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

Panos Christakoglou (Nikhef)

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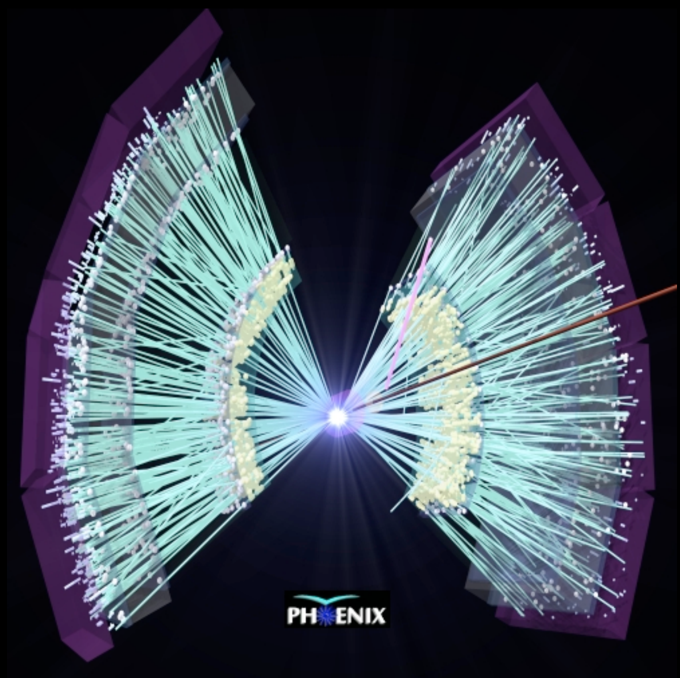
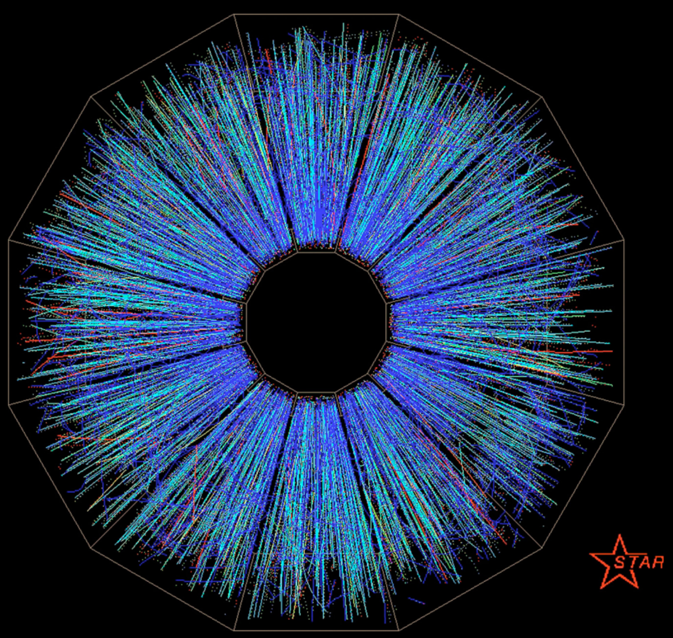
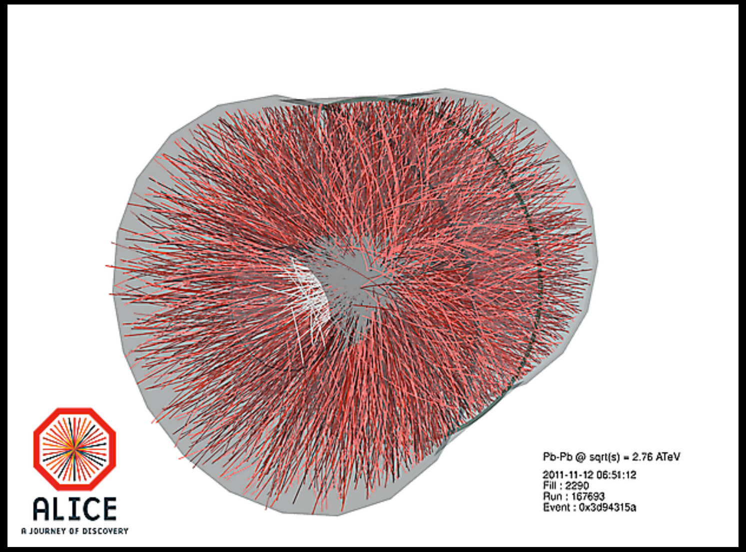
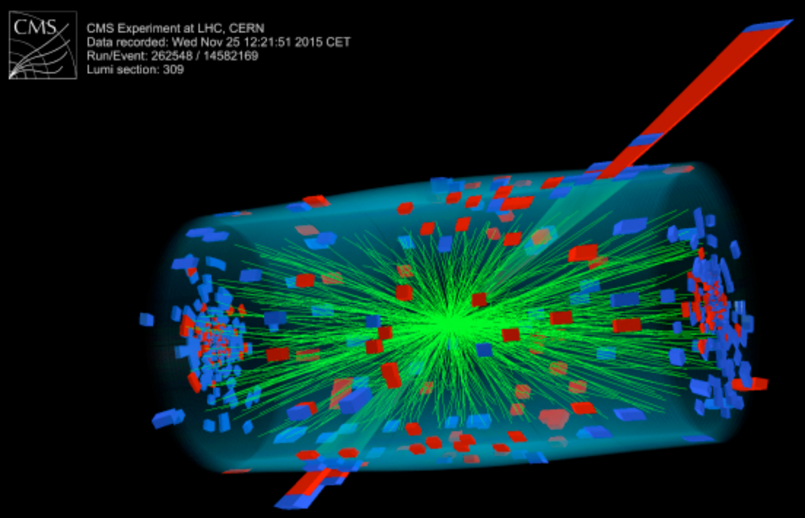








Panos Christakoglou (Nikhef)

Many thanks to the (flow) groups from PHENIX, STAR,CMS, ALICE

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

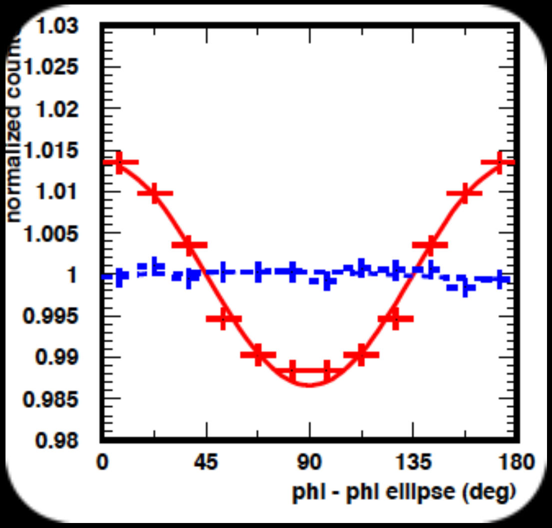
Could not help adding my (in some cases biased) interpretation of results

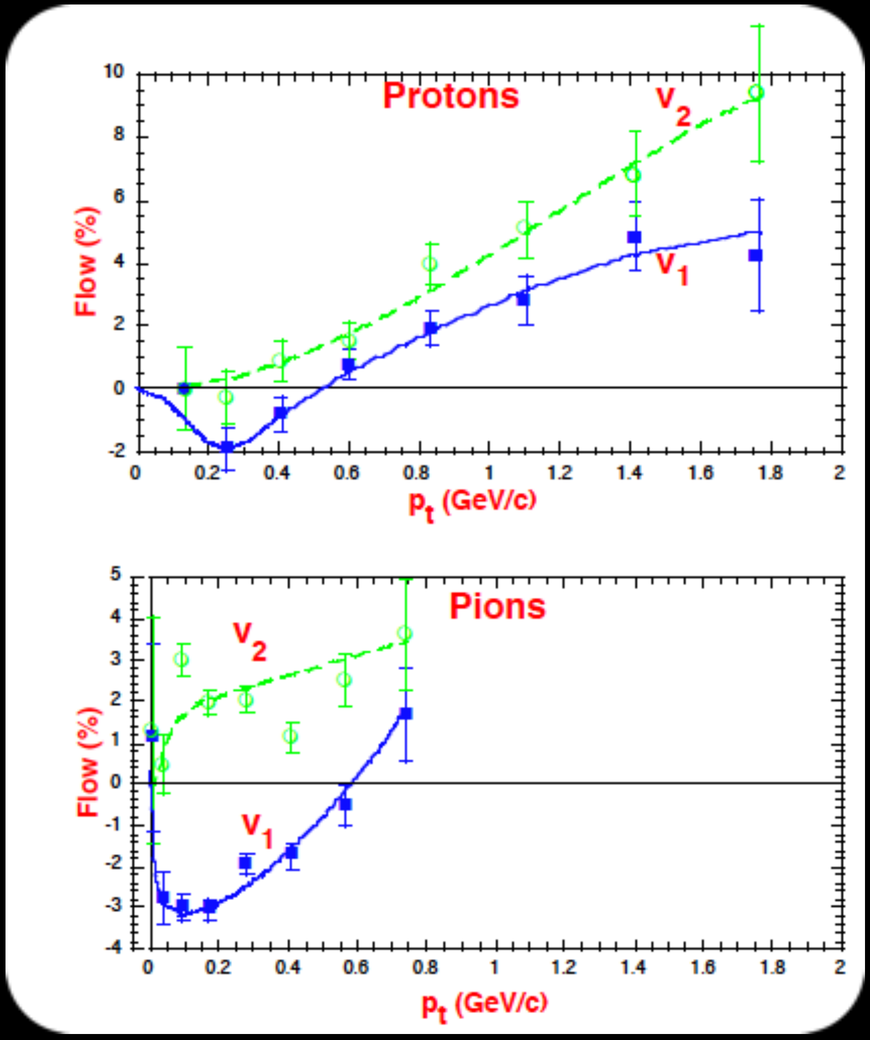
Panos Christakoglou (Nikhef)

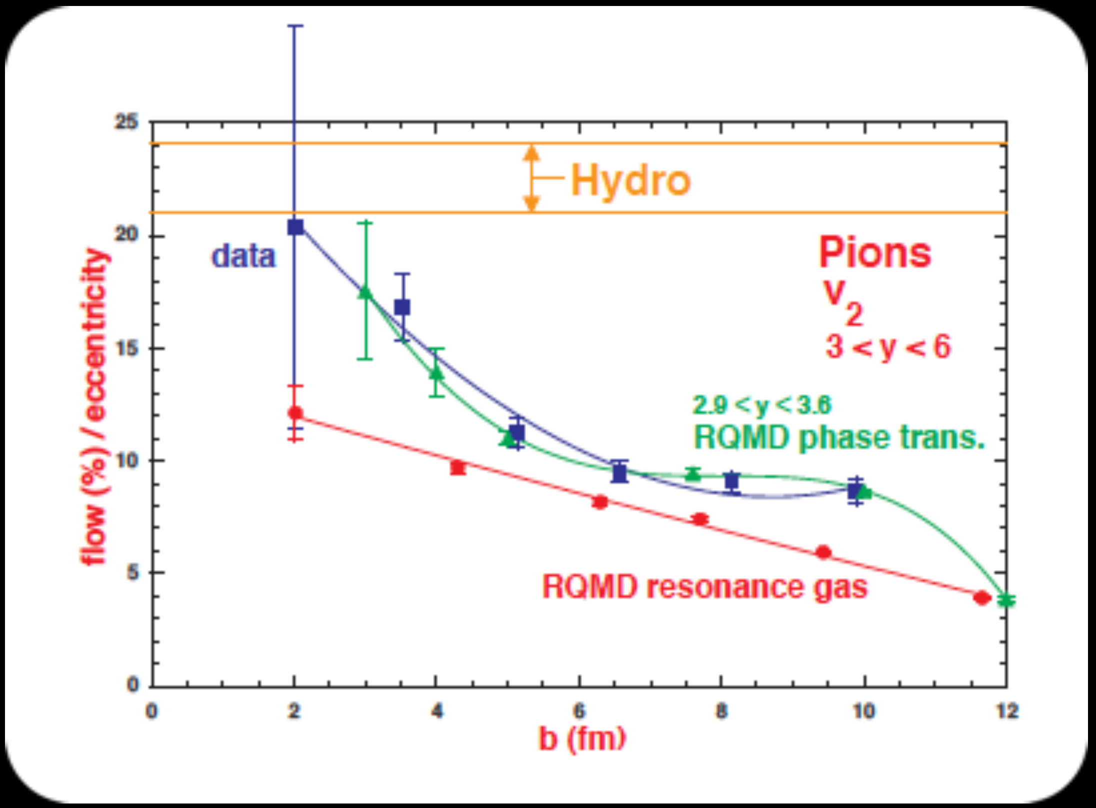
A bit of a history…

(NA49 Collaboration): Phys.Rev.Lett. 80 (1998) 4136

(NA49 Collaboration): Nucl.Phys. A661 (1999) 341-344







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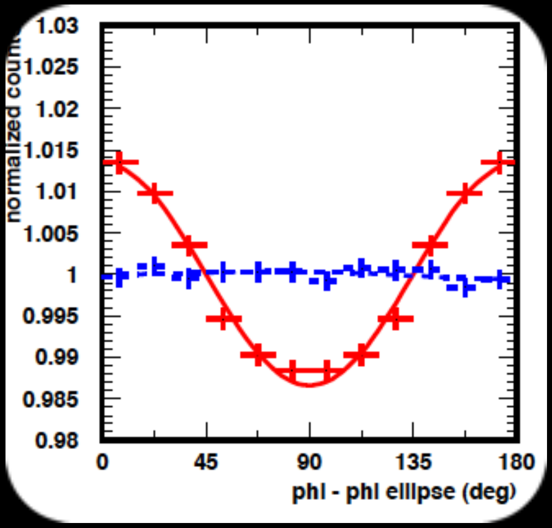

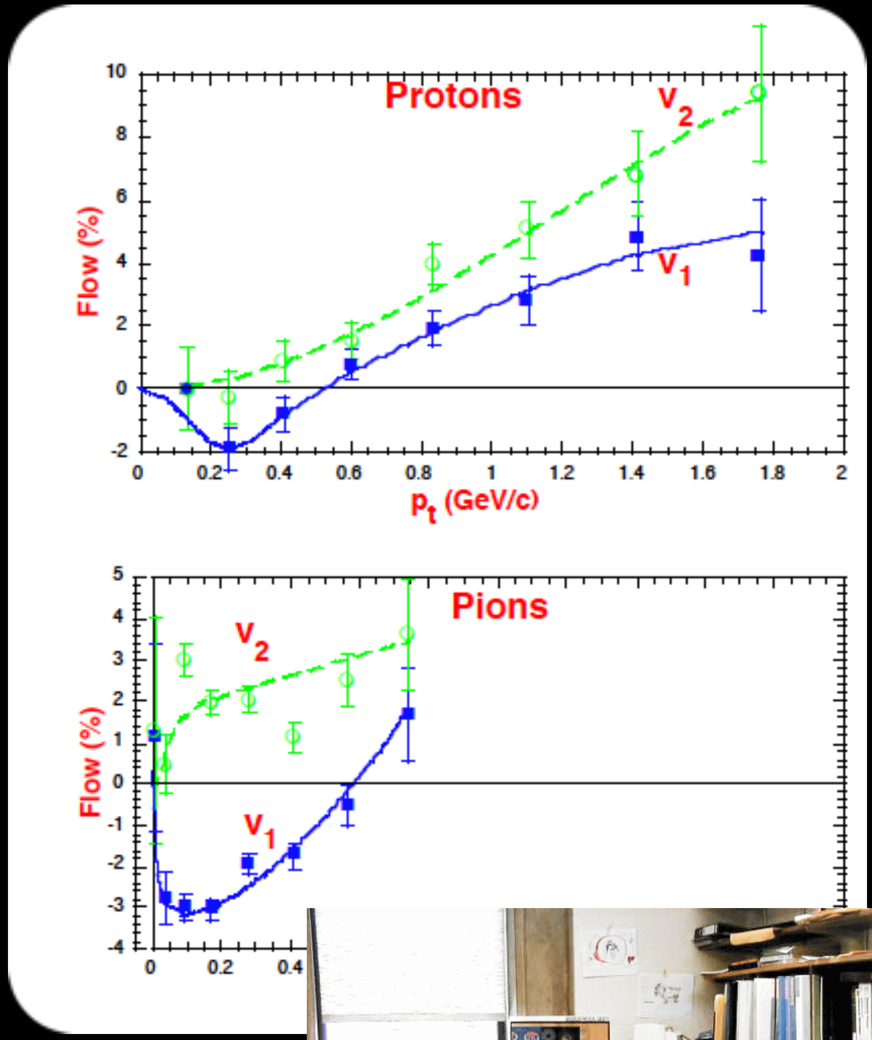

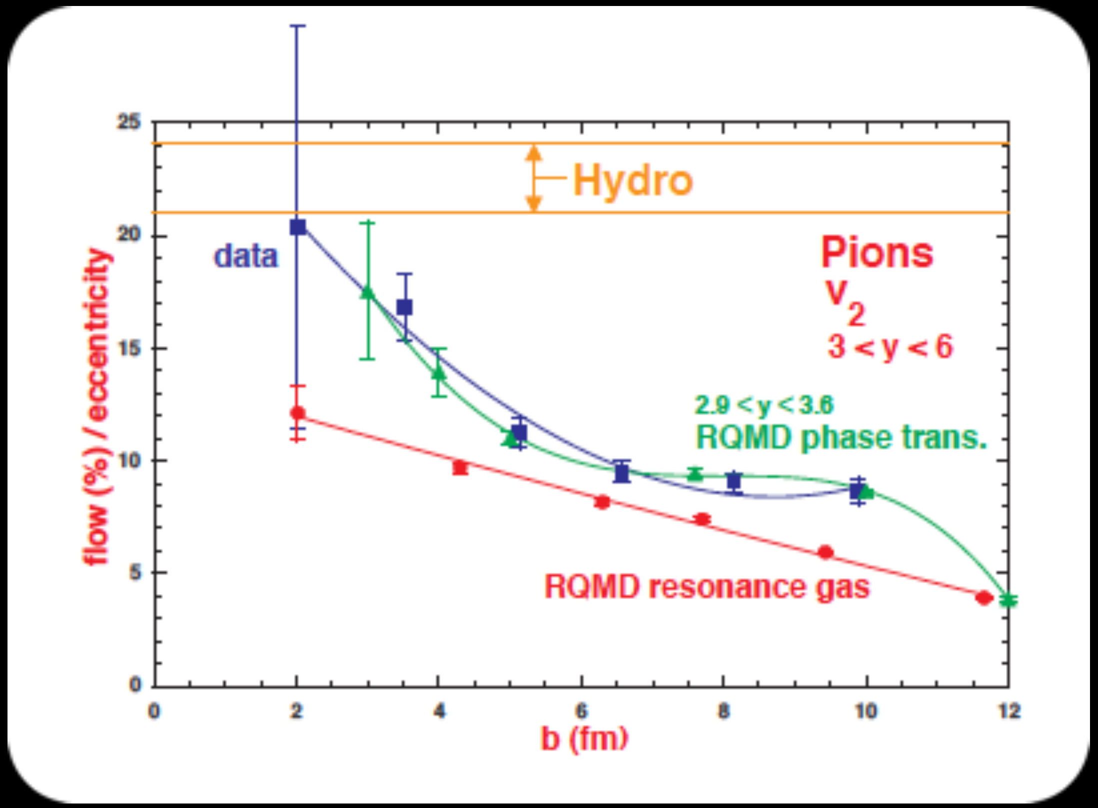

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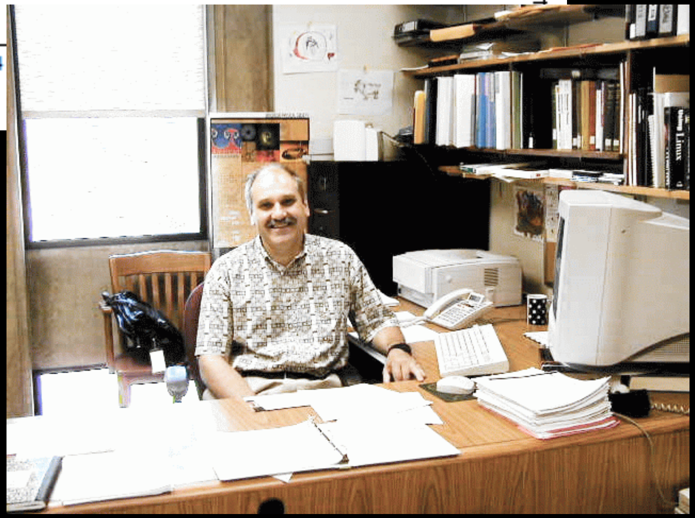

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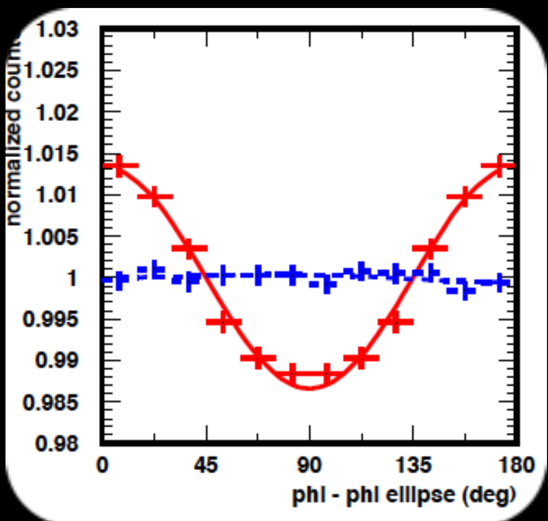

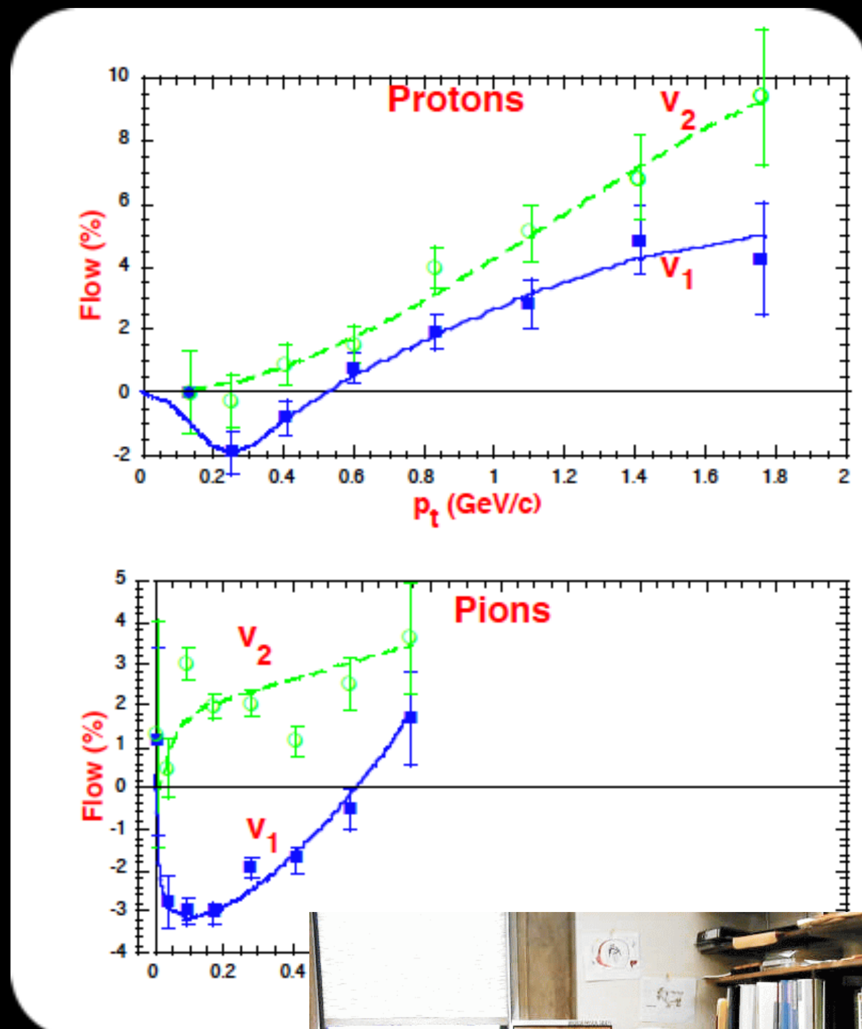

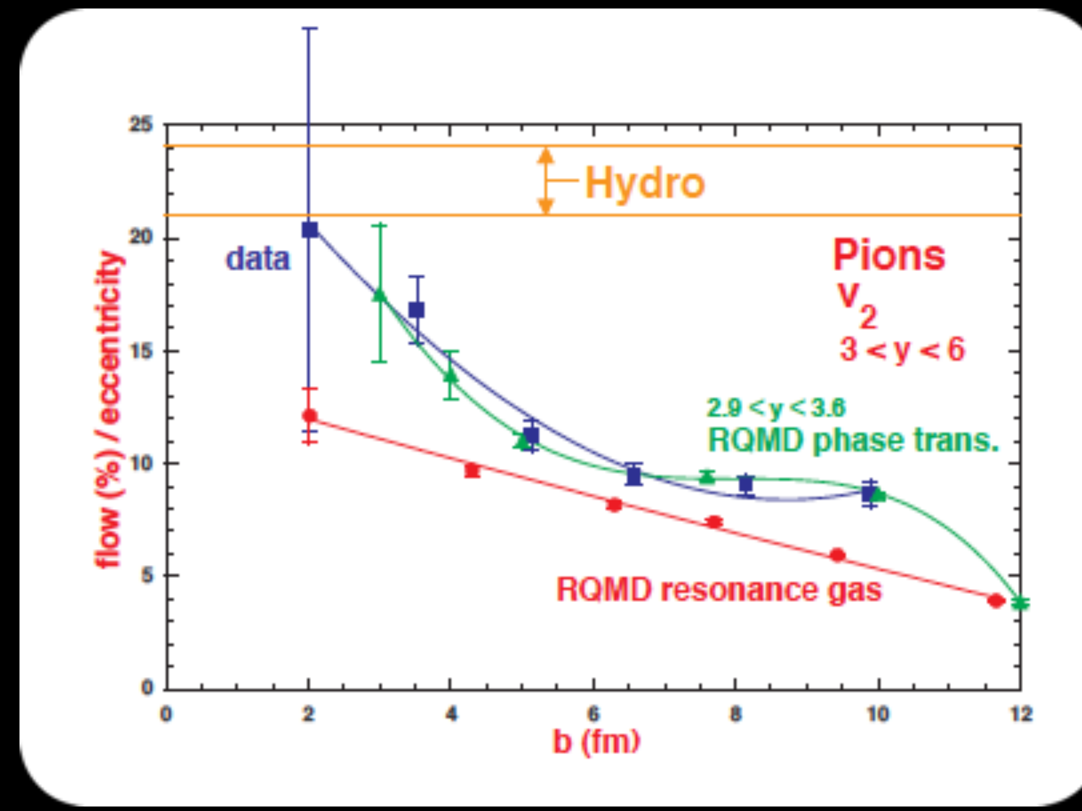

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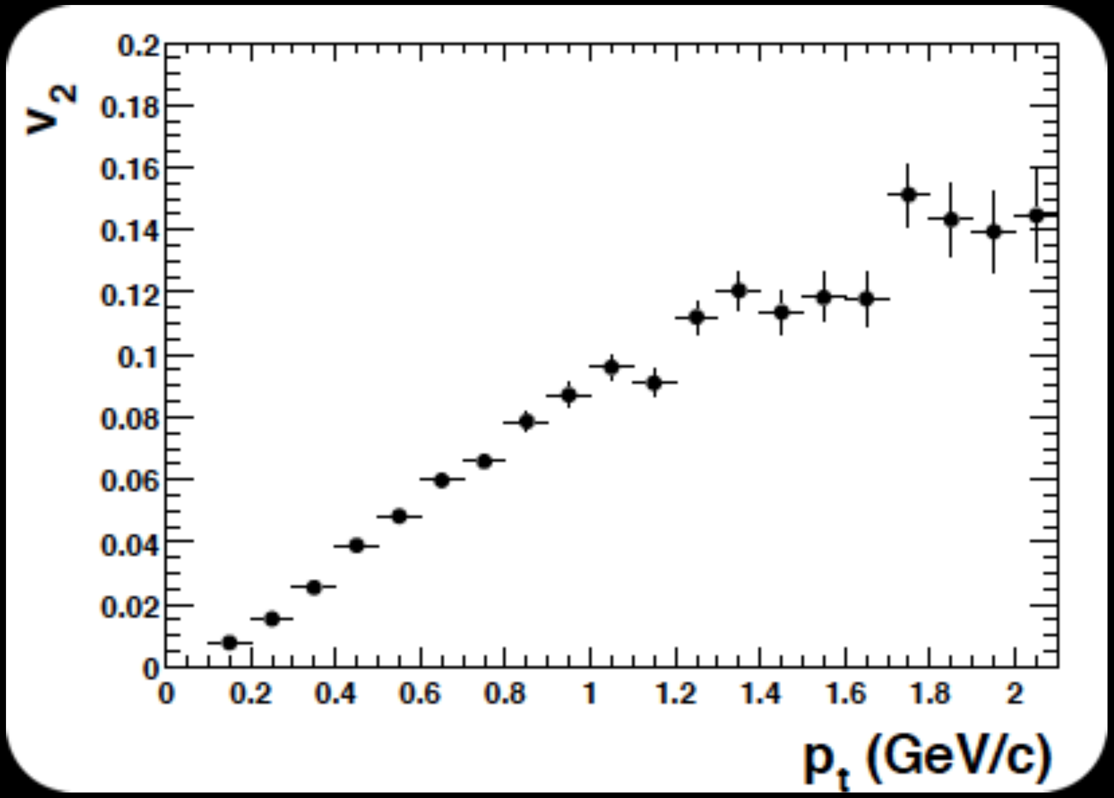
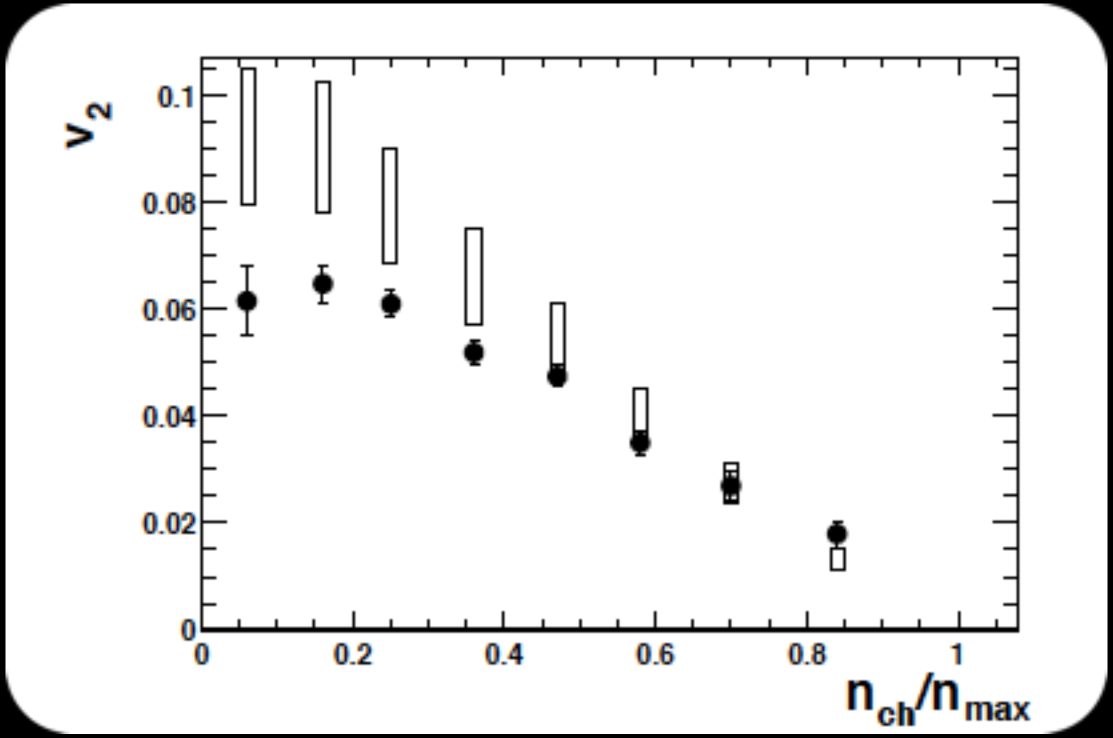
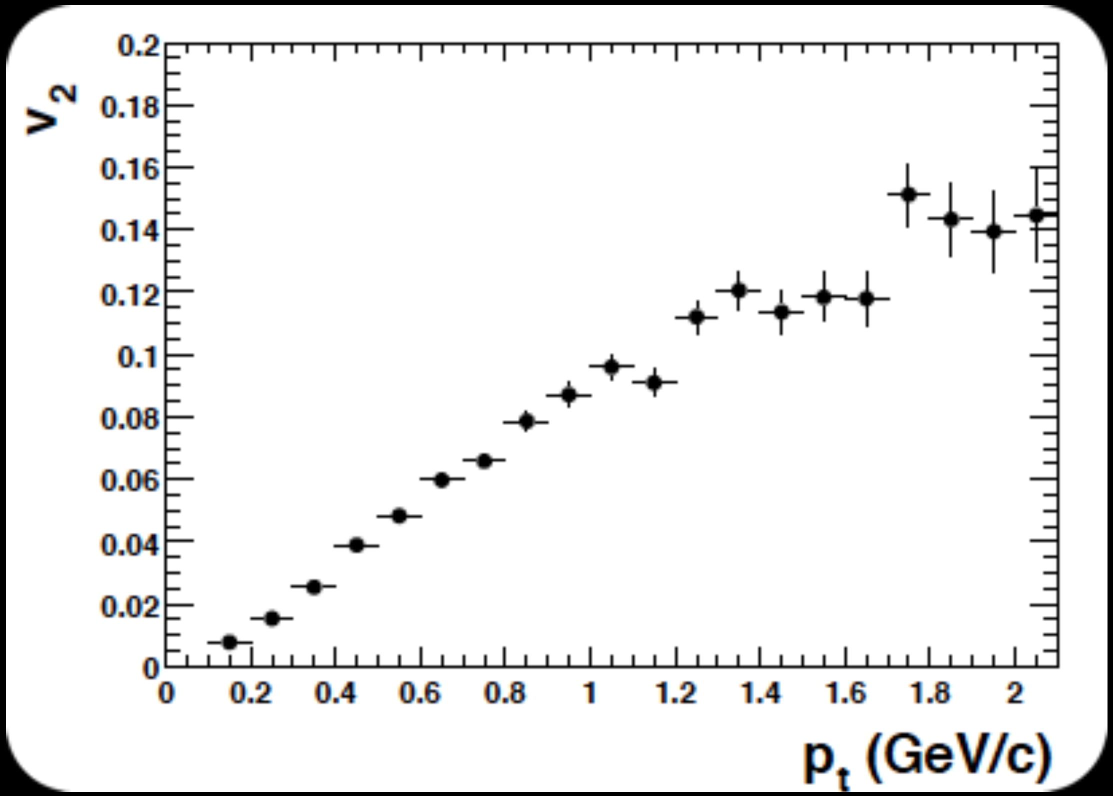
The birth of the sQGP paradigm…

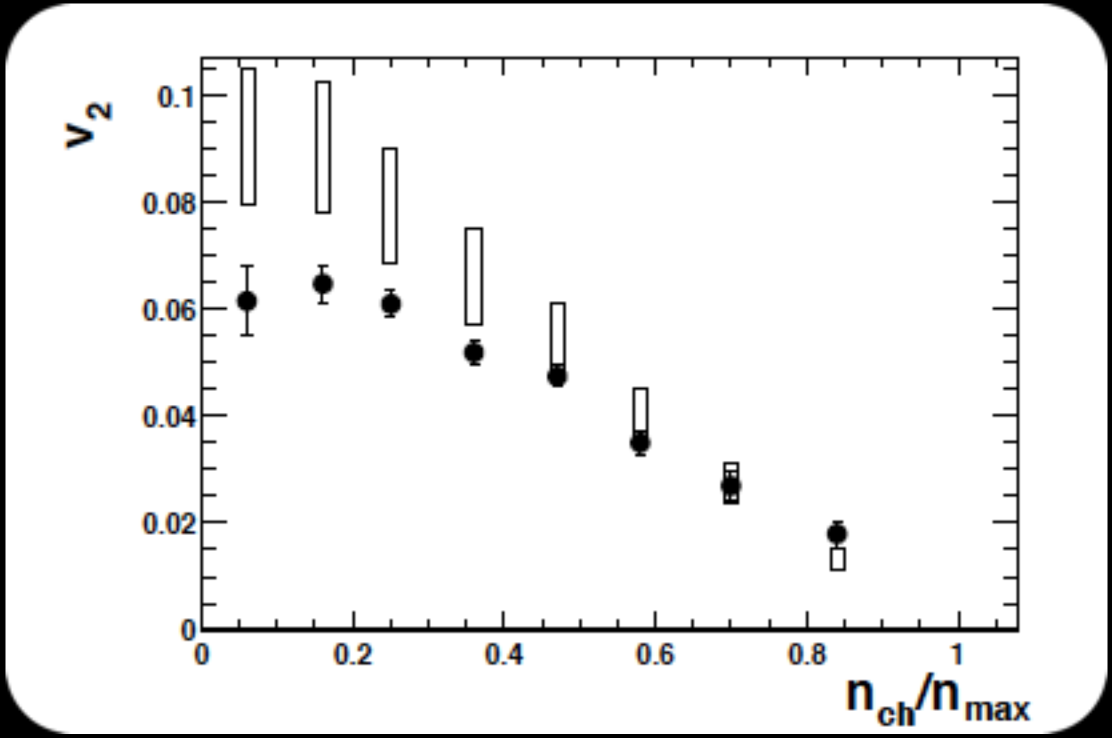
(STAR Collaboration) Phys. Rev. Lett. 86 (2001) 402





(STAR Collaboration) Phys. Rev. Lett. 86 (2001) 402



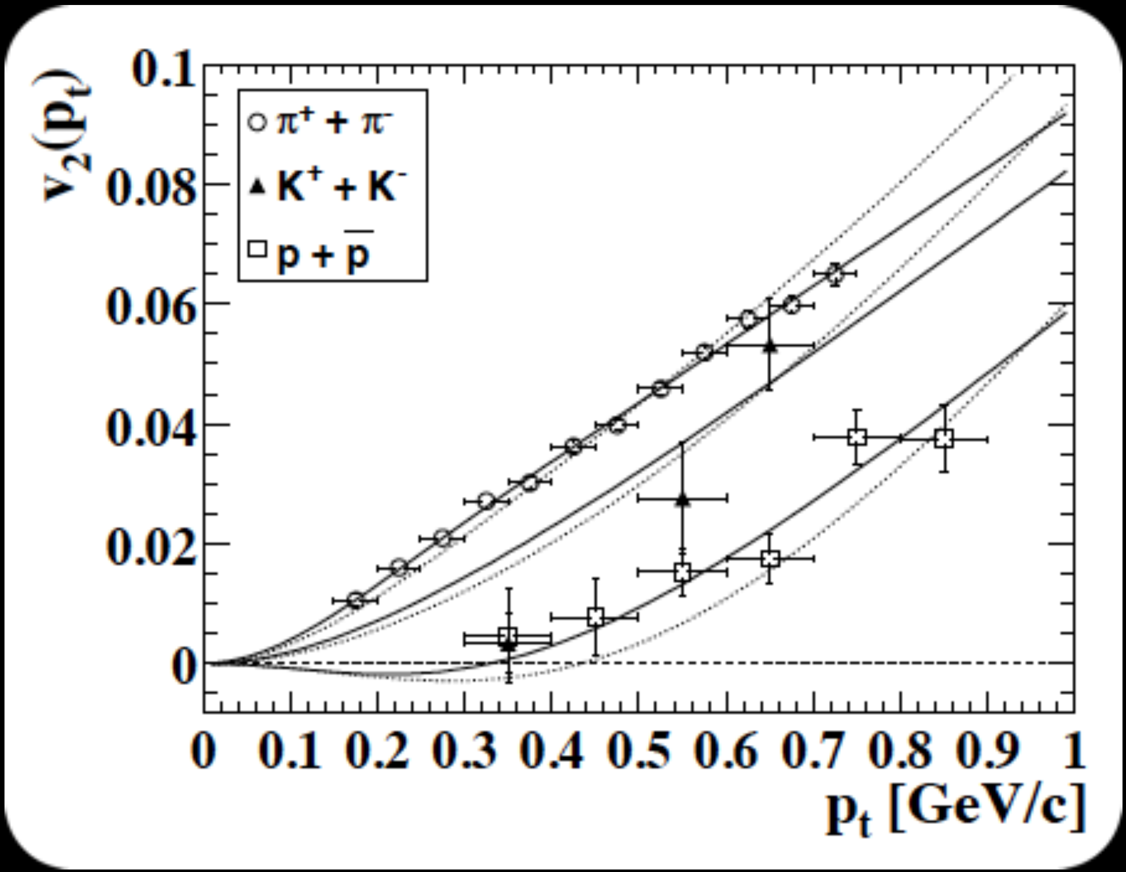


Random names (faces) from that author list:

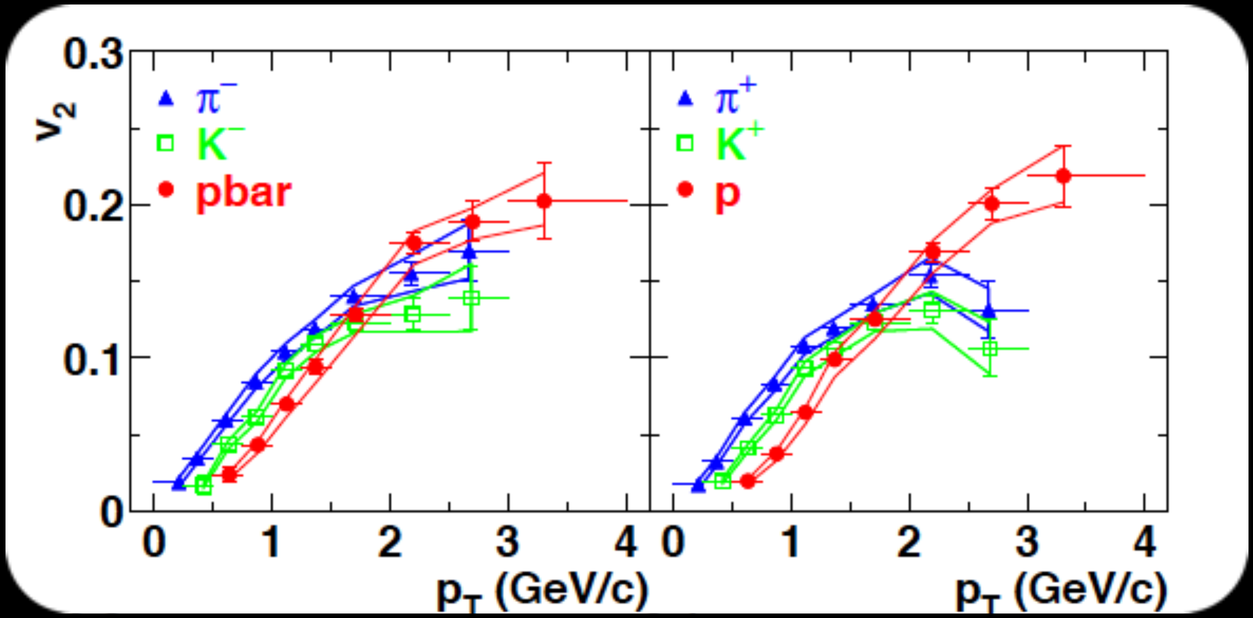
NIKHEF

…established by looking at the details

(STAR Collaboration): Phys. Rev. Lett. 87 (2001) 182301



(PHENIX Collaboration): Phys.Rev.Lett.91, 182301,2003



- Mass ordering at low p_T
- Good description by blast-wave parametrisation

…established by looking at the details

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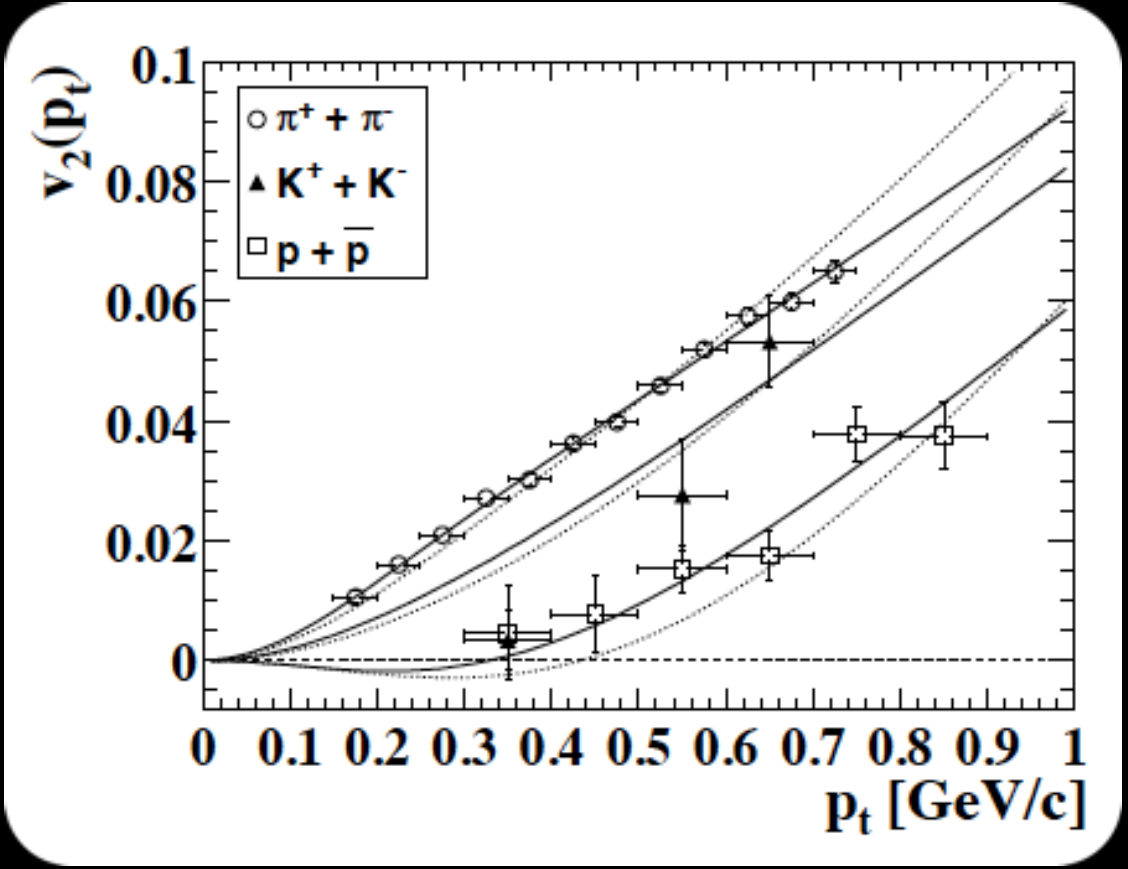

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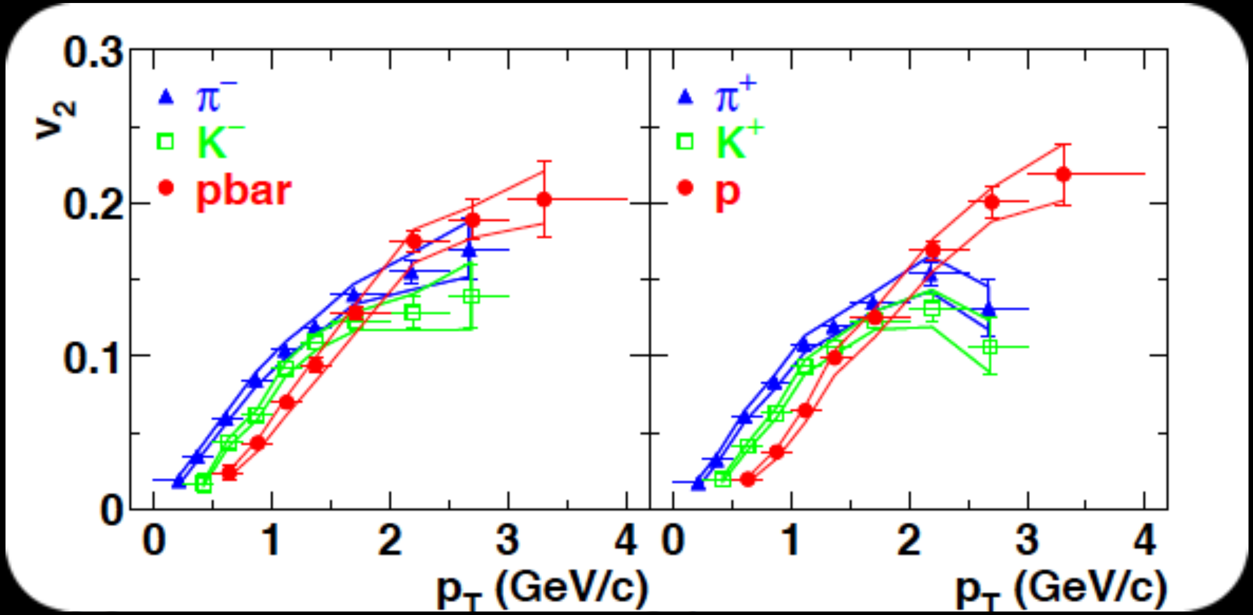

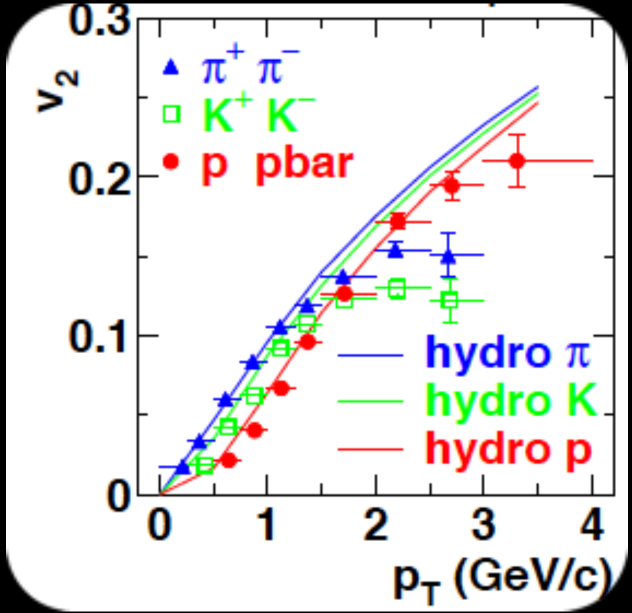

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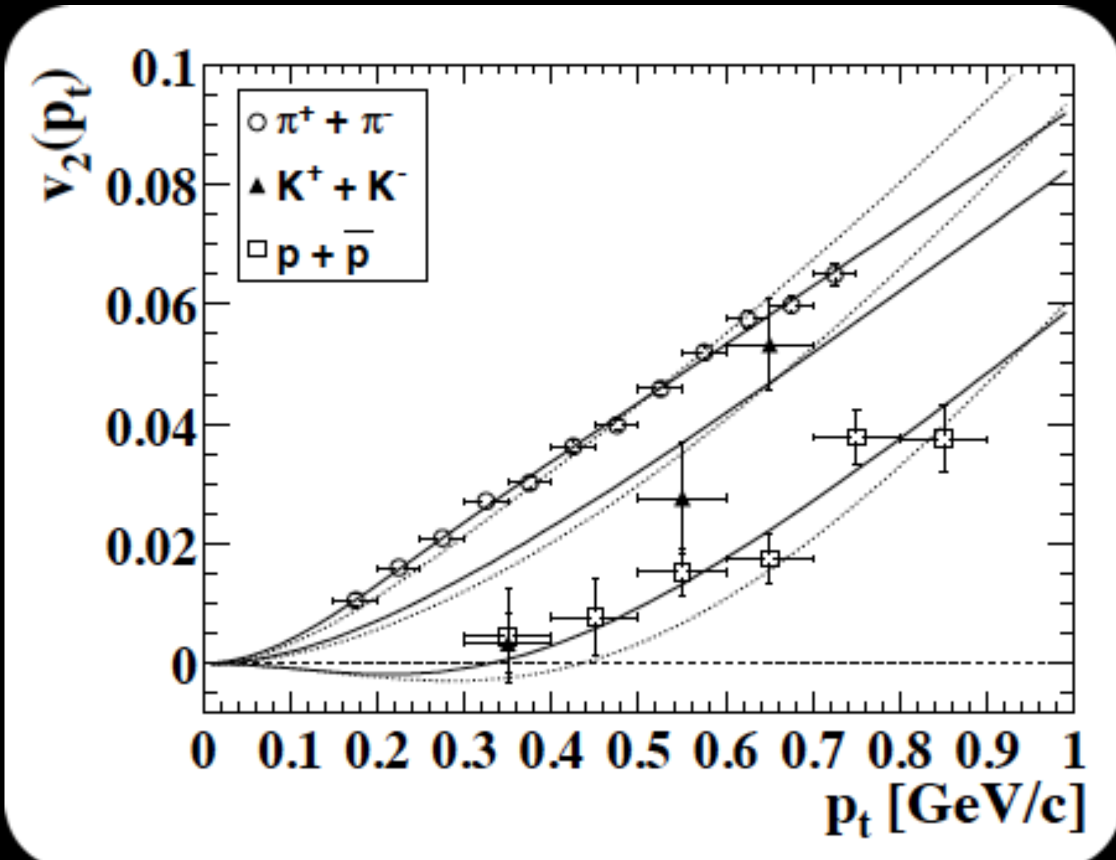
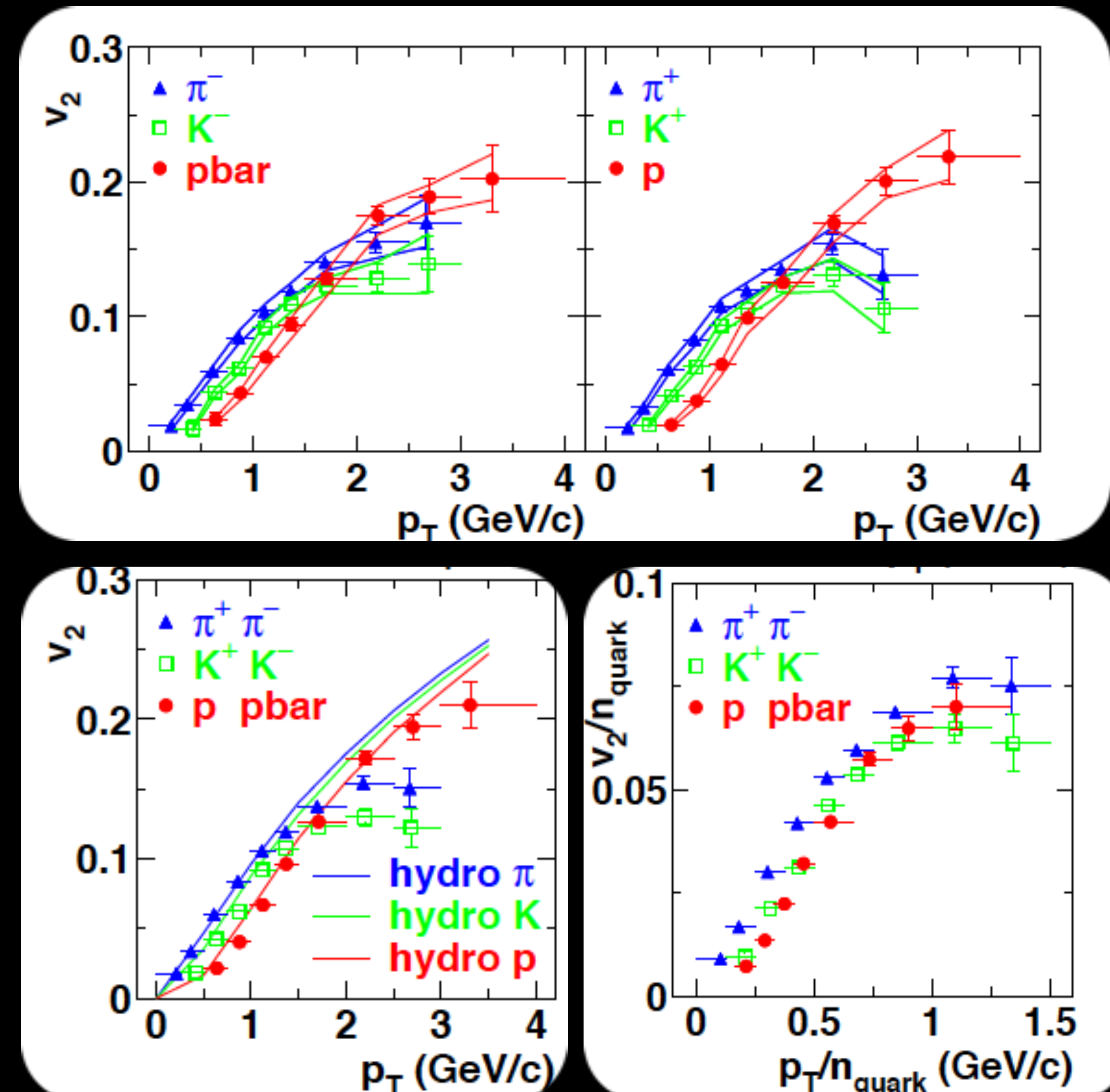
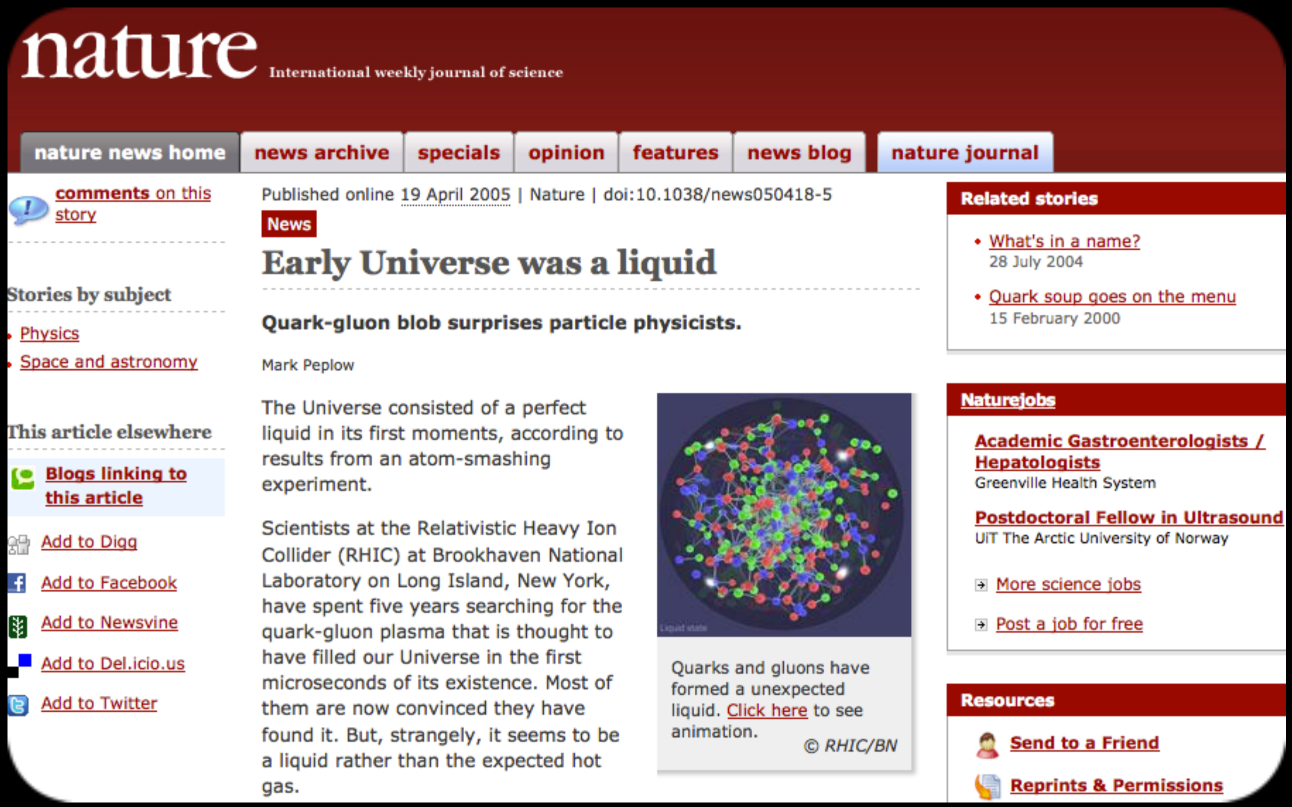


(PHENIX Collaboration): Phys.Rev.Lett.91, 182301,2003



- Mass ordering at low p_T
- Good description by blast-wave parametrisation
- Agreement with (ideal) hydrodynamical calculations
- Apparent NCQ scaling at intermediate p_T

The "perfect liquid" at RHIC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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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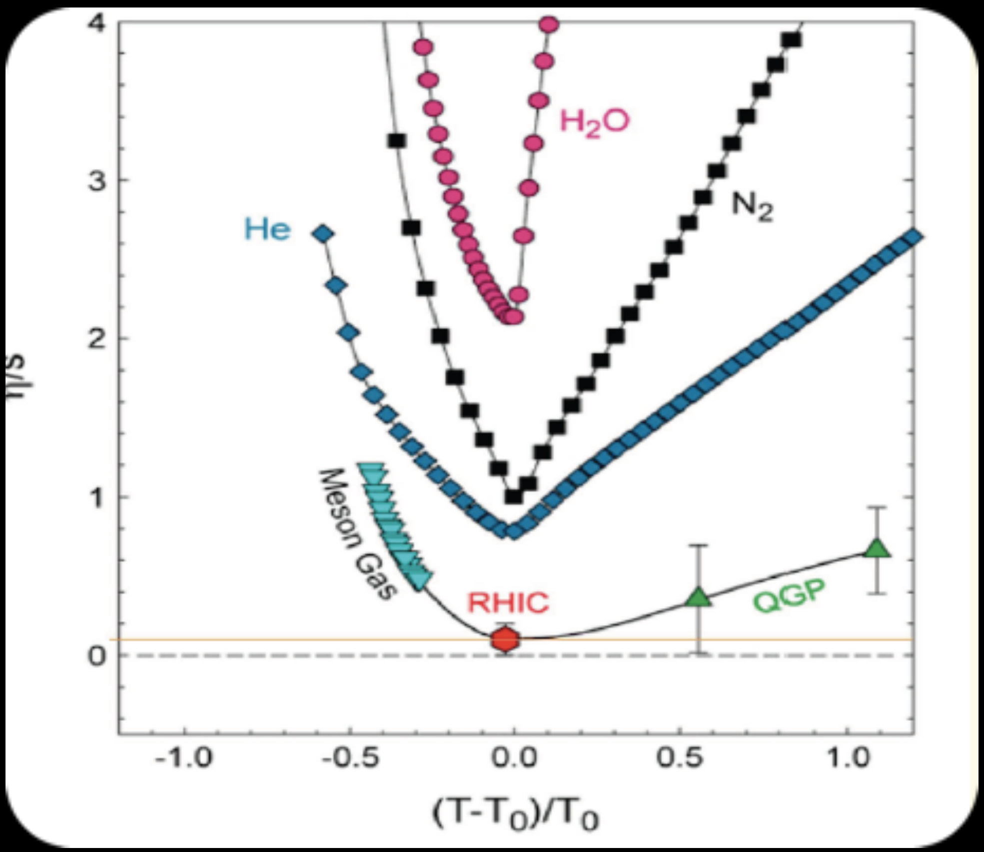

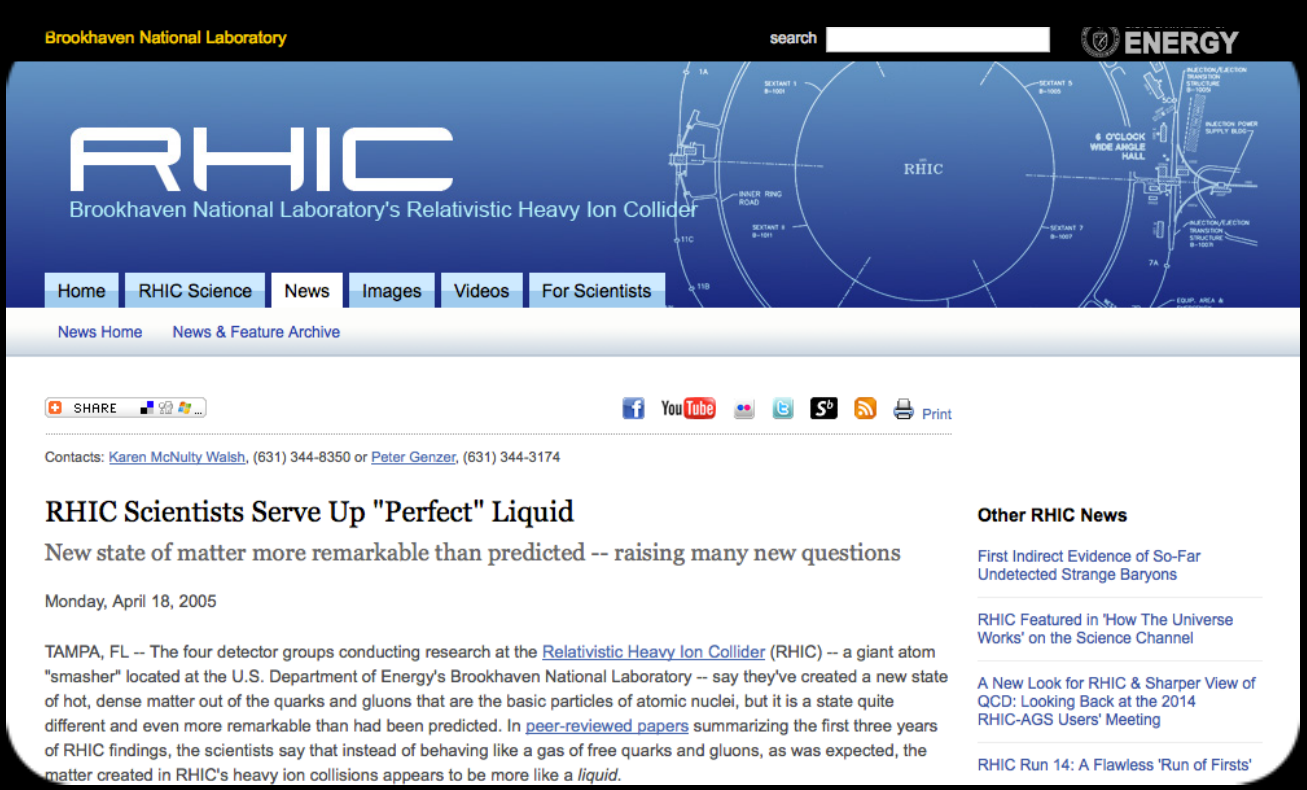
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RHIC — Brookhaven National Laboratory's Relativistic Heavy Ion Collider

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

RHIC Scientists Serve Up "Perfect" Liquid

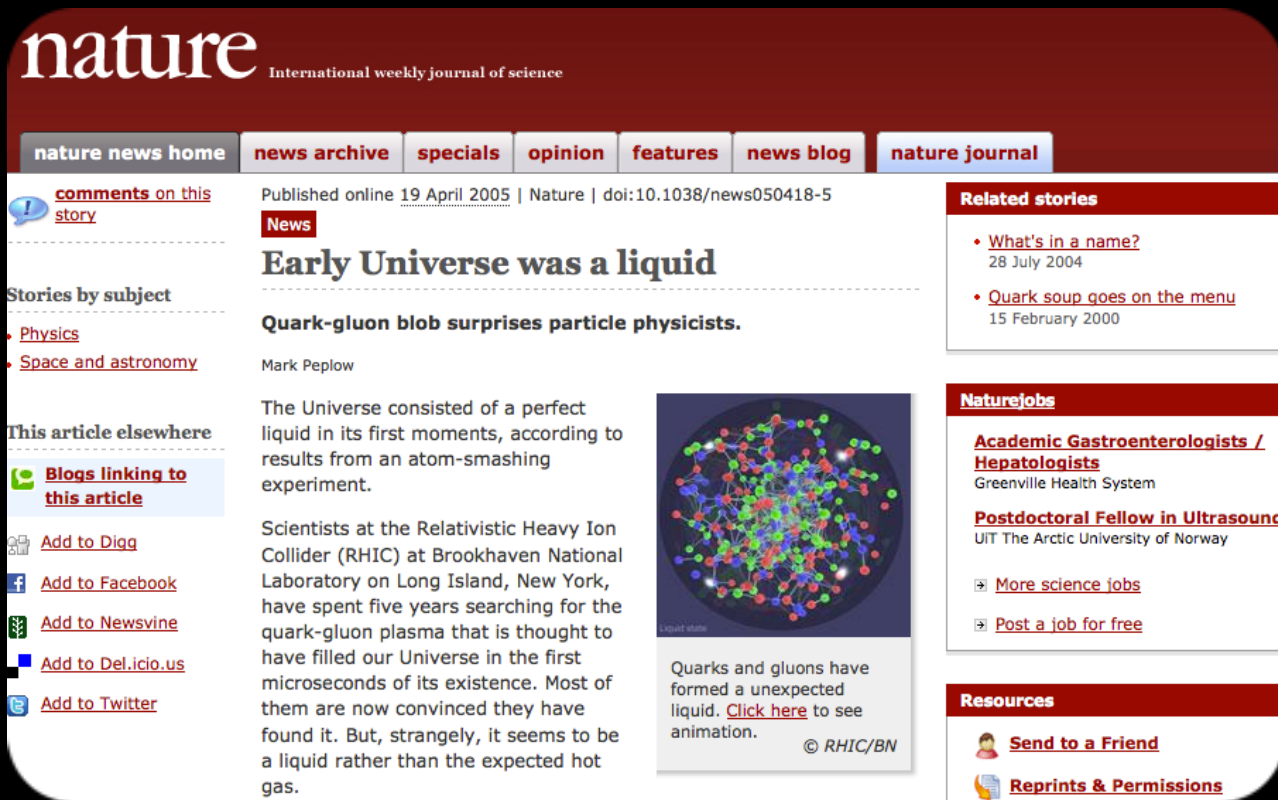
New state of matter more remarkable than predicted -- raising many new questions

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'

The "perfect liquid" at RHIC and LHC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Quarks and gluons have formed a unexpected liquid. Click here to see animation. © RHIC/BN

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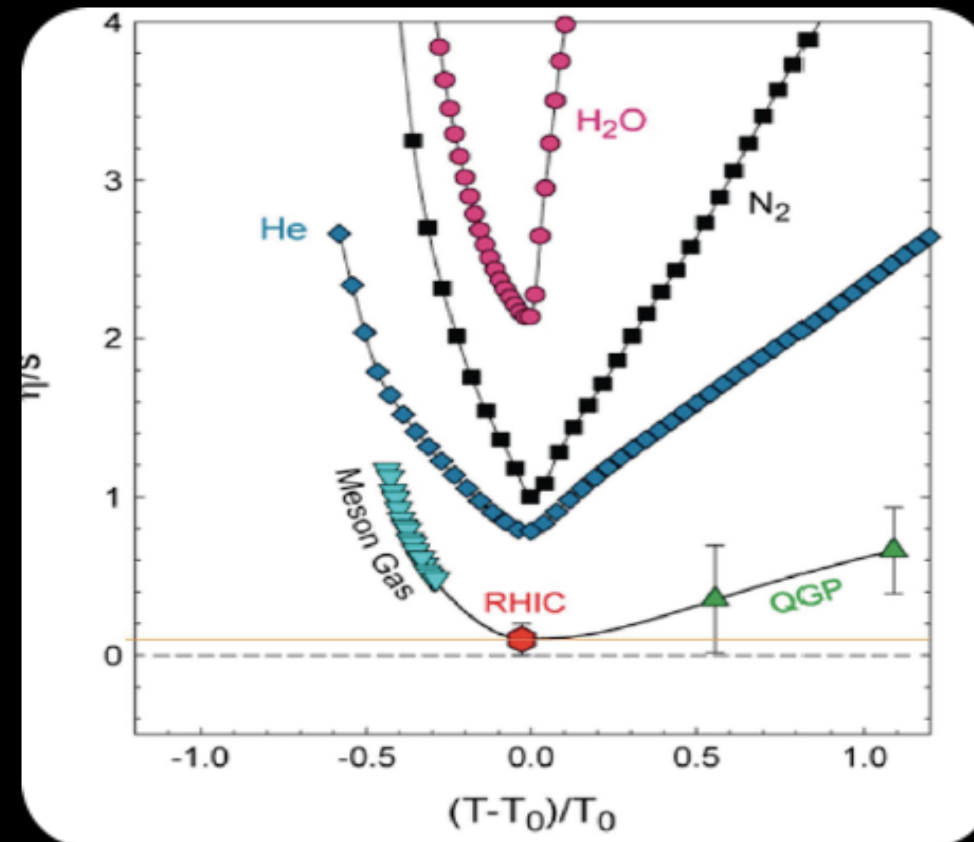

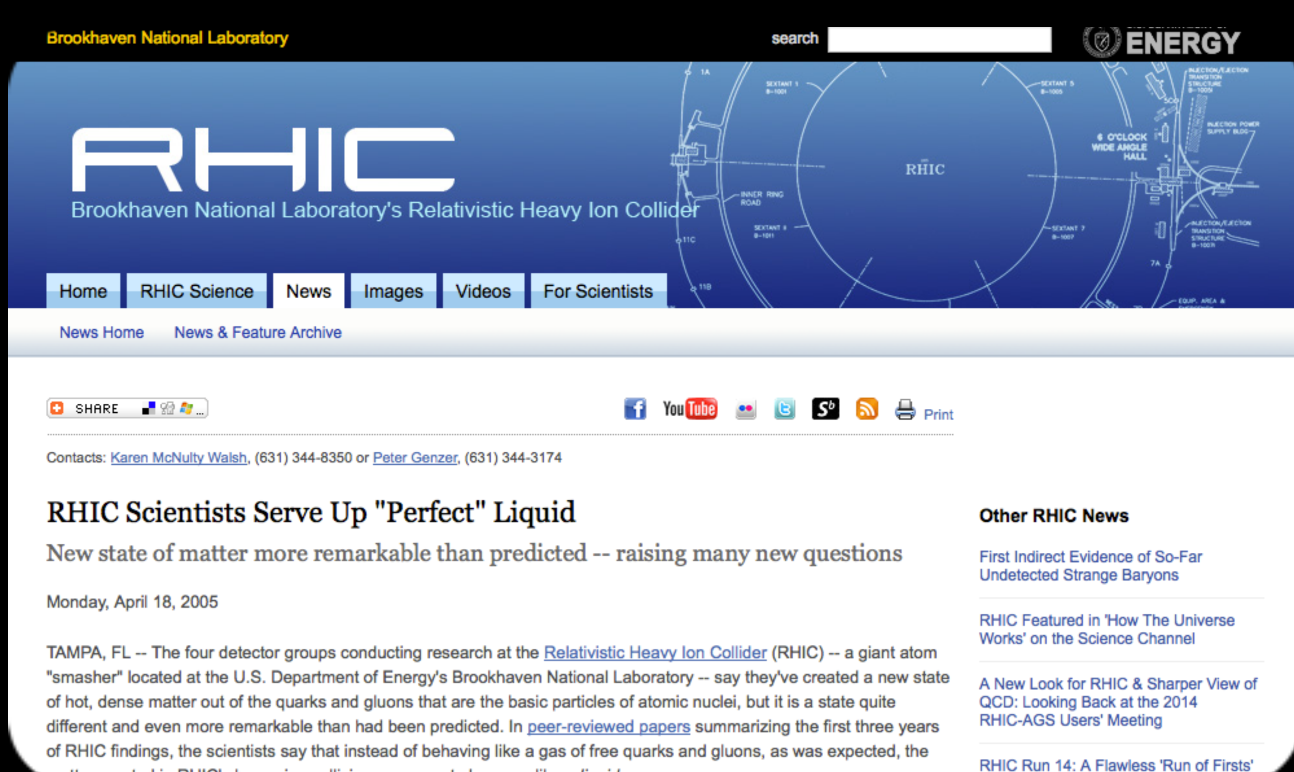
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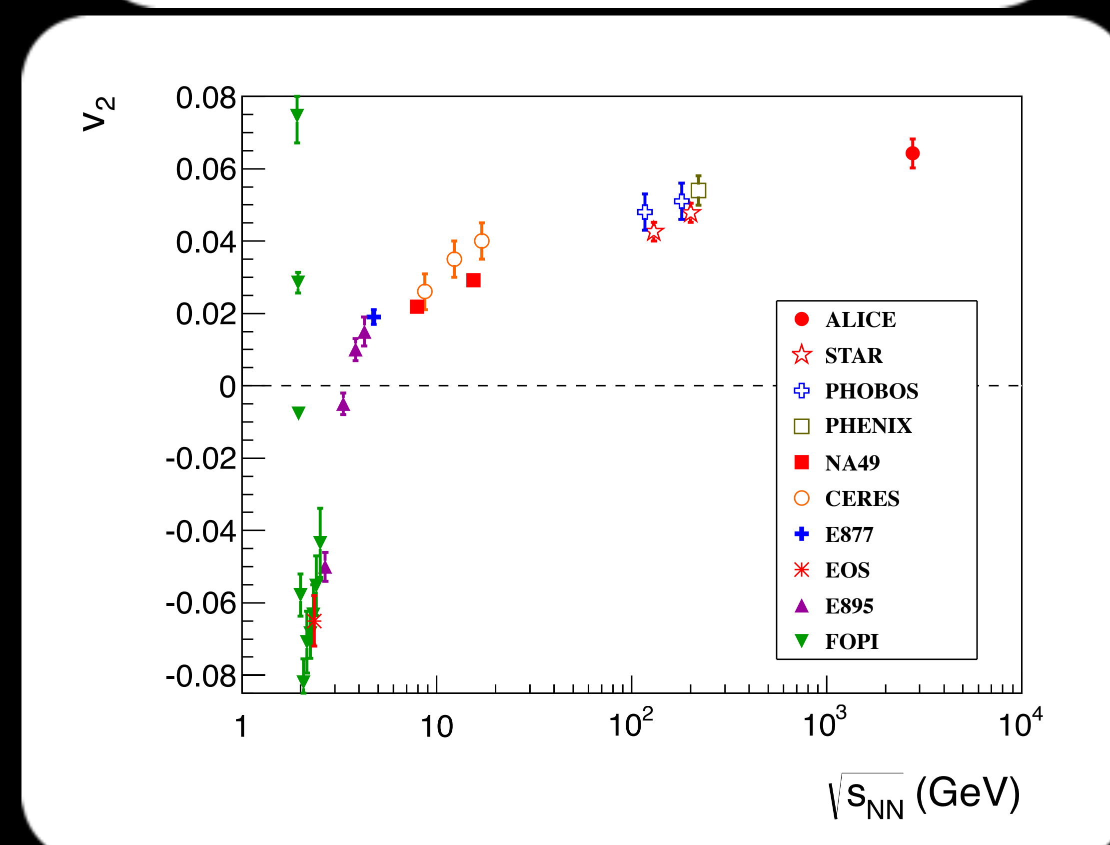
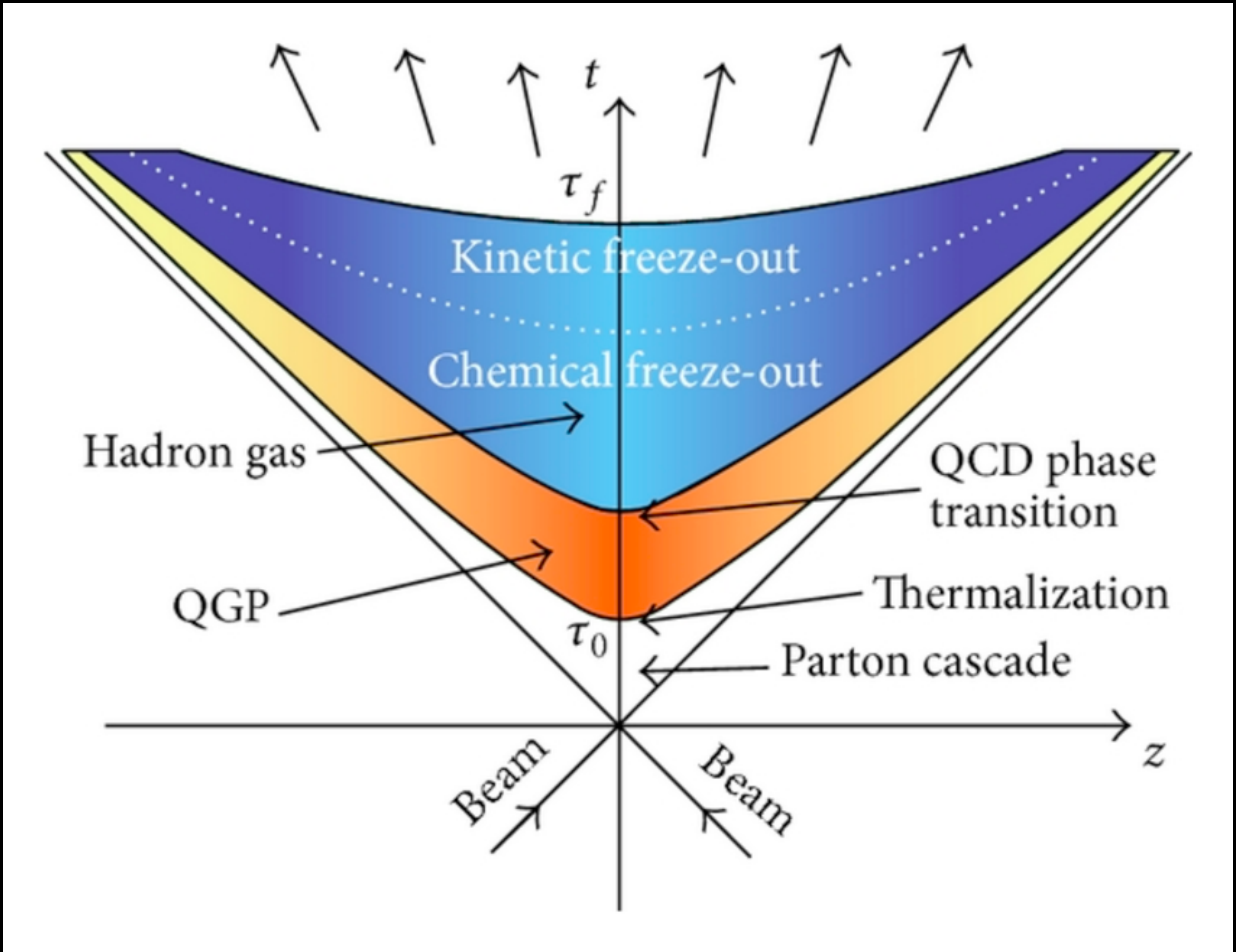


The sQGP paradigm

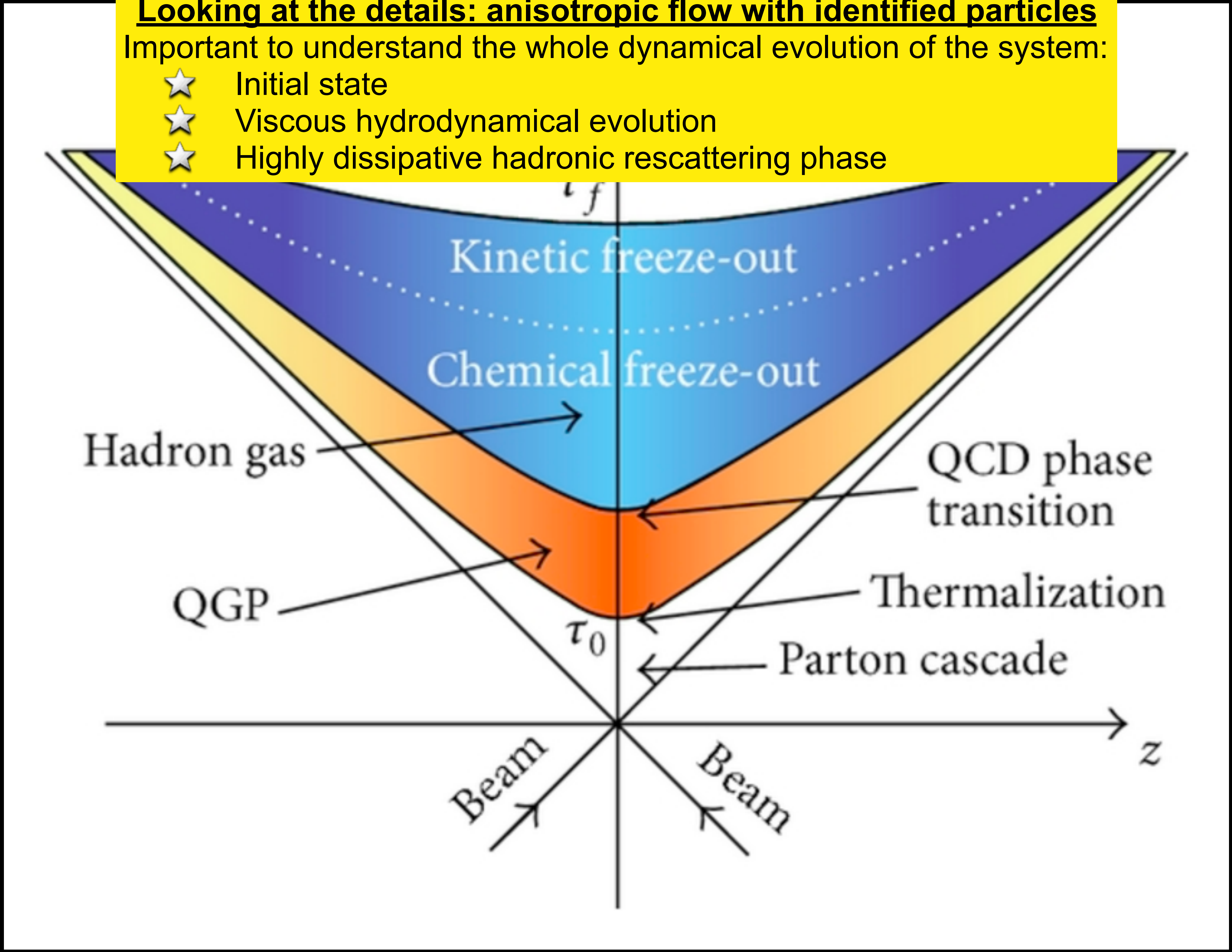


The sQGP paradigm

<u>Looking at the details: anisotropic flow with identified particles</u>

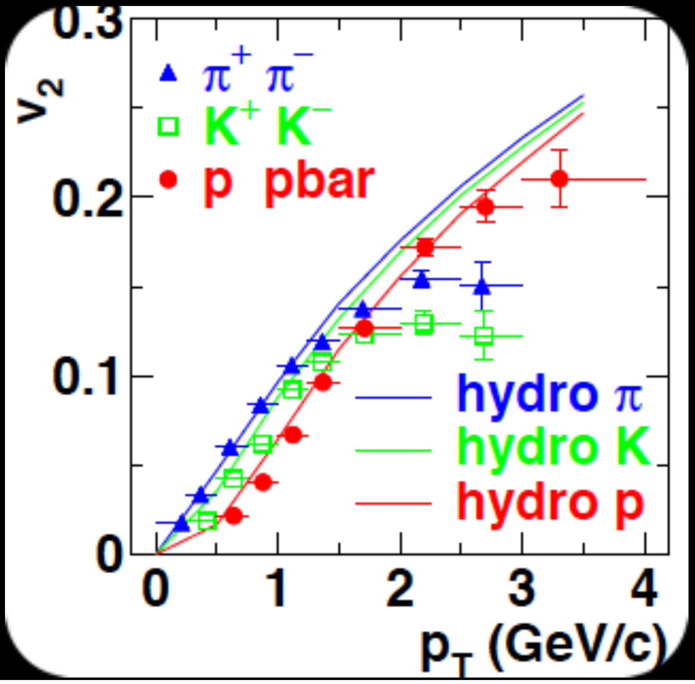
Important to understand the whole dynamical evolution of the system:

- Initial state
- Viscous hydrodynamical evolution
- Highly dissipative hadronic rescattering phase

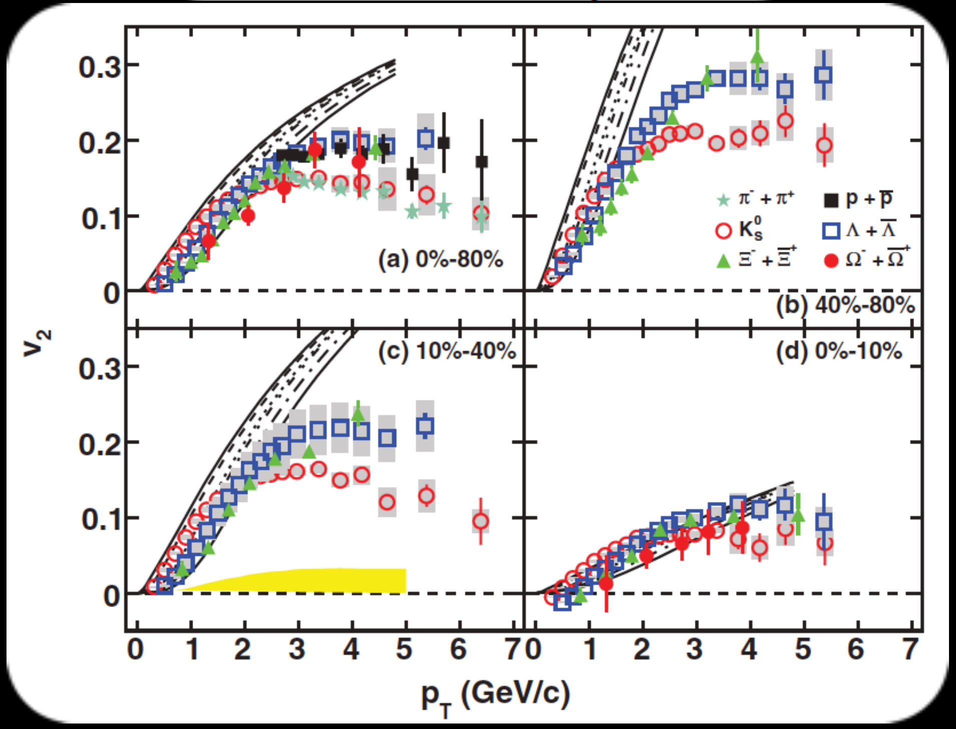


The three momentum scales: low p_T ($p_T < 3$ GeV/c)

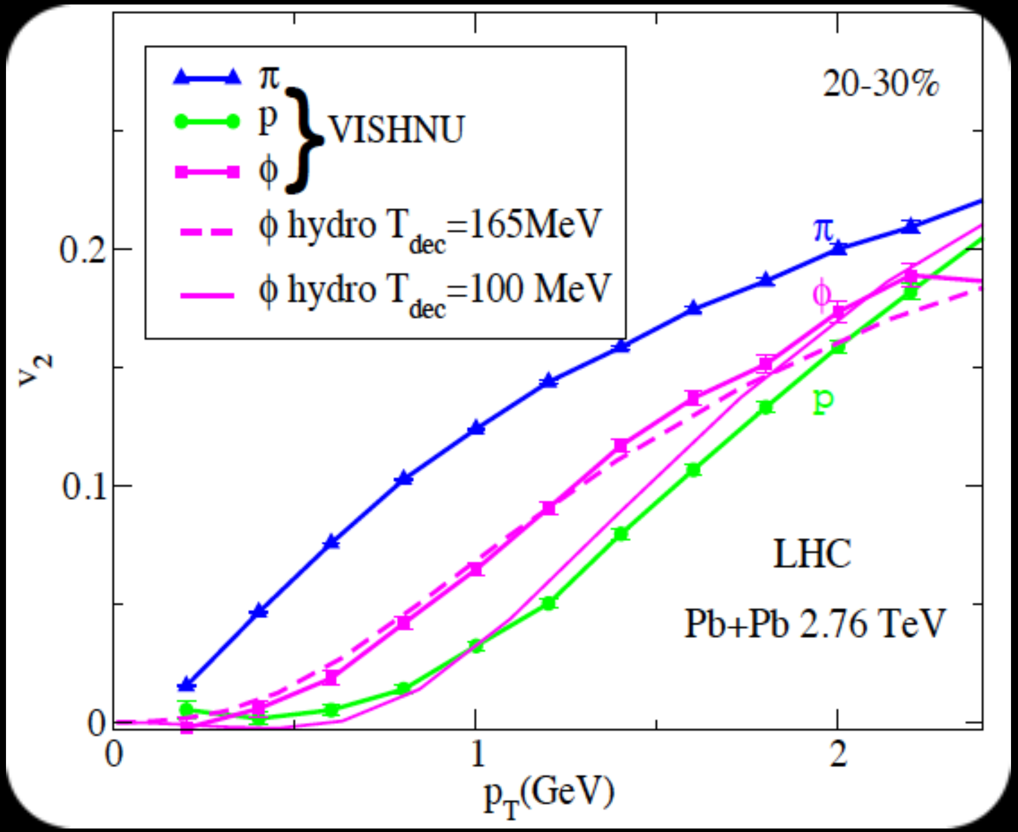
- Mass ordering observed at low p_T at RHIC energies
  - ★ expected by hydrodynamic calculations



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



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

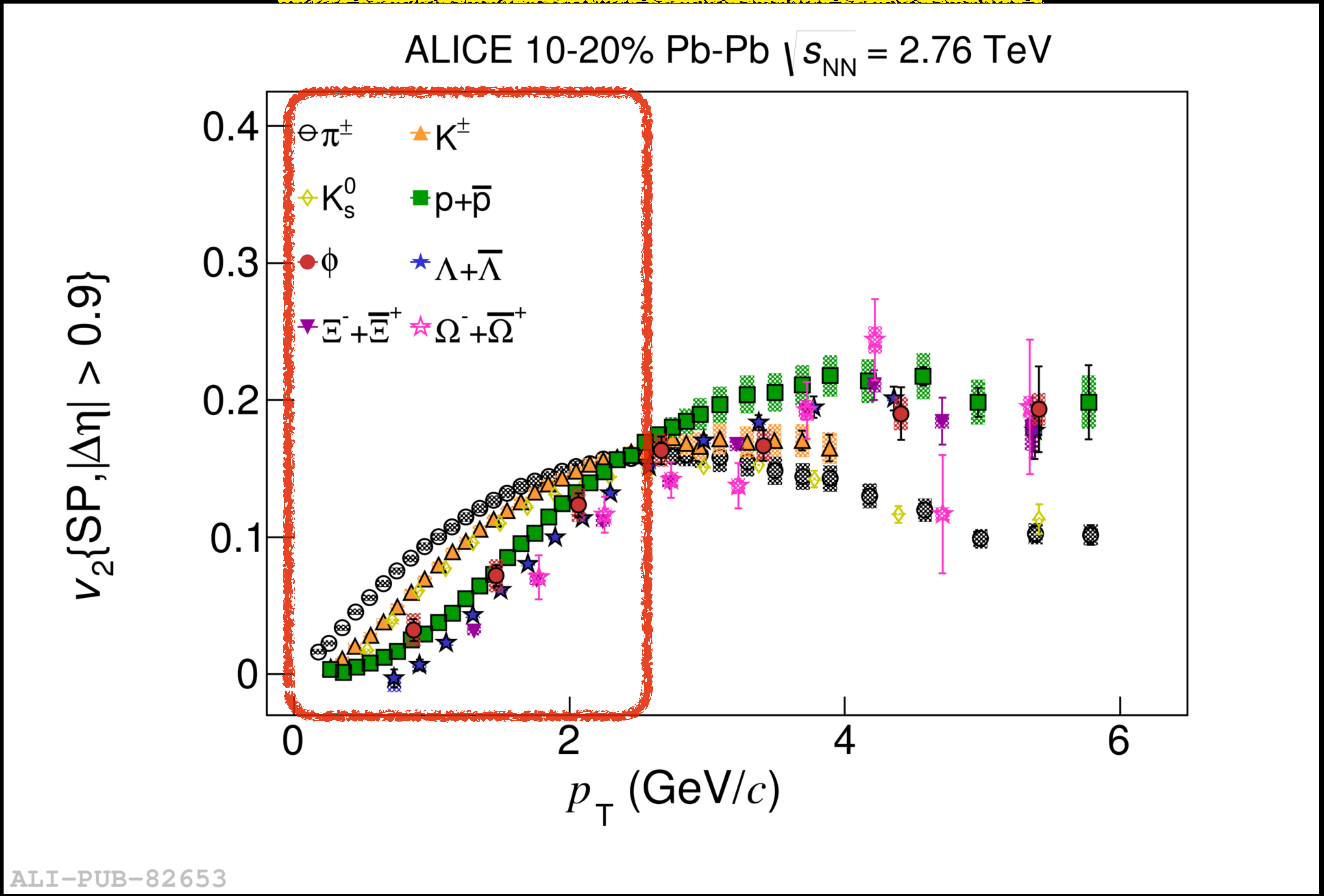


H. Song, S. Bass and U. Heinz arXiv:1311.0157 [nucl-th]

- New calculations expect the mass ordering to be violated

Mass ordering @ LHC

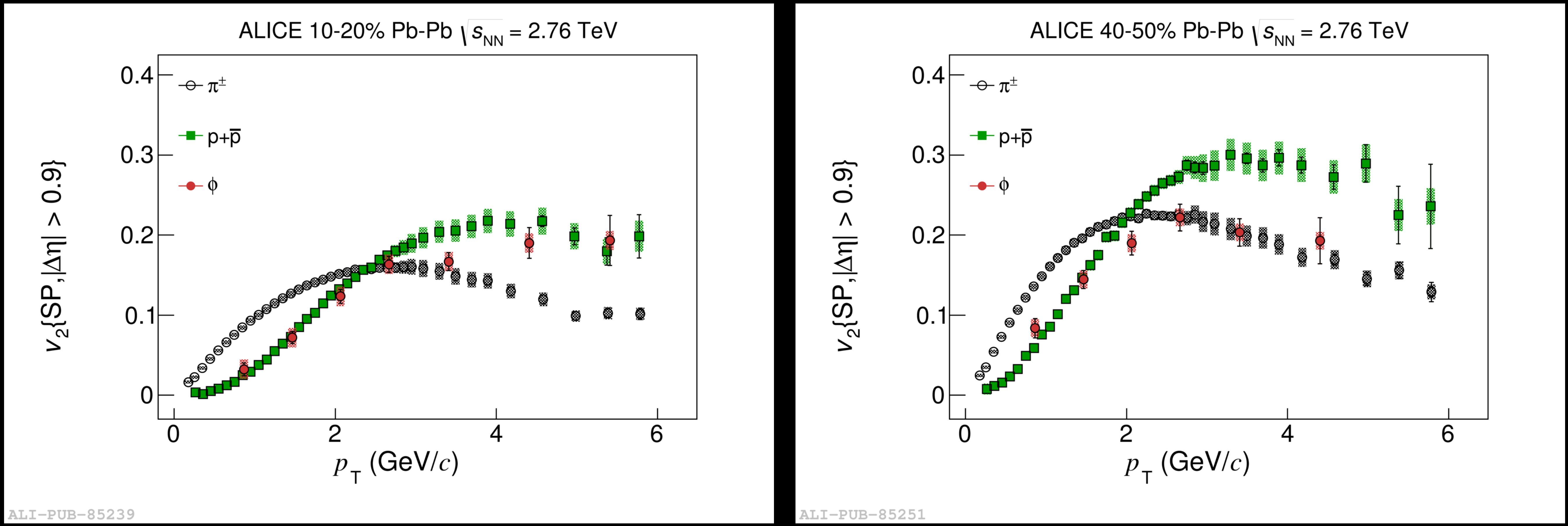
B. Abelev *et al.* (ALICE Collaboration), JHEP 06 (2015) 190



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

The special role of the φ-meson

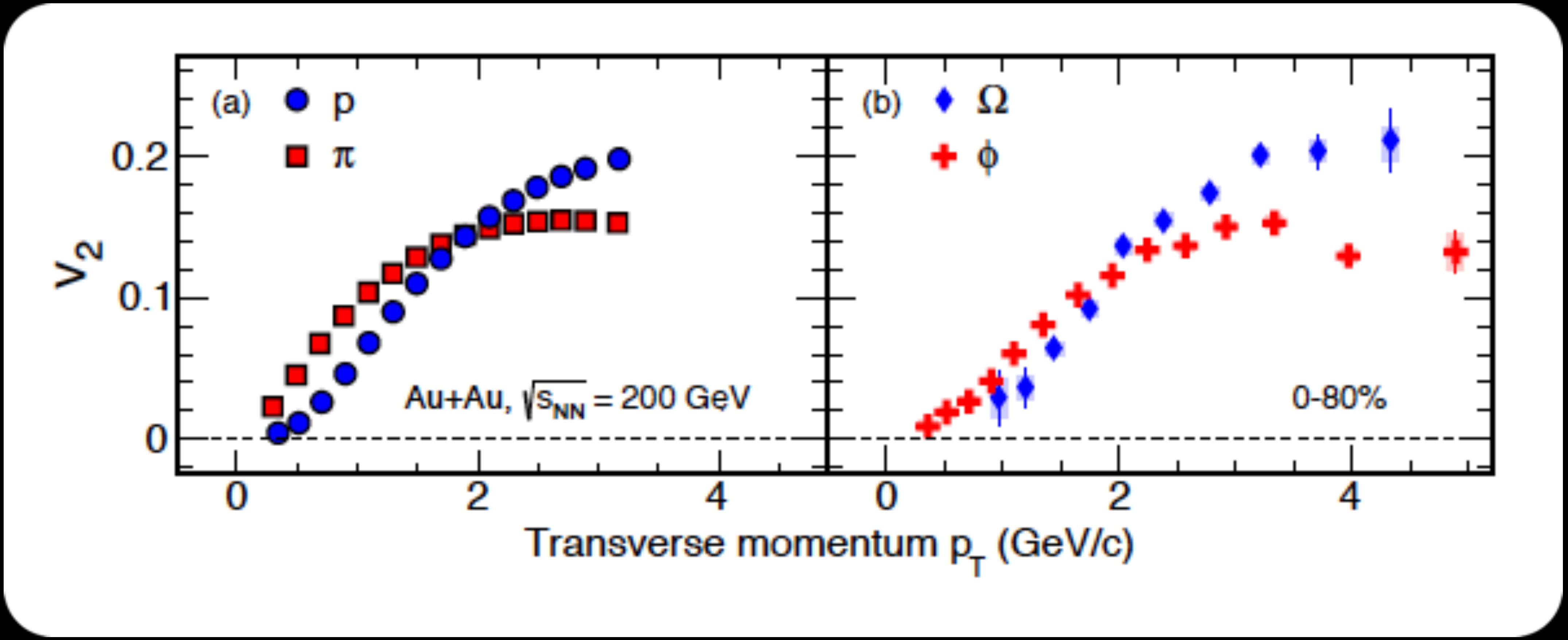
B. Abelev *et al.* (ALICE Collaboration), JHEP 06 (2015) 190



- 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…

Mass ordering @ RHIC

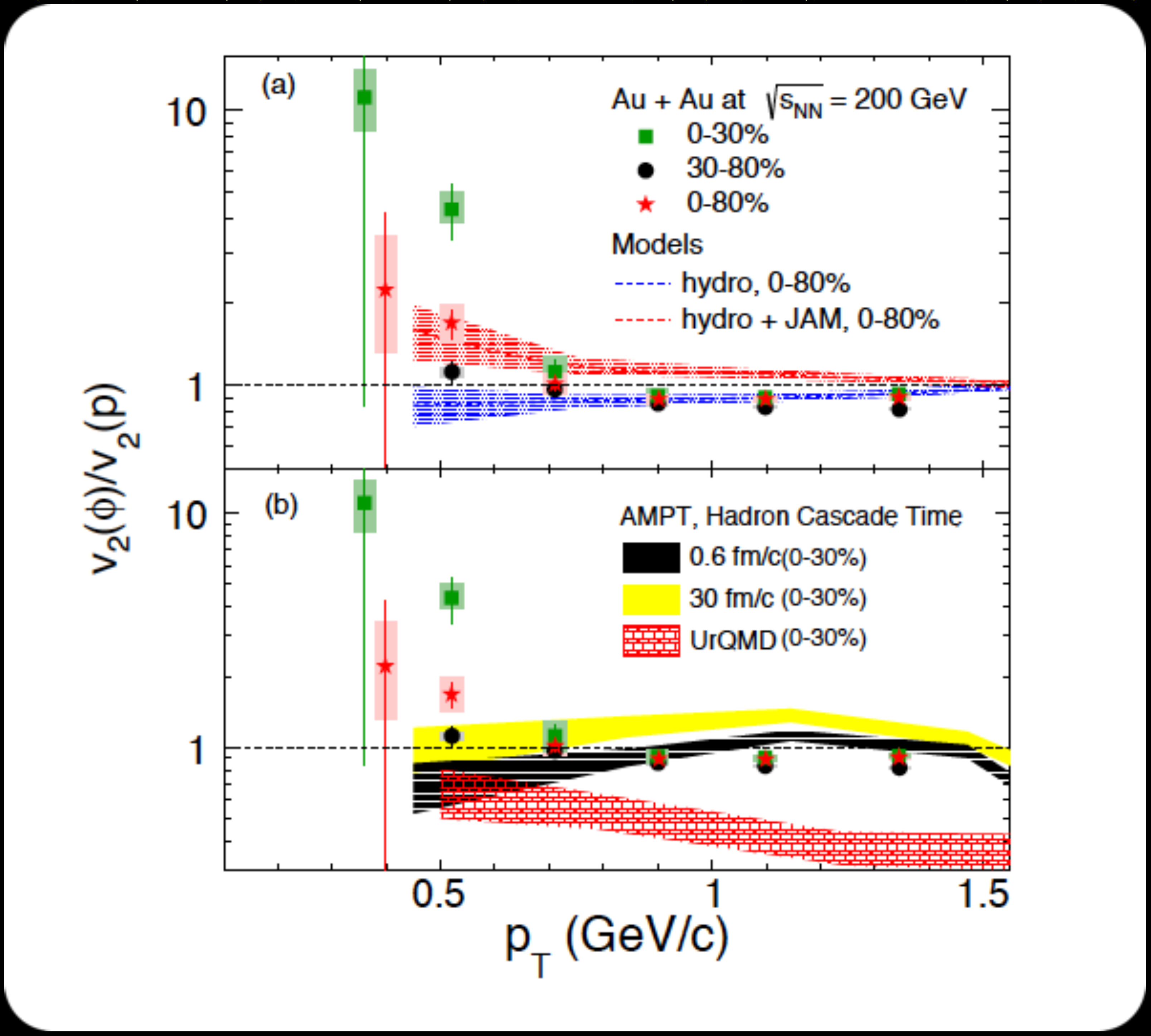
L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. Lett. 116, (2016) 062301



Mass ordering preserved at RHIC?

Mass ordering violation @ RHIC

L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. Lett. 116, (2016) 062301



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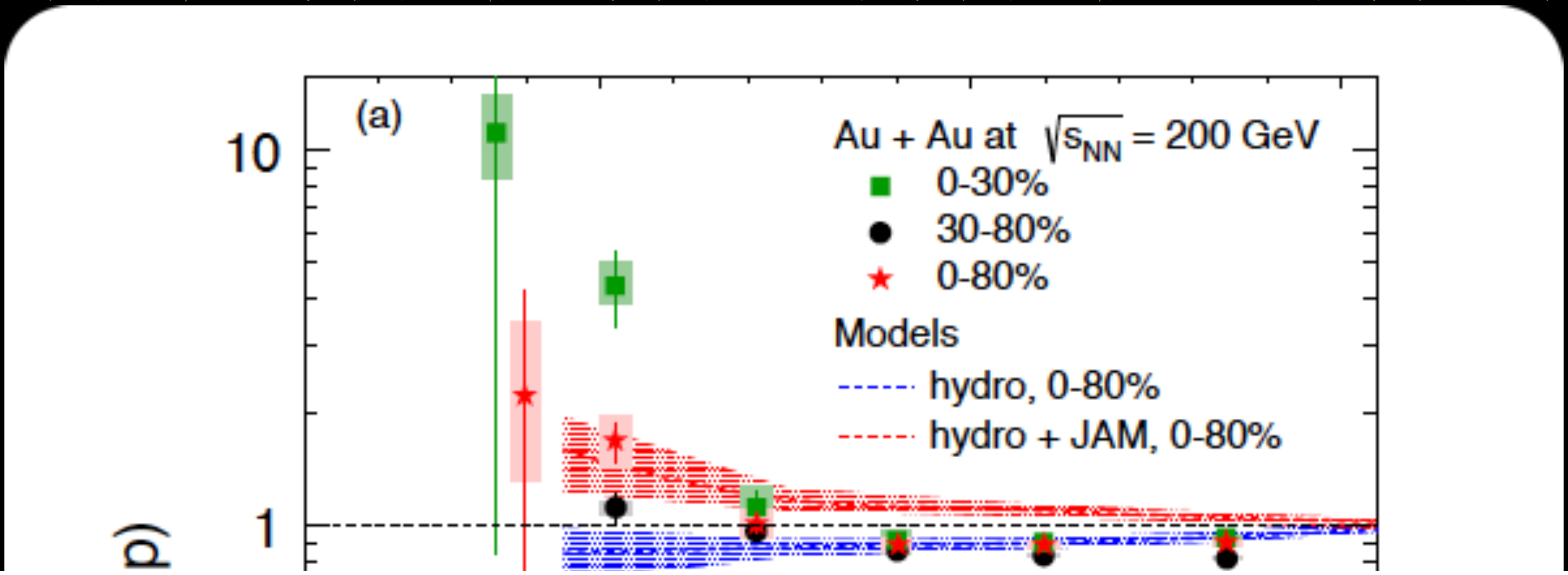
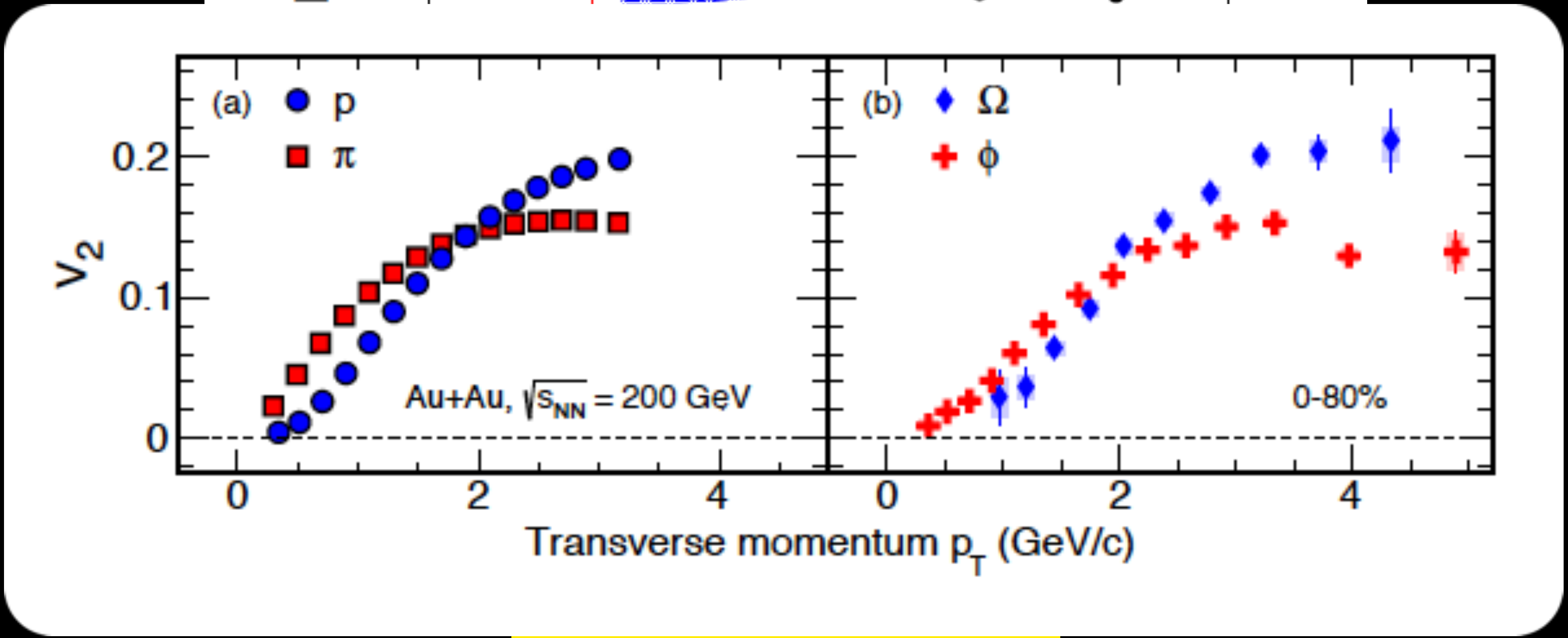




Probably also for cascades!!!

Violation of mass ordering: hadronic rescattering effect

T. Hirano *et al.*, Phys.Rev. C77 (2008) 044909

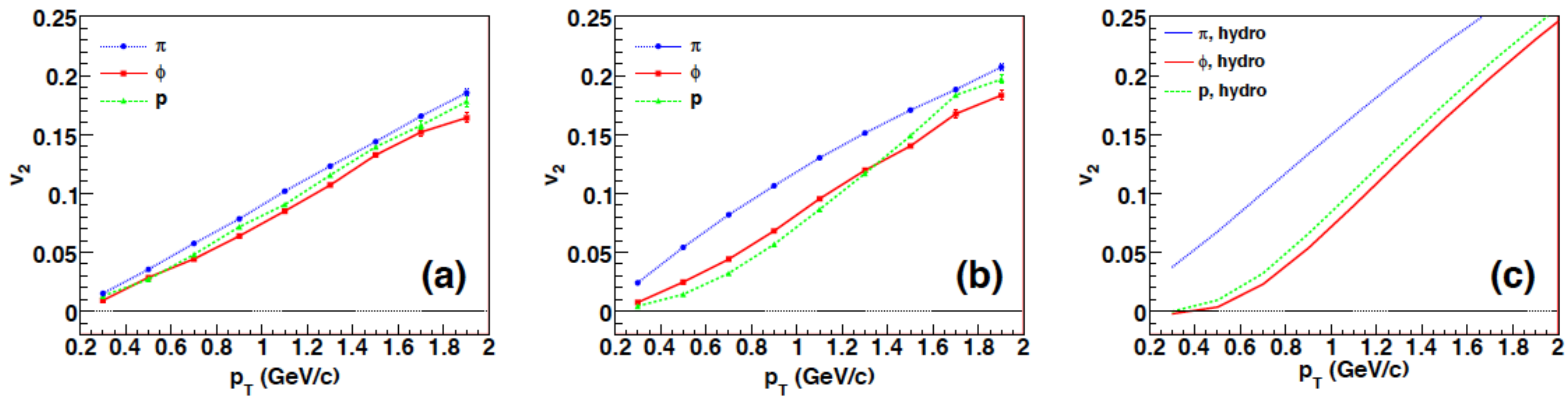
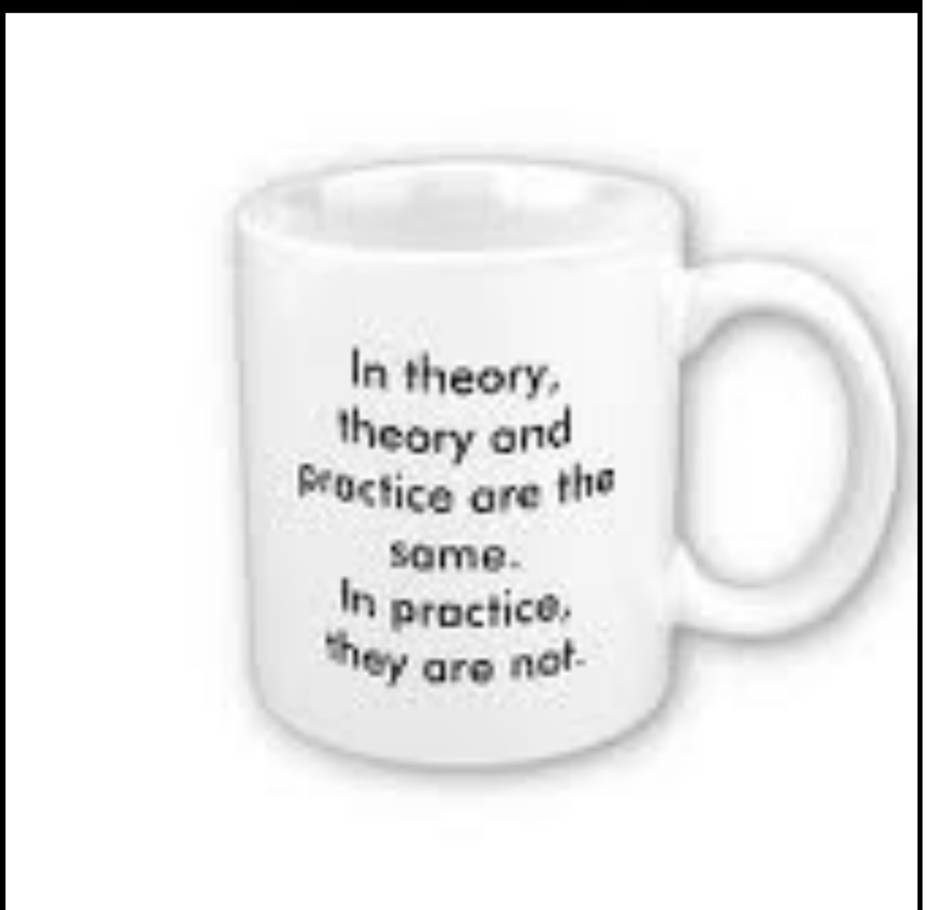
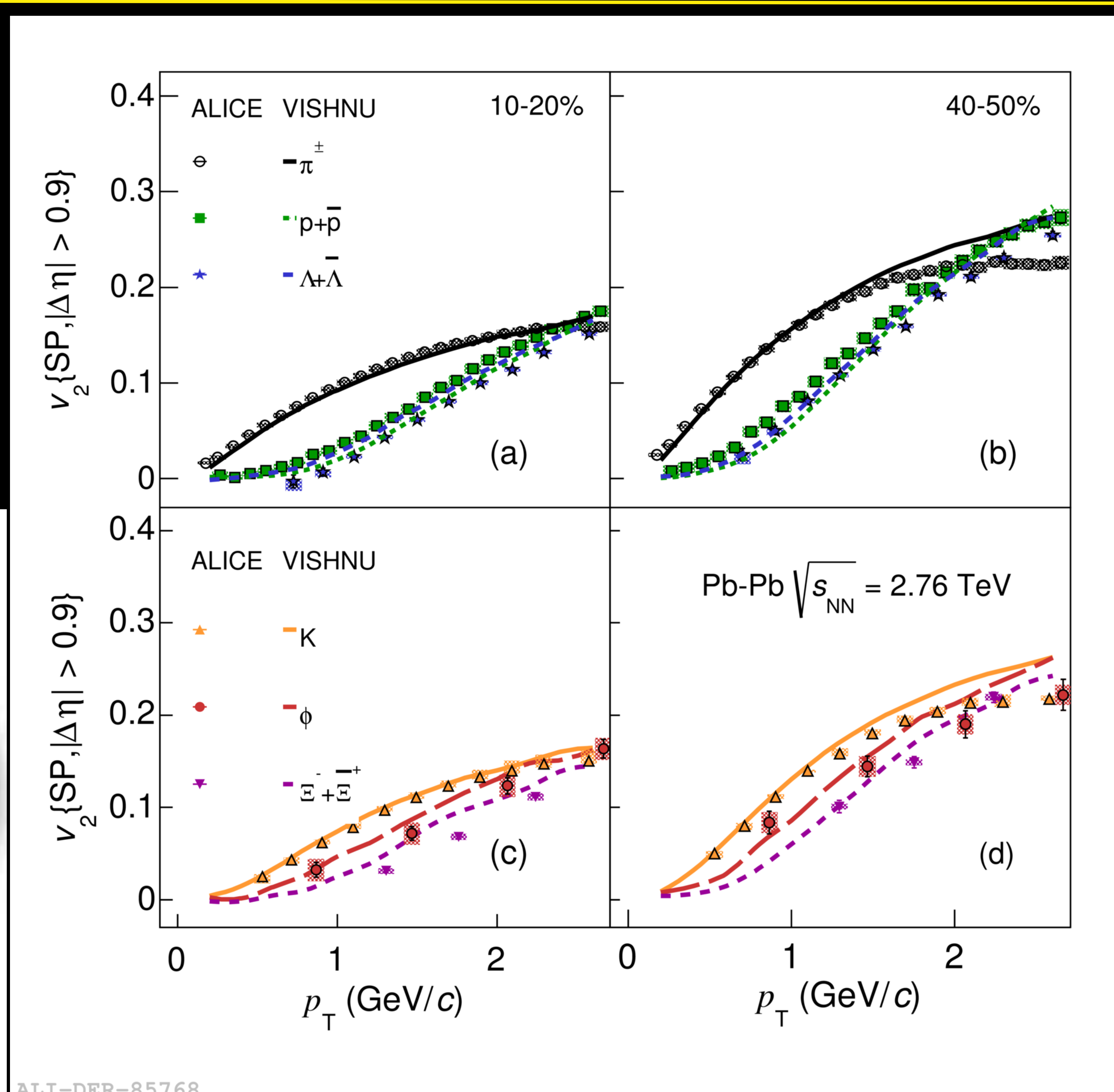


FIG. 9: (Color online) Transverse momentum dependence of the elliptic flow parameters for pions (dotted blue), protons (dashed green), and ϕ mesons (solid red), for Au+Au collisions at $b = 7.2$ fm. (a) Before hadronic rescattering. (b) After hadronic rescattering. (c) Ideal hydrodynamics with $T_{\rm th} = 100$ MeV. The results for pions and protons are the same as shown in Fig. 5.

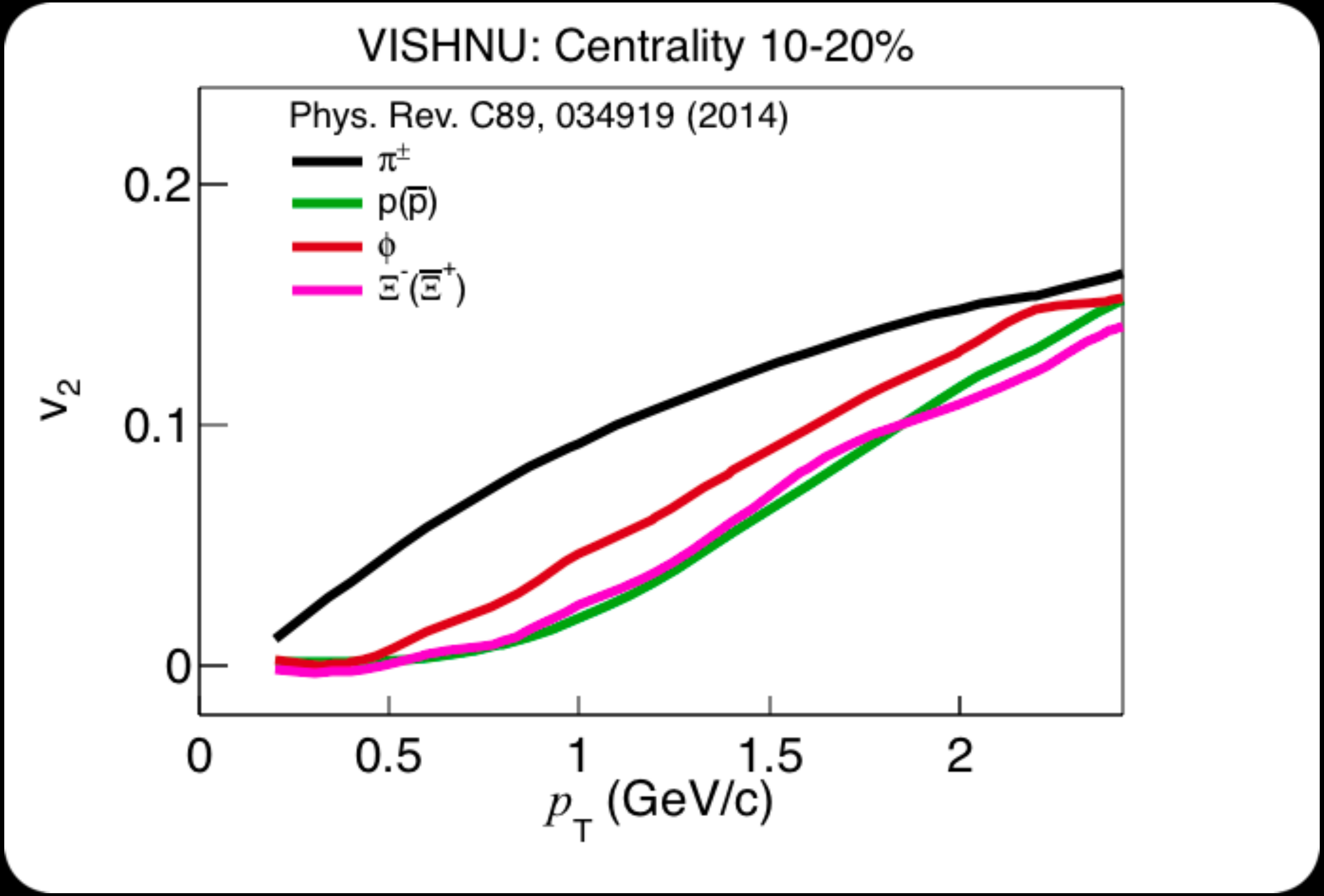
Comparison with hydrodynamic calculations

hydro curves from: H. Song, S. Bass and U. Heinz Phys. Rev. C 89, 034919



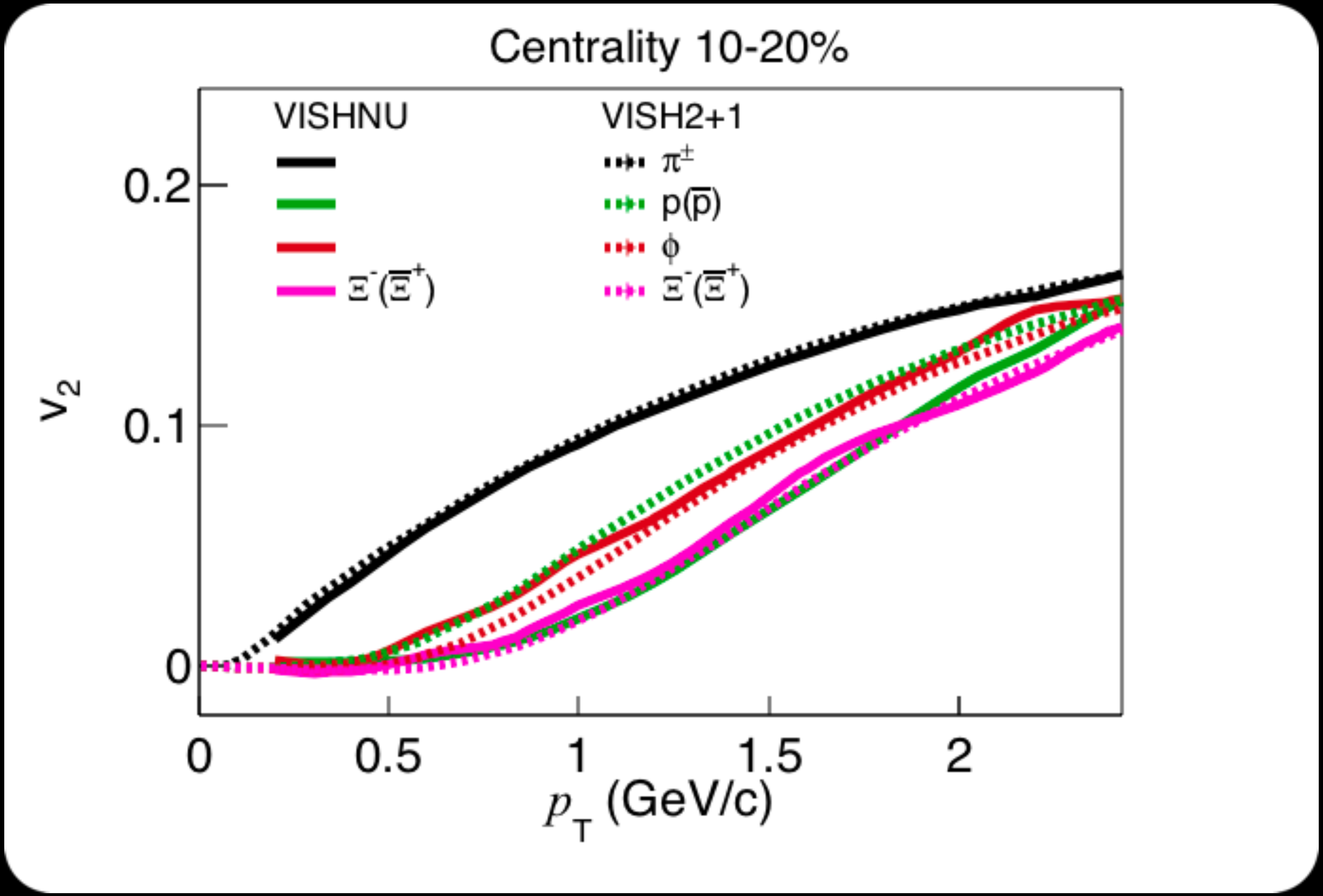


VISHNU in more detail



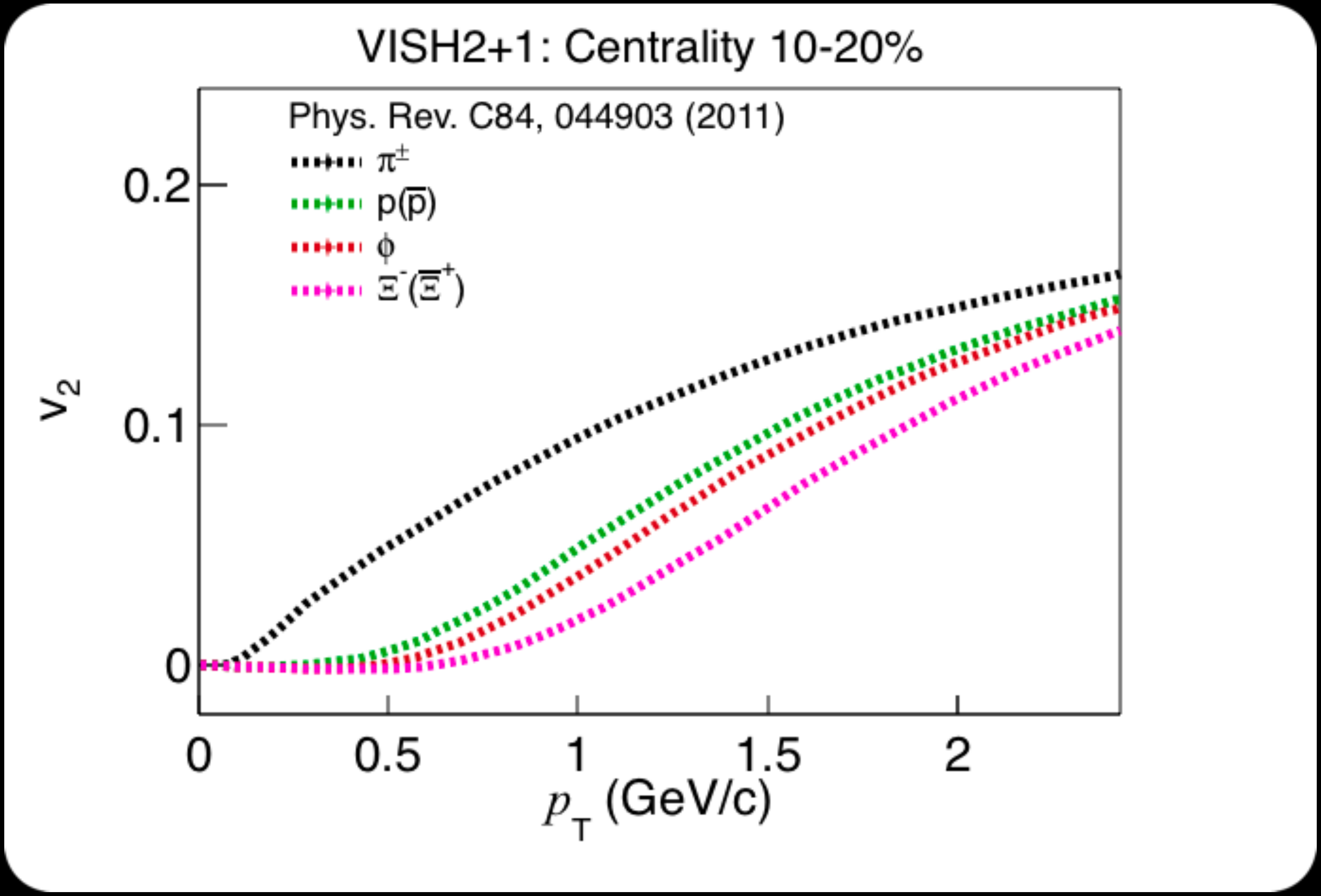
Mass ordering not preserved!!!

VISHNU vs VISH2+1



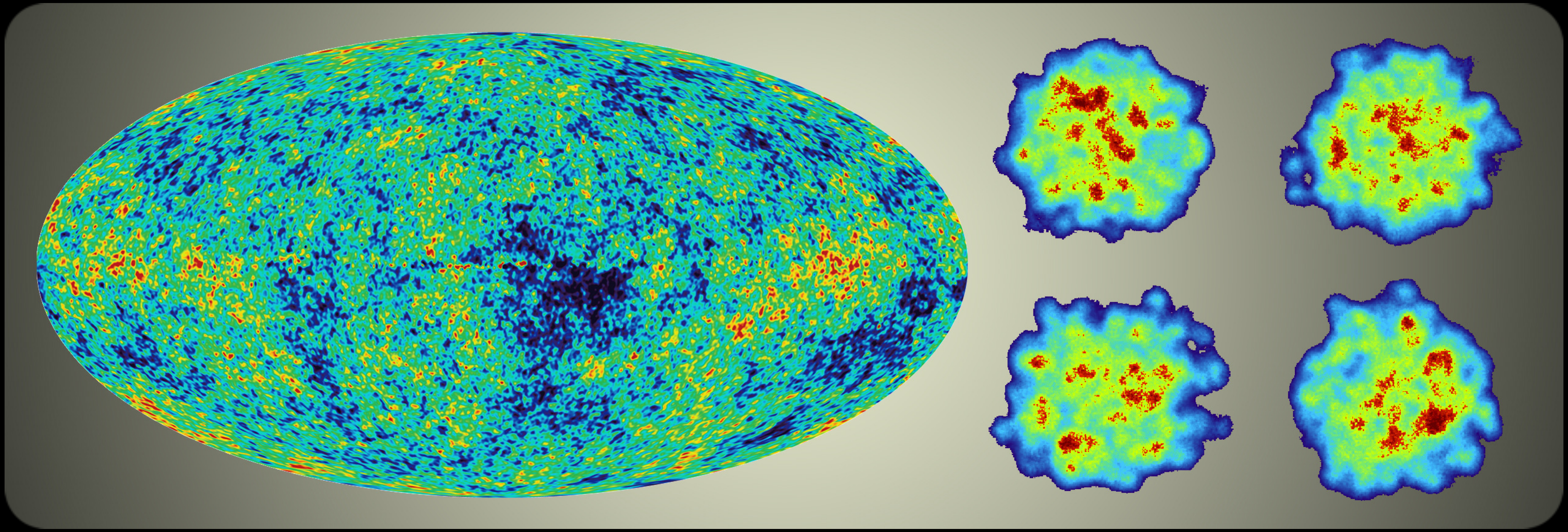
Particles with large hadronic x-section are "pushed" to higher p_T (e.g. p)
Particles with small hadronic x-section are affected less (e.g. φ, Ξ)

VISH2+1 in more detail



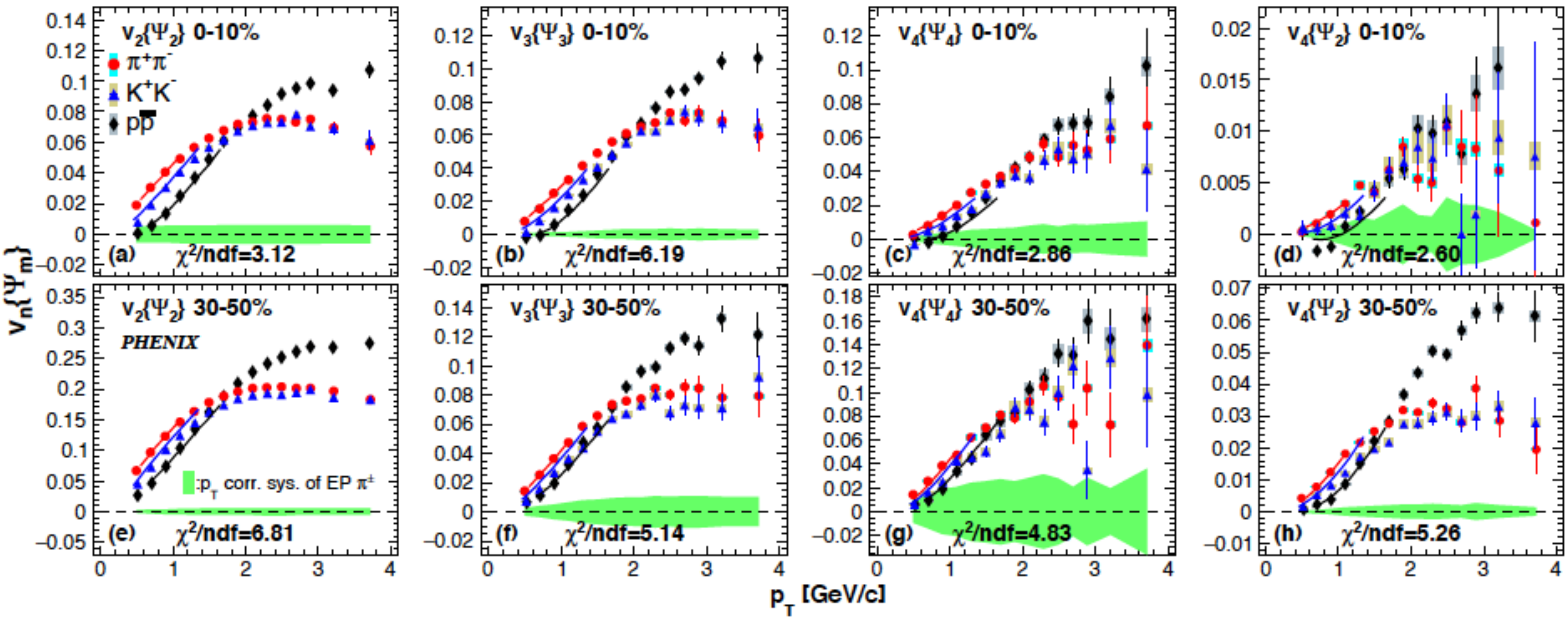
Mass ordering preserved

And there is more…: higher harmonics!



Higher harmonics @ RHIC

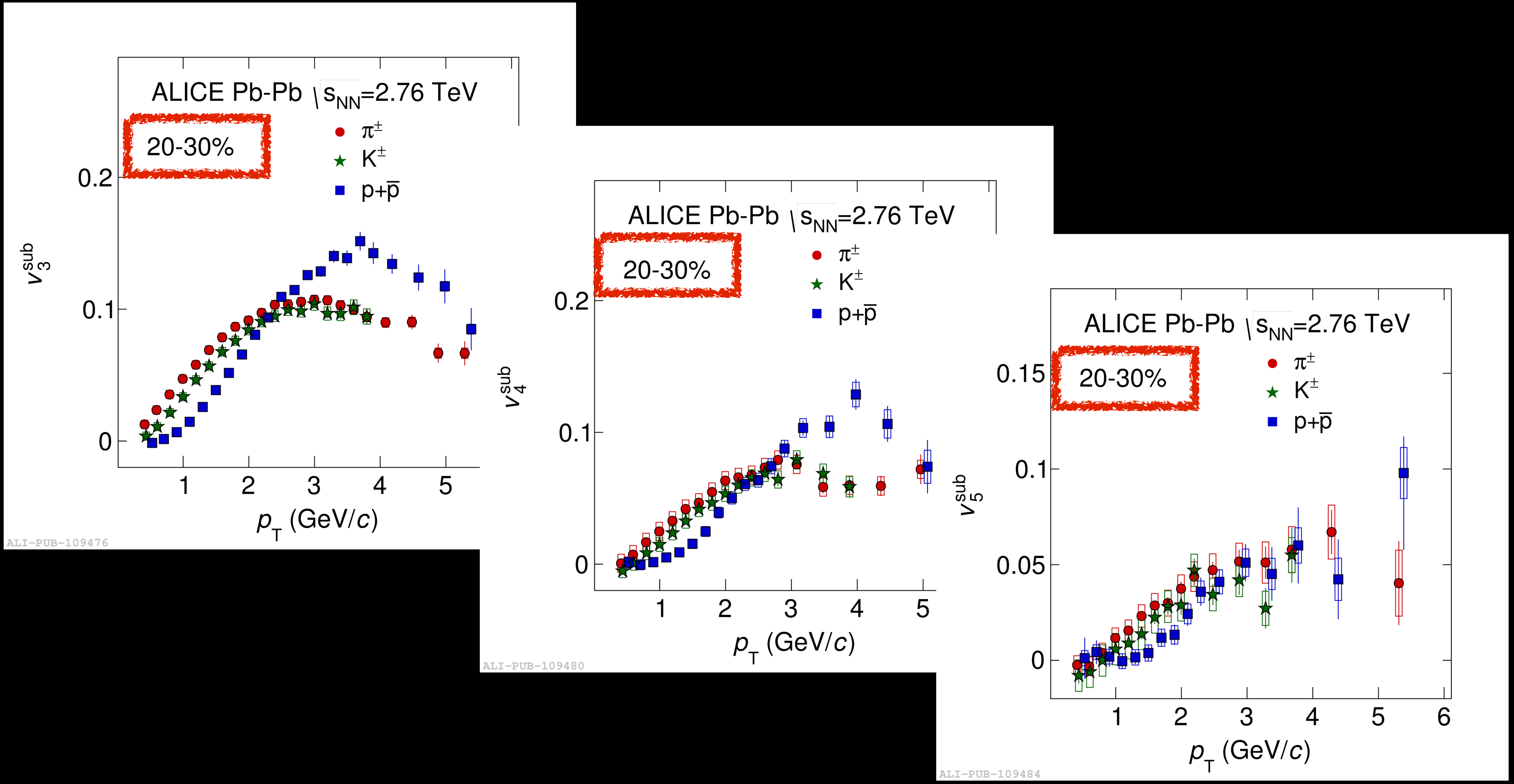
A. Adare *et al.* (PHENIX Collaboration), Phys.Rev. C93 (2016) 051902



Mass ordering at low p_T observed also for higher harmonics at RHIC

Higher harmonics @ LHC

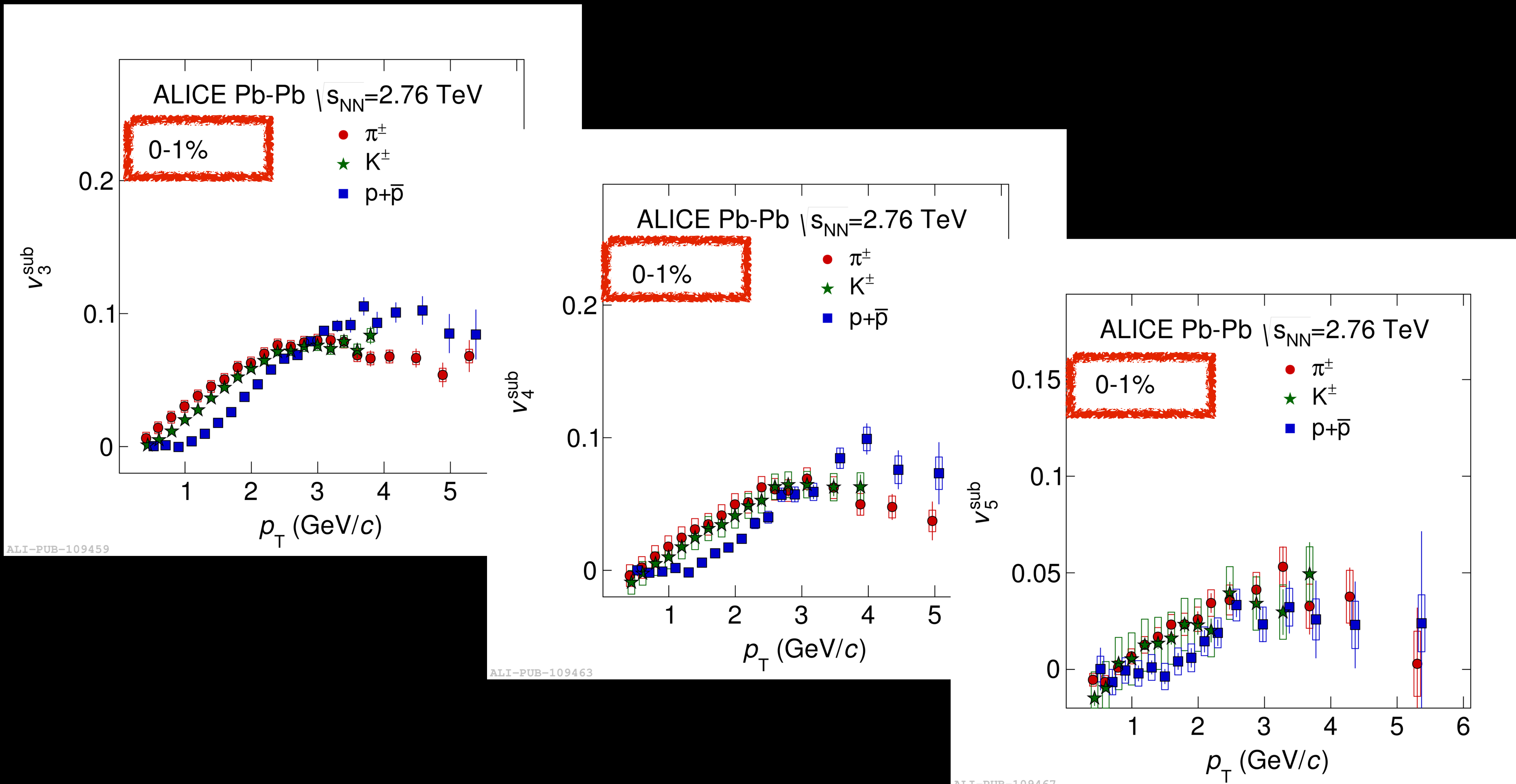
B. Abelev *et al.* (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]



Panos.Christakoglou@nikhef.nl

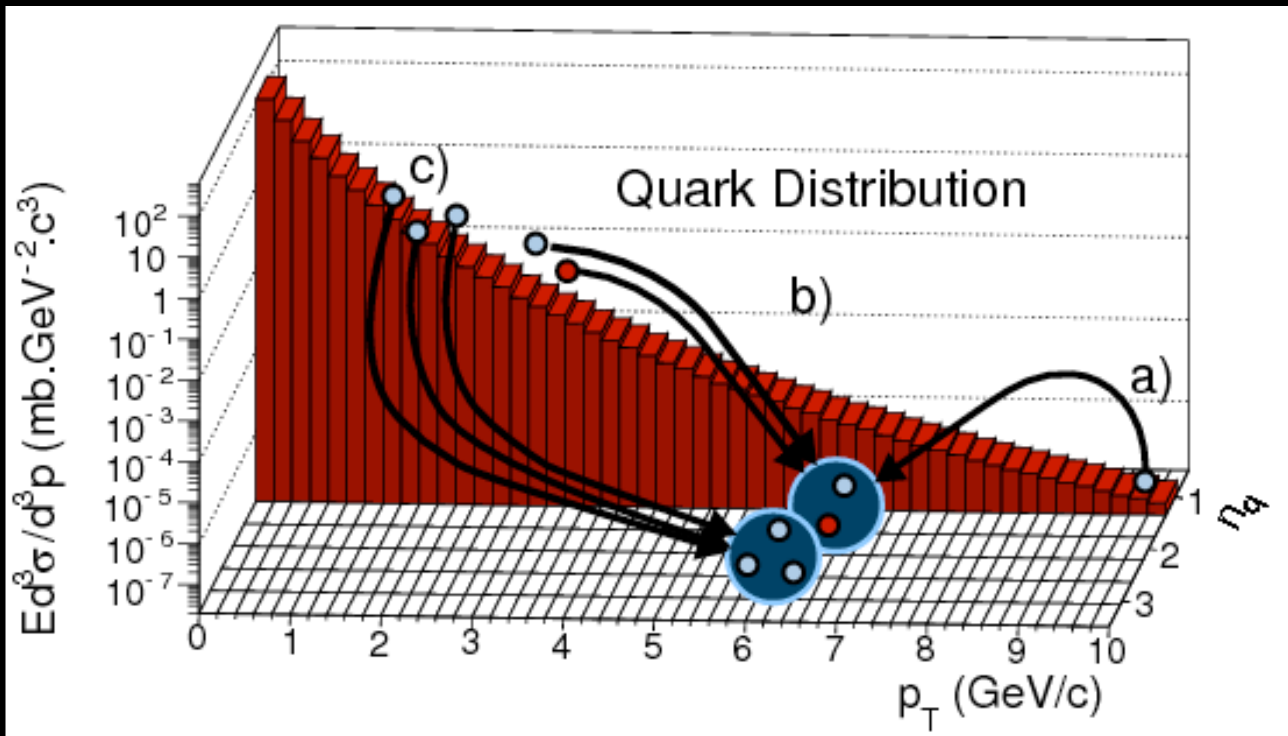
Higher harmonics @ LHC (ultra-central events)

B. Abelev *et al.* (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]

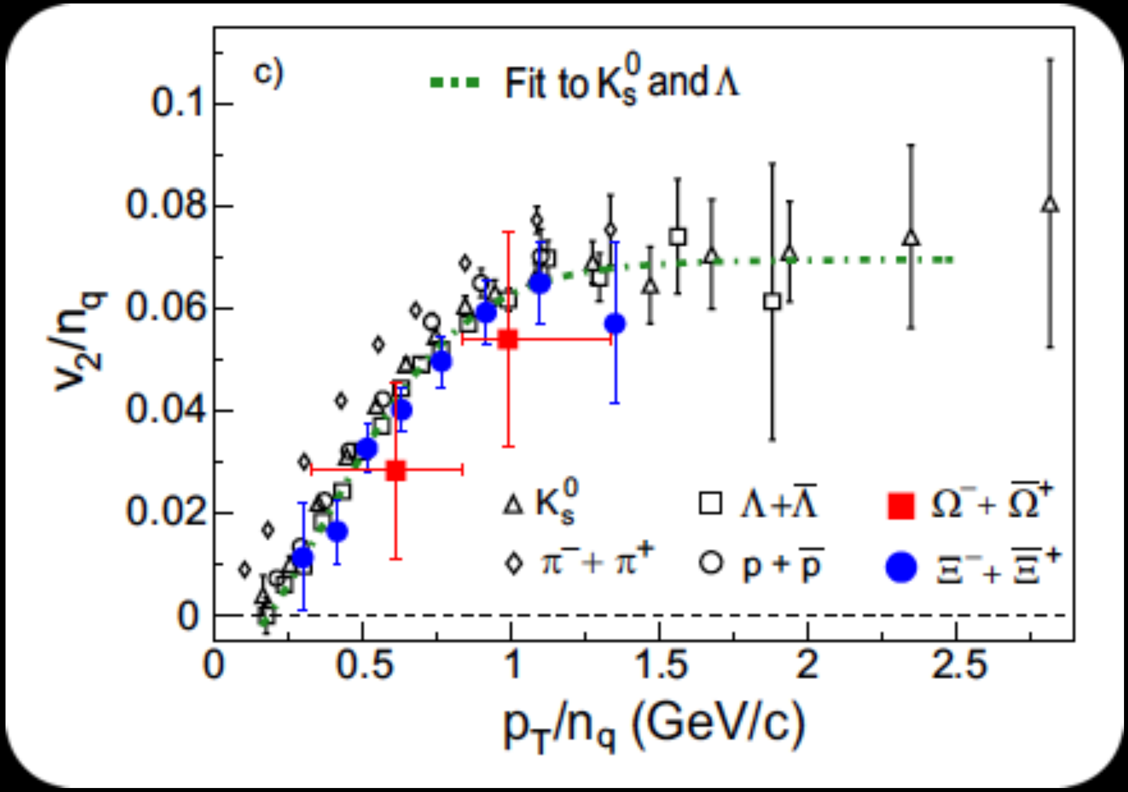


Same features for different v_n (up to v_5!) even for ultra-central collisions

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



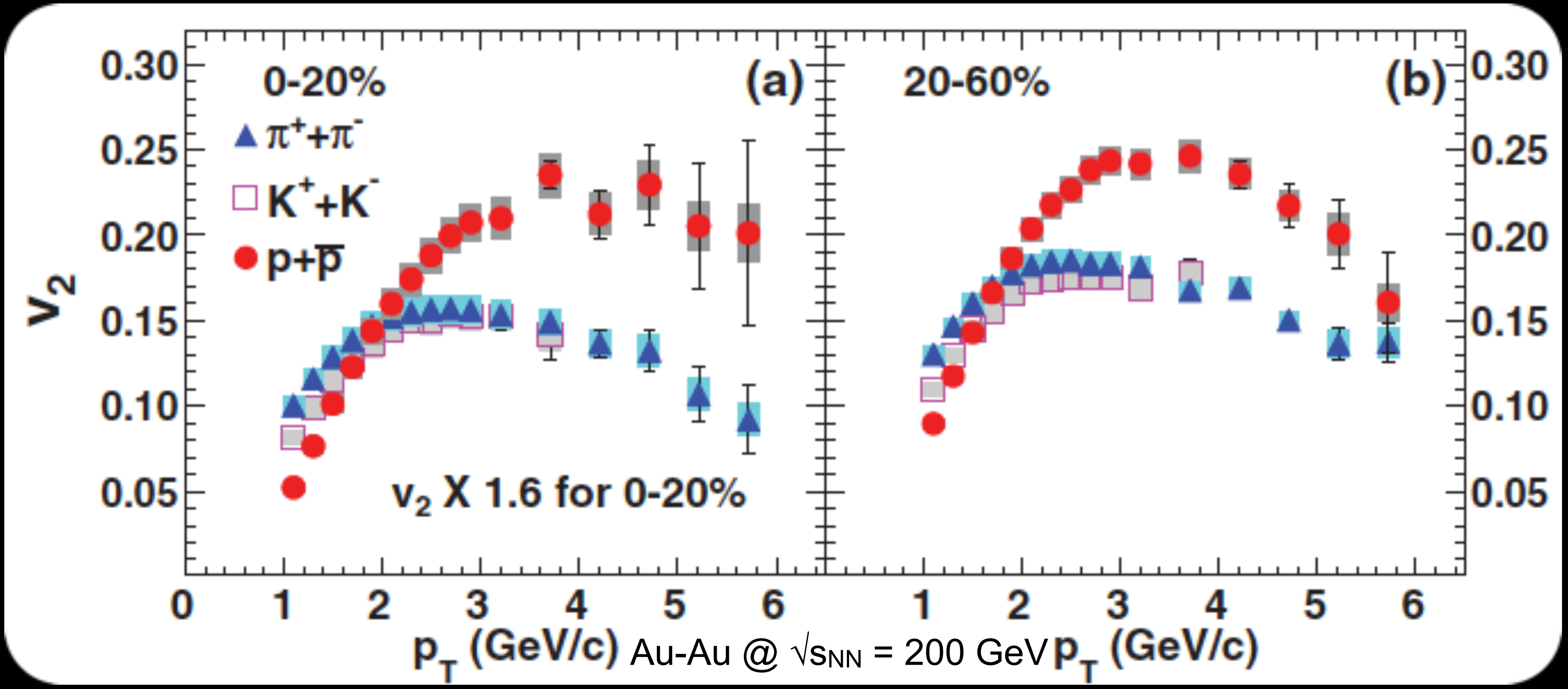
- Number of constituent quark (NCQ) scaling holding with good accuracy at RHIC
  - quarks coalesce forming hadrons?
  - NCQ scaling was considered as "evidence" of partonic degrees of freedom



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

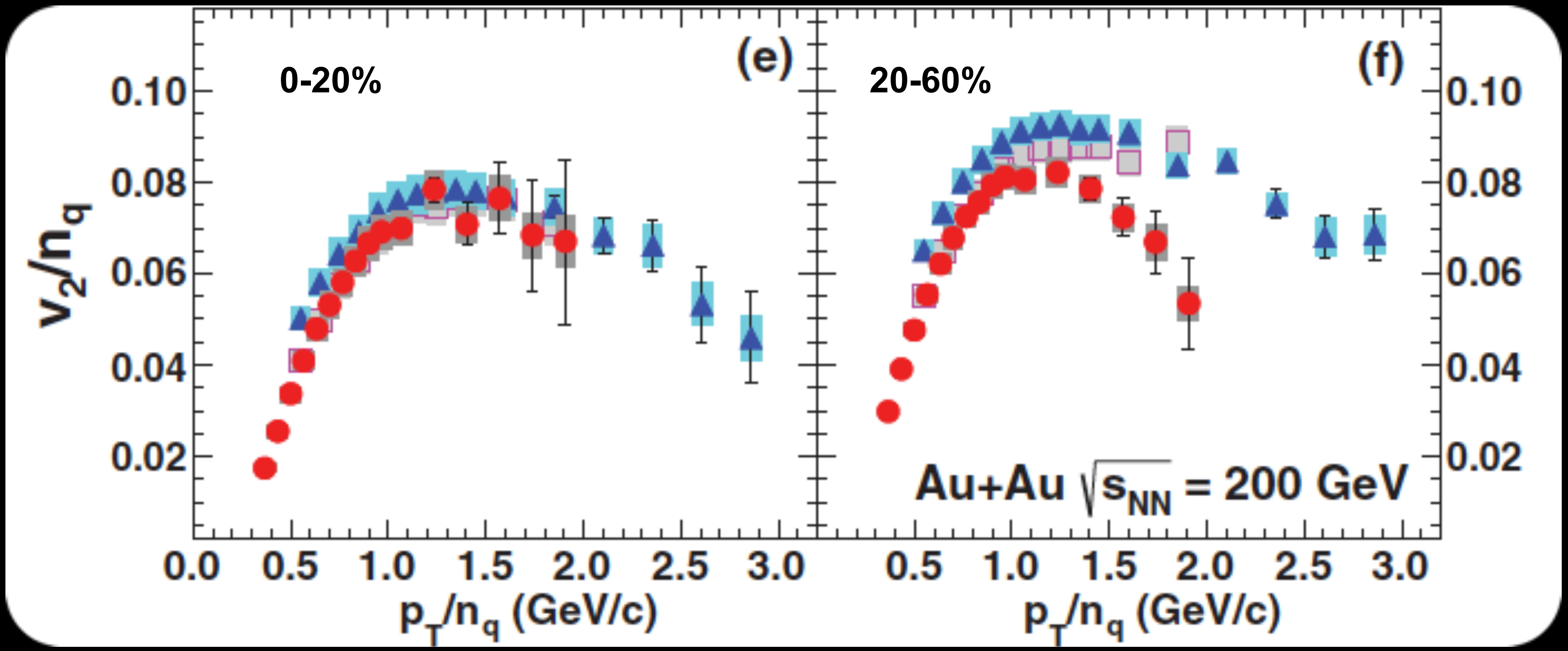
Deviations from the universal scaling at RHIC

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



Deviations from the universal scaling at RHIC

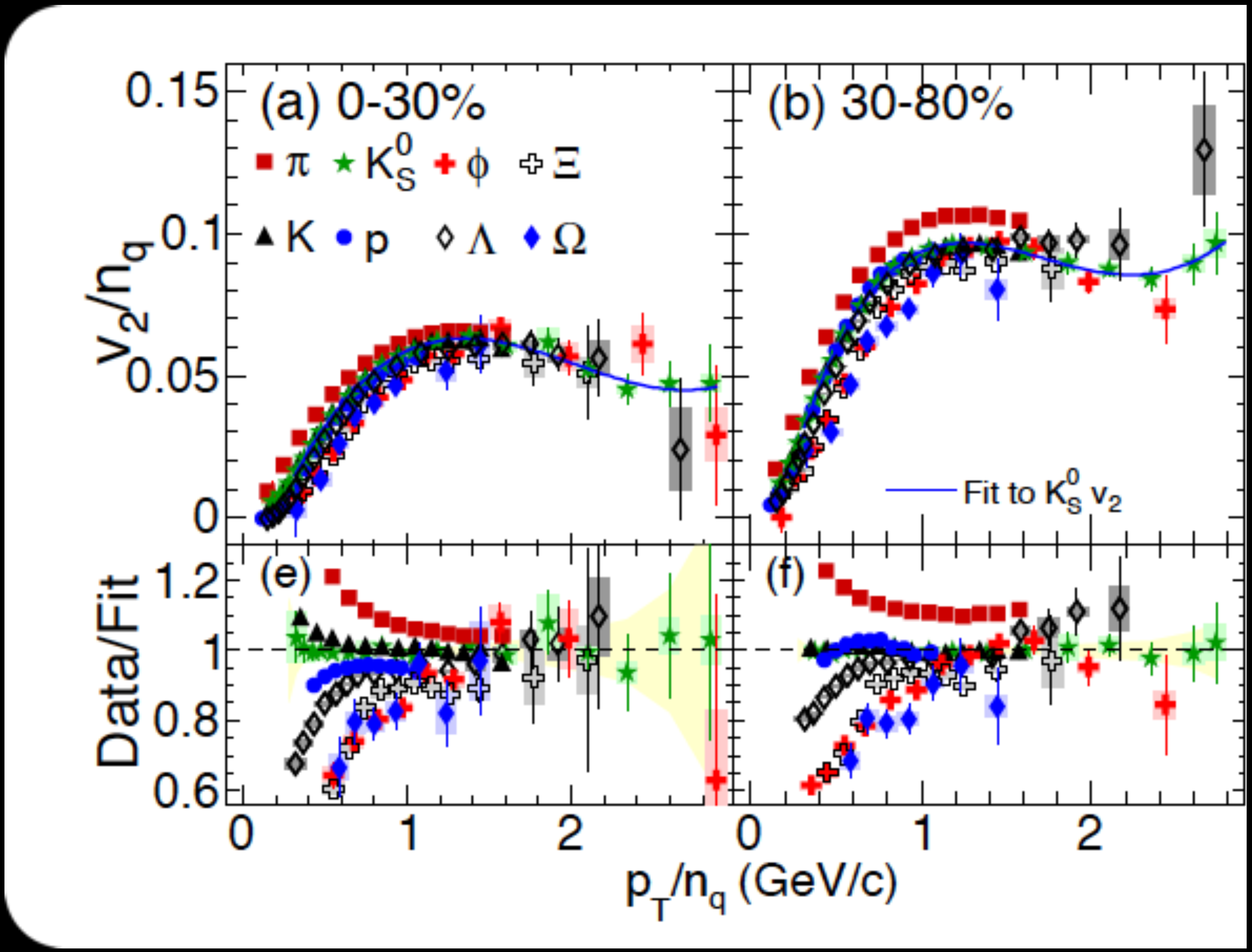
A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. **C85**, (2012) 064914



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

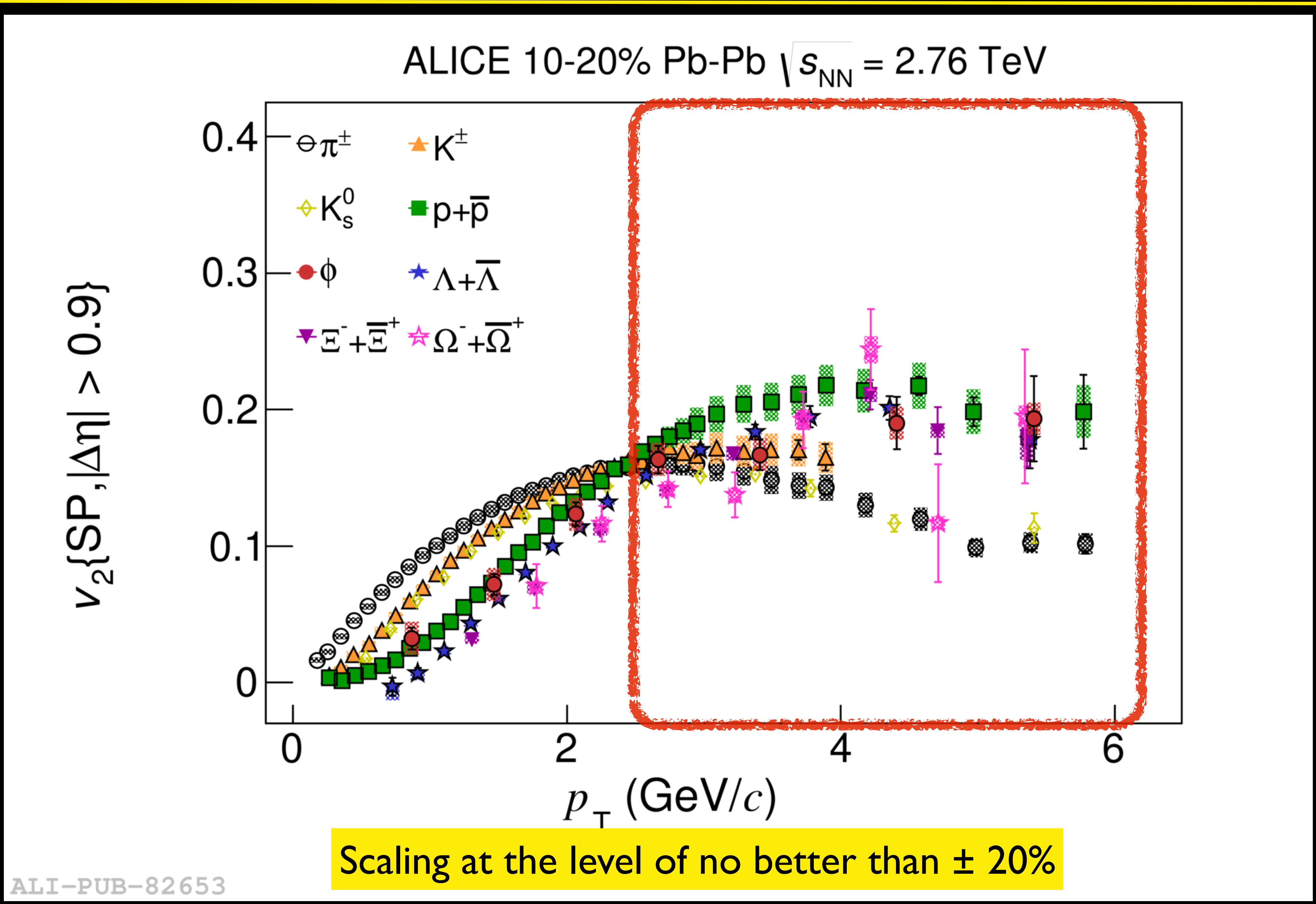
NCQ scaling @ RHIC

L. Adamczyk *et al.* (STAR Collaboration), Phys.Rev.Lett. 116 (2016) 062301



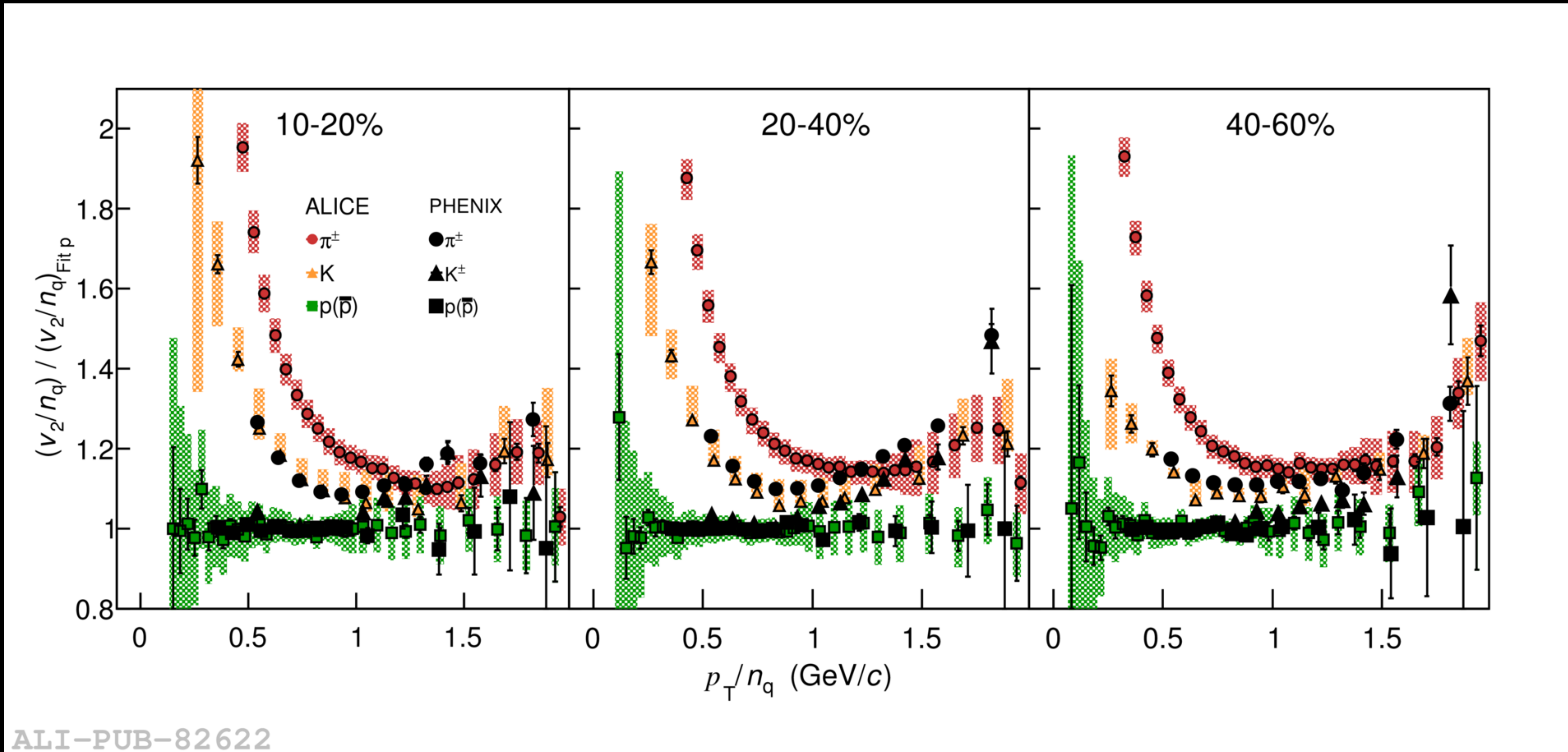
Scaling seems to hold at an approximate level of 10-15%
Good enough???

Scaling properties @ LHC



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

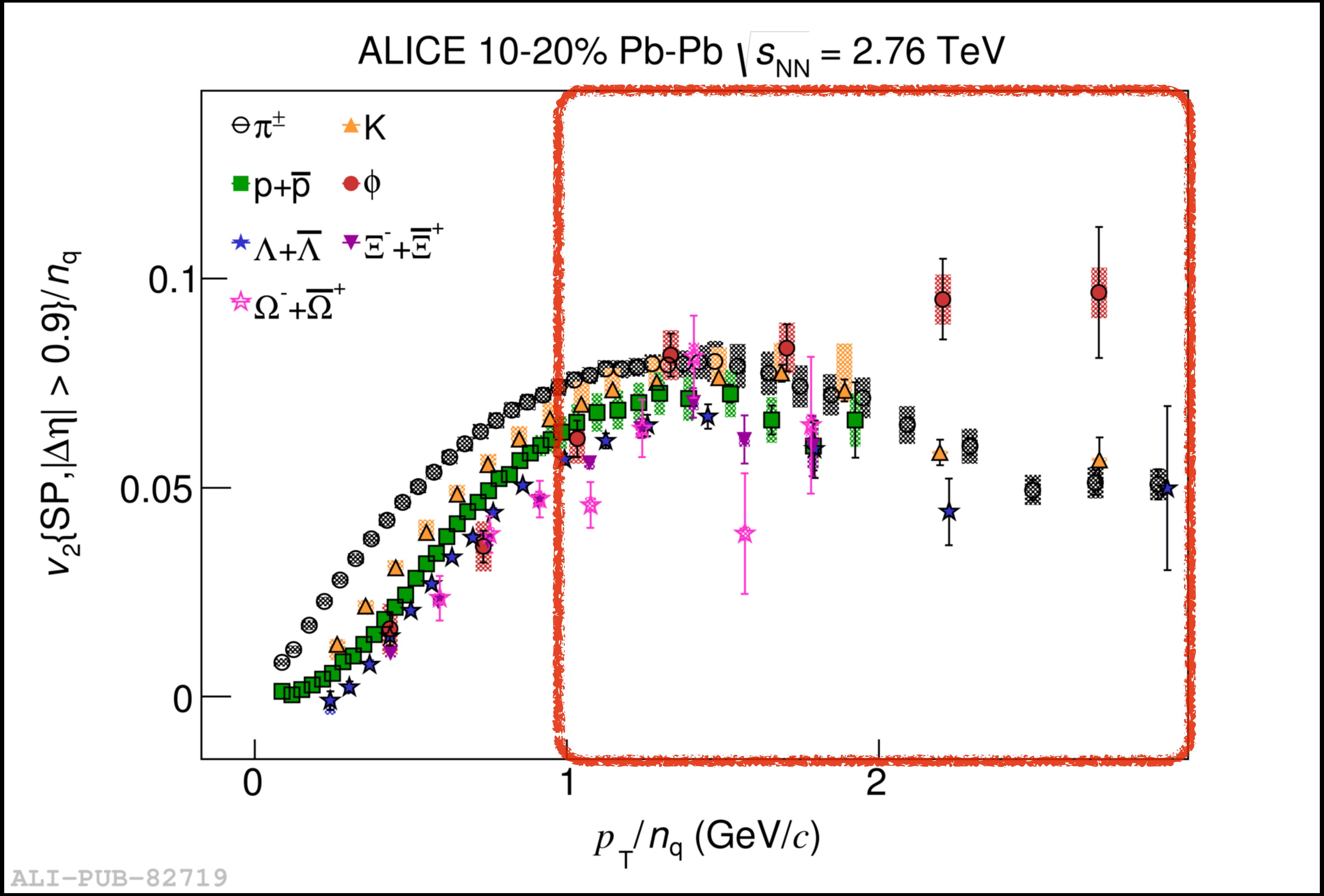
NCQ scaling in p_T/n_q (double ratio): evolution with energy



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

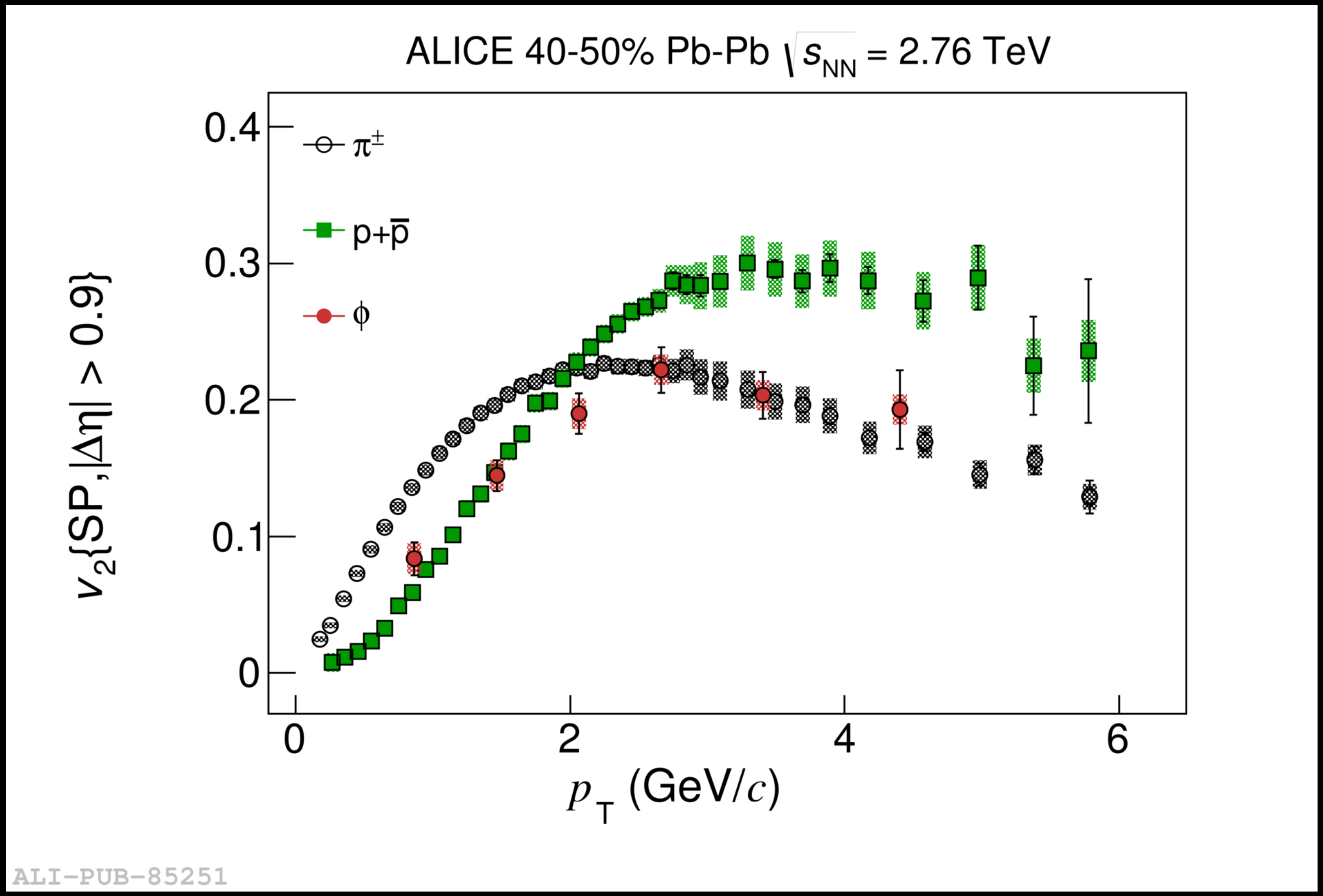
A. Adare *et al.*, [PHENIX Collaboration], Phys. Rev. **C85,** (2012) 064914

The elephant in the room…

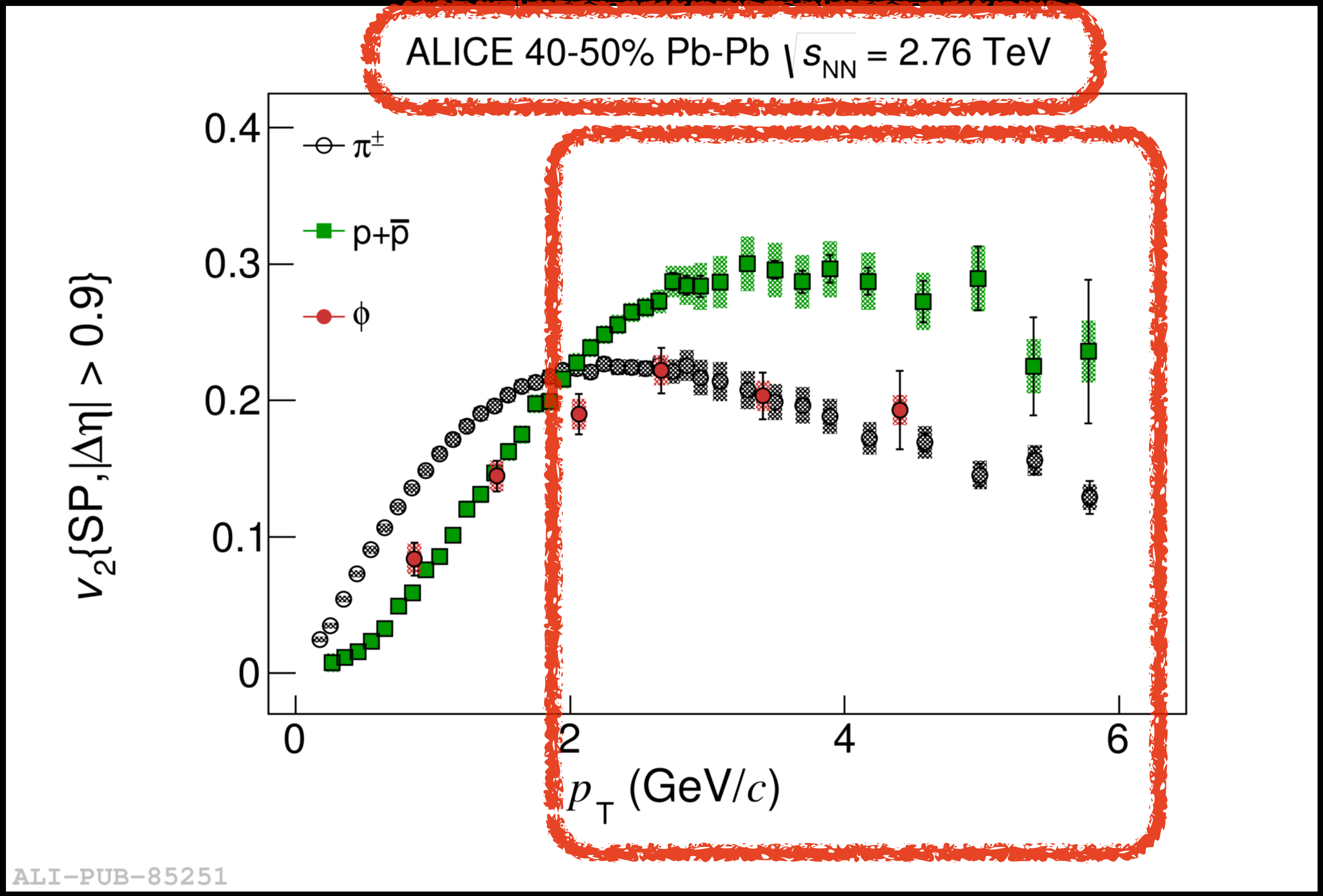


Scaling at the level of no better than ± 20%

The special role of the φ-meson

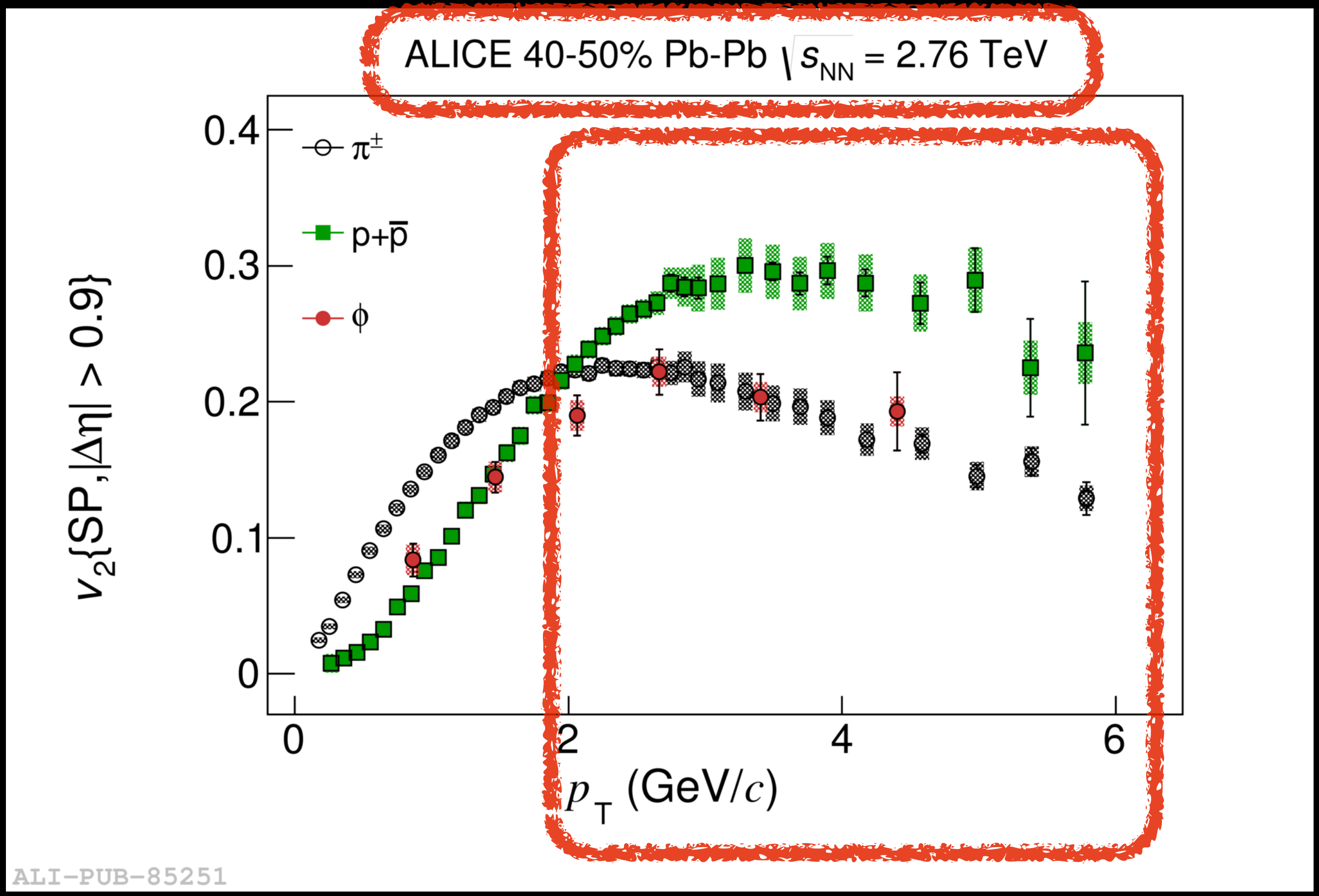


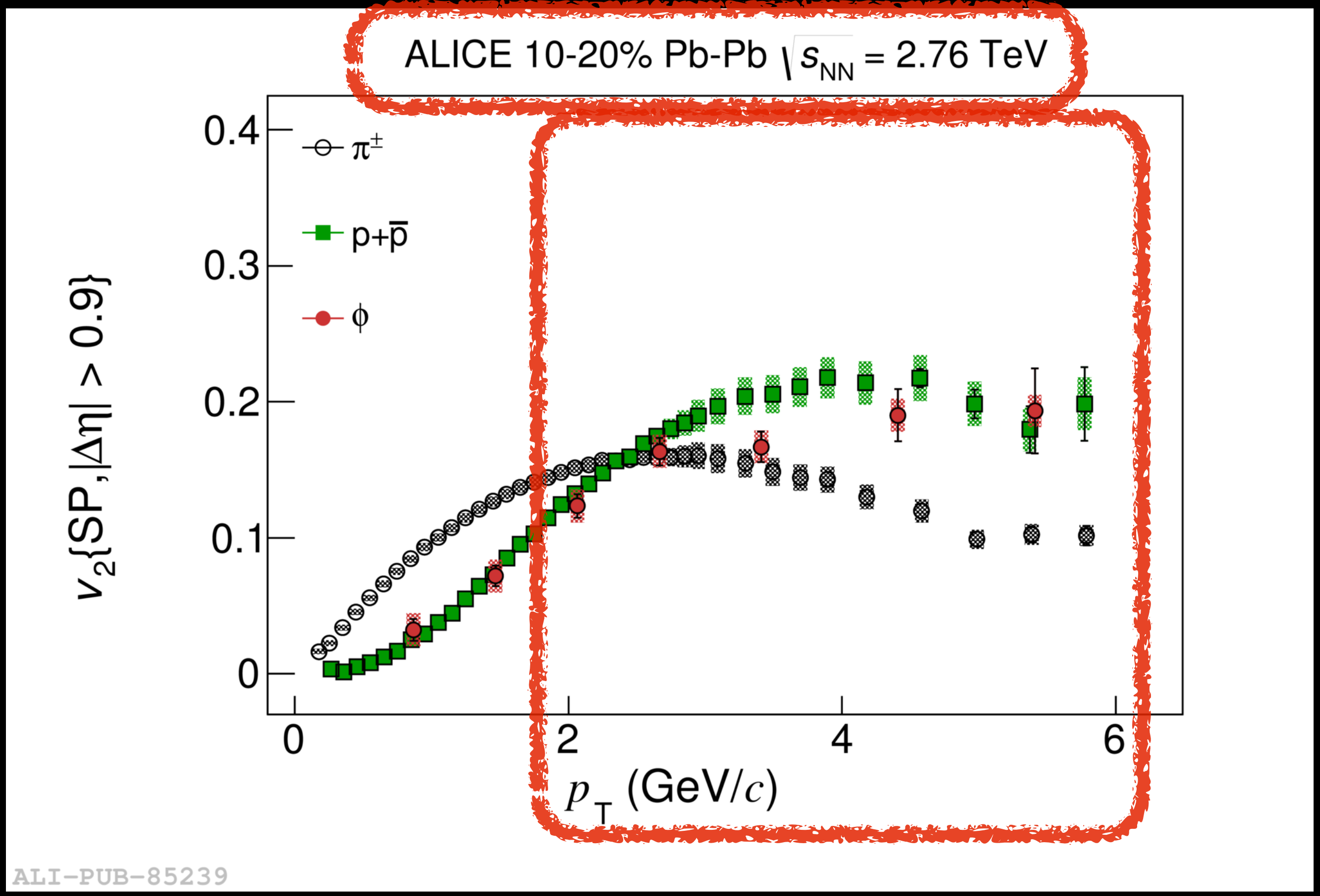
The special role of the φ-meson



- Intermediate p_T ($3 < p_T < 6$ GeV/c) the φ-meson follows
  - the meson band for peripheral events

The special role of the φ-meson

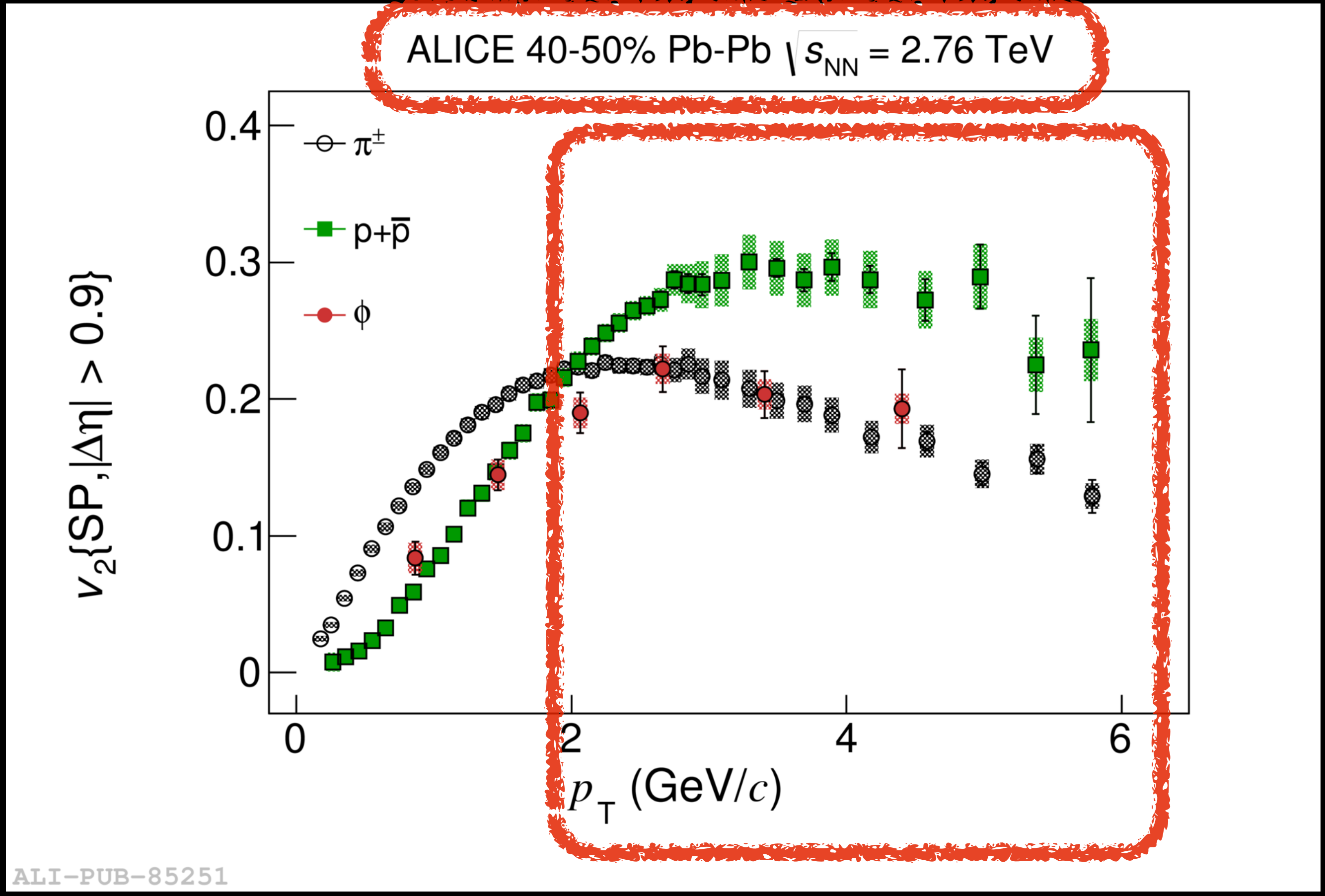


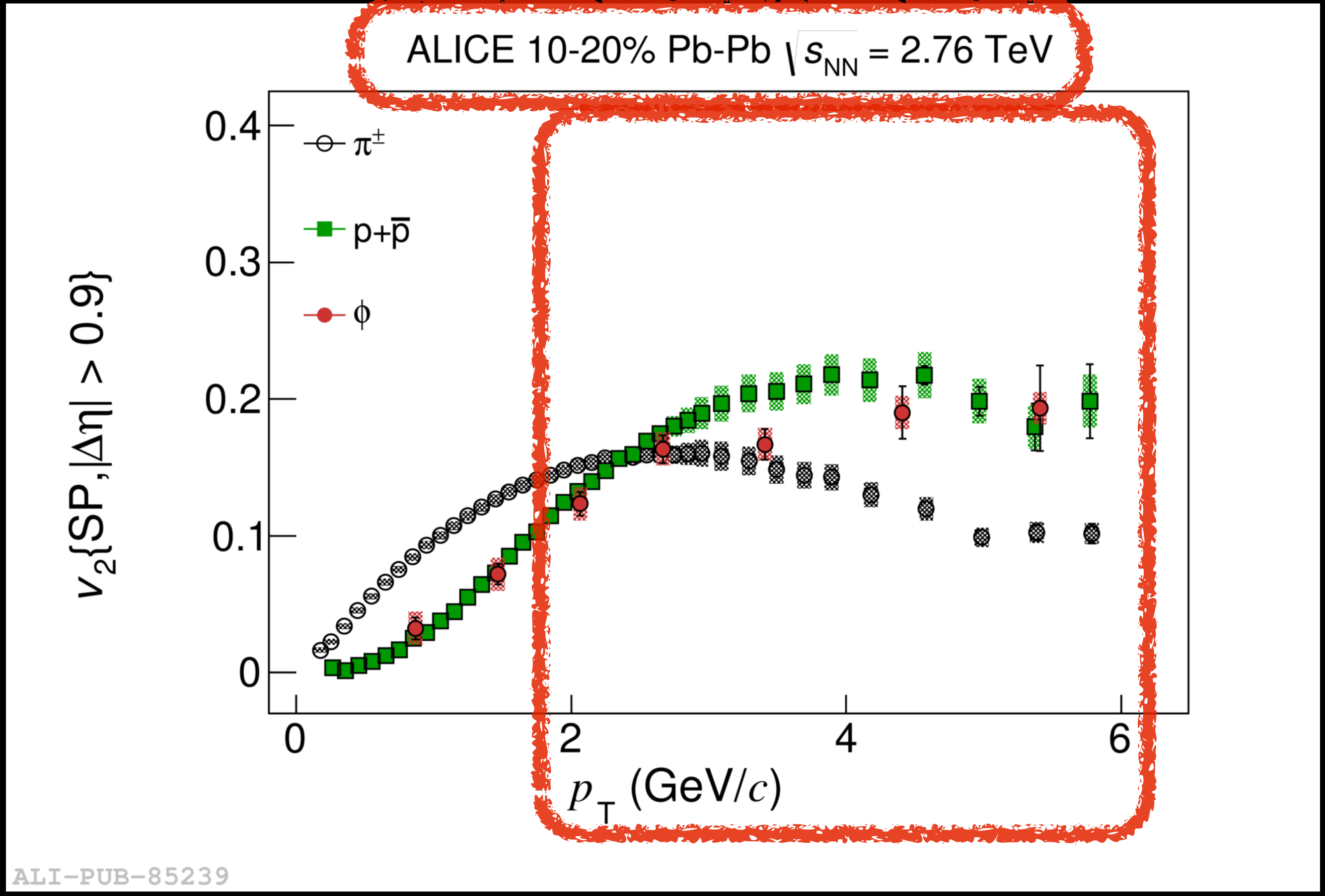


- Intermediate p_T ($3 < p_T < 6$ GeV/c) the φ-meson follows
  - the meson band for peripheral events
  - the baryon band for central events

The special role of the φ-meson

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



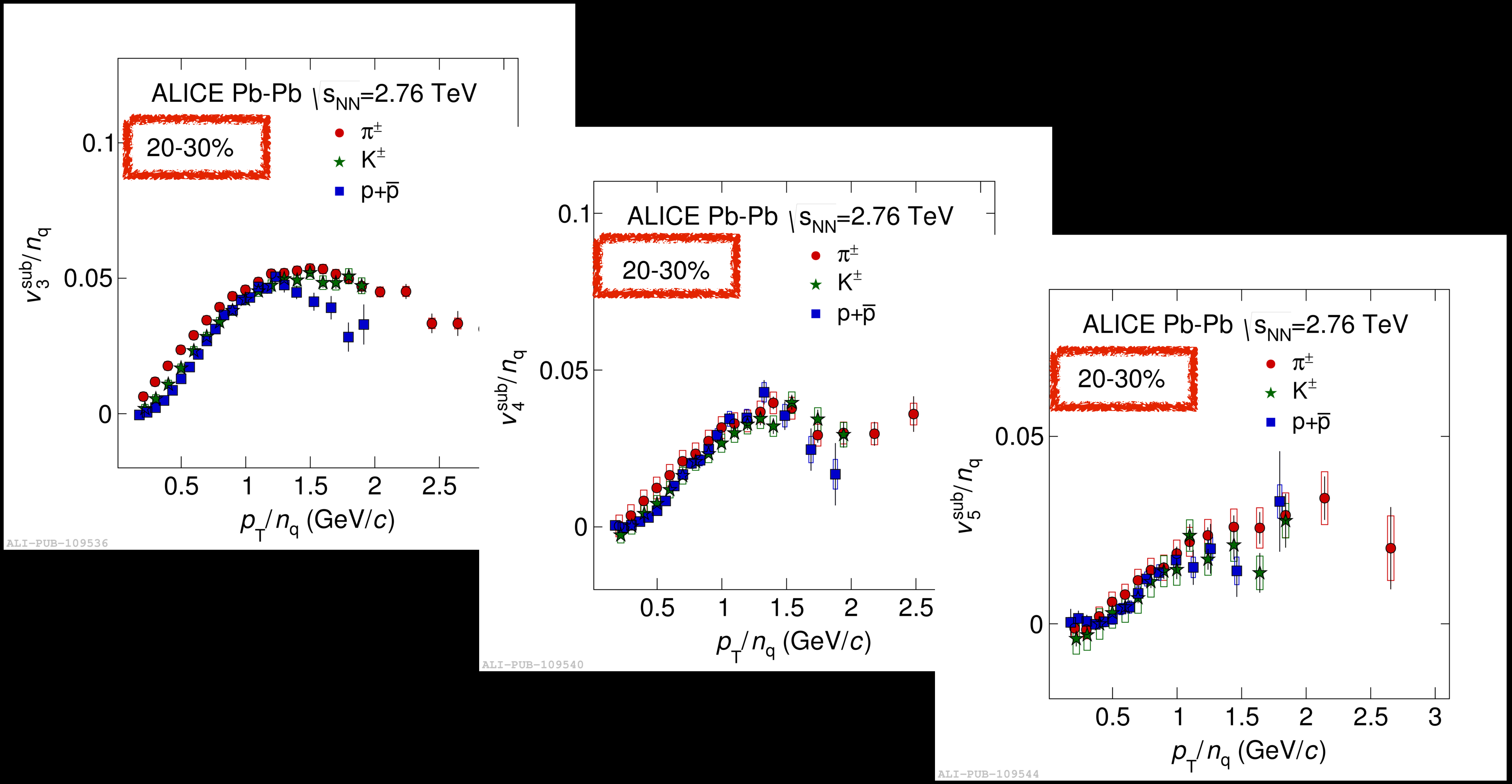


- Intermediate p_T ($3 < p_T < 6$ GeV/c) the φ-meson follows
  - the meson band for peripheral events
  - the baryon band for central events

Panos.Christakoglou@nikhef.nl

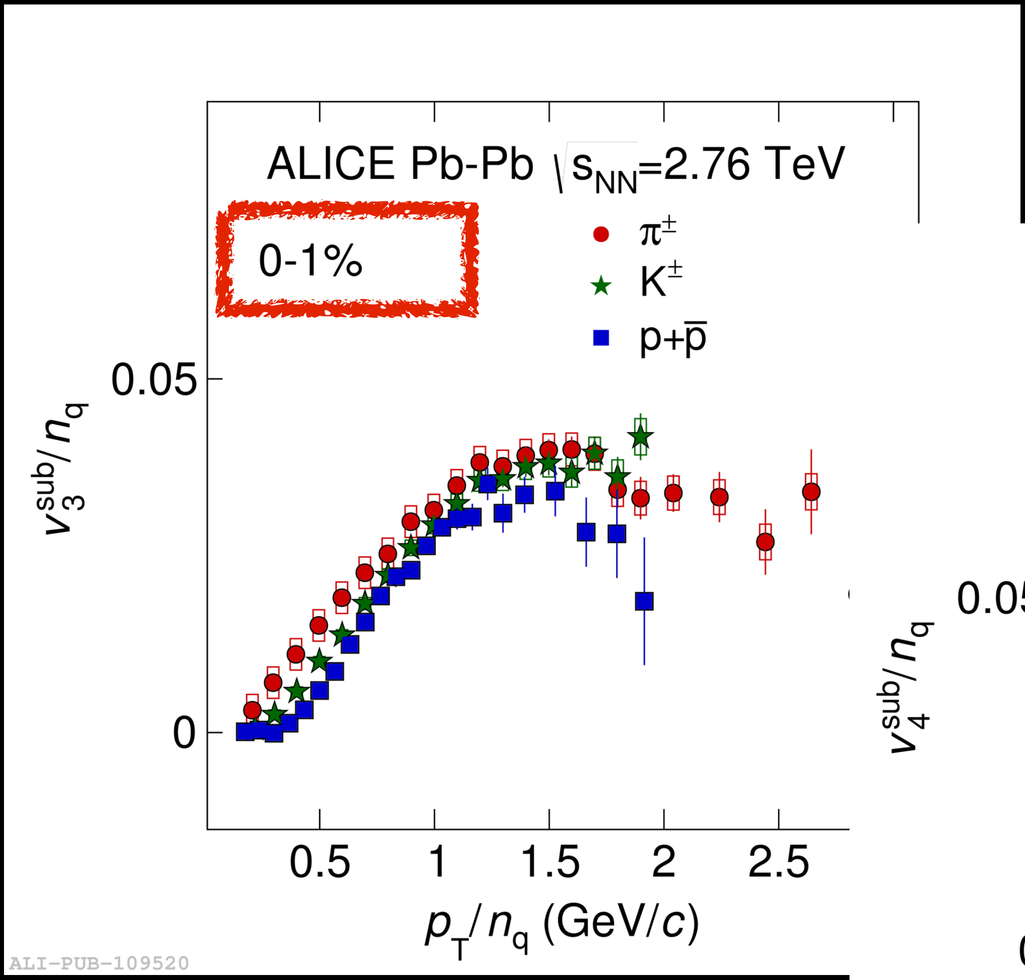
Scaling of higher harmonics @ LHC

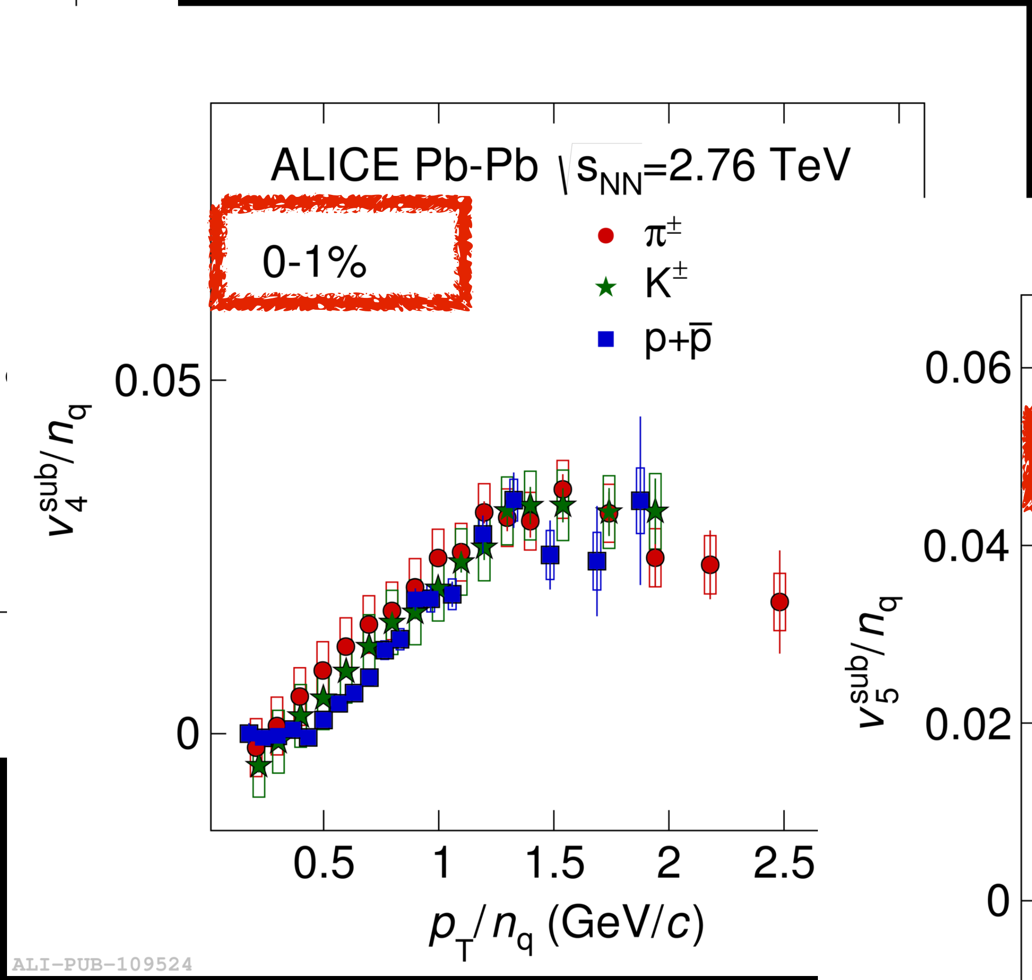
B. Abelev *et al.* (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]

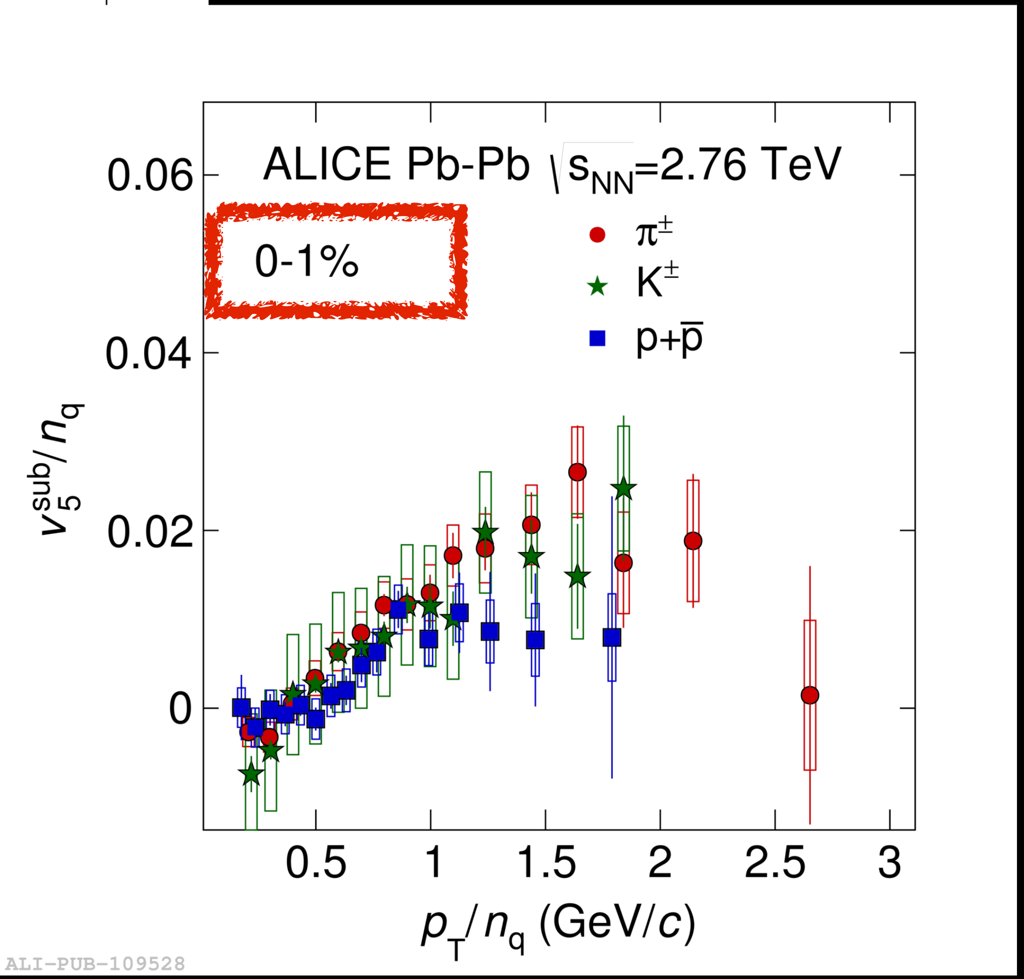


Scaling of higher harmonics @ LHC (ultra-central events)

B. Abelev *et al.* (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]





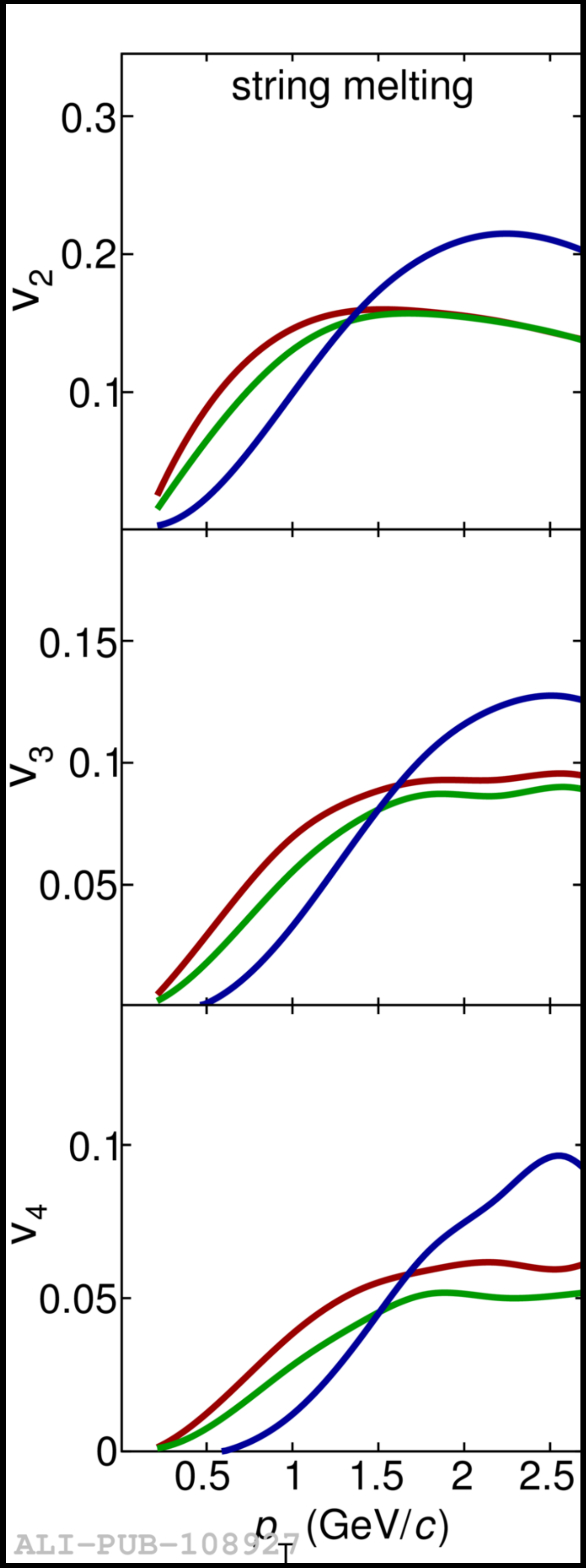


Scaling at the level of 10-20%

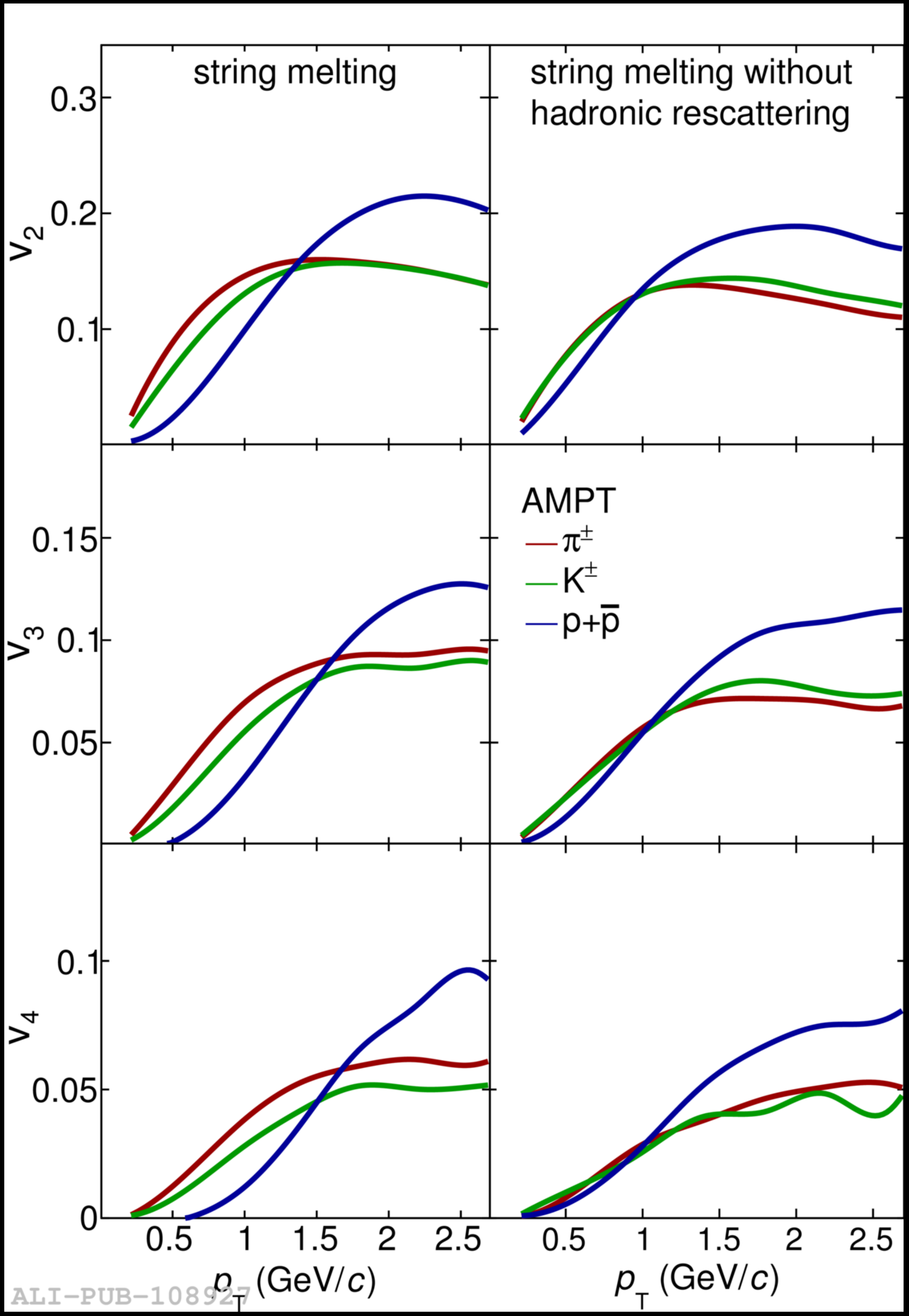
AMPT: mass ordering & scaling properties

- A Multi-Phase Transport model
  - String melting:
    - strings are melt into their partons
    - partons interact based on a partonic cross-section
    - coalescence to form hadrons
    - hadronic rescattering phase
  - Default
    - strings combined into hadrons via the Lund string fragmentation model
    - hadronic rescattering phase
- Possibility to probe the effects of the
  - partonic phase
  - coalescence mechanism
  - hadronic rescattering

AMPT


string melting
v_2
0.3
0.2
0.1
v_3
0.15
0.1
0.05
v_4
0.1
0.05
0
0.5
1
1.5
2
2.5
p_T (GeV/c)
ALI-PUB-108927

AMPT



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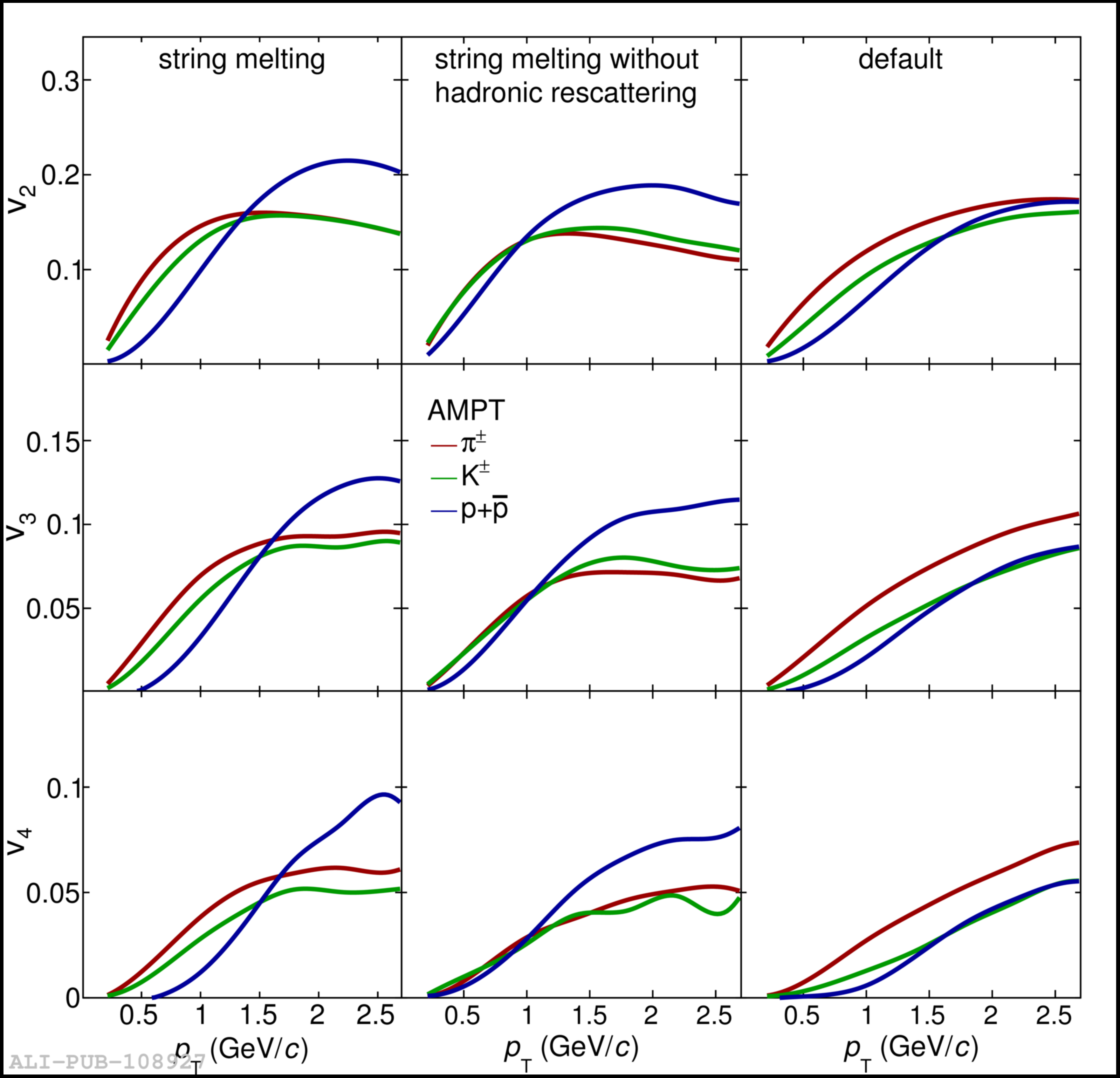
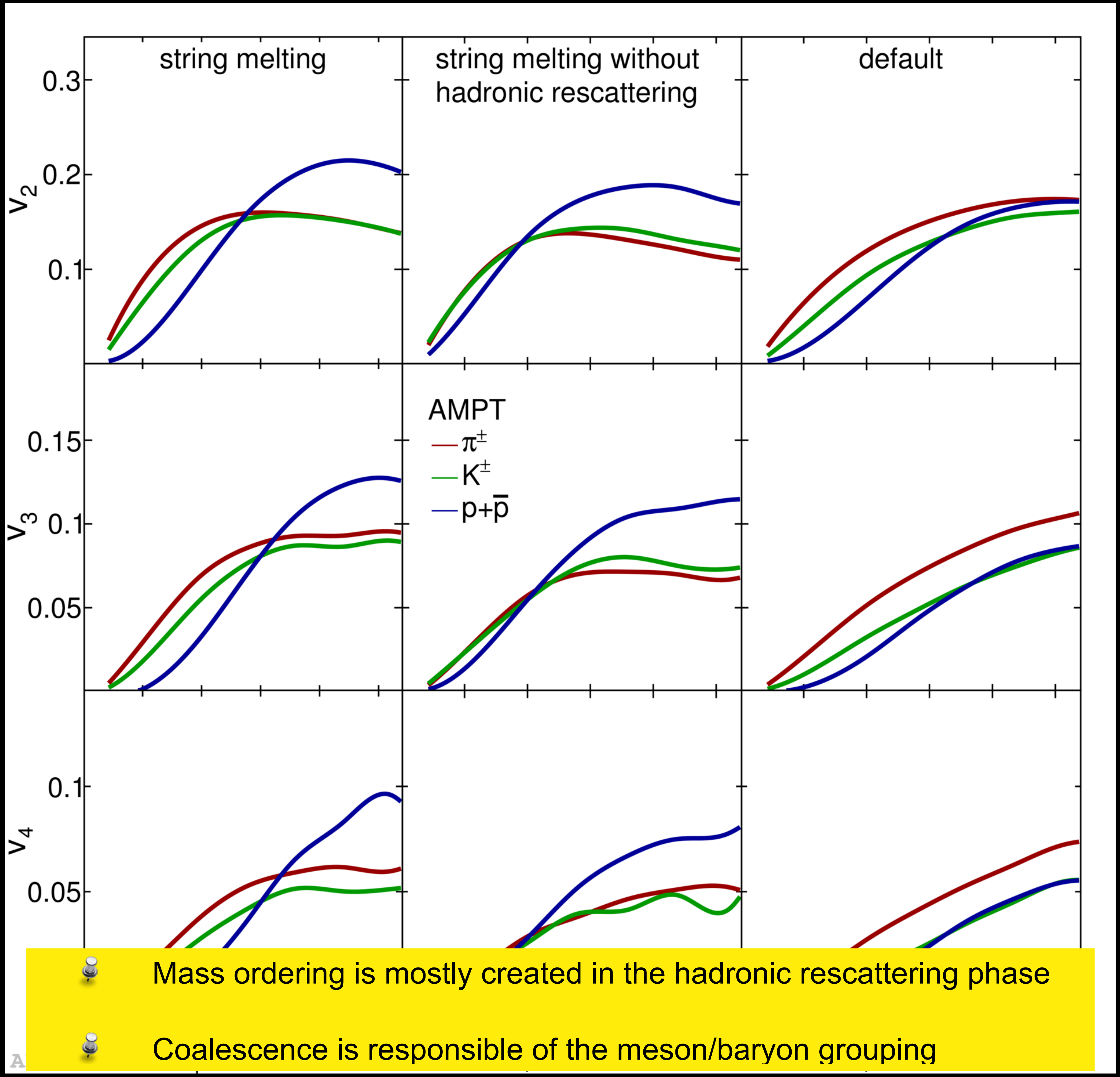
AMPT



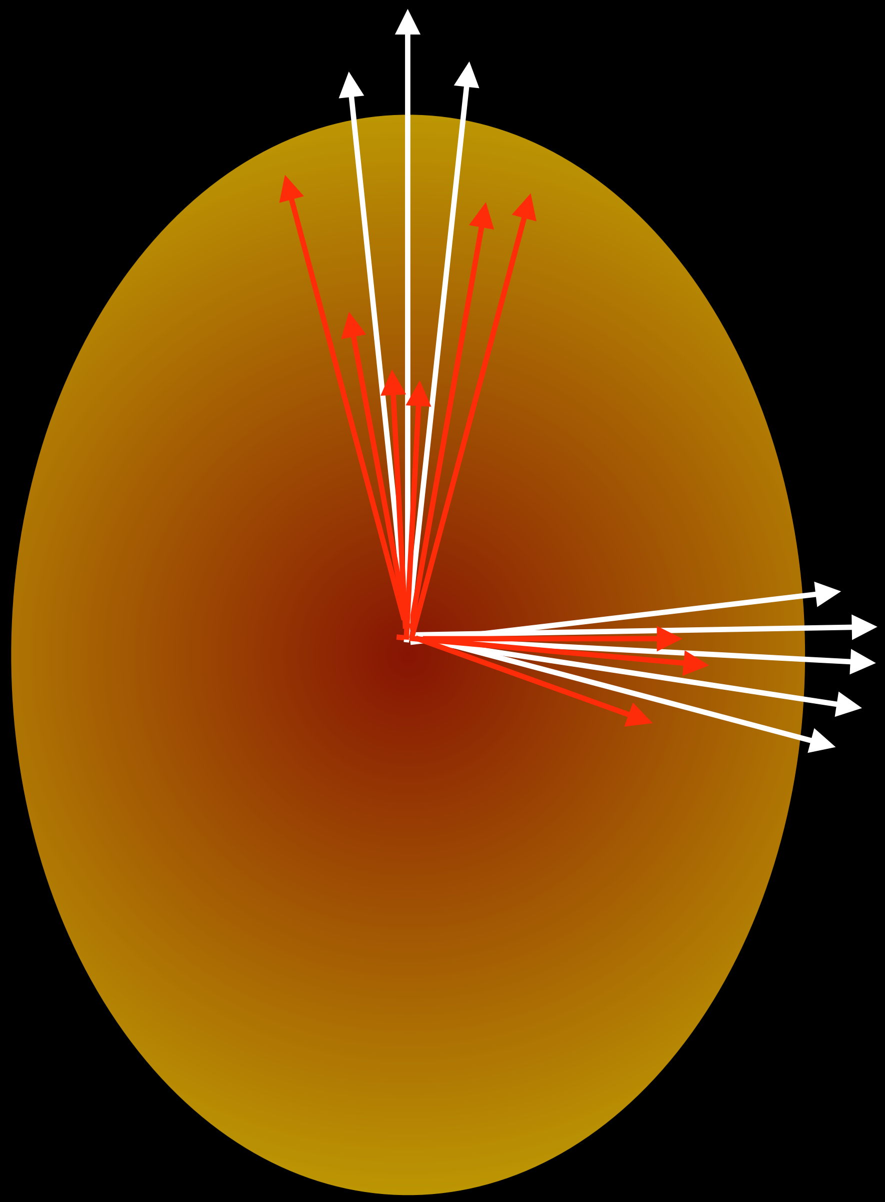
string melting
string melting without hadronic rescattering
default
AMPT
$\pi^{\pm}$
$K^{\pm}$
$p+\bar{p}$
v_2
v_3
v_4
0.3
0.2
0.1
0.15
0.1
0.05
0.1
0.05
0
0.5
1
1.5
2
2.5
p_T (GeV/c)
ALI-PUB-108927

AMPT

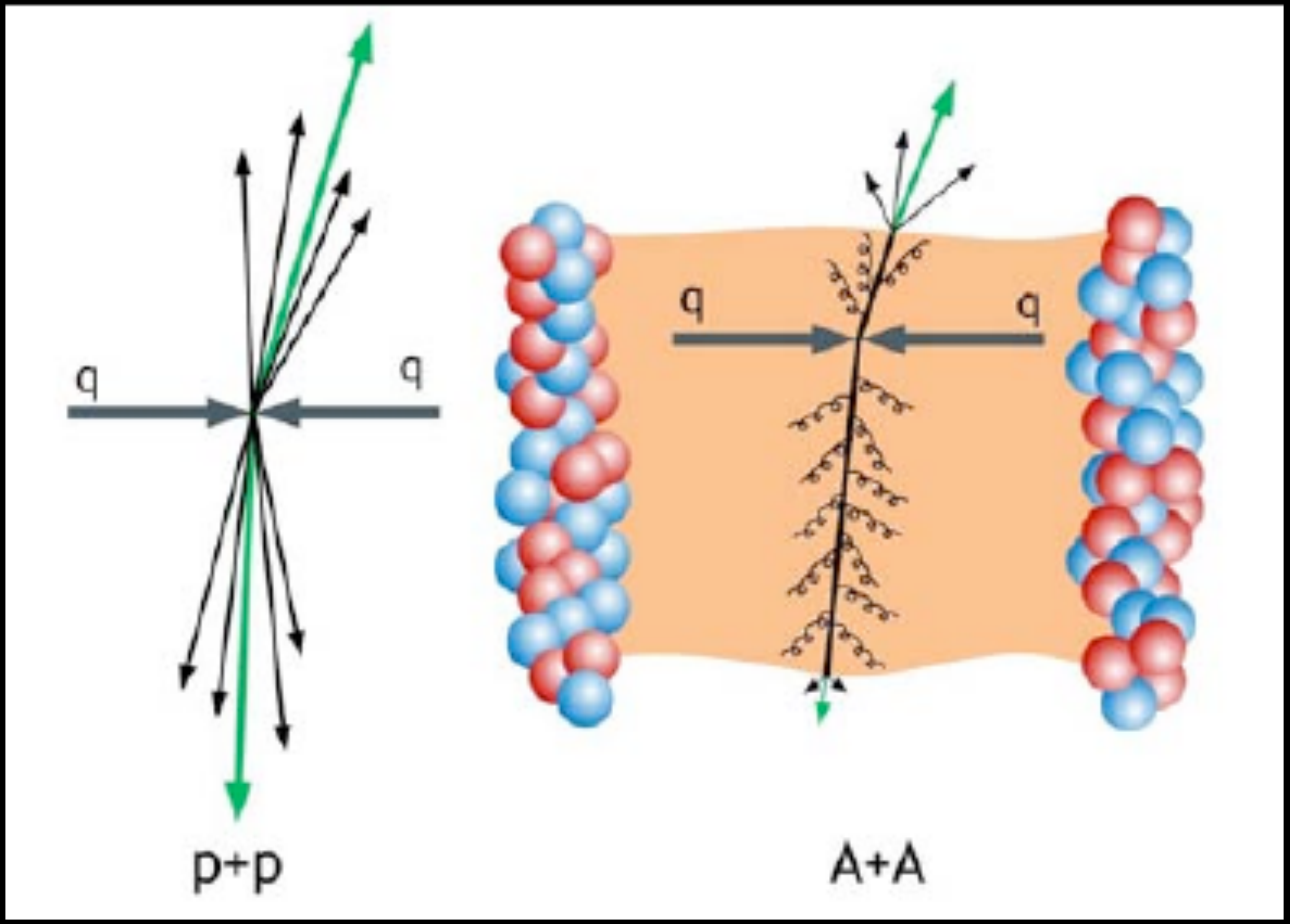


- Mass ordering is mostly created in the hadronic rescattering phase
- Coalescence is responsible of the meson/baryon grouping

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

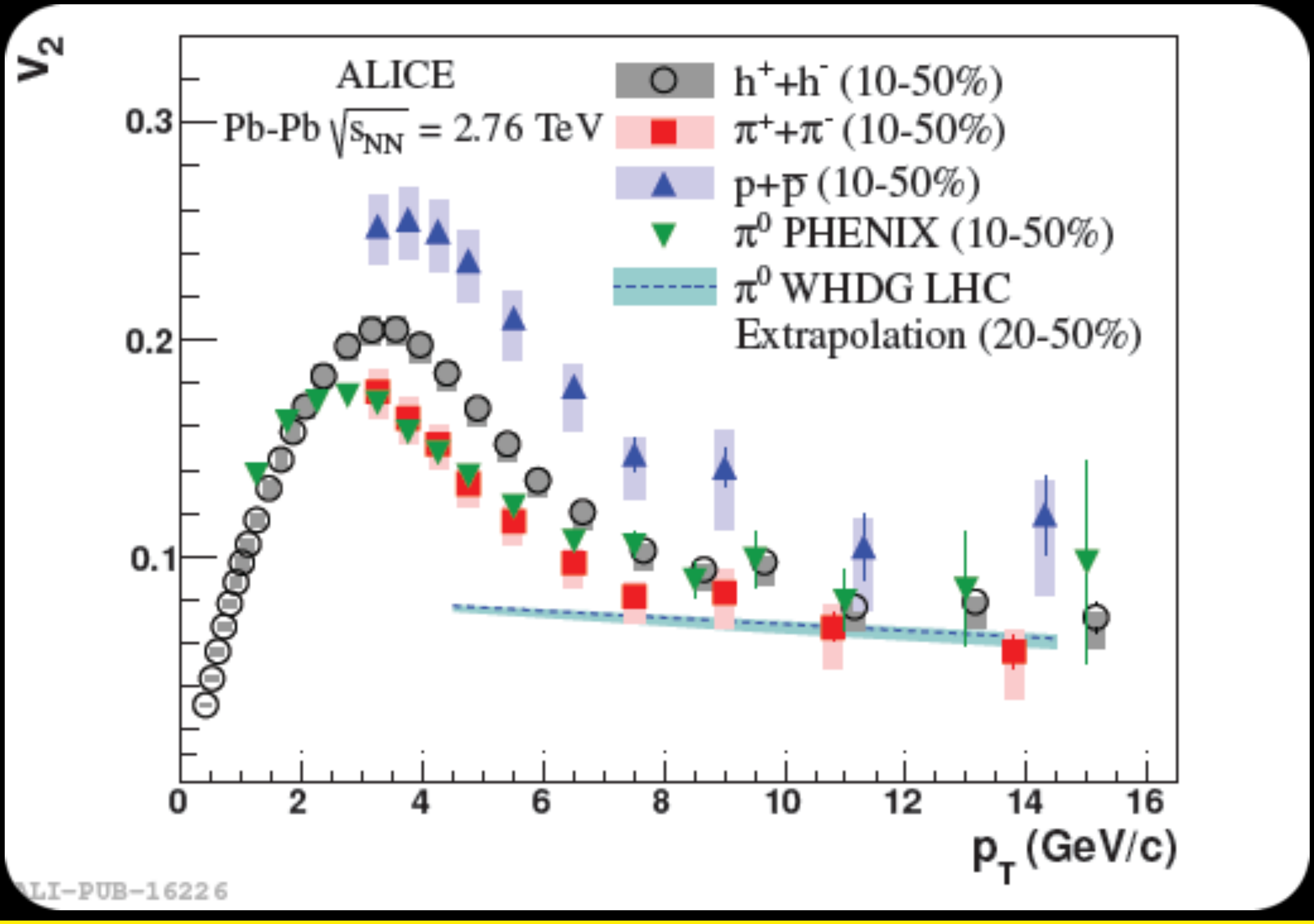


- Probing the path length dependence
  - particles flying in- (out-of)plane have to travel through less (more) medium
  - expect to see an azimuthal dependence of jets and high p_T particles



High p_T pions, kaons, protons @ LHC: v_2

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

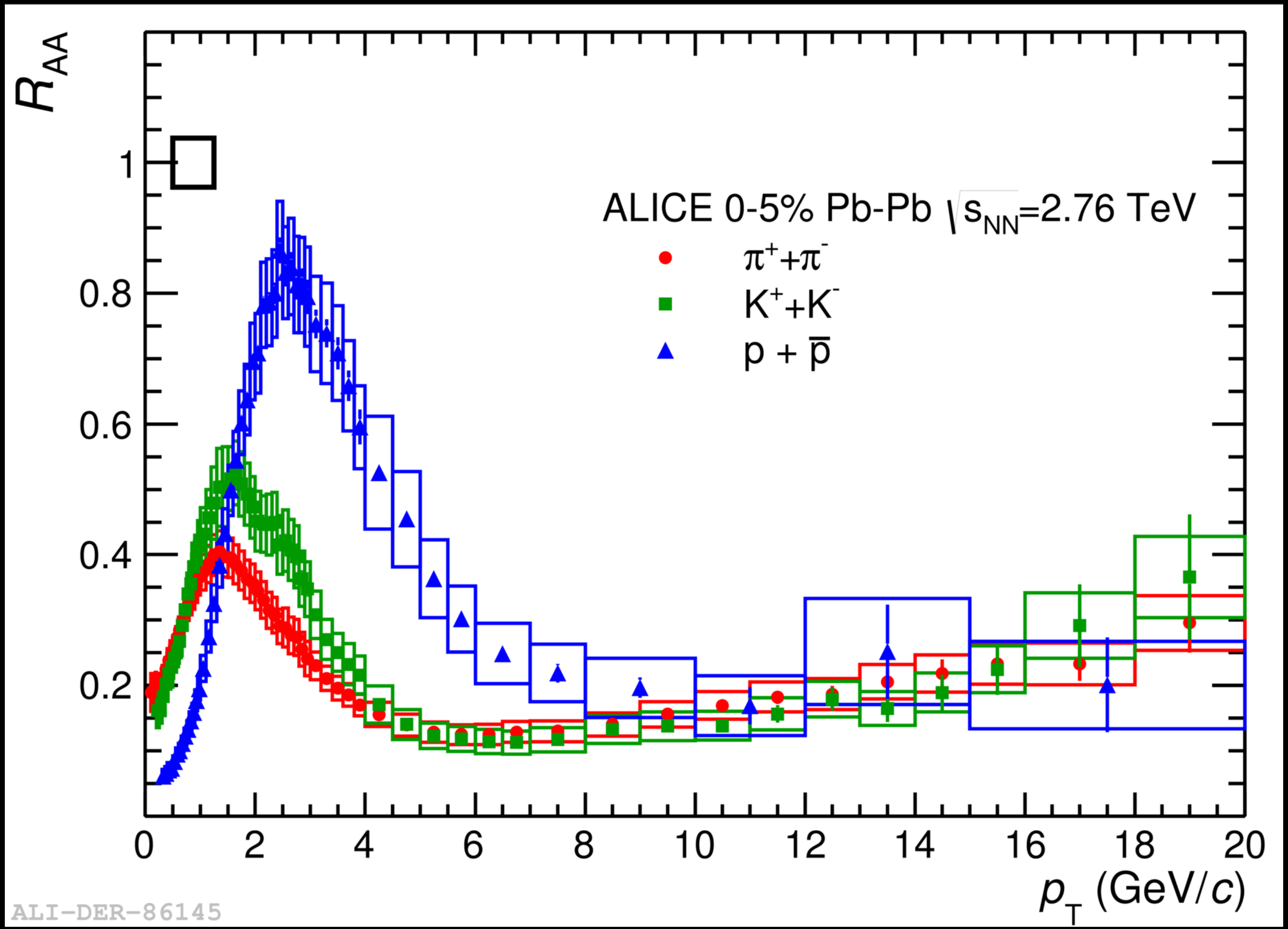


- Significant v_2 for all particle species at high p_T
  - azimuthal dependence of high-p_T particle yield
  - no significant particle species dependence for p_T > 10 GeV/*c*
- Theory curve describes data fairly well

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

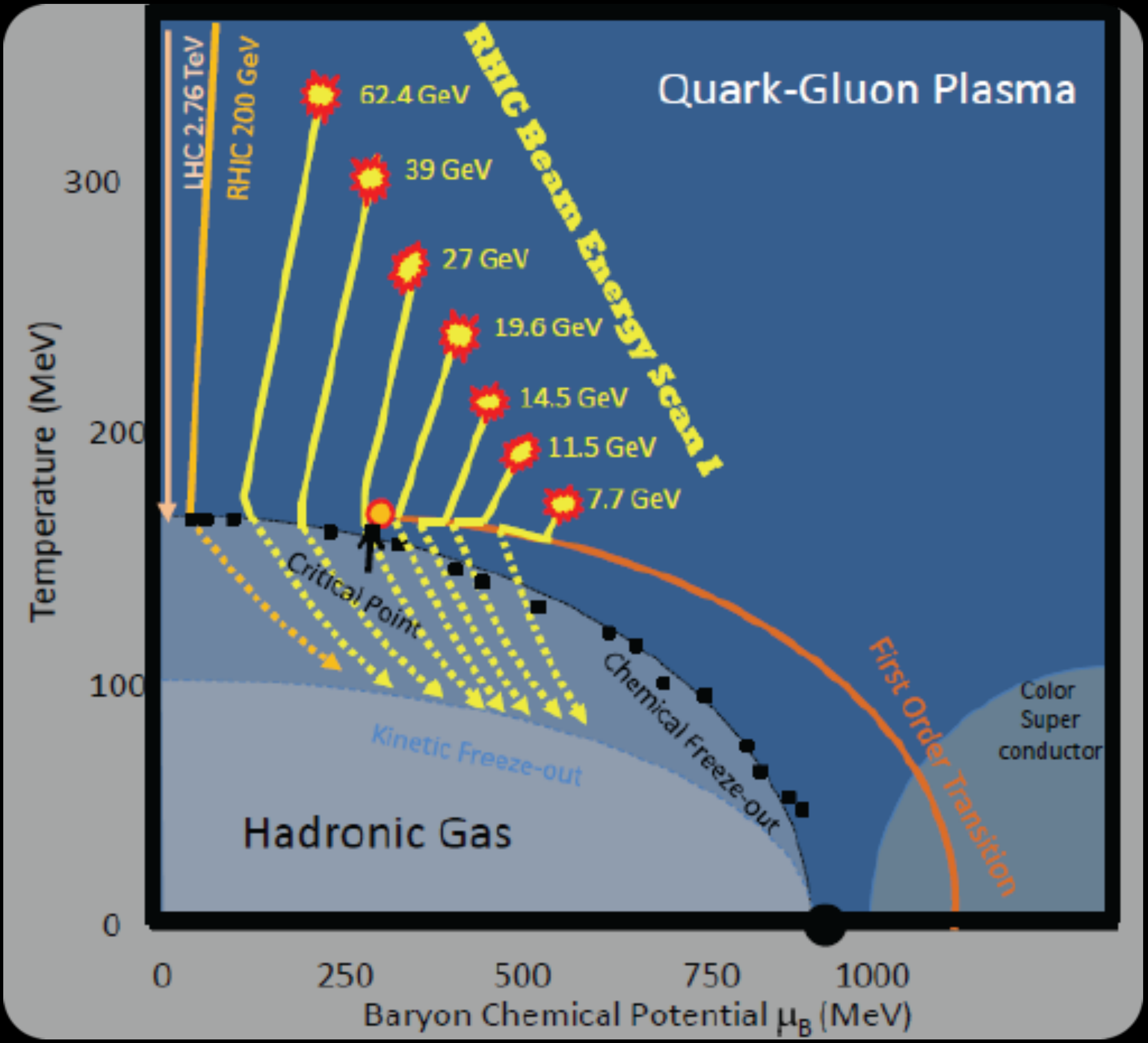
B. Abelev *et al.* (ALICE Collaboration), PLB 736 (2014) 196

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



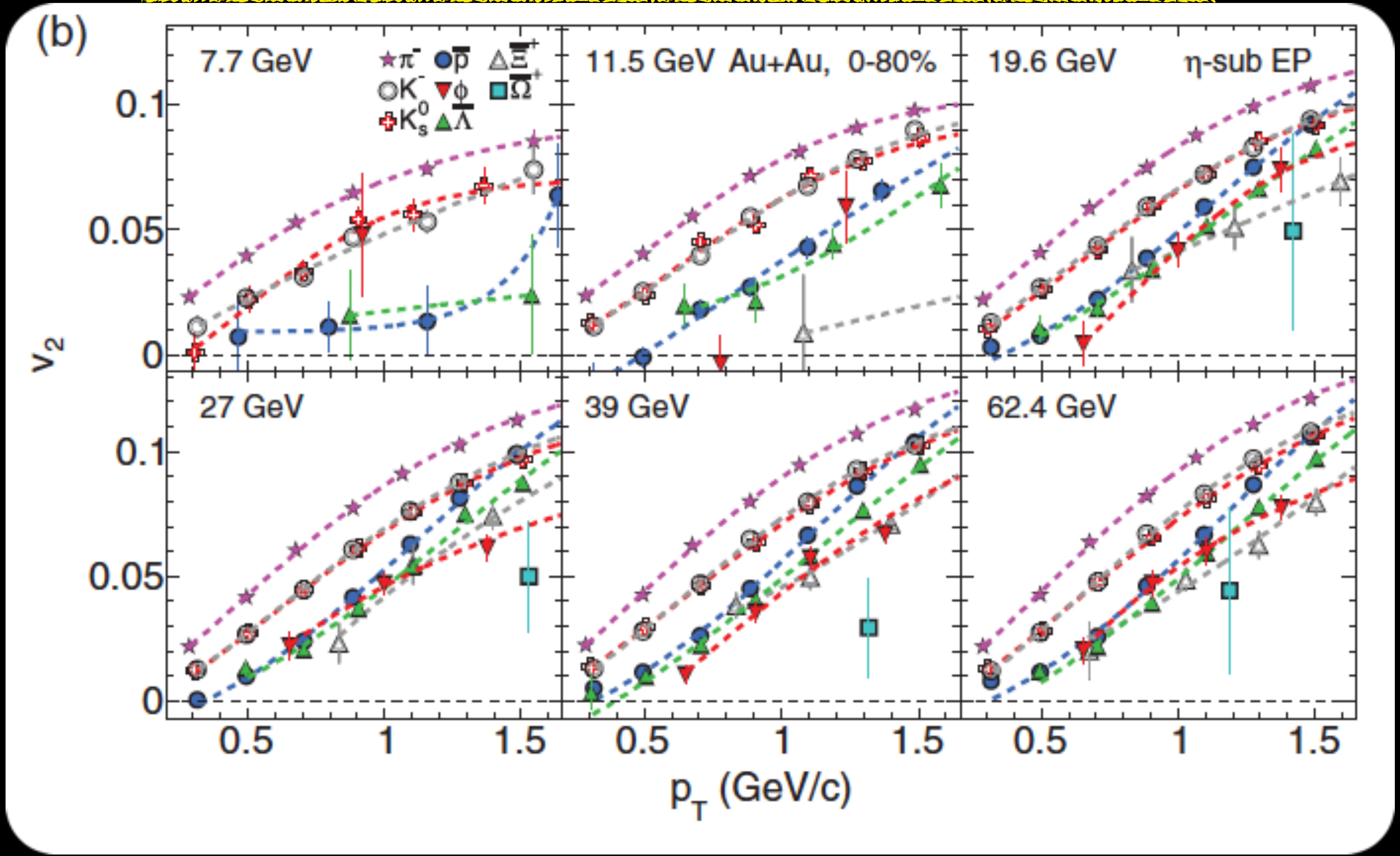
- Large suppression of high p_T particles
- Suppression does not depend on particle species for p_T > 10 GeV/*c*

Searching for the critical point



BES: v_2 of antiparticles

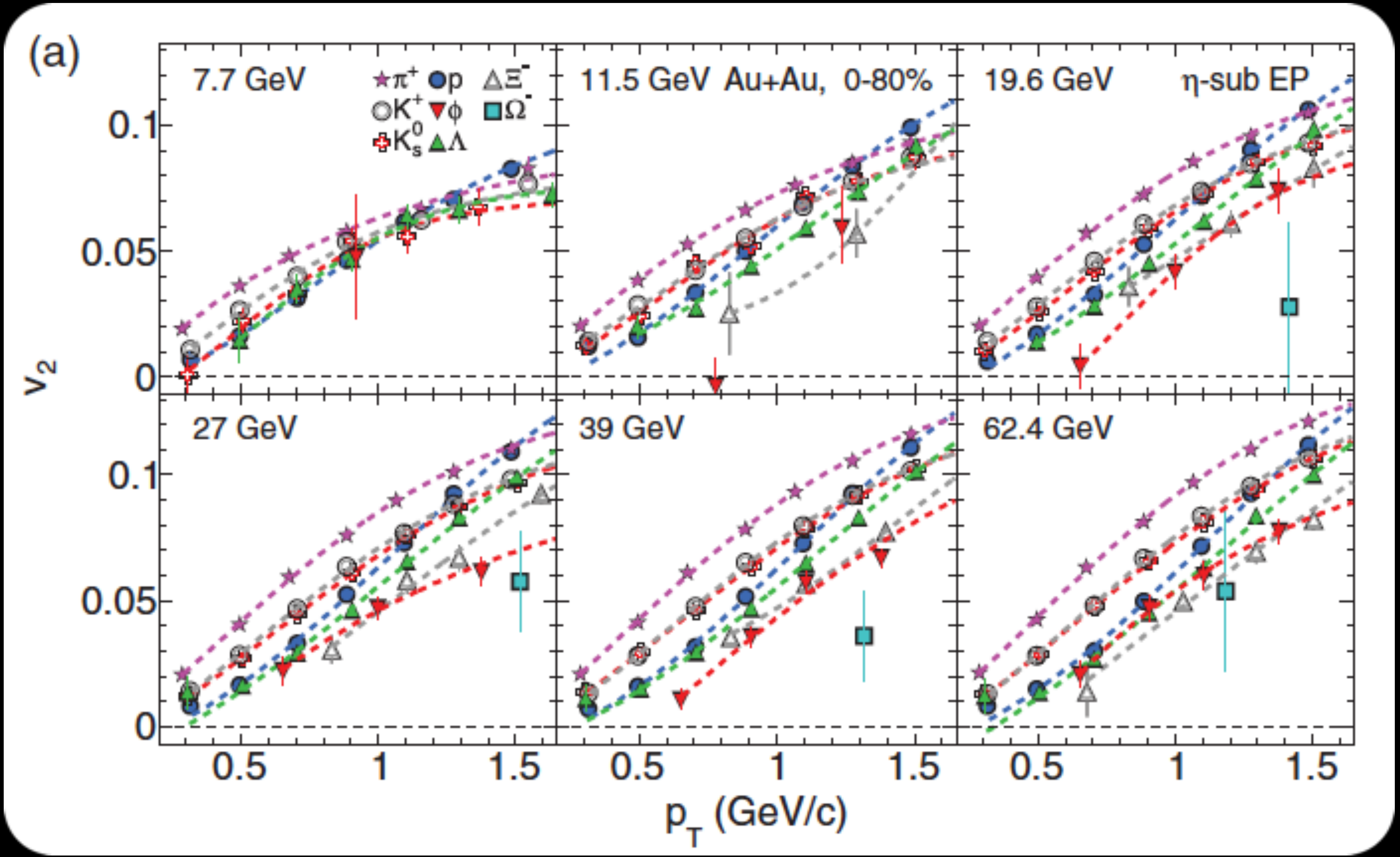
L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902



- 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

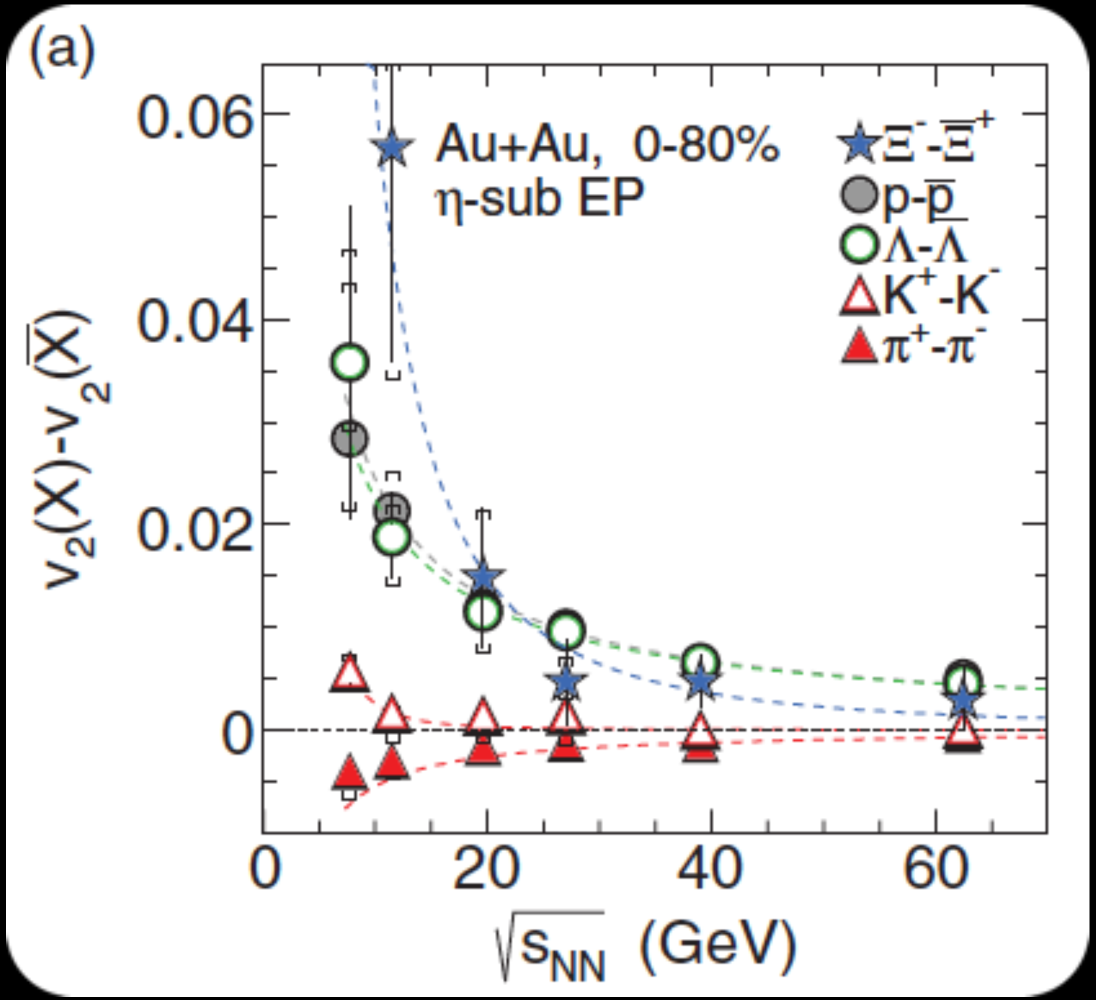
L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902



- 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

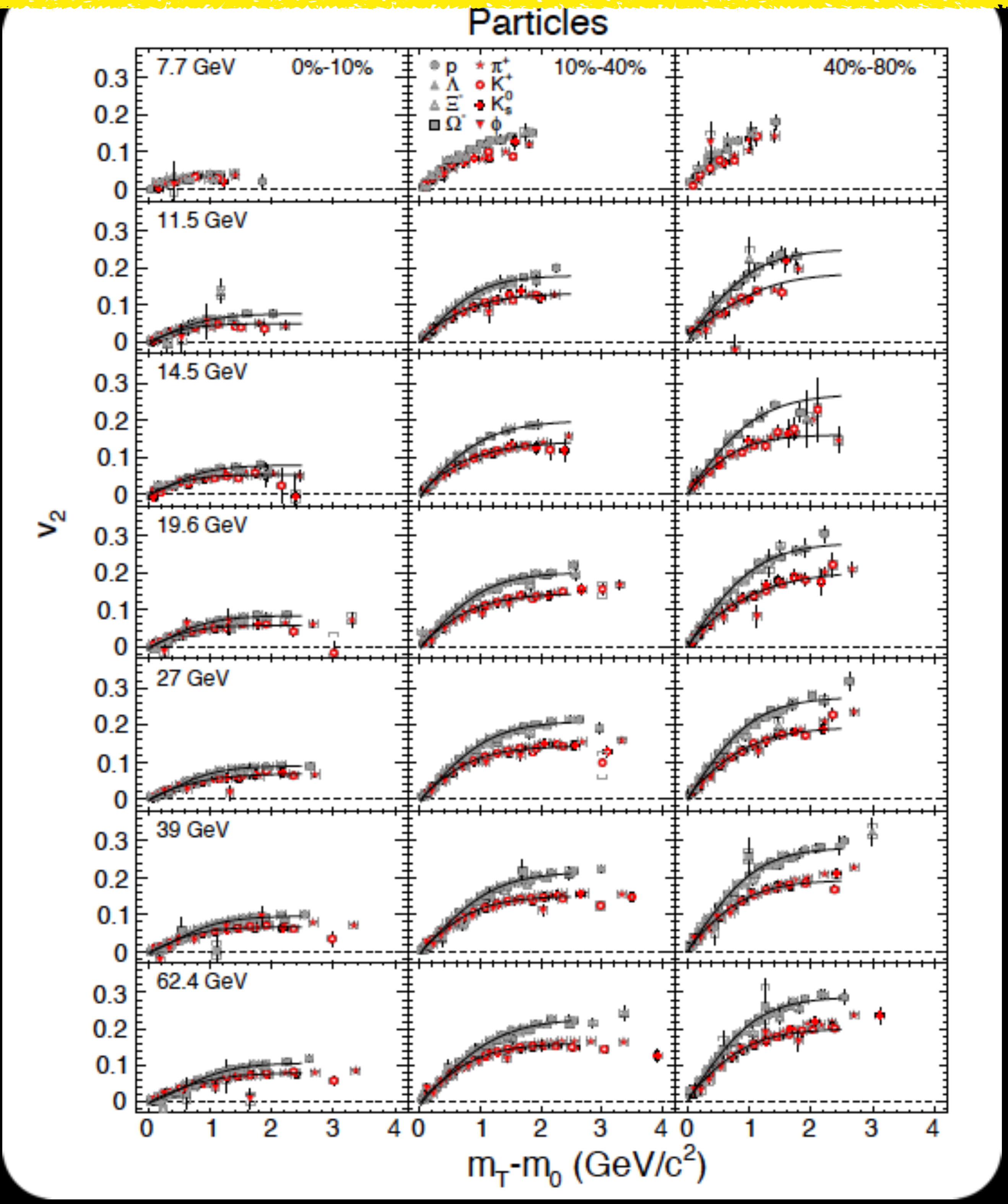
L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902



- 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

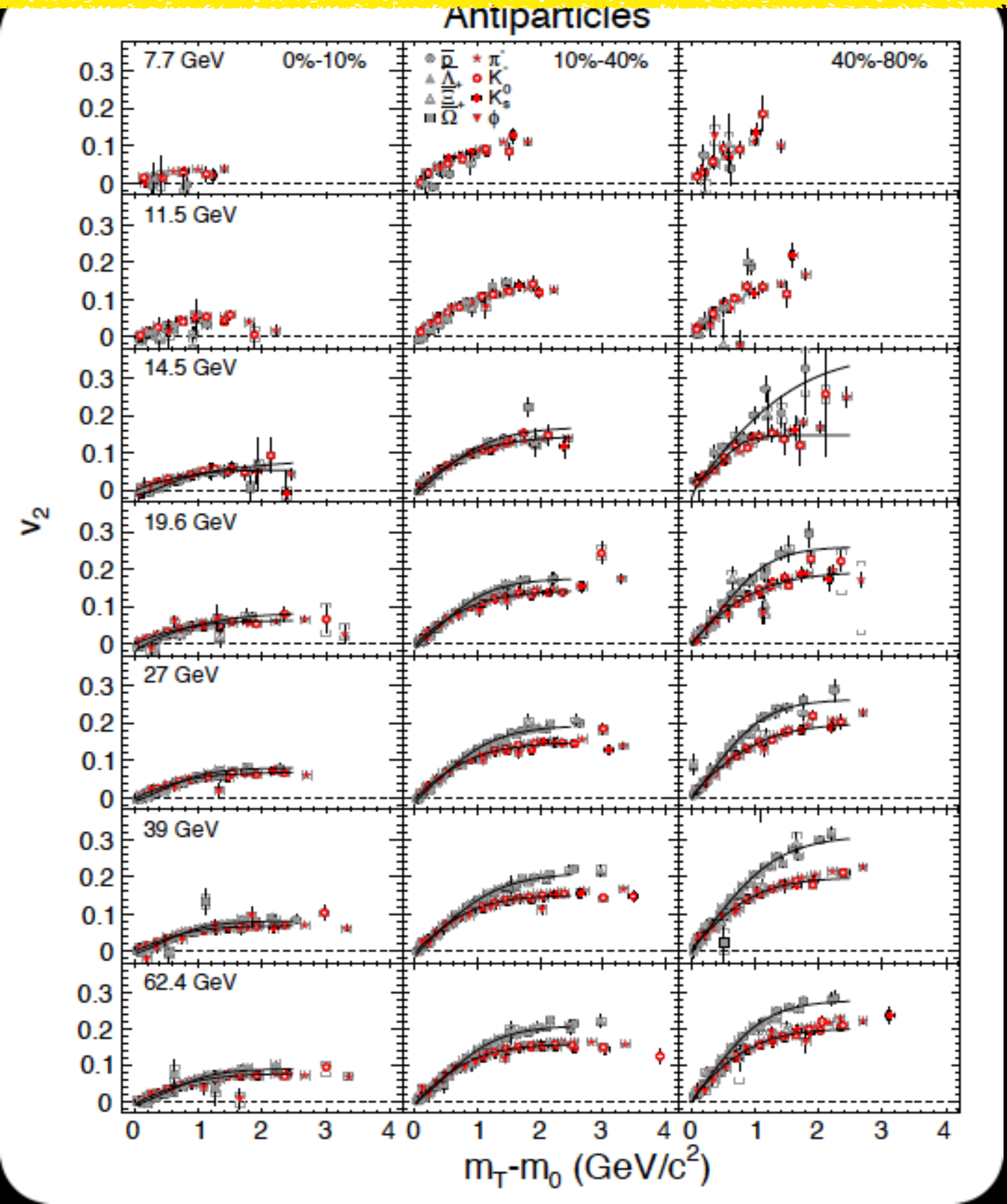
BES: Baryon/meson grouping (particles)

L. Adamczyk *et al*. (STAR Collaboration), Phys.Rev. C93 (2016) 014907



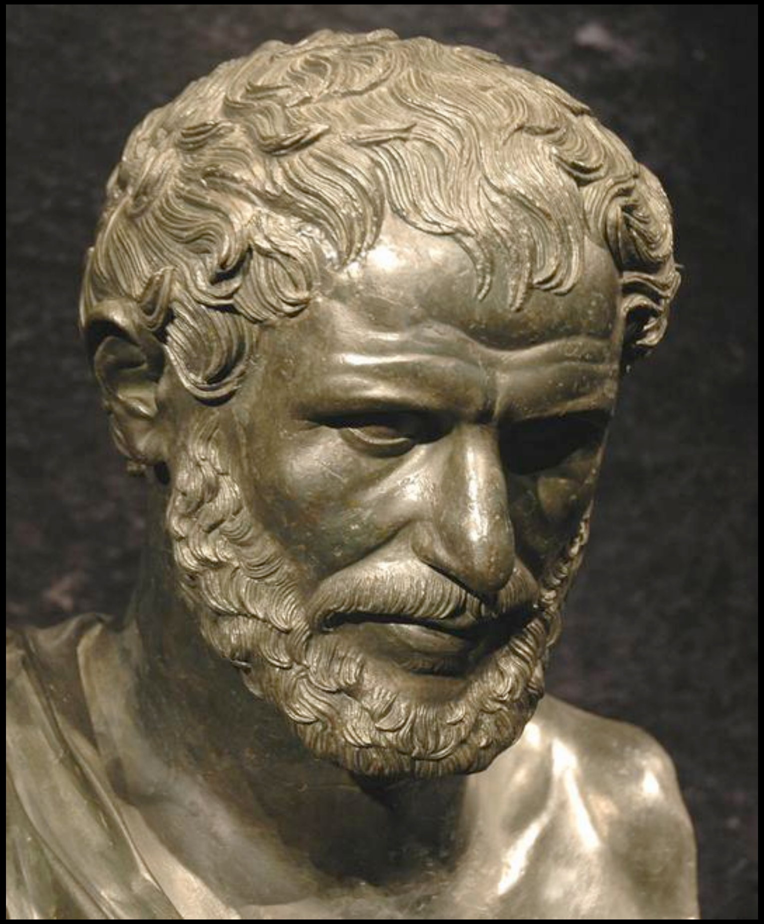
BES: Baryon/meson grouping (antiparticles)

L. Adamczyk *et al*. (STAR Collaboration), Phys.Rev. C93 (2016) 014907



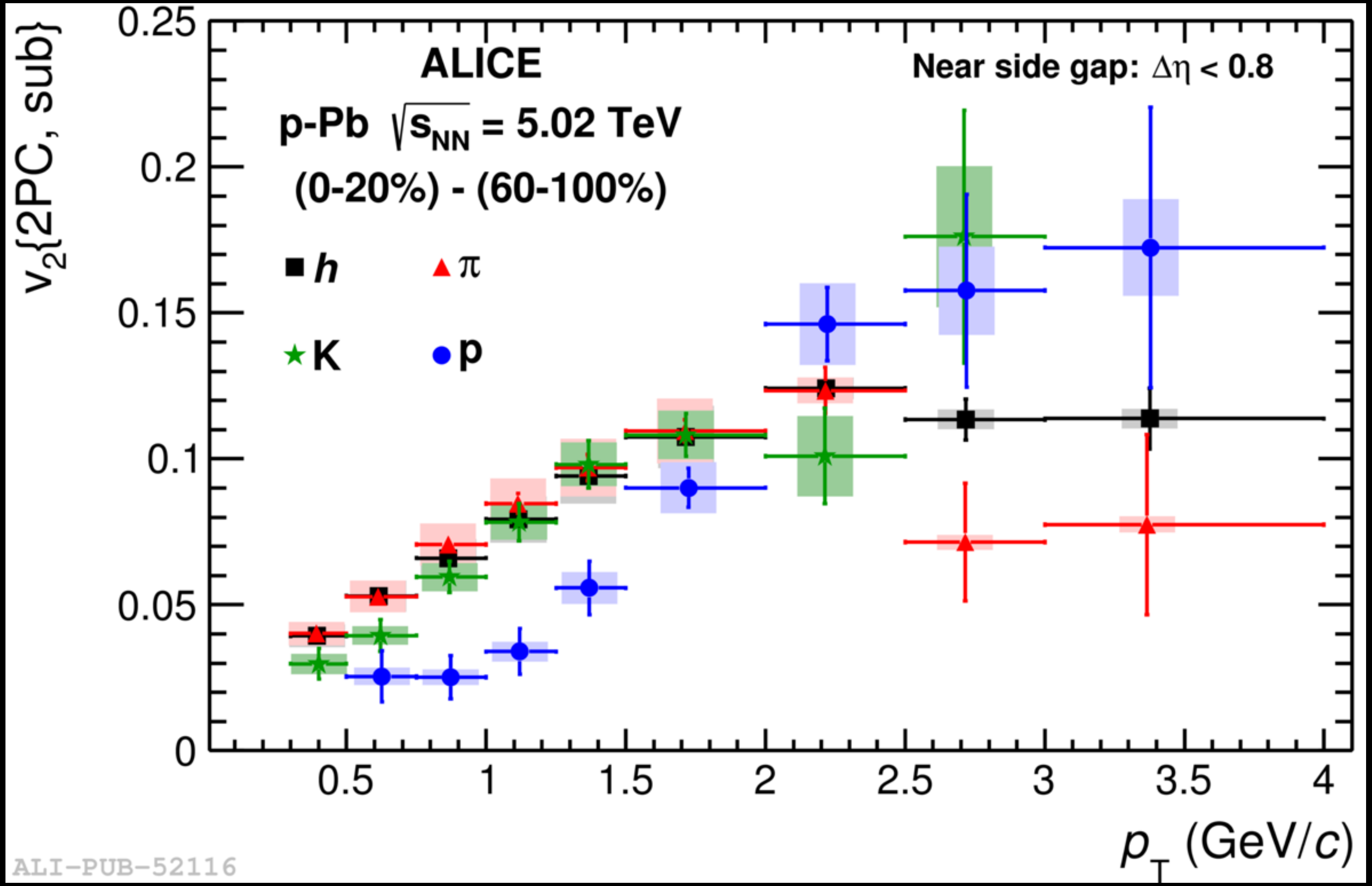
Τα πάντα ρει…(everything flows)

Ηράκλειτος (Heraclitus) ~535 - 475 BC

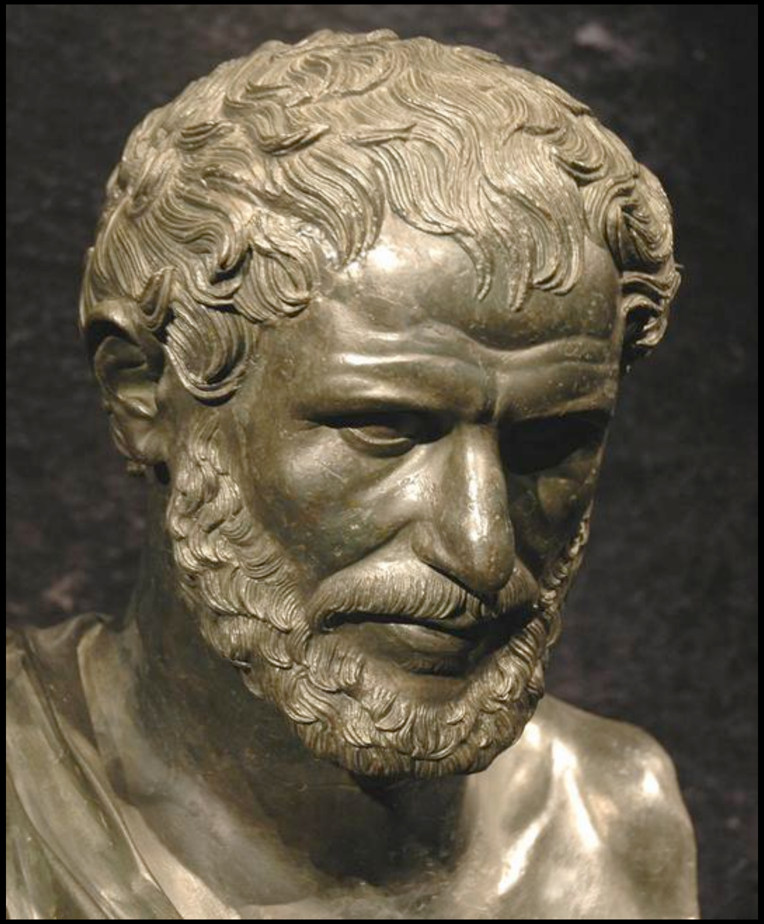


Τα πάντα ρει…(everything flows)

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



Ηράκλειτος (Heraclitus) ~535 - 475 BC

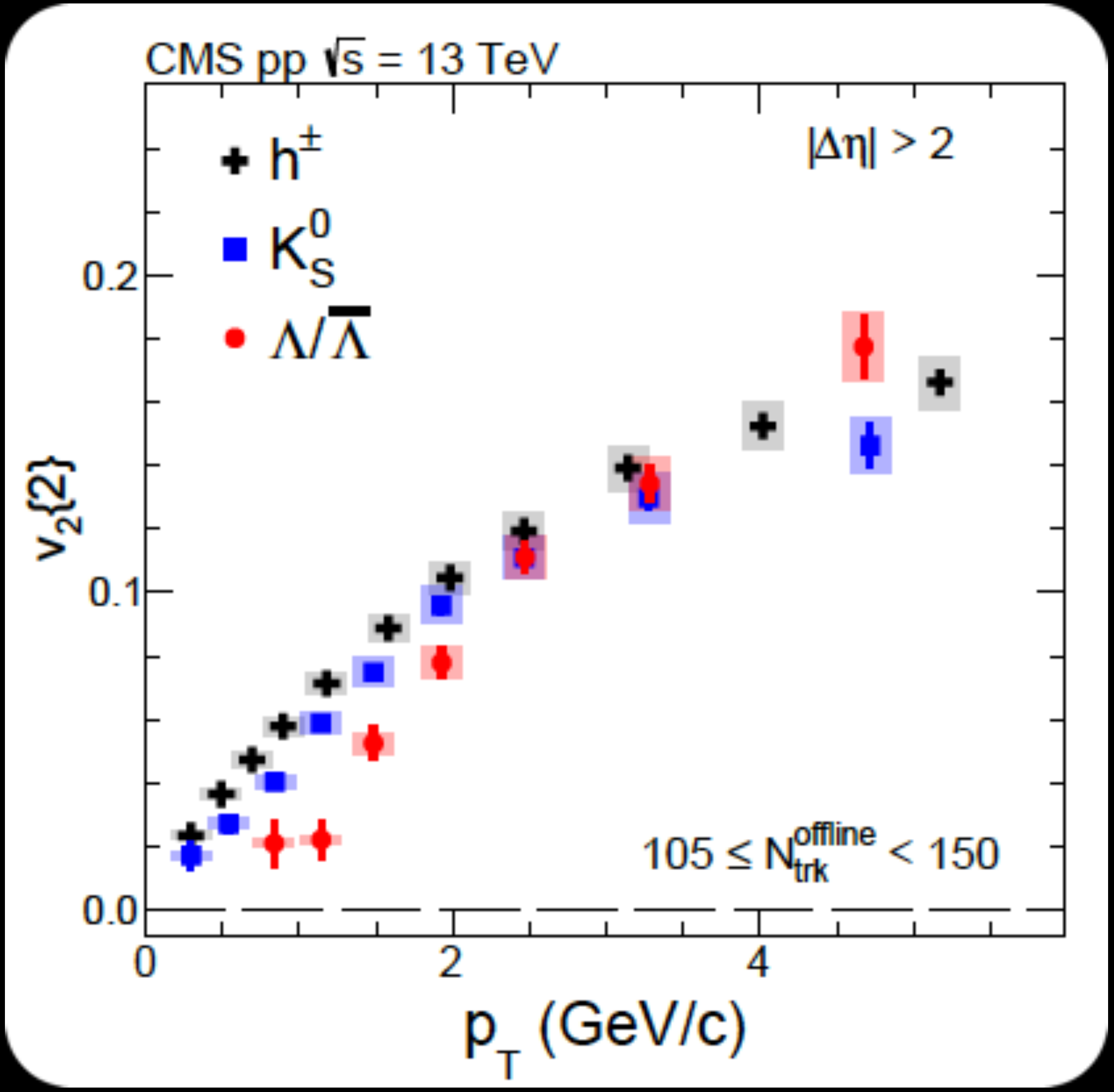


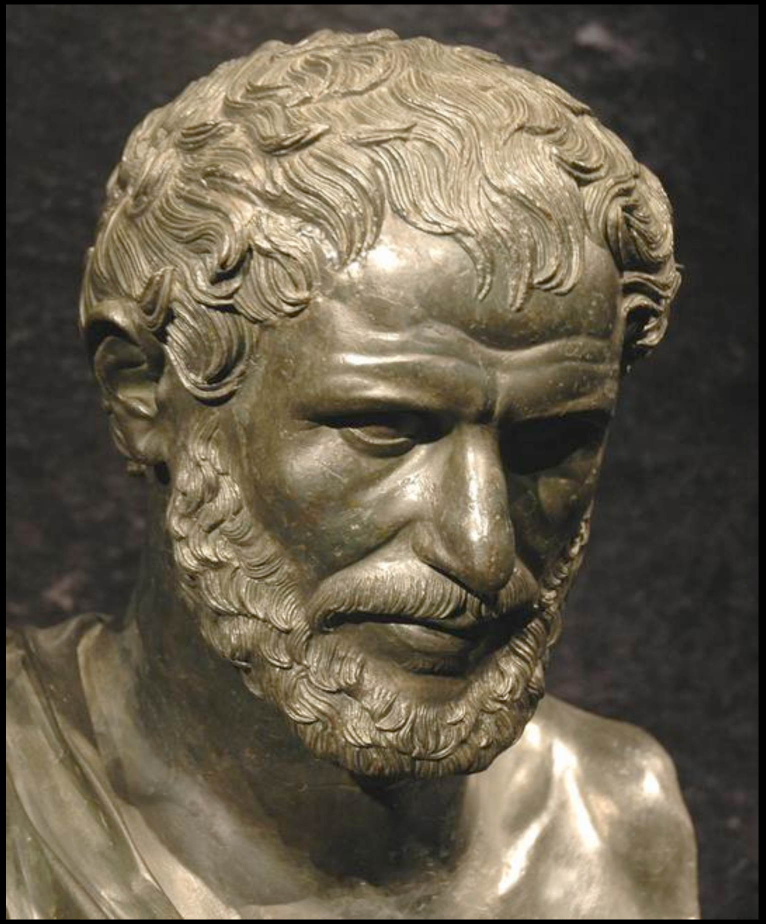
Not only in A-A it seems but also for smaller systems!

Τα πάντα ρει…(everything flows)

(CMS Collaboration) arXiv:1606.06198 [nucl-ex]

Ηράκλειτος (Heraclitus) ~535 - 475 BC





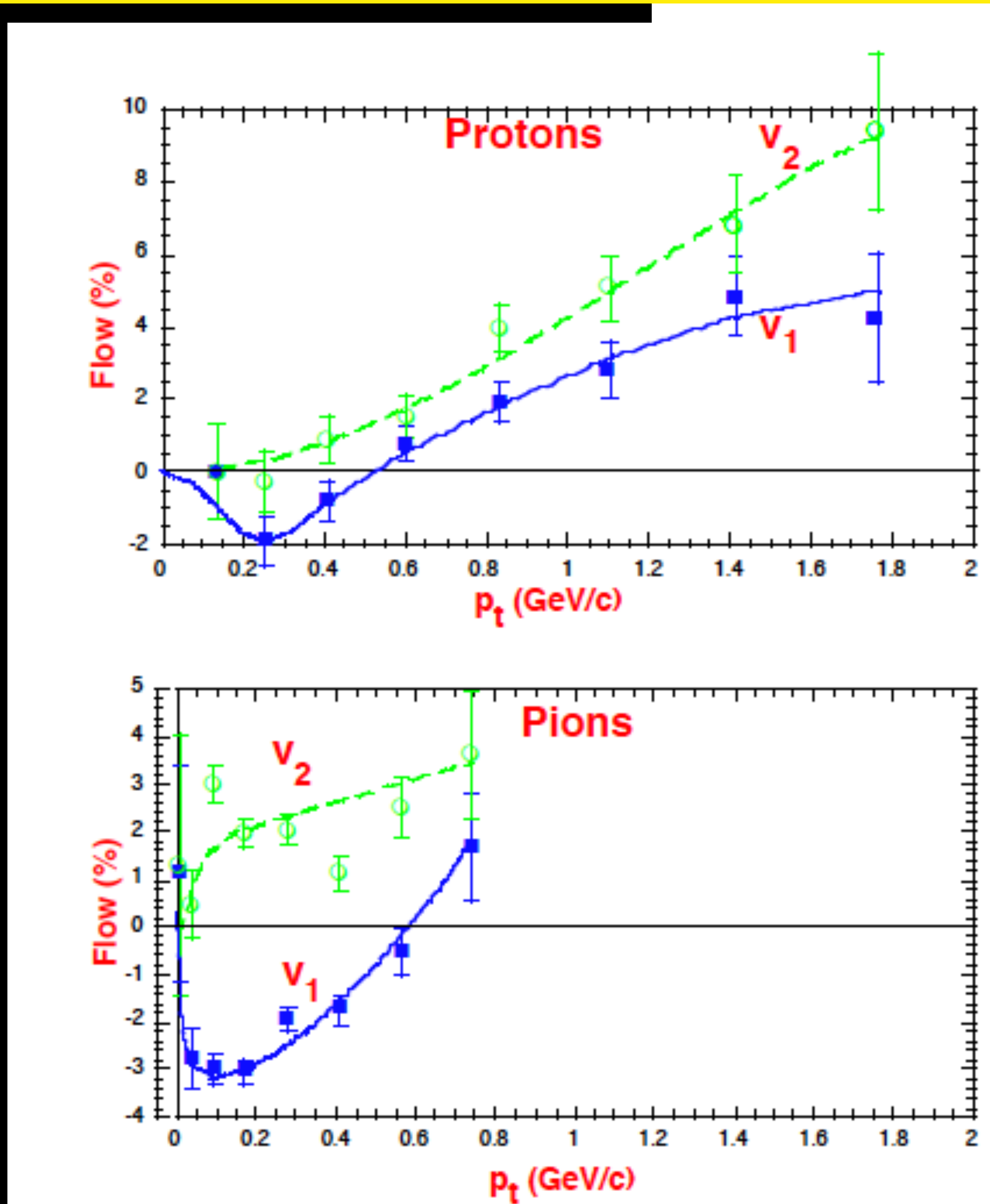
Not only in A-A it seems but also for smaller systems!

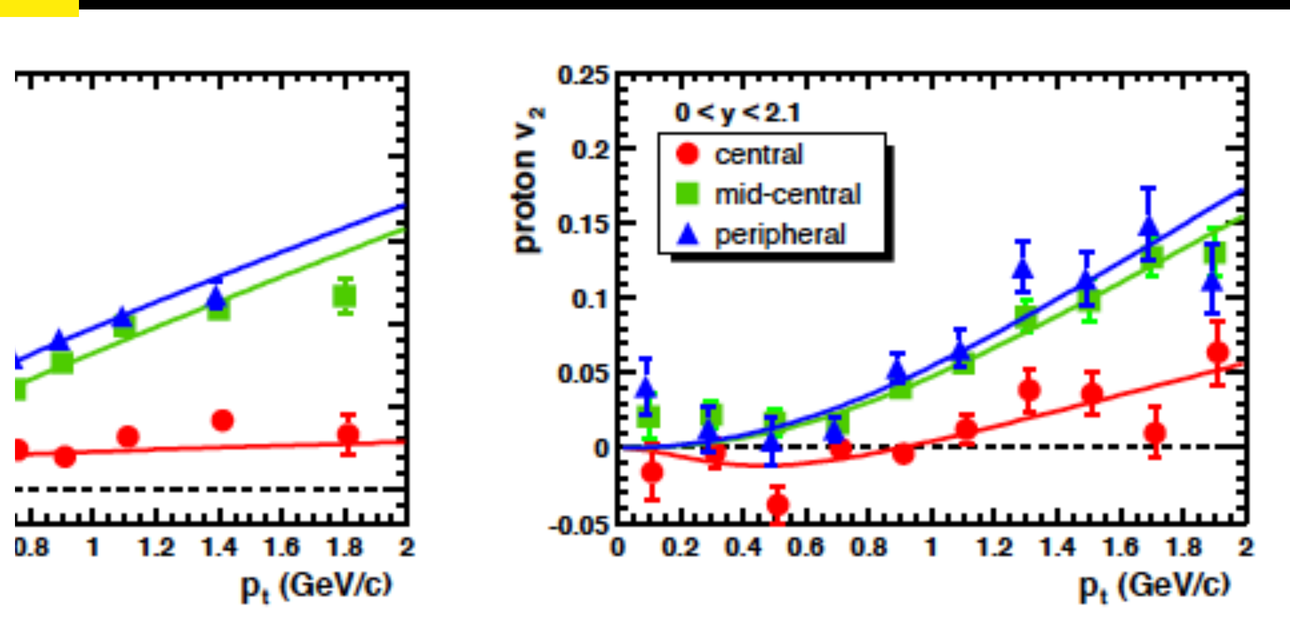
Backup

Not the first time people tried to look at the same details…

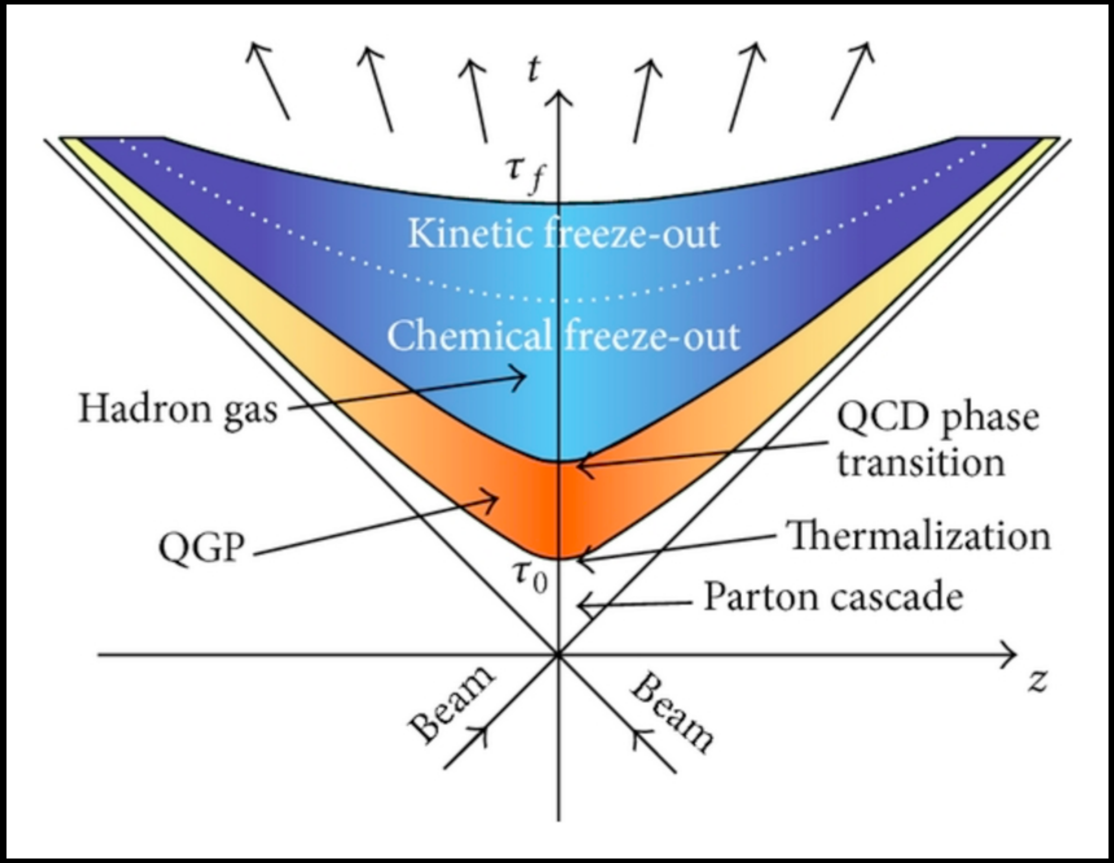
(NA49 Collaboration): Phys.Rev. C68 (2003) 034903

(NA49 Collaboration): Phys.Rev.Lett. 80 (1998) 4136

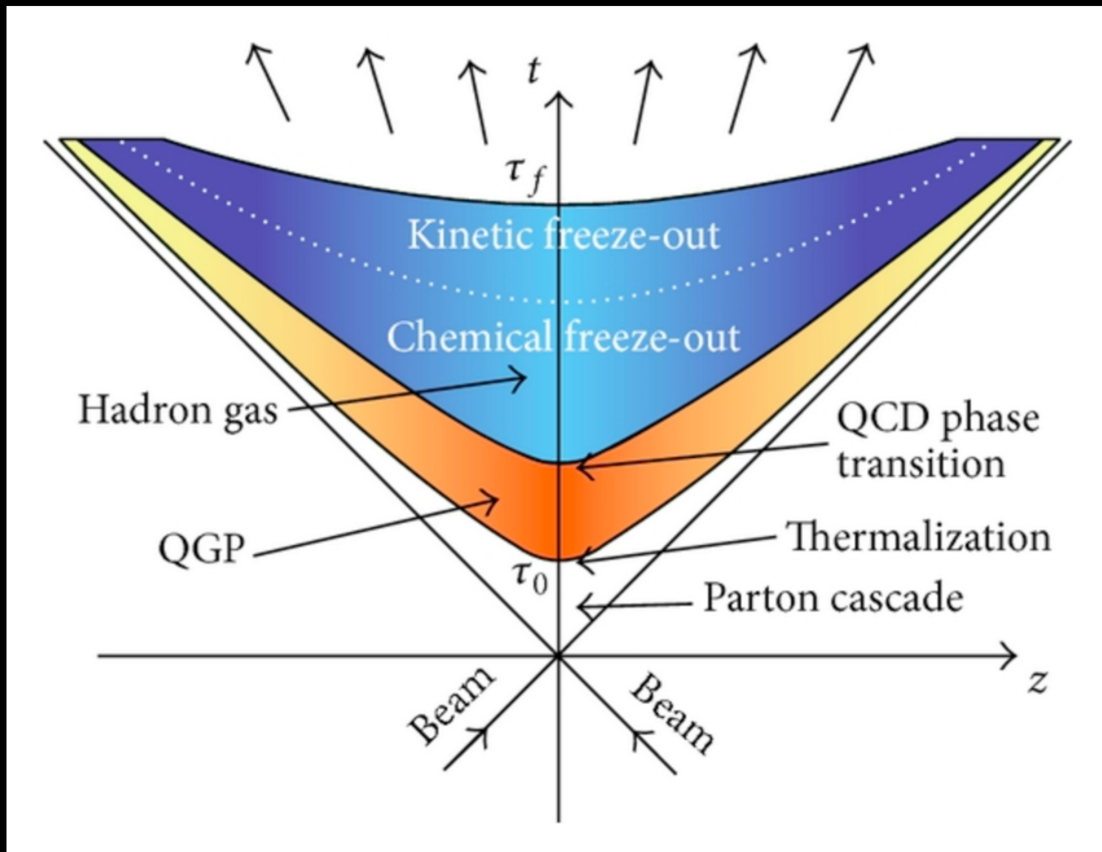


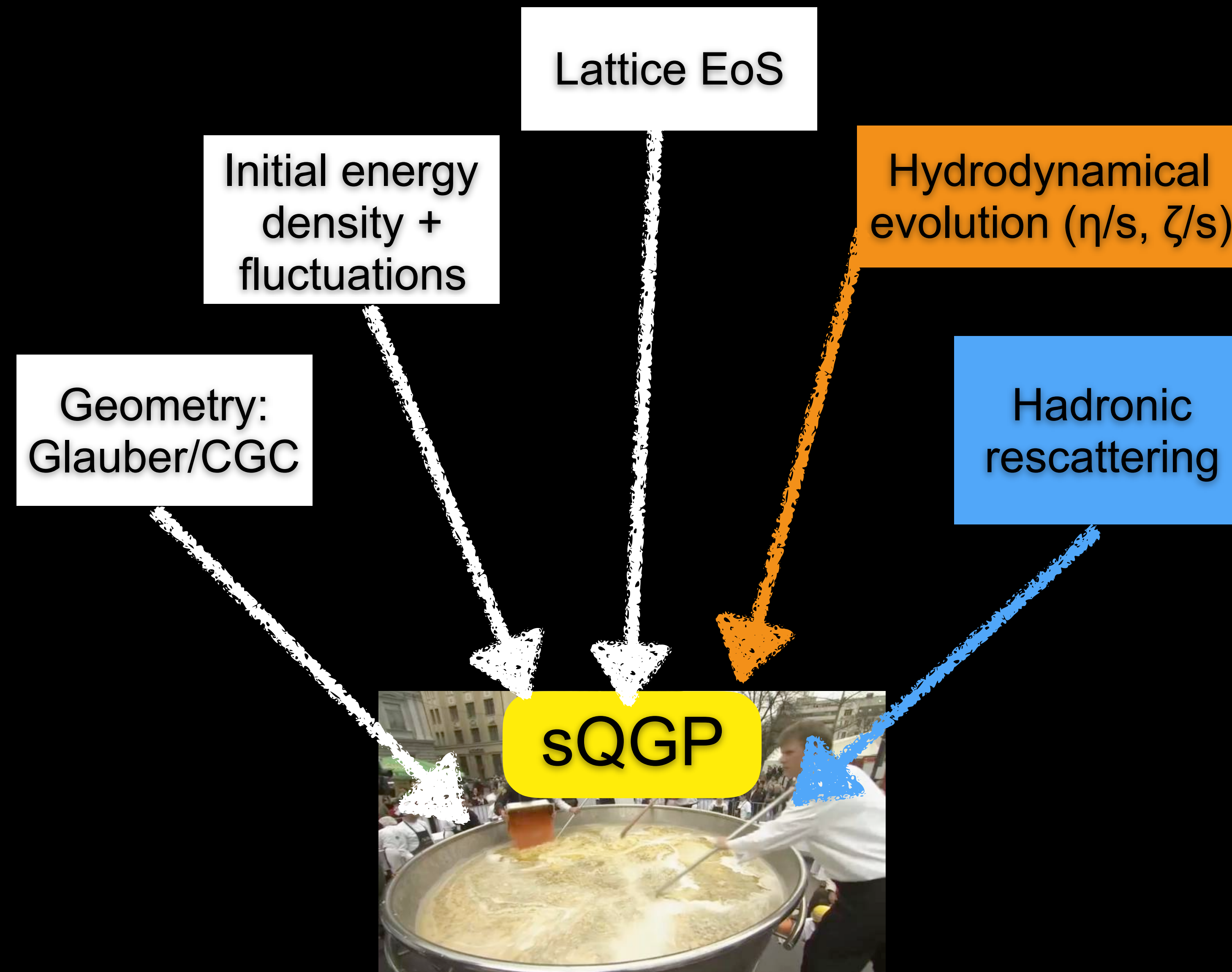


The sQGP paradigm

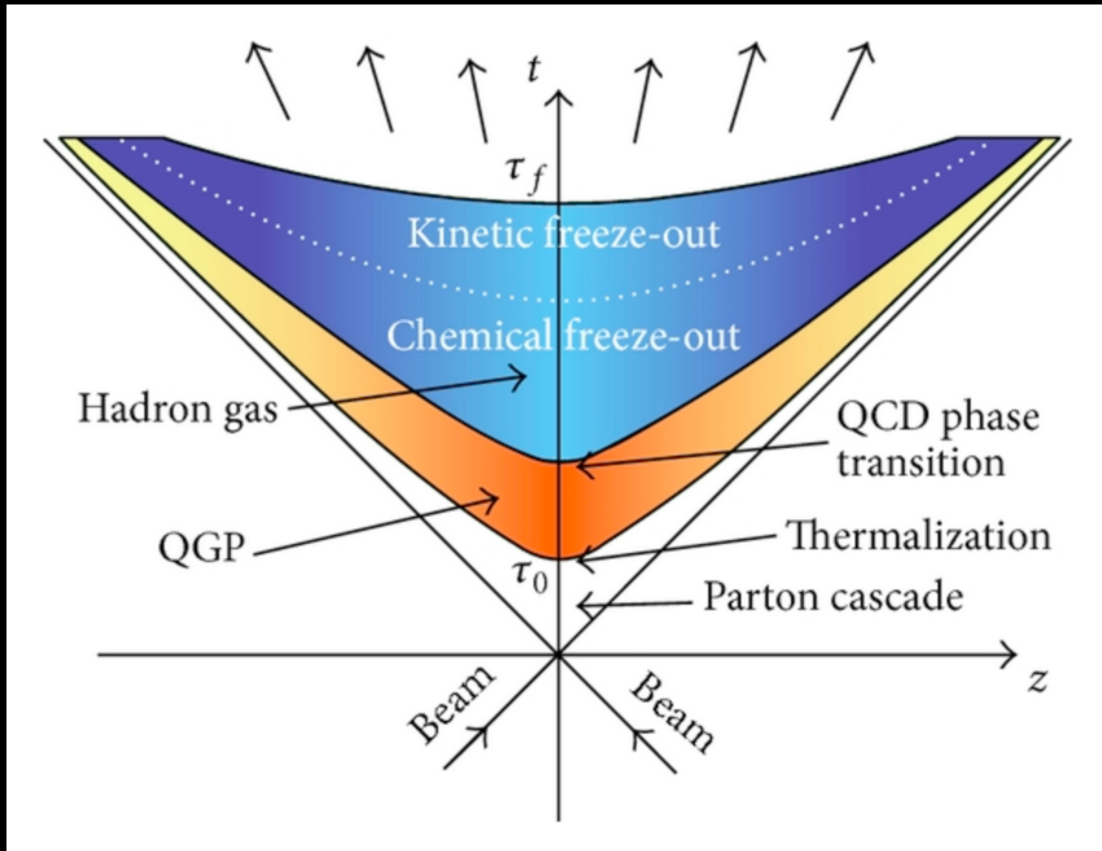


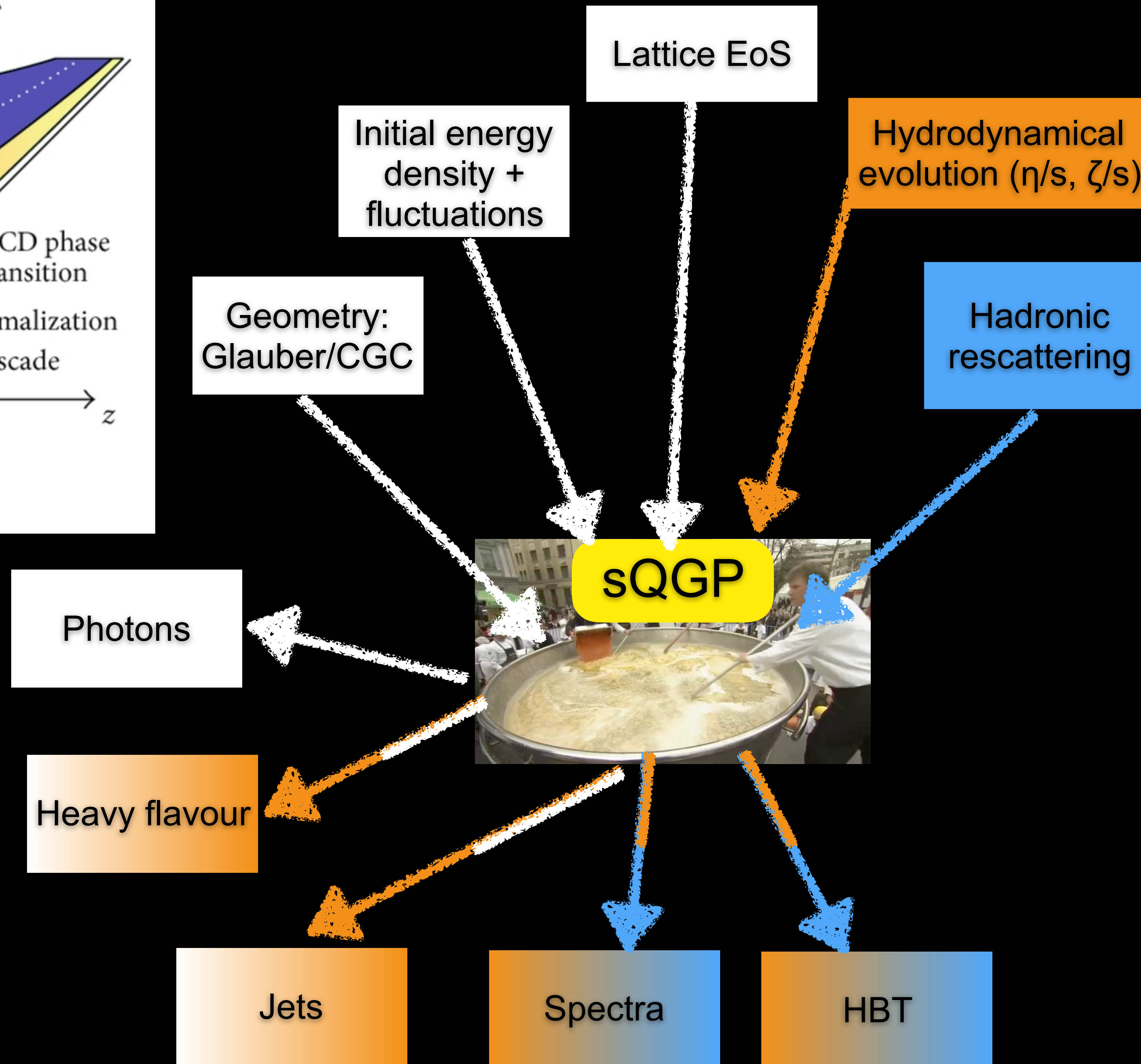
The sQGP paradigm



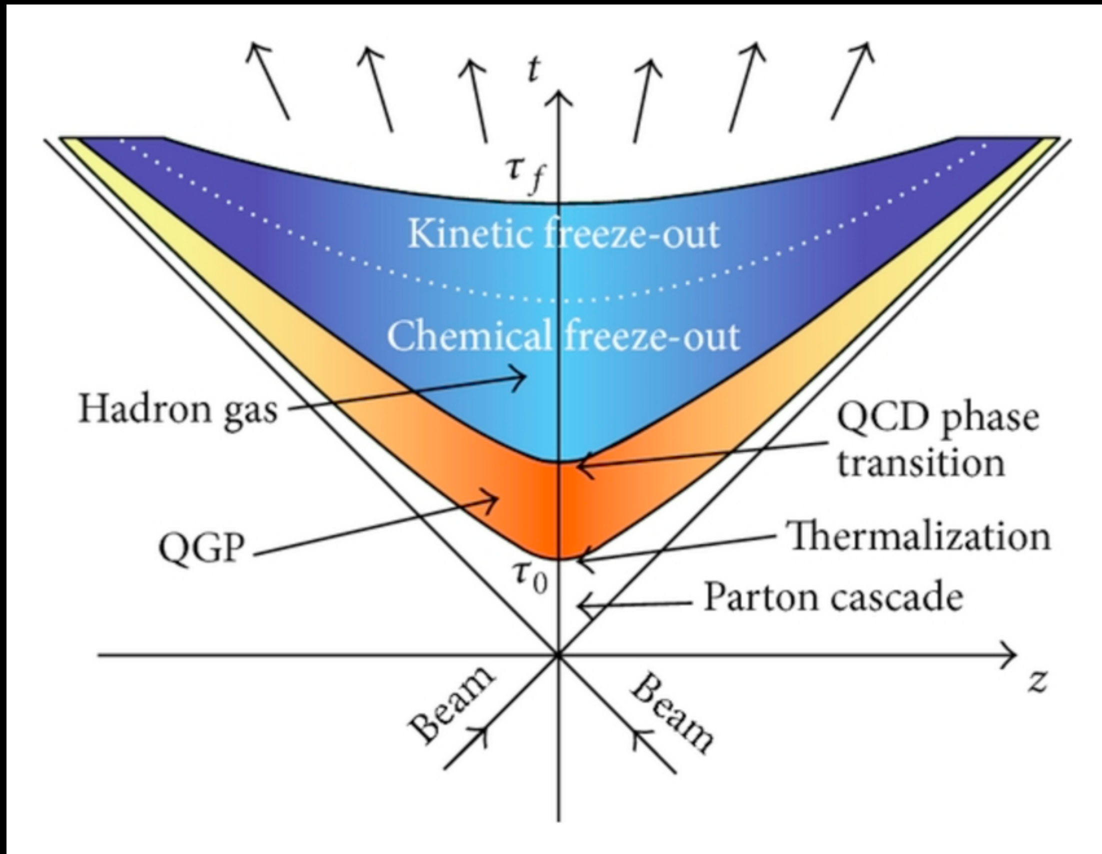


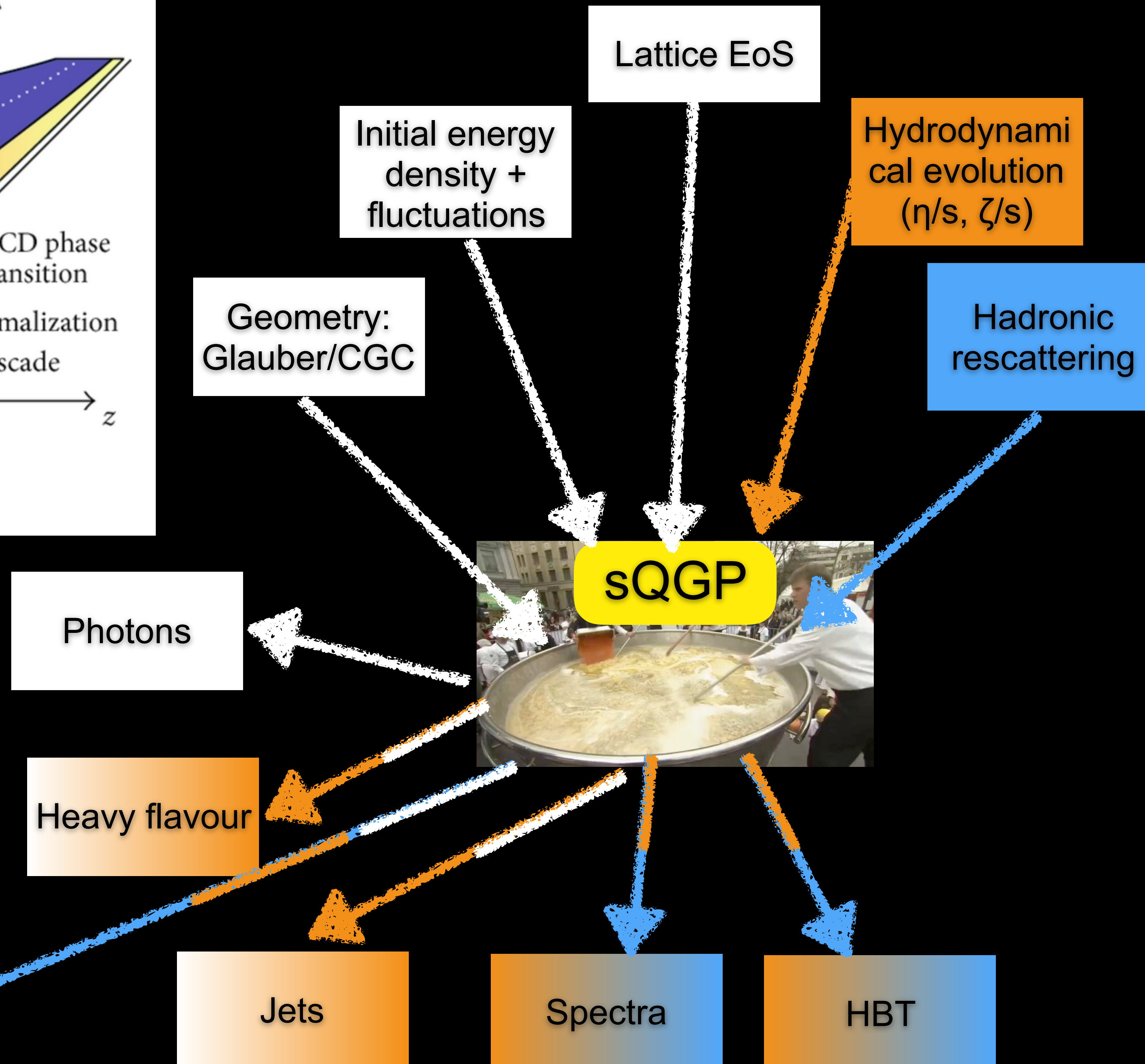
The sQGP paradigm



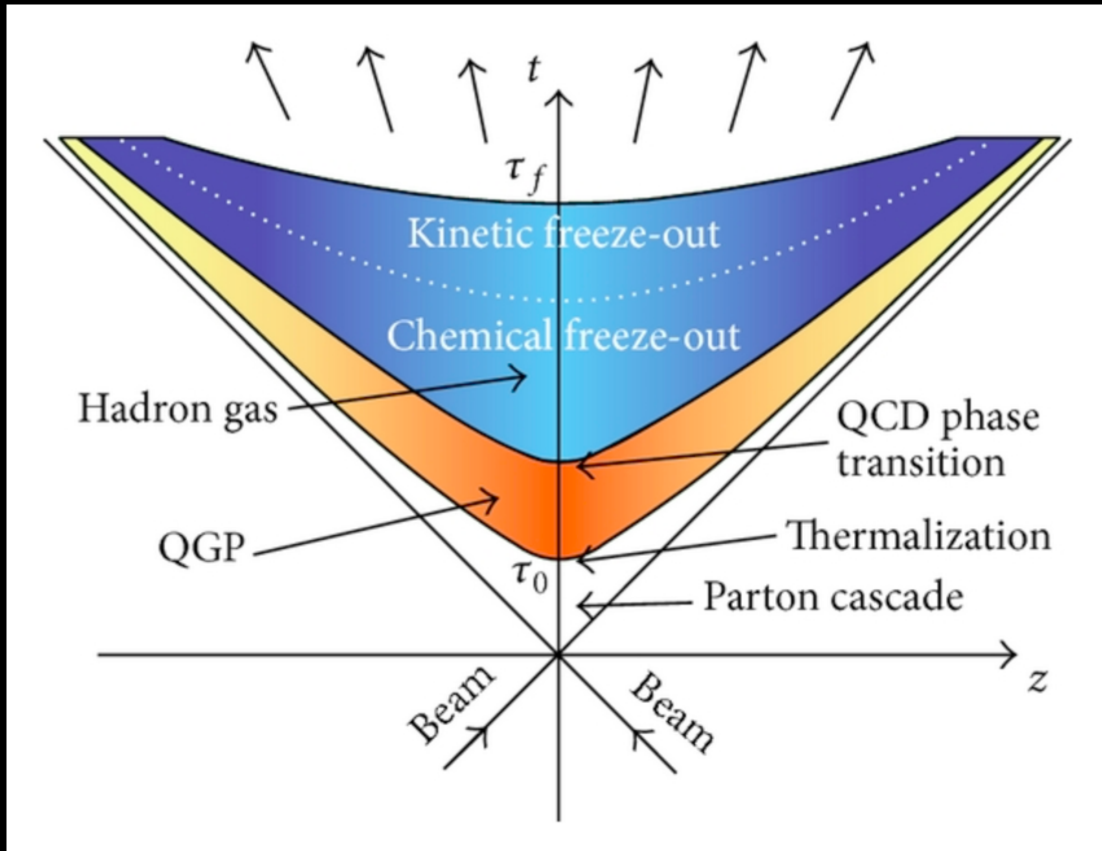


The sQGP paradigm





The sQGP paradigm



Looking at the details

Important to understand the whole dynamical evolution of the system:

- Initial state
- Viscous hydrodynamical evolution
- Highly dissipative hadronic rescattering phase

Lattice EoS

Initial energy density + fluctuations

Hydrodynamical evolution (η/s, ζ/s)

Geometry: Glauber/CGC

Hadronic rescattering

Photons

Heavy flavour

Anisotropic flow

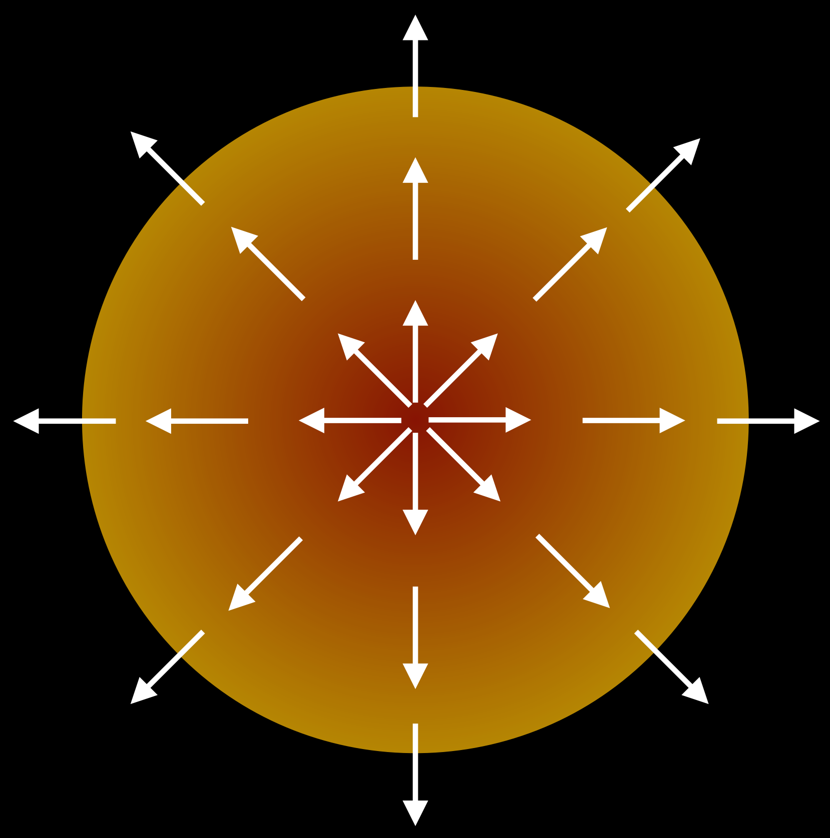
Jets

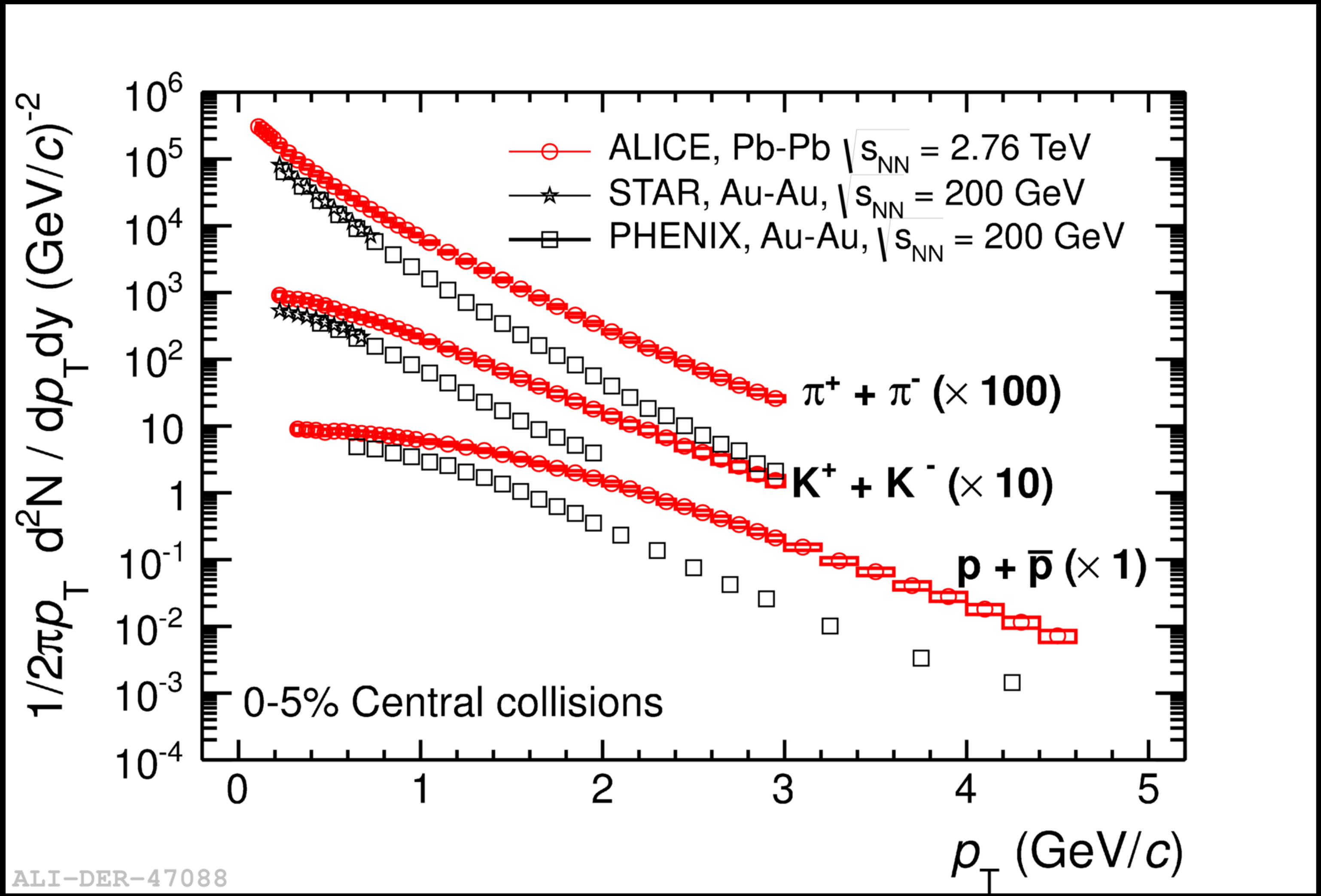
Spectra

HBT

How does mass ordering develop?

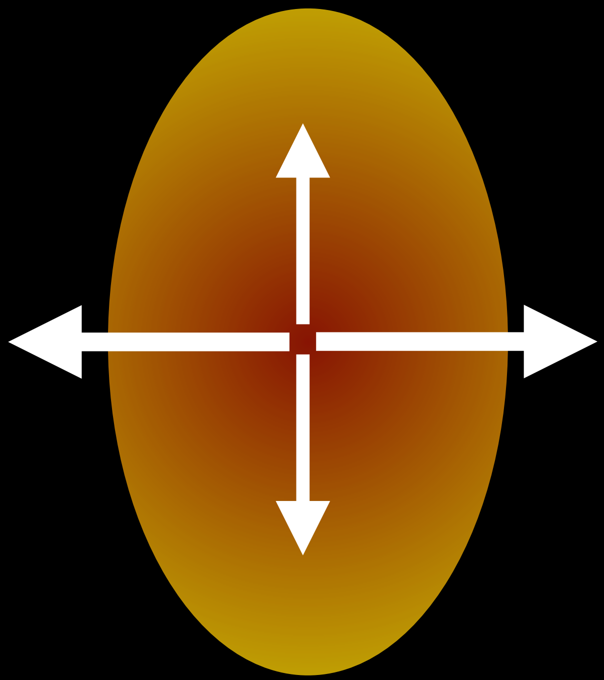
B. Abelev *et al*. (ALICE Collaboration), Phys. Rev. **C88**, (2013) 044910

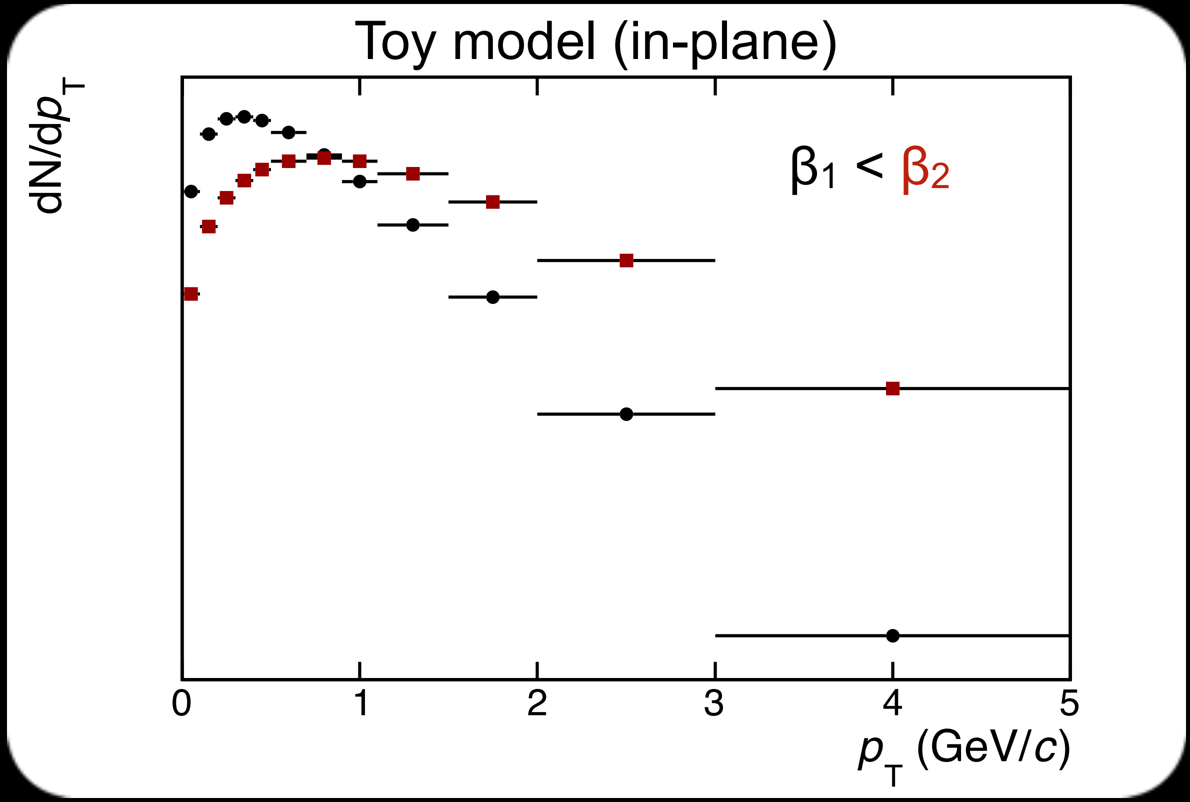


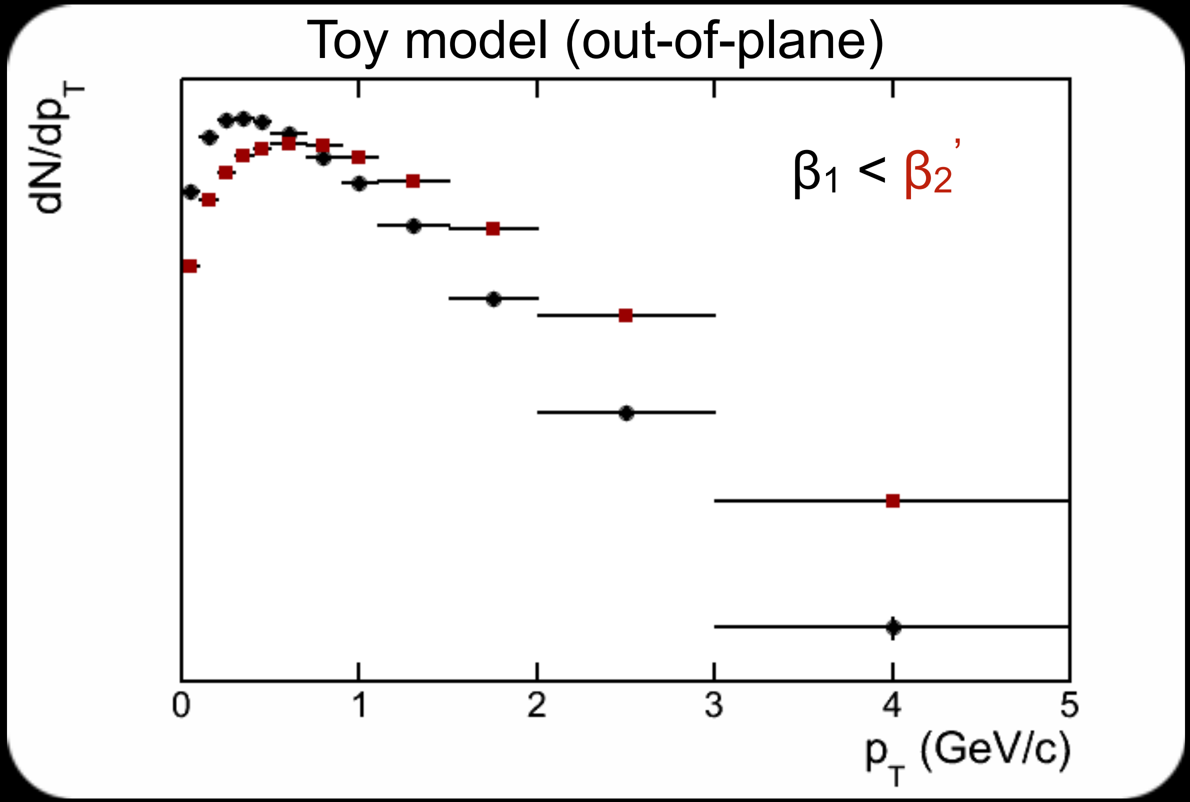


- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

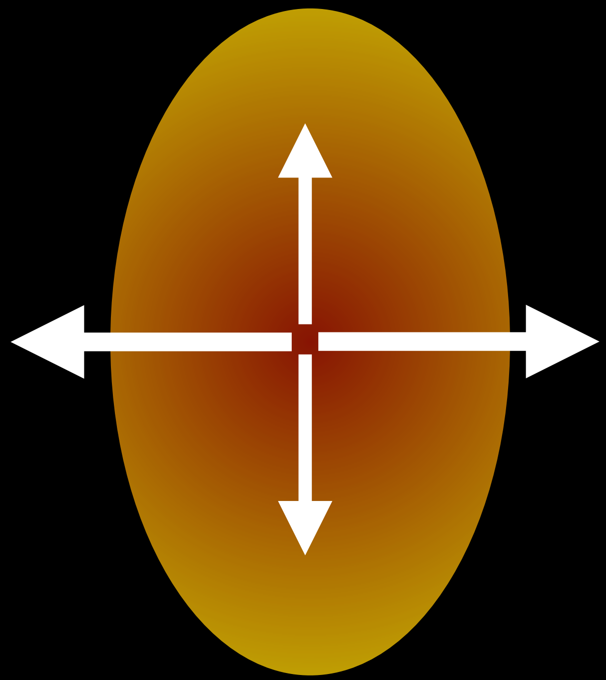
How does mass ordering develop?

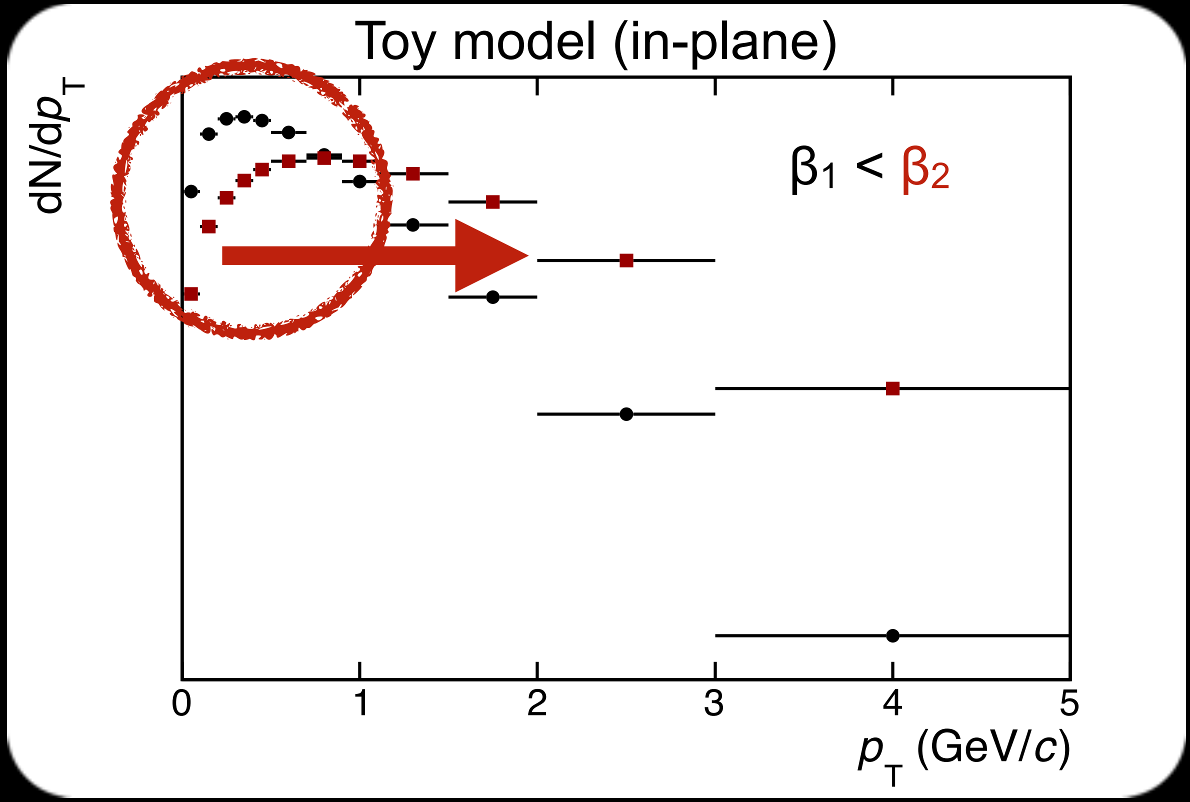


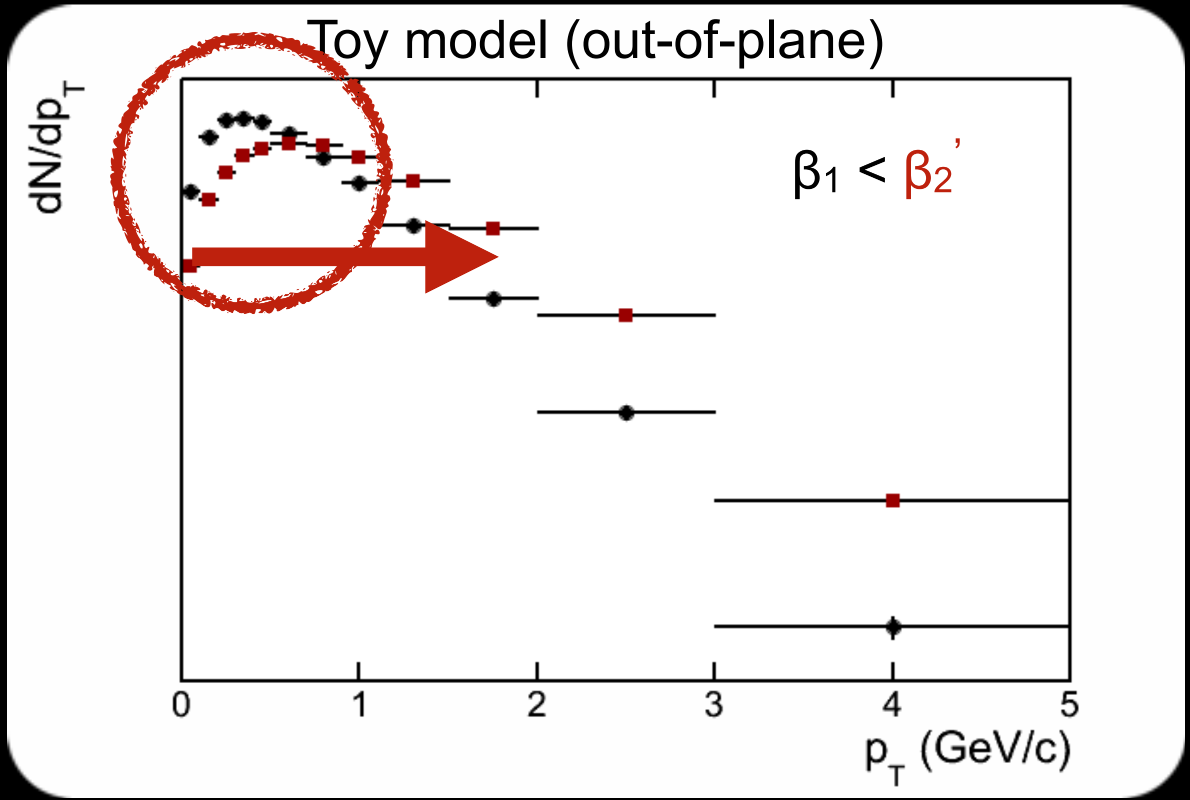




How does mass ordering develop?

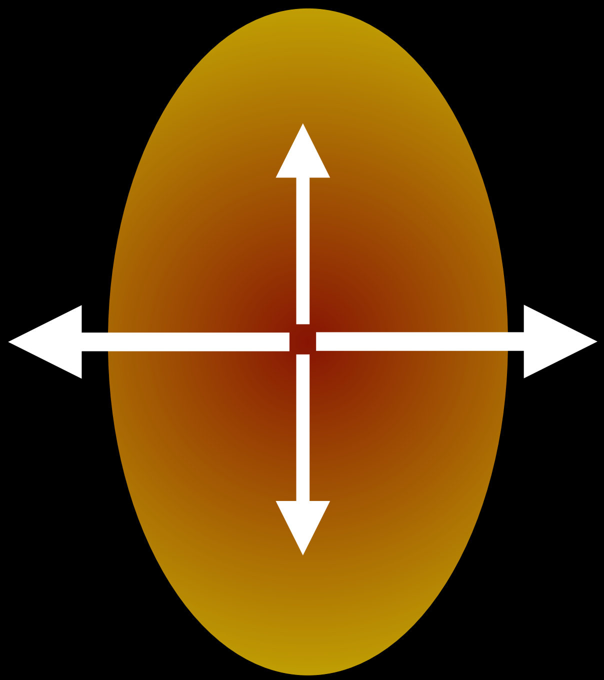






- Larger "push" in-plane than out-of-plane as a function of mass
  - ★ larger low-p_T depletion in-plane than out-of-plane → lower v_2 in a mass dependent way

How does mass ordering develop?



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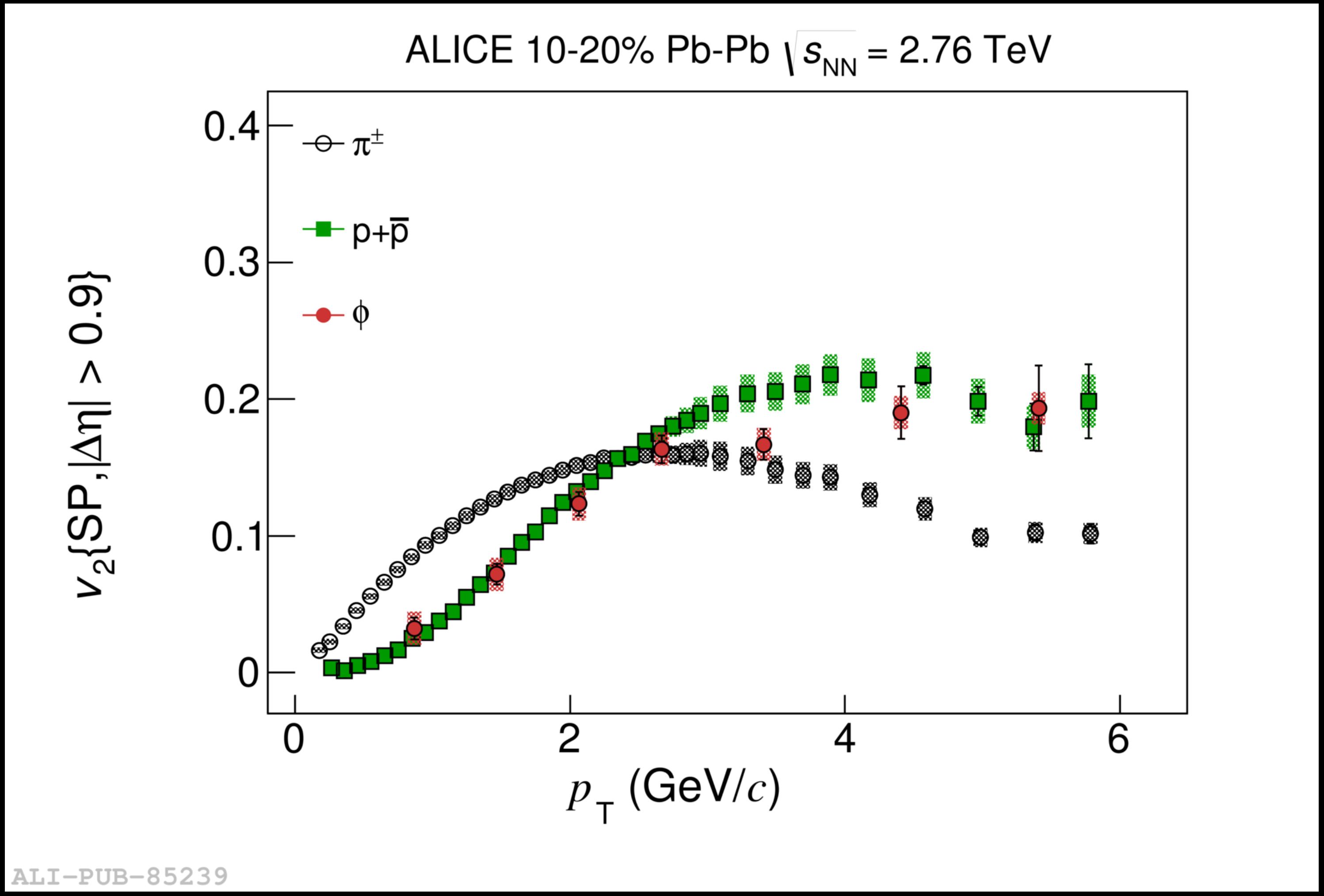
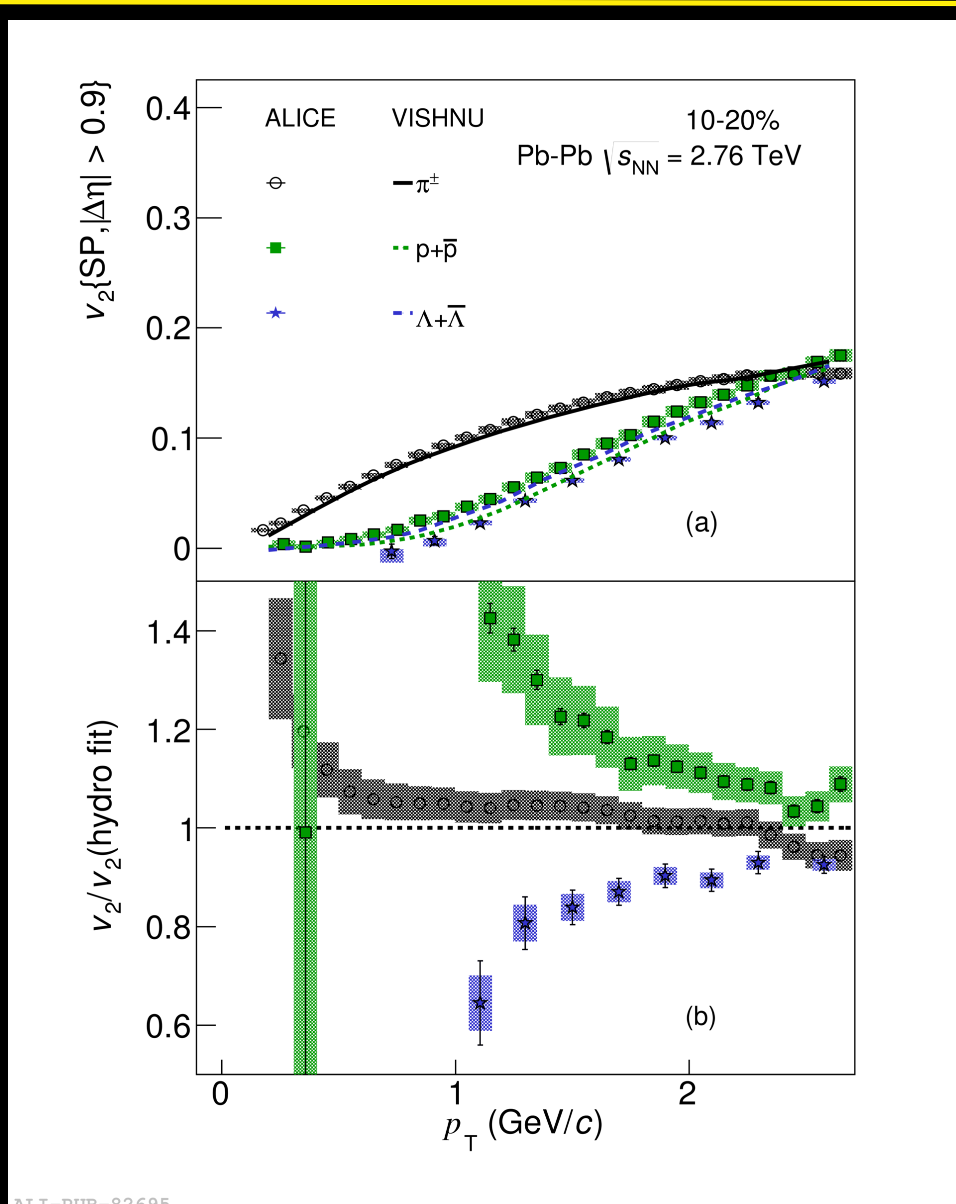
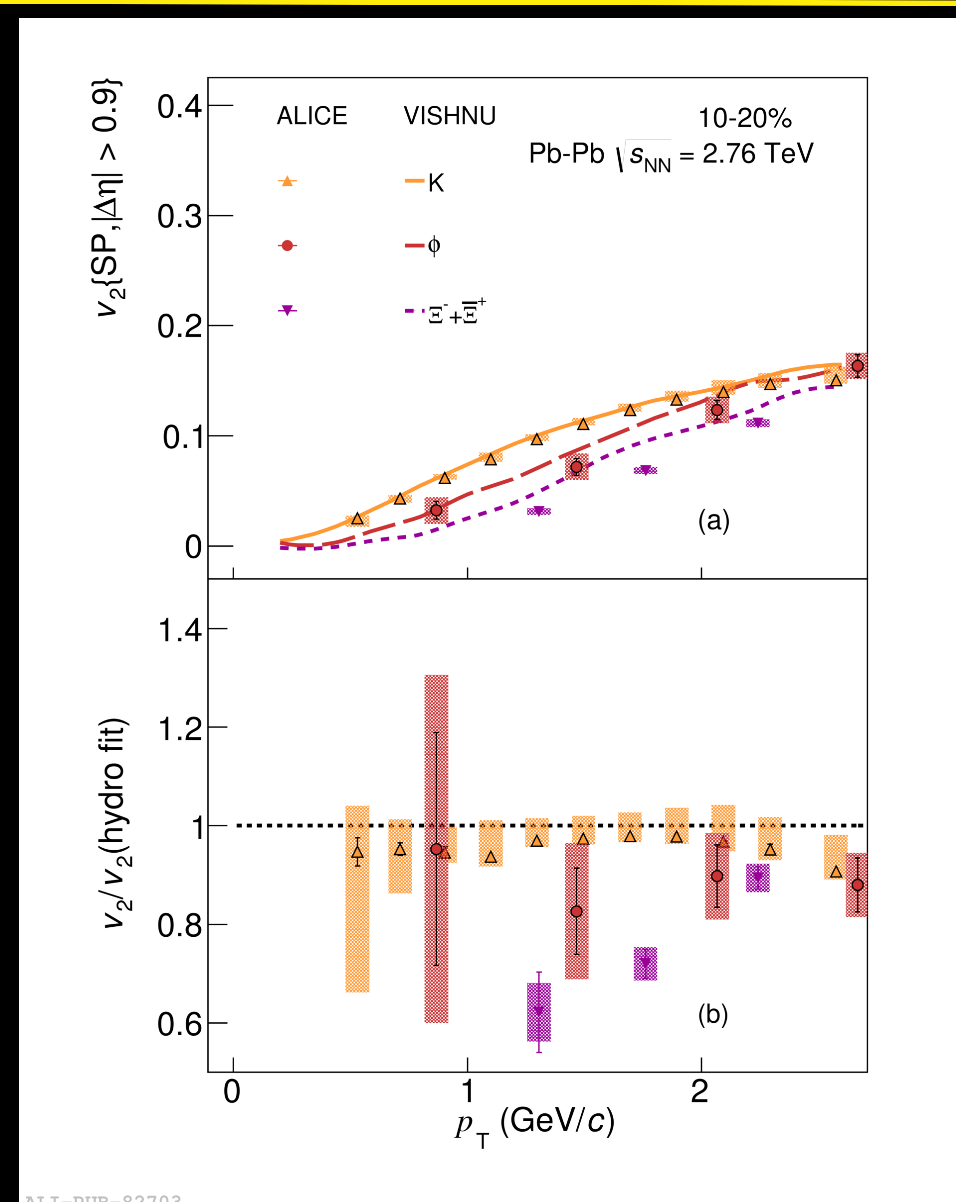


Heavy particles have lower v_2 at a fixed p_T than light particles

Looking at the details…: central events

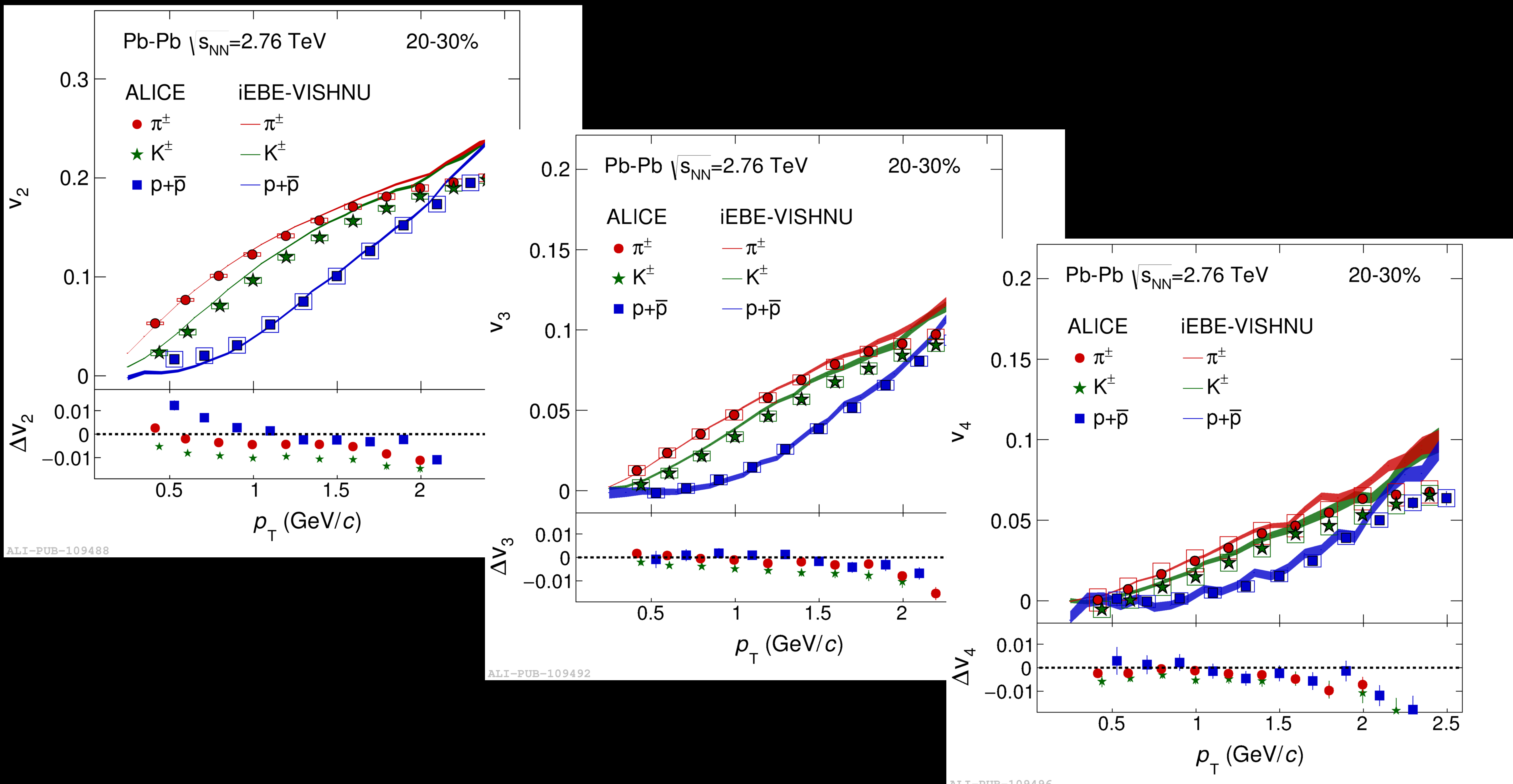




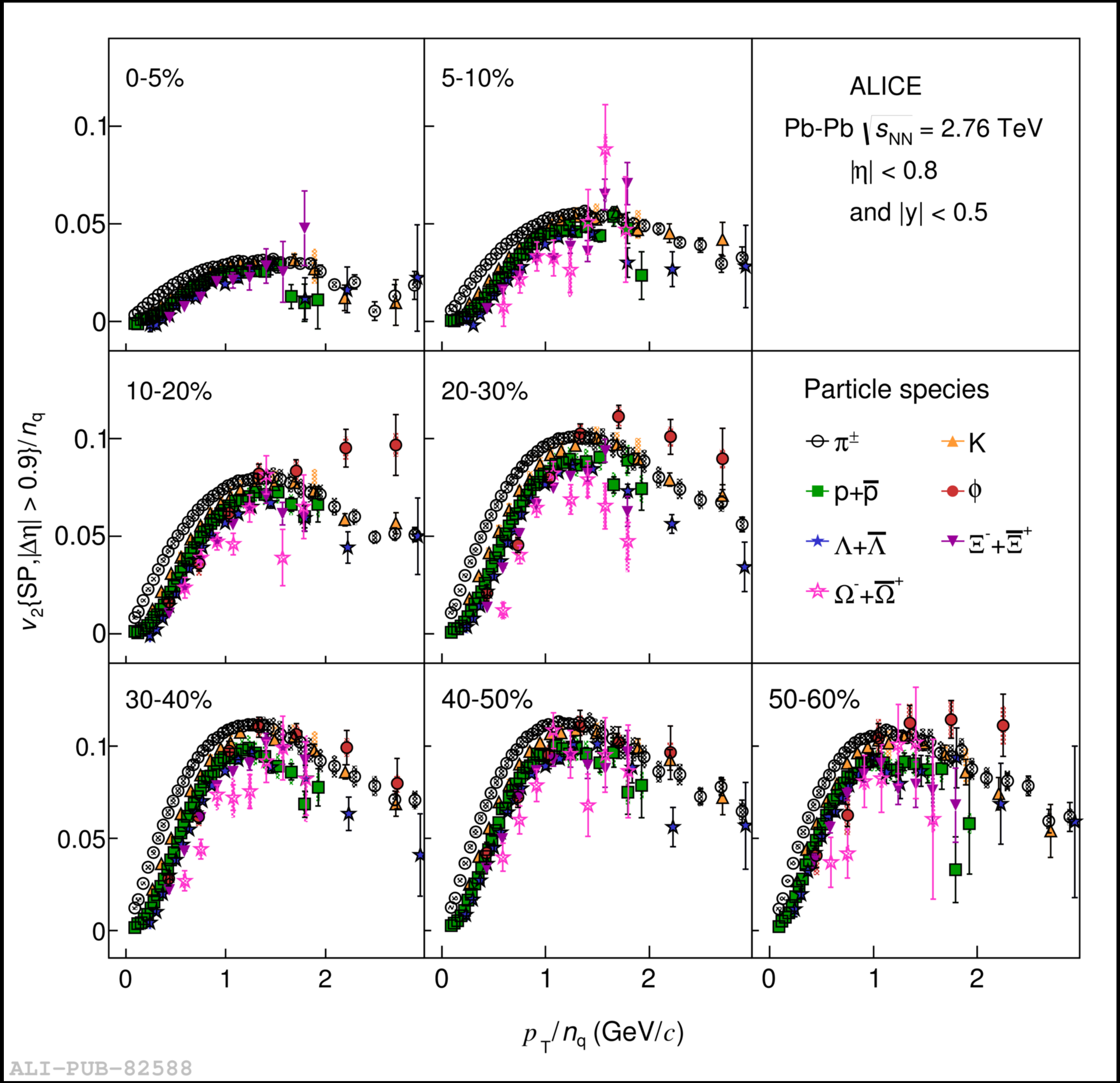
- Systematic deviations for the majority of particle species (with the exception of K)
- Proton v_2 underestimated (i.e. extra push expected in hydro) but Λ v_2 overestimated (i.e. less push expected in hydro)
- Mass ordering not preserved in VISHNU due to the hadronic cascade
  - not supported by ALICE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

How about higher harmonics?

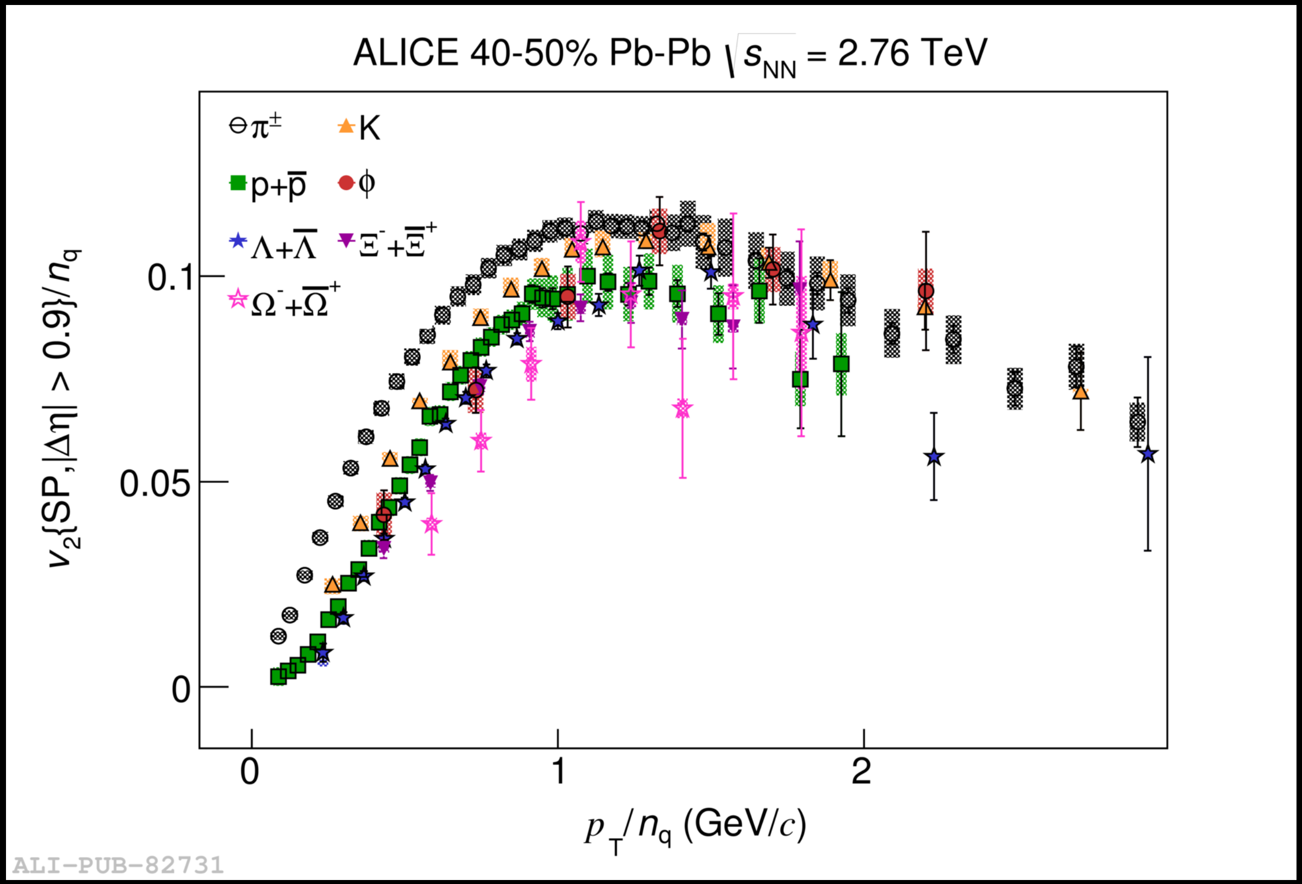
hydro curves from: H.-J. Xu, Z. Li, and H. Song, Phys. Rev. **C93**, 064905 (2016)



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



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



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

The special role of the φ-meson

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

Panos.Christakoglou@nikhef.nl

The special role of the φ-meson

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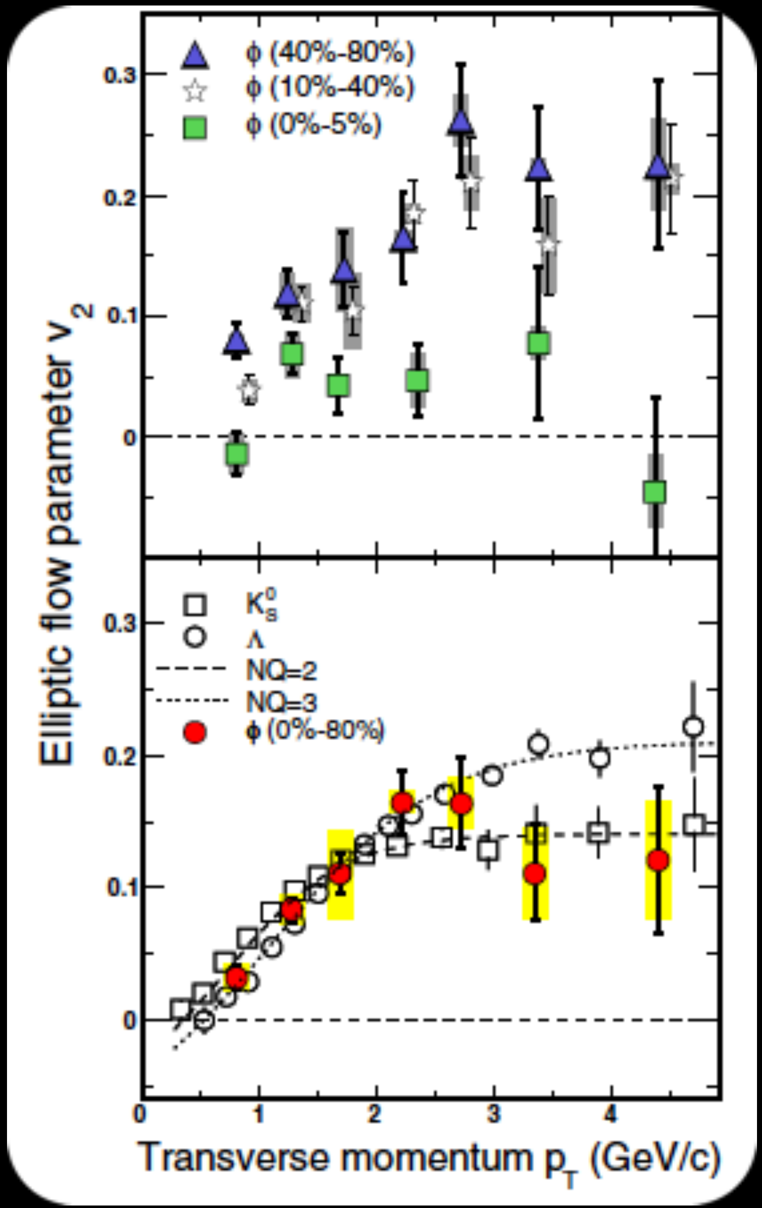
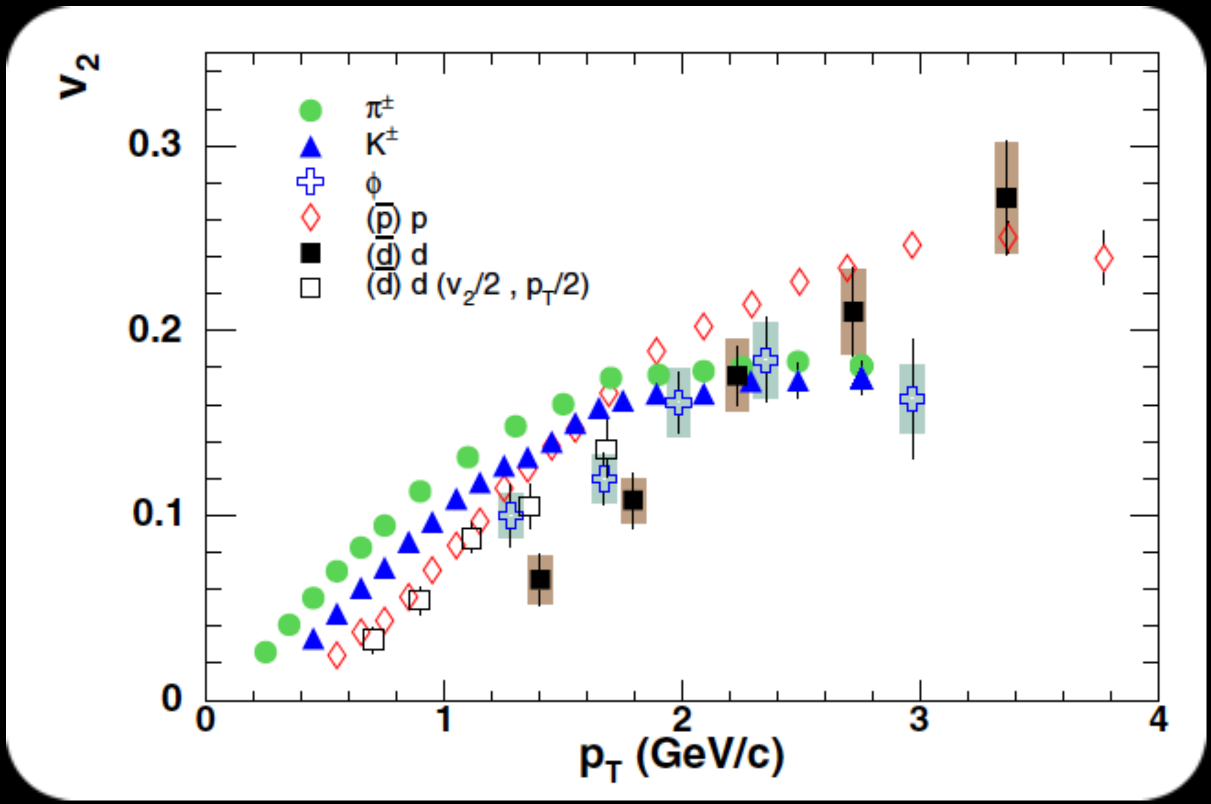
  - ★ the particle type grouping at intermediate p_T

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



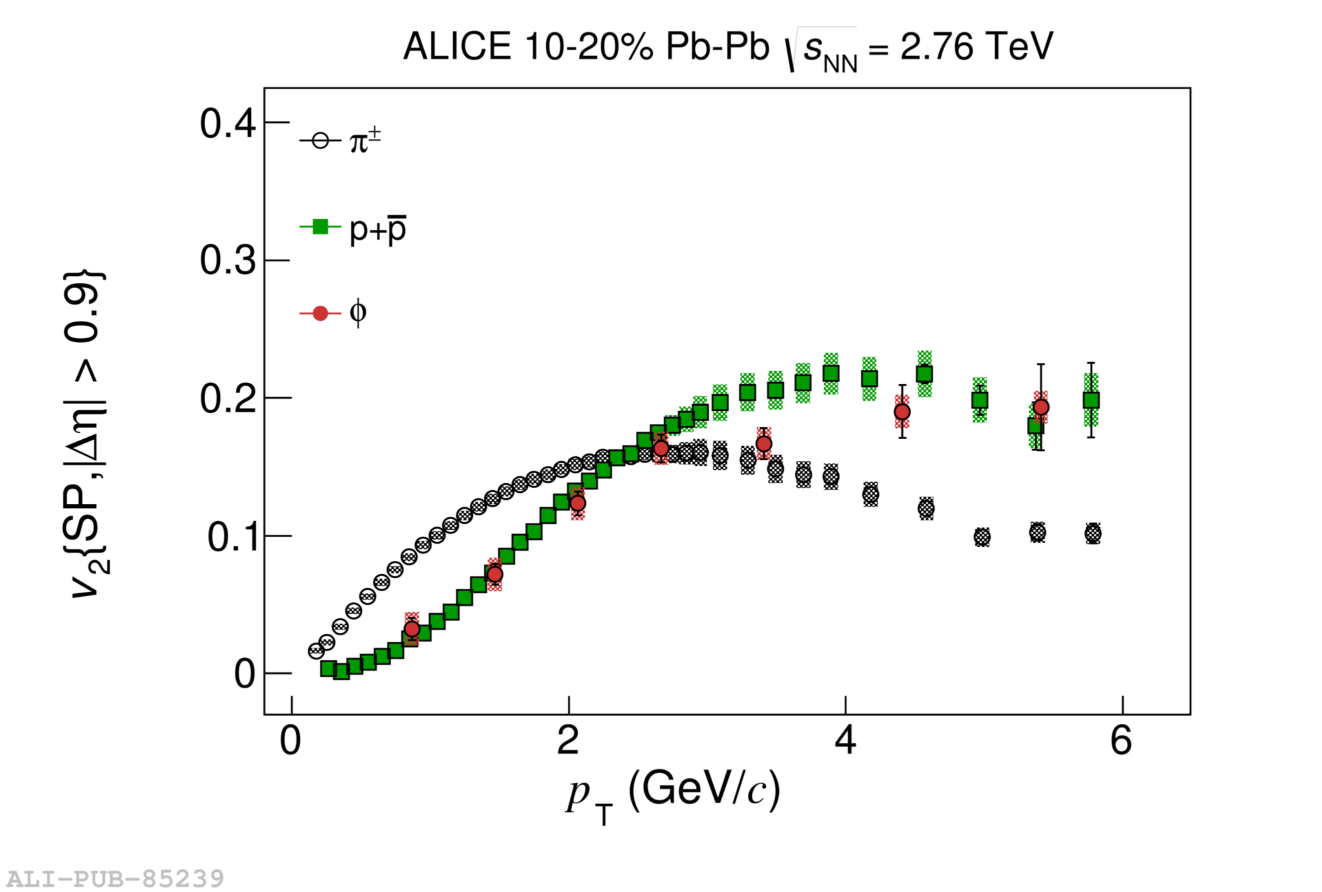
S. Afanasiev *et al*., (PHENIX Collaboration), Phys. Rev. Lett. **99**, (2007) 052301

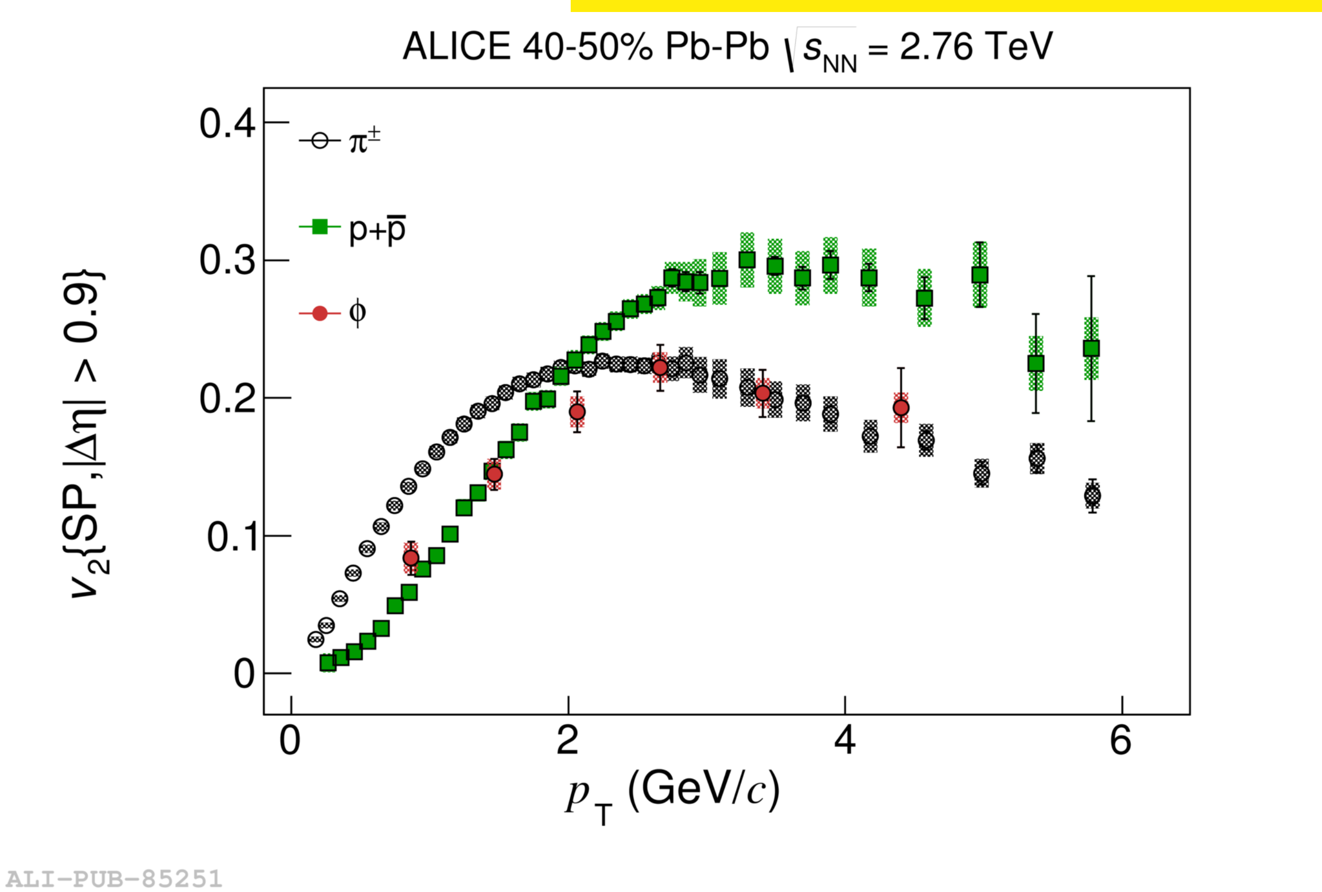


The special role of the φ-meson

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

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

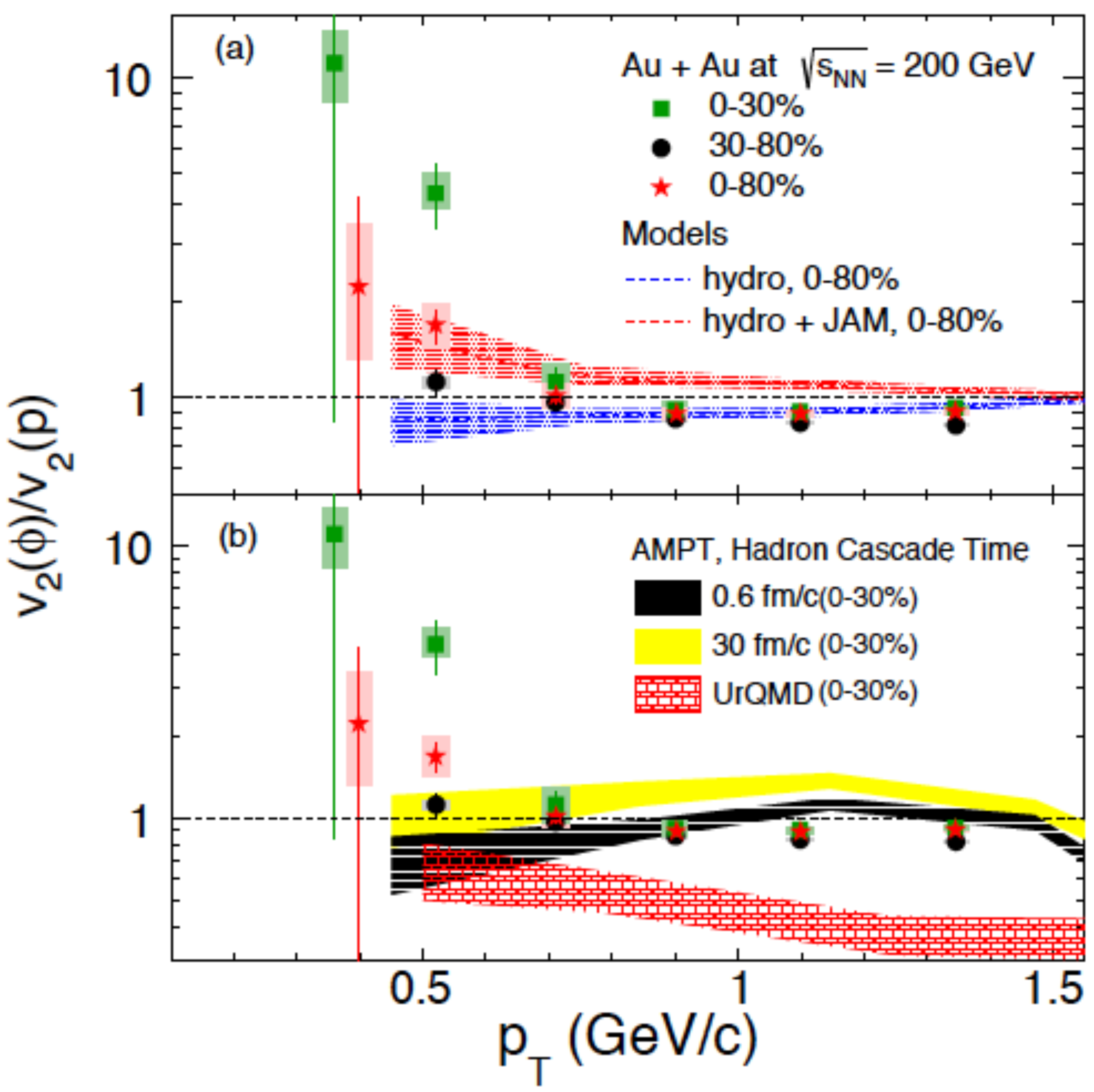




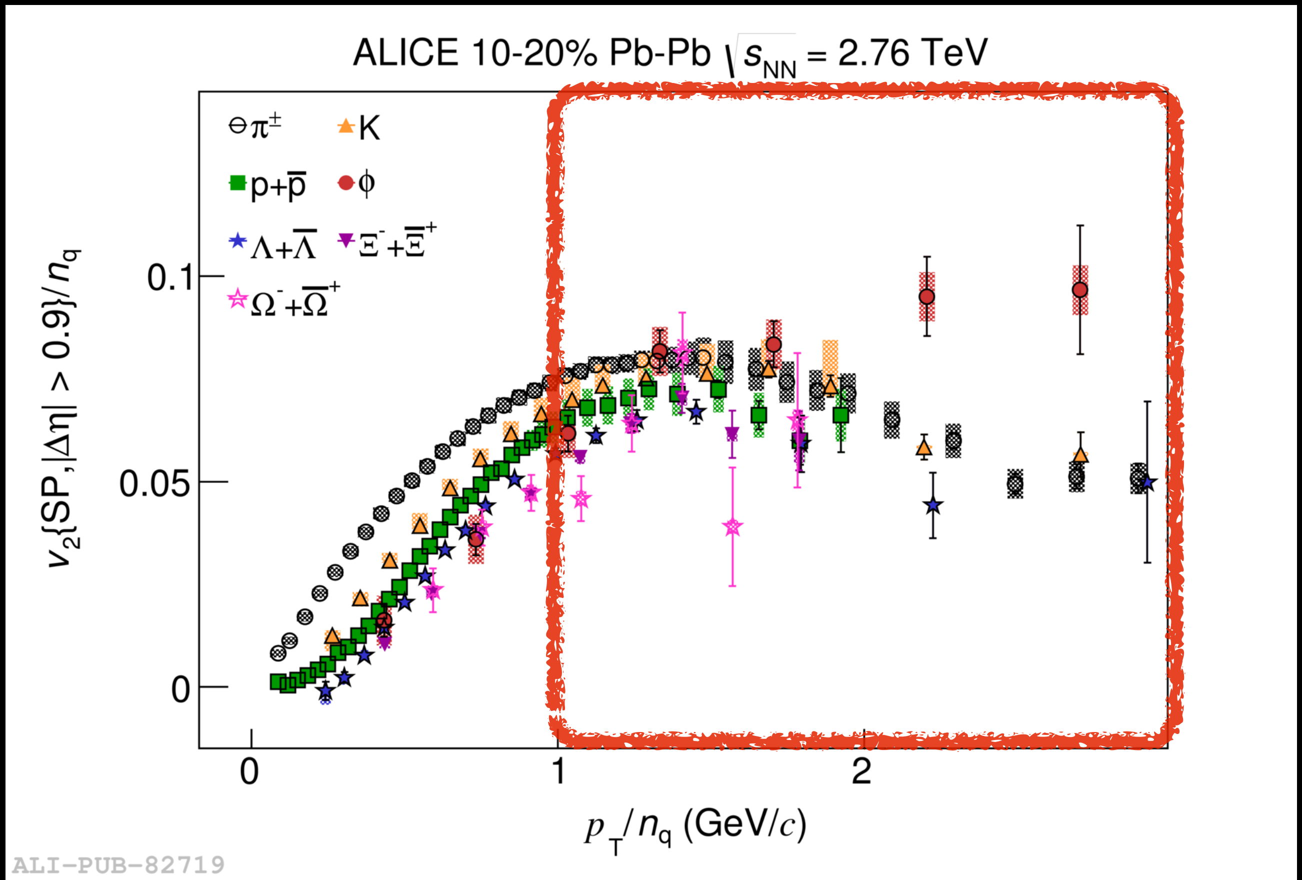
- At low p_T (p_T < 3 GeV/c): mass ordering ➜ elliptic/radial flow interplay
  - ★ First bins could hint to a different ordering? Still inconclusive…
- Intermediate p_T (3 < p_T < 6 GeV/c) the φ-meson follows
  - ★ the baryon band for central events
  - ★ the meson band for peripheral events

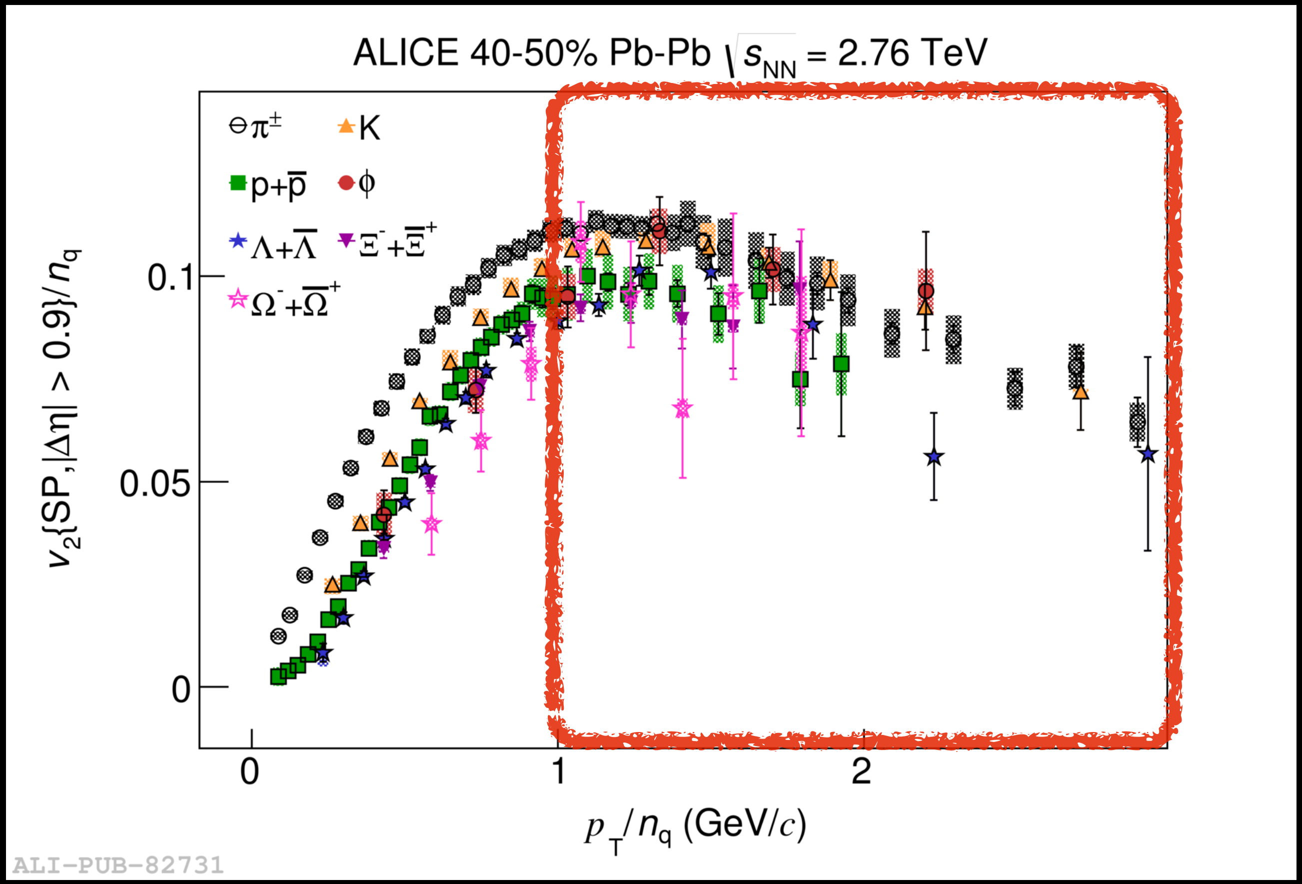
Violation of mass ordering at RHIC

L. Adamczyk *et al.* (STAR Collaboration), Phys.Rev.Lett. 116 (2016) 062301



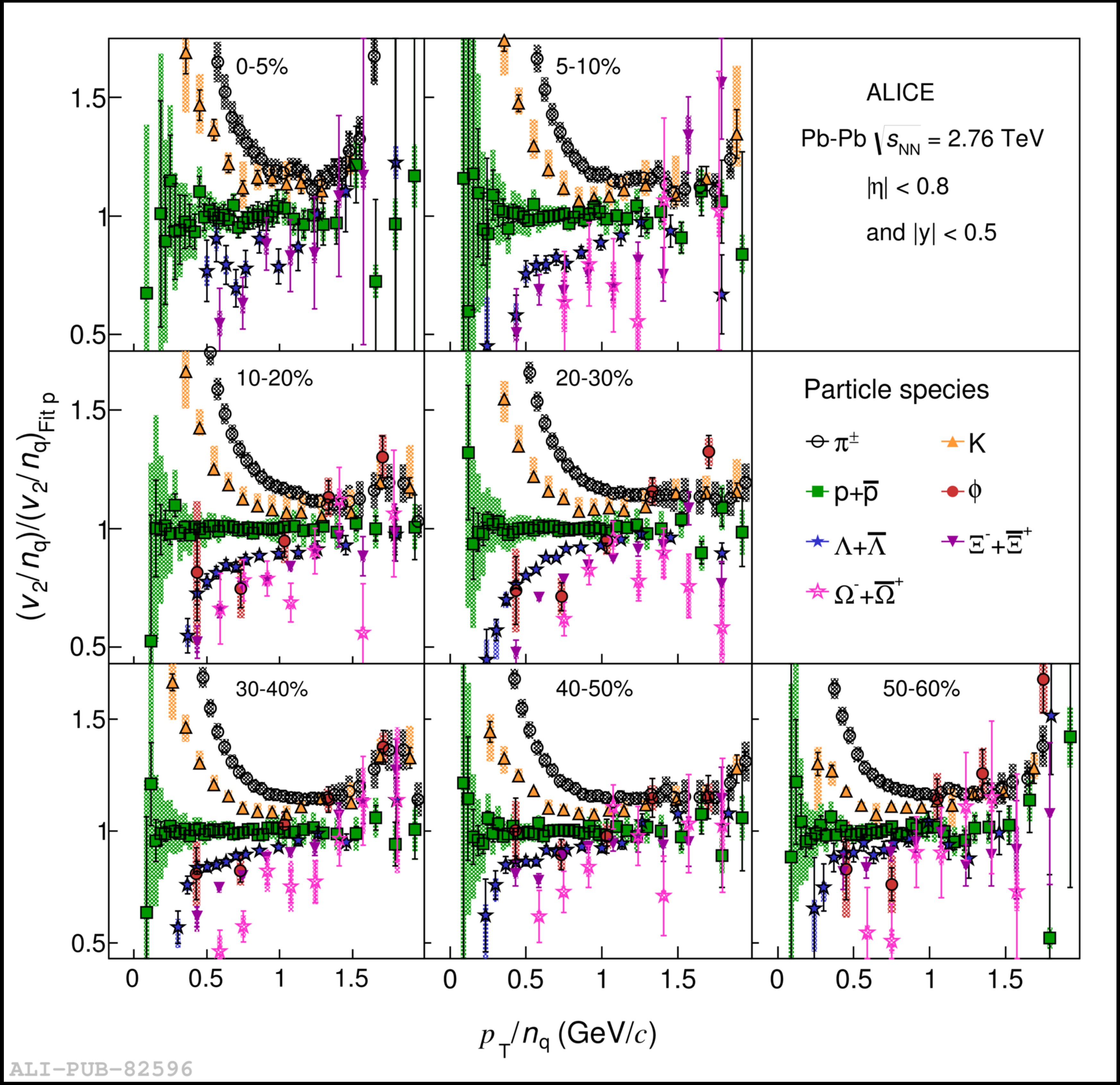
Number of constituent quark (NCQ) scaling in p_T/n_q





Scaling only approximate

NCQ scaling in p_T/n_q (double ratio)



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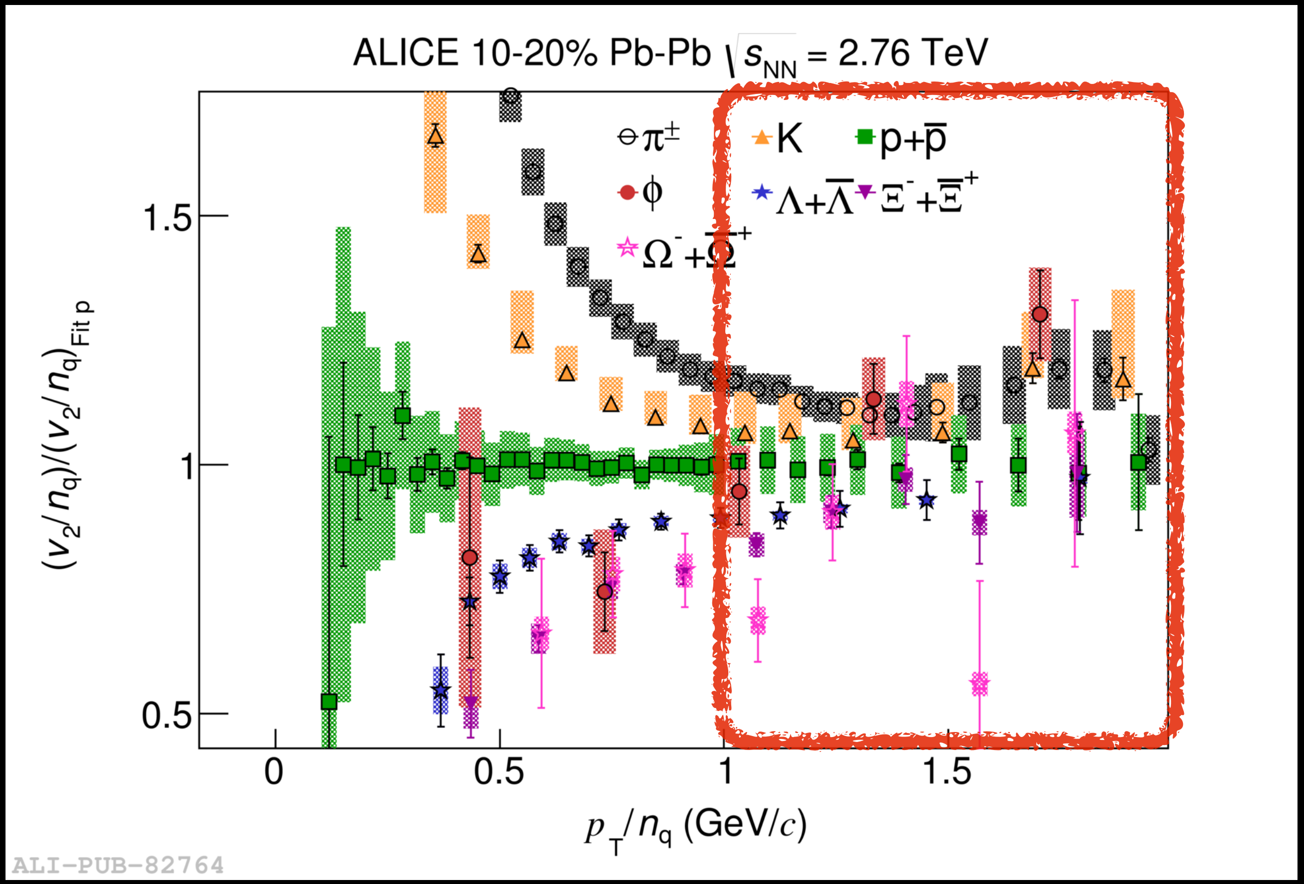
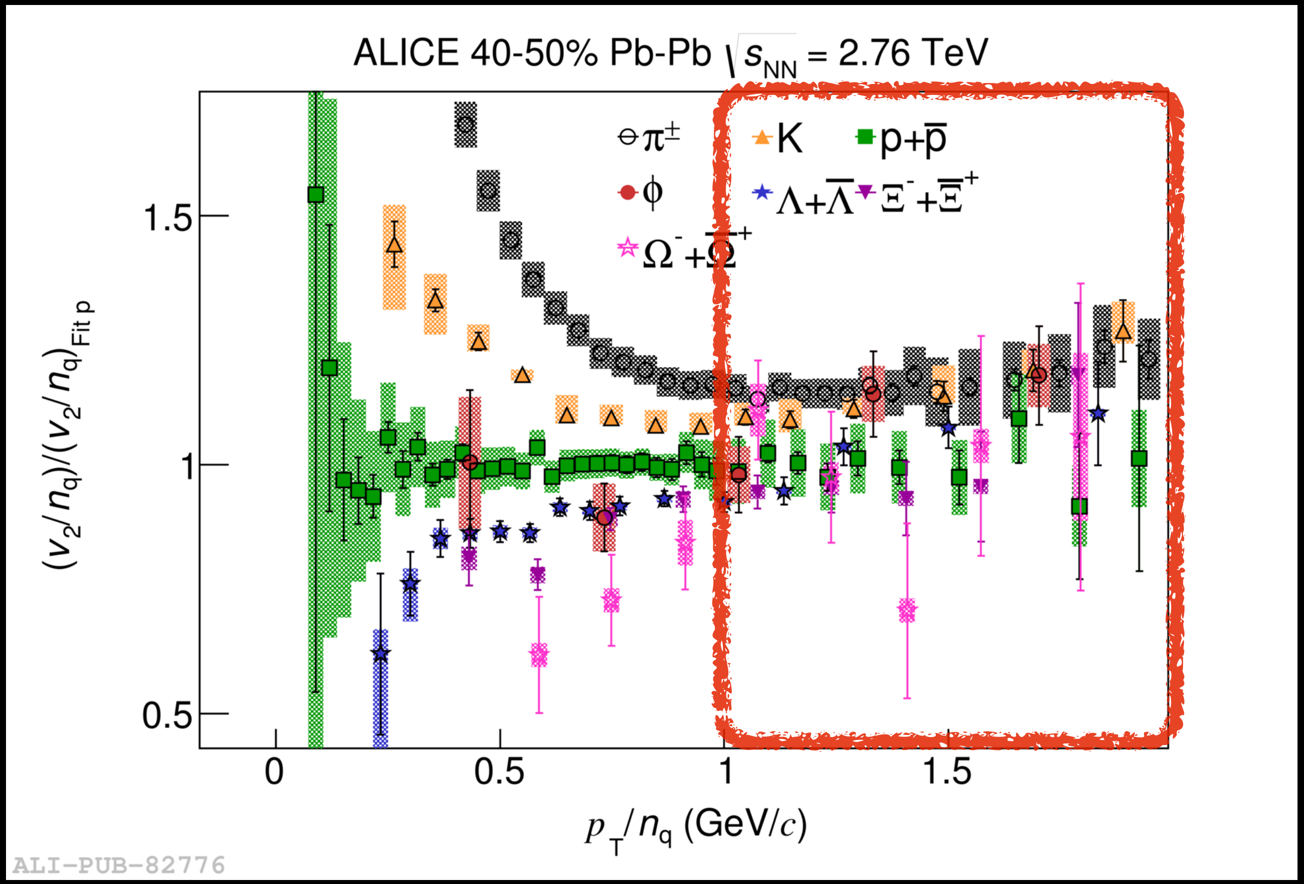
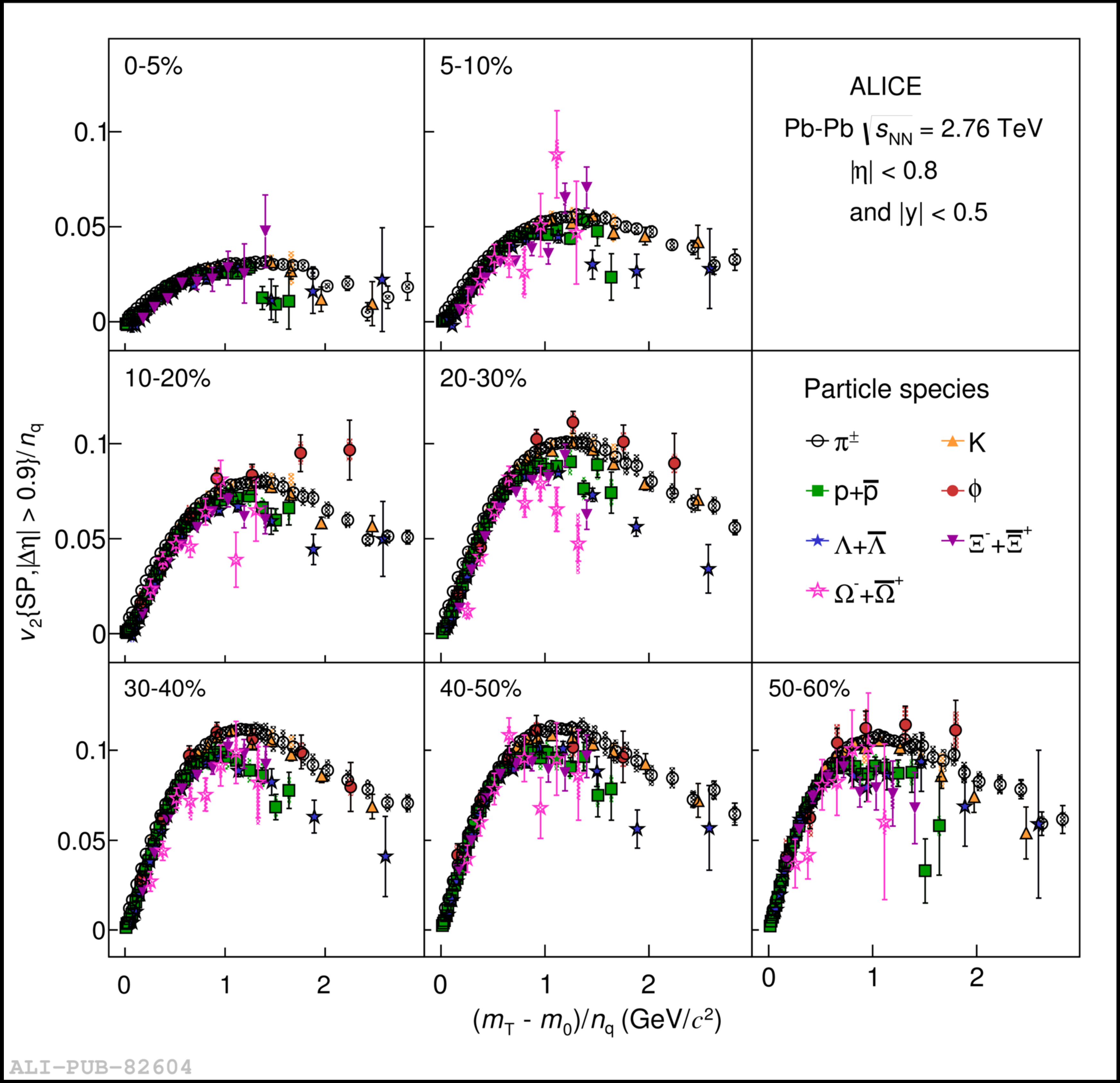


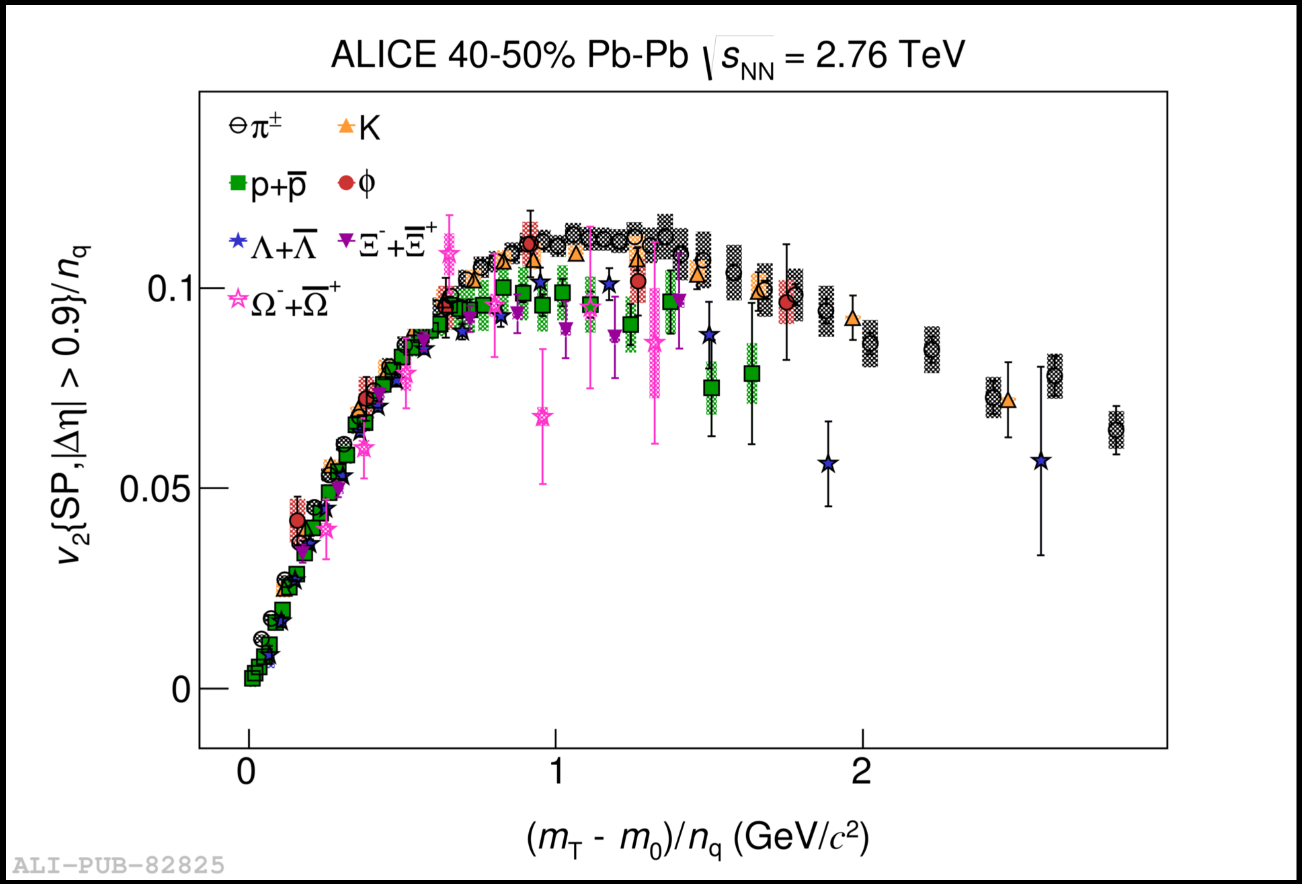


Scaling at the level of no better than ± 20%

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

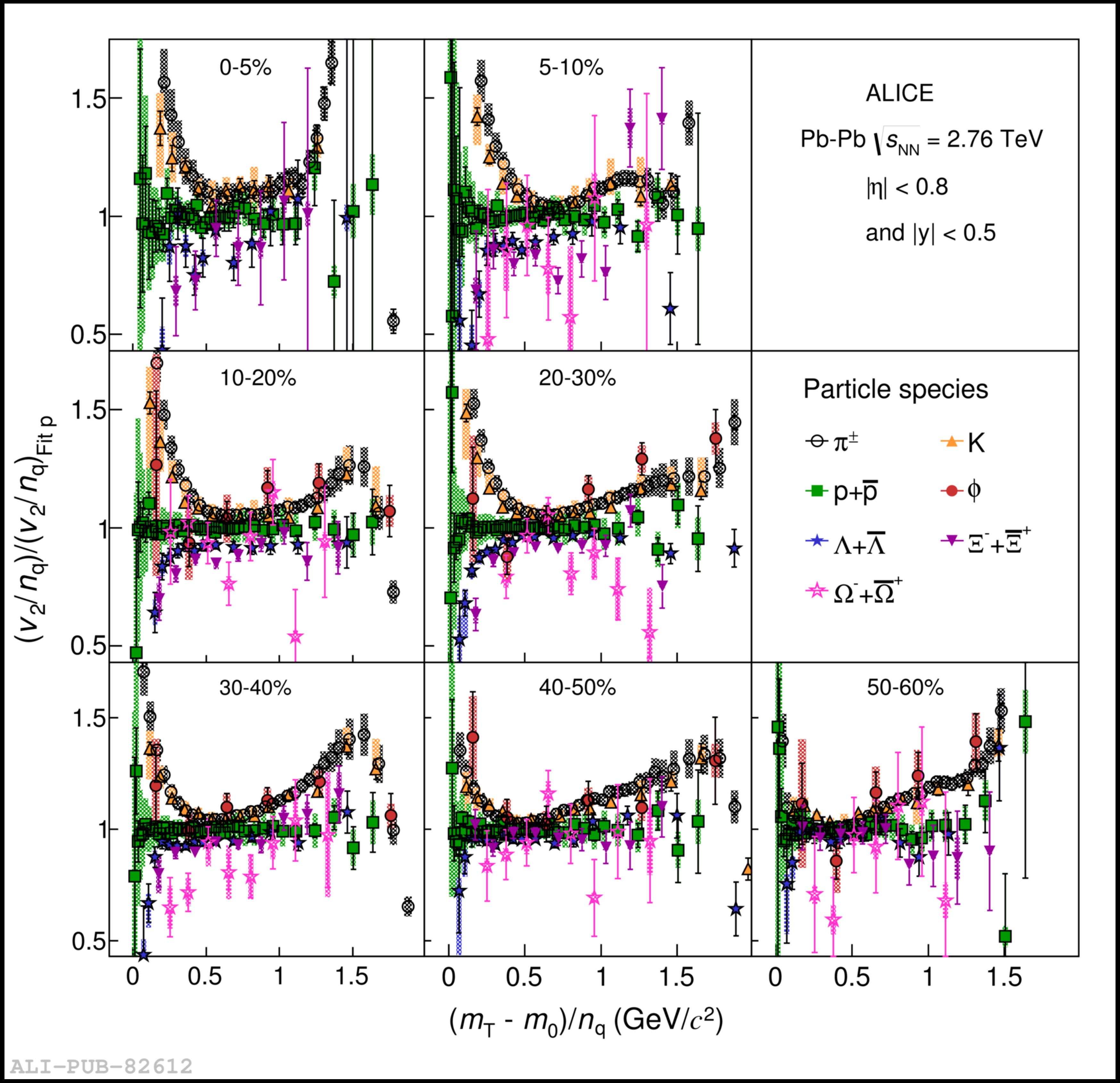


NCQ scaling in $(m_T - m_0)/n_q$



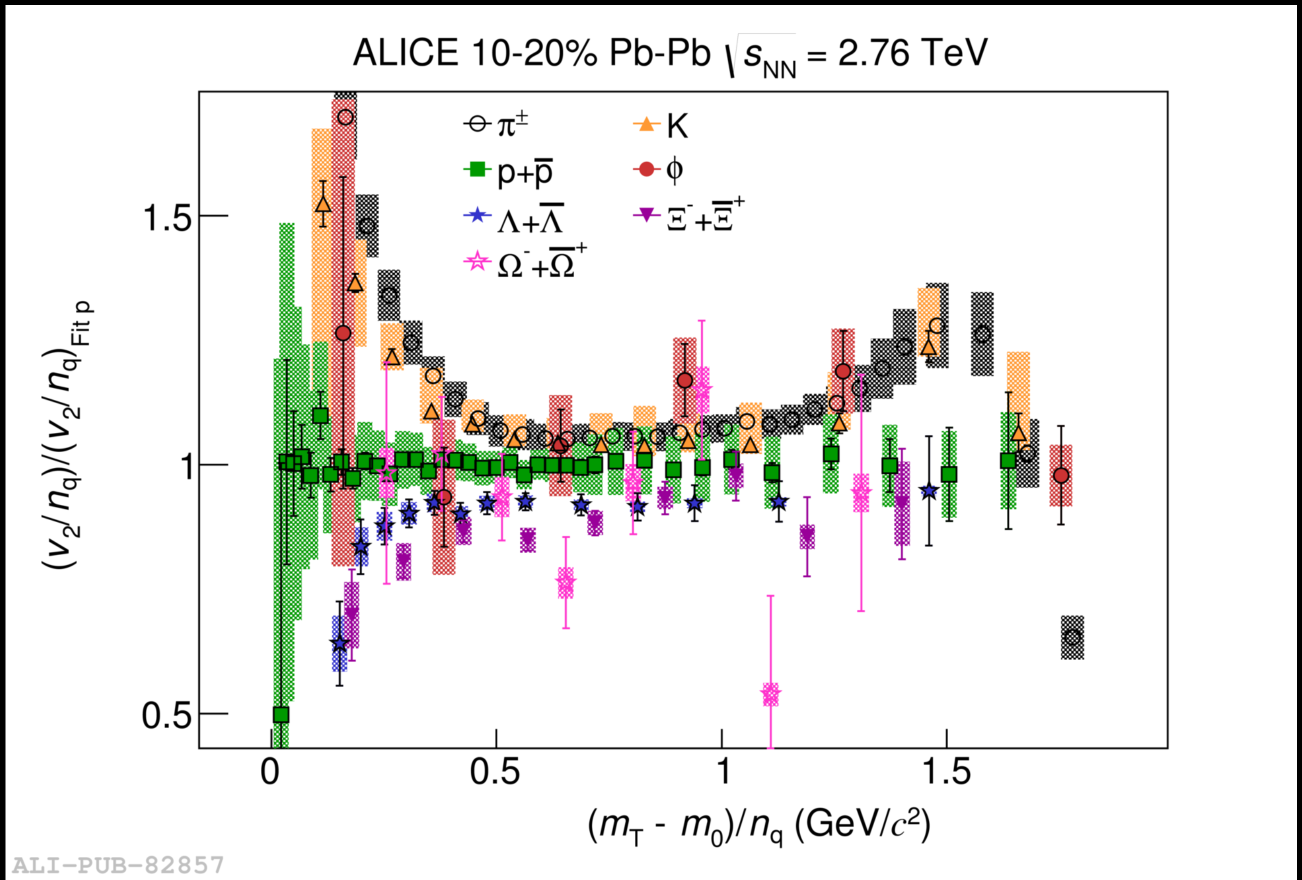
Introduced to extend the scaling to lower p_T

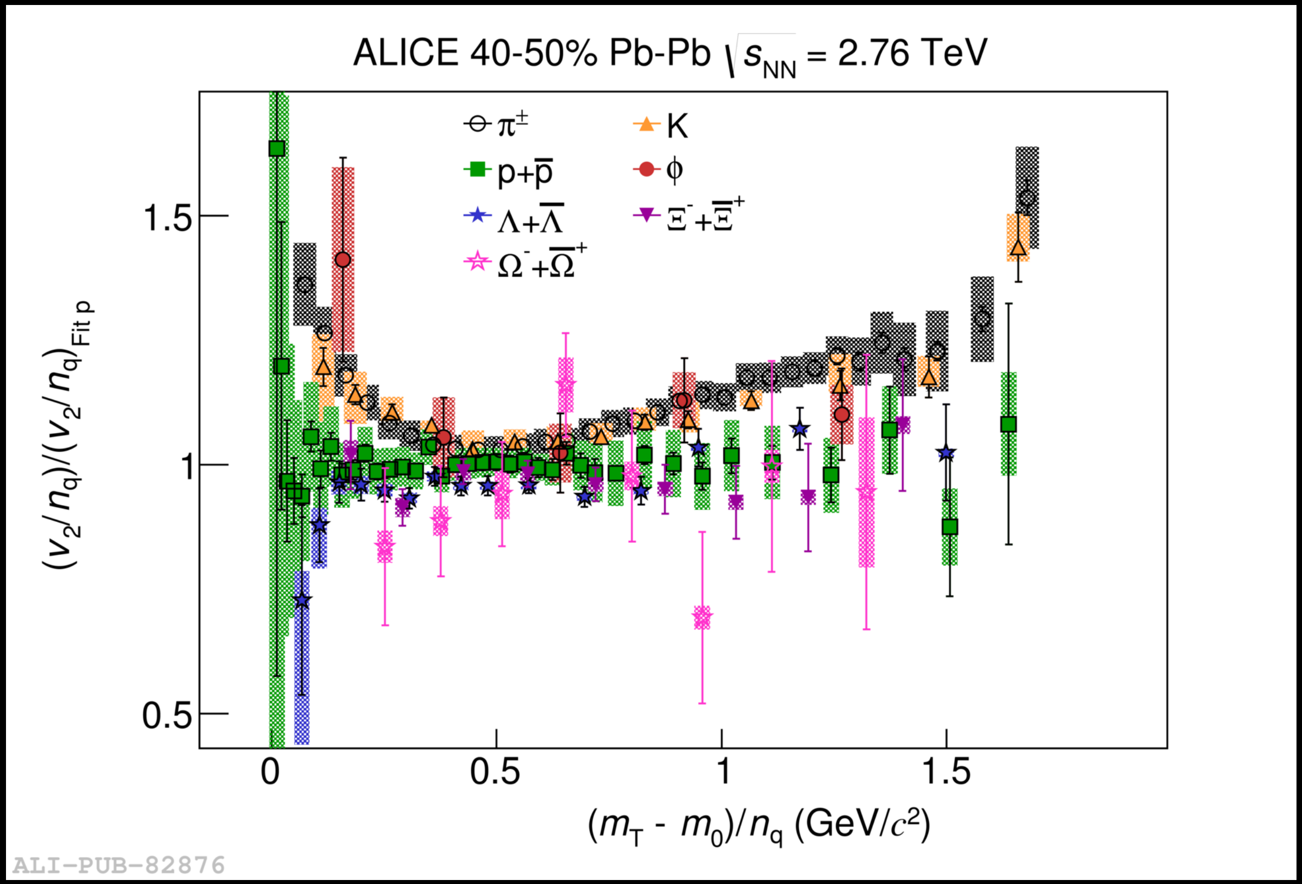
NCQ scaling in $(m_T - m_0)/n_q$ (double ratio)



Panos.Christakoglou@nikhef.nl

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

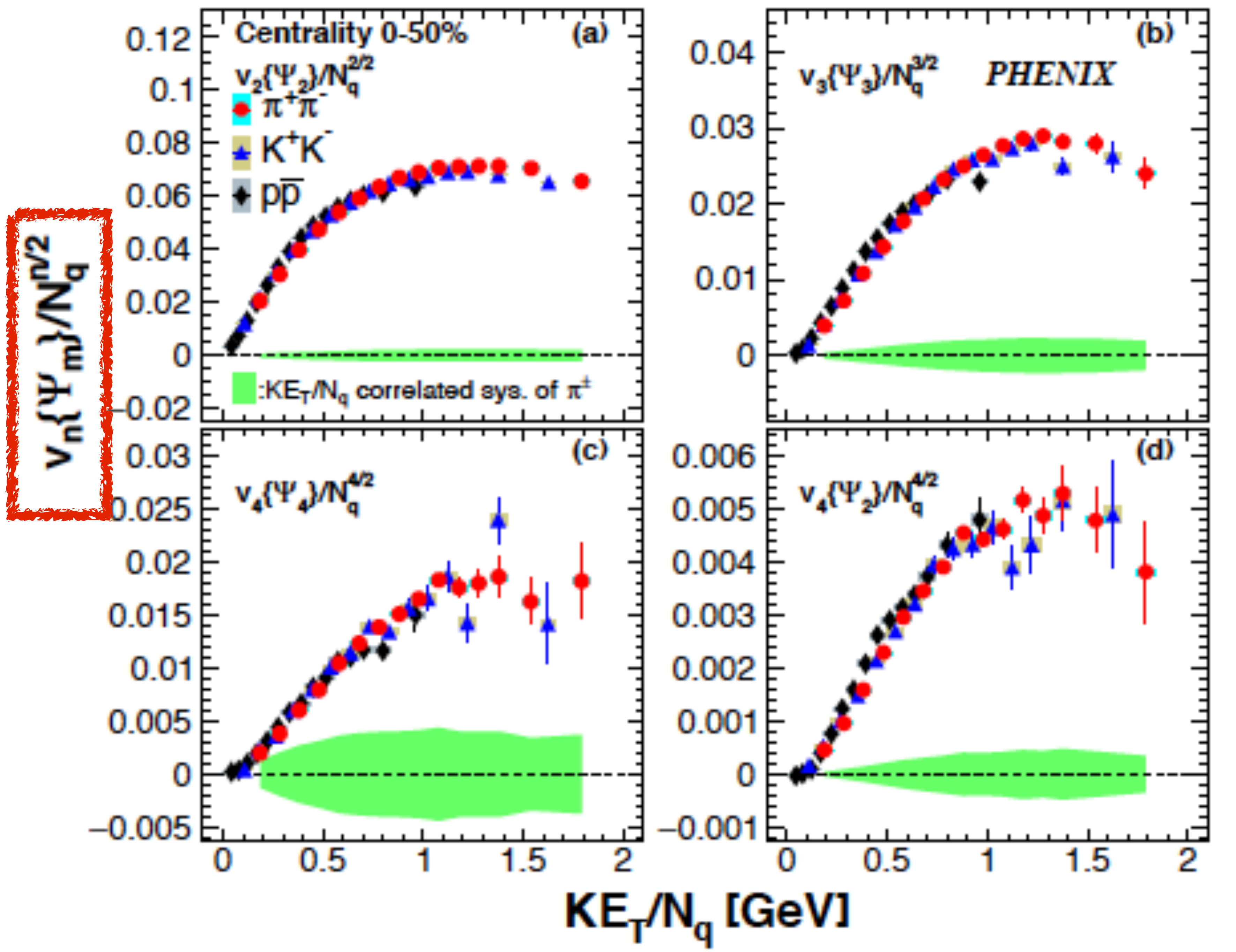




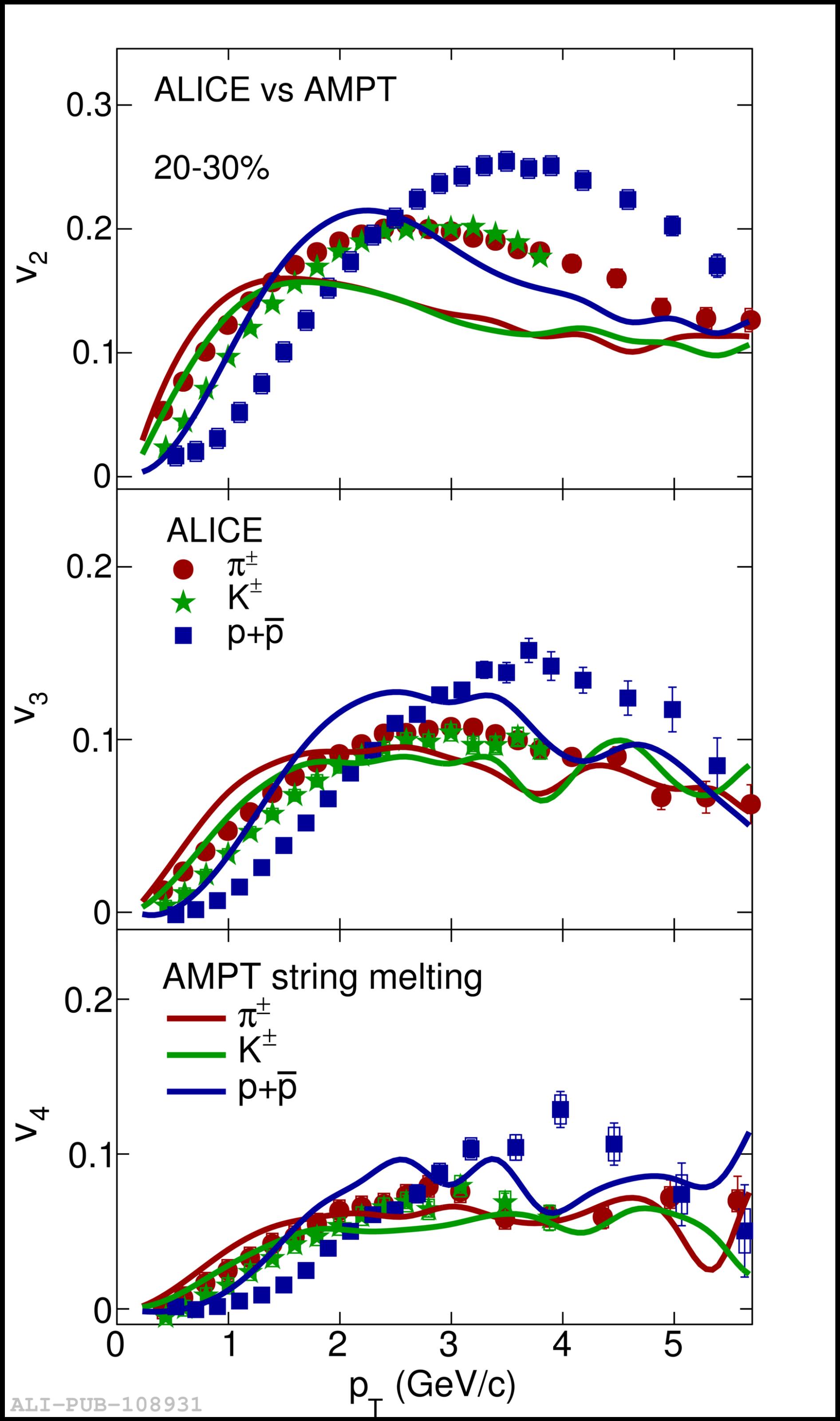
- For $(m_T - m_0)/n_q$ < 0.6 - 0.8 GeV/c^2: scaling is broken at the LHC
- For $(m_T - m_0)/n_q$ > 0.6 - 0.8 GeV/c^2: scaling is only approximate at the level of ± 20%

Scaling of higher harmonics @ RHIC

A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. C 93, 051902 (2016)

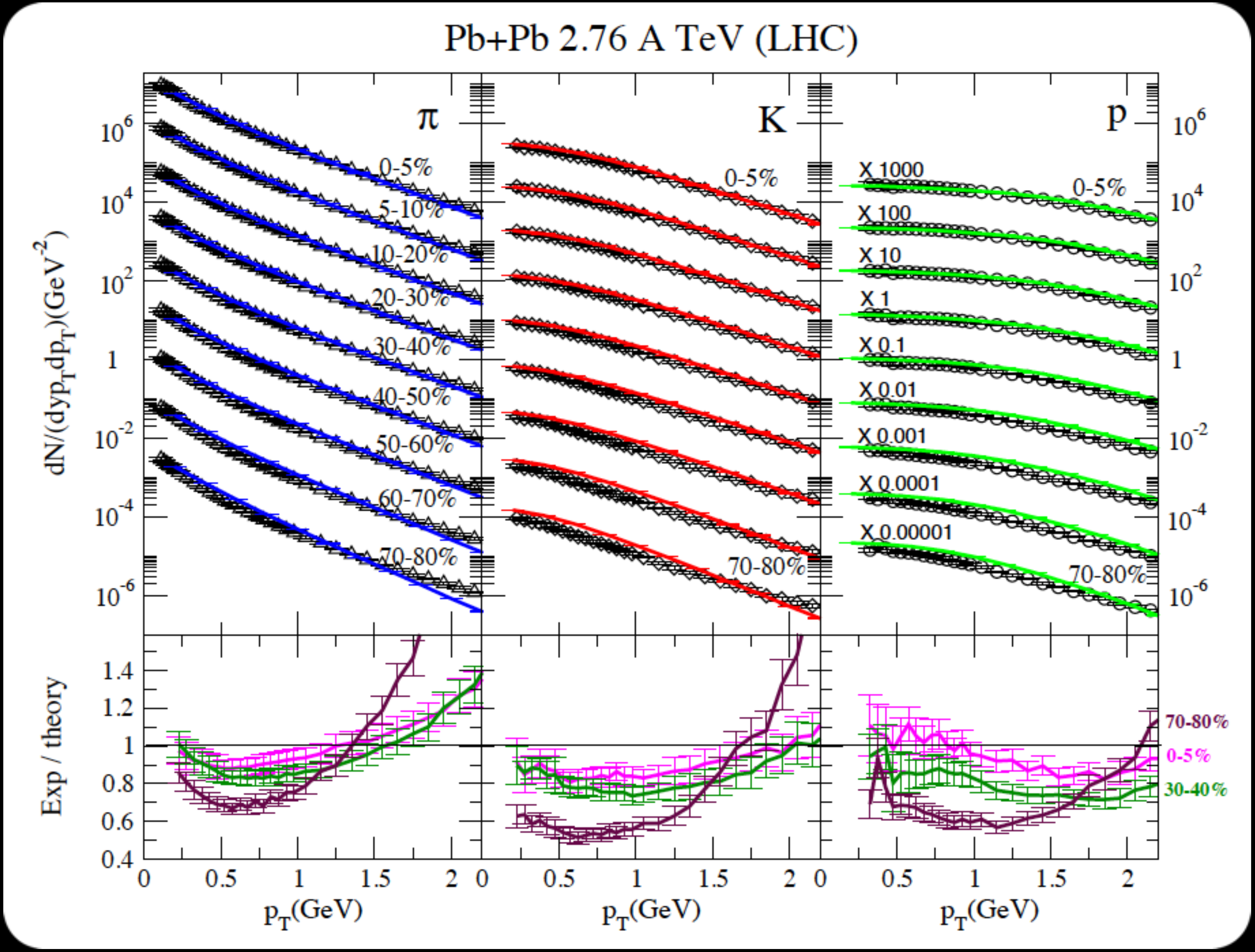


Data vs AMPT



- AMPT string melting describes the main features observed in data qualitatively
- Fails to describe data quantitatively
  - Radial flow reduced in AMPT by 25% compared with data

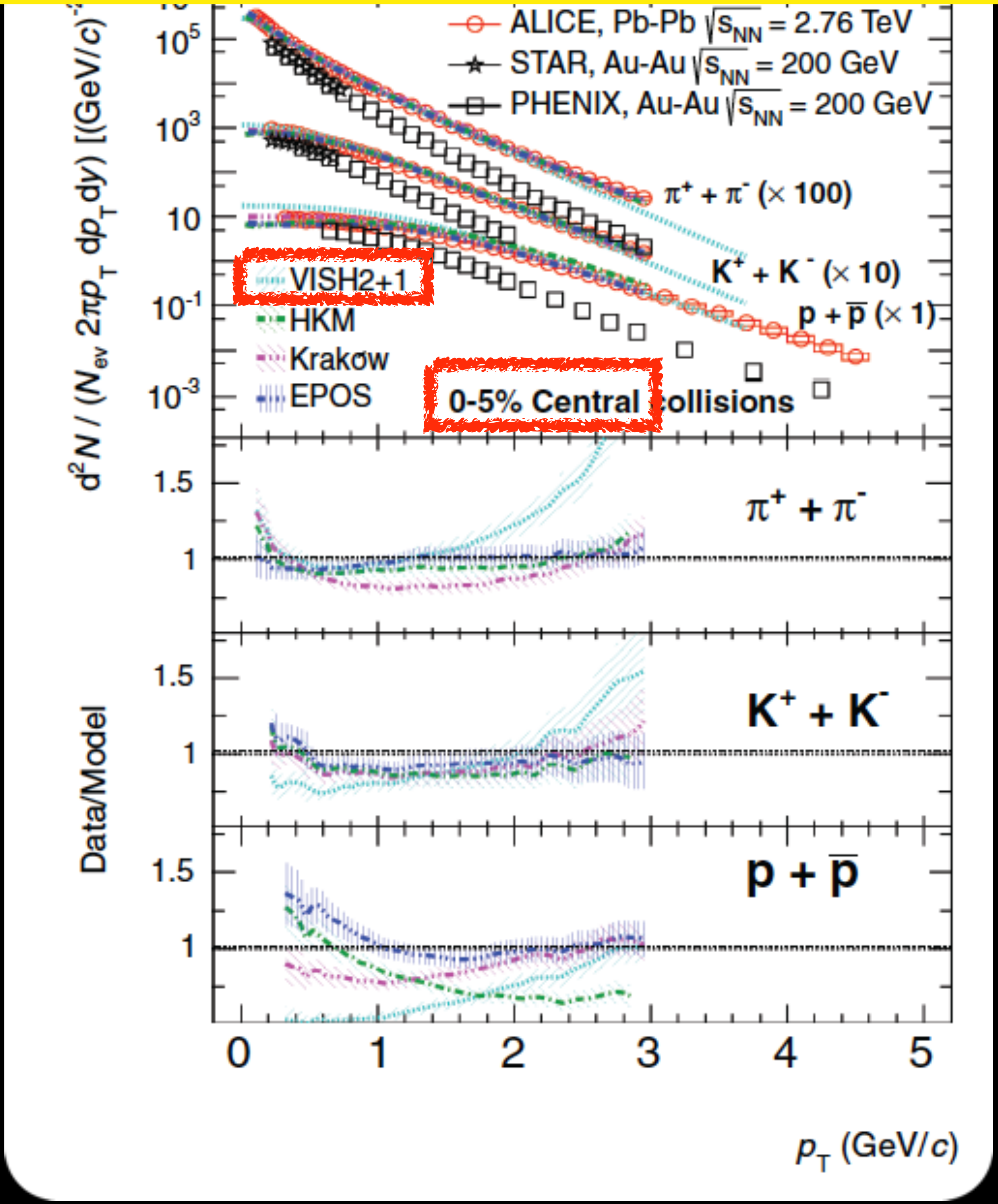
Spectra: How good is VISHNU doing?

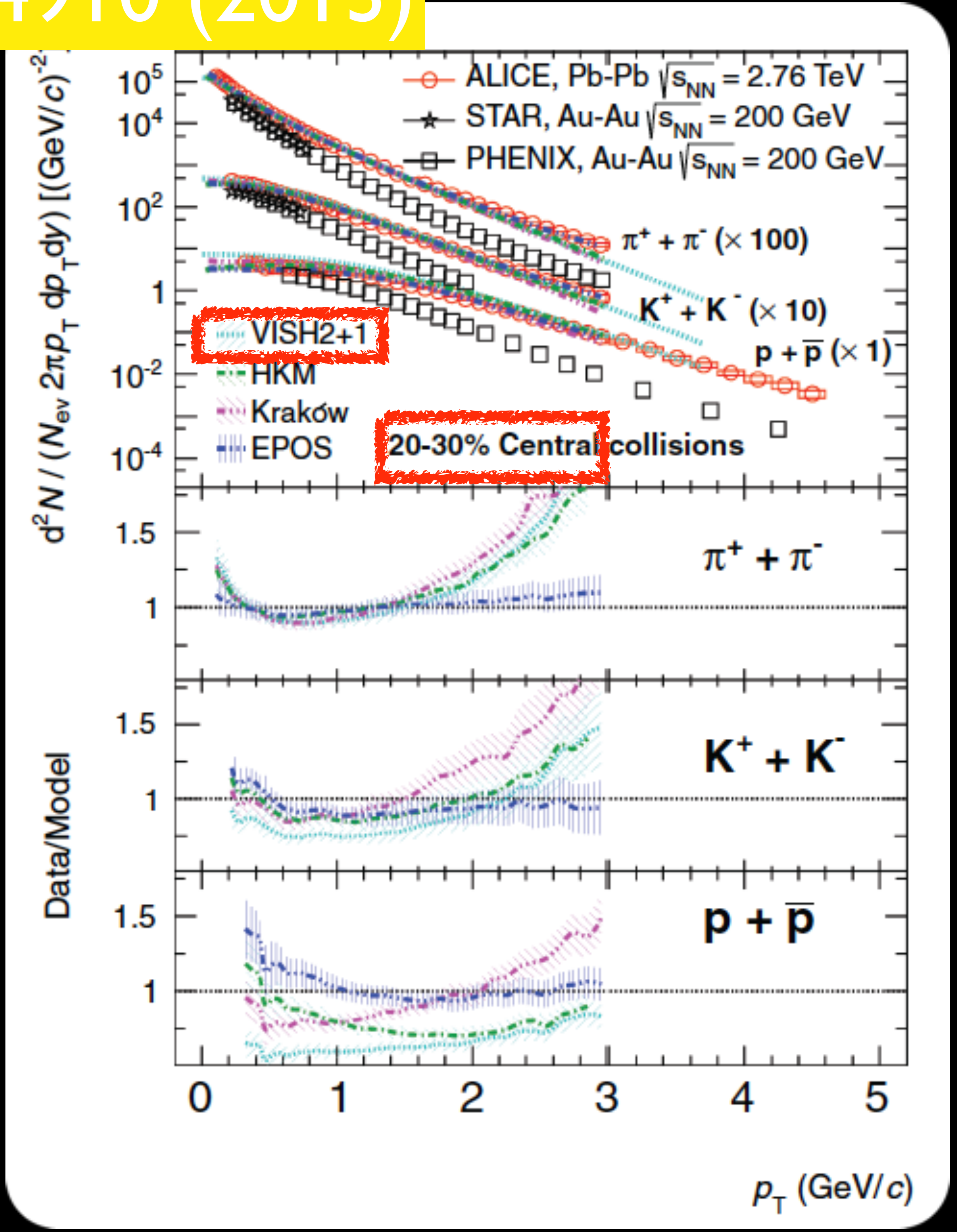


H. Song *et al.*, arXiv:1311.0157 [nucl-th]

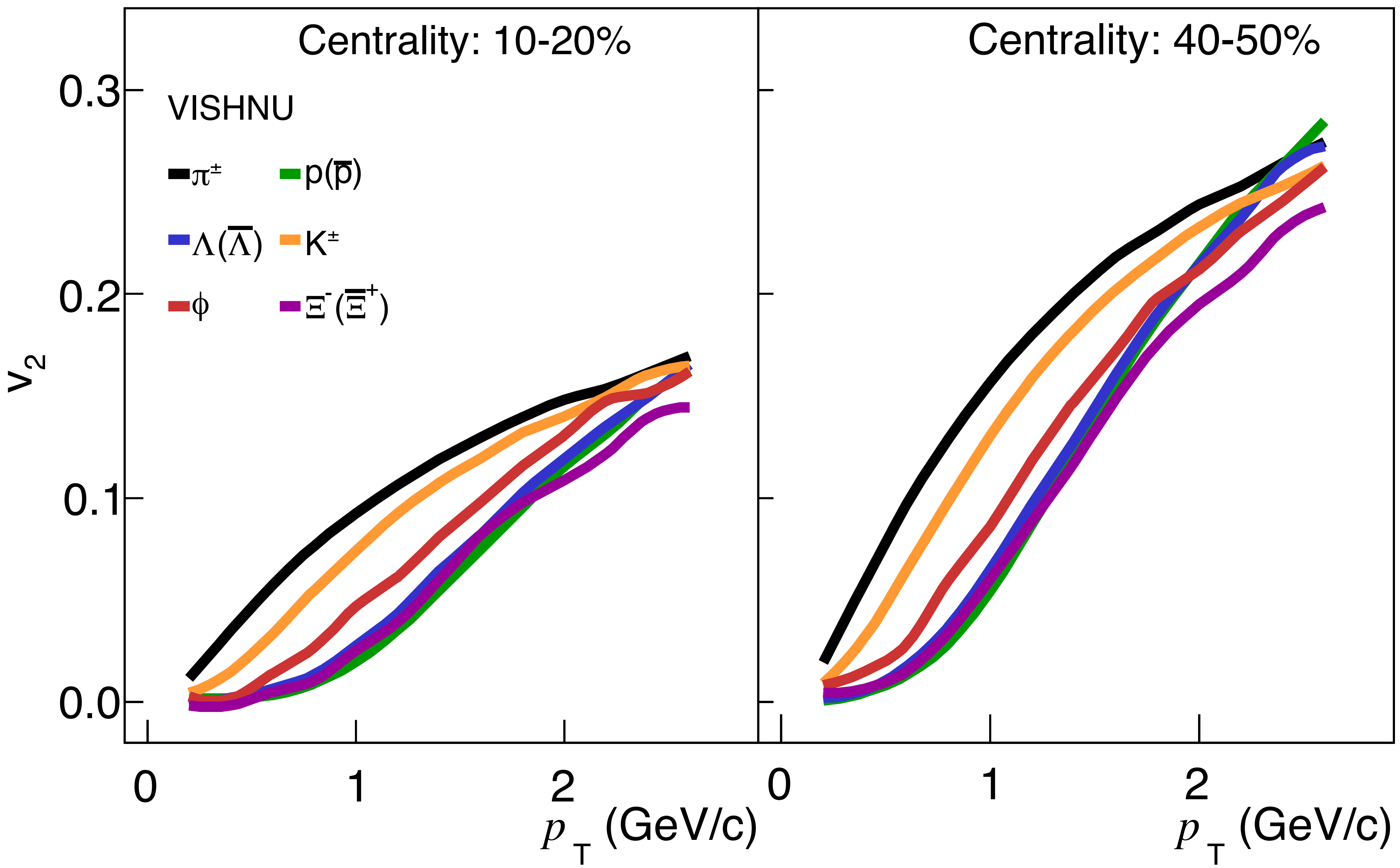
VISH2+1: comparison to spectra

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





VISHNU in more detail



Mass ordering not preserved!!!

...attering phase: VISHNU vs VISH2+1

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

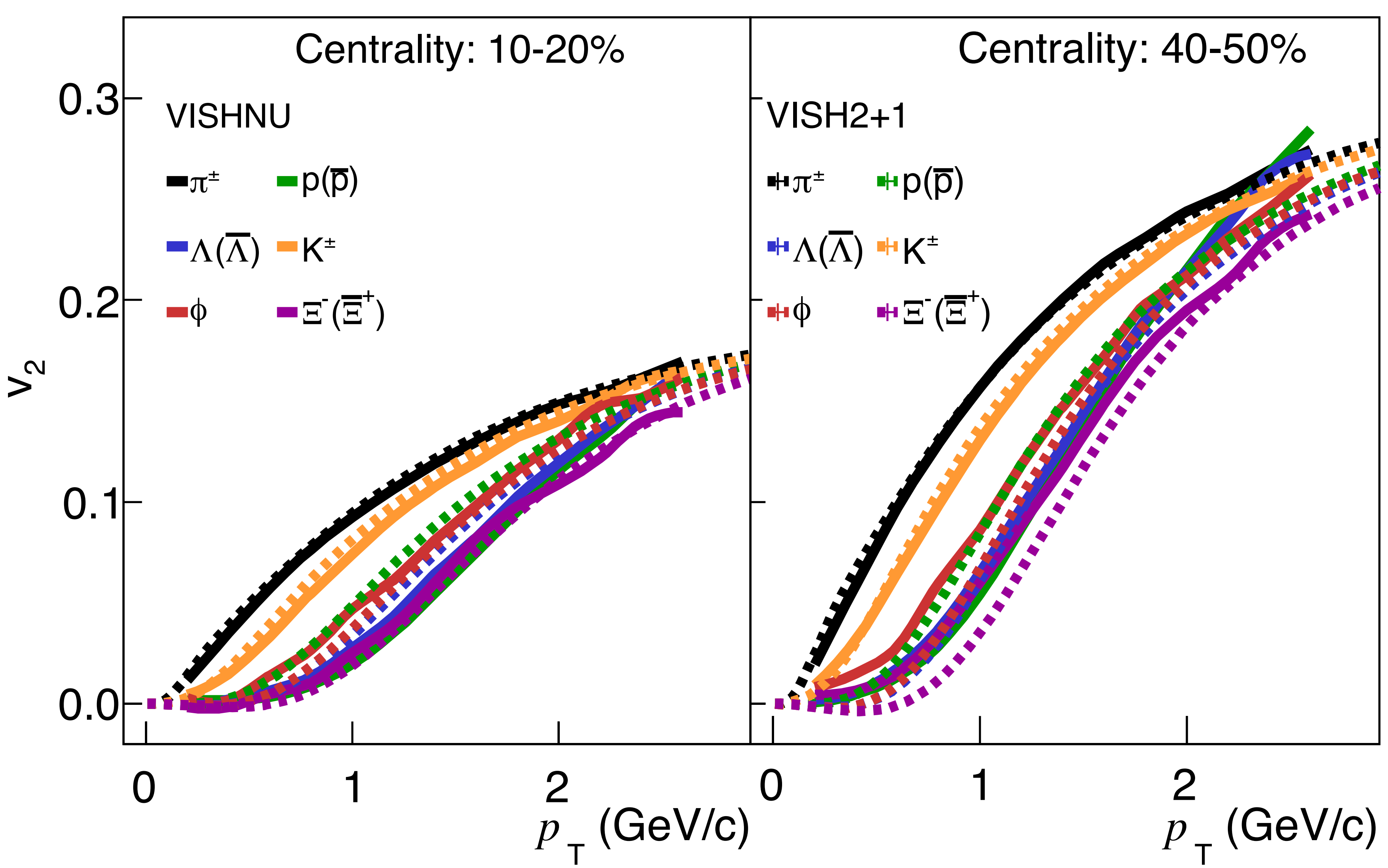
VISH2+1

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]].

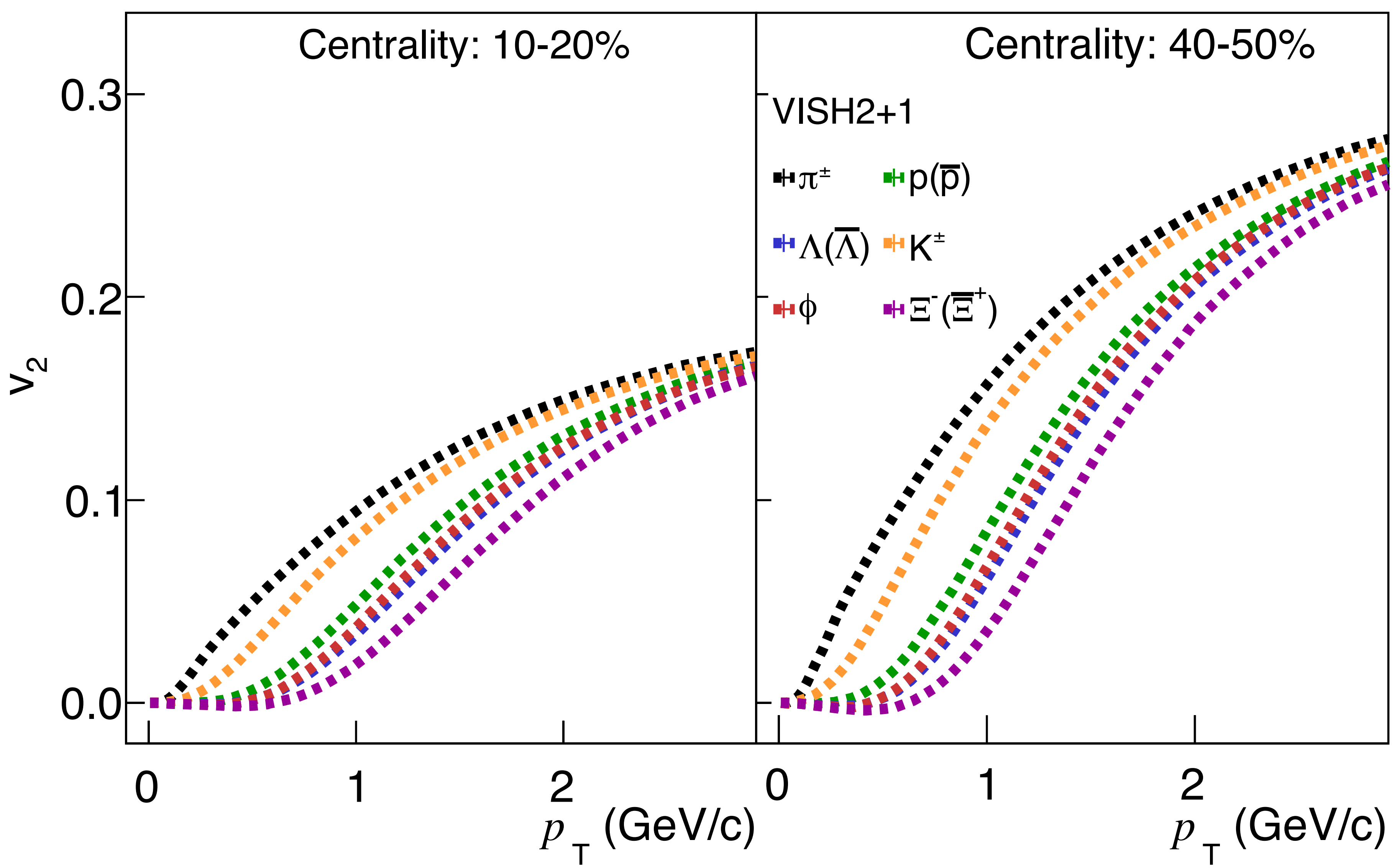
H. Song and U.W. Heinz, Phys. Rev. C 78 (2008) 024902 [arXiv:0805.1756 [nucl-th]].

VISHNU vs VISH2+1



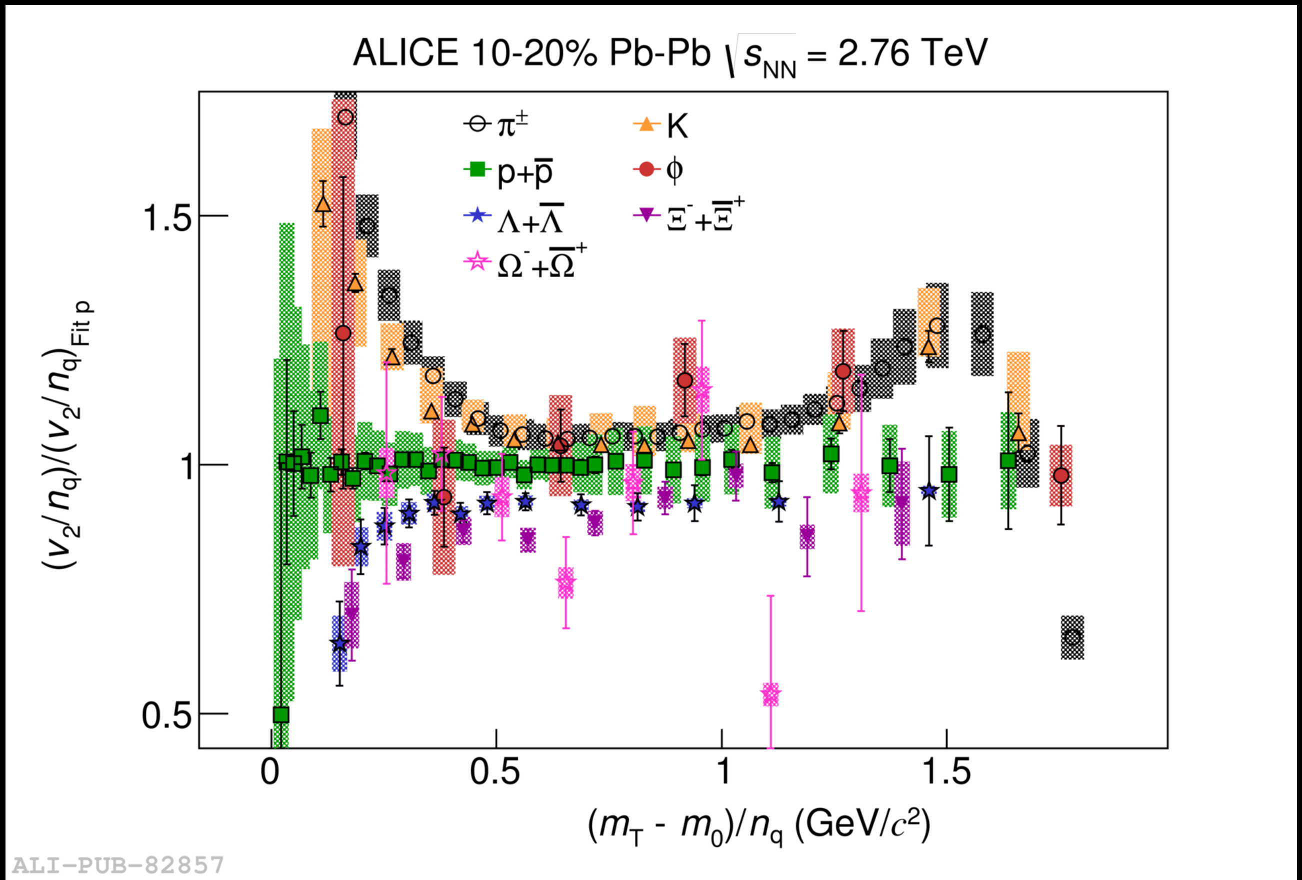
Not a clear trend: π, K similar for both centralities, φ similar for central events but different for peripheral, some baryons (e.g. p, Λ) "pushed" to higher p_T, while others (e.g. Ξ) to lower p_T

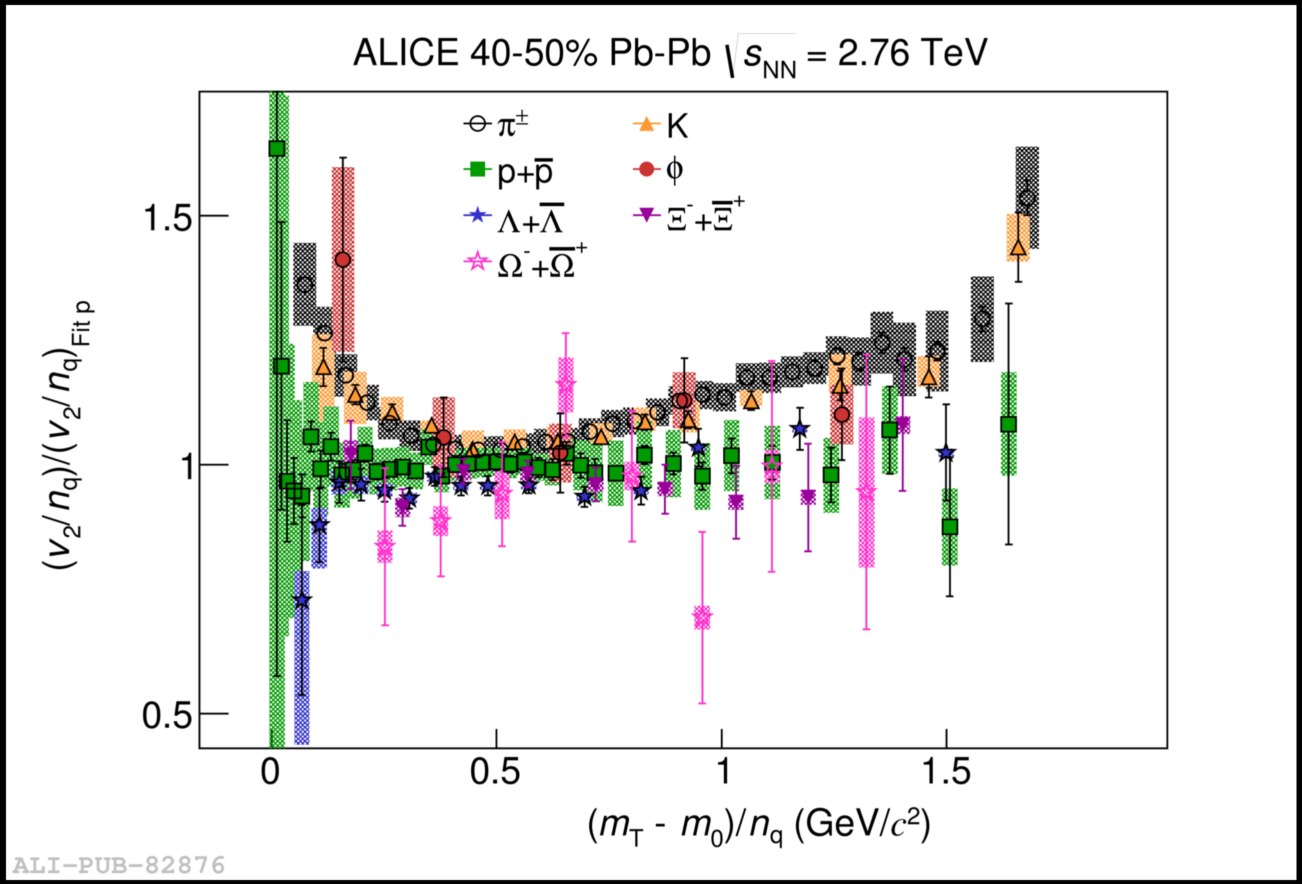
VISH2+1 in more detail



Mass ordering preserved

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





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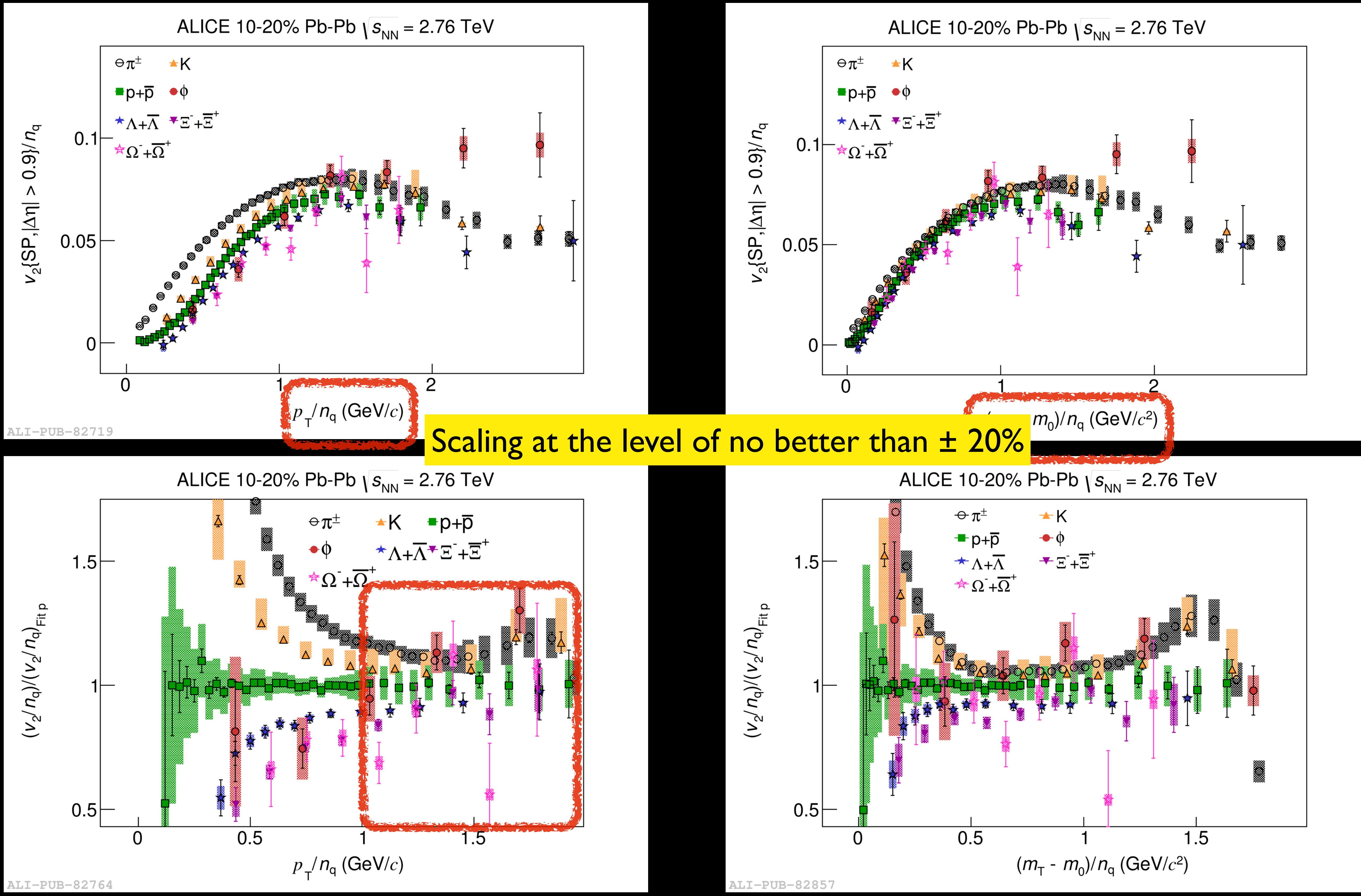
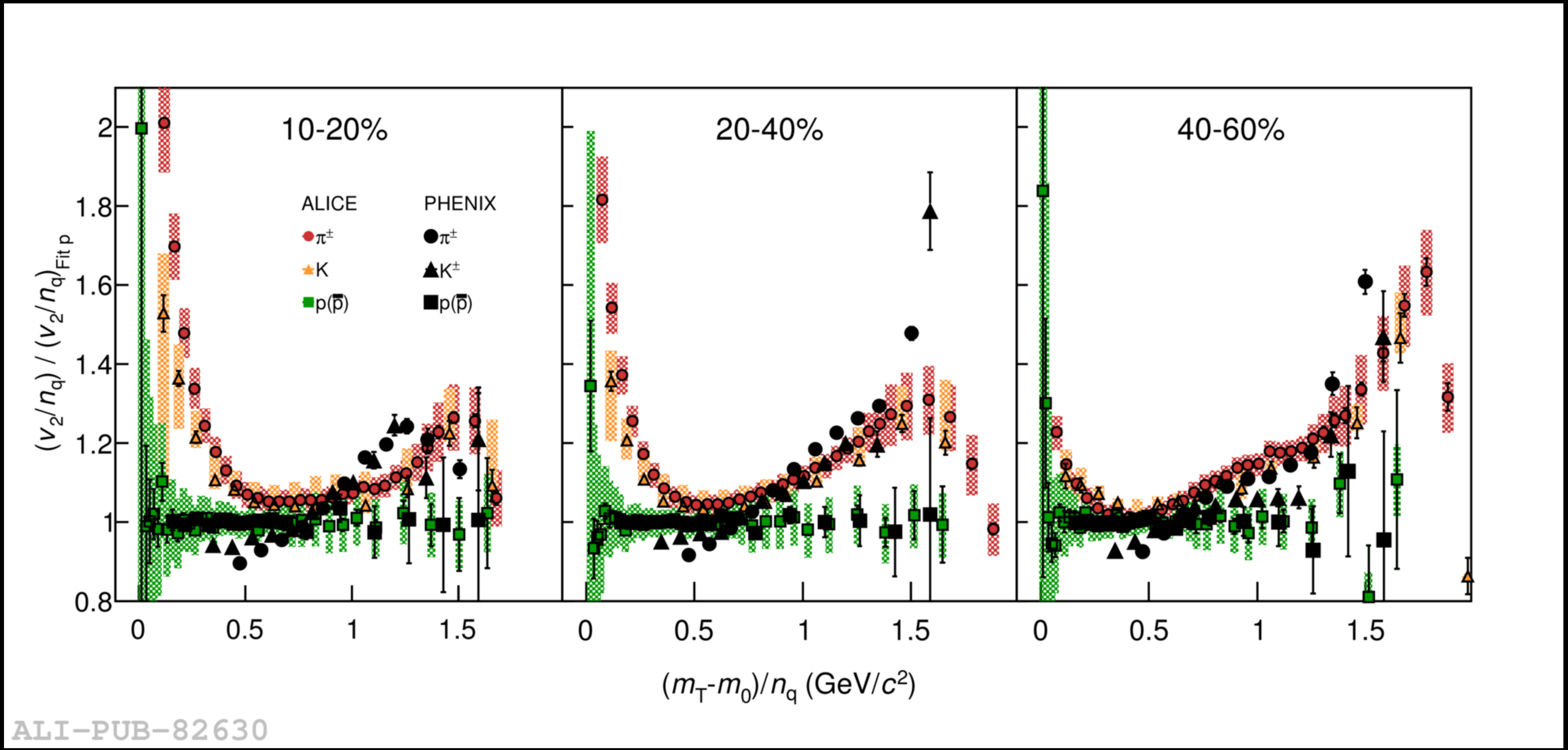
- For $(m_T - m_0)/n_q$ > 0.6 - 0.8 GeV/c^2: scaling is only approximate at the level of ± 20%

Scaling properties at the LHC

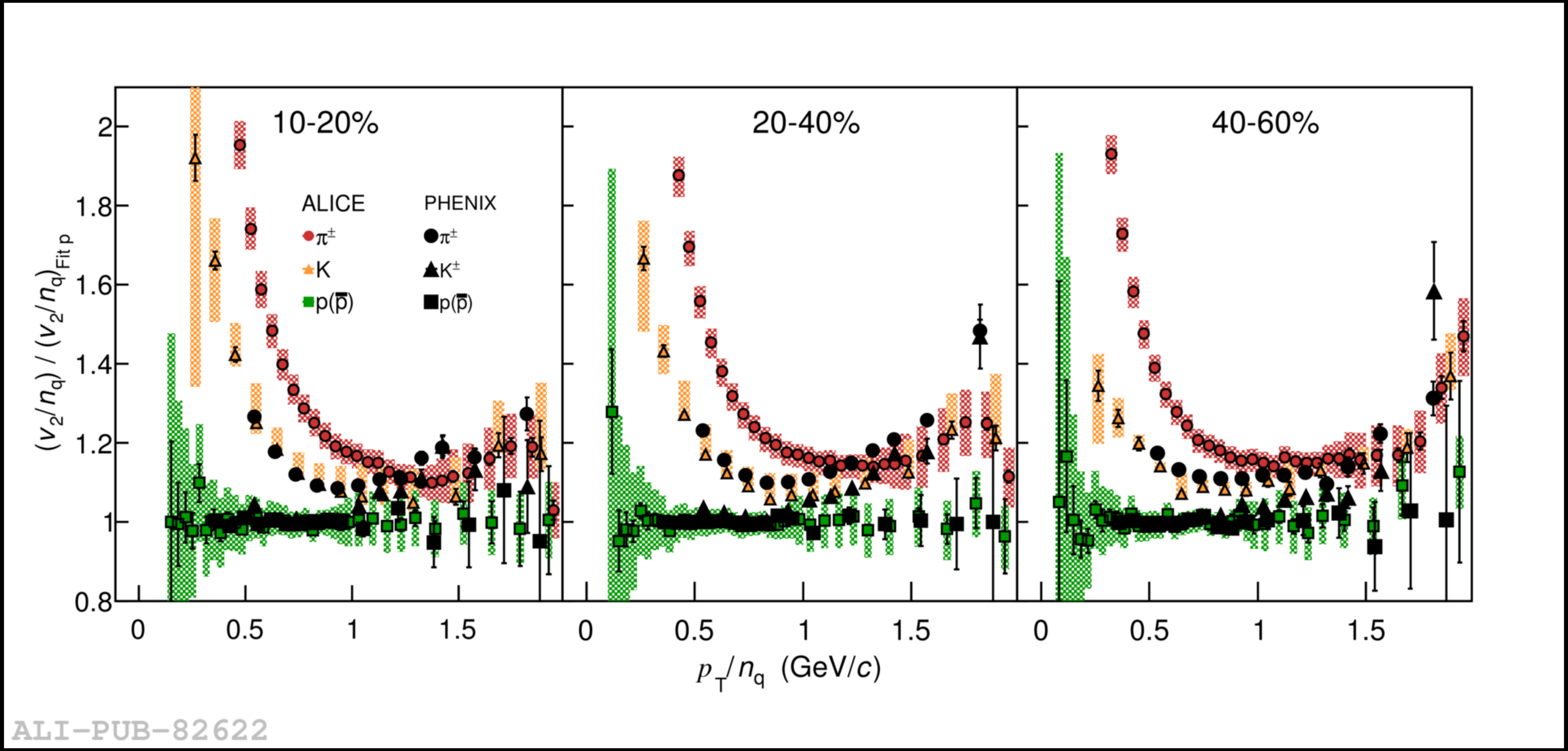


NCQ scaling in $(m_T - m_0)/n_q$ (double ratio): evolution with energy



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

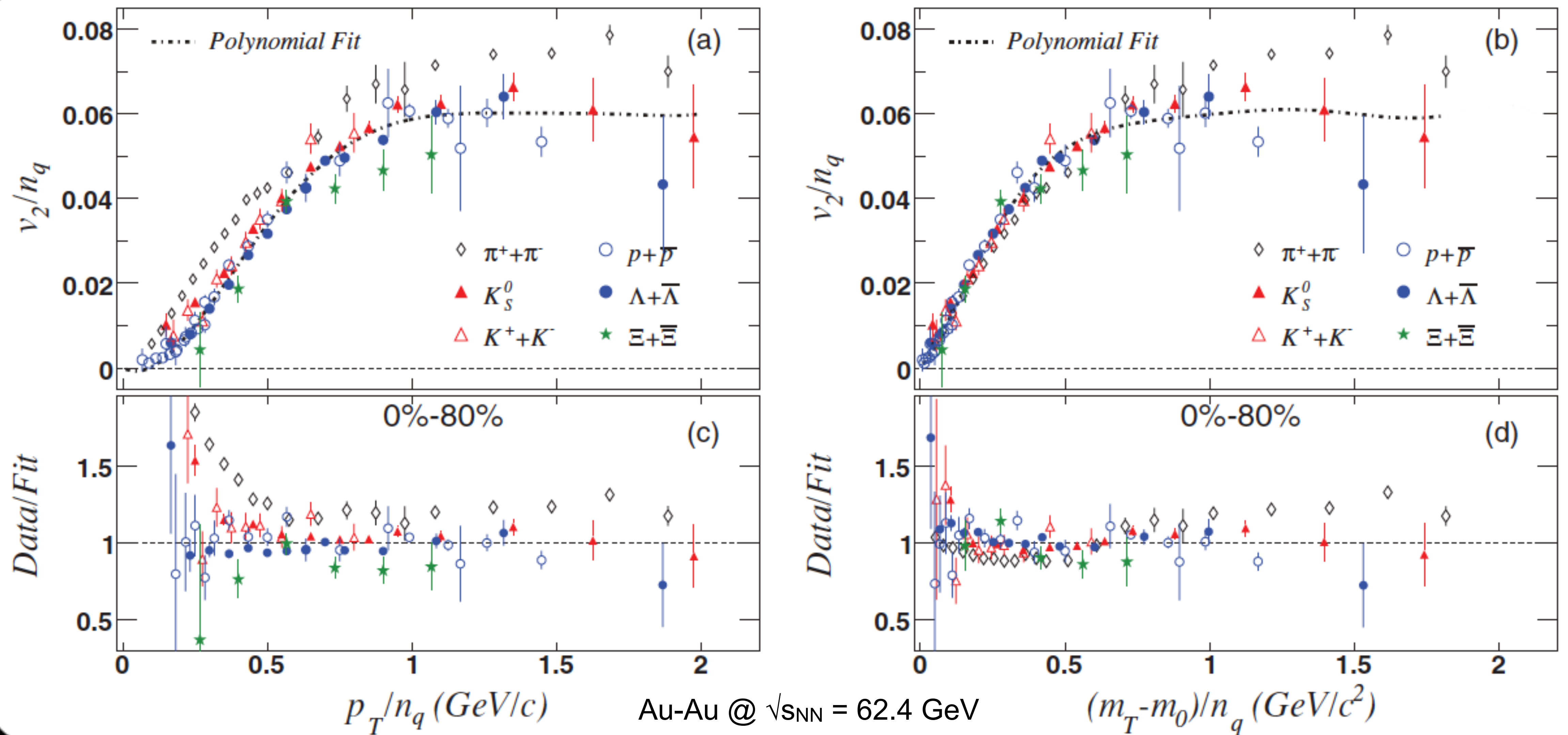
NCQ scaling in p_T/n_q (double ratio): evolution with energy



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?

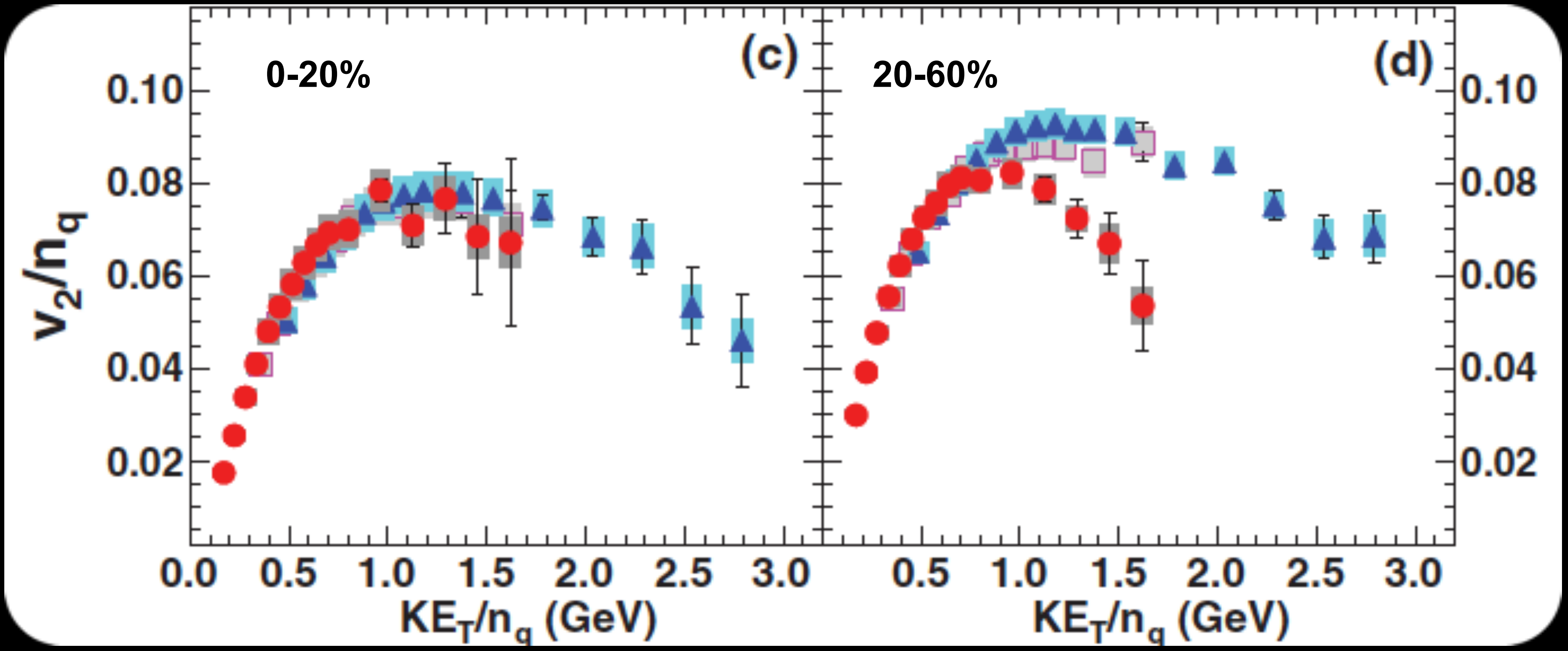


Au-Au @ $\sqrt{s_{NN}}$ = 62.4 GeV

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

Deviations from the universal scaling at RHIC

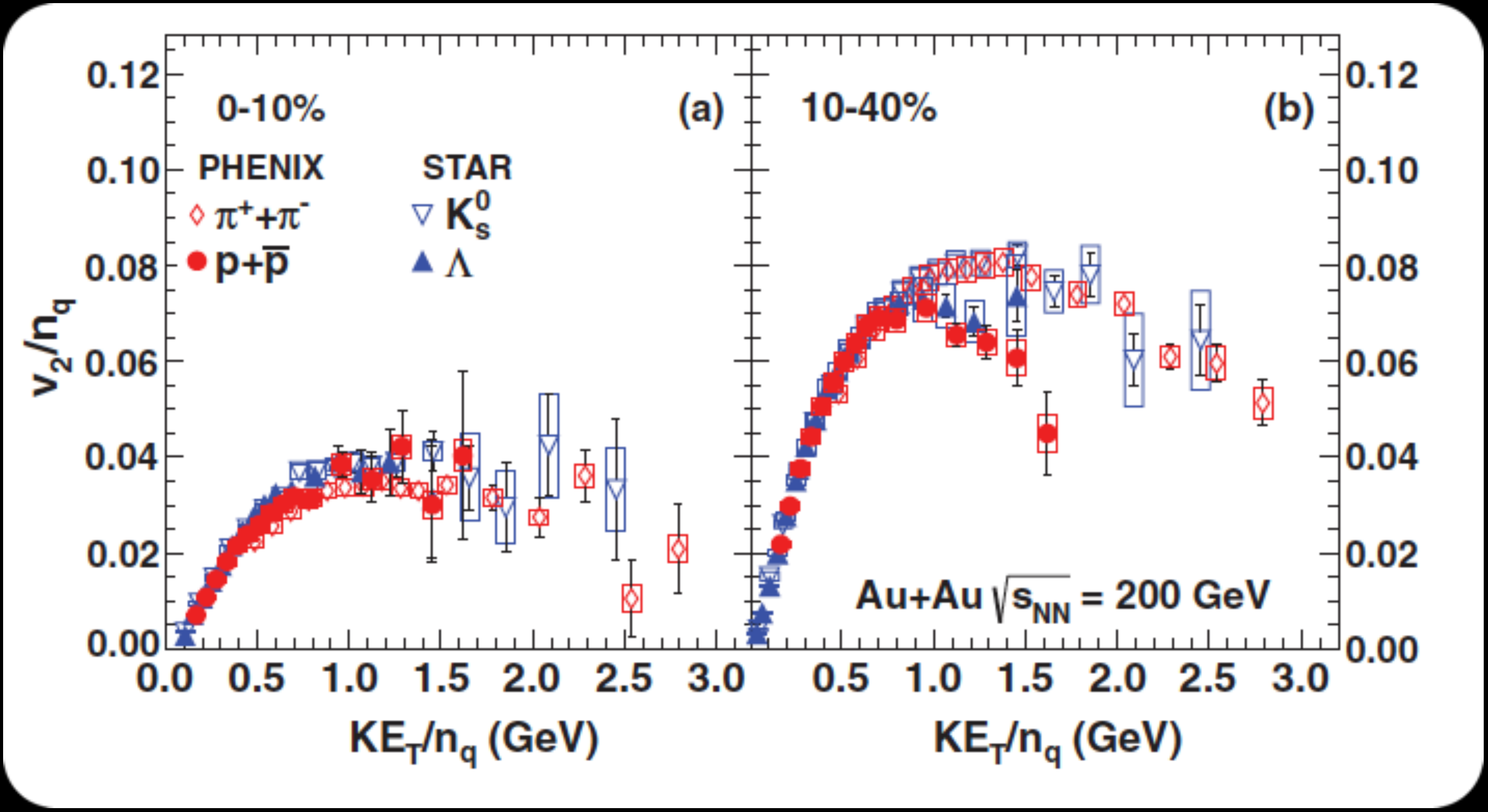
A. Adare *et al*. (PHENIX Collaboration), Phys. Rev. **C85**, (2012) 064914



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

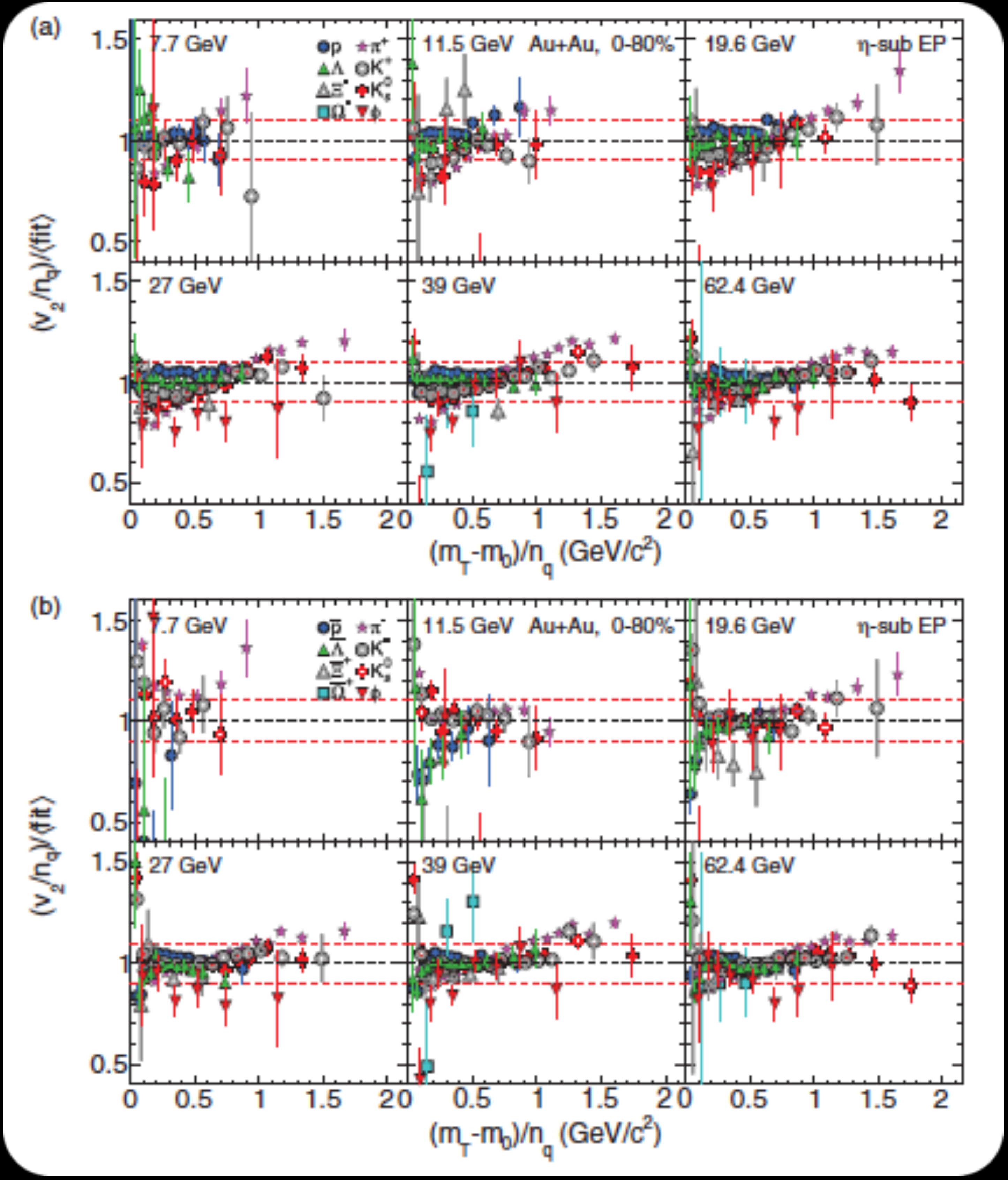
Deviations from the universal scaling at RHIC

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



Similar deviations observed by STAR?

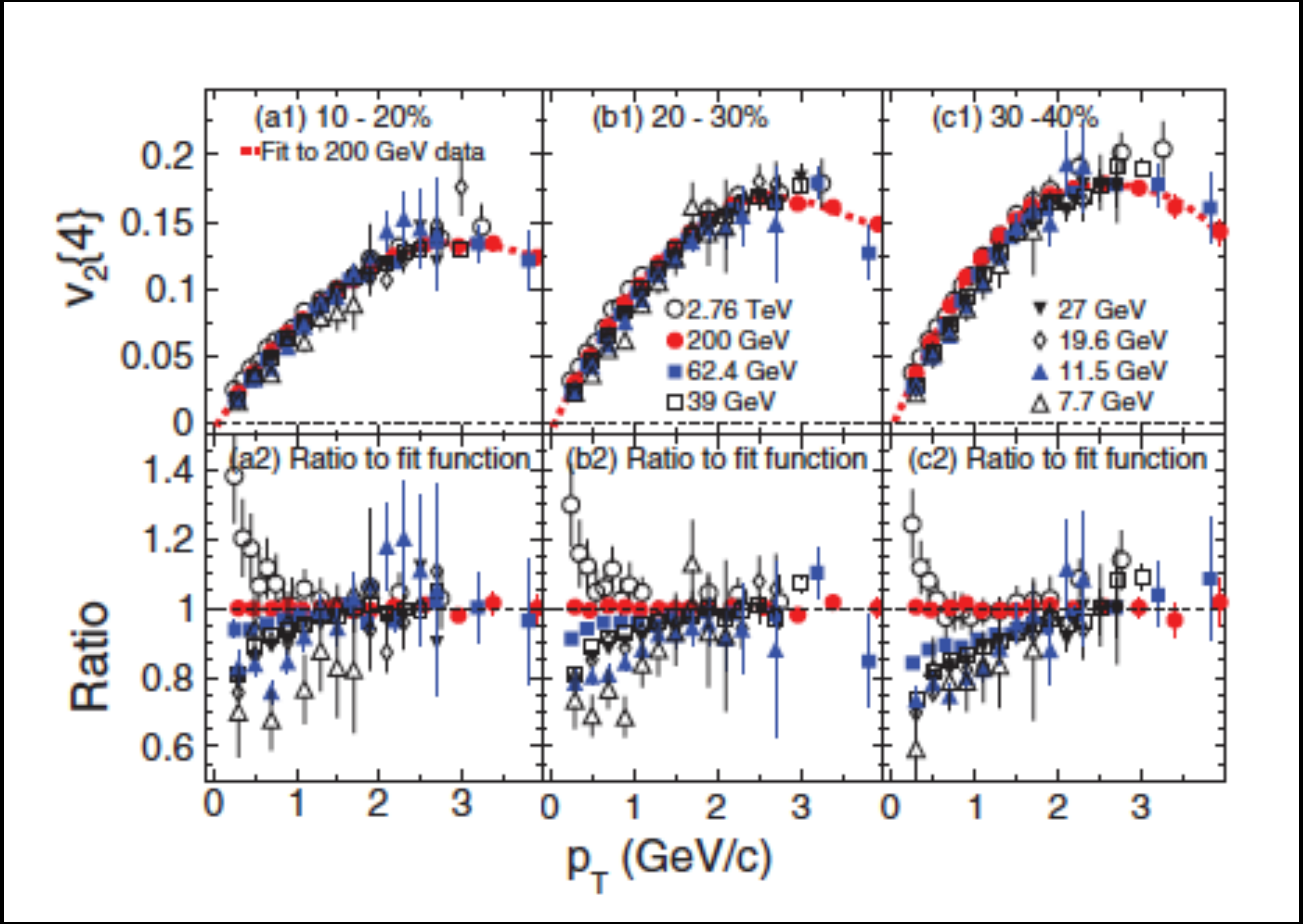
BES: NCQ scaling



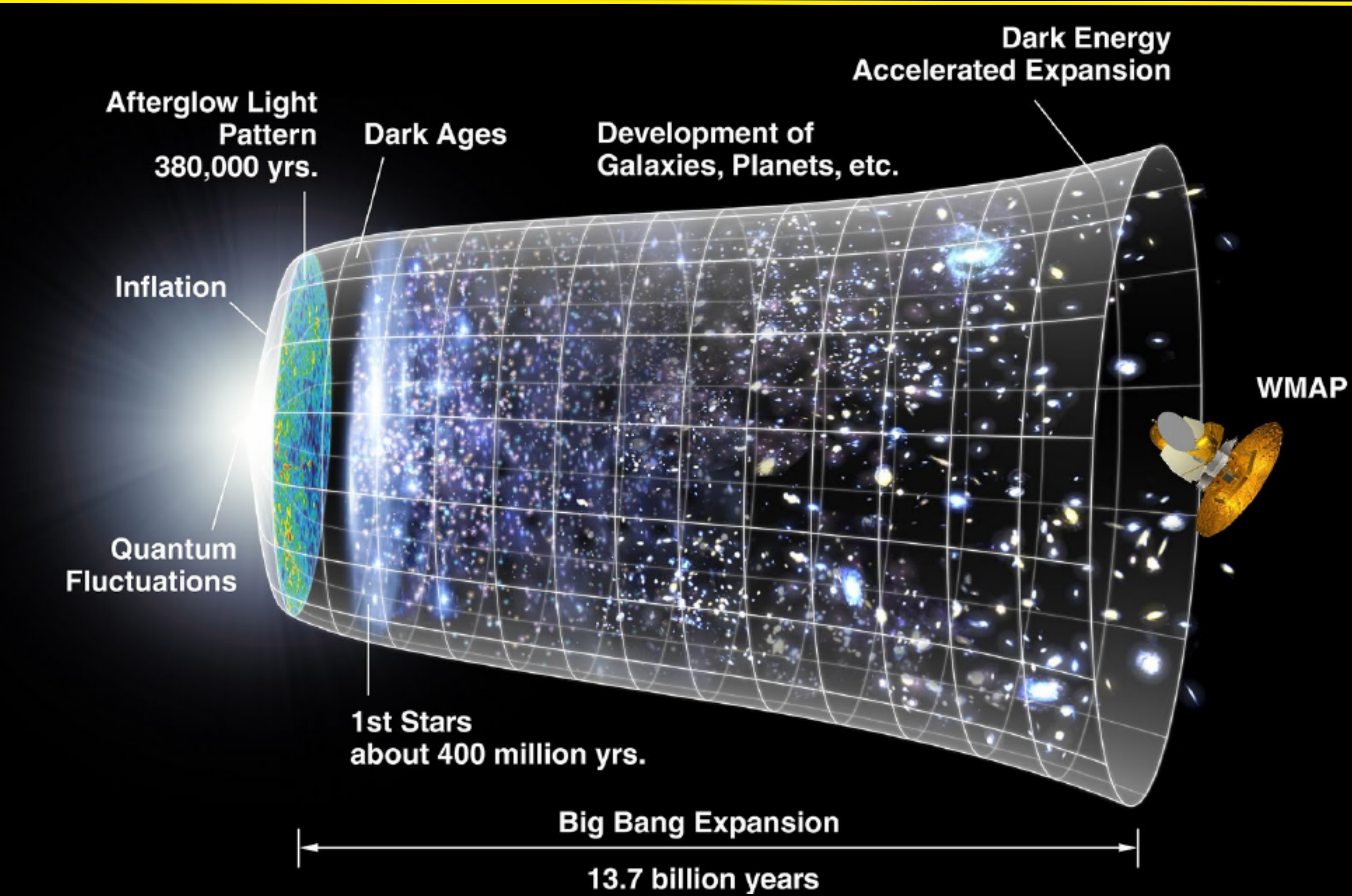
L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. **C88**, (2013) 014902

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

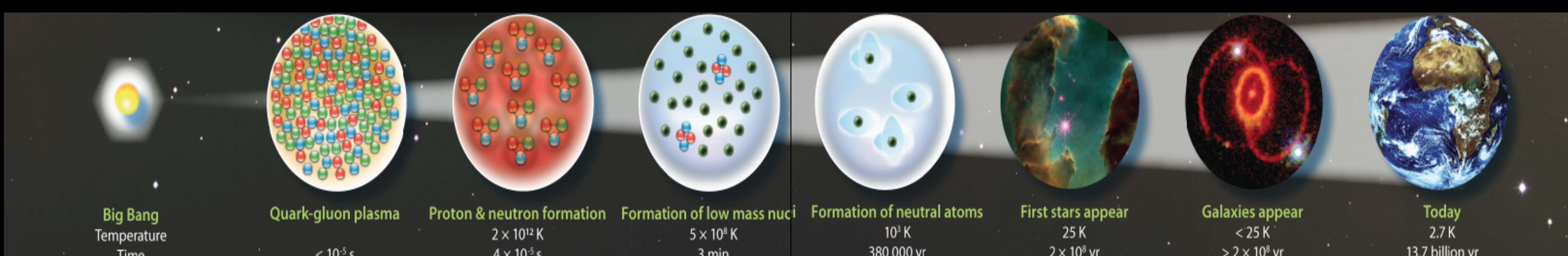
(STAR Collaboration): Phys.Rev. C86 (2012) 054908



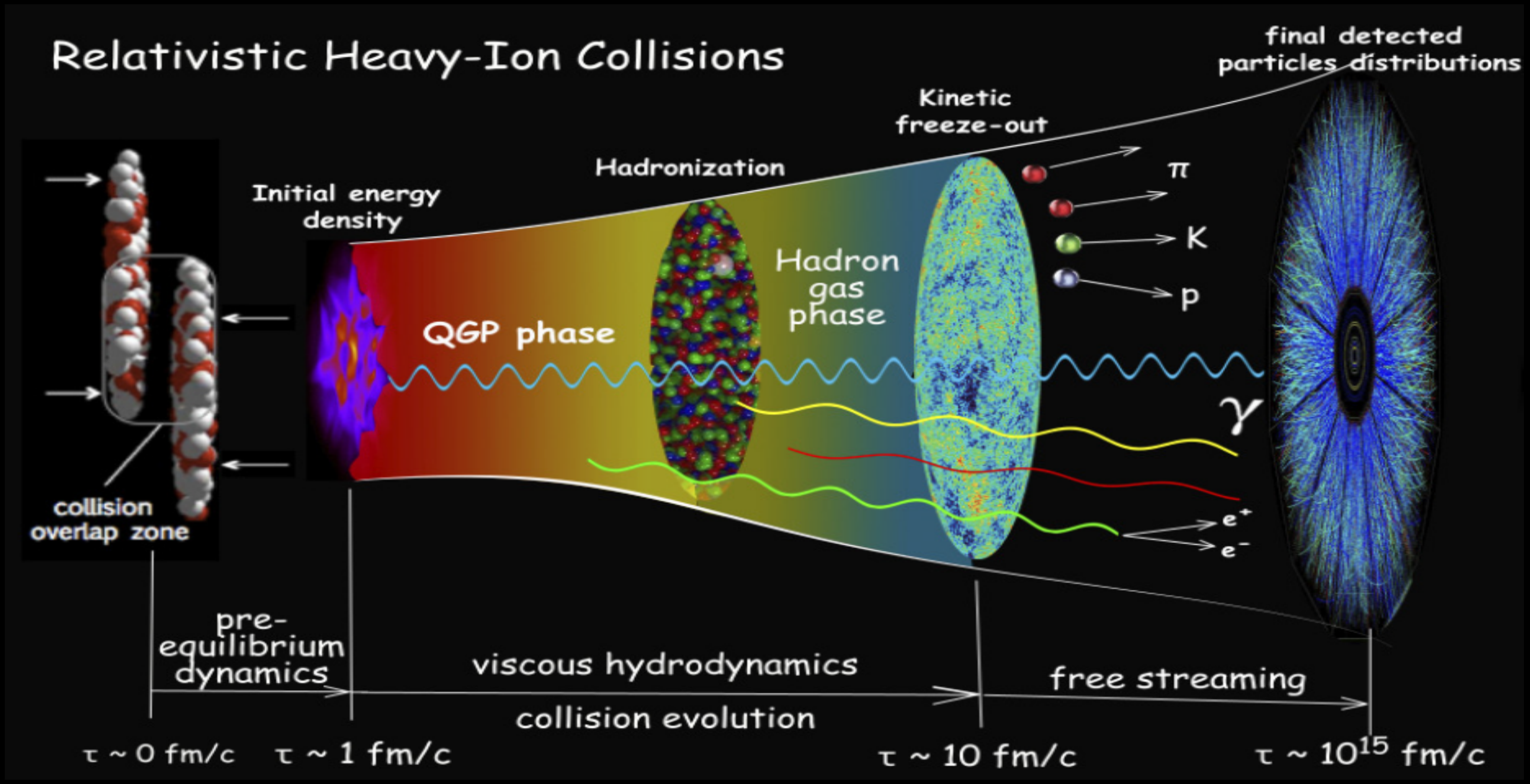
From the Big-Bang



- 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…



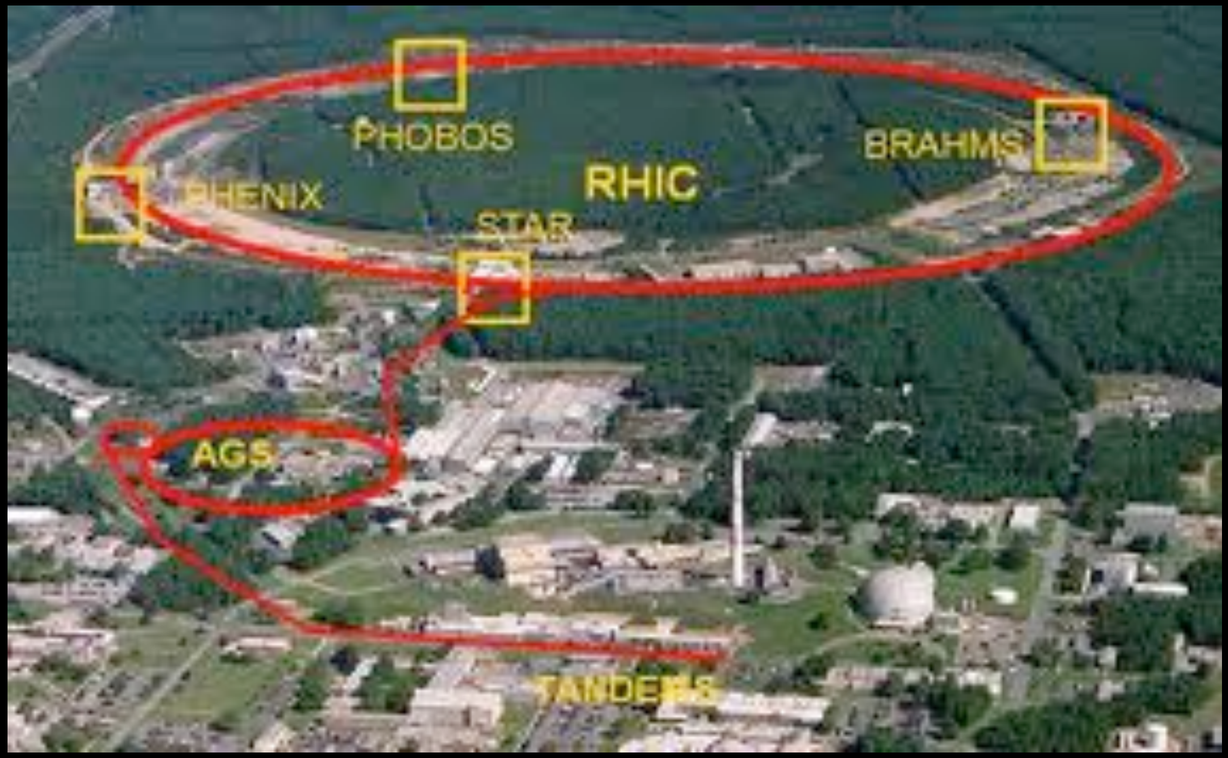
- QCD: Phase transition beyond a critical temperature (~170 MeV) and energy density (~0.5 GeV/fm^3) ➞ quarks and gluons are free ➞ Quark Gluon Plasma (QGP)
- The properties of the QGP and the QCD Phase transition are poorly known from first principles

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

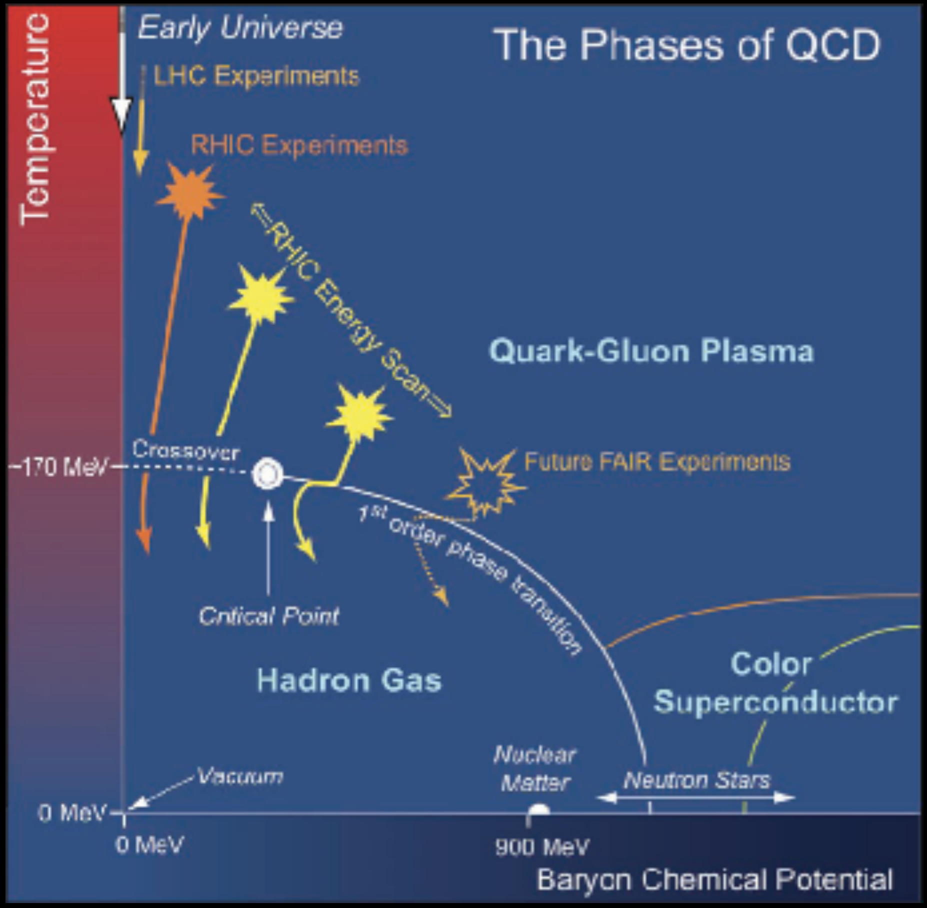
$T_{(Sun's\ core)}$~10^7 degrees

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

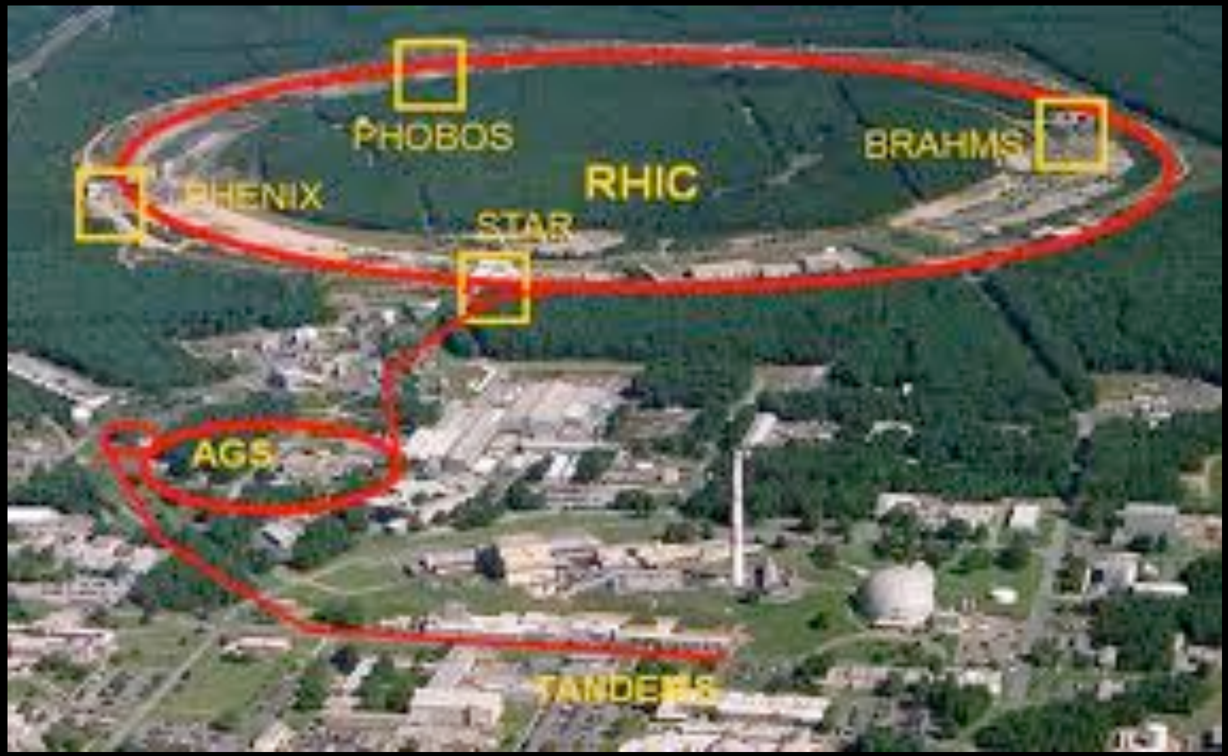
Little Bangs studied at RHIC and LHC



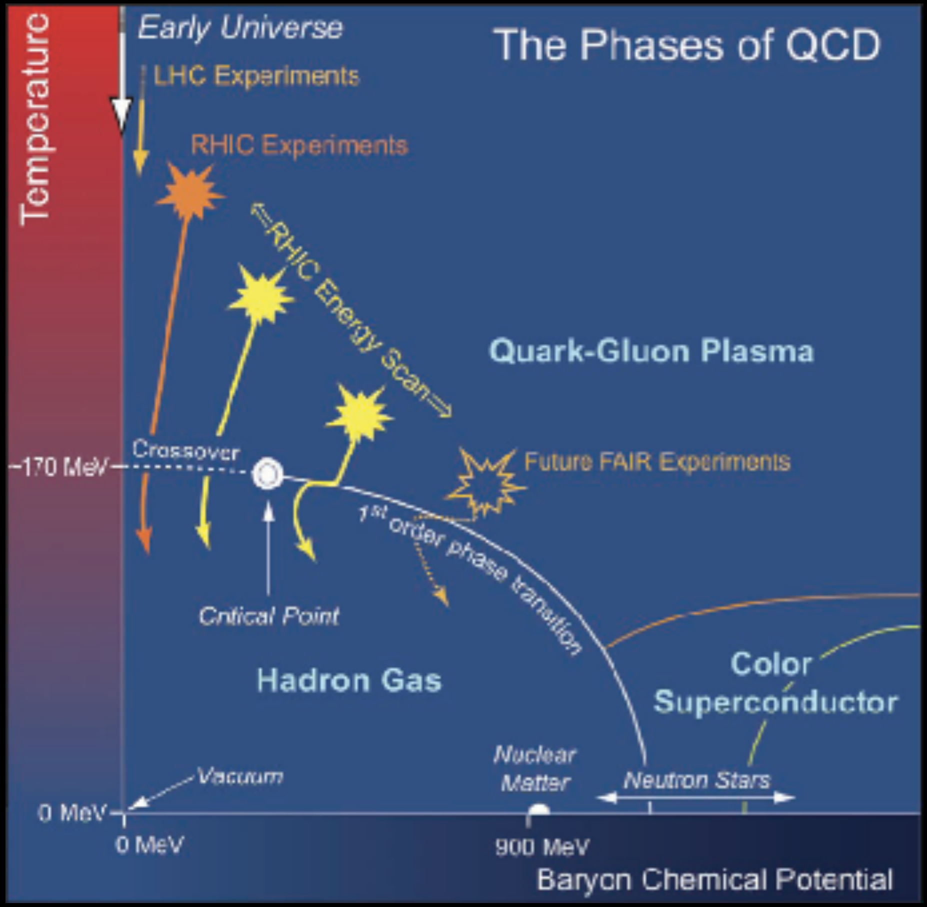
- Colliding Au-ions at
  - $\sqrt{s_{NN}}$ = 130 and 200 GeV (RHIC "high energies") ➞ mapping the crossover region for the first time
  - $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV ➞ searching for the critical point in the phase diagram (BES: Beam Energy Scan)



Little Bangs studied at RHIC and LHC



- Colliding Pb-ions at $\sqrt{s_{NN}}$ = 2.76 TeV ➞ quantifying the QGP properties at μ_B ~ 0



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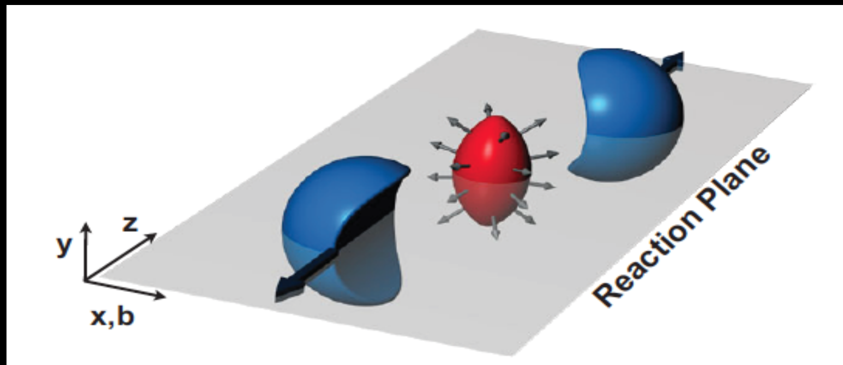
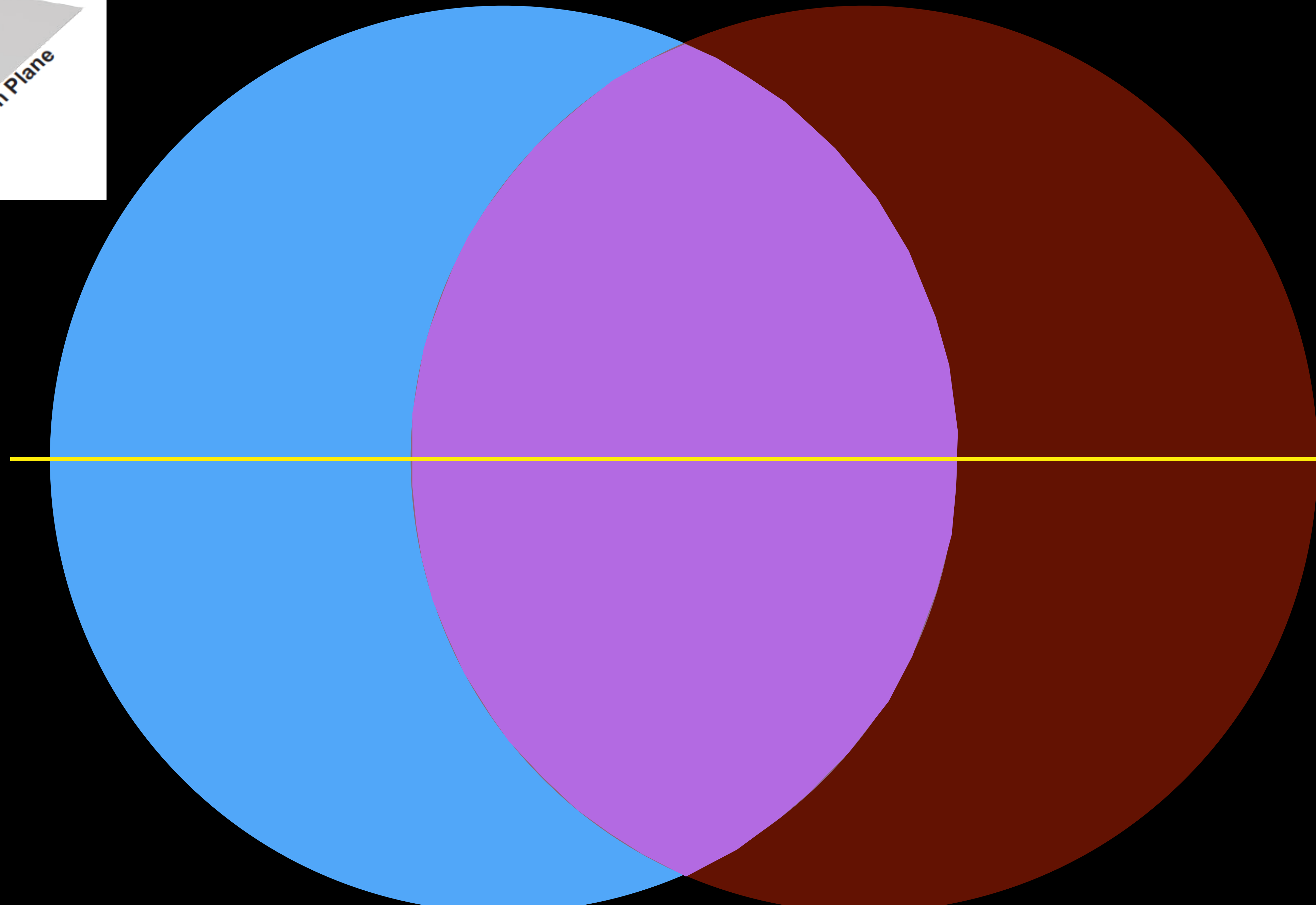
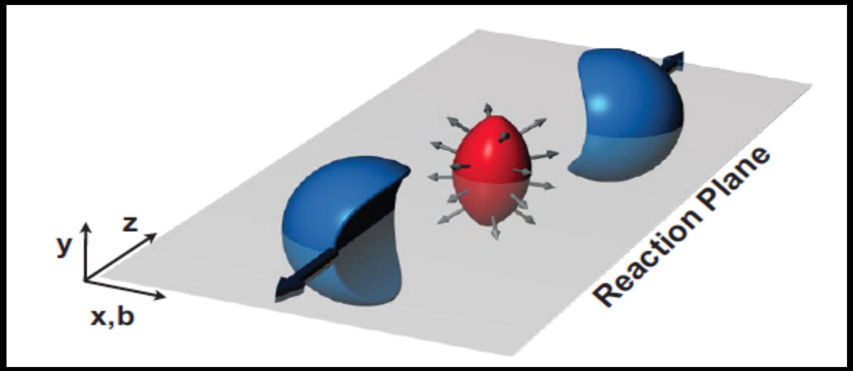
Elliptic flow

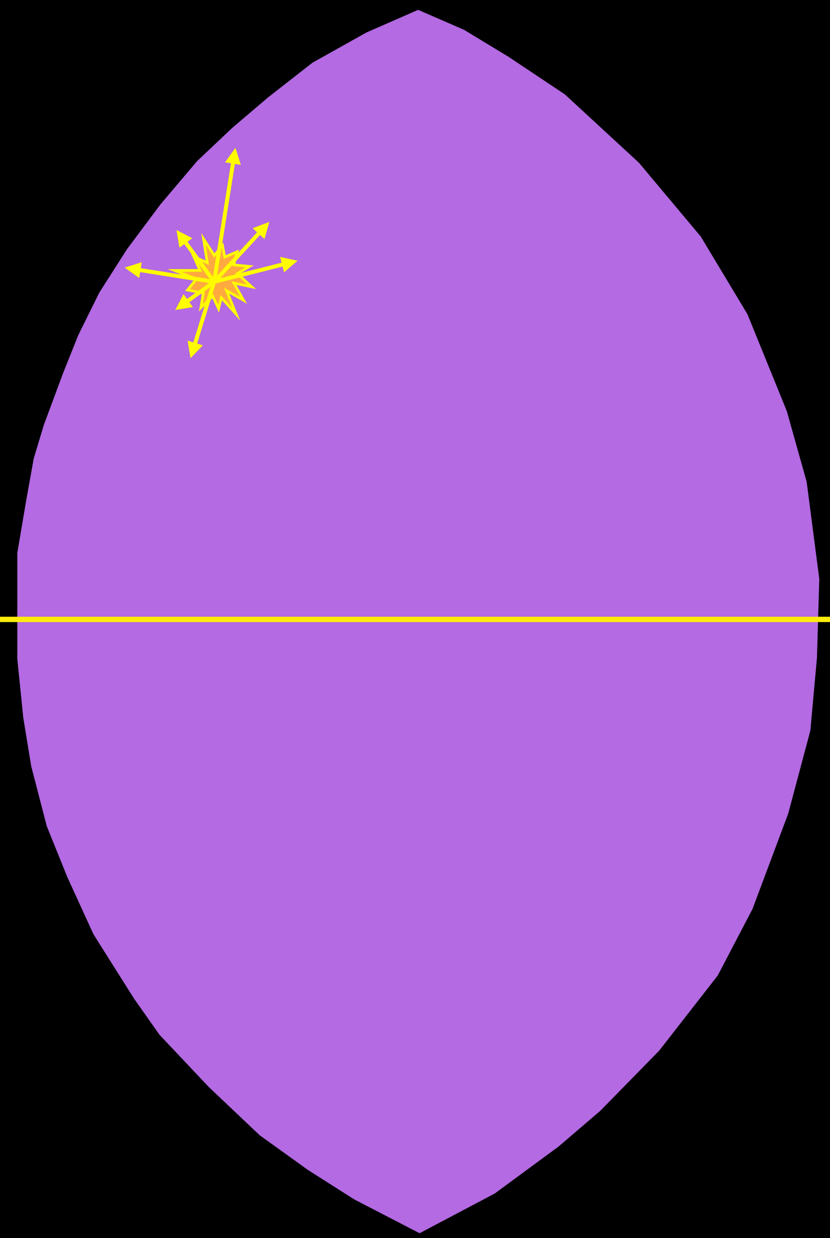




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

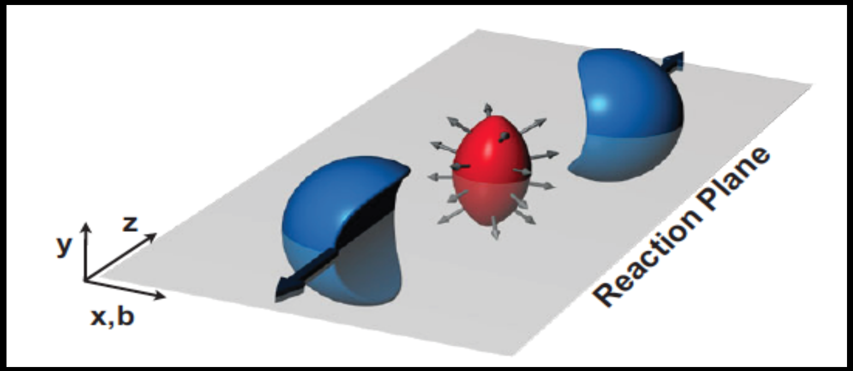
Elliptic flow



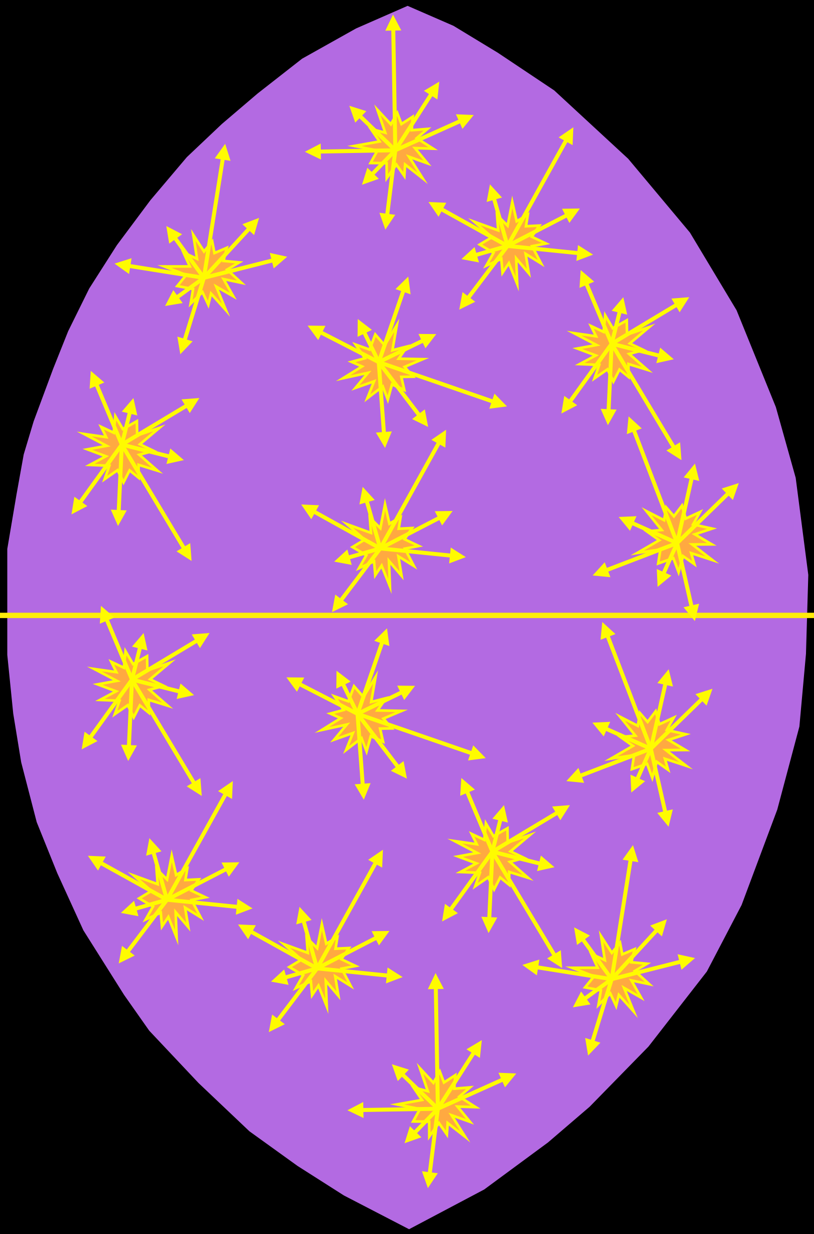


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow

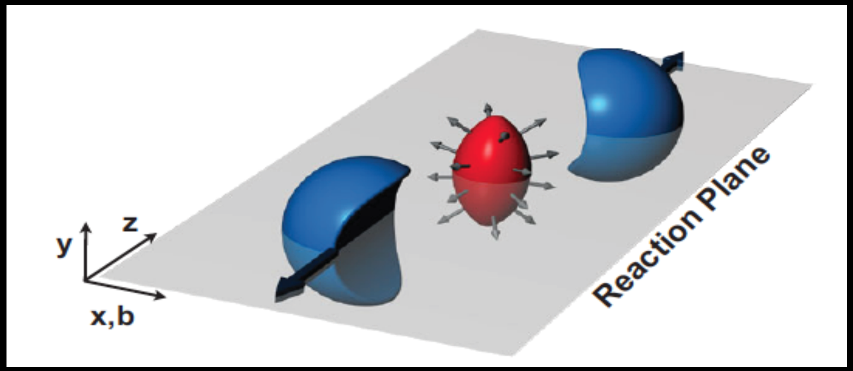


Superposition of independent pp collisions

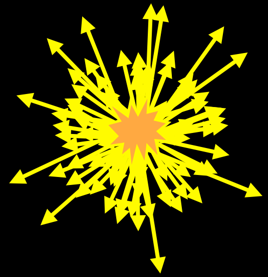


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

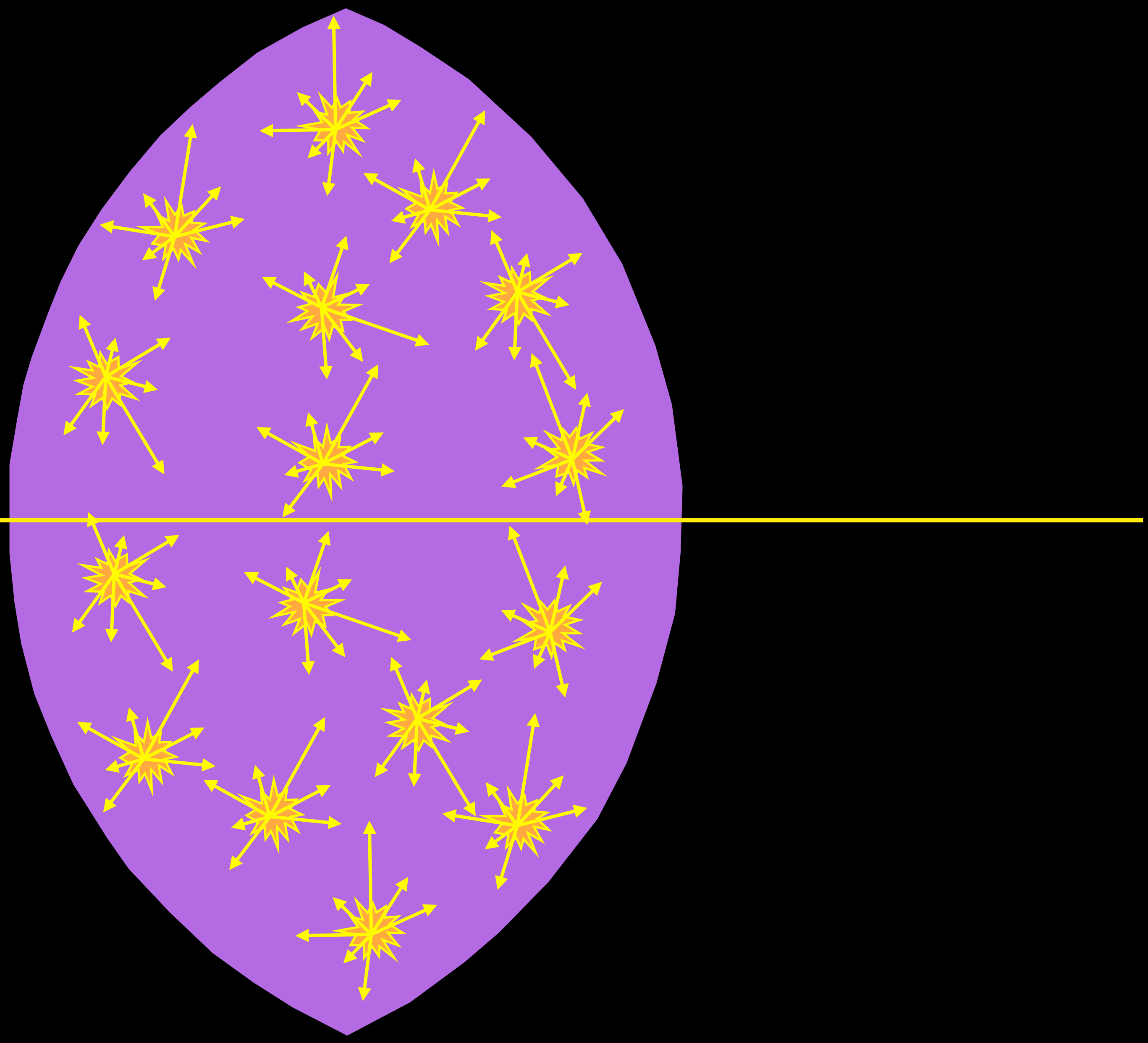
Elliptic flow



Superposition of independent pp collisions

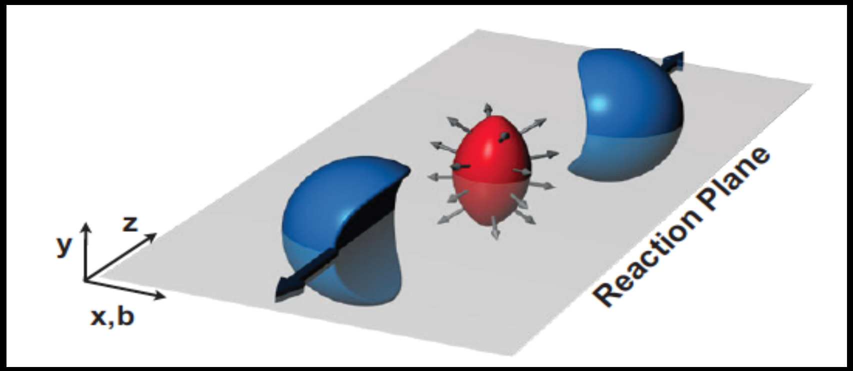


Momenta pointing at random directions

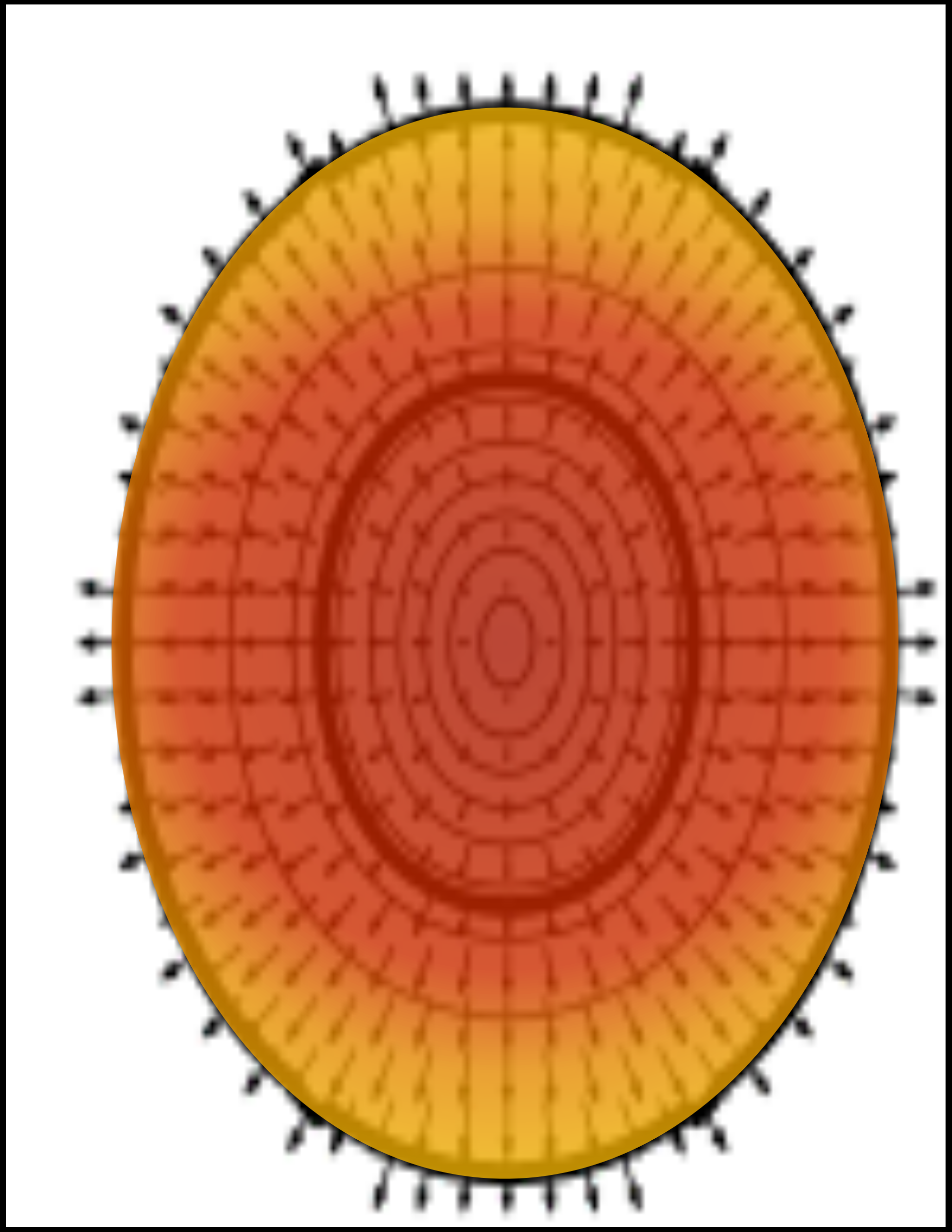


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow



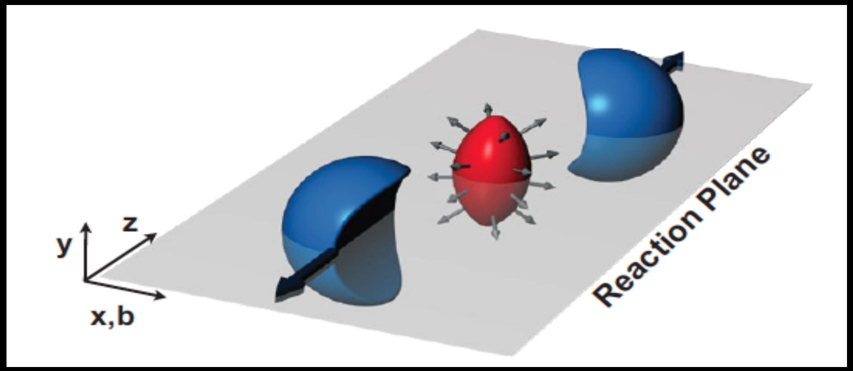
Development as a bulk system



high density and pressure at the center of the fireball

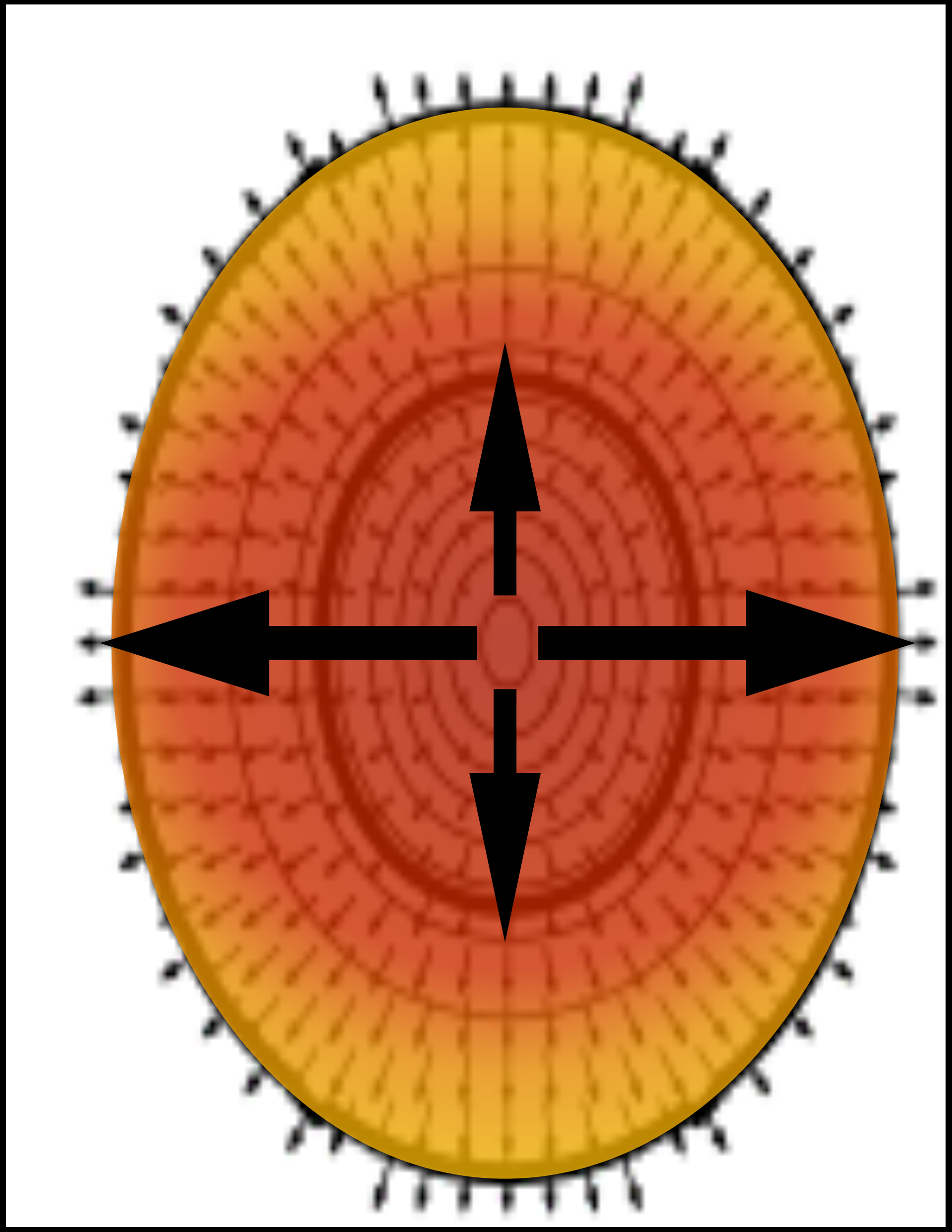
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow



Development as a bulk system

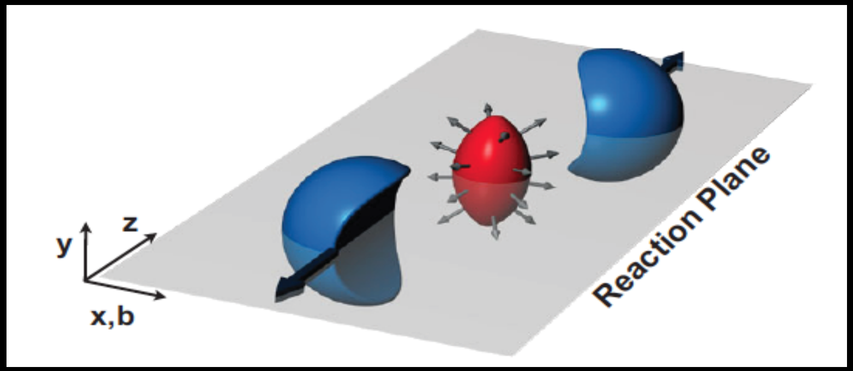
Asymmetric pressure gradients (larger in-plane than out-of-plane) push bulk out → flow

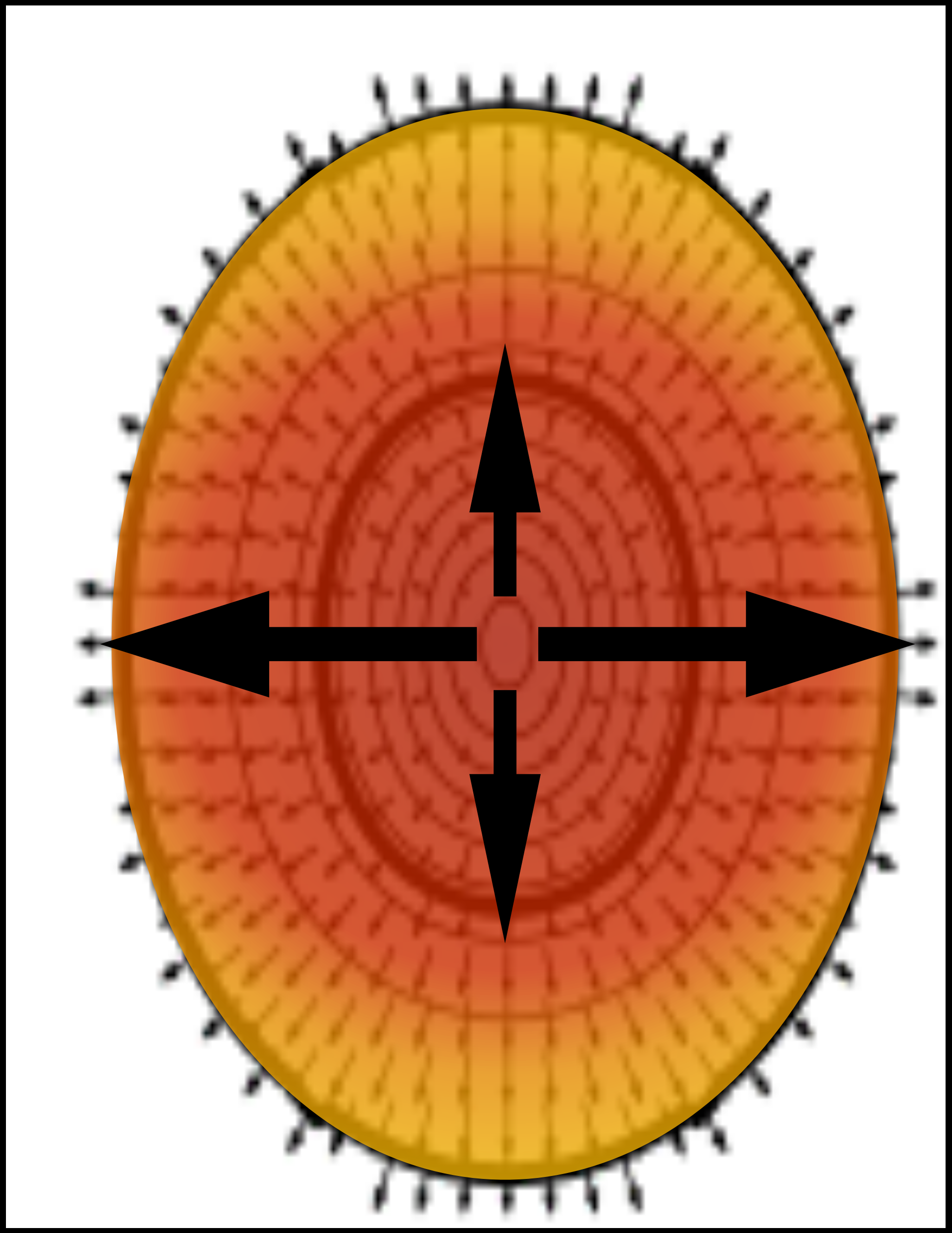


high density and pressure at the center of the fireball

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

Elliptic flow

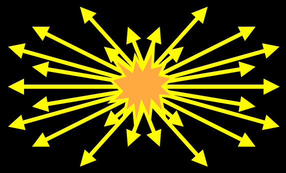




high density and pressure at the center of the fireball

Development as a bulk system

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

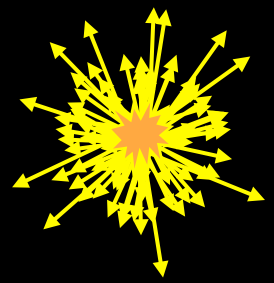


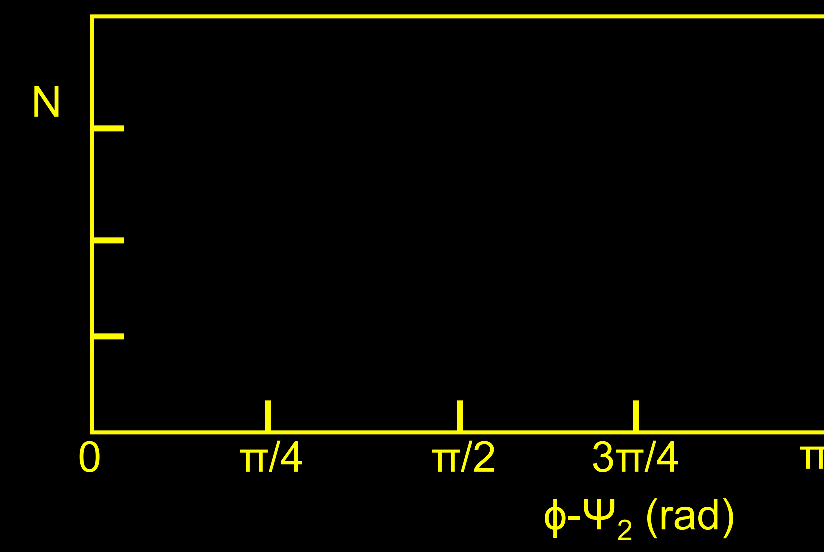
More and faster particles in-plane than out-of-plane

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

Elliptic flow

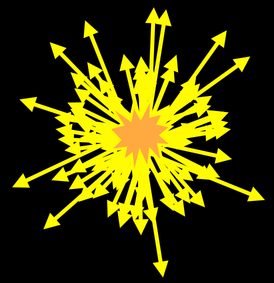
Superposition of independent pp collisions

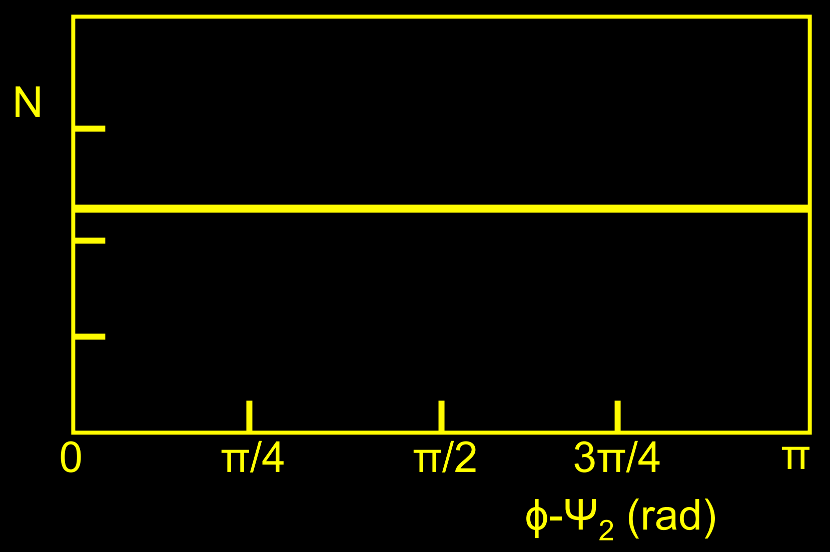




Elliptic flow

Superposition of independent pp collisions

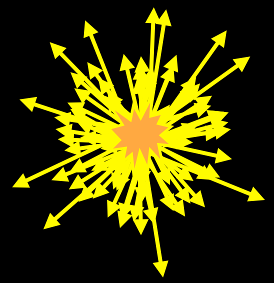


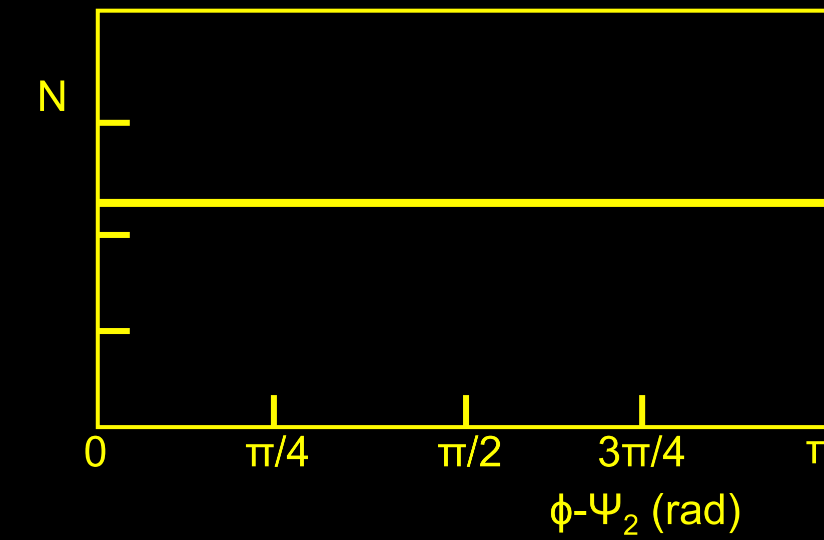


Panos.Christakoglou@nikhef.nl

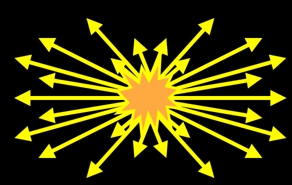
Elliptic flow

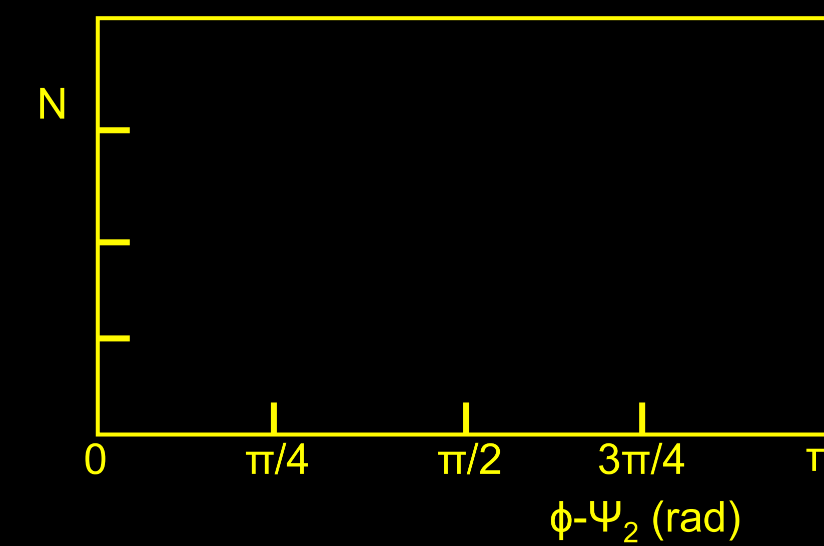
Superposition of independent pp collisions





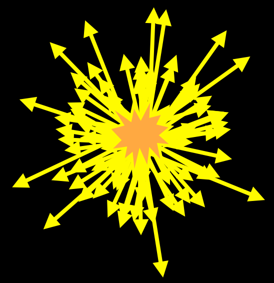
Development as a bulk system

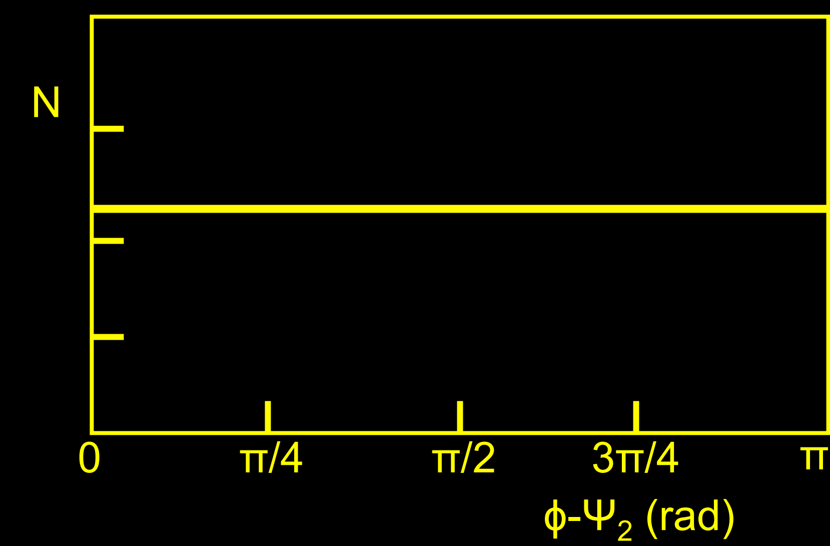




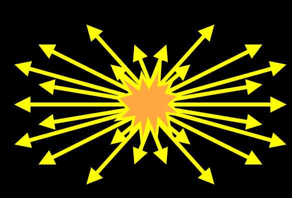
Elliptic flow

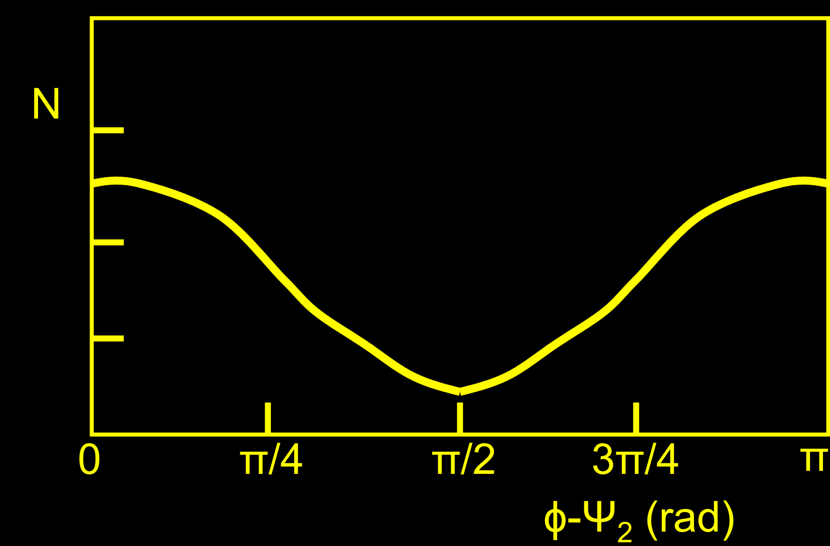
Superposition of independent pp collisions





Development as a bulk system

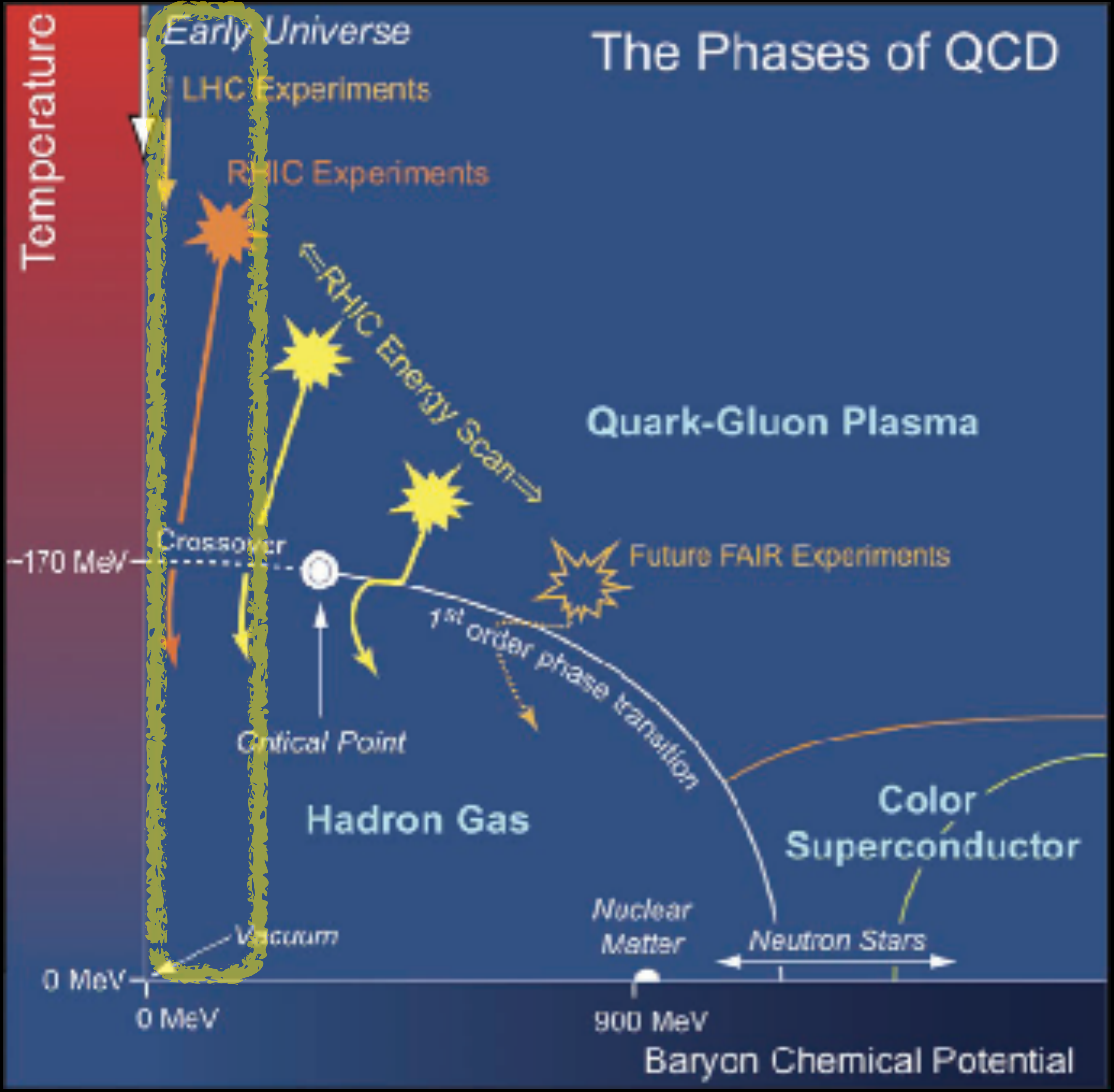




$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

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

Probing the properties of the QGP



Studying the properties of the QGP

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