

Cover Letter

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Systematic Integration of systemic risk management and Multi-Factor Pricing Dynamics in S&P 500 Price Discovery

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ABSTRACT

The modern financial landscape is defined by the rapid assimilation of diverse data streams into asset prices, a process known as price discovery. At the epicenter of this mechanism is the S&P 500 index, which serves as the primary benchmark for global equity risk. Traditionally, price discovery research focused on the lead-lag relationship between the cash market and the futures market. However, the proliferation of complex derivatives, high-frequency trading, and the elevation of volatility as a distinct asset class have rendered these classical views insufficient. A contemporary understanding of price discovery requires an integrated framework that acknowledges the forward-looking information embedded in the VIX microstructure and the systematic risk premiums captured by multi-factor models.

The relationship between the S&P 500 and its volatility gauge, the VIX, has evolved from a simple contemporaneous negative correlation—the "leverage effect"—to a sophisticated interdependency where the VIX microstructure informs the future trajectory of equity returns. Concurrently, the academic consensus has shifted toward a more granular decomposition of returns, incorporating factors that go beyond the market beta. Specifically, the integration of profitability signals, macroeconomic indicators, the futures-cash basis, and market microstructure frictions provides a robust lens through which the impounding of information can be analyzed. This report investigates this integration, proposes a new "Information Convergence Price Discovery Theory" (ICPDT), and outlines an academic path for validating these complex interactions in the world's most liquid equity market.

Keywords: VIX Microstructure, Systemic risk, Information Convergence Price Discovery Theory

INTRODUCTION

1. The Informational Content of the VIX Microstructure

The Chicago Board Options Exchange (CBOE) Volatility Index (VIX) is a model-free estimate of the 30-day implied volatility of the S&P 500, derived from a strip of out-of-the-money put and call options. While the spot VIX reflects immediate market sentiment—often termed the "investor fear gauge"—it is the VIX microstructure that provides a comprehensive view of the market's intertemporal risk expectations. The microstructure refers to the relationship between VIX futures

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contracts.

2. VIX Microstructure Regimes and Return Predictability

The VIX microstructure typically fluctuates between two primary states: contango and backwardation. Contango occurs when long-term volatility expectations exceed short-term levels. This is the "normal" state of the market, reflecting a variance risk premium where investors pay to hedge against long-term uncertainty. Backwardation, conversely, arises during acute market stress, causing the spot VIX to spike above future contracts as immediate panic outweighs long-term mean-reversion expectations.

Empirical evidence demonstrates that while the spot VIX itself has limited predictive power for future equity returns, the microstructure is a potent predictor of next-quarter S&P 500 returns. Specifically, the second principal component of the VIX microstructure captures nearly all the relevant information for predicting returns on synthetic S&P 500 variance swaps, VIX futures, and straddles. This predictability is incremental to other common proxies for the conditional variance risk premium, suggesting that the microstructure captures a unique dimension of market risk that standard asset pricing models fail to account for.

The VIX microstructure is inherently linked to the market's expected path of mean reversion. When the VIX is low relative to its long-term average, futures trade at a premium (contango) because participants expect volatility to rise. When the VIX is exceptionally high, futures trade at a discount (backwardation), reflecting the expectation that the market will eventually stabilize. This dynamic is essential for price discovery because it determines the cost of hedging; a steep contango makes it expensive for institutions to maintain long volatility positions, potentially forcing a reallocation into the cash index and influencing price levels.

DISCUSSION

3. The Four-Factor Model in the Context of Price Discovery

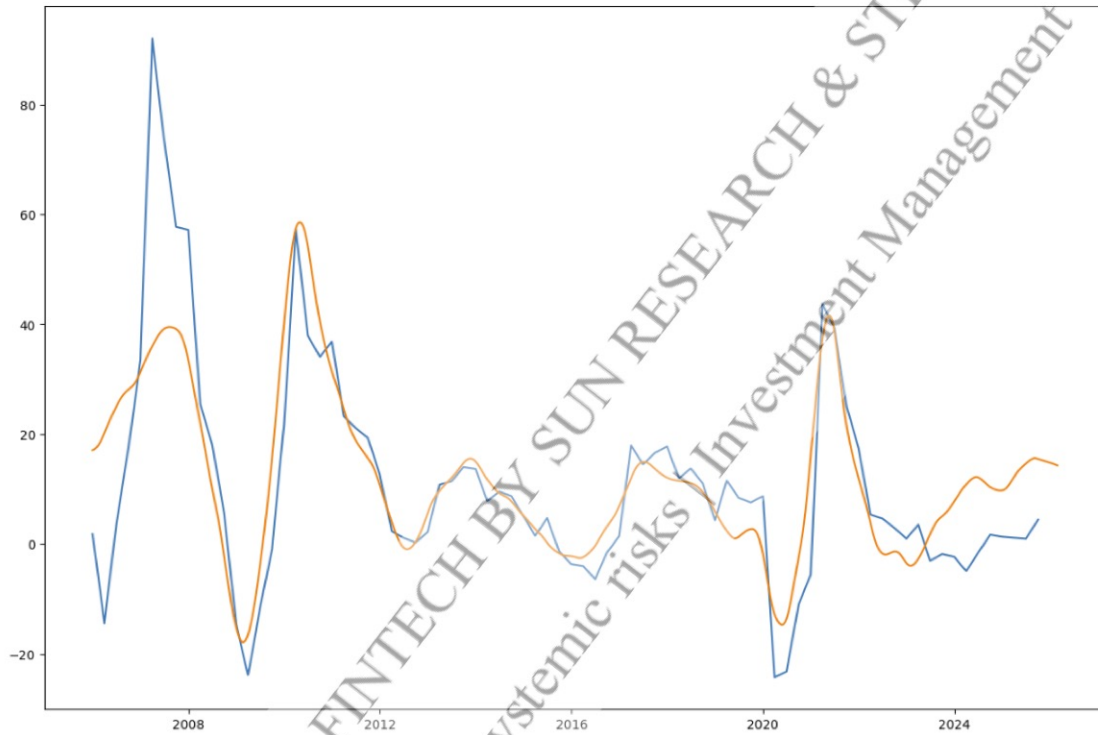
The classical price discovery literature, dominated by the Hasbrouck (1995) and Gonzalo and Granger (1995) models[†], often assumes that the "efficient price" is a latent variable driven primarily by the interaction of the cash and futures markets. To modernize this view, we integrate a four-factor model that identifies the specific economic drivers of this efficient price innovation. These factors—Profit, Macro, Basis, and Market Microstructure—represent the four pillars of the information set that traders attempt to impound into the S&P 500 price.

3.1. The Profit Factor

The profit factor acts as a stabilizer for the index's fundamental value. In our research paper, due to the unavailability of SP500 quarterly reported earnings data, I used China composite index quarterly reported earnings data as a proxy for the SP500, which will be the target variable. I constructed the proxy variables for the purpose of real-time forecasting the current earnings on a daily manner. The selection of proxy is very important for extrapolating a good forecasting power.

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I incorporated the leading indicators and the alternative data source, such as automobile production, steel production, PPI components of various metals, profits and loss of various size corporations, airports turnover, subway volume, freight index, FDI index, automobile sales volume, etc. for constructing a good casual relationship between the proxy variables and the target earnings. The proxy variables are firstly underwent a normalization and PCA decomposition, subsequently, the principle components fitted a linear regression model with the targeted quarterly earnings to get the model. Then the proxy variable can convert back to daily samples with the out of sample forecast of the current earnings on a daily basis. **Scheme 1** shows the predicted profit factor in comparison with the original but incomplete China quarterly reported earnings, as a substitute of the SP500 quarterly reported earnings, i.e. US profit factor.



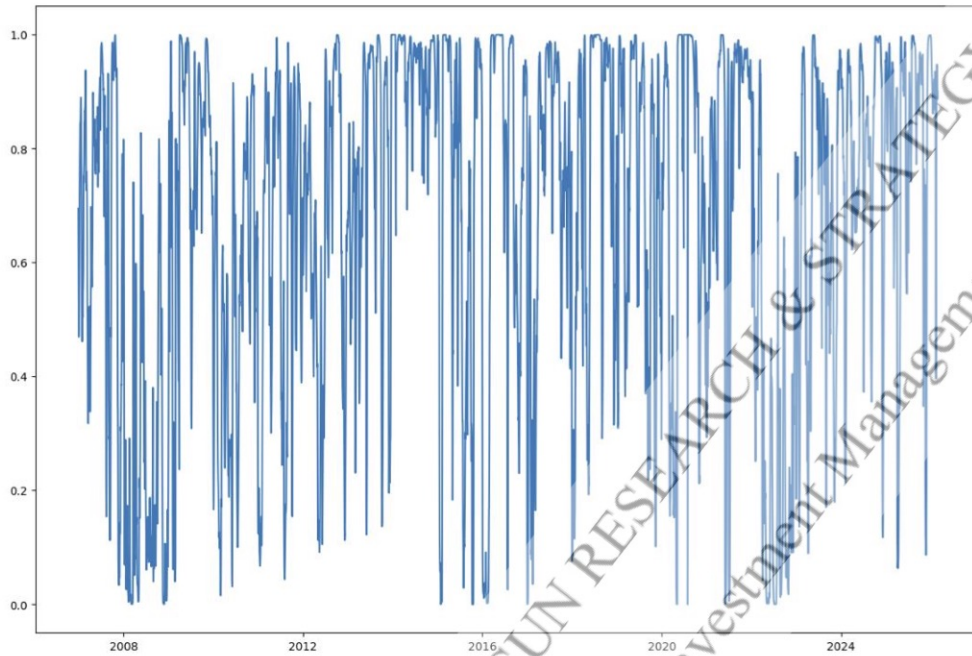
Scheme 1. The predicted profit factor(Orange line) in comparison with the original but incomplete China quarterly reported earnings(Blue line)

3.2. The Macro Factor

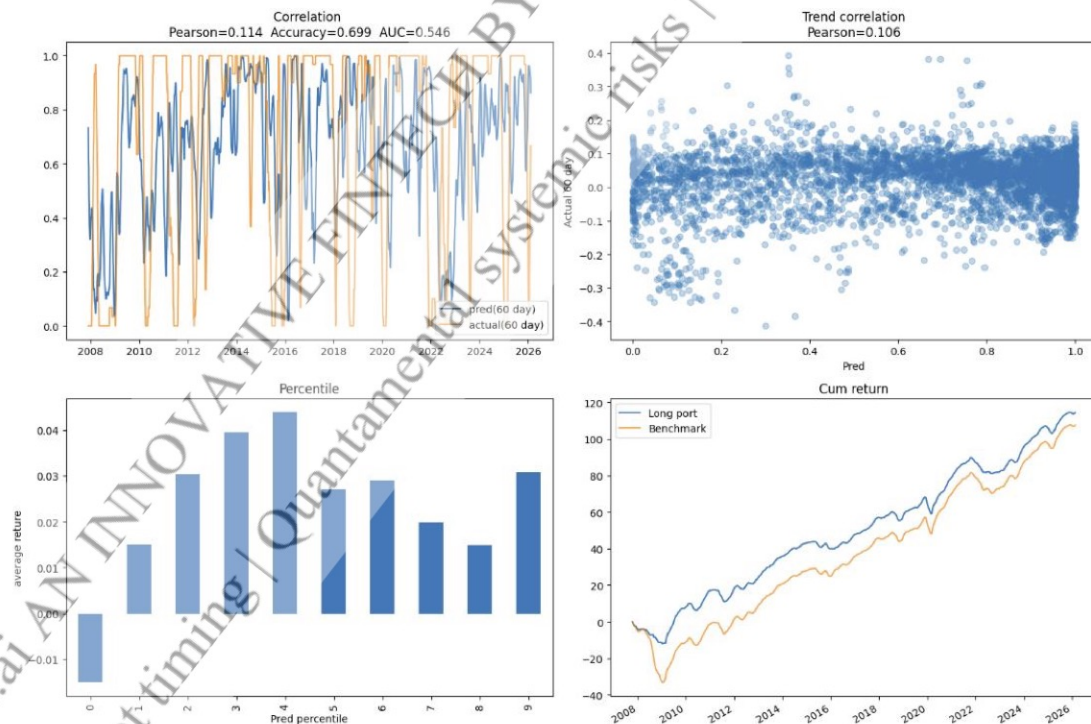
Macroeconomic factors provide the environment in which all S&P 500 constituents operate. Target variable is constructed by calculate SPX 60 days returns. It's very import to select the highly relevant and information rich components of macro variables. Macro variables such as Overnight Repo rates, SOFR, US Treasury ONRRP, US Treasury yields and spread, US Corporate Bond yields and spread, foreign exchange rates across major economic countries, Commercial Bank lending data, M1/M2, PMI of major economic regions, etc. contain information about the future changes in the investment opportunity set. All macro variables underwent a lagging and an EMA difference transformation, then the transformed macro variables fitted a logistic regression model against the target variable to get the model. Then the model can be used for the out of sample forecast of the

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current macro environment on a daily basis. **Scheme 2** shows the predicted macro factor from 2008 -2026. Macro factors are strongly leading indicator of the future market volatility. **Scheme 3** shows predicted returns versus the actual 60 days returns, the correlation between them, the average returns based on the predictions' percentiles, and the simulated portfolio performance based on the predicted macro environment.



Scheme 2. The predicted macro factor from 2007 -2026.



Scheme 3. Predicted returns versus the actual 60 days returns, the correlation between the prediction and actual trends, the average returns based on the predictions' percentiles, and the simulated portfolio performance based on the predicted macro environment.

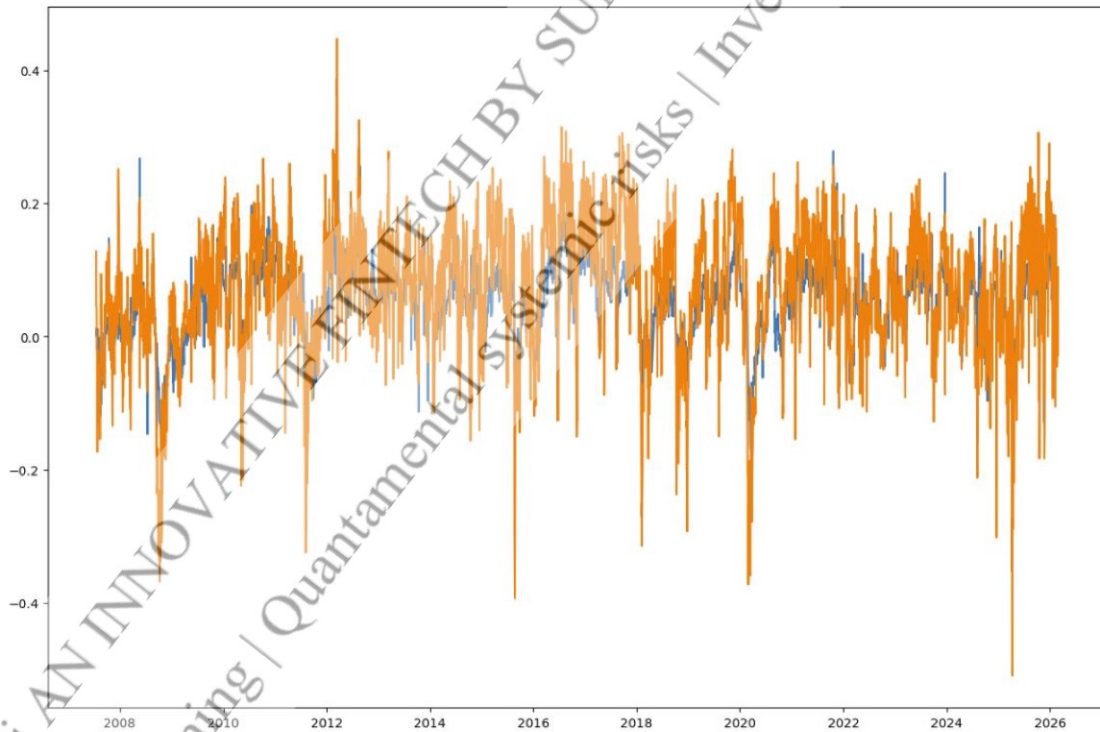
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3.3. The Basis Factor

The basis factor represents the price difference between the cash index and its various derivatives, as well as the relationships within the volatility market itself. In equity price discovery, the futures-cash basis is the primary mechanism through which arbitrageurs link the two markets. If the futures price moves ahead of the cash index, the basis widens, prompting arbitrage activity that pulls the spot price toward the futures price, thereby facilitating price discovery.

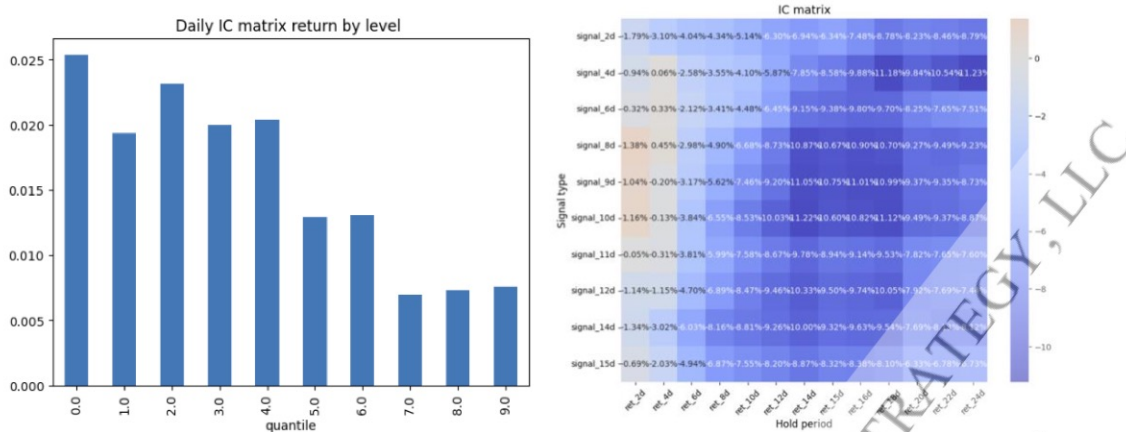
In the volatility domain, the "VIX futures basis"—the difference between the spot VIX and VIX futures—is a critical indicator of information leadership. An increase in the VIX futures basis typically follows a major market drop, as the spot VIX spikes more sharply than longer-term futures. This basis is a direct reflection of the VIX microstructure's major principle components. When the VIX futures basis is positive (backwardation), the contribution of VIX futures to price discovery increases relative to the spot index, as informed traders flock to the futures market to express views on volatility reversion.

To construct basis factor, I use a proprietary algorithm to generate the adjusted VIX basis, then calculate its daily returns and daily rolling ranks. Subsequently, I obtained daily rolling correlation between the ranks of VIX basis and SPX basis. The rolling average then applied to the correlation, and the percentile is derived from the rolling average. Lastly, I obtained the IC matrix and returns by percentile. **Scheme 4** shows the proprietary VIX basis. **Scheme 5** shows the IC matrix and returns by percentile. **Scheme 6** shows the final optimized basis factor.

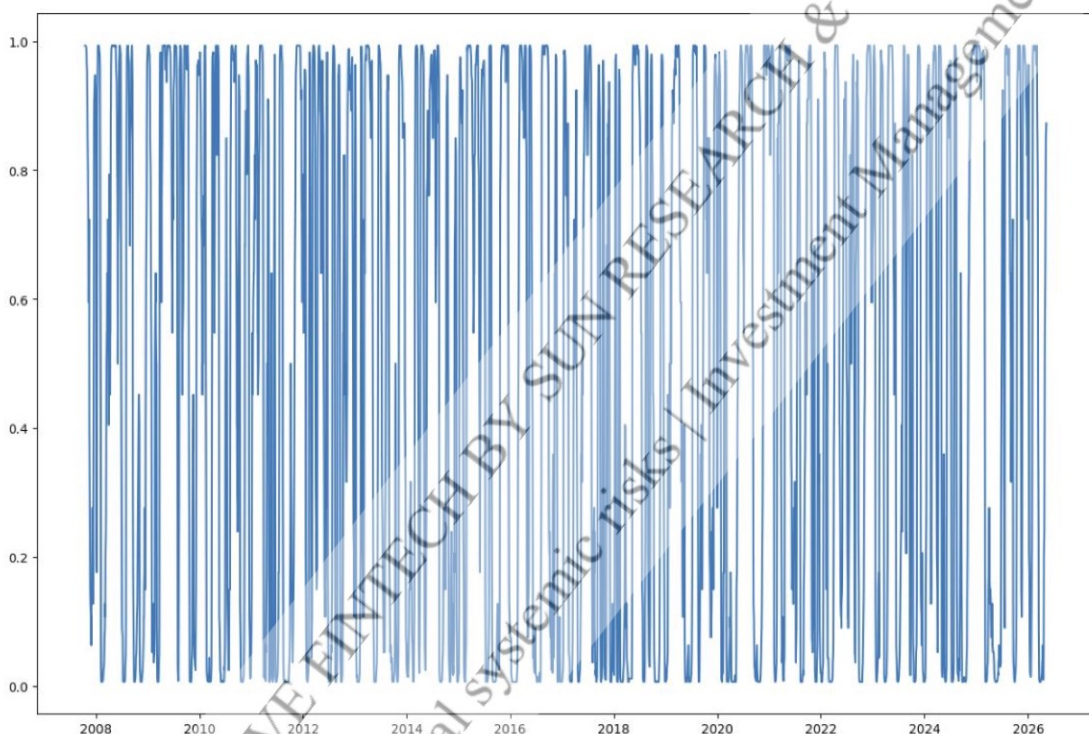


Scheme 4. The proprietary algorithm calculated VIX basis over 2007-2026

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Scheme 5. The IC matrix and returns by percentile.



Scheme 6. The final optimized basis factor 2007-2026.

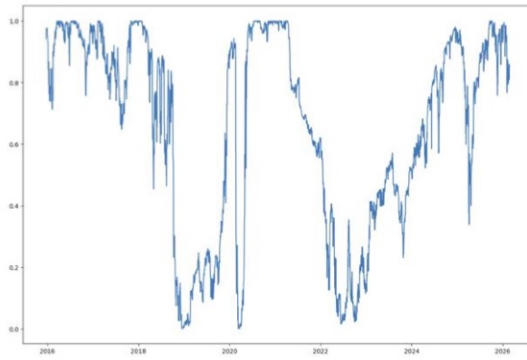
3.4. The Market Microstructure Factor

Market microstructure refers to the transactional level of price discovery, where trading frictions and asymmetric information dictate the speed and efficiency of price adjustments. I construct the market microstructure factor by combining the valuation level, risk premium, volatility and liquidity, synthesizing the final market microstructure.

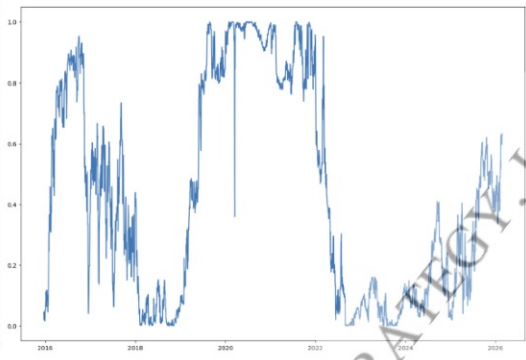
The valuation level is calculated by the 5 years rolling percentile of the SP500's PE. The risk premium is calculated by $ERP = 1/PE - \text{risk free interest rate (10 Year US Treasury real yield)}$. The volatility is calculated by the 20 days rolling volatility of SPX. The liquidity is calculated by the turnover rate of China A500 ETF, which serve as a proxy for the US equity market, as the turnover rate of SPY ETF data is not available. Subsequently, the four metrics are averaged on the daily level

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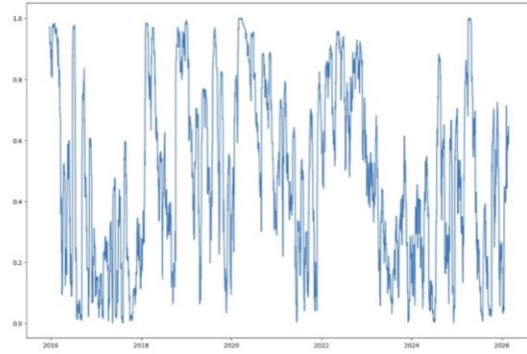
to get the market microstructure factor.



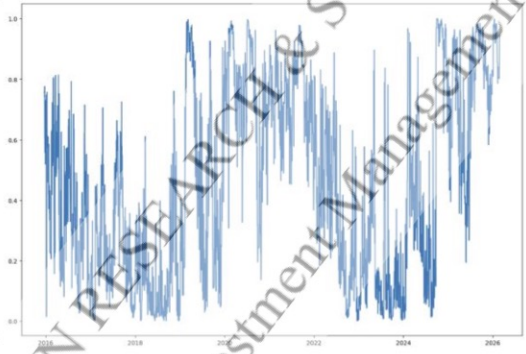
Scheme 7. The Valuation level of 2007-2026.



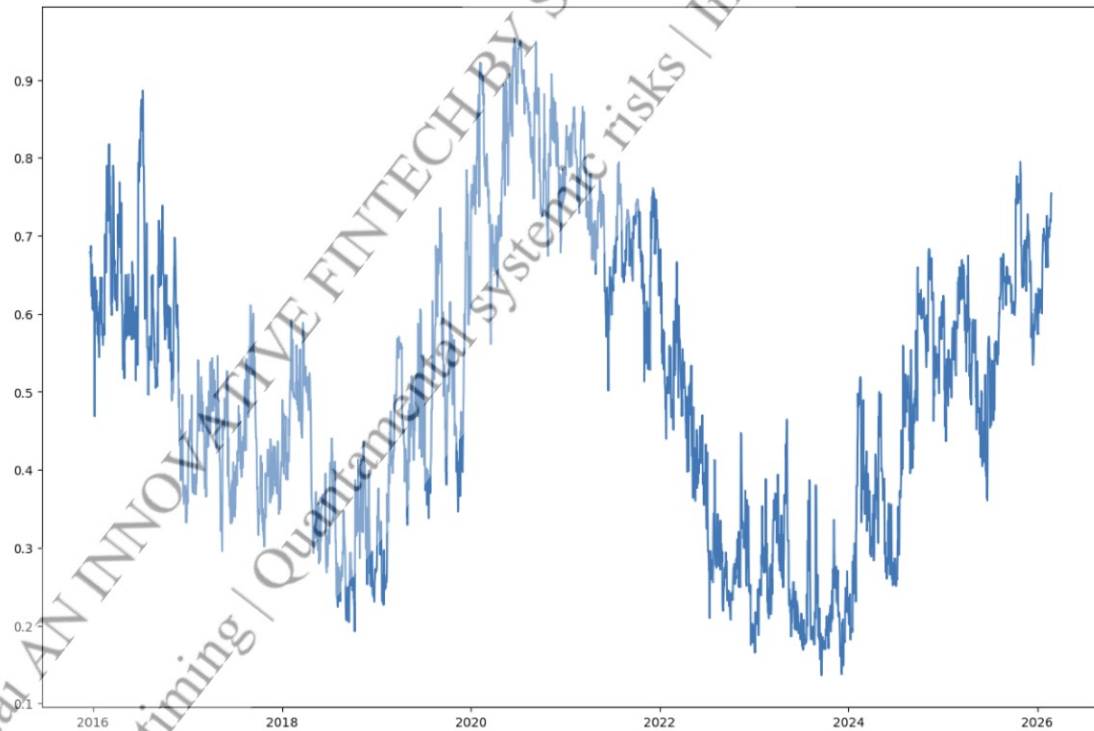
Scheme 8. The Risk Premium level of 2007-2026.



Scheme 9. The Volatility level of 2007-2026.



Scheme 10. The Liquidity level of 2007-2026.



Scheme 11. The final synthesized microstructure factor of 2007-2026.

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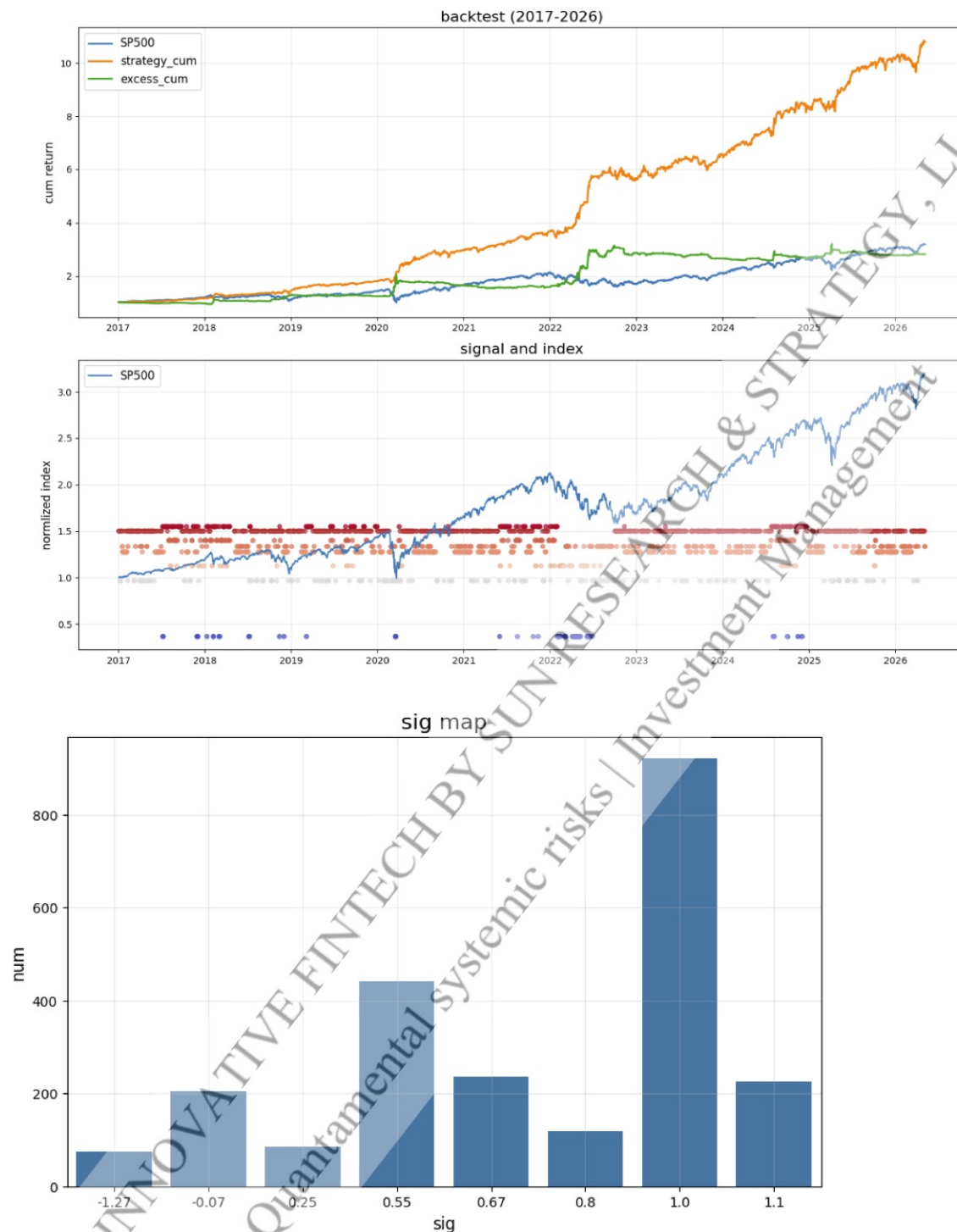
4. Backtest experimentation

In order to run a comprehensive backtest experimentation, I synthesized the multi-dimensional signals and established a multi-factor integrated framework for backtesting. The profit factor and the macro factor can form 8 distinctive regimes for synthesizing the framework. The dimensional framework is represented in the table below:

Regime	Factor Status	Dimensional status
#1 Prosperity	Macro Growth; Profit Growth; Prosperity	1
#2 Transitional prosperity	Macro Decline; Profit Growth; Prosperity	1
#3 Oscillation	Macro Growth; Profit Growth; Decline	0
#4 Transitional Oscillation	Macro Decline; Profit Growth; Decline	0
#5 Recovery	Macro Growth; Profit Decline; Prosperity	1
#6 Transitional Recovery	Macro Decline; Profit Decline; Prosperity	0
#7 Transitional Complacency	Macro Growth; Profit Decline; Decline	1
#8 Complacent Shock	Macro Decline; Profit Decline; Decline	0

Finally, I conducted a comprehensive backtest with the synthesized multi-factor model. For the purpose of making sure no look-ahead bias, all observational data are shifted so that no future data is used in the backtest. As the market environment changed dramatically since 2017, I first exam the backtest results from 2017 to 2026. The dimensional status is combined with the composite signal generation algorithm to get the signal map, which represents the portfolio proportions of the SPY ETF. This advanced framework delivers an annual return of 29.03% with a Sharpe ratio of 1.9 and a maximum drawdown of 8.54% based on the shifted market paradigm for the period of 2017-2026.

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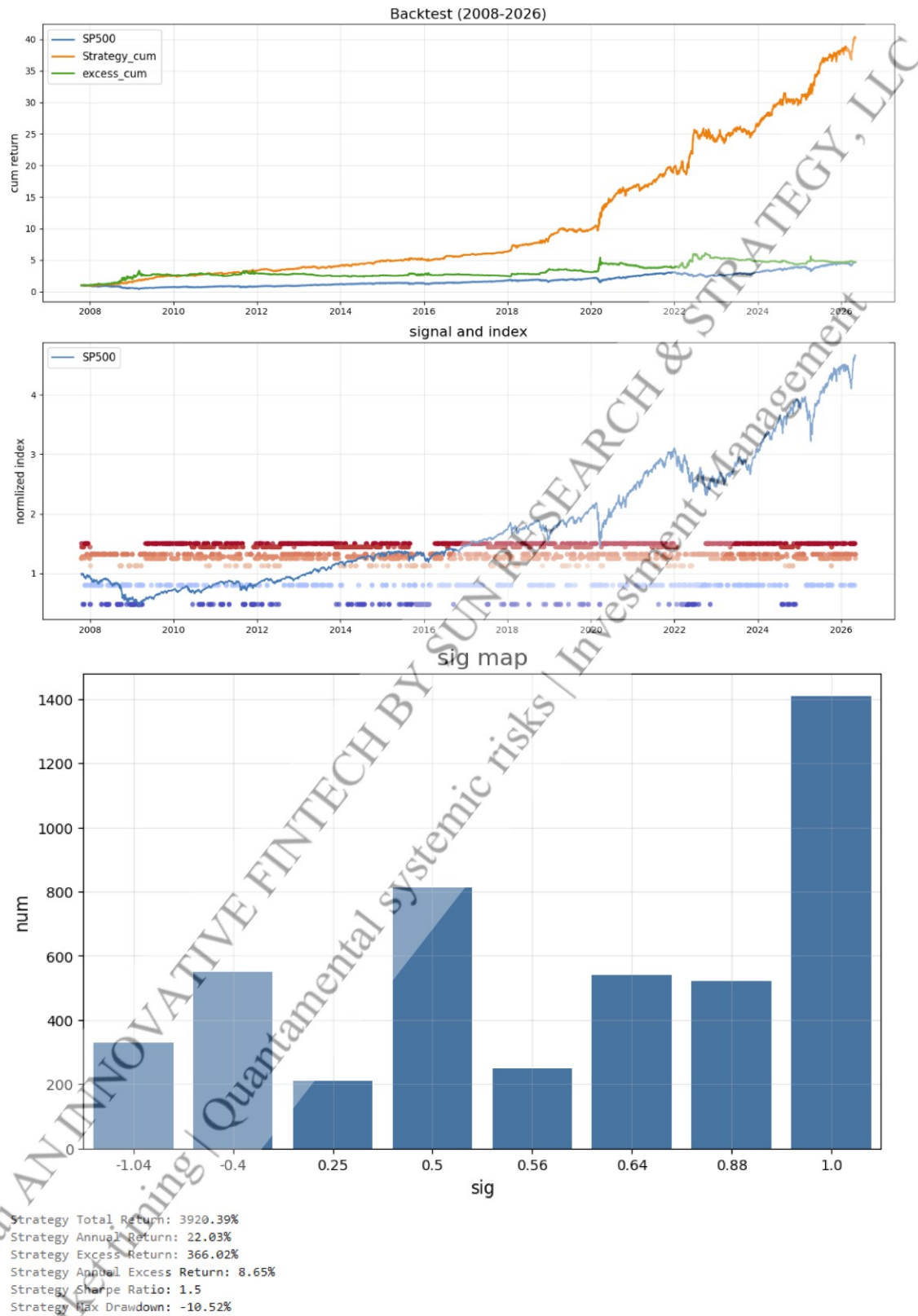
Strategy Total Return: 980.30%
 Strategy Annual Return: 29.03%
 Strategy Excess Return: 181.11%
 Strategy Annual Excess Return: 11.71%
 Strategy Sharpe Ratio: 1.9
 Strategy Max Drawdown: -8.54%

Scheme 12. The backtest results for 2017-2026.

In a full data set backtest incorporating all major shock events for stress testing purpose, I then exam the backtest results from 2008 to 2026. This advanced framework delivers an annual return of

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22.03% with a Sharpe ratio of 1.5 and a maximum drawdown of 10.52% based on the full market regime spectrum from 2008 to 2026.



Scheme 13. The backtest results for 2008-2026.

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5. The Information Convergence Price Discovery Theory (ICPDT)

The ensemble model of the VIX microstructure and US treasury yield model evaluates the systemic risk, synthesized with the four-factor model leads us to propose a new price discovery theory: the Information Convergence Price Discovery Theory (ICPDT).

ICPDT posits that price discovery in the S&P 500 is a multi-dimensional convergence process where information from different origins is synthesized through the lens of volatility regimes.

The Information Hierarchy: Short-term price movements are driven by systematic investing scheme, represented by VIX microstructure, the market microstructure and basis factor (the "transactional" layer), the VIX microstructure acts as the transmission mechanism between market microstructure and basis. These stochastic short-term movements converge toward an efficient price determined by the profit and macro factors (the "fundamental" layer).

Path-Dependency: The process of reaching the efficient price is not a random walk but a path-dependent process. The loading factors of the market are sensitive to the previous state of the VIX microstructure, meaning that the market "remembers" its recent volatility regime when processing new information.

VIX microstructure served as a forward looking proxy for pricing the expected volatility and the valuation of the market expectations. Reasonable stochastic oscillation of the expectation of market valuation contains all market information efficiently in real time, which constitutes the information convergence price discovery theory and the efficient market theory. In modern finance, VIX and its future derivatives priced from BSM model and global market making participants, by which essentially pricing the expected volatility and the valuation of the market expectations. Through this mechanism, the ensemble model of the VIX microstructure and US treasury yield models, synthesized with the four-factor model can robustly evaluate how the market perceives the systemic risks in real time, and this mechanism is impenetrable as it comprised of all global market making activities, so that no monopoly status can be formed or influenced by few market participants.

I have proposed the Information Convergence Price Discovery Theory (ICPDT) as a framework for understanding how different classes of information are synthesized. Offering high-frequency traders and risk managers a more nuanced tool for identifying who "leads" the market during periods of volatility expansion.

CONCLUSION

The integration of the VIX microstructure and US treasury yield models, synthesized with the four-factor model (Profit, Macro, Basis, and Microstructure) provides a transformative framework for understanding price discovery in the S&P 500. We move away from the simplistic "who-leads-whom" debate and toward a comprehensive view of how different regimes of risk dictate the mechanism through which information is impounded into prices.

The proposed Information Convergence Price Discovery Theory (ICPDT) highlights that price discovery is a path-dependent, regime-sensitive process. The "efficient price" is a moving target whose discovery is mediated by both fundamental news and mechanical trading frictions. As the financial ecosystem continues to evolve with the influence of AI and the growth of passive indexing, the need for this integrated, multi-factor approach will only increase. For researchers and

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practitioners, the VIX microstructure is no longer just a barometer of sentiment; it is the fundamental framework within which the price of the world's most important index is discovered.

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