LASH RISK AND INTEREST RATES[☆]

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October 25, 2024

Abstract

This paper studies a form of liquidity risk that we call *Liquidity After Solvency Hedging* or "LASH" risk. Financial institutions take LASH risk when they hedge against solvency risk, using strategies that lead to liquidity needs when the solvency of the institution improves. We focus on LASH risk relating to interest rate movements. Our framework implies that institutions with longer duration liabilities than assets—e.g. pension funds and insurers—take more LASH risk as interest rates fall, because solvency concerns rise in a low rate environment. Using UK regulatory data from 2019-22 on the universe of sterling repo and swap transactions, we measure, in real time and at the institution level, LASH risk for the non-bank sector. We find that at peak LASH risk, a 100bps increase in interest rates would have led to liquidity needs close to the cash holdings of the pension fund and insurance sector. Using a cross-sectional identification strategy, we find that low interest rates caused increases in LASH risk. We then find that the pre-crisis LASH risk of non-banks predicts their bond sales during the 2022 UK bond market crisis, contributing to the yield spike in the bond market.

Keywords: Liquidity, Monetary policy, Non-Bank Financial Intermediaries, Hedging

JEL Codes: E44, G10, G22, G23

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1 Introduction

Liquidity crises have become increasingly common in the non-bank financial sector. Recent examples include the pandemic-era liquidity crisis of Spring 2020, the 2022 commodity market turmoil following Russia's invasion of Ukraine, and the 2022 UK bond market crisis.[1] These liquidity crises are linked to the rising use of hedging instruments—such as swaps and repos—by pension funds, insurers, and alternative investment funds. This paper relates the crises to an understudied form of liquidity risk, related to hedging. We label this risk *Liquidity After Solvency Hedging* or "LASH" risk. Institutions take LASH risk when they hedge against losses, using strategies that lead to liquidity needs when the solvency of the institution improves. As such, LASH is distinct from other forms of liquidity risk, which typically materialize when solvency deteriorates.

As a preamble to the empirical contributions of the paper, we develop a simple framework to define LASH risk and differentiate it from other forms of liquidity risk. As an example, consider a fund such as a life insurer or pension fund, with long-duration liabilities and shorter-duration assets. A fall in interest rates lowers solvency, since the value of liabilities rises more than assets. The fund can hedge this solvency risk using an interest rate swap, whose value rises when rates fall. This hedging strategy creates liquidity needs when rates rise. As rates rise, the value of the swap falls, and the fund must pay liquid assets ("margin") to their counterparty equal to the fall in the swap's value (Biais, Heider and Hoerova, 2020). The margin requirement represents LASH risk, which materializes even if the solvency of the fund improves with rising rates.

We formalize LASH risk using a simple model of portfolio choice. There is a fund endowed with long duration liabilities, who faces duration risk from shocks to interest rates. The model has four empirically grounded ingredients. First, the fund faces costs from insolvency, which generates risk aversion and a desire for hedging. One literal interpretation of these costs is regulatory penalties from insolvency, but costs other than regulation may also matter. Second, the fund can hedge duration risk only by using linear interest rate derivatives requiring margin. The derivative is best interpreted as a swap, but we discuss how LASH risk applies to other hedging instruments such as repo. The fund cannot hold assets with long enough duration to hedge the liability. The third ingredient is that holding liquid assets is costly, since they command a liquidity premium. Fourth, the fund can hold

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[1] For work on the disruption in sovereign bond markets during the pandemic-era liquidity crisis, see e.g. Duffie (2022); He, Nagel and Song (2022) or Czech, Huang, Lou and Wang (2023). For the 2022 commodity market turmoil, see Avalos and Huang (2022); for the UK bond market crisis in the same year see Pinter (2023). The 1993 failure of the energy conglomerate Metallgesellschaft constitutes a previous example of LASH risk, see Culp and Miller (1994).

medium term assets, which have a higher return than the liquid assets, but incur a liquidity cost when they are sold. With these four ingredients, the fund optimally chooses its hedging strategy.

The model generates three predictions that will guide our empirical contributions. First, the optimal strategy partially hedges solvency risk from falling rates, at the cost of some liquidity risk from rising rates. After a shock that increases rates, the fund's solvency improves but the fund also needs liquidity to pay margin—which is LASH risk materializing. Second, incentives to take LASH risk are higher in a low interest rate environment. Since the fund is only partially hedged against interest rate risk, net worth is low when rates are low, meaning the fund is closer to insolvency. Funds can avoid insolvency by further hedging—at the cost of more LASH risk. Third, a large enough positive shock to rates leads to a "liquidity crisis". Funds exhaust their holding of short term and liquid assets, and require a costly sale of medium term assets to pay margin.

The simple framework clarifies that LASH risk is different from some other common forms of liquidity risk. LASH risk is associated neither with maturity transformation and callable claims (Diamond and Dybvig, 1983), nor with rollover risk (Calvo, 1988). Moreover, in our example, the fund is exposed to LASH risk precisely when their solvency improves due to rising rates. Therefore, LASH risk differs from the feedback between funding and market liquidity (Brunnermeier and Pedersen, 2009), which arises when solvency deteriorates. In the example, LASH risk applies to institutions with long duration liabilities and short duration assets, the opposite maturity structure of a typical bank.

We then make three empirical contributions that match the predictions of the model. First, we show that non-banks take on LASH risk in order to partially hedge solvency risk. We measure LASH risk for pound sterling interest rate contracts held by UK non-banks, and find that LASH risk is large. In this context, LASH risk measures the liquid assets an institution must pay as margin when interest rates change. For instance, suppose a pension fund holds an interest rate swap to hedge against falling rates. We measure the liquid assets the fund must pay to its counterparty when the value of the swap falls because rates have risen. We also discuss how to apply our methods to measuring LASH risk for other markets and hedging strategies, such as foreign exchange (FX) swaps. We apply the measure to regulatory data from the Bank of England on the universe of sterling repo transactions, the universe of pound sterling interest rate swap positions and the universe of UK government bond transactions. Our measure is available at the institution level and in real time, starting from 2019. We find that LASH risk is large: at the peak level of risk, a 100bps rise in interest rates would have generated liquidity needs close to the cash balances of the entire UK pension fund and insurance sector. During some crisis episodes, such as the 2022 UK bond market crisis that we will discuss shortly, rate rises have been significantly more than 100 bps. LASH risk concentrates in the pension fund sector. We also show that pension funds are partially, but not fully hedged against interest rate changes—since, as we show, their solvency increases when interest rates rise.

Our second empirical contribution is to argue that low interest rates cause LASH risk. To start, we find that in the aggregate time series, low interest rates associate with high LASH risk. LASH risk increases from 2019 through 2022 as interest rates fall; and then falls as interest rates rise. However, other factors could have caused these patterns. For instance, macroeconomic conditions could have affected both rates and LASH risk. Therefore, to identify the causal effect of interest rates on LASH risk, we pursue a cross-sectional identification strategy. We identify institutions that are particularly exposed to a decline in interest rates, as they hold relatively short-duration assets. These institutions experience a particularly large fall in solvency as interest rates fall. Our framework predicts these institutions should hedge more against interest rate risk to avoid costly insolvency, and in doing so raise LASH risk. Consistent with our framework, the exposed institutions raise their LASH risk as interest rates fall, relative to institutions with higher-duration assets.

Our third empirical contribution is to show and quantify that when rates rise sharply, the LASH risk caused by the previous decline in rates leads to liquidity crises. LASH risk is not itself the "root cause" of crises. Instead, LASH amplifies the root cause—a sudden, initial rise in rates. Due to margin calls, pension funds must sell bonds to raise liquid assets, which leads rates to rise by even more. We study the liquidity crisis in the UK pension fund sector in autumn 2022. That period was characterized by sharply rising interest rates, margin calls, and gilt sales by UK pension funds. We find that institutions with ex ante larger LASH risk sold substantially higher quantities of gilts during the crisis: a one standard deviation increase in pre-crisis LASH risk is associated with 15% higher daily sell volumes during the crisis. Gilt sales due to LASH risk exacerbated the crisis further. High LASH risk institutions significantly contributed to the yield spike in the gilt market: a one standard deviation increase in gilt sales due to LASH risk associates with a 4.1bps daily increase in gilt yields (or 66bps over the entire 16-day crisis period).

Consistent with our framework, the solvency of the pension fund sector *improved* during the liquidity crisis. Could pension funds have used their improving solvency to raise liquid assets and avert the crisis? Liquidity needs from LASH risk are hard to fulfil for four reasons. First, the improvement in solvency comes from a fall in the value of liabilities, which cannot be pledged as collateral. Second, the aggregate liquidity needs of the pension fund sector may have been too large or difficult to fulfil. Lenders in secured credit markets cannot easily expand capacity (see, e.g., Afonso, Cipriani, Copeland, Kovner, Spada and Martin, 2021), lending against collateral that is falling in value is challenging (see, e.g., Kuong, 2020), and dealers in bond markets may struggle to intermediate flows (see, e.g., Duffie, 2022). Repo rates spiked during the crisis in 2022 and funds that borrowed from repo lenders that were initially expensive, indicative of tighter capacity ex-ante, sold more ex-post. Moreover long duration bonds or bonds frequently used as repo collateral were particularly sensitive to LASH risk-induced selling pressure, meaning their value as collateral during this episode was low. Third, the institutions that took LASH risk were not sophisticated. Only about half of the institutions that were active in the swap market also participated in the repo market, which means that accessing liquidity was challenging. Funds with active repo relationship sold less in response to given liquidity needs. Fourth, many institutions outsourced their hedging by pooling together with other funds into specialized entities. The pooled structure slowed the transfer of liquidity to where it was scarce. We show that LASH risk had a particularly large impact on these pooled entities.

Given that LASH risk is different from other forms of liquidity risk, there are also different policy implications. With other forms of liquidity risk, policymakers worry about providing liquidity support during crises. For instance, Bagehot's Dictum states that policymakers should provide liquidity support during a crisis only at a penalty rate. The reason is that institutions often require liquidity support when their solvency deteriorates. Providing liquidity support ex post encourages solvency risk and moral hazard ex ante (Farhi and Tirole, 2012). LASH risk is different. Institutions increase LASH risk when they hedge against solvency risk. Therefore mitigating LASH risk ex post—for instance, by providing liquidity support during crises—may *reduce* solvency risk by encouraging hedging ex ante. Therefore, the policy trade-offs for preventing LASH risk are different from other liquidity crises. A full exploration is beyond the scope of the paper, but policymakers are actively debating these questions (e.g. Hauser, 2023a).

Related literature.

This paper relates to four literatures. First, we contribute to the literature on liquidity risk, which has traditionally centered on banks and liquidity risk stemming from maturity transformation or coordination failures (Diamond and Dybvig, 1983; Diamond and Rajan, 2001; Rochet and Vives, 2004; Morris and Shin, 2004). Closer to our work, Drechsler, Savov, Schnabl and Wang (2023) study how interest rates affect the trade off between liquidity and solvency in the context of the banking system. In their model, low rates reduce solvency, because the value of banks' deposit franchise falls. High rates create liquidity risk because the deposit franchise becomes a runnable asset. Our setting shares the feature that interest rates affect the tradeoff between liquidity and solvency. However, with LASH risk, the source of liquidity risk does not relate to the deposit franchise or to banks specifically. Instead, LASH risk applies to non-banks or, more generally, any institution that hedges solvency risks with strategies that raise liquidity risk.

Some research focuses on how deteriorating solvency raises liquidity risk via margin calls (e.g. Brunnermeier and Pedersen, 2009). LASH risk also operates via margin calls. However, LASH risk happens when solvency improves. As such, LASH risk is an instance of what is known to practitioners as"right-way risk": when a counterparty's solvency improves as its payment obligations increase (Canabarro and Duffie, 2003). The liquidity risk arising from falling solvency, as in Brunnermeier and Pedersen (2009), is an instance of "wrong way risk".[2]

Second, our paper relates to the vast literature linking interest rates and financial stability. Various papers document how lower interest rates raise risk taking (e.g. Adrian and Shin, 2010; Jiménez, Ongena, Peydró and Saurina, 2014) and lead to credit creation and subsequent financial instability (e.g. Grimm, Jordà, Schularick and Taylor, 2023). Other papers document the relationship between interest rates and risk taking 'reach for yield' behavior, in the context of insurers, pension funds, mutual funds, and banks (Becker and Ivashina, 2015; Domanski, Shin and Sushko, 2017; Martinez-Miera and Repullo, 2017; Lu, Pritsker, Zlate, Anadu and Bohn, 2023; Aramonte, Lee and Stebunovs, 2022) and the interaction with FX risk (Bertaut, Bruno and Shin, 2023).[3] We contribute to this literature by studying a specific mechanism: how low interest rates raise liquidity risk via hedging solvency risk with derivatives.

Third, we contribute to the literature studying pension funds and related non-bank institutions (see Scharfstein (2018) for an overview). Lucas and Zeldes (2009) and Lucas (2017) investigate how reforms to the discount rates applied to pension funds' liabilities affect the asset allocation of pension funds. Greenwood and Vayanos (2010), Greenwood and Vissing-Jorgensen (2018) and Jansen (2021) provide sharp evidence that pension funds' behavior affects interest rates and spills over to other sectors. Koijen and Yogo (2022) investigate how risk-based capital regulation affects the portfolio choice of life insurers. Foley-Fisher,

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[2] Precious previous literature has studied LASH risk in the specific context of the 1993 failure of the energy provider Metallgesellschaft (Culp and Miller, 1994; Culp and Miller, 1995; Mello and Parsons, 1995). Metallgesellschaft offered customers long term price guarantees for fuel and heating. These guarantees would lead to solvency risk if energy prices rose, which Metallgesellschaft hedged with derivatives. When the energy price ended up falling, the company's solvency improved but it faced margin calls leading to its failure. We argue that LASH risk is a broader phenomenon relative to this case study; we also measure LASH risk and trace out its causes and consequences with supervisory data.

[3] Adrian and Liang (2018) and Boyarchenko, Favara and Schularick (2022) provide comprehensive reviews.

Narajabad and Verani (2020) document self fulfilling runs within the life insurance industry. A closely related paper is Klingler and Sundaresan (2019), who show that under-funded pension funds have higher demand for hedging via swaps. We build upon their work by providing evidence of a link between interest rates and the demand for hedging, that operates via under-funding. Beyond their paper, we connect pension fund hedging to liquidity risk, which has various additional implications. A second related paper is Jansen, Klingler, Ranaldo and Duijm (2023), who study hedging with swaps in the Dutch pension fund sector exploring how regulation leads pension funds to use swaps, creating liquidity risk when interest rates rise. We complement the paper in various ways. Our paper points out that another cause of liquidity risk from hedging instruments is falling interest rates. We also connect pension funds' hedging strategies to a salient liquidity crisis, the 2022 UK bond market crisis. Most significantly, we emphasize how improving solvency accompanies the liquidity risk from these hedging strategies—which is crucial for regulation.

Fourth, we contribute to the large literature on liquidity crises. Brunnermeier (2009), Adrian, Kiff and Shin (2018), and Bernanke (2018) document mechanisms, causes, and effects of the liquidity crises during the Great Financial Crisis. Borio, Claessens, Schrimpf and Tarashev (2023) link liquidity crises to collateral use. Recent papers analyze the "Dash for Cash" liquidity crisis during the onset of the Covid-19 pandemic (Haddad, Moreira and Muir, 2021), including the role of mutual funds' and life insurers' liquidity transformation (Ma, Xiao and Zeng, 2022; Huang, Jiang, Liu and Liu, 2021; Foley-Fisher, Heinrich and Verani, 2023), and the role of holding dollar assets for UK investors (Czech, Huang, Lou and Wang, 2023; Cesa-Bianchi, Czech and Eguren-Martin, 2023). Pinter (2023) and Chen and Kemp (2023) dissect the market dynamics and policy response during the UK bond market crisis in autumn 2022. Pinter, Siriwardane and Walker (2024) provide a forensic account of how fire sales of safe assets, abetted by slow moving capital, was a key feature of the UK crisis. Our paper shows that solvency hedging is an important cause of certain liquidity crises, which implies distinct causes and policy implications.

Outline. The paper is organized as follows. Section 2 develops a simple framework, which predicts (i) funds partially hedge solvency risk by taking on LASH risk, (ii) incentives to take on LASH risk are greater in a low rate environment and (iii) a large enough positive shock to rates generates a liquidity crisis. Section 3 presents the context, data, and strategy to measure LASH risk. Section 4 shows that pension funds partially hedge solvency risk at the cost of taking on LASH risk. Section 5 shows that low rates cause higher LASH risk. Section 6 shows how LASH risk contributed to the UK bond market crisis in 2022. Section 7 concludes.

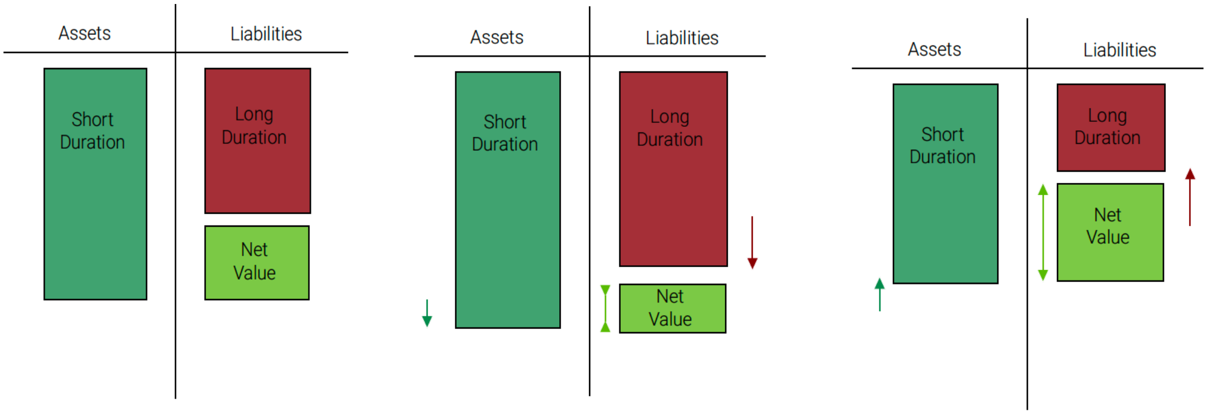
2 LASH Risk: A Simple Framework

As a preamble to the empirical contributions of the paper, this section uses a simple model to study LASH risk. The model generates three predictions that will structure our empirics, namely: (i) funds partially hedge solvency risk by taking on LASH risk, (ii) incentives to take on LASH risk are greater in a low rate environment and (iii) a large enough positive shock to rates generates a liquidity crisis.

2.1 LASH Risk Mechanics

We start with a discussion of the mechanics of LASH risk for interest rates. Consider a financial institution with a portfolio characterized by short-duration assets and long-duration liabilities, as in Figure 1. This institution could be a pension fund or insurer, with liabilities to its members that are far in the future. Due to the duration mismatch, a decline in interest rates increases the value of the institution's liabilities more than the value of its assets, and its solvency worsens (Figure 1.b). In contrast, when rates increase, the value of liabilities falls by more than assets, and its solvency improves (Figure 1.c).

Figure 1 Non-Bank Financial Intermediaries and Interest Rates



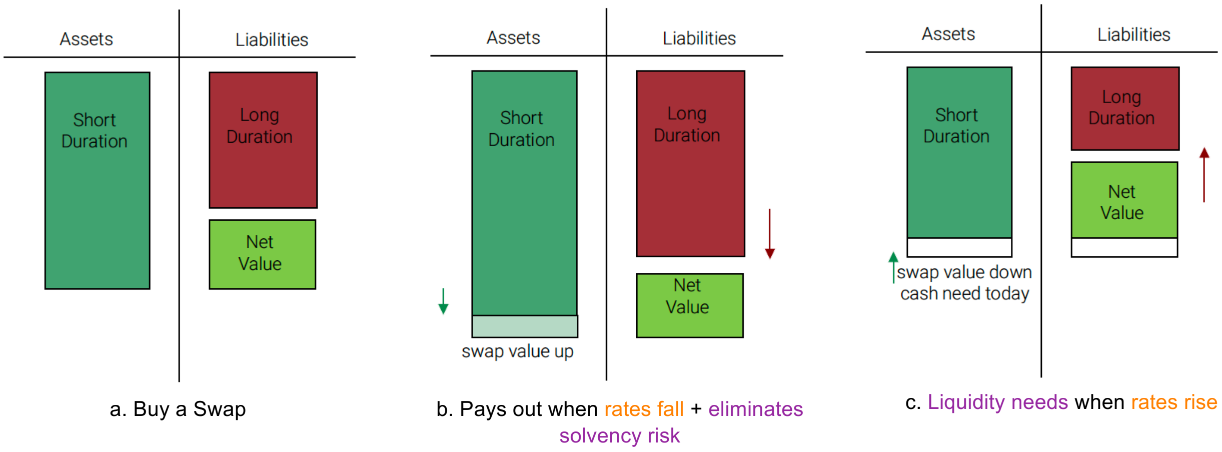
a. Fund with long-term liabilities vs assets

b. Rate fall worsens solvency

c. Rate rise improves solvency

How can the institution in Figure 1 hedge duration risk? One approach is to lengthen the duration of its assets. However, the liabilities of a pension fund can extend beyond three decades, exceeding the maturity of most outstanding bonds. The fund needs a hedge. One option is to write a derivative contract—such as an interest rate swap—where the institution pays a floating rate in exchange for a fixed rate (as in Figure 2). Such a contract will

Figure 2 Non-Bank Financial Institutions and Hedging



a. Buy a Swap

b. Pays out when rates fall + eliminates solvency risk

c. Liquidity needs when rates rise

appreciate in value when rates fall, partly offsetting the loss on the rest of the institution's portfolio (Figure 2.b).

Hedging with interest rate swaps generates liquidity risk as solvency improves—which we term LASH risk. When the value of a swap falls, the institution must pay liquid assets to its counterparty equal to the fall in value. This payment is "variation margin". When interest rates rise, the institution will become more solvent if some of its duration mismatch remains after hedging. However, rising interest rates lower the value of the swap. Consequently, the institution must make payments to its counterparty (Figure 2.c). Therefore the hedging strategy generates a need for liquidity even as solvency improves (Froot, Scharfstein and Stein, 1993). This coincidence of deteriorating liquidity and improving solvency, due to hedging with derivatives, is LASH risk materializing.

When LASH risk materializes, liquidity crises can happen. Financial institutions may have enough liquid assets to pay variation margins after small interest rate increases. However, large rate rises could require margin calls that are greater than liquid asset holdings. In this case, institutions may have to sell less liquid assets to raise cash and meet the margin call. If the asset sales include bonds, then interest rates may increase more—further improving solvency and deteriorating liquidity, and potentially leading to a liquidity crisis.

2.2 LASH Risk Formalization

We now formalize LASH risk with a model, which generates predictions that will structure our empirical work.

2.2.1 Environment

We consider the investment problem of a non-bank financial institution, or “fund”. Time runs from $t = 0, 1, \ldots, \infty$. The fund is endowed with a perpetual liability that requires paying a fixed l in every period. A natural example is a pension fund or an insurer, who typically have long duration commitments to their members.

The fund can invest in three assets. First, the fund holds a_t units of a one period bond, which pay total coupons a_t in period $t+1$. Second, there is a medium duration asset, which we model as a geometrically decaying multi-period bond with decay rate $\delta > 0$. The fund holds b_t units of the bond, with total coupons b_t in $t+1$. Absent sales or purchases of the bond, there is a passive equation of motion for bond holdings $b_{t+1} = \delta b_t$. Third, the fund holds s_t units of interest rate swaps. The fund cannot short bonds, meaning $a_t \geq 0$ and $b_t \geq 0$. However, the swap position, s_t, can be positive or negative.

Asset prices. All assets are priced by a deep pocketed marginal investor active in the bond and swap markets. The investor is competitive, risk neutral and discounts the future at rate R_t^{-1}. For our analytical results we assume $R_{t+1}^{-1} = R_t^{-1} + \varepsilon_{t+1}$, with ε_{t+1} a mean-zero, $t+1$ shock to the interest rate with bounded support $[\varepsilon^l, \varepsilon^h]$ such that the effective gross rate is positive and a density that converges to zero at the bounds, and $R_{t+j} = \bar{R} \;\; \forall j > 2$. For numerical results we simply assume the rate is i.i.d.[4] The marginal investor values the liquidity service from one period bond at rate η, which is non-pecuniary. The fund does not share this non-pecuniary value.

Let q_t^b denote the price of the geometric bond. The investor values the bond at $q_t^b = \mathbb{E}_t \left[\sum_{j=0} \delta^j \prod_{s=0}^{j} R_{t+s}^{-1}\right]$. Let q_t^l denote the price of a perpetuity paying one every period: $q_t^l = \mathbb{E}_t \left[\sum_{j=0}^{\infty} \prod_{s=0}^{j} R_{t+s}^{-1}\right]$. Last, the liquidity service implies that the price of the short term bond is given by $q_t^a = R_t^{-1}(1+\eta)$.

Interest rate swaps are priced fairly and have a fixed leg $\mathbb{E}_t\left[R_{t+1}^{-1}\right]$ and floating leg R_{t+1}^{-1}: buying the swap means paying fixed and receiving floating. Therefore the cashflows from the realised swap position are given by $s_t\left(R_{t+1}^{-1} - \mathbb{E}_t\left[R_{t+1}^{-1}\right]\right)$, i.e. the difference between the floating and the fixed leg.

We assume that the medium term bond is costly to sell. The fund bears a liquidation cost $q_t^b c$ per unit sold. The marginal investor does not discount the value of the bond due to the liquidation cost.

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[4] Our numerical findings go through if R_{t+1}^{-1} follows a generic positively auto-correlated time series process.

Fund Value. We can define the net asset value of the fund as $w_t = q_t^a a_t + q_t^b b_t - q_t^l l$, i.e. the value of the medium term and the one period bond holdings, deducting the value of the liability. Accounting for liquidity costs, w_t evolves according to

$$w_t = a_{t-1} + b_{t-1} - l + q_t^b \delta b_{t-1} + s_{t-1}\left(R_t^{-1} - \mathbb{E}_{t-1}\left[R_t^{-1}\right]\right) - cq_t^b \underbrace{\max\{0, \delta b_{t-1} - b_t\}}_{\text{sales of geometric bond}} - q_t^l l. \quad (1)$$

In this equation, net asset value is: coupons from the short- and medium-term bonds; deducting the payment associated with the long term liability; the continuation value of the previous holding of the medium-term bond; the value from the swap; the liquidation costs associated with possible sales of the medium term bonds; and deducting the value of the liability.

Liquidity needs. The fund must have sufficient resources in order to pay for any losses on the swap position. It is useful to define $m_t \equiv a_{t-1} + b_{t-1} + s_{t-1}\left(R_t^{-1} - \mathbb{E}_{t-1}\left[R_t^{-1}\right]\right) - l$ as liquid resources available to the fund—i.e. coupons from the short- and medium-term bond and swap payments, deducting the payment associated with the long-term liability. If liquid resources are positive, then the fund can fund can meeti any margin that may be required by the swap. If liquid resources are negative, then the fund must sell medium term bonds to pay margin. As such, liquid resources and medium term bonds must satisfy

$$(1-c)q_t^b \max\{0, \delta b_{t-1} - b_t\} \geq -\min[m_t, 0]. \quad (2)$$

This equation states that the value of sales of the medium term bond must exceed the liquidity needs of the fund, should these liquidity needs be negative.

Fund objective. There is a fund manager in charge of the fund until an exogenous period T.[5] The manager is risk neutral, does not enjoy limited liability and receives compensation in period T (that is negligible compared to the value of the fund) proportional to

$$\pi_T = (1 + \kappa \mathbf{1}(w_T < 0)) w_T. \quad (3)$$

Here, the marginal value to the fund manager of increasing wealth is linear. The marginal value is greater when the fund is in deficit, since $\kappa > 0$. The fund manager maximizes their

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[5] The fixed investment horizon is helpful for tractability. An infinite horizon model where the fund manager discounts the future and is compensated in proportion to the current value of the fund every period delivers similar results.

objective (3) by choosing holdings of swaps, short- and medium-term bonds $\{s_t, a_t, b_t\}_{t=0}^{T}$, subject to the law of motion for net worth (1), the liquidity constraint in (2), and the no-shorting requirement that $a_t, b_t \geq 0$.

2.2.2 Discussion of the Model's Main Ingredients

Our model contains four ingredients that are worth highlighting. These ingredients are empirically grounded and will combine to produce the distinctive predictions of the model.

1. **Costs from insolvency.** For the fund, reducing a deficit by \$1 is more beneficial than increasing a surplus by \$1, since $\kappa > 0$ in equation (3). This asymmetry could represent a regulatory penalty. In the UK, for example, pension funds are taxed if they have deficits.[6] These costs could also represent economic factors, such as companies' unwillingness to commit resources to their insolvent pension funds. Finally, the objective resembles "reference dependence" preferences, which may capture relevant behavioral factors (Lian, Ma and Wang, 2019).

2. **A duration mismatch with swaps for hedging.** The fund cannot hold assets with long enough duration to hedge the interest rate risk as the medium duration asset has lower duration than the perpetuity. Long duration assets such as 30 year government bonds are scarce, and command high premia (e.g. Greenwood and Vayanos, 2010). Funds with long dated liabilities, like pension funds or life insurers, end up with balance sheets with a negative duration gap as a result (e.g. Hartley et al., 2016). In our model, the fund can hedge interest rate risk using swaps. The assumption of a single period swap can be thought of as capturing variation margin: a long dated swap with strict margining rules is equivalent to repeatedly rolling over a short-dated swap (abstracting from the inconvenience and cost of restarting the contract including initial margin). Limiting the fund to using swaps means that the hedging strategy is linear.[7] The fund is unable to hedge using non-linear derivatives such as interest rate options. This has important implications for the model's outcomes which we will discuss and elaborate on below.

3. **Liquid assets command premia.** The fund can against liquidity needs by holding

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[6] Source: the UK Pension Protection Fund.

[7] As we will discuss in section 2.4, an equivalent linear hedge to the swap contract can be obtained by the fund borrowing short and to buy the medium duration asset. This would conflict with the no shorting condition, $a_t > 0$; however a borrowing based hedge could be added by assuming that the fund needs to meet its existing liquidity needs at the start of the period before it can borrow further to hedge. The economics of the problem would be very similar so we abstract from this aspect for simplicity.

short duration assets. However these assets command a liquidity premium, captured by η in the model and well known in the data (see e.g., Nagel (2016)). Self insurance is costly as a result. The liquidity premium can also be interpreted, in a reduced form way as the fee associated with arranging credit lines to manage liquidity risk. Although, in our empirical setting credit lines are not a key part of how funds manage liquidity risk in 6.3.

4. **Illiquidity of the medium term asset.** The medium term asset has a higher return than the short term asset, but incurs liquidation costs when sold. A reason for these costs could be the constrained balance sheets of broker-dealers (Duffie, 2022). We empirically investigate sources of illiquidity in Section 6.3.

The first ingredient generates risk aversion and motivates the hedging of interest rate risk. The second ingredient gives an incentive for the fund to choose to hedge interest rate risk by using swaps. The third and fourth ingredients ensure that liquidity needs generated by the hedge cannot be offset without a cost: either the fund must hold expensive liquid assets or run the risk of liquidating a portion of its long duration portfolio.

For the purpose of considering cases where the fund's problem is interesting and to derive analytical results we make a further assumption to restrict the problem. To do so, define the fund's net worth in period $t+1$ as a function of the shock ε_{t+1}, if the fund does not hedge and so sets $s_t, a_t = 0$: $y_{t+1}(\varepsilon_{t+1}) = b_t - l + q^b_{t+1}(\varepsilon_{t+1})\delta b_t - q^l_{t+1}(\varepsilon_{t+1})l$. We make the following assumption:

Assumption 1. *(i)* $y_{t+1}(0) > 0$ *and* $y_{t+1}(\varepsilon^h) < 0$*; (ii)* $c < \frac{y_{t+1}(0)}{y_{t+1}(0) - y_{t+1}(\varepsilon^h)}$*; and (iii)* $T = t+1$*.*

The first part of the assumption says, in the absence of hedging, the fund is solvent if rates are as expected but rates can fall sufficiently far for the fund to be in a deficit. This assumption is joint a restriction on downside interest rate risk and period-t fund value. This allows us to zoom in on the interesting case where the fund value is neither too great nor too small to render hedging irrelevant. The second and third assumptions are made for tractability. The second ensures that liquidations costs are never large enough at the optimal level of hedging to lead to a insolvency. The third allows us to ignore inter-temporal aspects by focusing on a single period investment horizon keeping the analysis tractable. We relax these assumptions in a numerical exploration of the model.

2.2.3 Predictions of the Model

The key feature of this model is that the fund uses swaps to trade off solvency risk from falling rates, versus liquidity risk from rising rates. Unless it hedges, the fund loses value from falling interest rates—since their liability has longer duration than their assets. As such, the fund should attempt to hedge interest rate risk. However, the fund will not do so perfectly as there is a cost to hedging in terms of illiquidity. With this logic in hand, we can derive the main three predictions of the model, which we collect in the following proposition.

Proposition 1. *If Assumption 1 holds, the liquidity premium on the short run asset, η, is sufficiently high, and the upside risk on the interest rate is sufficiently high, then*

(i) *The fund will partially hedge interest rate risk: the fund will choose an optimal level of hedging $s_t > 0$, but the risk of solvency will be positive, so that $Pr(w_T < 0) > 0$.*

(iii) *The optimal level of hedging, s_t, is decreasing in the interest rate, R_t.*

(ii) *There exists a threshold realization of the interest rate, such that if the rate exceeds that threshold the fund will sell medium duration assets.*

Proof. *See Appendix A.1*

To give some intuition behind this result, in Appendix A.1 we derive the first order necessary condition for the choice of swaps, s_t, associated with the fund manager's objective (3). The first order condition is:

$$\kappa Pr\left\{w_{t+1} < 0\right\}\left(\mathbb{E}_t\left[\varepsilon_{t+1}|w_{t+1} < 0\right]\right) = \frac{c}{1-c}Pr\left\{m_{t+1} < 0\right\}\left(\mathbb{E}_t\left[-\varepsilon_{t+1}|m_{t+1} < 0\right]\right). \quad (4)$$

The first order condition shows the fund's incentive to trade off solvency risk against liquidity risk. The term before the equality is the marginal value of holding swaps in states of the world in which the fund has a negative solvency, so that $w_{t+1} < 0$. These states occur after unexpected interest rate falls. Therefore this term represents the benefit of holding swaps, by reducing solvency risk from interest rate falls. The term after the equality is the marginal cost of holding swaps in states of the world where the fund has negative liquidity, so that $m_{t+1} < 0$. In these states, the cost of swaps is the liquidation of medium term assets. These states happen when interest rates rise, in which case the value of the swap falls and margin payments are required. In these states solvency may improve: the coincidence of better solvency and worse liquidity with rising rates is LASH risk materializing.

Given this, the intuition for the first part of the proposition is straightforward. As we have discussed, the fund holds swaps in order to trade off the solvency risk from falling interest rates, against the liquidity risk from rising rates. The proposition establishes that, under our assumptions, the fund does not resolve this trade off by hedging all of the solvency risk. Since the liquidity premium is large, the fund optimally holds relatively few short term assets. As such, the fund must hold medium term bonds, which must be liquidated when the value of the swap falls. Since liquidation is costly, the fund does not hold too many swaps, which prevents complete hedging.

The intuition for the second part of the proposition is as follows. By the first part, the fund only partially hedges against interest rate risk. Therefore falling interest rates lower the solvency of the fund. Since insolvency is costly and nearer, the fund has a greater incentive to hedge against interest rate risk. For given s_t lower rates raise the left hand side of equation (4) but have no impact on the right hand side. As such, low rates make the fund raise its swap holdings. The third part of the proposition is straightforward. A large increase in interest rates implies a large payment is required to cover the loss on the swap position. This necessarily exhausts the fund's holding of liquid assets. As such, the fund must sell medium term bonds to satisfy the margin call. Liquidation of the medium term asset is what we term a "liquidity crisis". However, the underlying solvency of the fund will have improved.

Inspecting equation (4) is also beneficial as it provides an insight into the importance of the restricting attention to linear hedging strategies. The fund does not care about the payoff from the swap contract in the states of the world where it is neither illiquid nor insolvent. Hence, essentially, what buying the swap does is endow the fund with a valuable put option that pays out when rates fall and the fund has a deficit. This is what the left hand side of equation (4) captures. The right hand side captures that buying the swap also forces the fund to sell a call option that is costly to cover in states where the fund is illiquid. Therefore, if the fund could trade the appropriate interest rate options it could buy the put without selling the call and so would be able to hedge solvency risk in a manner that avoids illiquidity. The justification for limiting our attention two linear strategies is twofold. First, implementing an option based strategy to avoid liquidity risk requires a high degree of financial sophistication and the ability to accurately forcest c (which is problematic if c rises sharply when there is correlated selling). Second, as we will shown, in practice, hedging strategies are linear. Interest rate options trade in a thin market, are expensive and thus have very limited trading volumes.

Last, our analytical results rely on some strong assumptions for tractability. In Appendix C, we explore a calibrated version of the model with $T > t + 1$ and interest rate risk at all horizons and show that with reasonable liquidity premia, swaps holdings and LASH risk indeed rises as interest rates fall.

In the coming sections, we will confront the three predictions of our model with data.

2.3 LASH vs. Other Liquidity Risk

Our framework shows that LASH risk is different from other forms of liquidity risk. Consider, for instance, liquidity risk from maturity transformation, and bank runs (Diamond and Dybvig, 1983). In this case, the risk of a bank run is linked to the bank's long term and illiquid assets versus their short term and callable liabilities to savers. However, LASH risk is independent from callable claims. In our example of a pension fund, liabilities are long term and assets are shorter term—the opposite pattern of the traditional bank.

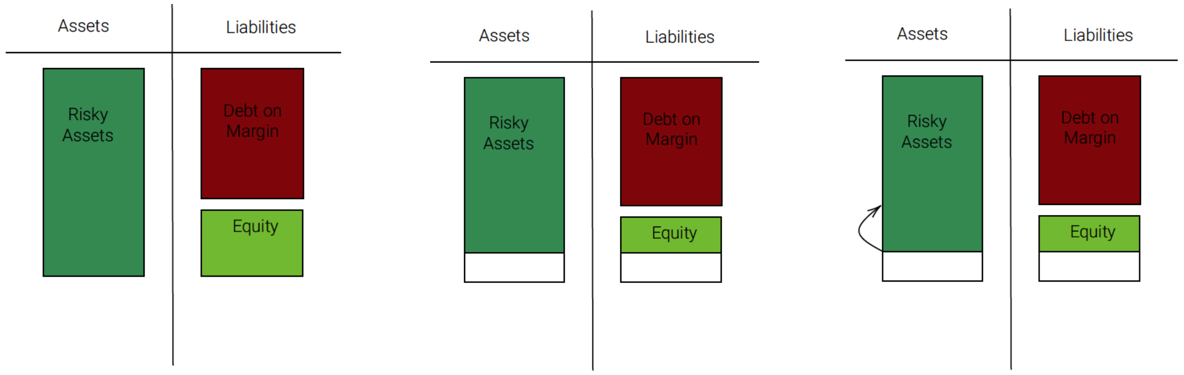
LASH risk is also different from the various kinds of liquidity risk from rolling over short term debt (e.g. Calvo, 1988; Cole and Kehoe, 2000; Morris and Shin, 2004; He and Xiong, 2012; Aguiar et al., 2022). In our example, LASH risk occurs even though liabilities are long term and debt is not rolled over.

Finally, LASH risk is different from the liquidity risk studied by Brunnermeier and Pedersen (2009) and others. The key feature of this form of liquidity risk is that liquidity and solvency deteriorate at the same time. With LASH risk, liquidity deteriorates as solvency improves. To elaborate, the Brunnermeier-Pedersen model studies how traders' funding liquidity—which relates to margin calls—depends on the liquidity of assets in the market. In their analysis, margin requirements mean that market liquidity and funding liquidity interact to create adverse liquidity spirals. To illustrate the mechanism and how it differs from LASH risk, consider a fund that has entered a leveraged bet on a risky asset with a margin requirement as in Figure 3. A shock leads to an initial loss, which wipes out some of the bank assets/net worth, which leads to margin calls (Figure 3.b). The financial institution sells assets to meet margin calls, which pushes down asset prices, further raising margin requirements and causing further asset sales (Figure 3.c), leading to a "liquidity spiral" (see Figure 2 of Brunnermeier, 2009). With LASH risk there is no fall in solvency; instead, solvency improves as liquidity risks materialize.

2.4 Beyond Swaps and Interest Rate Risk

We now discuss LASH risk more broadly, for other hedging instruments and other risks to solvency. The fund could also manage interest rate risk with other strategies. One strategy is to shorten the duration of fund's liabilities by borrowing using short term debt. In doing so,

Figure 3 Comparison: Funding Liquidity (Brunnermeier and Pedersen, 2009)



a. Fund has leveraged bet on a risky asset with a margin requirement.

b. Initial loss wipes out some of bank assets/net worth..
- Leads to margin calls...

c. Leads to margin calls...
- ... leading to asset sales...
- ... pushing down asset prices...
- ... raising margin requirements...
- ... add causing further asset sales.

the fund's interest rate exposure falls as the gap between the duration of liabilities and assets shrinks. Specifically, the institution could use a repurchase agreement (repo) to do short term borrowing, and use the proceeds to invest in longer-duration assets. This strategy replicates an interest rate swap. The institution pays a short term floating rate on its borrowing and receives the fixed, long term rate on the assets it purchases.

Repo borrowing requires variation margin to be paid when interest rates rise—meaning there is again LASH risk. With repo, the borrower sells a financial security to a lender, and agrees to buy it back at a later date and a higher price. The security serves as collateral and is typically a long term bond. If the collateral falls in value, the borrower must pay liquid assets equal to the fall in value. Again, interest rate rises, and falling bond prices, generate liquidity needs.

The pension fund can hedge the risk from long term liabilities and short term assets with another strategy. The pension fund can hold a stake in a second fund that has the opposite duration structure, that is, short term liabilities and long term assets. In the context of pensions, this latter fund is known as a Liability-Driven Investment (LDI) fund. The LDI fund exclusively borrows with repo to buy longer-duration assets (or engages in equivalent interest rate swap transactions). The payoff from holding the LDI fund replicates the payoff from employing the equity hedging strategy directly. Again, lower interest rates raise solvency risk, while higher interest rates raise liquidity risk.[8]

Interest rate risk is one important application of LASH risk, but the concept applies to other forms of solvency risk. An institution that wishes to hedge foreign exchange (FX) risk can use derivatives (e.g., swaps or forwards) to hedge movements in exchange rates. Again, this strategy reduces solvency risk but raises liquidity risk due to margin calls from the FX swaps. Large movements in exchange rates can then lead to liquidity needs when the solvency of the institutions improves. This pattern contributed to the Pandemic liquidity crisis of Spring 2020 (Czech et al., 2023).

3 Data and Measurement of LASH Risk

This section discusses our data sources, and how we use these data to measure LASH risk.

3.1 Data Sources and Coverage

To measure LASH risk for interest rates, we construct a database of: i) the universe of UK government bond (gilts) transactions; ii) the universe of gilt repo transactions; iii) the universe of sterling interest rate swap positions and iv) hand-collected UK pension fund balance sheet data. The consolidated sample period across all datasets is January 2019 to March 2023.

Bond market. To analyze trading in the UK bond market, we use the transaction-level MiFID II database maintained by the UK's Financial Conduct Authority (FCA). The MiFID II data provide detailed reports of all secondary-market trades of UK-regulated firms or branches of UK firms regulated in the European Economic Area (EEA). Given that all bond dealers are UK-domiciled and hence FCA-regulated institutions, our data cover virtually all transactions in the market. Each transaction report contains information on the transaction date and time, ISIN (a unique identifier for each bond issuance), execution price, transaction size, and the legal identities of the buyer and seller. We will focus on the UK government, or gilt, segment of the wider bond market, and from now on, our usage of the term bond refers to those issued by the UK government (unless stated otherwise).

Repo Market. The Bank of England's Sterling Money Market data (SMMD) is a transaction-level dataset covering the sterling unsecured and secured (gilt repo) money mar-

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[8] LDI funds benefit smaller pension funds, who lack the scale to manage hedging strategies in-house, and outsource to the LDI funds. Pension funds are subject cash calls to provide liquidity to LDI funds that they own in the case of margin calls that the LDI fund cannot itself cover.

kets. The data are obtained from dealers in the respective money markets and have been collected since 2016. The data cover 95% of activity in which a bank or dealer is a counterparty, but the data do not capture the small segment of non-bank to non-bank repo transactions. We are again able to identify the identity of the counterparties, the collateral ISINs associated with each transaction, the transaction size, and the execution price.

Interest Rate Swap Market. To analyse the interest rate swap positions, we use transaction-level data from two European Markets Infrastructure Reporting (EMIR) Trade Repositories, DTCC and LSEG Regulatory Reporting Limited (previously Unavista). We collect weekly positions on outstanding over-the-counter (OTC) GBP interest rate swap (IRS) and overnight index swap (OIS) trades where at least one of the counterparties is a UK entity. The IRS dataset contains trade-level information on the counterparties' identities, notional, currency, floating rate, the direction of trade, maturity and execution date. The cleaning process of the database is largely based on Khetan et al. (2023), with several additions that allow us to better exploit and understand the outstanding positions of these entities.

In addition, to compute discount rates and construct our measure of LASH risk, we use Bank of England data on OIS and yield curves as well as daily data on modified duration of gilts from Bloomberg.

Pension Fund Balance Sheets. We construct, to the best of our knowledge, the largest dataset with individual UK pension fund balance sheet details. We hand-collect data from annual reports and newsletters for 100 individual pension funds from 2017 to 2022, covering more than 40% of the UK pension sector by asset size in 2020.[9] Our database includes information on net investments, cash, bonds and derivative holdings. Tables E.1 and E.2 summarise the cross-section of actuarial assets and liabilities, and the evolution of funding ratios over time.

3.2 Measurement: Interest Rate LASH Risk for Non-Banks

We now describe how to measure LASH risk arising from interest rate hedging. Similar methods can be used to, for instance, measure LASH risk from FX hedging.

General Concept. We wish to measure how margin calls of a given contract change after a shock to interest rates. As such, given a shock to interest rates R_t, LASH risk for

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[9] There is limited fund-level data on UK pension fund balance sheets. The closest exercise in collecting UK data is done by Konradt (2023), covering 12 UK pension funds worth $300bn in asset size. In 2020, we observe 65 pension funds worth £1046.9bn in actuarial assets, out of the total average of £2497bn in the UK pension fund sector that year. Our sample also includes 20 out of the largest 25 pension funds by asset size.

hedging contract i is

$$LASH_{i,t} \approx \Lambda_i \times \frac{\partial NPV_{i,t}}{\partial R_t}, \tag{5}$$

where $NPV_{i,t}$ is the net present value of the hedging contract. For a swap, $NPV_{i,t}$ is the present value of the fixed leg minus the floating leg. For a repo contract, $NPV_{i,t}$ is the value of the repo collateral. One can interpret $\partial NPV_{i,t}/\partial R_t$, sometimes referred to as dollar duration or DV01, as the effect of a uniform shift in the yield curve on the present value of the hedging contract. Λ_i captures liquidity needs per unit of NPV change, which may differ based on the contract type. We assume Λ_i to be a constant ($\partial\Lambda_i/\partial R_t = 0$), which abstracts from changing margin requirements or an increase in repo haircuts.[10]

For a given institution j that holds $Q_{i,j,t}$ of a given hedging contract, its aggregate LASH risk is given by

$$LASH_{j,t} = \sum_i Q_{i,j,t}\mathrm{LASH}_{i,t}. \tag{6}$$

Letting $Q_{i,t}$ denote the aggregation of contracts across institutions, aggregate LASH risk is given by

$$LASH_t^A = \sum_i Q_{i,t}\mathrm{LASH}_{i,t} = \sum_j LASH_{j,t}^A, \tag{7}$$

where $LASH_{j,t}^A$ is LASH risk held by institution j.

Two observations are in order. First, contracts with long maturity have higher LASH risk, since their NPV is more sensitive to changes in interest rates. Second, LASH risk goes in both directions—firms can receive or pay liquidity, depending on the direction of their exposure and the price change of the underlying instrument. If the contract value $Q_{i,t}$ decreases (increases) from the perspective of institution j, then the firm is obliged to post (receive) margin. For example, pension funds are exposed to liquidity demands when yields rise, whereas their counterparties (mainly dealer banks) have to post margin when rates fall.

Therefore, given that each contract involves two counterparties, the aggregate measure of $LASH_t^A$ for all institutions in the economy is close to zero. When we document positive LASH risk for the non-bank financial sector, it implies that another set of agents in the economy has negative LASH risk exposures (in the UK, for example, that would be the banking sector—see, e.g., Khetan et al., 2023). We describe in detail how to apply our methodology to repos and interest rate swaps in Appendix D.

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[10] This assumption is innocuous in our context. For both swaps and repos on government debt, we have $\Lambda_i \approx 1$. Margin requirements on interest rate swaps are typically set so that the variation margin equals the change in the value the swap, while repo haircuts on government debt are fairly close to zero (for example, the average gilt repo haircuts for LDI funds were only around 25 basis points in the first three quarters of 2022, see Ivan, Lillis, Maqui and Salazar, 2024).

Mechanical versus Discretionary LASH risk. The term $\partial NPV_{i,t}/\partial R_t$ in equation (5) is not constant at the contract level, as it depends on the level of interest rates. By convexity, the value of a bond or the fixed leg of a long-dated swap both become more sensitive to interest rate movements when rates are lower. One goal of the paper is to explore how funds choose different levels of LASH risk as interest rates vary. Therefore we must account for this automatic link. We introduce a simple decomposition of LASH risk into two separate parts, which we label its "mechanical" and "discretionary" components. The mechanical component captures convexity. The discretionary factor captures how the financial institutions have shifted their allocation of hedging, $Q_{i,j,t}$, towards contracts i with ex-ante higher or lower LASH risk.

Consider the definition of aggregate LASH risk in equation (7). We can separate the discretionary and mechanical components via a standard first-order decomposition. In particular, we can write the change in aggregate LASH risk as

$$\overbrace{\Delta \sum_i Q_{it}\text{LASH}_{i,t}}^{\text{aggregate change}} = \underbrace{\sum_i Q_{i,t}\Delta\text{LASH}_{i,t}}_{\text{mechanical change}} + \overbrace{\sum_i \text{LASH}_{i,t-1}\Delta Q_{i,t}}^{\text{discretionary change}}. \tag{8}$$

The discretionary component measures how LASH risk changes as firms' holdings of different hedging contracts change, holding fixed the duration and convexity of the hedging contracts themselves. One can obtain a similar measure of discretionary LASH risk at the institution level.

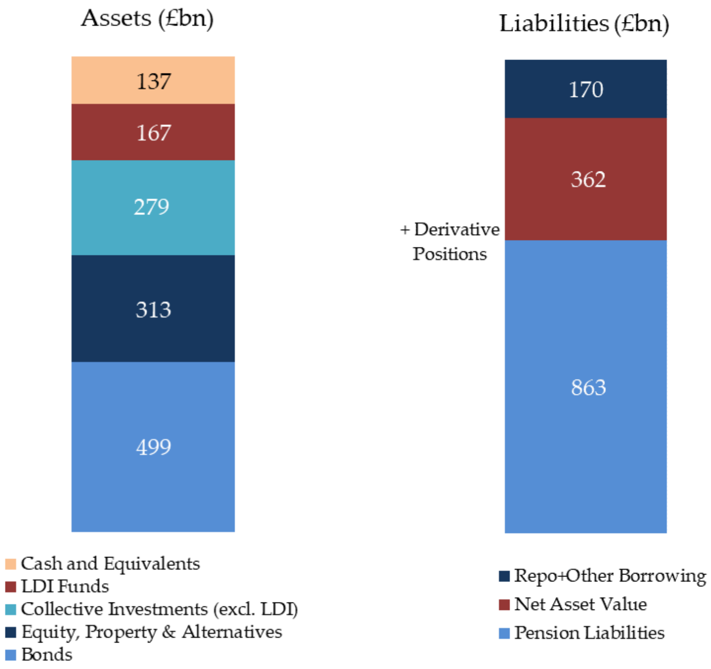
4 LASH Risk from Interest Rates: Descriptive Facts

This section shows that, consistent with our model, UK pension funds take on significant LASH risk. We provide additional descriptive facts about the nature of this LASH risk. Finally, we show that despite LASH risk, pension funds are partially hedged: meaning their net worth rises with interest rates.

4.1 Context: the Balance Sheet of Pension Funds

Before presenting the formal measurement of LASH risk, we stress two facts about UK pension funds that suggest LASH risk could be important. First, pension funds face interest rate risk from a gap between long duration liabilities and short term assets. Second, they

Figure 4 UK Pension Funds: Aggregate Balance Sheet



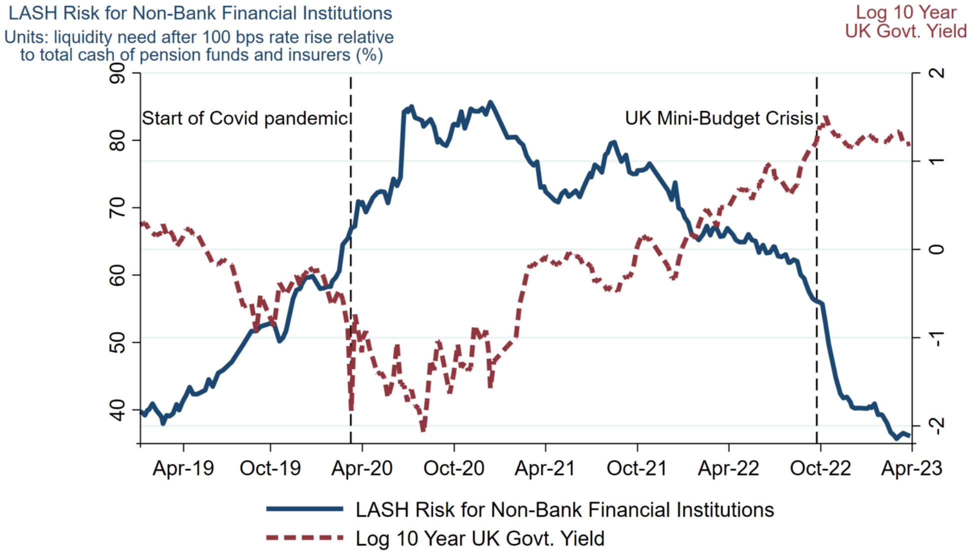
NOTE. Calculations based on 2023 ONS data and 2023 PPF 7800 data.

use various hedging strategies to counteract this interest rate risk.

Pension funds have a duration gap between short term assets and long term liabilities. Liabilities consist of long term payment promises to pensioners or contingent insurance beneficiaries. Funds typically invest in a mix of shorter duration assets. Other non-banks include, inter alia, life insurers, asset managers, hedge funds, and money market funds. Insurance companies traditionally have a smaller duration gap than pension funds. Hedge funds and money market funds have a very small duration gap, and are unlikely to use swaps to hedge interest rate risk. Figure 4 presents the aggregate balance sheet of UK defined benefit private pension funds at the end of 2022. Major assets include equity, property, alternatives and goverment bonds, which have shorter duration than pension liabilities. As such, pension funds are potentially exposed to interest rate risk, which may require hedging.

Pension funds hedge interest rate risk. Figure 4 also shows significant interest rate hedging. In the figure, liabilities include repo and assets include LDI funds. As we have discussed, both LDI and repo hedge interest rate risk. Swaps, the third hedging strategy, are held off-balance sheet. We plot notional interest rate swap positions of the pension fund sector in Appendix Figure E.1. In total, hedging against interest rate risk is large. Combining swaps, repo, and LDI investments, the UK pension fund sector has interest rate hedges with a notional value equivalent to more than 50% of pension liabilities, and three

Figure 5 LASH RISK: NON-BANK FINANCIAL INSTITUTIONS



NOTE. Estimated liquidity needs after 100bps rise in interest rates relative to total cash holdings of UK pension funds and insurers (%). The measure corresponds to $LASH^{A}_{i,t}$ as defined in equation 8 in Section 3.2. Cash is from the UK flow of funds and cash is defined as currency, deposits of any sort and holdings of money market fund liabilities.

times aggregate cash holdings of the pension fund sector.

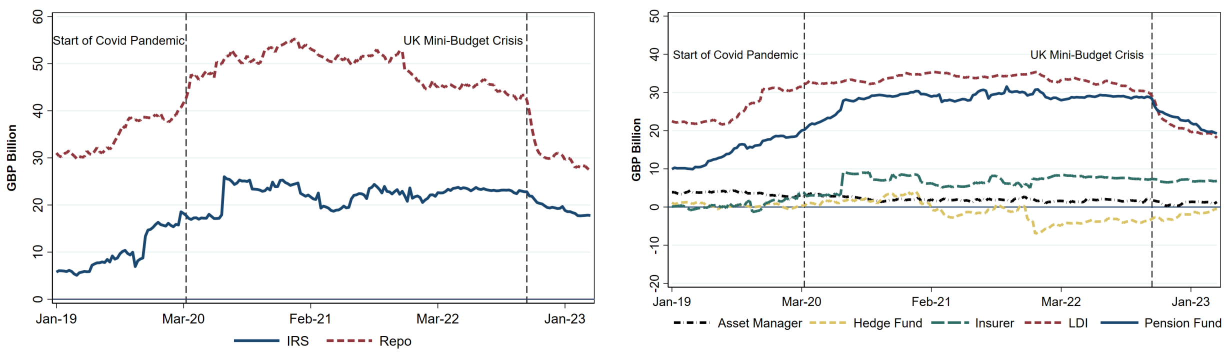
We provide additional institutional details about UK pension funds in Appendix B. Appendix Section C is a detailed discussion of swaps, repos, and margin calls in the UK.

4.2 LASH Risk—Descriptive Facts

This section presents four descriptive facts about our measure of LASH risk, for non-bank financial institutions and sterling rates. In brief, we find that (i) LASH risk is large and higher when interest rates are low; (ii) movements in LASH risk are largely due to discretionary rather than mechanical reasons; (iii) LASH risk is large for both interest rate swaps and repo contracts; and (iv) LASH risk is concentrated in the pension fund sector, including LDI funds.

i. LASH risk is large, and higher when interest rates are low. Figure 5 demonstrates this fact, by reporting aggregate LASH risk at weekly frequency, in the non-bank financial sector, from 2019 to 2023. To give a sense of scale, we normalize LASH risk by the cash holdings of UK pension funds and insurers (who, as we will see, are the main holders of LASH risk). The units indicate that at the peak, a 100bps increase in interest rates would have induced liquidity needs that would almost deplete the entire cash positions of both

Figure 6 LASH: Swaps vs. Repo and Sectoral Breakdown



(a) Swaps vs. Repo

(b) Sectoral Breakdown

NOTE. Panel (a) shows the evolution of the discretionary LASH risk by instrument in £bn for all non-banks, separately for swaps versus repo. Panel (b) shows the evolution of the discretionary LASH risk across different sectors in £bn, for pension funds, insurers, LDI funds, hedge funds and asset managers, respectively.

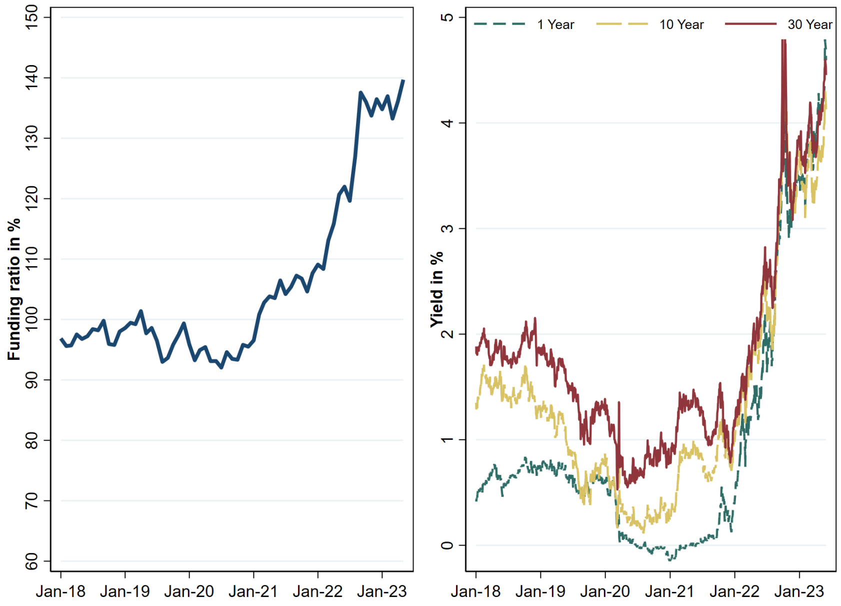
sectors—in other words, LASH risk is very large. For context, though a 100bps interest rate increase is large, it is also smaller than the trough-to-peak 130bps increase in the 30 year yield during the 2022 UK bond market crisis. Moreover, LASH risk moves inversely with interest rates. The figure plots the log of the 10 year UK government bond (gilt) yield. When long-dated government bond yields are relatively low, as in 2020, LASH risk is relatively high. Our framework predicts this pattern.

ii. Movements in LASH risk are largely due to discretionary rather than mechanical reasons. Recall that LASH risk can vary for two reasons: first, institutions might reallocate funds towards instruments with higher LASH risk; and second, the LASH risk of individual contracts mechanically rises as interest rates fall due to convexity. Appendix Figure E.2 demonstrates that discretionary effects dominate—the total LASH risk is shown in blue, and the discretionary component in red. The two series co-move closely. Therefore, movements in LASH risk over time primarily reflect how institutions reallocate funding and hedging towards instruments with greater LASH risk.

The third and fourth facts describe where LASH risk concentrates.

iii. LASH risk is large for both interest rate swaps and repo contracts. These are the two primary hedging strategies that we consider, both prevalent throughout the non-bank financial system. In practice, both strategies generate significant LASH risk. Figure 6a reports this result. In the figure, the blue line captures LASH risk for repo contracts, whereas the red line is LASH risk for swaps. Both swap and repo exposures are large, and the LASH risk from repo tends to be £20-30bn higher than the LASH risk from swaps.

Figure 7 Pension Funds' Funding Ratios and Bond Yields



NOTE. The left panel shows the aggregate funding ratio (defined as total market value of assets divided by total market value of liabilities) of UK pension funds in %. Source: Pension Protection Fund 7800 Data. The right panel displays the yields of UK government bonds (gilts) at different maturities in %.

iv. LASH risk is concentrated in the pension fund sector. Figure 6b displays this result. In the figure, we disaggregate LASH risk across five sectors, namely regular pension funds, LDI funds, insurers, funds, and hedge funds. Broadly defined, LDI funds belong to the pension fund sector. Considering LDI funds and regular pension funds jointly, it is apparent that the broad pension fund sector is the primary holder of LASH risk for interest rates.

4.3 Partial Hedging of Interest Rate Risk

Our framework predicts that pension funds partially hedge interest rate risk by taking on LASH risk. We have established the presence of LASH risk. We now show that there is partial hedging—as rates rise, pension fund solvency improves.

The solvency of a pension fund is typically measured via its funding ratio, which is defined as the fraction of the market value of its assets to the market value of its discounted value of liabilities, discounted at the UK government bond yield. Figure 7 shows that the aggregate funding ratio rose from around 90% in 2020 to almost 140% at the end of 2022. Over this period, interest rates rose. As such, despite hedging against some interest rate risk, pension funds are not fully hedged.

5 Low Interest Rates and High LASH Risk

Our descriptive evidence shows a striking pattern: in aggregate, LASH risk is high when interest rates are low. This pattern matches our conceptual framework, which predicts that a decline in rates lowers solvency loss for pension funds, which raises hedging demand and LASH risk. This section tests and confirms that low interest rates cause an increase in LASH risk using a cross-sectional identification strategy.

To make our claim, we exploit the cross-sectional variation from our regulatory data. Our identification strategy analyzes how the assets held at the beginning of the sample influence solvency afterwards. Specifically, institutions that hold relatively high duration assets will experience lower capital losses as interest rates fall, relative to institutions holding lower duration assets. Therefore, as interest rates fall, solvency should deteriorate more for institutions holding low duration assets.

Since low duration institutions face greater solvency risk following a decrease in interest rates, they require more hedging. As such, our simple framework predicts that low duration institutions should disproportionately increase LASH risk after interest rate falls. Appealingly, the cross-sectional variation captures the same mechanism that we conjecture should operate at the aggregate level. That is, LASH risk increases because falling interest rates reduce solvency.

Technically, it is *net* duration that matters for solvency, rather than our measure of *gross* asset duration. However, asset duration will be a proxy for net duration, unless within each institution asset duration is perfectly negatively correlated with liability duration. The supervisory data does not record pension funds' net duration. However we can study the relation between asset duration and net duration in a subsample of institutions in our hand-collected balance sheet data. As we describe in Appendix F.1, we measure net duration using the sensitivity of a pension fund's individual funding ratio to changes in interest rates. Appendix Figure E.3 shows the comparison between net duration and asset duration. The figure confirms that there is a negative correlation between the two, i.e. institutions with low asset duration have net worth that is more sensitive to rate changes.

To implement our cross-sectional strategy, we estimate the following quarterly panel regression:

$$\Delta LASH_{j,t}^{Disc.} = \alpha_t + \beta_1 \Delta Yield_t^{10Y} + \beta_2 \Delta Yield_t^{10Y} \times (\sum_i^I \omega_{j,i,t=0} \times AD_{i,t}) + \varepsilon_{j,t}, \qquad (9)$$

where $\Delta LASH_{j,t}^{Disc.}$ measures the quarterly change in the discretionary LASH risk of institution j at the end of quarter t. $\sum_i^I \omega_{j,i,t=0} \times AD_{i,t}$ is the weighted modified duration of institution j's assets, calculated from the institution-specific weights at the beginning of the sample for each gilt (as proxied by institution j's repo collateral portfolio) and multiplying these with the quarterly change in a given gilt's duration. $\Delta Yield_t^{10Y}$ is the quarterly change in the ten-year gilt yield. To facilitate the interpretation of the coefficients, the dependent variable is transformed using the Inverse Hyperbolic Sine method. Therefore, the regression coefficients measure the percent change in LASH risk, even if LASH risk is negative (see, e.g., Czech et al. 2023). The yields are denoted in percentage points, and the weighted duration variable is standardized. We cluster standard errors at the quarterly level and include time fixed effects α_t to control for all time-varying macroeconomic trends.

Our framework predicts that β_2 is positive. That is, as interest rates fall, institutions with high duration assets take on less LASH risk. These institutions have lower falls in solvency as rates fall, and less of a need for more hedging. Our framework also predicts that β_1 is negative. Overall, as rates fall and solvency declines, LASH risk rises.

The identification assumption is that institutions with an initial short asset duration would not have altered their hedging behavior in response to interest rate movements for reasons other than how rate movements affect solvency. To probe this identification assumption, in various specifications, we also include institution, institution times yield level (ten-year gilt yields) and institution times yield slope (ten-year minus two-year gilt yields) fixed effects. These fixed effects absorb, for instance, fixed differences in how different funds respond to interest rate changes—which could reflect differences in fund manager style.

Table 1 presents the results. We find that the effect is statistically and economically significant and, as predicted, β_1 is negative and β_2 is positive. Column (1) shows that a 100bps quarterly decrease in the gilt yield index is associated with a 133% increase in the discretionary LASH Risk of institution j. Importantly, the coefficient of the interaction term reveals that this effect is reduced to a 44% increase (=-1.33+0.89) when the initial asset duration of institution j increases by one standard deviation. Therefore, when yields decrease, the LASH risk of low-duration institutions increases more compared to the one their high-duration counterparts.The estimate of β_2 is similar in columns (2)-(4), as we progressively add time and institution times yield curve fixed effects.

Overall, falling interest rates lead to significantly greater LASH risk taken by low duration institutions, consistent with our framework. Our cross-sectional identification strategy suggests that low interest rates associate with high LASH risk—using a different source of variation from the descriptive time series patterns of the previous section.

Table 1 RATES AND INSTITUTION-LEVEL LASH RISK

	(1)	(2)	(3)	(4)
		$\Delta LASH^{Discretionary}$		
$\Delta Yield^{10Y}$	-1.33***			
	(0.37)			
$\Delta Yield^{10Y}$ × Duration	0.89**	0.95**	1.08***	0.87**
	(0.37)	(0.35)	(0.35)	(0.37)
Observations	4657	4657	4657	4657
R squared	0.016	0.024	0.040	0.063
Time FE	no	yes	yes	yes
Institution FE	yes	yes	yes	yes
Institution-Yield Level FE	no	no	yes	no
Institution-Yield Slope FE	no	no	no	yes

NOTE. For each non-bank financial institution, we calculate the quarterly change in the discretionary LASH Risk. The independent variable is the quarterly change in the 10-year gilt yield, interacted with the modified duration of institution j's assets at the beginning of the sample. The dependent variable is transformed using the Inverse Hyperbolic Sine method; the yield change is denoted in percentage points; and the modified duration is standardized. Clustered standard errors on the quarter level are reported in parentheses. We include institution, quarter, institution-yield level (ten-year gilt yields) and institution-yield slope (ten-year minus two-year gilt yields) fixed effects. fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

6 Consequences: LASH Risk and Liquidity Crises

We now show that, consistent with our conceptual framework, when LASH risk materializes, it can lead to liquidity crises. These crises materialize even if solvency rises at the same time. We focus on the 2022 UK bond market crisis. LASH risk was not itself the "root cause" of this crisis. Instead, the root cause was a sudden, initial rise in rates—which was then amplified by LASH risk.

6.1 Background: 2022 UK Bond Market Crisis

Background. On 23 September 2022, the Chancellor at the time, Kwasi Kwarteng, presented a "Mini-Budget" proposal to the UK Parliament. The abrupt change in the fiscal stance initiated a sharp, initial rise in interest rates.

Over the subsequent days, there was a combination of (i) margin calls (ii) sales of bonds in order to raise liquidity and (iii) further rises in interest rates and then further margin calls. These three factors characterized the liquidity crisis. Financial institutions faced margin calls on their term repo and IRS positions and sold assets to raise cash. As institutions sold assets, interest rates increased by even more, and margin calls increased further. From trough-to-peak during the crisis, 30-year gilt yields rose by 130bps in a matter of days. In total, pension and LDI funds sold nearly £30bn in the period between September 23 and October 14 (see Figure E.13 and Pinter, 2023).

As the liquidity crisis intensified, the Bank of England intervened to safeguard financial stability. The Bank's temporary and targeted backstop, announced on September 28 and scheduled to end on October 14, proved effective in ending the fire-sale dynamic and helped pension funds to adjust their portfolios by reducing their repo leverage (Hauser, 2023b; Alexander et al., 2023). Importantly, liquidity needs arose even as the solvency of the pension fund sector improved—the present value of pension liabilities decreased with higher discount rates (i.e. gilt yields, see Figure 7).

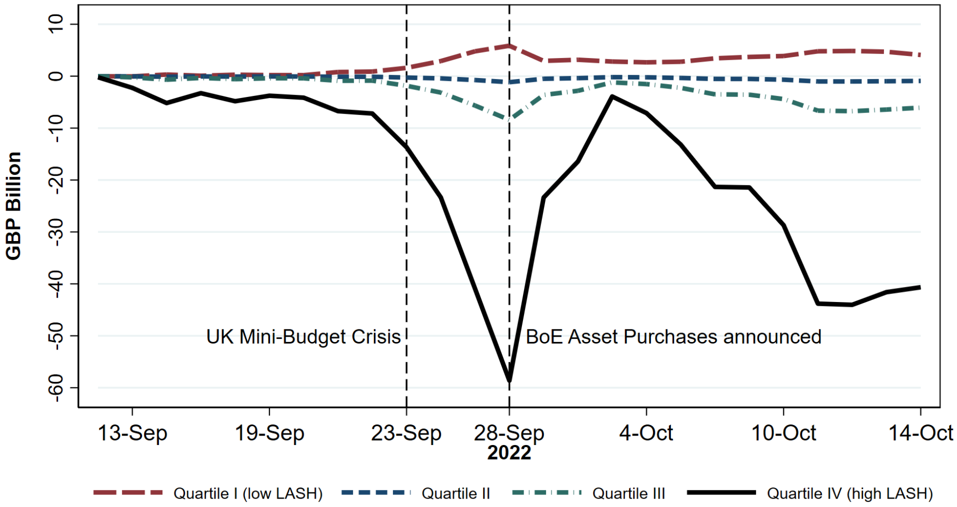
6.2 LASH Risk and the Liquidity Crisis

We argue that LASH risk amplified the initial rise in interest rates from the "mini-budget". As such, LASH risk led to the liquidity crisis—the combination of margin calls, gilt sales, and further rises in rates. We proceed in three steps. First, we show that as expected, institutions with greater ex ante LASH risk indeed faced more margin calls. Second, we show that institutions with greater LASH risk sold bonds. Third, we show that the sales induced by LASH risk seem to have caused higher interest rates.

To analyze the link between LASH risk, the liquidity demands and bond trading during the 2022 UK bond market crisis, we first divide the non-banks in our sample into four groups based on their pre-crisis LASH exposures, calculated from both their repo and IRS positions. We measure the institution-specific LASH exposure on August 30, hence well in advance of the onset of the crisis and before the election of Liz Truss as Prime Minister. Our main sample includes all non-banks, and not just pension and LDI funds. The choice of sample is natural—other non-banks such as hedge funds are not endowed with long term liabilities, and do not have incentives to take on LASH risk. These institutions serve as natural "control" observations. However as we discuss, results in this section are robust to studying only pension and LDI funds.

LASH risk and margin calls. First, we show greater margin calls for institutions with greater ex ante LASH risk. Figure 8 shows that institutions with greater ex ante LASH risk, indeed had greater liquidity needs via their margin calls. We plot cumulative change in repo collateral posted by institutions—a proxy for margin calls in the repo market—separately

Figure 8 Change in Repo Margin Calls by Pre-crisis LASH Exposure



NOTE. Aggregate estimated changes in the value of repo collateral posted by UK non-bank financial institutions in £bn during the 2022 UK bond market crisis, by quartile of their pre-crisis LASH risk: Quartile I captures the non-banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures. Source: Sterling Money Market data collection.

for each quartile of the ex ante LASH risk distribution.[11] The plot goes from the start to the end of the liquidity crisis. Funds with the most LASH risk faced the greatest margin calls. This group mainly consists of pension and LDI funds, who had large net exposures in term repo borrowing (see Figures E.5 & E.7). Consistent with this notion, we observe a similar pattern when plotting the same graph for pension funds only, as shown in Appendix Figure E.12. As such, funds who were hedging solvency to a greater extent, indeed had greater liquidity needs as rates rose. The figure also shows that in aggregate repo margin calls increased—though disproportionately driven by high LASH risk funds.

LASH risk and bond sales. Second, we show that funds with more ex ante LASH risk sold more bonds—in order to raise liquid assets and meet their margin calls. Figure 9 shows that the institutions with the highest pre-crisis LASH exposure (Quartile IV) sold many more government bonds compared to the other three groups. In total, this group sold more than £25bn during the crisis, while the group with the lowest LASH risk (Quartile I) was, in fact, buying around £15bn worth of bonds. Before the crisis, the net volumes are very similar for all four groups. We again observe a similar pattern when plotting the same graph for pension and LDI funds only: as shown in Figure E.11 of the Appendix, the net

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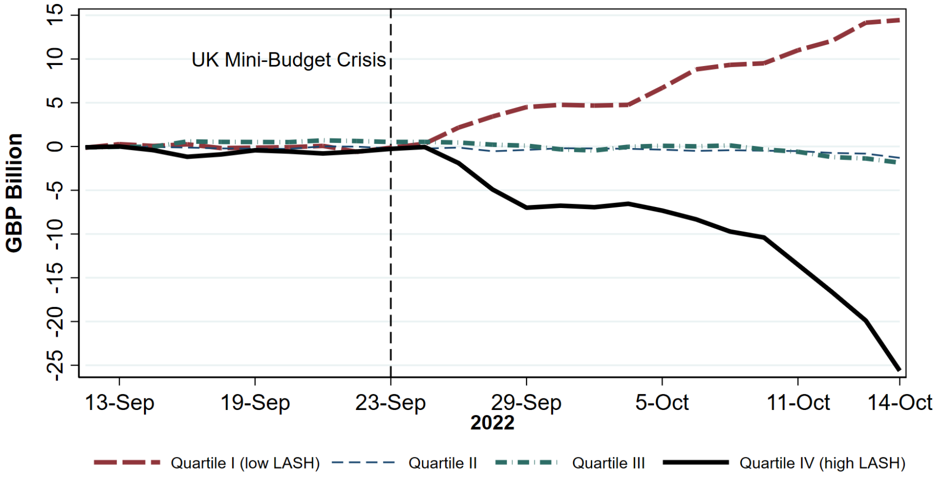
[11] This proxy for repo margin calls is exactly correct if haircuts do not change and there are no bilateral agreements to avert the margin call.

sales of the pension fund sector were concentrated in the group of funds with the largest pre-crisis LASH exposures (Quartile IV). Again, we do not observe any differential pre-crisis trends.

Figure 9 Cumulative Gilt Trading by Pre-crisis LASH Exposure



NOTE. Total net bond trading volumes of UK non-banks, by quartile of their pre-crisis LASH risk: Quartile I captures the banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures.

To test the link between LASH risk and gilt selling pressures more formally, we use the following regression specification:

$$Vol_{j,t} = \alpha + \alpha_{s,t} + \beta_1 LASH_{j,t=0} + \varepsilon_{j,t}, \tag{10}$$

where $Vol_{j,t}$ measures the net trading volume of institution j at time t, including all non-banks in our sample. We define the crisis period as the sixteen trading days between September 23 and October 14 (see Pinter, 2023). We calculate a "combined" LASH measure, which captures the LASH risk from both repo and IRS exposures, but we also run separate regressions for these two individual LASH risk components. The LASH variable is standardized to facilitate the interpretation of the coefficients. Furthermore, we also run separate regressions for institutions' sell volumes, which capture whether institution j was a net seller on a given day. Again, net and sell volumes are transformed using the inverse hyperbolic sine transformation to give the regression coefficient β_1 an approximate percent change interpretation even if volumes are negative. We include sector-day fixed effects and use standard errors clustered on the day and sector level.

Table 2 LASH Risk and Gilt Trading Volumes

	(1)	(2)	(3)	(4)
	Net Volume		Sell Volume	
LASH combined	-0.21***		0.15***	
	(0.04)		(0.02)	
LASH Repo		-0.16***		0.12***
		(0.04)		(0.02)
LASH IRS		-0.13*		0.08***
		(0.05)		(0.02)
Observations	8875	8875	8875	8875
R squared	0.035	0.035	0.046	0.046
Sector-Day FE	yes	yes	yes	yes

Note. For each non-bank financial institution, as defined in equation 7 in Section 3.2, "LASH" is measured as the potential liquidity needs following a 100bps shift in gilt yields, either for repo and IRS exposures combined, or separately for both instruments. The dependent variable is the institution's daily gilt net trading volume on day t in Columns (1) and (2), and the institution's sell volumes on day t in Columns (3) and (4). The dependent variables are transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Double-clustered standard errors on the day and sector level are reported in parentheses. We include sector-day fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

The results are shown in Table 2. Consistent with Figure 9, we find that institutions with larger pre-crisis LASH exposures sold substantially higher quantities of gilts during the UK bond market crisis: a one standard deviation increase in pre-crisis LASH risk is associated with 15% higher daily sell volumes during the crisis period (Column 3). Importantly, this effect is robust to the inclusion of sector-day fixed effects, hence not driven by time-varying sector characteristics. Furthermore, the effect is economically and statistically more significant for the LASH risk from repo exposures, consistent with the larger magnitude of overall LASH risk in the repo market. As a robustness check, we also conduct our analysis exclusively for the pension and LDI fund sector in Table F.1 of the Appendix. Consistent with our baseline results, a one standard deviation increase in LASH risk is associated with a 10% increase in pension fund daily sell volumes.

LASH risk and rising rates. The third factor characterizing the liquidity crisis was a continued rise in rates after the initial shock of the mini budget. We show that LASH risk contributed to the subsequent rise in rates. To isolate the impact of LASH risk on non-bank trading and, in turn, on yield movements, we follow Czech et al. (2023) and construct a measure of *LASH-induced trading (LASH-IT)*. Specifically, we calculate each institution's LASH-induced trading in bond b assuming that each institution proportionally scales up or down its holdings in response to liquidity demands. Due to the lack of complete information on bond holdings of individual institutions, we approximate the weight of bond b in institution j's portfolio, $w_{j,b}$, by measuring the weight of the given bond in institution's j pre-crisis repo collateral portfolio. LASH-induced trading (LASH-IT) in bond b on day t is then defined as:

$$LASH\text{-}IT_b = \frac{\Sigma_j LASH_{j,t=0} \times w_{j,b,t=0}}{Amount\ Outstanding_{b,t=0}} \tag{11}$$

where $LASH_{j,t=0}$ is the estimated pre-crisis LASH exposure of institution j, and $w_{j,b}$ is the weight of bond b in institution's j pre-crisis repo collateral portfolio, and *Amount Outstanding*$_{b,t=0}$ is the bond's amount outstanding before the crisis. We then employ the following regression specification to measure the impact of LASH-induced trading on gilt yields during the crisis:

$$\Delta Yield_{b,t} = \alpha + \alpha_{m,t} + \alpha_{g,t} + \beta_1 \times LASH\text{-}IT_b + \varepsilon_{b,t} \tag{12}$$

where $\Delta Yield_{b,t}$ is the daily change in yields. Again, we define the crisis period as the sixteen trading days between September 23 to October 14. We also include maturity bucket-day fixed effects ($\alpha_{m,t}$) as well as type gilt-day fixed effects ($\alpha_{g,t}$), which control for differential effects for nominal and index-linked gilts. Standard errors are clustered on the bond level.

Table 3 presents the results. The effect is statistically and economically highly significant. In the most conservative specification with maturity bucket-day and type gilt-day fixed effects (Column 4), a one standard deviation increase in LASH-IT is associated with a 4.1bps daily increase in gilt yields.

6.3 Sources of Illiquidity

Over the liquidity crisis, pension fund solvency improved (see Figure 7). What prevented pension funds from using their improving solvency to raise liquid funds and avert the crisis? This section presents some reasons why pension funds were illiquid despite better solvency.

First, securing liquidity against a "paper" decline in the value of pension funds' liabilities is hard. Moreover, as Appendix Figure E.3 makes clear, at the fund level there is substantial dispersion in the net duration of pension funds, hence creditors are unable to easily verify a genuine rise in solvency at the fund level. Accordingly, pension funds do not seem to borrow unsecured via credit lines. Stress test data from year-end 2021, i.e. the last period before the crisis, reveals no UK pension funds with available credit commitments from the listed exposures of major UK banks (UK banks do provide credit to funds in other jurisdictions,

Table 3 IMPACT OF LASH-IT ON GILT YIELDS

	(1)	(2)	(3)	(4)
	$\Delta Yield_{b,t}$			
LASH-IT	9.29***	9.72***	3.21**	4.13**
	(0.91)	(1.06)	(1.49)	(1.60)
Observations	1253	1253	1253	1253
R squared	0.261	0.321	0.616	0.649
Day FE	yes	-	-	-
Day × Type Gilt FE	no	no	yes	yes
Day × Maturity Bucket FE	no	yes	no	yes

NOTE. As the dependent variable, we measure the daily change in yields for each bond. The independent variable is the bond's LASH-induced trading (”LASH-IT”) in bond b on day t as defined in equation 11. The dependent variable is transformed using the Inverse Hyperbolic Sine method. The independent variable is standardized. Standard errors clustered on the bond level are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant and fixed effects not reported.

however). Instead, when they borrow, most UK pension funds rely on credit secured against assets via the repo market. Alternatively, they can meet liquidity needs by selling assets.

Second, LASH-risk is linked to aggregate interest risk rather than idiosyncratic shocks to a specific fund. The increase in aggregate demand for liquidity may have exhausted supply. In particular, there may be limits on the bond and repo markets to provide the necessary liquidity. The left panel in Figure E.16 makes this point by showing the evolution of overnight repo spreads during the crisis. The sharp spike of more than 30bps is indicative of such constraints.

Third, many of the funds in question were relatively unsophisticated in managing their liquidity needs. As the right panel in Figure E.16 shows, only around half of the institutions that are active in the swap market also engage in repo borrowing. Even if a fund had adequate assets to obtain financing, arranging secured credit at short notice, in a market in which the fund had previously not participated, will also likely present challenges as dealer-client relations tend to be relatively sticky in the repo market: as Appendix Figure E.14 shows, trades between a newly formed dealer-client pair only account for around 4% of all repo trades.

We present evidence for other mechanisms using our microdata. First, we consider whether “pooled” LDI funds face particular problems when trying to obtain liquidity. Second, we analyze whether frictions to entering and trading in the repo market prevent non-banks from obtaining funding through repo. Third, one potential explanation for the difficulties in obtaining financing is that it is difficult to borrow against an asset whose value is falling quickly, hence we investigate which types of bonds were particularly exposed to selling pressures during the crisis.

Pooled versus segregated funds An important feature of the UK bond market crisis was the pronounced selling by "pooled" LDI funds, in which multiple (often smaller) pension funds invest together—in contrast to segregated arrangements, where the assets of a single pension scheme are invested in a separate account.[12] The speed and scale of the moves in yields following the Mini-Budget announcement outpaced the ability of pooled funds' smaller clients—who typically rebalance their positions only on a weekly or monthly frequency—to provide new funds (Breeden, 2022). As a result, pooled funds became forced sellers and liquidated relatively large quantities of gilts (see Figure E.10 in the Appendix). To test this more formally, we use the following specification:

$$Sell\ Vol_{j,t} = \alpha + \alpha_{s,t} + \beta_1 LASH_{j,0} + \beta_2 \left(LASH_{j,0} \times Type\ Fund_j \right) + \varepsilon_{j,t}, \tag{13}$$

where $Type\ Fund_j$ is an indicator variable for segregated and pooled LDI funds, respectively. The remaining variables are defined as in equation (10). We again include sector-day fixed effects and use standard errors clustered on the day and sector level.

The results are presented in Table 4. We find that the effect is indeed substantially more pronounced for pooled LDI funds: a one standard deviation increase in LASH risk is associated with 93% higher daily sell volumes for pooled LDI funds relative to other non-banks (Column 5). Intriguingly, the coefficient for segregated LDI funds is insignificant, emphasizing that the coordination frictions in pooled LDI funds—in combination with elevated LASH risk—was a pronounced driver of gilt sales during the crisis. However, as shown in Figure E.10, it is important to emphasize at this point that pooled LDI funds' sales account for only around 15% of the total gilt selling pressure by pension funds and LDI funds.

Frictions to entering and trading in the repo market. We now analyze whether the selling pressure in cash gilts was more pronounced because of frictions to entering and trading in the repo market. As shown in Figure E.16, only around half of the non-banks use repo to obtain funding, and hence many investors who do not routinely access the repo market may it find it challenging to establish the trading infrastructure and relations during a severe crisis period (see also Figure E.14 in the Appendix). Moreover, as demonstrated by the rising repo spreads during the crisis (see Figure E.16), dealer banks may also restrict their repo lending during times of high volatility. This effect should be more pronounced for

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[12] At the end of 2021, approximately £200bn of the £1.4tn in UK LDI assets were invested in multi-institution pooled funds (Breeden, 2022).

Table 4 LASH RISK AND SOURCES OF ILLIQUIDITY

	(1)	(2)	(3)	(4)	(5)	(6)
			Sell Volume			
LASH	0.15***	0.14***	0.14***	0.20***	0.14***	0.12**
	(0.02)	(0.01)	(0.01)	(0.05)	(0.02)	(0.04)
LASH × Swap-only		0.15***				0.17*
		(0.04)				(0.07)
LASH × High Spread Exposure			0.14***			0.16*
			(0.03)			(0.08)
LASH × Segregated LDI Fund				-0.08		0.00
				(0.06)		(0.05)
LASH × Pooled LDI Fund					0.93***	0.95***
					(0.02)	(0.09)
Observations	8875	8875	8875	8875	8875	8875
R squared	0.046	0.047	0.047	0.047	0.050	0.051
Sector-Day FE	yes	yes	yes	yes	yes	yes

NOTE. For each non-bank financial institution, LASH is measured as the potential liquidity needs following a 100bps shift in gilt yields for repo and IRS exposures combined. The dependent variable is the institution's daily sell volume on day t. Segregated LDI Fund and Pooled LDI Fund indicate segregated and pooled LDI funds, respectively. Swap-only indicates institutions that have no activity in the repo market in the quarter prior to the crisis. High Spread Exposure indicates whether the majority (more than 50%) of repo borrowing of a given institution is with high-spread dealers (that charge more than the market median on average) in the quarter prior to the crisis. The dependent variable is transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Double-clustered standard errors on the day and sector level are reported in parentheses. We include sector-day fixed effects. *** p<0.01, ** p<0.05, * p<0.1. Coefficients corresponding to the constant, control variables and fixed effects not reported.

banks who are closer to their regulatory limits and, therefore, charged higher repo spreads to their clients prior to the crisis.

To test these hypotheses, we again employ a version of the regression model in equation (13), and first add an indicator variable called "Swap Only" that captures whether a given non-bank accessed only the swap market (and hence not the repo market) in the quarter prior to the crisis. Second, we also add another indicator variable that measures whether a given non-bank obtained the majority (more than 50%) of its funding from "high-spread" dealers—that, on average, charge their clients more than the market median for term repo borrowing—in the quarter prior to the crisis.

The results are shown in Table 4. Non-banks that only accessed the swap market in the quarter prior to the crisis have 15% higher sell volumes compared to other investors who also have access to the repo market (Column 2). Moreover, sell volumes are also 14% higher for non-banks that are more exposed to high-spread dealer banks prior to the crisis, and thus may have found it challenging to obtain additional funding due to binding constraints on the dealer level (Column 3). Overall, both effects underline that frictions in the repo market may have aggravated the selling pressure in the gilt market.

Table 5 LASH Risk and Bond-level Liquidation Choices

	(1)	(2)	(3)	(4)
	Sell Volume			
LASH	0.05***	0.04***	0.04***	0.04***
	(0.00)	(0.00)	(0.00)	(0.00)
LASH × Frequent Collateral Use		0.01*		
		(0.00)		
LASH × Low Duration			0.01	
			(0.01)	
LASH × High Duration			0.01*	
			(0.00)	
LASH × Inflation-linked				0.02**
				(0.01)
Observations	42481	42382	41667	42481
R squared	0.115	0.115	0.114	0.115
Bond-Day FE	yes	yes	yes	yes
Sector-Day FE	yes	yes	yes	yes

Note. For each non-bank financial institution, as defined in equation 7 in Section 3.2, "LASH" is measured as the potential liquidity needs following a 100bps shift in gilt yields, for repo and IRS exposures combined. The dependent variable is the institution's daily gilt sell volume in bond b on day t. "Frequent Collateral Use" indicates the frequent use of bond b as repo collateral, i.e. the top 50% of bonds based on their use as repo collateral. "Duration" indicates the duration bucket of bond b (long, medium, short). "Inflation-linked" indicate index-linked gilts. The dependent variable is transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Clustered standard errors on the day, sector and maturity-bucket level are reported in parentheses. We include sector-day fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Coefficients corresponding to the constant, control variables and fixed effects not reported.

Bond-level liquidation choices. We now turn to the question of whether the selling pressure was concentrated in bonds with particular characteristics. As the price of high-duration and index-linked assets fell most sharply during the crisis, our hypothesis is that it was more challenging to borrow against these assets and, therefore, these bonds were more likely to be sold.[13] Furthermore, we hypothesize that the selling pressure is also more pronounced for gilts that are frequently used as repo collateral, as the repo contract itself would be a source of liquidity risk for the institution. To test these hypotheses, we exploit

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[13] Figure E.15 in the Appendix shows a substantial decline in the average time-to-maturity of the gilt collateral used by pension funds and LDI funds in their term repo trades during the crisis. This indicates that dealers' risk-aversion likely increased, which may have led them to request shorter-dated collateral from their clients, similar to the dynamics during the Dash for Cash period (Czech et al., 2023).

the granularity of our data and run the following regression on the institution-bond-day level:

$$Sell\ Vol_{j,b,t} = \alpha + \alpha_{s,t} + \alpha_{b,t} + \beta_1 LASH_{j,0} + \beta_2 \left(LASH_{j,0} \times Bond\ Characteristics_b \right) + \varepsilon_{j,b,t} \tag{14}$$

where $Vol_{j,t}$ measures the net trading volume of institution j in bond b at time t. *Bond Characteristics* includes: i) three duration buckets (low, medium, high), ii) two groups measuring the frequency of the gilt's usage as repo collateral (as measured by the total pre-crisis repo borrowing amount for each bond across all non-banks), and iii) index-linked gilts. $LASH_{j,0}$ is defined as in equation (10). We include both sector-day and bond-day fixed effects and use standard errors clustered on the day, sector and maturity-bucket level.

The results are presented in Table 5. Consistent with our baseline results, we find that higher pre-crisis LASH risk predicts bond selling pressure, even when controlling for sector-day and bond-day fixed effects. Importantly, confirming our hypotheses, we find that the effect is particularly pronounced for high-duration gilts, gilts that are frequently used as repo collateral and index-linked gilts. For example, a one standard deviation increase in LASH is associated with 6% higher daily sell volumes in index-linked gilts (relative to 4% higher sales in nominal bonds).

Overall, there is a range of reasons why pension funds could not raise liquidity despite their improving solvency. This discussion emphasizes that the distribution of LASH risk across sectors matters. Banks tend to have better access to liquidity, via central bank facilities. Therefore LASH risk in the banking system may be less likely to lead to a liquidity crisis. LASH risk for non-banks is more problematic—because non-banks, such as pension funds, have worse access to liquidity.

7 Conclusion

In this paper, we introduce a framework to understand and measure the liquidity risk that arises from financial institutions' actions to mitigate solvency risk. *Liquidity After Solvency Hedging risk* or "LASH risk", arises when institutions use certain hedging strategies to reduce solvency risk, which leads to higher liquidity needs when the value of the hedge falls and solvency improves. We focus on LASH risk for non-banks, such as pension funds, with long duration liabilities and shorter duration assets. For these non-banks, LASH risk ought to rise as rates fall, because solvency deteriorates which requires more solvency hedging.

We then make three empirical contributions. First, we measure LASH risk for the universe of non-banks' sterling interest rate exposures, from interest rate swaps and repo, in the UK from 2019 onwards. LASH risk is large—at peak, a 100bps increase in interest rates leads to liquidity needs that would nearly deplete the entire cash holdings of the combined pension fund and insurance sector. While LASH risk is large, funds are partially but not fully hedged against interest rate risk. Second, we show that low rates increase LASH risk. In the time series, LASH risk is high when rates are low. We then exploit our granular data using a cross sectional identification strategy, comparing funds with different exposures to falling interest rates. Funds who are more exposed, due to having shorter duration assets, increase LASH risk by more. Third, we show that the LASH risk caused by low rates leads to liquidity crises. In particular, during the 2022 bond market crisis in the UK, fund-level LASH risk is a strong predictor of bond sales by pension funds. As such, LASH risk contributed to the spike in yields during the crisis.

The implications of LASH risk are different from some other forms of liquidity risk. LASH arises from 'responsible' institutions trying to hedge solvency risks, and the risk materializes precisely when solvency improves. LASH is thus different from other forms of liquidity risk that materialize when solvency deteriorates.Therefore mitigating LASH risk ex post—through measures such as liquidity support during a crisis—may not encourage solvency risk ex ante. As such, the policy tradeoffs from intervening during a crisis may be different from conventional liquidity crises. We leave a full investigation of these ideas to future work. Likewise, we leave the analysis of LASH risk and its implications in other market segments (e.g. foreign exchange or inflation) for future research.

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Appendix

A Additional theoretical results

A.1 Proof of Proposition 1

Proof preliminaries To start, we reformulate the problem and define some notation. Under our described process for the interest rate. The asset prices in period $t+1$ follow:

$$q^l_{t+1}(\varepsilon_{t+1}) = \frac{\varepsilon_{t+1} + R_t^{-1}}{1 - \bar{R}^{-1}},$$

$$q^b_{t+1}(\varepsilon_{t+1}) = \frac{\varepsilon_{t+1} + R_t^{-1}}{1 - \delta\bar{R}^{-1}}.$$

The shock, ε_{t+1}, has support $\varepsilon_{t+1} \in (\varepsilon^l, \varepsilon^h)$ with ε^h positive and finite so the gross rate cannot fall to zero, and $\varepsilon^l \geq -R_t^{-1}$ with an upper bound we will define below.Denote the cumulative density of the shock $F(\varepsilon)$, with corresponding p.d.f. $f(\varepsilon)$. The initial level of the R_t^{-1} can be treated as a primitive of the problem.

The proposition is for a liquidity premium on the short run asset that is sufficiently high, for simplicity we set $\eta \to \infty$, so $a_t = 0$. To ease notation we occasionally drop function dependencies on ε_{t+1} and s_t. The problem can then be recast as simply choosing the optimal amount of hedging at time t (with b_t given):

$$\max_{s_t} \mathbb{E}_t\left[\left(1 + \kappa\mathbf{1}\left[w_{t+1} < 0\right]\right) w_{t+1}\right], \tag{A.1}$$

subject to:

$$w_{t+1}(\varepsilon_{t+1}, s_t) = b_t - l + q^b_{t+1}\delta b_t + s_t\varepsilon_{t+1} + \frac{c}{1-c}\min\left\{m_{t+1}, 0\right\} - q^l_{t+1}l,$$

$$m_{t+1}(\varepsilon_{t+1}, s_t) = b_t + s_t\varepsilon_{r,t+1} - l.$$

It is useful to define:

$$y(\varepsilon_{t+1}) = b_t - l + q^b_{t+1}\delta b_t - q^l_{t+1}l,$$

This represents the unhedged value of the balance sheet. From assumption 1, the fund is solvent in period t in the sense that $y(0) > 0$ but $y(\varepsilon^h) < 0$. Given the definitions of q^b_{t+1} and q^l_{t+1}, it is straightfoward solvency condition requires that $b_t > l$. We also have:

$$\frac{dy}{d\varepsilon_{t+1}} = \frac{\left(\delta - \delta\bar{R}^{-1}\right) b_t - \left(1 - \delta\bar{R}^{-1}\right) l}{\left(1 - \delta\bar{R}^{-1}\right)\left(1 - \bar{R}^{-1}\right)}.$$

This is negative so long as $\frac{b_t}{l} < \frac{\left(1-\delta\bar{R}^{-1}\right)}{\delta\left(1-\bar{R}^{-1}\right)}$, and this is required by the first part of assumption 1. This means the fund is not so wealthy that the gain on its short duration assets offsets the duration mismatch from its longer duration liabilities. A negative value implies, absent hedging, the fund loses out the more positive the shock and the lower the rate.

Given the function $y(\varepsilon_{t+1})$ is exogenous and linear it is useful to parameterise it as:

$$y = y_0 + y_1\varepsilon_{t+1}, \tag{A.2}$$

where $y_0 \equiv y(0)$ and $y_1 \equiv \frac{dy}{d\varepsilon_{t+1}}$. At this point, it is worth emphasising that y_0 is decreasing in R_t^{-1} at rate y_1 and y_1 is invariant to R_t^{-1}.

The proposition states that the upside risk on the interest rate is sufficiently high. We now define the upper bound on ε^l which pins down how far interest rates could rise. We impose:

$$\varepsilon^l < \frac{b_t - l}{\left(\frac{y_0}{\varepsilon^h} + y_1\right)}. \tag{A.3}$$

As we shall see, this condition will ensure that if the fund hedges sufficiently to remove all risk of insolvency when rates fall, it will face a liquidity crisis if there is a sufficiently large rise in rates.

Hedging choices absent liquidity costs. Define, s_t^{**} as a value of s_t that solves problem (A.1) when $c = 0$. Since $\mathbb{E}_t\left[\varepsilon_{t+1}\right] = 0$ this is is equivalent to:

$$s_t^{**} = \max_{s_t} \mathbb{E}_t\left[\mathbf{1}\left[y_0 + \left(s_t + y_1\right)\varepsilon_{t+1} < 0\right]\left(y_0 + \left(s_t + y_1\right)\varepsilon_{t+1}\right)\right].$$

Note the maximand is weakly negative with a maximum at zero. From the linearity of

$y_0 + (s_t + y_1)\,\varepsilon_{t+1}$, the objective is maximized, for any s_t where both $y_0 + (s_t + y_1)\,\varepsilon^h_{t+1} \geq 0$ and $y_0 + (s_t + y_1)\,\varepsilon^l_{t+1} \geq 0$. Selecting

$$s_t^{**} = -y_1, \tag{A.4}$$

fully insures the fund against interest rate risk and hence guarantees the objective is at the maximum given $y_0 > 0$. However, there is a complete set of solutions given by $s_t^{**} \in [\underline{s}, \bar{s}]$ where

$$\underline{s} = -\left(\frac{y_0}{\varepsilon^h} + y_1\right) \leq |y_1|\,,$$
$$\bar{s} = -\left(\frac{y_0}{\varepsilon^l} + y_1\right) > |y_1|\,.$$

If $s_t^{**} = \underline{s}$ the fund does not remove all interest rate risk but hedges sufficiently to insure its solvency in the worse case scenario. If $s_t^{**} = \bar{s}$ the fund over-hedges so that its net worth is increasing in the interest rate but not so much that at the highest possible value of the rate the fund is insolvent.

Selecting $s_t < 0$ is never optimal as the probability of insolvency is always positive for negative values. Last, for any $0 < s_t < \bar{s}$ the probability of insolvency is positive and the fund's payoff can always be improved by increasing s_t towards $\underline{s}$.

Hedging choices with liquidity costs. Define, s_t^* as a value of s_t that solves problem (A.1) when $c > 0$. Conjecture that there exists an s_t^* that is unique, positive and less than $\underline{s}$. We will first characterize s_t^* under this conjecture, proving points $(ii) - (iii)$ in the proposition. Then we will confirming the conjecture is correct, thereby proving point (i).

For point (ii), note that

$$m_{t+1} = b_t + s_t\varepsilon_{t+1} - l.$$

so we can define a threshold realization $\varepsilon_0(s_t) = \frac{l-b_t}{s_t} < 0$, such that if the rate is sufficiently high ($\varepsilon_{t+1} < \varepsilon_0$) then $m_{t+1} < 0$ and the fund will be forced to sell assets. The threshold is increasing in s_t The condition in equation (A.3) guarantees $\varepsilon_0(\underline{s}) > \varepsilon^l$. What is left to show is that $\varepsilon_0(s_t^*) > \varepsilon^l$ such that a sufficient rate rise will cause selling given a choice s_t^*

As $s_t < \underline{s}$, there is also a threshold realization,

$$\varepsilon_1(s_t) = \frac{y_0}{-(y_1 + s_t)},$$

such that if the rate is sufficiently low ($\varepsilon_{t+1} > \varepsilon_1(s_t)$) then $w_{t+1} < 0$. Note that $\varepsilon_1(s_t) > 0$ as $y_0 > 0$ and $y_1 + s_t$ is negative for $s_t \leq \underline{s}$.

At this point, it is useful to distinguish between two cases. *Case (i)*: $w_{t+1}(\varepsilon^l, \underline{s}) > 0$; *Case (ii)*: $w_{t+1}(\varepsilon^l, \underline{s}) < 0$. In *Case (i)*, if the fund hedges sufficiently to avoid insolvency when rates fall, the losses from illiquidity when rates rise are never sufficient for it to also become insolvent for very large interest rate rises. In *Case (ii)*, the liquidation costs on the hedge can be sufficiently large that in the case of high rates such that fund is insolvent.

We will first with complete the proof assuming *Case (i)* holds, and then show that *Case (ii)* is ruled out by assumption 1. In *Case (i)*, problem (A.1) can be expressed as:

$$\max_{0<s_t<\underline{s}} \mathbb{E}_t \left[\kappa \int_{\varepsilon_1(s_t)}^{\varepsilon^h} (y_0 + (s_t + y_1)\,\varepsilon_{t+1})\, dF(\varepsilon_{r,t+1}) + \frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(s_t)} (b_t + s_t\varepsilon_{t+1} - l)\, dF(\varepsilon) \right].$$

Taking the first order condition yields:

$$\kappa \int_{\varepsilon_1(s_t^*)}^{\varepsilon^h} \varepsilon_{t+1} dF(\varepsilon) + \frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(s_t^*)} \varepsilon_{t+1} dF(\varepsilon) = 0 \tag{A.5}$$

The first term is strictly positive for $s_t < \underline{s}$ and is the marginal benefit of an additional unit of hedging in terms of reducing the risk of insolvency. The second term is weakly negative for $s_t < \underline{s}$, strictly if $\varepsilon_0(s_t^*) > \varepsilon^l$, and is the marginal cost of an additional unit hedging in terms of extra hedging costs.

The corresponding second order condition is (noting $\varepsilon_1 > 0$, $\varepsilon_2 < 0$ and $y_1 + s_t^* < 0$):

$$\kappa \frac{\varepsilon_1^2}{(y_1 + s_t^*)} f(\varepsilon_1) - \frac{c}{1-c} \varepsilon_0^2 f(\varepsilon_0) < 0,$$

hence s_t^* corresponds to an interior maximum where the probability $\varepsilon_0(s_t^*) > \varepsilon^l$of insolvency is positive. Now imagine that $\varepsilon_0(s_t^*) < \varepsilon^l <$, then, the fund could increase s_t and reduce the probability of insolvency with no corresponding costs of illiquidity. Hence, we must have that s_t^* is sufficient;y large $\varepsilon_0(s_t^*) > \varepsilon^l$. This proves point (ii).

We now prove point (iii) under *Case (i)*. Note that R_t^{-1} enters first order condition (A.5) solely through the definition of y_0 in ε_1. Recalling $\frac{dy_0}{dR_t^{-1}} = y_1$, and applying the implicit function theorem, we obtain:

$$\frac{ds_t^*}{dR_{t-1}^{-1}} = \underbrace{\left(\frac{1}{\frac{c}{1-c}\varepsilon_0^2 f(\varepsilon_0) - \kappa \frac{\varepsilon_1^2}{(y_1+s_t^*)} f(\varepsilon_1)} \right)}_{>0} \underbrace{\frac{\kappa \varepsilon_1 y_1}{(y_1 + s_t^*)} f(\varepsilon_1)}_{>0}.$$

Hence, the equilibrium level of hedging is decreasing in the initial level of the interest rate. This proves point (iii).

We now confirm that the conjectures regarding the equilibrium level of hedging s_t^* are true. Consider the bounds $0 < s_t^* < \underline{s}$. Start with the conjecture $s_t^* > 0$. Imagine, instead that s_t^* was mildly negative such that there was no liquidity risk from the swap position. This is equivalent to the $c = 0$ case and a marginal increase in the fund's swap position would add

$$\kappa \int_{\varepsilon_1(s_t)}^{\varepsilon^h} \varepsilon_{t+1} dF(\varepsilon) > 0$$

to the expected payoff. Expanding a negative swap position to the point where liquidity risk emerges only introduces an additional benefit increasing s_t through a reduction in from illiquidity rates fall. The same argument holds at $s_t = 0$. At $s_t = 0$, there is no liquidity risk so raising s_t unambiguously raises the expected payoff.

Now consider the conjecture $s_t^* < \underline{s}$. At the point $s_t^* = \underline{s}$, solvency risk is nil and s_t comes with a marginal cost of illiquidity of $\frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(\bar{s})} (-\varepsilon_{r,t+1}) dF(\varepsilon)$. Further increases in s_t from $\bar{s}$ would raise $\varepsilon_0(\bar{s})$ and hence liquidity costs further without any benefit in terms of reduced insolvency. Now a marginal reduction in s_t from $\underline{s}$ generates a cost of insolvency equal to $\kappa \varepsilon^h f(\varepsilon^h)$. However, as the probability density was arbitrarily small at the bounds this increase insolvency less than the marginal cost of illiquidity. Hence, $s_t^* = \underline{s}$ is not optimal.

Last consider the conjectured existence and uniqueness of s_t^*, note that first order condition can be expressed as:

$$\kappa \int_{\varepsilon_1(s_t^*)}^{\varepsilon^h} \varepsilon_{r,t+1} dF(\varepsilon) = \frac{c}{1-c} \int_{\varepsilon^l}^{\varepsilon_0(s_t^*)} (-\varepsilon_{r,t+1}) dF(\varepsilon).$$

For all $0 < s_t < \underline{s}$, the left hand side is positive and decreasing in s_t and from the assumptions on $F(\varepsilon)$ the left hand converges smoothly to 0 as $s_t \to \underline{s}$. For the right hand side, first note $\varepsilon_0(s_t)$ is increasing in s_t. For sufficiently low s_t, $\varepsilon_{r,0}(s_t) < \varepsilon^l$ then the right hand is zero and unaffected by a change in s_t. We know $\varepsilon_{r,0}(\underline{s}) > \varepsilon^l$, hence, for sufficiently large s_t, we will have $\varepsilon_{r,0}(s_t) > \varepsilon^l$ and the right hand side will be positive. Since, in the interval $s_t \in (0, \underline{s})$, the left hand side starts positive, is decreasing and tends to zero and the right hand side starts at zero, is weakly increasing and in positive at the upper end of the interval there exists a single crossing.

We now turn to ruling out *Case (ii)*. If $w_{t+1}(\varepsilon^l, \underline{s}) < 0$, there exists a potential third threshold $\varepsilon_2(s_t) < \varepsilon_0(s_t)$ whereby $y_0 + \left((1+\frac{c}{1-c})s_t + y_1\right)\varepsilon_2(s_t) + \frac{c}{1-c}(b_t - l) = 0$ and $w_{t+1} < 0$ if $\varepsilon_{t+1} < \varepsilon_2(s_t)$. Now,

$$\varepsilon_2(s_t) = -\frac{\frac{c}{1-c}(b_t - l) + y_0}{\left((1+\frac{c}{1-c})s_t + y_1\right)},$$

for this region to exist $s_t > \frac{-y_1}{(1+\frac{c}{1-c})} = -(1-c)y_1$. We also have $\underline{s} = -\left(\frac{y_0}{\varepsilon^h} + y_1\right)$. If $-(1-c)y_1\varepsilon^h > -\left(y_0 + y_1\varepsilon^h\right)$ this region cannot exist. This condition is satisfied by assumption 1.

A.2 Numerical Results with Model

Here we illustrate numerically that for a reasonable parameterization, as interest rates fall LASH risk increases. We solve the model numerically using value function iteration, assuming an i.i.d. interest rate and parameterizing the model as described in Table A.1:

We choose δ such that the duration of the long term bond is equal to 10 years. The values for c and η are from Harris and Piwowar (2006) and Nagel (2016), respectively. To show that funds are incentivized to increase their swap holdings after decreases in interest rates, We solve the model for $T = 10$ across a range of interest rates, assuming that R^{-1} has different uniform distributions. These distributions have varying means ranging from 0.9 to 0.98 while maintaining the same variance.

Table A.1 Summary of Parameters

Parameter	Description	Value
c	Cost of liquidation	0.015
δ	Decay rate of long term bond	0.91
l	Fund payment to its members at each period	0.04
η	Short term bond premium	0.014
κ	Penalty for fund's deficit	0.3

Figure A.1 displays the results, plotting the average s_t against against R^{-1}. As can be clearly seen, low rates (high R^{-1}) are clearly correlated with more demand for hedging.

Figure A.1 Optimal swap holdings across different average values for R^{-1}

B Institutional Background on UK Pension Funds

The pension fund sector, and specialized funds that service it, are a major source of LASH risk in the non-bank sector. Pension funds can be categorized as defined benefit (DB) or defined contribution (DC) funds. Defined benefit pension funds promise a guaranteed return to their beneficiaries upon retirement, while defined contribution funds have variable returns. By construction, defined benefit funds have higher hedging needs, as they need to meet certain guaranteed payments in the far future. For the UK pension fund system, out of the total £2.2tn of assets under management in Q1 2023, £1.8tn can be attributed to public and private defined benefit funds.[14]

Hedging strategies are not always the same—even for similar balance sheet structures—and depend not only on the duration gap and the pension fund type but also on the way future liabilities are discounted. Differences in regulations and discounting practices across jurisdictions lead to diverging optimal hedging strategies. For instance, UK pension funds predominantly use gilt yields to discount their liabilities, while Dutch pension funds include the euro interest rate swap rate in their calculations, and US pension funds take a more bespoke approach and use a so-called asset-led discounting approach. As a consequence, Dutch pension funds almost exclusively hedge using interest rate swaps (Jansen et al., 2023), US pension funds have higher incentives to take on riskier assets as a hedging strategy (Andonov et al., 2017), and in our paper, we find that UK pension funds more frequently use repos than swaps as part of their hedging strategy.

Pension fund market fragmentation also impacts the hedging landscape. In countries with a concentrated market, funds have sufficiently large balance sheets and in-house expertise to design and implement their individual hedging strategies. By contrast, in a fragmented pension fund system, small pension schemes would not have the size or capacity to make in-house hedging a viable solution, giving rise to alternative strategies. A solution is to delegate a part of the portfolio to alternative investment funds, which are designed to attract funds from one (segregated fund) or multiple pension funds (pooled fund). These funds then select their assets, derivatives, and repo leverage based on the desired duration profile of their

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[14] See The Office for National Statistics (2023) dataset for details.

clients.

The UK had over 5,300 defined benefit pension schemes in 2022, making it a very fragmented market.[15] It is, therefore, perhaps unsurprising that the UK saw a rapid rise in alternative investment funds in the recent decade, such as Liability Driven Investment funds (LDIs). In fact, we find that the LASH risk from repo exposures is mainly concentrated in the LDI sector, emphasizing the frequent use of repo leverage in this market segment.

C UK Margin Requirements and Market Standards

Margin practices in derivative and repo market changed dramatically following the 2008 financial crisis, driven by wide-reaching regulatory reforms. One of these reforms targeted collateral backing of derivative exposures to mitigate counterparty credit risk. Other reforms aimed to improve credit risk management through better collateral management in securities financing transactions, and so, short term money markets.

Interest rate risk can affect both derivatives and repo transactions through different channels. The value of an interest rate swap contract changes as the underlying market rate of the specified index (e.g., LIBOR, SONIA) changes, implicitly affecting counterparty credit risk. In addition, in a collateralized transaction, when the value of the underlying collateral changes as interest rates change (e.g., a government bond), the credit risk of the transaction changes as well. A common practice to mitigate these two risks—by regulation or choice—is regular margin posting.

Definition – initial margin and variation margin

In derivatives trading, margin requirements were introduced as part of post-GFC reforms to mitigate systemic risk. There are two types of margining: initial margin (IM) and variation margin (VM). Initial margin serves to protect parties from potential future exposure that may arise between a counterparty's default and the subsequent closing out of positions. It is recalculated regularly to account for changing risks. Typically, IM includes a core component related to market risk and factors in additional risks, such as liquidity and concentration risk

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[15] See Pension Regulator Annual report.

(BCBS and IOSCO, 2022).

Additionally, derivative users are required to settle changes in the trade's market value at least once daily through VM. Therefore, VM reflects the mark-to-market process, ensuring that positions are reset to a net value of zero after each payment (BCBS and IOSCO, 2020).

Margin practices for centrally and non-centrally cleared derivatives

Both centrally cleared and non-centrally cleared (bilateral) trades are subject to margin requirements. Since mid-2016, interest rate derivatives in certain currencies, including the pound sterling, have been subject to mandatory clearing, with phase-ins based on firm classifications and derivative volumes. The majority of trades in our sample fall under these mandatory clearing requirements. Globally, over 75% of all interest rate derivatives were centrally cleared in 2023 (BIS, 2023).

Both IM and VM are mandatory for centrally cleared trades, with specific requirements determined by central counterparties' (CCP) margin models. In UK clearing houses, variation margin is generally required to be posted in cash, though there are exceptions based on CCP-specific rules. For example, at LCH, intraday VM requirements can be met using excess pre-positioned initial margin. Unlike the stricter VM rules, there is more flexibility regarding initial margin. IM can be posted in cash or highly liquid non-cash collateral, depending on the rules of the specific CCP (BCBS and IOSCO, 2022).

Cash collateral offers advantages, such as lower haircuts (Benos et al., 2022). During periods of high market volatility, the preference for cash increases further due to rising haircuts and greater price volatility in other assets. While VM is typically exchanged at the end of the trading day, CCPs have the discretion to issue margin calls more frequently, especially in times of heightened volatility. For example, intraday margin calls surged during the "Dash for Cash" episode in March 2020 (BCBS and IOSCO, 2022).

For non-centrally cleared (bilateral) trades, counterparties may choose not to clear trades through a central counterparty if the derivatives and counterparty types do not fall under mandatory clearing requirements. In such cases, the Basel Committee on Banking Supervision (BCBS) and the International Organization of Securities Commissions (IOSCO) require that all financial counterparties and systemically important non-financial counterparties exchange VM for new trades initiated after March 1, 2017. Additionally, they must exchange IM if both counterparties are part of groups with a month-end average gross notional amount of non-centrally cleared derivatives of at least EUR 8 billion (BCBS, 2013).

This IM requirement was phased in and applies only to contracts entered into once the counterparties' outstanding gross notional exceeds the phased-in threshold for that month (see PS14/21 for details). The UK implementation specifies a list of eligible assets that financial and non-financial counterparties within scope can use to meet VM and IM requirements, including cash and specific assets subject to haircuts. However, for vanilla derivatives and standard agreements, it is likely that cash will be the preferred collateral for VM due to its frequent exchange requirements.[16]

Is the exchange of VM mandatory?

The obligation to post VM is always mandatory, with no discretion to waive this requirement. For centrally cleared trades, this includes the additional obligation to post VM exclusively in cash.

Where does the cash go?

Collateral collected by central counterparties (CCPs) is subject to strict and limited redeployment rules. IM is paid by both counterparties to the CCP, as required under Article 47 of EMIR, and is segregated in clearing member and client accounts. This ensures that, in the event of a CCP default, members will recover exactly the IM collateral they initially provided. In contrast, VM is passed directly through the CCP to the end-users. The counterparty that is out of the money pays VM to the CCP, which then transfers it to the counterparty that is in the money.

UK EMIR regulations require that at least 95% of cash positions in a CCP's margin account held overnight must be invested in safe and liquid assets. In the UK, CCPs are permitted to invest only in reverse repos, government bond purchases, and central bank deposits (Article 43 of UK EMIR). Given the short-term nature of margin calls, CCPs primarily invest in reverse repos (for a detailed discussion on CCP collateral usage, see

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[16] For rules on OTC derivatives not cleared by a CCP, see UK EMIR Art 11, and for eligible non-financial counterparties, see UK EMIR Art 10. The asset classes subject to mandatory clearing are outlined in the Technical Standards referenced in UK EMIR Art 5(2).

Benos et al., 2022). In contrast, there are no specific restrictions on how VM transferred to end-users can be used, to the best of our knowledge.

For non-centrally cleared trades, regulation mandates that IM must be segregated with a third-party holder or custodian, and the collecting counterparty is generally prohibited from rehypothecating, repledging, or reusing the collected IM, with a few exceptions (see Articles 19 and 20 of BTS 2016/2251). Similar to centrally cleared trading, VM can be redeployed and is only required to be segregated if the posting counterparty requests it (see Article 19.5 BTS 2016/2251). However, since VM is exchanged daily and counterparties may need it for liquidity purposes to meet future VM calls, it is likely that cash is used for limited investment opportunities, such as reverse repos.

Magnitudes: VM outweighs IM

Daily VM calls are typically much larger in magnitude than IM calls for both centrally cleared and non-centrally cleared trades, making VM the primary driver of liquidity needs. For example, aggregate VM calls across clearing members can be up to six times higher than IM calls (Czech et al., 2021).

During periods of stress, such as the onset of the COVID-19 pandemic, daily VM calls by CCPs surged from \$25 billion in February 2020 to \$140 billion on March 9, 2020, while the peak for IM calls was only half of that (BCBS and IOSCO, 2022). Similarly, at UK clearing houses, non-bank financial intermediaries faced VM calls exceeding £13 billion, while their IM demand rose by only £2.4 billion (Czech et al., 2023).

Differences with repo margining practices

Repurchase agreements are a type of Securities Financing Transaction (SFT) and are not subject to mandatory margining requirements like derivative contracts. Instead, they fall under Credit Risk Mitigation regulations, and counterparties are expected to adhere to best margining practices established by industry bodies (see, e.g., ICMA, 2023).

Best practices for repo margining align closely with those for derivatives, though they are generally less stringent. The International Capital Market Association (ICMA) recommends at least daily re-evaluation of net exposures, exchanges of VM, and delivery of cash margin on the same day that a margin call is made. Additionally, firms are encouraged to clear existing margin accounts (either paid or received) before issuing new margin calls.

These calls can be satisfied with cash or securities that are acceptable as general collateral in the repo market, or with securities that possess equal or superior characteristics to the original collateral posted. In practice, this often limits the options to High-Quality Liquid Assets (HQLA). Furthermore, counterparties have the option to delegate collateral and margin management to a third party, allowing custodians to handle margin calls in a manner similar to derivatives practices.

Anecdotal evidence from supervisory market intelligence suggests that the best practice rules for margining are largely followed, particularly for gilt-based repos.

D LASH Risk from Interest Rates: Measurement for Repo Contracts and Interest Rate Swaps

In this section, we apply equation (5) to repos and interest rate swaps.

Repos As explained in the previous section, repos are short-dated collateralized borrowing arrangements that allow institutions to shorten the duration of their liabilities. The majority of repo transactions are overnight, but pension funds and other interest rate hedgers predominantly use term repos with a maturity of one month or more. LASH risk arises via price changes of the underlying collateral. As the collateral value decreases, ceteris paribus, a counterparty would need to pledge more collateral (or cash) to be able to borrow the same amount.

We approximate LASH risk for repos using the modified duration of the underlying collateral, which measures the impact of a 100bps change in interest rates on the value of the bond. Therefore, in the context of repo, LASH risk resembles the conventional DV01 (or "dollar duration"). For each contract i with bond collateral b of maturity m years and coupon payments c times a year, LASH risk for a 100bps increase in interest rates at time t

reads:

$$LASH^{Repo}_{i,t} = \frac{Q_{i,t}}{100} \times \underbrace{\frac{\sum_{k=1}^{K}(1+r_t)^{-k_b} \cdot CF_{b,k} \cdot k_b}{P_{b,t}} \times \left(1 + \frac{YTM_{b,t}}{c_b}\right)^{-1}}_{\text{Modified duration of bond } b} \tag{D.1}$$

where $Q_{i,t}$ is the borrowing amount of a given repo contract. $P_{b,t}$ is the market price of bond b, k_b is the time to each cash flow $CF_{b,k^{\iota}}$ of bond b from time t perspective (in years), and $YTM_{b,t}$ is the bonds' yield to maturity. We assume zero haircuts as most of the LASH risk in our sample is due to longer-term repos, which are, of course, less frequently rolled over compared to overnight contracts (where haircuts play a bigger role, e.g., during the Great Financial Crisis). This implies a one-to-one liquidity need with respect to the cash flow sensitivity to interest rates, hence $\Lambda_i = 1$.

Interest Rate Swaps An interest rate swap is a contract where two counterparties agree to exchange a fixed interest rate with a variable one, e.g., LIBOR, SOFR, SONIA, c times a year, for a duration of m years. The interest is calculated on a notional amount, Q, but only the difference in interest payments is exchanged. The fixed interest rate is set so that the NPV of the contract is zero at initiation; that is, neither side needs to pay the other to enter the agreement. To guard against counterparty credit risk, entering a swap also requires a pledge of liquid collateral in the form of initial margin.

LASH risk arises in swaps mainly due to variation margin. The counterparties are required to exchange variation margin on a daily basis to maintain the zero net present value of the contract as interest rates change. The floating rate payer will post variation margin to the fixed rate payer when rates rise (and vice versa when rates fall). In practice, this is implemented through daily (cash) margin calls that reflect the change in the mark-to-market price of the contract.[17]

The size of the margin calls, and the demand for liquidity, depend on the sensitivity of the swap's fixed versus floating cash flows to changes in interest rates. We extend the methodology proposed by Bardoscia et al. (2021) to calculate the liquidity needs from a given interest rate move and hence to obtain an estimate of LASH risk. Imagine an interest

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[17] Variation margin is a regulatory requirement, and the requirements may differ between centrally-cleared and bilateral swaps. A centrally cleared swap requires daily cash pledges for variation margin, while bilateral swaps can have more bespoke conditions if permitted by regulation, e.g., the use non-cash collateral.

rate swap of net notional value Q. We are at time zero and the swap matures at year T, and makes c coupon payments per year. Let k index coupon periods. There is a swap curve which defines the time zero sequence of annualised forward floating rates given by $r_{k,k-1}$, and a fixed rate $\bar{r}$ (for an at the money swap ($\bar{r} \equiv r_{T,0}$)). Cashflows are discounted at rate:

$$d_k = (1 + \frac{r_{k,0}}{c})^{-k} \approx e^{-\frac{r_{k,0}}{c}k}$$

The present value of the floating and fixed leg of the swap is given by:

$$PV_{floating} = Q \sum_{k=1}^{cT} d_k \frac{r_{k,k-1}}{c}$$

$$PV_{fixed} = Q \sum_{k=1}^{cT} d_k \frac{\bar{r}}{c}$$

Now the NPV of the contract for the floating rate payer is given by:

$$NPV = PV_{fixed} - PV_{floating} = \frac{Q}{c} \sum_{k=1}^{cT} d_k (\bar{r} - r_{k,k-1}).$$

For a ex-post shift upwards of the swap curve, the sensitivity reads:

$$\frac{\partial NPV}{\partial r} = -\frac{Q}{c} \sum_{k=1}^{cT} \left[\underbrace{d_k + \frac{\partial d_k}{\partial r} r_{k,k-1}}_{\text{change in value of floating leg}} - \underbrace{\frac{\partial d_k}{\partial r} \bar{r}}_{\text{change in value of fixed leg}} \right]. \tag{D.2}$$

Solving in continuous time yields:

$$\frac{\partial NPV}{\partial r} = -\frac{Q}{c} \sum_{k=1}^{cT} \left[d_k + \frac{k}{c} d_k (\bar{r}_i - r_{k,k-1}) \right].$$

Hence, LASH risk from a 100bps increase in interest rates for a swap contract i with maturity T based on notional Q and with c cash flow swaps a year reads:

$$LASH_{i,t}^{IRS} = \frac{Q_i}{100c} \sum_{k=1}^{cT} \left[d_k + \frac{k}{c} d_k (\bar{r}_i - r_{k,k-1}) \right]. \tag{D.3}$$

where the discount rate for cash flow k, $e^{-R_{k,t}\cdot(T_k-t)}$, is evaluated based on the daily Overnight Index Swap (OIS) yield curve for maturity $T_k - t$ from time t perspective. We derive the forward rates $r_{k,k-1}$ as implied by the OIS curve. We assume the fixed rate to be the prevailing OIS rate at the start of contract i corresponding to the trade maturity. Lastly, standard contracts have bi-annual coupons, so $c = 2$, without loss of generality.[18] The LASH risk for swaps via variation margin implies a one-to-one liquidity need with respect to the cash flow sensitivity to interest rates, hence $\Lambda = 1$.

E Data: Additional Information & Summary Statistics

This section of the Appendix provides additional information and summary statistics for the various data sources used in the empirical analysis.

Table E.1 SUMMARY STATISTICS: UK PENSION FUND BALANCE SHEETS

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
N	10	22	50	65	68	69	10
Total assets (£bn)	115.0	553.7	801.3	1046.9	956.5	876.9	55.1
Total liabilities (£bn)	117.2	560.7	815.2	1099.9	900.0	807.9	50.8
Actuarial assets (£m)							
Min	907	933	179	62	145	177	916
Mean	11501	25170	15711	15863	14066	12709	5513
Median	3600	4360	3767	3676	3611	3029	2364
Max	60000	358175	395867	444167	463022	406597	23500
Std deviation	18973	75692	55560	55490	56579	49732	7605
Actuarial liabilities (£m)							
Min	1074	1044	193	95	125	162	835
Mean	11724	25485	15985	16665	13235	11709	5078
Median	3673	4501	3499	3642	3511	2960	2195
Max	67500	368981	404974	475130	418665	366574	20300
Std deviation	20615	78046	56894	59416	51396	45031	6659

NOTE. Cross-sectional dispersion and total actuarial values and liabilities for the UK pension funds in our hand-collected sample. Values are reported in £m, unless otherwise stated, and N denotes the total number of pension funds in each year of our sample.

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[18] In ongoing work, we incorporate second order effects coming from non-linearity of the yield curve.

Table E.2 SUMMARY STATISTICS: UK PENSION FUND FUNDING RATIOS

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
N	13	23	52	70	76	74	11
Underfunded PFs	0.62	0.52	0.56	0.60	0.33	0.27	0.27
Pension fund funding ratios							
Min	0.81	0.78	0.81	0.65	0.80	0.91	0.91
Mean	0.98	1.02	1.00	0.98	1.04	1.06	1.07
Median	0.94	1.00	0.99	0.98	1.04	1.05	1.07
Max	1.31	1.39	1.40	1.49	1.54	1.42	1.23
Std. deviation	0.13	0.12	0.11	0.12	0.10	0.10	0.09

NOTE. Cross-sectional dispersion of funding ratios for the UK pension funds in our hand-collected sample. N denotes the total number of pension funds in each year of our sample, and the underfunded PFs denotes the share of pension funds with a negative funding ratio (so assets<liabilities) in the given year. A ratio of 1 indicates that the actuarial value of assets exactly matches the actuarial value of liabilities.

Table E.3 SUMMARY STATISTICS: AVERAGE NET POSITIONS AND LASH RISK

	Repo net borrowing					**IRS net receive fixed**				
Sector	2019	’20	’21	’22	’23	2019	’20	’21	’22	’23
Pension fund	38	64	74	69	48	65	96	101	132	112
LDI	99	121	130	113	73	17	37	40	38	23
Insurer	0	0	0	0	0	10	23	27	72	60
Hedge Fund	-7	11	-3	-34	-15	59	82	-14	-108	-81
Fund	9	7	7	4	4	23	21	11	18	15
Other financial	7	20	18	10	5	-8	-11	-3	-9	-14
	Repo discretionary LASH					**IRS discretionary LASH**				
Sector	2019	’20	’21	’22	’23	2019	’20	’21	’22	’23
Pension fund	8	15	18	16	11	5	11	12	12	10
LDI	22	28	30	26	17	2	5	5	5	3
Insurer	0	0	0	0	0	0	6	6	8	7
Hedge Fund	0	1	-1	-3	-1	1	0	-1	-1	-1
Fund	2	1	1	1	1	2	1	1	0	0
Other financial	2	4	3	2	1	-2	-2	-1	-1	-1

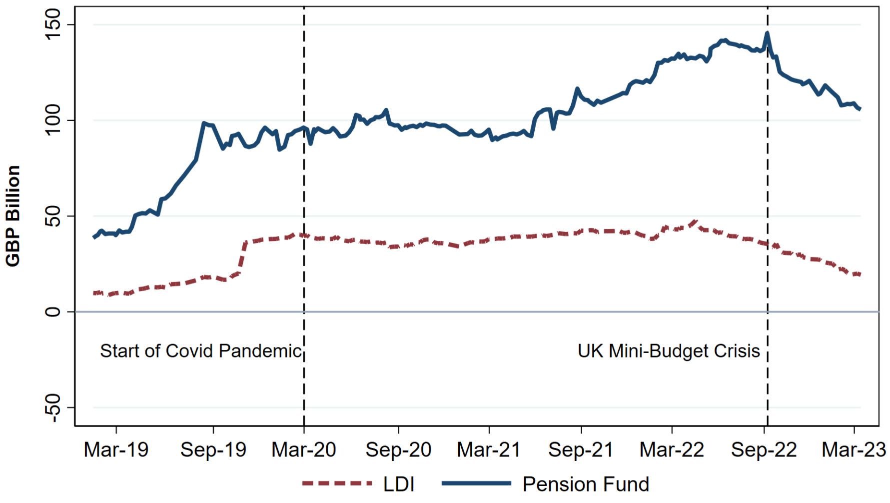
NOTE. Sample: Summary statistics on repo and IRS positions from 2019 to 2023. Values reported in £bn. Repo net borrowing captures the daily average cash borrowing per sector in a given year. The IRS net position captures the average holding of net receive fixed positions (negative values read as net pay fixed) per sector in a given year. Behavioural LASH risk captures the average for each sector in a given year.

Table E.4 Summary Statistics: Cross-sectional variation of Net positions and LASH risk

		Repo net borrowing			Repo discretionary LASH		
Sector	N	Mean	Median	Std dev	Mean	Median	Std dev
Pension fund	273	259.3	144.3	388.3	59.4	31.5	89.3
LDI	337	360.6	113.6	1275.5	82.6	25.5	300.6
Insurer	16	45.2	36.7	205.3	6.3	3.6	43.4
Hedge Fund	284	-59.7	-0.6	561.4	-4.0	0.0	65.6
Fund	203	117.6	3.7	626.6	22.9	0.6	143.7
Other financial	13	-10.5	0.0	116.7	-1.1	0.0	21.1
		IRS net receive positions			**IRS discretionary LASH**		
Sector	N	Mean	Median	Std dev	Mean	Median	Std dev
Pension fund	450	297.9	32.0	1372.2	29.9	2.6	183.9
LDI	231	199.3	48.2	477.1	24.9	3.0	72.6
Insurer	76	971.4	17.0	4034.6	139.2	0.2	691.3
Hedge Fund	149	-231.0	10.0	19493.3	-7.4	0.0	186.4
Fund	869	54.2	0.8	565.0	2.6	0.0	29.4
Other financial	217	-148.8	-6.5	1266.4	-14.1	-0.2	107.3

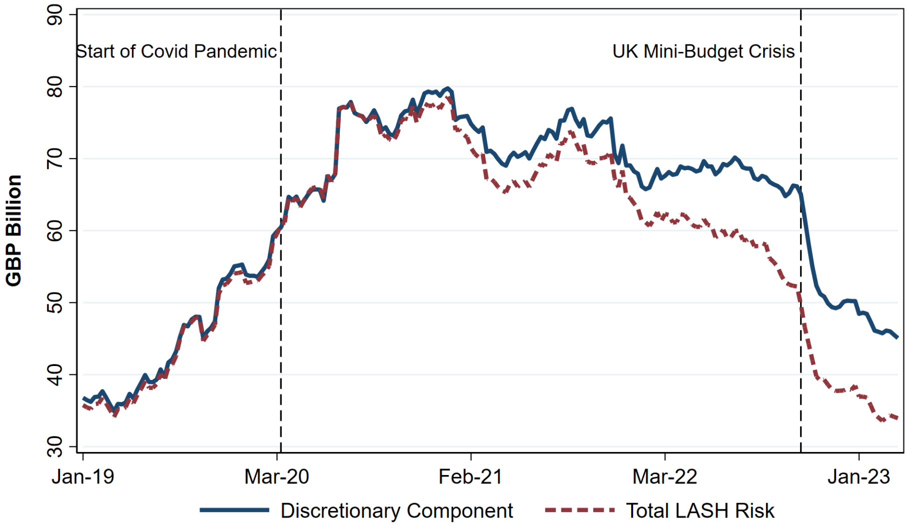
Note. Sample: Firm level summary statistics for repo (2017-2023) and IRS positions (2019-2023). Values are reported in £m, and N denotes the number of firms in each sector of our sample. The mean and median of repo net borrowing capture the total daily cash borrowing in the cross-section, and the IRS net position captures the outstanding net receive fixed positions (negative values read as net pay fixed). Behavioural LASH risk measures the outstanding LASH exposure at firm level in a given day.

Figure E.1 Pension & LDI Funds' IRS Net Notionals by Sector



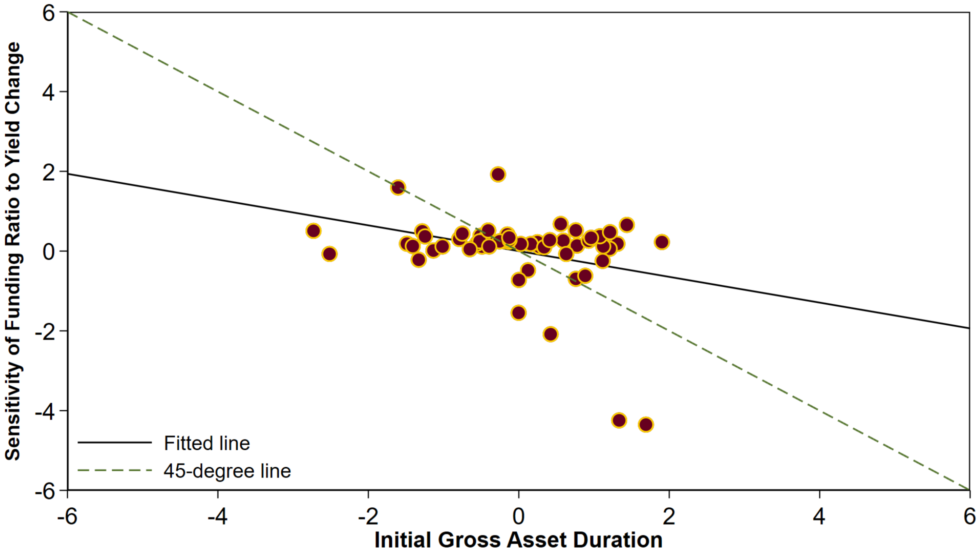
NOTE. Aggregate IRS net notionals of UK pension and LDI funds in £bn. Source: EMIR Trade Repository Data.

Figure E.2 LASH: DISCRETIONARY COMPONENT



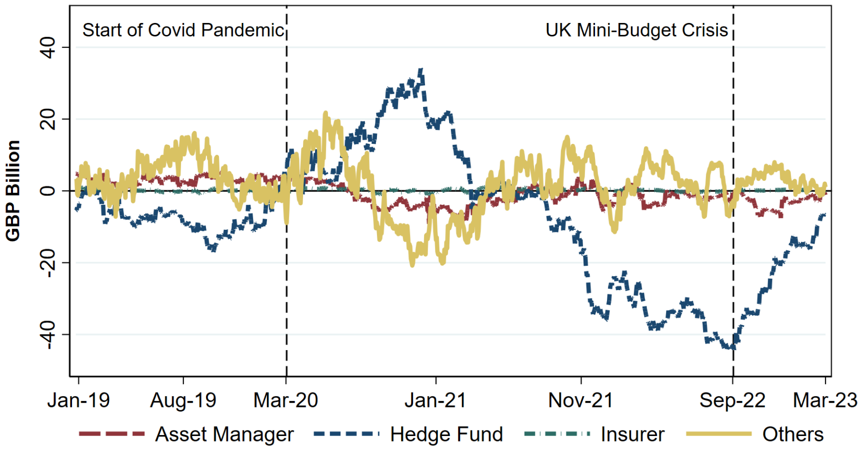
NOTE. This figure shows the evolution of the total LASH risk and the discretionary LASH risk component in £bn for all non-banks. The *Discretionary Component* is defined as $\sum_i \text{LASH}_{i,t-1}\Delta Q_{i,t}$ for interest rate swaps and repos, as shown in equation 8 in Section 3.2.

Figure E.3 SENSITIVITY OF PENSION FUNDS' FUNDING RATIOS TO YIELD CHANGES AND GROSS ASSET DURATION



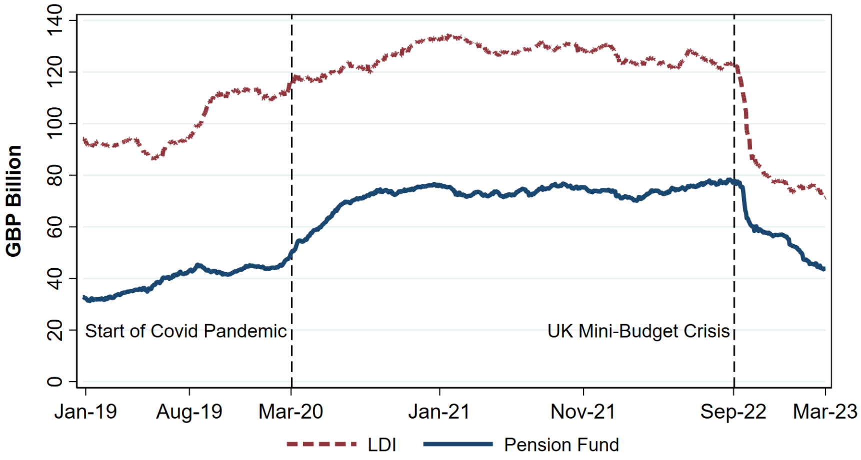
NOTE.This figure shows a scatter plot of the sensitivity of individual pension funds' funding ratios to changes in the yield of the ten-year UK gilt yield, and the funds' gross asset duration. Each are in standardized units, the funding ratio sensitivities on the vertical axis, and the gross asset duration on the horizontal axis. Funding ratios are the ratio of the market value of assets to liabilities.

Figure E.4 Repo Net Borrowing Stocks Across Sectors



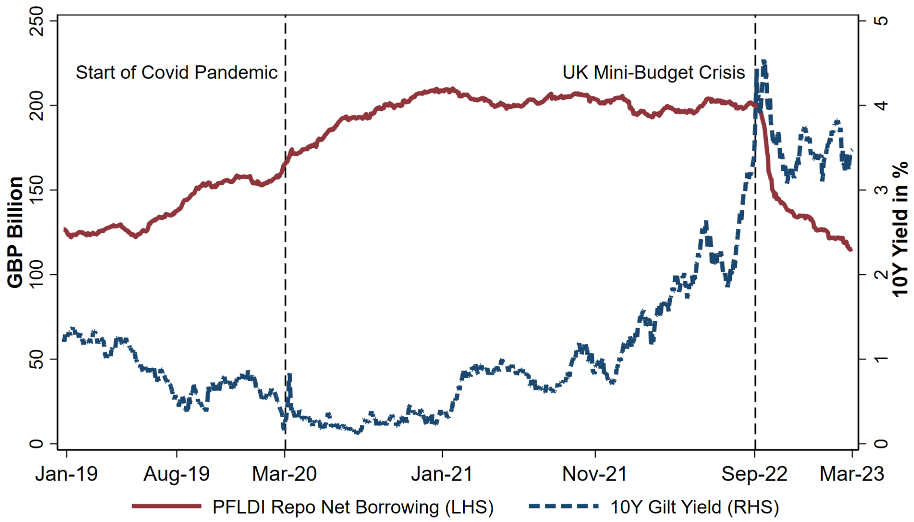
NOTE. Aggregate repo net borrowing across all sector types in £bn. "Others" include sovereign entities and other financials. Source: Sterling Money Market data collection.

Figure E.5 Pension & LDI Funds' Repo Net Borrowing Stocks



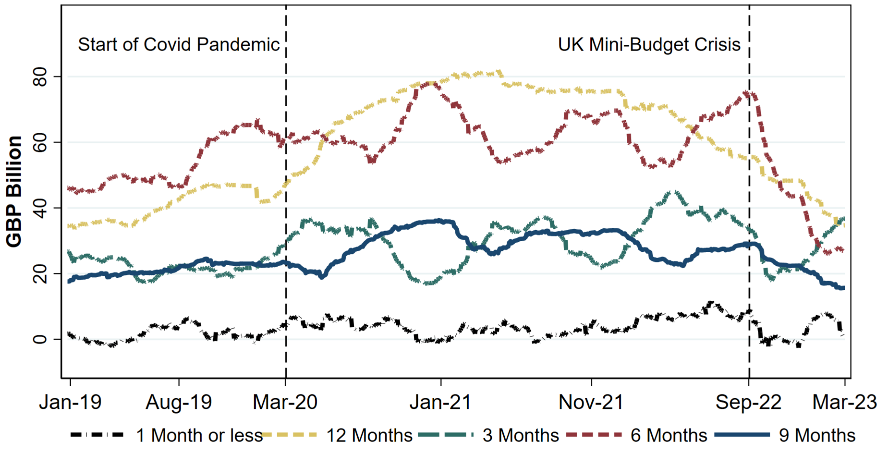
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds in £bn. Source: Sterling Money Market data collection.

Figure E.6 Pension & LDI Funds' Repo Net Borrowing Stocks & 10Y Gilt Yields



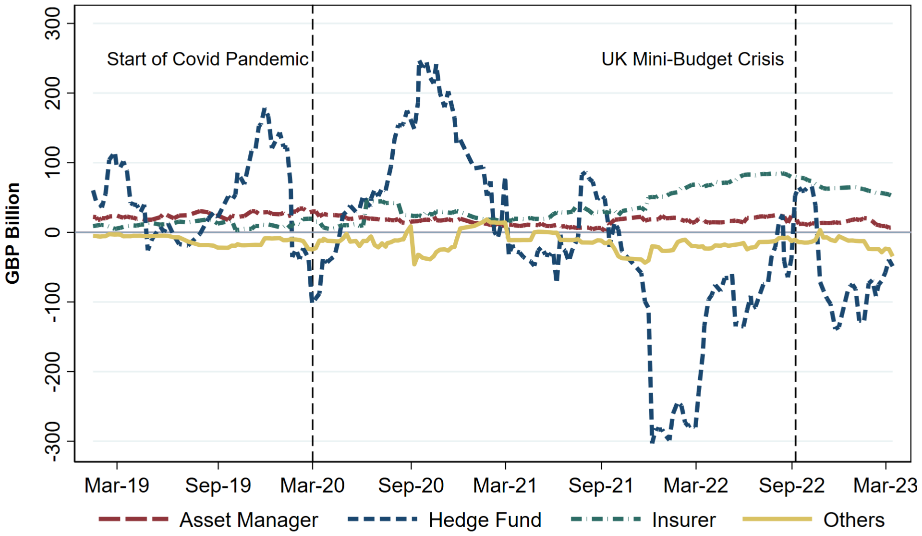
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds in £bn and 10Y gilt yields in %. Source: Sterling Money Market data collection & Bank of England.

Figure E.7 Pension & LDI Funds' Repo Net Borrowing Stocks by Maturity



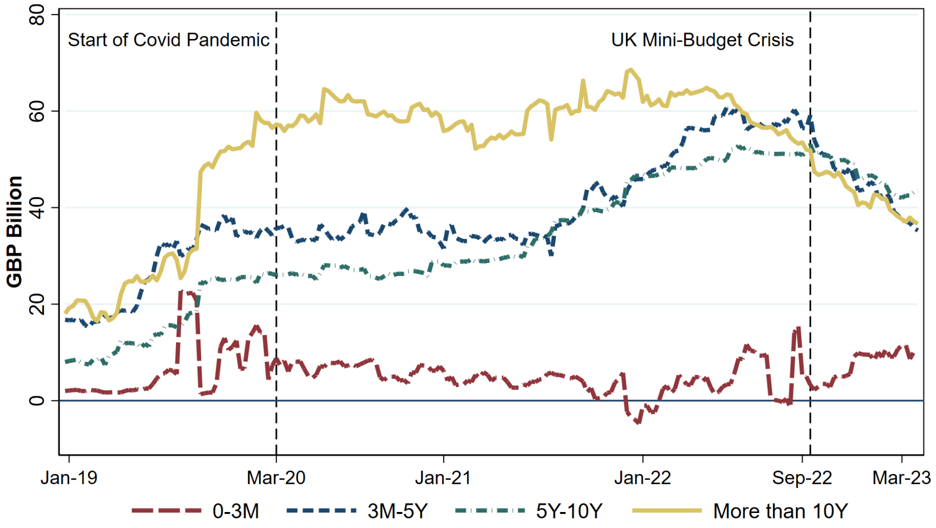
NOTE. Aggregate repo net borrowing stocks of UK pension and LDI funds by the maturity bucket at initiation in £bn. Source: Sterling Money Market data collection.

Figure E.8 IRS NET NOTIONALS ACROSS SECTORS



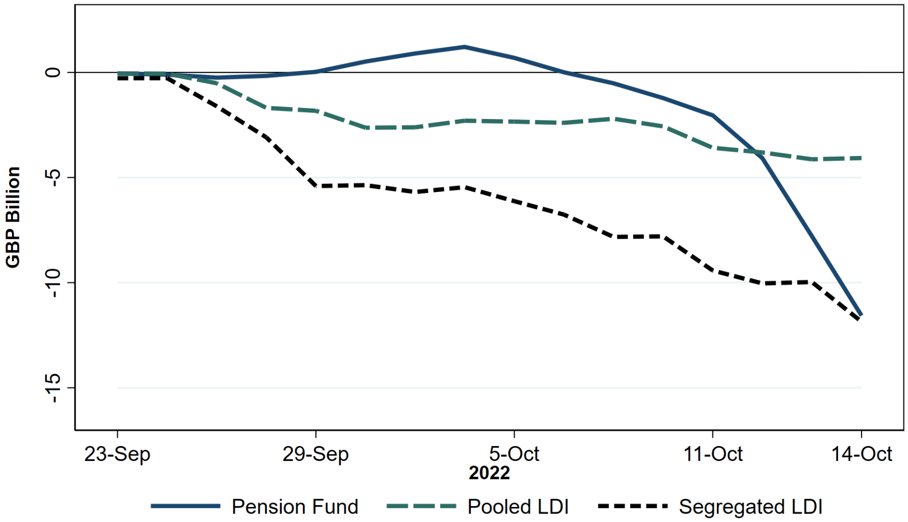
NOTE. Aggregate IRS net notionals across all sector types in £bn. "Others" include sovereign entities and other financials. Source: EMIR Trade Repository Data.

Figure E.9 PENSION & LDI FUNDS' IRS NET NOTIONALS BY MATURITY



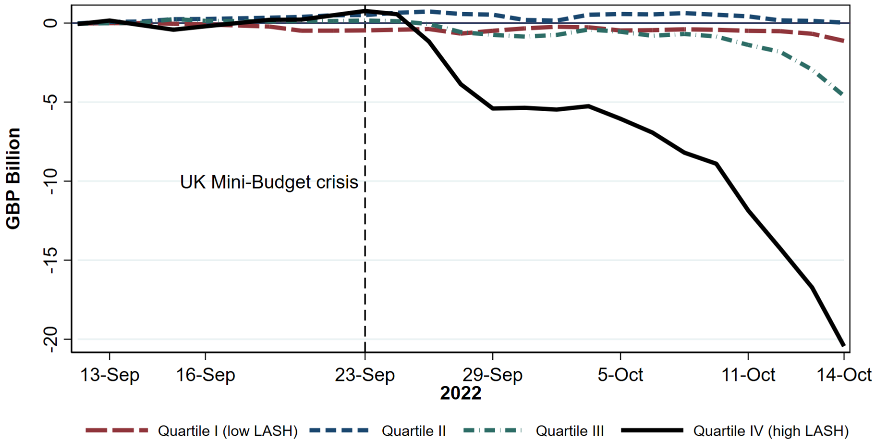
NOTE. Aggregate IRS net notionals of UK pension and LDI funds by maturity bucket in £bn. Source: EMIR Trade Repository Data.

Figure E.10 UK Bond Market Crisis: Pension & LDI Funds' Gilt Trading Volumes



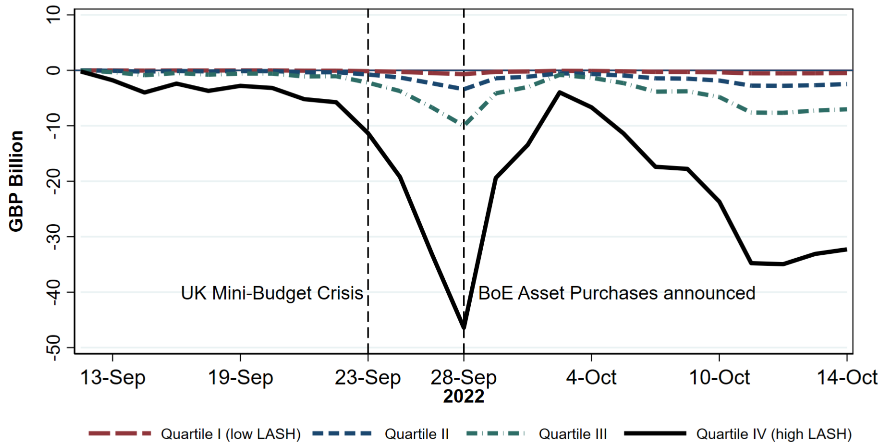
NOTE. Total net gilt trading volumes of UK pension & LDI funds' (split into pension funds, segregated LDI funds and pooled LDI funds) following the Mini-Budget announcement on September 23 up until the end of the BoE intervention on October 14.

Figure E.11 UK Bond Market Crisis: Pension & LDI Funds' Cumulative Gilt Trading Volumes based on pre-crisis LASH exposure



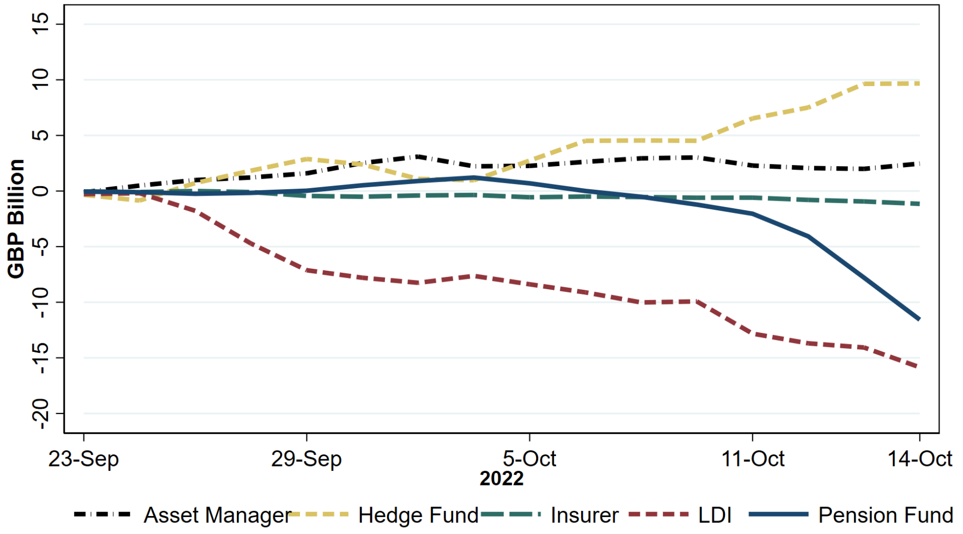
NOTE. Total net gilt trading volumes of UK pension funds and LDI funds, by quartile of their pre-crisis LASH risk: Quartile I captures the non-banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures.

Figure E.12 UK Bond Market Crisis: Estimated Cumulative Changes in the Value of Repo Collateral posted by Pension & LDI Funds



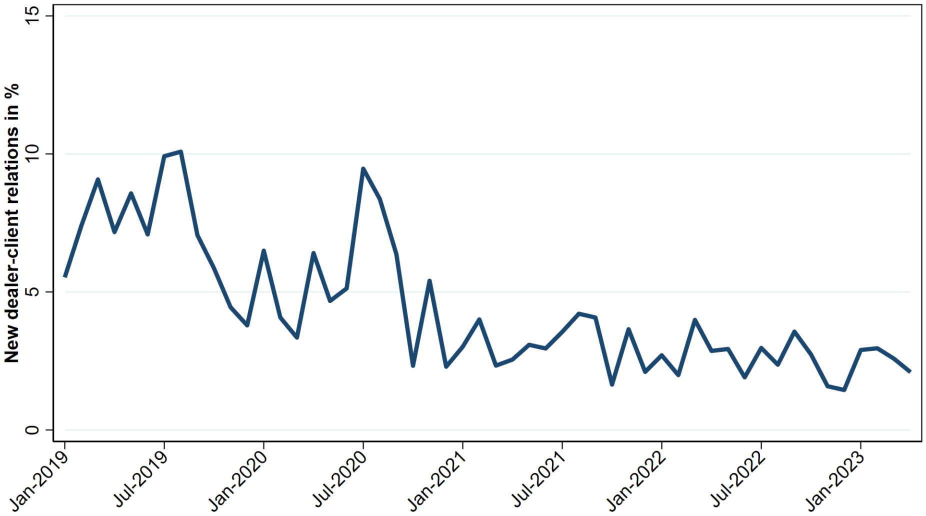
NOTE. Aggregate estimated changes in the value of repo collateral posted by UK pension and LDI funds in £bn during the 2022 UK bond market crisis, by quartile of their pre-crisis LASH risk: Quartile I captures the non-banks with the lowest pre-crisis LASH exposures, while Quartile IV captures those with the highest pre-crisis LASH exposures. Source: Sterling Money Market data collection.

Figure E.13 UK Bond Market Crisis: Non-Banks' Bond Trading Volumes



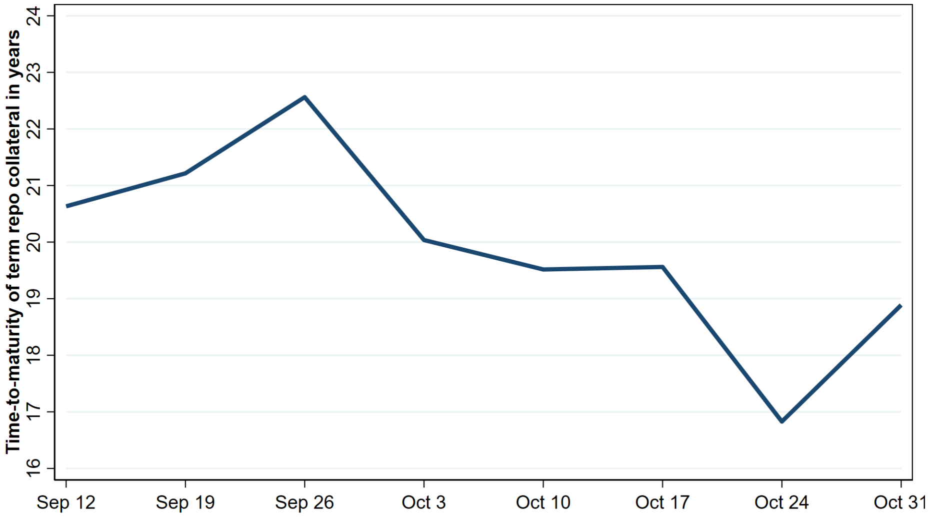
NOTE. Total net gilt trading volumes of UK non-bank financial institutions following the Mini-Budget announcement on September 23 up until the end of the BoE intervention on October 14.

Figure E.14 Repo Market: New Dealer-Client Relationships



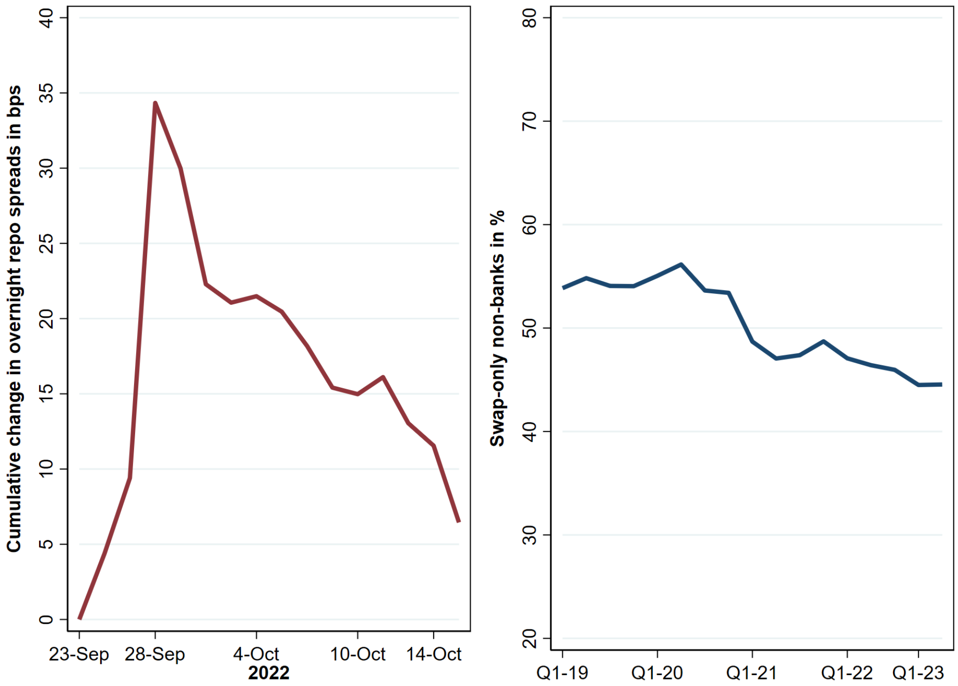
NOTE. Average monthly share of trades in the repo market that constitute a newly formed relation between a dealer and a non-bank client. Source: Sterling Money Market data collection.

Figure E.15 UK Bond Market Crisis: Average Time-to-maturity of Gilt Repo Collateral



NOTE. Weekly average of the time-to-maturity of gilt collateral in term repo trades of pension funds and LDI funds during the 2022 UK bond market crisis. Source: Sterling Money Market data collection.

Figure E.16 Overnight Repo Spreads and Limited Access to Repo Market



NOTE. Left Panel: Cumulative change in overnight gilt repo spreads (in bps) during the 2022 UK bond market crisis. Right Panel: Share of non-banks that only hold interest rate swaps in their portfolios, and are not borrowing or lending via the repo market, measured quarterly for the period from Q1 2019 to Q1 2023. Source: Sterling Money Market data collection & EMIR Trade Repository Data.

F Additional Results

F.1 Pension Funds' Gross Asset Duration and Solvency

In Section 5, we show that falling interest rates lead to an economically and statistically significantly greater LASH risk taken by institutions with low asset duration. Technically, rather than gross asset duration, the duration gap between assets and liabilities (i.e. net duration) is what matters for solvency. In the absence of granular information on the duration of institutions' liabilities, however, we use institutions' initial gross asset duration (measured via the bonds in their repo collateral portfolio) as a proxy for their duration gap. To test the correlation between net and gross duration, we use our hand-collected balance sheet data for UK pension funds.

First, we measure the net duration of pension funds. To do so, we estimate the sensitivity of the funding ratios of individual pension funds to changes in the ten-year UK gilt yield using seemingly unrelated regressions:

$$\Delta FundingRatio_{j,t} = \alpha + \beta_f \Delta Yield_t + \varepsilon_{j,t}, \tag{F.1}$$

where $\Delta FundingRatio_{j,t}$ measures the annual change in the funding ratio—which is defined as the value of the fund's assets over liabilities—of pension fund j in year t. $\Delta Yield_t$ is the annual change in the ten-year UK gilt yield. β_f is our measure of the funds' net duration.

Appendix Figure E.3 in the main text shows scatter plot relating our estimate of fund level net duration to the gross asset duration of these funds. Each are in standardized units, the funding ratio sensitivities on the vertical axis, and the gross asset duration on the horizontal axis. The association is clearly negative, even though the number of matched funds is relatively small. In other words, the funding ratio of funds with lower asset duration is more sensitive to a change in yields—and hence the solvency of these funds will decrease more sharply in response to lower interest rates relative to funds with higher asset duration. Therefore, the results emphasize the negative correlation between gross and net duration, and support our choice of gross asset duration as a viable proxy for institutions' duration gap.

F.2 Pension & LDI Funds' LASH Risk and Gilt Trading Volumes

Table F.1 LASH risk and Gilt Trading Volumes - Pension & LDI Funds only

	(1)	(2)	(3)	(4)
	Net Volume		Sell Volume	
LASH combined	-0.12**		0.10***	
	(0.05)		(0.02)	
LASH Repo		-0.10***		0.08***
		(0.03)		(0.02)
LASH IRS		-0.04		0.05
		(0.07)		(0.04)
Observations	2325	2325	2325	2325
R squared	0.036	0.036	0.044	0.044
Day FE	yes	yes	yes	yes

Note. For each pension & LDI fund, as defined in equation 7 in Section 3.2, "LASH" is measured as the potential liquidity needs following a 100bps shift in gilt yields, either for repo and IRS exposures combined, or separately for both instruments. The dependent variable is the institution's daily gilt net trading volume on day t in Columns (1) and (2), and the institution's sell volumes on day t in Columns (3) and (4). The dependent variables are transformed using the Inverse Hyperbolic Sine method. The LASH variable is standardized. Clustered standard errors on the day level are reported in parentheses. We include day fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Coefficients corresponding to the constant, control variables and fixed effects not reported.