New Collectivity Measurements of Light Ions at CMS

1st July, 2026

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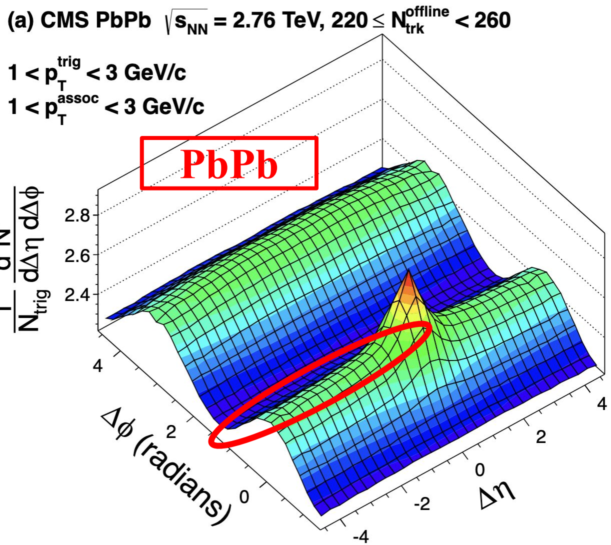
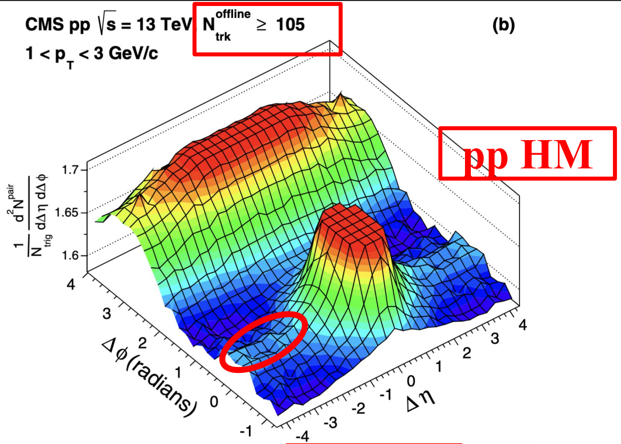
5th International Workshop on Emergent QCD Collectivity Across Scales: From Small System Collisions to Jets

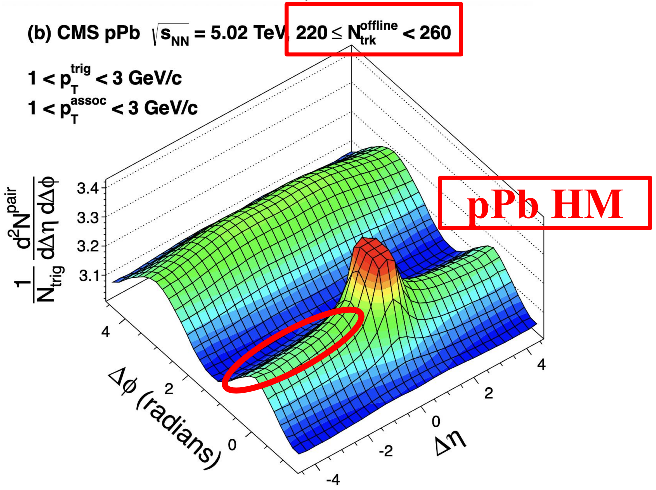
Collectivity across systems

- Long-range ("ridge") correlations in all systems
- Possible universality in the underlying dynamics
- *What is common? What is different? (Flow vs non-flow)*



Ridge observed in the smallest systems

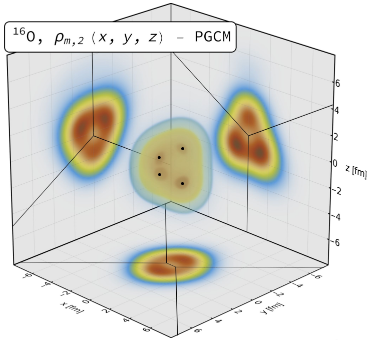




Phys. Lett. B 724 (2013) 213
Phys. Lett. B 765 (2017) 193

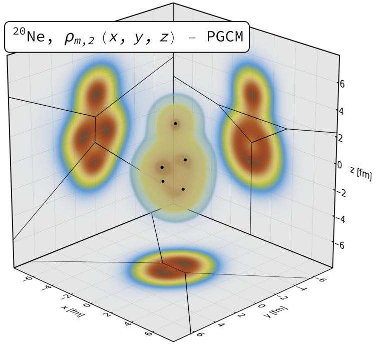
Why study light ions?

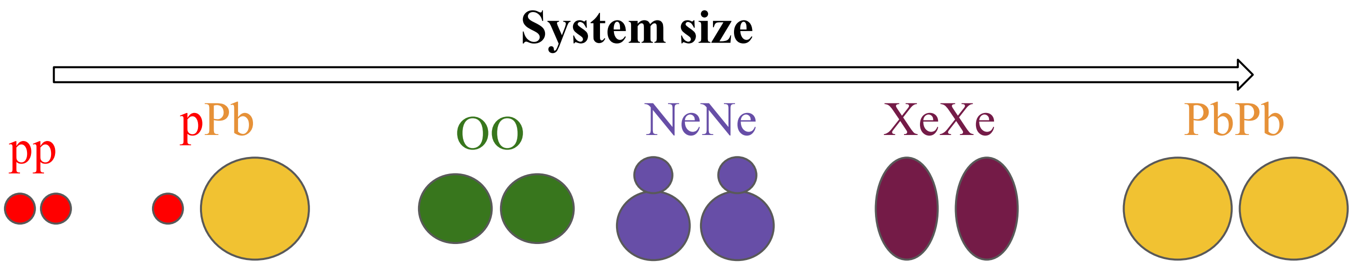
- QGP formed in large systems (PbPb, XeXe) - heavy-ion collisions
- Small systems (pp, pPb) show “medium-like” effects
- Light ions provide the **missing link** in the system-size scan
  - Test **onset of collectivity** & QGP formation
  - Study **geometry and clustering effects** in light nuclei
  - **Bridge the gap** between small systems and heavy-ion collisions using both soft and hard probes



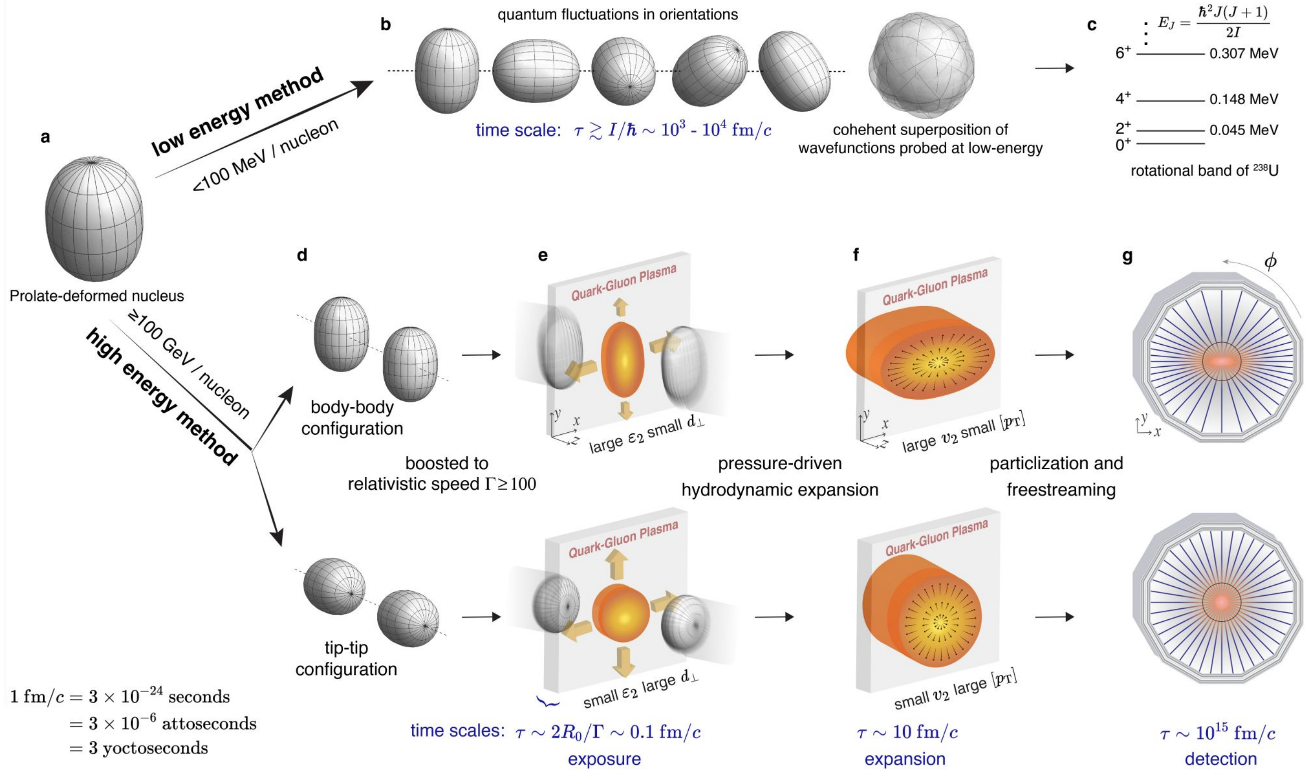
O

Ne





Nuclear structure from heavy-ion collisions



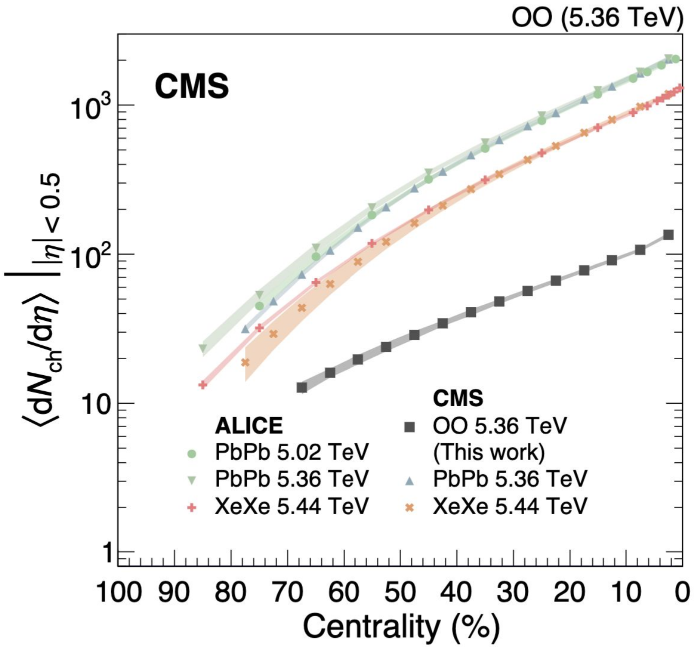
- Ultra-relativistic heavy-ion collisions provide femtosecond-scale snapshot of initial spatial distribution
- Freeze out long-timescale quantum fluctuations that complicate low-energy spectroscopy

[Nature 635 (2024) 8037]

Charged-particle multiplicity in OO 5.36 TeV

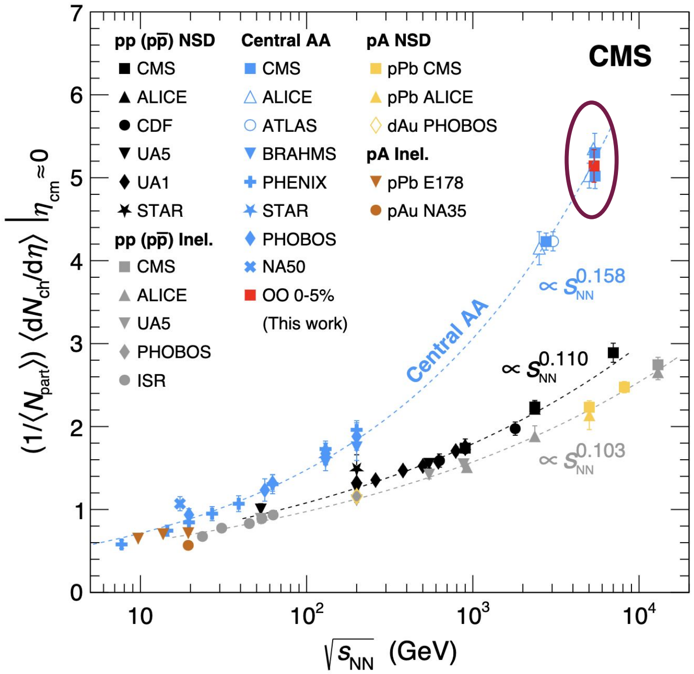
- Central PbPb : $dN_{ch}/d\eta \sim 2032 \pm 91$ (syst)
- Central XeXe : $dN_{ch}/d\eta \sim 1190 \pm 40$ (syst)
- Central OO : $dN_{ch}/d\eta \sim 135 \pm 4$ (syst)

- Central OO (per N_{part}) is HI-like in terms of multiplicity production
- Very far from superposition of pp or pA collisions

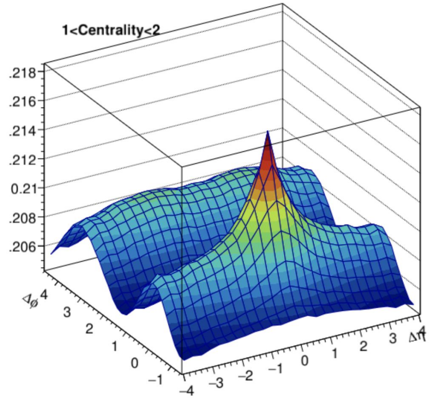


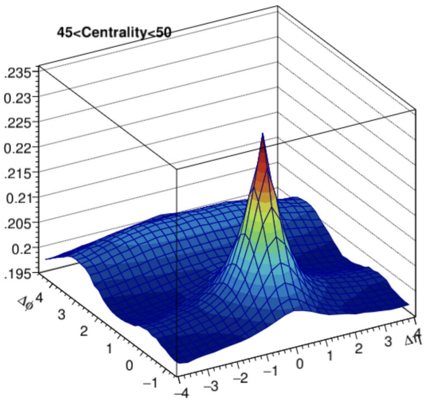
System size

arxiv:2606.02285, **submitted to PLB**

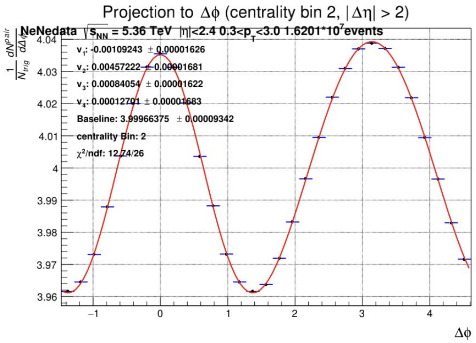


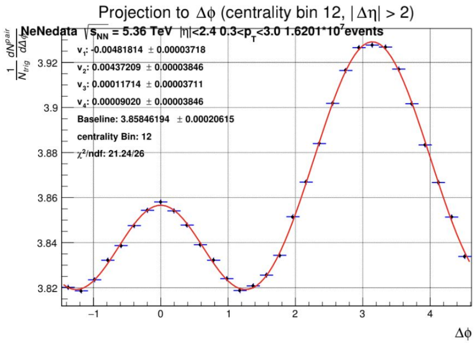
Two-particle correlation - the ridge





1 < Centrality (%) < 2   45 < Centrality (%) < 50





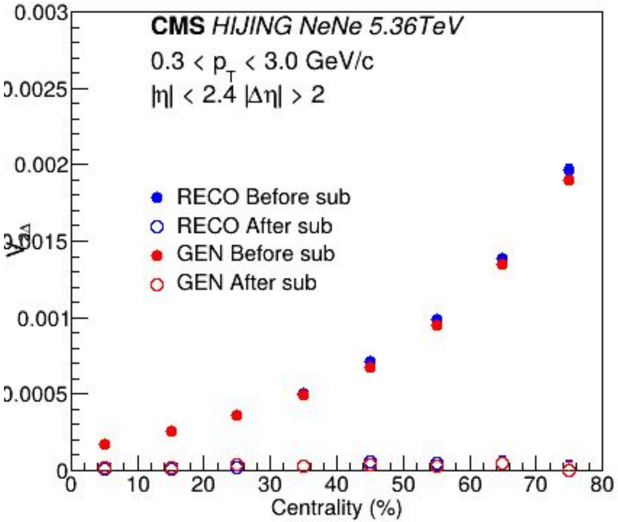
2-D correlation functions $C_2(\Delta\eta, \Delta\phi)$

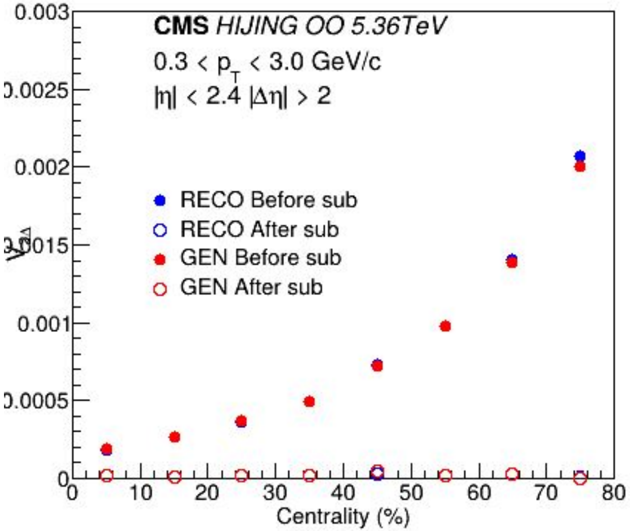
Long-range $(2 < |\Delta\eta| < 4)$ 1-D projection on $\Delta\phi$

- For finding out $V_{2\Delta}$: (i) $\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}N^{\text{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left[1+\sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$ (ii) $v_n\{2, |\Delta\eta| > 2\} = \sqrt{V_{n\Delta}}$

Peripheral subtraction for nonflow removal - HIJING

$$V_{n\Delta}^{sub} = V_{n\Delta} - V_{n\Delta}(cent:70-80\%)\frac{N_{assoc}(cent:70-80\%)}{N_{assoc}}\frac{Y_{jet}}{Y_{jet}(cent:70-80\%)}$$

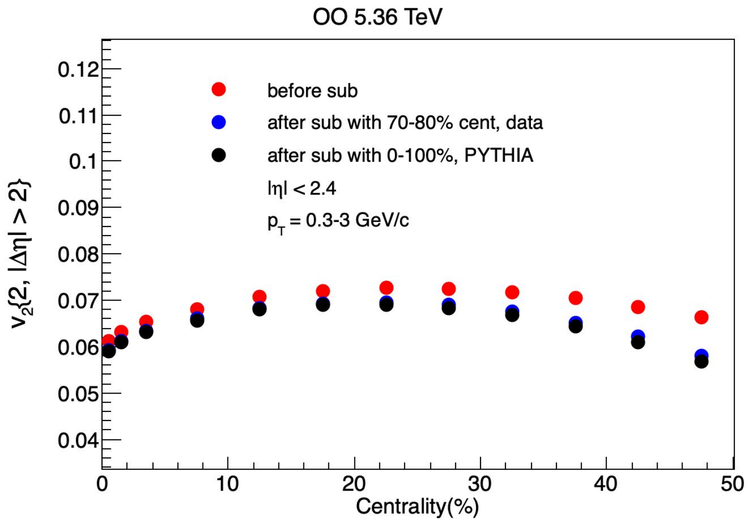


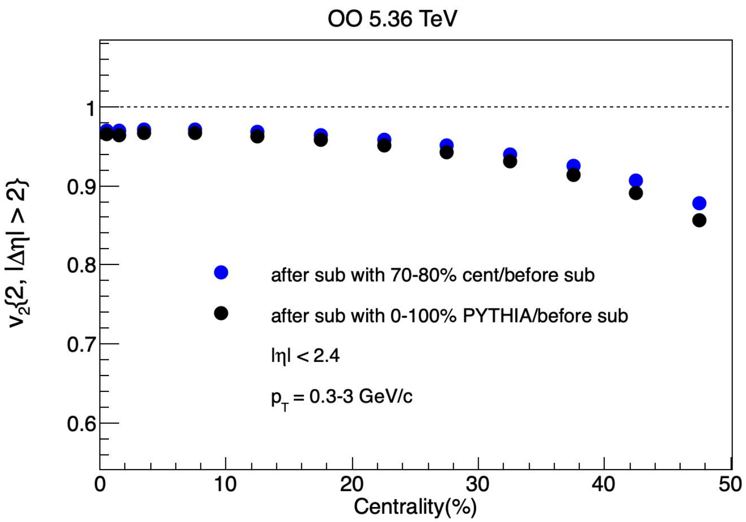


- Sanity check in HIJING shows good removal of non-flow

Peripheral subtraction for nonflow removal - Data

$$V_{n\Delta}^{sub} = V_{n\Delta} - V_{n\Delta}(cent:70-80\%)\frac{N_{assoc}(cent:70-80\%)}{N_{assoc}}\frac{Y_{jet}}{Y_{jet}(cent:70-80\%)}$$

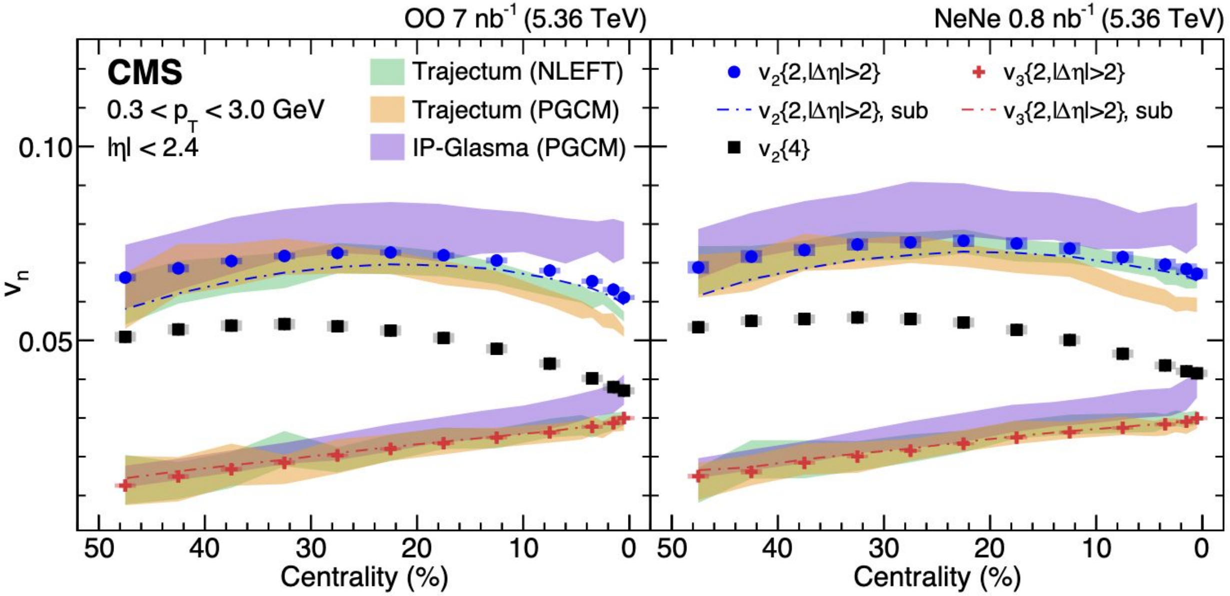




- Subtraction with 5.36 TeV PYTHIA shows reasonable agreement with 70-80% centrality (within 2%)
  - The unsubtracted results are main results while subtracted results provided

$v_n\{2, 4\}$ (n = 2, 3) vs centrality

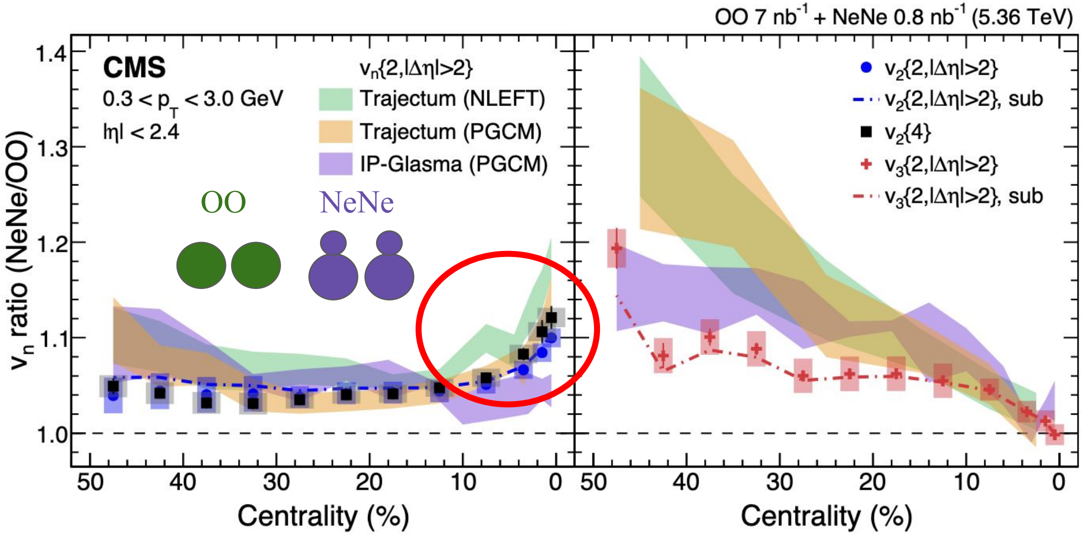
arxiv:2510.02580, **accepted by PRL**

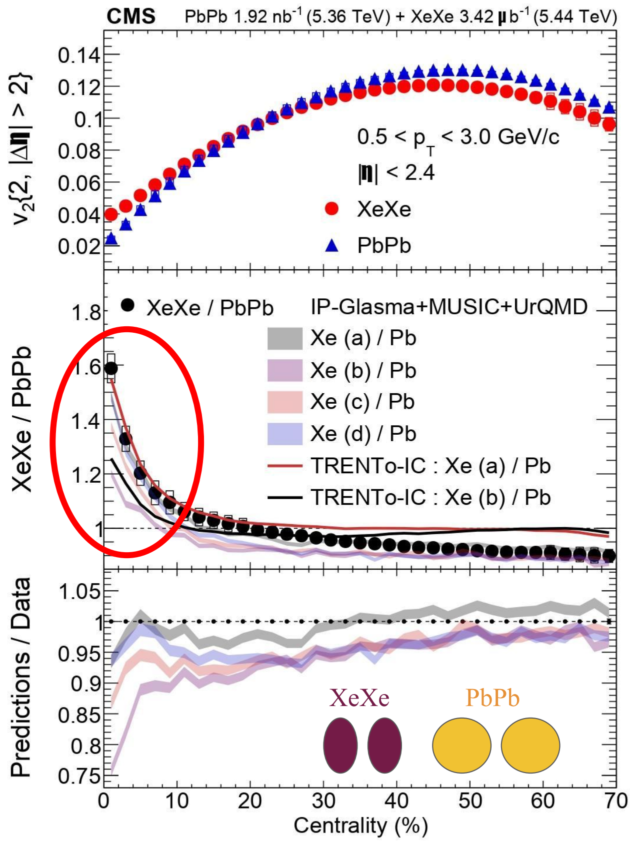


- $v_2\{2\}$ and $v_2\{4\}$ show similar trend as large AA collisions – increase and decrease starting from central region
  - $v_3\{2\}$ decrease monotonically from central, different than large AA

v_2 ratio : Probe of nuclear deformation

arxiv:2510.02580, **accepted by PRL**



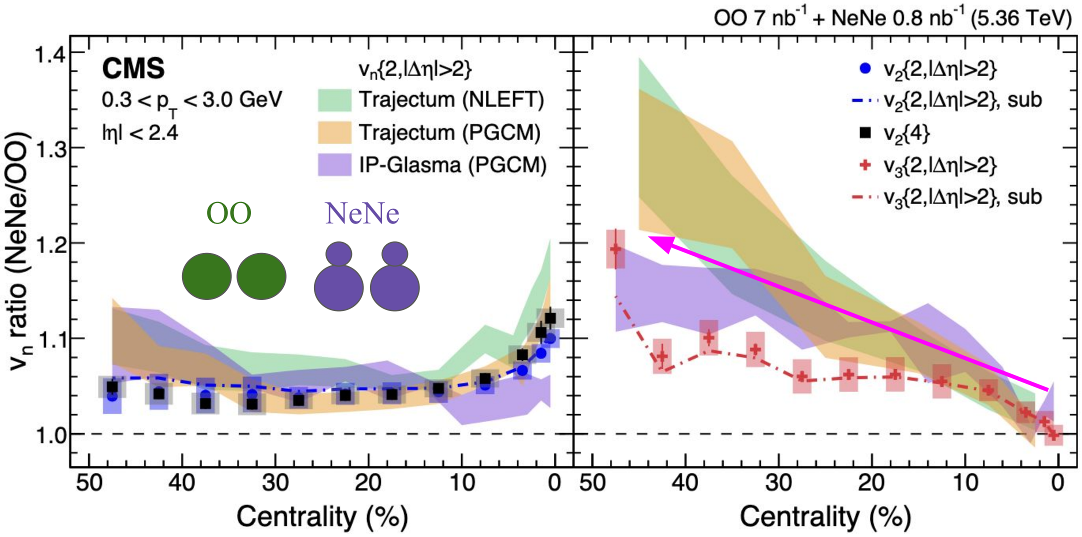


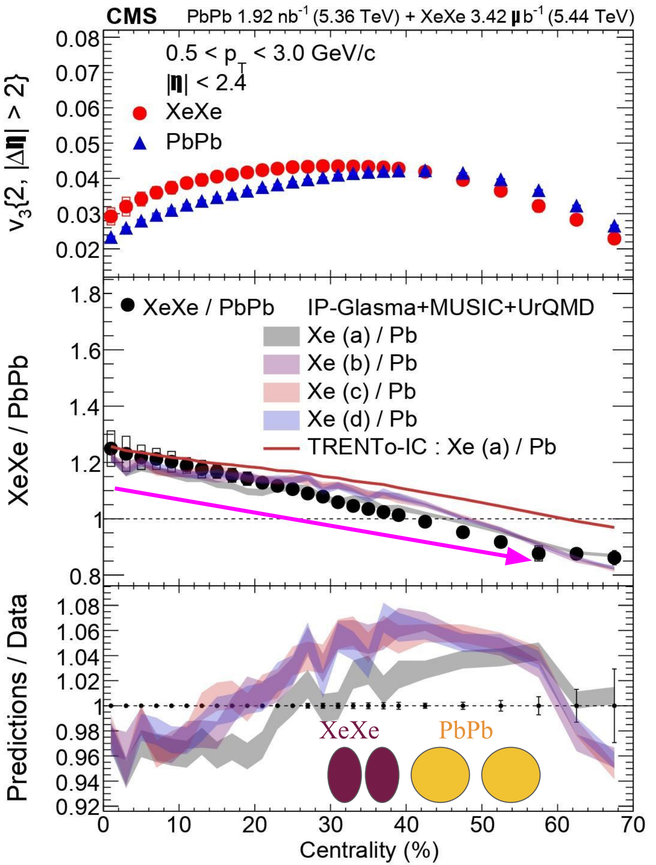
PLB 876 (2026) 140359

- NeNe/OO vs XeXe/PbPb
  - Rising trend towards central collisions : deformation-sensitive
- Trajectum predictions - capture the rising trend
  - PGCM is a better fit that NLEFT

v_3 ratio : Probe of fluctuation dynamics

arxiv:2510.02580, **accepted by PRL**

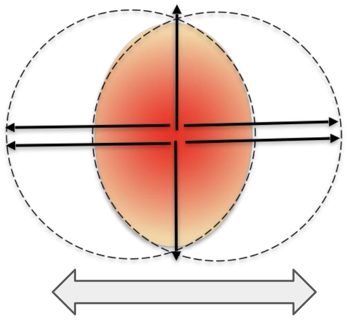




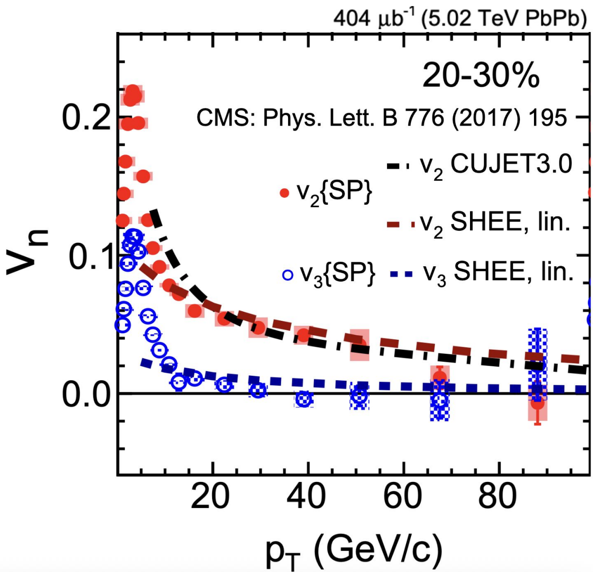
PLB 876 (2026) 140359

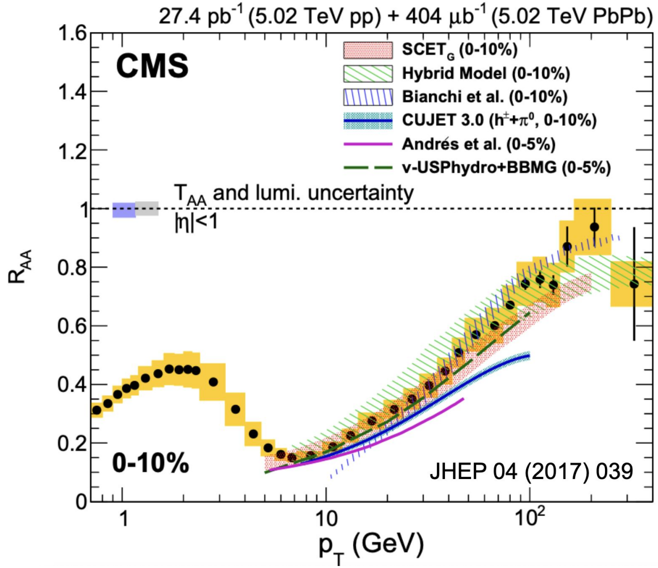
- NeNe/OO vs XeXe/PbPb
  - NeNe/OO > 1 throughout, decreases towards central collisions
- Model predictions overestimate v_3 ratio away from central collisions

High-p_T flow in large collision systems



- Shorter path length
- Lesser energy loss
- $v_2 > 0$ at high p_T



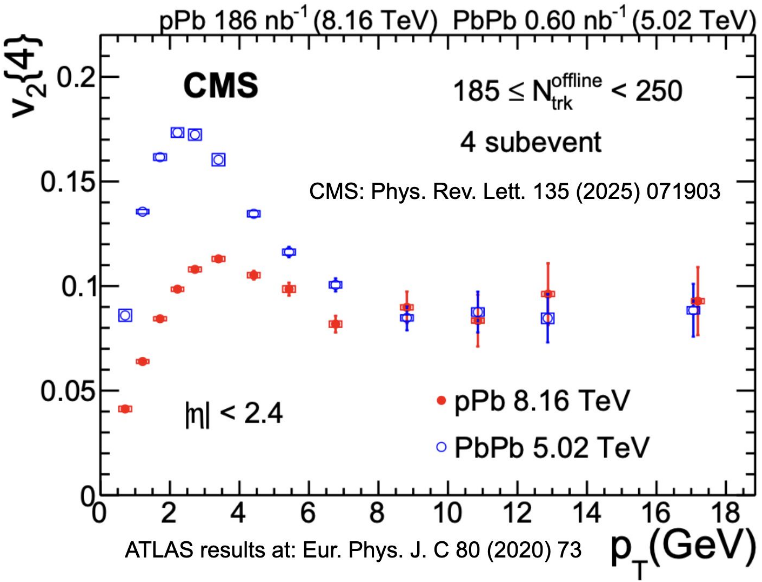


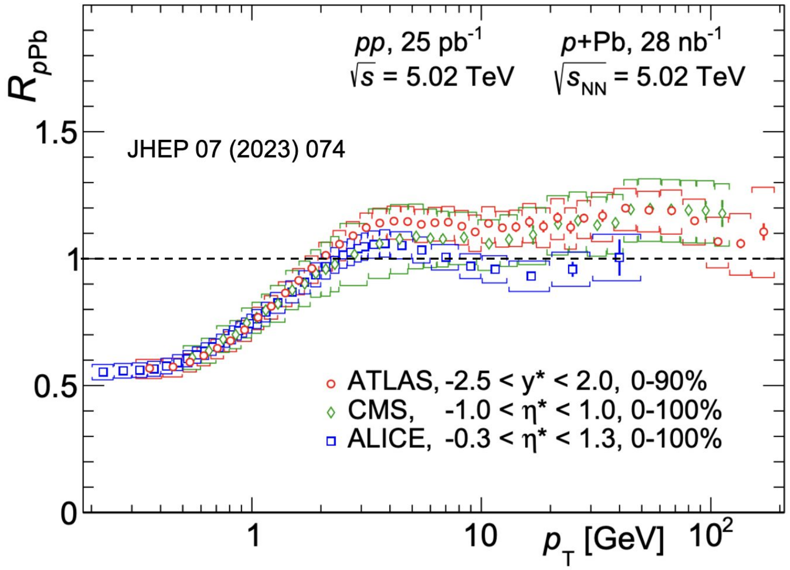
$v_2(p_T) > 0$ ⟷ $R_{AA}(p_T) < 1$

azimuthal angle dependent jet quenching, sensitive to path length dependence of energy loss

jet quenching, averaged over azimuthal angle

Small system puzzle





$v_2(p_T) > 1$ at high p_T ⟷ $R_{AA}(p_T) \sim 1$ at high p_T

What is the origin of high p_T v_2?

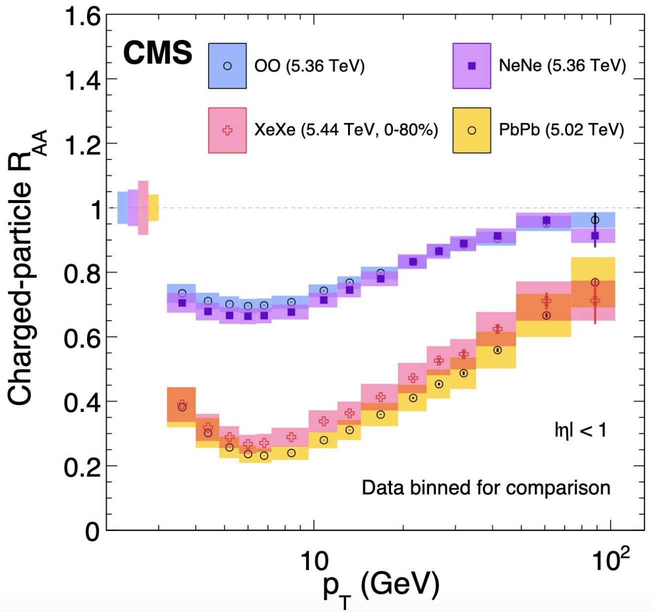
Initial-state effect

Quantum diffraction

no clear jet quenching

Light ions?

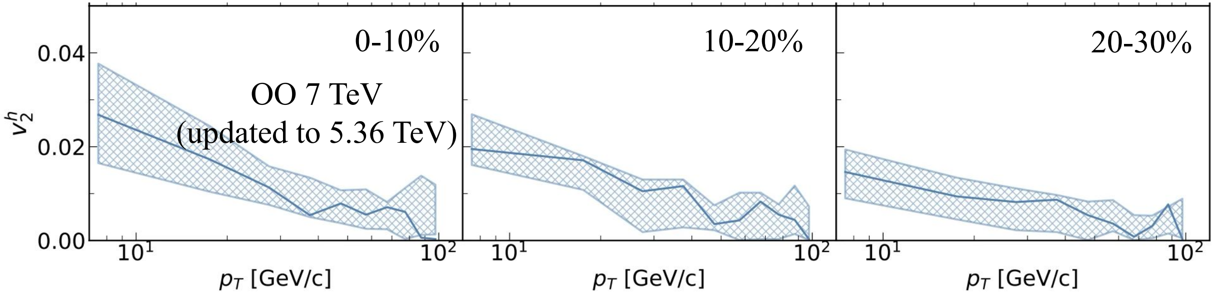
What about $v_2(p_T)$?



$R_{AA}(p_T) < 1$ at high p_T

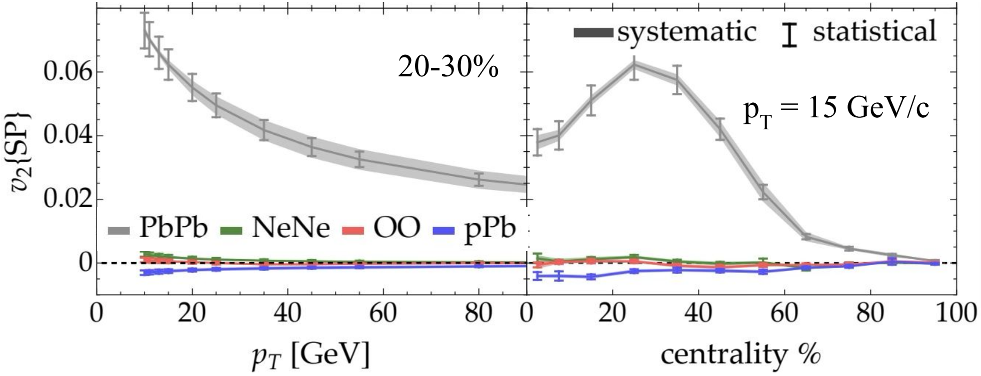
arxiv:2602.21325

Model predictions for $v_2(p_T)$ in OO



[Phys. Rev. C 109 (2024) 6, 064917](https://doi.org/10.1103/PhysRevC.109.064917)
M. Xie, W. Ke, H. Zhang, and X.-N. Wang

$\hat{q}/T^3$: Extracted from Bayesian analysis using PbPb and AuAu collision data

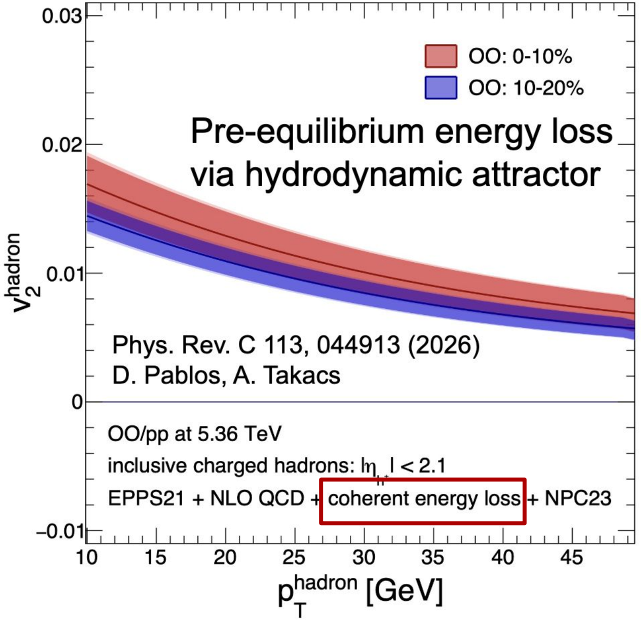


[arXiv:2603.21861](https://arxiv.org/abs/2603.21861)
B. Bert, C. Faraday, W.A. Horowitz

Model with energy loss :

- reproduce RAA in OO, but
- predict $v_2 = 0$ in OO
  - due to geometric decorrelation between hard and soft sectors

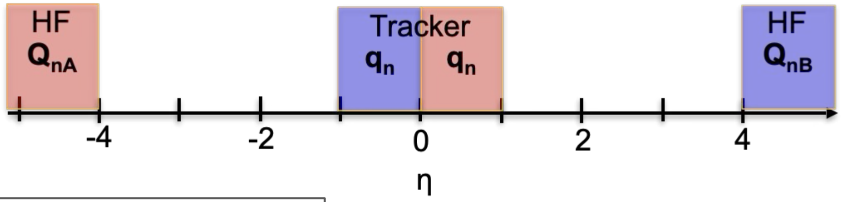
[Phys. Rev. C 113, 044913 (2026)](https://doi.org/10.1103/PhysRevC.113.044913)
D. Pablos, A. Takacs



Analysis technique - scalar product (SP) method

2-subevent SP method with |Δη| > 4.0

Suppresses nonflow



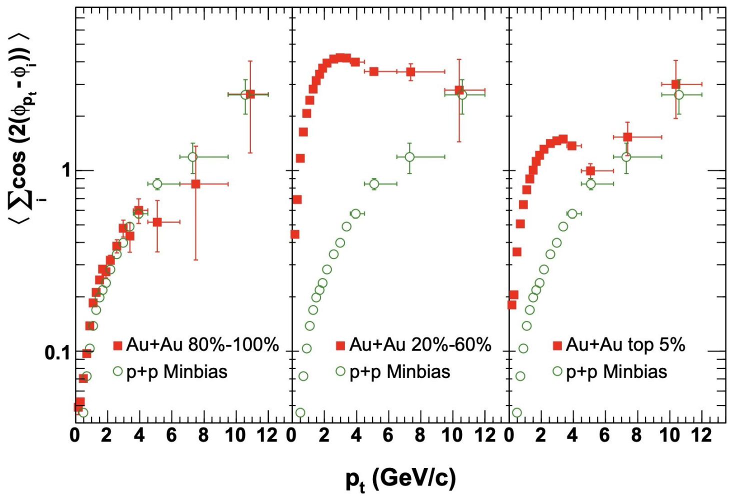
$$v_n\{\mathrm{SP}\} \equiv \frac{\langle q_n Q^*_{nA}\rangle}{\sqrt{\langle Q_{nA} Q^*_{nB}\rangle}}$$

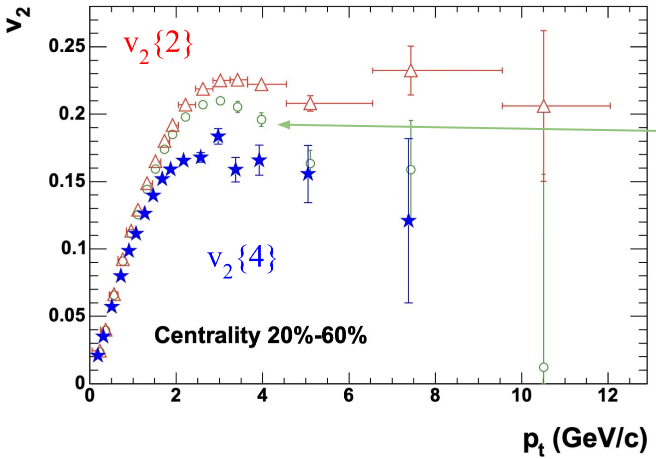
$$q_n = \frac{\sum_{k=1}^{M} \omega_k e^{in\phi_k}}{\sum_{k=1}^{M} \omega_k}$$

$$Q_n \equiv \sum_{k=1}^{M} \omega_k\, {}^{in\phi_k}$$

NOTE : numerator and denominator should have the same set of events

Nonflow subtraction technique





STAR, Phys.Rev.Lett.93:252301,2004

$$\left\langle \sum_i \cos n(\phi_{p_t} - \phi_i) \right\rangle = M\, v_n(p_t)\, \bar{v}_n + \{\text{nonflow}\}$$

Applying to OO and pp :

$$\left\langle \sum_i \cos n(\phi_{p_t} - \phi_i) \right\rangle_{\rm OO} = M\, v_n(p_t)\, \bar{v}_n + \{\text{nonflow}\}_{\rm OO}$$

$$\left\langle \sum_i \cos n(\phi_{p_t} - \phi_i) \right\rangle_{\rm pp} = M * 0 + \{\text{nonflow}\}_{\rm pp}$$

Subtracting :

$$\left\langle \sum_i \cos n(\phi_{p_t} - \phi_i) \right\rangle_{\rm OO} - \left\langle \sum_i \cos n(\phi_{p_t} - \phi_i) \right\rangle_{\rm pp} = M\, v_n(p_t)\, \bar{v}_n$$

Assumptions :

- $v_n = 0$ for zero bias pp data
- $\{\text{nonflow}\}_{OO} = M_{pp}/M_{OO} * \{\text{nonflow}\}_{pp}$

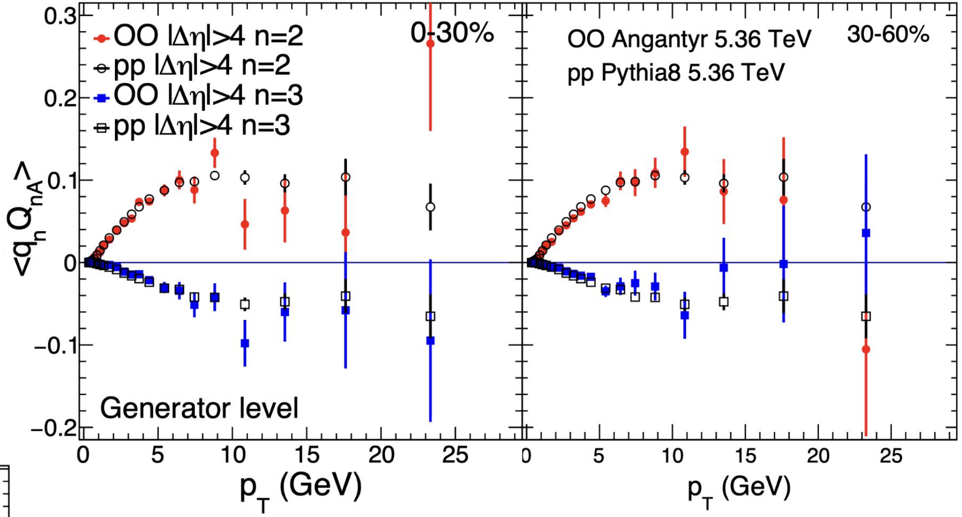
Nonflow subtraction validation : Angantyr

$$\left\langle \sum_i \cos n(\phi_{p_t} - \phi_i) \right\rangle = M\, v_n(p_t)\, \bar{v}_n + \{\text{nonflow}\}$$

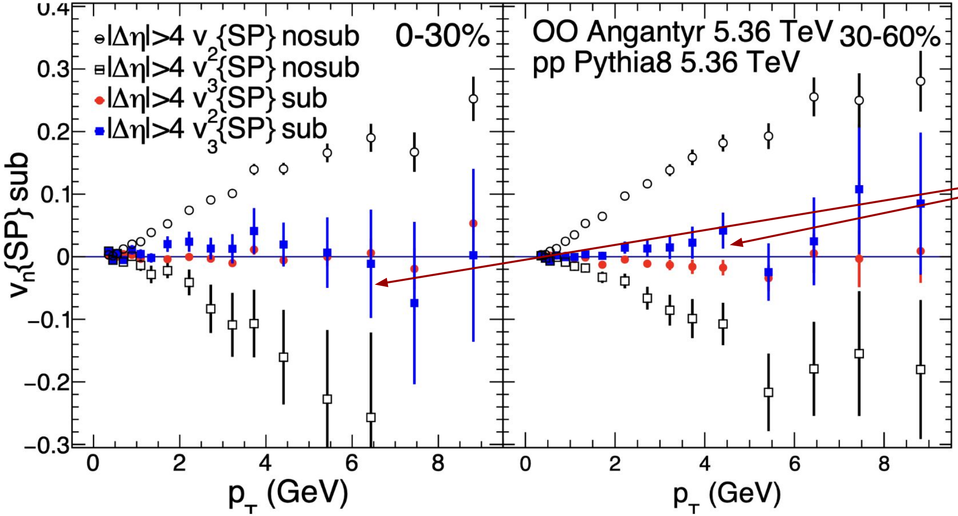
Numerator of scalar product : $\langle q_n Q^*_{nA} \rangle$

CMS-PAS-HIN-26-005

Before subtraction



After subtraction



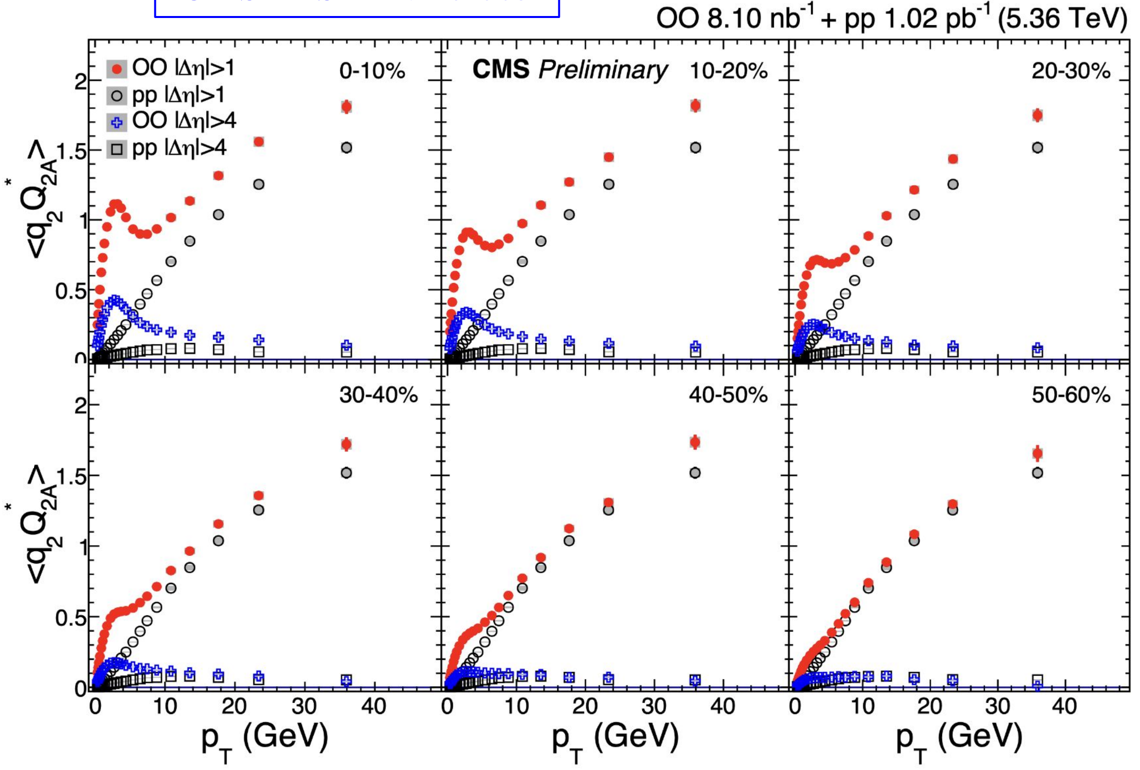
$v_n \sim 0$ after subtraction

$$v_n\{\text{SP, sub}\} = \frac{\langle q_n Q^*_{nA} \rangle_{OO} - \langle q_n Q^*_{nA} \rangle_{pp}}{\sqrt{\langle Q_{nA} Q^*_{nB} \rangle_{OO} - \langle Q_{nA} Q^*_{nB} \rangle_{pp}}}$$

Nonflow with scalar product (n = 2)

CMS-PAS-HIN-26-005

$$v_n\{\mathrm{SP}\} \equiv \frac{\langle q_n Q^*_{nA}\rangle}{\sqrt{\langle Q_{nA} Q^*_{nB}\rangle}}$$

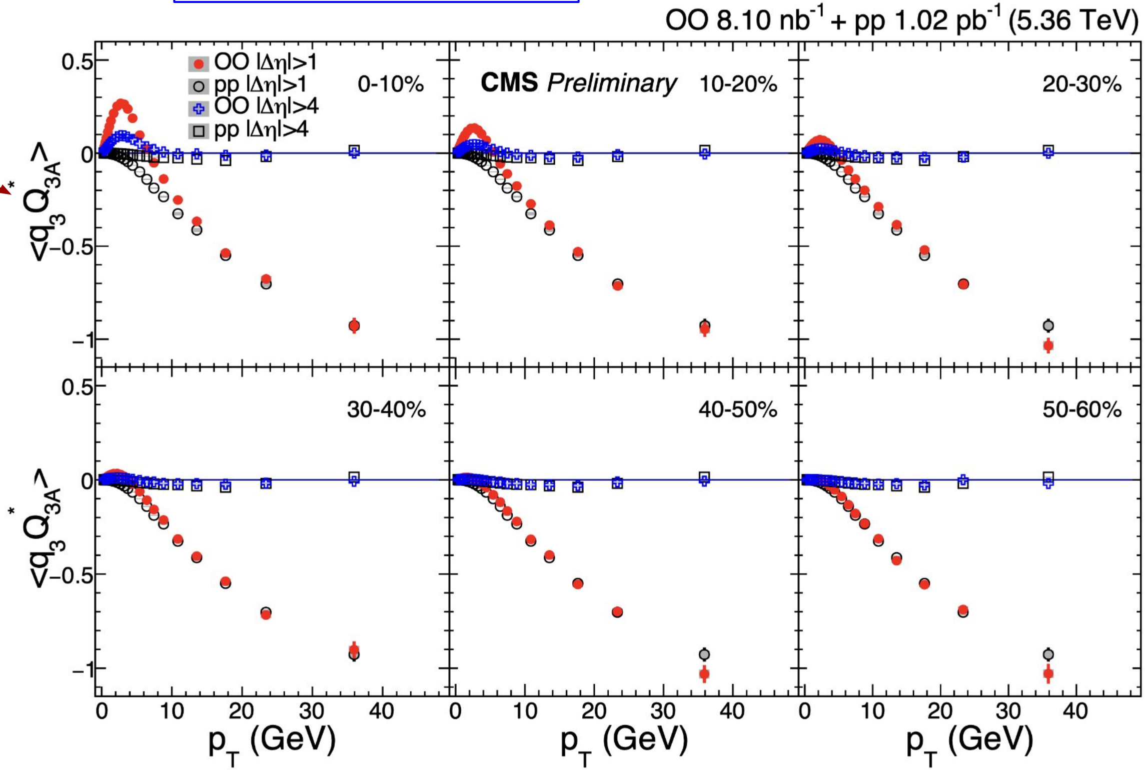


- Clear nonflow contribution
- Most of the high p_T signals are from nonflow (OO ~ pp zero bias at high p_T)

Nonflow with scalar product (n = 3)

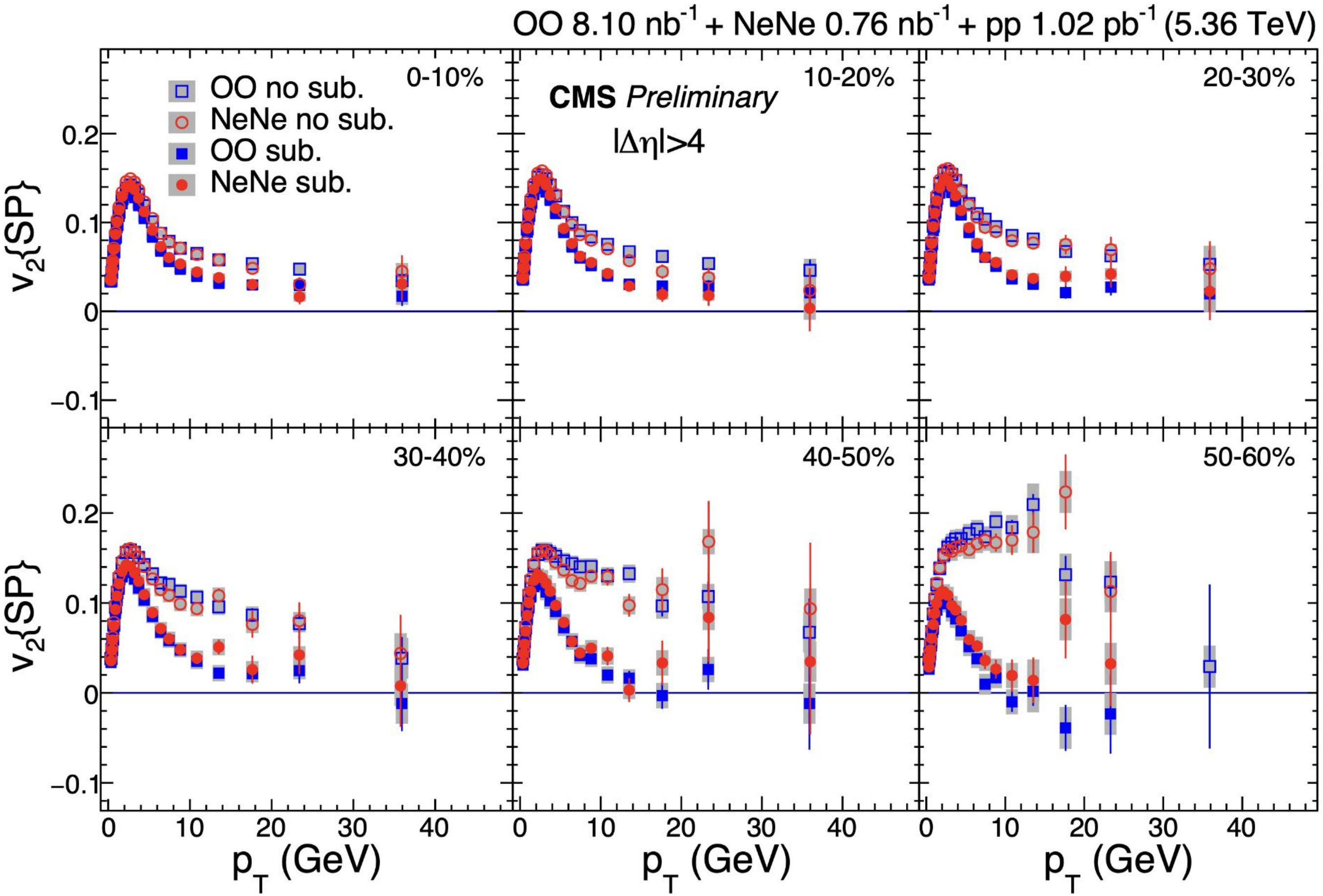
CMS-PAS-HIN-26-005

$$v_n\{\mathrm{SP}\} \equiv \frac{\langle q_n Q^*_{nA}\rangle}{\sqrt{\langle Q_{nA} Q^*_{nB}\rangle}}$$



- Clear nonflow contribution
- Most of the high p_T signals are from nonflow (OO ~ pp zero bias at high p_T)

$v_2(p_T)$ in OO and NeNe collisions



OO no sub.
NeNe no sub.
OO sub.
NeNe sub.

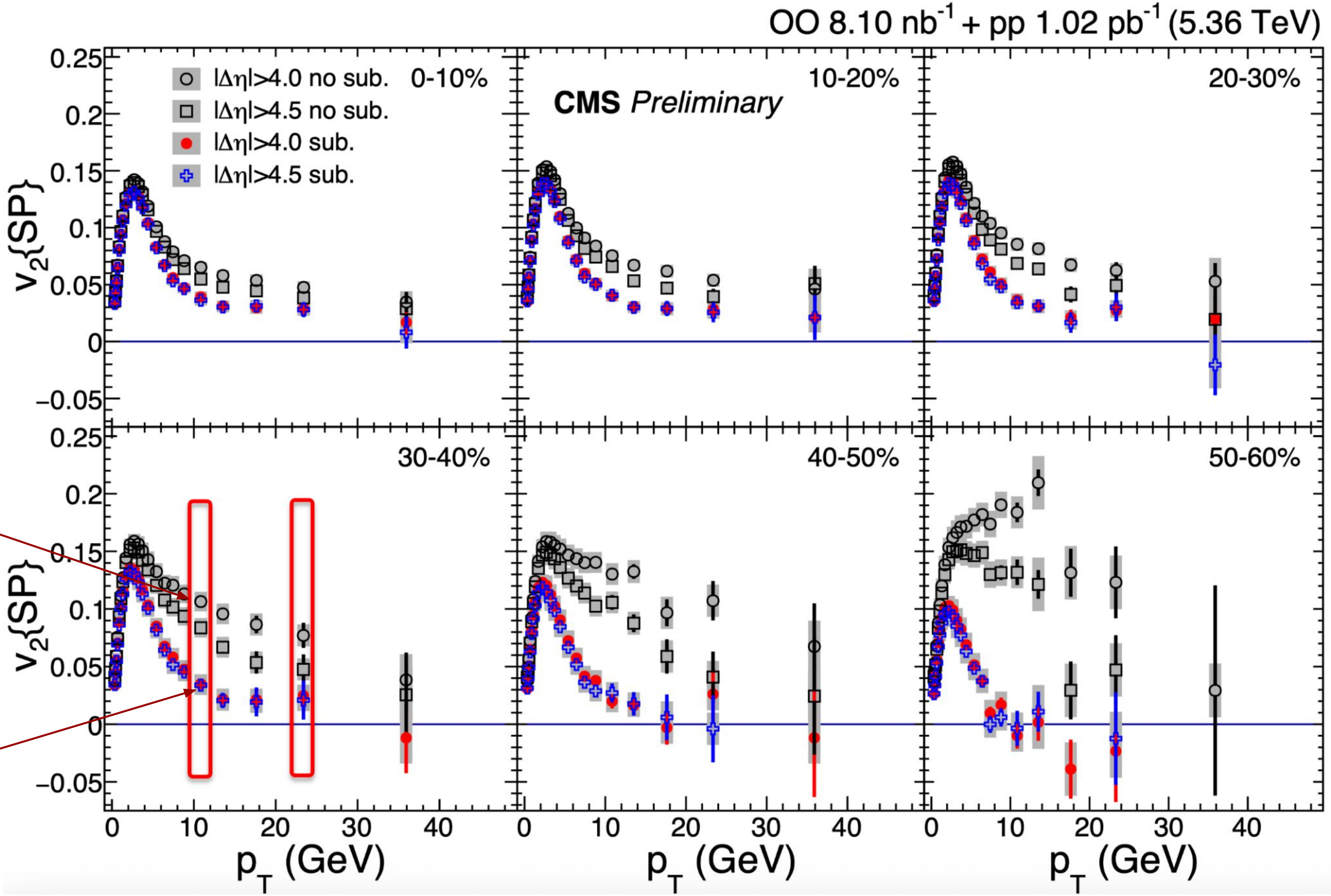
v_2 (NeNe) ~ v_2 (OO) at high p_T

CMS-PAS-HIN-26-005

$v_2(p_T)$ in OO - η gap dependence before and after subtraction

CMS-PAS-HIN-26-005

- |Δη|>4.0 no sub.
- |Δη|>4.5 no sub.
- |Δη|>4.0 sub.
- |Δη|>4.5 sub.



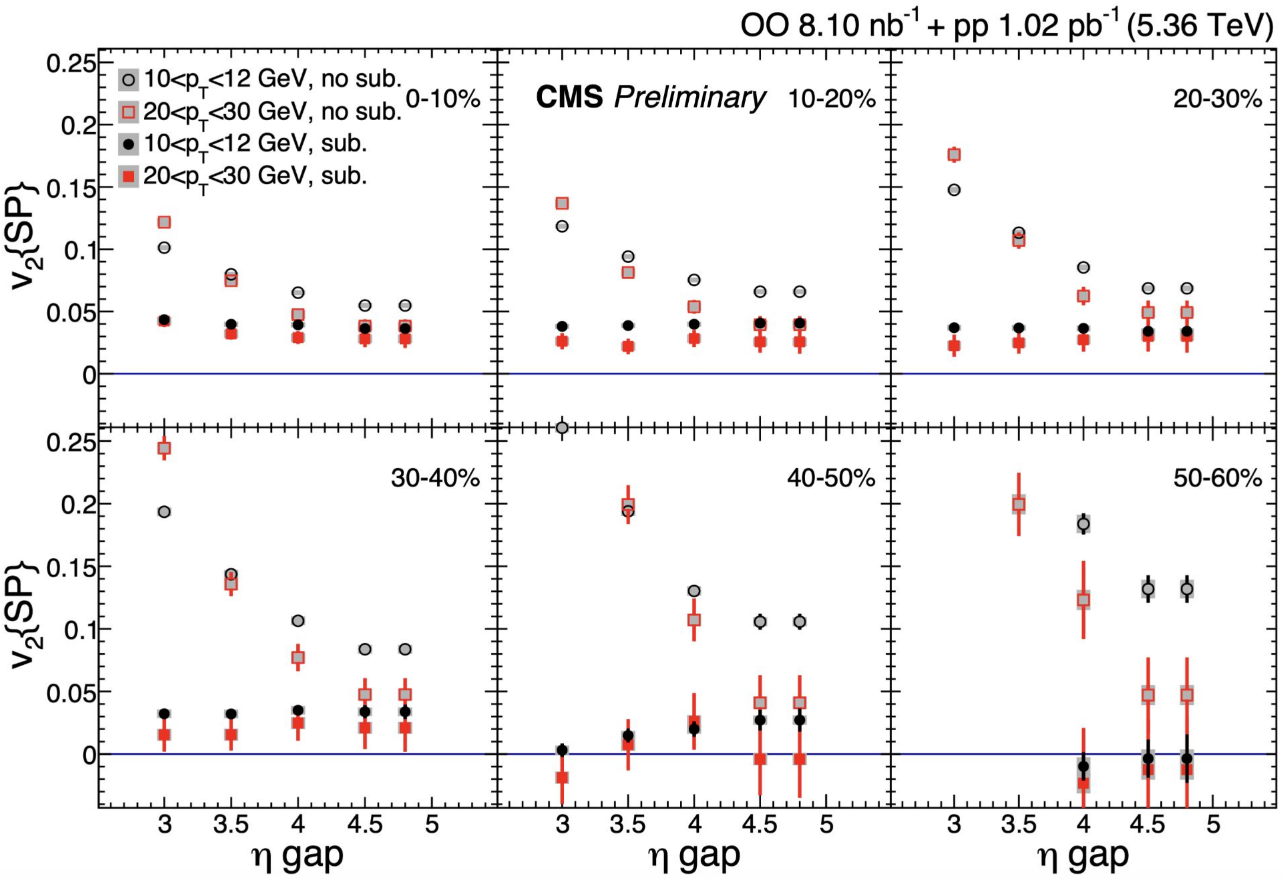
Before subtraction :

- Significant difference between gaps 4.0 and 4.5

After subtraction :

- Results start to converge between different gaps

$v_2(p_T)$ in OO - η gap dependence before and after subtraction



CMS-PAS-HIN-26-005

- $10<p_T<12$ GeV, no sub.
- $20<p_T<30$ GeV, no sub.
- $10<p_T<12$ GeV, sub.
- $20<p_T<30$ GeV, sub.

HF regions

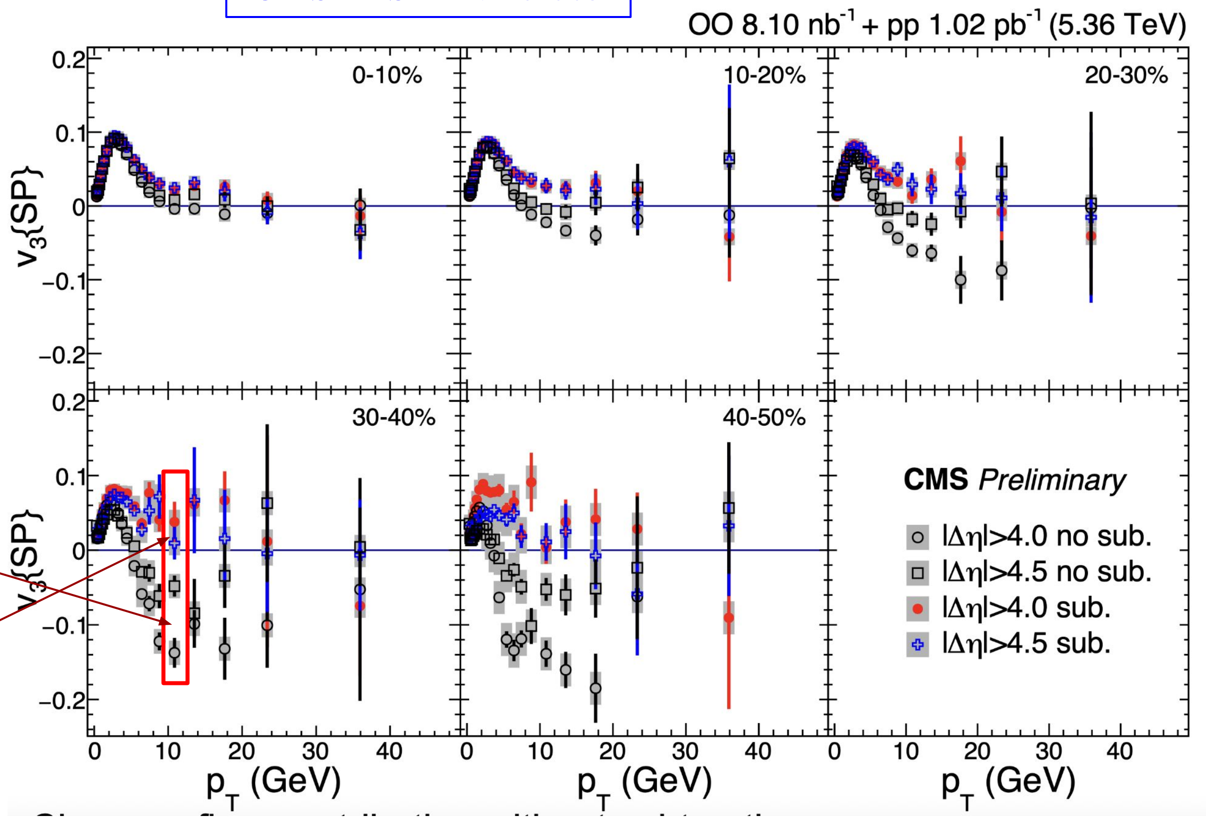
Gap 3.0: (3.0, 5.2)
Gap 3.5: (3.5, 5.2)
Gap 4.0: (4.0, 5.2)
Gap 4.5: (4.5, 5.2)
Gap 4.8: (4.8, 5.2)

After subtraction :
Results start to converge between different gaps

$v_3(p_T)$ in OO - η gap dependence before and after subtraction

CMS-PAS-HIN-26-005

- ○ |Δη|>4.0 no sub.
- □ |Δη|>4.5 no sub.
- ● |Δη|>4.0 sub.
- ✚ |Δη|>4.5 sub.



Before subtraction :

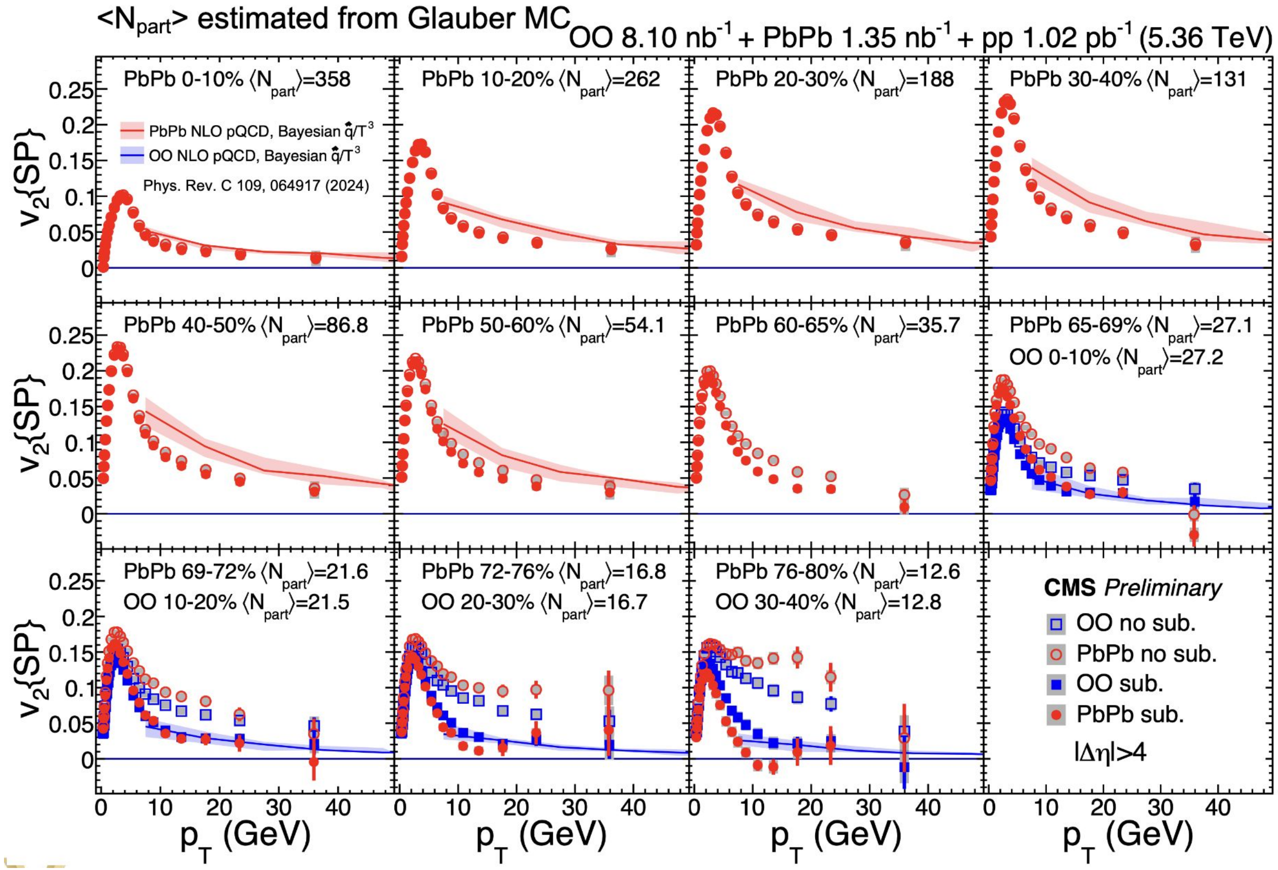
- Significant difference between gaps 4.0 and 4.5

After subtraction :

- Results start to converge between different gaps

$v_2(p_T)$ in PbPb vs OO at same N_{part}

CMS-PAS-HIN-26-005



- OO 0-10% ~ PbPb 65-69% centrality
- NLO pQCD reproduce OO results for p_T > 10 GeV but overestimate PbPb results by a little bit

$v_2(p_T)$ in OO : Comparison with theory

Phys. Rev. C 109 (2024) 6, 064917
M. Xie, W. Ke, H. Zhang, and X.-N. Wa

Phys. Rev. C 113, 044913 (2026)
D. Pablos, A. Takacs

arXiv:2603.21861
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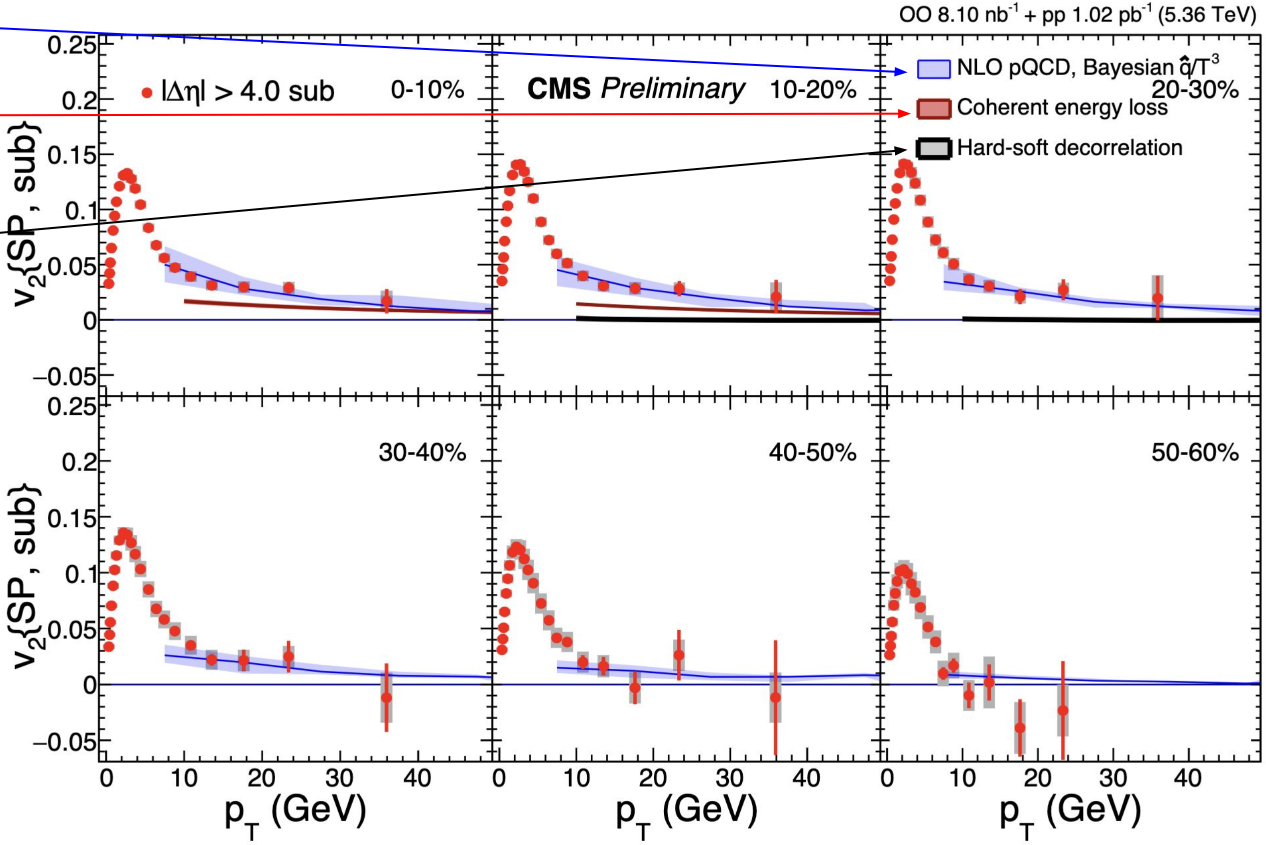


- NLO pQCD with Bayesian extracted $\hat{q}/T^3$ reproduce the data for high p_T
- Coherent energy loss underestimates the results
- Geometric decorrelation between hard and soft sector participant planes predicts $v_2 = 0$

CMS-PAS-HIN-26-005

Summary

Soft collectivity

- Long-range collectivity persists from heavy ions to light ions, reinforcing the system-size evolution picture.
- OO and NeNe exhibit significant collective flow.
- The NeNe/OO ratios provide new sensitivity to nuclear deformation and fluctuation dynamics.

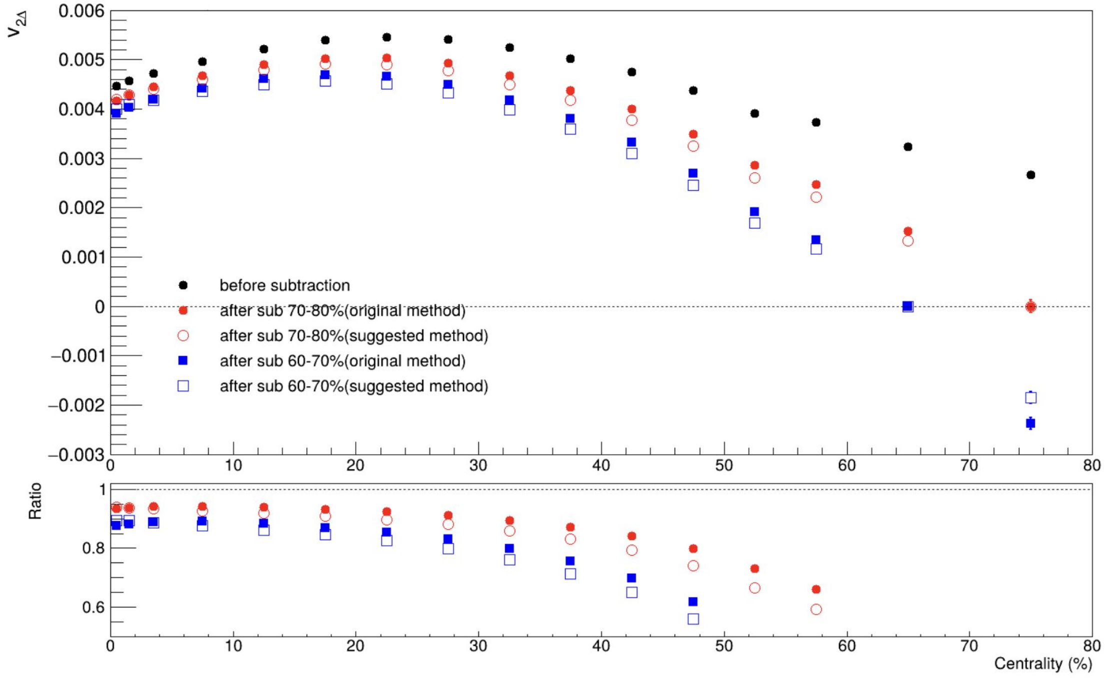
High-p_T v_2

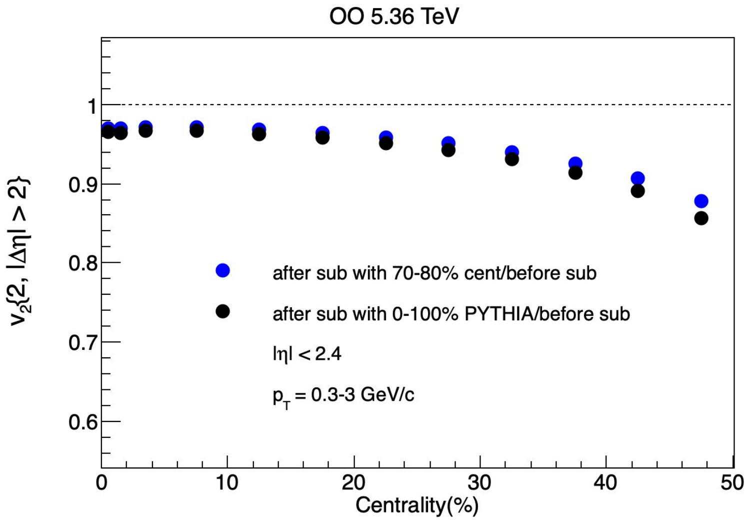
- First measurements of high-p_T flow in OO and NeNe using the scalar-product method.
- Nonflow is carefully evaluated using pp subtraction and validated with Angantyr studies.
- After subtraction, the high-p_T signal is significantly reduced, but greater than 0 upto 30-40% centrality in OO/NeNe.

Light-ion collisions bridge the gap between small and large systems, providing a unique laboratory to simultaneously probe the onset of collectivity, nuclear structure, and jet-medium interactions.

BACKUP

Subtraction with 60-70% centrality





Size of PbPb and OO collisions

https://arxiv.org/pdf/2507.05853

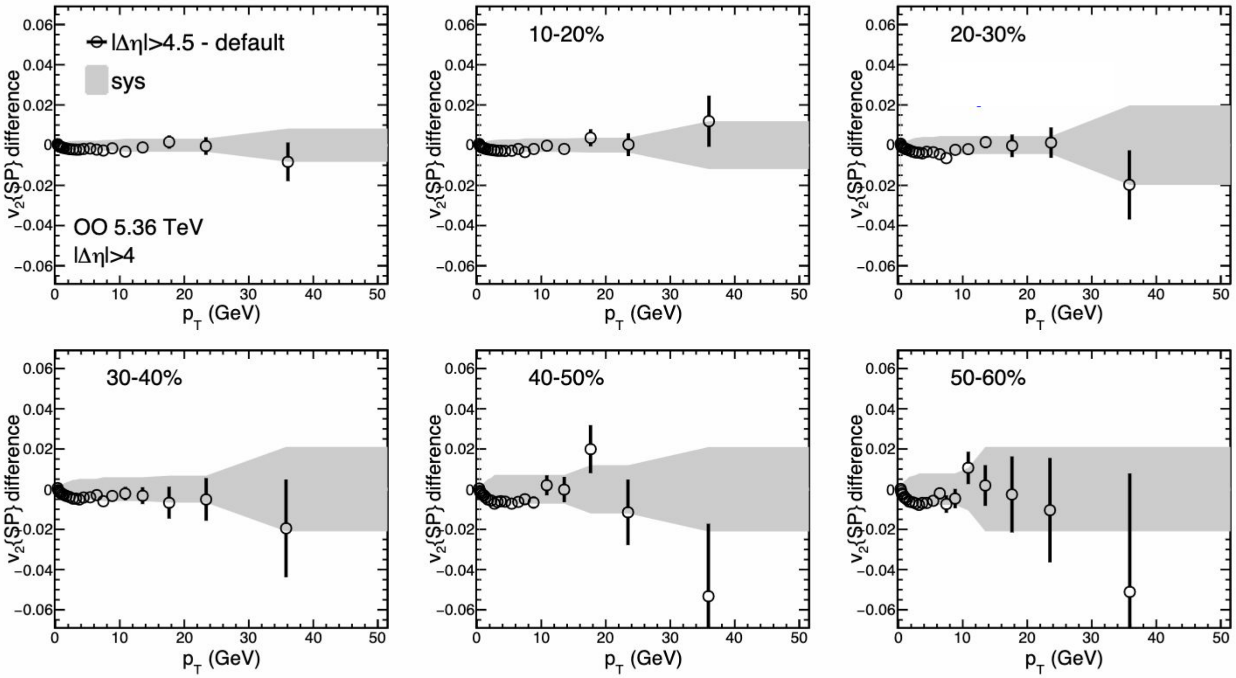
https://arxiv.org/pdf/1710.07098

PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV

Centrality	b_{min} (fm)	b_{max} (fm)	$\langle N_{coll} \rangle \pm$ rms	$\langle N_{part} \rangle \pm$ rms	$\langle T_{AA} \rangle \pm$ rms (mb^{-1})	$\varepsilon_2 \pm$ rms	$\varepsilon_3 \pm$ rms
0–5%	0	3.49	1762 ± 147	384.3 ± 16.6	26.1 ± 2.2	0.072 ± 0.0391	0.0843 ± 0.0451
5–10%	3.49	4.93	1380 ± 113	331.2 ± 17.7	20.4 ± 1.7	0.112 ± 0.0575	0.112 ± 0.0585
10–15%	4.93	6.04	1088 ± 93.4	283 ± 16.8	16.1 ± 1.4	0.158 ± 0.073	0.134 ± 0.0697
15–20%	6.04	6.98	855.3 ± 80.8	240.9 ± 16	12.7 ± 1.2	0.202 ± 0.086	0.154 ± 0.0797
20–25%	6.98	7.8	667.6 ± 71.6	204 ± 15.3	9.88 ± 1.1	0.243 ± 0.0977	0.173 ± 0.0895
25–30%	7.8	8.55	515.7 ± 63.9	171.6 ± 14.7	7.63 ± 0.95	0.282 ± 0.109	0.192 ± 0.0992
30–35%	8.55	9.23	392.9 ± 57	143.2 ± 14.1	5.81 ± 0.84	0.318 ± 0.12	0.212 ± 0.109
35–40%	9.23	9.87	294.5 ± 50	118.3 ± 13.6	4.36 ± 0.74	0.352 ± 0.131	0.234 ± 0.119
40–45%	9.87	10.5	216.4 ± 43.3	96.49 ± 13	3.2 ± 0.64	0.385 ± 0.142	0.257 ± 0.129
45–50%	10.5	11	155.5 ± 36.6	77.48 ± 12.4	2.3 ± 0.54	0.418 ± 0.154	0.281 ± 0.139
50–55%	11	11.6	109.2 ± 30.2	61.19 ± 11.7	1.62 ± 0.45	0.45 ± 0.166	0.307 ± 0.15
55–60%	11.6	12.1	74.73 ± 24.3	47.31 ± 10.9	1.11 ± 0.36	0.484 ± 0.177	0.335 ± 0.159
60–65%	12.1	12.6	49.88 ± 19.1	35.74 ± 9.96	0.738 ± 0.28	0.52 ± 0.189	0.362 ± 0.169
65–70%	12.6	13.1	32.38 ± 14.7	26.26 ± 8.95	0.479 ± 0.22	0.557 ± 0.2	0.385 ± 0.179
70–75%	13.1	13.5	20.54 ± 11.1	18.75 ± 7.79	0.304 ± 0.16	0.596 ± 0.209	0.402 ± 0.19
75–80%	13.5	14	12.85 ± 8.16	13.09 ± 6.55	0.19 ± 0.12	0.634 ± 0.219	0.409 ± 0.209
80–85%	14	14.4	8.006 ± 5.82	9.038 ± 5.22	0.118 ± 0.086	0.672 ± 0.232	0.407 ± 0.239
85–90%	14.4	14.9	5.084 ± 4.08	6.304 ± 3.98	0.0752 ± 0.06	0.715 ± 0.245	0.39 ± 0.277
90–95%	14.9	15.6	3.27 ± 2.77	4.452 ± 2.86	0.0484 ± 0.041	0.766 ± 0.254	0.349 ± 0.313
95–100%	15.6	20	2.035 ± 1.72	3.103 ± 1.8	0.0301 ± 0.025	0.844 ± 0.241	0.255 ± 0.328
0–100%	0	20	382.2 ± 506	113.8 ± 116	5.65 ± 7.5	0.439 ± 0.277	0.272 ± 0.205

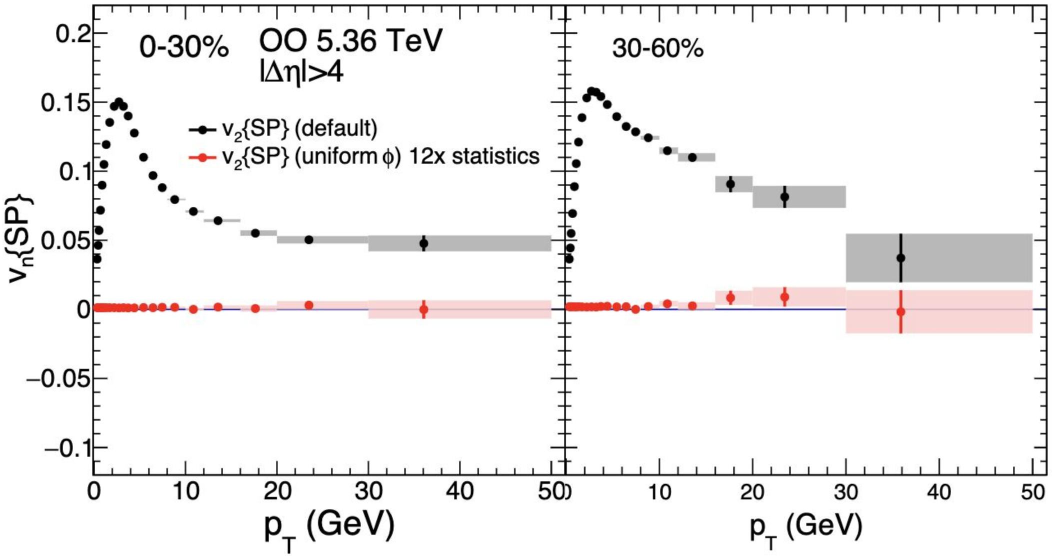
	OO					NeNe				
Centrality	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$	$\langle N_{mpi} \rangle$	R	$\frac{2}{N_{part}} dN/d\eta$	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$	$\langle N_{mpi} \rangle$	R	$\frac{2}{N_{part}} dN/d\eta$
0–1%	28.5	57.7	183.3	1.084	7.72±0.24	35.2	73.9	231.4	1.067	7.78±0.23
1–2%	27.7	50.1	155.7	1.061	7.37±0.29	34.3	64.4	198.6	1.052	7.44±0.28
2–3%	27.1	46.4	143.2	1.053	7.23±0.31	33.7	60.1	183.7	1.043	7.30±0.30
3–4%	26.6	43.8	134.4	1.047	7.12±0.32	33.0	56.6	172.3	1.038	7.20±0.31
4–5%	26.1	41.8	127.4	1.041	7.05±0.34	32.5	54.0	163.4	1.032	7.12±0.33
0–5%	27.2	48.0	149.1	1.059	7.30±0.30	33.8	61.9	190.3	1.05	7.37±0.29
5–10%	24.8	37.0	111.8	1.029	6.89±0.36	30.6	47.5	142.5	1.023	6.96±0.35
10–15%	22.4	30.6	91.2	1.017	6.70±0.39	27.4	38.7	115.1	1.013	6.76±0.38
10–20%	20.0	25.4	75.3	1.011	6.56±0.41	24.3	31.7	93.7	1.007	6.61±0.40
20–30%	16.7	19.2	56.3	1.000	6.40±0.43	19.9	23.4	68.4	0.999	6.43±0.43
30–40%	12.7	12.8	37.0	0.986	6.20±0.46	14.8	15.1	43.8	0.987	6.22±0.46
40–50%	9.3	8.3	23.6	0.968	6.03±0.48	10.7	9.7	27.5	0.972	6.05±0.48
50–60%	6.7	5.3	14.8	0.943	5.89±0.51	7.6	6.2	17.2	0.952	5.92±0.50
60–70%	4.7	3.3	8.8	0.901	5.75±0.53	5.2	3.8	10.3	0.920	5.79±0.52
70–100%	2.6	1.5	3.0	0.679	5.43±0.57	2.8	1.6	3.4	0.720	5.47±0.57
0–100%	10.8	12.8	37.6	1	6.02±0.21	12.7	15.7	46.0	1	6.06±0.21

Nonflow systematic uncertainty



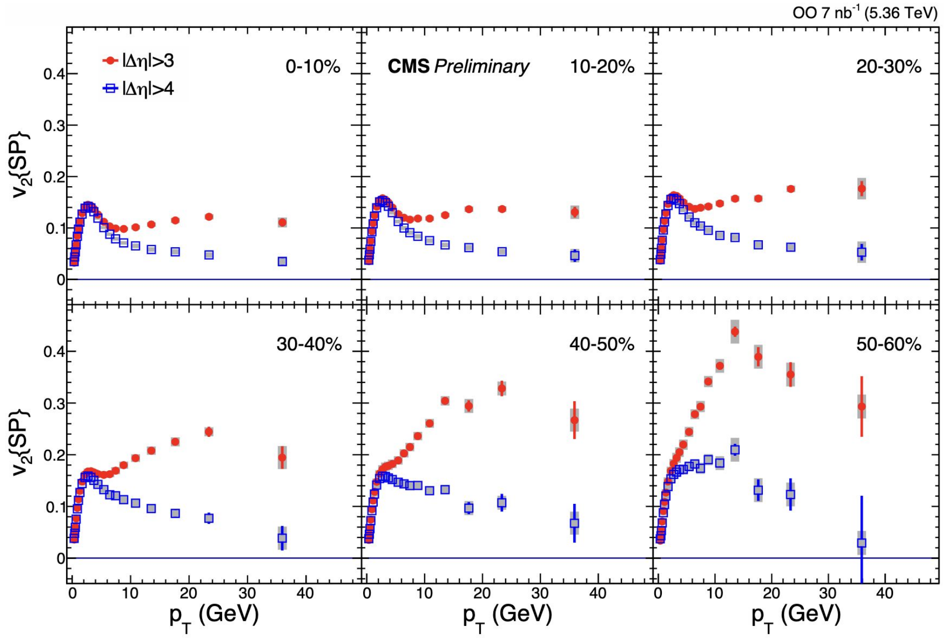
- Nominal : $|\Delta\eta| > 4.0$
- Systematic variation : $|\Delta\eta| > 4.5$

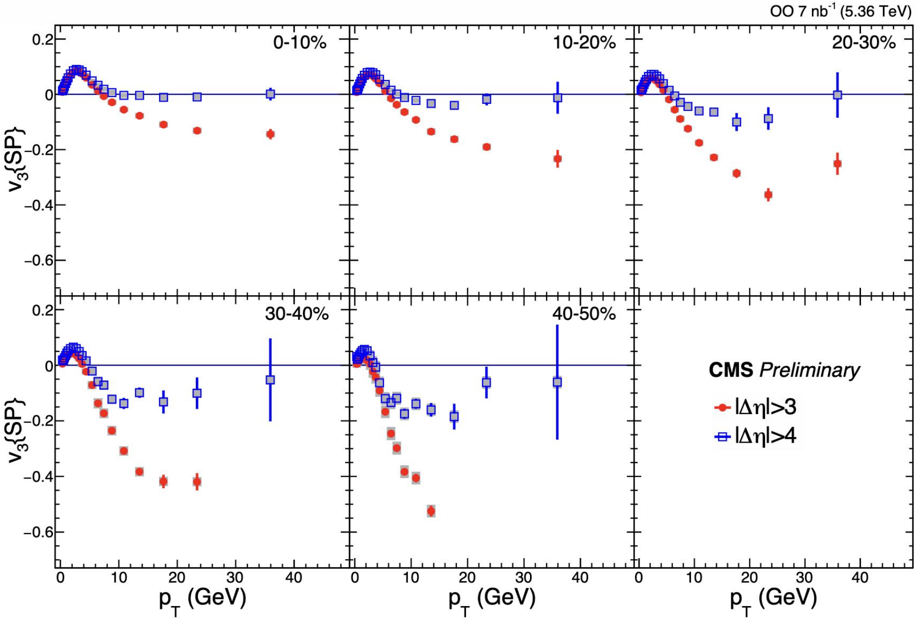
Cross-check with zero input signal



- Confirmed that the scalar-product method is robust.
- Using real data to study this effect.
- The actual phi angle of tracks and HF towers are replaced with random numbers from a uniform distribution.
- The expected flow is 0 in this case.
- To increase the statistics, the full dataset is run 12 times for the uniform phi study.

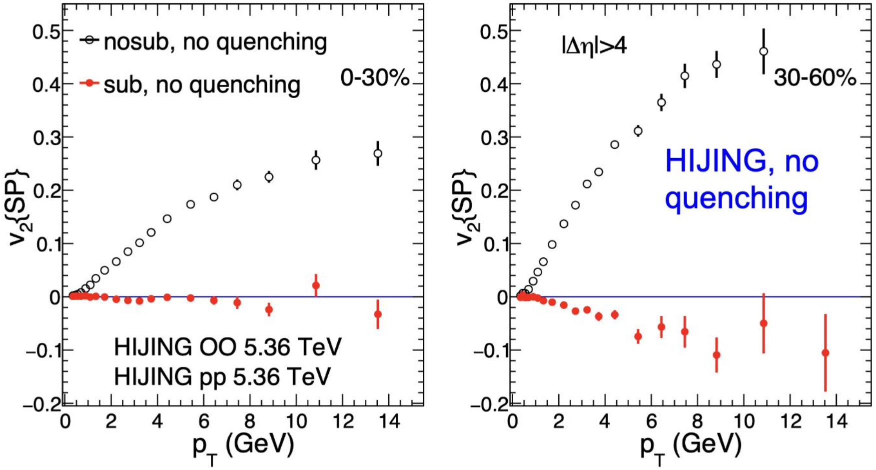
v_2 with different eta gaps

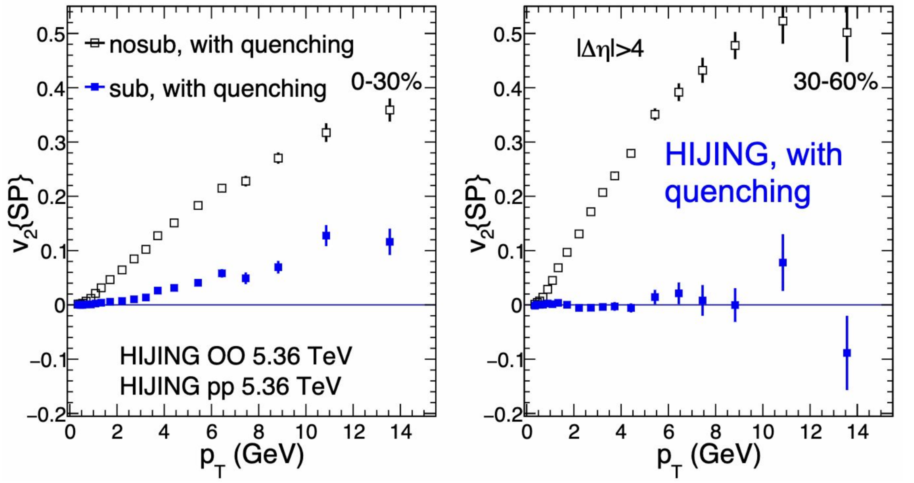


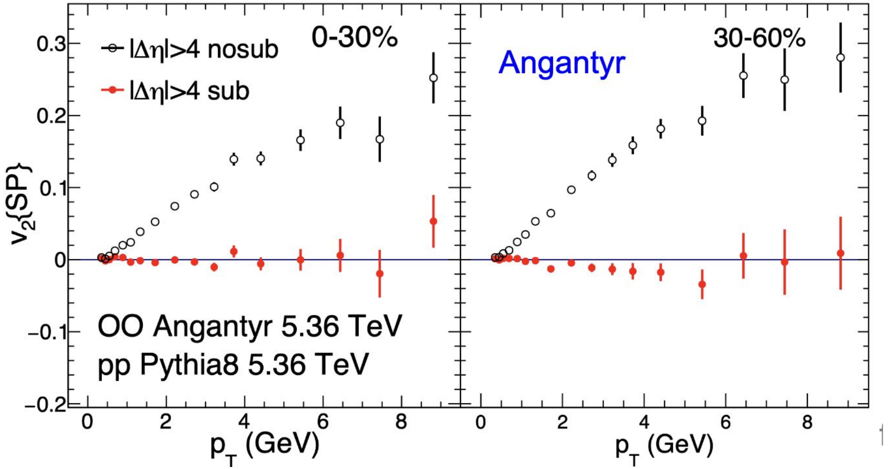


- Clear nonflow contribution with $|\Delta\eta| > 3$
- Not clear how much nonflow left even with $|\Delta\eta| > 4$

Nonflow subtraction with and without quenching in HIJING

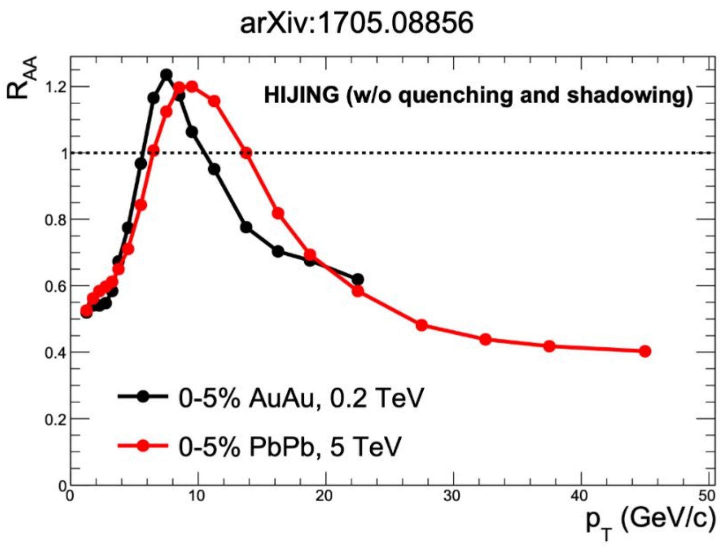


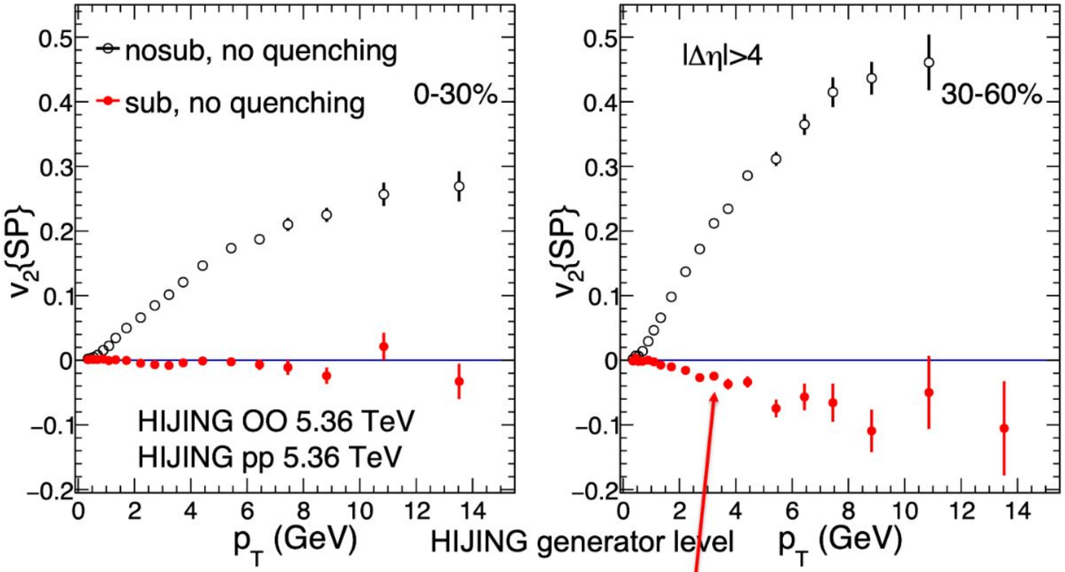




- HIJING no quenching: possible over-subtraction at 30-60% after pp subtraction
- HIJING with quenching: non-zero results after subtraction for 0-30% due to v_2 signal from quenching (not nonflow background)
- Possible small over-subtraction for Angantyr 30-60% after subtraction

Testing nonflow subtraction using HIJING without quenching





R_{AA} in HIJING is not unity, even without quenching and shadowing, due to ”Cronin” effects and other “physics” in the model

- Residual correlations in HIJING persist after pp baseline subtraction, even with jet quenching turned off

HIJING ~ not independent superposition of pp