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REALIZED MOMENTS AND BOND PRICING

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Realized Moments and Bond Pricing

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Abstract:
This paper examines both intertemporal and contemporaneous relationship between excess US Treasury futures returns and realized moments - realized volatility, realized skewness and realized kurtosis using high-frequency data. We find realized skewness to have significant negative effect on future excess returns, on the contrary realized volatility and realized kurtosis remain insignificant. Moreover, in addition to strong explanatory power of realized skewness for contemporaneous excess returns, we find evidence of intra-temporal returnvolatility trade-off dependent on skewness regime (i.e. positive or negative skewness).

JEL: C32, C55, G12
Keywords: Realized moments, bond pricing, risk-return trade-off, high-frequency data

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1 Introduction

Thorough understanding of the risk-return relationship is of key importance for asset pricing. In spite of the indisputable importance of Treasury bills and bonds in investors' portfolios, the existing literature analysing the famous risk-return trade-off has been in vast majority focused on equities.

Our study aims to extend the existing risk-return literature in multiple aspects. First, as mentioned above, we have the ambition to enhance the rather scarce literature dedicated to the risk-return trade-off analysis of government bonds since the vast majority of the studies cover the issue on equity markets. Our ambition is mainly motivated by different fundamentals of bonds as compared to equities or corporate bonds and therefore, the comprehensive empirical analysis of the risk-return analysis is relevant. Second, with respect to the ambiguity of already published empirical results of the contemporaneous and inter-temporal risk-return relationship, we would like to present a consistent analysis of both topics using the identical dataset applied to multiple model specifications inspired by existing risk-return literature. Third, since the majority of the risk-return literature followed the famous work by Fama and French (1993), the risk measures were predominantly derived from low-frequency data. Having an extensive high-frequency dataset on hand, we would like to leverage the additional information present in higher frequencies for our comprehensive risk-return analysis of government bonds.

Benefiting from our rich high-frequency dataset, we inspect effects of realized moments (namely volatility, skewness and kurtosis) on future and contamporaneous bond futures returns and find a significant explanatory power of realized skewness both for inter-temporal and intra-temporal modification.

The remainder of the text is structured as follows. Section 2 provides brief summary of key asset pricing fundamentals and reviews existing relevant theoretical and empirical work. Methodological approach is outlined in Section 3, followed by data presentation in Section 4. Empirical findings of both intra-temporal and inter-temporal risk-return relationship are provided in Section 5 whereas Section 6 concludes.

2 Risk-return relationship on fixed income markets

2.1 Fundamentals of asset pricing

Asset pricing theory has attracted significant attention since 1970s when the capital asset pricing model, random walk, or efficient market theory had been introduced (Cochrane, 2009). Generally, the theories were based on the idea that market prices reflect the relevant fundamental information, i.e. the markets are informationally efficient (Malkiel and Fama, 1970). Concretely for bonds, the key proposition claimed bond returns to be unpredictable. According to the expectations model the fact that yield curve is usually upward sloping signals the expectation of rising short-term interest rates in the future and does not imply anything about long-term bond returns to outperform the short-term instruments. However, as Cochrane (2009) reminds, the recent empirical literature revisiting the aforementioned concepts gradually arrived to broader application of multi-factor models for explanation of future returns (rather than models relying on market betas of the respective assets). In fixed income context, more recent works show bond returns to be predictable to some extent.

Starting from a very general asset pricing principle, as comprehensively summarized by Cochrane (2009), price of an asset must be equal to the present value of future cash flows arising out of holding the asset. An investor always compares future payoffs related to an asset discounted to present value in order to reflect her impatience in consumption and aversion to risk. This decision in a form of a basic asset pricing formula can be expressed as:

$$p_t = E(m_{t+1}x_{t+1}) \tag{1}$$

where p_t refers to an asset price and x_{t+1} is an asset payoff. Discount factor m_{t+1} reflecting an investor's preferences subject to constraints is defined as:

$$m_{t+1} = \beta \frac{u'(c_{t+1})}{u'(c_t)} \tag{2}$$

reflecting the investor's trade-off between loss in utility in time of the investment $u'(c_t)$ due to lower consumption c_t and upside in utility due to extra payoff in the next period and the investor's subjective factor capturing her willingness to postpone the consumption in time. As Cochrane (2009) recalls, the above summarized consumption-based model is a starting point to most asset pricing approaches since they are in essence trying to tie the discount factor m_{t+1} to various variables - this stream of literature is mostly associated with factor pricing models.

Concretely in case for fixed income instruments, nominal price of a bond is driven by multiple factors which can be classified into two groups. First, the factors having an actual effect on cash flows such as expected inflation while the second class consists of discount rate effects such as expectations of future interest rates and of future bond excess returns.

2.2 Literature review

The existing empirical literature of the risk-return relationship can be generally classified into two streams. First, there are works having the ambition to challenge the traditionally widely expected principle of no predictability of returns on financial markets, and second, there are studies empirically inspecting the contemporaneous risk-return trade-off. Though understanding the contemporaneous relationship of risk and returns is definitely interesting, forecasting perspective (i.e. intertemporal analysis) attracted more attention in the literature, often with ambiguous or contradicting results.

Classic literature related to predictability of bond returns challenging the expectation hypothesis include significant portion of literature claiming that term spreads carry significant predictive power for bond returns. These influential works such as Fama (1976), Fama (1984), Fama and French (1989) or Campbell and Shiller (1991) are built upon widely accepted hypothesis that the term spread reflects the term risk premium compensating investors for their exposure to interest rate (or discount rate) and duration risks. In addition to term spread, Fama and French (1989) find bond market default spread to contribute to stock and bond returns predictions. Other works finding certain level of bond return predictability includes Fama and

Bliss (1987) who analysed predictive power of spread of forward rates and one-year yields in case of bond excess returns. In the past decade, number of studies surged as a reaction on the work by Cochrane and Piazzesi (2005) who show the predictability of US bond returns using a tent-shaped linear combination of forward rates on monthly data. Since their work became to a large extent a benchmark study in this field, multiple authors enhanced the Cochrane-Piazzesi approach by adding additional factors improving the predictive power such as Wright and Zhou (2009) who augmented the original model by multiple volatility measures (e.g. realized volatility, implied volatility, jumps-related measures) and concluded that jump-related measures significantly improved the excess bond return predictability. Recent works challenging the study by Cochrane and Piazzesi (2005) include the work by Adrian et al. (2013) who introduce a three-step ordinary least squares estimator to the pricing of interest rates and claim to outperform the benchmark by Cochrane and Piazzesi (2005).

Other relevant works documenting the failure of the expectation hypothesis include Duffee (2011) or Ludvigson and Ng (2009) who analysed the predictive ability of a hidden term structure factor or macroeconomic variables, respectively. Recently, Gargano et al. (2017) tested the models (and their combinations) proposed by Fama and Bliss (1987), Cochrane and Piazzesi (2005), Ludvigson and Ng (2009) and compared the results to expectation hypothesis benchmark and concluded the combination model to perform the best in out-of-sample forecasts.

As already mentioned the empirical literature of risk-return trade-off is significantly dominated by the studies of equity markets and often led to ambiguous results. The fact that the literature has not reached a consensus regarding the existence and nature of the risk-return relationship on equity markets might be also caused by the concept of risk taken into account in the analyses. Bali and Peng (2006) argued that since conditional volatility of returns is unobservable, different approaches to its estimation might be responsible for contradicting results of the empirical evidence.

Since Andersen and Bollerslev (1998) or Andersen et al. (2003) made volatility observable by introduction of realized volatility concept, authors such as Bali and Peng (2006) confronted the intertemporal risk-return analysis using both latent- and observable-volatility approaches and inspected risk-return tradeoff using high-frequency S&P 500 cash index data. Further, a comprehensive analysis of high-frequency causality between equity returns and volatility was carried out by Dufour et al. (2012). With respect to clear lack of consensus in empirical evidence of existence and nature of the link between return and risk, i.e. whether there is a causal link from return to volatility (also called leverage effect in literature), from volatility to return (also called volatility feedback phenomenon) or whether the link is instantaneous, Dufour et al. (2012) started his study with a complex inspection of Granger-causality of risk and return measures.

Recently, Mueller and Whelan (2017) performed an empirical analysis of relationship between volatility risk and expected returns both in case of equities and US bond market with a conclusion that neither implied nor realized variance did not exhibit a predictive ability for returns, but their spread (variance risk premia) did.

There were also works exploring the role of various volatility components or volatility-related state variables in explaining future excess returns. Among others, Adrian and Rosenberg (2008) documented that excess stock returns are not only governed by covariation of the assets returns with the market returns but there is also a contribution of state variables related to volatility. Adrian and Rosenberg (2008) conclude his study by detecting a positive relationship with long-run volatility and negative with short-run volatility components. This discrepancy between the nature of the relationship of volatility components and returns might explain the lack of consensus in the empirical literature of basic risk-return trade-off. Using the volatility decomposition framework by Campbell et al. (2001), Cai and Jiang (2008) demonstrated the link between corporate bond excess return and (decomposed) volatility. Predictive power of implied variance components for bond and equity returns was studied by Feunou et al. (2013). Further, relationship between volatility and returns in cross-section of bond returns was recently inspected also by Chung (2018) who detected the negative relationship between volatility innovations of VIX index. Information content of VIX term structure was tested by Johnson (2017) or Wang and Yen (2017) who found the first two principal components to be informative for future stock returns.

Further, Dotsis (2017) analyzed market price of individual principal components of VIX term structure in the cross-section of asset returns and found that slope of the VIX term structure captures changes in excess returns over longer horizons whereas level and curvature components were more related to short-term variations in excess returns.

Adding to the academic debates as summarized above an practitioners' angle, Amromin and Sharpe (2012) conducted a survey among stock investors and showed that the risk-return link was perceived differently under different macroeconomic conditions. For example, in case of macroeconomic expansion investors tend to expect high returns and low volatility (i.e. that risk and return are inversely correlated), which is in contradiction to standard theory that high volatility is remunerated by higher expected returns.

In addition to traditional risk-return trade-off, there has been a surge of literature exploring relationship between equity returns and higher moments of return distributions (namely skewness and kurtosis). Early work connecting skewness and stock returns was the theory of Kraus and Litzenberger (1976) who claimed coskewness to determine cross-section of stock returns. Recently, there has been multiple empirical works focusing on relationship between skewness and expected returns predominantly on equity markets elaborating on later theoretical concepts claiming negative relationship between skewness and expected returns.

One of these is the work by Mitton and Vorkink (2007) who take into account also behavioural biases of investors, meaning that investors' preferences are heterogeneous. The authors argue that in addition to "traditional" investors there are also "lottery-type" investors preferring assets with positively skewed return distributions, and therefore, returns to these lottery-type stocks deteriorate due to overpricing. According to Mitton and Vorkink (2007), the overpricing is not arbitraged due to short-selling restrictions.

Similarly, theory by Barberis and Huang (2008) arrives to similar conclusions though by different reasoning. The authors revisit the cumulative prospect theory by Kahneman and Tversky (1979) which states that investors' utility functions are concave over gains and convex over losses. Barberis and Huang (2008) amend the theory in terms of its probability weighting component reflecting the tendency of investors to overshoot the probability of extreme outcomes. This again leads to willingness of investors to overpay for the positively skewed assets, in other words, that a stock's skewness is priced and affects excess returns. Other theoretical pieces of work supporting risk-averse investor's preference for positively skewed assets include Scott and Horvath (1980), Kimball et al. (1990) or Ebert and Wiesen (2011). Theoretical works assesing relation of higher moment (i.e. kurtosis) and investors' preferences are even more scarce, most referenced works include Kimball et al. (1990) or Haas (2007) suggesting investor aversion to kurtosis.

In contrast to theoretical consensus of negative effect of skewness on (equity) returns, empirical evidence is rather ambiguous. Negative effect of skewness on future equity returns was documented by Kumar (2009) who confirm the lottery-type stocks to underperform or by Bali et al. (2011). Bali et al. (2011) find significant negative effect of occurence of extreme (lottery-type) returns on future returns and by that succeed to explain puzzling negative return-volatility effect found by Ang et al. (2006) or Ang et al. (2009). Further, negative correlation between expected idiosyncratic skewness and stock returns was demonstrated by Boyer et al. (2009), and effect of ex ante moments on expected stock returns was inspected by Conrad et al. (2013). Further, significant effect of skewness (or gambling preference) on equity option returns was found by Bali and Murray (2013), Boyer and Vorkink (2014) or Byun and Kim (2016). Informational content of realized moments for future stock return were examined by Amaya et al. (2015) who found significant power of realized skewness to predict cross-section of equity returns. From the relevant recent studies, Jondeau et al. (2019) found that monthly average return skewness across firms performs well in future market return predictions. As far as other than equity market is concerned, Fernandez-Perez et al. (2018) detected skewness to be valuable predictor of commodity futures returns. In contrast, some studies find also positive relationship between skewness and stock returns (e.g. Rehman and Vilkov (2012)).

3 Methodology

As Cochrane (2009) reminds, cornerstone of asset pricing is the reflection of investors' concerns about states of world which have impact on their returns in their investment decisions. In other words, that investors face the trade-off between average returns and (bad) states of the world. In case of factor pricing models, the factor variables should be the indicators of these bad states of world (Cochrane, 2009). Motivated by these considerations we inspect informational content of various return moments for Treasury bond returns of different maturities.

We examine both contemporaneous and inter-temporal relationship between risk and return on the US fixed income market, i.e. whether volatility (eventually higher moments) have any informational content for current or future returns. Inspecting also simple contemporaneous relationship of moments and returns is motivated by the fact that, contrary to the lack of consensus regarding the predictability of asset returns, literature generally agrees on forecastability of volatility. Therefore, having in mind the predictability of volatility, we examine the empirical evidence on the contemporaneous (i.e. intra-temporal) link between risk and return and hypothesize that robust empirical evidence of contemporaneous relationship between return and volatility might be eventually useful for the desired task of bond return predictions. Moreover, since the relevant literature is rather silent on this topic, we perceive the rigorous analysis of link between return moments and bond prices to be meaningful adding to the bond-related literature. Finally, we also believe that analysis of risk-return relationship for bonds across different maturities is contributive since bonds with different maturities are traded on different market segments and the respective risk-return relationship might be perceived (and also grounded) differently.

3.1 Realized moments

3.1.1 Realized variance

Inspecting (and also modeling and forecasting) volatility is complicated by the fact that the actual volatility is not directly observable. Therefore, researchers developed multiple approaches relying on strict parametric assumptions to capture the latency of volatility. These methodologies include autoregressive conditional heteroskedasticity (ARCH) or stochastic volatility (SV) models, or alternatively, option-based implied volatility measures. As Andersen and Teräsvirta (2009) summarize, in order to approximate current and future levels of volatility, some literature also employs historical volatility measures (i.e. backward-looking sample return standard deviation), which generally do not provide with outcomes consistent with basic properties of volatility (such as mean reversion).

Thanks to availability of high-frequency data on various financial assets and to increasing computational power needed for efficient processing of large-scale datasets, we can observe in recent literature stronger presence of model-free data-driven volatility measurements to the detriment of parametric conditional volatility models. As Andersen and Bollerslev (1998) or Andersen et al. (2003) show that realized volatility measures based on intra-day data bring significant reduction in noise and improve stability of the results as compared to the measures relying on daily return observations.

We use *medRV* estimator as formulated by Andersen et al. (2012) constructed as:

$$medRV_t = \frac{\pi}{6 - 4\sqrt{3} + \pi} \left(\frac{N}{N-2} \right) \sum_{i=2}^{N-1} med(|r_{t,i-1}|, |r_{t,i}|, |r_{t,i+1}|)^2 \tag{3}$$

where $r_{t,i}$ generally represents the $i-$th return on trading day t and N is the number of equispaced returns on the trading day. We work also with associated volatility measure $medRVol$ referring to square root of $medRV$.

As discussed in Andersen et al. (2012), *medRV* performs better compared to bi-power or multi-power RV measures in terms of robustness in finite sample with respect to jumps and occurrence of spurious zero returns caused by quote or trade price duplicates.

Within robustness checks we also employ realized variance measure as formulated by Andersen et al. (2003):

$$RV_t = \sum_{i=1}^{N} r_{t,i} r'_{t,i} \tag{4}$$

where $r_{t,i}$ generally represents the $i-$th return on trading day t and N is the number of equispaced returns on the trading day. Analogously, measure $RVol$ refers to square root of RV.

3.1.2 Realized skewness

As Jondeau et al. (2019) recalls, skewness reflecting occurrence of extreme events can be associated with concepts such as tail risk (e.g. Bollerslev et al. (2015)) or disaster risk (e.g. Kozhan et al. (2013)). Motivated also by up-to-date practice to include skewness of returns as an additional risk factor, we include its realized measure to our fixed income risk-return analysis.

Similarly as in case of volatility measure, we suspect varying approaches to skewness estimation as one of the possible sources of result inconsistencies of empirical analyses of skewness-return relationship. Therefore, thanks to availability of high-frequency data we use realized skewness measure which was first introduced by Neuberger (2012). Specifically, we construct the measure following Amaya et al. (2015):

$$rSkew_t = \frac{\sqrt{N}\sum_{i=1}^{N}(r_{t,i})^3}{RV_t^{3/2}} \tag{5}$$

in which $r_{t,i}$ generally represents the $i-$th return on trading day t, N is the number of equispaced returns on the trading day and RV_t refers to realized variance.

3.1.3 Realized kurtosis

Similarly as in case of lower moments, problematic measurement (or estimation) of the fourth moment might be responsible for scarceness and ambiguity of empirical literature testing moment predictive power with respect to future asset returns. Again, having high-frequency data at our disposal, in construction of realized kurtosis we follow the pioneering work by Amaya et al. (2015):

$$rKurt_t = \frac{N\sum_{i=1}^{N}(r_{t,i})^4}{RV_t^2} \tag{6}$$

in which $r_{t,i}$ generally represents the $i-$th return on trading day t, N is the number of equispaced returns on the trading day and RV_t refers to realized variance.

3.2 Model

Our basic model capturing effect of return moments on future bond excess return is expressed in the following equation:

$$r_{t+1} = \alpha + \beta_1 RVol_t + \beta_2 RSkew_t + \beta_3 RKurt_t + \epsilon_t \tag{7}$$

where r_{t+1} is bond excess return and the explanatory variables refer to realized measures of volatility, skewness and kurtosis, respectively, as defined in the preceding section.

Following Bali and Peng (2006), we extend the basic model with a lagged return to mitigate the potential spurious effect due to serial correlation in returns and compare the results of the original specifications.

In order to filter out the effects already priced in traditionally used risk factors, we augment our basic model by multiple control variables. For final model specification we have decided to use similar logic to traditional Fama-French bond factors being able to capture business cycle fluctuations. We restrict ourselves to additional two control variables which proved to be priced in (bond) excess returns - term spread and default spread. The former is in our case defined as difference between yields on 10-year Treasury bond and 3-month Treasury bill, whereas the default spread is calculated as difference between yields on BAA-rated and AAA-rated US corporate bonds. Thus, final full-scope model with all the control variables is constructed as follows:

$$r_{t+1} = \alpha + \beta_1 RVol_t + \beta_2 RSkew_t + \beta_3 RKurt_t + \gamma_1 r_t + \gamma_2 Term_t + \gamma_3 Def_t + \epsilon_t \tag{8}$$

where the additional control variables refer to lagged excess return, term spread and default spread, respectively.

As mentioned earlier in text, in sake of compactness of the analysis we also analyze contamporaneous trade-off between excess returns and realized moments controlling for traditional risk factors and past returns. In that case, the model specification remains with an exception of explained excess return r_{t+1} being replaced by r_t and explanatory past excess return r_t being obviously replaced by r_{t-1}.

Moreover, motivated by puzzling results by variance-return relationship, we decided to amend the contamporaneous analysis by an additional angle capturing different effect of volatility on returns for positive and negative skewness:

$$r_t = \alpha + \beta_1 RVol_t + \beta_2 RSkew_t + \beta_3 RKurt_t + \beta_4 (I_t \times RVol_t) + \gamma_1 r_{t-1} + \gamma_2 Term_t + \gamma_3 Def_t + \epsilon_t \tag{9}$$

where I_t refers to skewness indicator equal to 1 if realized skewness is positive and 0 otherwise.

4 Data

4.1 US Treasury futures prices

For our analysis we use 1-minute US Treasury futures data (active contracts) from Tick Data, Inc.[1] database. We examine contracts for each US Treasury benchmark tenors, i.e. 2-year (CME global ticker: TU), 5-year (CME global ticker: FV), 10-year (CME global ticker: TY) and 30-year (CME global ticker: US) traded at the world's leading electronic platform CME Globex under Chicago Board of Trade trading rules.

There are multiple reasons why to analyze futures instead of cash market in order to examine the risk-return relationship. First, as long as this paper applies data-driven methodology in order to estimate volatility (as well as higher moments), immediate availability of clean 1-minute high-frequency futures data from renowned database is extremely beneficial. Second, observing situation on US bond market in past decade, futures market has been gaining relative importance to the cash market[2]. Third, due to delivery mechanism of US Treasury futures contracts, futures prices are tightly linked to underlying bond prices (and yields), and moreover,

[1] http://www.tickdata.com/

[2] See The New Treasury Market Paradigm, CME Group, June 2016, available at https://www.cmegroup.com/education/files/new-treasury-market-paradigm.pdf.

also due to lower transaction costs, futures market was detected to be dominant to cash market in reaction to news and price discovery process (see e.g. Brandt et al. (2007), Andersen et al. (2007) or Engle (1998)). Panzarino et al. (2016) found that volatility on the futures market tends to spread to cash market, whereas the reverse flow is rather much weaker.

For our analysis we restrict ourselves to futures price observations in the period from 1/2/2001 to 12/31/2015. The selection of the inspected timeframe is beneficial, as long as throughout the entire period the futures contracts have consistent specifics and delivery conditions especially in terms of annual coupon rate of the underlying bond contract which changed to 6% in 2000. We believe that 15 years of 1-minute high-frequency observations covering also turbulent period of recent financial crisis represent wide variety possible market situations reflected in various volatility regimes on the respective markets.

Figure 1 presents time series of US Treasury futures prices in the period from January 2001 to December 2015.

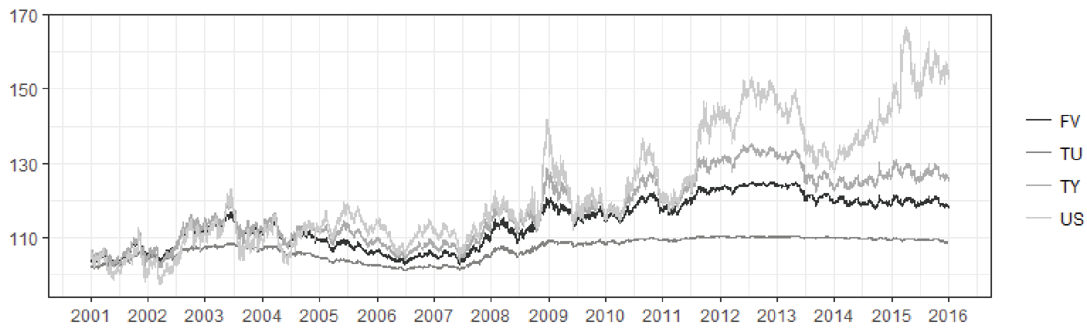

Figure 1: US Treasury futures prices development (TU: 2-year, FV: 5-year, TY: 10-year, US: 30-year)

The data show diverging futures prices, especially in case of the longest 30-year tenor. As the bond prices are inversely related to yield levels, the significant growth price of the 30-year bond future relatively to the shorter tenors reflect the flattening of the US yield curve (measured by decreasing spread between 30-year and 2-year bonds) observable on the market since the global financial crisis. General rise in the Treasury futures prices due to low-interest policy pursued by the Federal Reserve (and associated uncertainty and speculations of the potential policy change) impacted the long-term contracts more due to their inherent higher sensitivity to the interest rates changes.

The raw high-frequency data on US Treasury futures prices are clean and validated by TickData in-house system. However, we need to perform several more steps in order to acquire solid and representative time series for meaningful calculation of realized volatility and open-close log-returns used for the analysis

First step is to exclude non-active days such as weekends or public holidays in the USA. We also drop days having only a single unique futures price observation during the trading day. This procedure leaves us with 3,814 days.

In order to inspect trading activity on US Treasury futures market we plot intra-day distribution of trading volume by calculating mean over the entire period of volumes traded in a given minute (see Figure 2). We observe that largest activity is present during Chicago Mercantile Exchange trading hours, i.e. 07:20 to 14:00 CT. However, due to operation of trading electronic platform CME Globex, significant trading activity is observable also outside the CME trading hours. Therefore, we decide to extend the interval for purposes of realized volatility calculation by two hours on each pole and to define the trading day for our realized volatility calculation purposes from 05:20 CT to 16:00 CT in order to include all significant activity to our calculations (see the shaded area in Figure 2). Moreover, this window includes the regular announcements issued by Federal Reserve System and other relevant authorities which represent significant determinants of changes on the US Treasury market (Andersen and Benzoni, 2010).

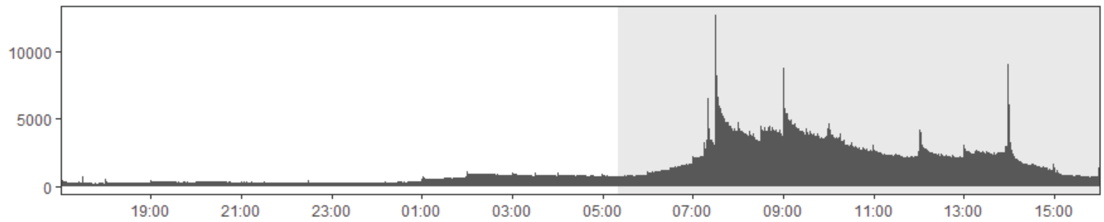

Figure 2: Trading activity: sum of mean trading volumes for TU (2-year), FV (5-year), TY (10-year) and US (30-year)

Based on the findings in the relevant literature (summarized in e.g. Liu et al. (2015), Hansen and Lunde (2006)), we aggregate our data to 5-minutes sampling interval in order to benefit from optimal trade-off between bias and variance, which leaves us with final number of 491,981 observations.

Summarized, using the dataset described above, we calculate open-close log-returns and realized moments (variance, skewness and kurtosis) for each tenor. It should be noted that all independent variables were satisfactorily tested for stationarity in order to reject the unit-root contamination of the regressions.

	Mean	Median	Std	Skew	Kurt	AR(1)
Panel A: Daily returns [%]						
2-year (TU)	0.005	0.000	0.101	-0.254	10.546	-0.014
5-year (FV)	0.009	0.014	0.252	-0.245	3.714	-0.025
10-year (TY)	0.012	0.024	0.378	-0.180	3.258	-0.032
30-year (US)	0.009	0.027	0.617	-0.114	2.095	-0.019
Panel B: Realized volatility [%]						
2-year (TU)	0.088	0.074	0.044	2.467	9.695	0.686
5-year (FV)	0.207	0.185	0.098	1.972	7.611	0.614
10-year (TY)	0.318	0.285	0.137	2.058	8.002	0.592
30-year (US)	0.541	0.499	0.203	2.441	17.670	0.559
Panel C: Realized skewness						
2-year (TU)	0.022	0.000	1.894	0.001	7.251	0.003
5-year (FV)	0.009	-0.007	2.057	-0.029	5.476	-0.003
10-year (TY)	-0.014	-0.025	1.891	-0.045	5.880	-0.012
30-year (US)	-0.055	-0.039	1.577	-0.251	6.738	0.015
Panel D: Realized kurtosis						
2-year (TU)	10.120	4.737	14.324	3.620	15.755	0.115
5-year (FV)	11.079	5.313	15.032	3.327	12.820	0.082
10-year (TY)	10.151	5.222	13.436	3.543	14.772	0.046
30-year (US)	8.519	5.010	10.510	4.062	20.074	0.041

Table 1: Summary statistics of US Treasury futures daily returns and realized moments

Table 1 presents summary statistics of daily returns and realized moments. In Panel A we observe average open-close returns of approximately 0.01% for all maturities. Annualized returns range from 1.3% to 3.0%. Median daily returns as well as their standard deviations increase in maturity. Skewness of daily open-close returns is for all maturities negative and closer to zero for longer maturities. Excess kurtosis is especially apparent in case of the shortest maturity and indicates thicker tails as compared to normal distribution. Commonly for all maturities, AR(1) coefficient is negative and relatively close to 0.

Panel B of Table 1 indicates that both mean and median values of realized volatility are apperently increasing with maturity of the underlying US Treasury as illustrated also in Figure 3 including confidence interval[3]. Annualized realized volatility is ranging from 1.4% for 2-year to 8.6% for 30-year US Treasury bond. First-order serial correlation of realized volatility is for all maturities above 0.5 indicating highly persistent series.

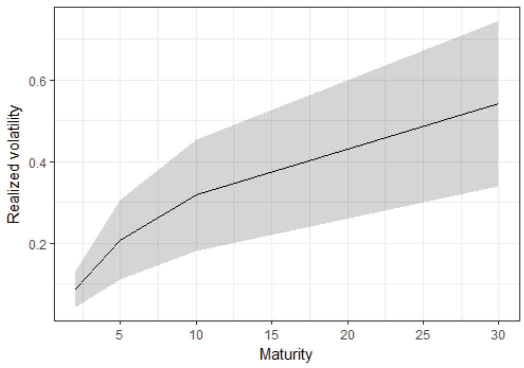

Figure 3: Mean realized volatility term structure

Contrary to the second moment, realized skewness is both in median and average close to zero and not systematically positive or negative. AR(1) correlation is very close to 0. Aslo in case of realized kurtosis there are hardly observable any links with its distributions with maturity.

As mentioned above, instead of explaining real returns we comply with best practice in the literature and work with excess returns earned above risk-free three-month T-bill rate. Further, with respect to trade-off between noisiness and meaningful frequency, we employ the above mentioned variables in weekly frequencies in our model. Whereas weekly log-returns and realized volatility are aggregated by summations of the respective daily observations, weekly measures of realized skewness and kurtosis correspond to weekly means.

Figure 4 presents above specified variables of 10-year US Treasury (other maturities available in Appendix).

[3]The term structure was constructed based on mean realized volatility for maturities of 2, 5, 10, and 30 years.

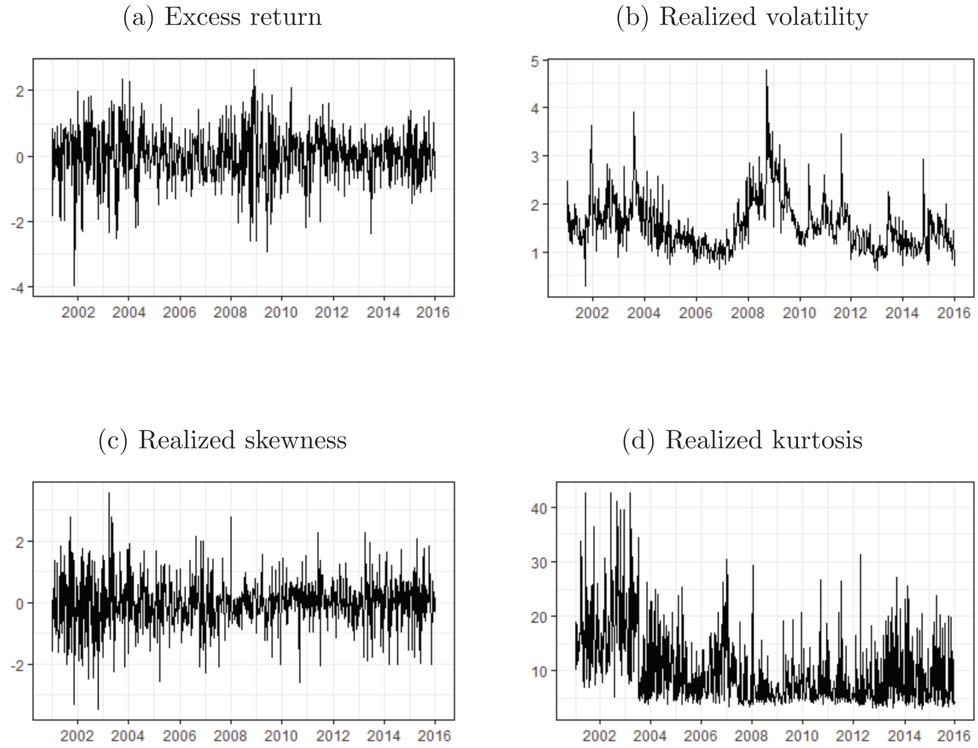

Figure 4: 10-year US Treasury (weekly)

4.2 Control variables

As mentioned earlier, we include control factors proved in the bond return literature to have a certain explanatory power - term spread and default spread. We follow Bali and Peng (2006) who define the spreads as difference between yields on the 10-year Treasury bond and 3-month T-bill, and difference in long-term Moodys BAA-rated and AAA-rated corporate bond yields,respectively. The respective daily yields were obtained from Federal Reserve Bank of St. Louis[4] and are displayed in Figure 5 (descriptive statistics are provided in Appendix).

It is apperent that the spread developments have been reflecting business conditions in the country. Significant flattening of US yield curve (i.e. term spread decreasing to - or even below - zero) has been usually a signal for a forthcoming economic slowdown (Estrella, 2005). Since term spreads are proxy for (unobservable) term premiums investors require for their exposure to longer maturity, term spreads tend to follow the business cycle (Domian and Reichenstein, 1998). Thus, term premiums (and term spreads) increase under poor business conditions and decrease in prosperity. Similarly, default spreads widen during recessions since investors' demand for safer bonds pushes the top-rated yields down. On contrary, when the economy starts to recover and investors trust increases they again shift their interest also to lower-rated bonds which again narrows the default spread[5].

[4]Link to databank: https://fred.stlouisfed.org/categories/22. Weekly observations were in line with FRED practice constructed as averages. Possible missing observations completed by linear interpolations.

[5]It is worth noting that the same economic conditions are captured by dividend yields (Fama and French, 1989).

(a) Term spread (b) Default spread

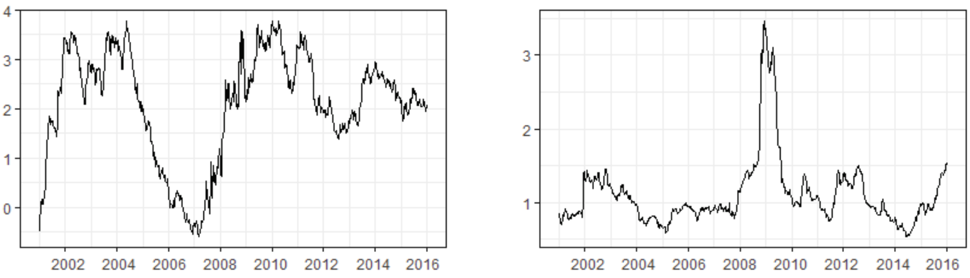

Figure 5: Control variables (weekly): term spread and default spread

5 Results

5.1 Effect of realized moments on future excess bond returns

Contribution of realized moments (and control variables) for future excess bond returns predictions is summarized in Table 2. On the first sight the prediction model is underperforming in case of the shortest 2-year maturity bond since the intercept turns out to be significant. We assign this finding to different nature (and drivers) for maturities on the short-end of US Treasury term structure as compared to medium- and long-term maturities as might be observed on Figure 1. On the contrary, in all other cases the variables appear to explain the variations in weekly bond excess returns well leaving the intercept insignificant. Therefore, when interpreting the results of inter-termporal risk-return tradeoff, we refer to returns of 5-year (FV), 10-year (TY) and 30-year (US) Treasury futures.

Inter-temporal	**TU**	**FV**	**TY**	**US**
(Intercept)	**-0.077 ***	-0.064	-0.058	-0.010
	(0.032)	(0.081)	(0.125)	(0.224)
medRVol	-0.042	-0.079	-0.102	-0.064
	(0.057)	(0.056)	(0.078)	(0.095)
RSkew	-0.020	**-0.070 ***	**-0.119 ****	**-0.206 ***
	(0.016)	(0.031)	(0.047)	(0.081)
RKurt	-0.002	-0.003	-0.002	-0.010
	(0.001)	(0.003)	(0.004)	(0.009)
ret_{t-1}	0.034	0.083	0.081	0.064
	(0.063)	(0.054)	(0.057)	(0.052)
Term	**0.037 *****	**0.065 *****	**0.097 *****	**0.143 *****
	(0.008)	(0.018)	(0.027)	(0.042)
Def	0.029	0.047	0.054	-0.028
	(0.022)	(0.067)	(0.115)	(0.211)
N	782	782	782	782
R^2	5.1%	3.1%	2.5%	1.9%

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table 2: Inter-temporal regression of excess returns on realized moments and control variables. Dependent variable excess bond return is regressed on lagged median realized volatility (medRVol), lagged realized skewness (RSkew), lagged realized kurtosis (RKurt), lagged excess bond return (r_{t-1}), lagged term spread (Term), and lagged default spread (Def). Heteroskedasticity and autocorrelation robust standard errors are provided in parantheses. Asterisks indicate significance levels.

In line with ambiguous existing empirical evidence of volatility affecting future returns, we find insignificant result for median realized volatility[6]. The effect remains insignificant even if we control for skewness regime (i.e. whether returns were skewed positively or negatively in the respective week). On the other hand, we find significantly negative effect of realized skewness which is in line both with theory and majority of available empirical studies (though focused on equities). We find the effect to be stronger in its magnitude for longer maturities[7]. As far as realized kurtosis is concerned, we confirm that also in case of Treasury bond futures there si no clear empirical evidence of the effect on future returns. From control variables, we comply with existing research and find positive significant effect[8] of term spread while both past return and default spread remain insignificant. It is worth mentioning that we have also tested other control variable, namely forward rates[9] as successfully applied by Cochrane and Piazzesi (2005) gained from database accompanying the work by Gürkaynak et al. (2007). The effects of realized moments remained whereas the forward rates turned out to be insignificant[10].

With respect to the noise in the high-frequency return data the adjusted R^2 varying around 2-3% for estimation results on weekly data seems reasonable and is also consistent with the previous comparable studies (e.g. Bali and Peng (2006)). Further, it is worth mentioning that due to exclusion of low-activity periods (overnight) realized measures tend to underestimate the daily variation in returns.

5.2 Effect of realized moments on contemporaneous excess bond returns

In addition to the predictive power, we have also inspected to what extent are realized moments priced in contemporaneous excess returns of US Treasury futures. Similarly as in forward-looking model, we find intercept significant in case of 2-year Treasury which leads us to the analogical conclusion that the realized moments are not satisfactory in explaining variations in contemporaneous returns for short-end maturities. Estimation results of model formulated in Equation 9 are summarized in Table 3.

With respect to Singleton and Wingender (1986) conclusion that positive skewness of returns is likely to be followed by negative skewness in the following period, we get reversed signs of skewness effect on contemporaneous returns. This finding is also in line with propositions by Xu (2007) who claimed that due to price convexity (i.e. behavioural premise of over-reaction to good news and under-reaction to bad news) the contemporaneous correlation of returns and skewness is positive.

As far as return-volatilty is concerned, when tested without interaction term of skewness regime and volatility, median realized volatility turned out to be insignificant [11]. On the contrary, after accounting for positive (or negative) skewness, we have obtained significant estimates

[6] We estimated also the same model specification with realized volatility measure as defined by Andersen et al. (2003) as: $RV_t = \sum_{i=1}^{N} r_{t,i} r'_{t,i}$ with very similar results in terms of magnitude and significance (results available upon request).

[7] This finding holds even for standardized returns.

[8] For standardized returns the effect magnitude is approximately stable across maturities.

[9] 2-year, 3-year, 4-year and 5-year forward rates were used as control explanatory variables.

[10] We assign this finding to different structure and frequency of the dataset.

[11] Results available upon request.

Intra-temporal	TU	FV	TY	US
(Intercept)	**-0.083** ***	-0.096	-0.016	0.056
	(0.024)	(0.059)	(0.090)	(0.176)
medRVol	**-0.076**	**-0.204** ***	**-0.225** **	**-0.233** **
	(0.053)	(0.057)	(0.072)	(0.085)
RSkew	**0.119** ***	**0.227** ***	**0.348** ***	**0.688** ***
	(0.011)	(0.027)	(0.042)	(0.079)
RKurt	**-0.002** *	0.001	0.001	-0.001
	(0.001)	(0.002)	(0.004)	(0.008)
ret_{t-1}	0.033	0.047	0.034	0.026
	(0.032)	(0.028)	(0.033)	(0.032)
Term	**0.028** ***	**0.030** *	0.021	0.021
	(0.006)	(0.013)	(0.020)	(0.032)
Def	0.013	0.063	0.081	0.149
	(0.015)	(0.050)	(0.072)	(0.129)
I × medRVol	**0.233** ***	**0.335** ***	**0.342** ***	**0.322** ***
	(0.046)	(0.054)	(0.053)	(0.050)
N	782	782	782	782
R^2	45.7%	45.0%	42.2%	41.4%

*** p < 0.001; ** p < 0.01; * p < 0.05.

Table 3: Intra-temporal regression of excess returns on realized moments and control variables. Dependent variable excess bond return is regressed on median realized volatility (medRVol), realized skewness (RSkew), realized kurtosis (RKurt), excess bond return (r_{t-1}), term spread (Term), default spread (Def), and interaction term of skewness regime and median realized volatility (I × medRVol). Heteroskedasticity and autocorrelation robust standard errors are provided in parantheses. Asterisks indicate significance levels.

on volatility effect on contemporaneous returns which contributes to proposition of Theodossiou and Savva (2015) about risk-return tradeoff being affected by skewness. For zero or negative weekly skewsness negative return-volatility relation is found. On the contrary, for positive skewness the relationship turns to out to be positive for all maturities.

In addition to inspection of the entire 2001 - 2015 period, we have estimated rolling regressions of yearly windows. Having the highest explanatory power, we focus on analyzing return-skewness relationship which was found to be significant for the entire timeframe. Period of global financial crisis appears to be specific in significantly higher effect of skewness on returns. Corresponding slope coefficients and their p-values are provided in Figure 6.

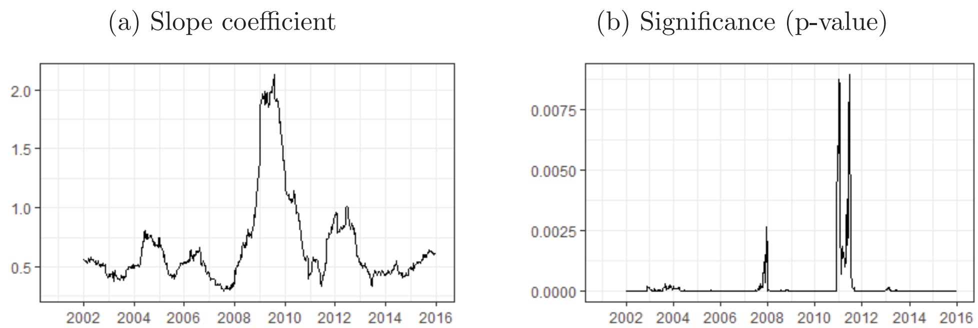

Figure 6: Effect of skewness on contemporaneous excess bond return over time - TY case: Rolling regressions of weekly excess TY return on TY realized skewness (and other independent variables - see Equation 9) are estimated based on rolling windows of past 52 (year equivalent) observations.

Searching further for ambiguity of volatility-return relationship, we dive to higher frequency and inspect correlation structure of daily open-close return to realized volatility of the particular fixed income instrument in various volatility-based clusters. The four clusters are constructed according to the degree of volatility observed on that day. We have sorted the daily observations on return and volatility to four groups according to the corresponding quartile of the realized volatility during the concrete day, i.e. the first quartile (Q1) contains the days with the lowest volatility whereas the fourth quartile (Q4) contains the most volatile days. Correlation results are summarized in Figure 7.

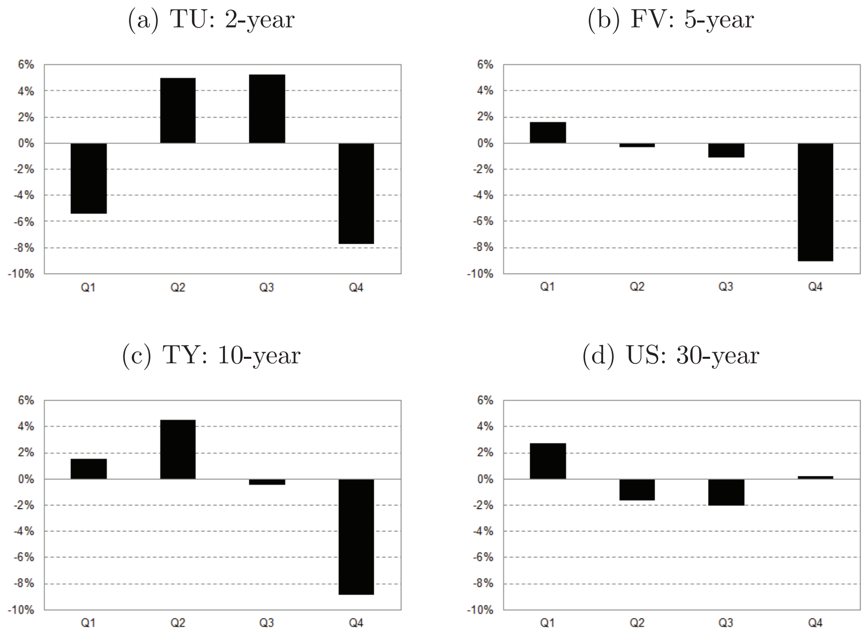

Figure 7: Correlation analysis of realized volatility and return

The correlation structure suggests that the ambiguity of the empirical evidence based on the entire dataset irrespective of the volatility regime might be driven by the differences in the return-risk correlations for individual volatility quartiles. It might be immediately observed that risk-return correlation is varying both in sign and size when conditioned on the volatility quartiles for all the maturities. Interestingly, 2-year, 5-year and 10-year tenors commonly exhibit significant negative correlation of risk and return in the high-volatility regime. For completeness we also attach the analysis of mean daily returns conditioned on volatility quartiles in Appendix (Figure 12) contributing to the observed empirical phenomena of insignificance or ambiguity of the contemporaneous risk-return analysis.

6 Conclusion

Motivated by mixed empirical evidence of the risk-return trade-off on the financial markets and sparse literature focusing on government bonds we contribute by performing the analysis of informational content of realized moments on bond returns across the entire term structure both in inter-temporal and intra-temporal perspective.

First, we find significant predictive contribution of realized skewness on subsequent excess bond returns. We conclude that the effect of realized skewness has negative impact on the next week excess returns which is in line with existing theoretical and empirical works focused on stock returns. On the contrary, effects of the second and the fourth moment remain insignificant.

Second, we inspect contemporaneous relationship between excess bond returns and realized moments. In this case all moments except realized kurtosis are found to be priced in bond returns. Interestingly the direction of the volatility effect is dependent on skewness regime (i.e. negative or positive skewness).

Finally, we have also inspected the features of daily returns and the risk-return relationship (in terms of correlations) conditioned on the volatility regimes (defined as volatility quartiles). We have detected structural differences in the risk-return relationships ranging from slightly positive to distinctly negative correlations. Moreover, the average of daily returns in individual volatility classes significantly differ from the unconditional means and, most notably, turn to be relatively large and negative under high-volatility.

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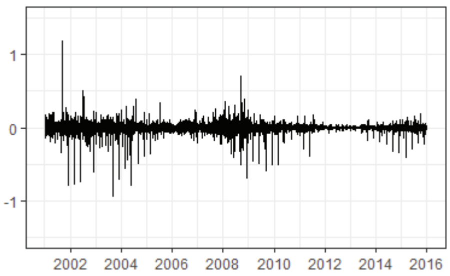
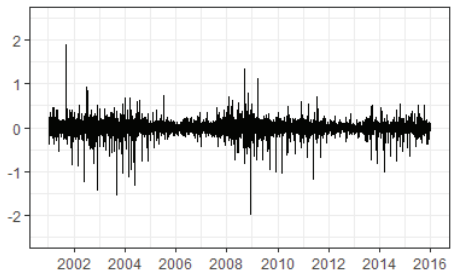
Appendix

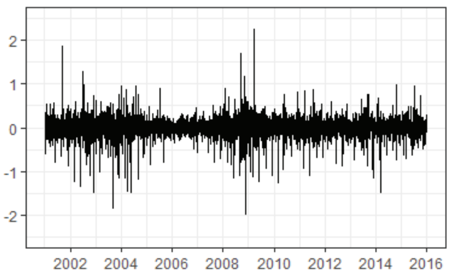
(a) TU: 2-year



(b) FV: 5-year



(c) TY: 10-year



(d) US: 30-year

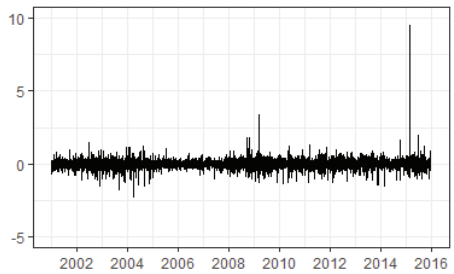
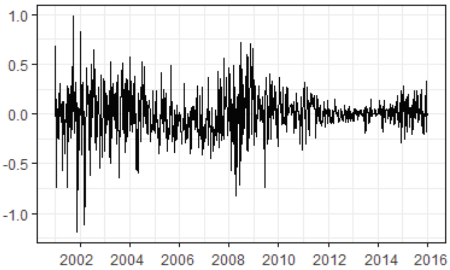


Figure 8: Treasury futures log-returns in percent

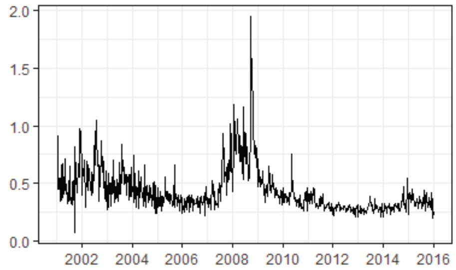
		Excess return				MedRVol				RSkew				RKurt				Controls	
		TU	**FV**	**TY**	**US**	**TU**	**FV**	**TY**	**US**	**TU**	**FV**	**TY**	**US**	**TU**	**FV**	**TY**	**US**	**Term**	**Def**
Excess return	**TU**	1.00																	
	FV	0.90	1.00																
	TY	0.81	0.96	1.00															
	US	0.66	0.84	0.92	1.00														
MedRVol	**TU**	0.04	0.01	-0.02	-0.05	1.00													
	FV	0.02	-0.01	-0.03	-0.05	0.90	1.00												
	TY	0.06	0.01	-0.02	-0.05	0.80	0.94	1.00											
	US	0.09	0.05	0.02	-0.03	0.60	0.79	0.92	1.00										
RSkew	**TU**	0.63	0.56	0.50	0.40	-0.02	0.00	0.00	0.02	1.00									
	FV	0.58	0.61	0.58	0.50	-0.04	-0.04	-0.03	0.00	0.84	1.00								
	TY	0.55	0.60	0.59	0.53	-0.05	-0.04	-0.02	0.01	0.80	0.94	1.00							
	US	0.50	0.57	0.59	0.59	-0.06	-0.05	-0.04	-0.02	0.69	0.83	0.90	1.00						
RKurt	**TU**	-0.07	-0.03	-0.02	-0.02	0.22	0.21	0.10	0.02	-0.03	-0.04	-0.05	-0.06	1.00					
	FV	-0.04	-0.02	-0.02	-0.03	0.14	0.10	0.05	-0.01	-0.02	-0.03	-0.03	-0.04	0.87	1.00				
	TY	-0.06	-0.03	-0.03	-0.03	0.10	0.08	0.02	-0.04	-0.03	-0.04	-0.04	-0.06	0.83	0.94	1.00			
	US	-0.09	-0.06	-0.07	-0.07	0.09	0.07	0.03	-0.04	-0.08	-0.10	-0.09	-0.14	0.72	0.82	0.89	1.00		
Controls	**Term**	0.15	0.08	0.05	0.03	0.13	0.25	0.38	0.41	0.00	0.01	0.04	0.05	-0.02	0.07	0.02	0.02	1.00	
	Def	0.10	0.06	0.03	0.00	0.36	0.39	0.53	0.56	0.01	-0.01	-0.01	-0.03	-0.09	-0.10	-0.11	-0.07	0.22	1.00

Table 4: Correlation matrix of variables: weekly excess returns, weekly sum of median realized volatility (MedRVol), weekly mean of realized skewness (RSkew), weekly mean realized kurtosis (RKurt), weekly term spread (Term) and weekly default spread (Def)

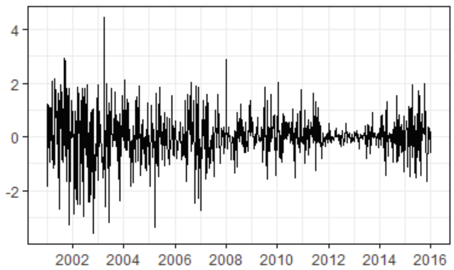
(a) Excess return



(b) Realized volatility



(c) Realized skewness



(d) Realized kurtosis

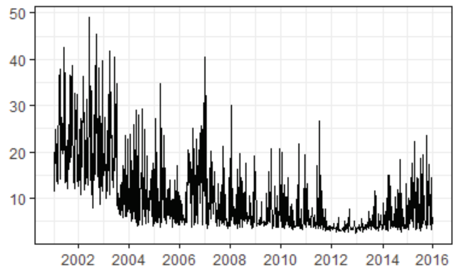
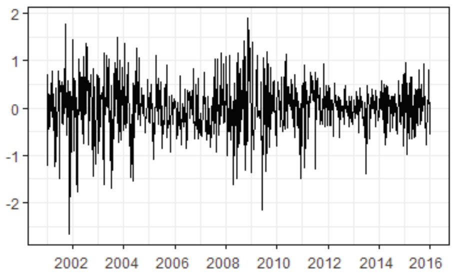
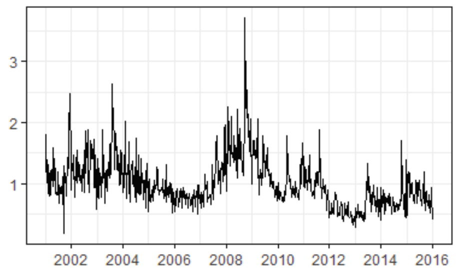


Figure 9: 2-year US Treasury (weekly)

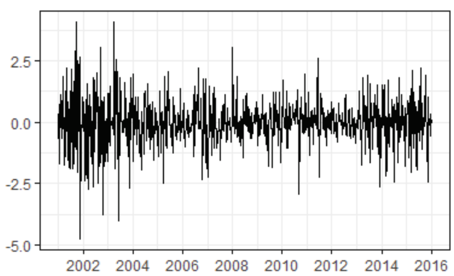
(a) Excess return



(b) Realized volatility



(c) Realized skewness



(d) Realized kurtosis

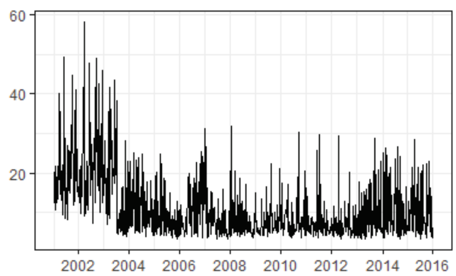
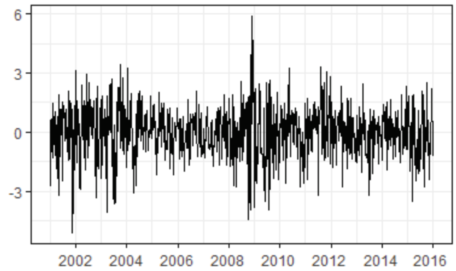
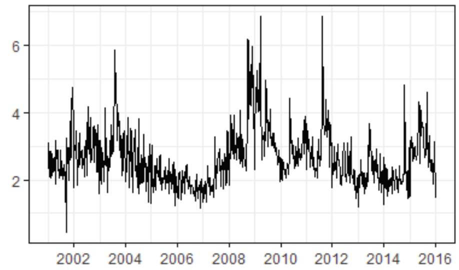


Figure 10: 5-year US Treasury (weekly)

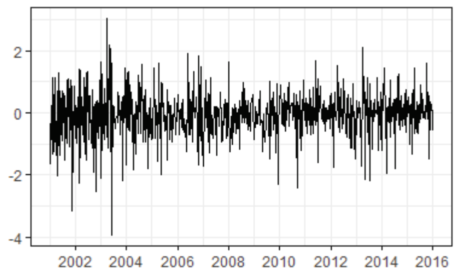
(a) Excess return



(b) Realized volatility



(c) Realized skewness



(d) Realized kurtosis

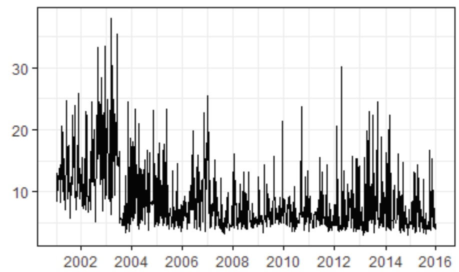
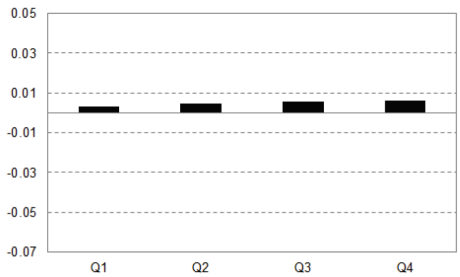
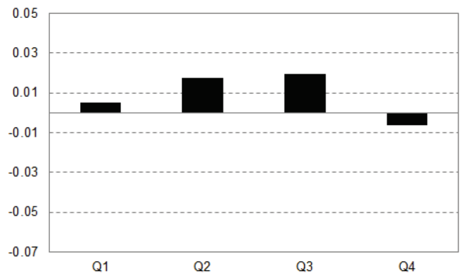


Figure 11: 30-year US Treasury (weekly)

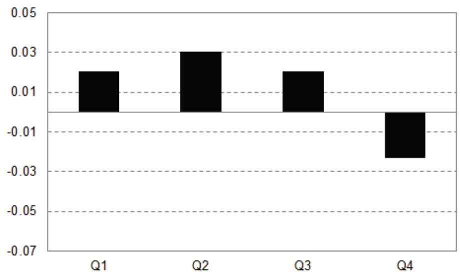
(a) TU: 2-year



(b) FV: 5-year



(c) TY: 10-year



(d) US: 30-year

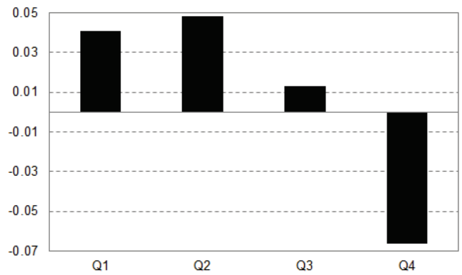


Figure 12: Mean daily return conditioned on realized volatility quartiles (in %)

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