Limits to credit risk arbitrage: Evidence from intraday euro sovereign debt markets*

Jacob Gyntelberg† Peter Hördahl‡ Kristyna Ters§ Jörg Urban¶

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Abstract

In euro area sovereign credit markets, a persistent positive basis between credit default swap (CDS) and sovereign bond spreads points to the presence of liquidity frictions that prevent a complete adjustment of market prices to the theoretical no-arbitrage condition, i.e. a zero basis. Using a threshold vector error correction model (TVECM), we show that the adjustment process intensifies once the CDS-bond basis exceeds a certain level, indicating that arbitrageurs step in and carry out basis trades only when the the expected gain from the trade is greater than the cost of the transaction. This finding holds only prior to the recent euro area sovereign debt crisis, suggesting that normal market mechanisms essentially broke down as the crisis intensified and liquidity largely dried up in peripheral sovereign credit markets.

JEL classification: G12, G14 and G15.

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† Danske Bank, Copenhagen, Denmark. email: jacobgyntelberg@danskebank.dk

‡ Bank for International Settlements, Basel, Switzerland. email: peter.hoerdahl@bis.org

§ University of Basel, Basel, Switzerland. email: kristyna.ters@unibas.ch

¶ Bank for International Settlements, Basel, Switzerland. email: joerg.urban@bis.org

1 Introduction

The theoretical no-arbitrage condition between CDS and bonds based on Duffie (1999) is a cornerstone for empirical research on price discovery of credit risk. This condition requires that CDS spreads and (par floating rate) spreads on bonds issued by the entity referenced in the CDS contract must be equal, as any discrepancy would present investors with an arbitrage opportunity. For this no-arbitrage condition to hold, markets must be perfect and frictionless. In practice, however, frictions and imperfections often make such arbitrage trades difficult and costly to varying degree. These imperfections include limited and time-varying liquidity across market segments, unavailability of instruments with identical maturity and payout structures, and the fact that some arbitrage trades require tying up large amounts of capital for extended periods of time. As a result, the difference between the CDS premium and the bond spread, the so-called basis, is typically not zero. Moreover, the basis can become sizeable and persistent in times of market stress.

A persistent non-zero CDS-bond basis is therefore likely to reflect the unwillingness of arbitrageurs to try to exploit it, unless the pricing mismatch is greater than the cost of undertaking the arbitrage trade. Empirically, we would therefore expect to see such arbitrage forces intensifying as the magnitude of the basis exceeds some level that reflects the costs that traders face in the market. This suggests that the adjustment process towards the long-run equilibrium is nonlinear, in that it differs depending on the level of the basis. In order to capture such behaviour, we extend the linear vector error correction model (VECM) which has been the convention in existing studies (see for example Blanco et al. (2005) and Zhu (2004) for corporates, Ammer and Cai (2007) for emerging markets, and Gyntelberg et al. (2013), Palladini and Portes (2011), Fontana and Scheicher (2010), Mayordomo et al. (2011) for euro area sovereigns) to a nonlinear set-up using a threshold VECM (TVECM).

The importance of liquidity in credit risk modelling is well-known. However, only few empirical studies analyse the effect of liquidity frictions on the price discovery process for credit risk. Several papers conclude that liquidity affects corporate bond spreads significantly (e.g. Elton et al. (2001), Ericsson and Renault (2006), Chen et al. (2007)). By contrast, other papers argue that CDS spreads reflect pure credit risk, i.e. that they are not significantly affected by liquidity (e.g. Longstaff et al. (2005)). However, there are numerous papers reporting that CDS spreads are too high to represent pure credit risk (e.g. Berndt et al. (2005), Blanco et al. (2005), Pan and Singleton (2005)). Tang and Yan (2007) find that the level of liquidity and liquidity risk are important factors in determining CDS spreads. Hull and White (2000) address the effects of market frictions from a theoretical point of view and determine conditions under which CDS prices are affected. Longstaff et al. (2005) study price differences between CDS and bonds and attribute them to liquidity and counterparty risk. Also Zhu (2004) concludes that liquidity matters in CDS price discovery. Ammer and Cai (2007), Levy (2009) and Mayordomo et al. (2011) find evidence that liquidity (as measured by the bid-ask spread) is a key determinant for price discovery, but without explicitly modelling any market frictions. One of the few empirical studies that specifically examines the role of liquidity in CDS is Tang and Yan (2007) who focus on pricing effects. They show that the liquidity effects on CDS premia are comparable to those on treasury and corporate bonds (Tang and Yan; 2007).

One of the key contributions of our paper to the existing literature on price discovery in credit markets is that, in contrast to all studies mentioned above, we allow for a nonlinear adjustment of prices in CDS and bond markets towards the long-run equilibrium. As mentioned, this will allow us to capture the possibility that arbitrageurs step into the market only when the trading opportunity is sufficiently profitable. Our TVECM approach can directly quantify the threshold beyond which such trading opportunities are seen by investors as 'sufficiently profitable'. Moreover, our analysis relies on intraday price data for both CDS and bonds, allowing us to estimate the spread dynamics and the price discovery implications substantially more accurately than existing studies.

The rest of the paper is structured as follows. Section 2 discusses in more detail the relationship between sovereign CDS and bonds. Section 3 details our data, while Section 4 discusses the set-up and estimation of our TVECM. Section 5 provides the empirical results and Section 6 concludes.

2 Relation between sovereign CDS and bonds

In a frictionless market, the CDS premium should equal the spread on a par fixed-rate bond (issued by the same entity as referenced by the CDS) over the riskfree interest rate (Duffie (1999)). Both the CDS premium and the risky bond's yield spread is compensation to investors for being exposed to default risk, and must therefore be priced equally in the two market segments. However, for this to hold exactly, a number of specific conditions must be met, including that markets are perfect and frictionless, that bonds can be shorted without restrictions or cost, that there are no tax effects, etc. Any departures from this perfect environment will introduce potential wedges between the pricing of credit risk in CDS contracts and in bonds.

Moreover, given that floating rate notes are relatively uncommon, in particular for sovereigns, any comparison between CDS spreads and bond spreads based on fixed-rate bonds will introduce other distortions. Hence, the observed difference between the CDS premium and the bond spread, the basis, is typically not zero. To ensure proper comparability between the bond and the CDS, Gyntelberg et al. (2013) employ asset swap spreads (ASW) for the bond leg of the basis, but nevertheless document that the basis persistently deviates from zero.

2.1 Market with frictions

There are a number of recent papers that focus on the pricing of sovereign credit risk in the euro area, which all find that the theoretical no-arbitrage condition between CDS spreads and bond spreads does not hold (for example Gyntelberg et al. (2013), Fontana and Scheicher (2010), Arce et al. (2012), and Palladini and Portes (2011)). Gyntelberg et al. (2013) find that the basis across seven euro area sovereigns[1] is almost always positive over the sample period for all tenors. Moreover, they find that the basis varies substantially across countries, with means ranging from 74 to 122 bps for the 5-year tenor, and from 58 to 175 bps for the 10-year tenor. Empirical research on corporate credit risk also points towards a non-zero basis as shown for example in Nashikkar et al. (2011), Blanco et al. (2005) and Zhu (2004), and for emerging markets sovereign credit risk according to Ammer and Cai (2007).

The CDS market is a search market as the security is traded over-the-counter (OTC) where parties have to search for each other in order to bargain and match a trade. Therefore, market trading is not continuous in the sense that any amount can not be bought or sold immediately (Black; 1971). Moreover, other frictions and imperfections may make arbitrage trades difficult and costly. These imperfections include limited and time-varying liquidity in some or all market segments, unavailability of instruments with identical maturity and payout structures, and the fact that some arbitrage trades require tying up large amounts of capital for extended periods of time. Furthermore, the no-arbitrage condition relies on the ability to short sell the bond, which is not always costless and sometimes even impossible due to illiquid markets. All of these imperfections contribute to explaining why the basis between CDS and bond spreads can deviate from zero, often substantially and persistently. However, we would expect to see arbitrage forces come into play if the basis becomes "too wide", thereby pushing it back towards zero.

Clearly, market liquidity conditions are crucial for investors that take positions in CDS and bond markets in order to exploit pricing differences, as high liquidity will tend to facilitate such transactions and keep the cost of doing so low. However, empirical evidence points towards the presence of liquidity frictions in CDS and bond markets which prevent a complete adjustment to the theoretical no-arbitrage condition. Arbitrageurs will only carry out a basis trade when the cost of the transaction is smaller than the expected gain from the trade. We would therefore expect to see stronger adjustment forces in CDS and bond markets when the basis exceeds some critical threshold. This would reflect the

[1] France, Germany, Greece, Ireland, Italy, Portugal, Spain; 5- and 10-year tenor from October 2008 to end-May 2011

various costs traders face in markets, including for illiquidity as well as for tying up costly capital of possibly long periods of time.

3 Data

For our empirical analysis we use intraday price quotes on CDS contracts and government bonds for France, Germany, Greece, Ireland, Italy, Portugal and Spain. We choose this group of countries because they include those that were most affected by the euro sovereign debt crisis. Germany is included as a near-riskfree reference country, and France which we consider as a low-risk control country. We use 5- and 10-year USD-denominated CDS quotes for all countries in our sample. As documented in Gyntelberg et al. (2013), the 5-year segment is more liquid than the 10-year segment, particularly as the sovereign debt crisis intensified.

Our sovereign bond price data comes from MTS (Mercato Telematico dei Titoli di Stato) while the CDS data consists of price quotes provided by CMA (Credit Market Analysis Ltd.) Datavision. We construct intraday time series based on a 30-minute sampling frequency from 2008 to end-2011 (see Gyntelberg et al. (2013) for details). We choose to start our sample in 2008 since euro area sovereign CDS markets were very thin prior to this, making any type of intraday analysis before 2008 impossible (for a fuller discussion see Gyntelberg et al. (2013)).

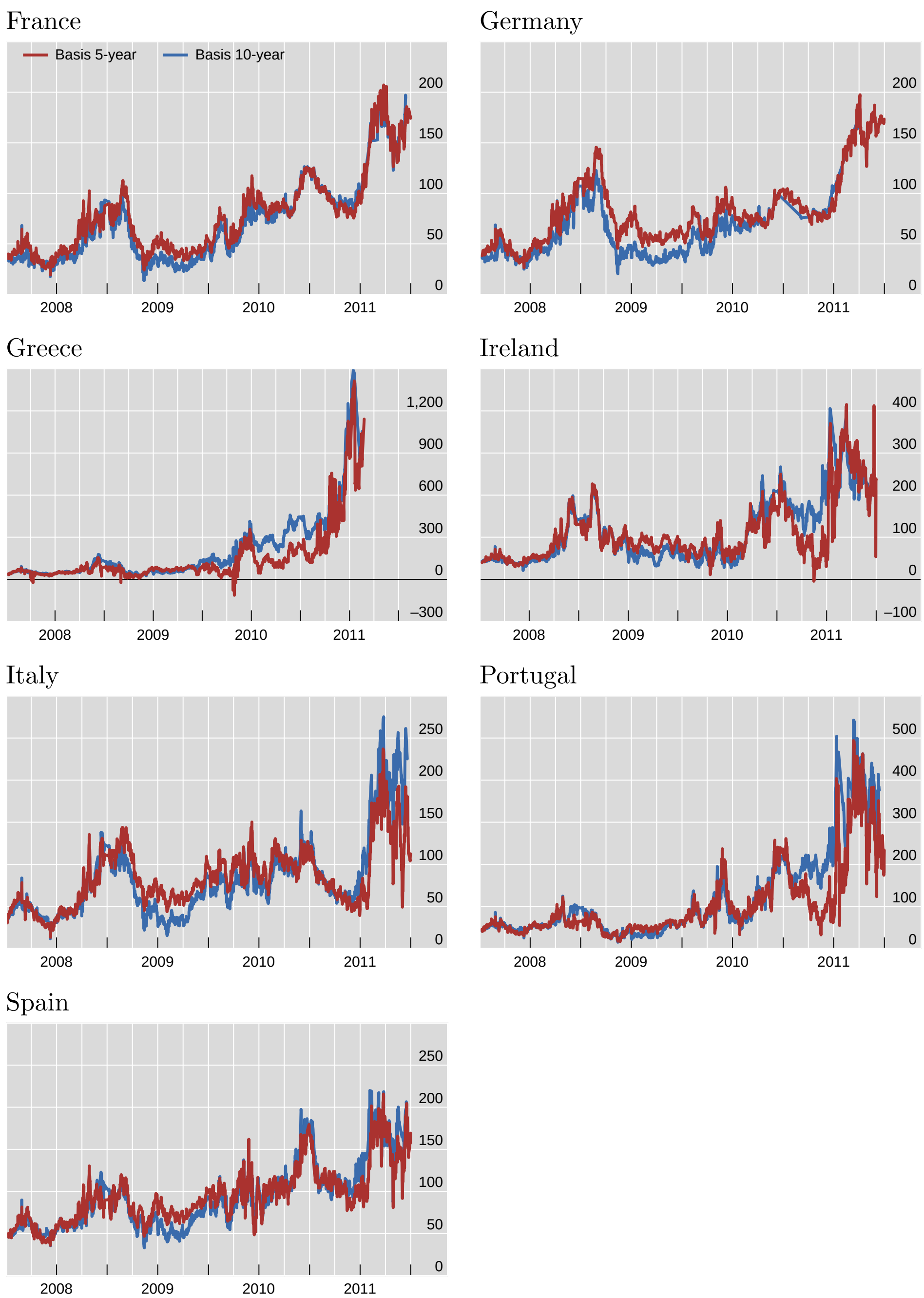
When implementing our analysis we split the data into two sub-samples. The first sub-sample covers the period January 2008 to end-March 2010, and as such represents the period prior to the euro area sovereign debt crisis (van Rixtel and Gasperini; 2013). While this period includes the most severe phase of the financial crisis, including the default of Lehman Brothers, it is relatively unaffected by any major market concerns about the sustainability of public finances in euro area countries. The second sub-sample covers the euro area sovereign debt crisis period and runs from April 2010 to December 2011.

In order to accurately match the maturities and the cash flow structures of the CDS and the cash components for the measurement of the CDS-bond basis, we calculate intraday asset swap (ASW) spreads based on estimated zero-coupon government bond prices according to Nelson and Siegel (1987). The use of ASW spreads is also in line with the practice used in commercial banks when trading the CDS-bond basis. By calculating ASW spreads we ensure that we are comparing "apples with apples" in our empirical analysis, and we avoid introducing distortions by using imperfect cash spread measures, such as simple "constant maturity" yield differences. For an in-depth discussion on the construction of our intraday ASW, see Gyntelberg et al. (2013) and for a general discussion see O'Kane (2000). Finally, we note that using intraday data in our empirical analysis enables us to obtain much sharper estimates and clearer results with respect to market mechanisms and price discovery compared to any analysis carried out with a lower data frequency (see Gyntelberg et al. (2013)).

Using the above methodology, we derive the intraday asset swap spreads for each country for the 5- and 10-year maturities (displayed in Appendix A). The corresponding CDS-bond basis are shown in Figure 1.

Figure 1: CDS-ASW basis

The basis is the difference between the CDS spread and the ASW spread expressed in basis points for the period from January 2008 until December 2011. The figure shows data with 30 minute sampling frequency. Due to the Greek debt restructuring the data for Greece ends in September 2011.



4 Threshold vector error correction model (TVECM)

Analysis of the statistical properties of our spread time series show that they are I(1) and that the CDS and ASW series are cointegrated (see also Gyntelberg et al. (2013) for detailed statistical test results). As a result, we can employ the VECM methodology to study the joint price formation process in both markets. The VECM concept implies that every small deviation from the long-run equilibrium leads instantaneously to an error correction mechanism. From the estimated error correction model one can then calculate measures that indicate which of the two markets is leading the price discovery process. Two VECM-based measures are used to assess the contributions to price discovery: i) the information share or Hasbrouck (1995) measure (HAS) and ii) the common factor component weight or Gonzalo and Granger (1995) measure (GG). We also compute the half-lives of shocks from the error correction models based on the speed of adjustment of the two time-series.

We extend the common VECM approach[2] to a threshold vector error correction model (TVECM). Threshold cointegration was introduced by Balke and Fomby (1997) as a feasible means to combine regime switches and cointegration. The TVECM model allows for nonlinear adjustments to the long-term equilibrium in CDS and bond markets. Enders (2010) argues that if the basis is lower than the cost of undertaking an arbitrage trade based on the observed basis, then there is no incentive to carry out the trade. Only when the deviation from the long-term equilibrium exceeds a critical threshold, such that the expected profit exceeds the costs, will economic agents act to move the basis back towards its long-term equilibrium (Balke and Fomby; 1997). As a result, adjustments to the long-term equilibrium are likely to be regime-dependent, with a relatively weak adjustment mechanism below the threshold (a 'neutral' regime) and a stronger mechanism above it.

The TVECM approach extends the VECM by allowing the behaviour of y_t to depend on the state of the system. One can formulate a general TVECM as follows[3]:

$$\Delta y_t = \lambda^j \beta^\mathsf{T} y_{t-1} + \Gamma^j(L)\Delta y_t + \varepsilon_t \qquad \text{if } \theta^{j-1} < \beta^\mathsf{T} y_{t-1} \leq \theta^j. \tag{1}$$

$y_t = (CDS_t \quad ASW_t)^\mathsf{T}$ is a vector of price quotes for CDS and asset swap spreads (ASW) at time t for a specific sovereign, while $\varepsilon_t = (\varepsilon_t^{CDS} \quad \varepsilon_t^{ASW})^\mathsf{T}$ is a vector of i.i.d. shocks and $j \in \{1, 2, ..., l\}$ are the regimes. Equation (1) constitutes a vector autoregressive model in first-order difference with $\Gamma^j(L) = \sum_{k=1}^{p} \alpha^{j,k} L^k$ and L as lag operator, p as number of VAR lags, and an additional error correction term $\beta^\mathsf{T} y_{t-1}$. This error correction term represents the long-term equilibrium of the two time series which has to be an AR(1) process by construction (Johansen; 1988). The error correction term would be equal to

[2] As in e.g. Gyntelberg et al. (2013), Blanco et al. (2005), and Fontana and Scheicher (2010).

[3] for a derivation of the TVECM see for example Balke and Fomby (1997)

our CDS-bond basis if $\beta_0 = 0$ and $\beta_1 = 1$. The VAR-term represents the short-run dynamics coming from market imperfections (Baillie et al.; 2002). The error correction term $\beta^\intercal y_{t-1} = (CDS_{t-1} - \beta_0 - \beta_1 ASW_{t-1})$ denotes the deviation from the long-term equilibrium and is motivated by our no-arbitrage discussion in Section 2 as β_0 represents a persistent non-zero basis. The speed of adjustment parameters $\lambda^j = (\lambda_1^j \quad \lambda_2^j)^\intercal$ and the lagged VAR terms are regime-dependent conditioned on the state of the error correction term $\beta^\intercal y_{t-1}$.

The speed of adjustment parameters characterize to what extent the price changes in $\Delta y_t = (\Delta CDS_t \quad \Delta ASW_t)^\intercal$ react to deviations from the long-term equilibrium. In case price discovery takes place only in the bond market we would find a negative and statistically significant λ_1^j and a statistically insignificant λ_2^j, as the CDS market would adjust to correct the pricing differentials from the long-term relationship. In other words, in this case the bond market would move ahead of the CDS market as relevant information reaches investors. Conversely, if λ_1^j is not statistically significant but λ_2^j is positive and statistically significant, the price discovery process takes place in the CDS market only - that is, the CDS market moves ahead of the cash bond market. In cases where both λ's are significant, with λ_1^j negative and λ_2^j positive, price discovery takes place in both markets.

In our data, the basis for all reference entities is almost always positive. Hence, we expect to find at most two regimes ($l = 2$) with one threshold θ. The lower regime (neutral regime) is defined as $\beta^\intercal y_{t-1} \leq \theta$, and the upper regime as $\beta^\intercal y_{t-1} > \theta$.

The TVECM model in Equation (1) may for a two-regime TVECM be written as:

$$\Delta y_t = \left[\lambda^1 \beta^\intercal y_{t-1} + \Gamma^1(L)\Delta y_t\right] d_{1t}(\beta, \theta) + \left[\lambda^2 \beta^\intercal y_{t-1} + \Gamma^2(L)\Delta y_t\right] d_{2t}(\beta, \theta) + \varepsilon_t \qquad (2)$$

where

$$d_1 t(\beta, \theta) = I(\beta^\intercal y_{t-1} \leq \theta)$$
$$d_2 t(\beta, \theta) = I(\beta^\intercal y_{t-1} > \theta)$$

and $I(\cdot)$ denotes the indicator function.

We expect to find the speed of adjustment parameters to indicate that arbitrageurs exploiting CDS-ASW basis trade if the basis exceeds the threshold θ. In a market with a positive basis (CDS > ASW), arbitrageurs bet on a declining basis and will short credit risk in the bond market and go long credit risk in the CDS market, i.e. sell the bond *and* sell the CDS (Gyntelberg et al.; 2013). In case of a negative basis (ASW > CDS), arbitrageurs bet on an increasing basis while carrying out the reverse trade. In markets where the basis regularly would fluctuate between being poitive and negative, we would expect to find a 3-regime TVECM. With a lower regime $\beta^{\intercal} y_{t-1} < \theta^1$, a middle regime (neutral regime) $\theta^1 < \beta^{\intercal} y_{t-1} \leq \theta^2$, and a upper regime $\theta^2 \leq \beta^{\intercal} y_{t-1}$. As mentioned, given the fact that the basis is consistently positive in our sample, we only focus on the 2-regime TVECM set-up.

From the speed of adjustments we compute the HAS and GG measures of price discovery for each regime. As pointed out by de Jong (2001) neither method can be considered universally superior as both measures are closely related by definition. However, only the information share or Hasbrouck measure (HAS) takes into account the variability of the innovations in each market's price. From Equation (1) we calculate the independent set of values HAS_1 and HAS_2 for each regime. HAS and GG measures greater than 0.5 imply that more than 50% of the price discovery occurs in the CDS market. When the measures are close to 0.5 both markets contribute equally to price discovery without evidence on which market is dominant. GG and HAS below 0.5 suggest price leadership for the bond market. For thorough discussion see Man and Wu (2013) or Gyntelberg et al. (2013).

Finally, we are interested in examining the speed of adjustment towards the long-term equilibrium in each regime. As the CDS and ASW spreads in the bivariate VECM share a common stochastic trend, the impulse response function for the cointegrating residual can be used to determine the speed of adjustment to the long-run equilibrium (Zivot and Wang (2006)). The vector error correction mechanism directly links the speed of adjustment of CDS and ASW spreads to the regime dependent cointegrating error u_t^j which follows an implied AR(1) process:

$$u_t^j = (1 + \lambda_1^j - \beta_1 \lambda_2^j) u_{t-1}^j + \varepsilon_t^{CDS} - \beta_1 \varepsilon_t^{ASW} \equiv \phi^j u_{t-1}^j + \varepsilon_t^{CDS} - \beta_1 \varepsilon_t^{ASW} . \tag{3}$$

The half-life of a shock for each regime, n^j, can now be calculated from the AR(1) coefficient ϕ^j as:

$$n^j = \frac{ln(0.5)}{ln(\phi^j)} . \tag{4}$$

4.1 Estimating the threshold

As discussed in Section 4, the positive basis in our sample suggests the presence of at most one threshold. In order to test for the presence of a threshold effect, we follow the method proposed by Hansen and Seo (2002) who extend the literature by examining the case of an unknown cointegrating vector.[4] They implement maximum likelihood estimation (MLE) of a bivariate TVECM with two regimes. Their algorithm involves a joint grid search over

[4] Balke and Fomby (1997) and Tsay (1989) transform the TVECM specification into a univariate regression while the cointegrating vector is known a priori.

the threshold and the cointegrating vector while using the error-correction term as the threshold variable (see Equation (1)).

In the TVECM in Equation (2) all coefficients are allowed to switch between these two regimes. Only the cointegrating vector β remains fixed across all regimes, by construction.

As in Hansen and Seo (2002) we estimate the model while imposing the following additional constraint:

$$\pi_0 \leq P(\beta^{\mathsf{T}} y_{t-1} \leq \theta) \leq 1 - \pi_0 \tag{5}$$

where $\pi_0 > 0$ is a trimming parameter and P is the percentage of observations in each regime. This constraint allows us to identify a threshold effect only if the percentage of observations in each regime is greater than π_0. If this condition is not met, the model reduces to a linear VECM.

Andrews (1993) argues that setting π_0 between 0.05 and 0.15 are typically good choices. As we use intraday data of the order of 10000 observations, we set the trim to $\pi_0 = 0.05$, which will still ensure an adequate number of observations in both regimes. As a robustness check, we also use a trim of $\pi_0 = 0.10$ (see Appendix F).

The maximum likelihood estimator (MLE) $(\hat{\lambda}^1, \hat{\lambda}^2, \hat{\Sigma}, \hat{\beta}, \hat{\theta})$ are the values which maximize $\mathscr{L}_n(\lambda^1, \lambda^2, \Sigma, \beta, \theta)$. For computational reasons, Hansen and Seo (2002) suggest to hold (β, θ) fixed and compute the constrained MLE for $(\lambda^1, \lambda^2, \Sigma)$, which corresponds to a grid search over a 3-dimensional space $(\beta_0, \beta_1, \theta)$.

To implement the estimation, we follow the approach of Hansen and Seo (2002) and sort the values of the observations on the threshold variable, which is the error correction term $\beta^{\mathsf{T}} y_{t-1}$. We set $\hat{\Sigma} = \hat{\Sigma}(\hat{\beta}, \hat{\theta})$, $\hat{\lambda}^1 = \hat{\lambda}^1(\hat{\beta}, \hat{\theta})$, $\hat{\lambda}^2 = \hat{\lambda}^2(\hat{\beta}, \hat{\theta})$, and $\hat{\varepsilon}_t = \hat{\varepsilon}_t(\hat{\beta}, \hat{\theta})$. For each value of (θ, β) on the grid, we calculate $\hat{\lambda}^1, \hat{\lambda}^2$, and $\hat{\Sigma}$. The grid search is performed conditional on $\pi_0 \leq n^{-1} \sum_{t=1}^{n} I(\beta^{\mathsf{T}} y_{t-1}) \leq 1 - \pi_0$ to impose the constraint in Equation (5). The remaining N values of the observations of the threshold variable $\beta^{\mathsf{T}} y_{t-1}$ constitue the values of θ which can be searched for $\hat{\theta}$. For the grid, Hansen and Seo (2002) suggest to choose a region over which to search by calibration on the consistent estimate of $\hat{\beta}$ obtained from the linear VECM and constructing a large confidence interval $[\beta_L, \beta_U]$. In addition, we also search over a grid around the theoretical basis $\beta_1 = 1$ and $\beta_0 = 0$. The grid search examines all combinations of (β, θ) conditional on the constraint in Equation (5). The value of the evenly spaced grid search that yields the largest value of $\log \hat{\Sigma}(\beta, \theta)$ is the consistent estimate of $\hat{\theta}$. We employ 150 gridpoints for our grid search, but we also experimented with more and fewer gridpoints. Our results are extremely robust to the gridsize.

4.2 Testing for a threshold

Once a threshold has been identified, the next step is to determine whether the estimated threshold $\hat{\theta}$ is statistically significant. Under the null hypothesis, there is no threshold, so the model reduces to a conventional linear VECM where $\lambda^1 = \lambda^2$. The two regime TVECM is the alternative hypothesis $\mathscr{H}_1$ with $\lambda^1 \neq \lambda^2$ under constraint in Equation (5). The linear VECM under the $\mathscr{H}_0$ is nested in Equation (2), hence, a regular LM test with an asymptotic $\chi^2(N)$-distribution can be calculated based on Equation (2). However, the LM test can only be applied if the cointegrating vector β and the threshold variable θ are known a priori (Hansen and Seo; 2002). While the point estimate under the $\mathscr{H}_0$ of β is $\hat{\beta}$ from the linear model, there is no estimate of θ under the $\mathscr{H}_0$. This implies that there is no distribution theory for the parameter estimates and no conventionally defined LM statistic.

Following Hansen and Seo (2002) we employ a supremum LM statistic based on the union-intersection principle, proposed by Davies (1987):

$$\text{SupLM} = \sup_{\theta_L \leq \theta \leq \theta_U} LM(\hat{\beta}, \theta) \tag{6}$$

According to the constraint in Equation (5) we set the search region $[\theta_L, \theta_U]$ that θ_L is the π_0 percentile of $\hat{\beta}^{\mathsf{T}} y_{t-1}$, and θ_U is the $(1 - \pi_0)$ percentile. This grid evaluation over $[\theta_L, \theta_U]$ is necessary to implement the maximization defined in Equation (6) as the function LM$(\hat{\beta}, \theta)$ is non-differentiable in θ.

We follow Hansen and Seo (2002) and perform two different bootstrap methodologies in order to estimate the asymptotic distribution for our model specification in Equation (1). First, we implement a non-parametric bootstrap on the residuals, called the "fixed regressor bootstrap", which resamples (Monte-Carlo) the residuals from the estimated linear VECM. The second bootstrap methodology, called "residual bootstrap", is parametric. Here, it is assumed, that the residuals are i.i.d. Gaussian from an unknown distribution with fixed initial conditions. The parametric bootstrap then calculates the sampling distribution of the supremum LM test in Equation (6) using the parameter estimates obtained under $\mathscr{H}_0$. The distribution is bootstrapped using Monte-Carlo simulations from the residual vector under $\mathscr{H}_0$ while the vector series y_t are created by recursion given the linear VECM model.

According to Hansen and Seo (2002) neither of these two proposed methods is considered superior. We consider our model as threshold cointegrated if we can reject the null hypothesis of a linear VECM by either the "residual bootstrap" or the "fixed regressor bootstrap" methodology.

5 Main results

In this section we first present results for the period before the euro area sovereign debt crisis. These are followed by our findings using the debt crisis period.

As a general result, we find a functioning relationship between the CDS and the ASW during the first sub-sample. In cases where we find threshold cointegration, the adjustment process towards the long-term equilibrium is faster in the upper regime compared to the lower regime, in line with our reasoning on the behaviour of arbitrageurs. As expected we find more thresholds for the 10-year tenor in the pre-crisis period, because less liquid markets have more frictions and thus are more likely to exhibit multi-regime behaviour. For the second sub-period (sovereign debt crisis) our results show strong indications that the CDS and ASW markets became dysfunctional.

5.1 Results for the pre-debt-crisis period

The results for the first sub-sample from January 2008 to end-March 2010, i.e. prior to the euro area sovereign debt crisis, confirm our assumption that arbitrage trading intensifies in CDS and bond markets once some basis threshold is exceeded. In the lower (neutral) regime we find as expected either no adjustment dynamics, or speed of adjustments that are much smaller in magnitude than in the upper regime. The price discovery results for the 5-year and 10-year tenor with 5% trim are presented in Table 1. As a robustness test we present results with a 10% trim in Appendix F, which show that our results are robust with regard to the trim. For the 5-year tenor, we fail to find any threshold effect for most countries. By contrast, we do find threshold cointegration for the majority of countries in the 10-year tenor. This result confirms our hypothesis that the more illiquid a market is, the higher are the frictions, and the more likely are we to find non-linear multi-regime behaviour.

Our results are also supportive of our hypothesis regarding arbitrageurs behaviour in markets with frictions. We find faster adjustments towards the long-term equilibrium in the upper regime compared to the lower regime for the 10-year tenor. For the 5-year tenor we find no adjustment dynamics in the lower regime. Furthermore, the half-life of any basis widening is significantly shorter in the upper regime compared to the lower regime. This suggests that arbitrage trading activity is much higher in the upper regime and therefore pricing differences due to credit risk shocks are reabsorbed much faster once the threshold is exceeded (Table 2). Typically, the upper regime can be viewed as an extreme regime as the bulk of observations is in most cases concentrated in the lower (neutral) regime.

In general, we find that the CDS market leads the price discovery process for sovereign credit risk in both regimes as displayed in Figures 2 and 3 with HAS and GG ratios that are significantly above 0.5 in most cases. Spain is an exception, where in the lower regime for the 10-year tenor the adjustment dynamics is driven by both the CDS and the bond market. However, once the threshold is exceeded the CDS market is found to lead in terms of the pricing of credit risk.

The only case for which the results are not in line with our expectations is the 10-year tenor for Ireland, where we find a slower adjustment process in the upper regime compared to the lower regime. This can be explained by the fact that, in contrast to most other countries, the estimated upper regime in Ireland is the 'normal' regime, since it contains around 90% of all observations. The same is true for the 5-year German case, but here the relative speed of adjustment is as expected.

The inference for the TVECM results for the pre-crisis period are based on asymptotic standard errors, which should be reliable given that we have approximately 10000 observations for each time series. Nevertheless, we also employ a standard bootstrap method as described in Benkwitz et al. (1999), where we use 100,000 Monte-Carlo simulations to generate 95% confidence bands for the λ^j parameters, as well as the HAS and GG measures in each regime (see Appendix E). The bootstrapped results for the pre-crisis period are overall in agreement with the asymptotic results.

Table 1: Price discovery TVECM - pre-crisis period

This table reports the price discovery analysis for intraday data on a 30 minutes sampling frequency from the TVECM according to our specification of Equation (2) with $\mu^j = 0$ and $\beta = (\beta_0 \quad \beta_1)^\mathsf{T}$ for the period from January 2008 to end-March 2010 with 5% trim for the 5- and 10-year tenor. The superscript ^{a} indicates that the GG measure has to be interpreted as 1, because the VECM coefficient λ_1 is not significant; the superscript ^{b} indicates that GG has to be interpreted as 0, because λ_2 is not significant. The values of the VECM coefficients λ^j are expressed in units of 10^{-4}. In case of no significance of both λ^j coefficients in a regime, we do not report VECM based HAS and GG measures.

Panel A - 5-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Germany	-35.2	0.87	0.84	0.77	12.1	0.05	-41.0	0.00	94.4%
Portugal	63.9	0.27	0.00	-0.49^b	-71.9	0.07	-23.7	0.29	5.3%

lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Germany				-6.8	0.52	-0.8	0.50	5.6%
Portugal				8.8	0.42	22.8	0.12	94.7%

Panel B - 10-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Greece	44.5	0.53	0.72	0.50^a	-55.6	0.21	56.3	0.09	5.3%
Ireland	-33.3	0.86	0.85	0.63^a	-11.0	0.14	18.7	0.00	94.3%
Italy	2.2	0.84	0.84	1.18^a	18.3	0.14	122.2	0.08	14.2%
Portugal	28.2	1.00	1.00	1.01^a	1.5	0.90	174.8	0.05	5.4%
Spain	53.8	0.88	0.83	1.23^a	4.8	0.29	26.1	0.01	13.0%

lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Greece	0.89	0.91	0.76^a	-15.2	0.22	47.9	0.00	94.7%
Ireland	0.85	0.95	1.97^a	25.3	0.32	51.2	0.00	5.7%
Italy	0.83	0.86	0.68^a	-2.7	0.25	5.9	0.01	85.8%
Portugal	0.52	0.54	0.50^a	-5.6	0.12	5.7	0.07	94.6%
Spain	0.54	0.56	0.52	-17.7	0.00	19.5	0.01	87.0%

Table 2: Half-life of shocks in days - pre-crisis period

This table reports the half-life of shocks of 5-year and 10-year CDS and ASW for the period from January 2008 to end-March 2010 with 5% trim. The half-lives of shocks are expressed in days, and are calculated using the impulse response function to a one unit shock on the cointegrating error, using Equations 3 and 4. In case of no significance of both λ_i coefficients in a regime, we do not report the VECM based half-life of shocks.

Panel A: 5-year tenor

Sovereign	lower	upper
Germany		2.9
Portugal		5.3

Panel B: 10-year tenor

Sovereign	lower	upper
Greece	5.1	4.4
Ireland	3.4	9.5
Italy	21.1	1.0
Portugal	25.5	0.8
Spain	5.0	4.8

Figure 2: Impulse response functions for 5-year tenor - pre-crisis period, 5% trim

This figure illustrates the impulse response for CDS and ASW to a one unit shock on the co-integrating error for the period from January 2008 to end-March 2010 for the lower regime (left-hand panel) and the upper regime (right-hand panel). The vertical lines represent the half-life of shocks while the number days are described by the x-axis. The blue and yellow lines are the speed of adjustment for the ASW and CDS. When only one of the error correction coefficients is significant, the corresponding non-significant variable will adjust instantaneously to its long-run equilibrium level. This is represented by a horizontal line after the instantaneous adjustment. The red line plots the response of the system towards its long-run equilibrium.

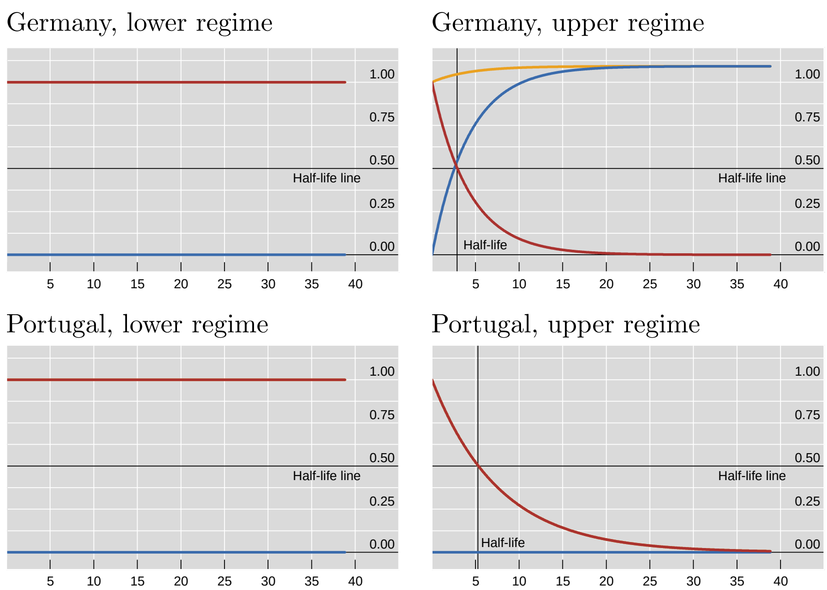
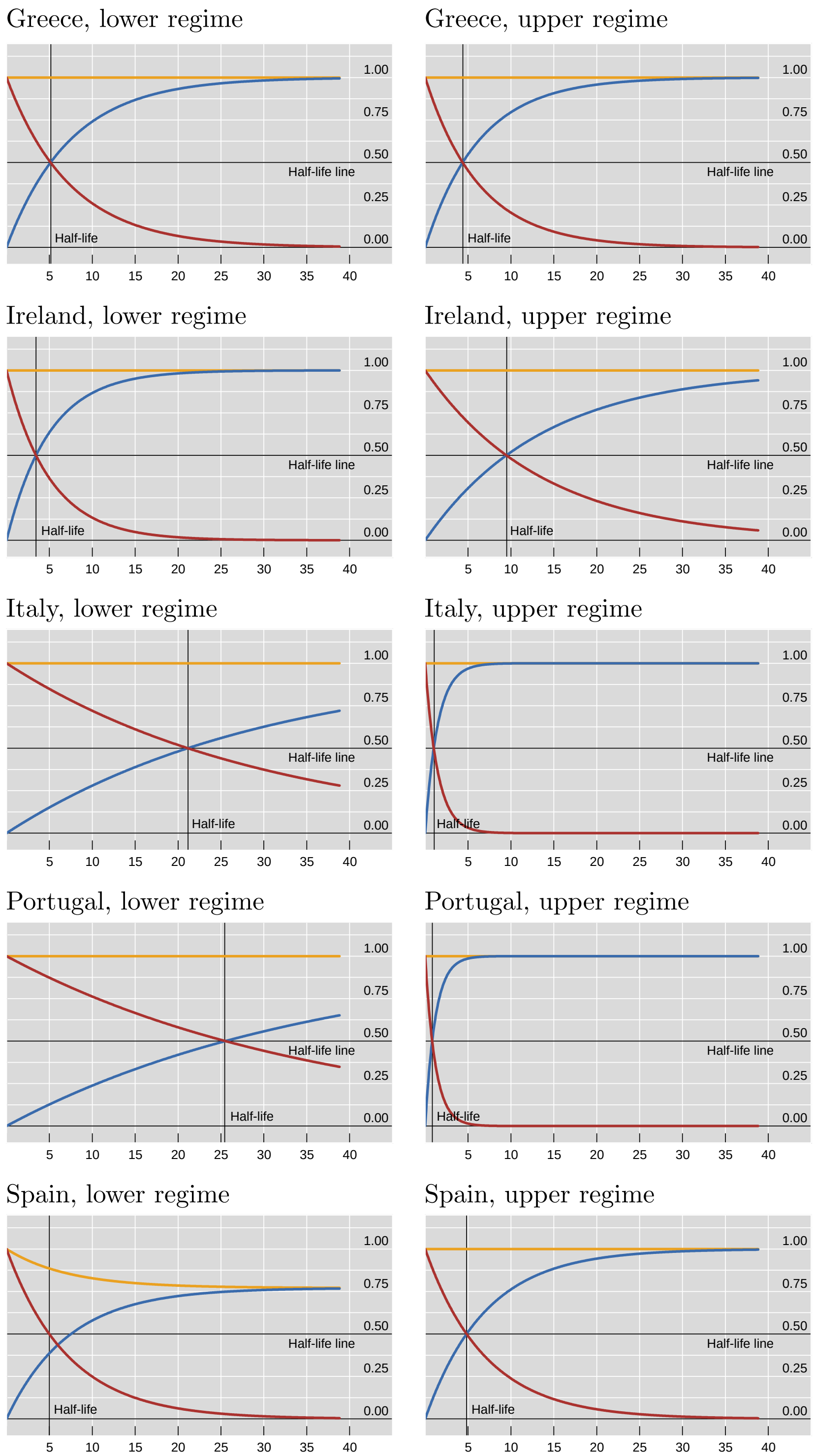


Figure 3: Impulse response functions for 10-year tenor - pre-crisis period, 5% trim

For details see Figure 2



5.2 Results for the euro area sovereign debt crisis period

The results for the euro area sovereign debt crisis period that spans from April 2010 to end-December 2011 show that markets became dysfunctional as the crisis deepened. As a result, we obtain counterintuitive reults in a number of cases, as shown in Table 3. These include significant λ_2 coefficients with the wrong sign in the upper regime (Portugal, 10-year) or evidence of no adjustment in the upper regime (France, 5-year). If the speed of adjustment parameter is of the wrong sign, this means that the ASW moves away from the long-term equilibrium when exceeding the threshold. In other words, as the crisis intensified, the basis continued to widen even though it was already at high levels, possibly reflecting a break-down in normal market functioning.

The only case where we can confirm our theoretical assumption about arbitrage forces in markets with frictions is for the 10-year tenor in France. We find much faster adjustment dynamics towards the long-term equilibrium in the upper regime with shorter half-lives of shocks compared to the lower regime. Price discovery in the lower regime is driven by the bond market while we find CDS leadership in the upper regime.

During the crisis period we cannot make a general conclusion on which market is typically leading in the price discovery for credit risk as we find mixed results. For the 5-year tenor, we find strong CDS leadership in France (lower regime) and Italy (upper regime). In the upper regime for the 5-year tenor in Ireland we find that the bond market leads in the price discovery of credit risk. All half-lives and impulse response functions are displayed in Figures 4 and 5.

Given the high credit spread volatility during the crisis period, we employ the same standard bootstrap method as described in the previous Section 5.1 based on (Benkwitz et al.; 1999). The bootstrapped results in Appendix E confirm the asymptotic results on distorted markets during the crisis period.

Table 3: Price discovery TVECM - crisis period

This table reports the price discovery analysis for intraday data on a 30 minutes sampling frequency from the TVECM for the period from April 2010 to end-December 2011 with 5% trim for the 5- and 10-year tenor. For futher details see Table 1.

Panel A - 5-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	73.1				-1.5	0.89	8.8	0.30	5.0%
Ireland	163.4	0.13	0.18	0.40^b	-50.6	0.01	34.1	0.26	5.0%
Italy	30.7	0.98	0.97	1.29^a	8.4	0.74	38.0	0.04	5.3%

lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	0.76	0.87	0.78^a	-3.7	0.48	12.8	0.08	95.0%
Ireland	0.57	0.51	2.75	-14.7	0.01	-23.0	0.01	95.0%
Italy				-7.8	0.38	3.8	0.66	94.7%

Panel B - 10-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	25.6	0.96	1.00	0.94^a	-2.0	0.92	32.3	0.01	14.0%
Portugal	108.7	1.00	0.95	0.81^a	21.5	0.66	-89.1	0.08	6.0%

lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	0.15	0.15	-1.07^b	-8.9	0.02	-4.6	0.36	86.0%
Portugal				-57.5	0.14	24.2	0.47	94.0%

Table 4: Half-life of shocks in days - crisis period

This table reports the half-life of shocks of 5-year and 10-year CDS and ASW for the period from April 2010 to end-December 2011 with 5% trim. For futher details see Table 2. Negative half-lives are meaningless as they represent a market dysfunction because markets move away from the long-term equilibrium condition.

Panel A: 5-year tenor

Sovereign	lower	upper
France	10.1	
Ireland	-74.0	7.6
Italy		6.6

Panel B: 10-year tenor

Sovereign	lower	upper
France	43.3	12.4
Portugal		-3.5

Table 4, shows several half-lives with negative sign. The reasons behind are speed of adjustments and a cointegrating error with wrong signs. These results show explicitly that the markets during the period with crisis are dysfunctional and hence will be discarded. In the following figures of the impulse response function we will ignore countries which have a significant threshold, but the results do not hint towards a functioning threshold VECM.

Figure 4: Impulse response functions for 5-year tenor - crisis period, 5% trim

This figure illustrates the impulse response for CDS and ASW to a one unit shock on the co-integrating error for the period from April 2010 to end-December 2011 for the lower regime (left-hand panel) and the upper regime (right-hand panel). The vertical lines represent the half-life of shocks while the number days are described by the x-axis. The blue and yellow lines are the speed of adjustment for the ASW and CDS. When only one of the error correction coefficients is significant, the corresponding non-significant variable will adjust instantaneously to its long-run equilibrium level. This is represented by a horizontal line after the instantaneous adjustment. The red line plots the response of the system towards its long-run equilibrium. The lower regime for the 5-year tenor in Ireland is not displayed as it exhibits a negative half-life. Negative half-lives are meaningless as they represent a market dysfunction because markets move away from the long-term equilibrium condition.

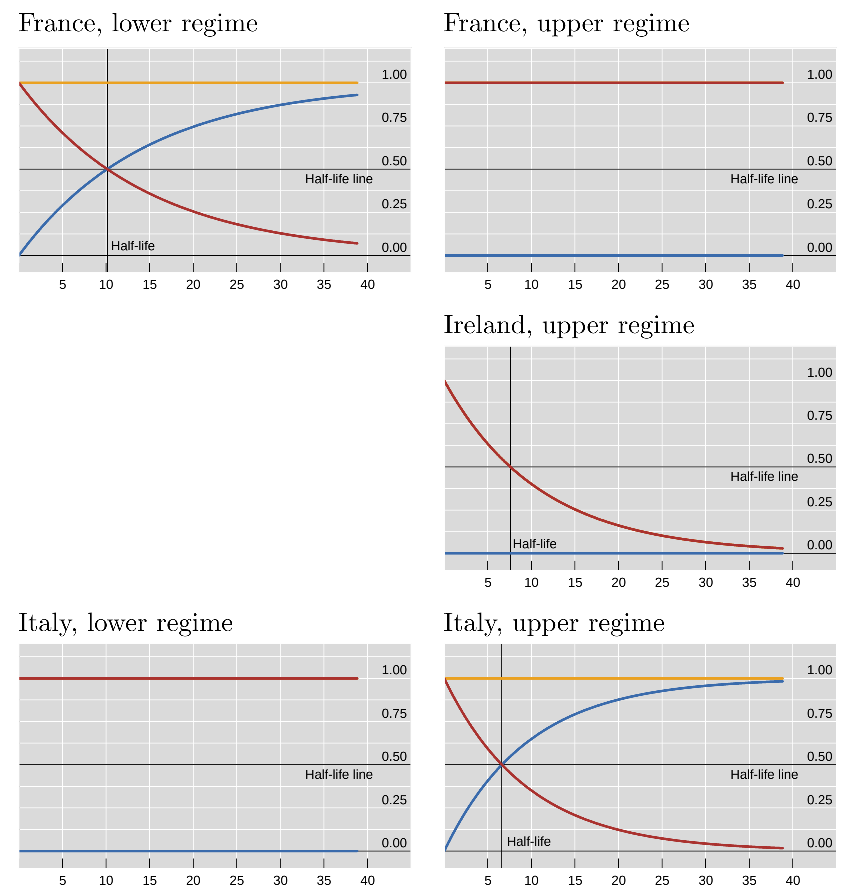
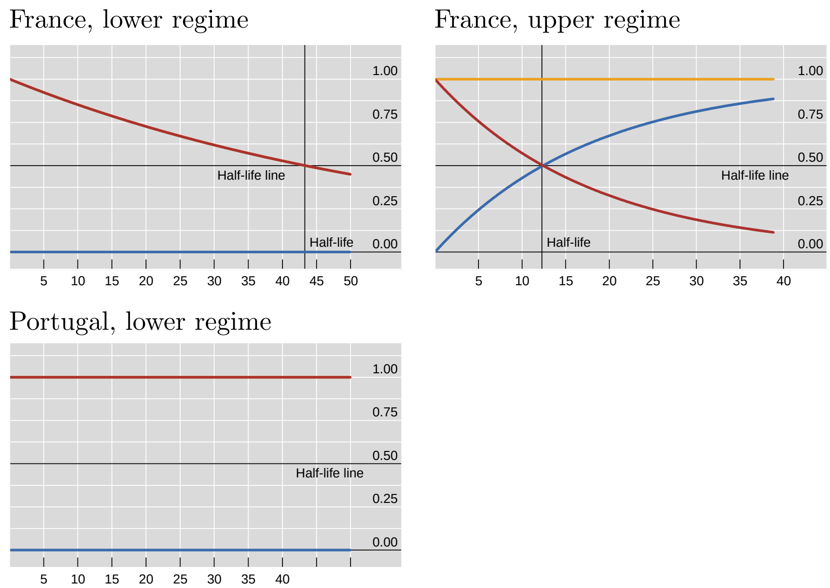


Figure 5: Impulse response functions for 10-year tenor - crisis period, 5% trim

The upper regime for the 10-year tenor in Portugal is not displayed as it exhibits a negative half-life. Negative half-lives are meaningless as they represent a market dysfunction because markets move away from the long-term equilibrium condition. For details see Figure 4.



6 Conclusion

A persistent positive basis between CDS and sovereign bond spreads in the euro area points to the presence of liquidity frictions that prevent a complete adjustment of market prices to the theoretical no-arbitrage condition of a zero basis. Using a TVECM approach with intraday data, we show that the adjustment process towards the long-run equilibrium intensifies once the CDS-bond basis exceeds a certain level. Specifically, we find much faster adjustment dynamics towards the long-term equilibrium once the estimated threshold is exceeded (upper regime) compared to the lower regime. Furthermore, the half-life of any basis widening is significantly shorter in the upper regime compared to the lower regime. This indicates that arbitrageurs step in and carry out basis trades only when the the expected gain from the arbitrage trade is greater than the cost of the transaction.

In line with evidence using linear VECM models (Gyntelberg et al. (2013)), we find that the CDS market generally leads in the price discovery process for credit risk in euro area sovereign credit markets.

We also find more threshold cointegrated cases for the less liquid 10-year tenor than for the 5-year tenor. This is in line with the notion that the more illiquid a market is, the higher are the frictions and the more likely it is that the adjustment process is non-linear. Furthermore, we show that typically the observed basis is lower than the estimated threshold most of the time. On average, the basis exceeds the estimated threshold less than 20% of all observations in the 10-year tenor.

However, these findings generally hold only prior to the recent euro area sovereign debt crisis (2008 - March 2010). During the subsequent debt crisis period (April 2010 - end-2011), our results instead suggest that normal market mechanisms essentially broke down as the crisis intensified and liquidity largely dried up in peripheral sovereign credit markets. As a result, we find instances of either no significant adjustment towards equilibrium in the upper regime or that the estimated adjustment goes in the wrong direction: already high basis levels tend to widen even more subsequently. Hence, with liquidity in markets increasingly drying up as the crisis deepened, normal arbitrage activity also stalled in euro area sovereign credit markets.

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A CDS and ASW spreads

Figure A.1: CDS and ASW spreads in basis points

The figures are based on data with a 30 minute sampling frequency.

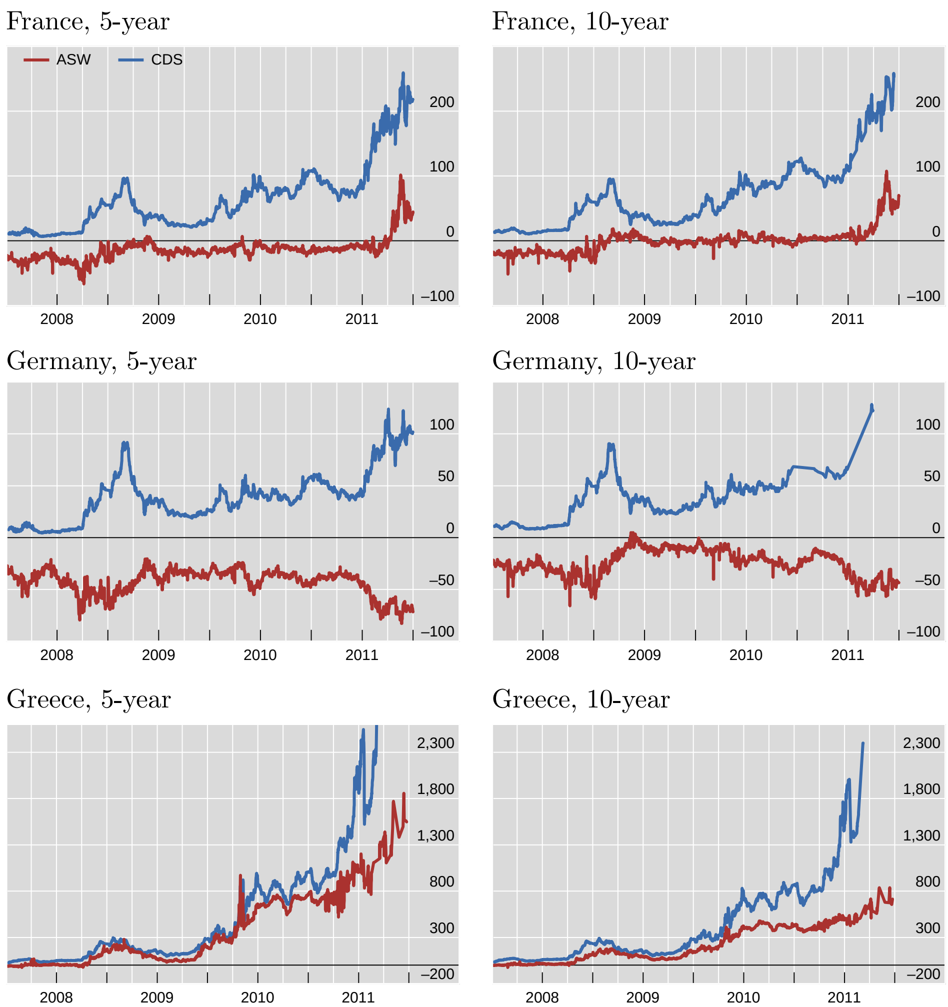
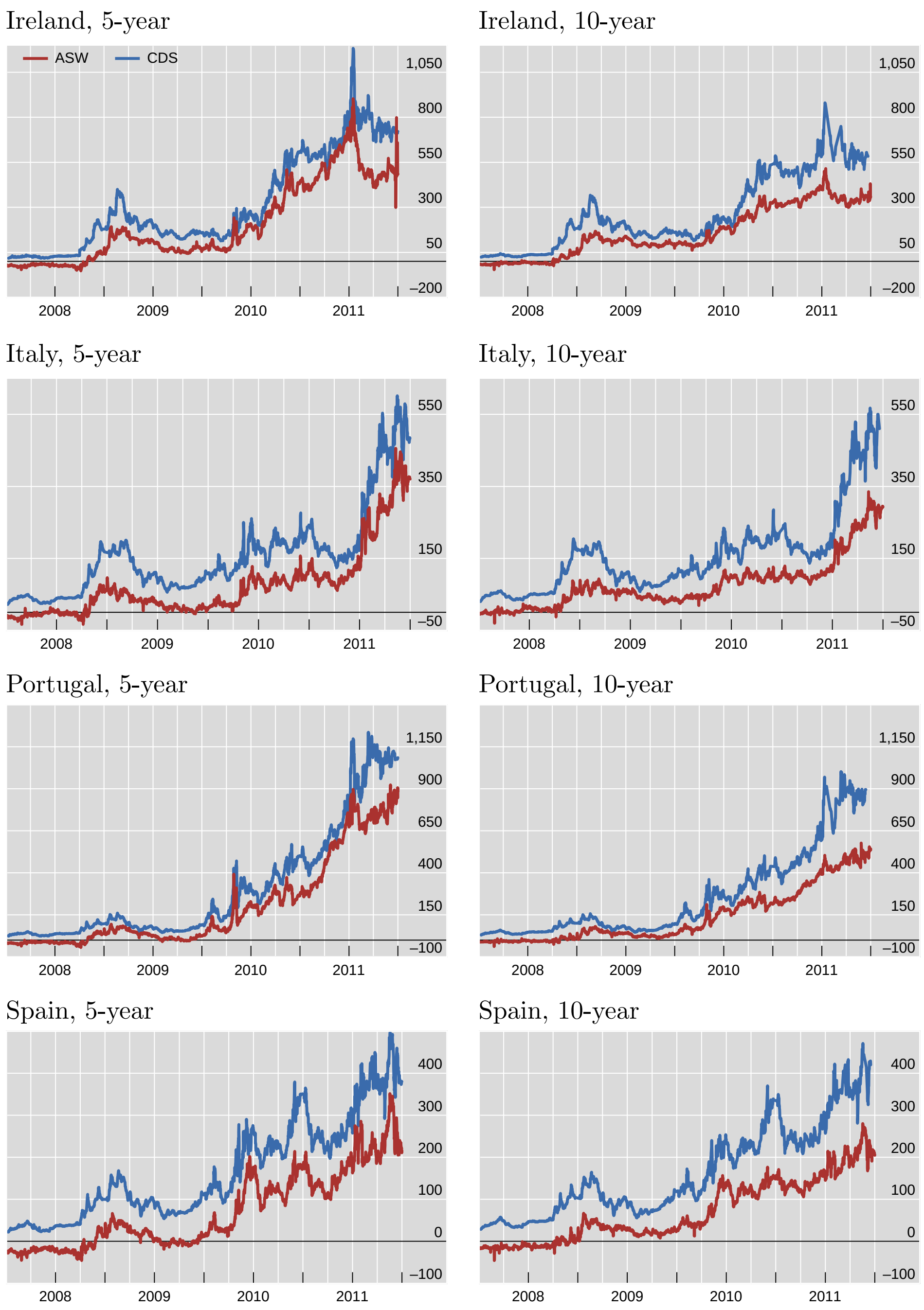


Figure A.1: (Cont.) CDS and asset swap spreads



B Optimal lag length - TVECM

We employ the Schwarz (Bayesian) information criterion (SIC) to determine the VAR order in our TVECM.

For robustness, we test for the optimal TVECM lag length with a trim of 5% and 10% and find that the optimal lag length is extremly robust to the trim selection.

Table B.1: Optimal lag length TVECM - Schwarz criterion

This table reports the number of Schwarz (Bayesian) information criteria (SIC) lags for the TVECM for the 5- and 10-year tenor for the pre-crisis and the crisis sample.

	pre-crisis period		crisis period	
Sovereign	5-year	10-year	5-year	10-year
France	4	1	5	1
Germany	4	3	1	4
Greece	1	1	18	7
Ireland	18	3	6	2
Italy	3	2	4	13
Portugal	3	2	18	10
Spain	5	2	4	18

C Threshold test

In order to estimate the asymptotic distribution as discussed in Section 4.2 we follow Hansen and Seo (2002) and implement a non-parametric bootstrap on the residuals, called the ”fixed regressor bootstrap”, which resamples (Monte-Carlo) the residuals from the estimated linear VECM. The second bootstrap methodology is parametric, called ”residual bootstrap”.

As there is practically no empirical research using the proposed methodology of Hansen and Seo (2002) for TVECMs, we test the power of the two proposed LM tests. For the first data generating process we simulate data for 1000 periods that always remains in the lower regime, thus not a TVECM but a linear VECM. The second data generating process is a simulation of data for 1000 periods that switches between two regimes, thus a TVECM and not a linear VECM. Both processes are tested with 1000 Monte-Carlo simulations.

In particular, we wanted to test the power of the two different bootstrap methodologies as the values of θ which maximize Equation (6) are different from the MLE $\hat{\theta}$ in Section

4 as Equation (6) are LM tests that are based on parameter estimates obtained under the $\mathscr{H}_0$. Also, the test statistic is calculated with a HAC-consistent covariance matrix estimates which leads to differing $\hat{\theta}$ estimates compared to the estimate in Section 4.1.

We find consistent results between the two bootstrap methodologies with very small discrepancies between the two tests. In case of no threshold the tests reject the $\mathscr{H}_0$ in around 11% of all cases at 90% confidence level. When a treshold effect is present, the tests do not reject the $\mathscr{H}_0$ in around 20% of all cases at 90% confidence level.

We find for our data sets, that the reported p-values are overall robust to the selection of the trimming parameter. Only in the pre-crisis period for the 10-year tenor in Greece we find deviations with different trimming parameters.

Table C.1: Threshold test - pre-crisis period

This table reports the p-values from the fixed regressor and parametric bootstrap for the period from January 2008 to end-March 2010. The null hypothesis test for the linear VECM with the TVECM as alternative. The distribution is bootstraped using 5000 Monte-Carlo simulations.

Panel A: 5-year tenor

	5% trim		10% trim	
	bootstrap p-values		bootstrap p-values	
Sovereign	fixed regressor	parametric	fixed regressor	parametric
France	0.16	0.24	0.22	0.29
Germany	**0.02**	**0.05**	**0.06**	**0.10**
Greece	0.49	0.58	0.62	0.68
Ireland	0.63	0.62	0.66	0.64
Italy	0.22	0.24	0.21	0.24
Portugal	**0.08**	**0.10**	**0.07**	**0.10**
Spain	0.15	0.14	0.15	0.13

Panel B: 10-year tenor

	5% trim		10% trim	
	bootstrap p-values		bootstrap p-values	
Sovereign	fixed regressor	parametric	fixed regressor	parametric
France	0.26	0.31	0.24	0.28
Germany	0.48	0.54	0.48	0.51
Greece	**0.05**	**0.10**	0.43	0.55
Ireland	**0.07**	**0.08**	**0.05**	**0.06**
Italy	**0.00**	**0.00**	**0.00**	**0.00**
Portugal	**0.04**	**0.05**	**0.04**	**0.05**
Spain	**0.01**	**0.03**	**0.01**	**0.02**

Table C.2: Threshold test - crisis period

This table reports the p-values from the fixed regressor and parametric bootstrap for the period from April 2010 to end-December 2011. The null hypothesis test for the linear VECM with the TVECM as alternative. The distribution is bootstraped using 5000 Monte-Carlo simulations.

Panel A: 5-year tenor

	5% trim		10% trim	
	bootstrap p-values		bootstrap p-values	
Sovereign	fixed regressor	parametric	fixed regressor	parametric
France	**0.01**	**0.02**	**0.01**	**0.02**
Germany	0.79	0.84	0.82	0.87
Greece	0.24	0.43	0.22	0.43
Ireland	**0.05**	**0.05**	**0.04**	**0.04**
Italy	**0.00**	**0.01**	**0.00**	**0.00**
Portugal	0.21	0.28	0.23	0.30
Spain	0.37	0.45	0.33	0.39

Panel B: 10-year tenor

	5% trim		10% trim	
	bootstrap p-values		bootstrap p-values	
Sovereign	fixed regressor	parametric	fixed regressor	parametric
France	0.34	**0.10**	0.41	**0.05**
Germany	0.47	0.19	0.47	0.16
Greece	0.22	0.21	0.23	0.21
Ireland	0.75	0.79	0.72	0.73
Italy	0.44	0.44	0.42	0.41
Portugal	0.17	**0.10**	0.17	**0.08**
Spain	0.79	0.74	0.79	0.69

D TVECM coefficients

Table D.1: TVECM coefficients - pre-crisis period

This table reports the TVECM coefficients for the period from January 2008 to end-March 2010.

	5-year tenor				10-year tenor			
	5% trim		10% trim		5% trim		10% trim	
Sovereign	β_1	β_0	β_1	β_0	β_1	β_0	β_1	β_0
Germany	-3.50	-87.09	-2.64	-109.98				
Greece					1.56	15.30		
Ireland					2.18	-46.73	2.62	-57.26
Italy					3.09	20.88	3.09	20.88
Portugal	0.80	45.90	1.36	44.21	2.64	40.31	1.63	40.31
Spain					3.05	23.47	3.05	23.47

Table D.2: TVECM coefficients - crisis period

This table reports the TVECM coefficients for the period from April 2010 to end-December 2011.

	5-year tenor				10-year tenor			
	5% trim		10% trim		5% trim		10% trim	
Sovereign	β_1	β_0	β_1	β_0	β_1	β_0	β_1	β_0
France	2.95	129.60	2.50	115.02	0.96	118.91	0.96	118.91
Ireland	0.86	219.32	1.23	118.32				
Italy	1.52	46.31	1.29	88.93				
Portugal					1.22	102.83	0.94	231.37

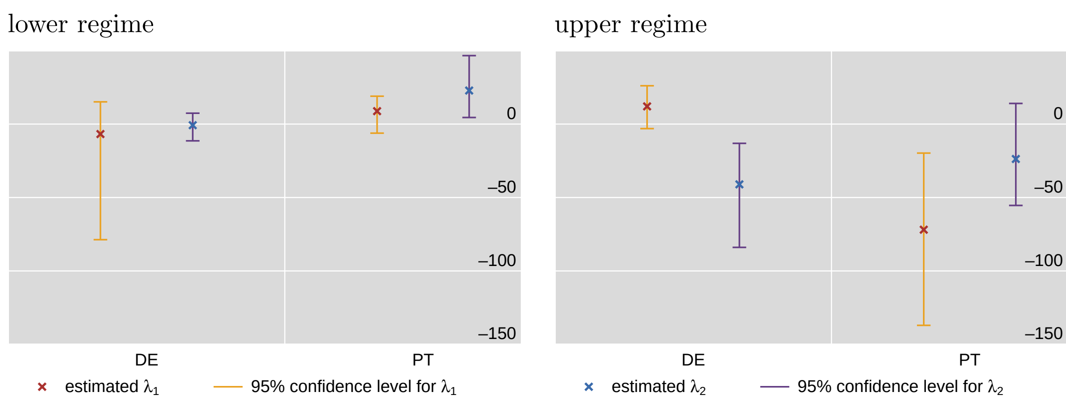
E Confidence bands

The inference for the TVECM results for the pre-crisis and crisis period are based on asymptotic standard errors, which should be reliable given that we have approximately 10,000 observations for each time series (see Section 5). Nevertheless, given the high credit spread volatility during the sample period, we also employ a standard bootstrap method as described in Benkwitz et al. (1999), where we use 100,000 Monte-Carlo simulations to generate 95% confidence bands for the λ_i parameters, the HAS, and GG measures in each regime.

Figure E.1: Confidence bands for adjustment speeds - pre-crisis period

Confidence bands for λ_1^j and λ_2^j for the period from January 2008 to end-March 2010 and 5% trim. The bootstrap confidence intervals are estimated according to Benkwitz et al. (1999) with 100,000 iterations. The lower bound is the 2.5% percentile. The upper bound is the 97.5% percentile. The λ_i are expressed in units of 10^{-4}. We do not report the confidence bands in cases when both λ_i point estimates are not statistically significant in a regime (VAR process).

Panel A: 5-year tenor



Panel B: 10-year tenor

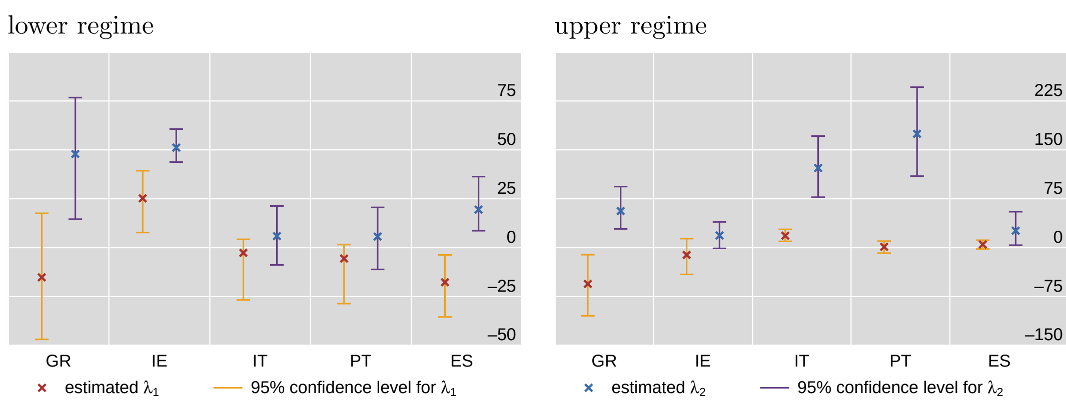
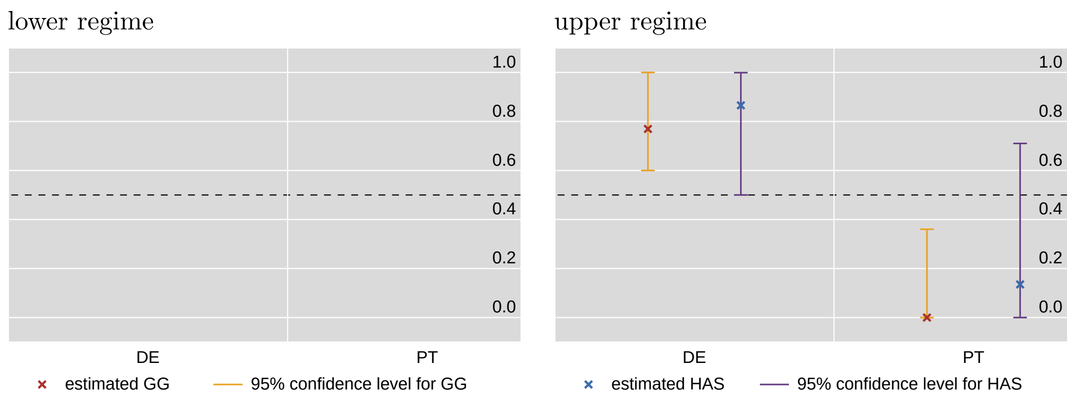


Figure E.2: Confidence bands for HAS and GG - pre-crisis period

Confidence bands for the HAS and GG measures for the period from January 2008 to end-March 2010 and 5% trim. The HAS ratio is the average of HAS_1 and HAS_2. Bootstrap confidence intervals are estimated according to Benkwitz et al. (1999) with 100,000 simulations. The lower bound is the 2.5% percentile. The upper bound is the 97.5% percentile. We do not report the VECM based HAS and GG confidence bounds in case of no significance of both λ_i coefficients in a regime (VAR process).

Panel A: 5-year tenor



Panel B: 10-year tenor

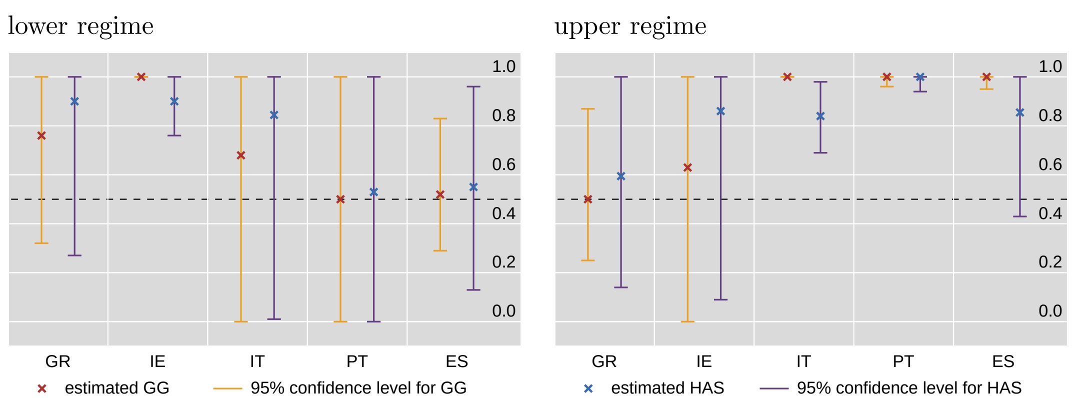
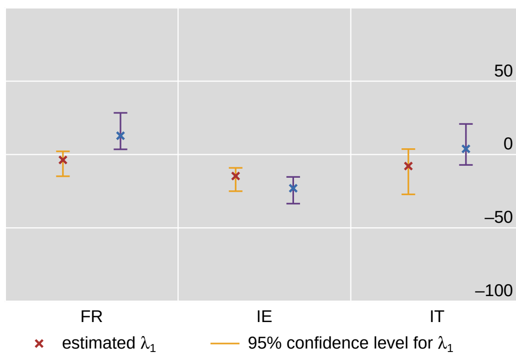


Figure E.3: Confidence bands for adjustment speeds - crisis period

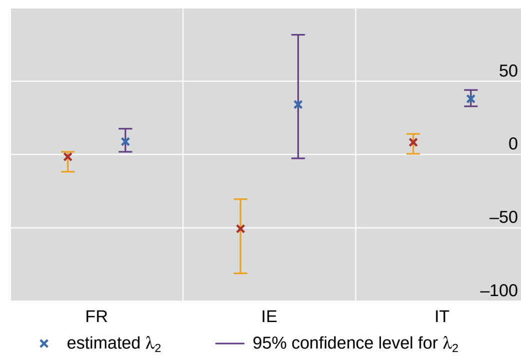
Confidence bands for λ_1^j and λ_2^j for the period from April 2010 to end-December 2011 and 5% trim. The bootstrap confidence intervals are estimated according to Benkwitz et al. (1999) with 100,000 iterations. The lower bound is the 2.5% percentile. The upper bound is the 97.5% percentile. The λ_i are expressed in units of 10^{-4}. We do not report the confidence bands in cases when both λ_i point estimates are not statistically significant in a regime (VAR process).

Panel A: 5-year tenor

lower regime

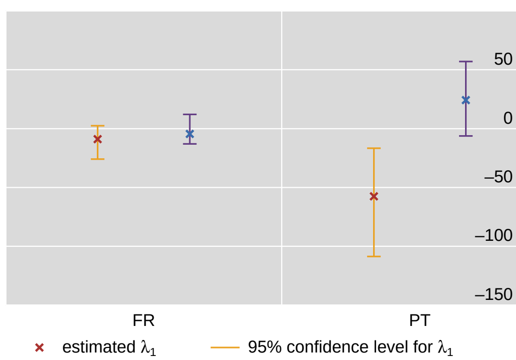


upper regime



Panel B: 10-year tenor

lower regime



upper regime

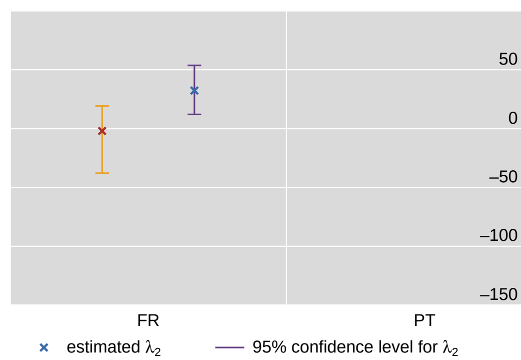
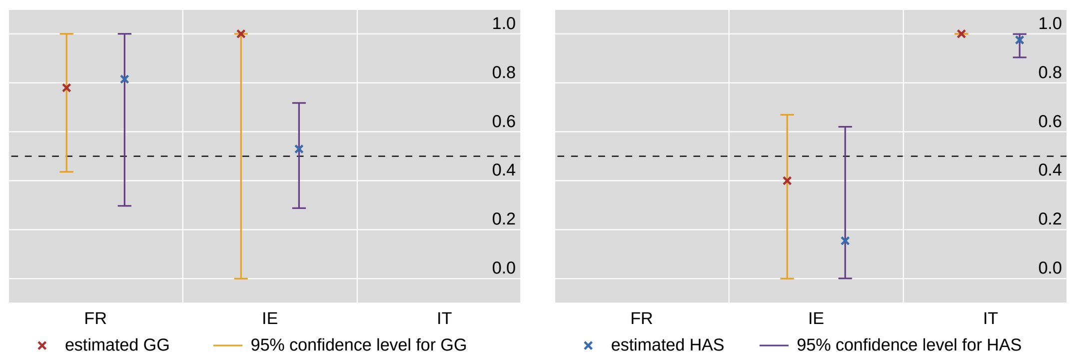


Figure E.4: Confidence bands for HAS and GG - crisis period

Confidence bands for the HAS and GG measures for the period from April 2010 to end-December 2011 and 5% trim. The HAS ratio is the average of HAS_1 and HAS_2. Bootstrap confidence intervals are estimated according to Benkwitz et al. (1999) with 100,000 simulations. The lower bound is the 2.5% percentile. The upper bound is the 97.5% percentile. We do not report the VECM based HAS and GG confidence bounds in case of no significance of both λ_i coefficients in a regime (VAR process).

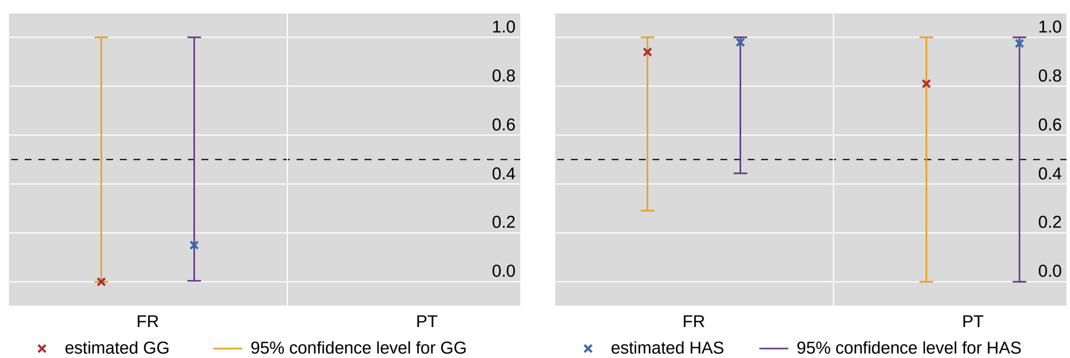
Panel A: 5-year tenor

lower regime upper regime



Panel B: 10-year tenor

lower regime upper regime



F Robustness

This section reports the TVECM results with a 10% trim as robustness test.

Table F.1: Price discovery TVECM with 10% trim - pre-crisis period

This table reports the price discovery analysis for intraday data on a 30 minutes sampling frequency from the TVECM according to our specification of Equation (2) with $\mu^j = 0$ and $\beta = (\beta_0 \quad \beta_1)^\mathsf{T}$ for the period from January 2008 to end-March 2010 with 10% trim for the 5- and 10-year tenor. The superscript ^{a} indicates that the GG measure has to be interpreted as 1, because the VECM coefficient λ_1 is not significant; the superscript ^{b} indicates that GG has to be interpreted as 0, because λ_2 is not significant. The values of the VECM coefficients λ^j are expressed in units of 10^{-4}. In case of no significance of both λ_i coefficients in a regime, we do not report VECM based HAS and GG measures.

Panel A - 5-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Germany	32.0	0.86	0.83	0.74 ^{a}	1.9	0.31	-5.4	0.03	90.0%
Portugal	-19.5	0.28	0.47	0.45	-58.3	0.05	48.5	0.06	81.2%

lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Germany	0.88	0.93	1.16 ^{a}	8.0	0.53	58.4	0.08	10.0%
Portugal	0.31	0.34	0.46	-28.5	0.02	23.8	0.07	18.8%

Panel B - 10-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Ireland	-63.5	0.75	0.76	0.55	-7.6	0.10	9.4	0.00	89.8%
Italy	2.2	0.84	0.84	1.18^a	18.3	0.14	122.2	0.08	14.2%
Portugal	7.8	0.87	0.87	0.74 ^{a}	-39.8	0.23	116.1	0.01	25.2%
Spain	53.8	0.88	0.83	1.23 ^{a}	4.8	0.29	26.1	0.01	13.0%

Panel B: lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
Ireland	0.97	0.99	1.14^a	4.6	0.71	36.8	0.00	10.2%
Italy	0.83	0.86	0.68^a	-2.7	0.25	5.9	0.01	85.8%
Portugal	0.61	0.67	0.57	-15.3	0.03	20.6	0.00	74.8%
Spain	0.54	0.56	0.52	-17.7	0.00	19.5	0.01	87.0%

Table F.2: Half-life of shocks in days with 10% trim - pre-crisis period

This table reports the half-life of shocks of 5-year and 10-year CDS and ASW for the period from January 2008 to end-March 2010 with 10% trim. The half-lives of shocks are expressed in days, and are calculated using the impulse response function to a one unit shock on the cointegrating error, using Equations 3 and 4. In case of no significance of both λ_i coefficients in a regime, we do not report the VECM based half-life of shocks. Negative half-lives are meaningless as they represent a dysfunction because markets move away from the long-term equilibrium condition.

Panel A: 5-year tenor

Sovereign	lower	upper
Germany	-2.5	27.1
Portugal	6.3	3.1

Panel B: 10-year tenor

Sovereign	lower	upper
Ireland	4.0	11.9
Italy	21.1	1.0
Portugal	7.8	2.0
Spain	5.0	4.8

Table F.3: Price discovery TVECM with 10% trim - crisis period

This table reports the price discovery analysis for intraday data on a 30 minutes sampling frequency from the TVECM for the period from April 2010 to end-December 2011 with 10% trim for the 5- and 10-year tenor. For futher details see Table 1.

Panel A - 5-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	48.7				-4.7	0.52	3.2	0.62	10.0%
Ireland	-70.9	0.01	0.04	0.13^b	-27.6	0.07	4.1	0.83	51.5%
Italy	5.8				-138.3	0.11	34.6	0.50	10.1%

lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	0.83	0.94	0.84^a	-5.3	0.48	28.3	0.01	90.0%
Ireland	0.13	0.16	0.42^b	-12.1	0.01	8.7	0.31	48.5%
Italy				-9.8	0.24	1.9	0.81	89.9%

Panel B - 10-year tenor: upper regime

Sovereign	$\hat{\theta}$	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	25.6	0.96	1.00	0.94^a	-2.0	0.92	32.3	0.01	14.0%
Portugal	44.2				-38.1	0.44	-41.7	0.37	10.5%

Panel B: lower regime

Sovereign	HAS_1	HAS_2	GG	λ_1	p	λ_2	p	% of obs.
France	0.15	0.15	-1.07^b	-8.9	0.02	-4.6	0.36	86.0%
Portugal	0.68	0.58	10.51^a	-14.0	0.23	-15.5	0.08	89.5%

Table F.4: Half-life of shocks in days with 10% trim - crisis period

This table reports the half-life of shocks of 5-year and 10-year CDS and ASW for the period from April 2010 to end-May 2011 with 10% trim. For futher details see Table 2. In case of no significance of both λ_i coefficients in a regime, we do not report the VECM based half-life of shocks. Negative half-lives are meaningless as they represent a dysfunction because markets move away from the long-term equilibrium condition.

Panel A: 5-year tenor

Sovereign	lower	upper
France	5.4	
Ireland	31.9	13.9
Italy		

Panel B: 10-year tenor

Sovereign	lower	upper
France	43.3	12.4
Portugal	-26.5	