Elliptic anisotropy of identified particles from parton scatterings in small collision systems

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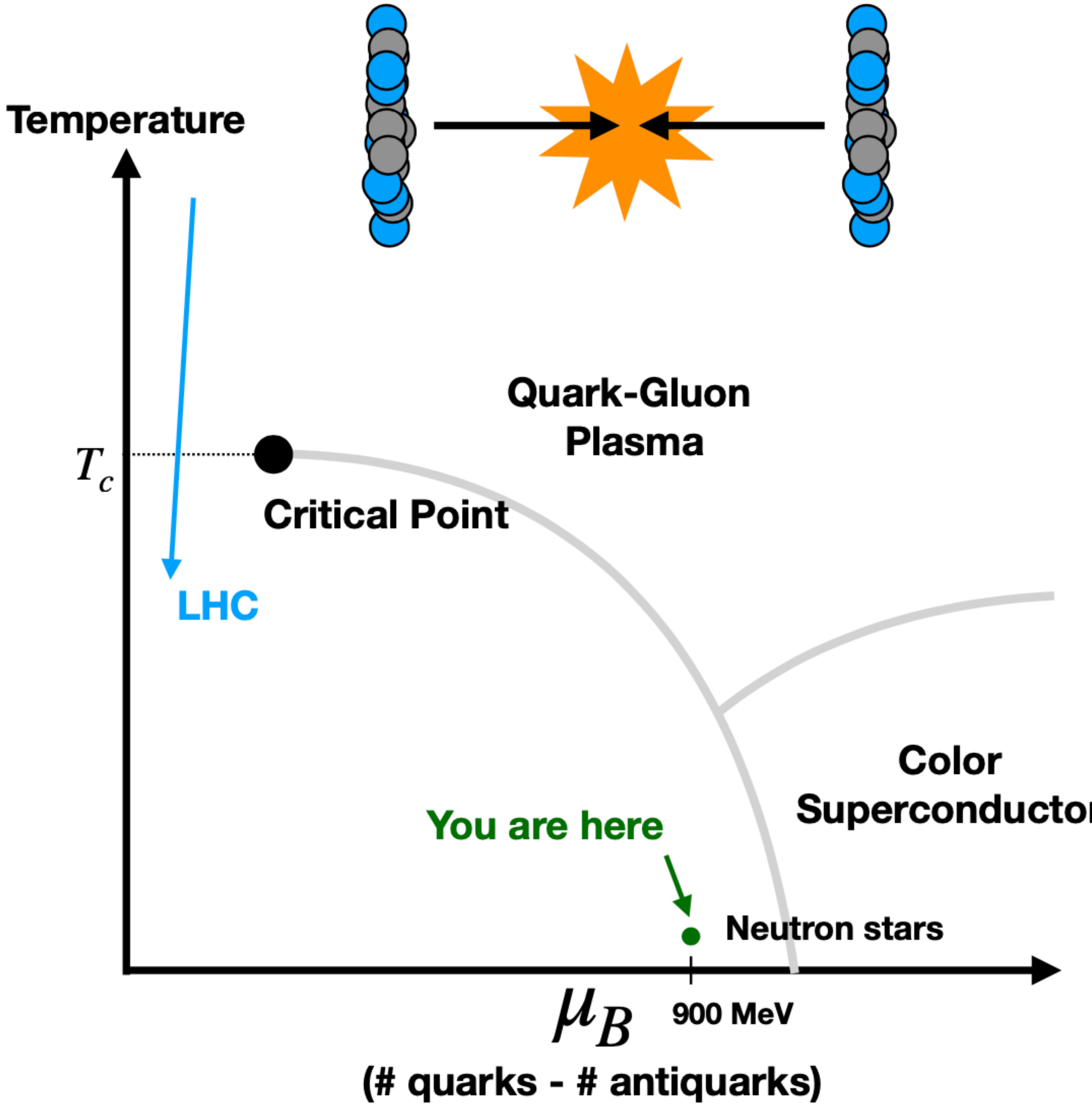
More details are shown in: arXiv:2303.06577

Heavy-ion collisions and QGP

A.Baty, LPCC LHC Seminar, July 18th, 2023

- A phase transition from hadronic matter to a deconfined partonic medium, the **quark-gluon plasma (QGP)**, is predicted under extreme conditions:
  - High/low baryon density/temperature: neutron stars
  - High/low temperature/baryon density: early universe after the Big Bang, heavy-ion collisions



- Variety of observables to study the QGP:
  - Jet quenching
  - Heavy flavors
  - Collective behavior of produced particles

Hydrodynamic flow

- The azimuthal anisotropy is studied by a Fourier expansion of azimuthal distribution of final-state particles:

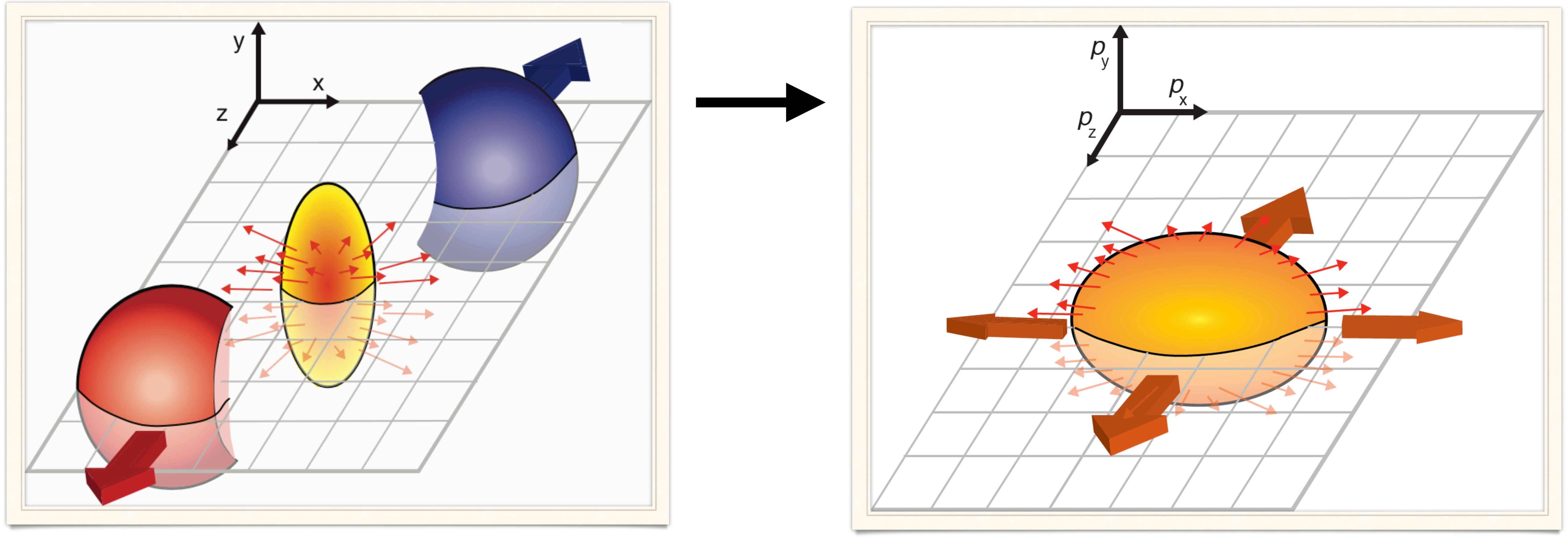
$$v_n = \langle \cos(n(\varphi - \Psi_n)) \rangle$$

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_n))\right)$$

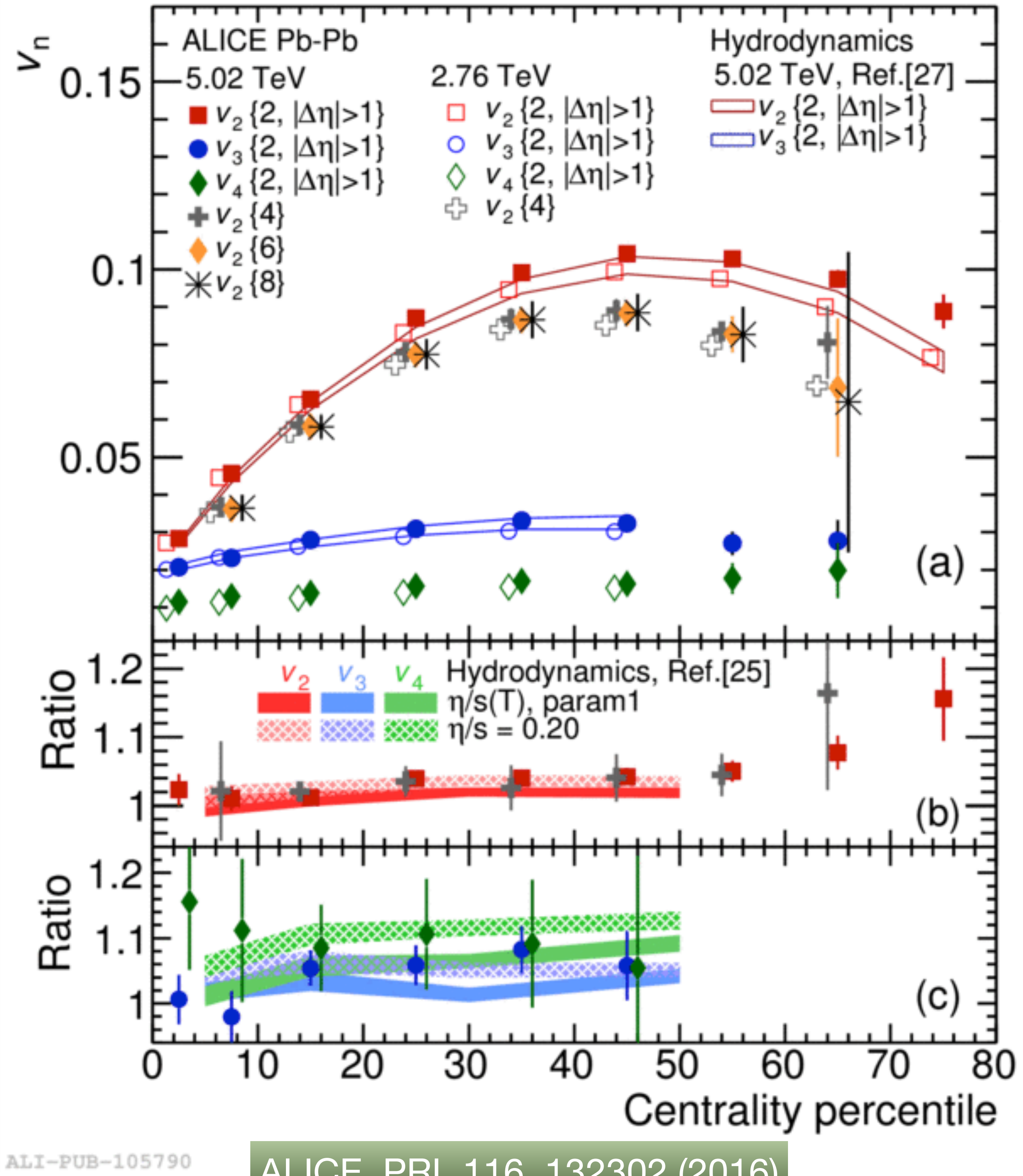
Flow coefficients

***n*=2, elliptic flow v_2**

Initial spatial anisotropy **Final anisotropy in momentum space**



* Pressure gradient
* Expansion of the QGP



ALICE, PRL 116, 132302 (2016)

Hydrodynamic flow

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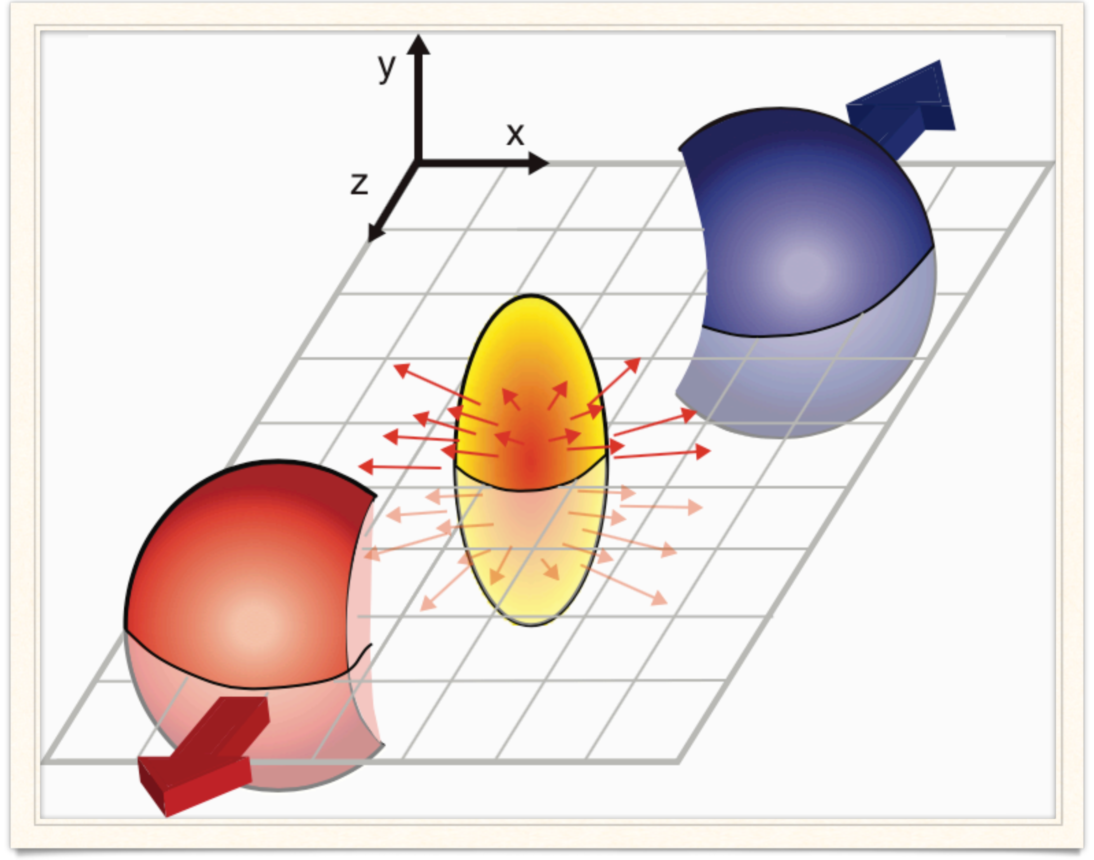
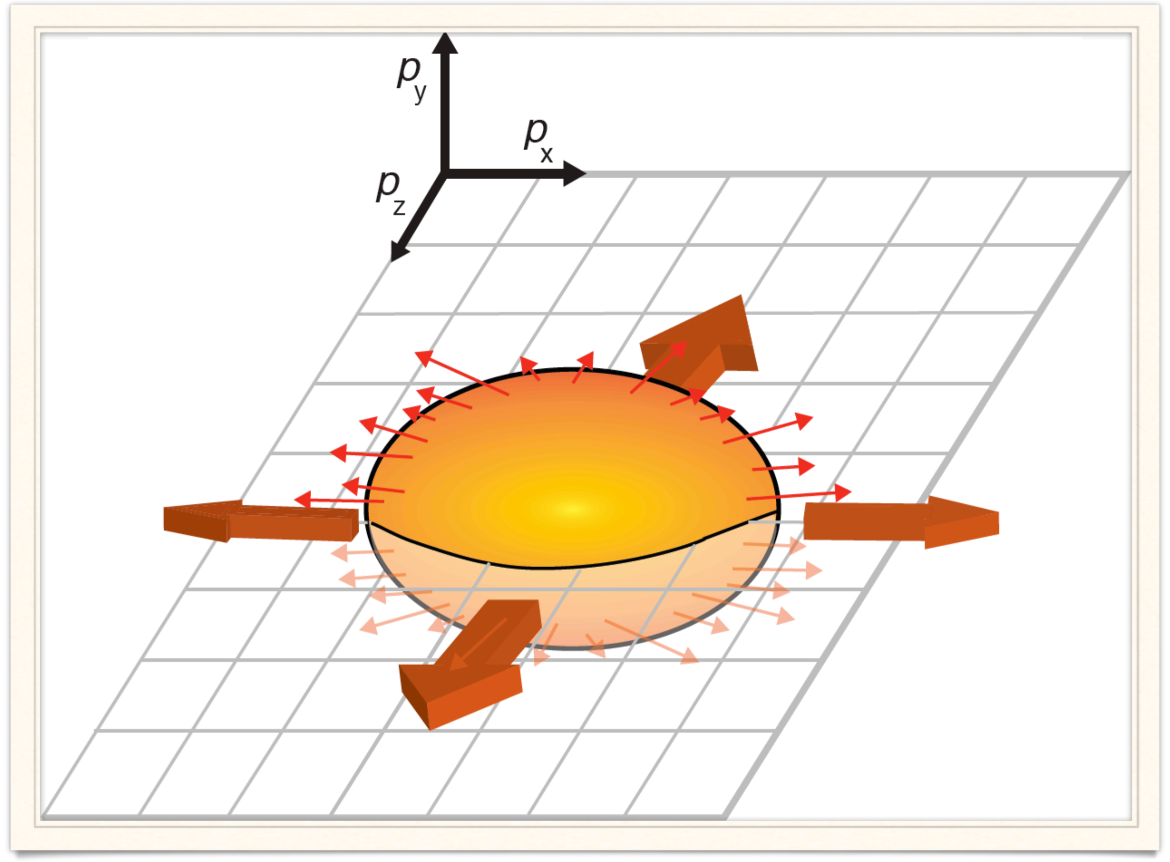
Initial spatial anisotropy

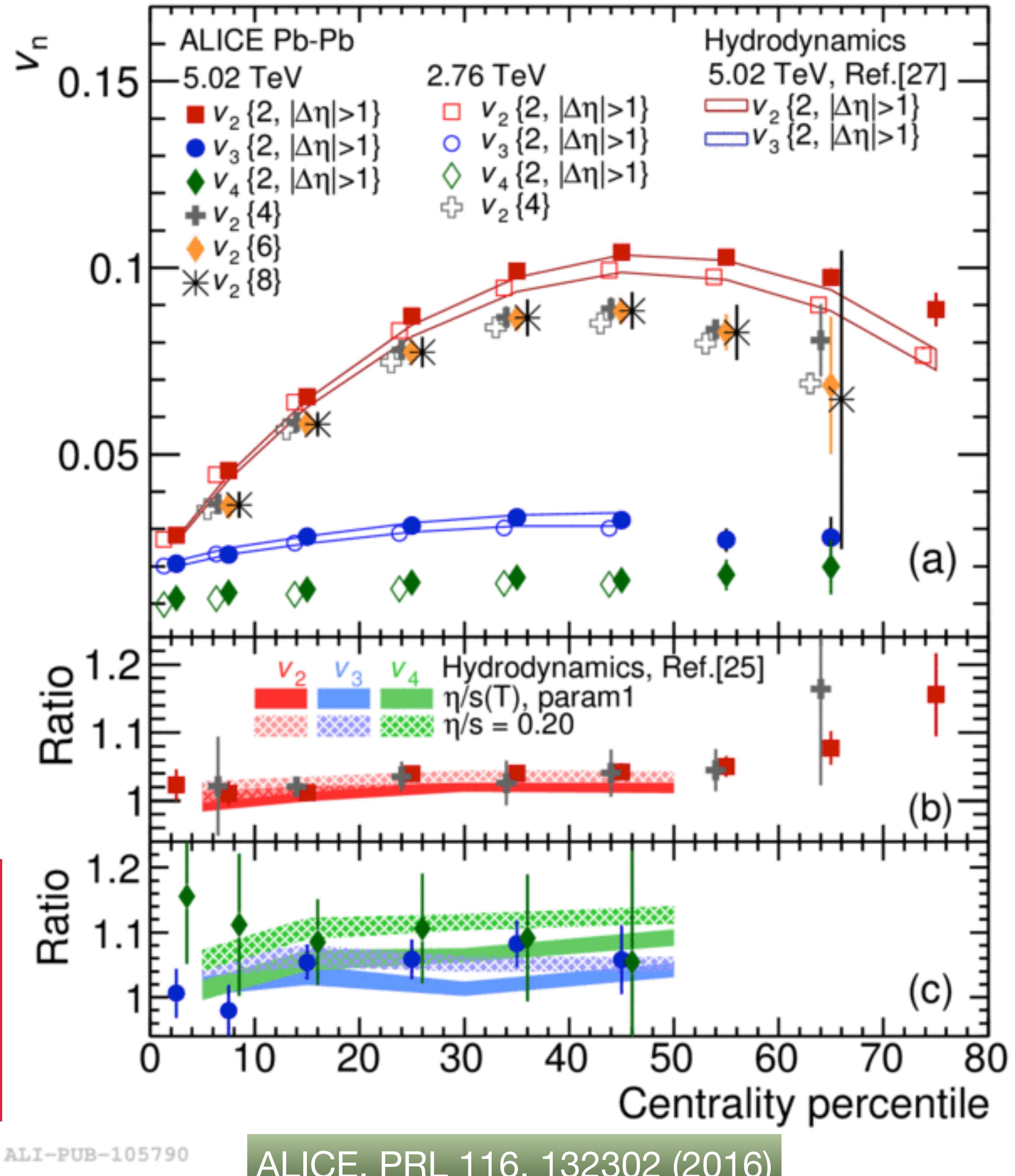


Final anisotropy in momentum space



* Pressure gradient
* Expansion of the QGP

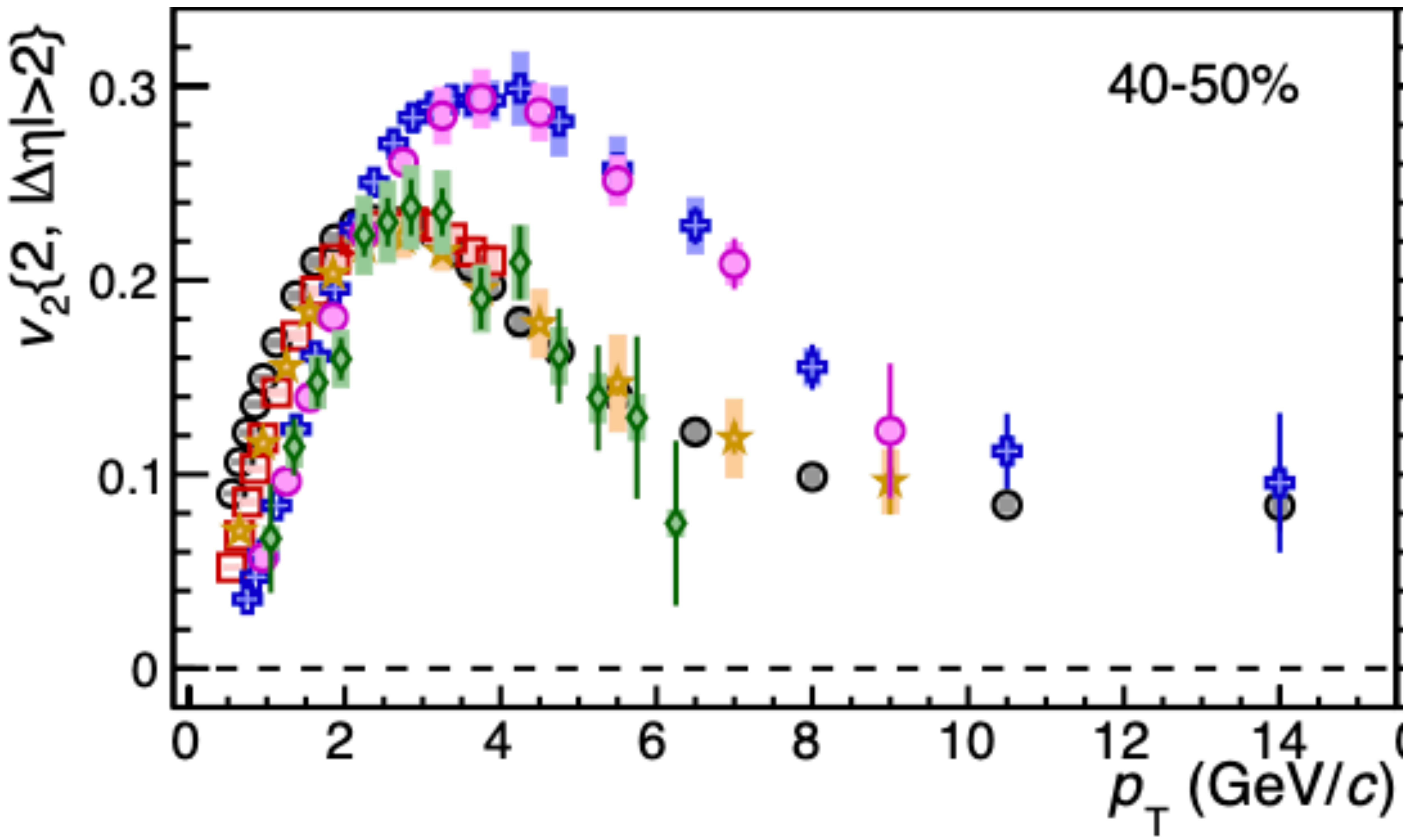
Hydrodynamics effectively describes the QGP

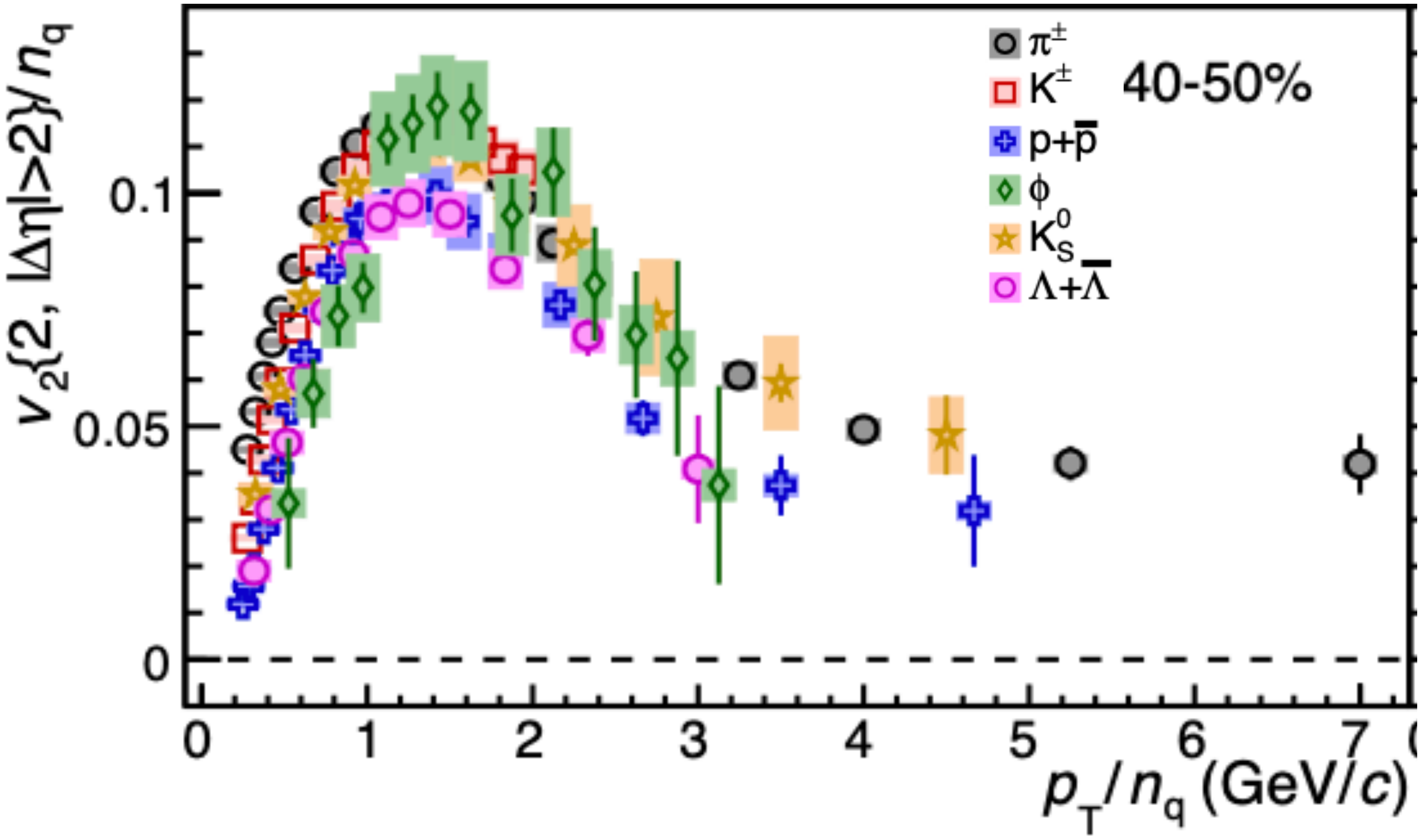


ALICE, PRL 116, 132302 (2016)

Identified particle flow

ALICE, JHEP 05(2023)243

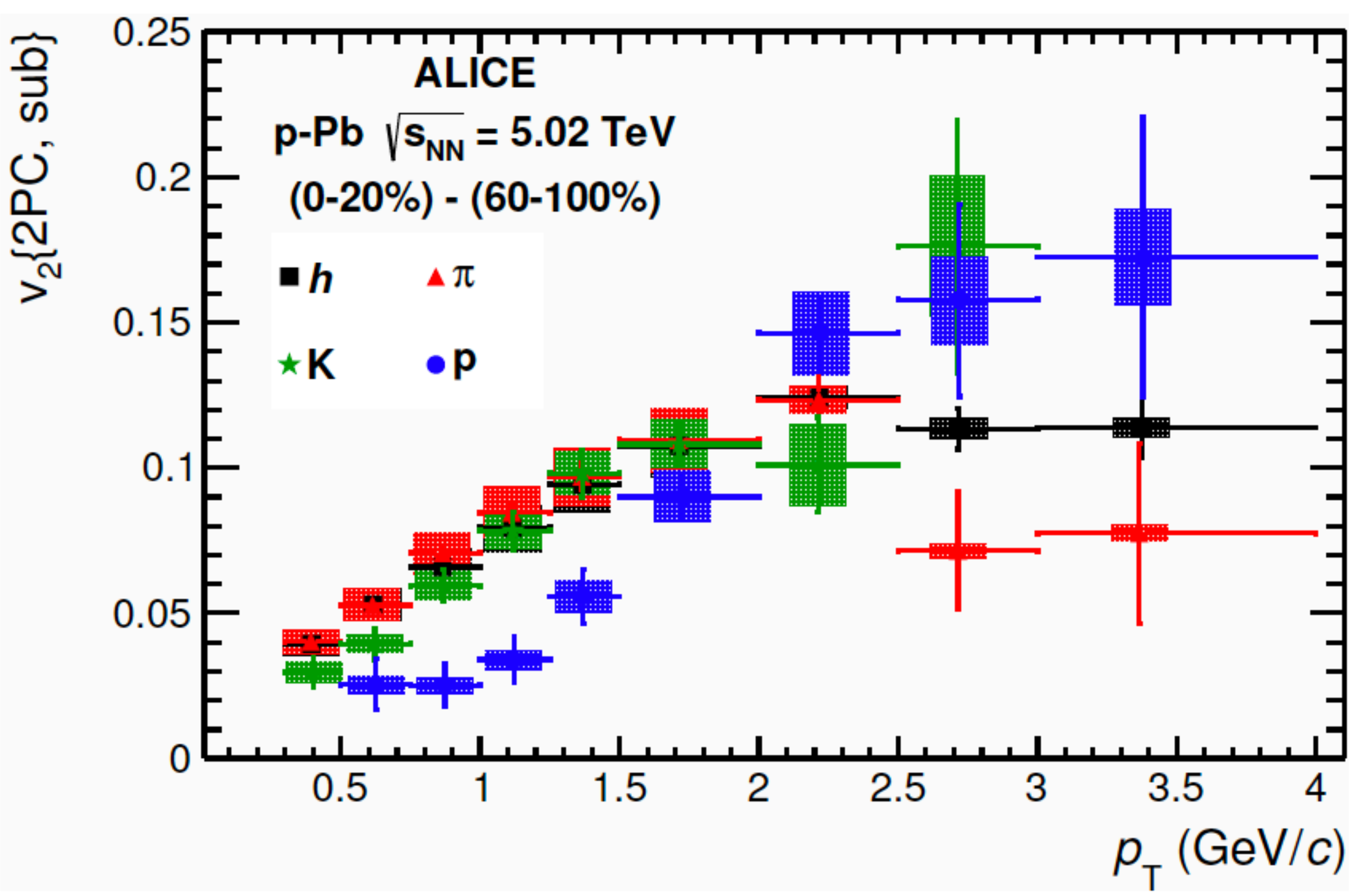




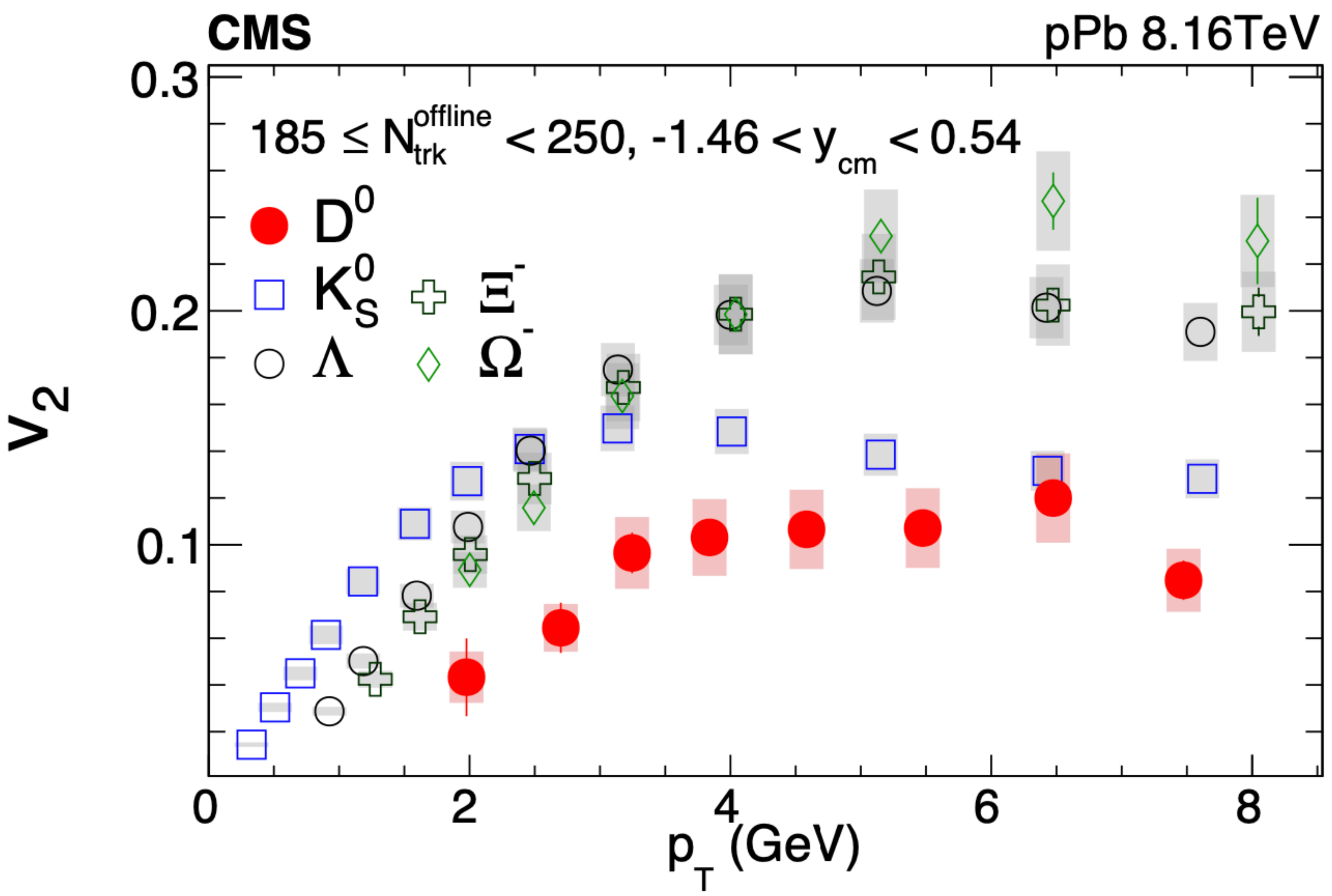
- Mass ordering at low p_T and baryon-meson grouping at intermediate p_T are observed
  - Common boost from the medium + partonic collectivity
  - The number of constituent quarks (NCQ) scaling holds approximately for $1 < p_T/n_q < 3$ GeV/c

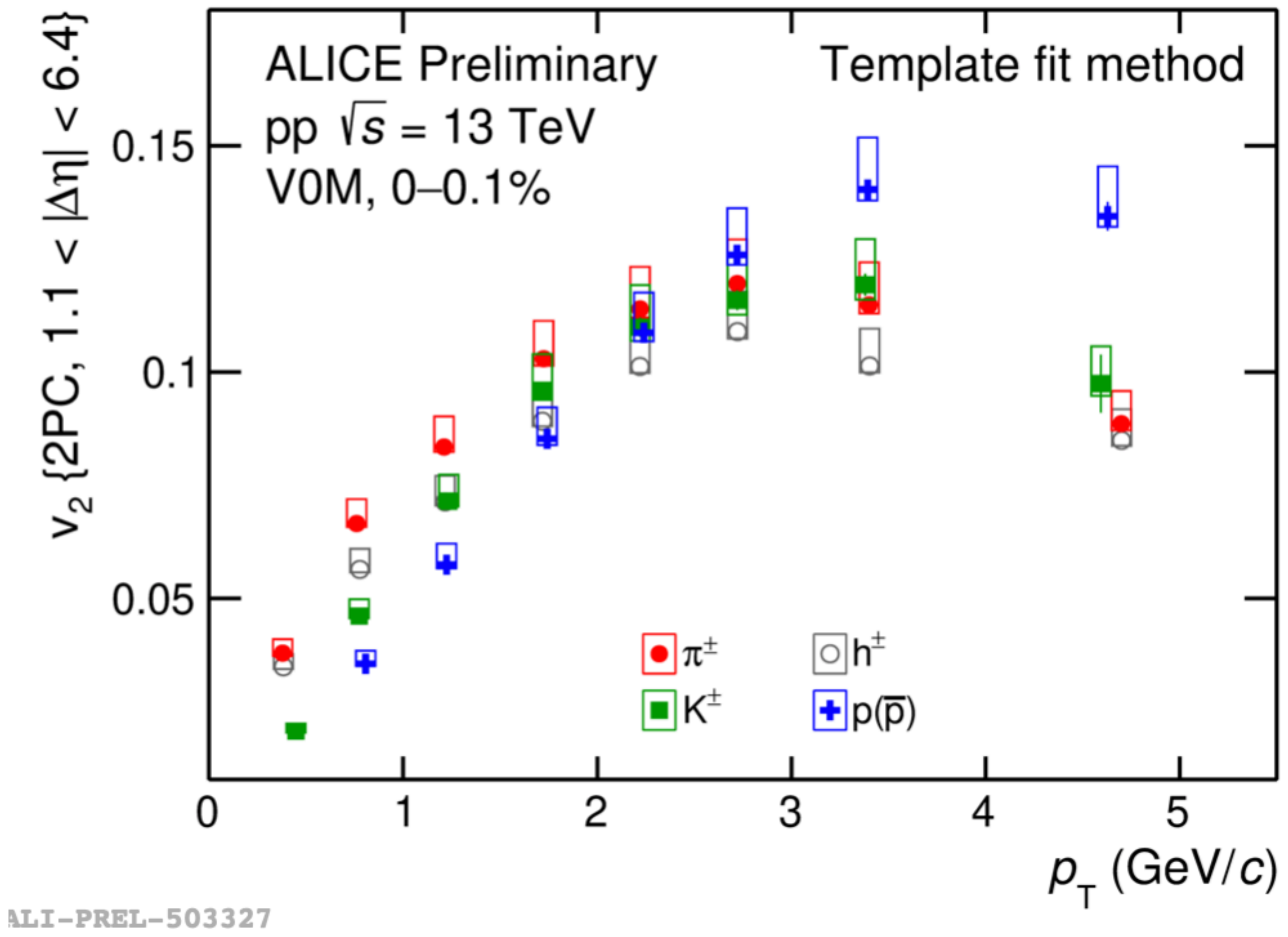
Puzzles in small collision systems

ALICE, Phys. Lett. B 726 (2013) 164–177



CMS, Phys. Rev. Lett. 121, 082301 (2018)





- Long-range flow-like angular correlations are observed in high-multiplicity small collision systems
  - A clear **mass ordering effect** at low p_T and **baryon-meson splitting** at intermediate p_T is observed in p–Pb even pp collisions

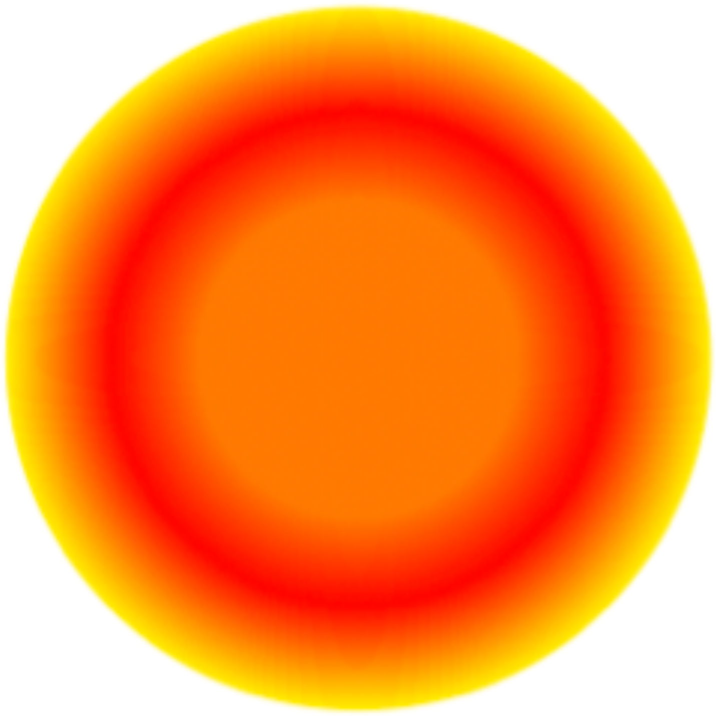
➡ hydrodynamics? initial-state effects? or other finals-state effects?

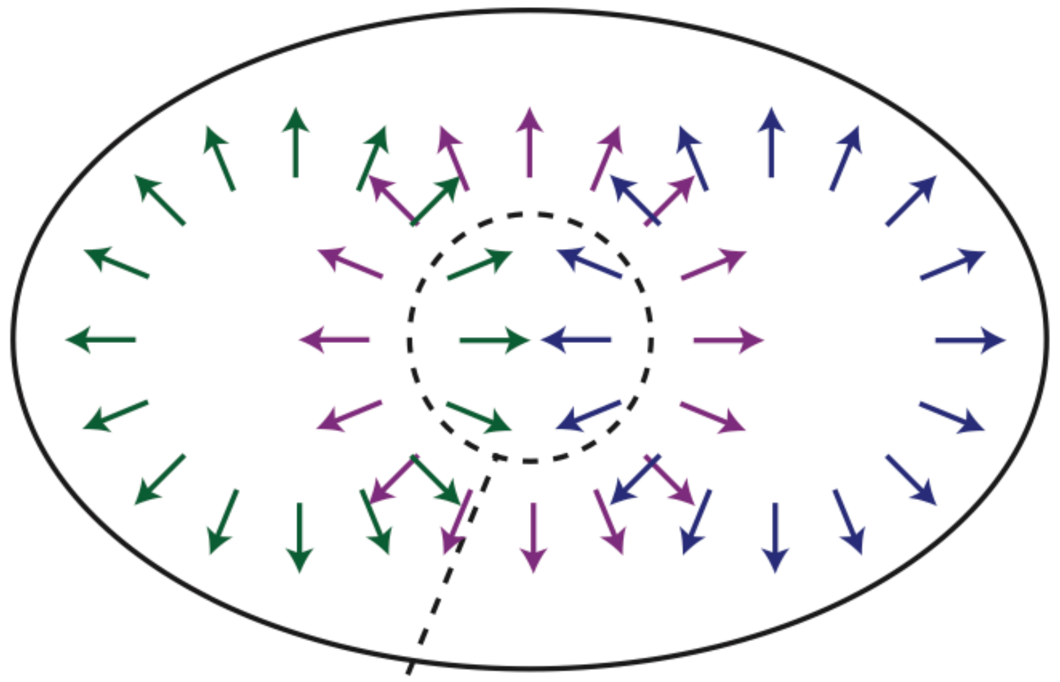
Possible Explanations

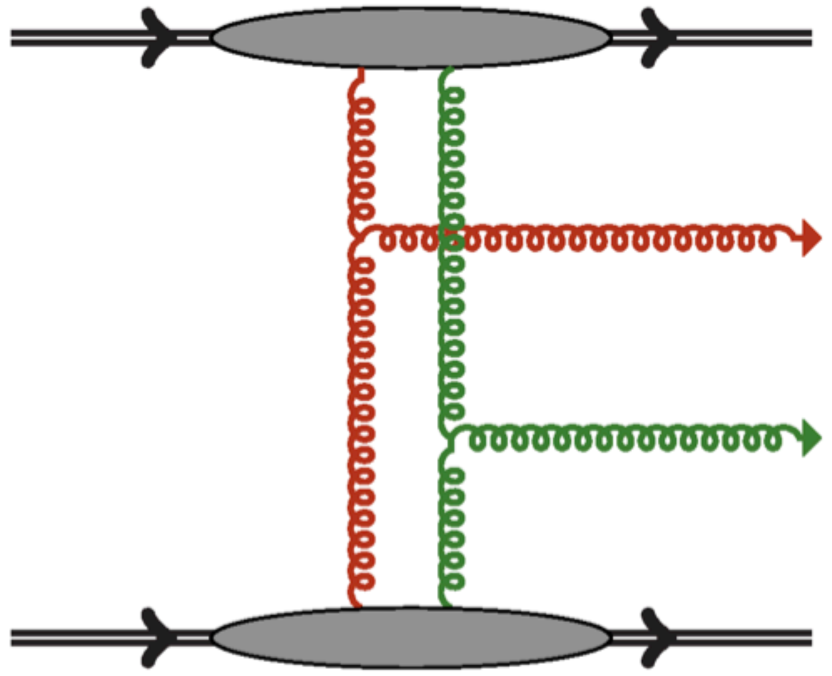
Many scatterings

Few scatterings

Initial conditions







parton escaping

hydrodynamics

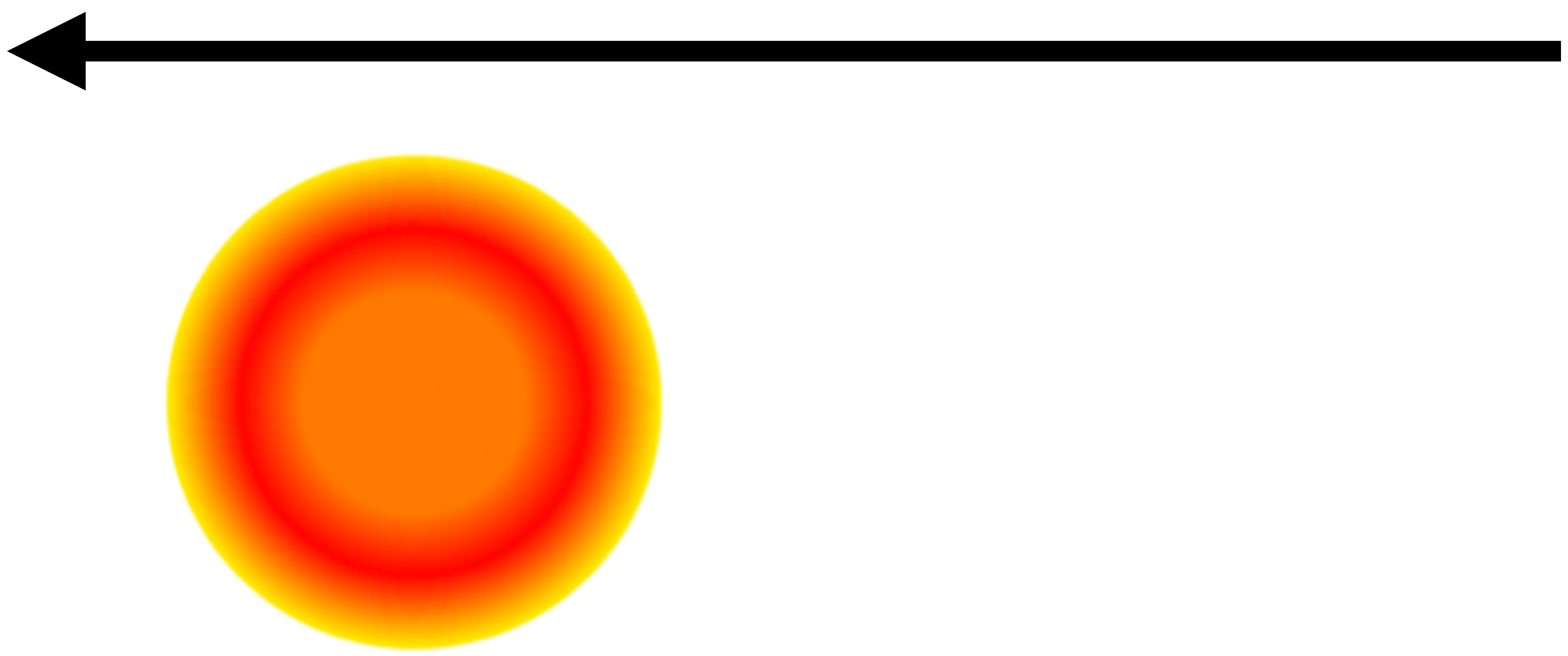
Initial-momentum correlations

(Perfect) fluid dynamics

Free streaming limit

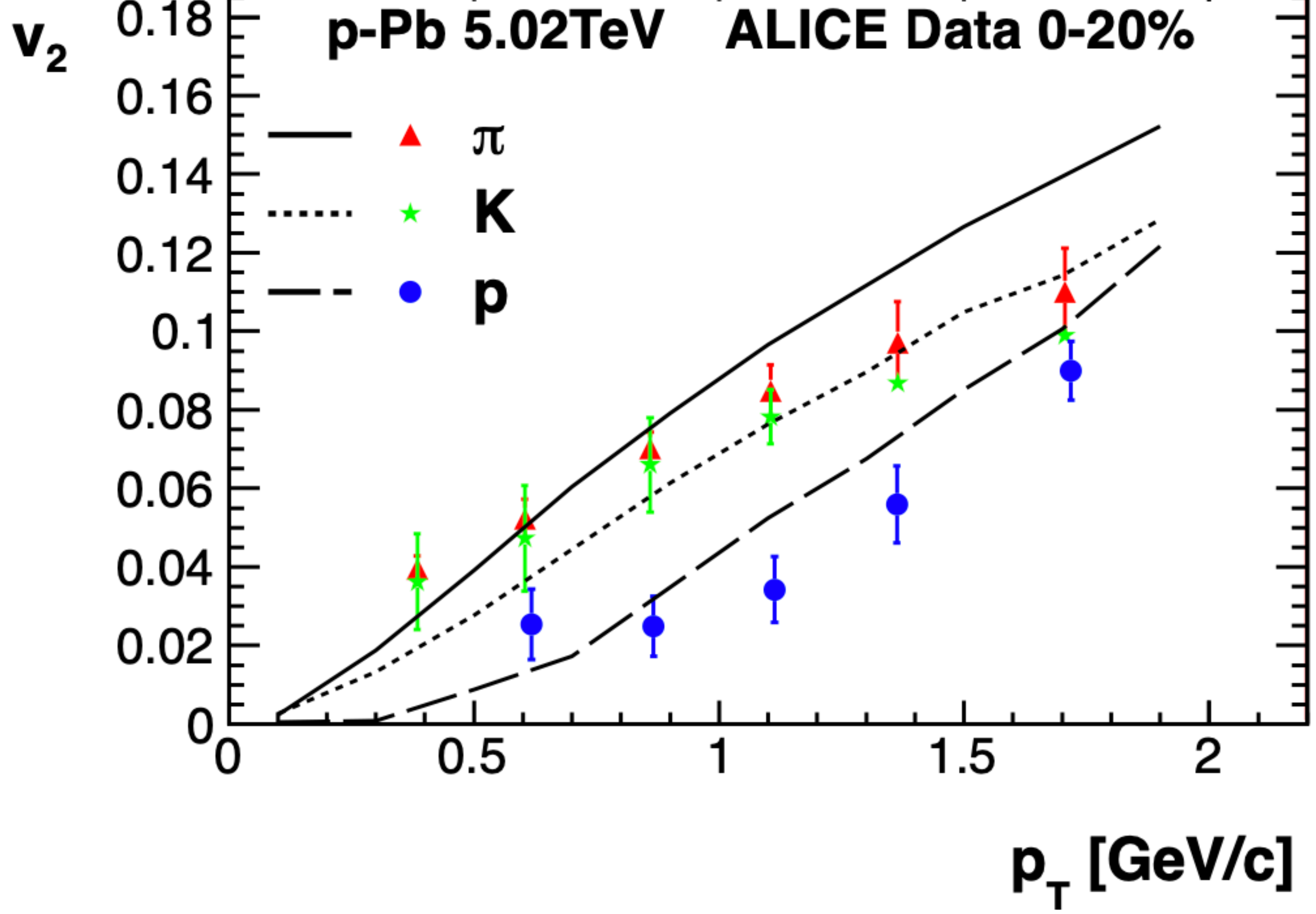
Possible Explanations: hydrodynamics

Many scatterings



hydrodynamics

P.Bożek, Phys. Rev. Lett. **111**, 172303



$\langle N_{trk} \rangle$	v_2 model	v_2 CMS [6]	v_3 model	v_3 CMS [6]
154.5	0.057	0.063	0.023	0.02
96	0.059	0.057	0.022	0.016
45	0.061	0.043	0.020	0.006

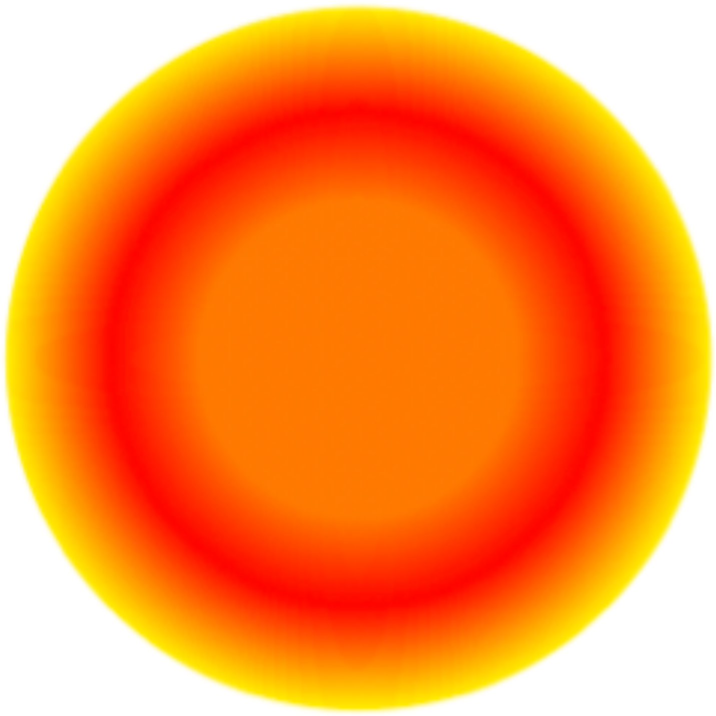
- Hydrodynamics requires local thermal equilibrium, assuming that many interactions between constituents in a short time
- A quantitative description of v_2 is given by hydrodynamic calculations

Possible Explanations

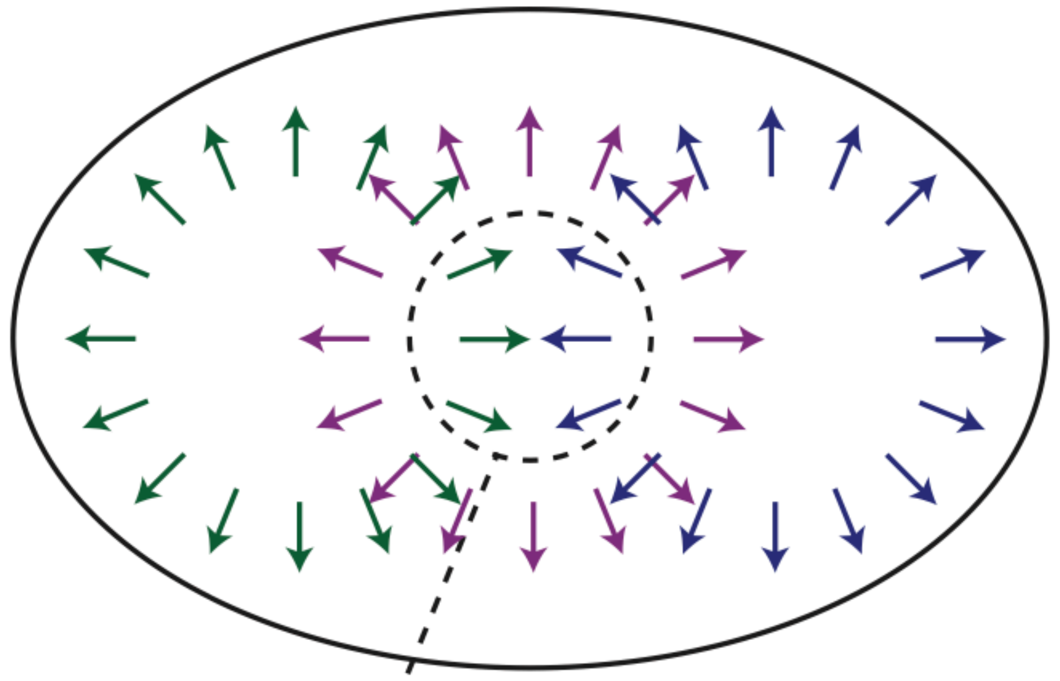
Many scatterings

Few scatterings

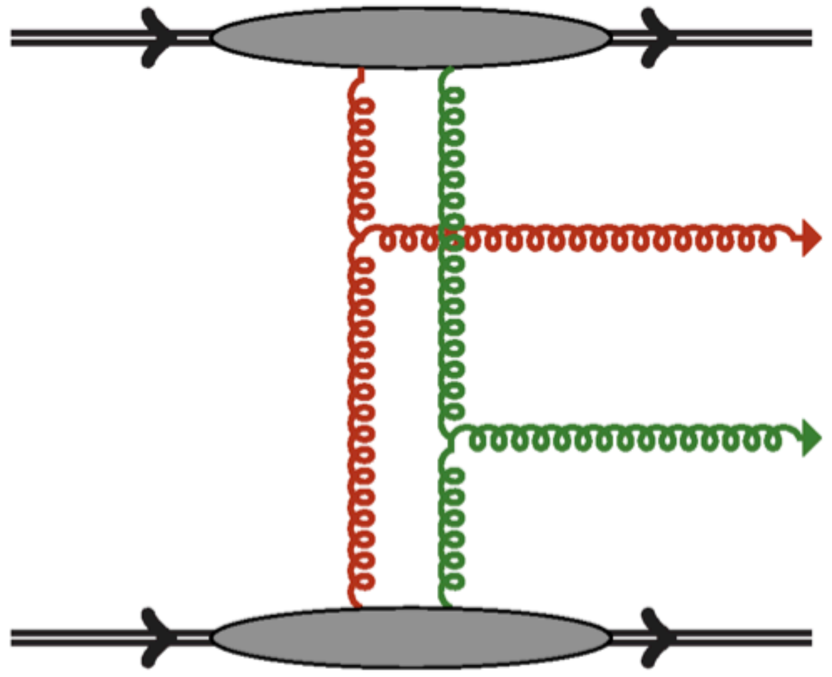
Initial conditions



hydrodynamics



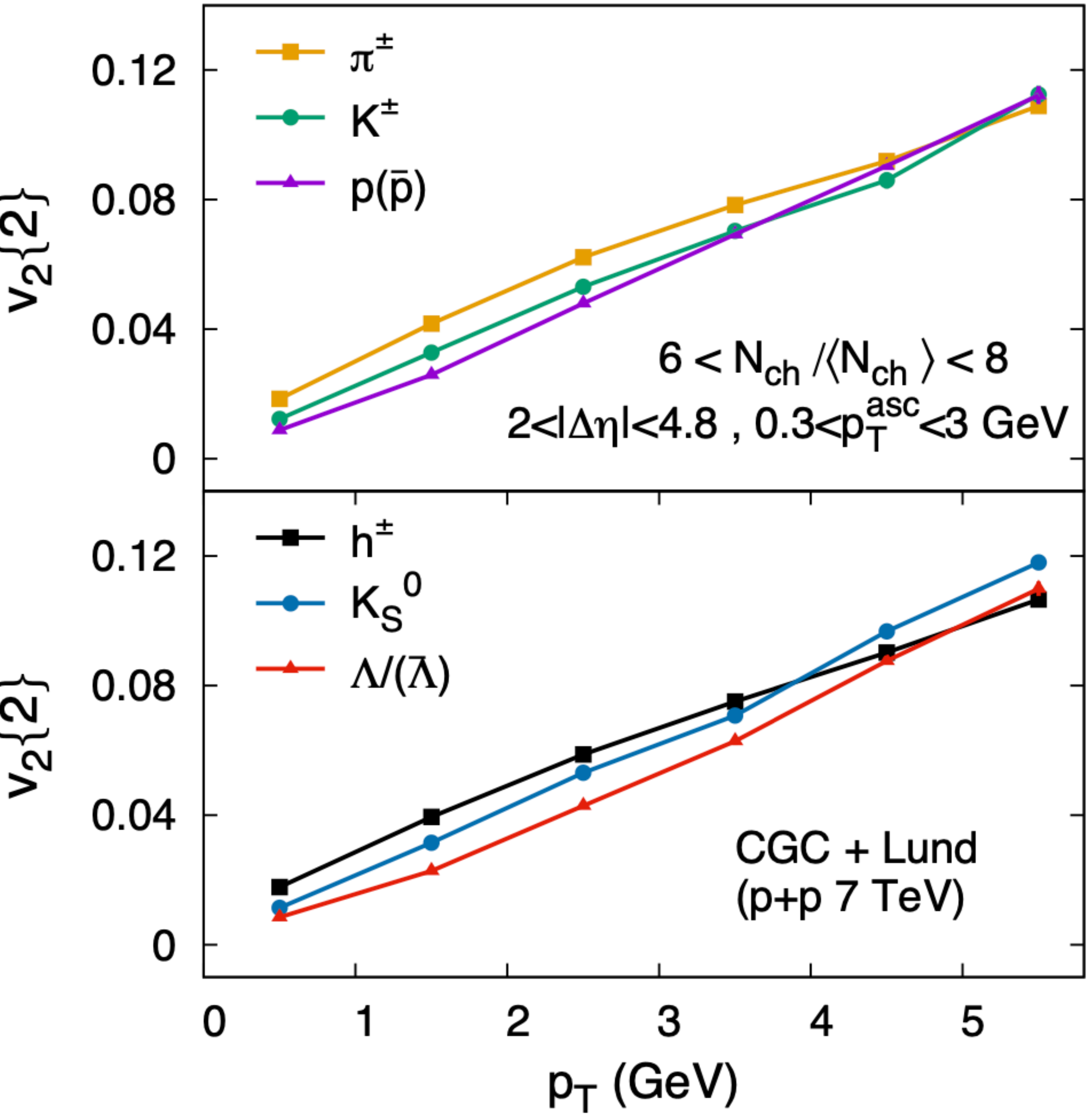
parton escaping



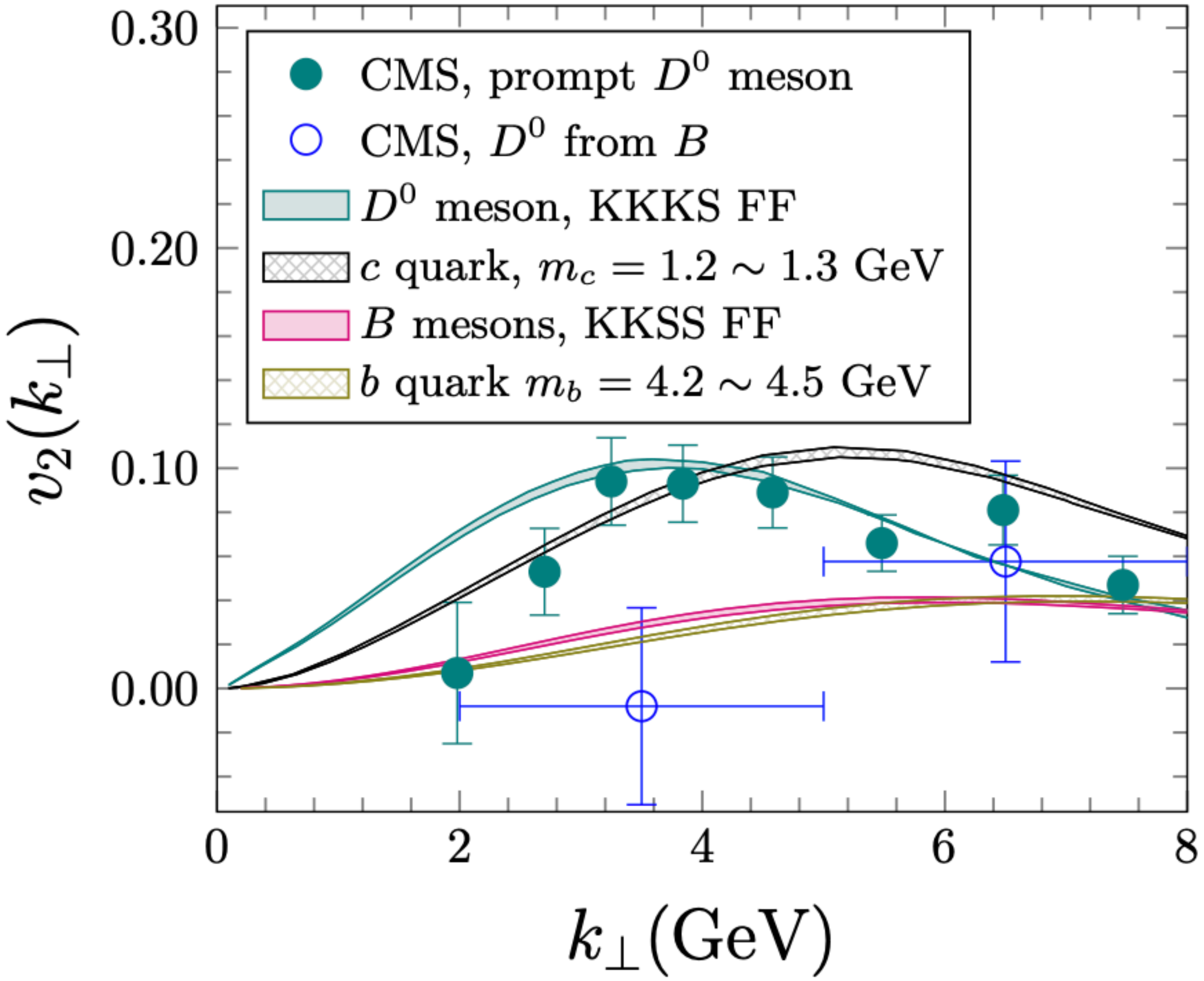
Initial-momentum correlations

Possible Explanations: initial-momentum correlations

B.Schenke et al., Phys. Rev. Lett. 117,162301(2016)

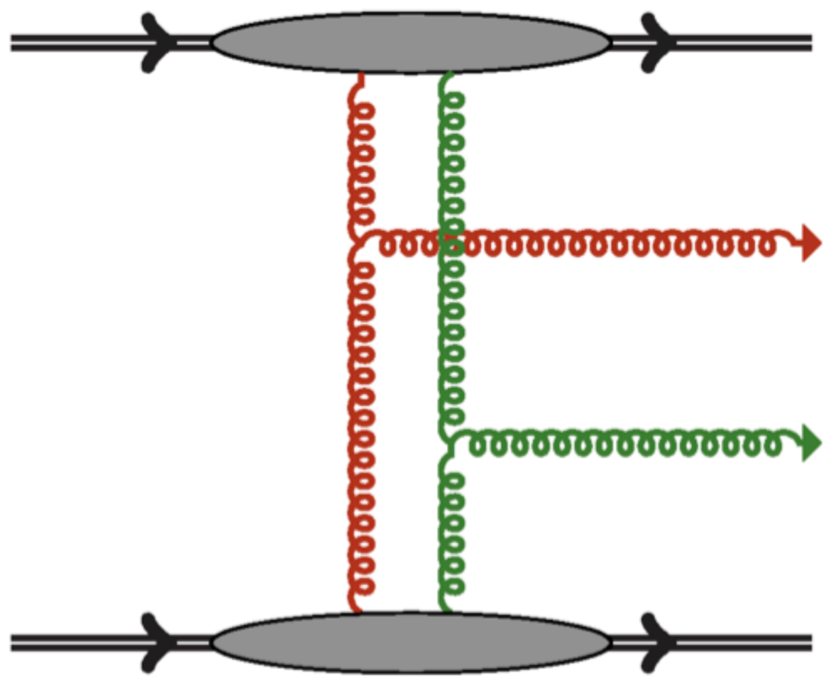


C.Zhang, et al., Phys. Rev. D **102**, 034010



Initial conditions

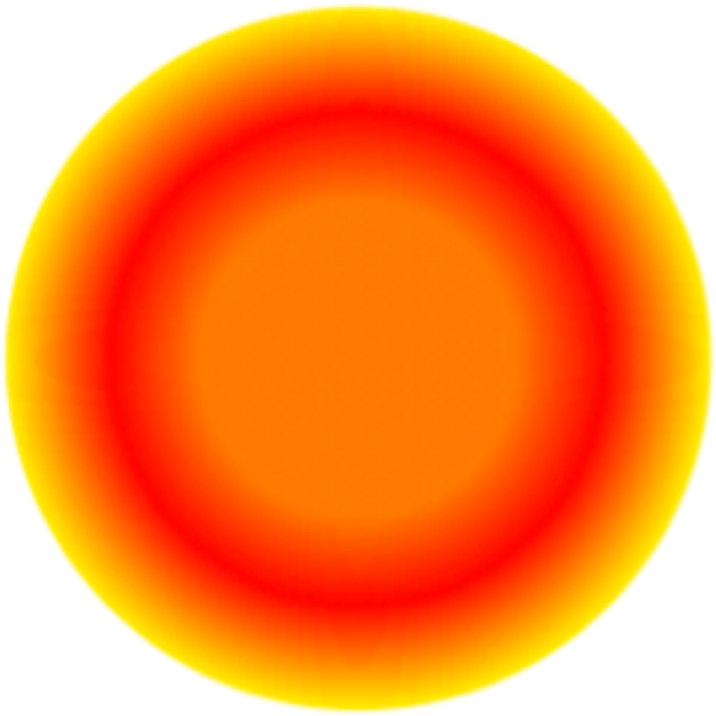
Initial-momentum correlations



The initial state correlation can also generate significant collectivity correlations and mass ordering in small collision systems

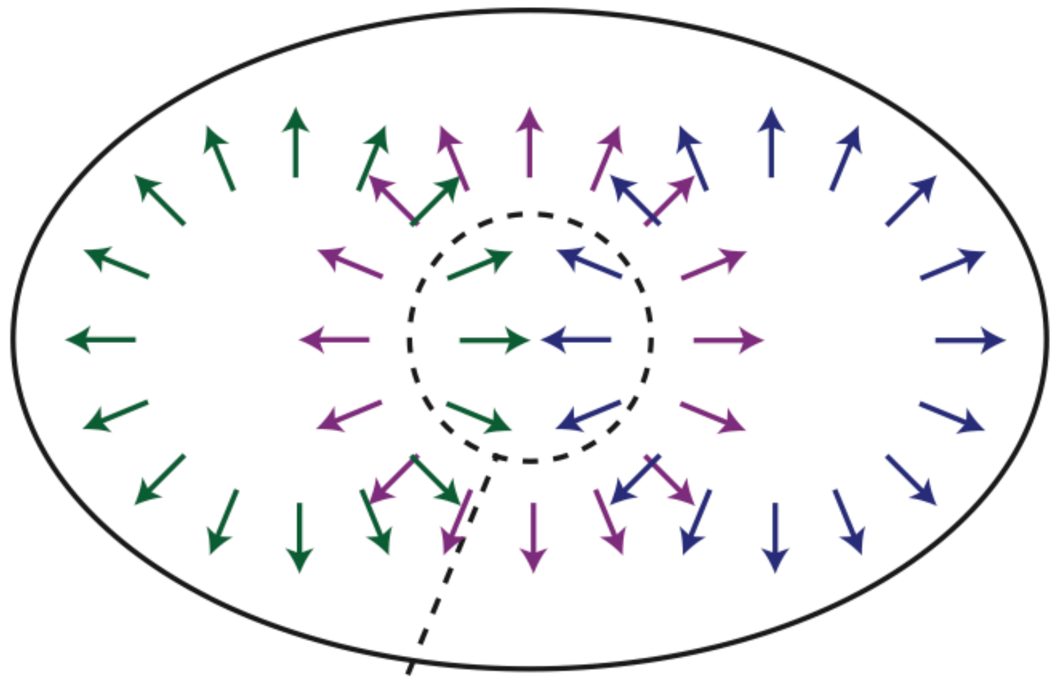
Possible Explanations

Many scatterings



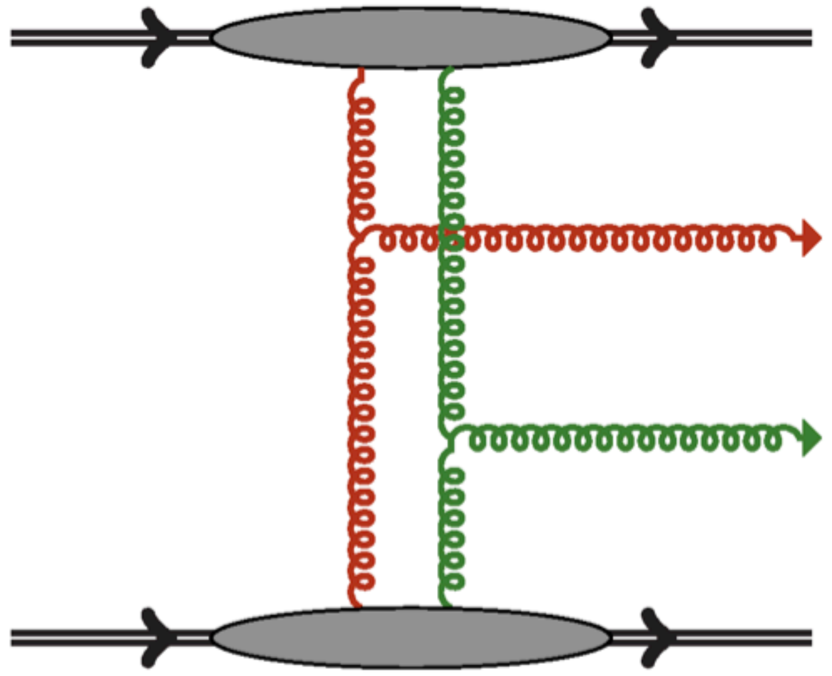
hydrodynamics

Few scatterings



parton escaping

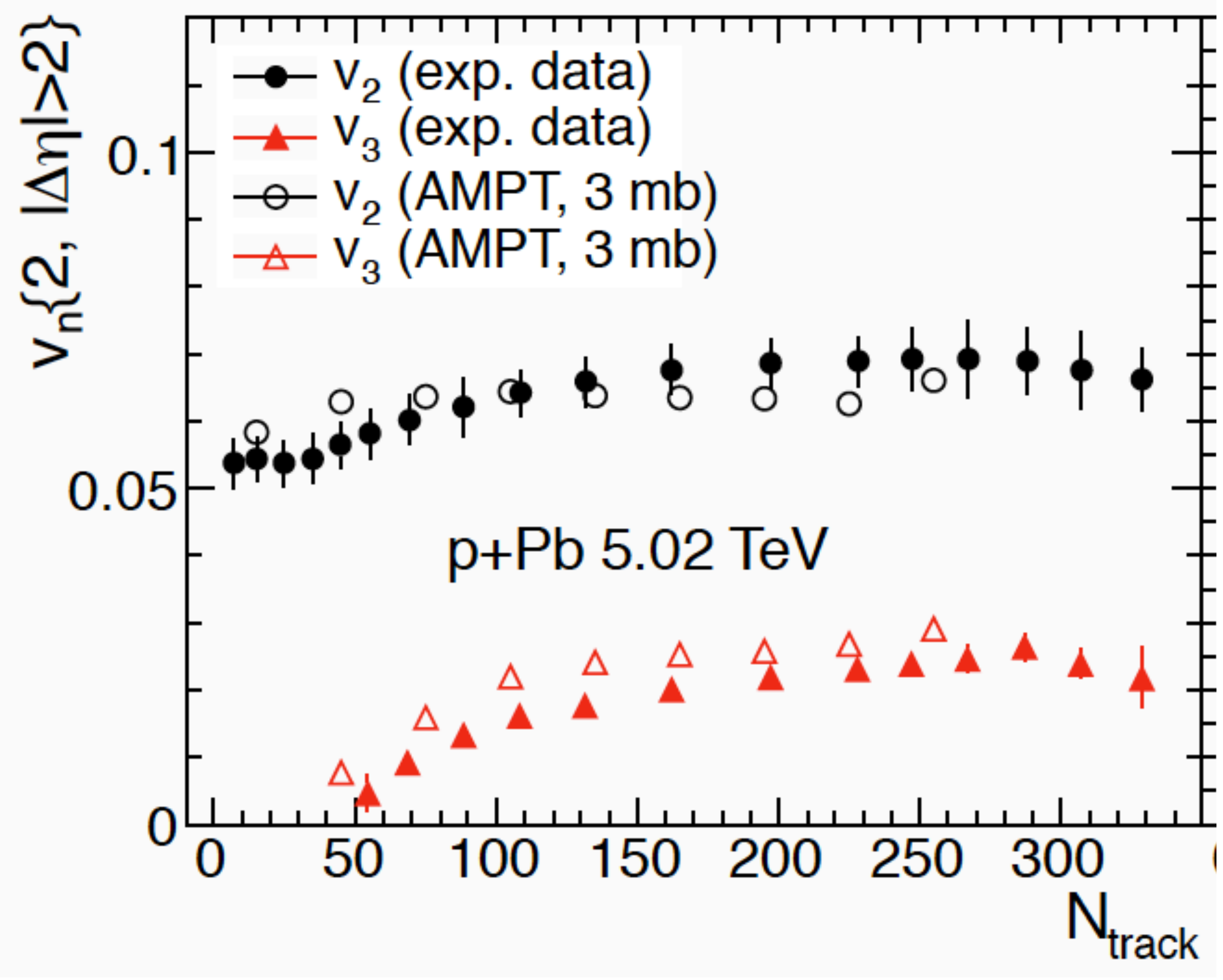
Initial conditions

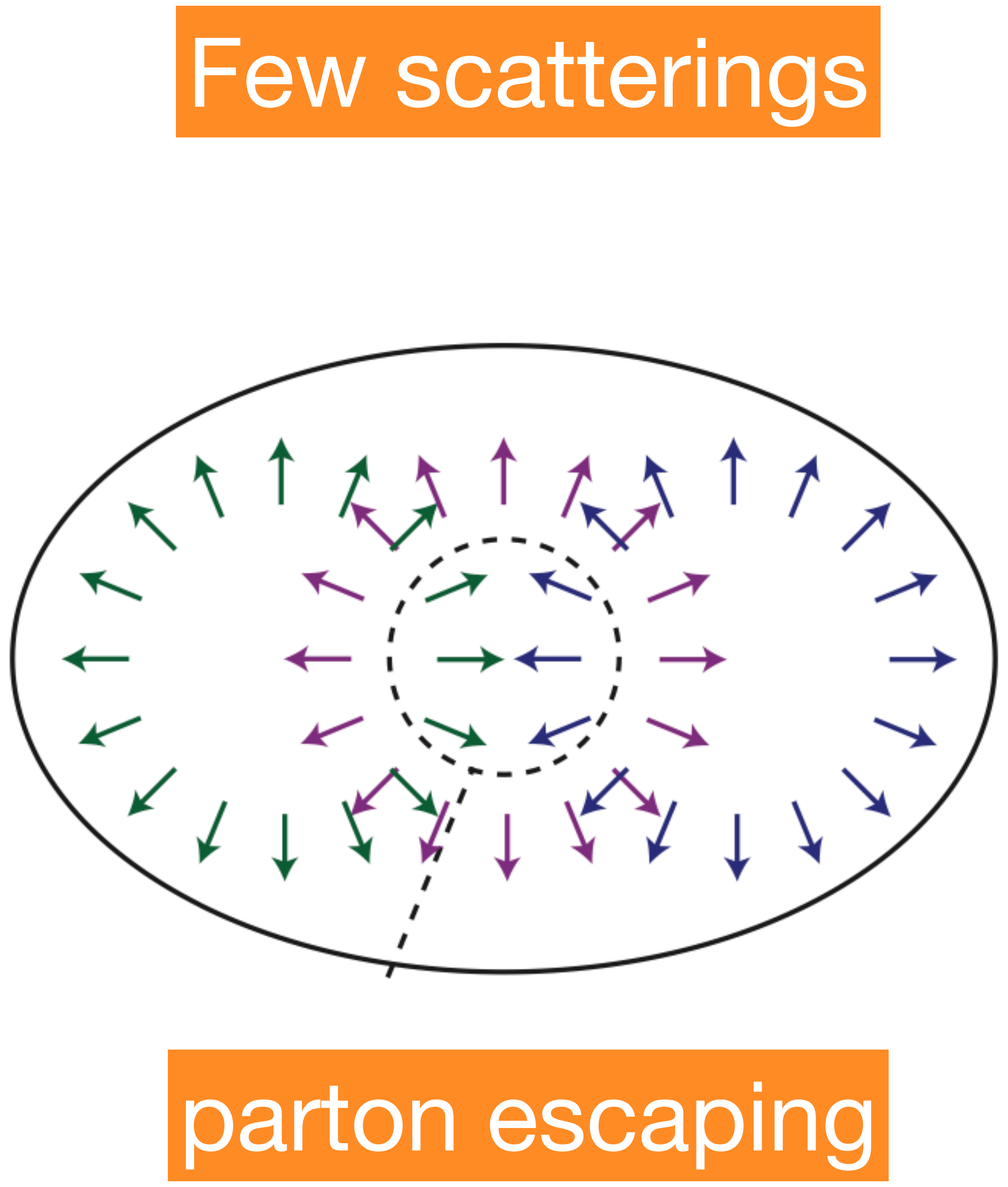


Initial-momentum correlations

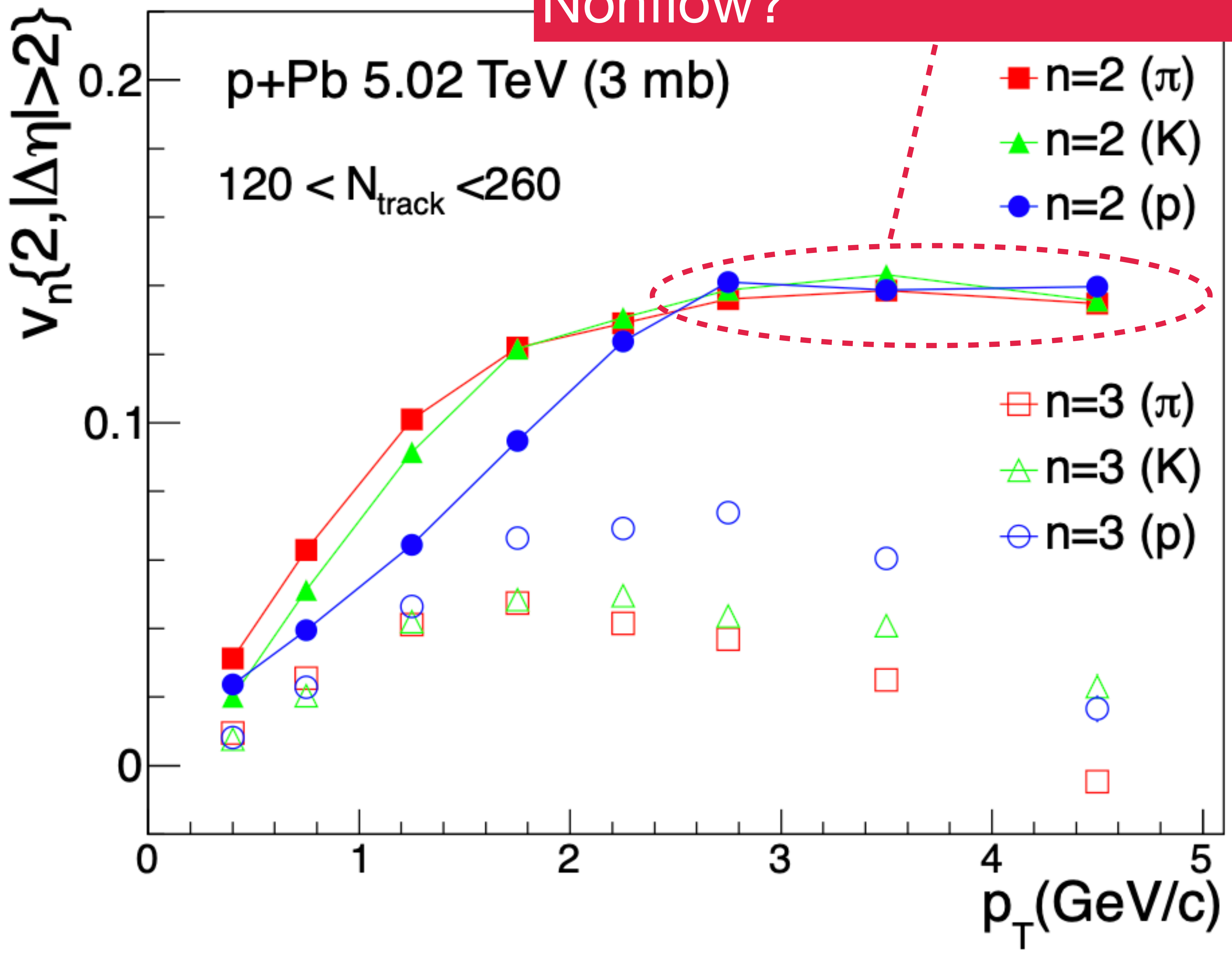
Possible Explanations: parton escaping

A.Bzdak et al, Phys. Rev. Lett. 113, 252301 (2014)





No baryon-meson splitting?
Nonflow?



- The AMPT calculations with string melting can nicely describe the v_2 and v_3 with a modest elastic cross section (σ = 1.5 – 3 mb)
  ➡ Parton escape mechanism is responsible for the anisotropy build up in AMPT
- The mass ordering is also reproduced, but the v_2 of baryon and meson converged at $p_T > 2$ GeV/c

A Multi-Phase Transport (AMPT) model

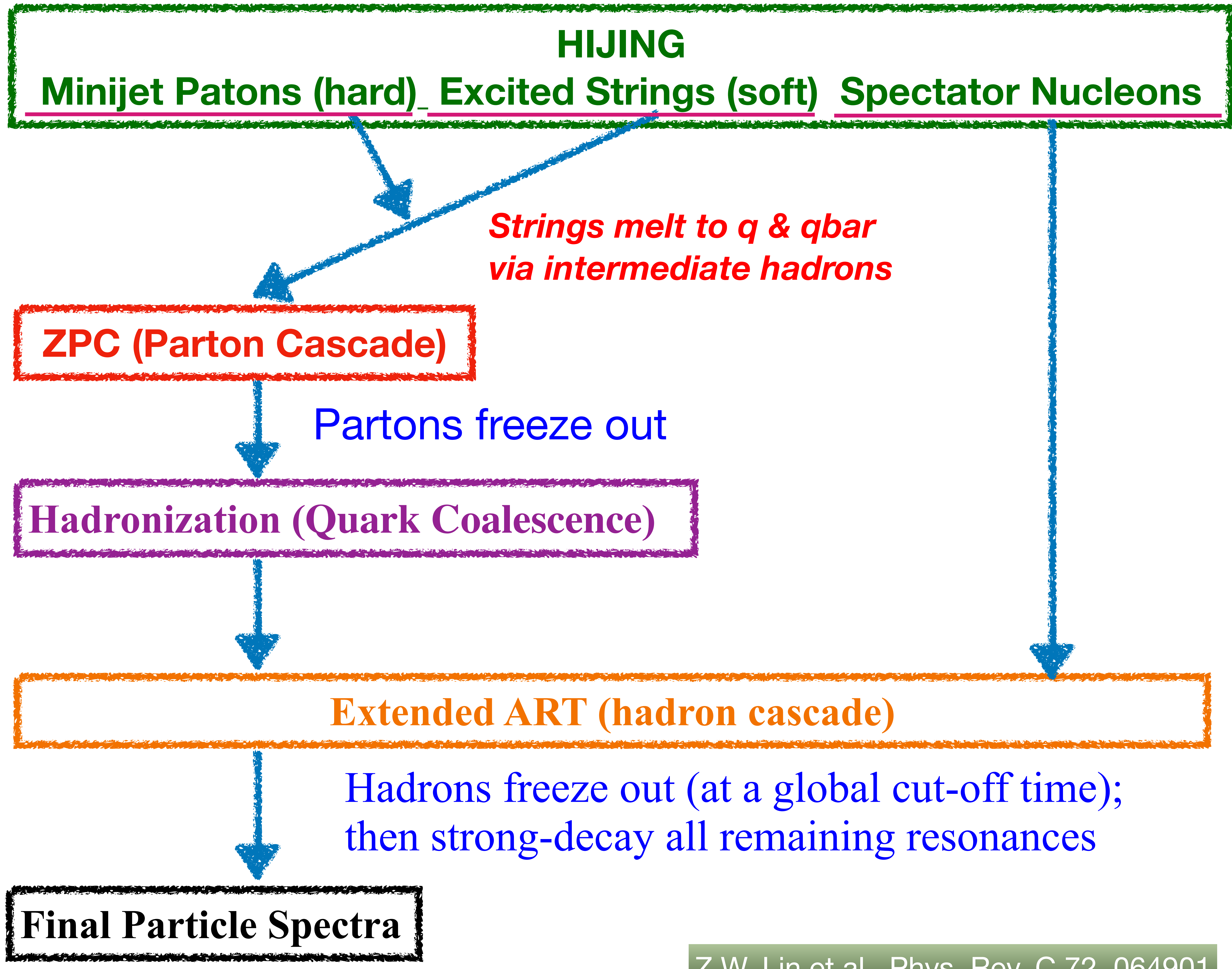
- **Initial conditions:** HIJING two-component model
- **String melting:** hadrons from string fragmentation are melted into primordial quarks and antiquarks
- **Parton cascade:** two-body elastic scattering described by ZPC model

Debye screening mass

$$\frac{d\sigma}{dt} = \frac{9\pi\alpha_s^2}{2}\left(1+\frac{\mu^2}{s}\right)\frac{1}{(t-\mu^2)^2}$$

- **Coalescence:** combine nearest quarks to meson/baryon
- **A Relativistic Transport** (ART) to describe hadron scatterings

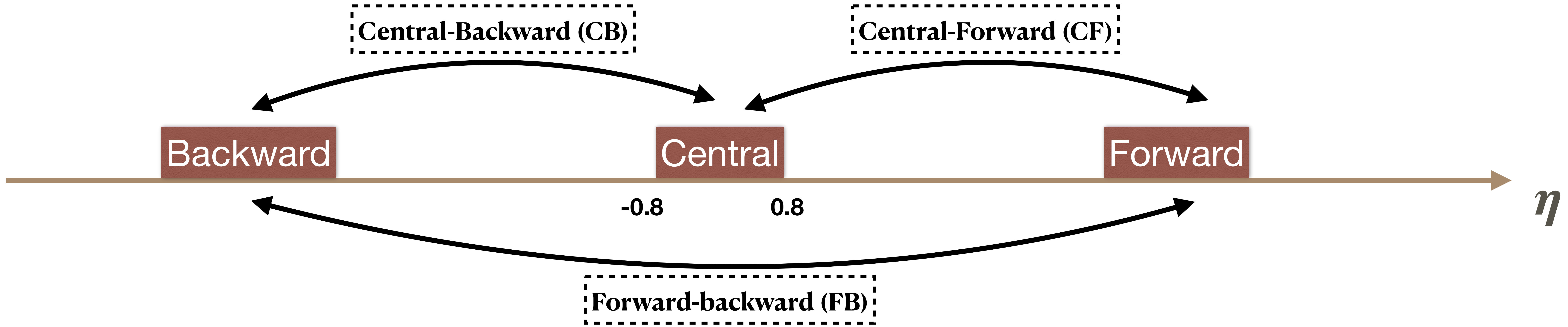
Structure of AMPT v2.xx (String Melting Version)



Z.W. Lin et al., Phys. Rev. C 72, 064901

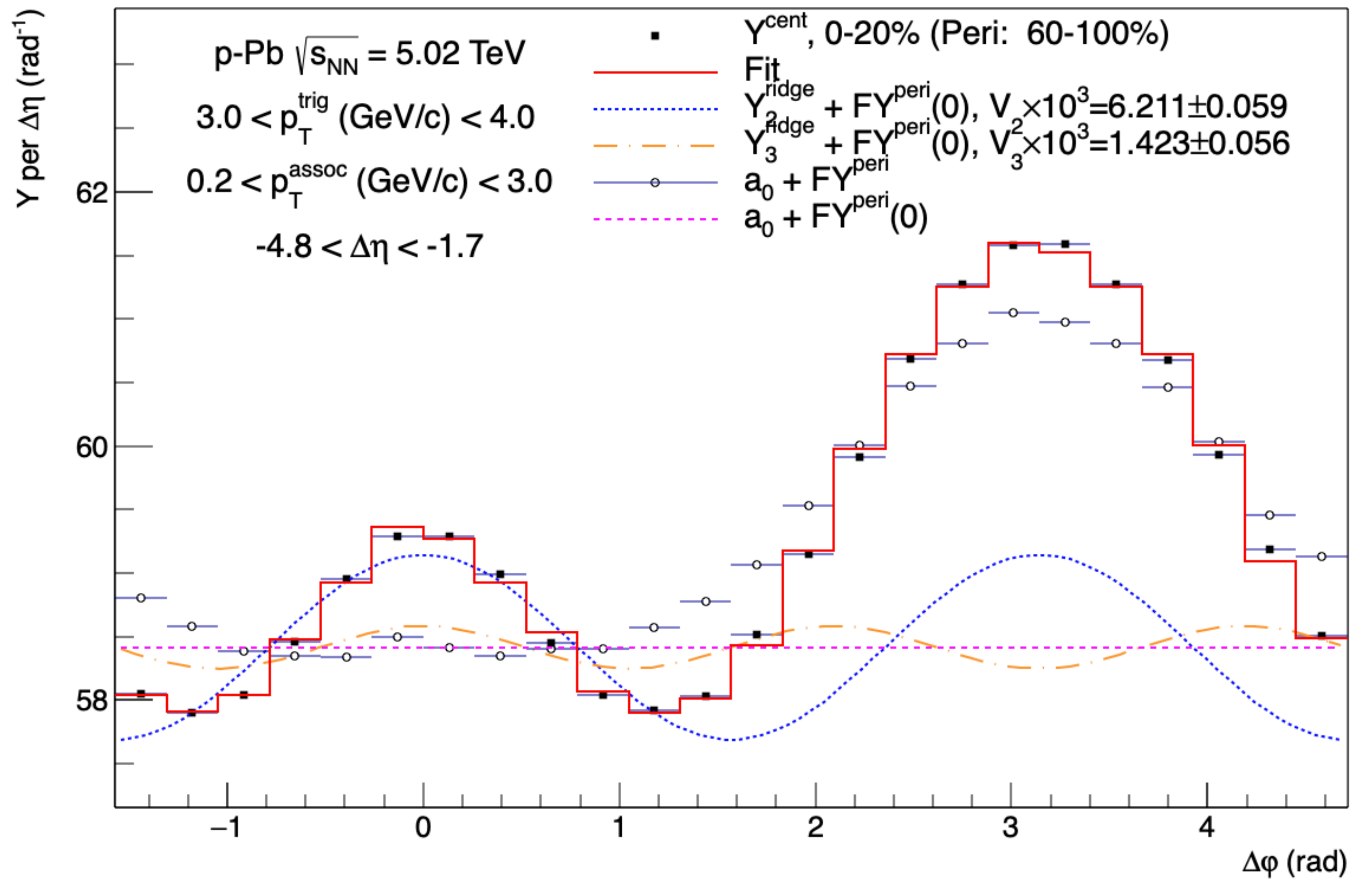
Calculation Method

Two-particle correlation



Factorization: $$v_2 = \sqrt{\frac{V_{2\Delta}(\mathrm{CF})V_{2\Delta}(\mathrm{CB})}{V_{2\Delta}(\mathrm{FB})}}$$

PHENIX, Phys. Rev. C 107, 024907 (2023)

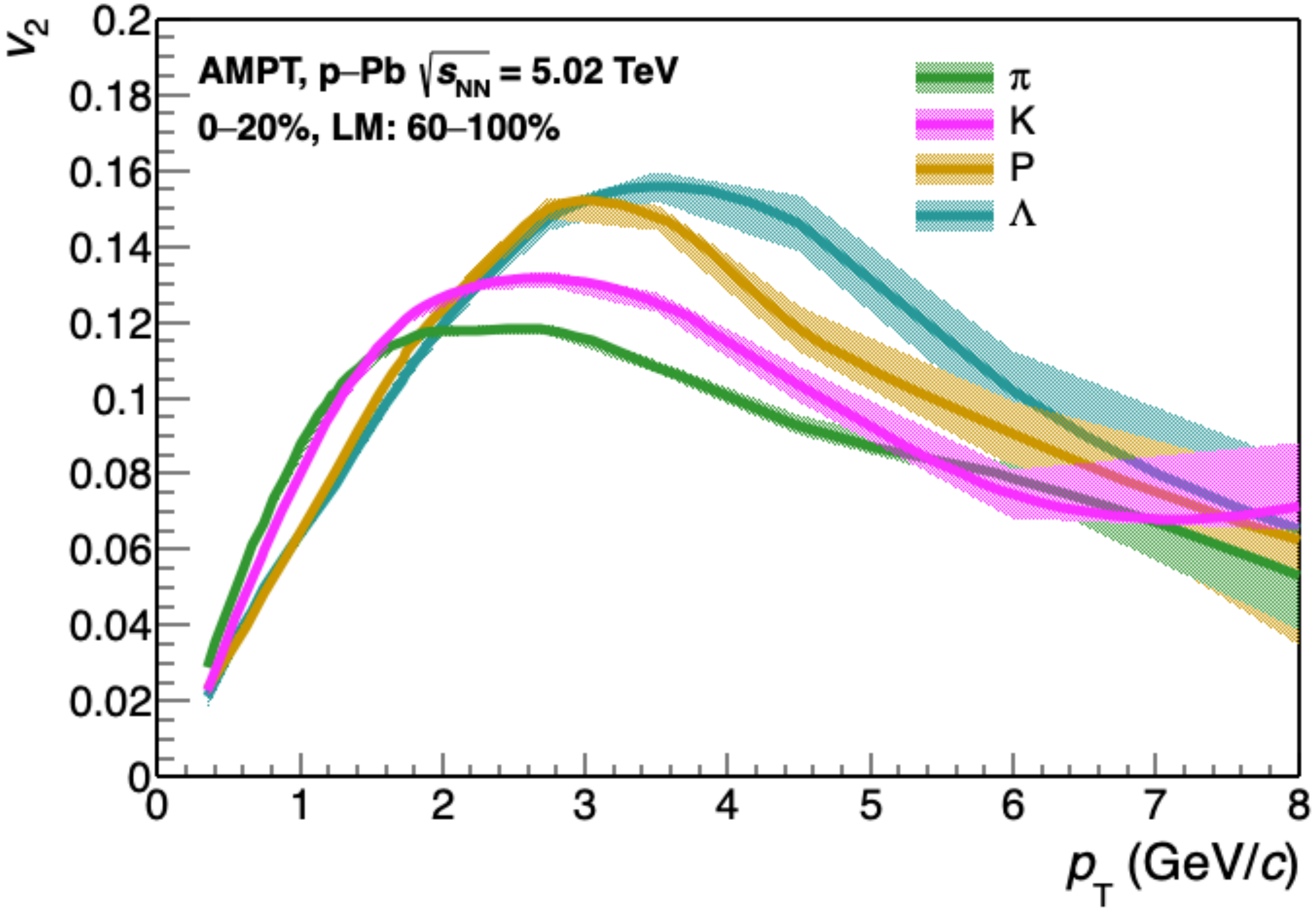


Nonflow subtraction:

template fit method with low-multiplicity (60-100%) subtraction

$$C(\Delta\varphi) = FC^{\mathrm{LM}}(\Delta\varphi) + G(1 + 2\sum_{n=1}^{3} V_{n\Delta}\cos(n\Delta\varphi))$$

Identified particle v_2



- Positive v_2 of identified particles is reproduced by AMPT
- A clear mass ordering effect is observed at p_T < 2 GeV/c
- The baryon-meson splitting is shown at intermediate p_T, while all particle species converged at higher p_T

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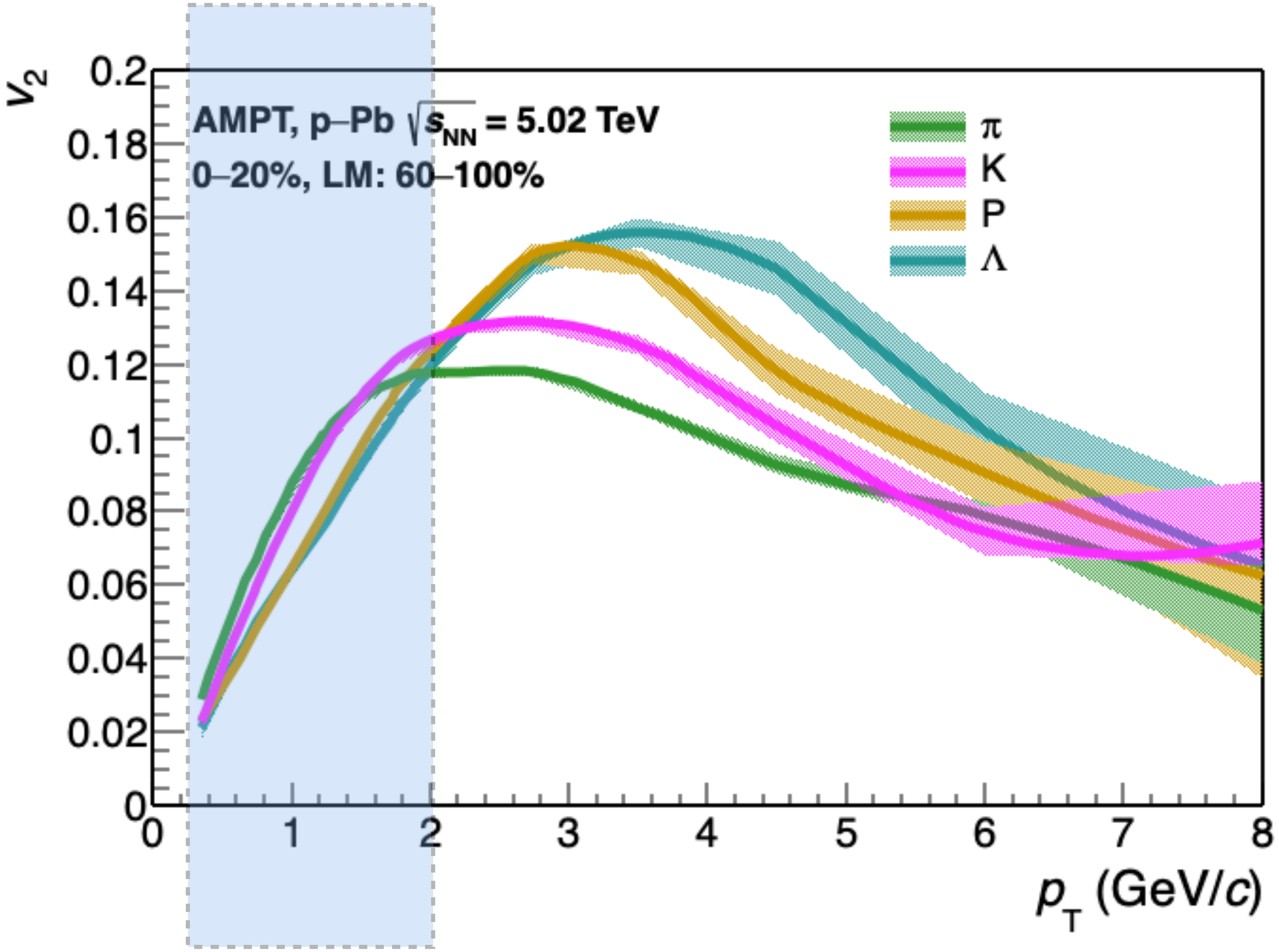

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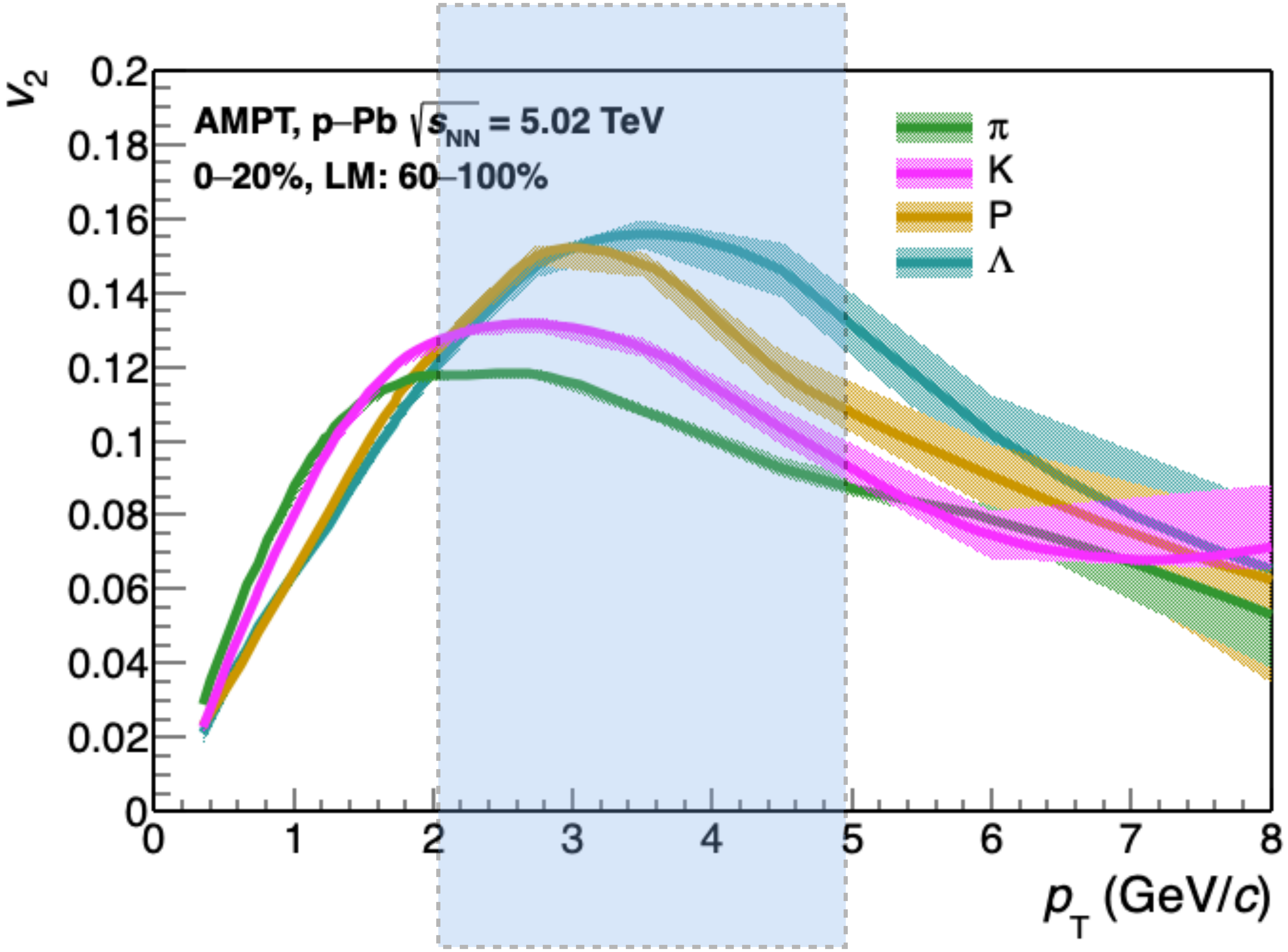

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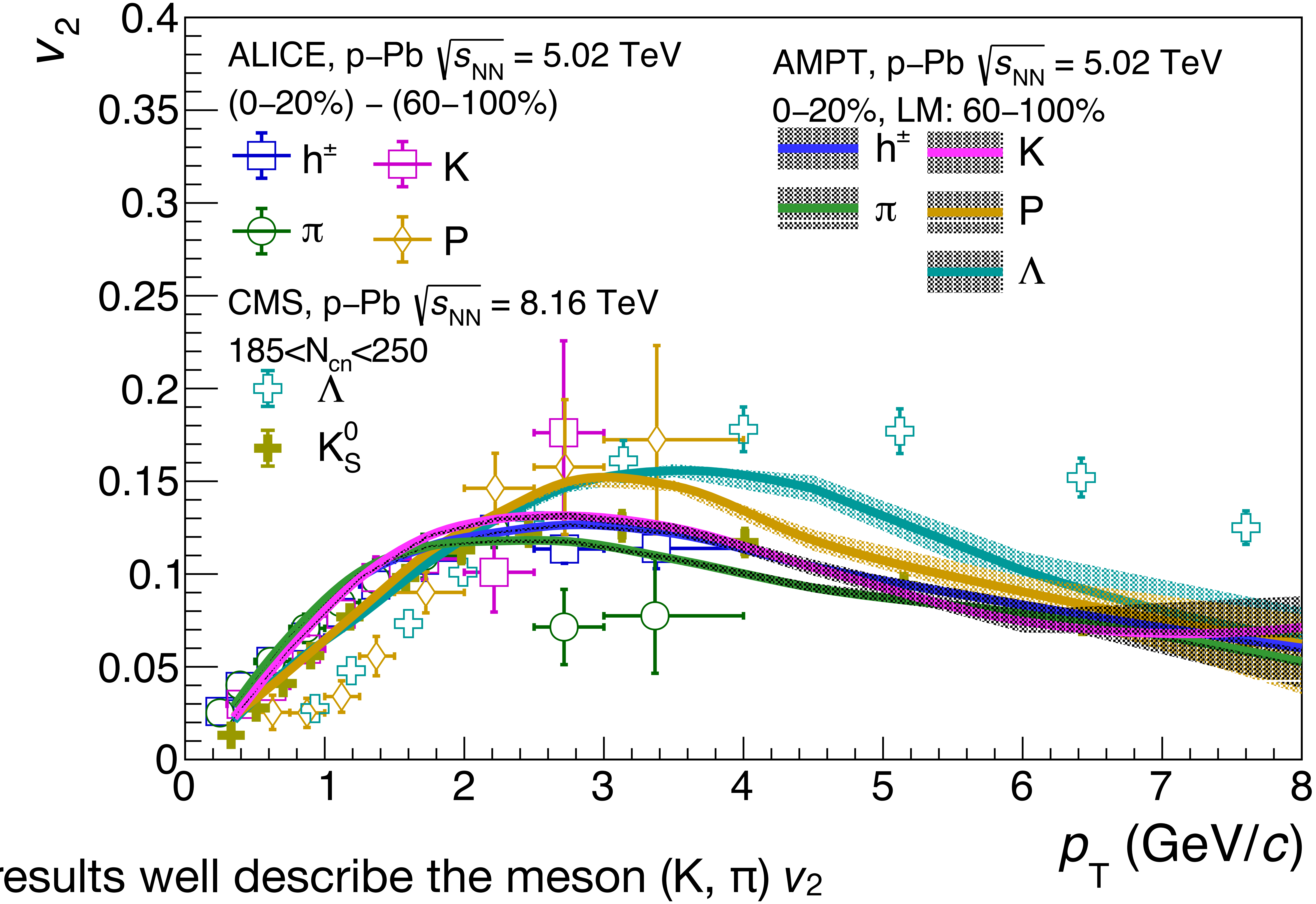
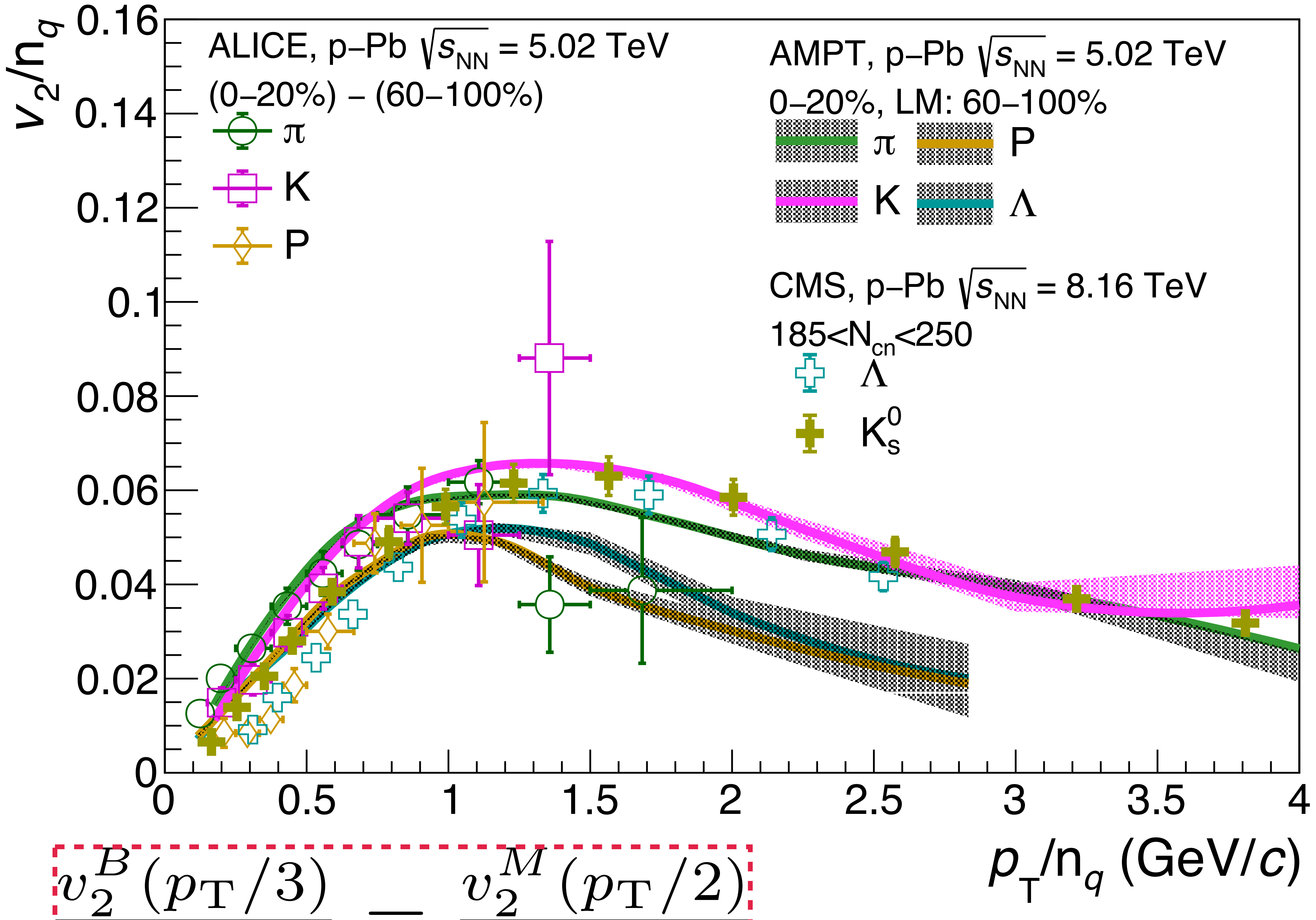
Identified particle v_2 (compared to data)

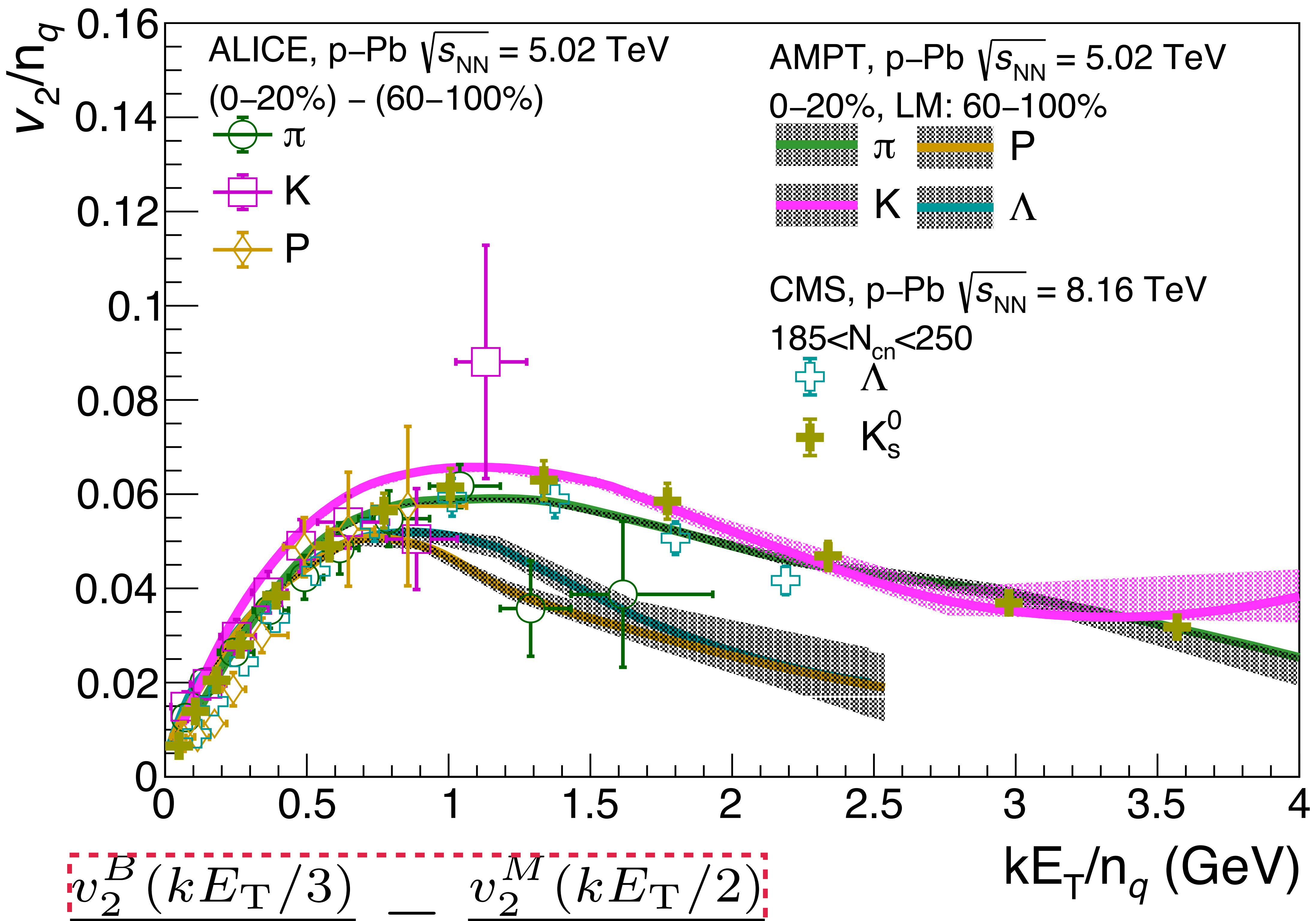


- The AMPT results well describe the meson (K, π) v_2
  - but overestimate and underestimate the baryon (P, Λ) v_2 at low and intermediate p_T, respectively

NCQ scaling



$$\frac{v_2^B(p_T/3)}{3} = \frac{v_2^M(p_T/2)}{2}$$

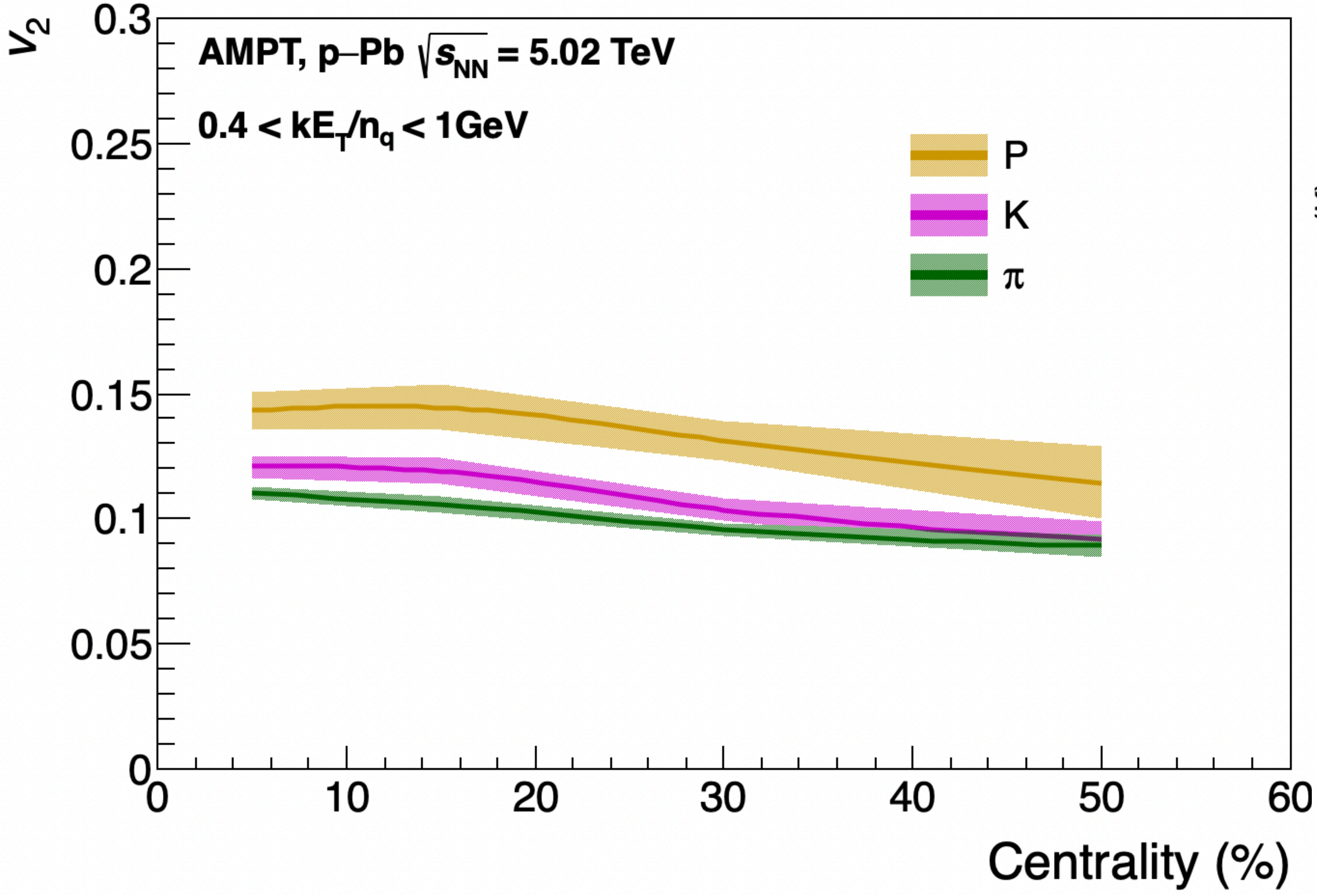


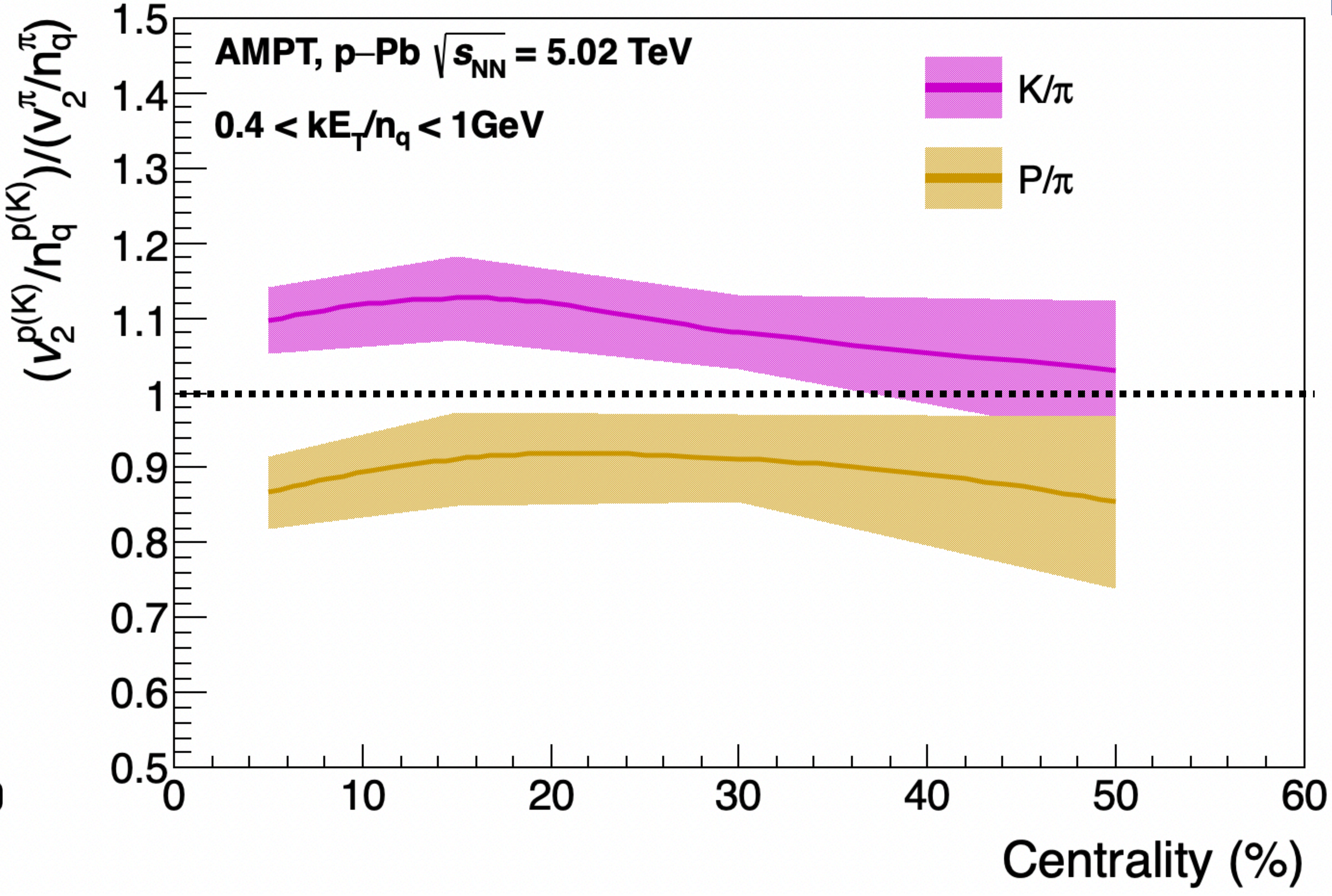
$$\frac{v_2^B(kE_T/3)}{3} = \frac{v_2^M(kE_T/2)}{2}$$

- The NCQ scaling is a clean signal to probe the partonic degree of freedom in heavy-ion collisions
  - An **approximative** NCQ scaling of v_2 at intermediate p_T (kE_T) is obtained as data shown
  - however, the scaling is violated at $kE_T > 1$ GeV

$$kE_T = m_T - m_0 = \sqrt{p_T^2 + m_0^2} - m_0$$

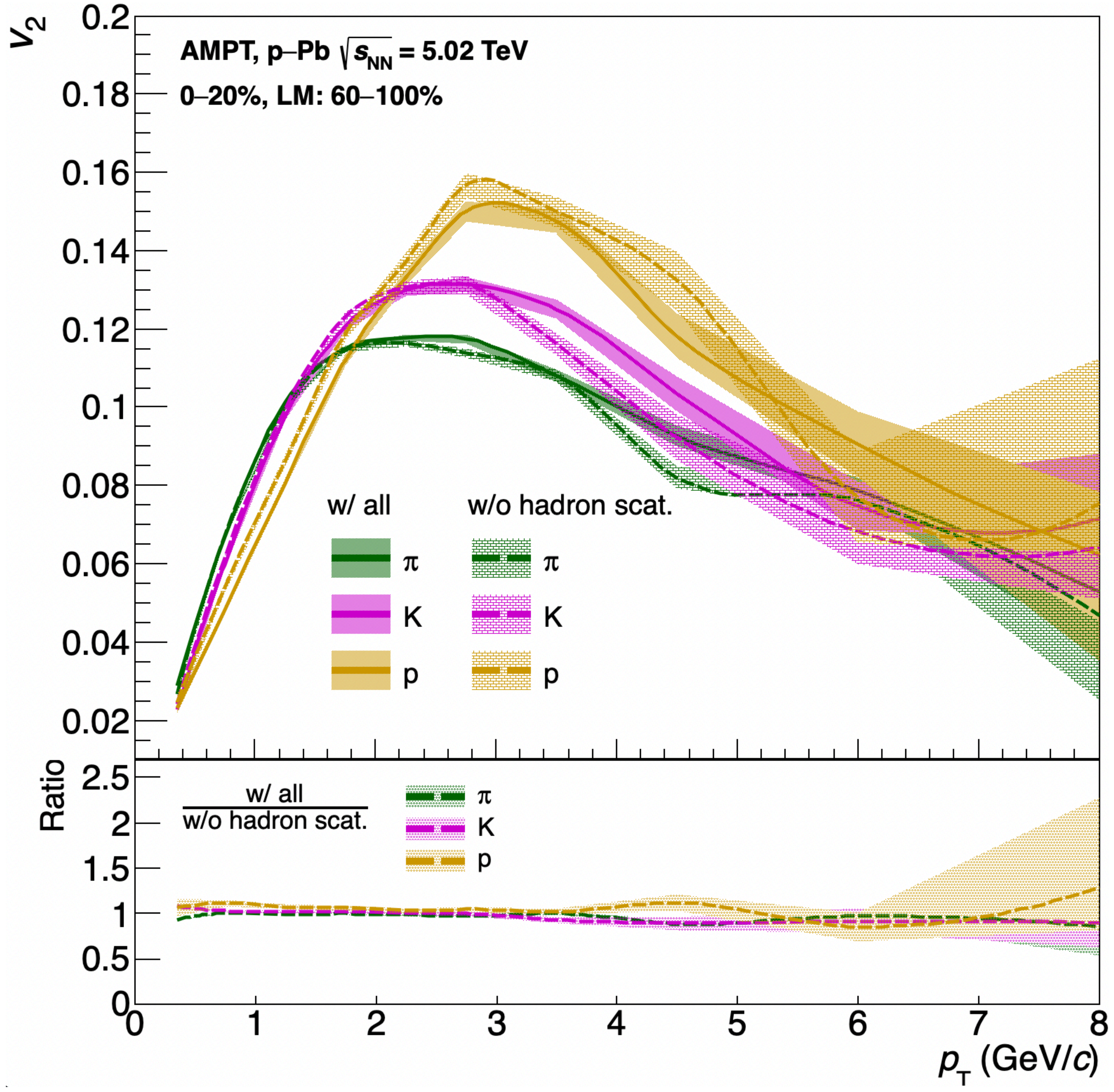
NCQ scaling (centrality dependence)

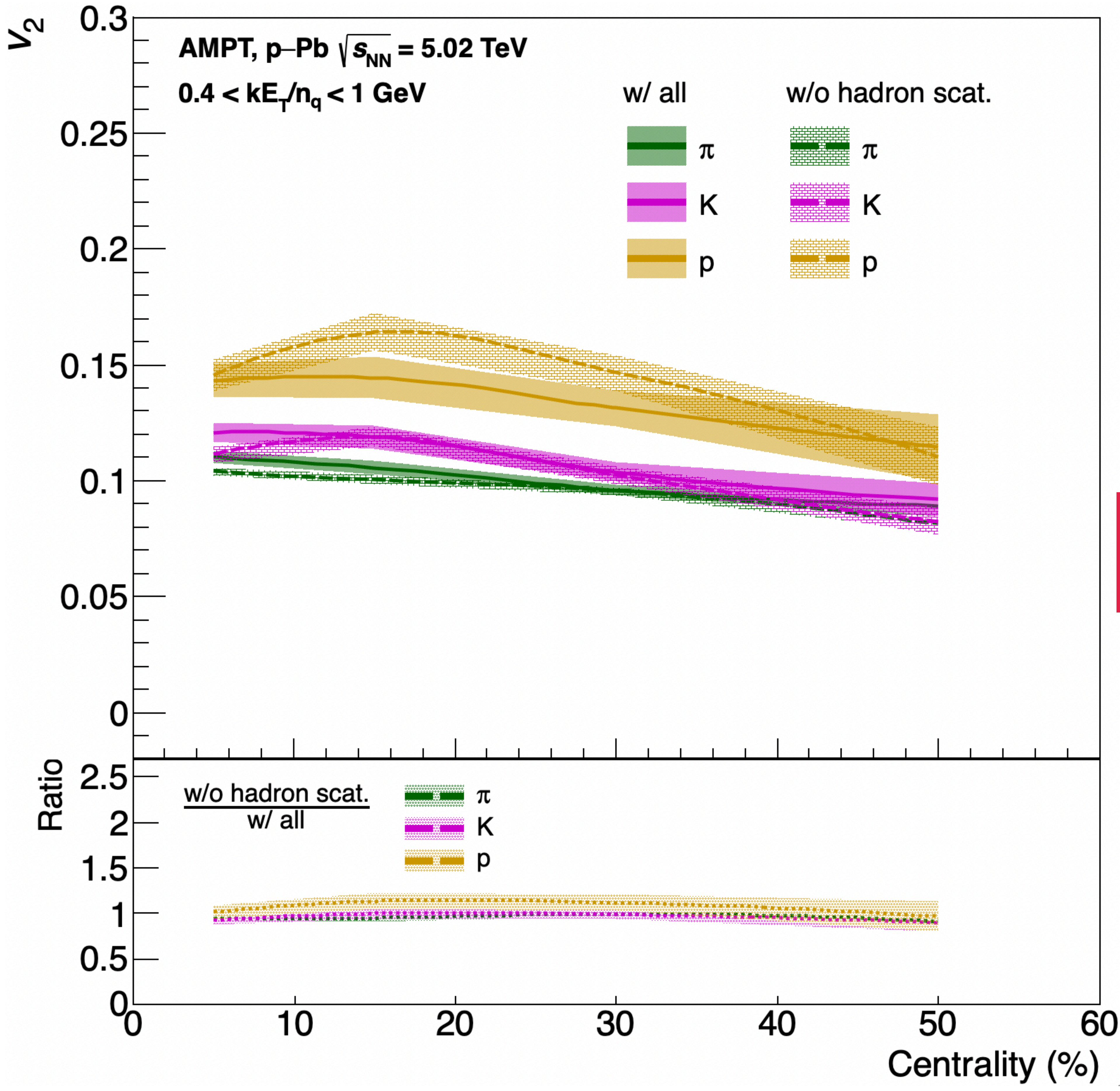




- The integrated v_2 in 0.4 < kE_T/n_q <1 GeV slightly decreases from central to peripheral collisions
- The ratio of n_q scaled integrated v_2 between meson K/proton and π has slight dependence on the centrality selections

Impact from hadronic scattering

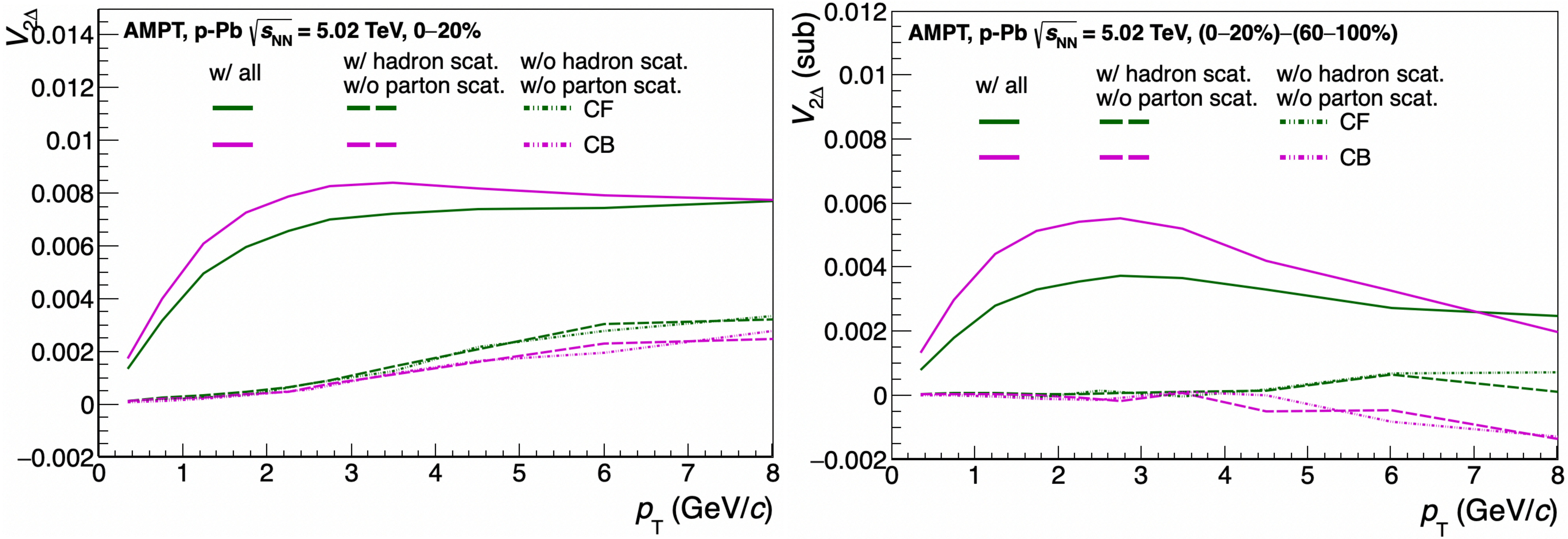




w/o hadron scat: the resonance decay is still included

- The hadronic scattering has almost no influence on v_2 in high-multiplicity p–Pb collisions
- The impact from hadronic scattering is independent on the centrality selections

Impact from parton cascade



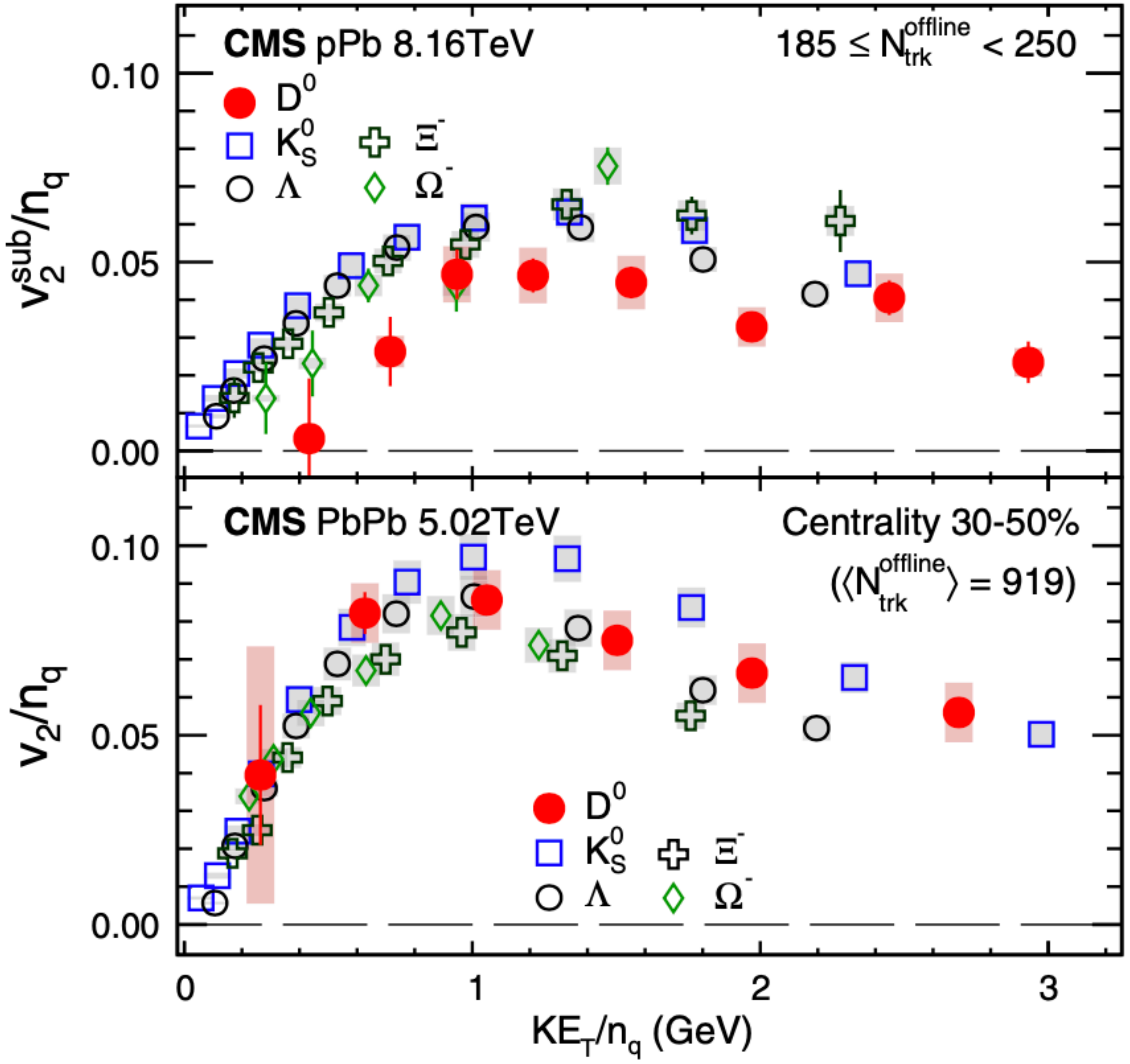
- **After nonflow subtraction,** no elliptic anisotropy is observed when the partonic scattering is turn off

➡ dominant mechanism for v_2 in small collision systems

w/o parton scat.:
the parton scattering cross section is set to 0 mb

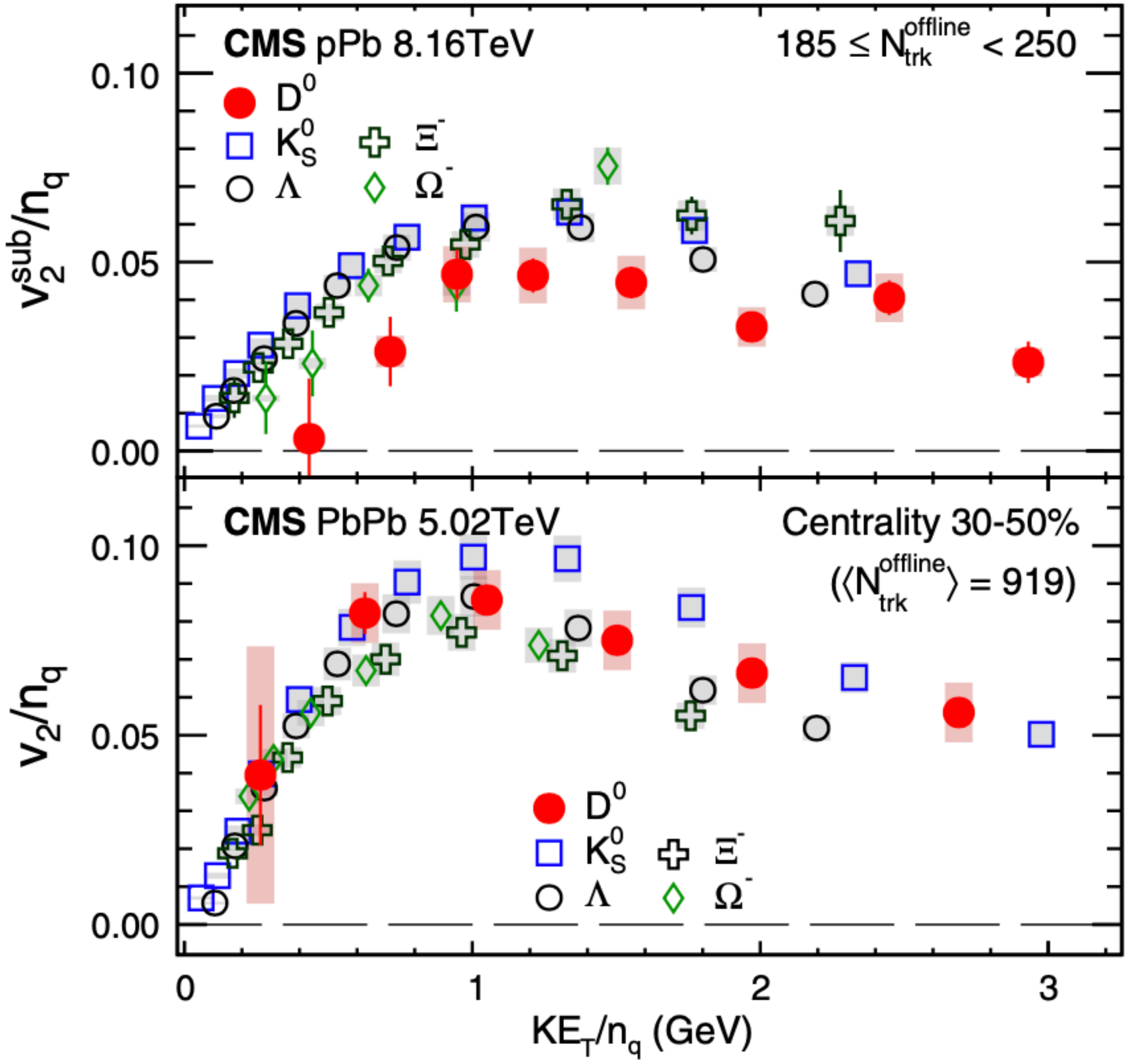
$$v_2 = \sqrt{\frac{V_{2\Delta}(\mathrm{CF})V_{2\Delta}(\mathrm{CB})}{V_{2\Delta}(\mathrm{FB})}}$$

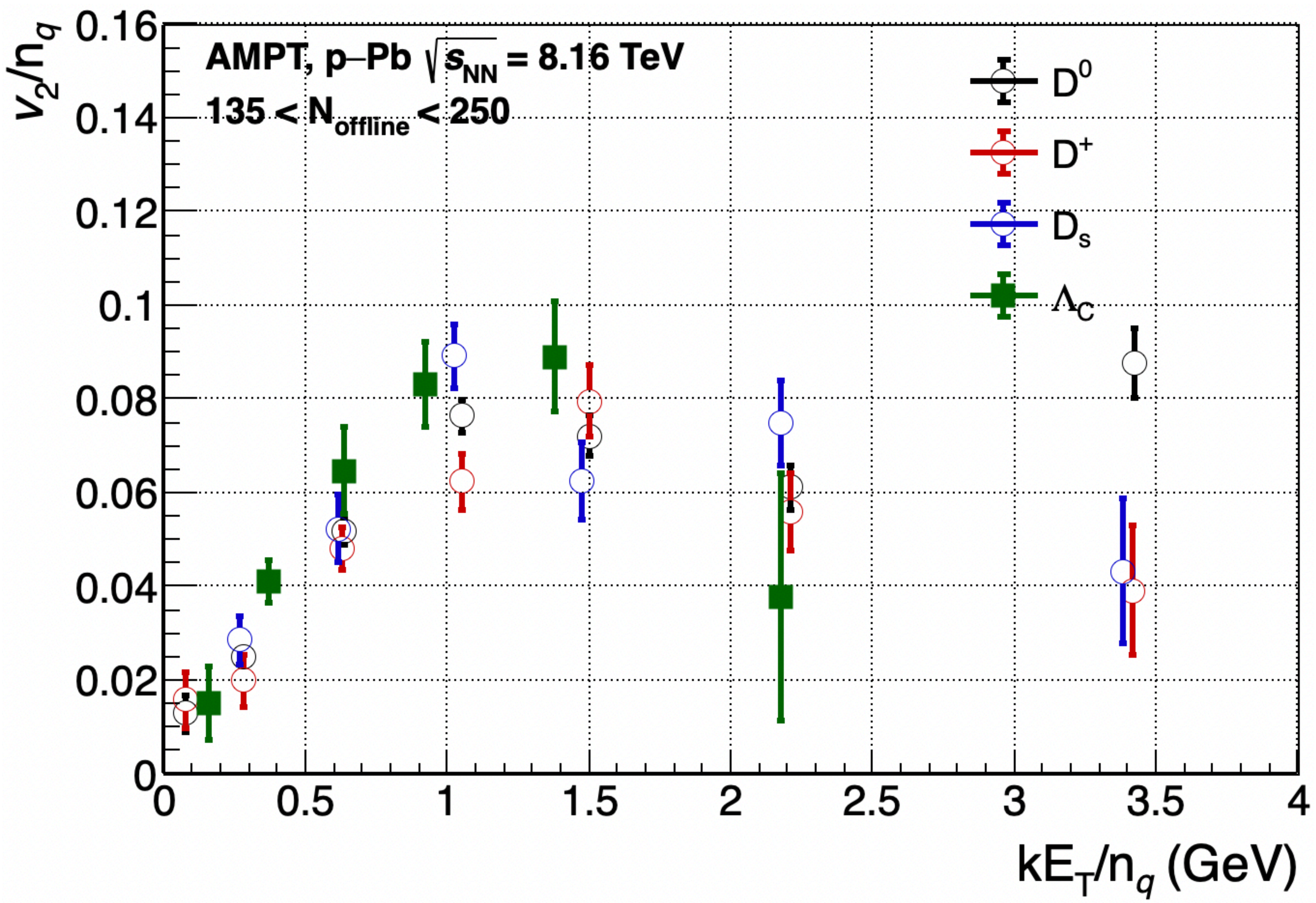
What about heavy flavors?



Lower D^0 v_2 indicates that the collective behavior of charm quarks is weaker than that of the light-flavor quarks

What about heavy flavors?





The heavy flavor baryon and meson approximately follow the NCQ scaling in AMPT!

Lower D^0 v_2 indicates that the collective behavior of charm quarks is weaker than that of the light-flavor quarks

More studies are needed in the future!

Summary and outlook

- We study the elliptic anisotropy of identified particles (π, K, P, Λ) from low to intermediate p_T with AMPT model in p–Pb collisions
- Mass ordering effect and baryon-meson grouping can be reproduced at low and intermediate p_T
  - Parton scattering instead of hadron scattering play an important role in generating the v_2 in small collision systems
  - Parton cascade combine with coalescence mechanism together can describe approximately NCQ scaling for $kE_T/n_q < 1$ GeV
- More studies will be performed for hard probes (heavy flavors and jets) in the near future

Thank you for your attention!

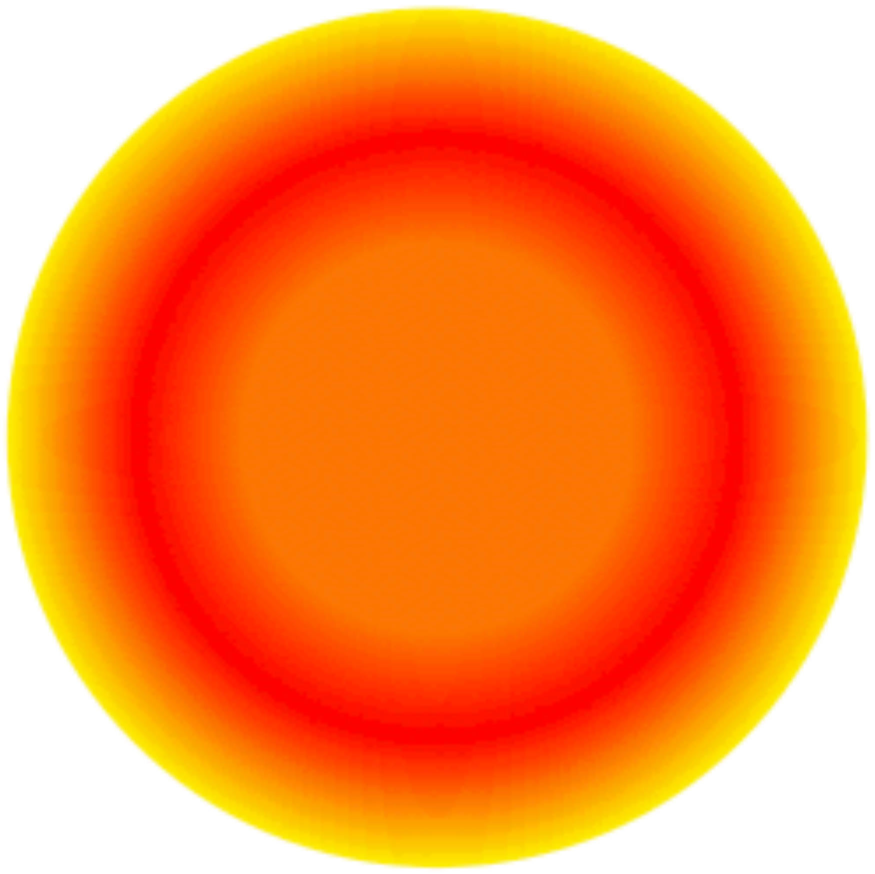
Back up

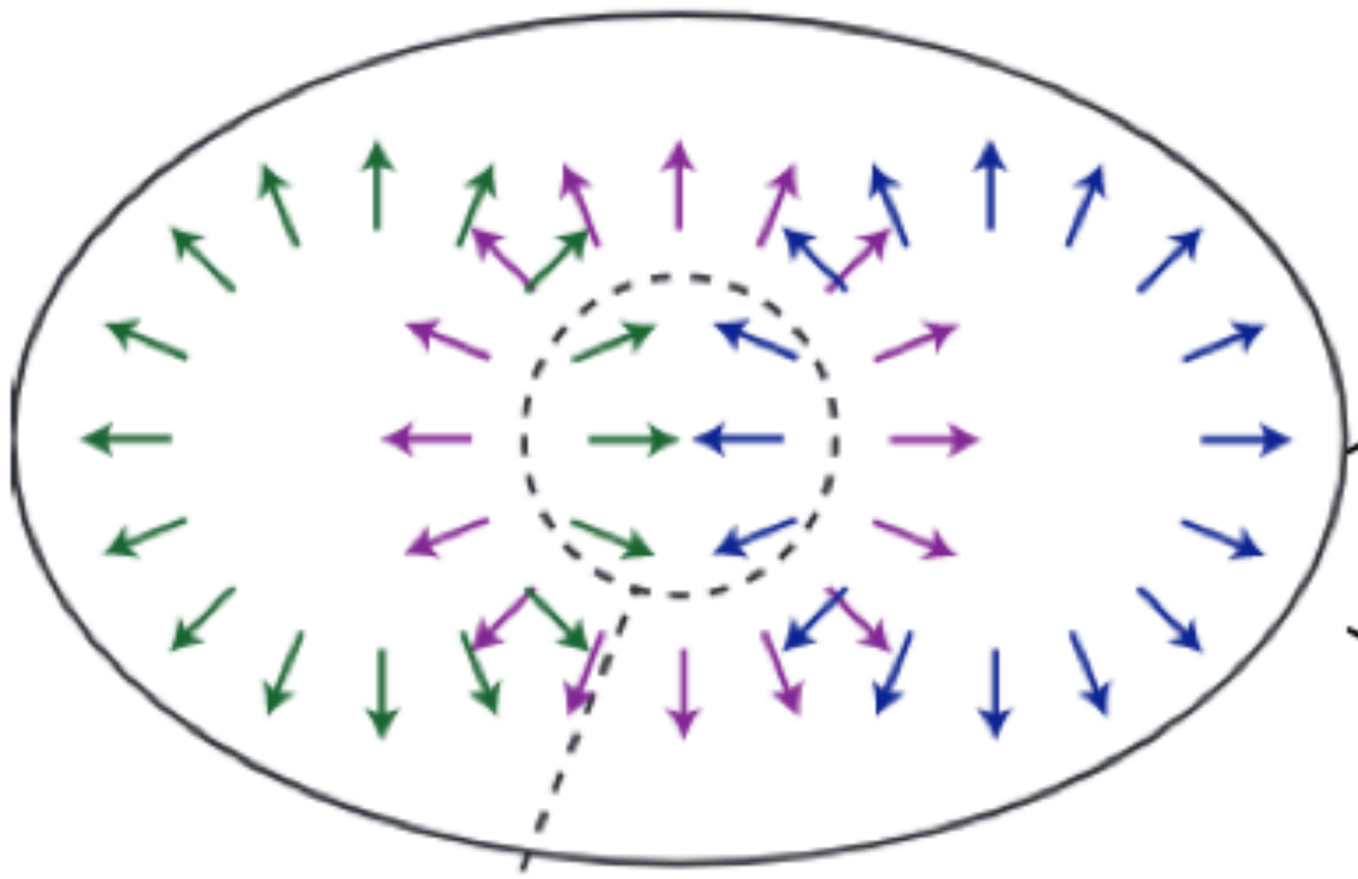
Possible Explanations

Hydrodynamic evolution

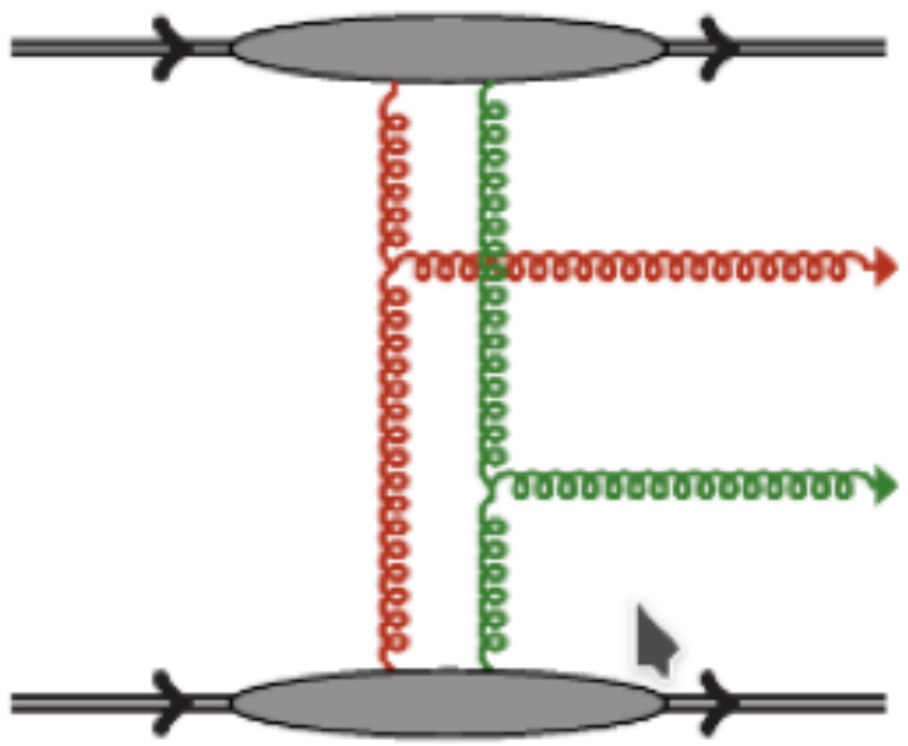
Escape mechanism

Initial-momentum correlations





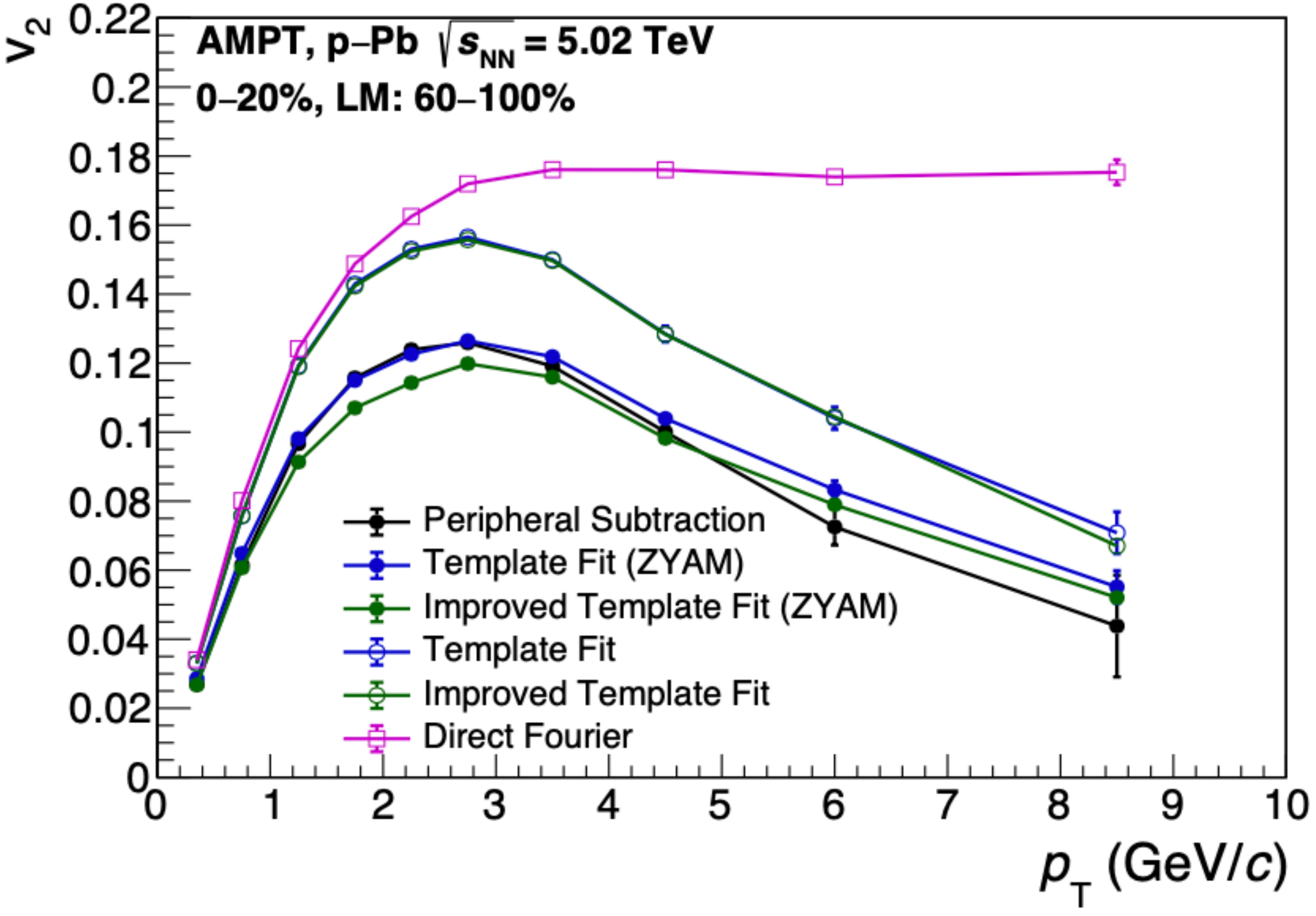
PLB783(2018) 274
PLB753(2016)506



PRD87(2013) 9,094034

Many scatterings ⟷ Few scatterings ⟷ Initial conditions

Different non flow subtraction



W-B.Zhao et al, Phys. Rev. Lett. 125, 072301 (2020)

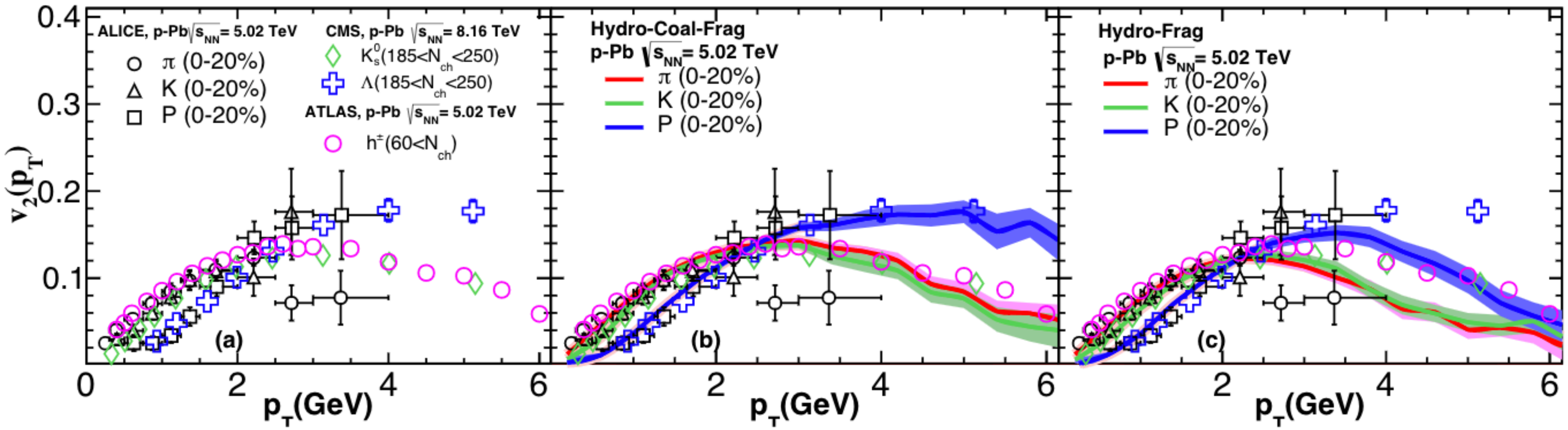


FIG. 2. (Color online) Differential elliptic flow $v_2(p_T)$ of pions, kaons and protons in 0-20% p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV measured in experiments (left window) and calculated with the `Hydro-Coal-Frag` model (middle window) and the `Hydro-Frag` model (right window). The ALICE, CMS and ATLAS data are taken from [11], [64] and [65], respectively.

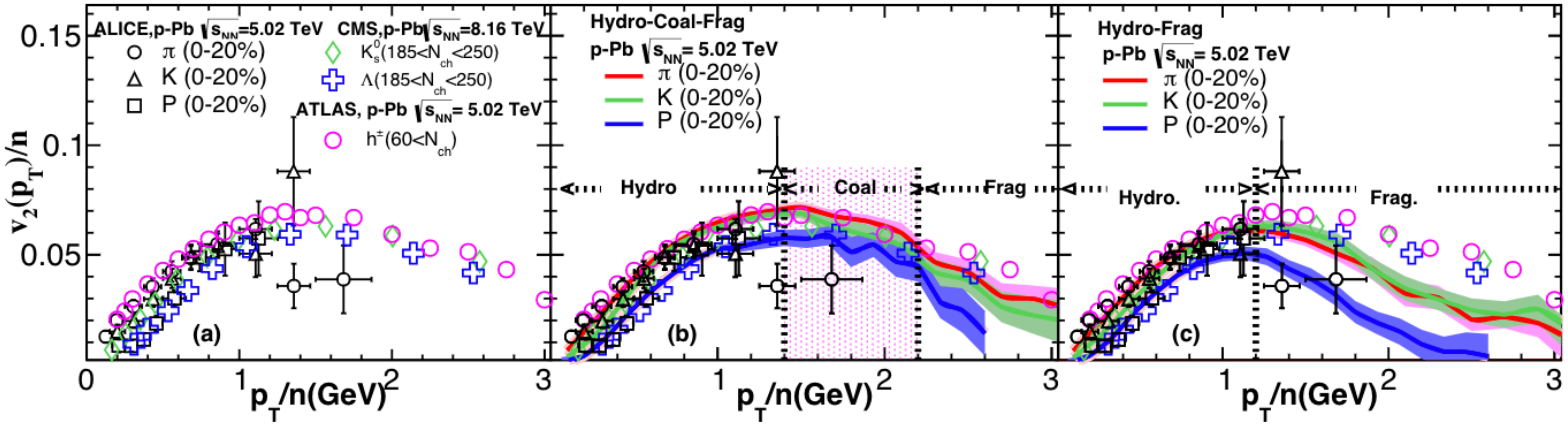


FIG. 3. (Color online) Similar to Fig. 2, but for the number of constituent quark scaled $v_2(p_T)$ of pions, kaons and protons.