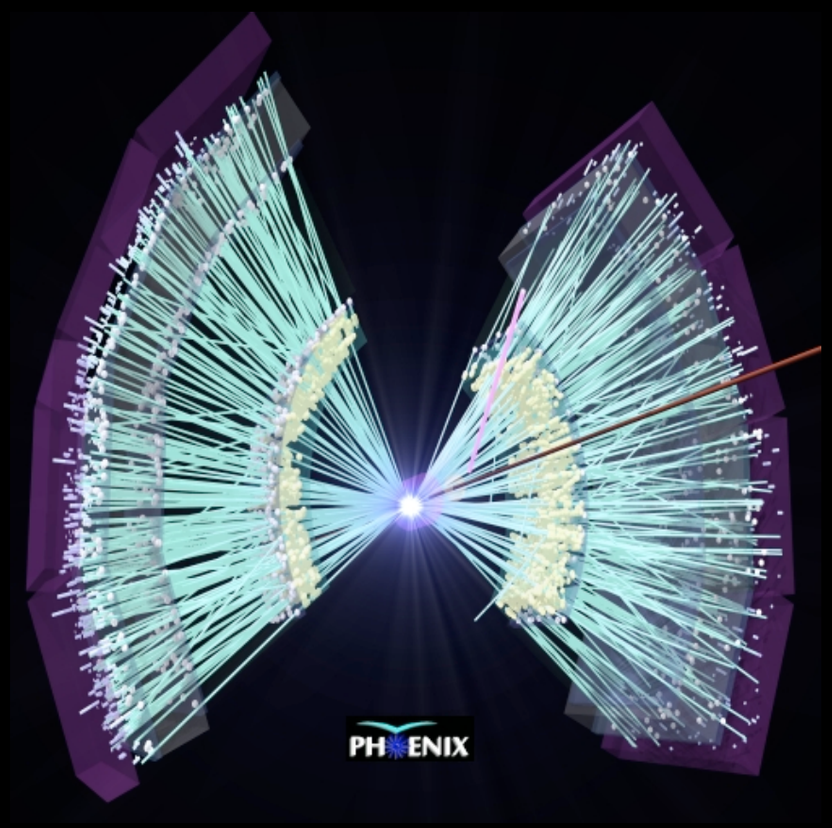
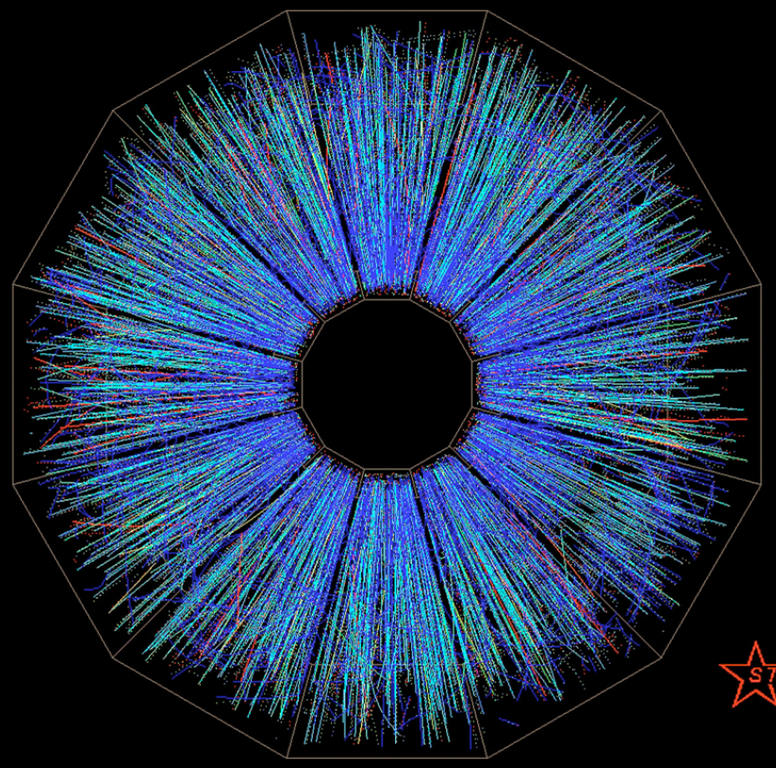
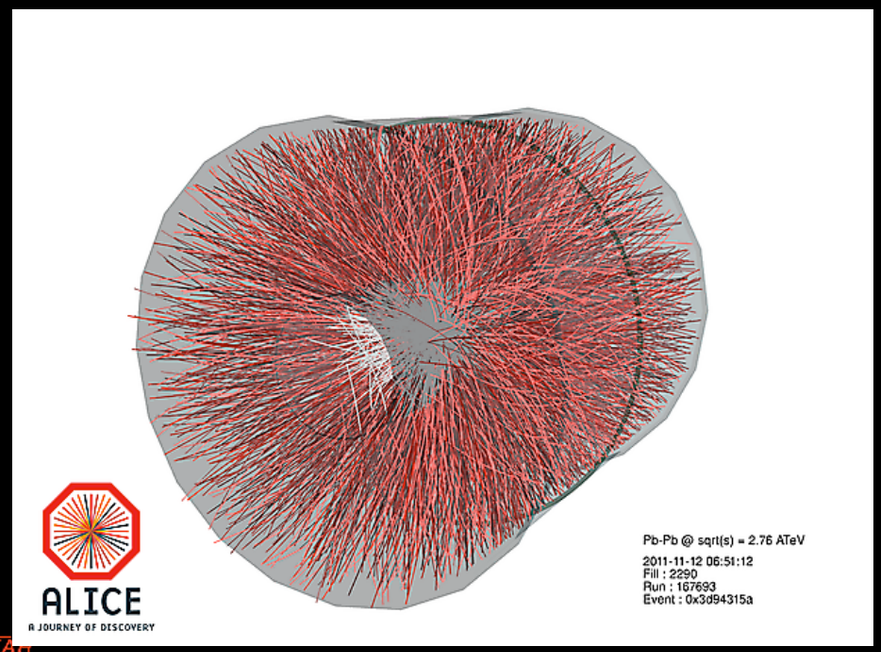
Experimental overview of collective flow with identified particles at RHIC and the LHC

Panos Christakoglou (Nikhef)

Experimental overview of collective flow with identified particles at RHIC and the LHC







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Many thanks to the flow groups from PHENIX, STAR, ALICE

Experimental overview of collective flow with identified particles at RHIC and the LHC

Disclaimer

Could not help adding my (in some cases biased) interpretation of results

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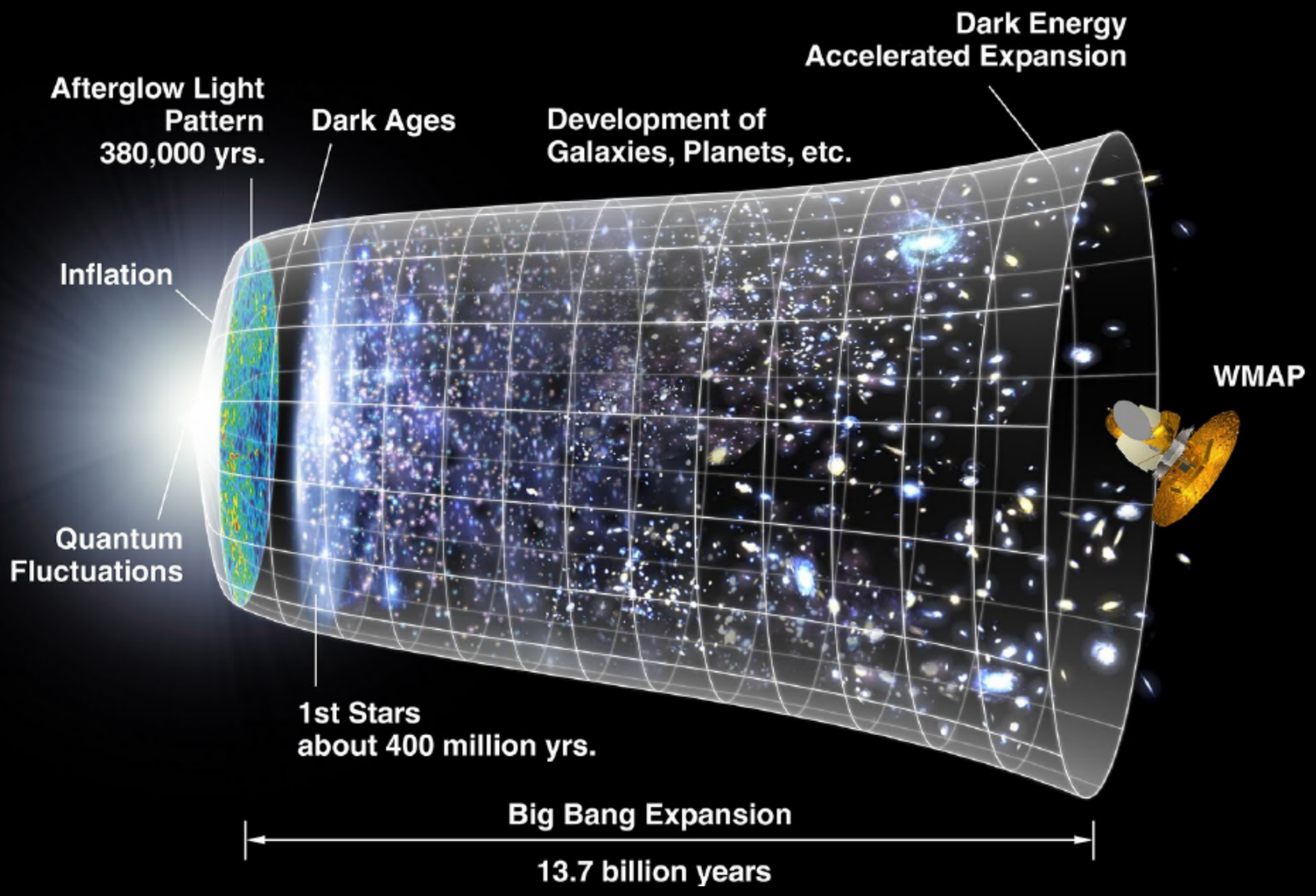
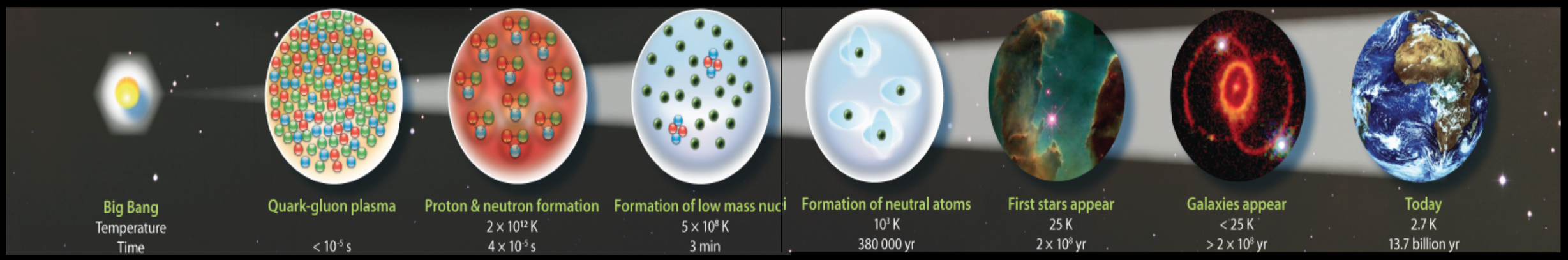
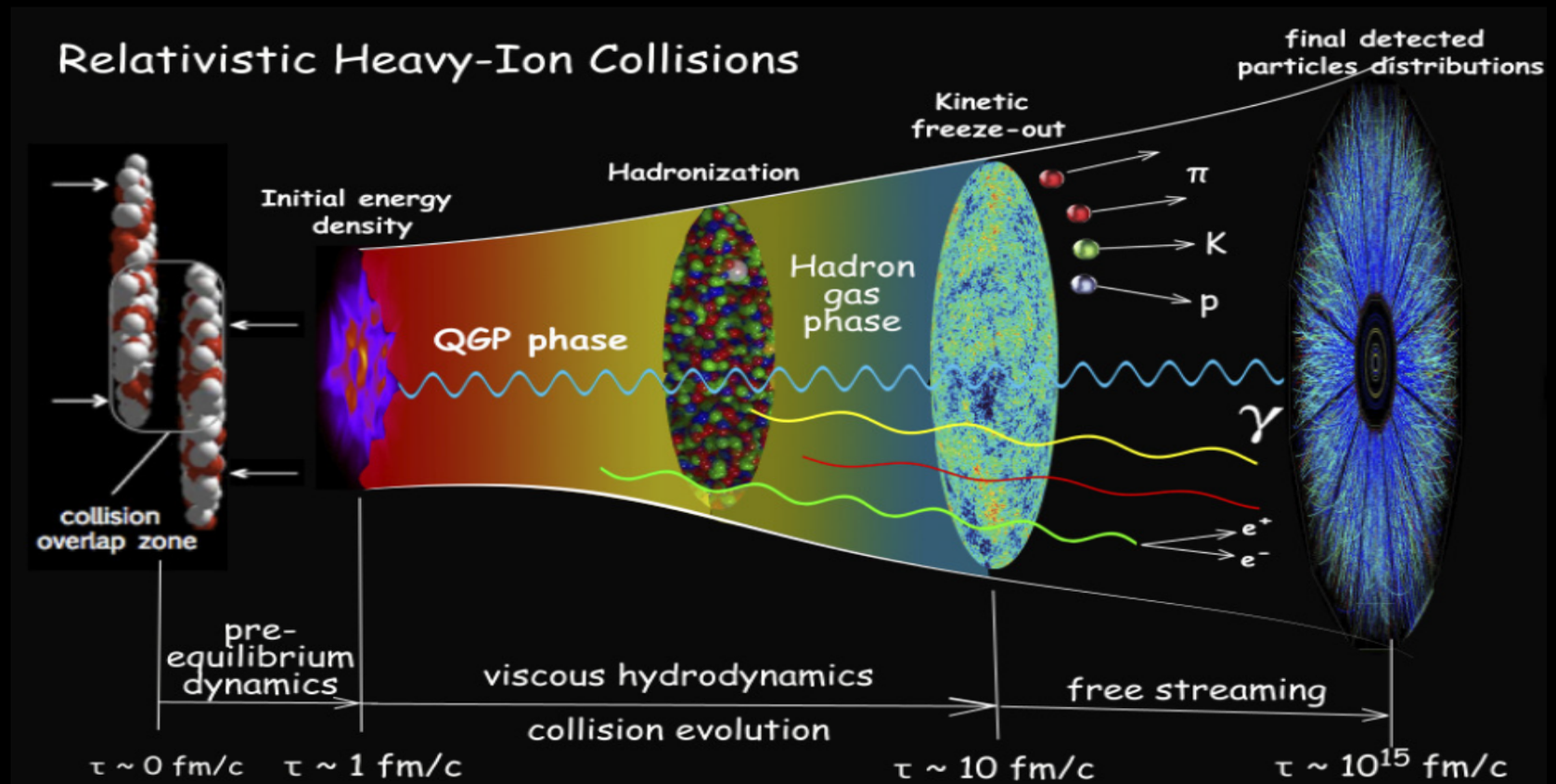
From the Big-Bang



- The Quark-Gluon Plasma (QGP): a state of matter where the quarks and gluons are the relevant degrees of freedom
- We believe that the universe after expanding and cooling down went through this phase few μs after the Big-Bang
- Studying the strong phase transition → study primordial matter



From the Big-Bang to the Little-Bangs…



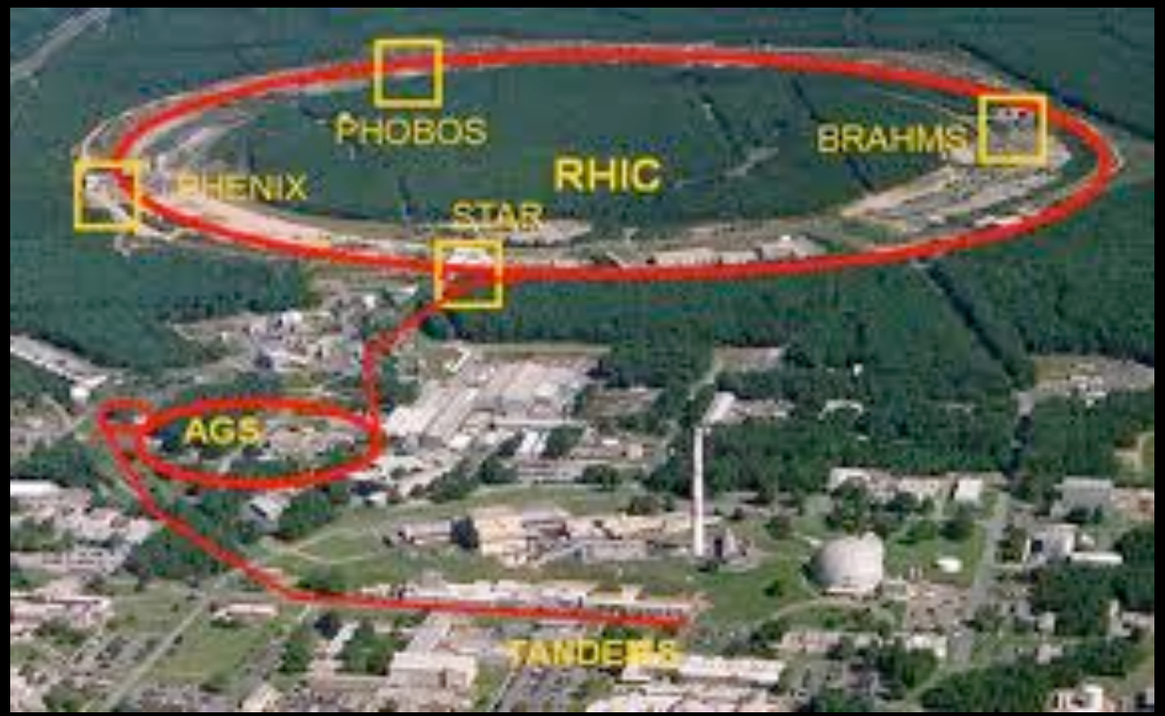
- QCD: Phase transition beyond a critical temperature (~170 MeV) and energy density (~0.5 GeV/fm^3) → quarks and gluons are free → Quark Gluon Plasma (QGP)
- The properties of the QGP and the QCD Phase transition are poorly known from first principles

$T_{(QGP\text{-}transition)} \sim 170MeV \rightarrow 10^{12}$ degrees

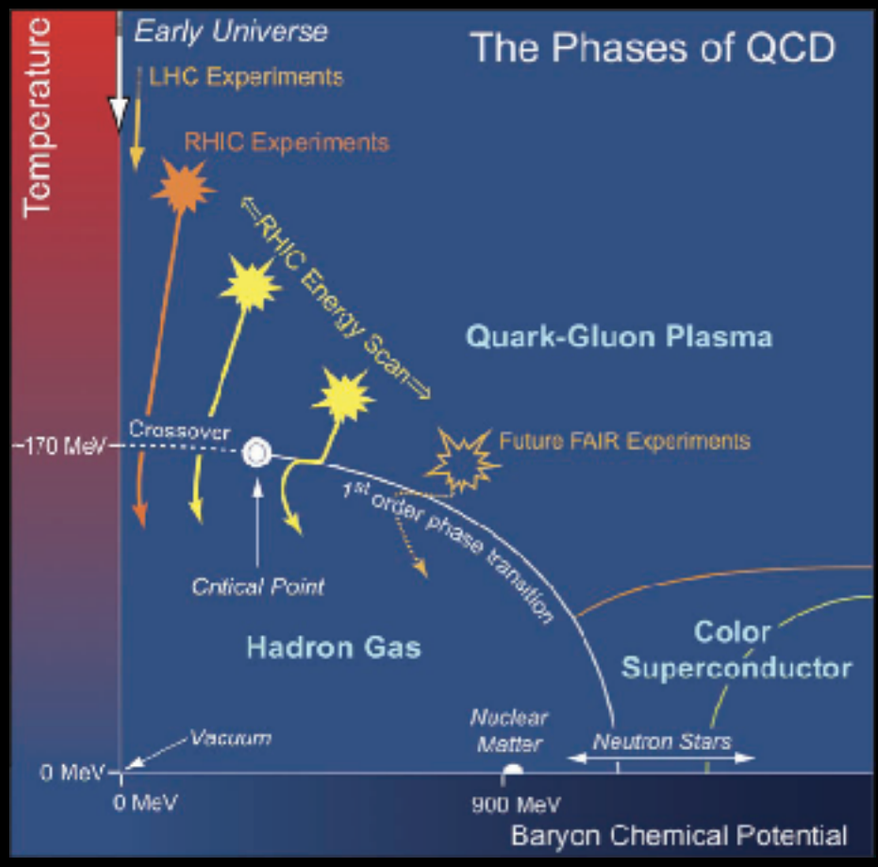
$T_{(Sun's\ core)} \sim 10^7$ degrees

$T_{(QGP\text{-}transition)}\ 10^5 x T_{(Sun's\ core)}$

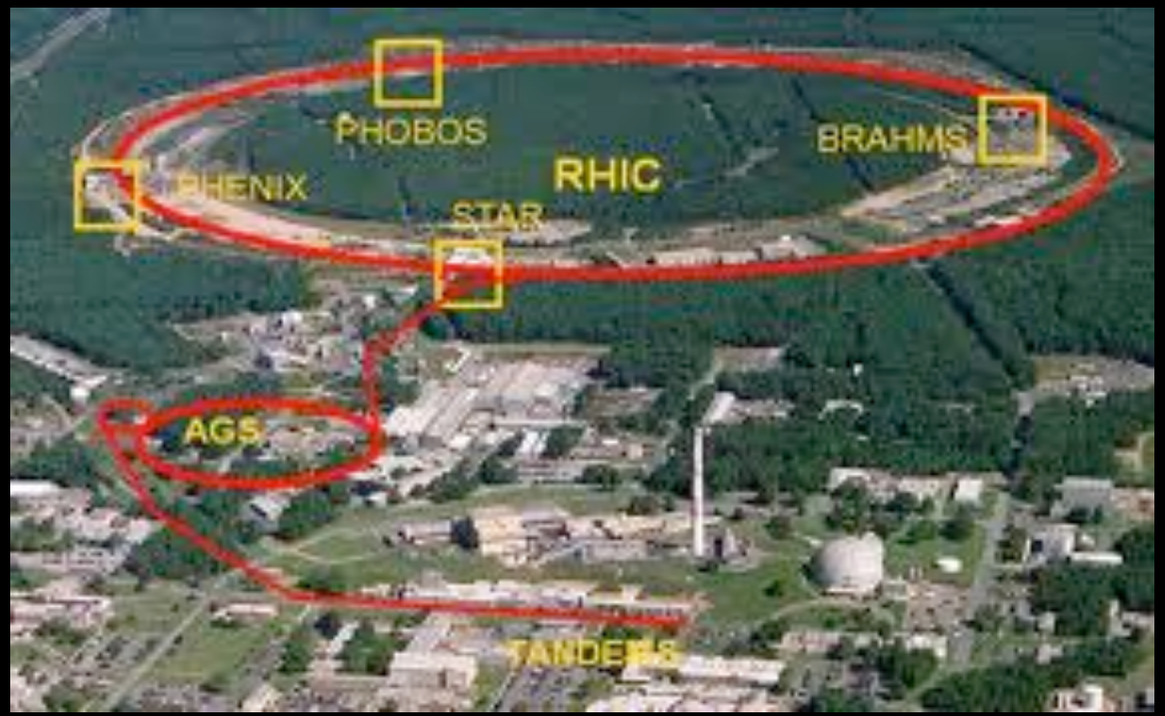
Little Bangs studied at RHIC and LHC



- Colliding Au-ions at
  - ★ $\sqrt{s_{NN}}$ = 130 and 200 GeV (RHIC “high energies”) → mapping the crossover region for the first time
  - ★ $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV → searching for the critical point in the phase diagram (BES: Beam Energy Scan)



Little Bangs studied at RHIC and LHC



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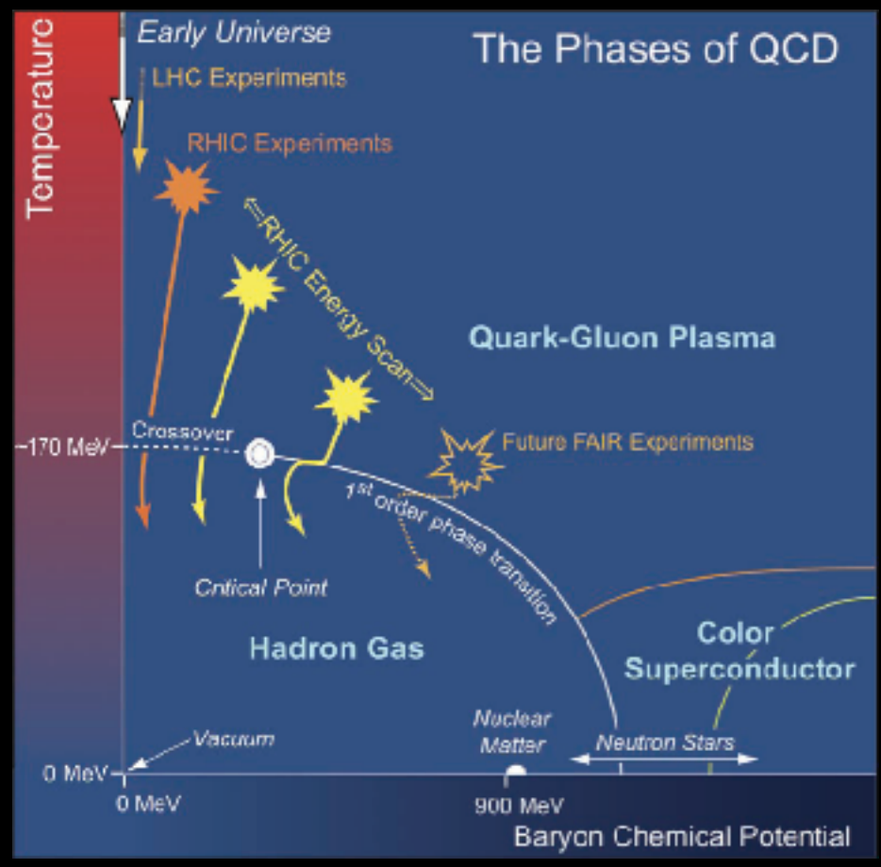
- Colliding Pb-ions at $\sqrt{s_{NN}}$ = 2.76 TeV → quantifying the QGP properties at $\mu_B \sim 0$



Studying the properties of the QGP

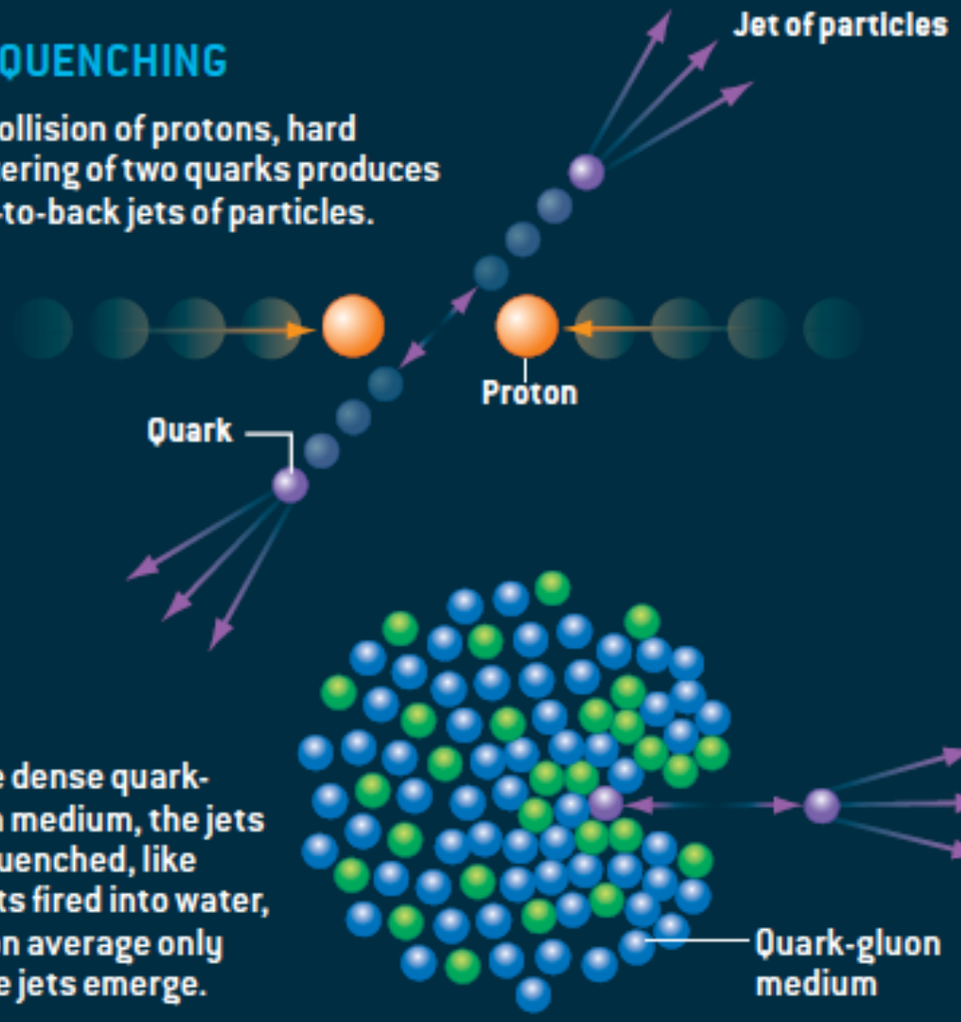
M. Roirdan and W. Zajc, Scientific American 34A May (2006)

EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

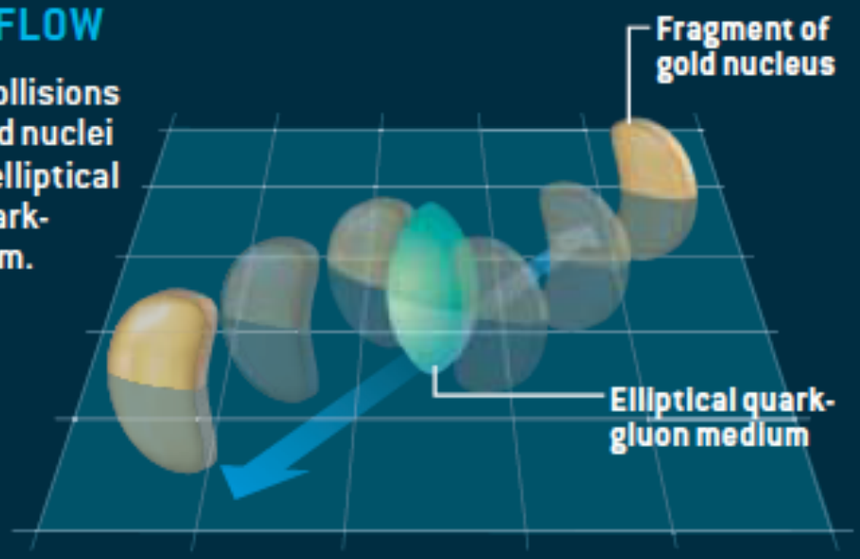
In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.



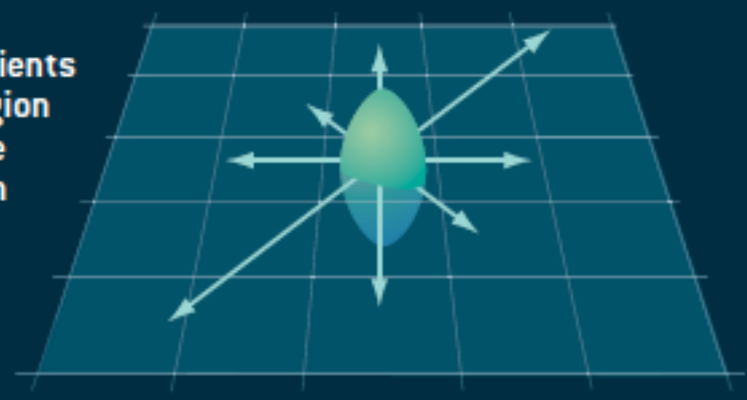
In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

ELLIPTIC FLOW

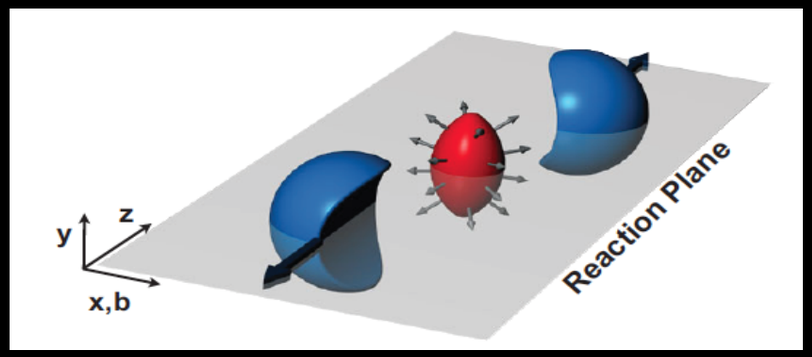
Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

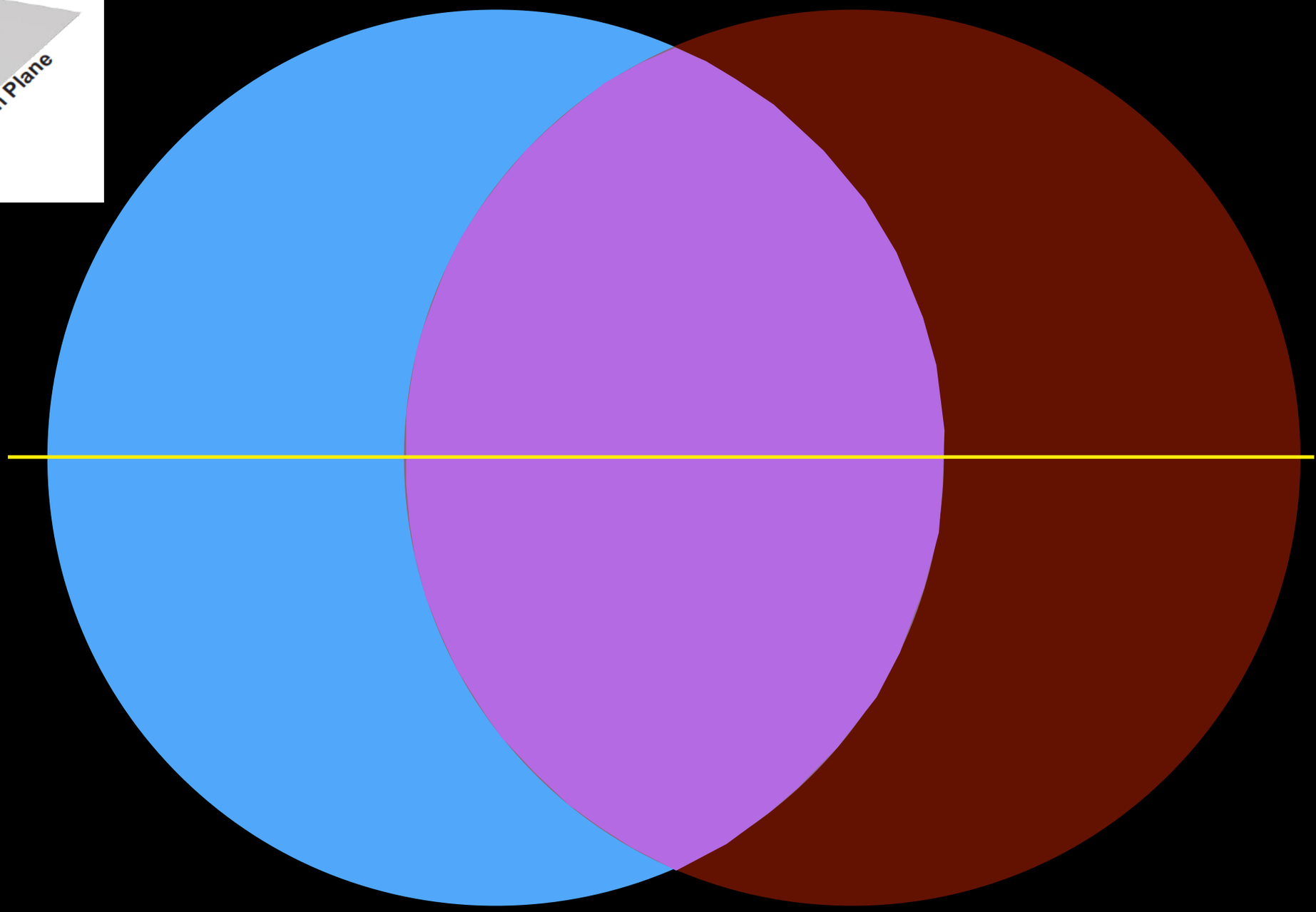


The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).



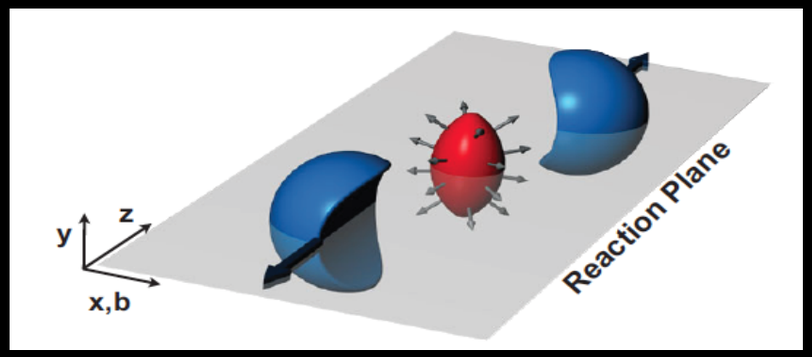
Elliptic flow

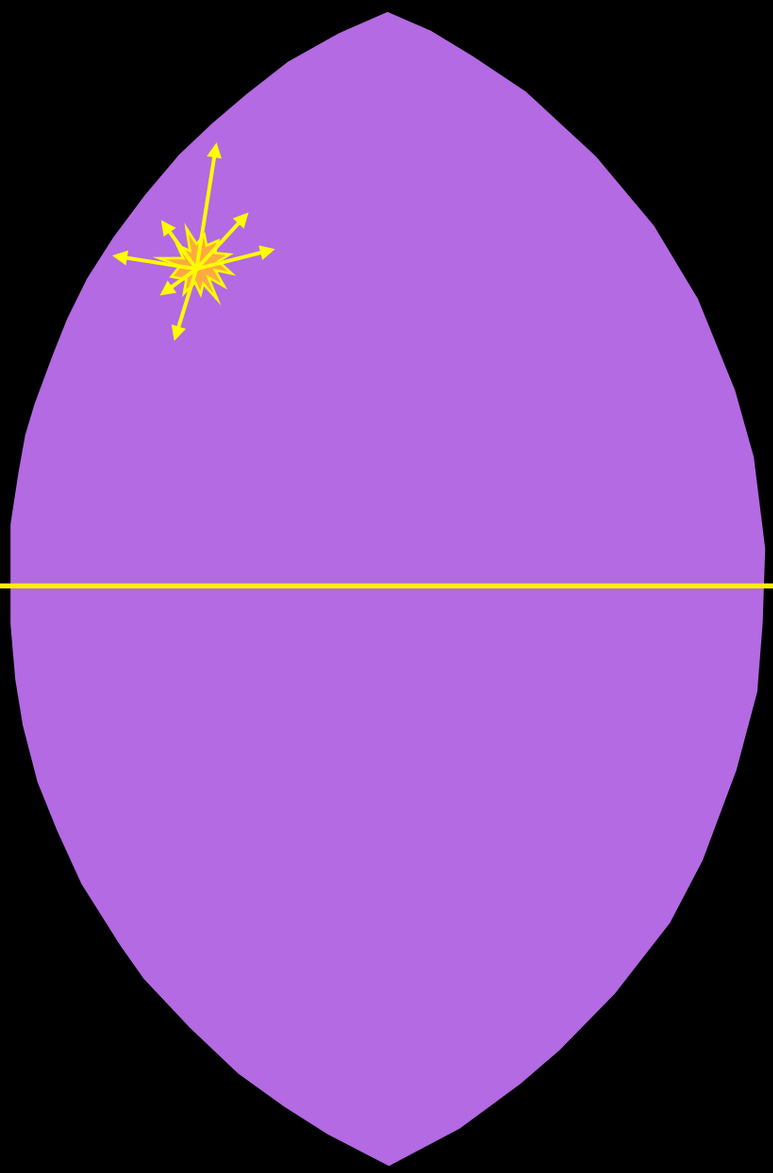




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow





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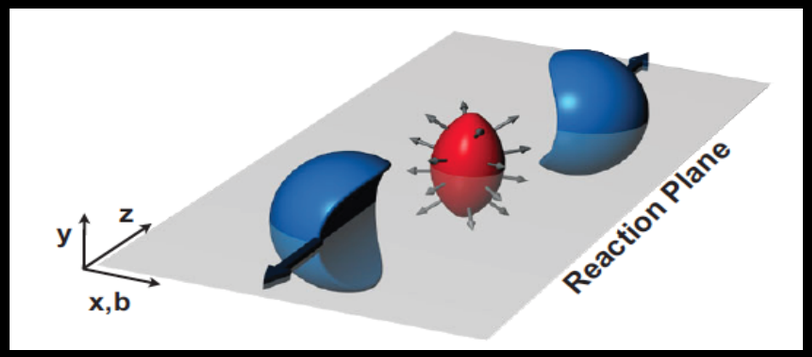
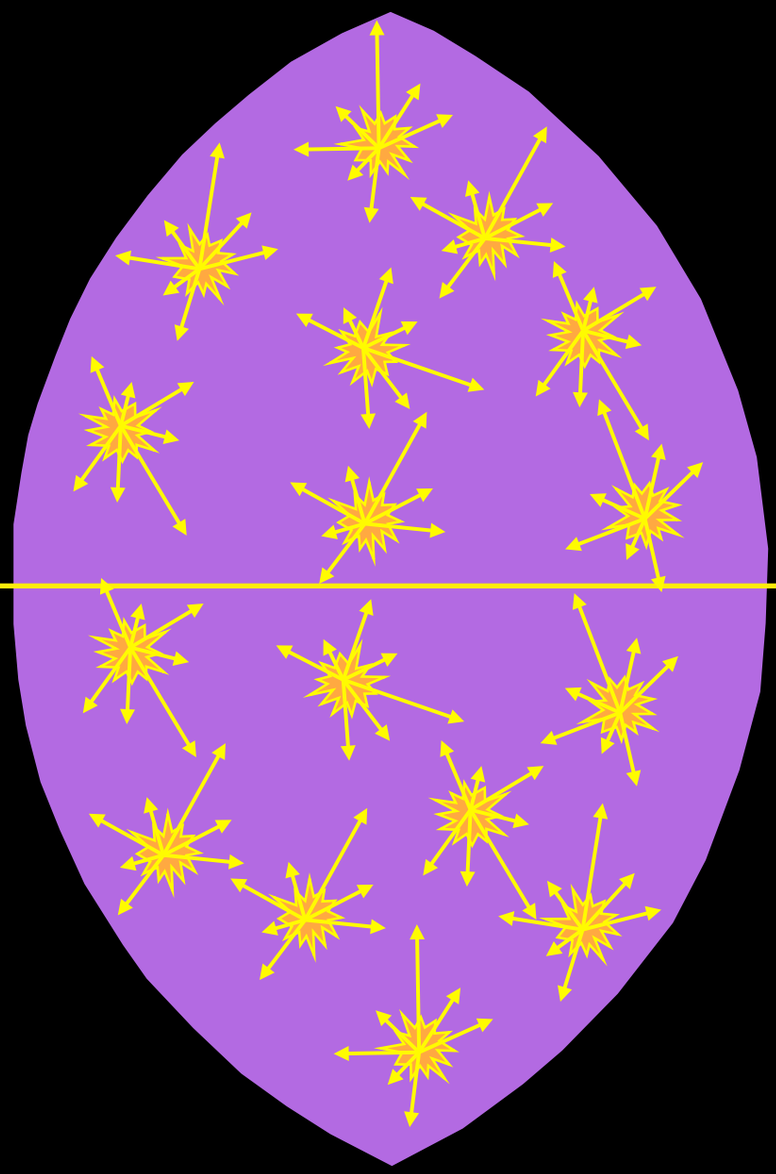
Elliptic flow



Superposition of independent pp collisions



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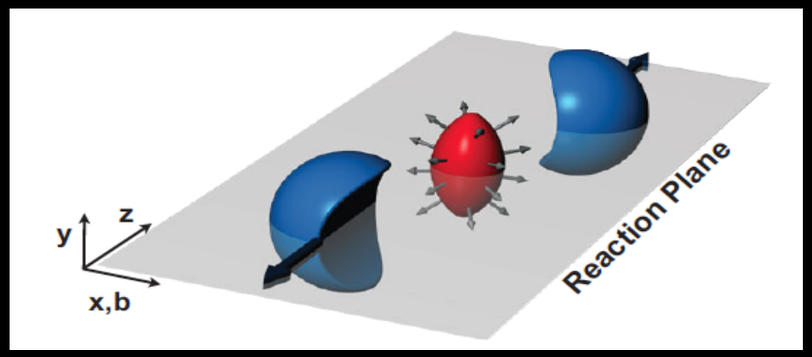
Elliptic flow



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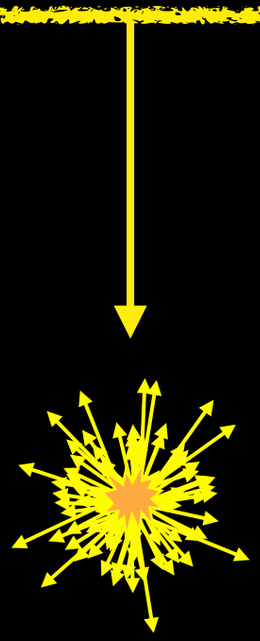
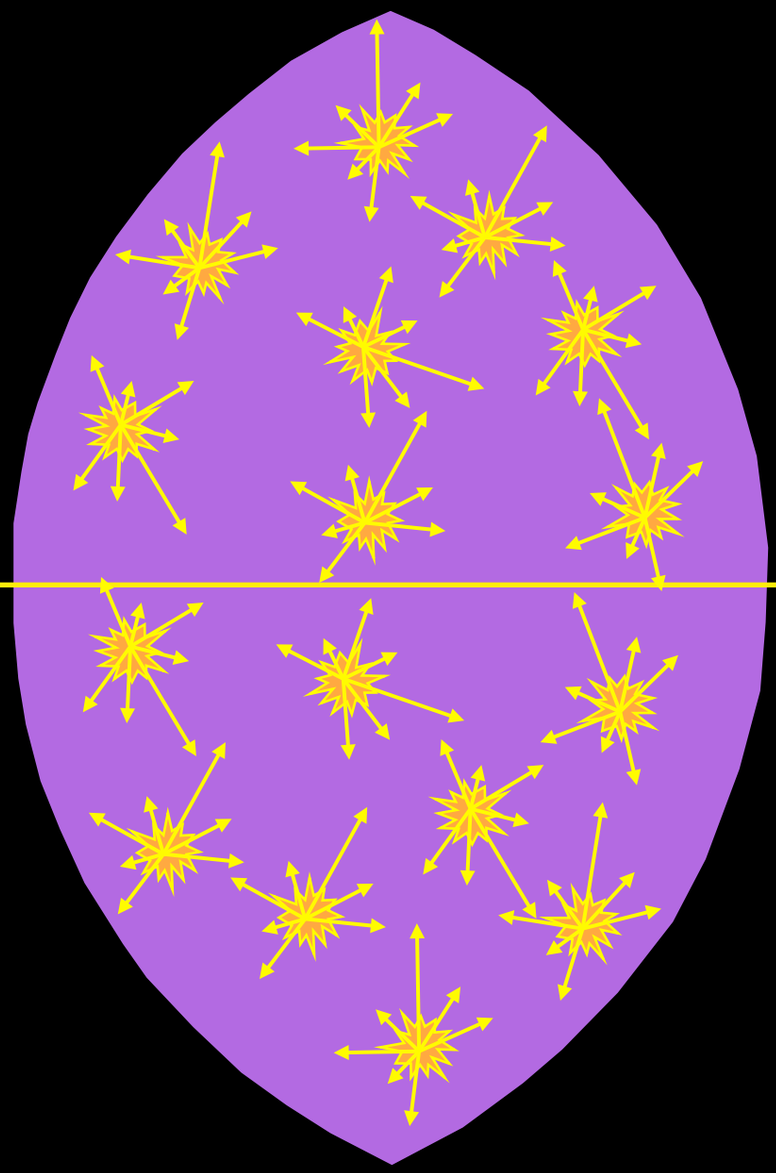


Momenta pointing at random directions



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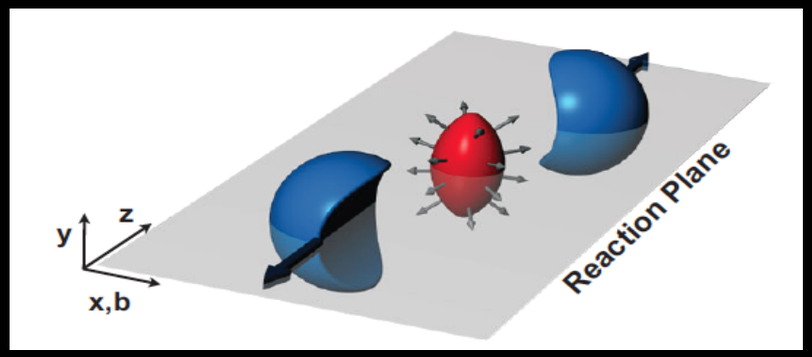
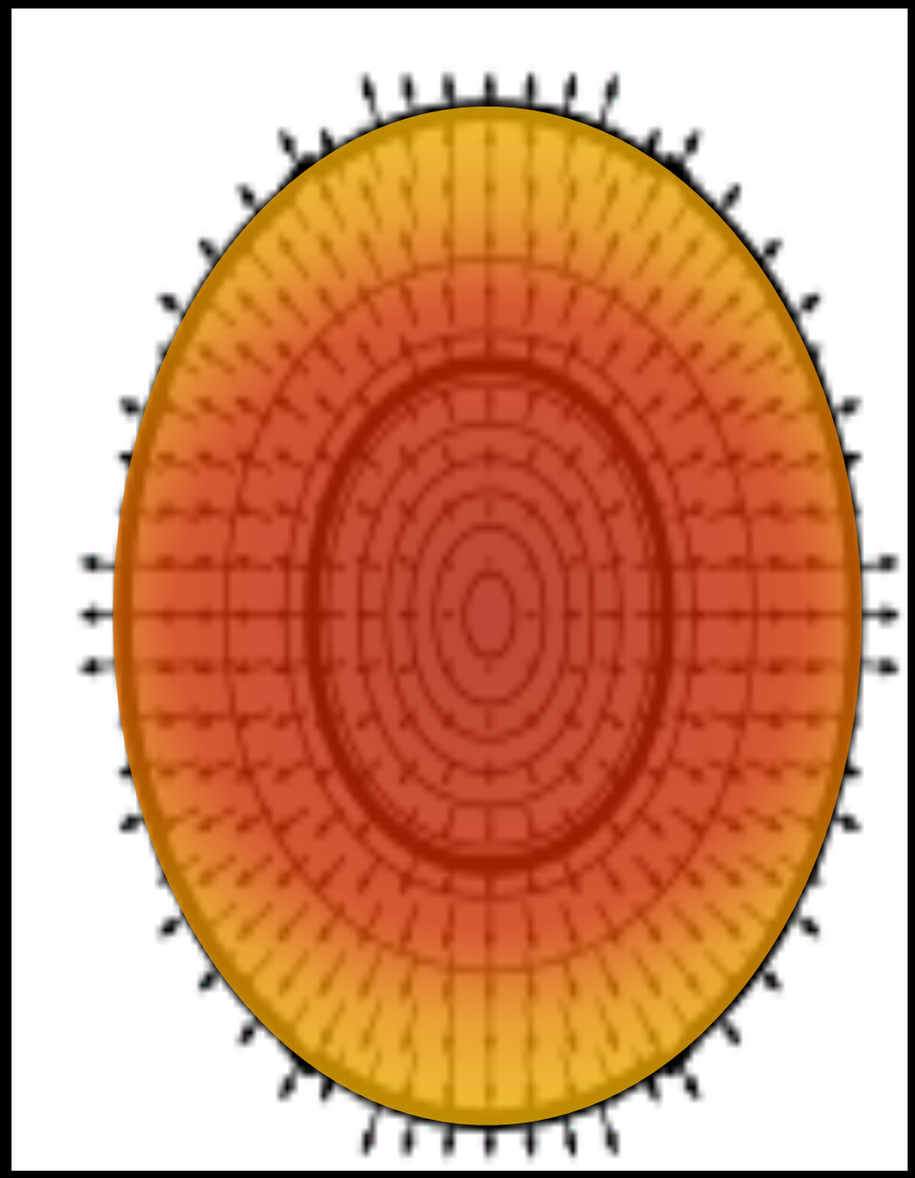
Elliptic flow



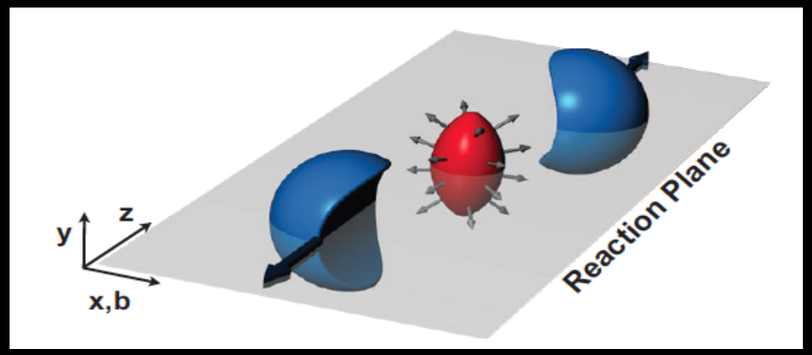
Development as a bulk system



high density and pressure at the center of the fireball

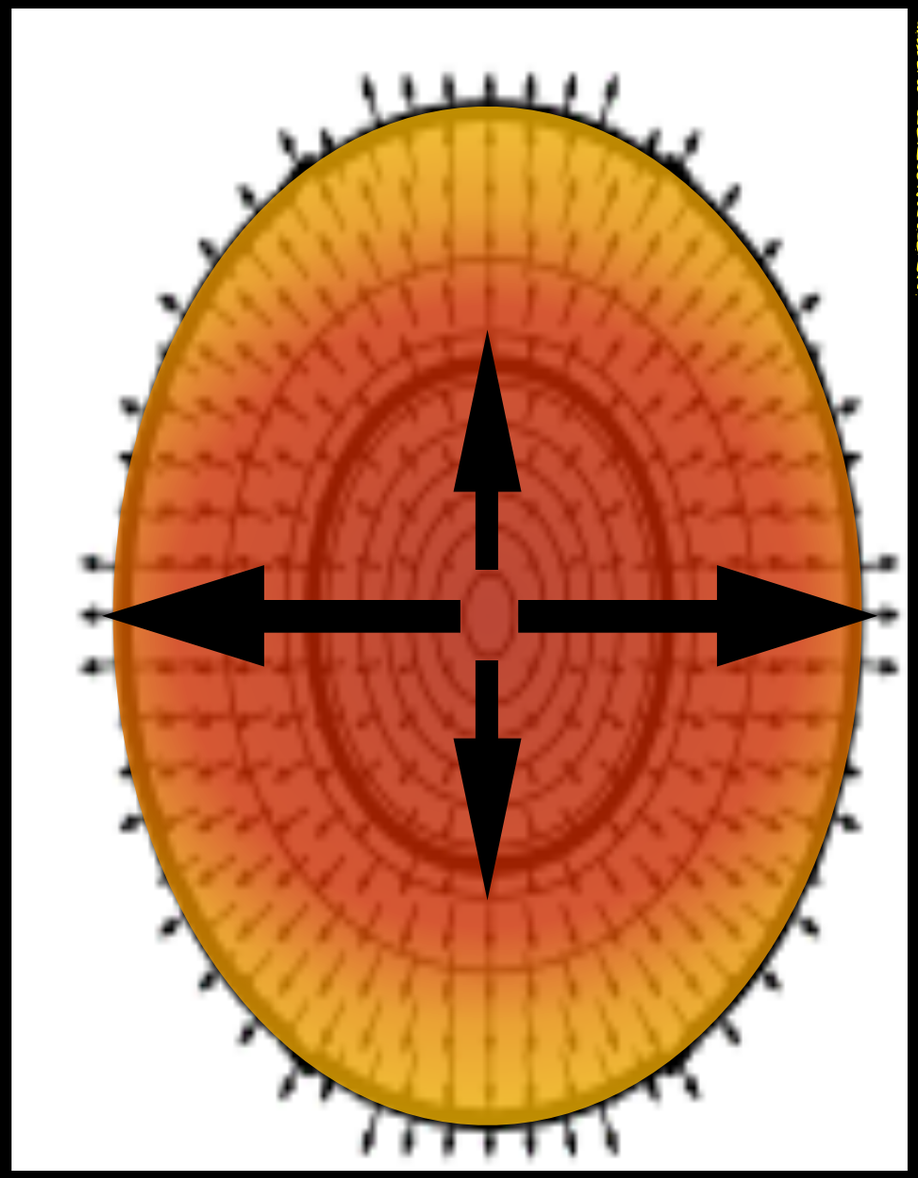
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow



Development as a bulk system

Asymmetric pressure gradients (larger in-plane than out-of-plane) push bulk out → flow



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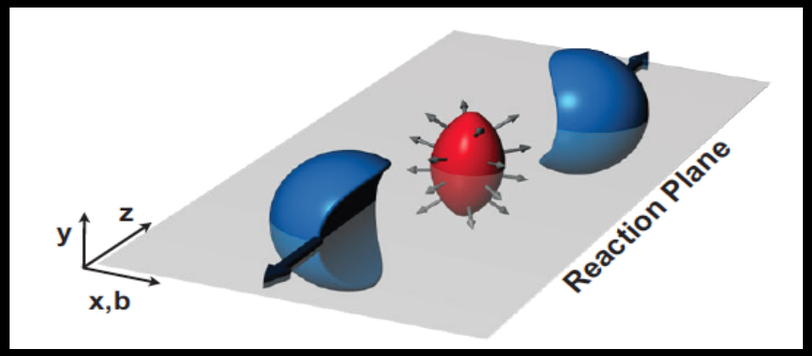
Elliptic flow



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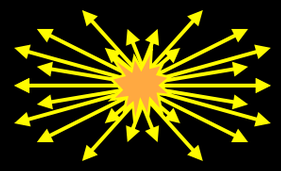
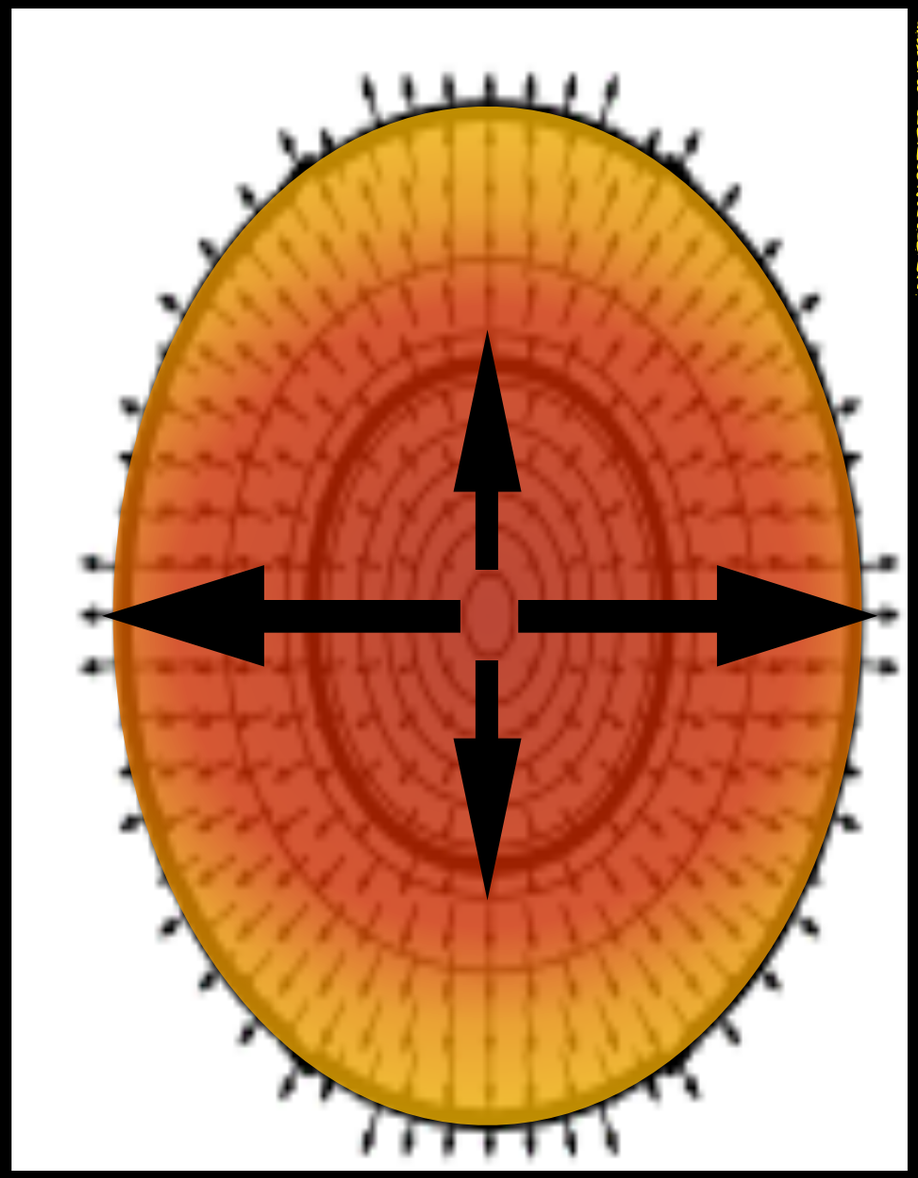


More and faster particles in-plane than out-of-plane

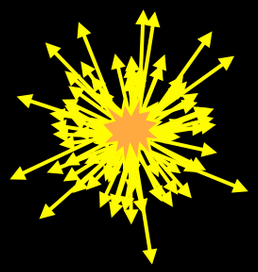


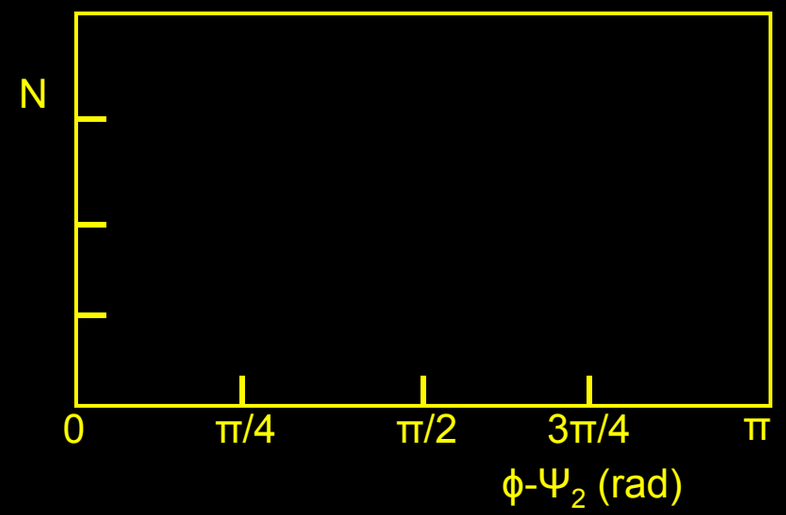
high density and pressure at the center of the fireball

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow

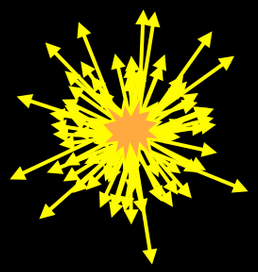
Superposition of
independent pp collisions

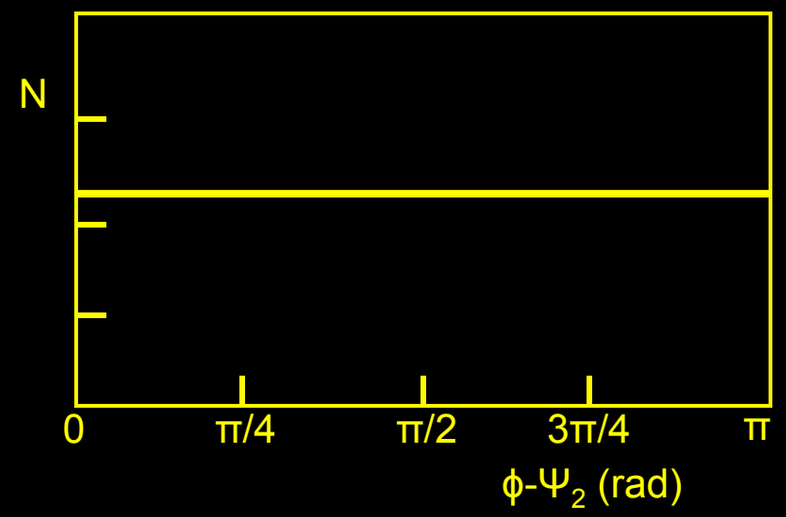




Elliptic flow

Superposition of independent pp collisions





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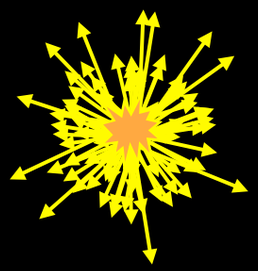

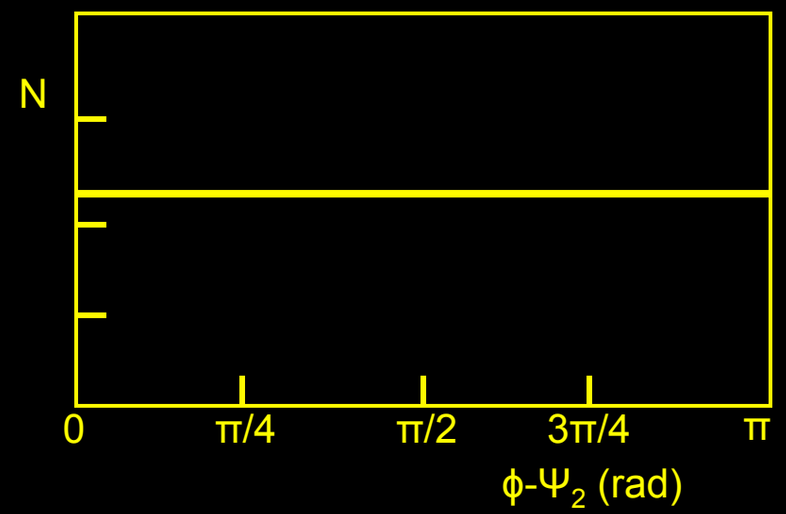

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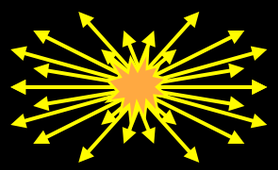

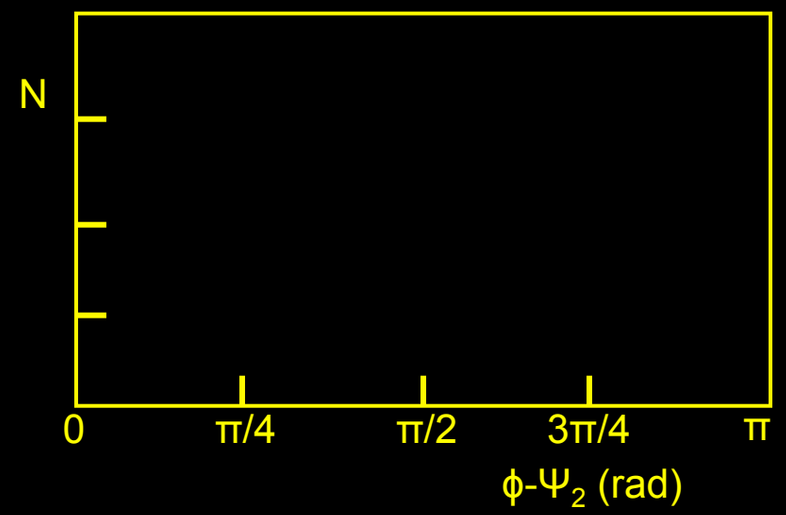

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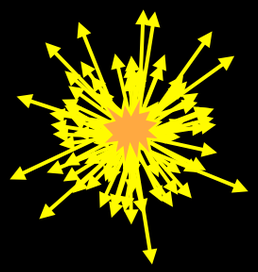

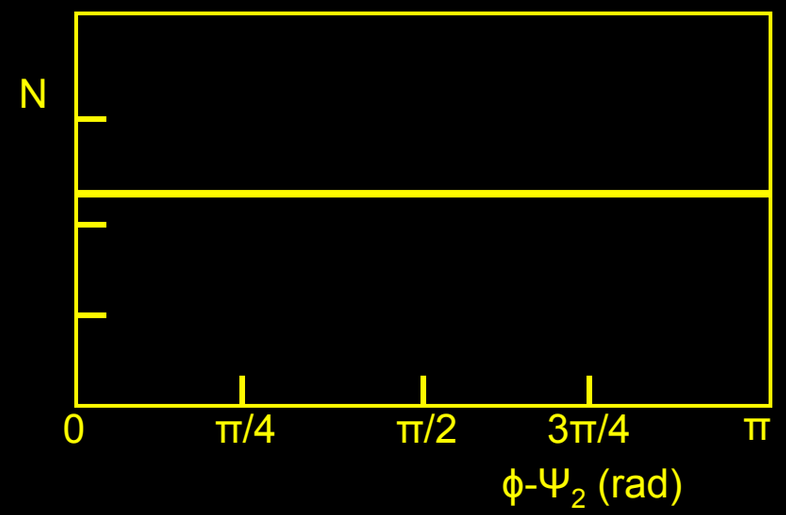

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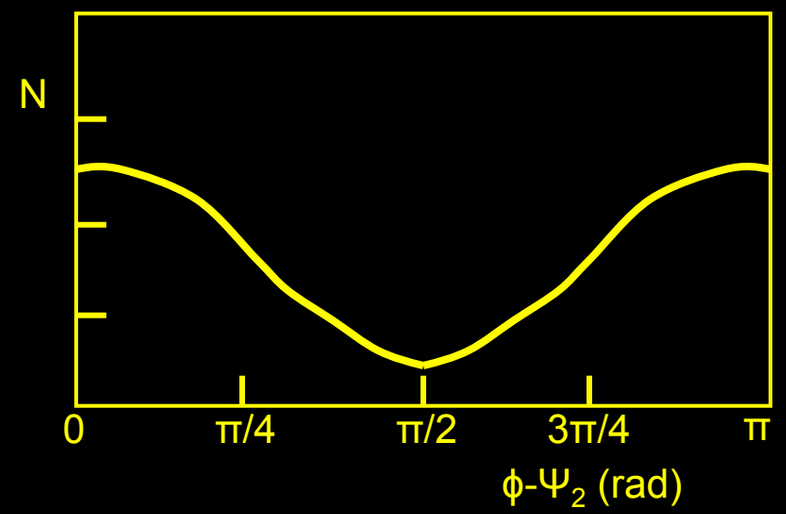
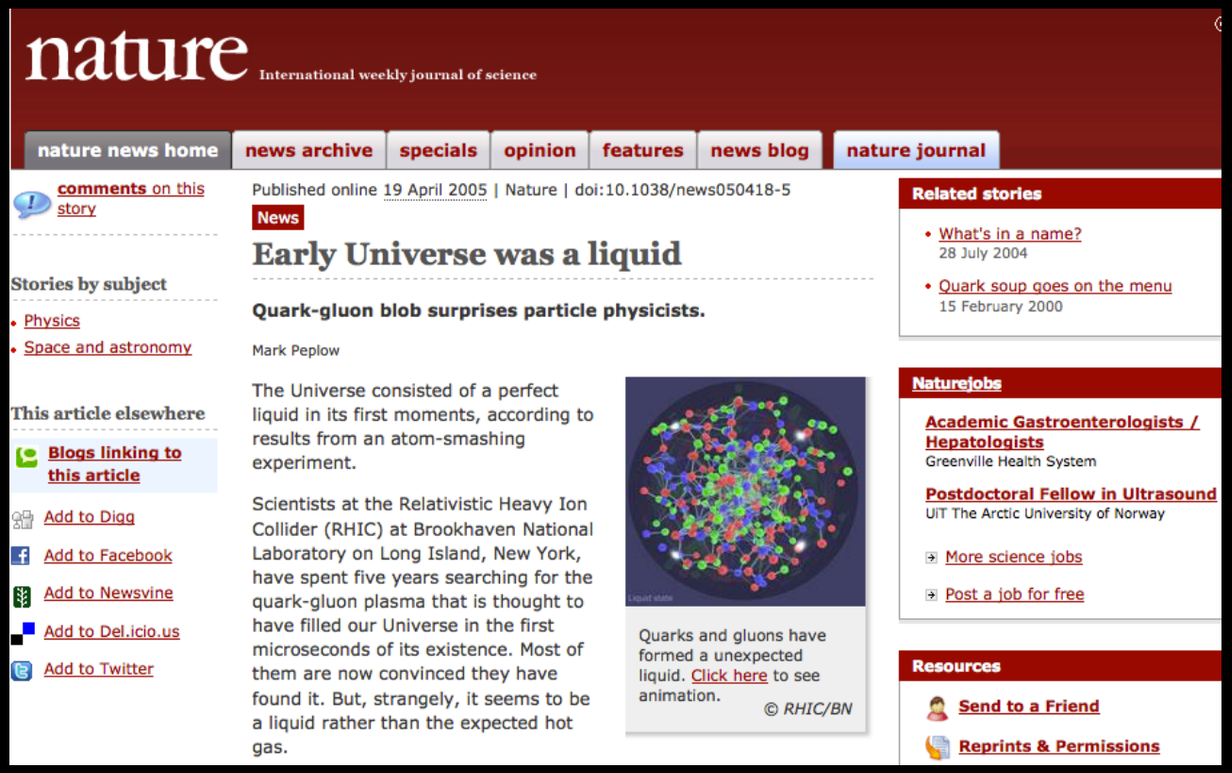
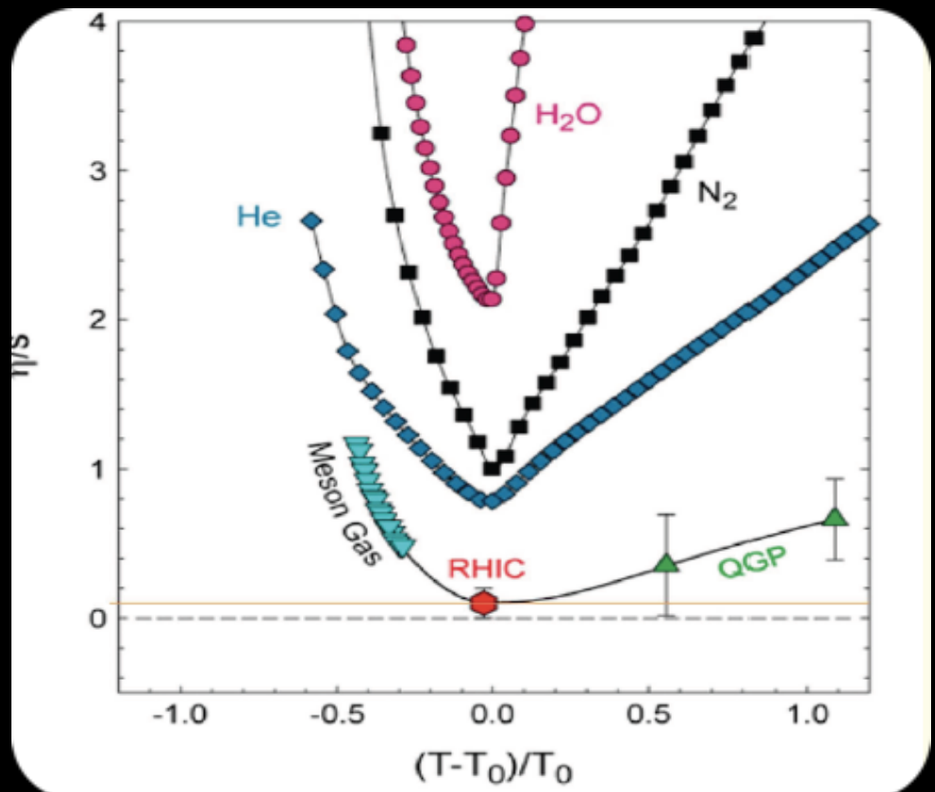


$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

$$v_2(p_T, \eta) = \langle cos[2(\varphi - \Psi_2)] \rangle$$

The “perfect liquid” at RHIC and LHC





The "perfect liquid" at RHIC and LHC

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Published online 19 April 2005 | Nature | doi:10.1038/news050418-5

News

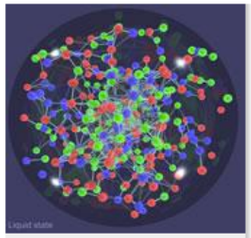
Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.



Quarks and gluons have formed a unexpected liquid. Click here to see animation.
© RHIC/BN

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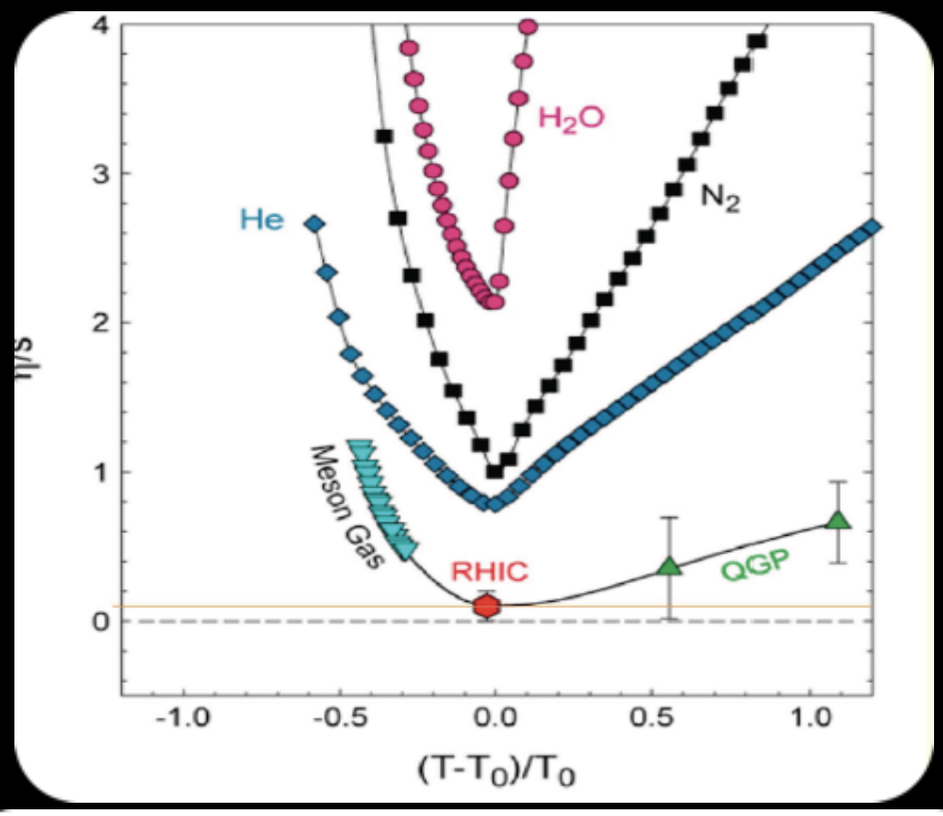

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Brookhaven National Laboratory's Relativistic Heavy Ion Collider

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Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

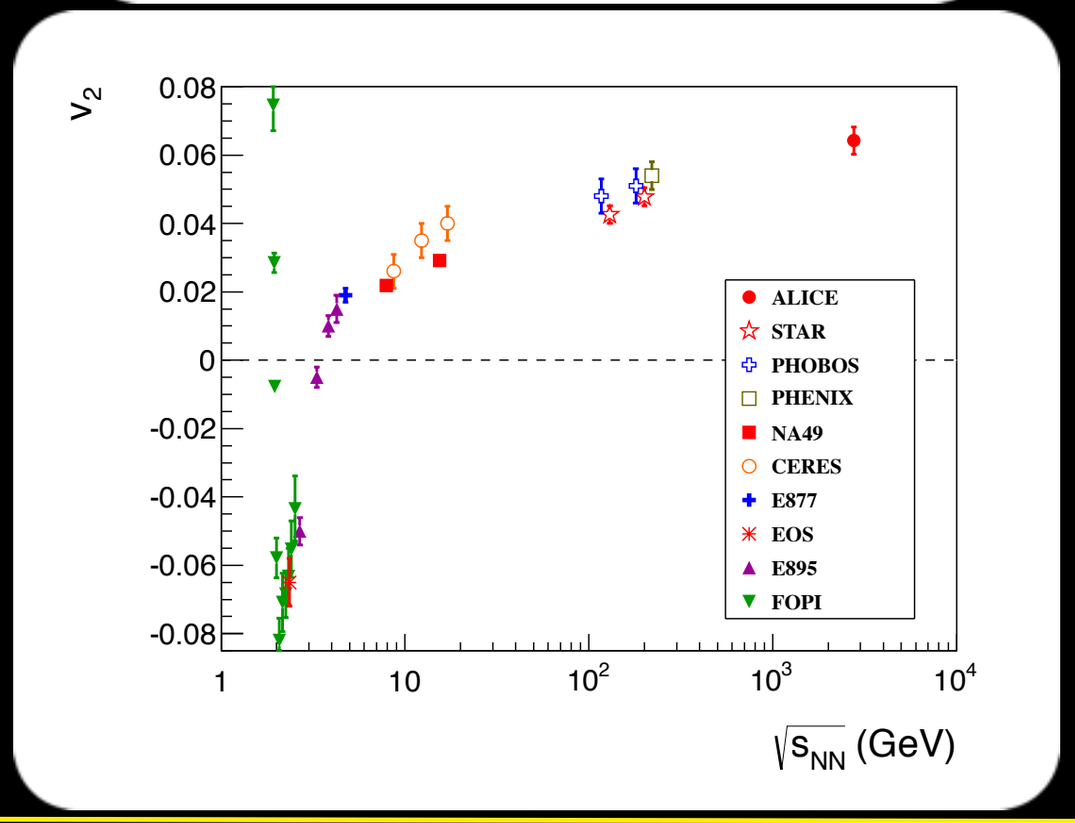
RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

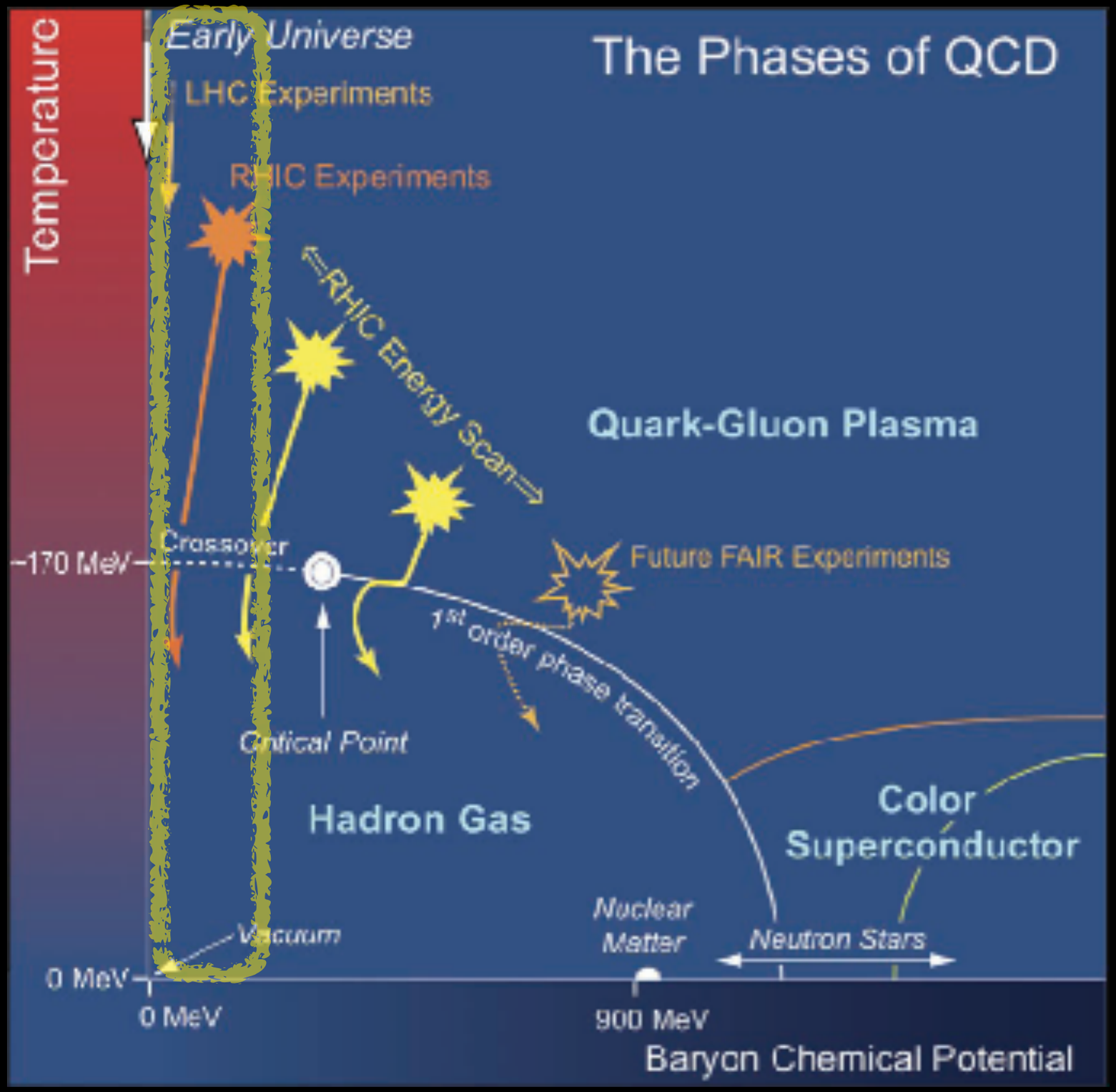
Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Other RHIC News
- First Indirect Evidence of So-Far Undetected Strange Baryons
- RHIC Featured in 'How The Universe Works' on the Science Channel
- A New Look for RHIC & Sharper View of QCD: Looking Back at the 2014 RHIC-AGS Users' Meeting
- RHIC Run 14: A Flawless 'Run of Firsts'



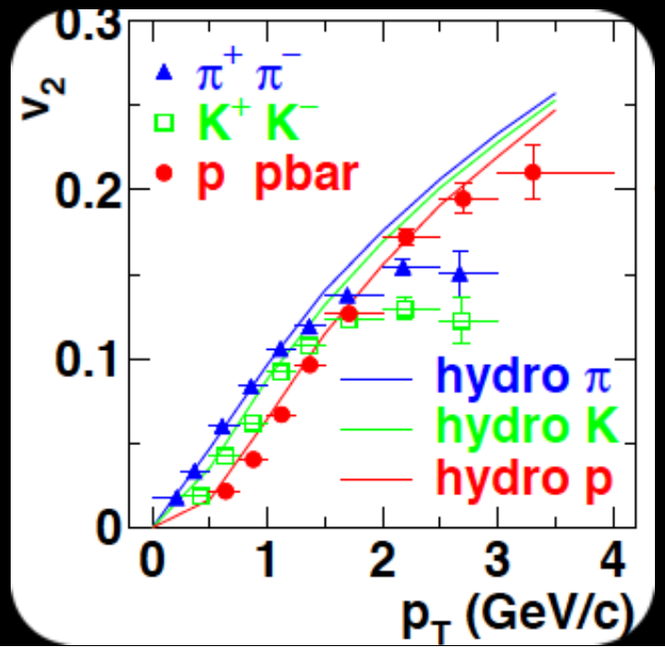
Probing the properties of the QGP

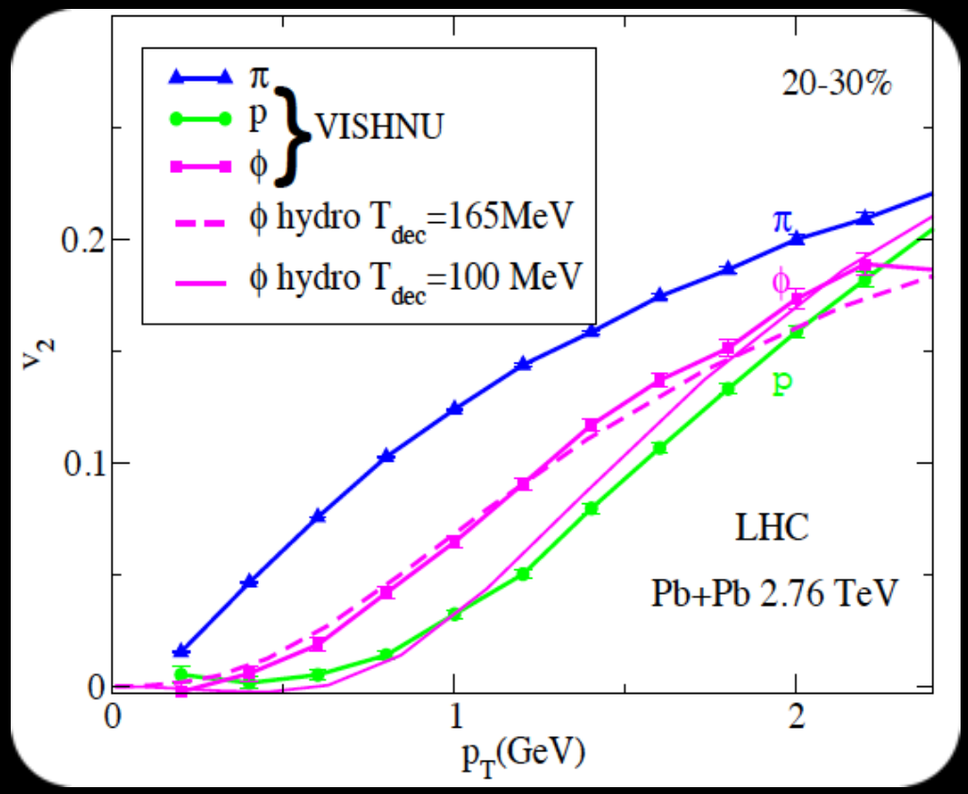


The three momentum scales: low p_T (p_T < 3 GeV/c)

- Mass ordering observed at low p_T at RHIC energies
  - ★ expected by hydrodynamic calculations

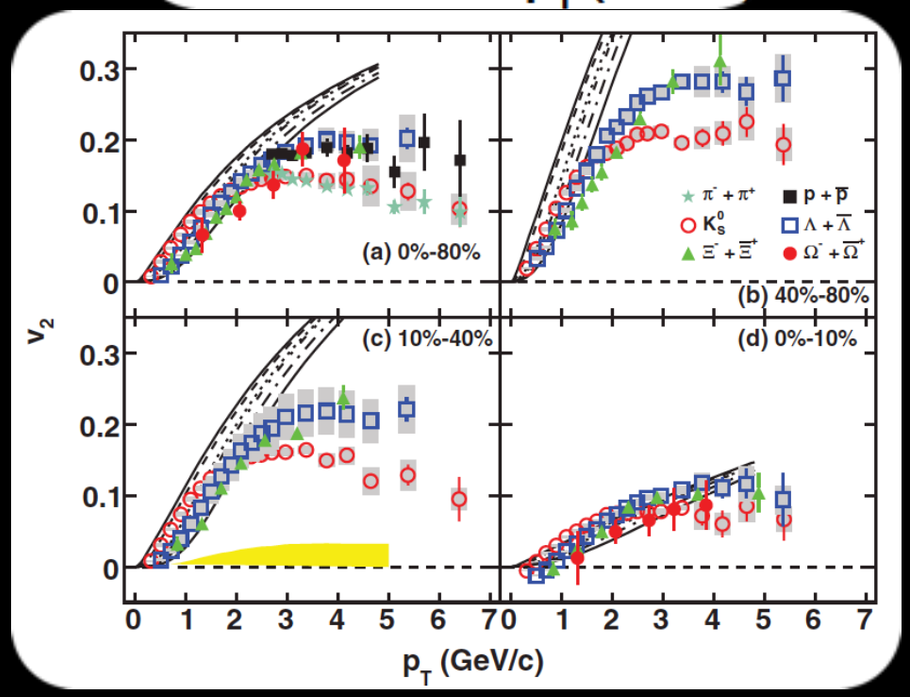
S. S. Adler *et al*. (PHENIX Collaboration), Phys. Rev. Lett. **91**, (2003) 182301





H. Song, S. Bass and U. Heinz arXiv:1311.0157 [nucl-th]

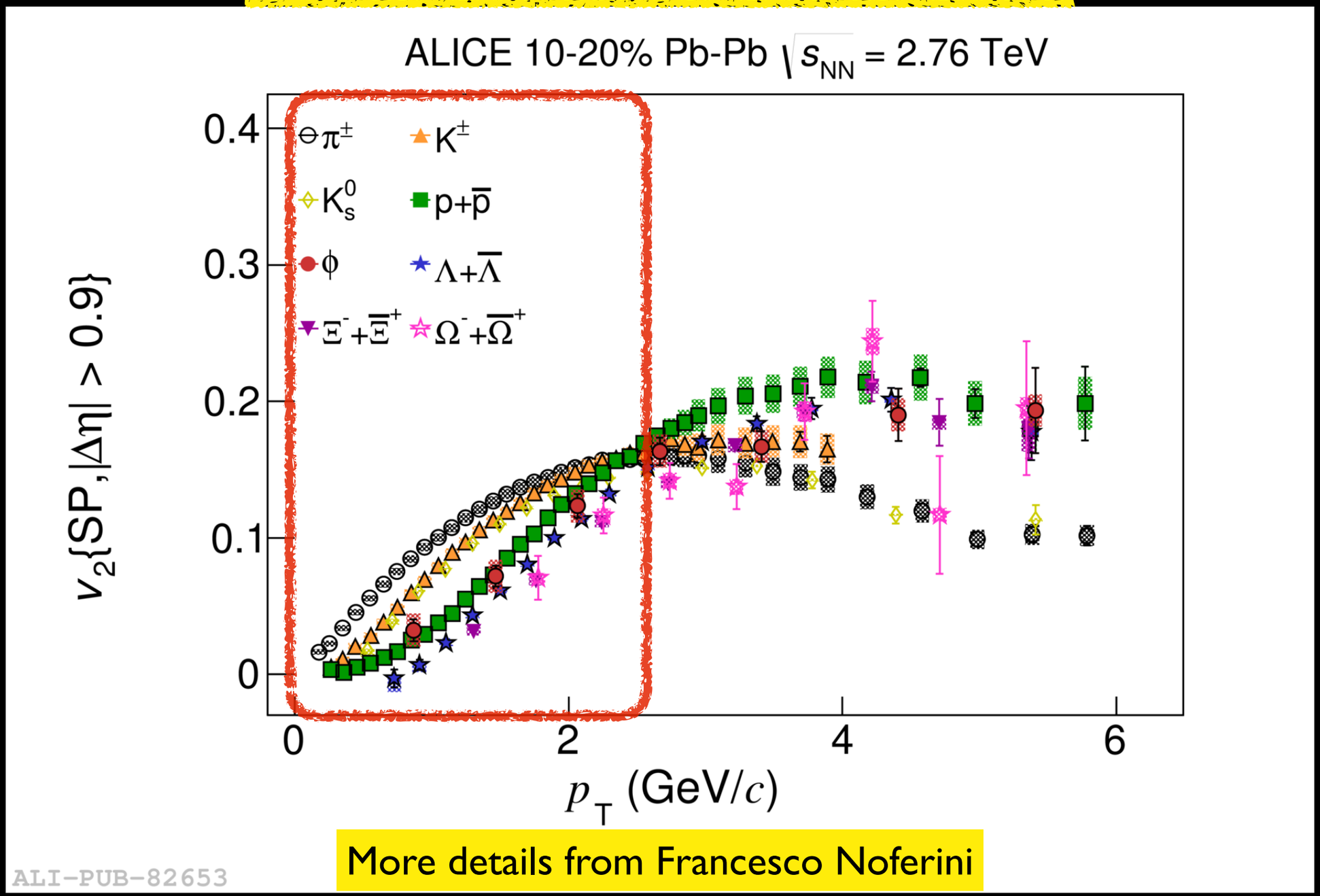
B. Abelev *et al*. (STAR Collaboration), Phys. Rev. **C77**, (2008) 054901



- New calculations expect the mass ordering to be violated

Mass ordering @ LHC

B. Abelev *et al*. (ALICE Collaboration), arXiv:1405.4632 [nucl-ex]

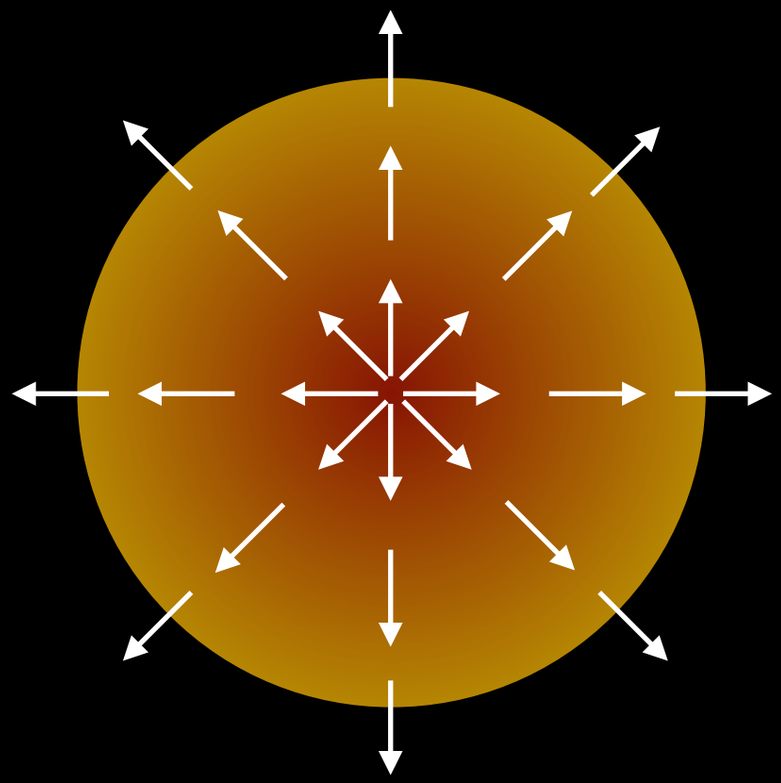


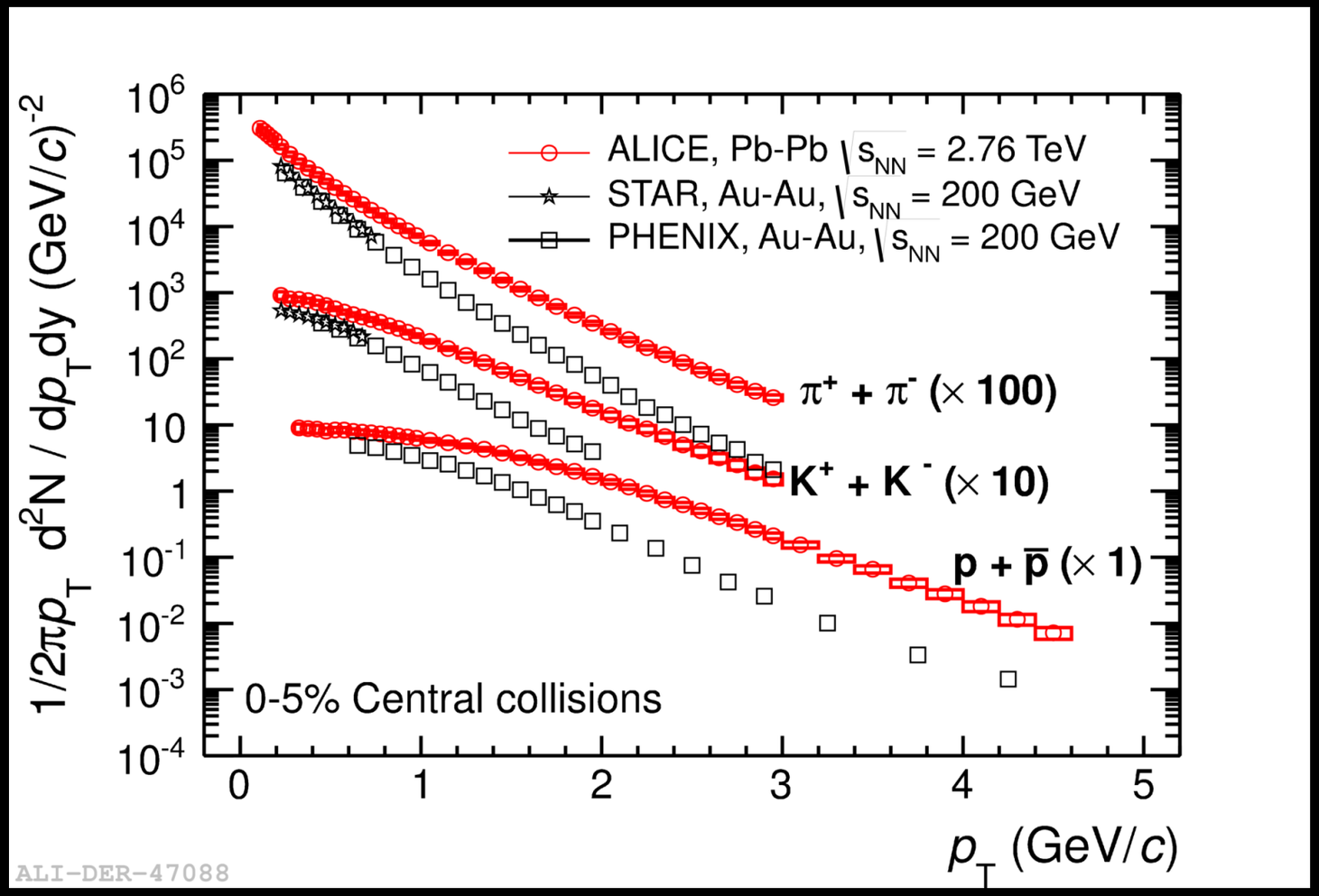
More details from Francesco Noferini

Low p_T (p_T < 3 GeV/c): mass ordering ➜ elliptic/radial flow interplay

How does mass ordering develop?

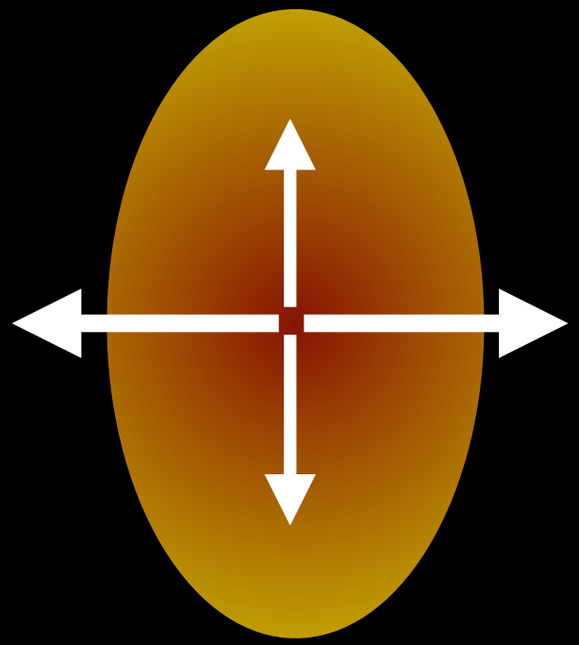
B. Abelev *et al*. (ALICE Collaboration), Phys. Rev. **C88**, (2013) 044910

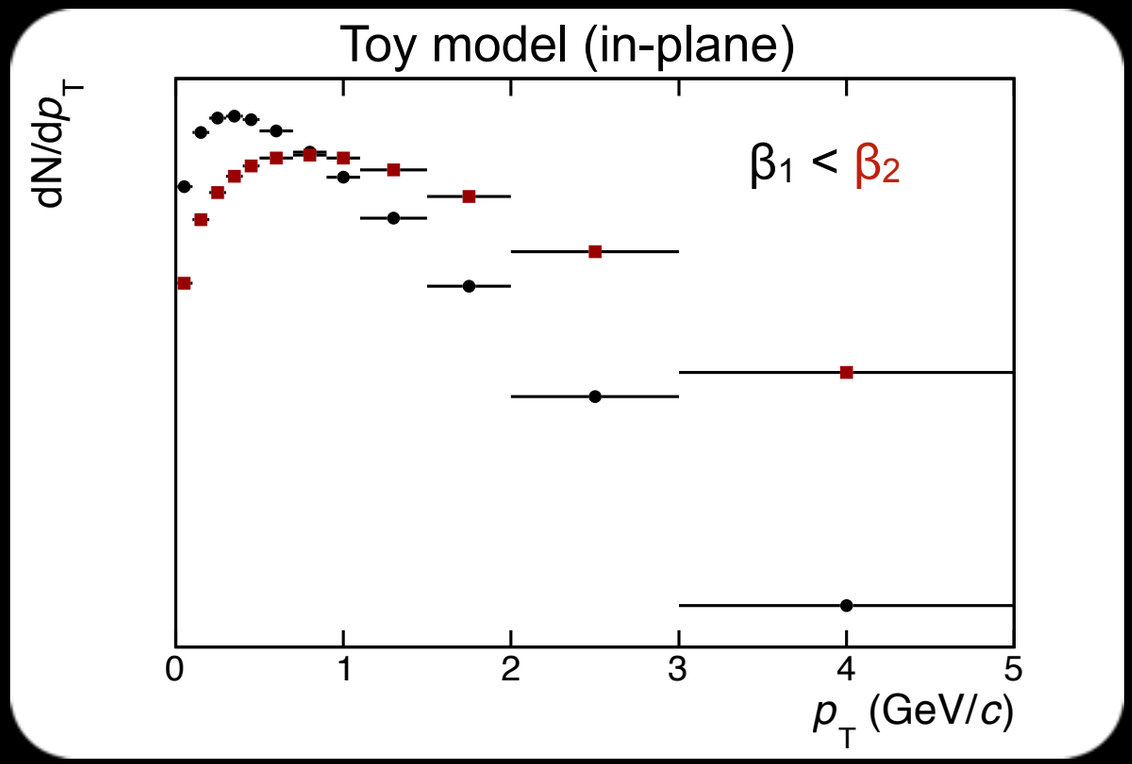


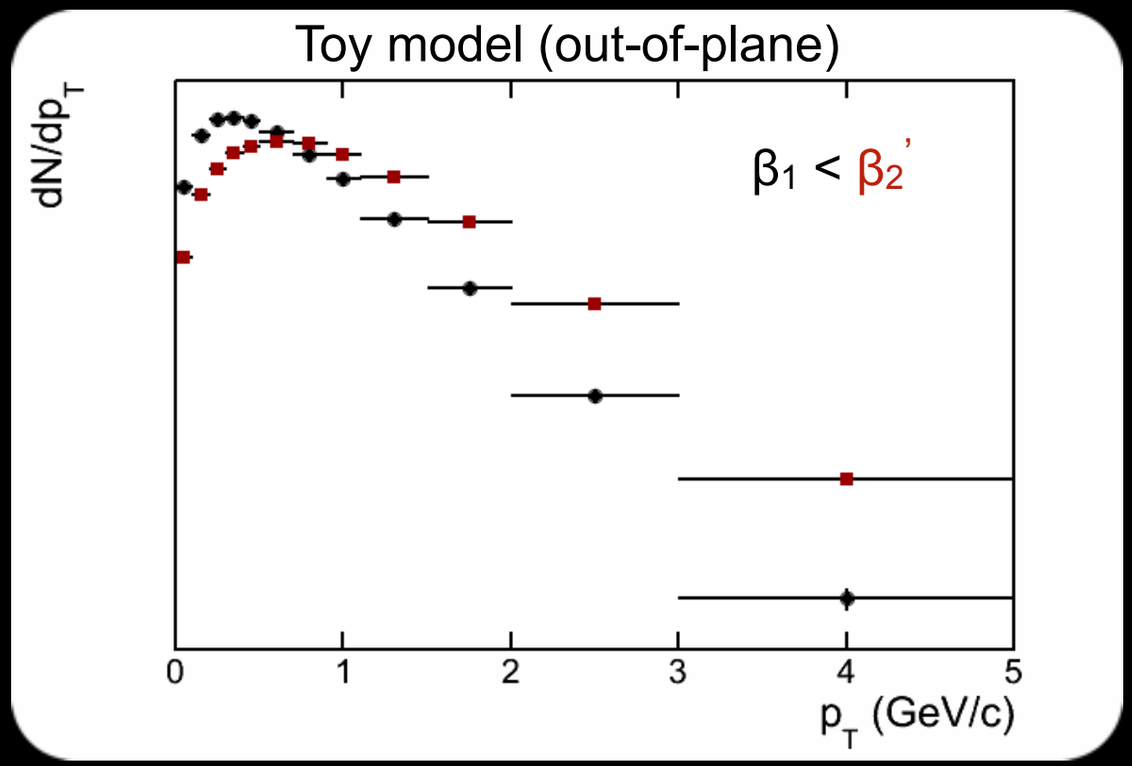


- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - ★ heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

How does mass ordering develop?







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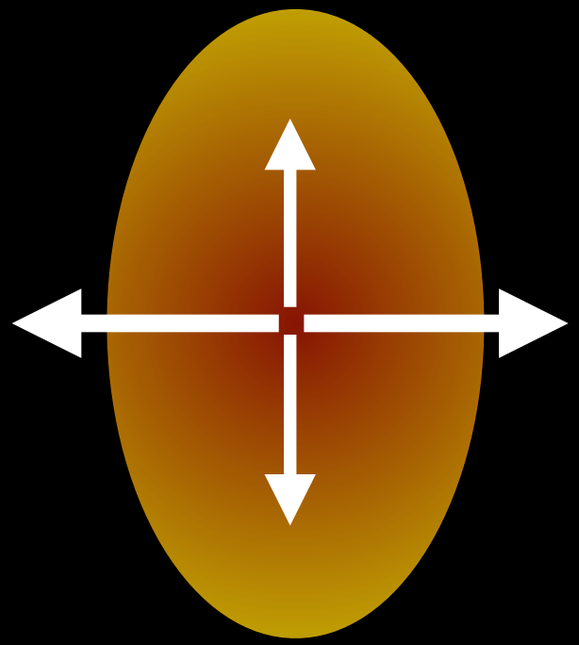
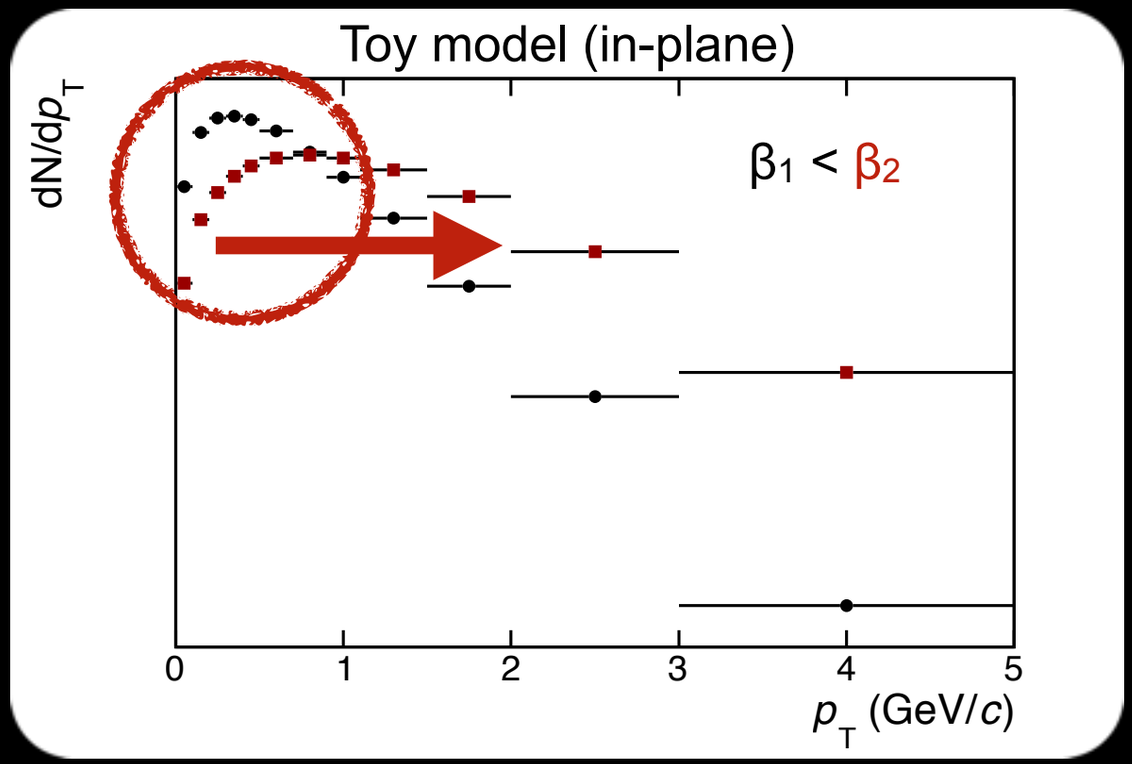
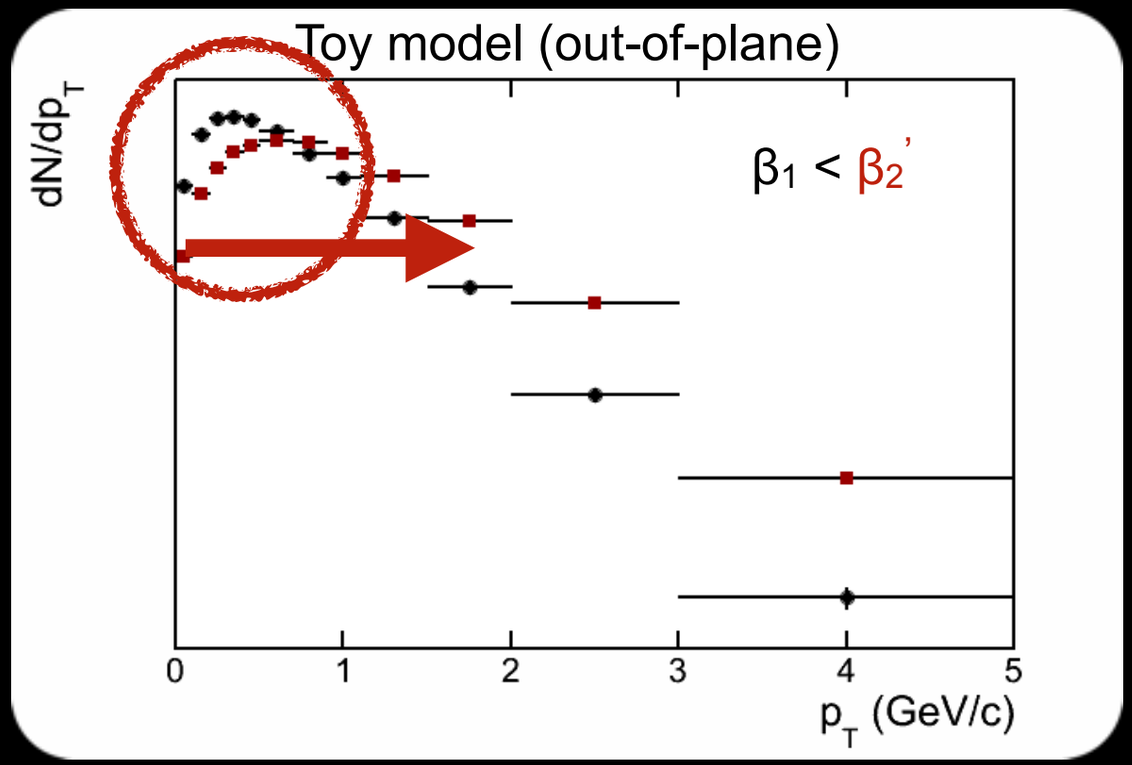




- Larger “push” in-plane than out-of-plane as a function of mass
  - ★ larger low-p_T depletion in-plane than out-of-plane ➞ lower v_2 in a mass dependent way



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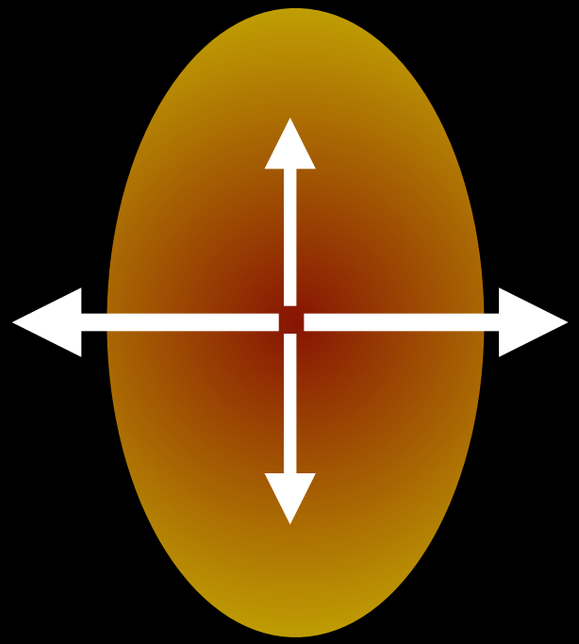

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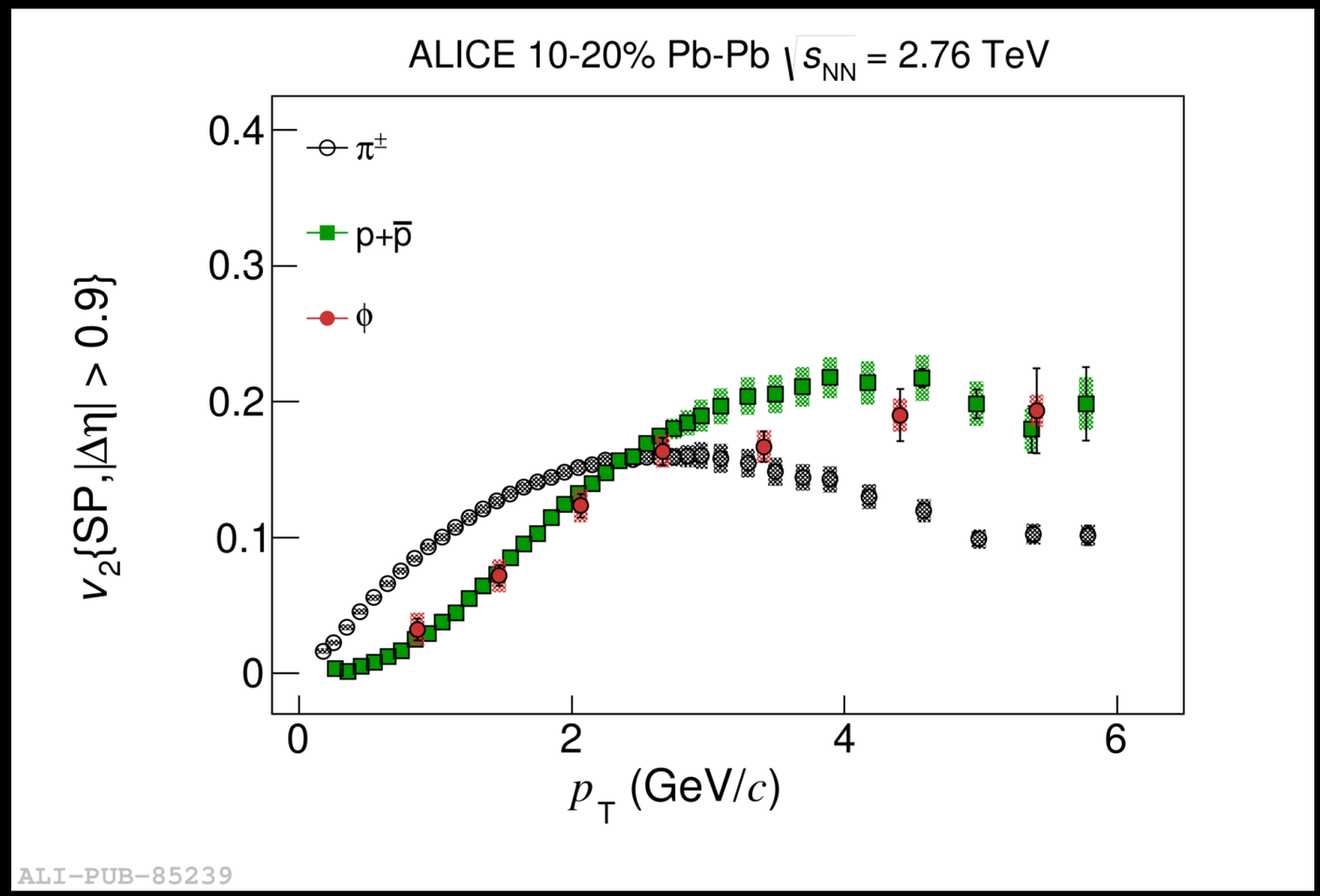
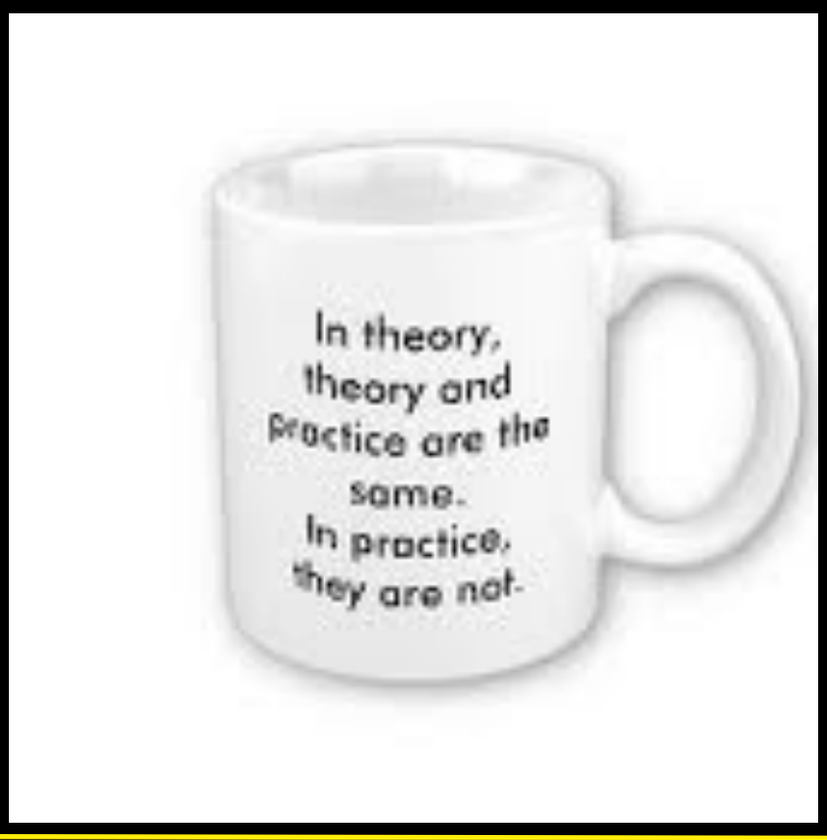
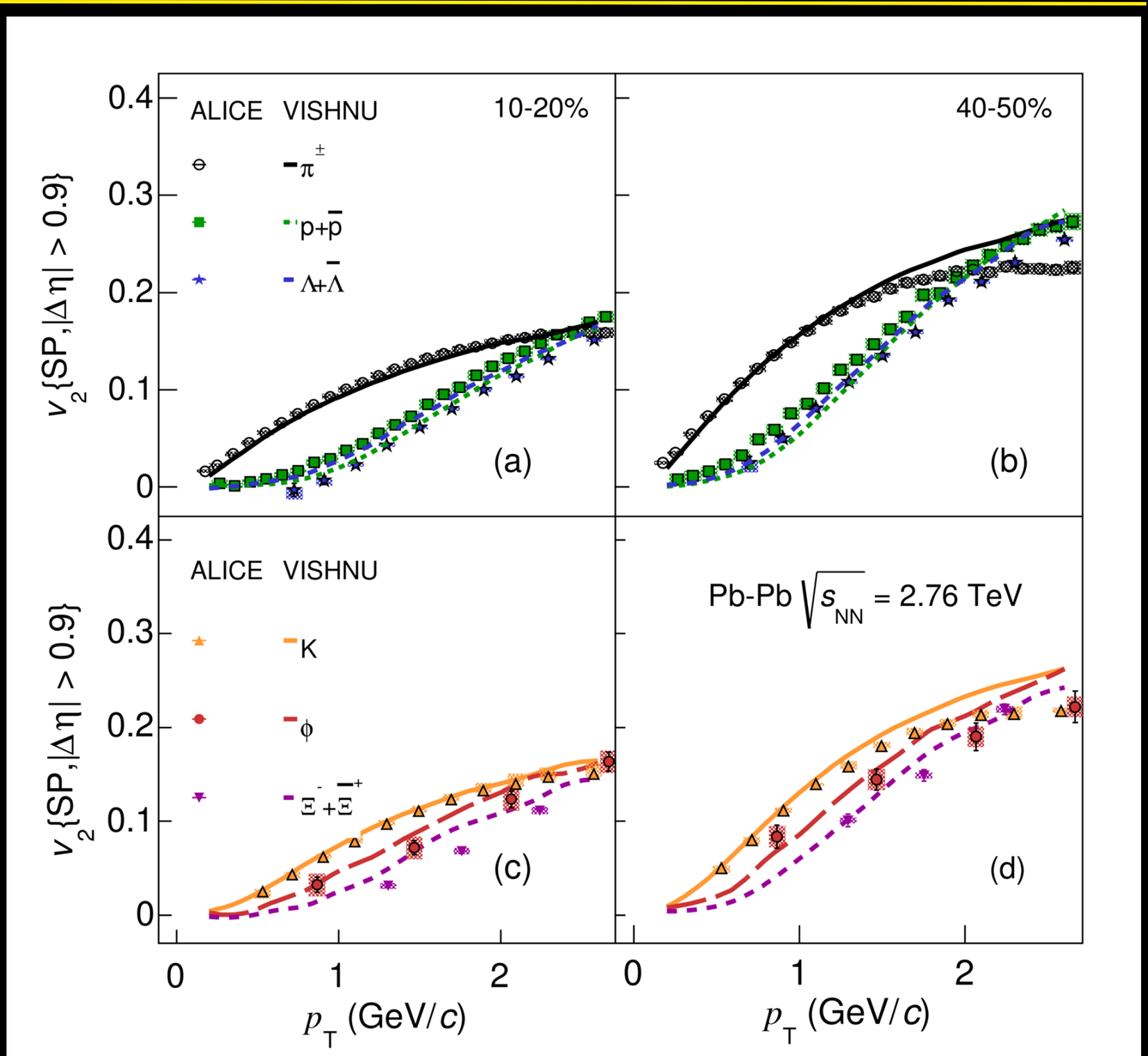


Heavy particles have lower v_2 at a fixed p_T than light particles

Comparison with hydrodynamic calculations

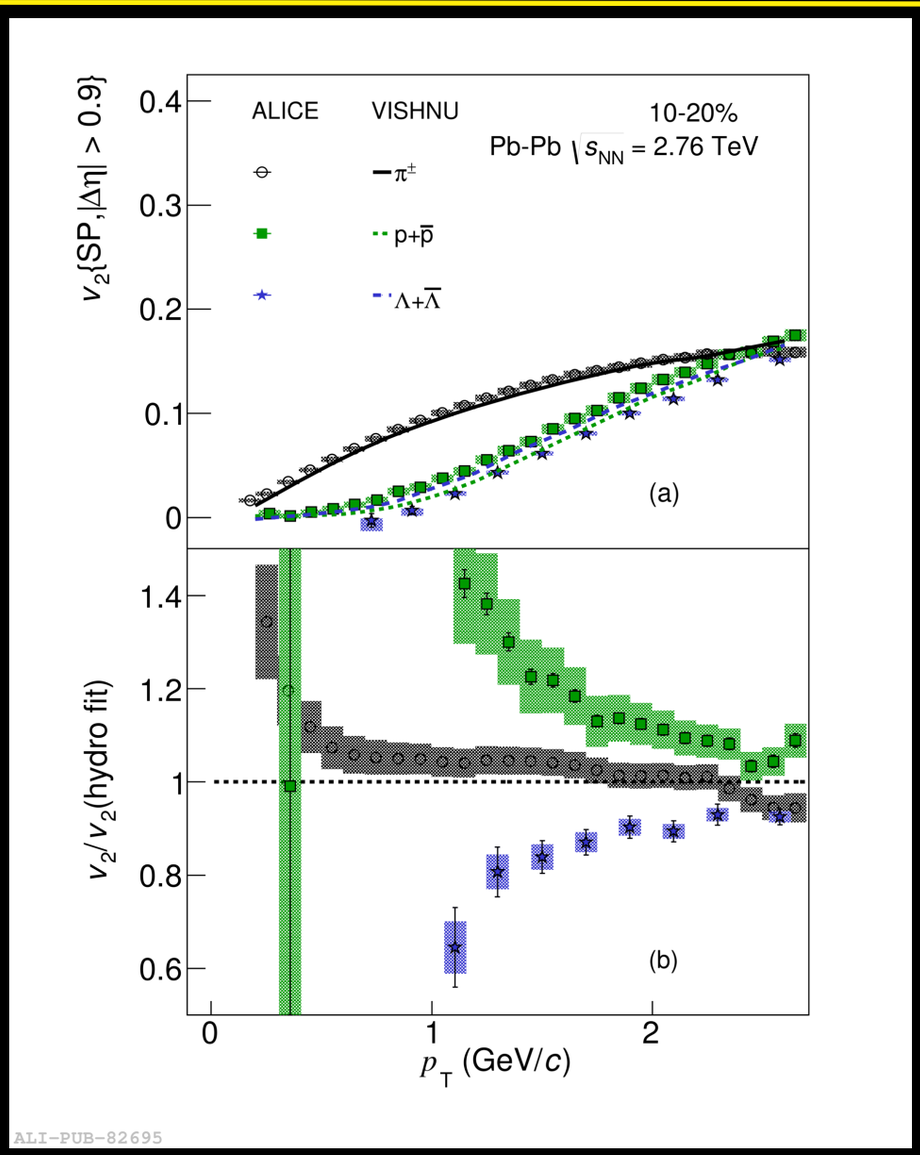
hydro curves from: H. Song, S. Bass and U. Heinz arXiv:1311.0157 [nucl-th]

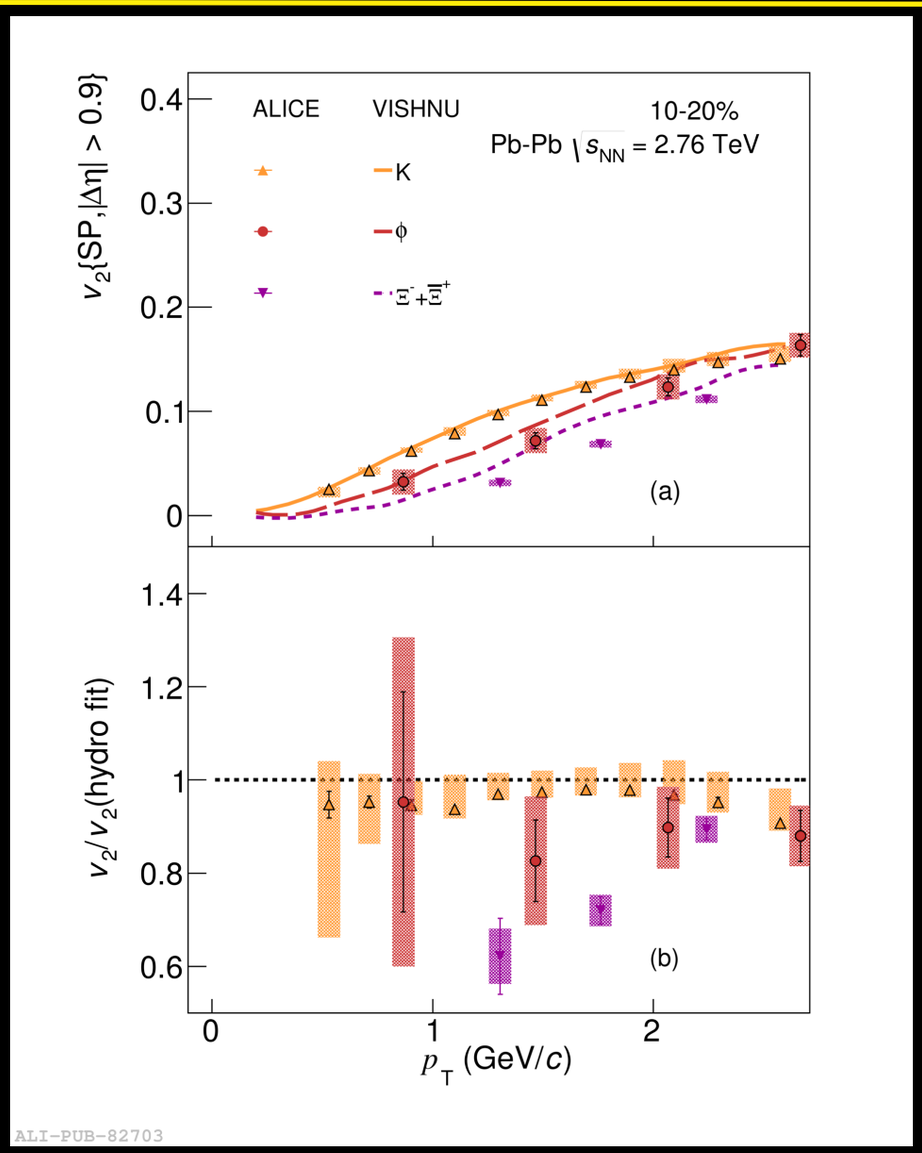




ALI-DER-85768

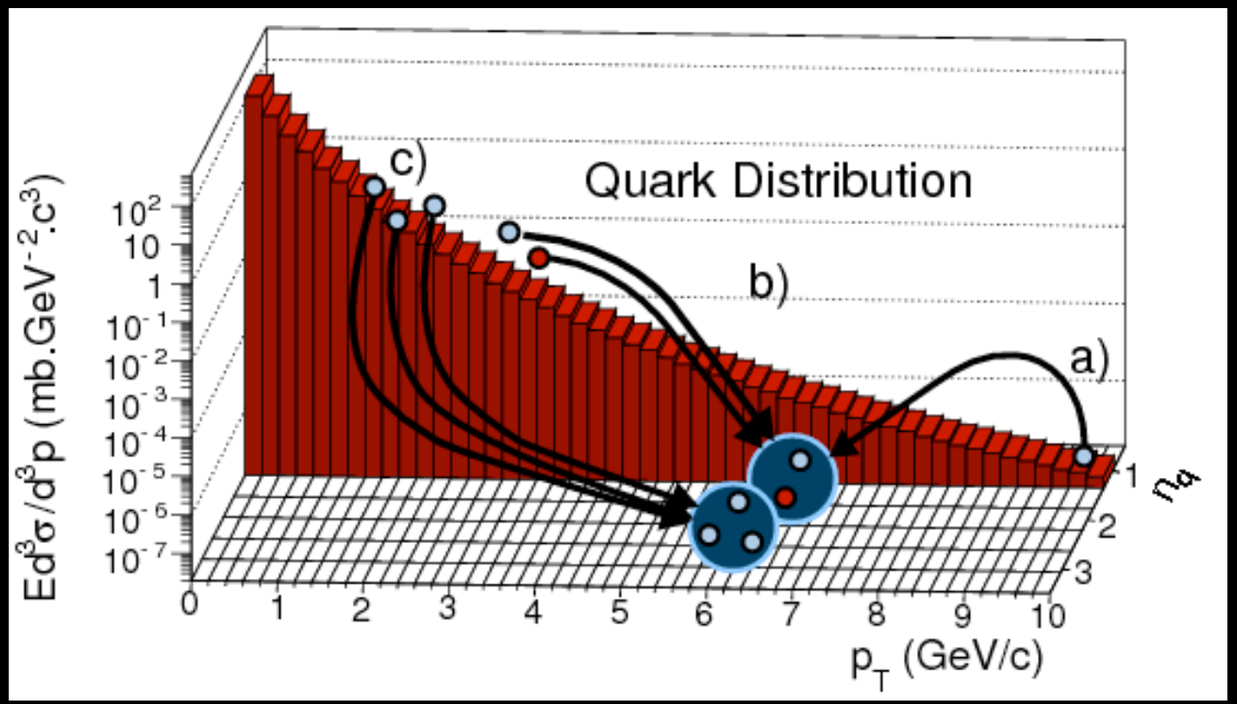
Looking at the details…: central events



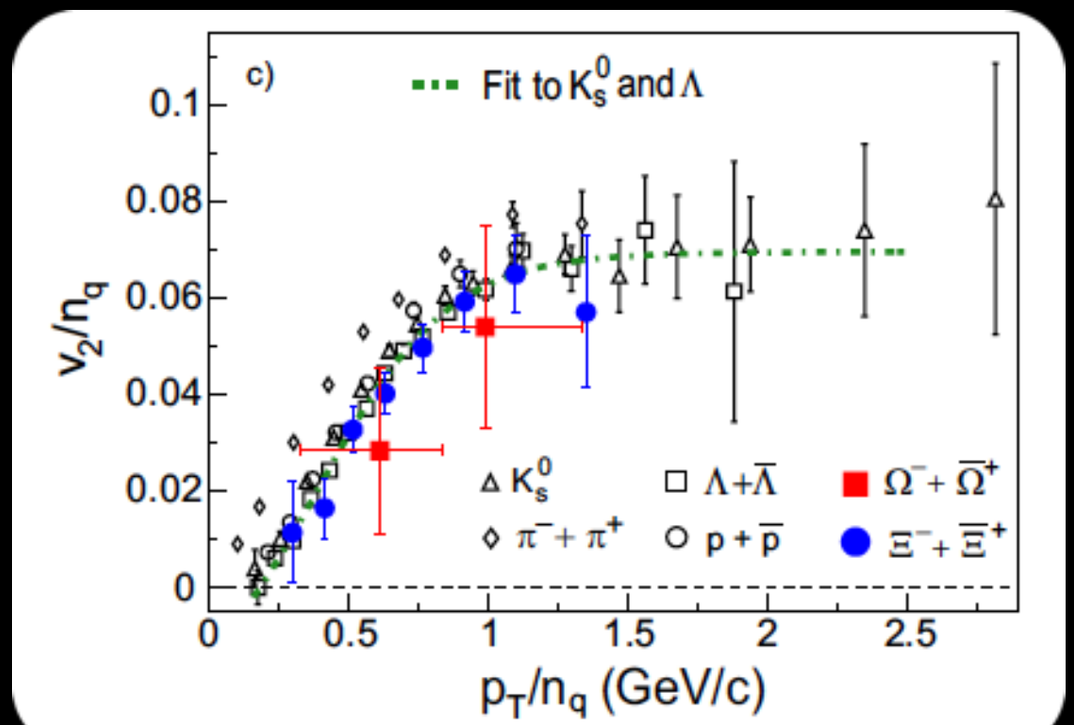


- Systematic deviations for the majority of particle species (with the exception of K)
- Proton v_2 underestimated (i.e. extra push expected in hydro) but Λ v_2 overestimated (i.e. less push expected in hydro)
- Mass ordering not preserved in VISHNU due to the hadronic cascade
  - not supported by ALICE data

The three momentum scales: intermediate p_T ($3 < p_T < 6$ GeV/c)



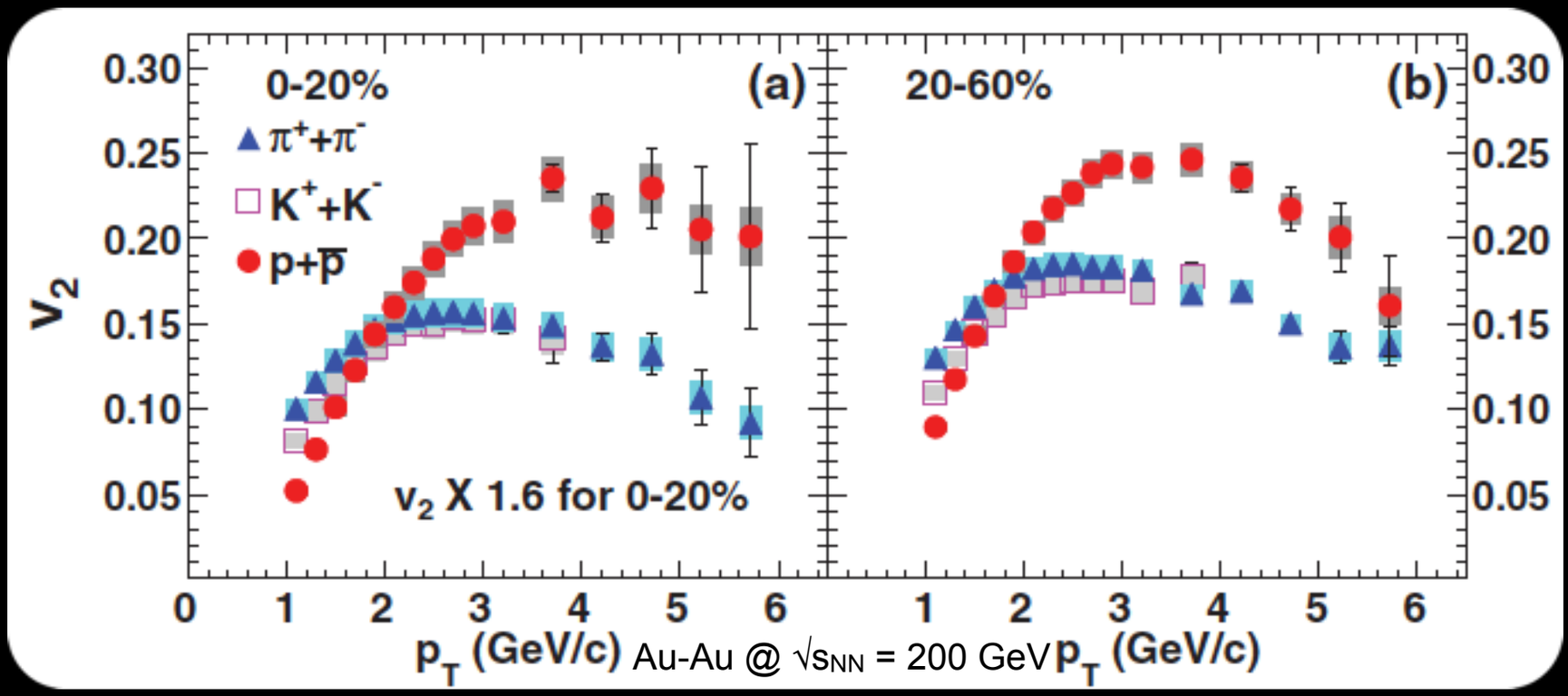
- Number of constituent quark (NCQ) scaling holding with good accuracy at RHIC
  - ★ quarks coalesce forming hadrons?
  - ★ NCQ scaling was considered as "evidence" of partonic degrees of freedom



J. Adams *et al*., (STAR Collaboration), Nucl.Phys. **A757** (2005) 102
K. Adcox *et al*., (PHENIX Collaboration), Nucl. Phys. **A757**, (2005) 184

Deviations from the universal scaling at RHIC

A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. **C85**, (2012) 064914



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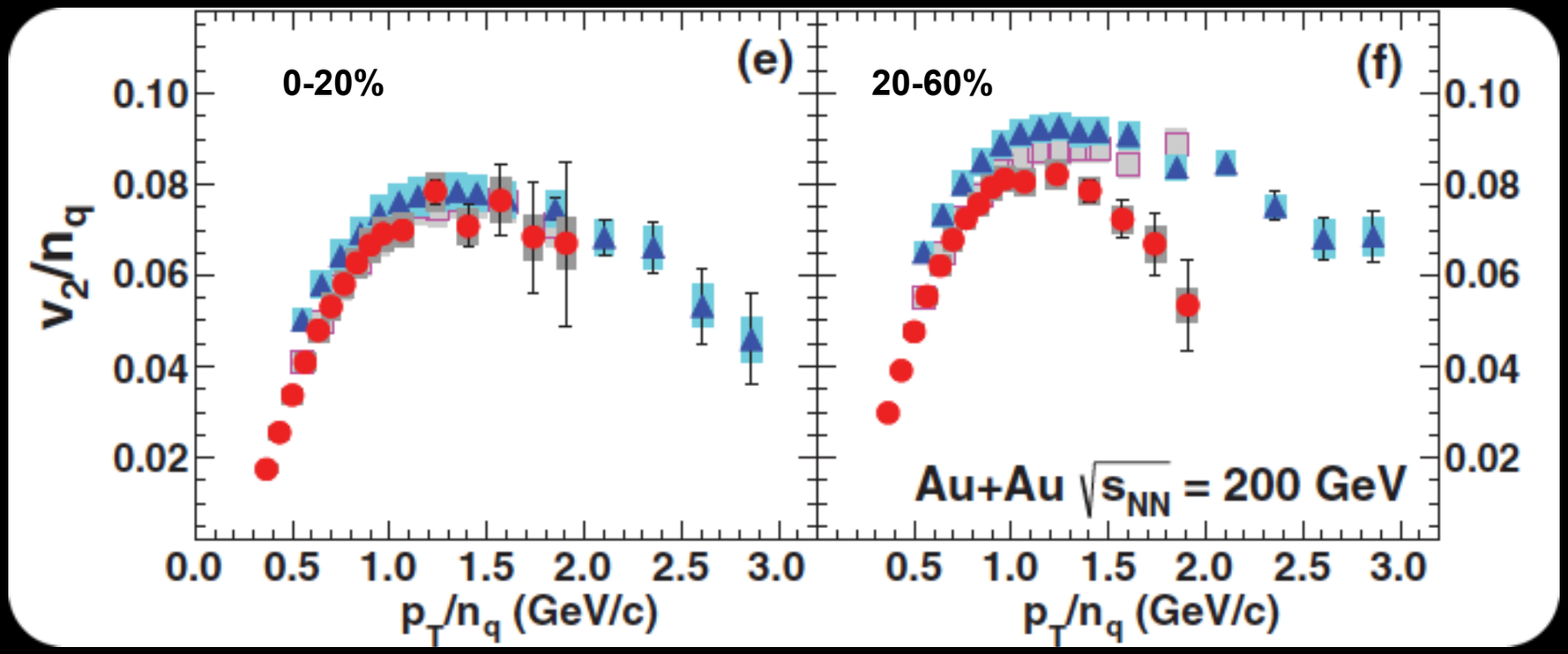
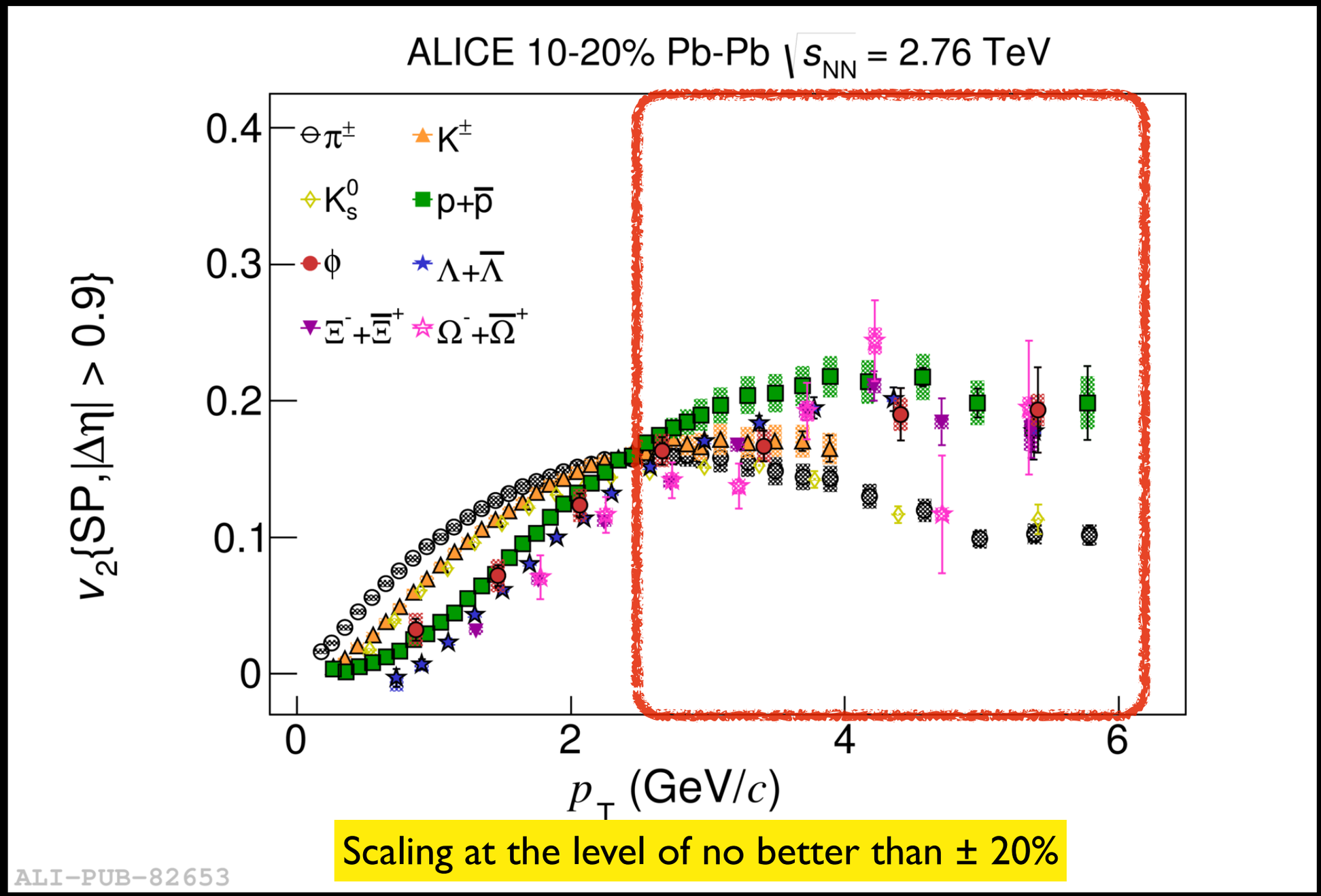


Deviations for $p_T/n_q > 1$ GeV/c depend on centrality

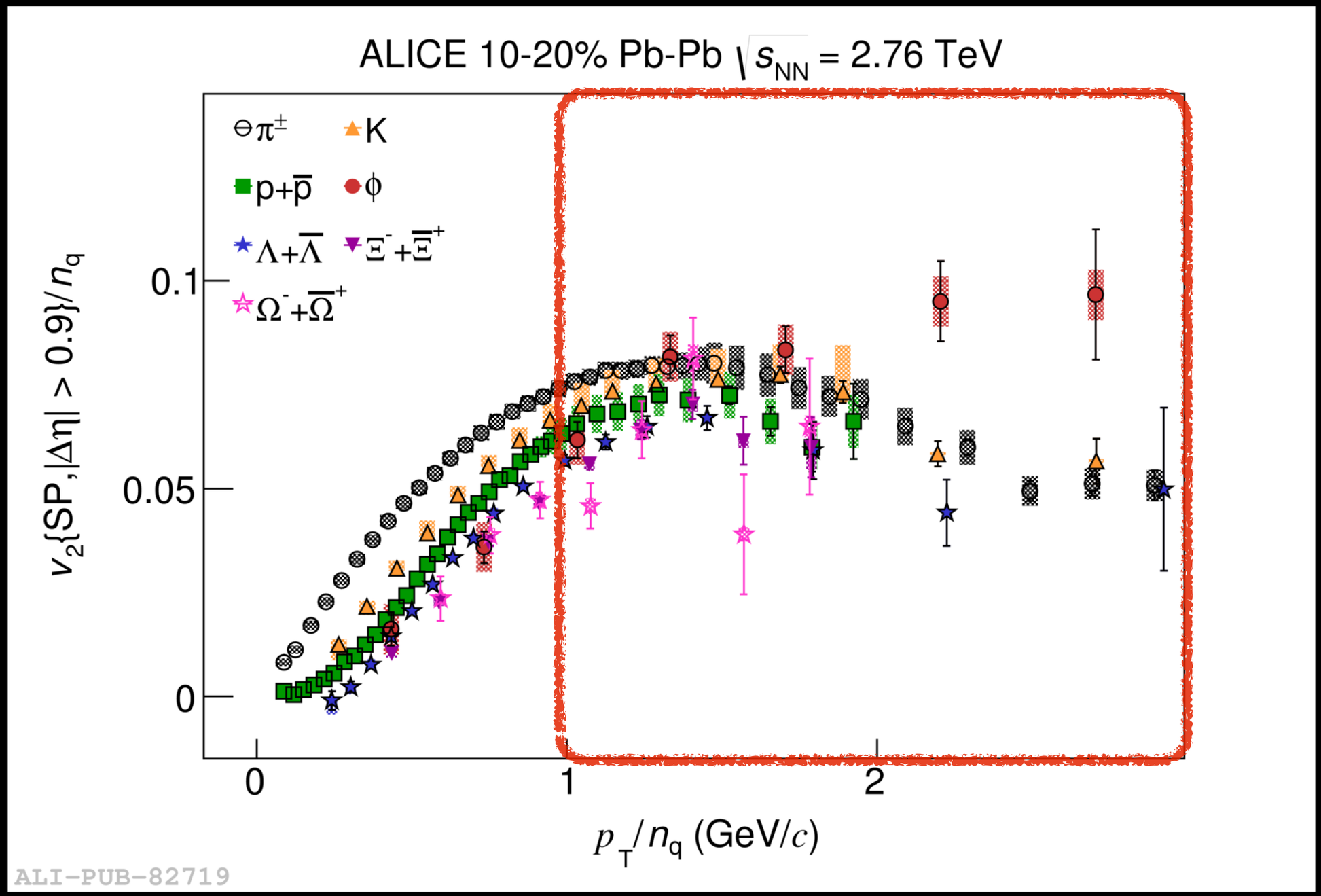
Scaling properties at the LHC



Scaling at the level of no better than ± 20%

- Intermediate p_T ($3 < p_T < 6$ GeV/c): ~grouping based on type (mesons/baryons)

Scaling properties at the LHC



Scaling at the level of no better than ± 20%

The special role of the φ-meson

- Important test of:
  - ★ mass ordering at low p_T
  - ★ the particle type grouping at intermediate p_T

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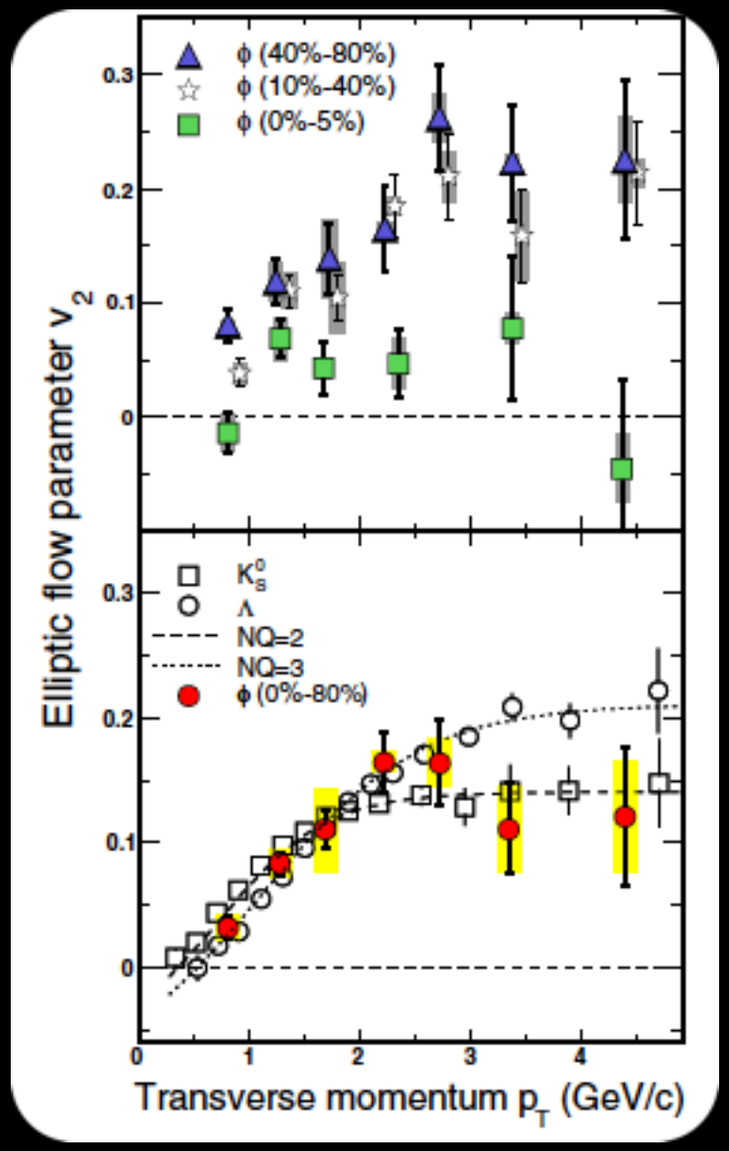
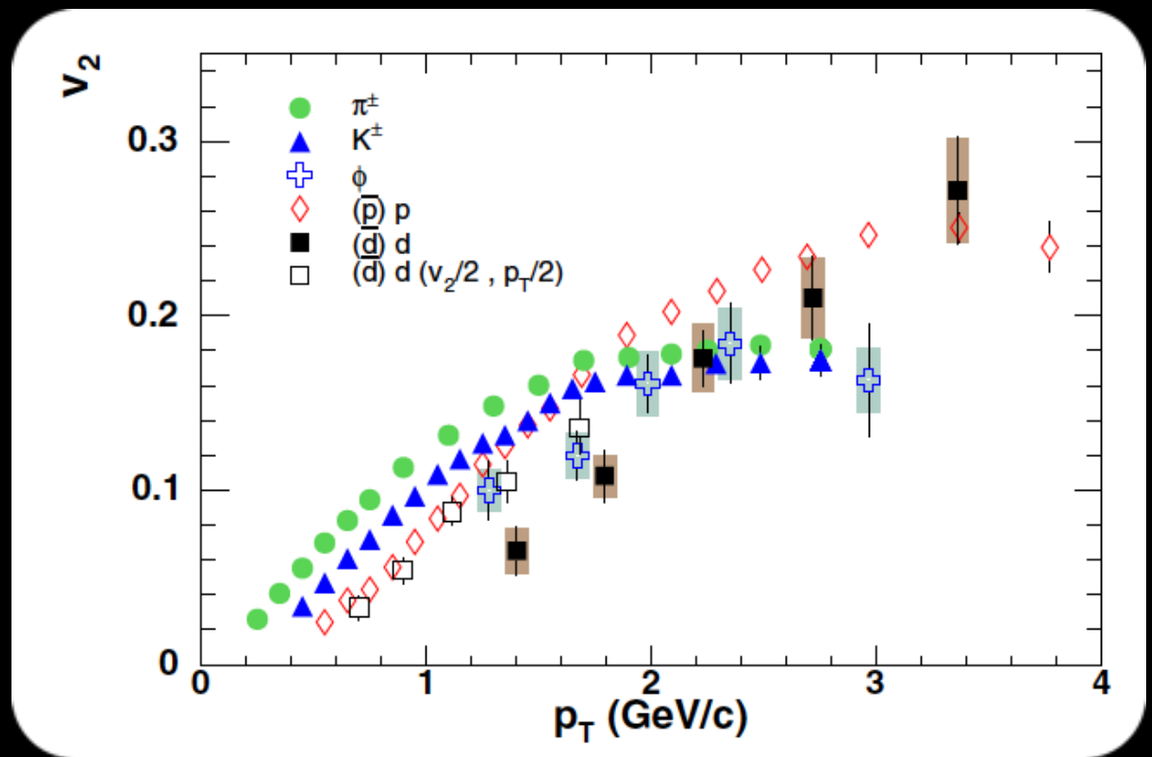
B. Abelev *et al.*, (STAR Collaboration), Phys. Rev. Lett. 99, (2007) 112301



S. Afanasiev *et al.*, (PHENIX Collaboration), Phys. Rev. Lett. **99**, (2007) 052301



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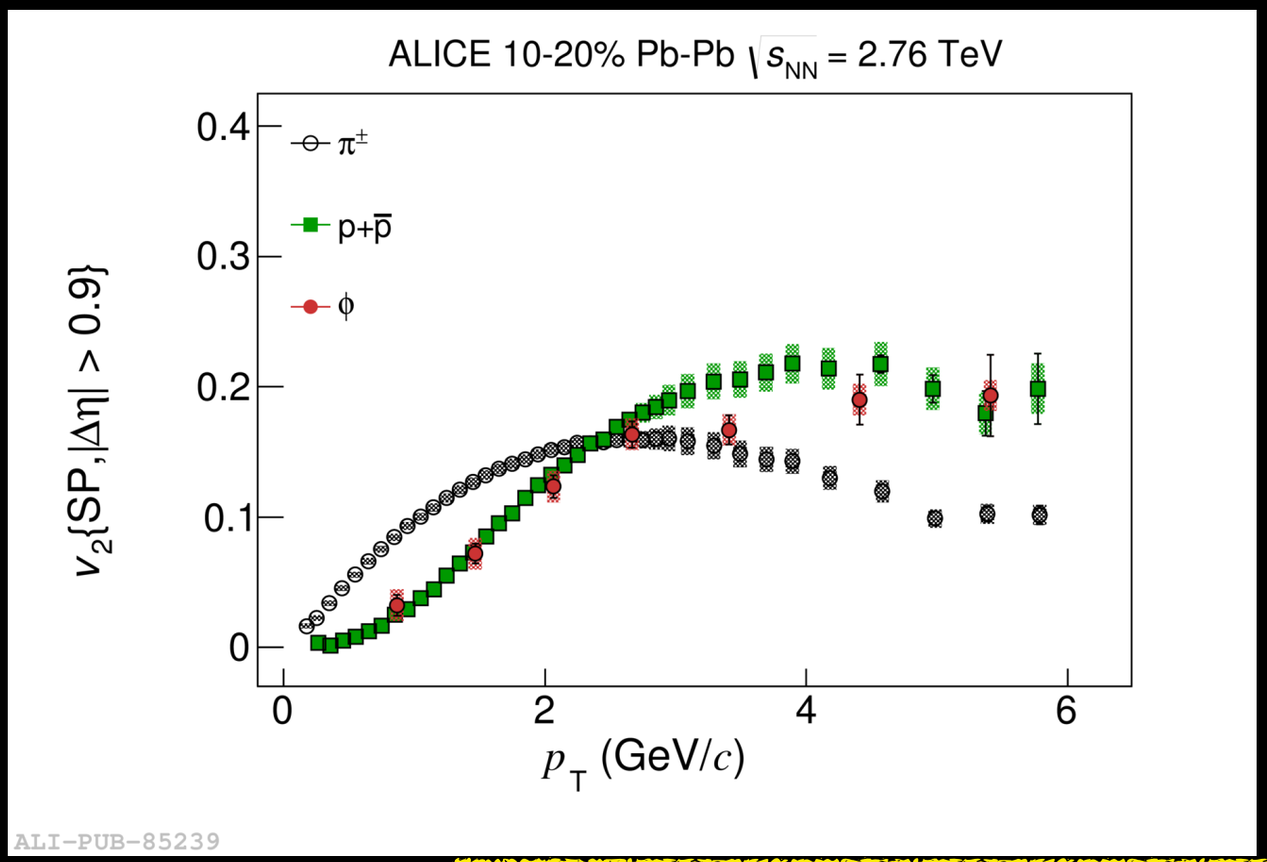

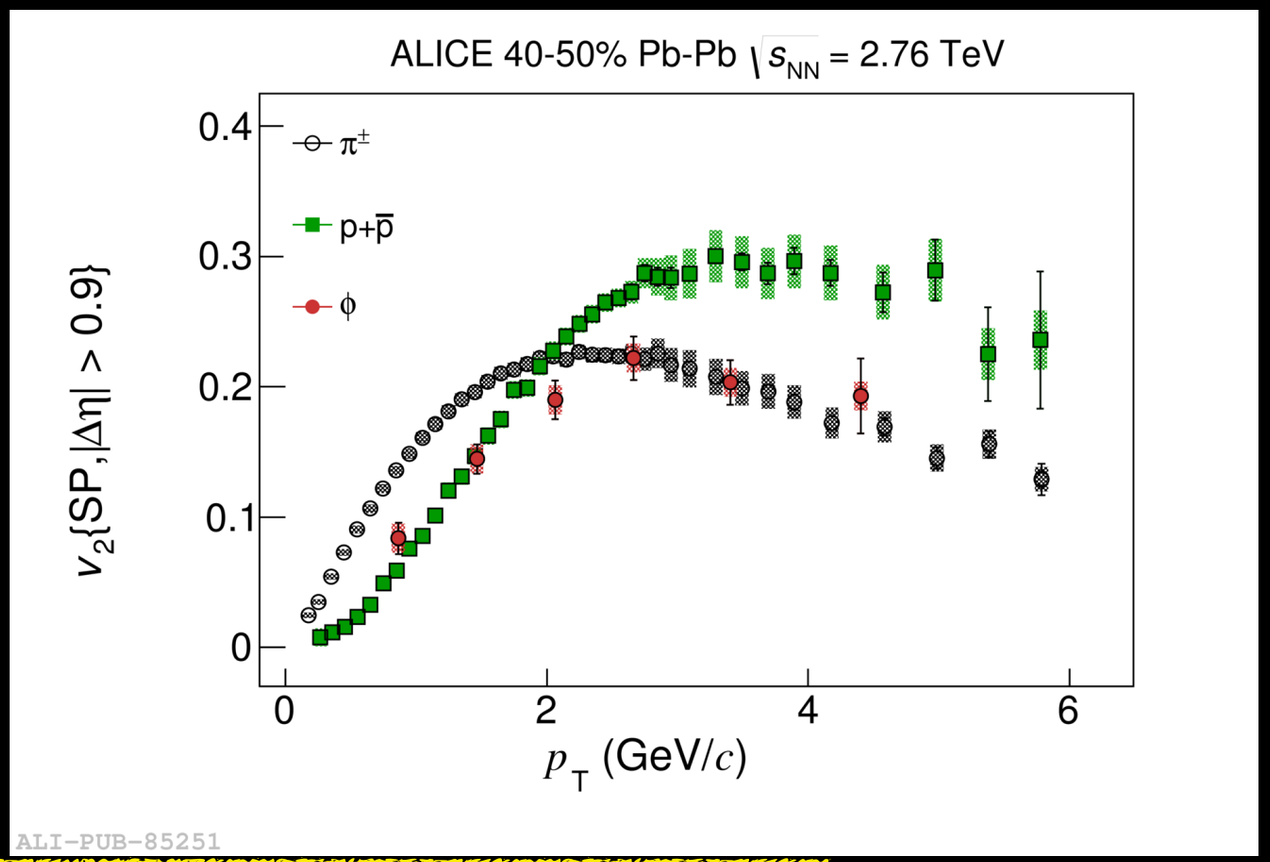

- At low p_T (p_T < 3 GeV/c): mass ordering ➜ elliptic/radial flow interplay
  - ★ First bins could hint to a different ordering? Still inconclusive…
- Intermediate p_T (3 < p_T < 6 GeV/c) the φ-meson follows
  - ★ the baryon band for central events
  - ★ the meson band for peripheral events

The special role of the φ-meson

- Important test of:
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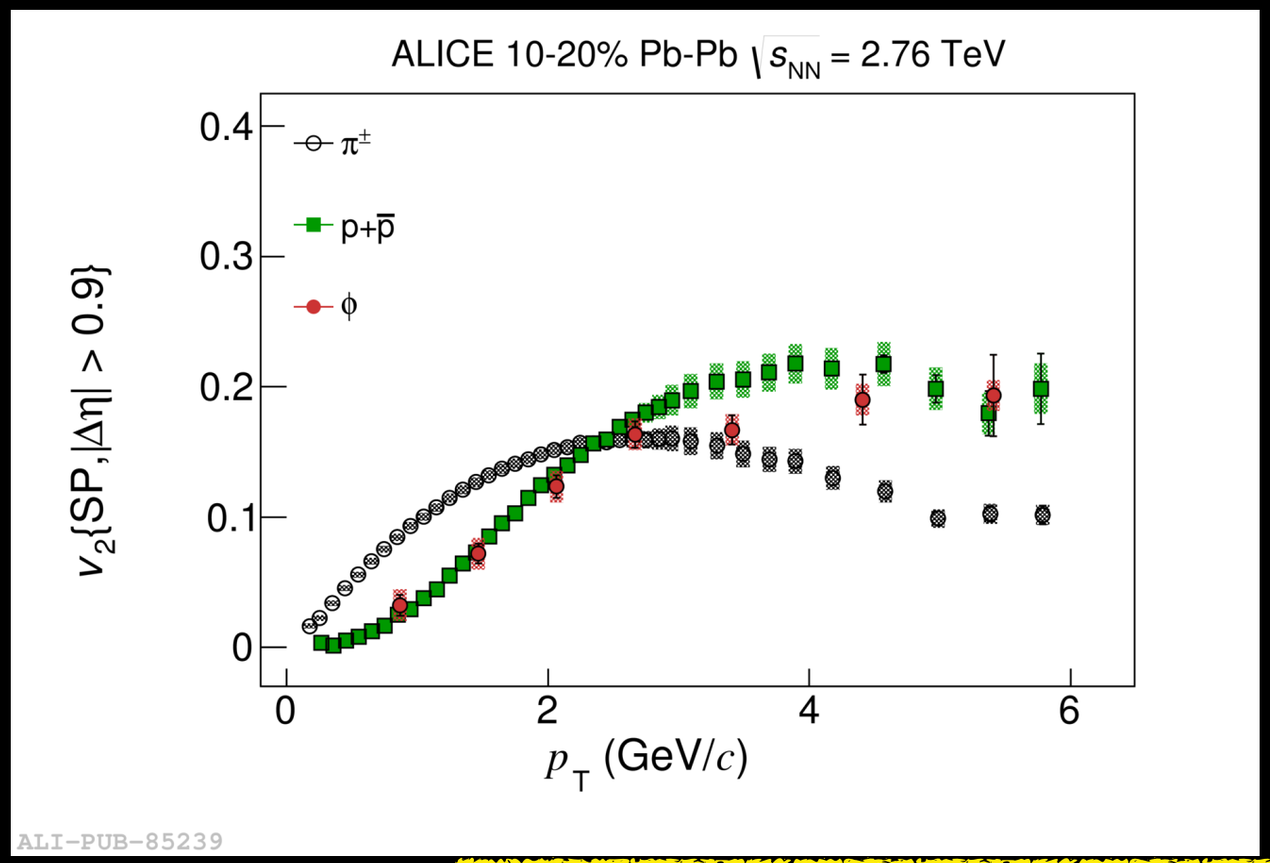
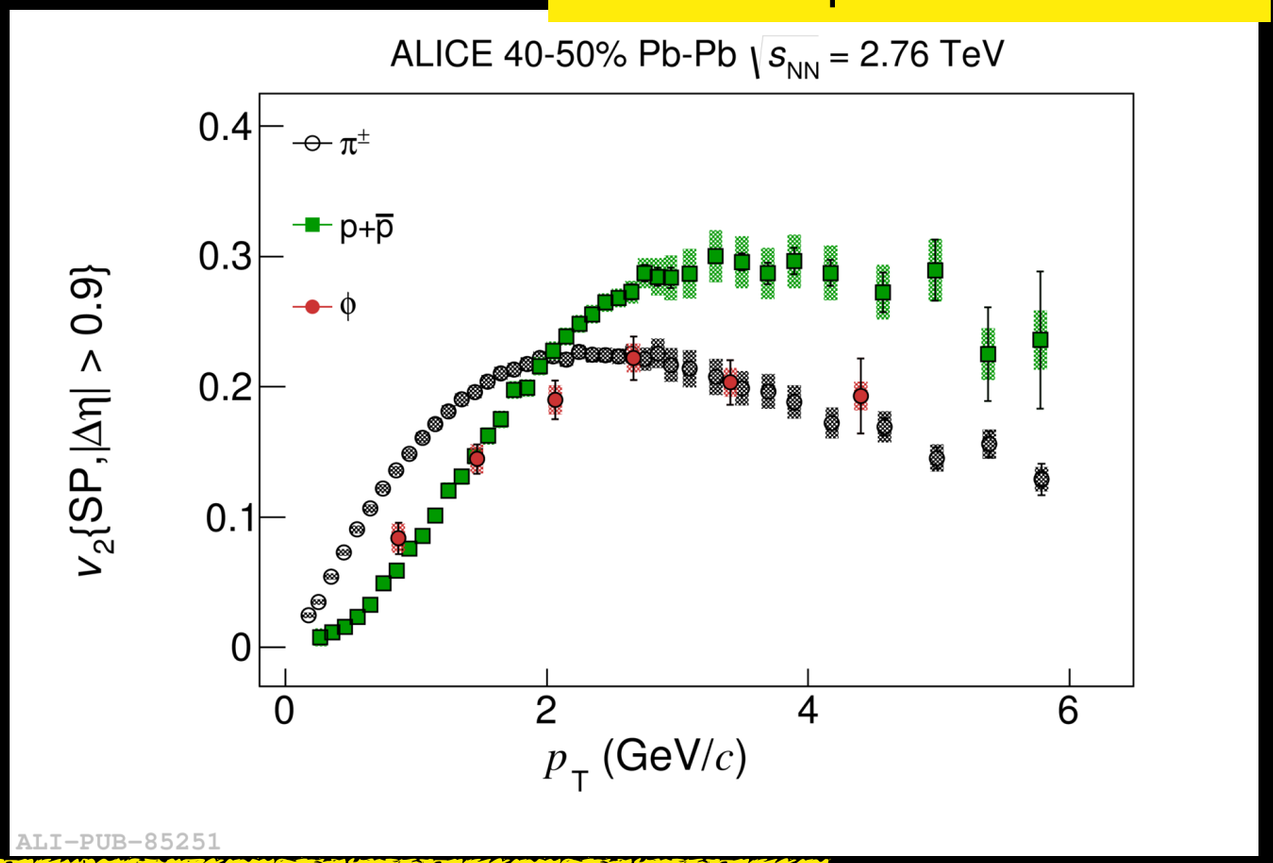
  - ★ the particle type grouping at intermediate p_T

Mass effect also at the intermediate p_T range! Challenges the coalescence picture





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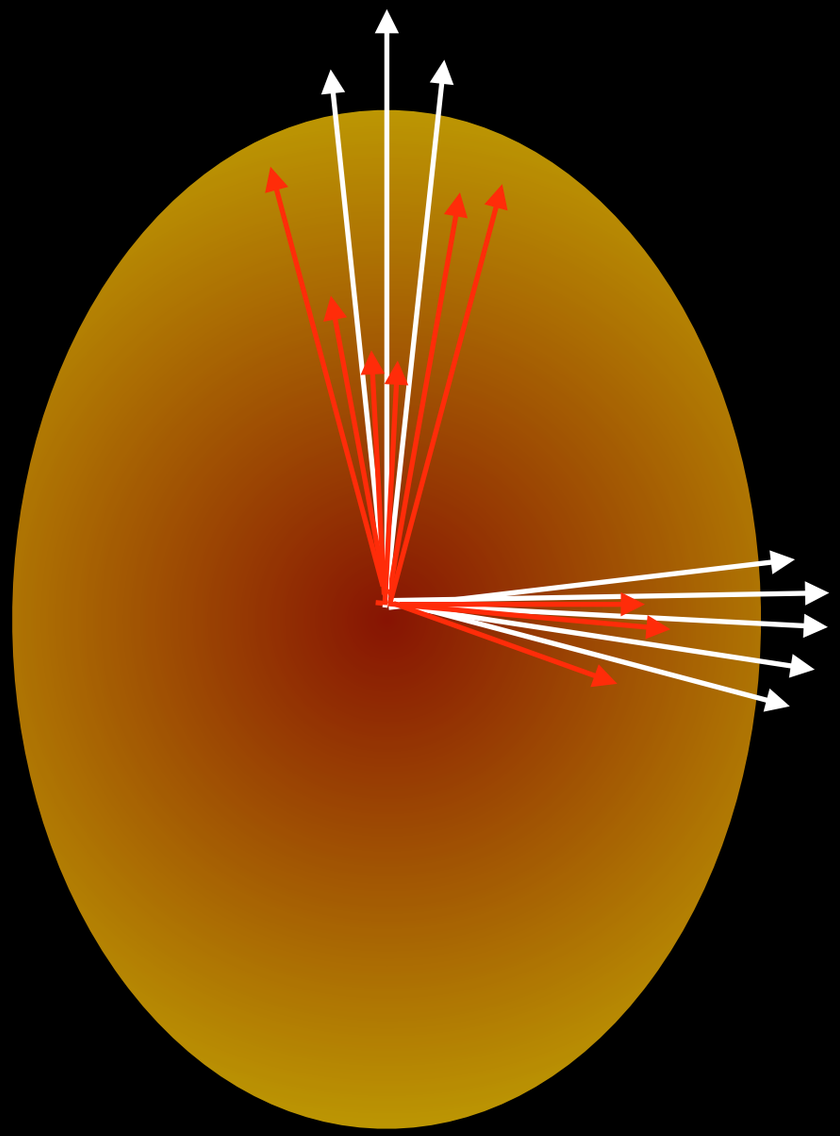
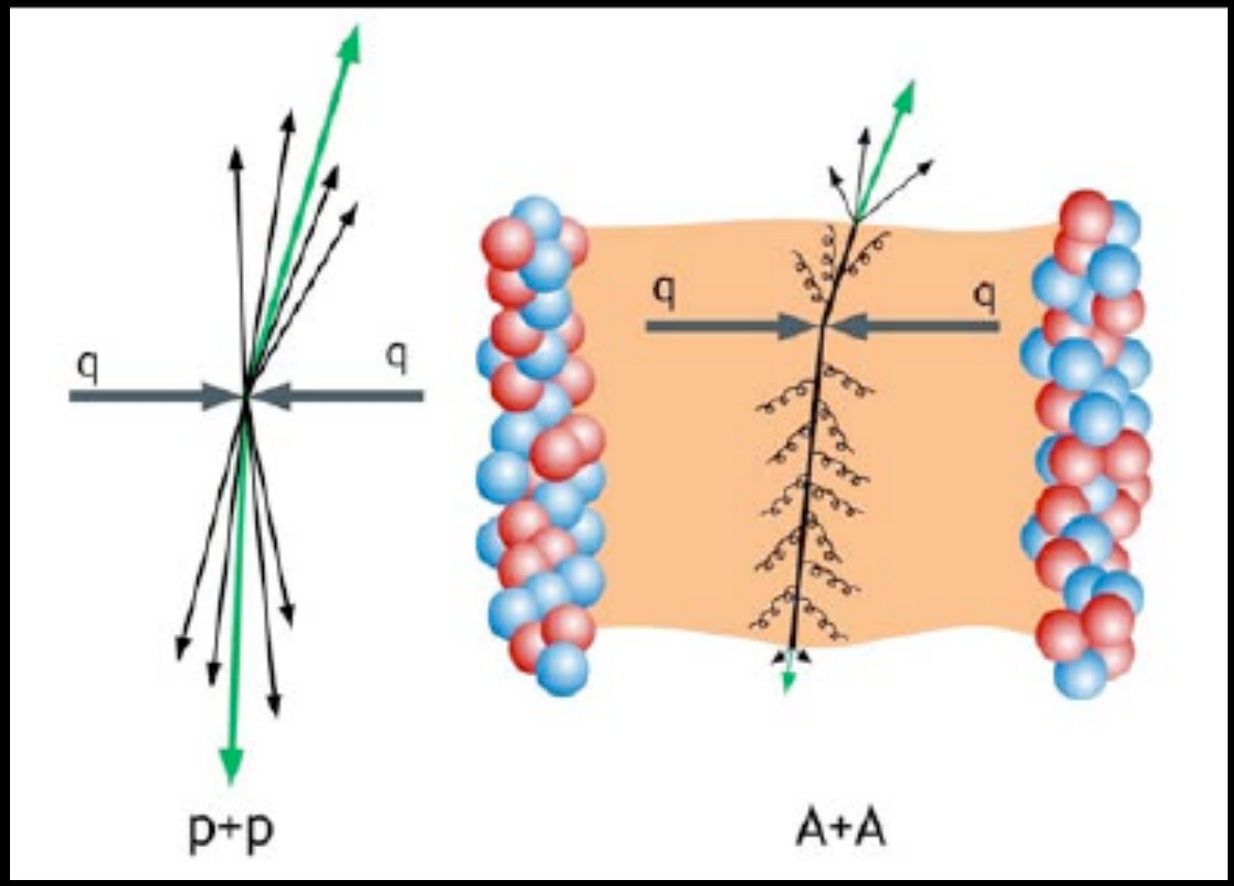
The three momentum scales: high p_T (p_T > 6 GeV/c)

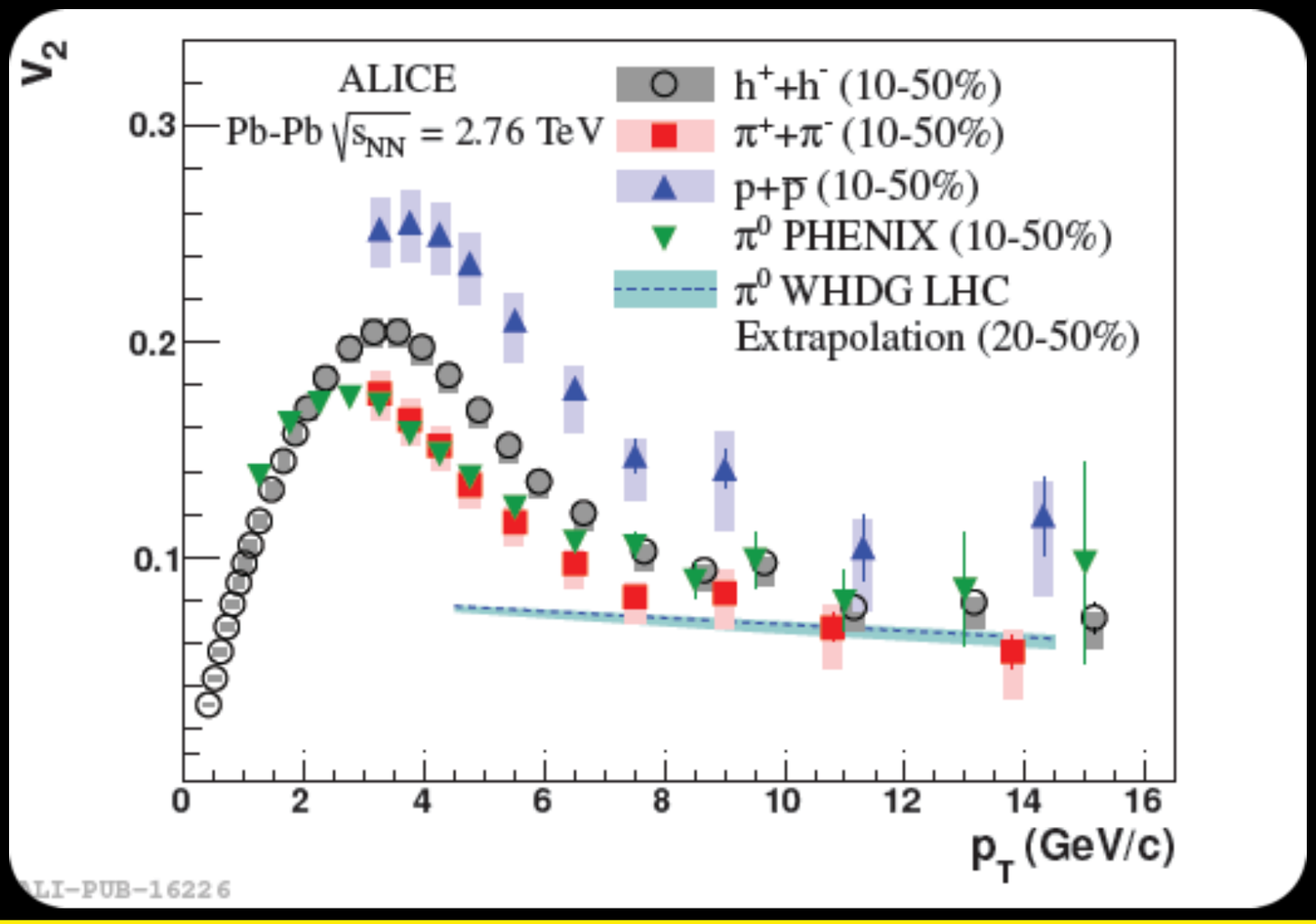


- Probing the path length dependence
  - ★ particles flying in-plane have to travel through less (more) medium
  - ★ expect to see an azimuthal dependence of jets and high p_T particles



High p_T pions, kaons, protons @ LHC: v_2

B. Abelev *et al*. (ALICE Collaboration), Phys. Lett. **B719**, (2013) 18

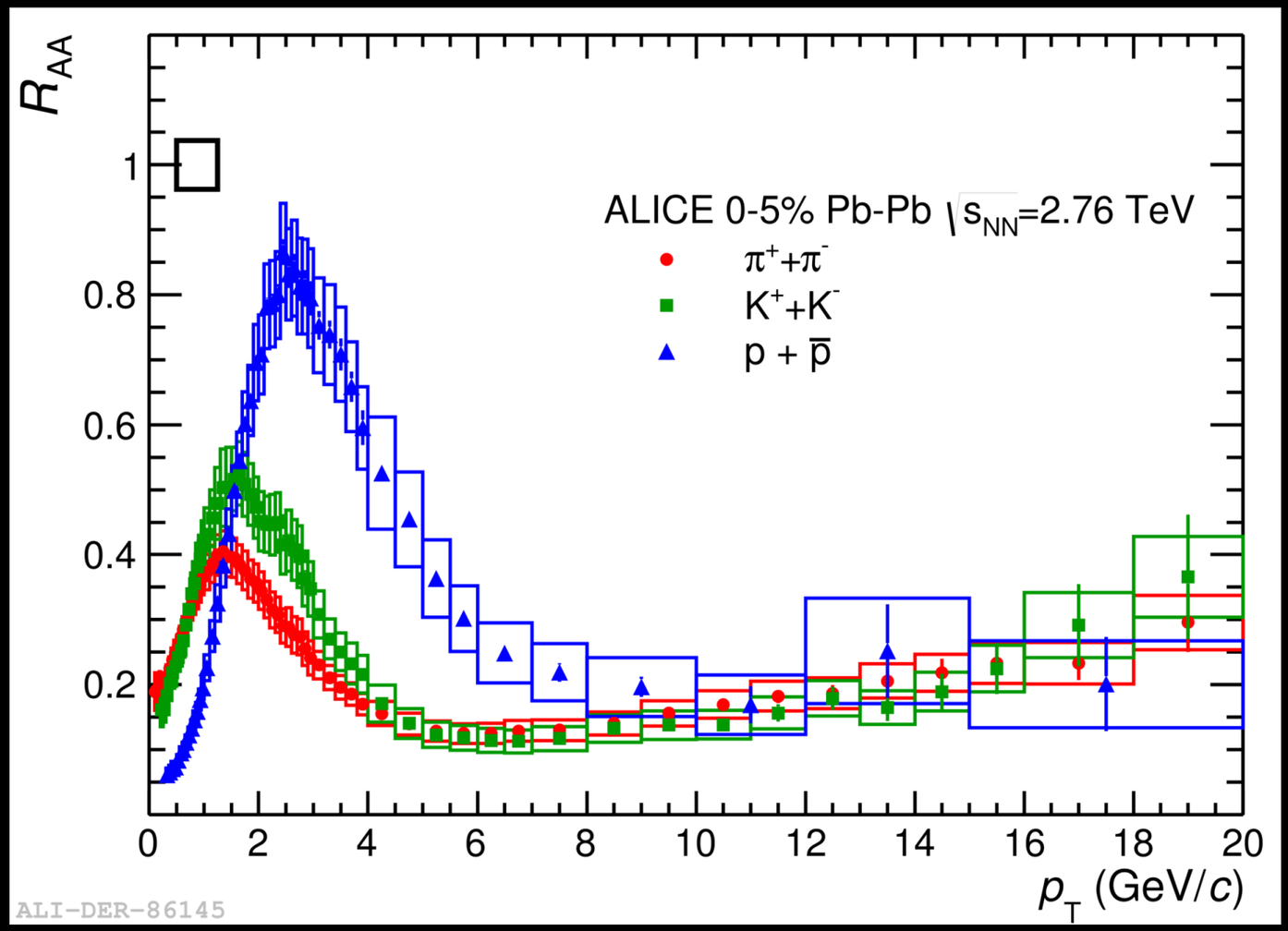


- Significant v_2 for all particle species at high p_T
  - ★ azimuthal dependence of high-p_T particle yield
  - ★ no significant particle species dependence for p_T > 10 GeV/c
- Theory curve describes data fairly well

High p_T pions, kaons, protons @ LHC: nuclear modification factor

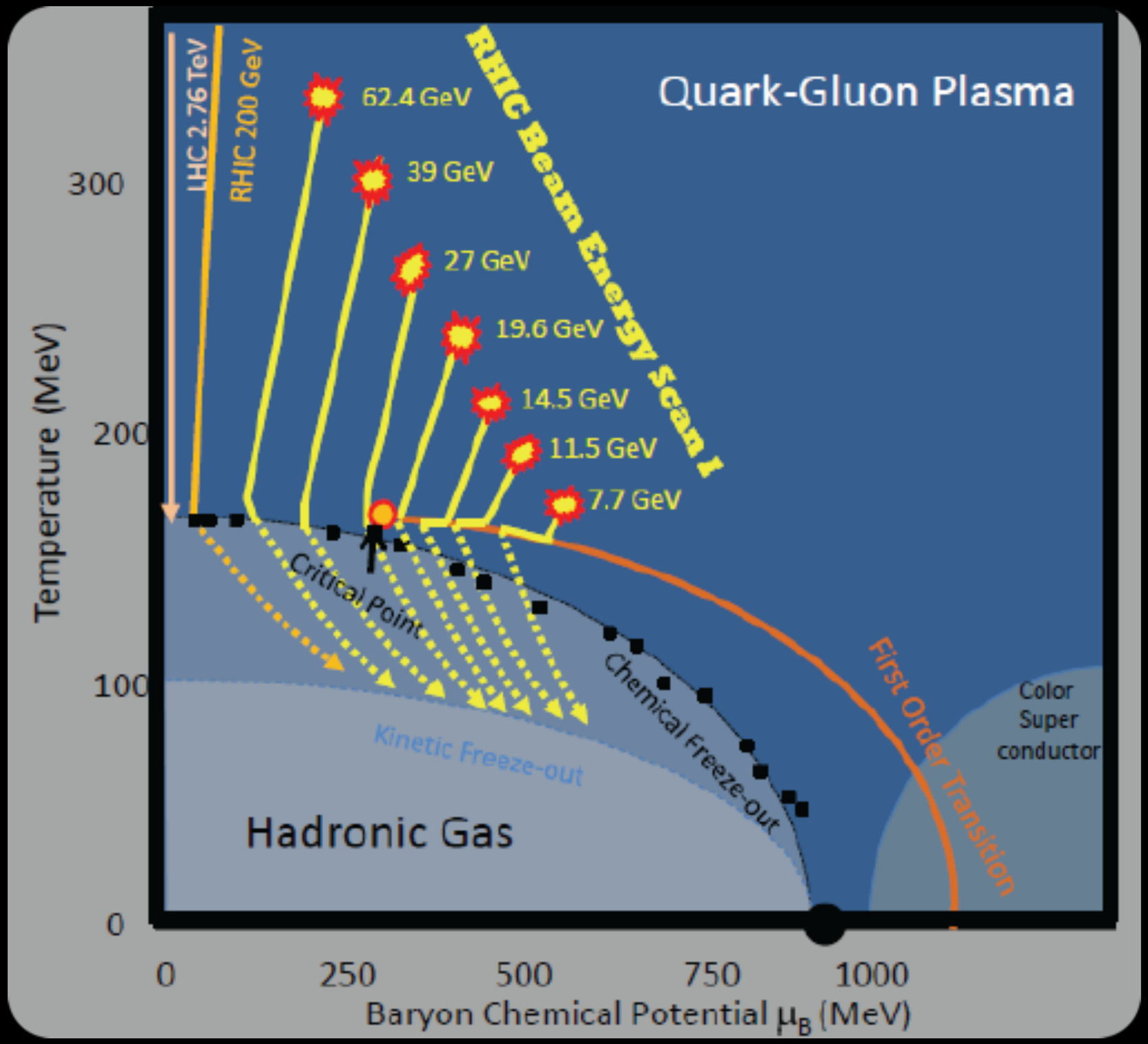
B. Abelev *et al*. (ALICE Collaboration), arXiv:1401.1250

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$



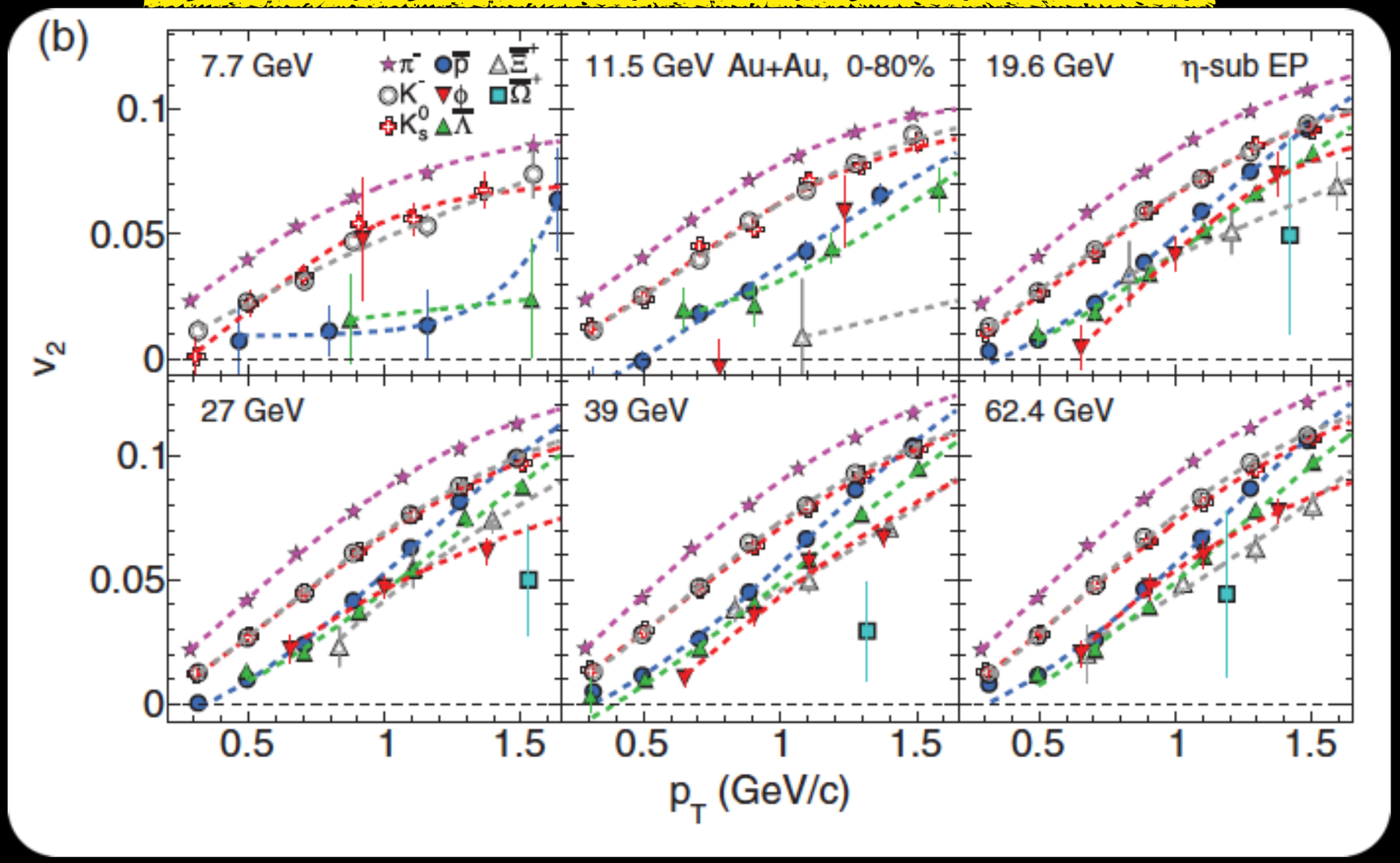
- Large suppression of high p_T particles
- Suppression does not depend on particle species for p_T > 10 GeV/c

Searching for the critical point



BES: v_2 of antiparticles

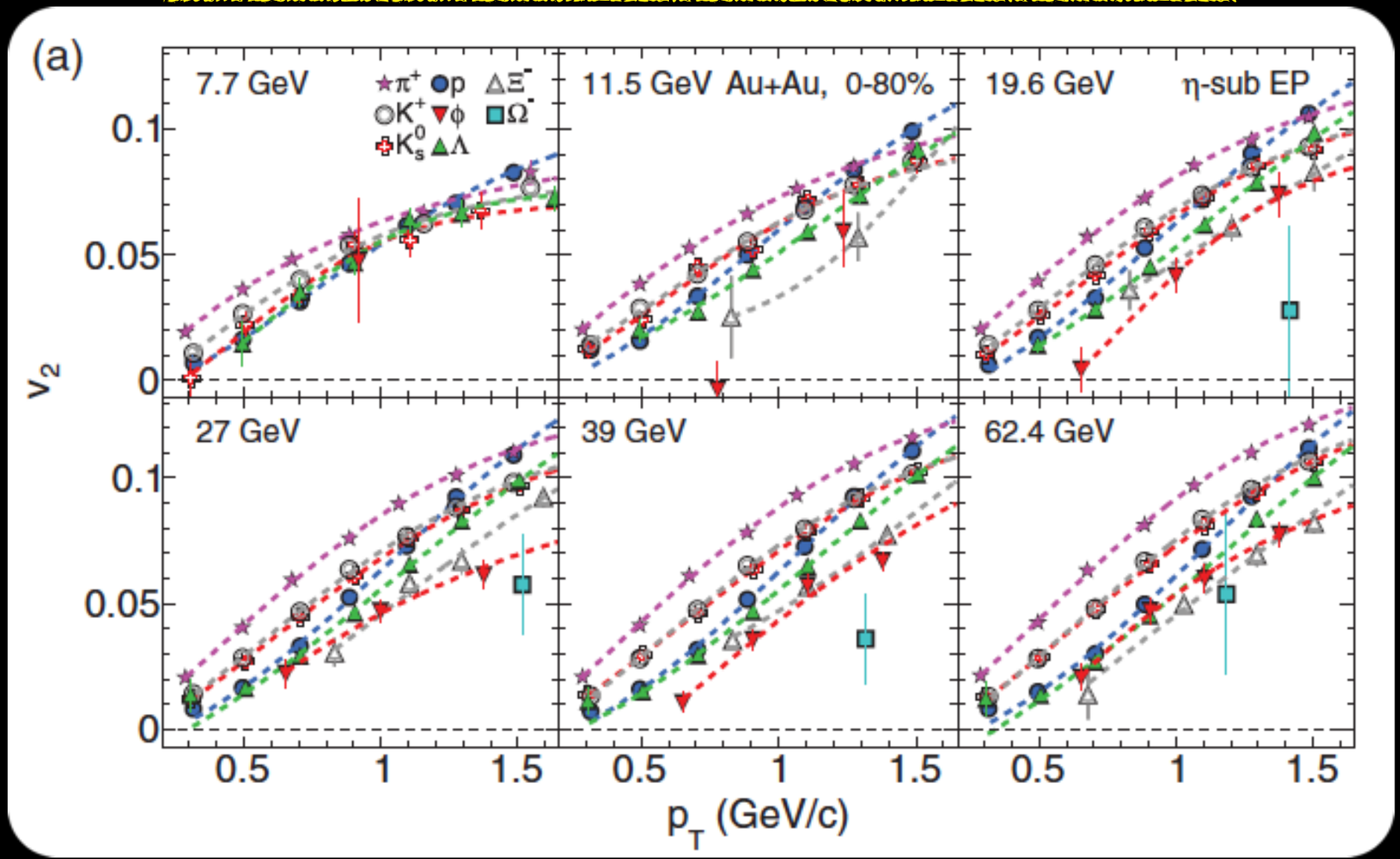
L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902



- Similar mass ordering at low p_T as the one reported for higher energies
- The φ seems to deviate from the ordering at lower energies

BES: v_2 of particles

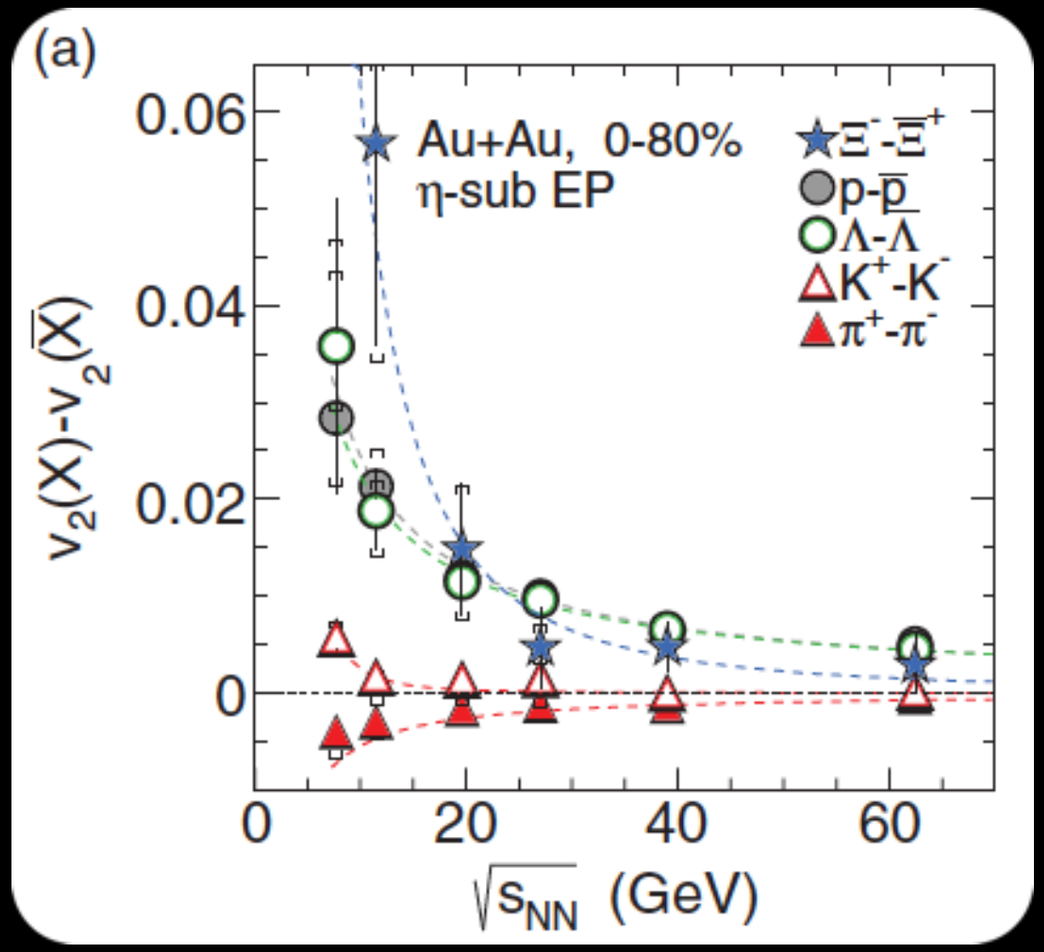
L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902



- Similar mass ordering at low p_T as the one reported for higher energies
- Spread of $v_2(p_T)$ narrows with energy (not for antiparticles!)

BES: v_2 difference between particles and antiparticles

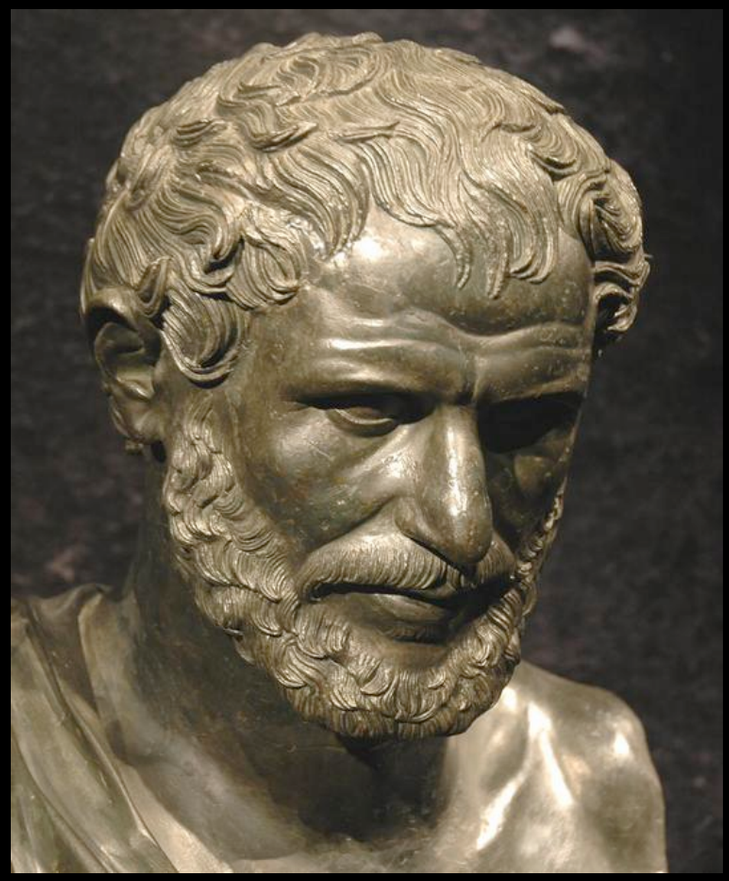
L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902



- Particle composition, baryon stopping change with energy
  - ★ Is the difference a “trivial” effect or does it signal the transition to hadronic degrees of freedom?
- Models that couple hydro to baryon stopping seem to be getting similar differences with energy
- Situation is still quite unclear → need for further input from theorists

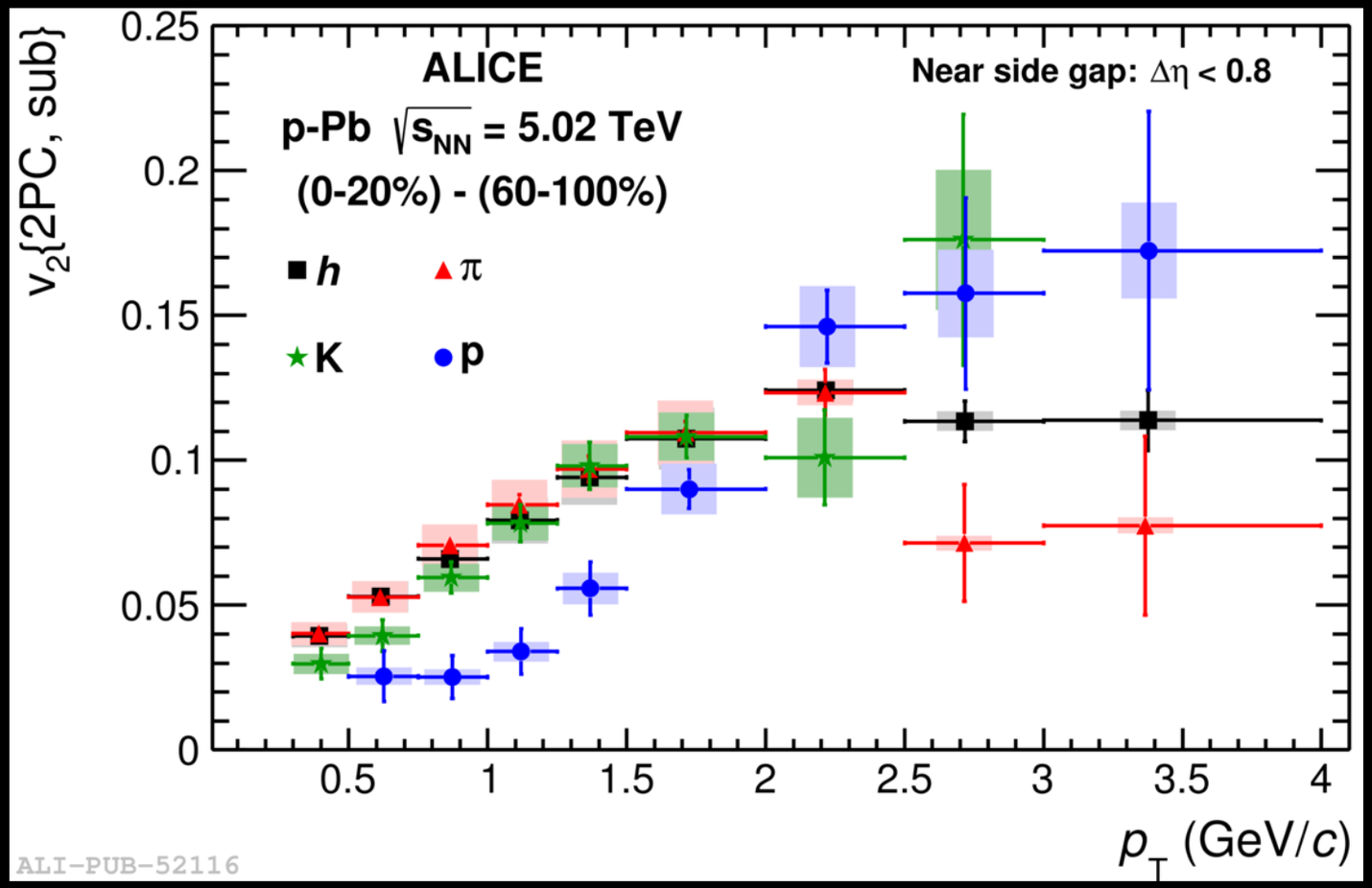
Τα πάντα ρει…(everything flows)

Ηράκλειτος (Heraclitus) ~535 - 475 BC

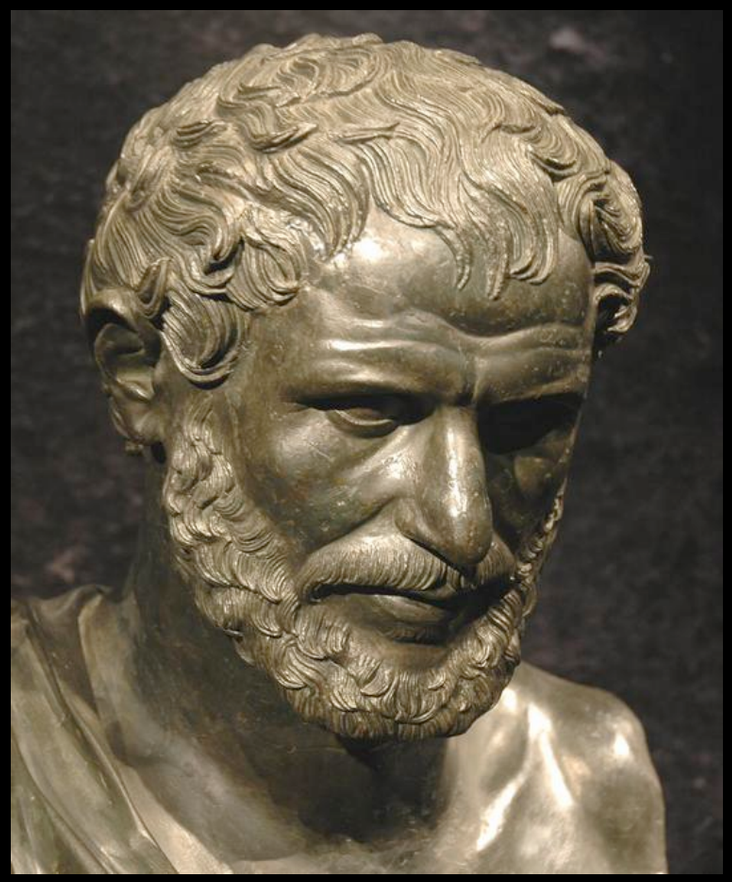


Τα πάντα ρει…(everything flows)

B. Abelev *et al*. (ALICE Collaboration: Phys. Lett. **B726**, (2013) 164



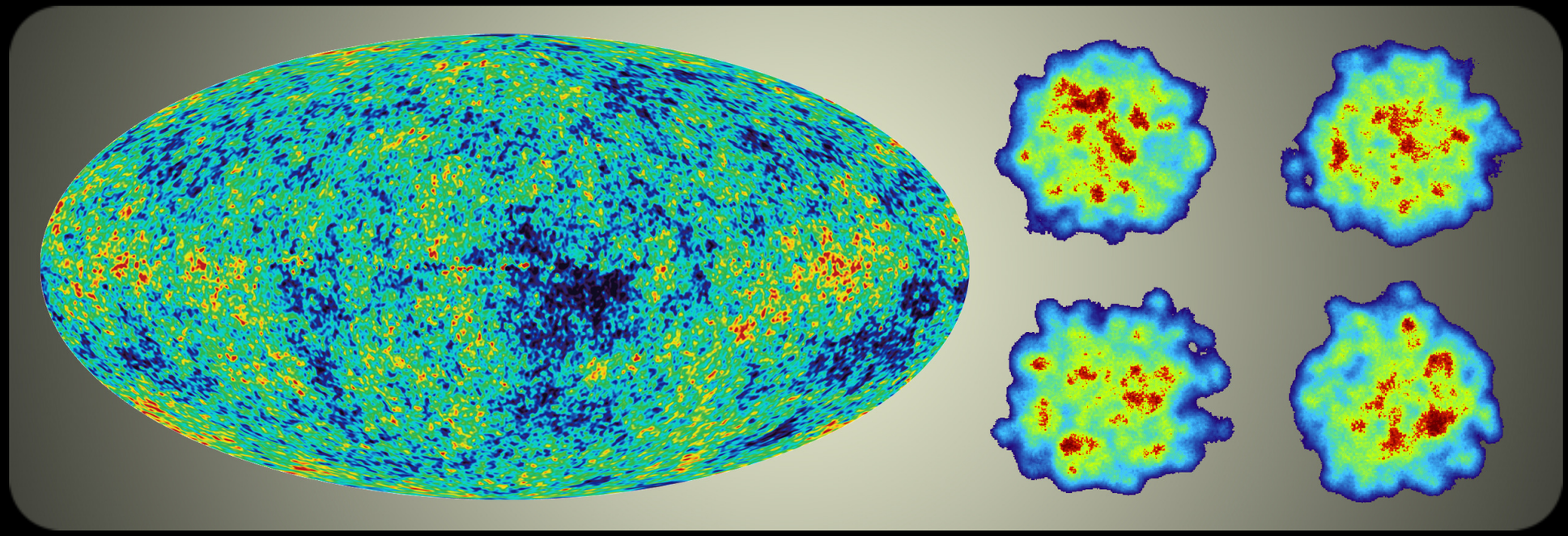
Ηράκλειτος (Heraclitus) ~535 - 475 BC

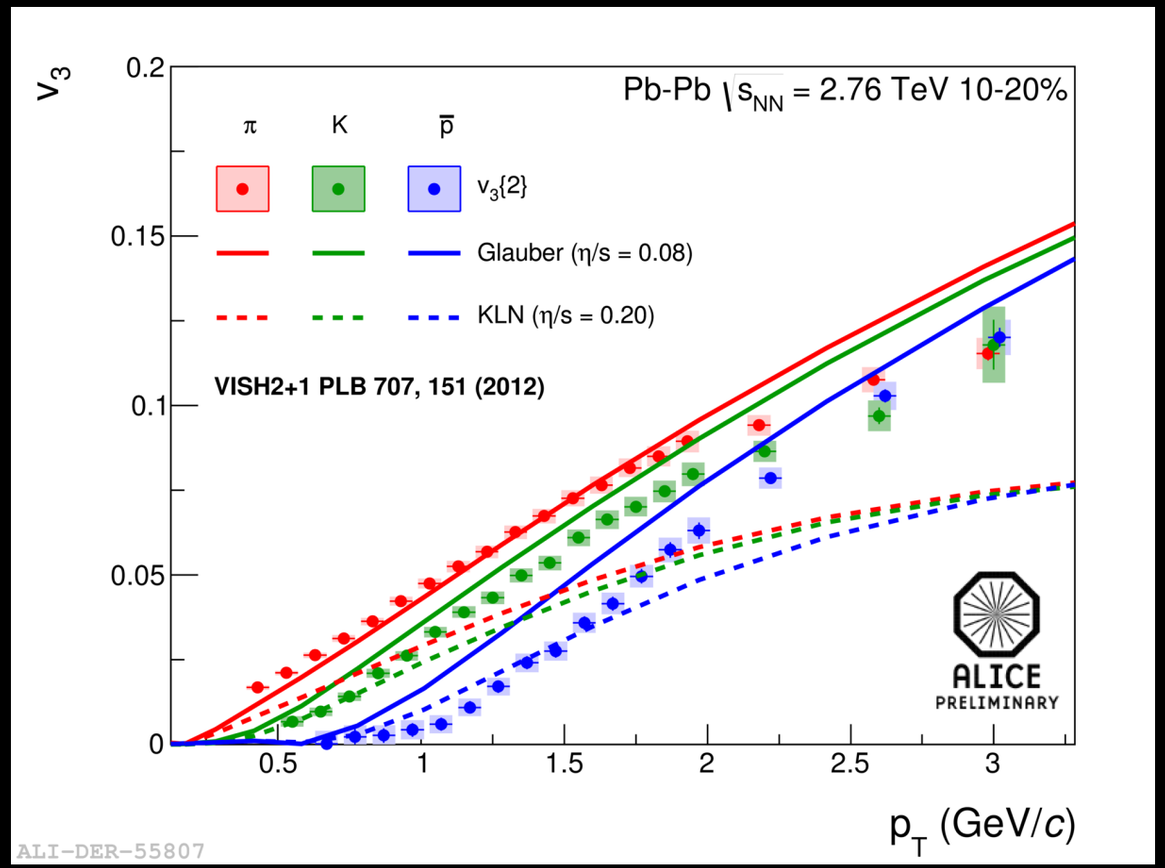


Not only in A-A it seems but also for smaller systems!

For details see the talk from Quan Wang

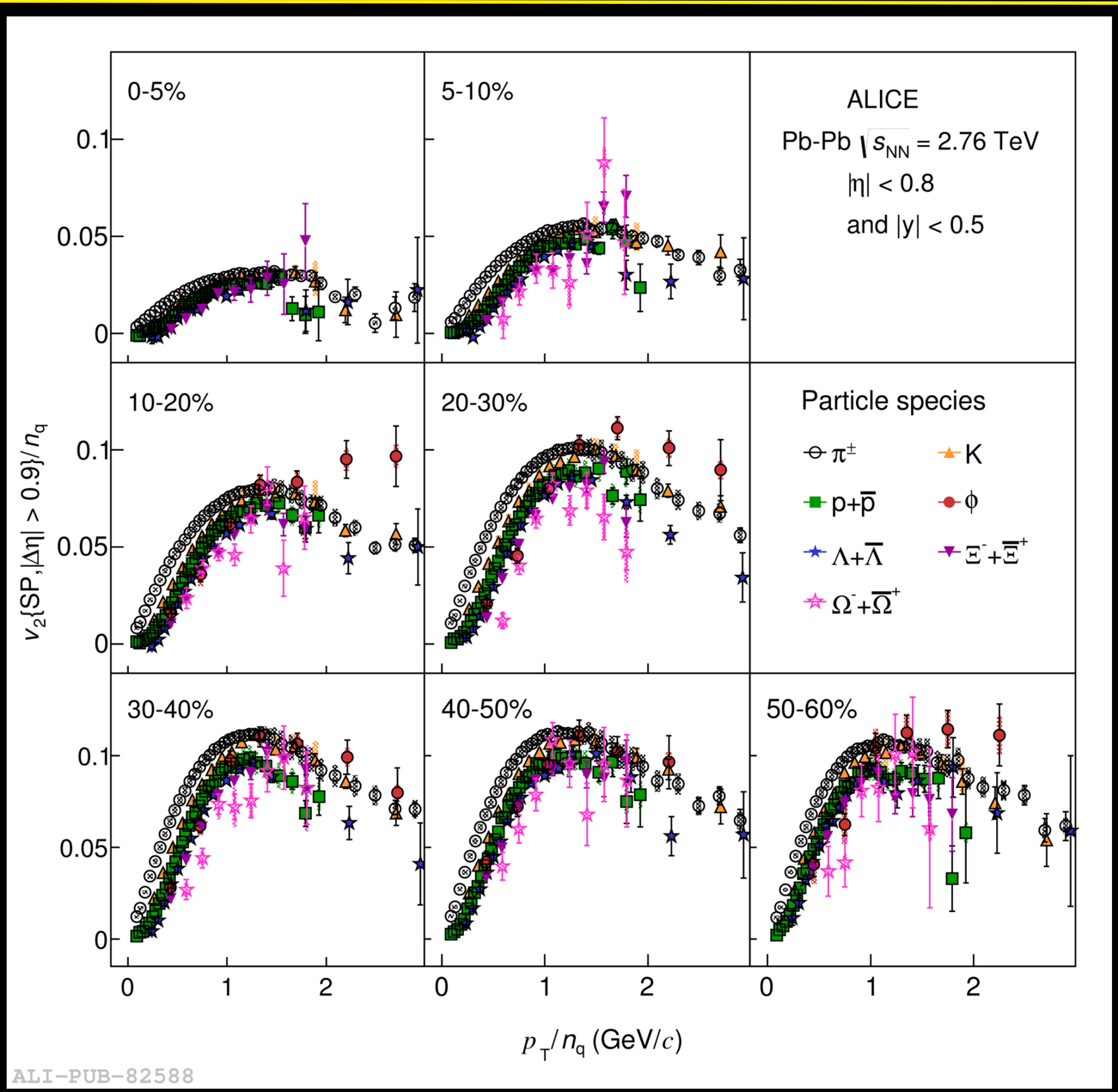
And there is more…: higher harmonics!





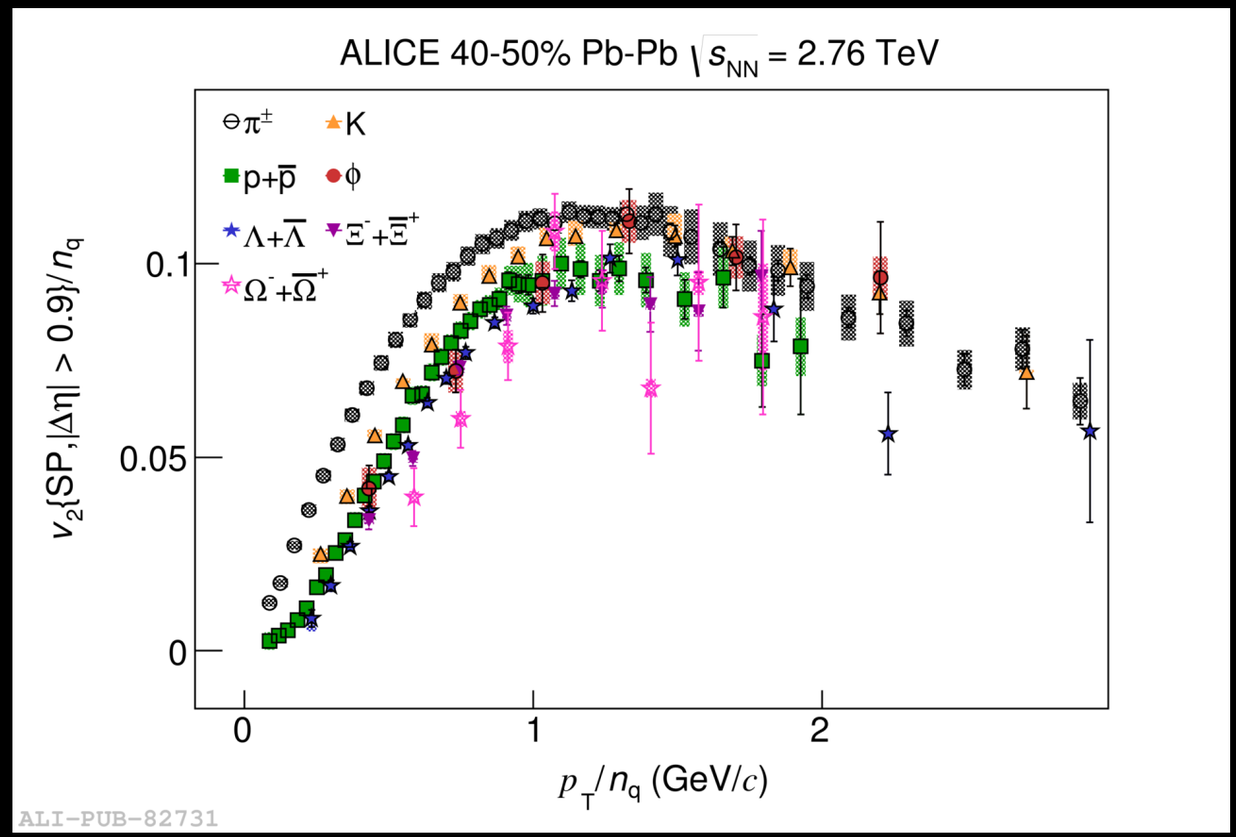
Backup

Number of constituent quark (NCQ) scaling in p_T/n_q



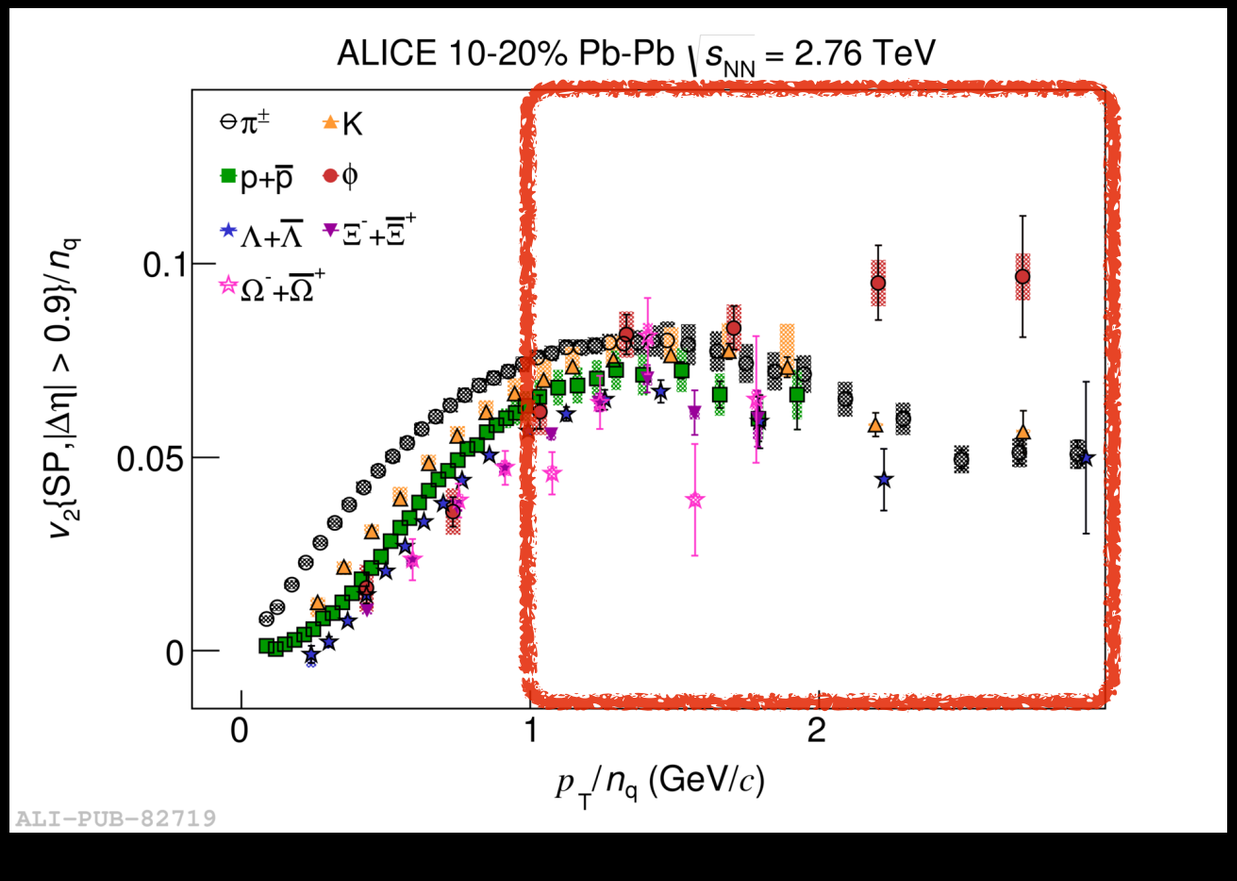
ALI-PUB-82588

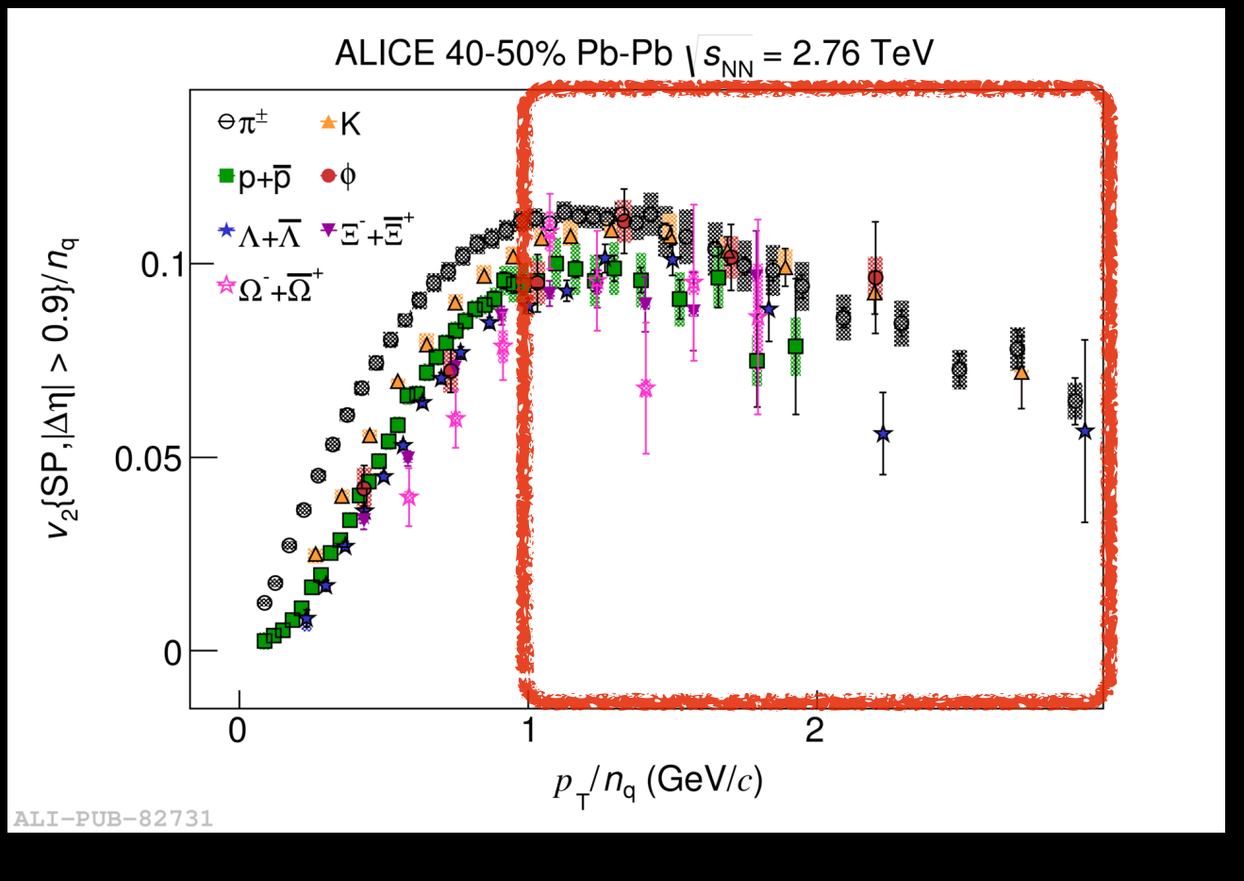
Number of constituent quark (NCQ) scaling in p_T/n_q



Relevant range: $p_T/n_q > 1$ GeV/c

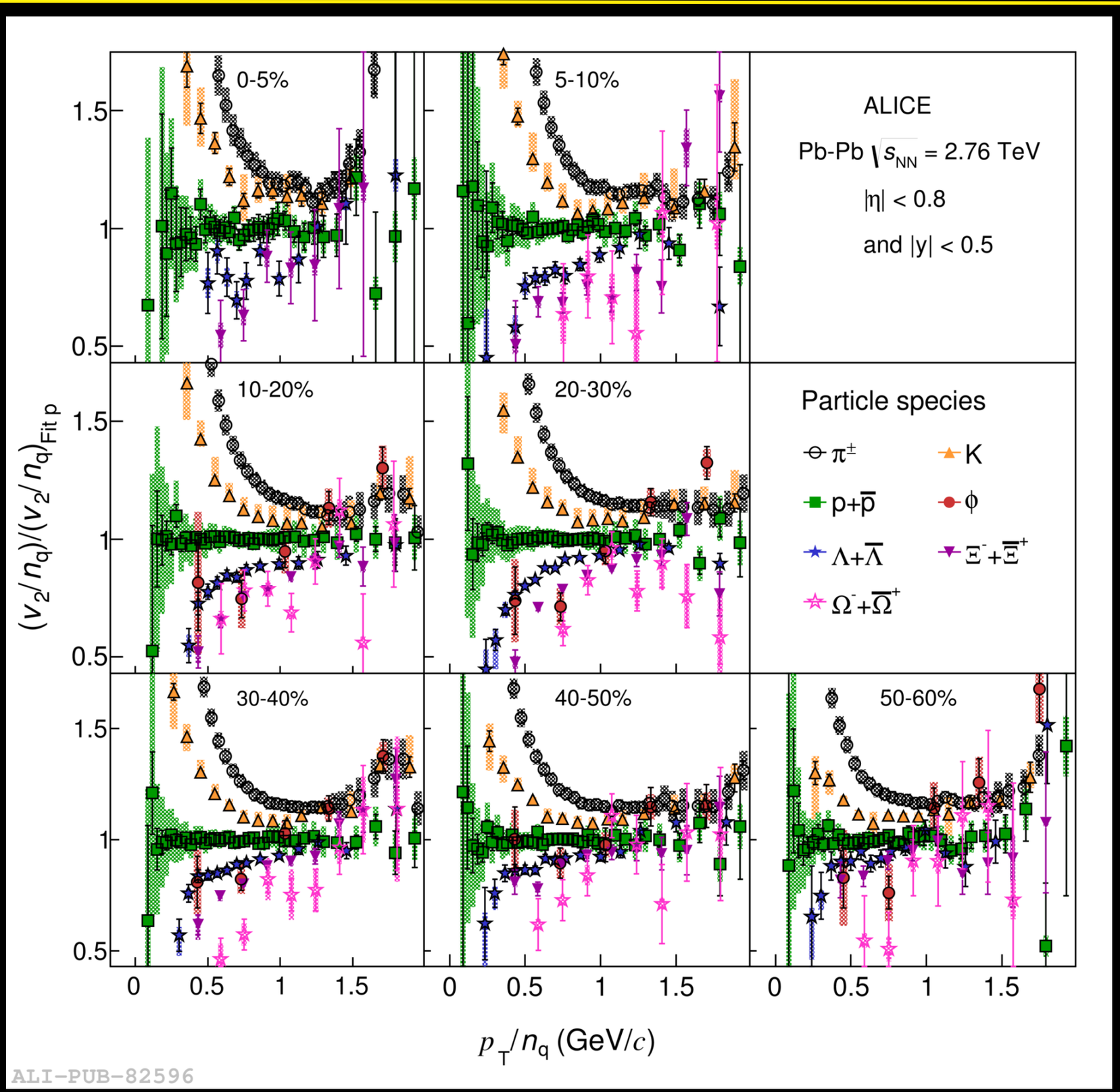
Number of constituent quark (NCQ) scaling in p_T/n_q



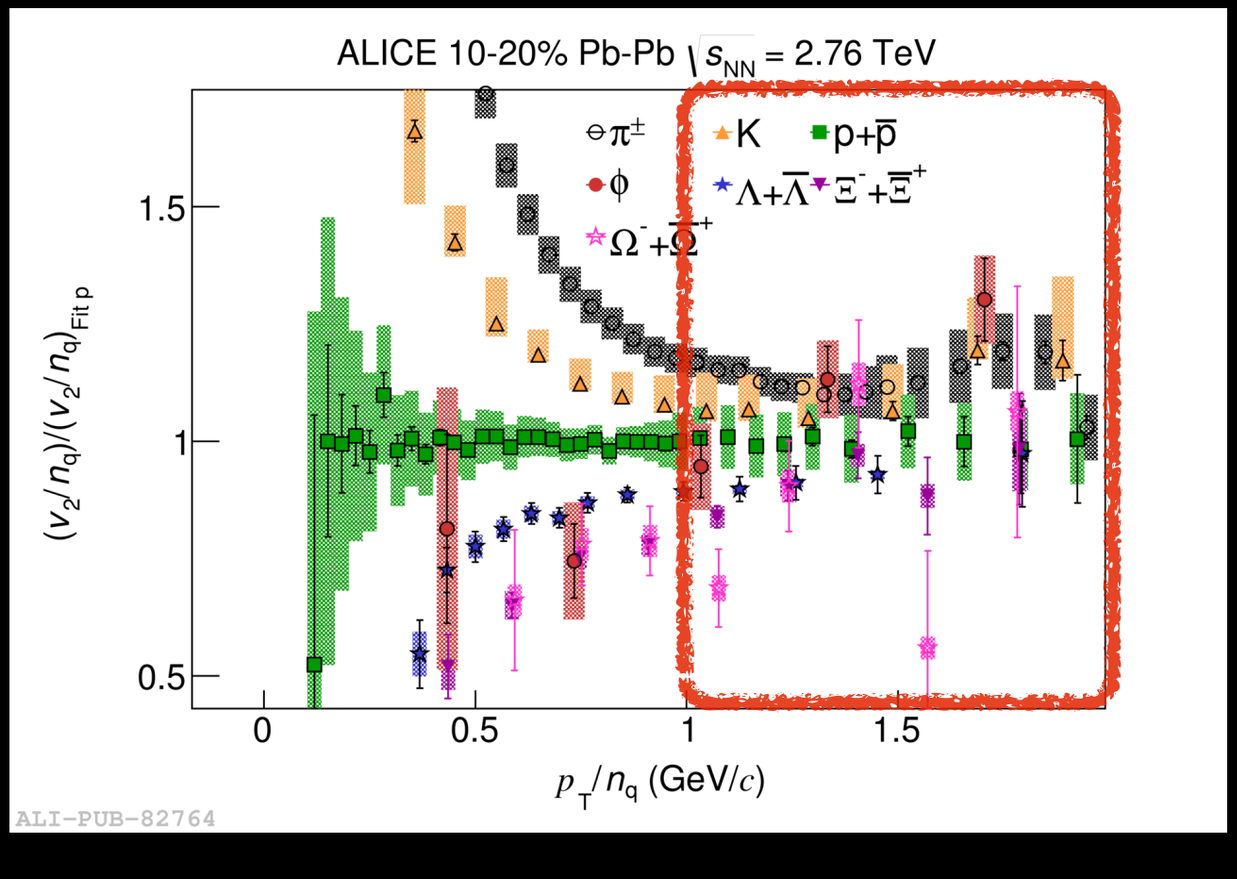


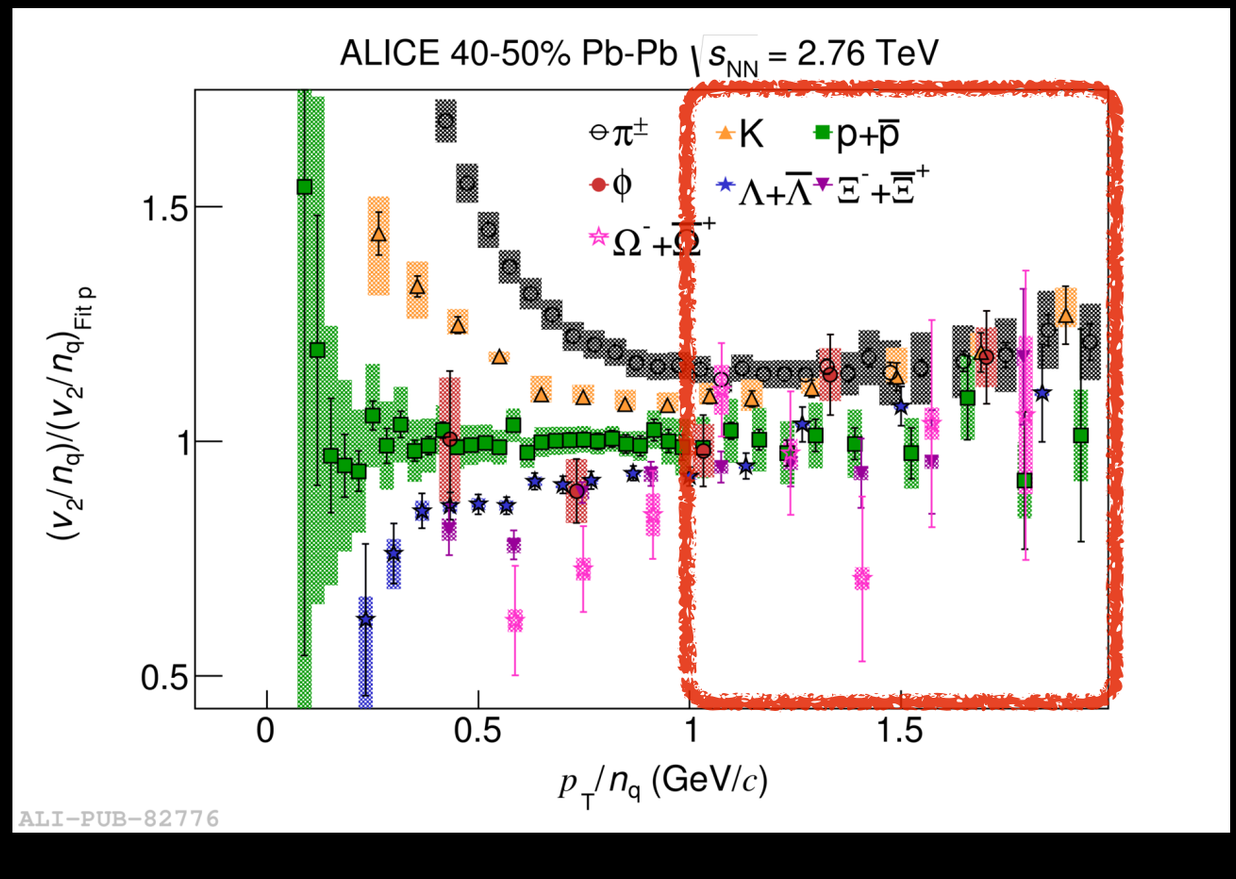
Scaling only approximate

NCQ scaling in p_T/n_q (double ratio)



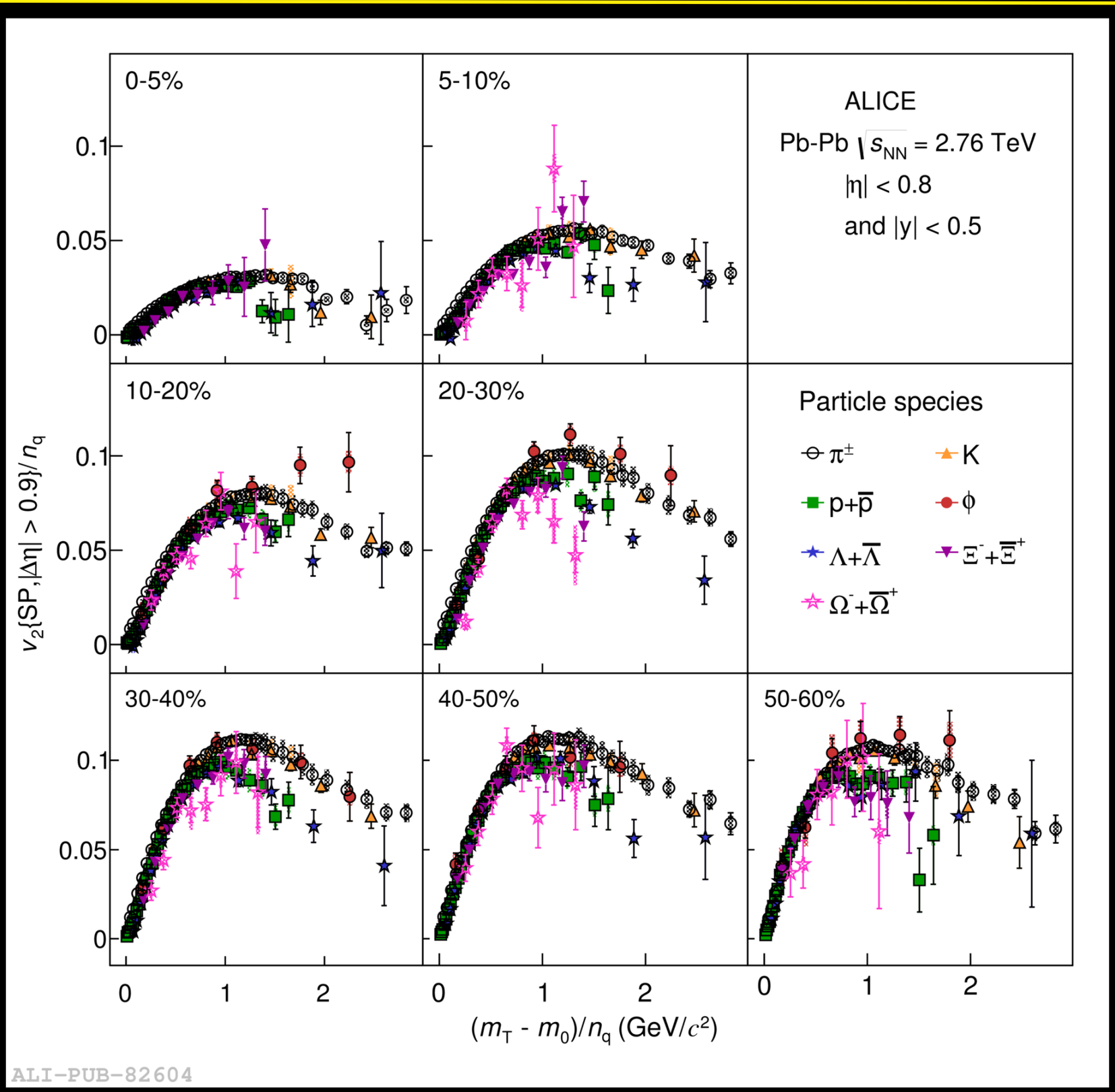
NCQ scaling in p_T/n_q (double ratio)



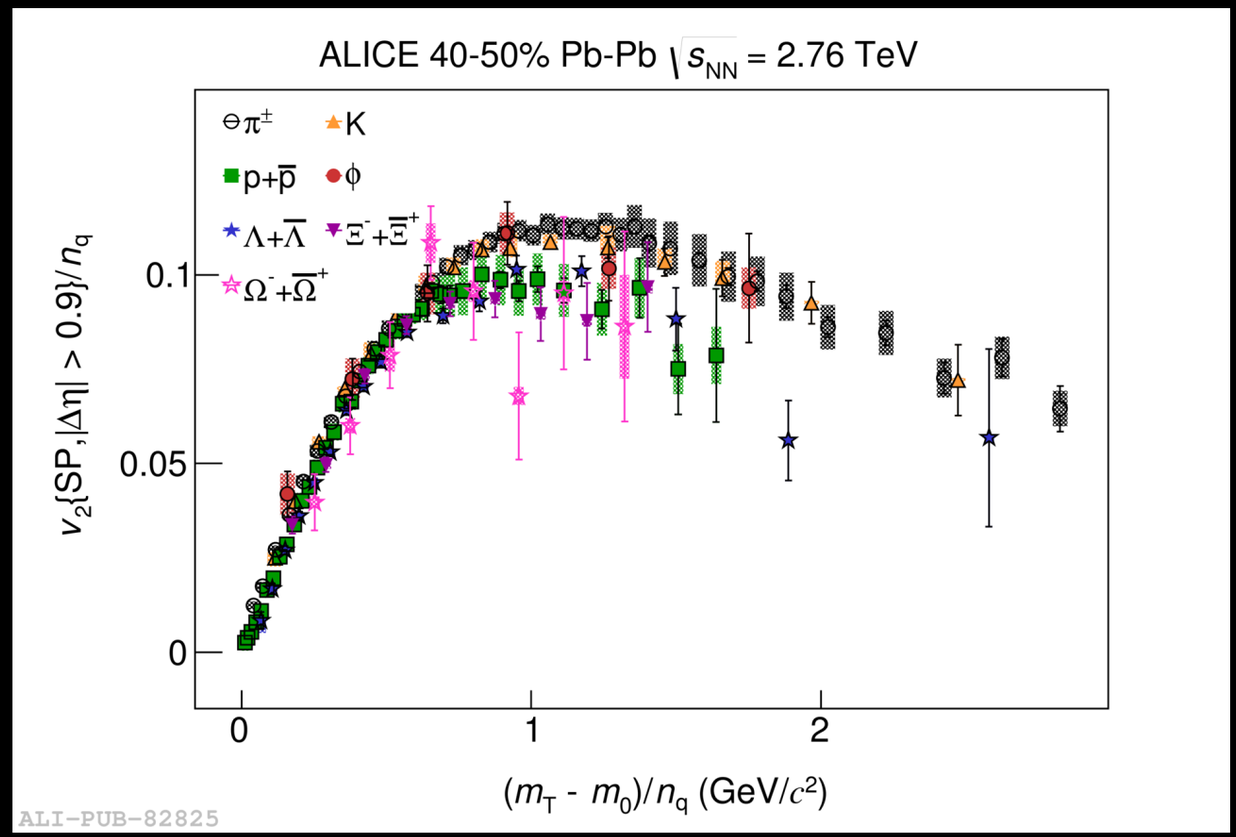


Scaling at the level of no better than ± 20%

NCQ scaling in $(m_T - m_0)/n_q$

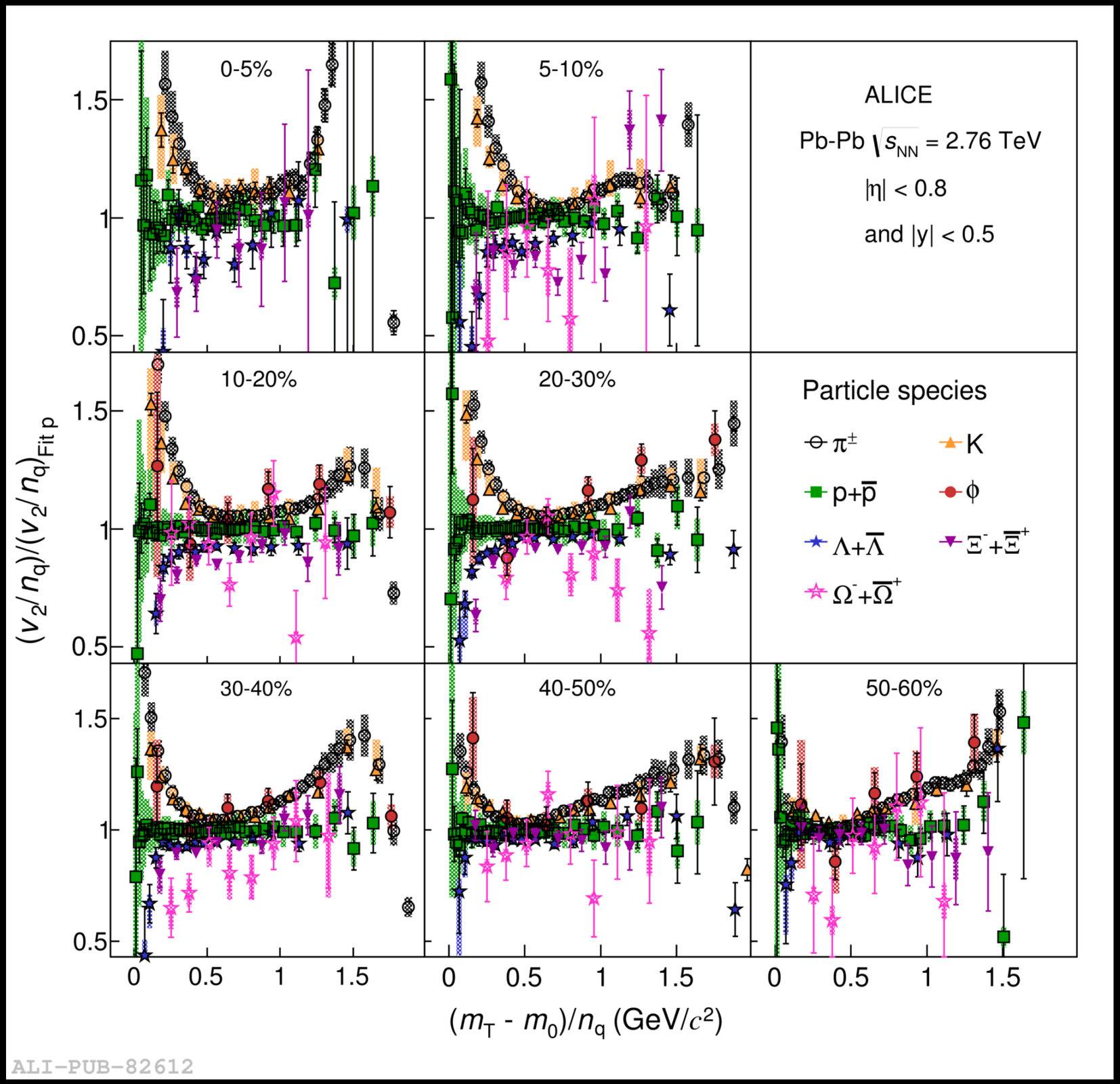


NCQ scaling in $(m_T - m_0)/n_q$

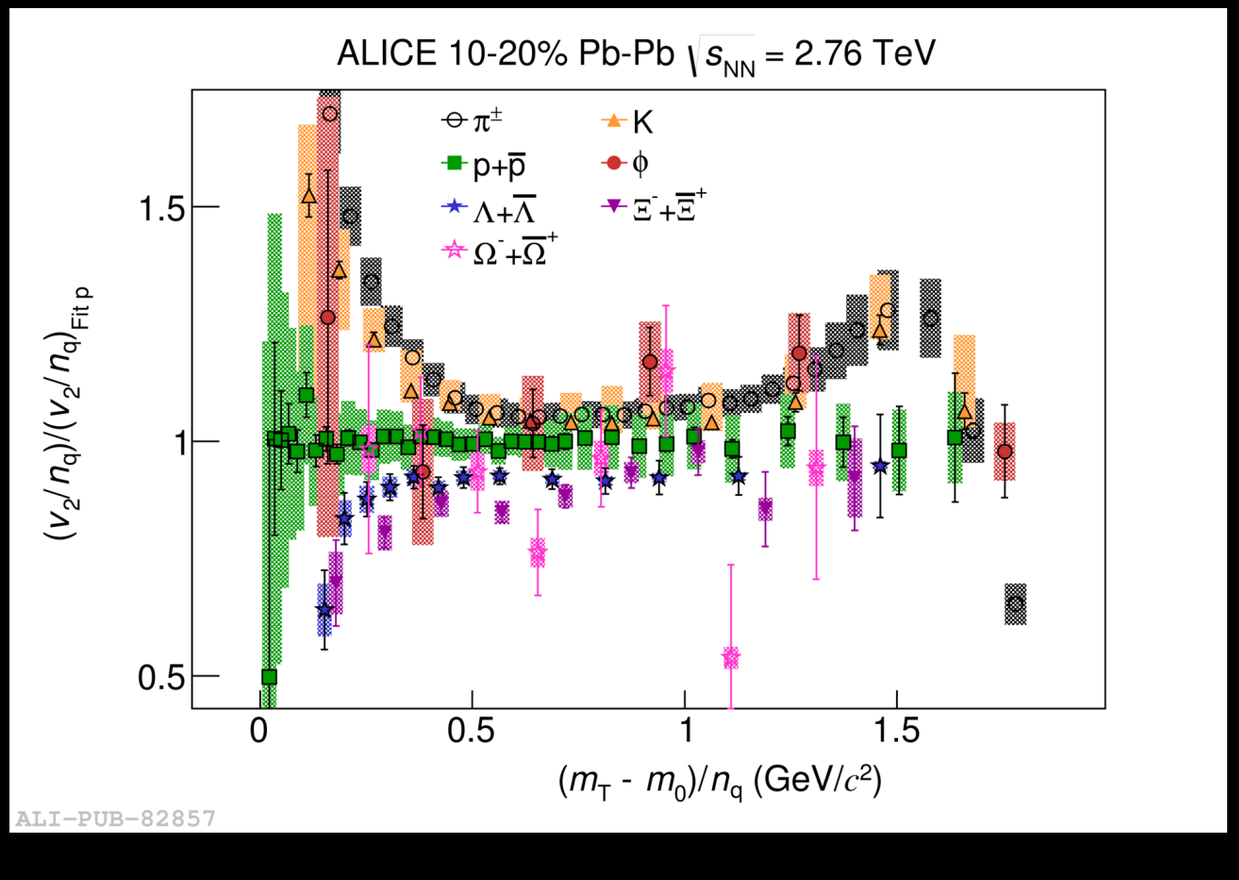


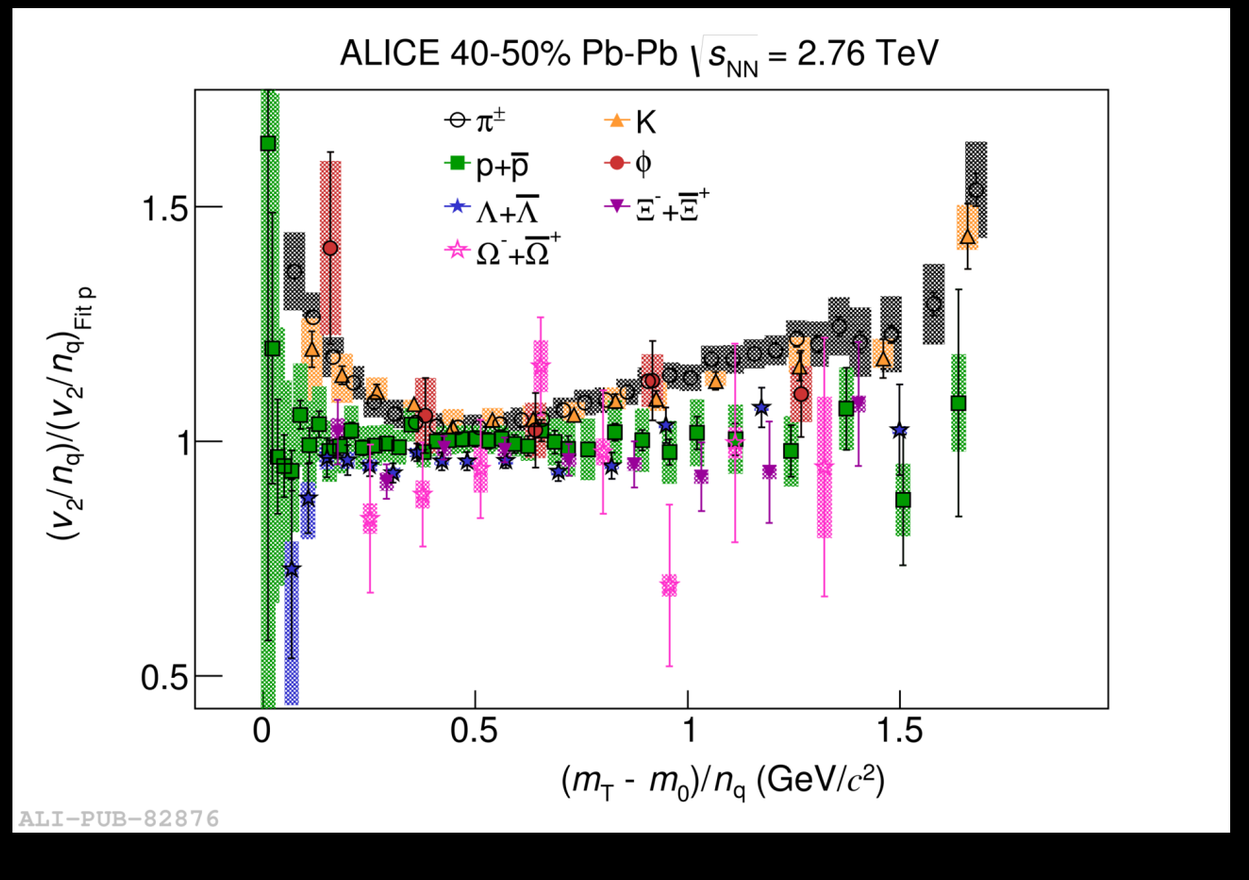
Introduced to extend the scaling to lower p_T

NCQ scaling in (m_T - m_0)/n_q (double ratio)



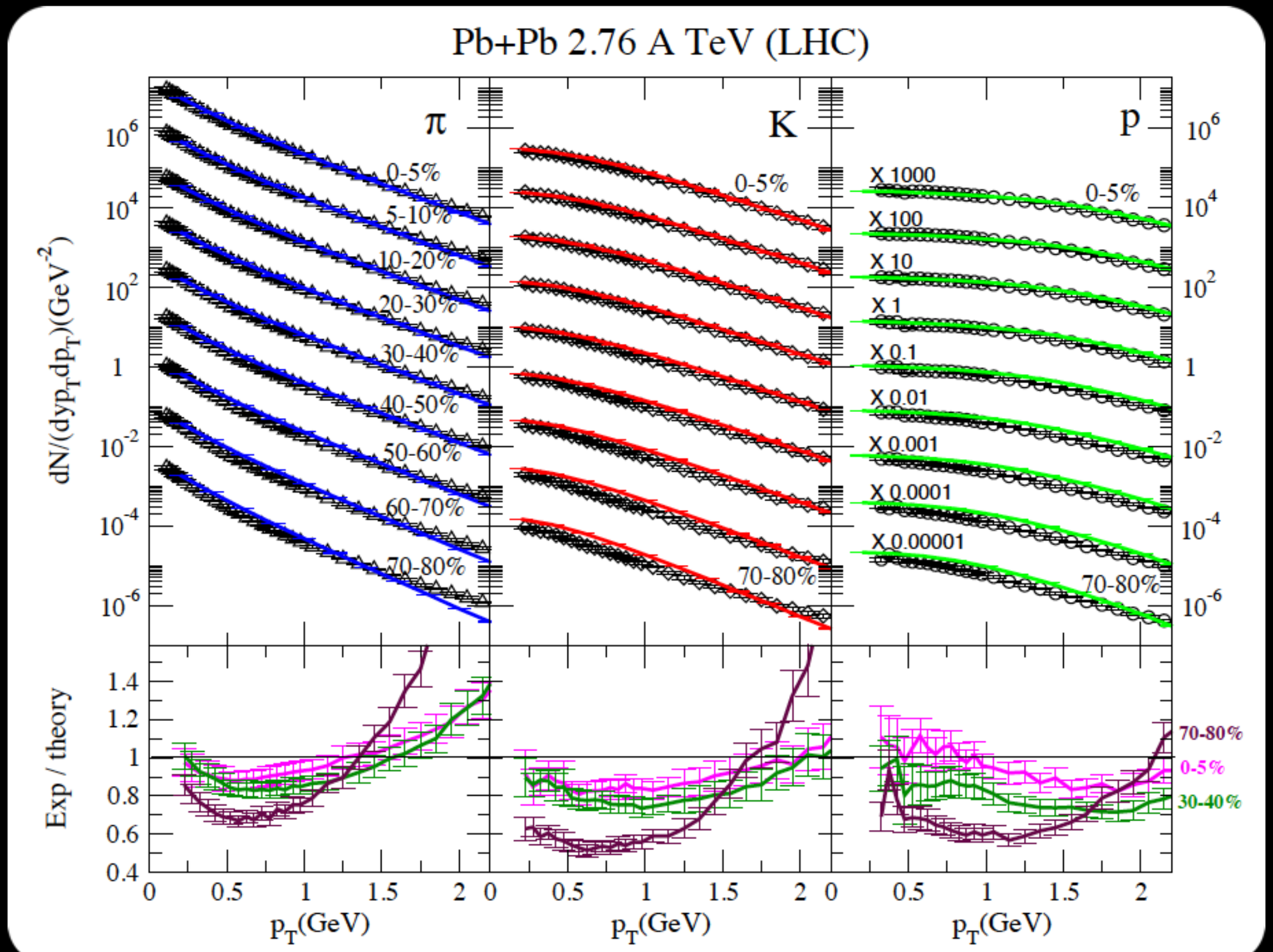
NCQ scaling in $(m_T - m_0)/n_q$ (double ratio)





- For $(m_T - m_0)/n_q$ < 0.6 - 0.8 GeV/c^2: scaling is broken at the LHC
- For $(m_T - m_0)/n_q$ > 0.6 - 0.8 GeV/c^2: scaling is only approximate at the level of ± 20%

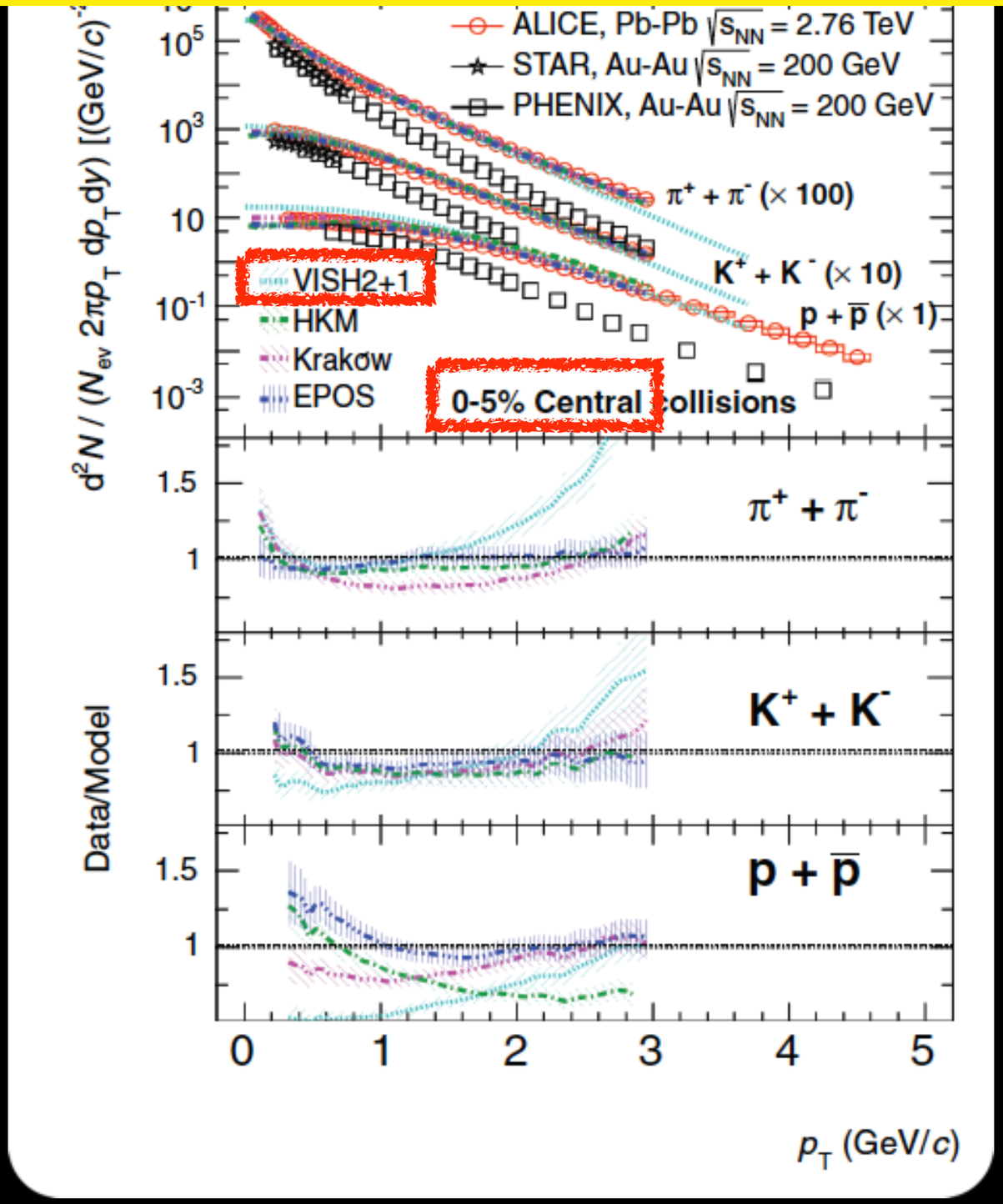
Spectra: How good is VISHNU doing?

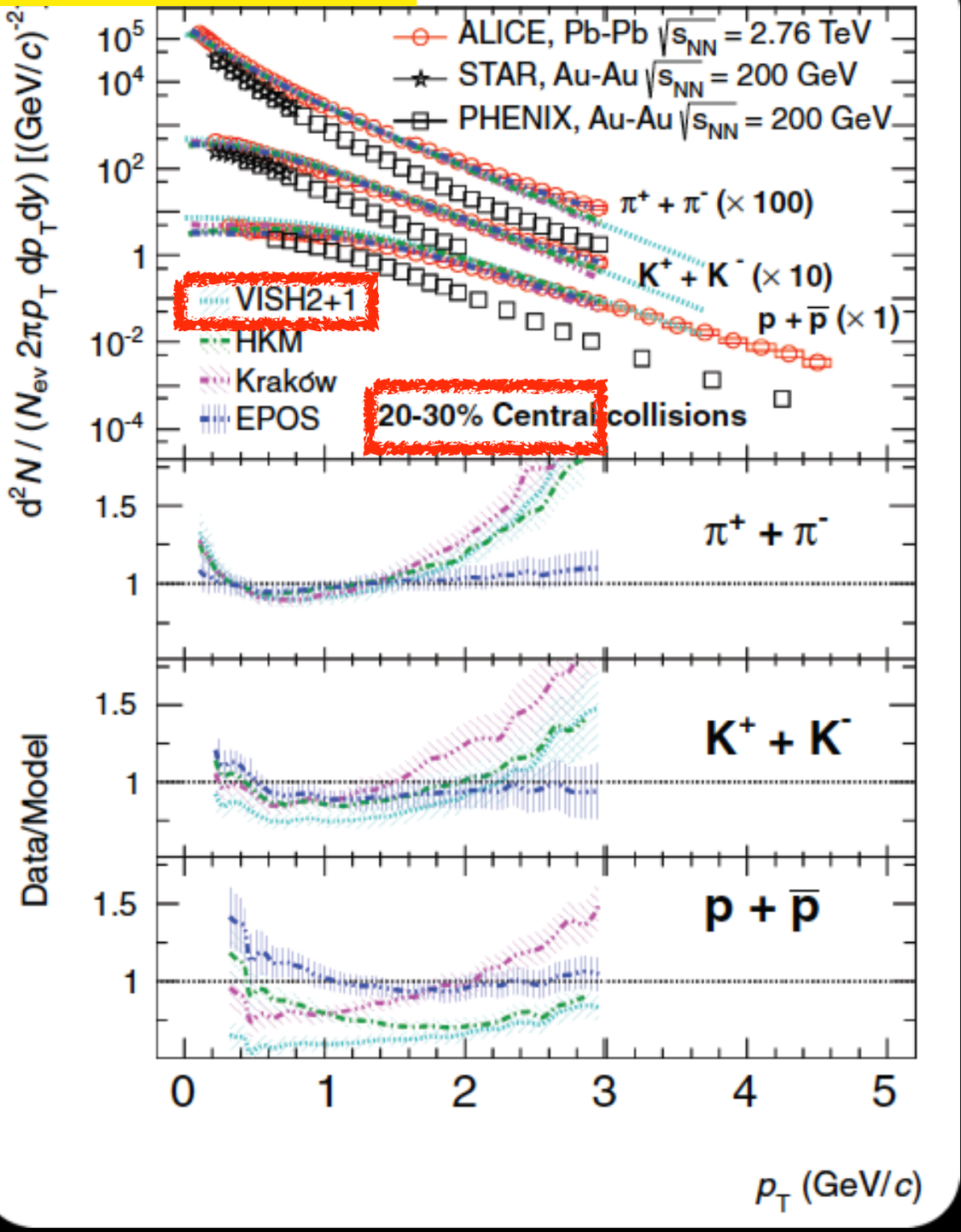


H. Song *et al.*, arXiv:1311.0157 [nucl-th]

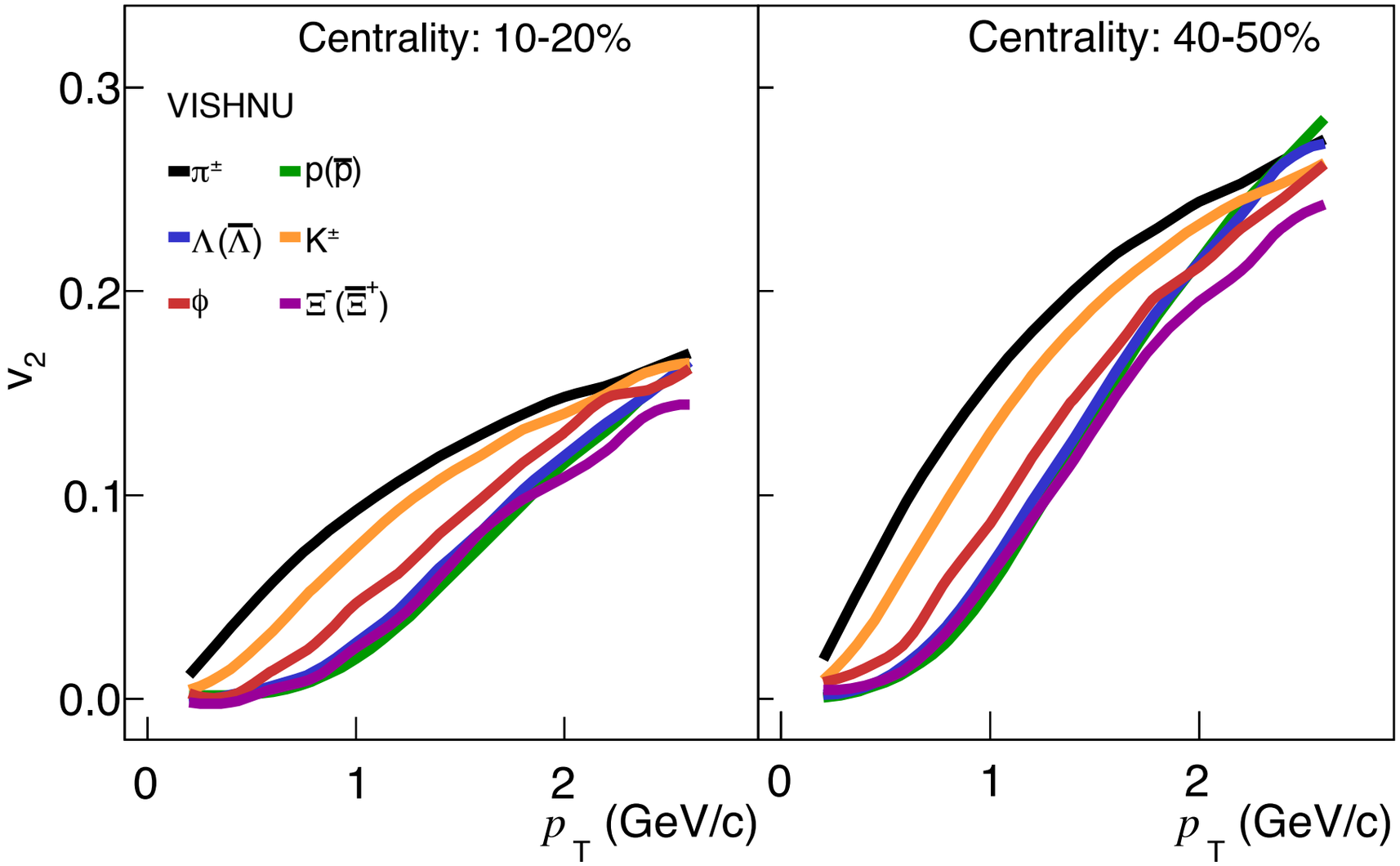
VISH2+1: comparison to spectra

ollaboration: Phys. Rev. C 88, 044910 (2013)





VISHNU in more detail



Mass ordering not preserved!!!

attering phase: VISHNU vs VISH2+1

H. Song, S.A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. Lett. 106 (2011) 192301 [Erratum-ibid. 109 (2012) 139904] [arXiv: 1011.2783 [nucl-th]].

H. Song, S.A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. C 83 (2011) 054910 [Erratum-ibid. C 86 (2012) 059903] [arXiv:1101.4638 [nucl-th]].

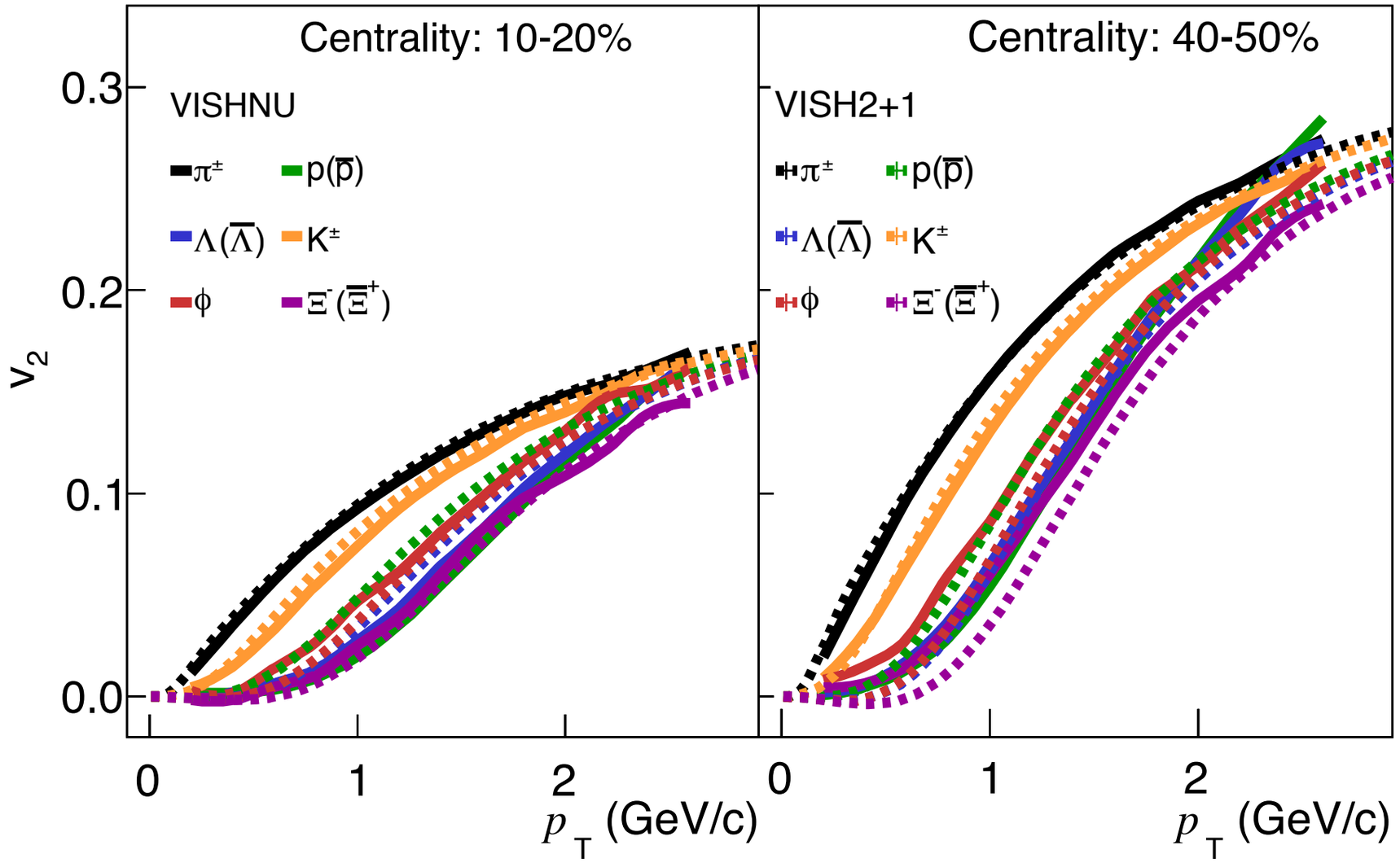
VISH2+1

H. Song and U.W. Heinz, Phys. Lett. B 658 (2008) 279 [arXiv: 0709.0742 [nucl-th]].

H. Song and U.W. Heinz, Phys. Rev. C 77 (2008) 064901 [arXiv: 0712.3715 [nucl-th]].

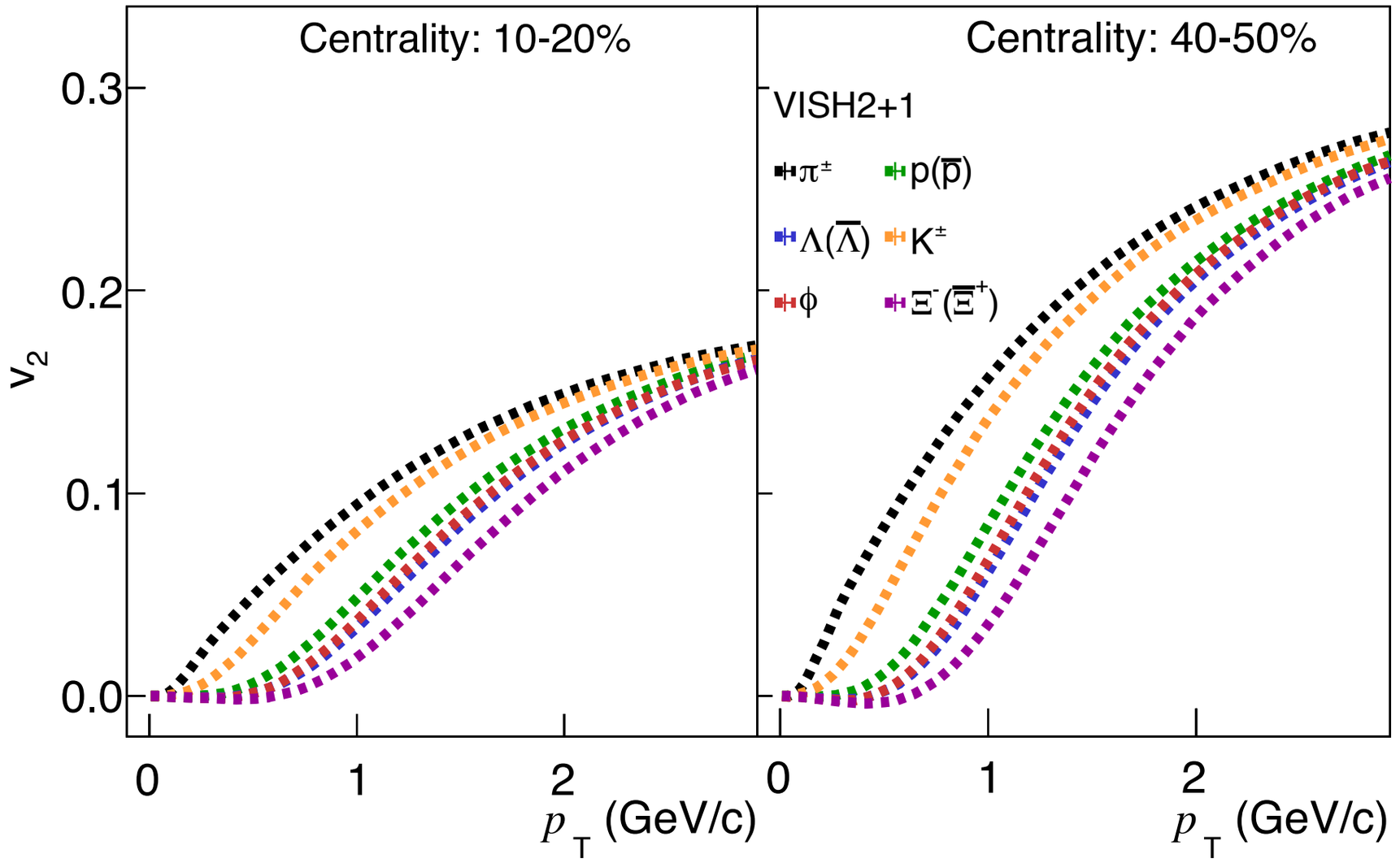
H. Song and U.W. Heinz, Phys. Rev. C 78 (2008) 024902 [arXiv: 0805.1756 [nucl-th]].

VISHNU vs VISH2+1



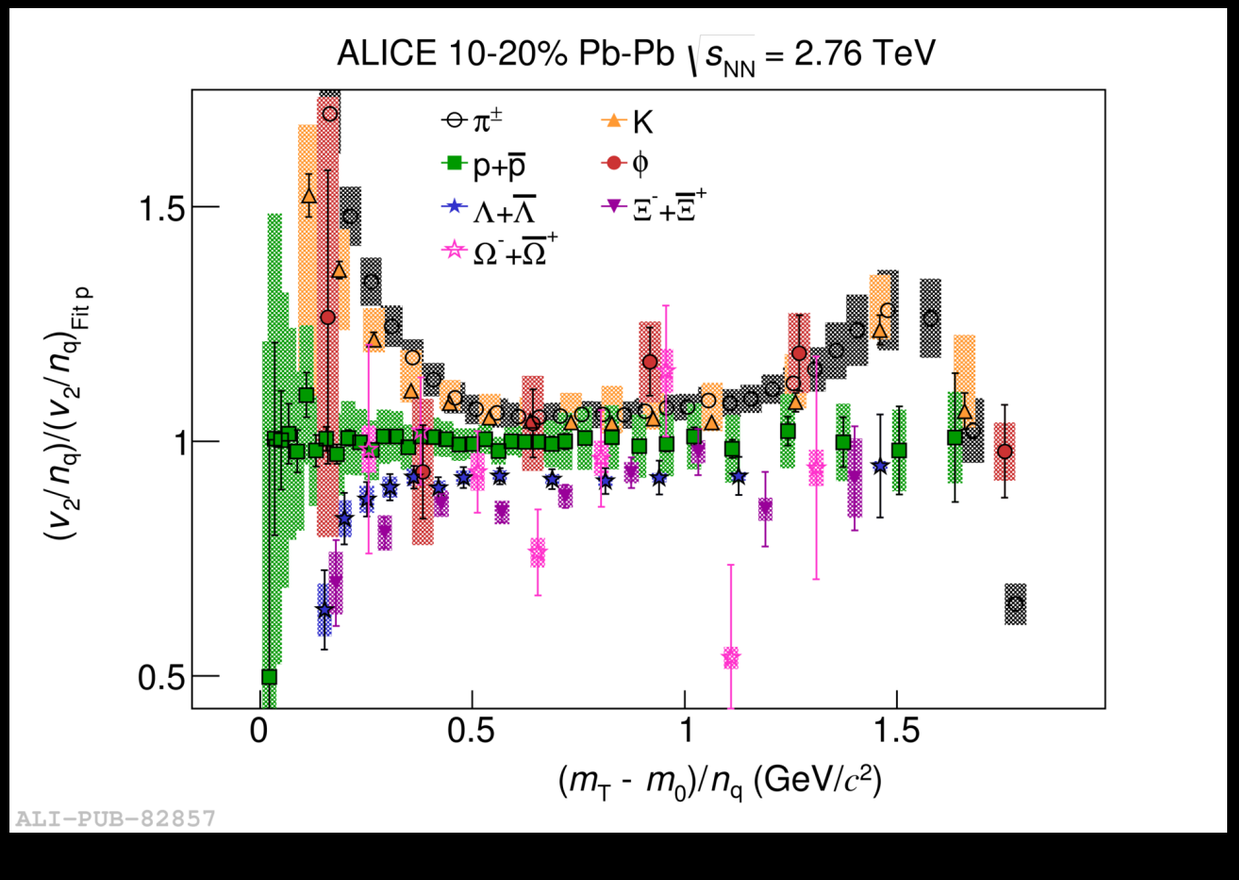
Not a clear trend: π, K similar for both centralities, φ similar for central events but different for peripheral, some baryons (e.g. p, Λ) "pushed" to higher p_T, while others (e.g. Ξ) to lower p_T

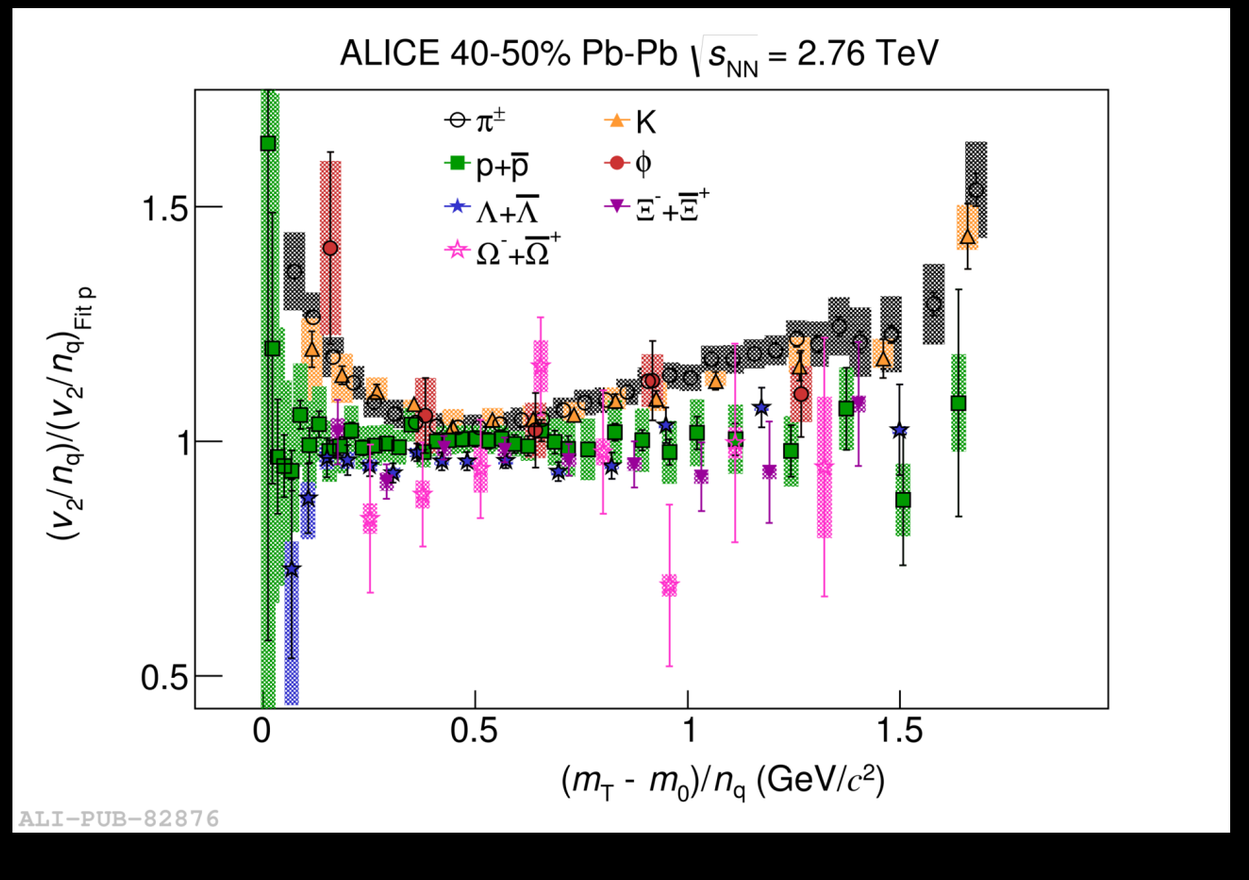
VISH2+1 in more detail



Mass ordering preserved

NCQ scaling in $(m_T - m_0)/n_q$ (double ratio)





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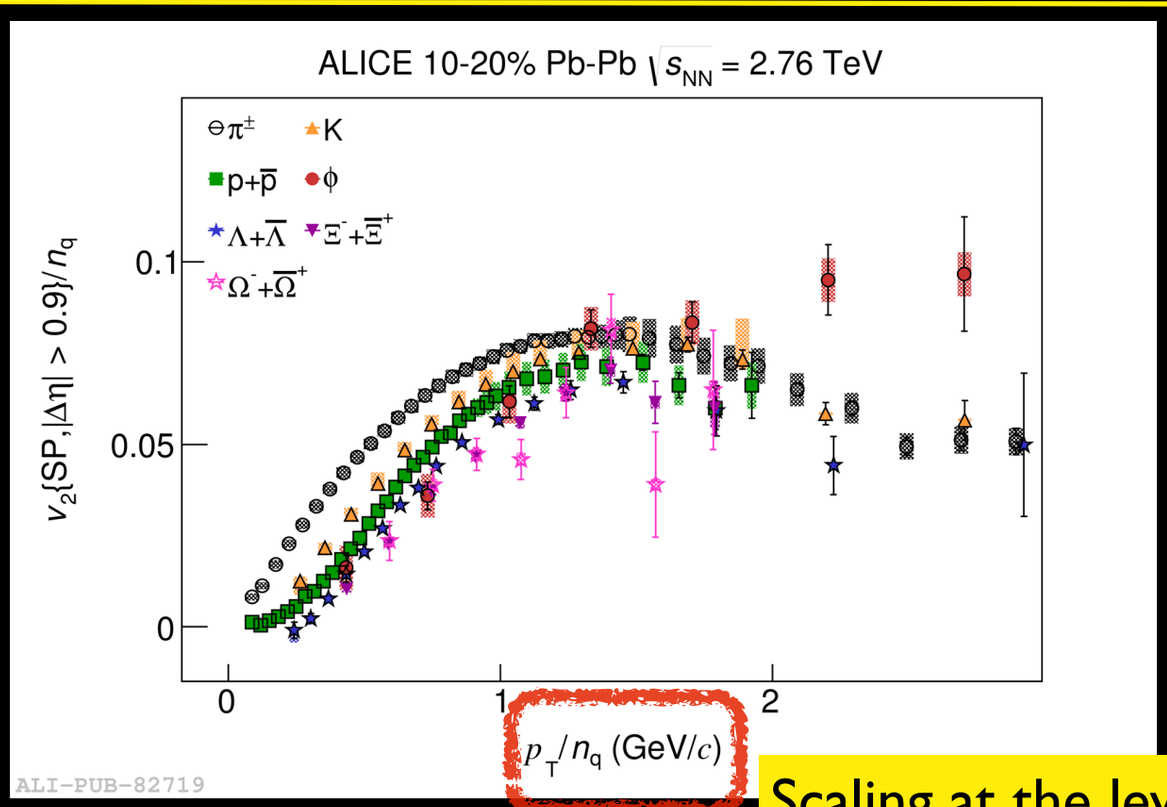
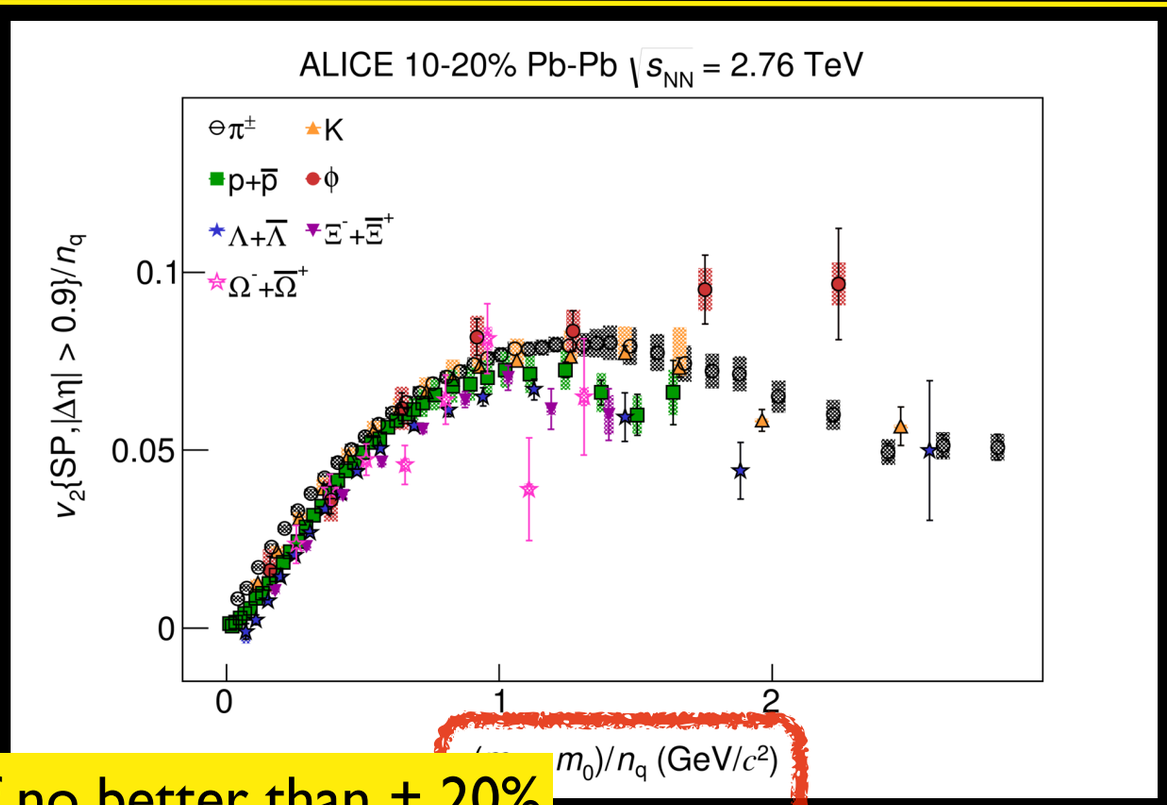
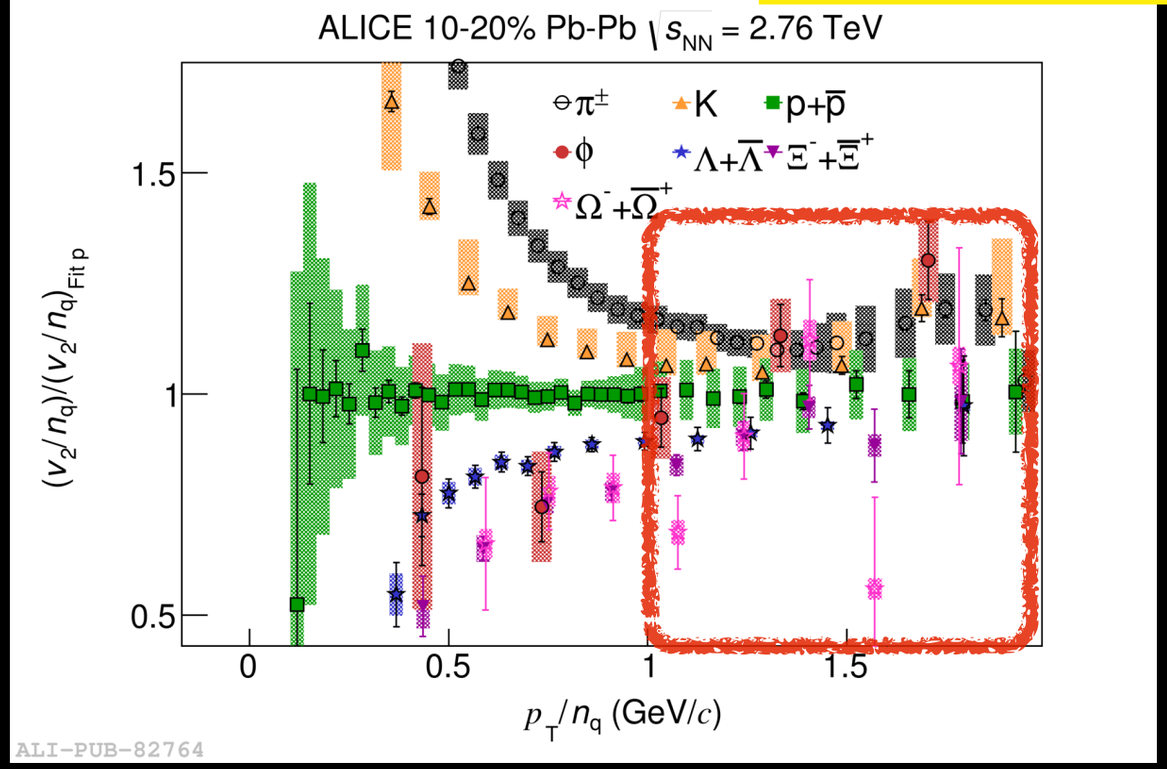
- For $(m_T - m_0)/n_q$ > 0.6 - 0.8 GeV/c^2: scaling is only approximate at the level of ± 20%

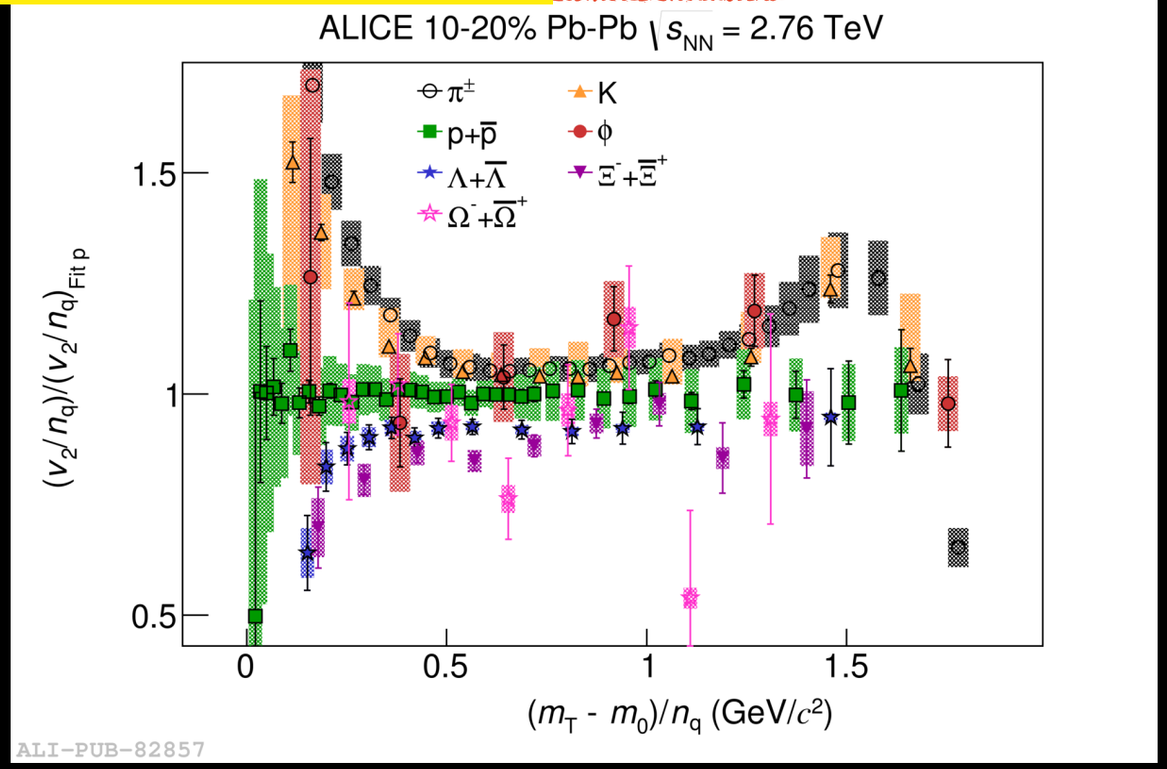
Scaling properties at the LHC



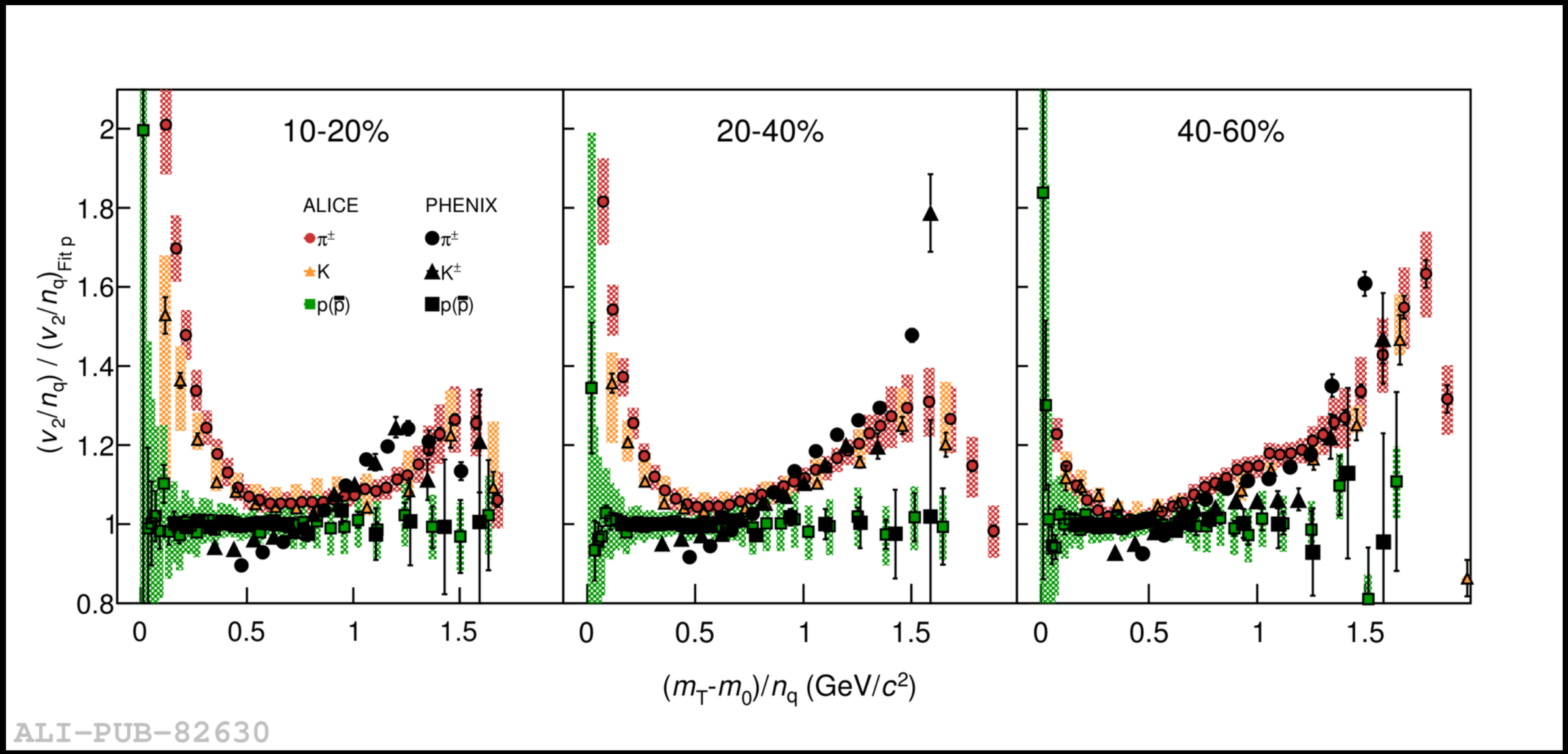


Scaling at the level of no better than ± 20%



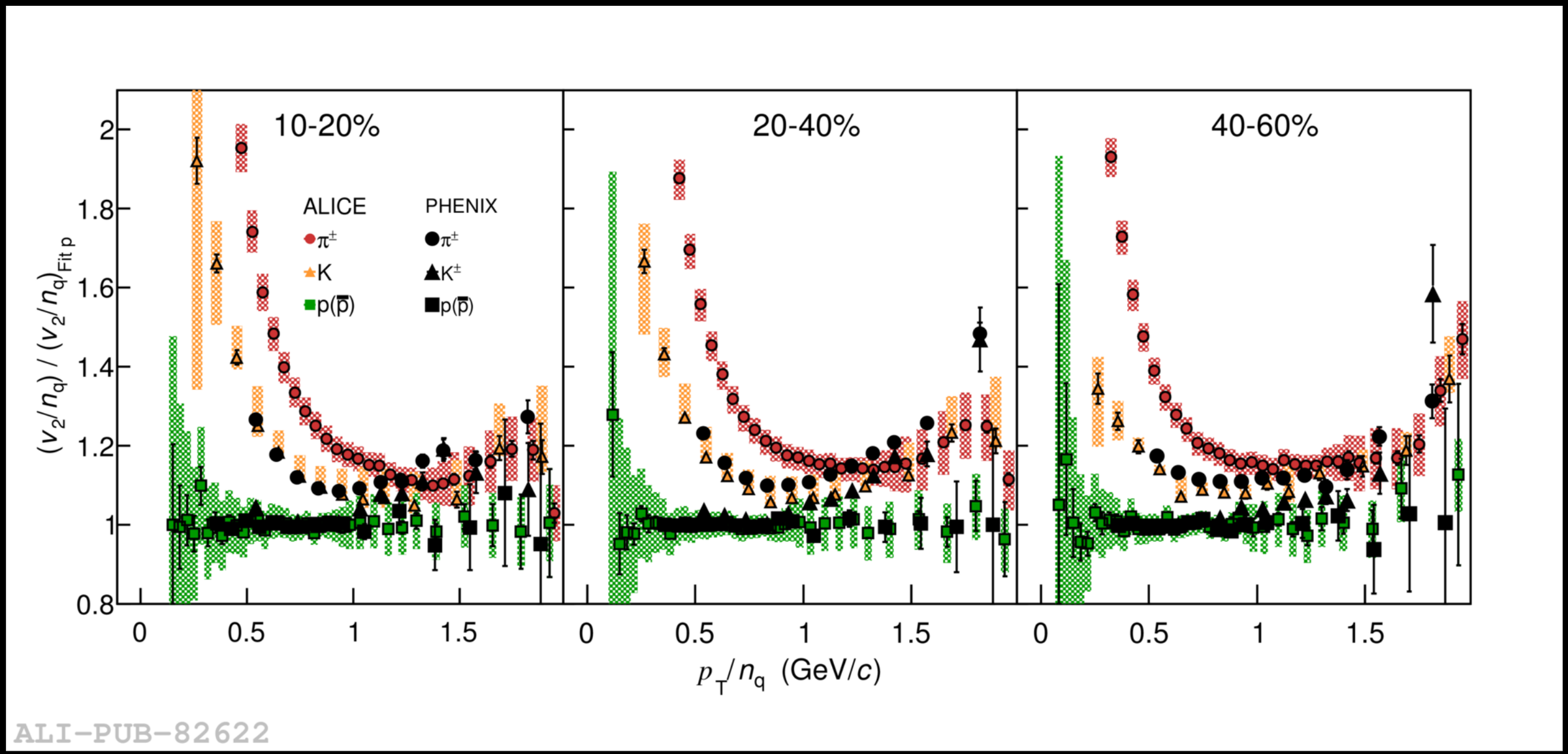


NCQ scaling in $(m_T - m_0)/n_q$ (double ratio): evolution with energy



Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species

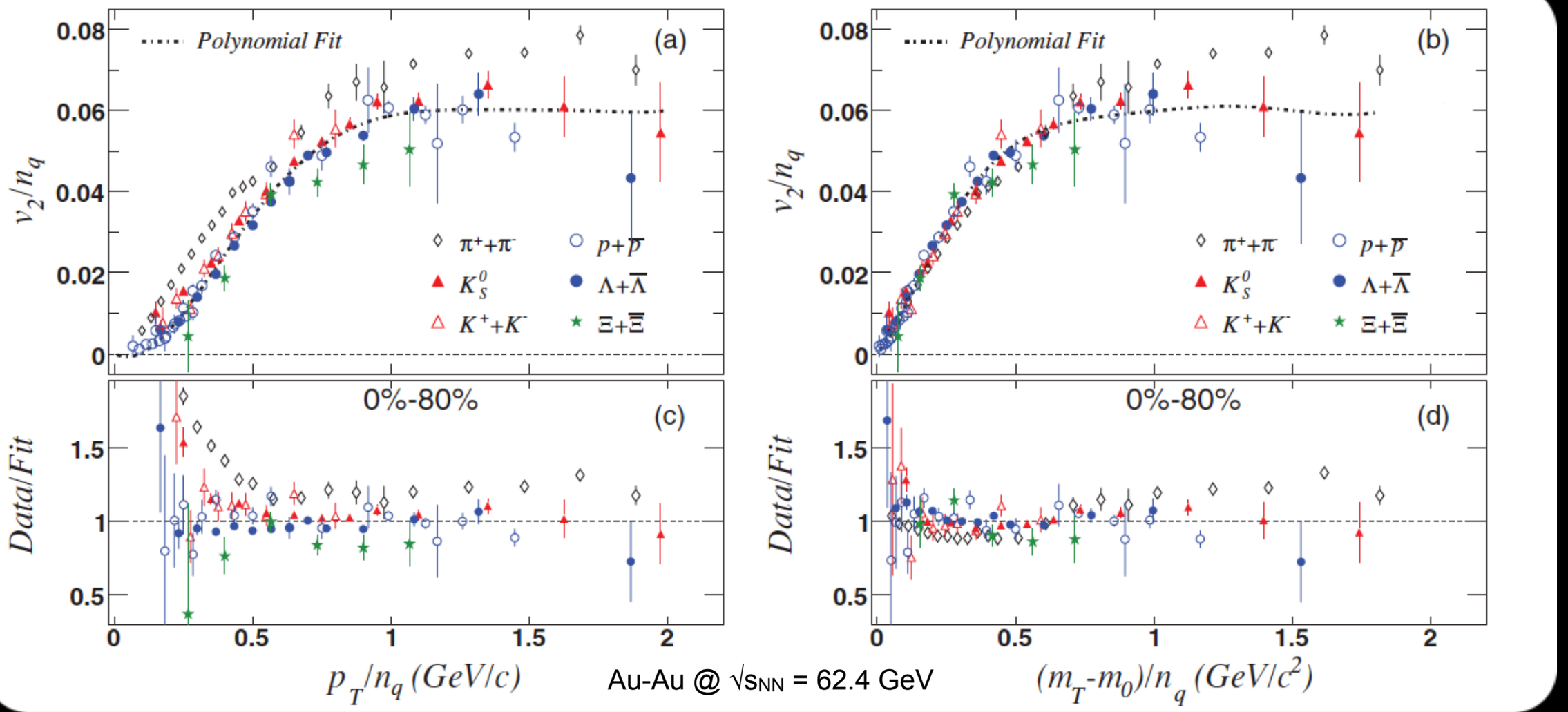
NCQ scaling in p_T/n_q (double ratio): evolution with energy



Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species

A. Adare *et al.,* [PHENIX Collaboration], Phys. Rev. **C85,** (2012) 064914, [arXiv:1203.2644 [nucl-ex]].

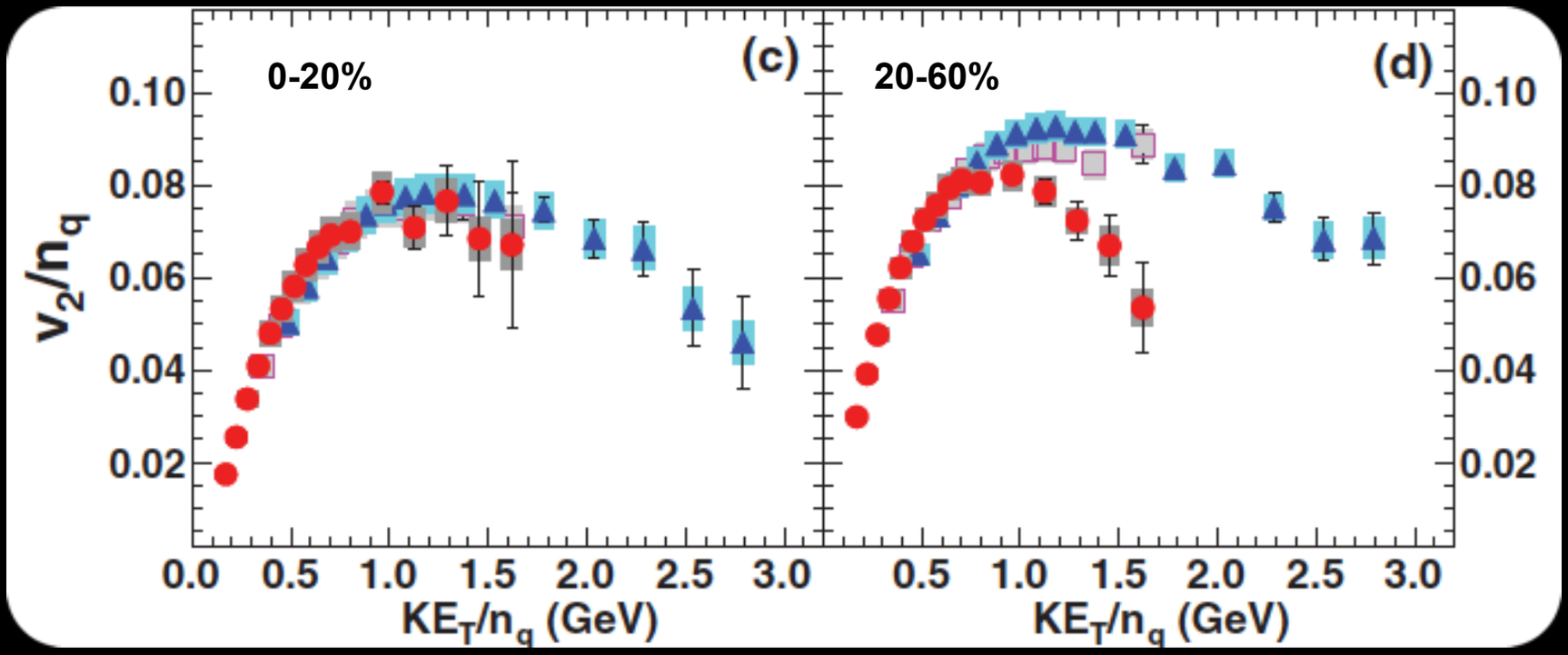
Universal scaling of v_2 observed at RHIC?



B. Abelev *et al.*, (STAR Collaboration), Phys. Rev. **C75**, (2007) 054906

Deviations from the universal scaling at RHIC

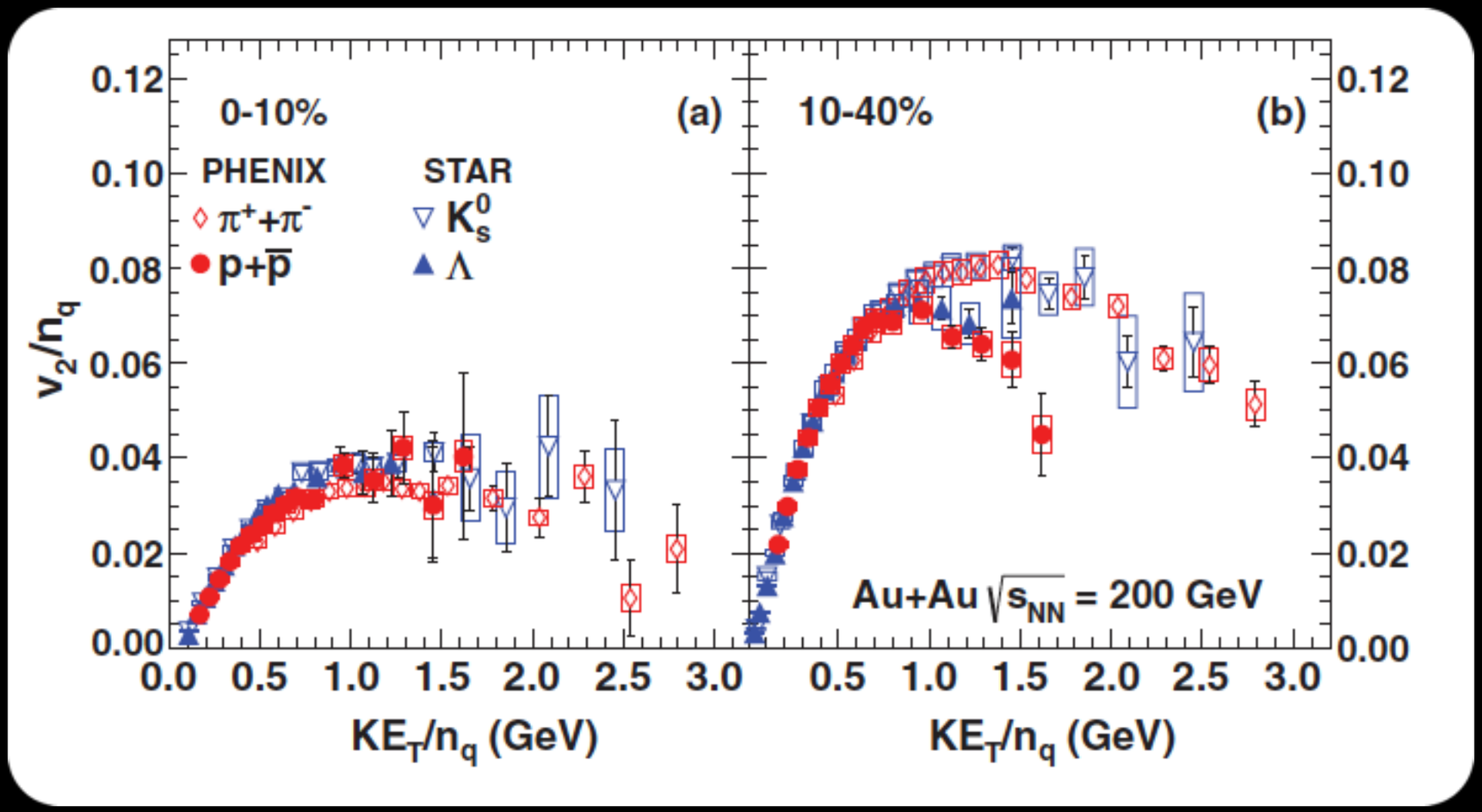
A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. **C85**, (2012) 064914



Deviations for $KE_T/n_q > 0.8$ GeV/c^2 depend on centrality

Deviations from the universal scaling at RHIC

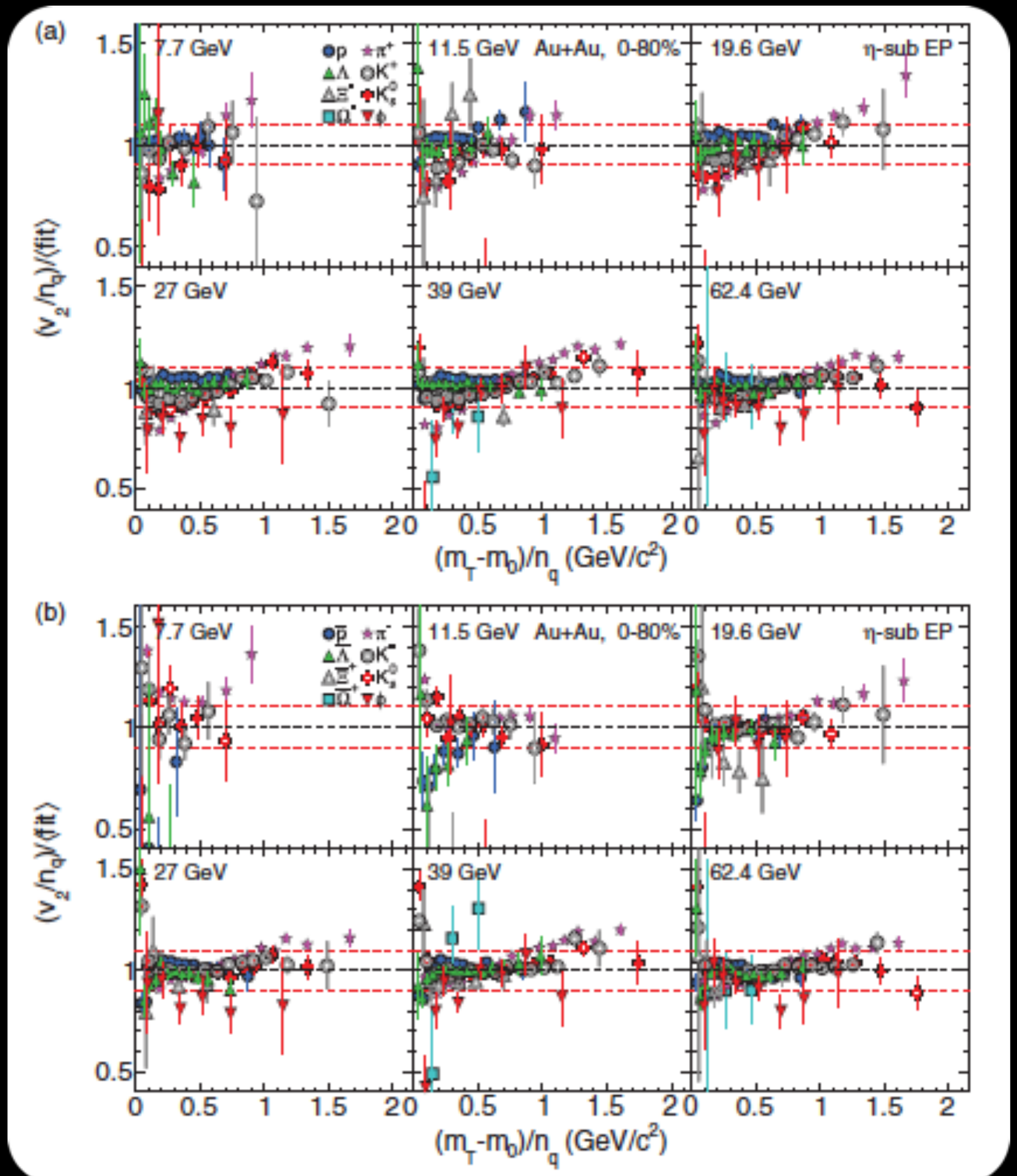
A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. **C85**, (2012) 064914



Similar deviations observed by STAR?

BES: NCQ scaling

- Scaling holds at the same level (±10-15%) as for higher energies for particles and antiparticles separately



L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902