Student Day:
Bulk Physics - Flow and Correlations

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- **Flow**
- Introduction;
- Directed flow;
- Elliptic flow;
- Hydrodynamics;

- **Correlations**
- Introduction;
- Geometry and dynamics;
- Strong interactions and EoS;
- Collectivity;

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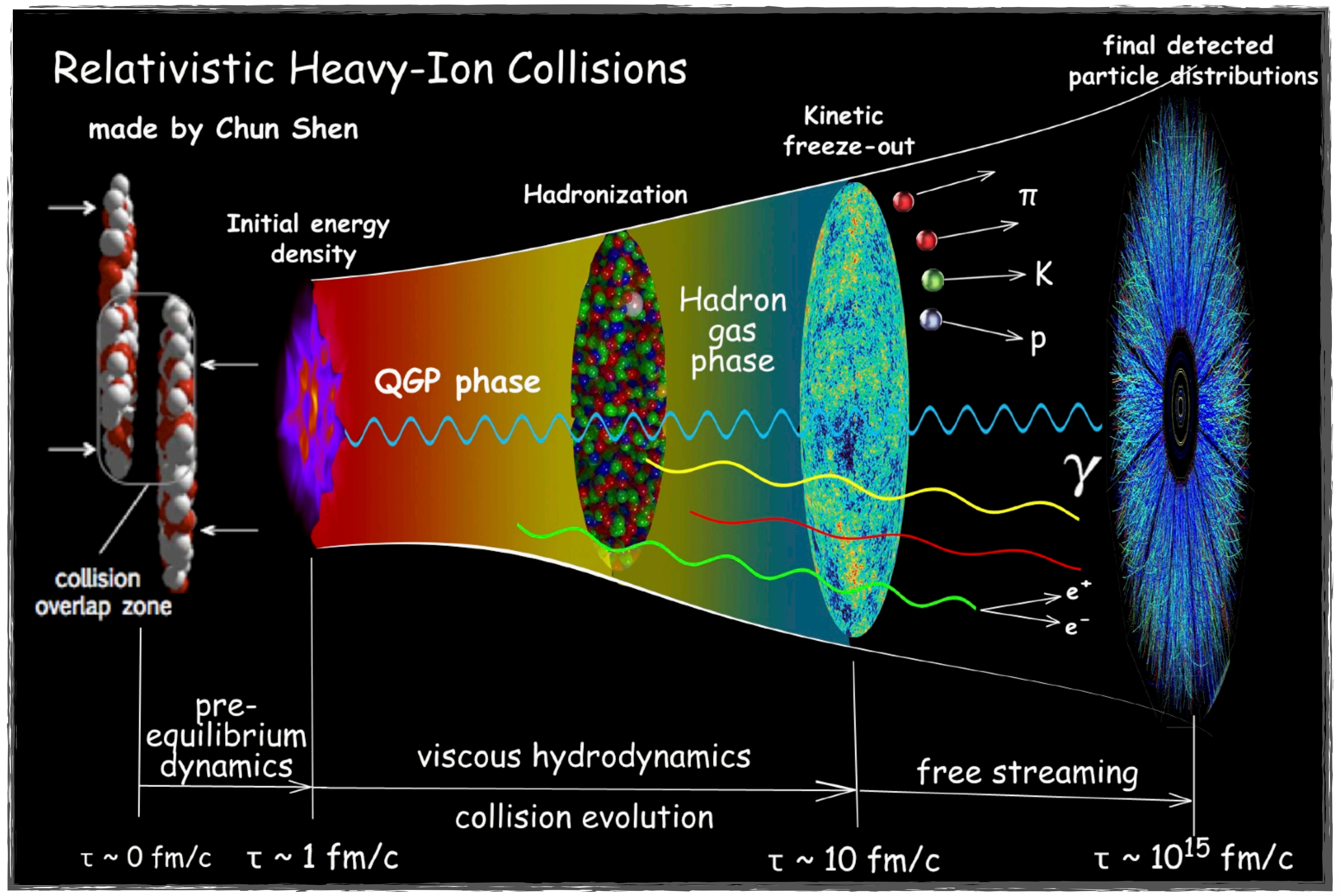
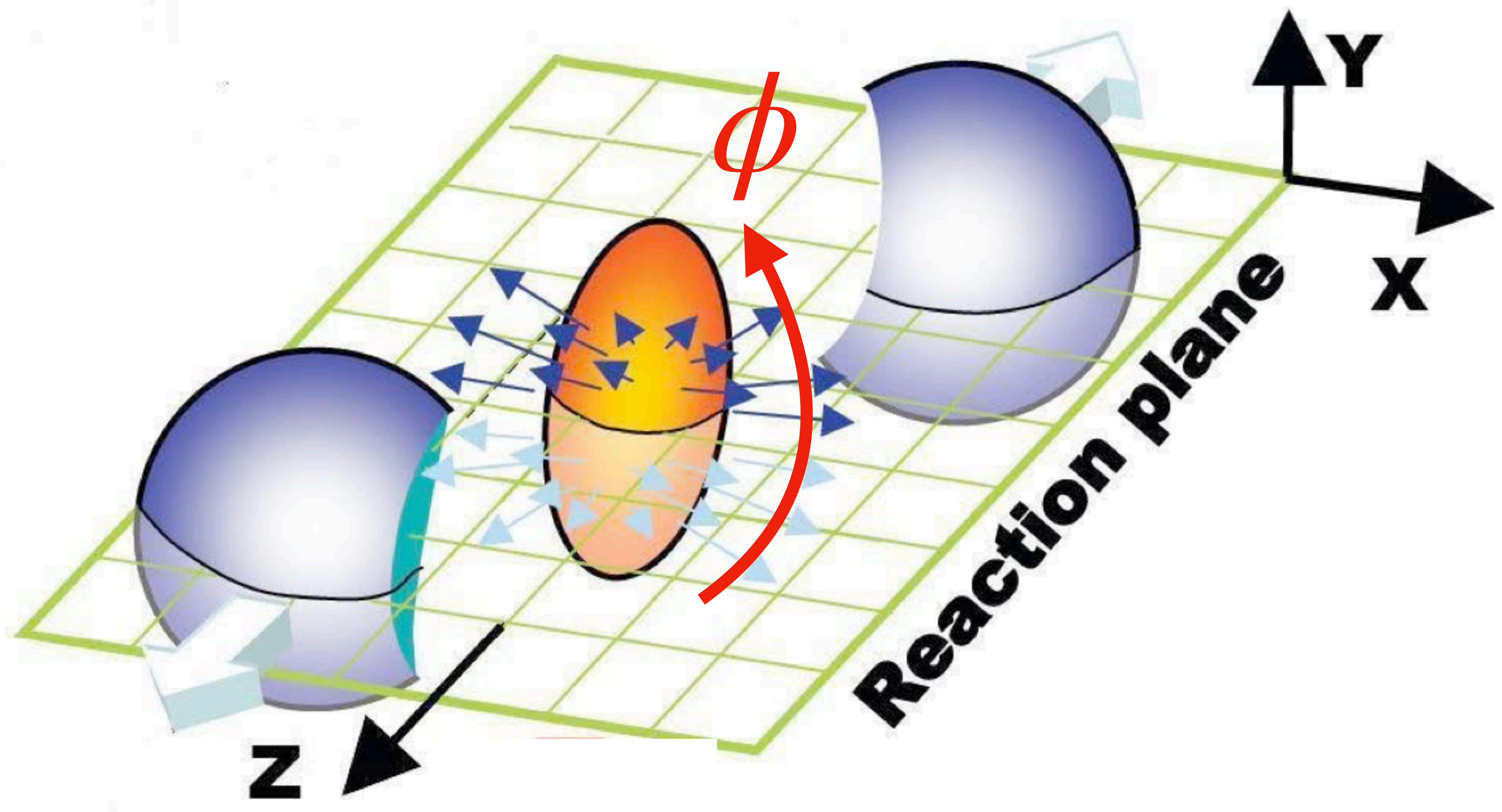
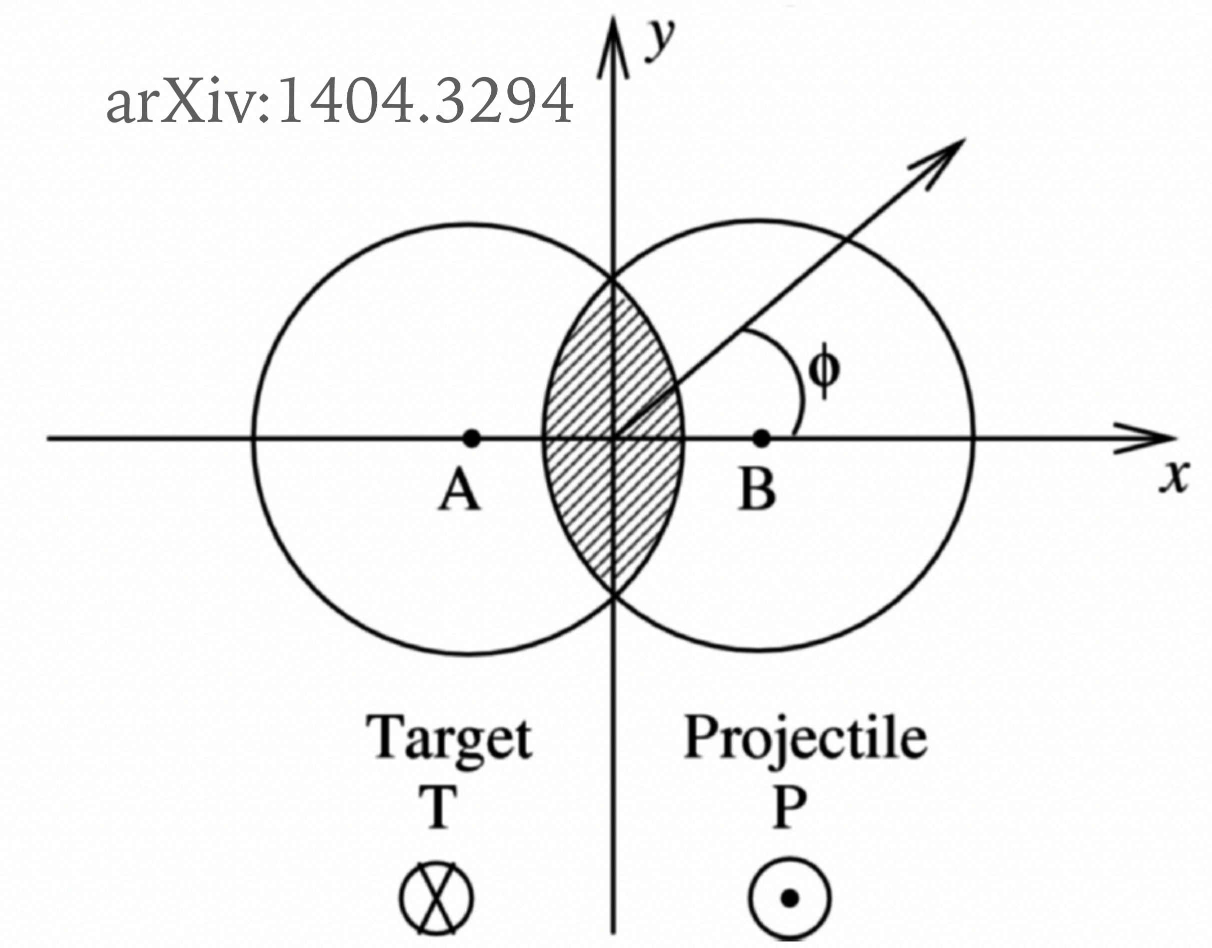
Flow

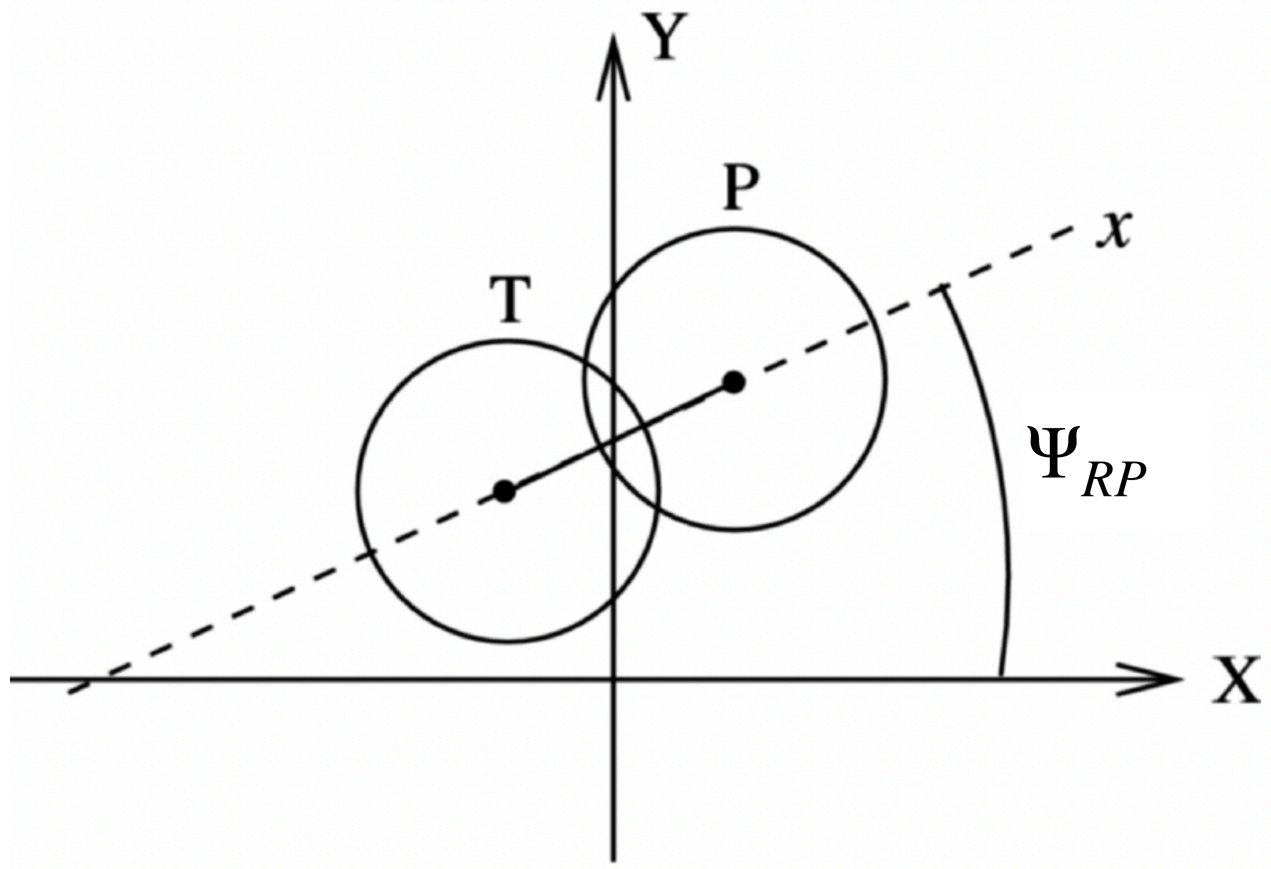
Introduction

Collectivity in heavy-ion collision





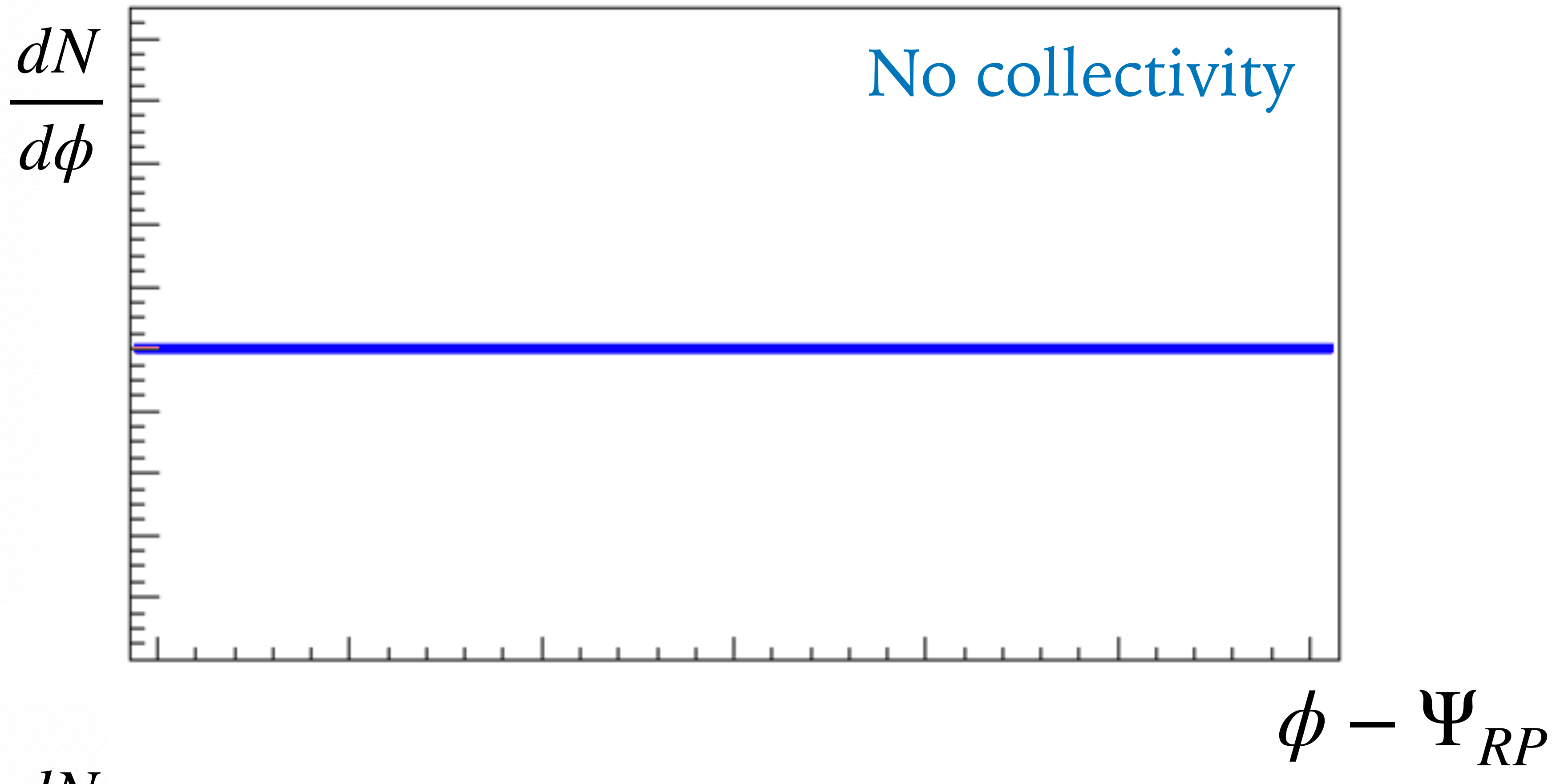


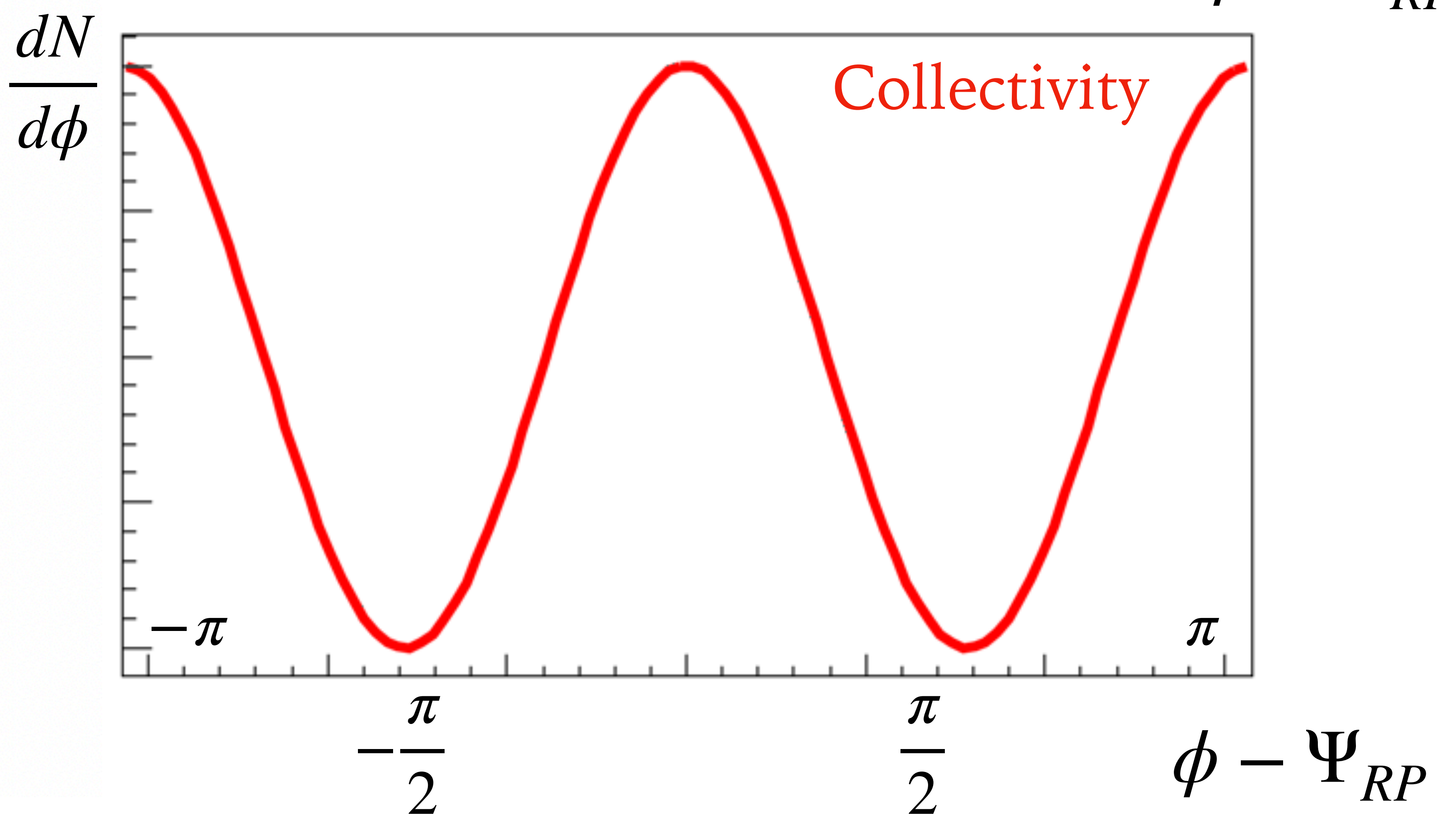


Independently for each collision

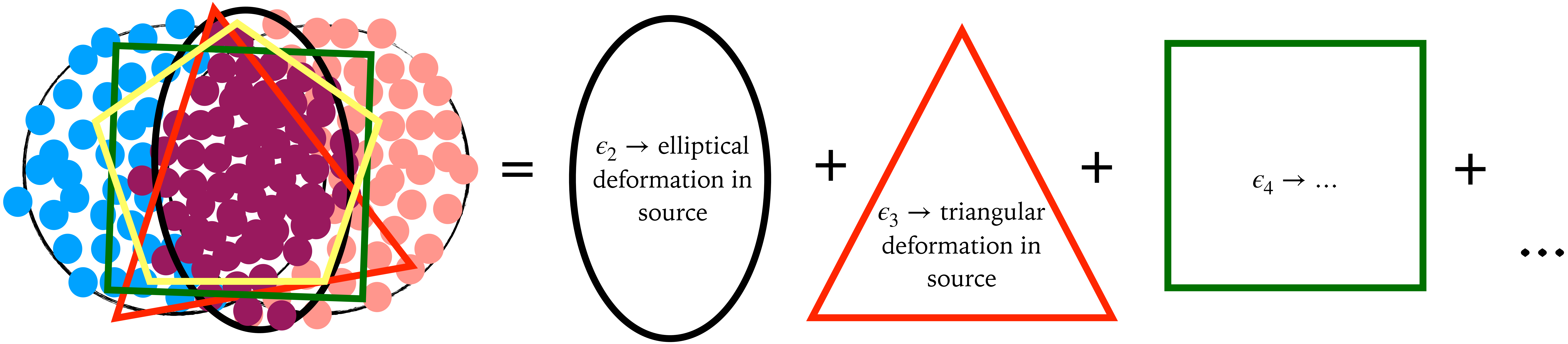
Inclusive distributions

$$\frac{dN}{d\phi}\left(\frac{dN}{d(\phi-\Psi_{RP})}\right) \text{ of } (\phi-\Psi_{RP})$$

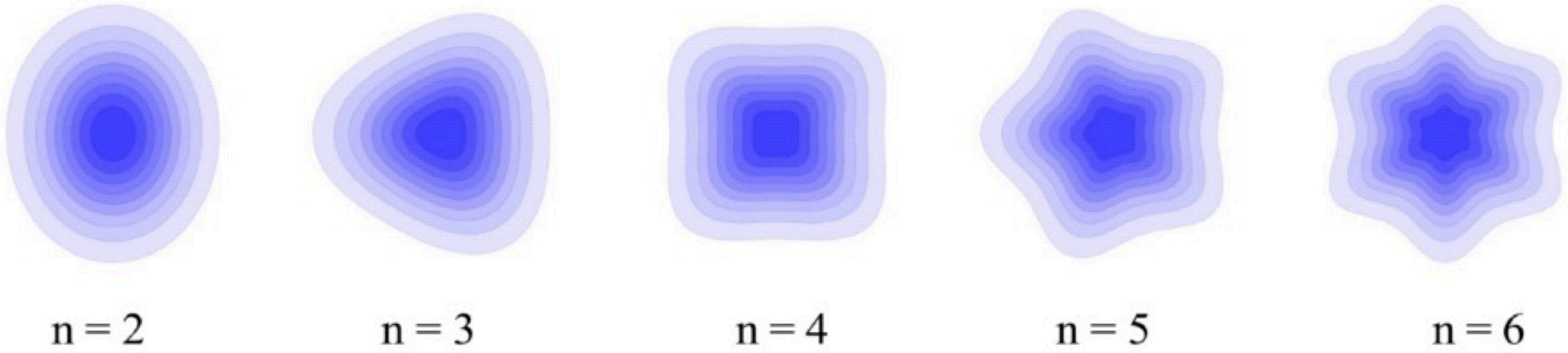




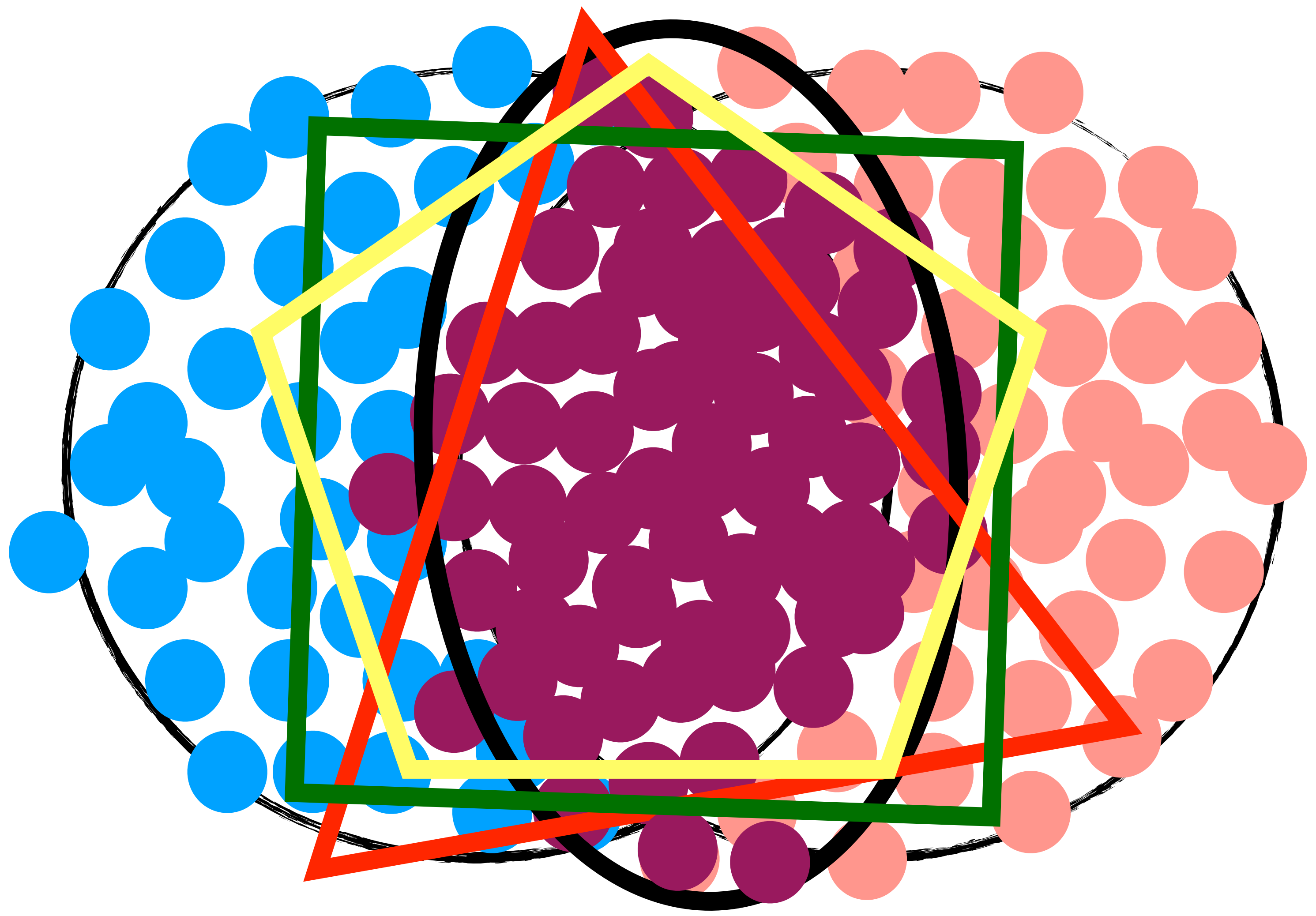
Initial state and anisotropic flow harmonics



Non-zero **higher flow harmonics** carry important information about the space-time evolution of QCD-matter and its initial fluctuations



Collective flow



Collective flow $v(x)$

Longitudinal flow $v_L(x)$

Transverse flow $v_T(x)$

Radial flow $< v_T >_\phi$

(averaged over azimuthal angle ϕ)

Anisotropic flow

v_1 - **directed** flow

v_2 - **elliptic** flow

v_3 - **triangular** flow

$v_{4,5,..}$ - **higher** harmonics

Evolution of the A+A collision

$$\frac{d^3\sigma}{dp^3/E} = \frac{d^3\sigma}{p_T dp_T dy d\phi} \rightarrow \int d\phi \frac{d\sigma}{2\pi p_T dp_T dy}$$ No anisotropy (central collisions)

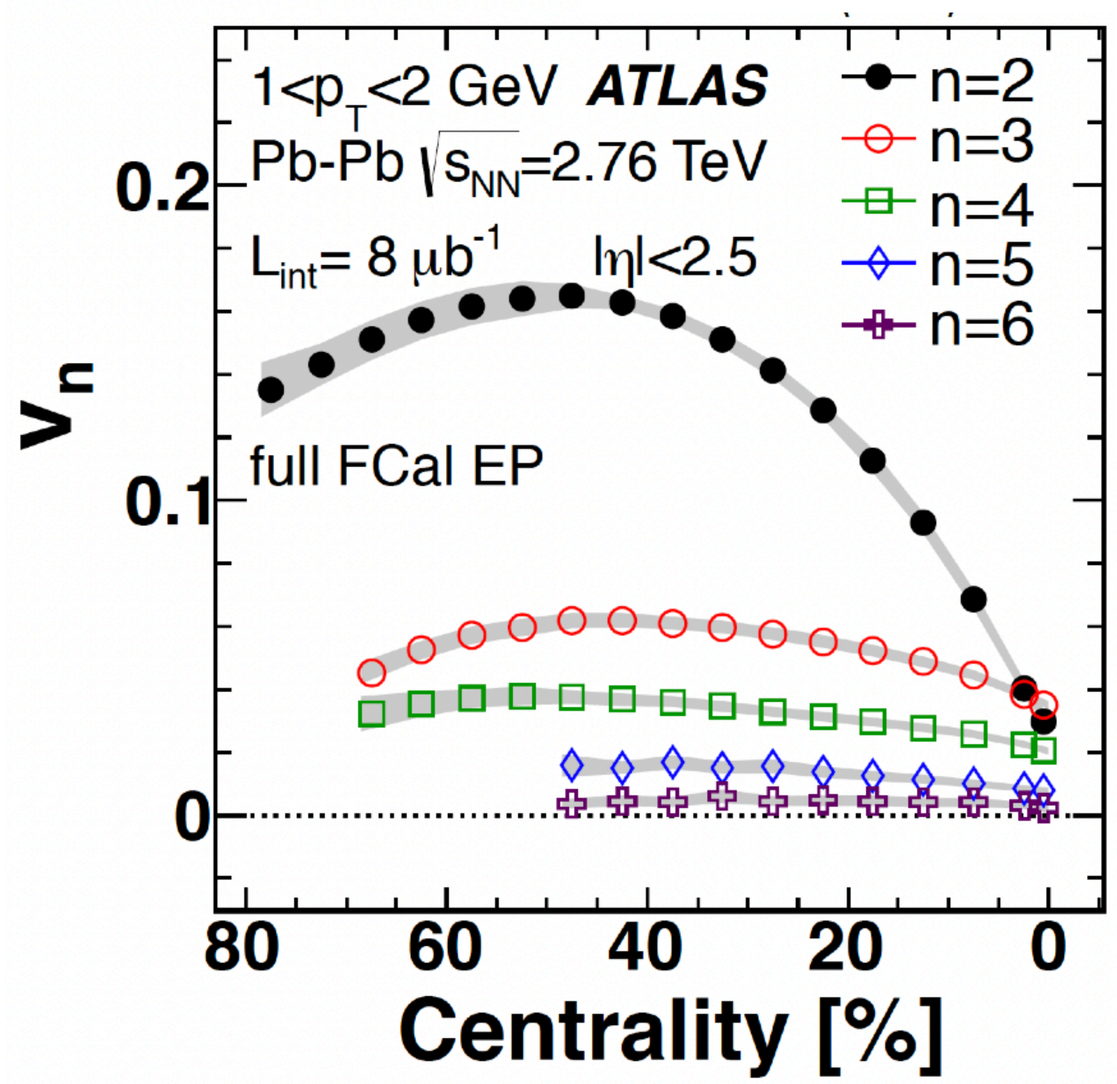
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + 2\sum_{n=1}^{\infty} v_n cos[n(\phi - \Psi_{RP})])$$

Anisotropy present (non-central collisions)

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + 2v_1 \cos(\phi - \Psi_R) + 2v_2 \cos[2(\phi - \Psi_{RP})] + 2v_3 \cos[3(\phi - \Psi_{RP})] + \ldots)$$

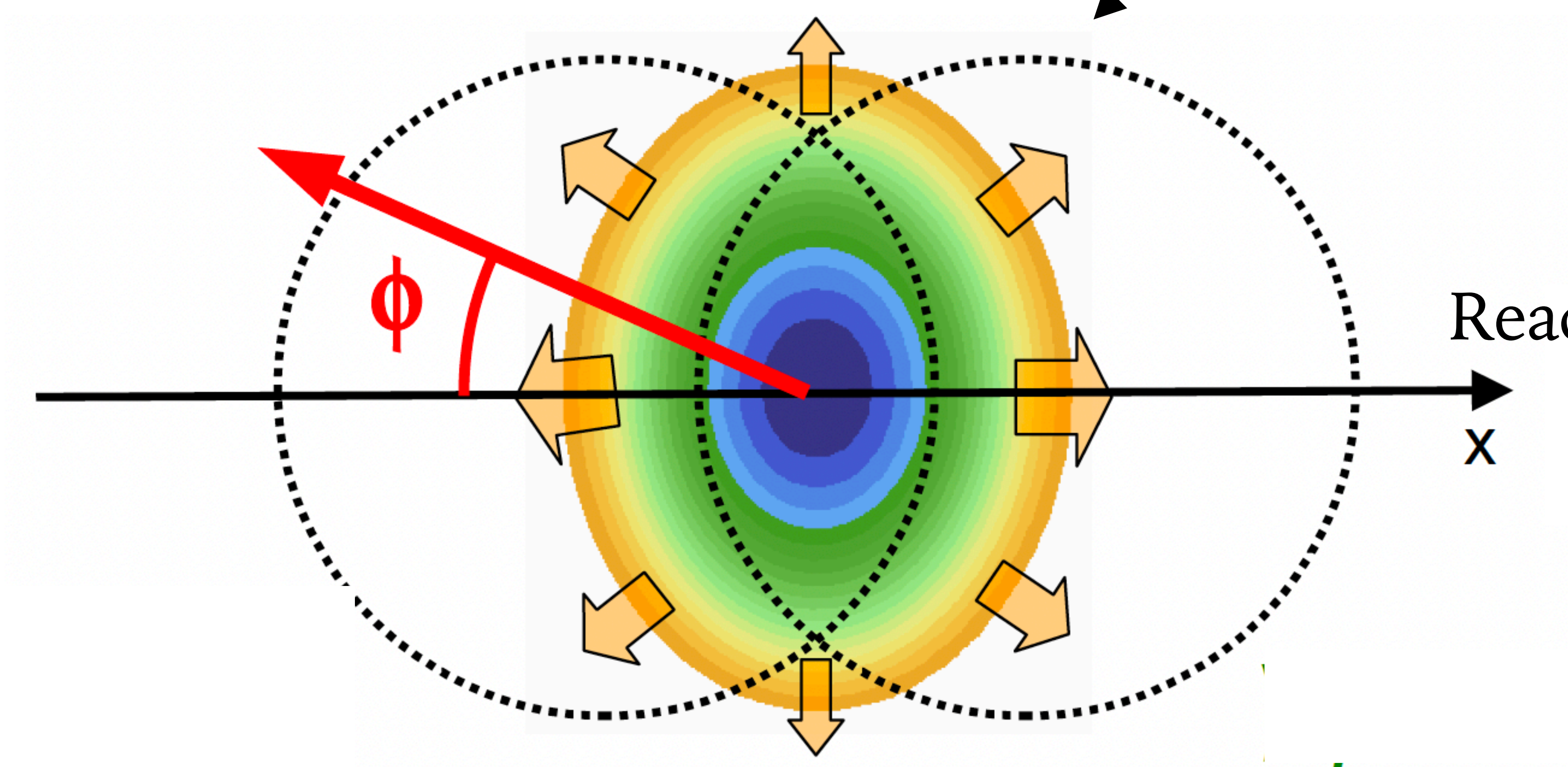
Radial flow Directed flow Elliptic flow Triangular flow

PRC 86 (2012) 014907



Geometry response:
$v_n \sim \epsilon_n$

System size:
Less interactions develop less flow

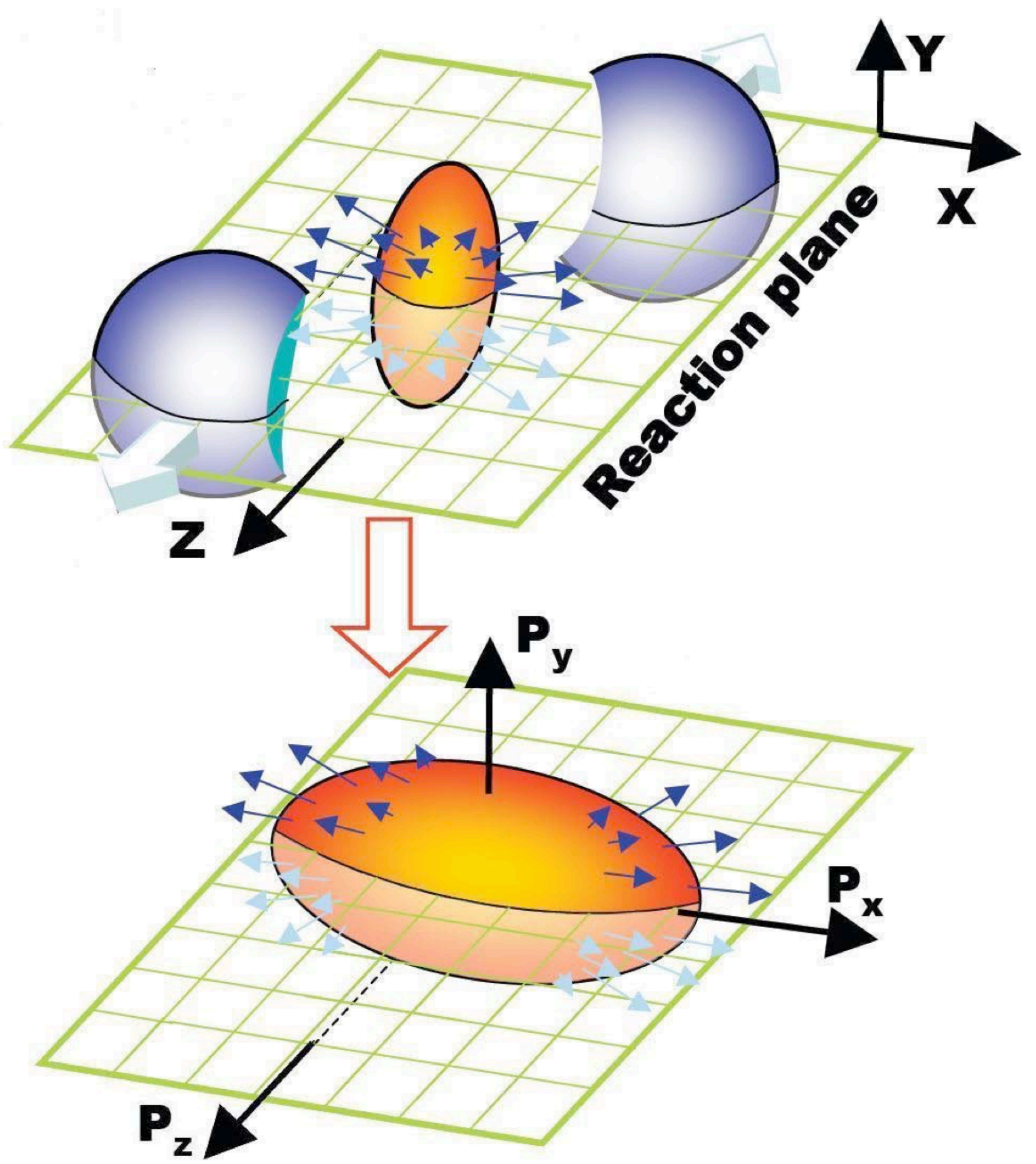


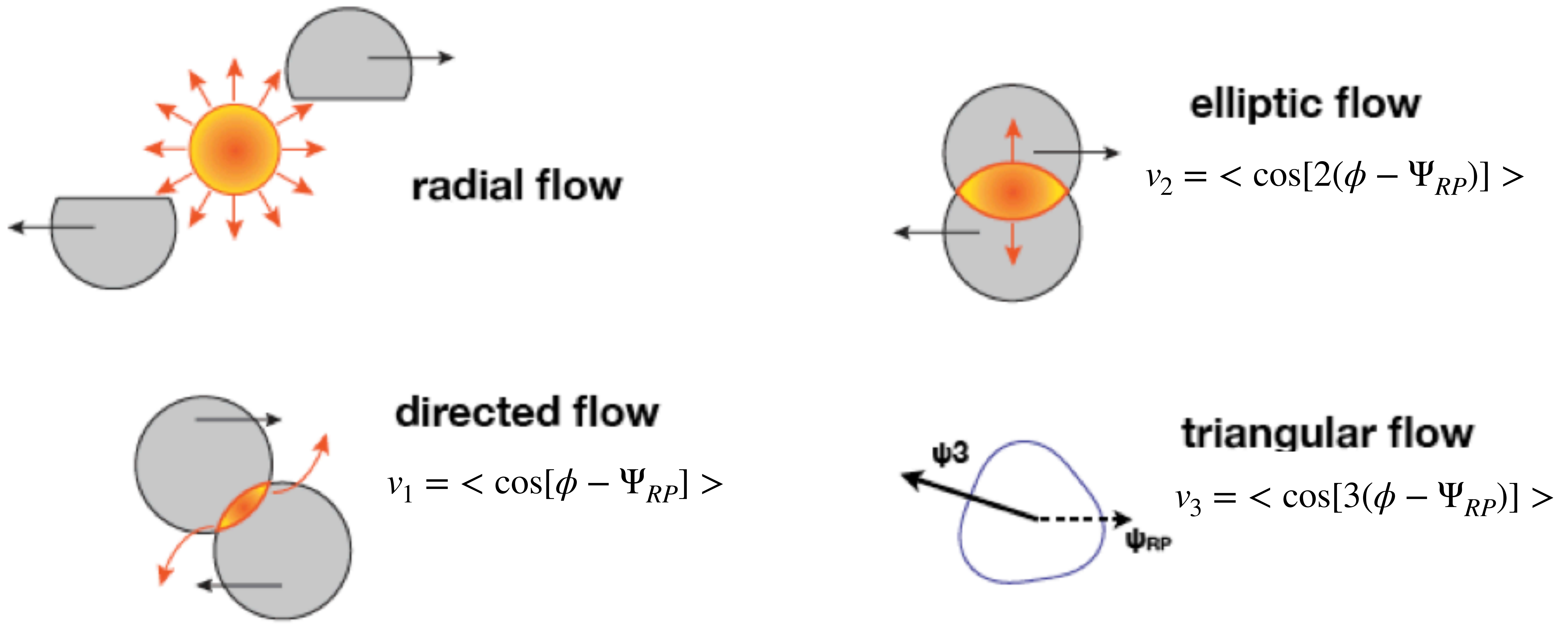
Courtesy of F. Retiere

Bigger pressure gradients *in-plane* that *out-plane*

- **Radial flow** continues to increase until thermal freeze-out (sensitive to **early** and **late stages** of collision);
- **Directed flow** is sideward motion of produced particles and nuclear fragments (sensitive to **early phase**);
- **Elliptic flow** built in **early phase** (saturates after spatial asymmetry and pressure gradients disappear);
- **Triangular** flow sensitive to **initial state** e-b-e fluctuations

Collective flow





Initial spatial anisotropy → final momentum anisotropy

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + 2\sum_{n=1}^{\infty} v_n cos[n(\phi - \Psi_{RP})])$$

$$v_n = < \cos[n(\phi - \Psi_{RP})] >$$

STAR: PRC 88 (2013) 14902
Phys. Rev. C 93, 014907 (2016)
Phys. Rev. Lett. 116, 062301 (2016)

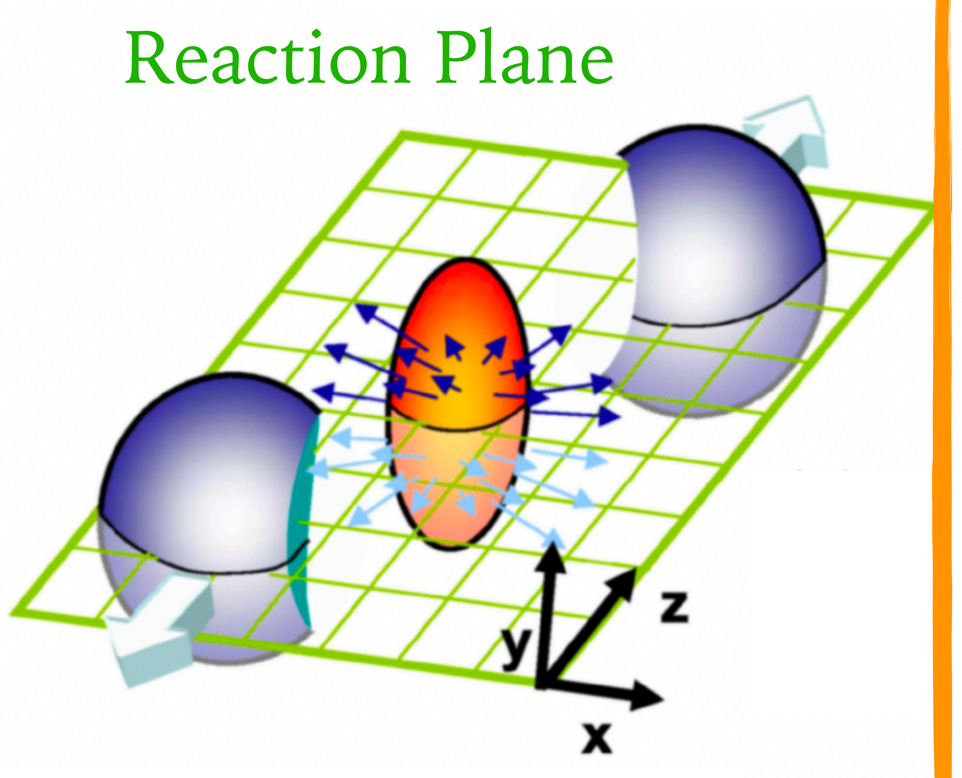
Evolution of the A+A collision, anisotropic flow

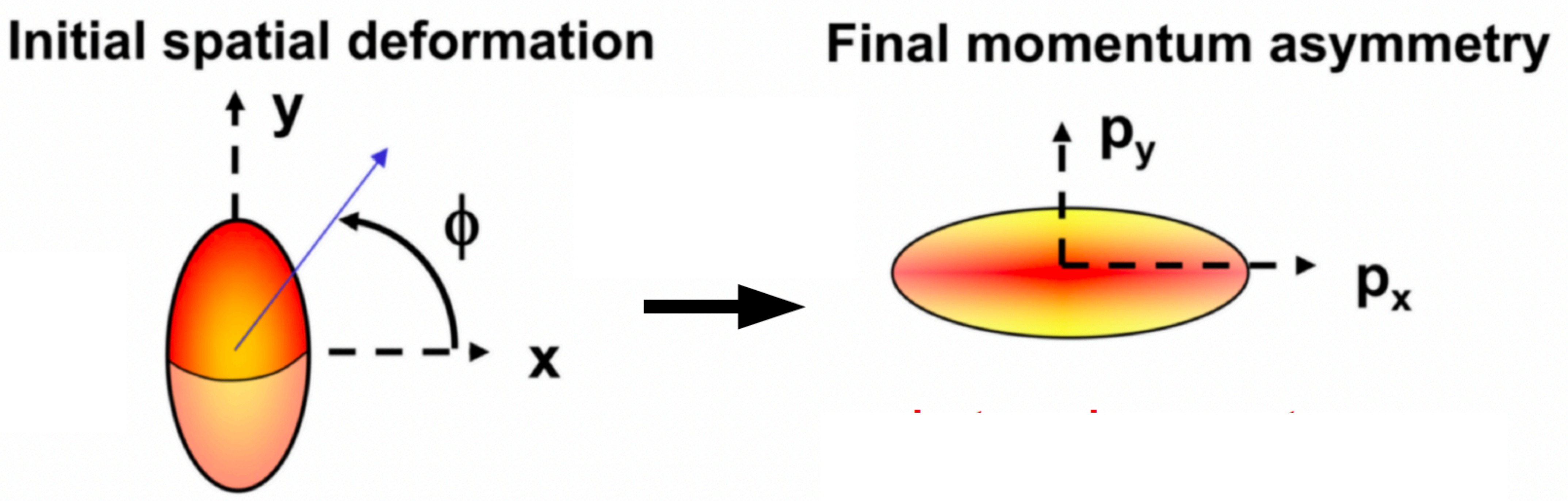
The **initial spatial deformation** (described by spatial eccentricity) leads to the **final momentum asymmetry** caused by different pressure gradients towards the Reaction Plane (larger gradient) and in the direction perpendicular to the Reaction Plane (smaller gradient).

Interactions in the system play a key role in building collectivity;

- Without **interactions**, the anisotropic flow would not develop;
- The largest anisotropic flow expected for **the most strongly interacting medium** (the shortest mean free path of particles);
- In the absence of interactions, the particles expected to **freely** and independently **fly** in all directions.

$$\phi = atan\frac{p_y}{p_x}$$





- **Initial spatial deformation** (density gradient)
- Interactions

Pressure gradient

Collective flow

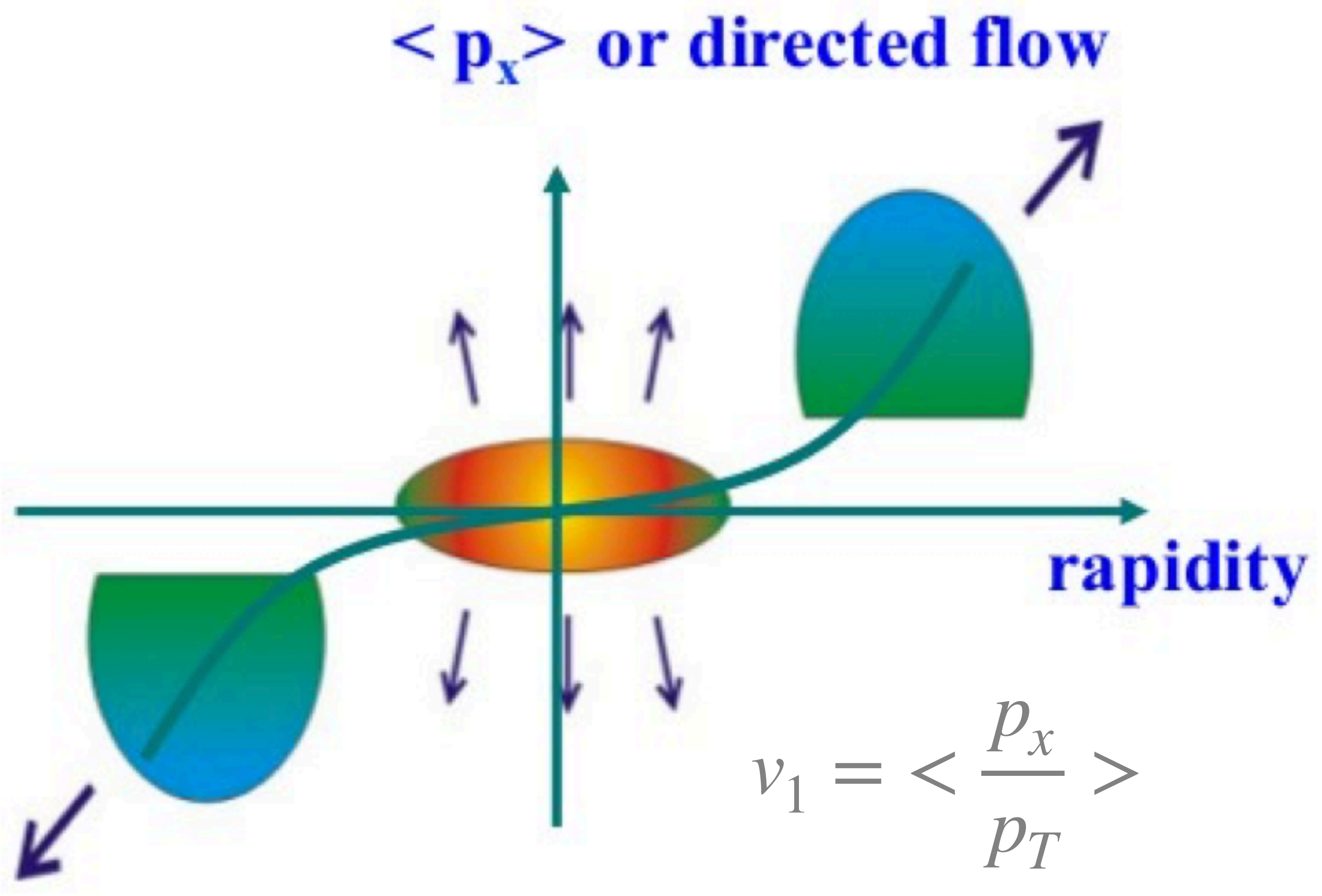
- **Final momentum asymmetry**

Spatial eccentricity

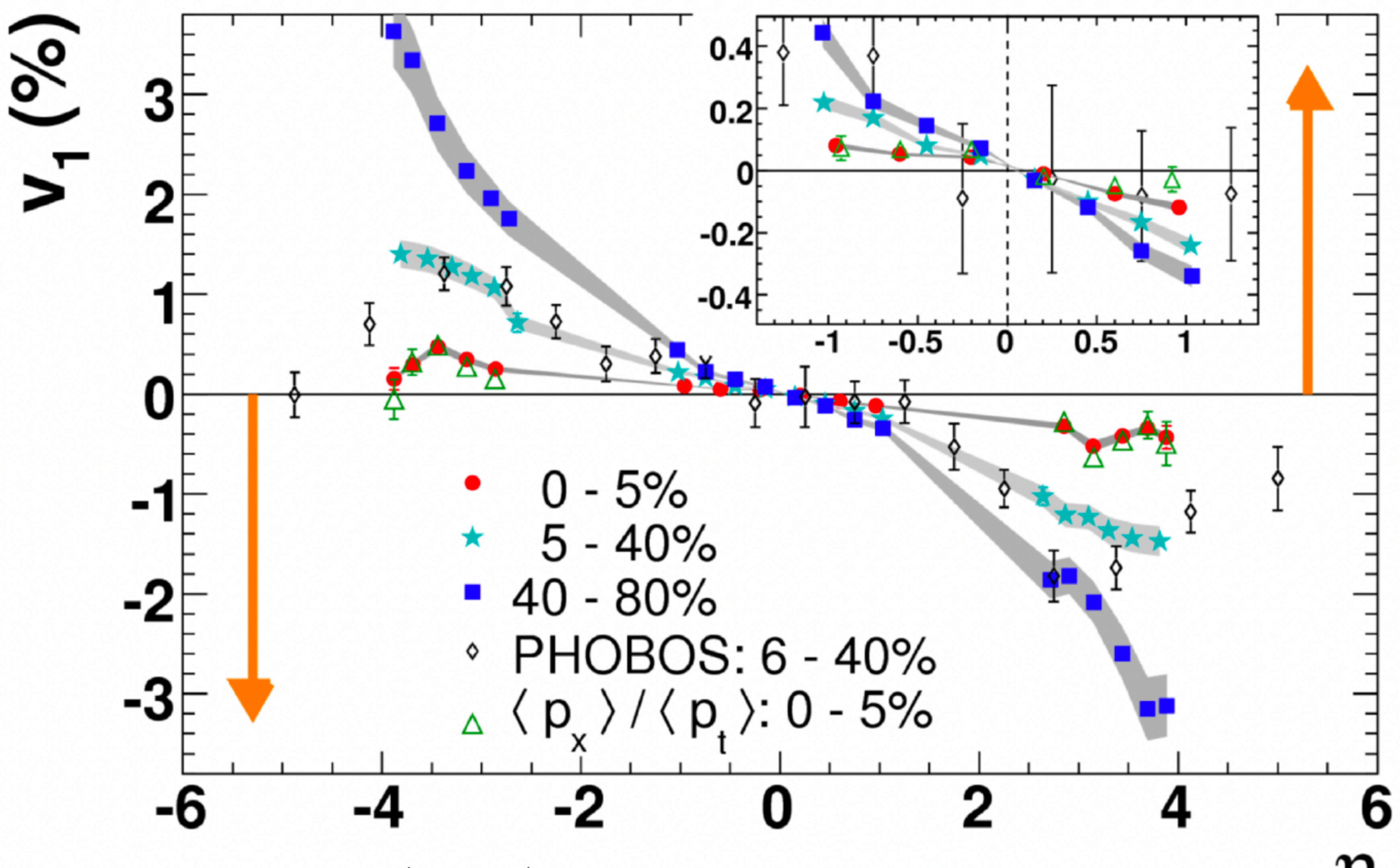
$$\epsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}$$

Directed flow

Directed flow

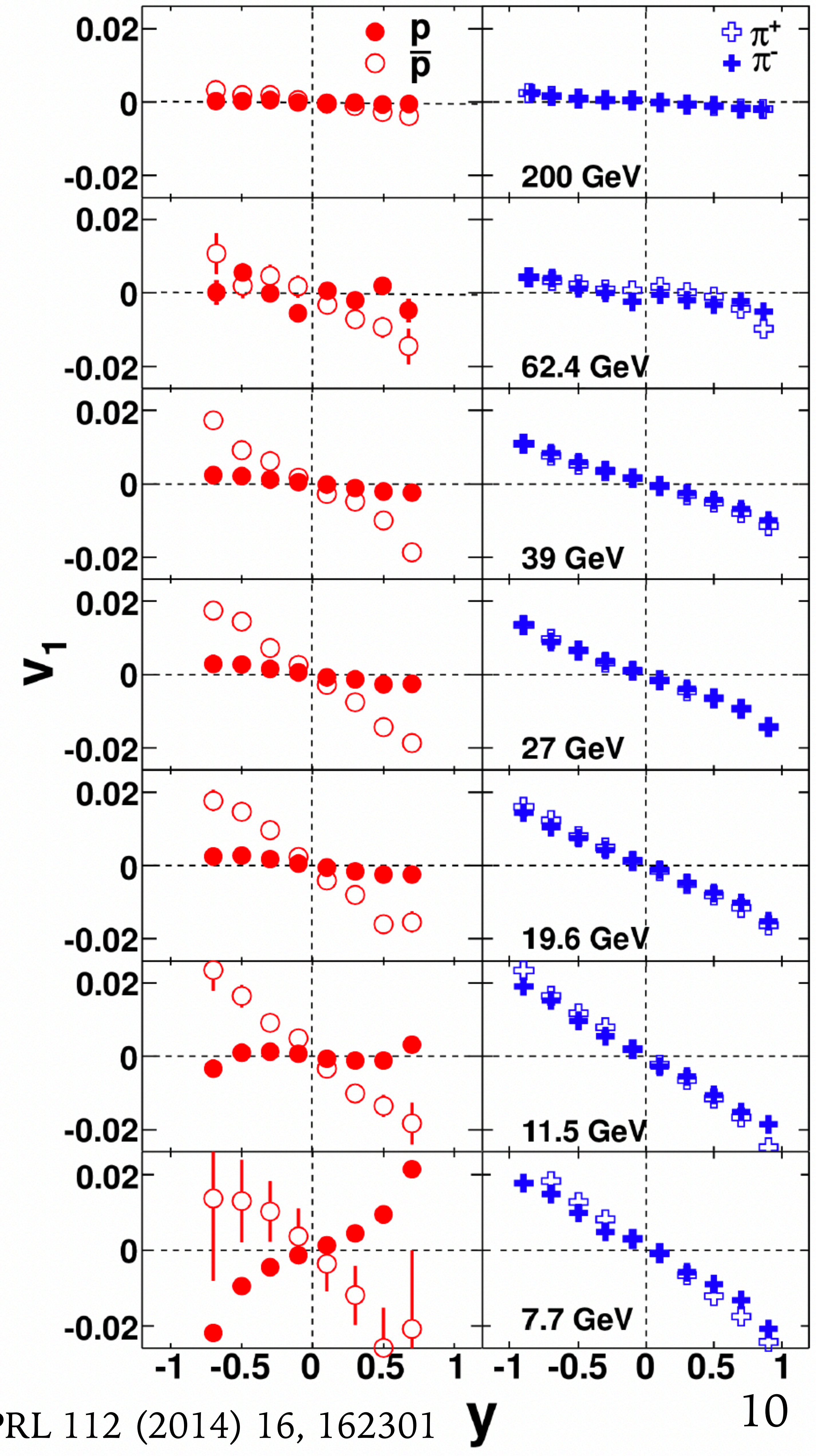


- Directed flow (v_1): **sideward motion of produced particles and nuclear fragments;**
- Transverse transfer of momentum in the reaction plane;
- v_1: **interplay between protons transported from beam-rapidity to mid-rapidity, and produced ones;**
- v_1 of antiprotons is proxy of produced protons;



PRL 101 (2008), 252301

- "Slope" v_1 always negative for $\pi^{\pm}$, $\bar{p}$;
- "Slope" v_1 for p changes sign at low $\sqrt{s_{NN}}$;



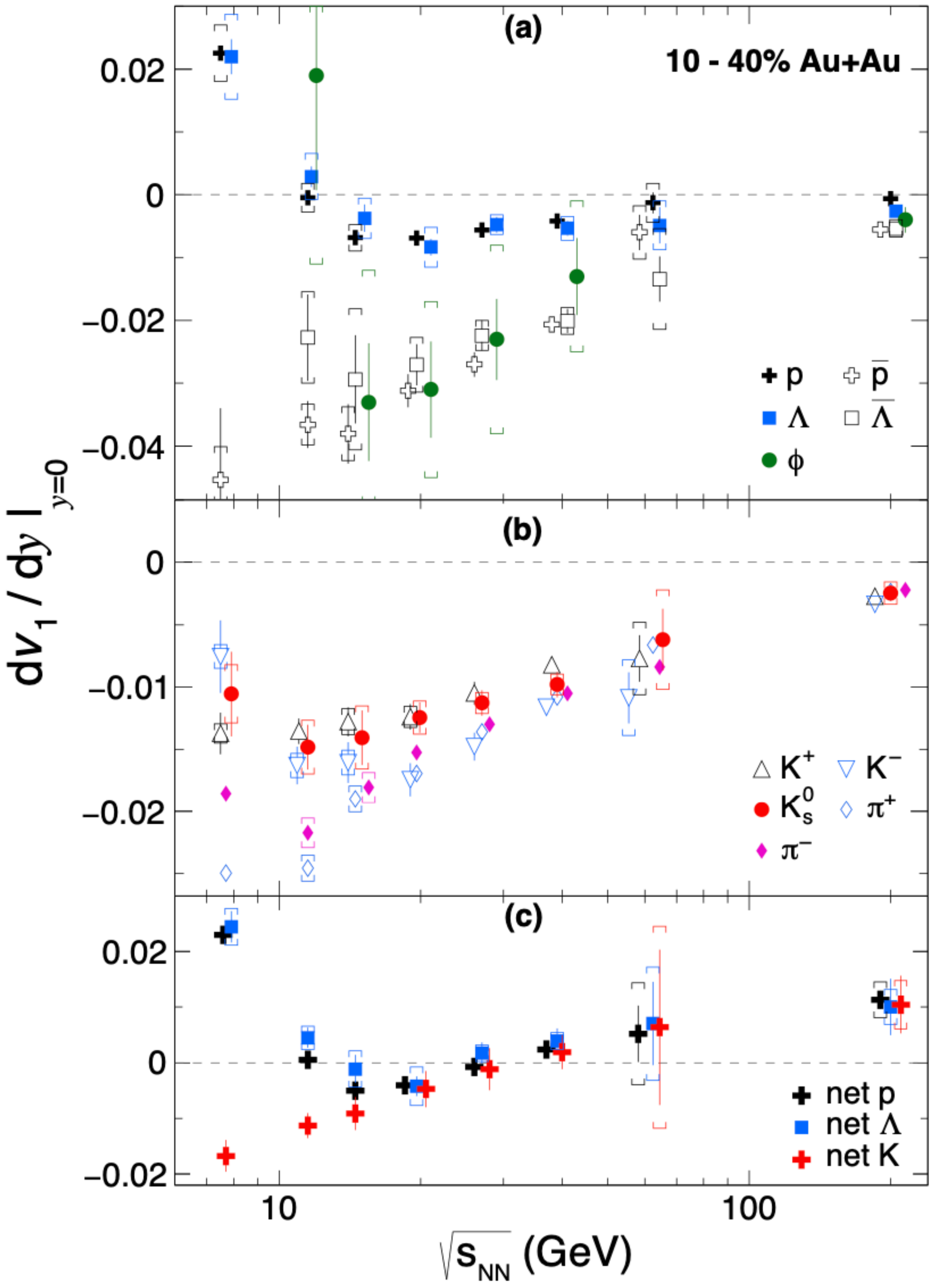
PRL 112 (2014) 16, 162301

Directed flow

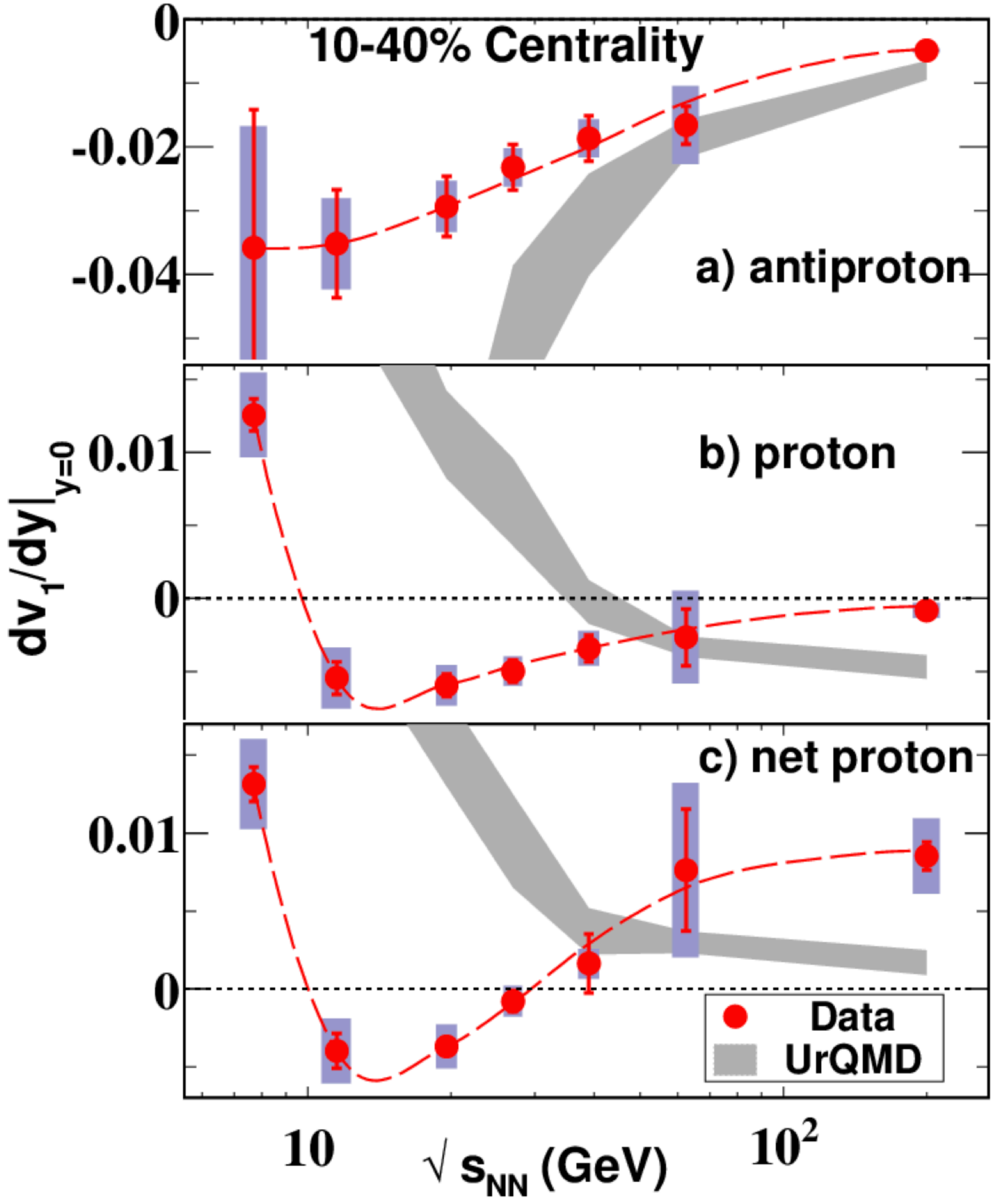
- **Change of sign in the slope of** $\frac{dv_1}{dy}$ (for baryons, or net-baryons) as a probe to the **softening of EoS** and/or **first-order phase transition;**

- If a system undergoes a first-order phase transition, due to formation of **mixed phase, pressure gradient is small (minimum** in the $\frac{dv_1}{dy}$ **slope** parameter);

PRL 120 (2018) 6, 062301



PRL 112, 162301 (2014)



Elliptic flow

Methods of flow measurements

2023

- Many methods for determining v_n;
- Experimental determination of v_n difficult (not a simple adjustment of parameters in the $\Delta\phi = (\phi - \Psi_{RP})$ distribution);

1. **Standard method** (Reaction Plane method) - based on the definition of $v_n = <\cos(n\Delta\phi)>$; requires determining Ψ_{RP} separately for each collision;

2. **Two-particle correlation method** - to determine $v_n^2 = v_n\{2\}^2 = <\cos[n(\phi_a - \phi_b)]>$
ϕ_1, ϕ_2 - the angles of two particles (in the LAB frame).
Advantage: no need to determine Reaction Plane;
Disadvantage: v_n determined without sign precision;

3. **Cumulant method** (multi-particle correlations) - can be used to reduce non-flow correlations;

4. **Mixed-harmonic methods**;

...

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Event Plane method [Phys.Rev.C 58, 1671 (1998)]:

Event plane's vector: $\overrightarrow{Q_n} = [X_n, Y_n] = [Q_n\cos(n\Psi_n), Q_n\sin(n\Psi_n)]$

$$[X_n, Y_n] = [\sum_i w_i\cos(n\phi_i), \sum_i w_i\sin(n\phi_i)]$$

$$\Psi_{EP,n} = \frac{1}{n}\tan^{-1}\frac{\sum_i w_i\sin(n\phi_i)}{\sum_i w_i\cos(n\phi_i)}$$

$$v_n\{EP\} = \frac{<cos[n(\phi - \Psi_{EP,n})]>}{R_n}$$

R_n - EP's resolution

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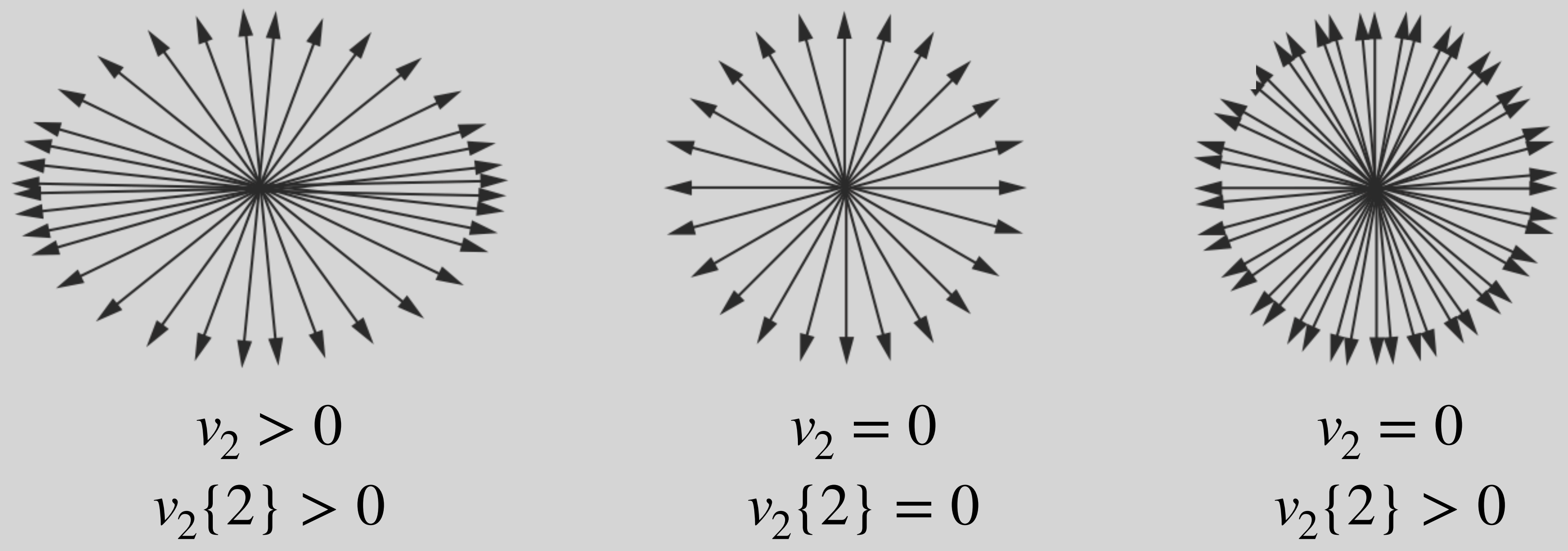
…

$$v_2 = <\cos(2\phi)>$$
$$v_2\{2\} = \sqrt{\cos[2(\phi_1 - \phi_2)]}$$

New J.Phys.13:055008,2011



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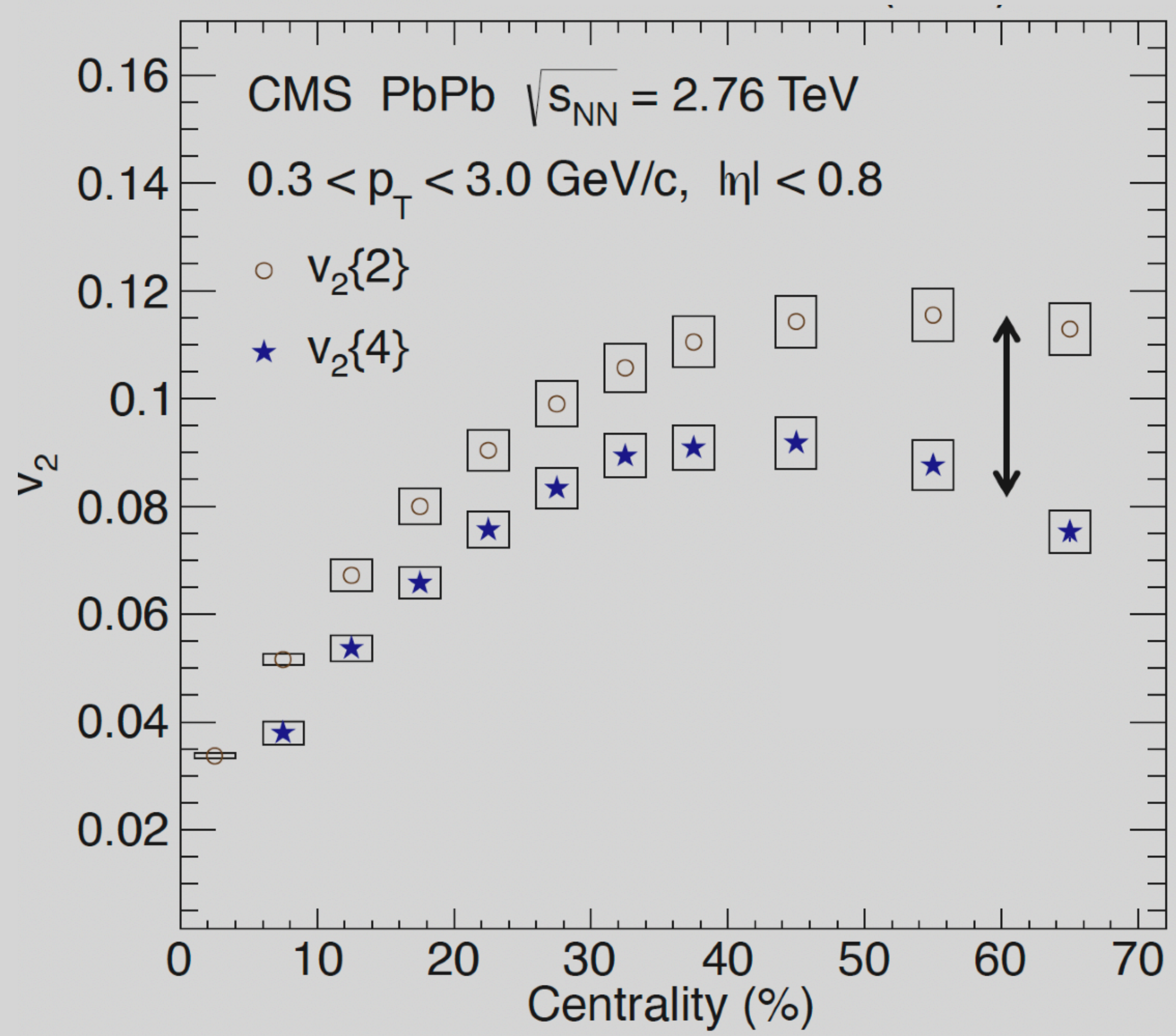
$$\boxed{\begin{aligned} v_2\{2\}^2 &= < v_2 >^2 + \sigma_{v_2}^2 \\ v_2\{4\}^2 &\simeq < v_2 >^2 - \sigma_{v_2}^2 \end{aligned}}$$

$$\sigma^2 = < \epsilon_n^2 > - < \epsilon_n >^2$$
$$(\epsilon_n\{2\})^2 = < \epsilon_n >^2 + \sigma^2$$
$$(\epsilon_n\{4\})^2 \simeq < \epsilon_n >^2 - \sigma^2$$

$\epsilon_2\{4\}/\epsilon_2\{2\}$ affected by fluctuations

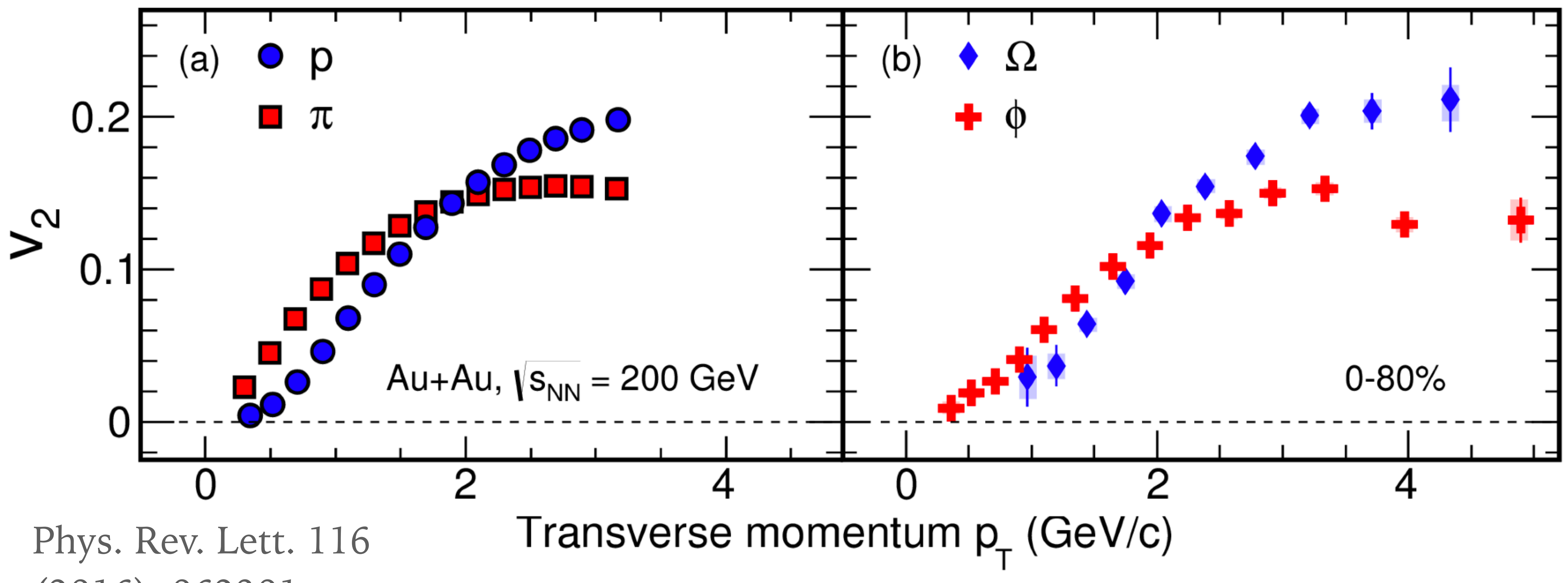
PRC 87 (2013) 014902



$$c_2\{2\} = << e^{i2(\phi_1 - \phi_2)} >> = < v_2^2 + \delta_2 >$$
$$c_2\{4\} = << e^{i2(\phi_1 + \phi_2 - \phi_3 - \phi_4)} >> - 2 << e^{i2(\phi_1 - \phi_2)} >>^2$$
$$c_2\{4\} = < - v_2^4 + \delta_4 >$$
$$\delta_2 \sim 1/M_c,\ \delta_4 \sim 1/M_c^3$$

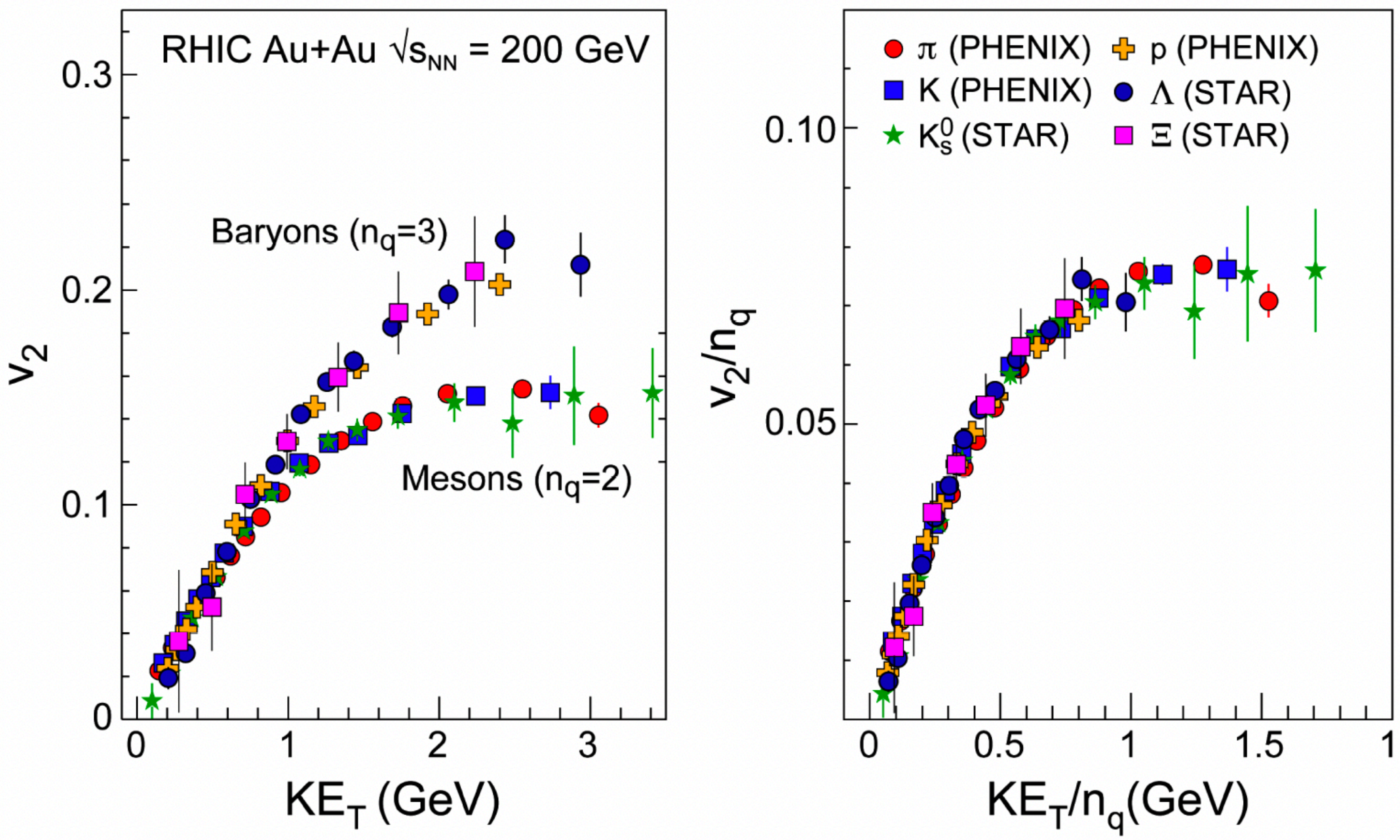
M_c - number of independent particles' clusters.

Different particles species



Phys. Rev. Lett. 116 (2016), 062301

Phys. Scripta 78, 028005 (2008)



Further evidence of partonic collectivity:

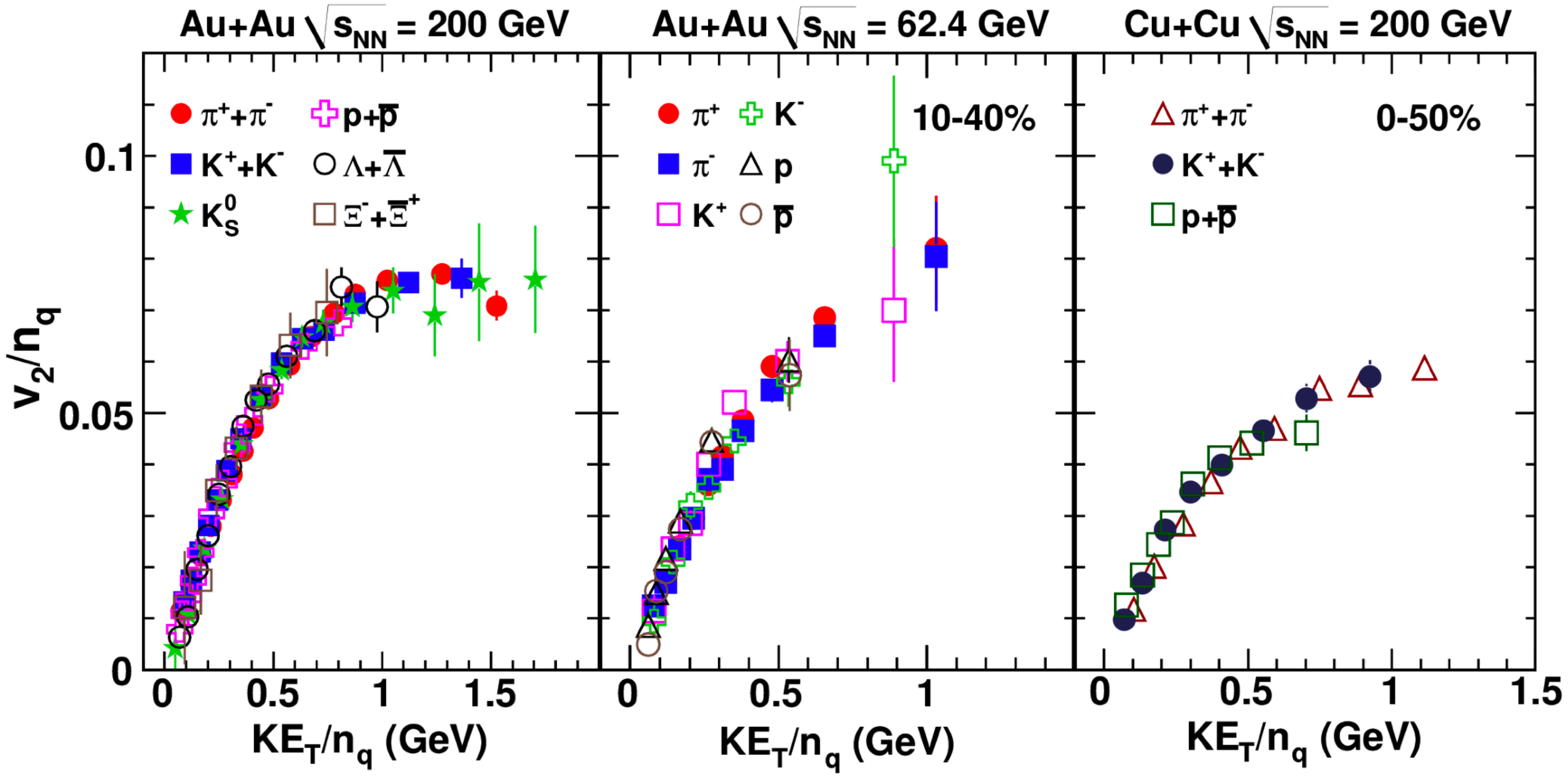
ϕ mesons heavy as protons, behave like other mesons;

- The number of quarks is important, not the mass;
- Heavier ***s*** quarks flow as strongly as light ***u*** and ***d***;

- v_2 **scales with** n_q (**N**umber of **C**onstituent **Q**uarks) (2→ mesons, 3 →baryons);
- **Evidence of partonic collectivity - quarks flow in QGP.**

- Flow is partonic (developed at quark level) and universal;
- Quarks, gluons interpreted as DoF involved in flow;
- Partonic collectivity - one of key QGP signature.

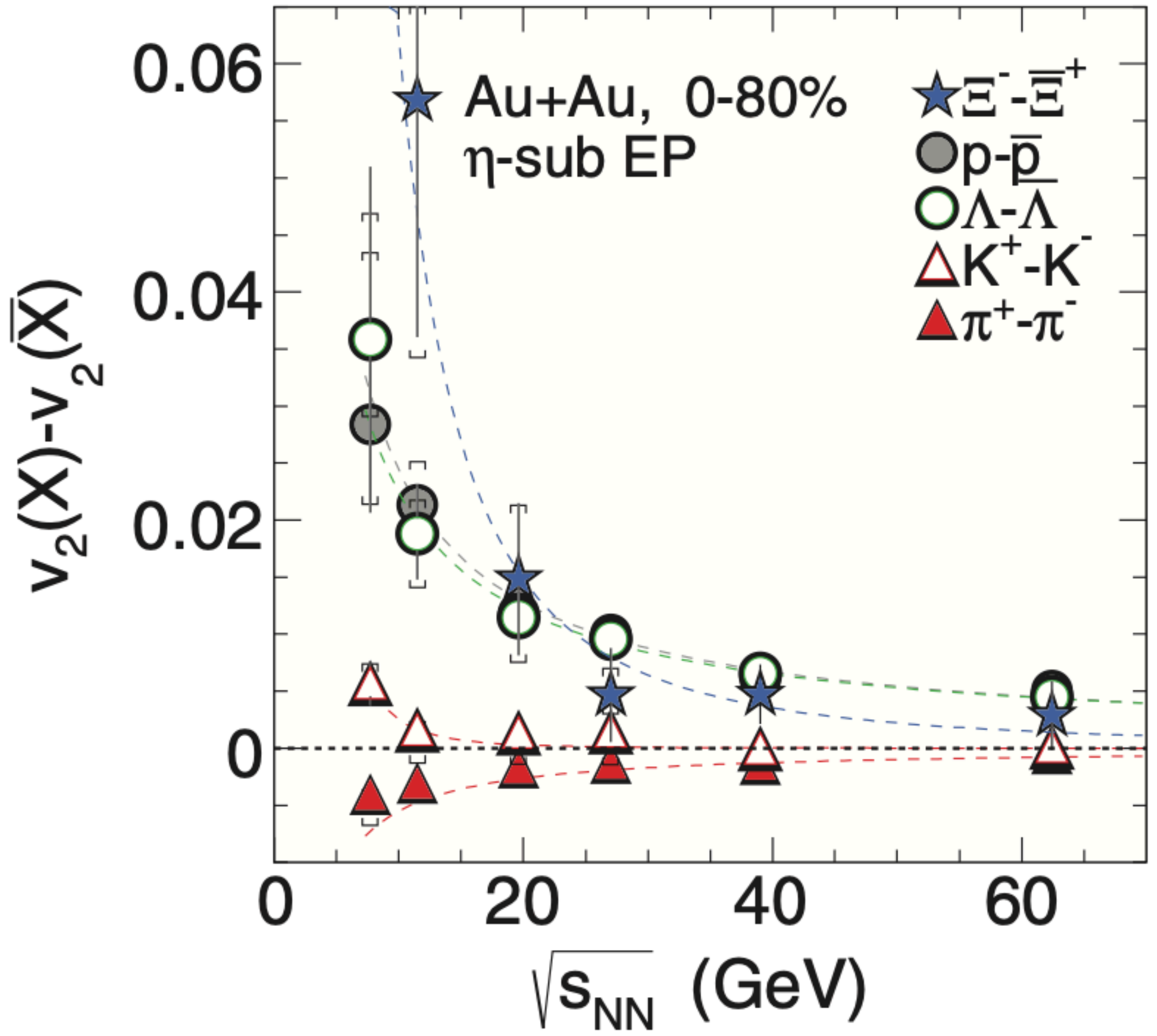
Different systems and $\sqrt{s_{NN}}$



STAR, PRL 111, 052301 (2013)

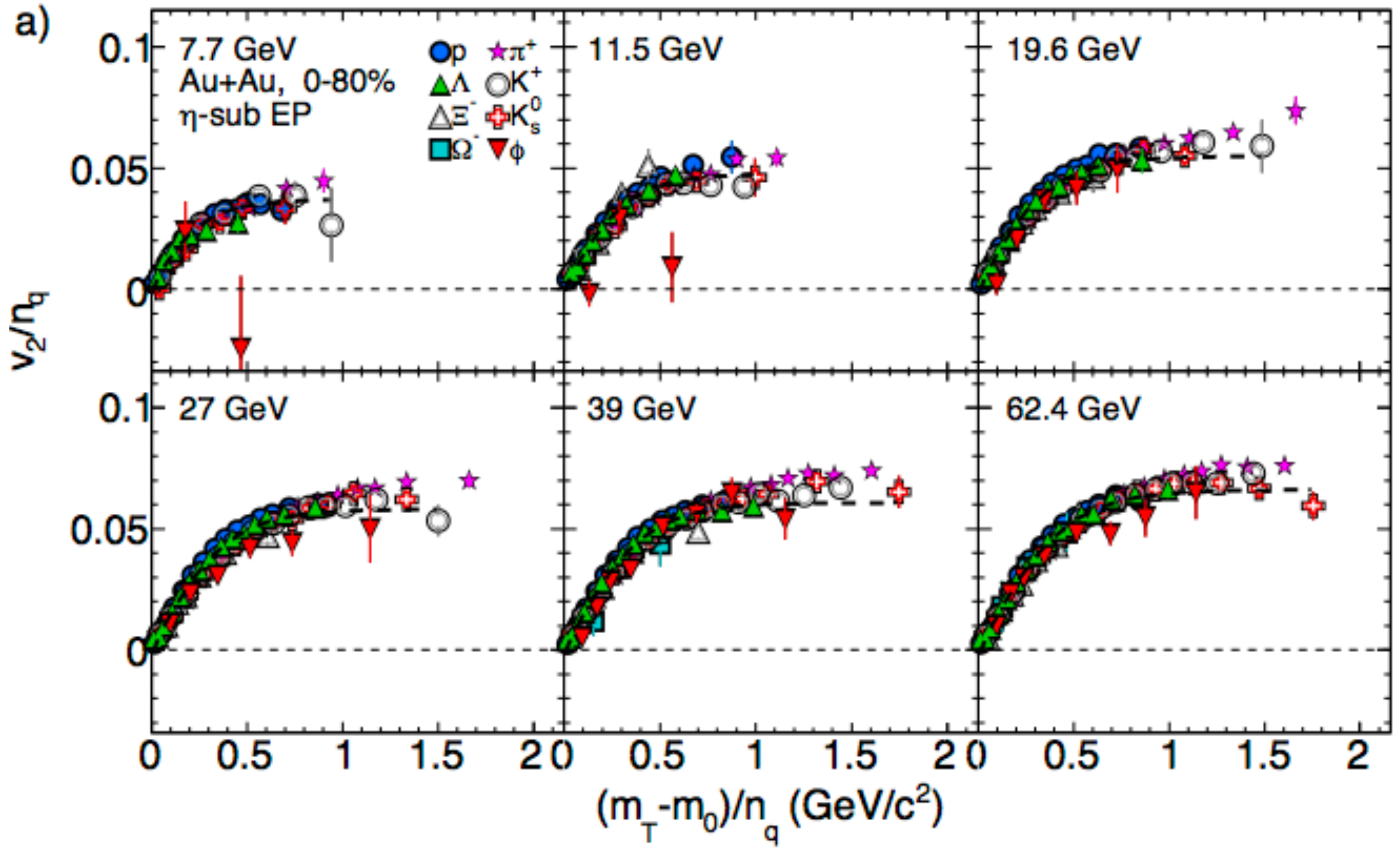
What energies can we go down to still see NCQ scaling?

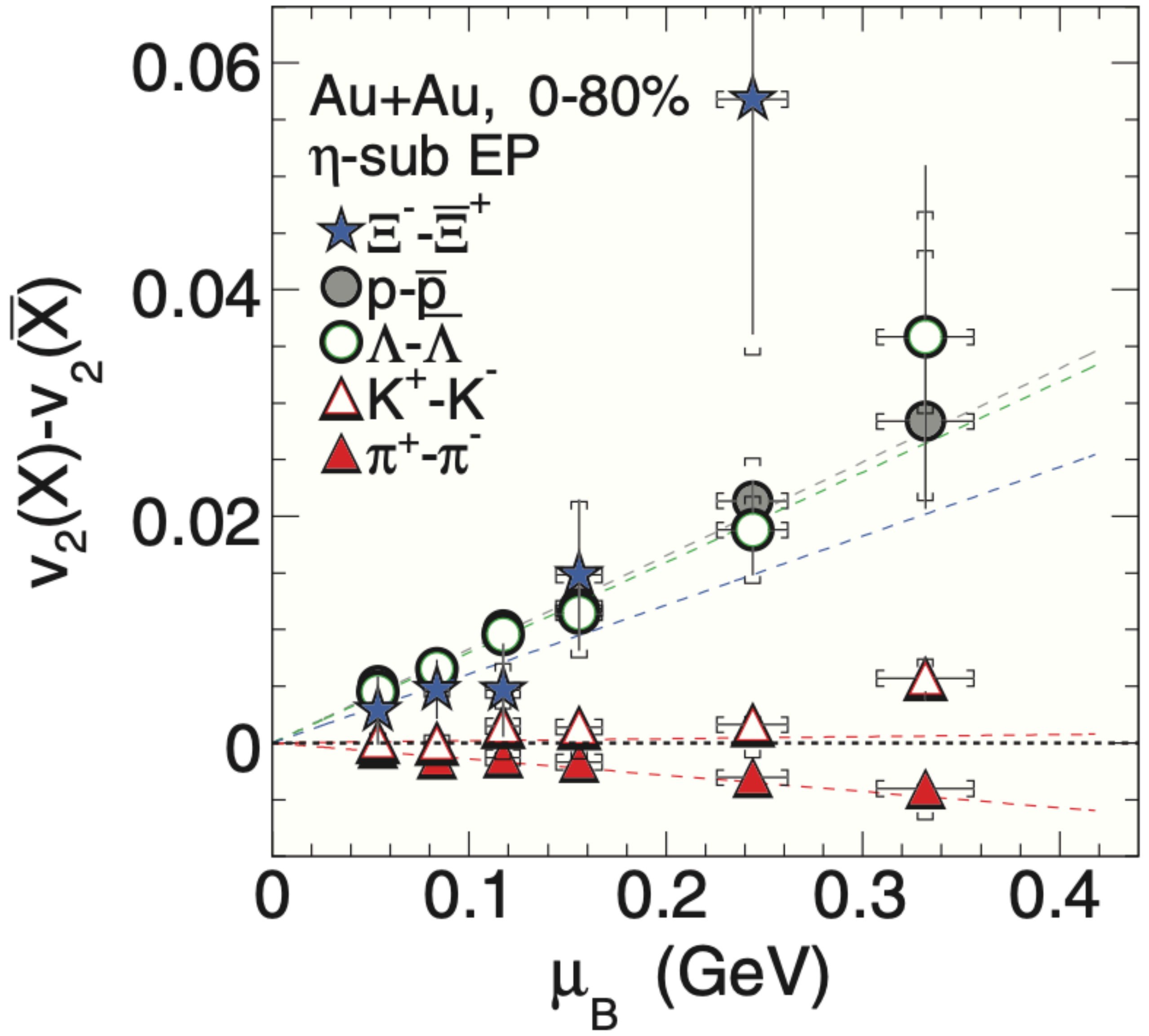
Energy dependence



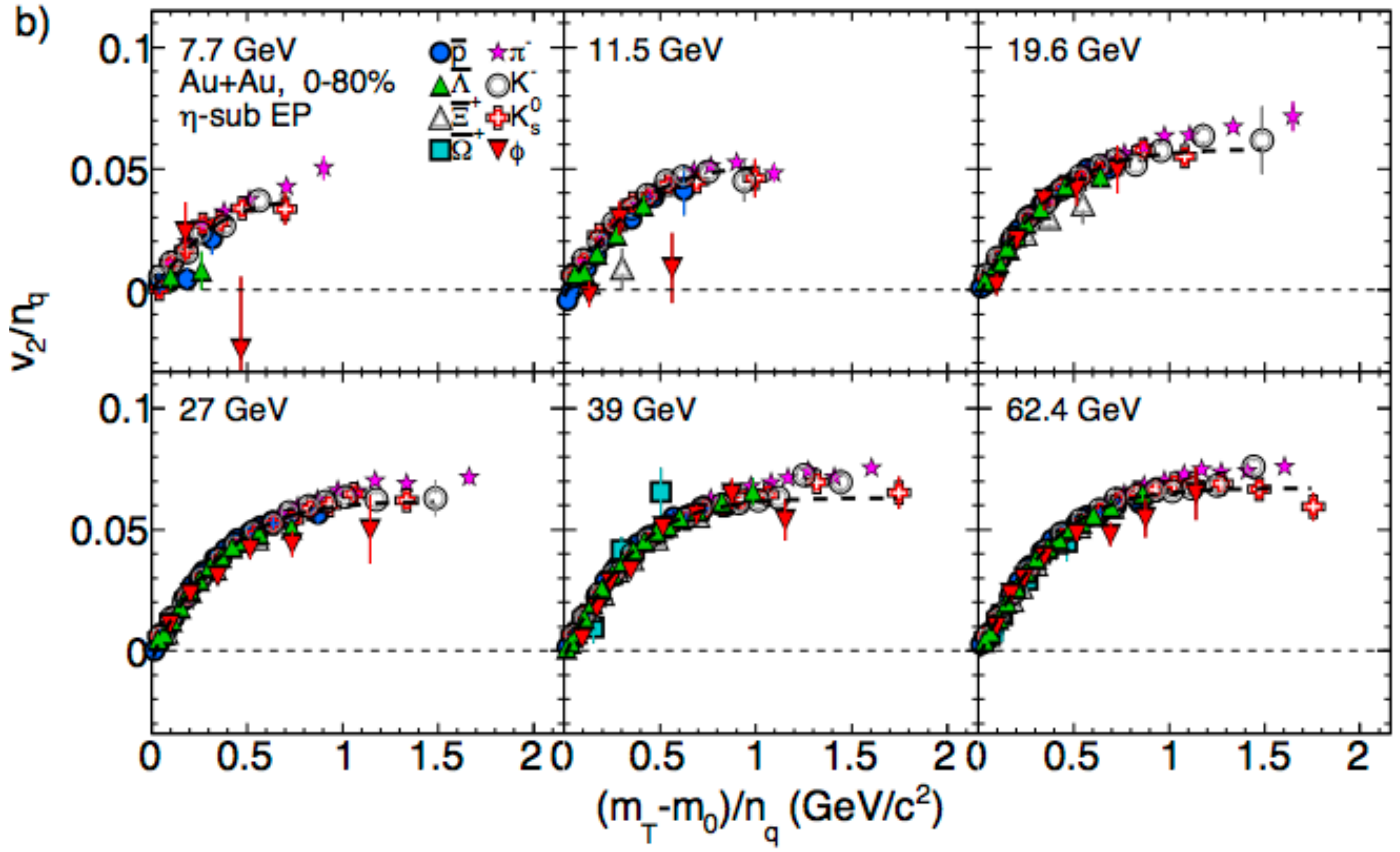
$v_2(KE)$ scales universally;

- ϕ meson v_2 falls the trend from other hadrons at $\sqrt{s_{NN}}$ = 11.5 GeV, (low statistics);
- NCQ scaling between particles is broken and consistent with hadronic interactions becoming dominant.





- $v_2(X) - v_2(\bar{X})$ positive, except mesons π (hadronic interactions at low energies);
- **Significant difference between baryon-antibaryon v_2.**



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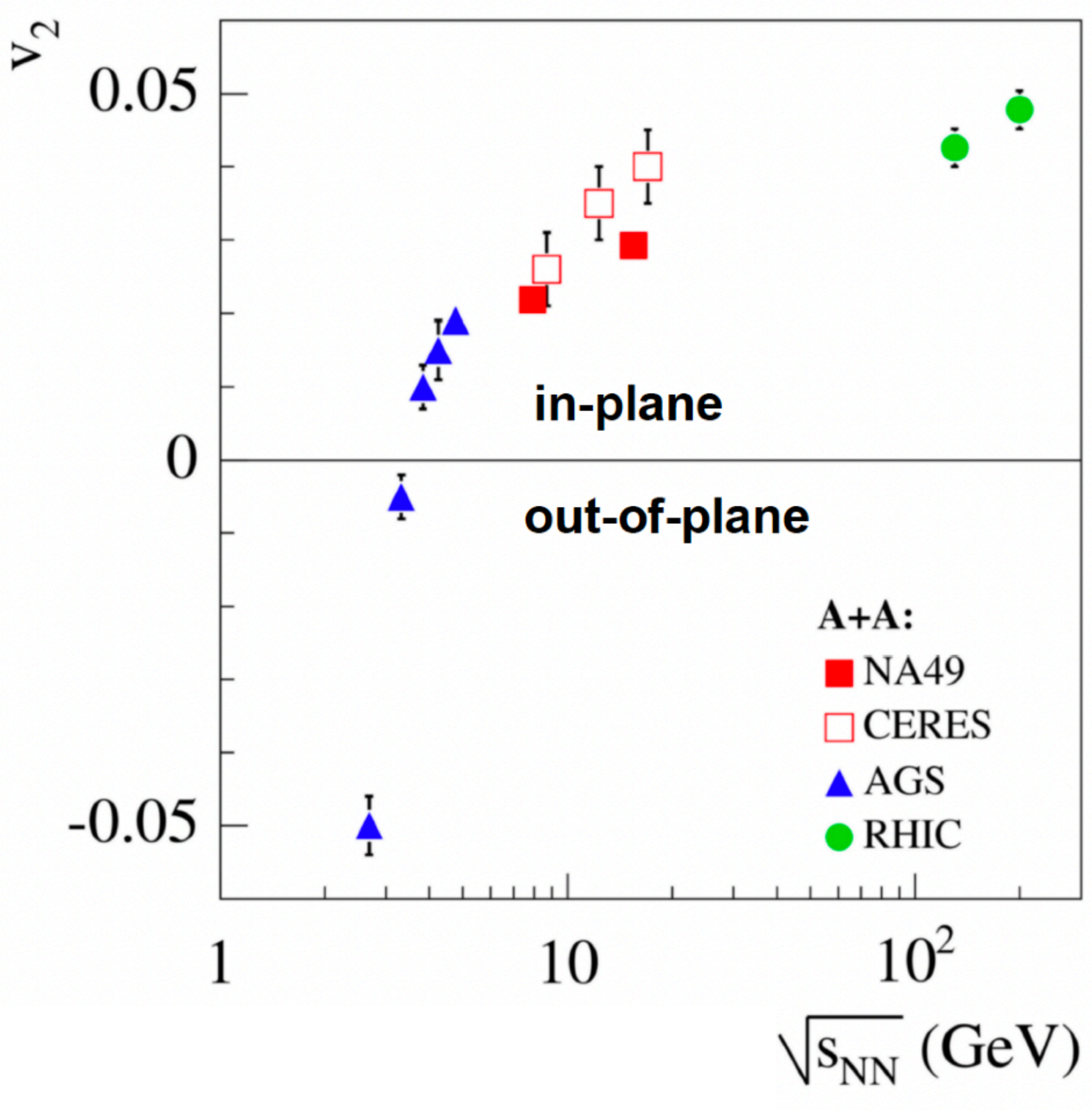
Phys. Rev. C 93, 014907 (2016)
Phys. Rev. Lett. 116, 062301 (2016)

$\sqrt{s_{NN}}$ dependence of elliptic flow

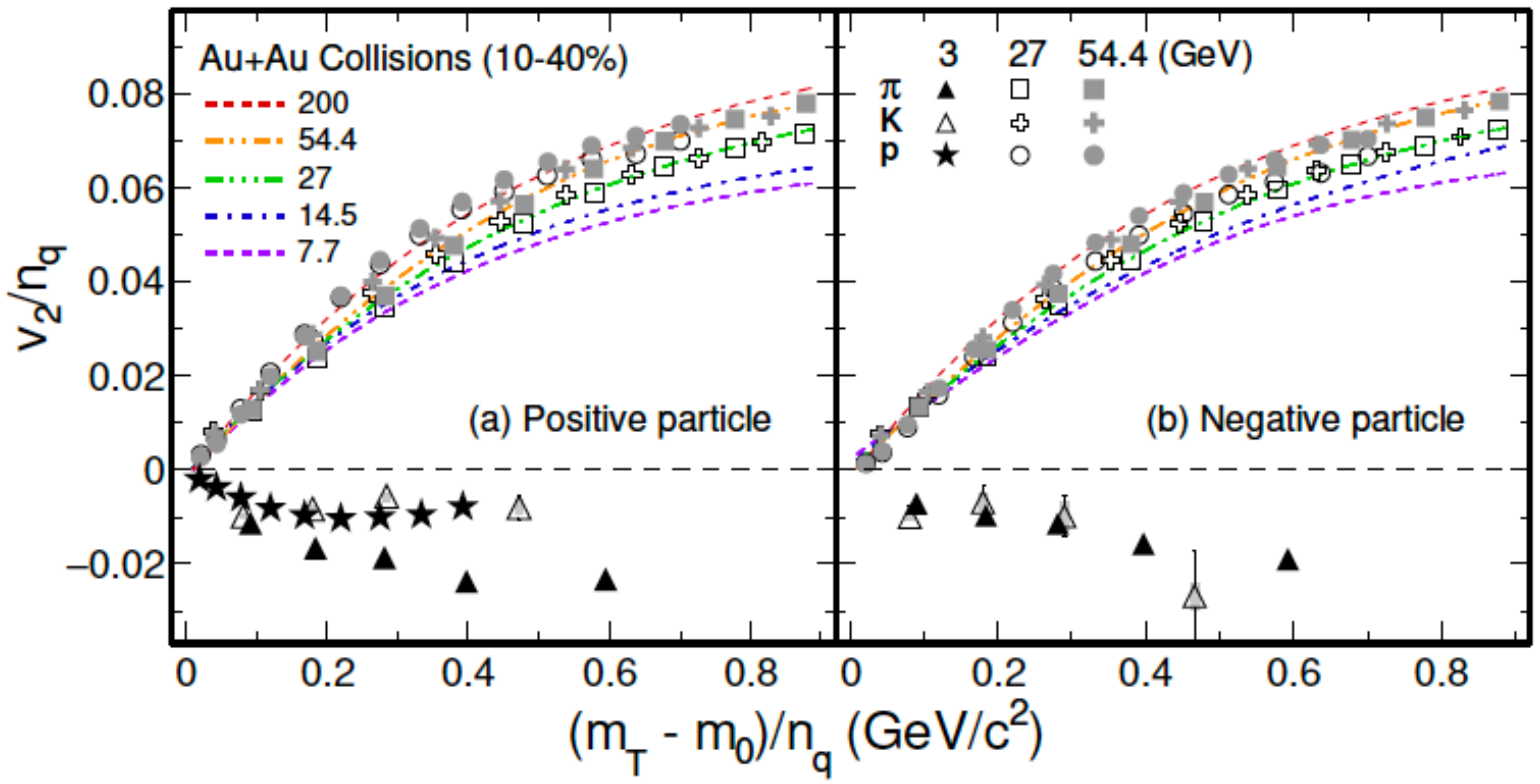
Positive v_2: at higher energies, the collision **spectator** fragments immediately **escape** from the area of interactions, nothing stops the development of v_2

Negative v_2: at low energies, fragments of **spectators** (do **not** immediately **escape** from the area of interactions) inhibit the production of particles in-plane. To get rid of the pressure gradient, the fireball produces particles in an out-plane direction (negative v_2 values).



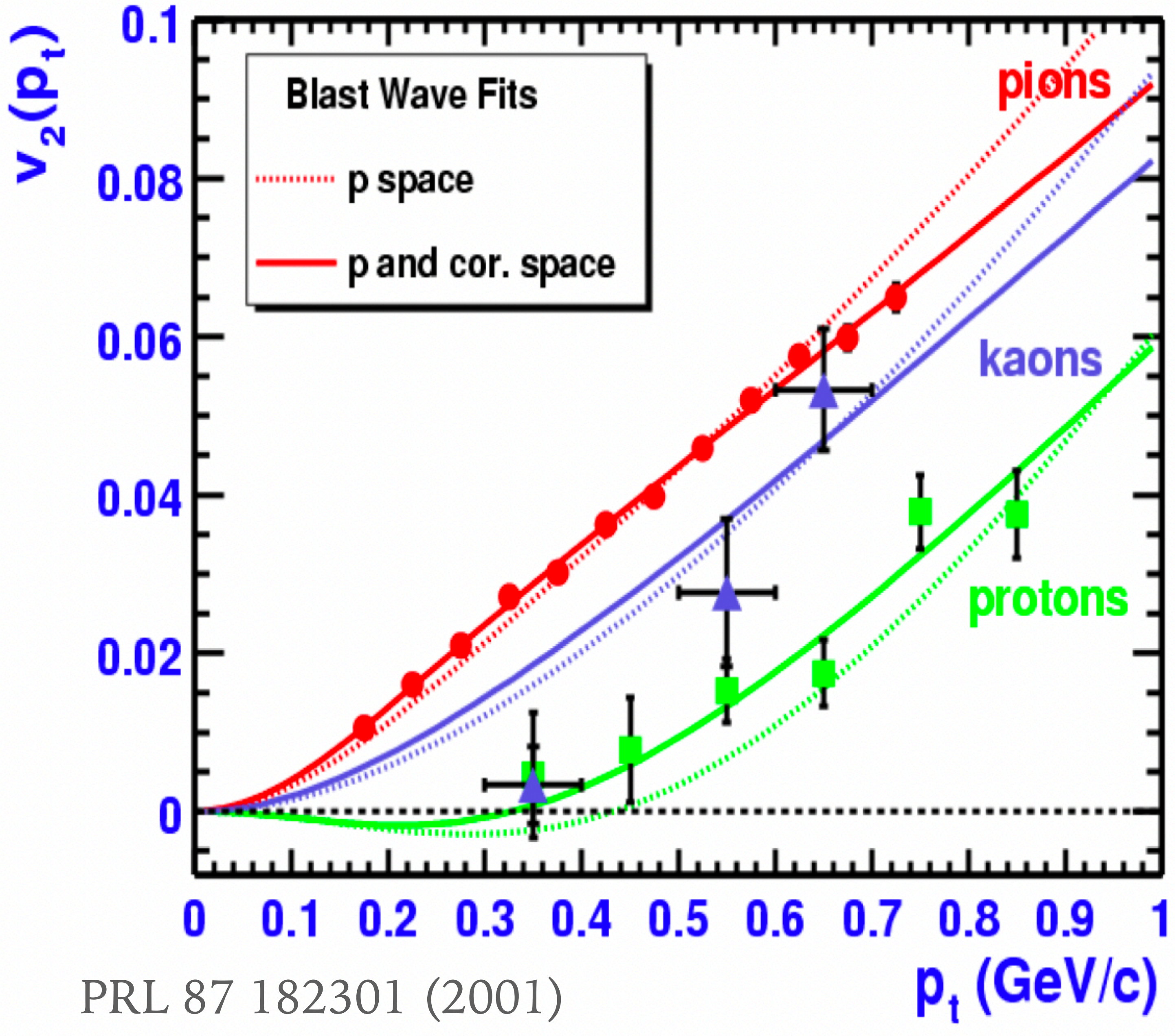
- $v_2 > 0 \rightarrow$ formation of the **QGP**, scaling of NCQ
- v_2 <0, slope of the v_1 <0 ($\sqrt{s_{NN}} = 3$ GeV) $\rightarrow$ NCQ scaling absent $\rightarrow$ **hadronic** system

Phys. Lett. B **827** (2022) 137003



Hydrodynamics

Hydrodynamic description of v_2

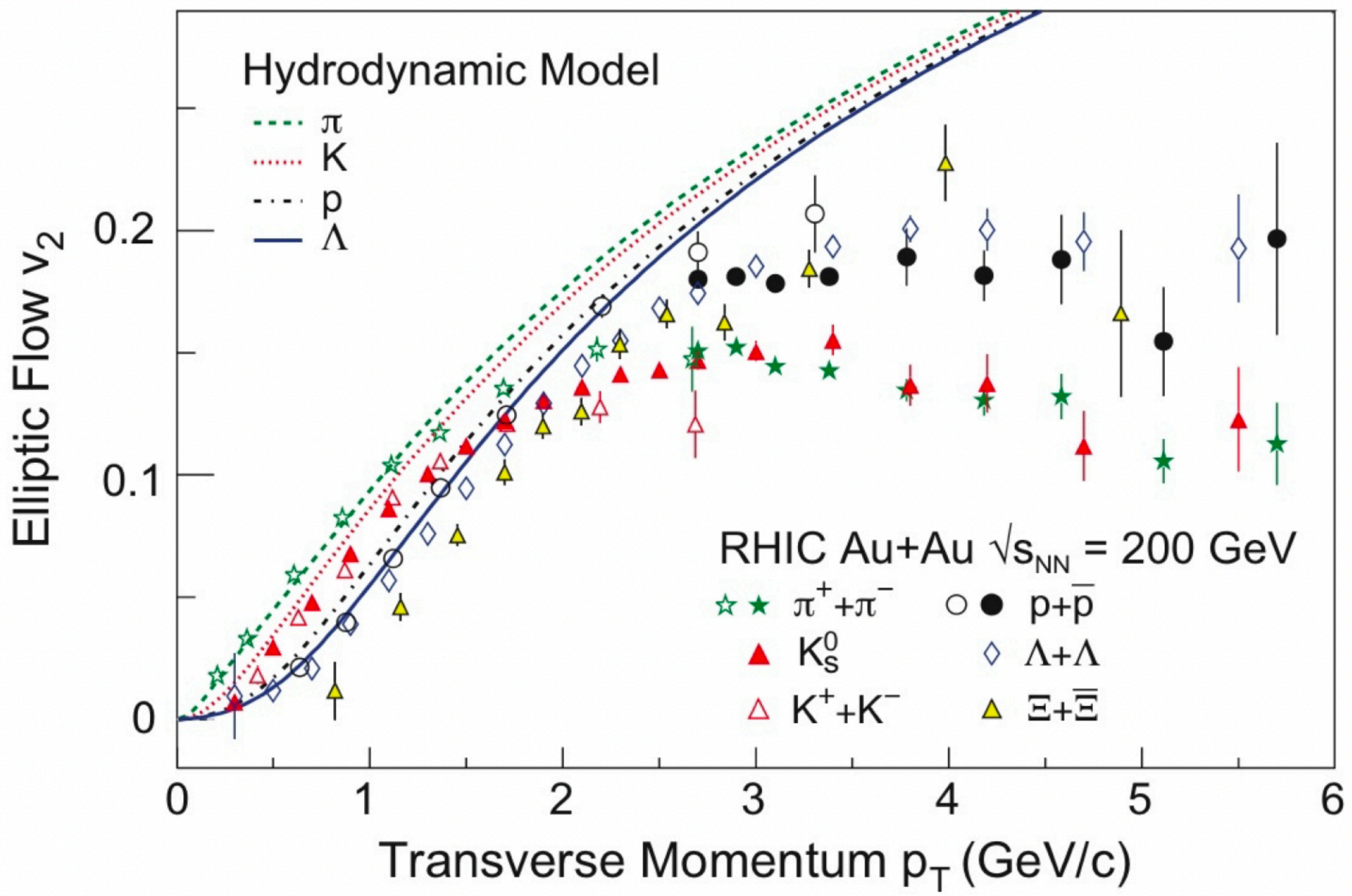


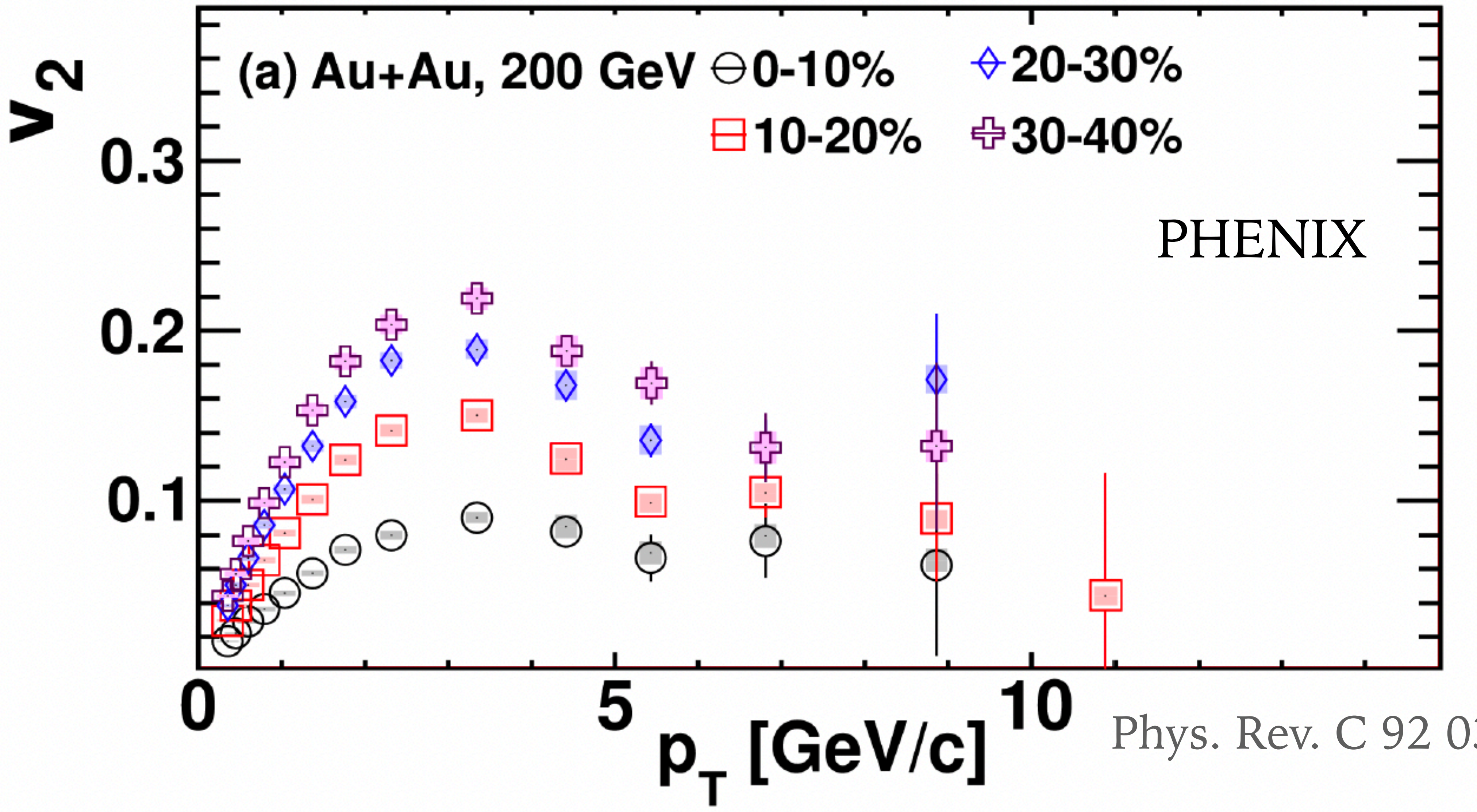
PRL 87 182301 (2001)

Visible **mass hierarchy** (small p_T) - reproduced by hydrodynamic models ($\pi \to K \to p \to \ldots$); the same p_T, heavier hadrons show smaller v_2.

- Smaller p_T: bulk matter;
- Higher p_T: mostly jets;

Acta Phys. Polon.B38 (2007) 3705

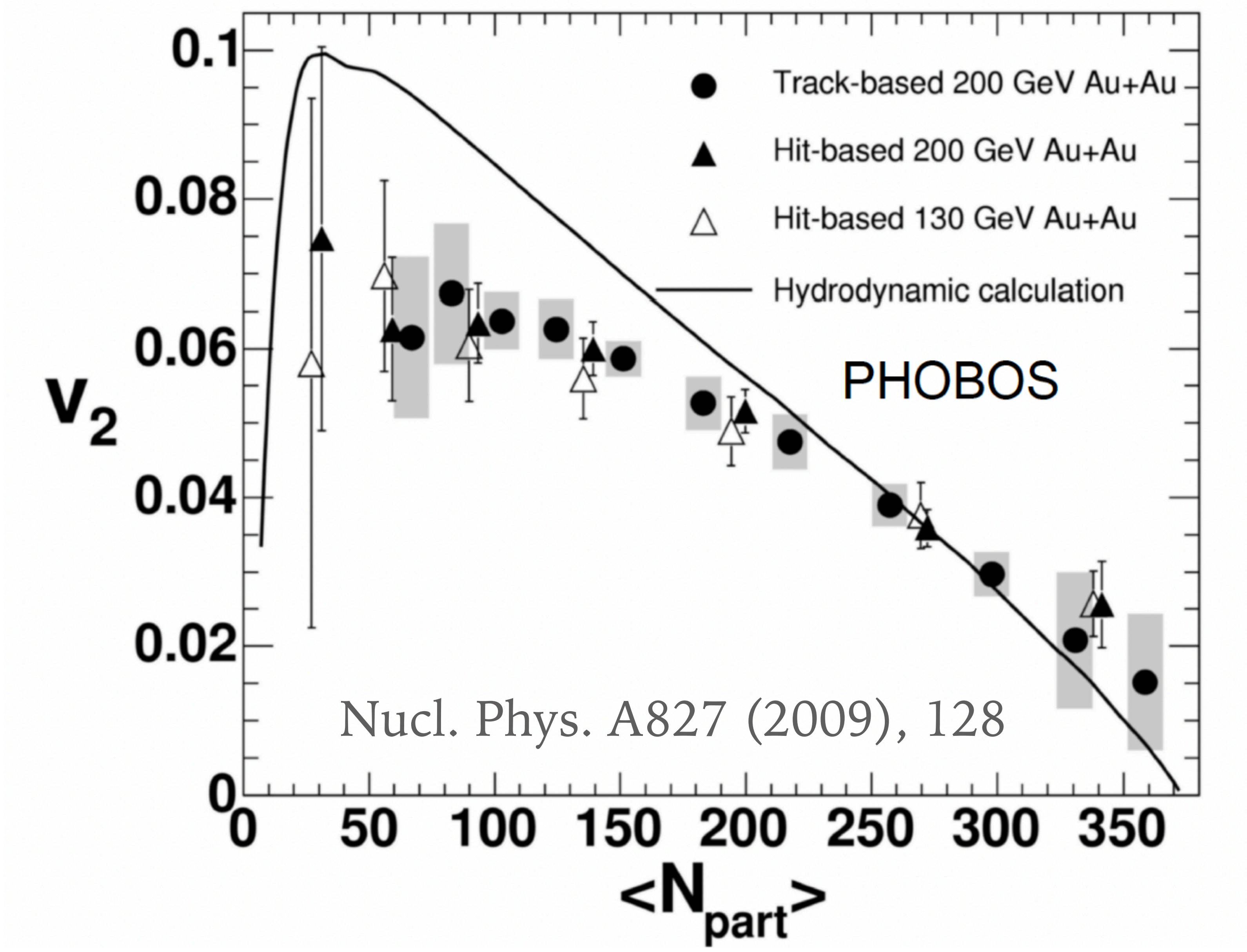


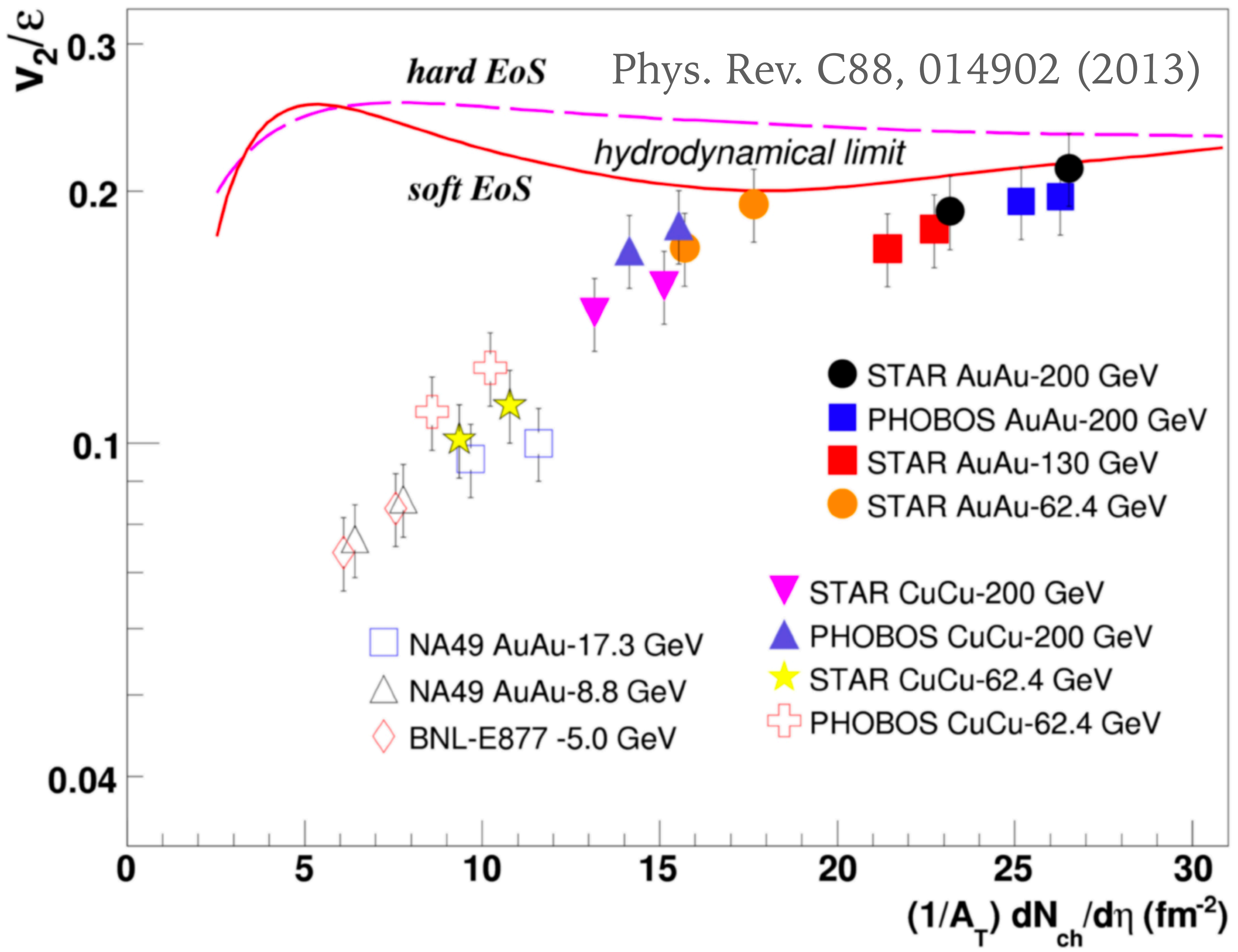


Phys. Rev. C 92 03491 (2015)

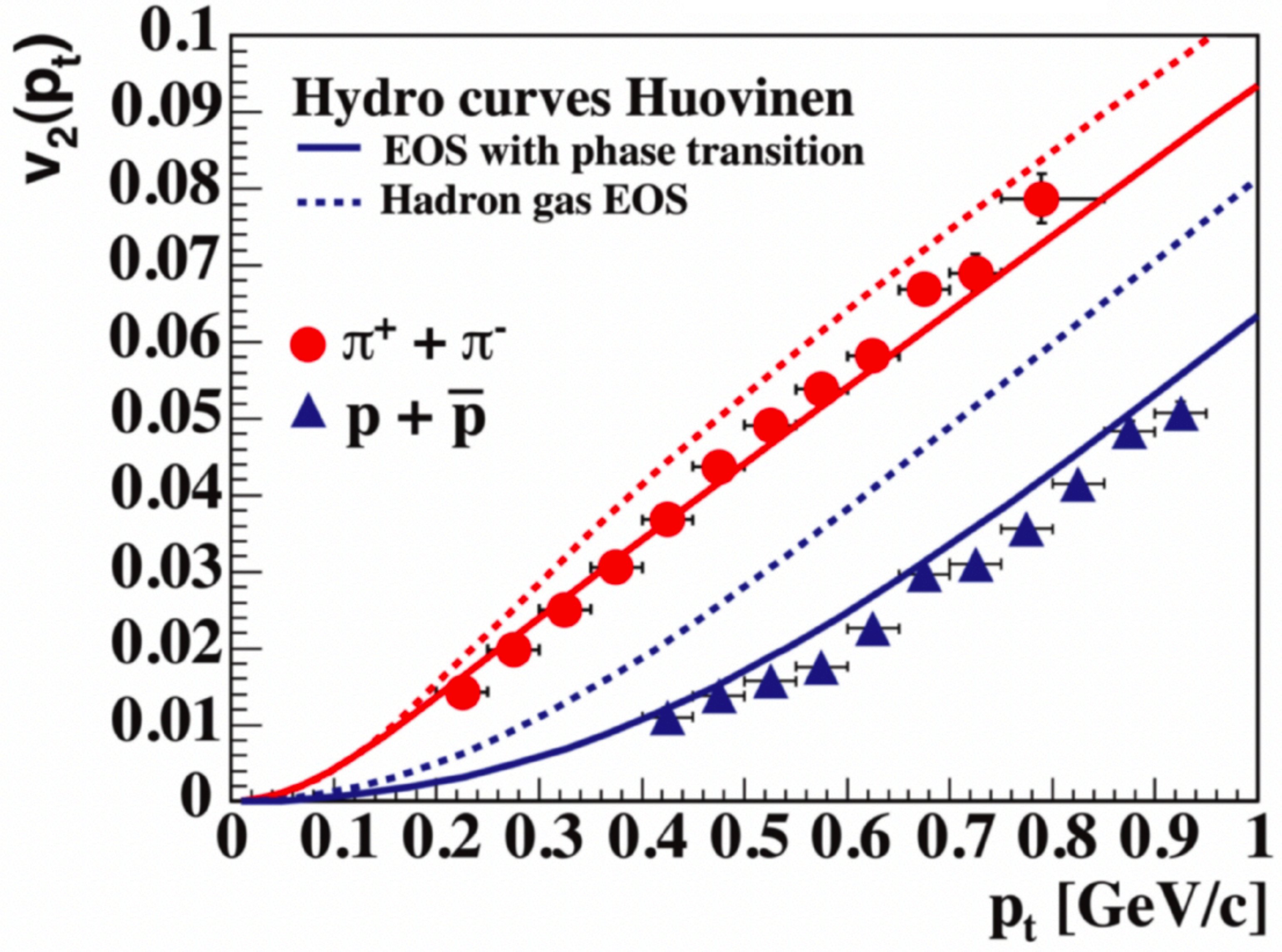
- $p_T < 1.5 - 2$ **GeV/c**: hydrodynamic models agree with data:
  - QGP is almost ideal liquid;
  - very small viscosity;
  - assumed rapid thermalization;
  - matter equilibrium $\sim 0.6 - 1$ *fm/c;*
  - energy densities ~*15–30 GeV/fm*^{3};
  - EoS similar to the predictions of LQCD);
- $p_T \simeq 2$ **GeV/c:** flow deviates from hydrodynamic predictions (mass hierarchy also breaks).

Hydrodynamic limit for v_2





STAR, PRL 86, 402 (2001)



Deviations from hydrodynamic models for the more peripheral (small system) – a consequence of incomplete local thermal equilibrium.

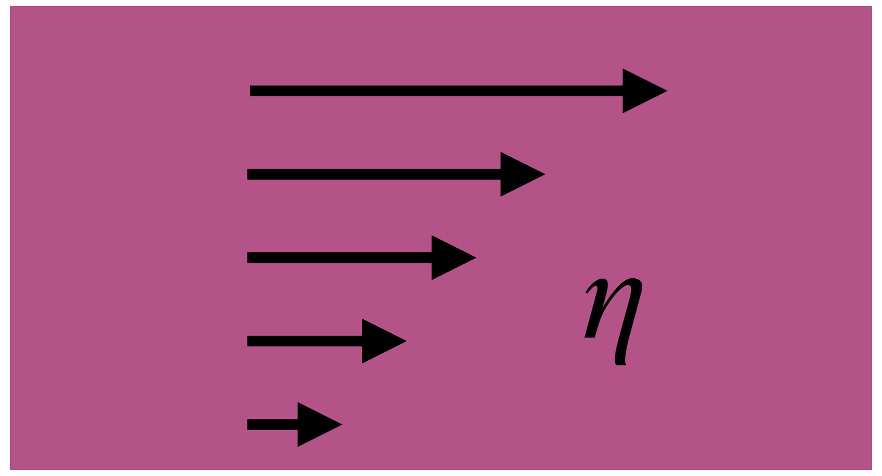
v_2 calculated from hydro enables verification of EoS:

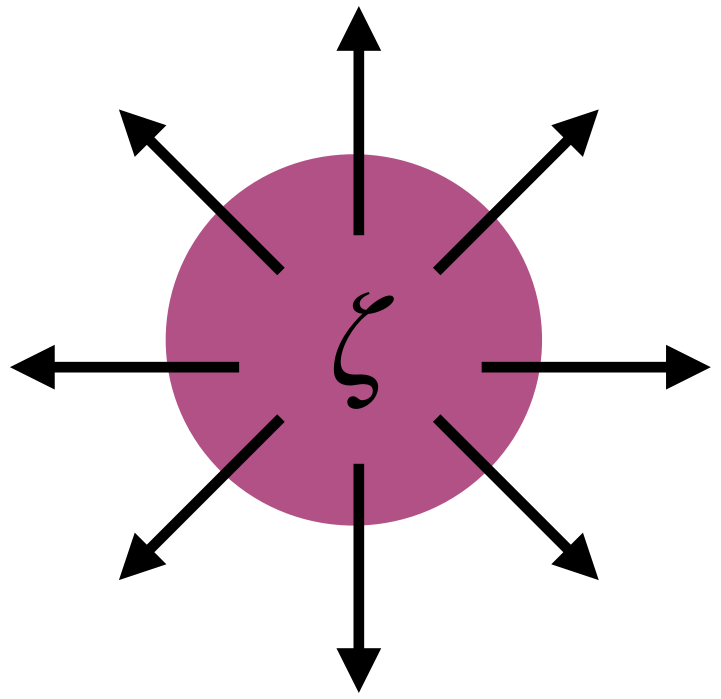
- Possible hard / soft EoS;
- Phase transition / no phase transition EoS.

Ideal gas or perfect liquid?

Ideal hydro: system in local equilibrium
Hydro response is controlled by QCD EoS

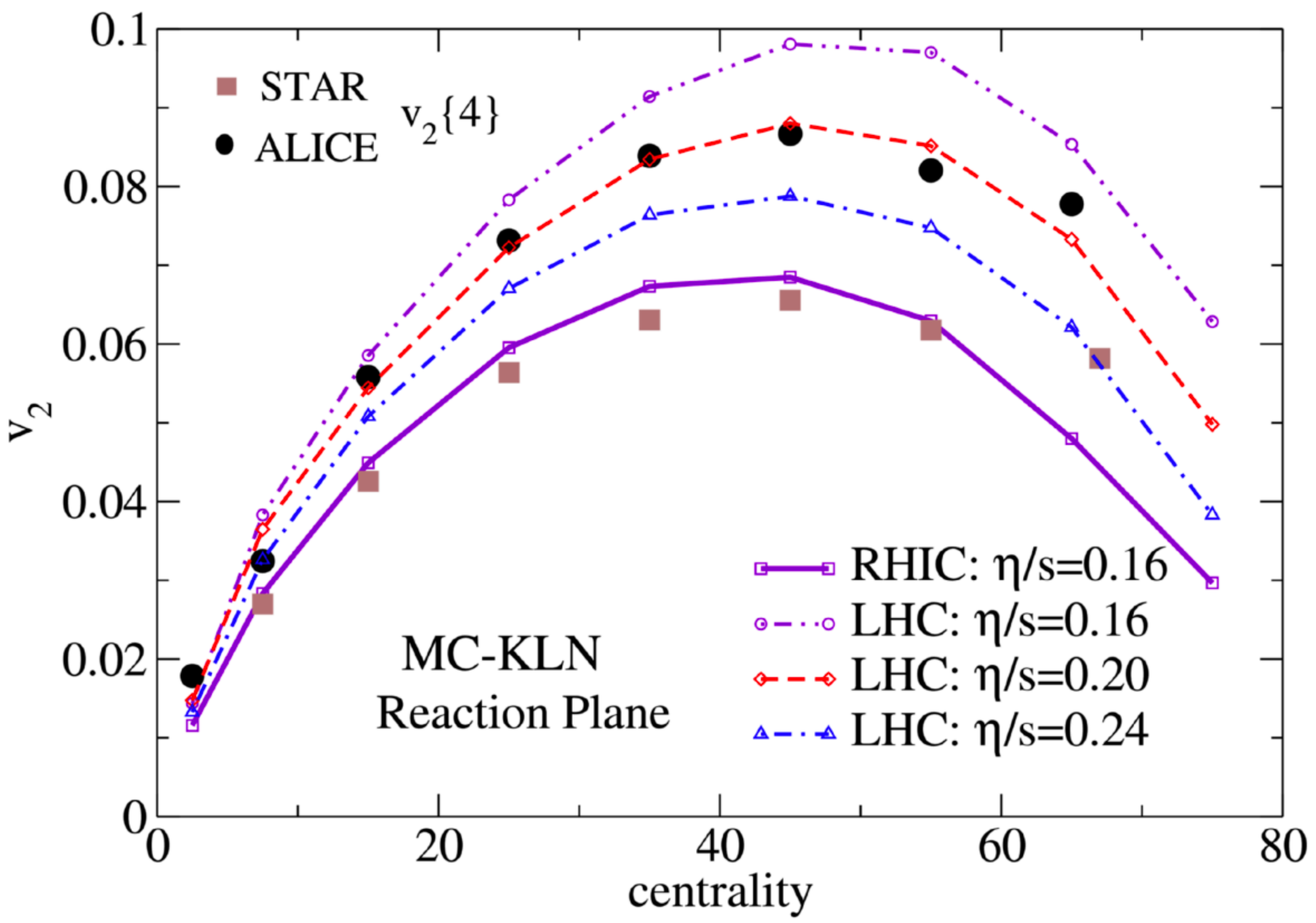
Viscous hydro: includes near-equilibrium corrections
η **- shear viscosity**
ζ **- bulk viscosity**





- Many years ago **QGP** expected as „**ideal gas**" (at least system of very weekly interacting quarks and gluons);
- An observation →QGP closer to „**perfect liquid**" (viscosity close to 0, collective effects);
- $\eta/s \simeq 0.1$ **at RHIC**;

- sQGP - strongly interacting QGP;
- wQGP - weakly coupled gas; (models predicts in case of wQGP η/s would have bigger values, non-zero viscosity reduces collectivity - v_2)



$\eta/s \simeq 0.16$ **(RHIC)**
$\eta/s \simeq 0.20 - 0.24$ **(LHC)**

(difficult to determine $0.08 < \eta/s < 0.2$, depending on the initial conditions, and EoS in the model).

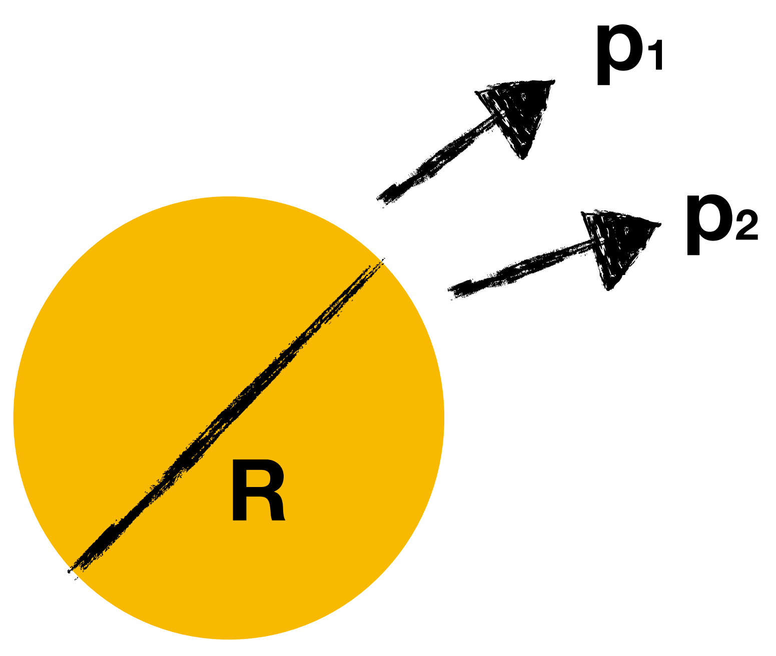
More: arXiv:1712.05815

Correlations (femtoscopy)

Introduction

Traditional and non-traditional femtoscopy

Femtoscopy (originating from HBT):
the method to probe geometric and dynamic properties of the source



Space-time properties ($10^{-15}m$, $10^{-23}s$) can be determined due to two-particle correlations that arise due to:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

$$C(k^*, r^*) = \int \overbrace{S(r^*)}^{\text{determined}} |\overbrace{\Psi(k^*, r^*)}^{\text{assumed}}|^2 d^3r^* = \overbrace{\frac{Sgnl(k^*)}{Bckg(k^*)}}^{\text{measured}}$$

Pairs from the same collision

Pairs from different collisions

$S(r^*)$ - source function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

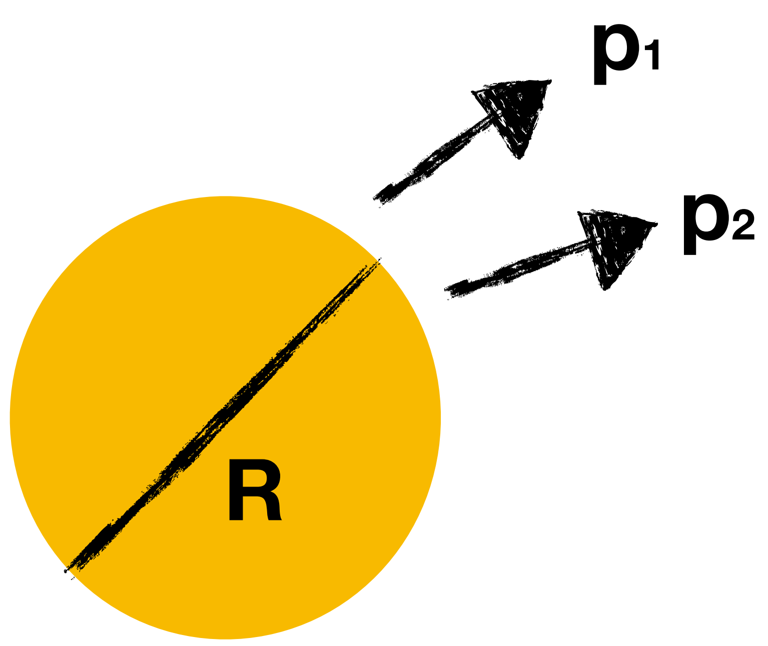
$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

$q, q_{inv}, k^* \rightarrow$ pair-momentum component (depending of the reference frame)

Traditional and non-traditional femtoscopy

2023

If we assume we know the emission/source function, measured correlation function used to determine parameters of Final State Interactions



Space-time properties $(10^{-15}m,\ 10^{-23}s)$ can be determined due to two-particle correlations that arise due to:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

assumed | determined | measured

$$C(k^*, r^*) = \int S(r^*)|\Psi(k^*, r^*)|^2 d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

Pairs from the same collision

Pairs from different collisions

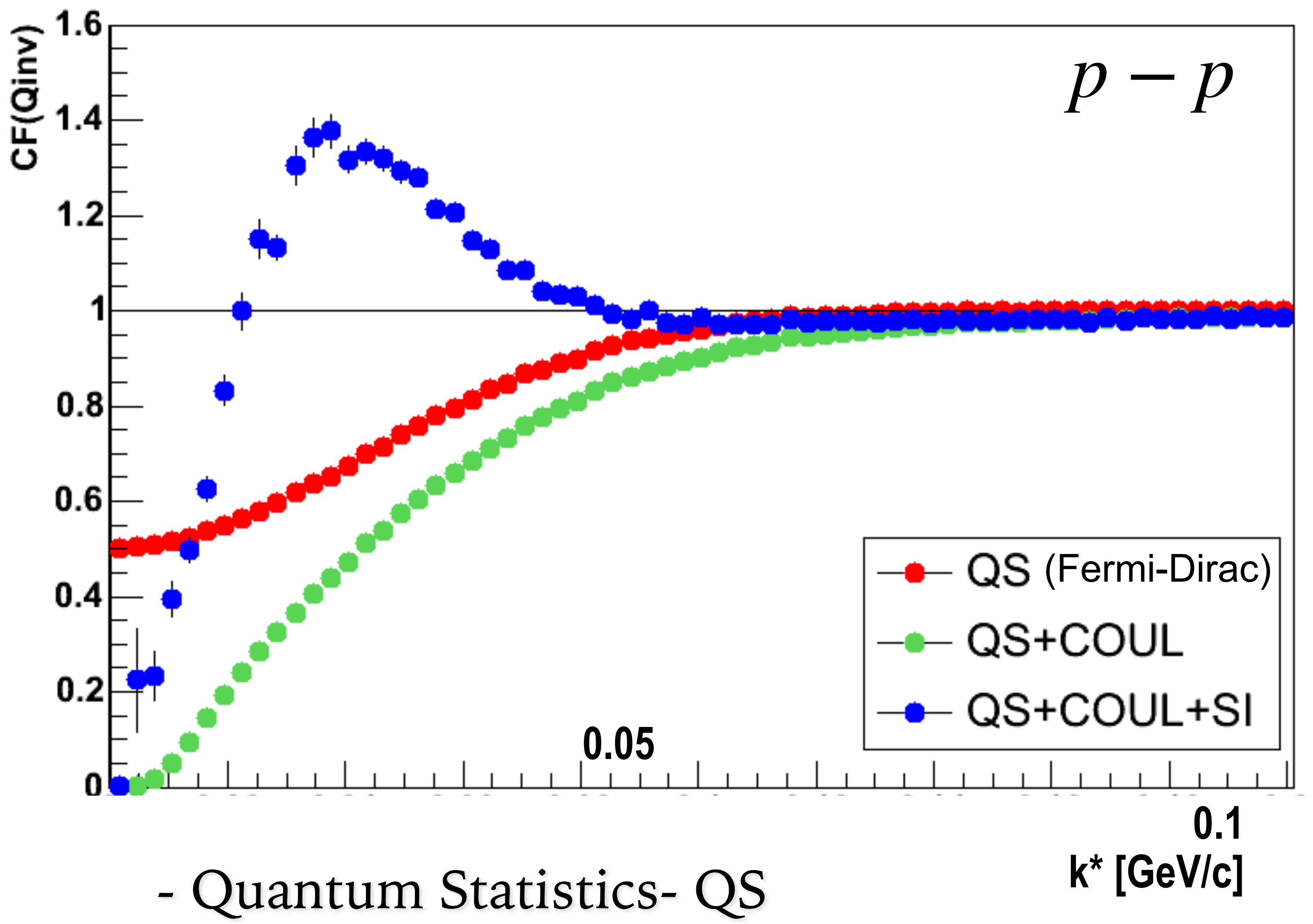
$S(r^*)$ - source function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

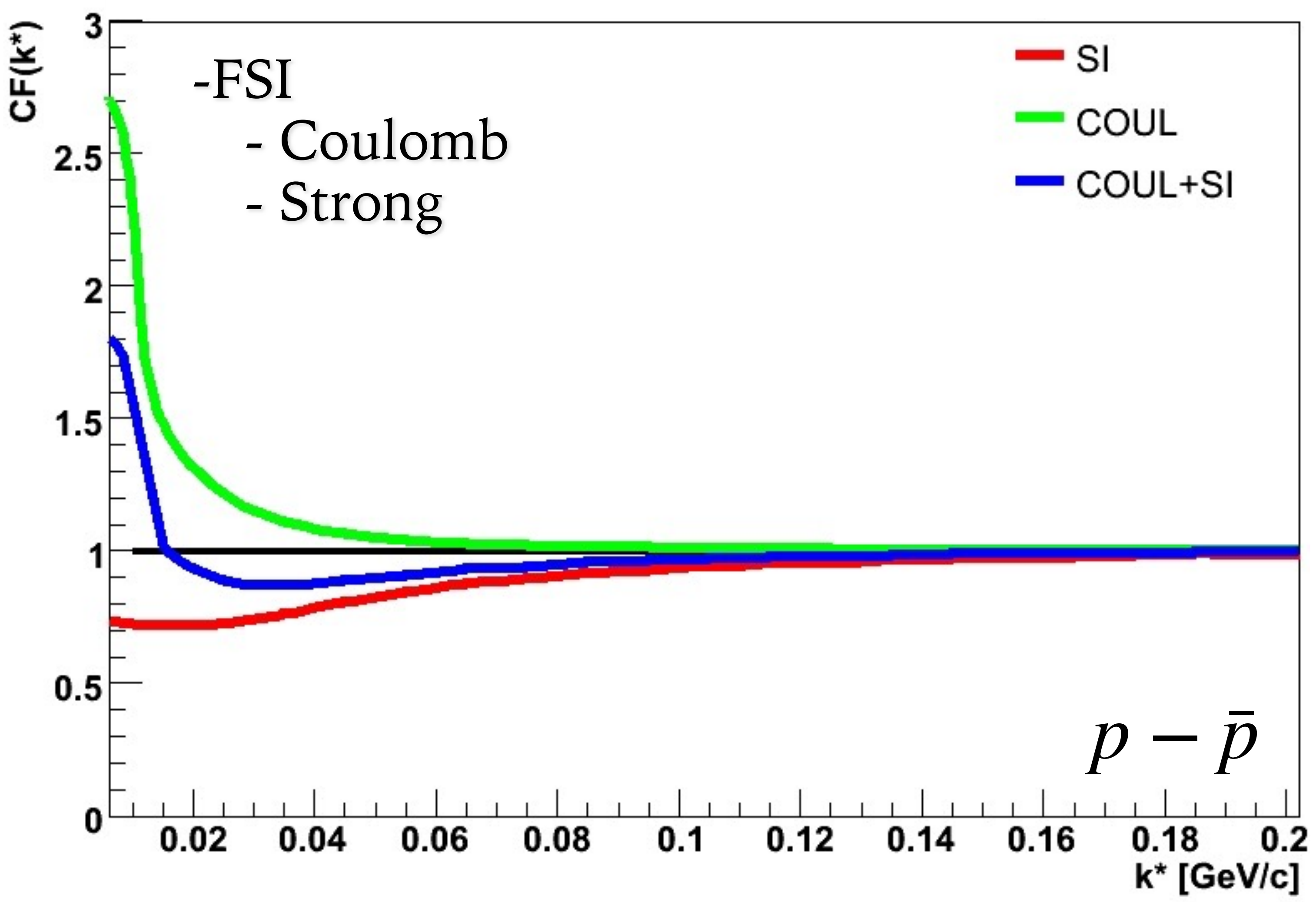
$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

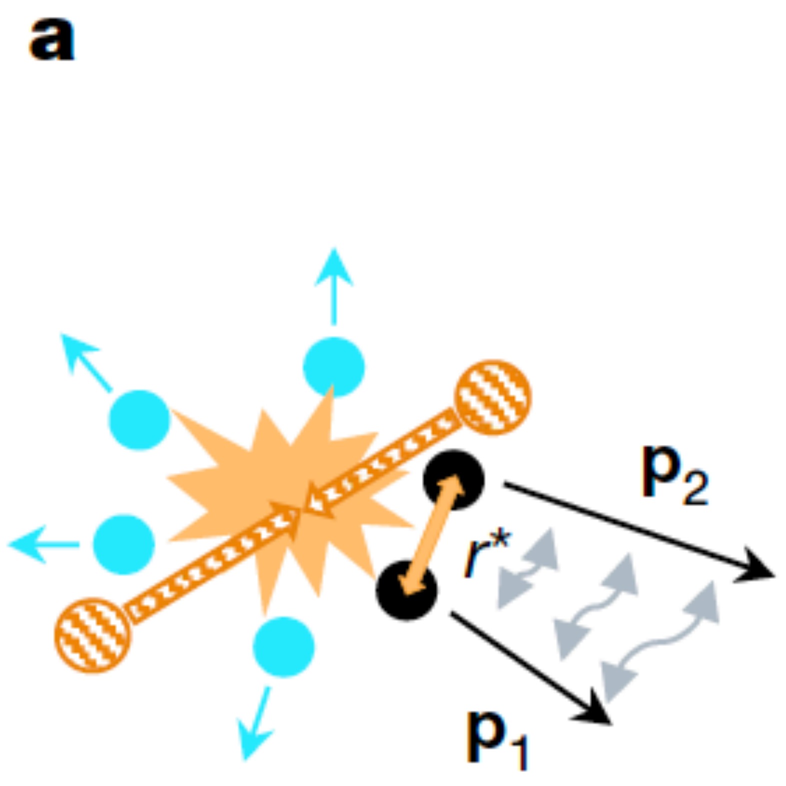
$q, q_{inv}, k^* \rightarrow$ pair-momentum component (depending of the reference frame)

Traditional and non-traditional femtoscopy

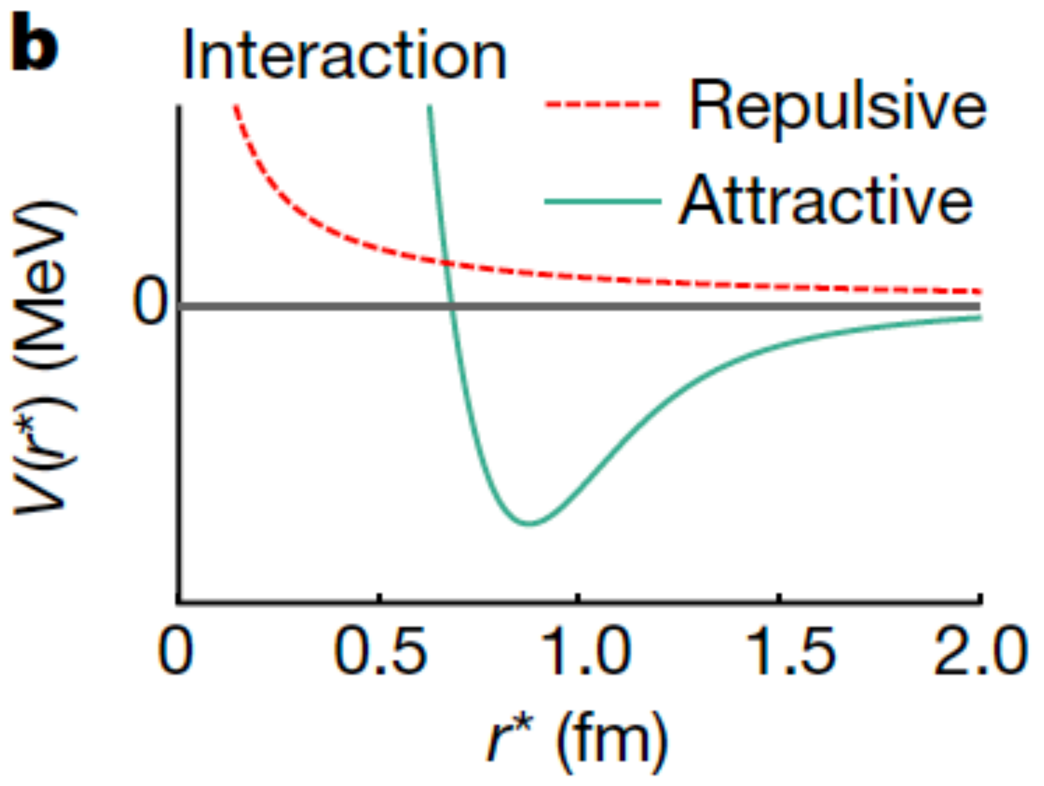


- Quantum Statistics- QS
- Final State Interactions
  - Coulomb
  - Strong





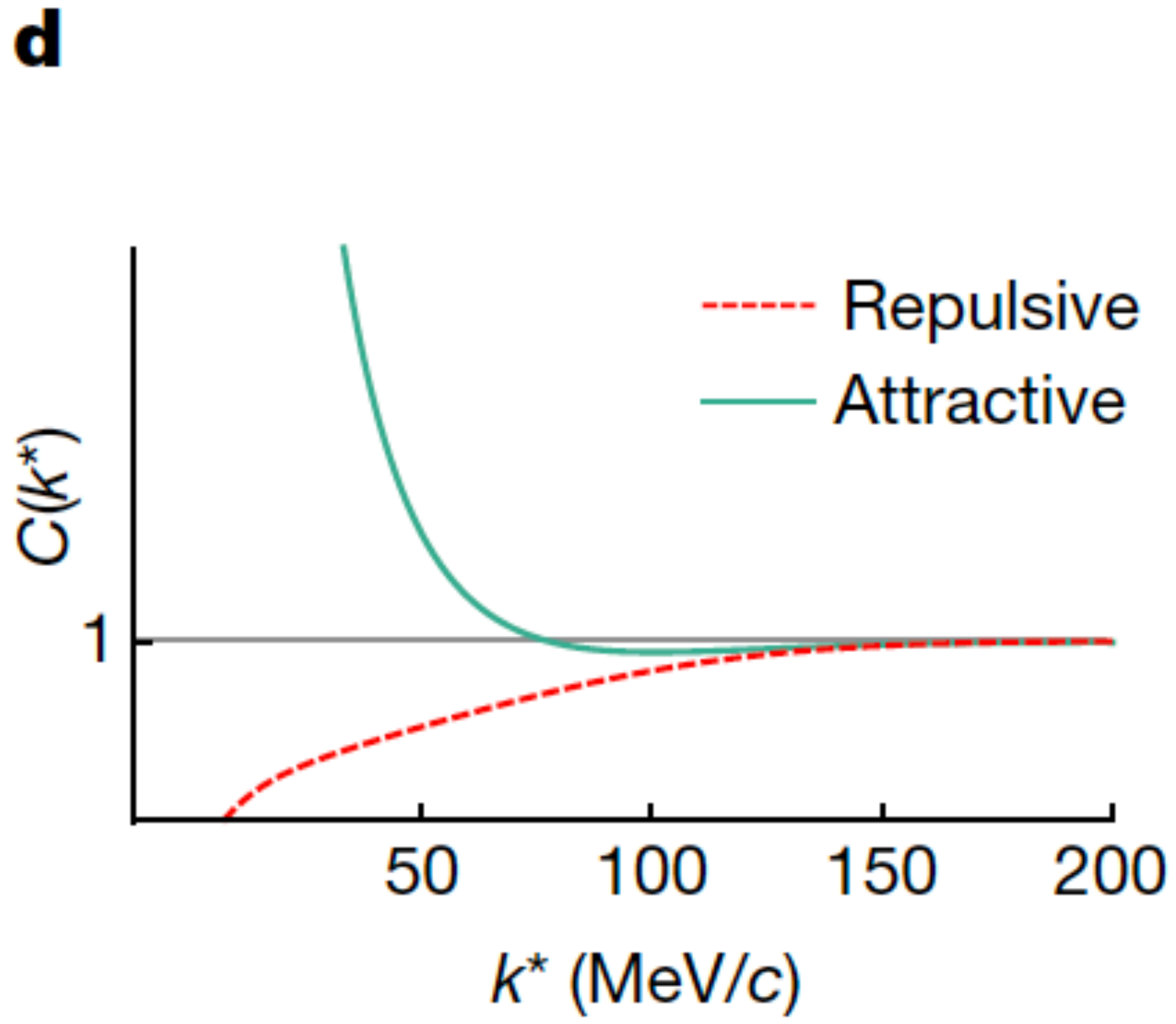
Emission source $S(r^*)$



Schrödinger equation

Two-particle wavefunction

$|\psi(\mathbf{k}^*, \mathbf{r}^*)|$



Correlation function

c

$$C(k^*, r^*) = \int S(r^*)\,|\Psi(k^*, r^*)|^2 d^3r^* = \frac{Sgnl(k^*)}{Bckg(k^*)}$$

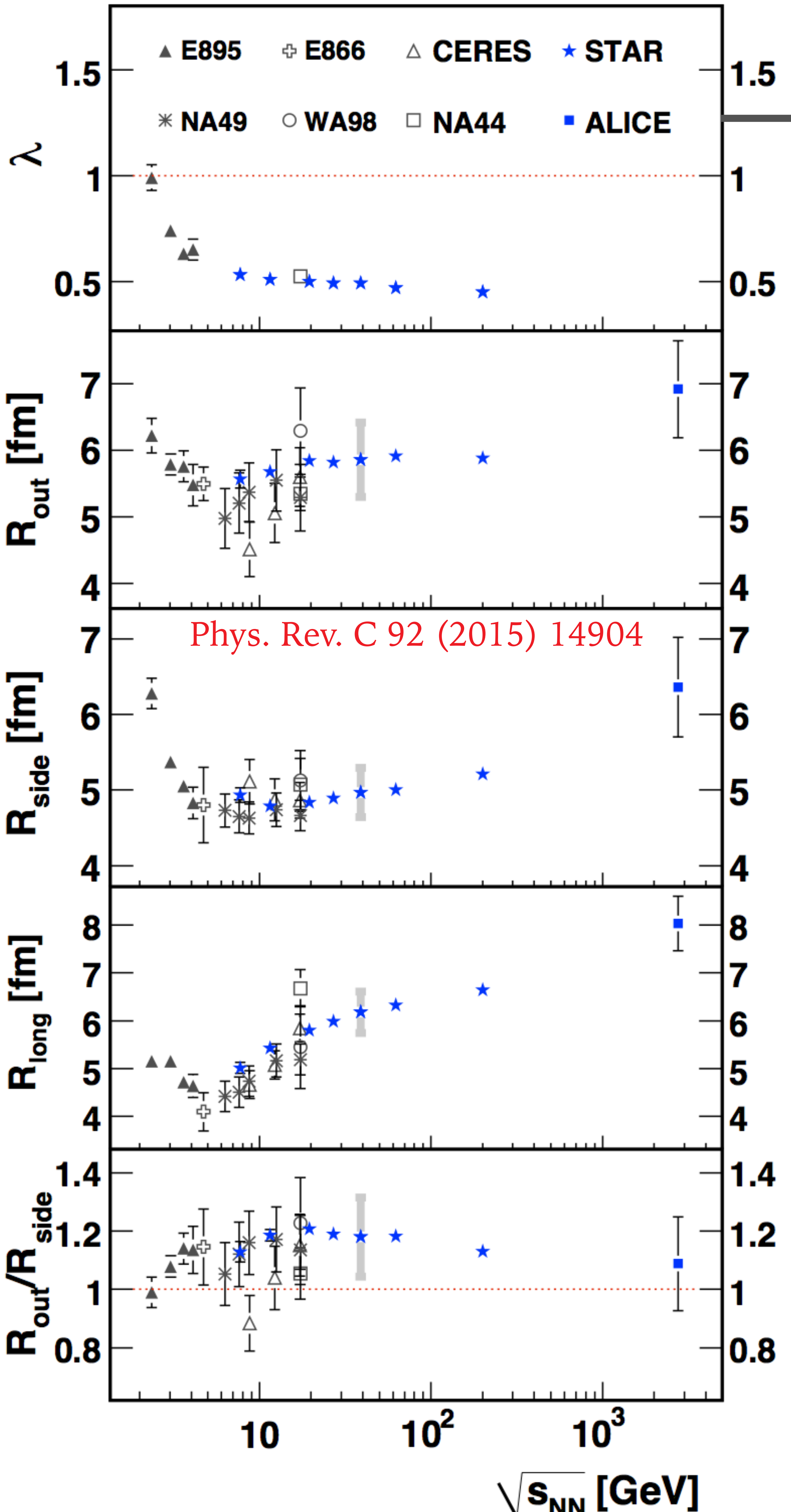
Pairs from the same collision

Pairs from different collisions

Object of study of Traditional femtoscopy

Object of study of non-traditional femtoscopy

Geometry and dynamics

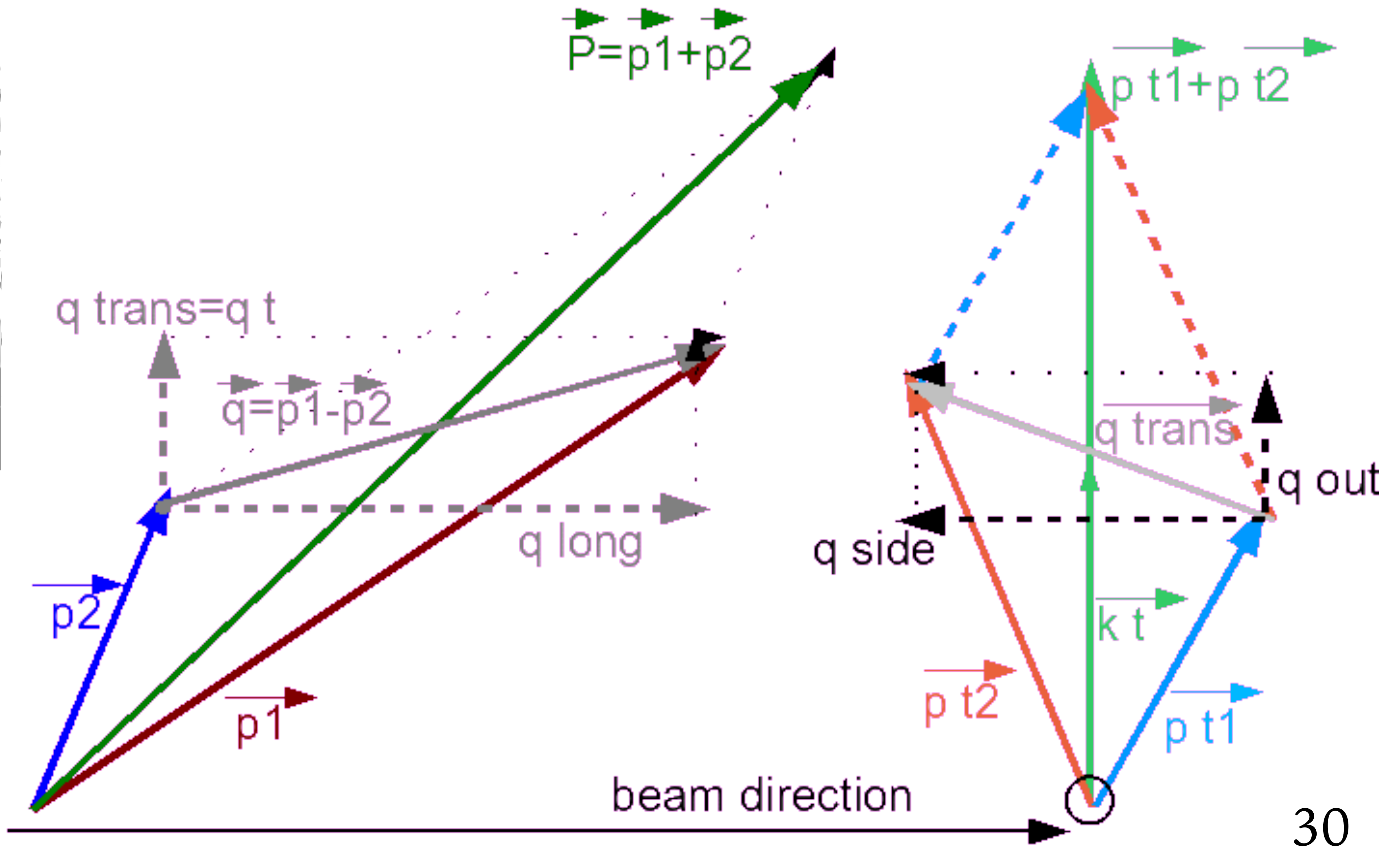


Identical pion femtoscopy

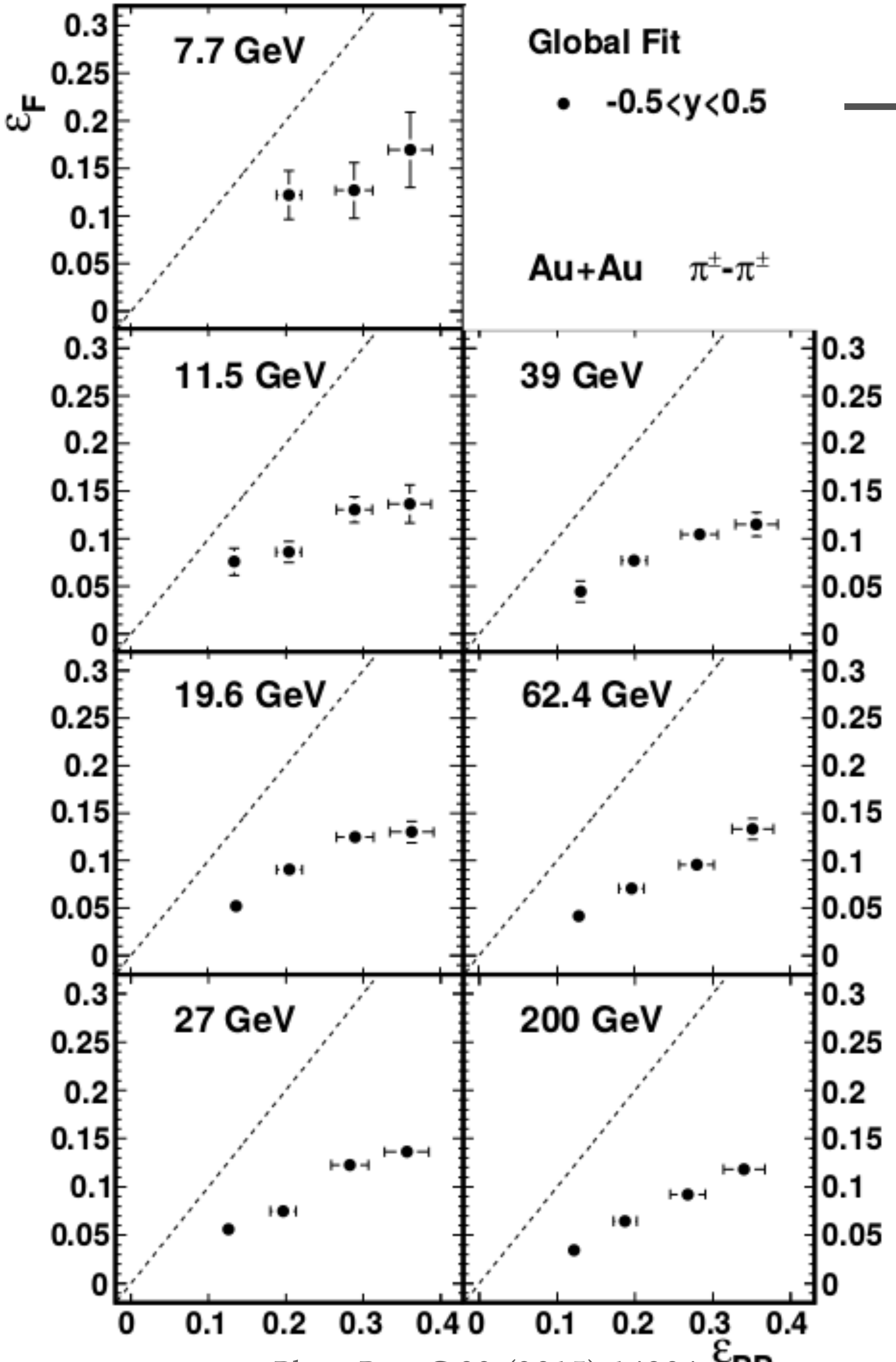
- → R_{side} spatial source evolution in the transverse direction
- → R_{out} related to spatial and time components
- → R_{out}/R_{side} signature of phase transition
- → $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
- → R_{long} temperature of kinetic freeze-out and source lifetime

$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2R_o^2 - q_s^2R_s^2 - q_l^2R_l^2 - 2q_oq_sR_{os}^2 - 2q_oq_lR_{ol}^2\right)$$

HBT source sizes determined for wide range of collision energy; Non-monotonic behavior seen in three directions



Fireball's evolution



Phys. Rev. C 92 (2015) 14904

$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \cos(n\Phi) \qquad (\mu = o,s,l,ol)$$

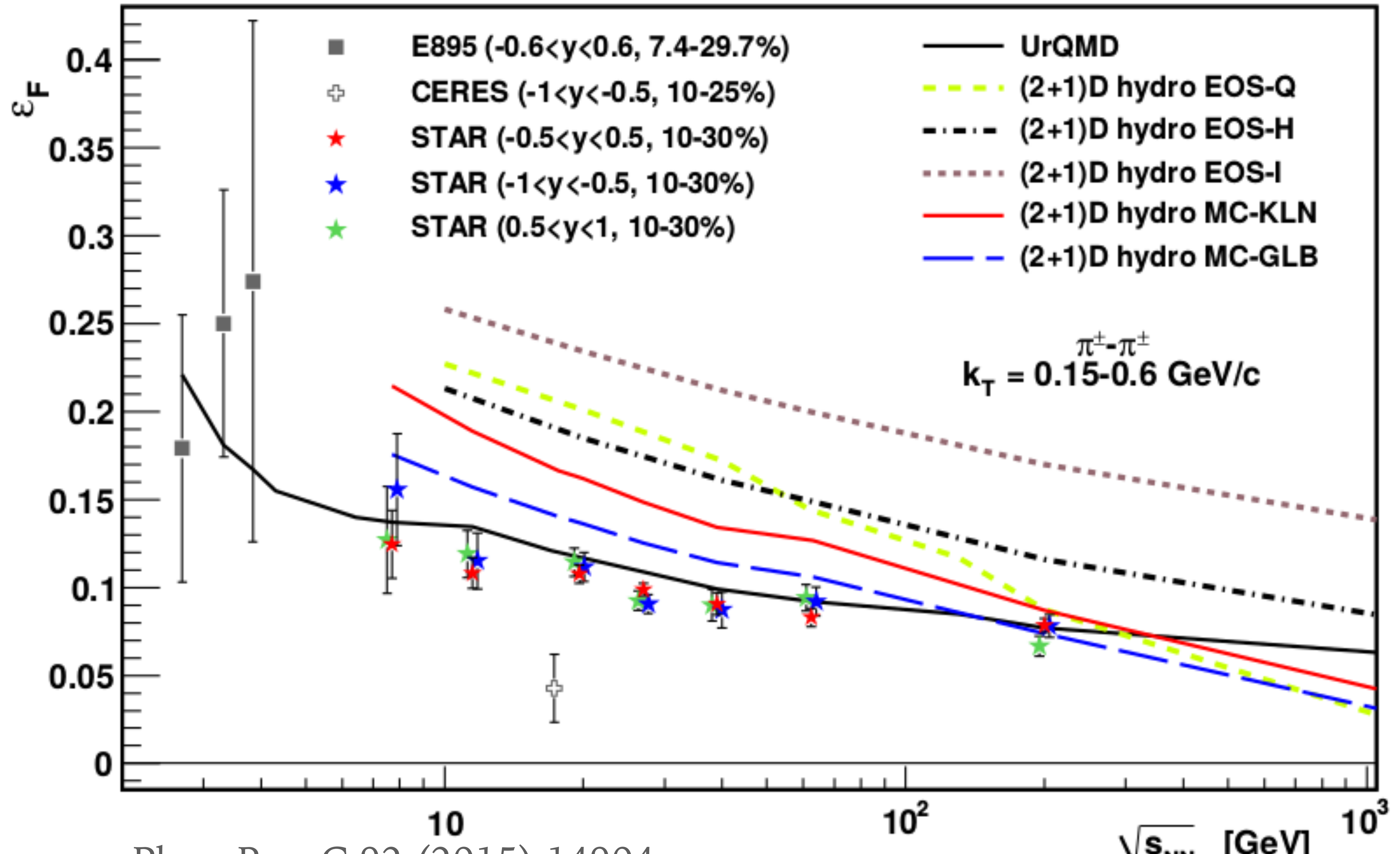
$$\varepsilon_{PP} = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_x^2+\sigma_y^2}.$$

$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2\sum_{n=2,4,6\ldots} R_{\mu,n}^2 \sin(n\Phi) \qquad (\mu = os)$$

$$\varepsilon_F = \frac{\sigma_y'^2-\sigma_x'^2}{\sigma_y'^2+\sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

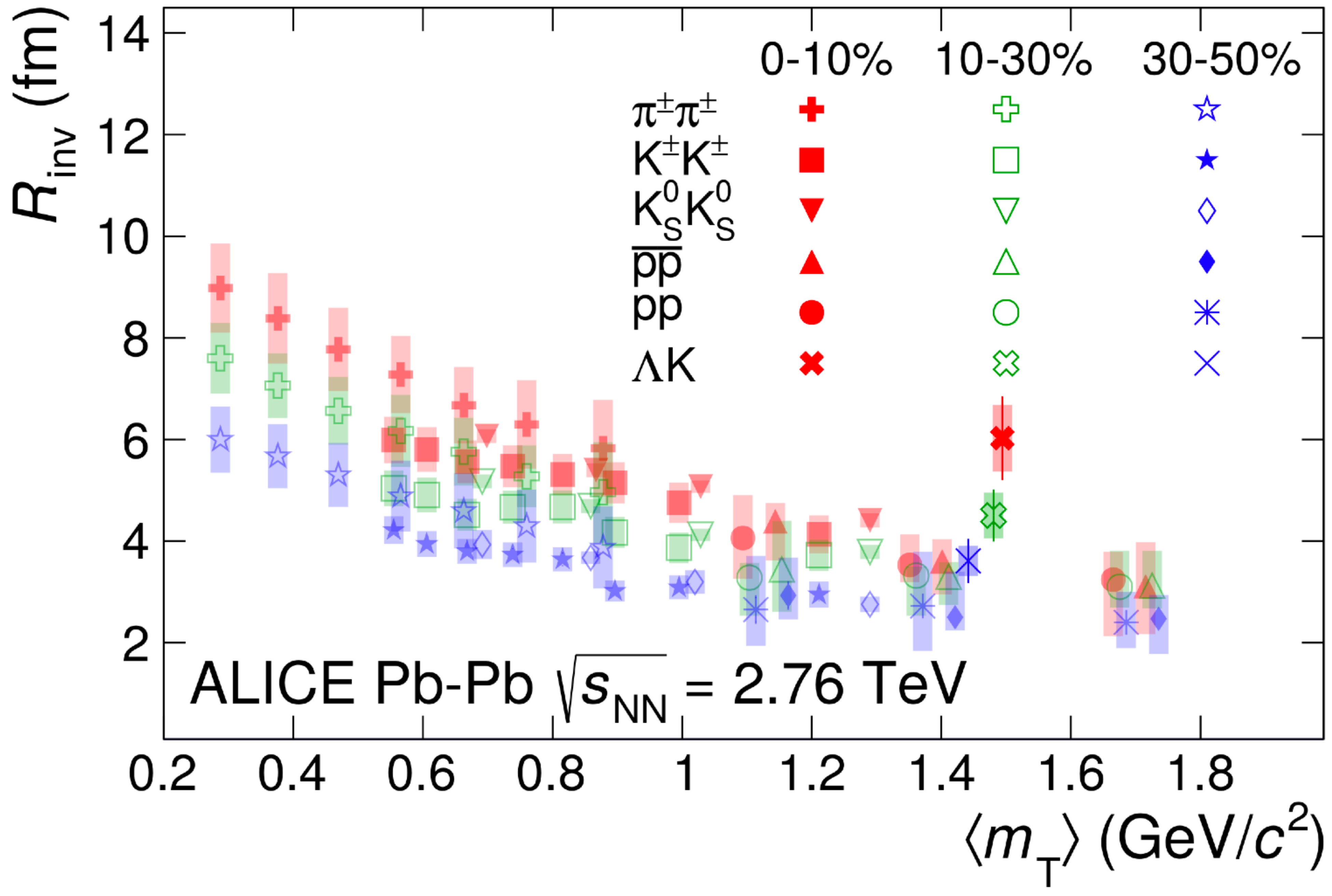
$$\sigma_x^2 = \{x^2\} - \{x\}^2 \text{ and } \sigma_y^2 = \{y^2\} - \{y\}^2$$

System evolves faster in the reaction plane



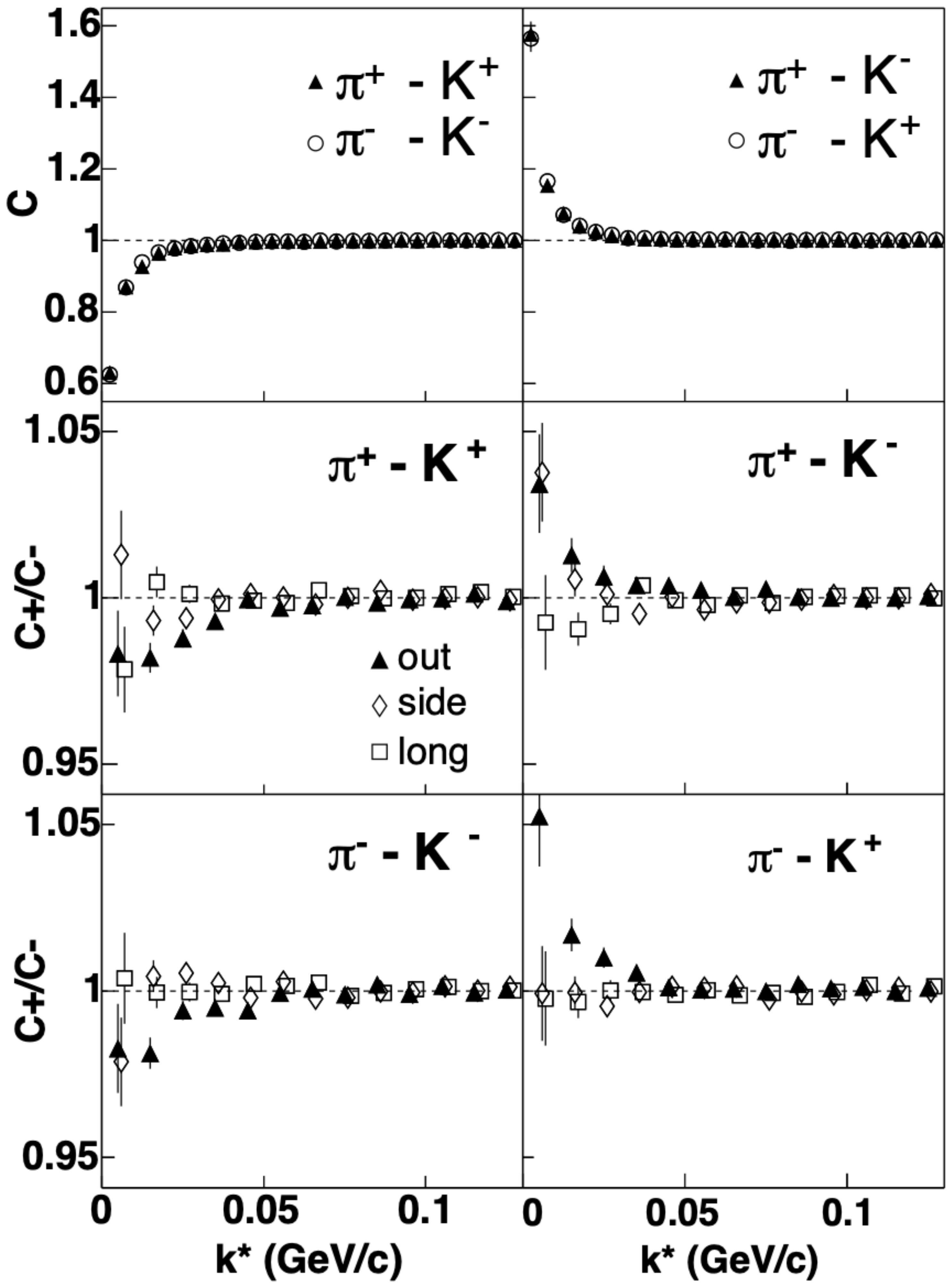
Phys. Rev. C 92 (2015) 14904

Collectivity from femtoscopy

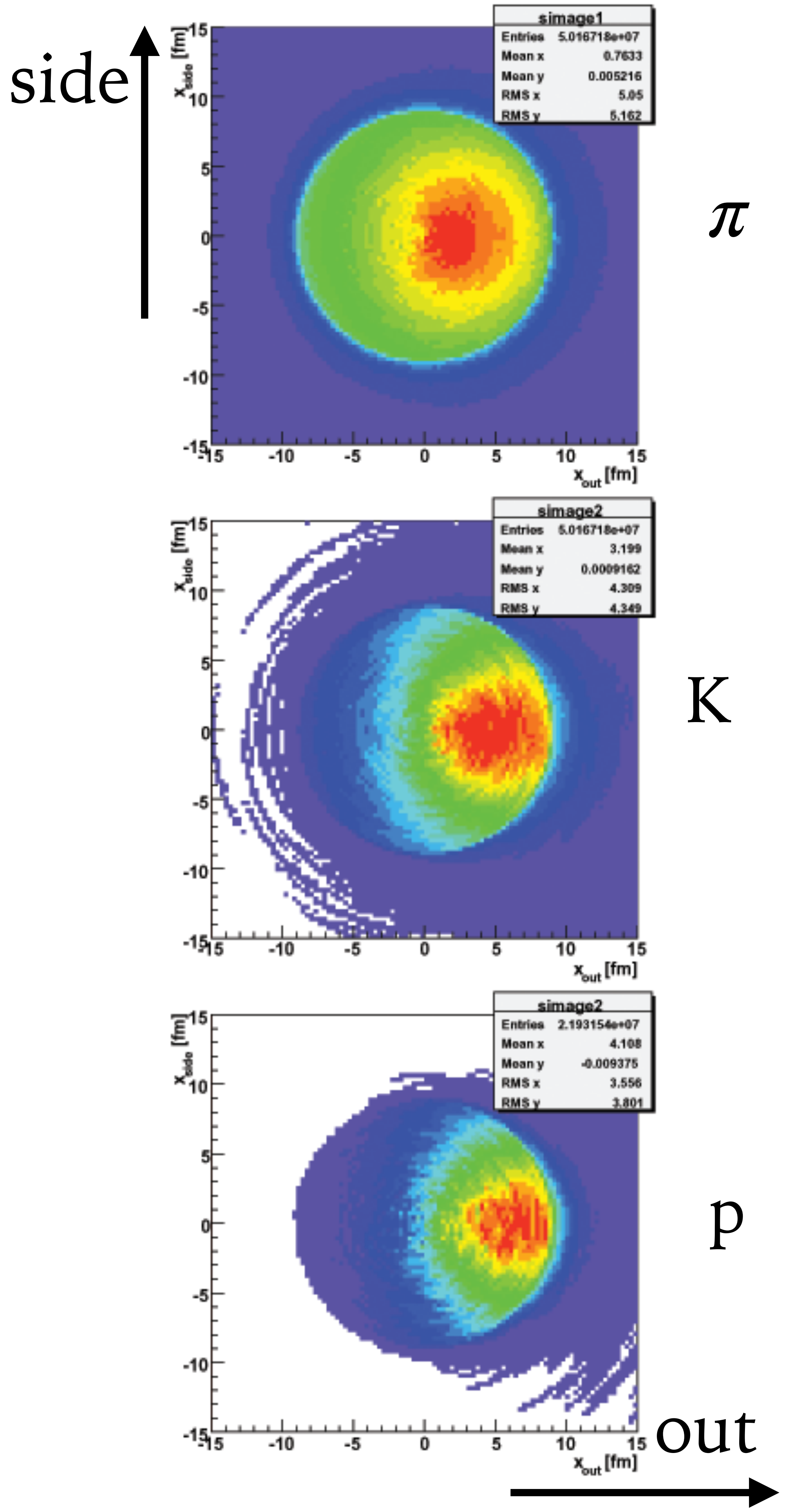


Phys. Rev. C 103 (2021) 5, 055201

Signal of collective flow,
Confirmed by measurement of non-identical particle correlations.



Phys. Rev. Lett. **91** (2003) 262302



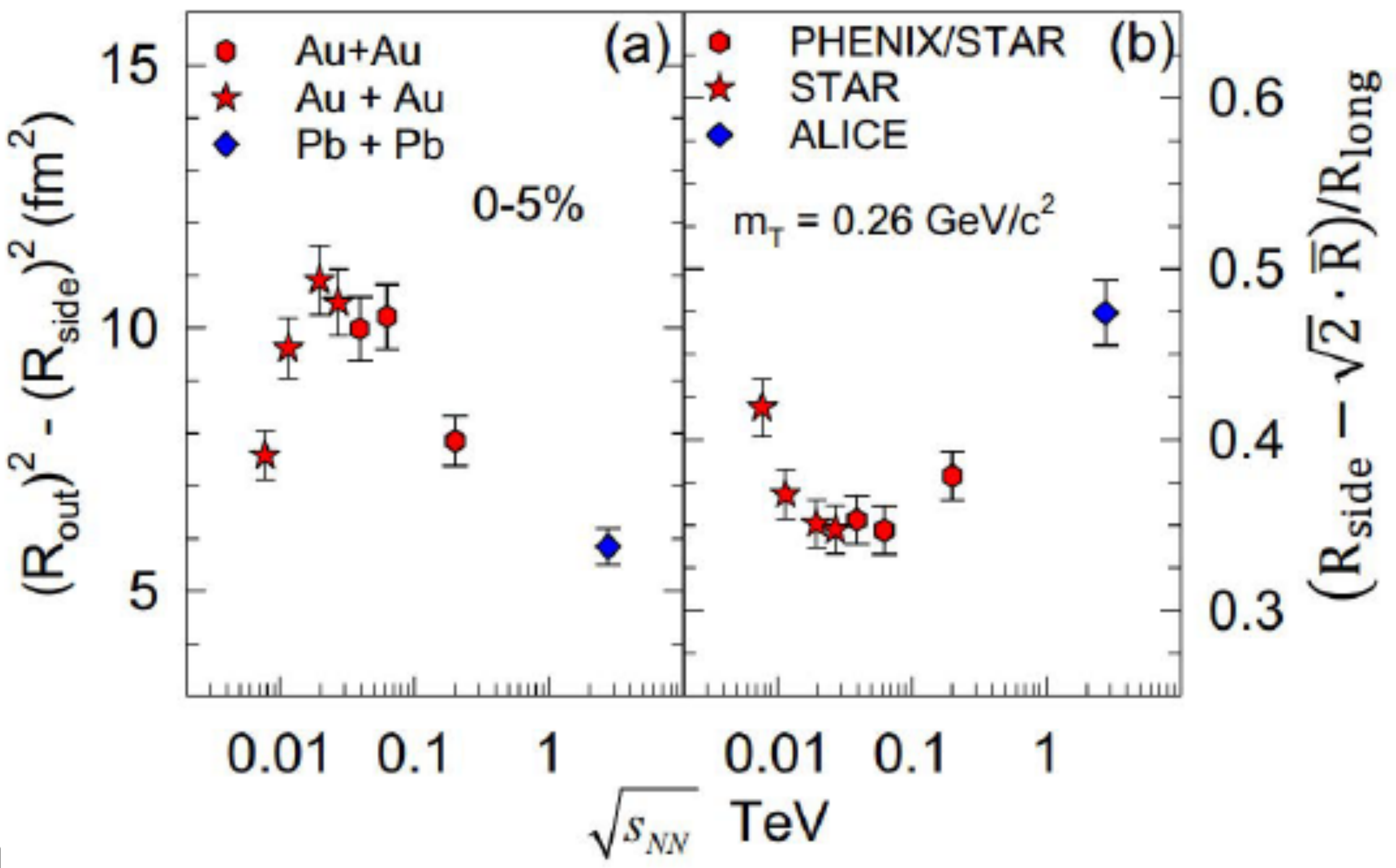
Braz. J. Phys. 37 (3a), 2007

Shift of the mean emission points toward „out” direction

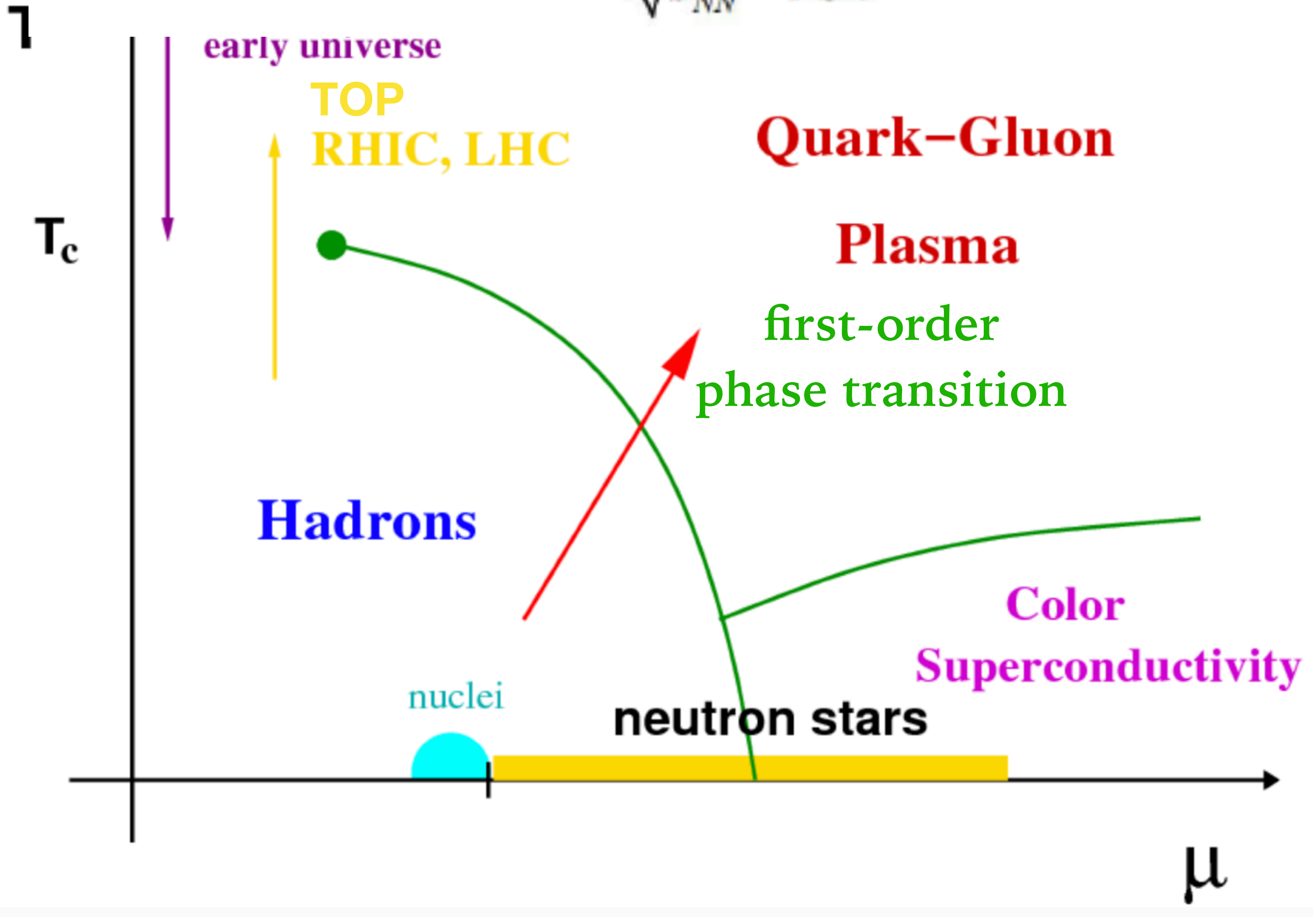
EoS, SI, production mechanisms

Identical pion femtoscopy

arXiv: 1410.2559

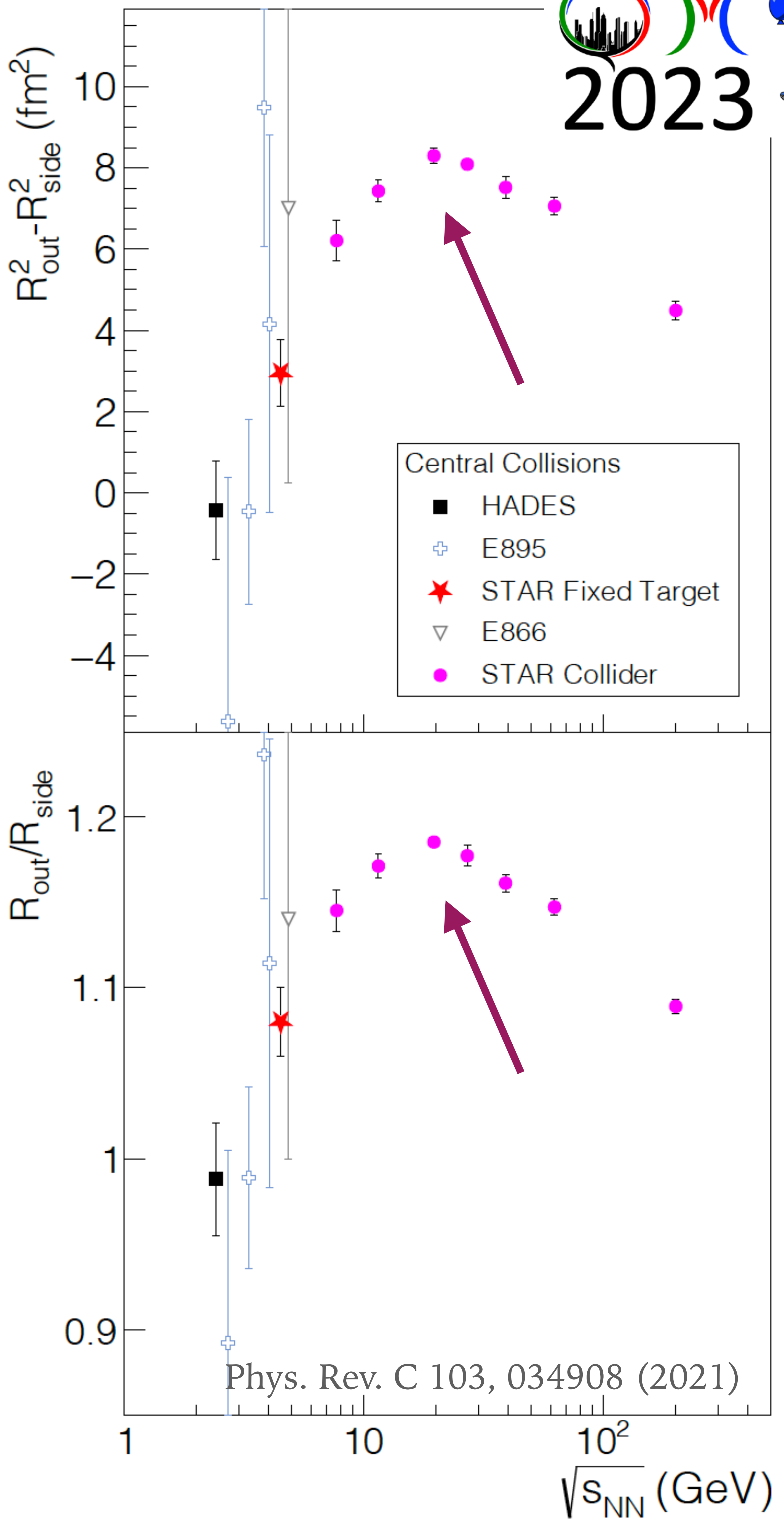


- $R_{out}^2 - R_{side}^2 = \beta_t^2 \Delta\tau^2$: related to emission duration;
- $(R_{side} - \sqrt{2}\bar{R})/R_{long}$: related to expansion velocity,
  $\bar{R}$: initial transverse size;
- Indication of the critical behavior?



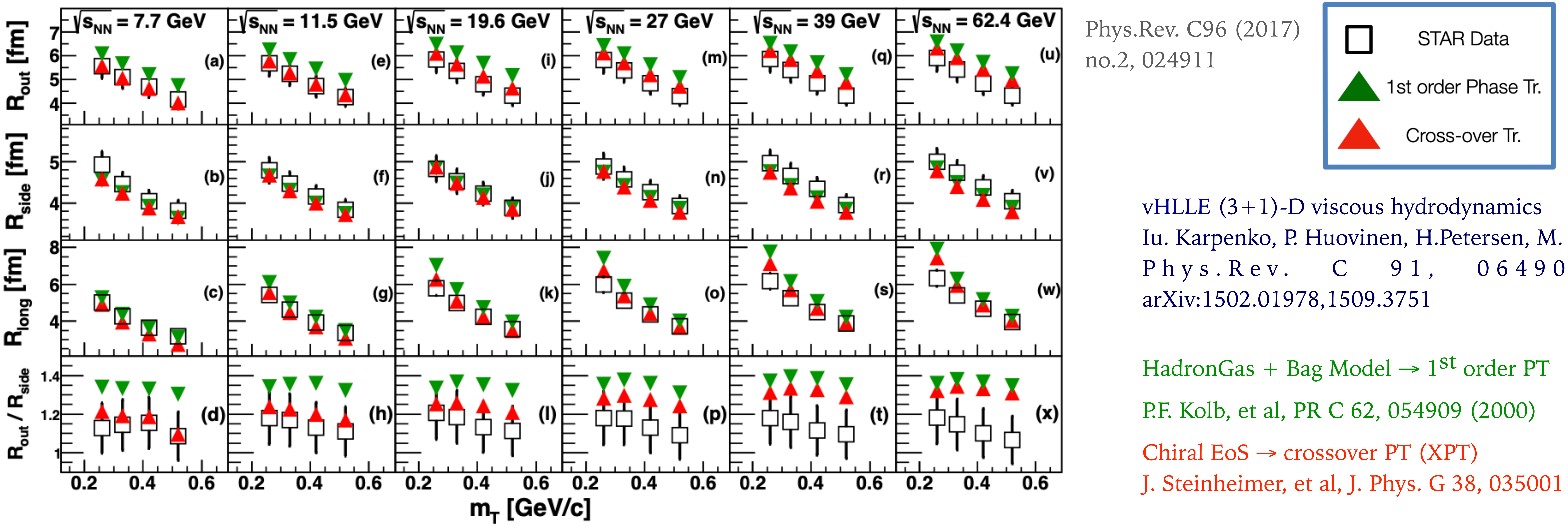
Courtesy of J. Schaffner–Bielich

- Visible **peak** in $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ near $\sqrt{s_{NN}} \simeq 20$ GeV
- QCD calculations predict a peak near to the QGP transition threshold - signature of first-order phase transition?



Phys. Rev. C 103, 034908 (2021)

Femtoscopy and EoS



Phys.Rev. C96 (2017) no.2, 024911

vHLLE (3+1)-D viscous hydrodynamics
Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher
Phys.Rev. C 91, 064901 (2015),
arXiv:1502.01978,1509.3751

HadronGas + Bag Model → 1st order PT

P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT)
J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

Pre-thermal phase → Hydrodynamical phase → Hydronic cascades

UrQMD | vHLEE | UrQMD

vHLEE+UrQMD model shows sensitivity of HBT measurements to the first-order phase transition.

N-Y correlations

- **Hyperons**: expected in the core of neutron stars; **conversion of N into Y energetically favorable.**

- Appearance of Y: The relieve of Fermi pressure → **softer EoS → mass reduction (incompatible with observation).**

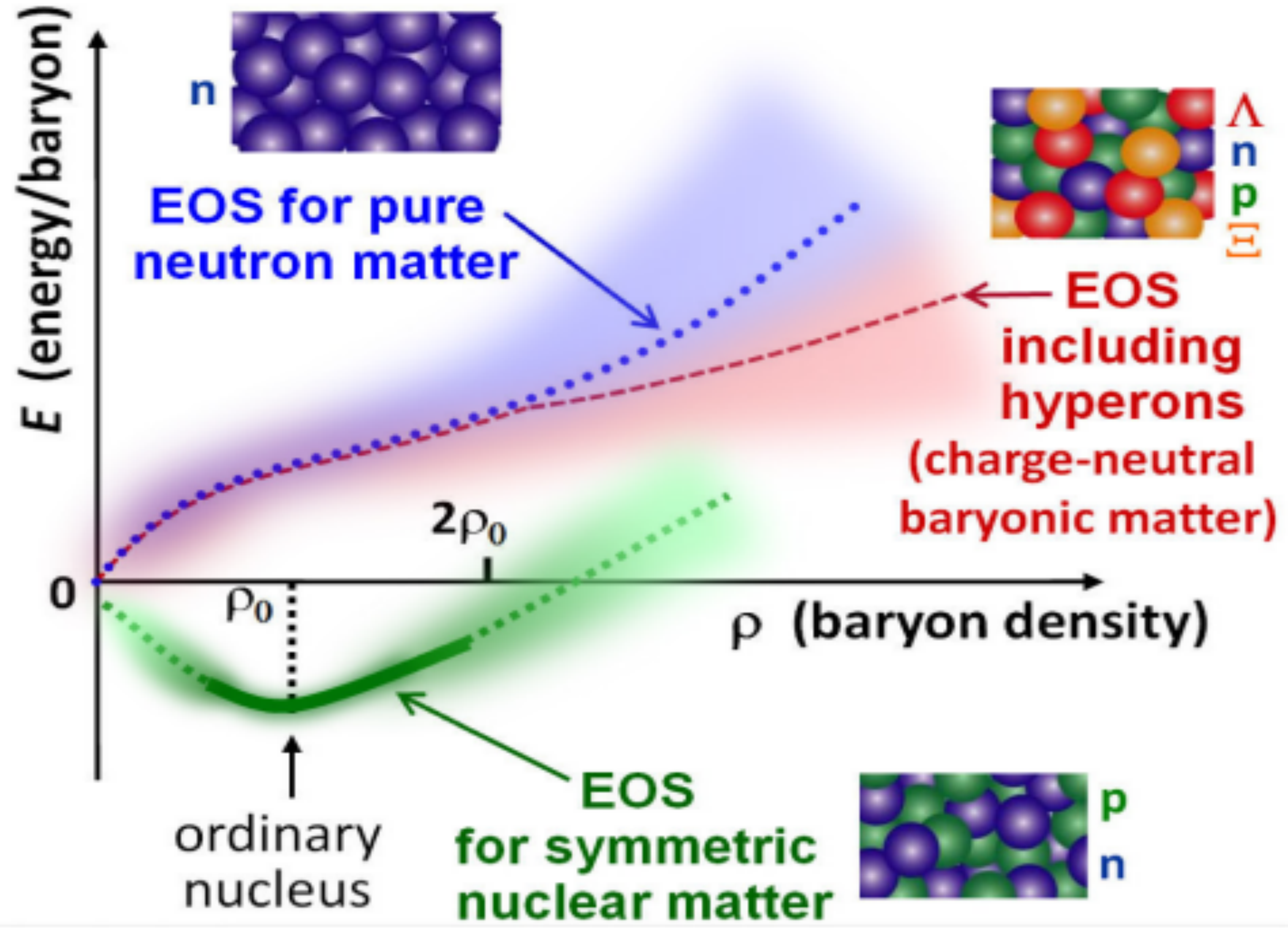
The solution: a mechanism providing the **additional pressure** to make the EoS stiffer.

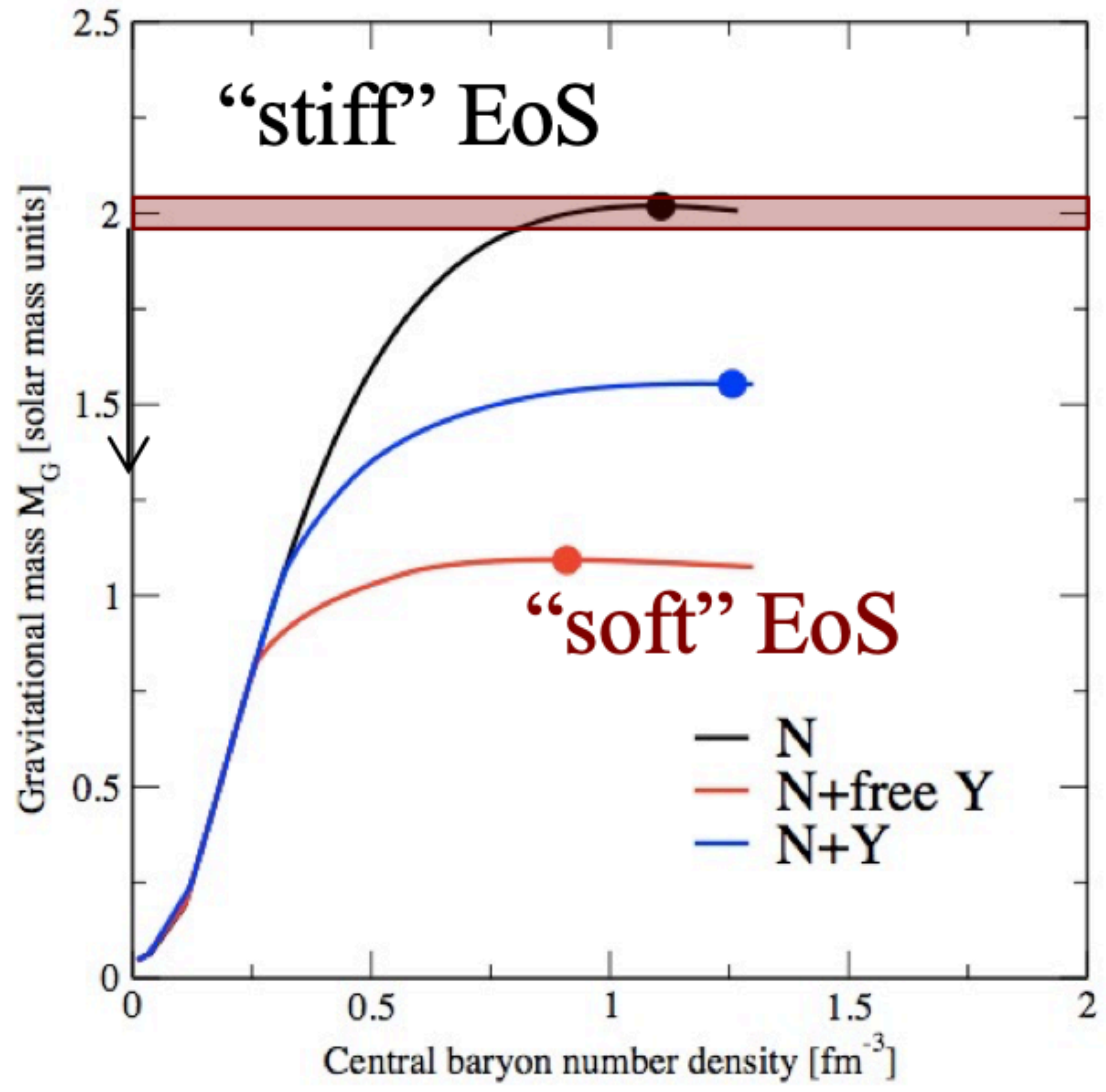
Possible mechanisms:

- **Two-body YN & YY interactions**
- Chiral forces
- Hyperonic Three Body Forces
- Quark Matter Core - Phase transition at densities lower than hyperon threshold

$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx$ 10-12 km
$\rho \approx 3 \div 5\ \rho_0$

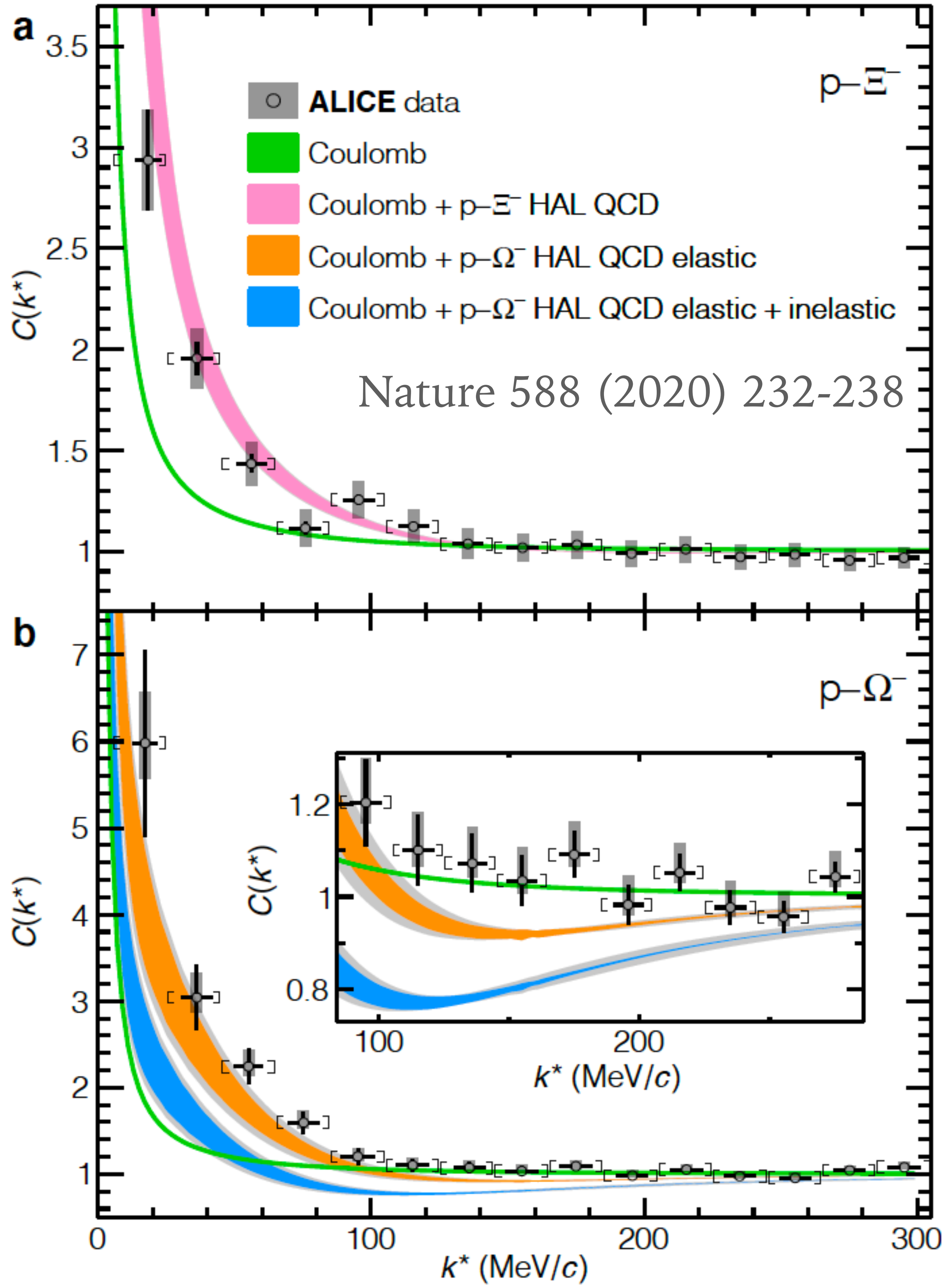
H.Tamura, JPS Conf. Proc. , 011003 (2014)





$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

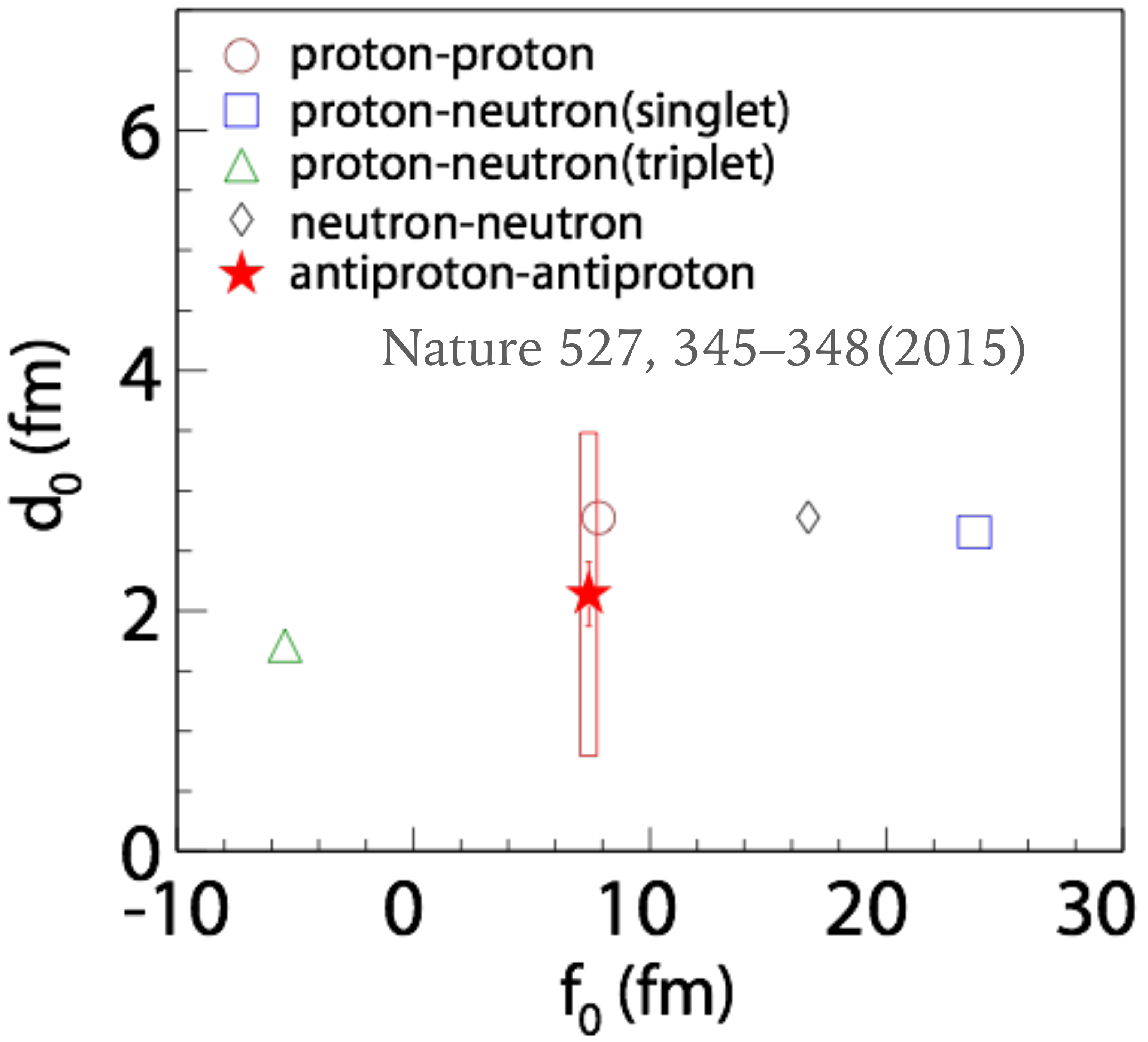
$p - \Xi^-$ and $p - \Omega^-$ strong interactions studied with HAL QCD models



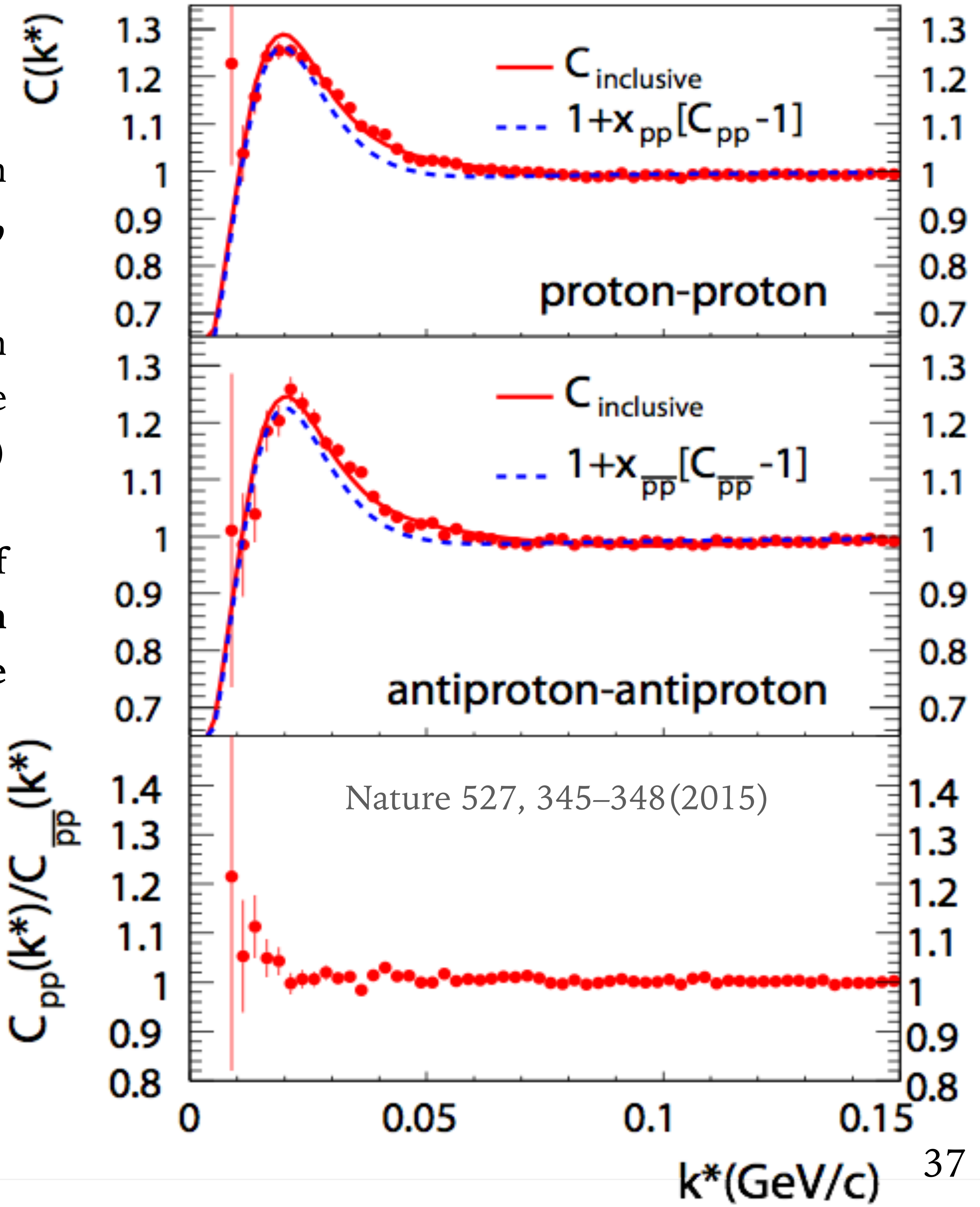
Nature 588 (2020) 232-238

Strong interactions between anti-nucleons

The knowledge of **interaction** between two **anti-protons** fundamental to understand the properties of more sophisticated anti-nuclei.



- f_0 and d_0 for $\bar{p}-\bar{p}$ interaction consistent with parameters for $p-p$ interaction;
- Descriptions of the interaction among antimatter (based on the simplest systems of anti-nucleons) determined;
- **A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei.**

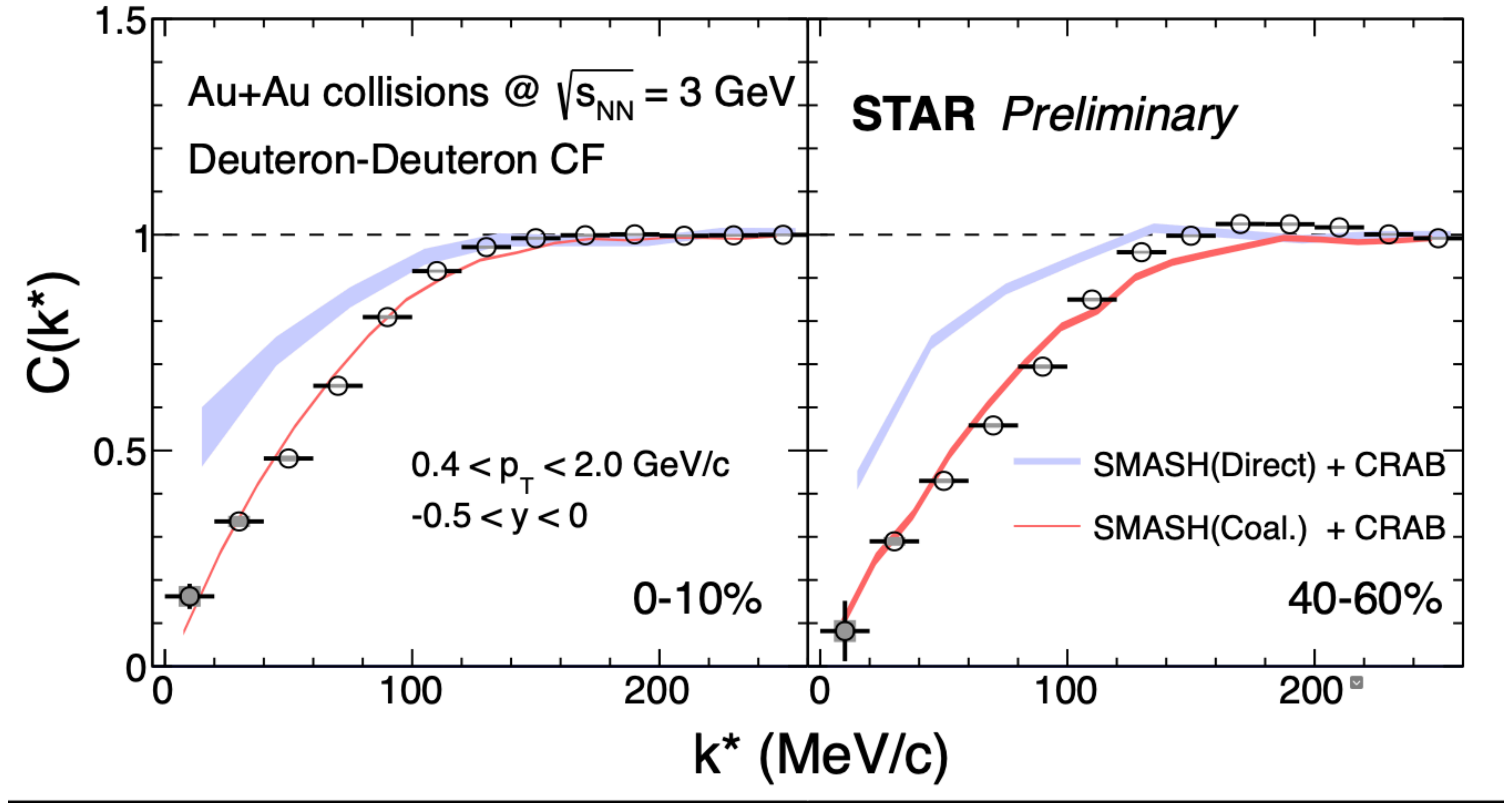


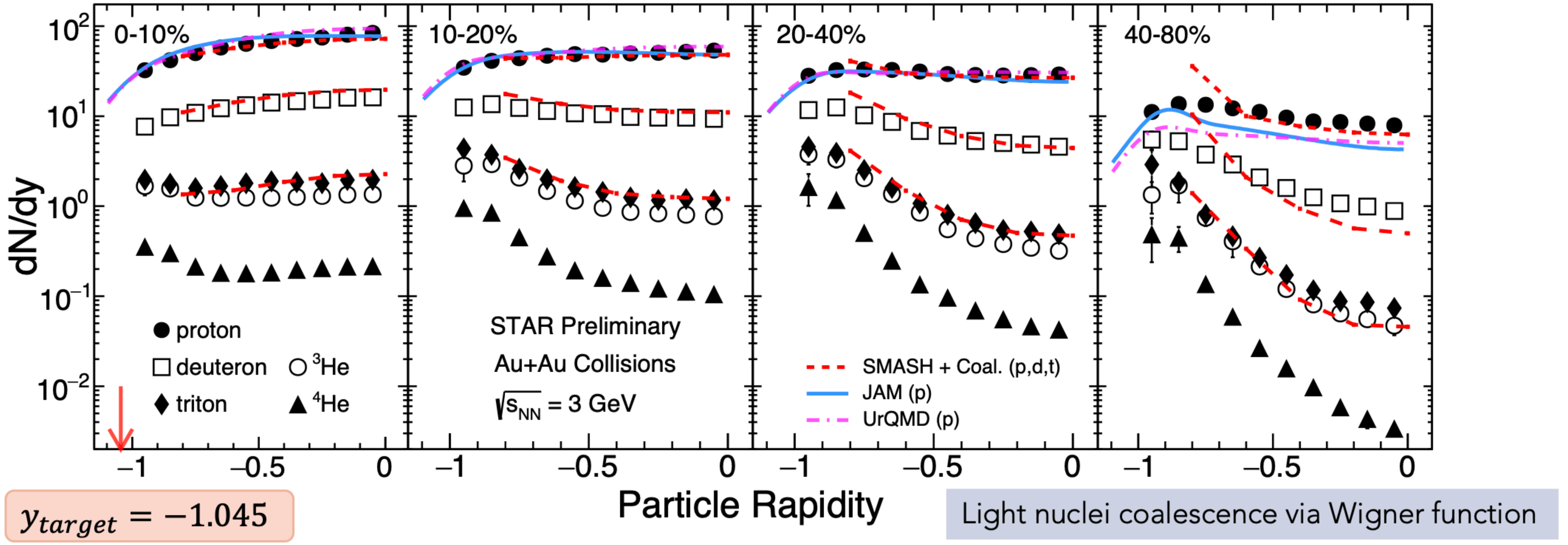
f_0 and d_0 - parameters of strong interaction.
Theoretical correlation function (k*) depends on: R ,f_0 and d_0.

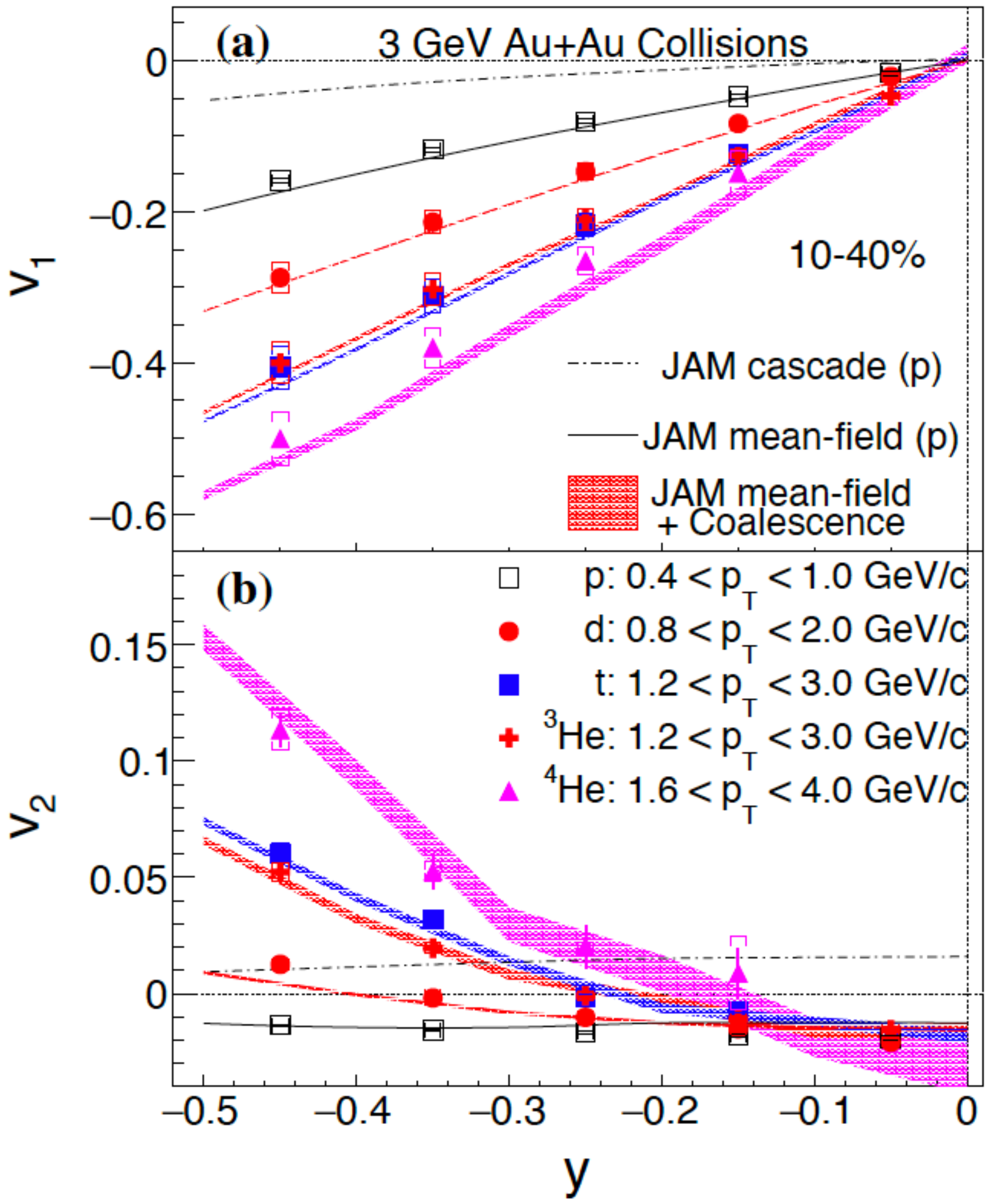
f_0 - the scattering length, determines low-energy scattering.
The elastic cross section, σ_e , (at low energies) determined by the scattering length, $\lim_{k\to 0} \sigma_e = 4\pi f_0^2$

d_0 - the effective range, corresponds to the range of the potential (simplified scenario - the square well potential.

Coalescence at $\sqrt{s_{NN}} = 3$ GeV (light nuclei)







- Compared with SMASH model;
- Correlations calculated with coalescence deuterons in better agreement with data;
- **Support the deuteron formation at $\sqrt{s_{NN}}$ = 3 GeV dominated by coalescence.**

- The JAM model (mean-field + nucleon coalescence) reproduce v_1 and v_2;
- The JAM model (cascade + coalescence) fail to reproduce v_1 and v_2;
- **The light nuclei formed via the coalescence of nucleons where baryonic interactions dominate the collision dynamics.**

- Yields of d and t described by the SMASH + Coal. model except (0-80% centrality);
- dN/dy of p reproduced by SMASH, JAM, and UrQMD models.

Summary

Summary

Flow:

- Initial spatial deformation leads to the final momentum asymmetry;
- Interaction play a crucial role in building the collectivity;
- Directed flow v_1 probes the softening of the EoS and/or the first-order phase transition;
- Elliptic flow v_2 measure how „perfect liquid" QGP is;
- v_2/n_q measures whether created medium is partonic / hadronic;

Correlations:

- Femtoscopy probes geometric and dynamic properties of the fireball;
- Hadron's correlations help to determine fireball's evolution;
- Collectivity is studied with close-momentum particles' correlations too;
- Femtoscopy helps to determine EoS and sensitivity to (phase) transitions;
- Very helpful method to study FSI (including determination properties of NS);
- Production's mechanisms (thermal / coalescence) concluded as well.

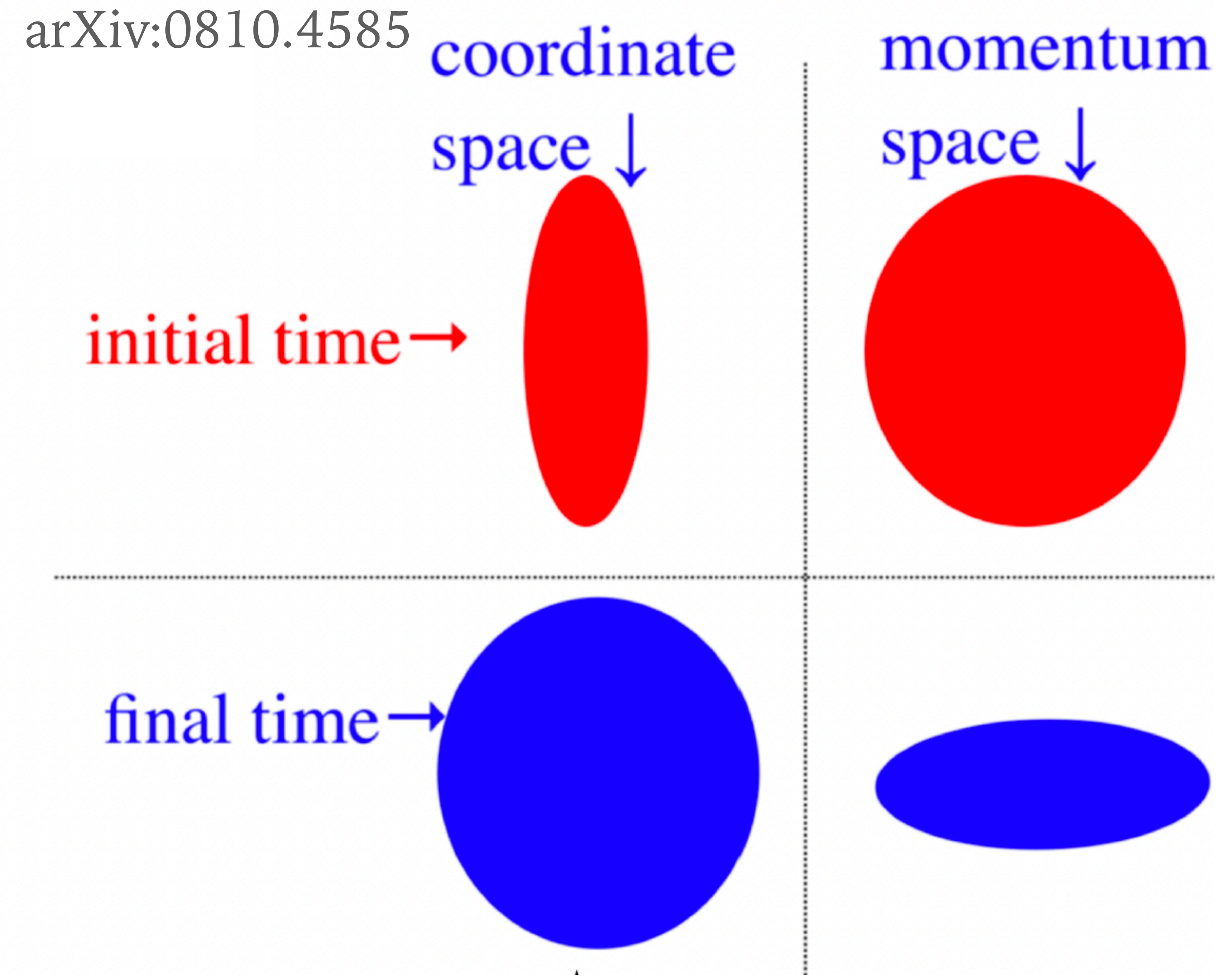
Thank you!

Do not hesitate to contact me!

hanna.zbroszczyk@pw.edu.pl

Evolution of the A+A collision

arXiv:0810.4585

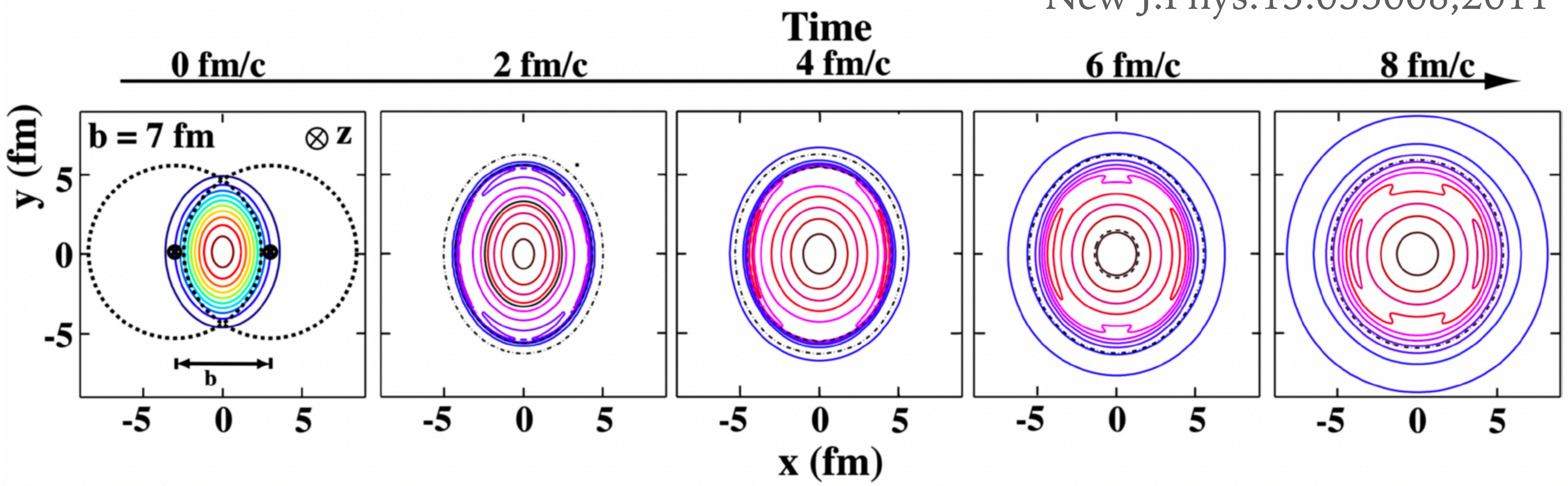


- Initial spatial asymmetry caused by the collision geometry;
- Spherical initial momentum distribution;

Stronger acceleration of matter observed in-plane (due to faster system's expansion);

- Final particles located in-plane carry more momentum.

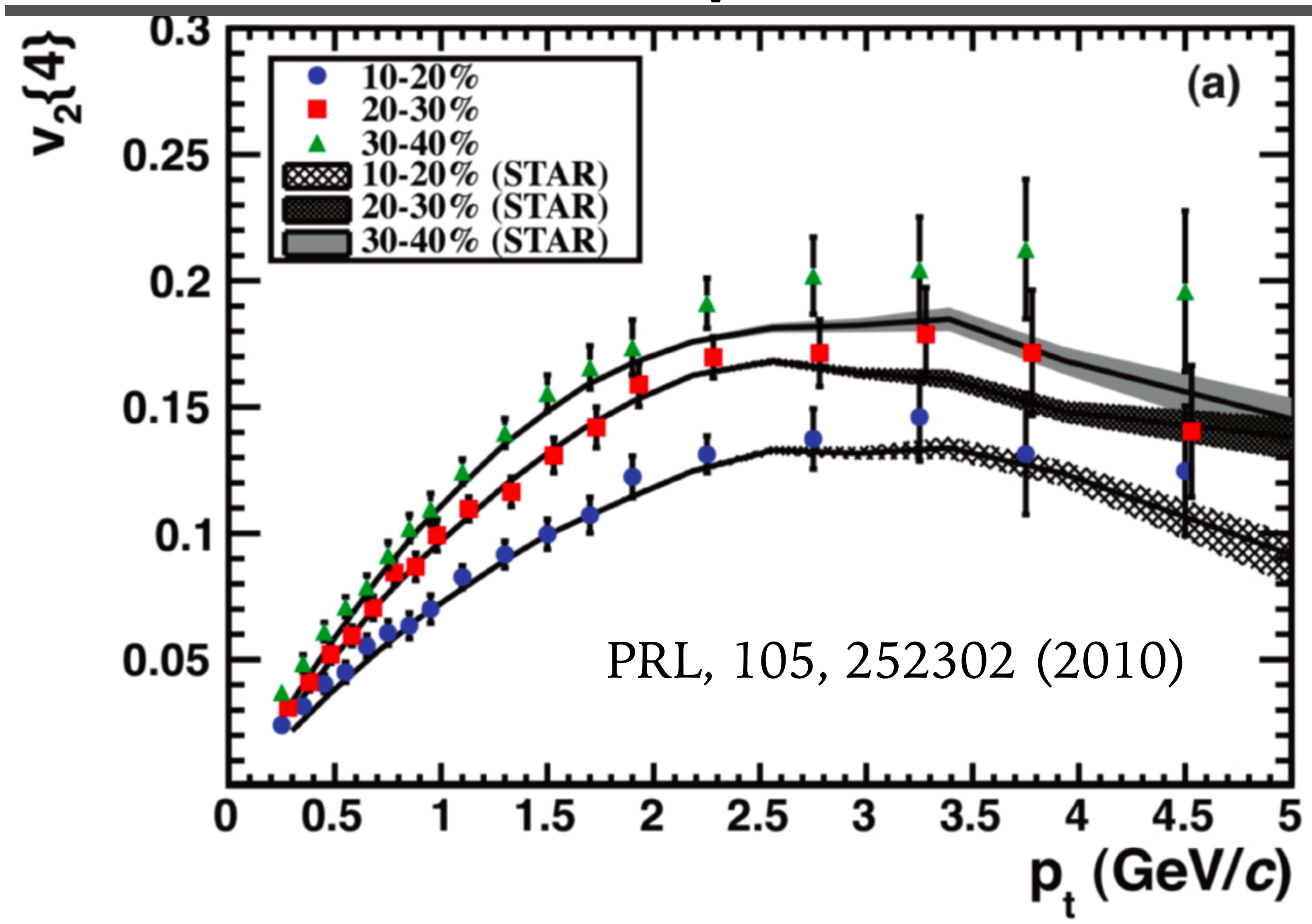
New J.Phys.13:055008,2011

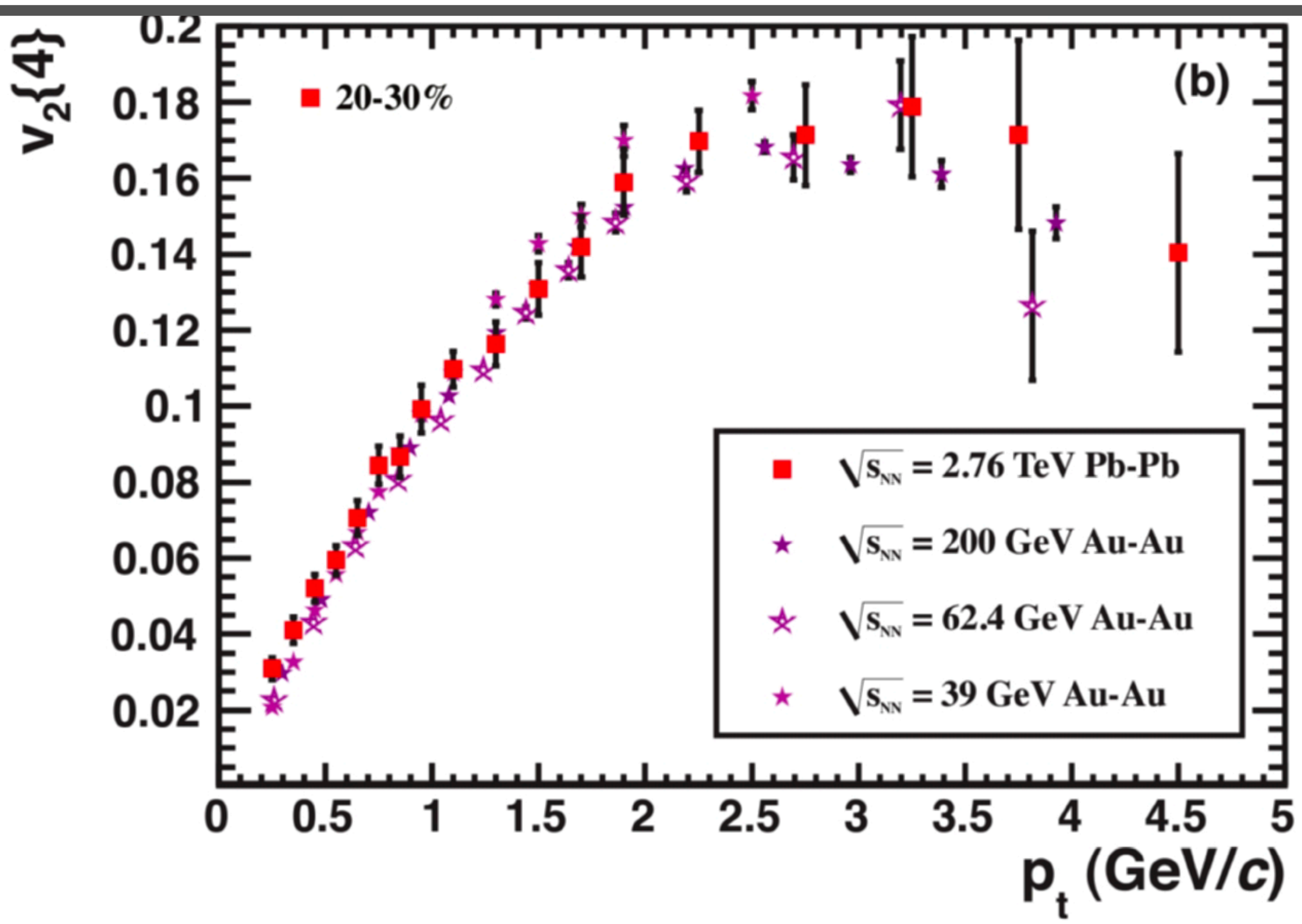


Hydrodynamics: initial spatial asymmetry eliminated early ($\sim 6-8$ fm/c), v_2 built in the early phase after the collision (the lifetime of QGP $\sim 5-7$fm/c, freeze-out time $\sim$ 10 fm/c).

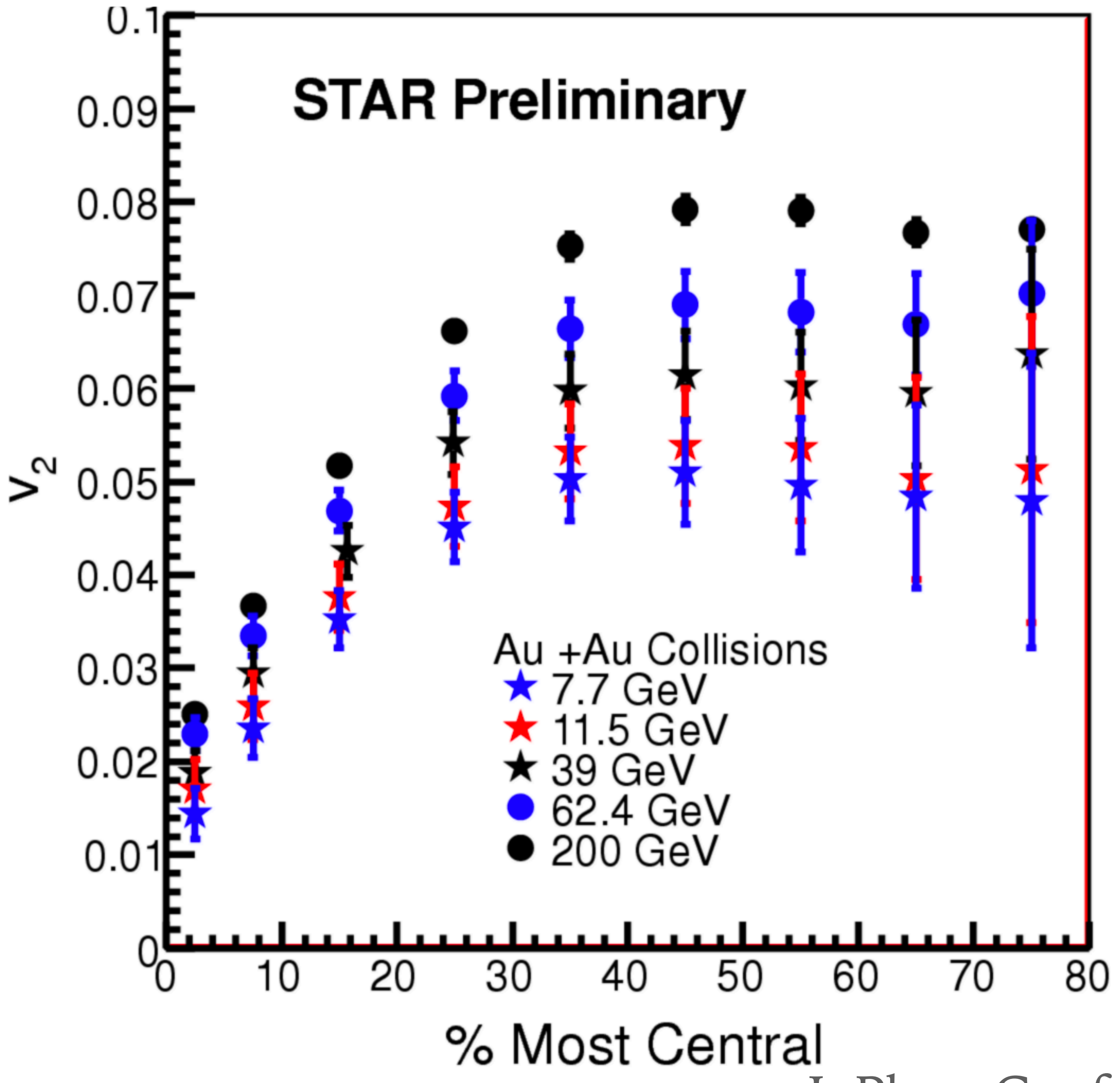
- v_2 generated mainly in the early phase of the system's evolution (before the spatial asymmetry disappears);
- **v_2 brings information about the early stage!**

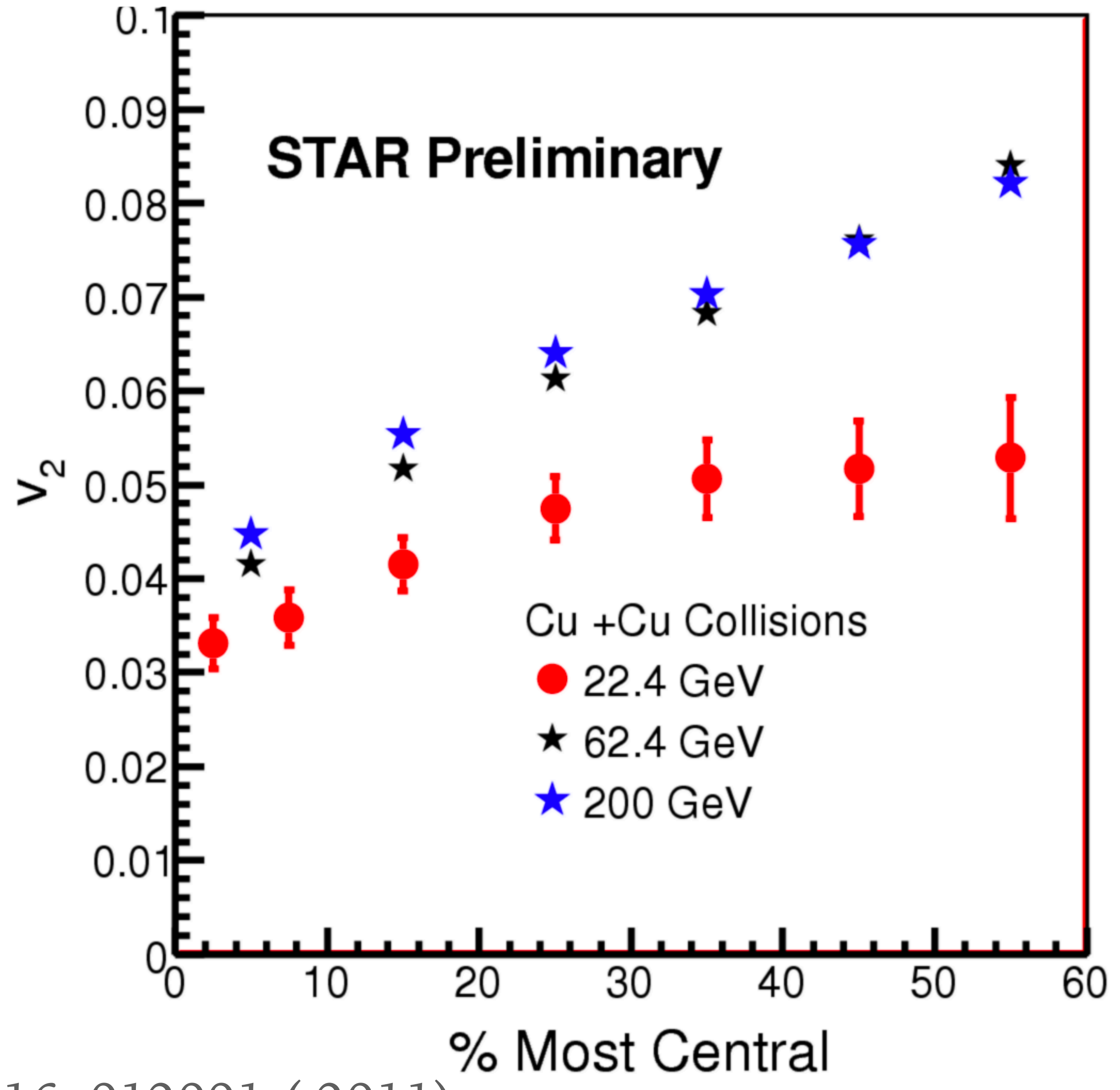
v_2 vs. p_T, $\sqrt{s_{NN}}$ and centrality





- $v_2(p_T)$: similar ($\sqrt{s_{NN}}$ = 39 – 2760 GeV, the same centrality - 20-30%);

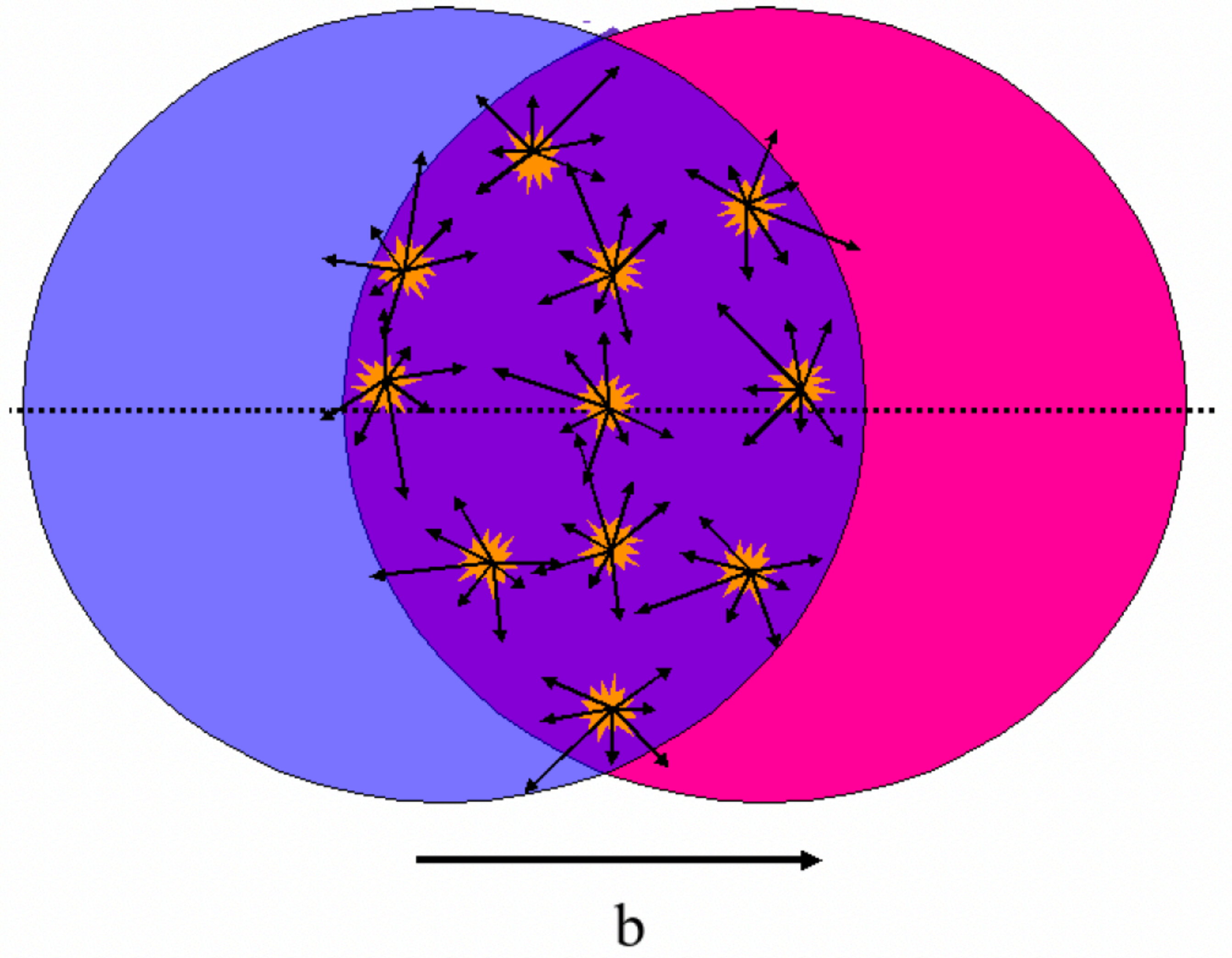




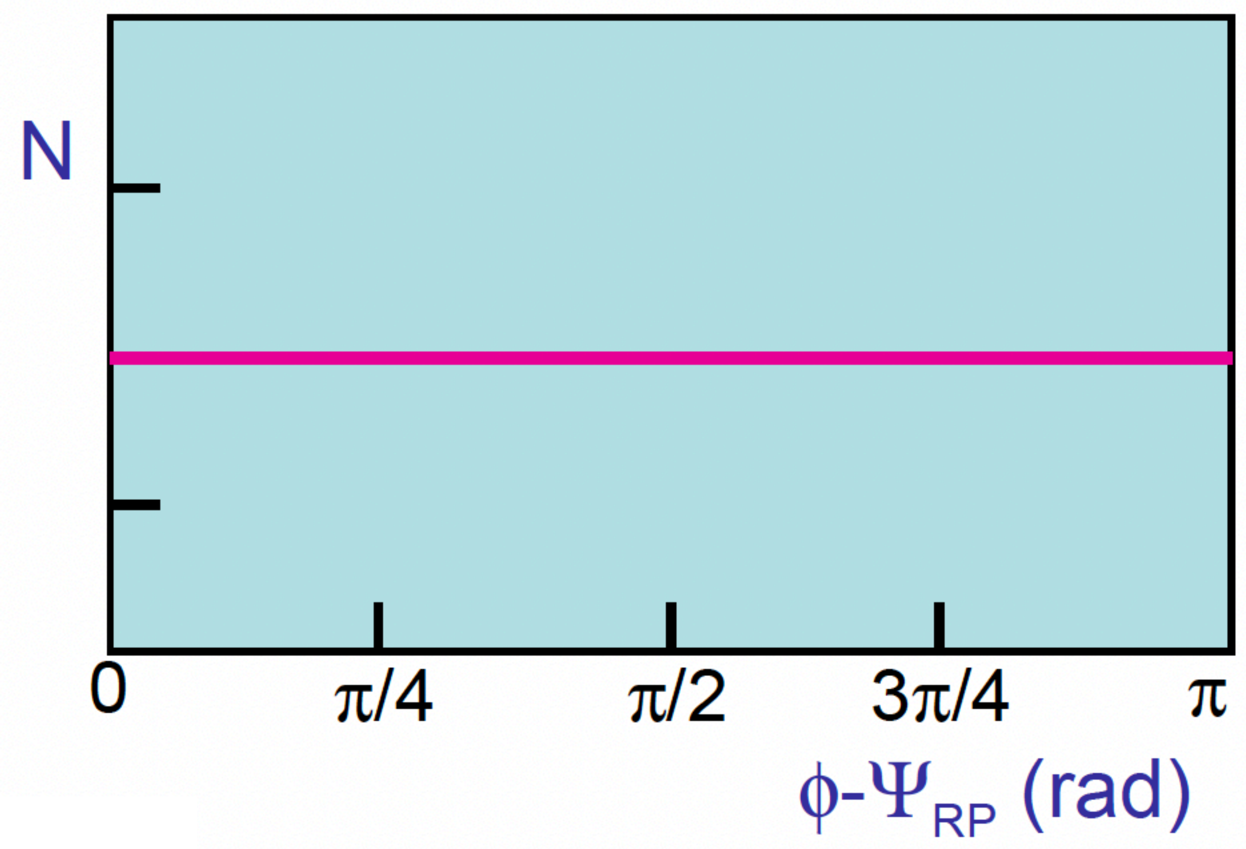
J. Phys. Conf. Ser. 316, 012001 (2011)

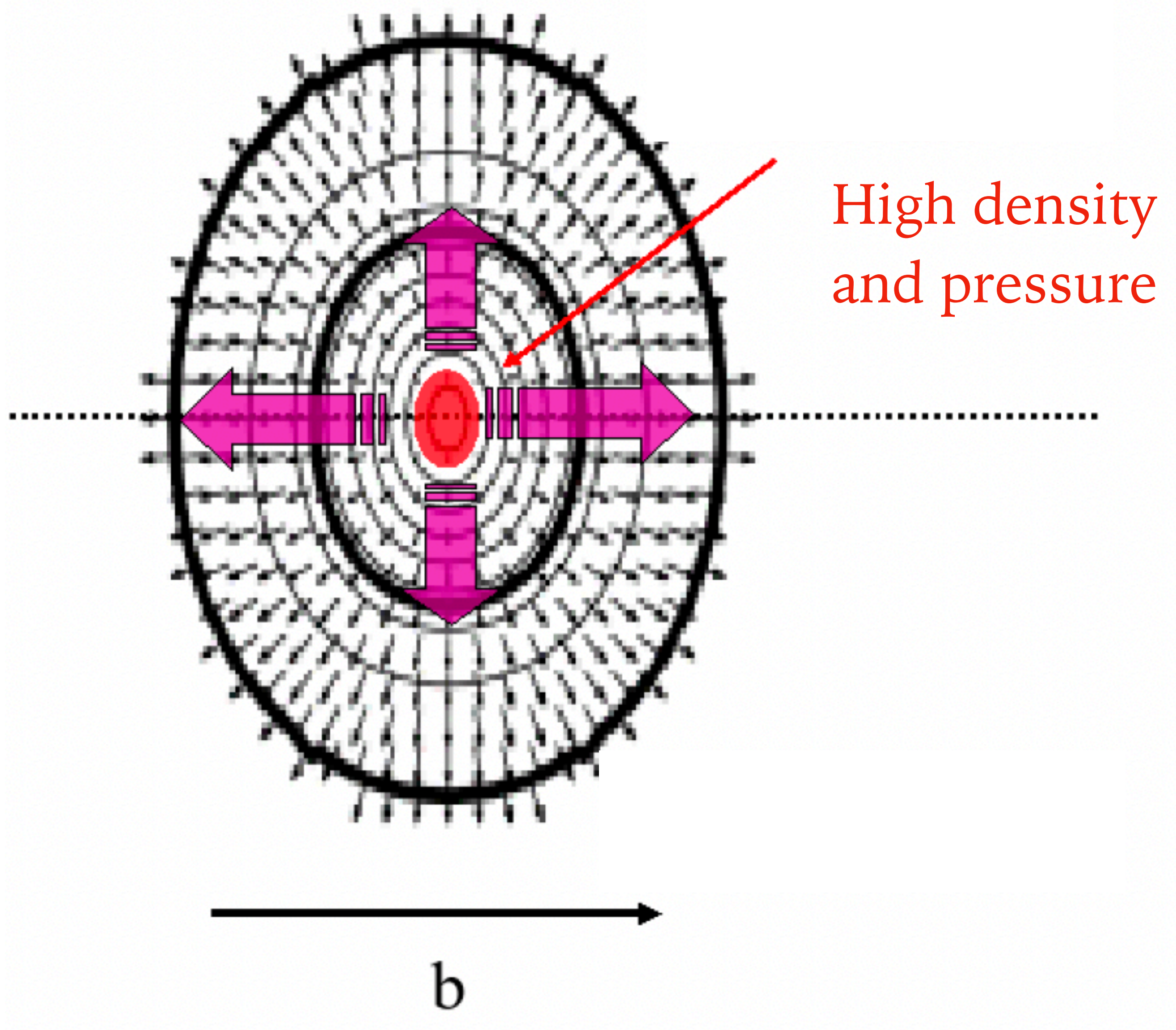
- $v_2(\%)$ increases with $\sqrt{s_{NN}}$.

A+A collision as superposition of N+N

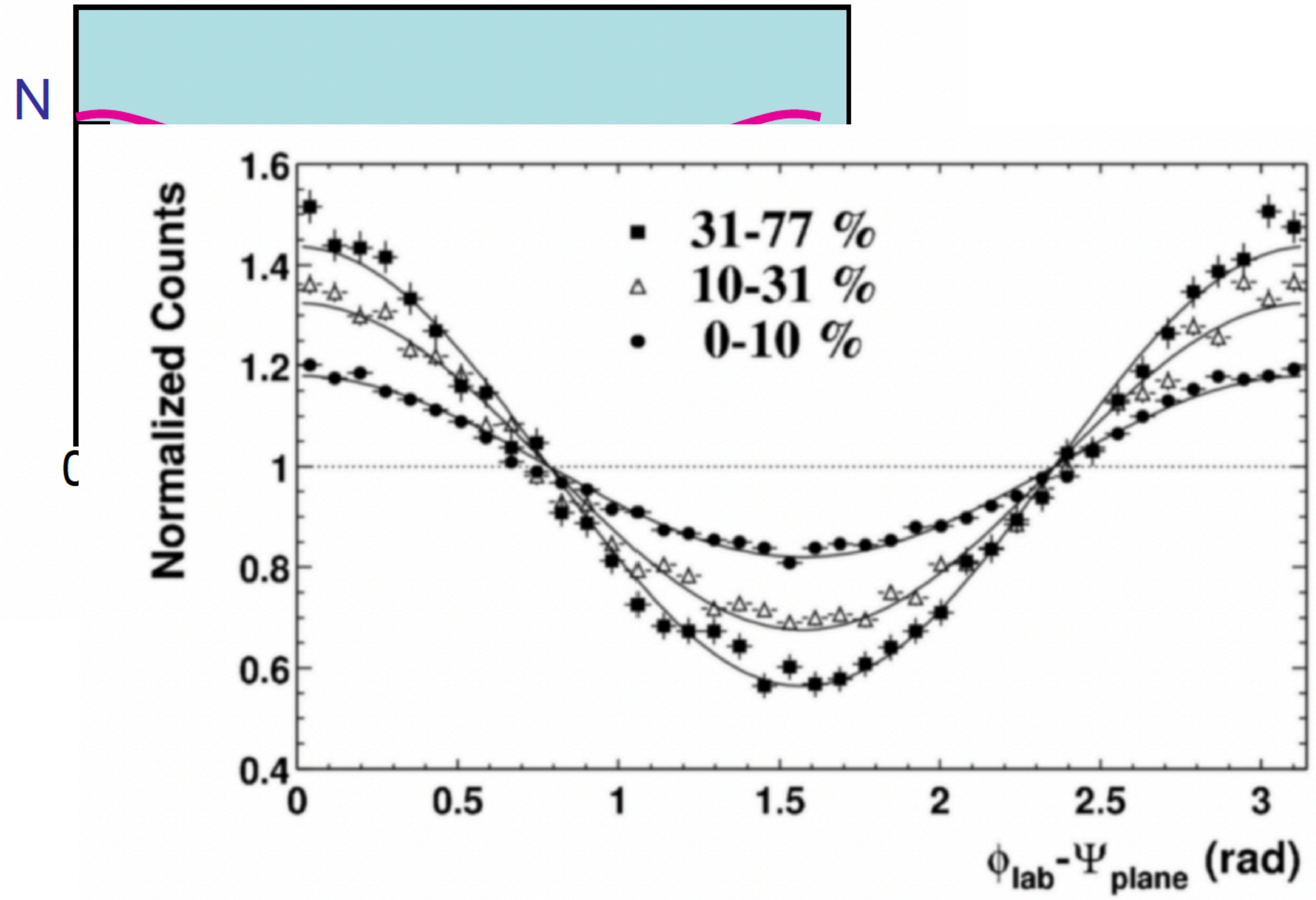


Superposition of independent N+N collisions – momenta positioned randomly w.r.t. the reaction plane.



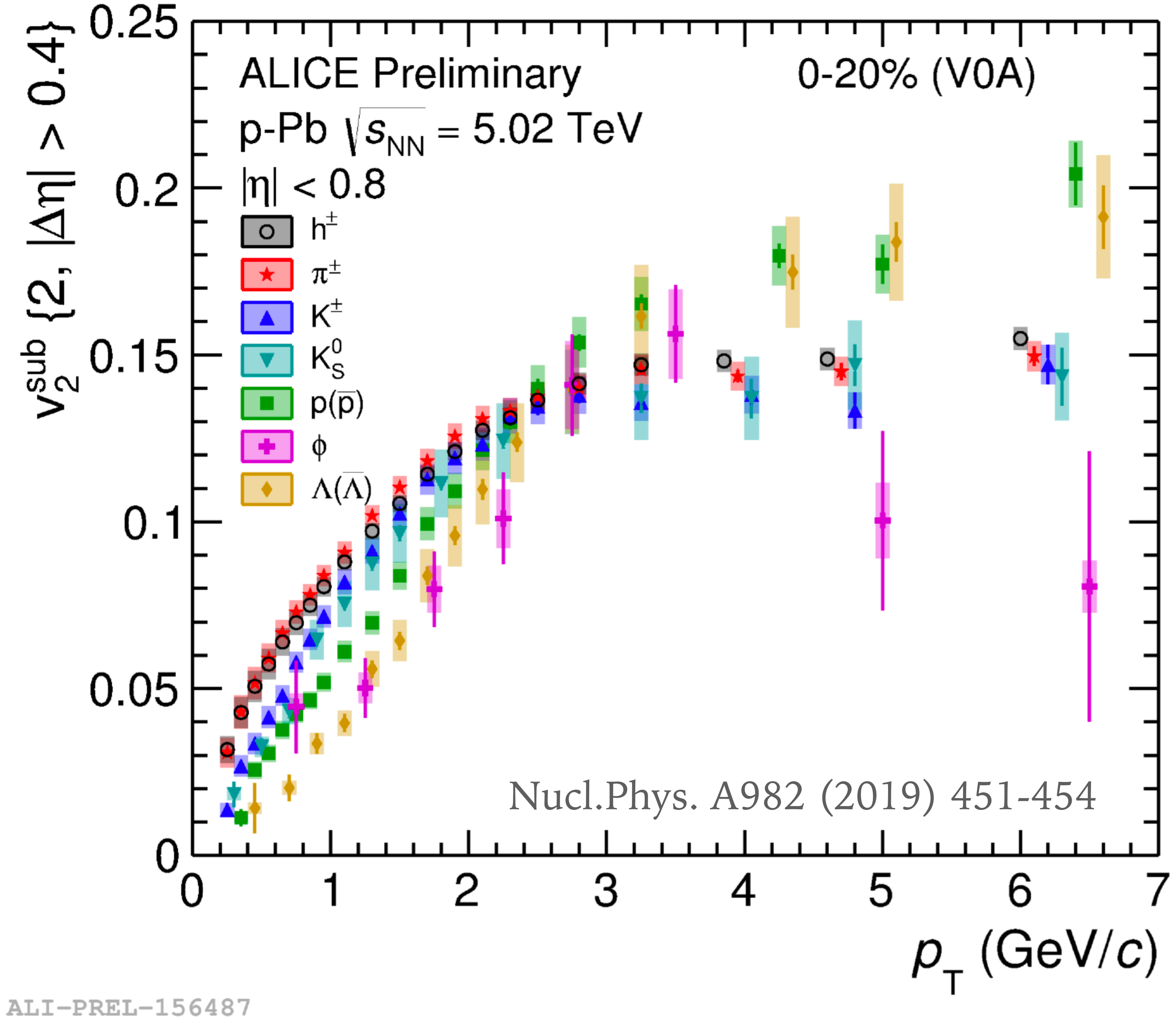


Evolution of A+A as a collective system - pressure gradients greater "in-plane" cause elliptical flow”

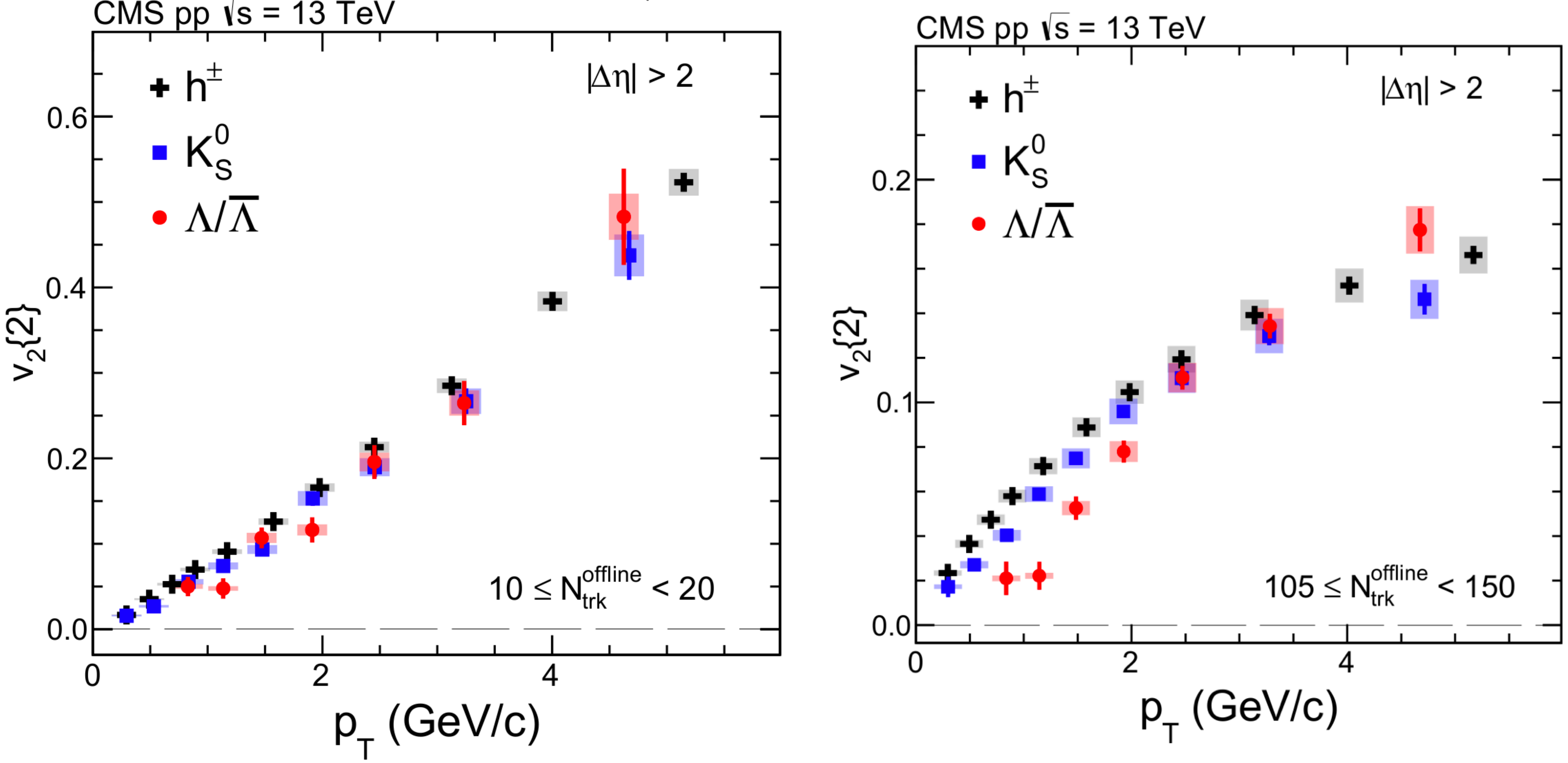


Courtesy of M. Lisa

Small systems



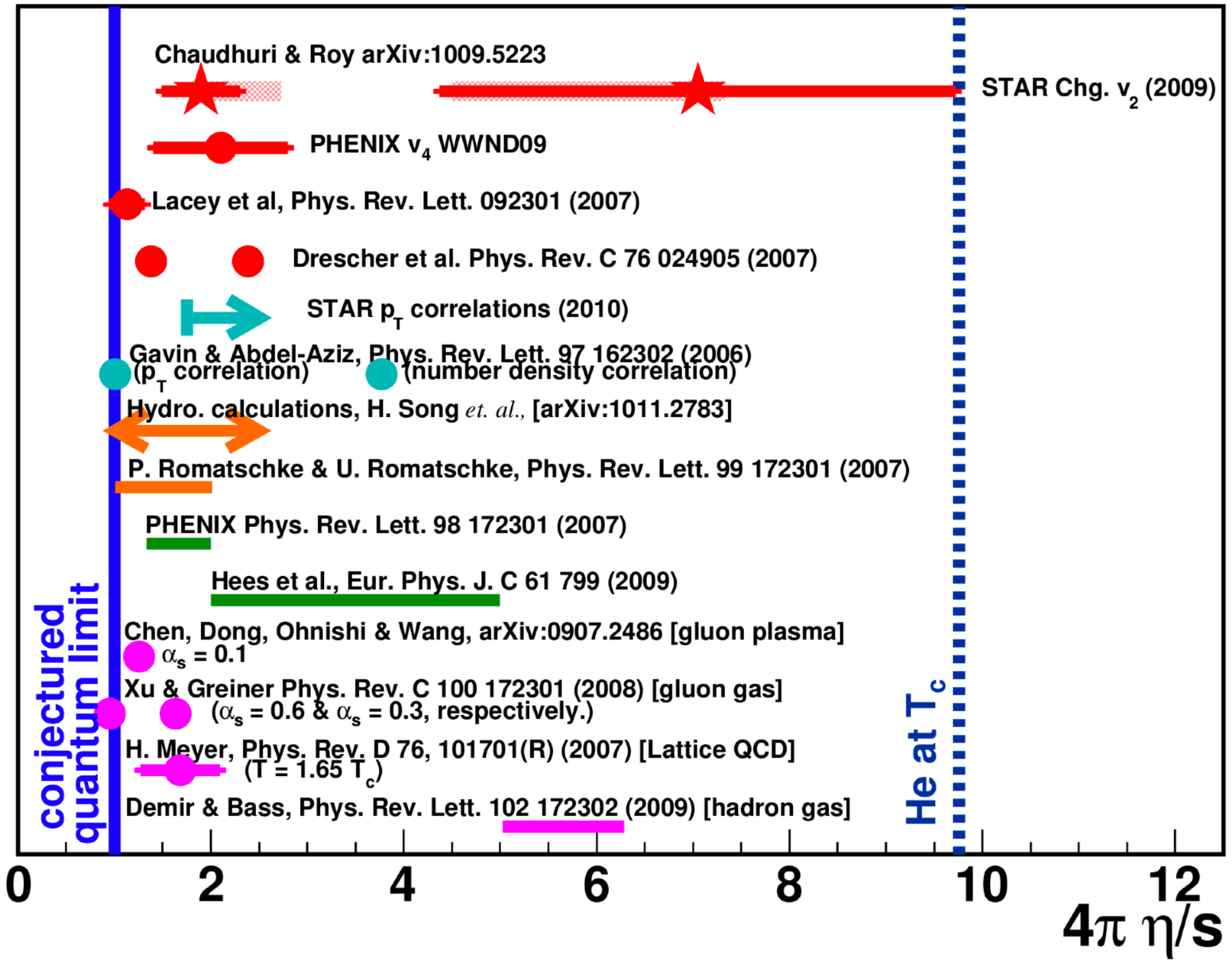
Phys. Lett. B765 (2017)



Collective behaviors present in collisions of small systems with high multiplicities.

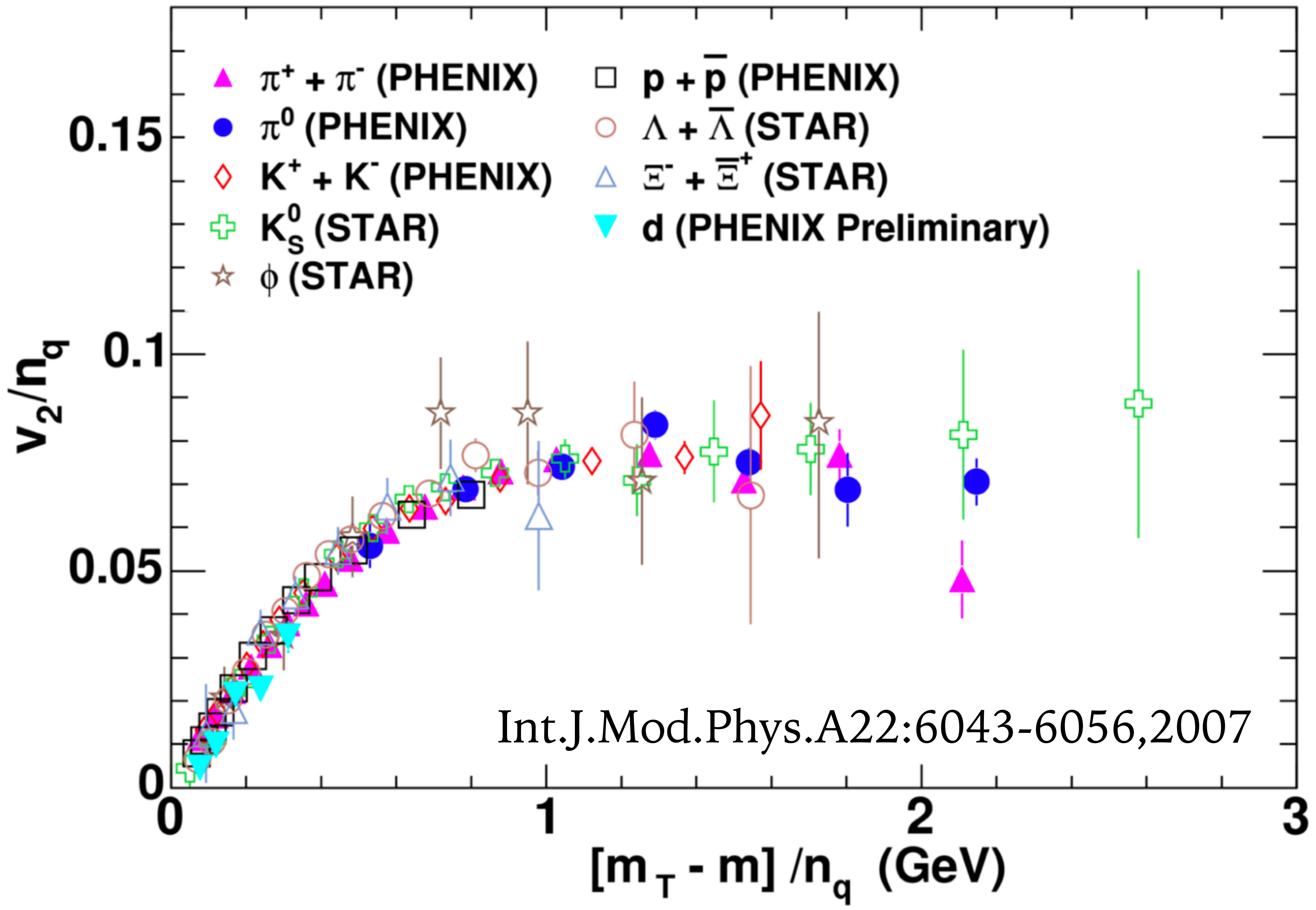
Viscosity

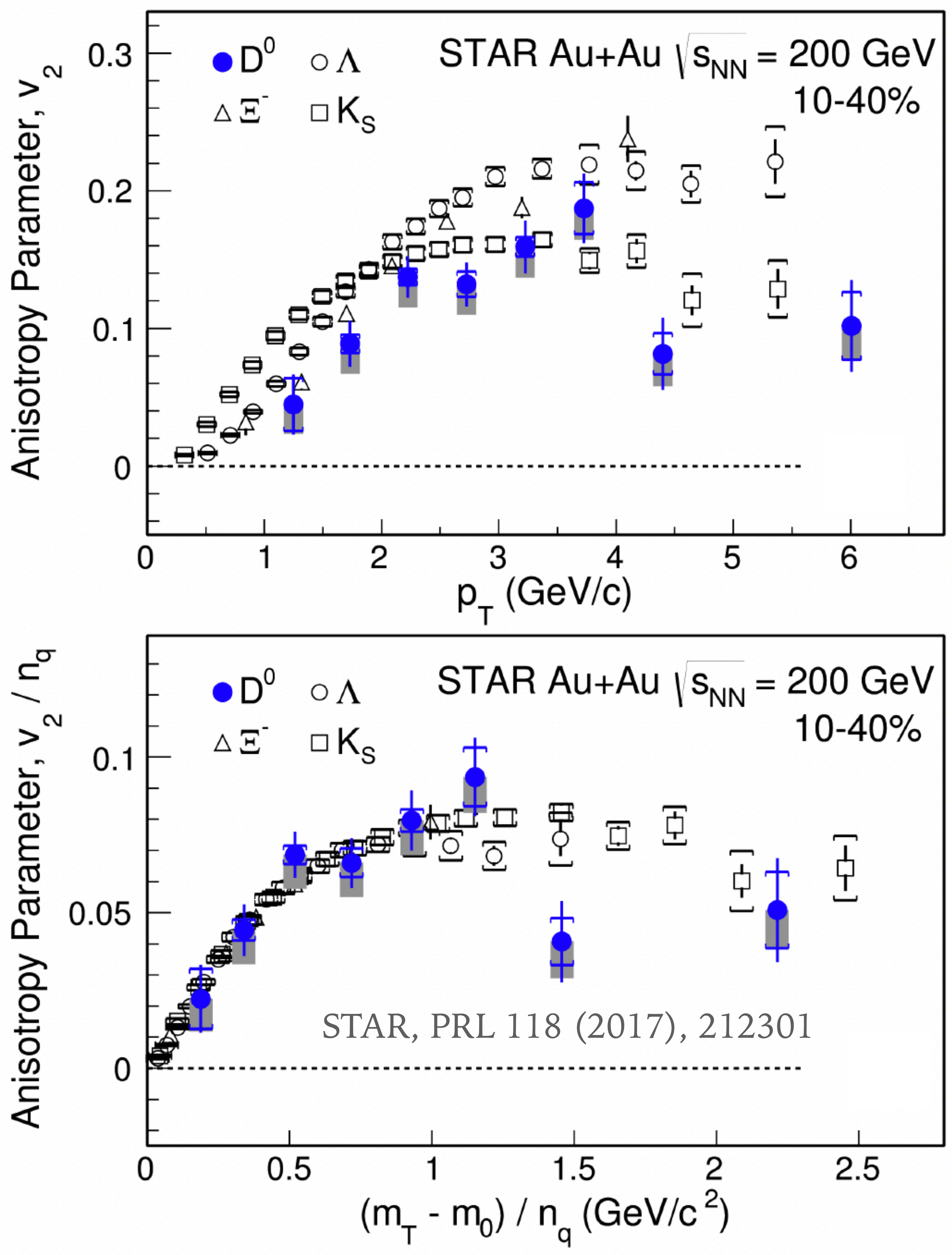
R. Lacey et al. arXiv:0905.4368: **based on v_2 measurements and v_4 (Au+Au top RHIC) :**
$4\pi\eta/s = 1.3 \pm 0.3$;
mean free path (QGP) λ= 0.25 - 0.3 fm →sQGP



- η/s calculated for RHIC mostly appears at 0.1; sQGP: the most knows perfect liquid (λ small, system shows strong collectivity).

Heavier particles species



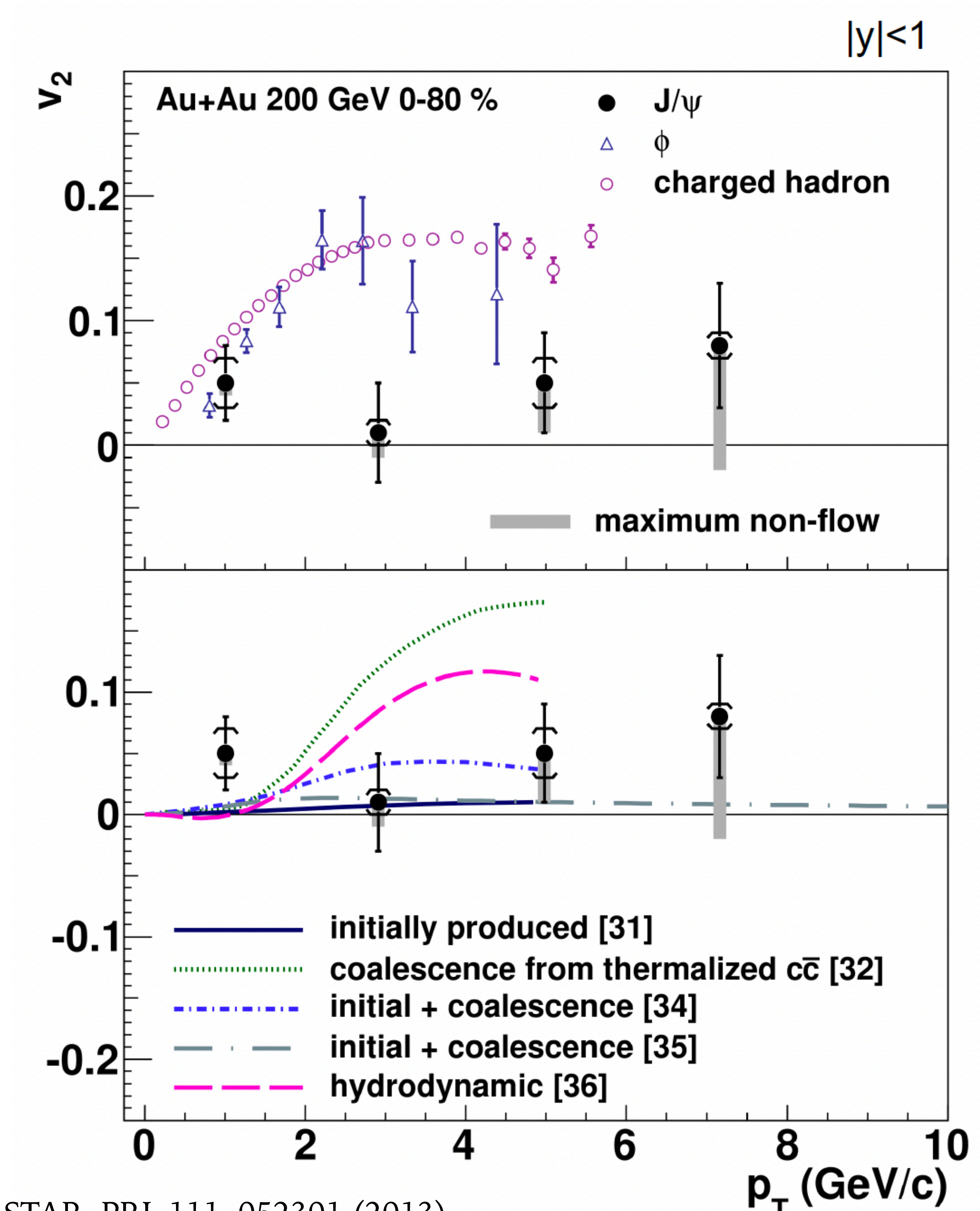


The scaling still correct even for heavier particles, incl. **deuterons** (n_q=6).

Assumed quark coalescence / recombination.

- Heavy D^0 mesons (incl. *c* quark) flow with matter similarly to light particles;
- *c* quarks reach (local) thermal equilibrium with the medium - thermalization of *c* quarks.

Heavier particles species



STAR, PRL 111, 052301 (2013)

$v_2 \simeq 0$ of J/Ψ contradicts the coalescence / recombination scenario (when J/Ψ formed from thermalized c quarks):

1. complete thermalization of c quarks not achieved (or)
2. recombination of c quarks has little influence on the production (rather early production of some mesons)

- Heavy D^0 mesons (incl. c quark) flow with matter similarly to light particles;
- c quarks reach (local) thermal equilibrium with the medium - thermalization of c quarks.

Flow harmonics correlations with $[p_T]$

p_T fluctuations from e-b-e caused by fluctuations in the initial size of the fireball.

Correlations between the $[p_T]$ and the $v_n\{2\}^2$ reveal information

- on the **correlation in the initial state between the size and the eccentricities**, and
- on the **correlations of the strength of the hydro response and flow coefficients.**

$$v_n\{2\}^2 = \frac{1}{N(N-1)} \sum_{j \neq k = 1} e^{in(\phi_i - \phi_k)}$$

$$cov(v_n\{2\}^2, [p_T]) = < \frac{1}{N(N-1)(N-2)} \sum_{i \neq k \neq j} e^{in(\phi_i - \phi_j)} (p_k - <[p_T]>) >$$

$$\rho(v_n\{2\}^2, [p_T]) = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{Var(v_n\{2\}^2) Var([p_T])}}$$

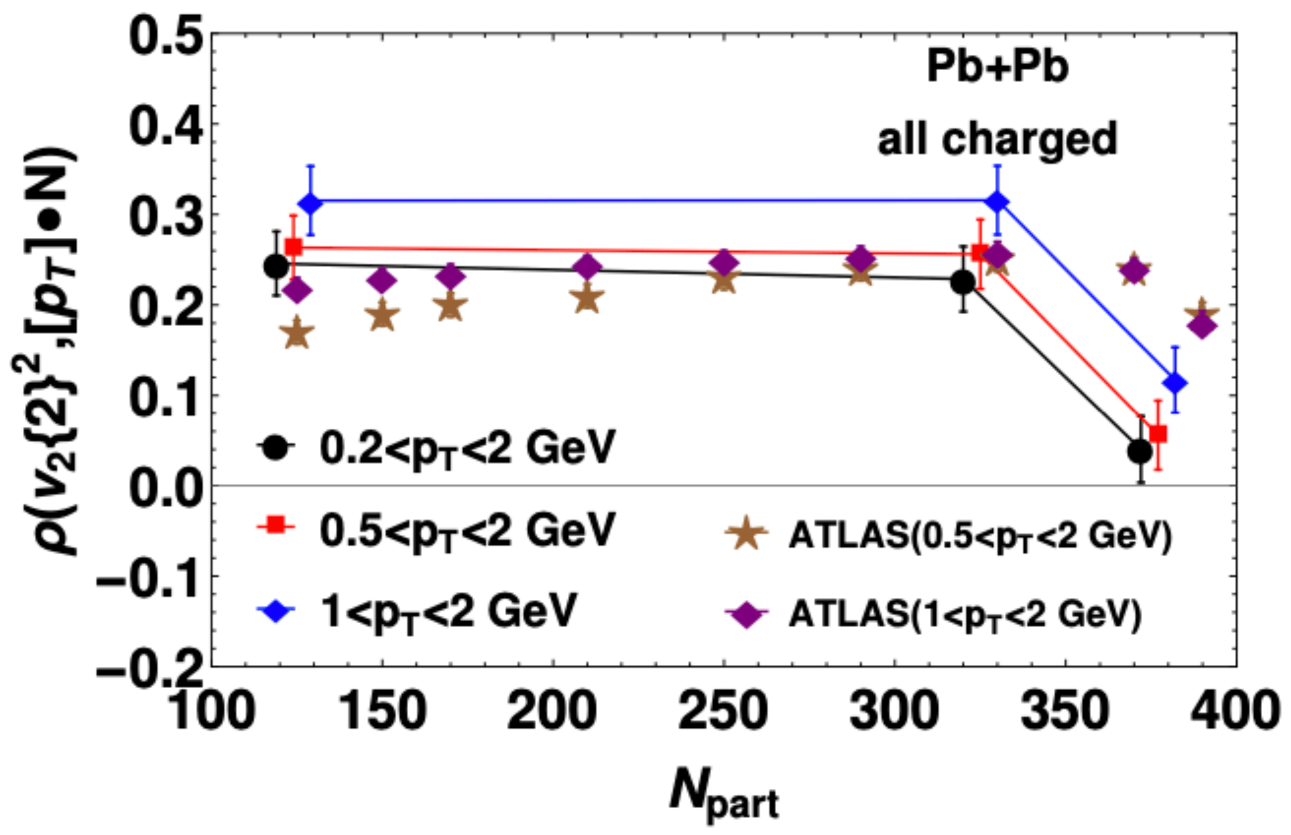
$$[p_T] = \frac{1}{N} \sum_i p_T^i$$

$$Var([p_T]) = < \frac{1}{N(N-1)} \sum_{i \neq j} (p_i - <[p_T]>)(p_j - <[p_T]>) >$$

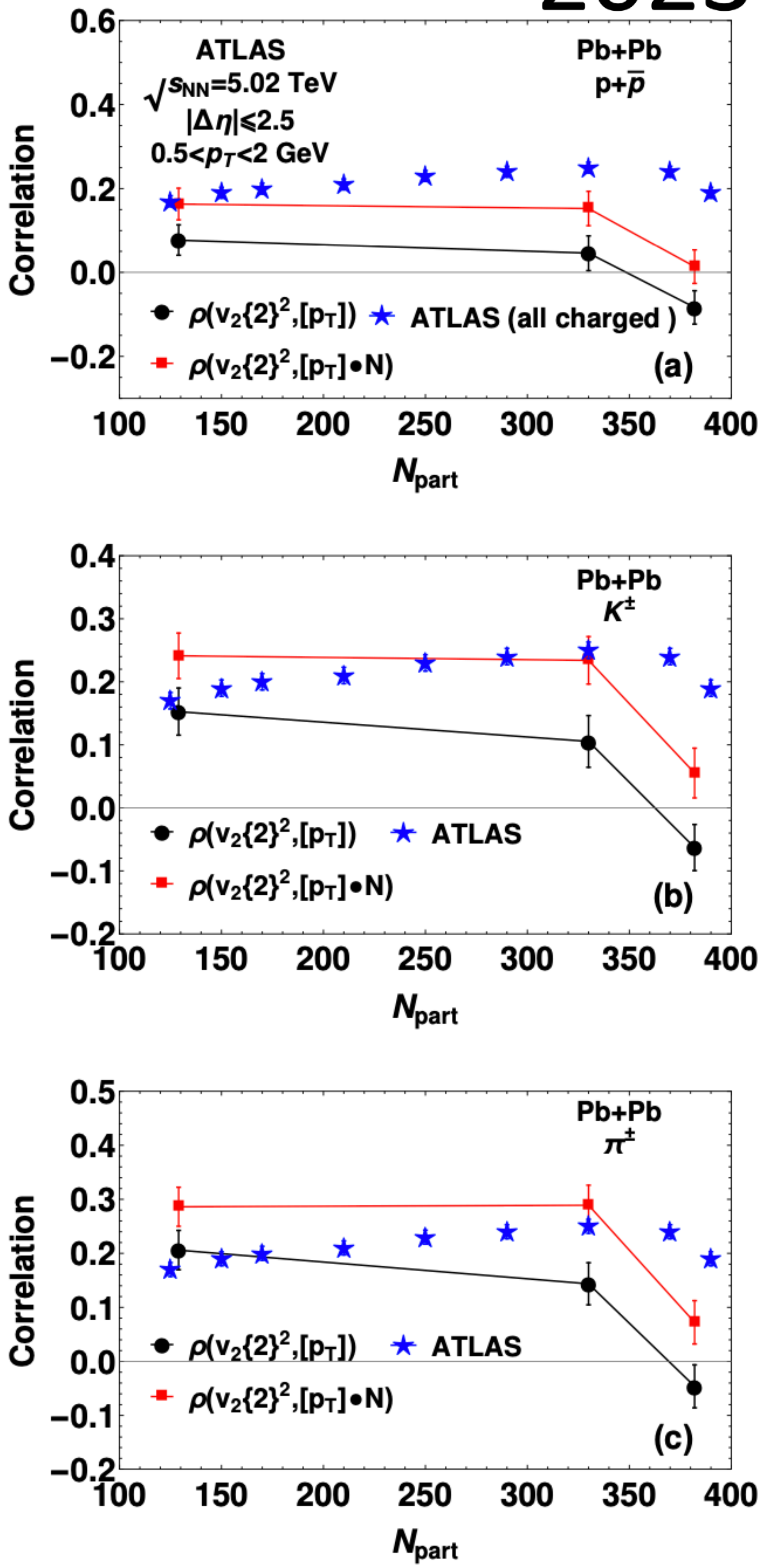
$$Var(v_n^2)_{dyn} = v_2\{2\}^4 - v_2\{4\}^4$$

$$\rho(v_n\{2\}^2, [p_T]) = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{Var(v_n\{2\}^2) Var(p_T)}} \quad (p_T \text{ flow correlation coefficient})$$

$$C_{p_T} = < \frac{1}{N(N-1)} \sum_{i \neq j} (p_i - <[p_T]>)(p_j - <[p_T]>)$$



Correlation between $v_n\{2\}^2$ and $[p_T]$. Hydrodynamic predictions compared with ATLAS

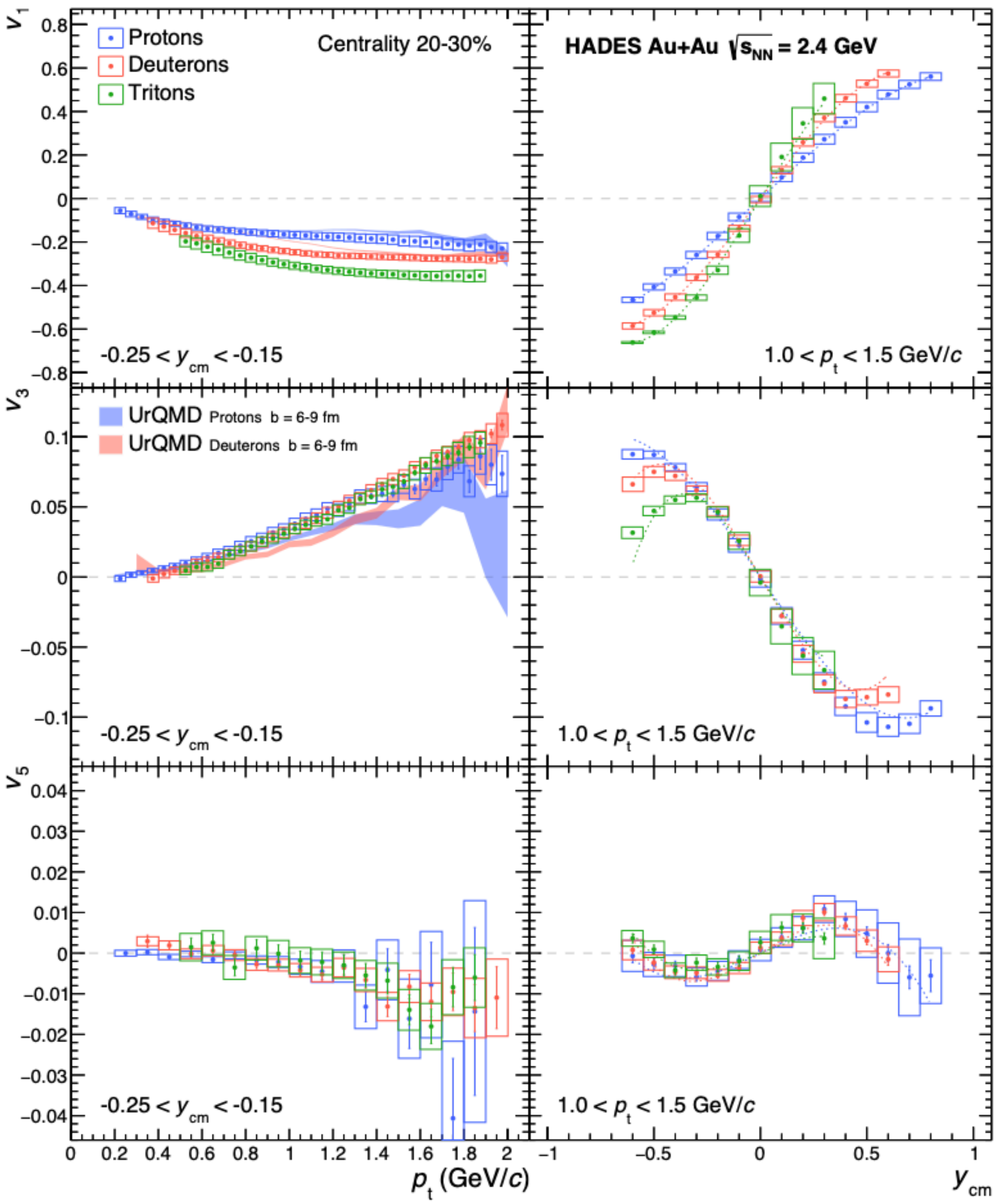


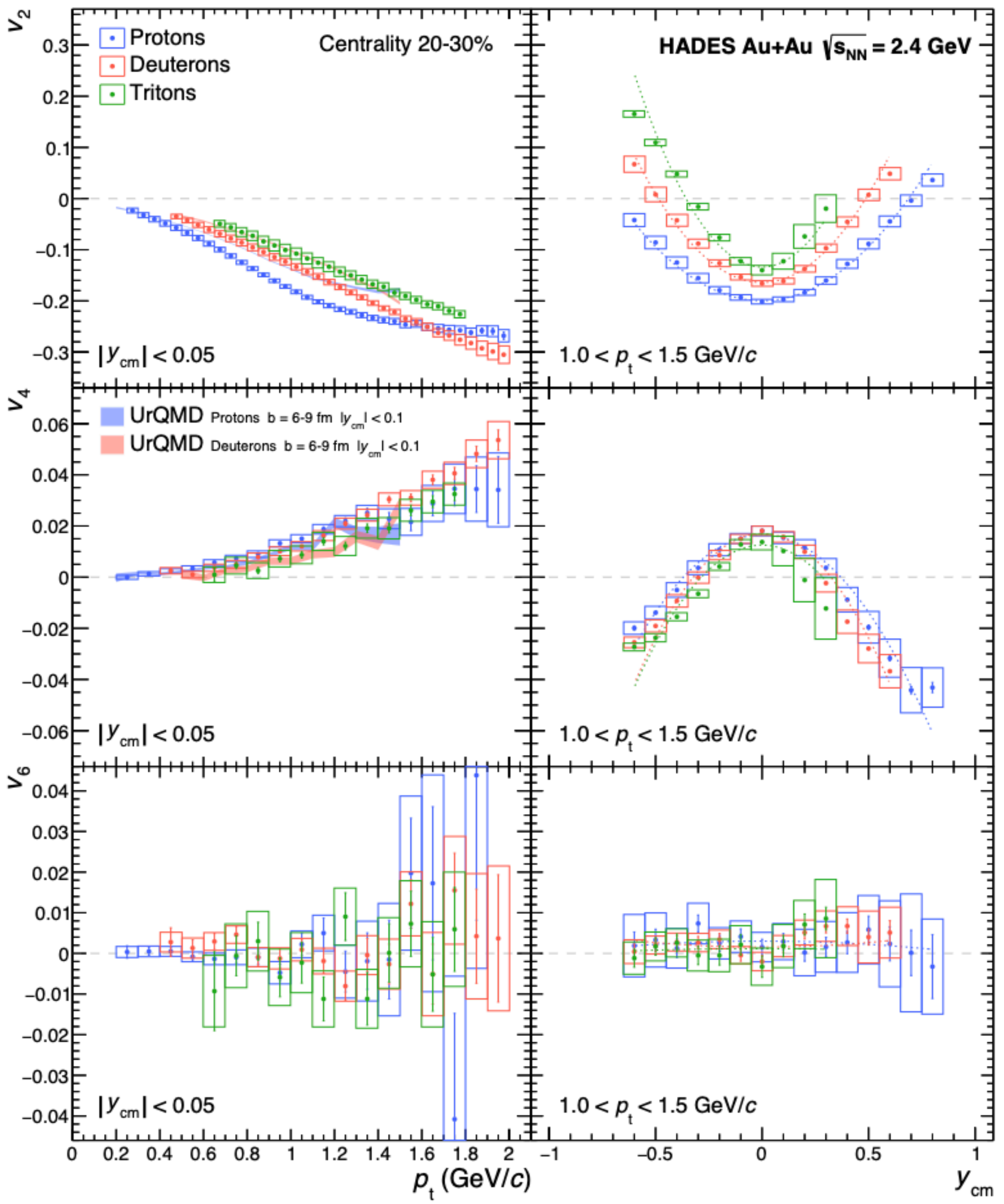
P. Bożek, Phys. Rev. C 101, 064902 (2020)

Azimuthal flow at HADES (Au+Au, $\sqrt{s_{NN}} = 2.4$ GeV)

Phys. Rev. Lett. **125**, 262301

- $\sqrt{s_{NN}} \simeq$ 1-10 GeV: strongly interacting matter at high μ_B;
- v_1 of protons: sensitivity to the EOS of a hadronic medium (based on UrQMD);
- v_4: constrain of the nuclear mean field at high μ_B
- Flow sensitive to determine η/s (higher energies)





$|v_1(p)| < |v_1(d)| < |v_1(t)|$

$|v_3(p)| > |v_3(d)| > |v_3(t)|$

$|v_2(p)| > |v_2(d)| > |v_2(t)|$

$|v_4(p)| > |v_4(d)| > |v_4(t)|$

Azimuthal flow at HADES (Au+Au, $\sqrt{s_{NN}} = 2.4$ GeV)

- $v_n \sim v_2^{n/2}$ (hydro prediction)
- $v_4(p_T)/v_2^2(p_T) = 1/2$ (ideal fluid scenario);
- $v_4(p_T)/v_2^2(p_T)$ more complex behavior (RHIC, LHC);
- flow at lower $\sqrt{s_{NN}}$ affected by the presence of slow spectator nucleons

Higher-order flow harmonics measured w.r.t first order RP, not related to the initial fluctuations.

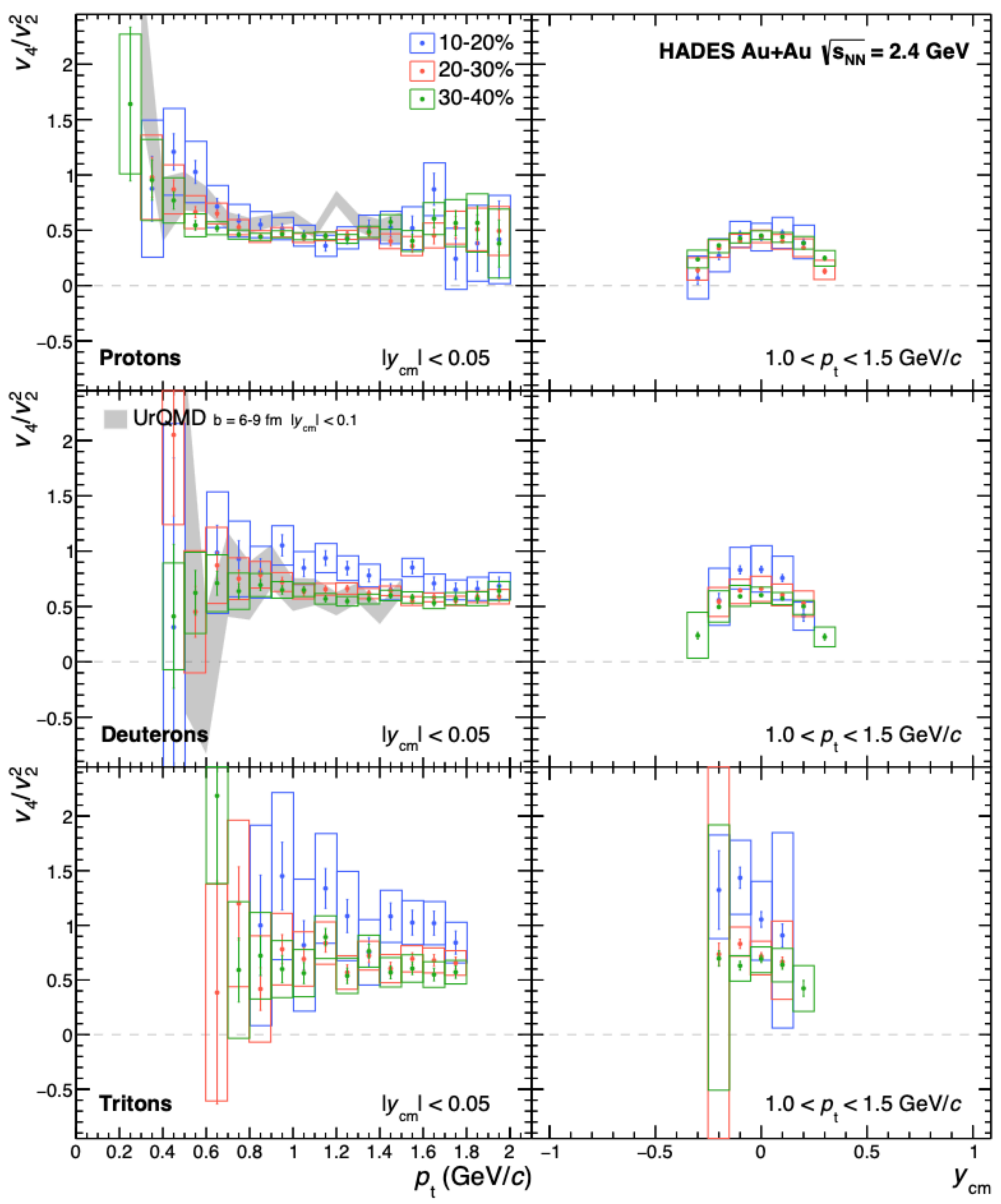
$$\Psi_{RP,1} = \tan^{-1}(Q_{1,y}/Q_{1,x})$$

$$\overrightarrow{Q_n} = (Q_{n,x}, Q_{n,y}) = \left(\sum w\cos(n\phi_{FW}), \sum w\sin(n\phi_{FW})\right)$$

$$w = |Z|$$

Hits of projectile spectators in the Forward Wall detector.

Phys. Rev. Lett. **125**, 262301



η/s for high μ_B is relatively high, not the ideal fluid scenario.

Different methods of flow measurements

Event Plane method [Phys.Rev.C 58, 1671 (1998)]:

Event plane vector: $\overrightarrow{Q_n} = [X_n, Y_n] = [Q_n \cos(n\Psi_n), Q_n \sin(n\Psi_n)]$

$[X_n, Y_n] = [\sum_i w_i \cos(n\phi_i), \sum_i w_i \sin(n\phi_i)]$

$$\Psi_{EP,n} = \frac{1}{n} \tan^{-1} \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}$$

$v_n\{EP\} = \dfrac{< cos[n(\phi - \Psi_{EP,n})] >}{R_n}$; R_n - EP's resolution

$R_n = < \cos(km(\Psi_m - \Psi_r)) >$

here: $R_n = \sqrt{\dfrac{< \cos[n(\Psi_A - \Psi_B)] > < \cos[n(\Psi_A - \Psi_c)] >}{< \cos[n(\Psi_B - \Psi_C)] >}}$

Cumulant method:

$$< 2 >_n = < e^{in(\phi_1 - \phi_2)} >$$

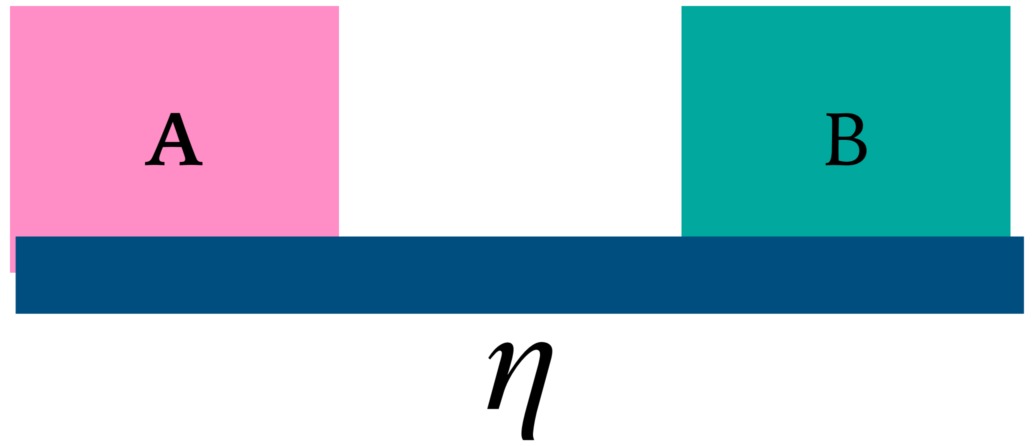
$$< 4 >_{nm} = < e^{in(\phi_1 - \phi_2) + im(\phi_3 - \phi_4)} >$$

$$v_n^4\{4\} = < 4 >_{nm} - 2 < 2 >_n < 2 >_n$$

$$NSC(n,m) = \frac{< 4 >_{nm} - < 2 >_n < 2 >_m}{< 2 >_n^{sub} < 2 >_m^{sub}}$$

$$< 2 >_n^{sub} = < e^{in(\phi_A - \phi_B)} >$$

$$v_n^2\{2\} = c_n\{2\} = < 2 >_n^{sub}$$

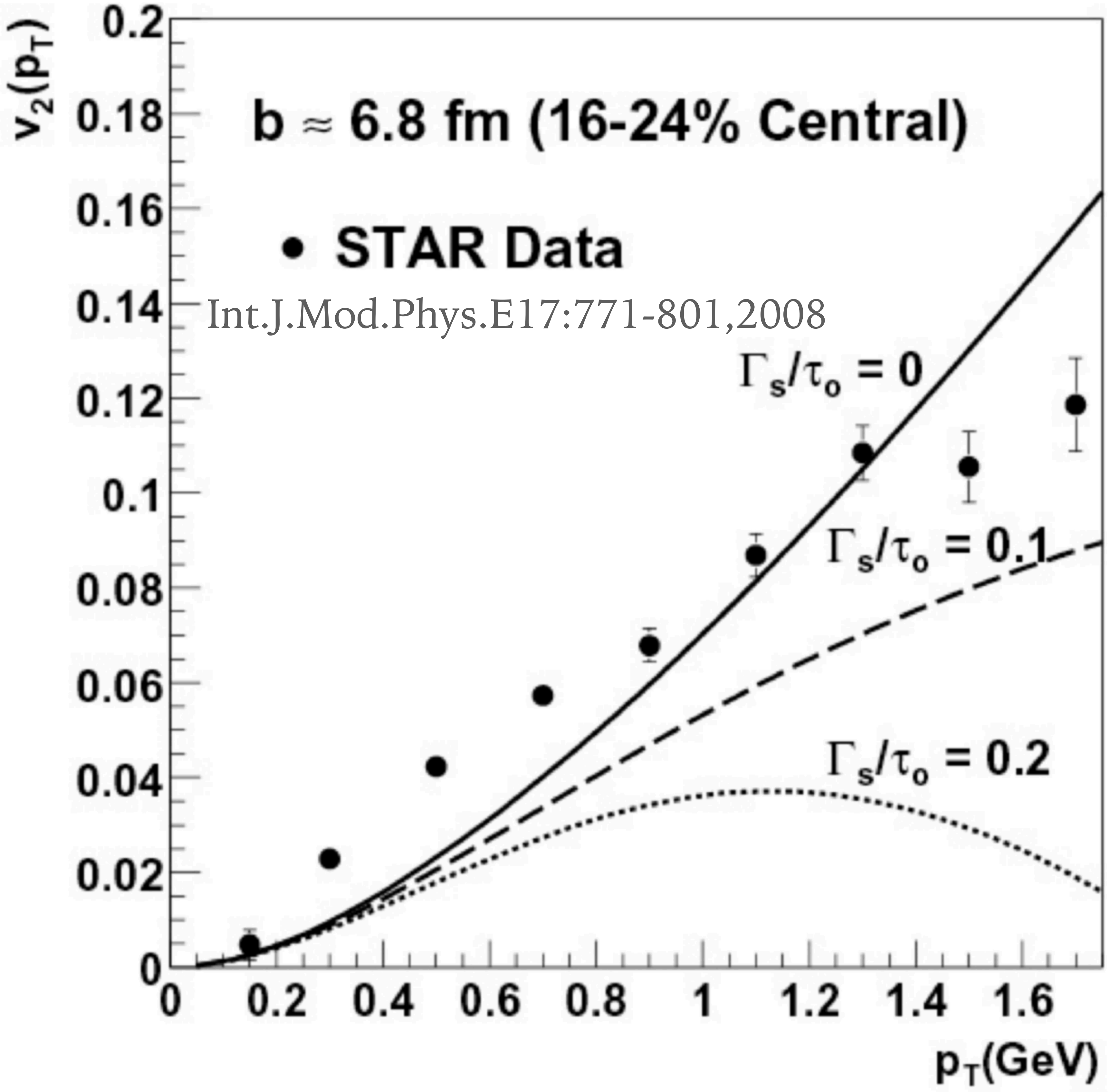


$$v_n\{4\} = 2 < v_n^2 >^2 - < v_n^4 >$$

$$\frac{(v_n\{4\})^4}{(v_n\{2\})^4} = 2 - \frac{< v_n^4 >}{< v_n^2 >^2}$$

Flow fluctuations

Ideal gas or perfect liquid?



- Many years ago **QGP** expected as „ideal gas" (at least system of very weekly interacting quarks and gluons);
- An observation →QGP closer to „perfect liquid" (viscosity close to 0, collective effects);
- $\eta/s \simeq 0.1$ **at RHIC**;

- sQGP - strongly interacting QGP;
- wQGP - weakly coupled gas; (models predicts in case of wQGP η/s would have bigger values, non-zero viscosity reduces collectivity - v_2)

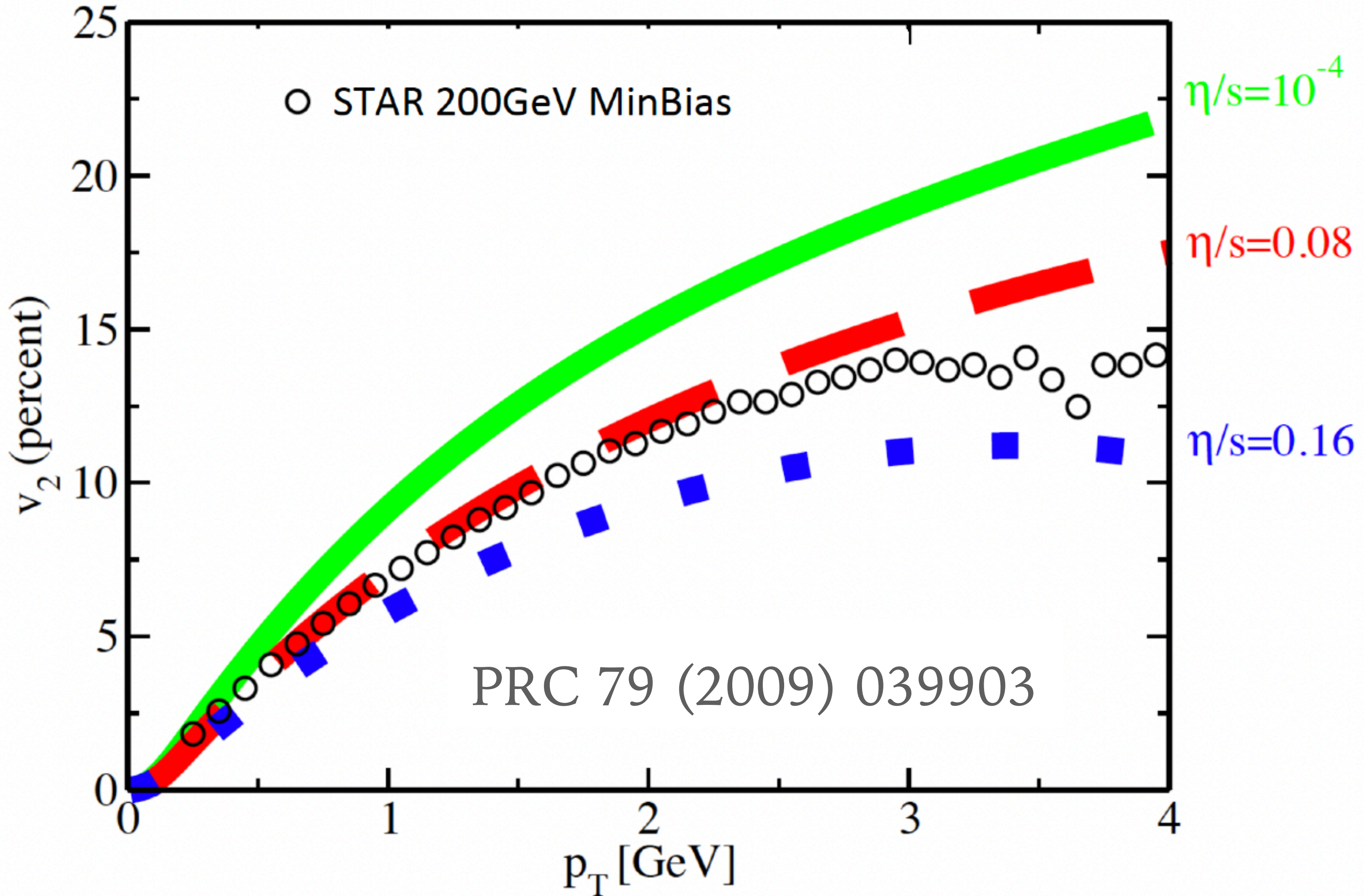
$$\Gamma_s = \frac{4}{3T}\frac{\eta}{s}$$

Γ_s - sound attenuation length

η - shear viscosity

$s = S/V$ - entropy density

τ_0 - time scale of the expansion



Strong constraint on viscosity reveal the nature of the „perfect" liquid;

Ads / CFT lower limit is $\eta/s = 1/4\pi \simeq 0.08$

PRL 94 (2005) 11601

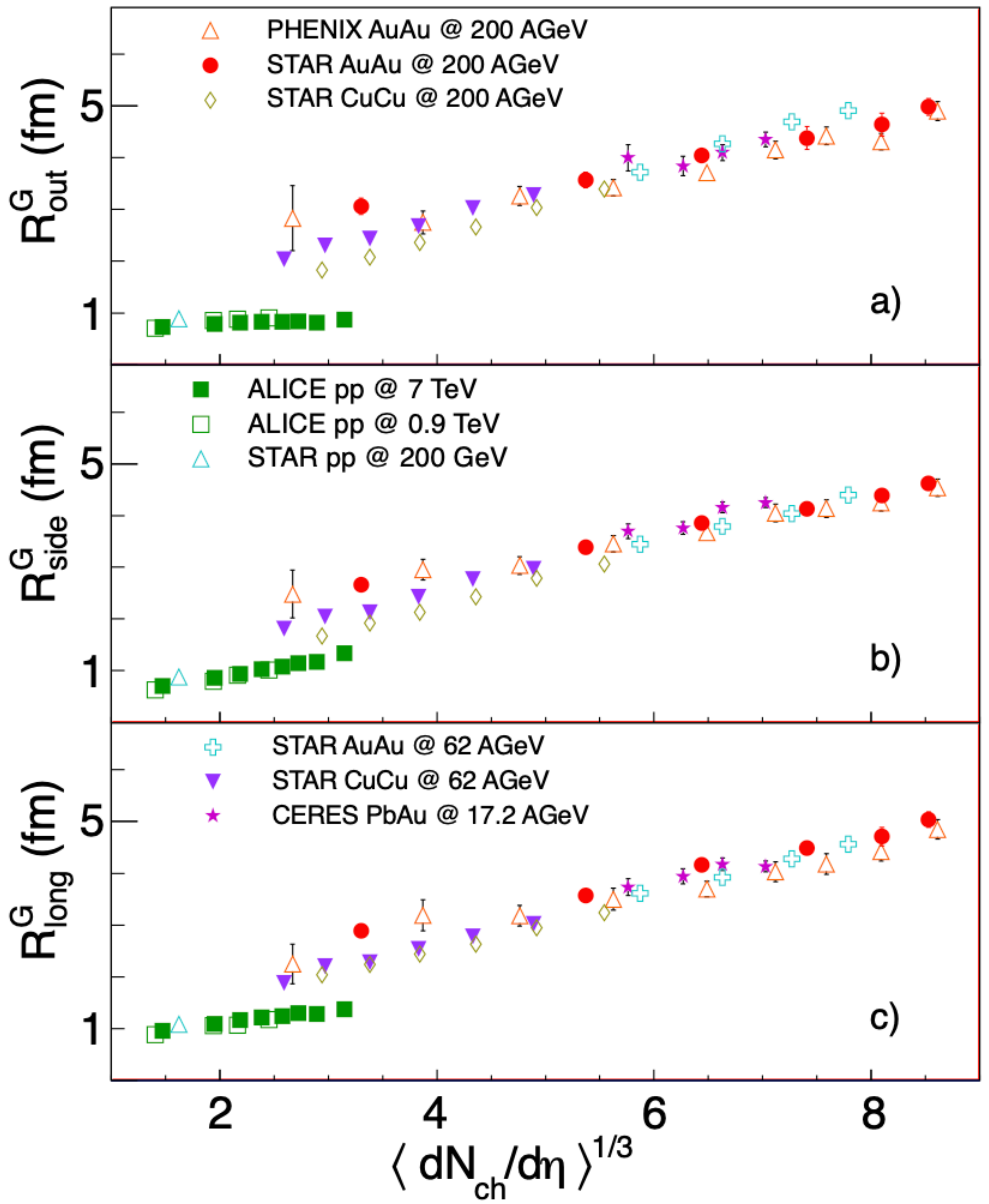
$< dN/d\eta >^{1/3}$ scaling of source sizes

$< dN/d\eta >^{1/3}$ **scaling broken for p-p collisions.**
Possible scenario: two types of collisions at similar multiplicity.

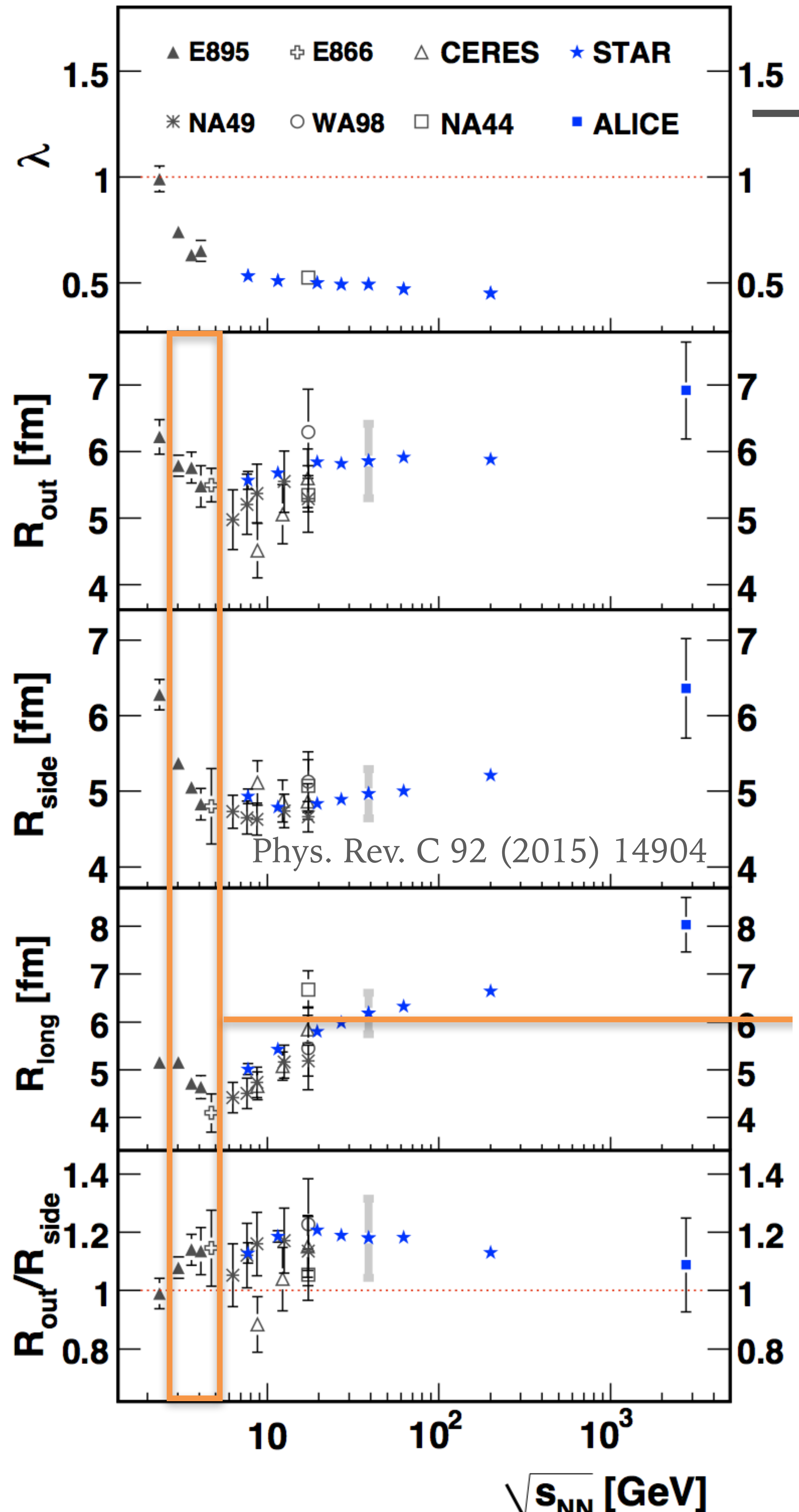
p-p: production of many soft particles;
size of the region of particle's creation ~proton size;
the growth of $R(mult.)$ from particle's interactions;

Heavy-ions: many elementary nucleon scatterings, each producing a relatively low multiplicity.

Phys. Rev. D 84 (2011) 112004



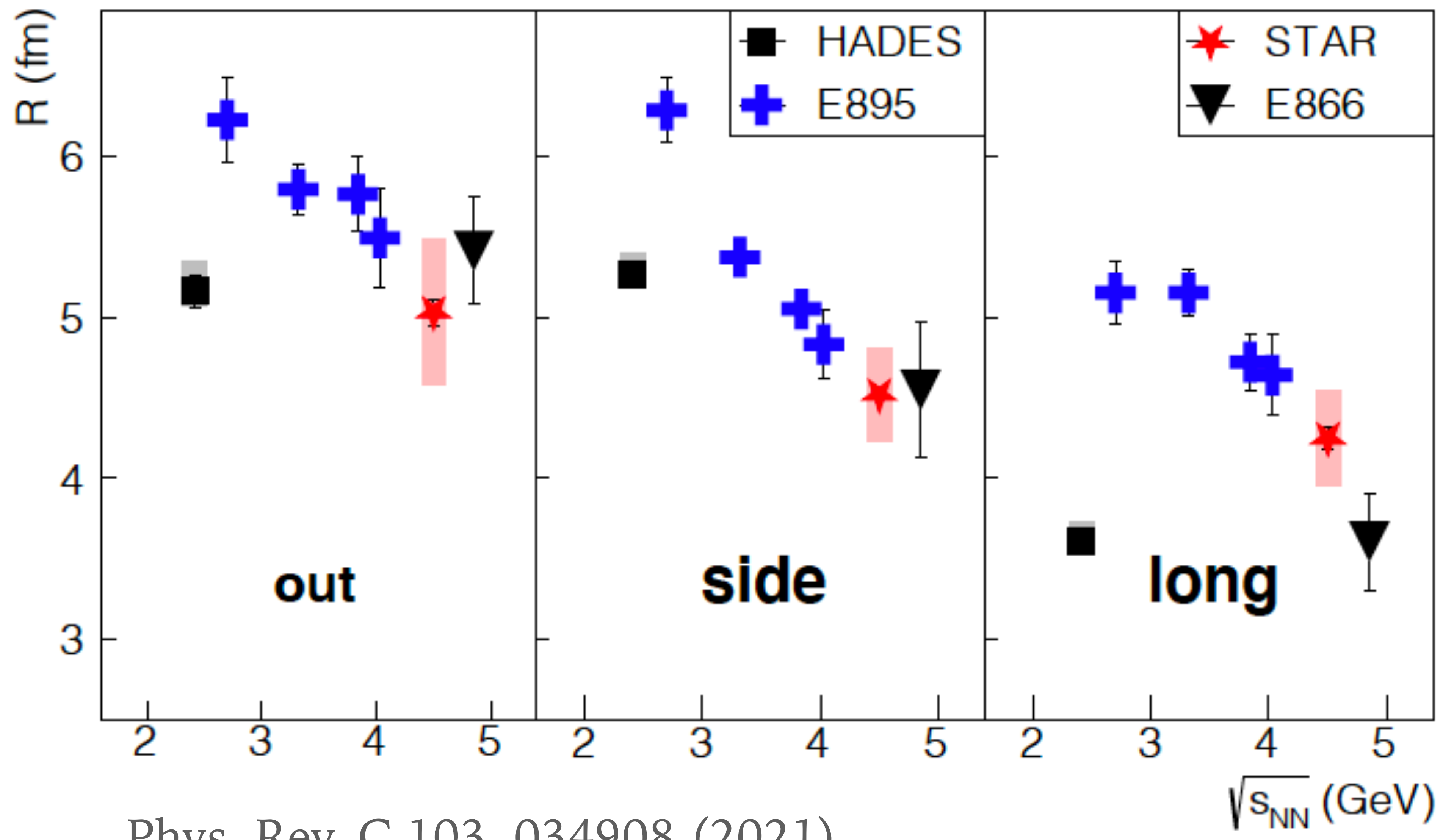
Identical pion femtoscopy



Clear evolution in the freeze-out shape indicated

Lower energies: system more oblate
($R_{side} > R_{long}$)
Higher energies: system more prolate
($R_{side} < R_{long}$)
$\sqrt{s_{NN}}$ = 4.5 GeV: round system ($R_{side} \simeq R_{long}$)

Transition region between dynamics dominated by stopping and boost-invariant dynamics.



Phys. Rev. C 103, 034908 (2021)

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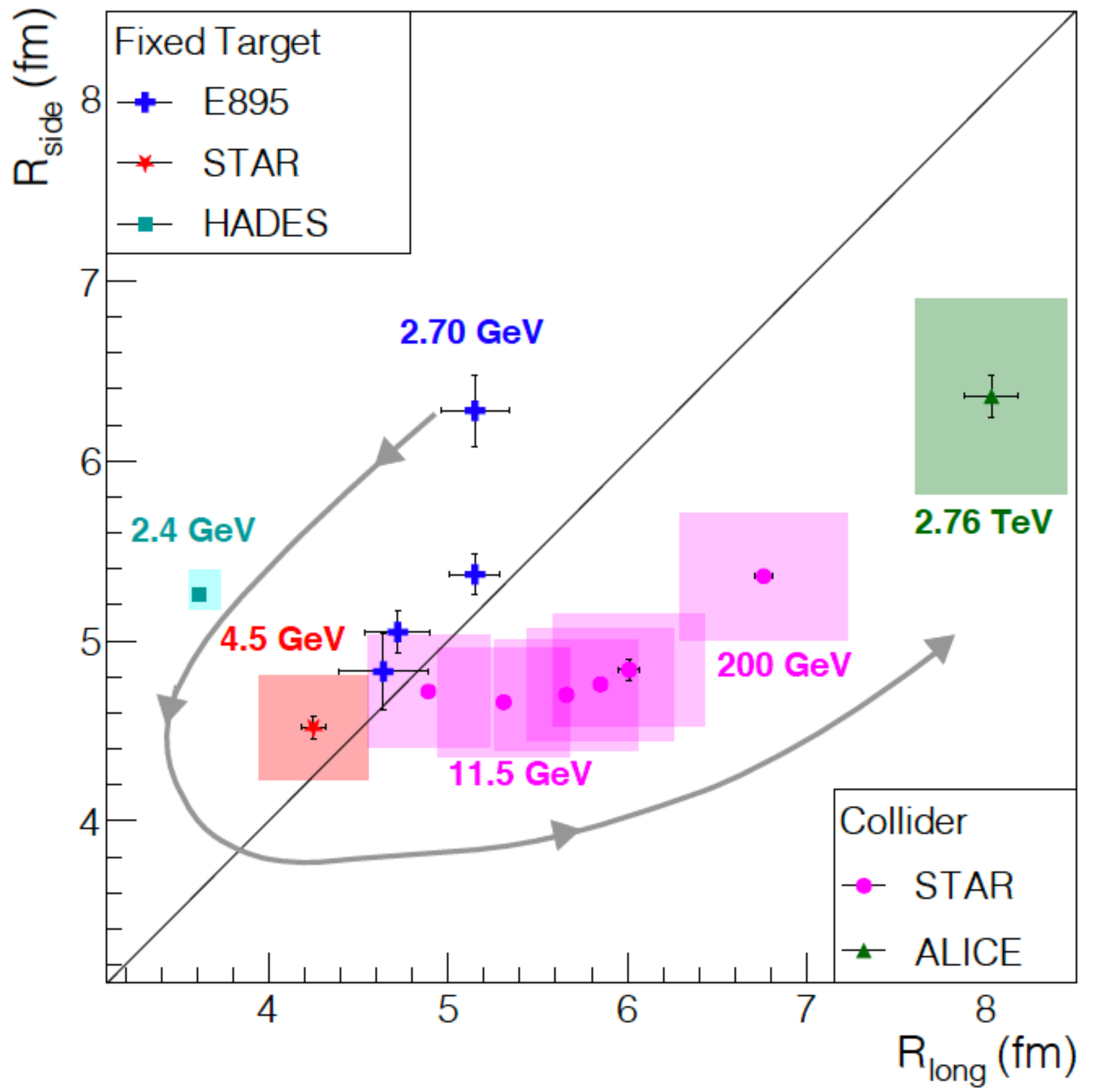

HBT puzzle

Hydrodynamical models successfully describing flow (at RHIC) did not reproduce HBT results.

Uniform description working on:

- Flow (v_2);
- Spectra (p_T, m_T);
- HBT source sizes.

Solution on HBT puzzle:

2. **S. Pratt**: earlier hydrodynamical expansion, inclusion of the viscosity and modification EoS (cross-over transition), Phys.Rev.Lett.102:232301,2009, S. Pratt, M. Lisa: arXiv:0811.1352.

2. **W Florkowski**: modified initial density distributions - smaller source described by Gaussian profile (instead of the Glauber one): J.Phys.G36:064067,2009

3. **G. Torrieri**, inclusion of the bulk viscosity (ζ), arXiv:0901.0226