J.P.Morgan

Investable AI for Volatility Trading

Deep Learning Model for Cross Asset Volatility Strategies

- We introduce an attention-based deep learning mechanism leveraging high-frequency data to determine relative value among the volatility of over 50 assets across a variety of asset classes, including Equity, FX, Commodities, Rates and Credit.
- We have provided two ways to construct a cross asset portfolio: a risk parity style portfolio aggregating intra-asset RV strategies, as well as a narrow but liquid universe for cross asset RV trading.
- The model achieves solid performance at both individual asset and the portfolio levels after accounting for transaction costs, over an extended back test period from 2010 to 2023. Its performance in recent years is comparatively strong.

Global Quantitative and Derivatives Strategy

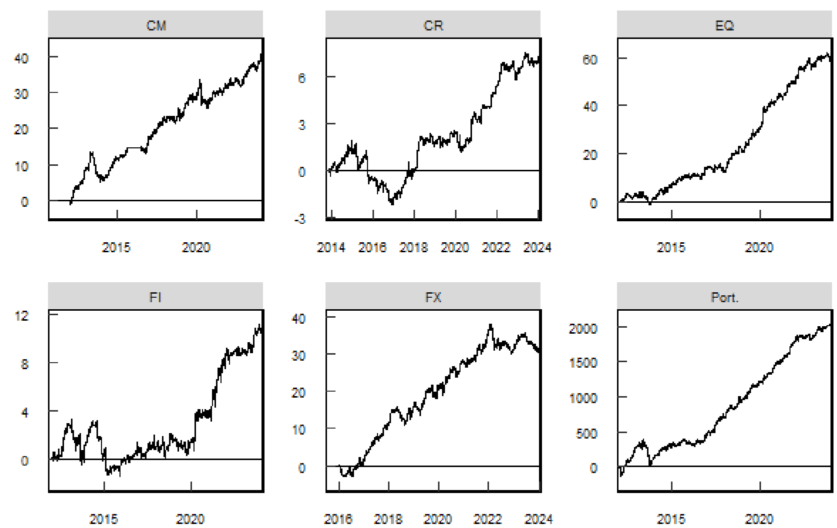
Emma Wu AC
(1-212) 834-2174
emma.wu@jpmorgan.com

Peng Cheng, CFA AC
(1-212) 622-5036
peng.cheng@jpmorgan.com

Ladislav Jankovic AC
(1-212) 834-9618
ladislav.jankovic@jpmchase.com

Marko Kolanovic, PhD
(1-212) 622-3677
marko.kolanovic@jpmorgan.com
J.P. Morgan Securities LLC

Figure 1: Model performance by asset class



Source: J.P. Morgan

See page 11 for analyst certification and important disclosures.

Emma Wu AC
(1-212) 834-2174
emma.wu@jpmorgan.com

Introduction

Attention mechanisms are known to lead to improvements in learning long term dependencies and have recently been harnessed for time-series modeling. Readers may recall that a newer version of the ETF Relative Value Volatility model was launched this April. In contrast to the old hierarchical regression model with daily frequency data which covers 80 ETFs over three month tenor, the new methodology leverages attention based neural network and high frequency data to determine the richness/cheapness of one-month implied volatility for 30 highly liquid ETFs. Thanks to the improvement in computational power and availability of high frequency data, we explored opportunities to extend the framework to other asset classes, including FX, Equities, Credit and Commodities.

The rest of the report is divided into three sections: we first review in detail the methodology of our deep learning based framework; then illustrate its uses and the backtest results within each individual asset class as well as at the portfolio level; finally, we select 23 underliers as representatives and build a Cross Asset Relative Value (CARV) model.

Data and Methodology

The main idea behind our RV model is to find the relationship between the current implied volatility with model forecast “fair” value of realized volatility across names at one point in time. The complete list of assets can be found in the Appendix. In our model setting, we continue using each security’s first two moments of the return distribution, daily return and daily realized power, to forecast the realized volatility. Daily realized power is defined as the sum of five-minute absolute returns across trading hours within a trading day. In the previous note, we discussed and proved this variable outperforms realized volatility when predicting future volatility. Our approach coincides with Ghysels, Santa-Clara and Valkanov (2006) [1], which applied the same concept to equities data and found realized power dominates other predictors such as squared returns and absolute returns at all horizons. Daily returns are used as an additional feature to account for the leverage effects. For both, we use a truncation over the last 60 business days.

Each security’s volatility is modeled using its own historical data instead of a cross-sectional sample with other securities’ history. Therefore, for each security, there are 2 features / day * 60 days = 120 features. These features are first passed through an attention layer with sigmoid activation. We discussed our preference to self-attention mechanism than other deep learning methods such as RNN and LSTM here. As a reminder, the attention mechanism incorporates a learnable similarity score to assign a measure of importance to previous time-steps, and the weights don’t have to obey a specific decay rate (i.e. the recent observations are always assigned higher weights than the distant ones). A flatten layer is then added to make the output linear before passing onto a dense layer. We applied 20% dropout for the hidden units given the large number of neurons and to prevent over-fitting. Mean squared logarithmic error is chosen to be our loss function so that securities with different vol levels are treated the same.

1. Ghysels, E., P. Santa-Clara, R. Valkanov, 2006, "Predicting volatility: getting the most out of return data sampled at different frequencies", Journal of Econometrics, Volume 131, Issues 1-2, 2006

Emma Wu [AC]
(1-212) 834-2174
emma.wu@jpmorgan.com

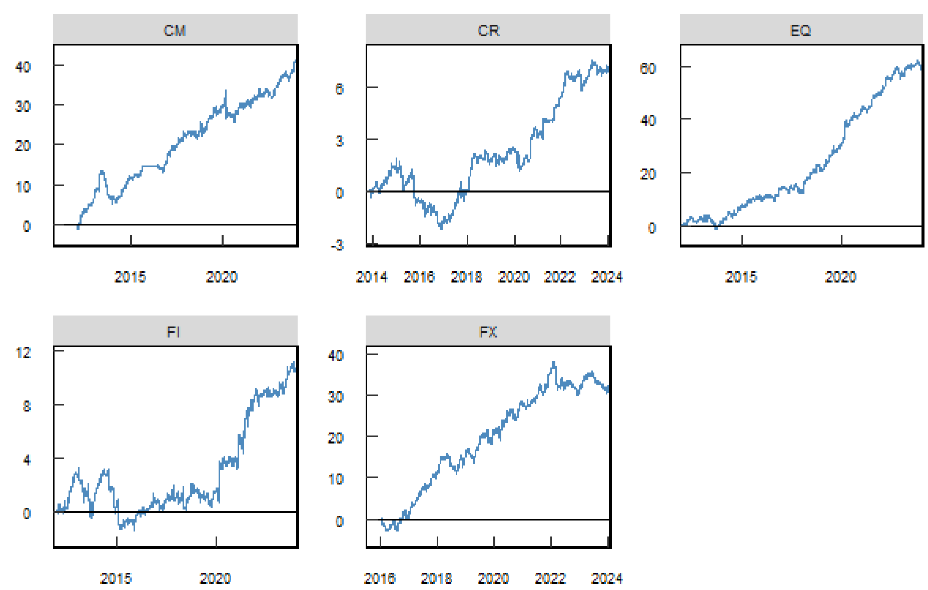
We keep using an expanding window approach and retrain the model on a monthly basis. The initial training period is 2 years. We leave one-month window between training and testing period to avoid forward looking bias, and use the trained model to predict realized volatility for the subsequent month. For example, the first prediction for majority of assets is as of 2012-02-01 using training sample from 2010-01-01 to 2011-12-31; the last prediction is as of 2023-12-31 using training sample from 2010-01-01 to 2023-10-31.

Intra-asset Strategy and Portfolio Performance

In our first back-test, the trading strategy is implemented within each asset class individually (as seen in Appendix): on a daily basis, we rank each asset based on model prediction and construct a portfolio with the same number of long vol and short vol candidates. Each position is scaled by its inverse vol level when entered and positions are held for 1 month. PNL is calculated MtM everyday. The number of names in the trading basket (n) can be different for asset classes, depending on the number of securities contained in each asset (N) (Figure 5). Effectively, in each portfolio, we hold n x 22 short and same number of long overlapping positions. On any given day, the P&L is calculated on a mark-to-market basis. The out-of-sample performance are shown in Figure 2.

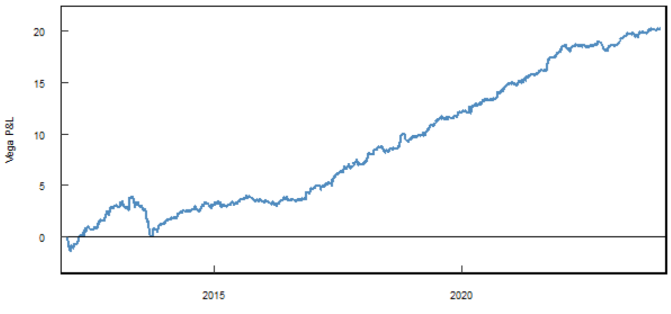
Our cross asset portfolio is then constructed by aggregating those five individual strategies (Figure 3), where the allocation to each is determined by its inverse volatility (Figure 4). Note that Credit and FX were added later due to the limitation of data prior to 2012 and 2014, respectively. On average, we allocate the largest weights to Credit (34%) and Fixed Income (30%), relatively evenly between Commodities and Equities (16% and 13%), and least to FX (7%).

Figure 2: Individual strategy performance



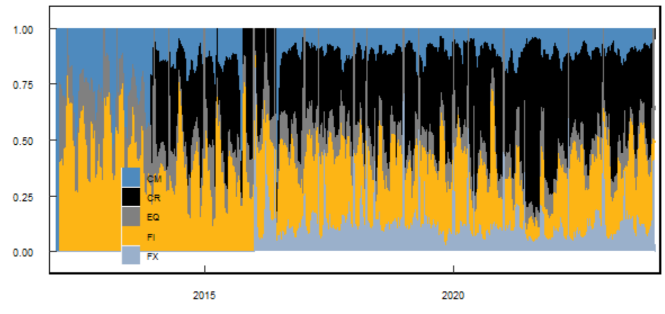
Source: J.P. Morgan

Figure 3: Portfolio performance



Source: J.P. Morgan

Figure 4: Portfolio allocation



Source: J.P. Morgan

We detailed out the metrics for each assets as well as the portfolio level for below categories (Figure 5), in order to provide insight into the relative strengths and weaknesses of each architecture. Since we completely rerun each experiment five times, we have reported the average across all runs, for each metric.

1) **Profitability** through annualized vega P&L, and percentage of positive captured returns;

2) **Risk** through annualized volatility, annualized downside deviation, skewness and maximum drawdown;

3) **Risk-adjusted** performance through annualized Sharpe and Sortino.

The model performs best on Equities and Commodities, and reasonably well on FX, which could have simply benefitted from breadth. The average hold-to-maturity hit ratio is 53%. Our portfolio has delivered an annualized vega profit of 1.63 through the past 12 years, with a lower vol (1.26 vega) and a higher Sharpe (1.29) than any individual asset, suggesting the portfolio is benefit from diversification.

Figure 5: Performance metrics for individual strategy and the entire diversified portfolio

Excl. TC.

Asset	N	n	PNL (Vega)	Vol (Vega)	Sharpe	Down.Dev. (Vega)	Sortino	Skewness	MDD (Vega)	% Hit Ratio
CM	9	2	3.28	3.76	0.87	2.96	1.11	-4.34	-7.80	56.3
CR	4	1	0.68	1.33	0.52	1.41	0.49	-0.91	-1.61	50.8
EQ	13	3	4.71	4.33	1.09	3.35	1.41	1.13	-4.27	53.4
FI	4	1	0.89	2.06	0.43	1.8	0.49	0.43	-2.44	53.2
FX	23	5	3.74	4.53	0.82	4.8	0.78	-0.23	-4.30	52.9
Port.	-	-	1.63	1.26	1.29	-	-	0.14	-1.55	-

Source: J.P. Morgan

To make the strategy more realistic, we incorporate proper treatment to transaction cost: Instead of applying a universe assumption to all assets, we assume TC as x% of implied vol strike for each trade so that a reasonable transaction cost is applied for each asset across different vol regimes through time. Figure 5 exhibits the impact on P&L and Sharpe Ratio over a wide range of TC that taken from 0.5% to 4% of implied vol strike for each trade. When moving from raw returns to 4% TC, the portfolio experiences a total reduction of 1.69 vega, translating to a drop of 1.2 in Sharpe ratio. We see the

Emma Wu AC
(1-212) 834-2174
emma.wu@jpmorgan.com

model performs very well on Equities and Commodities as the average decay is 0.13 vega by every 0.5% increase of transaction cost, compared with FX which suffered an average loss of 0.61 vega every step up. It should be note that even when TC was taken at 3% of implied, Equities and Commodities perform well, and the portfolio still delivers a positive Sharpe at 0.3.

Figure 6: Transaction cost impact on Sharpe Ratio for individual strategy and for the entire diversified portfolio

TC ranges from 0.5% ~ 4% of implied vol strike for each trade.

		0.50%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%
CM	PNL (vega)	3.03	2.79	2.54	2.29	2.05	1.80	1.56	1.31
	Sharpe	0.81	0.74	0.68	0.61	0.55	**0.48**	0.41	0.35
CR	PNL (vega)	0.56	0.43	0.31	0.18	0.06	-0.07	-0.19	-0.32
	Sharpe	0.42	0.33	0.23	0.14	0.04	-0.05	-0.15	-0.24
EQ	PNL (vega)	4.33	3.96	3.58	3.21	2.83	2.45	2.08	1.70
	Sharpe	1.00	0.91	0.83	0.74	0.65	**0.57**	0.48	**0.39**
FI	PNL (vega)	0.76	0.64	0.51	0.38	0.26	0.13	0.01	-0.12
	Sharpe	0.37	0.31	0.25	0.19	0.13	0.06	0.00	-0.06
FX	PNL (vega)	3.13	2.51	1.90	1.29	0.67	0.06	-0.55	-1.17
	Sharpe	0.69	0.55	0.42	0.28	0.15	0.01	-0.12	-0.26
Port.	PNL (vega)	1.40	1.19	0.98	0.77	0.56	0.35	0.14	-0.06
	Sharpe	1.13	0.97	0.80	**0.63**	0.46	**0.29**	0.12	-0.05

Source: J.P. Morgan.

Cross Asset Relative Value Model

Next, we built up the cross asset model from another angle by shrinking our universe to the 23 assets shown in Figure 6. The universe selection is not intended to be exhaustive but instead represent the assets that are the most liquid within each asset class.

Based on the data and methodology described above, we obtain daily signals and rankings for each asset over the last 12 years. The lower the ranking, the greater richness bias from the model, and therefore the higher chance to profit from short vol. Figure 8shows that the ranking is effectively predicting the subsequent implied to realized vol spread. Figure 9 exhibits the correlation of ranking across asset classes. Commodities appear to be negatively correlated with all other asset classes, meaning when major names under commodities are identified as cheap, other assets are normally on the other side of the ranking. Equity vs. Credit and FX vs. Fixed Income have positive correlations. In Figure 10, we observed the Credit assets dominate the most expensive vol rankings, whereas Commodities and G3 tend to be ranked on the cheaper end. The model has a relatively neutral bias to equity indices.

Emma Wu [AC]
(1-212) 834-2174
emma.wu@jpmorgan.com

Figure 7: 1M vol of the following assets are used in this study

Name	Type	Asset
Gold	Metal	Commodity
Copper	Metal	Commodity
Soybean	Ags	Commodity
Crude Oil	Energy	Commodity
AUDUSD	USD-G10	FX
EURUSD	USD-G10	FX
GBPUSD	USD-G10	FX
NZDUSD	USD-G10	FX
USDJPY	USD-G10	FX
USDBRL	USD-EM	FX
UST10Y	UST	Fixed Income
UST5Y	UST	Fixed Income
UST2Y	UST	Fixed Income
AS51	Index	Equity
SPX	Index	Equity
SX5E	Index	Equity
NKY	Index	Equity
UKX	Index	Equity
RTY	Index	Equity
CDX-NAIG	IG	Credit
CDX-NAHY	HY	Credit
ITRAXX-Europe	Main	Credit
ITRAXX-Xover	XOver	Credit

Source: J.P. Morgan

Figure 8: RV ranking is strongly correlated with subsequent implied realized vol spread

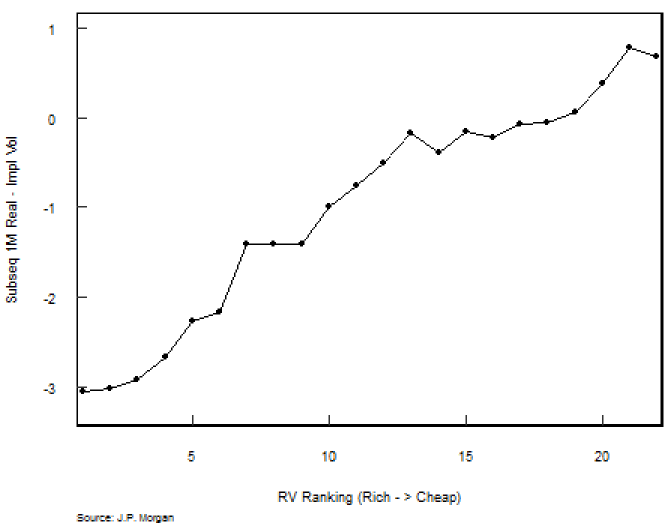
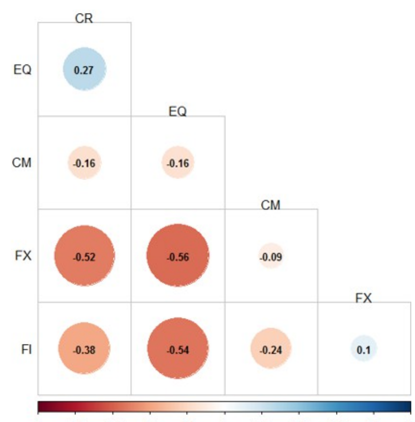


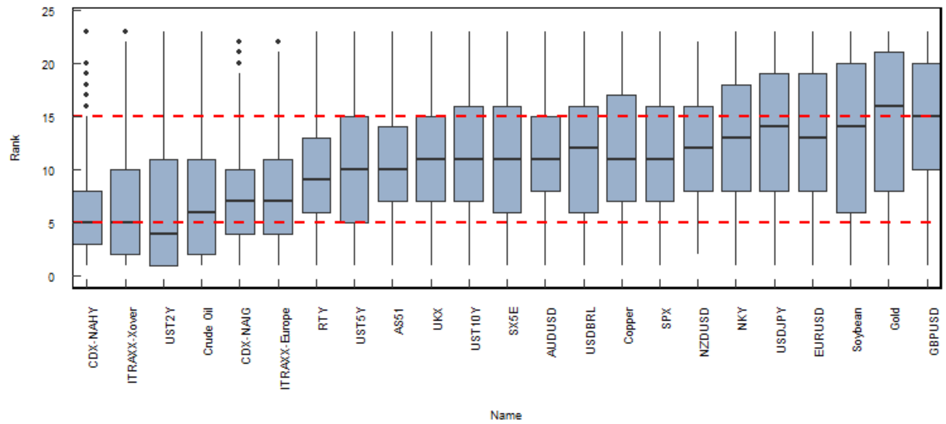
Figure 9: CARV ranking correlation across asset classes



Source: J.P. Morgan

Emma Wu [AC]
(1-212) 834-2174
emma.wu@jpmorgan.com

Figure 10: Average ranking per asset class

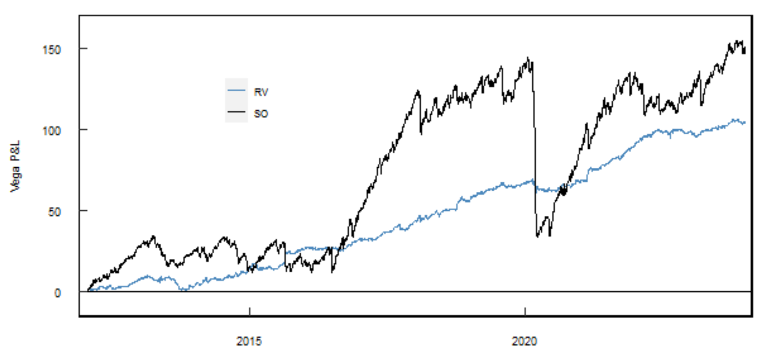


Source: J.P. Morgan

In Figure 11 and Figure 12, we show the hypothetical performance by allocating to the top 4 assets with the cheapest / richest volatility. As a comparison, we take short-only benchmark portfolio where we go short vol on all assets regardless of the signal. Our RV portfolio would have delivered an annual profit of 8.46 vega with a Sharpe of 1.49 prior transaction cost, outperforming the short-only benchmark portfolio significantly. We display the the impact on P&L and Sharpe Ratio over a wide range of TC in Figure 13. It should be highlighted that the portfolio would have performed well even net the transaction cost of 4% IV. Additionally, by varying the number of assets being invested in our portfolio (i.e. basket size) from 2 to 6, we didn't witness significant change in Sharpe ratio.

Figure 11: Hypothetical performance of long/short strategy on cross asset vol portfolios

Go long and short 4 names daily, holding for 1 month (i.e. 4 x 22 short and same amount of long overlapping positions). Excl. TC.



Source: J.P. Morgan

Emma Wu [AC]
(1-212) 834-2174
emma.wu@jpmorgan.com

Figure 12: Portfolio performance excl. TC

Excl.TC	PNL (Vega)	Vol (Vega)	Sharpe	Down.Dev. (Vega)	Sortino	Skewness	MDD (Vega)	% Hit Ratio
RV	8.46	5.66	1.49	4.34	1.95	-0.22	-5.60	55.8
SO	12.01	20.82	0.58	17.98	0.67	-5.27	-27.32	63.1

Source: J.P. Morgan

Figure 13: Transaction cost impact on Sharpe Ratio for CARV

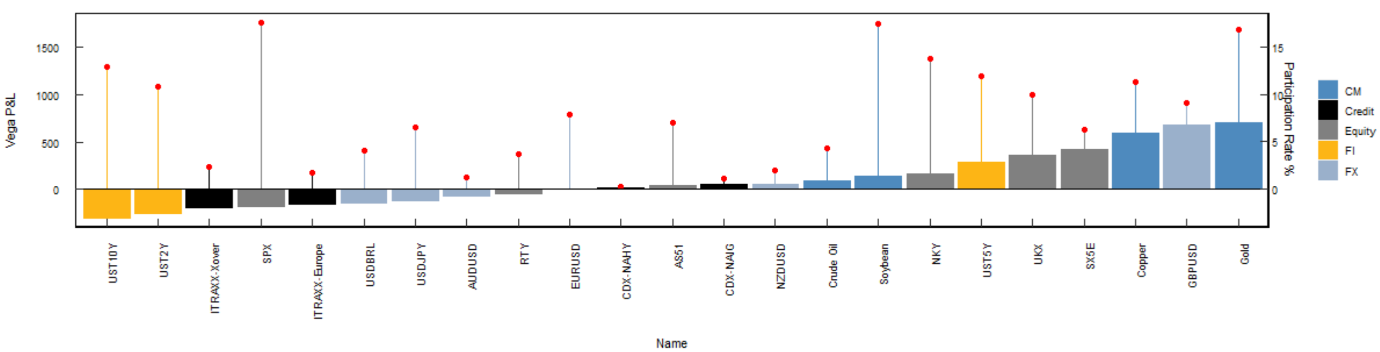
TC ranges from 0.5% ~ 4% of implied vol strike for each trade.

		0.50%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%
CARV	PNL (vega)	7.96	7.47	6.98	6.49	6.00	5.51	5.01	4.52
	Sharpe	1.41	1.32	1.23	1.15	1.06	0.97	0.89	0.80

Source: J.P. Morgan

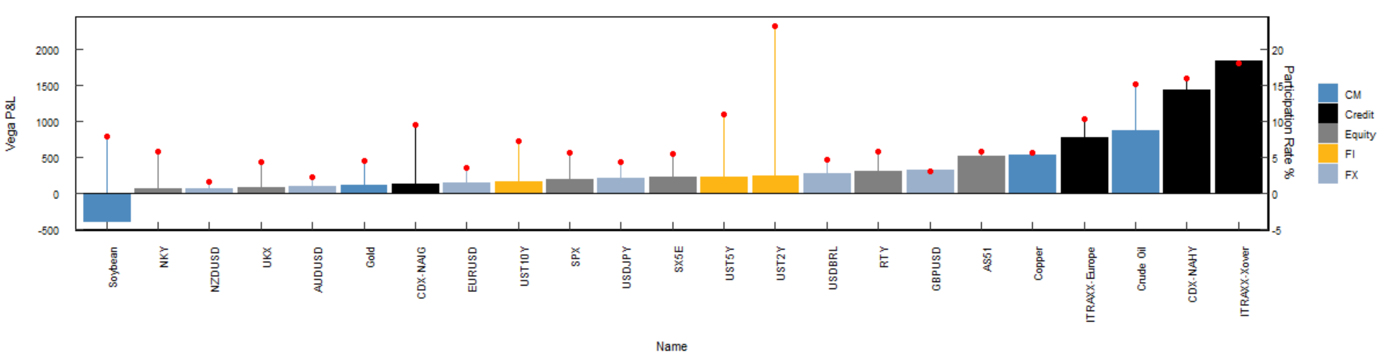
To add more colour, we plot the participation rate and P&L contribution by asset per each leg in Figure 14 and Figure 15. The short leg would have outperformed the long leg over the past years. The most notable feature is that credit and oil vol P&L dominates the short vol leg, whereas metals, sterling, and EU/UK equities vol were most profitable in long leg.

Figure 14: P&L contribution by asset class in long leg



Source: J.P. Morgan

Figure 15: P&L contribution by asset class in short leg



Source: J.P. Morgan

Conclusion

In this report, we build an attention-based deep learning framework leveraging high-frequency data to determine relative value among the volatility of over 50 assets across

Emma Wu AC
(1-212) 834-2174
emma.wu@jpmorgan.com

Equity, FX, Commodity, Fixed Income and Credit. We have illustrated the suitability of the model by back-testing over a long time period from 2012 to 2023 and noting its comparatively strong performance in recent years. Our detailed study of the results by asset class demonstrate Equities and Commodities are overall the best performers.

We provide two views of portfolio construction: a risk parity style portfolio aggregating intra-asset RV strategies; as well as a narrow but liquid universe for cross asset RV trading. It's important to note that the portfolio that constructed both ways achieve good performance net of transaction costs assumptions.

An interesting avenue of future study would be to further customize model selection and parameters to each asset class to account for their unique characteristics. Moreover, we intend to further explore model interpretability to extract more information embedded in the deep learning models.

Emma Wu AC
(1-212) 834-2174
emma.wu@jpmorgan.com

Appendix

Figure 16: Portfolio assets details

Asset	Name	TestFrom
Commodity	Gold	2011-12-01
Commodity	Silver	2011-12-01
Commodity	Copper	2011-12-01
Commodity	Platinum	2011-12-01
Commodity	Soybean	2011-12-01
Commodity	Wheat-SRW	2010-11-01
Commodity	Crude Oil	2011-12-01
Commodity	Brent	2011-12-01
Commodity	Natural Gas	2011-12-01
FX	AUDUSD	2015-07-01
FX	EURUSD	2015-12-15
FX	GBPUSD	2015-07-01
FX	NZDUSD	2015-12-01
FX	USDCAD	2015-12-01
FX	USDCHF	2015-12-01
FX	USDJPY	2015-07-01
FX	USDSEK	2015-12-01
FX	USDNOK	2015-07-01
FX	USDBRL	2015-12-01
FX	USDMXN	2015-12-01
FX	USDCZK	2015-07-01
FX	USDHUF	2015-07-01
FX	USDKRW	2015-12-03
FX	USDPLN	2015-12-01
FX	USDZAR	2015-12-01
FX	AUDJPY	2015-12-01
FX	GBPJPY	2015-12-01
FX	CADJPY	2015-12-01
FX	CHFJPY	2015-11-19
FX	AUDCAD	2015-12-01
FX	AUDNZD	2015-12-01
FX	GBPCHF	2015-12-01
Fixed Income	UST10Y	2011-12-01
Fixed Income	UST5Y	2011-12-01
Fixed Income	UST2Y	2011-12-01
Fixed Income	UST20Y	2011-12-01
Equity	AS51	2011-12-01
Equity	SPX	2011-12-01
Equity	NDX	2011-12-01
Equity	HSCEI	2011-12-01
Equity	HSI	2011-12-01
Equity	NIFTY	2011-12-01
Equity	SX5E	2011-12-01
Equity	NKY	2011-12-01
Equity	KOSPI2	2011-12-01
Equity	DAX	2011-12-01
Equity	UKX	2011-12-01
Equity	SMI	2011-12-01
Equity	RTY	2014-11-03
Credit	CDX-NAIG	2013-10-01
Credit	CDX-NAHY	2014-07-01
Credit	ITRAXX-Europe	2013-10-01
Credit	ITRAXX-Xover	2013-10-01

Source: J.P. Morgan.

Disclosures

Analyst Certification: The Research Analyst(s) denoted by an “AC” on the cover of this report certifies (or, where multiple Research Analysts are primarily responsible for this report, the Research Analyst denoted by an “AC” on the cover or within the document individually certifies, with respect to each security or issuer that the Research Analyst covers in this research) that: (1) all of the views expressed in this report accurately reflect the Research Analyst’s personal views about any and all of the subject securities or issuers; and (2) no part of any of the Research Analyst's compensation was, is, or will be directly or indirectly related to the specific recommendations or views expressed by the Research Analyst(s) in this report. For all Korea-based Research Analysts listed on the front cover, if applicable, they also certify, as per KOFIA requirements, that the Research Analyst’s analysis was made in good faith and that the views reflect the Research Analyst’s own opinion, without undue influence or intervention.

All authors named within this report are Research Analysts who produce independent research unless otherwise specified. In Europe, Sector Specialists (Sales and Trading) may be shown on this report as contacts but are not authors of the report or part of the Research Department.

Important Disclosures

Company-Specific Disclosures: Important disclosures, including price charts and credit opinion history tables, are available for compendium reports and all J.P. Morgan–covered companies, and certain non-covered companies, by visiting https://www.jpmm.com/research/disclosures, calling 1-800-477-0406, or e-mailing research.disclosure.inquiries@jpmorgan.com with your request.

Explanation of Equity Research Ratings, Designations and Analyst(s) Coverage Universe:
J.P. Morgan uses the following rating system: Overweight [Over the next six to twelve months, we expect this stock will outperform the average total return of the stocks in the analyst’s (or the analyst’s team’s) coverage universe.] Neutral [Over the next six to twelve months, we expect this stock will perform in line with the average total return of the stocks in the analyst’s (or the analyst’s team’s) coverage universe.] Underweight [Over the next six to twelve months, we expect this stock will underperform the average total return of the stocks in the analyst’s (or the analyst’s team’s) coverage universe.] Not Rated (NR): J.P. Morgan has removed the rating and, if applicable, the price target, for this stock because of either a lack of a sufficient fundamental basis or for legal, regulatory or policy reasons. The previous rating and, if applicable, the price target, no longer should be relied upon. An NR designation is not a recommendation or a rating. In our Asia (ex-Australia and ex-India) and U.K. small- and mid-cap equity research, each stock’s expected total return is compared to the expected total return of a benchmark country market index, not to those analysts’ coverage universe. If it does not appear in the Important Disclosures section of this report, the certifying analyst’s coverage universe can be found on J.P. Morgan’s research website, https://www.jpmorganmarkets.com.

J.P. Morgan Equity Research Ratings Distribution, as of January 01, 2024

	Overweight (buy)	Neutral (hold)	Underweight (sell)
J.P. Morgan Global Equity Research Coverage*	47%	39%	13%
IB clients**	48%	43%	32%
JPMS Equity Research Coverage*	46%	42%	12%
IB clients**	68%	63%	46%

***Please note that the percentages may not add to 100% because of rounding.**
****Percentage of subject companies within each of the "buy," "hold" and "sell" categories for which J.P. Morgan has provided investment banking services within the previous 12 months.**
For purposes of FINRA ratings distribution rules only, our Overweight rating falls into a buy rating category; our Neutral rating falls into a hold rating category; and our Underweight rating falls into a sell rating category. Please note that stocks with an NR designation are not included in the table above. This information is current as of the end of the most recent calendar quarter.

Equity Valuation and Risks: For valuation methodology and risks associated with covered companies or price targets for covered companies, please see the most recent company-specific research report at http://www.jpmorganmarkets.com, contact the primary analyst or your J.P. Morgan representative, or email research.disclosure.inquiries@jpmorgan.com. For material information about the proprietary models used, please see the Summary of Financials in company-specific research reports and the Company Tearsheets, which are available to download on the company pages of our client website, http://www.jpmorganmarkets.com. This report also sets out within it the material underlying assumptions used.

A history of J.P. Morgan investment recommendations disseminated during the preceding 12 months can be accessed on the Research & Commentary page of http://www.jpmorganmarkets.com where you can also search by analyst name, sector or financial instrument.

Analysts' Compensation: The research analysts responsible for the preparation of this report receive compensation based upon various factors, including the quality and accuracy of research, client feedback, competitive factors, and overall firm revenues.

Other Disclosures

J.P. Morgan is a marketing name for investment banking businesses of JPMorgan Chase & Co. and its subsidiaries and affiliates worldwide.

UK MIFID FICC research unbundling exemption: UK clients should refer to UK MIFID Research Unbundling exemption for details of JPMorgan's implementation of the FICC research exemption and guidance on relevant FICC research categorisation.

All research material made available to clients are simultaneously available on our client website, J.P. Morgan Markets, unless specifically permitted by relevant laws. Not all research content is redistributed, e-mailed or made available to third-party aggregators. For all research material available on a particular stock, please contact your sales representative.

Any long form nomenclature for references to China; Hong Kong; Taiwan; and Macau within this research material are Mainland China; Hong Kong SAR (China); Taiwan (China); and Macau SAR (China).

J.P. Morgan Research may, from time to time, write on issuers or securities targeted by economic or financial sanctions imposed or administered by the governmental authorities of the U.S., EU, UK or other relevant jurisdictions (Sanctioned Securities). Nothing in this report is intended to be read or construed as encouraging, facilitating, promoting or otherwise approving investment or dealing in such Sanctioned Securities. Clients should be aware of their own legal and compliance obligations when making investment decisions.

Any digital or crypto assets discussed in this research report are subject to a rapidly changing regulatory landscape. For relevant regulatory advisories on crypto assets, including bitcoin and ether, please see https://www.jpmorgan.com/disclosures/cryptoasset-disclosure.

The author(s) of this research report may not be licensed to carry on regulated activities in your jurisdiction and, if not licensed, do not hold themselves out as being able to do so.

Exchange-Traded Funds (ETFs): J.P. Morgan Securities LLC ("JPMS") acts as authorized participant for substantially all U.S.-listed ETFs. To the extent that any ETFs are mentioned in this report, JPMS may earn commissions and transaction-based compensation in connection with the distribution of those ETF shares and may earn fees for performing other trade-related services, such as securities lending to short sellers of the ETF shares. JPMS may also perform services for the ETFs themselves, including acting as a broker or dealer to the ETFs. In addition, affiliates of JPMS may perform services for the ETFs, including trust, custodial, administration, lending, index calculation and/or maintenance and other services.

Options and Futures related research: If the information contained herein regards options- or futures-related research, such information is available only to persons who have received the proper options or futures risk disclosure documents. Please contact your J.P. Morgan Representative or visit https://www.theocc.com/components/docs/riskstoc.pdf for a copy of the Option Clearing Corporation's Characteristics and Risks of Standardized Options or http://www.finra.org/sites/default/files/Security_Futures_Risk_Disclosure_Statement_2018.pdf for a copy of the Security Futures Risk Disclosure Statement.

Changes to Interbank Offered Rates (IBORs) and other benchmark rates: Certain interest rate benchmarks are, or may in the future become, subject to ongoing international, national and other regulatory guidance, reform and proposals for reform. For more information, please consult: https://www.jpmorgan.com/global/disclosures/interbank_offered_rates

Private Bank Clients: Where you are receiving research as a client of the private banking businesses offered by JPMorgan Chase & Co. and its subsidiaries ("J.P. Morgan Private Bank"), research is provided to you by J.P. Morgan Private Bank and not by any other division of J.P. Morgan, including, but not limited to, the J.P. Morgan Corporate and Investment Bank and its Global Research division.

Legal entity responsible for the production and distribution of research: The legal entity identified below the name of the Reg AC Research Analyst who authored this material is the legal entity responsible for the production of this research. Where multiple Reg AC Research Analysts authored this material with different legal entities identified below their names, these legal entities are jointly responsible for the production of this research. Research Analysts from various J.P. Morgan affiliates may have contributed to the production of this material but may not be licensed to carry out regulated activities in your jurisdiction (and do not hold themselves out as being able to do so). Unless otherwise stated below, this material has been distributed by the legal entity responsible for production. If you have any queries, please contact the relevant Research Analyst in your jurisdiction or the entity in your jurisdiction that has distributed this research material.

Legal Entities Disclosures and Country-/Region-Specific Disclosures:
Argentina: JPMorgan Chase Bank N.A Sucursal Buenos Aires is regulated by Banco Central de la República Argentina ("BCRA"- Central Bank of Argentina) and Comisión Nacional de Valores ("CNV"- Argentinian Securities Commission - ALYC y AN Integral N°51). **Australia:** J.P. Morgan Securities Australia Limited ("JPMSAL") (ABN 61 003 245 234/AFS Licence No: 238066) is regulated by the Australian Securities and Investments Commission and is a Market, Clearing and Settlement Participant of ASX Limited and CHI-X. This material is issued and distributed in Australia by or on behalf of JPMSAL only to "wholesale clients" (as defined in section 761G of the Corporations Act 2001). A list of all financial products covered can be found by visiting https://www.jpmm.com/research/disclosures. J.P. Morgan seeks to cover companies of relevance to the domestic and international investor base across all Global Industry Classification Standard (GICS) sectors, as well as across a range of market capitalisation sizes. If applicable, in the course of conducting public side due diligence on the subject company(ies), the Research Analyst team may at times perform such diligence through corporate engagements such as site visits, discussions with company representatives, management presentations, etc. Research issued by JPMSAL has been prepared in accordance with J.P. Morgan Australia's Research Independence Policy which can be found at the following link: J.P. Morgan Australia - Research Independence Policy. **Brazil**: Banco J.P. Morgan S.A. is regulated by the Comissao de Valores Mobiliarios (CVM) and by the Central Bank of Brazil. Ombudsman J.P. Morgan: 0800-7700847 / 0800-7700810 (For Hearing Impaired) / ouvidoria.jp.morgan@jpmorgan.com. **Canada**: J.P. Morgan Securities Canada Inc. is a registered investment dealer, regulated by the Canadian Investment Regulatory Organization and the Ontario Securities Commission and is the

participating member on Canadian exchanges. This material is distributed in Canada by or on behalf of J.P.Morgan Securities Canada Inc. **Chile:** Inversiones J.P. Morgan Limitada is an unregulated entity incorporated in Chile. **China:** J.P. Morgan Securities (China) Company Limited has been approved by CSRC to conduct the securities investment consultancy business. **Dubai International Financial Centre (DIFC)**: JPMorgan Chase Bank, N.A., Dubai Branch is regulated by the Dubai Financial Services Authority (DFSA) and its registered address is Dubai International Financial Centre - The Gate, West Wing, Level 3 and 9 PO Box 506551, Dubai, UAE. This material has been distributed by JP Morgan Chase Bank, N.A., Dubai Branch to persons regarded as professional clients or market counterparties as defined under the DFSA rules. **European Economic Area (EEA):** Unless specified to the contrary, research is distributed in the EEA by J.P. Morgan SE ("JPM SE"), which is authorised as a credit institution by the Federal Financial Supervisory Authority (Bundesanstalt für Finanzdienstleistungsaufsicht, BaFin) and jointly supervised by the BaFin, the German Central Bank (Deutsche Bundesbank) and the European Central Bank (ECB). JPM SE is a company headquartered in Frankfurt with registered address at TaunusTurm, Taunustor 1, Frankfurt am Main, 60310, Germany. The material has been distributed in the EEA to persons regarded as professional investors (or equivalent) pursuant to Art. 4 para. 1 no. 10 and Annex II of MiFID II and its respective implementation in their home jurisdictions ("EEA professional investors"). This material must not be acted on or relied on by persons who are not EEA professional investors. Any investment or investment activity to which this material relates is only available to EEA relevant persons and will be engaged in only with EEA relevant persons. **Hong Kong**: J.P. Morgan Securities (Asia Pacific) Limited (CE number AAJ321) is regulated by the Hong Kong Monetary Authority and the Securities and Futures Commission in Hong Kong, and J.P. Morgan Broking (Hong Kong) Limited (CE number AAB027) is regulated by the Securities and Futures Commission in Hong Kong. JP Morgan Chase Bank, N.A., Hong Kong Branch (CE Number AAL996) is regulated by the Hong Kong Monetary Authority and the Securities and Futures Commission, is organized under the laws of the United States with limited liability. Where the distribution of this material is a regulated activity in Hong Kong, the material is distributed in Hong Kong by or through J.P. Morgan Securities (Asia Pacific) Limited and/ or J.P. Morgan Broking (Hong Kong) Limited. **India**: J.P. Morgan India Private Limited (Corporate Identity Number - U67120MH1992FTC068724), having its registered office at J.P. Morgan Tower, Off. C.S.T. Road, Kalina, Santacruz - East, Mumbai – 400098, is registered with the Securities and Exchange Board of India (SEBI) as a 'Research Analyst' having registration number INH000001873. J.P. Morgan India Private Limited is also registered with SEBI as a member of the National Stock Exchange of India Limited and the Bombay Stock Exchange Limited (SEBI Registration Number – INZ000239730) and as a Merchant Banker (SEBI Registration Number - MB/ INM000002970). Telephone: 91-22-6157 3000, Facsimile: 91-22-6157 3990 and Website: http://www.jpmipl.com. JPMorgan Chase Bank, N.A. - Mumbai Branch is licensed by the Reserve Bank of India (RBI) (Licence No. 53/ Licence No. BY.4/94; SEBI - IN/CUS/014/ CDSL : IN-DP-CDSL-444-2008/ IN-DP-NSDL-285-2008/ INBI00000984/ INE231311239) as a Scheduled Commercial Bank in India, which is its primary license allowing it to carry on Banking business in India and other activities, which a Bank branch in India are permitted to undertake. For non-local research material, this material is not distributed in India by J.P. Morgan India Private Limited. Compliance Officer: Spurthi Gadamsetty; spurthi.gadamsetty@jpmchase.com; +912261573225. Grievance Officer: Ramprasadh K, jpmipl.research.feedback@jpmorgan.com; +912261573000.

Investment in securities market are subject to market risks. Read all the related documents carefully before investing. Registration granted by SEBI and certification from NISM in no way guarantee performance of the intermediary or provide any assurance of returns to investors.

Indonesia: PT J.P. Morgan Sekuritas Indonesia is a member of the Indonesia Stock Exchange and is registered and supervised by the Otoritas Jasa Keuangan (OJK). **Korea**: J.P. Morgan Securities (Far East) Limited, Seoul Branch, is a member of the Korea Exchange (KRX). JPMorgan Chase Bank, N.A., Seoul Branch, is licensed as a branch office of foreign bank (JPMorgan Chase Bank, N.A.) in Korea. Both entities are regulated by the Financial Services Commission (FSC) and the Financial Supervisory Service (FSS). For non-macro research material, the material is distributed in Korea by or through J.P. Morgan Securities (Far East) Limited, Seoul Branch. **Japan**: JPMorgan Securities Japan Co., Ltd. and JPMorgan Chase Bank, N.A., Tokyo Branch are regulated by the Financial Services Agency in Japan. **Malaysia**: This material is issued and distributed in Malaysia by JPMorgan Securities (Malaysia) Sdn Bhd (18146-X), which is a Participating Organization of Bursa Malaysia Berhad and holds a Capital Markets Services License issued by the Securities Commission in Malaysia. **Mexico**: J.P. Morgan Casa de Bolsa, S.A. de C.V. and J.P. Morgan Grupo Financiero are members of the Mexican Stock Exchange and are authorized to act as a broker dealer by the National Banking and Securities Exchange Commission. **New Zealand**: This material is issued and distributed by JPMSAL in New Zealand only to "wholesale clients" (as defined in the Financial Markets Conduct Act 2013). JPMSAL is registered as a Financial Service Provider under the Financial Service providers (Registration and Dispute Resolution) Act of 2008. **Philippines**: J.P. Morgan Securities Philippines Inc. is a Trading Participant of the Philippine Stock Exchange and a member of the Securities Clearing Corporation of the Philippines and the Securities Investor Protection Fund. It is regulated by the Securities and Exchange Commission. **Singapore**: This material is issued and distributed in Singapore by or through J.P. Morgan Securities Singapore Private Limited (JPMSS) [MCI (P) 030/08/2023 and Co. Reg. No.: 199405335R], which is a member of the Singapore Exchange Securities Trading Limited, and/or JPMorgan Chase Bank, N.A., Singapore branch (JPMCB Singapore), both of which are regulated by the Monetary Authority of Singapore. This material is issued and distributed in Singapore only to accredited investors, expert investors and institutional investors, as defined in Section 4A of the Securities and Futures Act, Cap. 289 (SFA). This material is not intended to be issued or distributed to any retail investors or any other investors that do not fall into the classes of "accredited investors," "expert investors" or "institutional investors," as defined under Section 4A of the SFA. Recipients of this material in Singapore are to contact JPMSS or JPMCB Singapore in respect of any matters arising from, or in connection with, the material. **South Africa**: J.P. Morgan Equities South Africa Proprietary Limited and JPMorgan Chase Bank, N.A., Johannesburg Branch are members of the Johannesburg Securities Exchange and are regulated by the Financial Services Conduct Authority (FSCA). **Taiwan**: J.P. Morgan Securities (Taiwan) Limited is a participant of the Taiwan Stock Exchange (company-type) and regulated by the Taiwan Securities and Futures Bureau. Material relating to equity securities is issued and distributed in Taiwan by J.P. Morgan Securities (Taiwan) Limited, subject to the license scope and the applicable laws and the regulations in Taiwan. According to Paragraph 2, Article 7-1 of Operational Regulations Governing Securities Firms Recommending Trades in Securities to Customers (as amended or supplemented) and/or other applicable laws or regulations, please note that the recipient of this material is not permitted to engage in any activities in connection with the material that may give rise to conflicts of interests, unless otherwise disclosed in the “Important Disclosures” in this material. **Thailand**: This material is issued and distributed in Thailand by JPMorgan Securities (Thailand) Ltd., which is a member of the Stock Exchange of Thailand and is regulated by the Ministry of Finance and the Securities and Exchange Commission, and its registered address is 3rd Floor, 20 North Sathorn Road, Silom, Bangrak, Bangkok 10500. **UK:** Unless specified to the contrary, research is distributed in the UK by J.P. Morgan Securities plc (“JPMS plc”) which is a member of the London Stock Exchange and is authorised by the Prudential Regulation Authority and regulated by the Financial Conduct Authority and the Prudential Regulation Authority. JPMS plc is registered in England & Wales No. 2711006, Registered Office 25 Bank Street, London, E14 5JP. This material is directed in the UK only to: (a) persons having professional experience in matters relating to investments falling within article 19(5) of the Financial Services and Markets Act 2000 (Financial Promotion) (Order) 2005 (“the FPO”); (b) persons outlined in article 49 of the FPO (high net worth companies, unincorporated associations or partnerships, the trustees of high value trusts, etc.); or (c) any persons to whom this communication may otherwise lawfully be made; all such persons being referred to as "UK relevant persons". This material must not be acted on or relied on by persons who are not UK relevant persons. Any investment or investment activity to which this material relates is only available to UK relevant persons and will be engaged in only with UK relevant persons. Research issued by JPMS plc has been prepared in accordance with JPMS plc's policy for prevention and avoidance of conflicts of interest related to the production of Research which can be found at the following link: J.P. Morgan EMEA - Research Independence Policy. **U.S.**: J.P. Morgan Securities LLC (“JPMS”) is a member of the NYSE, FINRA, SIPC, and the NFA. JPMorgan Chase Bank, N.A. is a member of the FDIC. Material published by non-U.S. affiliates is distributed in the U.S. by JPMS who accepts responsibility for its content.

General: Additional information is available upon request. The information in this material has been obtained from sources believed to be reliable. While all reasonable care has been taken to ensure that the facts stated in this material are accurate and that the forecasts, opinions and expectations contained herein are fair and reasonable, JPMorgan Chase & Co. or its affiliates and/or subsidiaries (collectively J.P. Morgan) make no representations or warranties whatsoever to the completeness or accuracy of the material provided, except with respect to any disclosures relative to J.P. Morgan and the Research Analyst's involvement with the issuer that is the subject of the material. Accordingly, no reliance should be placed on the accuracy, fairness or completeness of the information contained in this material. There may be certain discrepancies with data and/or limited content in this material as a result of calculations, adjustments, translations to different languages, and/or local regulatory restrictions, as applicable. These discrepancies should not impact the overall investment analysis, views and/or recommendations of the subject company(ies) that may be discussed in the material. J.P. Morgan accepts no liability whatsoever for any loss arising from any use of this material or its contents, and neither J.P. Morgan nor any of its respective directors, officers or employees, shall be in any way responsible for the contents hereof, apart from the liabilities and responsibilities that may be imposed on them by the relevant regulatory authority in the jurisdiction in question, or the regulatory regime thereunder. Opinions, forecasts or projections contained in this material represent J.P. Morgan's current opinions or judgment as of the date of the material only and are therefore subject to change without notice. Periodic updates may be provided on companies/industries based on company-specific developments or announcements, market conditions or any other publicly available information. There can be no assurance that future results or events will be consistent with any such opinions, forecasts or projections, which represent only one possible outcome. Furthermore, such opinions, forecasts or projections are subject to certain risks, uncertainties and assumptions that have not been verified, and future actual results or events could differ materially. The value of, or income from, any investments referred to in this material may fluctuate and/or be affected by changes in exchange rates. All pricing is indicative as of the close of market for the securities discussed, unless otherwise stated. Past performance is not indicative of future results. Accordingly, investors may receive back less than originally invested. This material is not intended as an offer or solicitation for the purchase or sale of any financial instrument. The opinions and recommendations herein do not take into account individual client circumstances, objectives, or needs and are not intended as recommendations of particular securities, financial instruments or strategies to particular clients. This material may include views on structured securities, options, futures and other derivatives. These are complex instruments, may involve a high degree of risk and may be appropriate investments only for sophisticated investors who are capable of understanding and assuming the risks involved. The recipients of this material must make their own independent decisions regarding any securities or financial instruments mentioned herein and should seek advice from such independent financial, legal, tax or other adviser as they deem necessary. J.P. Morgan may trade as a principal on the basis of the Research Analysts' views and research, and it may also engage in transactions for its own account or for its clients' accounts in a manner inconsistent with the views taken in this material, and J.P. Morgan is under no obligation to ensure that such other communication is brought to the attention of any recipient of this material. Others within J.P. Morgan, including Strategists, Sales staff and other Research Analysts, may take views that are inconsistent with those taken in this material. Employees of J.P. Morgan not involved in the preparation of this material may have investments in the securities (or derivatives of such securities) mentioned in this material and may trade them in ways different from those discussed in this material. This material is not an advertisement for or marketing of any issuer, its products or services, or its securities in any jurisdiction.

Confidentiality and Security Notice: This transmission may contain information that is privileged, confidential, legally privileged, and/or exempt from disclosure under applicable law. If you are not the intended recipient, you are hereby notified that any disclosure, copying, distribution, or use of the information contained herein (including any reliance thereon) is STRICTLY PROHIBITED. Although this transmission and any attachments are believed to be free of any virus or other defect that might affect any computer system into which it is received and opened, it is the responsibility of the recipient to ensure that it is virus free and no responsibility is accepted by JPMorgan Chase & Co., its subsidiaries and affiliates, as applicable, for any loss or damage arising in any way from its use. If you received this transmission in error, please immediately contact the sender and destroy the material in its entirety, whether in electronic or hard copy format. This message is subject to electronic monitoring: https://www.jpmorgan.com/disclosures/email

MSCI: Certain information herein (“Information”) is reproduced by permission of MSCI Inc., its affiliates and information providers (“MSCI”) ©2024. No reproduction or dissemination of the Information is permitted without an appropriate license. MSCI MAKES NO EXPRESS OR

IMPLIED WARRANTIES (INCLUDING MERCHANTABILITY OR FITNESS) AS TO THE INFORMATION AND DISCLAIMS ALL LIABILITY TO THE EXTENT PERMITTED BY LAW. No Information constitutes investment advice, except for any applicable Information from MSCI ESG Research. Subject also to msci.com/disclaimer

"Other Disclosures" last revised January 01, 2024.

Completed 10 Jan 2024 11:02 PM EST   Disseminated 11 Jan 2024 07:00 AM EST