Safe asset carry trade*

Benedikt Ballensiefen†, Angelo Ranaldo‡

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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 yield of collateral assets and increases in safety premium and liquidity premium reflecting asset scarcity and 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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†University of St. Gallen and World Bank Group, Unterer Graben 21, CH-9000 St.Gallen, Switzerland. Tel. +41 (0)79 808 92 56. E-mail: benedikt.ballensiefen@unisg.ch.

‡University of St. Gallen and Swiss Finance Institute, Unterer Graben 21, CH-9000 St.Gallen, Switzerland. Tel. +41 (0)71 224 70 10. E-mail: angelo.ranaldo@unisg.ch.

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 across 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 a differential between stable and wobbly convenience yields provided by truly and quasi-safe assets, respectively. We provide empirical evidence that our carry factor increases with the safety premium and the liquidity premium reflecting asset scarcity and opportunity cost. 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 predom-

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

inantly focused on U.S. Treasuries. Second, the market characteristics enable us to isolate 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 reflecting asset scarcity. 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. Notice that the carry captures daily movements in non-monetary convenience benefits.[3] Our carry measures

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

[3] In the European setting, the lender (cash provider) becomes the legal owner of the collateral while the borrower (cash taker) remains the beneficial owner and receives the income cash-flows on the collateral. A hypothetical repo carry trader operates on two fronts for the duration of one day: (i) he lends cash and temporarily becomes the owner of 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 in the carry trade therefore does not affect who 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

the return of an investor who holds bonds with high convenience yield and is disposed to exchange them for other bonds 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 lost benefits on the high-convenience collateral and the gained benefits on the low-convenience collateral from day two through 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.[5] 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 across all euro area countries (in green) as well as without GIIPS counties (in grey).[6] 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 of 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 counties is lower, pointing towards the safety premium of truly safe assets and a lower dispersion in rates within those counties. Since 2015, when the European Central Bank (ECB) set up the negative nominal rate regime and conducted asset purchasing programs leading to asset scarcity, the spread of the carry return

yield movements.

[4]With the aim of capturing non-pecuniary convenience, the main method adopted in this paper to calculate the carry excludes the cash-flows generated by the collateral assets. We consider alternative ways that incorporate the cash-flows on the underlying bonds. However, this approach mixes up the non-pecuniary convenience benefits with monetary income (price change, accrued interest). Applying such alternative methods that account for the bond portfolio return, we find that the performance of the carry factor remains positive and increases.

[5]We compare forward rates for the expectation (spot-next rates at time t) with realized rates for the realization (overnight rates at time t+2).

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

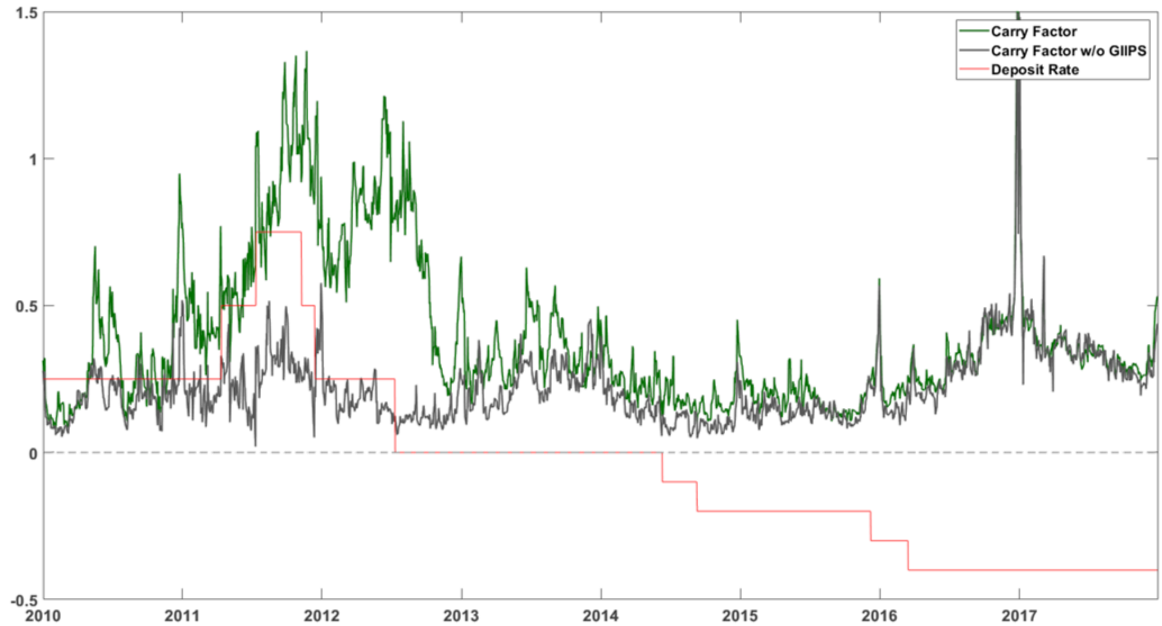


Figure 1: Development of the safe asset carry factor with/without GIIPS countries

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 truly safe assets.

Based on the portfolio results and the formation of our carry factor, we propose a simple two factor asset pricing model.[7] 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

[7] To motivate our analysis, we perform a principal component analysis of our portfolio returns. The first principal component accounts for about 95% of the common variation and can be interpreted as the *level factor* since all portfolios load equally on it. The second principal component accounts for the remaining 5% of the common variation and can be interpreted as the *slope factor* since the portfolio loadings increase monotonically from negative to positive, from the portfolio containing the repos with the lowest rate (highest convenience) to the one containing the repos with the highest rate (lowest convenience).

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% p.a.

In the second part of our paper, we employ the carry factor to gain insights into the determinants of convenience yields. Since the carry factor measures the difference in convenience yield 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.[8] 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 those providing more utility and being in short supply increases more with the opportunity cost (see Nagel, 2016).

To test these hypotheses, we construct variables capturing the different drivers of convenience yield (i.e., "risk," "asset supply," and "opportunity cost") following the literature.[9] We then proceed in three steps: First, we perform a time-series 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"), when their supply is scarcer, 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

[8]Krishnamurthy (2002) theorizes a lower repo rate collateralized by a newly issued ("on the run") U.S. Treasury bond compared to a repo secured by a similar bond issued previously ("off the run"). The specialness of the former repo is explained by a larger liquidity premium as the on-the-run bond offers more liquidity services. Our analysis extends to a larger and more diverse repo market which features government bond with varying degrees of safety and liquidity benefits.

[9]As the main source of risk relates to the sovereign and relative weaknesses of its fundamentals, we measure risk as the differential in the credit default swap (CDS) prices between the set of countries composing the high- and low-rate portfolios. The measure of collateral asset scarcity is based on debt-to-GDP ratios in the same vein as in (Krishnamurthy and Vissing-Jorgensen, 2012). Similar to Nagel (2016), the opportunity cost is measured via the main euro area short-term interest rate benchmark (Eonia).

our carry factor increases in the safety premium and in the liquidity premium reflecting asset scarcity and opportunity cost. These variables jointly explain a large share of the variability in our carry factor.[10]

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 only relates to differences in the liquidity premium since the sovereign risk is the same across all bonds of that country. The carry factor explains more of the within country dispersion for truly safe assets, which hints at the preponderance of the liquidity premium for those sovereigns. However, during flight-to-safety periods, such as during the European sovereign debt crisis, the carry factor explains less of the rate dispersion in safe collateral assets. This points towards smaller differences in the liquidity premium of safe assets during those periods, suggesting that safety attributes then 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. We thus perform an asset pricing analysis of European government bonds. Our results highlight that our two repo factors help 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 repo carry factor, suggesting that it captures additional convenience attributes such as the short-term funding ability (e.g.,

[10] 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. Our results are economically and statistically significant if we only consider general collateral (GC) repos, indicating that the carry factor is not only driven by specialness (Duffie, 1996). We also ascertain that the systemic risk of defaulting clearing houses (Boissel et al., 2017) cannot explain the cross-section of convenience yields.

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).[11] 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.[12] We also add to 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.[13] 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; Nagel, 2016; 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.

[11] 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.

[12] 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 (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.

[13] 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).

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").[14] 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 7.5 trillion in outstanding contracts (International Capital Market Association, 2019).[15] Several characteristics of its infrastructure are noteworthy:[16] The core segment is the interbank market in which banks trade anonymously via centralized electronic order book platforms supporting liquidity and a transparent price discovery process.[17] We focus on trades operated through central counterparties (CCP). CCP-based repos constitute the majority in the euro interbank repo market.[18] For them, 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.[19] Since the CCP is the counterparty to every trade, it guarantees scheduled settlement of the repo trade in case a CCP member defaults.[20]

[14]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 market rates.

[15]The euro money market survey (European Central Bank, 2018) shows that trading in the European money market has moved towards the repo market since the Global Financial Crisis; the size of the repo market is about 20 times that of the unsecured market.

[16]More detailed information about the European repo market infrastructure can be found in, e.g., European Central Bank (2018), Mancini et al. (2016), Nyborg (2016), and Bank for International Settlements (2017).

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

[18]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."

[19]Initial margins or haircuts are determined by the CCP. In addition to being exogenous to repo traders, haircuts are pretty stable over time.

[20]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 systematic default risk in clearing houses (European Securities and Markets Authority, 2015, 2017). Arguably,

The usual term types of repo 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 the true sale and repurchase of the collateral asset, i.e., the buyer (lender) becomes the legal owner of the collateral at the purchase date. As 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 (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, (iii) are collateralized by government bonds which are classified as high-quality liquid assets by regulators, (iv) and are subject to the homogeneous margin requirements. 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 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. Rather than the extant literature that has predominantly focused on U.S. (quasi) safe assets, 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 more than 70% of the total European repo market. For each transaction, we observe the

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. Later, 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.

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 lion's share 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.[21] Second, we exclude repos with term types other than ON, TN, and SN.[22] Third, we focus on sovereign bonds as a collateral asset as non-government bonds present a different risk profile and are rarely traded.[23] Fourth, we exclude repos with a floating rate.[24] Fifth, we exclude infrequently traded repos to guarantee the general validity of our carry factor and ease illiquidity issues.[25] 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.[26] However, we return to the variation on those days specifically in Table 2 when we show descriptive statistics of our

[21]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.

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

[23]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 two baskets from our analysis.

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

[25]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.

[26]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.

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 origin of the collateral, with representative shares for other European countries.[27] 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 (for each GC basket and ISIN) for each of the term types separately based on the trade date and across 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.[28]

[27]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).

[28]We compute transaction cost as the difference in repo rates between borrower-initiated and lender-initiated

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.

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.[29] For each day between a bond's issuance and maturity, we compute the daily volume-weighted average mid-quote, transaction price, and transaction cost. The size and liquidity of the MTS market make our bond data representative and tradeable.

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 and Italy in relation to the ECB's deposit and marginal lending facility rate (in red dashed lines).[30] Three patterns stand out. First, repo rates for Germany (depicted in green shades) are lower than those for Italy (in blue shades). Second, the spread between the two countries increased during the European sovereign debt crisis. Third, since 2016, 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.

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

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.

[29] 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.

[30] The deposit facility allows for overnight deposits with the ECB, while the marginal lending facility provides overnight central bank liquidity against the presentation of sufficient eligible assets. The rate on the deposit facility and the rate on the marginal lending facility define the ECB corridor for the overnight interest rate at which banks lend to each other.

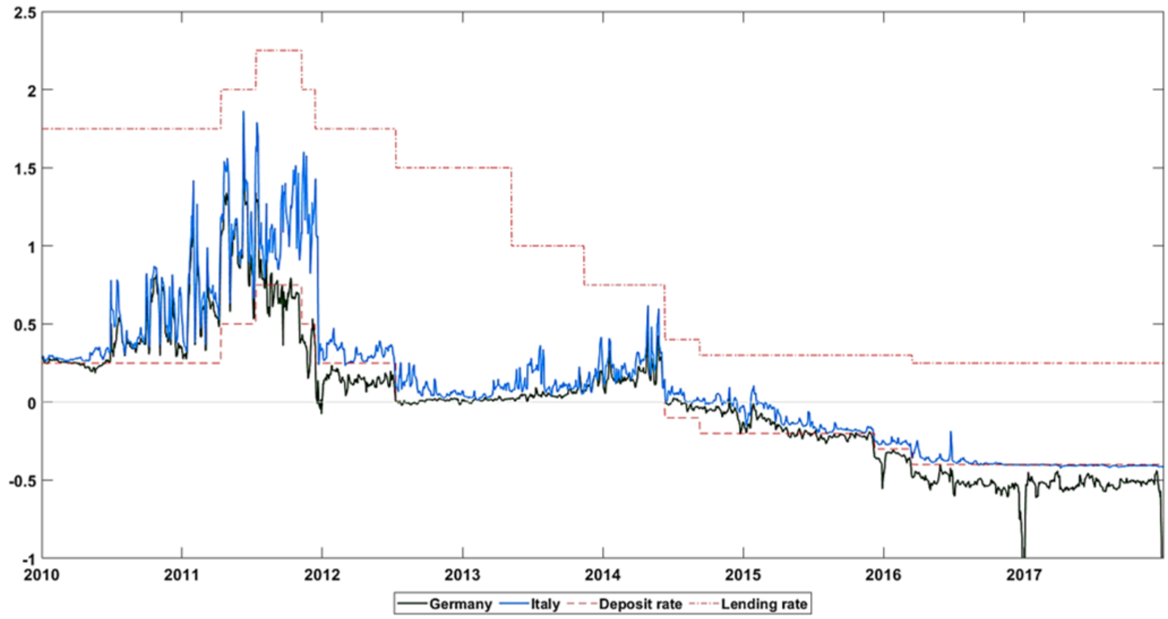


Figure 2: General collateral repo rate development

assets. Third, the increasing dispersion after 2016 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.

Another aspect is the *within country* dispersion in repo rates of the same sovereign country as depicted in Figure 3.[31] Until 2016, the dispersion in rates has been similar between German and Italian collateral. However, since 2016, the dispersion in German repo rates has increased, coinciding with the period of asset scarcity. 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

[31] We calculate the dispersion as the interquartile range across the set of each country's daily repo rates.

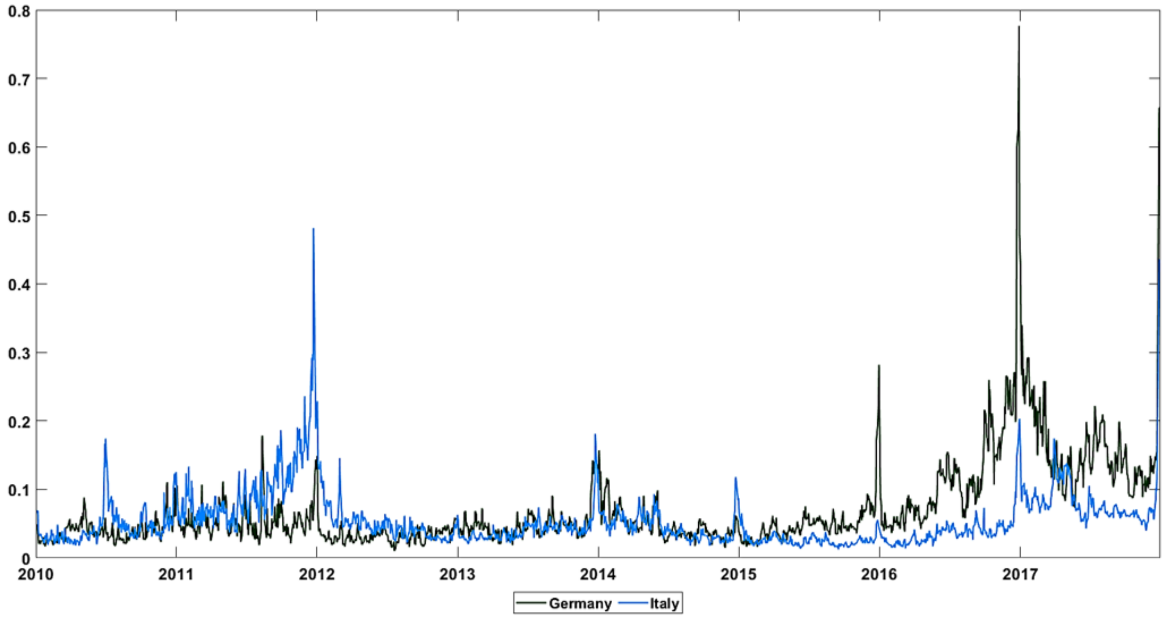


Figure 3: Repo rate dispersion

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.[32] 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 (reverse) repo (lender) borrower therefore loses (enjoys) the convenience of the collateral asset for the period between $t+2$ and $t+3$. This concept is illustrated in Figure 4.

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 funding demand and supply or changes in 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). The

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

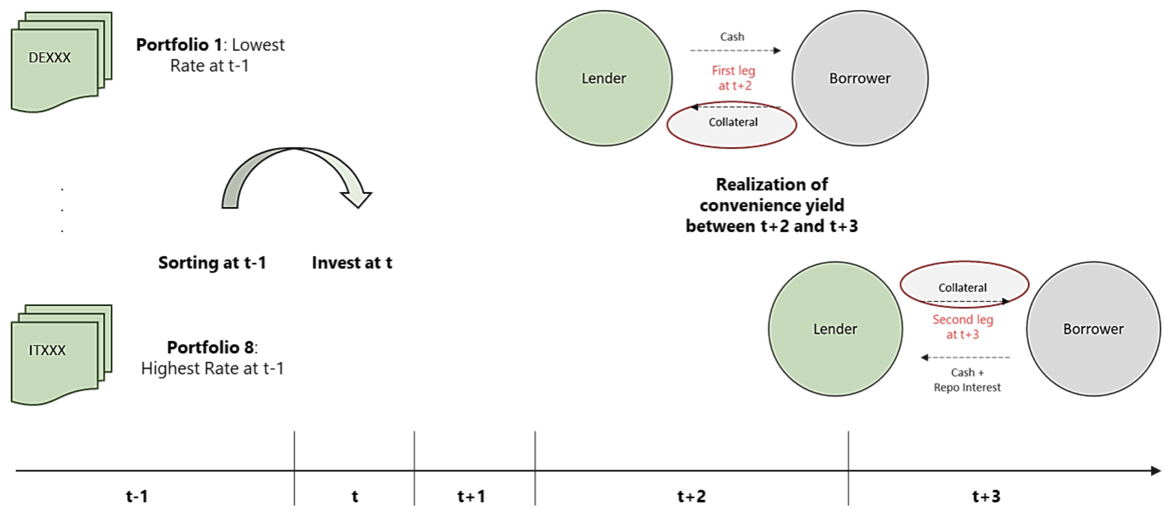


Figure 4: Convenience yield in repo trade

realized convenience yield is therefore ex-ante unknown.

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.[33] 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.[34] 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 premium. In our context, empirically we should observe that the forward interest rate (captured by the SN repo rate at time t) coincides with realized interest rates (captured by the ON repo rate at time t+2). Conversely, the dispersion in their difference suggests uncertainty in the

[33]As an alternative, we also calculate the realization using the tomorrow-next term type. For this, we study 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.

[34]The use of overnight repos allows us to reduce 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.

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 cost;[35] 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 and the realized net returns.[36] 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 assets. The standard deviation between the expected and the 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 0.43% in line with the idea that convenience benefits are more valuable on those days. While the overall effect seems to be small, it rep-

[35] 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.

[36] We calculate the standard deviation of the difference between the expected portfolio net return (using the SN rate at time t) and the realization of the portfolio net return (using the same portfolio constituents at the overnight rate at time t+2).

Table 2: Portfolio return (%)

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

Portfolio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	short	long	long	long	long	long	long	long
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

Portfolio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	short	long	long	long	long	long	long	long
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

Portfolio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	short	long	long	long	long	long	long	long
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	0.43
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. The return for portfolio 1 is multiplied by -1 to capture the short position for the high-minus-low return; 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.

resents an about 10% increase in the high-minus-low return. At the same time, the volatility indicator of convenience yield uncertainty also tends to be higher.

The daily transaction volume for all portfolios is substantial in absolute terms but not relative to the large market size, which ensures the rebalancing.[37]

Table 3: Portfolio constituents

Portfolio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**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 n=1, 2,...,8. 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

[37]For example, the average daily trading volume of portfolios 1 and 8 is more than euro 2 billion, respectively; the daily trading volume for any of the two portfolios never falls below euro 500 million. In Section 3, we return to the variation in the volumes of repo portfolios as one of the economic determinants for the cross-sectional dispersion in near-money rates.

the time-varying liquidity premium as an additional determinant of convenience yield which helps explain the within country variation in rates.[38]

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.

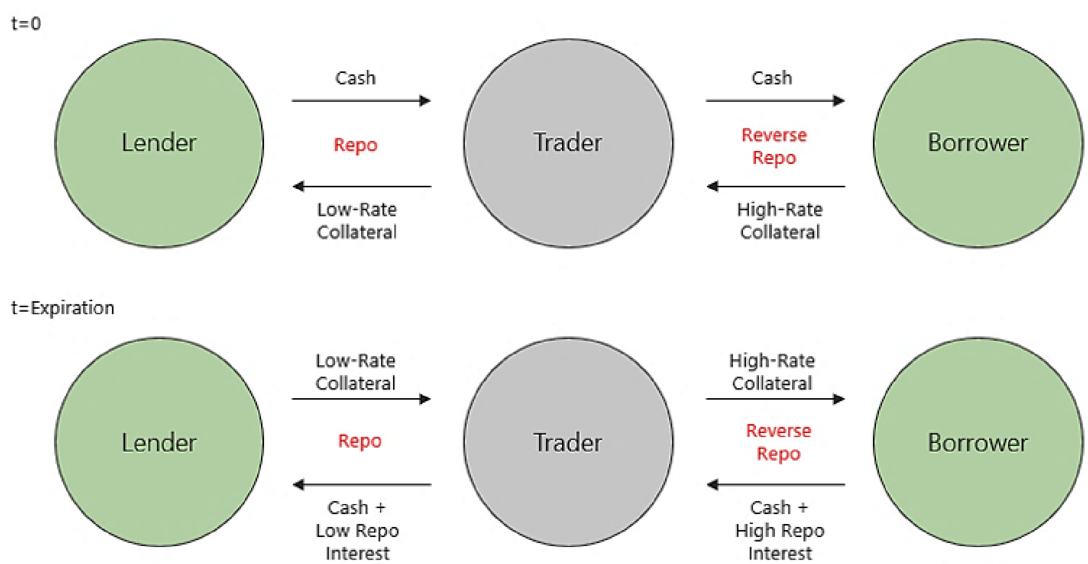


Figure 5: Carry trade

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

[38]Lastly, a breakdown of the portfolio transition matrix, i.e., what is the likelihood of a bond which is in a certain portfolio to stay in that portfolio tomorrow is presented in Appendix A.1. As expected, there is persistence, but we also observe movements across portfolios.

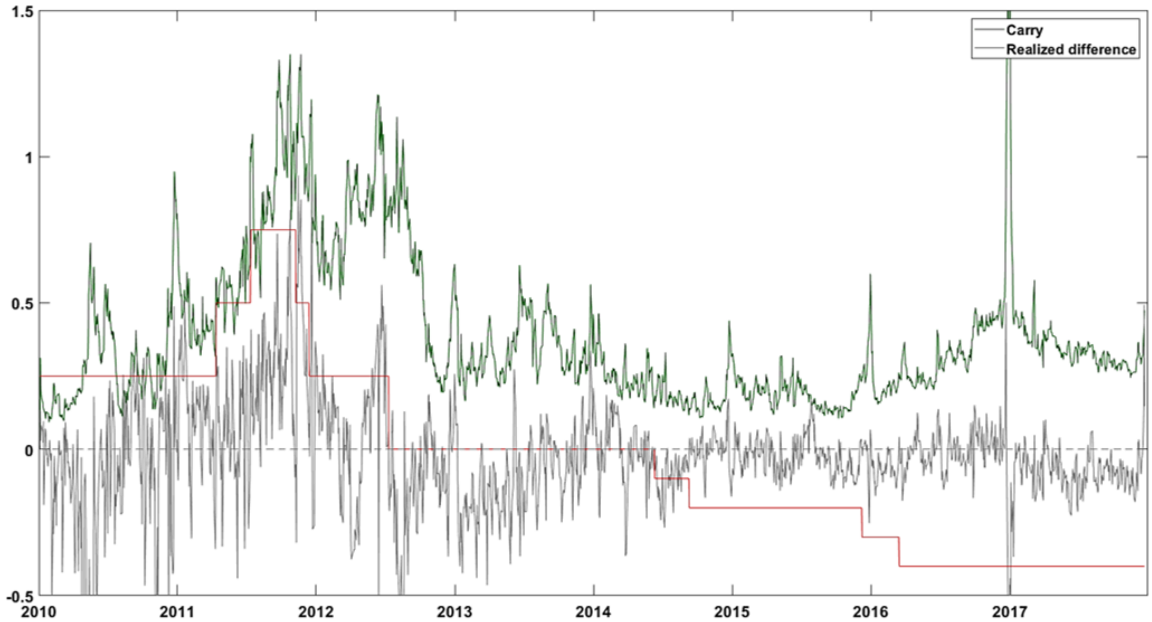


Figure 6: Carry factor and carry factor realization

transactions with different collateral bonds but the same settlement date.[39] Haircuts on the 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.[40] 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 (in green) as well as the difference (in grey) between the expectation and the actual realization is depicted in Figure 6, detailed summary

[39]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).

[40]Haircuts are reflected in the repo rate and were relatively stable during our period under review. The CCP determines ex-ante haircuts that are exogenous and thus the same for all market participants, which is different to the market practice in the U.S. (e.g., Gorton and Metrick (2012) and Copeland et al. (2014)). 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, those ECB haircuts were about 3% higher for assets in portfolio 8 compared to assets in portfolio 1.

statistics can be found in Table 4.[41] 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 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 and asset scarcity pointing towards the role of the liquidity premium.[42] The Dickey and Fuller (1979) and Phillips and Perron (1988) tests provide evidence that the null hypothesis of unit root can be rejected.[43]

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 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 way of measuring the return of such a 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

[41] A visual comparison between the realization of the carry return using the ON respectively TN rates is presented in Appendix A.2.

[42] 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.

[43] 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.

Table 4: Summary statistics (%)

Mean	0.39	Percentile		Percentile	
Min	0.08	1%	0.11	75%	0.47
Max	1.90	5%	0.14	95%	0.95
St. Dev.	0.18	25%	0.22	99%	1.21

The table reports summary statistics for our carry factor. It shows the mean, minimum, and maximum of the annualized carry return as well as the standard deviation of the difference between expected and realized carry factor using the same portfolio constituents at the day after tomorrow's ON rates; it also lists the standard percentiles of the carry return.

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, the lender becomes the legal owner of the collateral, however, income cash-flows on the collateral are passed to the borrower. Hence, incorporating income cash-flows from the underlying bonds would imply 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 (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 the cross-sectional differential in the one-day convenience premium. We show that the performance of our carry factor remains positive and increases once we account for the bond portfolio return (see Appendix A.3). However, the overall return is dominated by the bond price movements which capture other aspects than the one-day convenience yield. For example, bond prices also react to changes in convenience (Krishnamurthy, 2002). This relates to the present value of all future convenience yields and not to the one-day convenience yield.

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 all three repo tenors (i.e., ON, TN, and SN) and if we only consider trades executed on BrokerTec.[44] 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 documented that there is no systematic default risk in clearing houses (European Securities and Markets Authority, 2015, 2017).[45]

2.3 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. Table 5 reports the portfolio loadings on the eight principal components and the share of the total variance explained by each principal component. 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 -0.90 for the portfolio containing the repos with the lowest rate to 0.30 for the portfolio containing the repos with the highest rate. As we expect, the largest

[44]A visual comparison of the different carries is presented in Figure A.2.2 in Appendix A.2. Detailed results are reported in the Online Appendix.

[45]It should be noted that the framework of Boissel et al. (2017) cannot explain the developments of the repo market since 2016 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 are consistent with these patterns.

part of the common variation in short-term interest rates is explained by the level factor.[46] 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.[47]

Table 5: Principal component analysis

	PCA 1	**PCA 2**	**PCA 3**	**PCA 4**	**PCA 5**	**PCA 6**	**PCA 7**	**PCA 8**
Portfolio 1	0.28	−0.90	0.32	−0.01	−0.02	0.02	0.02	0.00
Portfolio 2	0.37	−0.06	−0.44	0.66	−0.08	−0.35	−0.28	−0.16
Portfolio 3	0.36	−0.01	−0.41	0.12	0.05	0.62	0.42	0.35
Portfolio 4	0.36	0.01	−0.33	−0.61	−0.45	−0.39	0.17	0.00
Portfolio 5	0.36	0.06	−0.12	−0.37	0.38	0.34	−0.52	−0.43
Portfolio 6	0.36	0.16	0.20	−0.07	0.57	−0.40	−0.03	0.56
Portfolio 7	0.36	0.25	0.37	0.15	0.11	−0.08	0.57	−0.55
Portfolio 8	0.37	0.30	0.48	0.11	−0.55	0.24	−0.35	0.23
% Variance	94.99%	4.28%	0.60%	0.06%	0.03%	0.02%	0.01%	0.01%

The table reports the portfolio loadings of portfolios n=1, 2,...,8, on the eight principal components as well as the share of the total variance explained by each principal component. Data are daily and include GC and special repos of term type SN for the period 2010–2017.

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[48] 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

[46] 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.

[47] 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 very short-term assets, momentum as constructed over a longer time horizon is not as relevant to our analysis.

[48] 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).

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).[49] The results of our asset pricing estimation are depicted in Table 6. Columns (1) - (8) report estimates of the factor loadings for the eight portfolios, while Column (9) depicts estimates of the two factor premia. We account for autocorrelation and heteroscedasticity in the error terms via the Newey and West (1987) estimator using the Bartlett kernel.

Table 6: Factor analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Portfolio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**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)	
β^{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)	
β^{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)	
λ^{Market}									-0.07
									(-1.52)
λ^{HML}									0.42^{***}
									(14.88)
N									14,960
Time Periods									1,870
adj. R^2									98.42%
χ^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 χ^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.

[49] Details about the GMM methodology and the different moment conditions which we consider can be found in Appendix A.4. 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.

Factor loadings

Columns (1) - (8) report the constants (a_n) and the slope coefficients (β_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 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.[50]

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

[50] 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.

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 provide results for the two-stage OLS estimation following Fama and MacBeth (1973) which are fully consistent and can be also be found in Appendix A.5. We also present the asset pricing estimations for each term type, for GC and special collateral separately and for trades executed on BrokerTec in the Online Appendix. The results show that our two factors are relevant for and apply to the entire repo market.

3. Economic determinants of convenience yield

The asset pricing analysis has shown that our carry factor helps explain the cross-sectional dispersion in near-money rates. Table 7 provides a different illustration of it, it reports the results of the time-series regressions of the eight repo portfolio returns net of the Eonia on a constant and the carry factor ("Carry"). The error terms are adjusted for autocorrelation according to Cochrane and Orcutt (1949), following Wooldridge (2015). The regression frequency is quarterly.[51]

By employing the portfolio returns net of the Eonia, we remove the level from our analysis and just focus on the cross-sectional dispersion. 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 factor, the assets in the high-rate portfolio (with the lowest convenience) have a positive loading. The $adj.R^2$ reflects how much of the individual repo rate variation is captured by our carry factor; it shows that the carry factor has the largest explanatory power 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.

[51] We choose a quarterly regression frequency (i) to match the economic variables embedded in our carry factor and (ii) to avoid any concerns that daily spikes or movements in rates impact our results. However, all our results are robust and consistent on a daily frequency and are reported in the Online Appendix.

Table 7: Safe asset dimensions of portfolio returns net Eonia

Return net Eonia Portfolio	(1) 1 b/t	(2) 2 b/t	(3) 3 b/t	(4) 4 b/t	(5) 5 b/t	(6) 6 b/t	(7) 7 b/t	(8) 8 b/t
Carry	-1.075^{***}	-0.295^{***}	-0.267^{***}	-0.249^{***}	-0.178^{***}	-0.022	0.087^{*}	0.125^{**}
	(-18.01)	(-4.90)	(-4.82)	(-5.06)	(-5.06)	(-0.59)	(1.92)	(2.45)
Constant	-0.098^{***}	-0.235	-0.148	-0.079	-0.077	-0.085^{***}	-0.090^{***}	-0.074^{**}
	(-3.38)	(-1.26)	(-1.15)	(-1.17)	(-1.46)	(-3.09)	(-3.23)	(-2.68)
N	31	31	31	31	31	31	31	31
adj. R^2	0.915	0.434	0.425	0.451	0.451	-0.022	0.082	0.143

The table reports the results of the time-series regressions of the return on the eight repo portfolios net of the Eonia on a constant and the carry factor ("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.

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 NQA) and safety" (Gorton, 2017).[52]

Krishnamurthy (2002) develops a theoretical model that determines the repo market equilibrium for the specialness of a bond (price) and the volume pledged of that bond as collateral (quantity). In his framework, investors value the liquidity services provided by the on-the-run U.S. Treasury security more than those provided by the off-the-run analogous security so that 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-

[52] A "safe asset" is an asset taken at face value with "no questions asked" (NQA).

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 safety premium and 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 and wobbling convenience yield perceived as quasi-safe assets.

Based on this understanding, three hypotheses about the economic determinants of the 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., 2019) 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- or wobbly 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.[53] The second hypothesis pos-

[53] Comparing two assets with the same fundamental value, Garleanu and Pedersen (2011) show that the asset providing larger liquidity benefits will trade at a higher price.

tulates 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 for a given level in repo convenience.

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 within 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 providing higher liquidity benefits should increase more with the opportunity cost.

The mechanisms are illustrated in a simple supply- and demand-framework which builds on Krishnamurthy (2002) as shown in Appendix A.6.

3.2 Safe asset dimensions of convenience yield

To test the empirical predictions, we want to replace the carry factor with the economic variables embedded in our carry factor. For this, we follow the literature to build our empirical measures. 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.[54] The opportunity cost is measured via the main euro area short-term interest rate benchmark Eonia.[55] To control for market frictions and arbitrage constraints, which can be particularly relevant in flight-to-quality periods (Longstaff, 2004), we compute 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).[56]

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, Table 8 reports the results of the time-series regressions of our eight repo portfolio returns on a constant, the CDS price difference between portfolios 8 and 1 ("Risk"), the difference in 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 ("Arbitrage Deviation"), and each portfolio's lagged repo rate ("Rate Lag1").

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 weakly significant. For example, a one-percentage point increase in our risk measure leads to a decrease in the rates of portfolio 1 by 33 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

[54]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.

[55]Eonia represents a weighted average of all overnight unsecured transactions in the euro interbank market. 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).

[56]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)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Return Portfolio	1	2	3	4	5	6	7	8
	b/t	b/t	b/t	b/t	b/t	b/t	b/t	b/t
Risk	-0.332^{***}	-0.006	-0.012	-0.034	-0.029	0.026	0.097^{**}	0.113^{**}
	(-3.21)	(-0.18)	(-0.41)	(-1.21)	(-1.06)	(0.84)	(2.67)	(2.79)
Asset Supply	-0.305	-0.211^{***}	-0.162^{**}	-0.104^{*}	-0.079	-0.065	-0.051	-0.058
	(-1.31)	(-2.94)	(-2.79)	(-1.94)	(-1.62)	(-1.20)	(-0.79)	(-0.82)
Opportunity Cost	0.327^{***}	0.843^{***}	0.883^{***}	0.928^{***}	1.001^{***}	1.109^{***}	1.164^{***}	1.208^{***}
	(3.58)	(15.75)	(19.11)	(21.20)	(25.32)	(26.61)	(24.74)	(23.51)
Arbitrage Deviations	-0.418^{***}	-0.314^{***}	-0.285^{***}	-0.240^{***}	-0.131^{***}	0.003	0.038	0.079^{*}
	(-4.45)	(-9.30)	(-9.78)	(-8.43)	(-4.67)	(0.08)	(1.02)	(1.90)
Rate Lag1	0.333^{***}	0.118^{**}	0.083^{*}	0.040	-0.017	-0.076^{*}	-0.060	-0.057
	(2.91)	(2.24)	(1.82)	(0.94)	(-0.46)	(-1.99)	(-1.47)	(-1.33)
N	30	30	30	30	30	30	30	30
adj. R^2	0.920	0.989	0.989	0.986	0.977	0.968	0.961	0.958

The table reports the results of the time-series regressions of the return on the eight repo portfolios on the static weighted CDS price difference between portfolios 8 and 1 ("Risk"), 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 ("Arbitrage Deviation"), and each portfolio's lagged repo rate ("Rate Lag1"). ***, **, 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.

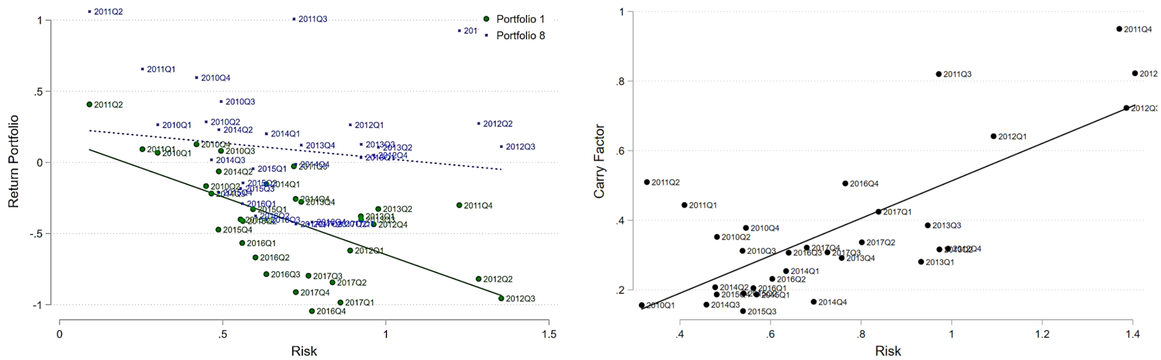
in portfolio 1 and 8 increases, the repo rates for portfolio 1 fall since investors prefer to hold these truly safe assets during moments of uncertainty. At the same time, the rates for assets in portfolio 8 do not increase significantly, which is at odds with the systemic risk hypothesis (Boissel et 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 as opposed to requiring compensation for higher risk on 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 decrease of the rates in portfolio 1 by 31 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 0.33 while portfolio 8 has the highest loading at 1.21. This result is in line with assets in the first portfolio carrying 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). The weaker response of portfolio 1 to an opportunity cost increase 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. The asset supply variable is not significant as we account for the opportunity cost of holding money, in line with the empirical evidence provided in 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 "Risk", while Figure 8 graphs portfolio 1 and 8's repo returns (Figure 8a) and the carry factor (Figure 8b) against "Asset Supply". 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), investors value their safety benefits and their repo rates are lower (i.e., the carry factor is higher). Similarly, when the supply of assets in portfolio 1 is scarce compared to assets in portfolio 8 (i.e., a high value of our asset supply measure), investors value their liquidity benefits, 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 yield. For this, we perform similar time-series regressions to explain our carry return (instead of portfolio returns) using the same sample period, quarterly data, and regressors as in the previous regression analysis (i.e., "Risk", "Asset Supply", "Opportunity Cost", "Arbitrage Deviation", and now "Carry Lag1").[57] The results are shown

[57]In contrast to the repo portfolio returns which also capture the overall level of short-term interest rates, the carry factor only accounts for the cross-sectional dispersion in rates.

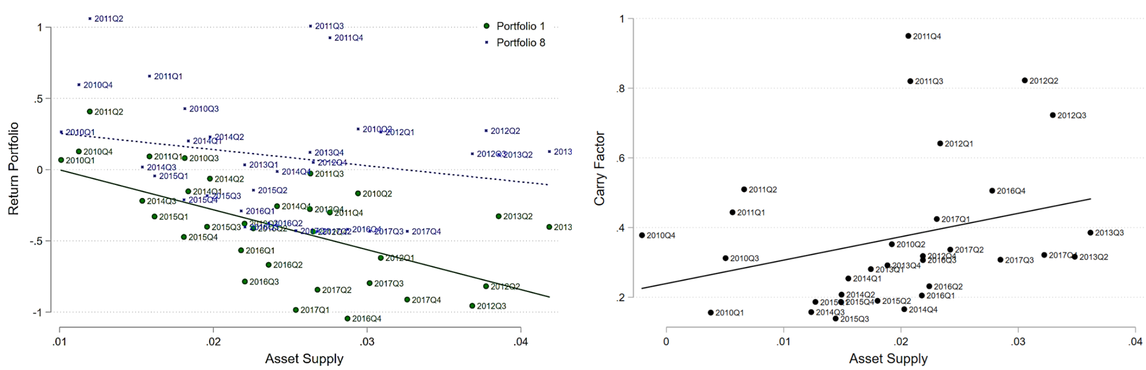


(a) Portfolio returns against risk

(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 ("Risk"), while Figure 7b depicts the scatter plot of the carry factor against risk.

Figure 7: Scatter plot for safety premium



(a) Portfolio returns against asset supply

(b) Carry factor against asset supply

Figure 8a depicts the scatter plot of portfolio 1 and 8's repo returns against the difference in the ratio of short-term debt to GDP ("Asset Supply"), while Figure 8b depicts the scatter plot of the carry factor against asset supply.

Figure 8: Scatter plot for liquidity premium

in Table 9. Columns (1) to (4) report the results for the univariate time-series regressions, while columns (5) and (6) report those for the multivariate time-series regressions.

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
Risk	0.526***				0.409***	0.403***
	(5.60)				(4.85)	(4.37)
Asset Supply		0.638***			0.285*	0.278
		(3.09)			(1.88)	(1.66)
Opportunity Cost			0.355**		0.456***	0.447***
			(2.33)		(5.78)	(5.42)
Arbitrage Deviation				0.401***	0.166*	0.168*
				(3.20)	(1.93)	(1.88)
Carry Lag1						0.036
						(0.35)
Constant	0.017	0.091	0.393***	0.276**	−0.101	−0.110
	(0.11)	(0.44)	(4.78)	(2.07)	(−1.35)	(−1.34)
N	31	31	31	31	31	30
adj. R^2	0.503	0.222	0.129	0.235	0.746	0.733

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 ("Risk"), 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 ("Arbitrage Deviation"), and the lagged carry factor ("Carry Lag1"). ***, **, 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.

Three main results emerge. First, the carry factor significantly increases in risk, providing empirical support for the safety premium hypothesis. In the multivariate setting (6), 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 significantly positive relationship between our carry factor and the relative scarcity of assets in portfolio 1 supporting the asset scarcity hypothesis. 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. 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. Similar to the previous results and in line with Nagel (2016), the supply variable loses part of its explanatory power after accounting for the opportunity cost.[58] In addition, our main results hold after controlling for market frictions and arbitrage constraints. The positive relationship between the CIP deviations and our carry factor suggests larger convenience premia in distressed markets.[59]

To validate our results, we perform a number of additional tests, which we briefly summarize here and report in the Online Appendix. First, we ensure that our results hold if we perform our analysis at a daily frequency. Second, we conduct various subsampling analyses, which clearly show that our main results hold for each term type, for GC and special repo transactions, and for trades executed on BrokerTec. This shows the general validity of our results and reinforces the idea that, for example, "specialness" and segmentation cannot be the driver of our carry factor. Third, we experiment with alternative variables capturing the different drivers of convenience yield.[60] Regarding the current period of unconventional monetary policy, we account for any ECB purchases under the public sector purchase program

[58]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.

[59]An increase in the absolute U.S. dollar euro CIP deviations by one standard deviation is accompanied by an increase in our carry factor of four basis points. The absolute U.S. dollar euro CIP deviation is on average 0.28, with a standard deviation of 0.23.

[60]We employ alternative measures of risk (i.e., the five-year CDS index of European banks), asset supply (i.e., debt to GDP), opportunity cost (i.e., one-month Euribor and average repo market rate), and market frictions (i.e., U.S. Treasury Bill Eurodollar difference also called TED spread, VIX, Composite Indicator of Systemic Stress in the Financial System (CISS), and a measure for the balance sheet cost of holding government bonds in line with He et al. (2021)). We also consider alternative weighting approaches for portfolios 1 and 8 in the construction of our risk and asset supply measures.

(PSPP).[61] In contrast to the asset supply measure, PSPP purchases retain their significance in the multivariate setting. The results show that when assets in portfolio 1 are relatively more purchased by the ECB (i.e., their scarcity increases), the carry factor also increases. This is consistent with the notion that the convenience yield stems from the collateral asset whose scarcity increases due to QE.

Finally, one can argue that the liquidity premium not only originates 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 countries forming portfolio 8 (high rates) and portfolio 1 (low rates), weighted by the respective shares of the countries in each portfolio.[62] We consider the same variables, except that now we add the supply of repos to the supply of the collateral assets. The results of this analysis at a monthly frequency are reported in Table 10.

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 this 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 (3), a one-percentage-point 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 of 68 basis points. 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 (7), the repo supply measure looses its significance while the asset supply measure retains its significance; this is consistent with the idea developed in this paper that the liquidity

[61] We employ the debt-to-GDP ratio (instead of the short-term debt-to-GDP ratio) for this part since only securities with a remaining time to maturity of more than one year are eligible for purchase under the PSPP.

[62] We use static weights (i.e., the average share of a country in a portfolio over the sample) for repo liquidity measures since repo liquidity is a dynamic measure that is available at a high frequency, which is consistent with how we handle the CDS measure.

Table 10: Economic analysis with repo liquidity

	(1) Carry b/t	(2) Carry b/t	(3) Carry b/t	(4) Carry b/t	(5) Carry b/t	(6) Carry b/t	(7) Carry b/t
Risk	0.262***					0.235***	0.185***
	(3.10)					(3.28)	(2.91)
Asset Supply		0.297***				0.222**	0.285***
		(3.07)				(2.55)	(3.25)
Repo Liquidity			-0.681***			-0.334**	-0.088
			(-4.20)			(-2.21)	(-0.72)
Opportunity Cost				0.285**		0.317***	0.278***
				(2.34)		(3.60)	(4.66)
Arbitrage Deviations					0.165***	0.134***	0.170***
					(3.71)	(3.21)	(4.01)
Carry Lag1							0.374***
							(4.63)
Constant	0.221**	0.281**	0.435***	0.392***	0.346***	0.077	-0.075*
	(2.09)	(2.37)	(4.87)	(4.92)	(3.17)	(1.07)	(-1.87)
N	95	95	95	95	95	95	95
adj. R^2	0.084	0.082	0.150	0.045	0.120	0.395	0.752

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 ("Risk"), the dynamic weighted difference in the log of the ratio of short-term debt to GDP between portfolios 8 and 1 ("Asset Supply"), the static weighted difference in the log of the ratio of repo volume to debt between portfolios 8 and 1 ("Repo Liquidity"), the Eonia rate ("Opportunity Cost"), the absolute U.S. dollar euro CIP deviations ("Arbitrage Deviation"), and the lagged carry factor ("Carry Lag1"). ***, **, 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 monthly and include GC and special repos of term type SN for the period 2010–2017.

premium/convenience yield is stemming from the collateral asset.

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 reflecting the supply of the collateral asset and the opportunity cost.

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, not only across portfolios but also for the within country dispersion in rates.

Inspired by Eisenschmidt et al. (2021), 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 time-series regressions 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"), and the lagged carry factor ("Carry Lag1"). The regression frequency is quarterly.[63]

The results show that the repo dispersion for safe countries such as Germany increases in the carry factor. In particular, the carry factor explains more of the within country dispersion for safer countries, which shows that the liquidity premium is larger for those sovereigns. For example, a one-percentage-point increase in the carry factor is accompanied by an increase in Germany's repo rate dispersion by 28 basis points. 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 Germany and decreases in the sovereign riskiness. This means that for quasi-safe

[63] We present consistent results at a daily frequency in the Online Appendix.

Table 11: Explanatory power of the carry factor

Repo Dispersion	(1) DE b/t	(2) NL b/t	(3) AT b/t	(4) FI b/t	(5) BE b/t	(6) ES b/t	(7) IT b/t
CDS	−0.022	0.016	0.004	0.059	0.001	0.042***	0.008
	(−0.40)	(0.76)	(0.21)	(1.23)	(0.09)	(3.78)	(0.75)
Carry	0.283***	0.147***	0.097***	0.049	0.102***	0.060	0.070
	(4.48)	(4.55)	(3.21)	(1.28)	(2.90)	(0.93)	(1.52)
Carry x High CDS	−0.196***	−0.099***	−0.063***	−0.044*	−0.086**	−0.097**	−0.018
	(−4.38)	(−5.14)	(−3.54)	(−1.76)	(−2.55)	(−2.65)	(−0.66)
Carry Lag1	0.018	−0.019	0.014	0.002	0.046**	0.067	0.036
	(0.54)	(−0.73)	(0.59)	(0.09)	(2.30)	(1.08)	(1.37)
N	30	30	30	30	30	29	30
adj. R^2	0.531	0.766	0.691	0.115	0.304	0.923	0.550

The table reports the results of the time-series regressions 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"), 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"), and the lagged carry factor ("Carry Lag1"). ***, **, 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). We exclude Irish and Portuguese repos since they have been traded infrequently during part of our sample period. Data are quarterly and include GC and special repos of term type SN for the period 2010–2017.

countries with a higher sovereign risk, the within country dispersion in convenience benefits and thus repo rates is lower.

During flight-to-safety periods, such as during the European sovereign debt crisis, the carry factor, however, explains less of the rate dispersion in safe collateral assets. 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.

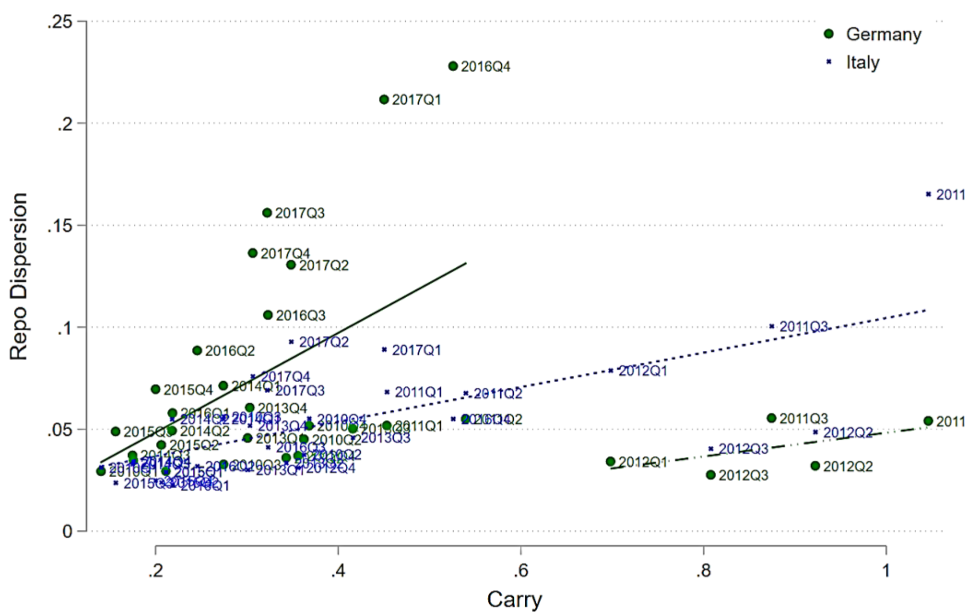


Figure 9: Scatter plot of Germany's and Italy's repo rate dispersion against the carry factor

This can also be seen in Figure 9 which graphs Germany's (in green) and Italy's (in blue) repo rate dispersion against the carry factor. During the European sovereign debt crisis (the periods on the right), there is few dispersion in German repo rates (i.e., all German collateral are considered safe). However, during the other periods, the carry factor tends to reflect repo rate dispersion within 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.[64] 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 factor.

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 to the carry factor; column (3) includes our measures for bond safety and liquidity in isolation, and column (4) combines our two repo factors and our measures for bond safety and liquidity.[65] All regressions include bond fixed effects and standard errors clustered at the maturity bucket-country level.[66]

Column (1) shows 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 (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., sovereign issuers 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 sizeable increase in the R^2 confirming that they serve as effective control variables. Column (4) shows that our two repo factors have explanatory power for bond pricing even after accounting for standard bond pricing factors. Our carry factor is able to capture the cross-sectional variation in the convenience yield that is reflected in bond yields. For example, an increase in our carry factor is accompanied by lower yields on German government bonds (reflected in a lower Nelson-Siegel residual) as opposed to a higher yields

[64]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.

[65]We do not include a constant in our regressions since we already account for the bond yield level.

[66]We group bonds into four different maturity buckets with the remaining time to maturity being (i) less than one year, (ii) one to five years, (iii) 5 to 10 years, and (iv) more than 10 years.

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^{**}		-0.013^{***}
	(-1.451)	(-2.094)		(-5.320)
Netherlands	0.001^{***}	0.000		-0.012^{***}
	(8.873)	(0.942)		(-4.783)
Austria	0.005^{***}	0.004^{***}		-0.011^{***}
	(37.193)	(10.897)		(-3.602)
Finland	0.002^{***}	0.001^{***}		-0.009^{***}
	(54.904)	(5.502)		(-4.190)
Belgium	0.011^{***}	0.010^{***}		-0.006^{*}
	(7.365)	(7.832)		(-1.880)
Spain	0.022^{***}	0.021^{***}		0.006^{*}
	(35.631)	(21.119)		(1.908)
Italy	0.023^{***}	0.022^{***}		0.008^{**}
	(29.075)	(25.550)		(2.627)
Ireland	0.042^{***}	0.041^{***}		0.017^{***}
	(124.028)	(143.891)		(3.650)
Portugal	0.077^{***}	0.076^{***}		0.052^{***}
	(15.217)	(15.058)		(8.590)
Repo Market Factor		0.006^{***}		0.000
		(2.966)		(0.115)
Bond Safety			0.013^{***}	0.012^{***}
			(3.869)	(4.488)
Bond Liquidity			0.004^{***}	0.003^{***}
			(4.642)	(5.703)
N	560,784	560,784	560,782	560,782
adj. R^2	0.688	0.706	0.742	0.818
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 safety denotes the log of the CDS spread, bond liquidity 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. Data are daily for zero and fixed-coupon bonds for the period 2010–2017.

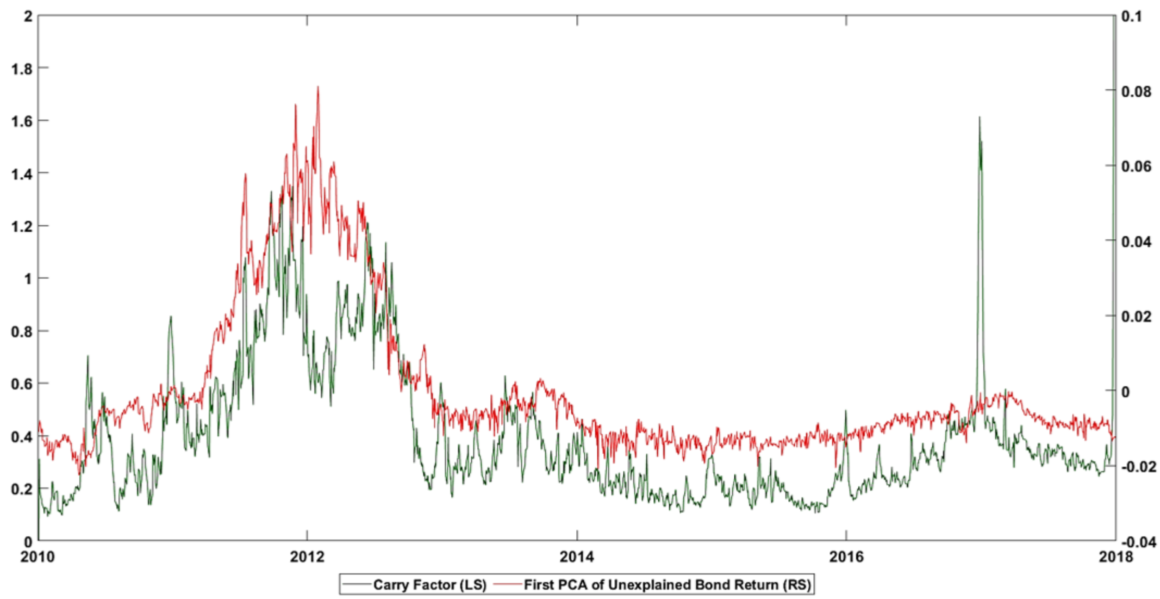


Figure 10: Carry factor and first PCA of unexplained bond return

on Italian bonds (reflected in a higher Nelson-Siegel residual). In economic terms, a one-basis-point increase in our carry factor implies a decrease (increase) in the Nelson-Siegel residual for German (Italian) government bond yields of about 1.3 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.[67]

Figure 10 and 11 provide visual evidence of the link between the bond return and our repo carry factor. Figure 10 plots 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) and our repo carry factor. Clearly, the two time-series seem to comove, motivating our choice of including the carry factor in the regression. Figure 11 shows the country loadings towards the first PCA of the unexplained part of the bond return and towards our carry factor. The results support the notion that our near-money carry factor consistently captures cross-sectional information about long-term bond yields beyond standard bond pricing factors.

Our results highlight that the two repo factors, in particular, the carry factor, have

[67] We report additional tests in the Online Appendix to ensure the robustness of our results. We show the results (i) by including the bond return as dependent variable and the Nelson-Siegel implied bond return as regressor, (ii) by considering different fixed effect specifications, and (iii) by including month-end and year-end dummies to account for the last trading day in a month and year, respectively.

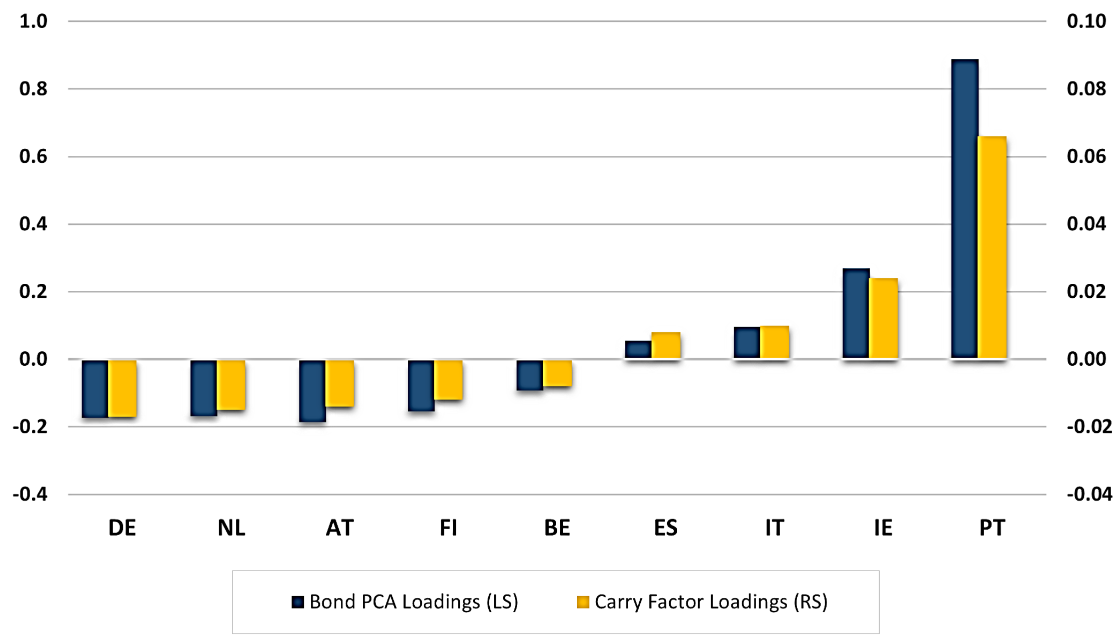


Figure 11: Country loadings on carry factor and bond PCA

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 suggest that it contains additional information about the cross-sectional variation in the convenience yield provided by long-term government bonds after controlling for measures of bond safety and liquidity. Thus, our carry factor seem to capture convenience services of a bond such as the safety premium and the short-term funding ability (e.g., in terms of asset fungibility and collateral (re-)pledgeability).[68] 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.

[68]For example, a German government bond and a German agency bond have the same sovereign default risk, still a German bond is likely to carry a higher safety premium. The carry factor also captures aspects such as repo liquidity which relates to an assets' fungibility. This squares well with the twofold source of supply inherent in a repo: the bond issuance and the repo trading volume.

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, which vary with asset scarcity and opportunity cost.

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.

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Appendix

A.1 Portfolio transition matrix

Table A.1.1: Portfolio transition matrix

		Portfolio today							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Portfolio yesterday	**1**	82.1%	13.3%	1.5%	0.7%	1.4%	0.5%	0.2%	0.2%
	2	12.5%	59.1%	17.8%	4.0%	4.4%	1.4%	0.5%	0.3%
	3	1.7%	16.3%	48.3%	20.1%	10.6%	2.0%	0.6%	0.3%
	4	0.7%	3.4%	17.0%	40.0%	34.2%	3.4%	0.9%	0.3%
	5	0.5%	1.5%	3.6%	13.3%	68.0%	10.7%	1.8%	0.6%
	6	0.5%	1.3%	1.9%	3.4%	27.2%	46.2%	16.1%	3.4%
	7	0.2%	0.6%	0.7%	1.1%	5.4%	17.7%	54.0%	20.4%
	8	0.2%	0.3%	0.4%	0.4%	1.7%	3.9%	20.6%	72.5%

The table reports the likelihoods of bonds in yesterday's portfolios n=1, 2,...,8 to be in today's portfolios n=1, 2,...,8. Data are daily and include GC and special repos of term type SN for the period 2010–2017.

A.2 Carry factor

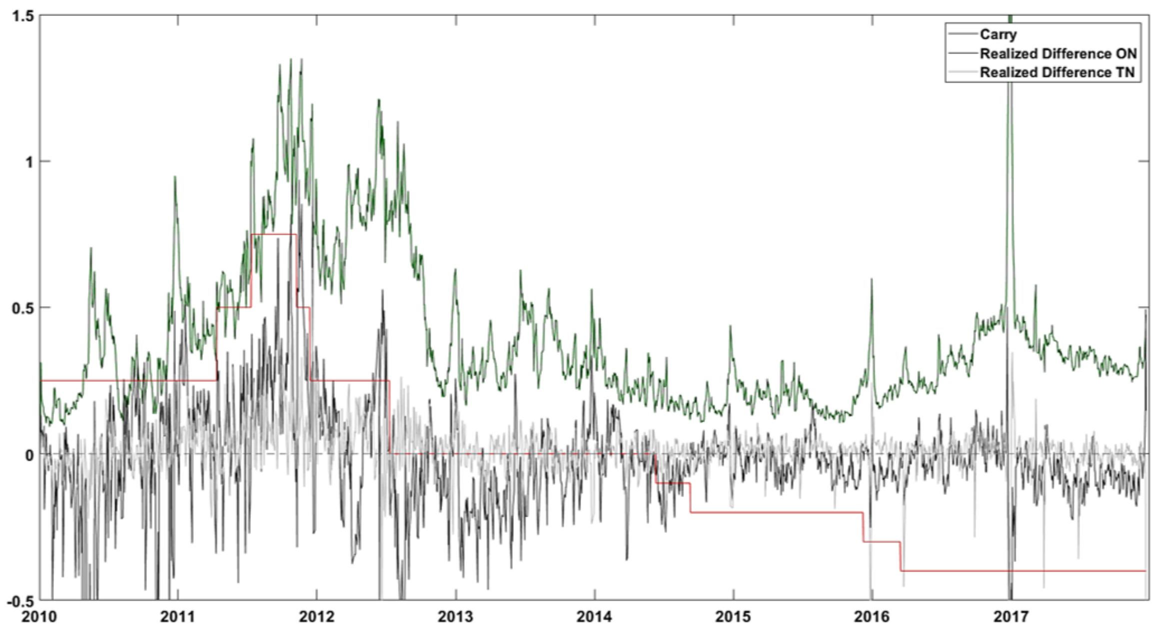


Figure A.2.1: Development of the safe asset carry factor as well as of the realization using TN and ON rates

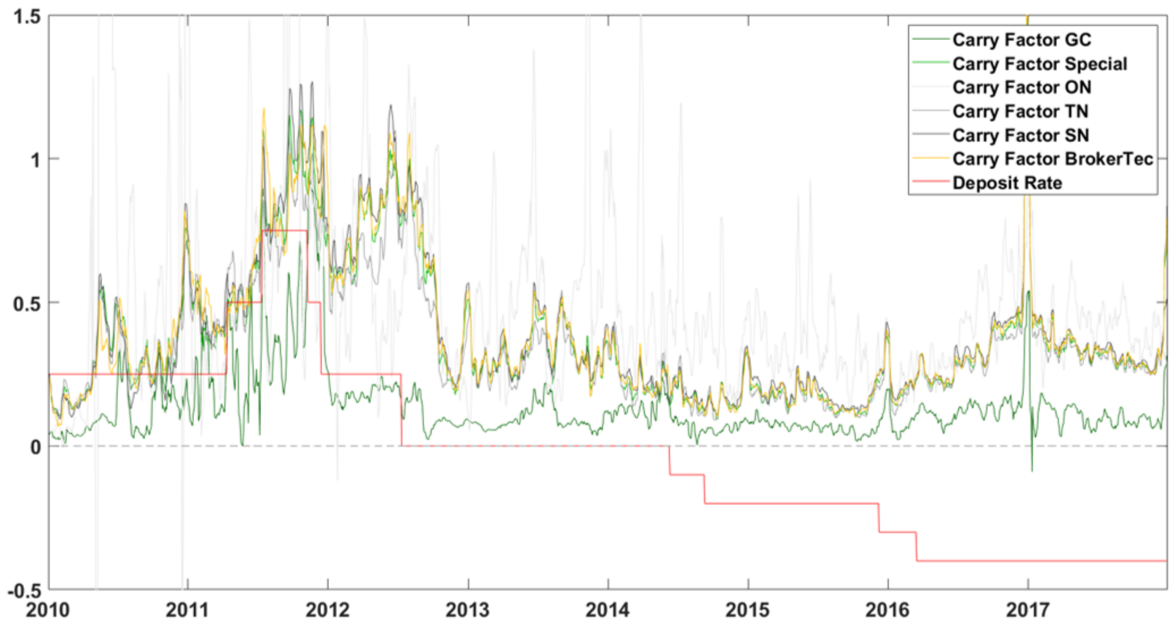


Figure displays one-week moving average for illustrative purposes.

Figure A.2.2: Development of different safe asset carry factors

A.3 Bond collateral

To establish the borrowing position in our carry trade, the hypothetical carry trader needs to own the collateral asset in the low-rate portfolio. The likelihood of holding or easily obtaining a given security depends on a bank's business model, size, and characteristics. For instance, dealer banks hold large portfolios, including government bonds, by acting as a market maker and by participating in government auctions. Similarly, CCPs hold large portfolios of government bonds due to their role as central counterparties. These institutions are best positioned to implement this carry trade.

Market participants could also establish a portfolio of government bonds. We consider the buy-and-sell approach for this. In this approach, the hypothetical carry trader buys and sells daily the securities needed to establish the high- and low-rate portfolios and is thus exposed to price changes on the underlying bonds. His position is positively (negatively) exposed to price changes of the securities pledged (obtained) on (from) the (reverse) repo side, i.e., the low-rate (high-rate) portfolio.[69] Table A.3.1 provides an overview of the return properties.

The buy-and-sell approach features returns that show a development consistent with our repo carry factor. However, in contrast to our repo carry factor which measures day-to-day movements in non-pecuniary convenience yield, this return also reflects monetary income flows (e.g., coupon payments) as well as changes in bond prices due to changes in e.g., risk and liquidity, as well as changes in all future convenience yields. As a results, the return of this trading strategy is consistent with our repo carry, however, the overall magnitude is larger as it reflects other aspects to day-to-day movements in convenience benefits.

[69]In both approaches, we account for coupon returns and funding cost. For the list of securities (i.e., by ISIN level) in the high- and low-rate portfolio, we refer to the SN term type.

Table A.3.1: Bond collateral

	Buy-and-Sell	
Year	Return	St. Dev.
2010	5.55%	2.72%
2011	9.21%	6.72%
2012	8.00%	8.67%
2013	1.30%	2.04%
2014	2.75%	2.17%
2015	0.72%	3.24%
2016	5.82%	3.70%
2017	0.20%	2.83%

In the buy-and-sell approach, the hypothetical carry trader buys and sells daily the securities needed to establish the high- and low-rate portfolios. The carry trader is therefore positively (negatively) exposed to price changes of the securities pledged (obtained) on (from) the (reverse) repo side, i.e., the low-rate (high-rate) portfolio. We account for coupon returns and funding cost. For the funding cost, we consider the overnight (unsecured) EONIA rate since it implies that the carry trader does not need to hold any additional collateral to finance the portfolio. Since we want to capture the value changes of the collateral assets, we do not account for transaction cost. As long as portfolio constituents are persistent over time, the actual transaction cost in implementing the buy-and-sell approach is lower. The buy-and-sell return is therefore defined as the positive (negative) price changes of the low-rate (high-rate) portfolio, plus coupon returns and less funding cost. We add the coupon returns (which are also reflected in the yield to maturity) since the owner of a government bond remains the beneficial owner even if a security is pledged as collateral. Since both approaches require a list of securities as well as the time period for which the securities need to be held, we refer to the SN term type.

A.4 GMM estimation

We consider the following linear asset pricing model in which the expected return is equal to the factor premia times the respective betas of each portfolio:

$$E[R] = \beta^{Market} \cdot \lambda^{Market} + \beta^{HML} \cdot \lambda^{HML}. \tag{1}$$

We consider repo rates (instead of excess returns) as the dependent variable since our market factor captures the interest rate level.[70] Our carry trade involves a collateral swap in which the collateral quality (differential) is ex ante unknown. For example, the safety and liquidity benefits of an asset can change during a day. The difference in convenience yield across assets is therefore uncertain and varies across time.[71]

For our estimation, we employ the GMM estimation based on Hansen (1982). Following Cochrane (2009), and by referring to the respective factor $k \in [Market, HML]$, we account for the three moment conditions illustrated in Equation 2:

$$\begin{bmatrix} E(R_{n,t} - a_n - \beta_n^k \cdot f_t^k) \\ E[(R_{n,t} - a_n - \beta_n^k \cdot f_t^k) * f_t^k] \\ E(R_n - \beta_n^k \cdot \lambda^k) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

The first two conditions require the error terms of the time-series regression $\epsilon_{n,t}$ to be estimated such that $E(\epsilon_{n,t}) = 0$ and $\text{Cov}(\epsilon_{n,t}, \mathbf{f_t^k}) = 0$. The third condition relates to the cross-sectional regression and requires the cross-sectional error term ζ_n to be estimated such that $E(\zeta_n) = 0$. For the estimation, we translate Equation 2 into the following moment conditions:

$$R_{n,t} - a_n - \beta_n^{Market} \cdot f_t^{Market} - \beta_n^{HML} \cdot f_t^{HML} = 0 \tag{3}$$

$$(R_{n,t} - a_n - \beta_n^{Market} \cdot f_t^{Market} - \beta_n^{HML} \cdot f_t^{HML}) \cdot f_t^{Market} = 0 \tag{4}$$

[70] Therefore, the intercept in the time-series regression does not need to be zero, and thus cannot be interpreted as a measure of mispricing.

[71] The uncertainty is related to the funding side of the repo (e.g., aggregate liquidity shock, liquidity hoarding, and unexpected monetary policy effects) as well as to the collateral side (e.g., asset price movements and margin calls).

$$(R_{n,t} - a_n - \beta_n^{Market} \cdot f_t^{Market} - \beta_n^{HML} \cdot f_t^{HML}) \cdot f_t^{HML} = 0 \quad (5)$$

$$R_n - \beta_n^{Market} \cdot \lambda^{Market} - \beta_n^{HML} \cdot \lambda^{HML} = 0. \quad (6)$$

In the estimation, n refers to the respective portfolio $n \in [1,..,8]$. Thus, β_n^{Market} denotes portfolio n's sensitivity to the market factor, β_n^{HML} denotes portfolio n's sensitivity to the carry factor, and λ^{Market} and λ^{HML} represent the respective factor premia. Equations 3 and 6 require the error terms of the time-series and cross-sectional regressions to be zero in expectation, and Equations 4 and 5 require the covariances of the error terms of the time-series regressions with the respective factors to be zero in expectation. For $n \in [1,..,8]$, we derive 32 conditions that we account for in the GMM estimation.

A.5 Fama & MacBeth (1973) estimation

In line with the "classical" approach introduced by Fama and MacBeth (1973), we follow the two-stage estimation procedure:

$$R_{n,t} = a_n + \beta_n^{Market} \cdot f_t^{Market} + \beta_n^{HML} \cdot f_t^{HML} + \epsilon_{n,t} \tag{7}$$

$$R_n = \beta_n^{Market} \cdot \lambda^{Market} + \beta_n^{HML} \cdot \lambda^{HML} + \zeta_n. \tag{8}$$

In the time-series regression 7, we determine the portfolios' betas, while in the cross-sectional regression 8, we determine the factor premia for the market and the carry. In the estimation, n refers to the respective portfolio $n \in [1, .., 8]$. Thus, β_n^{Market} denotes portfolio n's sensitivity to the market factor, β_n^{HML} denotes portfolio n's sensitivity to the carry factor, and λ^{Market} and λ^{HML} represent the respective factor premia. We do not include a constant in the cross-sectional regression since the market factor serves as a constant. Table A.5.1 reports the constants (a_n) and the slope coefficients (β_n^k) of the FMB time-series regressions of each portfolio's return on a constant, the market factor, and the carry factor (1)-(8) as well as estimates of the factor premia for the market and the carry obtained using the FMB approache (9).

Table A.5.1: FMB estimation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Portfolio	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	FMB
a	−0.01	−0.01	0.01	0.02***	0.02***	0.01	0.01	0.01	
	(−0.85)	(−1.09)	(1.52)	(2.87)	(4.40)	(1.25)	(0.82)	(1.25)	
β^{Market}	0.98***	1.06***	1.03***	1.01***	1.00***	0.98***	0.97***	0.98***	
	(81.66)	(76.70)	(113.33)	(166.11)	(191.06)	(98.10)	(90.98)	(89.76)	
β^{HML}	−0.83***	−0.02	0.02	0.04	0.10***	0.20***	0.30***	0.36***	
	(−17.18)	(−0.72)	(0.49)	(1.61)	(6.54)	(9.82)	(10.48)	(9.71)	
λ^{Market}									−0.06
									(−1.00)
λ^{HML}									0.41***
									(12.10)
N	1,870	1,870	1,870	1,870	1,870	1,870	1,870	1,870	14,960
Time Periods									1,870
adj. R^2	97.62%	99.03%	99.17%	99.15%	99.70%	99.58%	99.31%	99.01%	98.28%

The table reports the factor loadings for the eight portfolios estimated via the FMB time-series regression of each portfolio's return on a constant, the market factor, and the carry factor as well as estimates of the premia for the market factor and the carry factor obtained using the FMB approache. ***, **, 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. Data are daily and include GC and special repos of term type SN for the period 2010–2017.

A.6 Theoretical framework

We propose a simple supply- and demand-framework which builds on Krishnamurthy (2002) as shown in Figure A.6.3a.

The x-asis displays the quantity of a bond pledged as collateral in the repo market ("repo quantity"), the y-axis displays an asset's convenience ("convenience").[72] We consider two separate demand curves, one for truly safe assets and one for quasi-safe assets.[73] As investors value the higher convenience yield of truly safe assets, there is a higher demand for them leading to a lower equilibrium rate of the repo carrying this higher convenience. The supply of collateral is perfectly elastic as long as an asset's convenience is zero which is the case if the repo rate is close to the interest rate benchmark but becomes upward slowing for positive convenience levels.

In our setting, the supply curve is given as

$$c(Q) = A + b^S \cdot X^S + d^S \cdot max[Q - Q^*, 0], \tag{9}$$

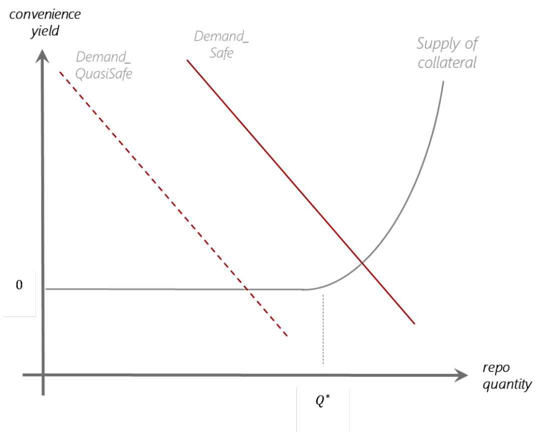
and the demand curve as

$$c(Q) = b^D \cdot X^D + b^R \cdot (\overline{Risk} - Risk^i) + b^L \cdot opportunitycost - d^D \cdot Q. \tag{10}$$

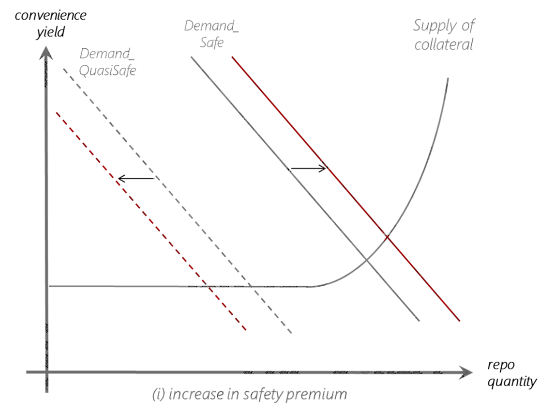
In the supply curve, the intercept is given by $A + b^S \cdot X^S$, which contains a parameter A and a shift in supply X^S. After a cut-off quantity Q^*, the supply curve increases in the quantity with a slope of d^S. The demand curve depends on the specific risk of the collateral asset i ($Risk^i$) relative to the overall risk ($\overline{Risk}$) and the opportunity cost. More specifically, the intercept increases (i) for bonds with below-average country risk ($\overline{Risk} - Risk^i$) and (ii) in the $opportunitycost$. The intercept also reacts to shifts in demand X^D. The demand curve

[72] In our setting, we consider general collateral and special repos and thus distinguish between specialness and convenience. In the spirit of Krishnamurthy (2002), the difference between the repo rate and the interest rate benchmark reflects the convenience premium whereas specialness is defined as the difference between the GC and the special repo rate. In that sense, a GC repo can carry a convenience yield without being special. The y-axis in our setting therefore reflects the convenience yield of a collateral asset.

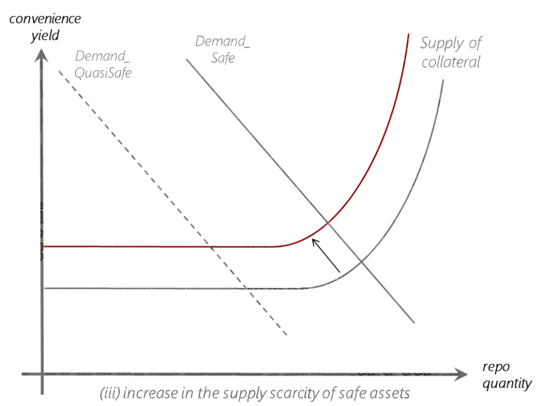
[73] The demand curves are downward sloping, i.e., there is a higher demand to lend against a given asset if it carries a lower convenience yield (and specialness) and higher repo rate.



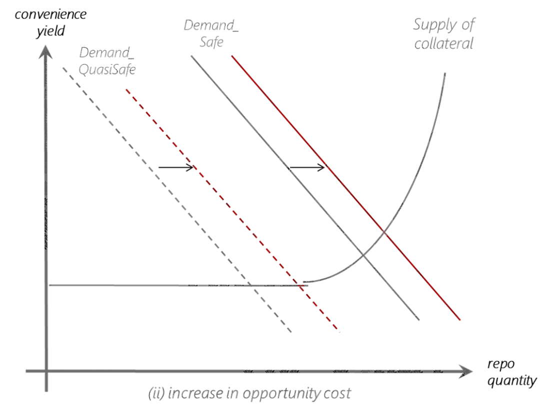
(a) Theoretical framework



(b) Safety premium



(c) Asset scarcity



(d) Opportunity cost

Figure A.6.3: Convenience yield framework

falls in the quantity with a slope of d^D.

As outlined in the demand equation and illustrated in Figure A.6.3b, an increase in the perceived sovereign risk of quasi-safe asset i relative to the overall risk ($\overline{Risk}$) 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.

Our framework accommodates changes in the liquidity premium due to changes in the supply of assets via a movement in the supply curve. For example, an increase in the relative scarcity of truly safe assets leads to a lower repo supply of those scarce assets for a given level in repo convenience (Figure A.6.3c). This is reflected in X^S in the supply curve.

In our graphical framework, an increase in the opportunity cost leads to an increase in the demand for safe assets. Since the demand for quasi-safe assets is met at the inelastic part of the supply curve, only the convenience for truly safe assets increases (Figure A.6.3d).