Convenience yields and the foreign demand for US Treasuries

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Abstract

This paper investigates the role of convenience yields in determining the yield sensitivity of the foreign demand for US Treasuries and the equilibrium interest rates of government bonds. A portfolio choice model featuring two sectors (banks and insurers) with heterogeneous risk aversion and preferences for holding US Treasuries shows that convenience yields reduce the sensitivity of portfolio shares to the mean and variance of excess returns. In equilibrium, excess returns for Treasuries are lower, and decrease more strongly in response to an increase in foreign debt supply. Structural parameters recovered from an estimation of the model on data from European banks and insurers reveal that convenience yields reduce the return sensitivity by 3 times for banks, and by 9 times for insurers. Convenience yields also explain virtually all of the difference in the sensitivity to excess returns across sectors, and they reduce Treasury excess returns by 79 basis points on average. The results imply that the sustainability of US public debt is reliant on the special status of US Treasuries as the global safe asset, and in turn that it is vulnerable to the loss of this special status.

JEL-Classification: E43, F30, G11, G21, G22.
Keywords: US Treasuries, convenience yield, portfolio choice, financial intermediaries, interest rates.

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1 Introduction

US Treasuries are the premier global safe asset, and their special role affords them a premium, or convenience yield, reflected in lower returns compared to other advanced economy sovereign debt (Du et al., 2018) and other dollar-denominated assets with similar safety and liquidity features (Longstaff, 2004, Krishnamurthy and Vissing-Jorgensen, 2012).

The convenience yield of US Treasuries is crucial for the sustainability of the burgeoning US government debt, as it allows the US government to borrow more cheaply than sovereigns with comparable credit rating; and it can explain the gap between the market value of US debt and projected government deficits (Jiang et al., 2019). This funding advantage is driven in large part by foreign investors, who are willing to accept a lower yield to meet their need for safe and liquid dollar-denominated assets, and display relatively yield-inelastic demand (Krishnamurthy and Vissing-Jorgensen, 2012, Jiang et al., 2022).

At the same time, there is substantial heterogeneity in the yield elasticity of safe asset demand across investor categories. Tabova and Warnock (2022) singles out the foreign official sector as particularly inelastic in its demand for Treasuries, while foreign private investors are especially sensitive to yields. Within private investors, Fang et al. (2023) finds that non-banks, including insurance companies and pension funds(ICPF), absorb a large amount of sovereign debt issuance, and display a particularly low yield elasticity for advanced-economy debt. In the context of corporate bonds, Bretscher et al. (2020) finds that insurers are inelastic to returns and prefer bonds by high-quality issuers.

On the contrary, the banking sector is generally more responsive to yields than insurers. (Timmer, 2018). This difference persists for US sovereign debt specifically: Eren et al. (2023) break down the ICPF sector into pension funds and insurers, finding a slightly larger yield elasticity than commercial banks for the former, but a much lower and not statistically significant response for the latter. Similarly, Koijen et al. (2021) report that, in the euro area, the yield elasticity of banks' demand for European government bonds is amongst the highest across sectors, while European ICPFs even have a *negative* elasticity. Since these sectors play a large role in absorbing new issuance of government debt (Fang et al., 2023), from the perspective of fiscal policy it is important to understand what drives the difference in their behaviour, and how changes in such features can affect the cost of government funding.

The literature explains the differences in demand elasticity mostly in terms of risk management practices (Eren et al., 2023), regulatory framework (Faia et al., 2022), or market-making versus speculative roles (Abbassi et al., 2016, Timmer, 2018). This paper quantifies the relative importance of risk aversion and special preferences for US Treasuries in explaining the cross-sectoral heterogeneity in the senstivity of demand, and the consequences of convenience yields on Treasury excess returns. I zoom in on the difference between insurers and banks because there is a well-established difference in their respective yield-sensitivity; and because ICPFs are likely more risk-averse due to their business model, so that the role of US Treasury preferences is not overstated by construction.

The theoretical framework consists of a simple mean-variance model of portfolio choice between US and domestic-currency government bonds in which investors have a preference for the special features of US Treasuries, modelled as an additional term in the investor's objective function following the approach of Krishnamurthy and Vissing-Jorgensen (2012), among others. Investors differ both in their risk aversion and in the degree of preference for Treasuries, so that the heterogeneity in yield sensitivity across sectors can be apportioned between these two features.

The model predicts that investors are less sensitive to the mean and the variance of excess returns on Treasuries than they otherwise would in the absence of convenience yields. Furthermore, they would be willing to hold a non-zero amount of US Treasuries even if they paid a lower return than domestic bonds, and did not provide a good hedge for income risk. This feature emerges uniquely from the convenience yield mechanism and cannot be explained by risk aversion: investors that value solely monetary payoffs hold assets only if they deliver an excess returns, or if they are a good hedge.

Equilibrium excess returns depend on the relative supply of US and domestic government debt, and they can be decomposed in a risk premium term and a convenience yield term. Preferences for Treasuries beyond their risk-return profile drive down excess returns and makes them more sensitive to changes in debt supply, in line with the safe asset supply channel of quantitative easing highlighted in Jiang et al. (2021b) and Christensen et al. (2023).

The portfolio equations for the two sectors, jointly with the expression for equilibrium returns, imply restrictions that allow to calculate the structural parameters regulating risk aversion and the preference for Treasuries from the estimated regression coefficients of a linear version of the model. The structural parameters are key in disentangling and quantifying the role of risk aversion and convenience yields, as the predictions of the model on demand sensitivity and excess returns concern counterfactuals.

Understanding the rationale for differences in demand sensitivity is crucial to assess the capacity of markets to absorb additional US government debt. If the yield-insensitive demand by foreigners is due to risk aversion, the elasticity is heavily dependent on contingent market developments as encapsulated by the variance of returns. Therefore, events such as a temporary uncertainty on fiscal sustainability, due for example to negotiations in Congress over the debt ceiling, could jeopardise the ability of the US government to fund its debt cheaply. Conversely, convenience yields are tightly linked to the status of the US dollar as reserve currency, and of US Treasuries as global safe assets. These are much more persistent phenomena (Coppola et al., 2023), liable to evolve only in the face of extreme events such as a default (Choi et al., 2024) or major geopolitical upheaval (Eichengreen and Flandreau, 2009). Therefore, the more is low sensitivity driven by convenience yields, the more likely is it to be stable, and hence reliable from the point of view of the US government.

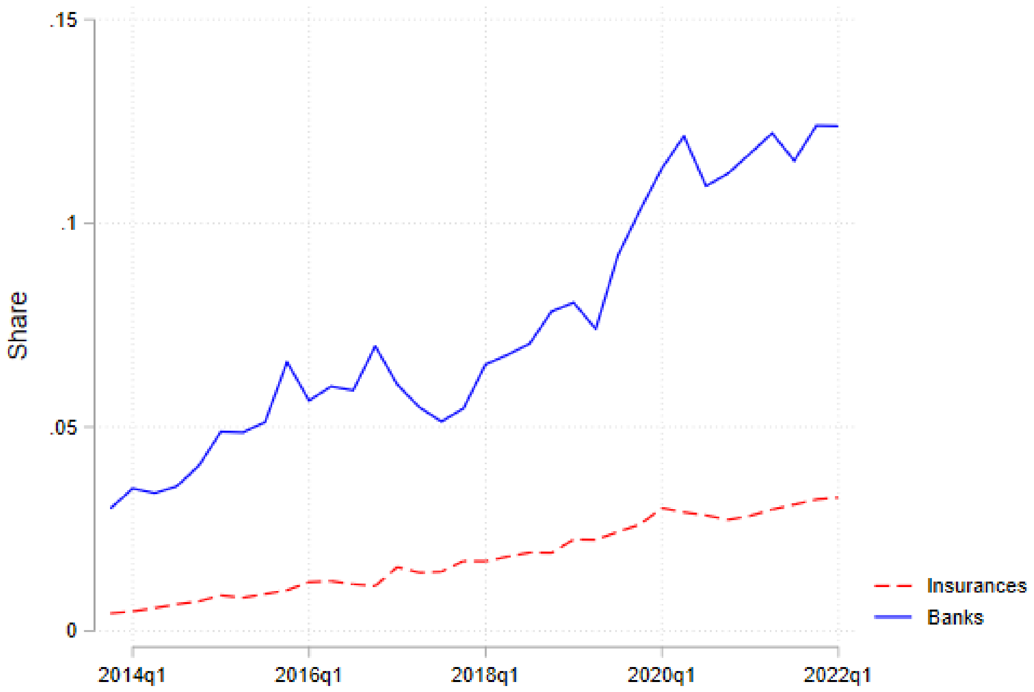
I estimate the model on data from the banking and insurance sector in the eurozone. The reason for this geographical focus is twofold. Firstly, the model implies that changes in debt supply are a valid instrument for excess returns in the portfolio equations using a two-stage least squares (2SLS) procedure. However, debt supply itself is likely endogenous to portfolio choice through general equilibrium effects, so it is necessary to isolate an exogenous component of debt supply to estimate the model. The Public Sector Purchase Programme (PSPP) by the European Central Bank (ECB) generates exogenous variation in the supply of sovereign debt issued by euro zone countries, solely as a function of the ECB's Capital Key and of the maturity structure of outstanding government bonds under the principle of market neutrality.[1] This structure provides an ideal laboratory to study responses to excess returns driven by exogenous changes in the relative supply of safe assets, thanks to an instrumental variables approach that matches the sets of equations derived from the theoretical model. The same identification strategy is exploited by Koijen et al. (2021) in the setting of demand for European government bonds.

Secondly, the very similar regulatory framework for banks and insurers in the realm of sovereign bonds and exposure to foreign exchange risk removes a potential alternative explanation for cross-sector differences in demand elasticity, thus sharpening the focus on differences in preferences.

[1] The Capital Key is the share of the ECB's capital held by each of the eurozone's national central banks.

The approach of estimating a mean-variance portfolio model through instrumental variables is related to the demand system asset pricing framework laid out in Koijen and Yogo (2019a) and adopted by a rapidly growing literature (Gabaix and Koijen, 2020, Bretscher et al., 2020, Haddad et al., 2021, Gabaix et al., 2022, Nenova, 2024). Differently from this methodology, I do not specify the full demand system but rather focus solely on the choice between US and domestic government bonds. This simpler approach allows to go beyond taking estimated elasticity as primitive parameters, but rather to back out directly the underlying preference parameters, and hence makes a step in the direction of understanding the nature of demand heterogeintiy at the core of the Koijen and Yogo (2019a) model. In this respect, the paper is related to the emerging literature that studies the theoretical foundations of demand-based asset pricing by endogenising heterogenoeus tastes (Fuchs et al., 2023).

Figure 1. US sovereign portfolio share for banks and insurers



Share of US Treasury holdings in a portfolio including US Treasuries and euro area government bonds for all banks (solid blue lines) and insurance companies and pension funds (dashed red line) domiciled in the euro area Source: European Central Bank Securities Holdings Statistics database.

Figure 1 plots the share of US Treasuries in a portfolio including euro area government bonds for banks (solid blue line) and ICPFs (dashed red line) domiciled in the euro area. It is evident at first glance that banks' share is much more volatile. While the comparison of unconditional volatility is not enough to draw any conclusions, it is certainly suggestive as to the plausible lower sensitivity of insurers' Treasury holdings to excess returns.

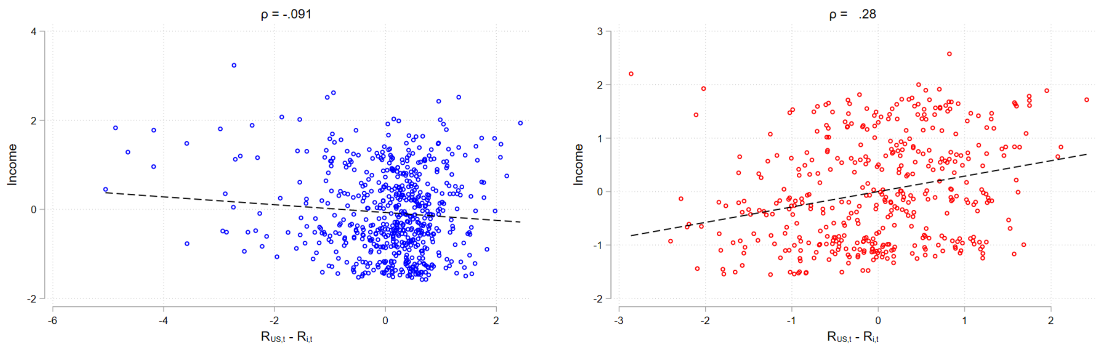
Figure 2 shows the correlation between the difference in the yield of Treasuries with respect to bonds issued by a given eurozone country, a rough proxy for excess returns, and the total balance sheet revenue of banks and ICPFs resident in the same country. The correlation is negative for banks and positive for insurance companies. Therefore, by this measure US government bonds are not a good hedge for the income risk of insurers. In the period between 2011 Q4 and 2023 Q3 over which the graph is constructed, Treasuries offer on average *negative* excess returns of about a quarter of a percentage point. [2] Therefore, insurance companies would have no incentive to include Treasuries in their portfolio under standard preferences that value assets solely for the balance of risks and rewards in monetary returns. This apparent contradiction can be resolved by the model presented in this paper: the presence of non-monetary payoffs motivates insurers to hold US Treasuries even in the face of a poor risk-return trade-off. Therefore, the observation in Acharya and Laarits (2023) that US Treasuries earn convenience yields because of their hedging properties againt stock market risk does not appear to extend to the case of income risk for European insurers.

Estimates of the portfolio equations via 2SLS reveal that banks increase their US Treasury portfolio share by 35.9 percentage points in response to a one percentage point increase in the excess returns of US Treasuries brought about by exogenous changes in the supply of eurozone governmnet debt. In contrast, ICPFs increase their portfolio share by only 6.24 percentage points.These findings are in line with existing evidence of lower sensitivity to excess returns of insurers' demand for government debt.

The structural parameters recovered from this estimation procedure imply that

[2] Here it is important to clarify the notion of excess returns used. In the model, US Treasury excess returns arise solely due to exogenous, stochastic fluctuations in exchange rates. Therefore, in this empirical proxy I account for the exchange rate expectations term in excess returns by adjusting for forward rates. This proxy is nonetheless imperfect due to the documented deviations in Covered Interest Parity stemming from frictions in FX markets (Borio et al., 2016, Rime et al., 2022). Other sources of variation that are disregarded in the model but likely affect the data, like sovereign credit risk, are allowed to influence this measure. In the empirical estimation, I will also correct yield differentials for credit risk to match the theoretical model.

Figure 2. Correlation between Treasury excess returns and sectoral income



(a) Banks (b) Insurers

Correlation between excess returns on US Treasuries compared to country j's government bonds, and the income of banks (left-hand side panel) or insurance companies (right-hand side panel) domiciled in country j. The correlation is calculated over the country-quarter distribution on data from 2011 Q4 to 2023 Q2 for all euro area countries excluding Greece. Excess returns are averaged over the 1,2,3,5, and 10 year maturities and over quarters, and are adjusted for exchange rate forward premia as a market-implied measure of expected changes in the exchange rate of the euro *vis à vis* the dollar. Income is calculated as total income for banks, and total income from premia for insurers. Sources: Refinitiv Eikon, European Central Bank Consolidated Banking database, and EIOPA Insurance Statistics.

ICPFs are about 1.5 times more risk averse than banks, and that preferences for Treasuries have a 75% weight in both sectors' utility functions, albeit slightly larger for insurers. To understand the implications of these parameters for both portfolio choice and equilibrium interest rates, I perform four counterfactual experiments in the model.

First, I show that the slight difference in the weight of Treasury preferences across sectors translates to a very large effect on elasticities, do to the high estimated curvature of the Treasury preference component. Absent convenience yields, banks would be 3 times as sensitive to the mean and variance of excess returns, while insurers would be 9 times as sensitive. Then, I calculate that virtually all of the difference in sensitivity between banks and insurers is attributable to preferences for Treasuries.

I then analyse the effect of convenience yields on equilibrium excess returns. A time-series decomposition of the model-implied excess returns reveals that the convenience yield term is large, about 0.35 basis points on average, and much more volatile than the excess return component, which fluctuates around 11 basis points.

Throughout the whole sample period, the convenience yield is large enough to turn the excess return negative, matching the empirical proxy for excess returns, as well as the low returns on Treasuries observed for foreign investors in particular (Jiang et al., 2022). Finally, I show that the model-implied excess returns are steeply increasing in the weight of the Treasury preference parameter for both investors, suggesting that the erosion of special status of US Treasuries can cost the government up to 79 basis points in higher interest rates on its debt from the loss of the convenience yield alone.

Therefore, the structural parameters recovered by taking the theoretical model to the data reveal that the convenience yield is a quantitatively important determinant of the portfolio choice for foreign banks and insurance companies, and it can explain almost all of the observed cross-section difference in the yield sensitivity of sovereign portfolio shares. Furthermore, the returns required to hold US Treasuries are substantially reduced by the presence of investors that value them because of their special status. On the other hand, Treasury returns would also rise very sharply should this special status be lost. Although limited to the context of banks and insurers in Europe, this result confirms that convenience yields are fundamental for the sustainability of US public debt, and at the same time casts a warning that the loss of credibility of US Treasuries as a global safe asset can be very costly from a fiscal perspective.

The remainder of the paper is organised as follows. Section 2 lays out a simple mean-variance portfolio problem with convenience yields, and derives propositions on portfolio shares and equilibrium excess returns. Section 3 estimates the coefficients of a linearised version of the model via 2SLS on data from eurozone banks and ICPFs. Section 4 recovers the structural parameters on investors' preferences from the estimated coefficients, and runs counterfactual experiments within the model. Section 5 concludes.

2 A model of portfolio choice with convenience yields

In this section, I build a simple model of sovereign portfolio choice with cross-sectoral heterogeneity in risk aversion and preference for US Treasuries, and derive the implications for asset pricing and the yield sensitivity of demand.

I model the static choice between euro-denominated government bonds issued by country j, offering a deterministic return, and US Treasuries, whose payoff is stochastic due to exogenous exchange rate fluctuations that are not modelled directly. Therefore, I implicitly assume no hedging of exchange rate risk. Importantly, the model also abstracts from sovereign credit risk, as the focus is on differences in returns that are motivated by convenience yields. Since credit risk is non-negligible for several countries in my sample, I control for it in the empirical analysis via credit default swaps (CDS) rates and country fixed effects. Investors also receive a stochastic income, which represents revenues from all other activities, for example loans for banks and premia from insurance. This assumption aims to capture succinctly other sources of income that are outside of the scope of this model of government bond portfolios, but nonetheless affect the investment choice by virtue of their correlation with sovereign returns.

I model the choice between US Treasuries and each country j's government bonds separately, to match the empirical setup that uses a panel of destination countries in the eurozone. In addition, note that the model abstracts from features like credit risk and home bias that would differentiate euro denominated assets. Therefore, all euro area sovereign bonds would be fungible and their optimal portfolio share would be indeterminate if I extended the analysis to the allocation of the entire portfolio jointly.

Two investor sectors populate the model: banks and insurance companies. They derive utility from wealth and additionally from holding US government bonds. This approach for modelling convenience yields is standard in the literature, and can be motivated by liquidity services(Nagel, 2016), for example by reducing transaction costs (Bansal and Coleman, 1996, Bansal et al., 2010), or by the desire to hold safe assets denominated in dollars, the dominant currency in both trade and financial markets (Maggiori et al., 2020, Coppola et al., 2023).[3]

2.1 Portfolio choice

Investors in sector k choose to allocate their initial wealth W_0^k between euro-denominated government bonds issued by country j, $b_{j,k}$, and US Treasuries $b_{US,k}$. By casting the choice in terms of shares $s_{j,k}$ and $s_{US,k}$ of fixed initial wealth $W_{0,k}$, the investor's problem is

[3]A non-exhaustive list of papers that adopt the bonds in the utility function approach includes Krishnamurthy and Vissing-Jorgensen (2012), Engel (2016), Engel and Wu (2018), Valchev (2021), Jiang et al. (2021b), Nagel (2016), Jiang et al. (2021a), and Bodenstein et al. (2023).

$$
\begin{aligned}
&\max_{s_{US,k}} \mathbb{E}[W_{0,k}] - 0.5\gamma_k \mathbb{V}[W_k] + \psi_k \frac{b_{US,k}^{1-\sigma} - 1}{1-\sigma} \\
\text{s.t.} \quad & W_k = W_{0,k}(R_j + (R_{US} - R_j)s_{US,k}) + Y_k \\
& s_{j,k} + s_{US,k} = 1,
\end{aligned}
$$

where $\gamma_k > 0$ is the investor's risk aversion parameter, W_k is their final wealth, Y_k is their stochastic income, $\psi_k > 0$ regulates the weight of the utility derived from holding Treasuries in the objective function, and $\sigma > 0$ regulates the curvature of the Treasury term in their preferences. Note that sectors are allowed to differ in their risk aversion and in the importance of US Treasuries in investors' preferences, but not in the curvature of the Treasury term in their utility. Thanks to this assumption, there are two structural parameters for each sector, which I then back out from the intercept and slope of each sector's estimated linearised portfolio equations. The common parameter σ is instead calculated from the slope of the equilibrium excess returns equation, which is also estimated in linear form. These structural parameters allow to perform counterfactual experiments on the relative importance of risk aversion and convenience yields for the sensitivity of portfolio shares and equilibrium excess returns.

The objective function is isomporphic to standard Markowitz (1952) mean-variance preferences, and can be derived from exponential utility over wealth and Treasury holdings, as shown in Appendix B .

The first-order condition for $s_{US,k}$ is

$$
\mathbb{E}\left[R_{US} - R_j\right] - \gamma_k W_{0,k} \mathbb{V}\left[R_{US} - R_j\right] s_{US,k} - \gamma_k Cov\left[R_{US} - R_j, Y_k\right] + \psi_k \left(W_{0,1} s_{US,k}\right)^{-\sigma} = 0 \tag{1}
$$

This condition is analogous to that of the standard mean-variance portfolio problem, save for the additional term in ψ_k. Since investors also derive utility from holding Treasuries directly, this term implies that they potentially choose a positive portfolio share even if Treasuries offer a disadvantageous risk-return profile ($\mathbb{E}\left[R_{US} - R_j\right] < 0$ and $Cov\left[R_{US} - R_j, Y_k\right] > 0$).

To solve for the optimal portfolio share, I linearise the first-order condition around $s_{US,k} = \bar{s}$, $\mathbb{E}\left[R_{US} - R_j\right] = \bar{e}$, $\mathbb{V}\left[R_{US} - R_j\right] = \bar{v}$, and $Cov\left[R_{US} - R_j, Y_k\right] = \bar{c}$. In the special case of log utility for Treasuries with $\sigma \to 1$, an analytical solution for $s_{US,k}$ exists. In Appendix C, I show how the results derived in this section extend to a nonlinear setting in the logarithmic case.

The optimal portfolio share for the linearised model is

$$s_{US,k} = \bar{s} - \gamma_k \frac{W_{0,k}\bar{s}\left(\mathbb{V}\left[R_{US} - R_j\right] - \bar{v}\right) + Cov\left[R_{US} - R_j, Y_k\right] - \bar{c}}{\gamma_k W_{0,k}\bar{v} + \sigma\psi_k W_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}} + \frac{1}{\gamma_k W_{0,k}\bar{v} + \sigma\psi_k W_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}}\left(\mathbb{E}\left[R_{US} - R_j\right] - \bar{e}\right) \tag{2}$$

Then, the derivative with respect to expected excess returns is

$$\frac{\partial s_{US,k}}{\partial \mathbb{E}\left[R_{US} - R_j\right]} = \frac{1}{\gamma_k W_{0,k}\bar{v} + \sigma\psi_k W_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}}. \tag{3}$$

Note that the derivative is higher for $\psi_k = 0$, where it collapses back to the standard mean-variance case. Therefore, convenience yields results in a *lower* sensitivity of investors' portfolio shares to excess returns compared to standard mean-variance preferences: as investors have a further motive to hold Treasuries beyond excess returns, they are less sensitive to changes in the latter. In general, both a higher risk aversion parameter γ_k and a higher Treasury preference parameter ψ_k would imply a lower sensitivity to excess returns, so that the simple comparison of elasticities across sector does not suffice to identify the effect of these two factors. In order to quantify their relative importance, it is then crucial to recover the structural parameters from the estimates of the intercept and slope of Equation 2 for both sectors.

Convenience yields also have implications for the sensitivity of Treasury demand to market voaltility. The derivative with respect to the variance of excess returns is

$$\frac{\partial s_{US,k}}{\partial \mathbb{V}\left[R_{US} - R_j\right]} = -\frac{\gamma_k W_{0,k}\bar{s}}{\gamma_k W_{0,k}\bar{v} + \sigma\psi_k W_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}}. \tag{4}$$

It is smaller in absolute value compared to the standard case without preference for US Treasuries. Therefore, investors rebalance away from Treasuries less intensely for any given increase in variance when they hold Treasuries for reasons other than their risk-return profile. To the extent that events that affect the variance of Treasury returns, such as monetary policy decisions or negotiations over the US debt limit, do not endanger the underlying special status of US Treasuries, represented by a lower ψ_k in the model, convenience yields also insulate Treasury demand from market volatility, resulting in a more stable source of funding for the government.

2.2 Equilibrium and pricing

The previous section analysed the response of investors' US Treasury portfolio share to changes in the mean and variance of excess returns, while remaining agnostic on the source of the latter. In this section, I derive excess returns in equilibrium as a function of the relative supply of euro area and US bonds. Thus, I obtain a theoretical counterpart for the empirical identificaiton strategy, which exploits exogenous changes in the supply of euro area government securities.

Equilibrium excess returns

The market clearing conditions for euro area and US government bonds, respectively, are

$$\sum_k b_{j,k} + b_{j,O} = B_j$$
$$\sum_k b_{US,k} + b_{US,O} = B_{US},$$

where B_j is the supply of euro-denominated bonds issued by country j, and likewise B_{US} is the supply of US Treasuries. The market clearing conditions also include holdings of country j and US government bonds held by other investors, respectively $b_{j,O}$ and $b_{US,O}$. While European banks and insurers are large players in the market for euro area sovereign bonds, their combined positions in US Treasuries add up to a maximum of 2.5 % of the total supply. Therefore, it is crucial to account for holdings of other investors to obtain realistic market-clearing conditions. These holdings are defined residually and maintained as exogenous throughout the model.

The equilibrium is a set of portfolio allocations $\{b_{j,k}, b_{US,k}\}$ for $k = \{B, I\}$ and Treasury excess returns $\mathbb{E}[R_{US} - R_j]$ such that the first-order conditions of banks and insurers hold, and the markets for euro area and US government bonds clear.

To derive equilibrium expected excess returns, sum the first-order conditions of both investors, defining for ease of exposition $\tau_k := \frac{1}{\gamma_k}$, the risk tolerance parameter of investor sector k.

$$
\mathbb{E}[R_{US} - R_j] = \underbrace{\frac{\sum_k \left(\mathbb{V}[R_{US} - R_j] b_{US,k} + Cov\left[R_{US} - R_j, Y_k\right]\right)}{\sum_k \tau_k}}_{\text{Risk premium} := RP} \\ \underbrace{- \frac{\sum_k \psi_k \tau_k b_{US,k}^{-\sigma}}{\sum_k \tau_k}}_{\text{Convenience yield} := \phi} \tag{5}
$$

Equilibrium excess returns of US Treasuries comprises two parts that can be interpreted intuitively. The first is a standard risk premium term: increasing in the volatility of excess returns and in the covariance between excess returns and income; and decreasing in the investors' risk tolerance. The second is specific to this model, and it can be interpreted as a convenience yield. The higher ψ_k, the weight of Treasuries in investors' preferences, the lower the equilibrium excess returns *ceteris paribus*. Since investors derive utility from holding Treasuries beyond their risk-return profile, they are willing to accept a lower monetary return, and this is is reflected in a convenience yield in equilibrium. This mechanism is well-studied in the literature on US Treasury pricing, since at least Krishnamurthy and Vissing-Jorgensen (2012), and it can explain the observed premium on US Treasuries (Du et al., 2018). Note that the convenience yield term is the average marginal benefit from Treasuries across investors, weighted by their risk tolerance. A higher risk tolerance for investor sector k implies a larger weight of their preferences on the equilibrium excess returns.

Much like the deviations from interest parity arising in open-economy macroeconomic models that incorporate convenience yields, the presence of Treasury holdings in the payoff function introduces a wedge in the pricing equation (Engel and Wu, 2018, Jiang et al., 2021a, Valchev, 2021). However, in this model Treasuries carry exchange rate risk from the perspective of European investors, so the usual interest parity condition does not generally hold even in the absence of Treasuries in the utility function. As a consequence, the observed negative excess returns of Treasuries could be explained by a strongly negative correlation between excess returns combined with a relatively low excess return volatility. However, in the data we observe a low $Cov\left[R_{US} - R_j, Y_k\right]$ for banks and insurers alike. Therefore, from the perspective of the asset pricing equation implied by the model, the risk-return profile of US Treasuries for European investors is not likely to be a convincing explanation for negative excess returns.

The effects of debt supply

Equilibrium excess returns depend on debt supply through the risk premium component: the higher the amount of risky asset B_{US}, the higher the risk premium required for investors to absorb it. However, quantities enter equation 5 through the convenience yield term too. Due to the diminishing marginal utility of US government bonds, the weight of the convenience yield term is decreasing in the amount investors hold. This result is discussed in Jiang et al. (2021b), which shows in a general equilibrium model how central bank quantitative easing affects asset prices also by altering the relative supply of safe assets with non-monetary payoffs.

To highlight this mechanism, re-write Equation 5 as a function of the supply of country j governemnt bonds B_j, using the market clearing conditions and the budget constraints of both agents.

$$\mathbb{E}[R_{US} - R_j] = \frac{\sum_k \mathbb{V}[R_{US} - R_j] \left(\sum_k W_{0,k} - B_j + b_{j,O}\right) + \sum_k Cov\left[R_{US} - R_j, Y_k\right]}{\sum_k \tau_k} - \frac{\sum_k \psi_k \tau_k \left(W_{0,k} - B_j + b_{j,O} + \sum_{l \neq k} b_{j,l}\right)^{-\sigma}}{\sum_k \tau_k}.$$

Excess returns then depend on the supply of euro-denominated government bonds B_j through both the risk-premium and the convenience yield terms. A change in B_j alters not only the relative amount of safe versus risky assets on the market, hence affecting the risk premium; but also the relative amount of US Treasuries that investors have to absorb, hence affecting the equilibrium convenience yield.

In the empirical estimation, I exploit exogenous changes in the supply of European government bonds due to the implementation structure of the PSPP programme by the European Central Bank. I use PSPP holdings as an instrument for changes in excess returns in a two-stage least squares setup. To understand the model-implied sign of the coefficient on PSPP amounts in the first-stage regression, I analyse the derivative of $\mathbb{E}[R_{US} - R]$ with respect to B_j. Furthermore, this derivative implies restrictions on ψ_k, γ_k and σ that I exploit to back out these structural parameters.

Proposition 1 (Reaction of excess returns to euro area debt supply)**.**

$$\frac{\partial \mathbb{E}[R_{US} - R_j]}{\partial B_j} = \frac{\mathbb{V}[R_{US} - R_j]\left(\frac{\partial b_{j,O}}{\partial B_j} - 1\right)}{\sum_k \tau_k \left(1 - \frac{\sigma \psi_k b_{US,k}^{-\sigma-1}}{\mathbb{V}[R_{US} - R_j]/\tau_k + \sigma \psi_k b_{US,k}^{-\sigma-1}}\right)} < 0. \tag{6}$$

Proof. In Appendix D.1. □

Note that the derivative depends on $\frac{\partial b_{j,O}}{\partial B_j} \in [0,1]$, the absorption rate of government debt by other investors. It is an exogenous object in the model, and I estimate it empitically in the calibration of the model. Proposition 1 predicts a compression in US Treasuries excess returns in response to a higher supply of country j government bonds, through both the risk premium and the convenience yield components. An increase in the supply of euro government bonds reduces the relative amount of US Treasuries that investors have to absorb in equilibrium. Since Treasuries are a risky asset, the relative reduction in supply leads to a lower risk premium. At the same time, due the concavity of the Treasury component of investors' utility, they are now willing to accept a lower return *ceteris paribus* on Treasuries as their relative supply decreased. [4].

The presence of convenience yield preferences represented by ψ_k makes the fall in excess returns larger than it would be with $\psi_k = 0 \, \forall \, k$, as the second term in the denominator vanishes. Therefore, for any given reduction in the relative size of US government debt, the funding cost of US government debt falls more strongly if investors derive utility from holding Treasuries.

Linearisation

In order to estimate the reaction of equilibrium excess return to debt supply as the first stage of a two-stage least squares system with portfolio equations as second stage, I sart by linearising equation 5. The approximation points are $\mathbb{E}\left[R_{US} - R_j\right] = \bar{e}$, $Cov[Y_k, R_{US} - R_j] = \bar{c}$, $\mathbb{V}\left[R_{US} - R_j\right] = \bar{v}$, $B_j = \bar{B}_j$, $b_{j,O} = \bar{b}_{j,O}$ and $b_{US,k} = \bar{b}_{US,k} = W_{0,k}\bar{s}$. Note that I treat initial wealth $W_{0,k}$ as a fixed parameter, as the model makes predictions on portfolio shares rather than quantities. The linearised excess returns equation is

$$\mathbb{E}[R_{US} - R_j] = \bar{e} + \frac{1}{\sum_k \tau_k}\left(\left(\sum_k W_{0,k} - \bar{B}_j + \bar{b}_{j,O} \right) (\mathbb{V}[R_{US} - R_j] - \bar{v}) - \bar{v}(B_j - \bar{B}_j + \bar{v}(b_{j,O} - \bar{b}_{j,O})) + \sum_k \left(Cov\left[R_{US} - R_j, Y_k\right] - \bar{c}\right) + \sigma \bar{b}_{US,k}^{-\sigma-1} \sum_k \tau_k \psi k (b_{US,k} - \bar{b}_{US,k}) \right). \tag{7}$$

Following the same steps as in the proof of proposition 1 for the nonlinear case, the derivative with respect to euro-denominated debt supply B_j is

[4] I implicitly assume that changes in B_j have no effect on variances and covariances, which are treated as fixed parameters.

$$\frac{\partial \mathbb{E}[R_{US} - R_j]}{\partial B_j} = \frac{\bar{v}\left(\frac{\partial b_{j,O}}{\partial B_j} - 1\right)}{\sum_k \frac{1}{\gamma_k}\left(1 - \frac{\sigma \bar{b}_{US,k}^{-\sigma-1}\psi_k}{\gamma_k \bar{v} + \sigma \psi_k \bar{b}_{US,k}^{-\sigma-1}}\right)} \tag{8}$$

In the empirical model, this equation will provide restrictions on structural parameters that, together with those imposed by the intercept and slope of linearised portfolio equations, allow me to identify γ_k, ψ_k, and σ.

3 Estimation

The model makes three key predictions on the role of convenience yields for the sensitivity of portfolio shares to excess returns, and on equilibrium excess returns. First, investors increase their US Treasury sovereign portfolio shares in response to higher expected excess returns, but by a smaller amount than they would if they did not derive a convenience yield from holding Treasuries. Second, the reduction in US Treasury portfolio shares in response to an increase in the variance of returns is smaller in absolute value than it would be absent convenience yields. Third, an increase in the supply of euro area government bonds induces a decline in equilibrium excess returns for Treasuries. These predictions concern unobserved counterfactuals, so I need to estimate the structural parameters γ_k, ψ_k and σ to test it within the model. Furthermore, the structural parameters are informative on the extent to which cross-sector differences in sensitivity to excess returns are attributable to heterogeneity in risk aversion versus preference for US Treasuries. I recover the structural parameters by relating the theoretical restricions implied by the model to estimable objects in a two-stage least square system applied to data from euro area banks and insurers.

3.1 Mapping the model to the data

In order to map the regression coefficients of the 2SLS system to the structural parameters directly, I use the linearised portfolio equation 2 for each sector, and an equation that models excess returns directly as a linear function of B_j, using the restriction on the linearised derivative implied by equation 8. In addition to recovering structural parameters, the estimates of this system can also confirm the predictions of the model on the sign of portfolio share and excess returns derivatives.

Estimation equations

The estimation equations in the 2SLS model are the following, disregarding time subscripts for notational ease:

$$s_{US,k} = \alpha_k + \beta_k \mathbb{E}[R_{US} - R_j] + \varepsilon_{j,k} \text{ for } k = \{B, I\}, \tag{9}$$
$$\mathbb{E}[R_{US} - R_j] = \iota + \pi B_j + \nu_j. \tag{10}$$

The first equation corresponds to the linearised portfolio share 2, while the second one specifies excess returns directly as a linear function of country j debt supply. As a result, the coefficients of the empirical model as a function of structural parameters are

$$\alpha_k = \bar{s} - \gamma_k \frac{W_{0,k}\bar{s}\left(\mathbb{V}\left[R_{US} - R_j\right] - \bar{v}\right) + Cov\left[R_{US} - R_j, Y_k\right] - \bar{c}}{\gamma_k W_{0,k}\bar{v} + \sigma\psi_k W_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}}, \tag{11}$$
$$\beta_k = \frac{1}{\gamma_k W_{0,k}\bar{v} + \sigma\psi_k W_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}} > 0, \tag{12}$$
$$\pi = \frac{\bar{v}\left(\frac{\partial b_{j,O}}{\partial B_j} - 1\right)}{\sum_k \frac{1}{\gamma_k}\left(1 - \frac{\sigma \bar{b}_{US,k}^{-\sigma-1}\psi_k}{\gamma_k\bar{v} + \sigma\psi_k\bar{b}_{US,k}^{-\sigma-1}}\right)} < 0. \tag{13}$$

The linearised portfolio share for each sector has two empirical parameters, α_k and β_k, providing two equations per sector. The linearised excess returns provides only one additional equation, because only the parameter π, the derivative of excess returns to country j sovereign debt supply in a linear model, has a direct theoretical equivalent in equation 8. This feature arises because the empirical model expresses $\mathbb{E}[R_{US} - R_j]$ directly as a function of B_j, while in the theoretical model the derivative to B_j exploits the property that in equilibrium $s_{US,k}$ depends on B_j through excess returns. Therefore, there is no theoretical restriction on ι, so it is not used in the recovery of structural parameters. In total, the estimation of this system results in five equations, which allow to solve for the five structural parameters: γ_k and ψ_k for $k = \{B, I\}$, and σ.

I estimate β_B, β_I, and π via a 2SLS procedure with equation 10 as first stage, and equations 9 as second stage for both sectors. I identify β_B and β_I using exogenous changes in B_j as an instrument for $\mathbb{E}[R_{US} - R_j]$ in 9. The theoretical equivalent of parameter π in equation 10 is obtained by linearising $\mathbb{E}[R_{US} - R_j]$ as a function of B_j and $b_{j,US}$, and differentiating with respect to B_j while taking into account that $b_{j,US}$, and so $s_{j,US}$, is a function of $\mathbb{E}[R_{US} - R_j]$ only through B_j. As a result, the linearised excess return implies that B_j satisfies the exclusion restriction as an instrument for $\mathbb{E}[R_{US} - R_j]$ in a model of s^B_{US}. The model also clearly implies that excess returns depend on B_j in equilibrium, so the requirement of instrument relevance is satisfied too.

3.2 Data

I estimate the equations outlined in the previous section on data from banks and ICPFs resident in the euro area, sourced from the publicly available Securities Holdings Statistics (SHS) dataset by the European Central Bank. The European setting provides an ideal context to study the role of convenience yields for the demand of US Treasuries by different types of investors because of several useful features.

First, the available data allows to observe the sovereign portfolios of different sectors operating under essentially the same regulatory regime. Existing literature on the demand for government bonds mainly relies on global data that does not provide a breakdown of government bond holdings by both country and sector. [5] While cross-sector differences in preferences are plausibly constant across jurisdictions, the regulatory regimes for banks relative to insurers might not be. Therefore, differences in the sensitivity of the demand for safe assets estimated in previous studies might confound heterogeneity in both preferences and regulation. In the European Union, banks and insurance companies are subject to very similar rules concerning investment in sovereign debt. Both Article 351 of the Capital Requirement Regulation (*EU Regulation No 575/2013*), applying to banks; and Article 180 of the Solvency II regulation(*EU Regulation No 35/2013*), applying to insurers, assign, with almost identical language, a zero weight for capital requirements to bonds that either have a high sovereign rating (like US Treasuries) or are denominated in euros. Therefore, from the regulatory standpoint, both banks and insurers are free to adjust the relative portfolio share of US and euro area sovereign bonds in response to returns without affecting their stock of risk-weighted assets relevant for capital buffers.[6] As a result, any observed discrepancy in the demand

[5] Some exceptions include Tabova and Warnock (2022), Eren et al. (2023)., and Fang et al. (2023)

[6] The only material difference in the regulatory treatment of euro area and US government bonds concerns exchange rate risk. Exposure to US Treasuries, if unhedged, counts against regulatory limits for foreign exchange risk exposure. Faia et al. (2022) uses this divergence, together with a different regime of capital requirements between insurance companies and mutual funds, to motivate differences in demand elasticity for these two sectors and deviations from covered interest parity. In this paper, I abstract from limits to foreign exchange exposure, which

sensitivity to convenience yields across these sectors is plausibly attributable to preferences. Thanks to this regulatory design, I can zoom in on differences in preferences only, using the estimates of structural parameters to disentangle the role of risk aversion and convenience yields.

Furthermore, the use of global data for different investor classes would introduce complications in mapping the model to the data. The theoretical model in this paper analyses the simple choice between US and domestic-currency government bonds. While euro-denominated sovereign bonds are a natural choice of domestic asset when focusing on the eurozone, this would not be the case when using global data.[7] Extending the exercise of this paper to global data would require either a more complex model of the whole sovereign portfolio with multiple assets, or the construction of a synthetic "domestic" asset for global foreign investors in US Treasuries from the data.

The rationale for comparing the sensitivity of demand of the banking and ICPF sector specifically also lies in the plausibly large difference in risk aversion due to their business models. As insurance companies are likely more risk-averse than banks in general, the structural model is less liable to overstate any difference in preferences for Treasuries due to the fact that it accounts only for these two parameters.

Finally, the peculiar structure of purchases under the PSPP quantiative easing policy by the ECB generates exogenous variation in the relative supply of government bonds across euro area countries. This policy intervention provides an ideal instrument to identify exogenous changes in US Treasury excess returns relative to euro area sovereign bonds. Therefore, I can estimate equations 9 and 10 with a panel 2SLS strategy.

3.3 Identification strategy

According to the model, changes in the supply of country j government bonds are a valid and relevant instrument for excess returns in estimating the portfolio equation 9, because the latter depends on B_j only through excess returns. However, the very stylised partial equilibrium model does not take into account that debt supply is likely endogenous to the portfolio choice of financial intermediaries through

would affect both banks and insurers equally.

[7] I use data on the portfolios of the aggregate banking and insurance sector in the eurozone, so the domestic asset is defined at the currency rather than country level. This approach is consistent with the assumption of risk premia stemming only from exchange rate fluctuations in the model.

general equilibrium effects. Even considering only changes in debt supply due to unconventional monetary policy is not enough to allay concerns of endogeneity, as these policies are adopted in response to highly endogenous macroeconomic conditions. This argument has particular bite for European banks, as they tend to load up on domestic government bonds in precisely the same turbulent times that motivate quantiative easing policies, either in a "gambling for resurrection" strategy (Acharya and Steffen, 2015) or due to "moral suasion" by their governments (De Marco and Macchiavelli, 2016, Ongena et al., 2019).

In order to obtain changes that are truly exogenous to investors' portfolio choice, I exploit the characteristics of the PSPP, implemented by the ECB starting in January 2015. The ECB bought government bonds issued by all countries with a credit rating of at least BBB-, and with maturities from 2 to 30 years.[8] The purchases are apportioned according to a scheme that aims at a market-neutral approach. They are proportional to each country's Capital Key, and they mirror as closely as possible the maturity structure of outstanding bonds.

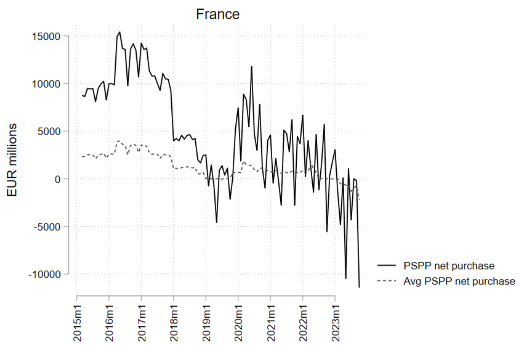
The Capital Key for each country is the equal-weighted average of its share of the euro zone's population and GDP. It is updated every five years, and whenever the membership of the European Union (EU) changes. In my sample, running from 2015 to 2022, the Capital Key changed twice: in 2019 due to a five-yearly update, and in 2020 due to the withdrawal of the United Kingdom from the EU. Since country size is plausibly independent of portfolio choice, and updates related to GDP are slow-moving, changes in Capital Key are likely exogenous. The other source of variation is the cross-country difference between the extant maturity structure of PSPP holdings, and that of the country's outstanding government bonds. Since this difference depends only on the governments' choice on the maturity of issuance and on the pre-existing PSPP term structure, it probably satisfies the exclusion restriction as well. Koijen et al. (2021) also uses PSPP purchases as an instrument for debt supply, but it relies on purchases predicted by the Capital Key rather than the actual amounts.

One step is missing to be able to claim PSPP holdings are a valid instrument for excess returns: while it can be argued that the *cross-sectional* variation in PSPP holdings is exogenous to investors' portfolio choice, this is not the case for the *time-series* dimension. Changes in total purchases over time track the overall size of the quantiative easing programme, which is obviously correlated to investors'

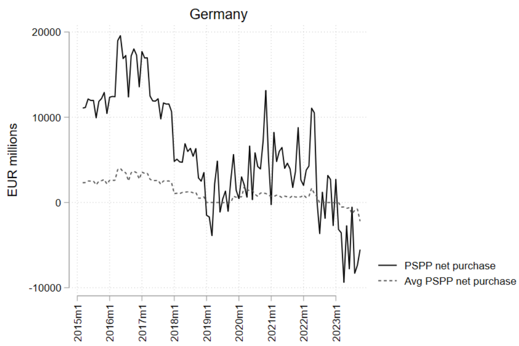
[8]The restriction on credit rating resulted in the exclusion of Greek bonds. In the context of this paper, the exclusion of Greece helps in ensuring that the empirical proxy for excess returns is driven by currency risk and not default risk, which reflects the assumption made in the model.

portfolios through macroeconomic fluctuations. To account for this issue, I use time fixed effects that soak up trends in the average amount of PSPP purchases across countries. Figure 3 illustrates the source of variation exploited for identification. The solid line represents purchases for each of the four largest euro area country, while the dashed line depicts average purchases across countries. By using time fixed effects, I rely only on the informtion contained in the differences between the solid and the dotted line for each country.

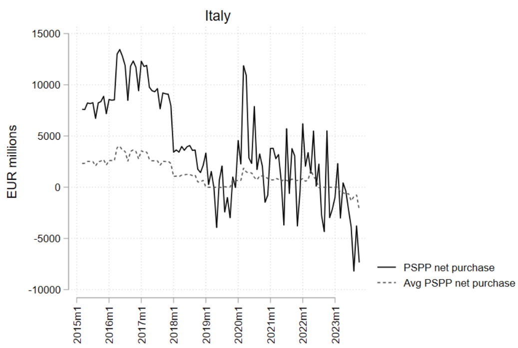
Figure 3. PSPP purchases



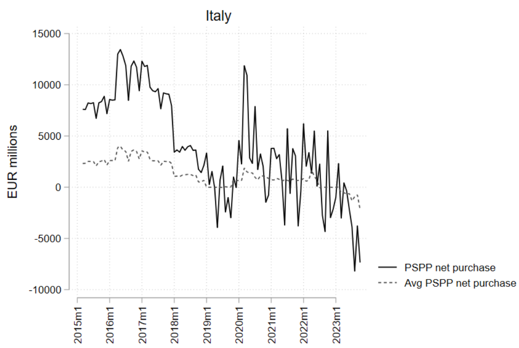
(a) France



(b) Germany



(c) Italy



(d) Spain

Monthly net purchases of sovereign debt under the Public Sector Purchase Programme, all maturities. The solid line depicts monthly net purchases for a country, the dashed line represents the cross-sectional average of monthly net purchases across all eligible countries over quarters. Source: European Central Bank

3.4 Estimation via two-stage least squares

In this section, I lay out the estimating equations for the empirical model and report the results. The starting point is the set of equations 9 and 10 derived from the linearised theoretical model. While they can be estimated directly as written above, I modify them to account for complications and nuances in the data that the model fails to capture. The baseline first-stage regression is

$$er_{j,t} = \iota_j + \iota_t - \pi PSPP_{j,t} + \lambda' \mathbf{V_{j,t}} + \kappa' \mathbf{W_{j,t}} + \nu_{j,t},$$

where $PSPP_{j,t}$ are PSPP holdings of country j government debt in quarter t, which proxy the exogenous component of B_j.[9] Note tht the coefficient π enters the equation with a minus sign because an increase in PSPP holdings corresponds to a *decrease* in the amount of country j's sovereign debt available to investors. The second-stage regression for $k = \{B, I\}$ is

$$s_{US,j,k,t} = \alpha_{k,j} + \alpha_{k,t} + \beta_k er_{j,t} + \delta_k' \mathbf{V_{j,t}} + \eta_k' \mathbf{W_{j,t}} + \varepsilon_{j,k,t}.$$

One difference from the theoretical model is due to the panel structure of the data. I rely on quarterly observations of sovereign holdings, so $s_{US,j,k,t}$ is the quarter t share of US Treasuries in a portfolio comprised of country j's government bond and US Treasuries for all euro area investors in sector k. Likewise, $er_{j,t}$ is a proxy for the excess returns of US Treasuries with respect to country j's government bonds, on average for quarter t. Expected excess returns in the model depend on a number of unobservable factors, such as investor's expectations on the future path of asset prices and exchange rates, and their investment horizion. Therefore, I follow the methodology in Koijen et al. (2021) and proxy $\mathbb{E}[R_{US} - R_j]$ as follows:

$$er_{j,t} = y_{US,t} - y_{j,t} + \rho_t - d_{j,t}$$

where $y_{US,t}$ and $y_{j,t}$ are the yields of US and country j government bonds; ρ_t is the market-implied forward premium for the euro against the dollar; and $d_{j,t} := CDS_{US,t} - CDS_{j,t}$ is the difference in sovereign CDS rates between the US and country j. All components are averaged over the 1,2,3,5, and 10 year maturities and over quarter t, weighted by the maturity structure of outstanding government debt for country j. This approach relies on using ρ_t as a measure of market-based expectations for exchange rates, and on controlling for differences in credit risk through $d_{j,t}$. The latter is pivotal in estimating the theoretical model, as it is assumed that excess returns arise only through currency fluctuations, while in the data sovereign risk is likely to play an important role, especially in a sample of

[9] Note that section 3.3 discusses the identification strategy in terms of PSPP purchases to build intuition, but here I use PSPP *holdings* because in the theoretical model excess returns depend on the *level* of government debt supply.

European government bonds. The macroeconomic and financial controls included as time fixed effects and in $\mathbf{V_{j,t}}$ and $\mathbf{W_{j,t}}$ complement the strategy by serving as potential predictors of excess returns, akin to the factor models popular in modern empirical asset pricing (Koijen and Yogo, 2019a,b).

The regressions also include fixed effects at both the country ($\alpha_{k,j}$ and $\iota_{k,j}$) and quarter ($\alpha_{k,t}$ and $\iota_{k,t}$) level. As explained in section 3.3, time fixed effects aid the identification strategy by isolating cross-country differences in PSPP holdings. Furthermore, they control for any global determinants of the demand and supply of safe assets. Country fixed effects account for time-invariant featrues such as idiosyncratic country risk, abstracted away in the theoretical model. Controlling for country risk is particularly important for bonds issued by distressed sovereign such as Italy, Ireland, Portugal and Spain. Given the "bank-sovereign nexus", whereby investment in risky sovereign bonds by domestic banks is often driven by political considerations (Andreeva and Vlassopoulos, 2016, Ongena et al., 2019, Saka, 2020), country-specific risk is especialy relevant in the model for bank portfolios. Country fixed effects also take care of any potential cross-country pattern in the correlation and variance of excess returns, which are kept as fixed parameters in the theoretical model.

I also augment the model with two sets of country-quarter level controls. The first set, $\mathbf{V_{j,t}}$ accounts for changes in the portfolio shares due to valuation effects. The theoretical model is cast in real terms, so in the data I need to control for valuation effects due to both bond prices and exchange rates, in order to isolate actual portfolio rebalancing. In the baseline specification with time and country fixed effects, $\mathbf{V_{j,t}}$ includes quartely changes in the all-maturity price index for country j's government bonds $\Delta BI_{j,t}$. Note that changes in the EUR/USD exchange rate $\Delta e_t^{EUR/USD}$ and in the dollar price of US bonds $\Delta BI_{US,t}$, which also affect portfolio shares, are subsumed in the quarterly fixed effects. They are included in $\mathbf{V_{j,t}}$ for specifications whose fixed effect structure allows it.

The second set of controls $\mathbf{W_{j,t}}$ include CPI inflation, real GDP growth and the ratio of government debt to GDP for country j in quarter t. The first two variables are included to succinctly capture macroeconomic factors that affect investment in country j, which might be correlated with the maturity choice of government debt issuance, in turn driving variation in PSPP holdings. The latter captures both a time-varying factor of country risk, and possible concerns of residual discretionality in PSPP purchases tilted towards highly indebted countries.

I estimate the model on country-quarter observations from 2015 Q1 to 2022 Q1 for all eurozone countries except Greece, as it is excluded from the PSPP; and Estonia and Luxembourg, due to data availability.

Summary statistics

Table 1 reports summary statistics for the variables used in the regression model. The shares of US Treasuries to country j government bonds are large, around 50% for ICPFs and more than 70% for banks on average. The empirical proxy for excess return is on average negative for Treasuries, at -26 basis points. Coupled with the positive correlation between Treasury excess returns and the income of insurance companies shown in Figure 3(b), this feature suggests that the risk-return profile of Treasuries is not sufficient to explain ICPF's holdings of US Treasuries and convenience yields might indeed be at play.

In order to benchmark the convenience yield implied by the estimation of structural parameters, I report an empirical proxy of the convenience yield component of excess returns.[10] The empirical convenience yield is negative, as predicted by the model, with an average of -25 basis points. It is on average very close to excess returns, implying a very small risk premium in the model. Therefore, we would expect convenience yields to also explain the lion's share of the excess returns implied by the estimated structural parameters.

First-stage regression

Table 2 displays results from the first-stage regression. The coefficient on $PSPP_{i,t}$ in the column 3, the preferred specification including both time and country fixed effects, reports a highly statistically significant increase of 1.47 percentage points in US Treasury excess returns in response to a one standard deviation increase in PSPP holdings, equivalent to about \$ 153 billion. The size of the coefficient is also significant, almost three times larger than the 0.64 percentage point standard deviation of the empirical proxy for excess returns.

The sign of the coefficient is consistent with the prediction of the model, as an increase in PSPP holdings corresponds to a decrease in the supply of country j government debt on the market. The increase in US Treasury excess returns, possibly through the convenience yield component, echoes the findings of Jiang et al. (2021b), which highlights the change in the relative supply of safe assets and convenience yields as an additional channel through which quantitative easing affects

[10] I follow Du et al. (2018) in estimating convenience yields as $\phi_{j,t} = y_{US,t} - y_{j,t} + \rho_t - bs_{j,t} - l_{i,t}$, where $bs_{j,t}$ is the EUR/USD cross-currency basis swap, a measure of CIP deviations in interbank rates that purges the measure of convenience yields of FX market frictions.

Table 1. Summary statistics

	N	Mean	SD	Min	P25	P50	P75	Max
A. Portfolio shares								
$s_{US,B,t}$	442	71.2	26.8	14.8	50.9	80.9	95.3	99.1
$s_{US,I,t}$	425	48.96	33.19	2.59	16.71	46.82	80.59	98.83
B. Financial variables								
$er_{j,t}$	463	-0.26	0.64	-5.21	-0.49	-0.16	0.08	0.77
$\phi_{j,t}$	387	-0.25	0.24	-2.04	-0.35	-0.25	-0.15	1.65
$\Delta BI_{j,t}$	371	0.20	4.39	-10.69	-1.89	0.42	3.10	14.09
$\Delta BI_{US,t}$	371	0.5	2.4	-4.7	-0.5	0.6	1.5	7.2
$\Delta e_t^{EUR/USD}$	463	0.4	3.9	-5.6	-1.8	0.1	2.5	13.7
C. Macroeconomic variables								
$Debt/GDP_{j,t}$	372	87.1	30.0	36.3	62.3	83.3	108.4	158.9
$\Delta CPI_{i,t}$	372	1.4	1.9	-2.2	0.2	1.1	2.0	11.7
$\Delta GDP_{i,t}$	343	0.6	3.5	-17.6	0.2	0.5	0.9	21.4

Summary statistics calculated on the data in which observations for PSPP holdings are non-empty. All variables in percentage points.

equilibrium interest rates.

Columns 1 and 2 show the results of models with no fixed effects, and with time fixed effects only, respectively. The inclusion of time fixed effects is crucial in my identification strategy as it allows to single out exogenous variation in relative debt supply that is independent of the ECB's overall unconventional monetary polcy stance. Column 2 shows how time fixed effects raise the F stat to 70.63, implying a stronger instrument as well as an arguably more valid one. Column 3 shows that the inclusion of country fixed effects does reduce the F statistic, albeit to a still high value of 23.86. Therefore, there is a tradeoff between having a strong instrument and controlling for important country-specific factors such as credit risk and the sovereign-bank nexus.

Second-stage regressions

Tables 3 and 4 report the estimation results of the second-stage equations for banks and ICPFs, respectively.

The preferred 2SLS specification with time and country fixed effects shows an in-

Table 2. First-stage regression

	(1)	(2)	(3)
$PSPP_{j,t}$	0.75***	1.37***	1.47***
	(0.10)	(0.16)	(0.30)
$\Delta BI_{j,t}$	-0.01*	-0.01*	-0.01
	(0.01)	(0.01)	(0.01)
$\Delta BI_{US,t}$	0.02**		
	(0.01)		
$\Delta e_t^{EUR/USD}$	-0.00		
	(0.00)		
N	309	309	309
F stat	58.71	70.63	23.86
Macro controls	Yes	Yes	Yes
Time fixed effects	No	Yes	Yes
Country fixed effects	No	No	Yes

Coefficients from regression model $er_{j,t} = \iota_j + \iota_t - \pi PSPP_{j,t} + \lambda' \mathbf{V_{j,t}} + \kappa' \mathbf{W_{j,t}} + \nu_{j,t}$. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

crease of the US Treasury portfolio shares in response to higher excess returns. The coefficient is statistically significant at the 1% level for both banks and insurers. Therefore, the prediction of a positive reaction to excess returns is verified for both sectors.

The comparison of coefficients on $er_{j,t}$ estimated via OLS (columns 1 to 3) and 2SLS (columns 4 to 6) suggests that the instrumental variable strategy purges the coefficients from the bias due to the endogeneity of supply and demand. The coefficient β represents the sensitivity of portfolio shares, an equilibrium quantity, to excess returns, tightly connected to equilibrium asset prices. Therefore, the observed price-quantity data points are likely driven by both demand and supply shocks. The former introduce a negative correlation between $s_{US,j,k,t}$ and $er_{j,t}$, while the latter a positive correlation. Therefore, failing to isolate supply shocks would result in a bias toward zero for β. PSPP-induced exogenous changes in B_j act as a supply shock, so by using them as instrument for $er_{j,t}$ the slope of the demand curve can be recovered. The larger and more significant coefficients across the board in the 2SLS models indicate that this strategy is indeed successful.

In order to understand what global variables are accounted for by time fixed effects, models in columns 1 and 4 replace them with the VIX, a key determinant of the demand for safe assets (Miranda-Agrippino and Rey, 2022); and with the debt/GDP ratio in the US to control for the supply of US Treasuries. The estimated β in columns 1 and 4 are very similar to those in columns 2 and 5, which replace global controls with quarterly fixed effects. Therefore, time fixed effects appear to capture well the role of global drivers of the demand and supply of safe assets. The lack of time fixed effects also allows to augment the vector of valuation effect controls $\mathbf{V_{j,t}}$ with changes in the exchange rate and US bond prices, which vary only in the time dimension. However, none of the valuation effects are statistically significant even at the 10% level, possibly because of relatively small quarter-on-quarter variation.

The models estimated in columns 2 and 5 include time fixed effects, but not country fixed effects. Comparing them to the coefficients in columns 3 and 6 reveals the imporance of controlling for country-specific characteristics, especially for banks, as argued in the previous section. In fact, the eclusion of country fixed effects in the bank regressions results in negative coefficients that do not seem particularly credible. The lower sensitivity of the models for insurance companies to country fixed effects corroborates the hypothesis that the political economy factors affecting investment of European banks in distressed sovereign bonds contribute to biasing the estimates. However, it is still important to include country fixed effects in the model for insurers. The reasons lie both in consitency with the estimates for banks, and in accounting for the time-invariant portion of country-specific credit risk, which the theoretical model abstracts away.

Figure 4 compares the coefficients on $er_{j,t}$ from column 6 of the models for banks and insurers. The US Treasury portfolio share of banks increases by 35.94 percentage points in response to a one percentage point increase in the convenience yield component of excess returns, while the portfolio share of insurers increases by 6.24 percentage points. The coefficients are statistically different from each other at the 1% significance level. The muted reaction of insurers' portfolio shares to excess returns is consistent with results in the literature (Timmer, 2018, Eren et al., 2023, Koijen et al., 2021), and suggests there is enough of a discrepancy in behaviour between the two sectors that more than risk aversion might be at play. However, it is not enough to test the predictions of the model on the effects of convenience yields on portfolio share sensitivity, as they concern a counterfactuals. In order to quantify the relative importance of risk aversion and preferences for Treasuries, it is necessary to recover the structural parameters γ_k, ψ_k and σ from the estimates of the empirical model. I turn to this task in the next section.

Table 3. Second-stage regression for banks

	OLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
$er_{j,t}$	-7.44	-15.20*	4.75**	22.86	-3.43	35.94***
	(6.98)	(8.79)	(2.32)	(24.19)	(25.08)	(9.94)
$\Delta BI_{j,t}$	0.01	0.89	-0.22	0.32	1.05	0.03
	(0.82)	(1.37)	(0.17)	(0.88)	(1.33)	(0.23)
$\Delta BI_{US,t}$	0.34			-0.47		
	(1.09)			(1.28)		
$\Delta e_t^{EUR/USD}$	0.19			0.35		
	(0.74)			(0.75)		
N	309	309	309	309	309	309
Macro controls	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	No	Yes	Yes	No	Yes	Yes
Country fixed effects	No	No	Yes	No	No	Yes
Underid test p-value				0.00	0.00	0.00
Weak id test stat				58.71	70.63	23.86

Coefficients from regression model $s_{US,j,B,t} = \alpha_{B,i} + \alpha_{B,t} + \beta_B er_{j,t} + \delta'_B \mathbf{V_{j,t}} + \eta'_B \mathbf{W_{j,t}} + \varepsilon_{j,B,t}$ estimated via OLS, or via 2SLS using $PSPP_{j,t}$ as an instrument for $er_{j,t}$. The underidentification test uses the Kleibergen and Paap (2006) LM statistic. The weak identification test uses the Kleibergen and Paap (2006) Wald F statistic. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4 Structural parameters and model experiments

4.1 Recovery of structural parameters

After obtaining the coefficient estimates $\hat{\alpha}_k$, $\hat{\beta}_k$ for $k = \{B, I\}$, and $-\hat{\pi}$ from the 2SLS model, I can back out values for the structural parameters by solving the system of equations 11, 12 and 13 for γ_k, ψ_k, and σ.

Equation 13 depends on $\partial b_{j,O}/\partial B_j$, the absorption rate of country B_j's government bonds by other investors. I estimate this parameter through absorption regressions that decompose total outstanding amounts of country j government bonds into sectoral holdings, and I replace the absorprion rate of other investors with its estimate $\hat{\theta}_O$.[11] Since it is an estimated parameter, I will have to account for estimation uncertainty in the simulation of confidence intervals for the struc-

[11] More details on this procedure, as well as the full regression results, can be found in Appendix E

Table 4. Second-stage regression for insurers

	OLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
$er_{j,t}$	-2.46	-4.99*	-0.45*	17.75***	10.03	6.24***
	(1.97)	(2.56)	(0.24)	(6.25)	(6.73)	(2.02)
$\Delta BI_{j,t}$	0.74	2.14	-0.17	1.72	3.15*	0.10
	(0.92)	(1.59)	(0.14)	(1.15)	(1.69)	(0.24)
$\Delta BI_{US,t}$	0.16			-2.56		
	(1.26)			(1.72)		
$\Delta e_t^{EUR/USD}$	0.49			0.98		
	(0.79)			(0.92)		
N	307	307	307	307	307	307
Macro controls	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	No	Yes	Yes	No	Yes	Yes
Country fixed effects	No	No	Yes	No	No	Yes
Underid test p-value				0.00	0.00	0.00
Weak id test stat				58.21	69.86	23.65

Coefficients from regression model $s_{US,j,I,t} = \alpha_{I,i} + \alpha_{I,t} + \beta_I er_{j,t} + \delta_I' \mathbf{V_{j,t}} + \eta_I' \mathbf{W_{j,t}} + \varepsilon_{j,I,t}$ estimated via OLS, or via 2SLS using $PSPP_{j,t}$ as an instrument for $er_{j,t}$. The underidentification test uses the Kleibergen and Paap (2006) LM statistic. The weak identification test uses the Kleibergen and Paap (2006) Wald F statistic. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

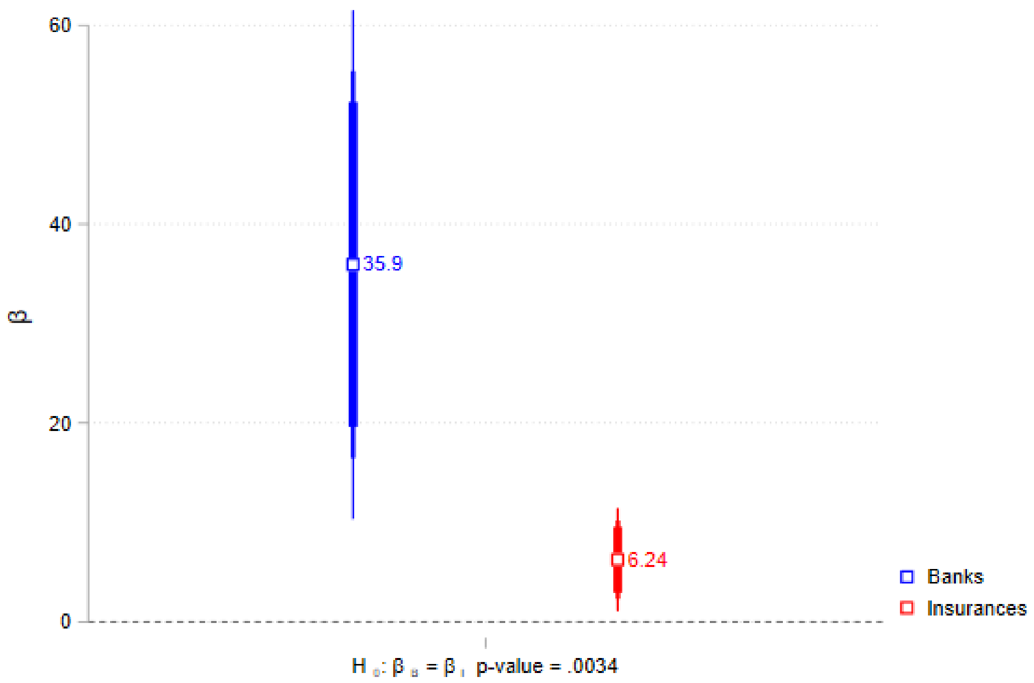
tural parameters.

I replace α_k, β_k and π with their estimates from the model with country and quarter fixed effects, and choose approximation points $\bar{e} = 0$, $\bar{c} = 0$, $\bar{v} = 1$, and $\bar{s} = 0.5$. [12] Computational convenience guided the choice of these points, and the summary statistics in Table 1 show hat they are reasonably close to their sample counterparts.

Finally, I calibrate the other parameters in the theoretical model to sample means. Note that this approach is equivalent to maximum likelihood estimation of these parameters, given the normality of the limiting distribution of estimated regression coefficients. $\mathbb{V}[R_{US} - R_j]$ and $Cov[R_{US} - R_j, Y_k]$ are replaced with their sample counterparts calculated over the full country-quarter distribution. Likewise, I use

[12] I calculate the intercept coefficient α_k as the average of estimated fixed effects $\hat{\alpha}_{k,j}$ and $\hat{\alpha}_{k,t}$ over the country-quarter distribution.

Figure 4. Comparison of β for banks and insurers



The blue-bordered dot represnets the coefficient β_B, and the red-bordered dot represents the coefficients β_I. Both coefficients are estimated via 2SLS in the model $s_{US,j,k,t} = \alpha_{k,i} + \alpha_{k,t} + \beta_k er_{j,t} + \delta_k' \mathbf{V_{j,t}} + \eta_k' \mathbf{W_{j,t}} + \varepsilon_{j,k,t}$ via 2SLS using $PSPP_{j,t}$ as an instrument for $er_{j,t}$. The bars around the dots represent confidence intervals at the 90%, 95% and 99% levels, in decreasing order of thickness. The p-value on the hypothesis $H_0 : \beta_B = \beta_I$ is calculated using the Clogg et al. (1995) method, which assumes that the coefficients are independent.

the average amount of the total holdings of US and country j government bonds over the country-quarter distribution for each sector as an estimate for $W_{0,k}$. Since the model places no restrictions on the unit of measure of initial wealth, I calibrate it to match the order of magnitude of the empirical proxy of excess returns. [13]

Table 5 reports the distribution of recovered structural parameters, simulated from the asymptotic distribution of the vector of estimated coefficients $\boldsymbol{\lambda} := (\hat{\alpha}_B, \hat{\beta}_B, \hat{\alpha}_I, \hat{\beta}_I, \hat{\pi}, \hat{\theta}_O)$. Risk aversion is 1.5 times higher for ICPFs, with a mean of 0.37 compared to 0.24 for banks. This result is intuitively appealing due to the

[13] Appendix E details the procedure to solve the system and simulate the distribution of structural parameters.

Table 5. Structural parameters

Structural parameter	Mean	95% CI lower bound	95% CI upper bound
A. Banks			
γ_B	0.24	0.02	0.2
ψ_B	3.34	1.0	978.64
B. Insurance companies			
γ_I	0.37	0.13	1.0
ψ_I	3.63	0.13	149.34
C. Common parameters			
σ	2.97	0.51	101.0

Confidence intervals are obtained by drawing 100,000 times from the joint asymptotic distribution of estimated parameters in the empirical model, solving for structural parameters for each joint draw, and computing the 5th and 95th percentiles of the simulated distribution.

intrinsic differences in business models for the two sectors.

The size of the parameter ψ reveals that convenience yields play a non-negligible role in the preferences of both investors. The mean values are above 3, corresponding to a weight of about 75% in their objective function. This result is striking as dollar-denominated government bonds carry exchange rate risk for European investors, highlighting the special role of US Treasuries in the internataional financial system even beyond their safety properties, and echoing Kaldorf and Röttger (2023)'s discussion of "convenient but risky" sovereign debt in the context of peripheral eurozone countries. Insurers appear to assign a slightly higher importance to Treasuries, with a mean of 3.63 for ψ, compared to 3.34 for banks, translating into a 1.5 percentage point difference in the weight of the US Treasuries component of their preferences.

Note that the mean value of 2.97 for the parameter σ implies a very high curvature of the Treasury term of the objective function. Therefore, the marginal benefit of holding Treasuries is steep, and even the seemigly small difference in the estimates of ψ between the two sectors can potentially translate in a large impact on the sensitivty of demand, and in turn on equilibrium excess returns.

However, the mere comparision of the size of estimated parameters is not enough to pin down the relative importance of the two facets of preferences analysed in the model. In the next section, I perform experiments on γ_k and ψ_k to investigate how parameter values translate into the relative strength of risk aversion and convenience yields in determining both portfolio choice and equilibrium interest rates.

4.2 Model experiments

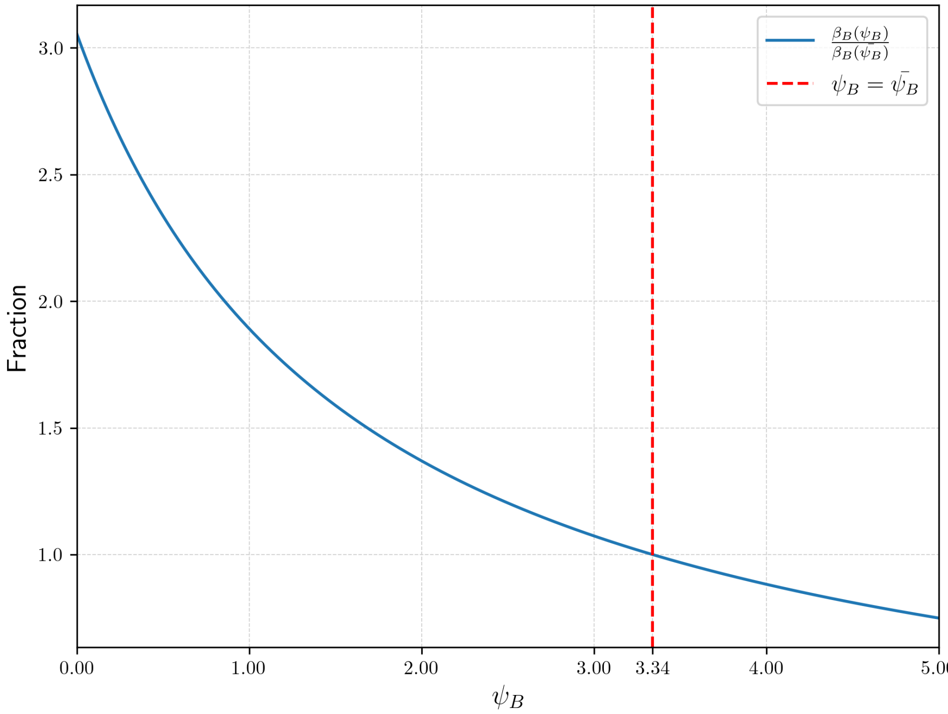
First, I perform two distinct but related exercises to quantify the importance of risk aversion versus convenience yields in explaining the magnitude of investors' portfolio share sensitivity to the mean and variance of excess returns, and their differences across sectors. Then, I investigate the effect of convenience yield investors on equilibrium excess returns.

Portfolio share sensitivity as a function of ψ_k

Equations 3 and 4 claim that the presence of convenience yield preference for Treasuries reduces investors' reaction to both the mean and the variance of excess returns compared to the case of $\psi_k = 0$. To test and quantify this prediction, I calculate the counterfactual values of β_k for both investors as a function of ψ_k, fixing risk aversion γ_k at its mean. To get a sense of the magnitude of the effect of ψ_k on the sensitivity to excess returns, I divide $\beta_k(\psi_k)$ by $\beta_k(\bar{\psi}_k)$, its value at the mean for ψ_k. Figures 5 and 6 plot this function against ψ_k (blue line). For values lower than the mean $\bar{\psi}_k$ (red dashed line), the function is positive, meaning that the corresponding β_k is larger. The sensitivity coefficient β_k at $\psi = 0$, in the absence of Treasuries in the utility function, is 3 times larger than at the mean value for banks, and more than 9 times larger for ICPFs. The estimated parameters imply that the Treasury component of preferences has a sizeable impact on the yield sensitivity, with large differences in the impact across sector. This gap is due to the curvature of the Treasury component of preferences magnifying the small differences in ψ_k.

The exact same conclusions of this counterfactual exercise hold for the sensitivity to the variance of excess return. As evident from equations 3 and 4, the two derivatives differ only by the numerator, while ψ_k affects only the denominator. Therefore, the ratios plotted are exactly the same for the model-implied reaction to the variance of excess returns. The sensitivity of investors' demand to volatility in the Treasuries market is then substantially lower then it would be absent convenience yields, implying that special preferences for US Treasuries make the funding of US government debt more stable even in the face of turbulent periods in the markets.

Figure 5. Percentage change in β_B as a function of ψ_B



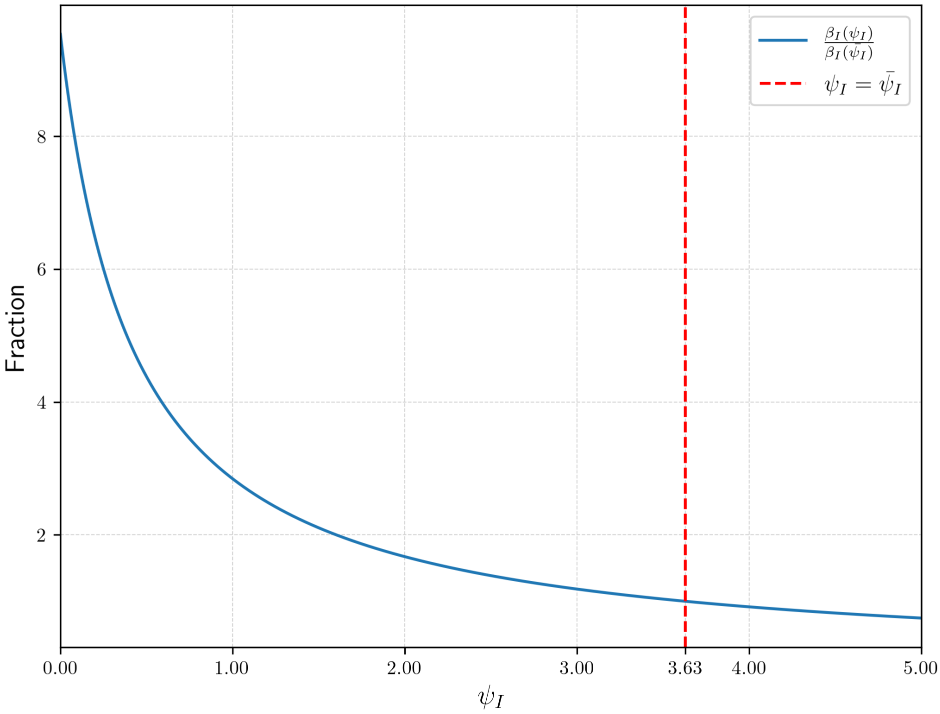
$\beta_B(\psi)$ is calculated using the means of parameters γ_B and σ drawn from the simulated distribution, letting ψ_B vary, and using the calibrated values displayed in Table A3 for other parameters. $\beta_B(\bar{\psi}_B)$ is calcualted using the same parameters as $\beta_B(\psi_B)$, but using the mean of ψ_B from the simulated distribution, defined as $\bar{\psi}_B$.

Difference in sensitivity across sectors as a function of γ_I

This exercise is aimed at quantifying the percentage of the difference in portfolio share sensitivity between banks and insurers that can be attributed to convenience yields versus risk aversion. The results of the previous experiment suggest that this percentage might be quite large, given the difference in the impact of ψ_k on sensitivity across sectors.

I compute the difference in coefficients $\beta_B - \beta_I$ as a function of γ_I, which influences only β_I. I then divide it by the same difference evaluated at the mean for both parameters, to obtain a fraction. Figure 7 plots this function against

Figure 6. Percentage change in β_I as a function of ψ_I

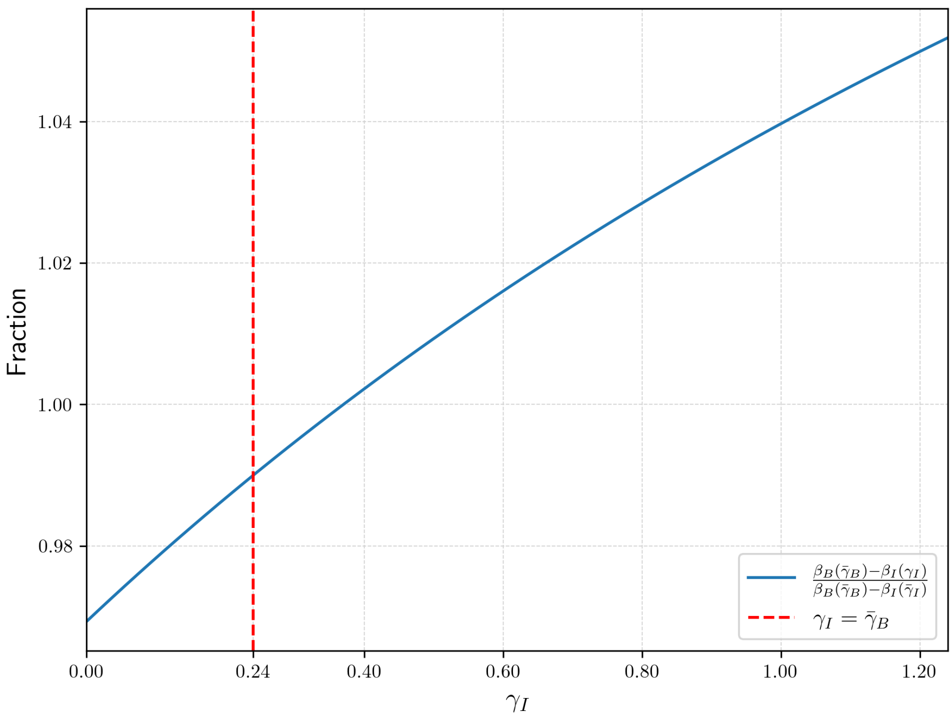


$\beta_I(\psi)$ is calculated using the means of parameters γ_I and σ drawn from the simulated distribution, letting ψ_I vary, and using the calibrated values displayed in Table A3 for other parameters. $\beta_I(\bar{\psi}_I)$ is calcualted using the same parameters as $\beta_I(\psi_I)$, but using the mean of ψ_I from the simulated distribution, defined as $\bar{\psi}_I$.

γ_I (blue line). The function is increasing because β^I is decreasing in γ_I: all else equal, a higher risk aversion translates into a weaker reaction to excess returns. The value at $\gamma_I = \bar{\gamma}_B$ (red dashed line) is of particular interest. By equalising the risk aversion of insurance companies and banks, according to the model any residual difference in β between the two sectors is attributable to the preference for Treasuries. According to this measure, convenience yields can explain about 99% of the difference in β, so they play a dominant role in explaining the observed cross-sector heterogeneity of reactions to excess returns.

However, it is important to underscore how this striking result relies critically on two aspects of the modelling approach. First, investors' utility is assumed to depend on two structural parameters only, so there is no place for other features such as regulation, differences in potential convenience yield preferences for euro area government bonds (Jiang et al., 2020), or heterogeneity in home bias across sectors. Second, as noted above, the steepness of the marginal utility of holding Treasuries implied by the estimated σ produces an outsized effect despite small differences in ψ.

Figure 7. Percentage change in $\beta_B - \beta_I$ as a function of γ_I



$\beta_I(\gamma_I)$ is calculated using the means of parameters γ_B, ψ_B and ψ_I drawn from the simulated distribution, letting γ_I vary, and using the calibrated values displayed in Table A3 for other parameters. $\beta_I(\bar{\gamma_I})$ is calcualted using the same parameters as $\beta_I(\gamma_I)$, but using the mean of γ_I from the simulated distribution, defined as $\bar{\gamma}_I$. $\beta_B(\bar{\gamma}_B)$ is calculated using the means of parameters γ_B, γ_I, ψ_B, and ψ_I drawn from the simulated distribution, and using the calibrated values displayed in Table A3 for other parameters.

Risk premium and convenience yield over time

The previous two experiments demostrated that preferences for Treasuries have a quantitatively strong effect on portfolio choice. However, preferences for US Treasuries affects equilibrium excess returns as well. Equation 5 shows that equilibrium excess returns can be decomposed in two components: the risk premium $RP > 0$, and the convenience yield $\phi < 0$.

After estimating structural parameters γ_k, ψ_k and σ, I can calculate the model-implied excess returns, broken down into the risk premium and convenience yield components, to gauge how they compare to their empirical counterparts displayed in Table 1. Figure 8 plots the model-implied risk premium $RP(\bar{\gamma}_k, \bar{\psi}_k, \bar{\sigma})_t$ (blue line) and the total excess return $ER(\bar{\gamma}_k, \bar{\psi}_k, \bar{\sigma})_t$ (red line) at the means for structural parameters, over the sample period from 2015 Q1 to 2022 Q1. The difference between the two lines (blue shaded area) then represents the absolute value of the convenience yield component $|\phi(\bar{\gamma}_k, \bar{\psi}_k, \bar{\sigma})_t|$. [14]

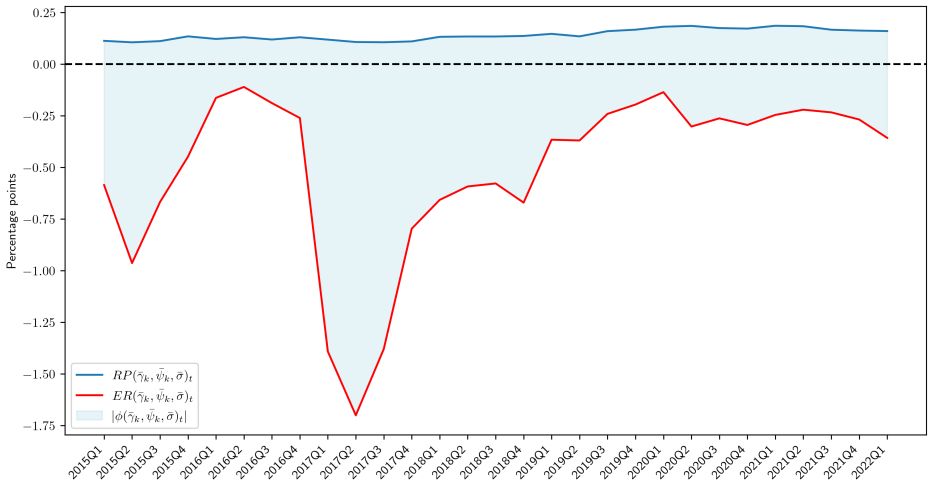
The order of magnitude of excess returns is a calibration target for in the calculation of structural parameters, so it is close to the empirical estimate by construction. However,contrary to its empirical counterpart, model-implied excess returns are always negative, implying that the convenience yield component dominates.Furthermore, it is less volatile, with a minimum value of about -1.75 percentage points compared to -5.21 percentage points for the empirical proxy.

The risk premium component is notably much less volatile than total excess returns, hovering at about 10 basis points throughout the sample. Once again, the discrepancy is attributable to the large value of σ, which magnifies movements of $b_{US,k,t}$, the source of time series variation, in the convenience yield term.

Overall, the model implies that convenience yields are quantitatively much larger than risk premia, driving excess returns consistently into negative territory and explaining much of their time-series variation. Interestingly, these properties match the behaviour of the empirical proxies for excess returns and convenience yields, which both have negative means and display a similar distribution.

[14] Note that the time-series variation in the figure is driven entirely by changes in the US portfolio share of the two sectors, which is the only term that is allowed to vary over time as I treat initial wealth, variances and covariances as fixed parameters. In order to purge excess returns from trends, for the purposes of this figure I scale US Treasury holdings $b_{US,k,t}$ by the total outstanding amount of US Treasuries.

Figure 8. Time-series decomposition of excess returns in risk premium and convenience yield



Excess returns ($ER(\bar{\gamma}_k, \bar{\psi}_k, \bar{\sigma})_t$), the risk premium ($RP(\bar{\gamma}_k, \bar{\psi}_k, \bar{\sigma})_t$) and the absolute value of convenience yields ($|\phi(\bar{\gamma}_k, \bar{\psi}_k, \bar{\sigma})_t|$) are calculated from equation 5 using the means of parameters γ_k, ψ_k and σ drawn from the simulated distribution, and using the calibrated values displayed in Table A3 for other parameters, except for $\bar{s}$. It is replaced by $s_{US,j,k,t}$ for each quarter-sector observation.

Effect of convenience yield on equilibrium excess returns

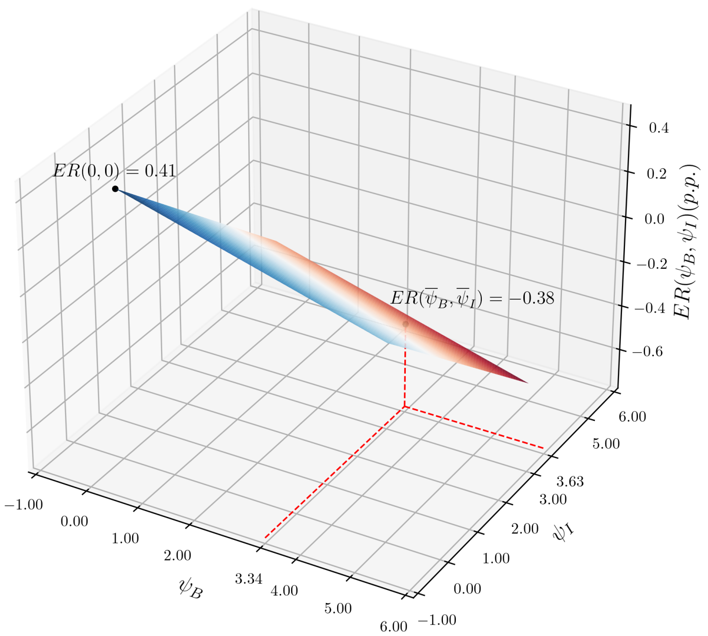
Finally, I perform a counterfactual experiment on the model-implied excess returns, asking how their mean varies as a function of the Treasury preference parameter ψ_k for each sector.

Figure 9 plots on the z axis the excess return $ER(\psi_B, \psi_I)$ as a function of varying levels of ψ_B (x axis) and ψ_I (y axis), leaving γ_k and σ at their mean values. Excess returns are steeply decreasing in both ψ_B and ψ_I, as the higher importance of US Treasuries in investors' utility functions implies that they require lower monetary returns. Therefore, any loss of confidence by foreign investors in the special value of US Treasuries, even partial, would result in a fast erosion of the US government's funding advantage.

In the extreme case of a complete loss of special status, represented by $\psi_k = 0 \, \forall \, k$, US Treasuries would have to pay a positive excess return of 41 basis points on euro area government bonds, a large jump of 79 basis points from their value of

-38 basis points at parameter means. The stark penalty implied by the model suggest that the sustainability of US public finances relies on the special role of US Treasuries as a global asset, as observed in previous studies (Jiang et al., 2019, Bonam, 2020, Choi et al., 2024).

Figure 9. Exces returns as a function of ψk



Excess returns $ER(\psi_B, \psi_I)$ (z axis) are calculated from equation 5 using the means of parameters γ_k and σ drawn from the simulated distribution, letting ψ_B (x axis) and ψI (y axis) vary, and using the calibrated values displayed in Table A3 for other parameters.

5 Conclusion

This paper shows that the convenience yield that foreign investors derive from US Treasuries plays a key role in explaining the observed differences in demand sensitivity across sectors. Differences in risk aversion are also substantial, but alone they cannot reconcile the joint observation of positive US Treasury portfolio shares for ICPFs; negative excess returns of Treasuries with respect to eurozone government bonds; and a positive correlation between Treasury excess returns and the income of insurers.

Thanks to the estimation of structral parameters in investors' preferences, the relative importance of convenience yields and risk aversion can be quantified. Both a high risk aversion and convenience yields imply a lower reaction of portfolio shares to excess returns, so a structural approach is necessary to disentangle their impact.

The model implies that, absent convenience yields, the demand of banks would be 3 times more sensitive to the mean and variance of excess returns, while insurance companies would be 9 times more sensitive. As a result, the absorption of additional US government debt by foreign investors would be much more fickle and volatile.

The sizeable impact of convenience yields on the yield sensitivity of portfolios is matched by an equally large effect on equilibrium rates. The decomposition in the model shows that the convenience yield term accounts for the vast majority of the volatility in excess returns, and that it is large enough to turn excess returns consistently negative. Furthermore, the model-implied excess return is steeply increasing in the Treasury preference parameter of both sectors, and it would jump from -38 basis points to 41 basis points in the absence of convenience yields.

The policy implications are twofold. First, the sustainability of persistent US government deficits heavily relies on yield-insensitive foreign investors to absorb additional sovereign debt at a low rate. Second, the high sensitivity of returns to the convenience yield component highlights the risks of US Treasuries losing their special status, leading to a potentially large increase in the borrowing cost for the US government.

While the quantitative conclusions of this paper are by costruction limited to the context of European banks and insurance companies, they nevertheless offer insights for further research on the nuances of the foreign demand for Treasuries by different sectors in a global perspective.

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A Data sources

Table A1. Data sources

Data	**Source**
Government bond holdings of eurozone banks and ICPFs	ECB Securities Holdings Statistics
Income of eurozone banks	ECB Consolidated Banking database
Income of eurozone insurers	EIOPA Insurance Statistics
Government debt purchases and holdings under PSPP	ECB
Government bond indices and yields	Refinitiv Eikon
Spot and forward exchange rates	Refinitiv Eikon
EUR/USD cross-currency basis swap	Refinitiv Eikon
CDS rates	Refinitiv Eikon
Amount of government debt outstanding	Bank for International Settlements
	and Federal Reserve Economic Data (FRED)
Real GDP growth	OECD
CPI inflation	ECB and IMF
Debt/GDP ratio	Eurostat and FRED

B Mean-variance preferences with convenience yields

Consider the problem of an investor allocating their initial wealth $W_{0,k}$ between domestic government bonds $b_{j,k}$ with riskless return R_j, and US Treasuries $b_{US,k}$ with return R_{US}, which is risky because of fluctuations in the exchange rate. The investor derives utility from their final wealth W_k, and from holding US Treasuries. The utility function is

$$U(W_k, b_{US,k}) = -e^{-\gamma_k (W_k + \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma})}$$

This utility function preserves the desirable properties of standard exponential utility, namely it is increasing and concave in W_k, and it displays constant absolute risk aversion with risk aversion coefficient γ_k.

Furthermore, by taking the first and second derivatives with respect to $b_{US,k}$,

$$U'(b_{US,k}) = \gamma_k \psi_k b_{US,k}^{-\sigma} e^{-\gamma_k (W_k + \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma})} > 0$$
$$U''(b_{US,k}) = -\gamma_k \psi_k b_{US,k}^{-2\sigma} \left(\gamma_k \psi_k + \sigma b_{US,k}^{\sigma-1}\right) e^{-\gamma_k (W_k + \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma})} < 0.$$

Therefore, due to the CES specification the marginal utility of holding Treasuries is declining, so investors require a higher monetary return to absorb more Treasuries in equilibrium. This mechanism is widely used in the literature to link the outstanding amount of US government debt with the equilibrium convenience yield (Krishnamurthy and Vissing-Jorgensen (2012) and Engel and Wu (2018), among others).

The investor maximises their expected utility subject to their budget constraint, expressed in terms of $b_{j,k}$ as the outside risk-free asset.

$$\max_{b_{US,k}} \mathbb{E}\left[-e^{-\gamma_k (W_k + \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma})}\right]$$
$$\text{s.t.} W_k = \quad RW_0 + (R_{US} - R_j) b_{US,k} + Y_k,$$

Assume that $R_{US} \sim N\left(\mu_{US}, \sigma_{US}^2\right)$ and $Y_k \sim N\left(\mu_Y, \sigma_Y^2\right)$, so that $W_k \sim \left(\mu_W, \sigma_W^2\right)$, with $\mu_W = RW_{0,k} + (\mu_{US} - R) B_{US} + \mu_Y$ and $\sigma_{W_k}^2 = B_{US}^2 \sigma_{US}^2 + \sigma_Y^2 + 2\sigma_{US,Y}$.

The objective function can be re-written as a generalisation of mean-variance preferences. First, write expected utility in terms of the density function of W_k,

$$\mathbb{E}\left[-e^{-\gamma_k (W_k + \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma})}\right] = \int_{-\infty}^{\infty} -e^{-\gamma_k (W_k + \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma})} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{W_k - \mu_W}{2\sigma_{W_k}^2}} dW_k$$
$$= e^{-\gamma_k \psi_k \frac{b_{US,k}^{1-\sigma}}{1-\sigma}} \int_{-\infty}^{\infty} -e^{-\gamma_k W_k} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{W_k - \mu_W}{2\sigma_{W_k}^2}} dW_k$$

Now, following the same steps as the derivation of standard mean-variance preferences by collecting the terms under the integral that depend on W_k,

$$
\begin{aligned}
\mathbb{E}\left[-e^{-\gamma_k(W_k+\psi_k\frac{b_{US,k}^{1-\sigma}}{1-\sigma})}\right] &= e^{-\gamma_k\psi_k\frac{b_{US,k}^{1-\sigma}}{1-\sigma}}\int_{-\infty}^{\infty}-e^{-\gamma_k\left(\mu_W-\frac{\gamma_k}{2}\sigma_{W_k}^2\right)}\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{\left(W_k-\mu_W+\gamma_k\sigma_{W_k}^2\right)^2}{2\sigma_{W_k}^2}}dW_k \\
&= e^{-\gamma_k\left(\mu_W-\frac{\gamma_k}{2}\sigma_{W_k}^2+\psi_k\frac{b_{US,k}^{1-\sigma}}{1-\sigma}\right)}\underbrace{\int_{-\infty}^{\infty}\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{\left(W_k-\mu_W+\gamma_k\sigma_{W_k}^2\right)^2}{2\sigma_{W_k}^2}}dW_k}_{=1} \\
&= e^{-\gamma_k\left(\mu_W-\frac{\gamma_k}{2}\sigma_{W_k}^2+\psi_k\frac{b_{US,k}^{1-\sigma}}{1-\sigma}\right)}.
\end{aligned}
$$

It follows that

$$
\max_{b_{US,k}}\mathbb{E}\left[-e^{-\gamma_k(W_k+\psi ln(B^{US}))}\right]=\max_{b_{US,k}}\mu_W-\frac{\gamma_k}{2}\sigma_{W_k}^2+\psi_k\frac{b_{US,k}^{1-\sigma}}{1-\sigma}.
$$

Therefore, maximising expected utility with an exponential utility function in wealth and US Treasuries reduces to standard mean-variance preferences with an additive term for US Treasury holdings, which is increasing and concave due to the CES specification for Treasuries in the utility function.

C Logarithmic preferences for Treasuries

Consider the preferences for investors introduced in Section 2 where $\sigma \to 1$, so that term for US Treasuries in investors' utility is logartihmic. In this case, an analytical nonlinear solution for the optimal portfolio share exists. The problem of sector k investor is

$$
\begin{aligned}
&\max_{s_{US,k}}\mathbb{E}[W_{0,k}]-0.5\gamma_k\mathbb{V}[W_k]+\psi_k\ln(b_{US,k}) \\
\text{s.t.}\quad & W_k=W_{0,k}(R_j+(R_{US}-R_j)s_{US,k})+Y_k \\
& s_{j,k}+s_{US,k}=1,
\end{aligned}
$$

The following sub-sections derive propositions on the optimal share and on its sensitivity to the mean and variance excess returns, showing how the results in Section 2.1 extend to a nonlinear setting.

C.1 Proposition 2: optimal portfolio share

Proposition 2 (Optimal portfolio share). (i) *The optimal portfolio share is*

$$s_{US,k} = \frac{\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k]}{2\gamma_k W_{0,k} \mathbb{V}[R_{US} - R_j]} + \frac{\sqrt{(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k])^2 + 4\gamma_k \psi_k \mathbb{V}[R_{US} - R_j]}}{2\gamma_k W_{0,k} \mathbb{V}[R_{US} - R_j]}. \tag{14}$$

(ii) $s_{US,k} \in \mathbb{R}^+$ *if* $\gamma_k > 0$, $\psi_k > 0$, *and* $\mathbb{V}[R_{US} - R_j] > 0$.

Proof. Proposition 2 (i): substitute the constraints in the objective function to re-cast the problem with $s_{US,k}$ as a choice variable. Take the first-order condition for $s_{US,k}$ to obtain the following quadratic equation:

$$\gamma_k \mathbb{V}[R_{US} - R](s_{US,k})^2 - (\mathbb{E}[R_{US} - R] - \gamma_k Cov[R_{US} - R, Y_k])\, s_{US,k} - \psi = 0.$$

The two solutions are

$$s_{US,k,1} = \frac{\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k]}{2\gamma_k W_{0,k} \mathbb{V}[R_{US} - R_j]} - \frac{\sqrt{(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k])^2 + 4\gamma_k \psi_k \mathbb{V}[R_{US} - R_j]}}{2\gamma_k W_{0,k} \mathbb{V}[R_{US} - R_j]}$$

and

$$s_{US,k,2} = \frac{\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k]}{2\gamma_k W_{0,k} \mathbb{V}[R_{US} - R_j]} + \frac{\sqrt{(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k])^2 + 4\gamma_k \psi_k \mathbb{V}[R_{US} - R_j]}}{2\gamma_k W_{0,k} \mathbb{V}[R_{US} - R_j]}.$$

To select a solution, consider the conditions for $s_{US,k,1}, s_{US,k,2} > 0$, for for $\gamma_k > 0$, $\psi_k > 0$, and $\mathbb{V}[R_{US} - R_j] > 0$.

$$\begin{aligned} s_{US,k,1} > 0 \iff & \mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k] \\ & > \sqrt{(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k])^2 + 4\gamma_k \psi_k \mathbb{V}[R_{US} - R_j]} \\ \iff & 4\gamma_k \psi_k \mathbb{V}[R_{US} - R_j] < 0 \end{aligned}$$

There is no solution for $\gamma_k > 0$, $\psi_k > 0$, and $\mathbb{V}[R_{US} - R_j] > 0$. Therefore, I choose the solution $s_{US,k} = s_{US,k,2}$, and derive the conditions for $s_{US,k,2} \in \mathbb{R}^+$ in the next proof.

Proposition 2 (ii): start with the conditions for $s_{US,k} \in \mathbb{R}$:

$$s_{US,k} \in \mathbb{R} \iff \left(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k]\right)^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US} - R] > 0.$$

It is immediate to see that it always holds for $\gamma_k > 0$, $\psi_k > 0$, and $\mathbb{V}[R_{US} - R_j] > 0$. Now consider the condition for $s_{US,k} > 0$.

$$\begin{aligned} s_{US,k} > 0 \iff & \mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k] \\ & < \sqrt{\left(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k]\right)^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US} - R_j]} \\ \iff & 4\gamma_k\psi\mathbb{V}[R_{US} - R_j] > 0 \end{aligned}$$

The condition also always holds for $\gamma_k > 0$, $\psi_k > 0$, and $\mathbb{V}[R_{US} - R_j] > 0$.

□

Note that, for $\gamma_k > 0$, $\psi_k > 0$, and $\mathbb{V}[R_{US} - R_j] > 0$, $s_{US,k} > s_{US,k}|_{\psi=0}$. In the logarithmic case, investors choose a higher portfolio share than they would absent convenience yields.

Furthermore,

$$\lim_{\psi_k \to 0} s_{US,k} = \frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US} - R_j]}\left(\mathbb{E}[R_{US} - R_j] - \gamma_k Cov[R_{US} - R_j, Y_k]\right).$$

Therefore, the optimal share collapses back to the standard case as the weight on Treasury preferences vanishes.

Proposition 2 (ii) states the conditions under which the insurers' problem admits a real, positive solution for $s_{US,k}$. Note that there are no requirements on the risk-return profile of US Treasuries. Therefore, $s_{US,k} > 0$ even for $\mathbb{E}[R_{US} - R] < 0$ and $Cov[R_{US} - R, Y_k] > 0$ simultaneously. Due to the convenience yield of Treasuries, investors choose to hold a positive amount even if they offer neither an extra return, nor good insurance for income risk.

C.2 Proposition 3: sensitivity to excess returns

Proposition 3 (Sensitivity to the mean of excess returns). (i)

$$\frac{\partial s_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} = \frac{1}{2}\frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]} \left(1 - \frac{\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j, Y_k]}{\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k])^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}\right) \tag{15}$$

(ii) *With* $\gamma_k > 0$*,* $\psi_k > 0$*, and* $\mathbb{V}[R_{US}-R_j] > 0$*,*
$\frac{\partial s_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} \in \left(0, \frac{1}{2}\frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]}\right)$ *for* $\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j, Y_k] > 0$*.*
$\frac{\partial s_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} \in \left(\frac{1}{2}\frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]}, \frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]}\right)$ *for* $\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j, Y_k] < 0$

Proof. Proposition 3 (i): it follows immediately from differentiating $s_{US,k}$ with respect to $\mathbb{E}[R_{US}-R_j]$. □

Proposition 3 (ii):

Proof.

$$\frac{\partial s_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} > 0 \iff$$
$$\mathbb{E}[R_{US_j}-R_j] - \gamma_k Cov[R_{US}-R_j, Y_k] <$$
$$\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k])^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}$$

This condition holds for $\mathbb{E}[R_{US}-R_j] - \gamma_k Cov[R_{US}, Y_k] > 0$, with $\gamma_k > 0$ and $\mathbb{V}[R_{US}-R_j] > 0$.

$$\frac{\partial s_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} < \frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]} \iff$$

$$\frac{1}{2}\frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]}\left(1-\frac{\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k]}{\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k])^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}\right)$$
$$< \frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]} \iff$$

$$\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k]$$
$$< \sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k])^2+4\gamma_k\psi\mathbb{V}[R_{US}-R_j]}$$
$$\iff 4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j] > 0.$$

This condition always holds for $\gamma_k > 0$ and $\mathbb{V}[R_{US}-R_j] > 0$.

$$\frac{\partial s_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} > \frac{1}{2}\frac{1}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]} \iff$$

$$-\frac{\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k]}{\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k])^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}} > 0 \iff$$

$$\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k] < 0.$$

□

C.3 Proposition 4: sensitivity to variance of excess returns

Proposition 4 (Sensitivity to the variance of excess returns)**.** (i)

$$\frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]} = \frac{1}{2W_{0,k}\mathbb{V}[R_{US}-R_j]^2}$$
$$\Bigg(-\frac{\sqrt{\left(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k]\right)^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}{\gamma_k}$$
$$+\frac{2\psi_k\mathbb{V}[R_{US}-R_j]}{\sqrt{\left(\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k]\right)^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}$$
$$+Cov[R_{US}-R_j,Y_k]-\frac{\mathbb{E}[R_{US}-R_j]}{\gamma_k}\Bigg) \tag{16}$$

(ii) $\frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]} < 0$ *for* $\gamma_k > 0$*,* $\psi_k > 0$*, and* $\mathbb{V}[R_{US}-R_j] > 0$

(iii) *With* $\gamma_k > 0$*,* $\psi_k > 0$*, and* $\mathbb{V}[R_{US}-R_j] > 0$*,*
$\frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]}|_{\psi_k=0} < \frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]}|_{\psi_k>0}$ *for* $\mathbb{E}[R_{US}-R_j]-\gamma_k Cov[R_{US}-R_j,Y_k] > 0$

Proof. Proposition 4 (i): it follows immediately from differentiating $s_{US,k}$ with respect to $\mathbb{V}[R_{US}-R_j]$. □

Proof. Proposition 4 (ii):

$$\frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]} < 0 \iff$$

$$-\frac{\sqrt{\left(\mathbb{E}[R_{US}-R_j]-\gamma_k \text{Cov}[R_{US}-R_j, Y_k]\right)^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}{\gamma_k}$$
$$+\frac{2\psi_k\mathbb{V}[R_{US}-R_j]}{\sqrt{\left(\mathbb{E}[R_{US}-R_j]-\gamma_k \text{Cov}[R_{US}-R_j, Y_k]\right)^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}$$
$$+\text{Cov}[R_{US}-R_j, Y_k] - \frac{\mathbb{E}[R_{US}-R_j]}{\gamma_k} < 0 \iff$$

$$-\left(\mathbb{E}[R_{US}-R_j]-\gamma_k \text{Cov}[R_{US}-R_j, Y_k]\right)^2 - 2\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]-$$
$$\left(\mathbb{E}[R_{US}-R_j]-\gamma_k \text{Cov}[R_{US}-R_j, Y_k]\right)$$
$$\sqrt{\left(\mathbb{E}[R_{US}-R_j]-\gamma_k \text{Cov}[R_{US}-R_j, Y_k]\right)^2 + 4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]} < 0 \iff$$

$$4\left(\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]\right)^2 > 0$$

This condition always holds.

□

Proof. Proposition 4 (iii):
For $\psi_k = 0$,

$$\frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]}|_{\psi_k=0} = -\frac{\mathbb{E}[R_{US}-R_j]-\gamma_k \text{Cov}[R_{US}-R_j, Y_k]}{\gamma_k W_{0,k}\mathbb{V}[R_{US}-R_j]^2}.$$

Then,

$$\frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]}|_{\psi_k=0} < \frac{\partial s_{US,k}}{\partial \mathbb{V}[R_{US}-R_j]}|_{\psi_k=0} \iff$$

$$2\frac{\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k]}{\gamma_k} <$$
$$+\frac{\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k])^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}{\gamma_k}$$
$$-\frac{2\psi_k\mathbb{V}[R_{US}-R_j]}{\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k])^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]}}$$
$$-\frac{\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k]}{\gamma_k} \iff$$

$$(\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k])$$
$$\sqrt{(\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k])^2+4\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]} <$$
$$(\mathbb{E}[R_{US}-R_j]-\gamma_k \mathrm{Cov}[R_{US}-R_j,Y_k])^2+2\gamma_k\psi_k\mathbb{V}[R_{US}-R_j] \iff$$

$$4\left(\gamma_k\psi_k\mathbb{V}[R_{US}-R_j]\right)^2 > 0$$

This condition always holds. □

Proposition ii shows that, even in the nonlinear solution, the derivative of the Treasury portfolio share to the variance of excess returns is negative. Furthermore, proposition iii confirms that the presence of convenience yields makes the reaction to market volatility more muted, that is less negative, compared to the standard mean-variance preferences case.

D Proofs

D.1 Proposition 1: reaction of excess returns to euro area debt supply

Proof. Proposition 1:

Differentiating equation 5 with respect to B_j, taking into account that $b_{US,k}$ is a function of B_j through excess returns only,

$$\frac{\partial \mathbb{E}\left[R_{US}-R_j\right]}{\partial B_j} = -\frac{\mathbb{V}[R_{US}-R_j]}{\sum_k \tau_k} + \frac{1}{\sum_k \tau_k}\frac{\partial b_{j,O}}{\partial B_j}$$
$$+\sigma\frac{\sum_k \tau_k \psi_k b_{US,k}^{-\sigma-1}\left(\frac{\partial b_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]}\frac{\partial \mathbb{E}[R_{US}-R_j]}{\partial B_j}\right)}{\sum_k \tau_k}$$

To find $\partial b_{US,k}/\partial \mathbb{E}[R_{US}-R_j]$, differentiate equation 1 with respect $\mathbb{E}[R_{US}-R_j]$, applying the implicit function theorem:

$$1-\gamma_k \mathbb{V}[R_{US}-R_j]\frac{\partial b_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} - \sigma\psi_k b_{US,k}^{-\sigma-1}\frac{\partial b_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} = 0 \iff$$

$$\frac{\partial b_{US,k}}{\partial \mathbb{E}[R_{US}-R_j]} = \frac{1}{\mathbb{V}[R_{US}-R_j]/\tau_k + \sigma\psi_k b_{US,k}^{-\sigma-1}}.$$

Then, substitute $\partial b_{US,k}/\partial \mathbb{E}[R_{US}-R_j]$ back into the expression for $\partial \mathbb{E}\left[R_{US}-R_j\right]/\partial B_j$

$$\frac{\partial \mathbb{E}\left[R_{US}-R_j\right]}{\partial B_j} = -\frac{\mathbb{V}[R_{US}-R_j]}{\sum_k \tau_k} + \frac{1}{\sum_k \tau_k}\frac{\partial b_{j,O}}{\partial B_j}$$
$$+\sigma\frac{\sum_k \frac{\tau_k \psi_k b_{US,k}^{-\sigma-1}}{\mathbb{V}[R_{US}-R_j]/\tau_k+\sigma\psi_k b_{US,k}^{-\sigma-1}}}{\sum_k \tau_k}\frac{\partial \mathbb{E}\left[R_{US}-R_j\right]}{\partial B_j} \iff$$

$$\frac{\partial \mathbb{E}\left[R_{US}-R_j\right]}{\partial B_j} = \frac{\mathbb{V}[R_{US}-R_j]\left(\frac{\partial b_{j,O}}{\partial B_j}-1\right)}{\sum_k \tau_k\left(1-\frac{\sigma\psi_k b_{US,k}^{-\sigma-1}}{\mathbb{V}[R_{US}-R_j]/\tau_k+\sigma\psi_k b_{US,k}^{-\sigma-1}}\right)}$$

To prove that $\partial \mathbb{E}\left[R_{US}-R_j\right]/\partial B_j < 0$, note that $\partial b_{j,O}/\partial B_j \in [0,1]$, so

$$\frac{\partial b_{j,O}}{\partial B_j} - 1 < 0$$

and

$$\frac{\partial \mathbb{E}\left[R_{US}-R_j\right]}{\partial B_j} < 0 \iff \sum_k \tau_k\left(1-\frac{\sigma\psi_k b_{US,k}^{-\sigma-1}}{\mathbb{V}[R_{US}-R_j]/\tau_k+\sigma\psi_k b_{US,k}^{-\sigma-1}}\right) > 0$$

A sufficient condition to satisfy this equaiton is

$$\tau_k \left(1 - \frac{\sigma\psi_k b_{US,k}^{-\sigma-1}}{\mathbb{V}[R_{US} - R_j]/\tau_k + \sigma\psi_k b_{US,k}^{-\sigma-1}}\right) > 0 \,\forall\, k \iff$$

$$\sigma\psi_k b_{US,k}^{-\sigma-1} < \mathbb{V}[R_{US} - R_j]/\tau_k + \sigma\psi_k b_{US,k}^{-\sigma-1} \iff$$

$$\mathbb{V}[R_{US} - R_j]/\tau_k > 0.$$

This condition always holds for $\tau_k > 0$ and $\mathbb{V}[R_{US} - R_j] > 0$. □

E Details on the recovery of structural parameters

E.1 Calibration

To solve for the structural parameters, I first proxy $\mathbb{V}[R_{US} - R_j]$ and $Cov[R_{US} - R_j, Y_k]$ with their empirical counterparts $\hat{\varsigma}_{ER}^2$ and $\hat{\varsigma}_{ER,Y_k}$. Likewise, initial wealth $W_{0,k}$ is measured as the total holdings of US and country j government bonds, averaged over the country-quarter distribution, $\bar{W}_{0,k}$. Note that the unit of measure of debt holdings is not specified in the theoretical model, so I calibrate it to hundreds of billions of euros so that the order of magnitude of model-implied excess returns matches the average of the empirical proxy of excess returns, $er_{j,t}$, as reported in Table 1.

I also convert the coefficient $-\hat{\pi}$ from the empirical model to account for the minus sign with respect to the theoretical model, and for the standardisation of PSPP purchases in the empirical model, such that the parameter $\tilde{\pi}$ used in the solution for structural parameters is

$$\tilde{\pi} = -\hat{\pi}\frac{\bar{B}}{\hat{\sigma}_{PSPP}}$$

where $\bar{B}$ is average outstanding government debt for euro area countries and $\hat{\varsigma}_{PSPP}$ is the sample standard deviation of PSPP purchases.

Finally, I estimate $\partial b_{j,O}/\partial B_j$ via an absorption regression. I start by breaking down the outstanding amount of government debt for country j in quarter t into holdings by four sectors: banks, insurance companies, the ECB, and other investors. The amount held by other investors is defined residually, while the amount held by the ECB includes only PSPP holdings. It is crucial to account for holdings by the ECB for this decomposition to map correctly to the model, as PSPP purchases are used to identify the parameter π and so should be excluded from the amount held by oher investors.

I then estimate the following regression separately for each sector on the same country-quarter panel used in the regressions in Section 3.4.

$$b_{j,k,t} = \zeta_j + \zeta_t + \theta_k B_{j,t} + \upsilon_{j,k,t}$$

where ζ_j and ζ_t are country and quarter fixed effects, added to account for common macroeconomic conditions and country-specific idiosyncracies. As shown in Table A2, coefficients θ_k of the absorption regression add up to 1 across sectors because sectoral holdings $b_{j,k,t}$ sum up to the total amount outstanding $B_{j,t}$ in each quarter. I use the estimated coefficient for other investors, from the model with time and country fixed effects, $\hat{\theta}_O$, as a proxy for $\partial b_{j,O}/\partial B_j$.

Table A2. Absorption regression

	(1)	(2)	(3)	(4)
$b_{j,B,t}$	0.19***	0.19***	0.02	0.04**
	(0.01)	(0.01)	(0.02)	(0.02)
$b_{j,I,t}$	0.22***	0.22***	0.16***	0.18***
	(0.01)	(0.01)	(0.02)	(0.01)
$b_{j,PSPP,t}$	0.19***	0.18***	0.63***	0.57***
	(0.01)	(0.01)	(0.05)	(0.04)
$b_{j,O,t}$	0.41***	0.41***	0.19***	0.20***
	(0.01)	(0.01)	(0.05)	(0.04)
Time fixed effects	No	Yes	No	Yes
Country fixed effects	No	No	Yes	Yes

Coefficients from regression model $b_{j,k,t} = \zeta_j + \zeta_t + \theta_k B_{j,t} + \upsilon_{j,k,t}$ estimated via OLS. Each row reports the estimates of coefficient θ_k for a different sector k. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3 displays the values of the calibrated parameters.

E.2 Solution algorithm

After replacing all estimates and calibrated parameters, I am left with the following system of five equations in five unknowns: γ_k and ψ_k for $k = \{B, I\}$, and σ.

Table A3. Calibrated parameters

Parameter	Unit of measure	Value
$\hat{\varsigma}^2_{ER}$	N.A.	0.81
$\hat{\varsigma}_{ER_j,Y_B}$	N.A.	-0.04
$\hat{\varsigma}_{ER_j,Y_I}$	N.A.	0.03
$\bar{W}_{0,B}$	€ 100 bn.	2.56
$\bar{W}_{0,I}$	€ 100 bn.	1.63
$\bar{B}_j$	€ 100 bn.	5.16
$\hat{\varsigma}_{PSPP}$	€ 100 bn.	1.54

$$\hat{\alpha}_k = \bar{s} - \gamma_k \frac{\bar{W}_{0,k}\bar{s}\left(\hat{\varsigma}^2_{ER} - \bar{\upsilon}\right) + \hat{\varsigma}_{ER_j,Y_k} - \bar{c}}{\gamma_k \bar{W}_{0,k}\bar{\upsilon} + \sigma\psi_k \bar{W}_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}} \quad \text{for } k = \{B, I\}, \tag{17}$$

$$\hat{\beta}_k = \frac{1}{\gamma_k \bar{W}_{0,k}\bar{\upsilon} + \sigma\psi_k \bar{W}_{0,k}^{-\sigma}\bar{s}^{-\sigma-1}} \quad \text{for } k = \{B, I\}, \tag{18}$$

$$\hat{\pi} = \frac{\bar{\upsilon}\left(\hat{\theta}_O - 1\right)}{\sum_k \frac{1}{\gamma_k}\left(1 - \frac{\sigma \bar{b}_{US,k}^{-\sigma-1}\psi_k}{\gamma_k\bar{\upsilon} + \sigma\psi_k \bar{b}_{US,k}^{-\sigma-1}}\right)}. \tag{19}$$

To solve it, I exploit the structure of the system whereby equations 17 and 18, derived from the portfolio choice of each investor sector, depend only on the risk aversion and Treasury preference parameter for that sector, γ_k and ψ_k, and on the common Treasury preference curvature parameter σ. On the other hand, equation 19, derived from equilibrium excess returns, depends on σ and on the preference parameters of all investors. I can then use the following iterative algorithm:

1. Pick a starting value σ_0.
2. Solve equations 17 and 18 for γ_k and ψ_k separately for each sector letting $\sigma = \sigma_0$, obtaining solutions $\gamma_{k,0}$ and $\psi_{k,0}$ $\forall\, k$.
3. Solve equation 19 for σ letting $\gamma_k = \gamma_{k,0}$ and $\psi_k = \psi_{k,0}$ $\forall\, k$, obtaining solution σ_1.
4. Let $\sigma = \sigma_1$ in step 1 and iterate until convergence for γ_k, ψ_k and σ.

After solving for the structural parameters, I simulate their distribution to obtain empirical confidence intervals. I start by drawing 100,000 times from the joint asymptotic normal distribution of $\boldsymbol{\lambda} \coloneqq (\hat{\alpha}_B, \hat{\beta}_B, \hat{\alpha}_I, \hat{\beta}_I, \hat{\pi}, \hat{\theta}_O)$, assuming independent coefficients across regressions, but accounting for the correlation of within portfolio equations. Then, for each joint draw I solve for the structural parameters as outlined above. Then, I calculate the mean, 5^{th} and 95^{th} percentile for γ_k, ψ_k and σ over all values of $\boldsymbol{\lambda}$ that admit a positive solution of equations 17, 18 and 19. I then use the 5^{th} and 95^{th} percentiles of the distribution of solutions as bounds for the simulated confidence intervals.