Evidence For the Collective Nature of Radial Flow in Pb+Pb Collisions with ATLAS.

-Is radial flow collective?

arXiv: 2503.24125

Somadutta Bhatta
(for the ATLAS Collaboration)
Stony Brook University

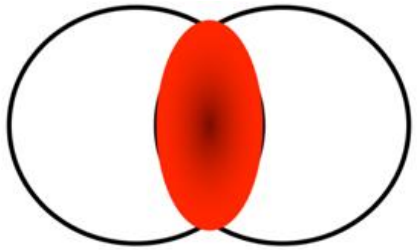
Quark Matter 2025, Frankfurt, Germany

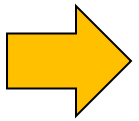
ATLAS EXPERIMENT

Stony Brook University

QM25

Anisotropic flow and Radial flow





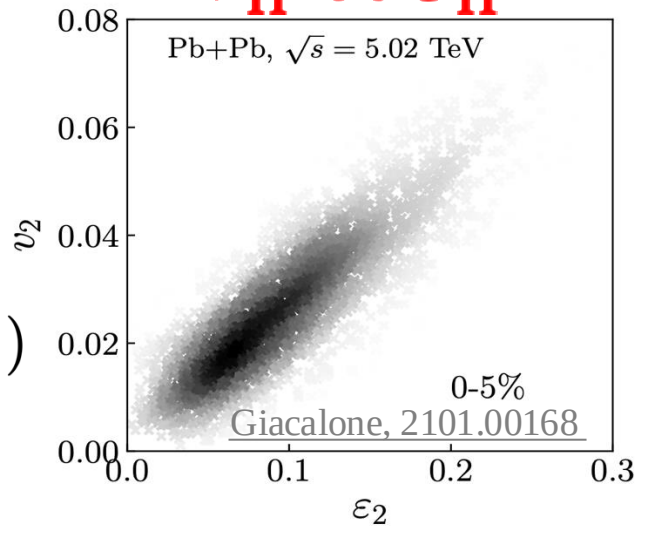
Shape $\varepsilon_n \propto \langle r_\perp^n e^{in\phi} \rangle$

Size $R_\perp^2 \propto \langle r_\perp^2 \rangle$

$$\frac{d^2N}{d\phi dp_T} = N(p_T)\,(1 + 2\Sigma_{n\geq 1} v_n \cos(n(\phi - \Psi_n))$$

Two types of collectivity: Radial flow v_0 Anisotropic flow v_n

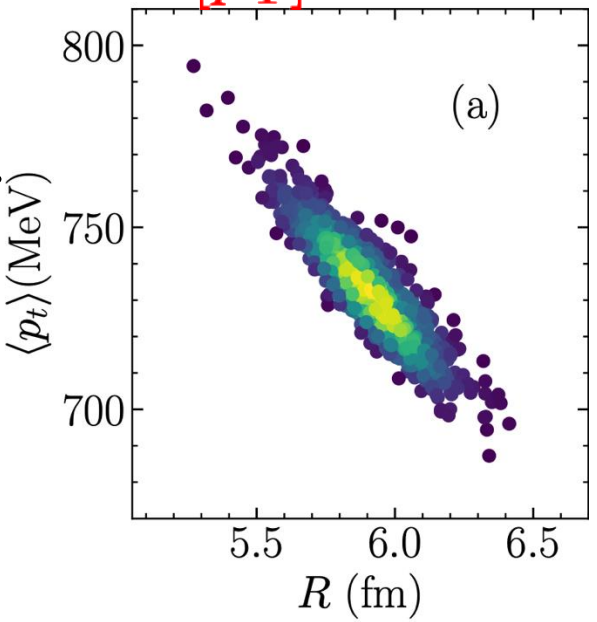
$\mathbf{v_n \propto \varepsilon_n}$



Sensitive to Initial Conditions

- Overlap "Shape" and its fluct. controls anisotropic flow fluctuations.
- Overlap "Size" and its fluct. leads to spectra fluctuations: radial flow.

$\delta[p_T] \propto -\delta R$



Giaacaalone et. al, PRC 103, 024909 (2021)

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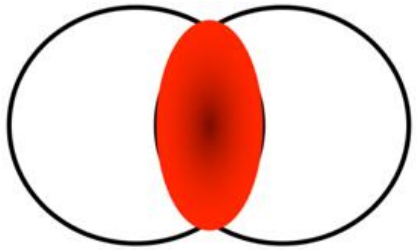

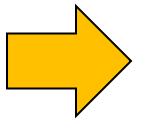

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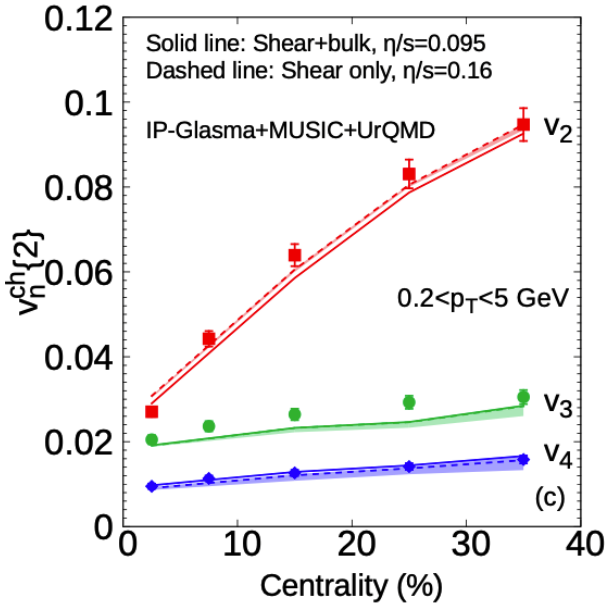

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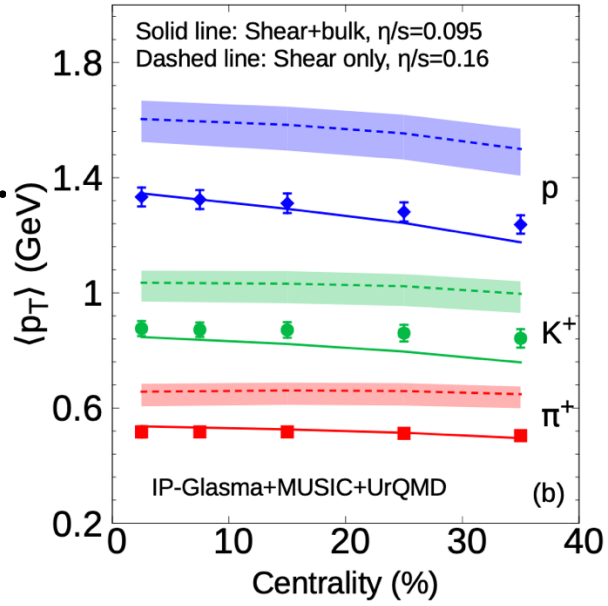

Sensitive to QGP transport properties

- Anisotropic flow sensitive to shear (η/s) and bulk (ζ/s) viscosities
- Radial flow is very sensitive to ζ/s.
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S. Ryu et. al, PRL. 115 (2015) 13, 132301

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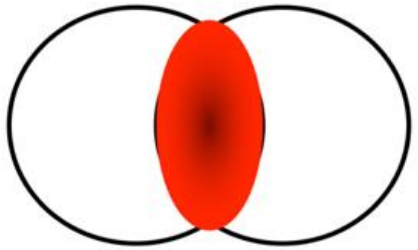

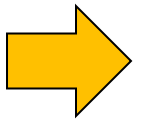

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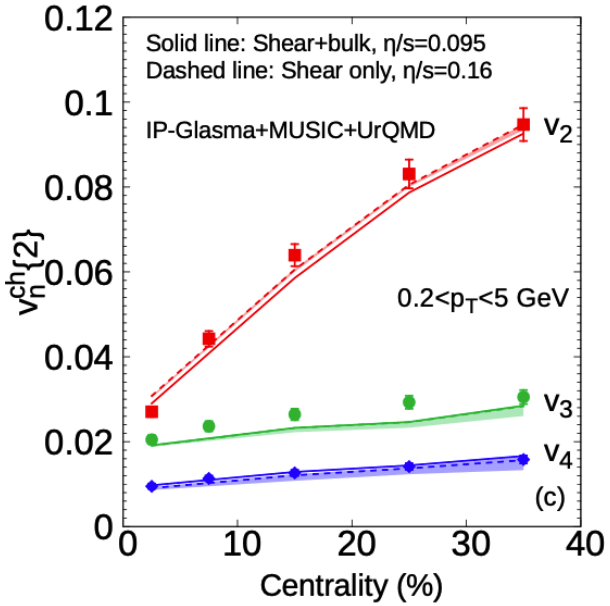

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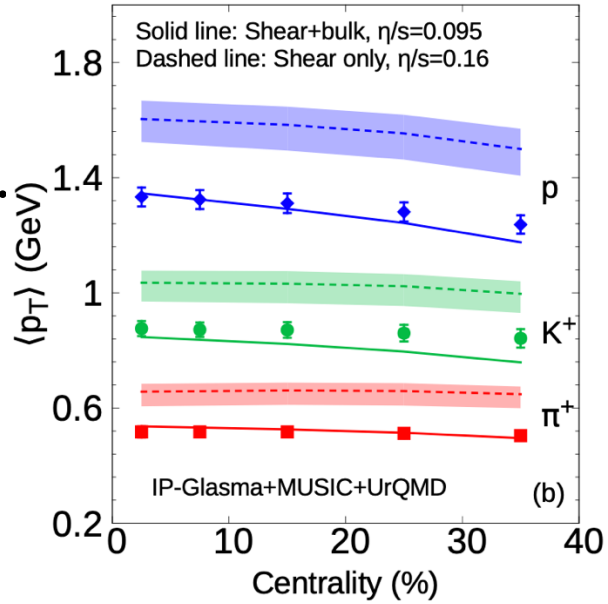

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Hallmarks of collectivity for anisotropic flow v_n

1. $v_n(p_T)$ factorizes into single particle flow.
2. $v_n(p_T)$ is long range phenomena.
3. $v_n(p_T)/v_n$ =hydro resp. is centrality independent.

Many other Signatures:
4. PID dependence of $v_n(p_T)$.
5. Higher-order v_n cumulants.
…

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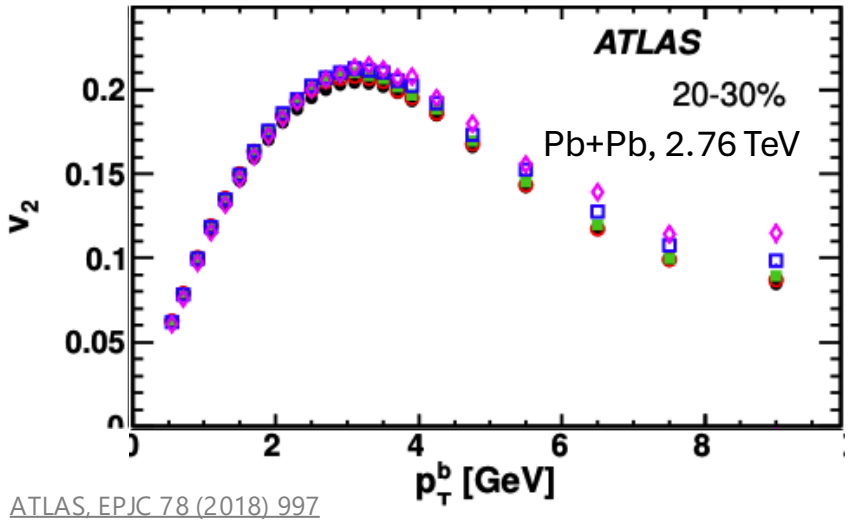
$$V_{n\Delta}(p_{T_a}, p_{T_b}) = v_n(p_{T_a})\, v_n(p_{T_b}) + \text{nonflow}$$



ATLAS, EPJC 78 (2018) 997

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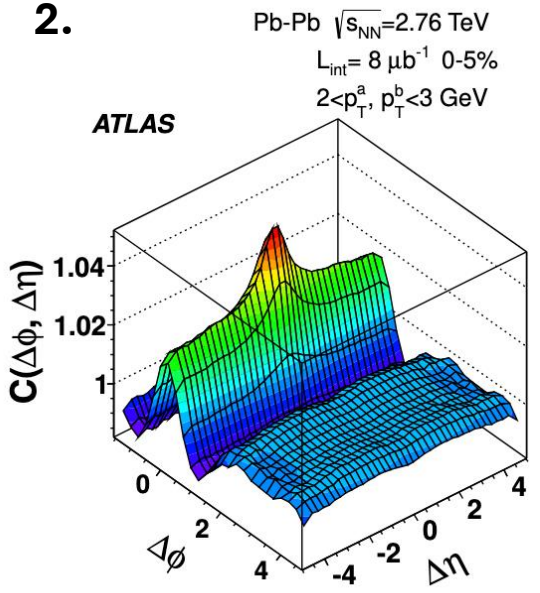

ATLAS, PRC 86 (2012) 014907

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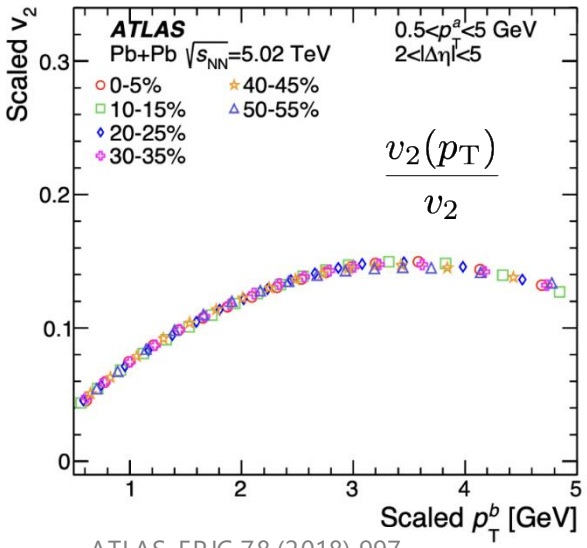

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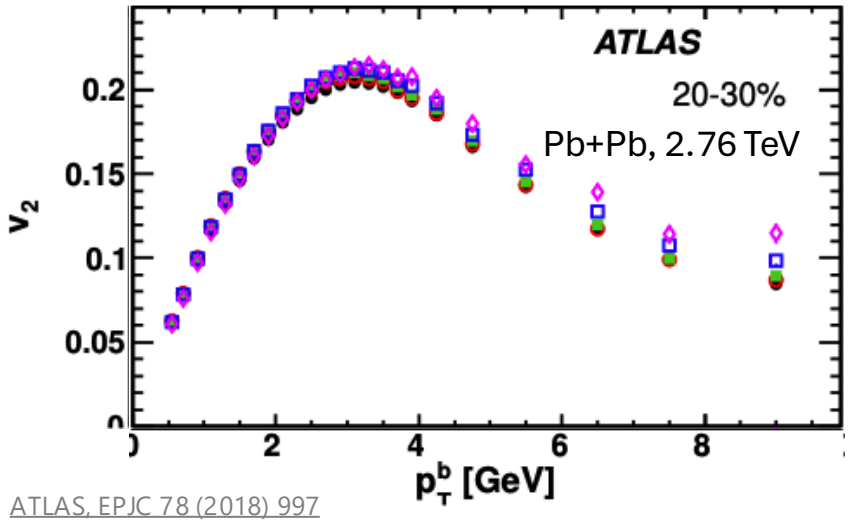

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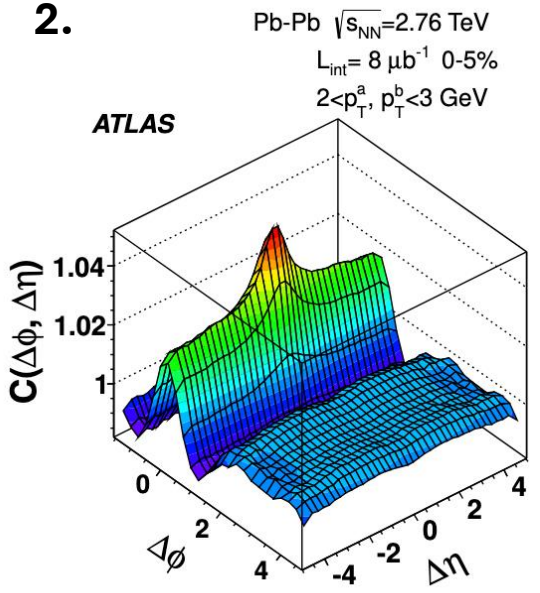

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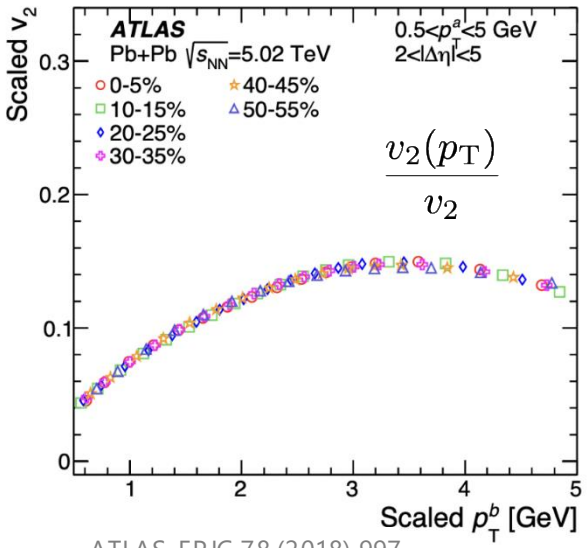

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- Assumed to hold for radial flow in model and data interpretation, NOT explicitly confirmed.
- We show this is indeed the case for radial flow via two-particle correlations.

Physics of radial flow: Initial condition

Previous study focused on Integrated v_0 observables:

$\langle [p_T] \rangle$ One-particle mean

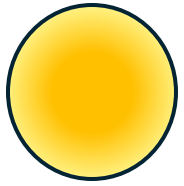
$k_2 = \frac{\langle (\delta [p_T])^2 \rangle}{\langle [p_T] \rangle^2}$ Two-particle variance

$k_3 = \frac{\langle (\delta [p_T])^3 \rangle}{\langle [p_T] \rangle^3}$ Three-particle Skewness

$\gamma = \frac{k_3}{k_2^{3/2}}$

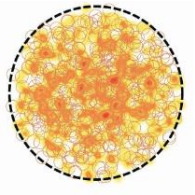
Initial Fluctuations:

Size



Geometrical

Local density



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ATLAS, PRL 133, 252301 (2024)

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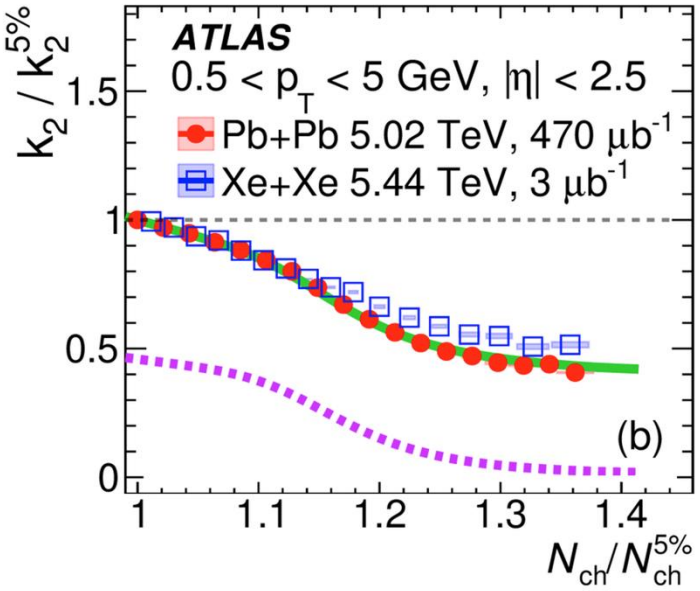

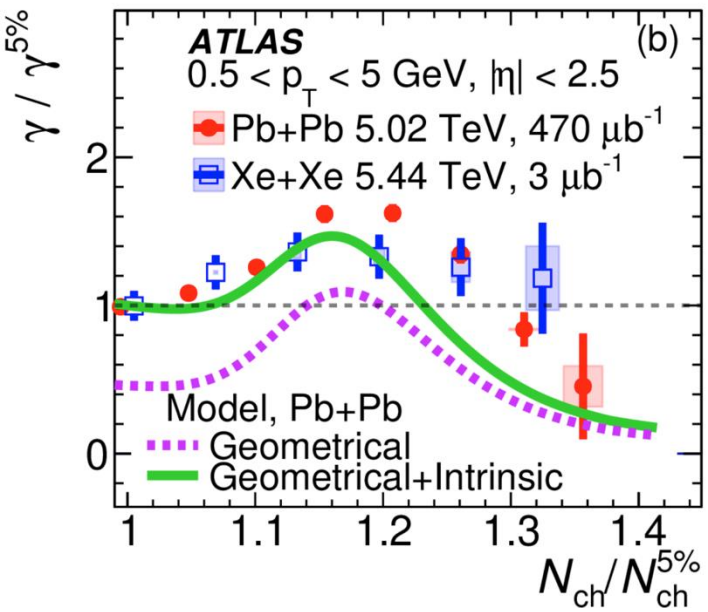

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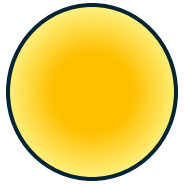

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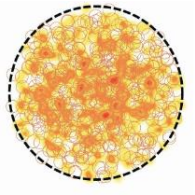

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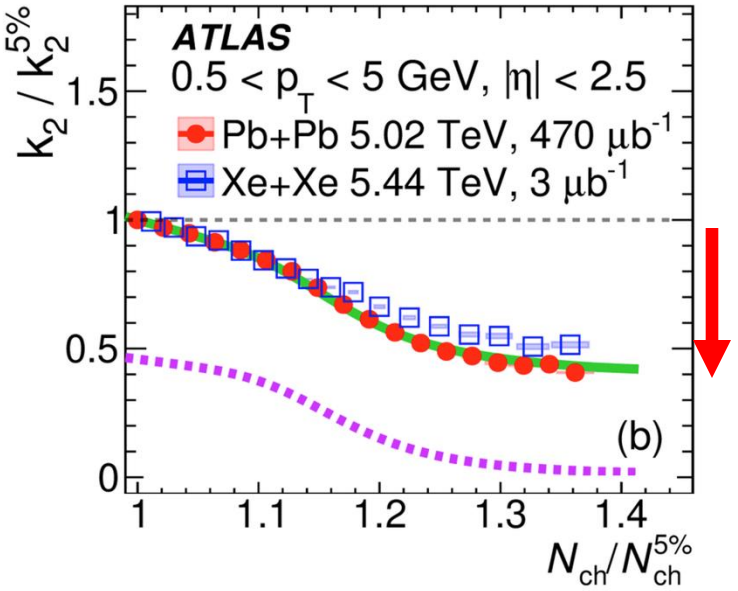

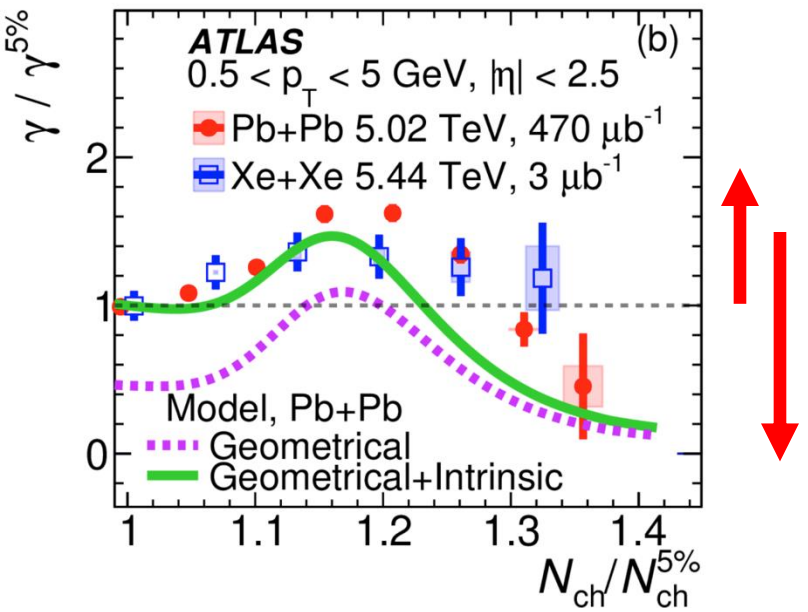

In Ultra-Central Collisions, Geometrical fluctuations suppressed:

Suppression of variance by 50%

Non-monotonic behavior of skewness

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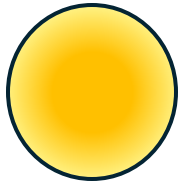

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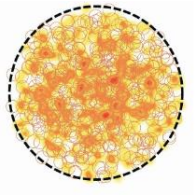

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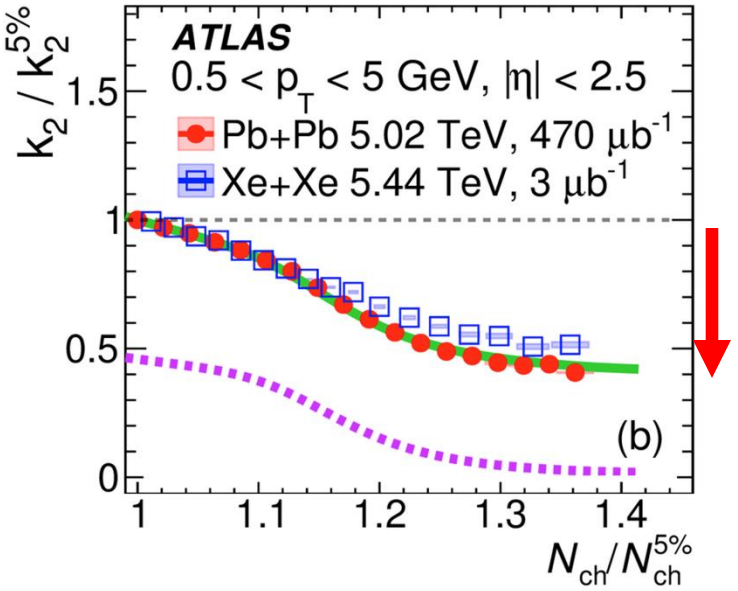

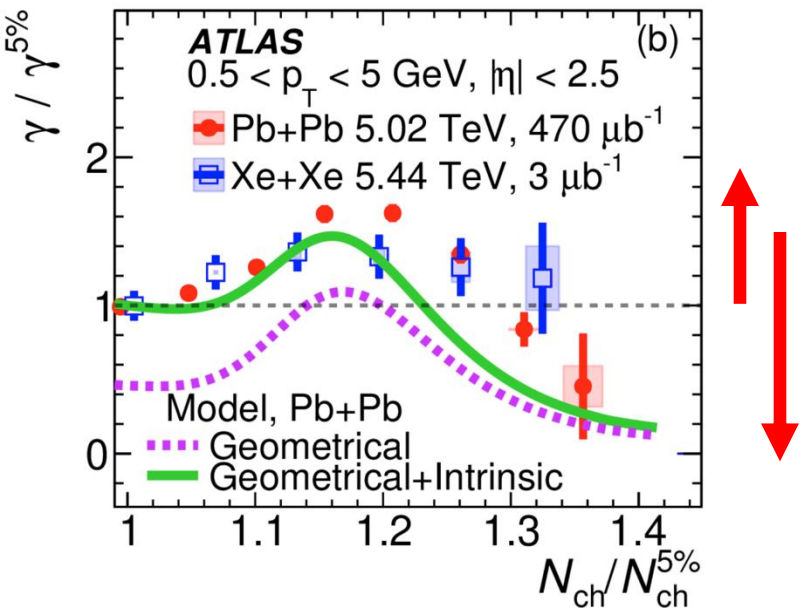

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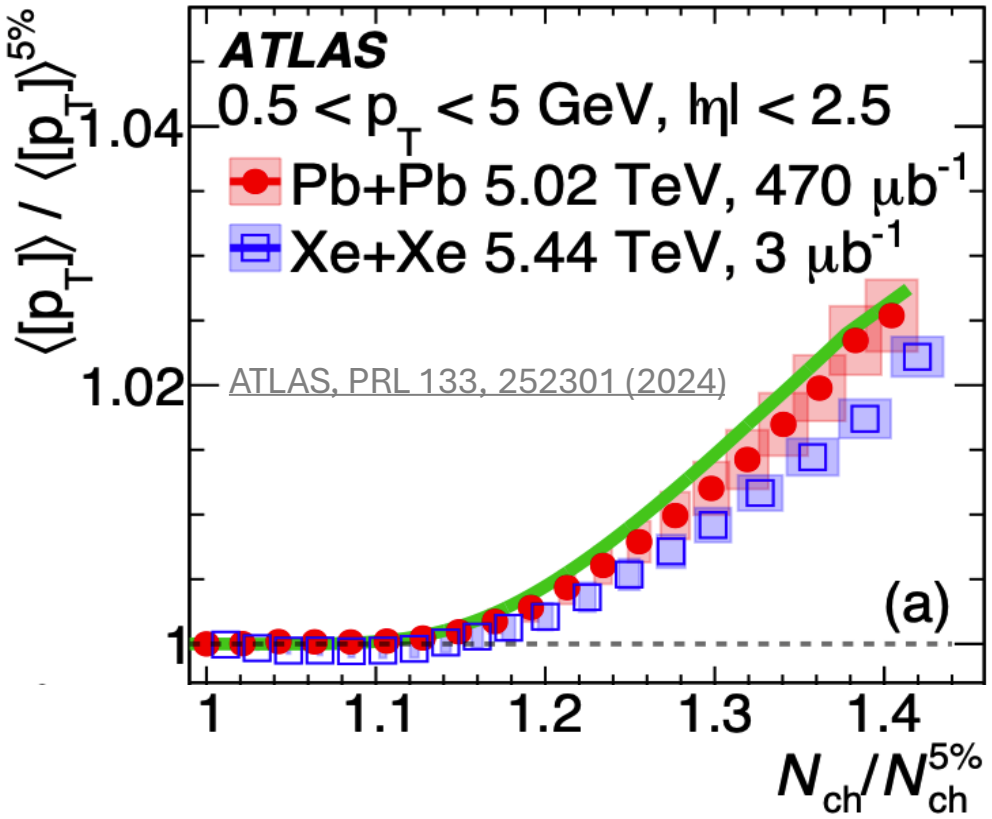
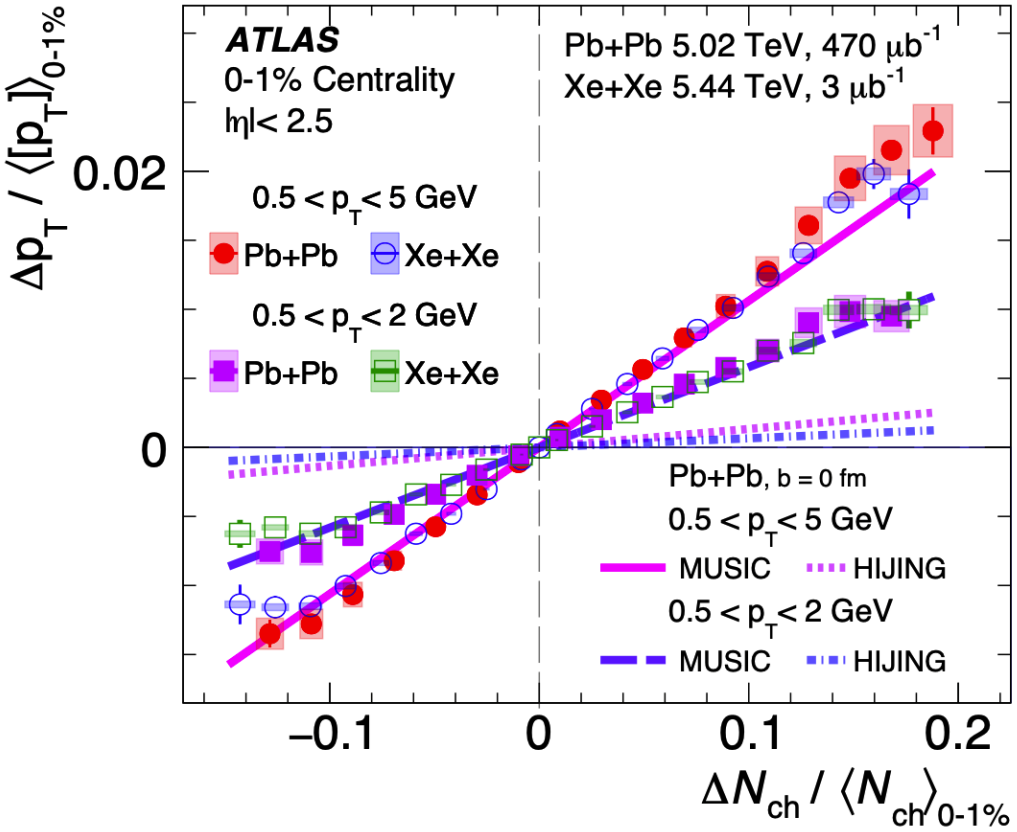
Demonstrate strong sensitivity of radial flow to initial geometry fluctuations

Physics of radial flow: QGP properties





At fixed size: ↑ N_{ch} ⟹ ↑ **Entropy Density** ⟹ ↑ $\langle[p_T]\rangle$

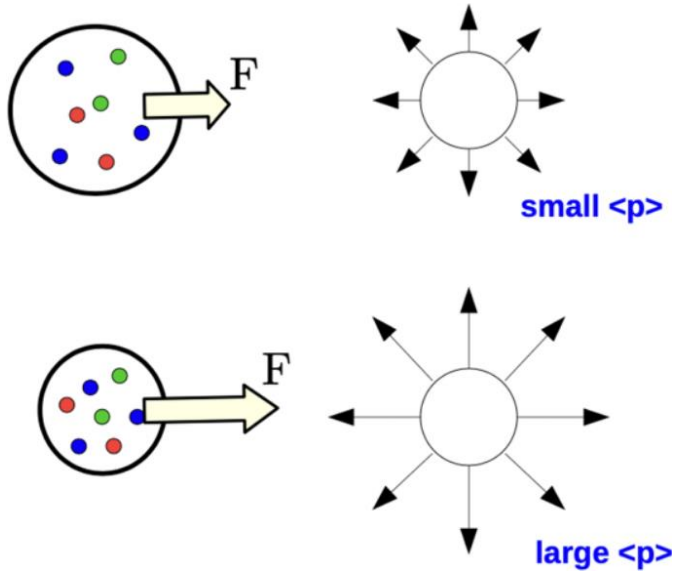
N_{ch} - $\langle[p_T]\rangle$ Correlation sensitive to speed of sound of QGP

$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d(lnT)}{d(lns)} = \frac{d(ln\langle p_T\rangle)}{d(lnN_{ch})}$$

Consistent with hydro model calculation with c_S^2= 0.23 at T_{eff}=0.22 GeV

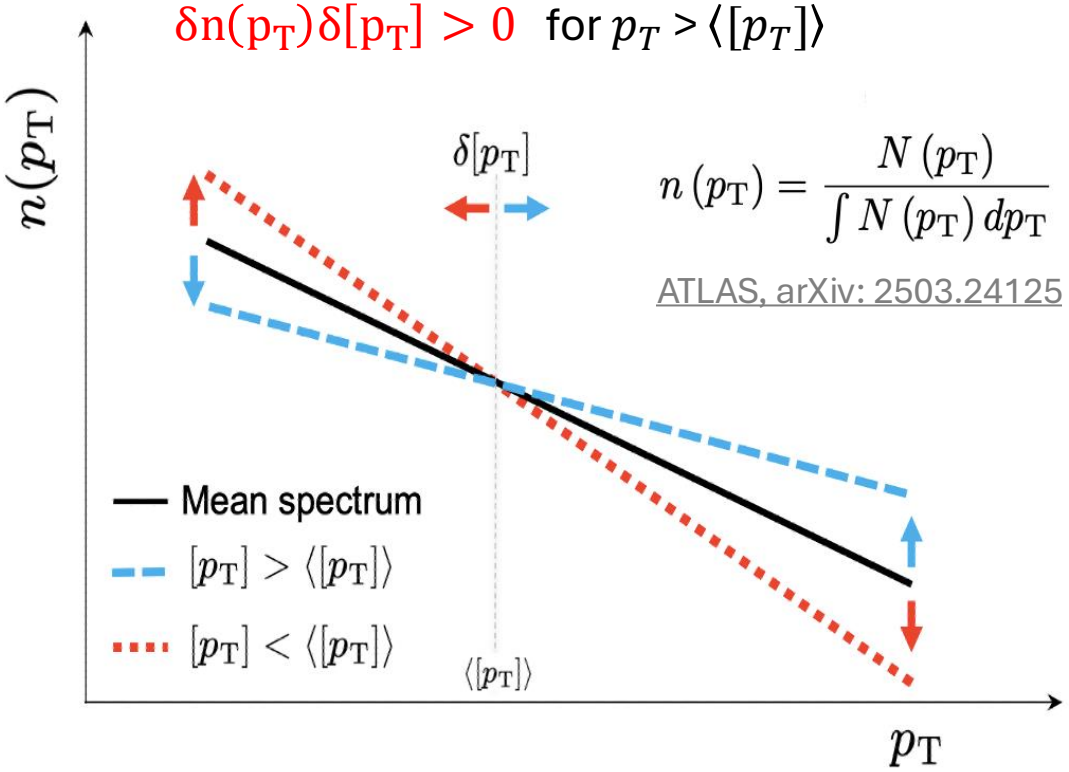
How to measure p_T-differential radial flow: $v_0(p_T)$?

- By measuring the correlation between EbE spectra shape $n(p_T)$ and $[p_T]$.



$\delta n(p_T)\delta[p_T] < 0$ for $p_T < \langle[p_T]\rangle$

$\delta n(p_T)\delta[p_T] > 0$ for $p_T > \langle[p_T]\rangle$



- Fluctuation of local yield $\delta n(p_T)$ and $\delta[p_T]$ are correlated→ measure $\langle\delta n(p_T)\delta[p_T]\rangle$.

Check if radial flow at the two-particle level arises from the single-particle level, like v_n.

How to measure p_T-differential radial flow: $v_0(p_T)$?

Covariance

$$v_0(p_{\mathrm{T}}) = \frac{\langle \delta n(p_{\mathrm{T}})\, \delta[p_{\mathrm{T}}] \rangle}{\langle n(p_{\mathrm{T}}) \rangle \langle [p_{\mathrm{T}}] \rangle} \times \frac{1}{v_{0,\mathrm{int}}} \qquad v_{0,\mathrm{int}} \equiv \frac{\sqrt{\langle (\delta [p_{\mathrm{T}}])^2 \rangle}}{\langle [p_{\mathrm{T}}] \rangle}$$

Schenke et. al, PRC 102, 034905 (2020)
Parida et. al, PLB, 857, 138985 (2024)

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For each p_T bin

In p_T^{ref} range

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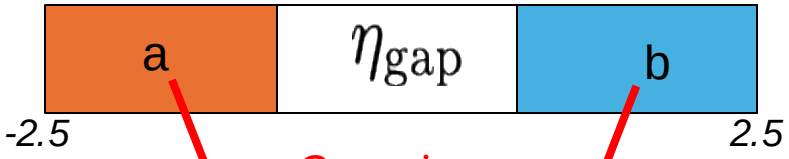

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For each p_T bin ***In p_T^{ref} range***

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- Two-subevent method: covariance, integral v_0.

$$v_{0,\mathrm{int}} = \sqrt{\langle \delta[p_T]_a \delta[p_T]_b \rangle} / \langle [p_T] \rangle$$

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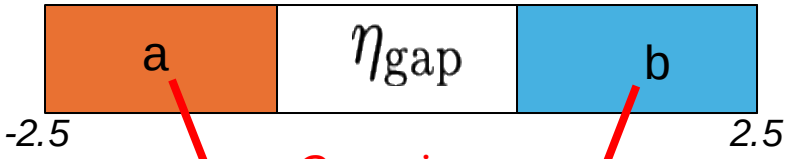


Covariance

$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta[p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$

For each p_T bin ***In p_T^{ref} range***

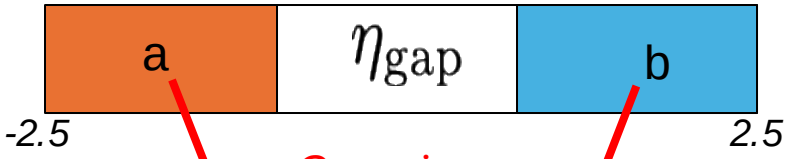
Schenke et. al, PRC 102, 034905 (2020)
Parida et. al, PLB, 857, 138985 (2024)

- Two-subevent method: covariance, integral v_0.

$$v_{0,\mathrm{int}} = \sqrt{\langle \delta[p_T]_a \delta[p_T]_b \rangle} / \langle [p_T] \rangle$$

- Divide covariance by $v_{0,int}$ to get $v_0(p_T)$.
- Calculate all observables in narrow bin of N_{ch}. Then combine within each centrality interval.

How to measure p_T-differential radial flow: $v_0(p_T)$?



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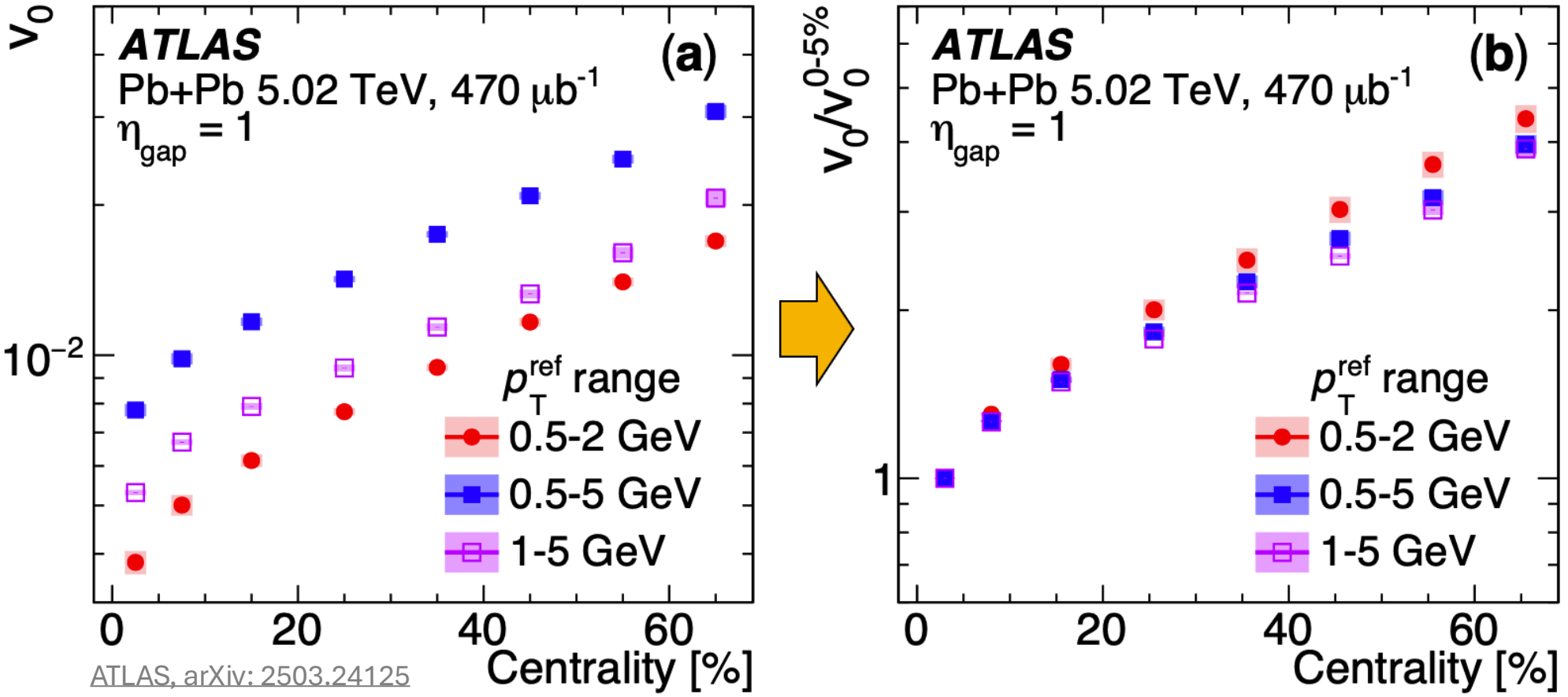
Scope of our study:

- Factorization check via three p_T^{ref} ranges:0.5-2, 0.5-5, 1-5 GeV
- Long-range behavior check using four η_{gap} variations from 0 to 3
- Centrality Scaling behavior in 0-70%
- Zero crossing of $v_0(p_T{}^c)$=0
  Expectation: $p_T{}^c \approx \langle [p_T] \rangle$
- Confirm the sum rules of $v_0(p_T)$.

Integral v_0 from two-subevents for three reference p_T

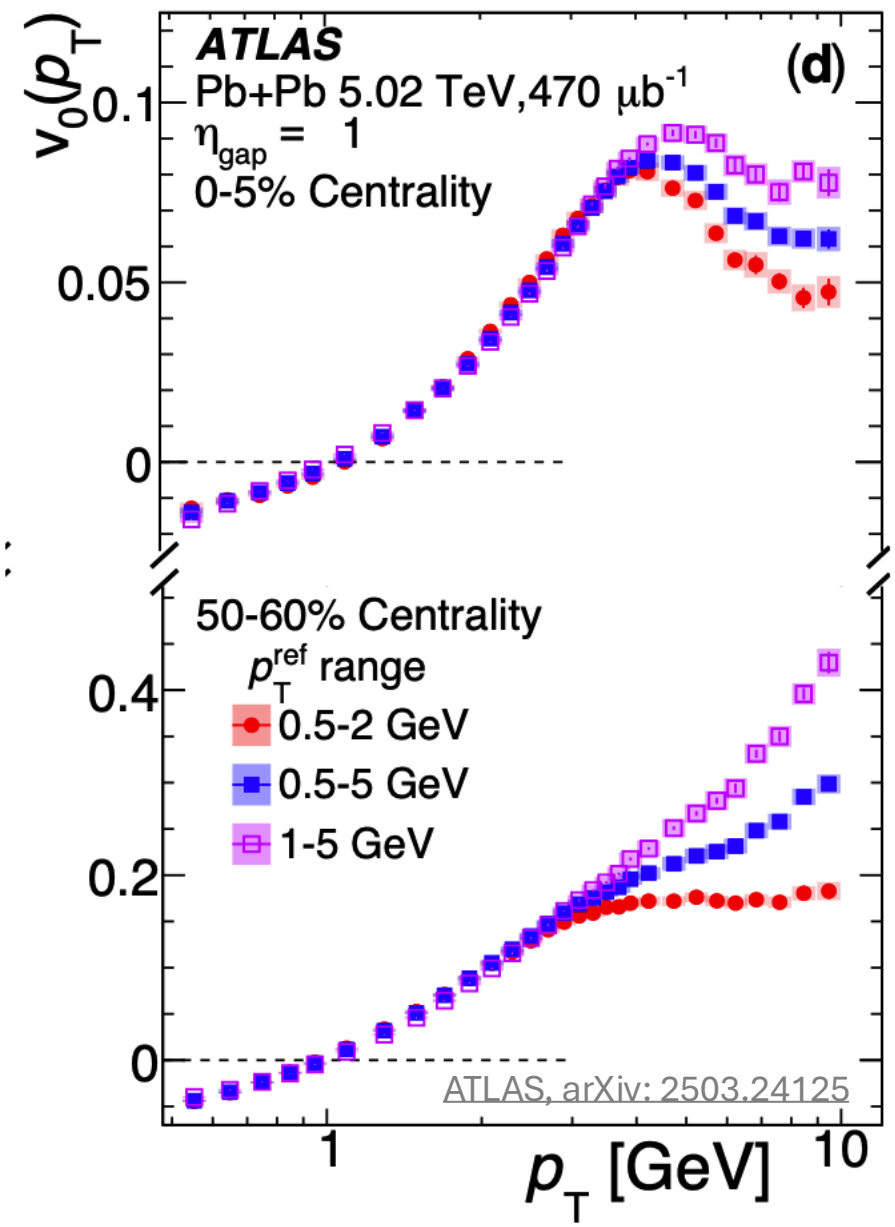
$$v_{0,\mathrm{int}} = \sqrt{\langle \delta[p_\mathrm{T}]_a \delta[p_\mathrm{T}]_b \rangle} / \langle [p_\mathrm{T}] \rangle$$



ATLAS, arXiv: 2503.24125

- Same centrality dep. for all $p_T{}^{\mathrm{ref}}$: v_0 captures overall global radial flow fluctuations.
  → Indicative of collective nature of radial flow.

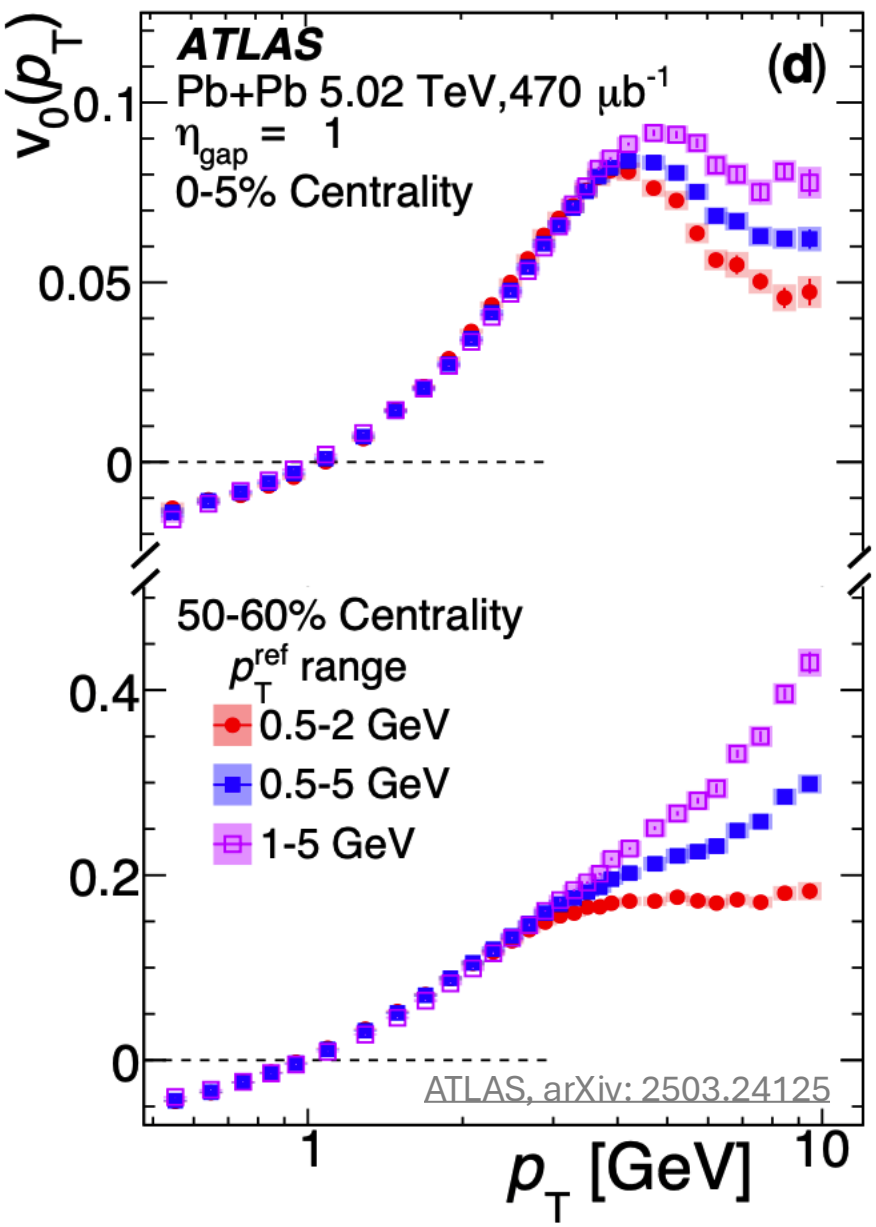
Factorization of $v_0(p_T)$: independence of reference v_0



$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta[p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$

- $v_0(p_T)$ independent of p_T^{ref} for $p_T < 3$ GeV.
- **Radial flow factorizes:** property of one-body distribution.

Factorization of $v_0(p_T)$: independence of reference v_0



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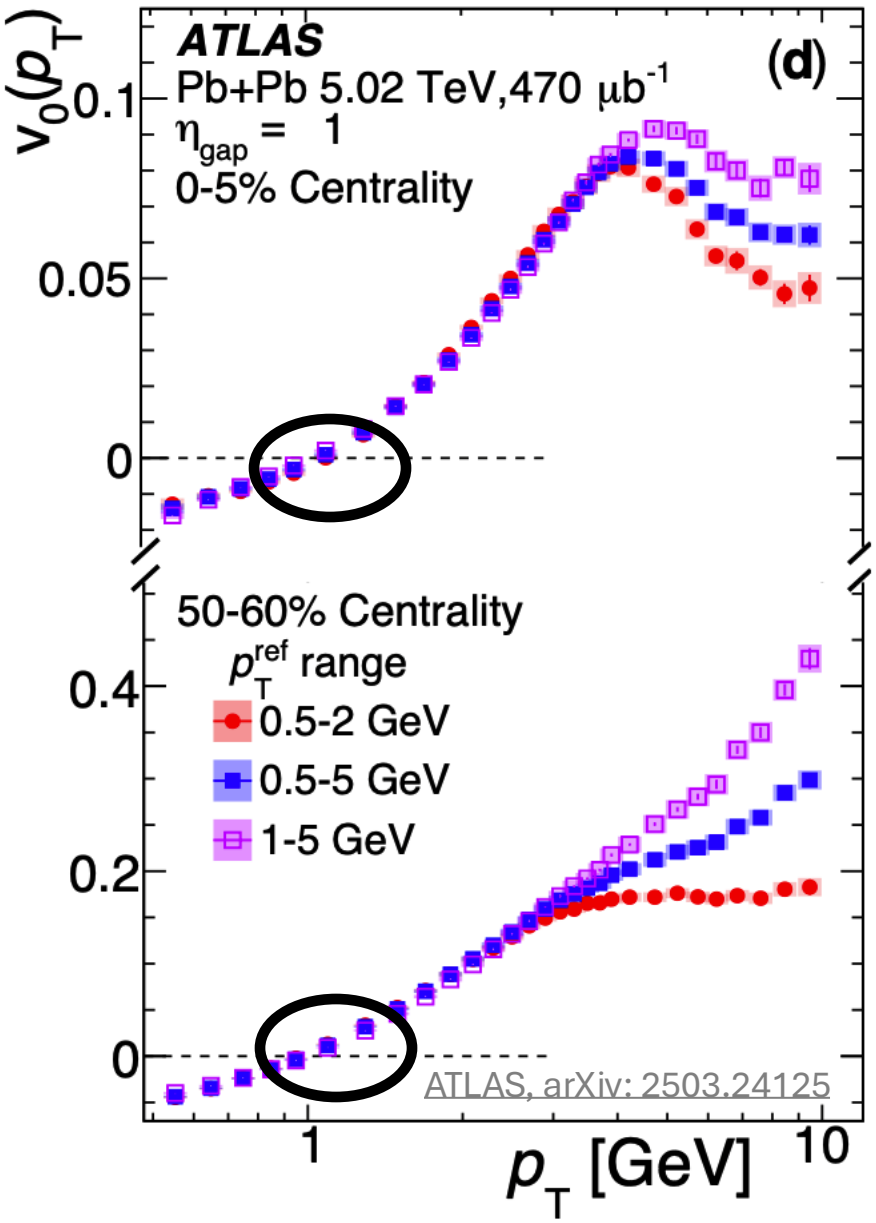
- $v_0(p_T)$ independent of p_T^{ref} for $p_T < 3$ GeV.
- **Radial flow factorizes:** property of one-body distribution.

- Decrease at higher p_T>4 GeV, consistent with transition to jet quenching dominated region.

- Dependence on p_T^{ref} also suggests influence of non-flow correlation

Zero-crossing point of $v_0(p_T)$

Expect $v_0(p_T)$ to cross zero at $p_T \approx \langle [p_T] \rangle$ of particle spectra.



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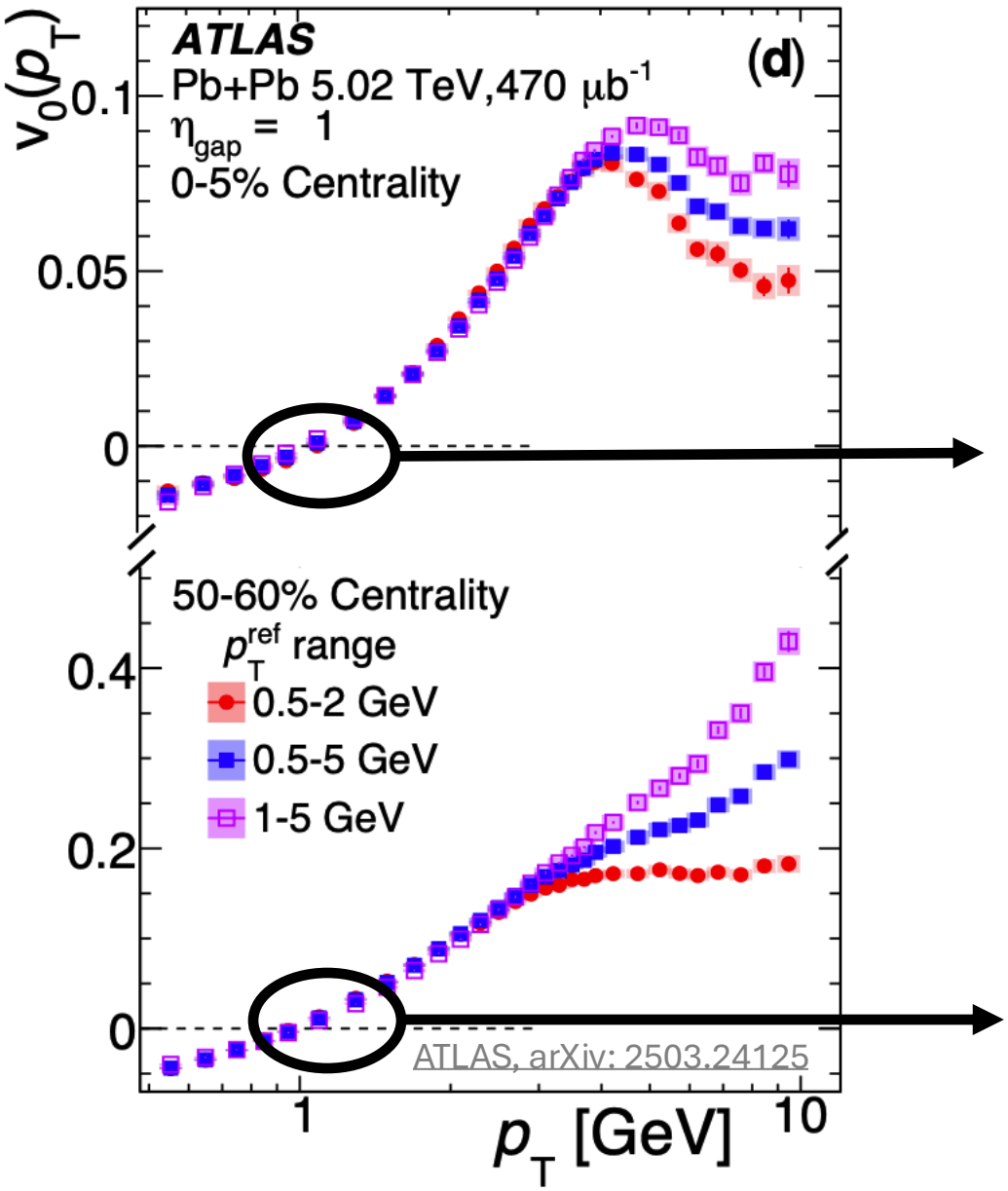
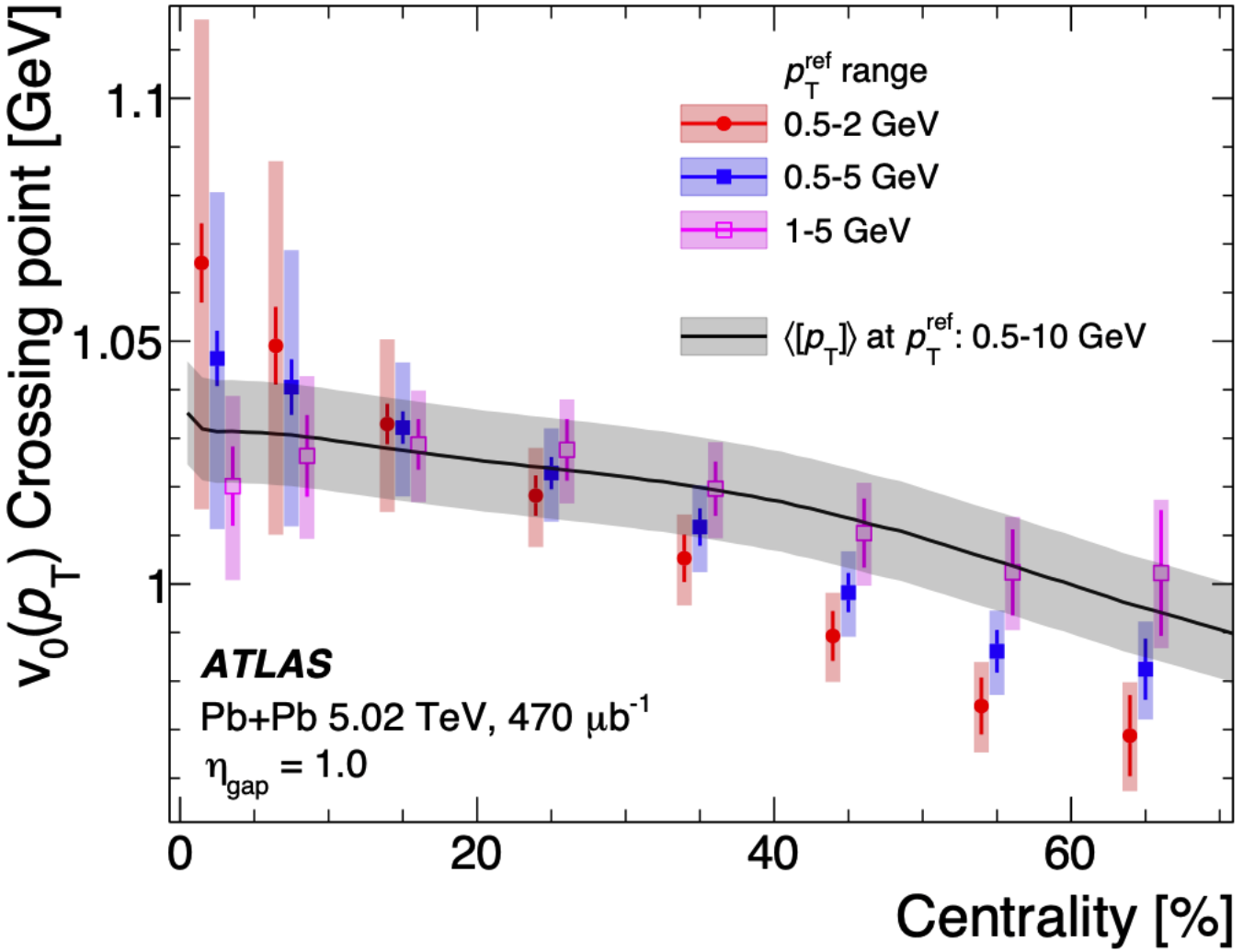




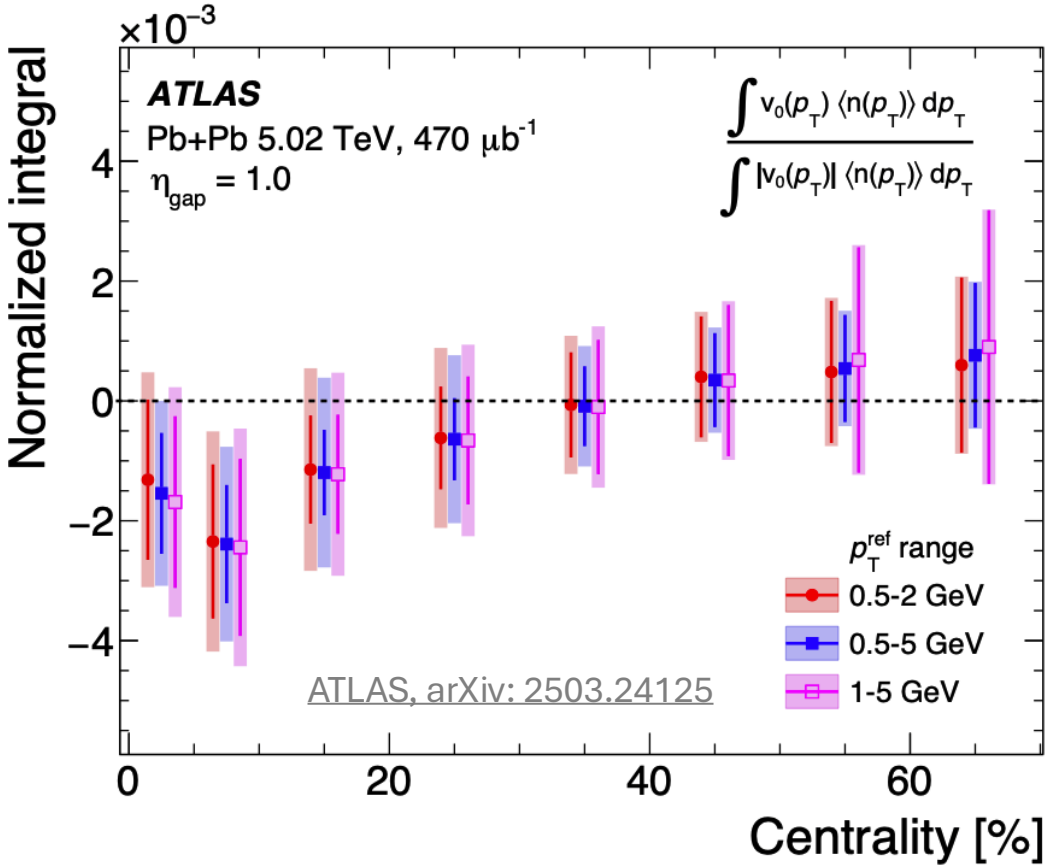
Expectation Confirmed!

Sum rules of $v_0(p_T)$

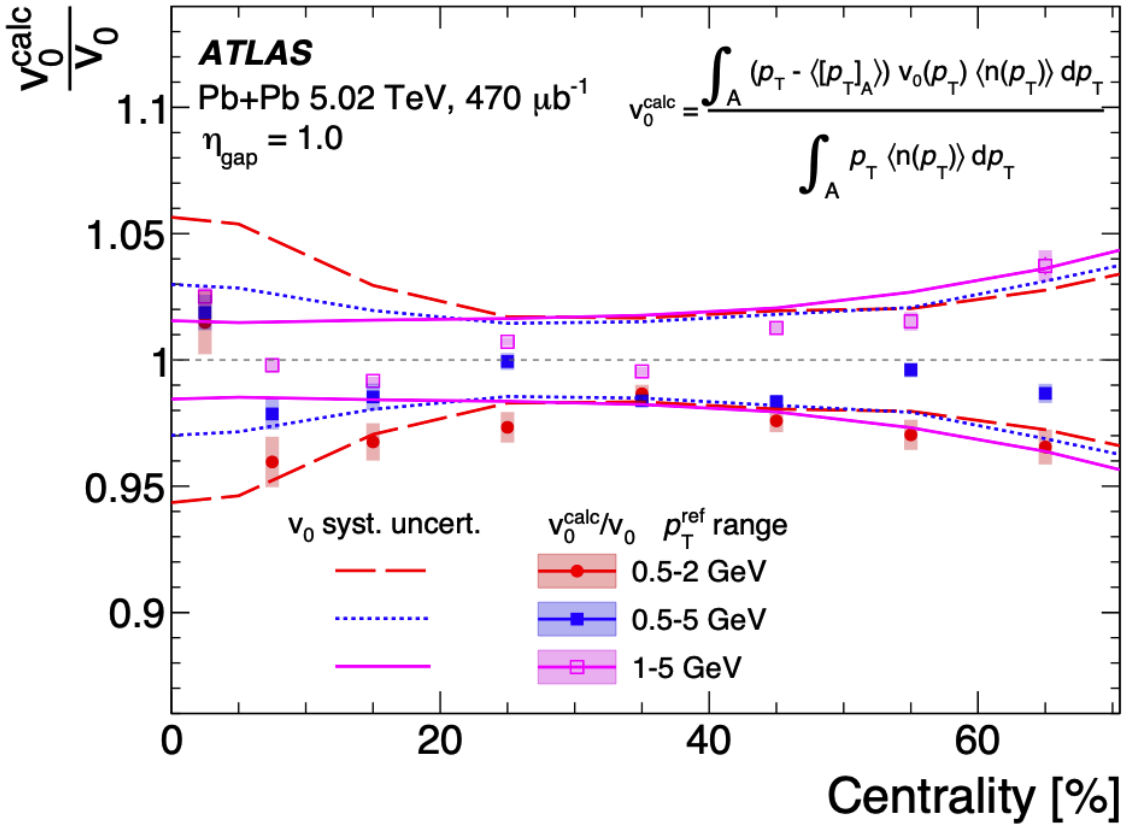
Sum rule 1: $\int v_0(p_T)\,\langle n(p_T)\rangle \mathrm{d}p_T = 0.$

Sum rule 2: $v_{0,int} = \dfrac{\int (p_T - \langle [p_T] \rangle)\, v_0(p_T) \langle n(p_T)\rangle \mathrm{d}p_T}{\int p_T \langle n(p_T)\rangle \mathrm{d}p_T}$

satisfy within 0.3%.

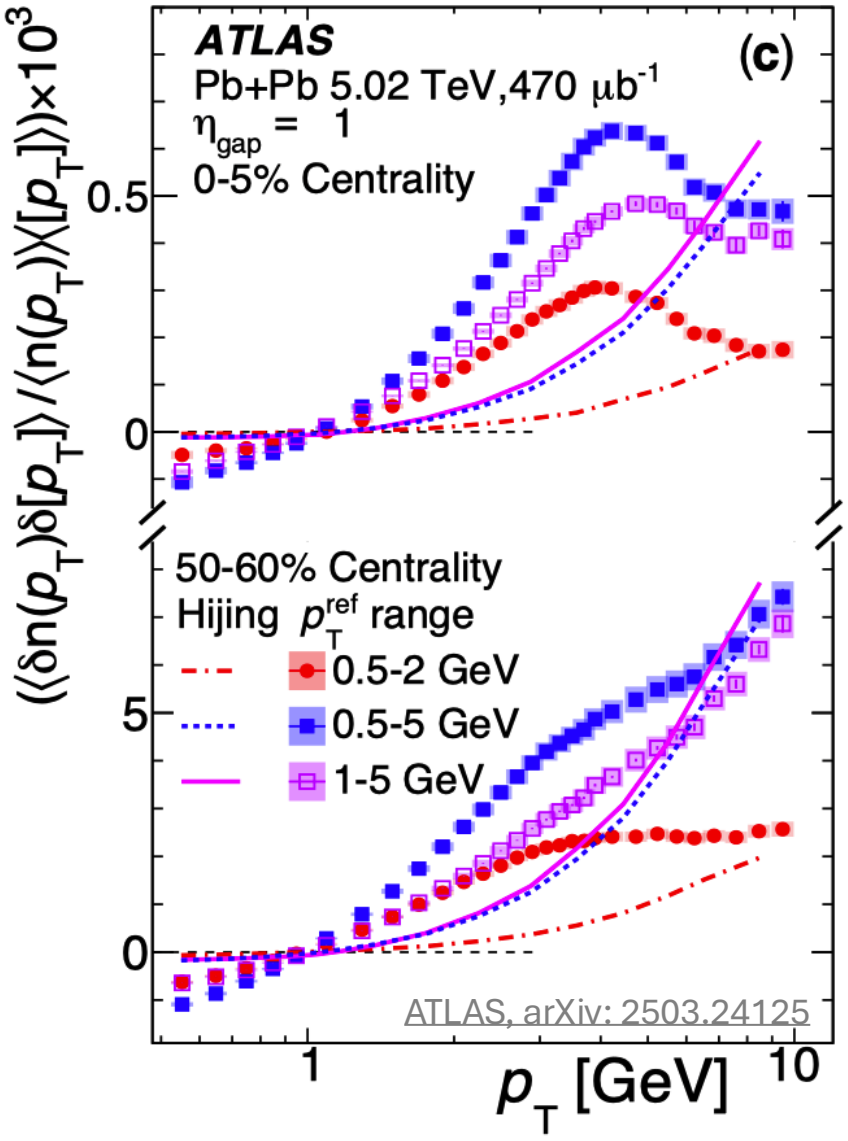


satisfy within 4% (within systematics)



Impact of non-flow

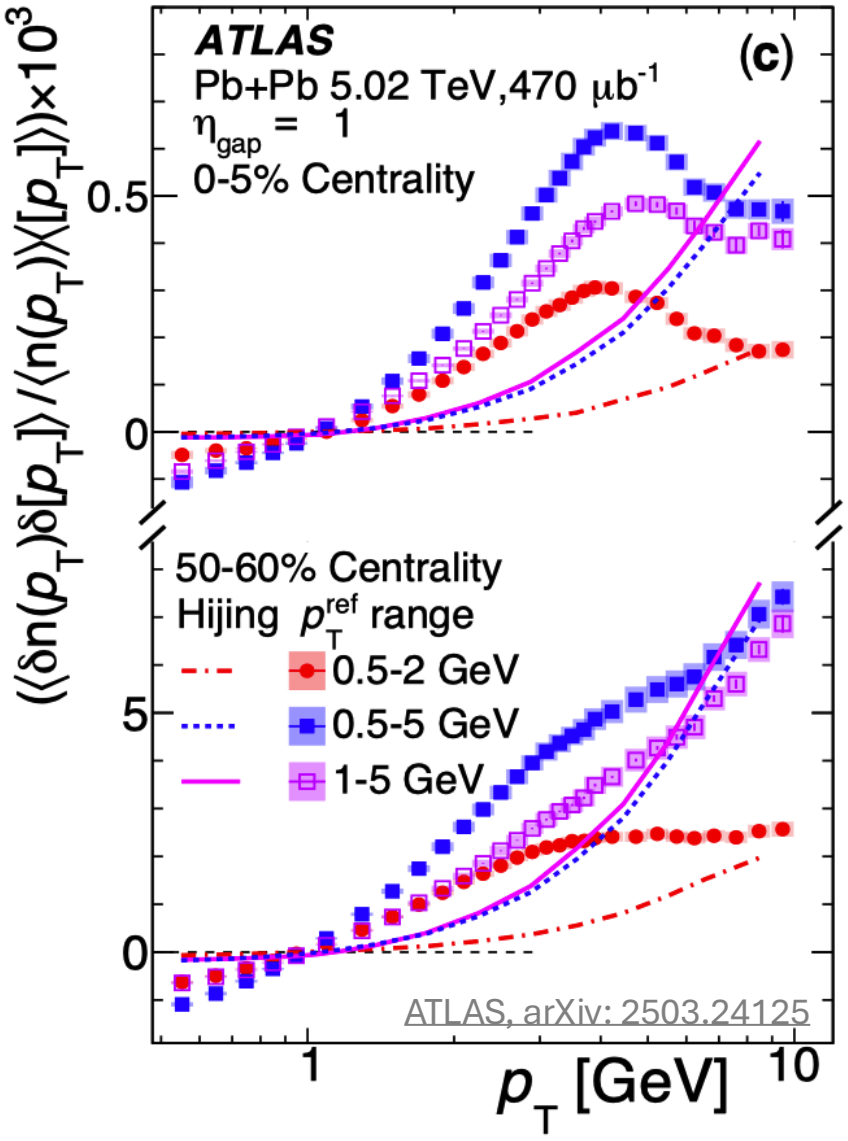
$$v_0(p_{\mathrm{T}}) = \frac{\langle \delta n(p_{\mathrm{T}})\, \delta[p_{\mathrm{T}}] \rangle}{\langle n(p_{\mathrm{T}}) \rangle \langle [p_{\mathrm{T}}] \rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$



- Estimate non-flow using HIJING:
  Less than data up to 6 GeV at 2-particle level.
- Most correlation in data from collective dynamics.

Impact of non-flow

$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta[p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle} \times \frac{1}{v_{0,\mathrm{int}}}$$



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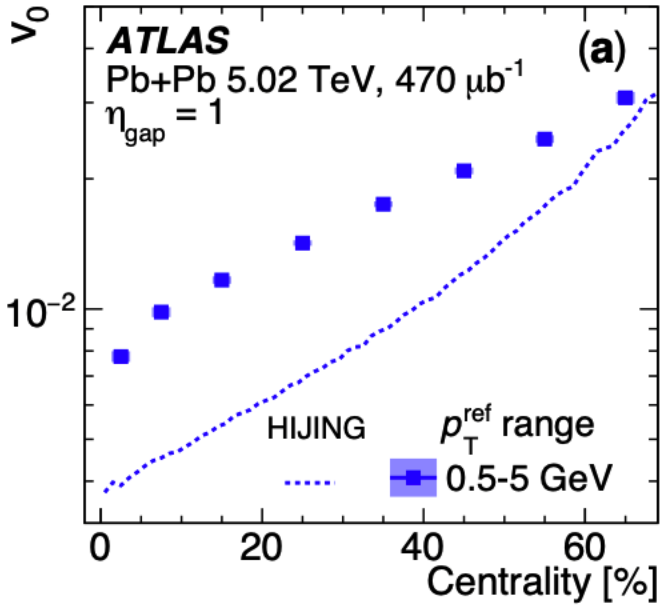

Integral v_0 is about factor 3 smaller than the data (depending on p_T^{ref}).

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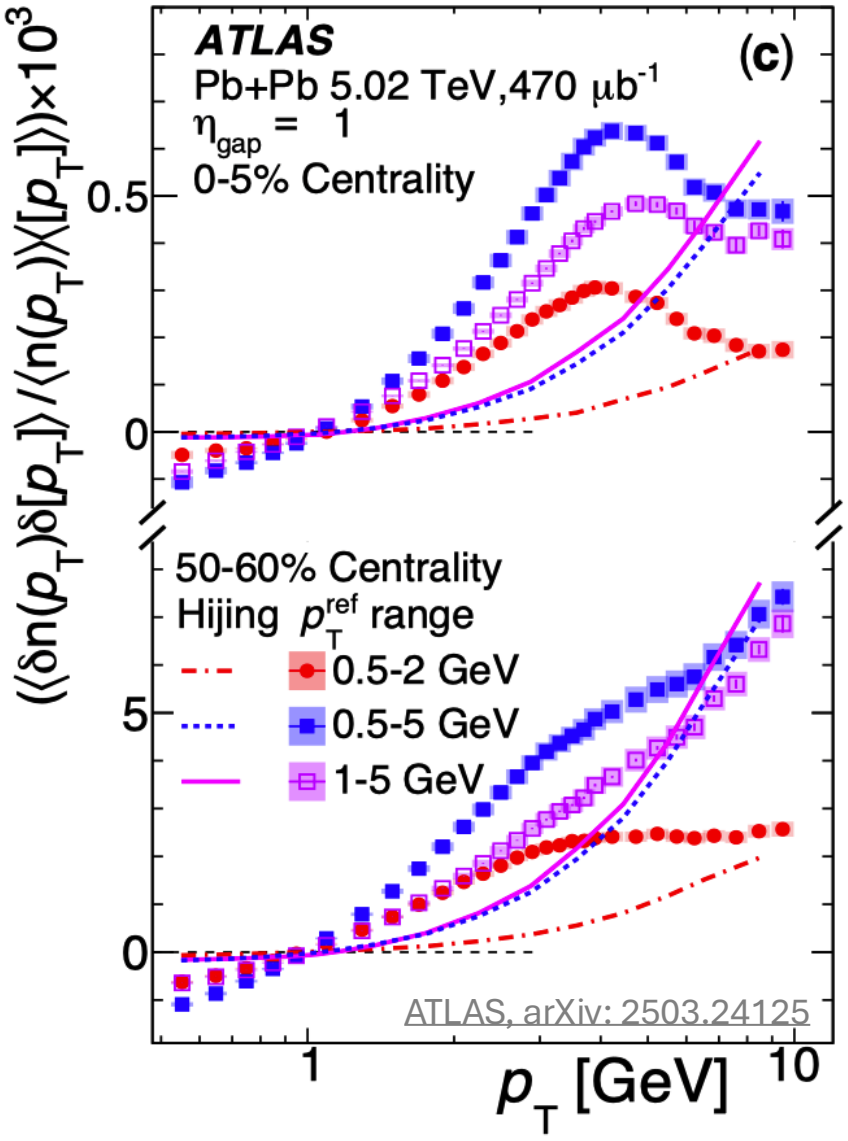

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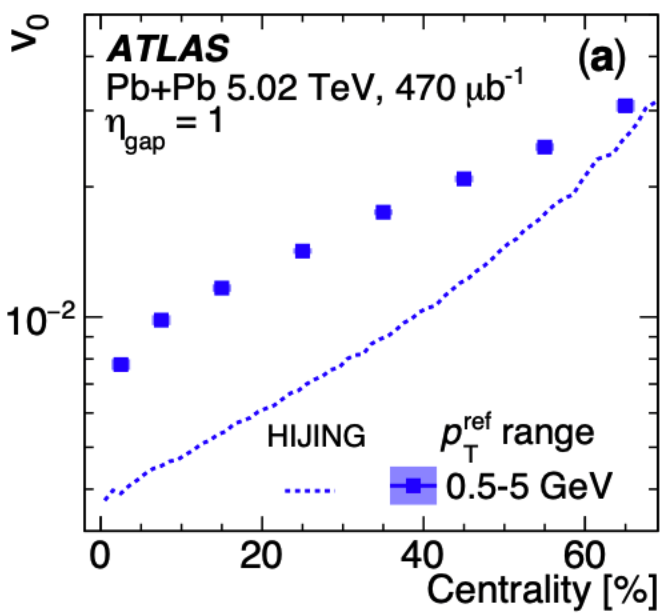
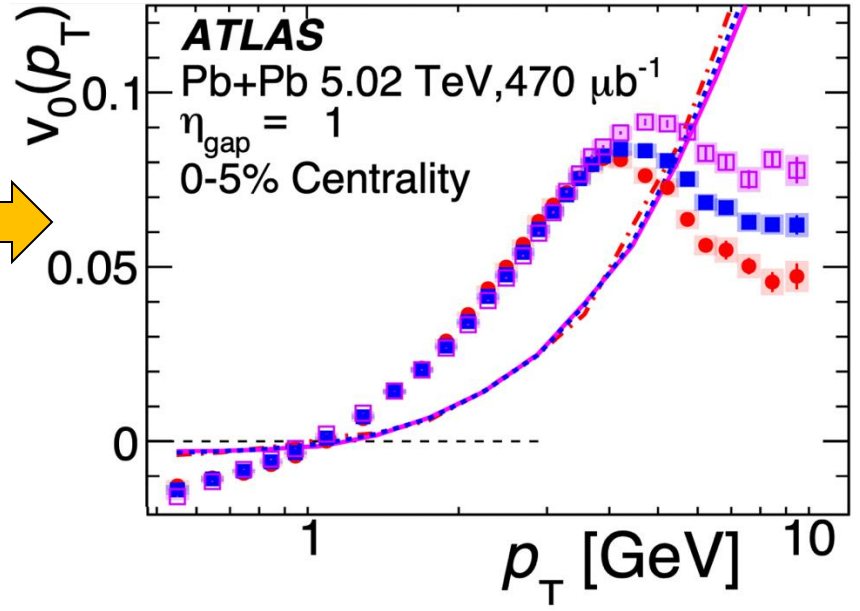
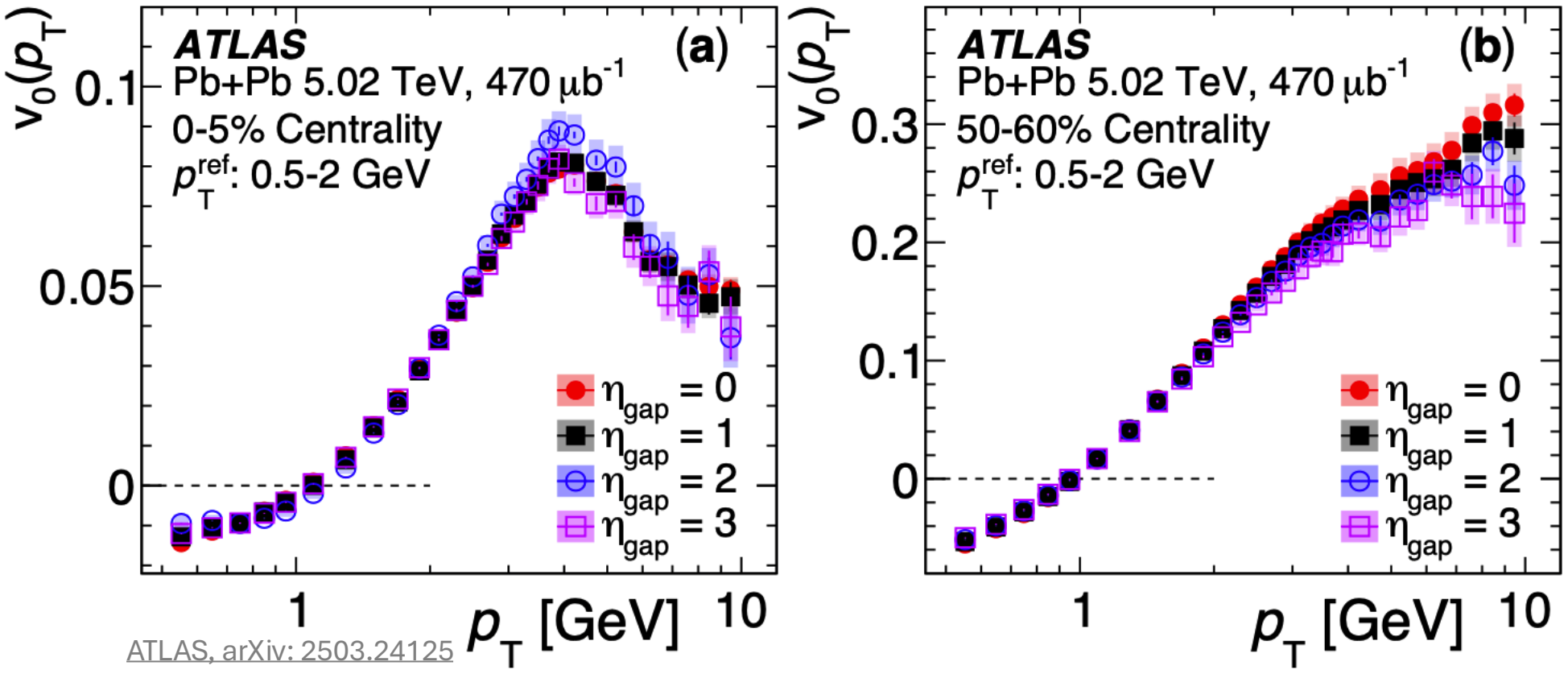




Integral v_0 is about factor 3 smaller than the data (depending on p_T^{ref}).

Non-flow comparison at $v_0(p_T)$ level is misleading!

Long-range behavior of $v_0(p_T)$



ATLAS, arXiv: 2503.24125

- $v_0(p_T)$ weakly depends on η_{gap}.

Radial flow is long-range, global correlation.

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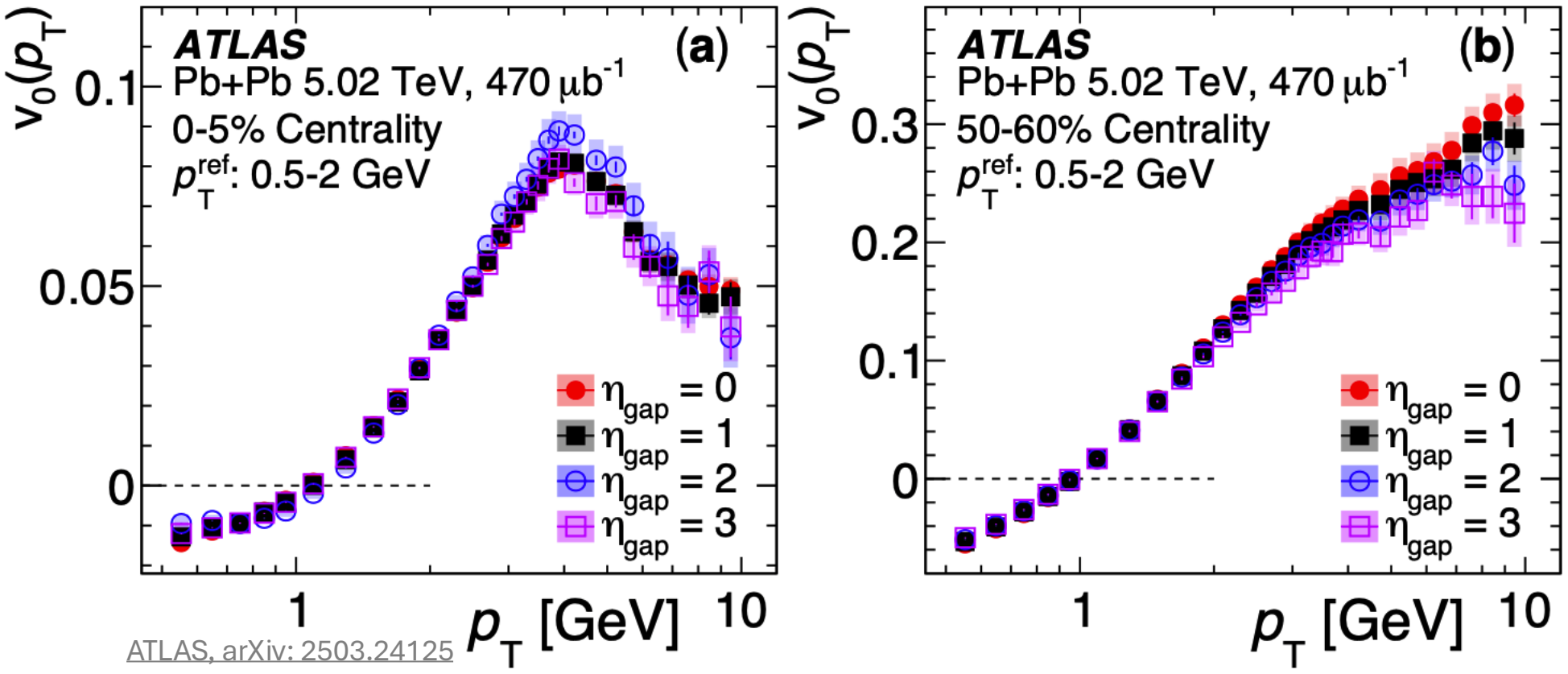


ATLAS, arXiv: 2503.24125

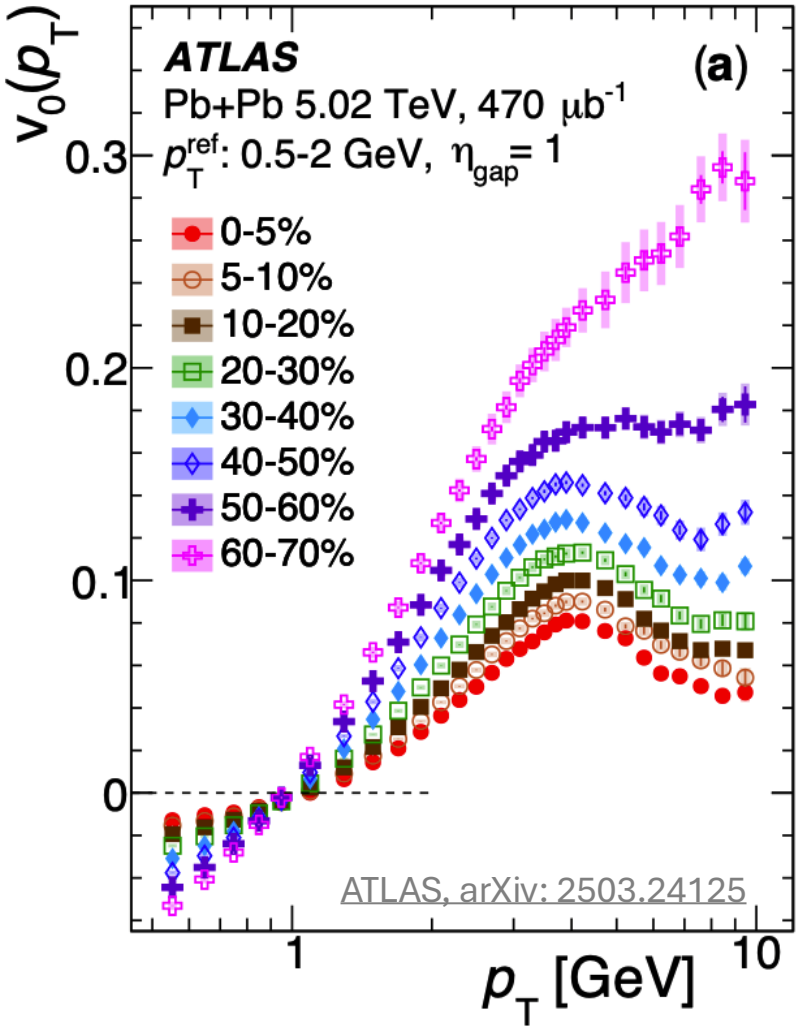
- $v_0(p_T)$ weakly depends on η_{gap}.

Radial flow is long-range, global correlation.

- Small split between η_{gap} observed for $p_T > 3$ GeV : residual non-flow from di-jets.

Centrality-independent shape of $v_0(p_T)$

Shape : $v_0(p_T)/ v_{0,int} = k_0(p_T)$, cancel initial-state effect, reflecting hydrodynamic response



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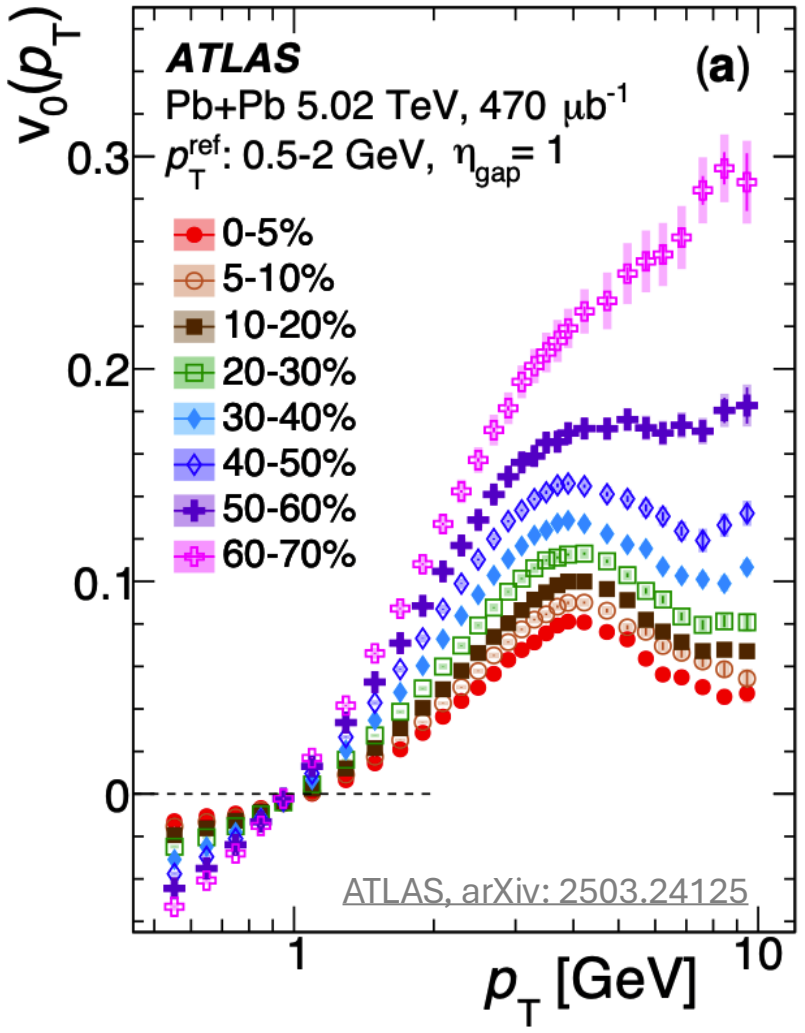

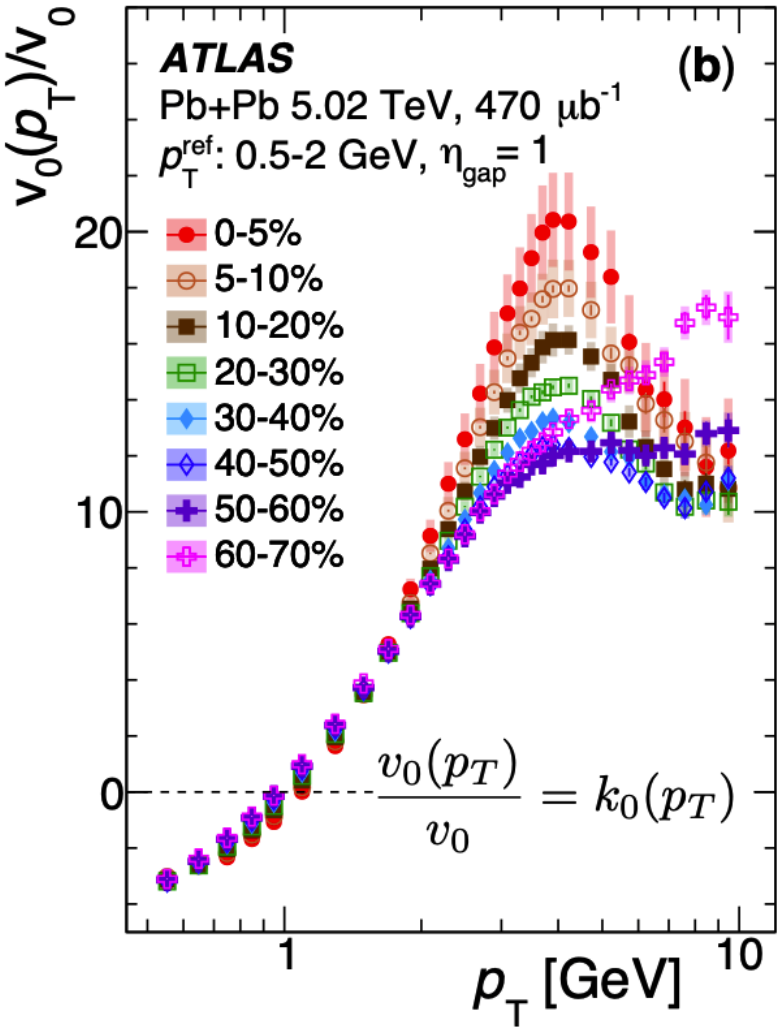

$v_0(p_T)$: centrality dependent.

$v_0(p_T)/v_0$, reflecting hydrodynamic response, is independent of centrality.

Centrality-independent shape of $v_0(p_T)$

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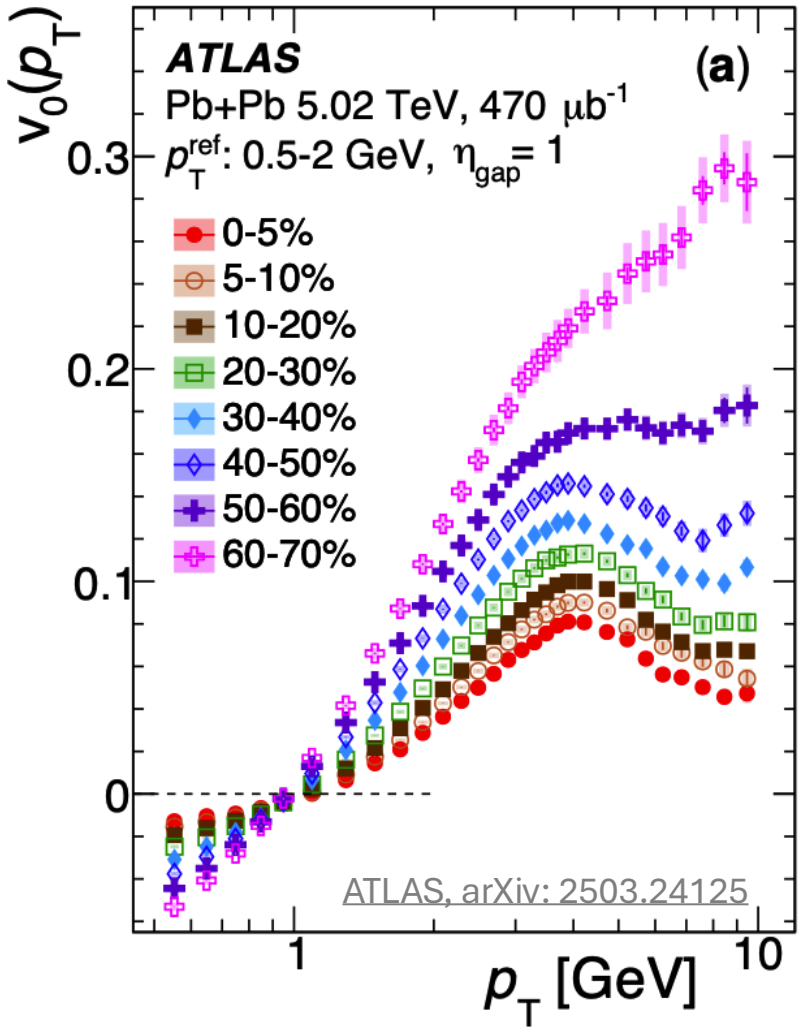
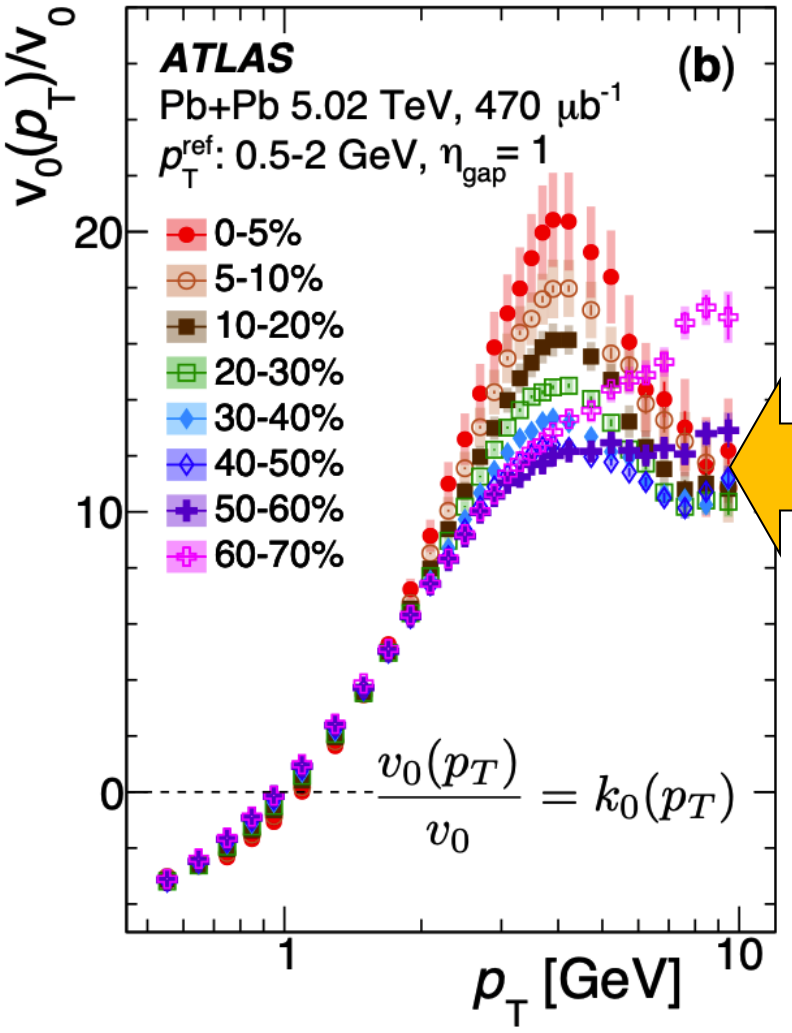


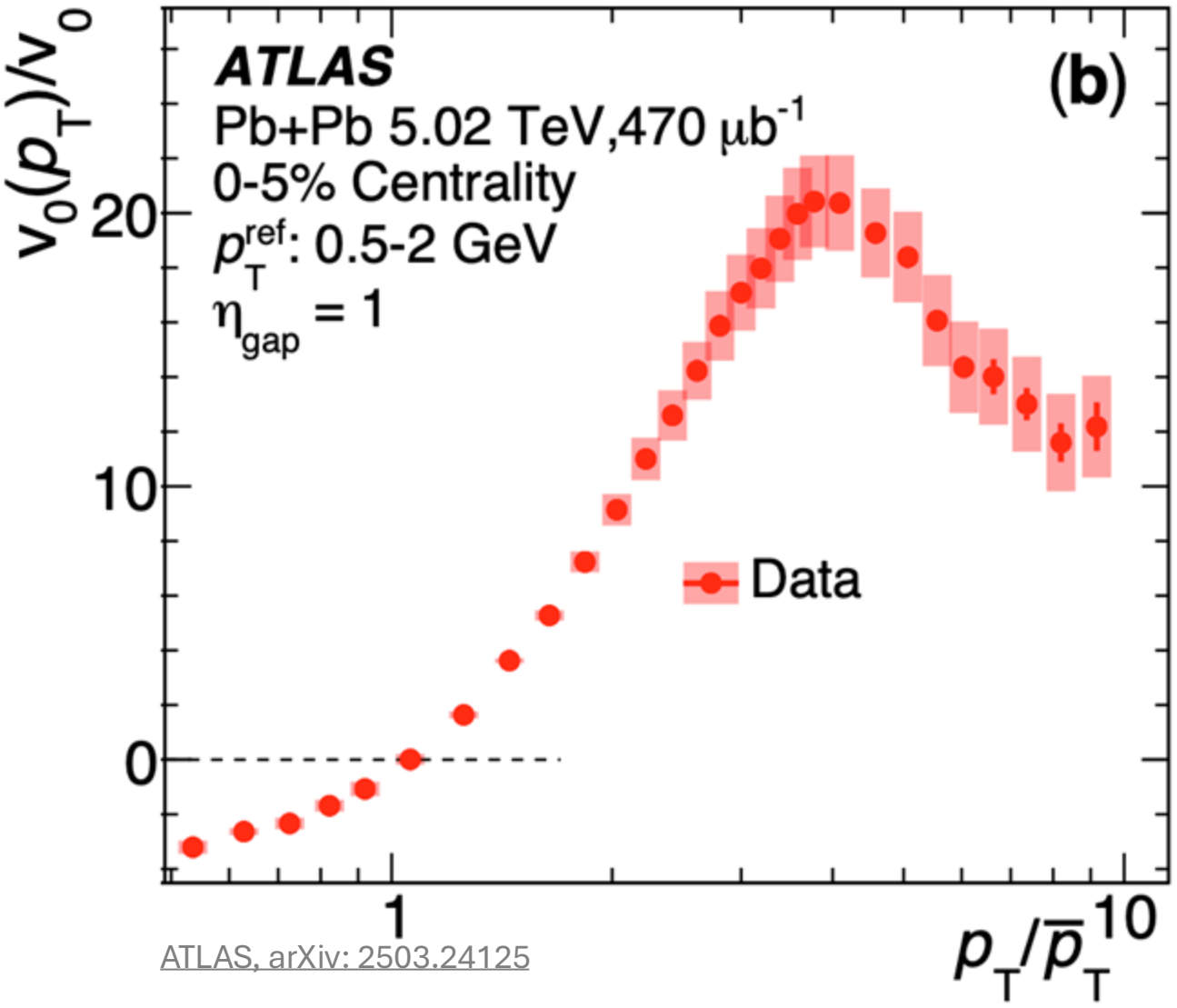


Decrease for $p_T > 4$ GeV:
Might arise from jet-quenching.

$v_0(p_T)$: centrality dependent.

$v_0(p_T)/v_0$, reflecting hydrodynamic response, is independent of centrality.

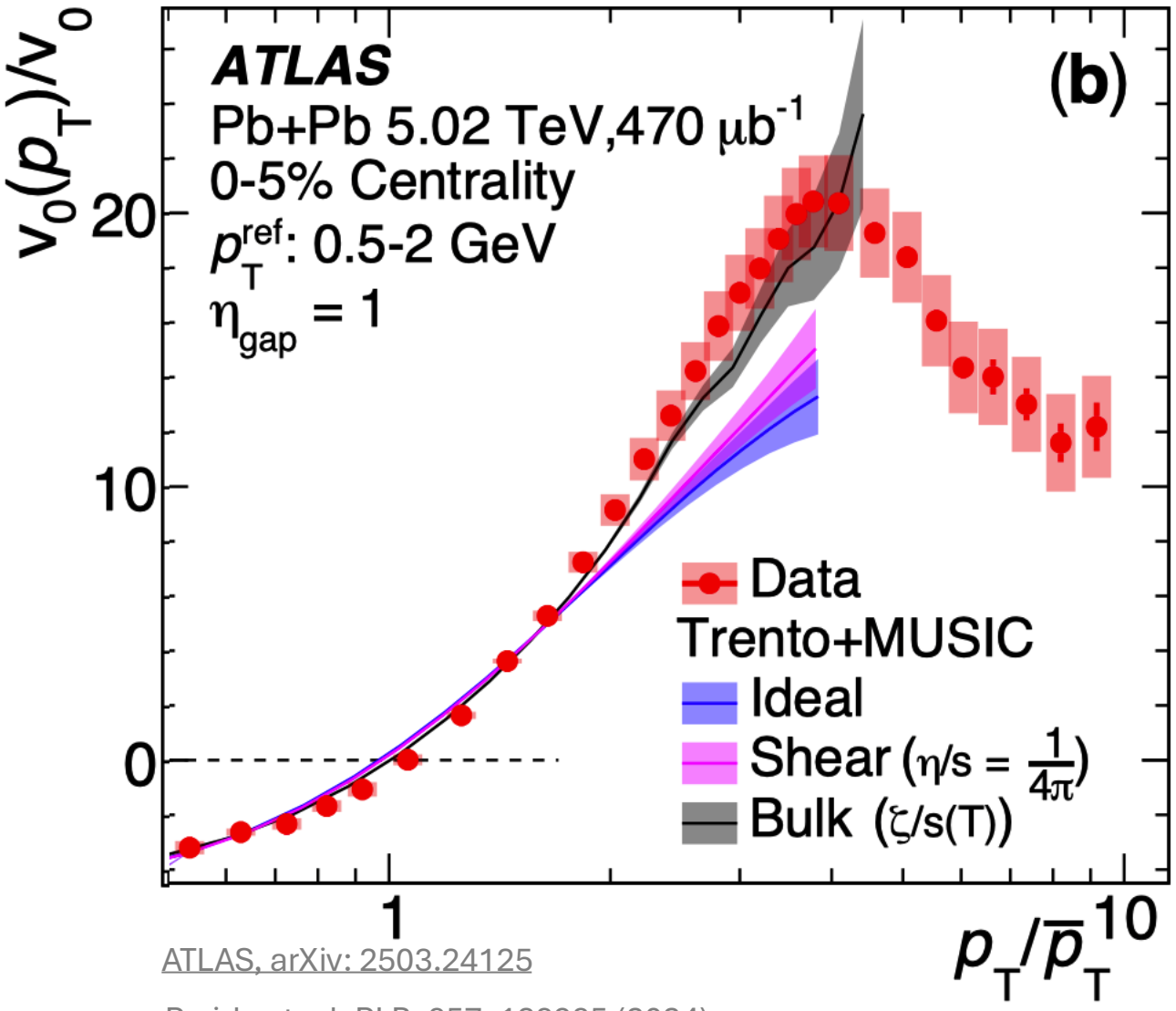
Sensitivity to bulk viscosity



ATLAS, arXiv: 2503.24125

- $v_0(p_T)/v_0$ cancels initial state effects.
- $p_T/\bar{p}_T$, accounts for $\langle[p_T]\rangle$ mismatch in model.

Sensitivity to bulk viscosity



ATLAS, arXiv: 2503.24125

Parida et. al, PLB, 857, 138985 (2024)

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$v_0(p_T)/v_0$ uniquely sensitive to bulk viscosity.

Summary

- First p_T-differential radial flow fluctuations $v_0(p_T)$ in Pb+Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV.

- The measurement shows that, $v_0(p_T)$:

  - Factorizes into single particle flow.
  - Exhibits long range behavior.
  - Has centrality-independent shape.

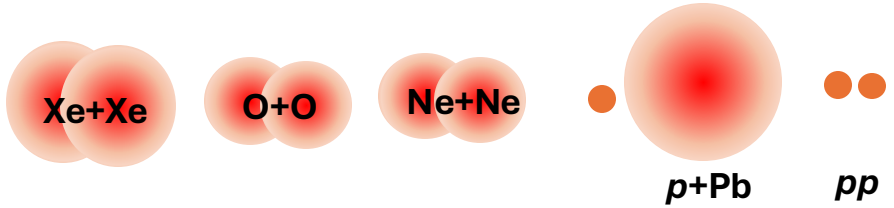
  Radial Flow is Collective!

  - $v_0(p_T)/v_0$ sensitive to bulk viscosity.

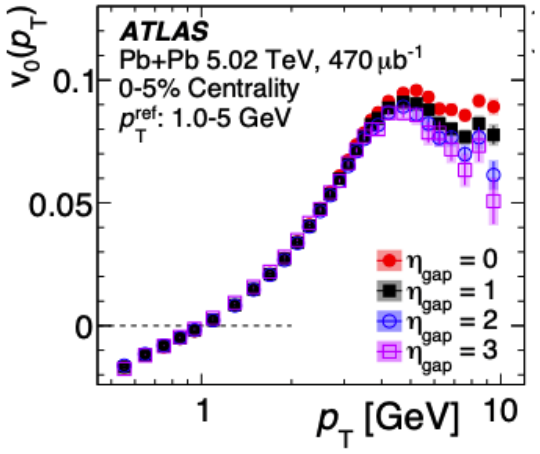
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2024-06/

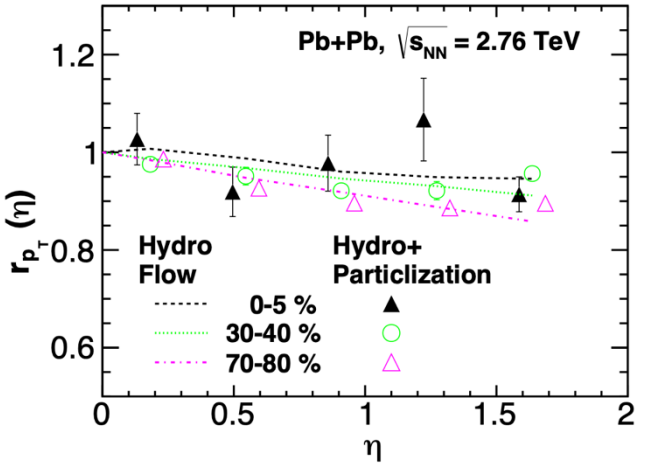
Many possible future directions:

1. System scan, small systems in particular.



2. Longitudinal dynamics via $v_0(\eta)$.





Chatterjee, Bozek, PRC 96, 014906 (2017)

3. $v_0(p_T)$ at high p_T as new probe for jet quenching, e.g. energy loss fluctuations.

4. Similar measurement for other rare probes: heavy flavor, quarkonium etc.

…

Backup

Two technical points

1) Normalization $\frac{\langle \delta N(p_T)\delta[p_T]\rangle}{\langle N(p_T)\rangle\langle[p_T]\rangle} = v_0'(p_T)v_0$ Vs. $\frac{\langle \delta n(p_T)\delta[p_T]\rangle}{\langle n(p_T)\rangle\langle[p_T]\rangle} = v_0(p_T)v_0$

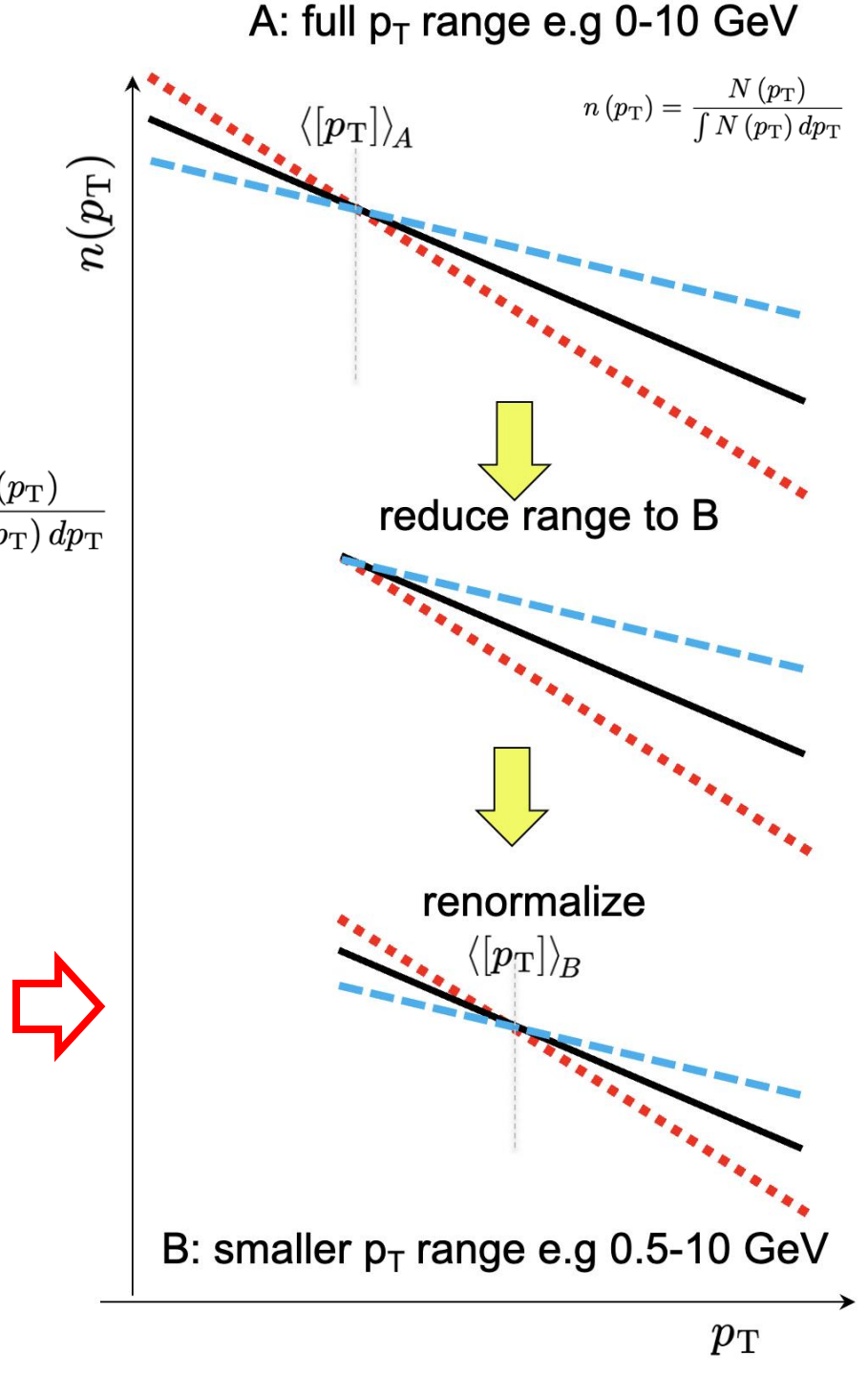
since $\delta N(p_T) = \delta(Nn(p_T)) \approx \delta N\, n(p_T) + N\, \delta n(p_T)$

Differs by overall multiplicity fluctuation

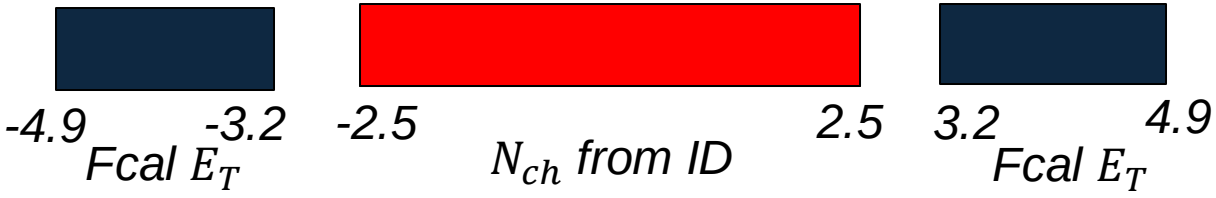
$$v_0'(p_T) - v_0(p_T) \approx \frac{\langle \delta N\, \delta[p_T]\rangle}{\langle N\rangle\sqrt{(\delta p_T)^2}}$$

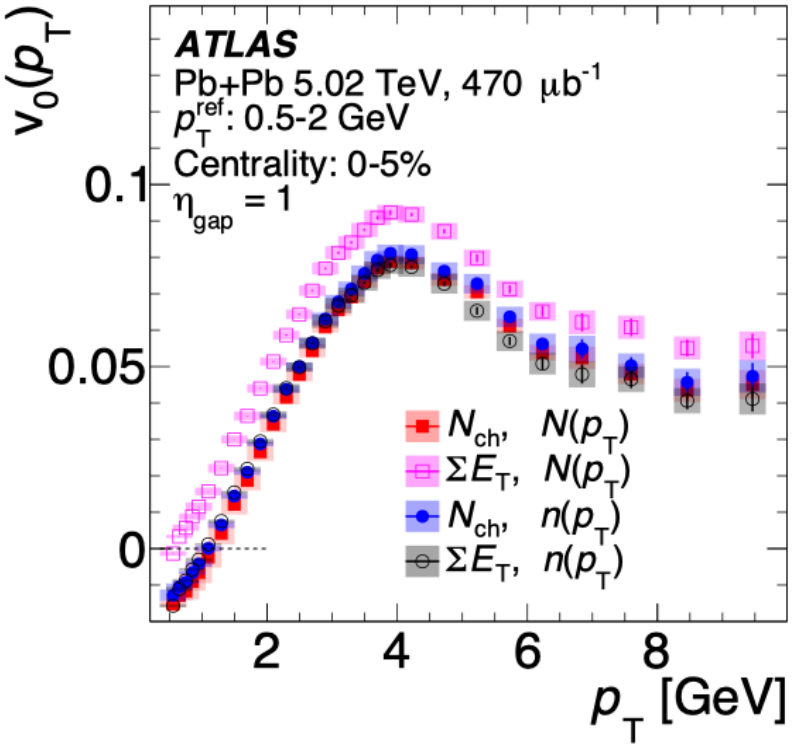
$$n(p_T) = \frac{N(p_T)}{\int N(p_T)\, dp_T}$$

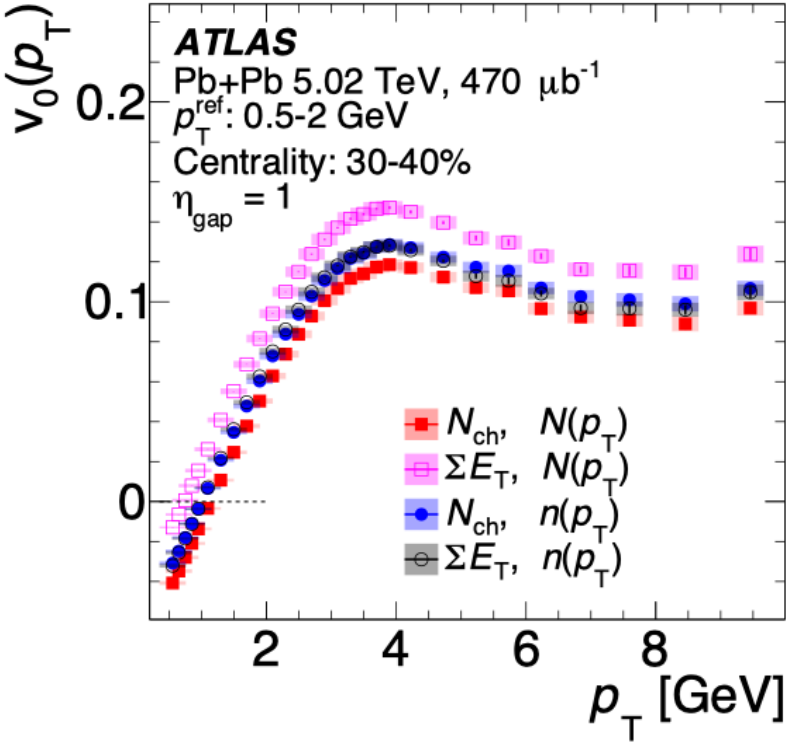
2) $v_0(p_T)$ depends on the range used to normalize spectra
we use B: 0.5-10 GeV, which is different from full range A: 0-10 GeV
$v_0(p_T)$ cross at $\langle p_T\rangle$ value that is higher than $\langle p_T\rangle$ for full range.

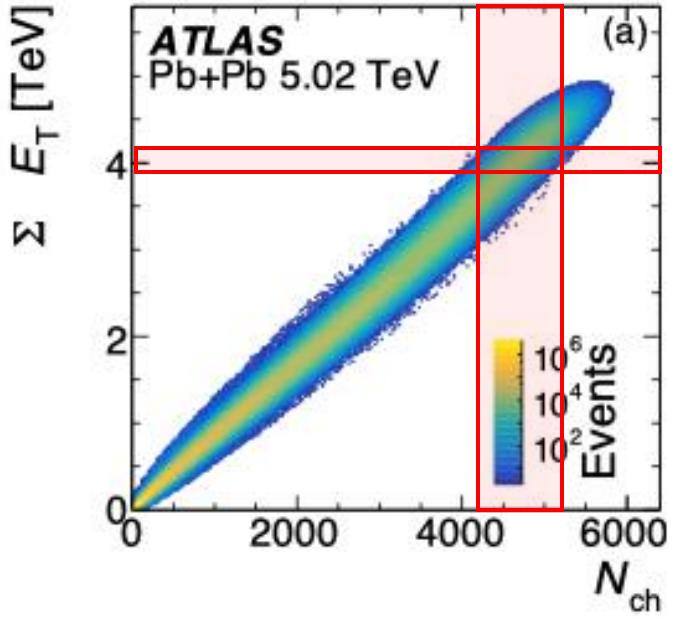


Multiplicity fluctuation check









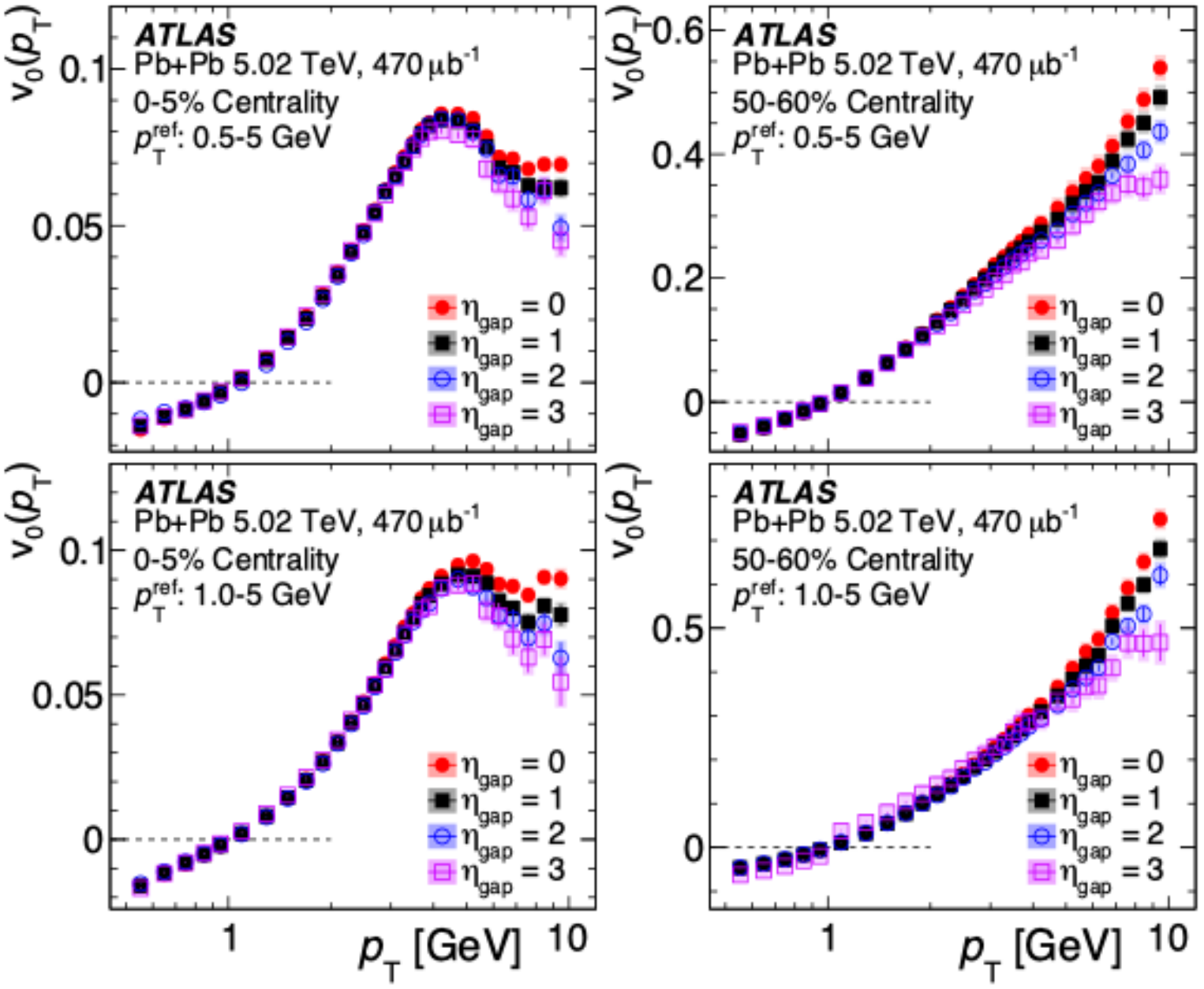
A narrow E_T range cover a wide range in N_{ch}

$$\frac{\langle \delta n(p_T)\delta[p_T]\rangle}{\langle n(p_T)\rangle\langle[p_T]\rangle} = v_0(p_T)v_0$$ ● N_{ch}, $n(p_T)$ ⊖ ΣE_T, $n(p_T)$

Using fractional spectra is insensitive to N fluctuation

$$\frac{\langle \delta N(p_T)\delta[p_T]\rangle}{\langle N(p_T)\rangle\langle[p_T]\rangle} = v_0'(p_T)v_0$$ ■ N_{ch}, $N(p_T)$ ⊟ ΣE_T, $N(p_T)$

Using spectra but event in unit N_{ch}, *is insensitive* to N fluctuation.

Using spectra but event in narrow E_T, *is sensitive* to N fluctuation.

η_{gap} dependence of $v_0(p_T)$