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**Abstract**

We provide the first systematic asset pricing analysis of one of the main safe asset categories, the repurchase agreement (repo). Based on the temporal and cross-sectional variation in short-term rates, we form a *carry* that, together with a market factor, prices these near-money assets in a linear pricing model. The carry depicts heterogeneity in non-pecuniary convenience yields of collateral assets and increases in the safety premium and the liquidity premium reflecting opportunity cost. Our carry helps explain the cross-section of short-term rates as well as of long-term bond returns after accounting for standard bond pricing factors.

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Investors pay a "convenience premium" for the safety and liquidity benefits provided by safe assets.[1] Prior research has shown that the convenience premium varies across securities (Krishnamurthy and Vissing-Jorgensen, 2012) and market conditions, such as the opportunity cost of holding money (Nagel, 2016) and uncertainty (Moreira and Savov, 2017). However, our understanding of the asset pricing implications and economic determinants of the temporal and cross-sectional variation in convenience premia and safe asset prices is still limited.

Our first contribution is to provide a systematic asset pricing analysis of one important category of safe assets, the repurchase agreement (repo). We find that a standard factor model with two factors, a *market factor* and a *carry factor*, is able to price these near-money assets. While the market factor determines the level of short-term interest rates, the carry factor accounts for their cross-sectional dispersion. The carry factor involves a long position in repos with higher rates and a simultaneous short position in repos with lower rates, and thus captures the within- and cross-country variation in short-term rates. Our second contribution is to explain the economic determinants of non-pecuniary convenience yield stemming from the collateral asset (e.g., Gorton, 2017 and Infante, 2020). From the perspective of the safe asset literature, our carry factor reflects the differential in convenience yields provided by truly and quasi-safe assets. We provide empirical evidence that our carry factor increases with the safety premium and the liquidity premium reflecting the opportunity cost of holding money. Our carry factor helps explain the cross-sectional variation in short-term rates as well as in long-term bond returns beyond the standard bond pricing factors, which points towards the external relevance of the carry for other asset classes.

The European repo market is particularly well suited for analyzing the asset pricing implications and economic determinants of heterogeneous convenience premia for several reasons. First, euro repos are overnight loans secured by government bonds with heterogeneous safety and liquidity attributes as they are issued by different euro area countries. This offers a new perspective to the extant literature on the convenience yield of safe assets that has predominantly focused on U.S. Treasuries. Second, the market characteristics enable us to isolate

[1] In this work, we refer to convenience yield as "non-pecuniary returns...in the form of liquidity or moneyness and safety" (Gorton, 2017).

safety and liquidity benefits by eliminating many confounding factors to convenience yield such as term premia, counterparty and currency risk.[2] Third, the legal framework prescribes that any collateral income payments during the repo term are transferred to the borrower who pledges the collateral. Hence, any convenience yield for the lender who receives the collateral for the term of the repo must consist of non-monetary benefits (e.g., strong protection and broad re-usability in case of truly safe assets). And fourth, it is the largest repo market worldwide and our data includes transactions covering more than 70% of the entire European repo market. The size and importance of the euro area repo market as well as the representativeness of our data provide general validity to our results.

We observe an increase in the dispersion in short-term rates between countries during the European sovereign debt crisis as well as since the period of quantitative easing (QE). While the former suggests the existence of the safety premium for truly safe assets, the latter points towards the liquidity premium. Further evidence of the liquidity premium is an increase in the dispersion within, for example, German repo rates during the QE-period. Based on this temporal and cross-sectional variation in short-term rates, we form our carry factor. On a daily basis, we build eight portfolios sorted by the respective repo rates: the first (last) portfolio contains the repos with the lowest (highest) repo rates observed during the previous trading day. By going long in the last portfolio (via a reverse repo) while shorting the first (via a repo), we create a collateral swap of assets with higher convenience premium for those with lower convenience premium. The carry therefore captures *daily* movements in non-monetary convenience benefits.[3] Our carry measures the return of an investor who holds bonds with high convenience yield and is disposed to exchange them for other bonds

[2]The euro area repo market infrastructure is based on central clearing and anonymous centralized electronic order book platforms, which guarantees homogeneous counterparty credit risk and an efficient price formation.

[3]In the European setting, the borrower remains the beneficial owner of the collateral which he pledges and therefore continues to receive the income cash-flows on the collateral for the term of the repo. A hypothetical repo carry trader operates on two fronts for the duration of one day: (i) he lends cash and temporarily receives a relatively low-convenience collateral (with higher rates) and (ii) he borrows cash and temporarily sells a high-convenience collateral (with lower rates). Note that the carry trader is not entitled to receive the cash-flows accrued from the collateral obtained in (i), while he continues to receive those from the collateral temporarily sold in (ii). Engaging into the carry trade therefore does not affect which counterparty receives the monetary cash-flows (i.e., coupon payments and exposure to bond price movements). Thus, by construction, our carry neatly isolates the non-monetary convenience benefits from monetary income and allows us to crystallize in a novel and clean way the cross-sectional differential in day-to-day convenience yield movements.

with lower convenience yield on a day-by-day basis.[4]

Although our results are of general validity, we focus on spot-next repos which constitute the lion's share of repos in the euro area. For those repos, settlement takes place two business days after the trading date. Given the length of the loan contract (one day), the collateral is returned on the third day. Hence, the carry reflects the foregone benefits on the high-convenience collateral and the gained benefits on the low-convenience collateral between day two and day three. The repo rate at which the carry trade is executed represents the *expectation* (Longstaff, 2000) about the convenience yield difference between the assets in portfolio 1 and 8. This is different from the actual future *realization* of the convenience yield as repo rates could have changed in the meantime due to changes in interest rates and collateral quality. To capture this, we compare forward rates (spot-next rates at time t) with realized rates (overnight rates at time t+2). Our carry therefore represents not only a compensation for the quality differential (safety and liquidity benefits) but also a compensation for the uncertainty in the realization of the convenience yield.

Figure 1 depicts the time-development of our carry return net of transaction cost formed across all euro area countries (green line) and without GIIPS countries (dashed grey line).[5] The average annualized carry return amounts to 0.39%, the standard deviation of the difference between the expected and realized carry, which is a proxy for time-varying uncertainty of the convenience yield, is 0.18%. When uncertainty increases, for instance during the European sovereign debt crisis, the carry return formed without GIIPS countries is lower, pointing towards the safety premium of truly safe assets and a lower dispersion in rates within those countries. Since 2015, when the European Central Bank (ECB) set up the negative nominal rate regime and conducted asset purchasing programs, the spread of the carry return to the ECB's deposit facility rate has also increased. Both carries are almost identical during this period, pointing towards the liquidity premium and an increasing rate dispersion even within

[4]Our approach to calculate the carry captures one-day movements in nonpecuniary convenience yields. We consider an alternative carry that incorporates the cash-flows from buying and selling the underlying bonds. However, bond price changes not only capture movements in one-day convenience yield, but also changes in the present value of all future convenience yields over the life of the bond and monetary benefits. We therefore feel that focusing on the repo trade is a more precise way of measuring daily movements in convenience yield.

[5]GIIPS countries are Greece, Ireland, Italy, Portugal, and Spain.

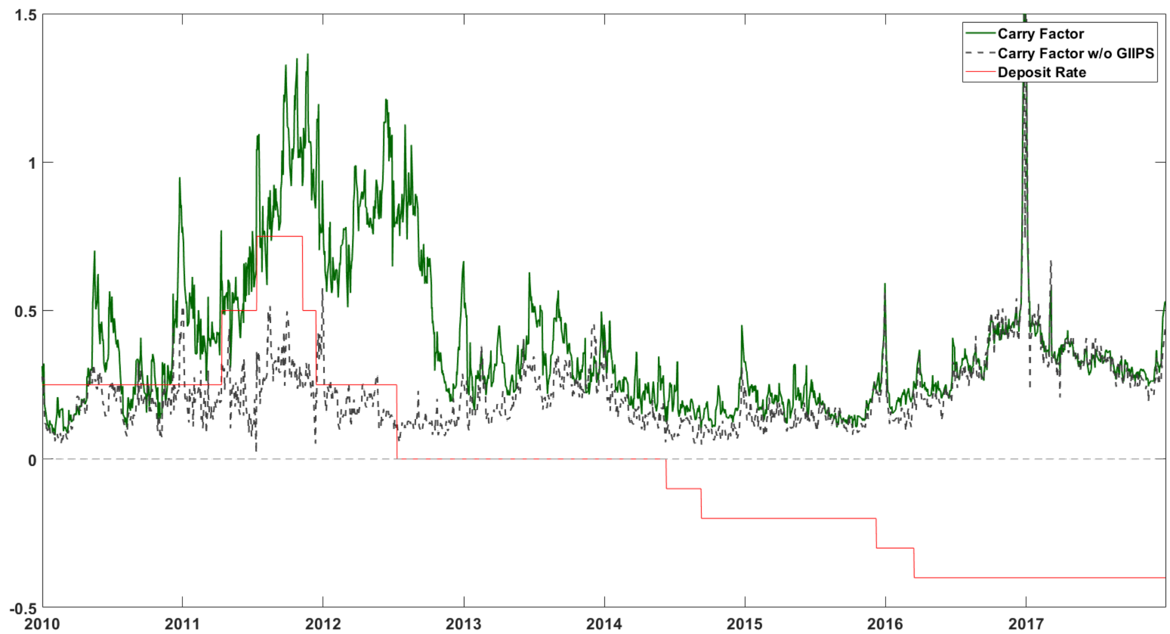



**Figure 1:** Development of the safe asset carry factor with/without GIIPS countries

truly safe assets.

Based on the portfolio results and the formation of our carry factor, we propose a simple two factor asset pricing model. For the asset pricing estimation, we apply a linear factor model and employ a generalized method of moments (GMM) estimation following Hansen (1982). We define the market factor to be the average repo market rate and the carry factor to be the high-minus-low carry return. The results reveal that our two pricing factors are able to explain a very large share of the price variation in near-money assets. The factor betas for the market factor are essentially all equal to one, while the factor betas for the carry factor increase monotonically from $-0.80$ for the first portfolio to 0.38 for the last portfolio. The results support the notion that the market factor explains the level of short-term interest rates, while the carry factor accounts for the cross-sectional dispersion. The market price of the carry factor is highly statistically significant at a level of 0.42% per annum. The 0.42% carry premium reflects the expected compensation for swapping assets in portfolio 1 and 8 over a one-year period.

In the second part of our paper, we employ the carry factor to gain insights into the economic determinants of convenience yields. Since the carry factor measures the difference in the convenience yields offered by truly safe assets (in the low-rate portfolio) versus quasi-safe assets (in the high-rate portfolio), we are able to explore how the varying degrees of safety and liquidity attributes of European collateral assets drive convenience. In the safe asset literature, convenience yield is associated with the safety and the liquidity premium. Against this background, three hypotheses about the carry factor can be brought forward: First, the larger the safety premium of truly compared to quasi-safe assets, the higher the carry factor. Second, when truly safe assets become scarcer compared to quasi-safe assets, their liquidity premium increases and so does the carry. And third, since truly and quasi-safe assets are imperfect substitutes, the liquidity premium of truly safe assets, which provide more utility and are in short supply, increases more with the opportunity cost.

To test these hypotheses, we construct variables capturing the different drivers of convenience yield following the literature (i.e., "CDS," "asset supply," and "opportunity cost"). We then proceed in three steps: First, we perform a panel regression of our eight repo portfolio returns on the different economic determinants of convenience yield. Our results show that the rates of the assets in portfolio 1 (with the higher convenience yield) are comparatively lower when risk increases ("safety premium") and when the opportunity cost is higher ("liquidity premium"). Second, we regress our carry factor (instead of the portfolio rates) on the different economic drivers of convenience yield. Our results support the safe asset predictions showing that the convenience yield embedded in our carry factor increases in the safety premium and the liquidity premium reflecting opportunity cost. Importantly, the opportunity cost of holding money drive away the explanatory power of asset supply in line with Nagel (2016), which highlights the importance of the level of interest rates in explaining the liquidity premium.[6]

And third, we want to understand how the liquidity premium interacts with sovereign default risk. For this, we consider the within-country dispersion in short-term rates. This within-country dispersion can only relate to differences in the liquidity premium since the

[6]We perform a number of additional tests to ensure that our results are robust across subsegments, term types, and market venues, and thus have general validity.

sovereign risk is the same across all bonds of the same country. The carry factor explains more of the within-country rate dispersion for truly safe assets, which implies a larger variation in the liquidity benefits offered by those assets. However, during flight-to-safety periods, such as during the European sovereign debt crisis, the differences in the liquidity premium of safe assets are smaller, suggesting that safety attributes gain in importance. This is reflective of the carries depicted in Figure 1. The carry formed only with truly safe assets (as opposed to including quasi-safe assets as well) is smaller during the European debt crisis pointing towards a smaller rate dispersion among truly safe assets during those moments of uncertainty. The rate dispersion within those countries has, however, increased during the QE-period, pointing towards difference in the liquidity premium, even within the universe of truly safe assets.

As a final step, we want to understand the explanatory power of our carry factor in terms of its external relevance. For this, we perform an asset pricing analysis of European government bonds. Our results highlight that the repo carry factor helps explain the cross-section of bond returns even after accounting for standard bond pricing factors, following Nelson and Siegel (1987), and controlling for *bond* safety and liquidity. The unexplained yield component of long-term bonds increases with our carry factor, suggesting that the carry captures additional convenience attributes such as the short-term funding ability (e.g., fungibility and (re-)pledgeability) with the advantage of being available in a timely fashion and at high frequencies.

Our analysis contributes to two strands of the literature. First, we contribute to the asset pricing literature. Fama and French (1993) document common factors in equity and bond markets and more recent research shows that common factors explain other assets such as currencies (Lustig et al., 2011).[7] Koijen et al. (2018) provide an overview of different carries in equity, fixed income, and option markets. We are the first to carry out a factor pricing analysis of near-money assets and to uncover two common pricing factors.[8] We also add to

[7]Lustig et al. (2011) identify a market-related dollar factor and a carry trade factor inspiring our methodology to build the level and slope factors.

[8]Although no study before ours proposes a repo asset pricing analysis, a growing body of the literature analyzes the cross-sectional dispersion in repo rates including, e.g., Gorton and Metrick (2012), Copeland et al. (2014), Krishnamurthy et al. (2014), Infante (2020) and Ranaldo et al. (2021). Some papers focus on special repos, for instance, Duffie (1996), Jordan and Jordan (1997), Buraschi and Menini (2002), Krishnamurthy

the bond pricing literature of, for example, Cochrane and Piazzesi (2005) and Fontaine and Garcia (2012) by showing that our (short-term) repo factors help explain the cross-section of (long-term) bond returns beyond the standard bond pricing factors.

Second, we add to the growing literature on safe assets.[9] We provide empirical support for safe asset theories predicting cross-sectional dispersion in (quasi-) safe assets and convenience yields (e.g., Krishnamurthy, 2002; Krishnamurthy and Vissing-Jorgensen, 2012; Stein, 2012; Sunderam, 2015; Caballero et al., 2016; Nagel, 2016; Moreira and Savov, 2017; He et al., 2019). By taking an asset pricing approach, we add to the related empirical literature (e.g., Longstaff, 2004; Fleckenstein et al., 2014; Greenwood and Vayanos, 2014; Krishnamurthy and Vissing-Jorgensen, 2015; Du et al., 2018a; and Kacperczyk et al., 2021).

# 1. Repo market

We start by explaining the main characteristics of the euro repo market and our data.

## 1.1 Market structure

In a repo contract, two counterparts exchange cash for collateral (first leg) for a predefined time period with a fixed repurchase obligation (second leg). The asset being used as collateral can be a particular asset ("special repo") or any asset from a predefined basket of assets ("general collateral repo").[10] Repurchase agreements are a form of short-term borrowing, as collateral is typically sold on an overnight basis.

We analyze the European repo market, which is the largest repo market in the world with more than EUR 8.5 trillion in outstanding contracts (International Capital Market Association, 2021). Several characteristics of its infrastructure are noteworthy: The core segment is the interbank market in which banks trade anonymously via centralized electronic

(2002), D'Amico et al. (2018), Arrata et al. (2020), and Corradin and Maddaloni (2020). Other studies investigate GC repos, for instance, Bartolini et al. (2011), Mancini et al. (2016), and Boissel et al. (2017). We study both special and GC repos.

[9] The shortage of safe assets and the macroeconomic and financial stability implications are analyzed in, e.g., Caballero and Krishnamurthy (2009), Caballero et al. (2017), and Caballero and Farhi (2017).

[10] In the U.S., a special repo is sometimes referred to as a "specific" repo, with the term "special" referring to specific repo rates being below prevailing short-term money market rates.

order book platforms supporting liquidity and a transparent price discovery process.[11] We focus on trades operated through central counterparties (CCP). CCP-based repos constitute the majority of trades in the euro interbank repo market.[12] For those trades, CCPs interpose themselves between each lender and borrower. This means the CCP is the borrower to every lender and the lender to every borrower, i.e., the structure eliminates any concerns regarding individual counterparty risk. The CCP acts as a clearinghouse and applies the same collateral and (credit) risk policies to all CCP members.[13] If the CCP is the counterparty to a trade, it guarantees scheduled settlement of the repo in case a CCP member defaults.[14]

The usual repo term types are overnight (ON), tomorrow-next (TN), and spot-next (SN), indicating purchase dates tonight, tomorrow, and the day after tomorrow, respectively, and the repurchase date one day thereafter. The most common collateral assets are government bonds on which we focus in our analysis. A repo represents a true sale and repurchase of the collateral asset, i.e., the buyer (lender) becomes the legal owner of the collateral at the purchase date. While the buyer of the collateral is the owner of the asset during the term of the repo, the seller retains the risk of the asset as he has agreed to buy it back at the repurchase date. Any income arising from the asset during the repo term (e.g., coupon payments) is therefore transferred to the seller.

We focus on repo trades that (i) are CCP-based, (ii) mature after one day, and (iii) are collateralized by government bonds which are classified as high-quality liquid assets by

[11]Market participants include commercial, retail, and investment banks, as well as other financial institutions (e.g., public banks, cooperatives, and saving banks).

[12]CCP-based repos account for more than two-thirds of the total turnover (European Central Bank, 2018). The CCP inserts itself as a counterparty into each transaction through "novation."

[13]Initial margins or haircuts, which are reflected in the repo rate, were relatively stable during our sample period. The CCP determines ex-ante haircuts that are exogenous and thus the same for all market participants, which is different to the U.S. market practice (e.g., Gorton and Metrick, 2012 and Copeland et al., 2014).

[14]In case of a member default, the CCP will replace the positions of the defaulting member and seek to recover any associated cost by drawing on a series of capital buffers (in the form of initial margins posted by members, committed and contingent contributions by members to a default fund, reserves, and equity capital). Besides the different layers of capital buffers, the CCP also needs to follow conservative investment policies (Ranaldo et al., 2021). Based on those protections, financial market regulators have concluded that there is no systemic default risk in clearing houses (European Securities and Markets Authority, 2016, 2018, 2020). Arguably, there could be (rare) states of the world in which CCP members default, sovereign issuers of the collateral asset default, and the CCP's buffers and equity capital fails. We provide a variety of additional tests showing that the cross-sectional dispersion of European repo rates depends on heterogeneous convenience yields rather than a compensation for such a systemic risk.

regulators. In this setting, given that income payments during the repo term are passed back to the borrower (even though the lender is the legal owner), any convenience yield for the lender must consist of non-monetary benefits (e.g., the ability to re-use the collateral). Hence, the temporal and cross-sectional variation in repo rates mostly stems from the difference in the convenience offered by the collateral asset as well as the uncertainty about the realization in the convenience yield. While the extant literature has predominantly focused on the U.S. Treasury market, our approach of looking at the European repo market is a novel way to capture cross-sectional differences in convenience yield.

### 1.2 Data

Our repo data consists of the near-total universe of all electronically traded interbank repo transactions in euro from the beginning of 2010 to the end of 2017. We obtain data from the three major trading platforms: BrokerTec, MTS, and Eurex. These trading venues account for transactions covering more than 70% of the total European repo market. For each transaction, we observe the trade date, the term, the trade volume, the rate, the collateral identified by a unique ISIN or basket, the aggressor type, and the trading platform. In our analysis, we focus on CCP-based euro repos with overnight tenors with general and specific collateral, which represent the majority of all euro repos. To be conservative, we exclude a very small fraction of repo contracts and trading days that by their nature would increase the rate dispersion: First, we remove bilateral repos and prearranged trades.[15] Second, we exclude repos with term types other than ON, TN, and SN.[16] Third, we focus on sovereign bonds as a collateral asset as non-government bonds present a different risk profile and are

[15] On Eurex, all transactions are CCP-based, whereas on BrokerTec and MTS, a very small fraction of repos are bilaterally traded. After prearrangement, a bilateral trade can also be reported to and cleared by the CCP. Since counterparties in those transactions are not anonymous anymore, we exclude those trades which represent about 5% of our data.

[16] This includes repos with a maturity longer than one day and transactions with open term. Together, we exclude only about 3% of our data.

rarely traded.[17] Fourth, we exclude repos with a floating rate.[18] Fifth, we exclude infrequently traded repos to guarantee the general validity of our carry factor and ease illiquidity issues.[19] Finally, we perform our main regression analyses based on a sample period which excludes transaction days that for institutional reasons are characterized by a greater dispersion of interest rates; namely trading days at the end of the month and the end of the ECB maintenance periods when repo rates vary considerably more during these (uncertain) times.[20] However, we return to the variation on those days specifically in Table 2 when we show descriptive statistics of our carry factor.

Our data sample construction has two main advantages: On the one hand, it guarantees the general validity of our results because only a small fraction of euro repos are excluded and we ascertain that our findings hold true across all the main market segments. On the other hand, it eliminates many confounding factors such as term premia and currency risk, thus buttressing the measurement accuracy of our results.

Table 1 summarizes our data set, which totals more than 441 trillion euro of transactions. Special repos secured by government bonds and repos of term type SN constitute the largest share of our data. While BrokerTec and MTS are the two largest trading platforms, Eurex mainly covers the GC pooling market. Germany and Italy constitute the largest share by

[17]This is true for special repos and GC trades whose baskets mostly contain government bonds. For special collateral, our data set essentially covers the universe of government bonds. Only about 2,000 trades with a trading volume of 0.02 EUR tn are collateralized by government-related and supra-national agencies (i.e., the German development agency KfW, the European Investment Bank, and the European Fund for Southeast Europe). For GC trades, those baskets mostly contain only government bonds as collateral. On Eurex, two GC pooling baskets allow highly rated assets (i.e., investment grade bonds), including assets issued by regional governments or "Pfandbrief" instruments of credit institutions, to be delivered. The two baskets do not play a major role in our analysis since we do not weight our portfolios by trading volume. Our results are unchanged if we exclude those special repos collateralized by government-related and supra-national agencies and the two GC pooling baskets from our analysis.

[18]Floating rate repos are quoted as a spread to Eonia and represent about 10% of the total trading volume.

[19]To be included in our analysis, a repo needs to be traded on at least 200 trading days (i.e., one year of data) and needs to be traded at least once a week, on average. We exclude repos that represent less than 3% of the total trading volume in the remaining data.

[20]For each term type, we exclude month-end dates and between 8 to 12 end-of-ECB maintenance period dates during a year. The exact date is different for each term type. For example, for the end of the ECB maintenance period on the 19th of December 2017, we exclude the 19th of December 2017 for an ON repo, while for a TN repo, we exclude the 18th of December 2017. For robustness purposes, we also ensure that the results are consistent if we exclude the entire weeks surrounding quarter-ends. The inclusion of these subsets of data and trading days boosts the performance of our carry factor as we show later in the paper.

**Table 1:** Breakdown of the repo data

| | Transactions (in mn) | Volume (in EUR tn) | Transactions (share in %) | Volume (share in %) |
|---|---|---|---|---|
| Centrally cleared euro repos | 16.87 | 441.39 | 100.00% | 100.00% |
| General collateral | 1.49 | 136.18 | 8.82% | 30.85% |
| Special collateral | 15.38 | 305.21 | 91.18% | 69.15% |
| *of which are government bonds* | *15.38* | *305.19* | | |
| BrokerTec | 10.35 | 241.88 | 61.38% | 54.80% |
| Eurex | 0.27 | 56.06 | 1.61% | 12.70% |
| MTS | 6.24 | 143.45 | 37.01% | 32.50% |
| overnight | 0.61 | 48.46 | 3.63% | 10.98% |
| tomorrow-next | 3.22 | 95.28 | 19.06% | 21.59% |
| spot-next | 13.04 | 297.65 | 77.31% | 67.44% |
| Austria | 0.71 | 10.88 | 4.49% | 2.59% |
| Belgium | 1.34 | 24.84 | 8.49% | 5.91% |
| Germany | 4.84 | 135.52 | 30.63% | 32.22% |
| European Union | 0.22 | 53.51 | 1.40% | 12.72% |
| Finland | 0.44 | 6.25 | 2.77% | 1.49% |
| France | 0.10 | 14.35 | 0.61% | 3.41% |
| Ireland | 0.31 | 3.49 | 1.99% | 0.83% |
| Italy | 6.26 | 143.24 | 39.68% | 34.06% |
| Netherlands | 1.12 | 22.86 | 7.08% | 5.44% |
| Portugal | 0.45 | 5.64 | 2.86% | 1.34% |
| Spain | 1.09 | 20.81 | 6.89% | 4.95% |

The table shows the breakdown of our repo data. Our data only include centrally cleared repos denominated in euro. The data are broken down by repo type, trading venue, tenor, and the collateral's country of origin. For special collateral, our data set essentially covers the universe of government bonds. Only about 2,000 trades with a trading volume of 0.02 EUR tn are collateralized by government-related and supra-national agencies (i.e., the German development agency KfW, the European Investment Bank, and the European Fund for Southeast Europe). For GC trades, those baskets typically contain only government bonds as collateral. On Eurex, two GC pooling baskets allow highly rated quasi-safe assets (i.e., investment grade bonds) to be delivered. The two baskets do not play a major role in our analysis since we do not weight our portfolios by trading volume. These are only 2 baskets out of a cross-section of 943 repos. Our results are unchanged if we exclude those two baskets from our analysis.

origin of the collateral, with representative shares for other European countries.[21] Overall, our data sample covers the largest segment of the euro area money market and the repo rates under inspection are the most representative available.

For all transactions in our data, we compute the daily volume-weighted average repo rate of each GC basket and ISIN, separately for each term type based on the trade date and across trades executed on the three repo trading venues. We include both GC and special repos in our sample. We choose this approach to provide general validity and the highest representativeness to our results. However, we ensure that our results are not biased by any specific segment or repo type as we provide robustness checks for each subcategory. Specifically, we show that our results do not depend on specialness (because they hold for GC only), illiquidity (because we exclude illiquid repos), term type (because we perform subsampling analysis for each term type), trading venues (because the results are valid for BrokerTec only), and currency (because we only consider euro repos). Our final data set features a cross-section of 943 repos, of which 907 are special repos and 36 are GC repos. Regarding the tenor, 75, 864, and 818 different repos are included in the ON, TN, and SN market segments, respectively. We compute transaction cost for each repo separately.[22]

To carry out the bond asset pricing analysis, we obtain bond quotes and trades from the MTS Cash market. The MTS market is the largest interdealer trading network for European government bonds; liquidity is ensured by active market making and a quote-driven electronic limit order book. We focus on the cross-section of European sovereign bonds that are posted as repo collateral and include all zero and fixed-coupon bonds.[23] For each day between a bond's issuance and maturity, we compute the daily volume-weighted average mid-quote,

[21]Our sample includes a relatively small share of French collateral for two reasons: First, French repos are mainly floating rate. Second, certificates of deposit are another source of short-term funding that is mostly common in the French market (Pérignon et al., 2018).

[22]We compute transaction cost as the difference in repo rates between borrower-initiated and lender-initiated trades. Borrower-initiated trades refer to the counterparty borrowing cash in the repo market as the aggressor (i.e., "ask" rate), whereas lender-initiated trades refer to the counterparty lending cash in the repo market as the aggressor (i.e., "bid" rate). The aggressor variable specifies whether a borrower or a lender has initiated a trade against the prevailing quotes, we therefore derive transaction cost from the prevailing bid and ask quotations against which trades are executed.

[23]In the construction of our data, we exclude suspicious quotes that show up as outliers relative to surrounding quotes. Those quotes represent a minimal share of 0.03% of our data.

transaction price, and transaction cost. The size and liquidity of the MTS market make our bond data highly representative.

## 2. Carry factor and repo pricing

We begin our analysis by looking at the *cross-country* dispersion in near-money rates. Figure 2 shows the development of GC repo rates for Germany (green line) and Italy (dashed blue line) in relation to the ECB's rates on the deposit and marginal lending facility (red lines). Three patterns stand out. First, repo rates for Germany are lower than those for Italy. Second, the spread between the two countries increased during the European sovereign debt crisis. And third, since 2015, German repo rates have fallen below the ECB's deposit facility rate, while Italian repo rates have stayed above or at the level of the deposit rate which evokes the greater convenience services of the former over the latter.

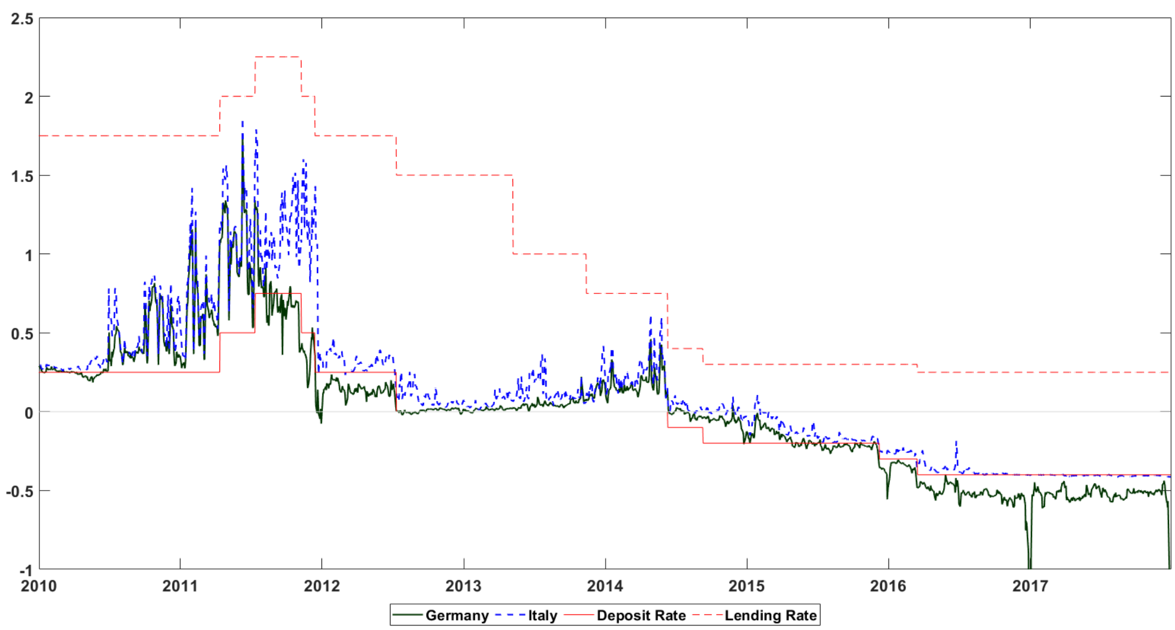



**Figure 2:** General collateral repo rate development

The safe asset literature suggests the following interpretation. First, the cross-country dispersion in GC repo rates points towards heterogeneity in convenience yields which are systematically higher for countries such as Germany. Second, an increasing dispersion during the European sovereign debt crisis suggests the existence of a safety premium for truly safe assets. And third, the increasing dispersion after 2015 coincides with collateral scarcity due to quantitative easing (Arrata et al., 2020) and prudential regulation (Ranaldo et al., 2021). The consequent reduction in the supply of safe assets seems to be leading to higher liquidity premia embedded in truly safe assets. At the same time, investors are not willing to accept a lower interest rate to receive an Italian collateral compared to storing their funds at the ECB's deposit facility, which reinforces the lower bound on Italian rates and indicates that the convenience benefits of quasi-safe assets are valued less.

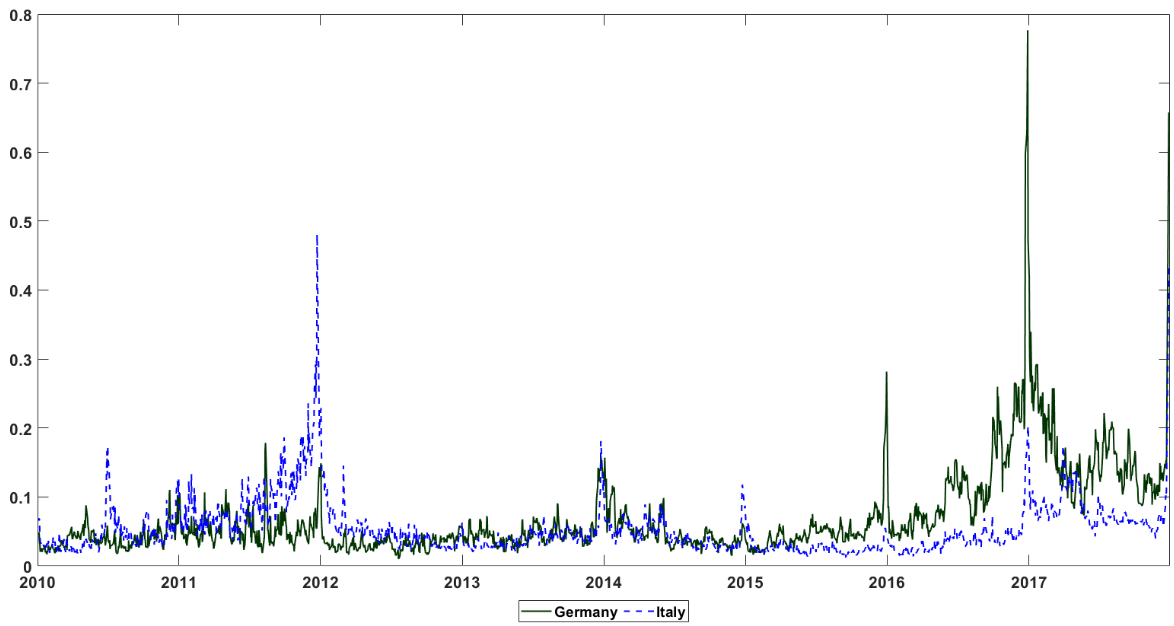



**Figure 3:** Repo rate dispersion

Another aspect is the *within-country* dispersion in repo rates of the same sovereign country as depicted in Figure 3. We calculate the dispersion as the interquartile range across the set of each country's daily repo rates. Until 2015, the dispersion in rates has been similar between German and Italian collateral, however, since 2015, the dispersion in German repo rates has increased. This underlines the importance of different liquidity benefits even within the universe of bonds of the same sovereign issuer.

## 2.1 Safe asset portfolios

To capture the dispersion in repo rates, we build portfolios of repos. For this, we focus on spot-next repos which constitute the lion's share of the repos in the euro area. At the end of each trading day *t-1*, we sort the repos in our sample according to the repo rate observed during that day. Based on this sorting, we allocate each of the repos into eight portfolios in which we invest on the following trading day $t$: The first portfolio contains the repos with the lowest rate during the previous day, while the last portfolio contains the repos with the highest rate.[24] Portfolios are rebalanced daily. Since we focus on SN repos, settlement of the repo takes place two business days after the trading date, i.e., the first leg settles at $t+2$, while the final repayment takes place at $t+3$. A repo borrower (lender) therefore foregoes (enjoys) the convenience of the collateral asset for the period between $t+2$ and $t+3$. This concept is illustrated in Figure 4.

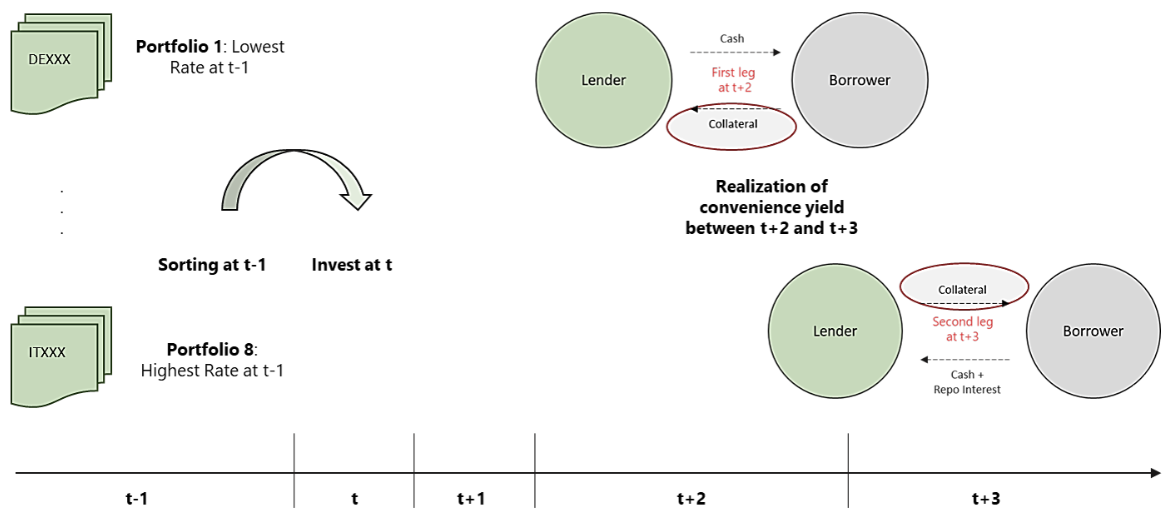



**Figure 4:** Convenience yield in repo trade

The repo rate at which the trade is executed at time $t$ represents the *expectation* about the convenience yield embedded in the collateral. This is different from the actual *realization* of the convenience yield between $t+2$ and $t+3$ as repo rates could have changed in the meantime. Potential reasons include general movements in the funding demand and supply

[24]Our results remain unaffected by a change in the number of portfolios to two or four as reported in the Online Appendix.

or changes in the net demand for individual securities due to, for example, (i) short sellers, (ii) deliverability into futures contracts, (iii) inventory rebalancing of market makers, (iv) movements in collateral prices, and (v) supply changes (e.g., induced by quantitative easing or bond issuances).

To study the actual realization in the convenience yield, we revisit the previous literature testing the expectations hypothesis using short-term interest rates (e.g., Longstaff, 2000; Della Corte et al., 2008) and take advantage of the euro repo market set-up. More precisely, we study portfolio returns at time $t+2$ by weighting the ON rates at $t+2$ with the portfolio constituents embedded in the initial trade that was executed at time $t$. Alternatively, we calculate the realization using the tomorrow-next term type which features higher trading volumes. For this, we analyze portfolio returns at time $t+1$ by weighting the TN rates at $t+1$ with the portfolio constituents embedded in the initial trade that was executed at time $t$.[25] Since our setting eliminates many confounding factors to convenience yield such as term premia, counterparty and currency risk, this is the most suitable approach to capture the convenience yield realization.[26] Applying the same intuition as in the expectations hypothesis, forward interest rates should be aligned with realized interest rates if there were no time-varying risk premia. In our context, we should empirically observe that forward interest rates (captured by SN repo rates at time t) coincide with realized interest rates (captured by ON repo rates at time t+2). Conversely, the dispersion in their difference suggests uncertainty in the realization of the convenience yield.

Table 2 provides an overview of the performance of the eight repo portfolios. For each portfolio $n$, we report the average expected portfolio returns gross and net of transaction

[25]ON repo trading volumes are lower than SN volumes. We account for this in the calculation of the realized carry by adjusting the portfolio weights in each of the portfolios in case fewer rates are observed on any given day. The analysis based on TN repos delivers consistent results suggesting that the lower trading volume in ON repos does not bias our results. The results can be found in the Online Appendix

[26]The use of overnight repos allows us to remove term premia and uncertainty over longer horizons. In addition, focusing on repos that are traded via a central counterparty and that are overcollateralized by government bonds reduces credit risk as it makes repos information insensitive (e.g., Gorton and Ordonez, 2014). We could look at longer-term repos, e.g., one-week repos, and compare them to overnight rates as an alternative to capture the realization in the convenience yield. This approach, however, has the disadvantage that longer-term repos are less frequently traded and that they carry a term premium.

**Table 2:** Portfolio return (%)

(i) without end of month and end of ECB maintenance periods (baseline)

| | Portf. 1 | Portf. 2 | Portf. 3 | Portf. 4 | Portf. 5 | Portf. 6 | Portf. 7 | Portf. 8 |
|---|---|---|---|---|---|---|---|---|
| Expected Gross Return | −0.35 | −0.07 | −0.03 | −0.01 | 0.01 | 0.05 | 0.08 | 0.11 |
| Expected Net Return | −0.30 | −0.09 | −0.04 | −0.02 | 0.00 | 0.03 | 0.07 | 0.09 |
| Expected High-Minus-Low Net Return | - | 0.21 | 0.26 | 0.28 | 0.30 | 0.33 | 0.36 | 0.39 |
| Standard Deviation of Expected minus Realized Net Return | 0.20 | 0.13 | 0.14 | 0.12 | 0.10 | 0.11 | 0.12 | 0.11 |

(ii) without end of month, end of ECB maintenance periods, and end of quarter

| | Portf. 1 | Portf. 2 | Portf. 3 | Portf. 4 | Portf. 5 | Portf. 6 | Portf. 7 | Portf. 8 |
|---|---|---|---|---|---|---|---|---|
| Expected Gross Return | −0.34 | −0.06 | −0.02 | −0.01 | 0.01 | 0.05 | 0.08 | 0.11 |
| Expected Net Return | −0.29 | −0.08 | −0.04 | −0.02 | 0.00 | 0.03 | 0.07 | 0.10 |
| Expected High-Minus-Low Net Return | - | 0.21 | 0.25 | 0.27 | 0.29 | 0.32 | 0.36 | 0.38 |
| Standard Deviation of Expected minus Realized Net Return | 0.20 | 0.14 | 0.14 | 0.12 | 0.10 | 0.11 | 0.12 | 0.11 |

(iii) at end of month, end of ECB maintenance periods, and end of quarter

| | Portf. 1 | Portf. 2 | Portf. 3 | Portf. 4 | Portf. 5 | Portf. 6 | Portf. 7 | Portf. 8 |
|---|---|---|---|---|---|---|---|---|
| Expected Gross Return | −0.40 | −0.10 | −0.06 | −0.03 | 0.00 | 0.07 | 0.11 | 0.15 |
| Expected Net Return | −0.34 | −0.13 | −0.08 | −0.05 | −0.02 | 0.04 | 0.09 | 0.13 |
| Expected High-Minus-Low Net Return | - | 0.21 | 0.26 | 0.29 | 0.32 | 0.38 | 0.43 | 0.46 |
| Standard Deviation of Expected minus Realized Net Return | 0.38 | 0.29 | 0.25 | 0.25 | 0.22 | 0.16 | 0.17 | 0.17 |

The table shows the average, annualized expected portfolio returns for portfolios $n$=1, 2,...,8, gross and net of transaction cost using SN repo transactions; the return on the high-minus-low investment strategy relates to the expected net portfolio return and shorts portfolio $n$=1 while going long in portfolios $n$=2, 3,...,8; and the standard deviation of the difference between the expected portfolio net return (using the SN rate at time t) and the realized portfolio net return (using the same portfolio constituents at the ON rate at time t+2). "Without end of month and end of ECB maintenance periods" excludes end of month and end of ECB maintenance period tradings days; "without end of month, end of ECB maintenance periods, and end of quarter" excludes end of month and end of ECB maintenance period tradings days as well as end of quarter trading weeks; and "at end of month, end of ECB maintenance periods, and end of quarter" includes only end of month and end of ECB maintenance period tradings days as well as end of quarter trading weeks.

cost;[27] the return on the high-minus-low investment strategy, which shorts portfolio $n$=1 while going long in portfolios $n$=2, 3,...,8; as well as the standard deviation between the expected net return (using the SN rate at time t) and the realization of the net return (using the same portfolio constituents at the ON rate at time t+2). It is well-known that euro area repo rates tend to spike at reporting dates such as quarter-end periods (e.g., Ranaldo et al., 2021). We therefore present the portfolio results for a sample (i) where we exclude end of month and end of ECB maintenance period trading days (baseline), (ii) where we additionally exclude the entire trading weeks surrounding quarter ends, and (iii) where we only include those periods.

In our baseline (i), the expected annualized net return increases monotonically from −0.30% for the repos in the first portfolio to 0.09% for the repos in the last portfolio. Similarly, the average annualized return on the high-minus-low investment strategy increases from 0.21%, considering the second portfolio, to 0.39%, considering the last portfolio. The high-minus-low return is largely driven by the low rates on the assets in portfolio 1 pointing towards (safety and liquidity) benefits of holding those truly safe assets. The standard deviation between the expected and realized rates is also highest for the assets in portfolio 1 as those assets tend to carry the highest convenience benefits. This variability, which is at least half as large as the carry, points towards the non-negligible role of uncertainty in the realization of the convenience yield. Additionally excluding the entire weeks surrounding quarter ends (ii) does not change the results materially. When we focus on those periods of higher volatility in (iii), the high-minus-low return increases to 0.46% in line with the idea that convenience benefits are more valuable on those days. While the overall effect seems to be small, it represents a more than 15% increase in the high-minus-low return. At the same time, the volatility indicator of convenience yield uncertainty also tends to be higher. While we show that this uncertainty exists, we do not include it in the calculation of the expected

[27] For the purpose of computing portfolio returns net of transaction cost, we assume borrower-initiated trades for portfolio $n$=1 (i.e., "ask" rate to borrow money) and lender-initiated trades for portfolios $n$=2, 3,...,8 (i.e., "bid" rate to lend money). We compute a volume-weighted average repo rate across borrower- and lender-initiated trades for each repo separately. We therefore add half the repo-specific borrower-lender spread to the average rate for repos in portfolio 1, while we subtract half the borrower-lender spread from the average rate for repos in portfolios $n$=2, 3,...,8.

carry at time $t$ on which we focus in the remaining part of the paper.

The daily transaction volume for all portfolios is substantial in absolute terms but not relative to the large market size, which ensures the rebalancing.[28]

**Table 3:** Portfolio constituents

| | Portf. 1 | Portf. 2 | Portf. 3 | Portf. 4 | Portf. 5 | Portf. 6 | Portf. 7 | Portf. 8 |
|---|---|---|---|---|---|---|---|---|
| Austria | 3.8% | 5.8% | 7.9% | 13.0% | 12.4% | 4.4% | 1.1% | 0.6% |
| Belgium | 8.0% | 9.7% | 11.3% | 15.1% | 22.8% | 7.4% | 1.5% | 0.8% |
| EU | 0.9% | 0.5% | 0.2% | 0.2% | 0.3% | 1.4% | 1.1% | 2.1% |
| Finland | 3.8% | 5.3% | 6.7% | 8.0% | 5.9% | 2.2% | 0.6% | 0.4% |
| France | 0.1% | 0.1% | 0.1% | 0.2% | 0.8% | 1.6% | 0.9% | 1.3% |
| Germany | 30.7% | 38.6% | 39.7% | 33.2% | 18.5% | 4.8% | 1.0% | 0.8% |
| Ireland | 8.6% | 3.1% | 1.8% | 1.5% | 2.7% | 3.8% | 2.3% | 5.1% |
| Italy | 11.7% | 11.1% | 8.9% | 8.8% | 15.7% | 45.5% | 73.3% | 67.0% |
| Netherlands | 4.9% | 11.3% | 15.3% | 13.3% | 7.1% | 2.5% | 0.7% | 0.3% |
| Portugal | 11.5% | 3.4% | 1.9% | 1.7% | 3.0% | 4.0% | 2.6% | 6.1% |
| Spain | 15.9% | 11.1% | 6.1% | 5.2% | 10.8% | 22.5% | 14.9% | 15.6% |

The table shows the average percentage that each country's collateral constitutes of the collateral in portfolios $n$=1, 2,...,8. On each day and for each portfolio, we compute the ratio of the number of collateral securities associated with a country relative to the total number of collateral securities in a portfolio. We compute the average of the daily shares for each country in each portfolio to account for changes in the number of portfolio constituents across time.

To assess the importance of the geographic origin, we analyze the composition of the long and short portfolios. Table 3 shows the average fraction that each country's collateral contributes to each portfolio. In support of the idea that the first portfolio hosts assets with a higher safety premium compared to the last one, countries associated with a strong economy and political stability have a larger share in portfolio 1. For instance, the average shares of Germany (Italy) in portfolios 1 and 8 are 30.7% and 0.8% (11.7% and 67%), respectively. However, bonds issued by the same sovereign country can differ quite a lot in repo rates as well, for example, German government bonds have a substantial share not only in portfolio 1, but also in portfolios featuring repos with higher rates, thus hinting at the time-varying liquidity premium as an additional determinant of convenience yield which helps explain the within-country variation in rates.[29]

[28]The average daily trading volume of portfolios 1 and 8 is more than euro 2 bn, respectively; the daily trading volume for any of the two portfolios never falls below euro 500 mn. In Section 3, we return to the variation in trading volumes of portfolios 1 and 8 as a potential economic determinant for the cross-sectional dispersion in near-money rates.

[29]A breakdown of the portfolio transition matrix, i.e., what is the likelihood of a bond which is in a certain

## 2.2 High-minus-low

Our goal is to capture the convenience premium differential between the set of assets comprising the high- and low-rate portfolios. The portfolio results therefore provide the motivation for our carry trade: By going long in the last portfolio with the highest repo rates (via a reverse repo) while shorting the first portfolio with the lowest rates (via a repo), we create a *collateral swap* that captures the convenience premium differential. The schematic view is illustrated in Figure 5.

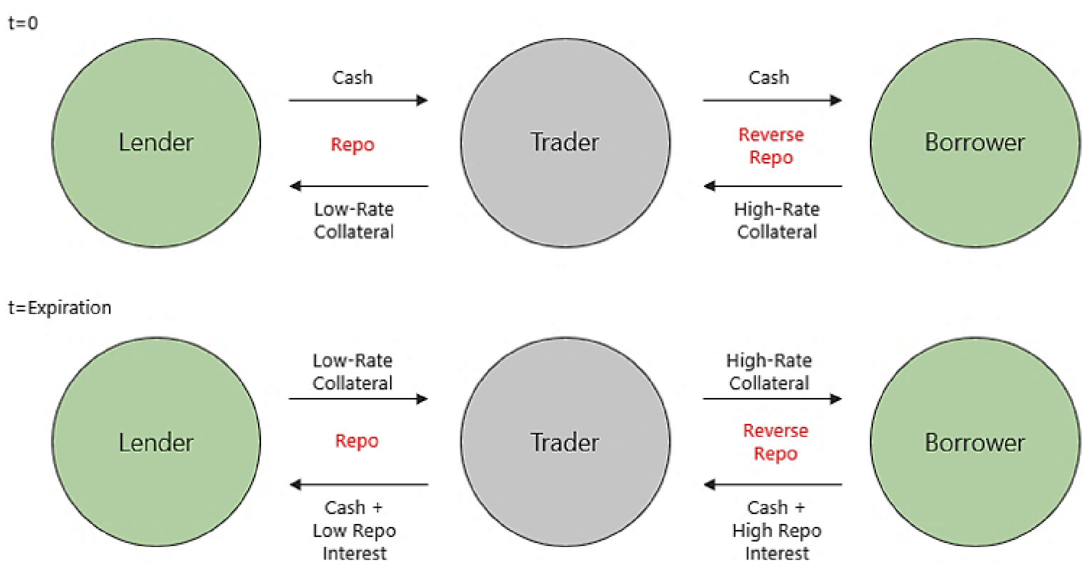



**Figure 5:** Carry trade

The trader in our example pledges the assets in the low-rate portfolio to borrow cash (repo), he then lends this cash in a reverse repo transaction for which he obtains the assets in the high-rate portfolio as collateral. As such, we consider matching repo/reverse repo transactions with different collateral bonds but the same settlement date.[30] Haircuts on the

portfolio to stay in that portfolio tomorrow is presented in the Online Appendix. As expected, there is persistence, but we also observe movements across portfolios.

[30]Since we exclude end of quarter and end of ECB maintenance period reporting dates, those matching repo/reverse repo trades do not affect the size of a bank's balance sheet as reported for regulatory purposes (Bank for International Settlements, 2017).

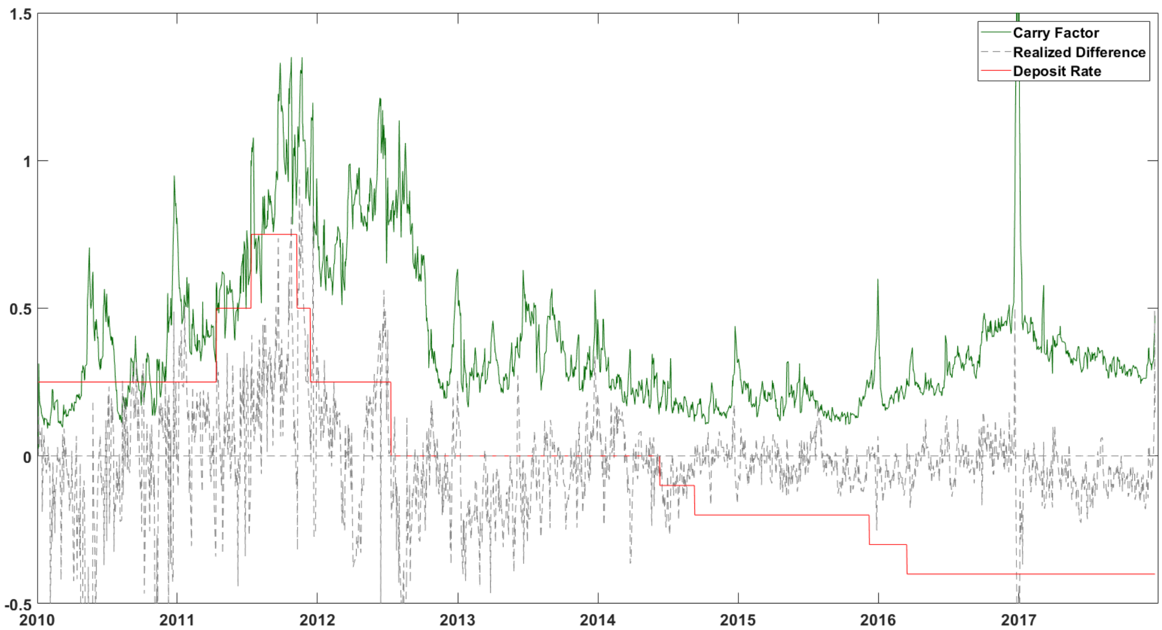



**Figure 6:** Carry factor and carry factor realization

high-rate portfolio tend to be larger than the ones on the low-rate portfolio, i.e., the amount borrowed by the trader is larger than the amount lent on the reverse repo side. In our analysis, we abstract from haircuts to be conservative.[31] Once the two positions are unwound on the next day, the carry materializes as the difference between the two repo rates. The trader receives the high repo rate (on the reverse repo side) while he pays the low repo rate (on the repo side). At the same time, he returns the high rate collateral while he receives back the low rate collateral.

The development of the carry return (green line) as well as the difference between the expectation and the actual realization (dashed grey line) is depicted in Figure 6, detailed summary statistics can be found in Table 4.[32] The average annualized carry return is 0.39%, with an annualized standard deviation of the difference between the expected and realized carry of 0.18%. Cross-sectional differences in convenience yield are time-dependent. We

[31] The ECB's collateral framework serves as a reference for the CCP's haircuts (https://www.ecb.europa.eu/paym/coll/assets/html/list-MID.en.html). For example, at the end of our sample, ECB haircuts were about 3%-points higher for assets in portfolio 8 compared to assets in portfolio 1.

[32] A visual comparison between the realization of the carry return using the ON respectively TN rates is presented in the Online Appendix.

**Table 4:** Summary statistics (%)

| | | | | | |
|---|---|---|---|---|---|
| Mean | 0.39 | Percentile | | Percentile | |
| Minimum | 0.08 | 1% | 0.11 | 75% | 0.47 |
| Maximum | 1.90 | 5% | 0.14 | 95% | 0.95 |
| Standard Deviation | 0.18 | 25% | 0.22 | 99% | 1.21 |

The table reports summary statistics for the carry factor. It shows the mean, minimum, and maximum of the annualized carry return as well as the standard deviation of the difference between the expected and realized carry factor; it also lists the standard percentiles of the carry return.

observe the highest annualized returns during the European sovereign debt crisis in 2011 and 2012 (0.73% and 0.70%, respectively) pointing towards the role of the safety premium. We also observe an increase in the carry return to about 0.36% in 2017 during the period of unconventional monetary policy pointing towards the role of the liquidity premium.[33] The Dickey and Fuller (1979) and Phillips and Perron (1988) tests provide evidence that the null hypothesis of unit root can be rejected.[34]

### 2.3 Economic interpretation

Within the context of the safe asset literature, the carry captures the convenience premium differential between the assets carrying a higher convenience (lower rate) and the ones carrying a lower convenience (higher rate). More precisely, the carry captures the forgone utility of one asset (or basket) against the utility of receiving and reusing another asset (or basket) for the time between the purchase and repurchase. We also observe that there is a sizeable volatility in the realization of the convenience yield. Our carry factor thus represents both a compensation for the quality differential (safety and liquidity benefits) as well as a compensation for the uncertainty in the realization of the convenience yield.

To operate the repo leg, the collateral asset must already be held in order to be sold, this collateral swap is not self-financing. The carry is thus a return available to an investor

[33] Despite the removal of year-end trading days, we observe window dressing effects in the days leading up to the end of the year (in particular in 2016 and 2017), which are reflected in the spikes of our carry return.

[34] Stationarity is the natural result of the tight connection of repo rates with the monetary policy rate. To ensure stationarity, our carry trade could also be implemented relative to the ECB's deposit facility rate since repo market rates are cointegrated with the ECB's target rate.

with these high convenience yield bonds in hand, and the ability/willingness to potentially use a lower convenience yield collateral on a day-by-day basis. An alternative carry trade would be to incorporate the cash-flows on the underlying bonds. For example, one could consider the cash-flows and price movements of the low-rate bonds which the trader needs to hold to implement this trade. However, what we are aiming to measure is the non-pecuniary convenience of a having a collateral at one's disposal for a period of one day. This convenience accrues to the counterparty receiving the pledged collateral. In the European setting, income cash-flows on the collateral during the repo term are passed to the borrower. Hence, incorporating cash-flows from the underlying bonds implies that our non-pecuniary convenience benefits are combined with monetary income (price change, accrued interest). By contrast, the way we choose to construct and measure the carry does not affect who receives the monetary cash-flows. Thus, by construction, our carry neatly isolates the non-monetary convenience benefits from monetary income and allows us to crystallize the cross-sectional differential in one-day convenience premia.

Following Krishnamurthy (2002), the bond price contains information about the convenience yield. However, bond price movements not only capture movements in one-day convenience yield, but also changes in the present value of all future convenience yields over the life of the bond as well as monetary benefits. Our method is more tailored to the purpose of our analysis in the sense that the repo carry factor reflects the part of the bond price change related to holding the bond for a period of one day. We show that the performance of our carry factor remains positive and increases once we account for the bond portfolio return (Online Appendix). However, the overall return is dominated by bond price movements which is consistent with the idea that the largest part of the price movements in the bond reflects changes in the present value of all future convenience yields as well as monetary benefits.

Regarding the repo rate dispersion, one may argue that our results can be explained by specialness, market segmentation, and systemic risk of defaulting clearing houses. Although these explanations are not at odds with our explanation, we perform various analyses that clearly discard these alternative explanations. First, we find that the carry factor is present for both GC and special repos separately, indicating that the carry return cannot only be driven by "specialness" (Duffie, 1996). Second, there could be market segmentation in the sense that agents prefer specific tenors, market venues, and collateral (Cœuré, 2019). Subsampling analyses show that our results are robust across different repo tenors and if we only consider trades executed on BrokerTec.[35] Third, explaining the carry return with the systemic risk of a joint default of a clearing house along with the sovereign issuers of collateral assets in the spirit of Boissel et al. (2017) does not square well with our empirical patterns. For example, as is displayed in Figure 1, the carry remains present when we exclude all GIIPS countries from the construction of our carry factor (which removes sovereign default risk from our carry factor). Financial market regulators have also repeatedly documented that there is no systemic default risk in clearing houses (European Securities and Markets Authority, 2016, 2018, 2020).[36]

### 2.4 Common factors

Based on our portfolio results and the formation of our carry factor, we propose a simple two factor asset pricing model. We motivate our asset pricing approach by a principal component analysis (PCA) of our portfolio returns.[37] The first principal component accounts for about 95% of the common variation in portfolio returns and can be interpreted as the level factor since all portfolios load equally on it. The second principal component accounts for the largest part of the remaining 5% of the common variation and can be interpreted as the slope factor since the portfolio loadings increase monotonically from the portfolio containing the repos with the lowest rate to the portfolio containing the repos with the highest rate. As we expect, the largest part of the common variation in short-term interest rates is explained

[35] A visual comparison of the different carries as well as detailed results are reported in the Online Appendix.

[36] It should be noted that the framework of Boissel et al. (2017) cannot explain the developments of the repo market since 2015 when most of the repo rates (including GC rates) have fallen below the rate of the ECB's deposit facility. Instead, our explanation of time-varying convenience yield is consistent with these patterns.

[37] The results of the PCA are reported in the Online Appendix.

by the level factor.[38] Still, as portfolio returns increase monotonically from the first to the last portfolio, we expect the slope factor to be the most plausible candidate to account for the cross-sectional dispersion in short-term interest rates.[39]

We build two pricing factors to mimic the explanatory power of the first two principal components: a market factor representing the first principal component and our carry factor representing the second principal component. We define the market factor to be the average repo rate across the repo market universe that represents the average borrowing cost[40] and the carry factor to be the high-minus-low carry return that represents the cross-sectional dispersion in repo rates. We compute both factors net of transaction cost. The correlation of the first principal component with our market factor is 0.99, and the correlation of the second principal component with our carry factor is 0.93. We can say that the first principal component measures the collateral quality and convenience level and the second principal component measures the difference in collateral quality and convenience.

For our estimation, we employ the GMM estimation based on Hansen (1982).[41] The results of our asset pricing estimation are depicted in Table 5. Columns (1) - (8) report estimates of the factor loadings for the eight portfolios, while Column (9) depicts estimates of the two factor premia.

[38] All repo rates have a common driver in the level of short-term interest rates such as the monetary policy rate and it is possible to form unbiased expectations about their short-term development (Longstaff, 2000). Repos are also less affected by risk and term premia, especially if they benefit from a safe market environment, as in our case. Consistent with our results, Lustig et al. (2011) show that the first principal component in the relatively more risky FX carry trade explains about 80% of the common variation in currency portfolio returns for developed countries.

[39] Our first two principal components measure most of the variation in short-term rates, there is very few variation that could be explained by other factors. Other term structure models also consider a convexity factor which is of less relevance in our setting due to the short-term nature of repos. Koijen et al. (2018) consider momentum, they use the return of the last 12 months excluding the most recent month in their bond analysis and find mixed results. Given that we are considering daily rates, momentum as constructed over a longer time horizon is not as relevant to our analysis.

[40] We compute the market factor as a volume-weighted average repo rate across the entire repo market, consistent with the methodology proposed by the European Money Market Institute (EMMI).

[41] Details about the GMM methodology and the different moment conditions are in the Online Appendix. For the estimation, we consider repo rates (instead of excess returns) as the dependent variable since our market factor captures the interest rate level. The intercept in the time-series regression therefore does not need to be zero and thus cannot be interpreted as a measure of mispricing.

**Table 5:** Factor analysis

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| | Portf. 1 | Portf. 2 | Portf. 3 | Portf. 4 | Portf. 5 | Portf. 6 | Portf. 7 | Portf. 8 | GMM |
| $a$ | $-0.02^{***}$ | 0.00 | $-0.01^{***}$ | $-0.01^{***}$ | $0.02^{***}$ | 0.00 | 0.00 | $0.01^{**}$ | |
| | $(-3.36)$ | $(-1.64)$ | $(-3.32)$ | $(-2.85)$ | (4.92) | (0.47) | (0.35) | (2.23) | |
| $\beta^{Market}$ | $0.97^{***}$ | $1.06^{***}$ | $1.02^{***}$ | $1.00^{***}$ | $1.00^{***}$ | $0.97^{***}$ | $0.97^{***}$ | $0.98^{***}$ | |
| | (95.16) | (107.00) | (99.65) | (103.44) | (200.84) | (175.77) | (119.01) | (124.48) | |
| $\beta^{HML}$ | $-0.80^{***}$ | $-0.05^{***}$ | $0.05^{***}$ | $0.09^{***}$ | $0.09^{***}$ | $0.22^{***}$ | $0.32^{***}$ | $0.38^{***}$ | |
| | $(-35.42)$ | $(-6.04)$ | (6.01) | (10.15) | (6.97) | (31.43) | (37.39) | (38.36) | |
| $\lambda^{Market}$ | | | | | | | | | $-0.07$ |
| | | | | | | | | | $(-1.52)$ |
| $\lambda^{HML}$ | | | | | | | | | $0.42^{***}$ |
| | | | | | | | | | (14.88) |
| $N$ | | | | | | | | | 14,960 |
| Time Periods | | | | | | | | | 1,870 |
| adj. $R^2$ | | | | | | | | | 98.42% |
| $\chi^2$ | | | | | | | | | 44.13% |

The table reports the factor loadings for the eight portfolios and estimates of the premia for the market factor and the carry factor estimated via the GMM approach. The GMM results are estimated jointly as part of a single, overidentified estimation. ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Error terms are adjusted according to Newey and West (1987) with the optimal number of lags chosen using the Bartlett kernel. $p$-values of $\chi^2$ tests are reported in percentage points. Data are daily and include GC and special repos of term type SN for the period 2010–2017.

**Factor loadings**

Columns (1) - (8) report the constants ($a_n$) and the slope coefficients ($\beta_n^k$). The slope coefficients for the market factor are essentially all equal to one for each portfolio, which confirms our expectation that the market factor explains the level of short-term interest rates. All estimates are highly statistically significant. The slope coefficients for the carry factor increase monotonically from $-0.80$ for the first portfolio to 0.38 for the last portfolio. The first two portfolios have betas that are negative and significant, while the other portfolios have betas that are positive and significant. Clearly, the results suggest that the carry factor explains the dispersion in short-term interest rates.

**Factor premia**

Column (9) reports the estimates of the factor premia for the market and the carry. The premium of the carry factor is highly statistically significant at a level of 0.42% per annum. This means that a portfolio with a sensitivity of one to the carry factor earns a premium of 0.42% per annum, consistent with the average level of the carry factor. The carry measures the expectation of the convenience yield difference between portfolios 1 and 8 at time t for the collateral assets swapped between time t+2 and t+3. The 0.42% carry premium therefore reflects the expected compensation for swapping assets in portfolio 1 and 8 over a one-year period. The market factor has a slightly negative price, consistent with the negative level of short-term interest rates during our sample period. The standard errors on the market factor are large, as it is the carry factor that explains most of the cross-sectional dispersion in short-term interest rates. As all portfolios have a beta close to one with respect to the market factor, the market factor essentially serves as a constant in the cross-sectional regressions. Hansen's $J$-test of the overidentifying restrictions shows that the null hypothesis that the over-identifying restrictions are valid cannot be rejected. The adj. $R^2$ proves that most of the development in short-term rates can be attributed to the market and carry factors.[42]

[42]The adj. $R^2$ is relatively high, consistent with the nature of the repo market. Koijen et al. (2018), for example, document an $R^2$ of 89% when considering fixed income carries in bond markets.

**Table 6:** Robustness summary asset pricing estimations

| | (1) Baseline | (2) TN | (3) GC | (4) Special | (5) Broker Tec | (6) FMB |
|---|---|---|---|---|---|---|
| $\lambda^{Market}$ | $-0.07$ | $-0.10^{**}$ | 0.03 | $-0.07^{*}$ | $-0.09^{**}$ | $-0.06$ |
| | $(-1.52)$ | $(-2.33)$ | (0.77) | $(-1.66)$ | $(-2.14)$ | $(-1.00)$ |
| $\lambda^{HML}$ | $0.42^{***}$ | $0.39^{***}$ | $0.15^{***}$ | $0.42^{***}$ | $0.42^{***}$ | $0.41^{***}$ |
| | (14.88) | (16.39) | (14.96) | (14.79) | (14.82) | (12.10) |
| $N$ | 14,960 | 14,960 | 14,960 | 14,960 | 14,960 | 14,960 |
| Time Periods | 1,870 | 1,870 | 1,870 | 1,870 | 1,870 | 1,870 |
| adj. $R^2$ | 98.42% | 95.65% | 98.83% | 98.39% | 98.16% | 98.28% |
| $\chi^2$ | 44.13% | 49.04% | 28.96% | 34.54% | 15.93% | – |

The table reports the estimates of the premia for the market factor and the carry factor estimated via the GMM approach using different carries in columns (1) to (5) and the FMB approach in column (6). The GMM results are estimated jointly as part of a single, overidentified estimation. ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Error terms are adjusted according to Newey and West (1987) with the optimal number of lags chosen using the Bartlett kernel. $p$-values of $\chi^2$ tests for the GMM estimation are reported in percentage points. Data include (1 & 6) the baseline set-up presented in the paper using GC and special repos of term type SN, (2) GC and special repos of term type TN, (3) GC repos of term type TN, (4) special repos of term type SN, and (5) GC and special repos of term type SN which have been traded on the BrokerTec platform. Data are daily for the period 2010–2017.

We are confident that our approach of implementing a factor structure with a level and a slope component is an innovative, yet intuitive way to capture the dynamics within the universe of short-term interest rates. Our results confirm the notion that a standard factor model with two pricing factors, a market factor and a carry factor, is able to explain the price of near-money assets: the market factor determines the level of short-term interest rates, while the carry factor accounts for the cross-sectional dispersion. To ensure the robustness of our results, we perform the asset pricing estimation separately for repos of term type TN, for GC respectively special repos, and for trades executed on the BrokerTec platform, as well as by employing the two-stage OLS estimation following Fama and MacBeth (1973). Table 6 summarizes the results of those estimations which are fully consistent and show that our two factors are relevant for and apply to the entire repo market (detailed results are in the Online Appendix).

# 3. Economic determinants of convenience yield

The asset pricing analysis has shown that our carry factor helps explain the cross-sectional dispersion in short-term rates. Table 7 provides a different illustration of it. Column (1) reports the results of the panel regression of the return on the eight repo portfolios net of the Eonia on a constant, the carry factor ("Carry") interacted with dummies for the eight repo portfolios, and each portfolio's lagged repo rate ("Lagged Rate"), Column (2) shows the Wald (1943) test for statistical equality between the coefficients for portfolios 1 and 8.

**Table 7:** Safe asset dimensions of portfolio returns net Eonia

| | (1) Return net Eonia b/t | | | | | | | | (2) Wald Test Portf. 1 & 8 p/F | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Panel A** | #Portf. 1 | #Portf. 2 | #Portf. 3 | #Portf. 4 | #Portf. 5 | #Portf. 6 | #Portf. 7 | #Portf. 8 | | | |
| | | | | | | | | | | $N$ | 14,952 |
| Carry | −0.329*** | −0.106*** | −0.081*** | −0.068*** | −0.052*** | −0.026*** | −0.001 | 0.018 | 0.000 | adj. $R^2$ | 0.806 |
| *daily* | (−4.26) | (−3.94) | (−3.74) | (−3.59) | (−3.45) | (−3.09) | (−0.19) | (1.58) | (17.57) | Constant | Yes |
| | | | | | | | | | | Lagged Rate | Yes |
| **Panel B** | | | | | | | | | | | |
| | | | | | | | | | | $N$ | 248 |
| Carry | −0.755*** | −0.229*** | −0.171*** | −0.144*** | −0.111*** | −0.052** | 0.007 | 0.053 | 0.000 | adj. $R^2$ | 0.926 |
| *quarterly* | (−7.33) | (−4.34) | (−3.72) | (−3.51) | (−3.87) | (−2.51) | (0.25) | (1.38) | (55.52) | Constant | Yes |
| | | | | | | | | | | Lagged Rate | Yes |

Column (1) reports the results of the panel regression of the return on the eight repo portfolios net of the Eonia on a constant, the carry factor ("Carry") interacted with dummies for the eight repo portfolios, and each portfolio's lagged repo rate ("Lagged Rate"). ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Standard errors are clustered at the portfolio-year level. Column (2) shows the Wald (1943) test for statistical equality between the coefficients for portfolios 1 and 8. The p-value and $F$-statistic in parentheses are reported. Data are daily in Panel A and quarterly in Panel B. The coefficients in the daily panel are smaller as more variation in portfolio returns is captured by the lagged rate. All data include GC and special repos of term type SN for the period 2010–2017.

By employing the portfolio returns net of the Eonia, we remove the level from our analysis and just focus on the cross-sectional dispersion.[43] The results confirm our intuition from the asset pricing analysis: While the assets in the low-rate portfolio (with the highest convenience) have a negative loading towards our carry, the assets in the high-rate portfolio (with the lowest convenience) have a positive loading. The Wald test confirms that the coefficients for portfolios 1 and 8 are statistically different from one another.

Panel A shows the results at a daily frequency, Panel B the results at a quarterly frequency. The quarterly data are calculated as the average of the daily data during a quarter after

[43] Eonia is the main short-term interest rate benchmark and represents a weighted average of all overnight unsecured transactions in the euro interbank market.

removing end of month and end of ECB maintenance period trading days. This way, the quarterly carry captures average convenience yield movements on "normal" trading days. We choose the quarterly regression frequency for the subsequent analysis since some of the economic variables proposed in the literature to capture convenience yield are only published quarterly. This approach is in line with the existing literature on convenience yield (e.g., Krishnamurthy and Vissing-Jorgensen, 2012; Nagel, 2016).[44] In fact, the $adj.R^2$ which reflects how much of the individual repo rate variation is captured by our carry factor, is higher at a quarterly frequency which reflects the smaller impact of daily spikes or movements in rates. Overall, the results at a daily and quarterly level are consistent so that the main message does not change depending on the frequency chosen. In both panels, the sensitivity to the carry is strongest for the assets in the low-rate portfolio. This points towards the idea that the carry factor is mainly driven by those truly safe assets with the highest convenience yield and hence raises the question about the economic determinants embedded in it.

### 3.1 Safety and liquidity benefits

The safe asset literature outlines differences across (quasi-) safe assets that make them imperfect substitutes (Sunderam, 2015). Each asset carries a different convenience yield, our carry factor thus reflects a differential in convenience yield as truly safe assets (in the low-rate portfolio) carry a higher convenience than quasi-safe assets (in the high-rate portfolio). An asset's convenience yield stems from its safety and liquidity attributes. For instance, Gary Gorton writes "the specialness of safe assets implies the existence of non-pecuniary returns (called the convenience yield), in the form of liquidity or moneyness (the money-like property of an asset taken at face value with no questions asked) and safety" (Gorton, 2017).

Krishnamurthy (2002) develops a theoretical model that determines the repo market equilibrium. In his framework, investors value the liquidity services provided by the on-the-run U.S. Treasury security more than those provided by its off-the-run counterpart so that

[44]For example, Krishnamurthy and Vissing-Jorgensen (2012) use data at an annual frequency to measure convenience yield, while Nagel (2016) uses monthly data since he focuses on two-year U.S. Treasury notes which are issued on a regular monthly auction cycle. In line with our approach, Nagel (2016) computes monthly averages for data available at a daily frequency.

the repo secured by the former is traded at a lower rate. Our analysis extends to a larger and more complex repo market which features collateral assets with various degrees of safety and liquidity attributes. In addition to different liquidity services coming from risk-free assets issued by the same country as in Krishnamurthy (2002), the repo rates in our context are determined by differing convenience yields of their collateral assets that vary in terms of the safety premium and the liquidity premium, which in turn is determined by the scarcity of collateral assets (Krishnamurthy and Vissing-Jorgensen, 2012) and the opportunity cost (Nagel, 2016). Broadening the existing literature on convenience that largely concerns U.S. Treasuries, our framework of the euro (single currency) setting encompasses government bonds perceived as truly safe assets with high convenience yield and other government bonds with lower convenience yield perceived as quasi-safe assets.

Based on this understanding, three hypotheses about the economic determinants of convenience yield can be brought forward: The first hypothesis is that the convenience yield of truly safe assets increases in the safety premium. In the case of secured debt instruments such as repos, heterogeneity in the safety premia depends on the collateral quality and risk. For government bonds, the primary source of risk stems from sovereign debt fragility and instability. If an asset is truly safe, it is "information insensitive" since economic agents have no reason to produce private information on fundamental risk and are not exposed to adverse selection (e.g., Gorton and Pennacchi, 1990; Gorton and Ordonez, 2014; Dang et al., 2015; Dang et al., 2017). In contrast, a larger public debt creates policy uncertainty, which raises default risk premia (Liu et al., 2021) so that collateral quality deteriorates with weak sovereign resources (He et al., 2019) and the government's inability to back its borrowing with taxation (Krishnamurthy and Vissing-Jorgensen, 2015). When a sovereign bond bears a convenience premium that is uncertain and adversely affected by risk, it becomes a quasi-safe asset. An increase in the perceived sovereign risk of quasi-safe asset relative to the overall risk levels in the economy leads to a weaker demand for those quasi-safe assets and a higher demand for assets such as German Bunds that remain safe even in flight-to-safety episodes such as the European sovereign debt crisis. Thus, truly safe assets feature the highest demand

and convenience yield, in particular during periods of uncertainty.

The next two hypotheses refer to the liquidity premium. The second hypothesis postulates that the liquidity premium and thus the convenience of truly safe assets increases in their scarcity. A repo's liquidity premium stems from the liquidity benefits provided by the collateral asset. High-quality sovereign bonds are money-like instruments that provide stable fungibility and high (re-)pledgeability, whereas the liquidity services of quasi-safe (sovereign) assets are more unstable (Gorton and Metrick, 2012). The scarcer the safe assets, the more agents are willing to pay a premium for their liquidity services (Krishnamurthy and Vissing-Jorgensen, 2012). An increase in the relative scarcity of truly safe assets therefore leads to a lower repo supply of those scarce assets and thus a higher convenience yield.

The third hypothesis puts forward that the liquidity premium and thus the convenience yield of truly safe assets increases with the opportunity cost of holding money. Nagel (2016) shows that the liquidity premium increases with the level of short-term interest rates. If near-money assets are perfect substitutes, their liquidity premia would perfectly correlate with the level of the short-term interest rate. If not, as we expect to be the case in the euro area context, heterogeneous effects would arise since safe assets providing more utility are more sensitive to the opportunity cost and the liquidity premium also depends on the supply of safe assets. More specifically, controlling for asset supply, the liquidity premium of repos that provide higher liquidity benefits should increase more with the opportunity cost.

We illustrate these mechanisms in a simple supply- and demand-framework which builds on Krishnamurthy (2002) as shown in the Online Appendix.

### 3.2 Safe asset dimensions of convenience yield

To test the empirical predictions, we follow the literature to build our empirical measures of convenience yield. Our main variable to capture risk reflecting the safety premium is the difference in 10-year CDS prices between the countries forming portfolio 8 (high rates) and portfolio 1 (low rates), weighted by the respective shares of the countries in each portfolio. In the spirit of Krishnamurthy and Vissing-Jorgensen (2012), we capture collateral asset supply by computing the difference in the log of the ratio of the face value of short-term debt to GDP between the countries forming portfolio 8 (high rates) and portfolio 1 (low rates), weighted by the respective shares of the countries in each portfolio.[45] The opportunity cost is measured via the main euro area short-term interest rate benchmark Eonia.[46]

We begin our empirical analysis by examining how the different economic determinants of convenience yield explain the return on the eight repo portfolios. To do so, we replace the carry factor with the different economic variables capturing the various aspects of convenience yield. More precisely, Column (1) in Table 8 reports the results of the panel regression of the return on the eight repo portfolios on the CDS price difference between portfolios 8 and 1 ("CDS"), the difference in the log of the ratio of short-term debt to GDP between portfolios 8 and 1 ("Asset Supply"), and the Eonia rate ("Opportunity Cost"), all variables interacted with dummies for the eight repo portfolios, as well as the absolute U.S. dollar euro CIP deviations ("Arbitrage Deviation") and each portfolio's lagged repo rate ("Lagged Rate") as controls.[47] Column (2) adds the Wald test for the coefficients of portfolios 1 and 8

Three main results emerge. First, portfolio 1 has a negative loading towards our risk measure while portfolio 8's loading is close to zero and not significant. For example, a one-percentage point increase in our risk measure leads to a decrease in the rates of portfolio 1 by 38 basis points. This result speaks to the safety benefits of truly safe assets in portfolio 1, in particular during flight-to-safety periods. Once the CDS difference between the assets

[45] We consider short-term debt since it is a purer measure of near-money liquidity services than the overall debt level. Short-term debt includes all government securities issued with an original maturity of up to one year. We use static weights (i.e., the average share of a country in a portfolio over the sample) for the CDS price measure, while we use dynamic weights (i.e., the average share of a country in a portfolio during a quarter) for the short-term debt-to-GDP ratio. Sovereign credit risk is a dynamic measure that is available at a high frequency, while sovereign debt and GDP are static measures that are published less frequently. While we are confident that this approach best captures the economic determinants embedded in our carry factor, we show that the results are robust to a change in the weighting scheme.

[46] We expect the differential in the liquidity premium between assets in the high- and low-rate portfolio to be correlated with the level of interest rates. In an interpretation of the model of Nagel (2016), the correlation would be perfect as the model abstracts from risk and assumes certain model parameters to be constant (e.g., asset supply).

[47] We control for market frictions and arbitrage constraints, which can be particularly relevant in flight-to-quality periods (Longstaff, 2004), by computing deviations from the covered interest parity (CIP basis) as short-term interest rates are interconnected with FX rates (Du et al., 2018a,b; Ranaldo et al., 2021; Jiang et al., 2021). We compute the absolute CIP basis between the U.S. dollar and the euro in percentage points using the one-month London interbank offered rate (Libor).

**Table 8:** Safe asset dimensions of portfolio returns

| | (1) Return Portfolio b/t | | | | | | | | (2) Wald Test Portf. 1 & 8 p/F |
|---|---|---|---|---|---|---|---|---|---|
| | #Portf. 1 | #Portf. 2 | #Portf. 3 | #Portf. 4 | #Portf. 5 | #Portf. 6 | #Portf. 7 | #Portf. 8 | |
| CDS | $-0.381^{**}$ | $-0.016$ | $-0.021$ | $-0.044^{**}$ | $-0.055^{***}$ | $-0.036$ | $-0.011$ | $-0.005$ | 0.025 |
| | ($-2.64$) | ($-0.75$) | ($-1.08$) | ($-2.51$) | ($-3.59$) | ($-0.75$) | ($-0.17$) | ($-0.06$) | (5.28) |
| Asset Supply | $-0.296$ | $-0.322^{***}$ | $-0.222^{***}$ | $-0.136^{**}$ | $-0.072$ | $-0.030$ | $-0.002$ | 0.042 | 0.138 |
| | ($-1.67$) | ($-4.94$) | ($-3.78$) | ($-2.58$) | ($-1.45$) | ($-0.37$) | ($-0.02$) | (0.35) | (2.25) |
| Opportunity Cost | $0.490^{***}$ | $0.815^{***}$ | $0.828^{***}$ | $0.832^{***}$ | $0.843^{***}$ | $0.862^{***}$ | $0.890^{***}$ | $0.927^{***}$ | 0.000 |
| | (9.10) | (21.01) | (21.58) | (21.86) | (22.49) | (22.71) | (22.65) | (22.36) | (67.90) |
| $N$ | 248 | | | | | | | | |
| adj. $R^2$ | 0.981 | | | | | | | | |
| Arbitrage Deviation | Yes | | | | | | | | |
| Lagged Rate | Yes | | | | | | | | |

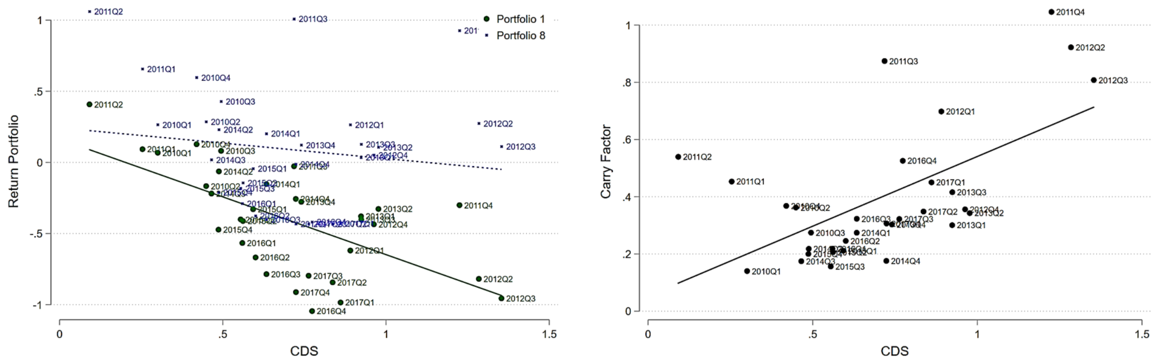
Column (1) reports the results of the panel regression of the return on the eight repo portfolios on the static weighted CDS price difference between portfolios 8 and 1 ("CDS"), the dynamic weighted difference in the log of the ratio of short-term debt to GDP between portfolios 8 and 1 ("Asset Supply"), the Eonia rate ("Opportunity Cost"), all variables interacted with dummies for the eight repo portfolios, as well as the absolute U.S. dollar euro CIP deviations ("Arbitrage Deviation") and each portfolio's lagged repo rate ("Lagged Rate"). ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Standard errors are clustered at the portfolio-year level. Column (2) shows the Wald (1943) test for statistical equality between the coefficients for portfolios 1 and 8. The p-value and $F$-statistic in parentheses are reported. Data are quarterly and include GC and special repos of term type SN for the period 2010–2017.

in portfolio 1 and 8 increases, the repo rates for portfolio 1 fall since investors prefer to hold those truly safe assets during moments of uncertainty. At the same time, the rates for assets in portfolio 8 do not increase significantly, which is at odds with the systemic risk hypothesis (Boissel et al., 2017). This reinforces our explanation that the European repo market is a quintessential safe environment in which investors value the safety benefits of truly safe assets in portfolio 1 as opposed to requiring compensation for the higher risk of quasi-safe assets in portfolio 8.

Second, the repo rates on the assets in portfolio 1 tend to be lower once truly safe assets become scarcer. A one-percentage-point increase in the debt to GDP difference between portfolios 1 and 8 (i.e., a relative increase in the scarcity of truly safe assets) leads to a decrease in the rates of portfolio 1 by 30 basis points. The loadings for portfolio 8 tend to be close to zero. And third, portfolio 1 has the lowest loading on the opportunity cost at 0.49 while portfolio 8 has the highest loading close to one. This result is in line with the idea that assets in the first portfolio carry a higher liquidity premium. More specifically, when the benchmark interest rate increases, two effects occur simultaneously: (i) the overall repo rate level increases and (ii) the liquidity premium increases in line with Nagel (2016). An increase in the liquidity premium reduces short-term rates and thus goes in a different direction than the overall increase in levels. The weaker response of portfolio 1 to an opportunity cost increase therefore reflects the larger retention of the liquidity premium inherent in truly safe assets. Thus, a lower loading towards the opportunity cost reveals the larger liquidity value attributed by investors to the underlying assets. In this set-up where we account for asset supply and opportunity cost as the two potential components of the liquidity premium, the asset supply variable is not significant for truly safe assets in portfolio 1. This suggests the prevailing effect of the opportunity cost of holding money in shaping the liquidity premium corroborating previous findings (Nagel, 2016).

The results in Table 8 suggest that the low-rate portfolio inherits the safety and liquidity benefits of truly safe assets while the high-rate portfolio's return is less sensitive to changes in safety and liquidity premia of quasi-safe assets. The results also suggest that the carry factor is driven by the same determinants, predominantly by the repos in portfolio 1. This conjecture can also be visualized: Figure 7 graphs portfolio 1 and 8's repo returns (Figure 7a) and the carry factor (Figure 7b) against the "CDS" variable, while Figure 8 graphs portfolio 1 and 8's repo returns (Figure 8a) and the carry factor (Figure 8b) against the "Opportunity Cost" variable. Both figures provide evidence for the convenience benefits of truly safe assets in portfolio 1 relative to quasi-safe assets in portfolio 8. When the risk of assets in portfolio 1 is low compared to assets in portfolio 8 (i.e., a high value of our risk measure using the CDS), investors value the safety benefits of truly safe assets and their repo rates are lower (i.e., the carry factor is higher). Similarly, when the opportunity cost are high (i.e., a high value of the Eonia rate), investors value the liquidity benefits of the assets in portfolio 1 more, again reflected in their repo rates being lower (i.e., the carry factor being higher).

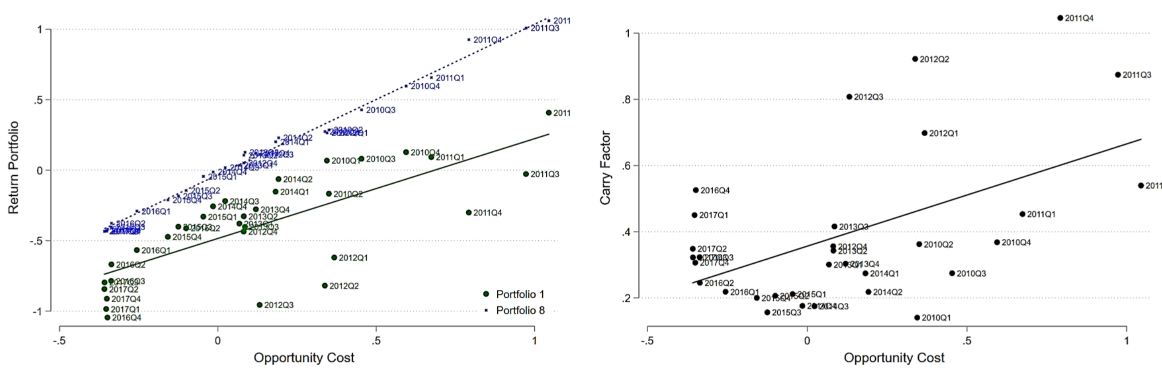
To substantiate these results, we relate our carry factor to the different economic determinants embedded in convenience yields. For this, we perform a set of time-series regressions




**(a)** Portfolio returns against risk **(b)** Carry factor against risk

Figure 7a depicts the scatter plot of portfolio 1 and 8's repo returns against the difference in the CDS prices ("CDS"), while Figure 7b depicts the scatter plot of the carry factor against the CDS variable.

**Figure 7:** Scatter plot for safety premium




**(a)** Portfolio returns against opportunity cost **(b)** Carry factor against opportunity cost

Figure 8a depicts the scatter plot of portfolio 1 and 8's repo returns against the Eonia ("Opportunity Cost"), while Figure 8b depicts the scatter plot of the carry factor against the opportunity cost variable.

**Figure 8:** Scatter plot for liquidity premium

to explain our carry return (instead of portfolio returns) using the same regressors as in the previous regression analysis (i.e., "CDS", "Asset Supply", "Opportunity Cost", "Arbitrage Deviation", and now "Lagged Carry"). In contrast to the repo portfolio returns, the carry factor only accounts for the cross-sectional dispersion in short-term rates. The results are shown in Table 9. Columns (1) to (3) report the results for the univariate time-series regressions, while column (4) reports those for the multivariate regression which also accounts for arbitrage deviations and the lagged carry factor.

Three main results emerge. First, the carry factor significantly increases in risk, providing empirical support for the safety premium hypothesis. In the multivariate setting (4), a one-percentage-point increase in the CDS prices of portfolio 8 relative to those of portfolio 1 is associated with an increase in our carry factor of 40 basis points. Second, we find a positive relationship between our carry factor and the relative scarcity of assets in portfolio 1. A one-percentage-point increase in the difference in the log of the ratio of short-term debt to GDP between portfolios 8 and 1 is accompanied by an increase in our carry factor of 28 basis points. And third, the carry factor significantly increases with the opportunity cost of holding money consistent with the imperfect substitutability of near-money assets. A one-percentage-point increase in the Eonia rate is associated with an increase in our carry factor of 45 basis points. In line with the portfolio results, when both liquidity variables capturing opportunity cost and asset scarcity are included in the encompassing specification (column 4), only the former remains significant driving away the explanatory power of the latter.[48]

In addition, the liquidity premium may not only originate from the collateral asset but also from the repo itself. To capture the repo supply, we compute the difference in the log of the ratio of repo volume to debt between the countries forming portfolio 8 (high rates) and portfolio 1 (low rates), weighted by the respective shares of the countries in each portfolio. Column (5) considers the repo liquidity variable in a univariate setting, while column (6) combines it with the previous convenience measures including the supply of the collateral assets.

[48]The partial variance decomposition as well as the Shapley $R^2$ suggest that, in line with our results, our risk variable and the opportunity cost have the largest explanatory power.

**Table 9:** Safe asset dimensions of carry factor

| | (1) Carry b/t | (2) Carry b/t | (3) Carry b/t | (4) Carry b/t | (5) Carry b/t | (6) Carry b/t |
|---|---|---|---|---|---|---|
| CDS | 0.526*** | | | 0.403*** | | 0.396*** |
| | (5.60) | | | (4.37) | | (4.14) |
| Asset Supply | | 0.638*** | | 0.278 | | 0.268 |
| | | (3.09) | | (1.66) | | (1.55) |
| Opportunity Cost | | | 0.355** | 0.447*** | | 0.415*** |
| | | | (2.33) | (5.42) | | (3.66) |
| Repo Liquidity | | | | | −1.033*** | −0.134 |
| | | | | | (−3.32) | (−0.40) |
| $N$ | 31 | 31 | 31 | 30 | 31 | 30 |
| adj. $R^2$ | 0.503 | 0.222 | 0.129 | 0.733 | 0.250 | 0.725 |
| Arbitrage Deviation | No | No | No | Yes | No | Yes |
| Lagged Carry | No | No | No | Yes | No | Yes |
| Constant | Yes | Yes | Yes | Yes | Yes | Yes |

The table reports the results of the time-series regressions of our carry factor on a constant, the static weighted CDS price difference between portfolios 8 and 1 ("CDS"), the dynamic weighted difference in the log of the ratio of short-term debt to GDP between portfolios 8 and 1 ("Asset Supply"), the Eonia rate ("Opportunity Cost"), the static weighted difference in the log of the ratio of repo volume to debt between portfolios 8 and 1 ("Repo Liquidity"), the absolute U.S. dollar euro CIP deviations ("Arbitrage Deviation"), and the lagged carry factor ("Lagged Carry"). ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Error terms are adjusted according to Cochrane and Orcutt (1949), following Wooldridge (2015). Data are quarterly and include GC and special repos of term type SN for the period 2010–2017.

We expect the repo volume of quasi-safe assets (in portfolio 8) relative to truly safe assets (in portfolio 1) to decrease and the carry factor to rise with uncertainty and market stress. As the repo is produced by financial firms, this result would be consistent with the idea of a "fragile liquidity transformation" (Moreira and Savov, 2017) that shrinks when financial institutions deleverage (Stein, 2012) or experience funding strains and losses in long-term and illiquid investments (Krishnamurthy and Vissing-Jorgensen, 2015). As expected, in the univariate setting (5), an increase in the difference in the log of the ratio of lending volume to debt between portfolios 8 and 1 is accompanied by a decrease in our carry factor. This result highlights that a decrease in the production of quasi-safe assets relative to truly safe assets is accompanied by an increase in the liquidity premium, as reflected by an increase in the carry factor. However, in the multivariate setting (6), the repo supply measure looses its significance; this is consistent with the previous results for asset supply and reinforces the idea developed in this paper that the part of the convenience yield attributable to the liquidity premium is captured by the opportunity cost of holding money.

To validate our results, we perform a number of additional tests. First, we conduct various subsampling analyses, which clearly show that our main results hold if we only consider repos of the TN term type, GC and special repo transactions separately, and trades executed on the BrokerTec platform. The corresponding results are shown in columns (2) to (5) in Table 10. This shows the general validity of our results and confirms that, for example, "specialness" and segmentation cannot be the sole drivers of our carry factor. Second, column (6) shows that our results are consistent if we employ the repo carry including the bond return. Interestingly, the explanatory power of the different economic determinants of convenience yield is lower in this set-up, which reinforces our interpretation that the repo carry is a more precise measure of convenience yield movements. And third, we provide additional robustness checks on different measures of convenience yield in the Online Appendix. There, we also account for ECB purchases under the public sector purchase program (PSPP). In contrast to the asset supply measure, PSPP purchases retain their significance in the multivariate setting. The results show that when the ECB purchases relatively more assets in portfolio 1 compared to portfolio 8 (i.e., the scarcity of assets in portfolio 1 increases), the carry also increases. This is consistent with the notion that the convenience yield stems from the collateral asset whose scarcity is impacted more by QE purchases then by variations in the overall issuance volumes.

In sum, all the analyses carried out indicate that the convenience yield embedded in our carry factor increases with (i) the safety premium and (ii) the liquidity premium.

**Table 10:** Robustness summary for economic analysis

| | (1) Baseline b/t | (2) TN b/t | (3) GC b/t | (4) Special b/t | (5) BrokerTec b/t | (6) Bond b/t |
|---|---|---|---|---|---|---|
| CDS | 0.403*** | 0.374*** | 0.025 | 0.393*** | 0.485*** | 0.232** |
| | (4.37) | (4.77) | (1.21) | (4.25) | (4.43) | (2.51) |
| Asset Supply | 0.278 | 0.250* | 0.175** | 0.297* | 0.111 | −0.010 |
| | (1.66) | (1.97) | (2.60) | (1.77) | (0.65) | (−0.06) |
| Opportunity Cost | 0.447*** | 0.324*** | 0.246*** | 0.437*** | 0.428*** | 0.133** |
| | (5.42) | (5.15) | (5.41) | (5.38) | (4.52) | (2.10) |
| $N$ | 30 | 30 | 30 | 30 | 30 | 30 |
| adj. $R^2$ | 0.733 | 0.775 | 0.809 | 0.732 | 0.694 | 0.374 |
| Arbitrage Deviation | Yes | Yes | Yes | Yes | Yes | Yes |
| Lagged Carry | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | Yes | Yes | Yes | Yes | Yes | Yes |

The table reports the results of the time-series regressions of our carry factor on a constant, the static weighted CDS price difference between portfolios 8 and 1 ("CDS"), the dynamic weighted difference in the log of the ratio of short-term debt to GDP between portfolios 8 and 1 ("Asset Supply"), the Eonia rate ("Opportunity Cost"), the absolute U.S. dollar Euro CIP deviations respectively the government bond OIS spread for Germany in column (6) ("Arbitrage Deviation"), and the lagged carry factor ("Lagged Carry"). ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Error terms are adjusted according to Cochrane and Orcutt (1949), following Wooldridge (2015). Data include (1) the baseline set-up presented in the paper using GC and special repos of term type SN, (2) GC and special repos of term type TN, (3) GC repos of term type TN, (4) special repos of term type SN, (5) GC and special repos of term type SN which have been traded on the BrokerTec platform, and (6) the baseline carry including the bond return using the Buy-and-Sell approach. Data are quarterly for the period 2010–2017.

### 3.3 Interaction of sovereign default risk and the liquidity premium

Another interesting aspect is to understand how the liquidity premium interacts with sovereign default risk. For this, we consider the within-country dispersion in short-term rates. This within-country dispersion only relates to differences in the liquidity premium since the sovereign risk is the same across all bonds of a given country. We therefore assess the explanatory power of our carry factor for the within-country dispersion in rates.

Inspired by Eisenschmidt et al. (2022), we calculate each country's interquartile range as the difference between the 25th and 75th percentile repo rate ("Repo Dispersion"). Table 11 reports the results of the panel regression of each country's repo dispersion on the country's CDS price ("CDS"), the carry factor ("Carry"), the interaction of the carry factor with a dummy variable for each country that is one if a country's CDS price is above the average CDS price for that country during the sample period ("Carry x High CDS"), all variables interacted with dummies for the different countries, and the lagged carry factor ("Lagged Carry"). We return to a daily regression frequency as all variables change on a daily basis.

**Table 11:** Explanatory power of the carry factor

| | (1) Repo Dispersion b/t | | | | | | |
|---|---|---|---|---|---|---|---|
| | #DE | #NL | #AT | #FI | #BE | #ES | #IT |
| CDS | −0.065** | −0.038 | −0.024 | −0.035 | −0.020 | 0.031*** | −0.002 |
| | (−2.12) | (−1.58) | (−1.66) | (−1.44) | (−1.67) | (5.27) | (−0.60) |
| Carry | 0.319*** | 0.142** | 0.094** | 0.141*** | 0.167*** | 0.095*** | 0.092*** |
| | (4.19) | (2.12) | (2.30) | (2.97) | (3.93) | (4.08) | (4.82) |
| Carry # High CDS | −0.225*** | −0.083** | −0.043* | −0.090** | −0.112*** | −0.054 | −0.024 |
| | (−4.19) | (−2.44) | (−1.73) | (−2.47) | (−3.31) | (−1.43) | (−0.85) |
| $N$ | 12,946 | | | | | | |
| adj. $R^2$ | 0.412 | | | | | | |
| Lagged Carry | Yes | | | | | | |

The table reports the results of the panel regression of the repo rate dispersion defined as a country's difference between the 25th and 75th percentile repo rate on the country's CDS price ("CDS"), the carry factor ("Carry") as well as the interaction of the carry factor with a dummy variable for each country that is one if a country's CDS price is above the average CDS price for that country during the observation period ("Carry x High CDS"), all variables interacted with dummies for the different countries, and the lagged carry factor ("Lagged Carry"). ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. Standard errors are clustered at the country-year level. We exclude Irish and Portuguese repos since they have been traded infrequently during part of our sample period. Data are daily and include GC and special repos of term type SN for the period 2010–2017.

The results show that the repo dispersion increases in the carry factor. This points towards a dispersion in repo rates related to within-country differences in the liquidity premium. The significance and economic magnitude of the carry factor for explaining within-country rate dispersion is highest for truly safe assets such as Germany and decreases in the sovereign riskiness. For example, a one-percentage-point increase in the carry factor is accompanied by an increase in Germany's repo rate dispersion of 32 basis points (compared to 9 basis points for Italy). This means that for quasi-safe countries with a higher sovereign risk, the within-country dispersion in liquidity benefits and thus repo rates is lower.

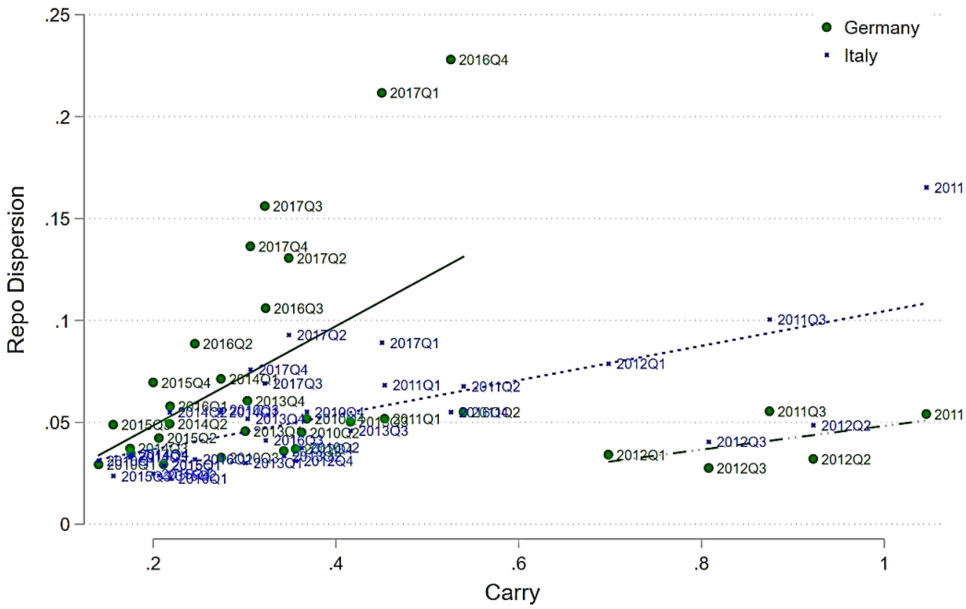



**Figure 9:** Scatter plot of Germany's and Italy's repo rate dispersion against the carry factor. The lower right dashed line refers to German repo rates during the European sovereign debt crisis.

During flight-to-safety periods, such as during the European sovereign debt crisis, the explanatory power of the carry factor for the rate dispersion in safe collateral assets, goes, however, down. This points towards smaller differences in the liquidity premium of truly safe assets during those periods when safety attributes gain in importance. This is consistent with the intuition obtained from our portfolio results. When uncertainty increases such as during the European sovereign debt crisis, truly safe assets feature the highest demand and convenience yield. This means that during such flight-to-safety periods, all German bonds are considered to be convenient, and the highly valued safety benefits (of all German bonds) outweigh differences in liquidity benefits, leading to a lower repo rate dispersion. This can also be seen in Figure 9 which graphs Germany's (green line) and Italy's (blue line) repo rate dispersion against the carry factor. The line for Germany is broken down into two periods. During the European sovereign debt crisis (the periods on the right), there is few dispersion in German repo rates (i.e., all German collateral assets are considered to be safe). However, during the other periods, the carry factor tends to reflect repo rate dispersion within safe countries like Germany as it captures differences in the liquidity premium.

### 3.4 Convenience premium and asset prices

As a final step, we relate our repo factors, in particular the carry factor, to a broader class of asset returns. Specifically, we analyze whether the two repo pricing factors help explain the cross-section of bond returns after accounting for the standard bond pricing factors and measures of bond safety and liquidity.

For this, we consider the cross-section of European sovereign bonds that are posted as repo collateral. Our dependent variable is the Nelson-Siegel residual of the daily log return of bond $i$ at time $t$.[49] We relate the unexplained part of the bond yield to our two repo factors and we control for bond safety (i.e., log of the CDS spread of the sovereign issuer) and bond liquidity (i.e., log of the relative bid-ask spread). We interact the carry factor with country dummies to analyze the different sensitivities of low-risk countries and high-risk countries to the carry. Table 12 reports the results of our panel regression. Column (1) shows the regression results of the Nelson-Siegel residual on the repo carry factor interacted with country dummies; column (2) adds our repo market factor; column (3) includes our measures for bond safety and liquidity in isolation; and column (4) combines our two repo factors with our measures for bond safety and liquidity.

Column (1) confirms that our carry factor contains information for bond pricing. Countries with a strong and resilient economy have a slightly negative loading towards our carry factor, while countries with a weak and vulnerable economy have a positive loading. Column

[49] The Nelson-Siegel residual is calculated as the difference between the daily log return of bond $i$ at time $t$ and the log return of bond $i$ at time $t$ implied by the Nelson and Siegel (1987) model estimated via German government bonds.

**Table 12:** Convenience premium and bond prices

| | (1) NS Residual b/t | (2) NS Residual b/t | (3) NS Residual b/t | (4) NS Residual b/t |
|---|---|---|---|---|
| Repo Carry Factor # | | | | |
| Germany | −0.000 | −0.001** | | −0.014*** |
| | (−1.455) | (−2.098) | | (−5.220) |
| Netherlands | 0.001*** | 0.000 | | −0.013*** |
| | (8.969) | (0.769) | | (−4.702) |
| Austria | 0.006*** | 0.005*** | | −0.011*** |
| | (40.370) | (10.547) | | (−3.564) |
| Finland | 0.002*** | 0.001*** | | −0.009*** |
| | (48.842) | (5.093) | | (−4.134) |
| Belgium | 0.011*** | 0.011*** | | −0.007* |
| | (7.324) | (7.802) | | (−1.903) |
| Spain | 0.023*** | 0.022*** | | 0.006* |
| | (42.696) | (23.248) | | (1.873) |
| Italy | 0.024*** | 0.023*** | | 0.008** |
| | (29.424) | (27.561) | | (2.572) |
| Ireland | 0.044*** | 0.043*** | | 0.018*** |
| | (102.088) | (137.568) | | (3.659) |
| Portugal | 0.083*** | 0.082*** | | 0.057*** |
| | (15.115) | (14.968) | | (8.752) |
| Repo Market Factor | | 0.007*** | | 0.000 |
| | | (2.961) | | (0.298) |
| Bond CDS | | | 0.013*** | 0.012*** |
| | | | (3.836) | (4.434) |
| Bond Bid-Ask Spread | | | 0.004*** | 0.003*** |
| | | | (4.494) | (5.513) |
| $N$ | 560,784 | 560,784 | 560,782 | 560,782 |
| adj. $R^2$ | 0.684 | 0.703 | 0.734 | 0.813 |
| Bond FE | Yes | Yes | Yes | Yes |

The table reports the results explaining the return on a cross-section of European sovereign bonds. The dependent variable is the Nelson-Siegel residual of the log return of bond $i$ at time $t$. The Nelson-Siegel residual is defined as the difference between the log return of bond $i$ at time $t$ and the log return of bond $i$ at time $t$ implied by the Nelson-Siegel model estimated via German government bonds. The market and carry factor are the two repo pricing factors. Bond CDS denotes the log of the CDS spread and bond bid-ask spread denotes the log of the relative bid-ask spread. ***, **, and * represent significance at a 1, 5, and 10% level, respectively; $t$-statistics are in parentheses. All regressions include bond fixed effects and standard errors clustered at the maturity bucket-country level. Bonds are grouped into four different maturity buckets with the remaining time to maturity being (i) less than one year, (ii) one to five years, (iii) five to ten years, and (iv) more than ten years. Data are daily for zero and fixed-coupon bonds for the period 2010–2017.

(2) adds our repo market factor. The market factor accounts for part of the Nelson-Siegel implied bond yield level and positively relates to the Nelson-Siegel residual. Column (3) confirms that both of our measures of bond safety and liquidity are positively related to the Nelson-Siegel residual, i.e., bonds issued by countries with a higher credit risk and more illiquid bonds carry a higher yield (lower price) than the ones estimated via (safe and liquid) German government bonds. Both factors account for a sizable increase in the $R^2$ and their inclusion reduces the high t-statistics in columns (1) and (2) which confirms that they serve as effective control variables. Column (4) shows that our carry factor has explanatory power for bond pricing even after accounting for standard bond pricing factors. The carry captures the cross-sectional variation in the convenience yield that is reflected in bond yields. For example, an increase in our carry is accompanied by lower yields on German government bonds (reflected in a lower Nelson-Siegel residual) as opposed to a higher yields on Italian bonds (reflected in a higher Nelson-Siegel residual). In economic terms, a one-basis-point increase in our carry implies a decrease (increase) in the Nelson-Siegel residual for German (Italian) government bond yields of 1.4 basis points (0.8 basis points). The $R^2$ increases by about 8% compared to regression (3) which confirms the statistical relevance of our carry factor.

Figures 10 and 11 provide visual evidence of the link between our repo carry factor and the bond return. Figure 10 plots our repo carry factor (green line) and the first PCA of the unexplained part of the bond return, i.e., unexplained by the Nelson-Siegel model and by our measures of bond safety and liquidity (dashed red line). Clearly, the two time-series comove. Figure 11 shows a scatter plot of each country's loadings towards the carry factor and towards the first PCA of the unexplained part of the bond return. In line with our regression results, truly safe assets have a negative loading towards the carry and the bond PCA, while quasi-safe assets have a positive loading.

Our results highlight that the two repo factors, in particular, the carry factor, have external relevance for pricing other asset classes. As we have shown in our economic analysis, the carry factor is a timely proxy for safety and liquidity benefits. These bond pricing results reveal that our near-money carry factor contains additional information about the cross-

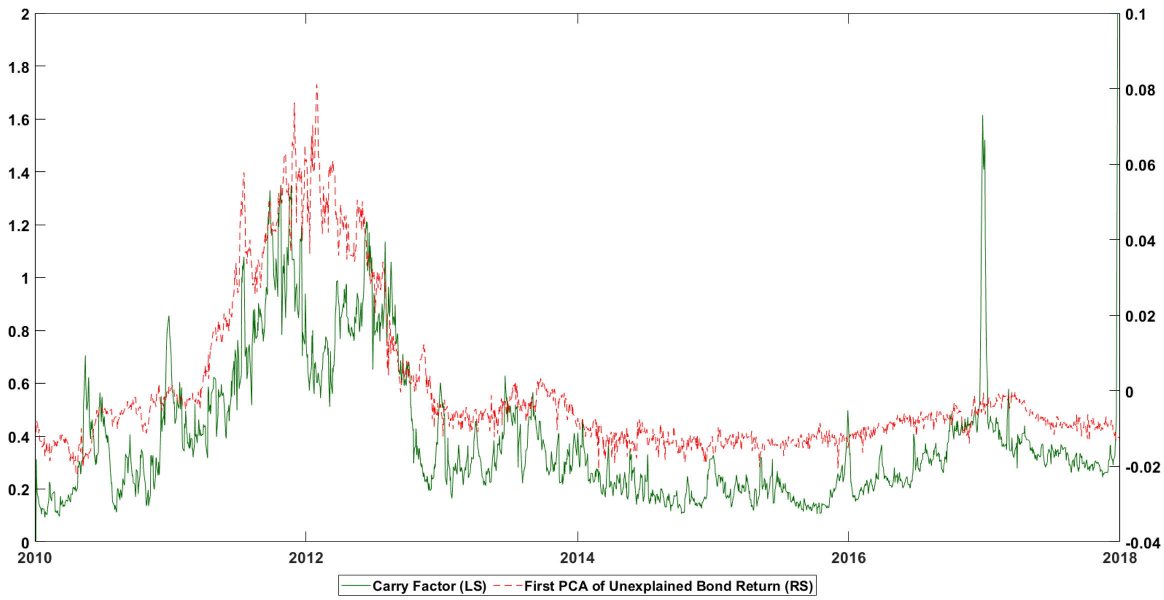



**Figure 10:** Carry factor and first PCA of unexplained bond return

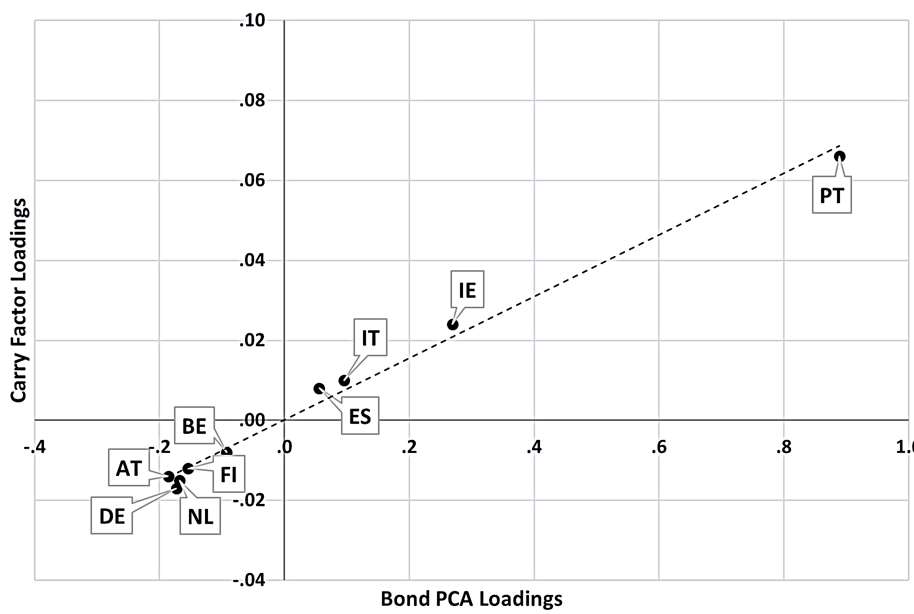



**Figure 11:** Scatter plot of each country's loadings on the carry factor and on the first PCA of the unexplained part of the bond return

sectional variation in the convenience yield provided by long-term government bonds beyond standard bond pricing factors. Thus, our carry factor seems to capture convenience services of a bond such as the safety premium and the short-term funding ability.[50] The advantages of our factors include the high frequency at which they are measured and their timeliness, which makes them suitable to capture e.g., the impact of monetary policy decisions.

## 4. Conclusion

We provide the first systematic asset pricing analysis of one of the main categories of safe assets, the repurchase agreement. Heterogeneity in repo rates is present within and across euro area countries. By going long in a portfolio consisting of repos with the highest rates while shorting a portfolio consisting of repos with the lowest rates, we create a carry trade that represents a collateral swap. The return on this carry trade, our carry factor, together with a market factor is able to explain the price of near-money assets within a linear factor model: while the market factor determines the level of short-term interest rates, the carry factor accounts for the cross-sectional dispersion. Consistent with the safe asset literature, we rationalize the dispersion in repo rates captured by our carry factor with the idea that market participants value the different convenience premia embedded in truly and quasi-safe collateral assets. We provide empirical evidence that our carry factor is explained by the safety premia and the liquidity benefits.

Our results shed new light on the dynamics of the main short-term funding market, which is key for an efficient allocation of liquidity and assets, the implementation of monetary policy, as well as financial stability. We show that the two repo pricing factors explain the price variation of European repos and help explain that of European bonds. Future research could apply our approach to other repo markets including the United States, and investigate whether the repo carry factor has pricing implications for other asset classes, such as equities and foreign exchange.

[50] For example, a German government bond and a German agency bond have the same sovereign default risk, still a German government bond is likely to carry a higher safety premium. The carry factor also captures funding aspects such as an assets' fungibility and (re-)pledgeability.

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