Methodological Challenges and New Observables in Differential Flow Measurements in Small Systems

Rohit Kumar Singh

Indian Institute of Technology, Madras

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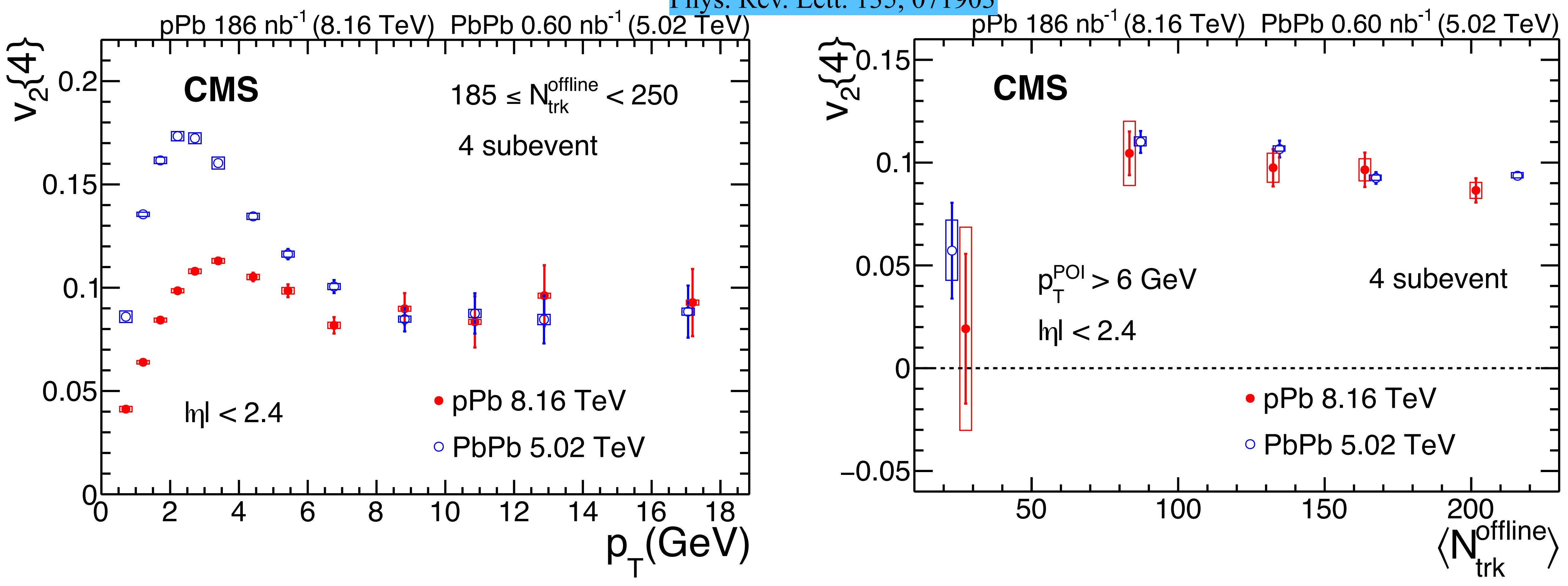
Part 1: Differential anisotropic flow

Differential flow in small systems

Significant v_2 at high p_T in pPb

Phys. Rev. Lett. 135, 071903



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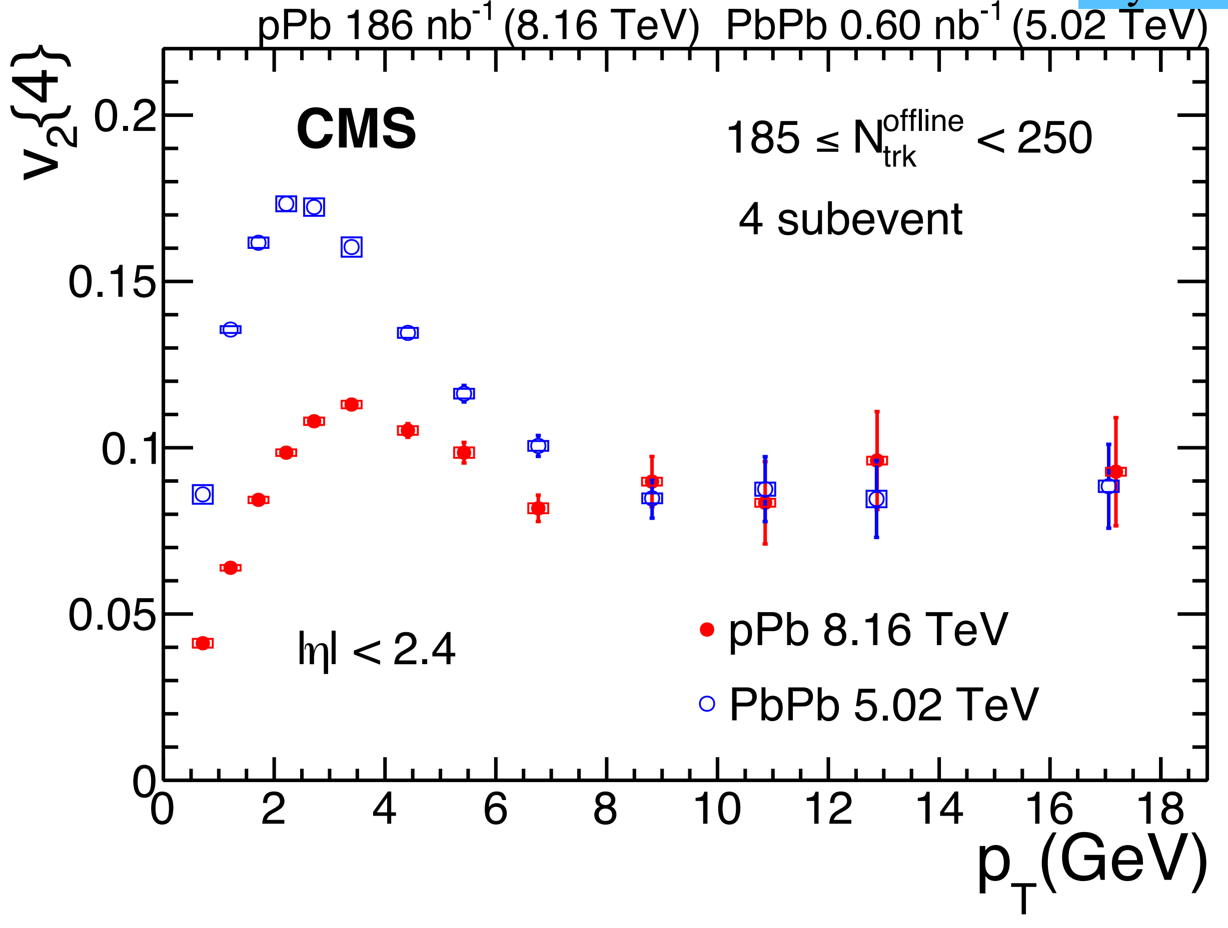
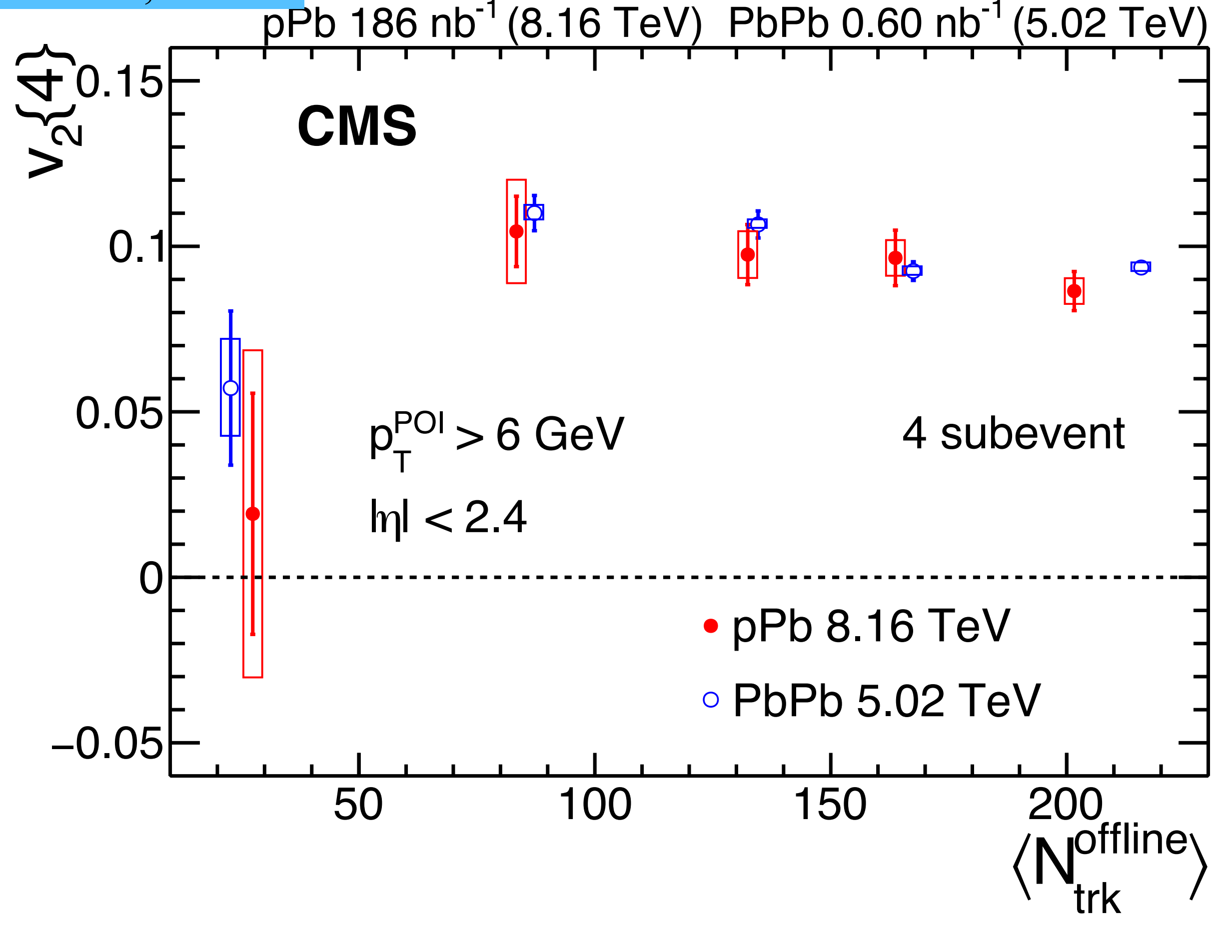
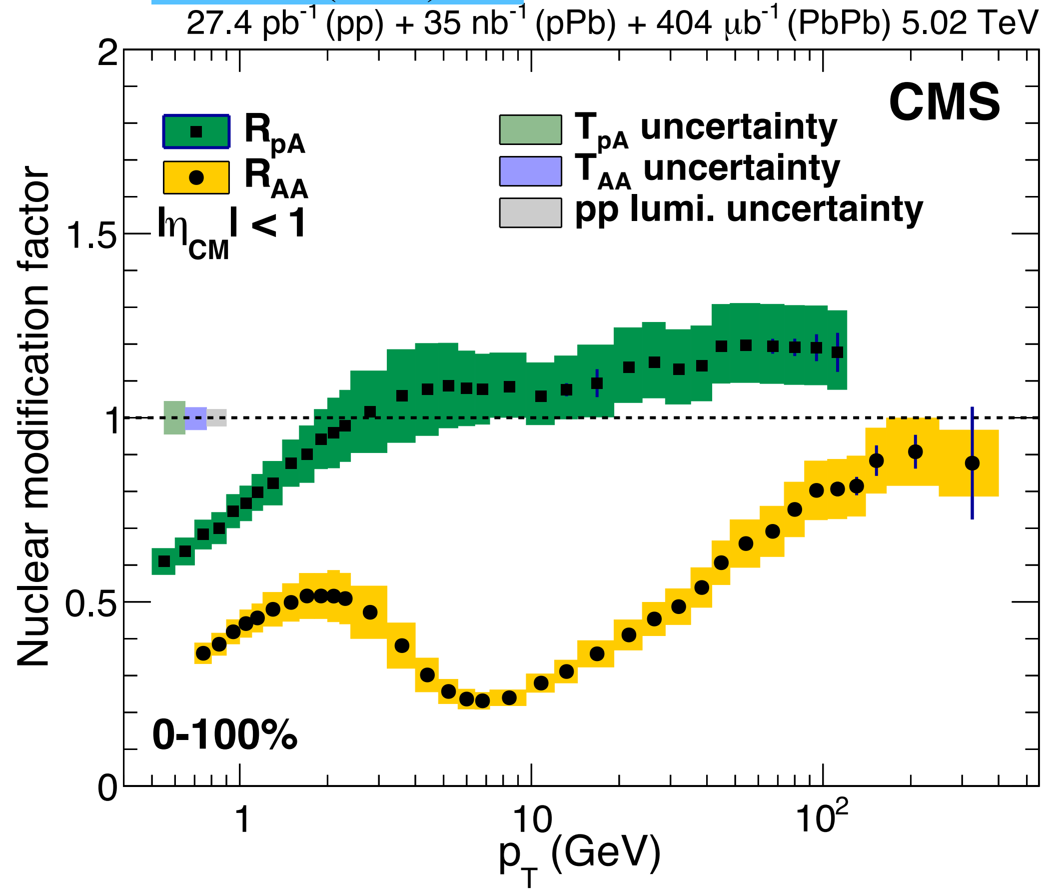


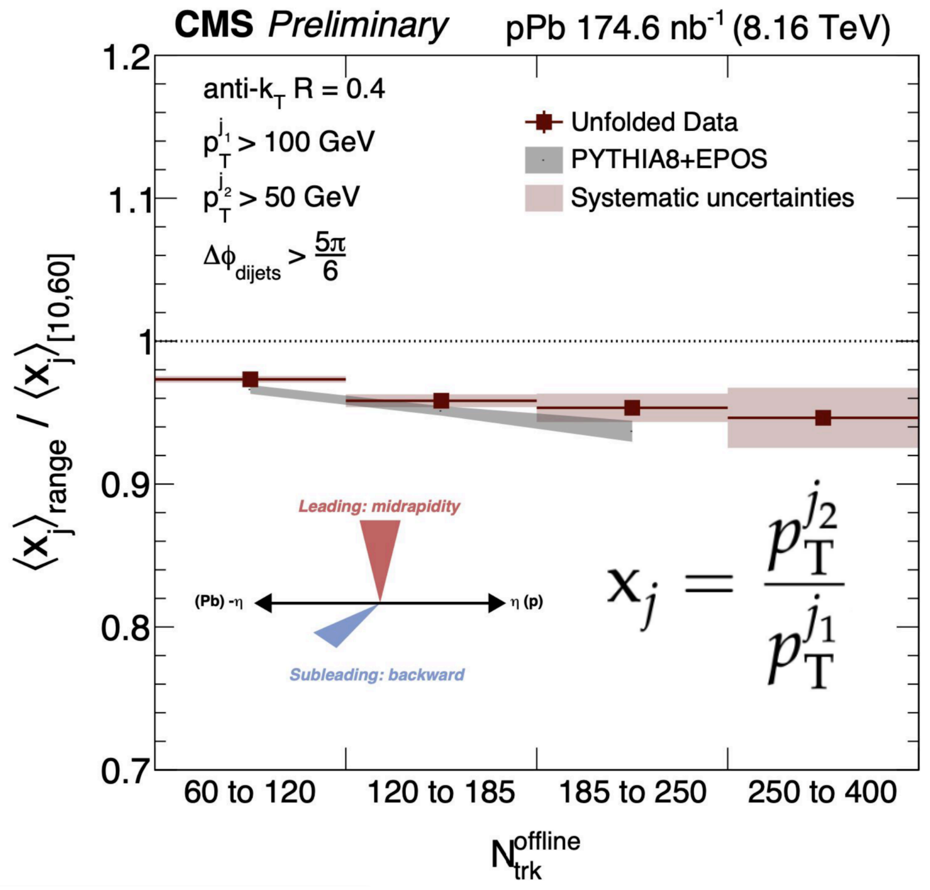


No jet quenching in pPb

JHEP 04 (2017) 039



JHEP 07 (2025) 118



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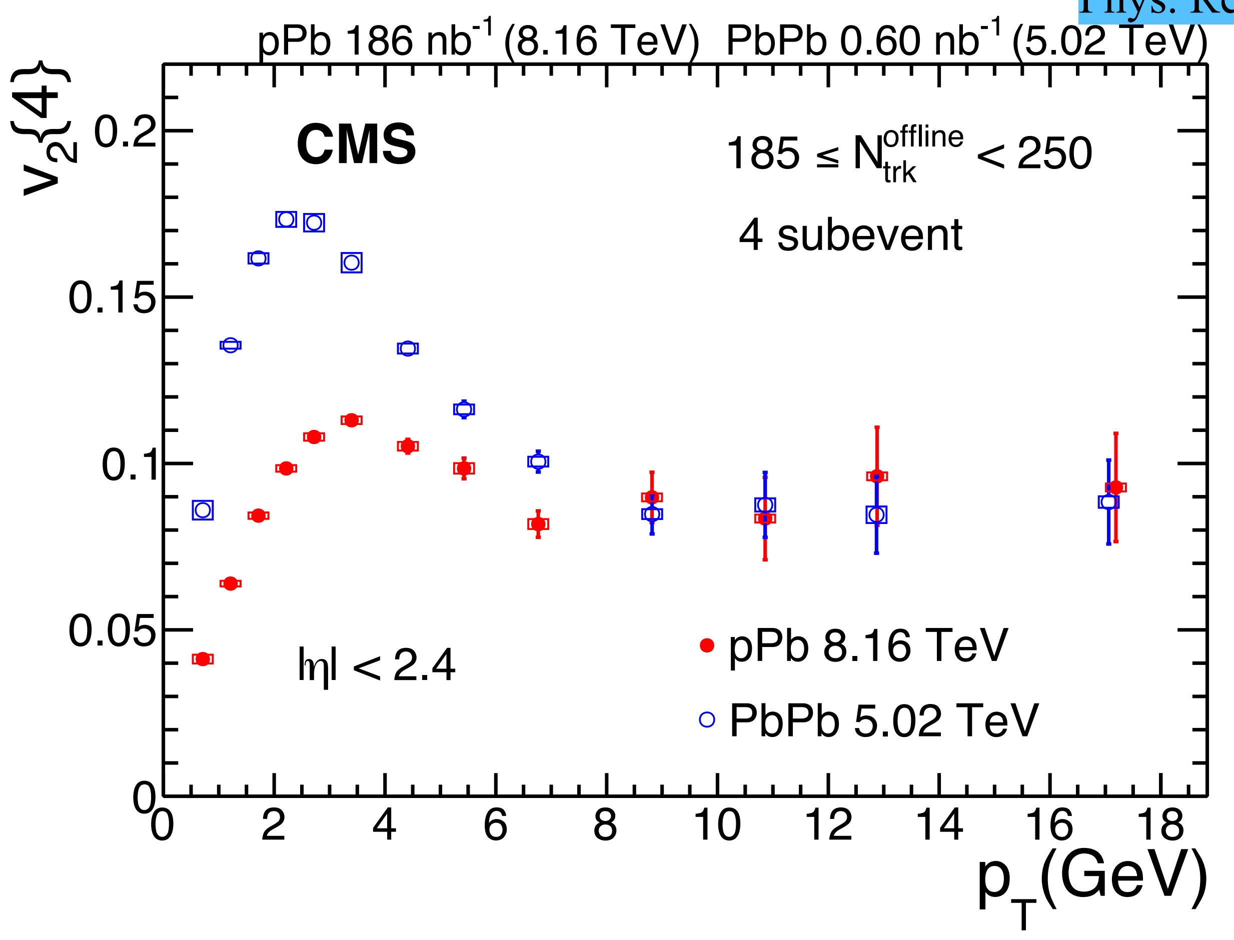

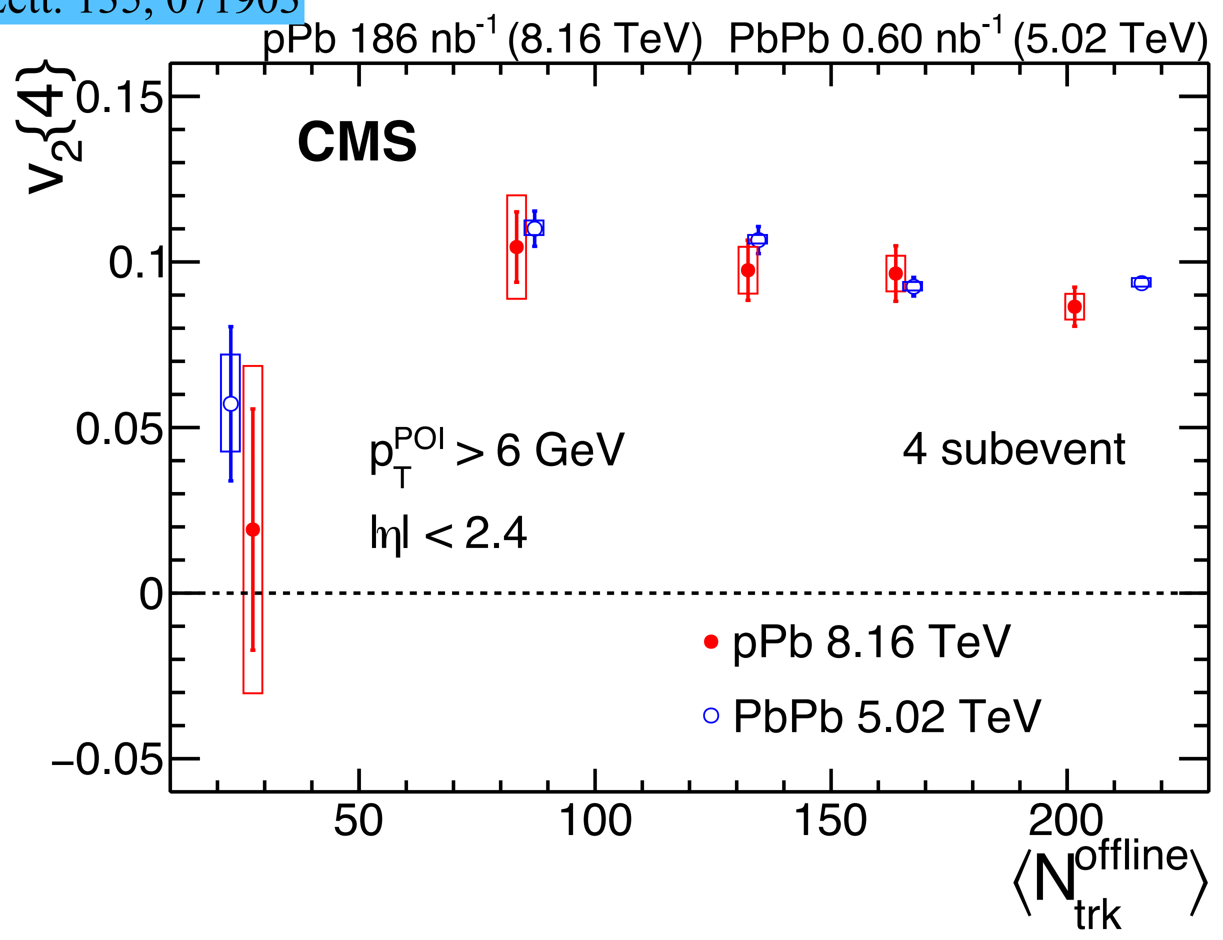

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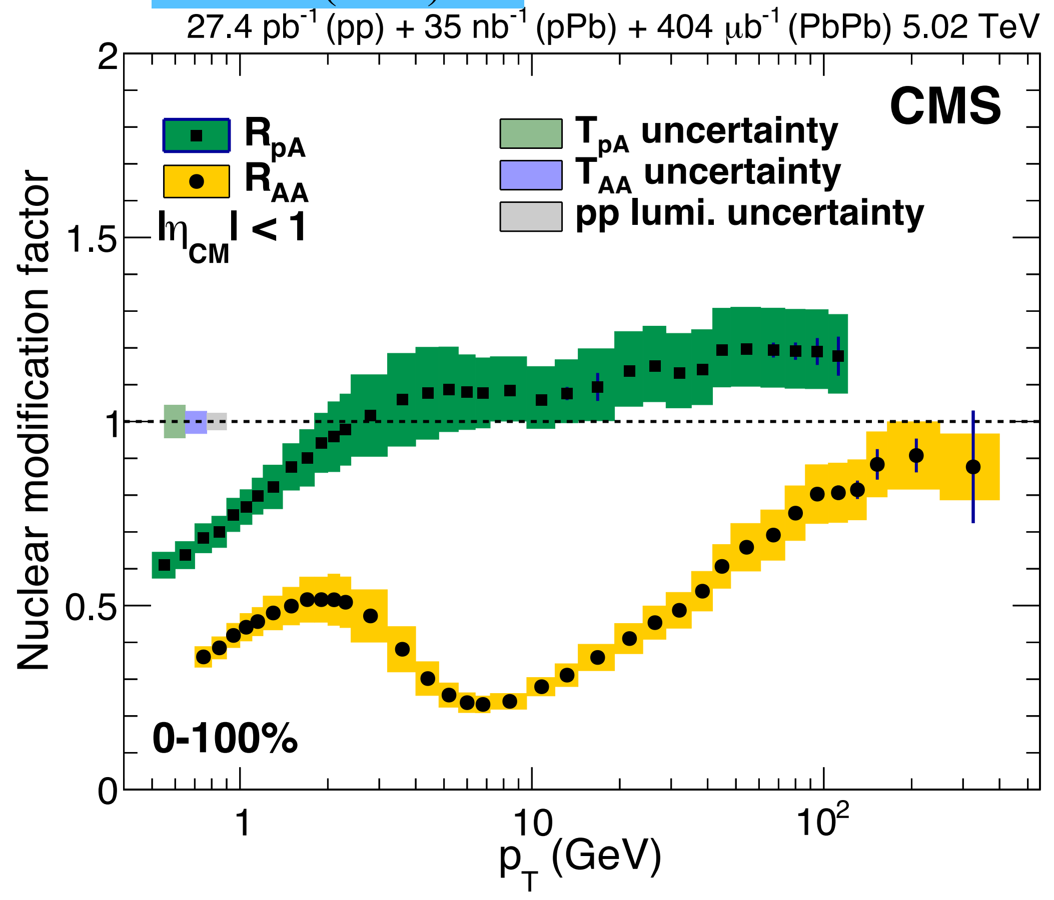

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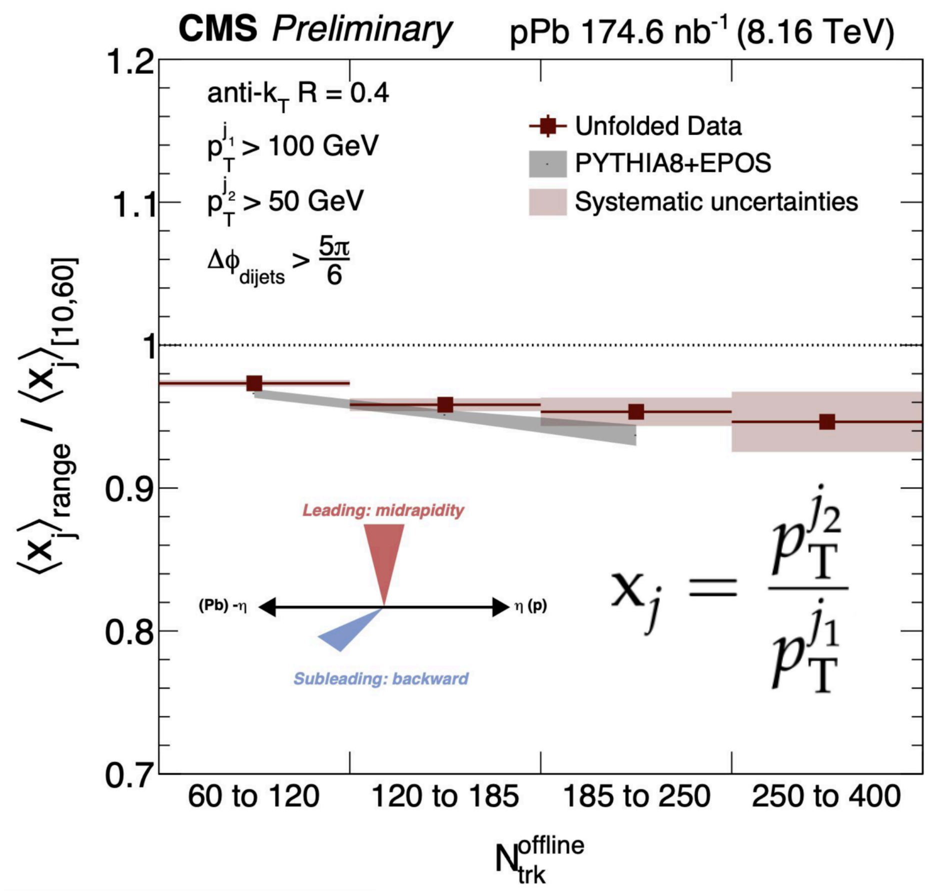
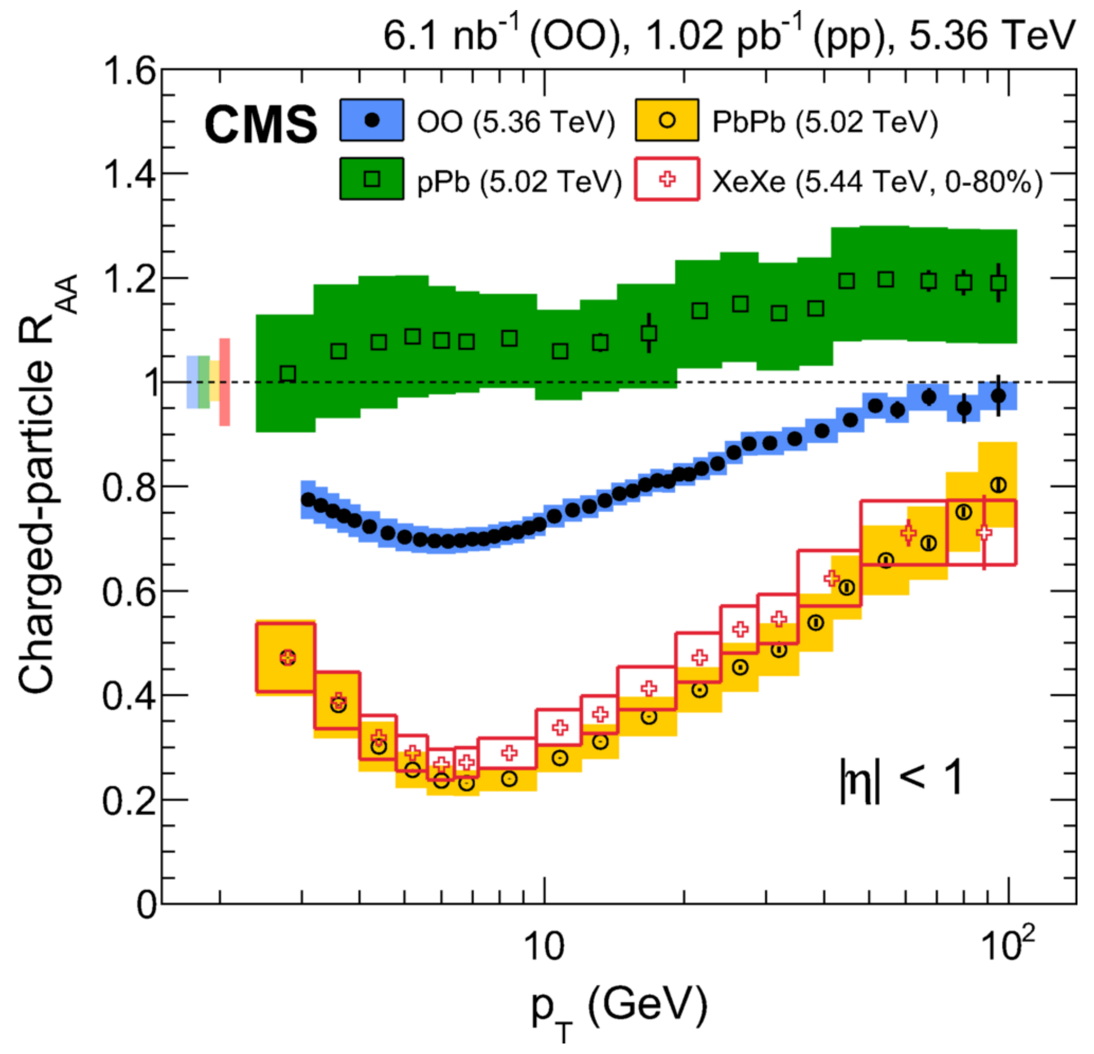


Quenching observed in OO/NeNe collisions

PRL 136 (2026), 162301



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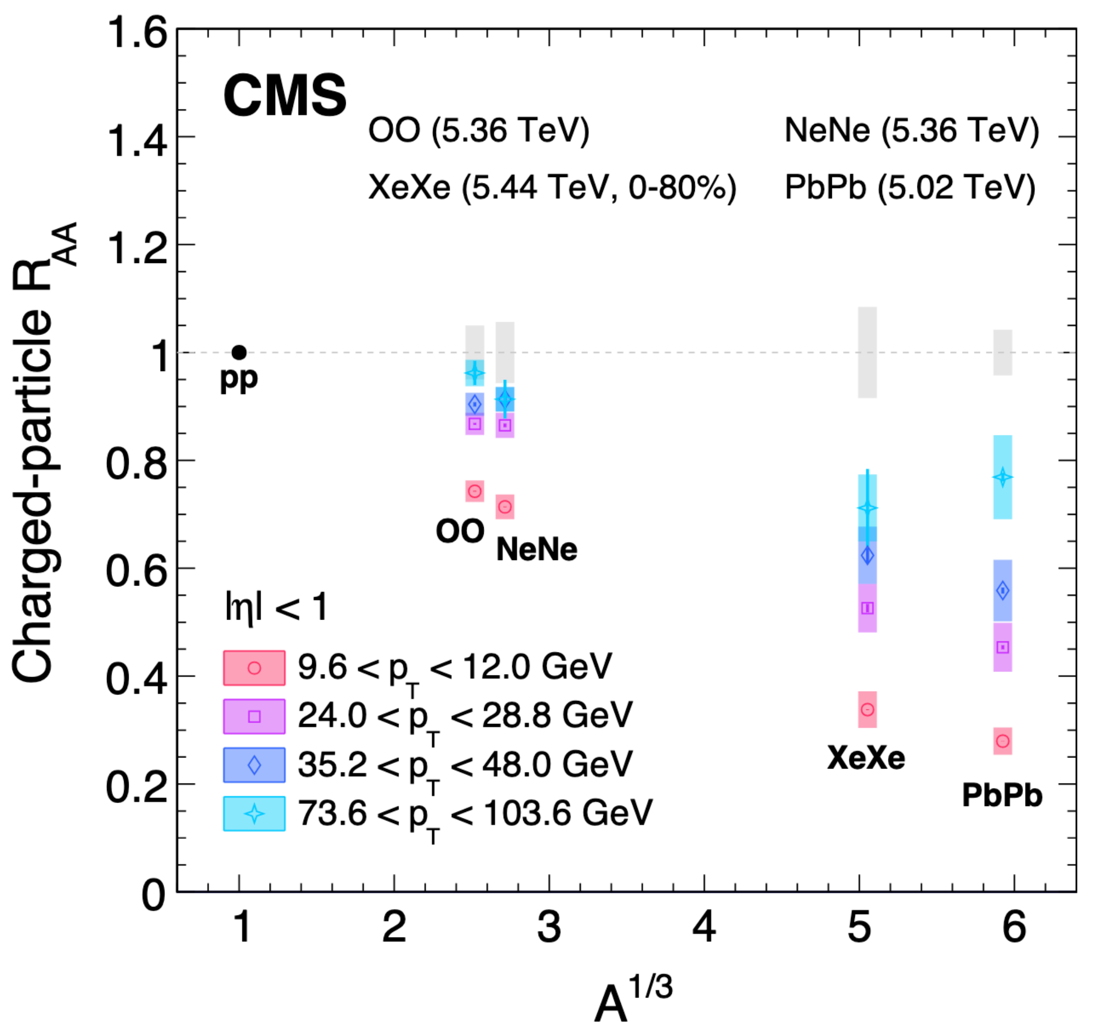

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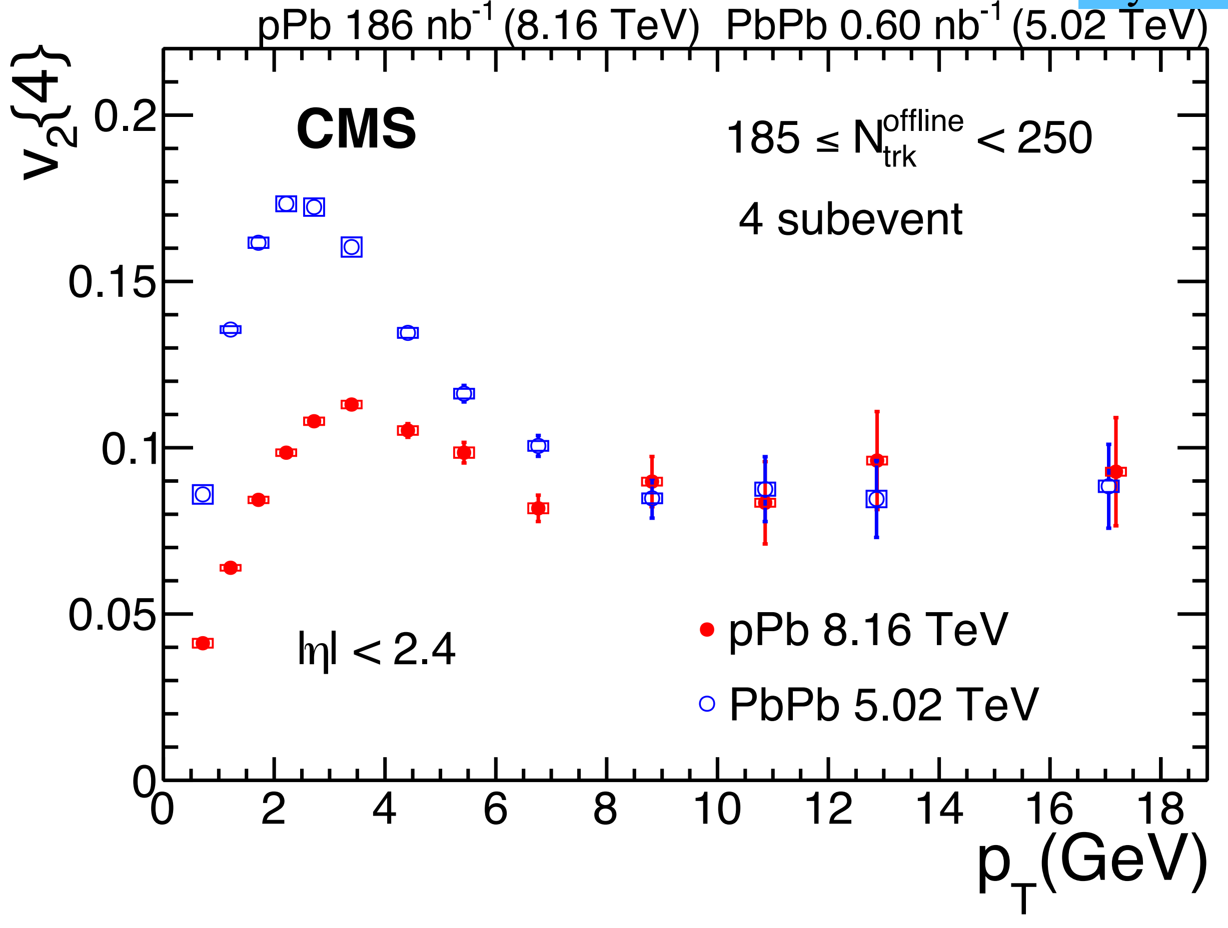

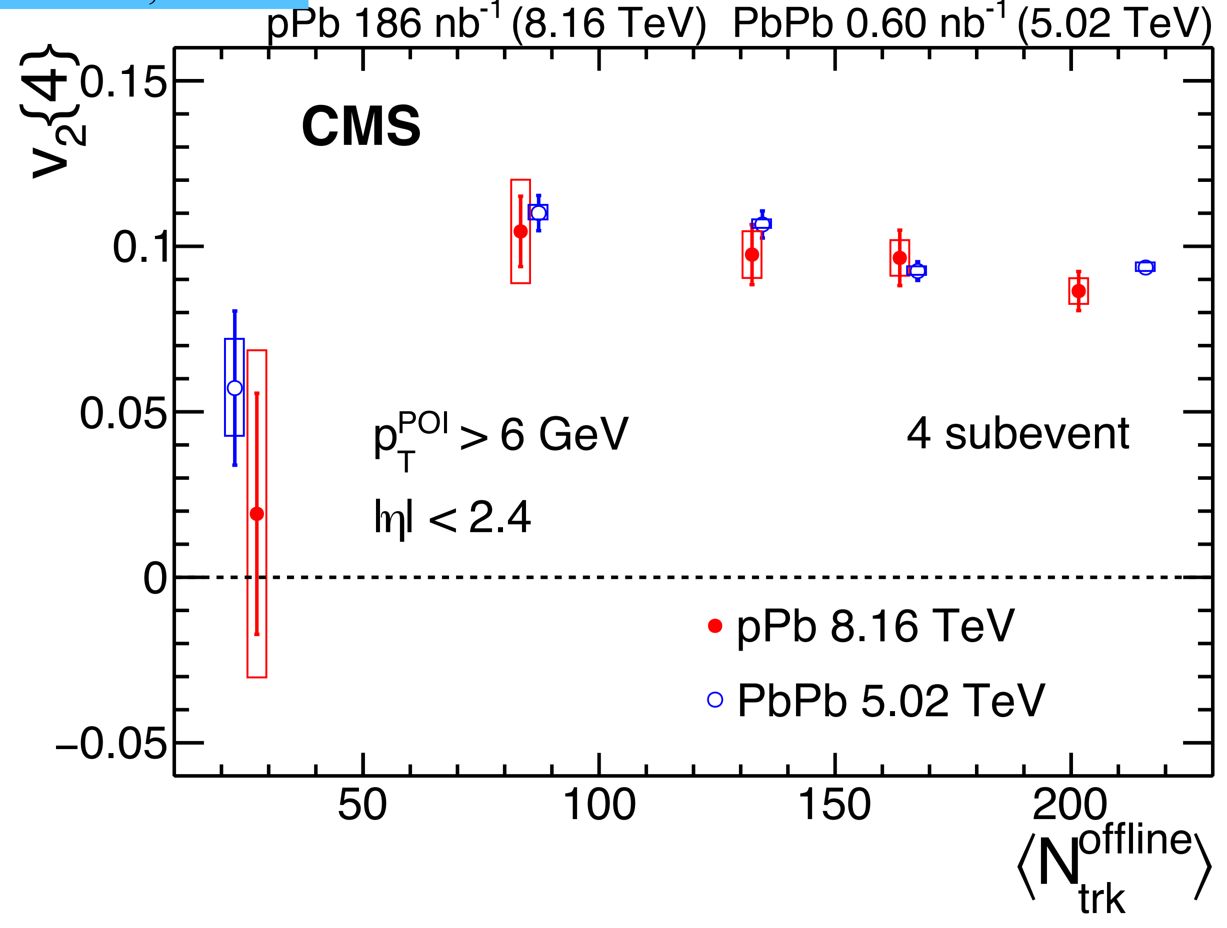

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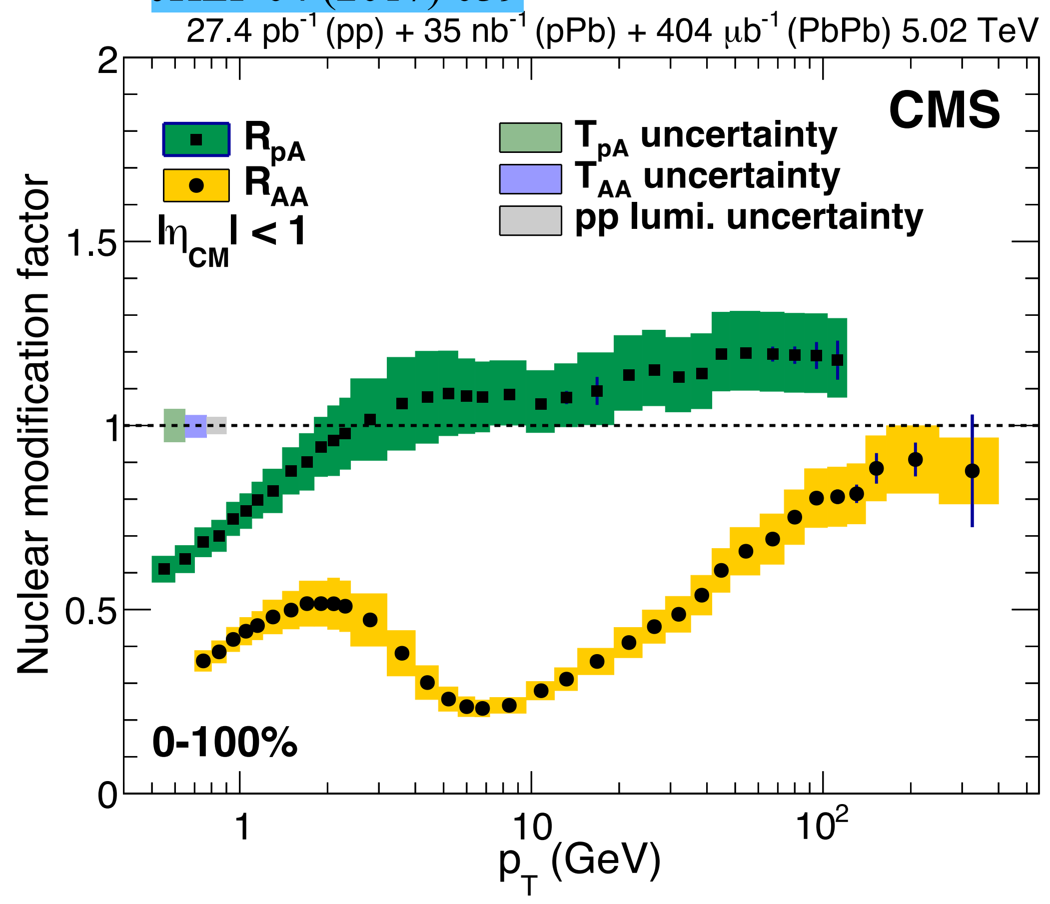

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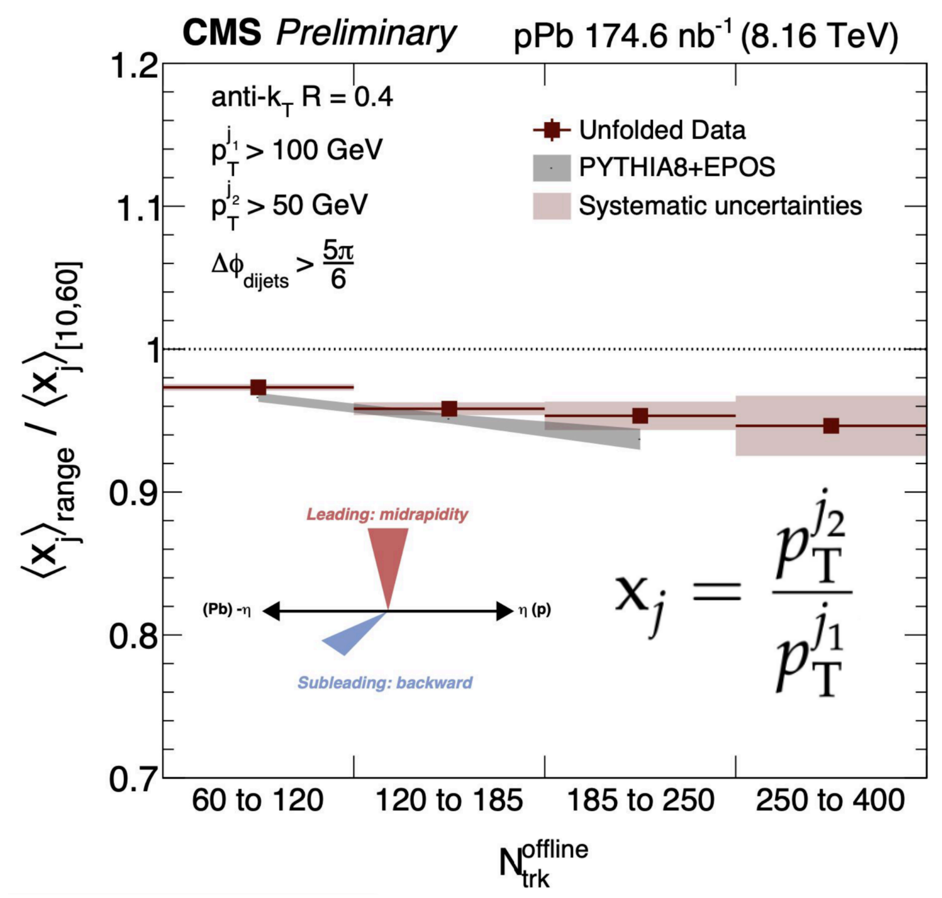

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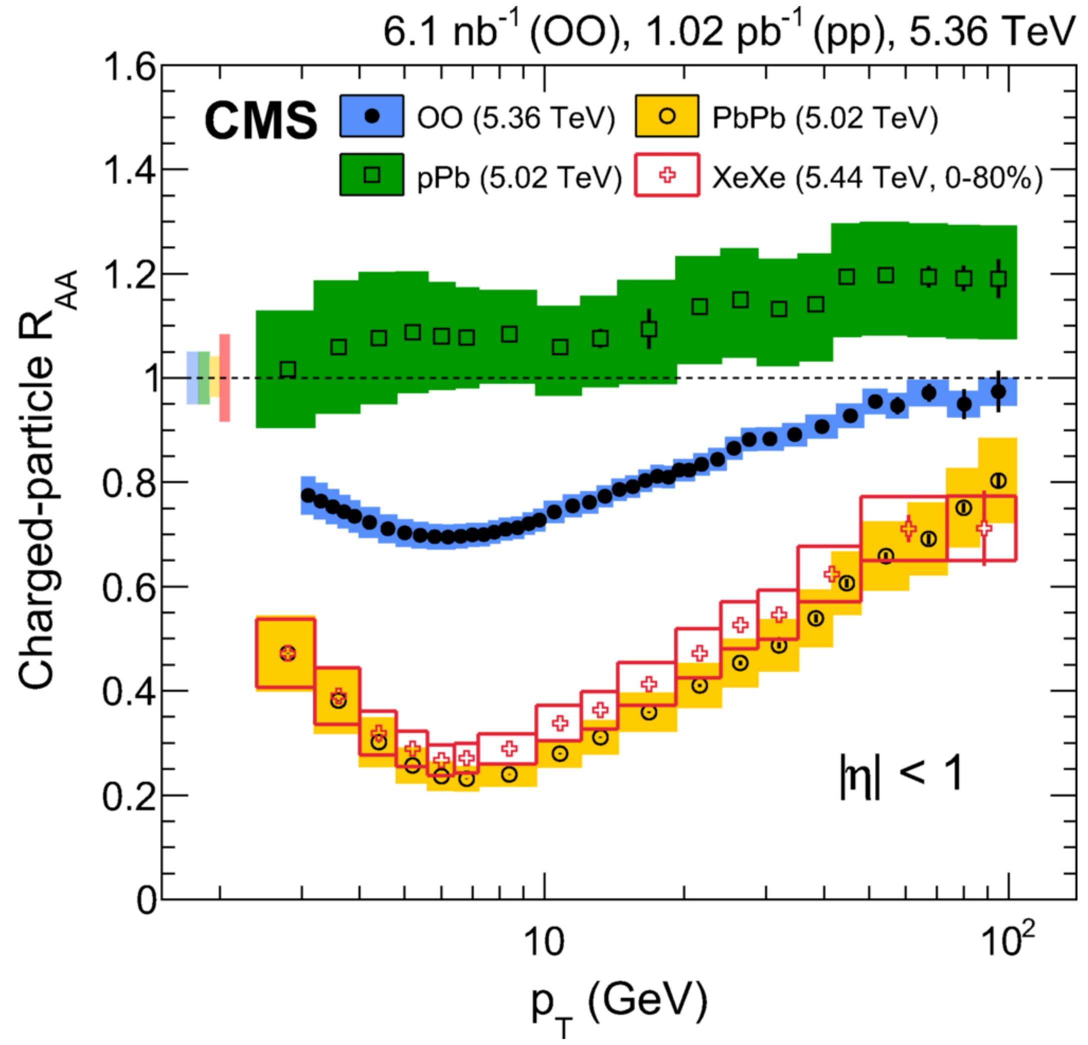

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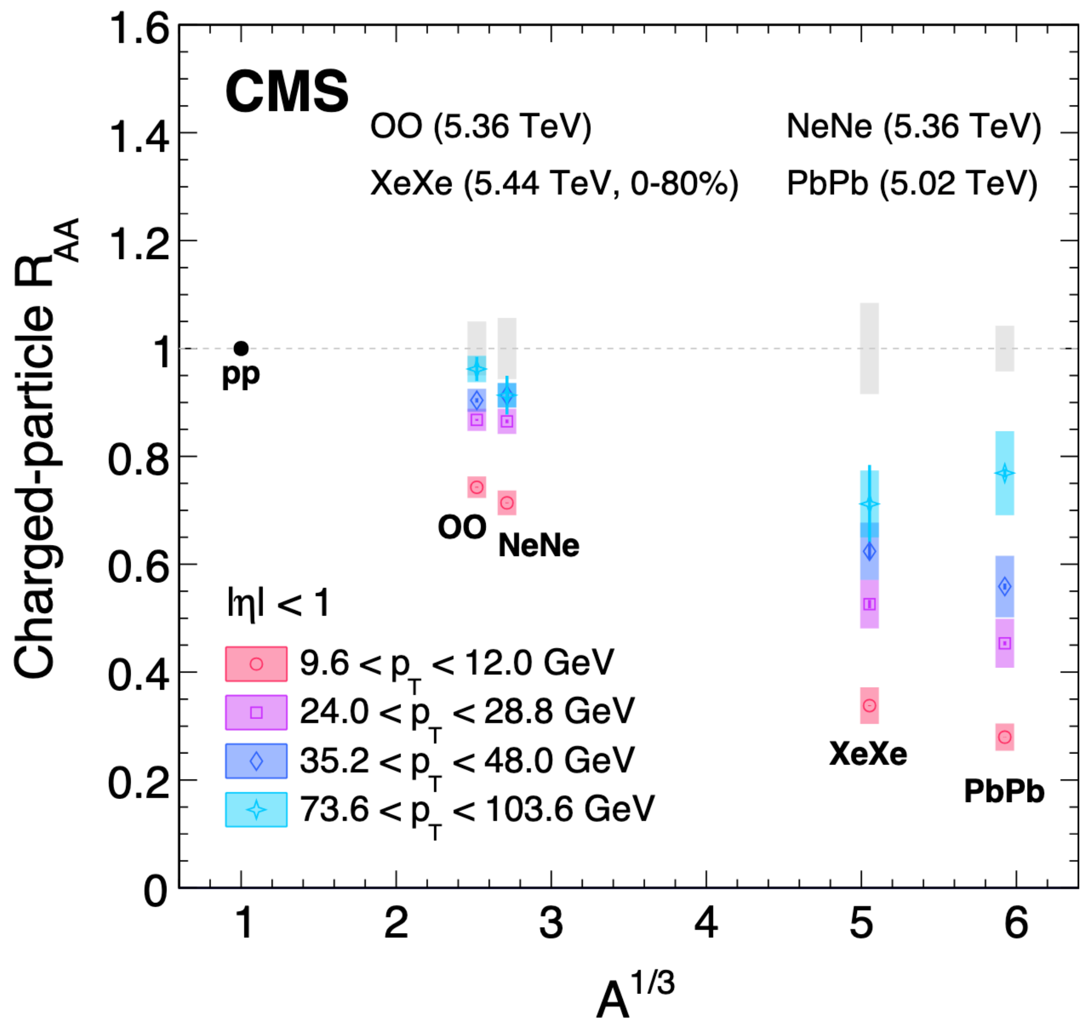

$v_2(p_T)$ in OO/NeNe collisions

💡Collectivity without quenching in pPb
What about a system of similar size but with quenching?

Need to first dive into a fundamental issue with differential flow measurements

The “Flaw” in the Flow

Flow is an event-by-event phenomenon. To measure $v_n(p_T)$, we must correlate a particle of interest (**POI**) with reference flow particles (**RFPs**). Averaged over event ensembles.

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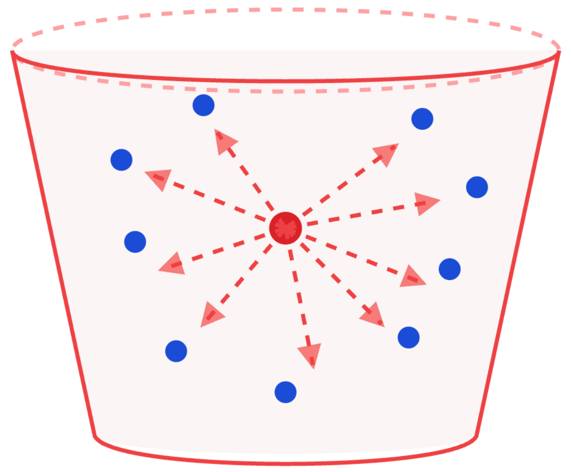
1 DIFFERENTIAL CUMULANT (d_n)

From POI events

Events requiring at least one track with POI

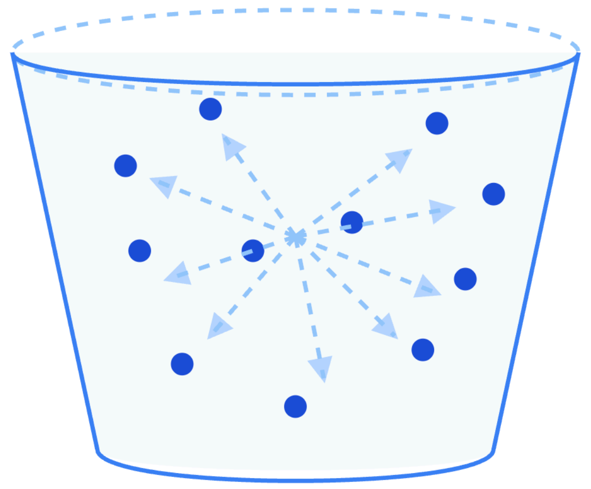
- **POI** (in given p_T bin)
- **RFPs** (0.3 < p_T < 3.0 GeV/c)



2 REFERENCE CUMULANT (c_n)

From inclusive events

Standard minimum bias selection.



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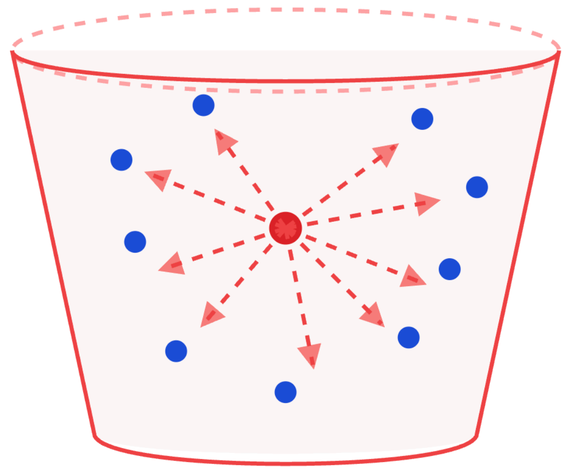

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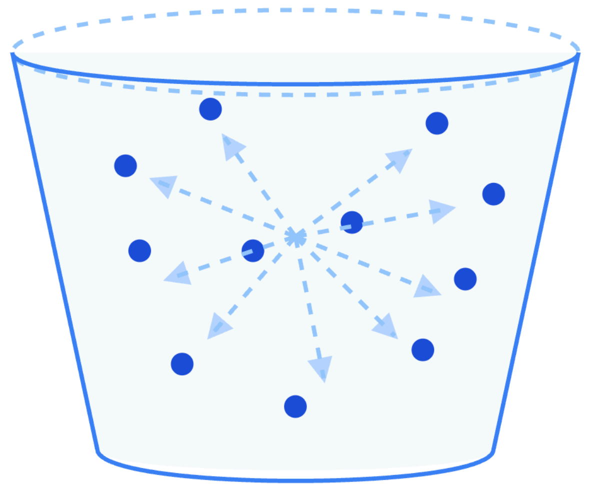

- **RFPs** (0.3 < p_T < 3.0 GeV/c)

No requirement on POI

$$v_n' \sim \frac{d_n}{c_n^{1/k}}$$

DIFFERENTIAL CUMULANT (correlation b/w POI and RFPs)

REFERENCE CUMULANT (correlation among RFPs)

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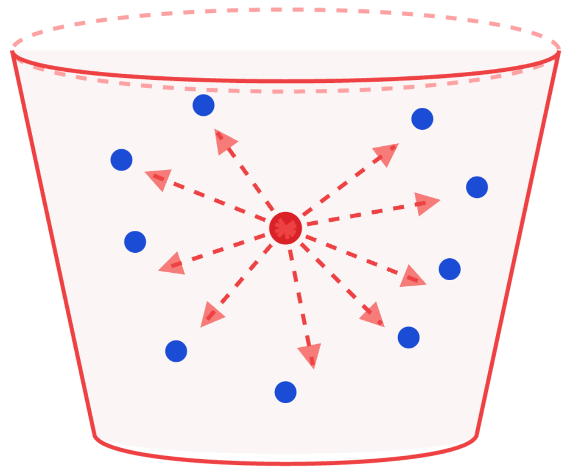

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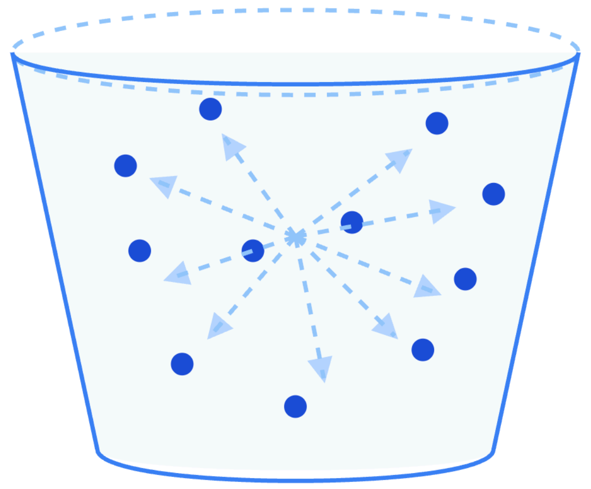

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DIFFERENT EVENT ENSEMBLES are used in numerator (d_n) and denominator (c_n).

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→ **DIFFERENTIAL CUMULANT** (correlation b/w POI and RFPs)

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CAN THESE TWO ENSEMBLES HAVE IDENTICAL FLOW? ?

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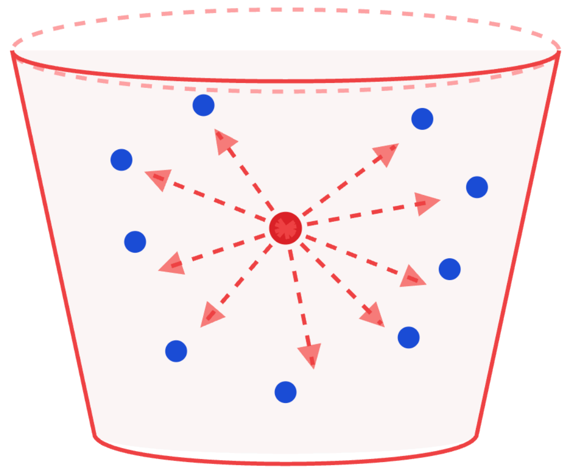

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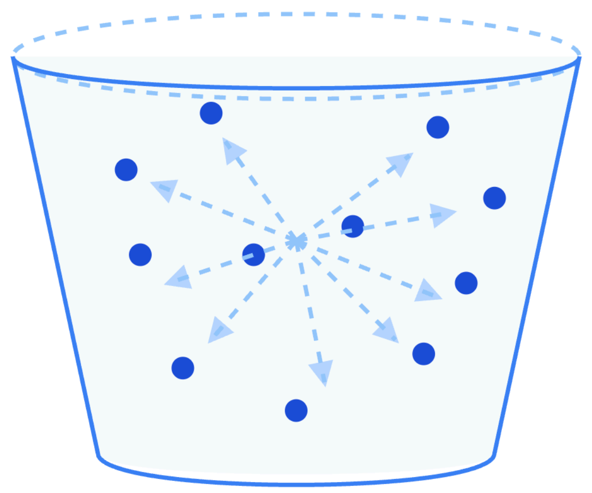

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CAN THESE TWO ENSEMBLES HAVE IDENTICAL FLOW? ?

All p_T differential flow measurements so far have assumed no difference between these ensembles.

This assumption has never been tested.

Results of the test

Light ions (OO/NeNe):

- **~2%** difference in $v_2\{2\}$ above **6 GeV**
- **~10%** difference in $v_2\{4\}$ above **6 GeV**

$$d_n\{2\} = \langle\langle 2' \rangle\rangle$$
$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle \cdot \langle\langle 2 \rangle\rangle$$
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle \cdot \langle\langle 2 \rangle\rangle$$

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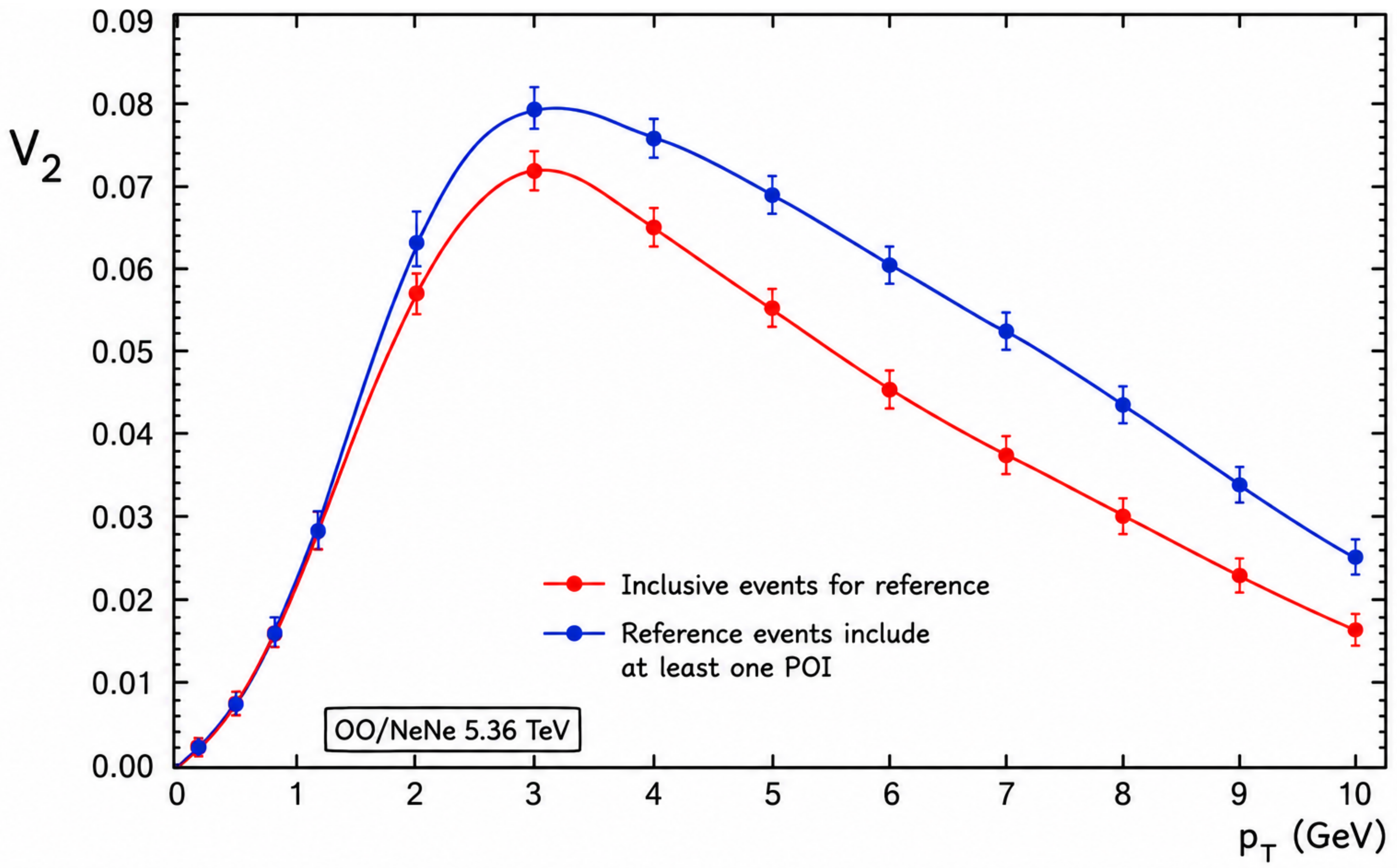

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No significant systematic difference observed for:

- v_2 in **pPb** and **pO**
- v_3 in all collision systems

The difference grows as we go to **higher p_T**.

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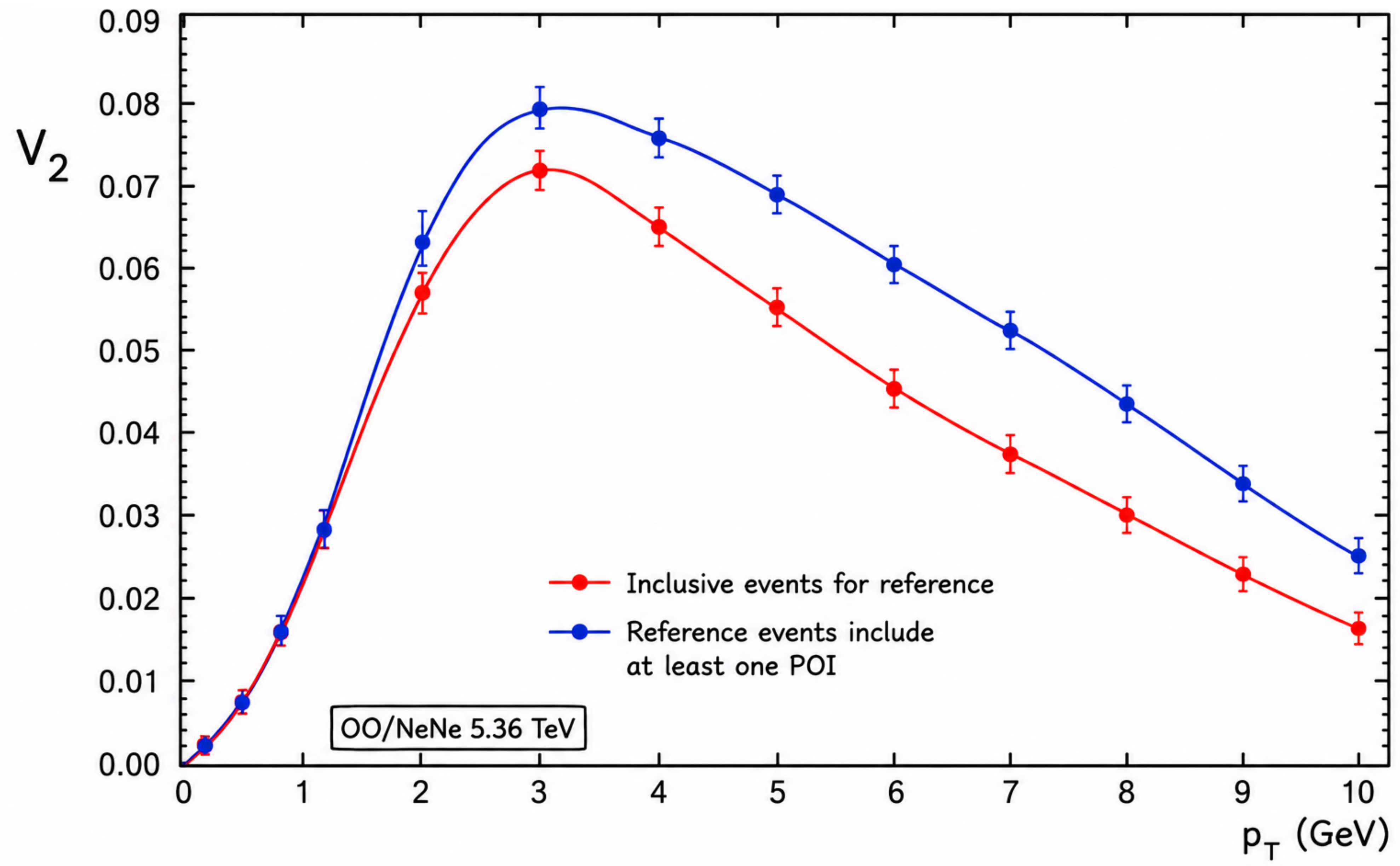
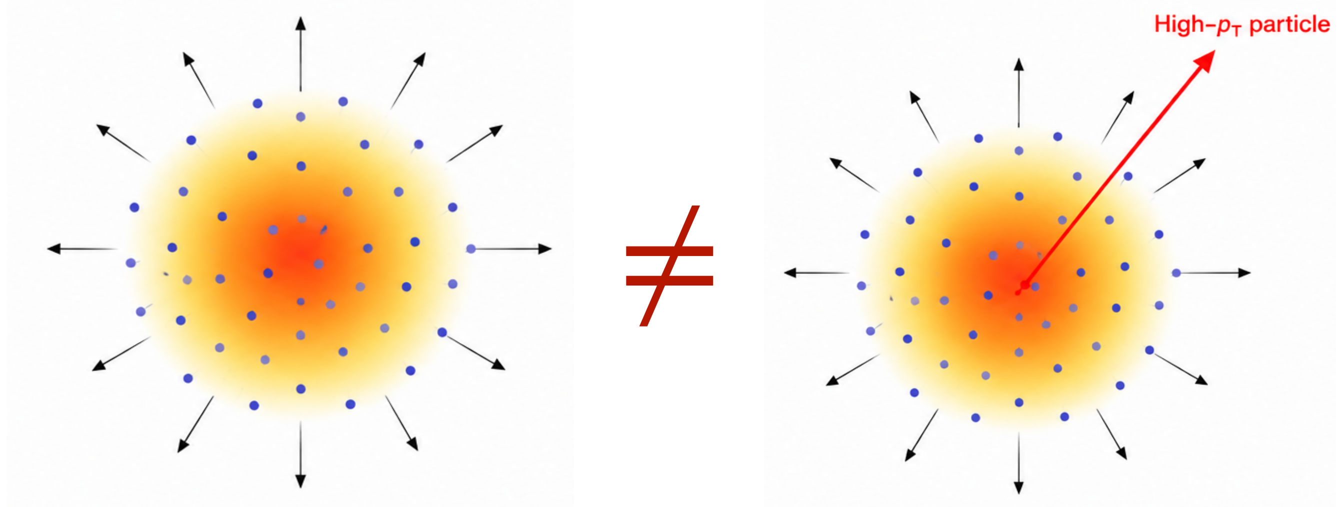


The new standard



- **Events with high-p_T particles constitute a physically distinct ensemble**
- **It is incorrect to use a universal "inclusive" reference for differential measurements**
- **New standard (approach):**
  - **Both differential and reference correlation from same set of events**

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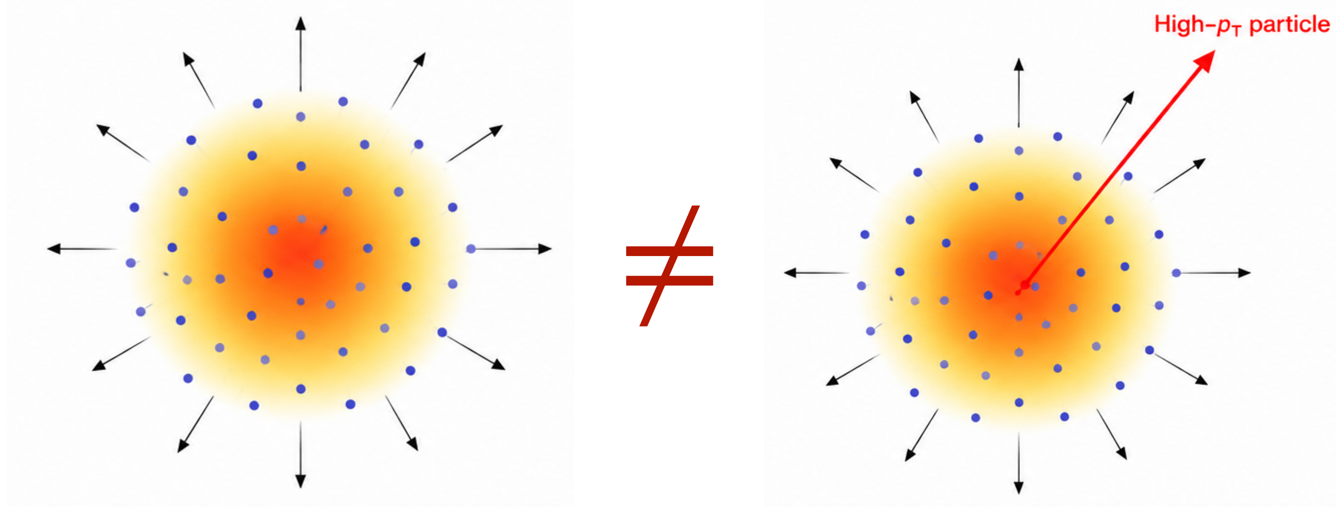
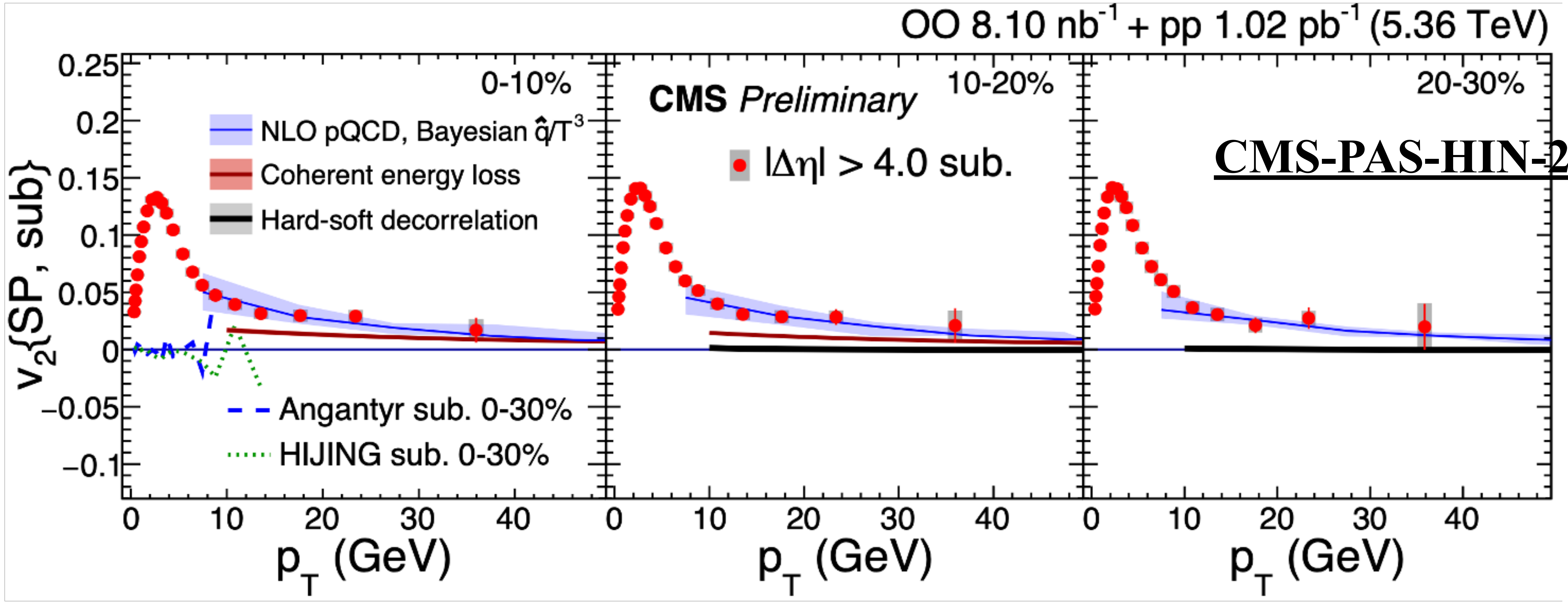


$v_2(p_T)$ in OO upto 50 GeV using SP method

A Dattamunsi (Wed)



CMS-PAS-HIN-26-005

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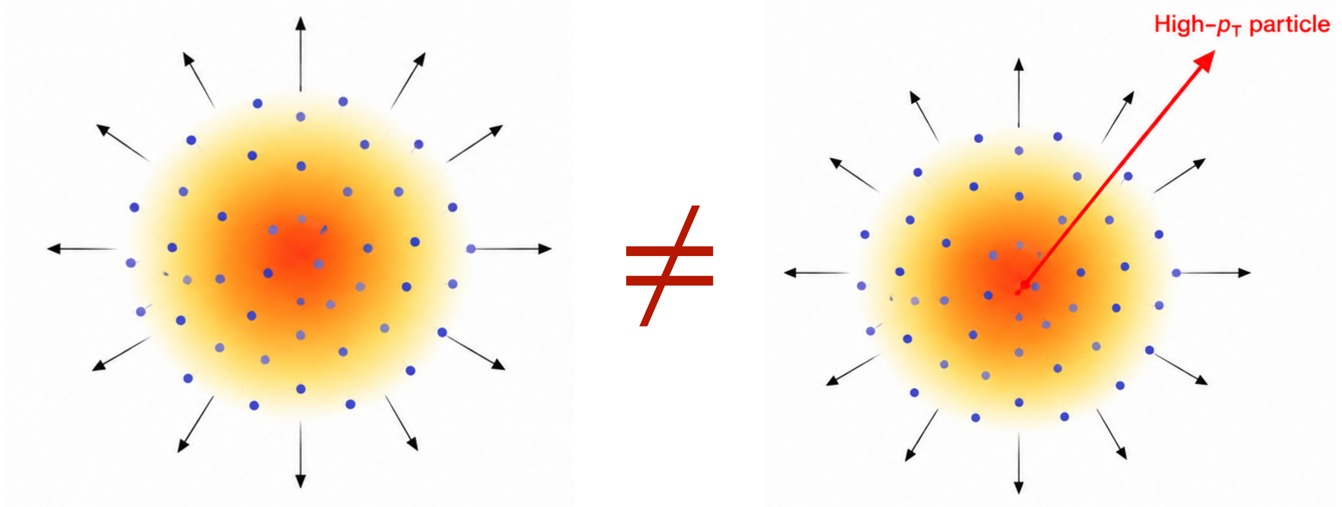

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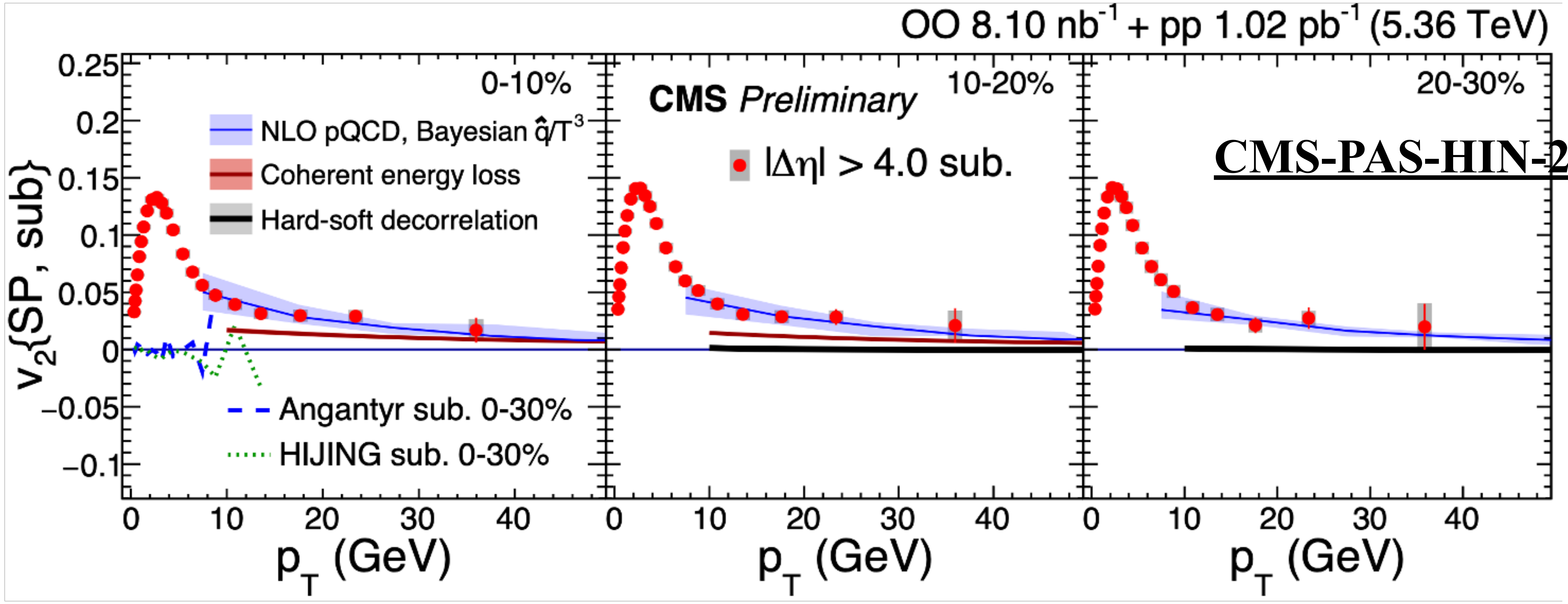


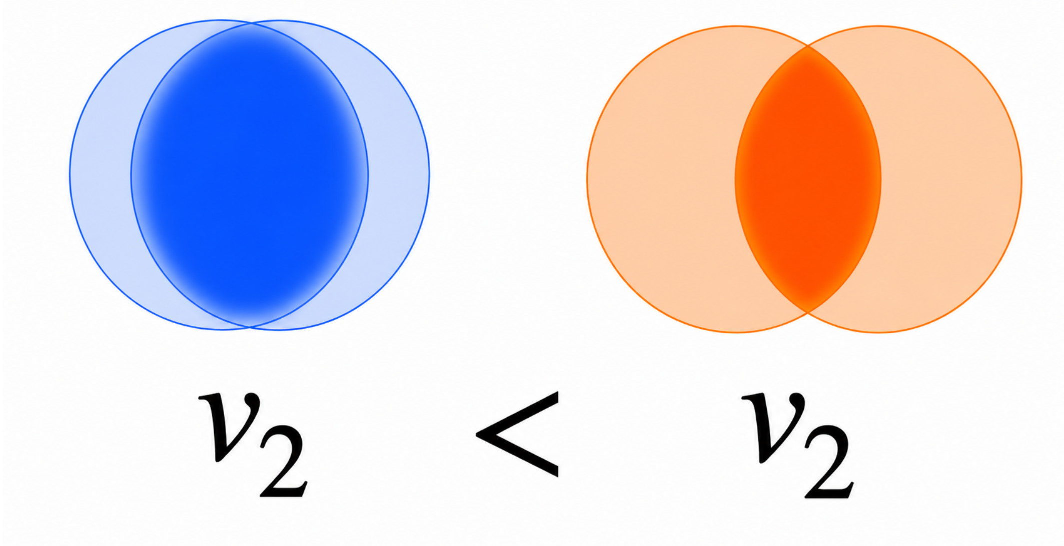
CMS-PAS-HIN-26-005

Key takeaway: Inclusive references are invalid, must use a unique reference for each p_T bin

Part 2: Differential radial flow

Two kinds of transmutation

Shape-flow transmutation



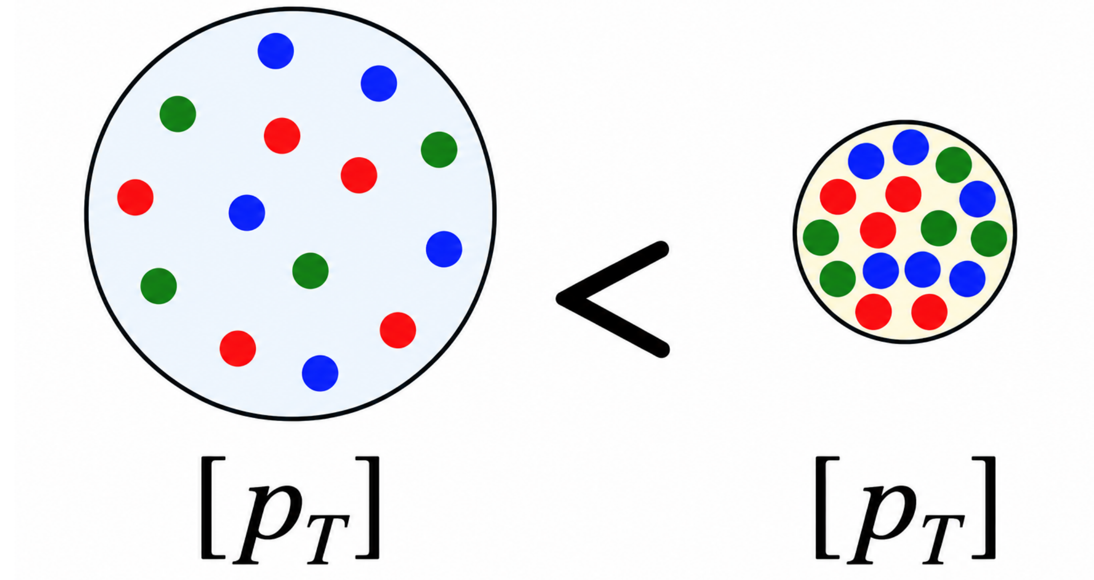
Observables: Anisotropic flow coefficient v_n

p_T differential: (more informative) $v_n(p_T)$, $n > 0$

Hallmarks of collectivity:

- **Long-range nature ($\Delta\eta$ independent)**
- **Factorization (p_T^{ref} independent)**
- **Centrality independence of $v_n(p_T)/v_n$**
- **Consistency b/w higher order cumulants**
- **Mass ordering, NCQ scaling**
- **Baryon-Meson splitting, heavy-flavor flow**

Size-flow transmutation



E-by-E $[p_T]$ fluctuations, σ_{p_T}

Not available

Less realized as a signature of collectivity

Two kinds of transmutation

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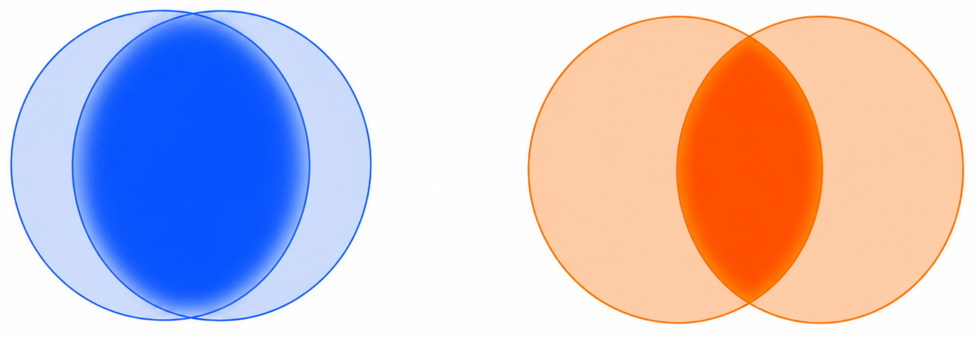

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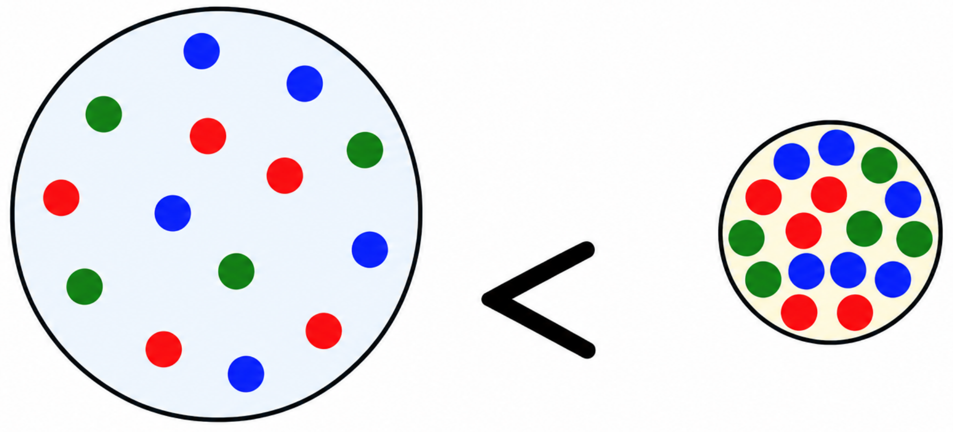


E-by-E $[p_T]$ fluctuations, σ_{p_T}

$$\boxed{v_0(p_T)}$$

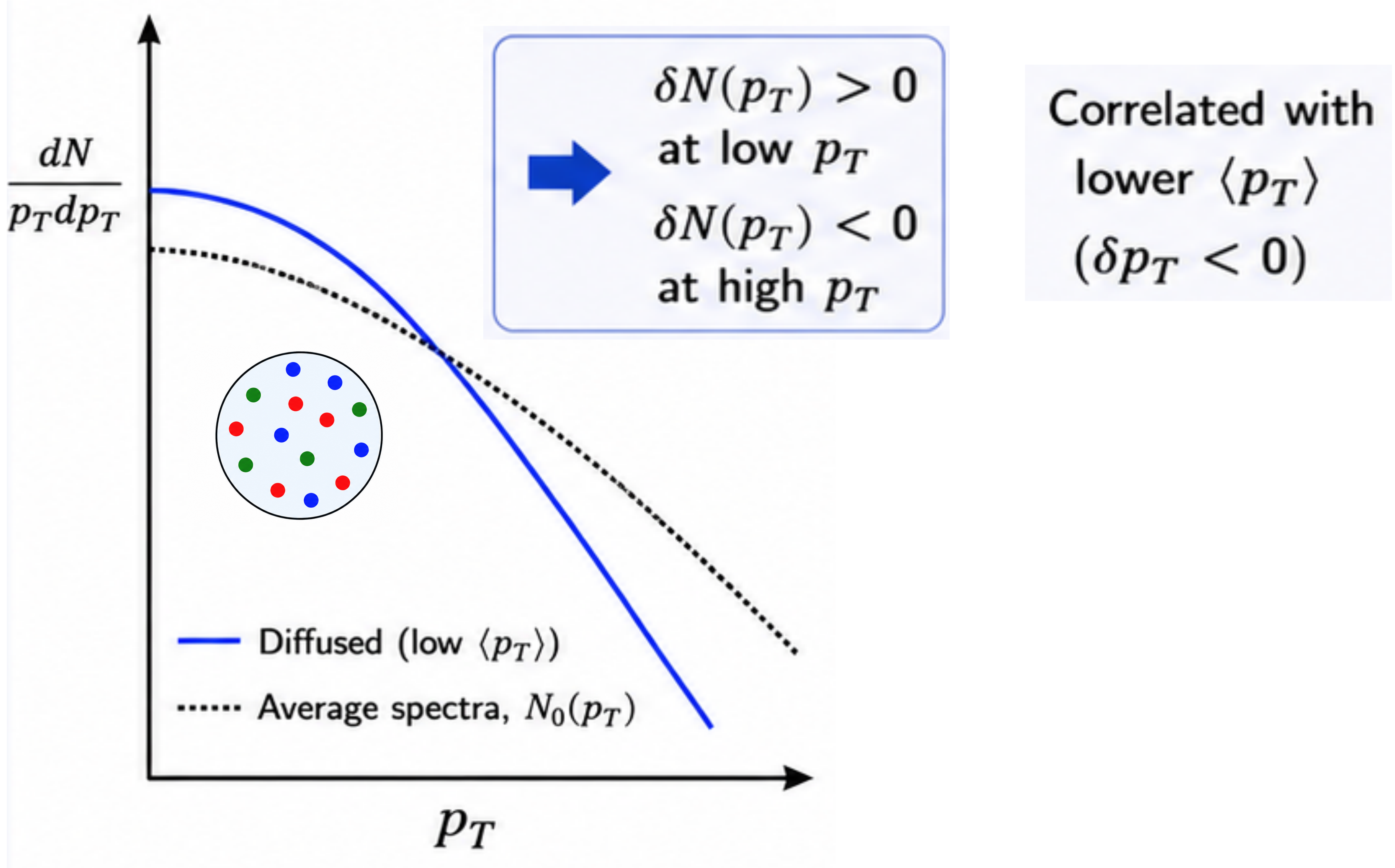
Teaney et.al.: Phys. Rev. C 102, 034905 (2020)

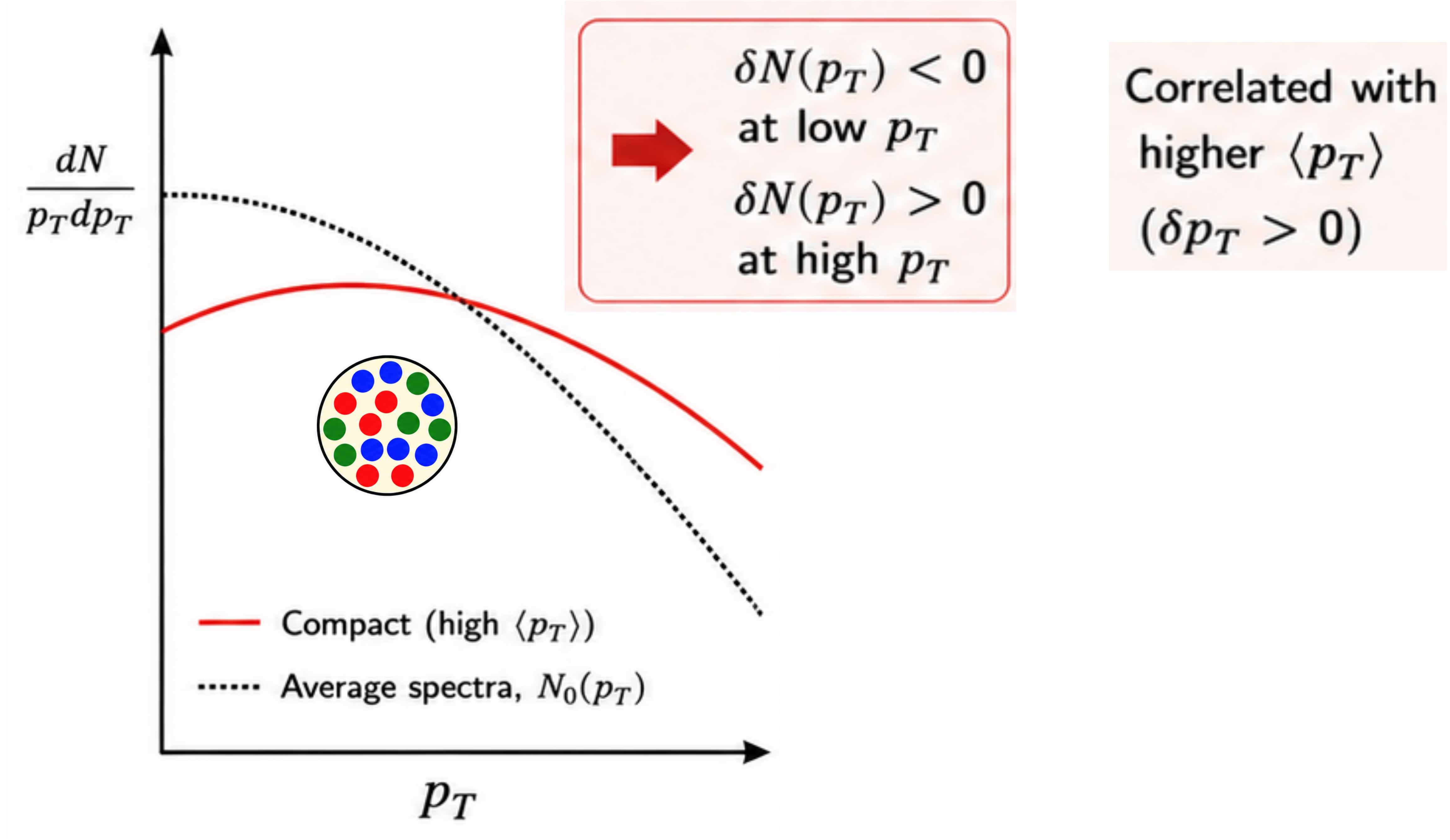
Do these hallmarks of collectivity also hold for radial flow?

Defining the differential radial flow

$$v_0(p_T) \sim \langle \delta N(p_T)\, \delta p_T \rangle$$

Correlation between the fluctuations of local yield ($\delta N(p_T)$) and mean transverse-momentum (δp_T)





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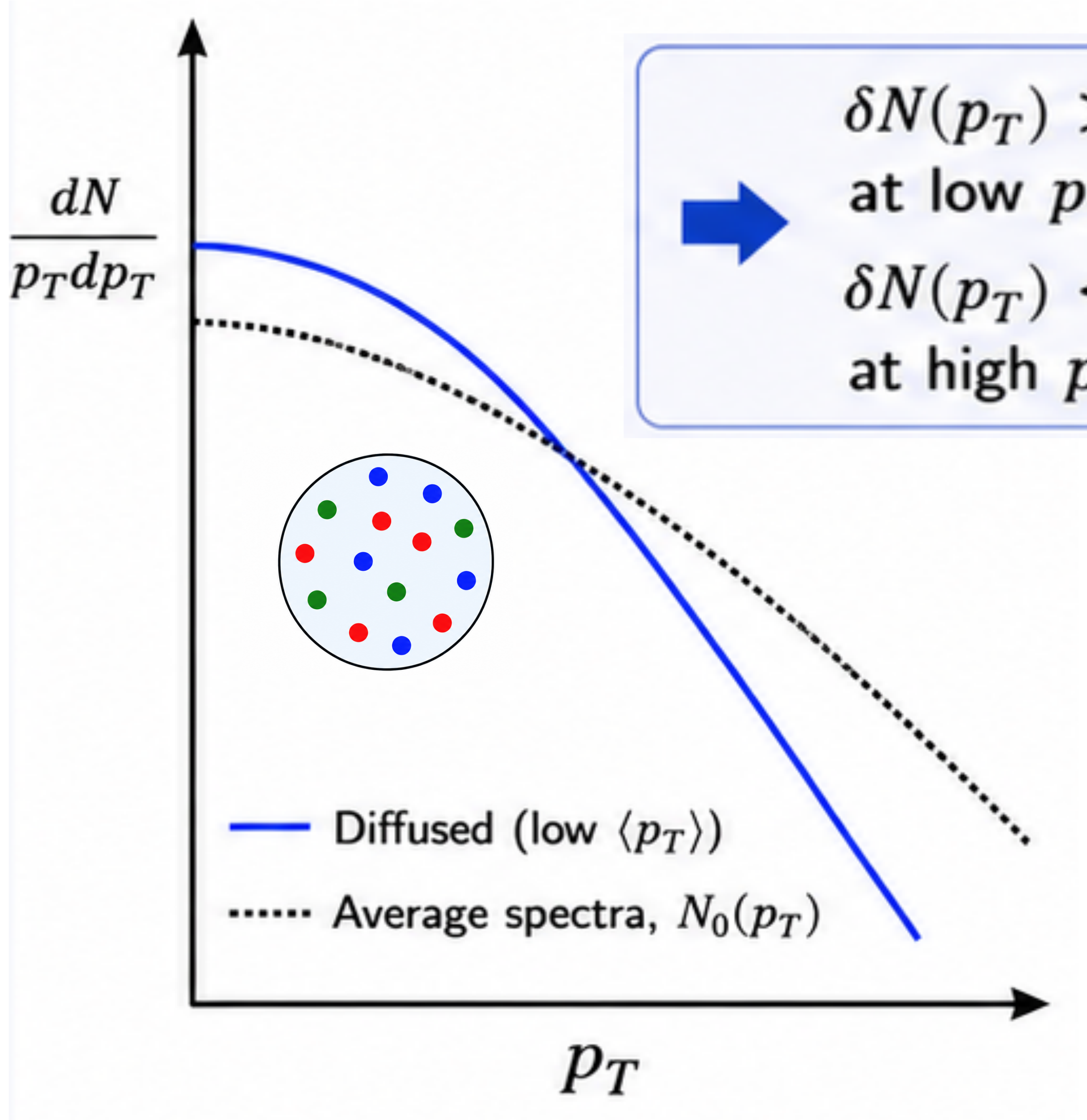
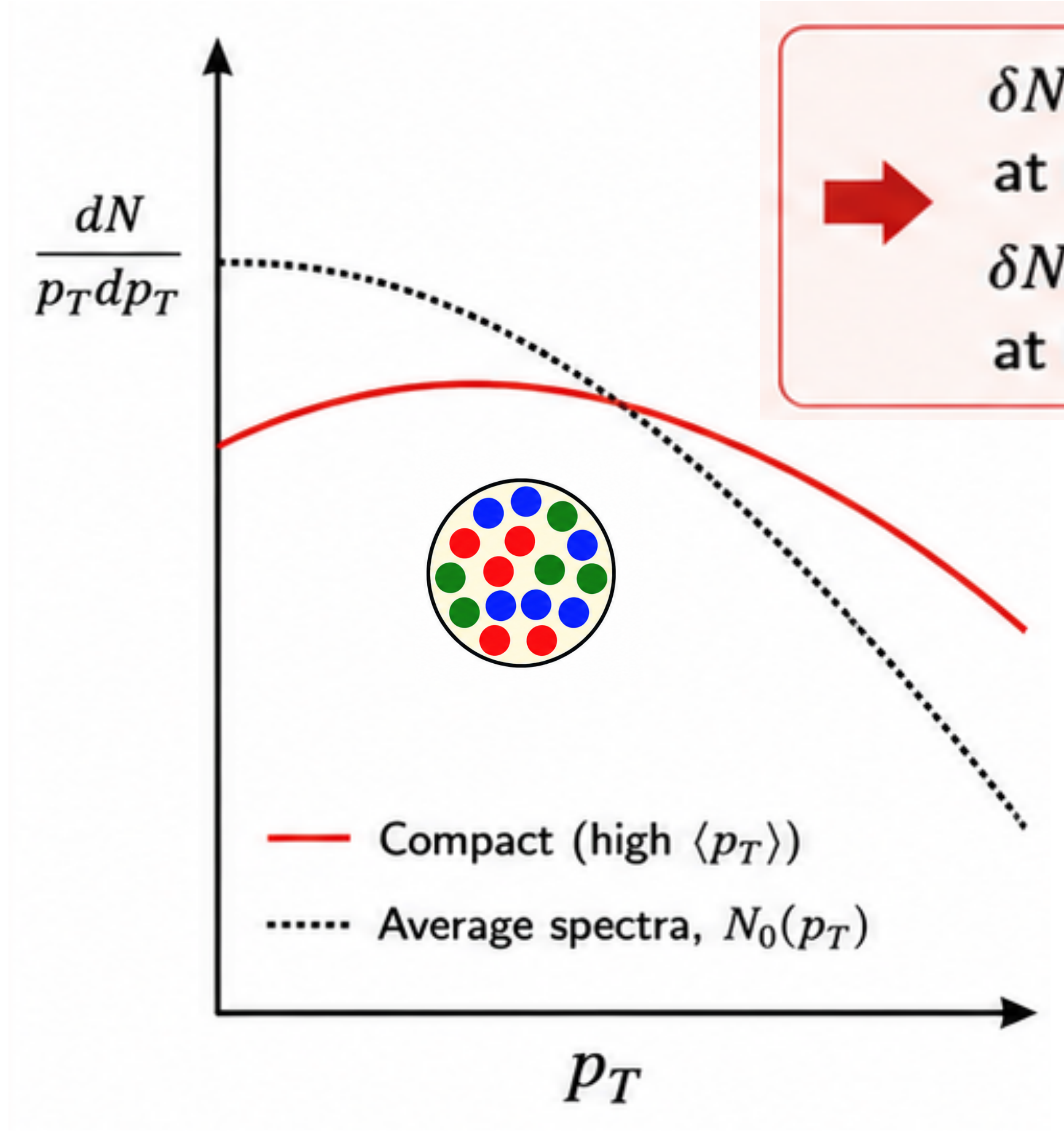


$\delta N(p_T) > 0$ at low p_T
$\delta N(p_T) < 0$ at high p_T

Correlated with lower $\langle p_T \rangle$ ($\delta p_T < 0$)

$v_0(p_T) < 0$ at low p_T

$v_0(p_T) > 0$ at high p_T



$\delta N(p_T) < 0$ at low p_T
$\delta N(p_T) > 0$ at high p_T

Correlated with higher $\langle p_T \rangle$ ($\delta p_T > 0$)

$v_0(p_T) < 0$ at low p_T

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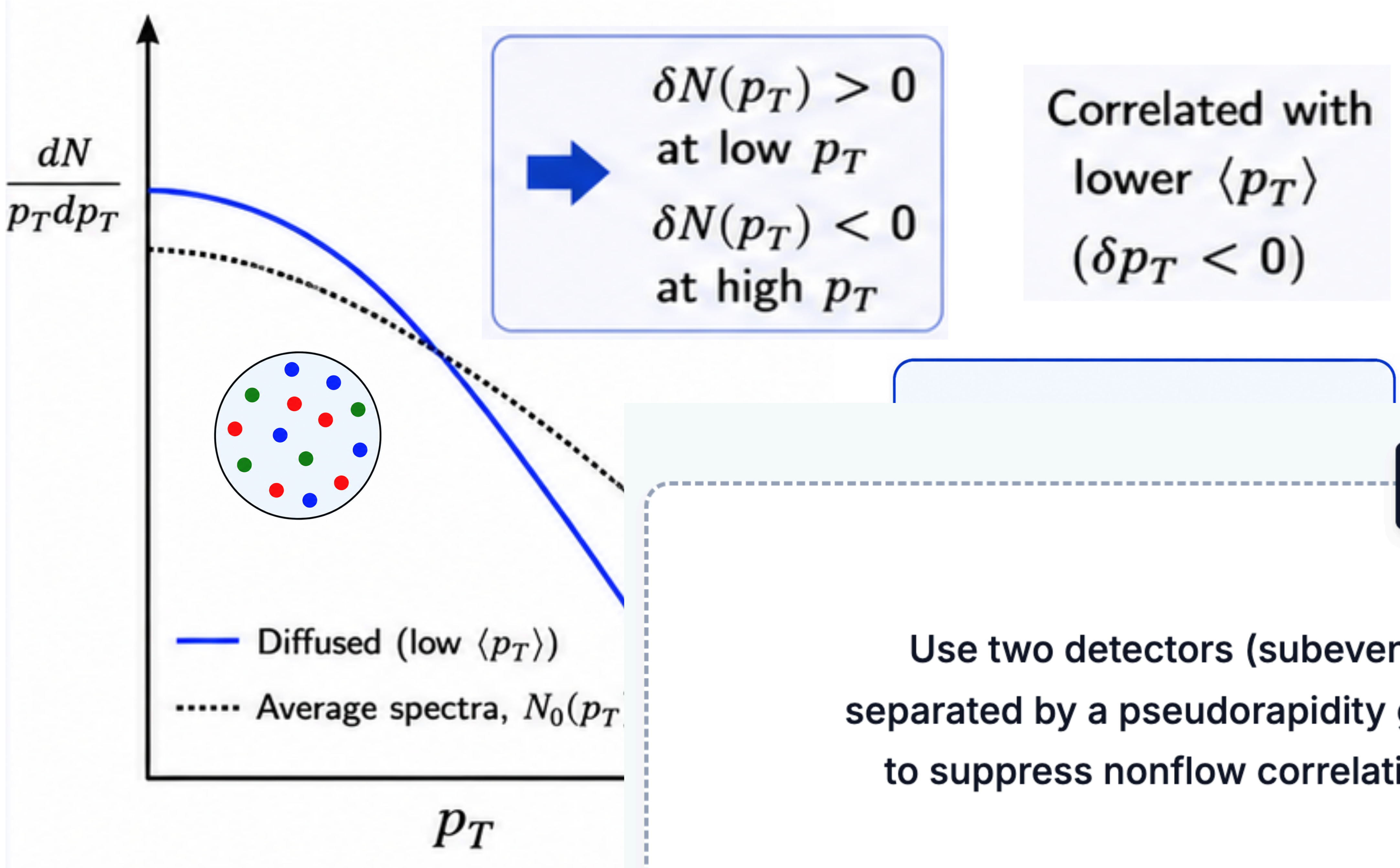
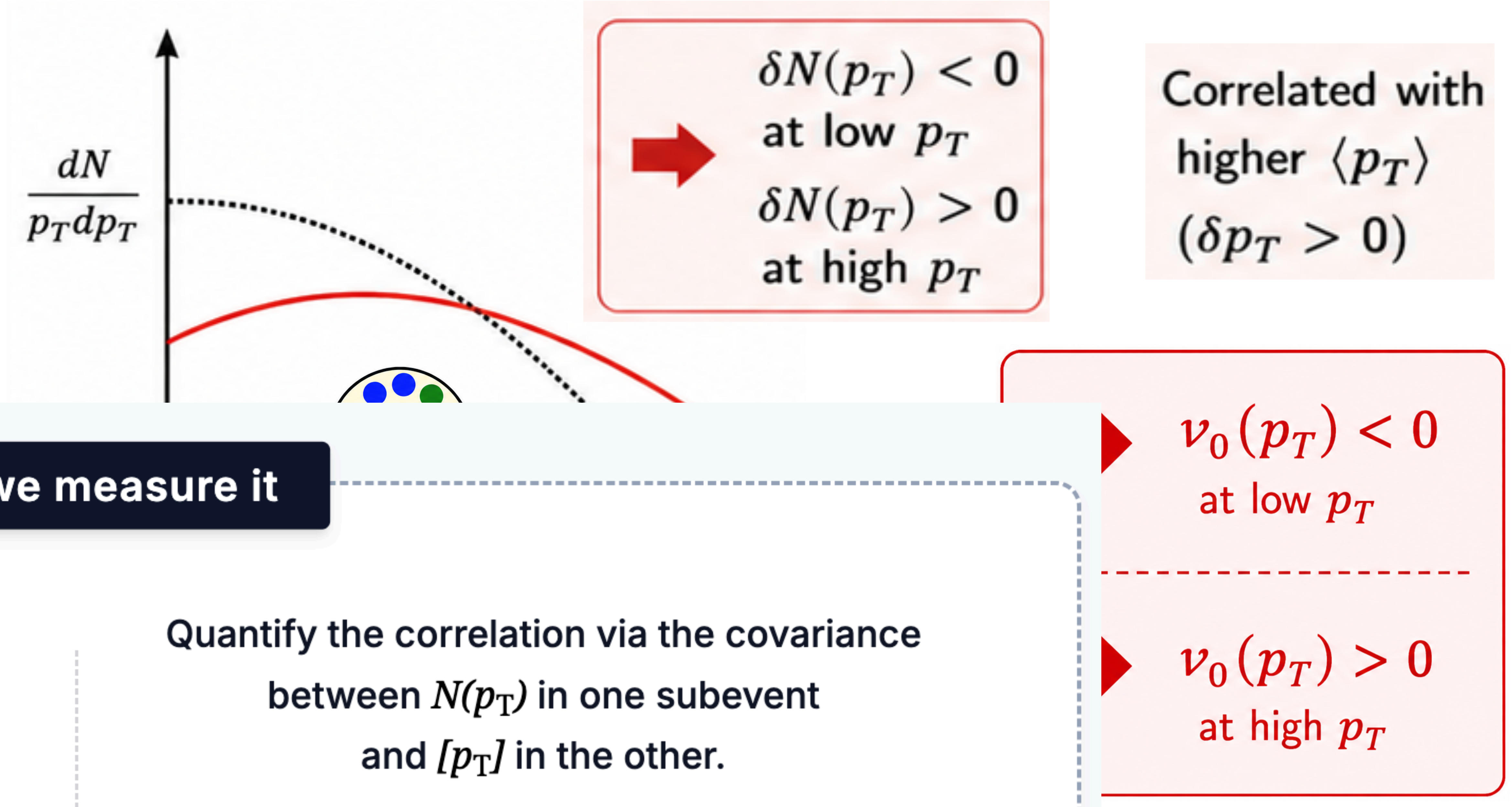
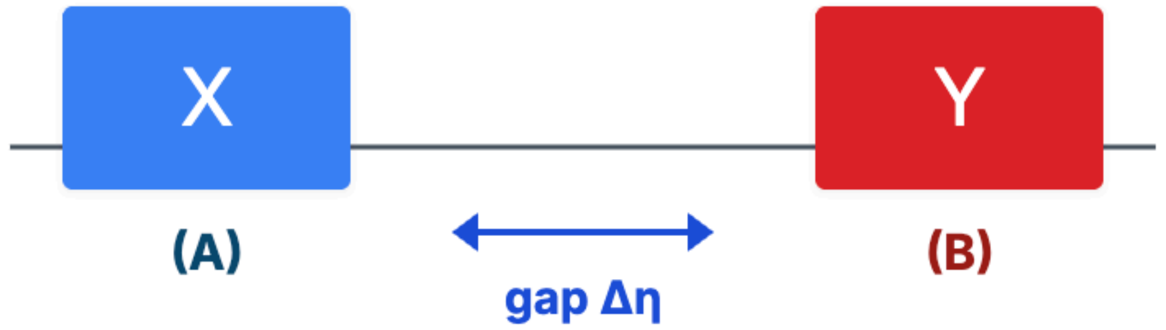




How we measure it

Use two detectors (subevents) separated by a pseudorapidity gap $\Delta\eta$ to suppress nonflow correlations.

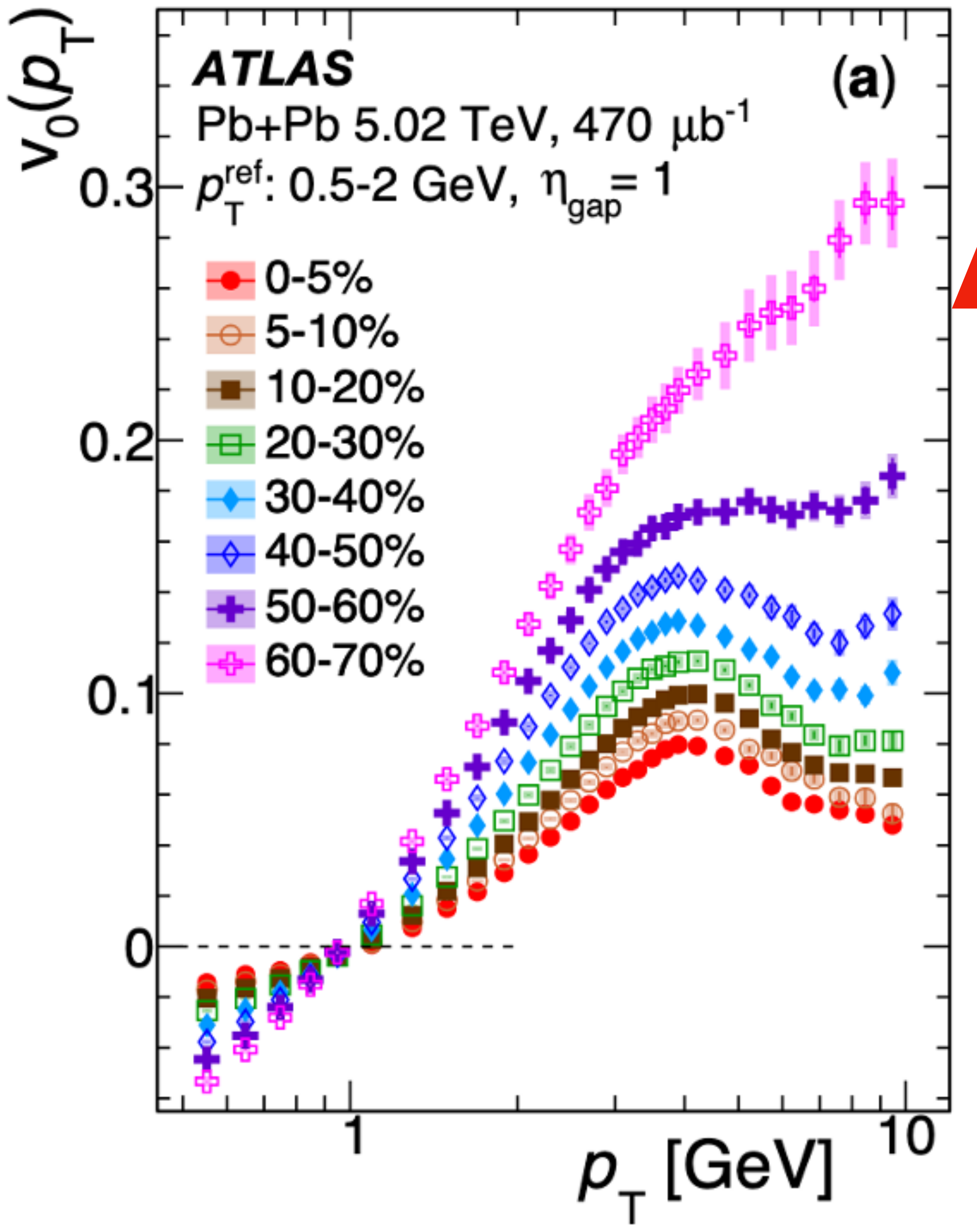


Quantify the correlation via the covariance between $N(p_T)$ in one subevent and $[p_T]$ in the other.

$$v_0(p_T) \propto \frac{\langle \delta N_X(p_T)\, \delta [p_T]_Y \rangle}{\langle N_X(p_T) \rangle\, \sigma_{p_T}}$$

Observations in Large System

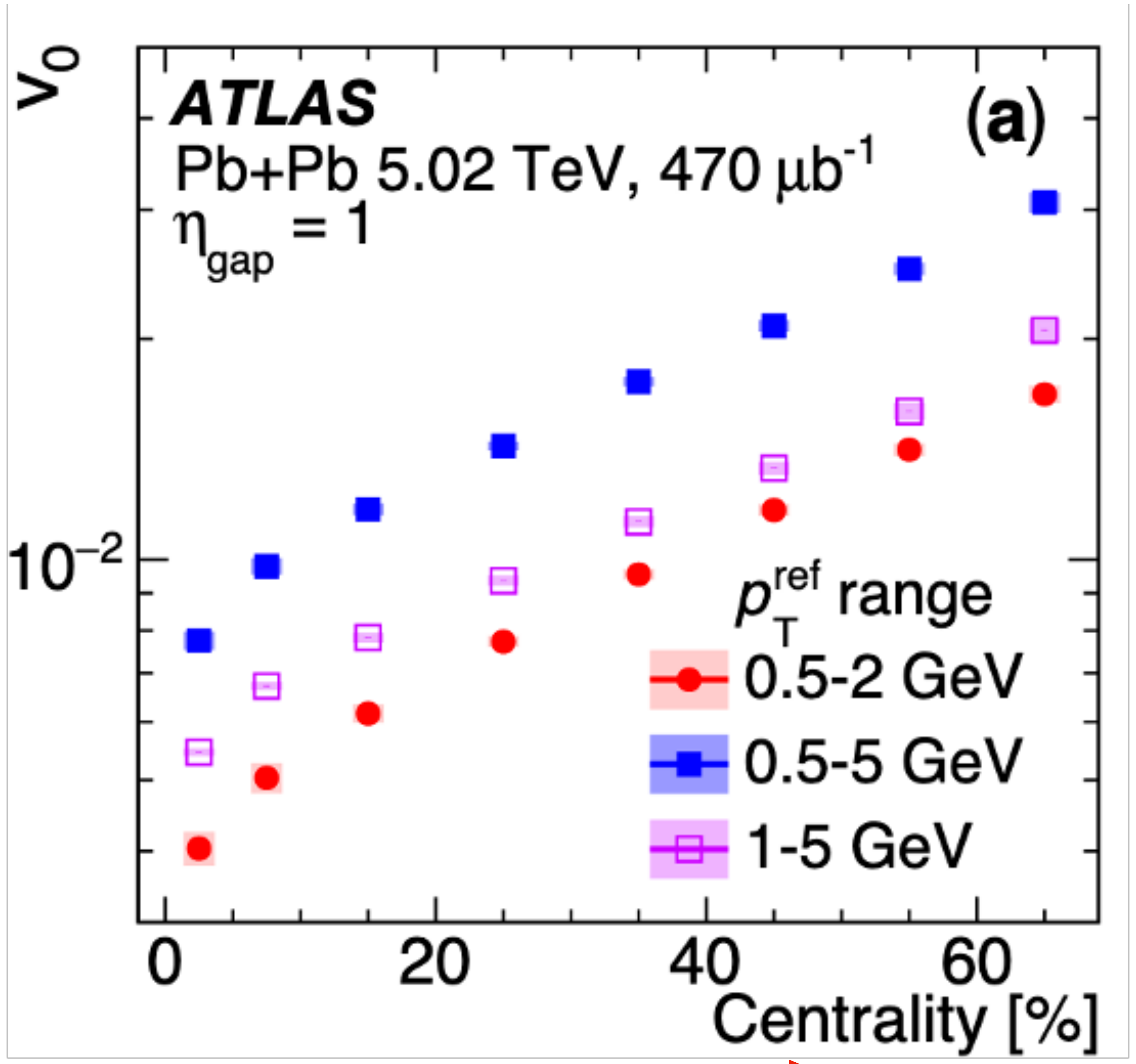
Phys. Rev. Lett. 136, 032301



Multiplicity ↓

Fluctuations ↑

$v_0 \equiv \int v_0(p_T)$ **determines the relative size of fluctuations**



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Hallmarks of Collectivity

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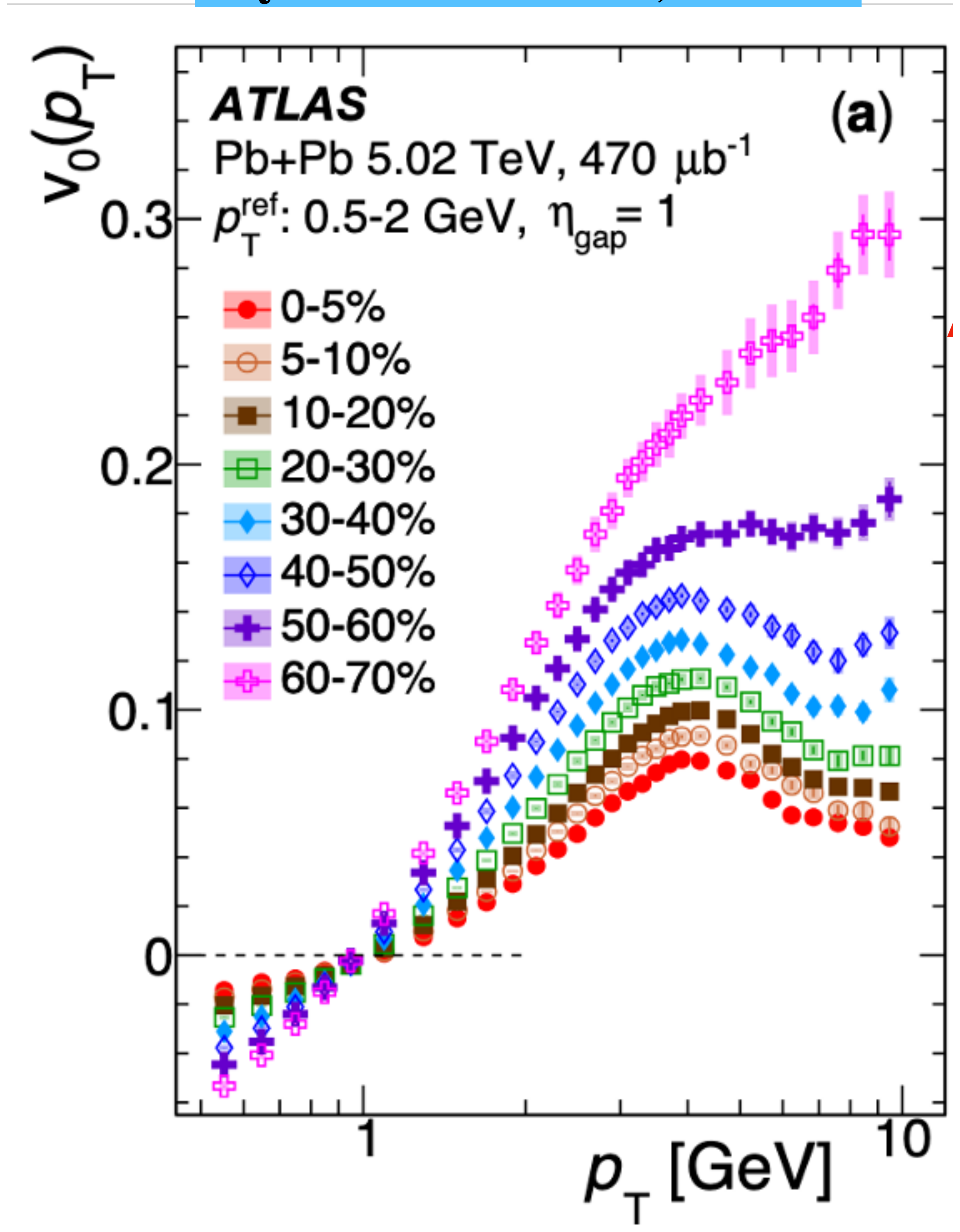
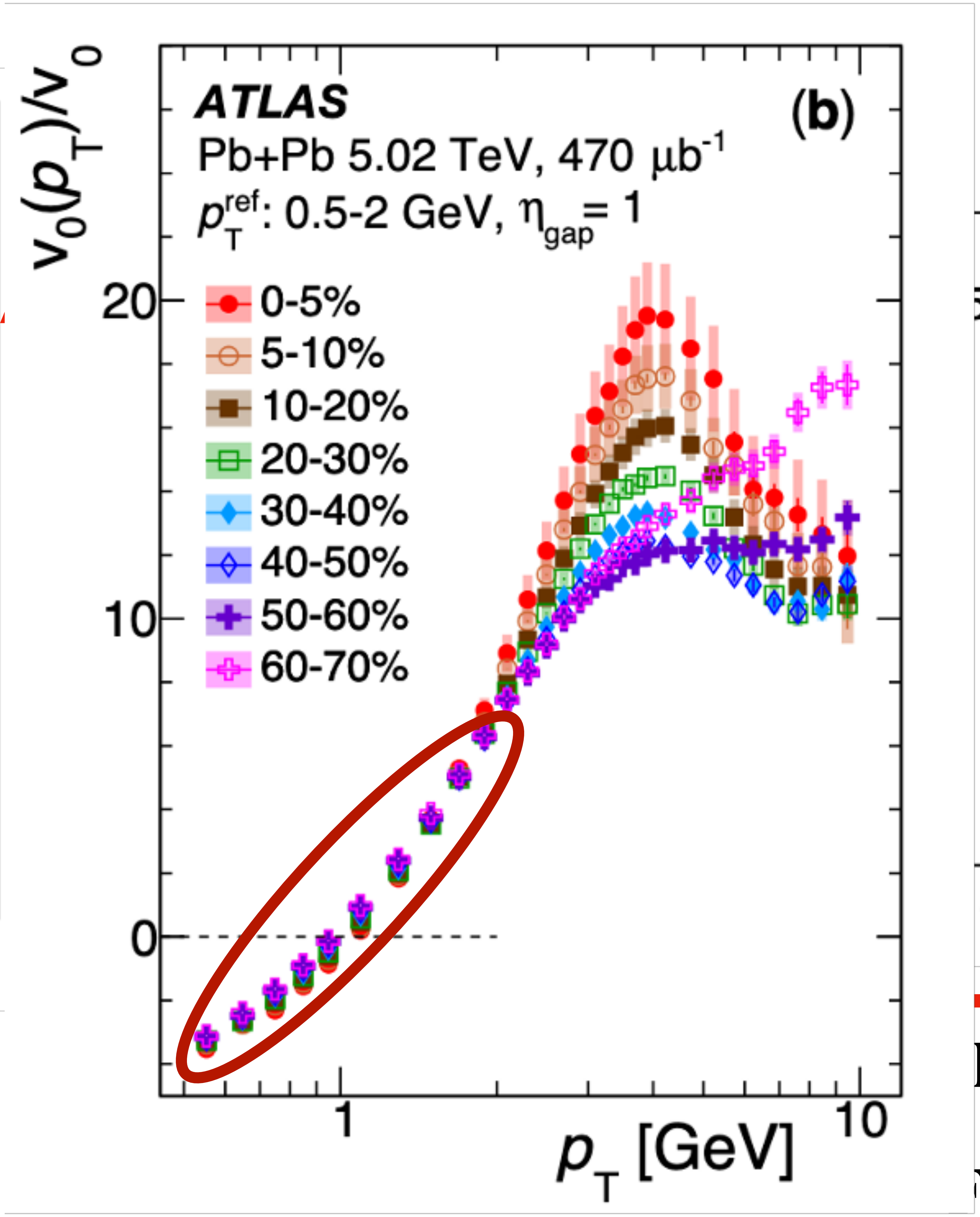
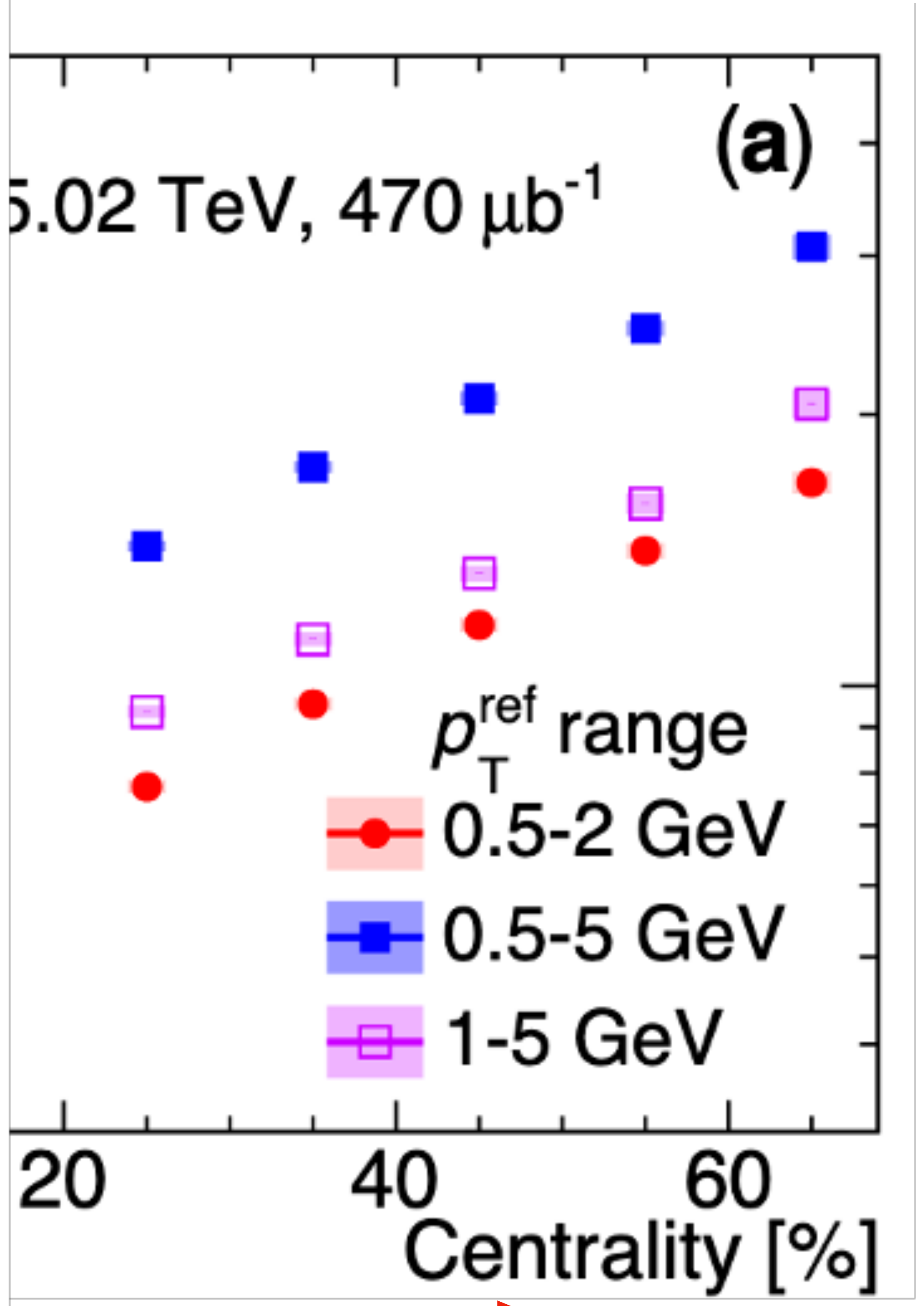




$v_0(p_T)/v_0$ **is independent of size of the fluctuations. Dependence on models of initial conditions is suppressed.**

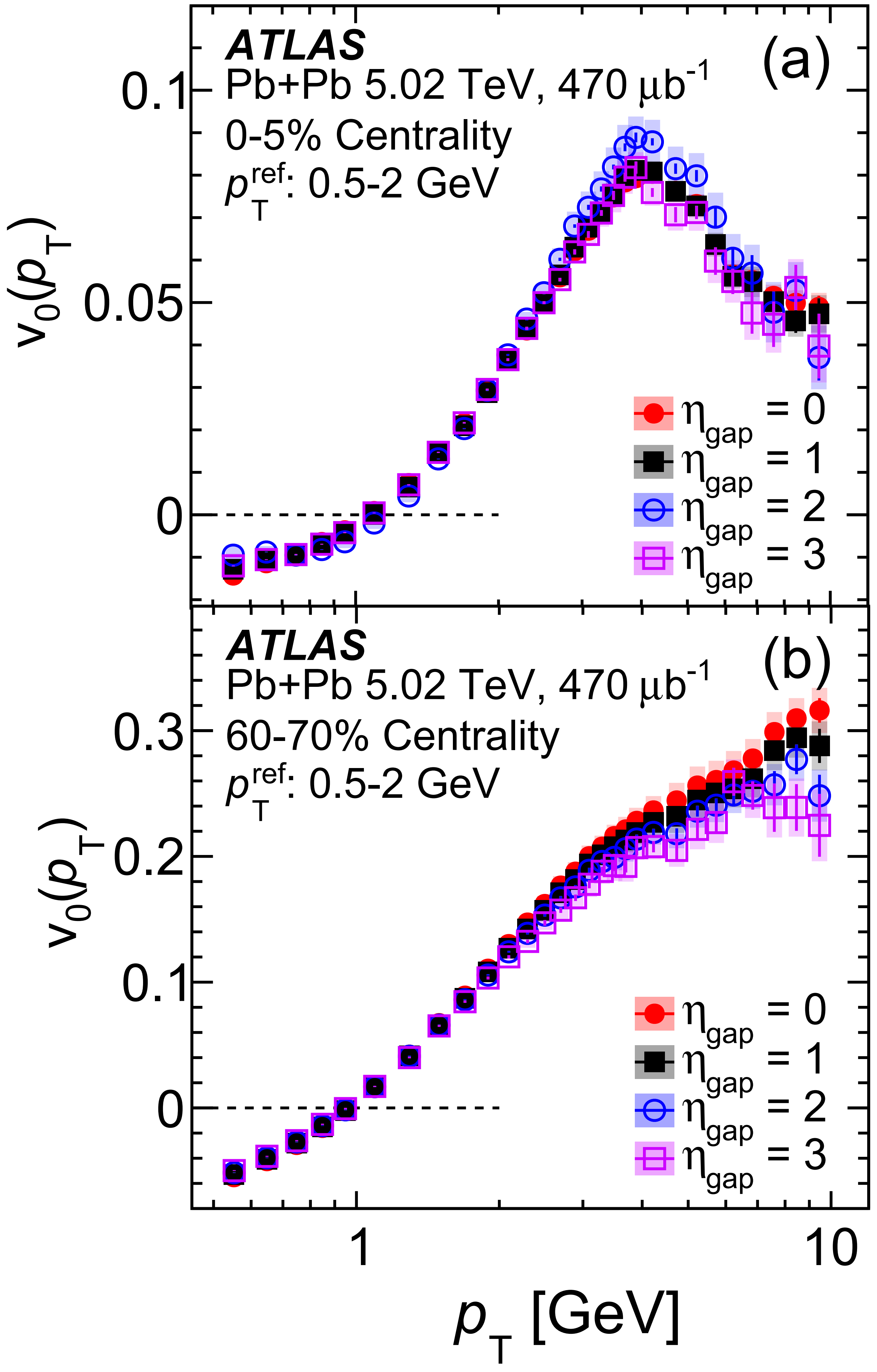


Multiplicity ↓

Fluctuations ↑

Hallmarks of Collectivity

Long-range nature:
$\Delta\eta$ independence



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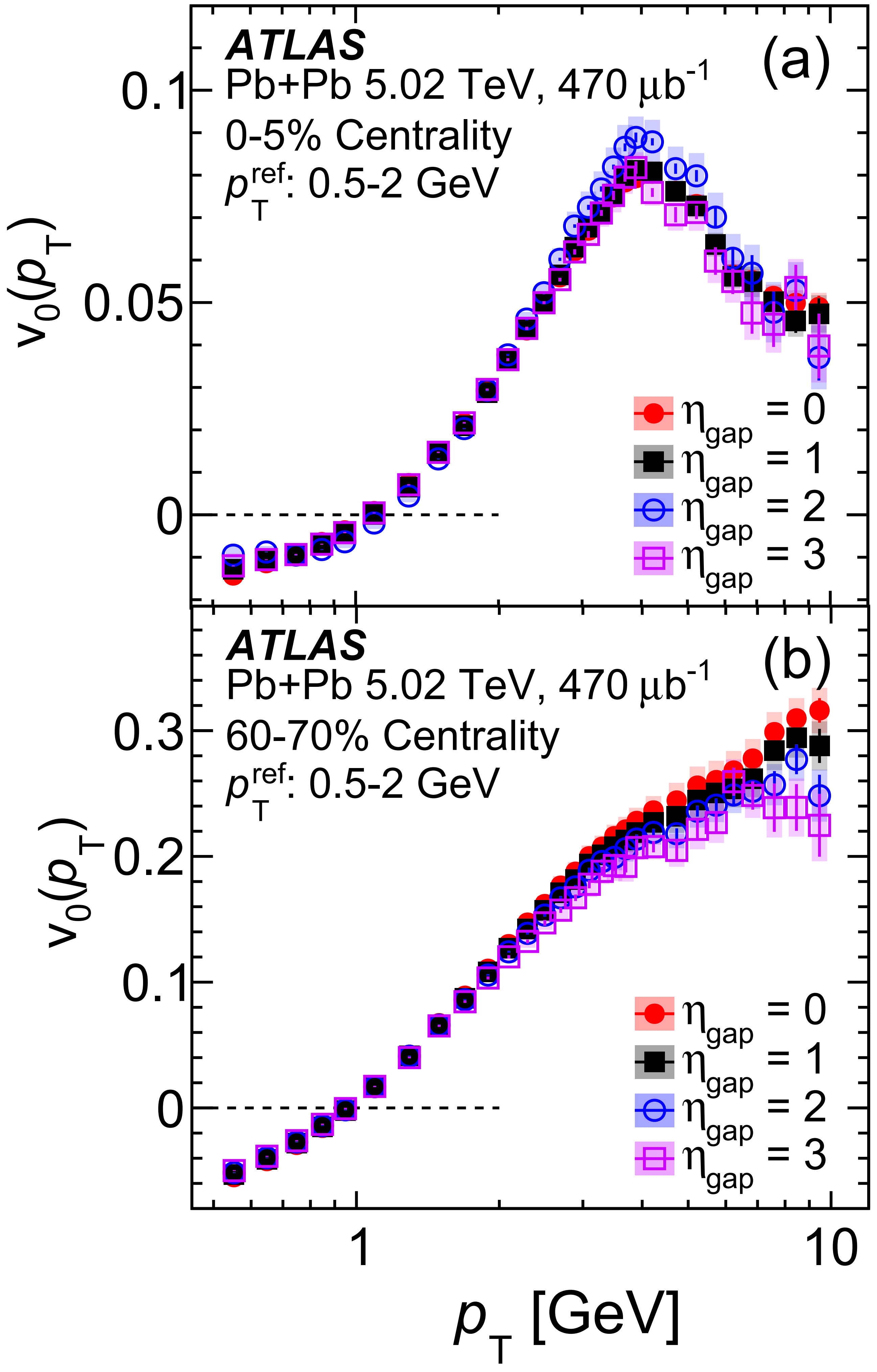
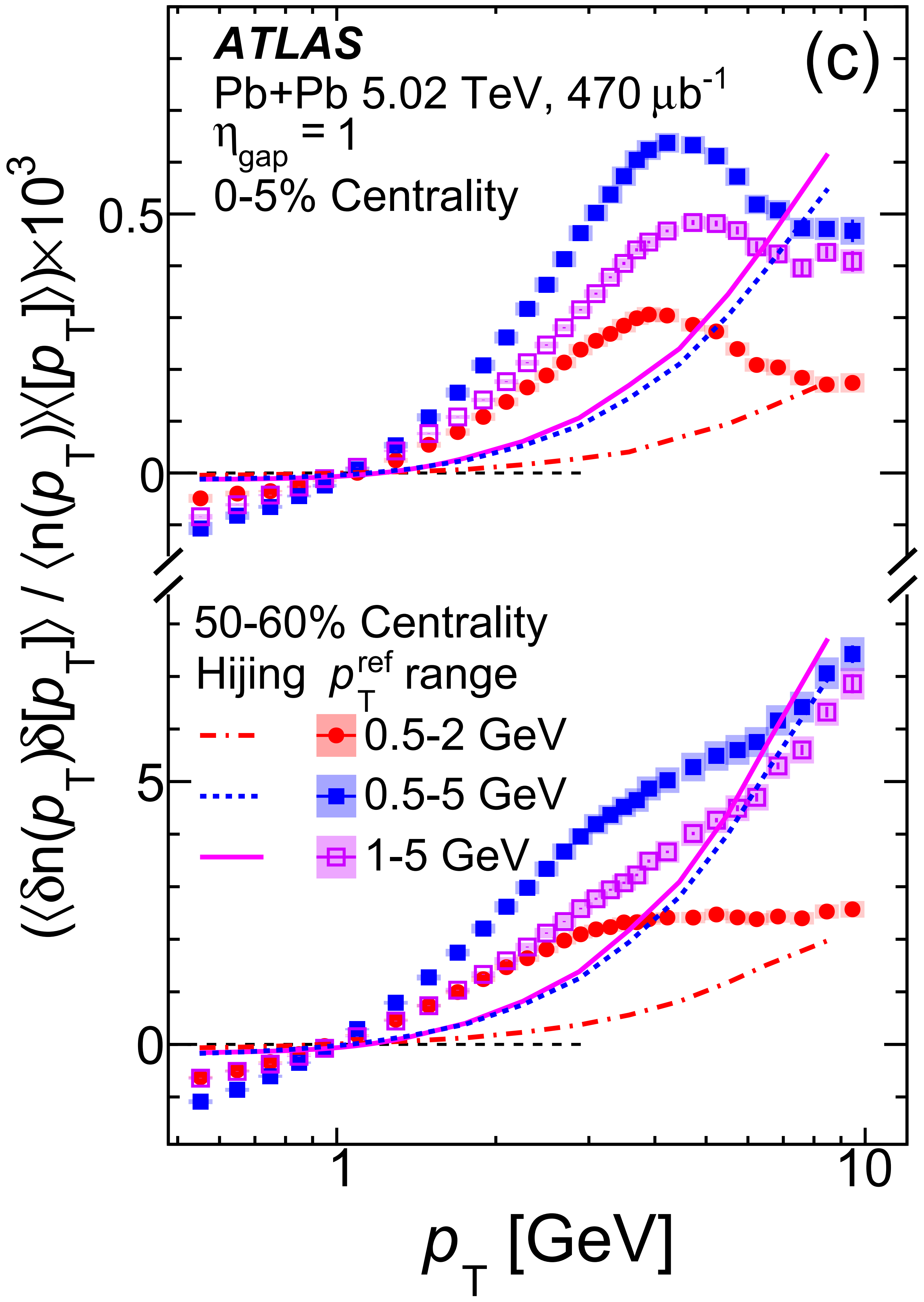


HIJING underpredicts strength of correlation



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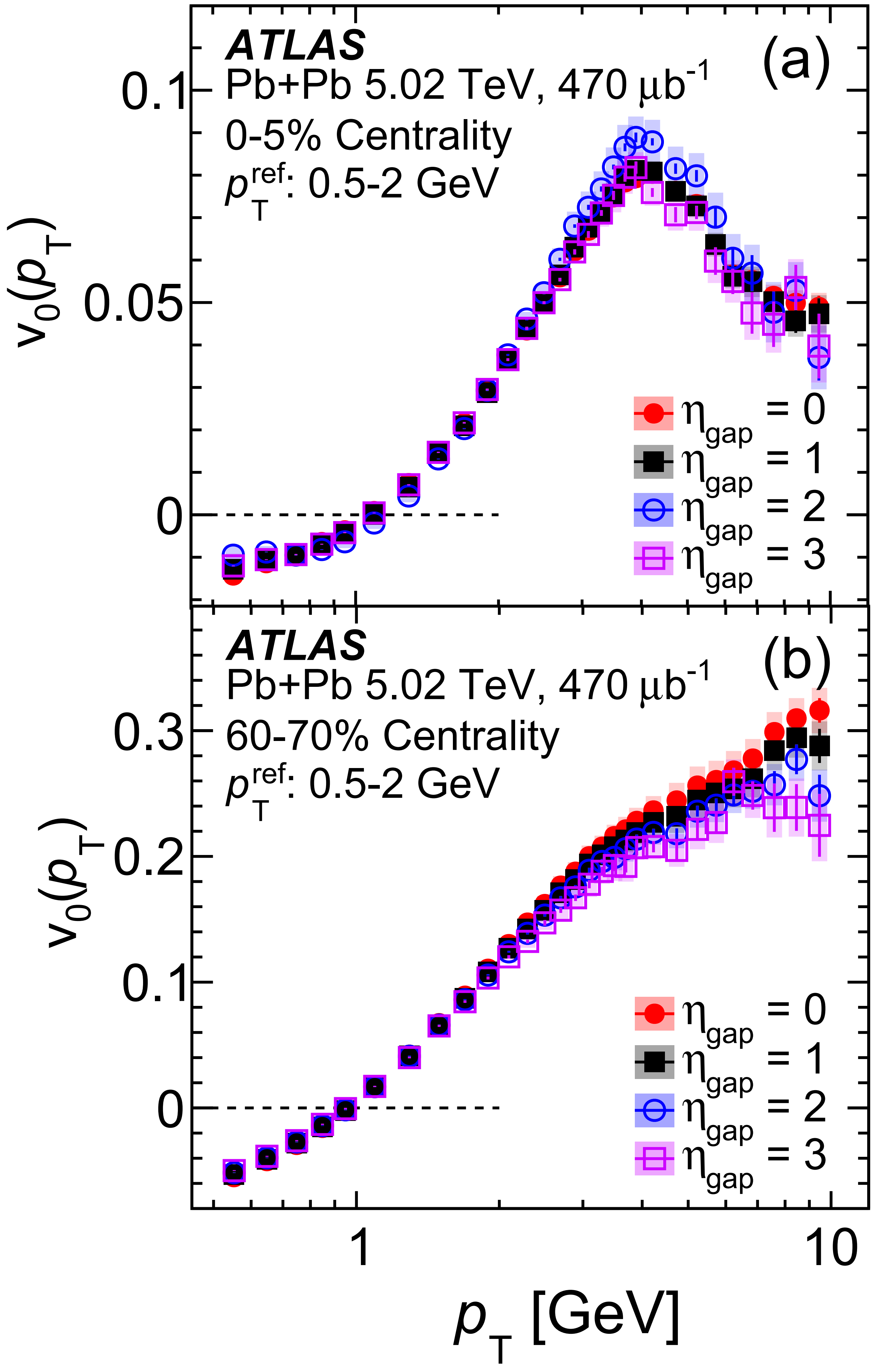

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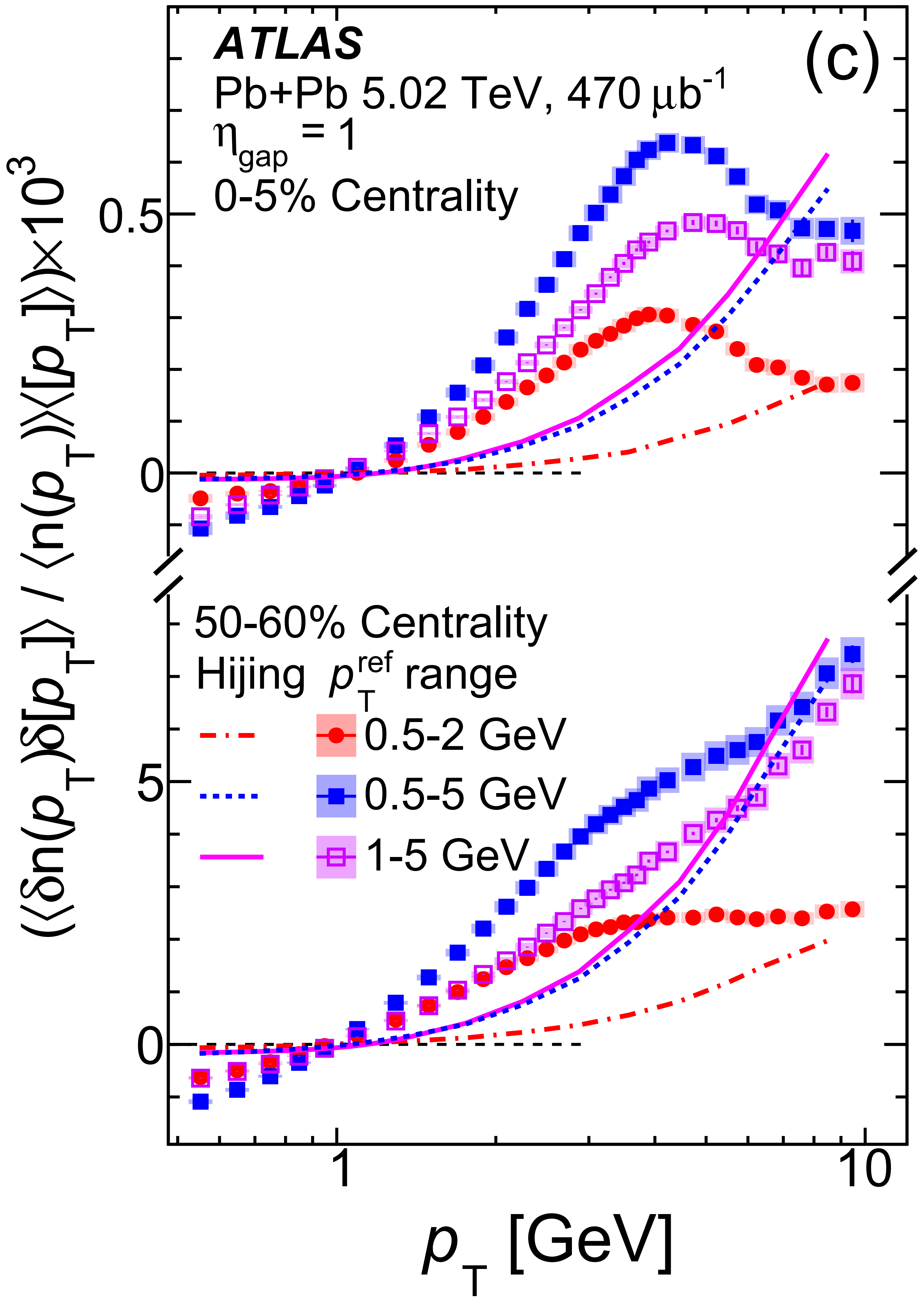
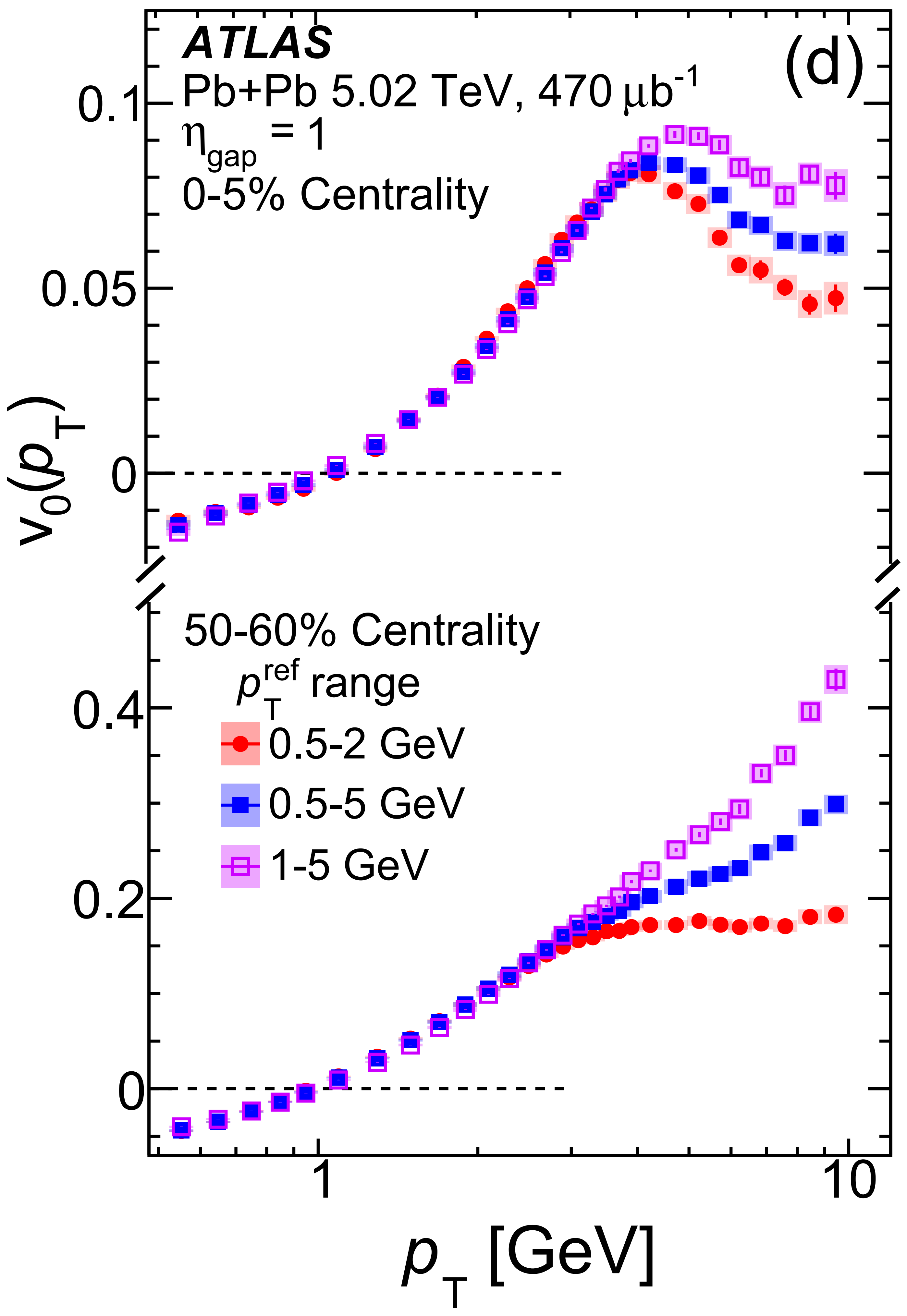
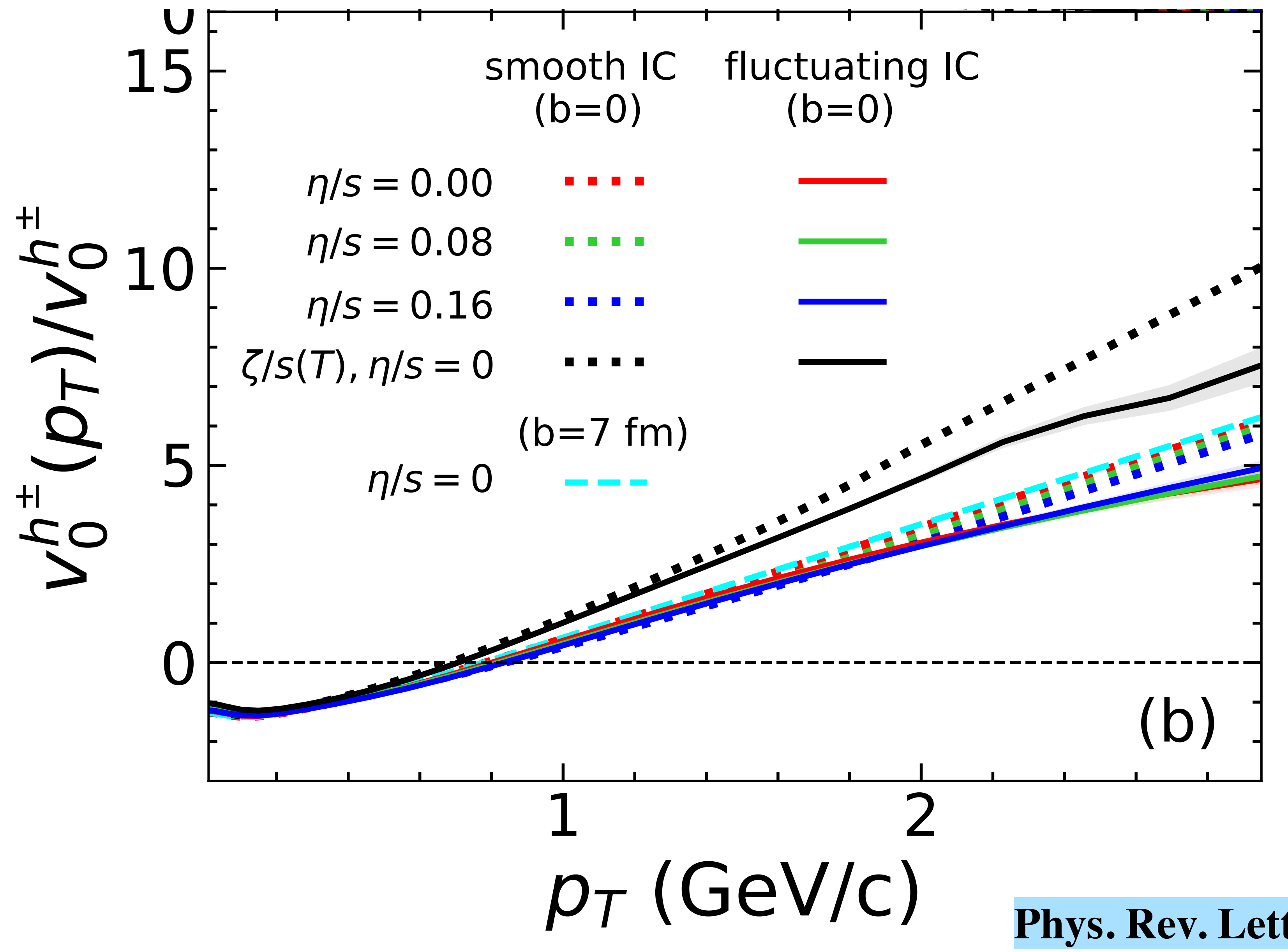


Factorization holds in flow dominated regime



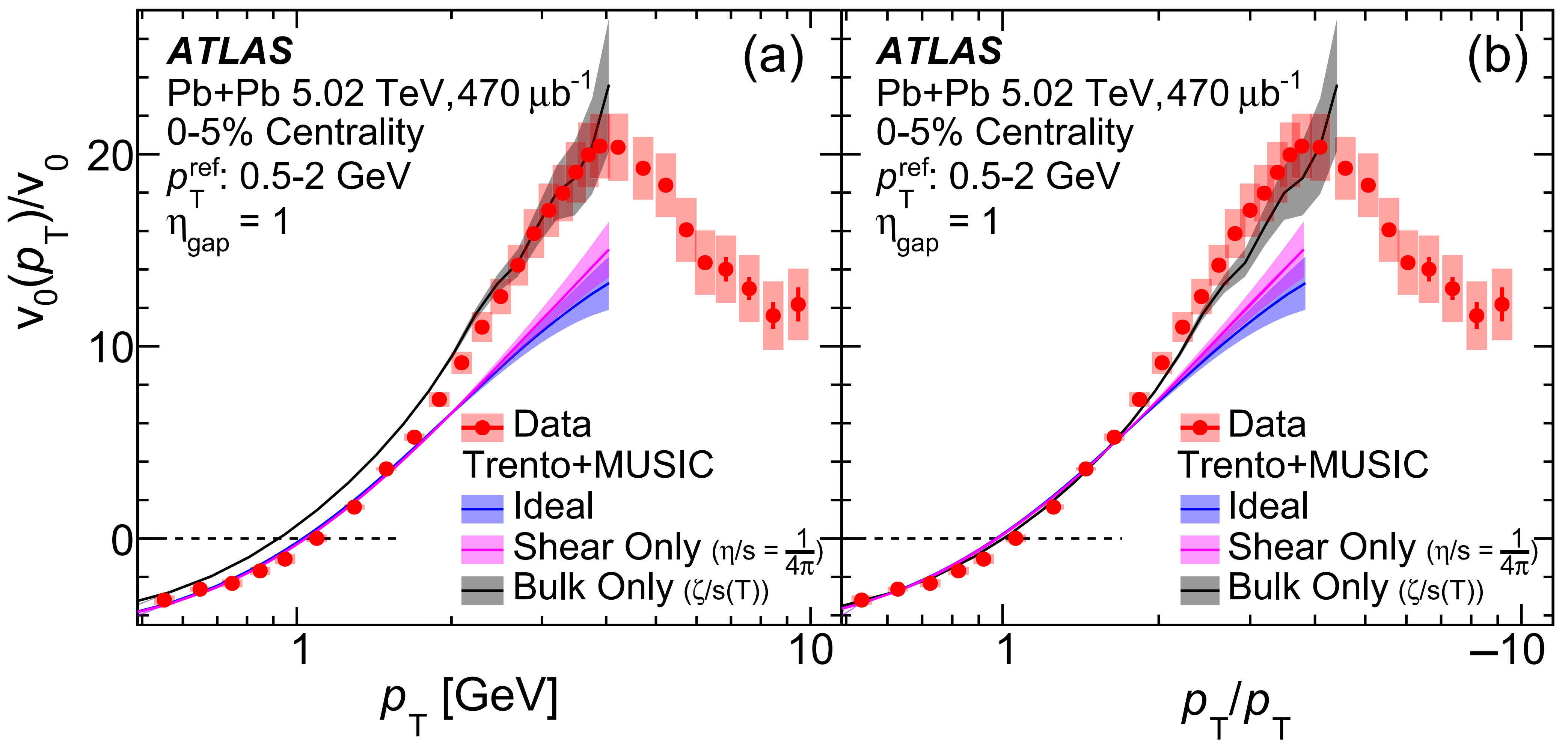
Hydro prediction for large systems

Ollitrault et.al: arXiv:2407.17313



- $v_0(p_T)/v_0$ **is independent of the modeling of initial density profile, also independent of centrality (multiplicity)**

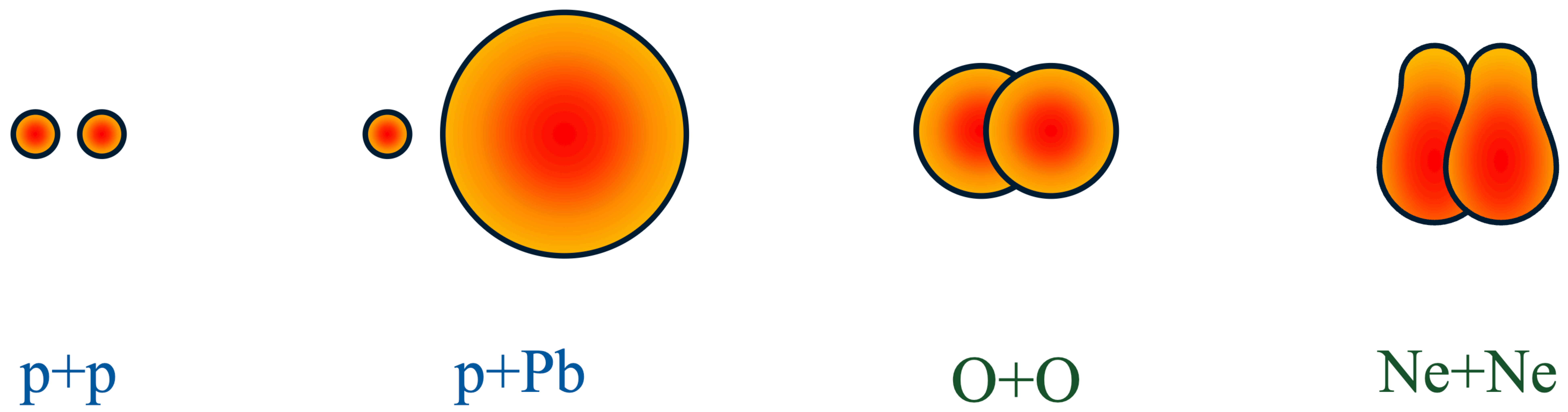
Phys. Rev. Lett. 136, 032301



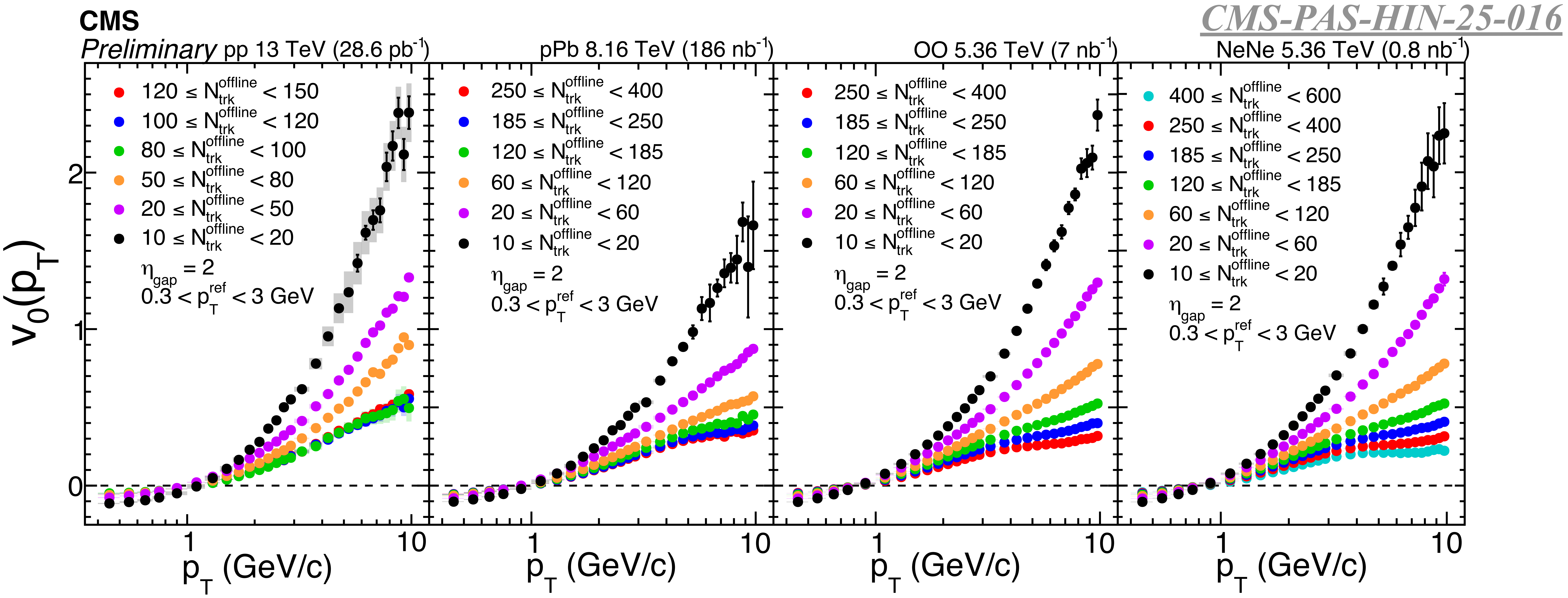
- **$p_T/\langle p_T\rangle$ reduces dependencies on model descriptions of $\langle p_T\rangle$**

The inevitable question

Is radial flow collective in small systems?

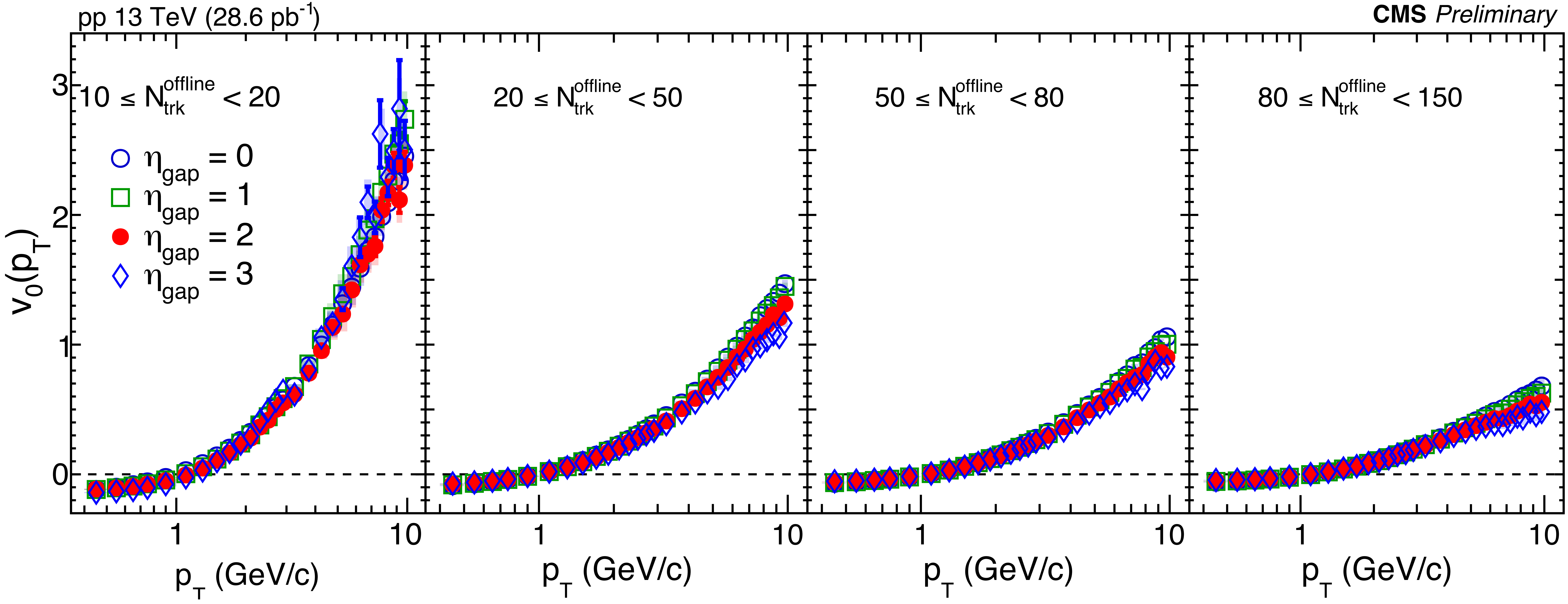


$v_0(p_T)$ results



- Increasing magnitude of $v_0(p_T)$ observed with decreasing multiplicity
- Sign change observed at near $<p_T>$ of the spectrum
- Splitting more cleaner in OO/NeNe compared to pp/pPb in HM range

Eta gap study: pp collisions



Nearly independent of η gap between subevents at low p_T

Hint of longitudinal decorrelation in 10-20 with $\eta_{gap} = 3$

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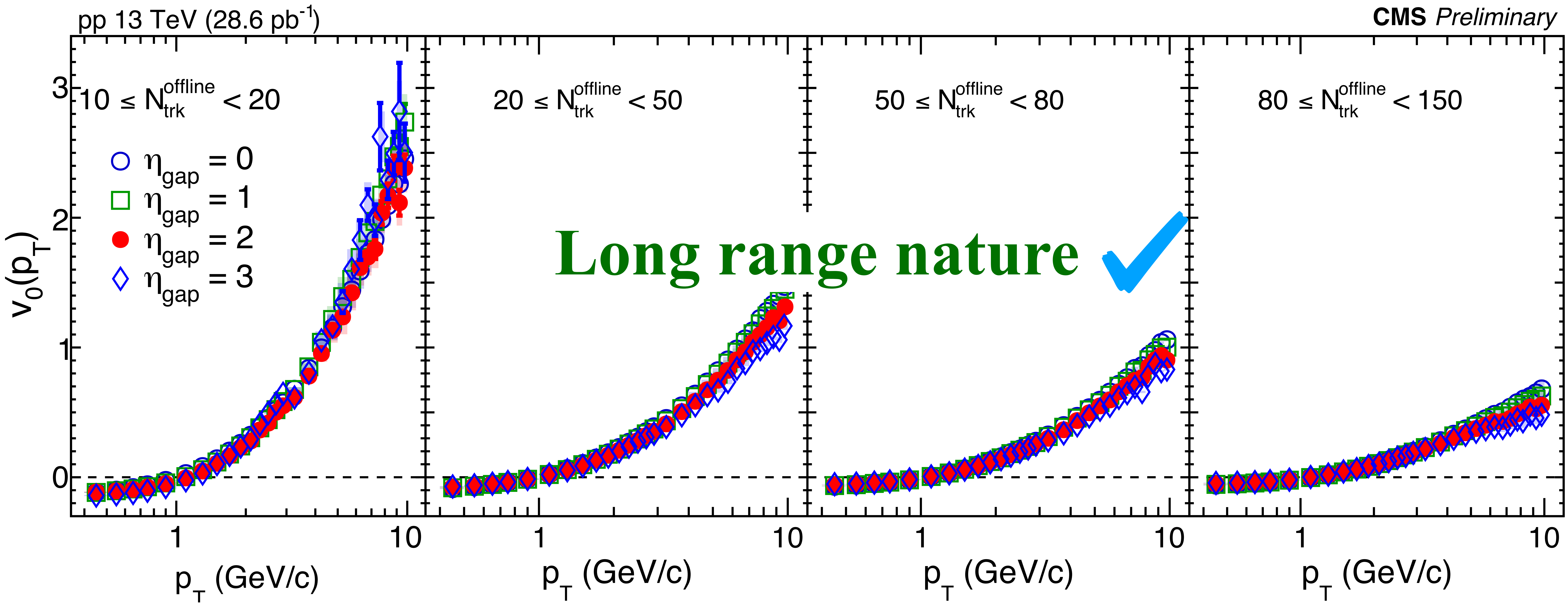

Nearly independent of η gap between subevents at low p_T

Hint of longitudinal decorrelation in 10-20 with $\eta_{gap} = 3$

Dependence on reference p_T range in pp

- $v_0(p_T)$ **nearly** p_T^{ref}**-independent upto ~3 GeV for HM pp**
- p_T^{ref} **of 1-5 GeV deviating in LM pp, opposite trend for 10-20**
- p_T^{ref} **of 0.3-3 are least affected by nonflow**

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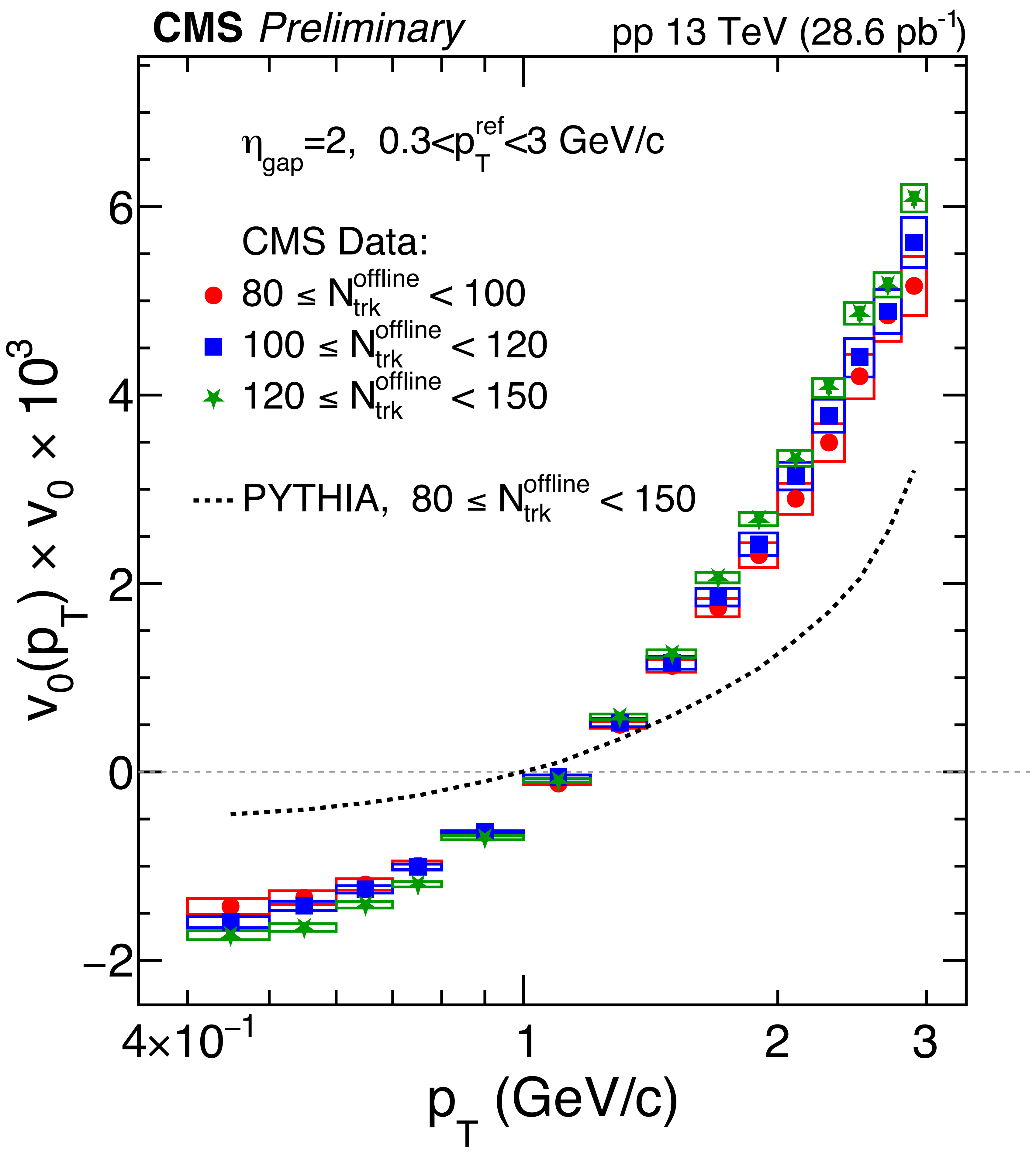
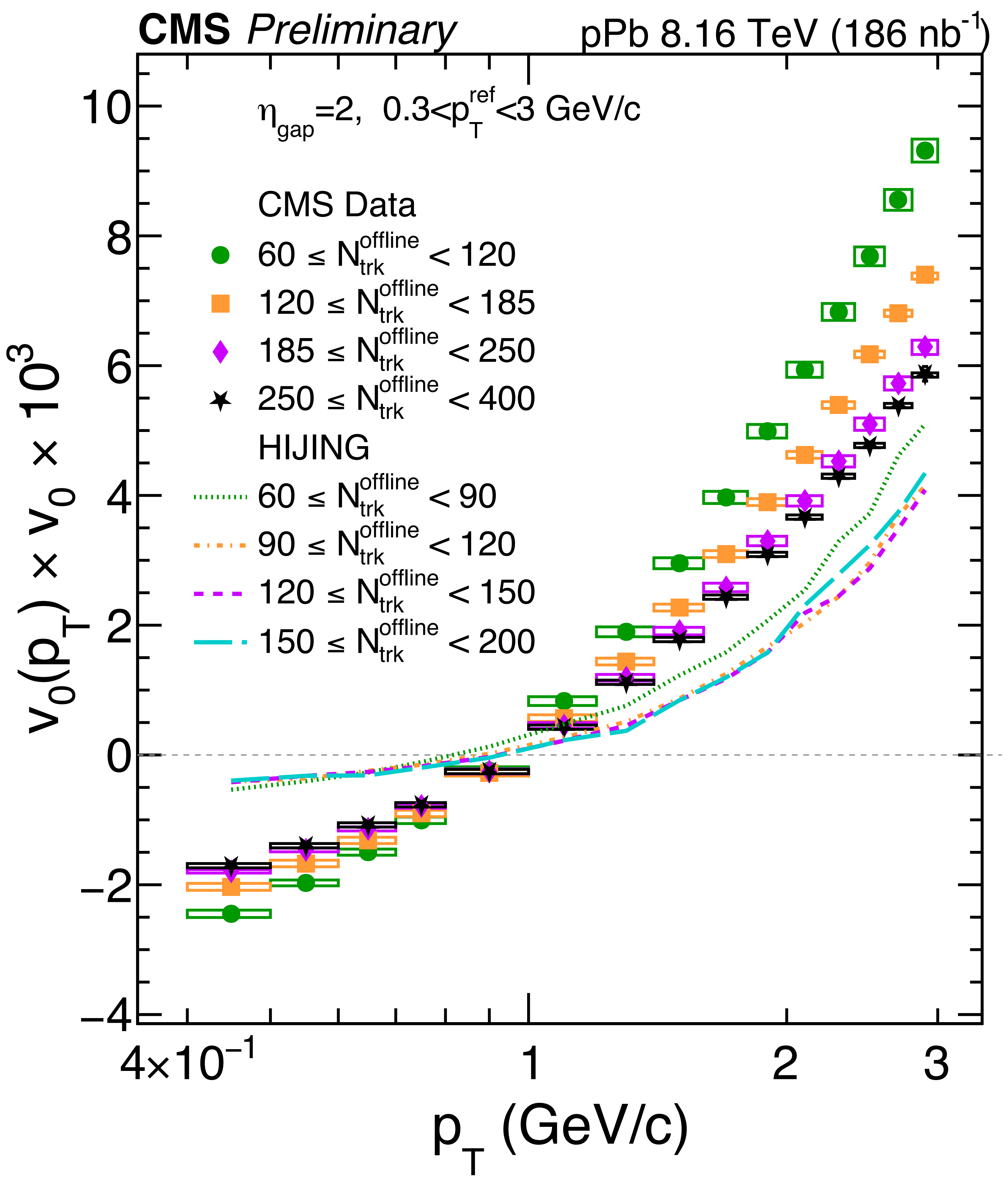
Studies in non-thermal models

v0(pT)·v0 gives the strength of the correlation





Both PYTHIA in pp and HIJING in pPb qualitatively underpredict the magnitude of v0(pT)·v0 measured in data

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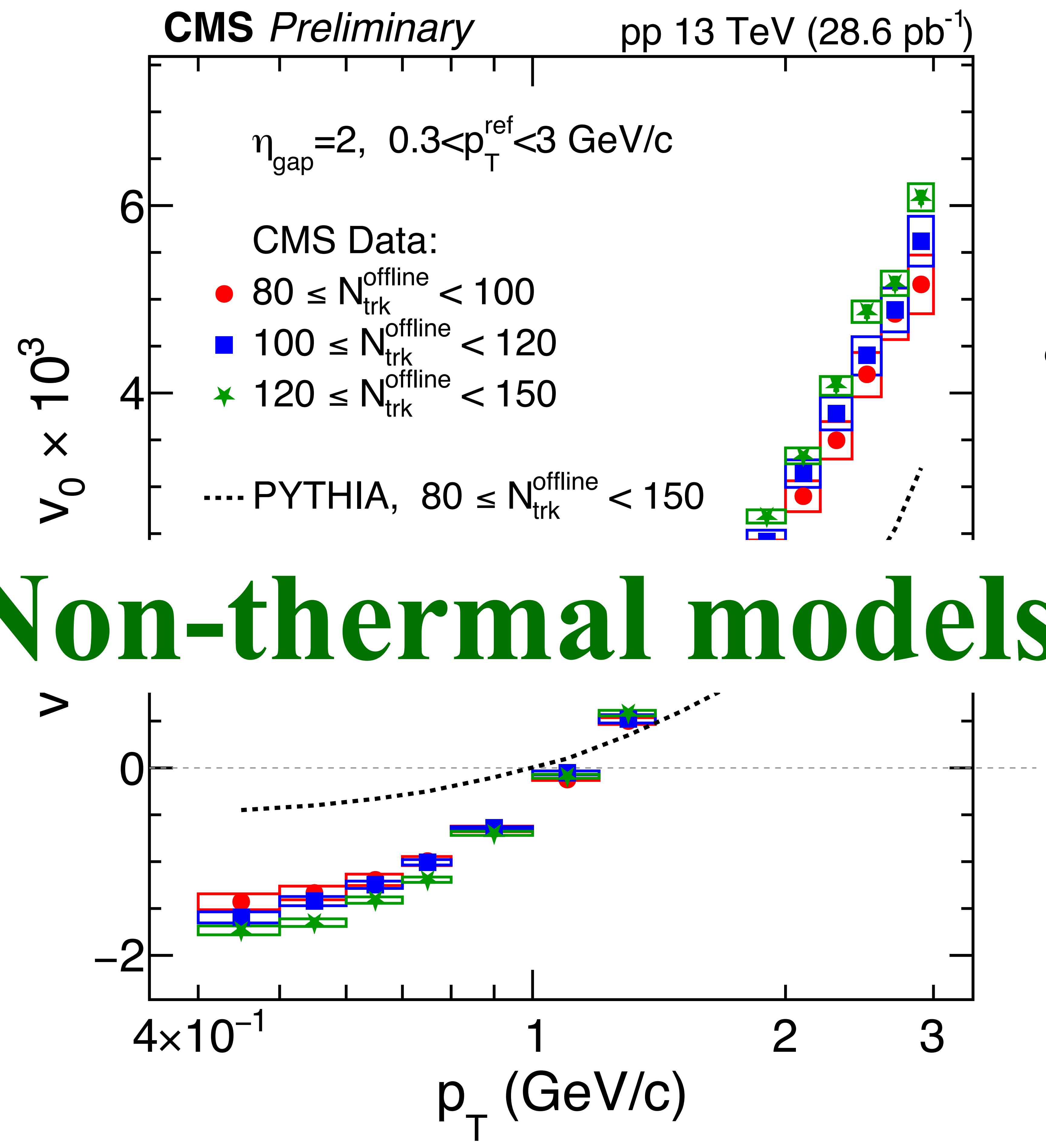

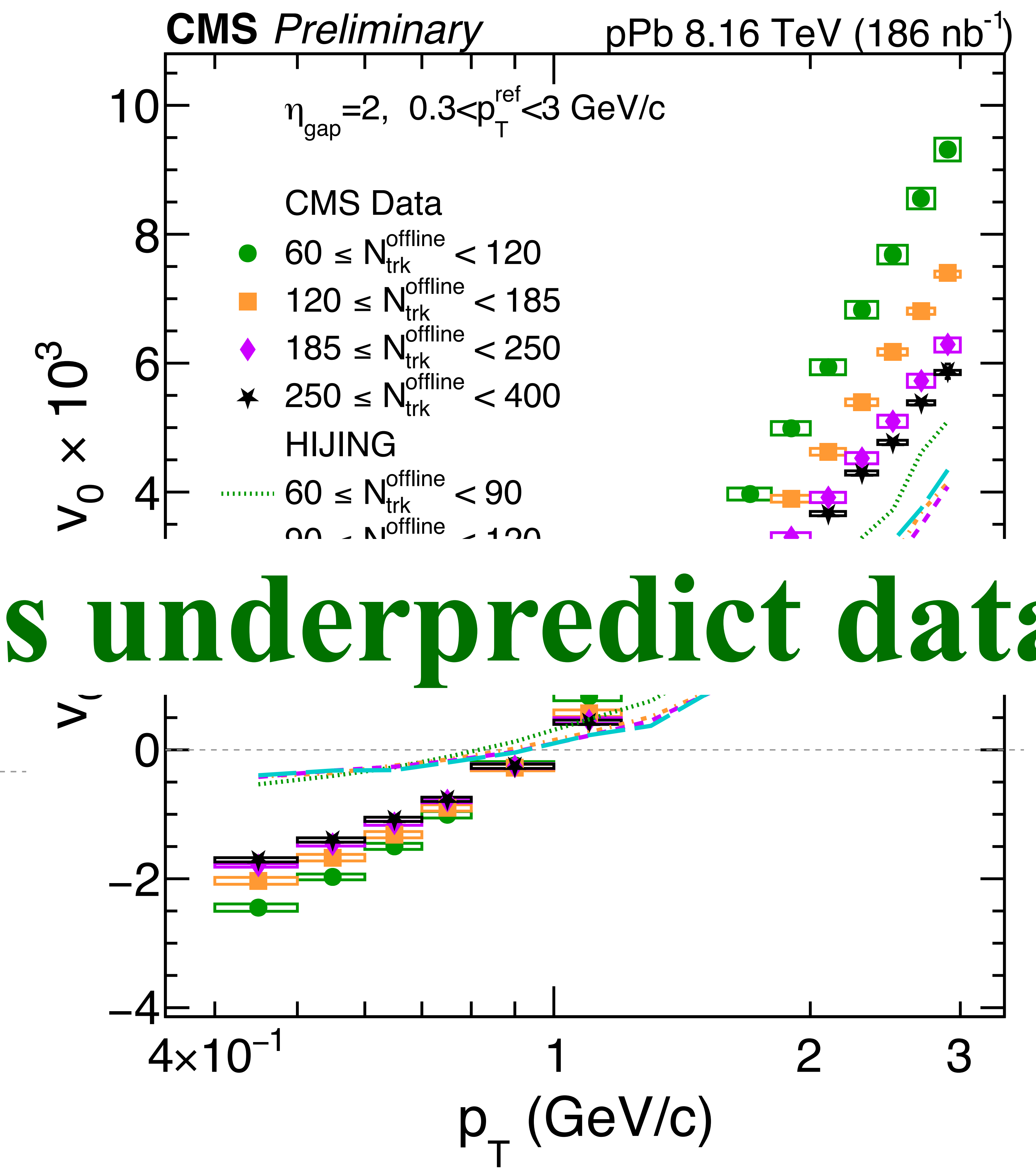

Non-thermal models underpredict data

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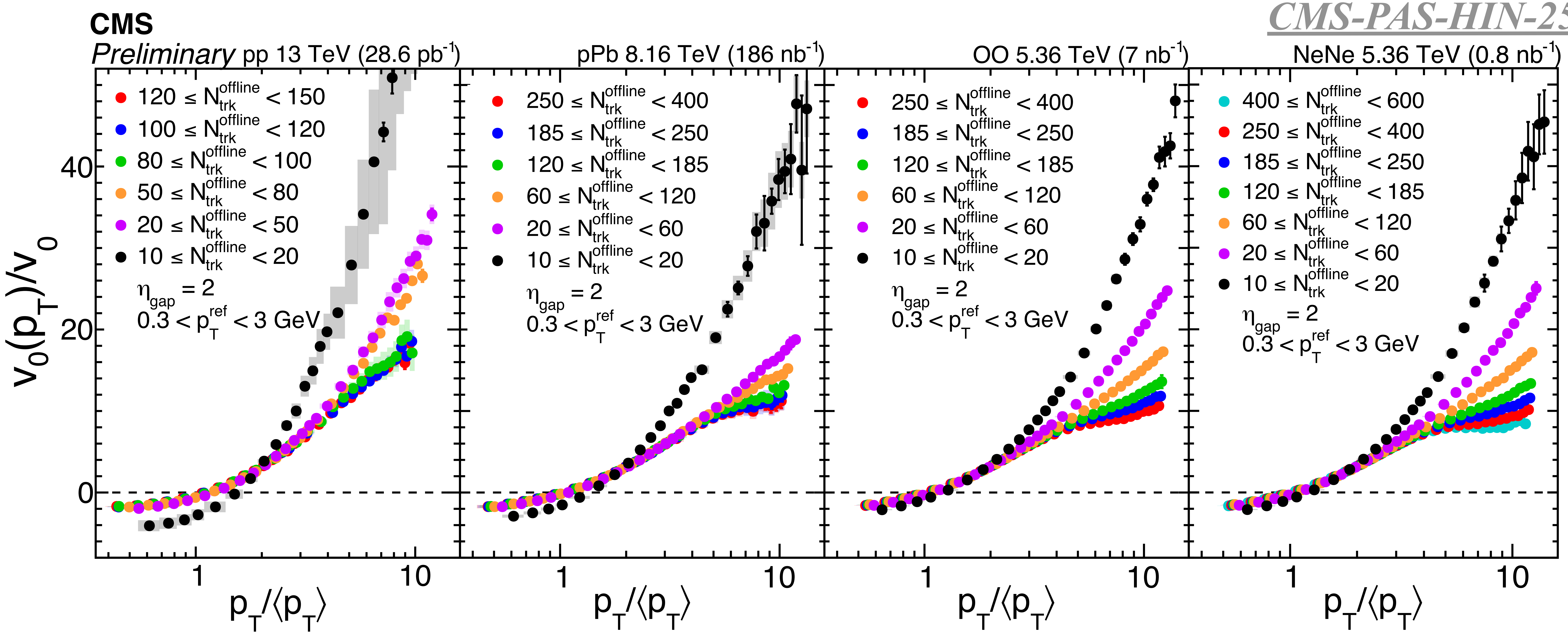
$v_0(p_T)$ normalized results

CMS-PAS-HIN-25-016



- Curves for different $N_{trk}^{offline}$ bin collapse onto a common shape at low p_T/ $<p_T>$
- The $10 \le N_{trk}^{offline} < 20$ bin deviates from this common shape, except in PbPb
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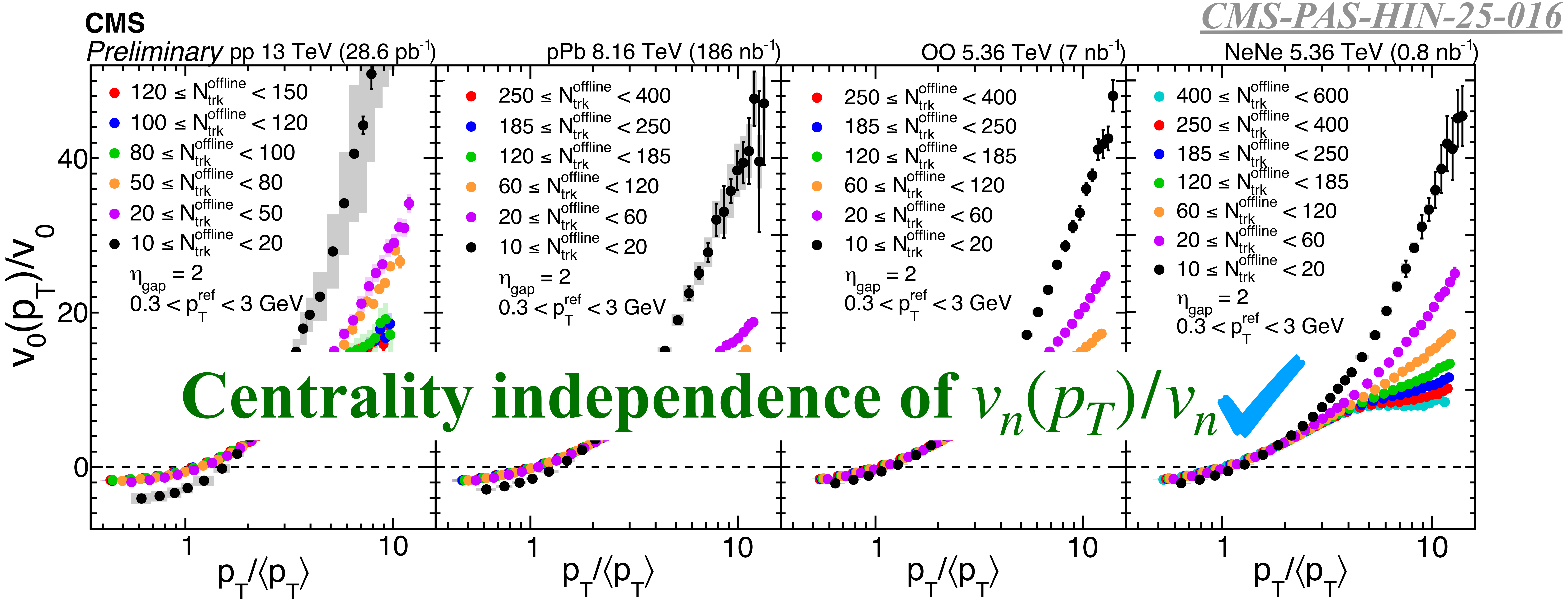
CMS-PAS-HIN-25-016



- **Curves for different $N_{trk}^{offline}$ bin collapse onto a common shape at low $p_T/ \langle p_T \rangle$**
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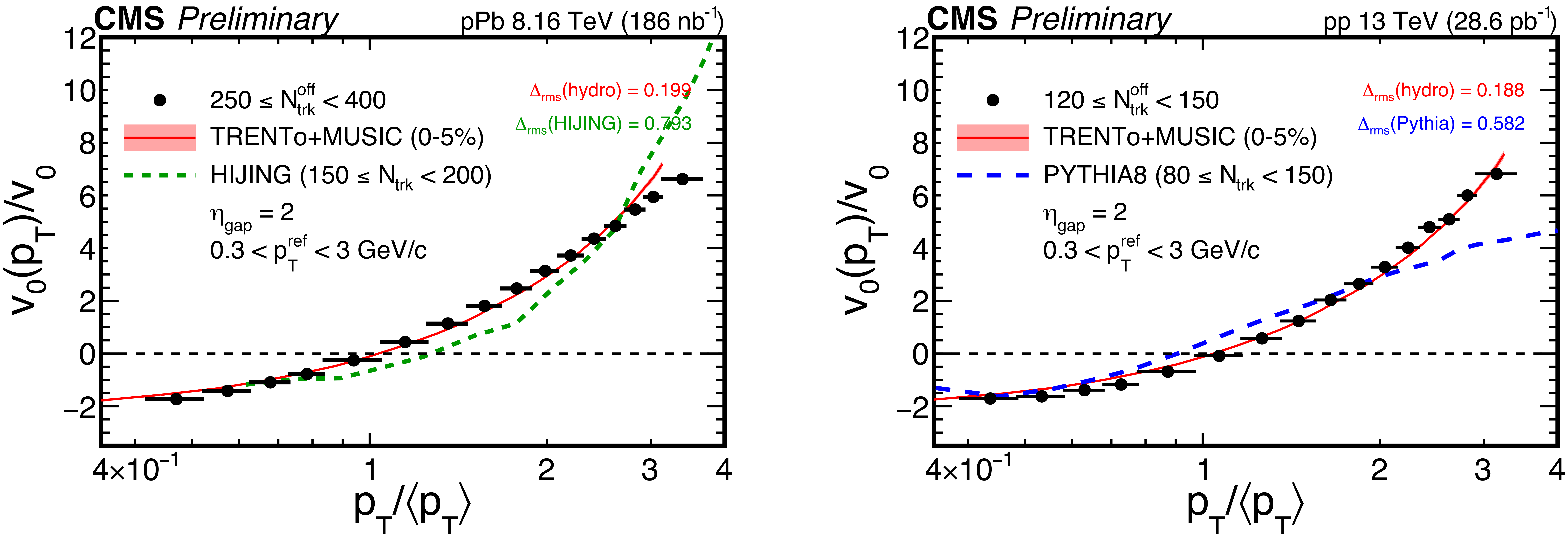
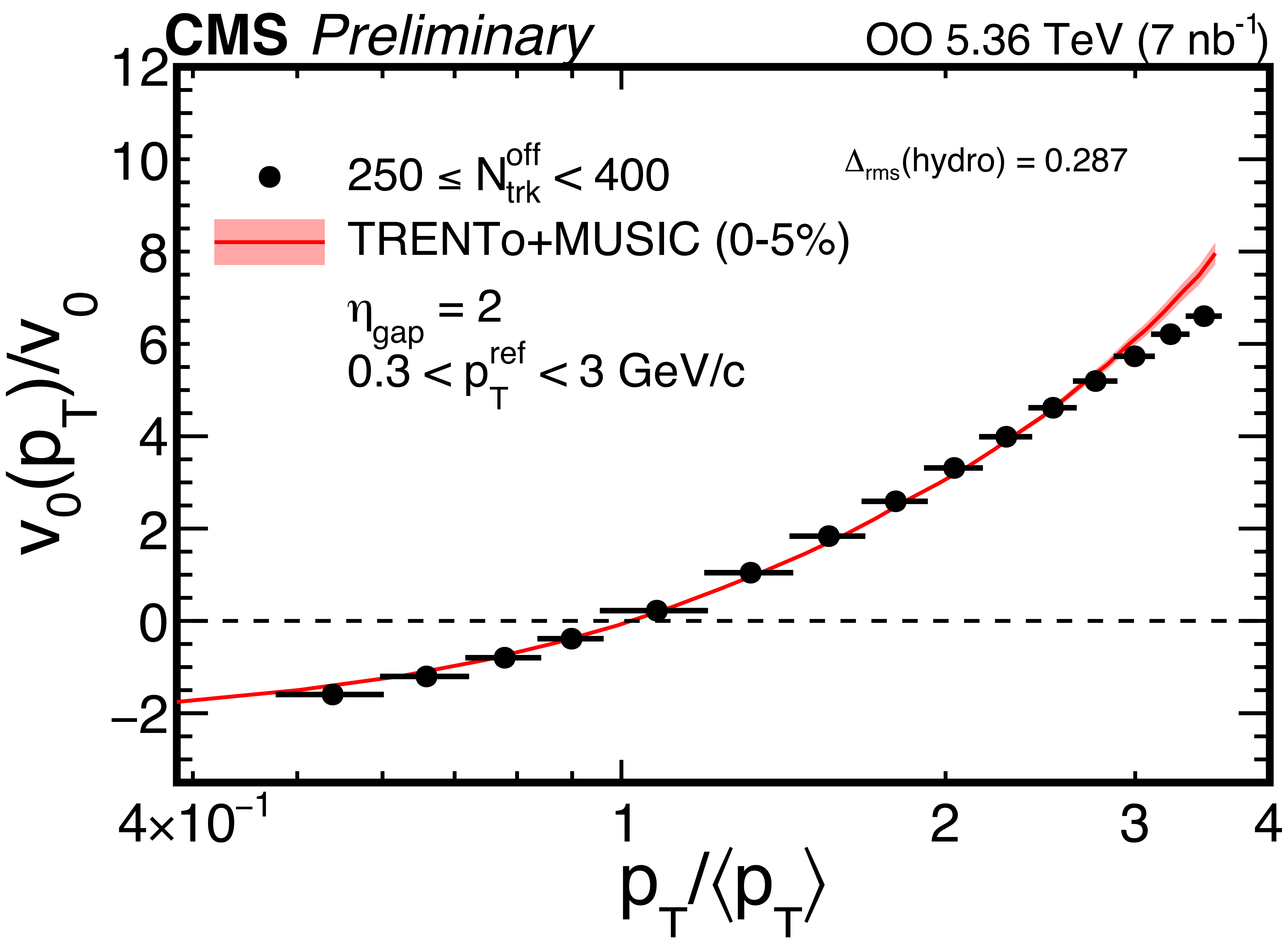
$v_0(p_T)$ norm results: Model comparison

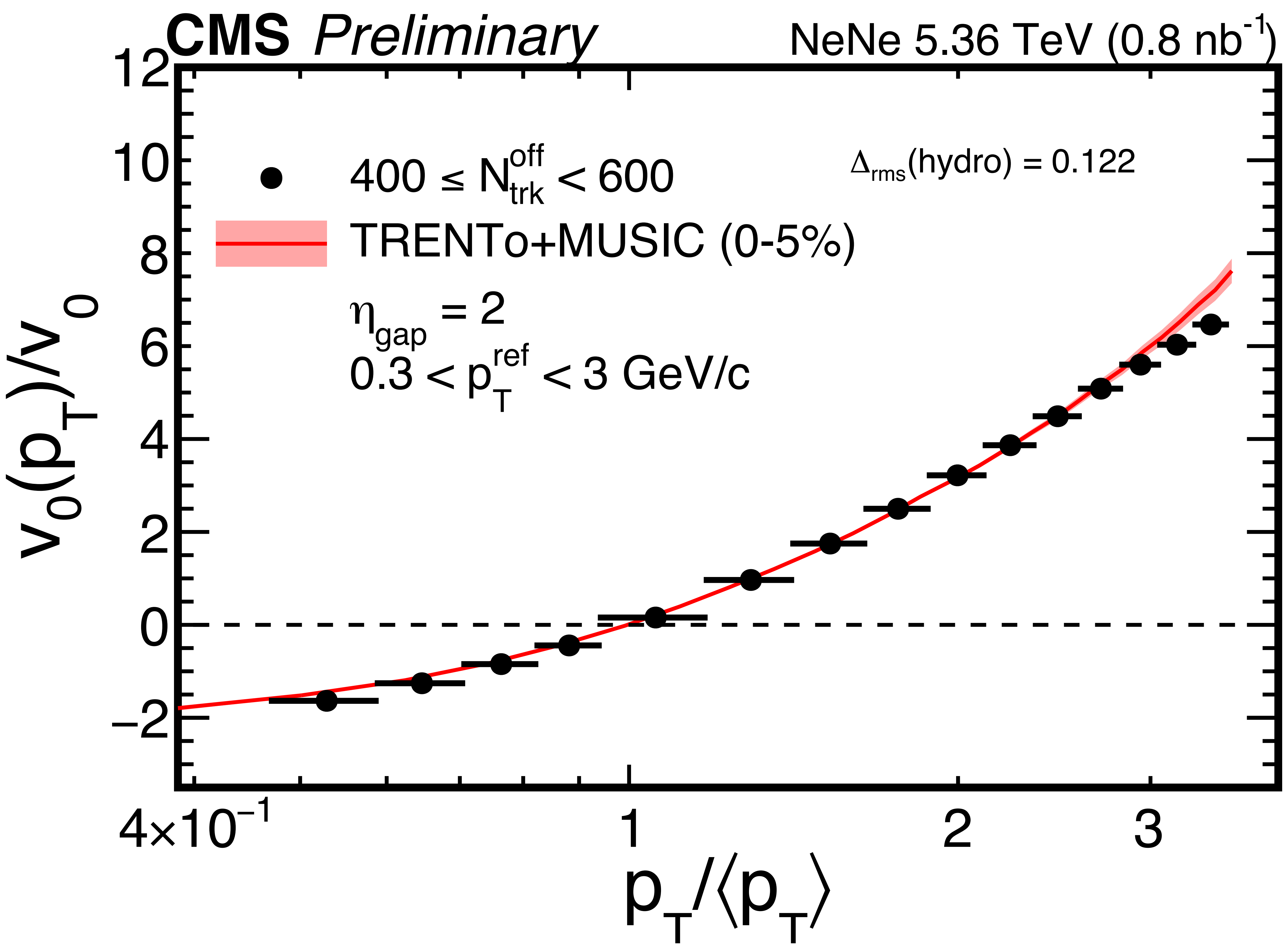


- **Comparison with TRENTo + MUSIC (hydro model) in pp and pPb**
- **Qualitatively good agreement observed between data and hydro model predictions till ~2.5 GeV**
- **Δ_{rms} value 5-7x larger for non-thermal models than hydro model**

$$\Delta_{\mathrm{rms}} = \sqrt{\frac{1}{N}\sum_j \left(\frac{y_j - f_{\mathrm{ref}}(x_j)}{f_{\mathrm{ref}}(x_j)}\right)^2}$$

$v_0(p_T)$ norm results: Model comparisons





- **Comparison with TRENTo + MUSIC (hydro model) in OO and NeNe**
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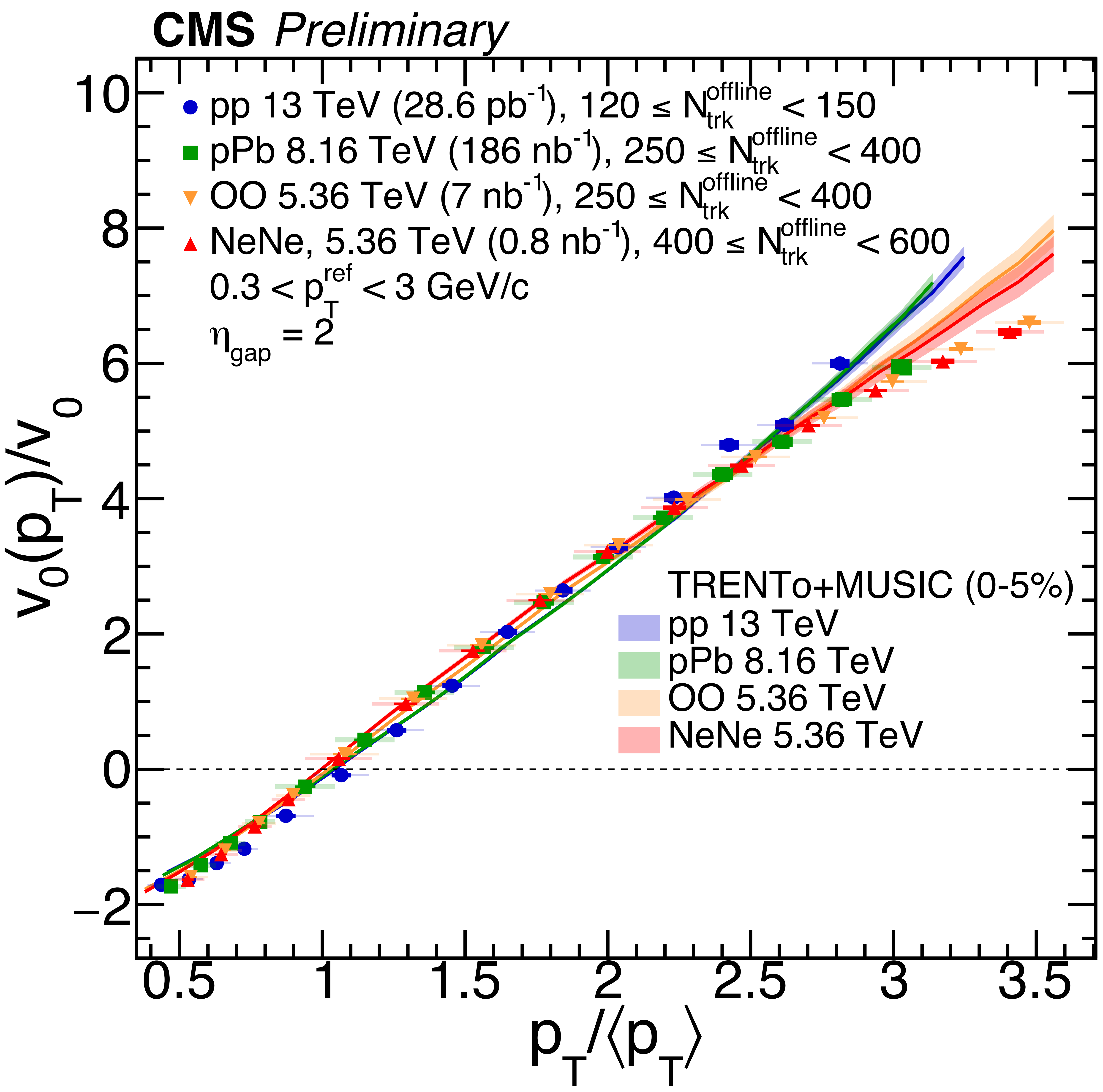
$$\Delta_{\rm rms} = \sqrt{\frac{1}{N}\sum_j \left(\frac{y_j - f_{\rm ref}(x_j)}{f_{\rm ref}(x_j)}\right)^2}$$

$v_0(p_T)$ norm results: Cross system comparison



The highest multiplicity bin of all systems following a universal curve as a function of $p_T/ \langle p_T \rangle$

Summary

- **First measurement of the** p_T**-differential radial flow fluctuations across different energies and systems**
- **Many hallmarks of collectivity observed above** $N_{trk}^{offline}$**>20 in small systems**
- **Non-thermal model underpredicts the strength of correlation in data**
- **Highest multiplicity bin compared with hydrodynamic predictions – all agreed well qualitatively**
- **Do we conclude that "Radial flow is collective in small systems" ?**

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Remaining hallmarks yet to be seen
Nonflow subtraction: Is η_{gap} enough?

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Nonflow subtraction: Is η_{gap} enough?

The results reveal strong signals of collectivity in small systems,
yet the nature of radial flow remains an open question.

Backup

Differential flow measurements: standard approach

JYO: Phys.Rev.C64:054901,2001

Phys.Rev.C83:044913,2011

POI = Particle of Interest

RFP = Reference Flow Particles ($0.3<p_T<3.0$)

2-particle

REFERENCE

Correlator $\langle\langle 2\rangle\rangle \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle$

Cumulant $c_n\{2\} = \langle\langle 2\rangle\rangle$

Flow $v_n\{2\} = \sqrt{c_n\{2\}}$

DIFFERENTIAL

Correlator $\langle\langle 2'\rangle\rangle \equiv \langle\langle e^{in(\phi_1'-\phi_2)}\rangle\rangle$

Cumulant $d_n\{2\} = \langle\langle 2'\rangle\rangle$

Flow $v_n'\{2\} = \dfrac{d_n\{2\}}{\sqrt{c_n\{2\}}}$

4-particle

REFERENCE

Correlator $\langle\langle 4\rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle$

Cumulant $c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle \cdot \langle\langle 2\rangle\rangle$

Flow $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$

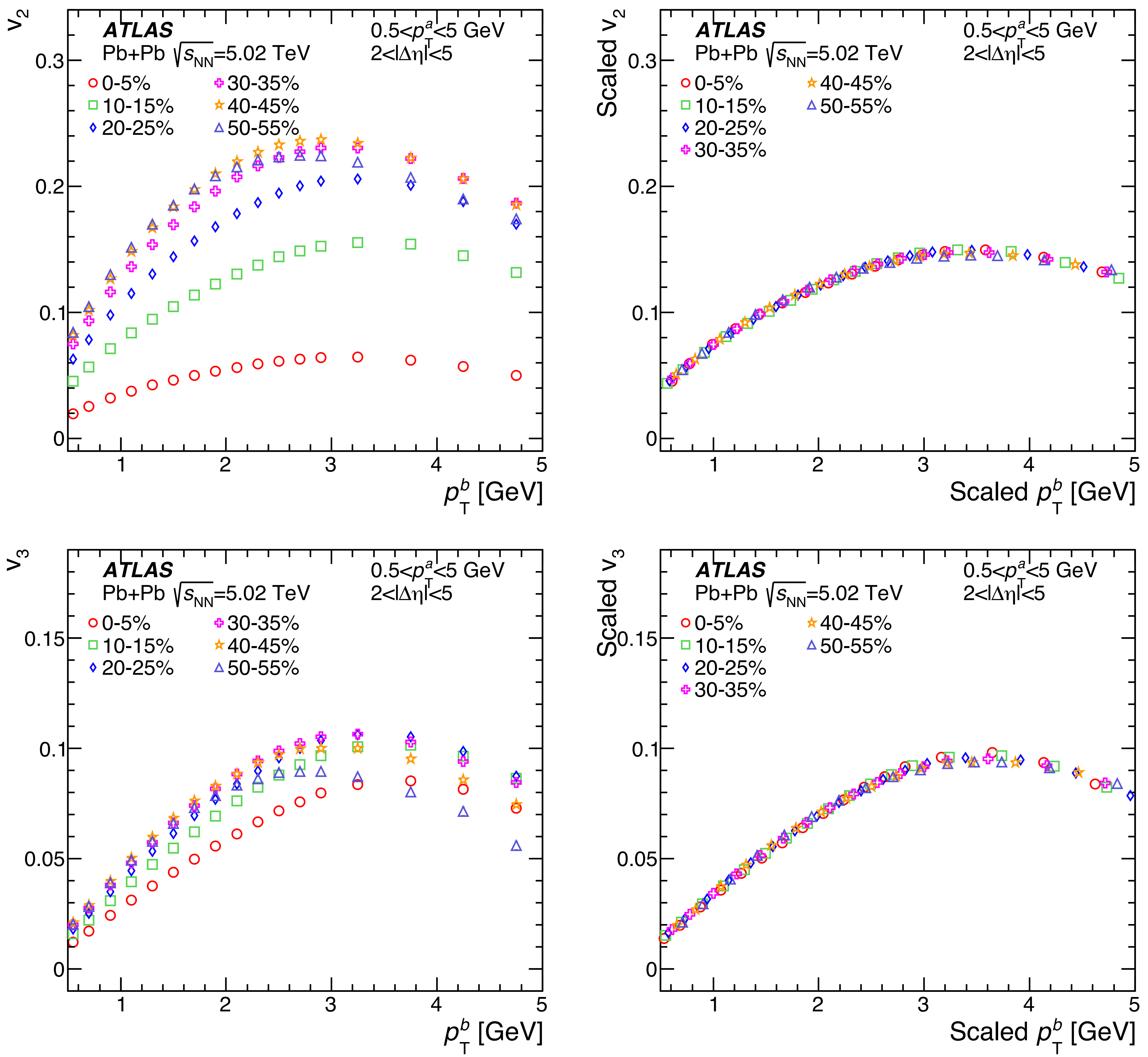
DIFFERENTIAL

Correlator $\langle\langle 4'\rangle\rangle \equiv \langle\langle e^{in(\phi_1'+\phi_2-\phi_3-\phi_4)}\rangle\rangle$

Cumulant $d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\langle\langle 2'\rangle\rangle \cdot \langle\langle 2\rangle\rangle$

Flow $v_n'\{4\} = -\dfrac{d_n\{4\}}{(-c_n\{4\})^{3/4}}$

Scaled differential flow



Once scaled by the integrated flow, the result is centrality independent (here, the x axis is also rescaled)