Probing Collectivity through p_T Spectrum Fluctuations in Heavy-Ion Collisions

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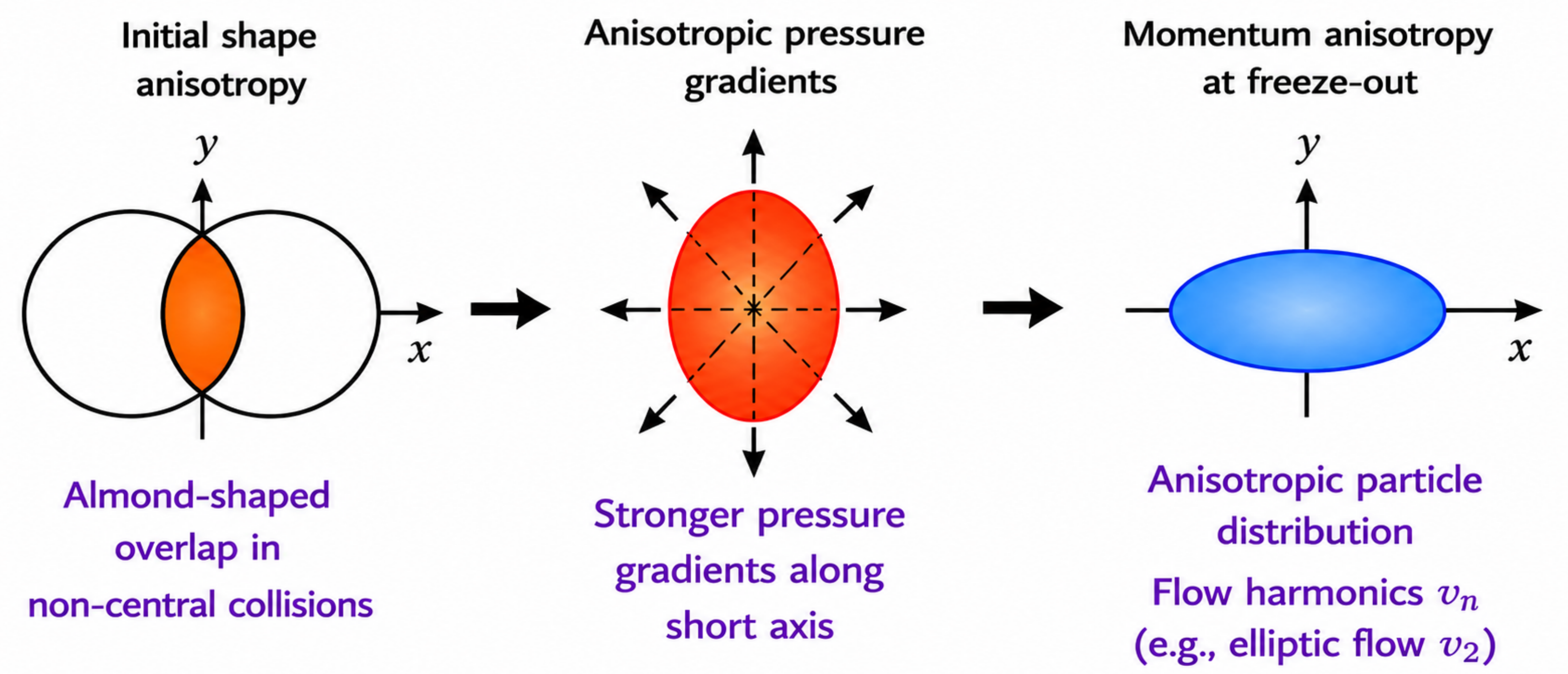
Shape-Flow Transmutation

(involves azimuthal angle)



Hydrodynamics converts initial shape anisotropy into momentum anisotropy v_n

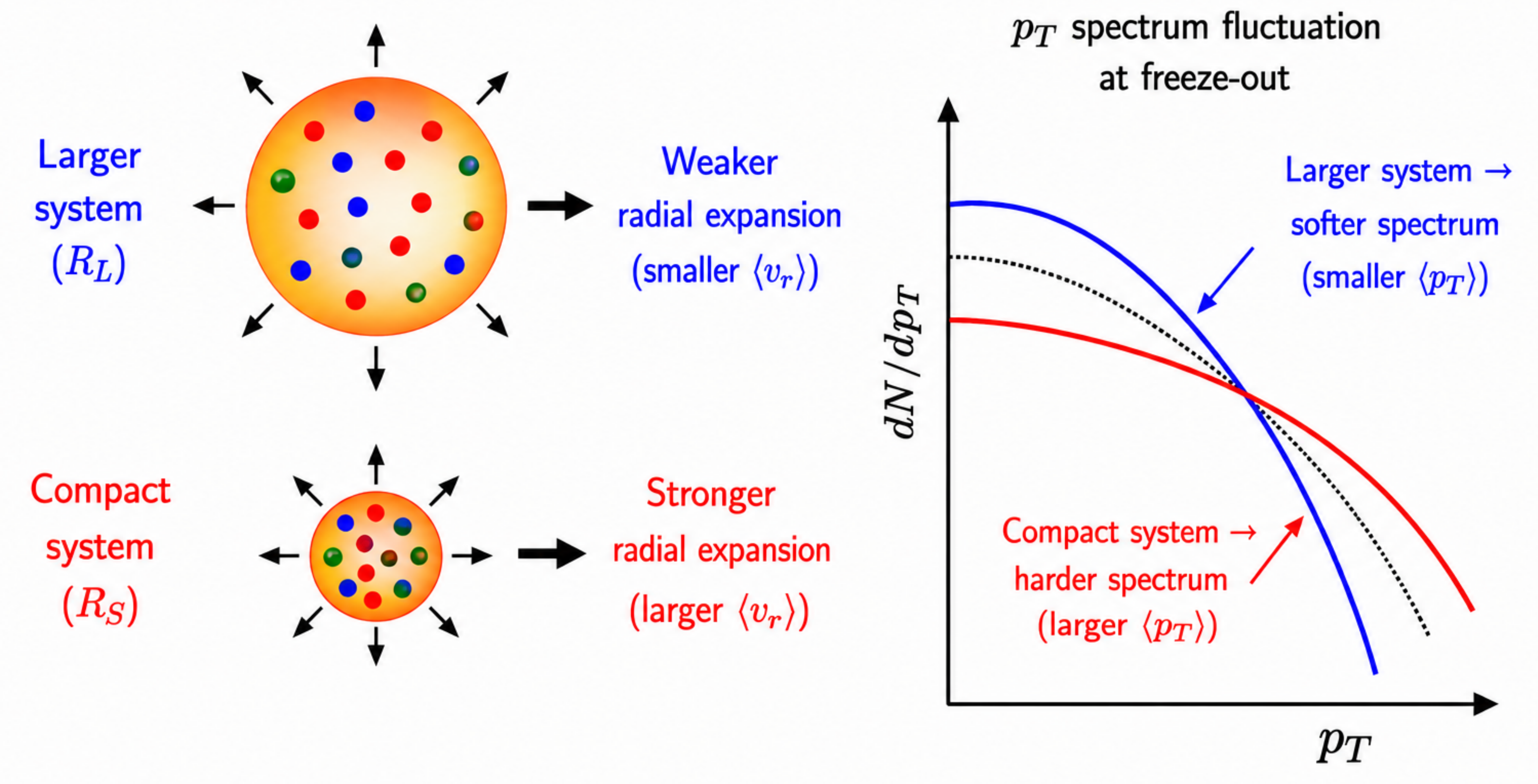
- Often considered as manifestation of collectivity.
- While measuring flow coefficients v_n, we correlate the azimuthal angles of particles in different rapidity windows, where such long range correlations are considered as signature of collectivity.

Bozek et. al. PRC 90, 064902 (2014)

Bozek, Broniowski PRC 96, 014904 (2017)

Size-Flow Transmutation

(does not involve azimuthal angle)

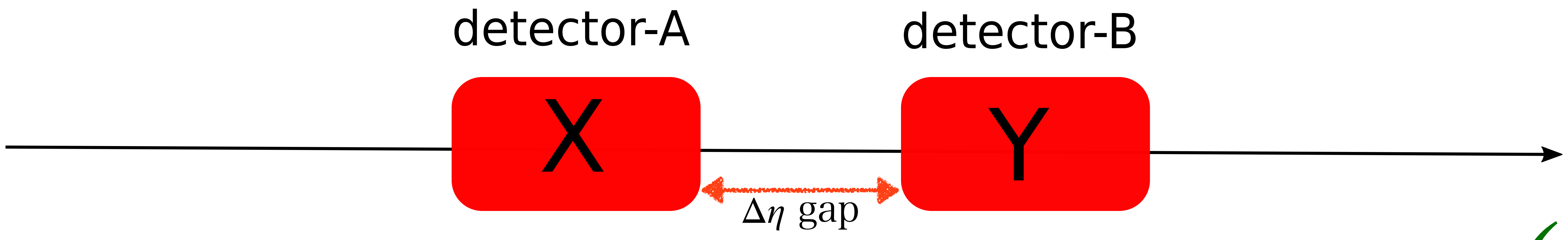


Hydrodynamics converts initial SIZE fluctuations into p_T spectrum fluctuations(mean-p_T fluctuation σ_{p_T})

- Less realised as signature of collectivity.
- To probe this collectivity arising due to radial flow, one could correlate the spectrum with a property of the fluid measured at other rapidity.

$v_0(p_T)$: correlation between spectra and mean p_T

Schenke, Shen & Teaney (2020)

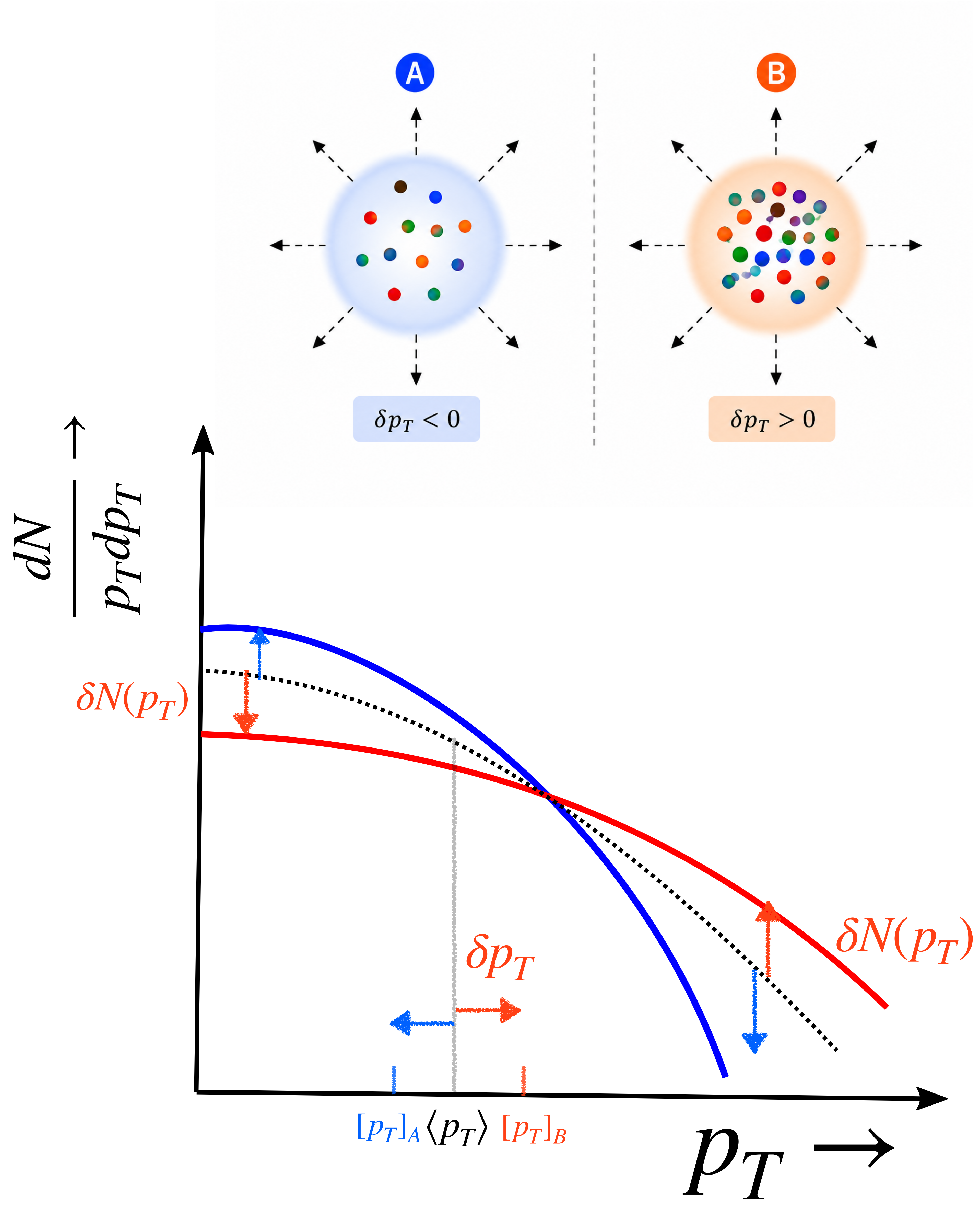


$v_n(p_T)$	$v_0(p_T)$
$X \equiv \sum_{k=1}^{N_A(p_T)} e^{in\phi_k}$ $\quad Y \equiv \frac{1}{N_B}\sum_{k=1}^{N_B} e^{-in\phi_k}$	$X \equiv N_A(p_T)$ $\quad Y \equiv \frac{1}{N_B}\sum_{k=1}^{N_B} (p_T)_k$
$v_n(p_T) \equiv \frac{\langle XY\rangle - \cancel{\langle X\rangle}\cancel{\langle Y\rangle}}{\langle N_A(p_T)\rangle v_n\{2\}}$	$v_0(p_T) \equiv \frac{\langle XY\rangle - \langle X\rangle\langle Y\rangle}{\langle N_A(p_T)\rangle \sigma_{p_T}}$

$$v_0 \equiv \frac{\sigma_{p_T}}{\langle p_T\rangle}$$

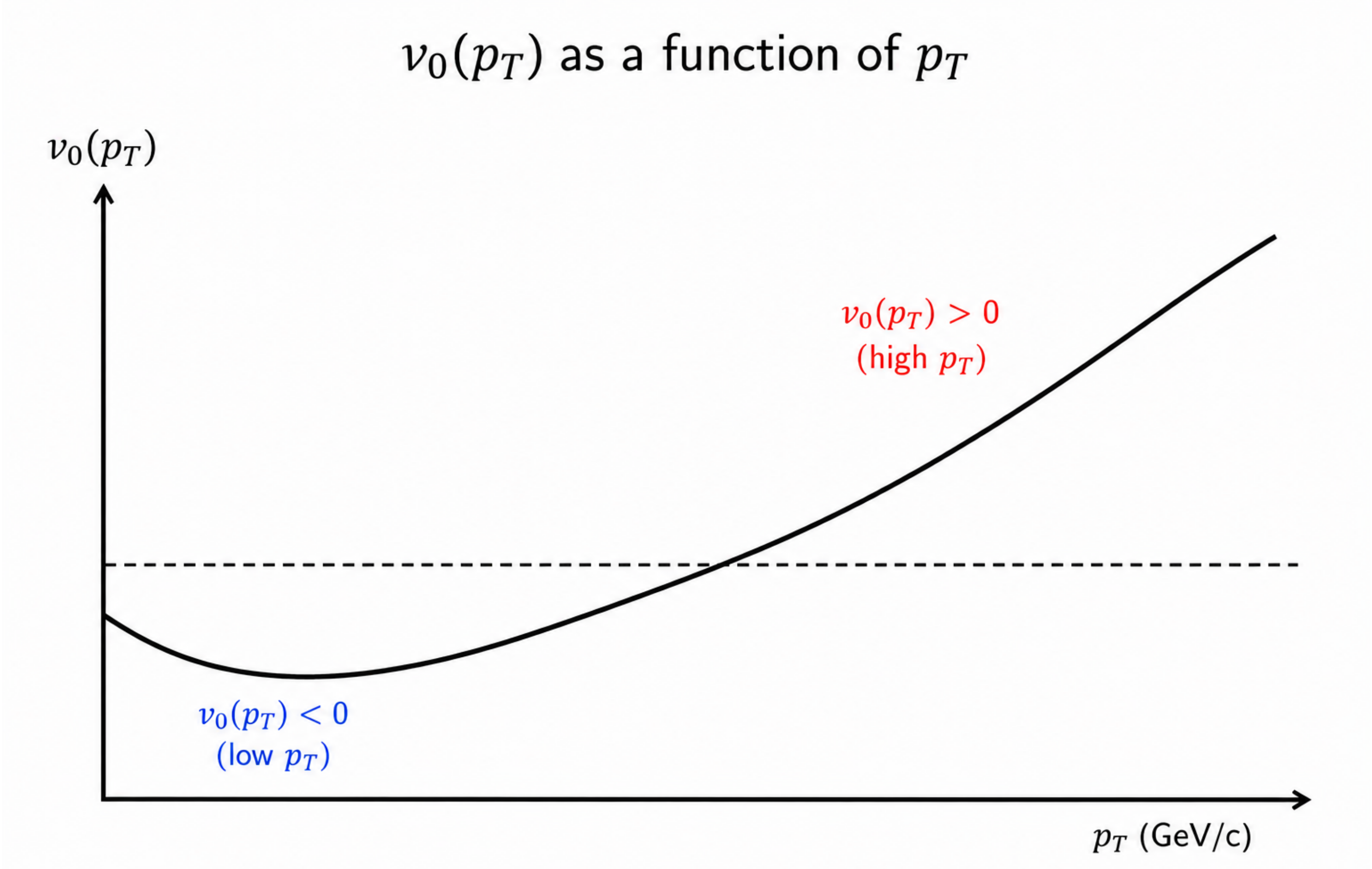
- Analysis of $v_0(p_T)$ is very similar to $v_n(p_T)$
- η - gap is useful to suppress non-flow.
- $v_0(p_T)$ is the p_T differential quantity of σ_{p_T}.

Sign change of $v_0(p_T)$



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

- At lower $p_T \lessapprox \langle p_T \rangle$: $\delta N(p_T) - \delta p_T$ anti correlated
- At higher $p_T \gtrapprox \langle p_T \rangle$: $\delta N(p_T) - \delta p_T$ positively correlated



Hydro model prediction

$v_0(p_T)$ is driven by temperature fluctuation

With fluctuating IC

We evaluate $v_0(p_T)/v_0$ by performing EbE hydro simulation.

$$\frac{v_0(p_T)}{v_0} = \frac{\delta \ln N(p_T)}{\delta \ln[p_T]}$$

$$= \frac{\ln \frac{N_2(p_T)}{N_1(p_T)}}{\ln \frac{[p_T]_2}{[p_T]_1}}$$

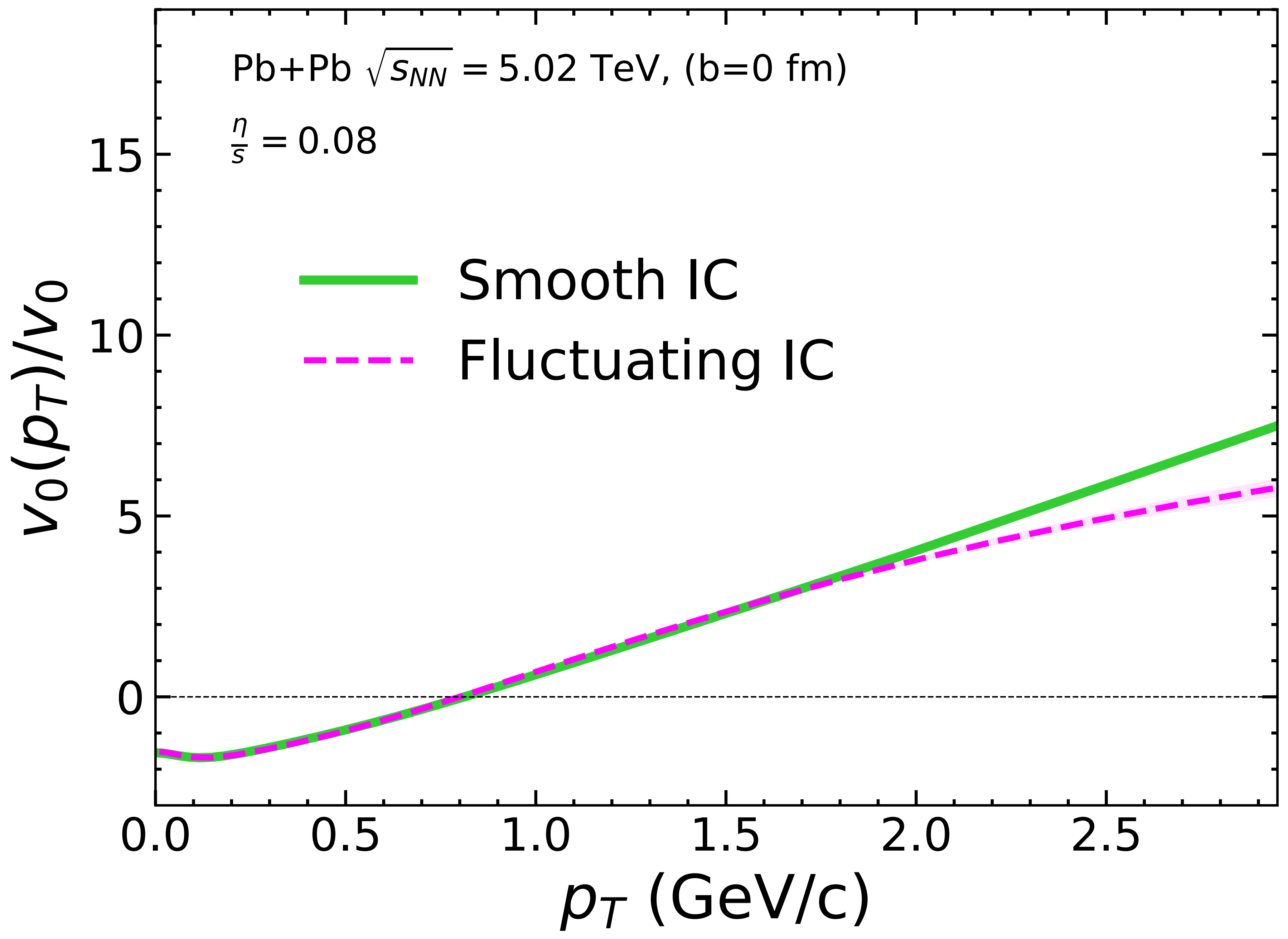
Event-2

Event-1

With smooth IC

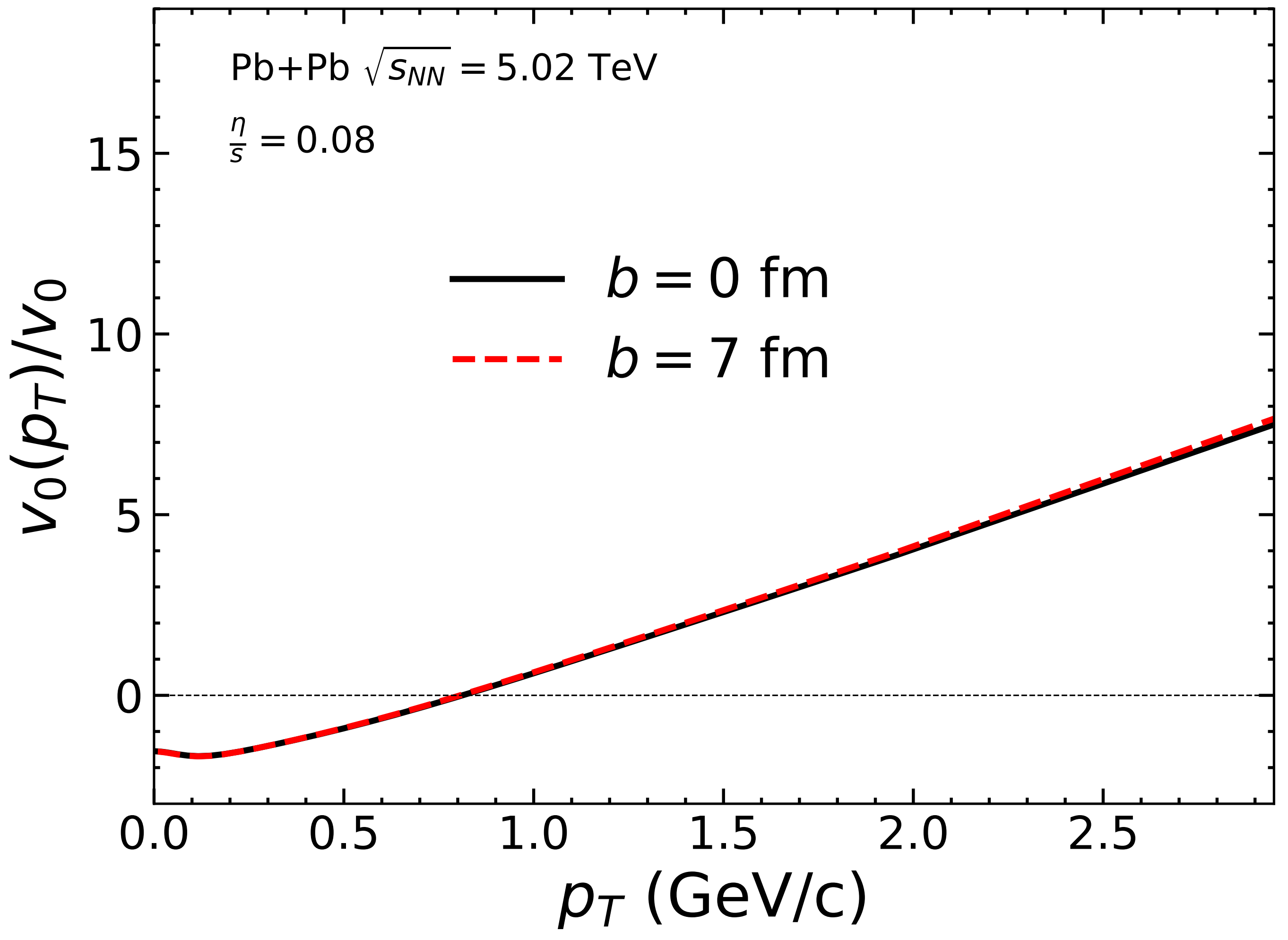
We run only 2 events

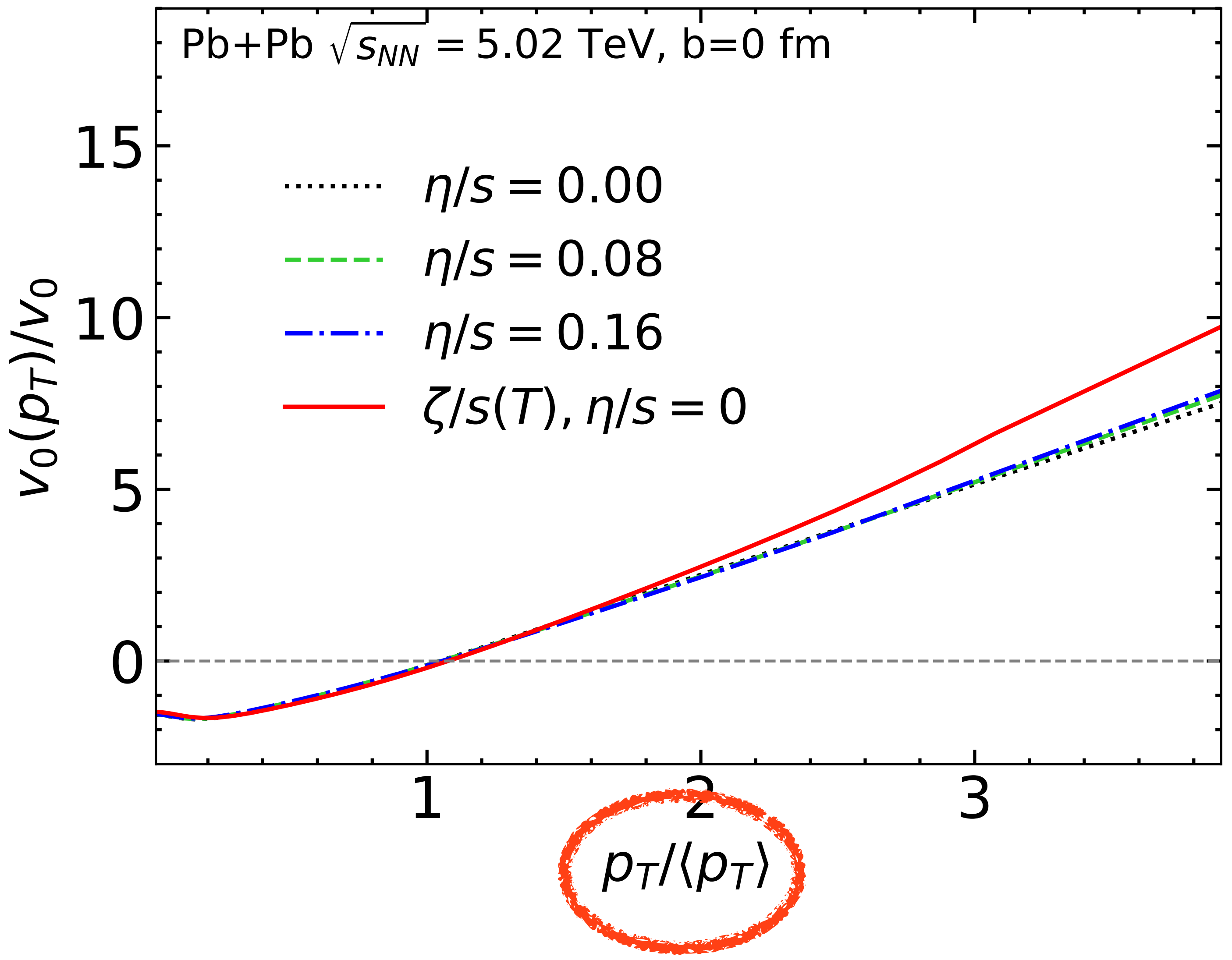
(1) Smooth initial profile by averaging over multiple Trento events + single-shot hydrodynamic evolution.
(2) Increment of the initial temperature by 1% + hydrodynamic evolution.

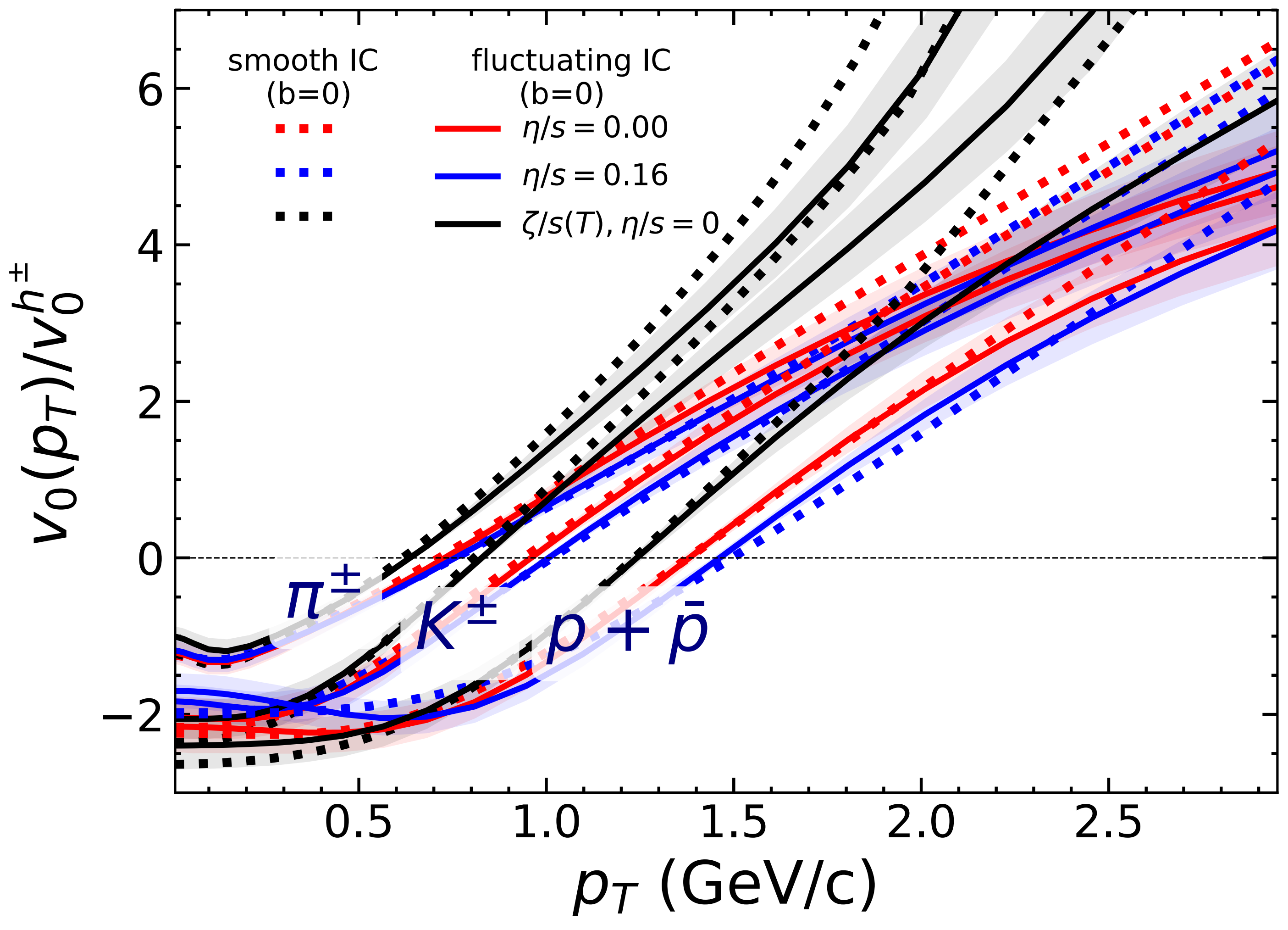


Hydro model prediction

We provide predictions for $v_0(p_T)/v_0$ rather than $v_0(p_T)$





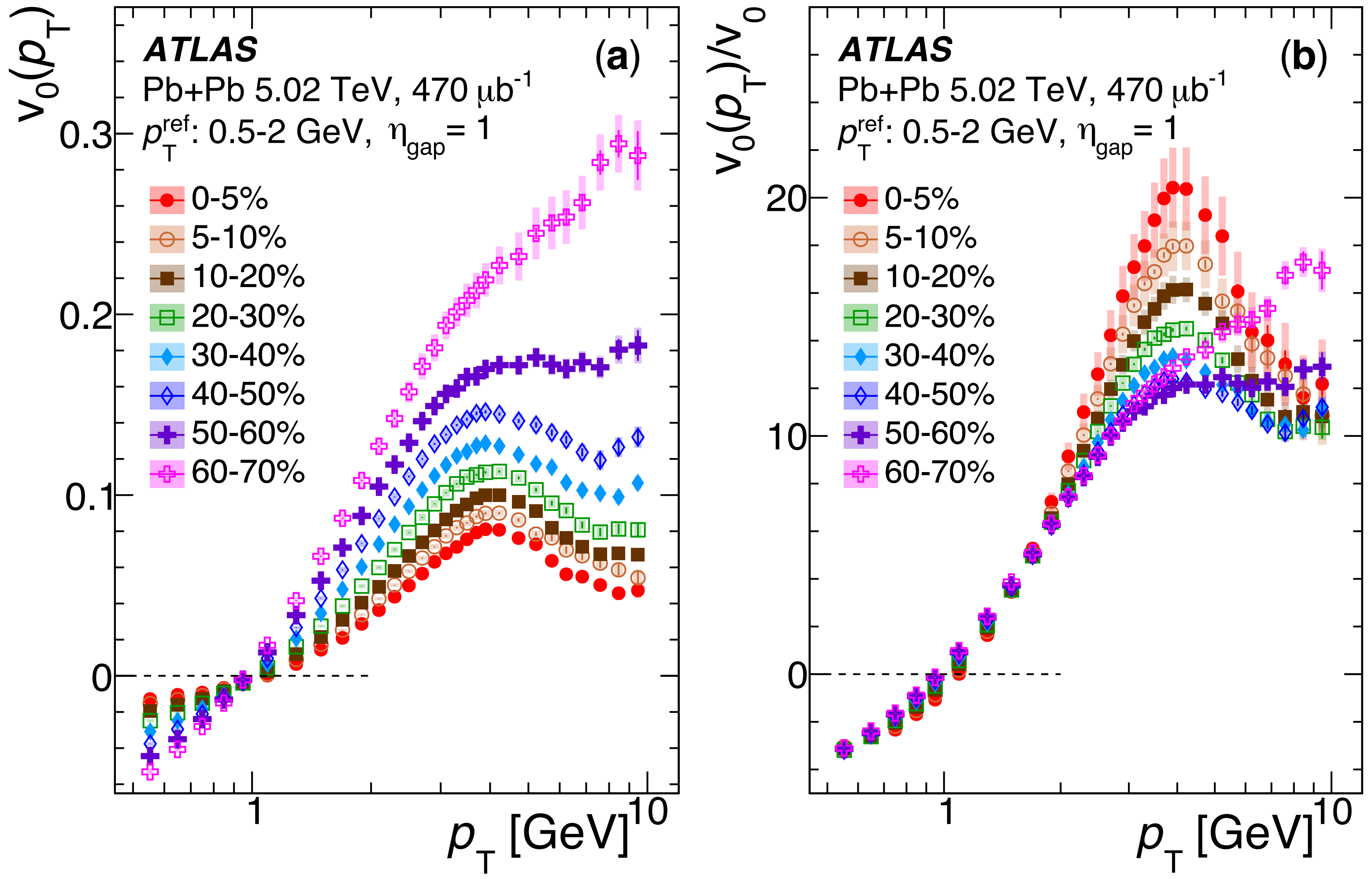


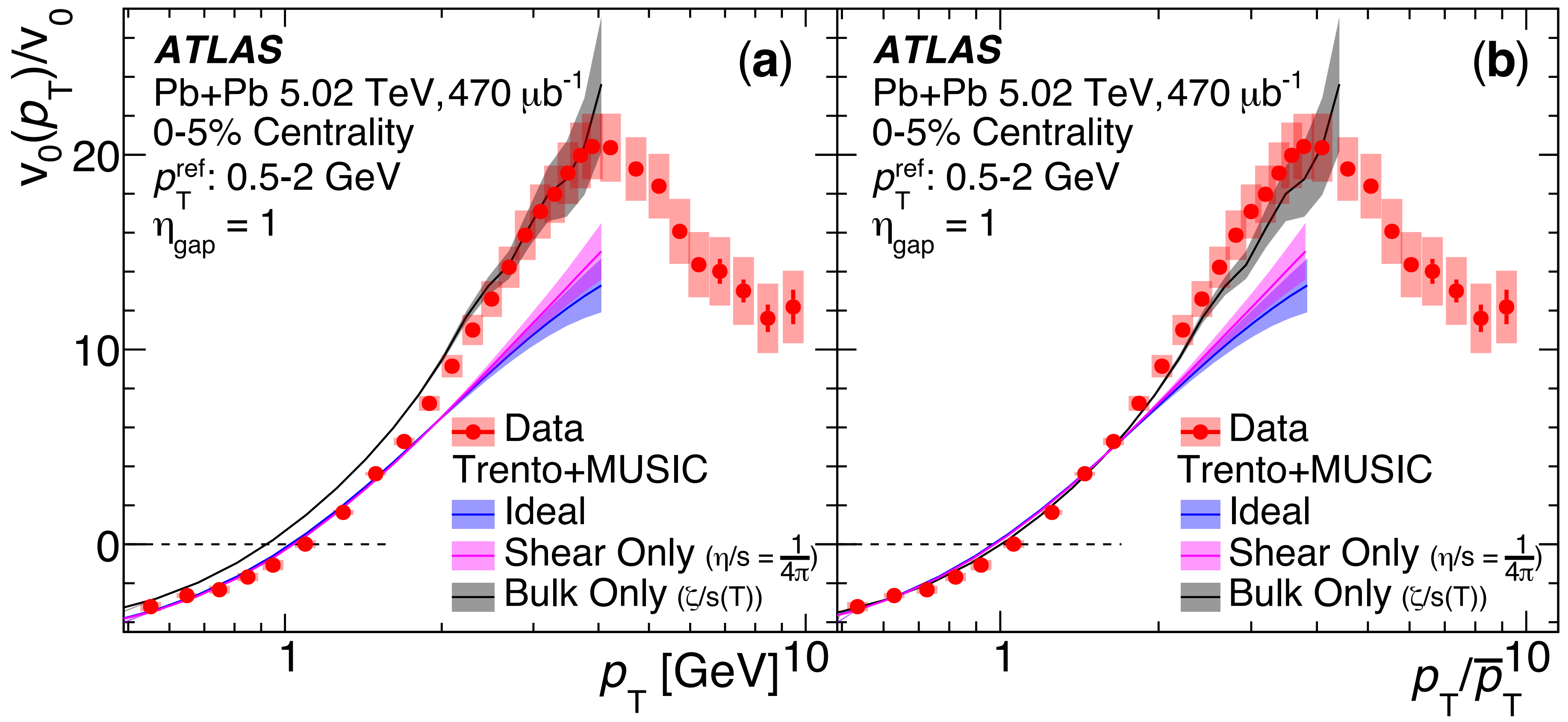
- ☑ $v_0(p_T)/v_0$ is independent of centrality, like $v_n(p_T)/v_n$

- ☑ Very less sensitive to η/s
- ☑ Sensitivity to ζ/s is partly due to change in $\langle p_T \rangle$

- ☑ Mass ordering like $v_n(p_T)$ - consequence of collective flow.

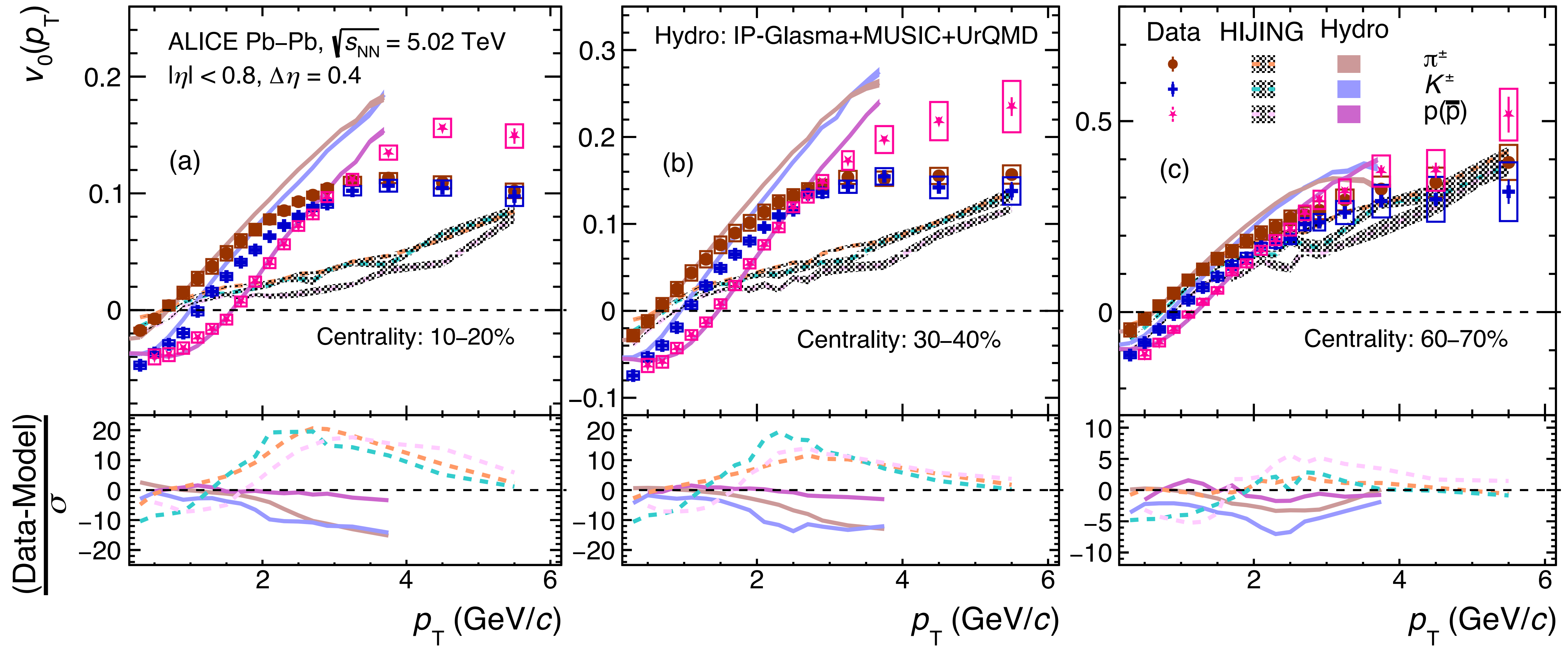
Experimental measurement





$v_0(p_T)/v_0$ is independent of centrality, like $v_n(p_T)/v_n$

Sensitivity to ζ/s .



Mass ordering like $v_n(p_T)$ - consequence of collective flow.

ATLAS Collaboration PRL 136, 032301 (2026)

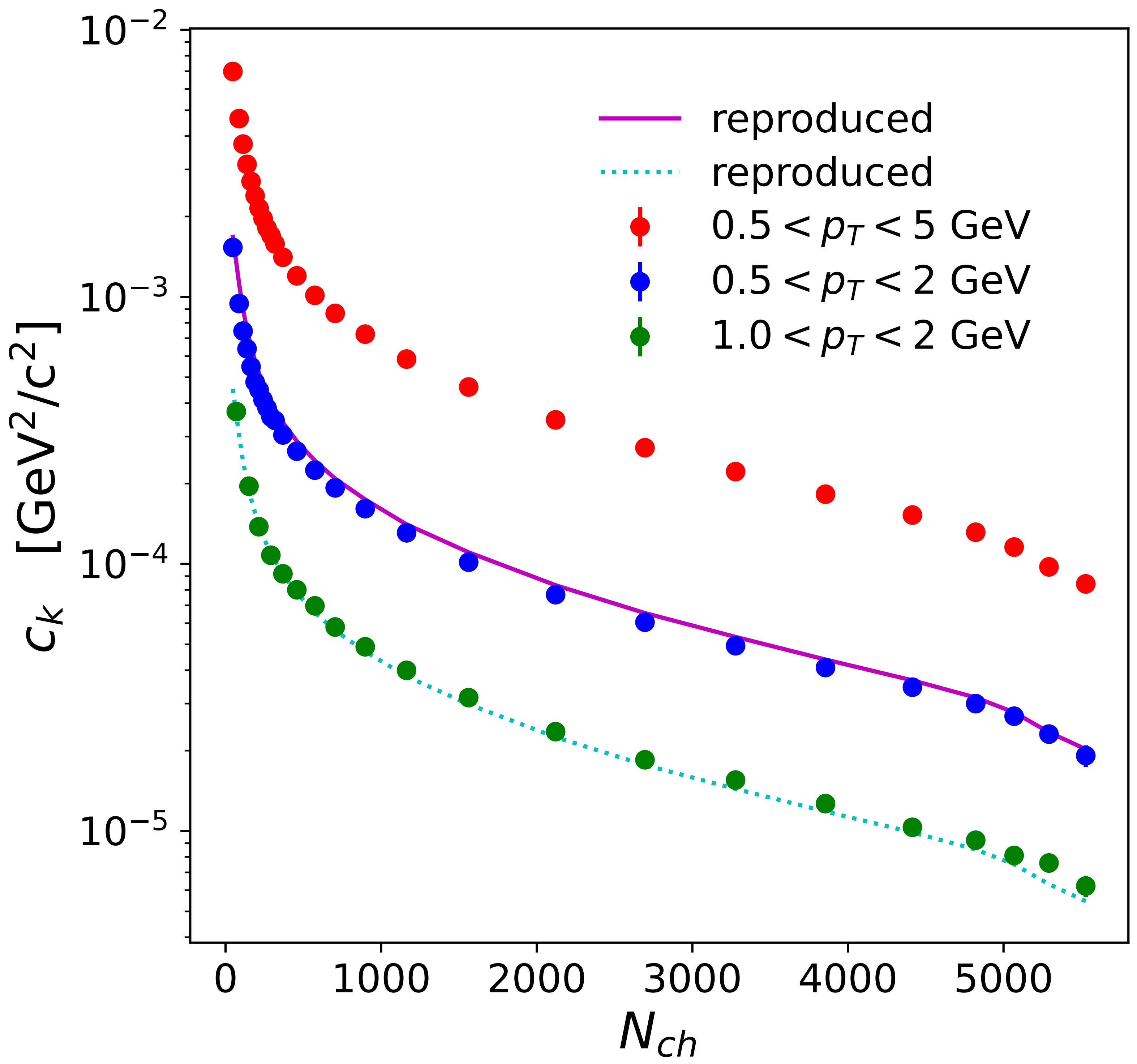
ALICE Collaboration PRL 136, 032302 (2026)

Application of $v_0(p_T)$

Comprehending p_T cut dependency of σ_{p_T}

TP, Samanta, Ollitrault EPJ Web Conf. 364(2026) 05004

- ☑ $v_0(p_T)$ - The differential observable of σ_{p_T} (c_k).
- ☑ Larger p_T acceptance $\rightarrow$ Larger σ_{p_T} : driven by $v_0(p_T)$
- ☑ Just need to integrate $v_0(p_T)$ in relevant window to capture the p_T cut dependency of σ_{p_T}



We use the σ_{p_T} or $\langle p_T \rangle$ of a given window as input and then predict for the other windows using $v_0(p_T)$ from hydro model.

Speed of sound(c_s^2) extraction of the medium

Alqahtani, TP, Ollitrault arXiv:2603.09647

- ☑ One can infer c_s^2 by analysing the increase of mean p_T with multiplicity in ultra central collisions. (ideal detector scenario).
- ☑ Low p_T particle escape detection, which biases the analysis. One can correct for this bias using the information from $v_0(p_T)$.

$$c_s^2 = \frac{d \ln \langle p_T \rangle}{d \ln N_{ch}}$$

A new proposal : $v_{02}(p_T)$

$v_0(p_T)$

1. Correlation between particle spectrum and mean p_T
2. Two particle correlation.
3. More non-flow (e.g. back to back jet correlation)
4. The integrated quantity $v_0 \equiv \frac{\sigma_{p_T}}{\langle p_T \rangle}$

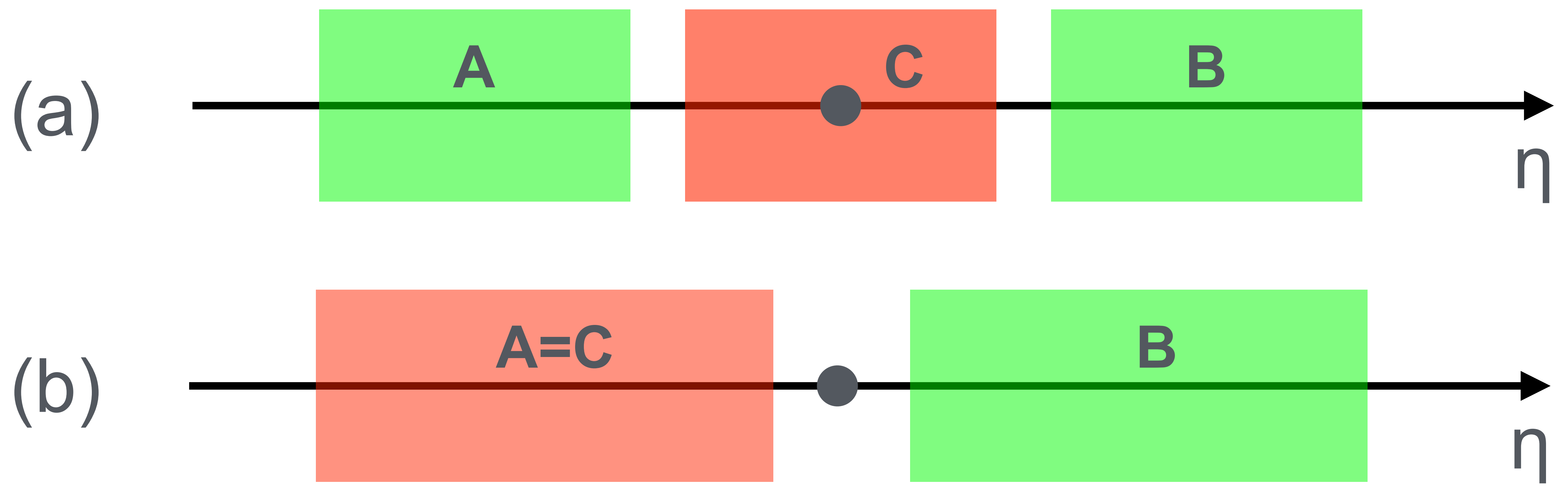
$$v_0(p_T) \equiv \frac{\langle \delta N(p_T) \delta p_T \rangle}{N_0(p_T)\sigma_{p_T}}$$

$v_{02}(p_T)$

1. Correlation between particle spectrum and elliptic flow, v_2^2
2. Three particle correlation.
3. non-flow supressed.
4. The integrated quantity : Bozek correlator $v_{02} \equiv v_0 \frac{\sigma_{v_2^2}}{\langle v_2^2 \rangle} \rho_2$

$$v_{02}(p_T) \equiv \frac{\langle \delta N(p_T) \delta v_2^2 \rangle}{N_0(p_T)\langle v_2^2 \rangle}$$

Experimental Measurement



$$X \equiv \sum_{k=1}^{N_A(p_T)} e^{in\phi_k}$$

$$v_{02} = \frac{\langle XYZ \rangle_c}{\langle XY \rangle_c \langle Z \rangle}$$

$$Y \equiv \frac{1}{N_B} \sum_{k=1}^{N_B} e^{-in\phi_k}$$

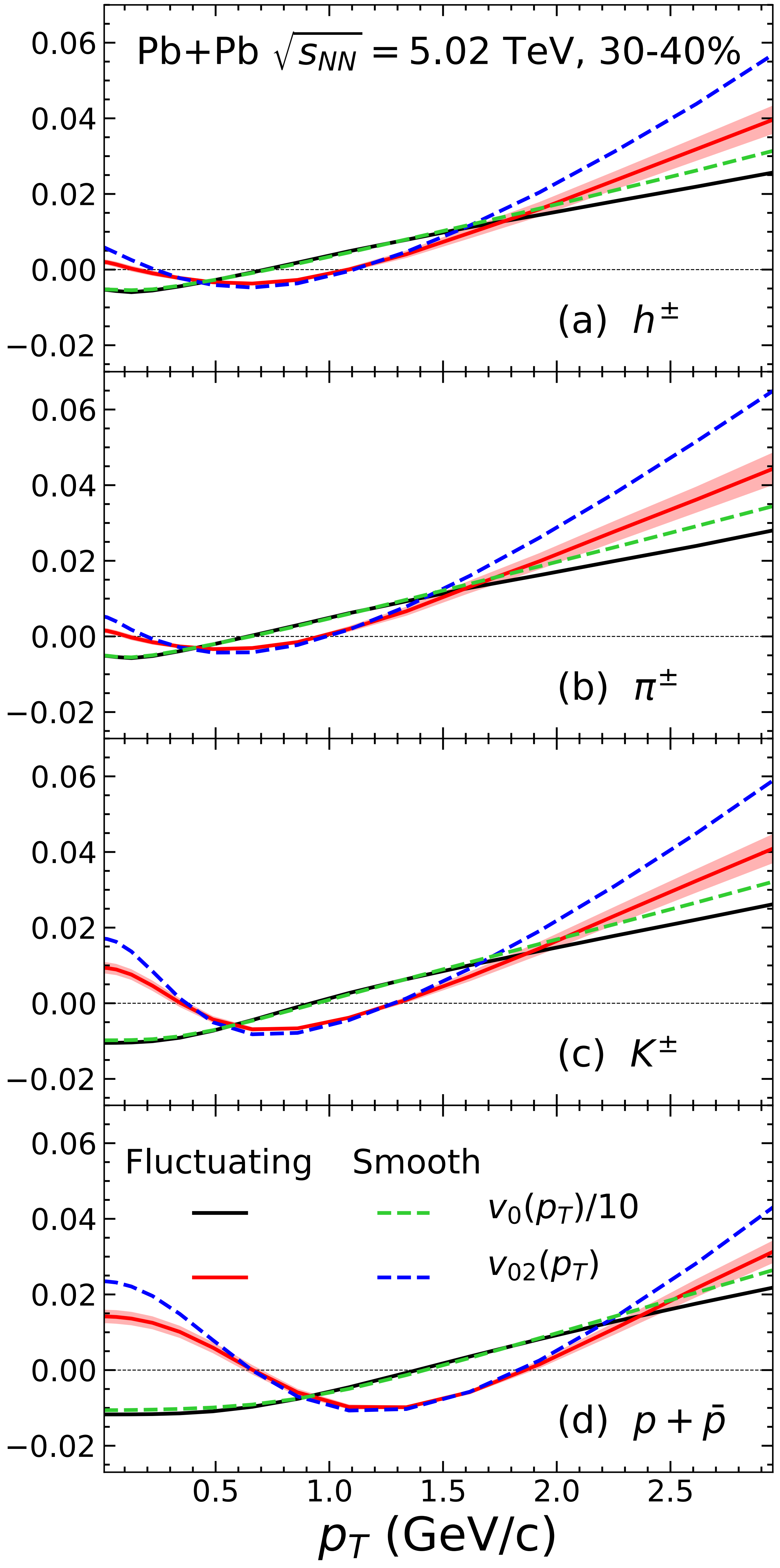
$$v_{02}(p_T) = \frac{\langle XYZ(p_T) \rangle_c}{\langle XY \rangle_c \langle Z(p_T) \rangle}$$

$$Z(p_T) \equiv \frac{N_C(p_T)}{N_C}$$

$$Z \equiv \frac{1}{N_C} \sum_{k=1}^{N_C} (p_T)_k$$

When A=C, particles present in X also present in Z, so need to remove self-correlation.

Hydro model prediction



- ☑ $v_{02}(p_T)$ magnitude is one order small than $v_0(p_T)$.
- ☑ Double sign change in $v_{02}(p_T)$ while single sign change in $v_0(p_T)$.
- ☑ No mass ordering in $v_{02}(p_T)$.

Double sign change in $v_{02}(p_T)$

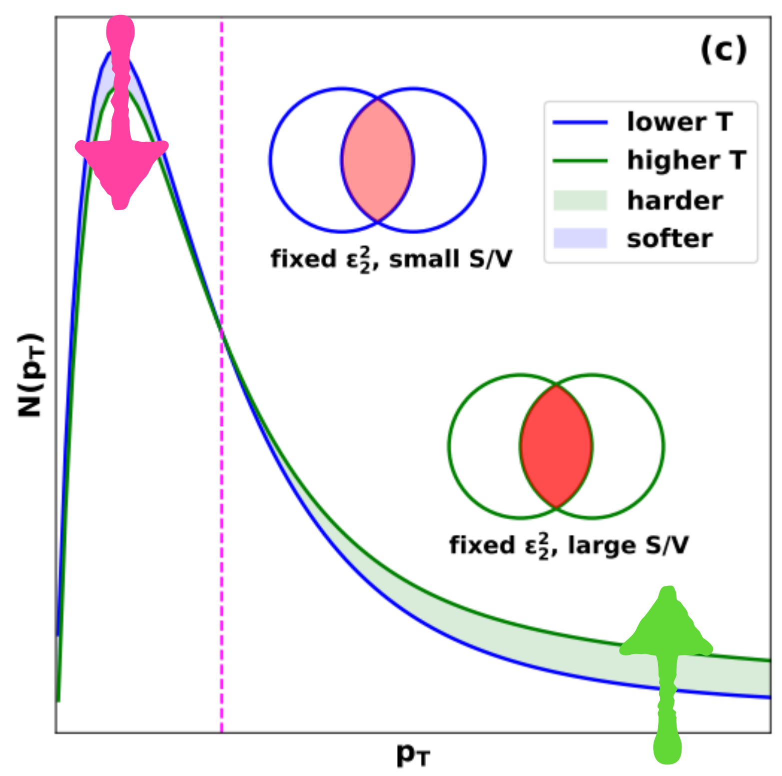
Spectra fluctuation can be modeled in a two-component way.

$$\frac{\delta N(p_T)}{\langle N(p_T)\rangle} = \alpha(p_T)\frac{\delta p_T}{\langle p_T\rangle} + \beta(p_T)\delta v_2^2$$

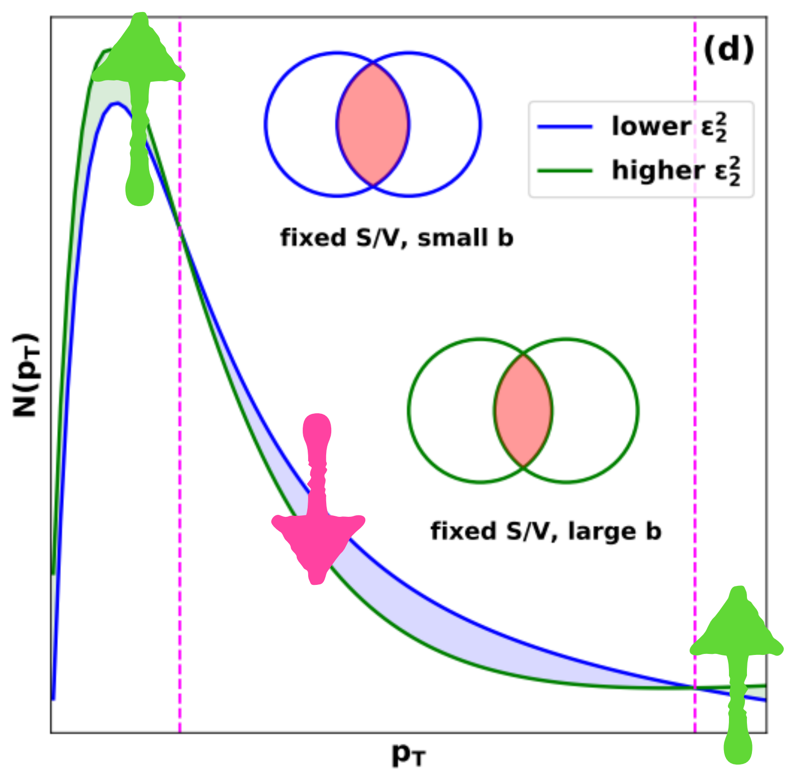
modification of the spectrum induced by a small variation of $[p_T]$ at constant v_2

change of the spectrum upon a variation of v_2 which leaves $[p_T]$ unchanged.

$v_0(p_T)$



$v_{02}(p_T)$



- ☑ Additional constraint in the $v_{02}(p_T)$ case : mean p_T remain fixed. So the spectra has to redistribute accordingly

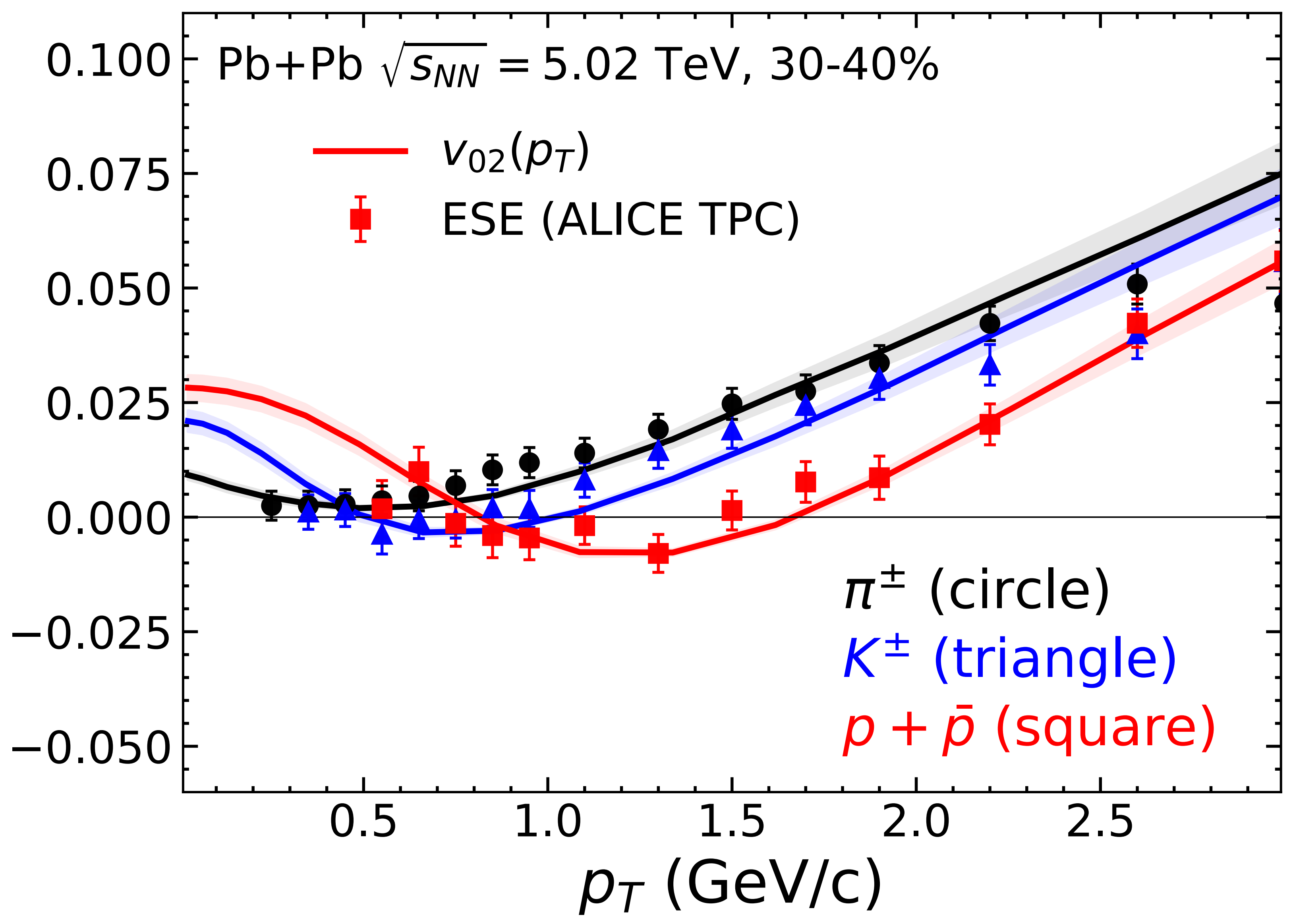
Figure taken from, Rupam Samanta, arXiv : 2604.26731

$v_{02}(p_T)$: relation with Event Shape Engineering analysis

- A hint of spectra-v_2 correlation has already been observed in ALICE Event Shape Engineering analysis.

$$\frac{\frac{dN}{dp_T d\eta}(\text{large } q_2) - \frac{dN}{dp_T d\eta}(\text{small } q_2)}{\frac{dN}{dp_T d\eta}(\text{unbiased})} = a v_{02}(p_T) + b, \quad (21)$$

Large $q_2 \implies$ Large v_2



ALICE Collaboration PRC 93, 034916 (2016)

Summary

- Two novel observable to probe radial flow through spectra fluctuation has been discussed, $v_0(p_T)$ and $v_{02}(p_T)$.

$v_0(p_T)$

1. Correlation between particle spectrum and mean p_T
2. Two particle correlation.
3. The integrated quantity $v_0 \equiv \dfrac{\sigma_{p_T}}{\langle p_T \rangle}$
4. p_T dependence changes than sign once below $p_T < 3$ GeV/c.

$v_{02}(p_T)$

1. Correlation between particle spectrum and elliptic flow, v_2^2
2. Three particle correlation, non-flow supressed.
3. The integrated quantity : Bozek correlator $\rho([p_T], v_2^2)$.
4. p_T dependence changes than sign twice below $p_T < 3$ GeV/c.

- $v_0(p_T)$ is already measured in experiments and shows features consistent with hydrodynamics prediction (e.g mass ordering, centrality independence of scaled $v_0(p_T)/v_0$), while for $v_{02}(p_T)$ it is yet to be measured.

Thanks