Probing collectivity with fluctuations of the p_t spectrum

Jean-Yves Ollitrault, IPhT Saclay

based on 2407.17313, with Tribhuban Parida & Rupam Samanta

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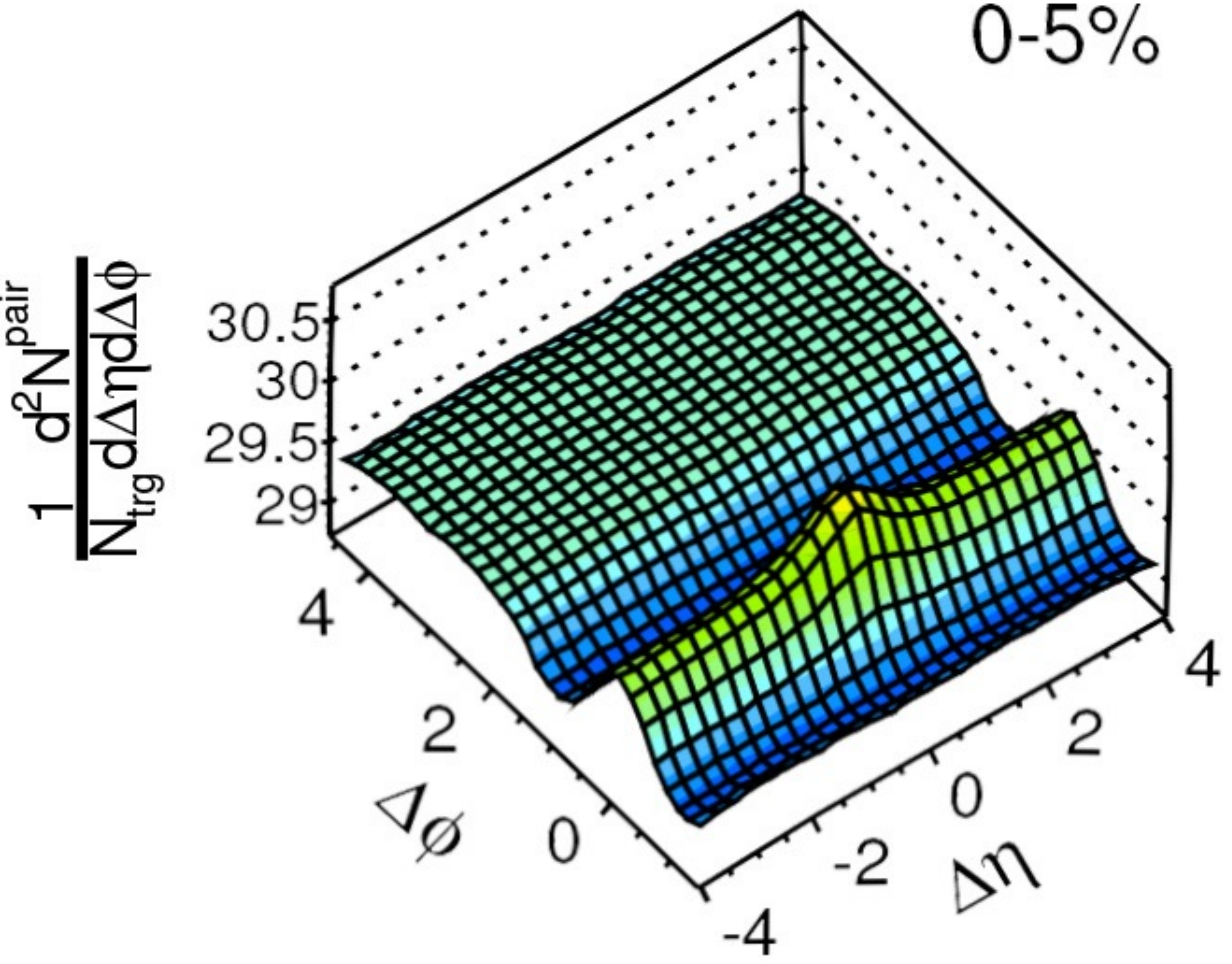
History: Hydrodynamics seen in Pb+Pb collisions

The observation of correlations which extend to large relative pseudorapidity $\Delta\eta$ (long-range correlations), almost independent of $\Delta\eta$, has been instrumental in establishing the formation of a little fluid, first at RHIC, than at LHC



Number of particle pairs versus $\Delta\phi$ and $\Delta\eta$

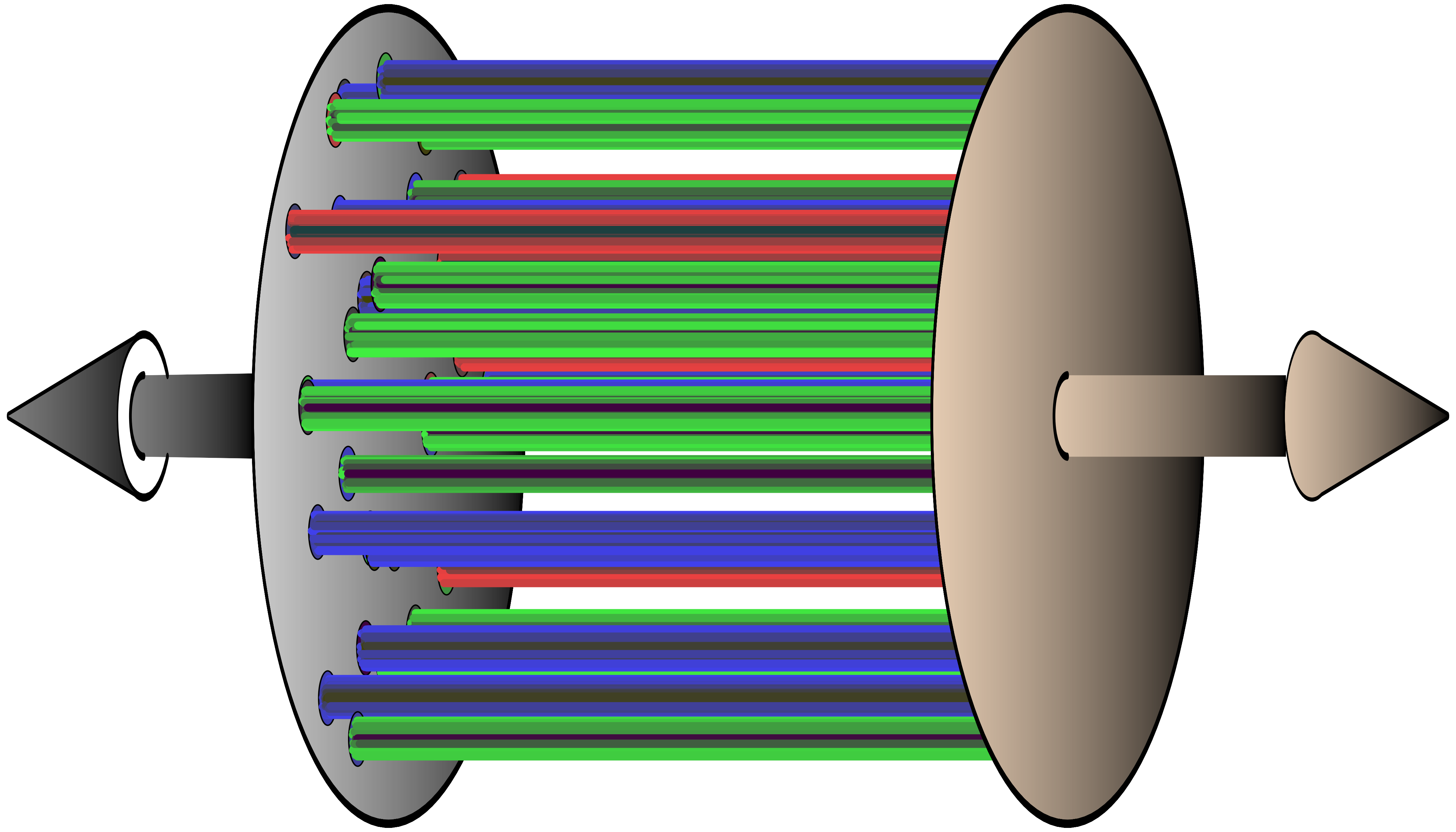
CMS 1201.3158

The origin of long-range correlations

Long-range correlations originate from the initial stages of the collision: strings or colour flux tubes are created, which span the whole rapidity range (or at least a large part of it).

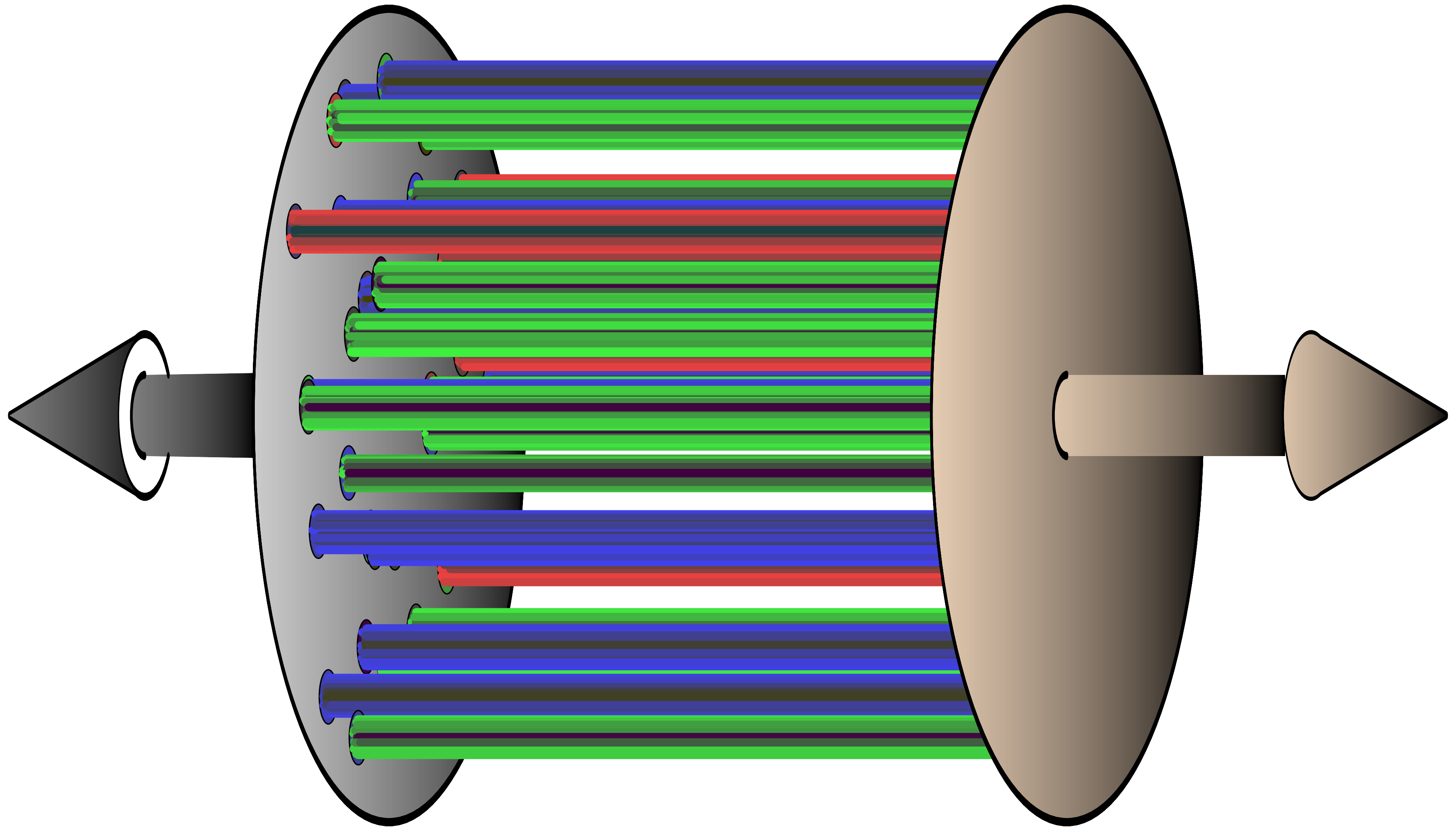
This picture of strong interactions is as old, or older than, QCD itself

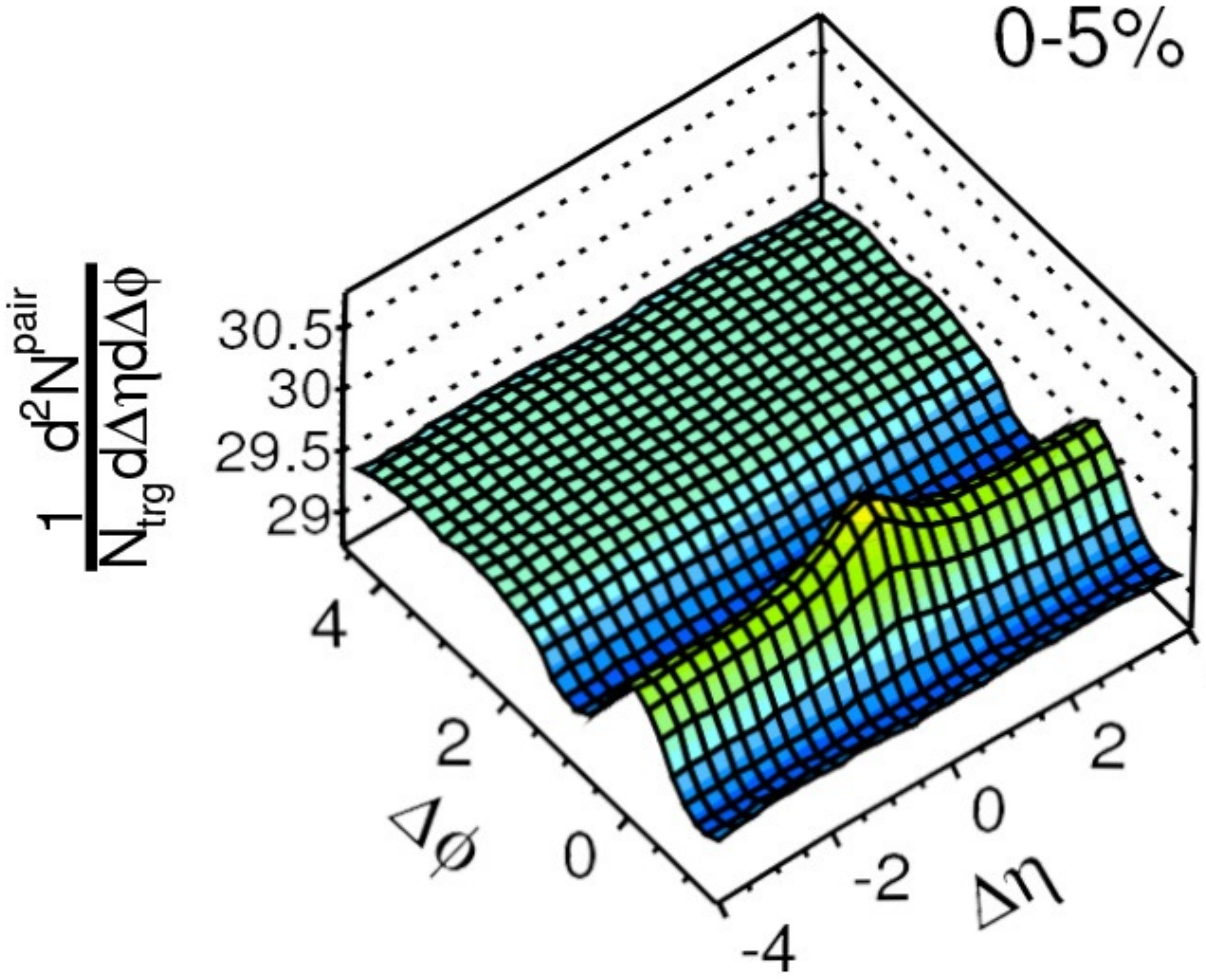
Artru Mennessier Nucl.Phys.B 70 (1974) 93-115



Gelis 1110.1544

Initial state + collectivity





In every event, the transverse density profile is independent of rapidity

The fluid pattern (temperature, fluid velocity) is also independent of rapidity. Generates the familiar "ridge" structure.

Probing collectivity with long-range pair correlations (outline)

Until now

Azimuthal (ϕ) correlations.

Observables:

1. Integrated anisotropic flow, v_n
Measures the *shape* of the fireball

3. Differential anisotropic flow $v_n(p_T)$, for identified particles when possible.

In this talk

p_t correlations: ϕ not needed!

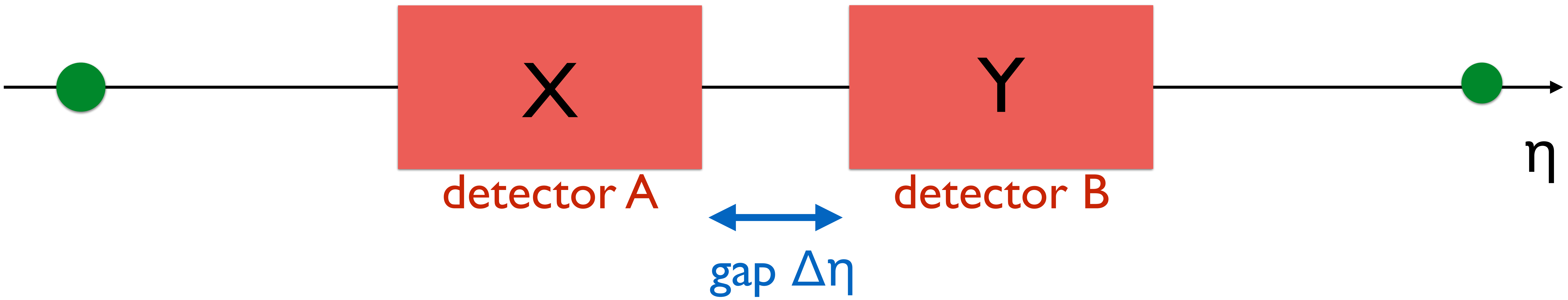
Observables:

2. Fluctuation of p_T per particle: σ_{p_T}
Measures the *temperature* of the fireball

4. Finally the differential $v_0(p_T)$, for identified particles when possible.

Schenke Shen Teaney 2004.00690

Measuring a long-range pair correlation

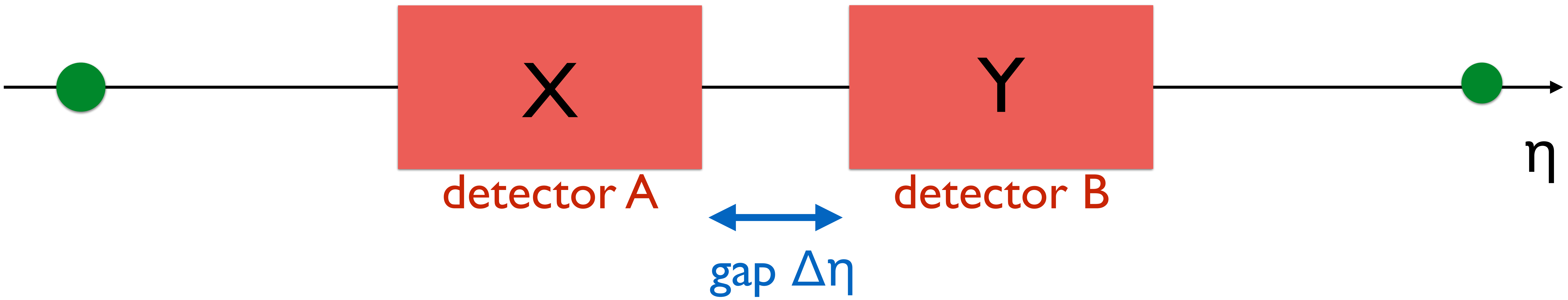


One uses two detectors, or two parts of a large detector,

- separated by a rapidity gap to suppress short-range nonflow correlations
- symmetric around mid-rapidity (simplest case, known as 2-subevent method)

Observables X and Y are measured in each event.
Generally, the correlation is $\langle XY\rangle - \langle X\rangle\langle Y\rangle$,
where $\langle\cdots\rangle$ is an average over many collision events in a centrality class.

1. Integrated anisotropic flow v_n



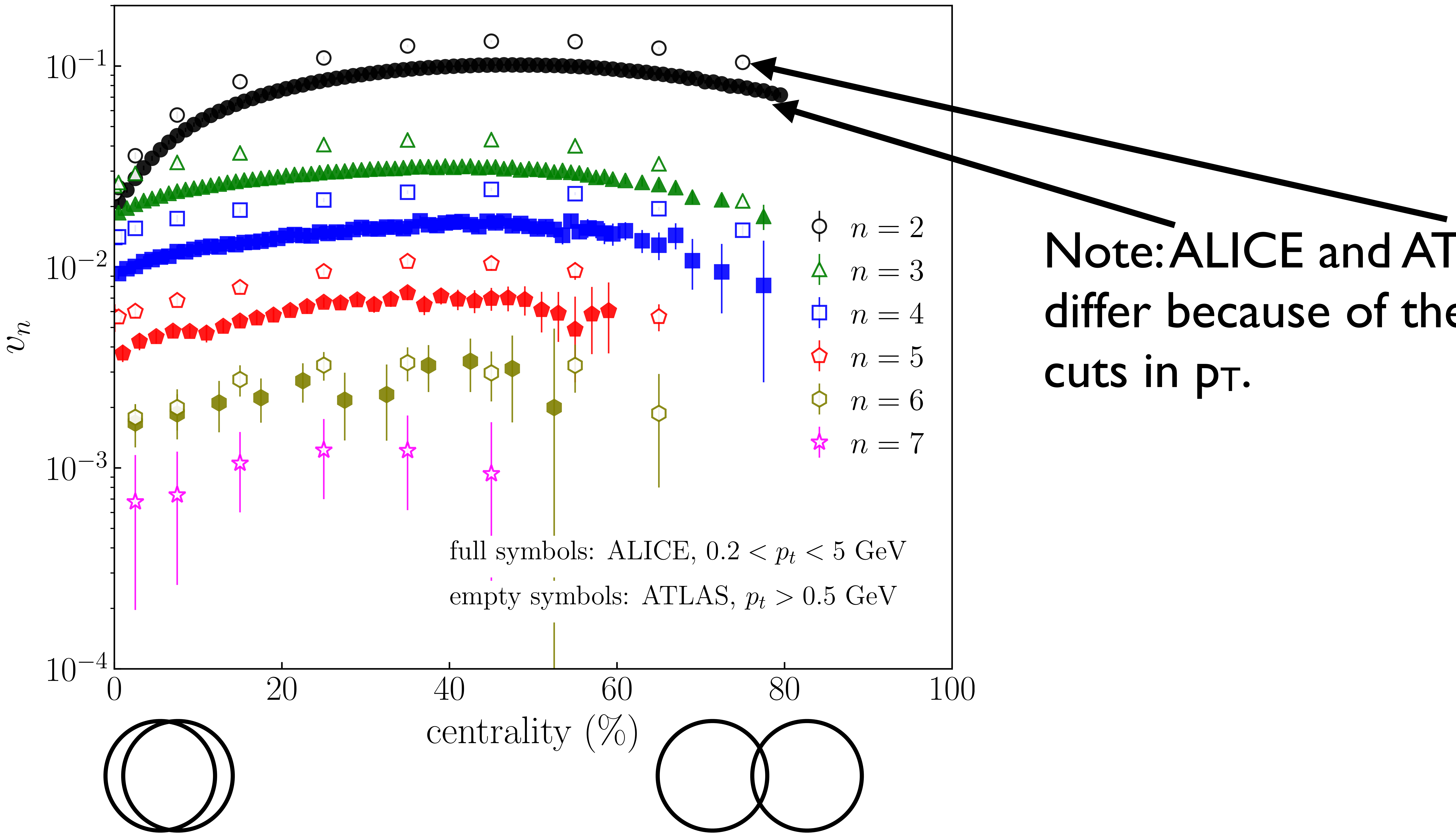
$$X \equiv \frac{1}{N_A}\sum_{k=1}^{N_A} e^{in\varphi_k} \qquad Y \equiv \frac{1}{N_B}\sum_{k=1}^{N_B} e^{-in\varphi_k}$$

One then defines

$$v_n\{2\} \equiv \sqrt{\langle XY\rangle - \langle X\rangle\langle Y\rangle}$$

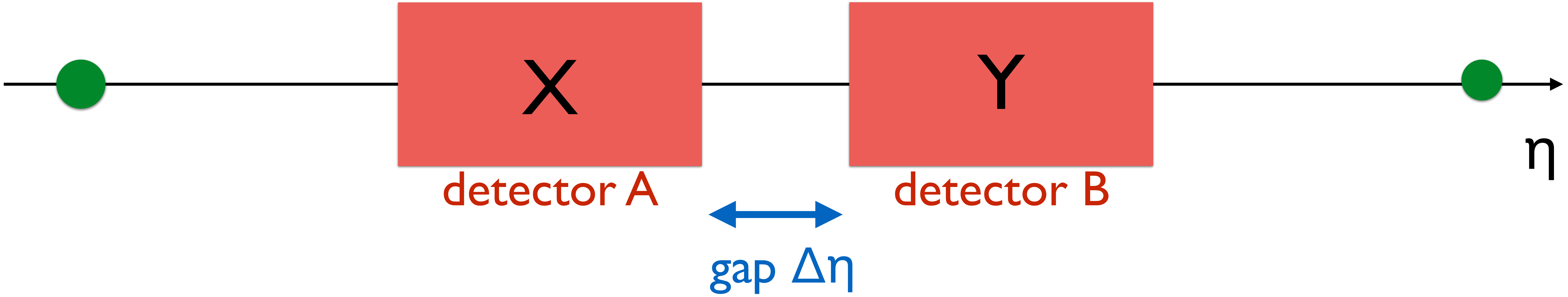
$\langle X\rangle = \langle Y\rangle = 0$ if detectors A and B have isotropic acceptance
(as a side note, the analysis works *just as well* if they don't)

1. Integrated anisotropic flow v_n



Note: ALICE and ATLAS results differ because of the different cuts in p_T.

2. Fluctuation of p_T per particle: v_0



$$X \equiv \frac{1}{N_A} \sum_{k=1}^{N_A} p_{T,k} \qquad Y \equiv \frac{1}{N_B} \sum_{k=1}^{N_B} p_{T,k}$$

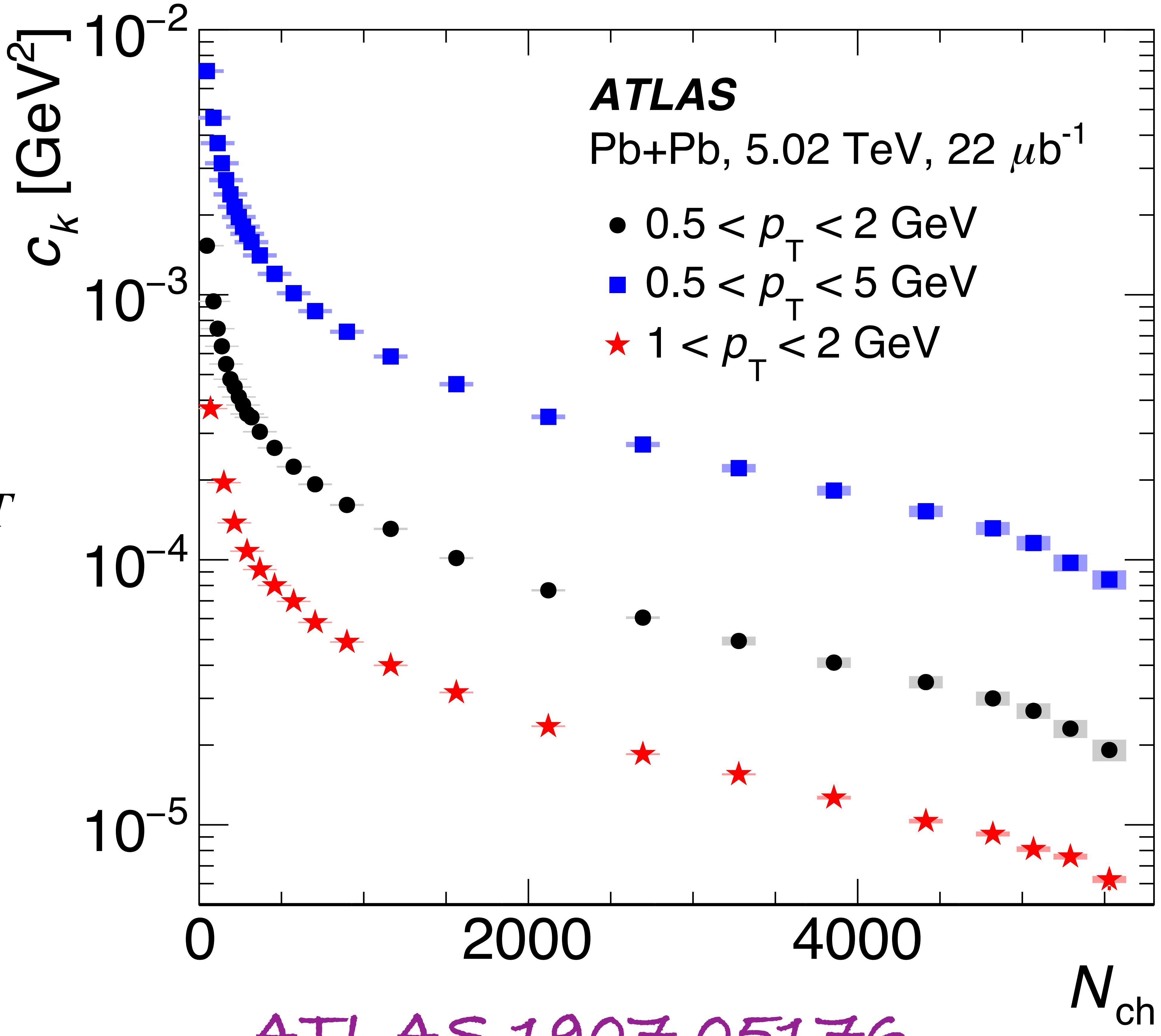
One then defines

$$\sigma_{p_t} \equiv \sqrt{\langle XY \rangle - \langle X \rangle \langle Y \rangle}$$

Physical interpretation: larger X or Y means larger initial temperature.
Temperature is identical in A and B, therefore,
$v_0 \equiv \sigma_{p_T} / \langle p_T \rangle$ = relative standard deviation of the temperature event to event

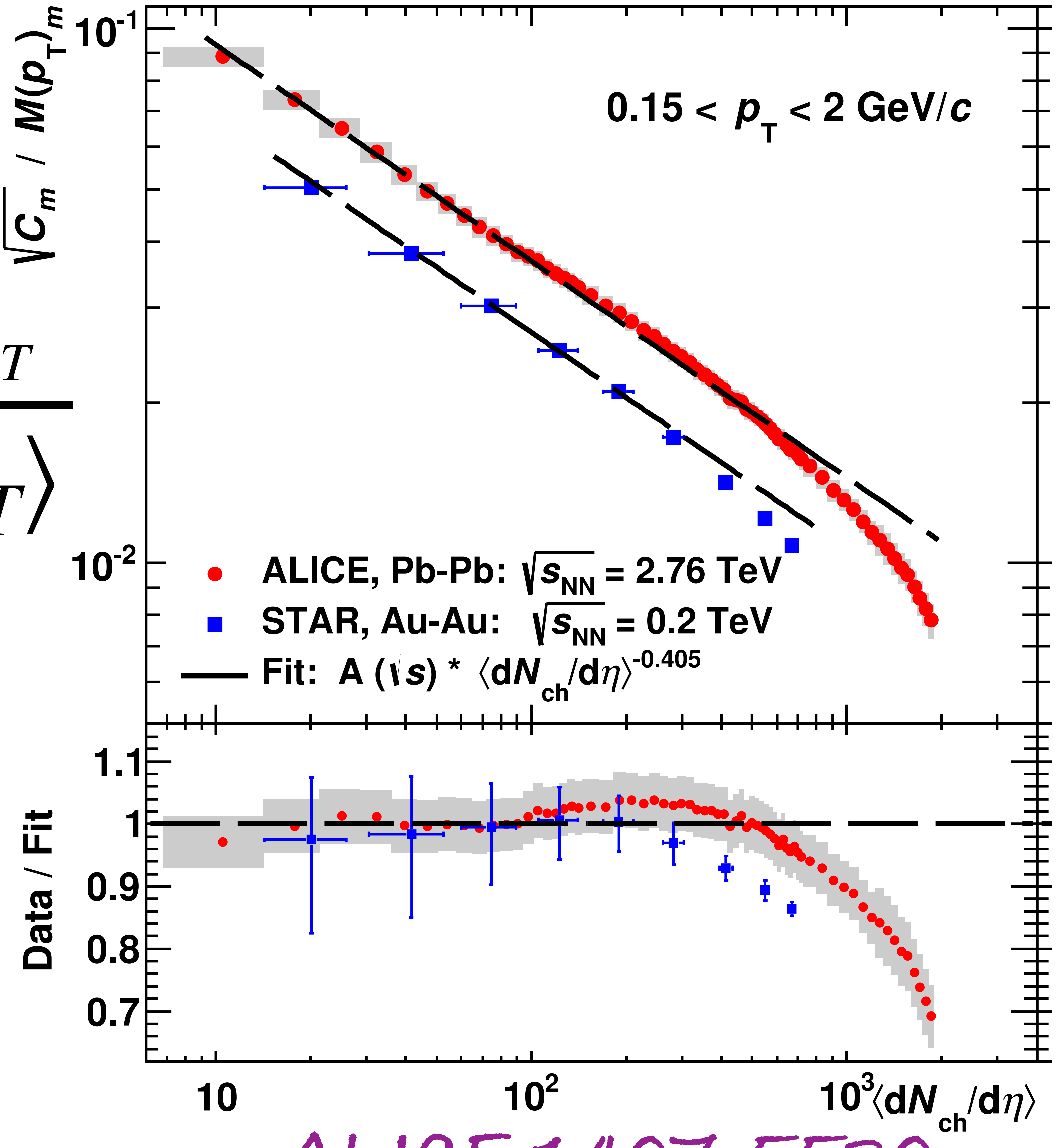
2. Fluctuation of p_T per particle: v_0

$\sigma^2_{p_T}$



ATLAS 1907.05176

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

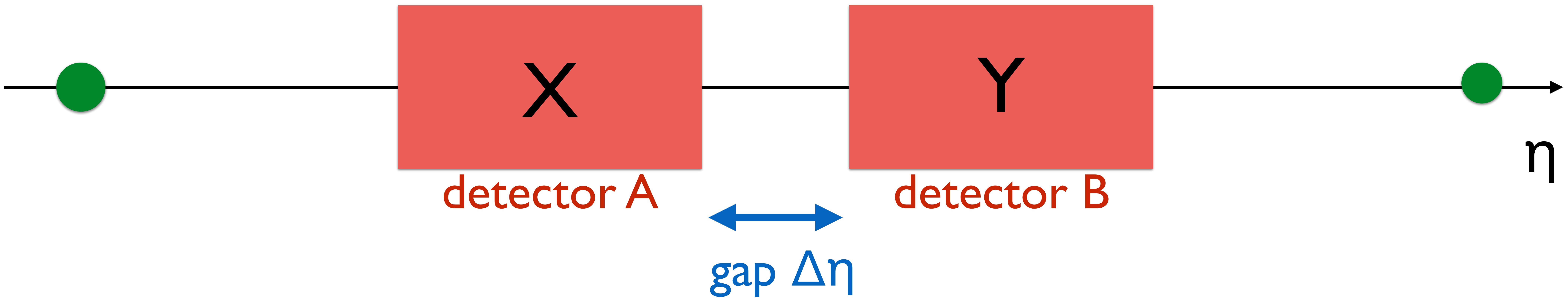


ALICE 1407.5530

None of these analyses implements a rapidity gap Δη !

This is *very wrong* for small systems, p+Pb and p+p (not shown)

3. Differential anisotropic flow $v_n(p_T)$

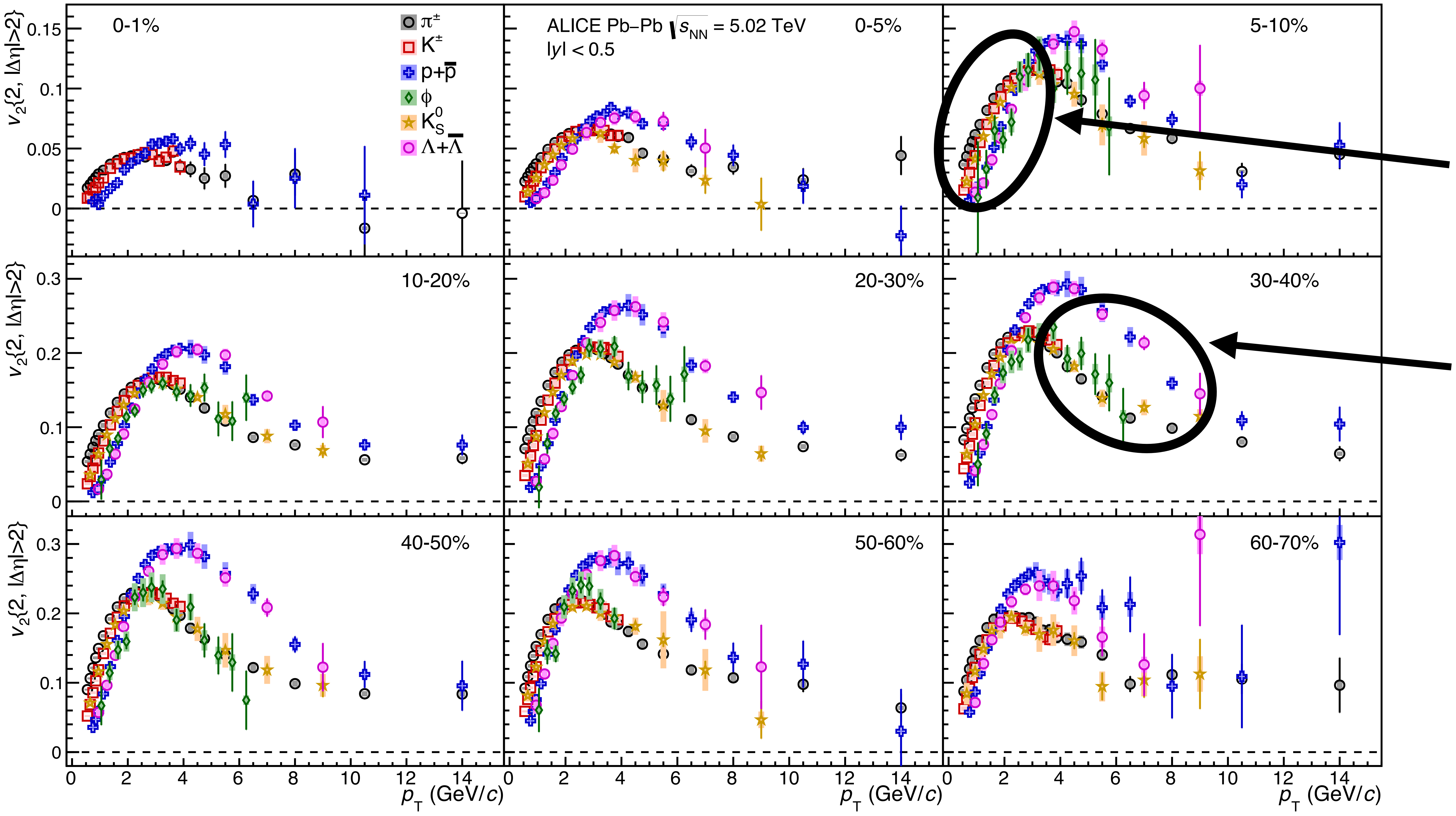


$$X \equiv \sum_{k=1}^{N_A(p_t)} e^{in\varphi_k} \qquad Y \equiv \frac{1}{N_B} \sum_{k=1}^{N_B} e^{-in\varphi_k}$$

In detector A, count only particles in the p_T bin. In B, take all particles.

$$v_n(p_T) \equiv \frac{\langle XY \rangle - \langle X \rangle \langle Y \rangle}{\langle N_A(p_T) \rangle v_n\{2\}}$$

3. Differential elliptic flow $v_2(p_T)$

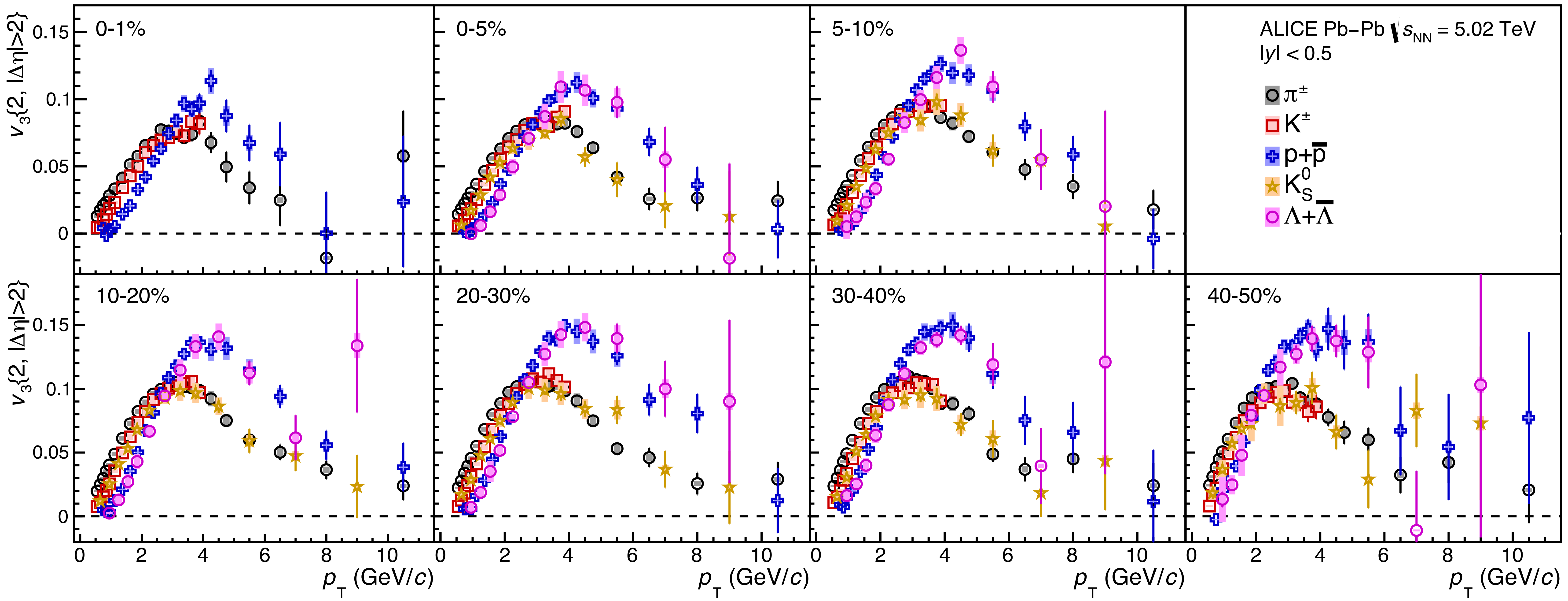


Mass ordering at low p_T, generic effect of hydro

Baryon-meson splitting at high p_T, not explained by hydro (hadronization through coalescence)

ALICE 1805.04390

3. Differential triangular flow $v_3(p_T)$

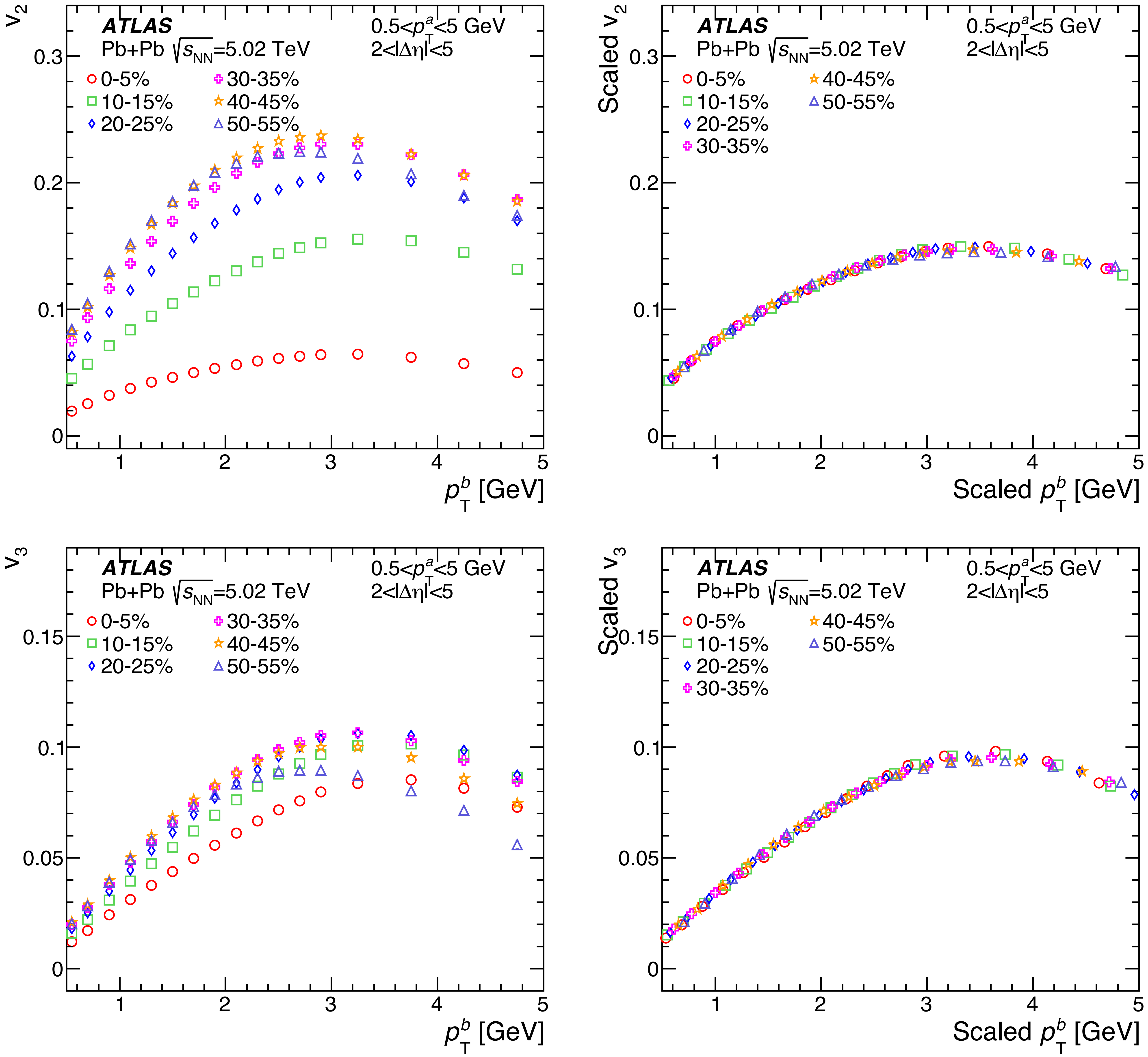


Mass ordering at low p_T, generic effect of hydro

Baryon-meson splitting at high p_T, not explained by hydro (hadronization through coalescence)

ALICE 1805.04390

3. Scaled differential flow $v_n(p_T)/v_n$

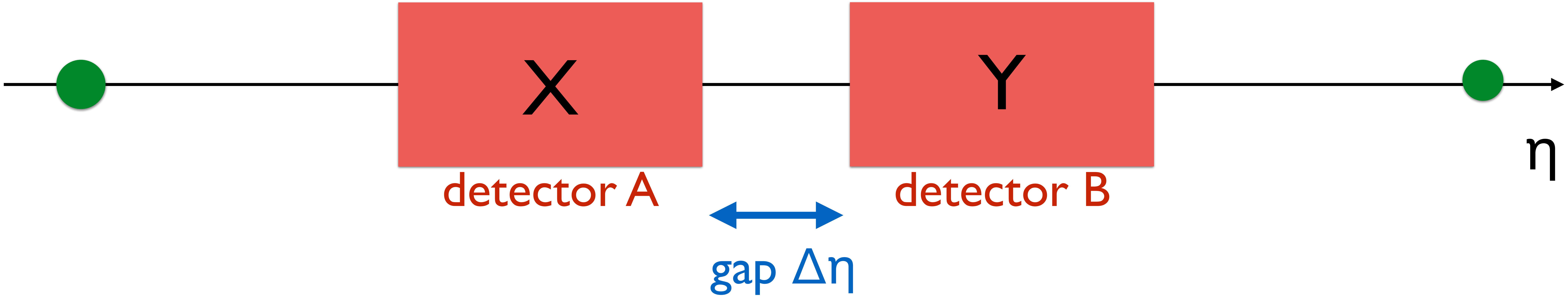


Once scaled by the integrated flow, the result is centrality independent (here, the x axis is also rescaled)

This scaled flow is in my opinion a useful observable that other experiments should also provide

ATLAS 1808.03951

4. *New* observable: Teaney's $v_0(p_T)$



$$X \equiv N_A(p_T) \qquad\qquad Y \equiv \frac{1}{N_B}\sum_{k=1}^{N_B} p_{T,k}$$

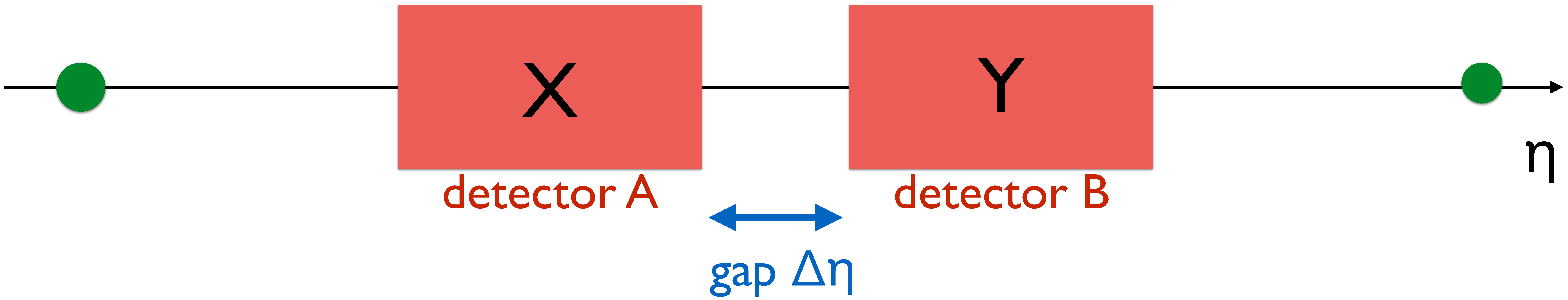
One then defines

$$v_0(p_T) \equiv \frac{\langle XY\rangle - \langle X\rangle\langle Y\rangle}{\langle N_A(p_T)\rangle \sigma_{p_T}}$$

Same definition as $v_n(p_T)$, where one replaces v_n with σ_{p_T}.

Schenke Shen Teaney 2004.00690

Physical interpretation of $v_0(p_T)$



$v_0(p_T)$ is the relative change in the spectrum in detector A induced by a change of p_T per particle (i.e., temperature) in detector B.

$v_0(p_T)$ represents the relative change in the spectrum induced by a temperature fluctuation.

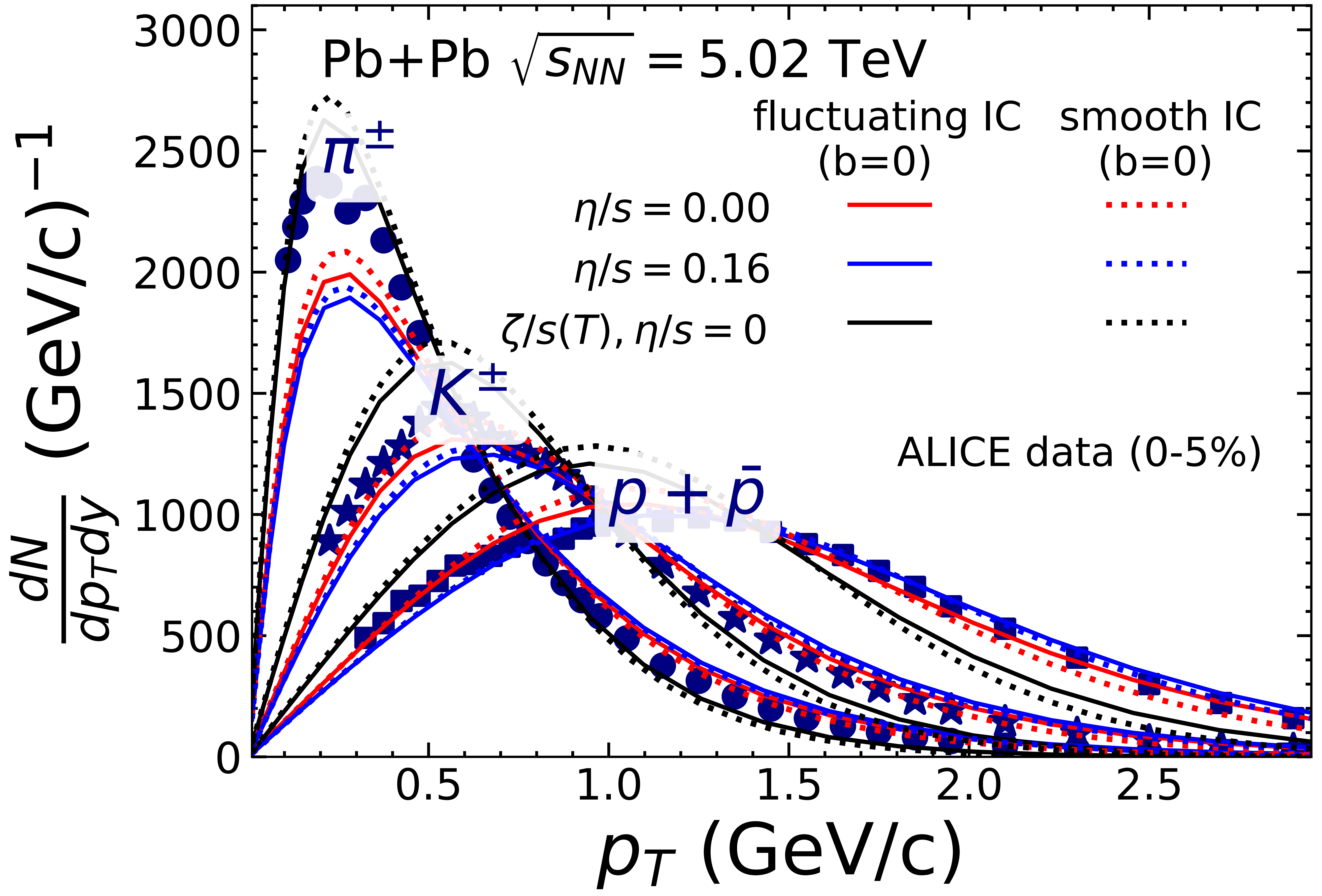
The scaled $v_0(p_T)/v_0$, like $v_n(p_T)/v_n$, is essentially independent of centrality.
We make predictions for $v_0(p_T)/v_0$, rather than $v_0(p_T)$ itself.

Hydrodynamic simulations

We carry out two sets of hydro calculations, both at b=0.

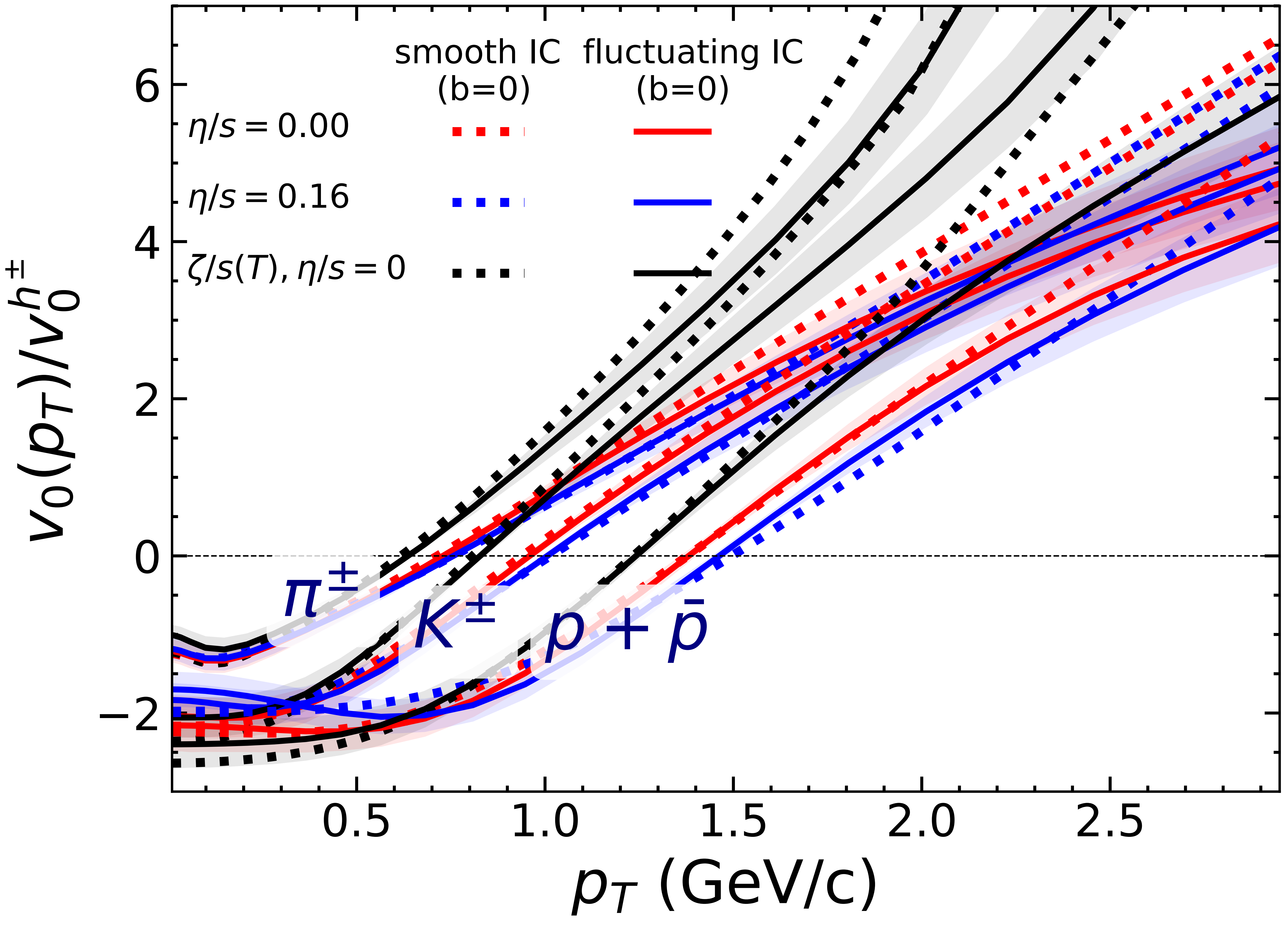
1. Fluctuating initial conditions, where we solve the hydro for each initial condition, mimicking an actual experiment.
2. Smooth initial conditions, where we average over initial fluctuations before running the hydro, just once.

Both give comparable spectra, in rough agreement with data (pion excess at low p_t is a generic failure of hydro).



Predictions for $v_0(p_T)/v_0$

1. With fluctuating IC, we evaluate $v_0(p_t)/v_0$ like in experiment
2. With smooth IC, we increase the initial temperature by ~1% and evaluate the relative change in the spectrum.
3. Note that the denominator $v_0^{h^\pm}$ is evaluated for all charged particles, not for the corresponding identified particles. It is a global normalization.



Sum rules

$v_0(p_T)$ is a spectrum fluctuation.
It must integrate to 0, hence changes sign:

$$\int_{p_T} v_0(p_T)\frac{dN}{dp_T}dp_T = 0$$

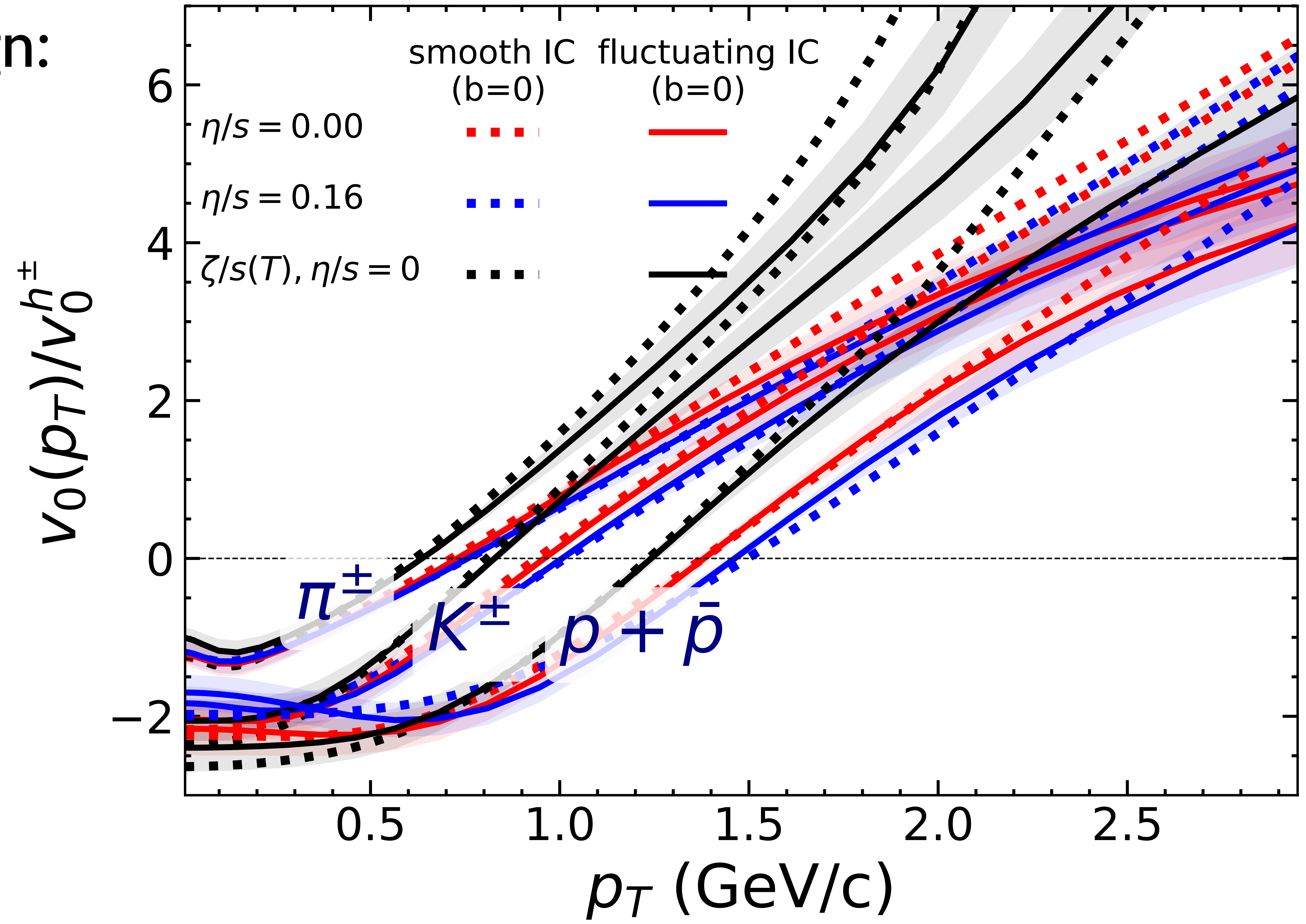
Anisotropic flow $v_n(p_T)$ usually >0

$$\int_{p_T} v_n(p_T)\frac{dN}{dp_T}dp_T = v_n N \text{ for } n \geq 2$$

The corresponding sum rule for v_0 is

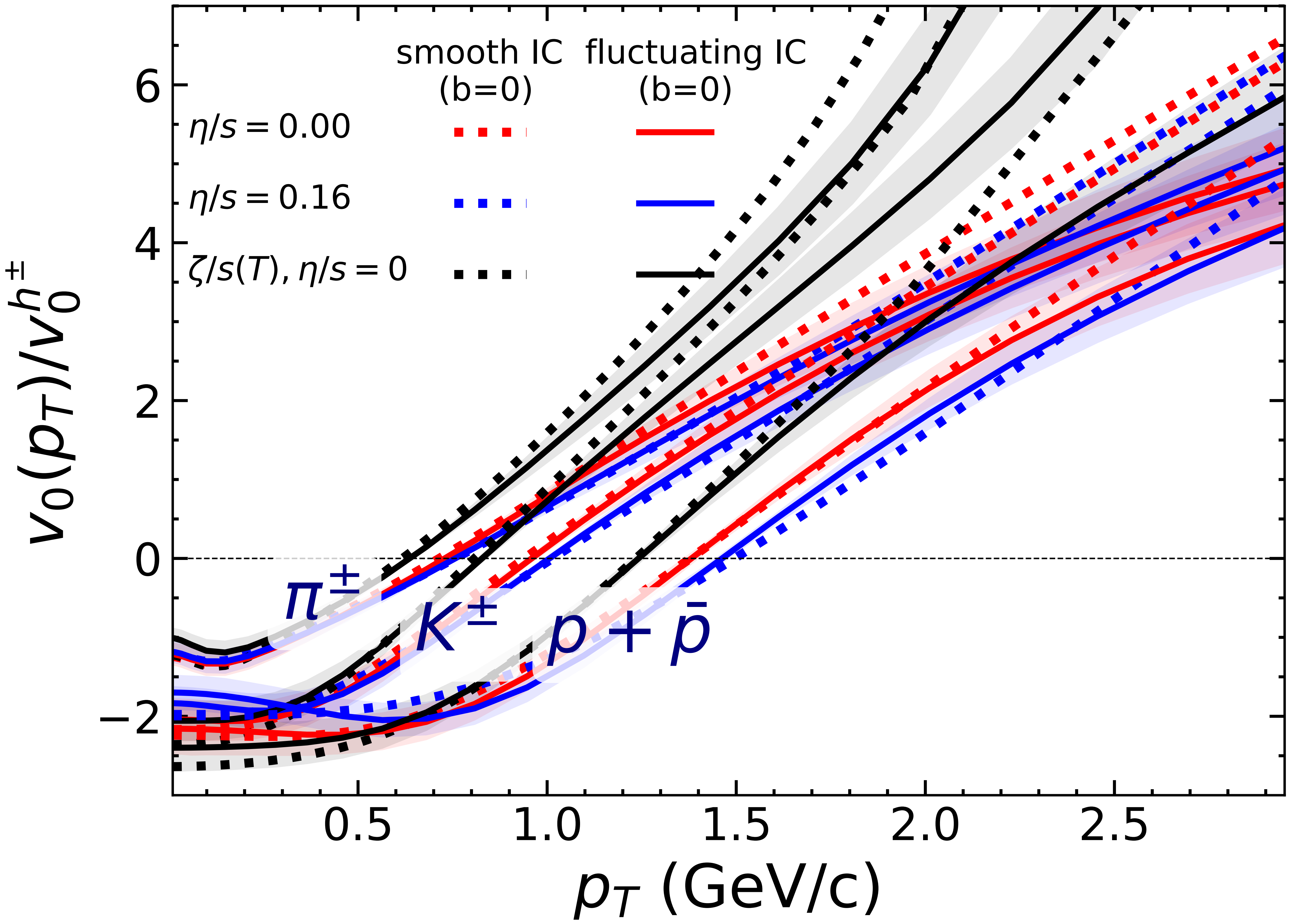
$$\int_{p_T} p_T v_0(p_T)\frac{dN}{dp_T}dp_T = \langle p_T\rangle v_0 N$$

(sum over all particle species implied)



What you should look for in data

1. Characteristic mass ordering, like $v_n(p_T)$, consequence of collective flow.
2. At larger p_T, where hydro fails, will there also be baryon/meson splitting, indicative of quark coalescence?
3. Are the same phenomena also seen in small systems?



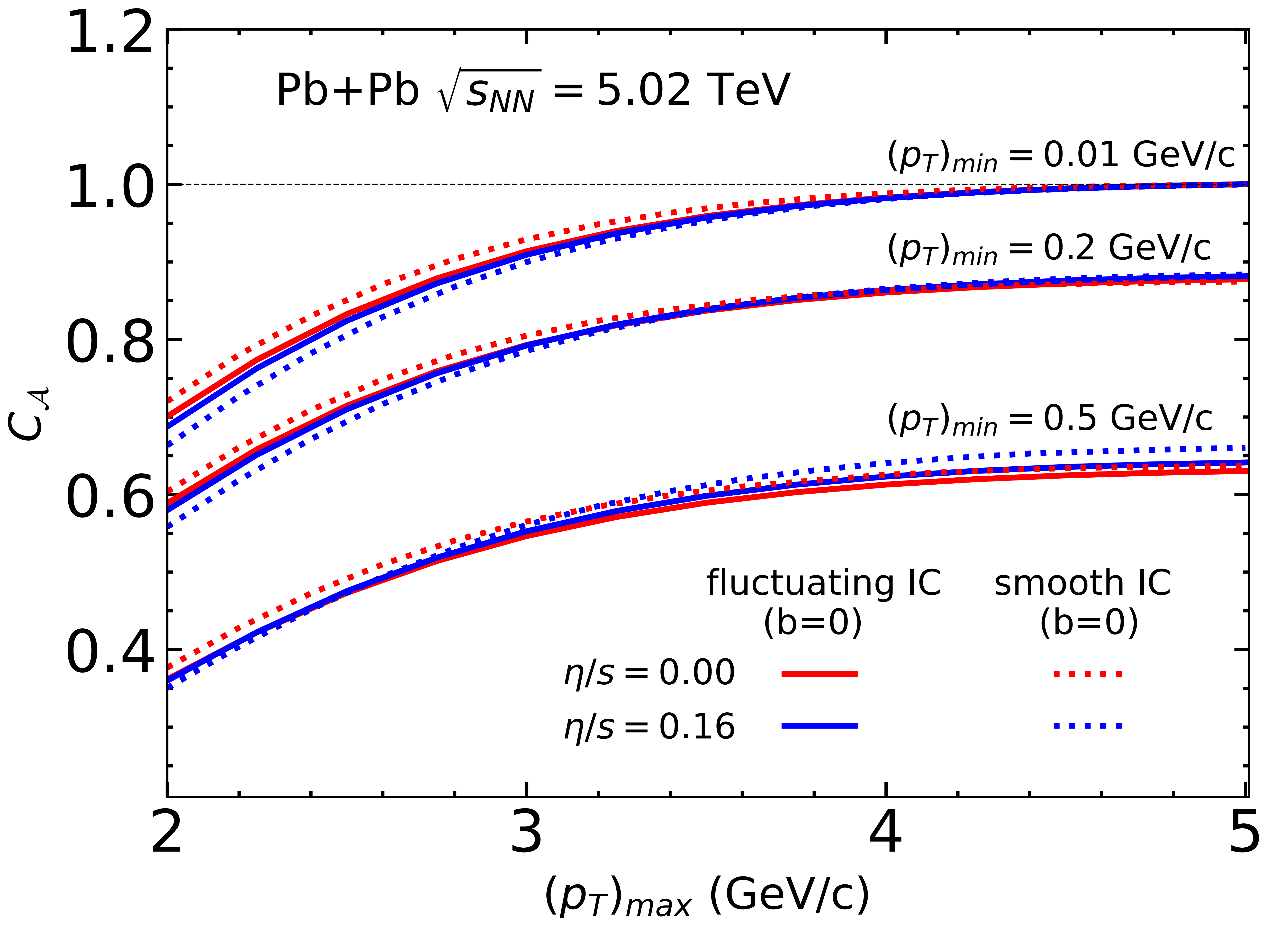
p_T acceptance

The p_T range depends on the detector.

Differential observables, $v_0(p_T)$ and $v_n(p_T)$, are independent of acceptance.

v_0 and v_n depend on integration range. Acceptance correction factor for v_0:

$$C_A \equiv \frac{\int_{(p_T)_{\min}}^{(p_T)_{\max}} \left(p_T - \langle p_T \rangle\right) \frac{v_0(p_T)}{v_0} \frac{dN}{dp_T} dp_T}{\int_{(p_T)_{\min}}^{(p_T)_{\max}} p_T \frac{dN}{dp_T} dp_T}$$

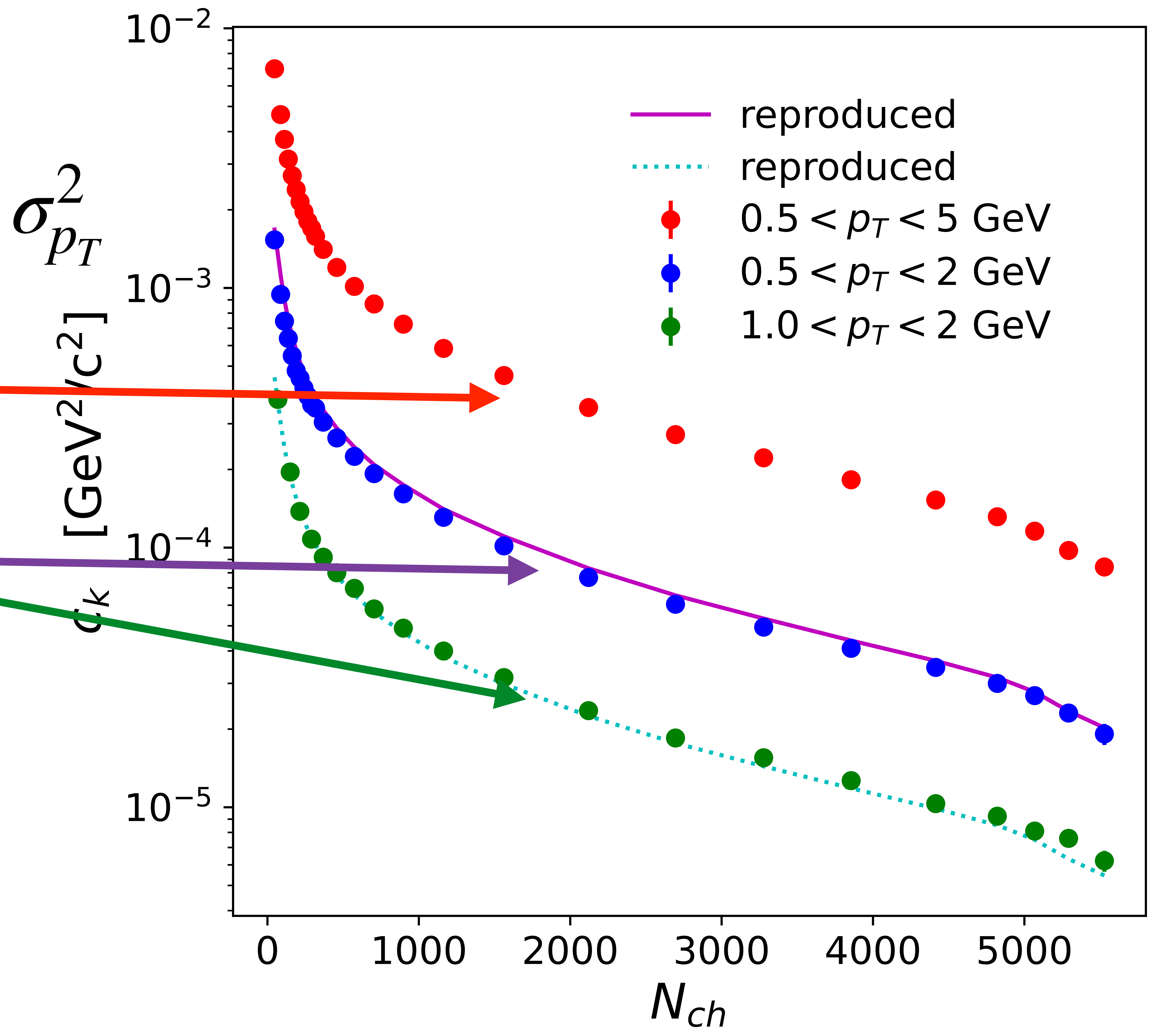


Dependence of σ_{p_T} on p_T cuts

ATLAS sees a strong dependence of σ_{p_T} on p_T cuts (notice the log scale!)

We use the largest value $0.5 < p_T < 5$ as input and infer the other values using the acceptance factor C_A calculated in hydro.

Calculation is in perfect agreement with data, which is a first hint that hydro is in the ballpark for $v_0(p_T)$.



$v_0(p_t)$ is the true radial flow

- The physics of p_T fluctuations, v_0, is similar to that of anisotropic flow, v_n
- Experiments should measure $v_0(p_T)$ and it should be called radial flow by analogy.
- So far, the analyses of p_T fluctuations and v_n of at RHIC and LHC have been done differently, because few people understood (I didn't until recently) that p_T fluctuations are a signature of collectivity. But v_0 and v_n should be analyzed in the exact same way.
- In hydrodynamics, v_n is suppressed by both shear (η/s) and bulk (ς/s) viscosities, while v_0 is sensitive to bulk only (not shown in this talk).
- Hydro makes a robust prediction for $v_0(p_T)/v_0$, which depends little on transport coeff. and initial conditions, like $v_n(p_T)/v_n$. In particular, mass ordering is expected at low p_T. What is $v_0(p_T)/v_0$ at high p_T, where we know that hydro fails?
- What about small systems? Are there still long-range p_T correlations? Not even the order of magnitude of v_0 is known in p+Pb or p+p, as no rapidity gap has been implemented so far.