Anomalous Trading Prior to Lehman Brothers' Failure

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Abstract

We study price discovery during the liquidity freeze of September 2008, when fundamental values were difficult to be assessed. We find that trading volume and trade size significantly increased two days before the public announcement of Lehman's lethal quarter loss. Nevertheless, informational risk as perceived by liquidity suppliers increased only after the public disclosure of this loss. The price impact of trades was minimal and stock markets kept on working efficiently for Lehman stocks until the insolvency announcement. Price efficiency is on average established after half a second, which could have been exploited by low-latency traders.

Keywords: Price Discovery, Price Impact, Trading Volume, Low-Latency Trading
JEL classification: G00, G14

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1 Introduction

We analyze market performance of the stock markets for the large U.S. banks around the bankruptcy of Lehman Brothers in September 2008, a period of extreme stress and high informational risk. Clearly this period has been challenging for any trading institution and, therefore, serves well for testing the limits of the market design of U.S. stock markets. Overall we find a surprisingly strong degree of resiliency and a remarkably high degree of efficiency of price discovery in this extreme period. Still, there are discernible patterns in trading activity heralding bad news just before the public disclosure of bad news and the terminal insolvency.

Price discovery is the hallmark of the benefits of a market economy. When prices are sufficient statistics of the relevant information, markets serve as marvellous aggregators of societal knowledge (Hayek (1945)).[1] Still as Hellwig (1980) shows asynchronous trading will impair price discovery to some potentially small degree, but enough to provide incentives for information production (Verrecchia (1982)). While markets seem to work smoothly in normal times, will they operate equally well in periods of distress? Informational risk has always been a well-known determinant of illiquidity (see Fohlin et al. (2015)). This is especially true in volatile markets when fundamental values are difficult to be determined and verified and insiders can easily hide. How will informational risk, and price discovery be impacted around the date of disclosure of disastrous fundamental information and how will the react after a sudden erosion of liquidity?

Market microstructure research typically models the price discovery mechanisms as in Glosten and Milgrom (1985), according to which uninformed competitive dealers protect themselves against adverse selection by charging a positive bid-ask spread. Substantial evidence provides empirical support of this approach not only in U.S. equity markets (e.g., Bernhardt and Hughson (2002) or Aragon and Strahan (2012)). What is less well understood is the timing of market makers' quote revisions and the dynamics of the price discovery process. This is what we concentrate on in this paper. By explicitly tracking informational risk and price efficiency over time, we are able to shed light on the informational efficiency of U.S. equity markets in times of great and increasing informational risk and liquidity freezes.

We specifically concentrate on the period of the disastrous events leading up to the bankruptcy of Lehman Brothers at the climax of the U.S. subprime crisis of 2007/8.

[1] See Foucault and Gehrig (2008) for implications of price discovery on real investment.

Ben Bernanke, then the chairman of the Federal Reserve System (FED) describes in his book "The Courage to Act: A Memoir of a Crisis and Its Aftermath" (Bernanke (2015)) that it was deliberately concealed that Lehman Brothers had too large of a debt position and that hence loans could not be granted by the FED. By concealing this fact, U.S. officials tried to withhold a panic as long as possible.

On September 10, 2008, at 07:30 am Lehman disclosed horrific quarter losses of $3.9 billion. As Figure 4 shows priced did decline significantly, well before the announcement already at both, September 8 and 9. The stock price of Lehman drops by 13 percent and 29 percent, respectively, on September 8 and 9. Yet, the steepest drop in Lehman's stock price happened on September 10 to 11, after Lehman announced the quarter loss and hence the prospects of insolvency. For this time period we observe a drop of 56 percent. So despite the attempts to conceal information by the supervisors, the market apparently did sense or (partially) learn bad information well before the official disclosure. Nevertheless, Figure 5 suggests that the martingale property of prices was not violated, implying informational efficiency (e.g., Fama (1970), LeRoy (1973), and Harrison and Kreps (1978)). As illustrated by the purple line in Figure 5, the hourly means of changes in the price of Lehman stocks remain constant at zero. In fact, the martingale property did uphold even after the disclosure of extremely bad information until the bankruptcy at September 15.

Figure 5, however, also suggests an extremely high degree of volatility at September 8 and 9 prior to the public disclosure of information. This observation suggests to scrutinize in greater detail the microstructure of trading and price determination. In fact, Figures 1 and 3 reveal significant abnormal trading activities on September 8 and 9, 2008; essentially all standard measures of liquidity shoot up in terms of means, medians, and even outliers, and despite the fact that Lehman had not yet released any public statement about their true state of affairs. On the other hand spreads have remained relatively constant throughout (see 6) suggesting that the drivers of prices have not been affected largely by trading activity.

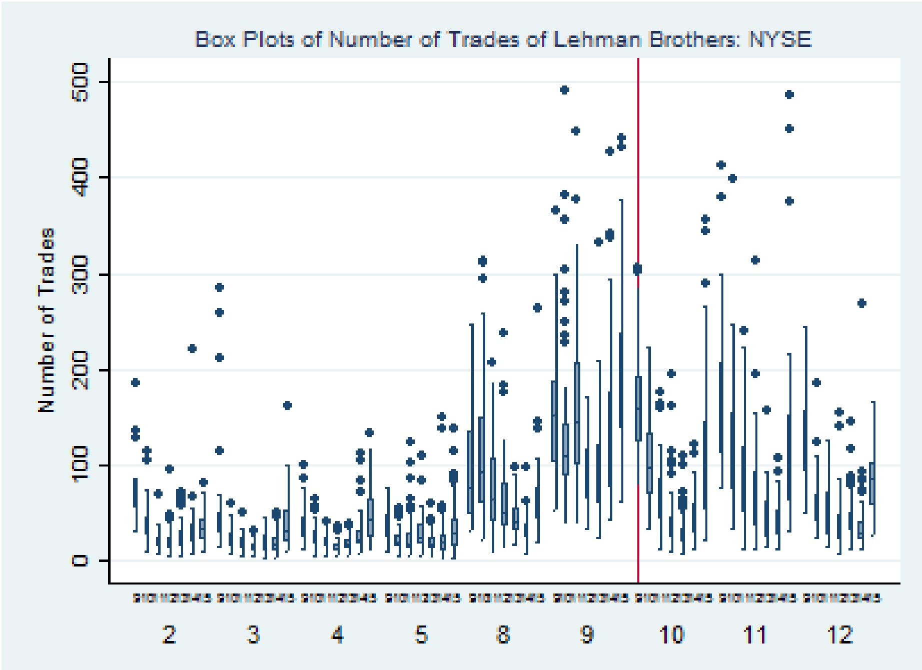

Figure 1: Number of Trades of Lehman Brothers: September 2008 (the red line indicates the quarter loss announcement)

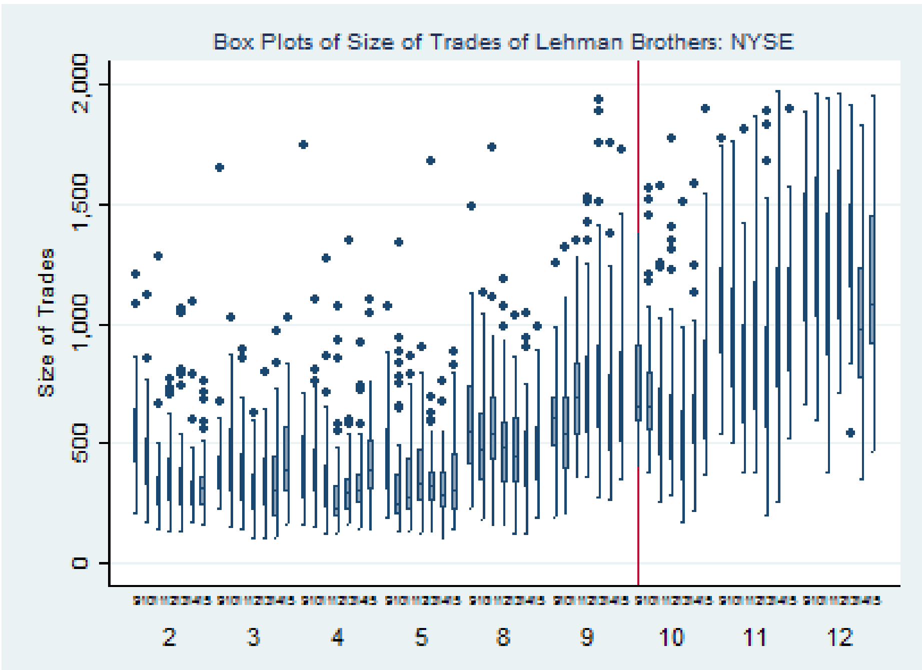

Figure 2: Size of Trades of Lehman Brothers: September 2008 (the red line indicates the quarter loss announcement)

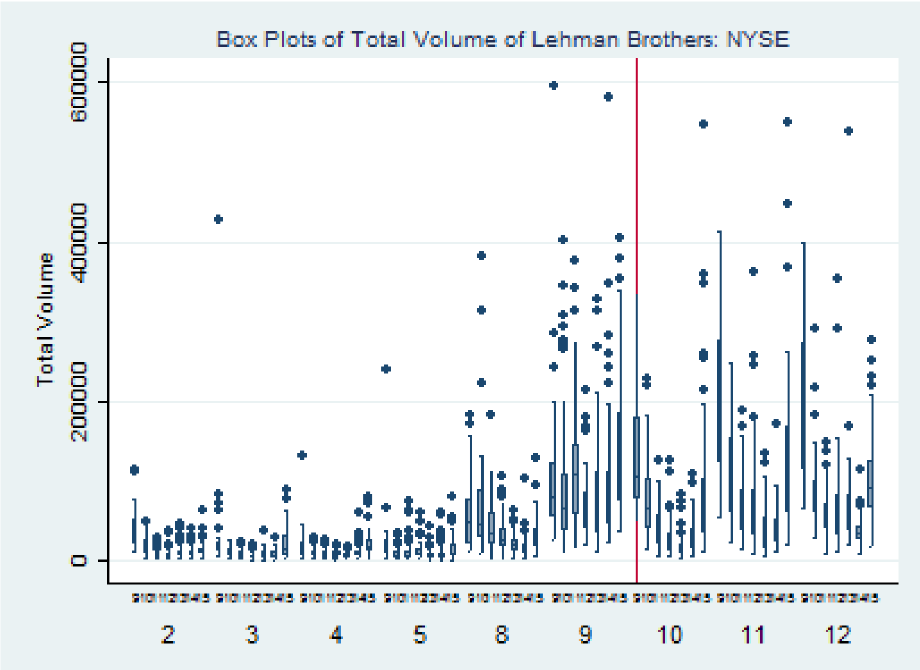

Figure 3: Total Trading Volume of Lehman Brothers: September 2008 (the red line indicates the quarter loss announcement)

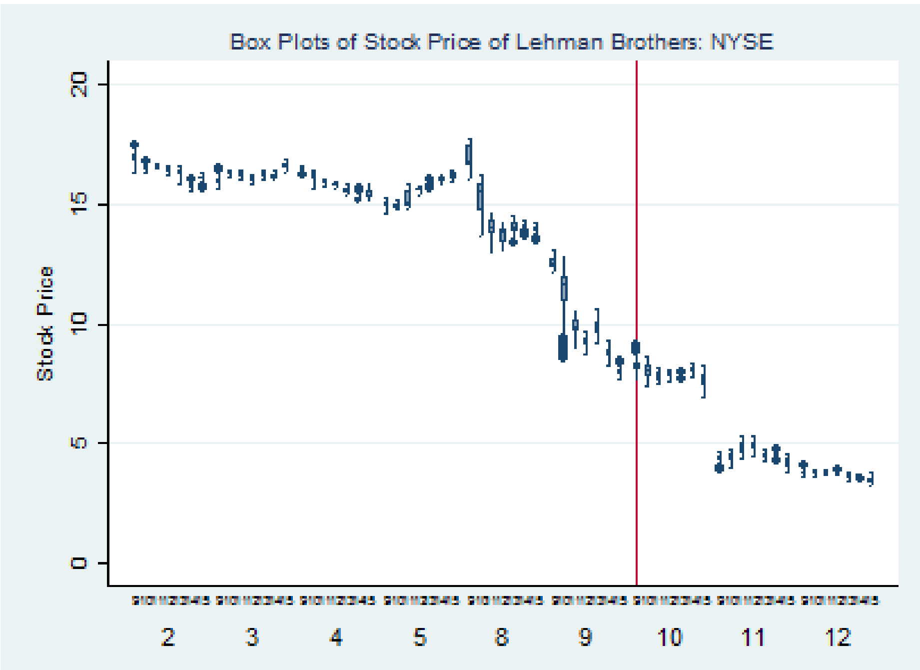

Figure 4: Stock Price of Lehman Brothers: September 2008 (the red line indicates the quarter loss announcement)

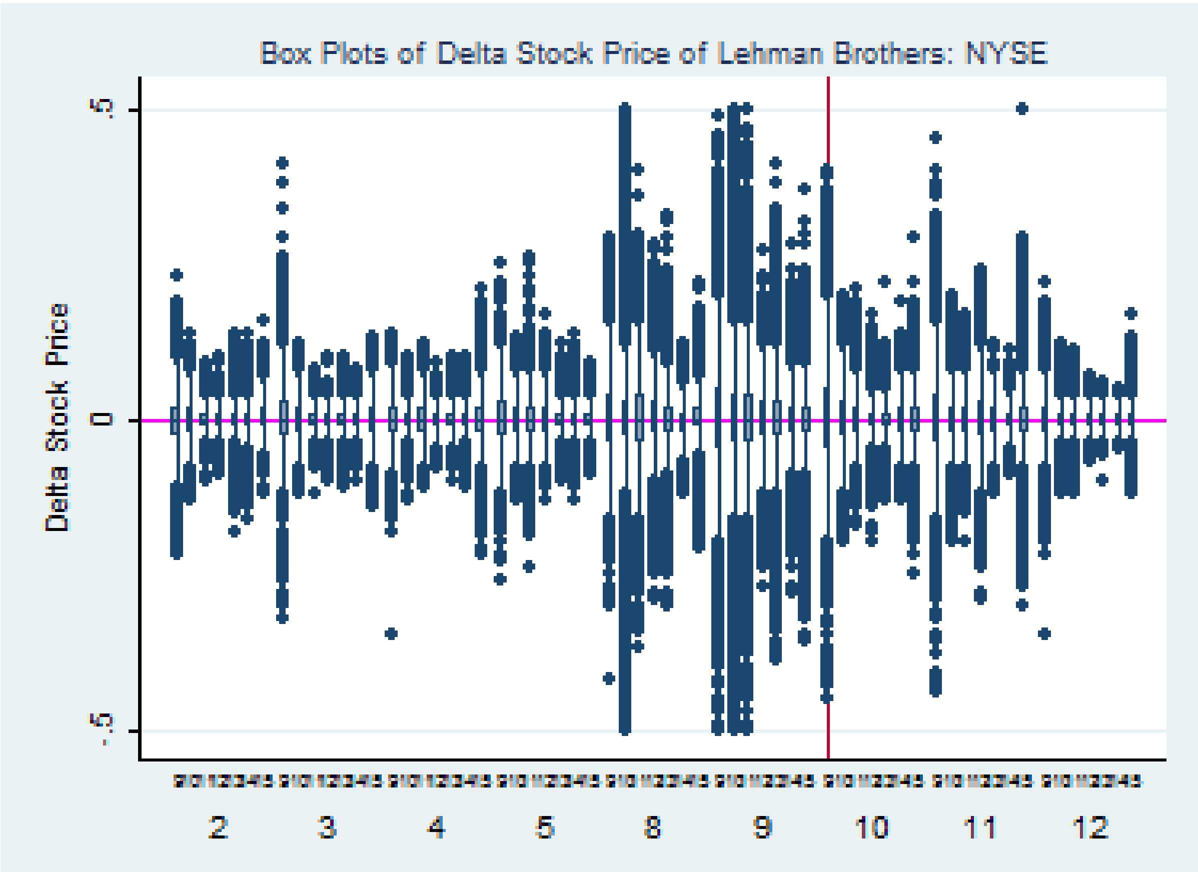

Figure 5: **Change in Stock Prices of Lehman Brothers: September 2008** (the red line indicates the quarter loss announcement)

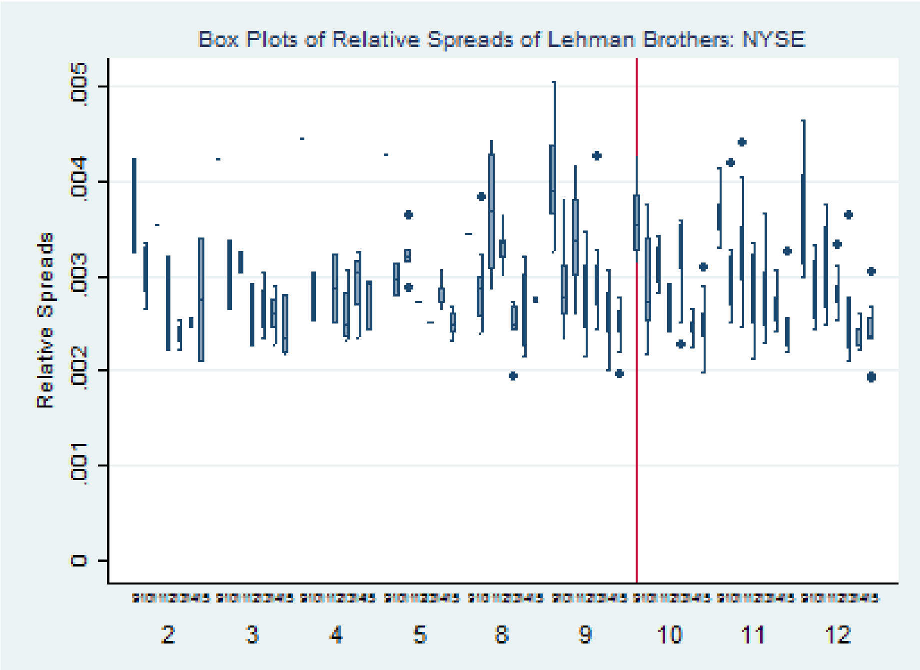

Figure 6: Relative Bid-Ask Spreads of Lehman Brothers: September 2008 (the red line indicates the quarter loss announcement)

While price discovery worked seemingly well and while apparently informationally efficiency was maintained until the end of Lehman stock trading, trading is increasingly hectic and characterized by unusually large variation on both September 8 and 9 (as depicted in Figures 5 and 6). This evidence supports the conjecture, that in fact there was abnormal trading in Lehmans stock *before* the announcement of fundamental news. But how can we explain this phenomenon for the two days prior to the quarter loss announcement? In case insiders - in their very true sense - learned about the pending insolvency, they might have traded on this information already before any public information was to be disclosed. In case market makers did not establish a connection between increased trading activity and fundamentally new information, but rather with liquidity trades, price discovery could have stayed unchanged. This might explain the above described phenomenon. Another explanation could be that our statistics are too rough. For example, by aggregating changes in prices and quotes at an hourly level, small price inefficiencies are overlaid by trading randomness and, hence, cannot be detected anymore. Still, they might exist either on a transaction-by-transaction level or second-by-second level, or in the tails of the price distribution. It is hence important to establish whether the above observed unchanged price efficiency holds for all levels of latency and prices. This is what we focus on and establish in this paper. By analyzing price efficiency as well as informational risk on an intra-daily level for the time period prior to the quarter loss announcement, we can determine whether market makers did indeed thought of the increased trading volume as being due to liquidity or portfolio adjustments, rather than to fundamentally new information.

We use both price-based as well as volume-based measures of informational risk to scrutinize traces of potential market information and, thus, the limits of pricing efficiency. For the volume-based informational risk measure we choose the so-called volume-synchronized probability of informed trading (VPIN) measure introduced by Easley et al. (2012). Their procedure is based on volume imbalance and trade intensity. Our price-based informed trading measure is based on Huang and Stoll (1997), who developed a decomposition approach with which to determine how much of transaction costs (i.e., bid-ask spreads) are due to adverse selection risk. Adverse selection risk is thereby defined as the risk that market makers face of trading with better informed market participants (i.e., insiders).

We find that the volume-based VPIN measure is much more sensitive to exceptional trading behavior than the price-based adverse selection measure. This is because it is able to capture elevated trading on September 8 and 9, 2008, which was two days before any fundamental problems of Lehman Brothers became public. This is not the case with the price-based informational risk measure, which only increases after the release of public information. The lagged reaction of the price-based informational risk measure is due to the fact that it relies on changes in means of spreads. If market makers do not adjust the mean of their spreads to new levels, increases in spreads can also be due to inventory holding costs or order processing costs. The VPIN measure on the contrary is based on the demand side, i.e., on rapidly changing trading volume. It detects a higher probability of informed trading even if traders shred their trades into many small trades because it is sensitive to also the number of trades.

Price efficiency is on average established after half a second on September 8 and 9. On the preceding days it took about five seconds for price efficiency to be established. Hence, these gaps could have been exploited by low-latency traders. Nevertheless, even though market makers were unquestionably confronted with severely increased trading without any fundamental news event, they kept their quoted prices at stable levels, and only increased spreads once fundamental news were processed.

2 Exceptional Trading Intensity Despite the Lack of Fundamental News

The insolvency of Lehman Brothers marks the climax of the 2007/8 financial crisis. With \$613 billion in debt against total assets of \$639 billion, this bankruptcy was the largest in the history of the United States (U.S.), causing unprecedented shock waves into the worldwide financial markets. While contagion in the form of direct follow-on insolvencies and domino effects has been rather limited[2], contagion did affect global financial markets through a system-wide drying-up of market liquidity, necessitating central banks to step in with liquidity support measures such as the "Troubled Asset Reliefs Program" (TARP) in the United States. The fading liquidity was reflected in a drastic increase in bid-ask spreads and in trading costs of the underlying stocks.

Lehman Brothers was a U.S. investment bank that was deeply involved in the business of securitizing mortgage loans and other collateralized debt obligations during the housing bubble in the run-up to the 2007/8 financial crisis (Zingales (2008)). Lehman Brothers was particularly aggressive in taking risks on its books (Report of Anton R. Valukas, Examiner of Chapter 11 Case No. 08-13555 (JMP)). On January 29, 2008, Lehman Brothers announced record revenues of approximately \$60 billion and earnings of about \$4 billion. Their share price traded at around \$65.73. Not even eight months later, on September 10, 2008, Lehman announced that it was projecting a \$3.9 billion loss for the third quarter of 2008.

On September 12, 2008, Lehman's share price traded at around \$4. Over the weekend of September 12-14, meetings were held among Treasury Secretary Paulson, Federal Reserve Bank of New York (FRBNY) President Timothy F. Geithner, Securities and Exchange Commission (SEC) Chairman Christopher Cox, and the chief executives of major financial institutions. They tried to come up with rescue measures for the failing investment bank. However, it turned out that Lehman's assets were insufficient to serve as collateral for a loan large enough to prevent Lehman from collapsing. On September 14 it seemed that a deal had been reached with Barclays. But later that same day, the deal fell apart when the Financial Services Authority (FSA), the United Kingdom's bank regulator, refused to waive U.K. shareholder approval requirements. Since Lehman no longer had sufficient liquidity to fund its daily operations, they had to declare bankruptcy basically that same day and did so early on September 15.

[2] The only direct causality "breaking the buck" was Primary Reserve Fund, a money market fund.

The shock brought about by both the quarter loss as well as the insolvency announcements of Lehman Brothers are exogenous to financial markets. This is due to the uncertainty surrounding these events as well as previous bank bailouts (such as Bear Stearns). Since Lehman's true state of affairs only became publicly known when it was too late, the uncertainty until the very end lends credibility to this exogenous shock. Figure 7 plots the evolution of Lehman's stock price and trading volume over the course of September 2008. It seems that only very shortly before the actual bankruptcy announcement (i.e., three days prior) did stock prices and trading volumes decrease and increase significantly, respectively, indicating that market participants still believed in Lehman despite the mounting turmoil. Furthermore, even though many guessed right about the deep trouble that Lehman was in, most expected Lehman to be either bailed out or acquired by another bank. This expectation was based on the case of Bear Stearns, which underwent similar turmoil earlier that same year and was both funded by the FED as well as taken over by JP Morgan Chase. The failed acquisition negotiations with Barclays as well as the mounting debt, which made it impossible to be granted a loan, came hence as a surprise to most market participants. Ben Bernanke, the then chairman of the FED describes in his book "The Courage to Act: A Memoir of a Crisis and Its Aftermath" that it was deliberately concealed that Lehman Brothers had too large of a debt position and that hence loans could not be granted by the FED. By concealing this fact, U.S. officials tried to withhold a panic as long as possible. Under such rare circumstances signals delivered to market participants with respect to volatility, liquidity levels, and informed trading can be crucial for the consequent fate and survival of such a troubled investment bank. In order to understand when markets became aware of Lehman's true state of affairs, we study the microstructure of stock markets of Lehman Brothers as well as its major competitors. By doing so, we expect to better understand the underlying mechanics of each informed trading measure as well as its respective predictive content. Because informed trading is usually considered to be a major driver of illiquidity, it is important to determine whether this drove the rise in illiquidity already before any information disclosure to the public or whether troubles only started thereafter.

Privileged information as a source of trading costs may have arisen both prior to Lehman's failure as well as after this event. Prior to the failure the possibility of informed trading arose in the run-up to the failure, both for Lehman stocks and for stocks of potential bidders for Lehman's assets. If there was speculation about certain bidders, this should be reflected in a larger part of illiquidity being due to adverse selection risk. Furthermore, if insiders to Lehman Brothers knew how deep in trouble the bank actually was, they could have traded on this information before any public confession by the bank itself. In case that this abnormally increased trading volume, market makers could have assigned a higher probability to insider trading and raised spreads.

The failure itself is informative about the (non-)validity of a potential "Too-Big-to-Fail"-doctrine. The failure of a government bailout exposes the industry to potentially higher risks than originally accounted for. In particular, counter-party risk has risen significantly. Moreover, since banks' balance sheets are exceedingly opaque, it is difficult for outside investors to precisely value the extent of counter-party risk. In this situation one might conjecture that informed trading in financial firms' stocks becomes more profitable making adverse selection risk increase.

Yet, in case that liquidity providers were completely oblivious of the fact that the "Too-Big-to-Fail"-doctrine might in fact fail, they might not have feared informed trading as much. In this case we might not even see an increase in illiquidity before the quarter loss announcement, let alone an increase in adverse selection risk. In this case the shocking aspect about Lehman was not so much the near-bankruptcy state they were in but rather the failure of the "Too-Big-to-Fail" guarantee. By evaluating both liquidity levels as well as different informed trading measures just before the public announcement of the huge quarter loss as well as after, we can shed more light on this question and help to better understand the true drivers of the massive liquidity freeze that followed Lehman's failure.

3 Informed Trading Before the Bankruptcy Announcement of Lehman Brothers

In order to establish the degree of informed trading during the time period that led to the bankruptcy announcement of Lehman Brothers, we analyze several different dimensions of liquidity and informed trading. Since all measures of informed trading are either price-based or volume-based, we start this section by defining the underlying liquidity measures first before moving on to the definition of the informed trading measures. Roughly speaking both prices and trading volumes serve as two dimensions of the broad concept of liquidity. The price dimension refers to relative bid-ask spreads, which is the difference of ask prices and bid prices divided by the average of the two. Trading volume is measured by number of shares traded. Since the dataset we analyze is based on milli-second data, we can expand the dimension of trading volume into more refined measures that tell us explicitly which trading maneuvers traders applied. Specifically, we measure the number of trades per day, the size of each trade, the total trading volume per day, as well as the total trading volume per day conducted as small trades (i.e., with a trade size smaller than 500 shares) and as large trades (i.e., with a trade size larger than 500 shares).

3.1 Price-based informed trading measure

Our price-based informed trading measure is based on Huang and Stoll (1997), who developed a decomposition approach with which to determine how much of transaction costs (i.e., bid-ask spreads) are due to adverse selection risk. Adverse selection risk is thereby defined as the risk that markets makers face of trading with better informed market participants (i.e., insiders) (see, for example, Bagehot (1971), Kyle (1985), and Easley and O'Hara (1987)). To decompose spreads, Huang and Stoll (1997) introduced a model that consists of three separate and sequential events. They denote the stock's fundamental value by V_t assuming that it is unobservable. The bid and ask quotes are set right after the fundamental stock value has been determined. M_t denotes the quote midpoint and is calculated from the quotes that were posted by a market maker just before a transaction happened. P_t denotes the respective transaction price. Q_t denotes the trade direction indicator variable. It takes the value of one if the transaction price exceeds the midquote, and it takes the value of -1 if the transaction price is smaller than the midquote. It equals zero if the transaction price is equal to the midquote. Trade flows are assumed to be serially correlated. The conditional expectation of the trade indicator variable Q_t at time *t-1* given Q_{t-2} is, therefore, shown to be:

$$E(Q_{t-1}|Q_{t-2}) = (1 - 2\pi)Q_{t-2}. \tag{1}$$

where π denotes the probability that the current trade is of opposite sign to the previous trade. Huang and Stoll (1997) estimate equation 1 simultaneously with equation 2 in order to estimate the different cost components of the spread. In equation 2 S_t denotes the equity bid-ask spread and α denotes the percentage of the spread that is associated with informational cost (i.e., adverse selection cost). As can be seen α is assigned to the difference of what the actual trade turned out to be (i.e., $\frac{S_{t-1}}{2}Q_{t-1}$) and what the market maker expected the trade to be based on the previous trade (i.e., $\frac{S_{t-2}}{2}\mathbb{E}[Q_{t-1}|Q_{t-2}]$). Hence, α, or informational costs, only arise if the current trade brings about a surprise relative to the previous trade. Of course, transaction costs do not only arise because of adverse selection risk. Other risk or cost factors that have been shown to be important are β, the percentage of the spread that is associated with inventory cost as well as γ, which is the remainder and usually associated with costs due to processing an order or market power of dealers. According to previous research in the field of market microstructure, these three types of costs should predominantly be responsible for the existence of the spread between equity bid and ask prices. Inventory holding costs hereby describe how economic uncertainty contributes to price setting by making liquidity suppliers alert to holding too many toxic securities or too few demanded securities (Ho and Stoll (1981) and Stoll (1978)). The latter, order processing costs, include potential rents to dealers due to market power and general administrative trading costs.

$$\Delta M_t = (\alpha + \beta)\frac{S_{t-1}}{2}Q_{t-1} - \alpha\frac{S_{t-2}}{2}(1 - 2\pi)Q_{t-2} + \epsilon_t. \tag{2}$$

The parameters of equation 1 and 2, α, β, and π, are estimated using the generalized method of moments (GMM) procedure outlined in Hansen and Singleton (1982) and Hansen (1982). The optimal weighting matrix is constructed using the method proposed in Wooldridge (2002). Under this procedure, the parameter estimates have to be chosen such that they minimize:

$$Q_N(\theta) = \left[N^{-1}\sum_{i=1}^{N} g(w_i, \theta)\right]' \widehat{\Lambda}^{-1} \left[N^{-1}\sum_{i=1}^{N} g(w_i, \theta)\right]. \tag{3}$$

Following the notation of Wooldridge (2002), θ is the vector of unknown coefficients. In this analysis, this vector includes the component for adverse selection risk (α), the component for inventory holding risk (β), and the trade direction reversal probability (π). The order processing cost component γ is computed by subtracting α and β from one. This is because those three components represent costs, which have to add up to 100% or one. $g(w_i, \theta)$ is an (L x 1) vector of moment functions (or orthogonality conditions). These functions are non-linear and given by:

1. $g_1 = (Q_{t-1} - (1 - 2\pi)Q_{t-2})\, Q_{t-2}$
2. $g_2 = (Q_{t-1} - (1 - 2\pi)Q_{t-2})\, S_{t-1}$
3. $g_3 = (Q_{t-1} - (1 - 2\pi)Q_{t-2})\, S_{t-2}$
4. $g_4 = \left(\Delta M_t - (\alpha + \beta)\frac{S_{t-1}}{2}Q_{t-1} + \alpha\frac{S_{t-2}}{2}(1 - 2\pi)Q_{t-2}\right) S_{t-1}$
5. $g_5 = \left(\Delta M_t - (\alpha + \beta)\frac{S_{t-1}}{2}Q_{t-1} + \alpha\frac{S_t t-2}{2}(1 - 2\pi)Q_{t-2}\right) S_{t-2}$
6. $g_6 = \left(\Delta M_t - (\alpha + \beta)\frac{S_{t-1}}{2}Q_{t-1} + \alpha\frac{S_{t-2}}{2}(1 - 2\pi)Q_{t-2}\right) (Q_{t-1} - (1 - 2\pi)Q_{t-2})\,.$

$\widehat{\Lambda}$ is the optimal weighting matrix which is determined by also following Wooldridge (2002):

$$\widehat{\Lambda} \equiv \frac{1}{N}\sum_{i=1}^{N} [g(w_i, \theta)]\, [g(w_i, \theta)]'\,. \tag{4}$$

As described before, the three different cost drivers of transaction costs represent costs or risk factors that dealers pass on to traders. Market makers do so because they want to be compensated for the different risks that they are facing, e.g., the risk of sitting on too much or too little inventory and the risk of losing against a better informed market participant. To make sure that, when estimating α and β, the resulting estimates lie between zero and one, we impose restrictions on the parameters. For this we follow Christensen et al. (2008). The key idea is to transform θ by means of a non-linear mapping, $\theta = g(\theta)$, between the constrained interval (0,1) and the real line. So θ would be the vector of parameters that we get from unconstrained optimization, with $\theta \in \mathbb{R}$. To derive parameter values that lie between zero and one, we use an inverse transform function of the following form:

$$g^{-1}(\theta) = \phi = \frac{1}{1 + e^{-\theta}}. \tag{5}$$

Obviously, altering θ and using ϕ demands that, when computing standard errors, it needs to be taken into account that one is working with scaled variables. Hence, the gradient of the objective function must be provided with respect to ϕ and not θ. Again, following Christensen et al. (2008), the gradient with respect to ϕ is computed by scaling the gradient with respect to θ by the gradient of the mapping with respect to ϕ.

3.2 Volume-based informed trading measure

For the volume-based informed trading measure we choose the so-called volume-synchronized probability of informed trading (VPIN) measure introduced by Easley et al. (2012). According to the authors, order flow may be "toxic" (i.e., disadvantageous) for market makers in cases in which they are unaware that they are providing liquidity at a loss. According to the microstructure literature the order arrival process is informative for both subsequent price movements in general and the "toxicity" of order flow. Easley et al. (2012) present a procedure with which to estimate this so-called order flow informativeness and toxicity, respectively. Their procedure is based on volume imbalance and trade intensity:

$$VPIN = \frac{\sum_{\tau=1}^{n} |V_\tau^S - V_\tau^B|}{nV}, \tag{6}$$

where τ is an index of equal volume buckets, V^B denotes the overall buy volume in each bucket, V^S denotes the sell volume in each bucket, V is the total trading volume, and n is the total number of buckets chosen for computing the VPIN metric.

We choose to concentrate on the analysis of the volatility of VPIN since this better reflects the uncertainty and risk aversion attached to a higher probability of informed trading. Volatility is hereby defined as the standard deviation of the VPIN measure per day.

The VPIN toxicity metric is based on the same model as is the original PIN (probability of informed trading) metric. Both approaches have the same theoretical foundation. In contrast to the estimation of the PIN metric, however, the VPIN metric does not require the estimation of unobservable variables and is updated in stochastic time, meaning it is calibrated to have an equal volume of trade in each time interval. According to the authors, this is why the VPIN measure is superior to the PIN measure and this is also why we follow Easley et al. (2012) in applying the VPIN metric as our volume-based informed trading measure.

3.3 Data

Our data consists of intradaily transaction prices, bid and ask prices, trading volumes, and trade size and is taken from data files provided by TickData, Inc. We use intradaily best bid and ask quotes (BBO) (milli-second level) to compute bid-ask spreads (ask price minus bid price) and midprices (average between ask and bid price). From this, we compute the trade direction following mainly Lee and Ready (1991). Because Lee and Ready treat trades that happened at the midprice differently than Huang and Stoll, we follow Huang and Stoll for those kinds of trades. Hence, our trade direction variable can take three possible values: $+1$ if the trade price exceeds the midprice, -1 if the midprice exceeds the trade price, and 0 if the trade price equals the midprice. Establishing a timing rule to apply the Lee-Ready algorithm is an important step in our data-cleaning process: Lee and Ready (1991) and Huang and Stoll (1997) matched trades with quotes that happened at least five seconds earlier. Since then, however, technology has become much faster and we need to reduce the time distance between matched trades and quotes. In doing so we follow the recent literature (e.g., Henker and Wang (2006)) and match trades with quotes in the same second.

We restrict our analysis to the eight biggest U.S. banks in 2008, including both what one generally considers to be commercial and investment banks. Those eight banks cover 80% of the total market capitalization of banks traded at U.S. stock markets, providing us hence with a fairly complete picture of the U.S. banking sector. Specifically, we chose the following banks as "commercial" banks:

1. Bank of America Corporation
2. Citigroup Inc.
3. JP Morgan Chase & Co.
4. Wells Fargo & Company,

and the following investment banks:

1. Goldman Sachs Group, Inc.
2. Lehman Brothers Holding Inc.
3. Merrill Lynch & Co., Inc.
4. Morgan Stanley

For our analyses we concentrate on data covering the New York Stock Exchange (NYSE). To ensure the integrity of the dataset, we only use quotes that are coded as regular quotes. Also, a selected stock must meet the following criteria to be eligible: (1) it must be a common stock and (2) it cannot change primary exchange, ticker symbol or its CUSIP code during the sample period. All of the above-listed banks and companies meet these criteria. We then apply the following screens to the trades and quotes data. Only quotes and trades during normal market hours (9:30 a.m. and 4:00 p.m.) are considered. We delete cases in which the bid is greater than or equal to the ask. We furthermore assume that bid (ask) quotes that have a bid (ask) price or bid (ask) size that is set to zero or a missing value have been withdrawn. We drop all withdrawn quotes. We also exclude the first transaction price of the day if it is not preceded by a quote. The time period that we use covers August 2008 to October 2008.

3.4 Testing procedure

In a first step, we evaluate the differences between the bankruptcy-endangered bank Lehman brothers and the rest of the banking industry based on descriptive statistics of the different liquidity measures. It is, however, important to note that the analysis of descriptive statistics can only serve as a first estimate of the differences in liquidity and informed trading between Lehman and the rest of the banks. To statistically measure the differences in liquidity and informed trading at Lehman and the rest of the banks, we apply the so-called difference-in-differences methodology. For this we introduce an indicator variable called D_i, which equals one if the stock analyzed is Lehman and zero if not. We furthermore examine two time periods that might have been crucial to Lehman Brothers. The first one is September 10 to September 12, 2008. On September 10, 2008, at 07:30 a.m. Lehman announced their quarter loss of \$3.9 billion. Until then, it was not known to the outside public that Lehman was that deep in trouble and so close to bankruptcy. But at the latest from September 10 on, it became obvious that either a bailout or a bankruptcy were unavoidable for Lehman Brothers. To specifically analyze this event, we introduce a second indicator variable called $P_{1,t}$, which takes the value of one after September 10, 2008, and zero before. A second time period, which is crucial especially in terms of the informed trading measures, is the time period just before the quarter loss announcement, namely September 8 and 9, 2008. Figures 1 to 3 visually show that on those two days there seem to have been abnormal trading activity as all measures of liquidity shoot up in terms of means, medians, and even outliers and despite the fact that Lehman had not yet released any public statement about their true state of affairs. In case that insiders - in their very true sense - were informed of a pending insolvency, they might have traded on this information already before any public information was to be disclosed. By analyzing the days just prior to the quarter loss announcement, we can determine whether this was at all the case and if so, which informed trading measure is sensitive enough to grasp this. To do so we introduce an additional indicator variable called $P_{2,t}$, which equals one on September 8 and 9, 2008, and zero otherwise. The respective regression equations then look as follows:

$$\left.\begin{array}{c}\text{Number of Trades}_{i,t}\\ \text{Size of Trades}_{i,t}\\ \text{Trading Volume}_{i,t}\\ \text{Trading Volume Small Trades}_{i,t}\\ \text{Trading Volume Large Trades}_{i,t}\\ \text{Relative Spreads}_{i,t}\end{array}\right\} = a_i + \beta_1 P_{1,t} + \beta_2 D_i \cdot P_{1,t} + \beta_3 P_{2,t} + \beta_4 D_i \cdot P_{2,t} + \beta_5 Y_{i,t-l} + \epsilon_{i,t} \quad (7)$$

i denotes the different banks and t is a time subscript. In order to control for potentially omitted systematic differences between firms, we also include firm fixed effects a_i. Note that the indicator variable D_i is constant over time (it differs cross-sectionally) and hence can be viewed as a firm fixed effect. This in turn implies that it is collinear with firm fixed effects. We additionally include lagged dependent variables of the respective dependent variable (i.e., $Y_{i,t-l}$ where l is a lag operator) in case of serial correlation.

We analyze a similar set of regressions for our informed trading measures:

$$\left.\begin{array}{c}\text{Adverse Selection Costs}_{i,t}\\ \text{Standard Deviation of VPIN}_{i,t}\end{array}\right\} = a_i + \beta_1 P_{1,t} + \beta_2 D_i \cdot P_{1,t} + \beta_3 P_{2,t} + \beta_4 D_i \cdot P_{2,t} + \beta_5 Y_{i,t-l} + \epsilon_{i,t} \quad (8)$$

3.5 Results

We start this section by analyzing descriptively how liquidity and informed trading evolved after Lehman Brothers had announced their huge quarter loss on September 10, 2008. The specific descriptive statistics can be found in Table 2. Immediately after Lehman announced their quarter loss, the total number of trades per day decreased. The number of trades conducted after September 10 decreased by four percent compared to the days before the announcement. Interestingly, the same was true for Lehman's peer banks, which faced a decrease in the number of trades of 20 percent. All other volume measures, such as the average size per trade and total trading volume increased sharply from September 10 on. The average trade size increased by 100 percent for Lehman (whereas it decreased for the other banks), and total trading volume increased by 70 percent. The increase in total trading volume was mostly driven by an increase in trading volume of large trades. This group of trades faced an increase of 77 percent, whereas trading volumes of small trades decreased by 13 percent. Contrary to this, Lehman's peers experienced decreased trading volumes for both small (minus 20 percent) and large (minus 35 percent) trades. It hence seems from these descriptive statistics that the quarter loss announcement shook traders awake and made them increasingly trade large blocks of stocks in fewer trades. Apparently, this suddenly increased activity and the bad news also were noticed by liquidity providers. We find an increase in relative spreads of Lehman Brothers of 82 percent, whereas spreads of Lehman's peers decreased by 26 percent.

First descriptive statistics of our two informed trading measures suggest that both, adverse selection costs measured à la Huang and Stoll as well as the VPIN measure reacted significantly to Lehman's quarter loss announcement. The adverse selection costs component of relative spreads increased on average by 190 percent from before the announcement to the time after. The VPIN measure increased as well, though not as much. Here we find an increase of 45 percent. Apparently, this increased probability of informed trading or adverse selection risk was very much confined to Lehman's stocks. Spreads and volumes of the competing banks did not show such an increase. On the contrary, we find that both the adverse selection component as well as the VPIN measure decreased by 40 percent and eight percent, respectively.

These first descriptive impressions are confirmed by regression analyses of both liquidity measures as well as informed trading measures. Estimating equations one and two yields the following results (as depicted in Table 6). Across all liquidity dimensions as well as informed trading measures, we find a statistically significant increase only for Lehman's stock for the time period after they announced their quarter loss compared to before this announcement. All other banks also reacted to this announcement. But contrary to Lehman Brothers, all other banks experienced a decrease in liquidity as represented by decreasing total trading volumes. Spreads of Lehman's peers did not react to the loss announcement. This implies that the intensified activity of traders was confined to the troubled investment bank of Lehman Brothers as only those liquidity measures reacted positively to the loss announcement. As such we find an increase in the average trade size of Lehman Brothers after the announcement of 277 shares. This was substantial and represented an increase of 50 percent compared to the time period before the announcement. Total trading volume per day decreased for all banks significantly after the announcement; again, this did not hold for Lehman for which we find a significant increase in trading volume of 70 percent. Most interestingly, this increase in trading volume was not evenly spread across all types of trades. As the increase in trade size might have suggested, the increase in trading volume was mainly driven by an increase in trading volume in large trades. Large trades faced increased trading volume indicating that the overall increase in trading volume was largely driven by the bigger trades or larger share blocks (we observe an increase of 17,000,000 shares traded per day). The number of trades, in which traders conducted their trades, also increased steeply by 23,500 trades per day for Lehman Brothers only. Again this shows the severe impact that the quarter loss announcement of Lehman had on the liquidity of its own stock. Finally, also the price dimension of liquidity, namely bid-ask spreads, reacted significantly for Lehman Brothers. Whereas spreads of all other banks did not react to the loss announcement, dealers in Lehman's stock increased spreads by 80 percent.

It seems that this increase in spreads was - to a large extent - driven by adverse selection risk. We find that both measures of informed trading increased significantly after Lehman's announcement. Adverse selection costs - measured according to the decomposition procedure of Huang and Stoll (1997) - increased by 190 percent right after the loss announcement; and the VPIN measure as introduced by Easley et al. increased by 45 percent.

Summarizing these findings we can hence conclude that the loss announcement of Lehman Brothers really pushed its stock into turmoil. Market participants traded Lehman stocks more intensively and in bigger blocks. Dealers reacted by increasing spreads, and the overall risk aversion towards adverse selection risk increased substantially. Arguably, all of these findings were to be expected after such negative news. The more interesting question is whether any of these measures also showed intensified trading before the quarter loss announcement. Is it possible that part of the market knew about the mounting troubles at Lehman Brothers before any information was made public, and if so did someone trade on this information? In order to investigate this question, we first descriptively show how all just described measures show intensified trading two days prior to the loss announcement (i.e., September 8 and 9, 2008), and then continue by presenting results of estimating equations three and four.

Across all liquidity measures as well as for one informed trading measure we find strong reactions. During September 8 and 9, the daily average number of trades increased significantly by 83 percent for Lehman indicating intensified trading already before the disclosure of sensitive information. Interestingly, this changing trading pattern did not translate in discernible price effects. It seems that buys and effectively offsetting sells just happened to increase in size. If there was speculation - or information - on one side of the market, the traces were offset on the other side of the market. This finding is compatible with the actions of dual capacity traders. Unfortunately, given the nature of our data we cannot identify the nature of buyers and sellers. Total trading volume also increased on September 8 and 9 by 22 percent. This increase in total trading volume was mainly driven by trades in small size. This is indicated by a decrease in the average trade size of about 26 percent as well as an increase in trading volume of small trades by 100 percent. Trading volume in large trades in fact decreased by ten percent. This suggests that some traders deliberately broke up their trades in order to minimize price impact. By trading smaller trade sizes, they could more easily hide their intentions avoiding others to notice their true intentions. Now presumably this would be a valid trading strategy for either a large institutional trader and/or an informed trader. Either way, it is important to determine which of the two informed trading measures pick up this effect. For adverse selection costs, measured according to the Huang and Stoll (1997) methodology, we surprisingly find a decrease of 13 percent on September 8 and 9. Whereas the VPIN measure reacted positively; we find an increase of 40 percent.

All of these descriptive results are confirmed by a statistical regression analysis (see Table 7). Across all liquidity measures as well as for one informed trading measure we find strong reactions. Total trading volume as well as the average trade size increased significantly on September 8 and 9 by 22 percent and 66 percent, respectively. Notably dealers did not react to this intensified trading. Effectively, we did not find a significantly different change in Lehman's spreads relative to their peers. Spreads actually decreased significantly across all banks on September 8 and 9. However, this decrease was less pronounced for Lehman Brothers, which effectively experienced a positive change in spreads of 40 percent. According to the decomposition procedure, this increase in spreads was not particularly due to increased adverse selection risk. The respective coefficient ("Lehman x Two days before quarter loss announcement") is significant. But when combined with the coefficient of the indicator variable of September 8 and 9, there was actually no change at all in adverse selection risk of Lehman Brothers on these two particular days. This indicates that inventory holding risks as well as order processing costs also played a role for market makers in their price setting. Our second informed trading measure on the other hand, namely the VPIN measure, did react significantly. We find an increase of 40 percent in the volatility of the volume-based probability of informed trading measure. As the name suggests, this measure is very much volume-based. This can explain why we only find a reaction in this measure but not in the adverse selection costs measure. As just described, trading in small trades intensified tremendously which might hint to someone trying to hide and avoid price impact. Ex post this seems easy to determine. But apparently market makers have only noticed this intensified trading, but did not specifically relate it to informed trading. No public statement had yet been released by Lehman Brothers, so supposedly market makers did not suspect insiders to trade on privileged information, but large institutional traders to trade for liquidity reasons. They hence did not apply more weight to adverse selection costs than what was usual under such circumstances.

Summarizing these findings we can conclude that the volume-based VPIN measure is much more sensitive to supposedly informed trading than the price-based adverse selection measure. This is due to the fact that the adverse selection measure relies on changes in means of spreads. If market makers do not adjust the mean of their spreads to new levels, increases in spreads can also be due to inventory holding costs or order processing costs. The VPIN measure on the contrary is based on the demand side, i.e., on rapidly changing trading volume. It detects a higher probability of informed trading even if traders shred their trades into many small trades because it is sensitive to also the number of trades. Of course, under circumstances such as the Lehman case, this measure delivers good results. However, it is likely that under normal circumstances, i.e., when it is really "just" a large trader shredding his orders and trading for liquidity reasons, that also the volatility of the VPIN measure would shoot up and indicate an increased probability of informed trading.

4 Informational Efficiency of Prices

We construct measures of informational efficiency based on price autocorrelations and innovations. Informational efficiency in this framework is usually defined as how closely transaction prices resemble the random walk (see e.g., Boehmer and Kelley (2009)).

4.1 Price Impact Regressions

We start with price impact regressions that evaluate the effect that the price of a current trade has on subsequent trade prices (Foucault et al. (2013)). There are two major reasons for the persistence of price effects, namely inventory holding costs and dynamic informed trading. Both suggest that a trade at date t should affect future trades at dates *t+1, t+2, ..., t+n*. Hence, future prices can be related to a current trade by so-called price impact regressions:

$$p_{t+k} = \lambda_k p_t + \epsilon_t \tag{9}$$

Additionally, we analyze the extent to which the persistence of the price effects is either due to inventory effects or due to the persistence of information. As established by Kyle (1985), the optimal dynamic strategy of informed traders implies piecemeal revelation of information over time. While the decomposition strategy of Huang and Stoll used earlier identifies inventory holding costs by means of autocorrelations, in an environment with dynamic informed trading this identification needs to be adjusted to a richer information environment. In order to identify the information effects, we rely on the innovation of a higher-order autoregression of transaction prices. This innovation is the unexpected news to a given observation and we may relate the persistence of this innovation to the persistence of the full price. Accordingly, we estimate impact regressions on price innovations as follows:

$$p_{t+k} = \alpha_k \eta_t + \epsilon_t, \tag{10}$$

where η_t, the surprise or innovation, is given by:

$$p_t = \beta_1 p_{t-1} + ... + \beta_n p_{t-n} + \eta_{t-n}. \tag{11}$$

We can furthermore ask if information might also be incorporated into trades themselves or trading volume and therefore lend robustness to the previous analysis of the VPIN measure. Hence, in order to analyze the role of volume and the informational content therein, we estimate a new set of regressions to assess the effect that signed trading volume has on subsequent prices. In particular, we estimate the following regressions:

$$p_{t+k} = \gamma_k q_t + \epsilon_t, \tag{12}$$

where q_t represents signed trading volume. As before, we treat innovations in the autoregressions of trading volume as innovations or news and analyze the persistence of this news on subsequent trades:

$$p_{t+k} = \beta_k \kappa_t + \epsilon_t, \tag{13}$$

where κ_t is given by:

$$q_t = \rho_1 q_{t-1} + ... + \rho_n q_{t-n} + \kappa_{t-n}. \tag{14}$$

4.2 Vector Autoregressions of Prices and Signed Order Flow

A second test of informational efficiency is based on autoregressions of first differences in prices (ΔP_t). Specifically, we estimate a vector autoregressive (VAR) system over P_t, Q_t, where Q_t is defined as signed trading volume (following for example Boehmer and Kelley (2009)). This VAR system is estimated for Lehman Brothers for the time period of September 2, 2008, to September 12, 2008, on an hourly basis. Price efficiency is afterwards evaluated based on the speed with which autocorrelations in first differences of prices become insignificant. The VAR system thereby looks as follows:

$$\Delta P_t = \alpha_0 + \beta_{1,0}\Delta P_{t-1} + ... + \beta_{1,n}\Delta P_{t-n} + \beta_{2,0} Q_t + ... + \beta_{2,n} Q_{t-n} + \epsilon_{1,t} \tag{15}$$

$$Q_t = \alpha_1 + \beta_{3,0} Q_{t-1} + ... + \beta_{3,n} Q_{t-n} + \beta_{4,0}\Delta P_t + ... + \beta_{4,n}\Delta P_{t-n} + \epsilon_{2,t} \tag{16}$$

4.3 Results

The values, that the coefficient λ takes for Lehman Brothers for September 2 - 12, 2008, over many lags, are plotted in Graphs 9 to 11.[3] While the values themselves are positive, the slope of the evolution of λ is negative for each day for Lehman Brothers. Hence, the effect that the transaction price of a current trade had on subsequent trades diminished with lags and time. The slope became particularly negative on September 10 - 12, 2008. Table 1 shows the time span that 1000 lags thereby comprised on average in September 2008.

Since 1000 lags comprised *less* minutes on September 10 to 12, 2008, than on all other days, the slope of the coefficients' evolution was even steeper than what the graphs of September 10, 11, and 12 suggest. This indicates that information was incorporated into prices much faster on September 10, 11, and 12, 2008 as compared to early September 2008.

[3]Note that upper (95%) and lower (5%) confidence intervals are denoted in light blue in each of the here described graphs. The legend of each graph denotes them with "_u" for the upper band, and "_l" for the lower band. This holds for Figures 9 to 26.

Table 1: 1000 lags in calender time:

Time	09/02	09/03	09/04	09/05	09/08	09/09	09/10	09/11	09/12
09:00 a.m.:	16 min	17 min	25 min	26 min	10 min	06 min	05 min	06 min	07 min
10:00 a.m.:	25 min	46 min	38 min	48 min	06 min	06 min	10 min	08 min	18 min
11:00 a.m.:	52 min	50 min	53 min	43 min	15 min	06 min	14 min	11 min	19 min
12:00 a.m.:	45 min	56 min	56 min	40 min	15 min	10 min	24 min	13 min	27 min
01:00 p.m.:	42 min	58 min	40 min	54 min	24 min	10 min	34 min	22 min	21 min
02:00 p.m.:	30 min	21 min	39 min	42 min	30 min	07 min	19 min	26 min	21 min
03:00 p.m.:	27 min	20 min	21 min	34 min	16 min	05 min	08 min	08 min	11 min

The values that the coefficient α takes are plotted in Graphs 12 to 14. α takes positive values over all examined lags for each day in September 2008. However, for September 2 - 9, the lower confidence bound was either zero or eventually hit zero which made the estimates insignificant. Apparently, these results provide some justification for the identification strategy used in the decomposition of Section 3 for the early period from September 2 - 9, 2008. However, the picture changes completely when we examine the evolution of α on September 10, 11, and 12, 2008. Here, all results are significantly positive. Therefore, in those three days the price innovation had a significant and positive effect on subsequent transaction prices. Since, with the Huang and Stoll approach, we interpreted all intertemporal effects as being caused by inventory holding considerations, it seems that our earlier decomposition underestimated the adverse selection and overestimated the inventory holding component in those three critical days. However, this finding reinforces the role of information prior to the insolvency. Both our main decomposition approach as developed by Huang and Stoll and these price innovation regression measures agree on a significant information component on September 10, 11, and 12.

The values, that the coefficient γ takes for Lehman Brothers for September 2 - 12, 2008, over many lags, are plotted in Graphs 15 to 17. The slope of the evolution of γ was negative with fairly small values and insignificant for most days in September 2008, except for September 8. Hence, the effect that the signed volume of a current trade had on subsequent trade prices diminished and was negligible. There was no significant persistence in trades. The "outlier" of September 8 in terms of significance supports the findings of the volume and demand-side measures in that volume abnormally spiked on September 8, which drove down stock prices (this was documented in Table 6).

Interestingly, unlike in the case of price innovations, there was virtually no persistence of innovations in trading volume. The coefficients over the first five to ten lags take positive and large values (see Figures 18 to 20), but this effect was statistically insignificant and vanished rather quickly after about ten lags. The only exception was again the day of September 8, where all lags turned out to be significant.

Summarizing these findings, it seems that by trading small volumes in higher frequencies, traders were effectively able to minimize trade impact on September 8 and especially so on September 9, 2008. It was only the VPIN measure, which was able to pick up the intensified trading before the quarter loss announcement and bankruptcy announcement of Lehman Brothers. All other here analyzed measures only reacted once fundamental news had been announced and were public knowledge.

Figures 21 to 23 plot the price autocorrelation coefficients of the VAR system over one hundred lags. It becomes obvious that price efficiency was achieved after two lags. This holds for all days in September 2008. The different graphs show that the first two lags still carried significance, but from the second lag onwards, autocorrelations turned insignificant. In real time this implies that it took three seconds in the beginning of September and 0.8 seconds from September 8 on for coefficients to become insignificant. Hence, the inefficiencies that we observe during lags one and two could have been exploited by professionals who were able to trade in milliseconds. This was especially the case for the days of September 8 to 12, when the trading frequency increased and two lags comprised less and less time. As mentioned above, on September 8 (or 9), for example, it took about 0.8 seconds for price inefficiencies to vanish. This was the fastest it could get during these days. Interestingly, after the announcement of fundamental news on September 10, the process was being slowed down to about one second for inefficiencies to vanish. Hence, also "slower" traders could profit from these inefficiencies (once the fundamental news were public knowledge). However, on the days of September 8 and 9, when we initially observed the abnormal trading patterns, only very fast traders could profit from the inefficiencies, which lasted about 0.8 seconds.

We also graphically evaluate volume efficiency, which is determined by autocorrelations of signed order flow. Results are depicted in Figures 24 to 26: Also autocorrelations in volumes turned insignificant quickly, at the latest after ten lags. In the beginning of September 2008, ten lags comprised about thirty seconds; from September 8 on, it comprised four seconds.

These results are in line with the steep increase in the price-based informational risk measure (ASC) described in Section 3.5. Price setting worked informationally efficiently until the public announcement of fundamental news. Privileged information about the true state of Lehman's troubles did not seem to have influenced the price setting of dealers, despite the fact that exceptionally large trades and volumes were observable already before the quarter loss announcement. The inefficiencies that we observe related to (milli-)seconds. Ultimately, those inefficiencies should only be usable by professional (high frequency) traders. Nevertheless, they existed both prior to the quarter loss announcement as well as thereafter.

5 Robustness Tests

5.1 Other determinants of illiquidity

We have established that the adverse selection component only picked up the mounting troubles at Lehman Brothers after the public disclosure of fundamental news and that prices continued to be informationally efficient throughout the analyzed sample period. In this subsection we turn to two other risk factors that have been found to drive the wedge between ask and bid prices, namely inventory holding costs and order processing costs. As described in Section 3, inventory holding costs are attributed to how much economic uncertainty contributes to price setting by making liquidity suppliers alert to holding too many toxic securities or too few demanded securities. Order processing costs on the other hand include potential rents to dealers due to market power and general administrative trading costs.

Table 8 statistically describes how both inventory holding costs as well as order processing costs changed both two days prior to Lehman's quarter loss announcement and right thereafter. Both cost types increased significantly two days prior to the quarter loss, however less so for Lehman itself. In fact, the respective change in both cost types is economically meaningless, which shows that - along with adverse selection risk - market makers did not pick up any of the intensified trading during September 8 and 9, 2008. Even though spreads at Lehman Brothers increased by 0.1 percent (which was an effective increase of 40 percent), this increase in spreads was not particularly due to adverse selection costs nor inventory or order processing costs. This suggests that all three cost types were responsible for this spread increase. This then changed significantly once the huge quarter loss became public information. From September 10 on, inventory holding costs were much smaller and adverse selection costs increased by 190 percent. Hence the risk perception of dealers with respect to the three cost types was significantly altered by the quarter loss announcement. Market makers feared the presence of insiders in the market to whom they might loose, which explains the steeply increased importance of adverse selection costs relative to both inventory holding as well as order processing costs.

5.2 Kyle's Lambda

Since we have identified that both price-based and volume-pased liquidity measures more than trippled in size after Lehman announced their quarter loss, we may check to what extent measures of information risk, that are price-based as well as volume-based, accord with our finding. In particular we check the evolution of Kyle's Lambda over the course of August and September 2008. We briefly describe the construction of this measure before using it in the above described regression framework.

In order to measure Kyle's lambda, we exploit information entailed in the transaction prices as well as signed trading volume.

$$p_t = f_t + \lambda Q_t + \epsilon_t \tag{17}$$

where λ^{-1} is a measure of market depth. Taking first differences we get:

$$\Delta p_t = \Delta f_t + \lambda \Delta Q_t + \Delta \epsilon_t \tag{18}$$

Table 9 shows the respective difference-in-differences results using the Kyle-measure instead of the VPIN or adverse selection component measure. The previous results, which were obtained from using a purely price-based and a purely volume-based liquidity measure, are confirmed when using an informed trading meausre which is simultaneously based on both prices and volumes. There was increased informational risk already entailed in both prices and volumes on the days of September 8 and 9, on which there was no revelation of fundamental information. This finding was enforced for the day of September 10, once fundamental information about Lehman's trouble were made public. This confirms our previous findings.

6 Conclusion

We find that overall markets work fairly efficiently in the sense of informational efficiency. If there was any informed trading prior to the public announcement sophisticated camouflage trading essentially prevented it from being revealed via prices. We find that information risk as perceived by liquidity suppliers increased only about three days before the insolvency and only after Lehman Brothers had announced the insolvency-bringing quarter losses. Some market participants obviously knew something as the demand-side of the markets did react two days before that. We find significantly increased trading volumes and larger trade sizes on September 8 and 9. However, at that stage it was difficult for liquidity suppliers to determine whether this was due to increased informed trading or liquidity reasons. The price impact was thus minimized and the stock market kept on working efficiently for Lehman until the public announcement of fundamental news.

Summarizing these findings we can conclude that the volume-based VPIN measure is much more sensitive to supposedly informed trading than is the price-based adverse selection measure. This is due to the fact that the adverse selection measure relies on changes in means of spreads. If market makers do not adjust the mean of their spreads to new levels, increases in spreads can also be due to inventory holding costs or order processing costs. The VPIN measure on the contrary is based on the demand side, i.e., on rapidly changing trading volume. It detects a higher probability of informed trading even if traders shred their trades into many small trades because it is sensitive to also the number of trades. Of course, under circumstances such as the Lehman case, this measure delivers good results. However, it is likely that under normal circumstances, i.e., when it is really "just" a large trader shredding his orders and trading for liquidity reasons, that also the volatility of the VPIN measure would shoot up and indicate an increased probability of informed trading.

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7 Figures and Tables

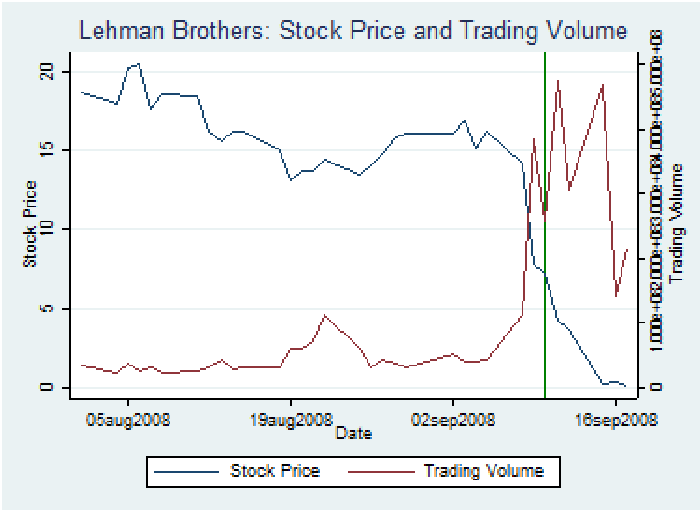

Figure 7: Average Daily Stock Price and Trading Volume of Lehman Brothers (the green line indicates the quarter loss announcement)

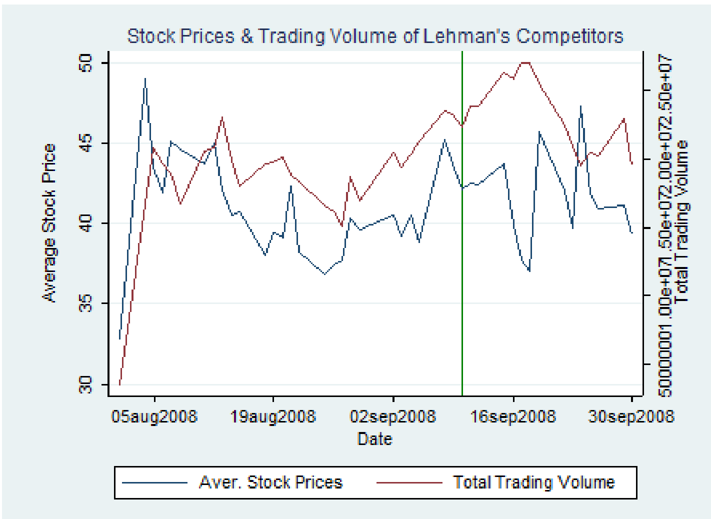

Figure 8: Average Daily Stock Price and Trading Volume of Lehman's Competitors (the green line indicates the quarter loss announcement)

Table 2: Firm-Level Descriptive Statistics

The table presents means, medians, standard deviations (Std), and the 25th and 75th quantiles. The sample consists of the eight biggest U.S. banks in 2008, including both what one generally considers to be commercial and investment banks. Results are reported separately for the two subsamples of Lehman Brothers and its competitors.

(A) Descriptive Statistics: Before and After September 10, 2008

	Mean	**Median**	**Std**	**Q25**	**Q75**	**Observations**
Number of Trades						
Lehman's Competitors: Before Loss Announcement	25,754	23,131	12,029	16,957	34,771	2.555e+06
Lehman's Competitors: After Loss Announcement	20,854	22,874	5,027	18,652	24,136	403,039
Lehman: Before Loss Announcement	24,114	21,747	13,332	8,782	39,186	96,692
Lehman: After Loss Announcement	22,966	22,539	2,999	18,868	26,276	67,683
Size of Trades						
Lehman's Competitors: Before Loss Announcement	408.9	354.3	189.8	304.6	482.7	2.555e+06
Lehman's Competitors: After Loss Announcement	355.0	348.9	92.38	286.5	426.6	403,039
Lehman: Before Loss Announcement	568.3	552.2	125.7	446.8	707.7	96,692
Lehman: After Loss Announcement	1,134	1,126	333.4	749.6	1,605	67,683
Total Trading Volume						
Lehman's Competitors: Before Loss Announcement	1.070e+07	9.377e+06	6.752e+06	5.622e+06	1.361e+07	2.555e+06
Lehman's Competitors: After Loss Announcement	7.653e+06	6.971e+06	3.143e+06	5.517e+06	9.997e+06	403,039
Lehman: Before Loss Announcement	1.536e+07	1.201e+07	1.066e+07	3.660e+06	2.773e+07	96,692
Lehman: After Loss Announcement	2.556e+07	2.960e+07	6.130e+06	1.689e+07	3.029e+07	67,683
Total Trading Volume (Small Trades)						
Lehman's Competitors: Before Loss Announcement	3.401e+06	3.170e+06	1.546e+06	2.173e+06	4.452e+06	2.122e+06
Lehman's Competitors: After Loss Announcement	2.756e+06	2.979e+06	650,235	2.491e+06	3.249e+06	332,251
Lehman: Before Loss Announcement	2.844e+06	2.714e+06	1.522e+06	1.166e+06	4.665e+06	70,107
Lehman: After Loss Announcement	2.462e+06	2.696e+06	429,528	2.696e+06	2.706e+06	37,585
Total Trading Volume (Large Trades)						
Lehman's Competitors: Before Loss Announcement	8.084e+06	6.033e+06	6.369e+06	3.972e+06	1.244e+07	321,407
Lehman's Competitors: After Loss Announcement	5.191e+06	4.411e+06	2.520e+06	3.221e+06	7.936e+06	52,594
Lehman: Before Loss Announcement	1.304e+07	8.624e+06	8.485e+06	2.982e+06	2.138e+07	19,621
Lehman: After Loss Announcement	2.315e+07	2.552e+07	6.002e+06	1.325e+07	2.792e+07	24,092
Relative Spreads						
Lehman's Competitors: Before Loss Announcement	0.00148	0.00130	0.000712	0.000905	0.00188	126
Lehman's Competitors: After Loss Announcement	0.00110	0.000982	0.000351	0.000907	0.00120	21
Lehman: Before Loss Announcement	0.00227	0.00197	0.000866	0.00179	0.00265	6
Lehman: After Loss Announcement	0.00415	0.00427	0.000939	0.00316	0.00503	3

Table 3: Firm-Level Descriptive Statistics ctd.

The table presents means, medians, standard deviations (Std), and the 25^{th} and 75^{th} quantiles. The sample consists of the eight biggest U.S. banks in 2008, including both what one generally considers to be commercial and investment banks. Results are reported separately for the two subsamples of Lehman Brothers and its competitors.

(A) Descriptive Statistics: September 8 & 9, 2008

	Mean	**Median**	**Std**	**Q25**	**Q75**	**Observations**
Number of Trades						
Lehman's Competitors: Before Sep. 8 & 9	14,499	15,156	3,878	11,688	17,821	368,452
Lehman's Competitors: Sep. 8 & 9	23,541	24,469	7,302	17,304	26,953	293,531
Lehman: Before Sep. 8 & 9	9,037	8,782	971.7	8,391	10,498	35,759
Lehman: Sep. 8 & 9	32,962	39,186	8,355	21,747	39,186	60,933
Size of Trades						
Lehman's Competitors: Before Sep. 8 & 9	356.8	353.6	98.86	288.3	418.2	368,452
Lehman's Competitors: Sep. 8 & 9	383.8	351.5	127.8	298.9	420.1	293,531
Lehman: Before Sep. 8 & 9	425.2	446.8	27.77	416.8	446.8	35,759
Lehman: Sep. 8 & 9	652.2	707.7	74.53	552.2	707.7	60,933
Total Trading Volume						
Lehman's Competitors: Before Sep. 8 & 9	5.396e+06	5.304e+06	2.352e+06	3.728e+06	7.364e+06	368,452
Lehman's Competitors: Sep. 8 & 9	9.688e+06	8.915e+06	5.467e+06	6.239e+06	1.075e+07	293,531
Lehman: Before Sep. 8 & 9	3.850e+06	3.660e+06	551,350	3.497e+06	4.690e+06	35,759
Lehman: Sep. 8 & 9	2.212e+07	2.773e+07	7.534e+06	1.201e+07	2.773e+07	60,933
Total Trading Volume (Small Trades)						
Lehman's Competitors: Before Sep. 8 & 9	1.911e+06	2.005e+06	513,314	1.613e+06	2.378e+06	300,368
Lehman's Competitors: Sep. 8 & 9	3.041e+06	3.217e+06	912,748	2.318e+06	3.317e+06	241,854
Lehman: Before Sep. 8 & 9	1.200e+06	1.166e+06	135,026	1.123e+06	1.402e+06	27,690
Lehman: Sep. 8 & 9	3.918e+06	4.665e+06	948,186	2.714e+06	4.665e+06	42,417
Total Trading Volume (Large Trades)						
Lehman's Competitors: Before Sep. 8 & 9	3.813e+06	4.077e+06	1.894e+06	2.224e+06	5.095e+06	51,285
Lehman's Competitors: Sep. 8 & 9	7.555e+06	6.212e+06	4.701e+06	3.804e+06	1.380e+07	38,877
Lehman: Before Sep. 8 & 9	2.390e+06	2.359e+06	422,948	2.074e+06	2.982e+06	5,815
Lehman: Sep. 8 & 9	1.753e+07	2.138e+07	5.858e+06	8.624e+06	2.138e+07	13,806
Relative Spreads						
Lehman's Competitors: Before Sep. 8 & 9	0.000802	0.000761	0.000246	0.000688	0.000837	168
Lehman's Competitors: Sep. 8 & 9	0.00103	0.000904	0.000333	0.000865	0.00108	21
Lehman: Before Sep. 8 & 9	0.00157	0.00156	0.000263	0.00137	0.00174	24
Lehman: Sep. 8 & 9	0.00412	0.00432	0.000872	0.00317	0.00488	3

Table 4: Firm-Level Descriptive Statistics ctd.

The table presents means, medians, standard deviations (Std), and the 25^{th} and 75^{th} quantiles. The sample consists of the eight biggest U.S. banks in 2008, including both what one generally considers to be commercial and investment banks. Results are reported separately for the two subsamples of Lehman Brothers and its competitors.

(A) Descriptive Statistics of Equity Markets (Matched Sample)

	Mean	**Median**	**Std**	**Q25**	**Q75**	**Observations**
Adverse Selection Costs						
Lehman's Competitors: Before Loss Announcement	0.000593	0.000491	0.000370	0.000339	0.000726	427
Lehman's Competitors: After Loss Announcement	0.000367	0.000370	8.56e-05	0.000324	0.000398	21
Lehman: Before Loss Announcement	0.000650	0.000627	0.000181	0.000546	0.000764	26
Lehman: After Loss Announcement	0.00189	0.00167	0.000462	0.00157	0.00242	3
Standard Deviation VPIN						
Lehman's Competitors: Before Loss Announcement	0.113	0.113	0.0350	0.0896	0.135	40,609
Lehman's Competitors: After Loss Announcement	0.104	0.106	0.0208	0.0902	0.123	7,000
Lehman: Before Loss Announcement	0.105	0.0873	0.0348	0.0785	0.136	1,754
Lehman: After Loss Announcement	0.153	0.152	0.00462	0.149	0.160	1,150

Table 5: Firm-Level Descriptive Statistics ctd.

The table presents means, medians, standard deviations (Std), and the 25$^{\text{th}}$ and 75$^{\text{th}}$ quantiles. The sample consists of the eight biggest U.S. banks in 2008, including both what one generally considers to be commercial and investment banks. Results are reported Sep.arately for the two subsamples of Lehman Brothers and its competitors.

(A) Descriptive Statistics of Equity Markets (Matched Sample)

	Mean	**Median**	**Std**	**Q25**	**Q75**	**Observations**
Adverse Selection Costs						
Lehman's Competitors: Before Sep. 8 & 9	0.000342	0.000334	8.82e-05	0.000292	0.000377	168
Lehman's Competitors: Sep. 8 & 9	0.000333	0.000342	0.000114	0.000269	0.000269	14
Lehman: Before Sep. 8 & 9	0.000648	0.000627	0.000148	0.000551	0.000743	24
Lehman: Sep. 8 & 9	0.000685	0.000685	0.000558	0.000291	0.000291	2
Standard Deviation VPIN						
Lehman's Competitors: Before Sep. 8 & 9	0.0926	0.0942	0.0282	0.0733	0.113	45,817
Lehman's Competitors: Sep. 8 & 9	0.119	0.109	0.0346	0.0964	0.0964	4,681
Lehman: Before Sep. 8 & 9	0.0910	0.0851	0.0297	0.0764	0.100	6,368
Lehman: Sep. 8 & 9	0.143	0.151	0.00732	0.136	0.136	756

Table 6: The Impact of Lehman's Loss Announcement on Trading Volumes

This table reports the results from difference-in-differences panel regression estimations using different trading volume measures as well as relative bid-ask spreads as variables of interest. The dependent variables are daily number of trades, (column 2), daily trade size (column 3), daily total trading volume(column 4), daily trading volume of small trades (column 5), of large trades (column 6), and daily relative spreads (column 7). The regressors include an indicator variable that indicates Lehman's quarter loss announcement (September 10, 2008) and which takes the value of one after this announcement and zero otherwise. A second regressor denotes an interaction term of both the event (September 10) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The regressors also include an indicator variable that indicates the two days prior to Lehman's quarter loss announcement (i.e., September 8 and 9, 2008) and which takes the value of one on these two days and zero otherwise. A fourth regressor denotes an interaction term of both the event (September 8 and 9) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The t-statistics are based on standard errors adjusted for heteroskedasticity and within-firm/year clustering (see Petersen (2009)), and are reported in parentheses below the coefficient estimates. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

VARIABLES	(1) No. of Trades	(2) Size of Trades	(3) Total Trading Volume	(4) Trading Volume Small Trades	(5) Trading Volume Large Trades	(6) Relative Spread
Sep. 8 & 9	-835	-42.3	-7.81e+06**	159,695	-242,150	-0.00012**
	(-1.19)	(-0.94)	(-2.37)	(1.69)	(-0.56)	(-2.42)
After Sep. 10	290	-78.7**	-1.01e+07**	-140,079	-3.52e+06*	-0.000040
	(0.37)	(-2.83)	(-2.77)	(-0.92)	(-2.34)	(-1.19)
Lehman x Sep. 8 & 9	1,430	465***	1.14e+07***	-432,326**	3.55e+06	0.00097***
	(1.04)	(4.33)	(3.90)	(-3.28)	(1.33)	(15.8)
Lehman x After Sep. 10	23,540***	277***	2.14e+07***	2.62e+06***	1.69e+07***	0.00045**
	(24.2)	(8.13)	(26.5)	(13.8)	(14.1)	(3.40)
L.No. of Trades	0.49***					
	(6.42)					
L.Trade Size		0.61**				
		(2.53)				
L.Volume Small Trades				0.71***		
				(17.1)		
L.Volume Large Trades					0.95***	
					(6.49)	
L.Relative Spreads						0.91***
						(17.2)
Constant	7,750***	143	1.18e+07***	596,878***	606,433	0.00017**
	(9.20)	(1.87)	(3.73)	(5.00)	(0.95)	(2.38)
Observations	119	119	119	119	119	372
Within R^2	0.859	0.726	0.791	0.593	0.581	0.713
Firm & Time FE	YES	YES	YES	YES	YES	YES

Table 7: The Impact of Lehman's Loss Announcement on Informed Trading Measures

This table reports the results from difference-in-differences panel regression estimations using two measures of informed trading as variables of interest. The dependent variables are daily adverse selection costs (measured according to Huang and Stoll (1997)) (column 2), and the volume-based measure VPIN (measured according to Easley et al. (2012)) (column 3). The regressors include an indicator variable that indicates Lehman's quarter loss announcement (September 10, 2008) and which takes the value of one after this announcement and zero otherwise. A second regressor denotes an interaction term of both the event (September 10) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The regressors also include an indicator variable that indicates the two days prior to Lehman's quarter loss announcement (i.e., September 8 and 9, 2008) and which takes the value of one on these two days and zero otherwise. A fourth regressor denotes an interaction term of both the event (September 8 and 9) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The t-statistics are based on standard errors adjusted for heteroskedasticity and within-firm/year clustering (see Petersen (2009)), and are reported in parentheses below the coefficient estimates. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)
VARIABLES	AS Cost	VPIN Volatility
Sep. 8 & 9	-0.0001***	0.004
	(-5.42)	(0.31)
After Sep. 10	-0.0001***	-0.016***
	(-4.26)	(-3.21)
Lehman x Sep. 8 & 9	0.00008**	0.04***
	(2.02)	(6.30)
Lehman x After Sep. 10	0.0003***	0.06***
	(6.62)	(21.6)
Relative Spread	0.14	
	(1.66)	
L.Relative Spread	0.41***	
	(16.37)	
L.AS Cost	0.068***	
	(2.58)	
L.VPIN Volatility		0.44***
		(7.89)
Constant	-0.000034***	0.055***
	(-3.80)	(10.6)
Observations	372	245
Within R^2	0.955	0.569
Firm & Time FE	YES	YES

Table 8: Robustness Test I: Informed Trading After Lehman's Loss Announcement?

This table reports the results from difference-in-differences panel regression estimations using inventory holding costs and order processing costs as variables of interest. The dependent variables are daily inventory holding costs (column 2), and order processing costs (column 3) (measured according to Huang and Stoll (1997)). The regressors include an indicator variable that indicates Lehman's quarter loss announcement (September 10, 2008) and which takes the value of one after this announcement and zero otherwise. A second regressor denotes an interaction term of both the event (September 10) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The regressors also include an indicator variable that indicates the two days prior to Lehman's quarter loss announcement (i.e., September 8 and 9, 2008) and which takes the value of one on these two days and zero otherwise. A fourth regressor denotes an interaction term of both the event (September 8 and 9) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The t-statistics are based on standard errors adjusted for heteroskedasticity and within-firm/year clustering (see Petersen (2009)), and are reported in parentheses below the coefficient estimates. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

VARIABLES	(1) IH Cost	(2) OP Cost
Sep. 8 & 9	0.000062**	0.000015**
	(2.95)	(2.02)
After Sep. 10	0.000049*	1.2e-06
	(2.23)	(0.19)
Lehman x Sep. 8 & 9	-0.000048*	-0.000060***
	(-1.73)	(-3.03)
Lehman x After Sep. 10	-0.00032***	0.000024*
	(-6.72)	(2.30)
Relative Spread	-0.0035	0.032
	(-0.25)	(1.88)
L.Relative Spread	0.55***	-0.026
	(23.9)	(-1.63)
L.IH Cost	-0.024	
	(-1.18)	
L.OP Cost		0.79***
		(4.26)
Constant	-0.000051	-6.5e-06
	(-1.80)	(-0.49)
Observations	372	372
Within R^2	0.970	0.799
Firm & Time FE	YES	YES

Robust t-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 9: Robustness Test II: Informed Trading After Lehman's Loss Announcement?

This table reports the results from difference-in-differences panel regression estimations using Kyle's Lambda as the variable of interest. The regressors include an indicator variable that indicates Lehman's quarter loss announcement (September 10, 2008) and which takes the value of one after this announcement and zero otherwise. A second regressor denotes an interaction term of both the event (September 10) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The regressors also include an indicator variable that indicates the two days prior to Lehman's quarter loss announcement (i.e., September 8 and 9, 2008) and which takes the value of one on these two days and zero otherwise. A fourth regressor denotes an interaction term of both the event (September 8 and 9) indicator variable and a treatment indicator variable, which takes the value of one if the stock analyzed was Lehman and zero otherwise. The t-statistics are based on standard errors adjusted for heteroskedasticity and within-firm/year clustering (see Petersen (2009)), and are reported in parentheses below the coefficient estimates. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

VARIABLES	(1) Kyle's Lambda
Sep. 8 & 9	-0.00000001*
	(-1.63)
After Sep. 10	0.0000000002
	(0.10)
Lehman x Sep. 8 & 9	0.00000001**
	(2.08)
Lehman x After Sep. 10	-0.00000001***
	(-4.54)
Constant	-0.000034***
	(-3.80))
Observations	310
Within R^2	0.426
Firm & Time FE	YES

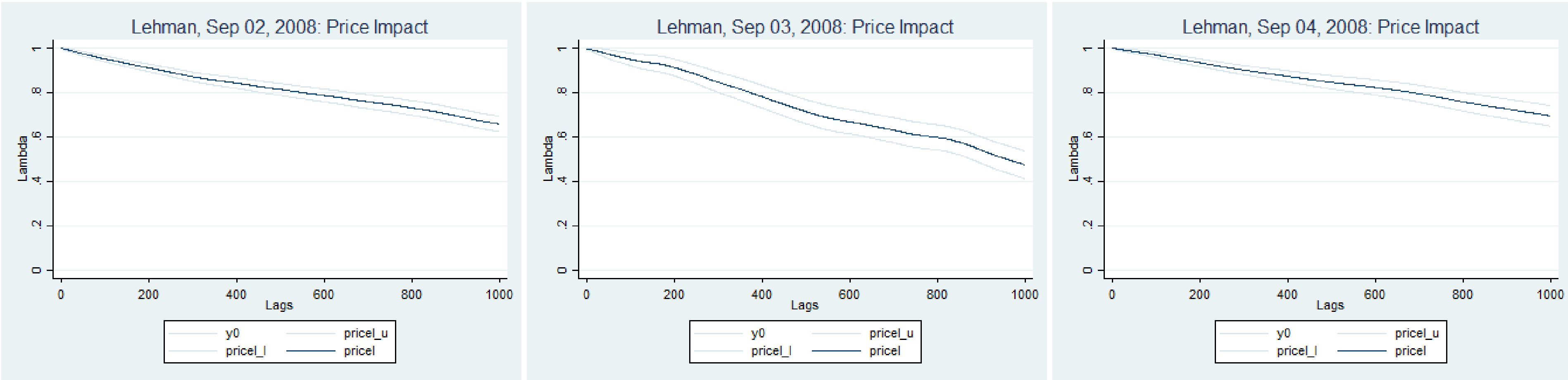

Figure 9: Evolution of Lambda: September 02, 03, & 04, 2008

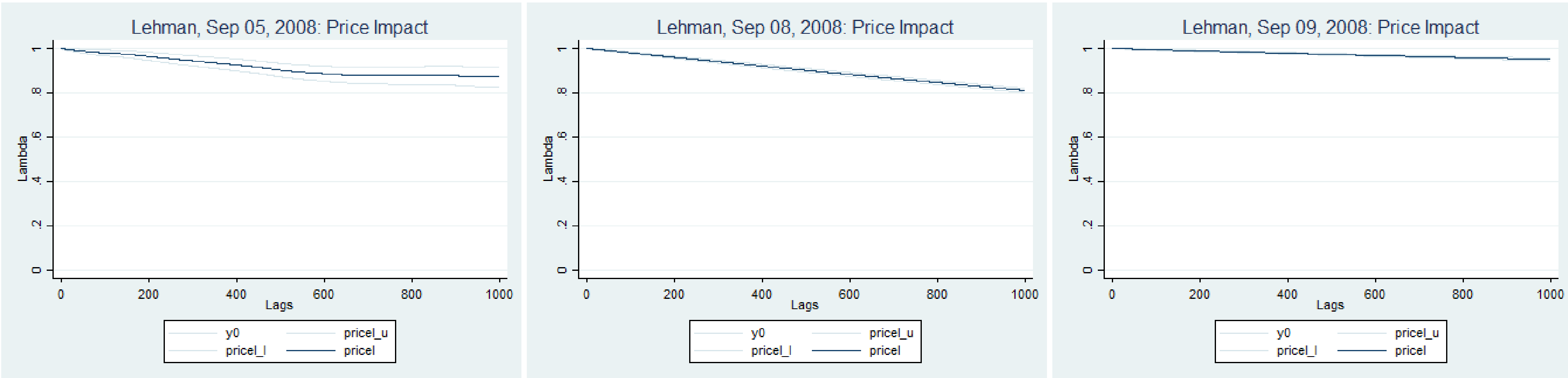

Figure 10: Evolution of Lambda: September 05, 08, & 09, 2008

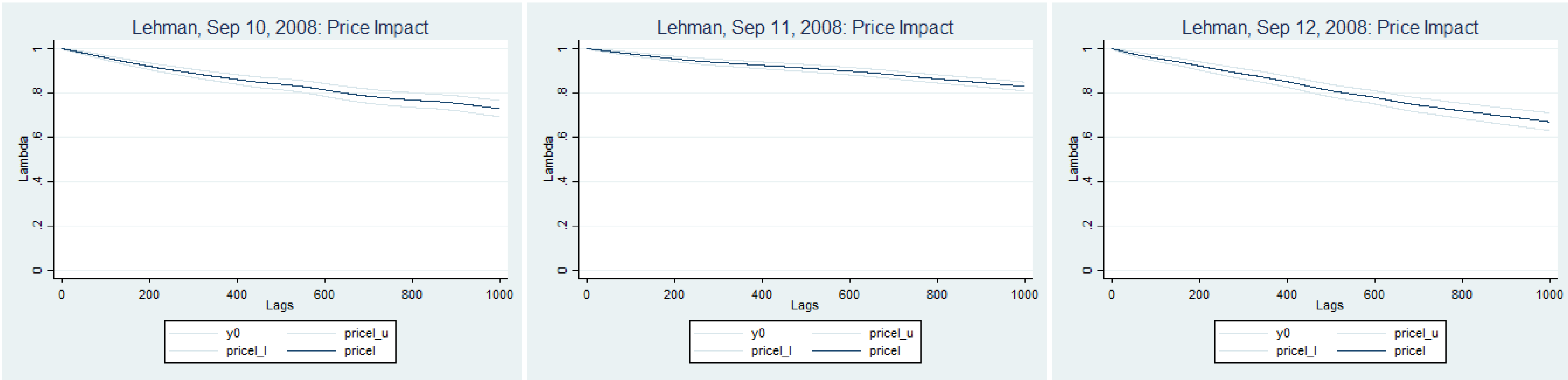

Figure 11: Evolution of Lambda: September 10, 11, & 12, 2008

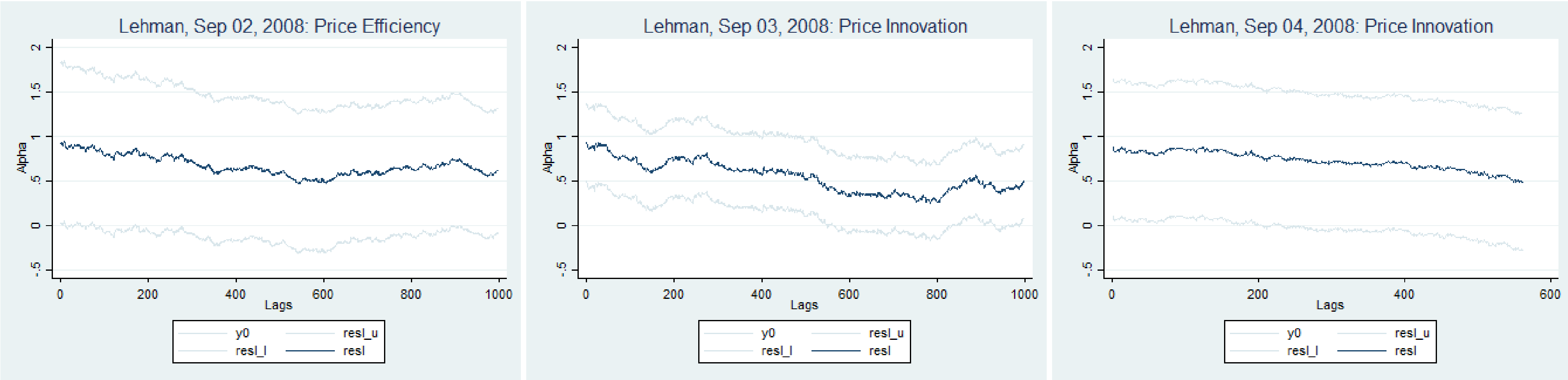

Figure 12: Evolution of Alpha: September 02, 03, & 04, 2008

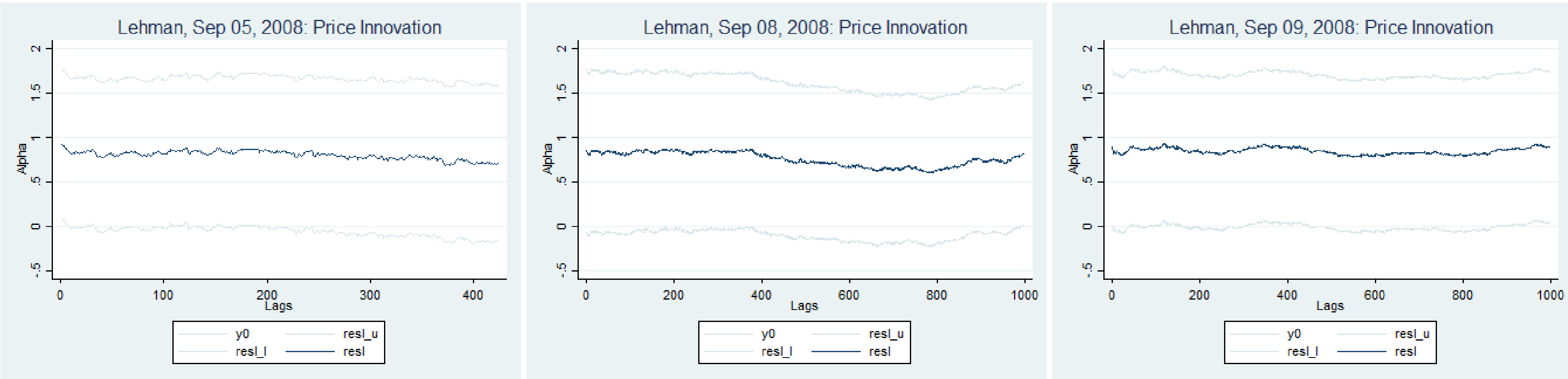

Figure 13: Evolution of Alpha: September 05, 08, & 09, 2008

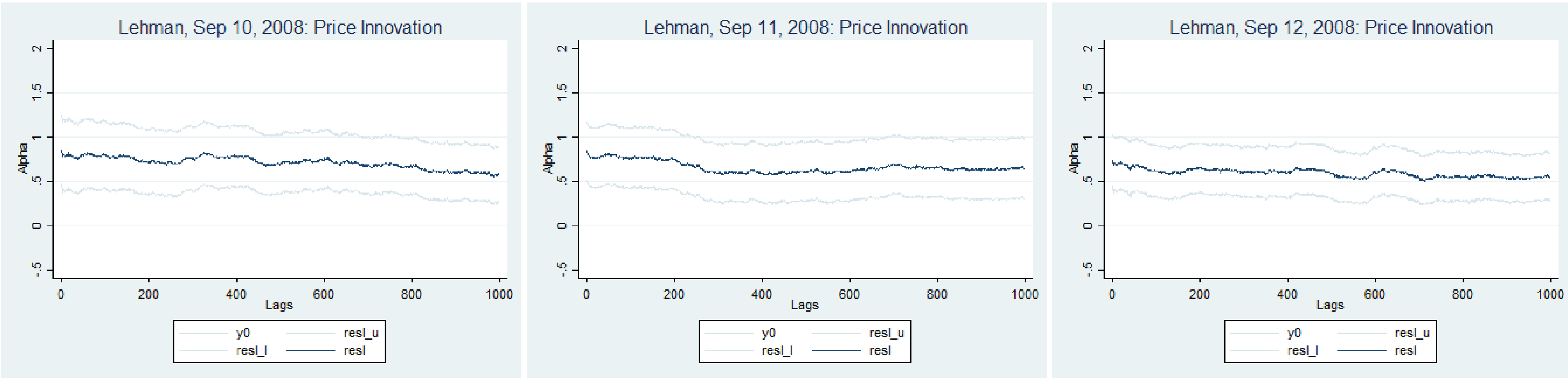

Figure 14: Evolution of Alpha: September 10, 11, & 12, 2008

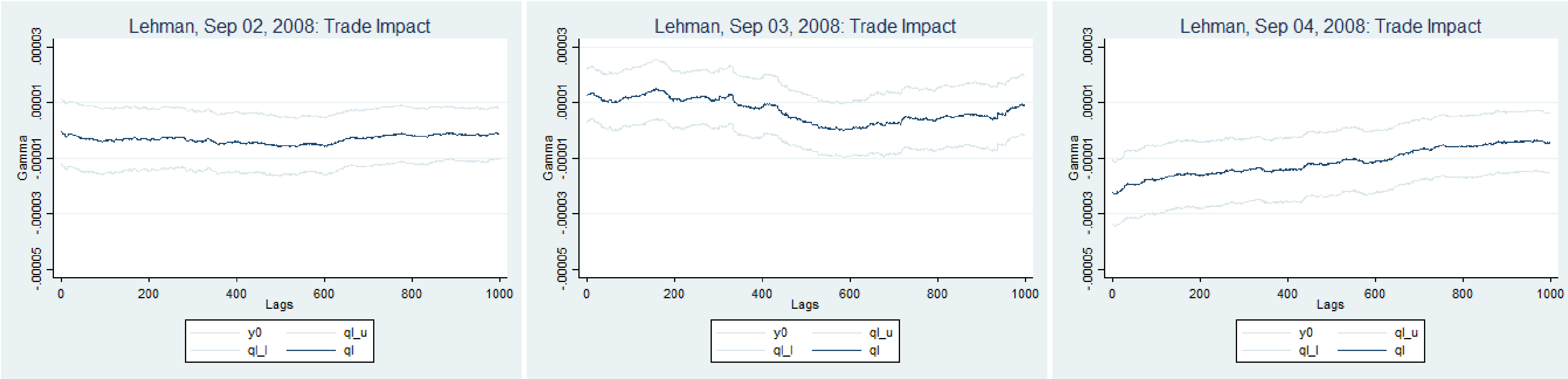

Figure 15: Evolution of Gamma: September 02, 03, & 04, 2008

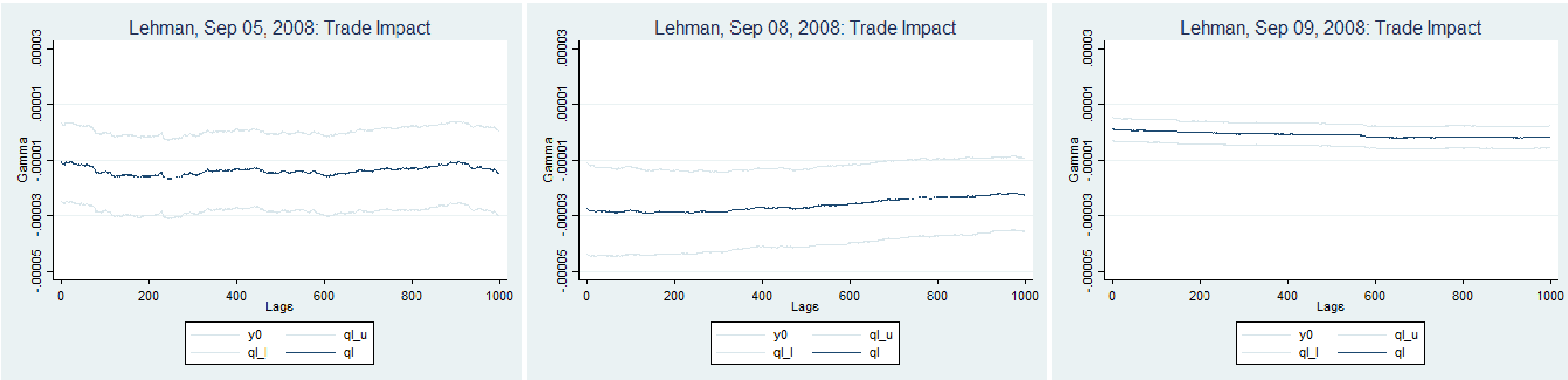

Figure 16: Evolution of Gamma: September 05, 08, & 09, 2008

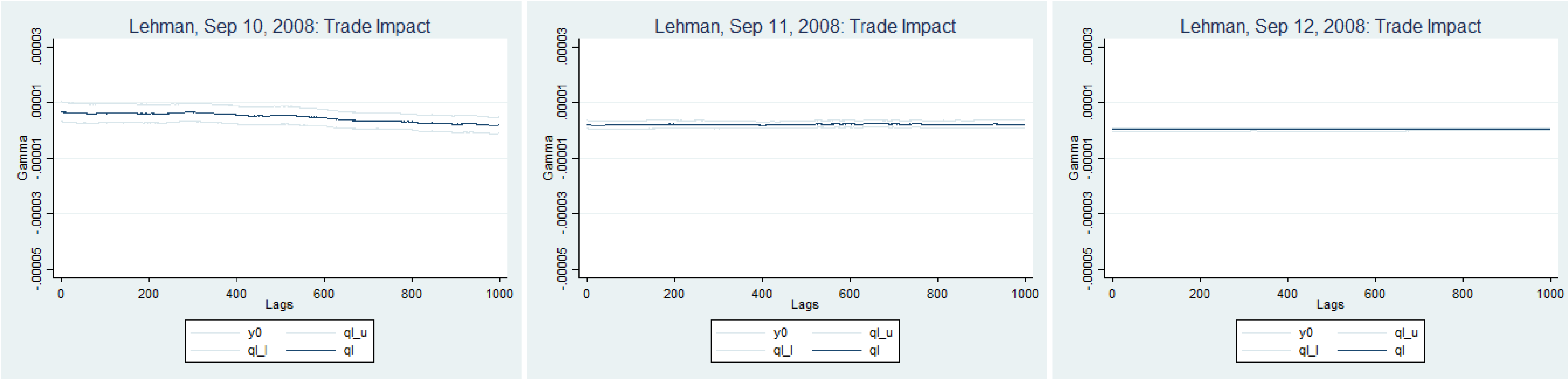

Figure 17: Evolution of Gamma: September 10, 11, & 12, 2008

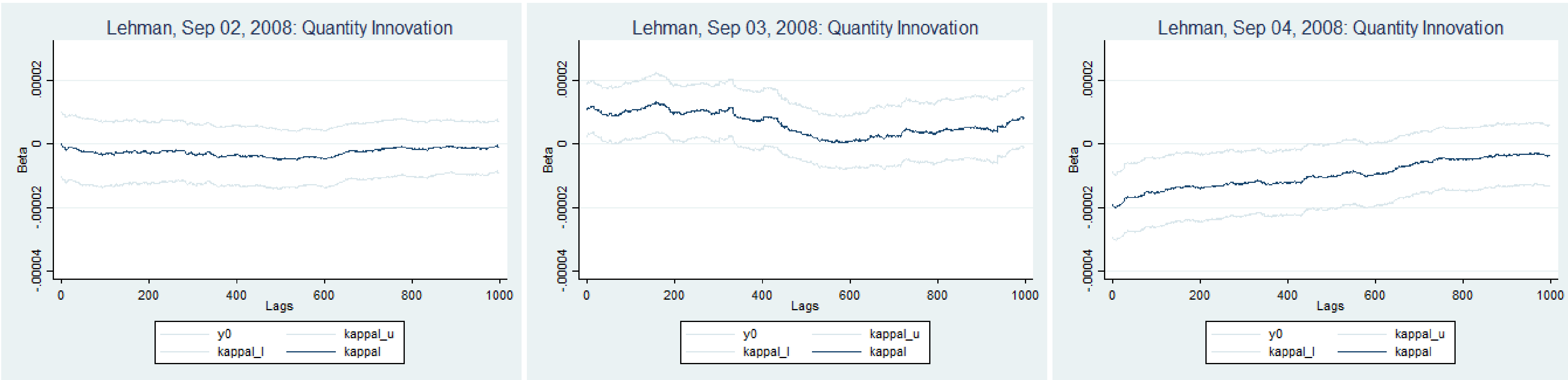

Figure 18: Evolution of Beta: September 02, 03, & 04, 2008

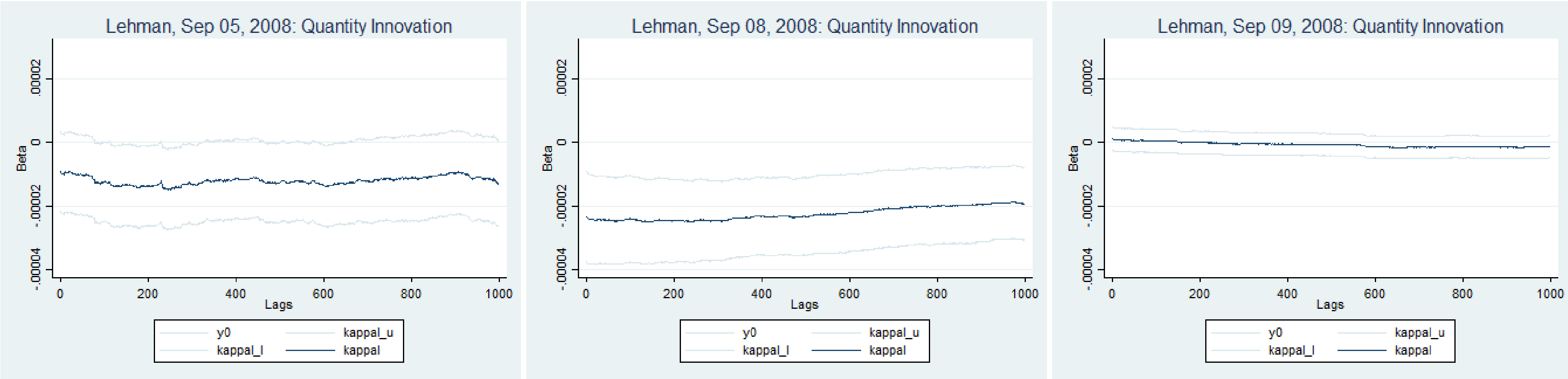

Figure 19: Evolution of Beta: September 05, 08, & 09, 2008

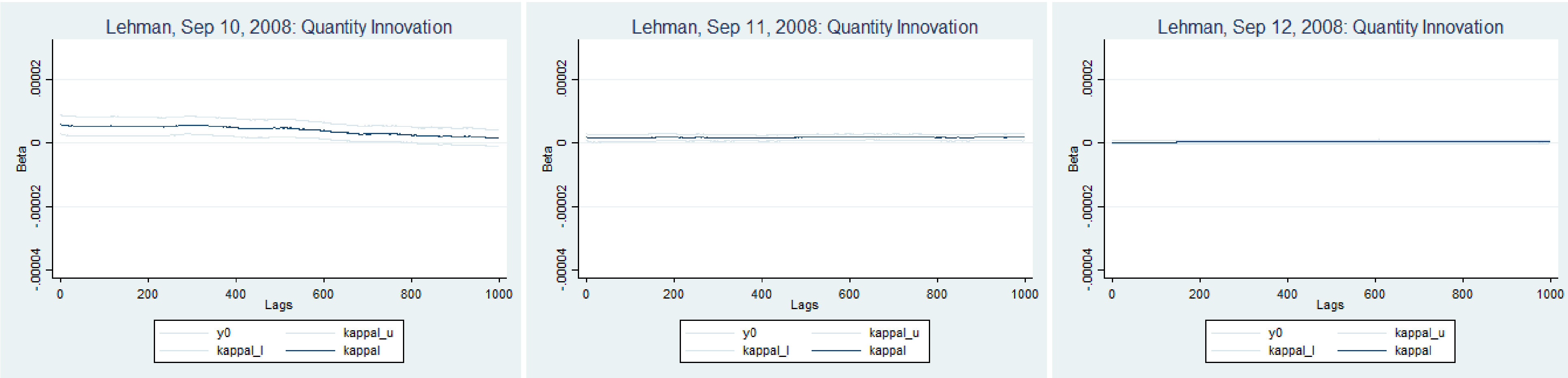

Figure 20: Evolution of Beta: September 10, 11, & 12, 2008

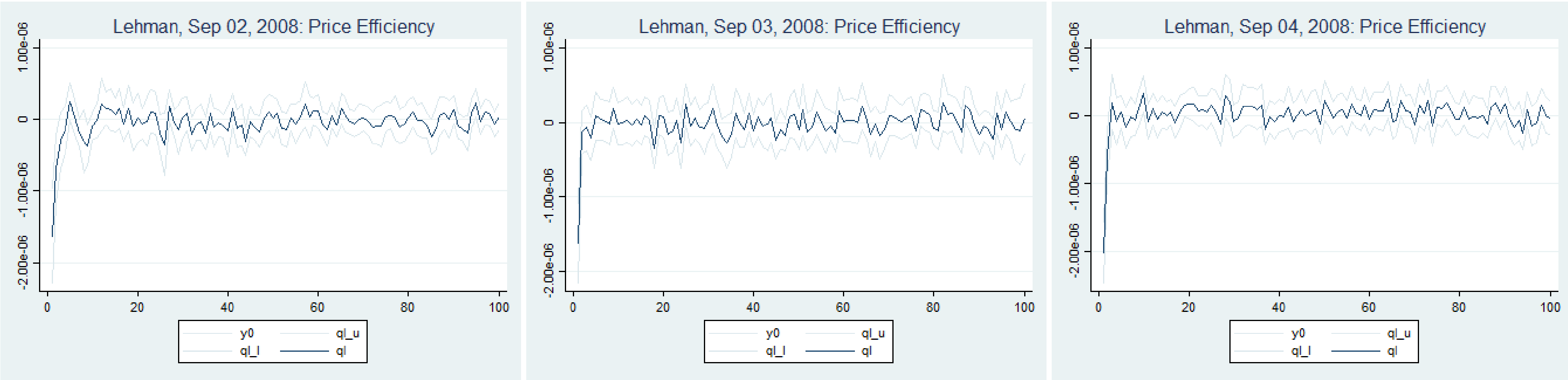

Figure 21: Price Effiency: September 02, 03, & 04, 2008

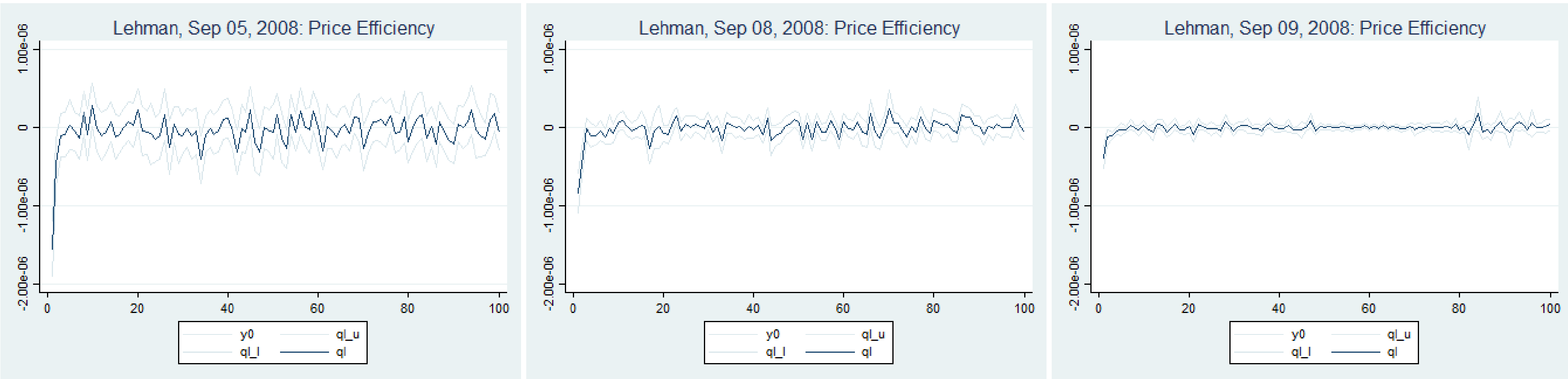

Figure 22: Price Effiency: September 05, 08, & 09, 2008

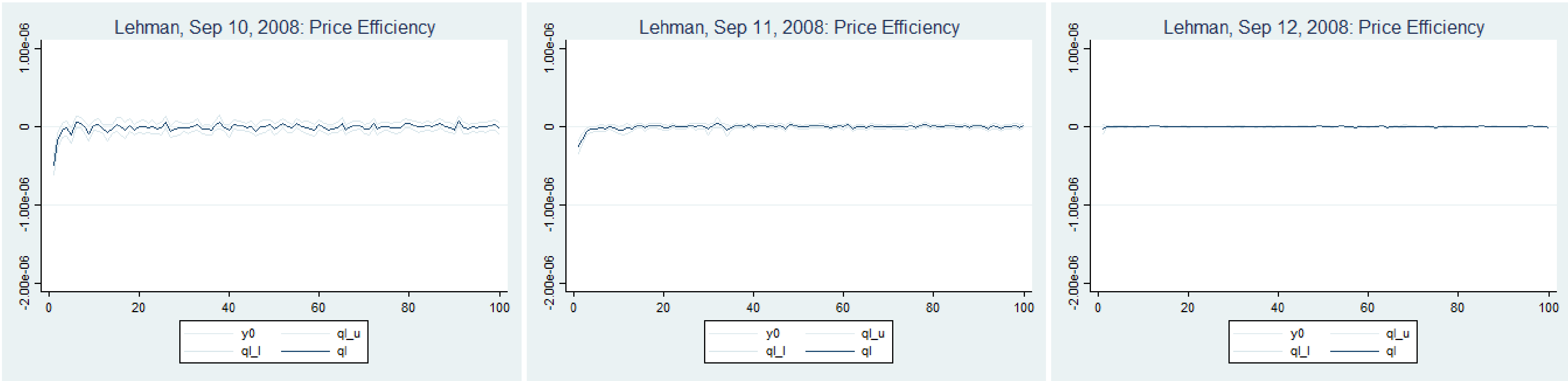

Figure 23: Price Efficiency: September 10, 11, & 12, 2008

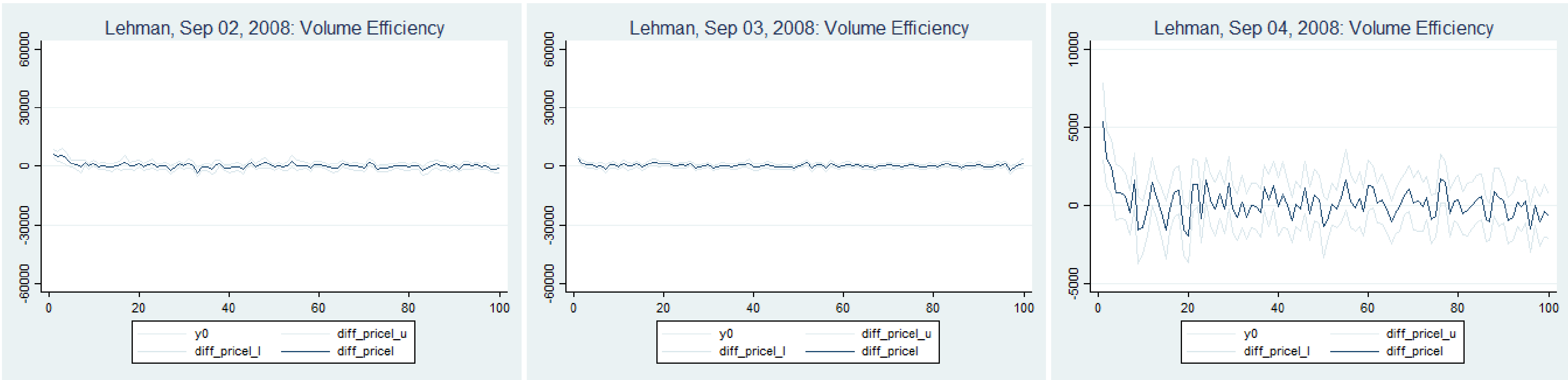

Figure 24: Volume Efficiency: September 02, 03, & 04, 2008

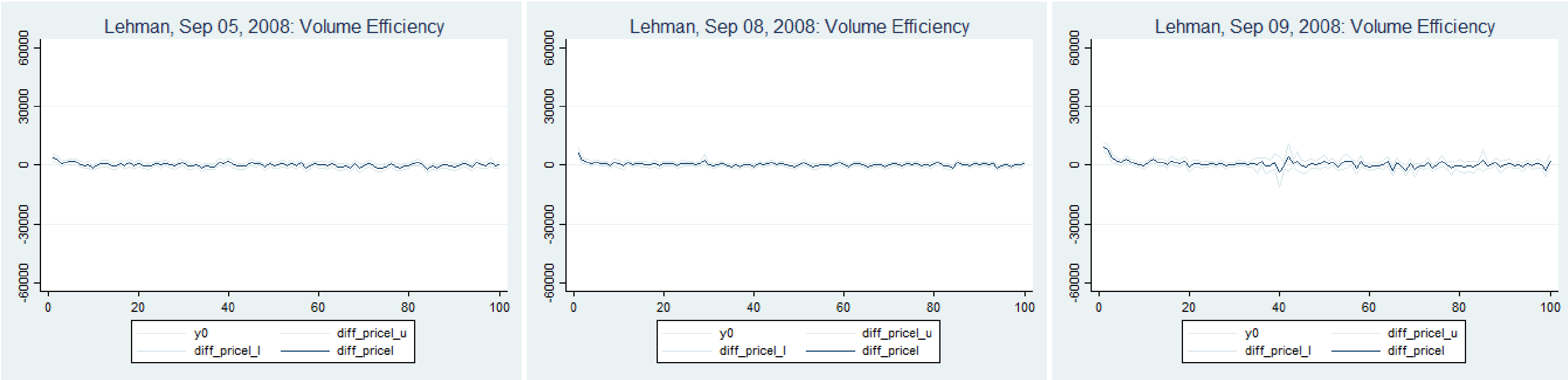

Figure 25: Volume Efficiency: September 05, 08, & 09, 2008

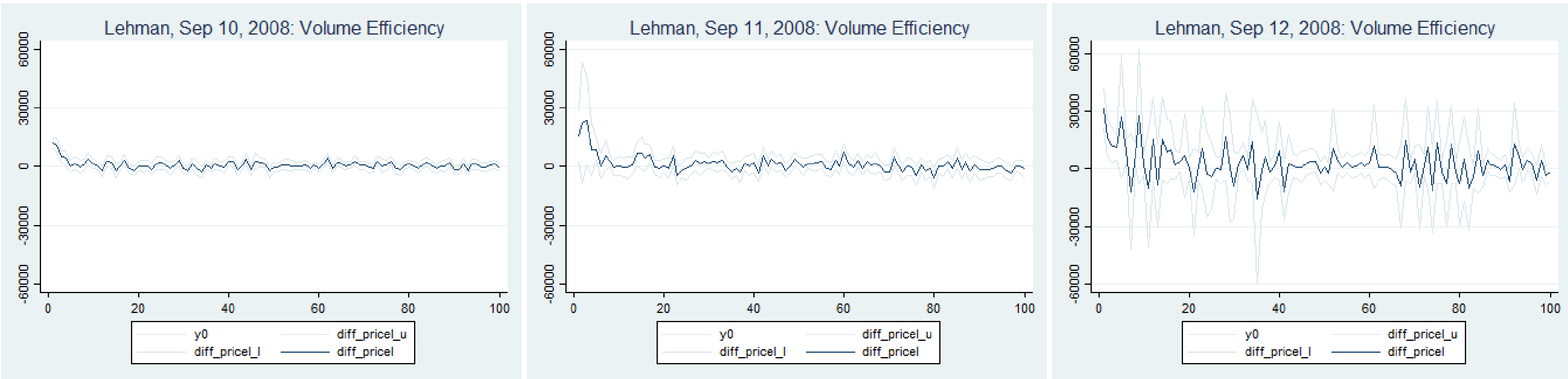

Figure 26: Volume Efficiency: September 10, 11, & 12, 2008