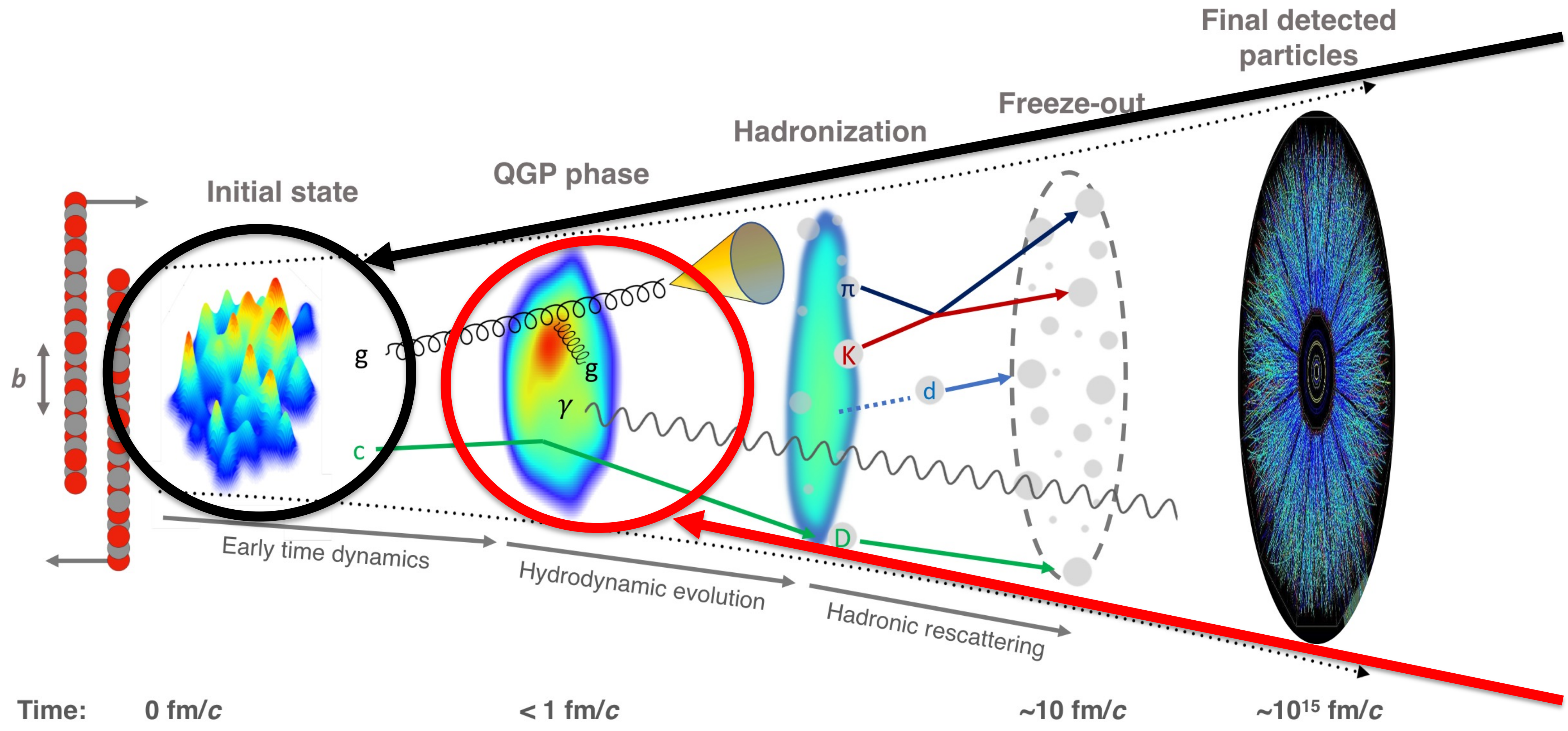
# Azimuthal flow and correlations in HI

Shengquan Tuo
(Vanderbilt University)
for the ALICE, ATLAS, CMS and LHCb collaborations

# Heavy ion collision overview




**Physics**

Initial conditions and Collision geometry

- Shape
- Size
- Fluctuations

Quark-gluon plasma

- Transport properties
  - Shear and bulk viscosities
- Speed of sound

# Azimuthal flow and correlations at LHC – recent results

## Observables

- Azimuthal flow: Fourier coefficients $v_n$
  - $v_n$ extended to forward region in pseudorapidity (ALICE and LHCb)
  - Ridge yield in low multiplicity (ALICE)
  - $v_2$ at high $p_T$, with/without jets, or inside jet cone (ATLAS and CMS)
  - Flow decorrelations (ALICE and ATLAS)
- Bose-Einstein correlations / Femtoscopic correlations
  - Correlation radius in pPb (LHCb)
  - Correlation radius in pp with event shape selection (ALICE)
- Mean transverse momentum
  - $\langle p_T \rangle$ fluctuations (ALICE and ATLAS)
  - $\langle p_T \rangle$ in ultra-central collisions (CMS)

## Physics

Initial conditions and Collision geometry

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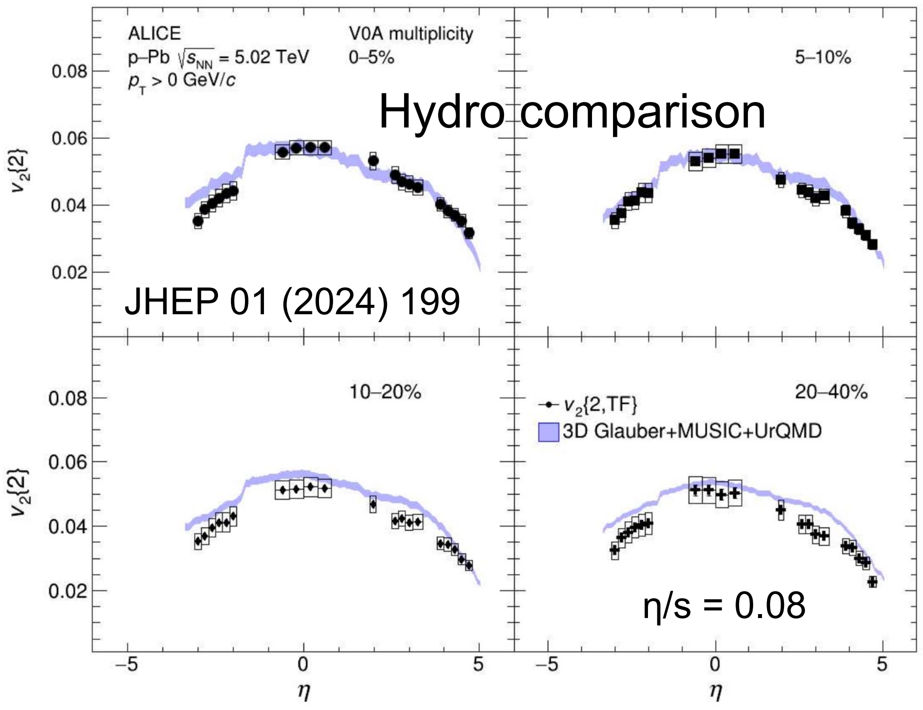
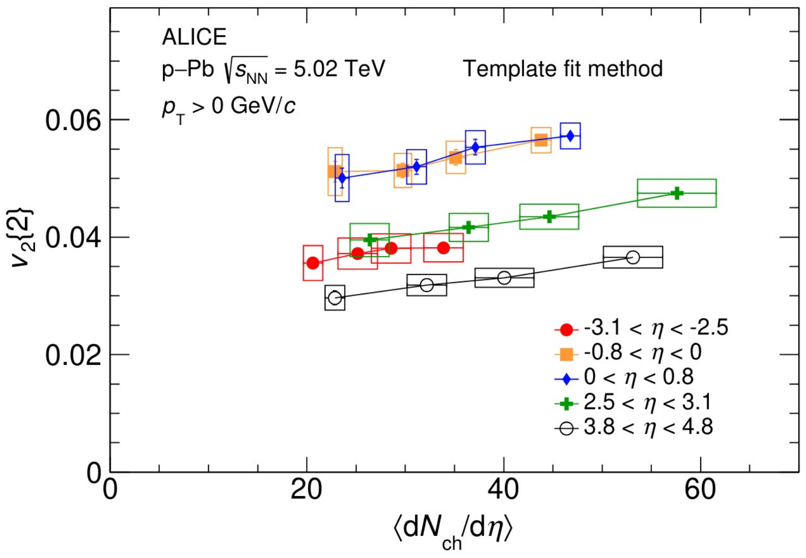
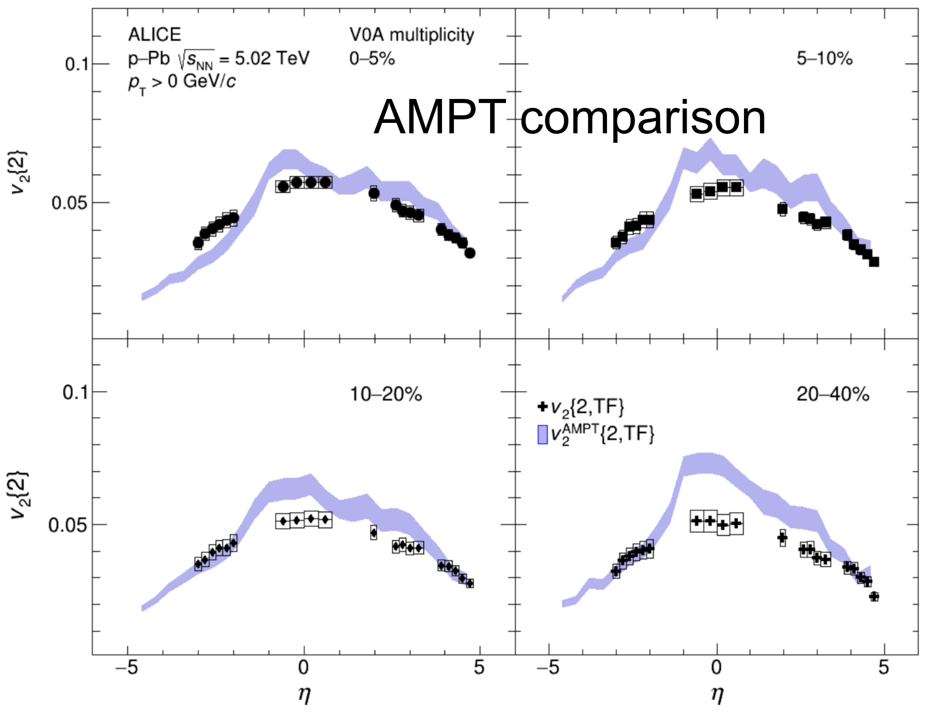
# $v_n$ extended to forward region (ALICE)

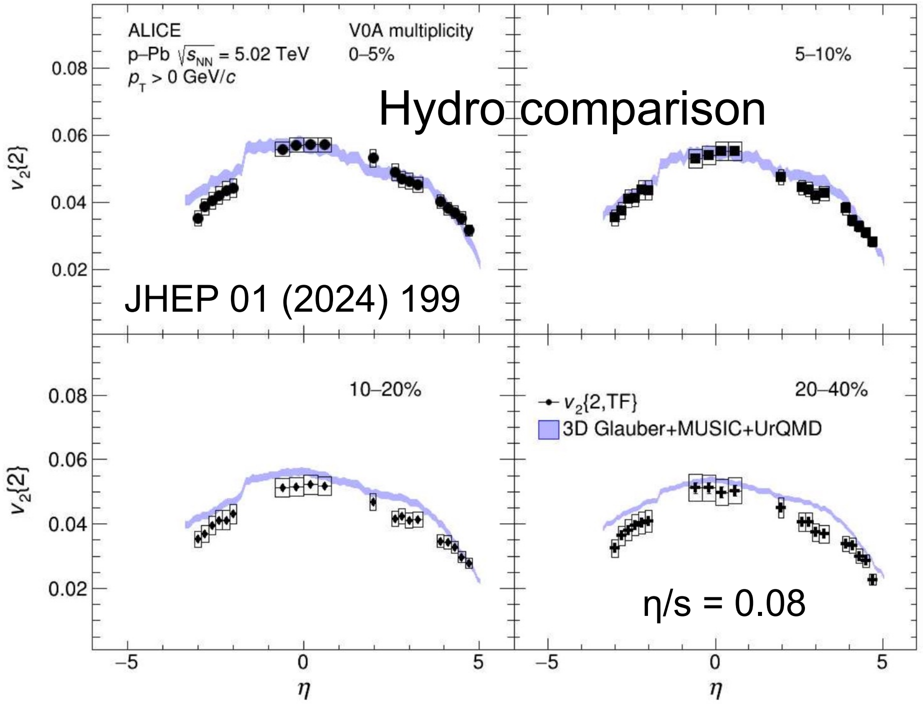


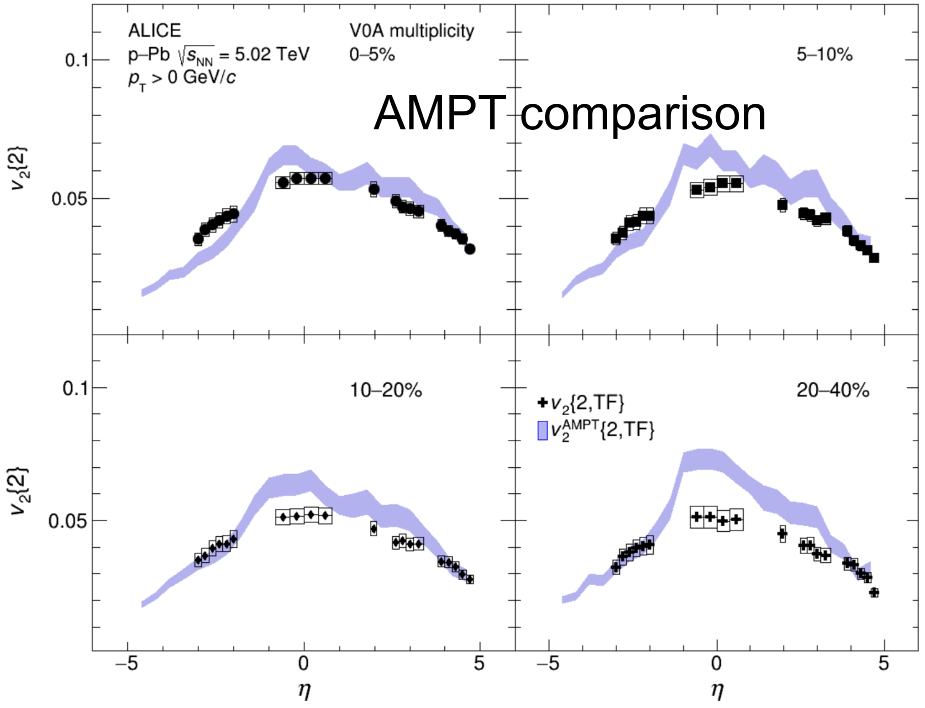



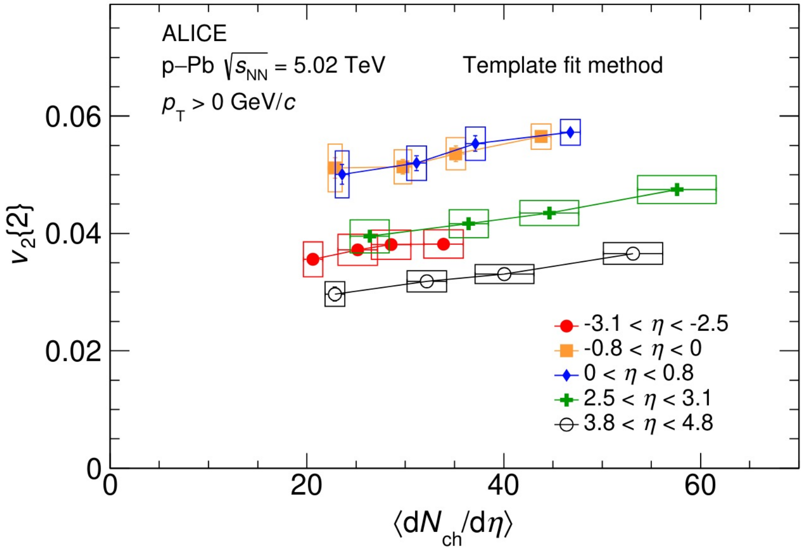



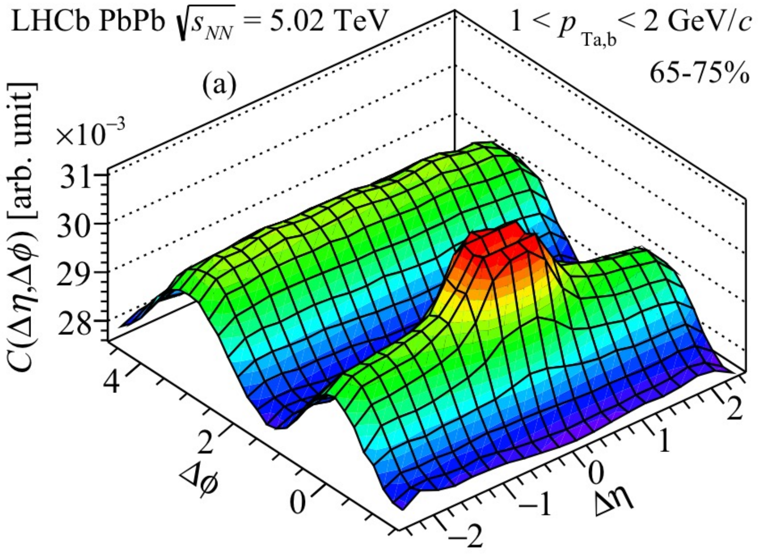

- The decrease in forward is described by hydrodynamics
- AMPT reproduces the asymmetry in p-going vs Pb-going

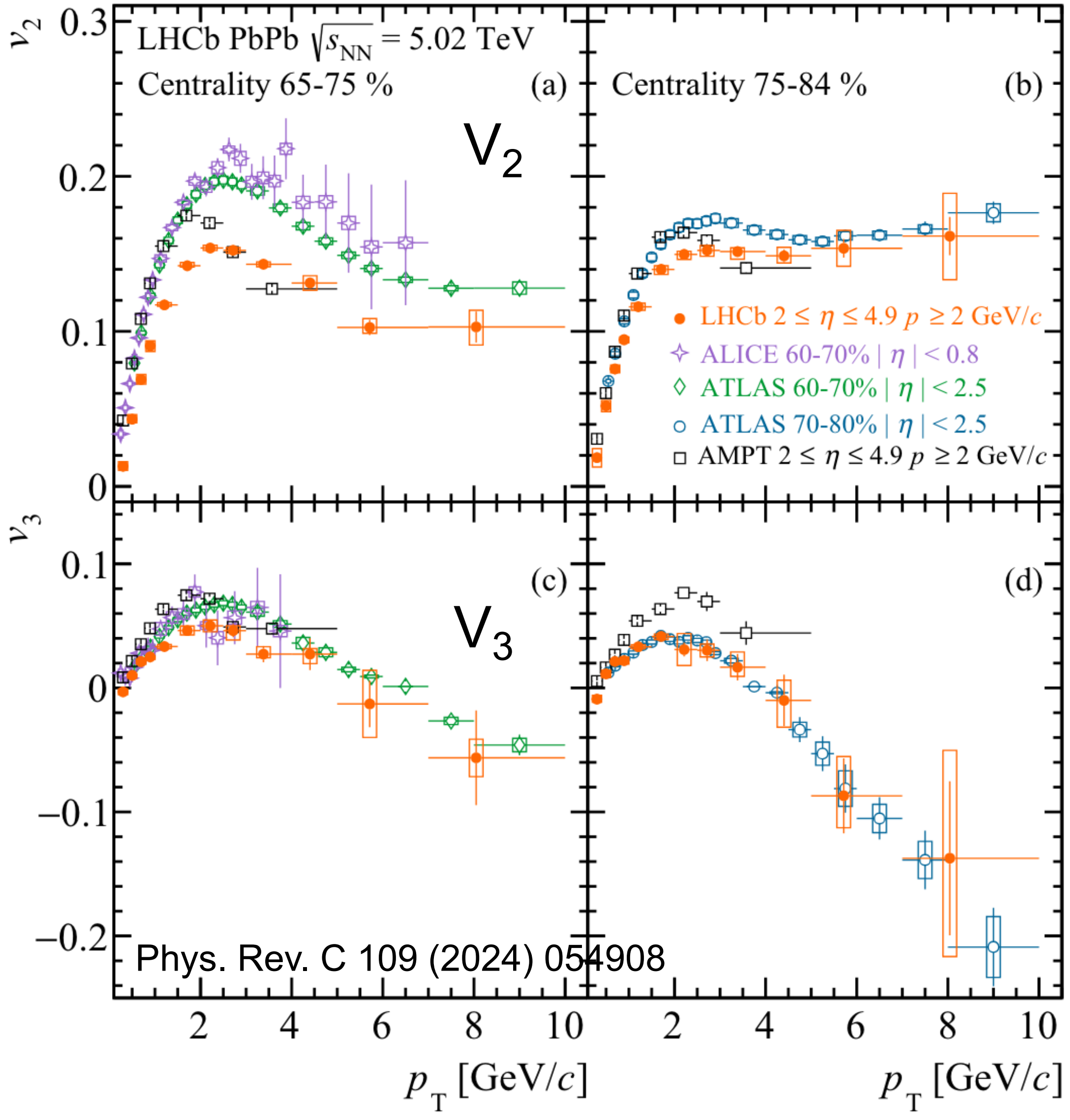
# $v_n$ extended to forward region (ALICE and LHCb)

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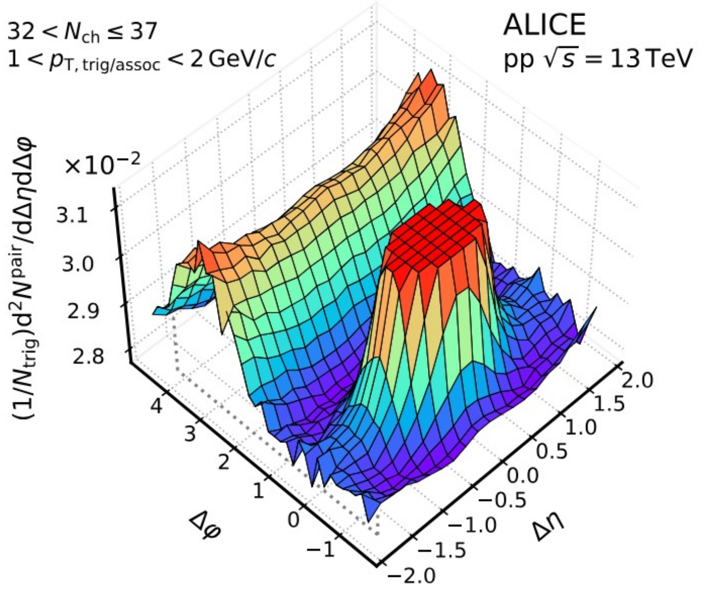
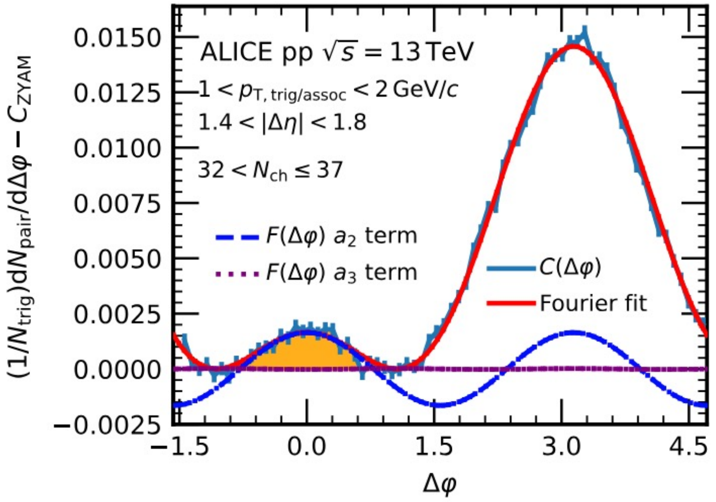
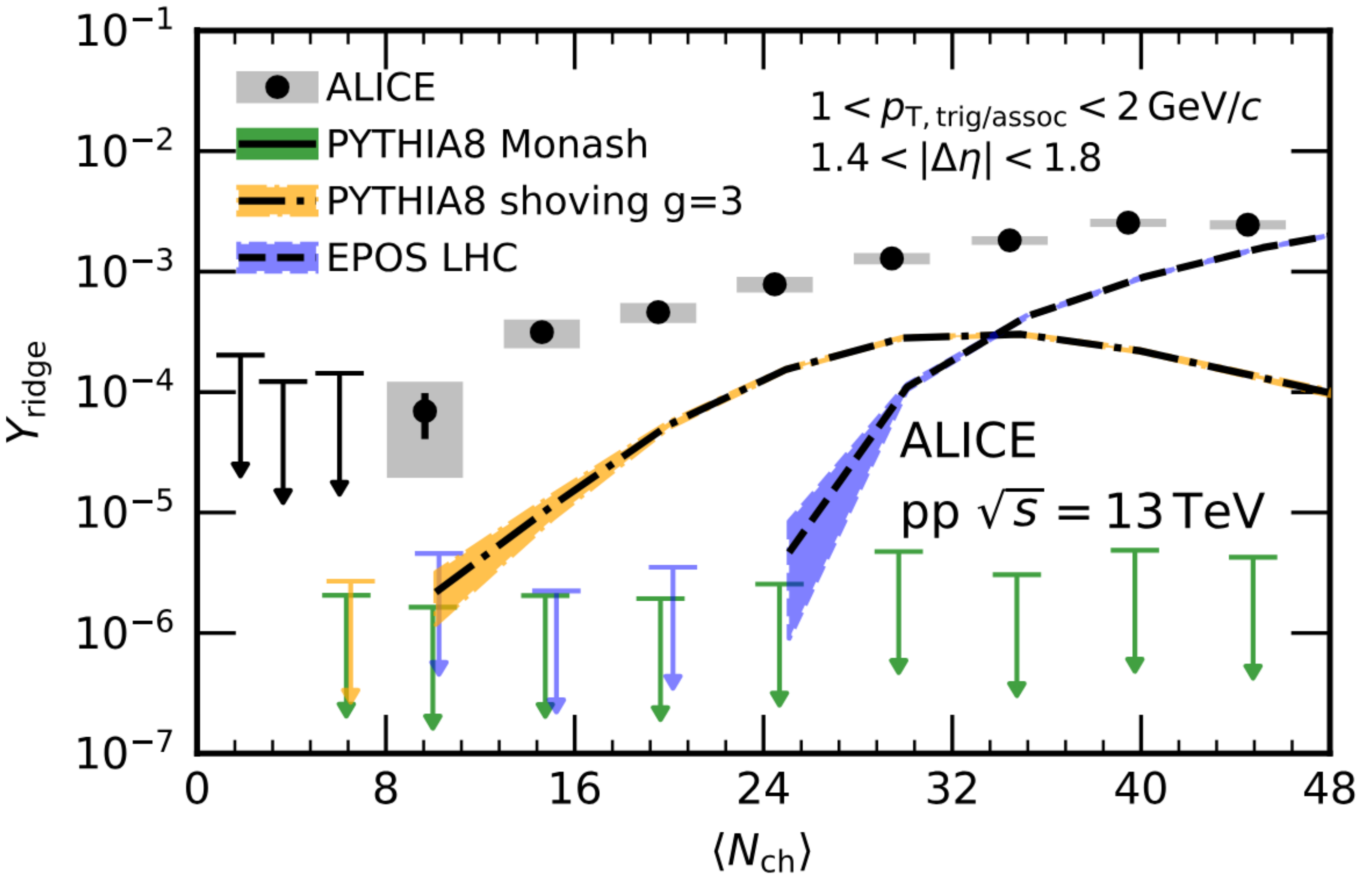
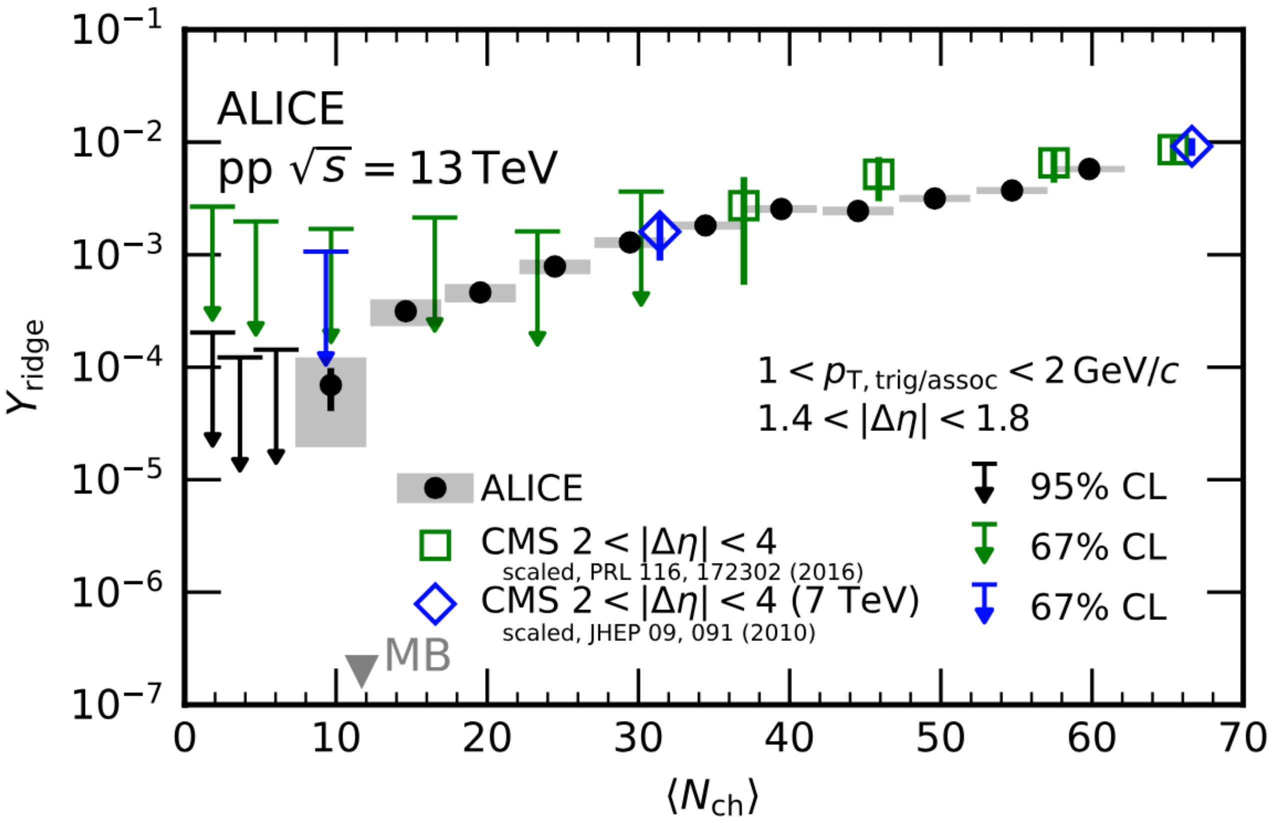
# Ridge yield in low multiplicity (ALICE)




Phys. Rev. Lett. 132, 172302 (2024)



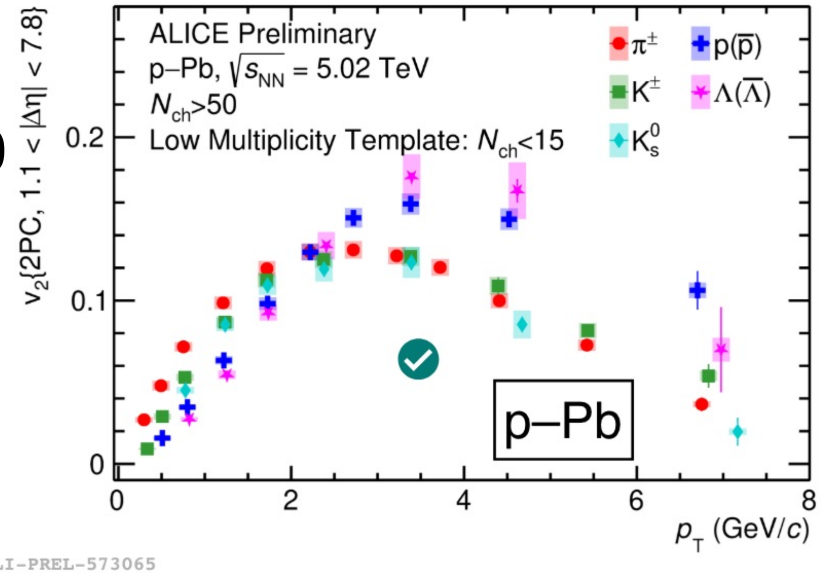



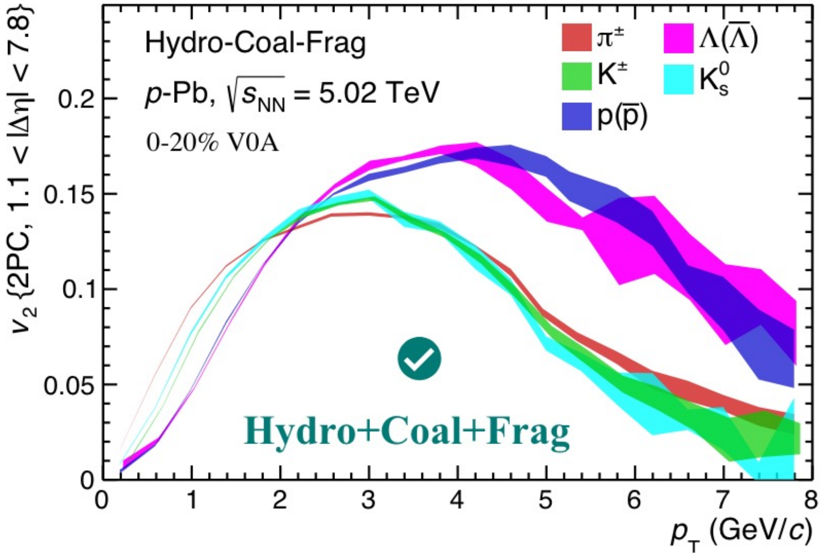



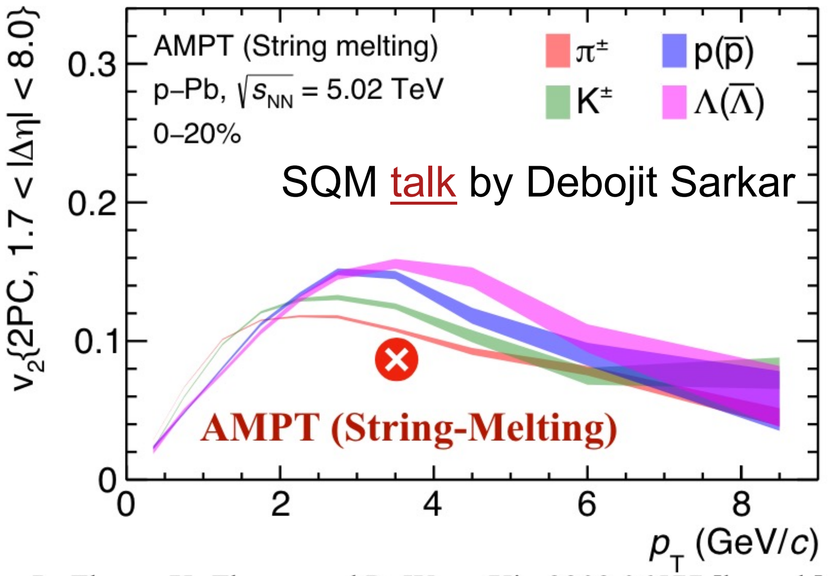

- Ridge yield extended to low multiplicity region
- Models cannot describe the yield at low multiplicity: mechanisms not understood

# Identified particle $v_2$ in low multiplicity (ALICE)

$N_{ch}$>50




W. Zhao et al., Phys. Rev. Lett. 125, 072301 (2020)   S. Tang, L. Zheng, X. Zhang, and R. WanarXiv:2303.06577 [hep-ph]

- Baryon-meson grouping and splitting of $v_2$ : described by Hydro+Coal+Frag, not transport

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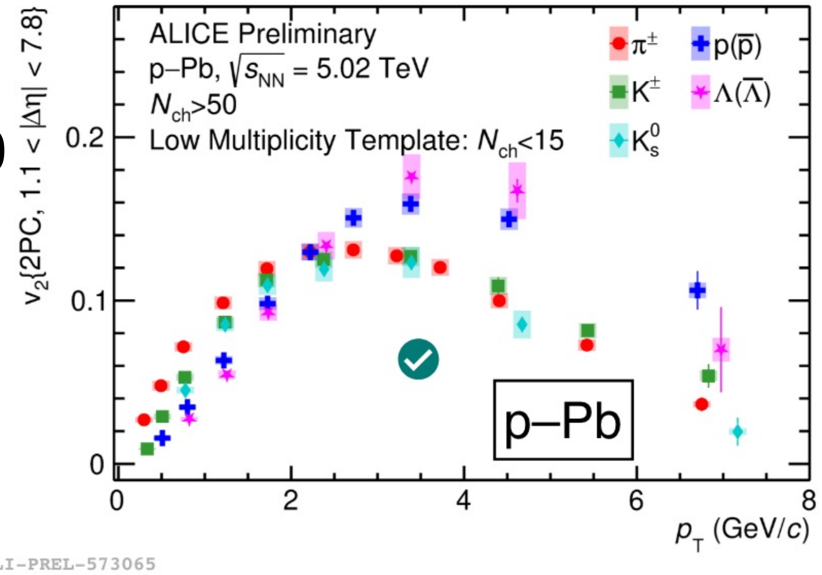


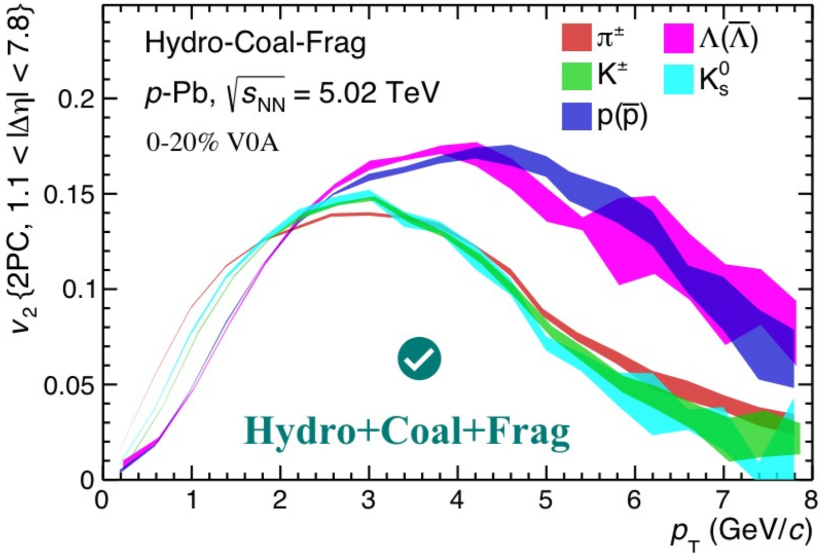


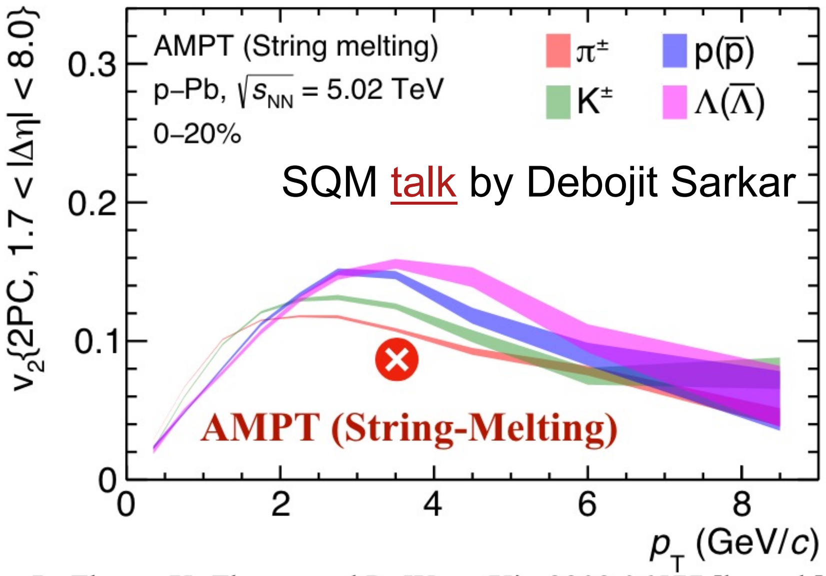


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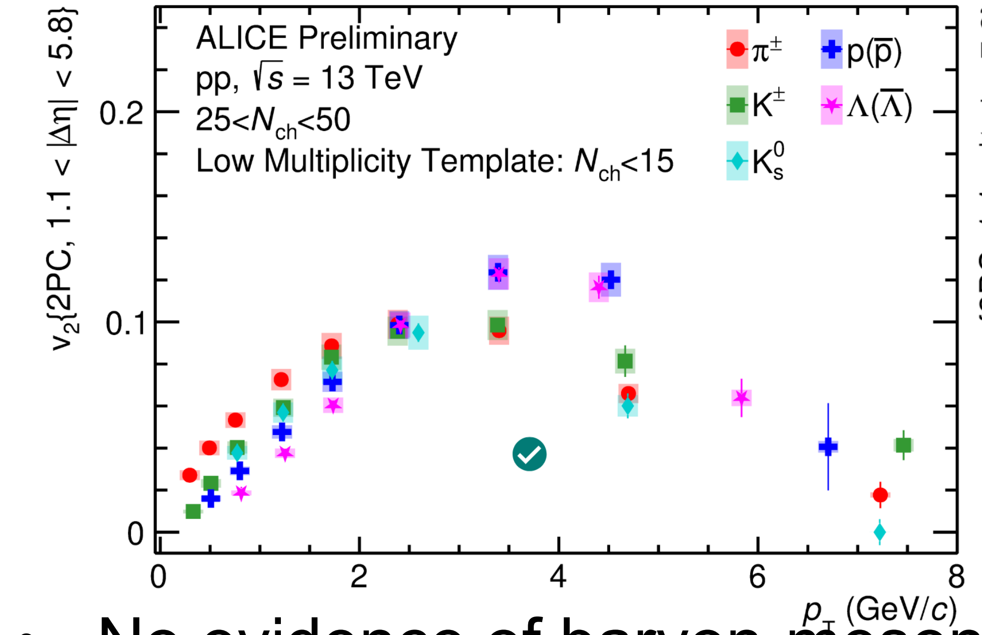
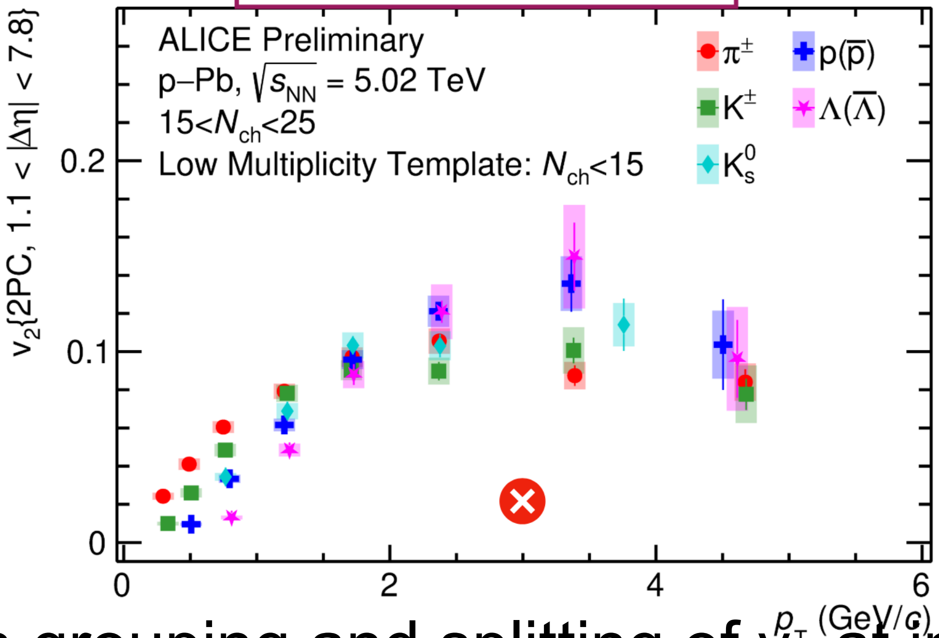
- Baryon-meson grouping and splitting of $v_2$ : described by Hydro+Coal+Frag, not transport

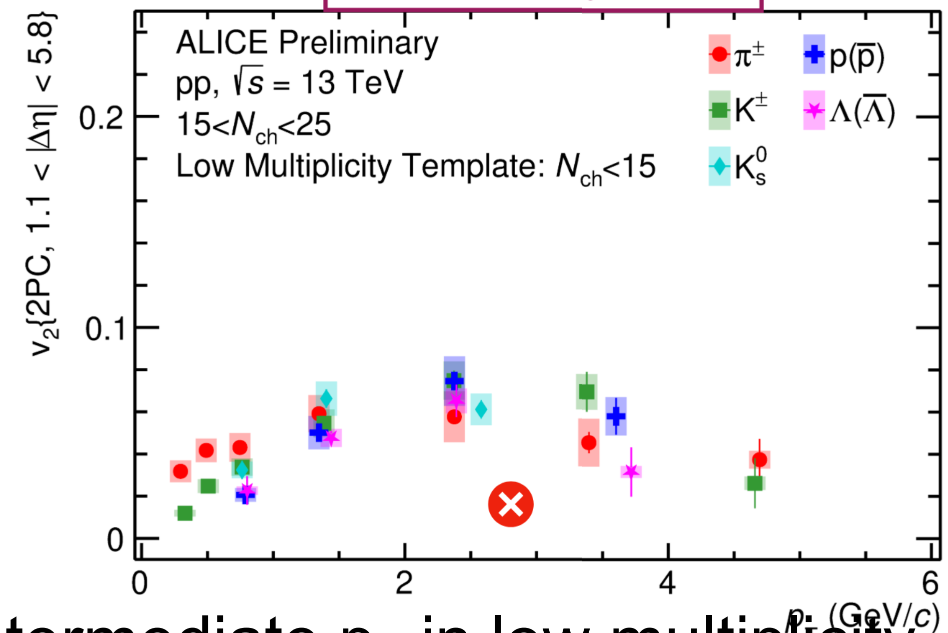
New $25 < N_{ch} < 50$

p–Pb: $15 < N_{ch} < 25$

pp: $15 < N_{ch} < 25$



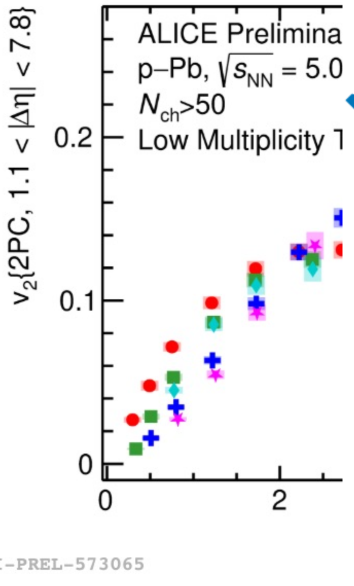



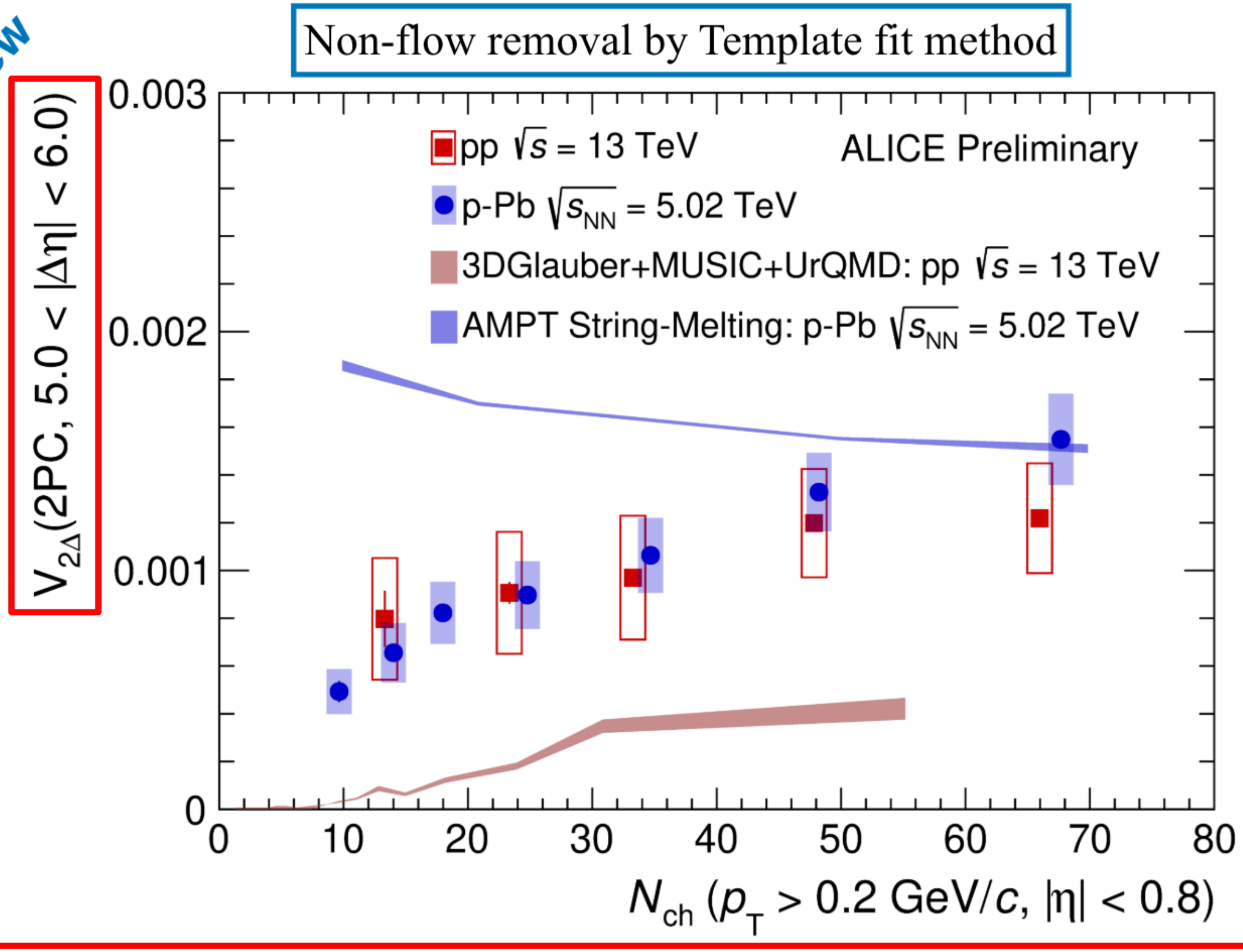

- No evidence of baryon-meson grouping and splitting of $v_2$ at intermediate $p_T$ in low multiplicity

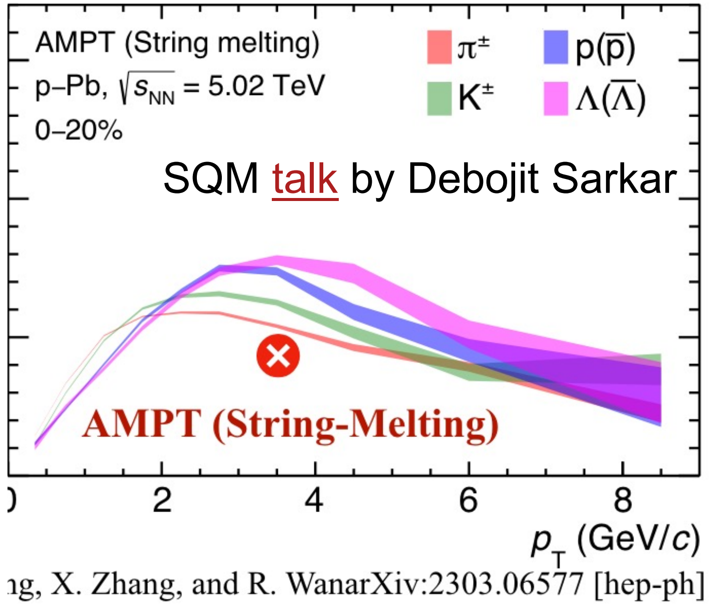
# Ultra long-range $v_2$ in low multiplicity (ALICE)

$N_{ch}$>50




New



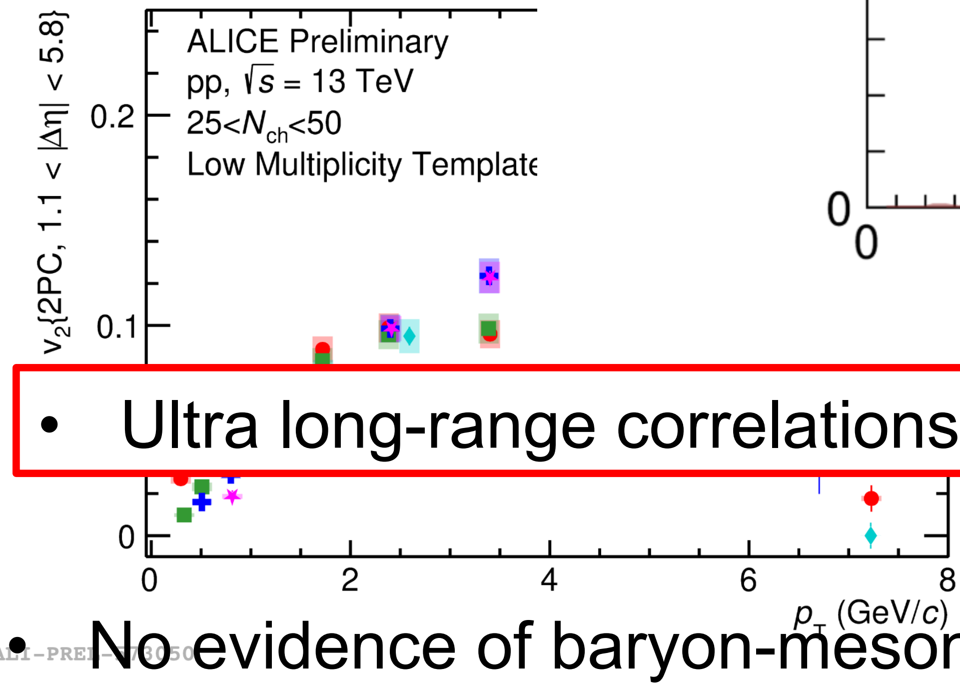

ng, X. Zhang, and R. WanarXiv:2303.06577 [hep-ph]

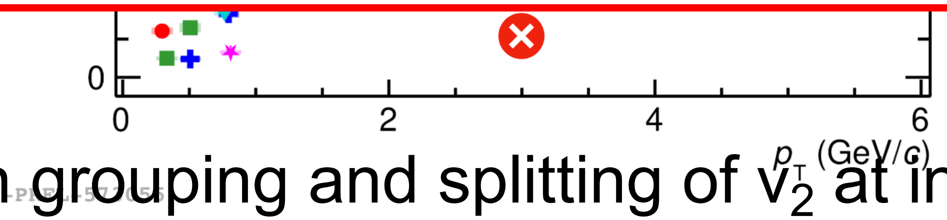
- Baryon-meson
- al+Frag, not transport

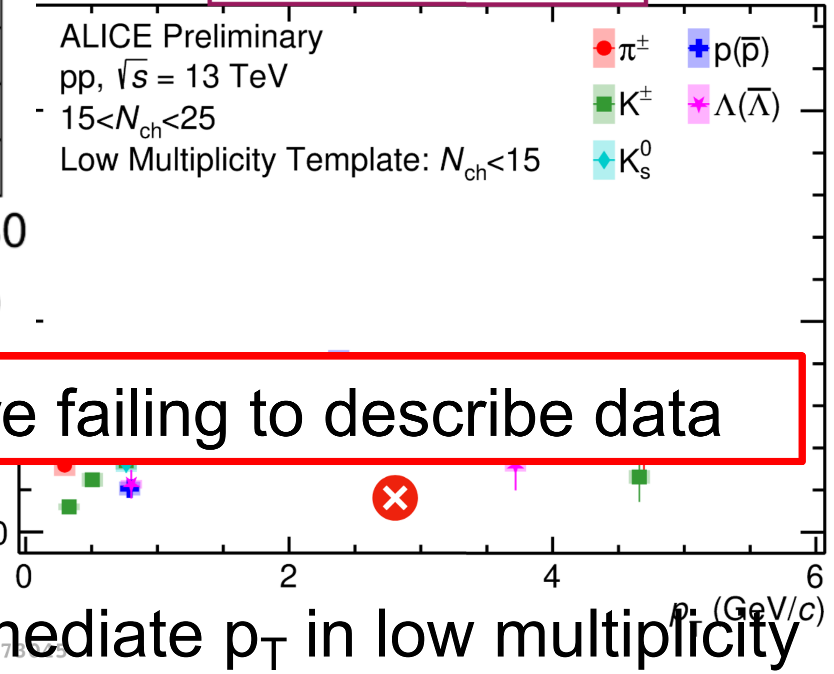
New

25 < N

pp: 15 < $N_{ch}$ < 25



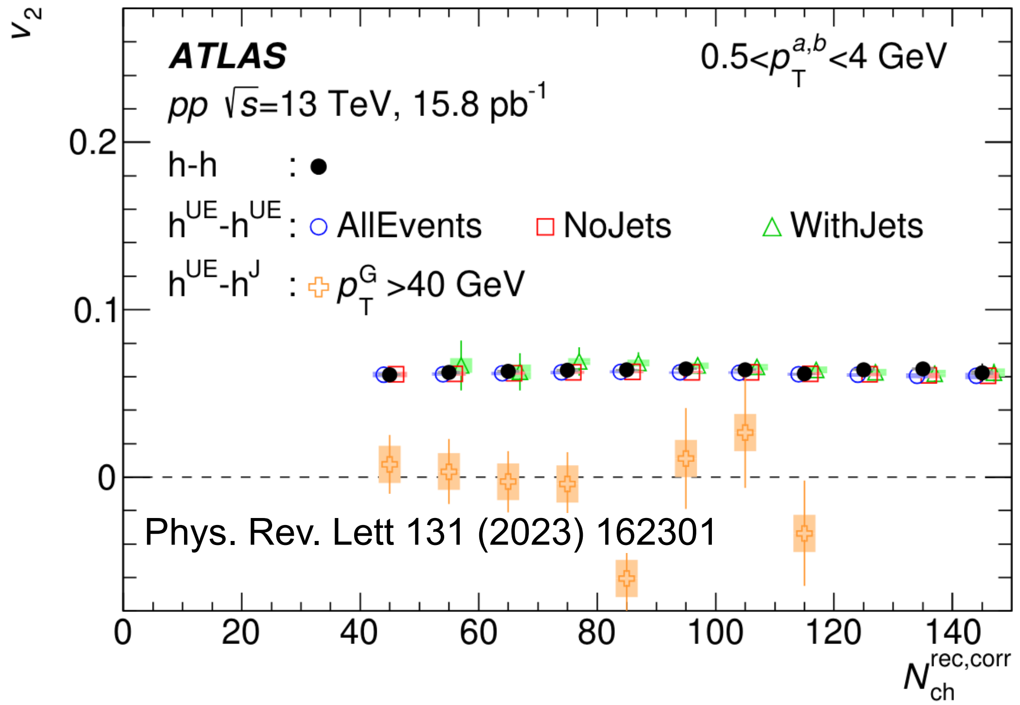



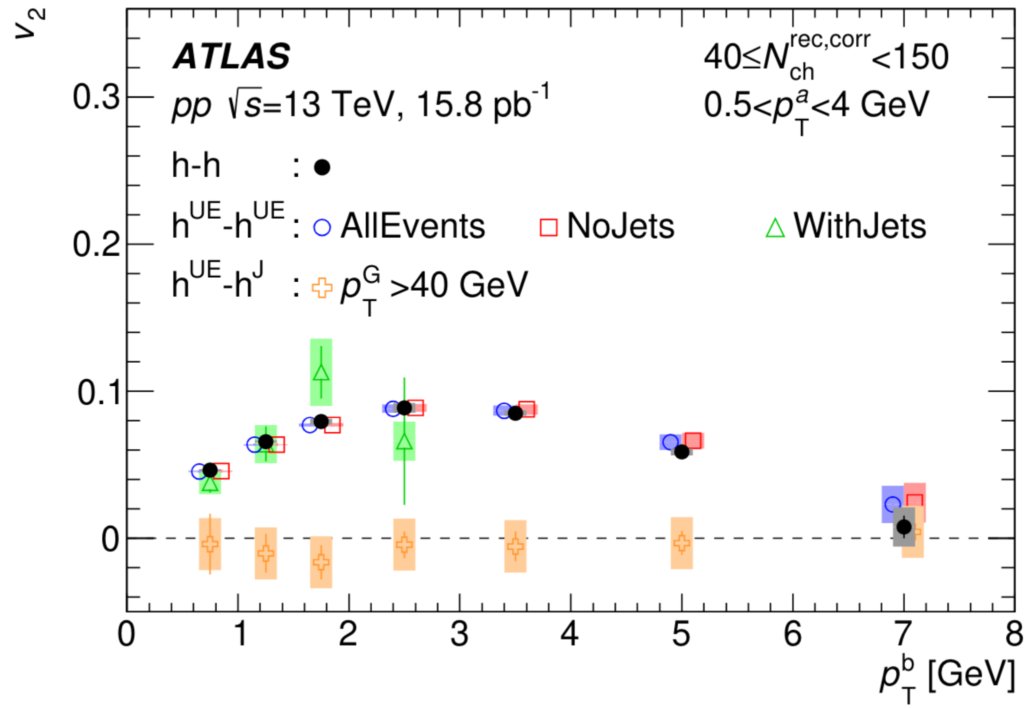



- Ultra long-range correlations: both hydro and transport models are failing to describe data

- No evidence of baryon-meson grouping and splitting of $v_2$ at intermediate $p_T$ in low multiplicity

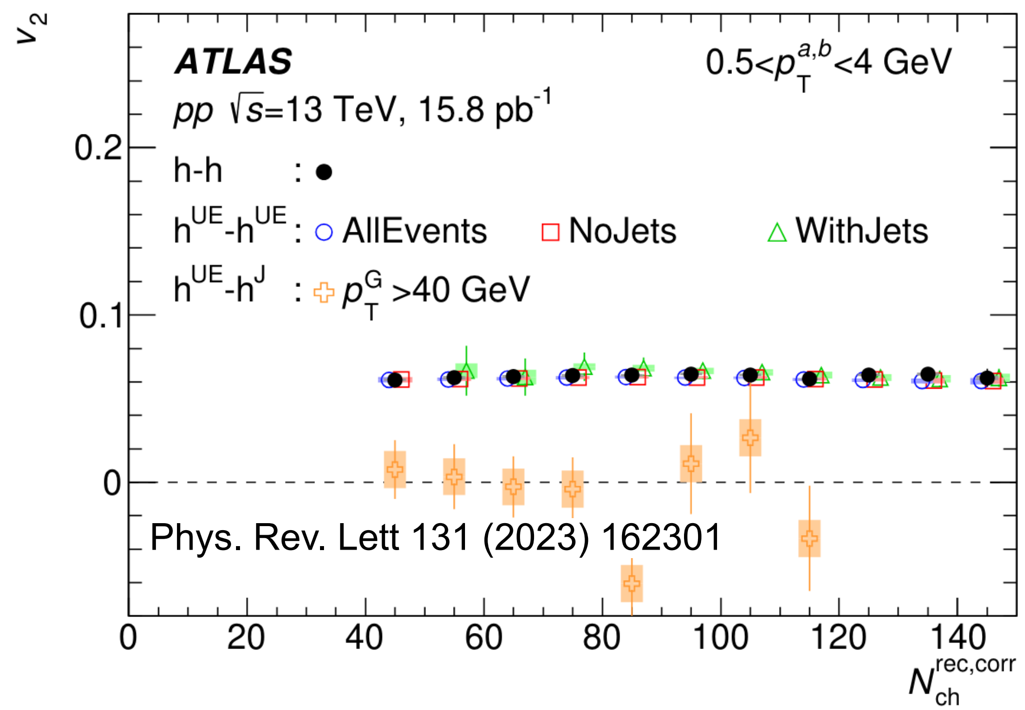
# $v_2$ in events WithJets/NoJets (ATLAS)

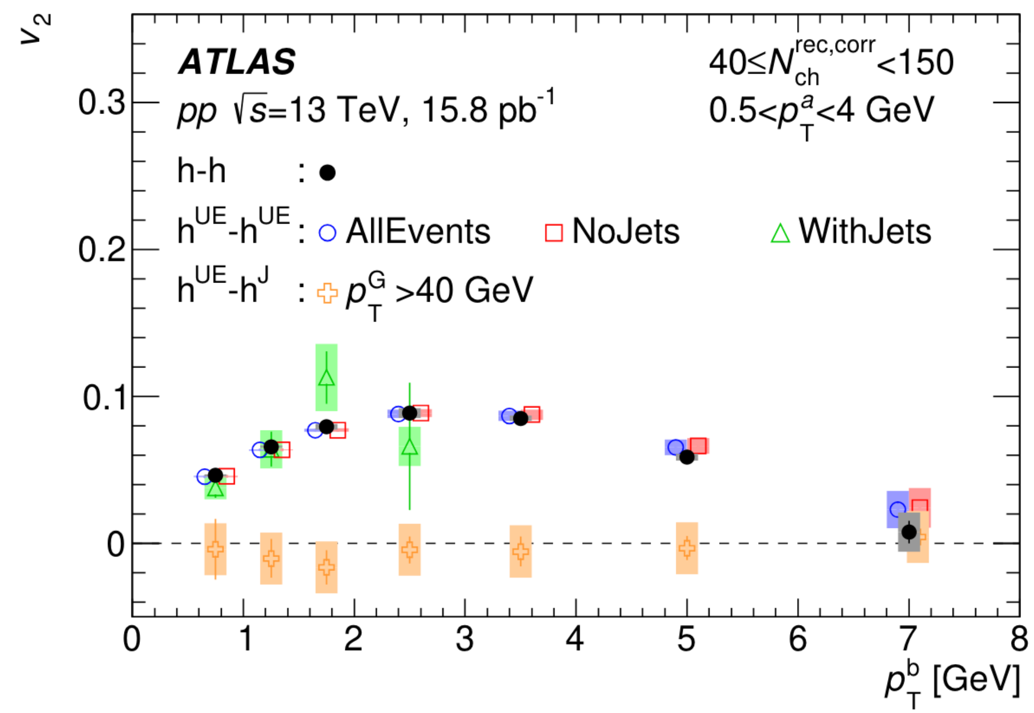


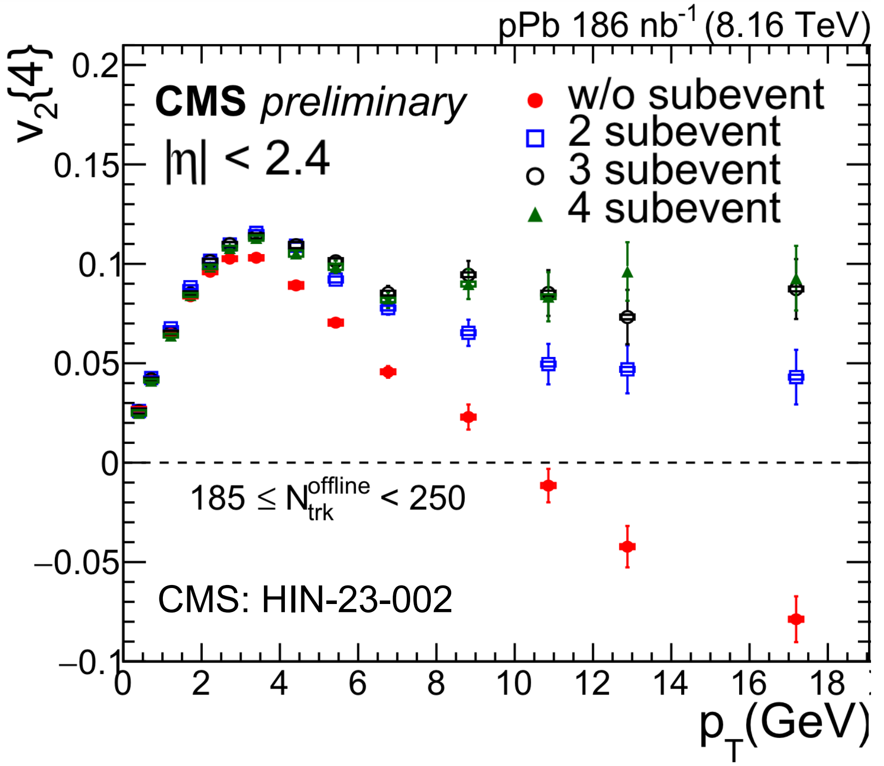



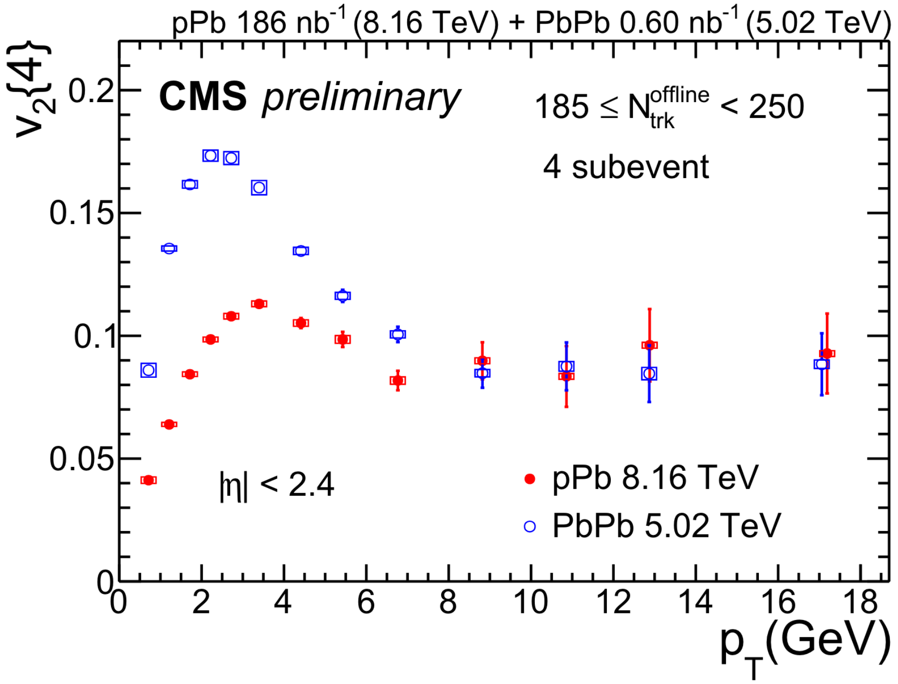

- $v_2$ is not affected by jets
- Jet constituents have zero $v_2$

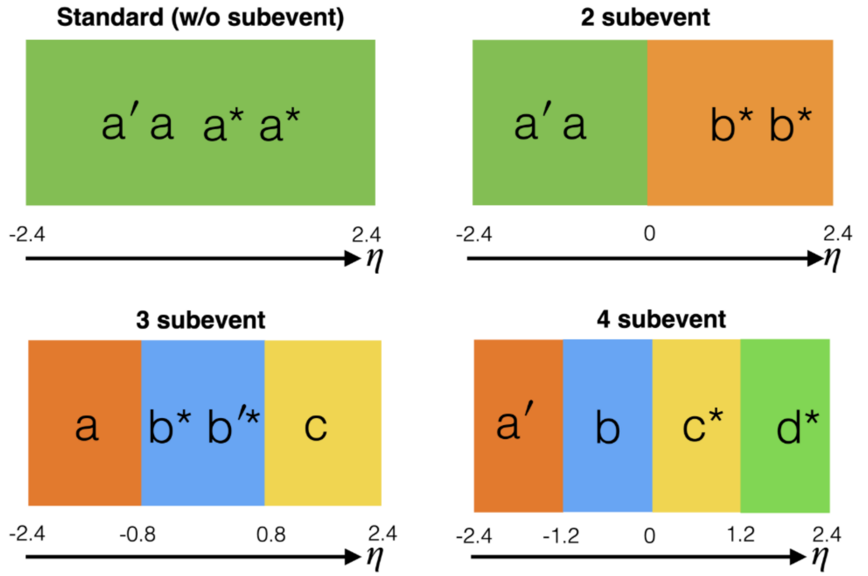
# $v_2$ in events WithJets/NoJets, at high $p_T$ (ATLAS and CMS)



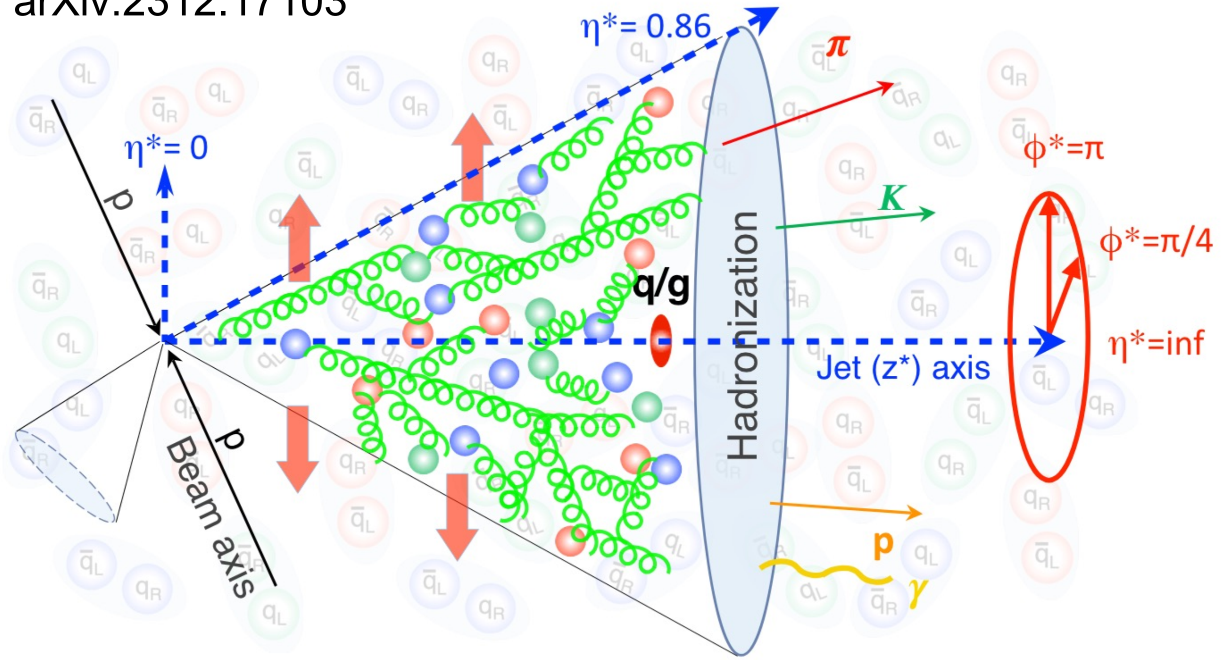



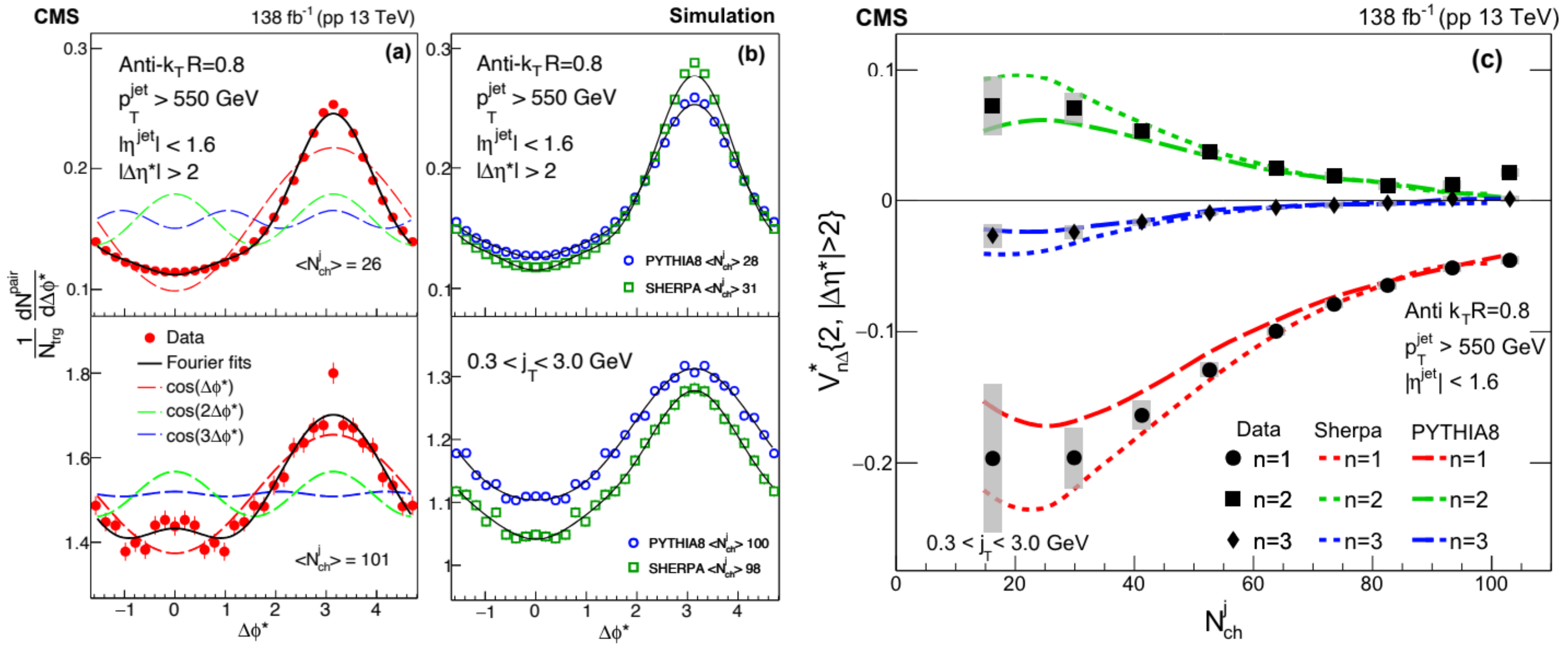



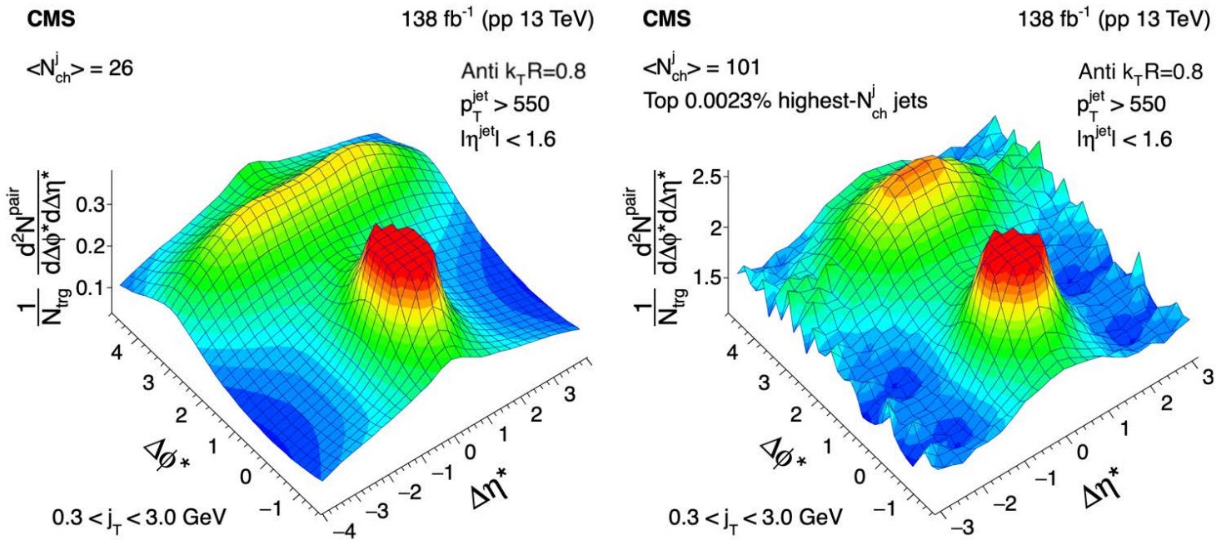

- $v_2$ is not affected by jets
- Jet constituents have zero $v_2$
- High $p_T$ $v_2$ nonflow removal needed with 3 or 4 subevents
- Same $v_2$ in pPb and PbPb at $p_T$ > 8 GeV

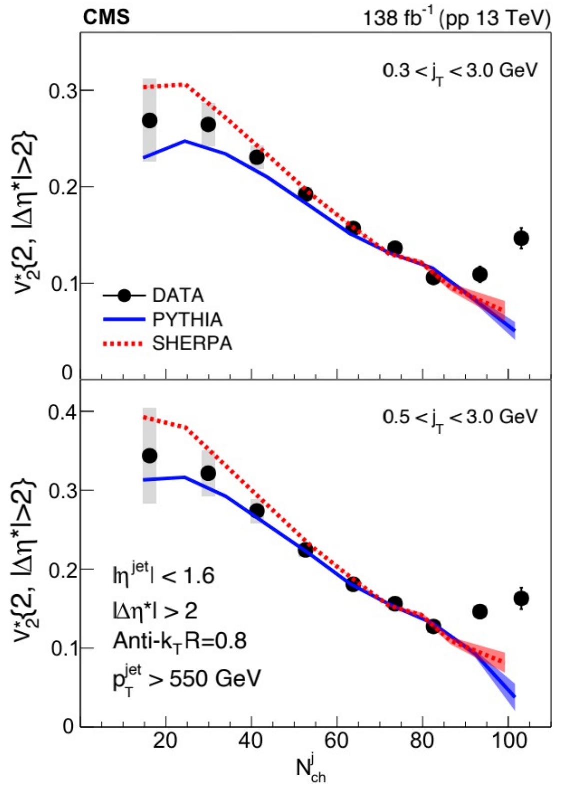
# $v_2$ inside jet cone (CMS)

arXiv:2312.17103



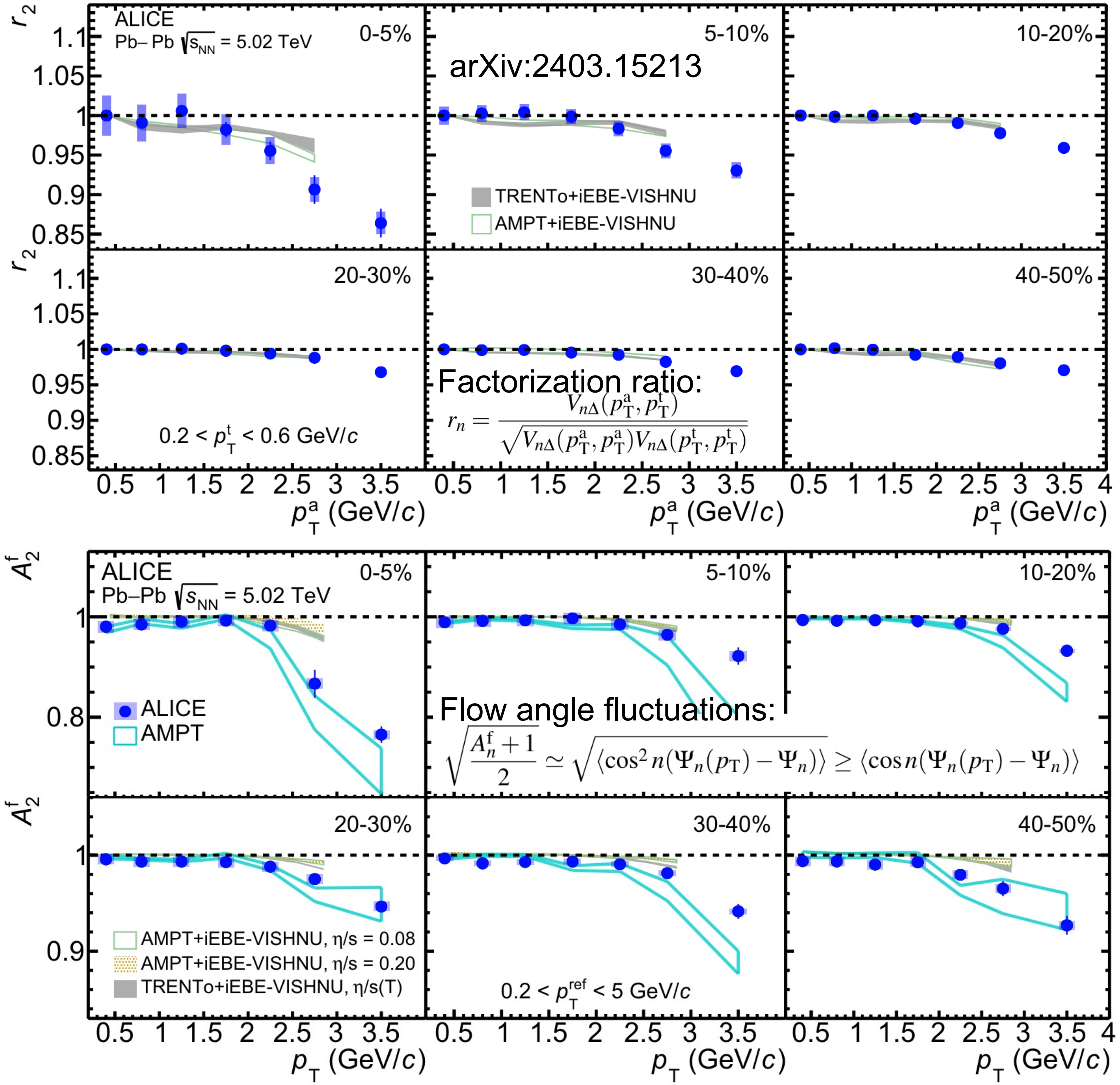



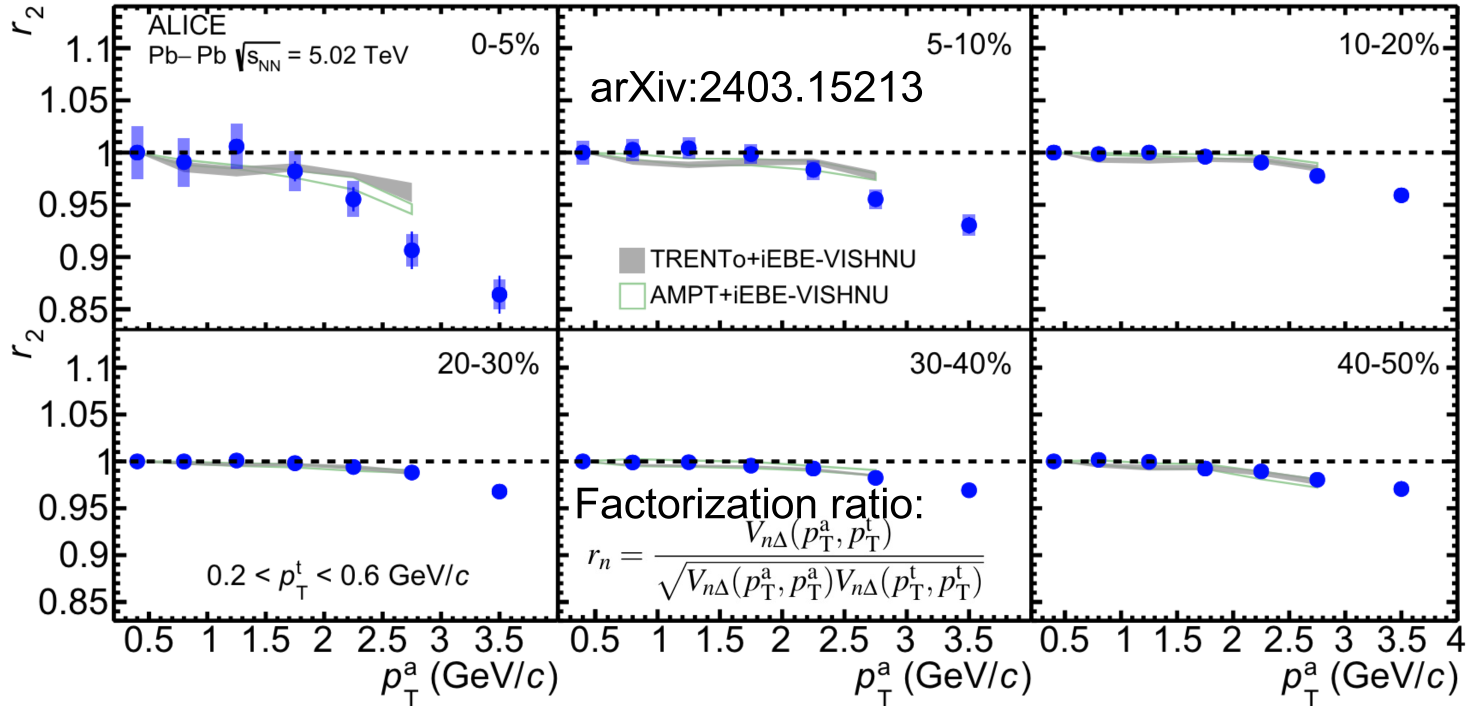

- Take jet direction as the z-axis and redefine kinematics
- Clear near side peak at long range observed in high $N_{ch}$
- $v_2$ shows a distinct increase for $N_{ch}$ >=80, not reproduced in models

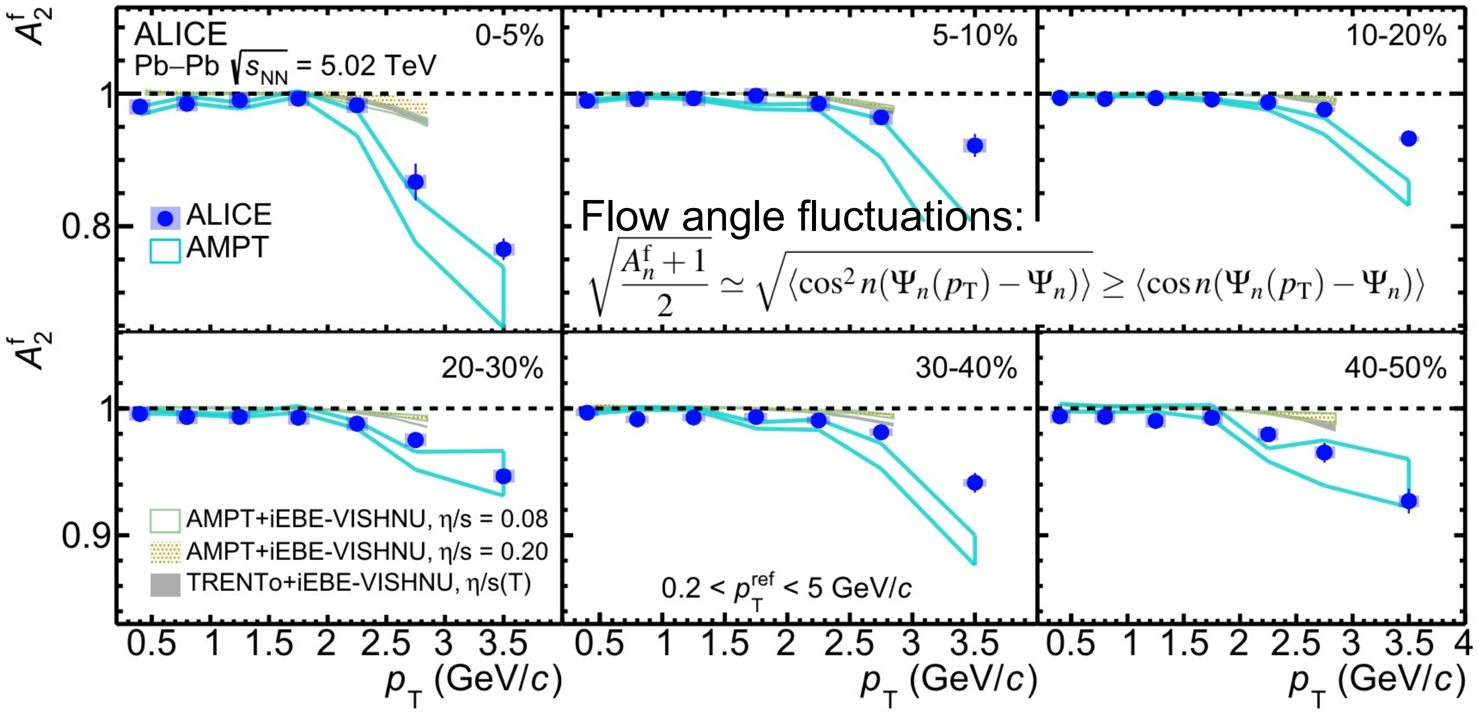
# Flow decorrelations (ALICE)

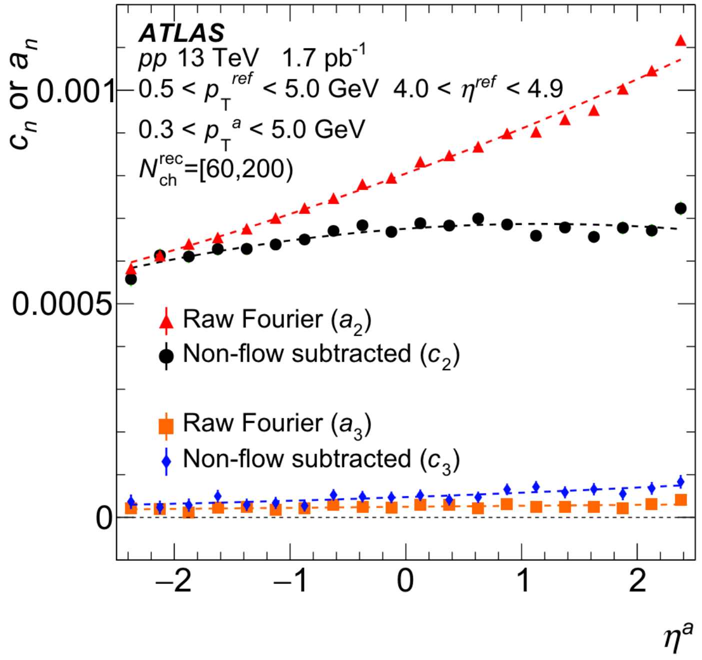



- Models can only reproduce trends for some of the decorrelation results

# Flow decorrelations (ALICE and ATLAS)



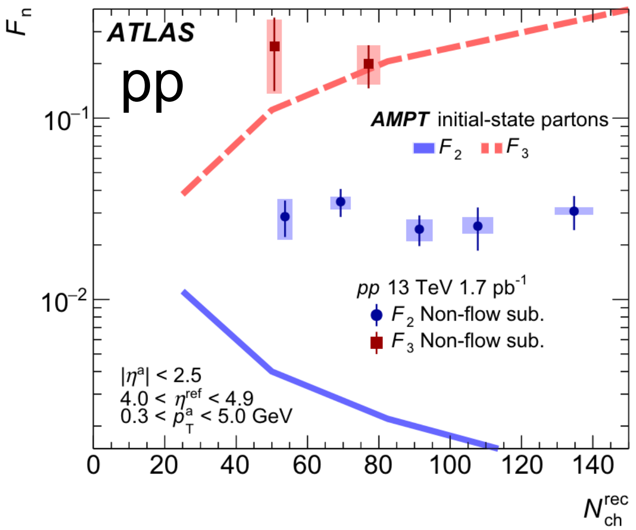



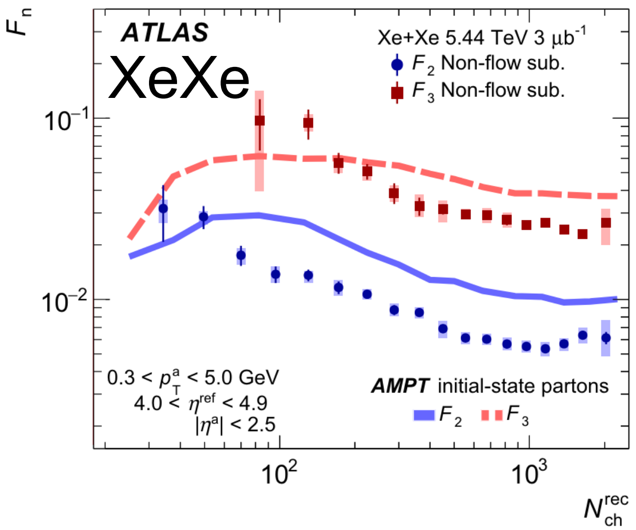

arXiv:2308.16745

Coefficients $c_n$ is fitted to:

$$A_n\left(1 + F_n \cdot \eta^a + S_n \cdot (\eta^a)^2\right)$$

Linear decorrelation strength




- Models can only reproduce trends for some of the decorrelation results

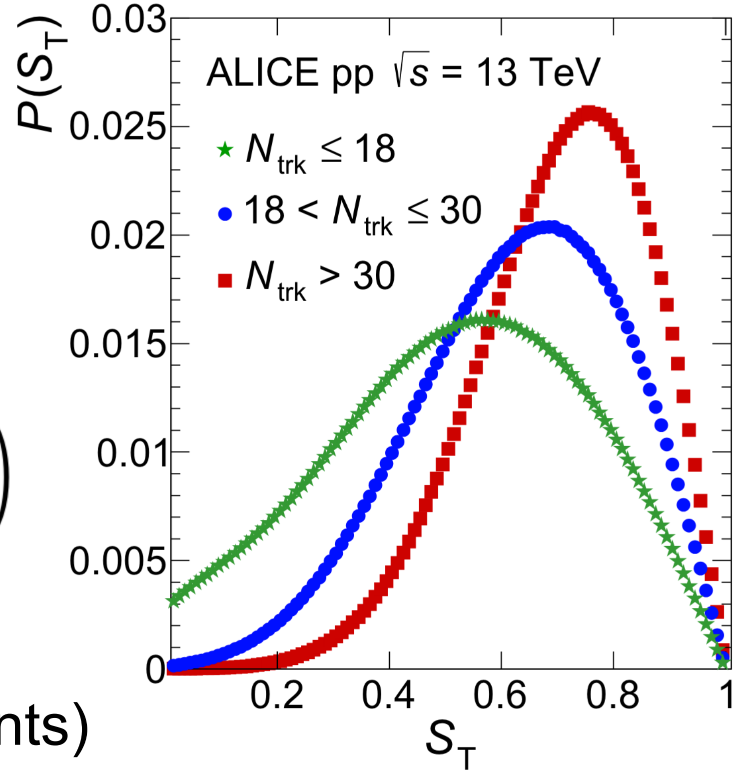
# Bose-Einstein correlations (ALICE)

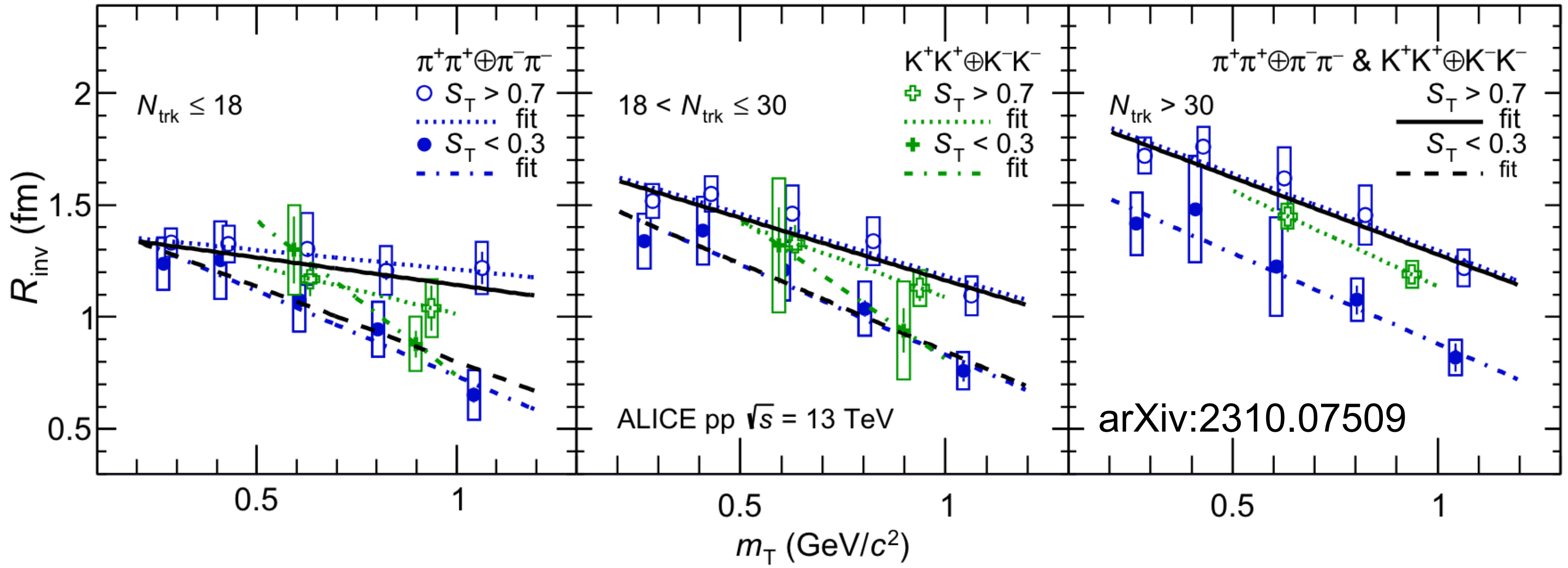
$$S_T = \frac{2\min(\lambda_1, \lambda_2)}{\lambda_1 + \lambda_2}$$

$\lambda_1$ and $\lambda_2$ are the eigenvalues of the matrix of $p_T$

$$S_T = \frac{1}{\sum_i p_T^i} \sum_i \frac{1}{p_T^i} \begin{pmatrix} (p_x^i)^2 & p_x^i p_y^i \\ p_x^i p_y^i & (p_y^i)^2 \end{pmatrix}$$

- $S_T$ -> 0: jetty limit (hard events)
- $S_T$ -> 1: spherical limit (soft events)




- Spherical events have larger emitting source
- $R_{inv}$ decreases as $m_T$ increases

# Bose-Einstein correlations (ALICE and LHCb)

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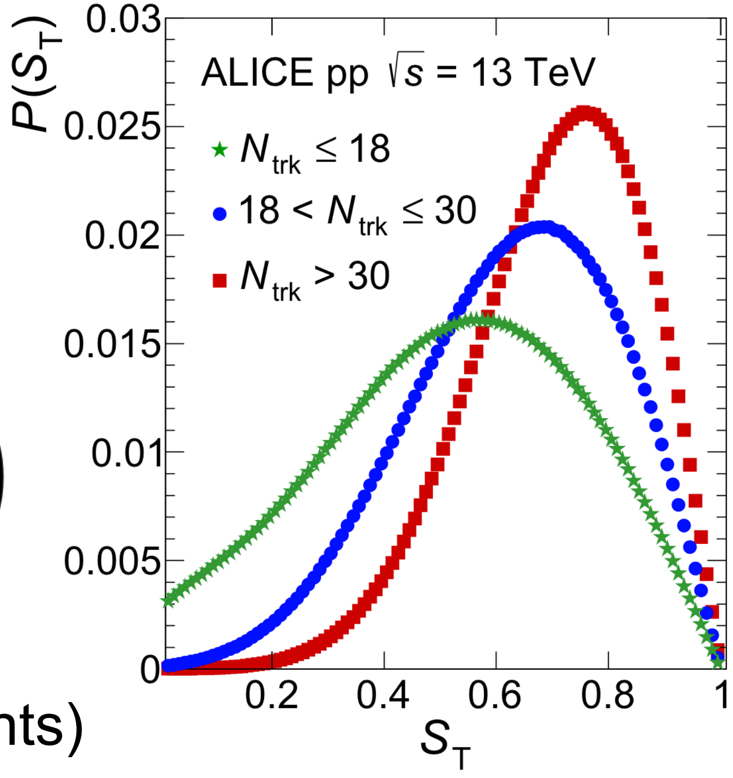
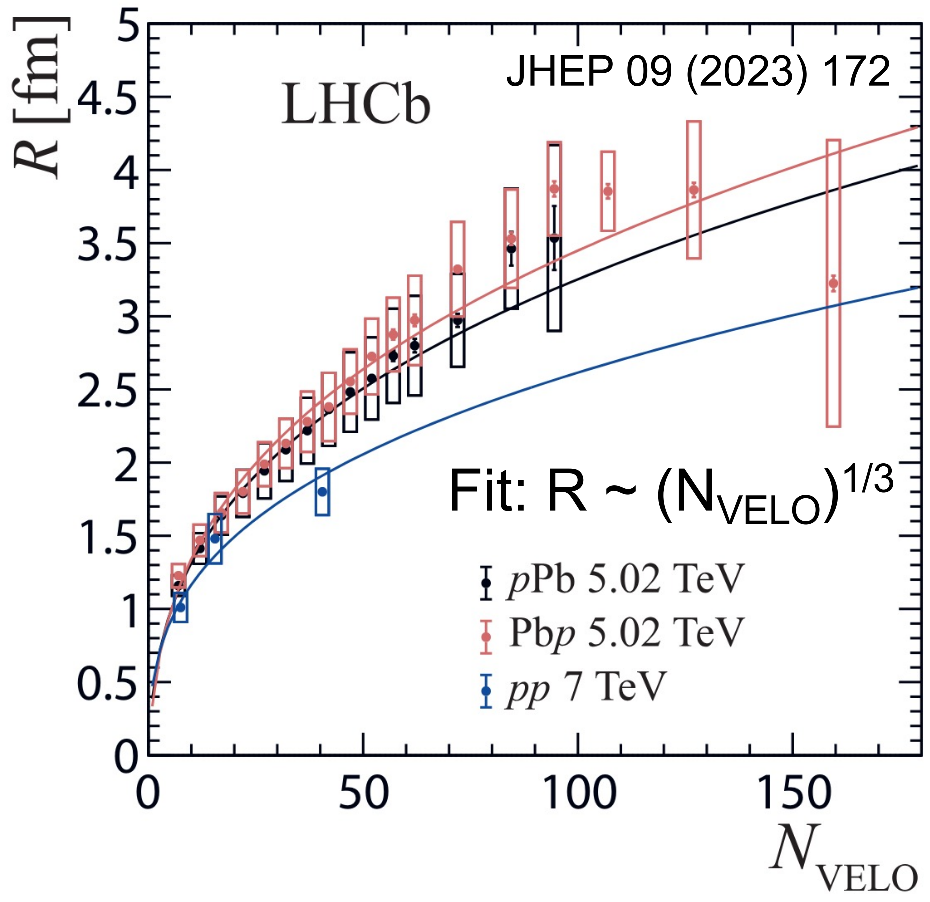
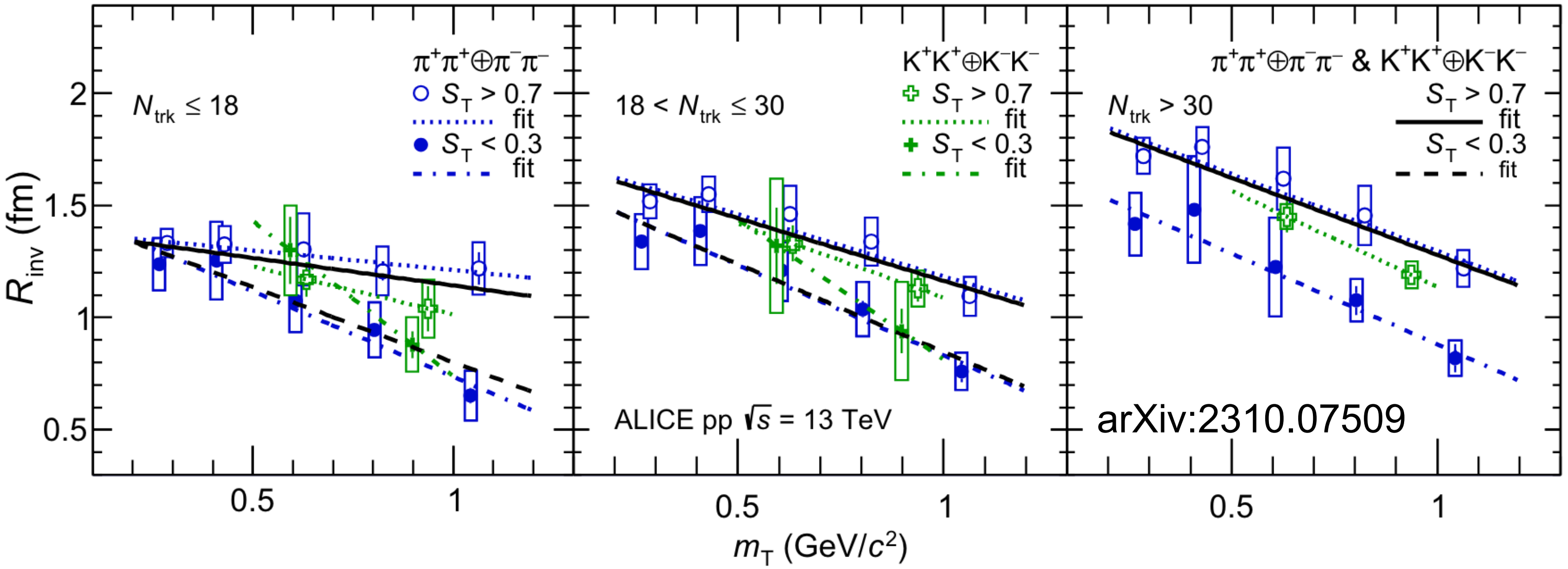
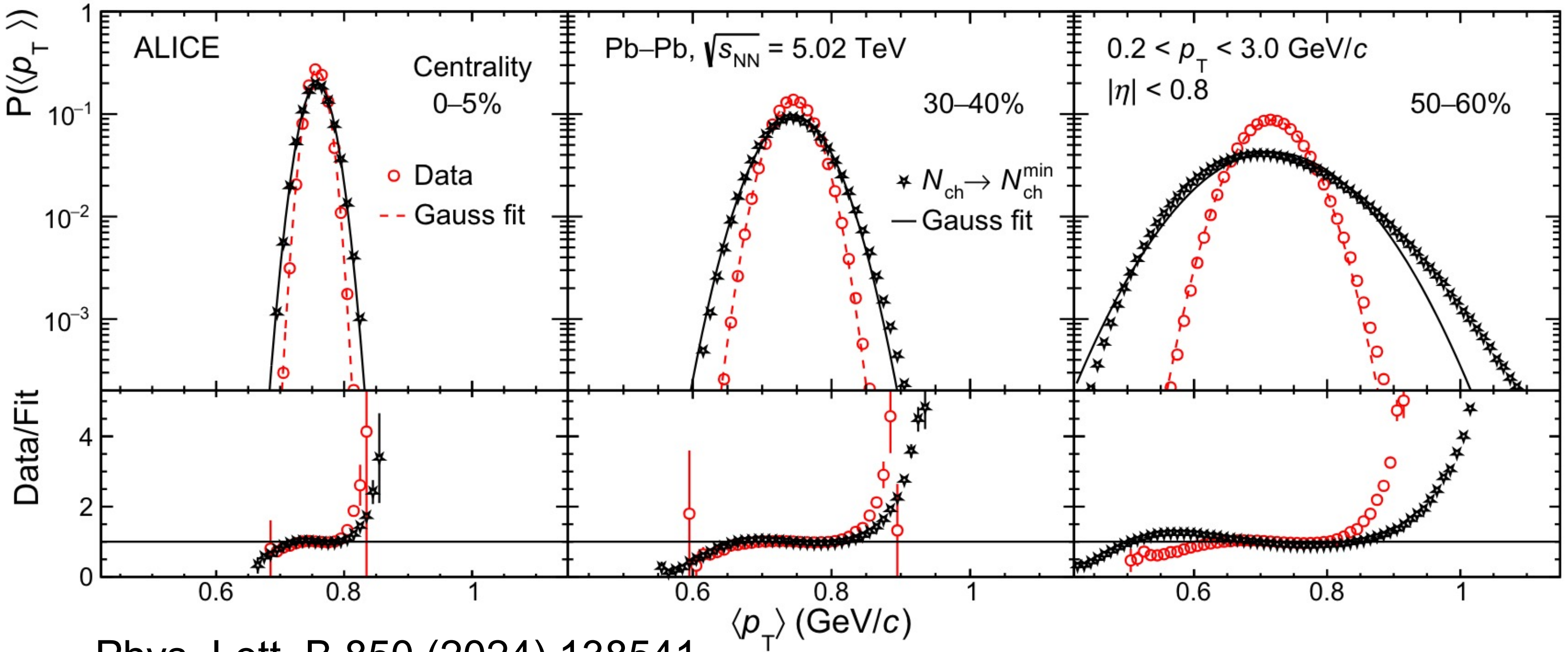


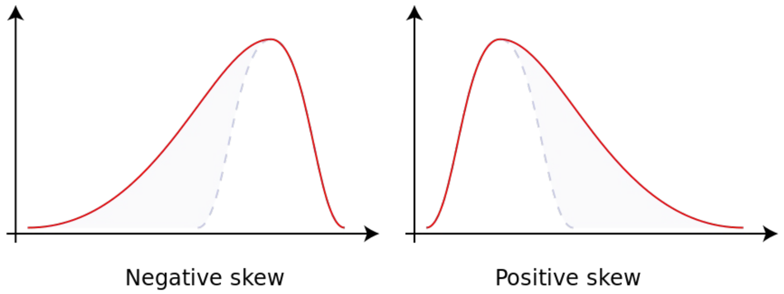



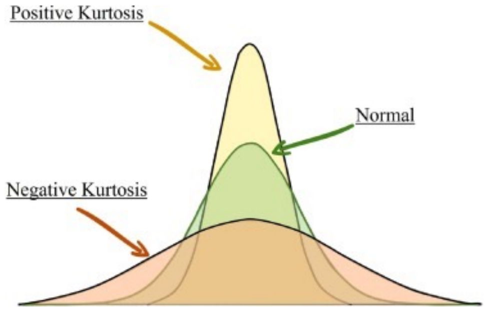

- Spherical events have larger emitting source
- $R_{inv}$ decreases as $m_T$ increases
- Scaling of R with cube root of $N_{VELO}$
  - Agree with hydrodynamic predictions

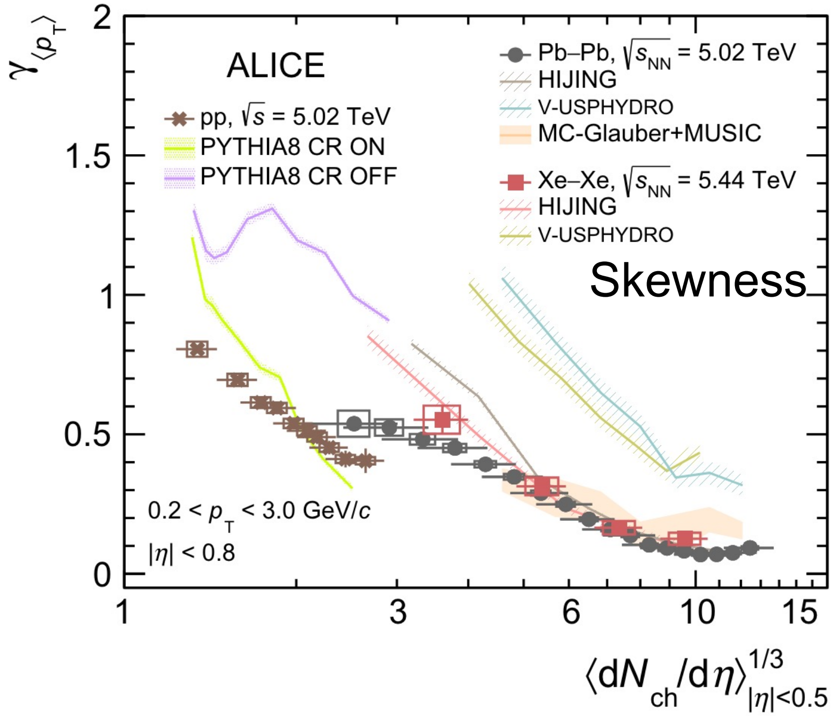
# $\langle p_T \rangle$ fluctuations (ALICE)

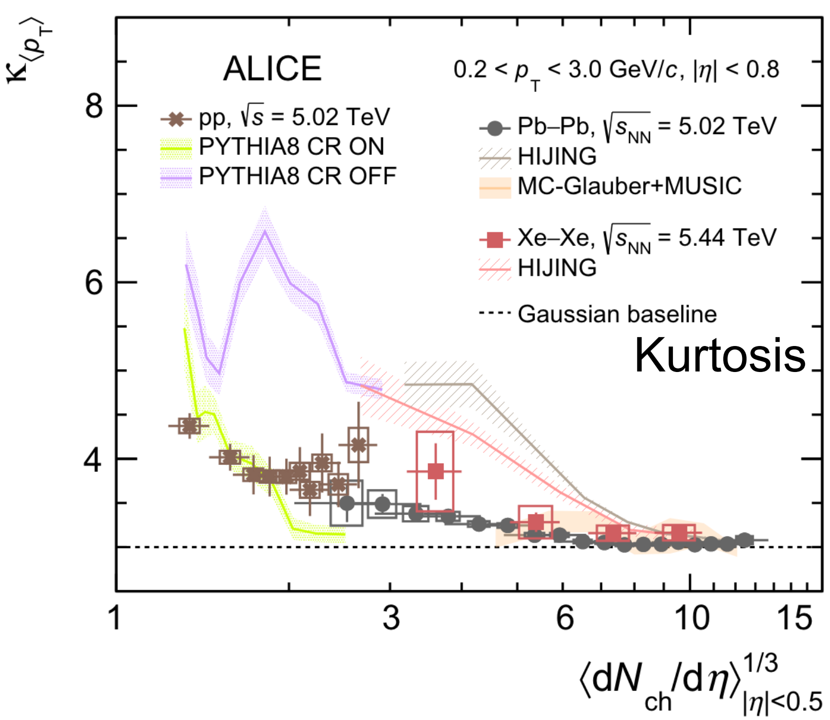



Phys. Lett. B 850 (2024) 138541



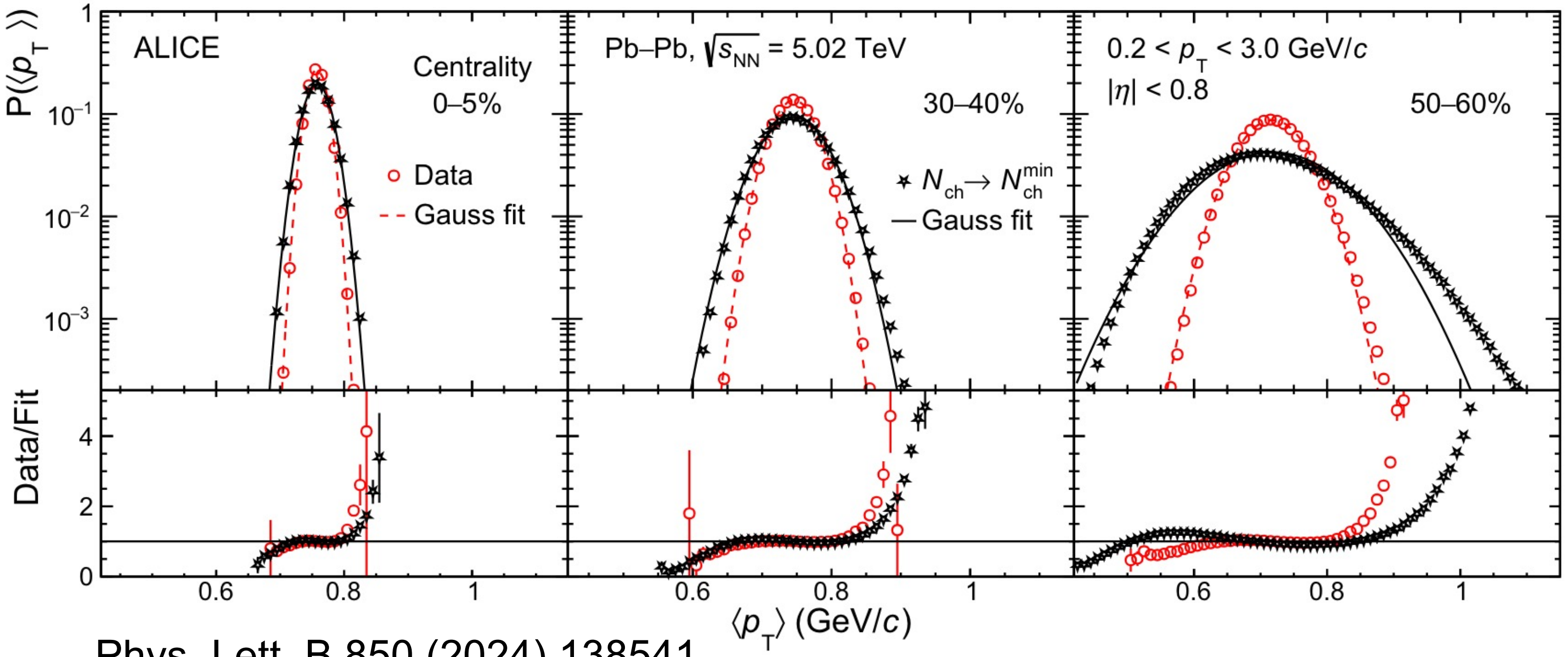




- Positive skewness and Kurtosis, both decrease as $dN_{ch}/d\eta$ increases

# $\langle p_T \rangle$ fluctuations (ALICE and ATLAS)

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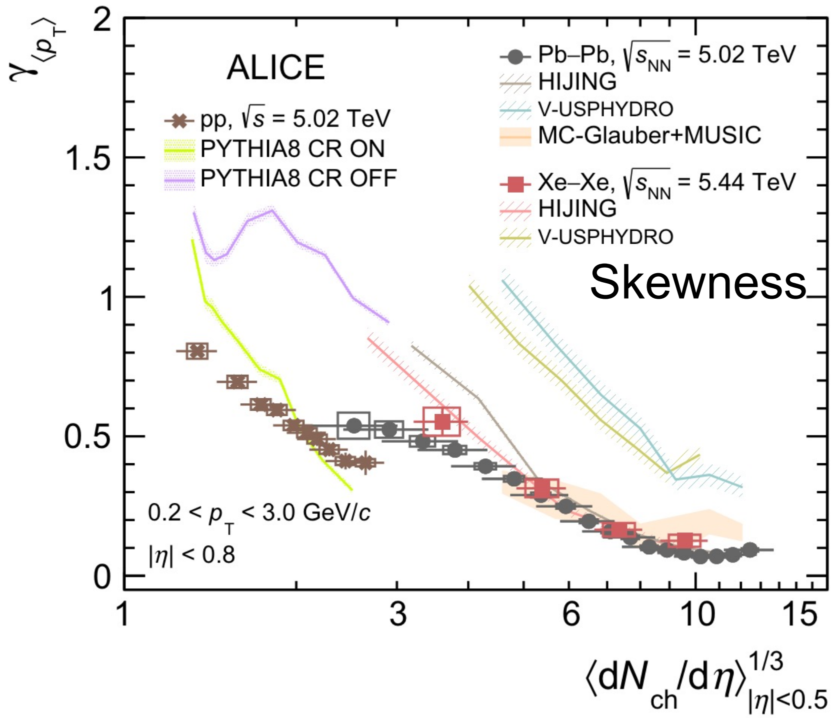
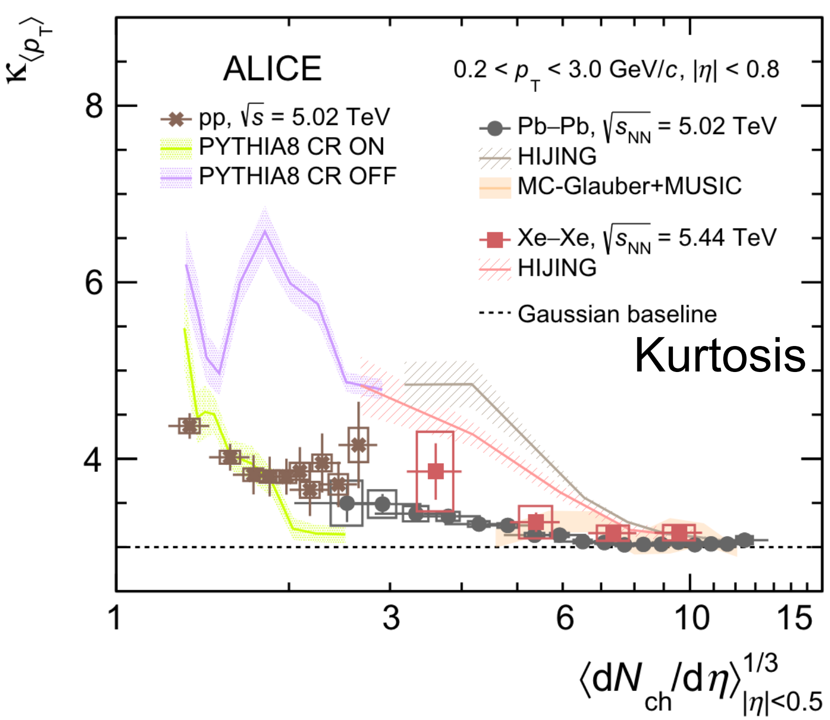
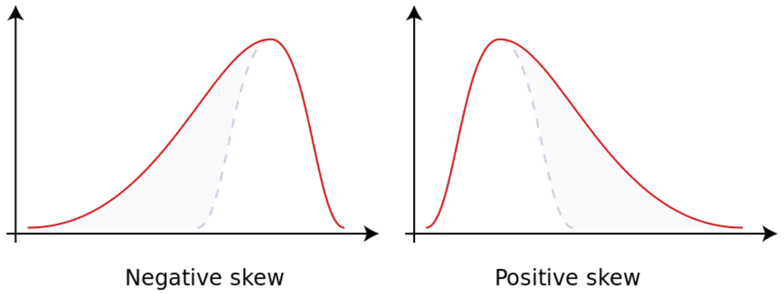
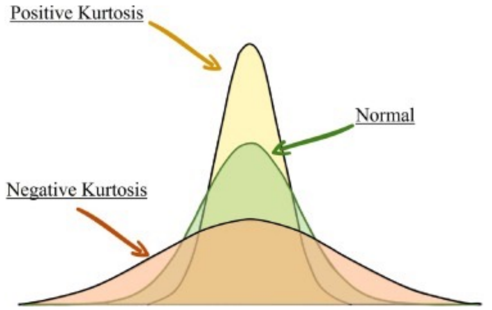
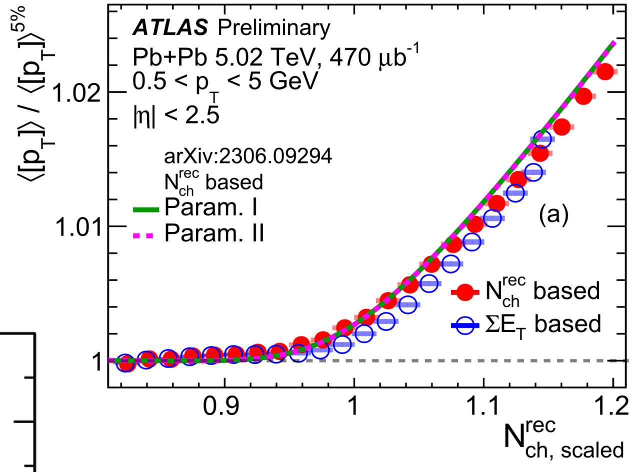


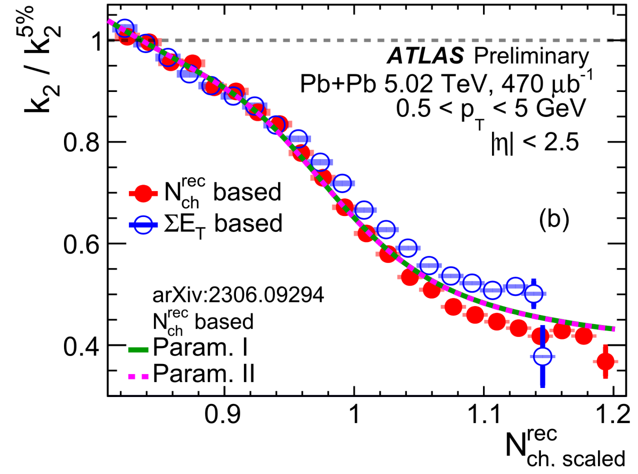



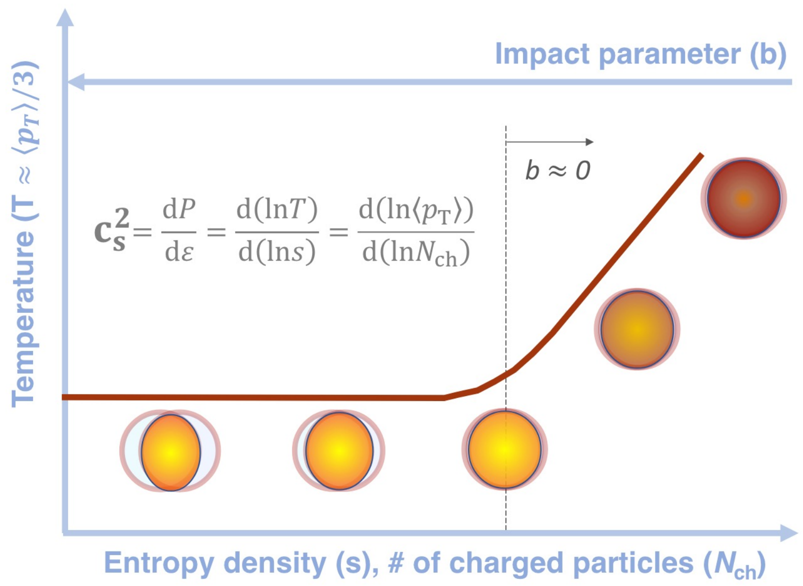

ATLAS-CONF-2023-061

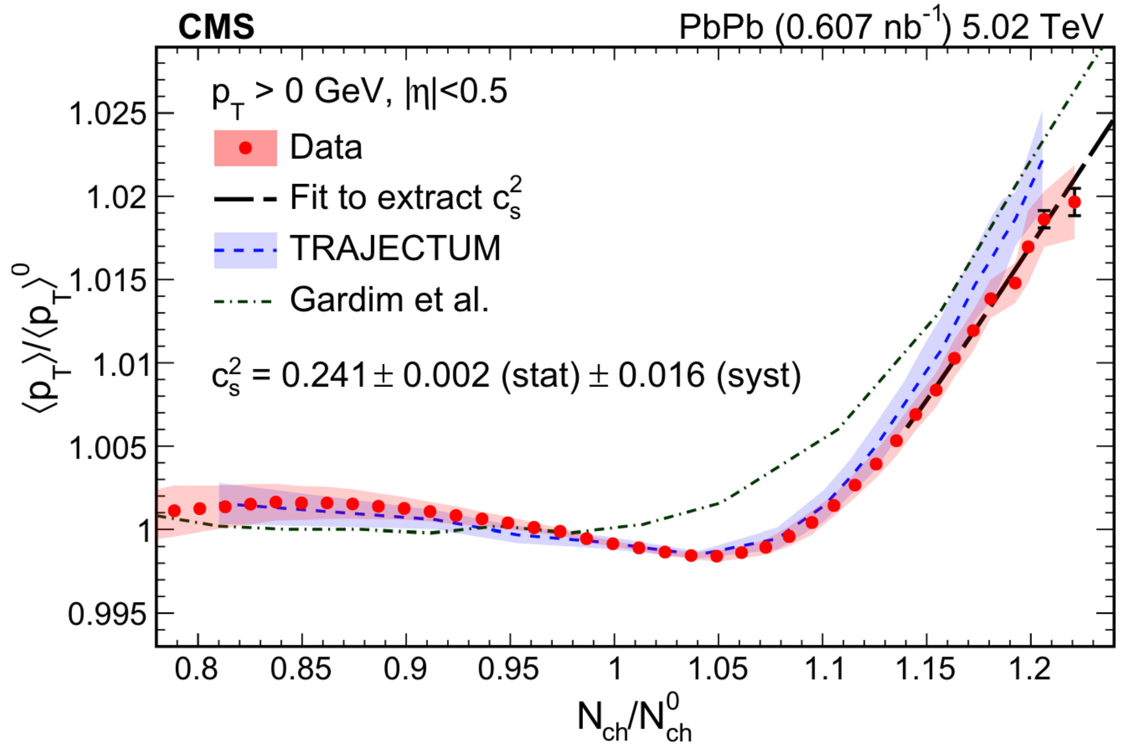



- Positive skewness and Kurtosis, both decrease as $dN_{ch}/d\eta$ increases
- Hydrodynamic models reproduce the results in central and mid-central collisions

# <$p_T$> in ultra-central collisions and speed of sound (CMS)

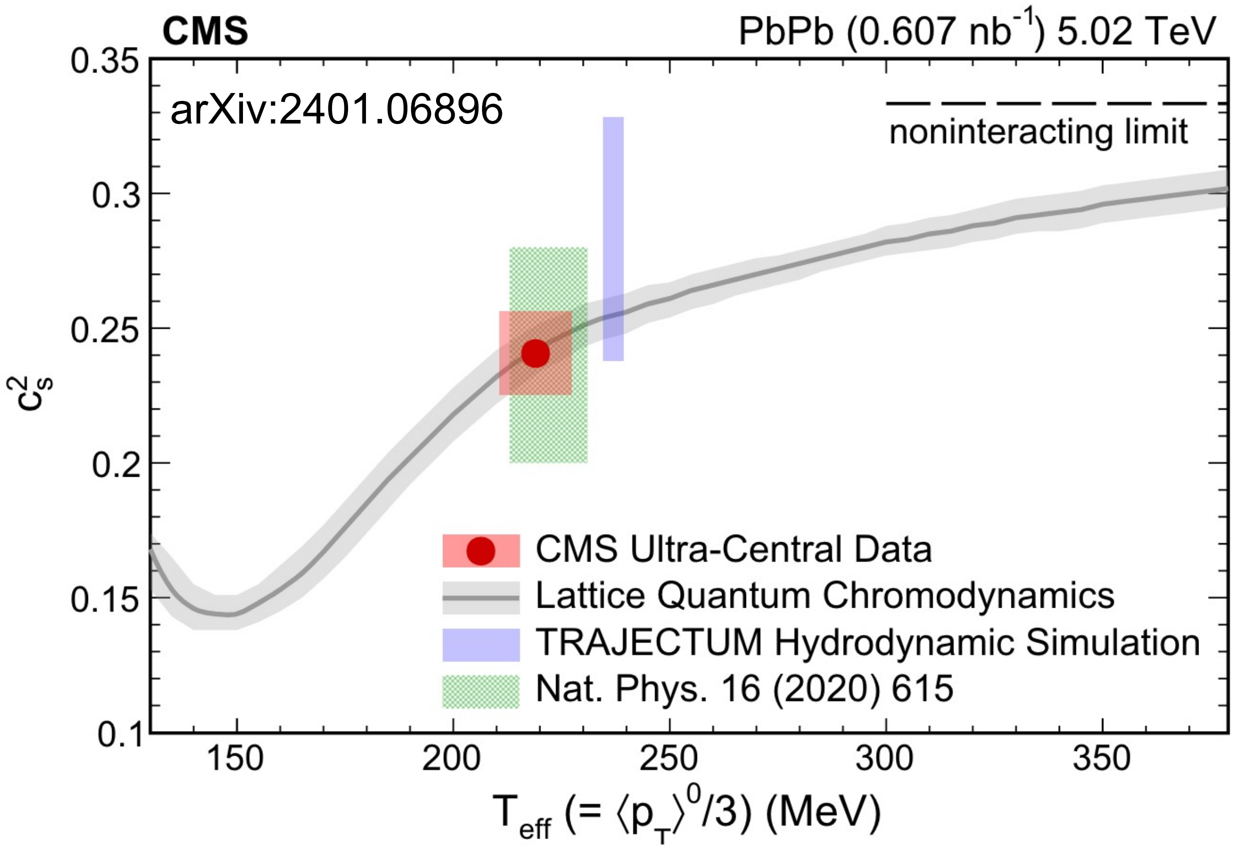



Extracting $c_s^2$ with:

$$\frac{<p_T>}{<p_T>^0} \sim \left(\frac{N_{ch}}{N_{ch}^0}\right)^{c_s^2}$$

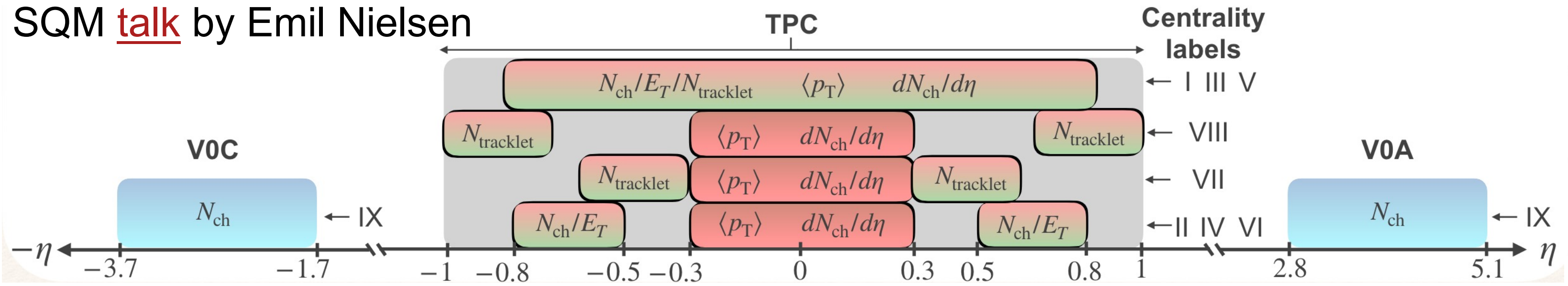
$N_{ch}^0$ and $< p_T >^0$ from 0-5% centrality



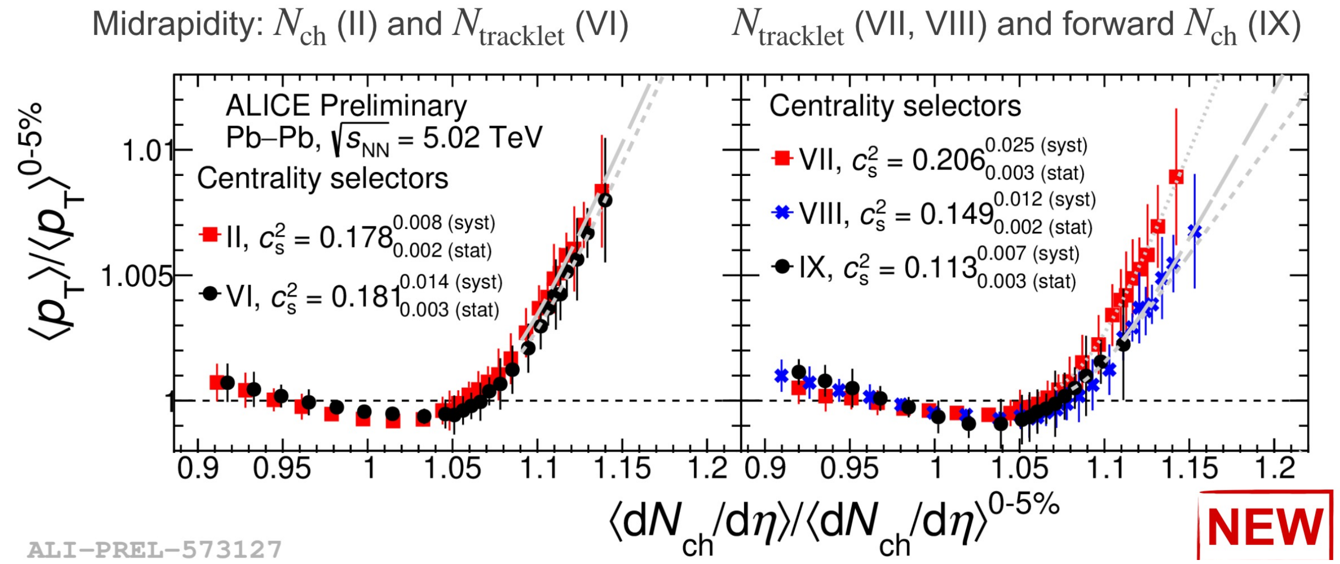

- Sound modes arising from longitudinal compression wave propagating in the fluid medium: $c_s$
  - Directly constrains the equation of state
- A steep rise of <$p_T$> is observed in ultra-central
  - Agree with hydrodynamic model predictions
- $c_s^2$ = 0.241 ± 0.002 (stat) ± 0.016 (syst)
- First time determination of $c_s$ with high precision

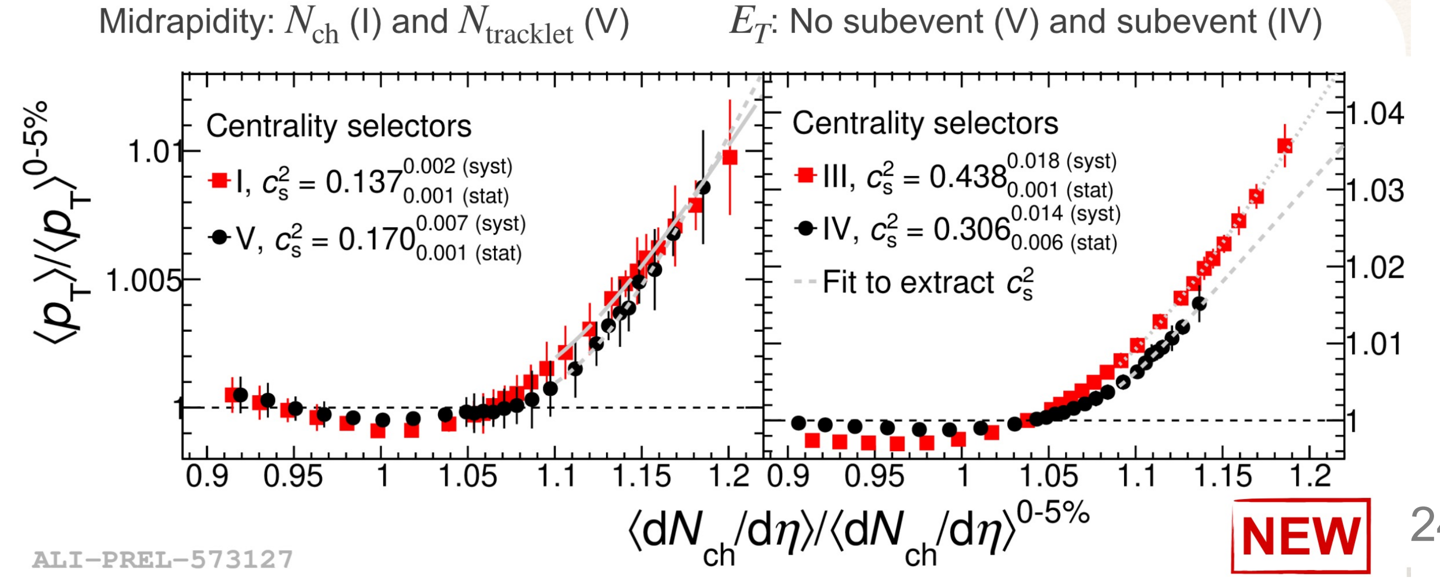
# Extracting speed of sound is more complicated (ALICE)

SQM talk by Emil Nielsen




| Observable | Label | Centrality estimation | $\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$ | $\eta$ gap |
|---|---|---|---|---|
| $N_{ch}$ in TPC | I | $\lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.8$ | 0 |
| | II | $0.5 \leq \lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.3$ | 0.3 |
| $E_T$ in TPC | III | $\lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.8$ | 0 |
| | IV | $0.5 \leq \lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.3$ | 0.3 |
| $N_{tracklets}$ in SPD | V | $\lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.8$ | 0 |
| | VI | $0.5 \leq \lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.3$ | 0.3 |
| | VII | $0.3 < \lvert\eta\rvert \leq 0.6$ | $\lvert\eta\rvert \leq 0.3$ | 0 |
| | VIII | $0.7 \leq \lvert\eta\rvert \leq 1$ | $\lvert\eta\rvert \leq 0.3$ | 0.4 |
| $N_{ch}$ in V0 | IX | $-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$ | $\lvert\eta\rvert \leq 0.8$ | 1.7 |




Extraction of $c_s^2$ depends on the centrality determination

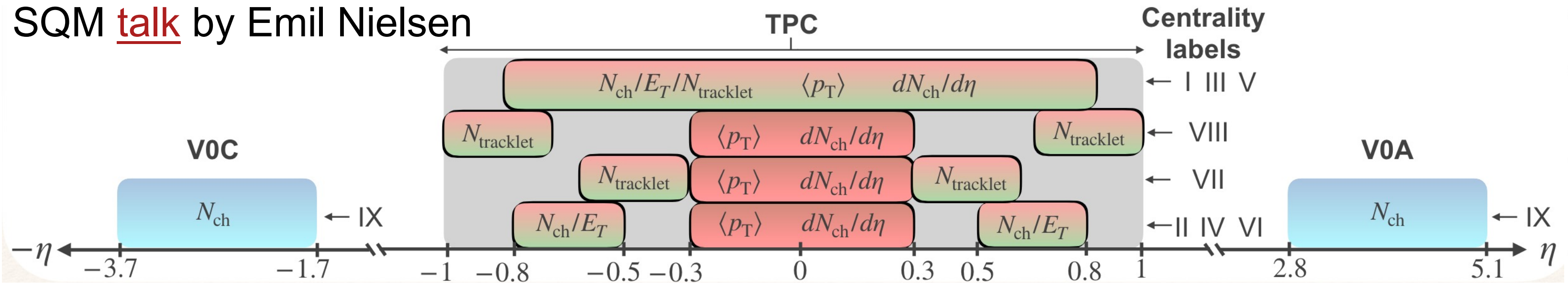
- Forward vs. midrapidity
- ITS tracklets vs full tracks
- $E_T$ vs $N_{ch}$

Decreased $c_s^2$ using forward centrality determination

Increased $c_s^2$ using $E_T$

# Extracting speed of sound is more complicated (ALICE)

SQM talk by Emil Nielsen




| Observable | Label | Centrality estimation | $\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$ | $\eta$ gap |
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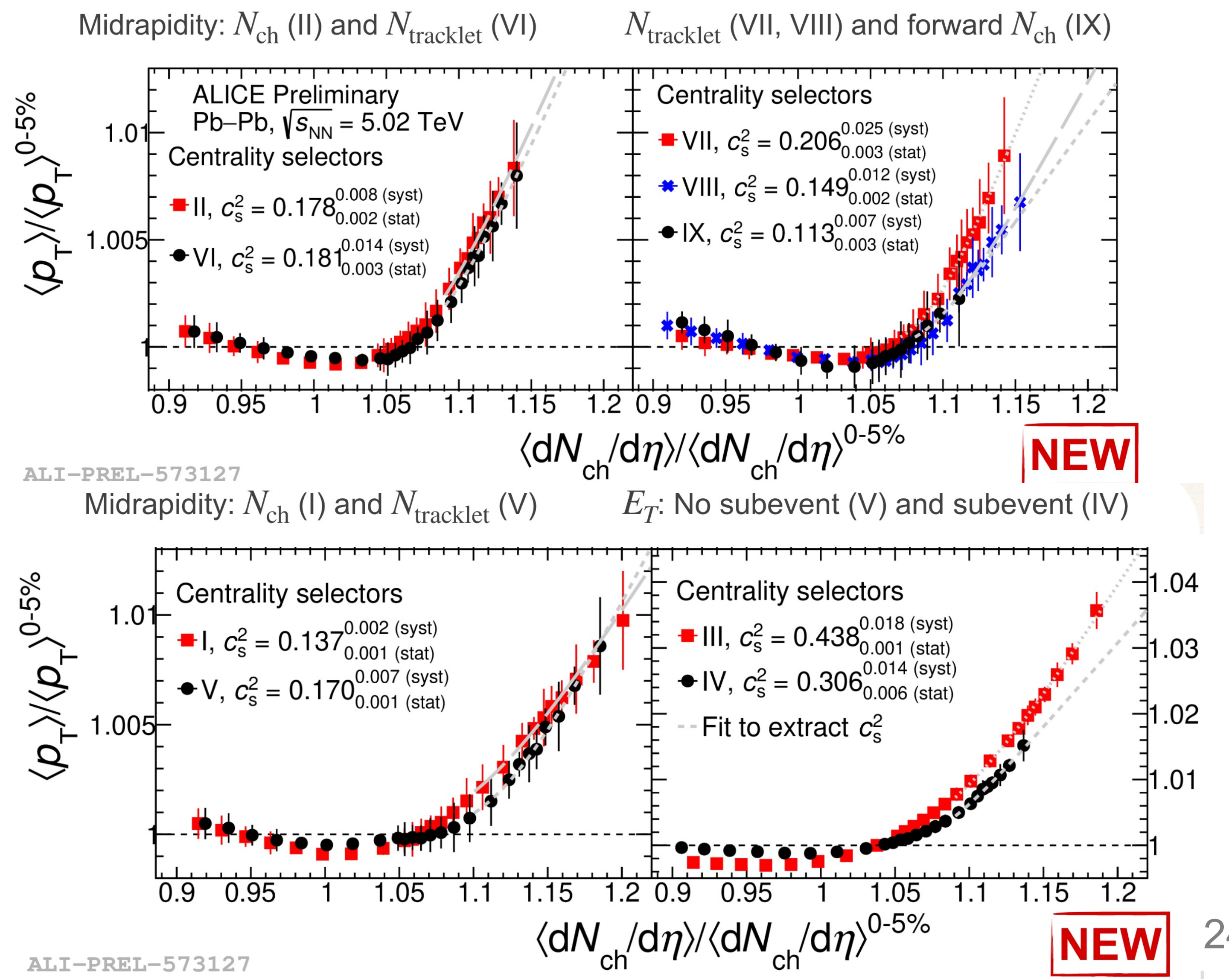
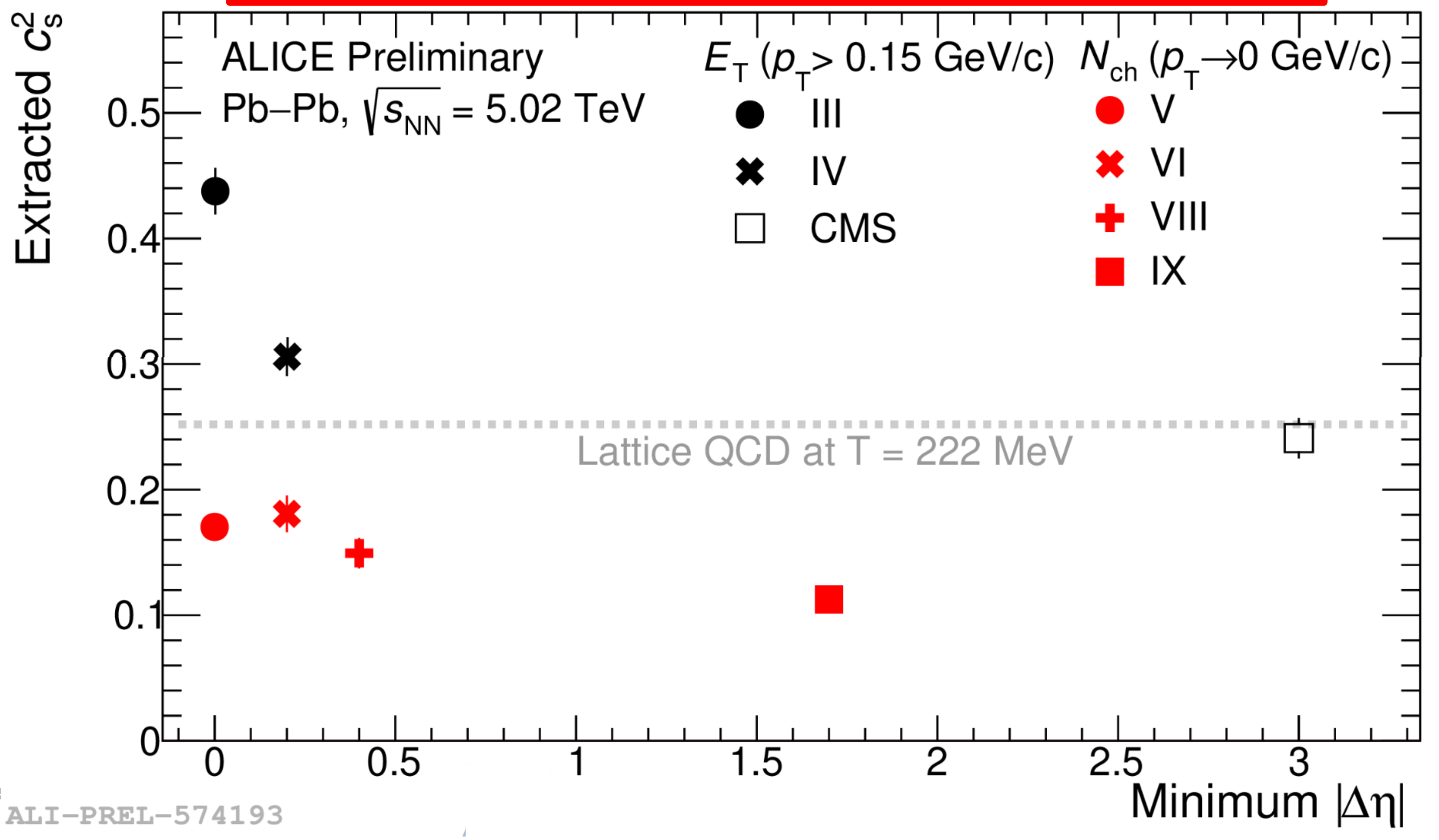
| | VI | $0.5 \leq \lvert\eta\rvert \leq 0.8$ | $\lvert\eta\rvert \leq 0.3$ | 0.3 |
| | VII | $0.3 < \lvert\eta\rvert \leq 0.6$ | $\lvert\eta\rvert \leq 0.3$ | 0 |
| | VIII | $0.7 \leq \lvert\eta\rvert \leq 1$ | $\lvert\eta\rvert \leq 0.3$ | 0.4 |
| $N_{ch}$ in V0 | IX | $-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$ | $\lvert\eta\rvert \leq 0.8$ | 1.7 |

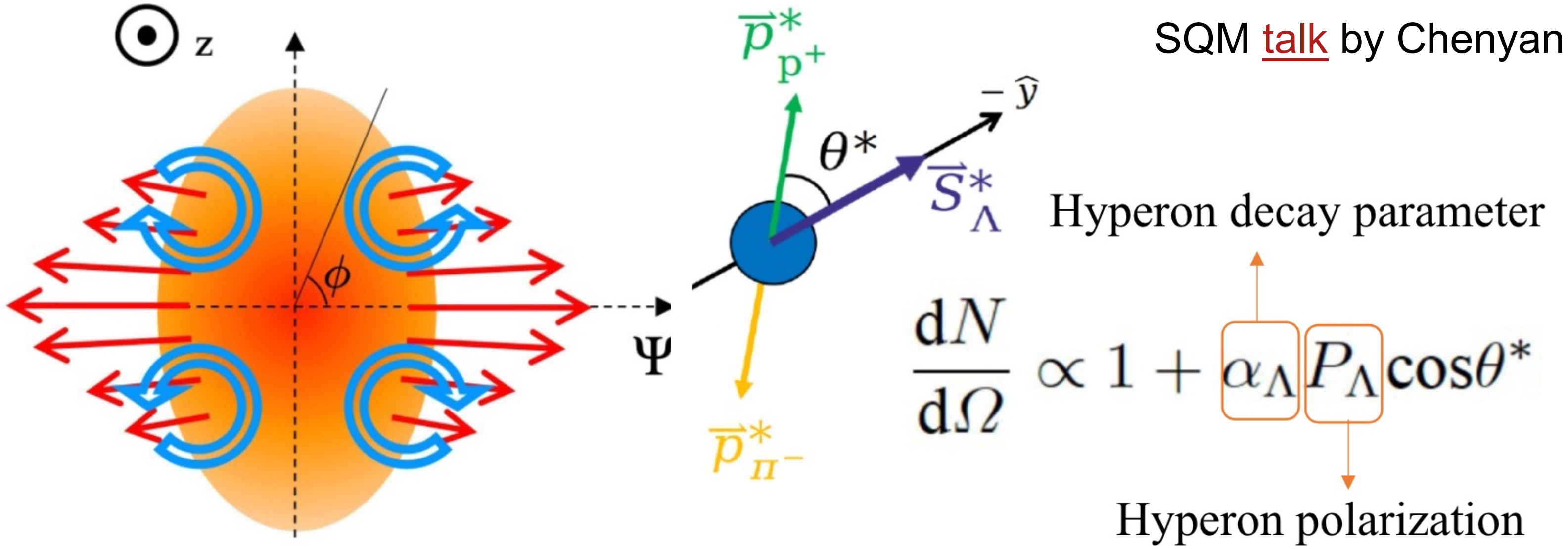



**Speed of sound vs. η gap; Robust?**



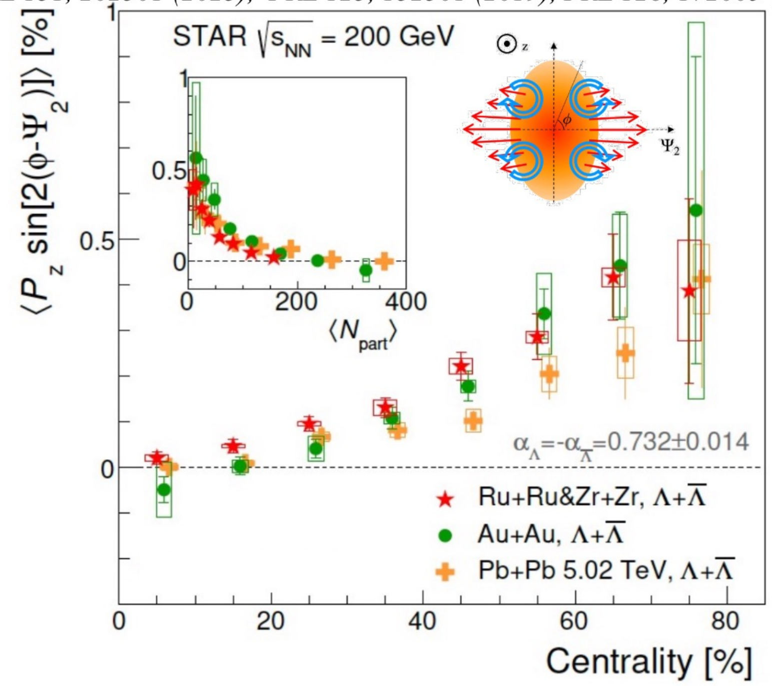
# Λ polarization in pPb (CMS)

SQM talk by Chenyan Li

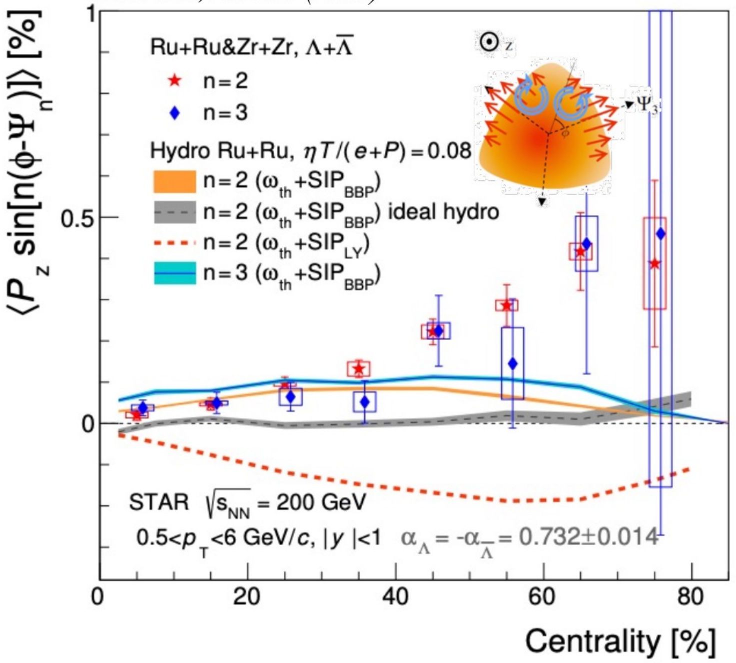


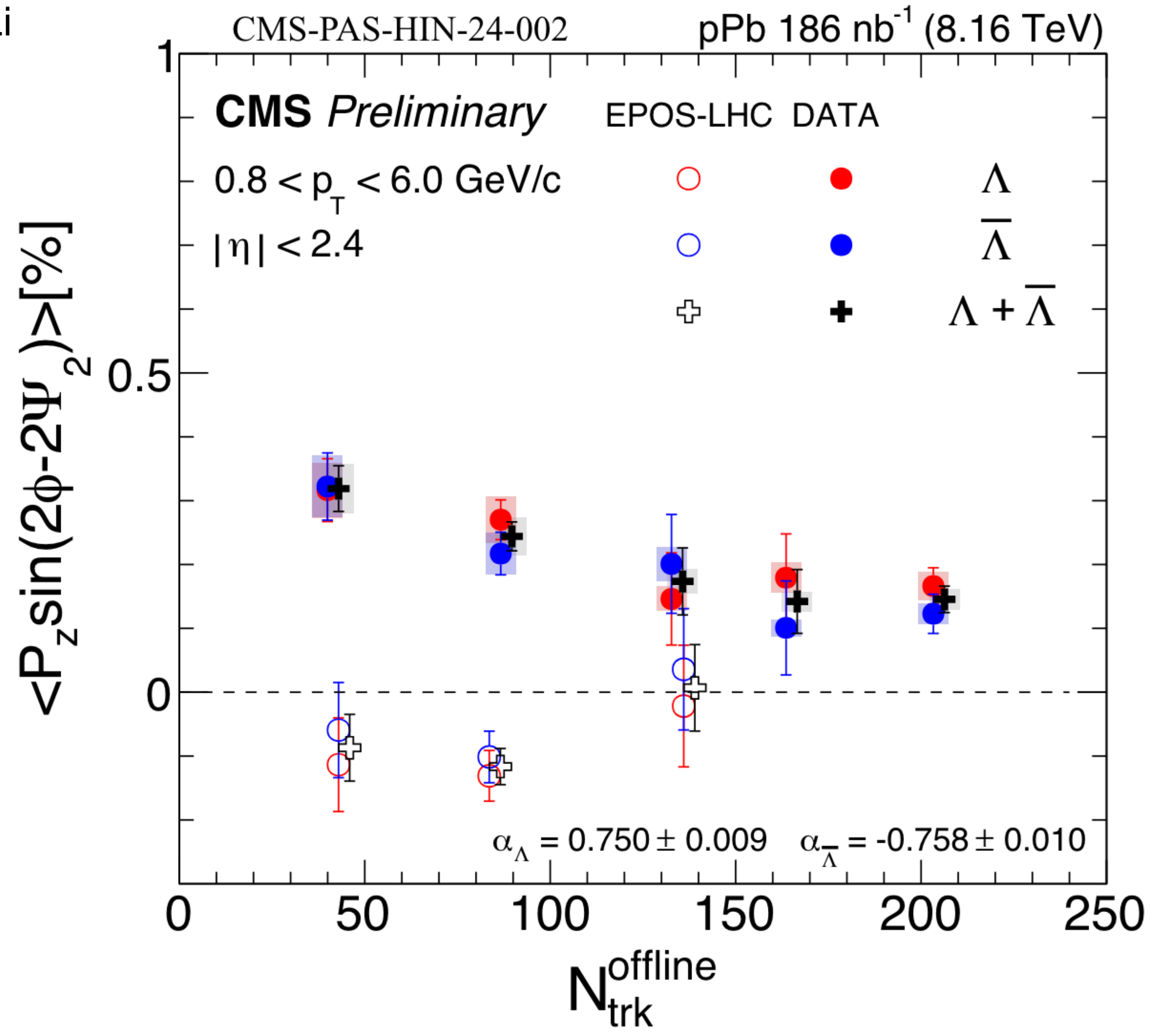

**Flow -> Vorticity -> Spin-orbit coupling -> polarization**

*PRL 131, 202301 (2023), PRL 123, 132301 (2019), PRL 128, 172005 (2022)*




*PRL 131, 202301 (2023)*




- The results might indicate complex vorticity structures in pPb collisions

# Summary

- Rich results from flow and correlations at LHC
  - Flow extended to forward region, including in pPb
  - Ridge yield and PID $v_2$ extracted at low multiplicity in pp and pPb
  - Relation between flow and jets studied in detail in small systems
  - New flow decorrelations for understanding longitudinal dynamics
  - Bose-Einstein correlations with event shape engineering
  - Power hiding behind $\langle p_T \rangle$ is ~~revealed~~ being revealed: speed of sound in QGP
  - $\Lambda$ polarization observed in pPb
- Work on Run3 data is ongoing

Full list of results at LHC:

ALICE ATLAS CMS LHCb