Investigation of the hot and dense QCD medium of different sizes

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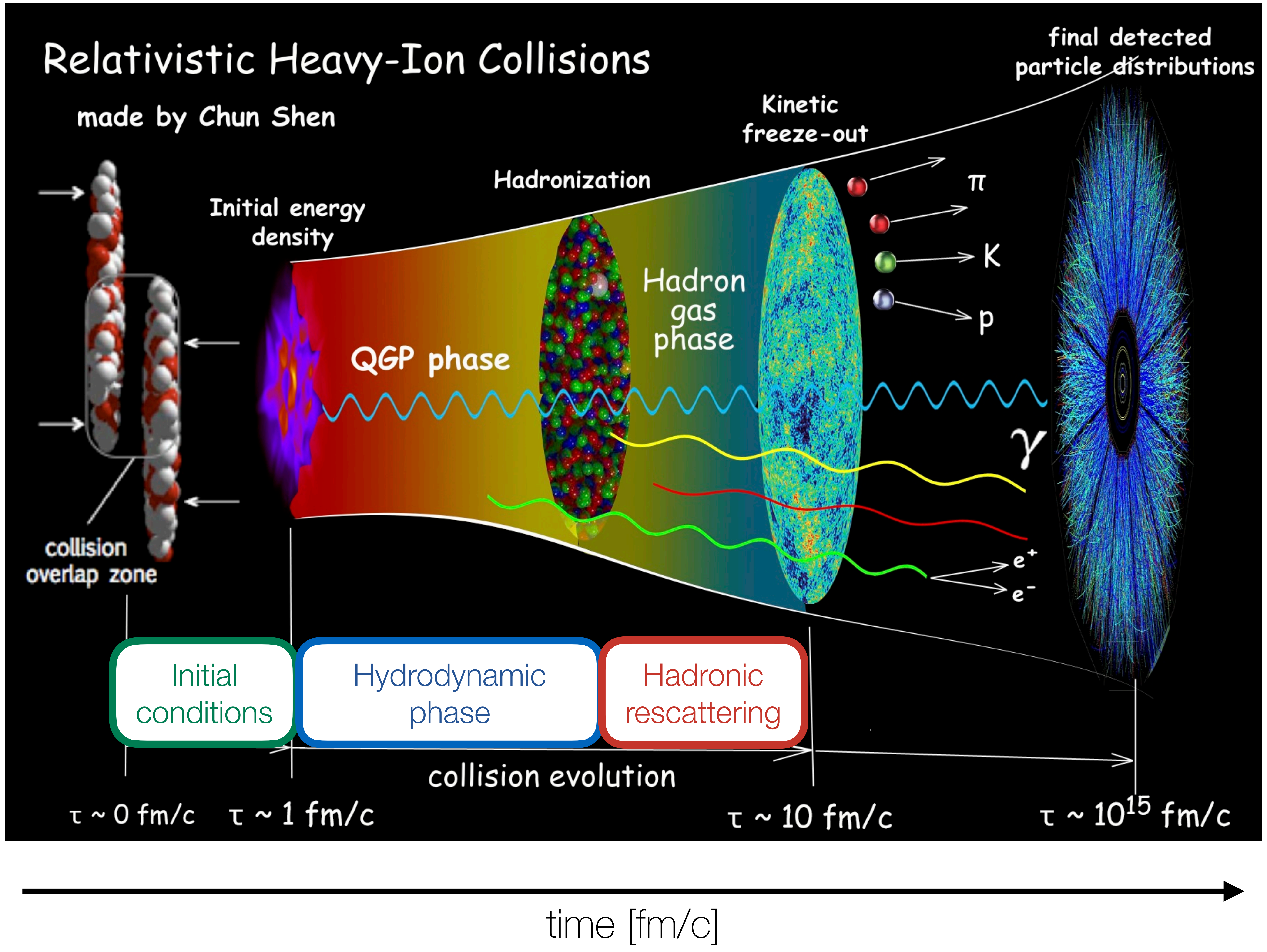
Creating the hot and dense QCD medium



- Lattice QCD predicts a phase transition from a hadron gas to a strongly interacting deconfined medium, **quark-gluon plasma (QGP)**
  - We are interested in studying the emergent phenomena of this QCD medium, and knowing its properties
- Relativistic heavy-ion collisions allow us to reach the necessary conditions to recreate this medium
  - Medium expands and cools down
  - Phase transition from QGP to hadron gas
  - Further interactions in the hadronic phase until freeze-out
  - Detection of final particles
- Comparison to phenomenological models

Relativistic Heavy-Ion Collider

Hadron collisions at RHIC

p → ← p	$\sqrt{s}$ = 200, 500 GeV
p / d / He → ← Au	$\sqrt{s_{NN}}$ = 200 GeV
Cu → ← Cu	$\sqrt{s_{NN}}$ = 200 GeV
U → ← U	$\sqrt{s_{NN}}$ = 193 GeV
Au → ← Au	$\sqrt{s_{NN}}$ = 200 GeV

and other …

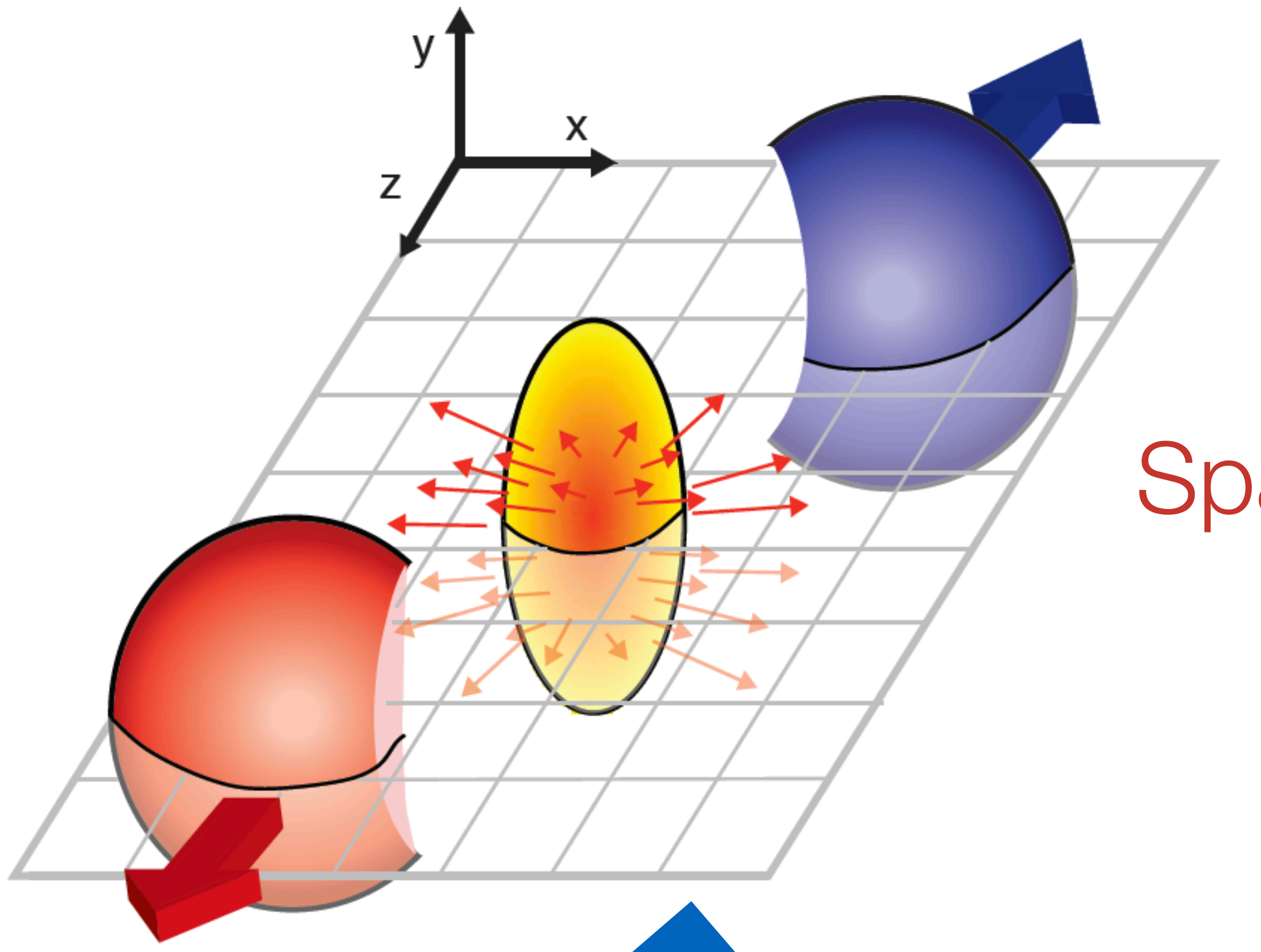
The Large Hadron Collider

Hadron collisions at the LHC

p → ← p	$\sqrt{s}$ = 7, 8, 13 TeV
p → ← Pb	$\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
Xe → ← Xe	$\sqrt{s_{NN}}$ = 5.44 TeV
Pb → ← Pb	$\sqrt{s_{NN}}$ = 5.02, 8.16 TeV

Anisotropic flow

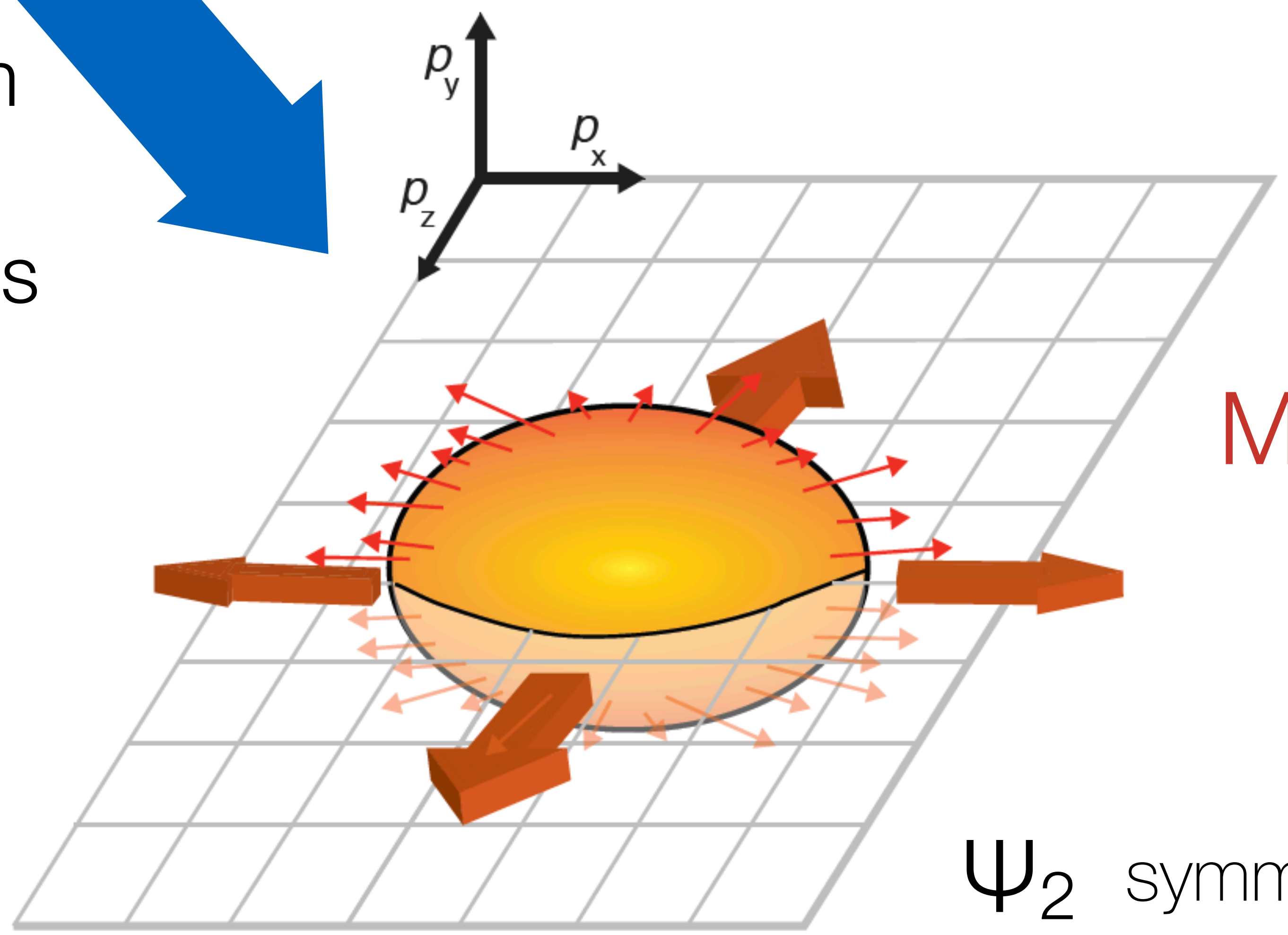
peripheral heavy-ion collision



Spatial anisotropy

system expansion
to the outer vacuum

collective interactions



Momentum anisotropy

Ψ_2 symmetry plane

- One of the many probes used to study the QGP is **anisotropic flow**
- Initial spatial anisotropy is converted to momentum anisotropy of particles in the final state via collective interactions in the medium
- Fourier decomposition of the particle azimuthal distribution measured with respect to the symmetry plane

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

Flow coefficients

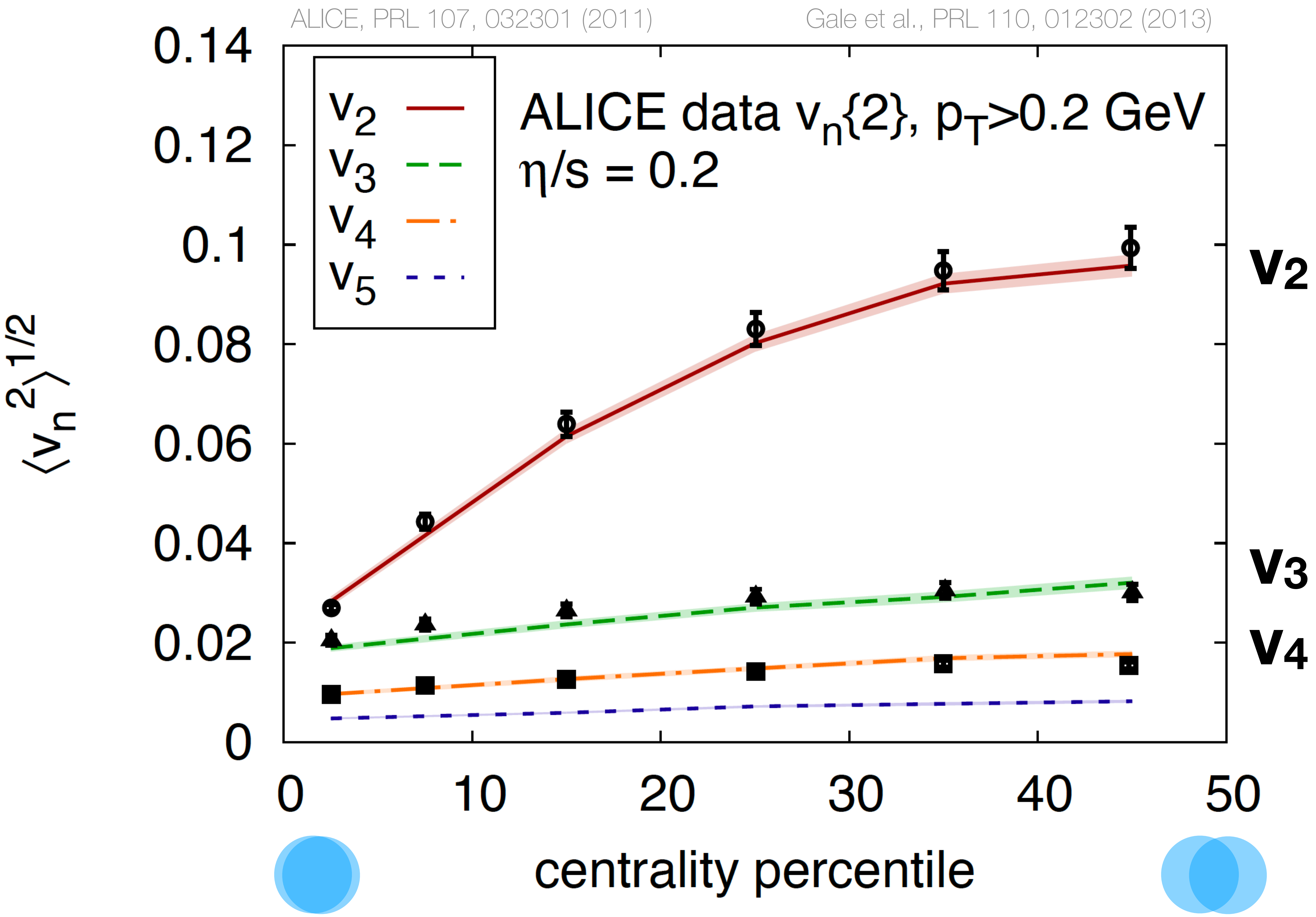
$$v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

Ψ_n symmetry plane of a collision

φ azimuthal angle of a particle

credit: Boris Hyppolyte

Anisotropic flow: measurements vs. models



- Data are well described by hydrodynamic calculations
- **QGP** is a **strongly interacting liquid** with small shear viscosity over entropy density ratio η/s

Wealth of experimental measurements

Measurements of anisotropic flow are **sensitive** to **initial conditions** and **transport properties of the QGP**

Flow coefficients (v_n)

Flow (v_n) fluctuations (p_T, η)

Flow angle ψ_n fluctuations (p_T, η)

Event shape engineering

Symmetric cumulants (correlation between v_n and v_m)

Non-linear flow modes

Flow of light hadrons

Flow of heavy hadrons

Correlation with mean p_T

...

+ Energy dependence
System dependence

→ Strong constraints on models

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Flow of light hadrons

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Correlation with mean p_T

…

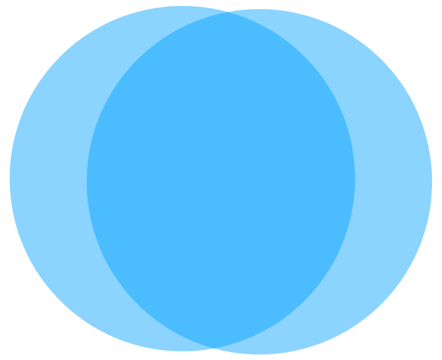
\+ Energy dependence
System dependence → Strong constraints on models

Correlation between v_n and mean p_T

- New way to **probe nuclear structure and deformation**

$$\rho_n = \frac{Cov(v_n^2, \langle p_T \rangle)}{\sqrt{Var(v_n^2) Var(\langle p_T \rangle)}}$$

Pearson correlation coefficient



overlapping nuclei in transverse plane

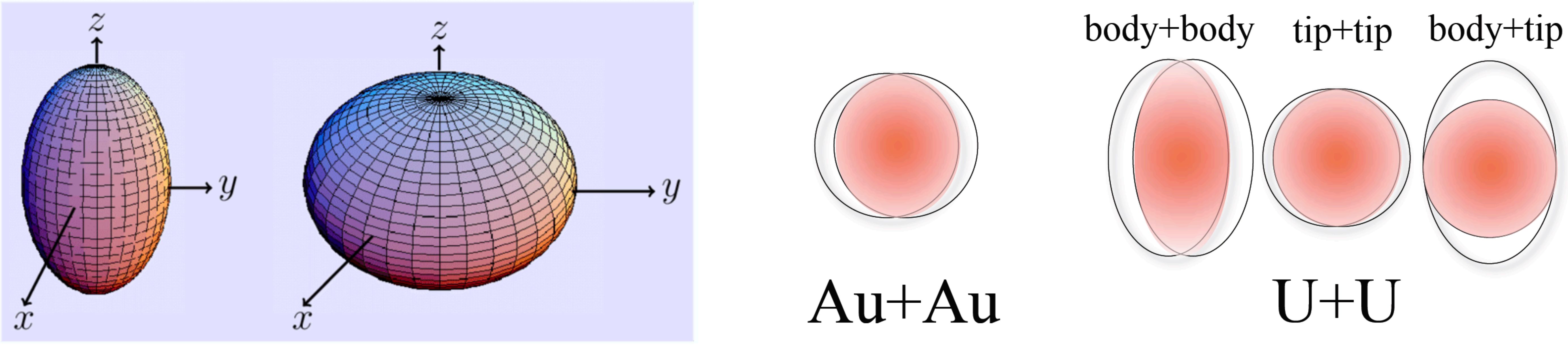
Size -> mean p_T

Shape -> anisotropic flow

Correlation in shape and size

↓

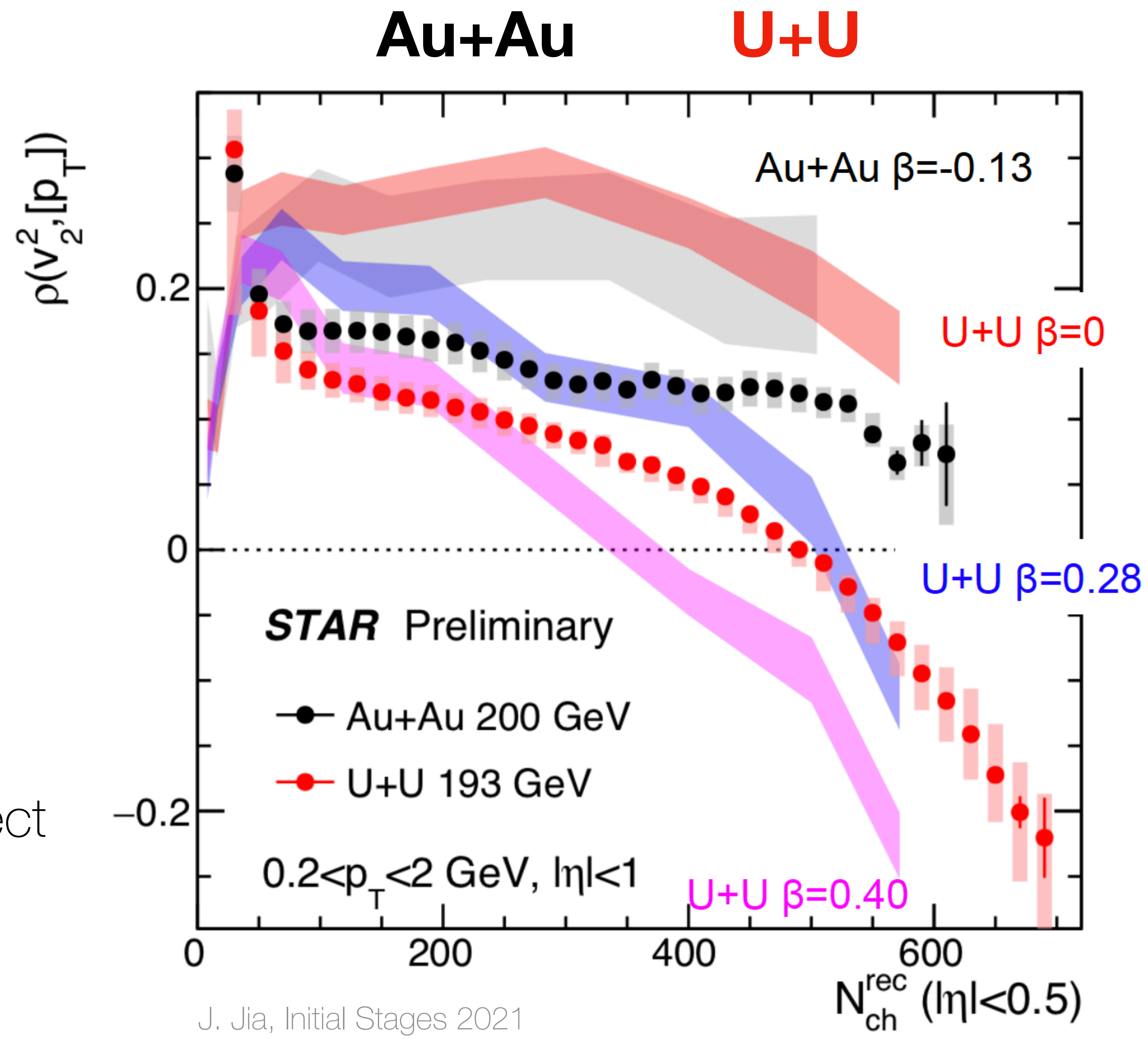
Correlation in mean p_T and v_n



$\beta > 0$ prolate $\beta < 0$ oblate

Au+Au $\beta \cong 0$

U+U $\beta \ncong 0$



J. Jia, Initial Stages 2021

- Observed sign change in U+U collisions (red points) is due to deformation effect
- Comparison to models with different nuclei deformation
  - Preferred deformation between $0.28 < \beta < 0.4$

Correlation between v_n and mean p_T

- New way to **probe nuclear structure and deformation**
- **Additional constraints to models** of heavy-ion collisions, in particular their initial conditions

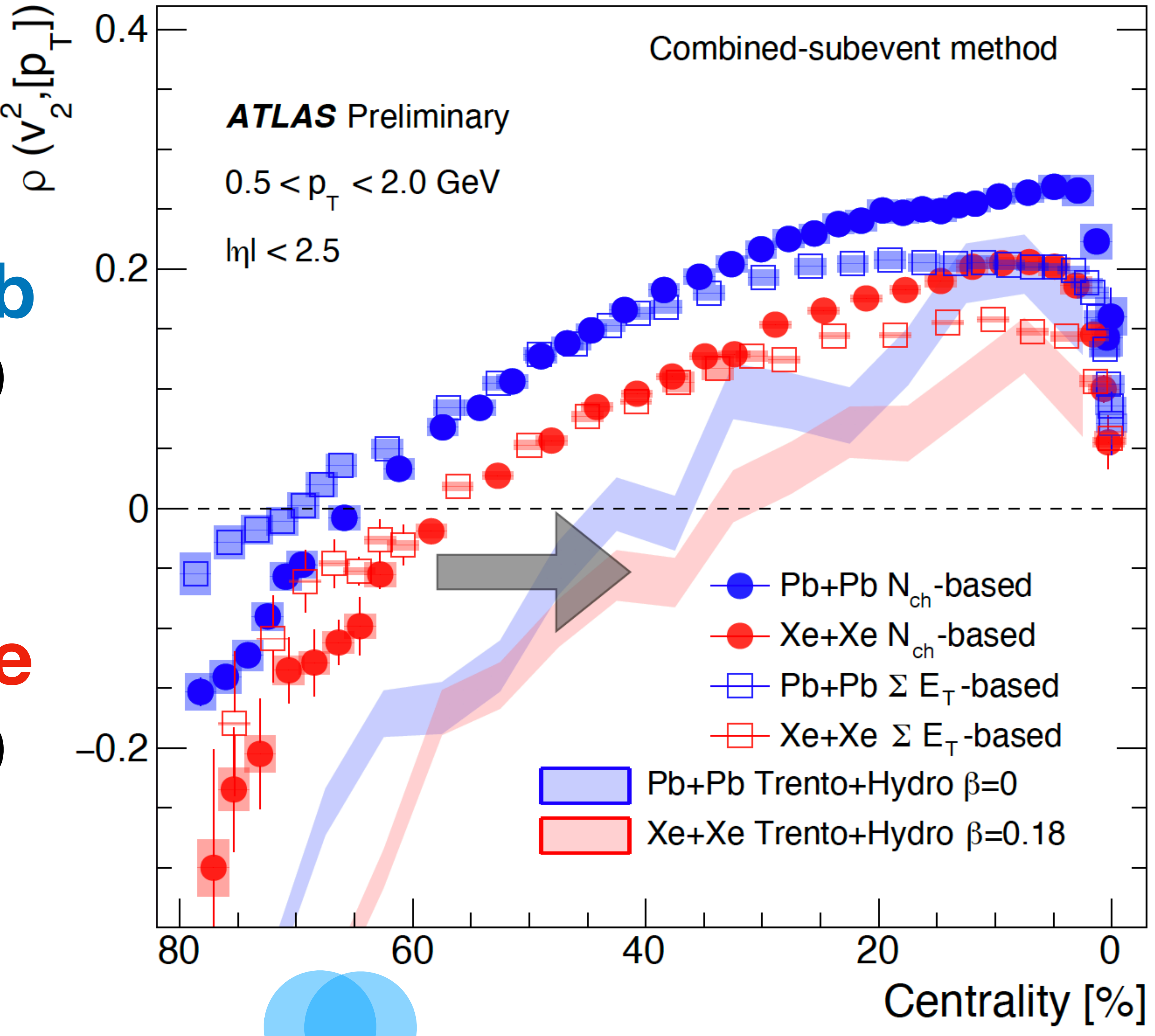
$$\rho_n = \frac{Cov(v_n^2, \langle p_T \rangle)}{\sqrt{Var(v_n^2) Var(\langle p_T \rangle)}}$$

Pearson correlation coefficient

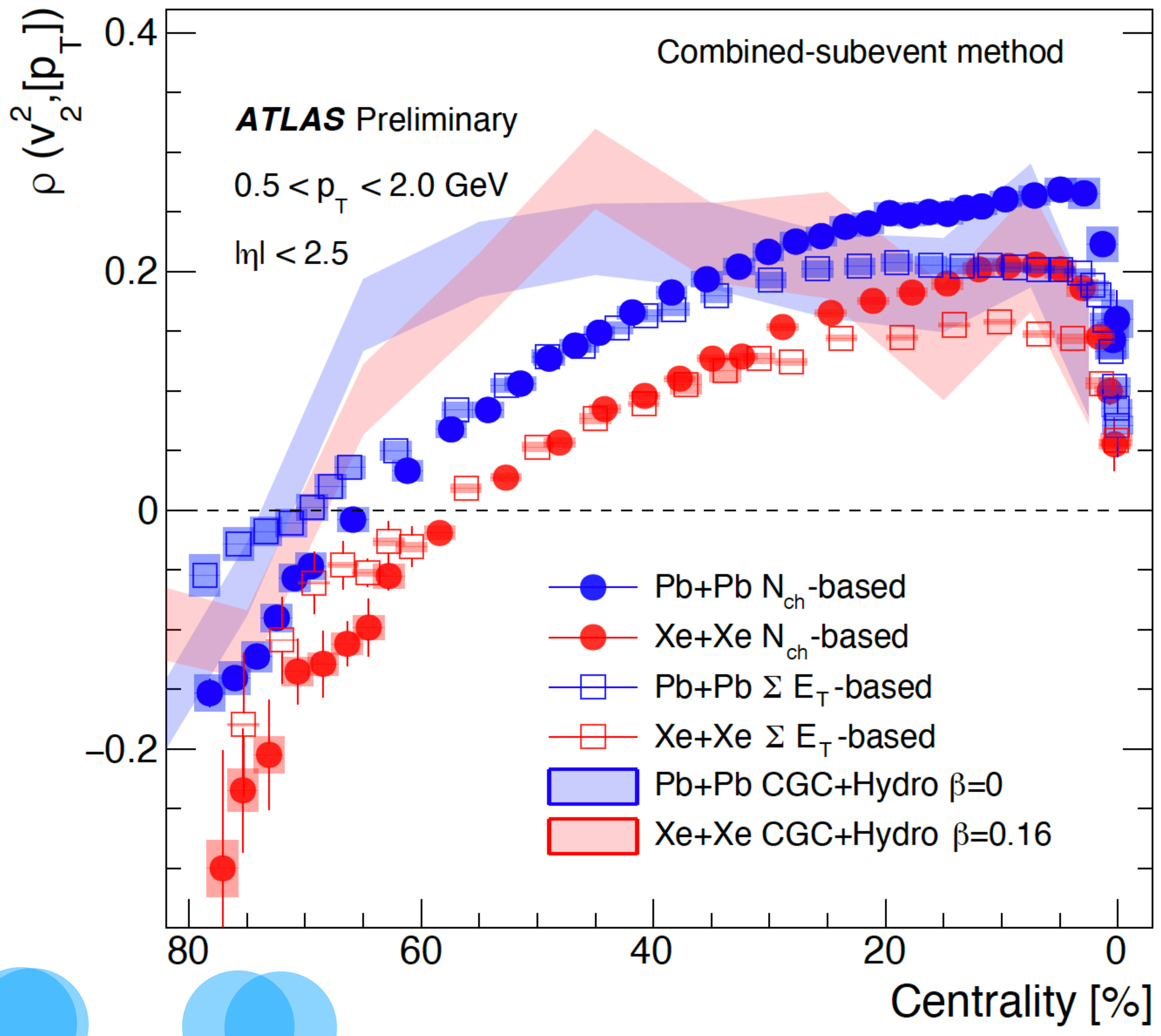
Pb-Pb $\beta \cong 0$

Xe-Xe $\beta \ncong 0$

Trento initial conditions + Hydrodynamic model



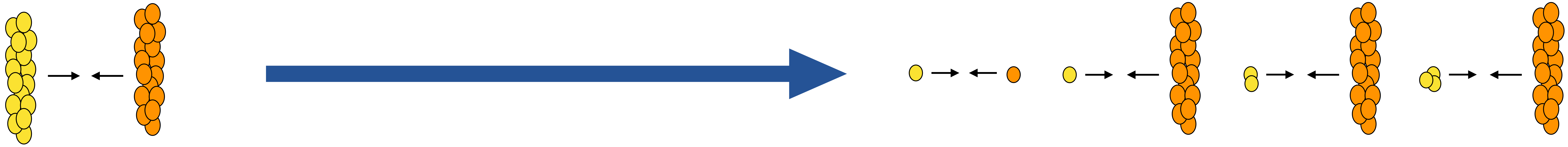
CGC initial conditions + Hydrodynamic model



- Significantly different results using different model calculations
  - Most likely due to different initial conditions

ATLAS-CONF-2021-001

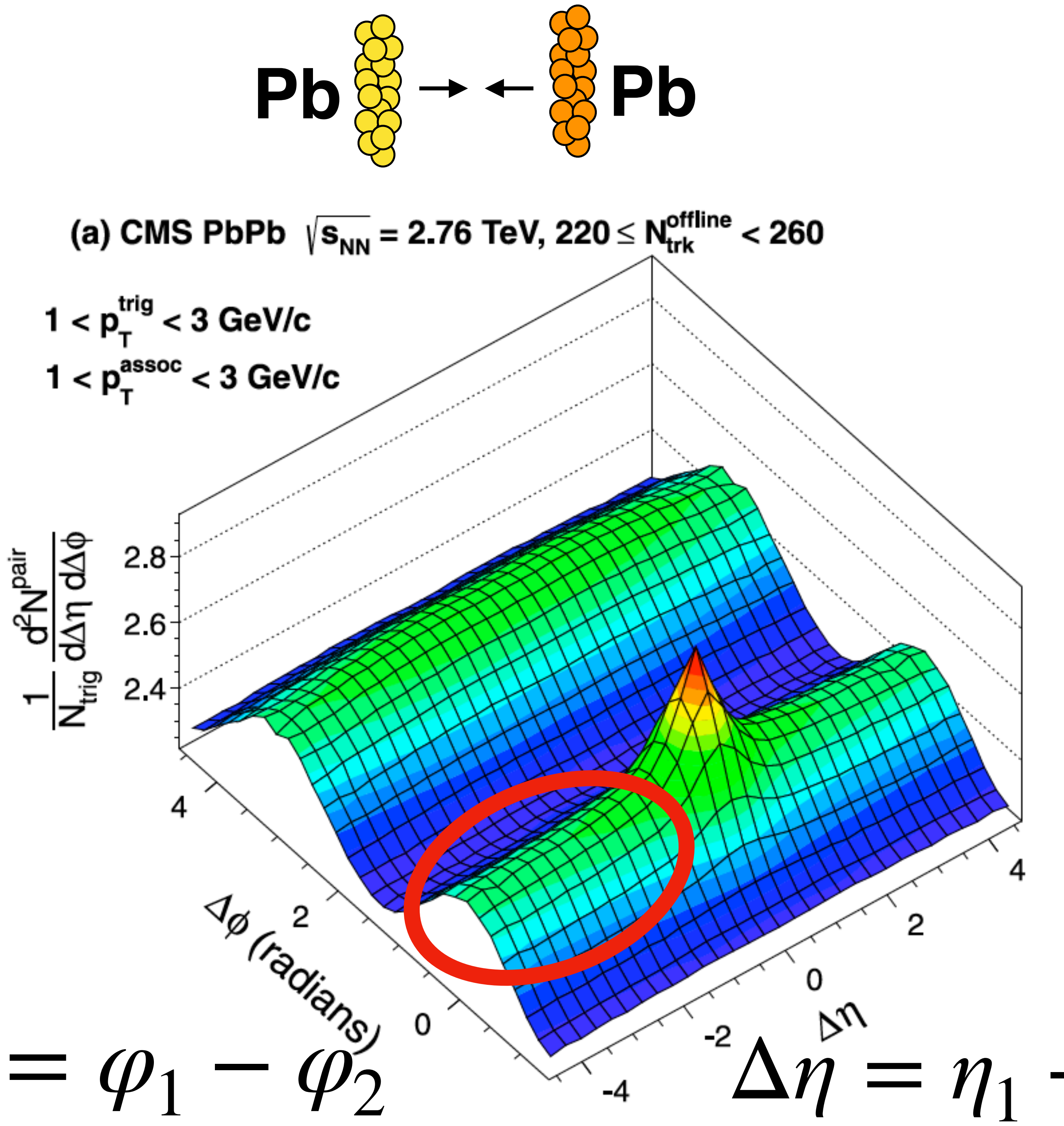
From large to small collision systems



- We are reaching a precision era of measurements of flow in heavy-ion collisions
- They provide important constraints on theory

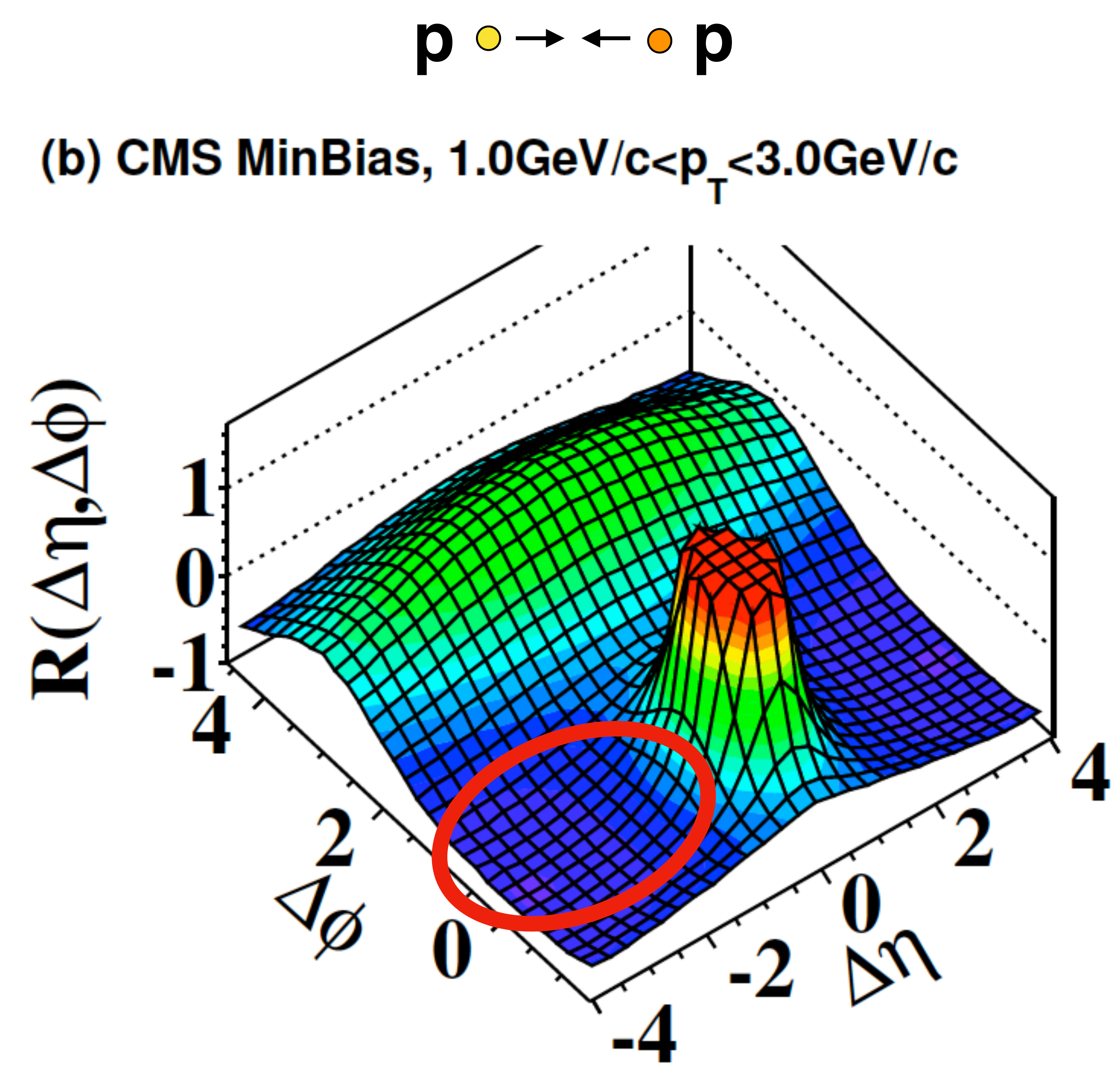
- Small collision systems provide a useful baseline for studies in heavy-ion collisions
- Recent measurements of anisotropic flow -> paradigm shift?

Small collision systems: old picture



$\Delta\varphi = \varphi_1 - \varphi_2$ $\Delta\eta = \eta_1 - \eta_2$

CMS, PLB 724 (2013) 213



CMS, JHEP 09 (2010) 091

Large collision systems

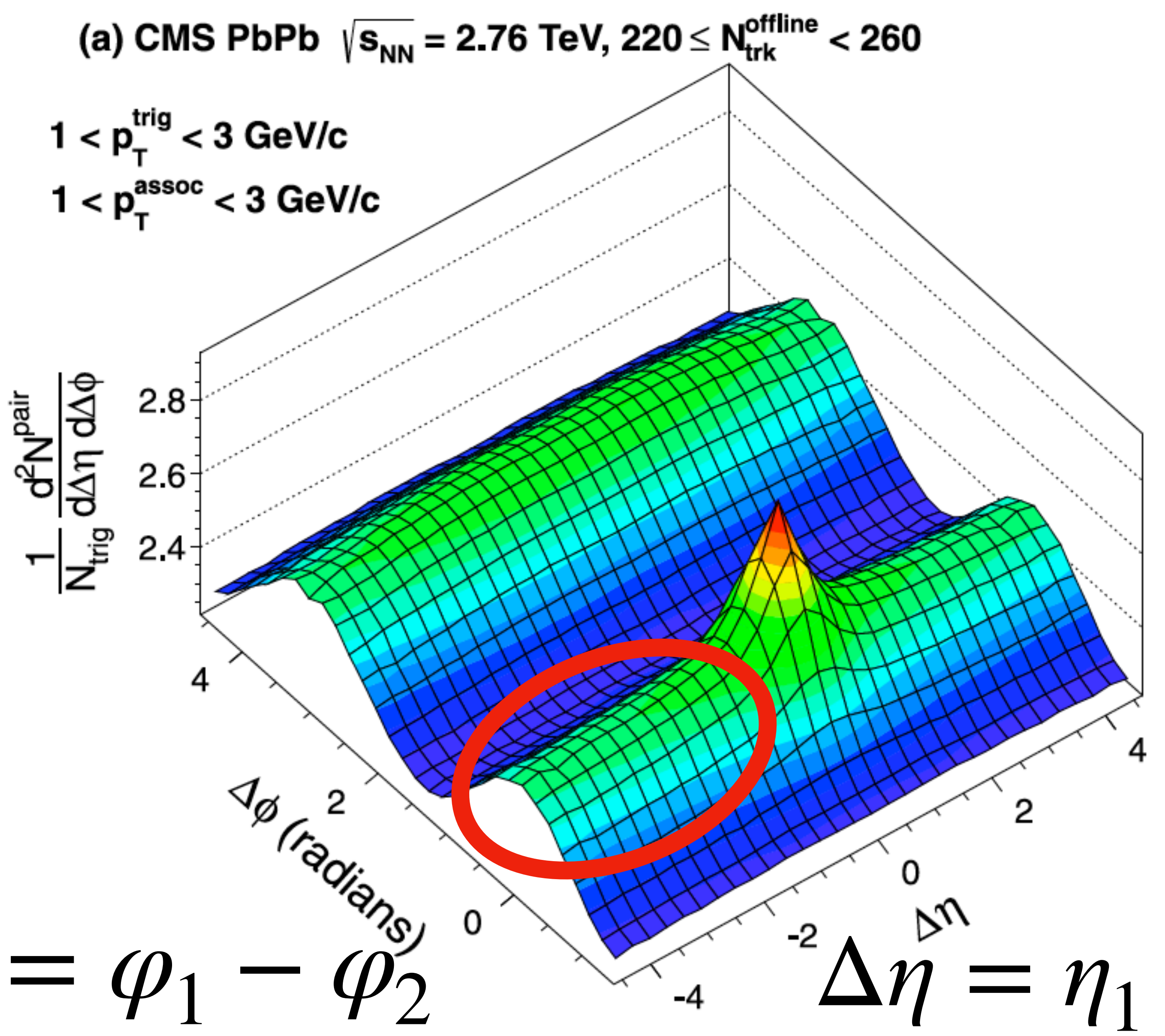
- Near-side long-range correlations (ridge)
- Hydrodynamic flow

Small collision systems

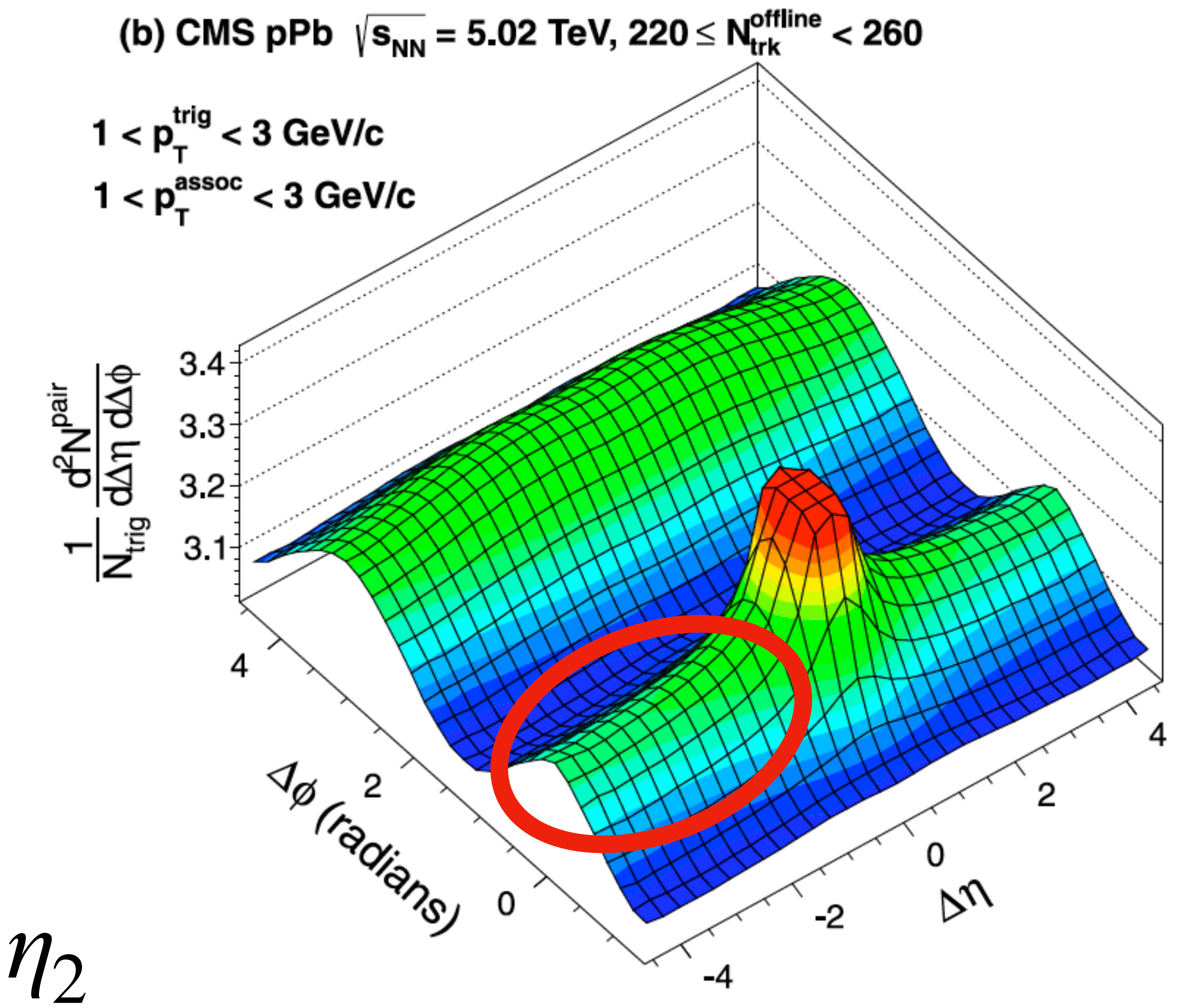
- No near-side long-range correlations
- No flow

Small collision systems: new picture

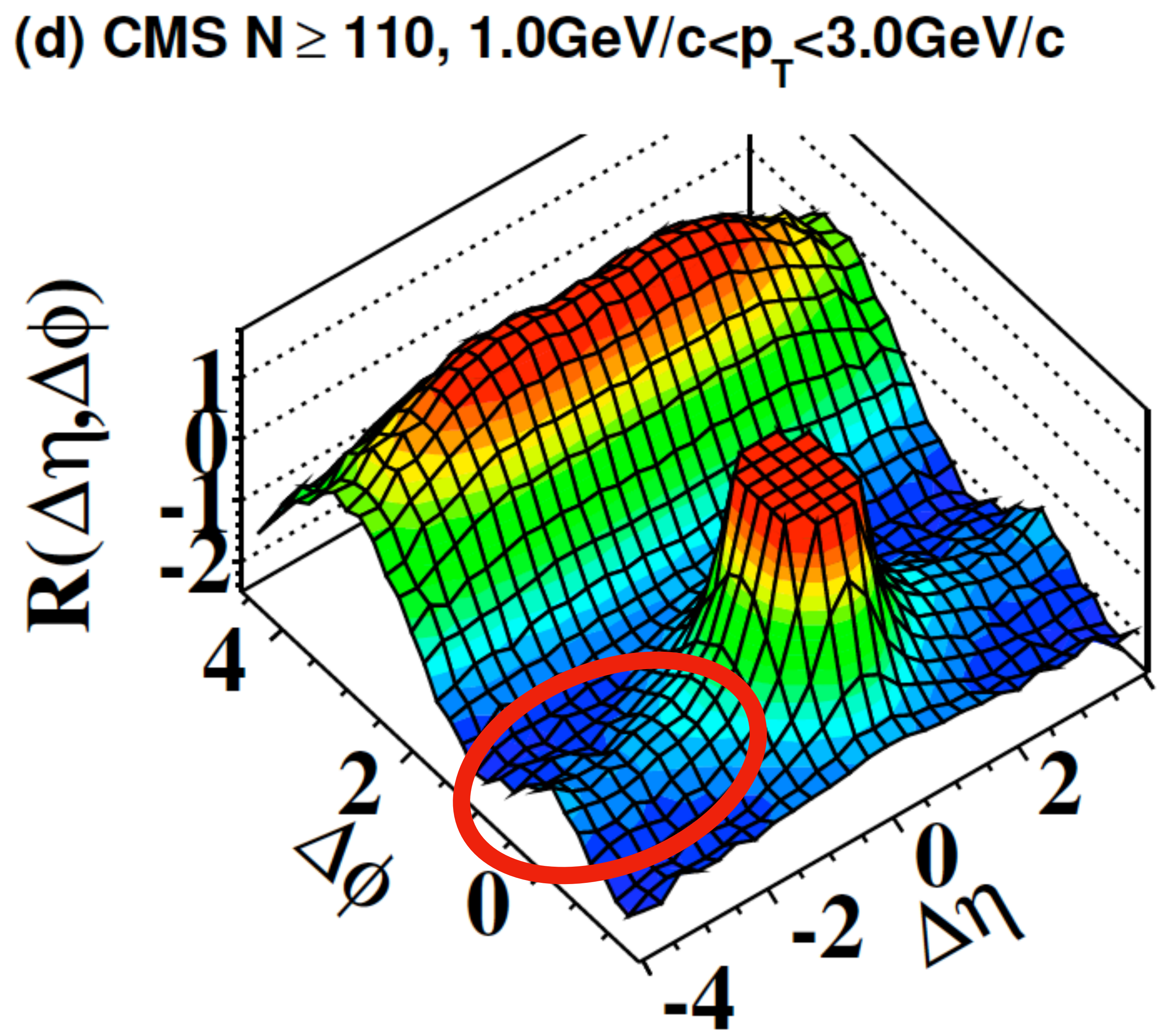
Pb → ← Pb



p → ← Pb



p → ← p



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CMS, PLB 724 (2013) 213

CMS, PLB 724 (2013) 213

CMS, JHEP 09 (2010) 091

Large collision systems

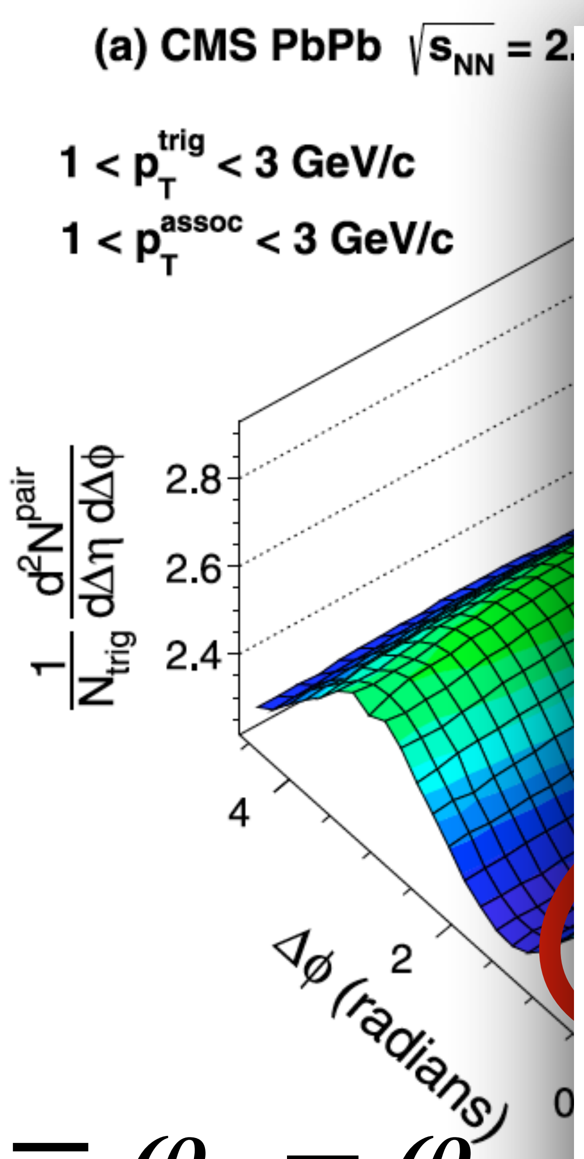
- Near-side long-range correlations (ridge)
- Hydrodynamic flow

High-multiplicity Small collision systems

- ~~No near-side long-range correlations~~
- No flow ?
- Ridge observed in pp and p-Pb collisions

Small collision systems: new picture

Pb → ← Pb p → ← Pb p → ← p



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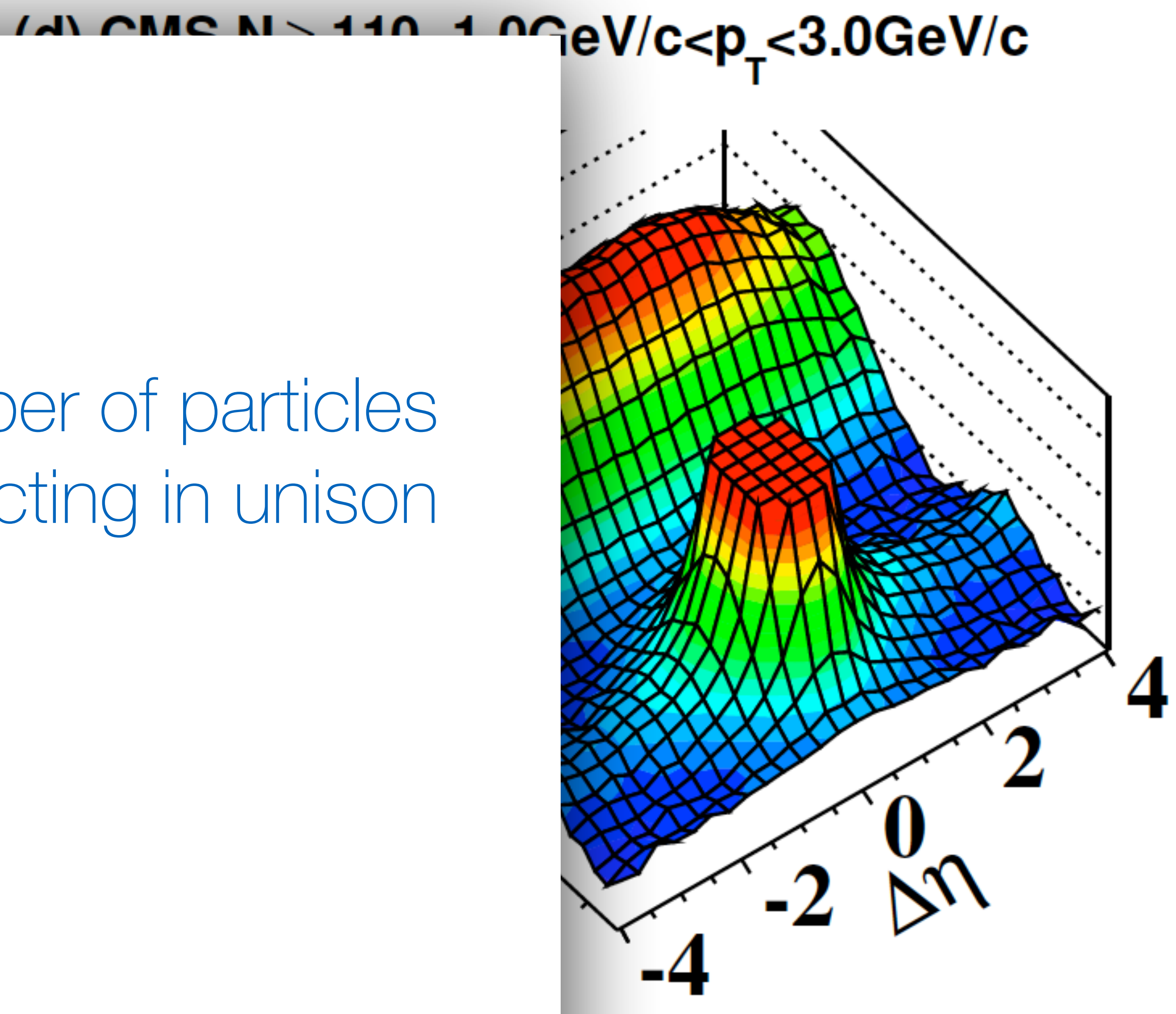
CMS, PLB 724 (2013) 213



CMS, JHEP 09 (2010) 091

Are small systems collective?

What is **collectivity**?
… (long-range) correlations where large number of particles are acting in unison

Is this a sign that we create a medium similar to that in large collision systems?

… more investigations needed

Large colli…

- Near-side long-range correlations (ridge)
- Hydrodynamic flow

…systems

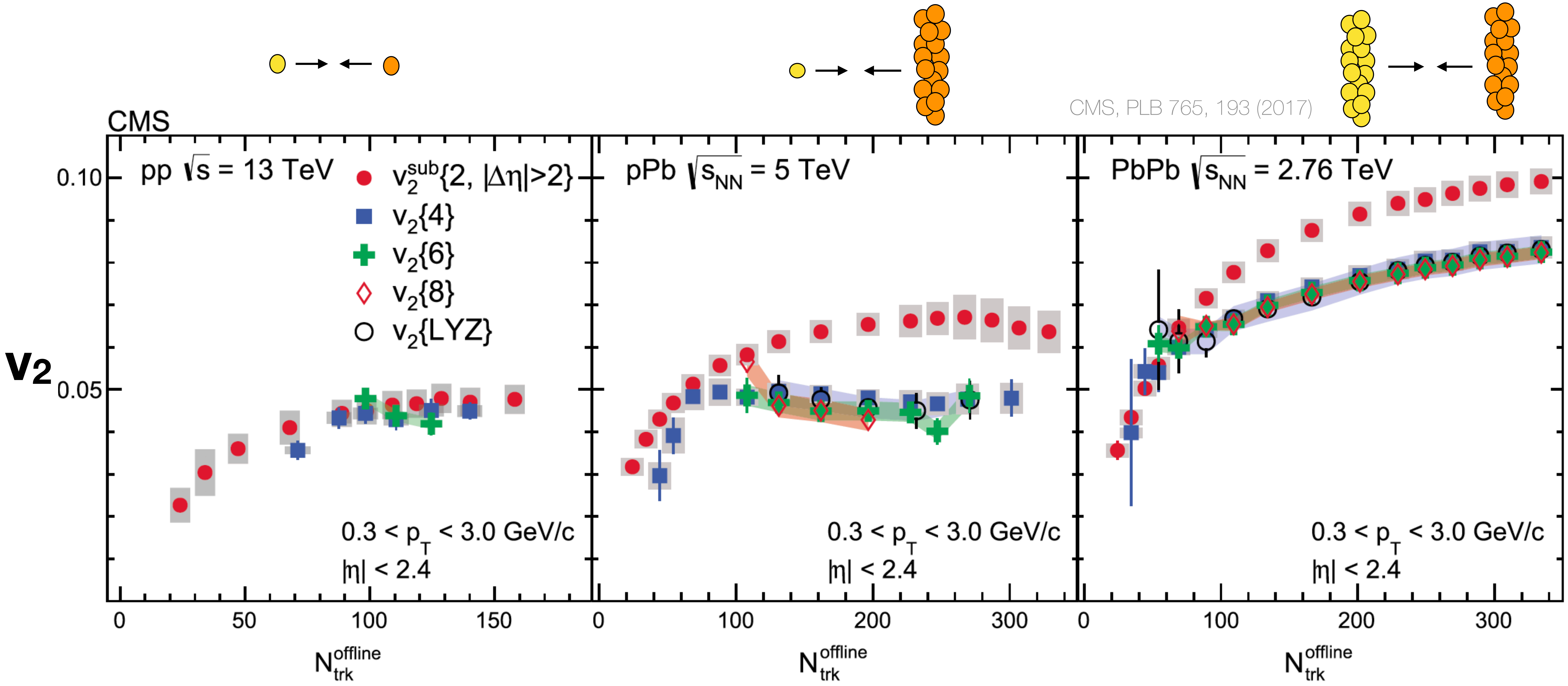
- ~~No near-side long-range correlations~~
- No flow ?
- Ridge observed in pp and p-Pb collisions

Correlations among many particles

2-particle correlations

4-particle correlations

6-particle correlations



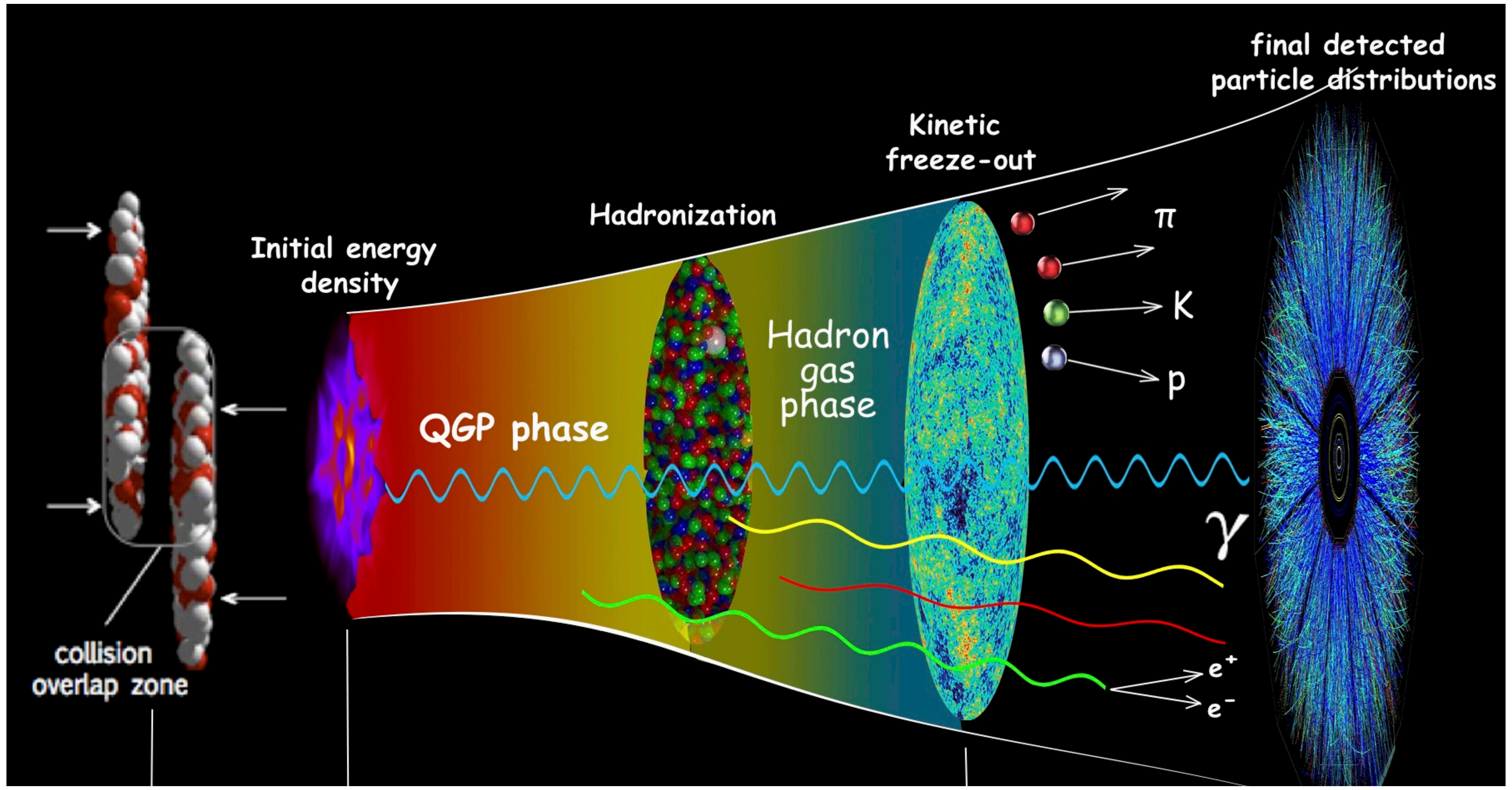
- A collective system: large number of particles are acting in unison
- Measurements of v_2 obtained with many-particle correlations compatible with each other
  - No matter how many particles do we take for correlation, we get the same signal

Small systems are **collective**

Origin of collectivity in small systems?

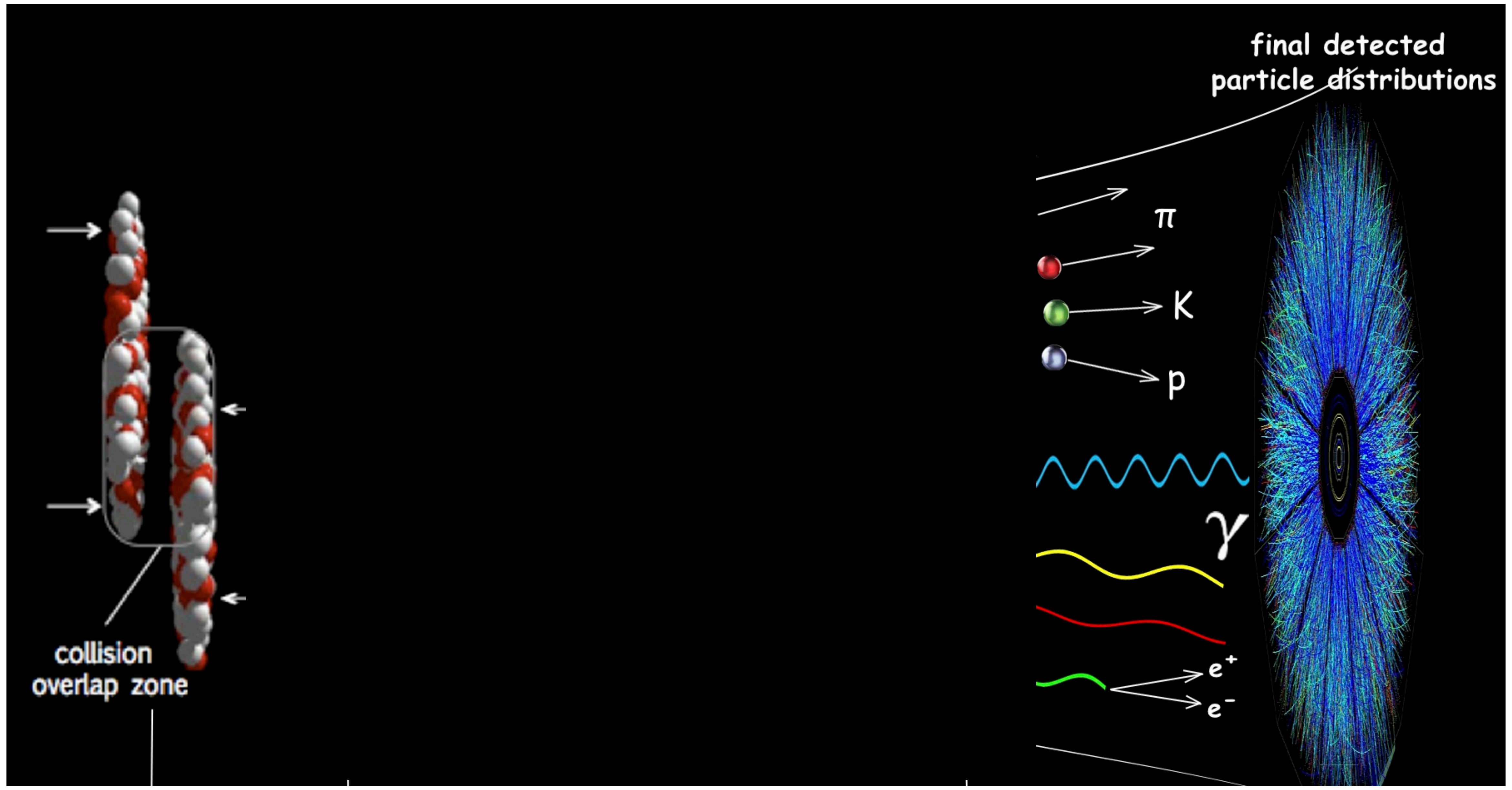
Final state (FS) effects AND / OR **Initial state (IS) effects**

initial spatial anisotropy → interactions in the created system → anisotropic flow



- Correlated with initial geometry
  - Subnucleon fluctuations become important
- Hydrodynamics

initial momentum anisotropy → anisotropic flow



- Not correlated with initial geometry
  - Correlations between partons scattering off the same color domains in the initial state
- Color Glass Condensate (CGC)

Flow in different collision systems

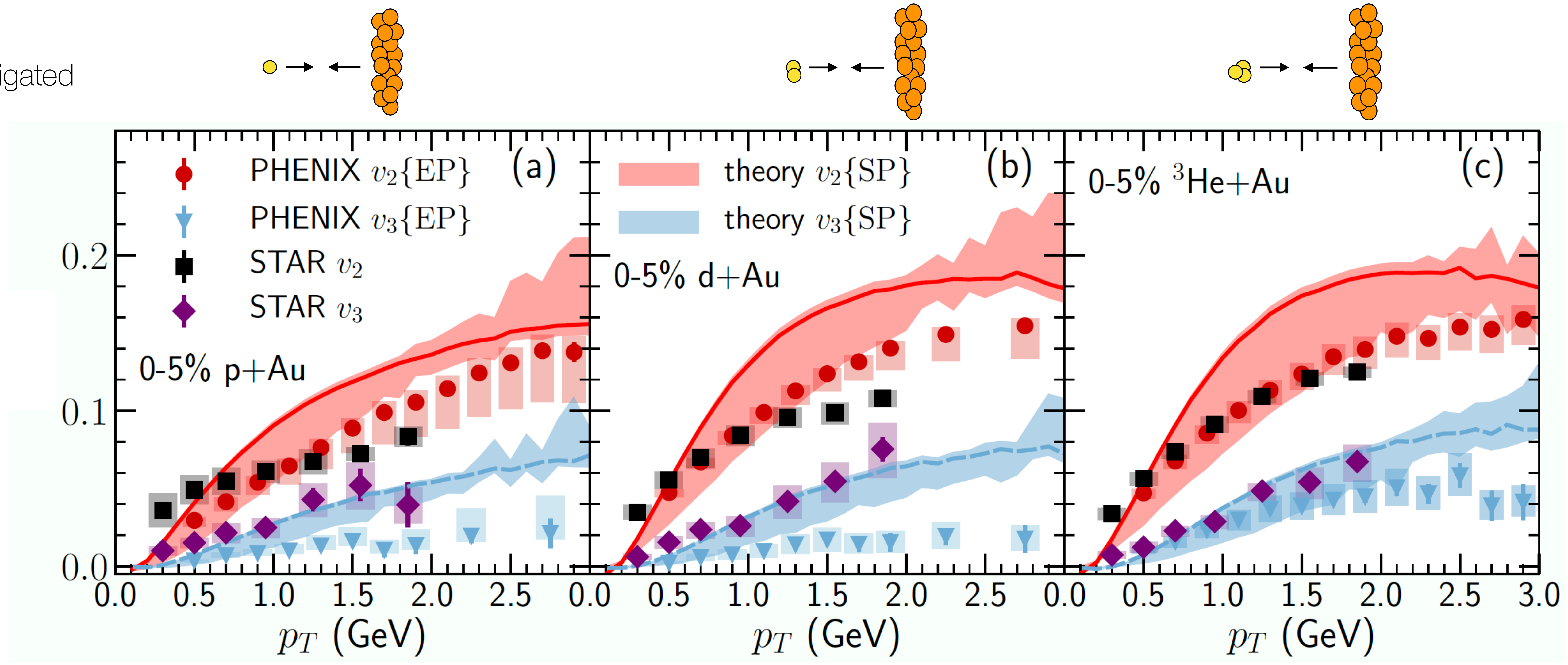
Note: differences between experiments are being investigated

Elliptic flow v_2

STAR PHENIX

Triangular flow v_3

STAR PHENIX



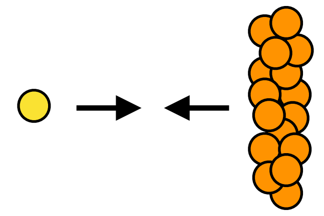
Schenke et al., PLB 803 (2020) 135322

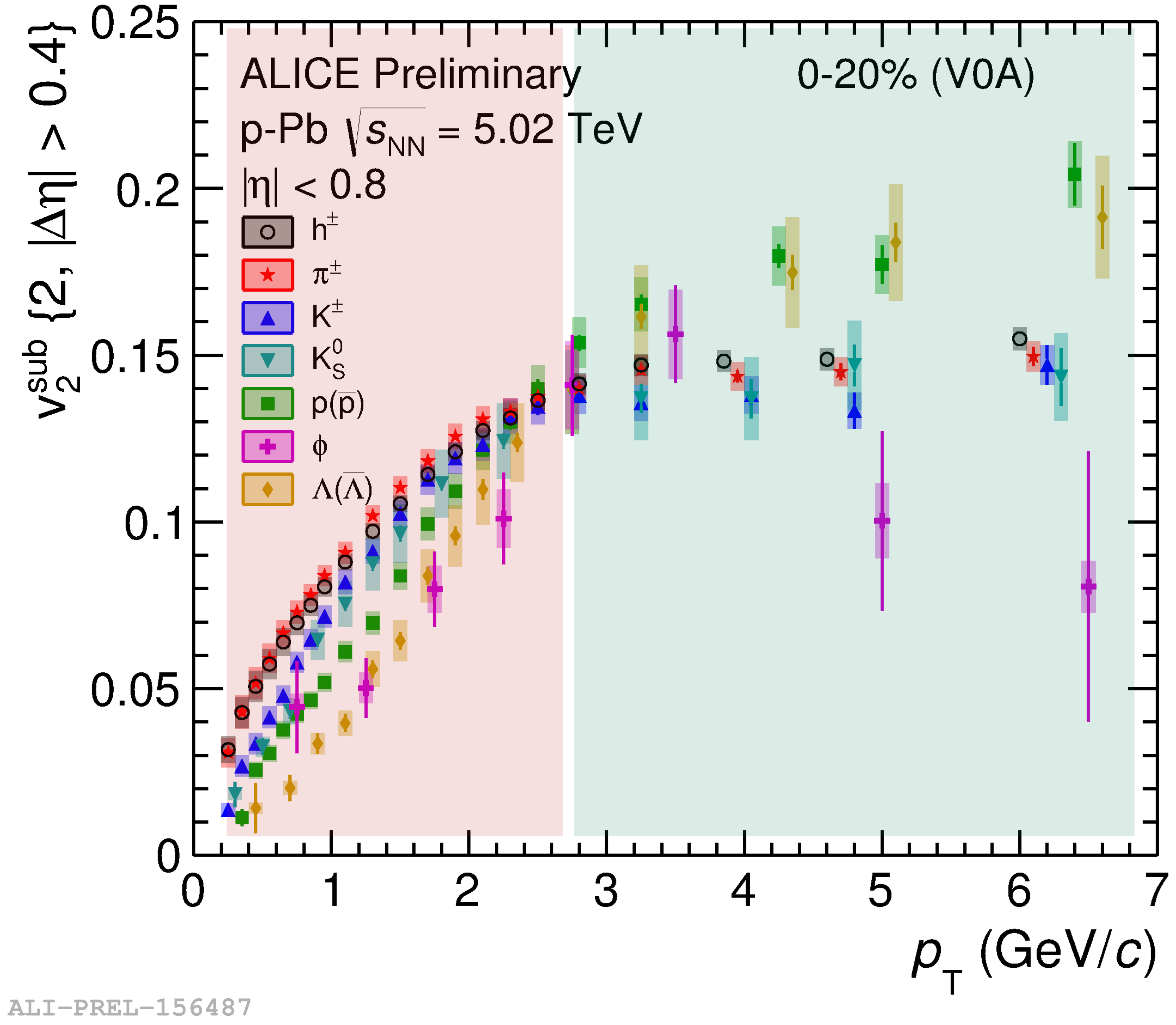
PHENIX, Nature Phys. **15**, 214-220 (2019)

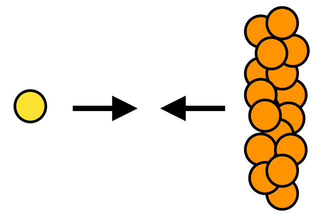
STAR Preliminary

- Measurements of v_2 and v_3 in different collision configurations
- Measurements **described by hydrodynamic model** (successful in describing flow in heavy-ion collisions)
- Flow **driven by** initial (subnucleon) **geometry**

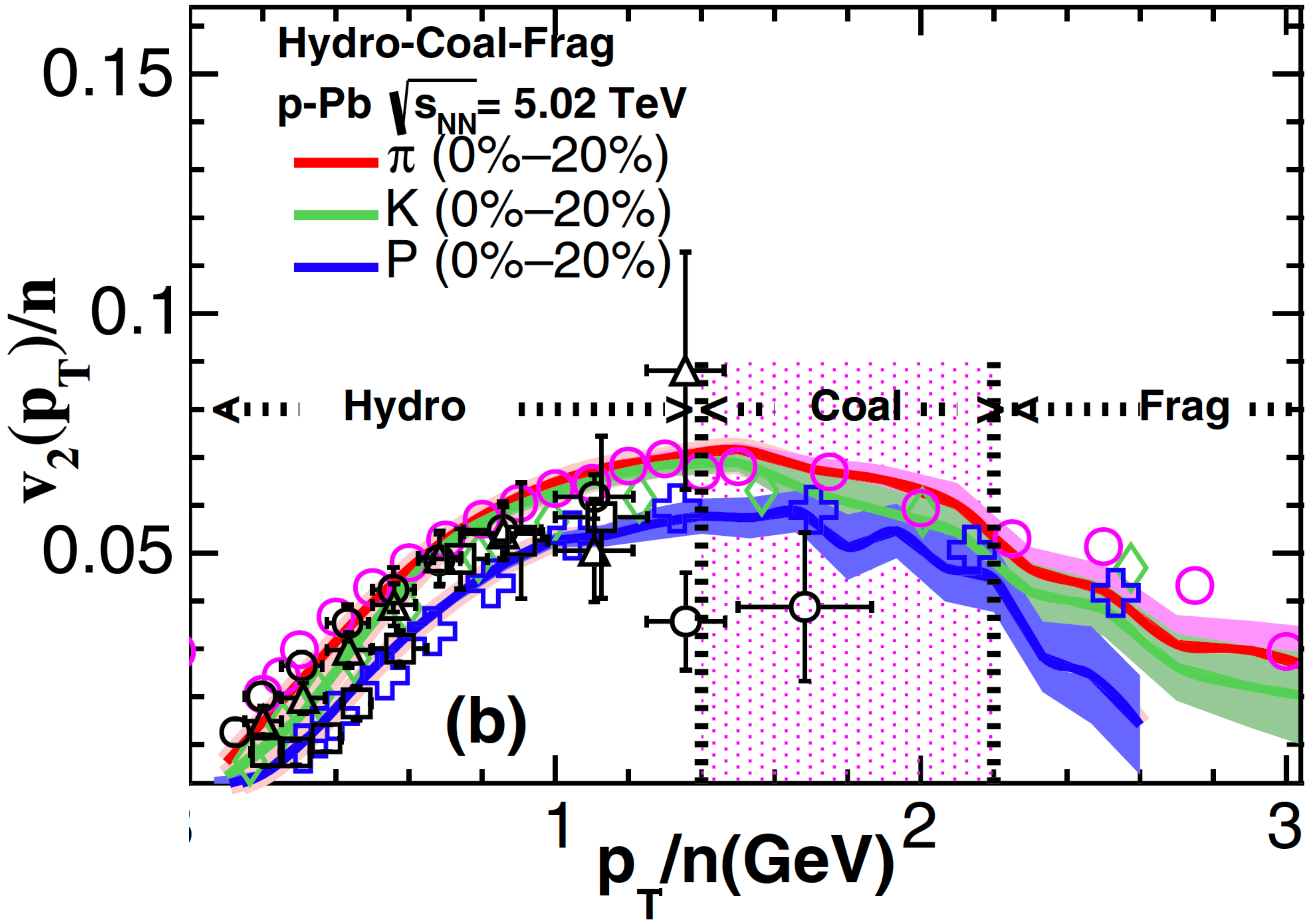
Flow of identified hadrons

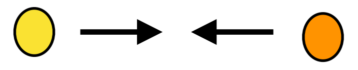






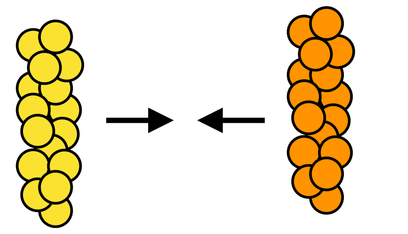
Zhao et al., PRL 125, 072301 (2020)



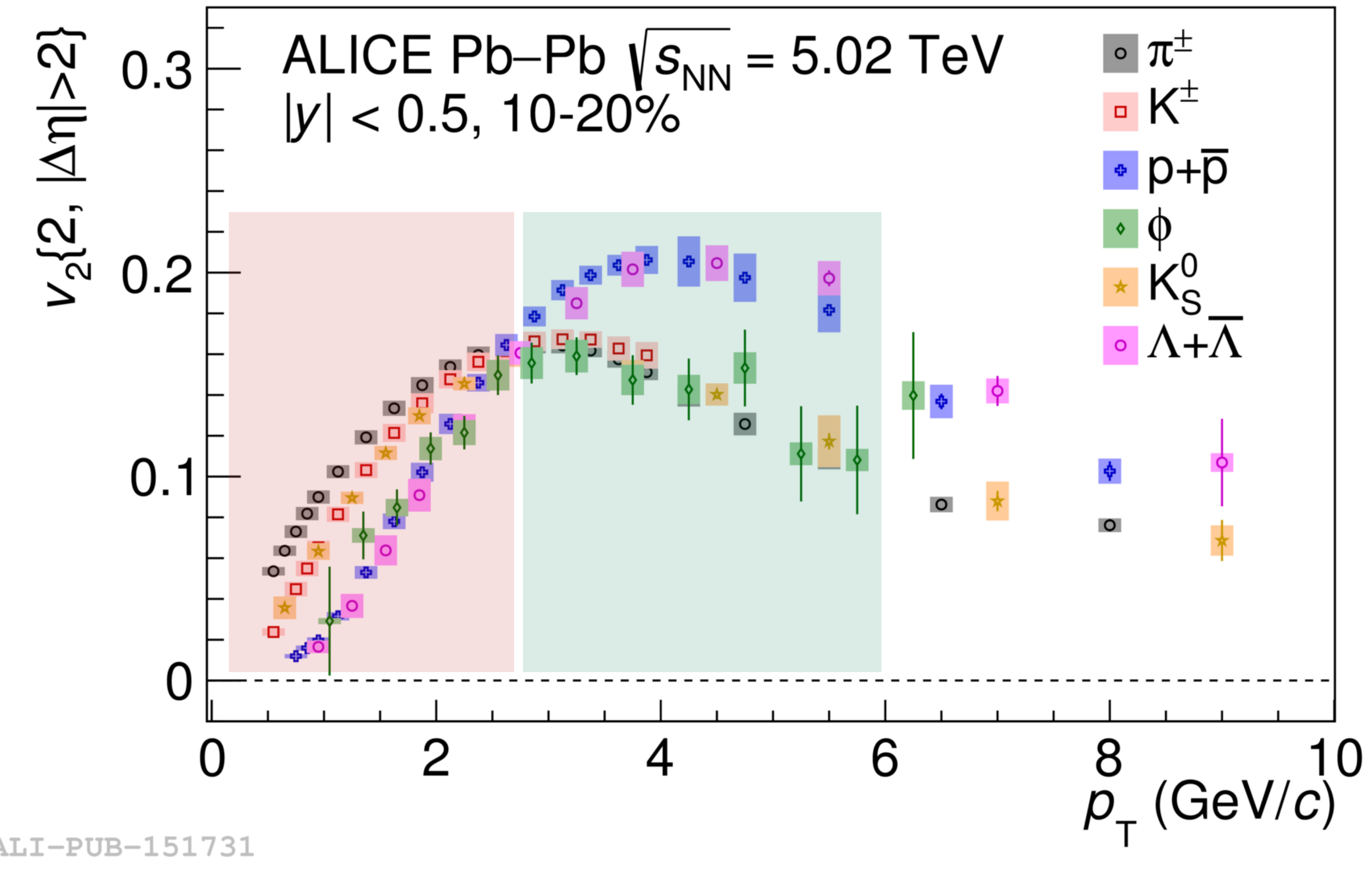


Note: hint for mass ordering also in pp collisions

CMS, PLB 765 (2017) 193



ALICE, JHEP09, 006 (2018)

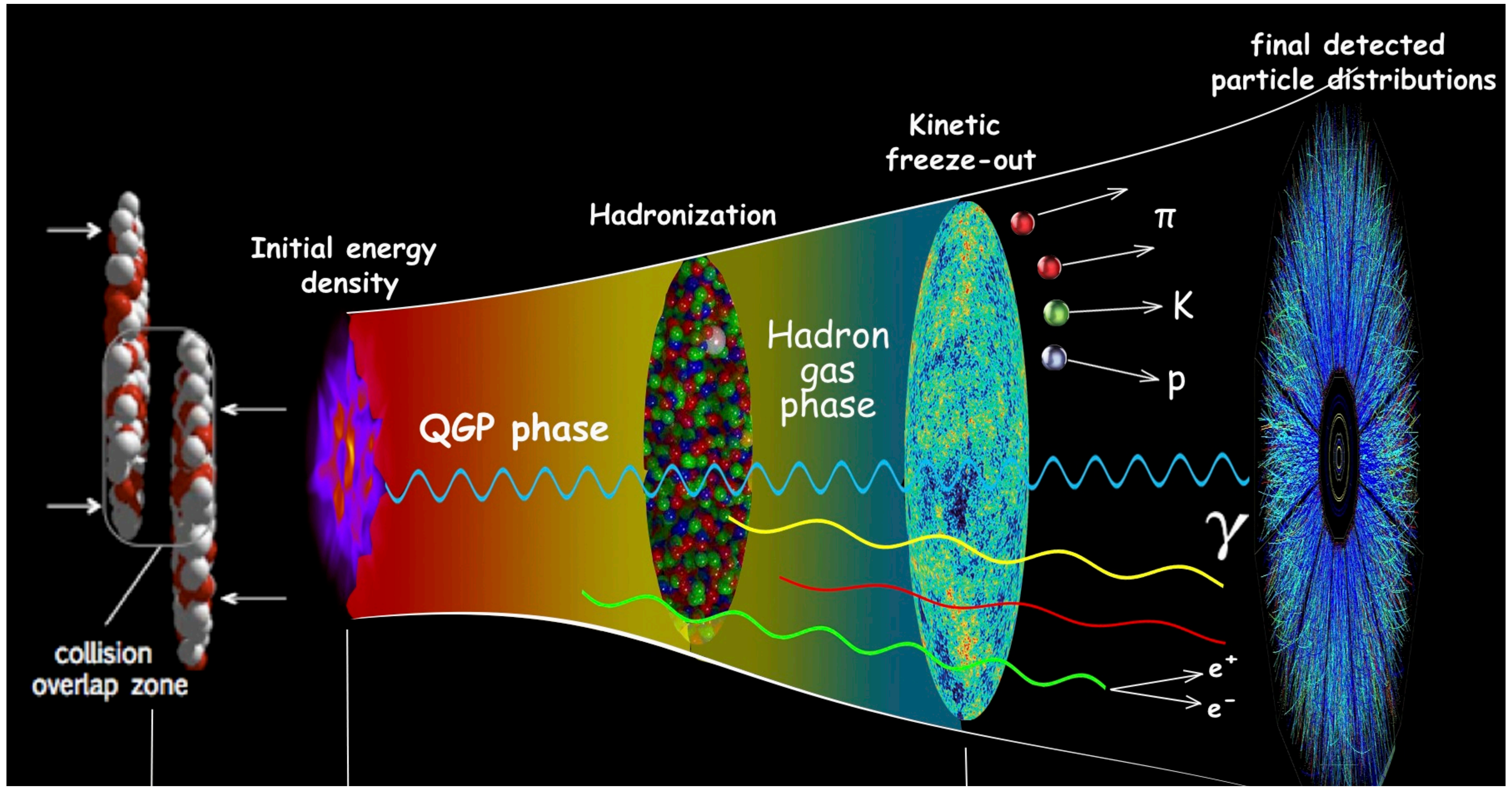


- We observe **mass ordering** and hint for a **particle type grouping**
  - Both believed to originate from hydrodynamic flow in heavy-ion collisions
- Measurements (in p-Pb collisions) described by hydrodynamic models
  - **Possible existence of the partonic phase** in high-multiplicity p-Pb collisions

Origin of collectivity in small systems?

Final state (FS) effects AND / OR **Initial state (IS) effects**

initial spatial anisotropy → interactions in the created system → anisotropic flow



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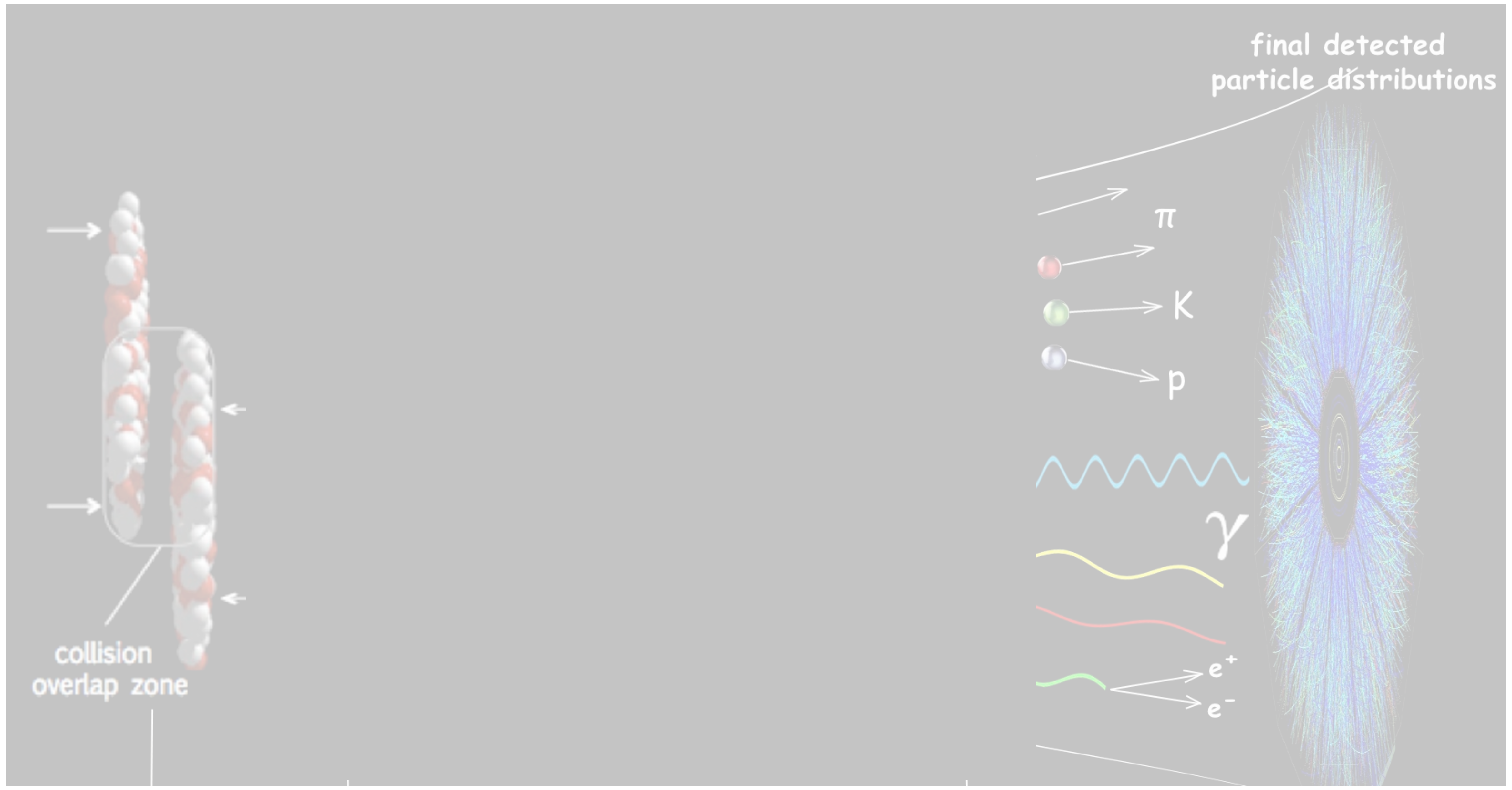
initial momentum anisotropy → anisotropic flow



- Not correlated with initial geometry
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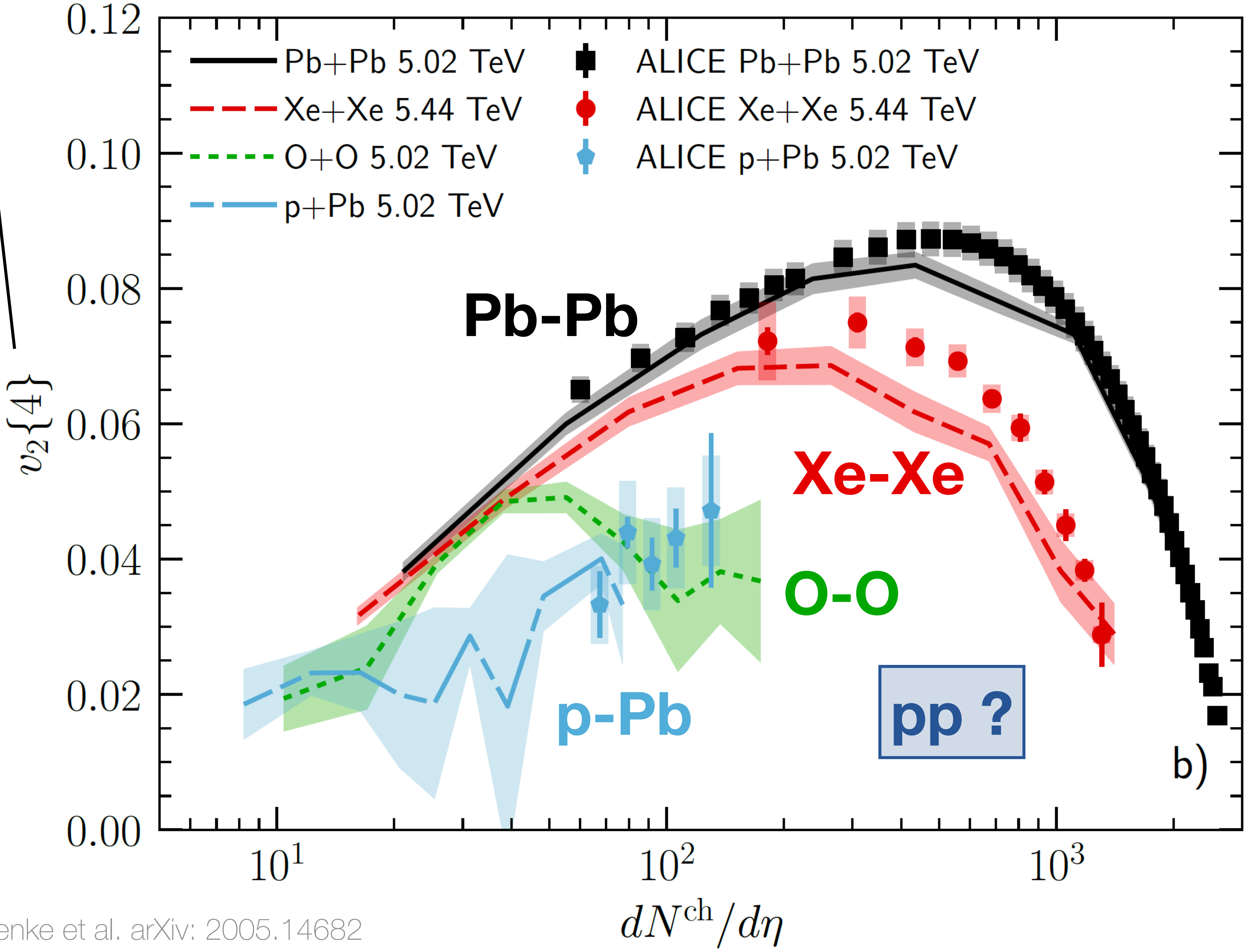
Caveats in the (FS) model description ?

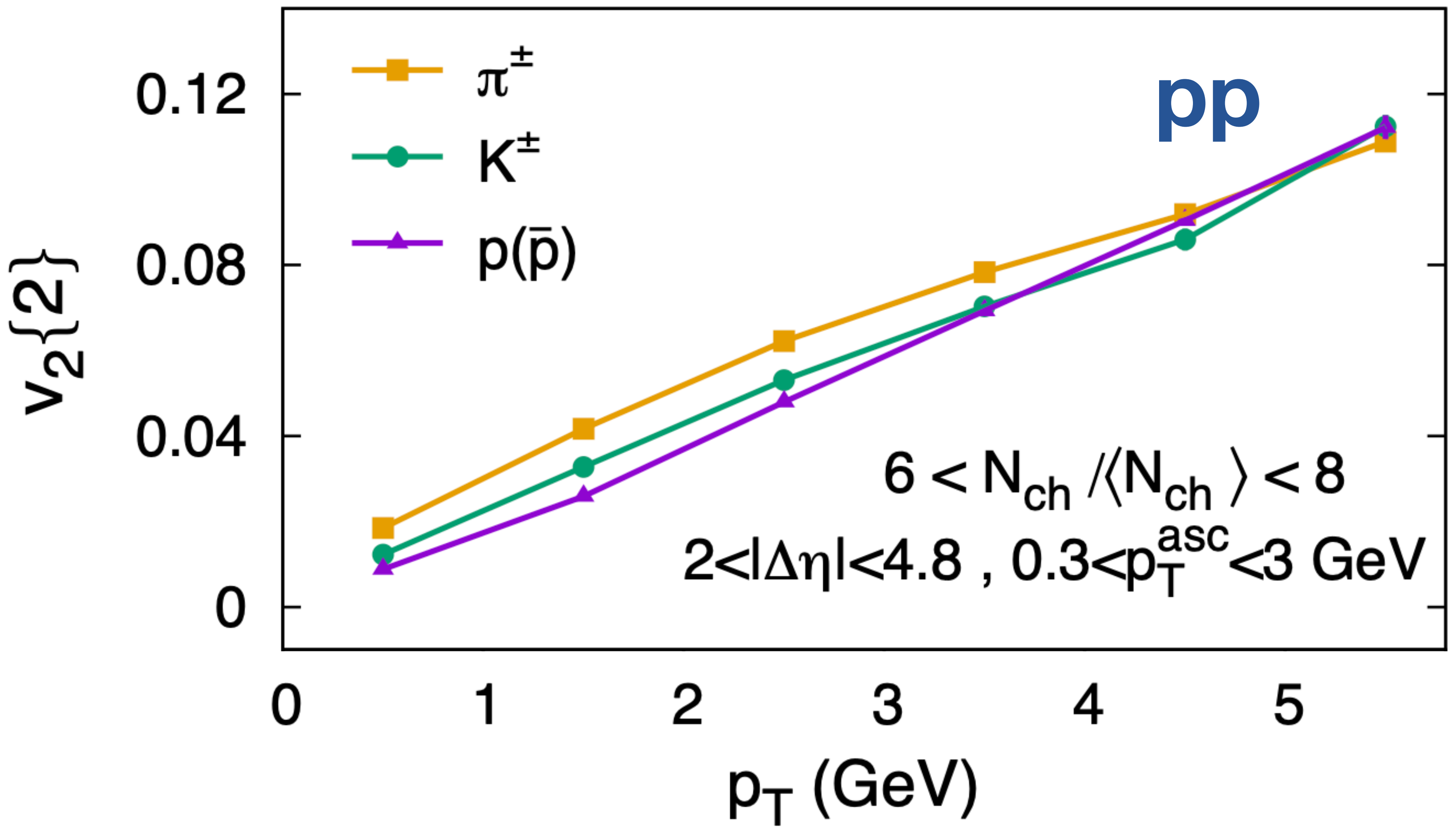
v_2 measured with **four**-particle correlations (cumulant)



Schenke et al. arXiv: 2005.14682

- Not all measurements are reproduced by hydrodynamic models (yet?)
  - Challenging to describe the measurements of four-particle correlations in pp collisions
- Some features of the measurements can be achieved in models without the creation of a hot and dense medium
  - Initial momentum correlations within a CGC-like framework

B. Schenke et al., PRL 117, 162301 (2016)



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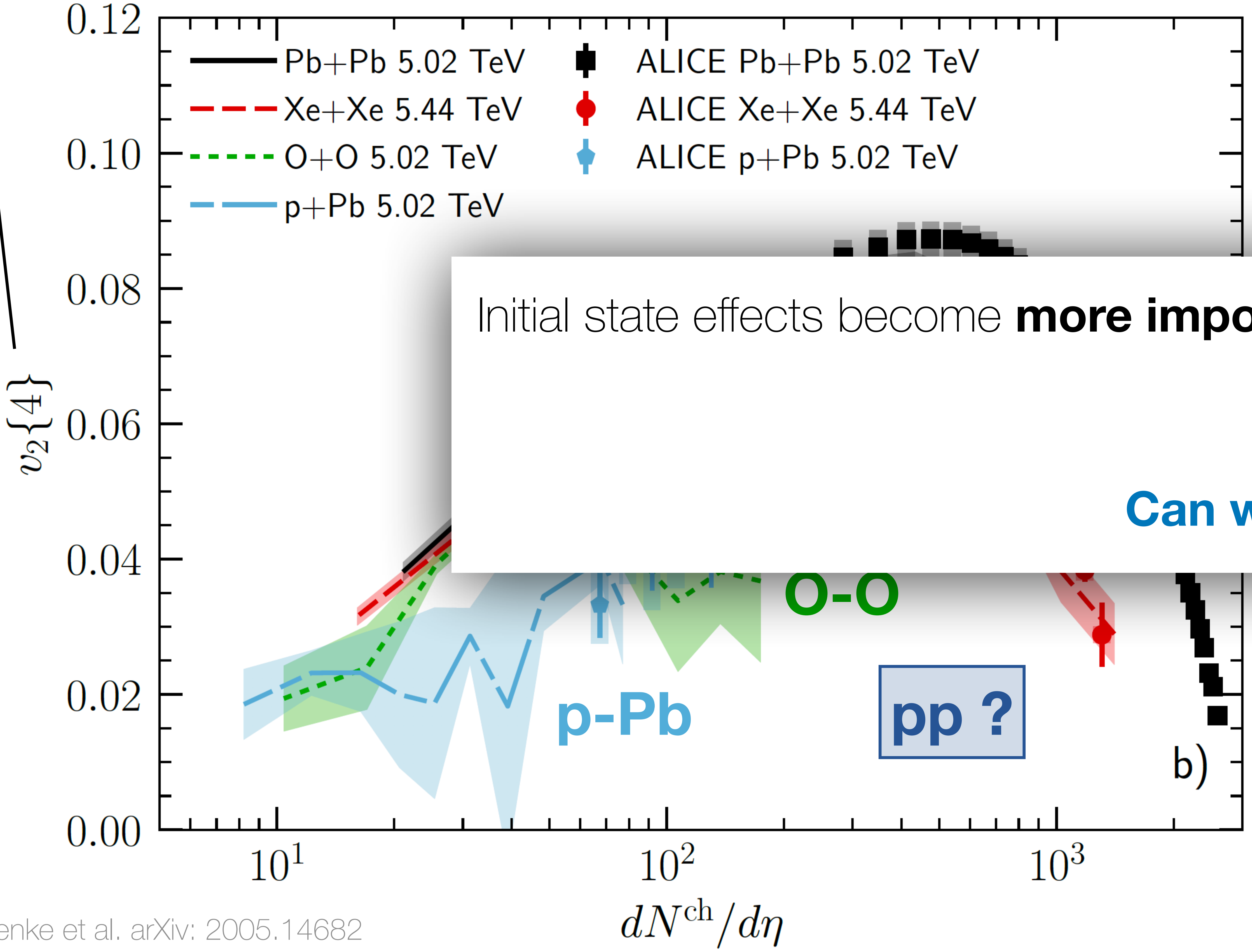

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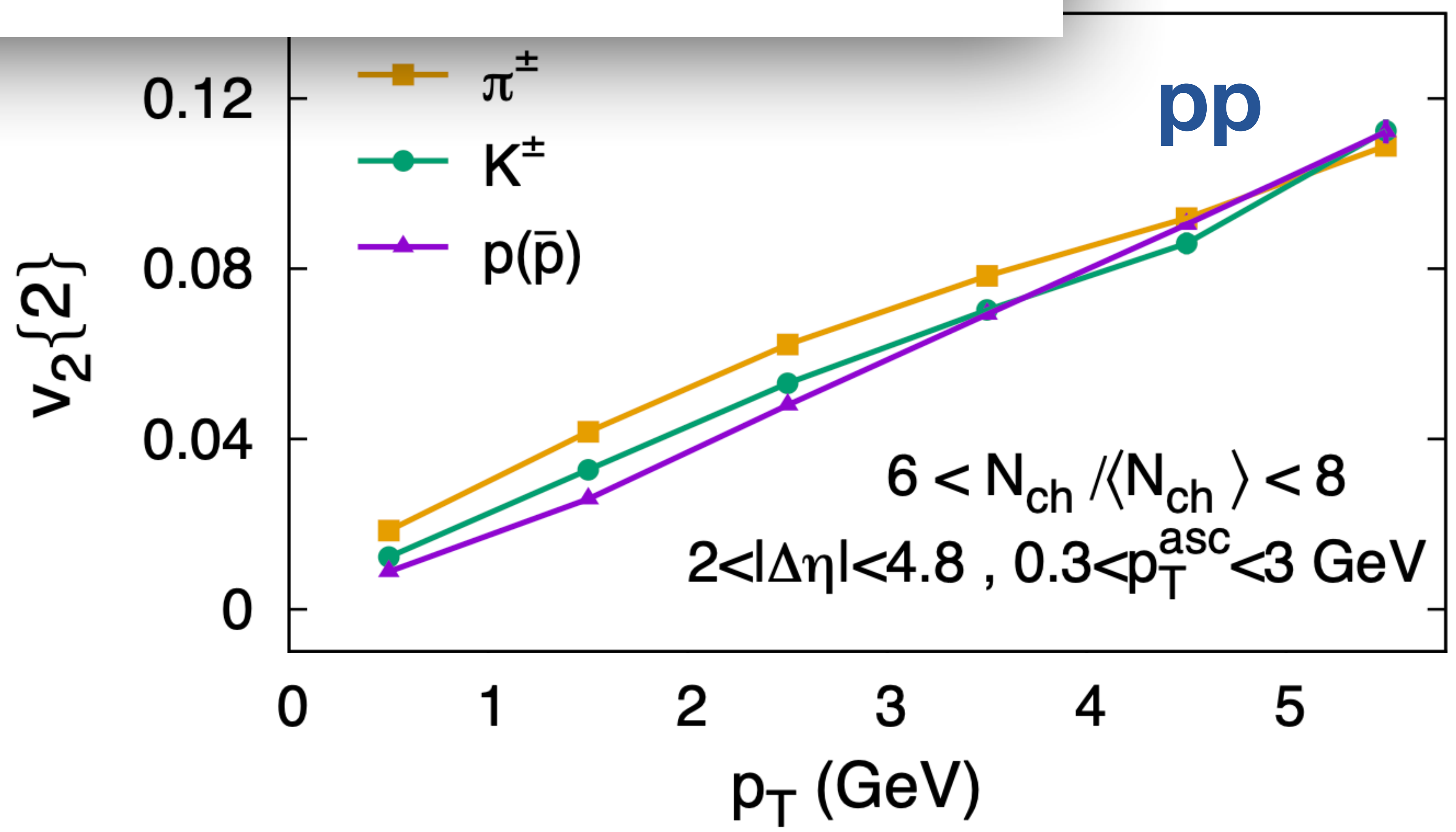
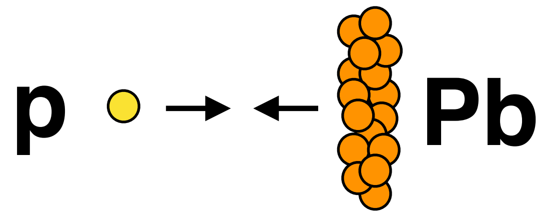
Initial state effects become **more important as we decrease the systems size**?

Can we study initial state effects experimentally?

117, 162301 (2016)



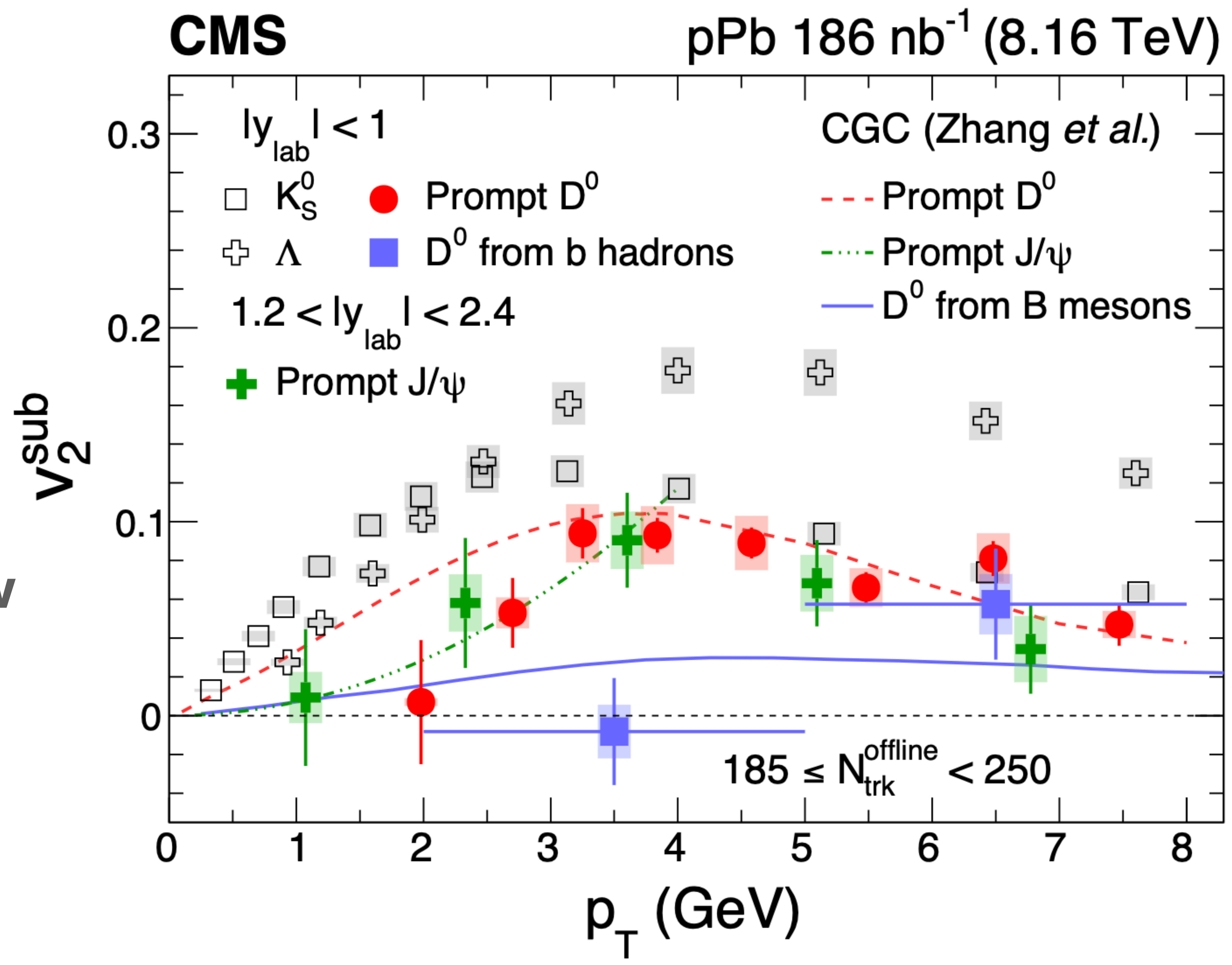
Flow of heavy flavor hadrons



light hadron flow

charm flow

bottom flow



CMS, PLB 813 (2021) 136036

Zhang et al., PRL 122, 172302 (2019)

Zhang et al., PRD 102, 034010 (2020)

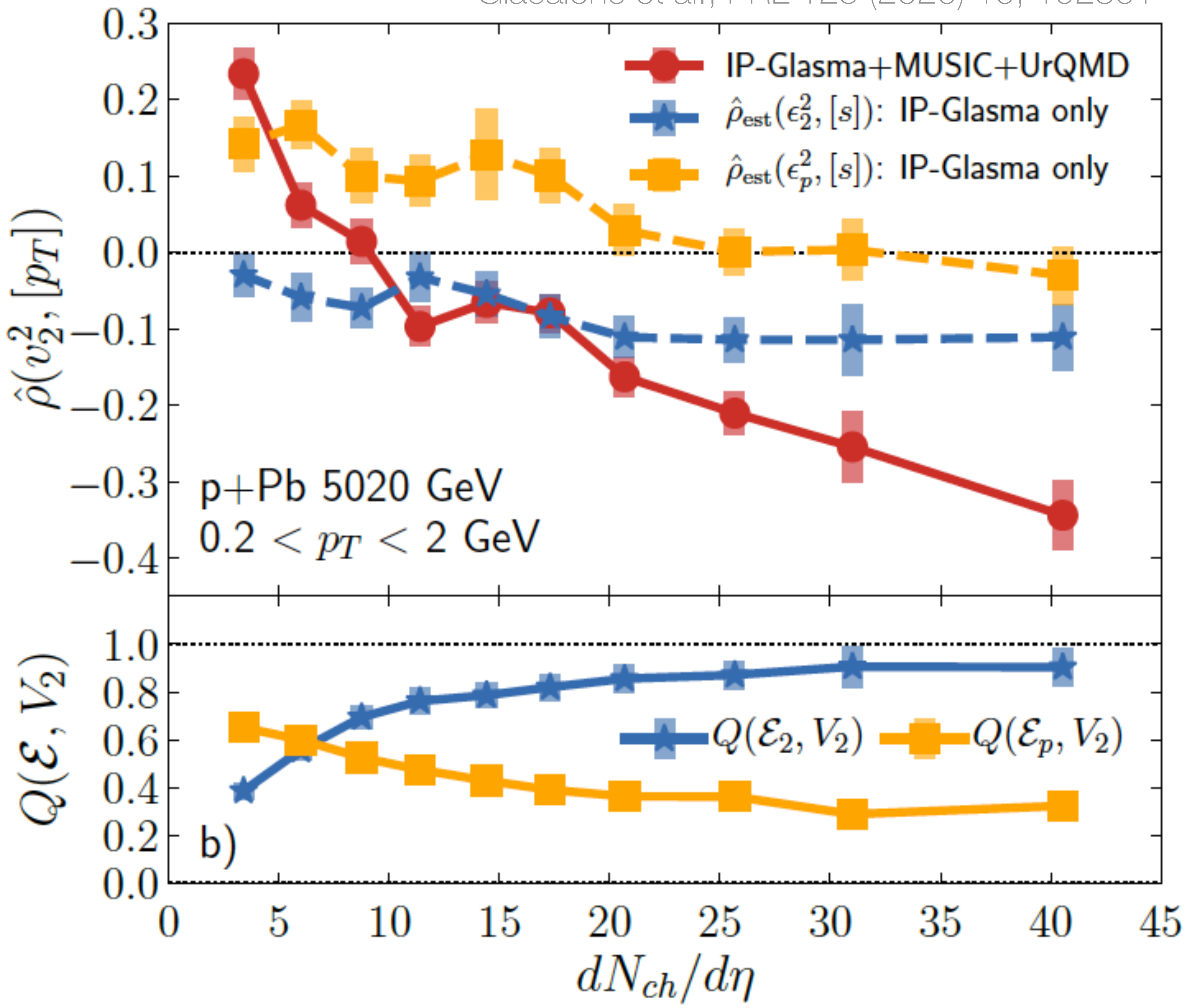
- The early formation time of heavy quarks may bring additional insight into the influence of the initial state correlations on measurements of flow
- Finite flow of heavy flavor particles (charm) in p-Pb and pp collisions — ATLAS, PRL 124, 082301 (2020)
  - Models based on final state effects do not have strong enough flow signal — Du, Rapp, JHEP 03 (2019) 015
  - Description of the results in p-Pb collisions with the CGC model -> collectivity of heavy flavor particles may be **largely influenced by initial state effects**

Probing the influence of the initial state

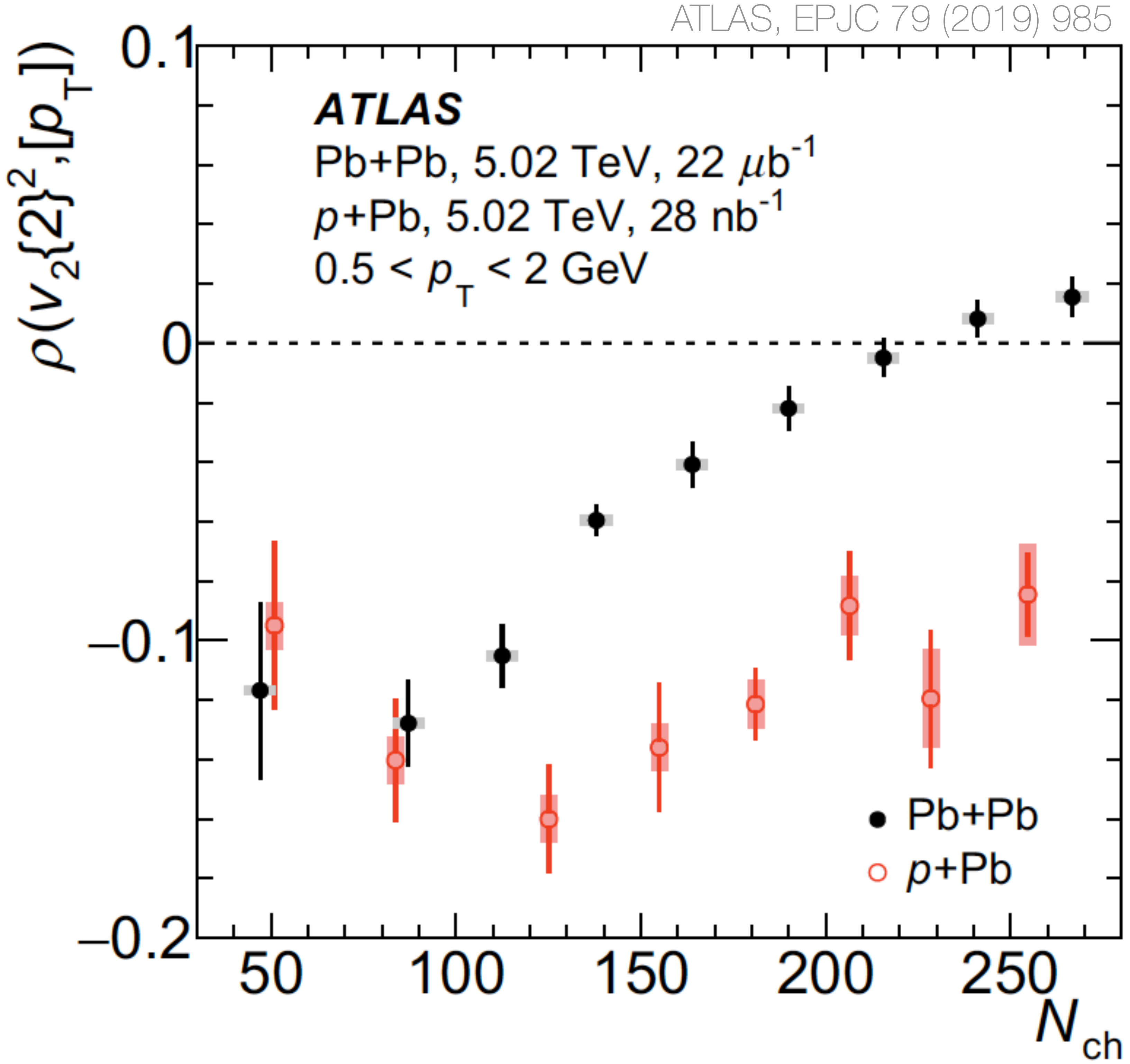
- Initial (gluon) momentum anisotropy important at low multiplicities
- Initial spatial anisotropy important at high multiplicities
- Final observable

$$Q(\mathcal{E}, V_2) = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

Giacalone et al., PRL 125 (2020) 19, 192301



ATLAS, EPJC 79 (2019) 985



$$\rho_n = \frac{Cov(v_n^2, \langle p_T \rangle)}{\sqrt{Var(v_n^2) Var(\langle p_T \rangle)}}$$

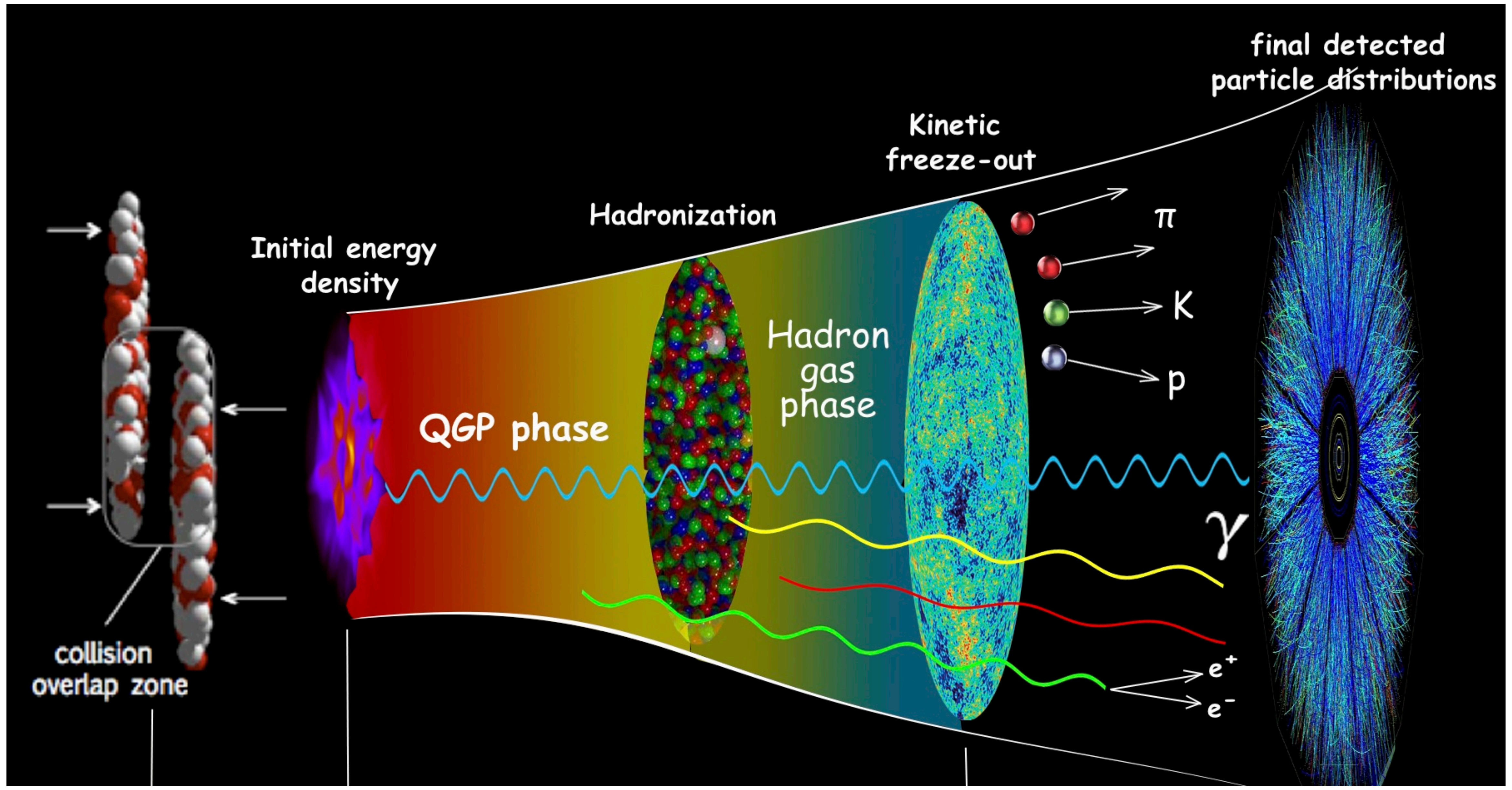
- The observable ρ is predicted to exhibit a **sign change in the presence of initial momentum anisotropy**
- Measurements down to such low multiplicity in small systems would be very interesting, but very challenging

A new promising way to determine the origin of collectivity in small collision systems

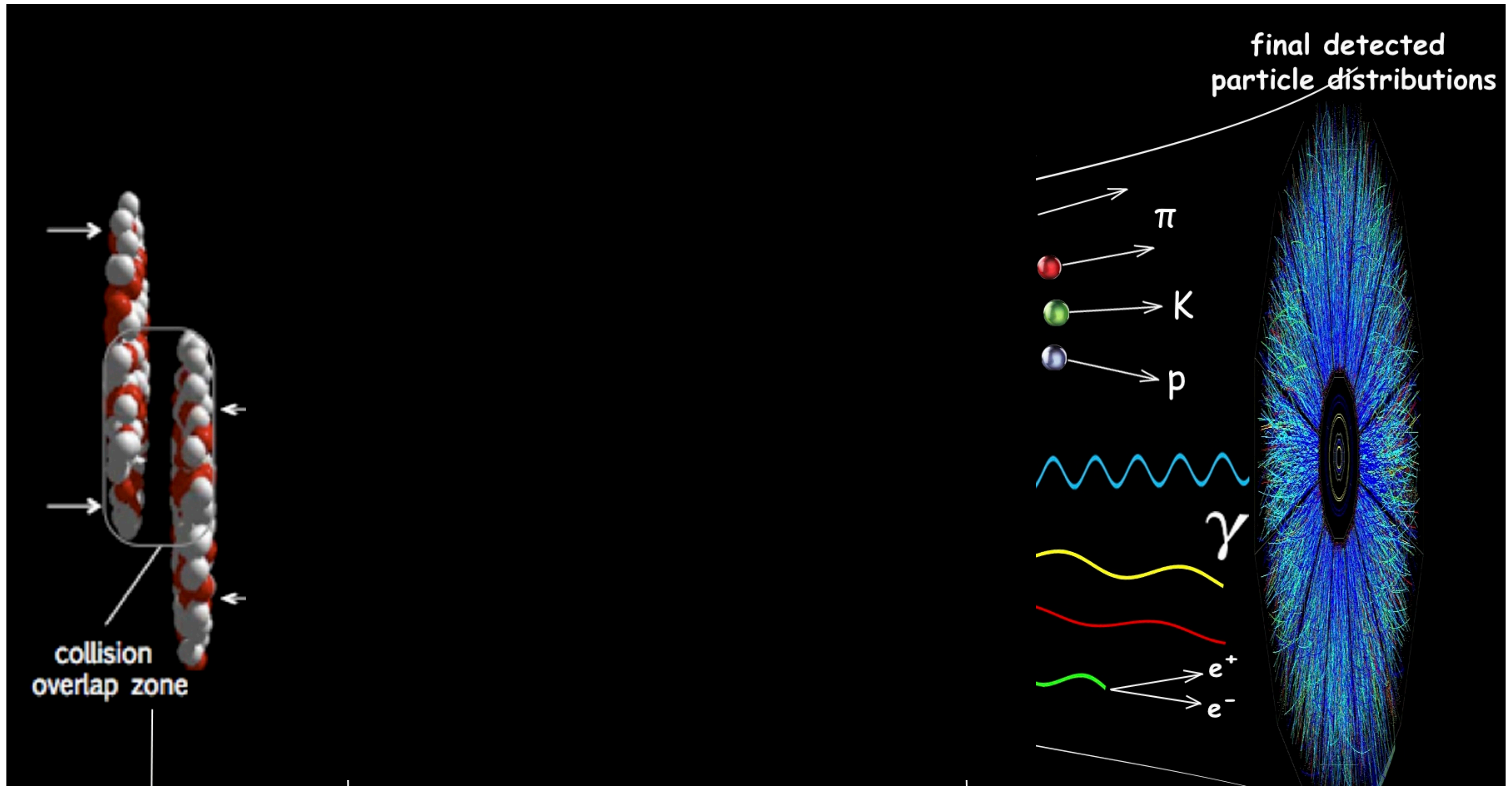
Origin of collectivity in small systems?

Final state (FS) effects AND / ~~OR~~ **?** **Initial state (IS) effects**

initial spatial anisotropy → interactions in the created system → anisotropic flow



initial momentum anisotropy → anisotropic flow



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  - Subnucleon fluctuations become important
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- Not correlated with initial geometry
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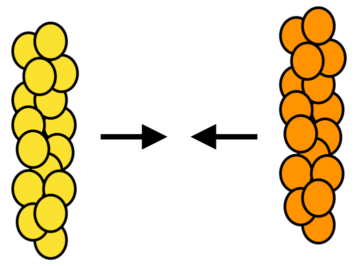
Summary

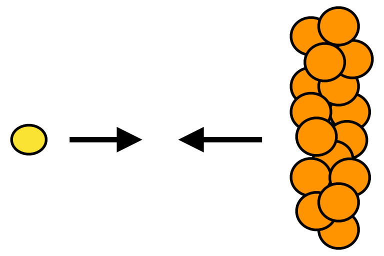
… of investigations of hot and dense QCD medium of different size

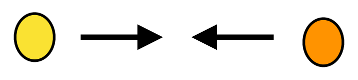
Heavy-ion collisions



- Measurements of anisotropic flow provide key information for studies of the properties of the hot and dense medium (QGP) created in heavy-ion collisions
- Era of precise measurements, and sensitive observables to different aspects of the theoretical models

Small collision systems

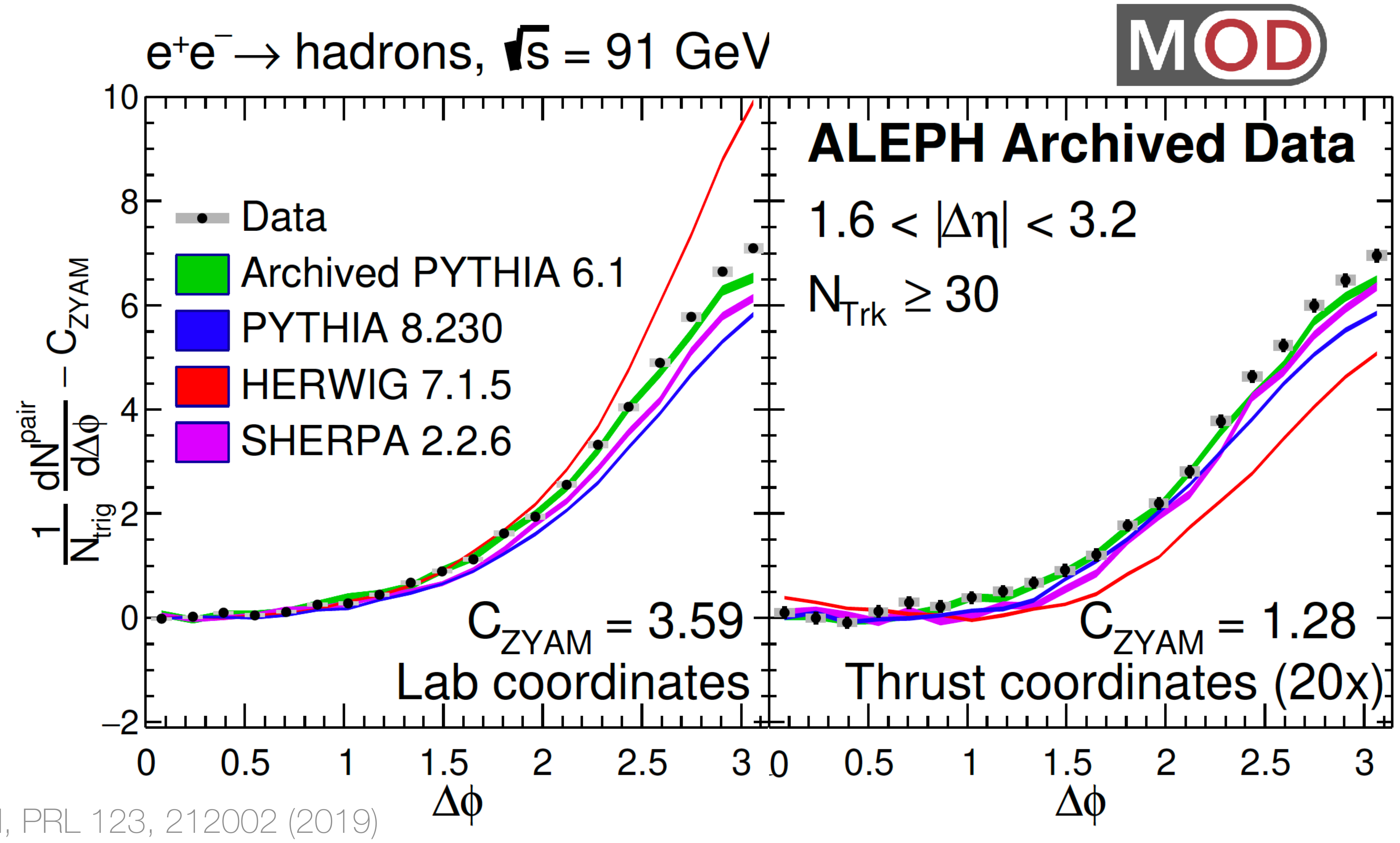




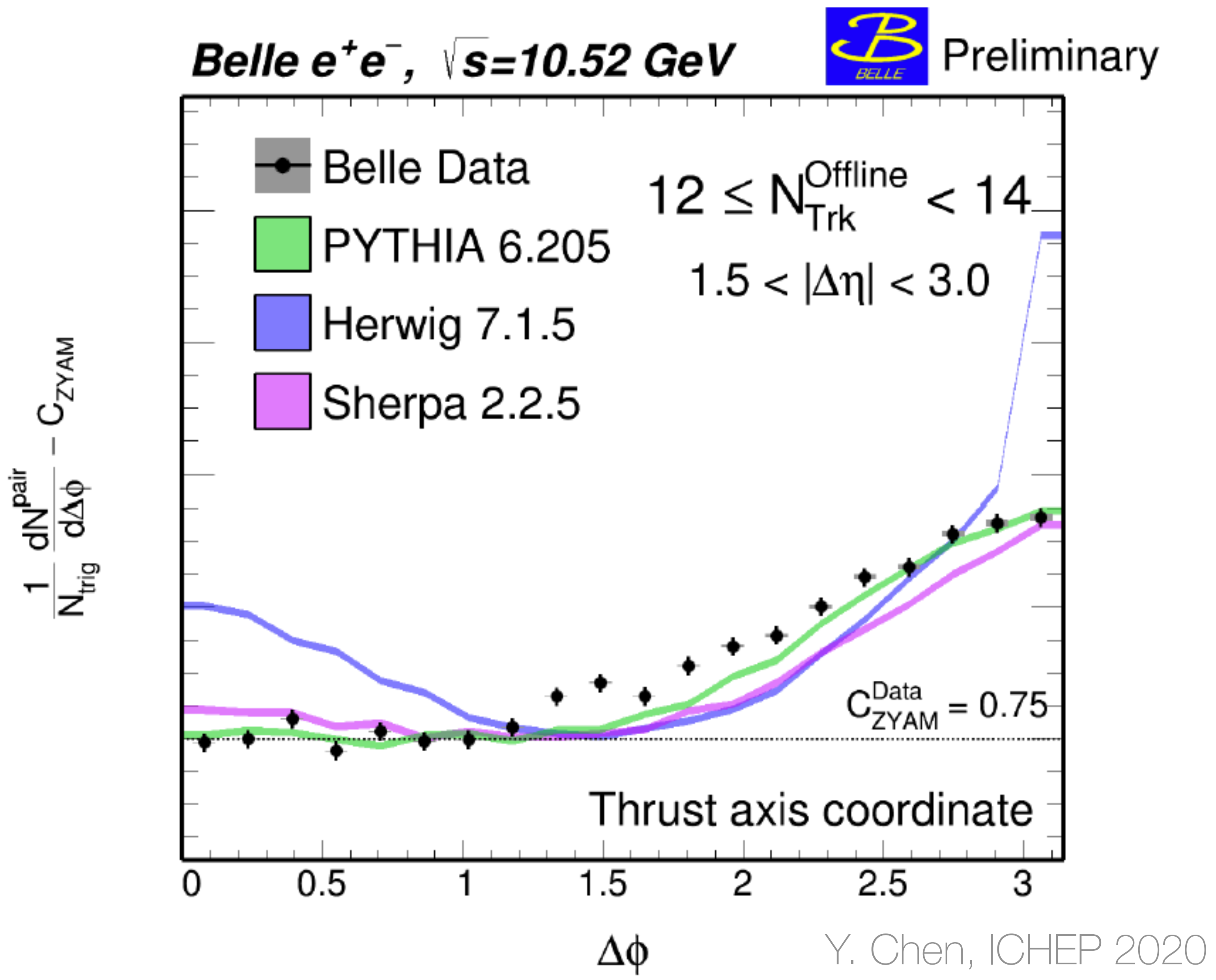
- Measurements of anisotropic flow show that small systems (at high multiplicities) also behave collectively
- Whether the origin of collectivity lies in a medium similar to that created in heavy-ion collisions, is still under debate
- Future data taking at RHIC and at the LHC will bring more insight into the nature of the system created in small collision systems

Backup

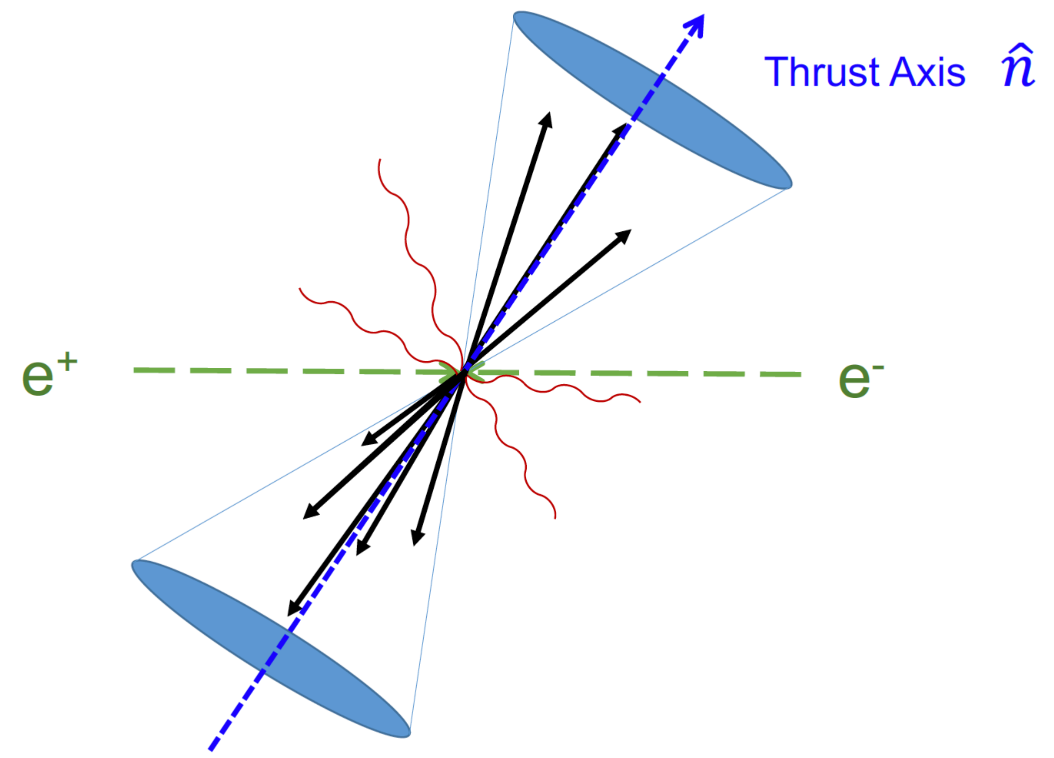
Can we switch collectivity off? (e^+e^-)



ALEPH, PRL 123, 212002 (2019)

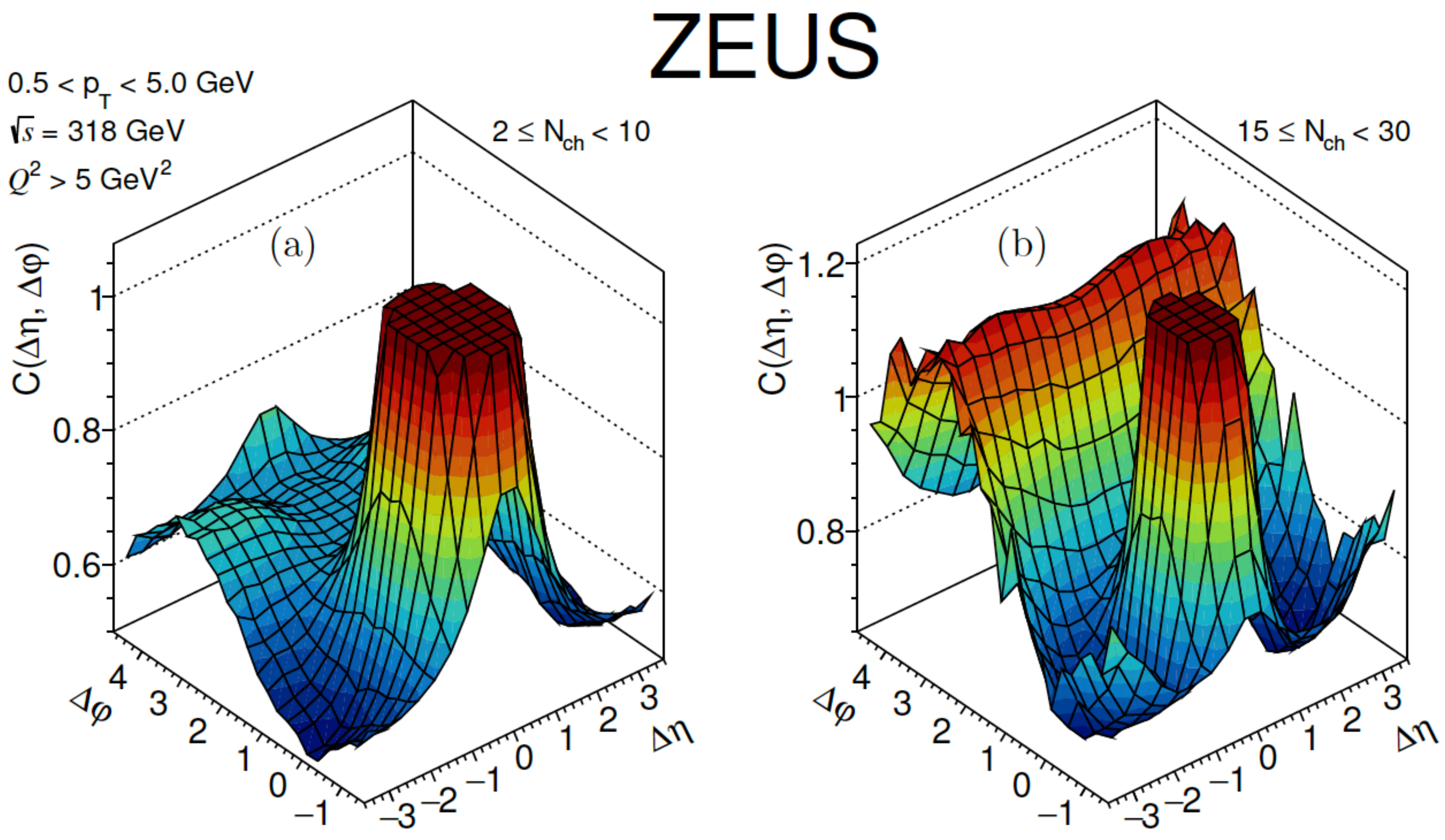


Y. Chen, ICHEP 2020

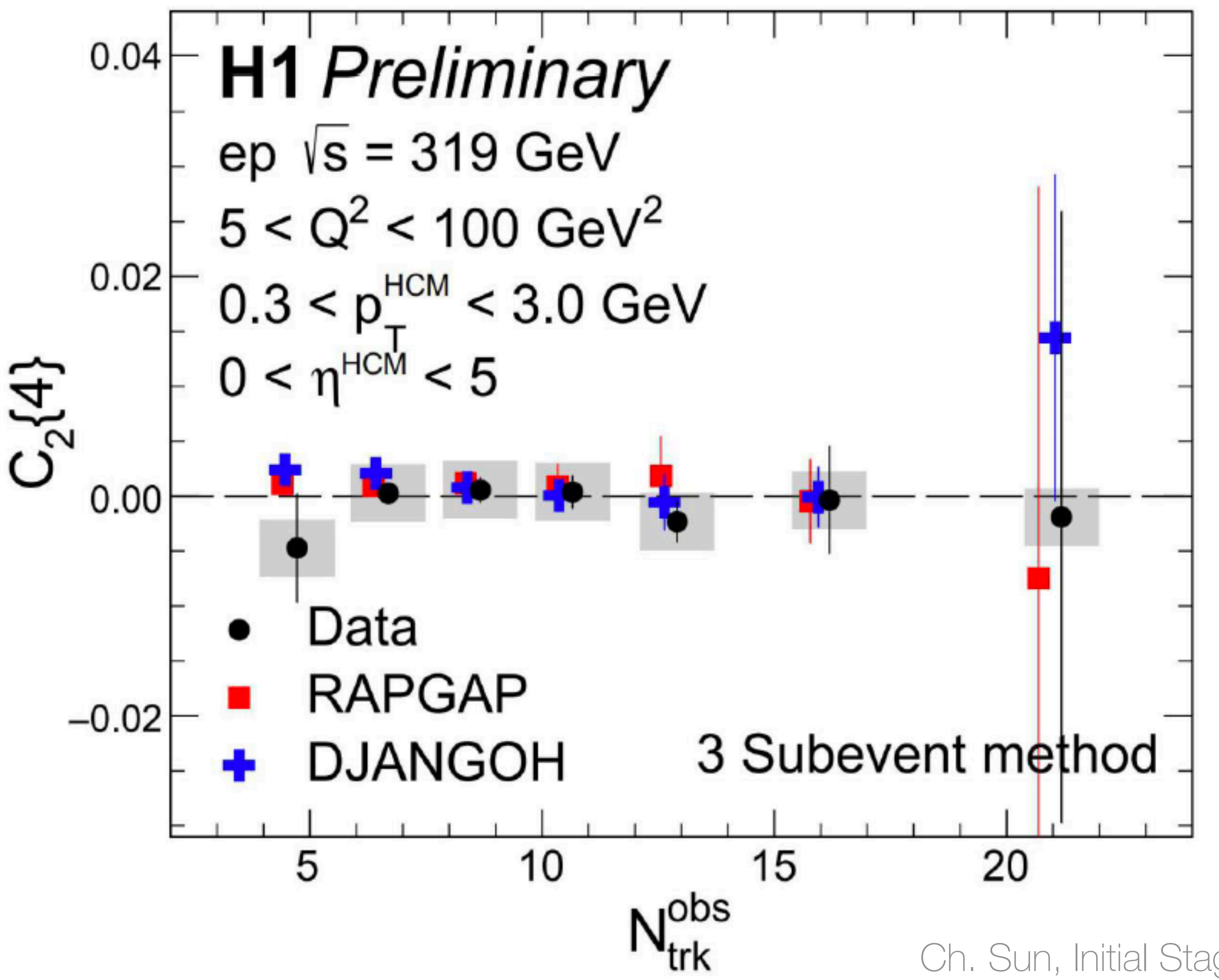


- Advantage: well-defined initial state
- No observation of near-side ridge
  - Data consistent with models that do not contain any final state interactions

Can we switch collectivity off? (ep)



ZEUS, JHEP 04 (2020) 070



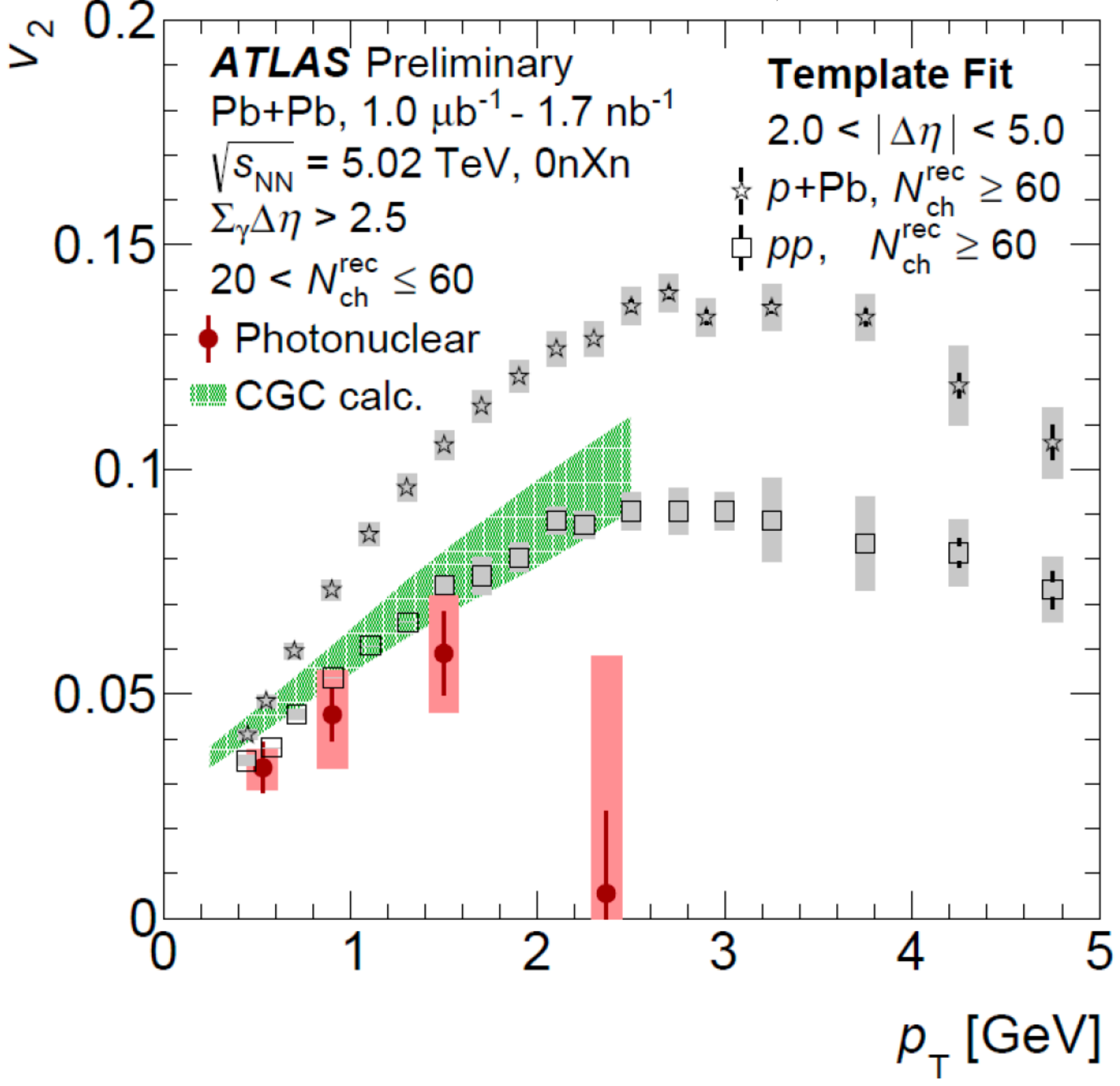
Ch. Sun, Initial Stages 2021

- No observation of near-side ridge in ep collisions either
  - Data consistent with models that do not contain any final state interactions

Ultra-peripheral collisions

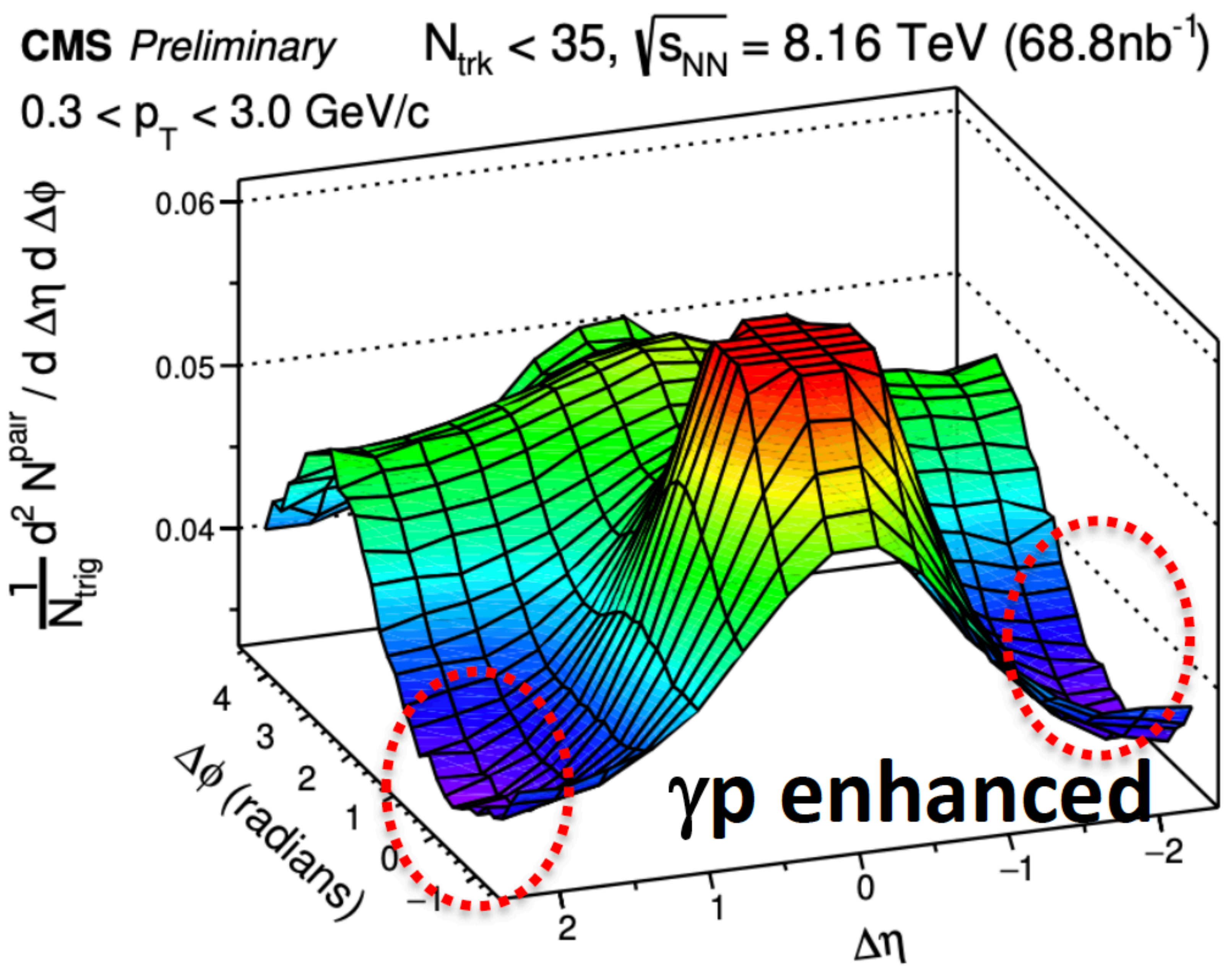
ATLAS, arXiv: 2101.10771

γPb



CMS, HIN-18-008-pas

γp



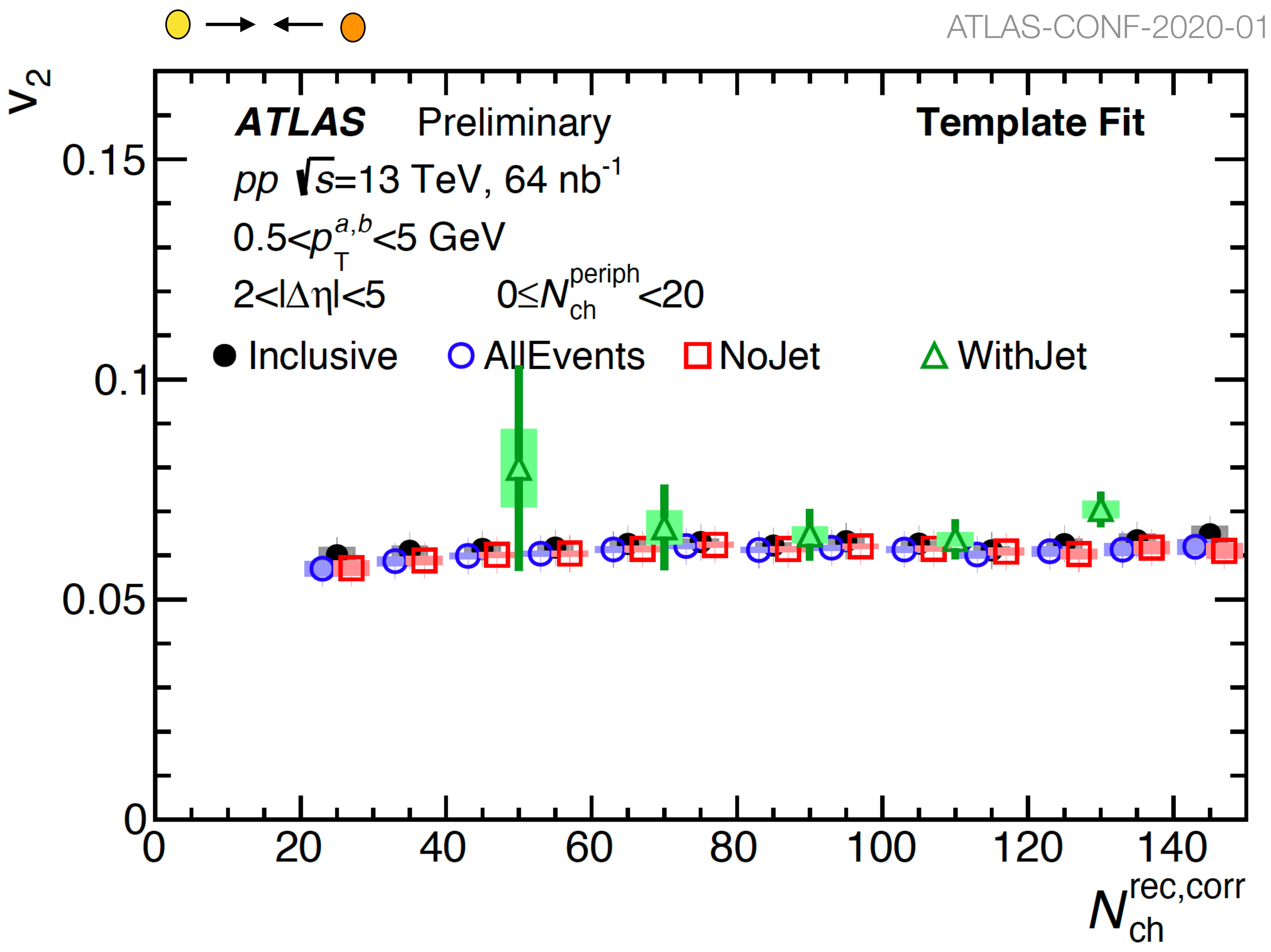
- gamma-p interactions (in collisions of p-Pb)
  - No evidence of ridge-like correlations
- Photonuclear collisions (gamma-Pb)
  - Non-zero flow, compatible with CGC calculations (what about calculations including final state effects ?)
- Relevant for future EIC collider

Origin of the ridge in hard processes?

- If the long-range ridge is an effect of hard or semi-hard processes:
  - Removing particles associated with jets may affect it
  - Selecting events with jets (while still removing particles associated with jets) may affect it

		jet particle rejection
	Inclusive	no
NoJet+WithJet	**AllEvents**	yes
without jets	**NoJet**	yes
with jets only	**WithJet**	yes

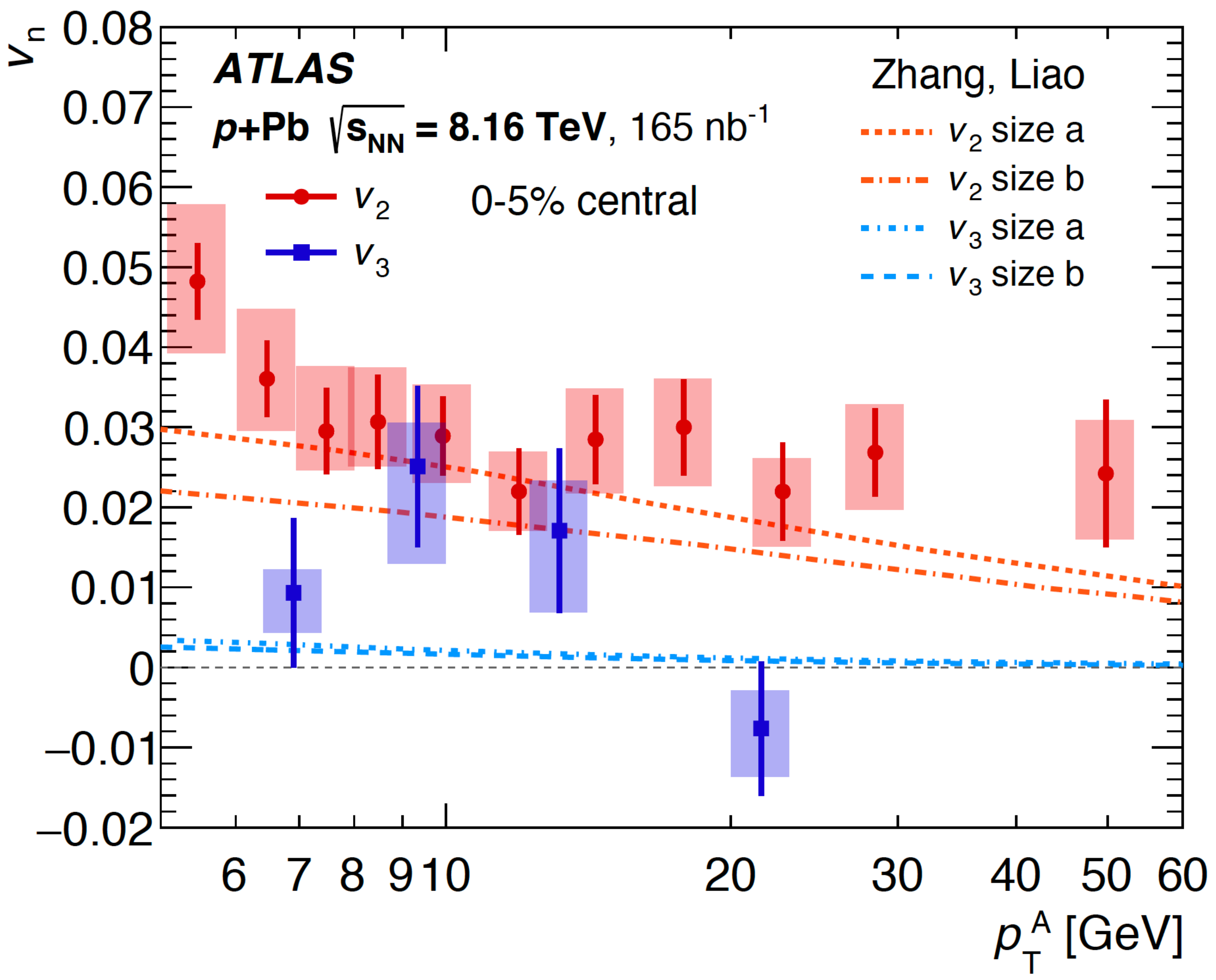
ATLAS-CONF-2020-018

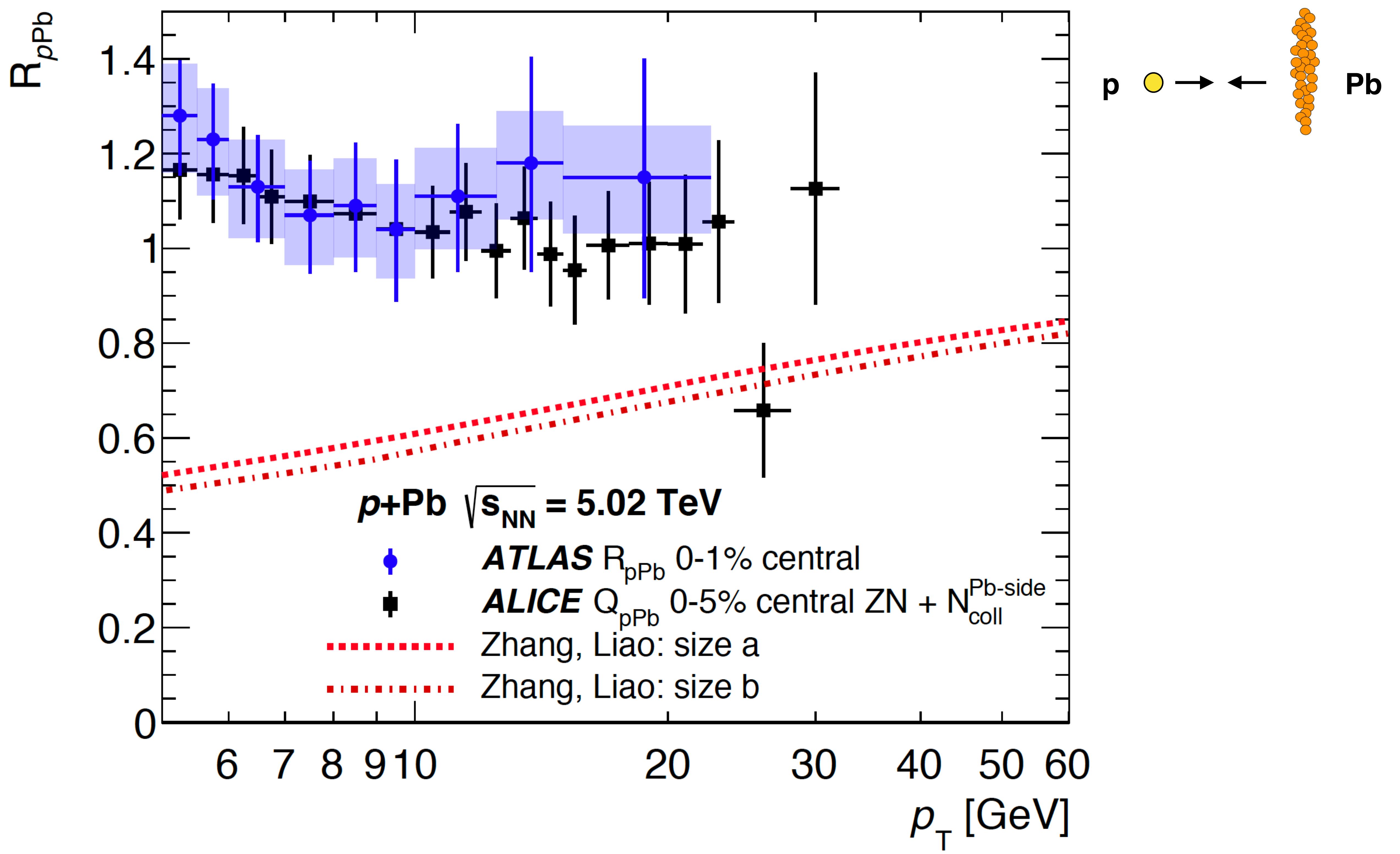


- Correlations are only slightly affected by the presence of hard or semi-hard processes
- Supports **collective behaviour of small systems**

Missing pieces

ATLAS, EPJC (2020) 80:73



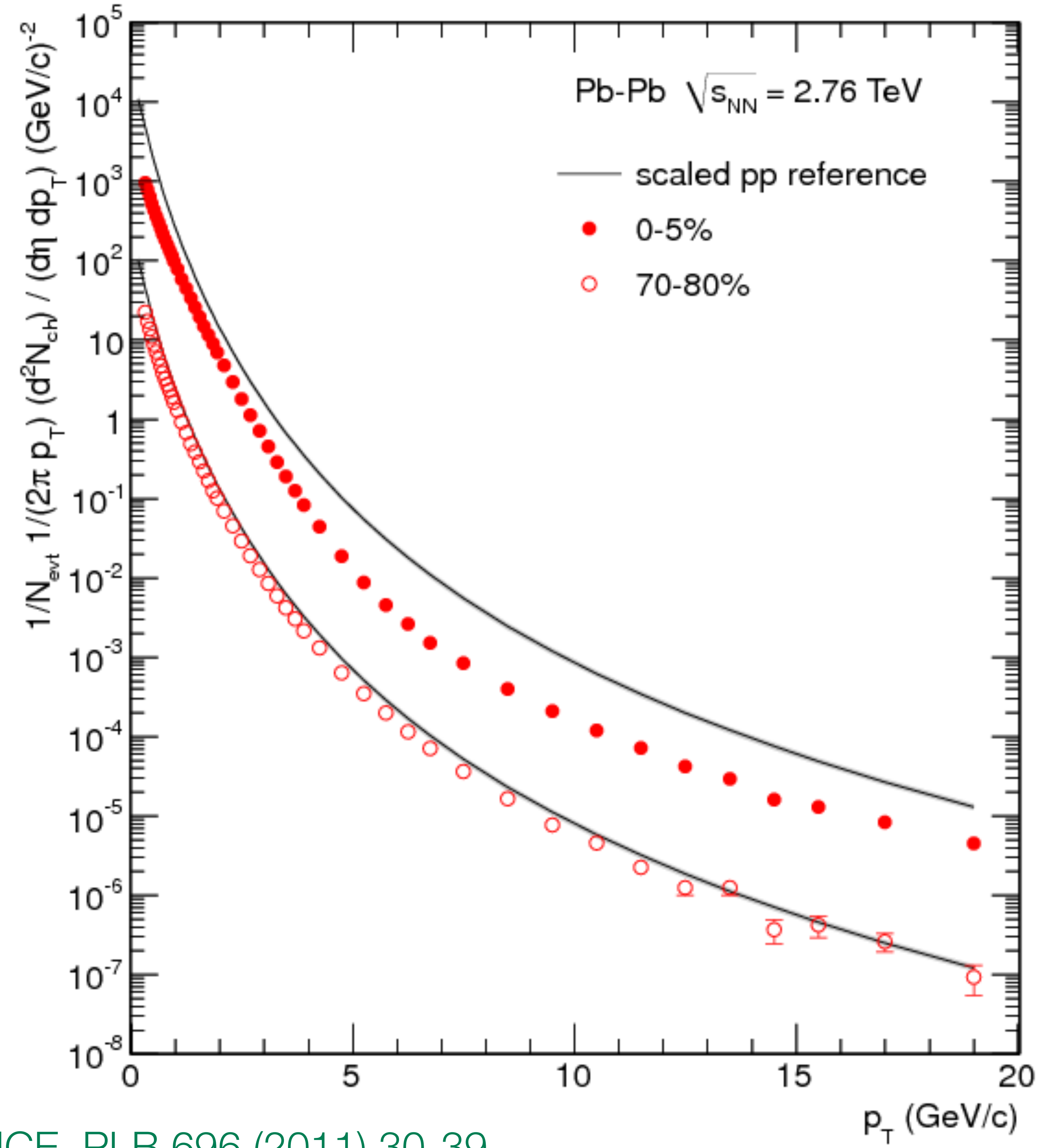


EXPERIMENT	THEORY
$v_2(p_T) > 0$	$v_2(p_T) > 0$
$R_{pPb} \approx 1$	$R_{pPb} < 1$

- Models with parton energy loss in a medium require both finite v_2 at high p_T and $R_{pPb} < 1$
  - Not supported by data
- **Other mechanisms responsible for the finite v_2 at high p_T ?**

AA vs. pp collisions

- Within the QGP studies, the **pp** (and p-Pb) **collisions** are used as a **medium-free reference**
- Example: modification of the p_T spectra by the medium

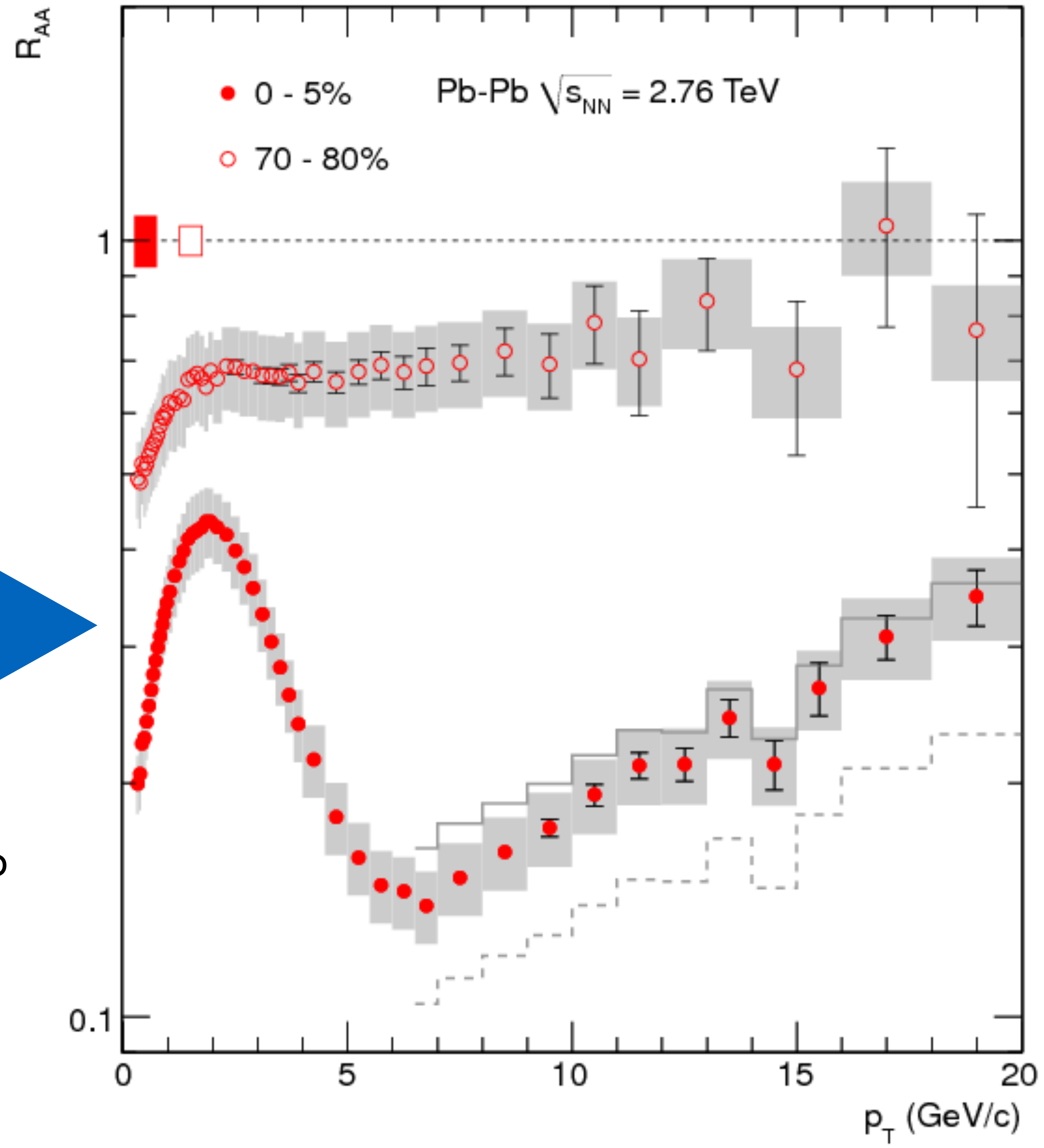


ALICE, PLB 696 (2011) 30-39

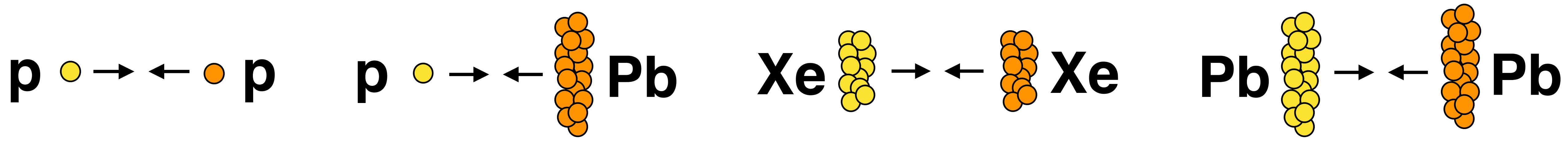
$$R_{AA} = \frac{\text{spectrum in Pb} - \text{Pb}}{\langle N_{coll}\rangle\ \text{spectrum in pp}}$$

Number of binary collisions

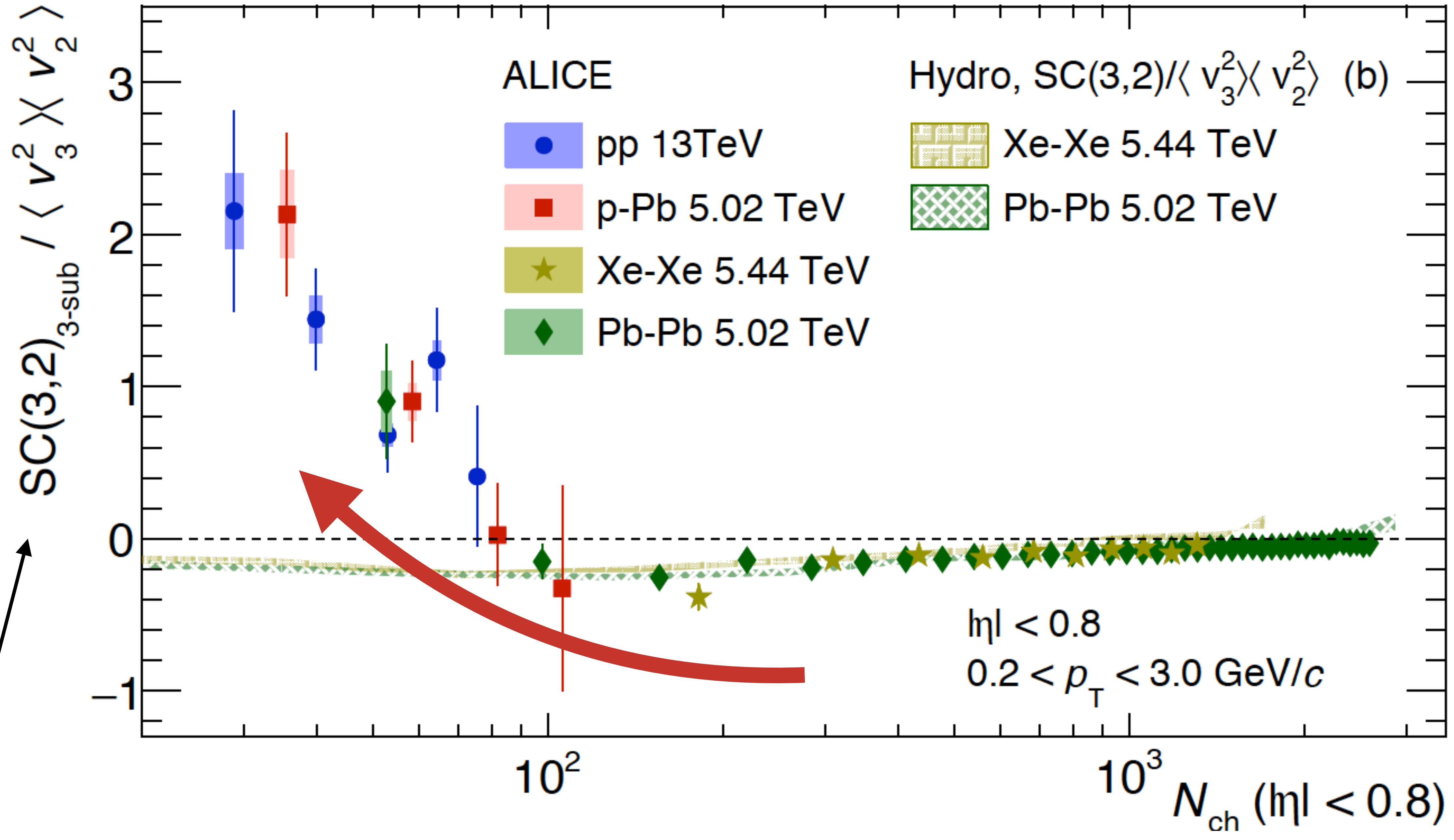
$R_{AA} < 1$ Presence of the QGP



Common origin, just evolving with N_{ch}?

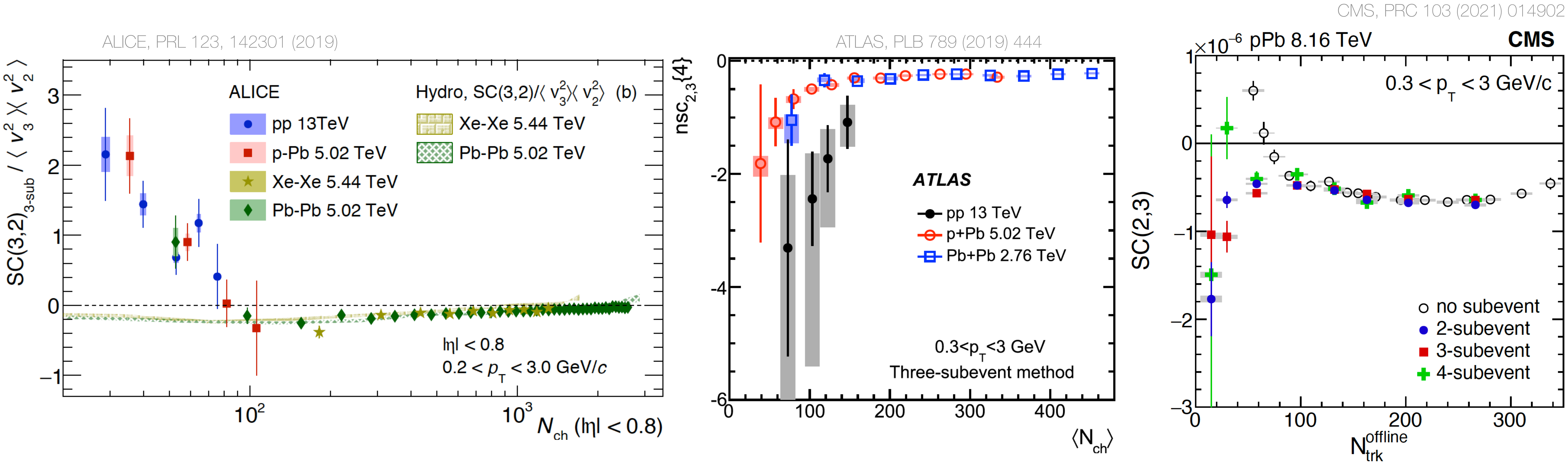


ALICE, PRL 123, 142301 (2019)



correlation between v_2 and v_3

- Symmetric Cumulants SC(n,m)
  - Correlation between v_n and v_m
  - The trend in the dependence on N_{ch} tends to be persistent from large to small collision systems (from large to small N_{ch})
- Whatever the correct description is, it seems that we have **smooth evolution with multiplicity**



- Note: the trend at low multiplicities is different for ALICE and ATLAS & CMS -> probably due to different acceptance and subsequent decorrelation effects and/or residual non-flow

Anisotropic flow - measurement method

- Using m-particle correlations we measure moments (cumulants) of the v_n distribution

Order of correlations used

2-particle correlation

$$\langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle = \langle\langle 2 \rangle\rangle = \langle v_n^2 \rangle \qquad \sqrt{\langle v_n^2 \rangle} = v_n\{2\}$$

assuming contamination has been removed

4-particle correlation

$$\langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle = \langle\langle 4 \rangle\rangle \qquad \sqrt[4]{-c_n\{4\}} = v_n\{4\}$$

$$\langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2 = c_2\{4\}$$

We use *cumulant* to get genuine 4-particle correlation

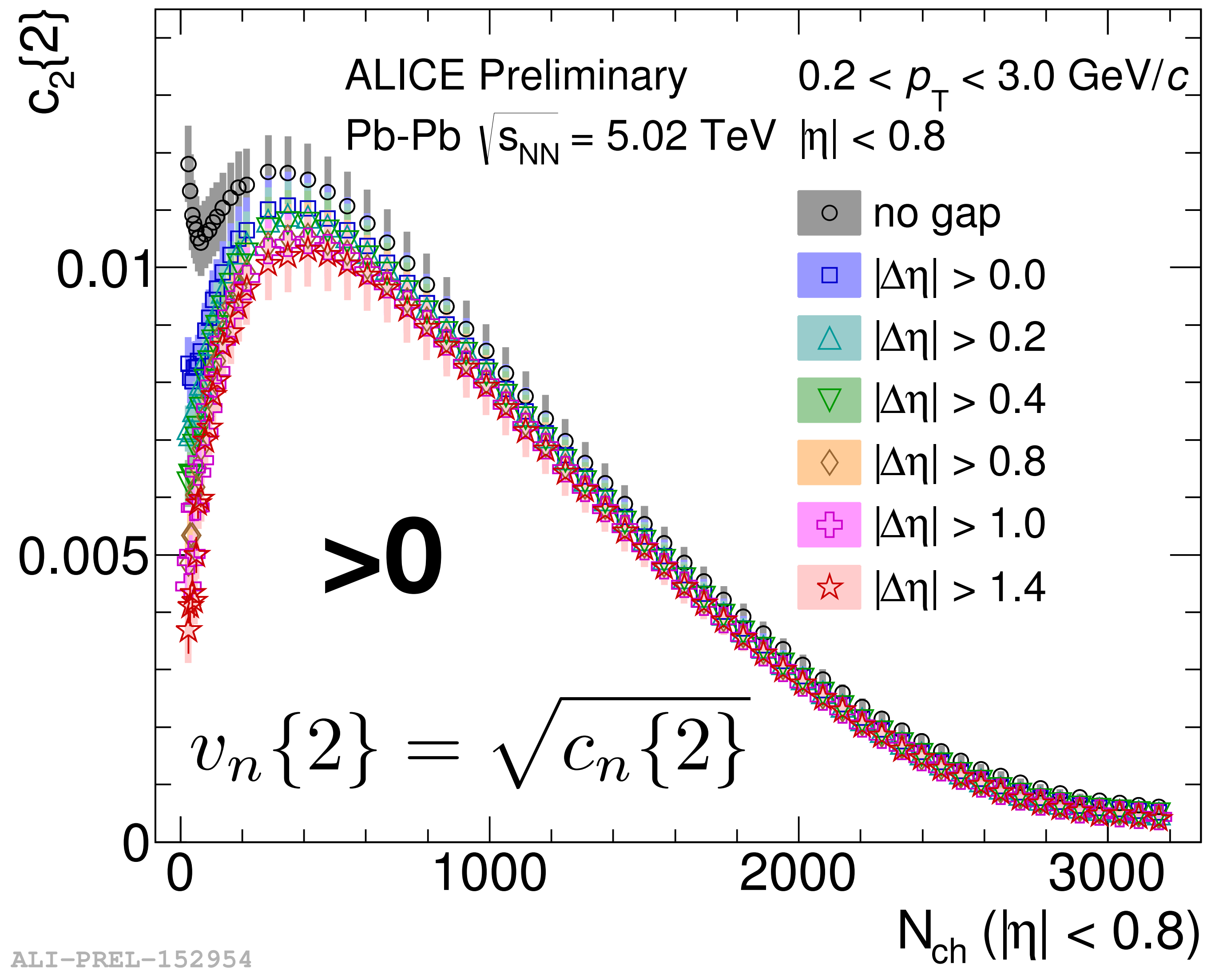
- Similarly for higher order correlations

$\sqrt{\langle v_n^2 \rangle} = v_n$ if the p.d.f. of v_n would be a delta function (no flow fluctuations)

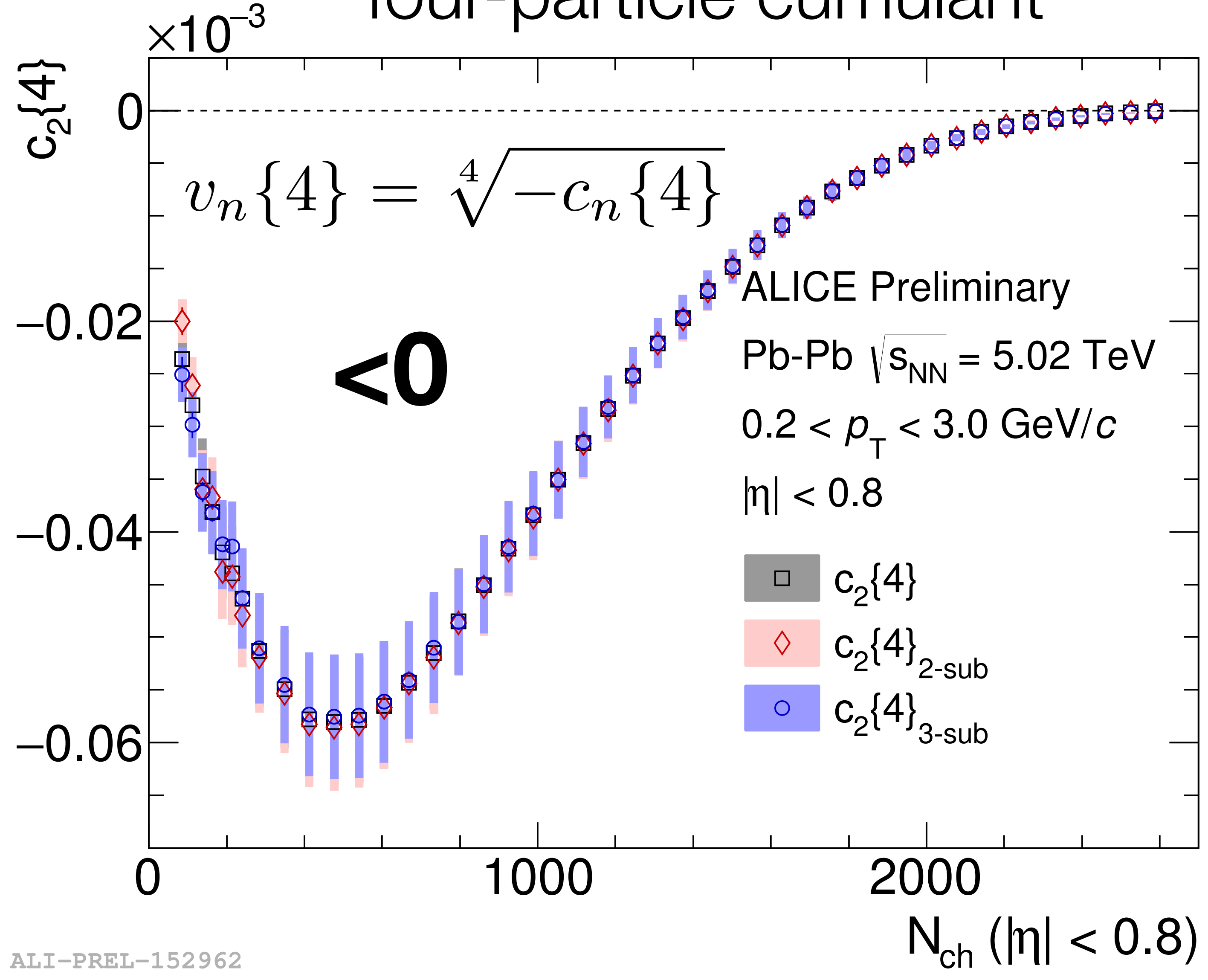
Multi-particle cumulants in Pb-Pb collisions

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

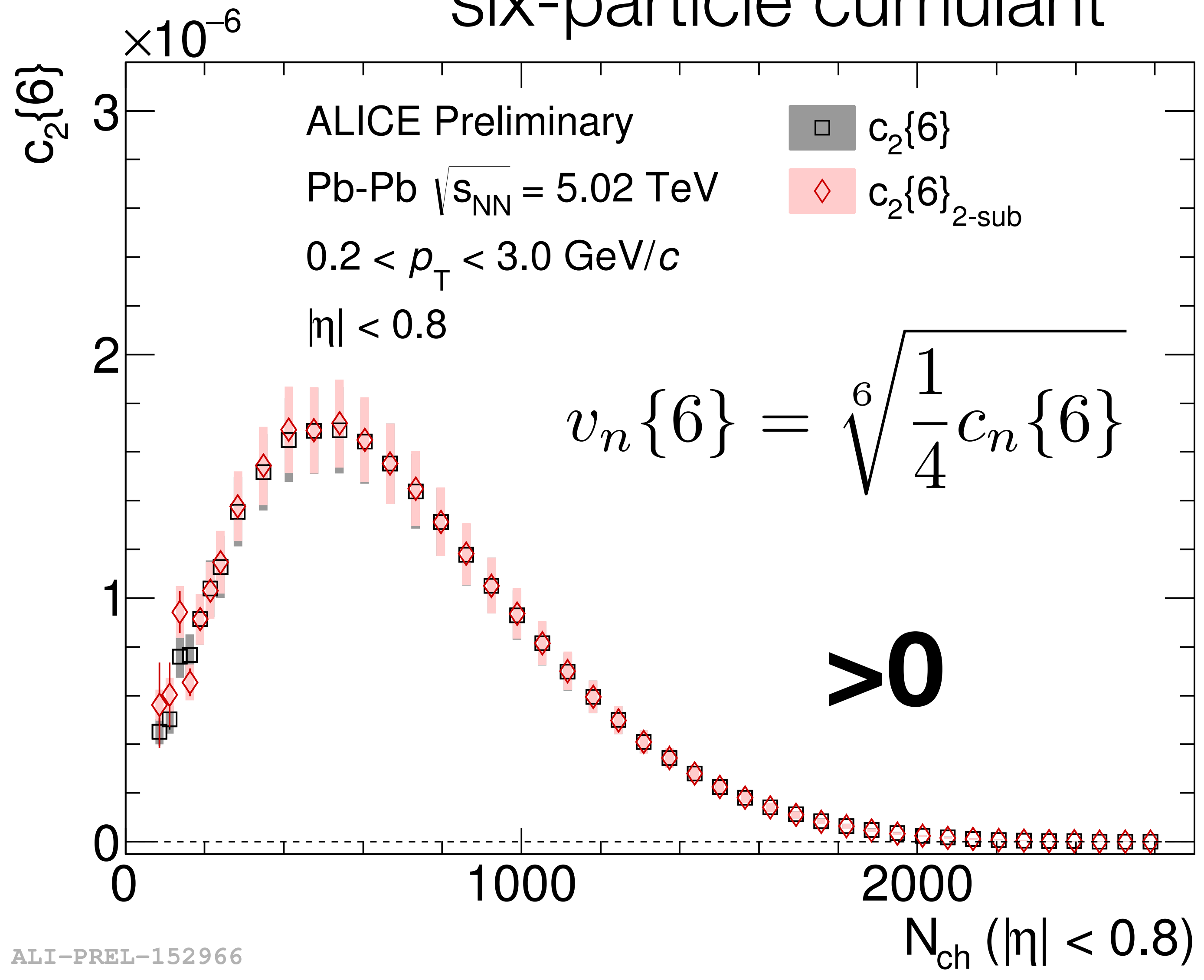
two-particle cumulant



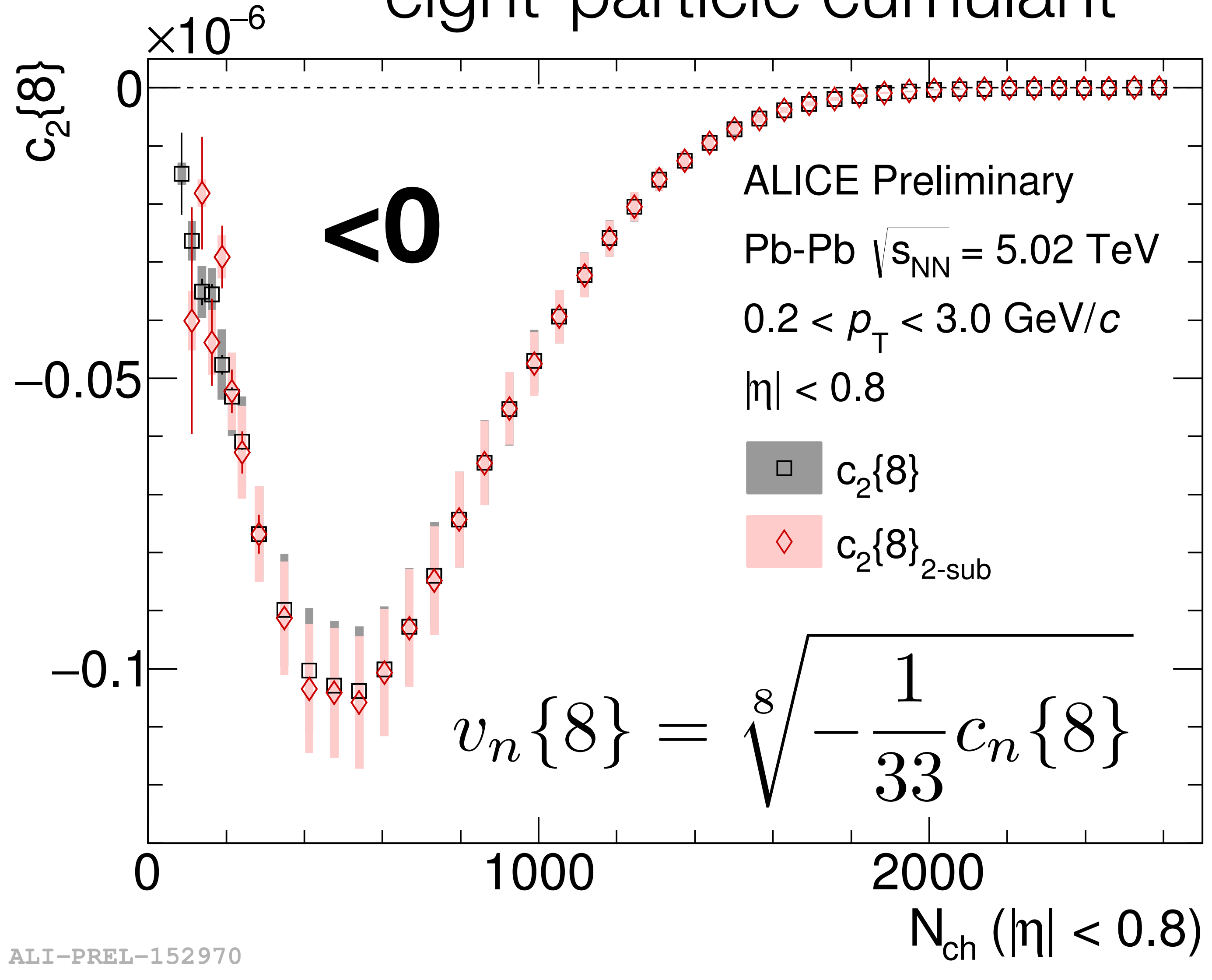
four-particle cumulant



six-particle cumulant

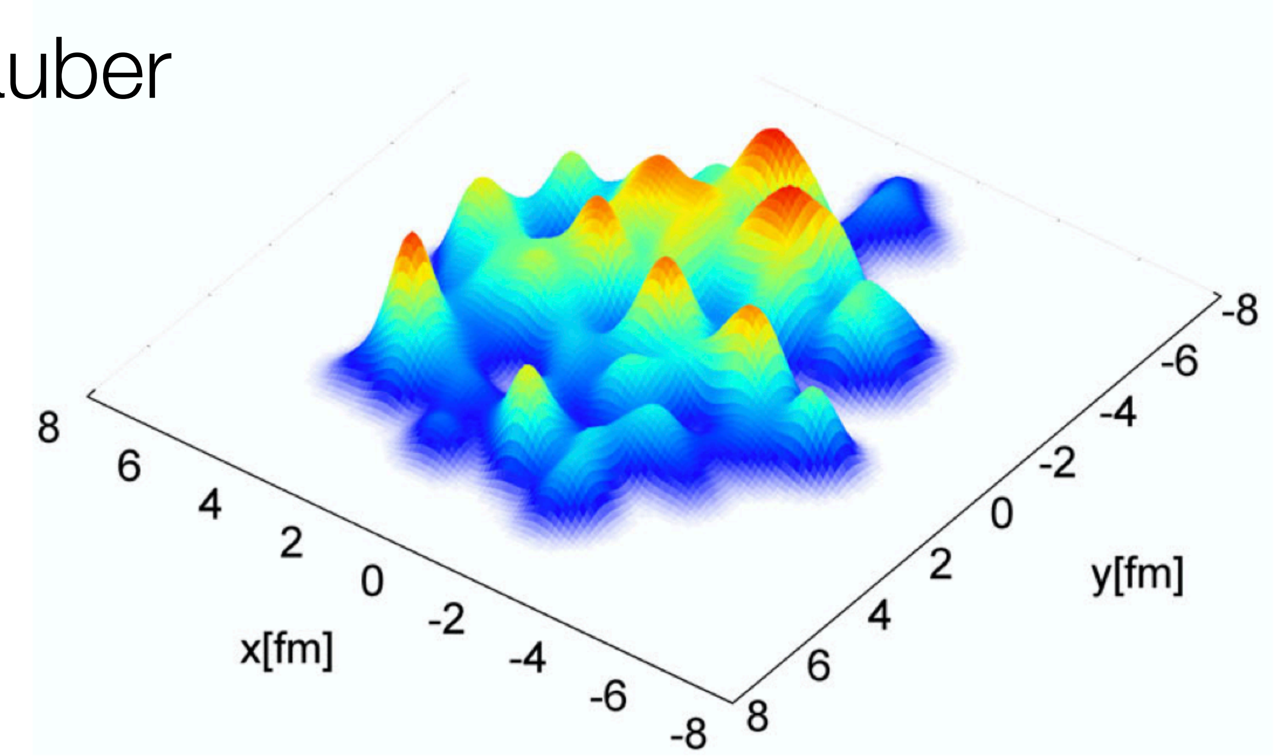


eight-particle cumulant

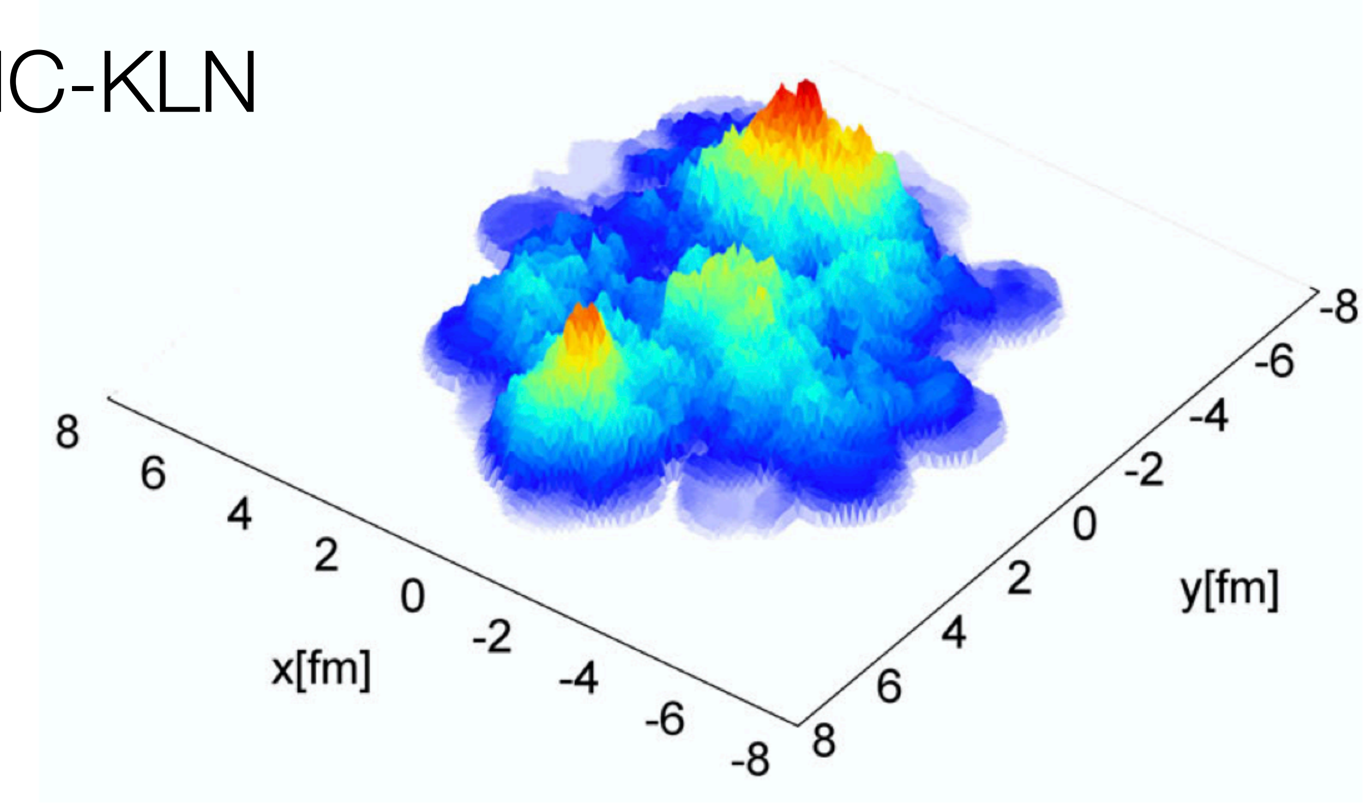


Anisotropic flow - models

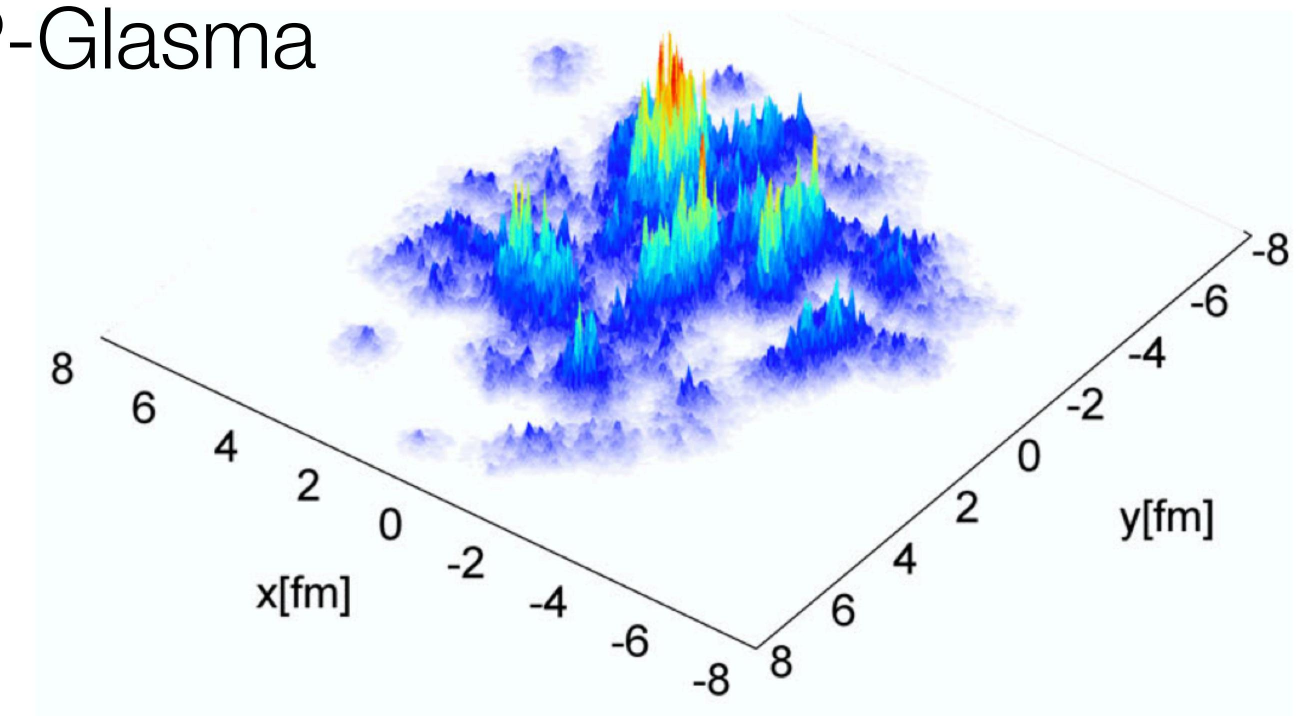
Glauber

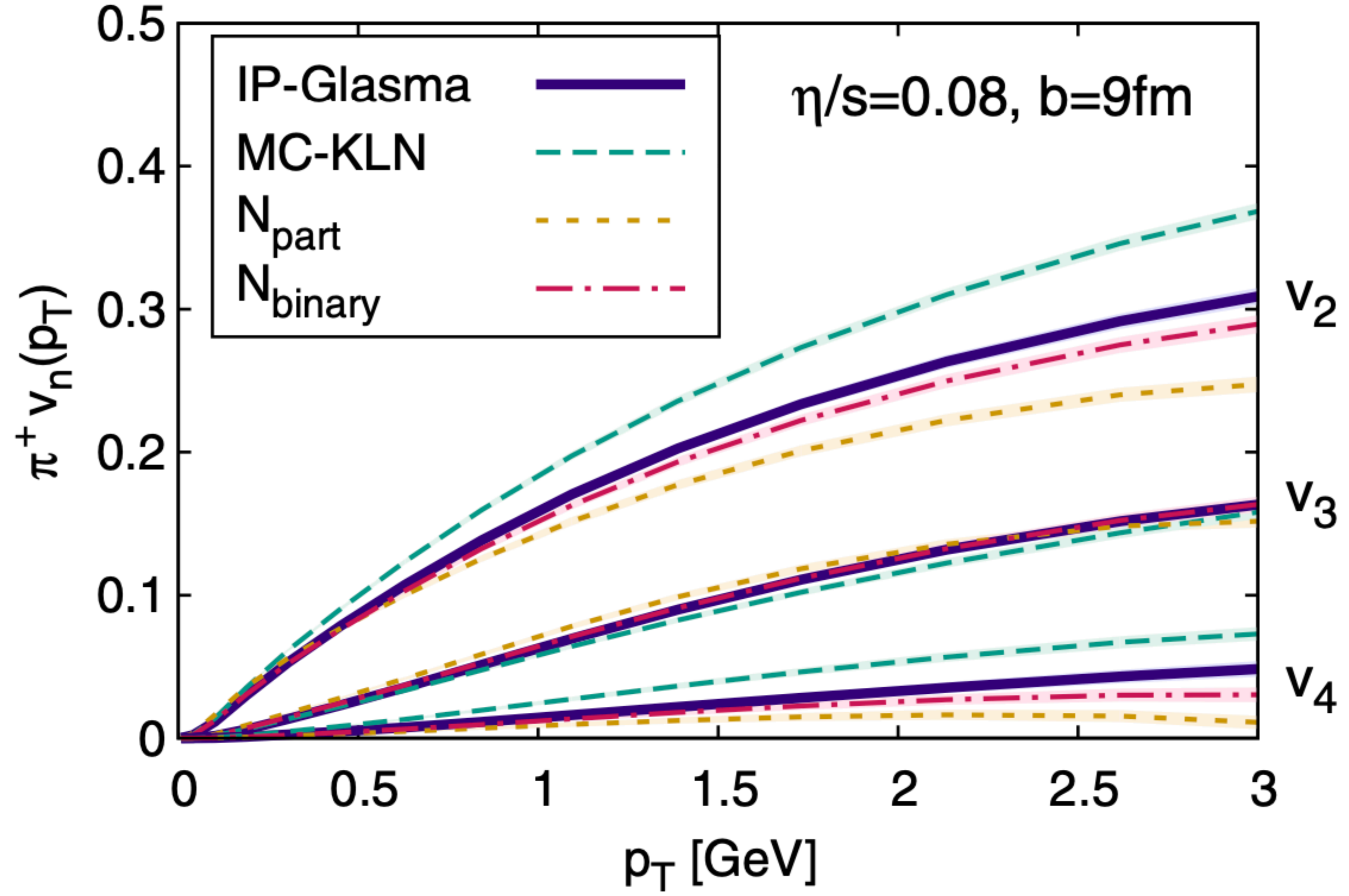


MC-KLN



IP-Glasma

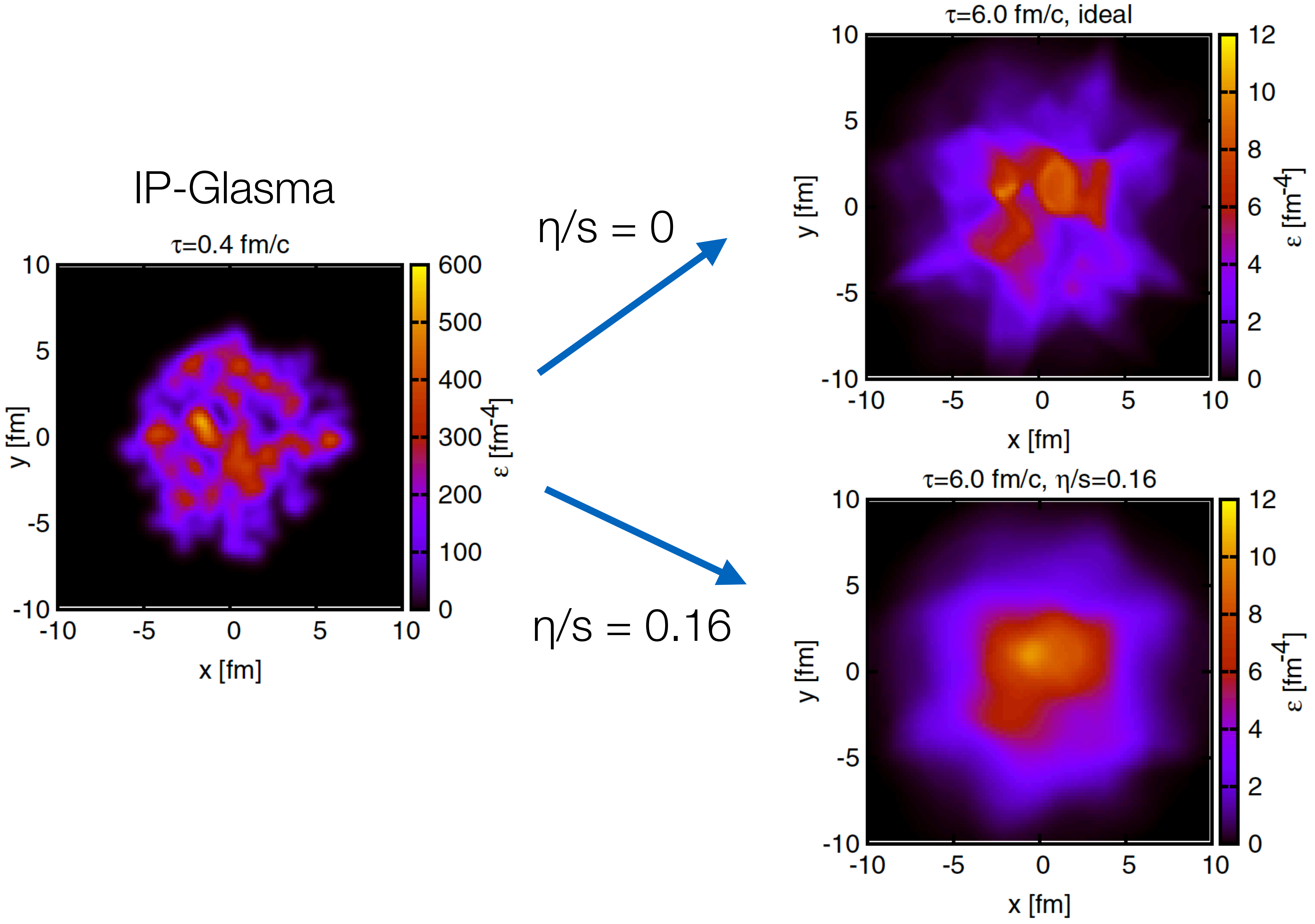


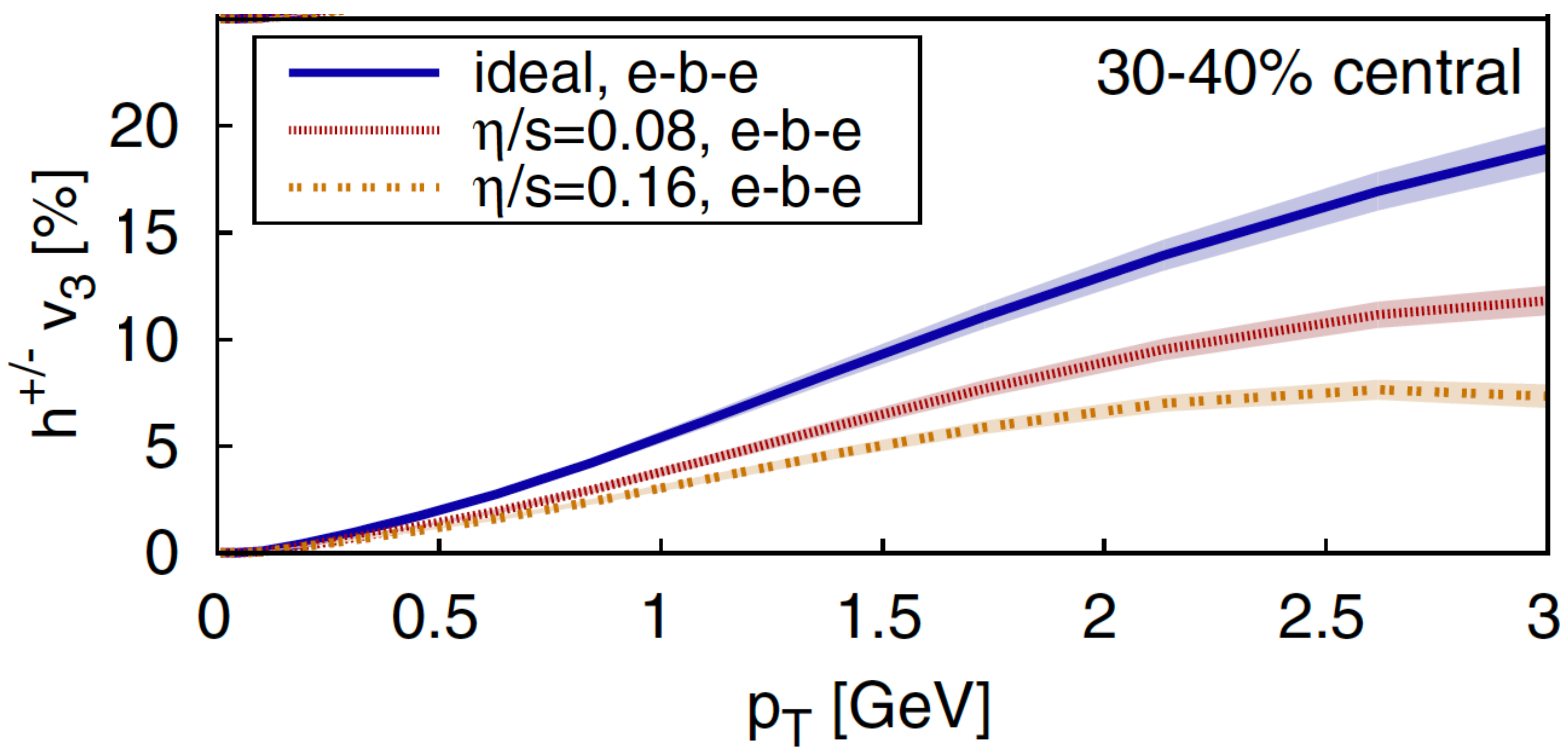


- Anisotropic flow is **sensitive to initial conditions** of heavy-ion collision
- Different models of initial conditions yield different starting energy density distribution
  - Different effect on the final flow

Schenke, Tribedy, Venugopalan, PRL 108, 252301 (2012)

Anisotropic flow - models



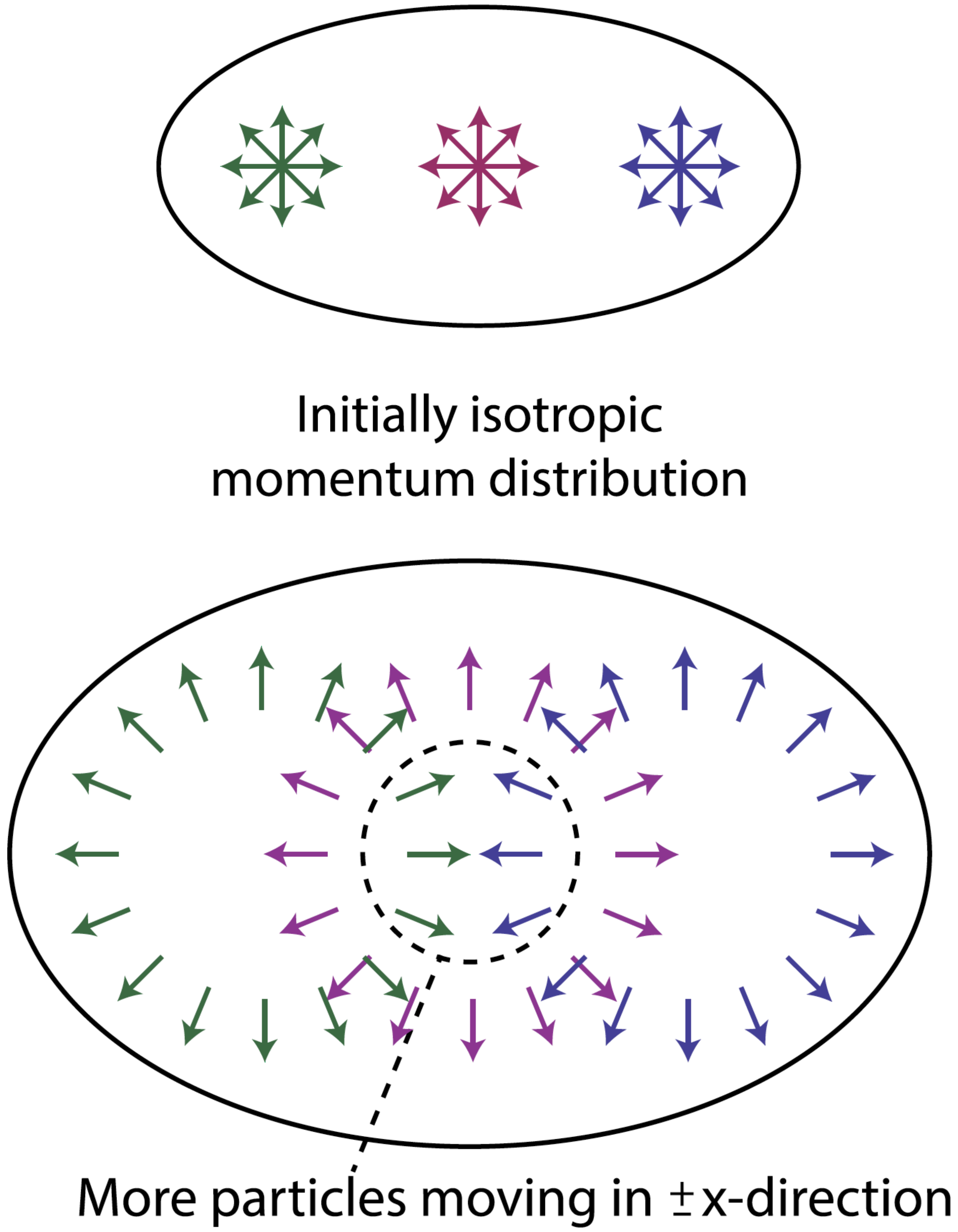


- Anisotropic flow **sensitive to transport properties of the QGP** (η/s)
- **Large** η/s -> **small** anisotropic flow
- **Small** η/s -> **large** anisotropic flow

Schenke, Jeon, Gale, PRL 106, 042301 (2011)

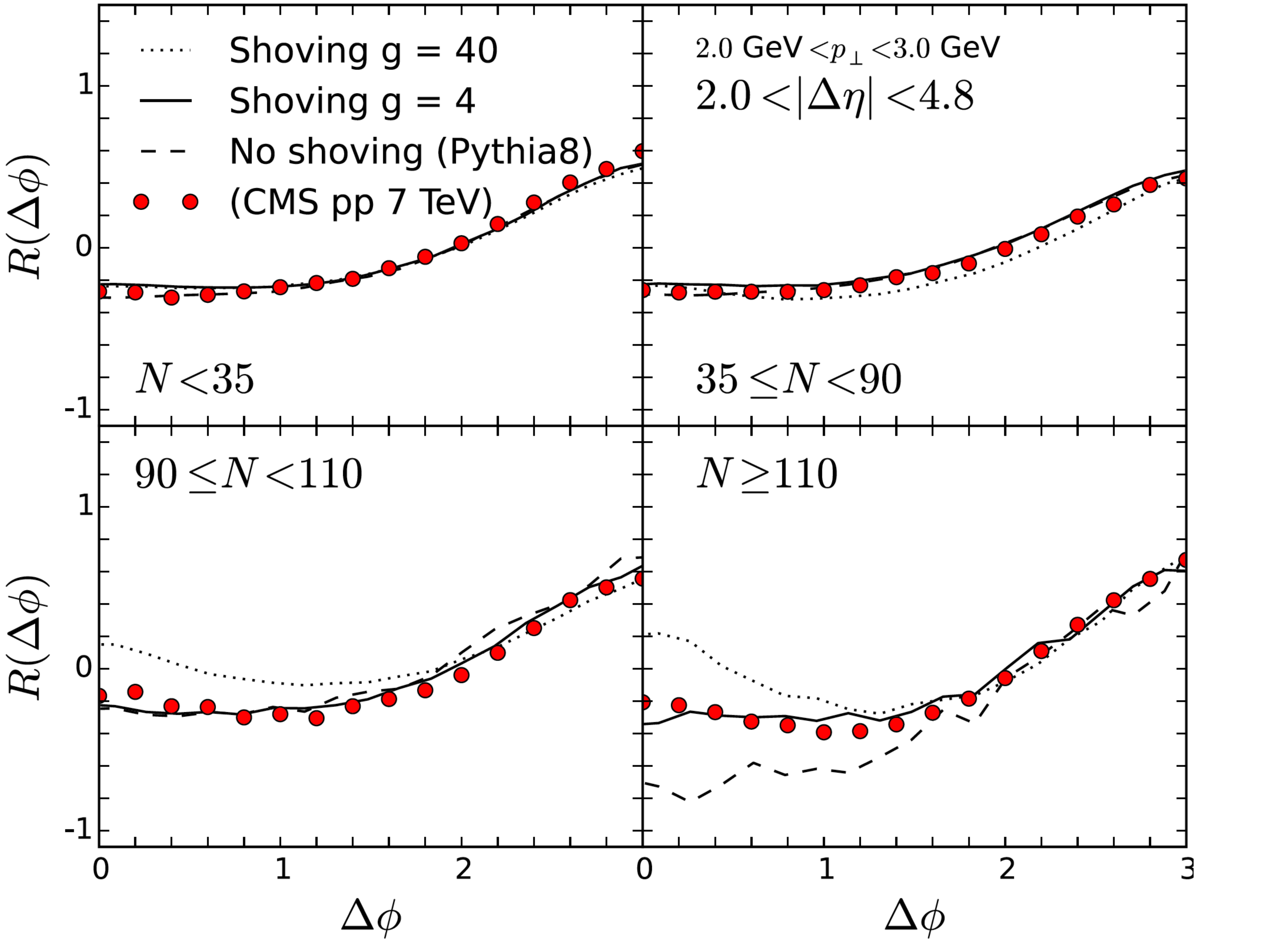
Microscopic model approaches?

- Within a **transport theory**, collectivity (global momentum space anisotropies) can be achieved via scatterings of free-streaming particles



A. Kurkela et al, PLB 783 (2018) 274-279

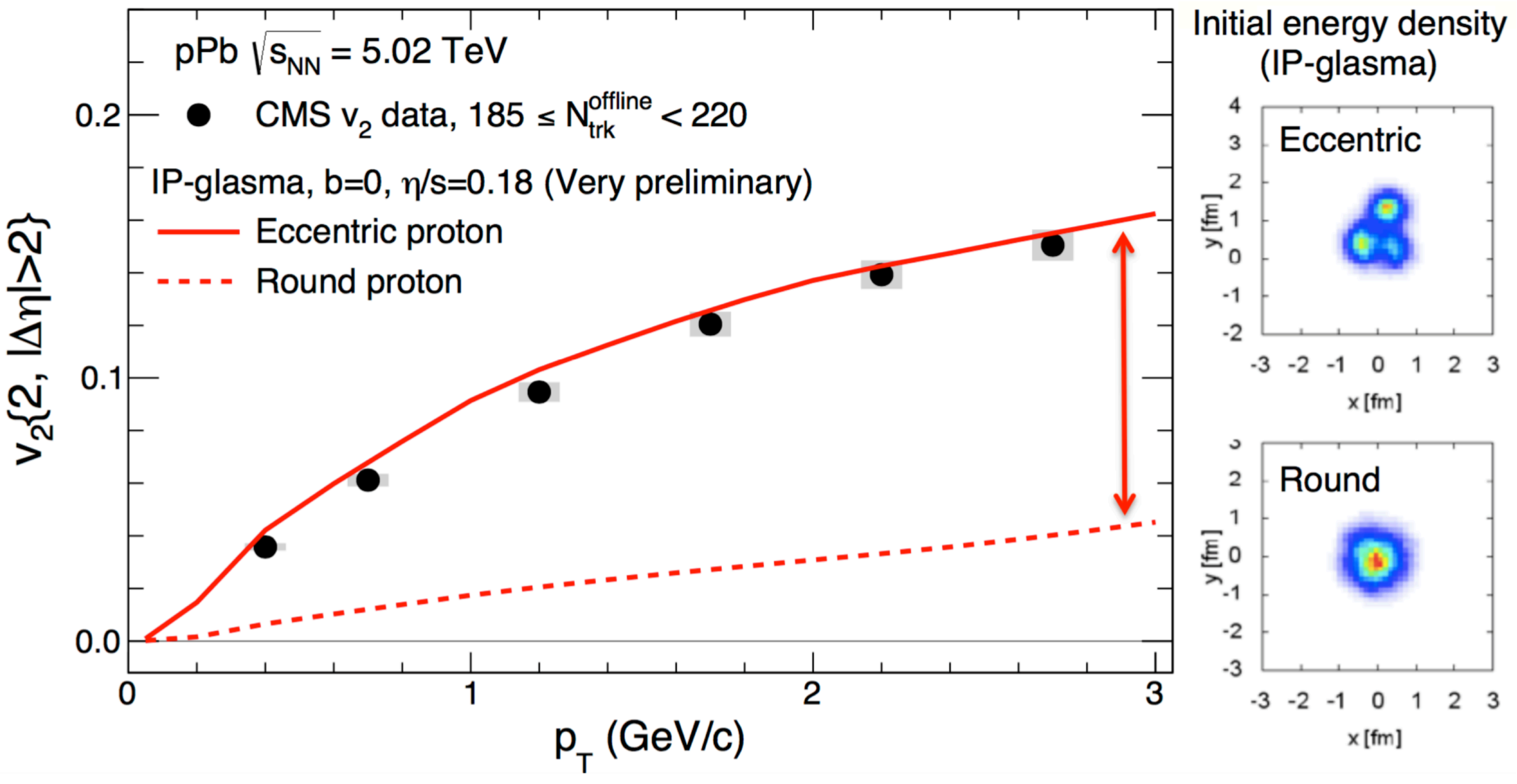
- The near-side ridge can be described by strongly interacting **overlapping strings** within PYTHIA model (shoving mechanism)



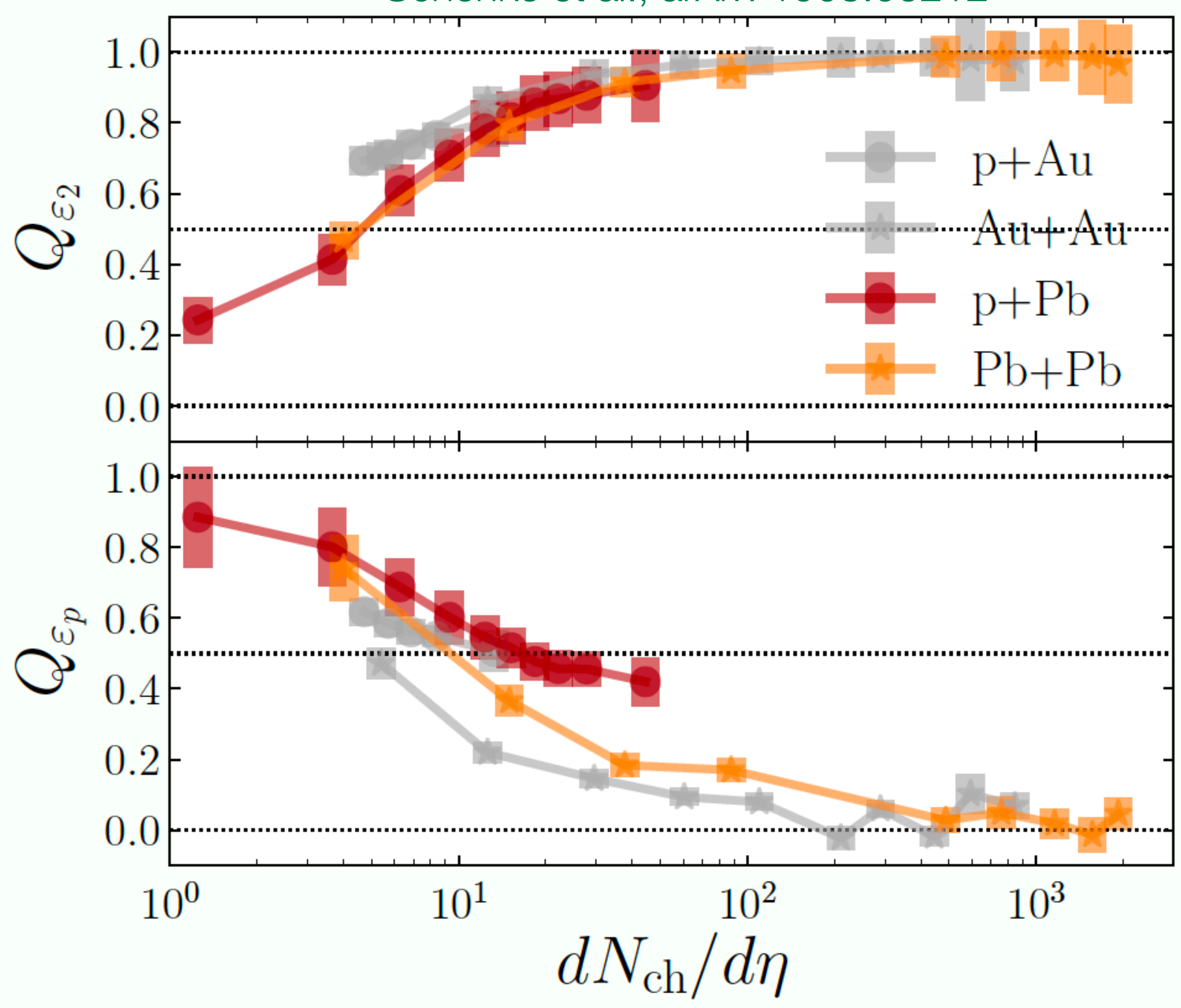
C. Bierlich et al, PLB 779 (2018) 58-63

Influence of the IS correlations

Schenke, SQM 2016



Schenke et al.,QM19
Schenke et al., arXiv: 1908.06212

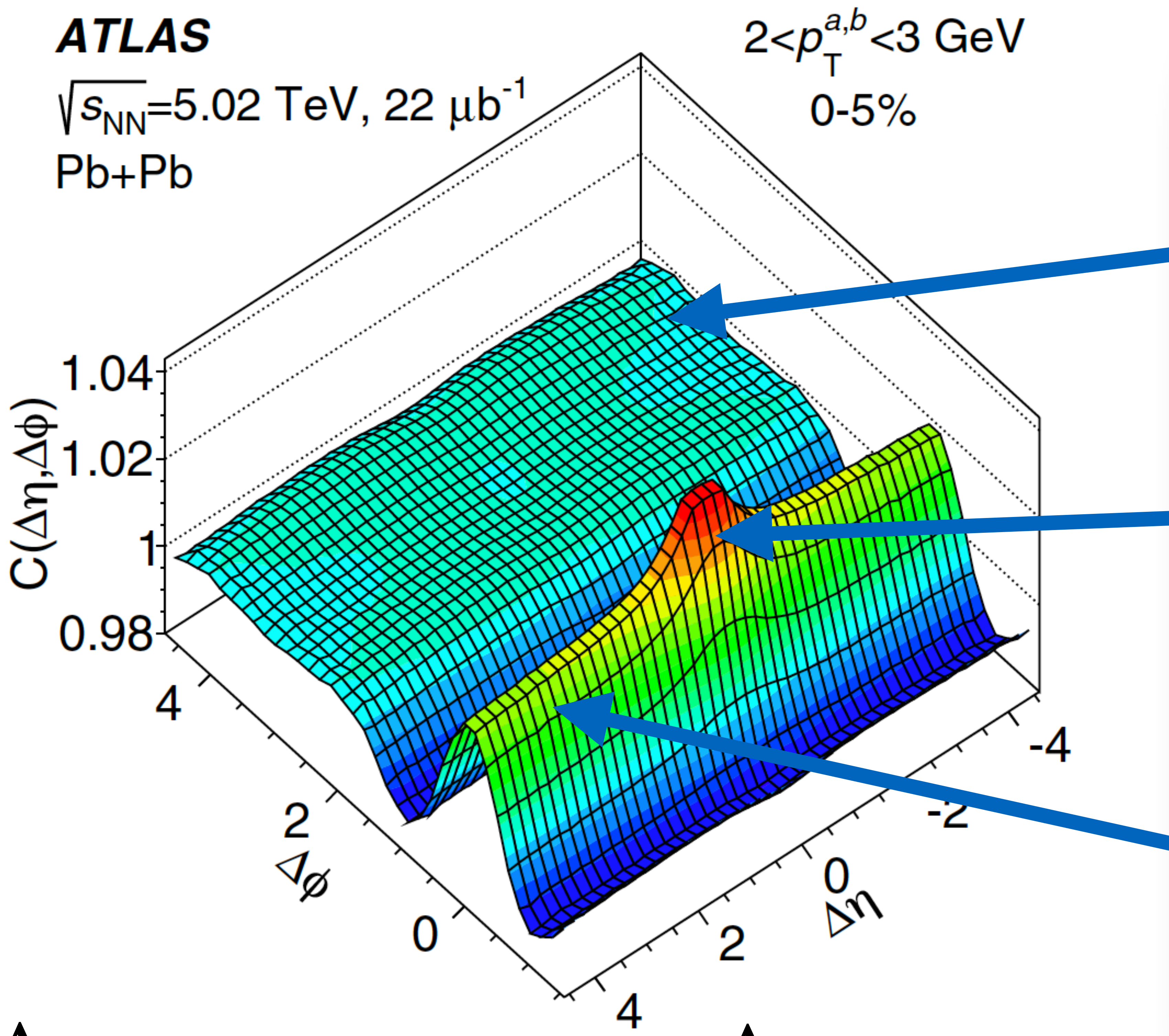


- Proton substructure becomes crucial to achieve correct data description
- Initial (gluon momentum) flow important in small systems (low N_{ch})
- Initial (spatial) geometery important in large systems (large N_{ch}) - “standard” hydro picture

$$Q_{\varepsilon_2} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_2 \cdot \vec{V}_2^{*} \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_2|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

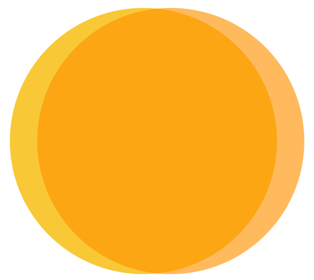
$$Q_{\varepsilon_p} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_p \cdot \vec{V}_2^{*} \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_p|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

Anisotropic flow - measurement method



$$\Delta\varphi = \varphi_1 - \varphi_2 \qquad \Delta\eta = \eta_1 - \eta_2$$

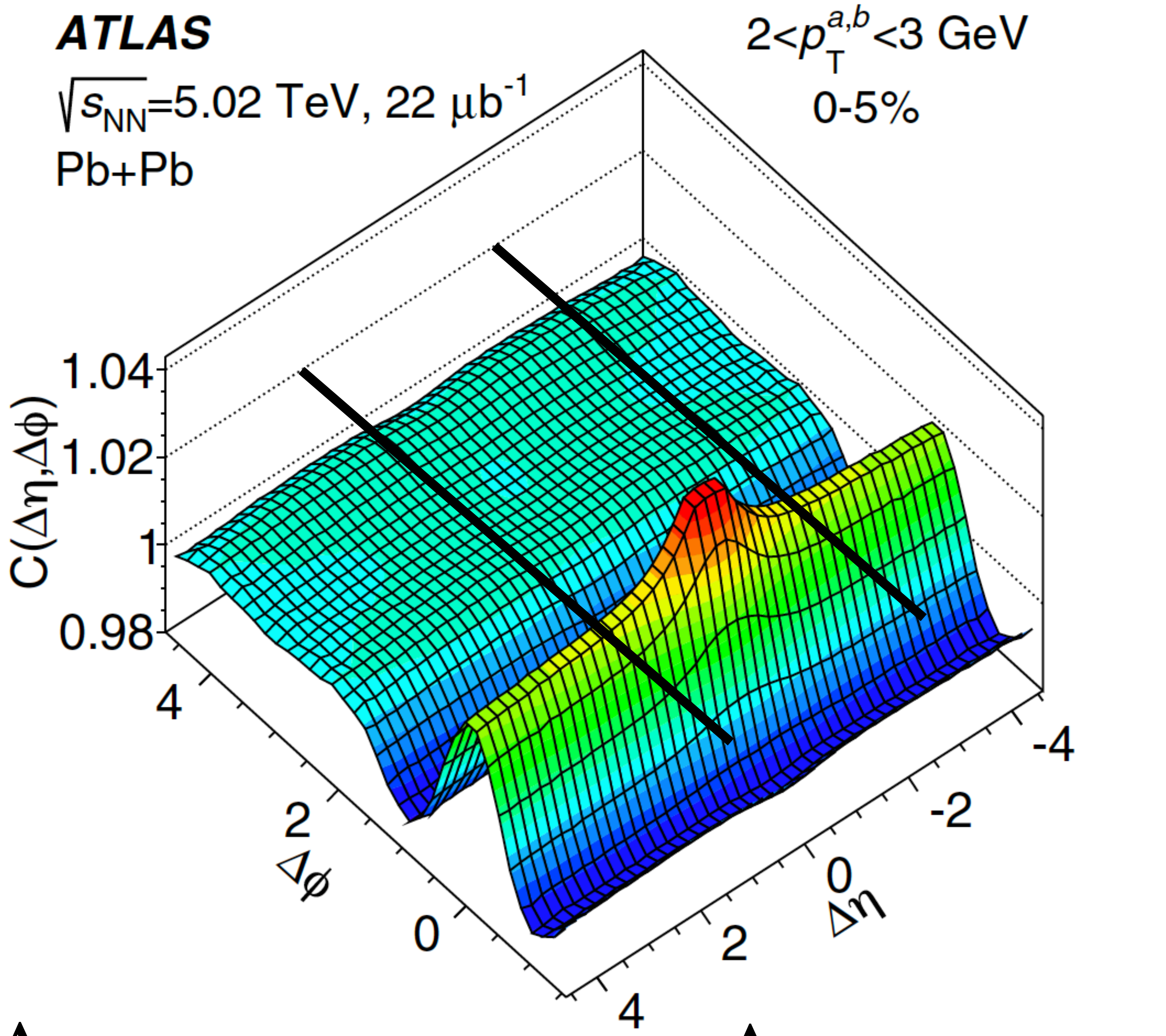
Away side region Jet + flow	$\Delta\varphi \approx \pi$	elongated in η
Near side region: peak Jet + resonances + … (Non-flow)	$\Delta\varphi \approx 0, \quad \Delta\eta \approx 0$	
Near side region: the ridge Flow	$\Delta\varphi \approx 0$	elongated in η



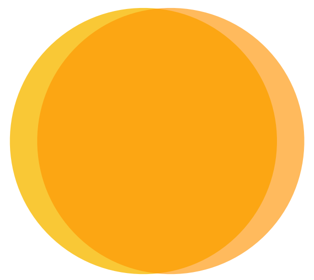
central collision

ATLAS, EPJC 78, 997 (2018)

Anisotropic flow - measurement method



$\Delta\varphi = \varphi_1 - \varphi_2$ $\Delta\eta = \eta_1 - \eta_2$

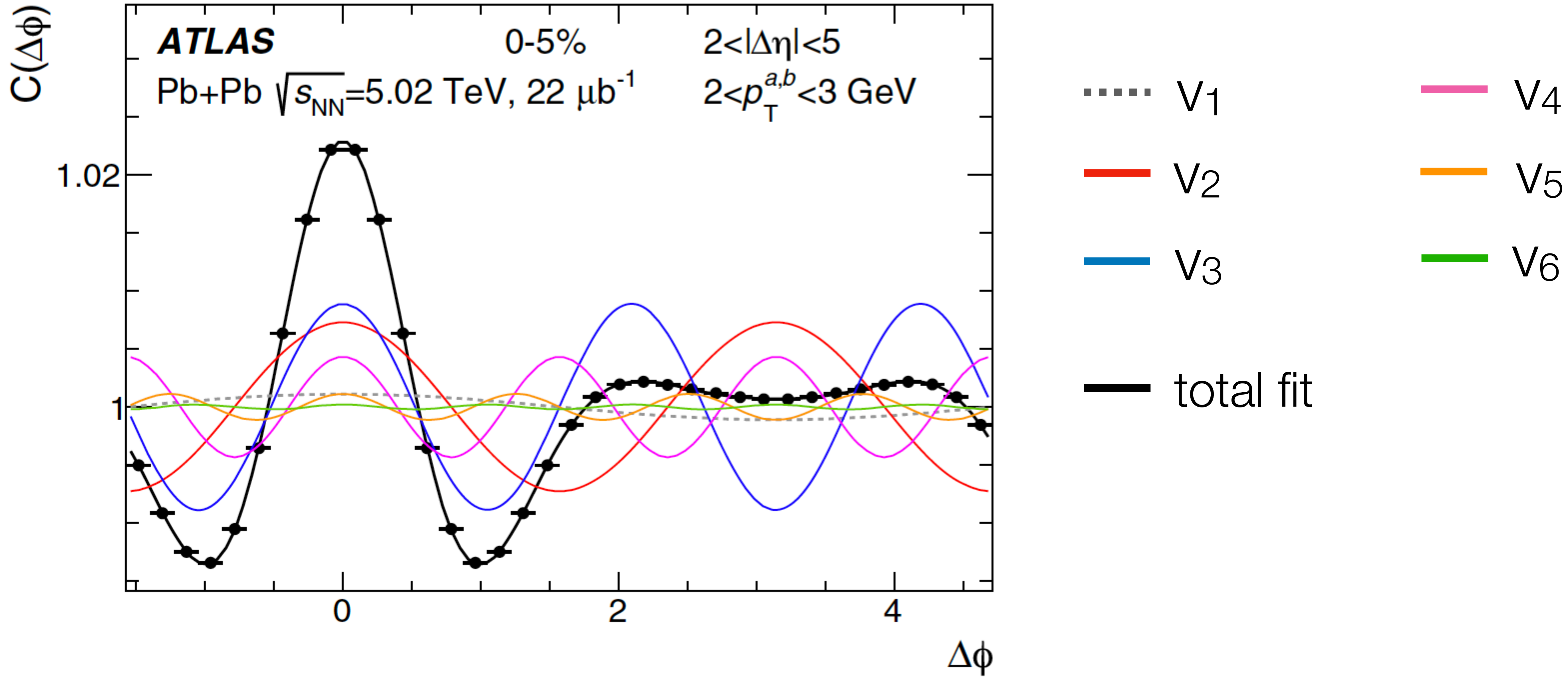


central collision

- The symmetry plane Ψ_n cannot be reliably measured -> we use particle correlations (using two or more particles)

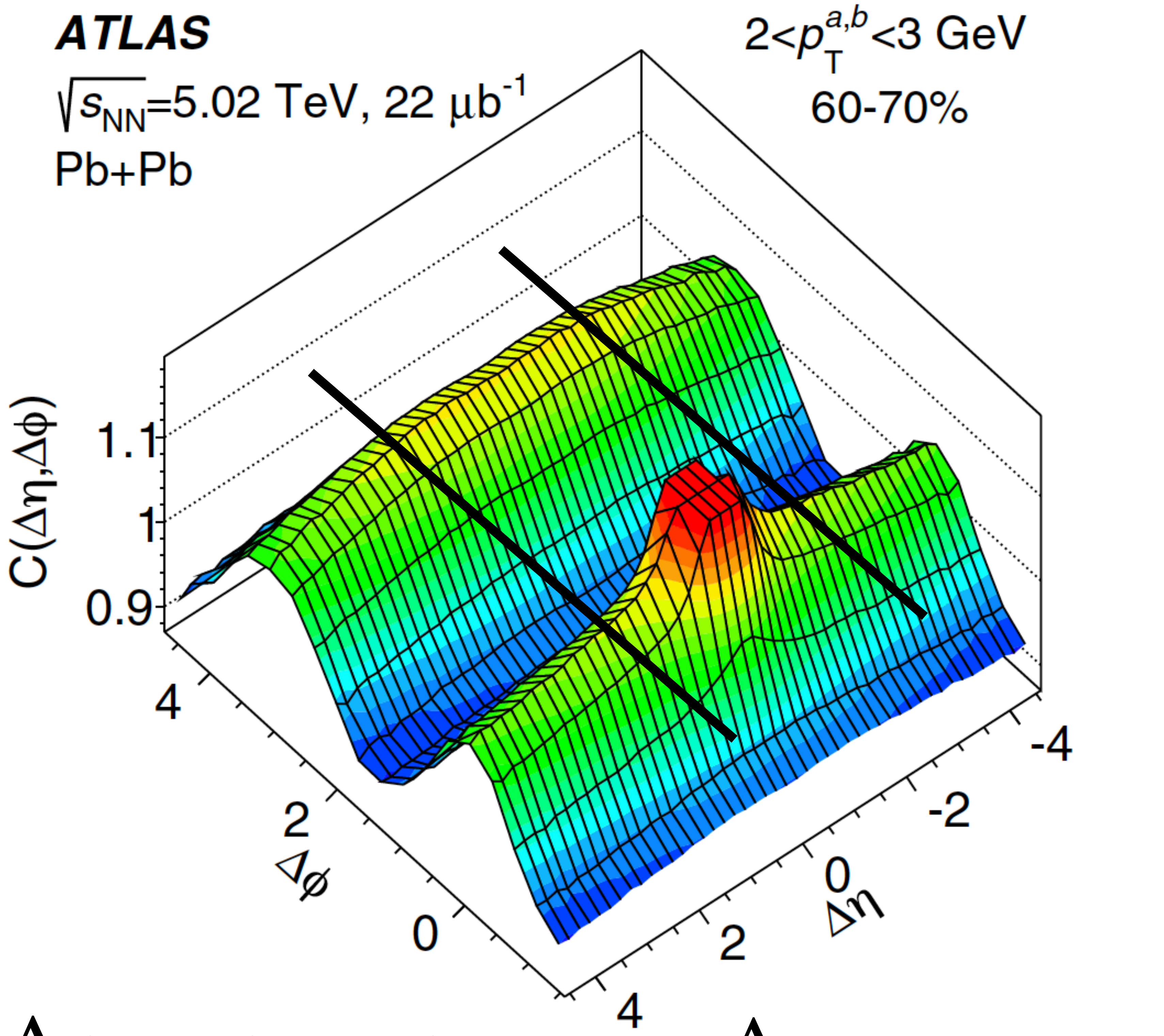
$$\langle v_n^2 \rangle = \langle\langle \cos(n\Delta\varphi) \rangle\rangle$$

- Example of a two-particle correlation
- Projection onto the azimuthal angle axis can be described by a Fourier series containing v_2 - v_6 flow harmonics



ATLAS, EPJC 78, 997 (2018)

Anisotropic flow - measurement method



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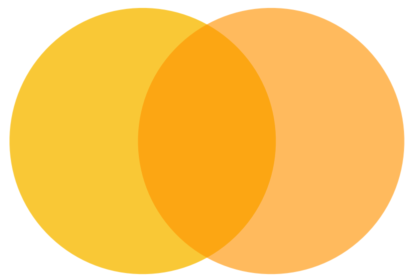

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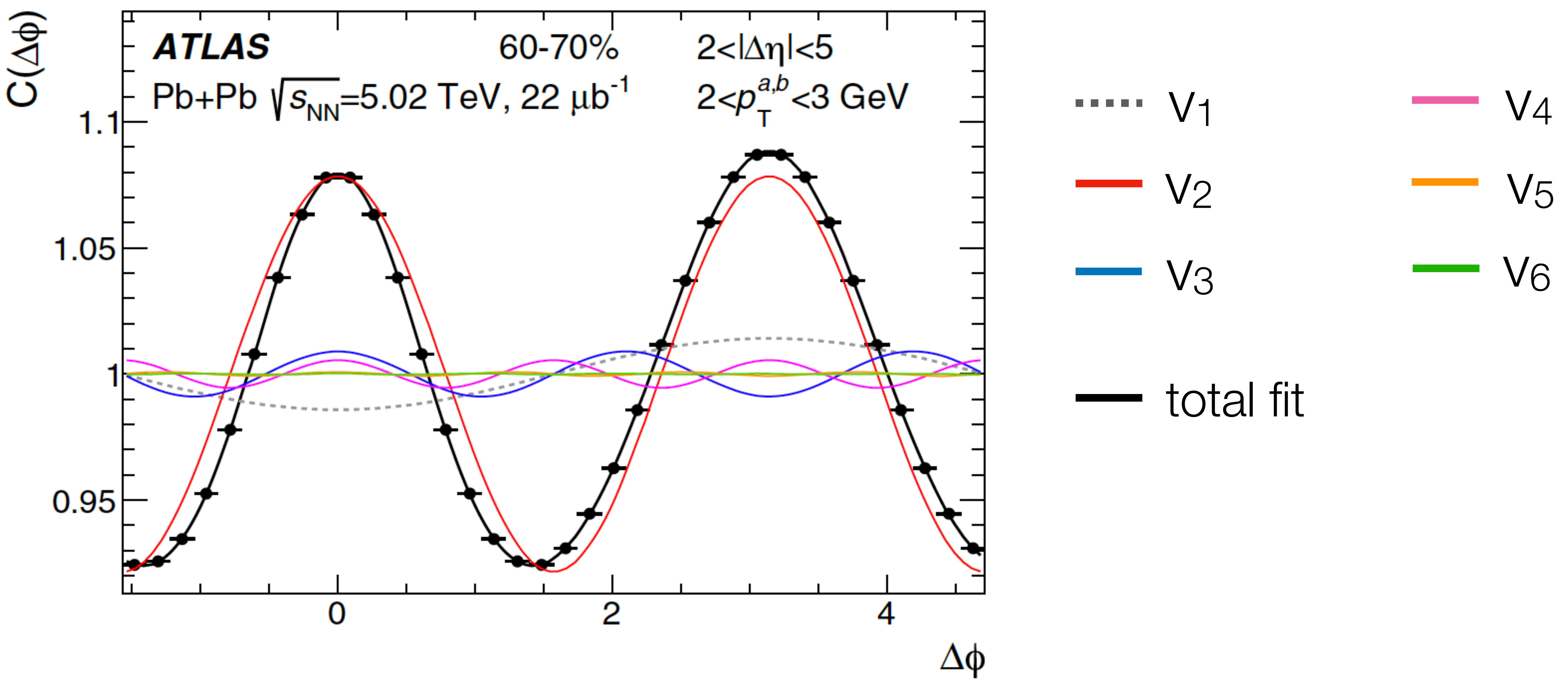
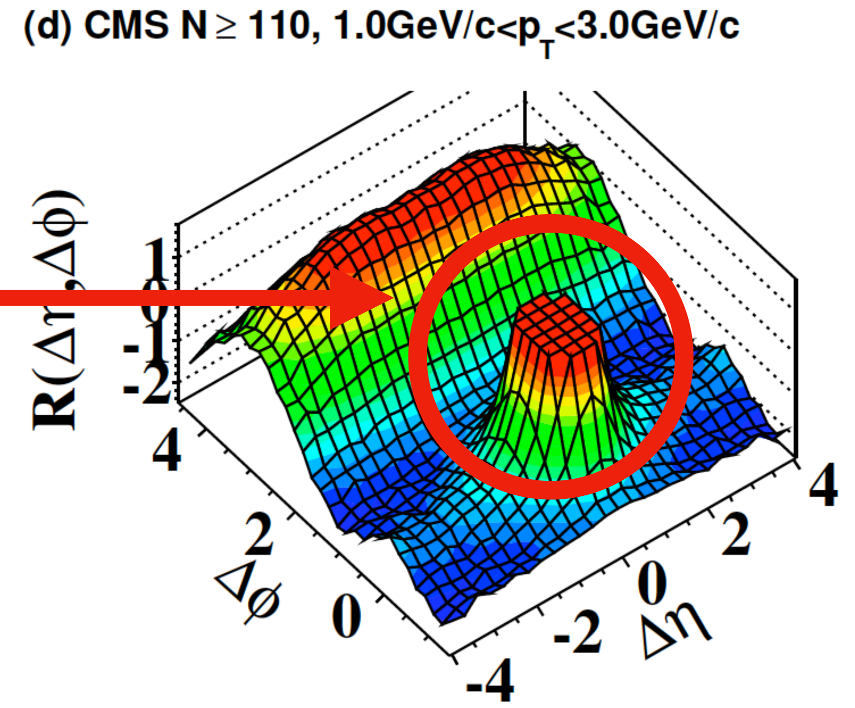


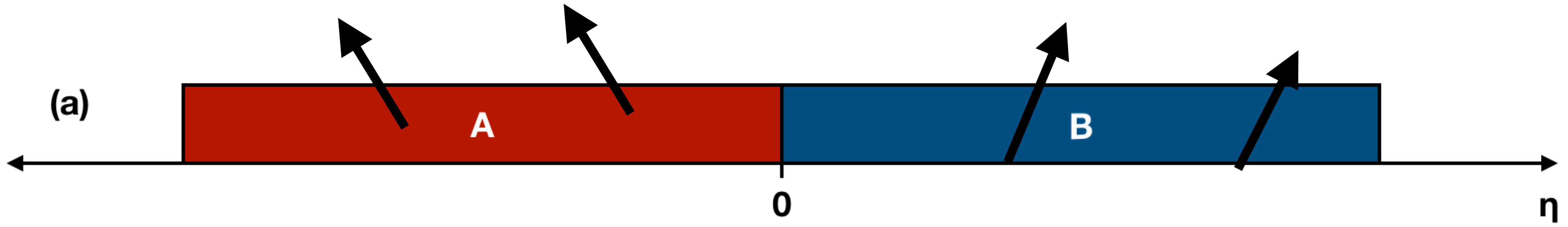
ATLAS, EPJC 78, 997 (2018)

Non-flow suppression

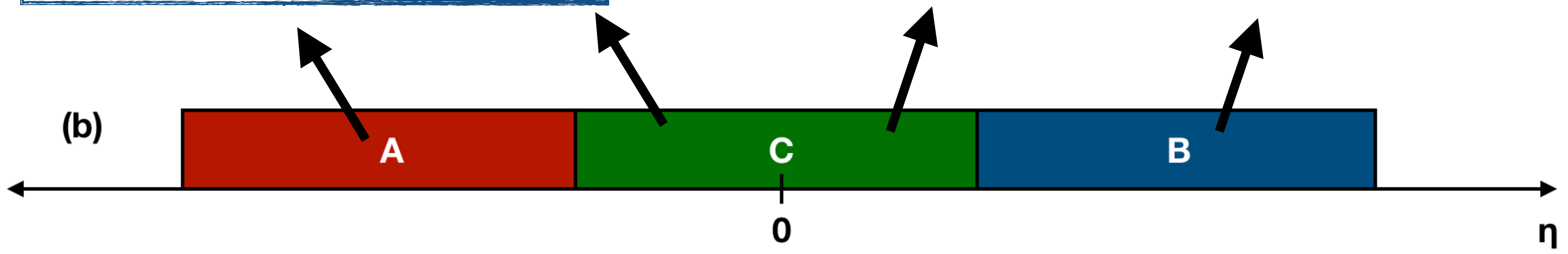


- Non-flow: correlations not associated with the common symmetry plane (jets, resonance decays, …)
- Subevent method: suppresses non-flow effects in m-particle correlations

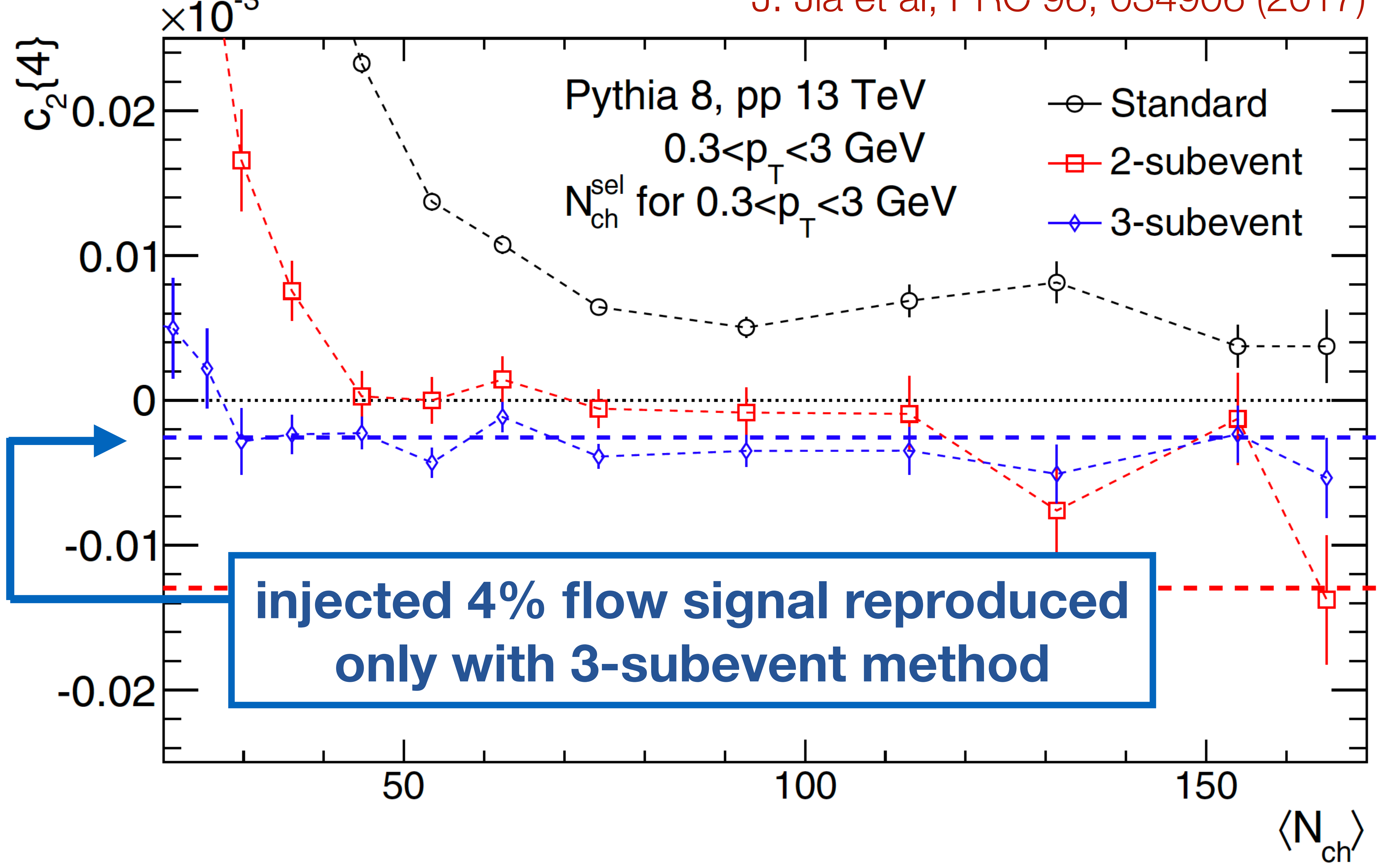
2-subevent method



3-subevent method

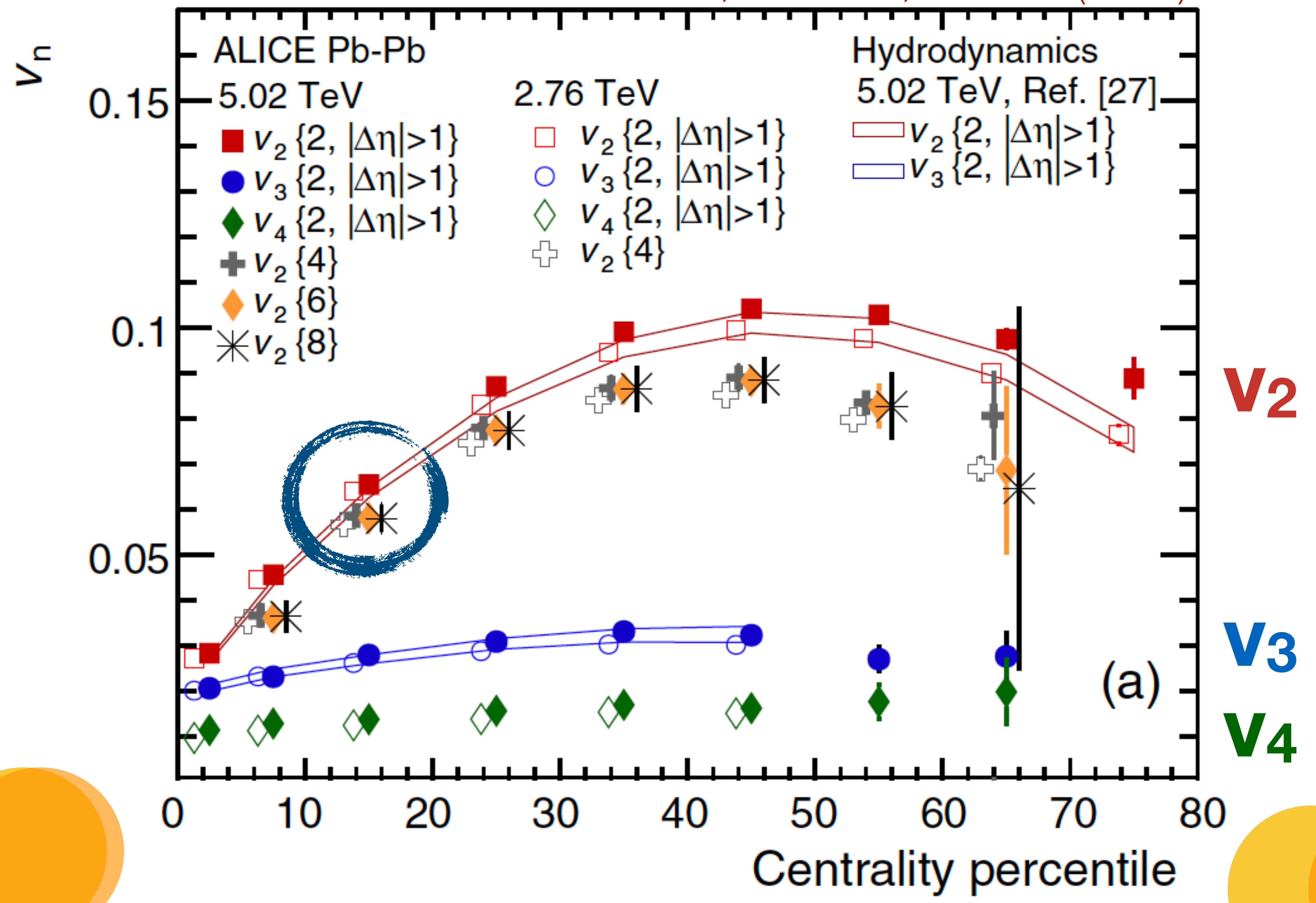


J. Jia et al, PRC 96, 034906 (2017)

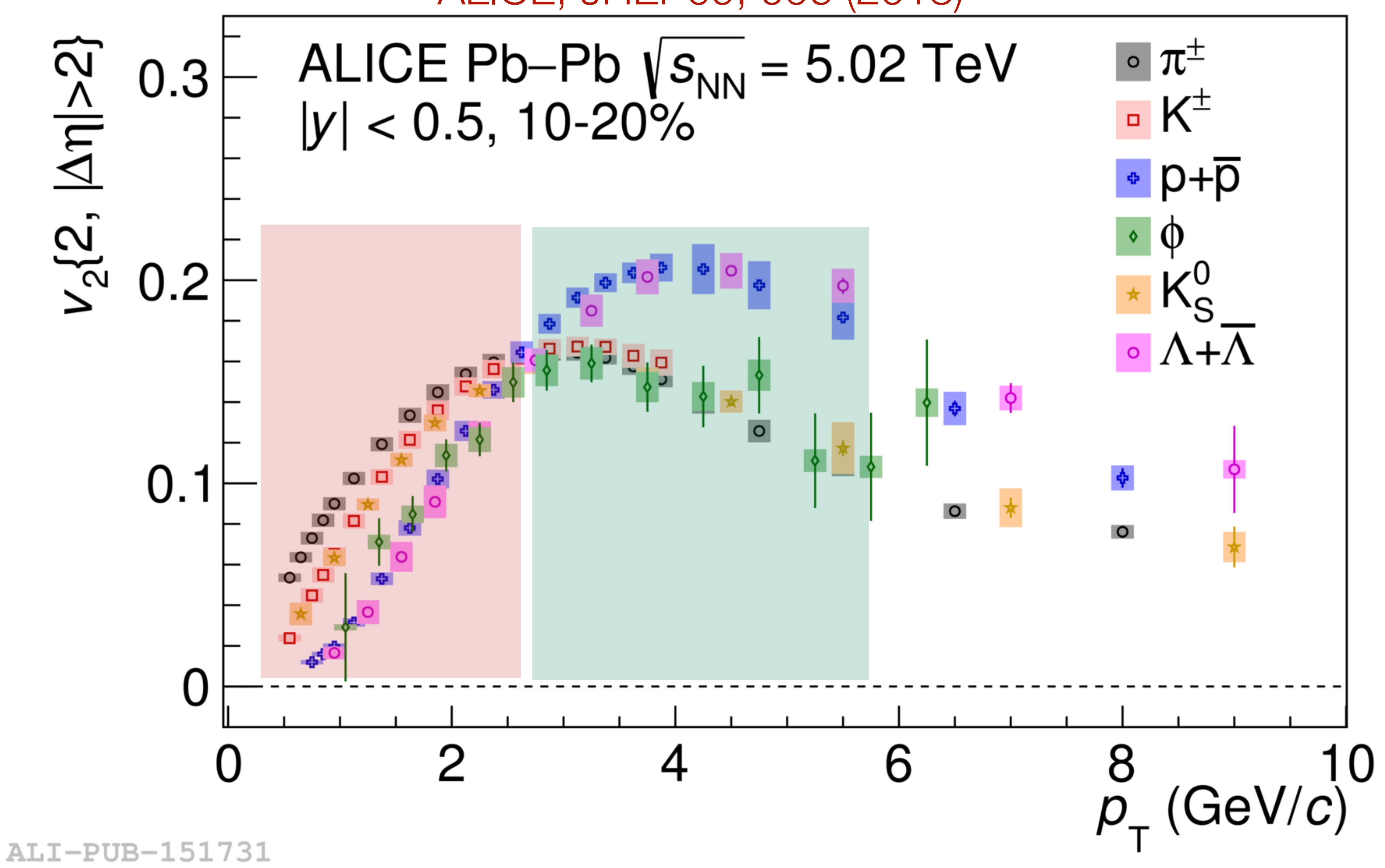


Anisotropic flow - measurements

ALICE, PRL 116, 132302 (2016)



ALICE, JHEP09, 006 (2018)



- **Elliptic flow** of (all) charged hadrons
  - Strong dependence on the collision centrality
    - Driven by the initial geometry
- **Higher order flow** of (all) charged hadrons
  - Weak centrality dependence
    - Driven by fluctuations in the initial geometry

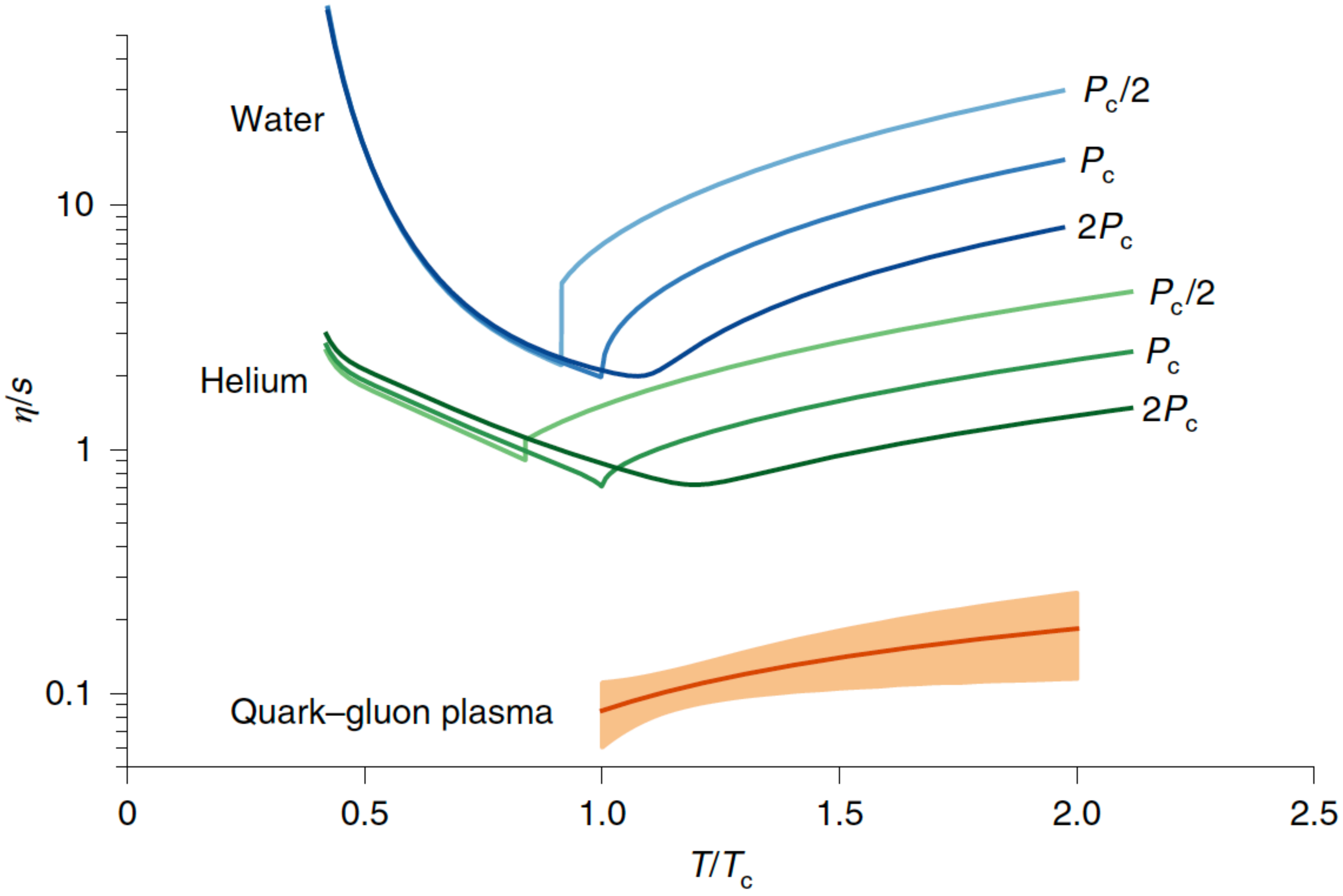
Flow of identified hadrons

- **Mass ordering** at low p_T
  - Collective expansion of the medium: common velocity -> heavier particles have larger p_T (the same v_2 at larger p_T)
- **Particle type grouping** at intermediate p_T
  - Partonic degrees of freedom (quarks flow, not hadrons)

Knowledge about the QGP

Bernhard et al., Nature Physics, 15, 1113 (2019)

Shear viscosity over entropy density ratio, η/s



- **Quark-gluon plasma is a "perfect" liquid with small η/s** close to the universal lower bound

Flow of heavy flavor hadrons

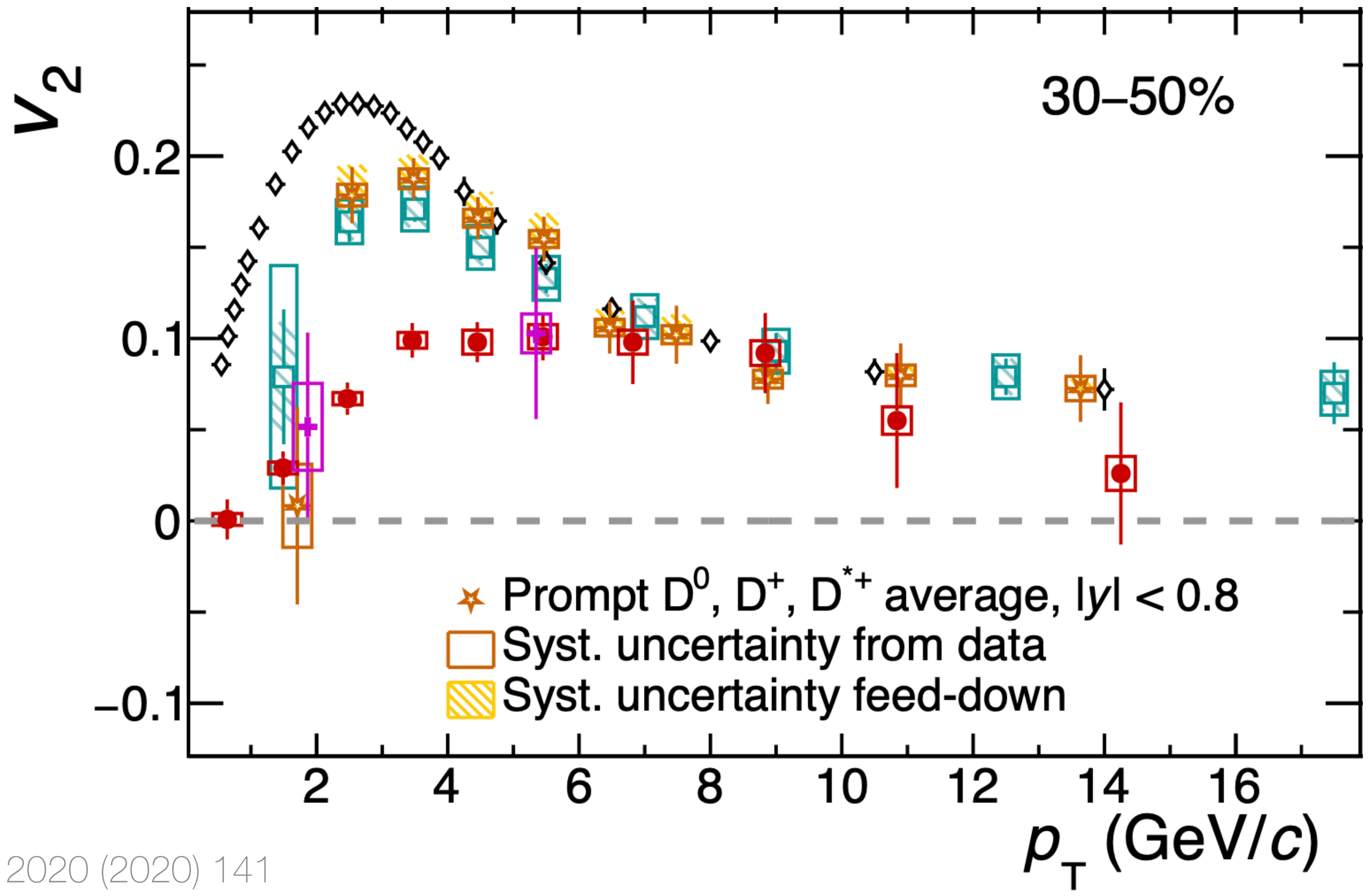
- Mass hierarchy $v_2^{\pi} > v_2^{D} > v_2^{J/\Psi}$
  - Charm quark participates in the flow of the medium
- Measurement of D meson flow using 4-particle correlations (cumulant)
  - New insights into flow fluctuations and its relation to fluctuations of the initial geometry

Pion v2

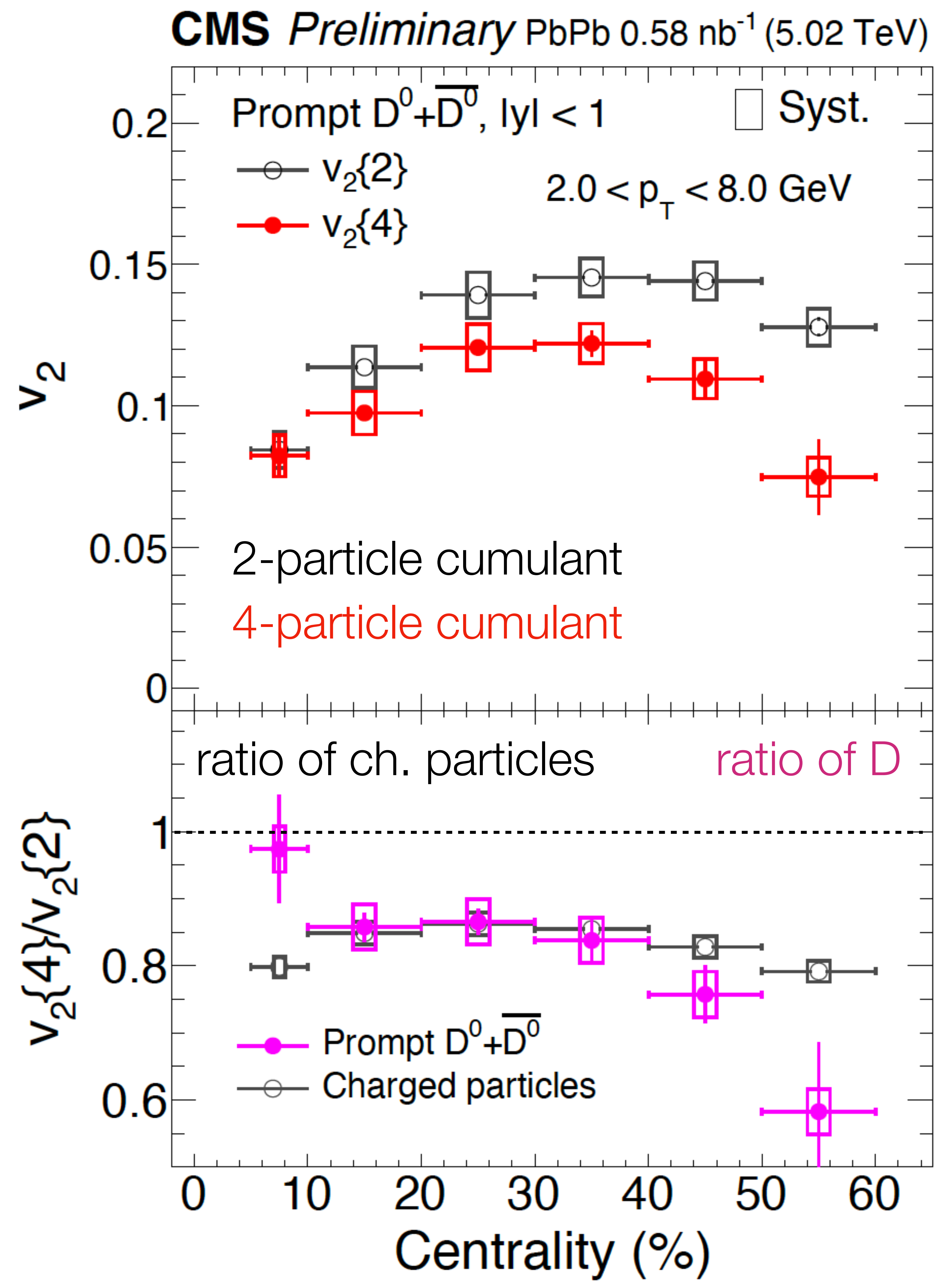
D meson v2 (ALICE)

D meson v2 (CMS)

J/ψ v2



ALICE, JHEP 2020 (2020) 141



CMS-PAS-HIN-20-001

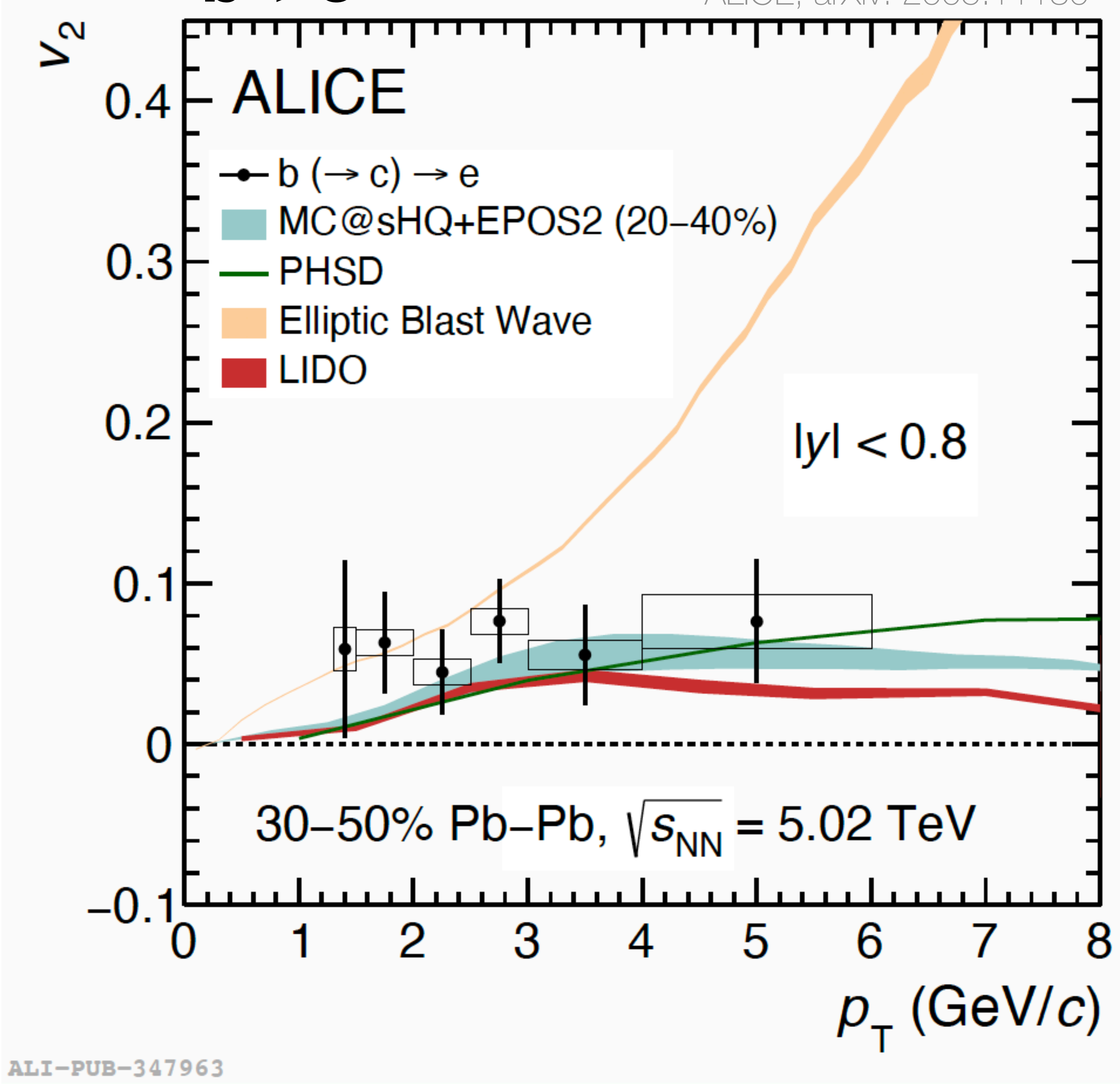
Flow of heavy flavor hadrons

- Mass hierarchy $v_2^{\pi} > v_2^{D} > v_2^{J/\Psi}$
  - Charm quark participates in the flow of the medium
- Measurement of D meson flow using 4-particle correlations (cumulant)
  - New insights into flow fluctuations and its relation to fluctuations of the initial geometry

- Positive v_2 of electrons coming from decays of b quark
- Flow of Υ consistent with 0
- Measurements help in modelling the interactions of beauty quarks in the medium

b->e

ALICE, arXiv: 2005.11130



$\Upsilon(1S)$

CMS, arXiv: 2006.07707