Credit Implied Volatility

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Abstract

We introduce the concept of a credit implied volatility surface. It is inverted from the CDS spread to provides a relative measure of CDS value across "moneyness" (leverage) and time to maturity, and offers simple diagnostic tests of candidate credit pricing models. In recessionary episodes, the slope across moneyness steepens dramatically. This is more pronounced for short maturity CDS, which leads to twisting motion in the surface over time. Similarly, the slope of the CIV term structure becomes more steeply negative in downturns and is positive during expansions. These dynamics place important restrictions on the types of asset pricing models that are consistent with credit prices. Twisting in the surface indicates that a multi-factor model is necessary to describe the data, and factor analysis suggests at least three factors are necessary to capture data dynamics. In ongoing work, we propose a three state variable model of firm assets with common and idiosyncratic risk components that provides an accurate match of the empirical CIV surface.

Keywords: CDS, credit risk modeling, implied volatility

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1 Introduction

We introduce the concept of a credit implied volatility surface. Like its option analogue, credit implied volatility (CIV) is inverted from the observable CDS spread to provides a relative measure of CDS value, after accounting for the effects of maturity, moneyness, and the risk-free rate via the Black-Scholes-Merton model, and is interpretable as risk-neutral asset volatility of the underlying firm or government. The study of option valuation has in large part centered around understanding the implied volatility surface because it provides such a simple visual summary of the relative pricing of insurance contracts that differ by time to maturity and "moneyness," or the probability of a positive payoff. We argue that the vast literature studying the pricing of CDS and risky bonds can be similarly organized in terms of understanding the behavior of the CIV surface.

As with options, CDS are available at a range of maturities for any single reference entity, thus CIV provides a direct comparison of the relative CDS value by maturity. Yet CIV differs from option implied volatility (OIV) in a number of dimensions. Options for a single underlying equity are typically available at a variety of strike prices. The implied volatility curve across strike (holding maturity fixed) provides a direct comparison of relative option prices for the same underlying. In contrast, a firm's CDS contract is available at a single "strike," which is defined by the default boundary and typically measured using firm leverage. Despite this limitation, we show that the data carry rich information about differential pricing of CDS by moneyness. In the wide universe of traded CDS, firms vastly differ in their leverage, which allows us to trace out the credit implied volatility "smirk" or "skew" by aggregating relative prices over the entire universe of CDS.

Consider comparing the implied volatility of identical CDS contracts (same maturity and other contract structure) for two different firms. One firm has high leverage and the other low leverage, but they are otherwise identical. We find that the firm with lower leverage (i.e., the firm with deeper "out-of-the-money" CDS) bears a higher insurance price per unit of risk – its credit implied volatility is higher. In reality, firms with different leverage differ on many other dimensions as well, and our construction of the CIV surface accounts for this. In particular, we define the volatility smile by a regression of CIV onto firm leverage, while saturating the model with controls for other observable characteristics of the firm and CDS contract. The regression allows for a polynomial basis in leverage, and typically estimates a decreasing, convex shape for CIV with respect to leverage, similar to the volatility "smirk" in options markets.

Our CDS data include liquid contracts for constant 1, 3, 5, 7, and 10 year contracts. On average, the term structure is decreasing during our sample (2001 to 2013). The average slope is more steeply negative for OTM (low leverage) firms, and is eventually slightly upward sloping for deep ITM (high leverage) firms. At any given maturity, the CIV moneyness smirk summarizes the relative pricing of CDS as a function of leverage, and we find that the shape of this skew varies with time-to-maturity.

The shape of the unconditional average CIV surface contrasts with the recent work of Feldhütter and Schaefer [2014], who argue that a simple Merton model can resolve the credit spread puzzle, as long the model is calibrated to credit spreads firm-by-firm. Our implied volatility calculation is effectively a firm-level calibration, but clearly illustrates the failures of the Merton model in the same manner that option volatility surfaces reject the Black-Scholes model. Nonetheless, the negative slope of the CIV moneyness smirk and the negative average slope of the term structure is consistent with the presence of jump risk in the firm-level asset process, which is consistent with recent regression-based analysis of CDS spreads.

Yet the deeper usefulness of the CIV surface lies in its ability to transparently illustrate the robust *dynamic* features CDS pricing. First, the surface fluctuates dramatically over time. In recessionary episodes, the slope across moneyness steepens dramatically. This is more pronounced for short maturity CDS, which leads to twisting motion in the surface over time. Similarly, the slope of the CIV term structure becomes more steeply negative in downturns and is positive during expansions. Again, there are differences in this effect across moneyness associated with twisting in the surface, as low leverage (OTM) CDS experience the most dramatic variation in term structure slope.

These dynamics of the CIV surface place important restrictions on the types of asset pricing models that are consistent with credit prices. The fact that the moneyness slope steepens in recession indicates that, on average, firm-level tail risk rises during recessions. A central task for understanding CDS prices is then whether this increased risk arises from an aggregate factor, or whether there is a common rise in idiosyncratic risks. For average tail risk to rise, one or both of these must be occurring (a rise in the idiosyncratic risk of a small number of firms will wash out in our large sample), and which one has different implications for credit risk premia. If the increase is coming from aggregate tail risk, a more nuanced question is whether this is a rise in physical tail risk of the macroeconomy, or a rise in risk-neutral tail risk originating for a spike in investor risk aversion?

Furthermore, the twisting behavior of the CIV surface strongly indicates that a multi-factor model is necessary to describe the data. A single state variable cannot simultaneously describe variation in moneyness slopes that differ across maturities. Principal components analysis indicates that at least three factors are necessary to describe the behavior of the surface. These seem to line up roughly with the CIV surface level, the slope in the moneyness dimension, and the differences in moneyness slope at the long and short end of the surface.

Lastly, we propose a three state variable model of firm assets with common and idiosyncratic risk components. We show that this structure is capable of matching the central behavior of the volatility surface that we document. We discuss potential limitations of this model and suggest directions for future research in this area. [Work in Progress].

2 Pricing Credit Default Swap

In this section we present how a credit default swap (CDS) contract is priced in the structural framework a la Merton [1974].

A CDS is a credit derivatives that insures the buyer against the default on the underlying obligation, usually a bond or loan, of a specific company. The buyer of the contract makes quarterly payments to the seller, and receives a compensation equal to the face value of the underlying bond net of the recovery rate upon the realization of the credit event. In case of companies, a credit event can be bankruptcy, obligation acceleration or default, failure to pay, repudiation and restructuring.

Let $CDS_t(T)$ be the annualized credit default swap spread paid by the buyer at time t and for maturity T, the stream of quarterly payments (premium leg) is

$$\frac{CDS_t(T)}{4}\sum_{i=1}^{4T} D_t(0,T_i)\,\mathbb{Q}_t(0,T_i)$$

whereas the commitment of the seller (contingent leg) is given by

$$(1-R)\sum_{i=1}^{4T} D_t\left(0,T_i\right)\left[\mathbb{Q}_t\left(0,T_{i-1}\right)-\mathbb{Q}_t\left(0,T_i\right)\right]$$

where R is the recovery rate, thus $1-R$ represent the loss given default, $\mathbb{Q}\left(0,T_i\right)$ is the risk-neutral probability of not defaulting over the quarterly period $\left(0,T_i\right)$ and $D\left(0,T_i\right)$ is the risk-free discount function.

Given that a swap contract is worth zero at inception, the pricing equation for a CDS contract is obtained by equaling the two legs, thus, we have

$$CDS_t\left(T\right) = \frac{4\left(1-R\right)\sum_{i=1}^{4T} D_t\left(0,T_i\right)\left[\mathbb{Q}_t\left(0,T_{i-1}\right)-\mathbb{Q}_t\left(0,T_i\right)\right]}{\sum_{i=1}^{4T} D_t\left(0,T_i\right)\mathbb{Q}_t\left(0,T_i\right)} \tag{1}$$

We specify the risk-neutral survival probability, $\mathbb{Q}\left(0,T_i\right)$, in a structural setting where the credit spread of firm is linked to its fundamentals, such as the leverage, the debt maturity and the asset volatility.

According to Merton [1974], a company defaults when the value of its assets is below the face value of debt at maturity. Therefore, the model relates credit risk to the capital structure of the firm. The underlying assumption is that the firm issues equity and debt, with the latter being simply a discount bond whose notional is promised at maturity T. If at maturity the firm's asset does not exceed the promised debt value D, it goes bankruptcy and lenders receive a payment equal to the asset value. Otherwise, if the asset value is enough to repay the debt back, shareholders receive the residual asset value (net of debt payment). Therefore, shareholders receive the $\left(A_T-D\right)^+$ where A_T is the firm's asset value at maturity and $+$ stands for the maximum value. In other words, equity is a call option on the asset value with strike equal to the debt value,

$$E_T = \max\left[A_T-D,0\right]$$

whose current value is (Black and Scholes [1973])

$$E_0 = A_0 N\left(d_1\right) - De^{-rT}N\left(d_2\right) \tag{2}$$

where

$$\begin{aligned} d_1 &= \frac{\ln\left(A_0 e^{rT}/D\right)}{\sigma_A\sqrt{T}} + \frac{1}{2}\sigma_A\sqrt{T} \\ d_2 &= d_1 - \sigma_A\sqrt{T} \end{aligned}$$

with r being the risk-free rate and σ_A the firm's asset volatility. Following Hull et al. [2004], we can write equation 2 in terms of firm's leverage $L = D^*/A_0$ where $D^* = De^{-rT}$, as follows

$$E_0 = A_0\left[N\left(d_1\right) - LN\left(d_2\right)\right] \tag{3}$$

where

$$\begin{aligned} d_1 &= \frac{-\ln\left(L\right)}{\sigma_A\sqrt{T}} + \frac{1}{2}\sigma_A\sqrt{T} \\ d_2 &= d_1 - \sigma_A\sqrt{T} \end{aligned}$$

The risk neutral default probability in this framework equals the probability that shareholders will not exercise their call option to buy the asset of the company for D at maturity. Therefore, it is given by

$$P = N\left(-d_2\right) \tag{4}$$

Interestingly, the default probability depends only on the leverage L, the asset volatility σ_A and the debt maturity T. Plugging equation 4 into 1 completes the pricing of CDS spreads.

3 Data

The empirical implementation of the Merton [1974] model requires both accounting and market data. To estimate the leverage for each company we collect quarterly current (DCLQ) and long-term (DLTTQ) liabilities, market capitalization (CSHOQ) and prices (PRCCQ) from Compustat. We measure market leverage as total debt (DCLQ plus DLTTQ) divided by asset value, that is, the sum of market capitalization (CSHOQ times PRCCQ) and total debt. To match the monthly frequency of credit spreads, we assume that quarterly accounting data are constant during the quarter. The monthly risk-free term structure is computed from constant maturity (CMT) bonds from H.15 data set of the Federal Reserve Board.[1] Single-name credit default swap spreads are collected from Markit for the maturities 1, 3, 5, 7 and 10 years, over the monthly period from January 2001 to November 2013. We select USD denominated spreads and the most traded clause, MR (Modified Restructuring[2]). Moreover, we collect monthly ratings for each company from Capital IQ. We proxy the company rating by the time series average of these ratings.

To avoid that illiquidity and CDS pricing errors drive our results, we employ a filter. In particular, we exclude spreads reported by only two dealers and very large spreads, i.e. spreads greater than 2000 basis points.

Tables 1, 2 and 3 report summary statistics for credit default swap spreads across maturities, rating classes and sectors, respectively. On average, across the sample period from 2001 to 2013, the credit term structure of U.S. firms is upward sloping as average spreads range from 77 to 154 basis points for the 1-year and 10-year maturities, respectively. Both standard deviations and minimum and maximum values signal time series and cross-sectional variations in credit risk profiles in the U.S. corporate credit market.

Tables 2 shows increasing average credit risk for the 5-year maturity among the investment grade companies (from AAA to BBB). The slightly lower average spreads for BB and B-rated companies is mainly due to the filter we apply to our sample.

Table 3 indicates heterogeneity in credit risk also across sectors. Financials are the riskiest with an average spreads and standard deviation of 112 and 135 basis points, followed by Consumer Goods and Services characterized by high volatile spreads.

[1] The risk-free discount function can be extracted also from Libor and interest rate swaps. However, Duffie [1999] shows that the risk-free discount function plays a negligible role in pricing credit default swap spreads. Therefore, the choice of it measurement has little impact on the pricing errors.

[2] The BIS Quarterly Review, March 2005, page 91, reports "While restructuring agreements still counted as credit events, the clause limited the deliverable obligations to those with a maturity of 30 months or less after the termination date of the CDS contract. Under this contract option, any restructuring event (except restructuring of bilateral loans) qualifies as a credit event."

4 Credit Implied Volatility

The CDS pricing formula in 1 can convey important information about the term structure of the unobservable firm's asset volatility, $\sigma_A(T)$. For a given leverage, maturity and risk-free term structure, we invert the pricing equation in 1 to extrapolate the term structure of credit asset implied volatility (CIV). In particular, we employ a non-linear least square method that minimizes the following objective function

$$\min_{\sigma_A(T)} \left[CDS_t(T) - \widehat{CDS_t}(T)\right]^2$$

where $CDS_t(T)$ is the observed CDS spread and $\widehat{CDS_t}(T) = h\left(\bar{L}, \bar{T}, \bar{r}, \sigma_A\right)$ is the fitted one, where $h(\cdot)$ is the pricing equation in 1.

Table 4, 5 and 6 report summary statistics for credit default swap spreads across maturities, rating classes and sectors, respectively. On average, the term structure is downward sloping as it ranges from about 47 to 32 percent for the 1-year and 10-year CIV. Moreover, the 1-year CIV is more volatile than the 10-year one, suggesting differences in market risk across time horizons. We do not observe differences in CIV across rating classes and sectors that averages around 35 percent.

5 Credit Implied Volatility Smirk

Unlike stock options, CDS spreads are only available for specific maturities and for one moneyness, the firm leverage. Therefore, to construct the volatility smile, we employ panel regressions of CIV onto firm leverage and controls for observable characteristics. We present regressions for each CIV maturity in Table 7and for the 5-year CIV across rating classes and sectors in Tables 8 and 9, respectively. CIV and leverage are significantly related across maturities, rating classes and sectors beyond firm specific controls. Moreover, the significance of higher order of leverage confirm the non-linear relation between CIV and moneyness.

Figures 1, 2 and 9 plot the fitted CIV where firm specific controls are kept constant at the sample average level. Specifically, these pictures plot the quadratic fit of fitted CIV. It is evident the CIV smirk, that is, the negative relation between CIV and leverage.

We further investigate the CIV smirk and perform cross-sectional regressions of CIV on leverage and controls. Figure 4 decpits the moneyness slope over time for each maturity. The moneyness slope steepens in period of high distress, indicating the presence, on average, of a higher tail risk.

5.1 CIV Characteristics and Principal Components

The behavior of CIV described in the previous section suggests the presence of more than one factor in the data. In this section we build observable factors, such as, level, slope and moneyness slode and compare them with latent factor or principal components.

We measure Level as the cross-sectional average CIV across all firms and maturities, the Skew Slope as the cross-sectional average of skew slope coefficients (Figure 4) across maturities, the Term Structure Slope as the cross-sectional average of term structure slopes for all the maturities and the Term Structure Skew Slope as the difference between the 7-year and 3-year skew slope coefficients. Figure 5 plots these four factors. Principal components are extracted from 50 CIV portfolios sorted on leverage (10 bins) for each of the five maturities. Figure 6 plots these four latent factors. Comparing the top-left graph of both figures we see that the first PC, that explains about the 83 percent of the CIV variability, has the same behavior of the Level. To further understand the ralation between latent factors and CIV characteristics, we regress the latter on the four PCs. Table 10 report the results. The first three PCs are all significantly related to Level, Skew Slope and Term Structure Slope.

Table 1: Credit Default Swap Spreads by Maturity

The table reports summary statistics of credit default swap spreads across maturities in basis points. For each maturity we take the average value of the cross-sectional average (*Mean*), standard deviation (*Std Dev*), minimum (*Min*), median (*Median*) and maximum (*Max*). The sample covers the monthly period from 2001 to 2013.

	Mean	Std Dev	Min	Median	Max
1Y CDS	77.30	111.16	30.77	40.34	371.62
3Y CDS	107.43	130.42	56.48	62.70	409.51
5Y CDS	134.29	148.79	81.61	84.21	435.44
7Y CDS	145.48	150.68	85.10	94.69	441.28
10Y CDS	154.54	151.58	92.17	105.25	448.04

Table 2: Credit Default Swap Spreads by Rating

The table reports summary statistics of 5-year credit default swap spreads across rating classes in basis points. For each maturity we take the average value of the cross-sectional average (*Mean*), standard deviation (*Std Dev*), minimum (*Min*), median (*Median*) and maximum (*Max*). The last column reports the mean cross-sectional average of the leverage for each rating class. N is the percentage number of companies for each rating class. The sample covers the monthly period from 2001 to 2013.

Rating	N(%)	Mean	Std Dev	Min	Median	Max	Leverage
AAA	7.49	102.62	94.37	94.56	66.29	378.88	31.21
AA	6.91	104.84	95.91	98.29	68.48	388.65	31.00
A	13.94	121.75	128.86	71.83	73.65	376.09	30.11
BBB	34.10	130.46	141.74	91.33	80.41	444.89	30.97
BB	27.07	125.92	139.81	86.45	75.48	433.20	30.46
B	10.48	117.44	114.60	81.30	74.27	405.26	30.21

Table 3: Credit Default Swap Spreads by Sector

The table reports summary statistics of 5-year credit default swap spreads across sectors in basis points. For each maturity we take the average value of the cross-sectional average (*Mean*), standard deviation (*Std Dev*), minimum (*Min*), median (*Median*) and maximum (*Max*). The last column reports the mean cross-sectional average of the leverage for each sector. N is the percentage number of companies for each sector. The sample covers the monthly period from 2001 to 2013.

Sector	N(%)	Mean	Std Dev	Min	Median	Max	Leverage
Basic Materials	6.52	94.78	88.32	60.47	61.32	334.27	26.28
Consumer Goods	15.25	110.41	132.92	59.62	66.68	373.48	27.86
Consumer Services	14.20	108.33	133.12	60.84	65.37	361.96	27.36
Energy	8.96	101.59	114.43	55.32	62.15	329.79	27.07
Financials	17.58	112.94	135.01	59.02	66.60	370.29	29.67
Healthcare	6.75	93.61	87.17	58.82	61.16	326.54	26.21
Industrials	11.76	100.15	109.40	57.63	64.29	320.60	26.86
Technology	4.89	92.19	83.96	70.05	59.79	331.99	26.49
Telecom Services	2.91	91.50	80.06	51.70	62.88	385.07	25.85
Utilities	11.18	101.65	110.86	58.59	65.03	326.49	27.01

Table 4: Credit Implied Volatility by Maturity

The table reports summary statistics of credit implied asset volatilities across maturities in basis points. For each maturity we take the average value of the cross-sectional average (*Mean*), standard deviation (*Std Dev*), minimum (*Min*), median (*Median*) and maximum (*Max*). The sample covers the monthly period from 2001 to 2013.

	Mean	Std Dev	Min	Median	Max
1Y CIV	47.75	18.33	34.16	47.80	64.80
3Y CIV	37.43	15.28	26.54	36.60	51.73
5Y CIV	34.89	13.81	24.86	34.08	49.13
7Y CIV	33.41	13.05	23.73	32.71	48.32
10Y CIV	32.28	12.22	23.02	31.65	47.58

Table 5: Credit Implied Volatility by Rating

The table reports summary statistics of 5-year credit implied asset volatilities across rating classes in basis points. For each maturity we take the average value of the cross-sectional average (*Mean*), standard deviation (*Std Dev*), minimum (*Min*), median (*Median*) and maximum (*Max*). The sample covers the monthly period from 2001 to 2013.

Rating	N(%)	Mean	Std Dev	Min	Median	Max
AAA	7.49	34.99	13.83	25.30	34.50	45.37
AA	6.91	35.69	13.32	25.36	34.69	46.75
A	13.94	36.50	13.24	26.02	35.04	51.02
BBB	34.10	35.01	13.56	24.42	34.16	49.39
BB	27.07	35.58	13.73	24.25	34.72	49.20
B	10.48	35.87	13.55	25.43	34.75	48.75

Table 6: Credit Implied Volatility by Sector

The table reports summary statistics of 5-year credit implied asset volatilities across sectors in basis points. For each maturity we take the average value of the cross-sectional average (*Mean*), standard deviation (*Std Dev*), minimum (*Min*), median (*Median*) and maximum (*Max*). The sample covers the monthly period from 2001 to 2013.

Sector	N(%)	Mean	Std Dev	Min	Median	Max
Basic Materials	6.52	36.35	13.11	26.04	35.85	50.14
Consumer Goods	15.25	36.40	13.46	25.69	35.33	50.04
Consumer Services	14.20	36.79	13.31	26.14	35.64	50.03
Energy	8.96	36.06	13.90	25.88	35.53	50.11
Financials	17.58	36.43	13.60	25.21	35.37	49.57
Healthcare	6.75	36.41	13.44	26.05	35.95	50.05
Industrials	11.76	36.63	13.52	26.44	35.48	49.85
Technology	4.89	37.16	13.32	28.22	35.92	52.15
Telecom Services	2.91	36.05	10.83	27.87	35.78	54.75
Utilities	11.18	36.59	13.66	26.36	35.40	49.62

Table 7: Panel Regressions by Maturity

The table reports the estimation of panel regressions of credit implied asset volatility on a set of variables for each maturity. These variables are the leverage and its non-linear terms (Lev, Lev^2 and Lev^3), log of firm's size ($\ln(size)$), stock volatility ($Stock^{Vol}$), skewness ($Stock^{Skew}$) and kurtosis ($Stock^{Kurt}$). The sample covers the monthly period from 2001 to 2013.

	1Y	3Y	5Y	7Y	10Y
$cons$	0.92	0.74	0.70	0.67	0.66
t-Stat	189.79	197.66	180.29	165.69	155.57
Lev	-2.36	-2.14	-1.91	-1.76	-1.57
t-Stat	-101.59	-152.44	-134.25	-118.27	-101.13
Lev^2	2.84	3.24	3.04	2.88	2.61
t-Stat	49.18	87.13	80.38	72.84	63.29
Lev^3	-1.53	-1.95	-1.90	-1.83	-1.69
t-Stat	-36.86	-70.01	-66.39	-61.21	-54.17
$\ln(size)$	-0.01	-0.01	-0.01	-0.01	-0.02
t-Stat	-14.83	-27.35	-39.43	-43.48	-49.70
$Stock^{Vol}$	0.24	0.22	0.22	0.21	0.21
t-Stat	91.03	101.11	98.28	90.99	85.77
$Stock^{Skew}$	-0.01	-0.01	-0.01	-0.01	-0.01
t-Stat	-26.33	-25.11	-24.24	-22.39	-21.68
$Stock^{Kurt}$	0.00	0.00	0.00	0.00	0.00
t-Stat	3.95	2.66	5.19	6.73	7.98
R^2	0.82	0.80	0.73	0.66	0.59

Table 8: Panel Regressions by Rating

The table reports the estimation of panel regressions of 5-year credit implied asset volatility on a set of variables for each rating class. These variables are the leverage and its non-linear terms (Lev, Lev^2 and Lev^3), log of firm's size ($\ln(size)$), stock volatility ($Stock^{Vol}$), skewness ($Stock^{Skew}$) and kurtosis ($Stock^{Kurt}$). The sample covers the monthly period from 2001 to 2013.

	AAA	AA	A	BBB	BB	B
$cons$	0.60	0.63	0.60	0.66	0.67	0.59
t-Stat	47.10	53.93	81.59	89.35	53.56	37.60
Lev	-1.90	-1.80	-2.15	-1.86	-1.75	-1.90
t-Stat	-44.61	-45.98	-96.75	-61.56	-35.89	-30.75
Lev^2	3.14	3.00	3.49	2.81	2.54	3.09
t-Stat	27.46	25.61	55.57	33.48	19.95	20.19
Lev^3	-2.15	-2.02	-2.09	-1.73	-1.50	-1.93
t-Stat	-24.31	-21.78	-44.97	-25.24	-15.22	-17.95
$\ln(size)$	-0.00	-0.01	-0.00	-0.01	-0.01	-0.00
t-Stat	-2.99	-8.67	-1.09	-11.08	-9.56	-1.73
$Stock^{Vol}$	0.20	0.19	0.18	0.21	0.26	0.24
t-Stat	30.48	26.28	42.05	53.24	47.69	30.89
$Stock^{Skew}$	-0.01	-0.01	-0.00	-0.01	-0.01	-0.01
t-Stat	-3.59	-7.61	-6.44	-13.22	-13.44	-10.74
$Stock^{Kurt}$	-0.00	-0.00	-0.00	0.00	0.00	0.00
t-Stat	-0.72	-0.10	-4.64	4.25	1.36	5.79
R^2	0.79	0.75	0.88	0.70	0.63	0.66

Table 9: Panel Regressions by Sector

The table reports the estimation of panel regressions of 5-year credit implied asset volatility on a set of variables for each sector. These variables are the leverage and its non-linear terms (Lev, Lev^2 and Lev^3), log of firm's size ($\ln(size)$), stock volatility ($Stock^{Vol}$), skewness ($Stock^{Skew}$) and kurtosis ($Stock^{Kurt}$). The sample covers the monthly period from 2001 to 2013.

	Basic Materials	Consumer Goods	Consumer Services	Energy	Financials	Healthcare	Industrials	Technology	Telecom Services	Utilities
$cons$	0.64	0.68	0.77	0.59	0.62	0.73	0.74	0.92	0.63	0.48
t-Stat	43.97	62.56	63.03	41.78	65.79	59.83	83.80	39.68	18.13	14.98
Lev	-2.37	-1.78	-1.83	-2.06	-1.09	-1.89	-1.90	-2.61	-2.68	-2.12
t-Stat	-31.09	-37.67	-41.16	-38.24	-27.16	-40.11	-51.33	-38.81	-11.43	-13.08
Lev^2	4.80	2.74	2.87	3.99	0.87	3.52	3.00	4.82	4.72	3.43
t-Stat	20.21	18.87	21.85	24.41	9.26	21.74	28.48	21.08	9.00	11.12
Lev^3	-3.53	-1.63	-1.80	-2.89	-0.35	-2.38	-1.85	-3.23	-2.87	-2.09
t-Stat	-15.92	-12.65	-16.57	-20.03	-5.68	-15.76	-21.44	-15.33	-8.07	-11.11
$\ln(size)$	-0.00	-0.01	-0.02	-0.01	-0.01	-0.02	-0.02	-0.02	0.00	0.01
t-Stat	-4.15	-13.94	-17.48	-5.74	-13.21	-15.78	-24.99	-12.06	2.28	9.63
$Stock^{Vol}$	0.23	0.20	0.16	0.31	0.14	0.19	0.22	0.20	0.23	0.29
t-Stat	28.53	30.44	21.11	43.43	35.71	20.31	35.39	18.52	15.24	36.30
$Stock^{Skew}$	-0.01	-0.01	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.02	-0.00
t-Stat	-3.25	-7.28	-9.63	-7.58	-11.92	-7.92	-11.00	-5.15	-5.92	-4.61
$Stock^{Kurt}$	-0.00	-0.00	0.00	0.00	-0.00	0.00	0.00	-0.00	0.00	0.00
t-Stat	-0.71	-1.11	3.69	3.31	-3.01	3.27	3.15	-3.91	0.24	2.18
R^2	0.60	0.56	0.62	0.70	0.87	0.58	0.73	0.73	0.48	0.50

Table 10: CIV Characteristics and Principal Components

The table reports regressions of CIV characteristics such as Level, Skew Slope, Term Structure Slope and Term Structure Skew Slope on the first four principal components. Level is the cross-sectional average CIV across all firms and maturities, Skew Slope is the cross-sectional average of skew slope coefficients (Figure 4) across maturities, Term Structure Slope is the cross-sectional average of term structure slopes for all the maturities and Term Structure Skew Slope is the difference between the 7-year and 3-year skew slope coefficients. Principal components are extracted from 50 CIV time series obtained by sorting CIV on leverage (10 bins) for each of the five maturities.

	Level	*Skew Slope*	*TS Slope*	*Skew TS Slope*
cons	0.00	-0.57	0.06	0.89
t-Stat	6.69	-6.95	133.45	9.26
PC1	0.14	-0.09	-0.05	-0.13
t-Stat	1956.93	-3.80	-392.61	-4.63
PC2	0.01	0.09	0.01	-0.10
t-Stat	109.46	2.08	25.76	-2.04
PC3	0.01	-0.63	0.01	0.08
t-Stat	37.56	-6.71	11.16	0.72
PC4	0.00	-0.21	-0.02	0.33
-tStat	8.65	-1.33	-21.48	1.75
R^2	1.00	0.33	1.00	0.48

Figure 1: Fitted Credit Implied Volatility by Maturity

The figure plots the average relation between leverage and credit implied asset volatilities for each maturity estimated from panel regressions in table 7. The sample covers the monthly period from 2001 to 2013.

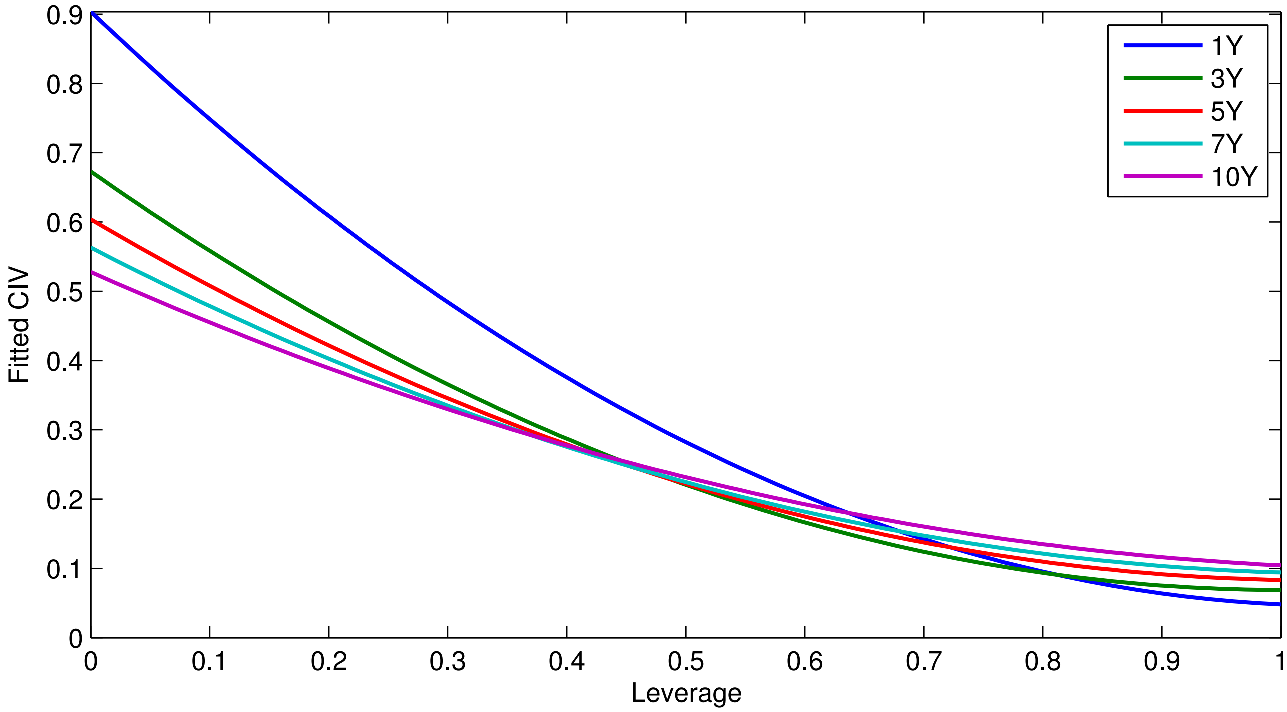


Figure 2: Fitted Credit Implied Volatility by Rating

The figure plots the average relation between leverage and 5-year credit implied asset volatilities estimated from panel regressions in table 8. The sample covers the monthly period from 2001 to 2013.

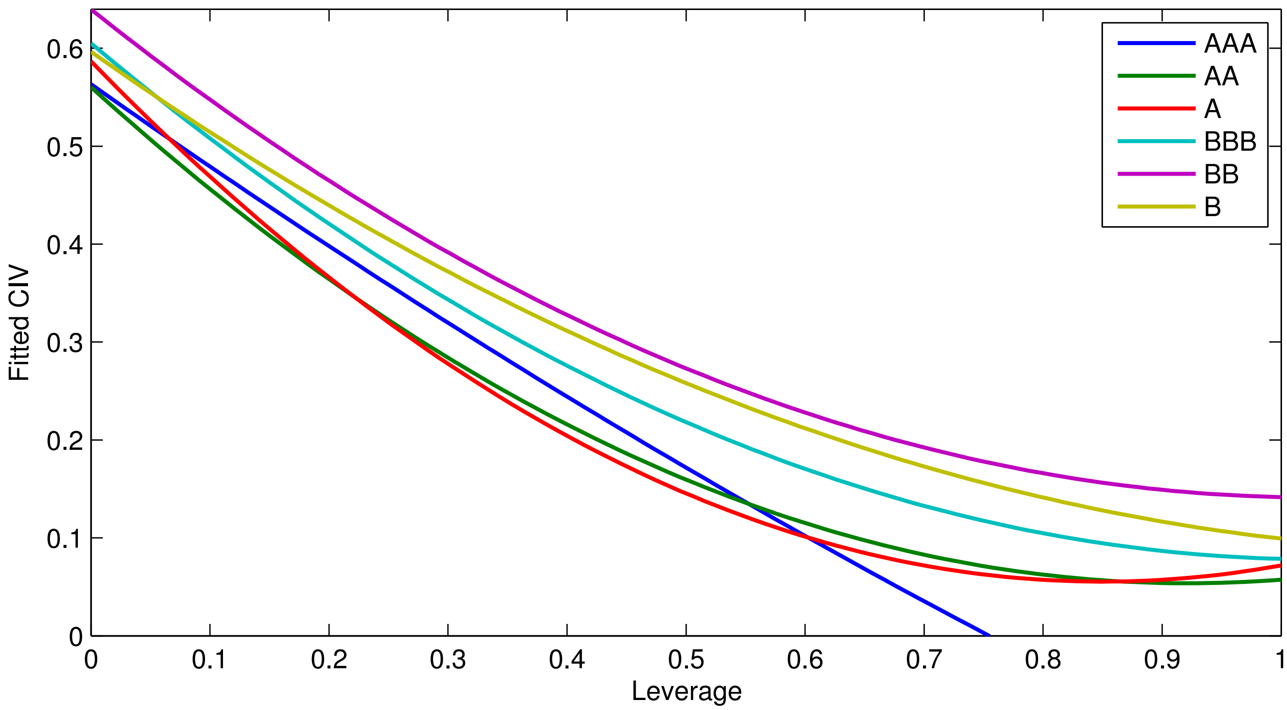


Figure 3: Fitted Credit Implied Volatility by Sector

The figure plots the average relation between leverage and 5-year credit implied asset volatilities estimated from panel regressions in table 9. The sample covers the monthly period from 2001 to 2013.

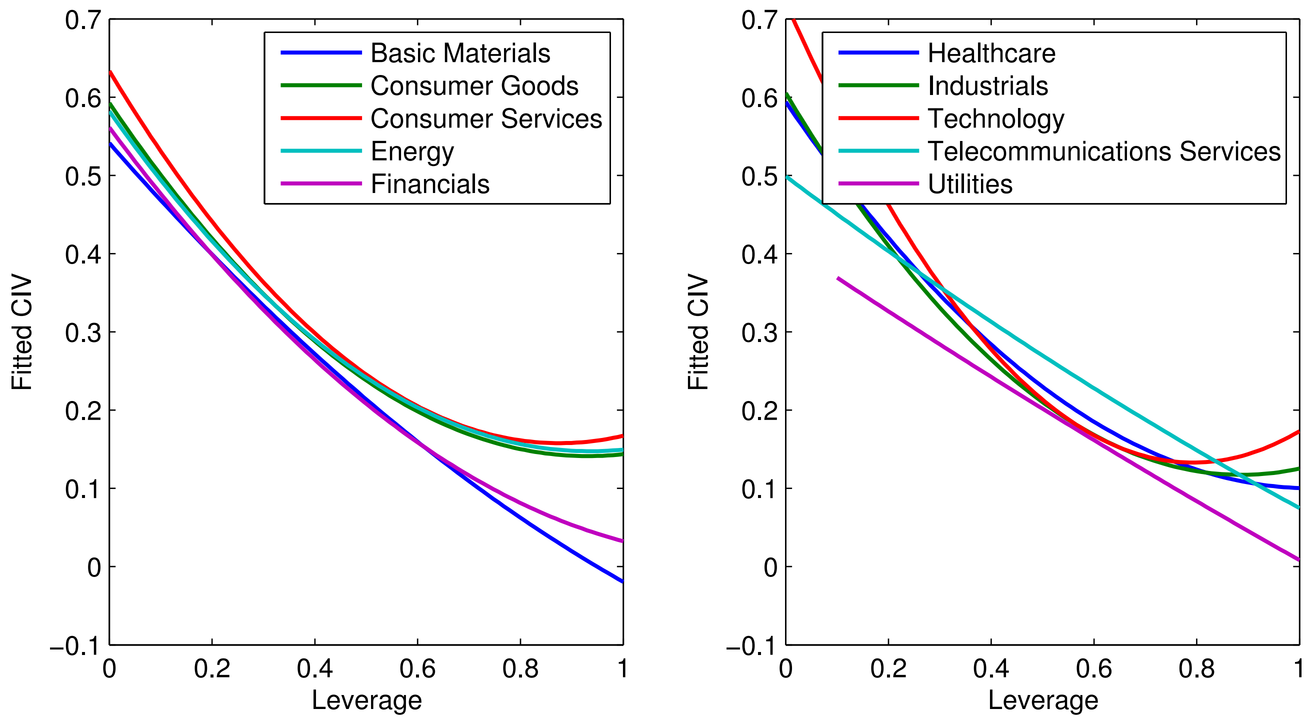


Figure 4: Cross-Sectional Regression

The figure plots the slope coefficient of credit implied asset volatility and leverage for each maturity, $\beta_{1,t}(M)$, estimated from the following regression

$$\begin{aligned} CIV_t(M) &= c_t + \beta_{1,t}(M)\, Lev_t + \beta_{2,t}(M)\, Lev_t^2 + \beta_{3,t}(M)\, Lev_t^3 + \beta_{4,t}(M) \ln(Size_t) \\ &\quad + \beta_{5,t}(M)\, Stock_t^{Vol} + \beta_{6,t}(M)\, Stock_t^{Skew} + \beta_{7,t}(M)\, Stock_t^{Kurt} + \epsilon_t \end{aligned}$$

The sample covers the monthly period from 2001 to 2013.

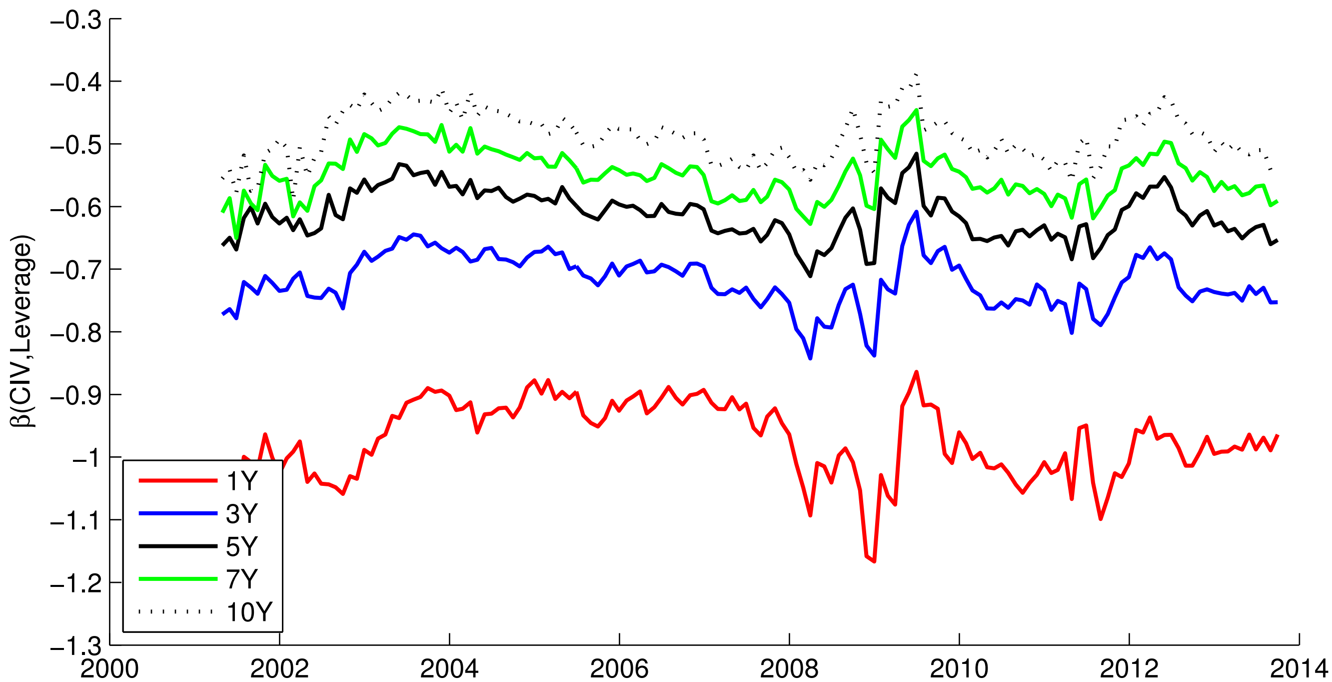


Figure 5: CIV Characteristics

The figure plots the Level, Skew Slope, Term Structure Slope and Term Structure Skew Slope on the first four principal components. Level is the cross-sectional average CIV by firm and maturities, Skew Slope is the cross-sectional average of skew slope coefficients (Figure 4) across maturities, Term Structure Slope is the cross-sectional average of term structure slopes for all the maturities and Term Structure Skew Slope is the difference between the 7-year and 3-year skew slope coefficients.

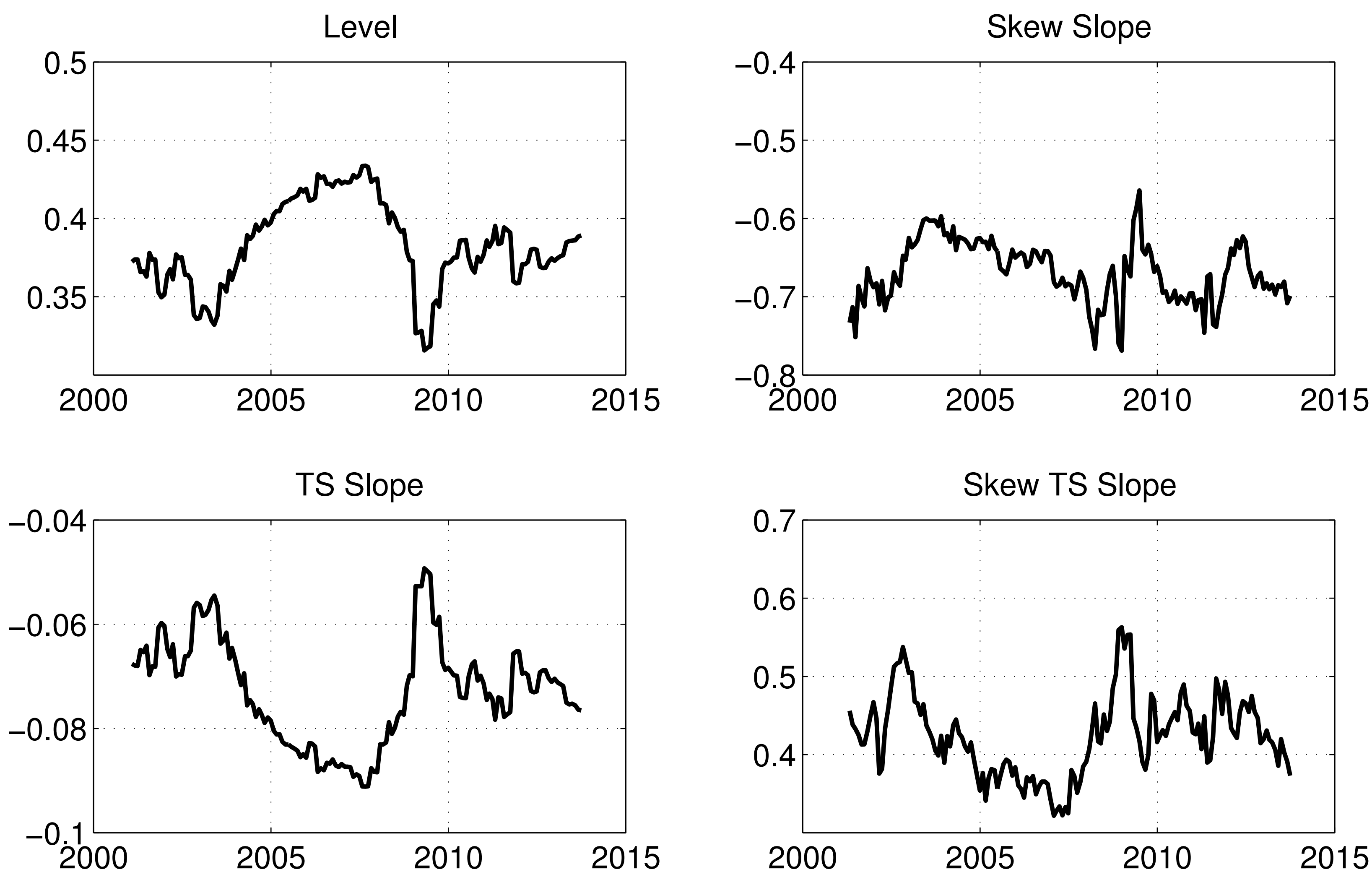
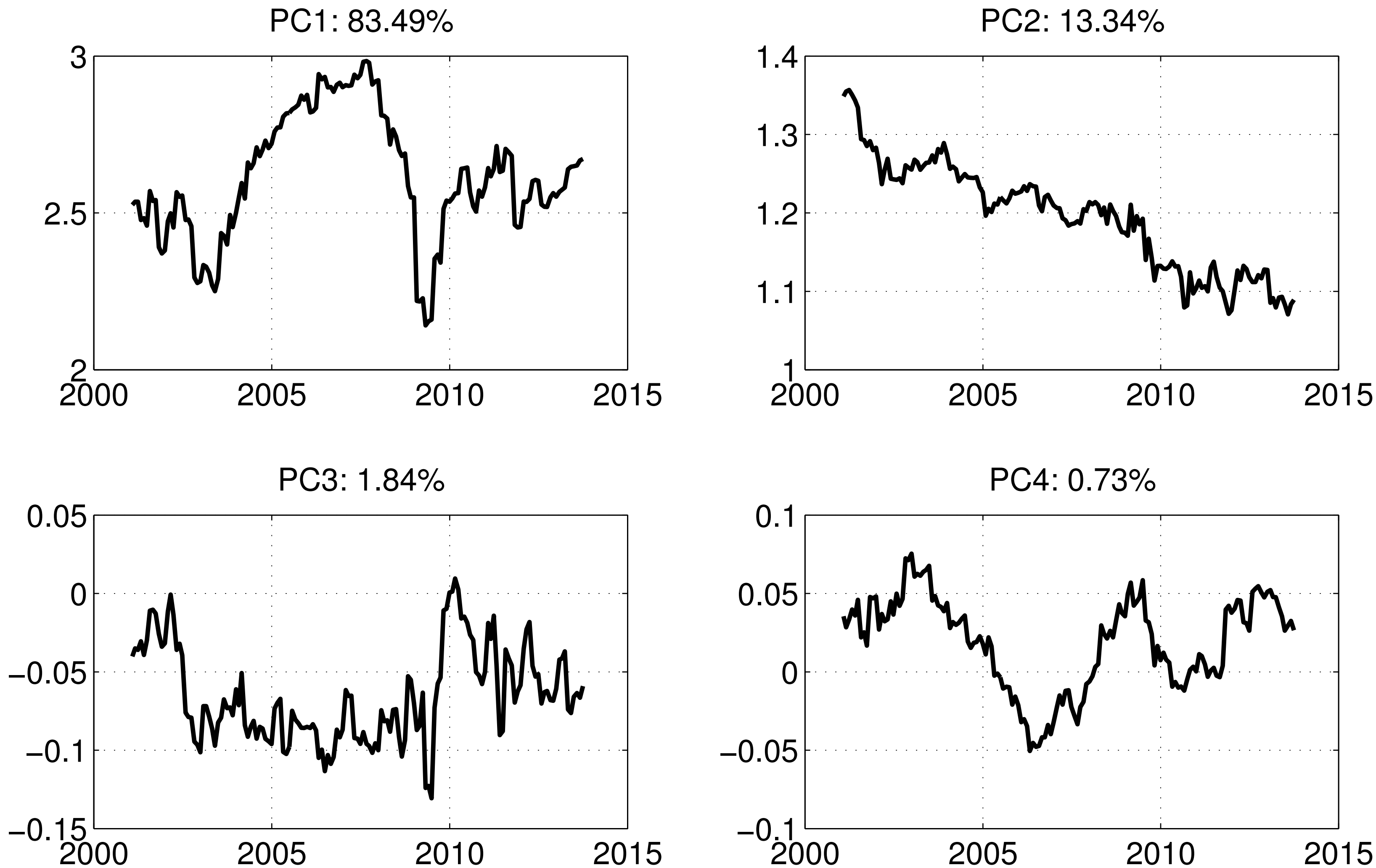


Figure 6: CIV Principal Components

The figure plots the first four principal components of CIV extracted by 50 portfolios of CIV sorted on 10 leverage bins for each of the five maturities. The explained variability of each PC is reported at the top of each graph.



References

Fischer Black and Myron Scholes. The pricing of options and corporate liabilities. *The journal of political economy*, pages 637–654, 1973.

Darrell Duffie. Credit swap valuation. *Financial Analysts Journal*, pages 73–87, 1999.

Peter Feldhütter and Stephen Schaefer. The credit spread puzzle-myth or reality? Technical report, Working paper, London Business School, 2014.

John Hull, Izzy Nelken, and Alan White. Merton model, credit risk, and volatility skews. *Journal of Credit Risk Volume*, 1(1):05, 2004.

Robert C Merton. On the pricing of corporate debt: The risk structure of interest rates. *The Journal of Finance*, 29(2):449–470, 1974.