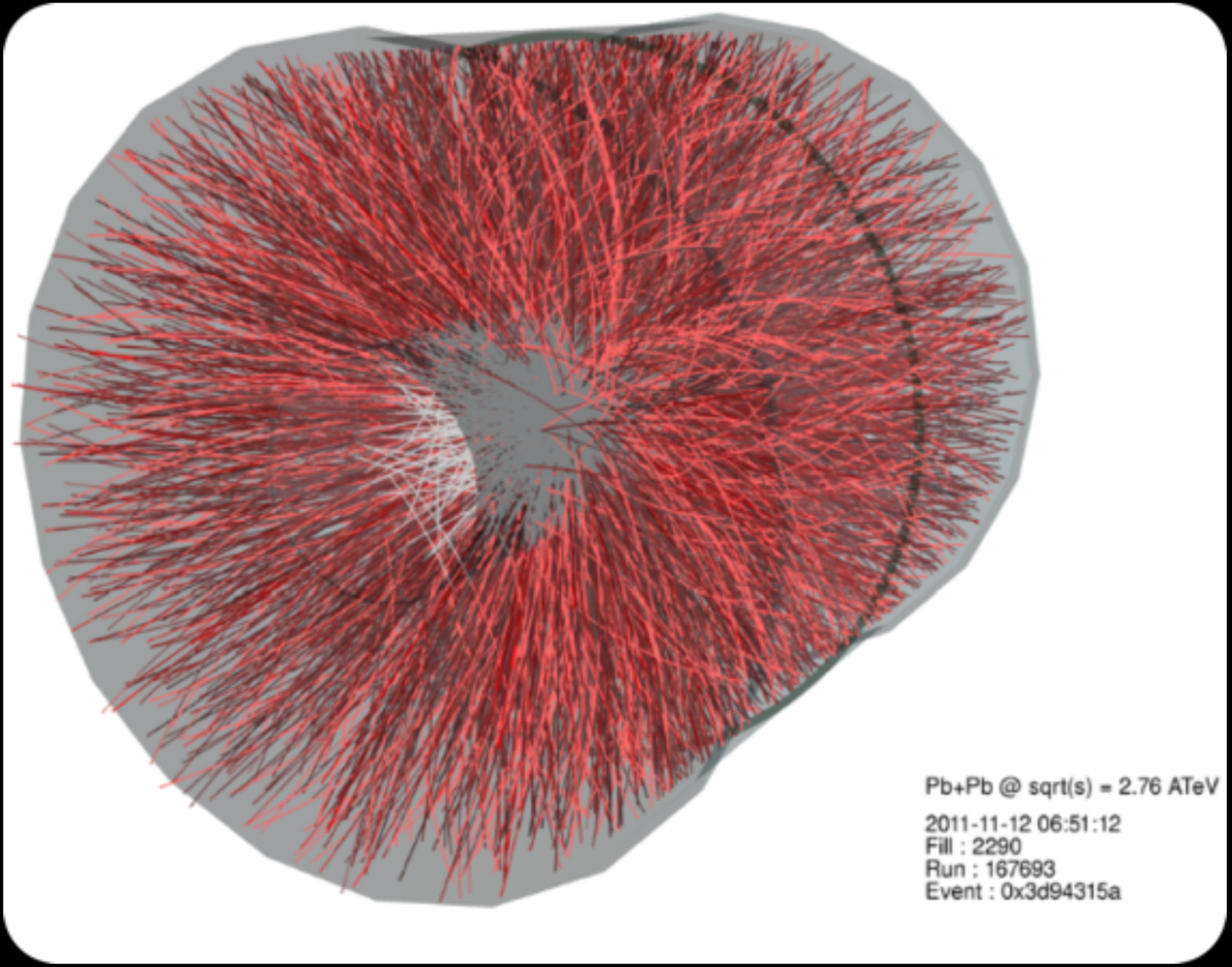
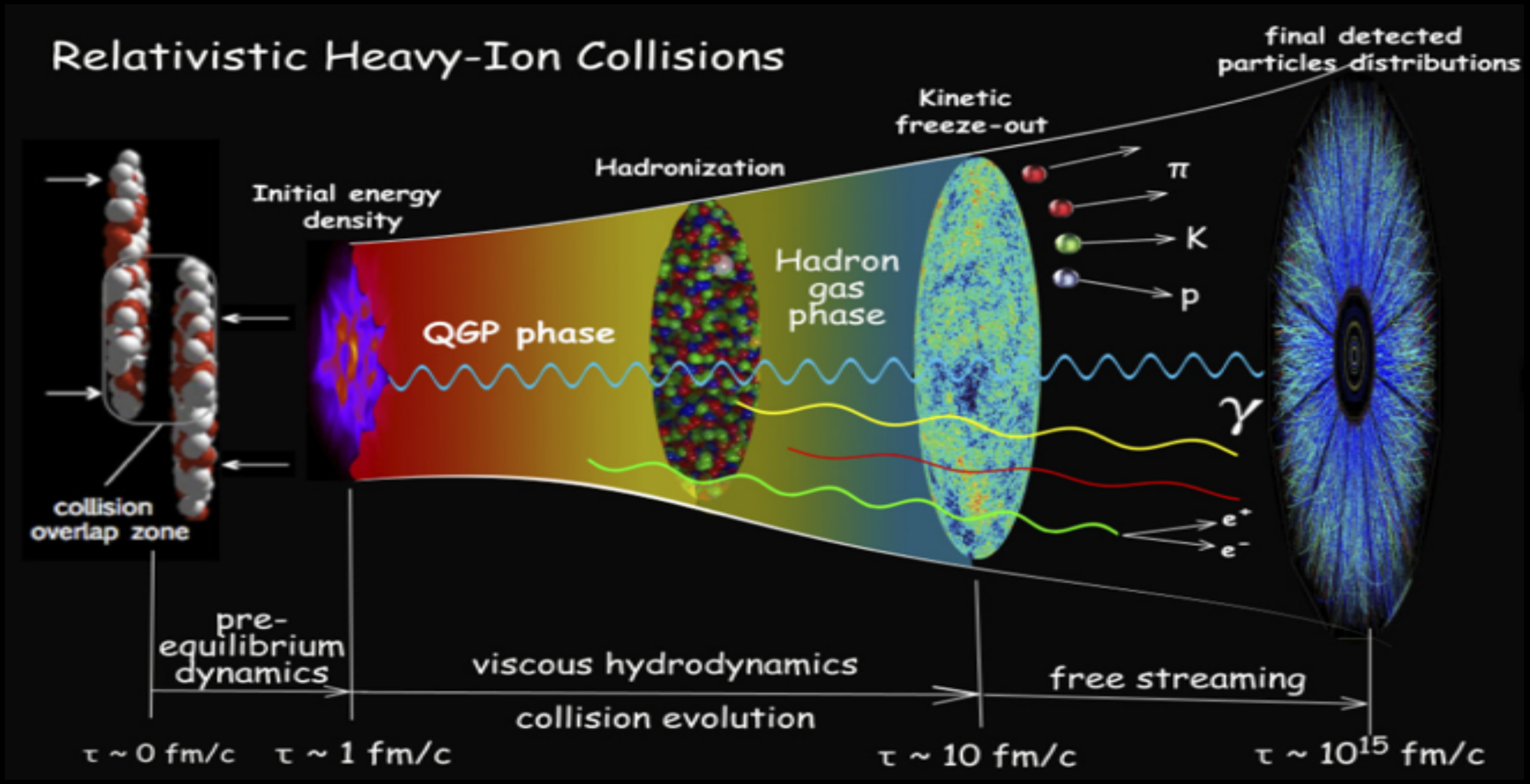
Azimuthal correlation studies from ALICE



Panos Christakoglou (Nikhef)

From the Big-Bang to the Little-Bangs…



- The Quark-Gluon Plasma (QGP):
  - a state of matter where the quarks and gluons are the relevant degrees of freedom
  - existed few μs after the Big-Bang (the universe crossed this phase after expanding and cooling down): Studying the strong phase transition ➞ study primordial matter
- QCD: Phase transition beyond a critical temperature (~170 MeV) and energy density (~0.5 GeV/fm^3) ➞ accessible in the laboratory ➞ heavy-ion collisions

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

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

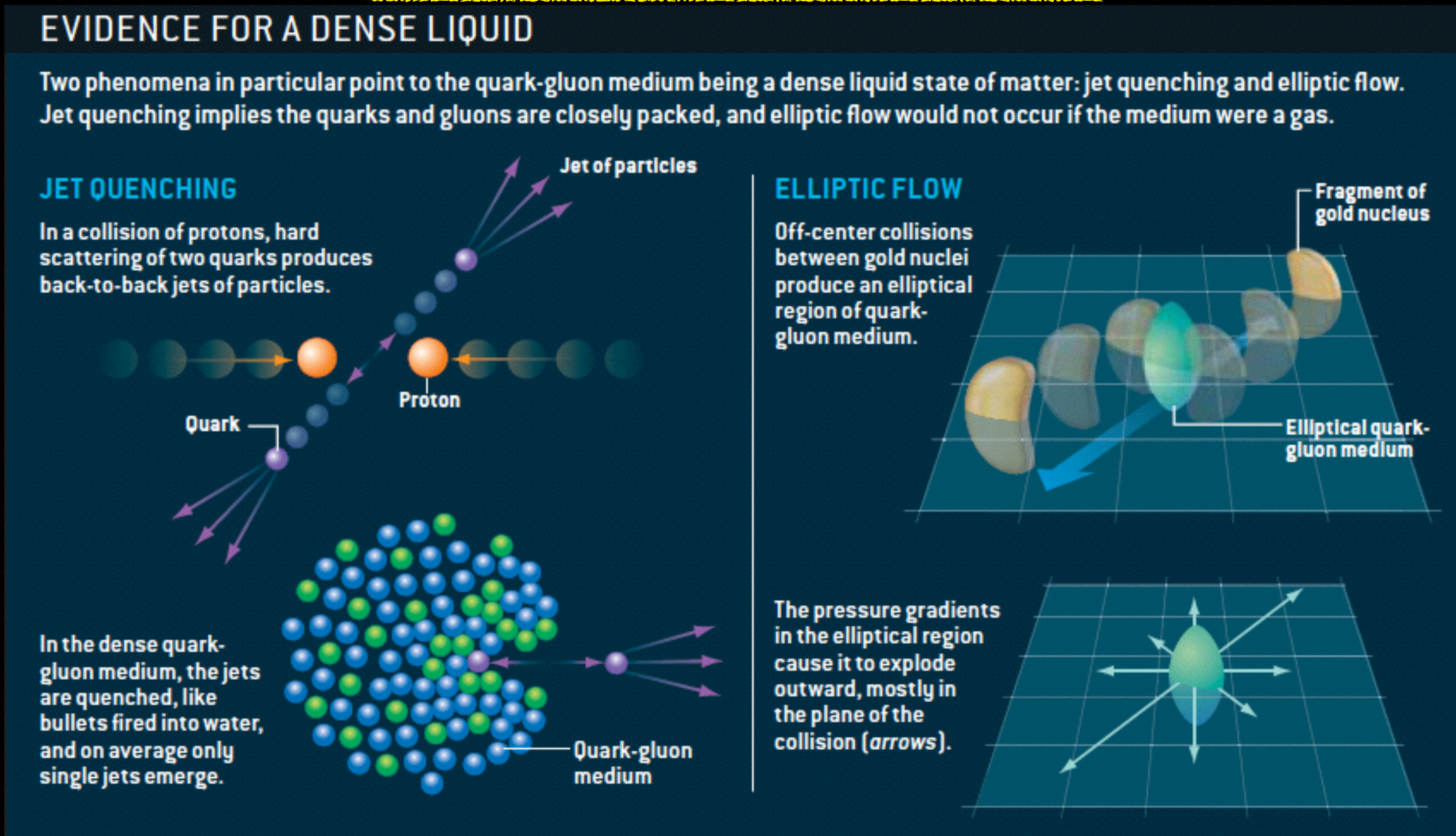
$T_{(QGP\text{-}transition)}$ 10^5x$T_{(Sun's\ core)}$

Can we constrain the equation of state and the transport properties of QGP?

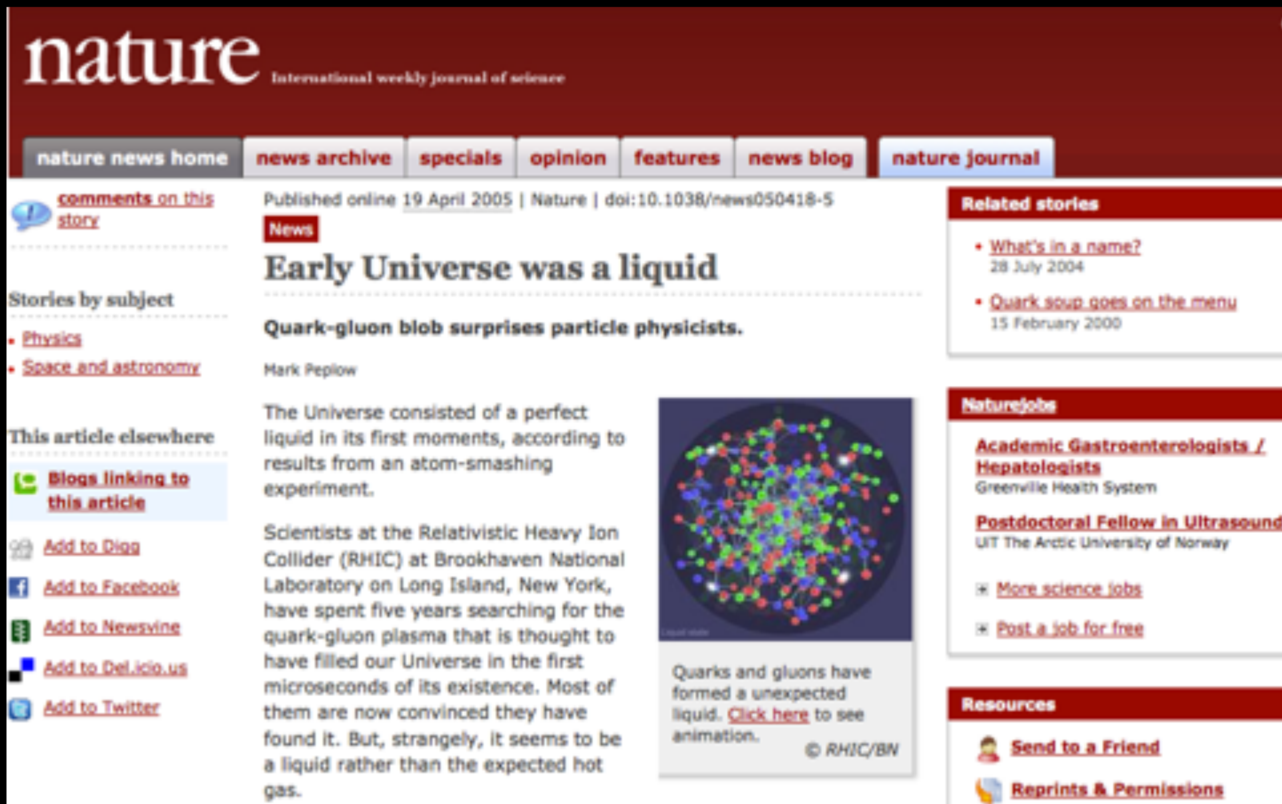
Panos.Christakoglou@nikhef.nl

Studying the properties of the QGP

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



The "perfect liquid" at RHIC and LHC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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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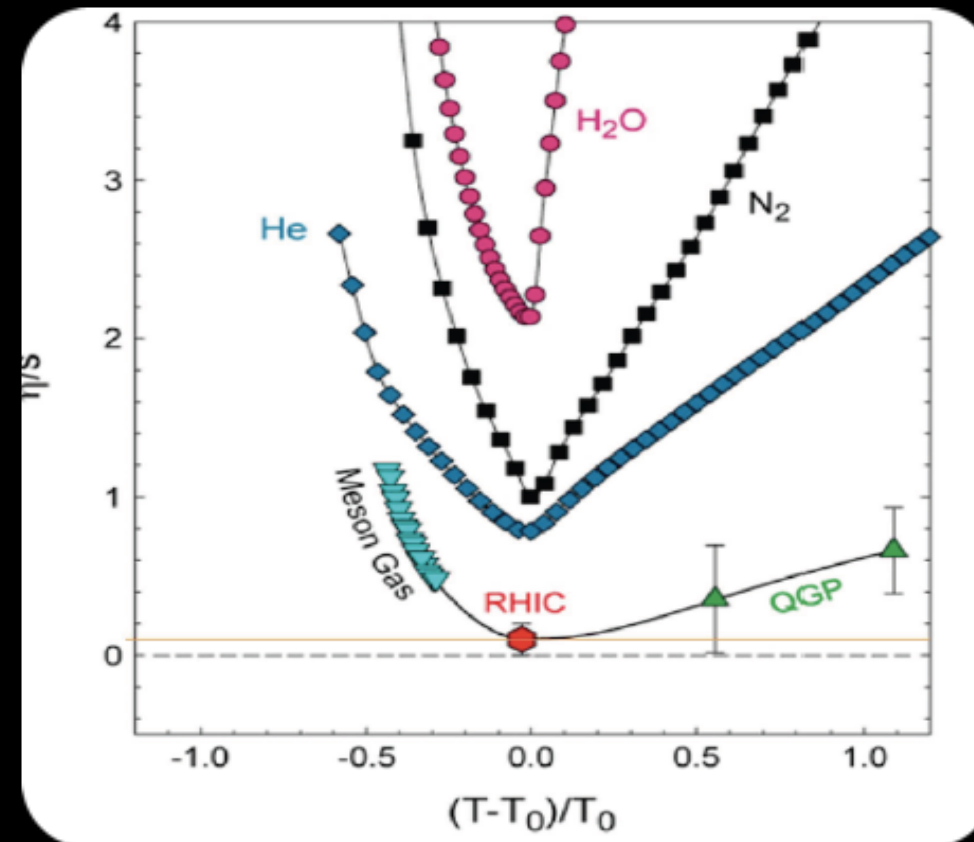


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Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

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.

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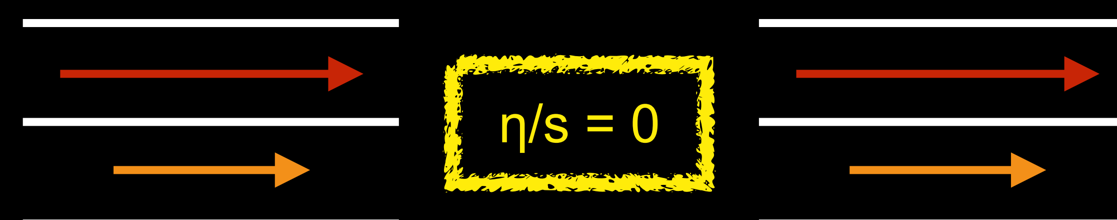

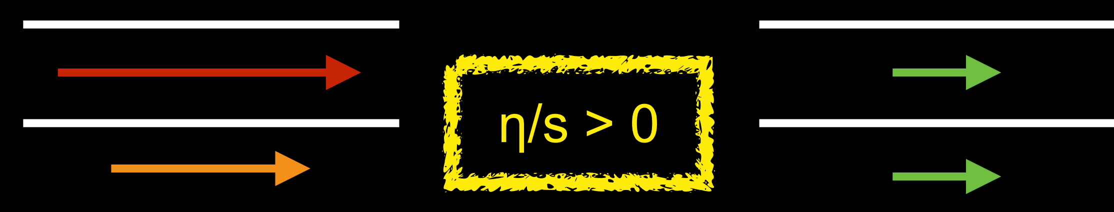

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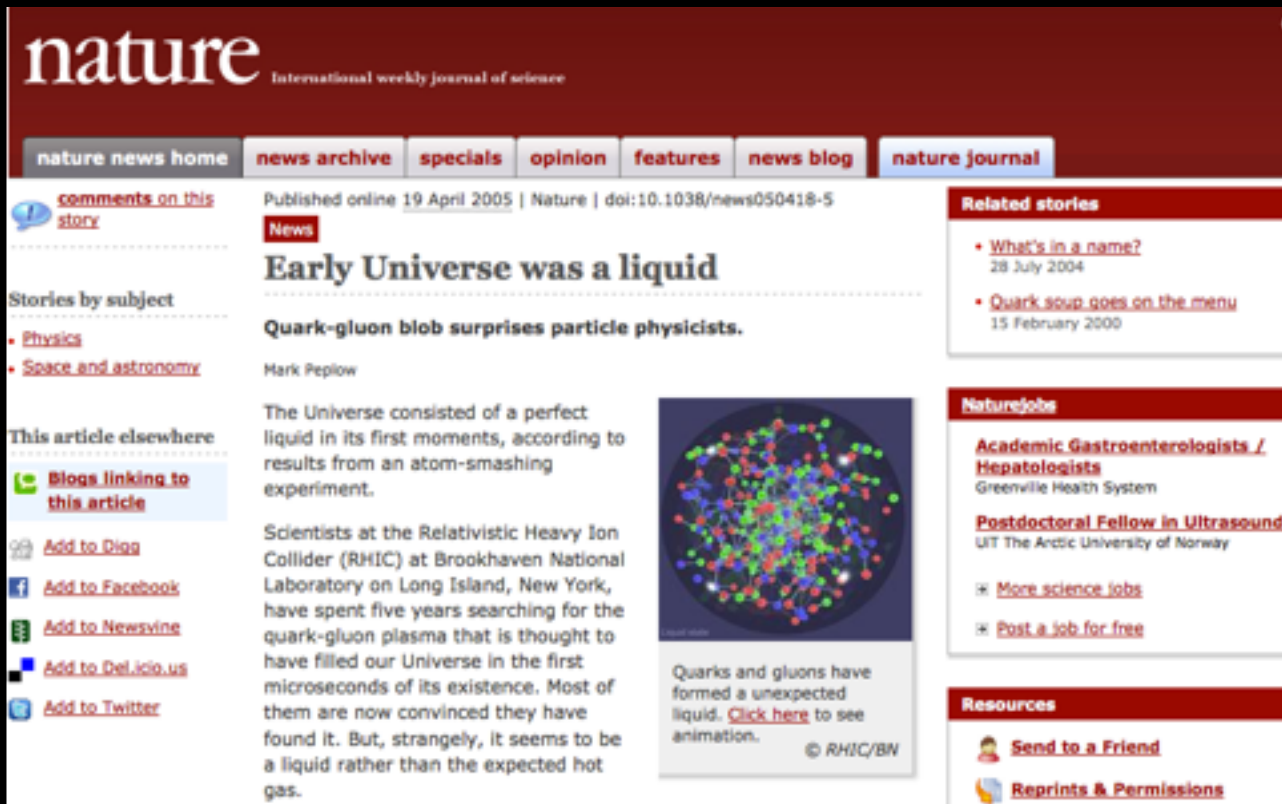

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Quarks and gluons have formed a unexpected liquid. Click here to see animation. © RHIC/BN

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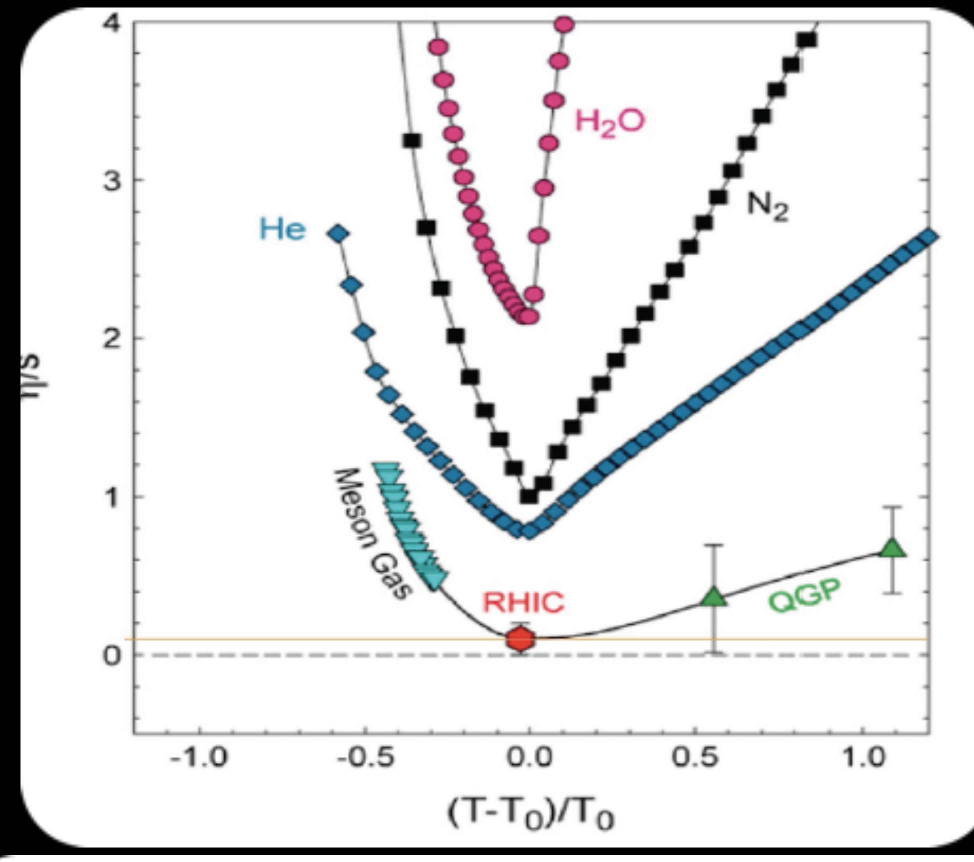

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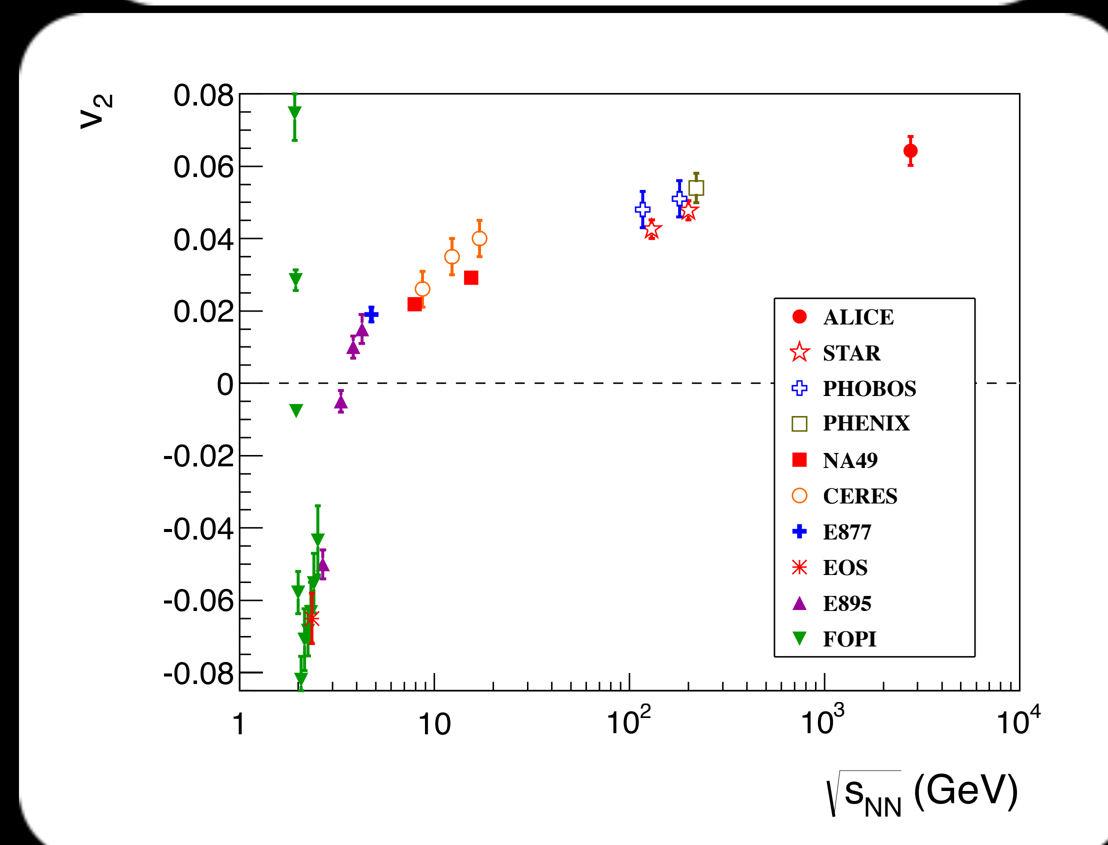
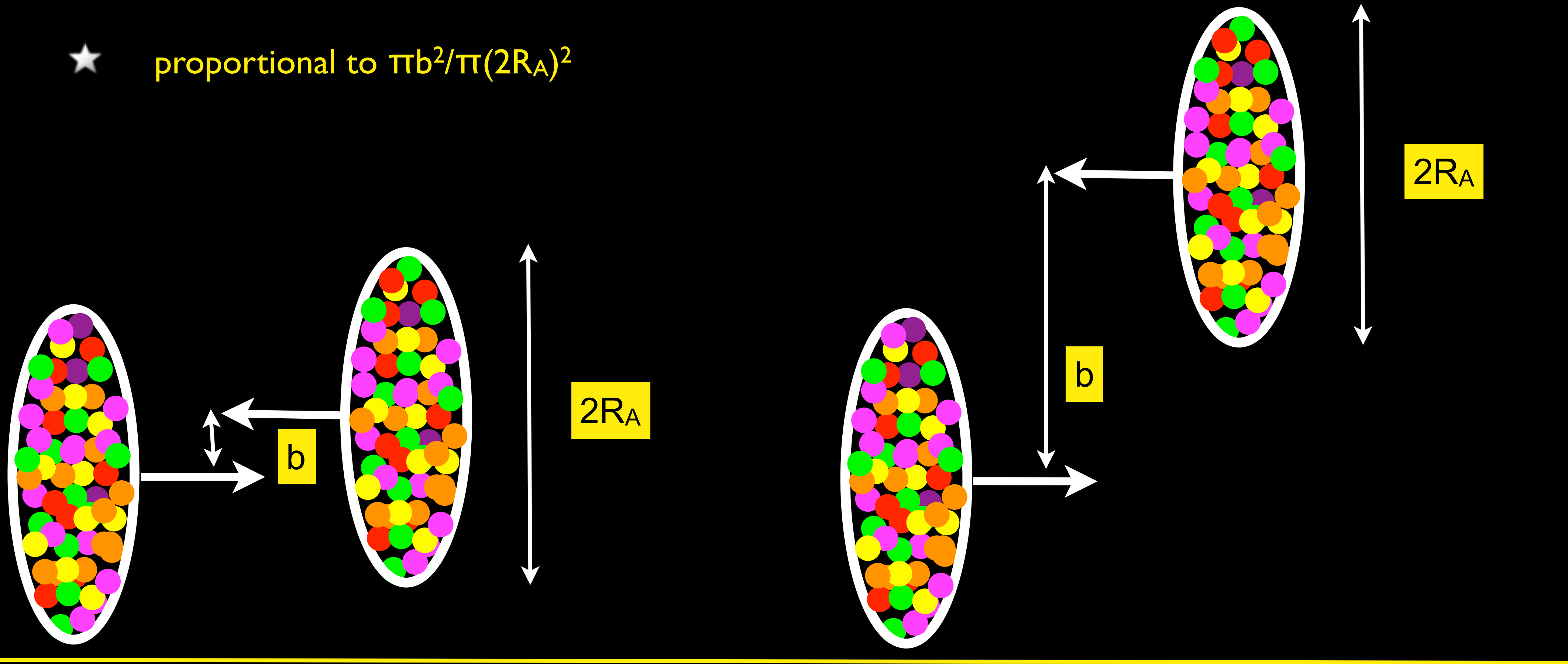
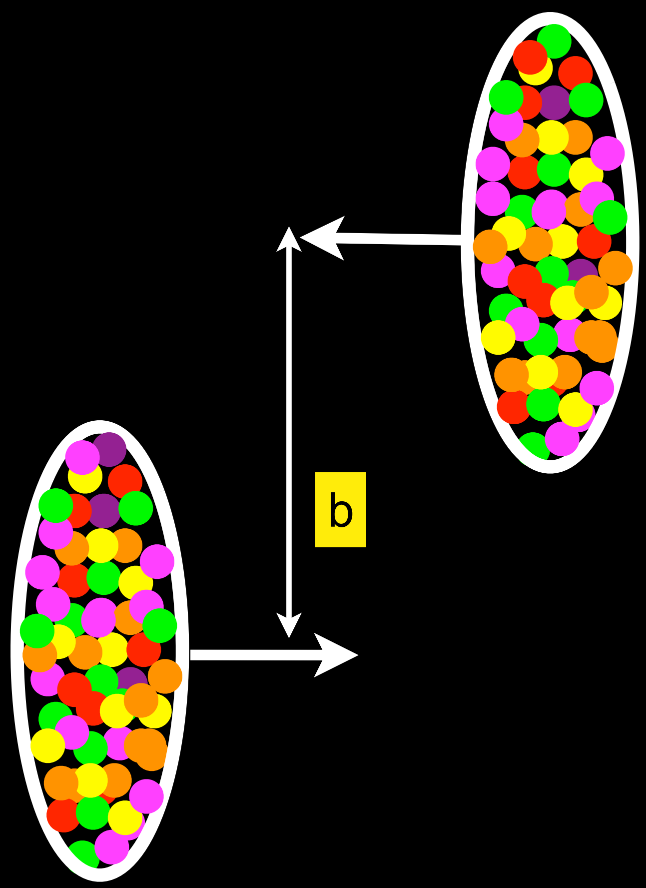


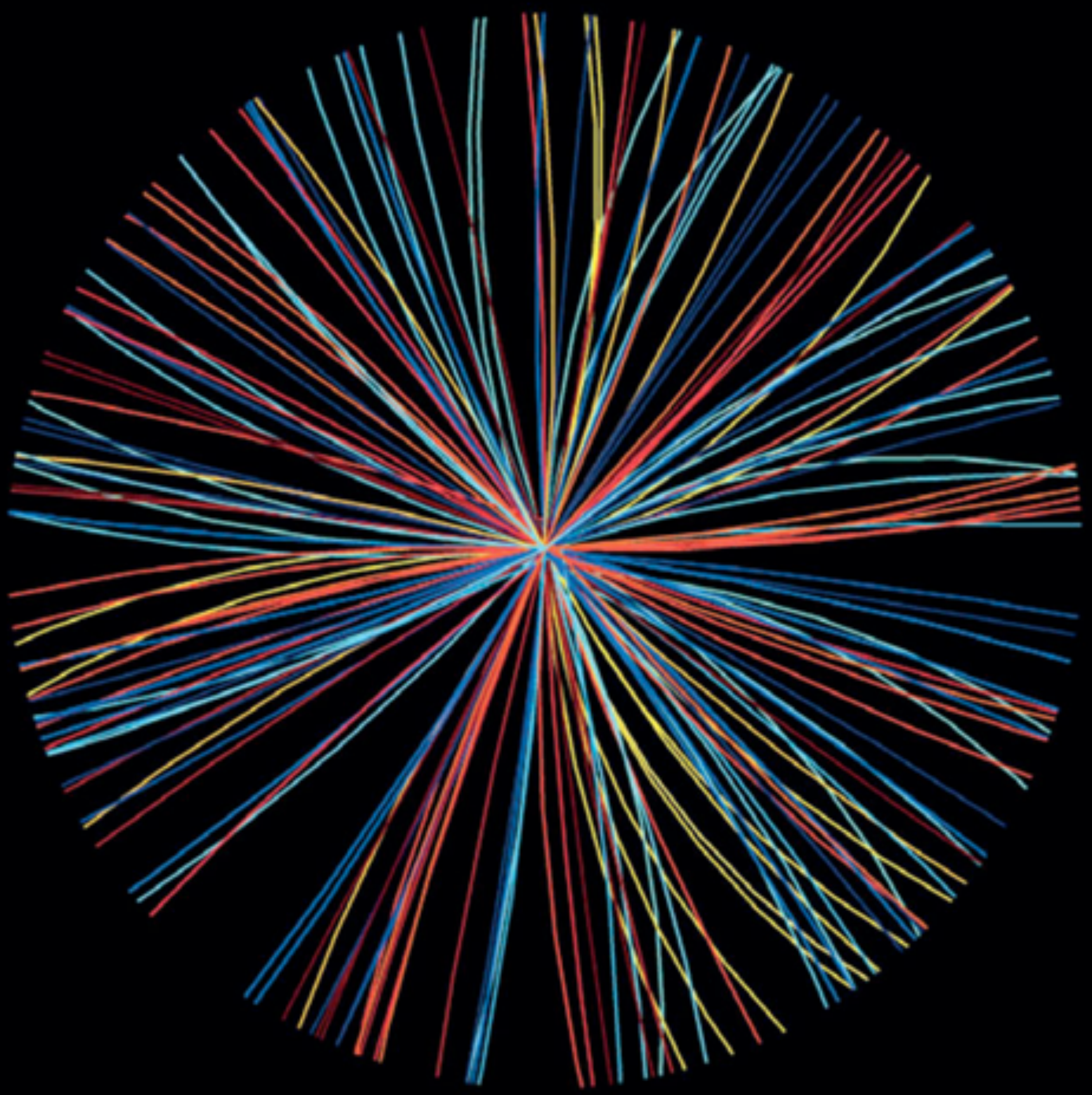
Defining centrality: impact parameter

- Heavy ions are not point-like objects
- Collisions can create systems with different properties depending on whether they are head-on (i.e. large overlap region) or if the nuclei graze each other (i.e. small overlap region)
- Centrality defined geometrically by the impact parameter b
  - Distance between the centers of the two nuclei
  - Perpendicular to the beam axis
- Centrality related to the fraction of the geometrical cross-section that overlaps
  - proportional to $\pi b^2/\pi(2R_A)^2$

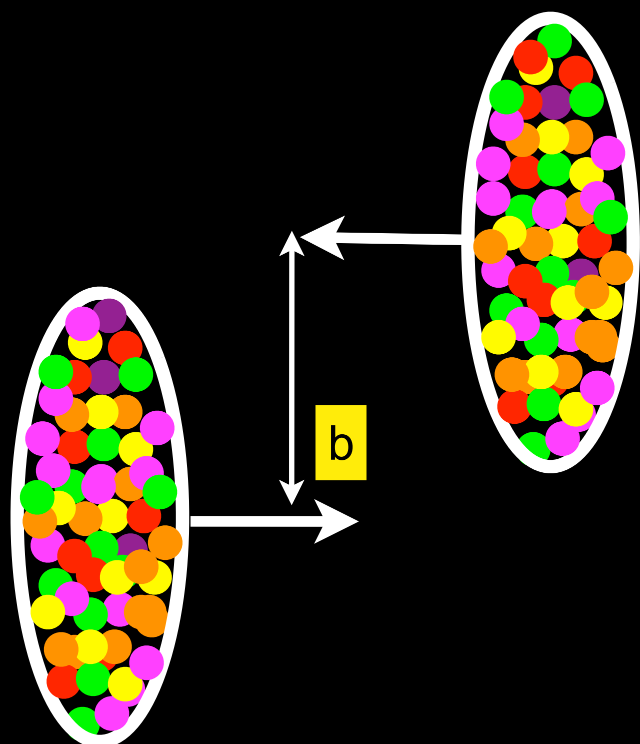


Peripheral collisions: few particles

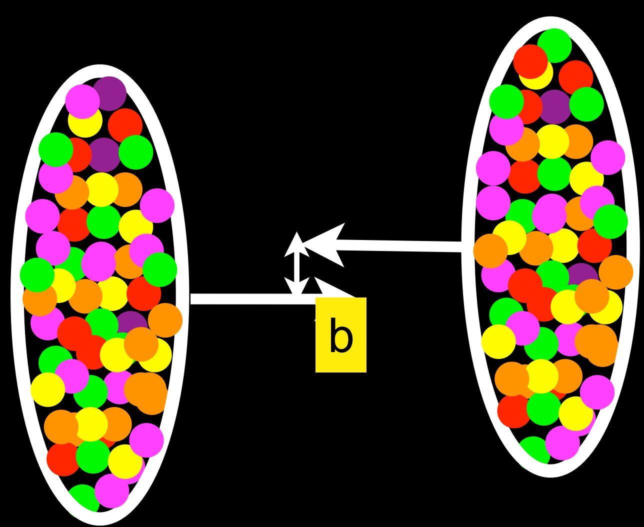


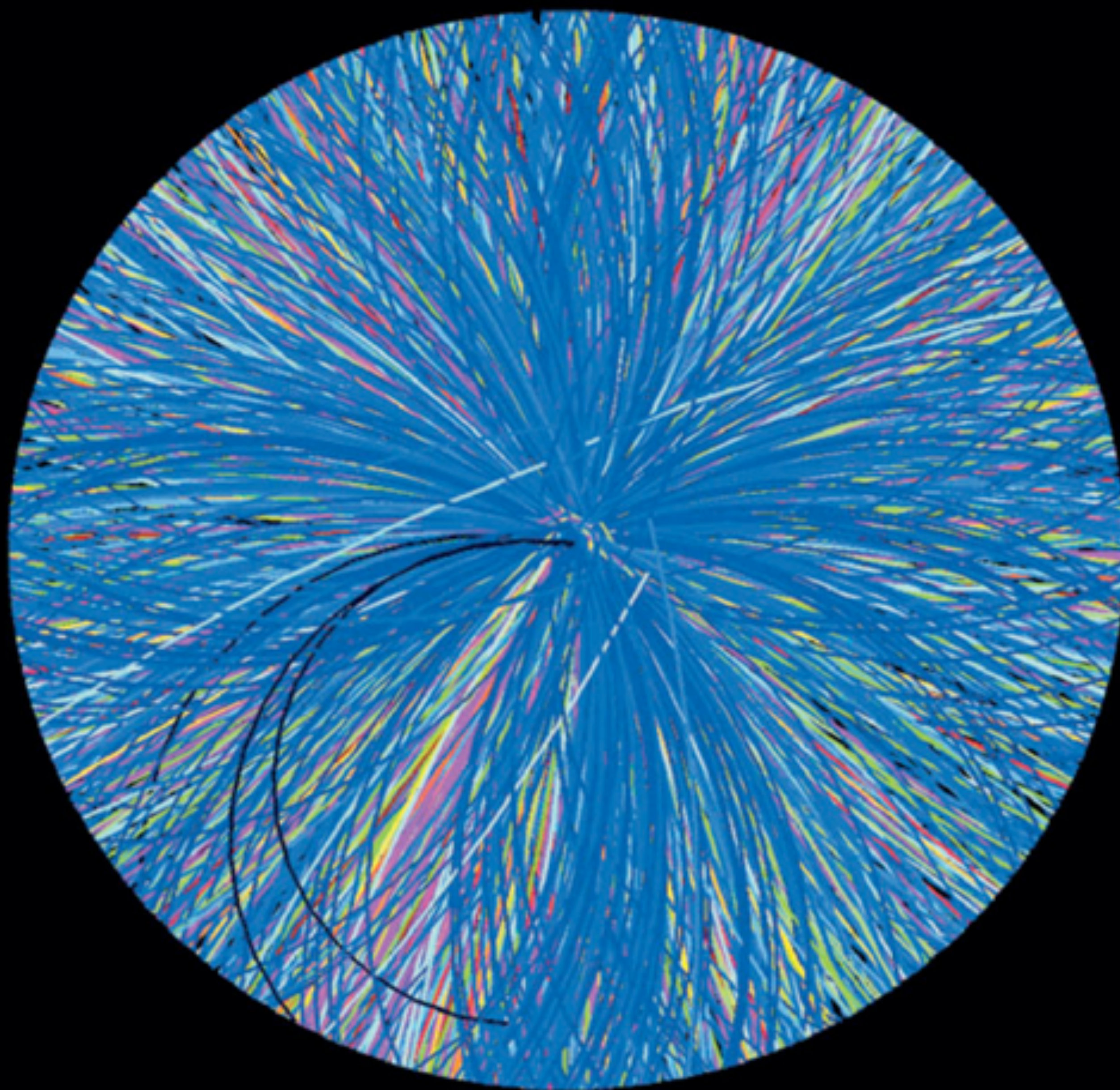


Mid-central collisions: more particles

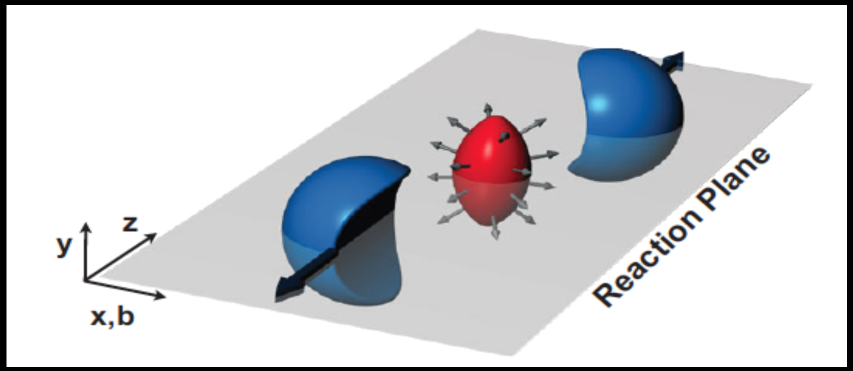


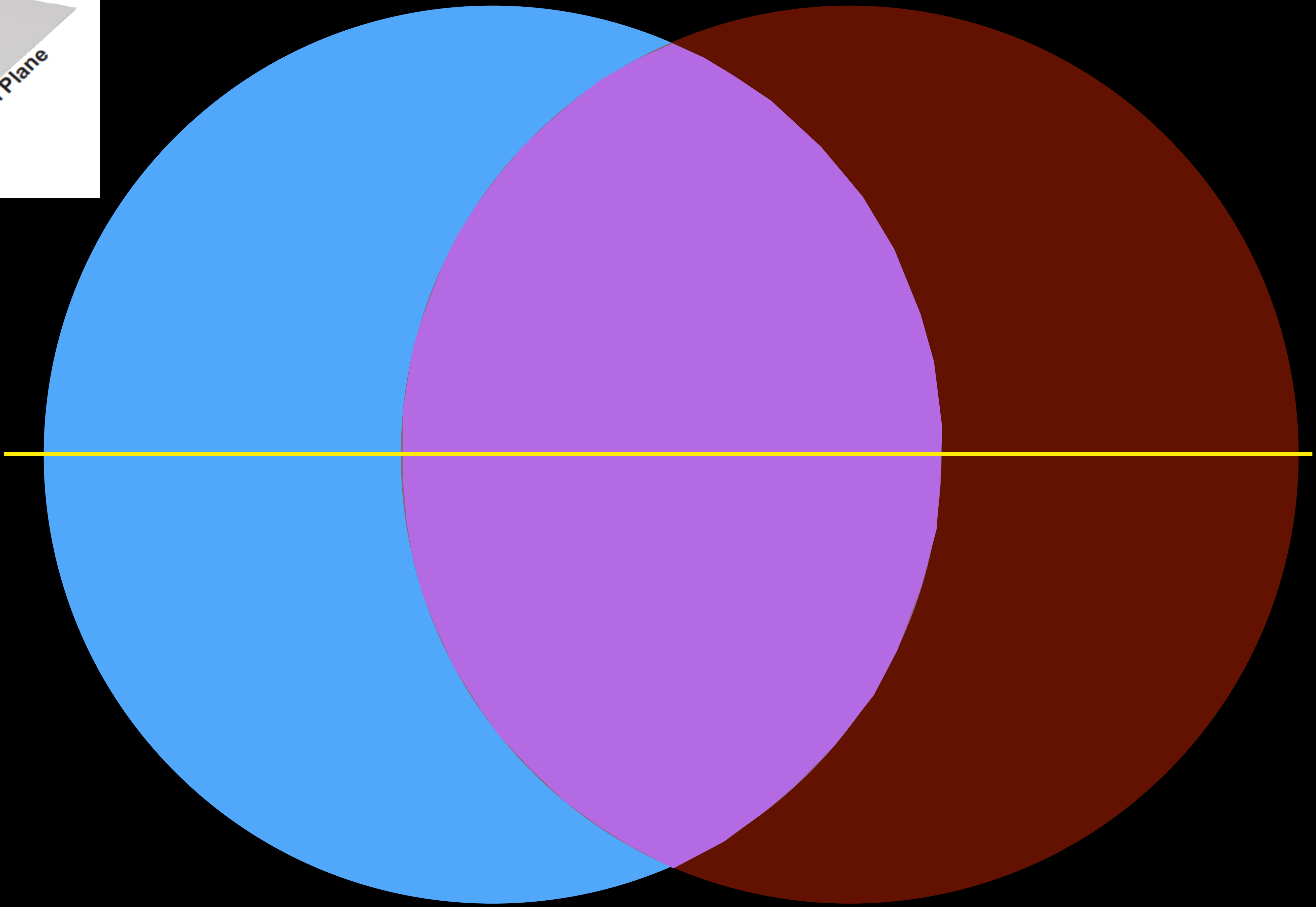
Central collisions: even more particles





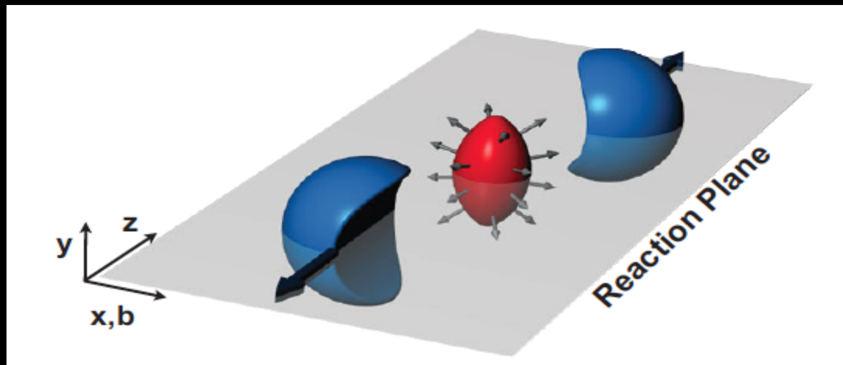
Elliptic flow

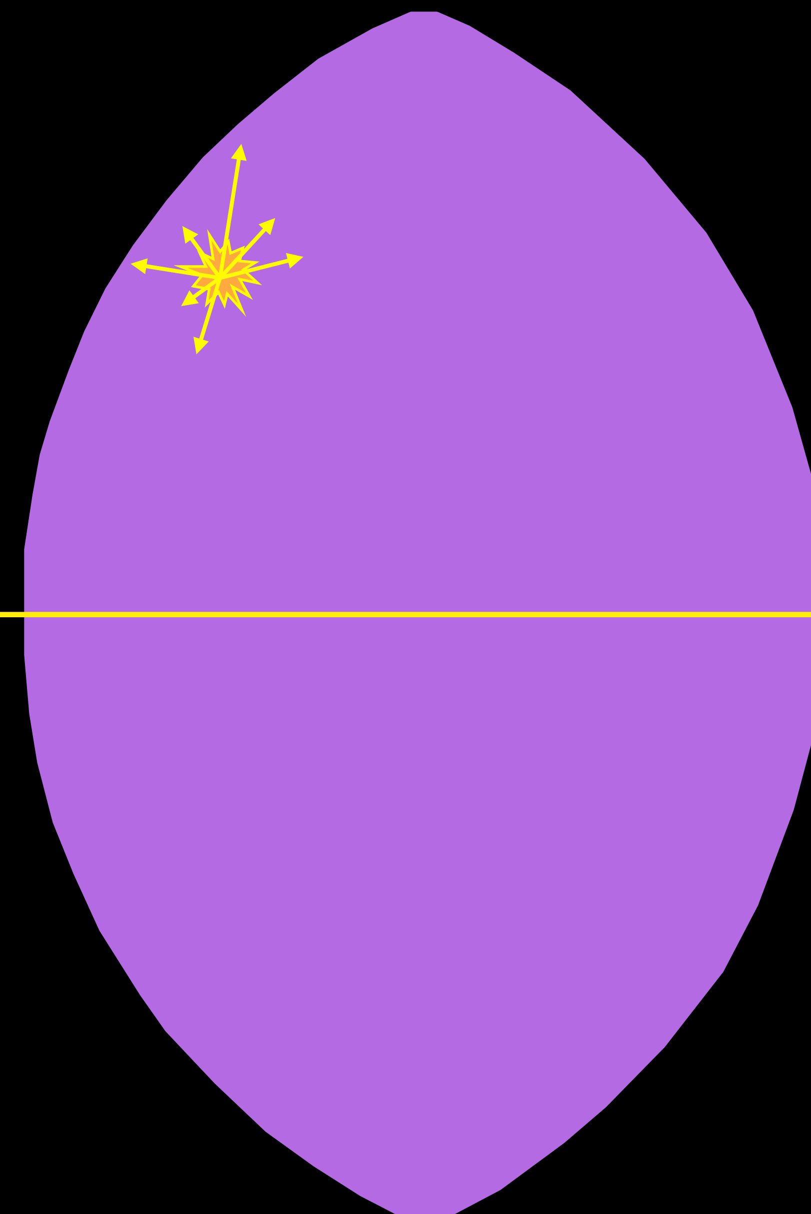




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow





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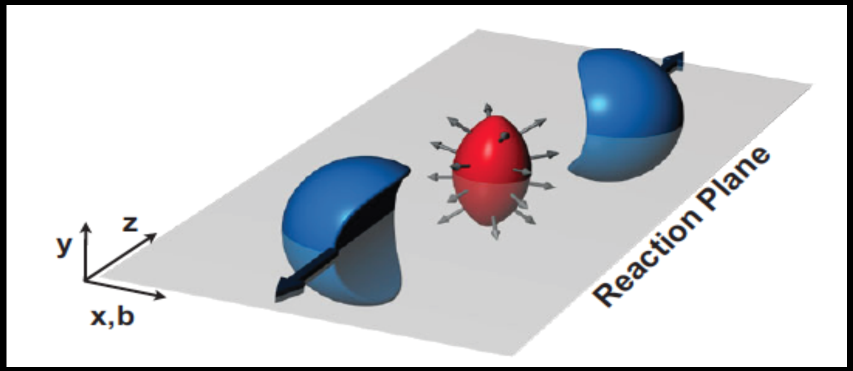
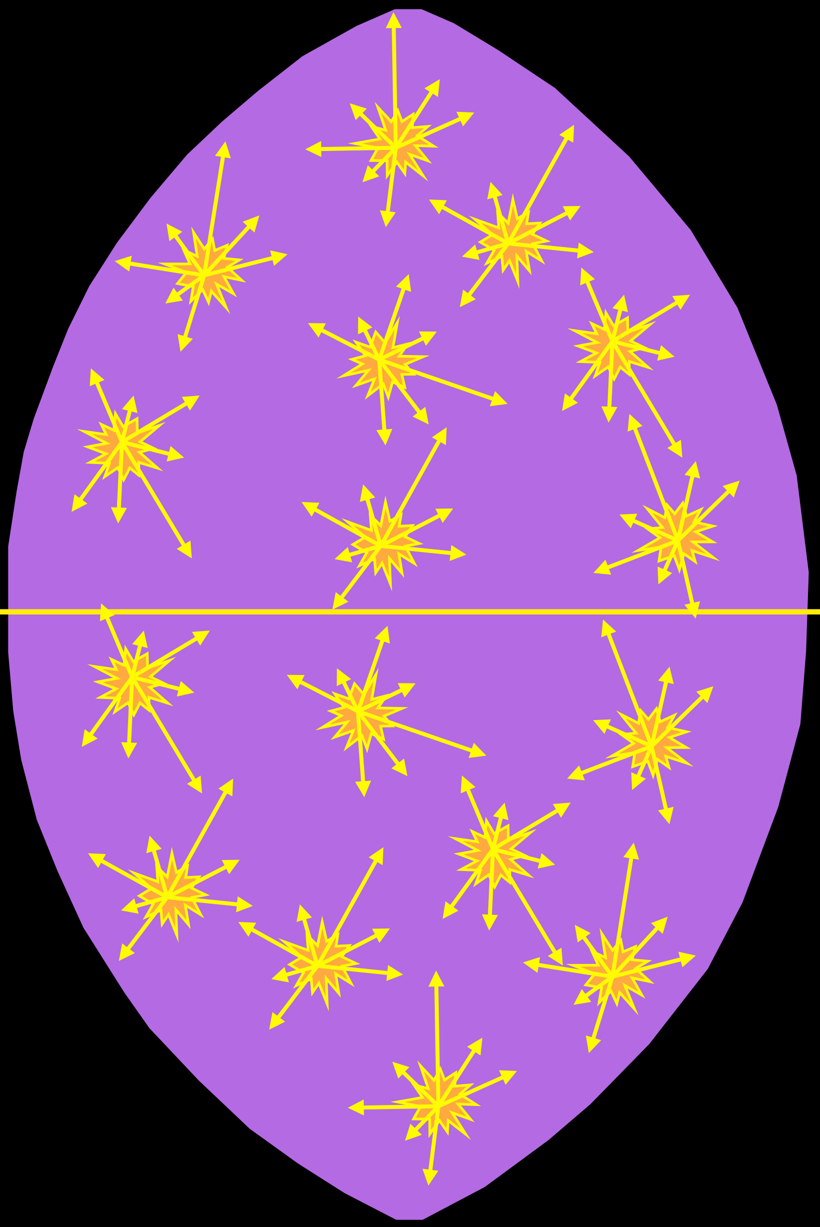


Superposition of independent pp collisions



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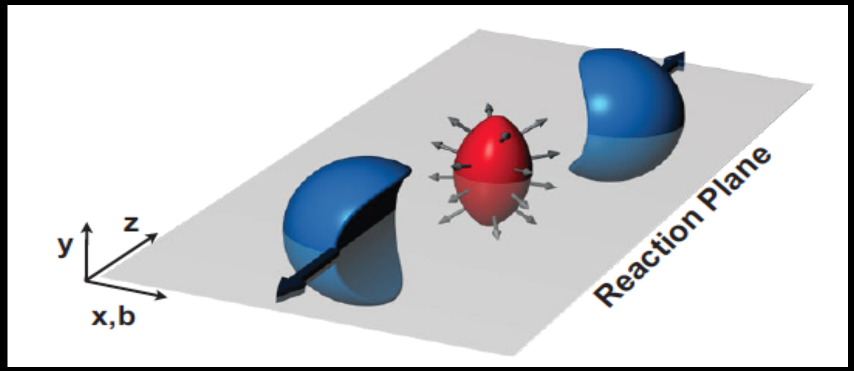

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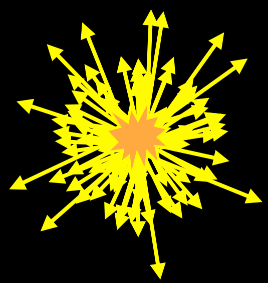
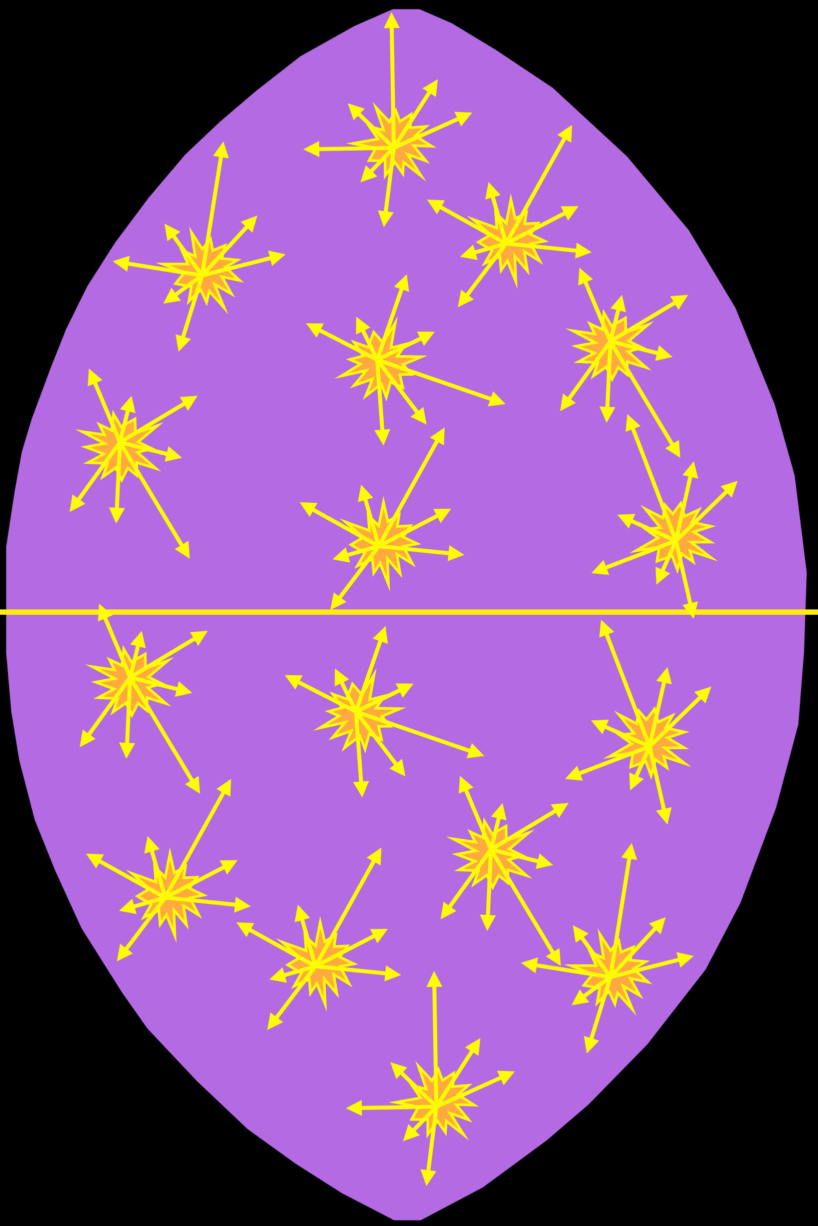


Momenta pointing at random directions



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Elliptic flow

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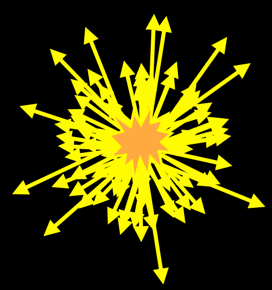

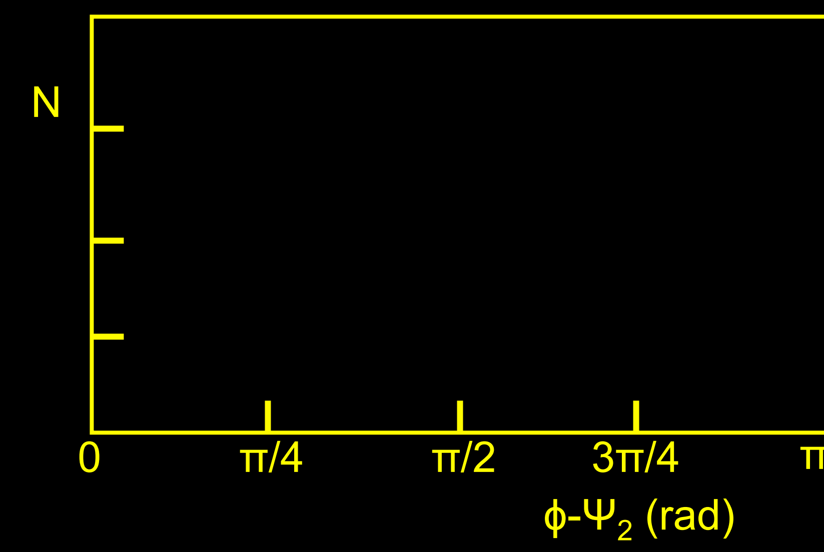

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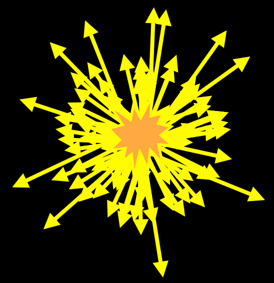

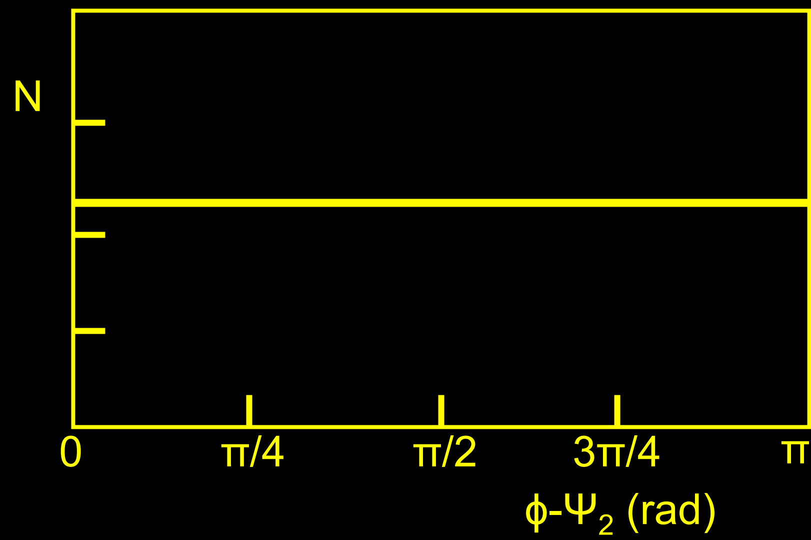

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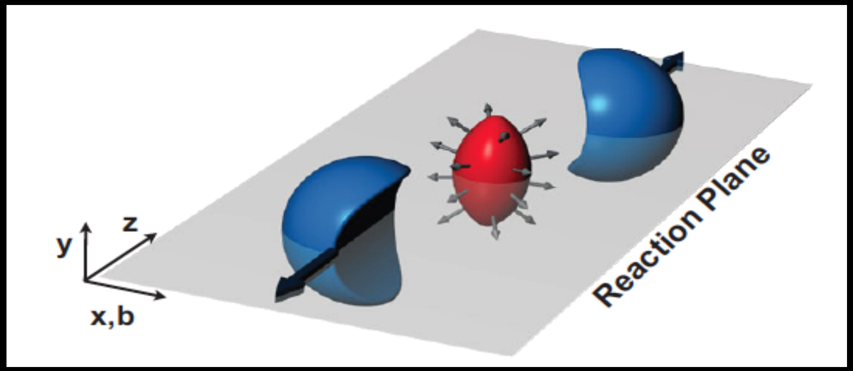
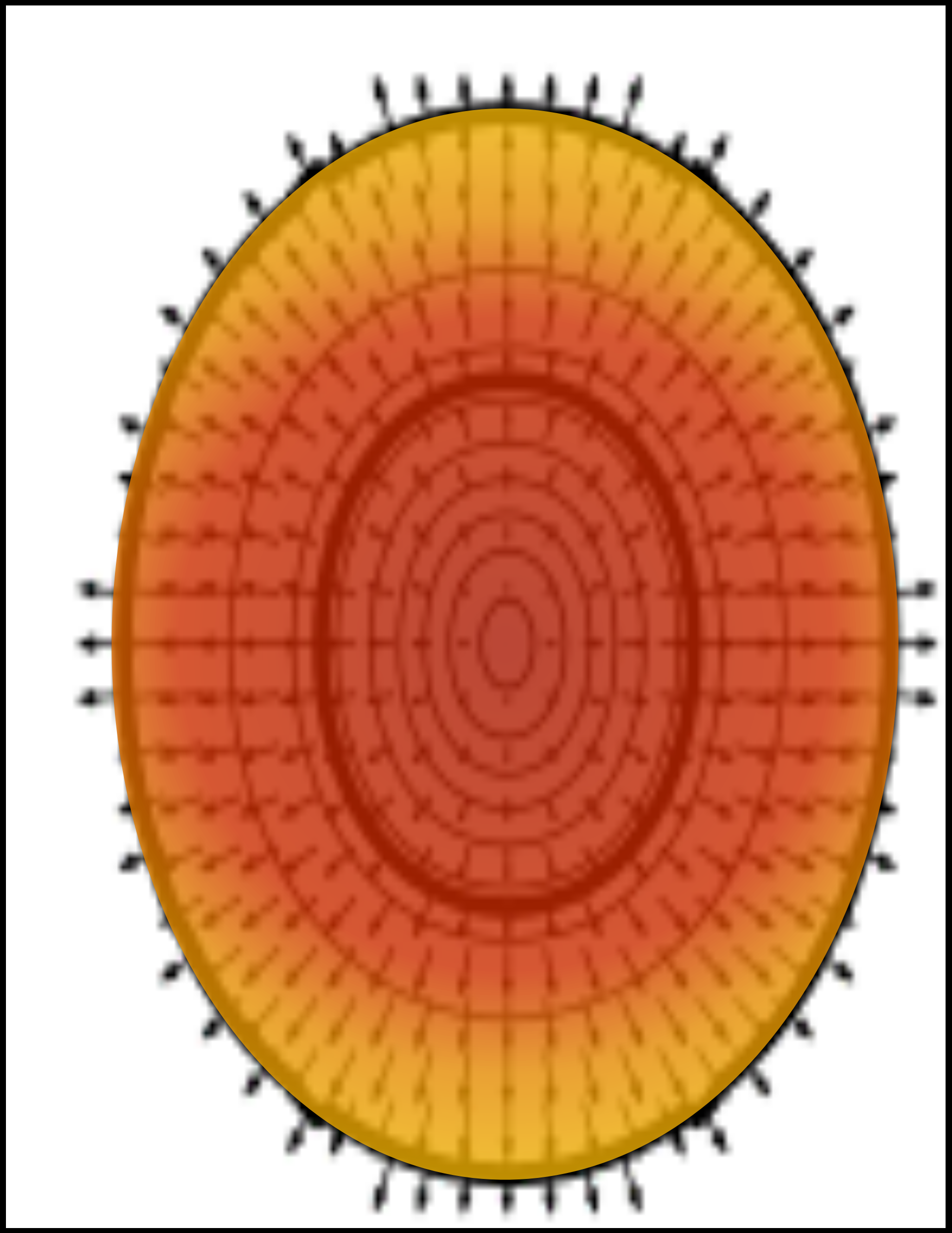


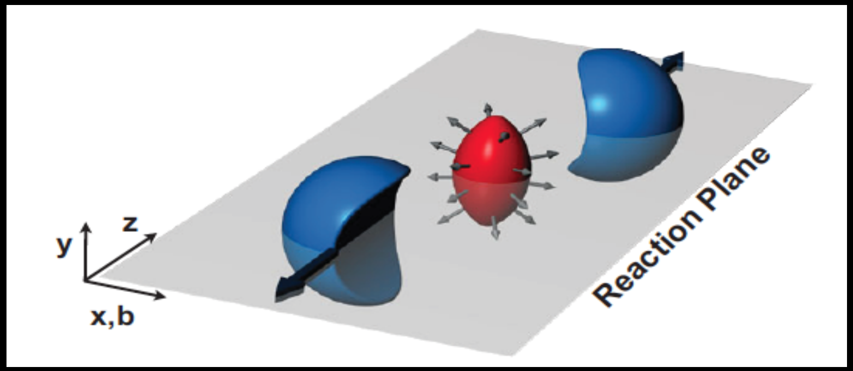
Development as a bulk system



high density and pressure at the center of the fireball

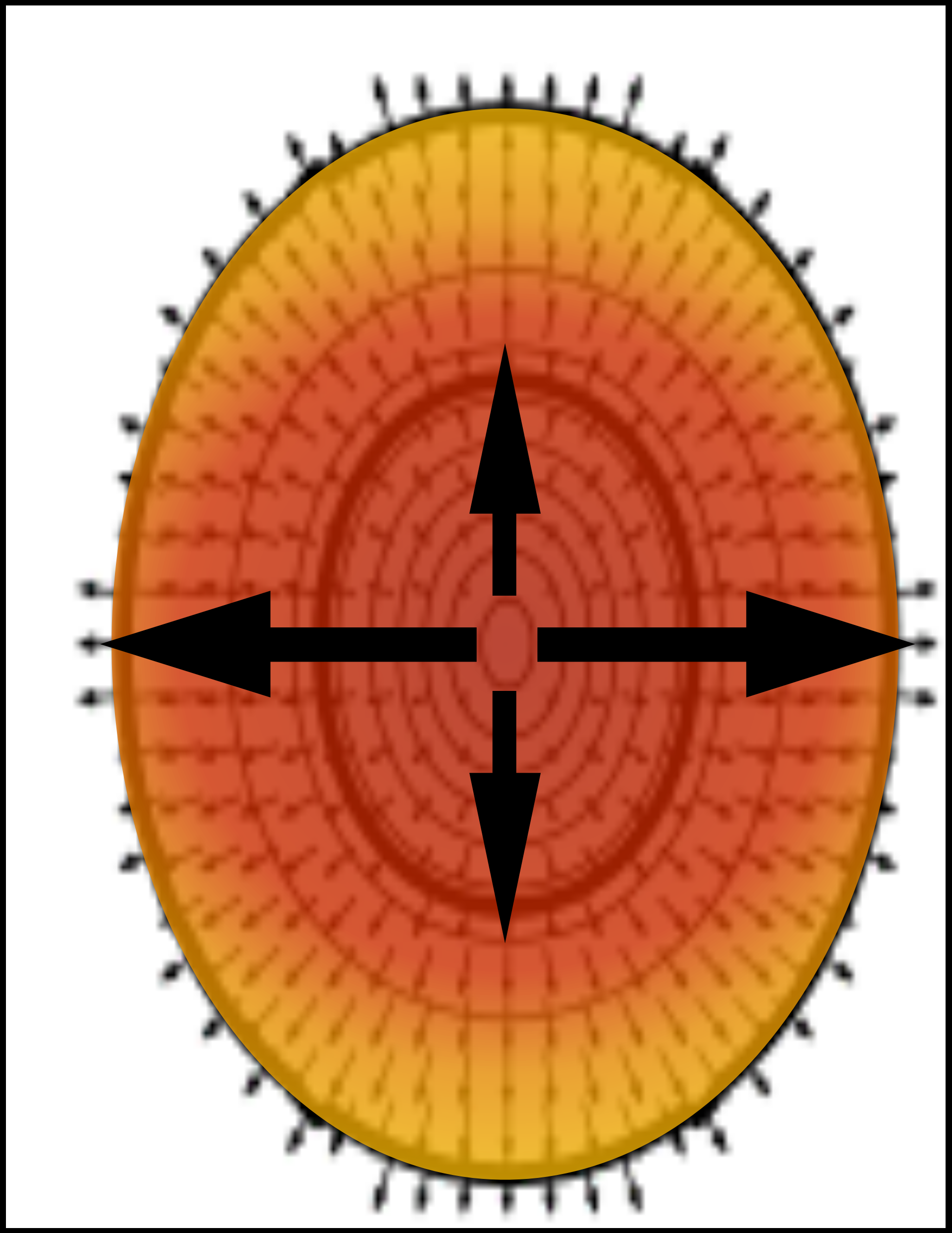
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

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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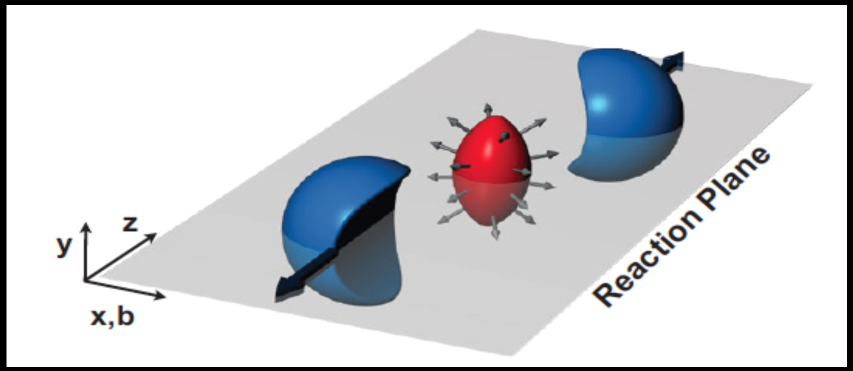

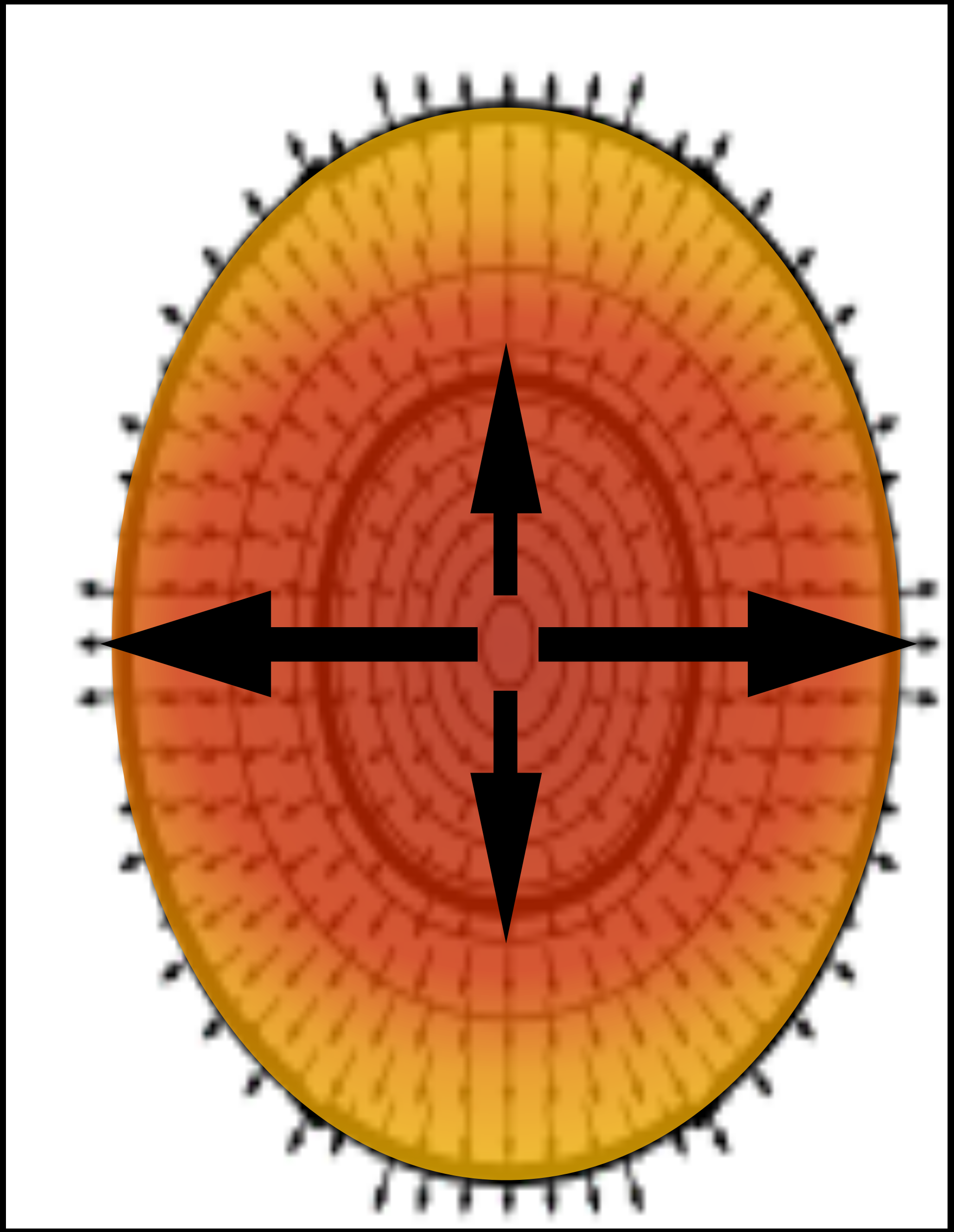

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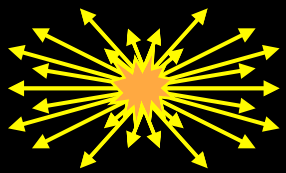


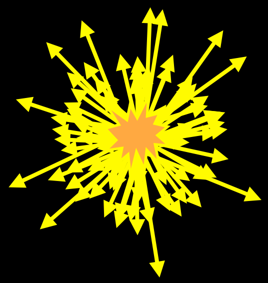
More and faster particles in-plane than out-of-plane

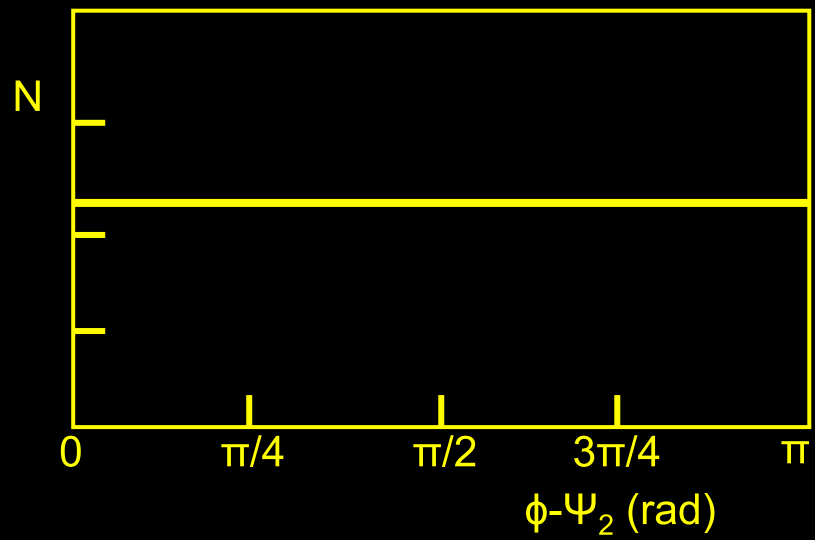
$$v_2(p_T,\eta) = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

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

Elliptic flow

Superposition of independent pp collisions





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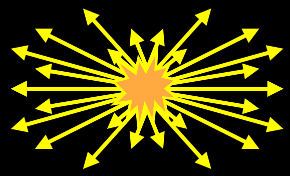

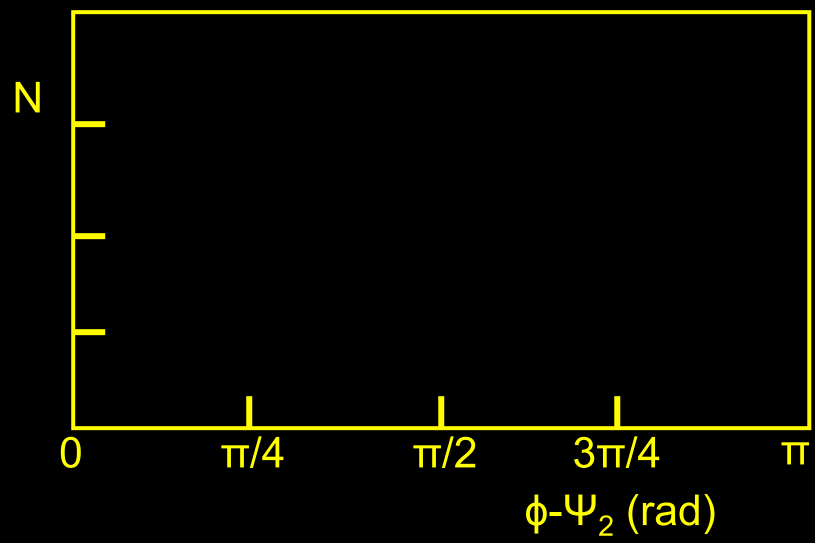

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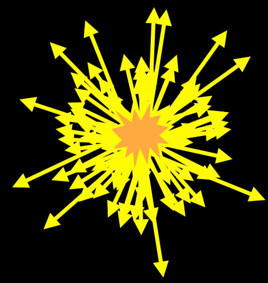

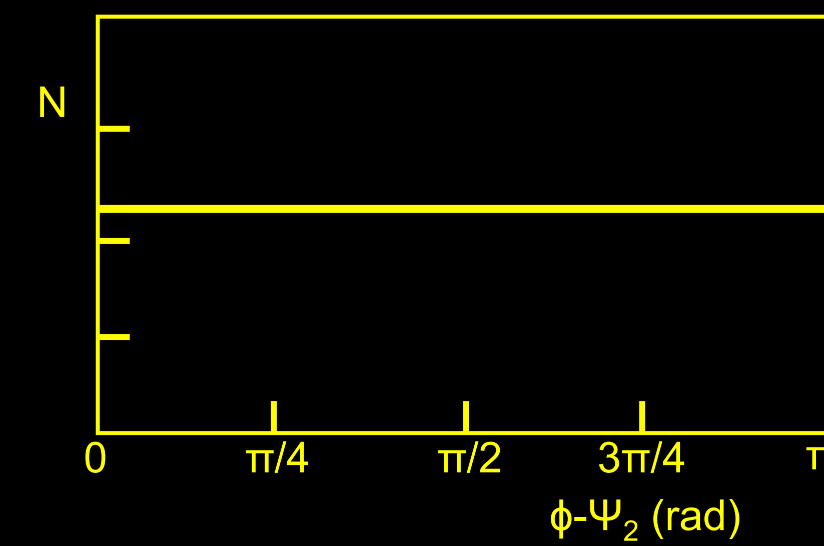

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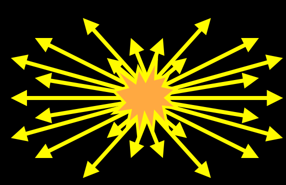
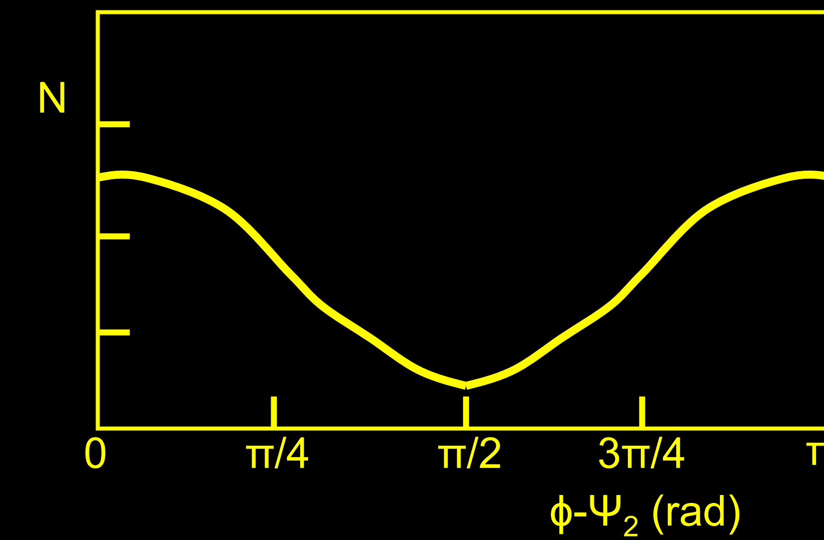
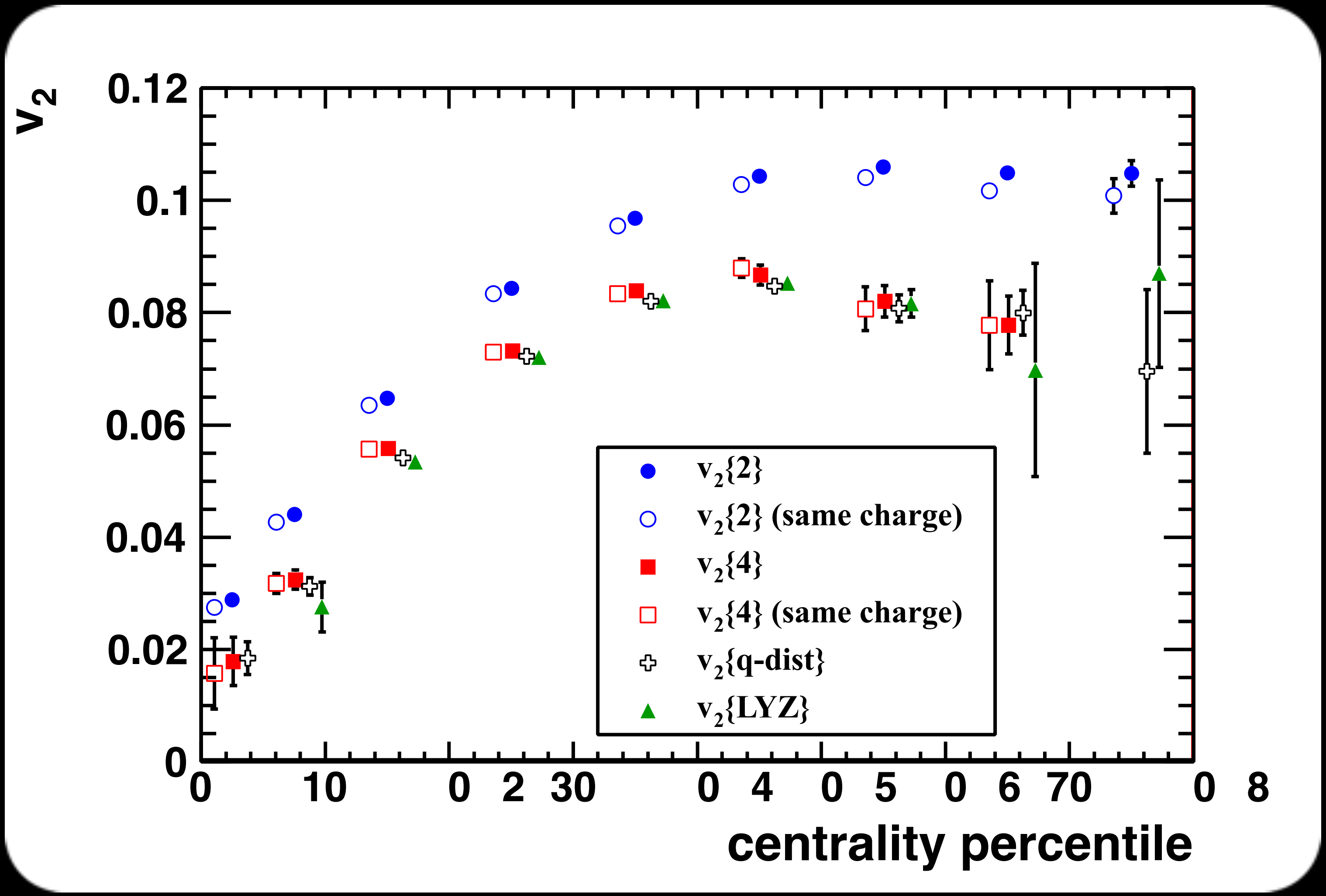




$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

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

Charged particles: integrated v_2



Different methods are affected in a different way by the background.
We have to use as many as possible!

Panos.Christakoglou@nikhef.nl

Non-flow contributions

- Correlations not connected to the reaction plane (resonances, jets, HBT,…)
- Suppression using multi-particle correlation techniques, η-gap analyses, different charge combinations,…

2-particle correlations

$$c_n\{2\} = \langle v_n^2 \rangle + \delta_2$$

$$\delta_2 \propto 1/M \Rightarrow v_n >> 1/M^{1/2}$$

4- (multi-) particle correlations

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2 =$$
$$= \langle v_n^4 \rangle + 4\langle v_n^2 \rangle \delta_2 + 2\delta_2^2 - 2\left(\langle v_n^2 \rangle + \delta_2\right)^2 + \delta_4 =$$
$$= -\langle v_n^4 \rangle + \delta_4$$

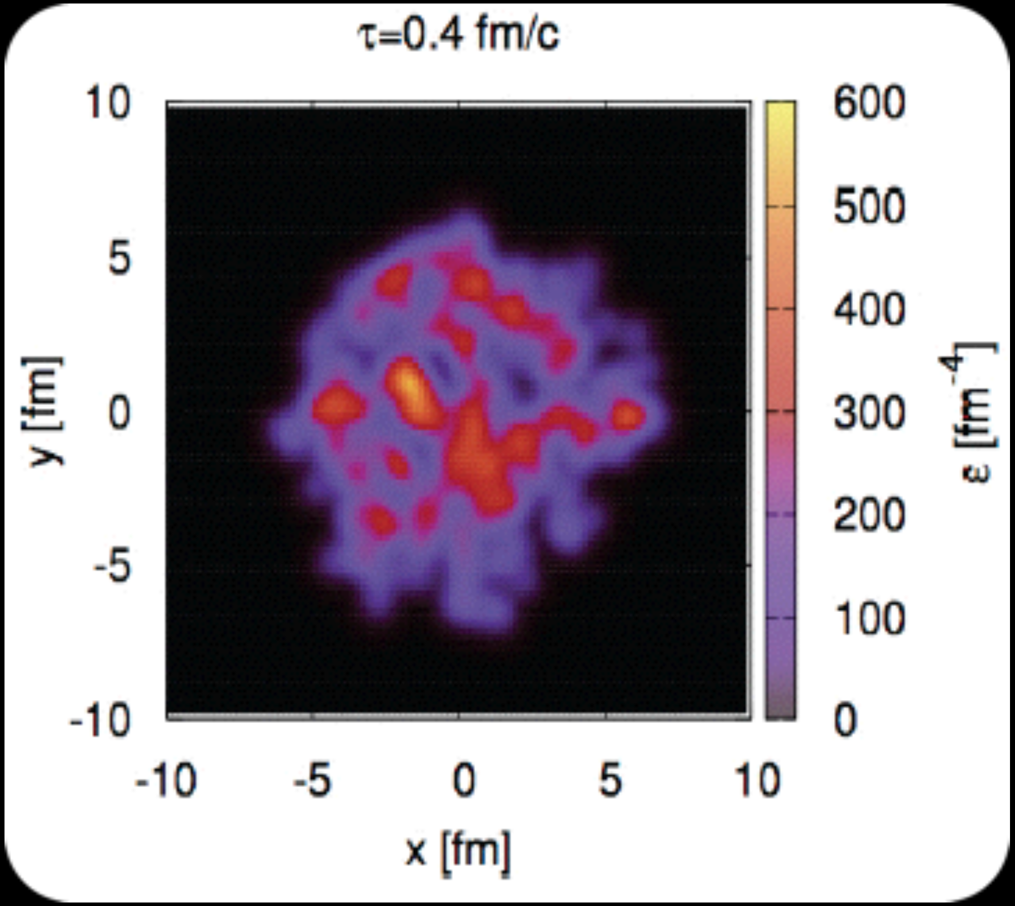
$$\delta_4 \propto 1/M^3 \Rightarrow v_n >> 1/M^{3/4}$$

- For a typical Pb-Pb collision at LHC energies in 30-40% centrality, M ~ 425
  - ★ v_n >> 4.8% for the 2-particle correlation technique
  - ★ v_n >> 1.1% for the 4-particle correlation technique

A. Bilandzic, R. Snellings, S. Voloshin, Phys. Rev. **C83**, 044913 (2011)

Flow fluctuations

- Originating from the fluctuations in the initial collision geometry.
  - ★ Fluctuations of initial energy/pressure distributions lead to “irregular” shapes that fluctuate event-by-event



$$\langle v_2^2\rangle = \langle v_2\rangle^2 + \sigma_v^2$$

$$\langle v_2^4\rangle = \langle v_2\rangle^4 + 6\sigma_v^2\langle v_2\rangle^2$$

$$\langle v_2^6\rangle = \langle v_2\rangle^6 + 15\sigma_v^2\langle v_2\rangle^4$$

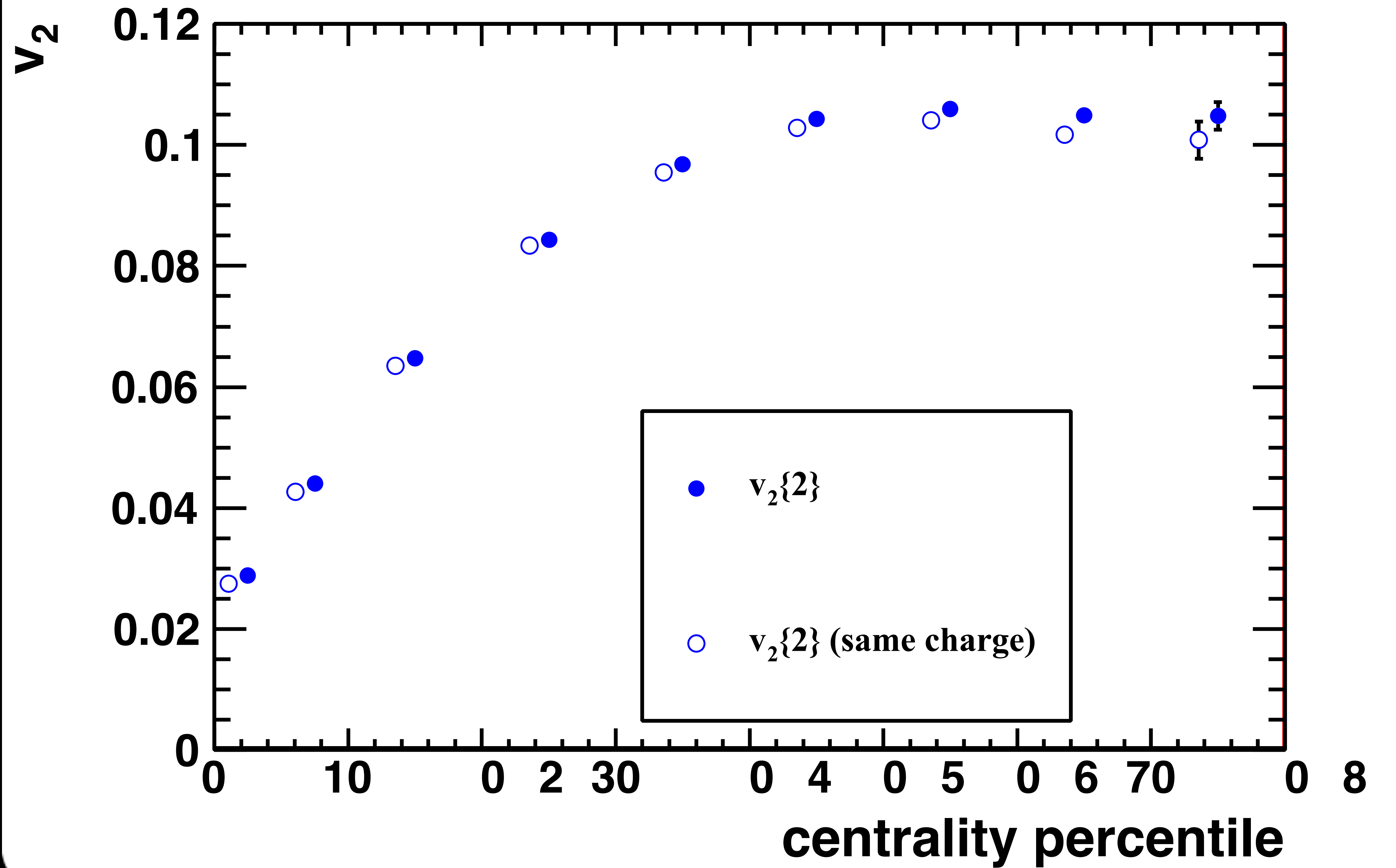
$$v_2\{2\} = \sqrt{\langle v_2^2\rangle} = \ldots = \langle v_2\rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

$$v_2\{4\} = \sqrt[4]{2\langle v_2^2\rangle^2 - \langle v_2^4\rangle} = \ldots = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

$$v_2\{6\} = \sqrt[6]{\frac{1}{4}\left(\langle v_2^6\rangle - 9\langle v_2^2\rangle\langle v_2^4\rangle + 12\langle v_2^2\rangle^3\right)} = \ldots = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

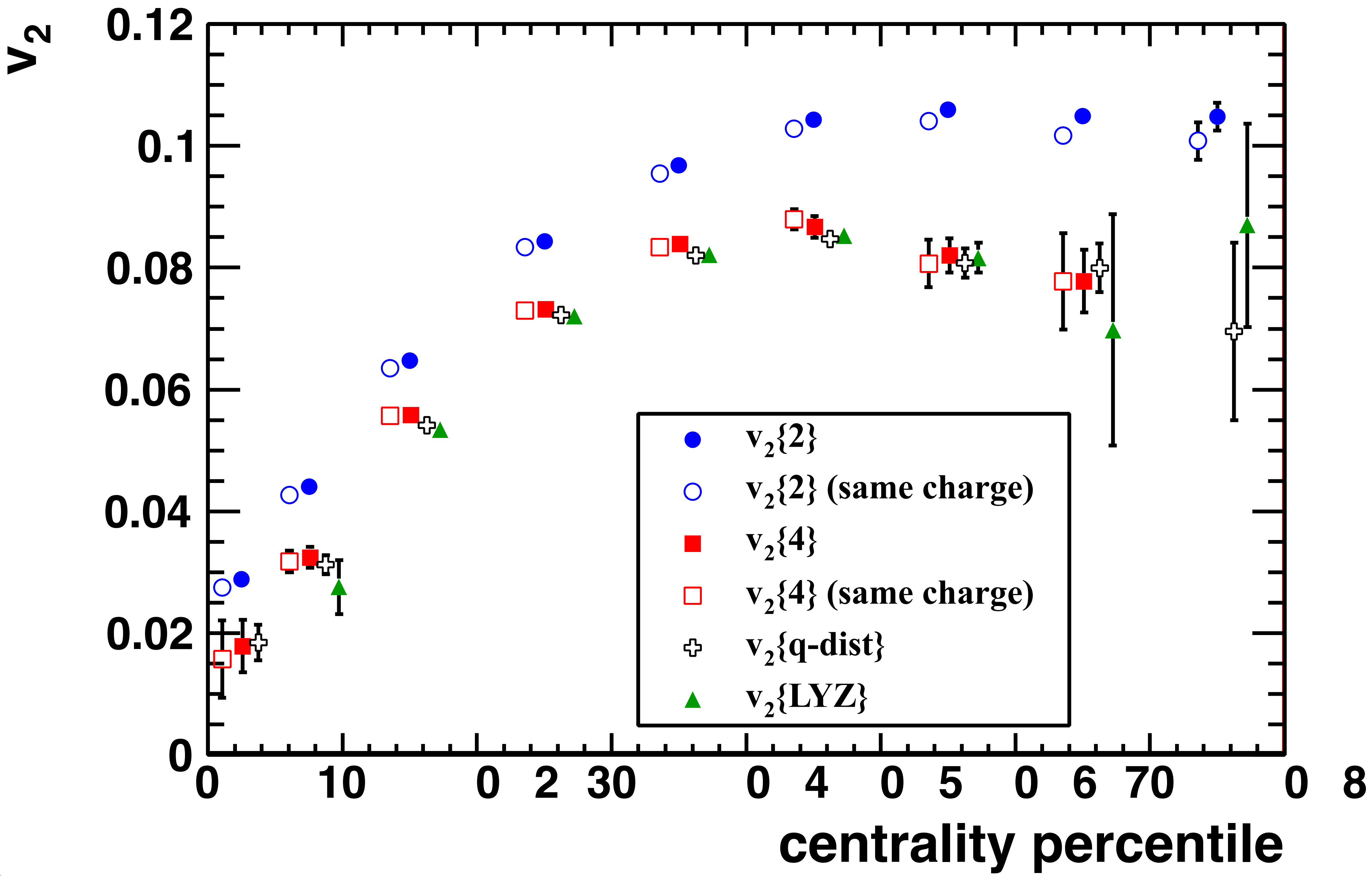
2-particle correlations

Biased by non-flow and by flow fluctuations (+)



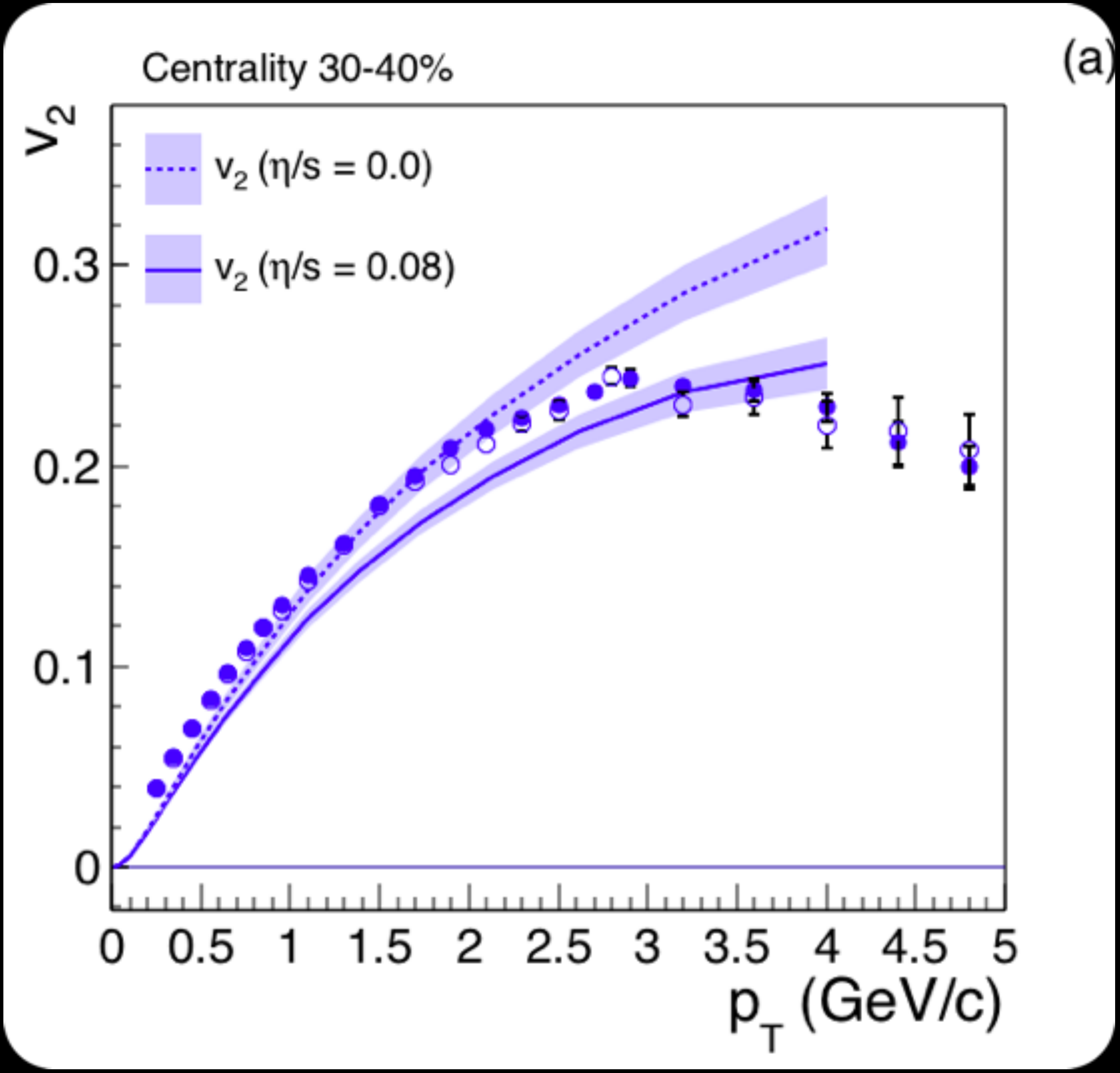
Multi-particle correlations

Suppresses non-flow (2p) but biased by flow fluctuations (-)



Panos.Christakoglou@nikhef.nl

Charged particles: p_T-differential v_2

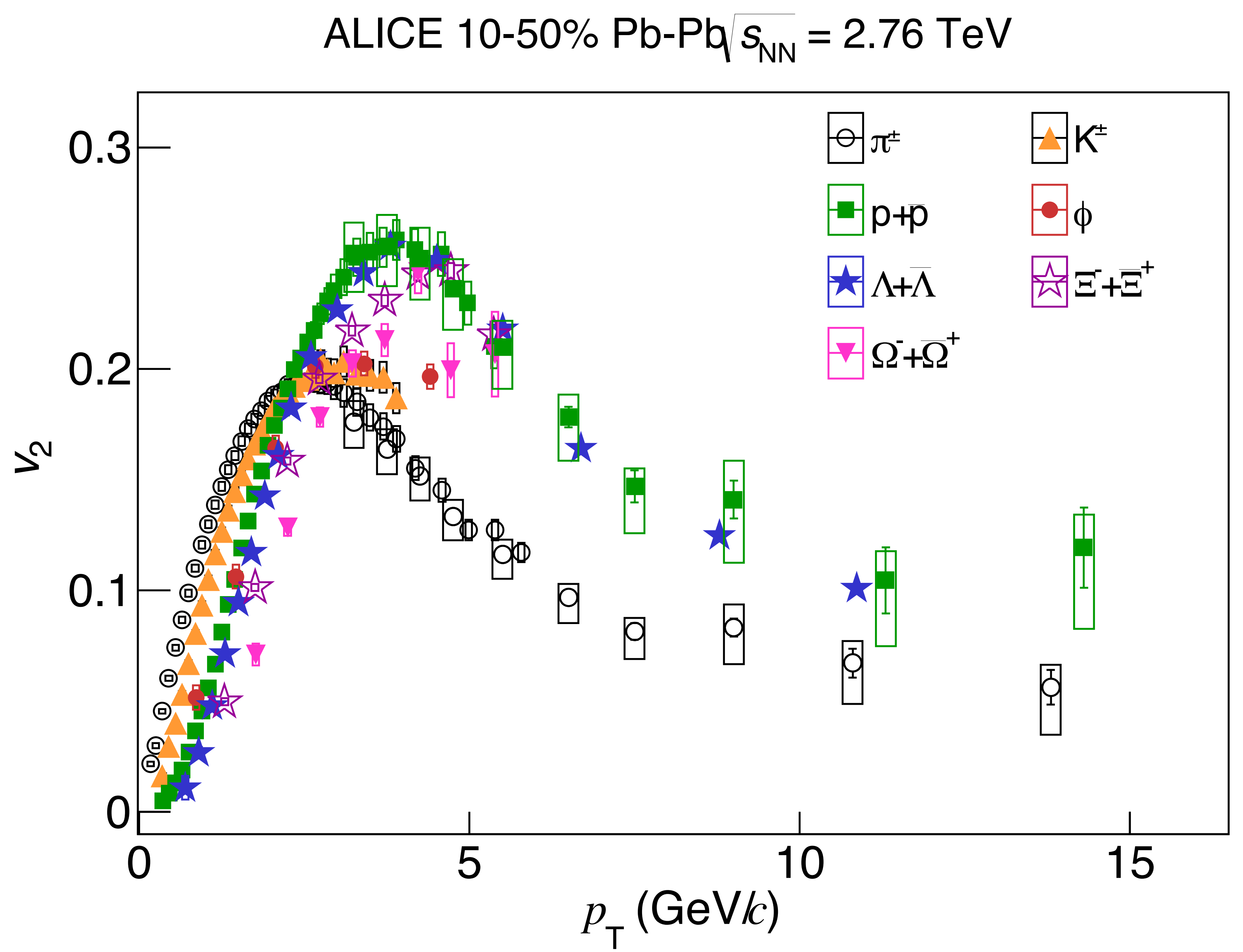


Hydrodynamic calculations describe the data fairly well!

Identified particles v_2 at the LHC

(ALICE), arXiv:1405.4632 [nucl-ex]

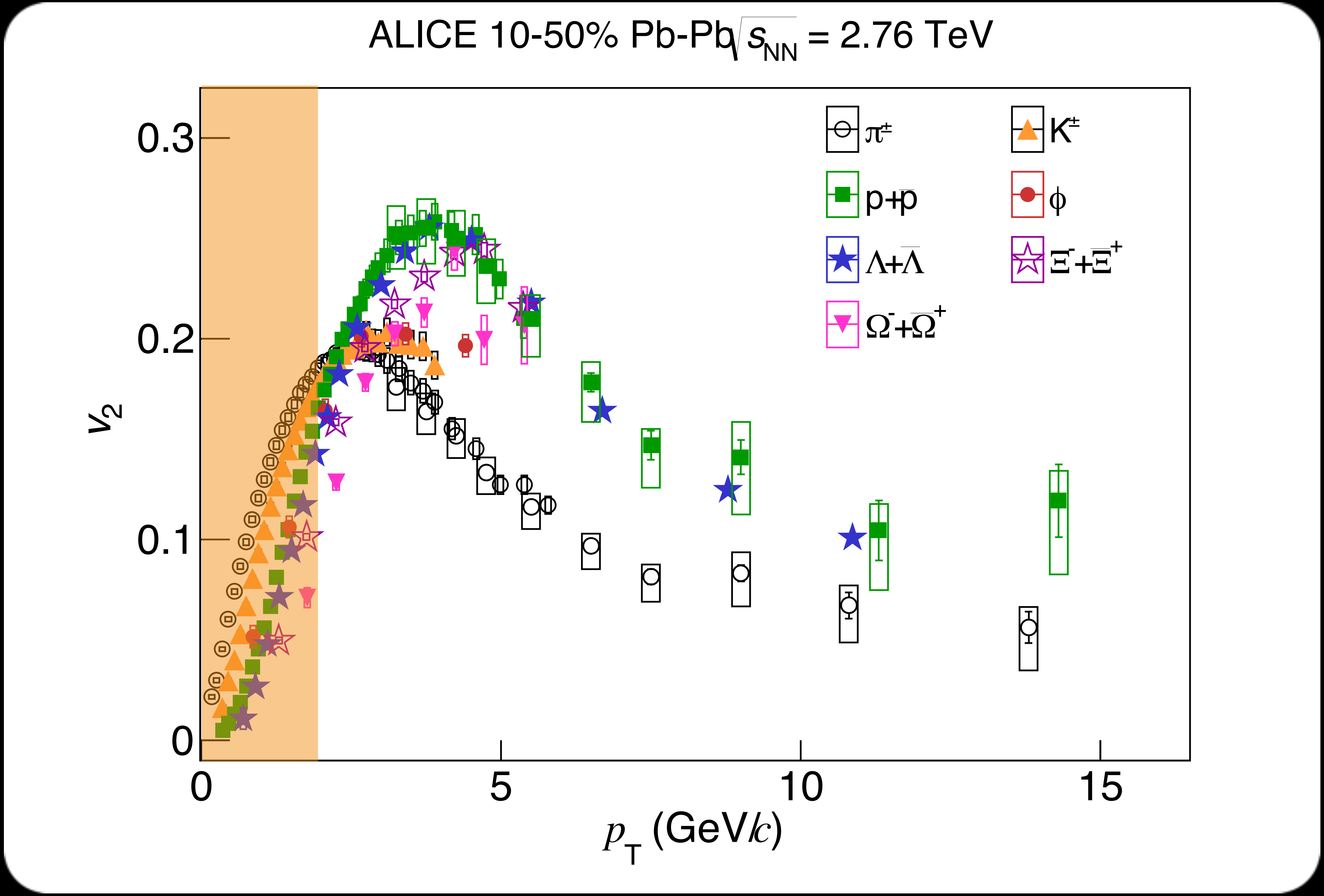
(ALICE), Physics Letters B 719 (2013) 18



Identified particles v_2 at the LHC: low p_T

(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

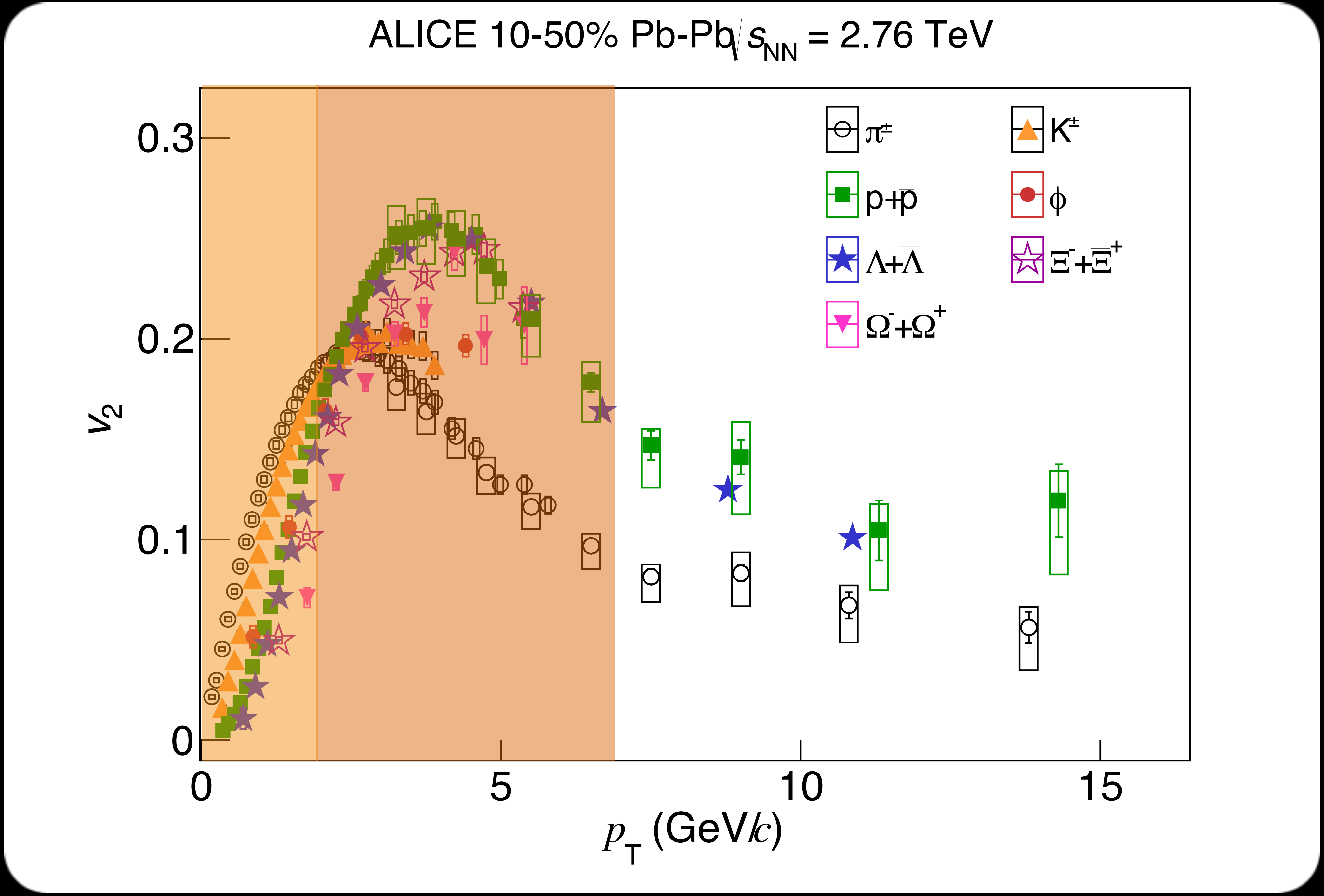


Bulk of particle production: described in terms of hydrodynamics

Identified particles v_2 at the LHC: intermediate p_T

(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

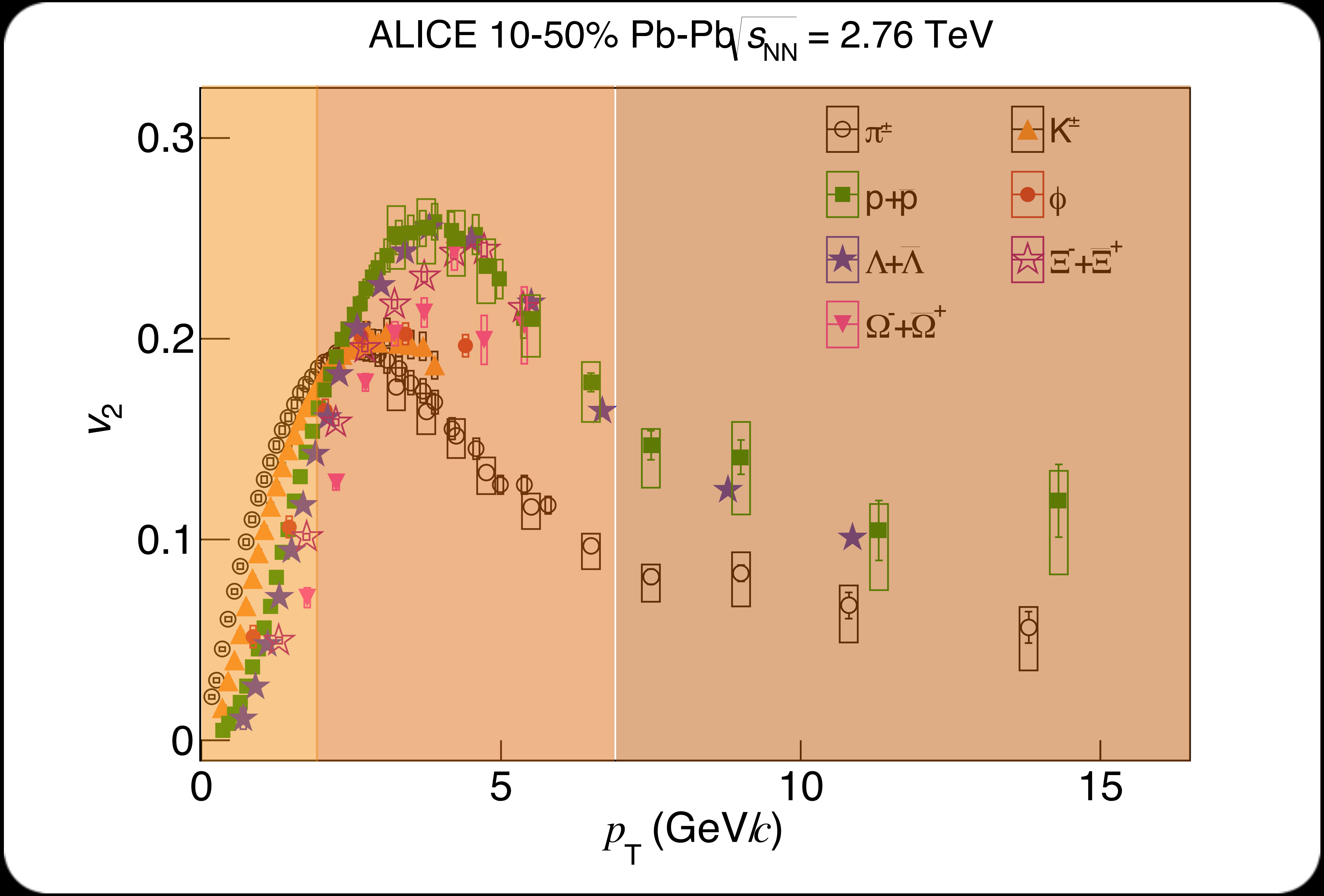


Quarks coalesce, producing hadrons?

Identified particles v_2 at the LHC: high p_T

(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

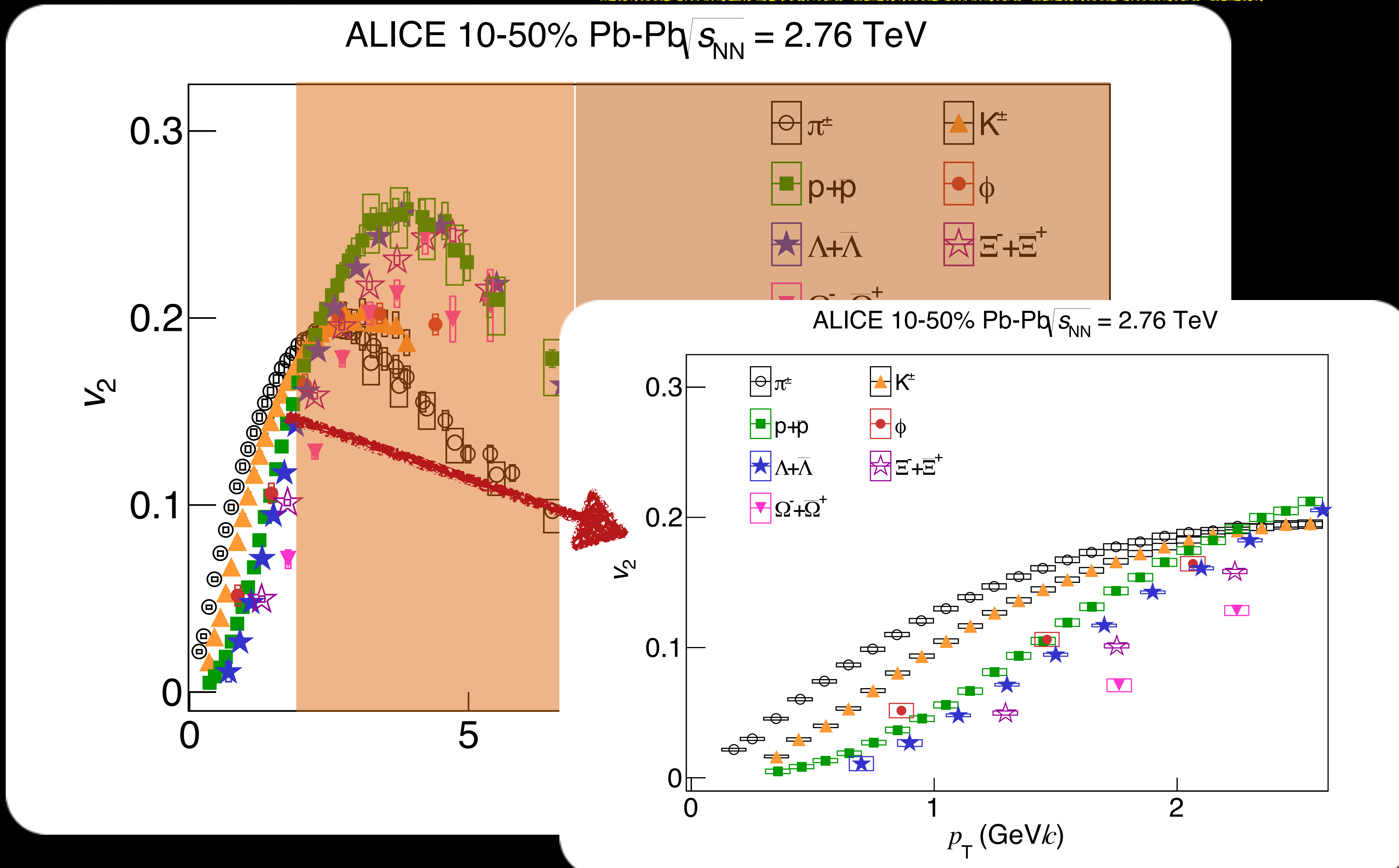


Parton fragmentation: path length dependence of energy loss

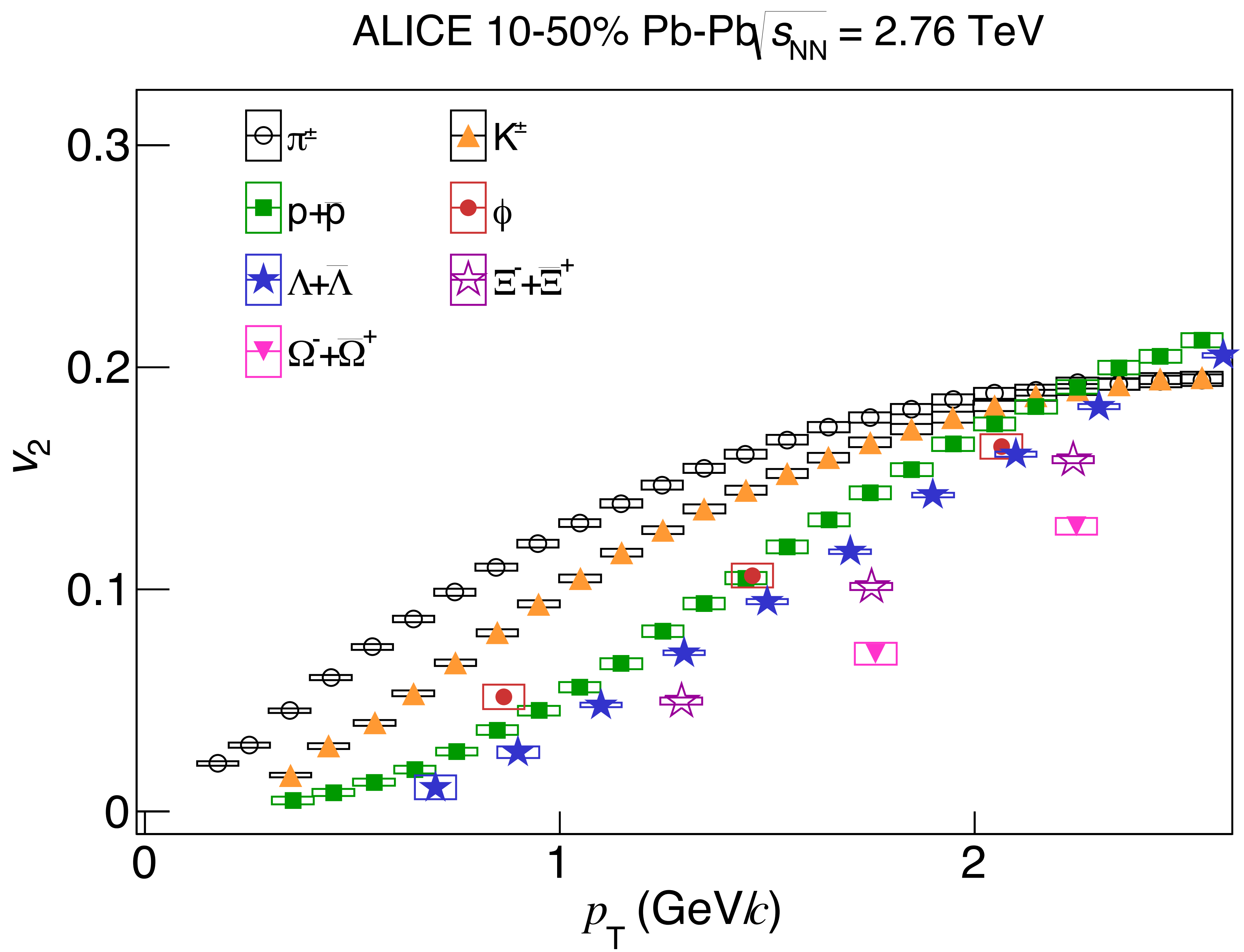
Identified particles v_2 at the LHC: low p_T

(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

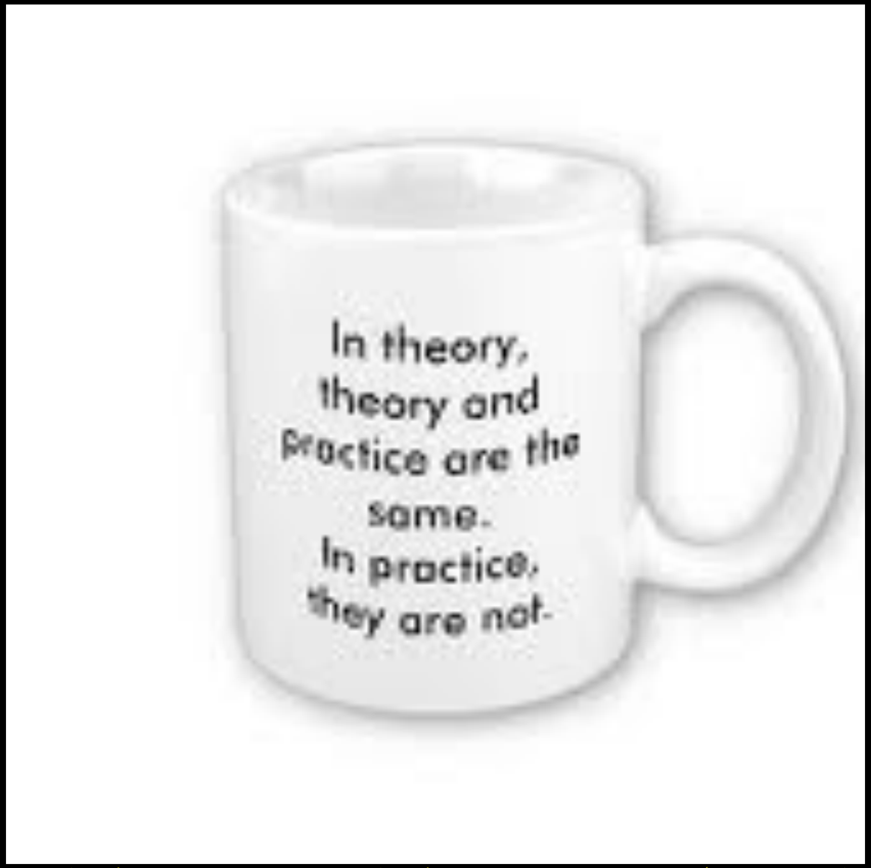


The three momentum scales: low p_T (p_T < 2 GeV/c)



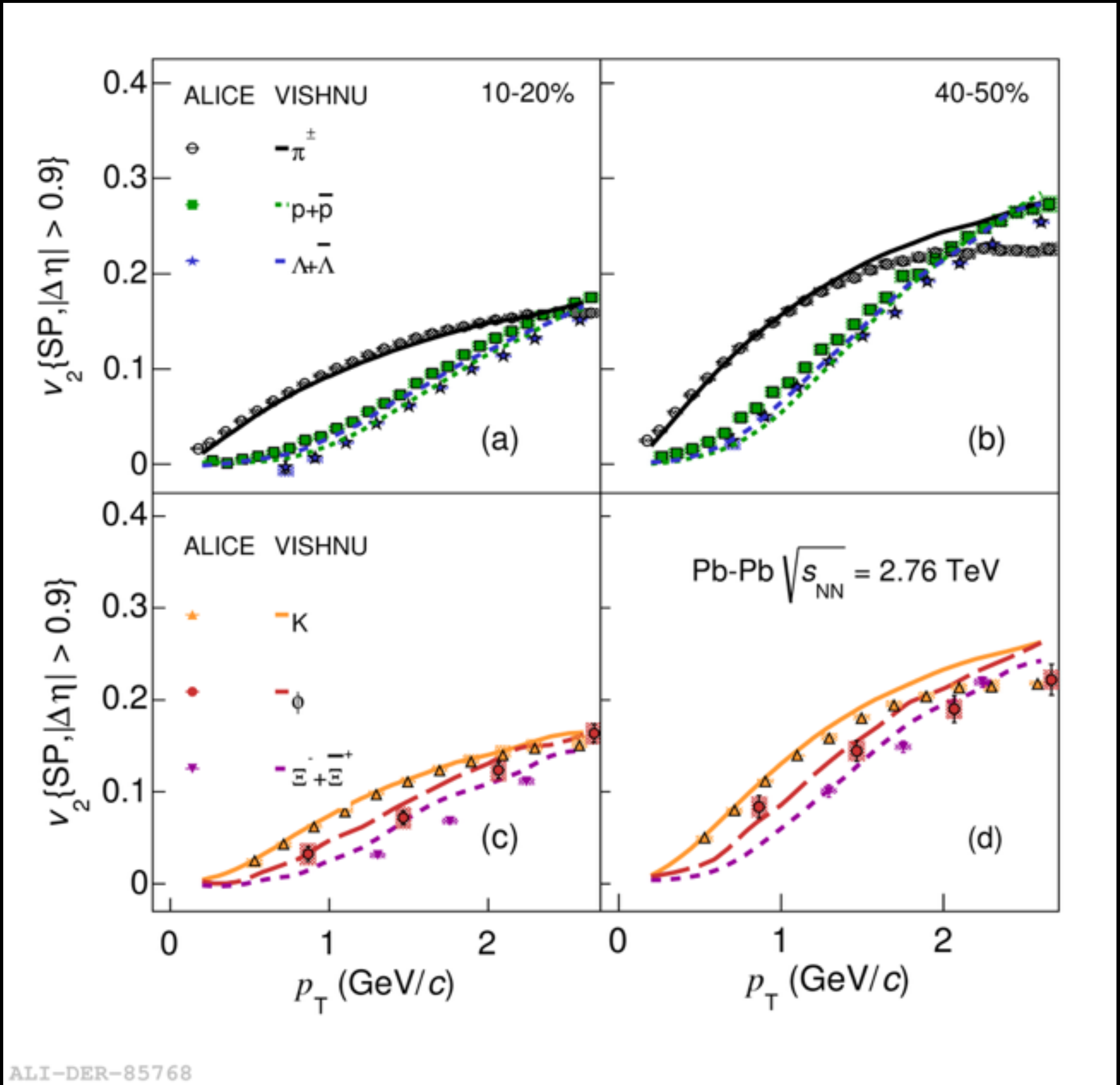
Low p_T: mass ordering ➜ elliptic/radial flow interplay

Comparison with hydrodynamic calculations

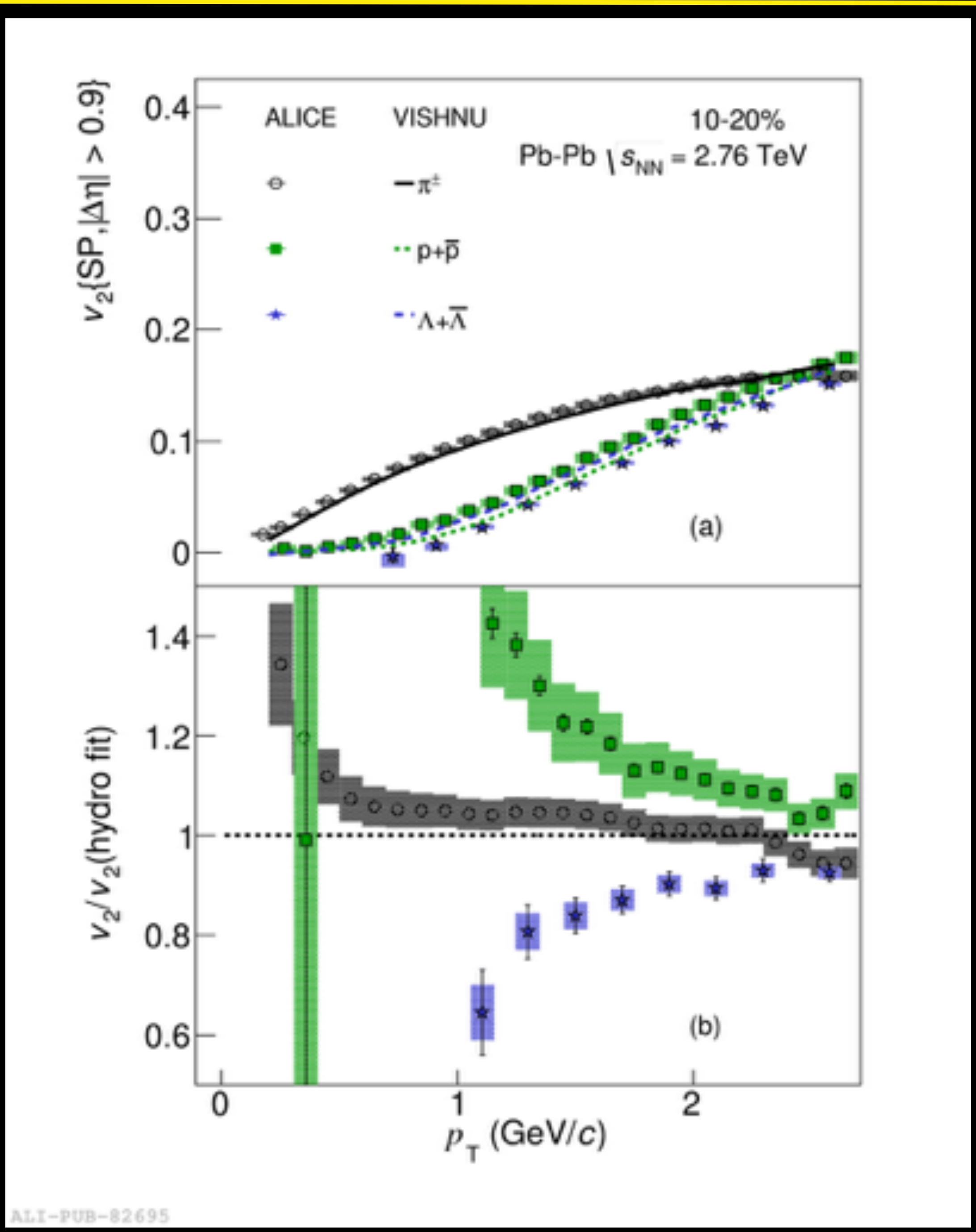


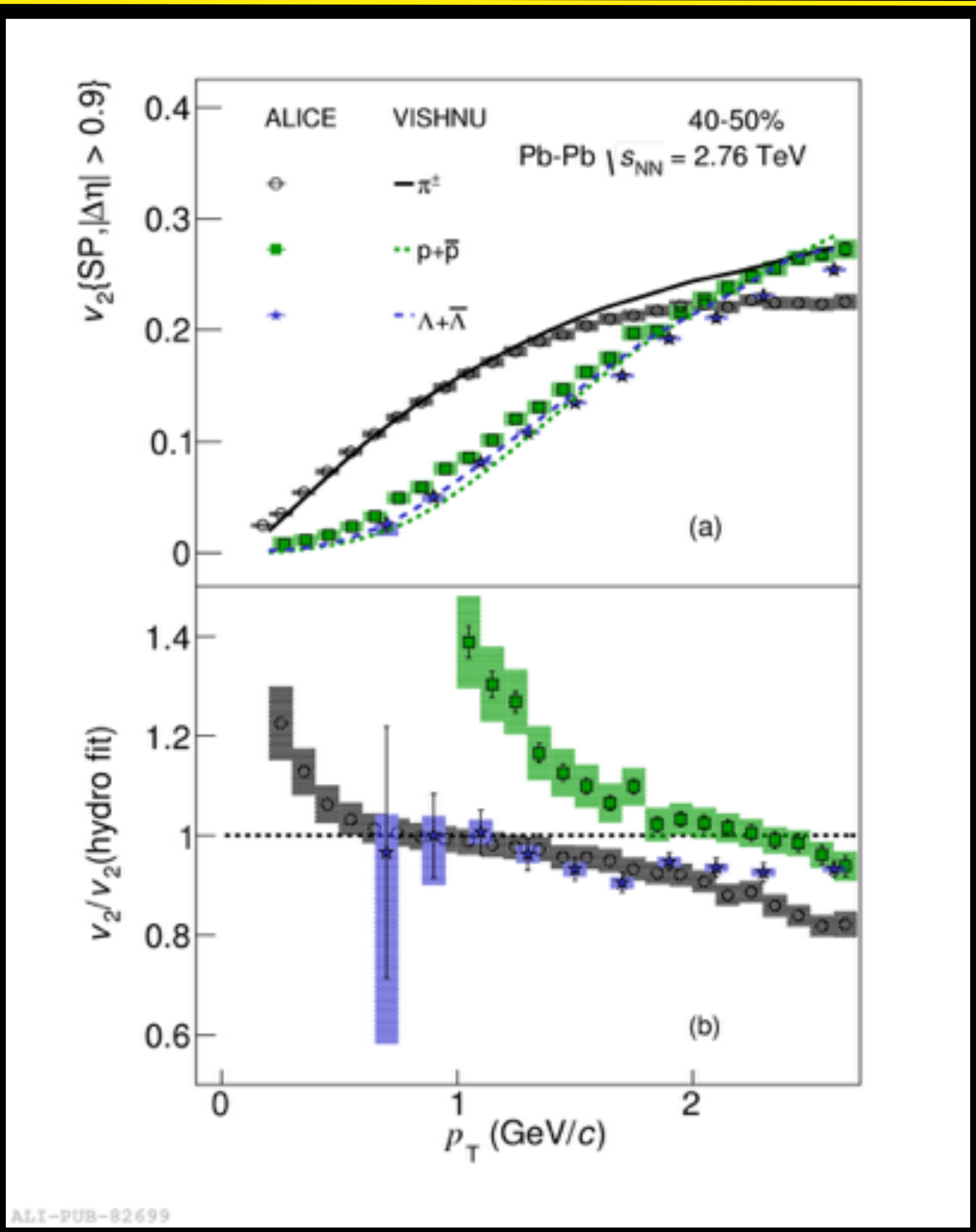
hydro curves from: H. Song, S. Bass and U. Heinz arXiv:1311.0157 [nucl-th]

Comparison with VISHNU



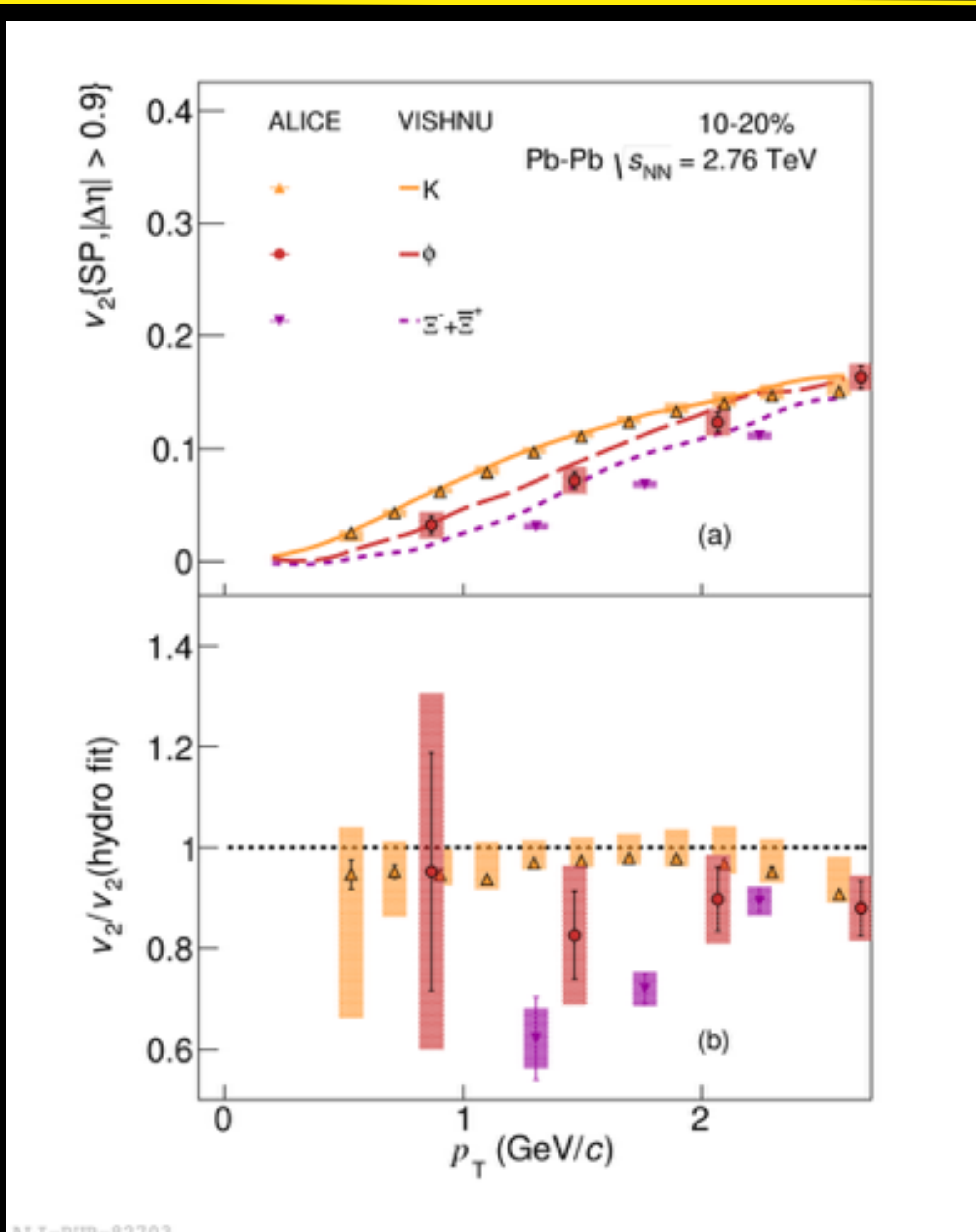
Looking at the details…: π, p, Λ

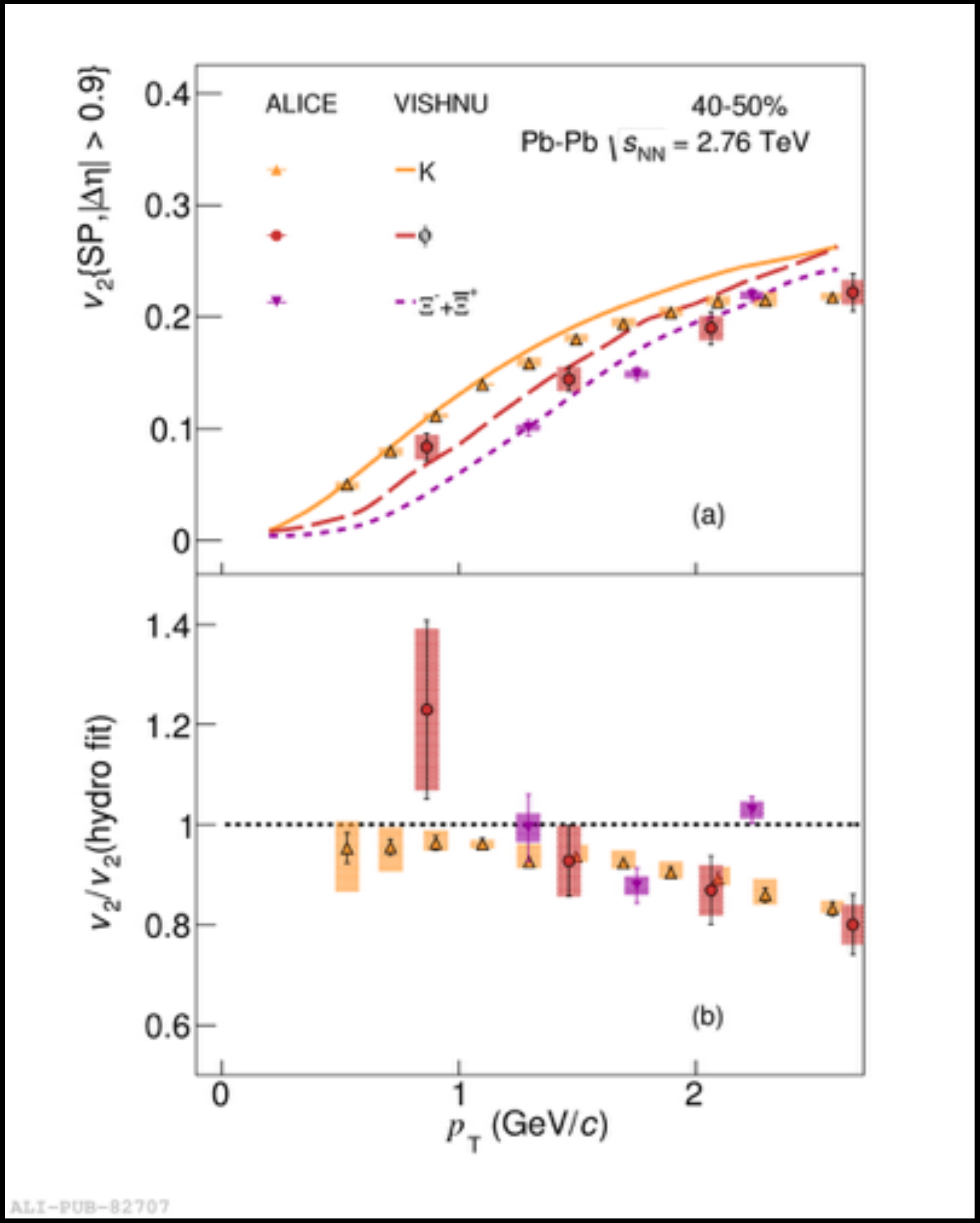




- Pion v_2 systematically underestimated for central events (for peripheral events the agreement is improved)
- Proton v_2 underestimated (i.e. extra push expected in hydro) for both centralities
- Λ v_2 overestimated (i.e. less push expected in hydro) for central events

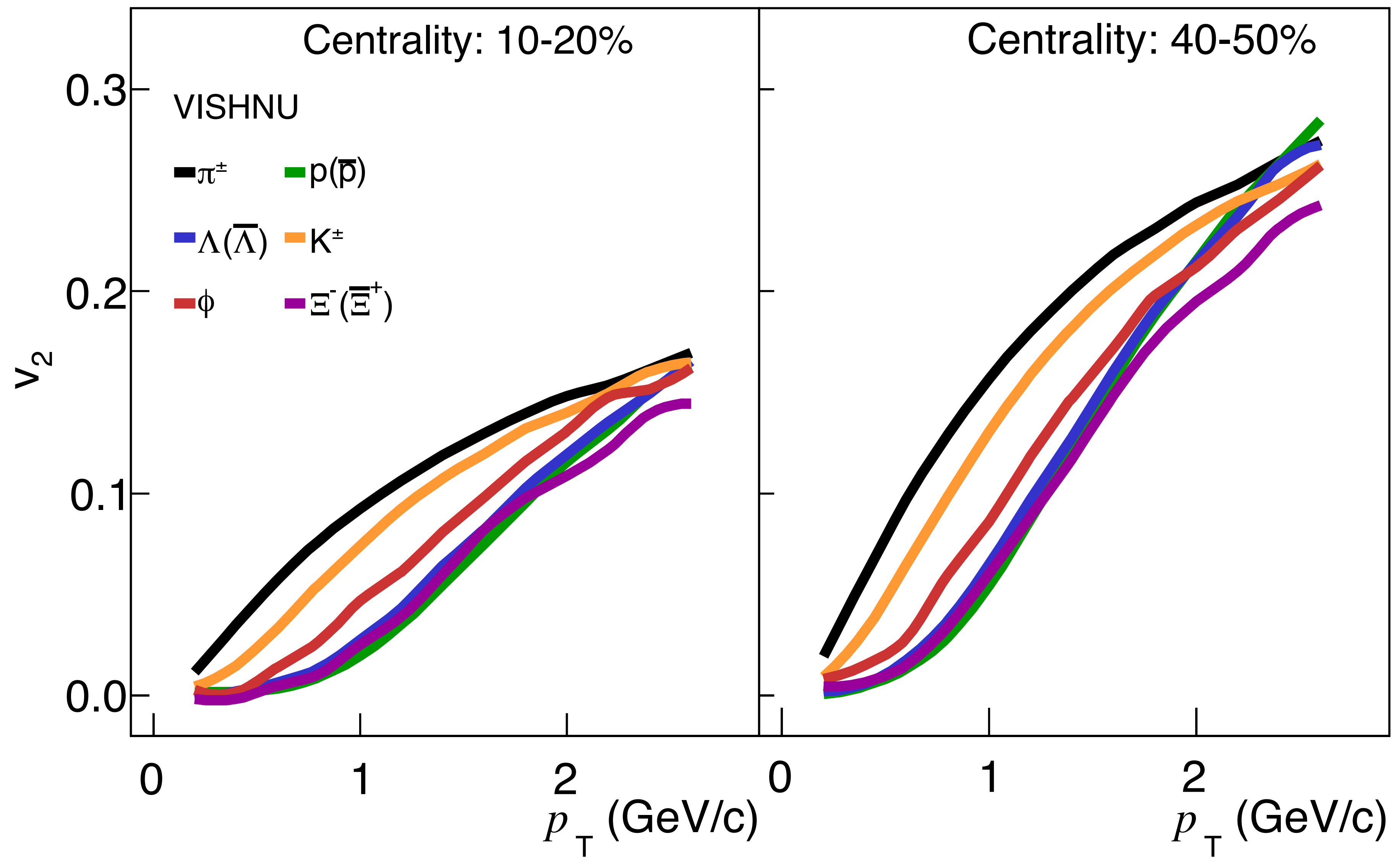
Looking at the details…: K, φ, Ξ





- Kaon v_2 described well for central collisions
- Ξ v_2 overestimated (i.e. less push in hydro) for both centralities
- φ v_2 overestimated for both centralities: not enough hadronic interactions?

VISHNU in more detail



Mass ordering not preserved!!!

Importance of hadronic rescattering phase: VISHNU vs VISH2+1

VISHNU

- Couples VISH2+1 to UrQMD
- MC-KLN density profiles
- $\eta/s = 0.16$
- $\tau_0 = 0.9$ fm/c

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]].

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

VISH2+1

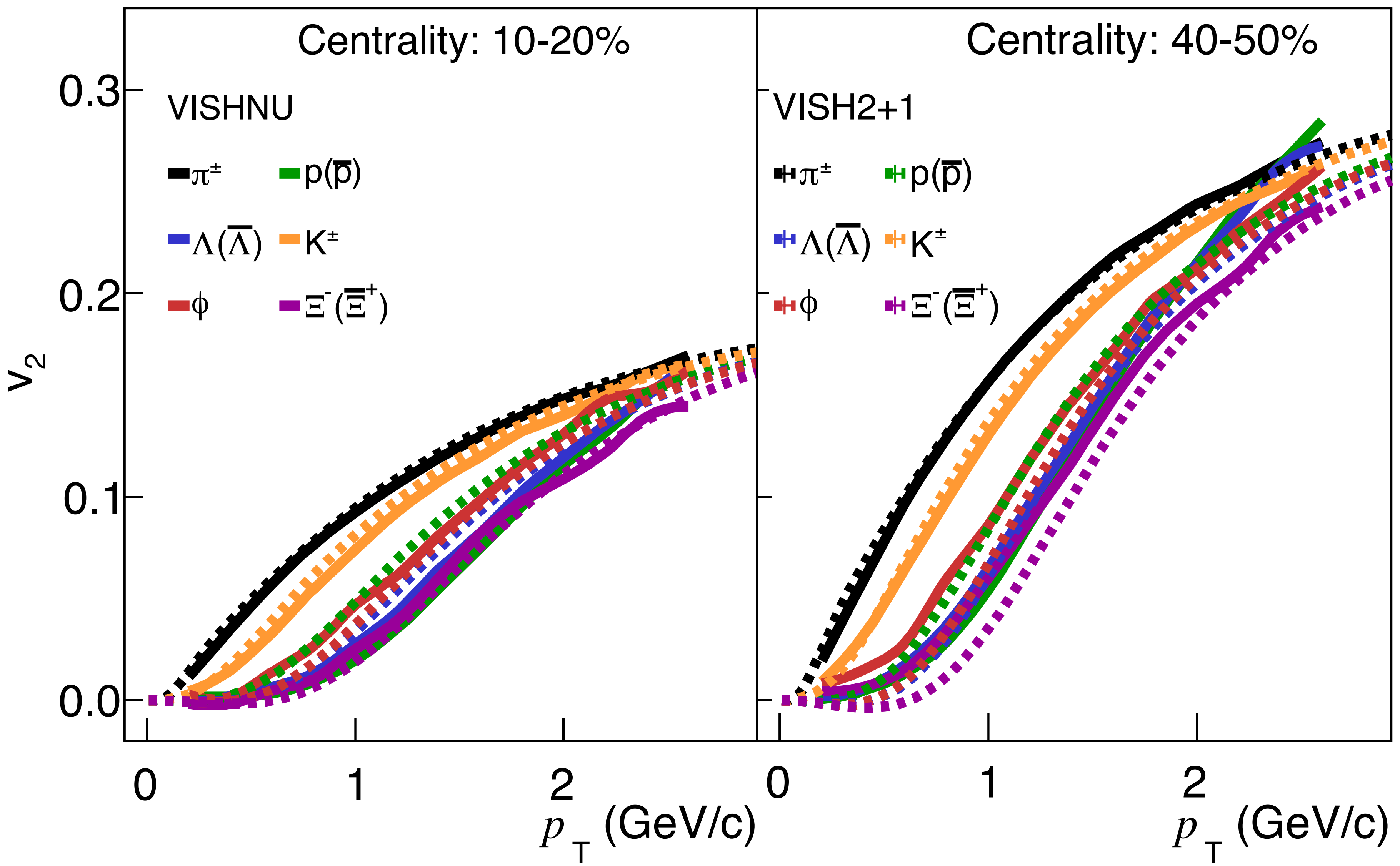
- 2+1 hydro without hadronic cascade
- Glauber density profiles
- $\eta/s = 0.08$
- $\tau_0 = 0.6$ fm/c

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]].

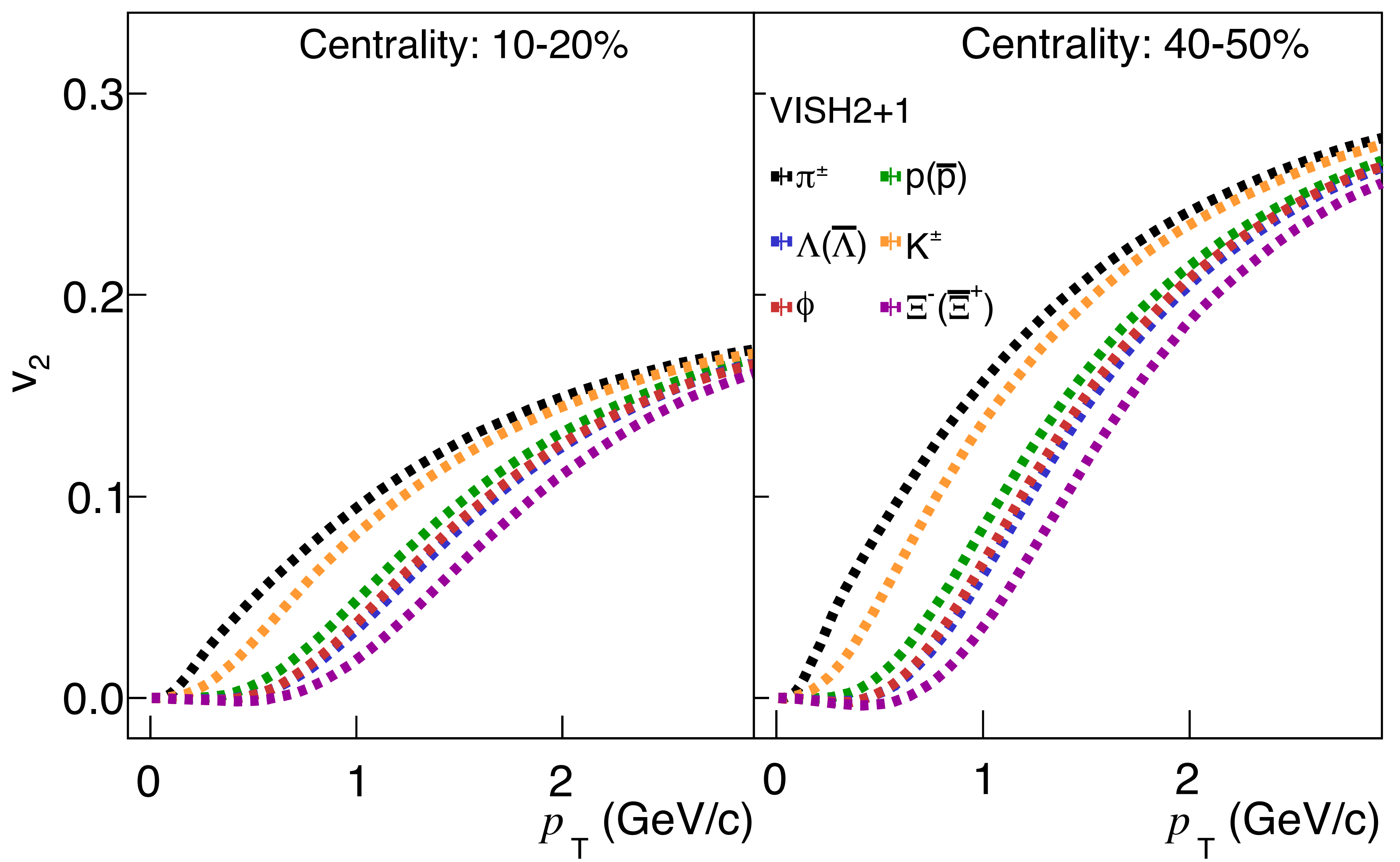
H. Song and U. W. Heinz, Phys. Rev. C 78 (2008) 024902 [arXiv:0805.1756 [nucl-th]].

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

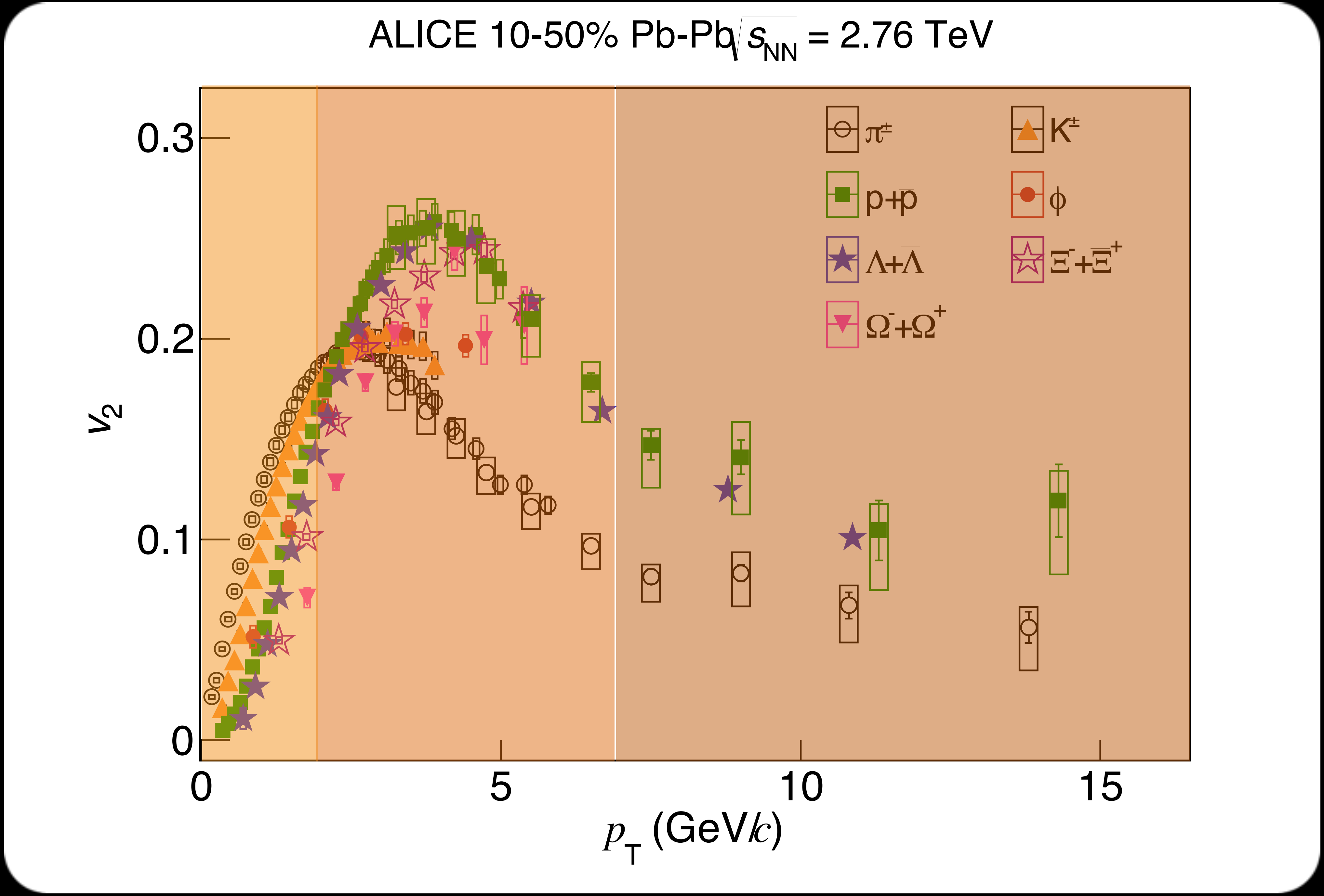


Mass ordering preserved

Identified particles v_2 at the LHC

(ALICE), arXiv:1405.4632 [nucl-ex]

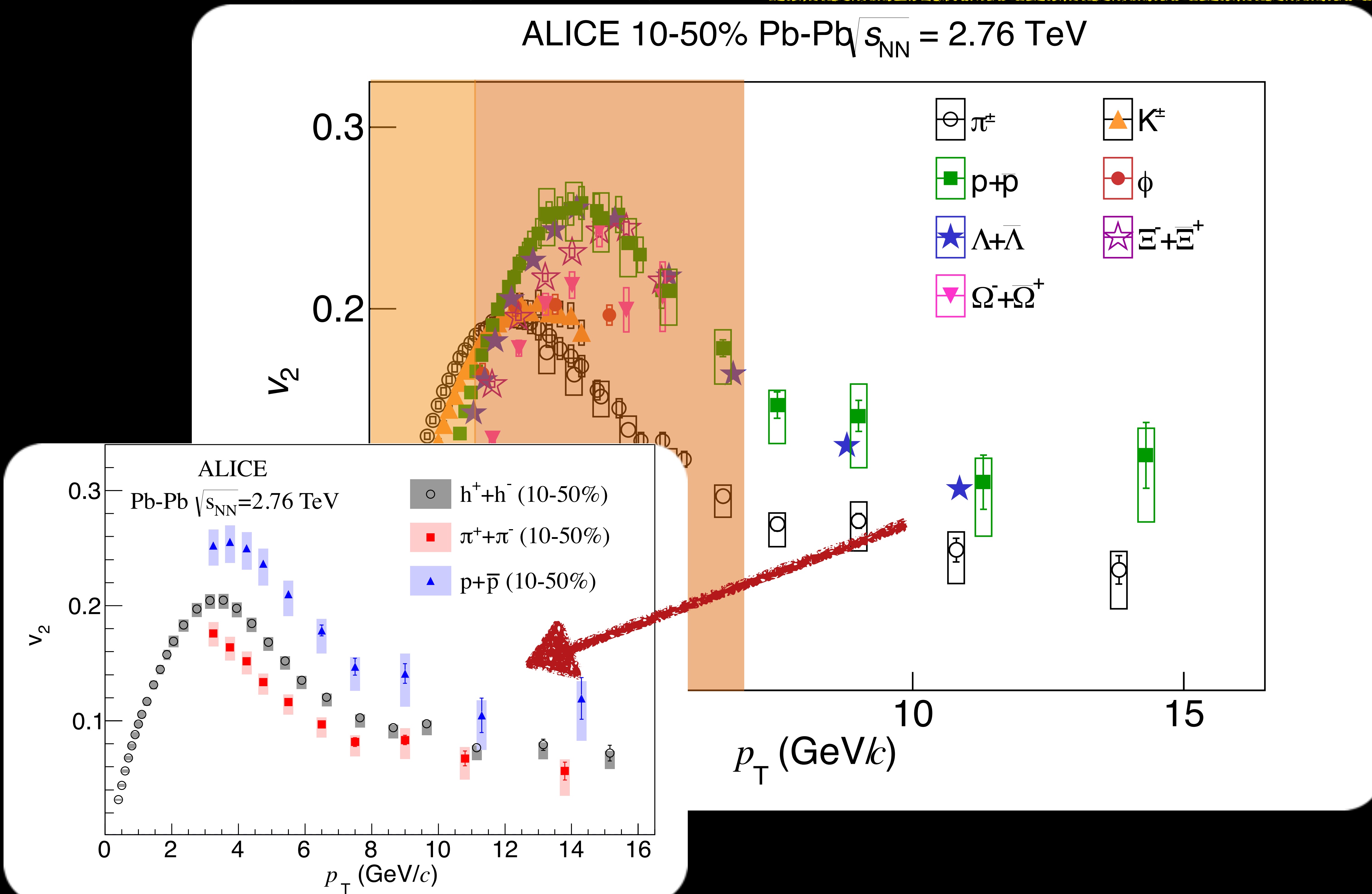
(ALICE), Physics Letters B 719 (2013) 18



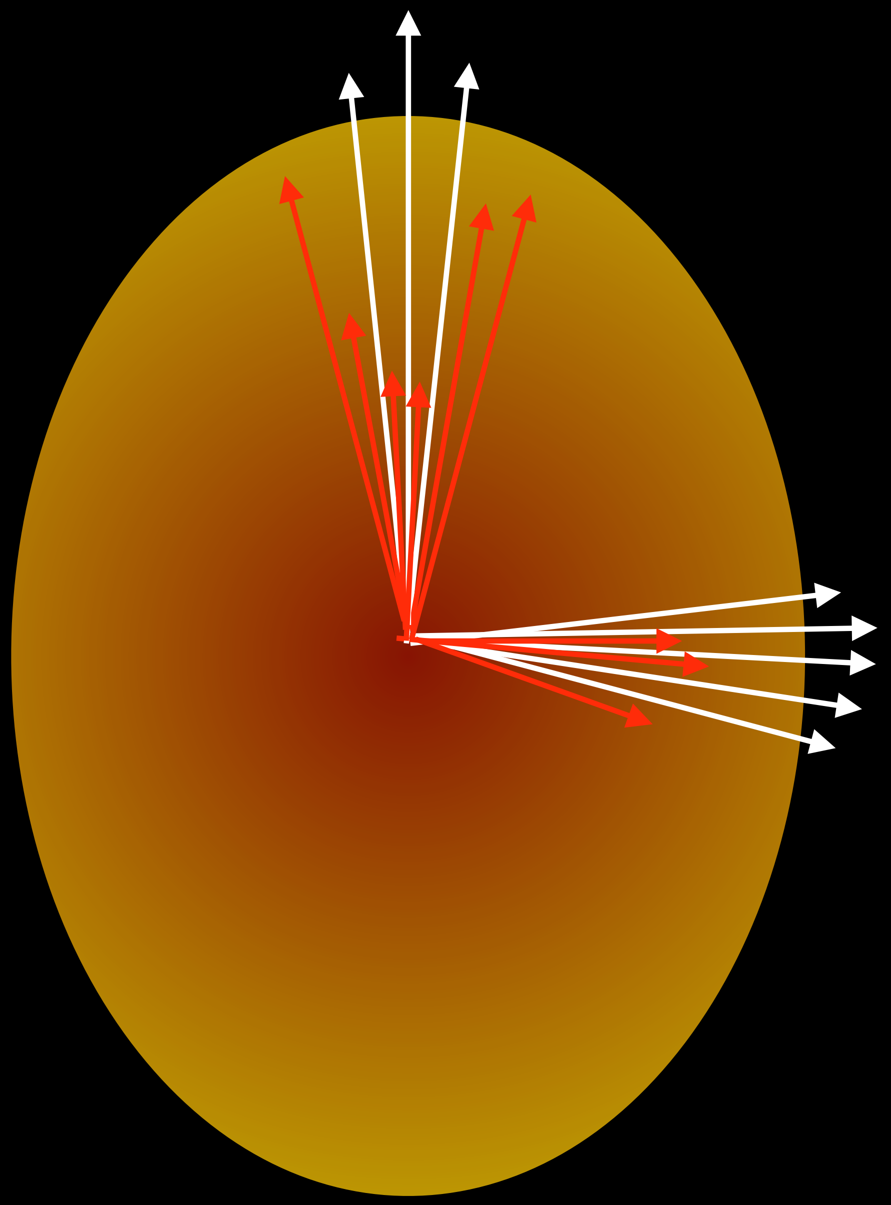
Identified particles v_2 at the LHC: high p_T

(ALICE), arXiv:1405.4632 [nucl-ex]

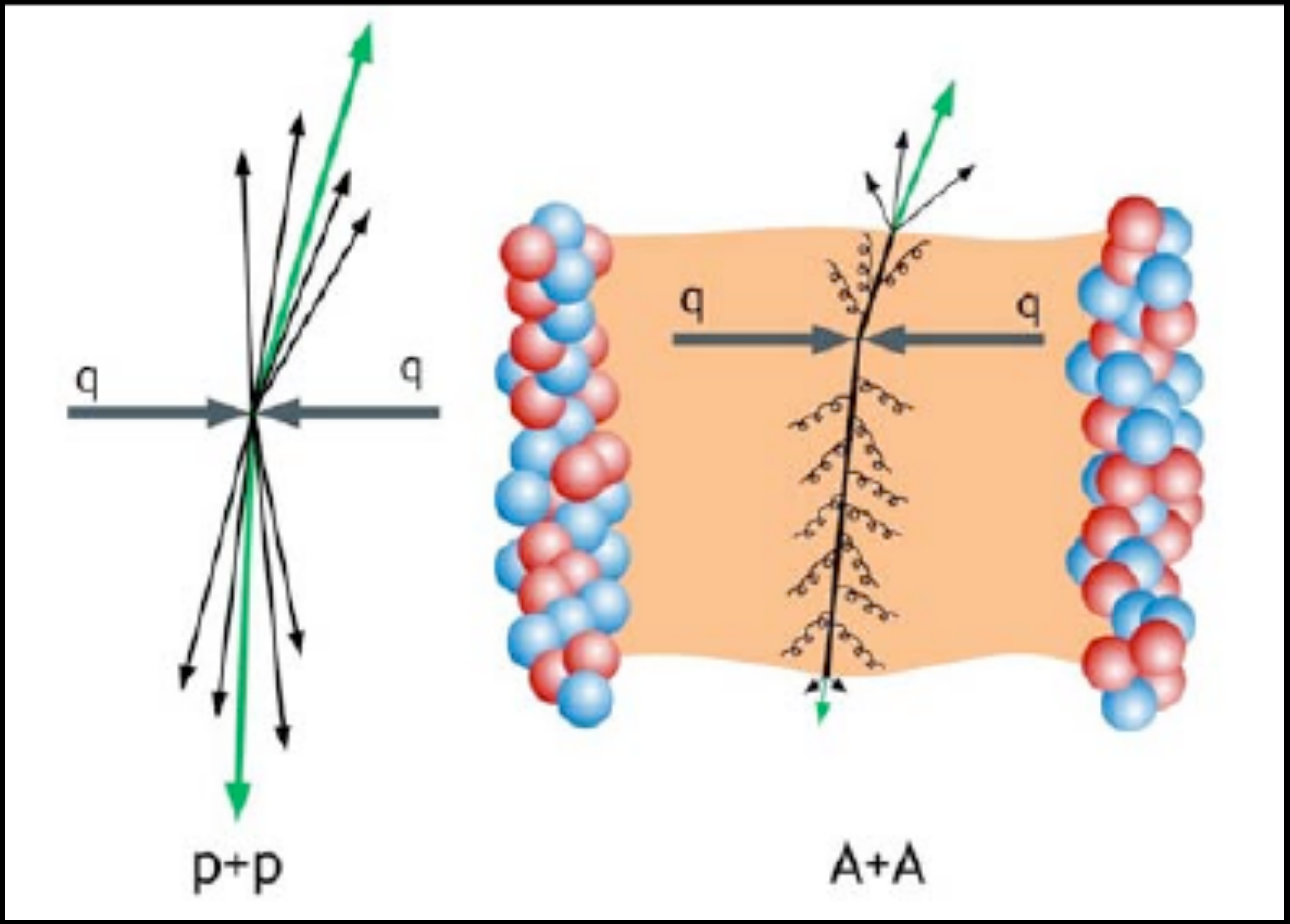
(ALICE), Physics Letters B 719 (2013) 18



The three momentum scales: high p_T (p_T > 8 GeV/c)

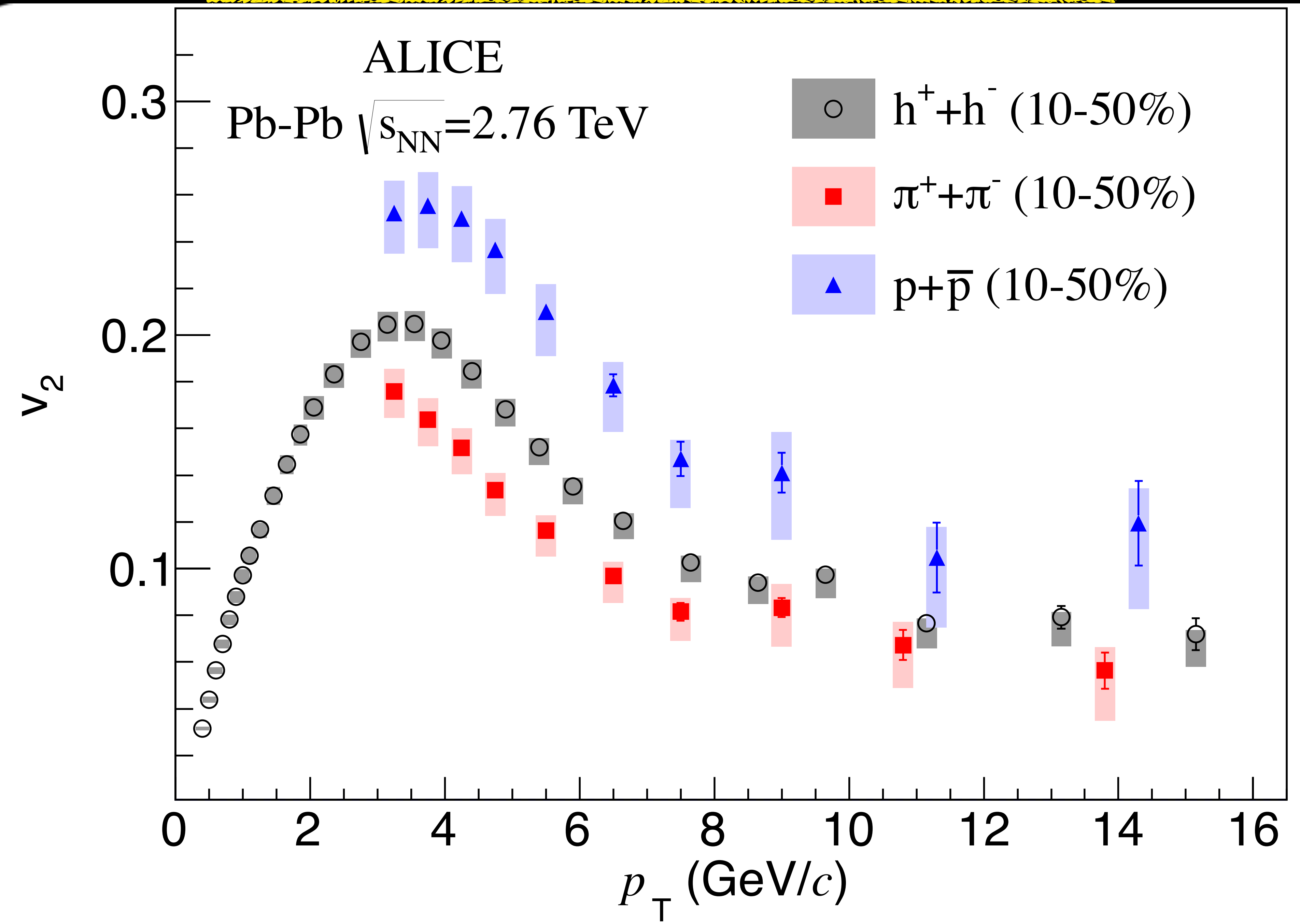


- Probing the path length dependence of energy loss
  - particles flying in-plane have to travel through less (more) medium
  - expect to see an azimuthal dependence of jets and high p_T particles



High p_T pions, kaons, protons @ LHC: v_2

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

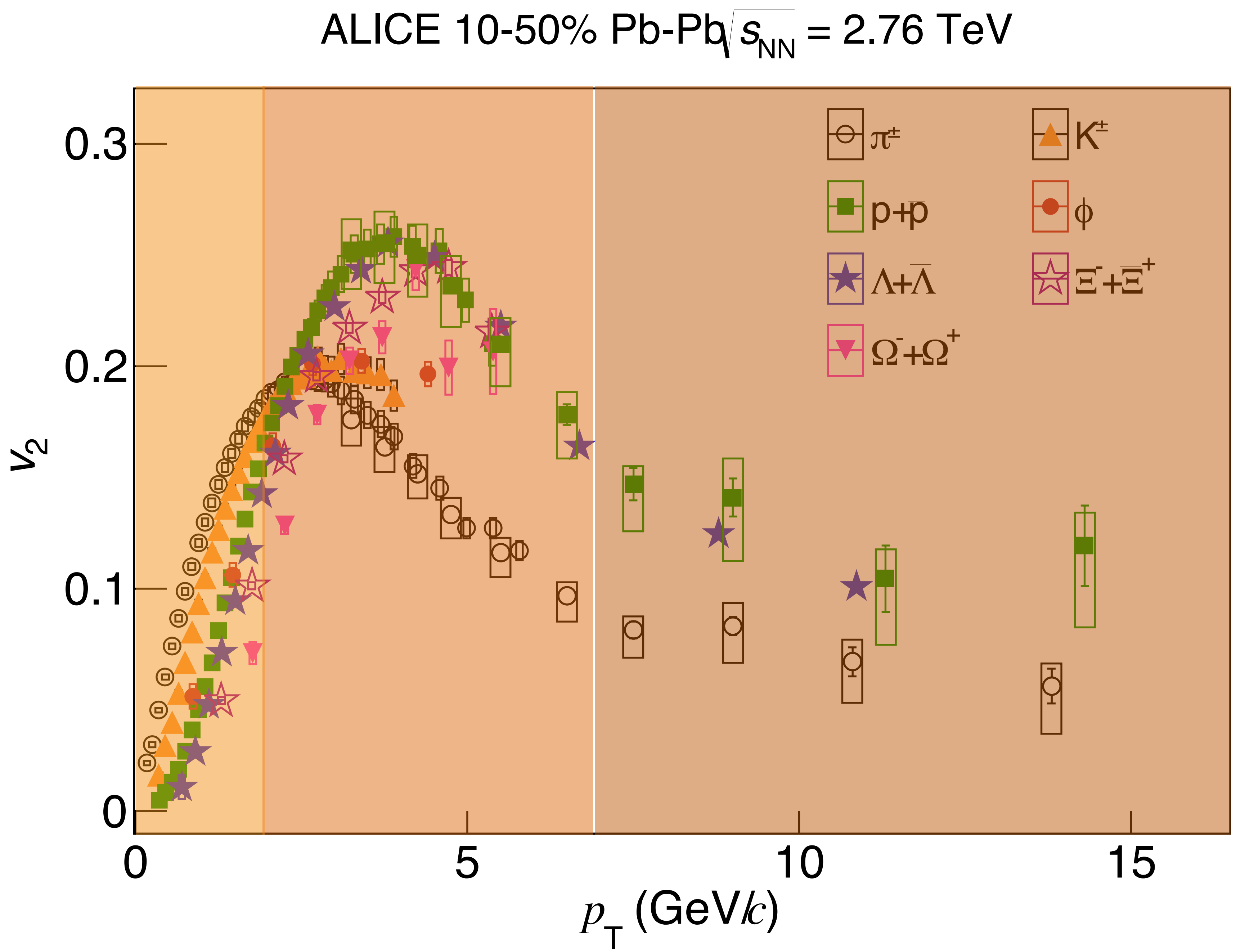


- Significant v_2 for all particle species at high p_T with no significant particle species dependence for p_T > 10 GeV/*c*

Identified particles v_2 at the LHC

(ALICE), arXiv:1405.4632 [nucl-ex]

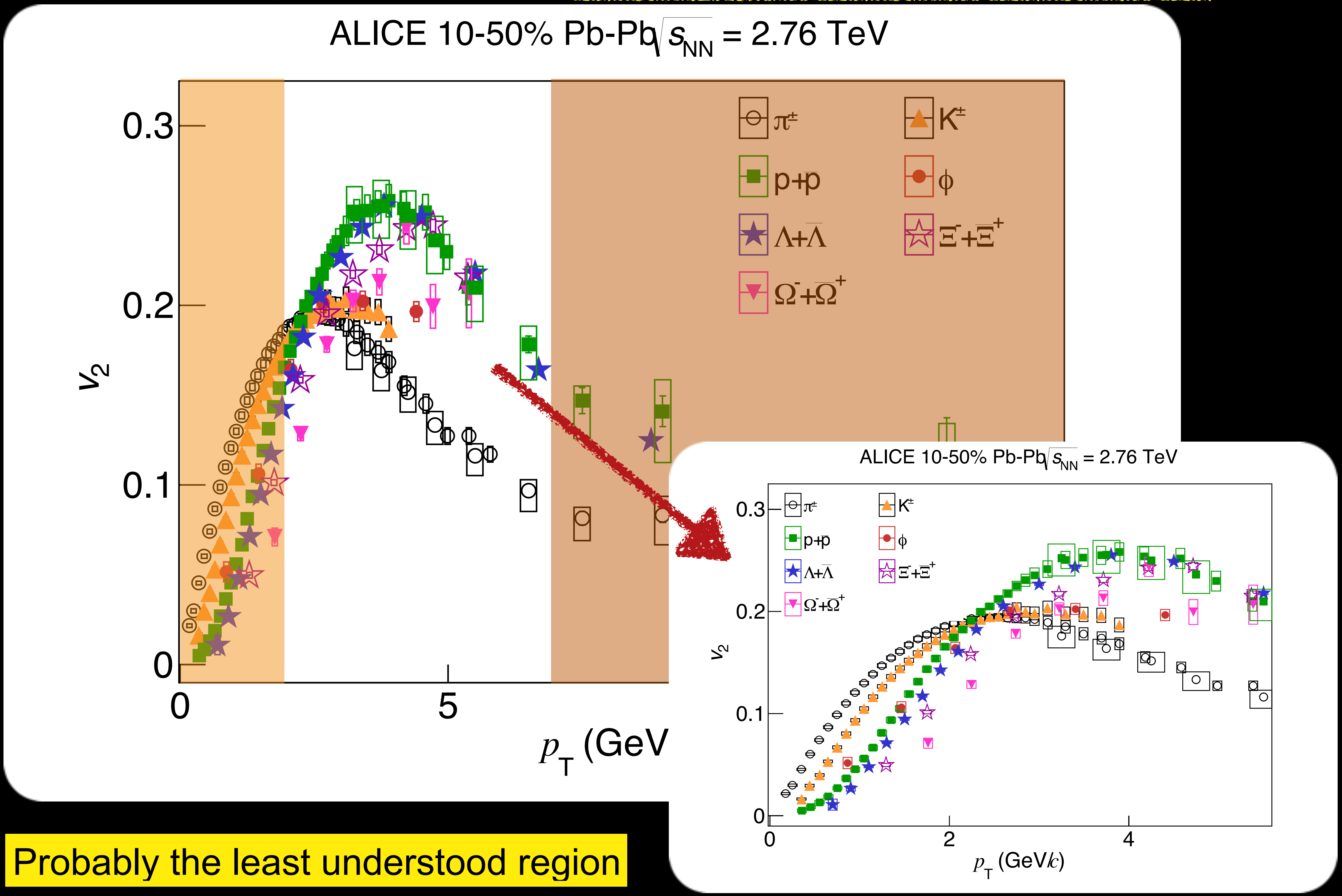
(ALICE), Physics Letters B 719 (2013) 18



Identified particles v_2 at the LHC: intermediate p_T

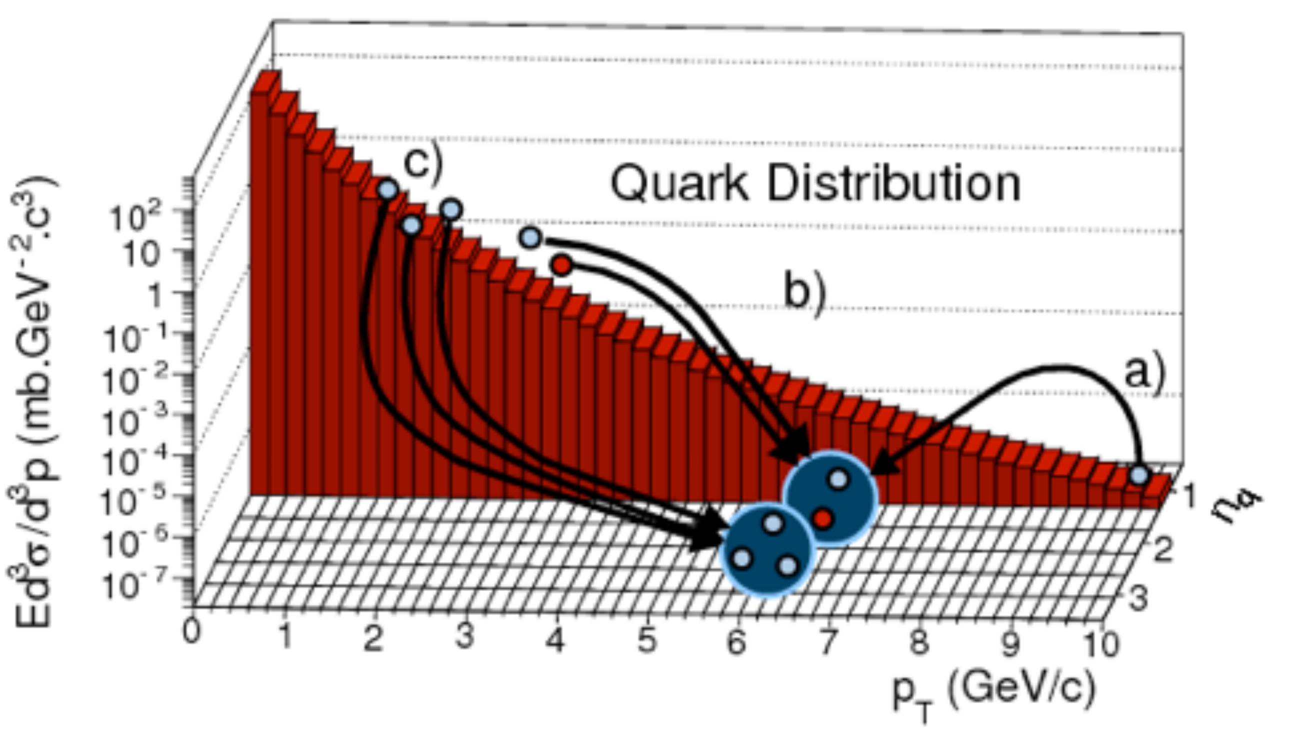
(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

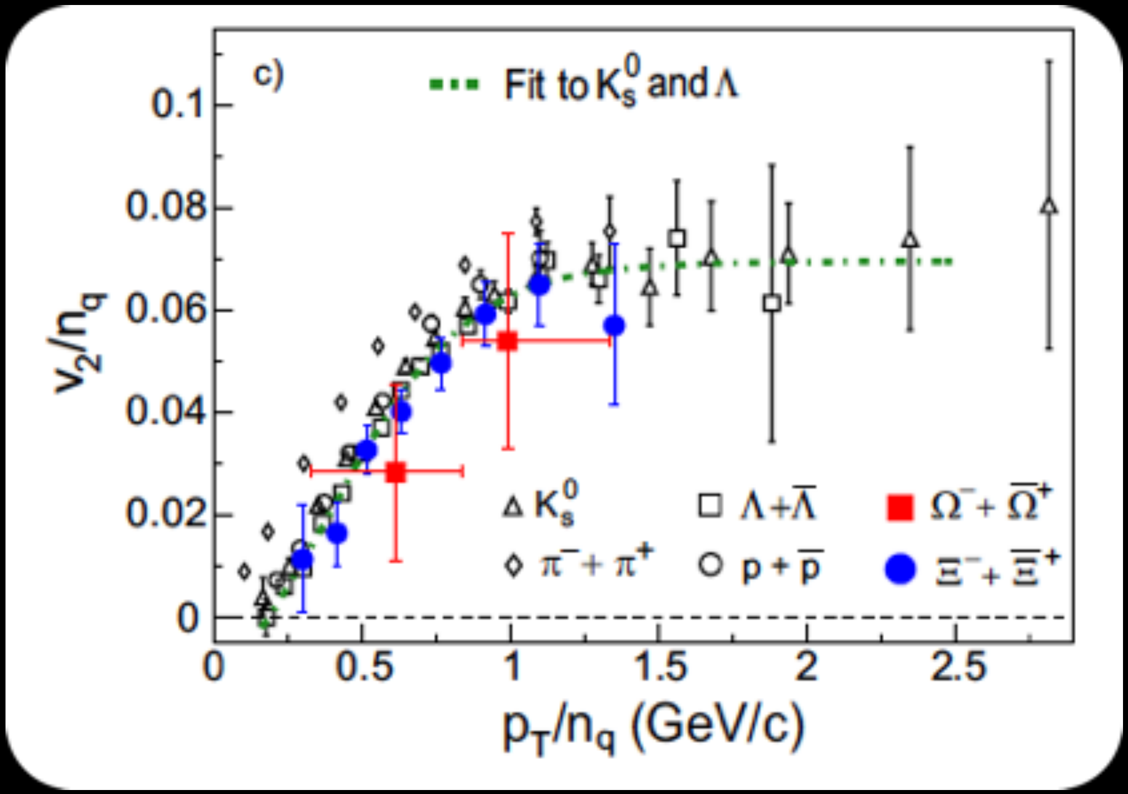


Probably the least understood region

The three momentum scales: intermediate p_T ($2 < p_T < 8$ GeV/c)

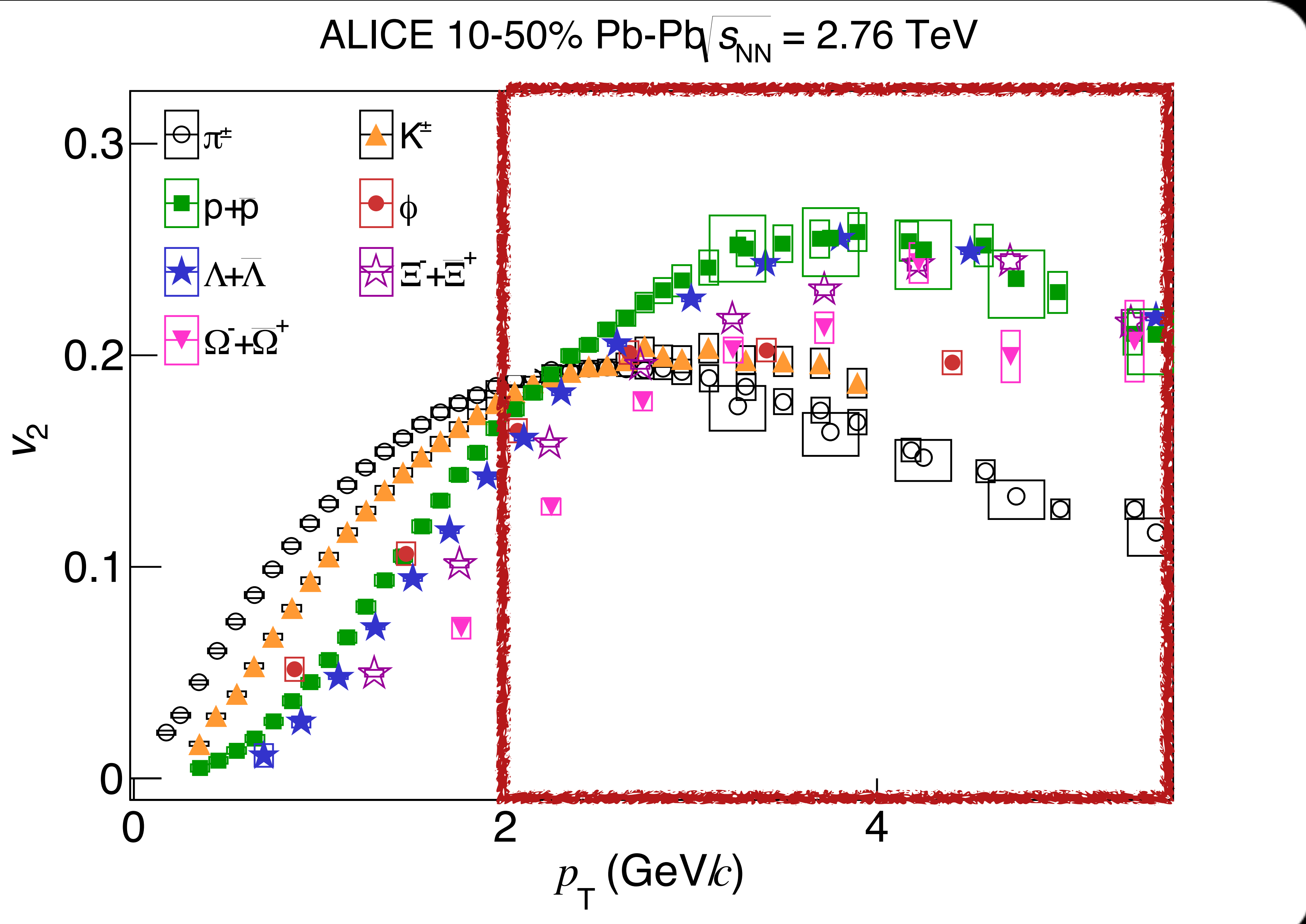


- Number of constituent quark (NCQ) scaling holding with good accuracy at RHIC
  - quarks coalesce forming hadrons?
  - NCQ scaling was considered as “evidence” of partonic degrees of freedom



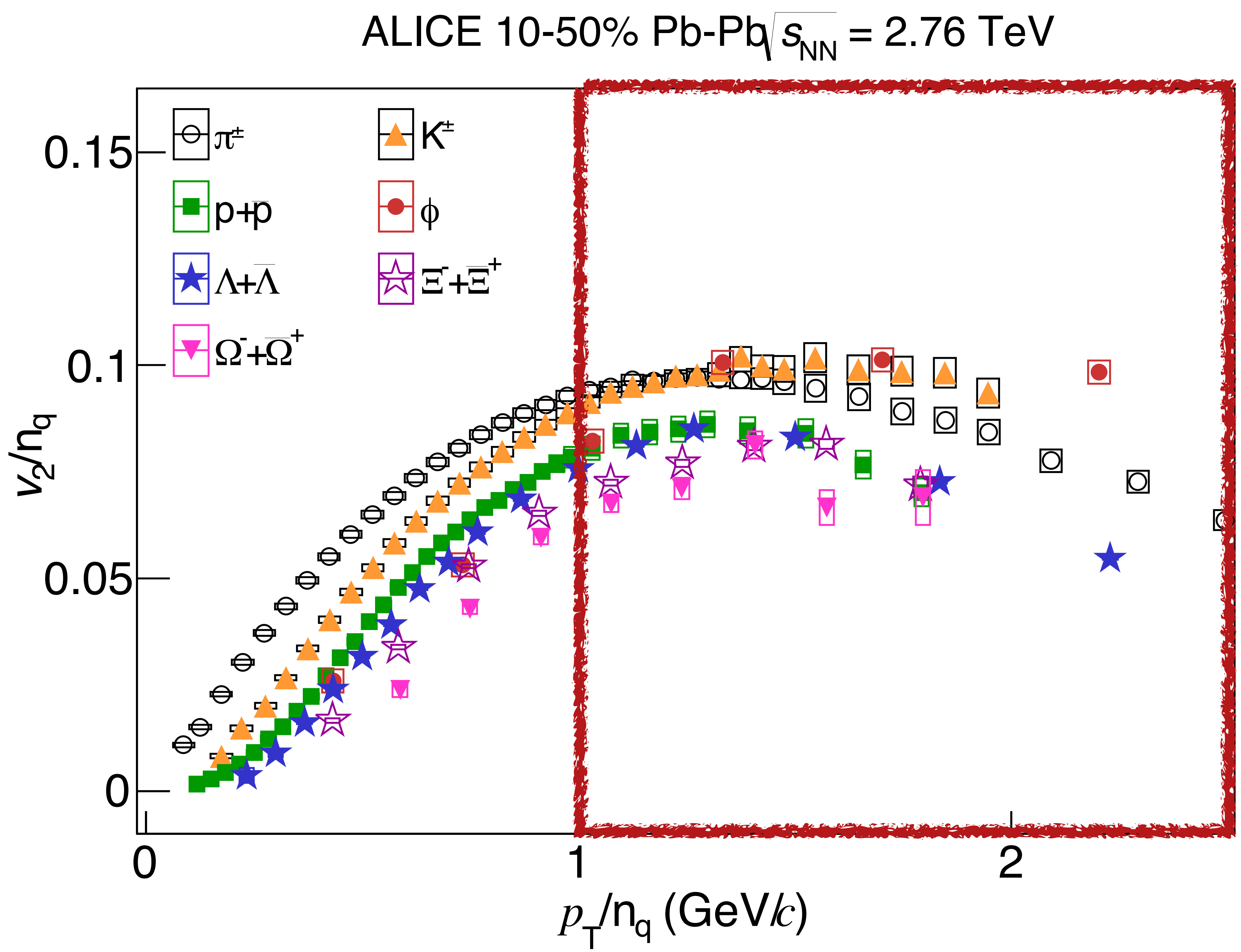
J. Adams *et al.*, (STAR Collaboration), Nucl.Phys. **A757** (2005) 102
K. Adcox *et al.*, (PHENIX Collaboration), Nucl. Phys. **A757**, (2005) 184

NCQ scaling at the LHC

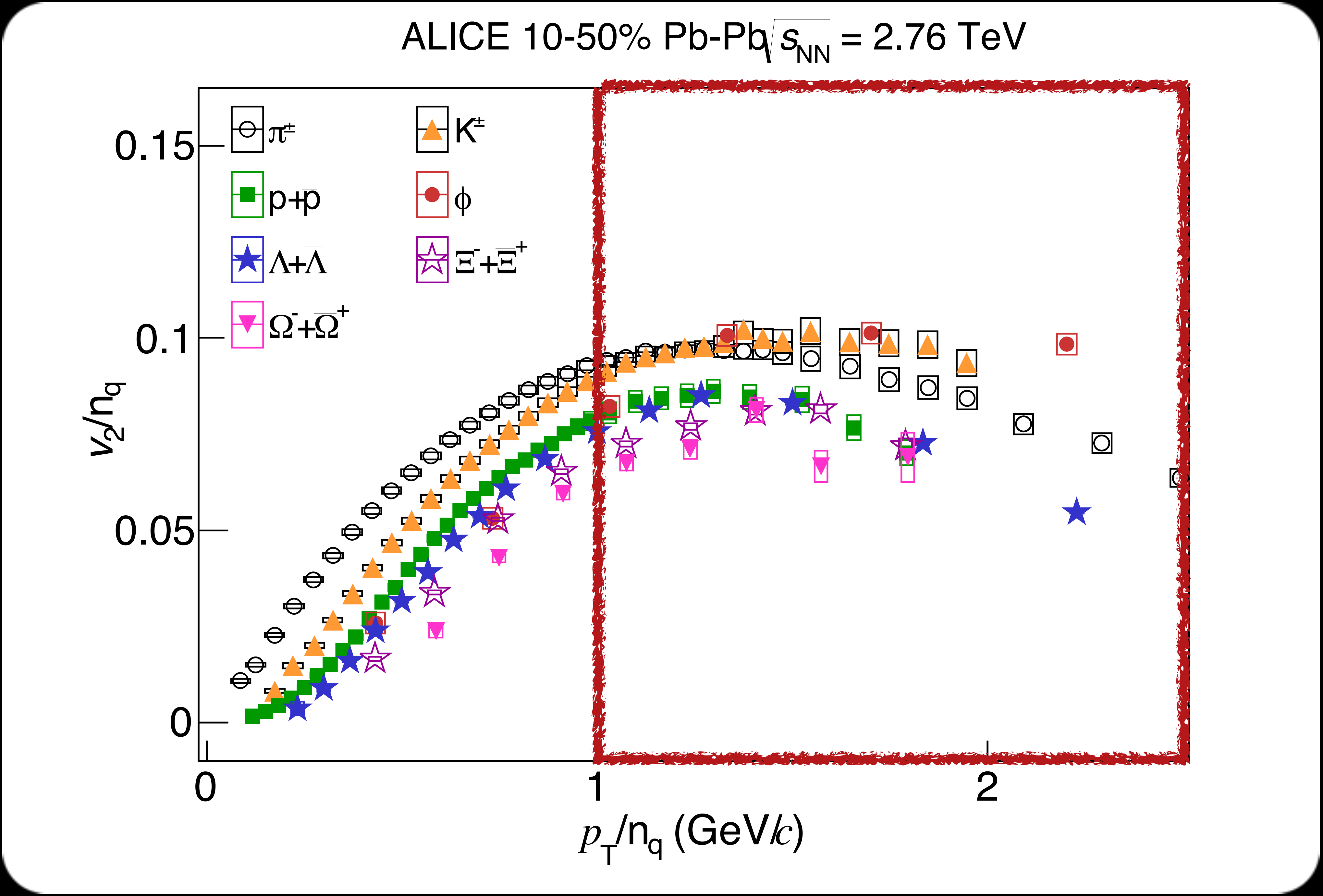


Panos.Christakoglou@nikhef.nl

Scaling properties at the LHC

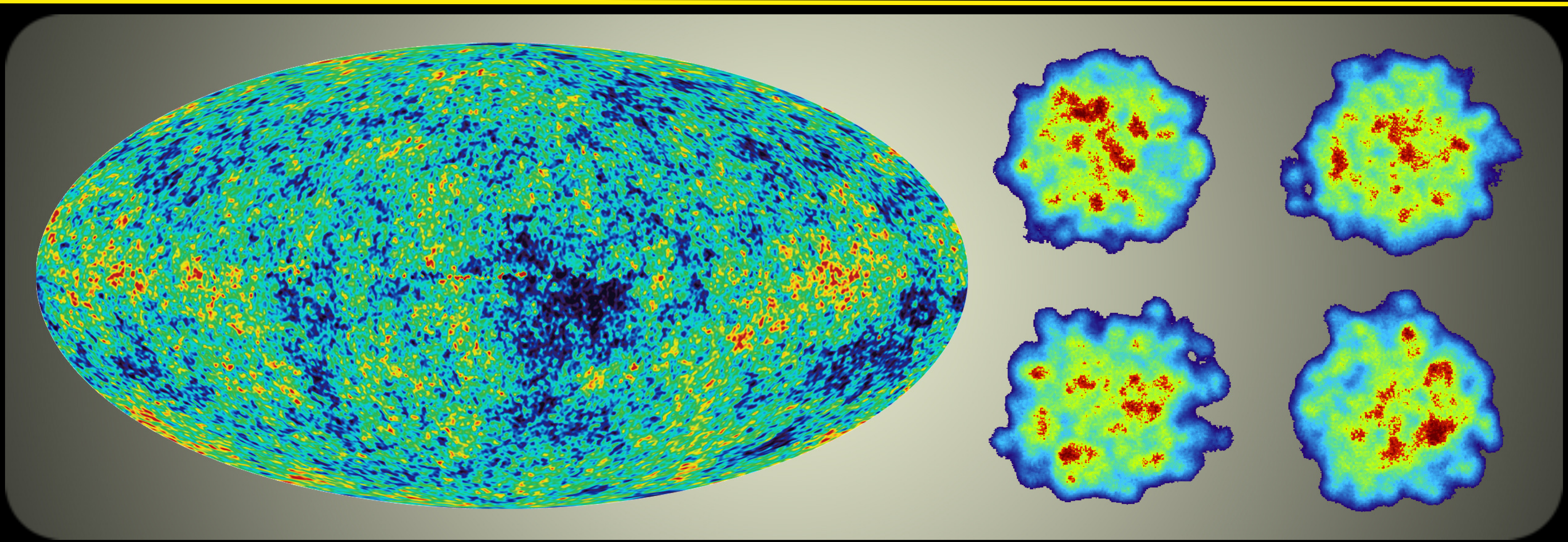


Intermediate p_T : scaling at an approximate level

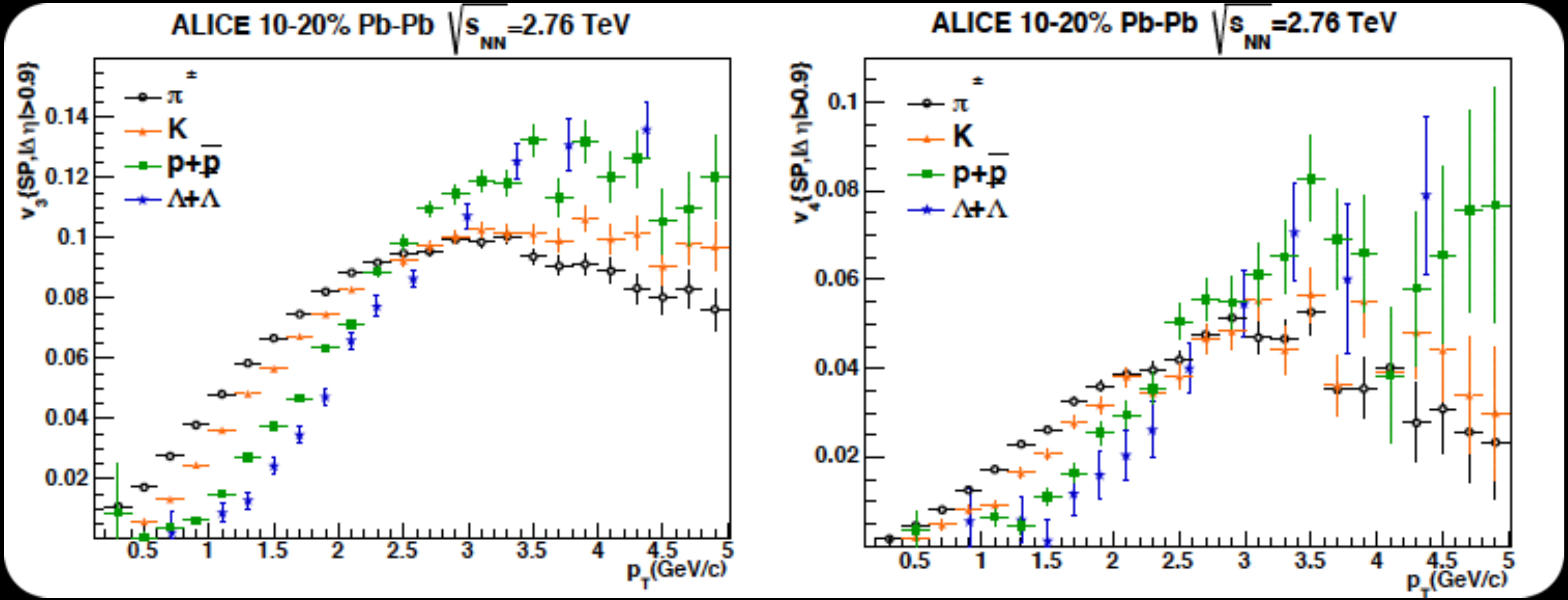


Theory was already based on approximations → need for refinement (e.g. how does hadronic rescattering affect the scaling?)

And there is even more…: higher harmonics!



Due to the low value of η/s, higher harmonics survive at the final state
Allow the study of initial conditions of heavy-ion collisions for the first time!



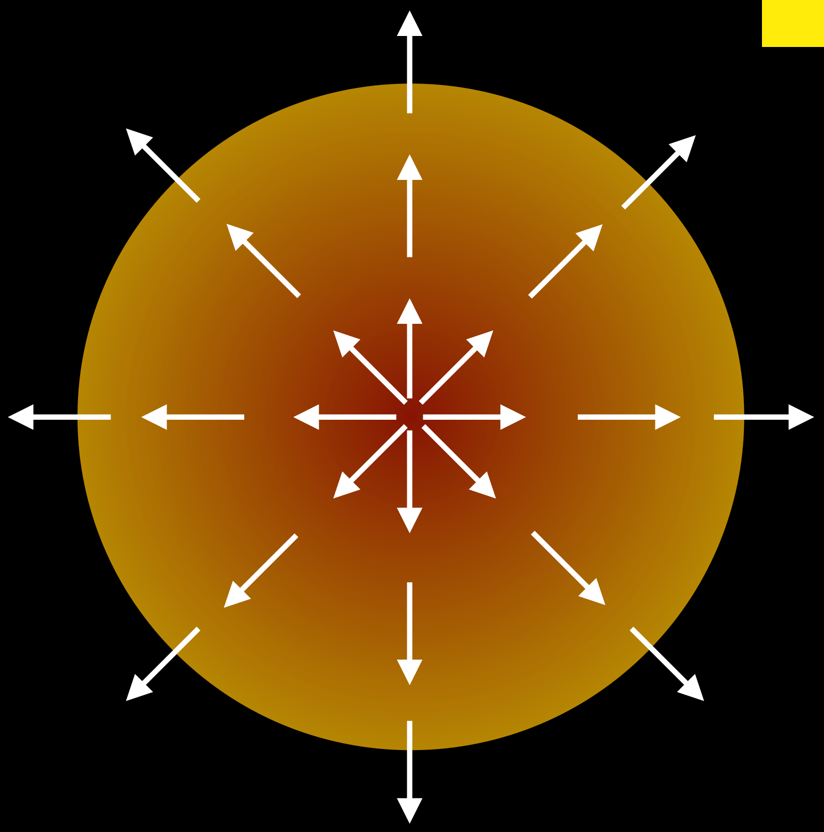

Yes, We Can!

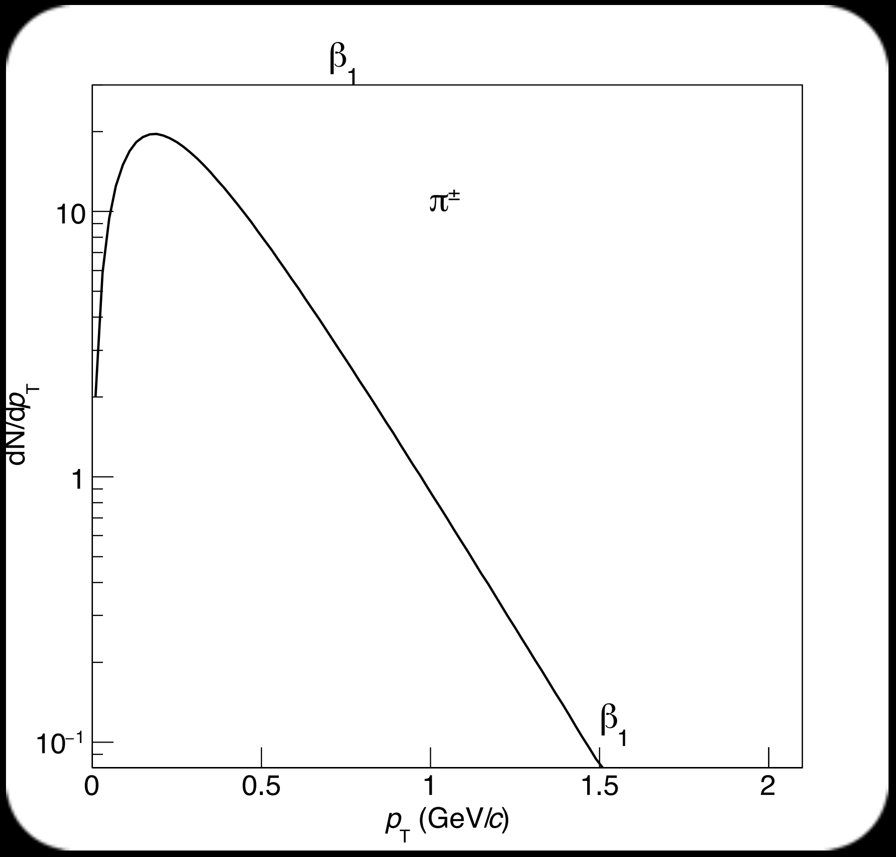
Thank you for your attention!

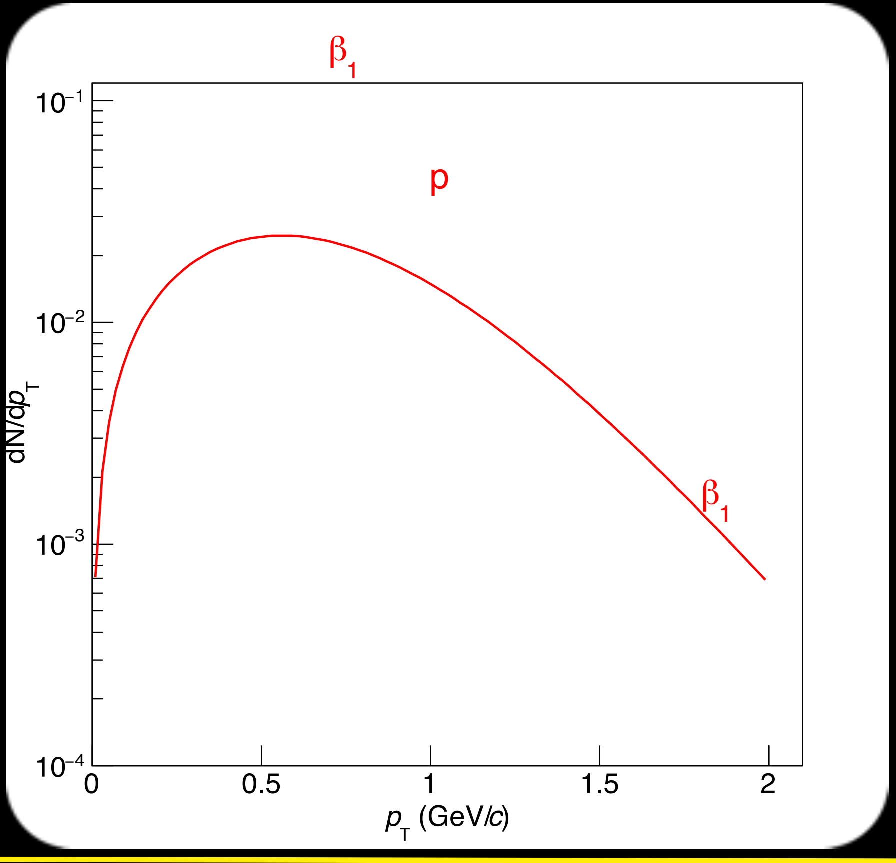
Backup

How does mass ordering develop?

Toy model



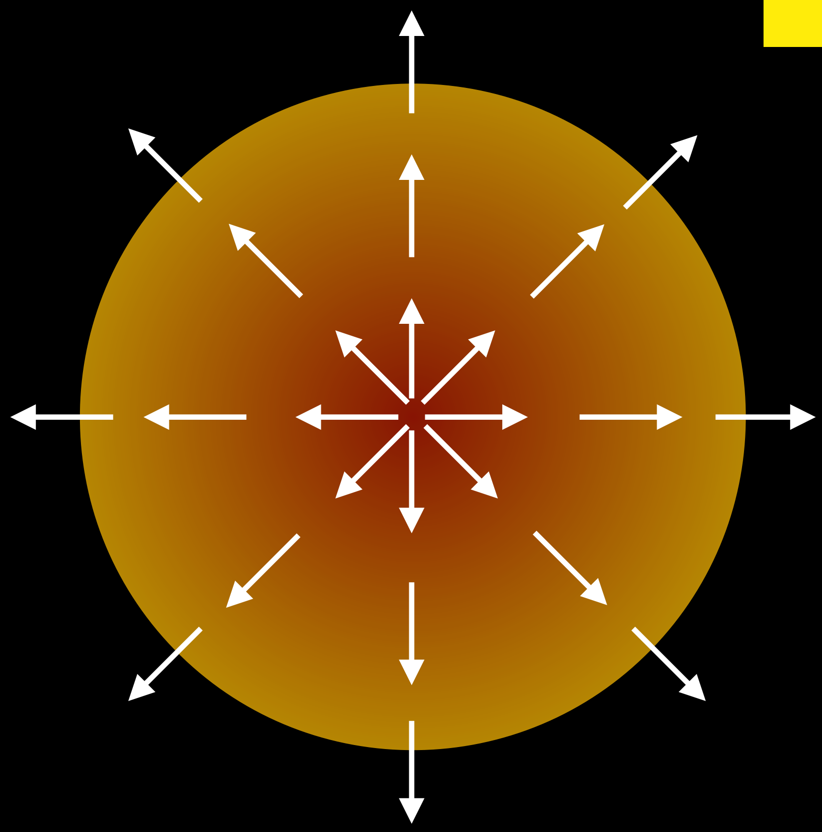


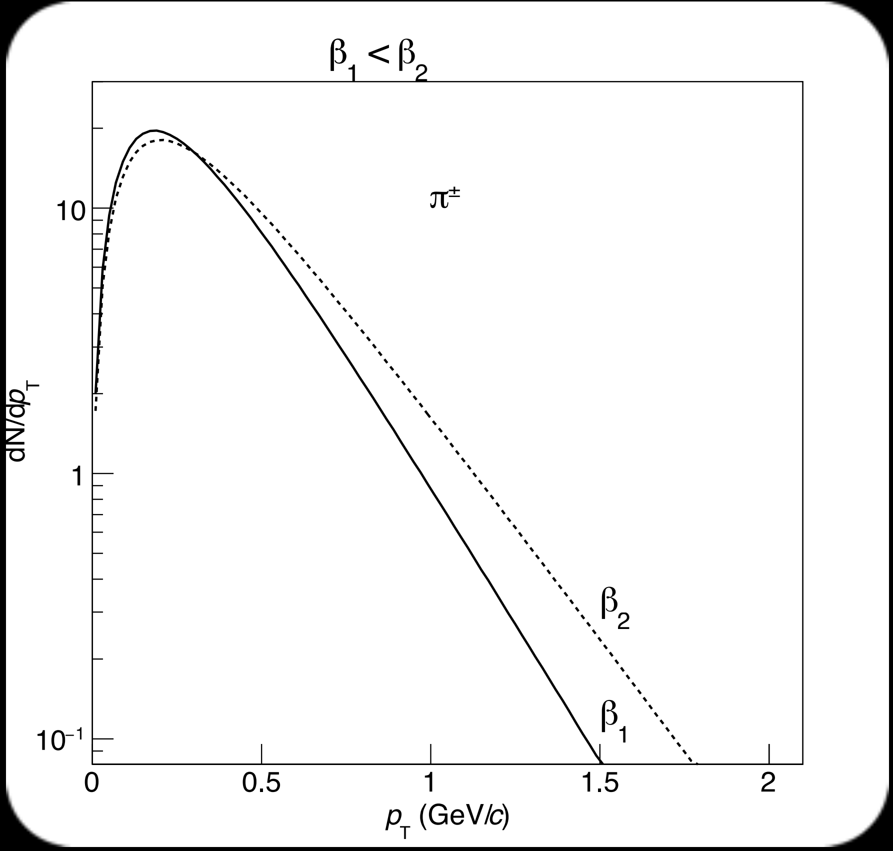


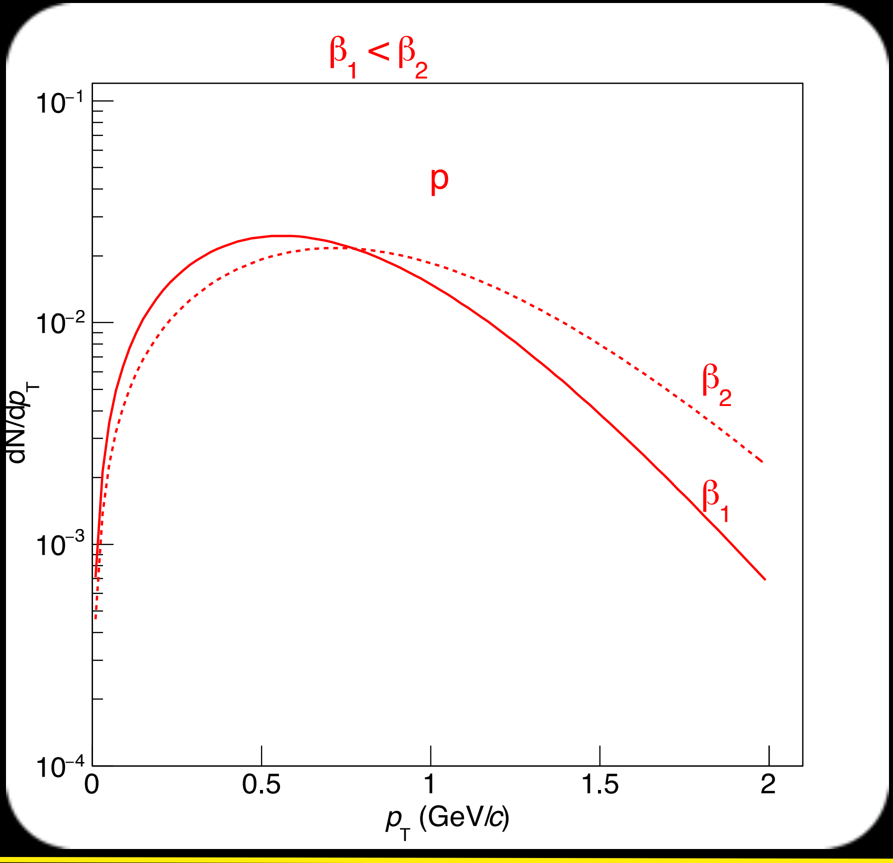
- Radial flow pushes particles to higher p_T → depletion at lower p_T
  - heavier particles "feel" more the boost → the higher the mass the larger the low p_T depletion

How does mass ordering develop?

Toy model







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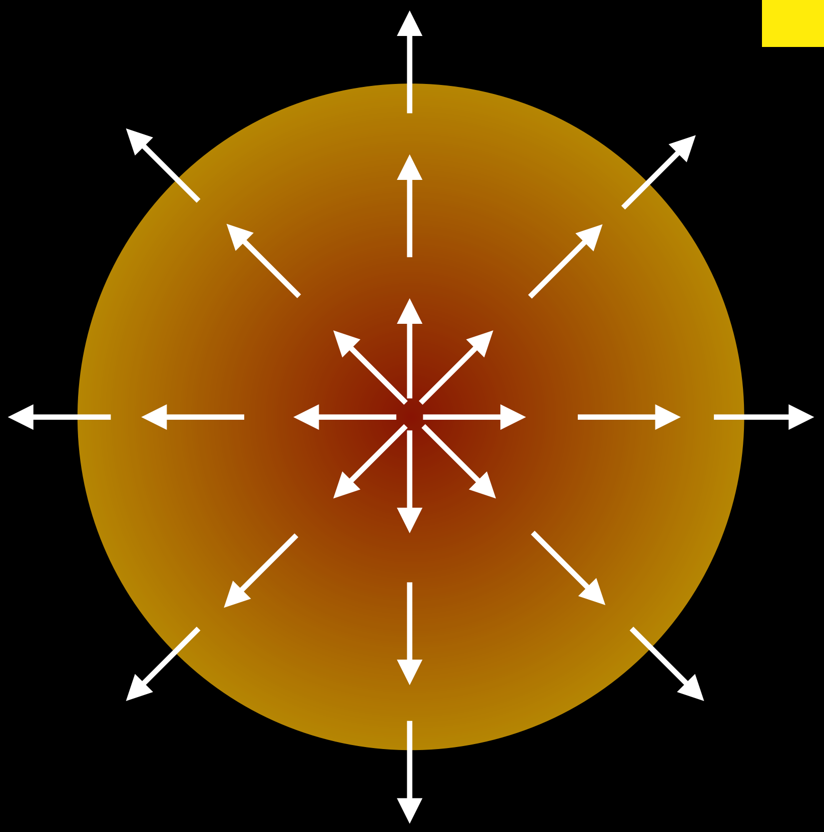
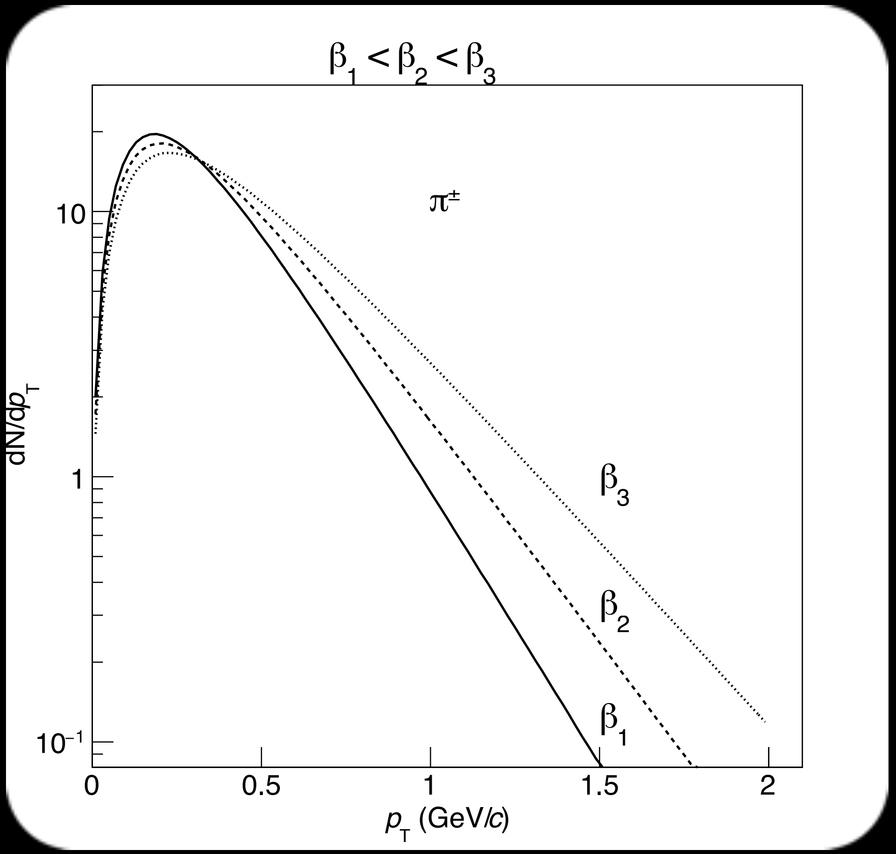
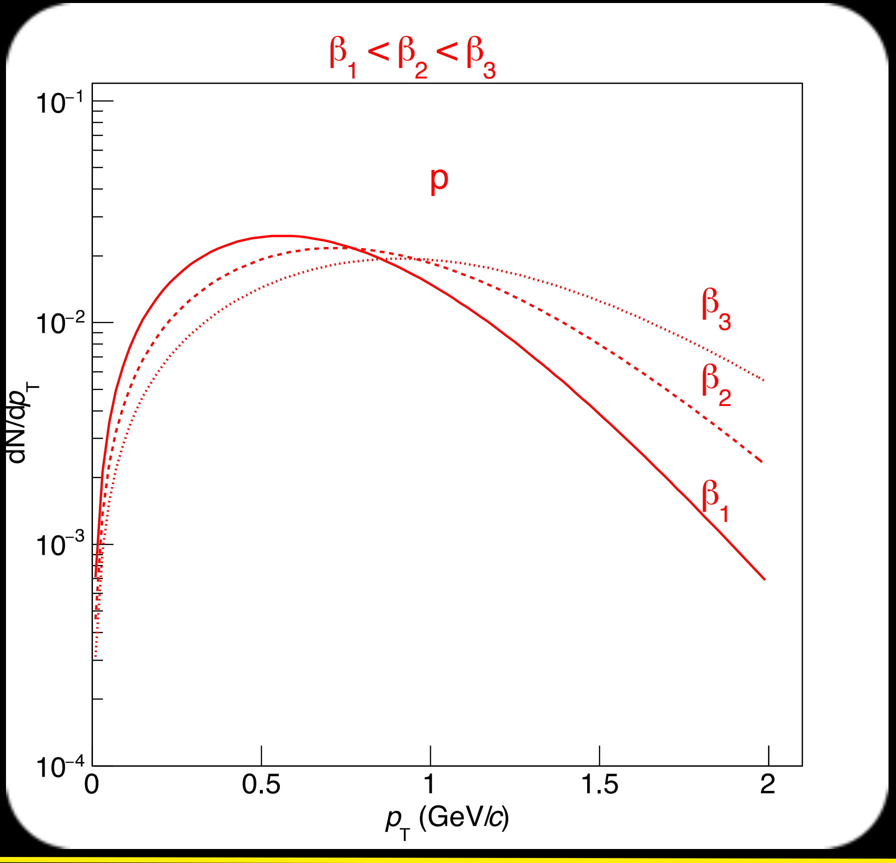
How does mass ordering develop?

Toy model







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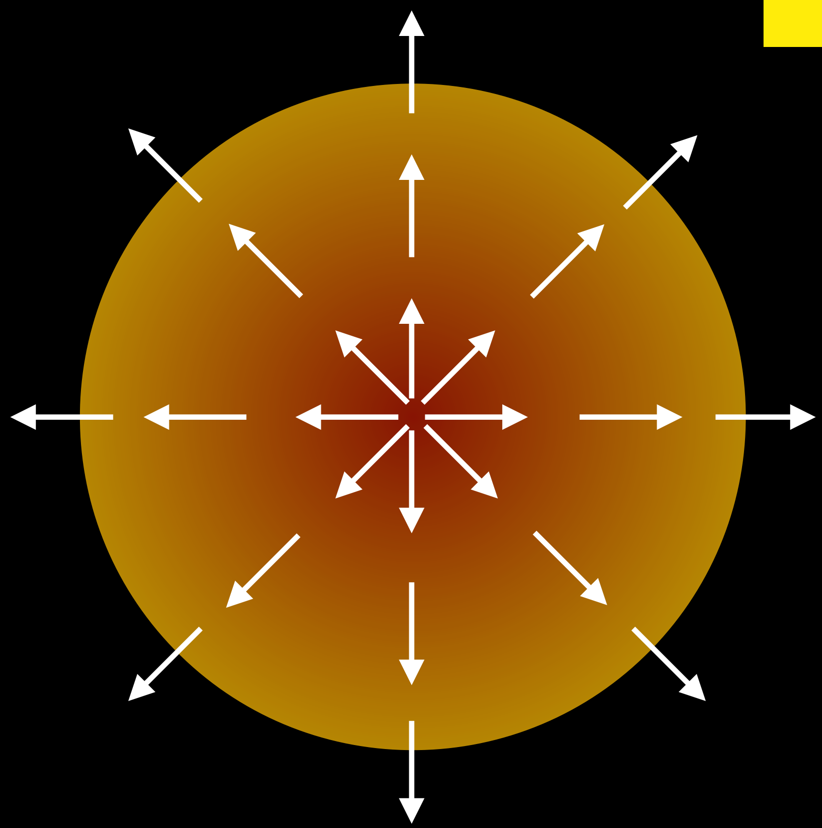
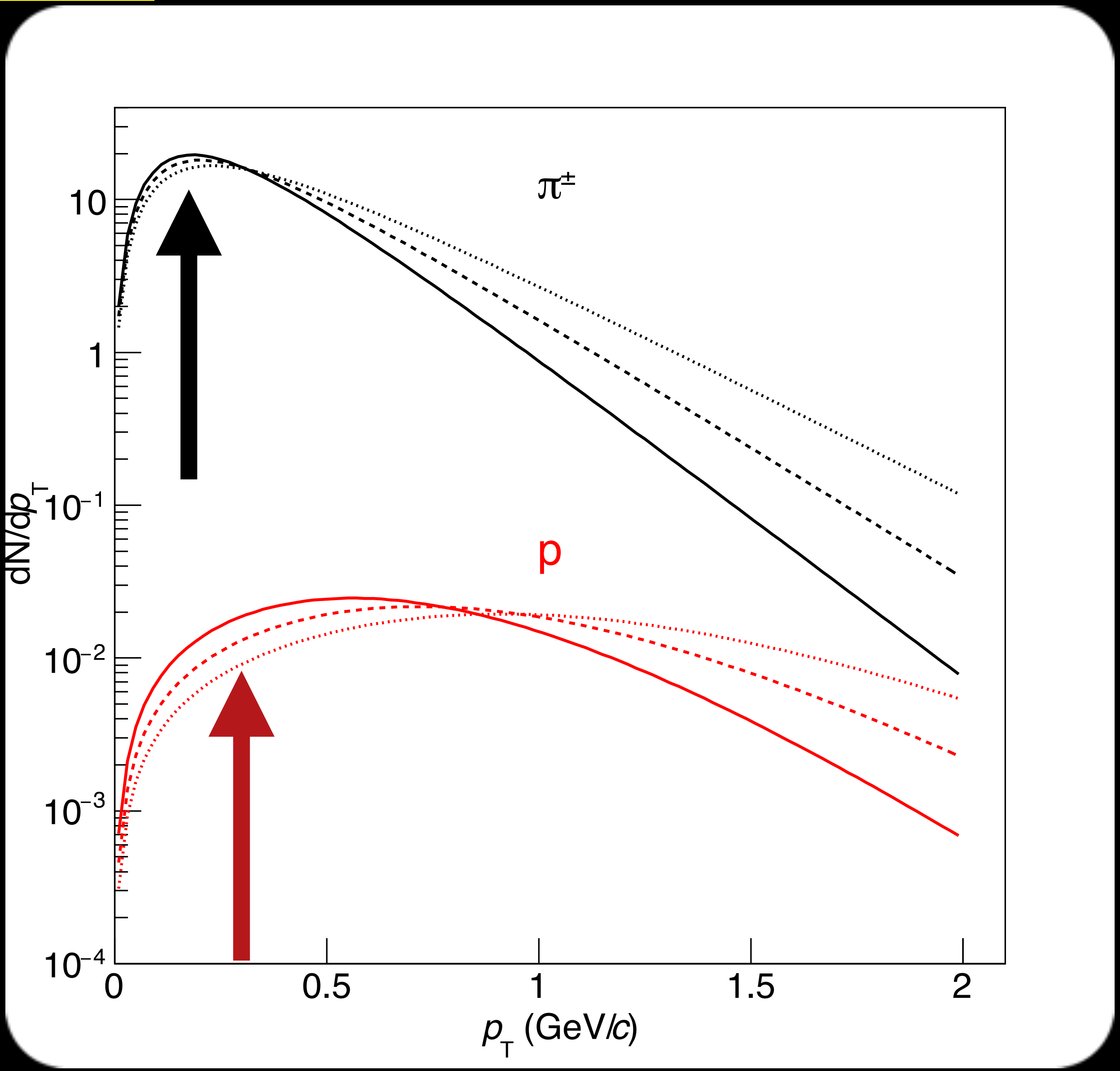
How does mass ordering develop?

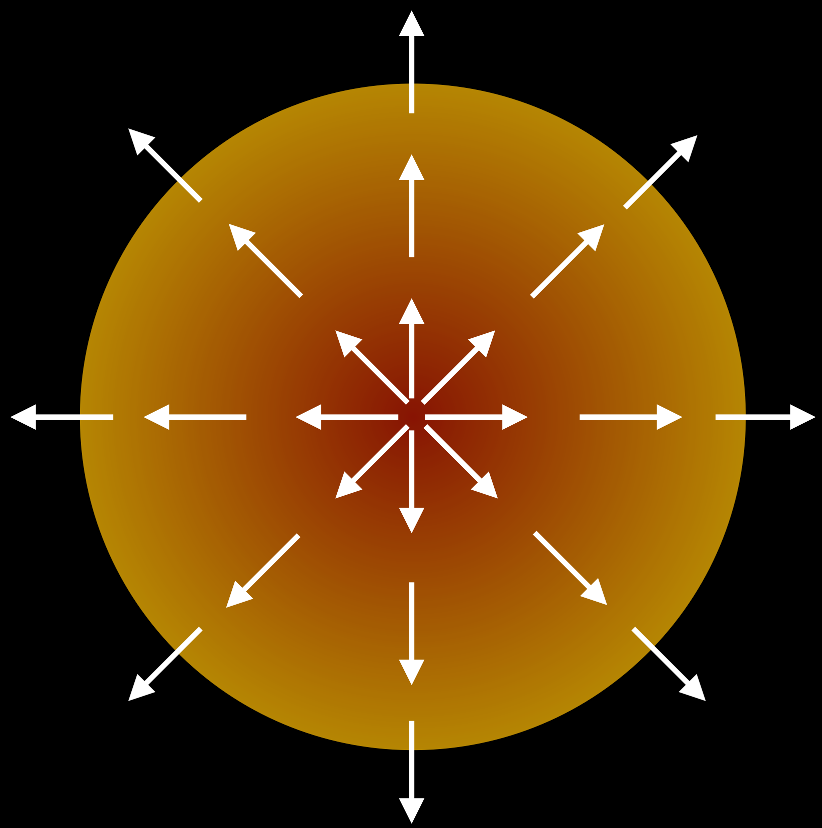
Toy model



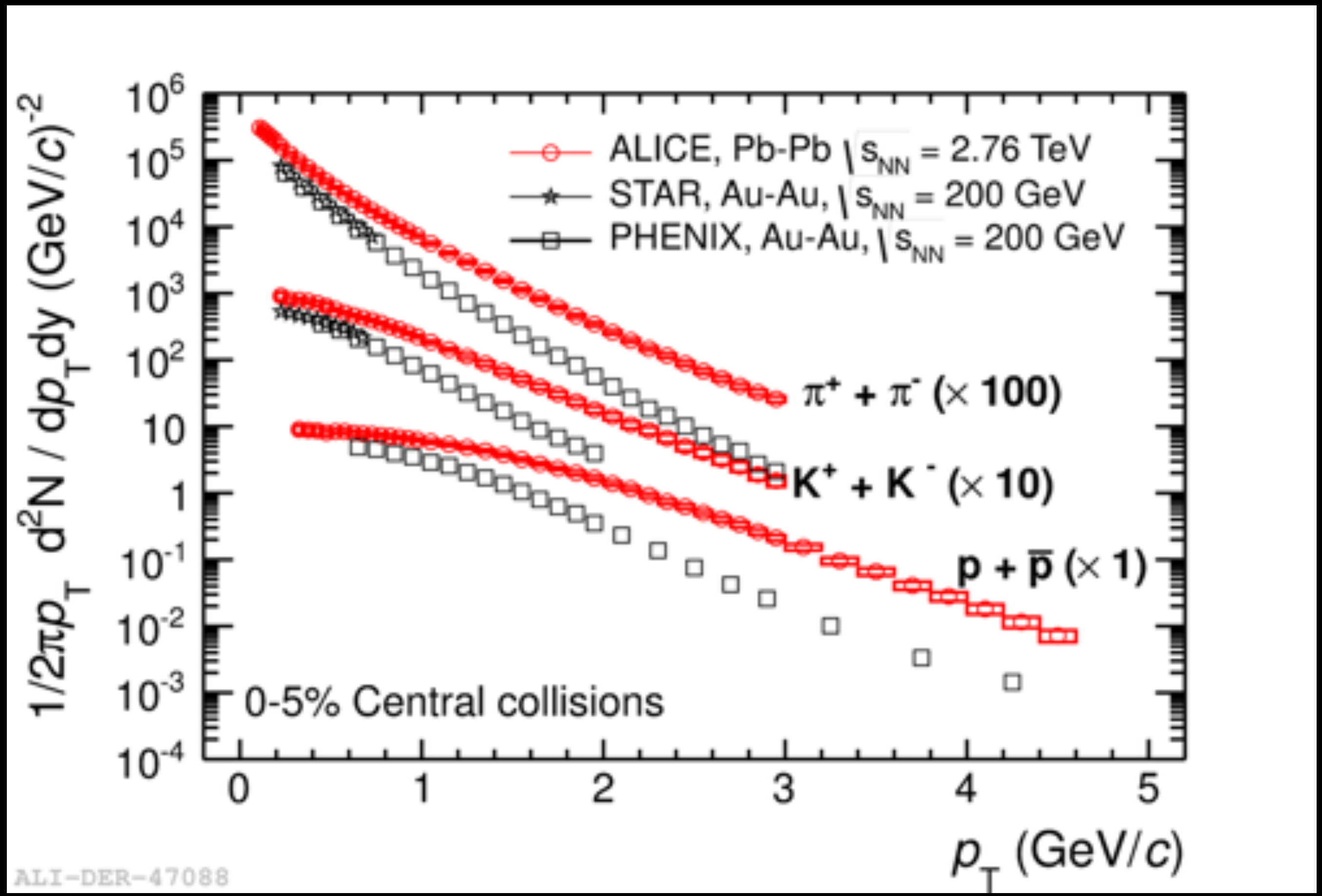


- Radial flow pushes particles to higher p_T ➞ depletion at lower p_T
  - heavier particles "feel" more the boost ➞ the higher the mass the larger the low p_T depletion

How does mass ordering develop?



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



- Radial flow pushes particles to higher p_T ➞ depletion at lower p_T
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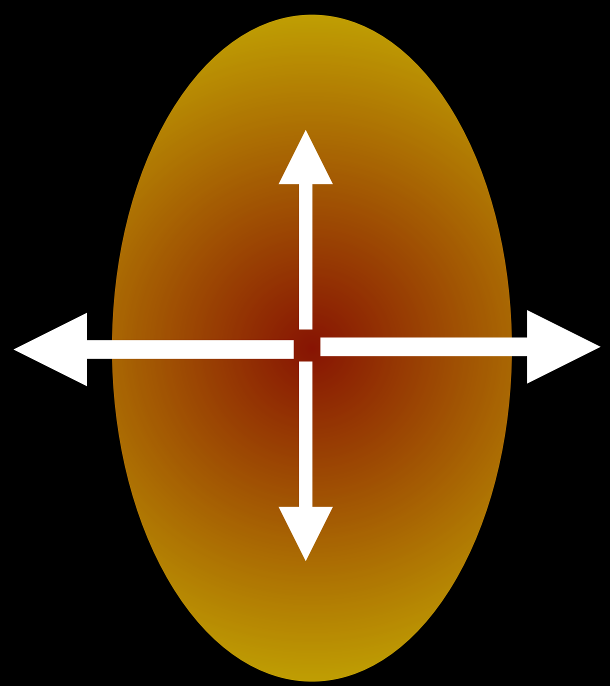
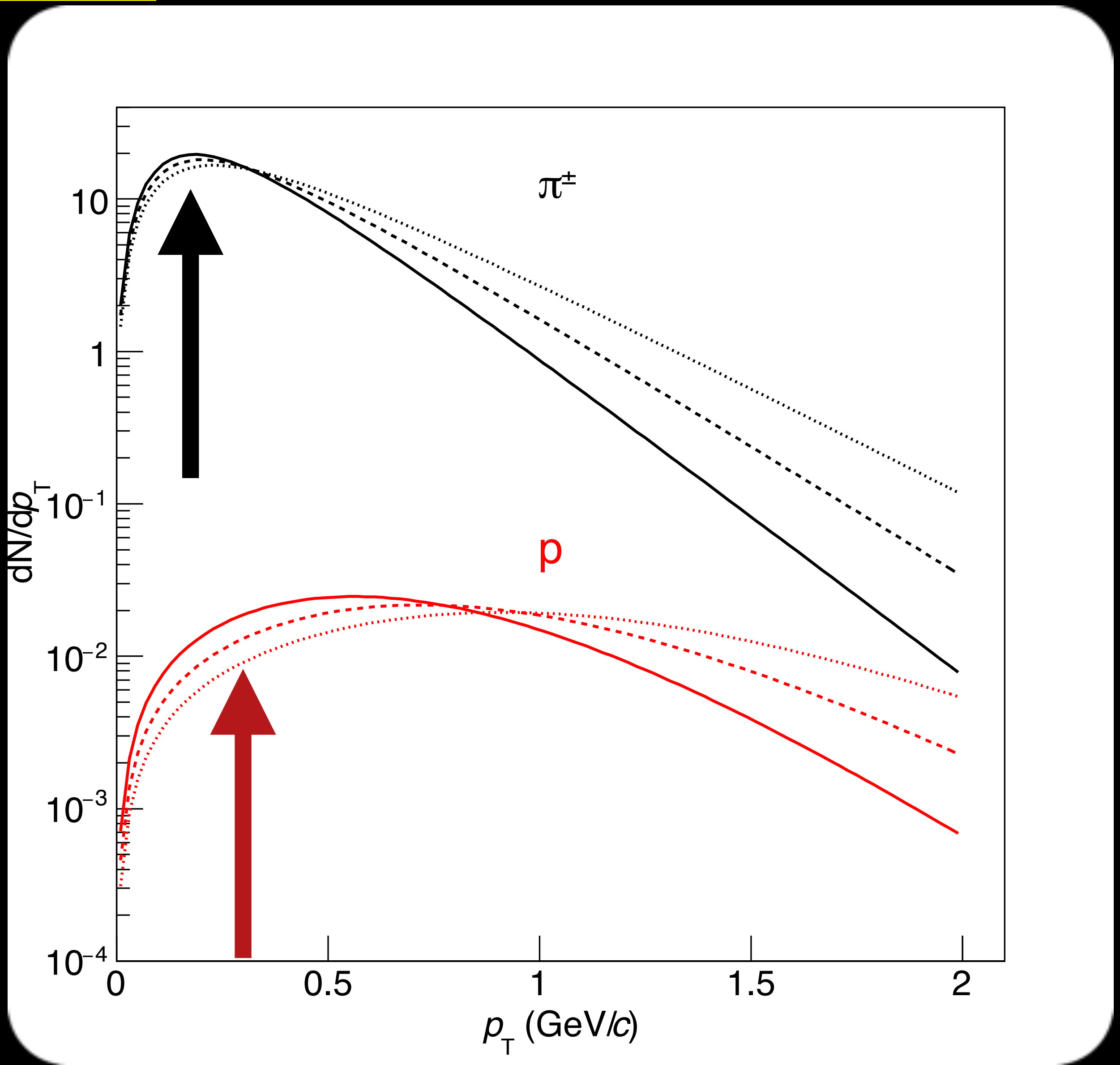
Collision data

How does mass ordering develop?

Azimuthally asymmetric system



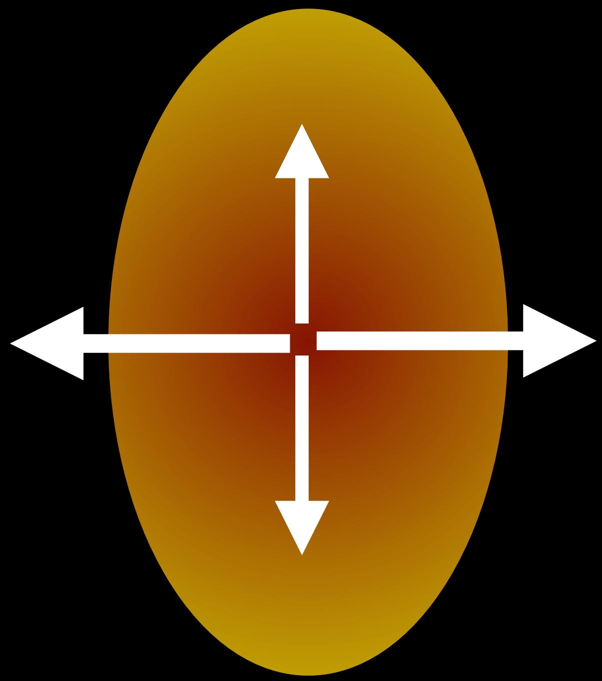
Toy model



- 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

$$v_2 \sim \frac{N_{in-plane} - N_{out-of-plane}}{N_{in-plane} + N_{out-of-plane}}$$

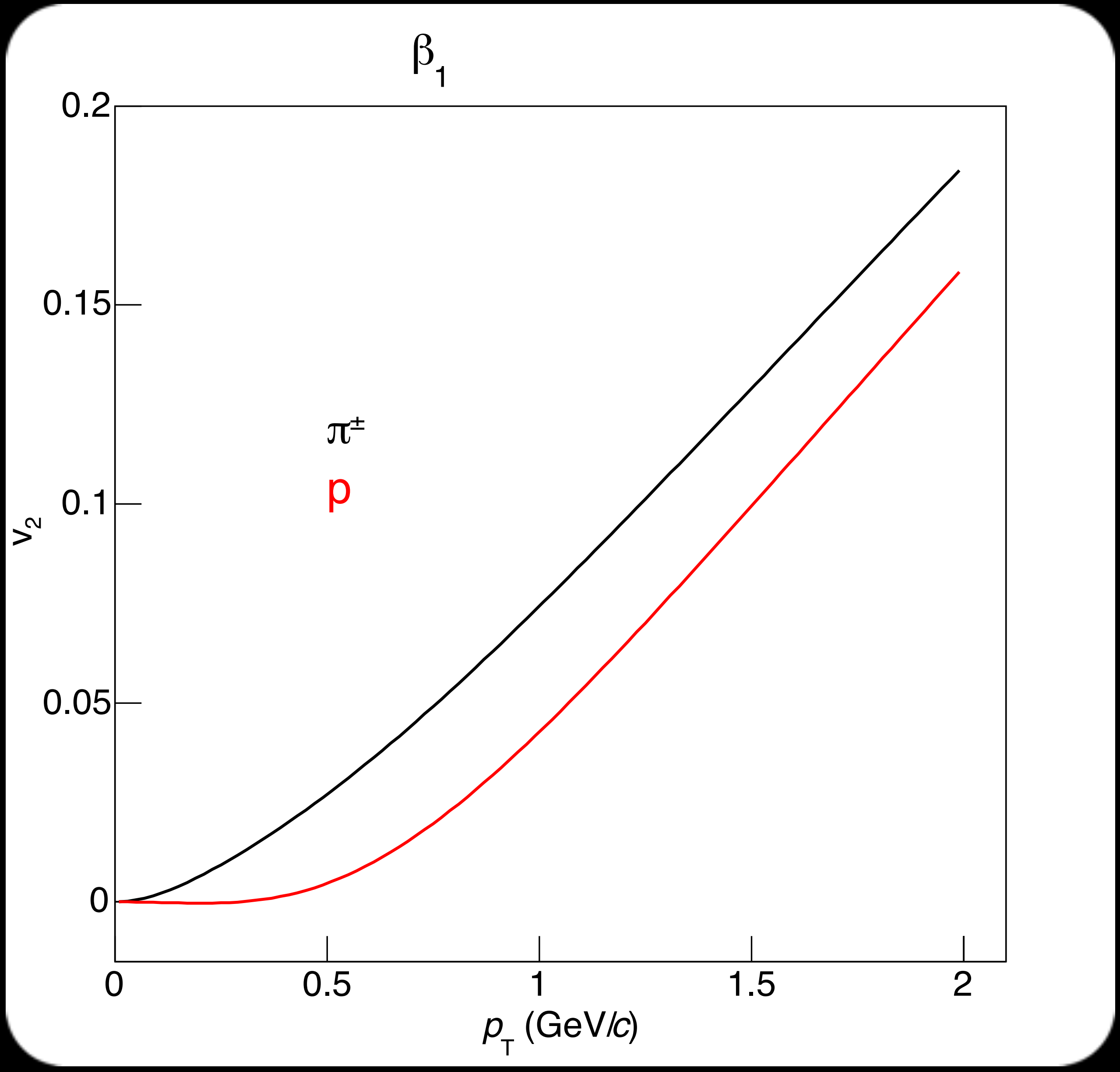
Azimuthally asymmetric system



- 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

Toy model

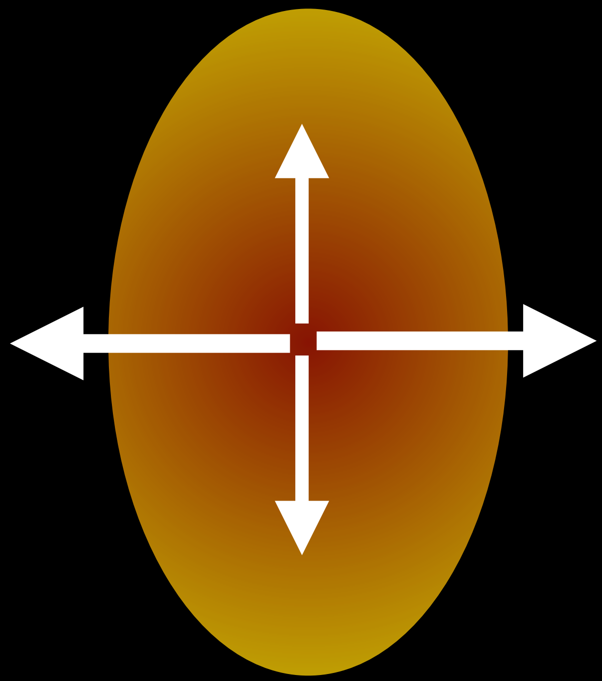
Heavy particles have lower v_2 at a fixed p_T than light particles

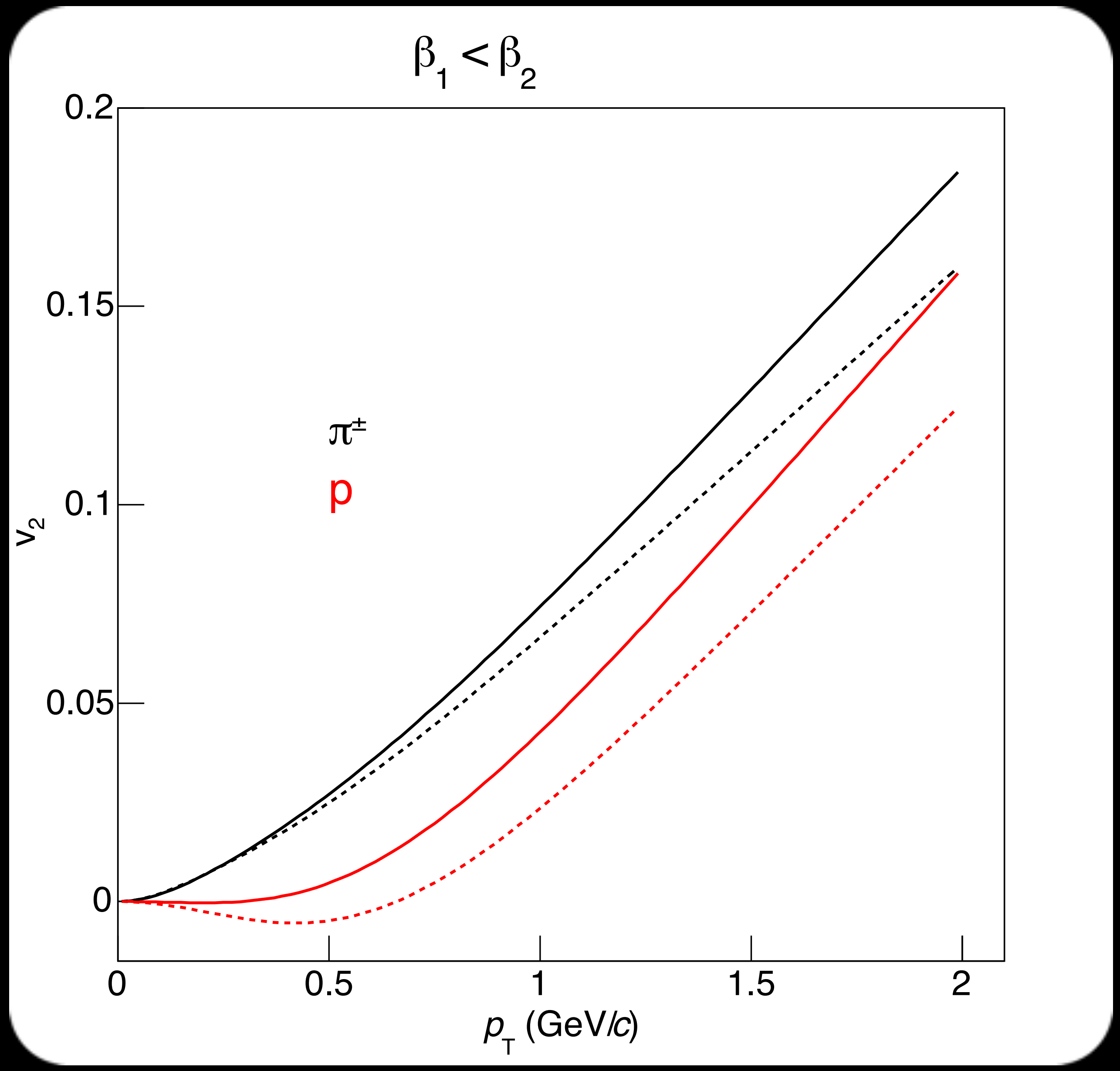


Toy model

Azimuthally asymmetric system

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





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  - larger low-p_T depletion in-plane than out-of-plane → lower v_2 in a mass dependent way

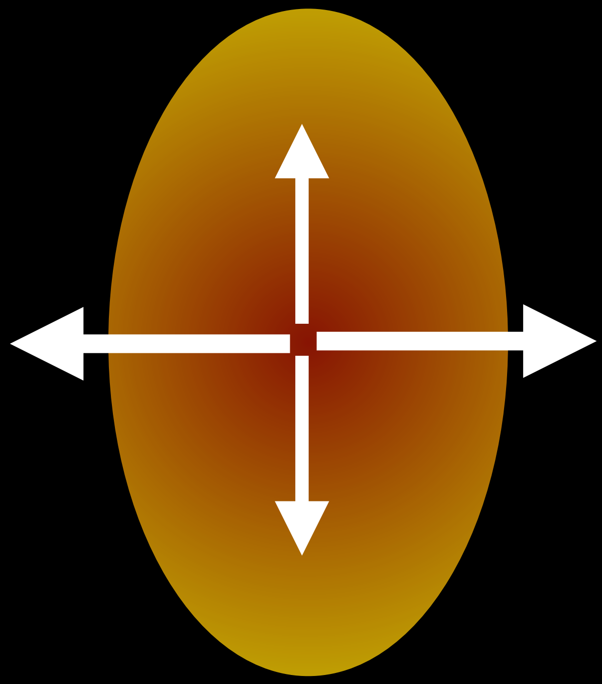
Panos.Christakoglou@nikhef.nl

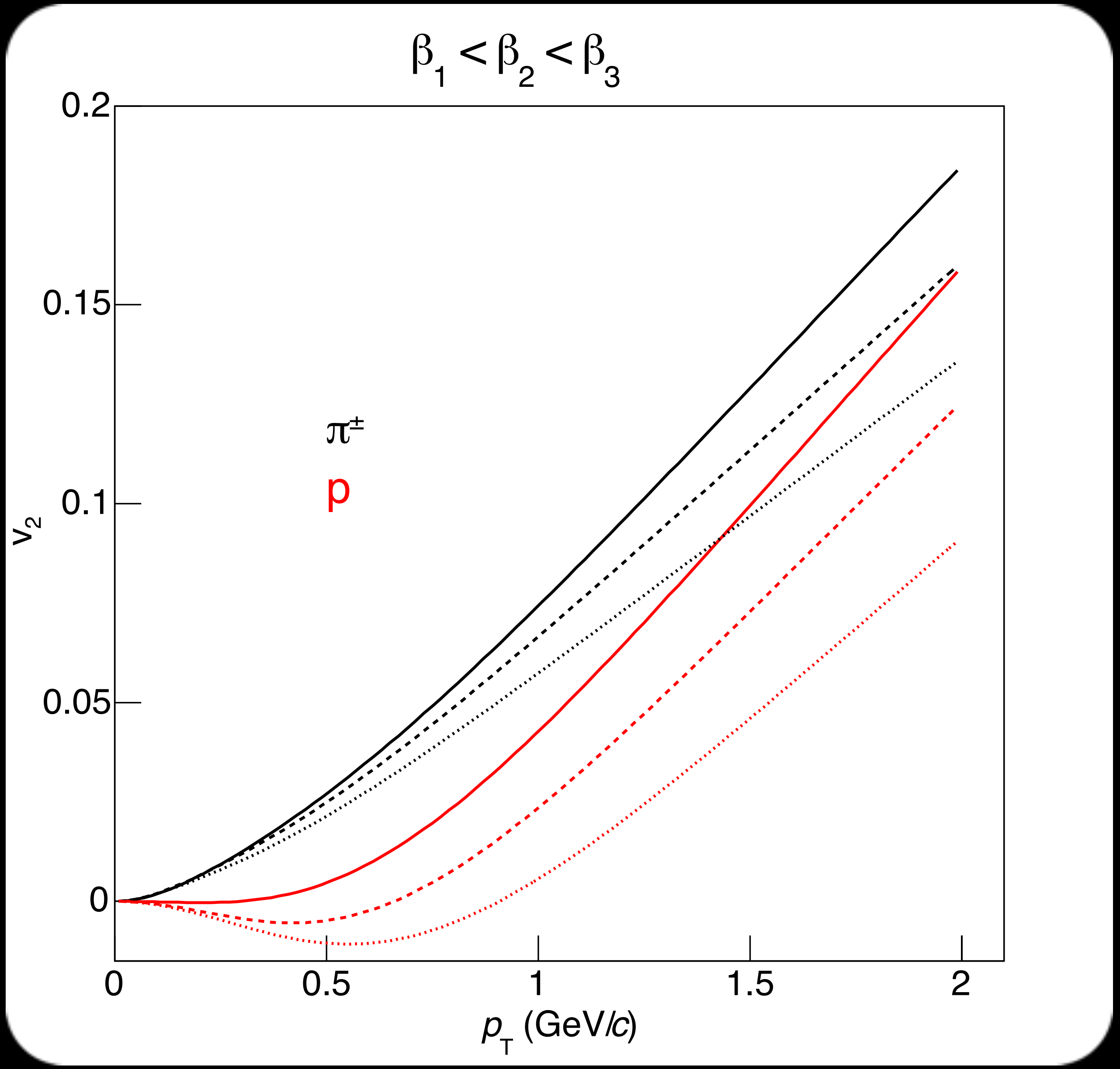
How does mass ordering develop?

Azimuthally asymmetric system

Toy model

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





- Larger "push" in-plane than out-of-plane as a function of mass
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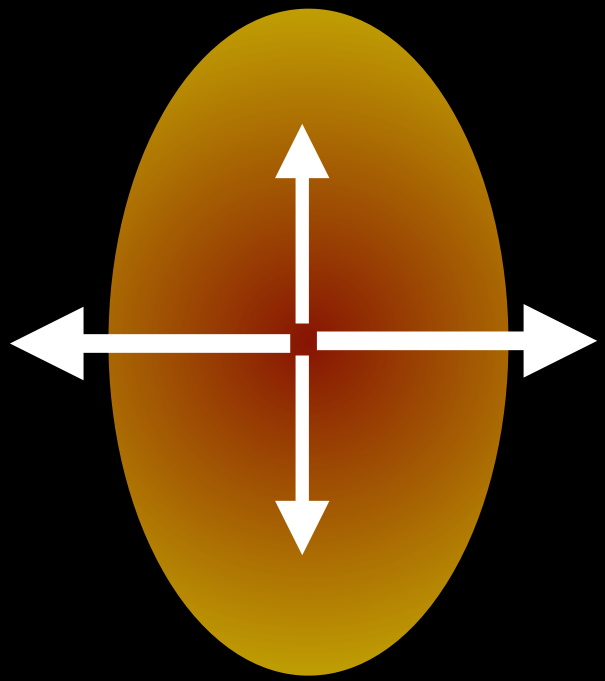
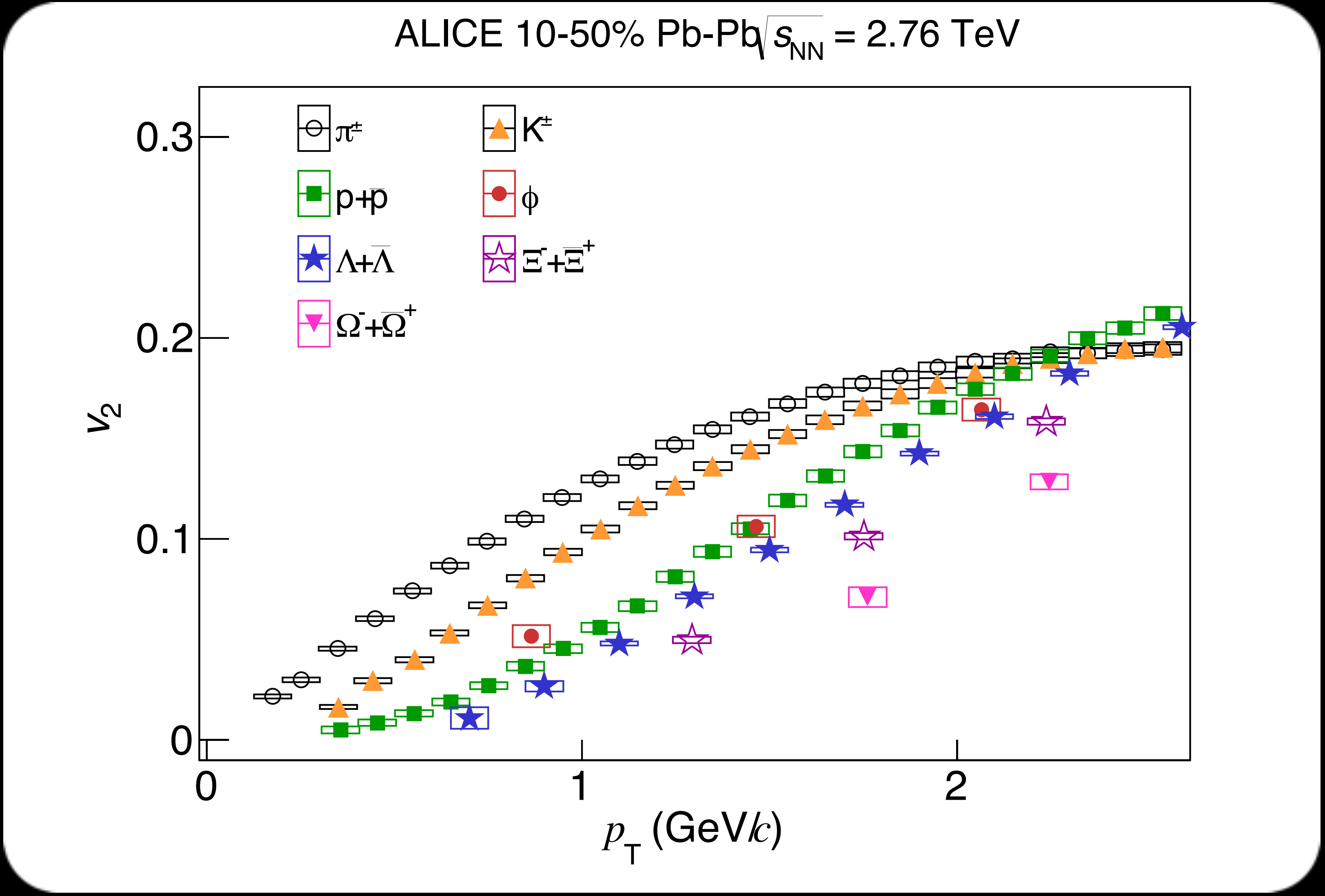
Heavy particles have lower v_2 at a fixed p_T than light particles

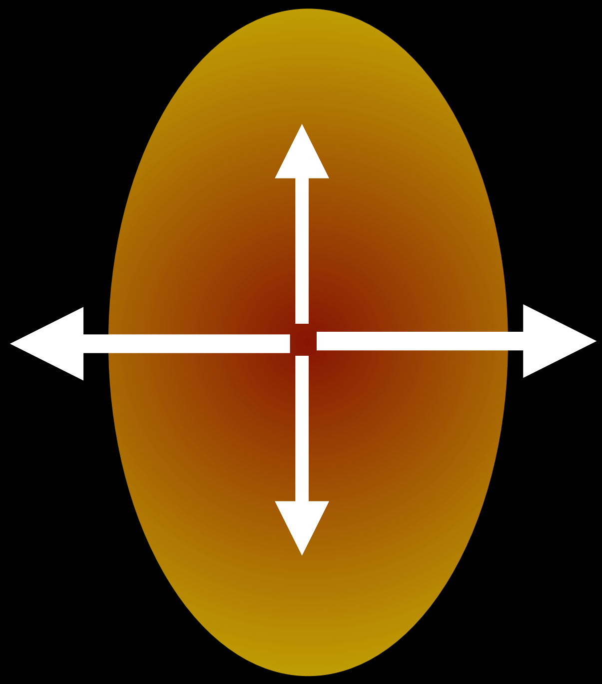




- Larger “push” in-plane than out-of-plane as a function of mass
  - larger low-p_T depletion in-plane than out-of-plane ➞ lower v_2 in a mass dependent way

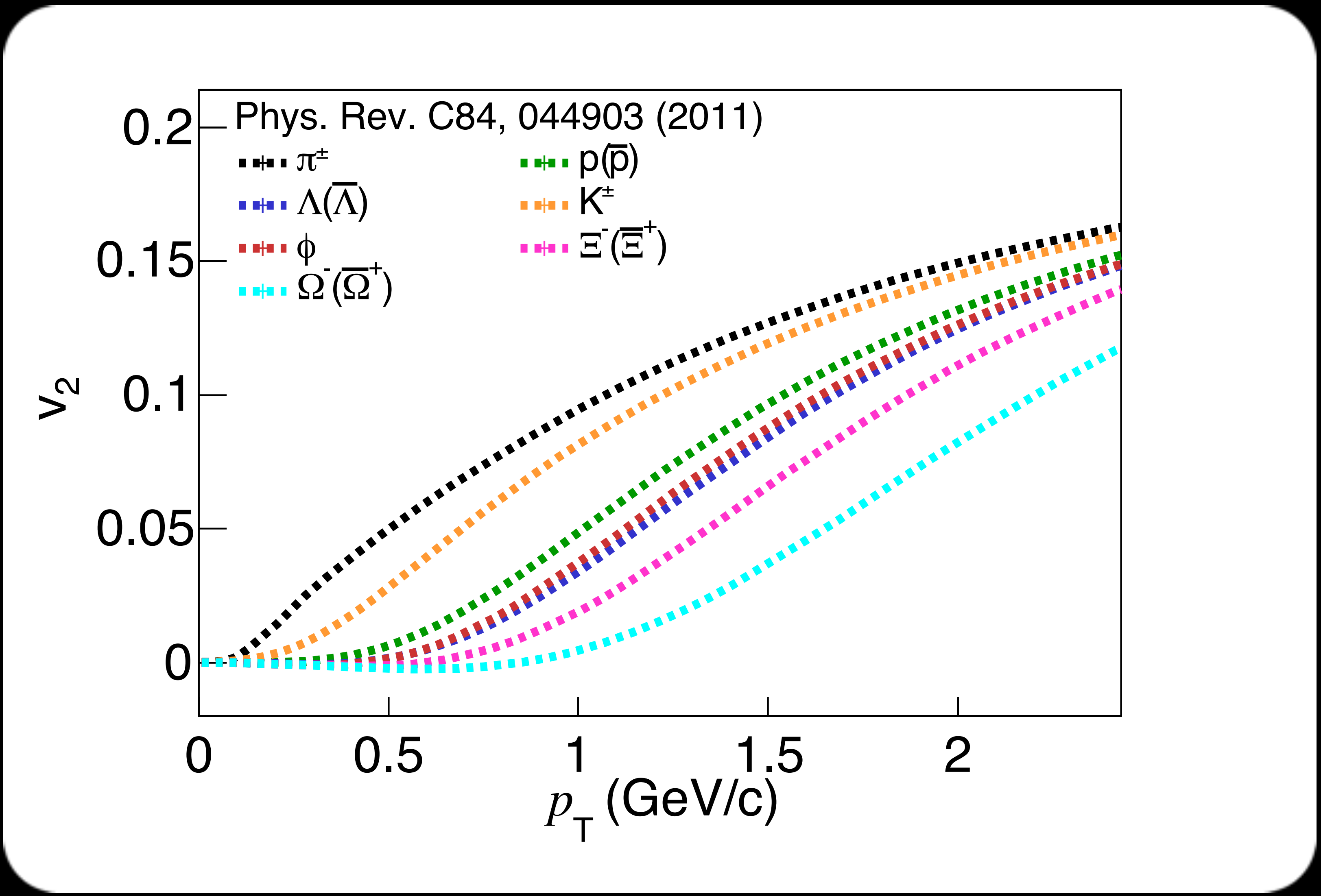
How does mass ordering develop?

Azimuthally asymmetric system



- 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

Hydrodynamical calculations



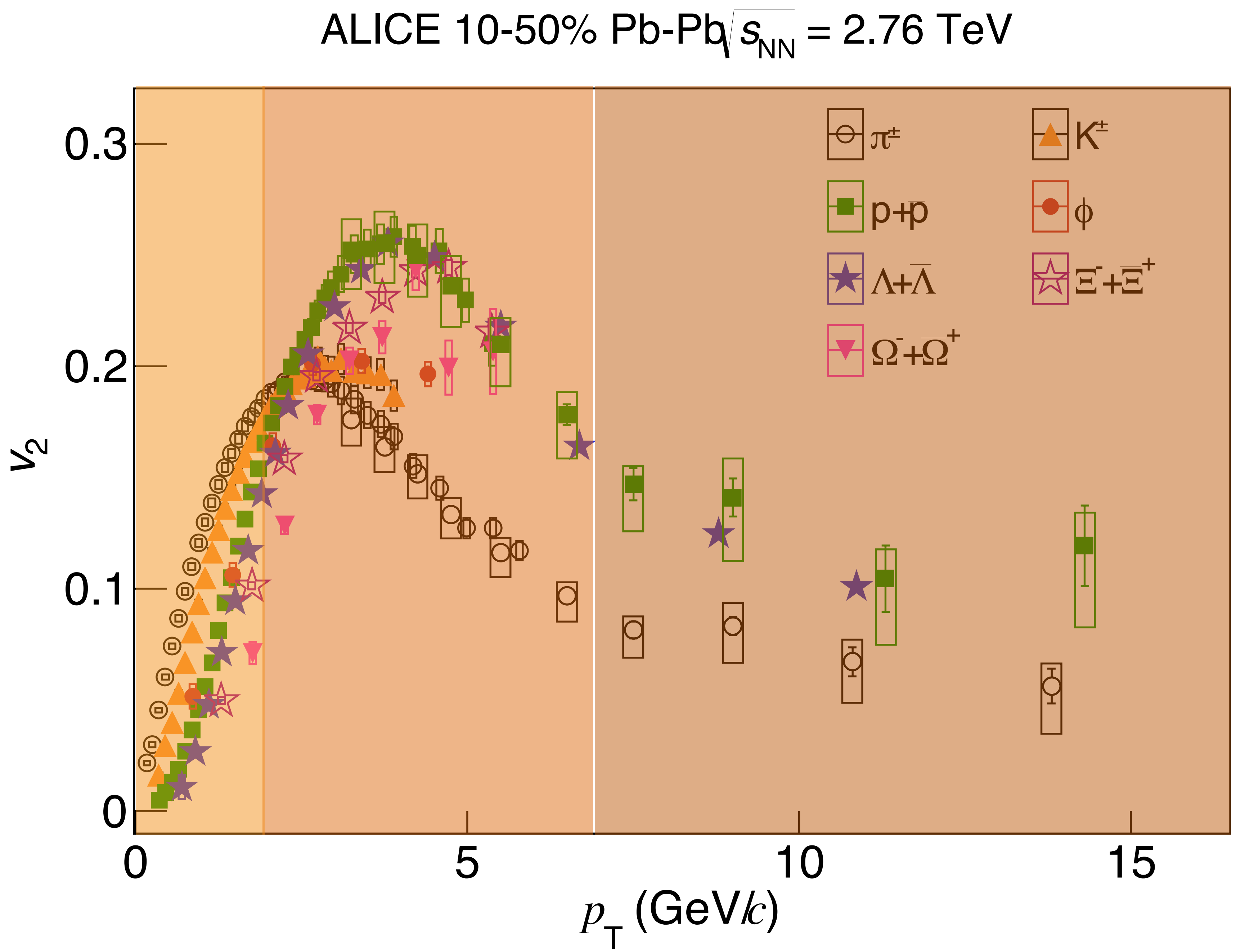
Mass ordering expected by hydrodynamical calculations

Panos.Christakoglou@nikhef.nl

Identified particles v_2 at the LHC

(ALICE), arXiv:1405.4632 [nucl-ex]

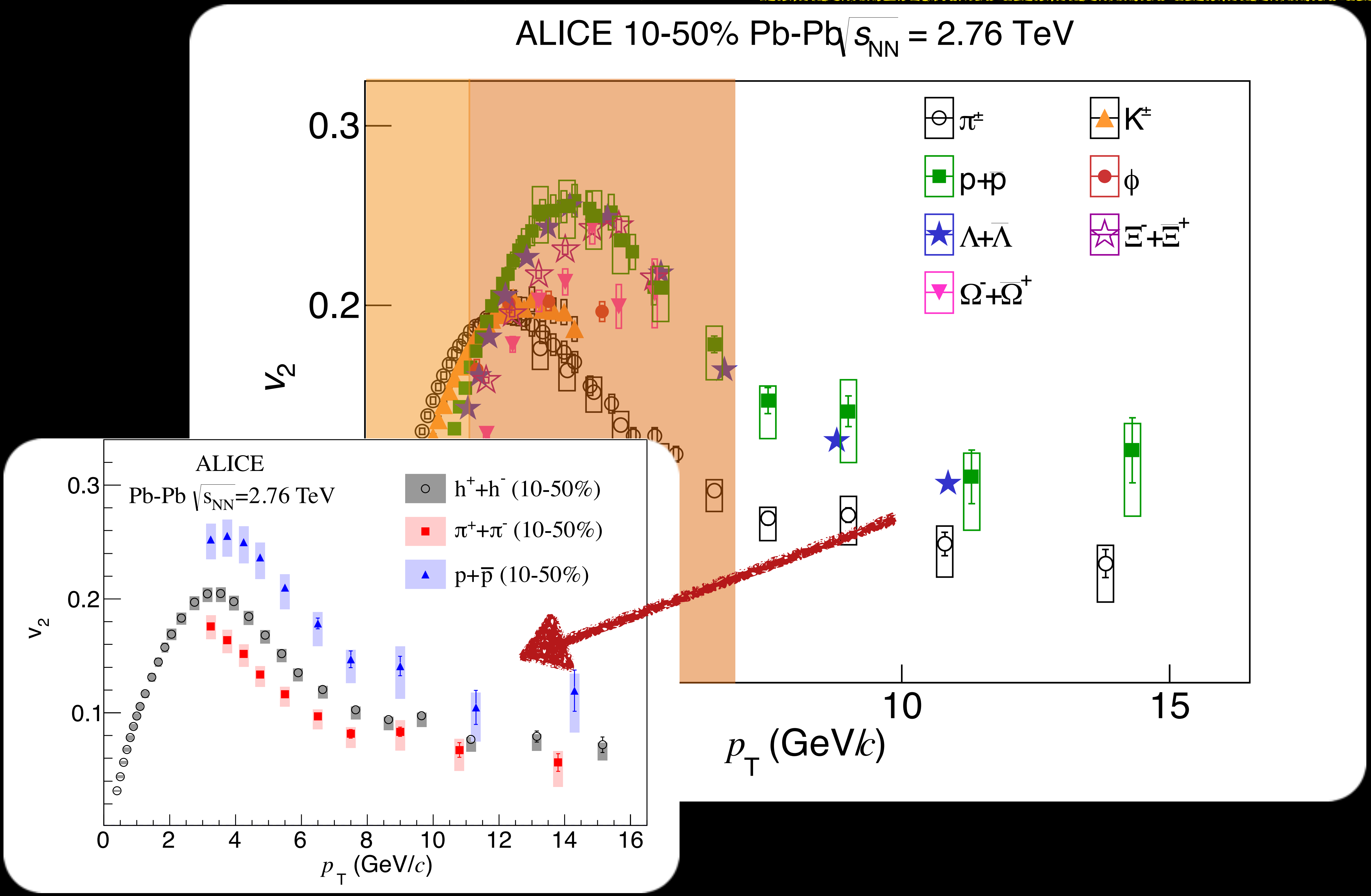
(ALICE), Physics Letters B 719 (2013) 18



Identified particles v_2 at the LHC: high p_T

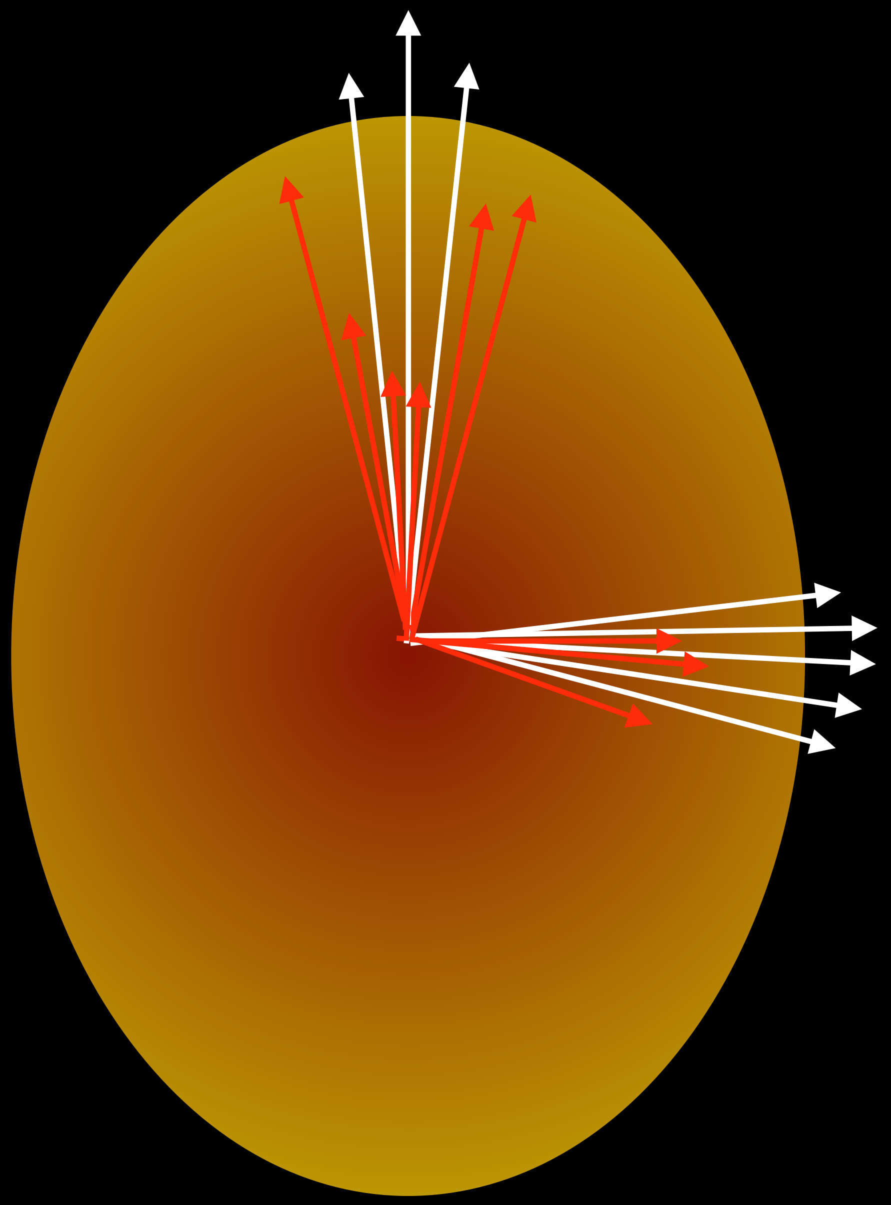
(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

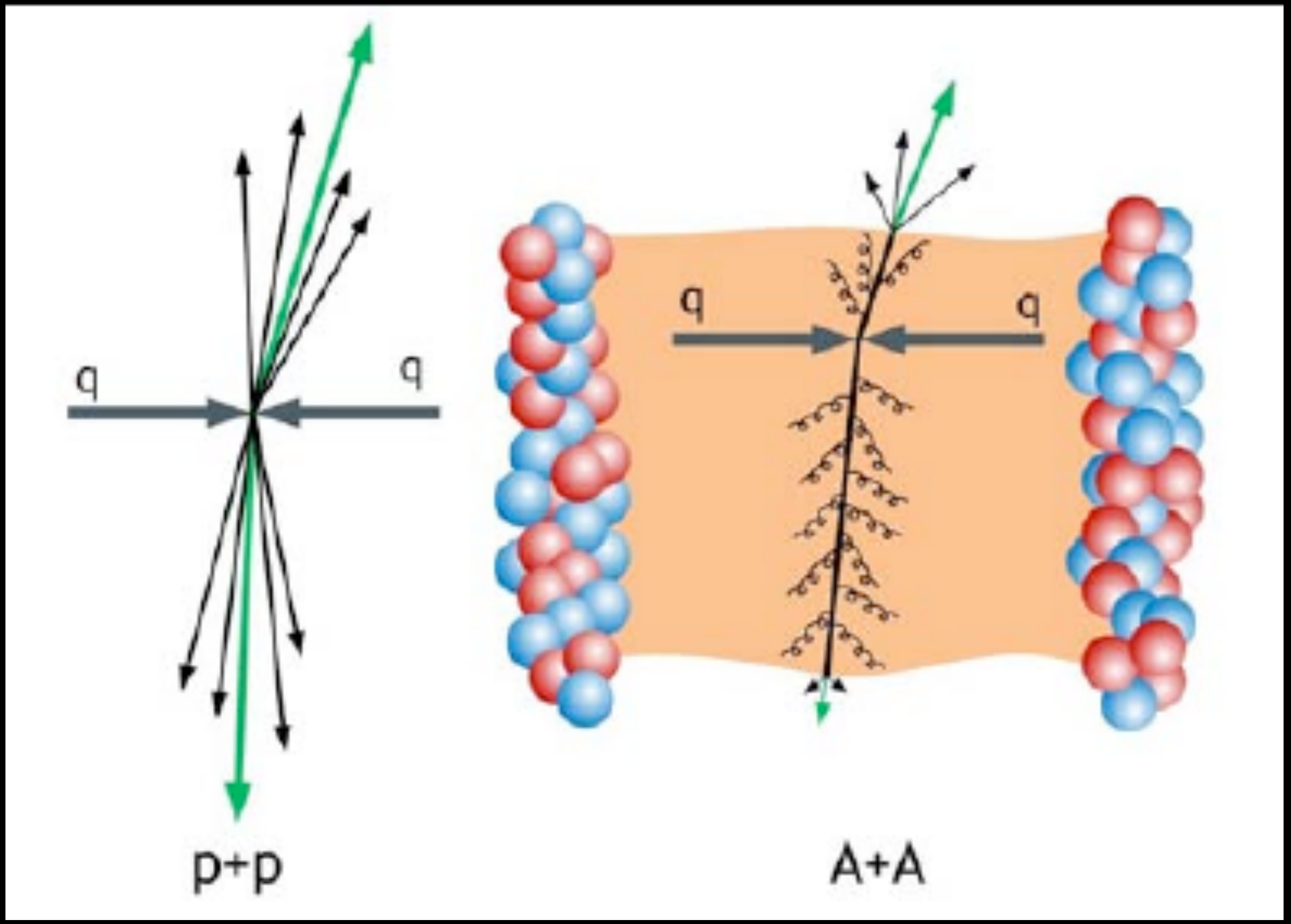


Panos.Christakoglou@nikhef.nl

The three momentum scales: high p_T (p_T > 8 GeV/c)

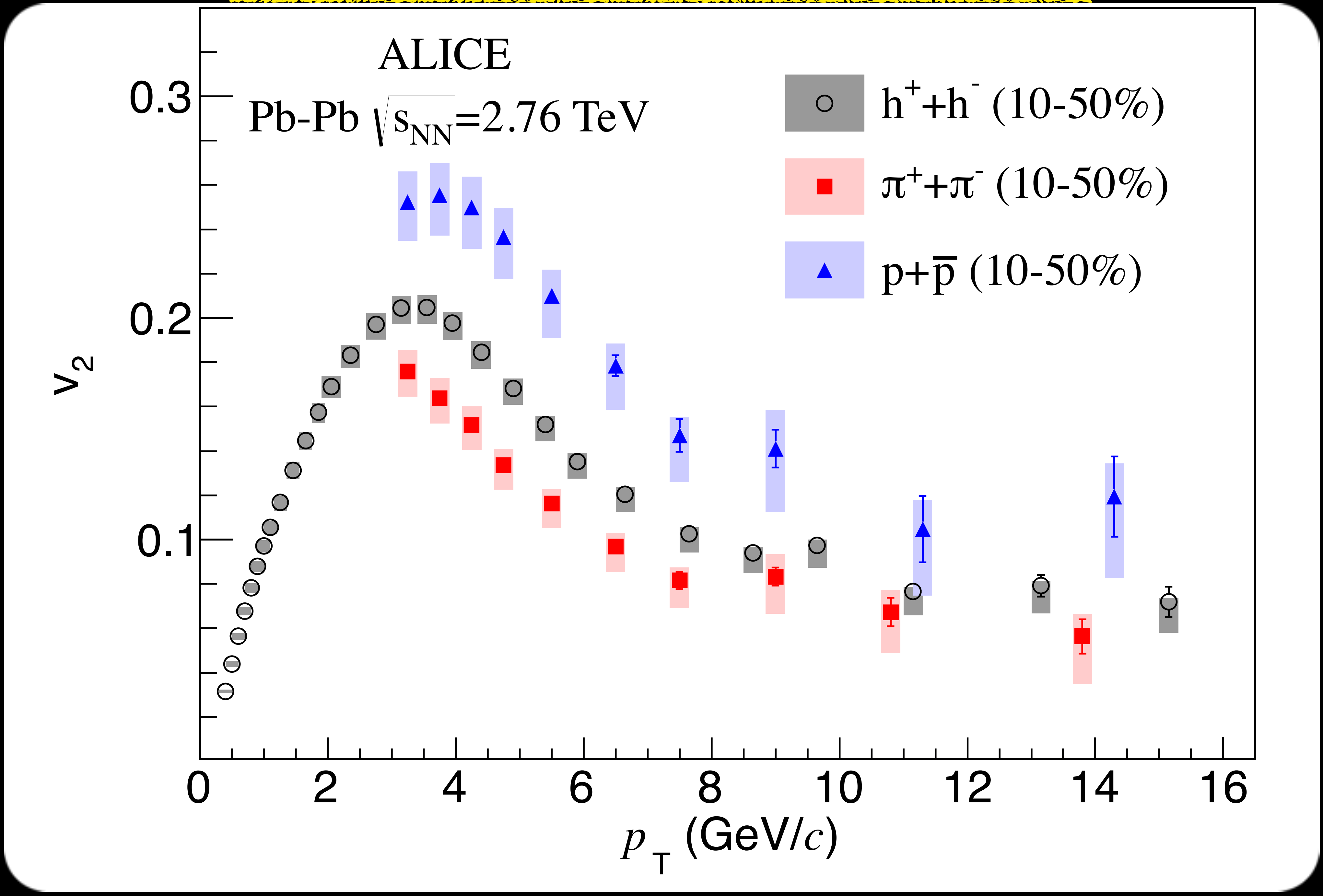


- Probing the path length dependence of energy loss
  - particles flying in-plane have to travel through less (more) medium
  - expect to see an azimuthal dependence of jets and high p_T particles



High p_T pions, kaons, protons @ LHC: v_2

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

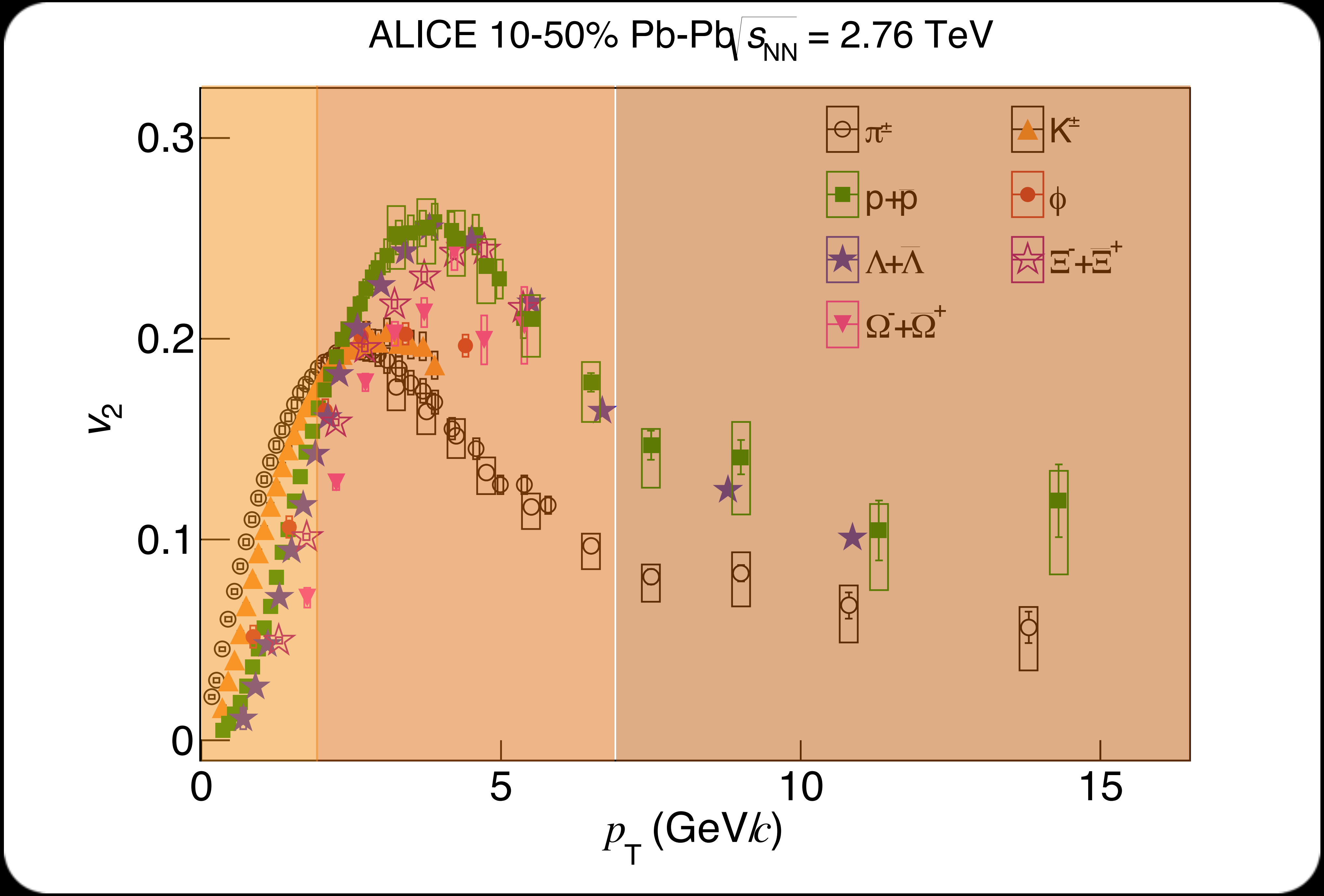


- Significant v_2 for all particle species at high p_T with no significant particle species dependence for p_T > 10 GeV/c

Identified particles v_2 at the LHC

(ALICE), arXiv:1405.4632 [nucl-ex]

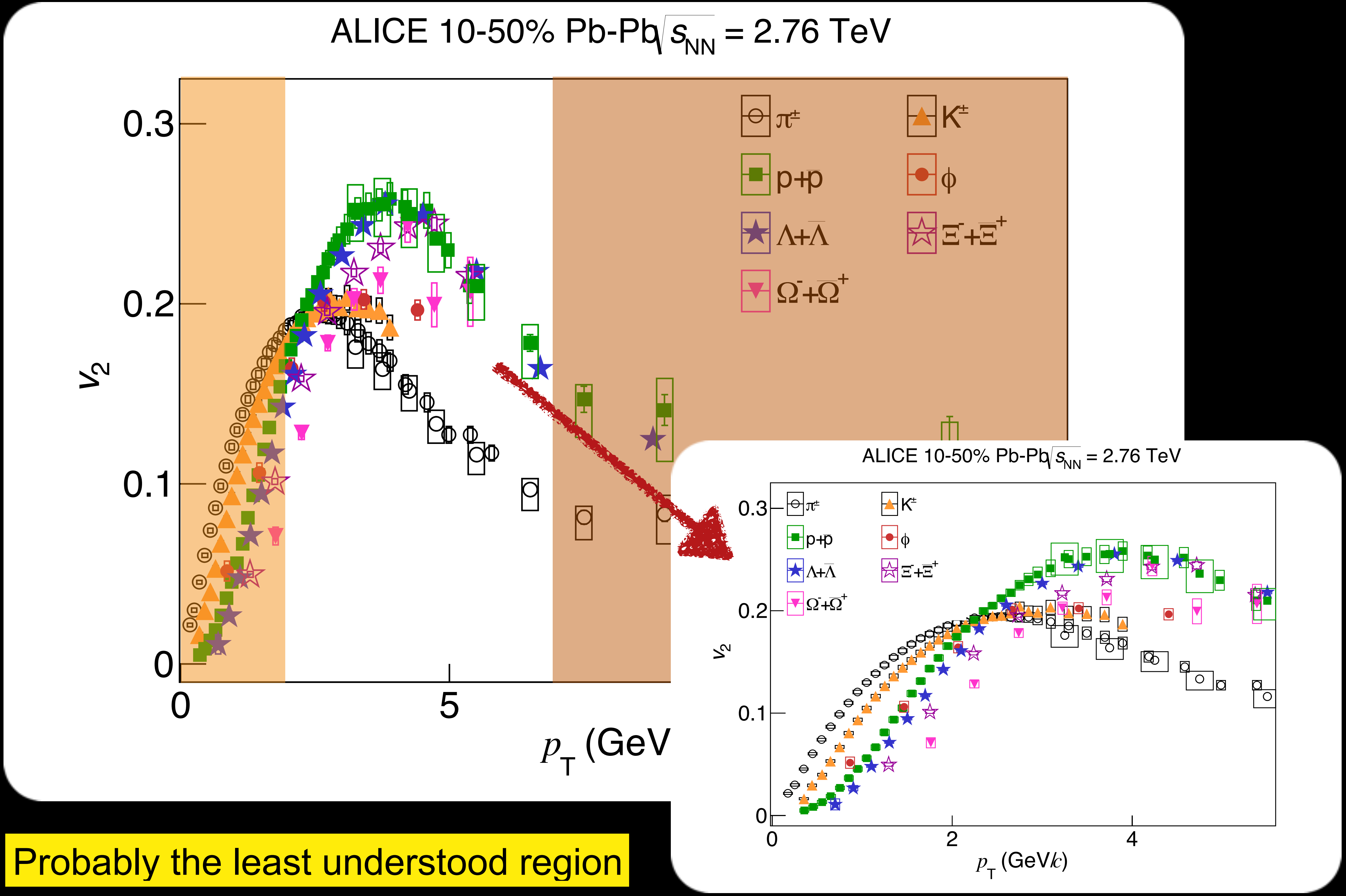
(ALICE), Physics Letters B 719 (2013) 18



Identified particles v_2 at the LHC: intermediate p_T

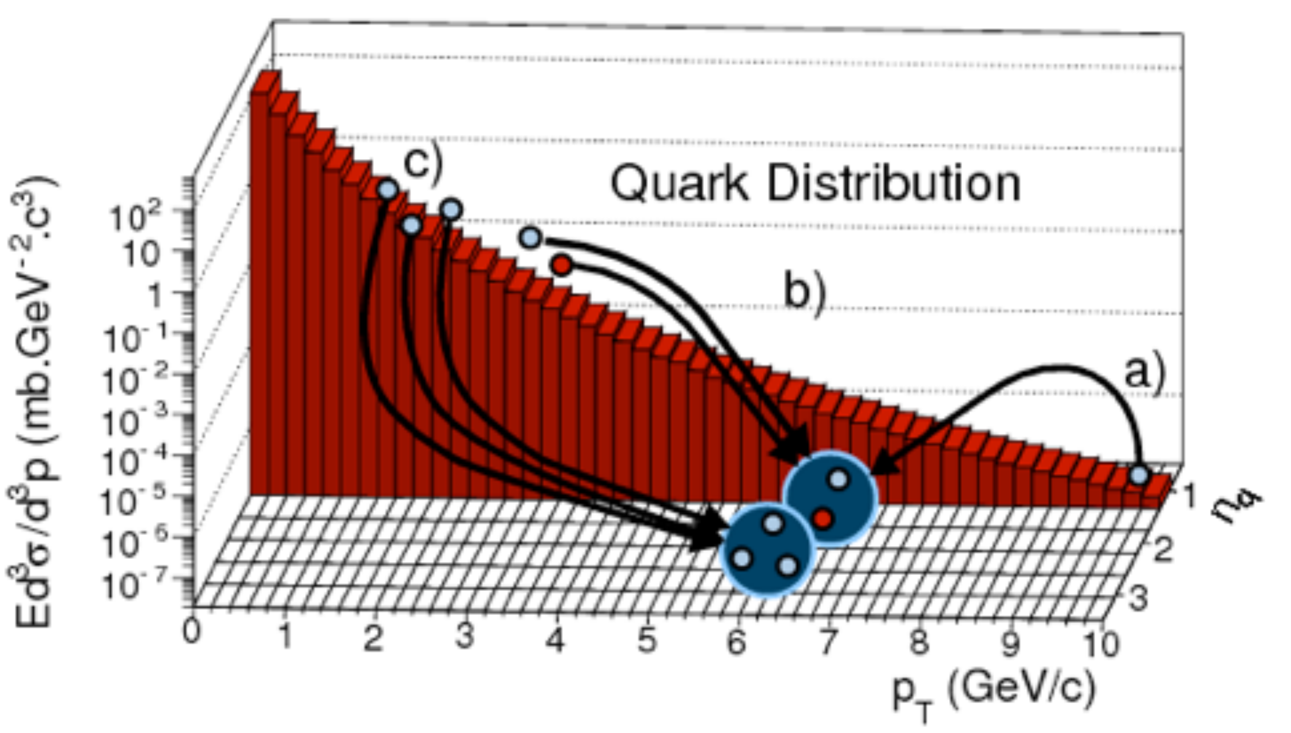
(ALICE), arXiv:1405.4632 [nucl-ex]

(ALICE), Physics Letters B 719 (2013) 18

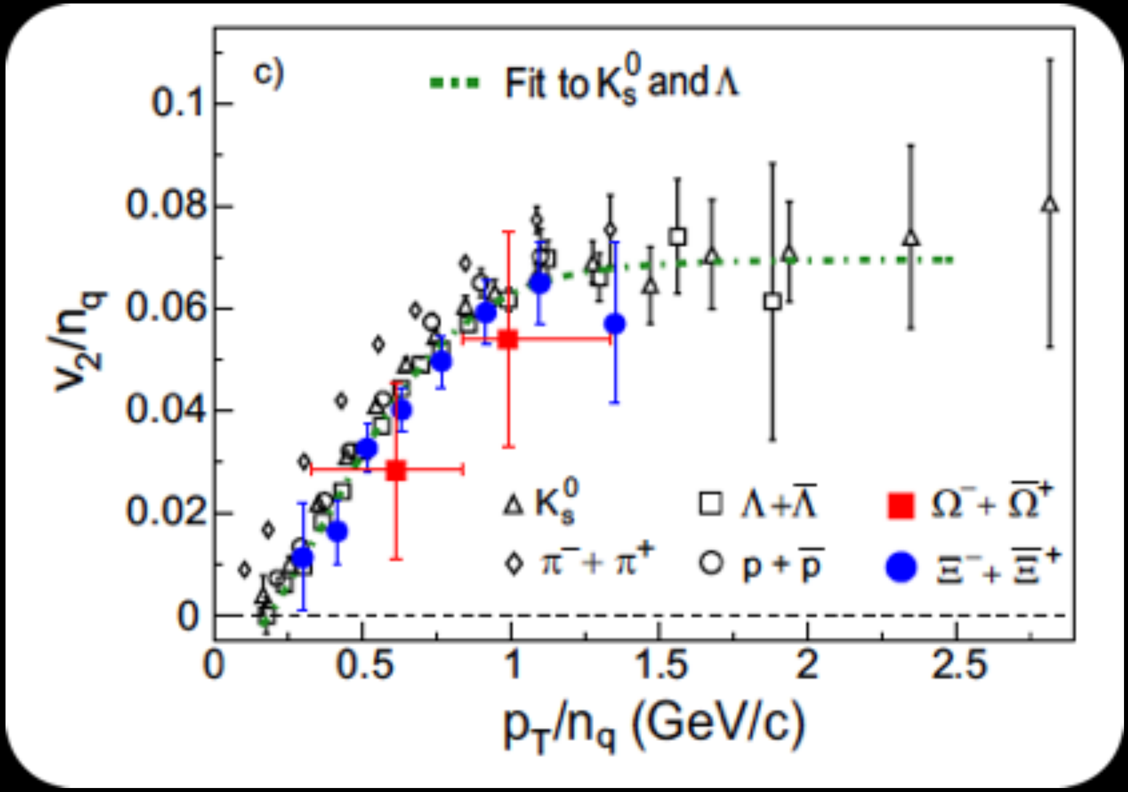


Probably the least understood region

The three momentum scales: intermediate p_T ($2 < p_T < 8$ GeV/c)

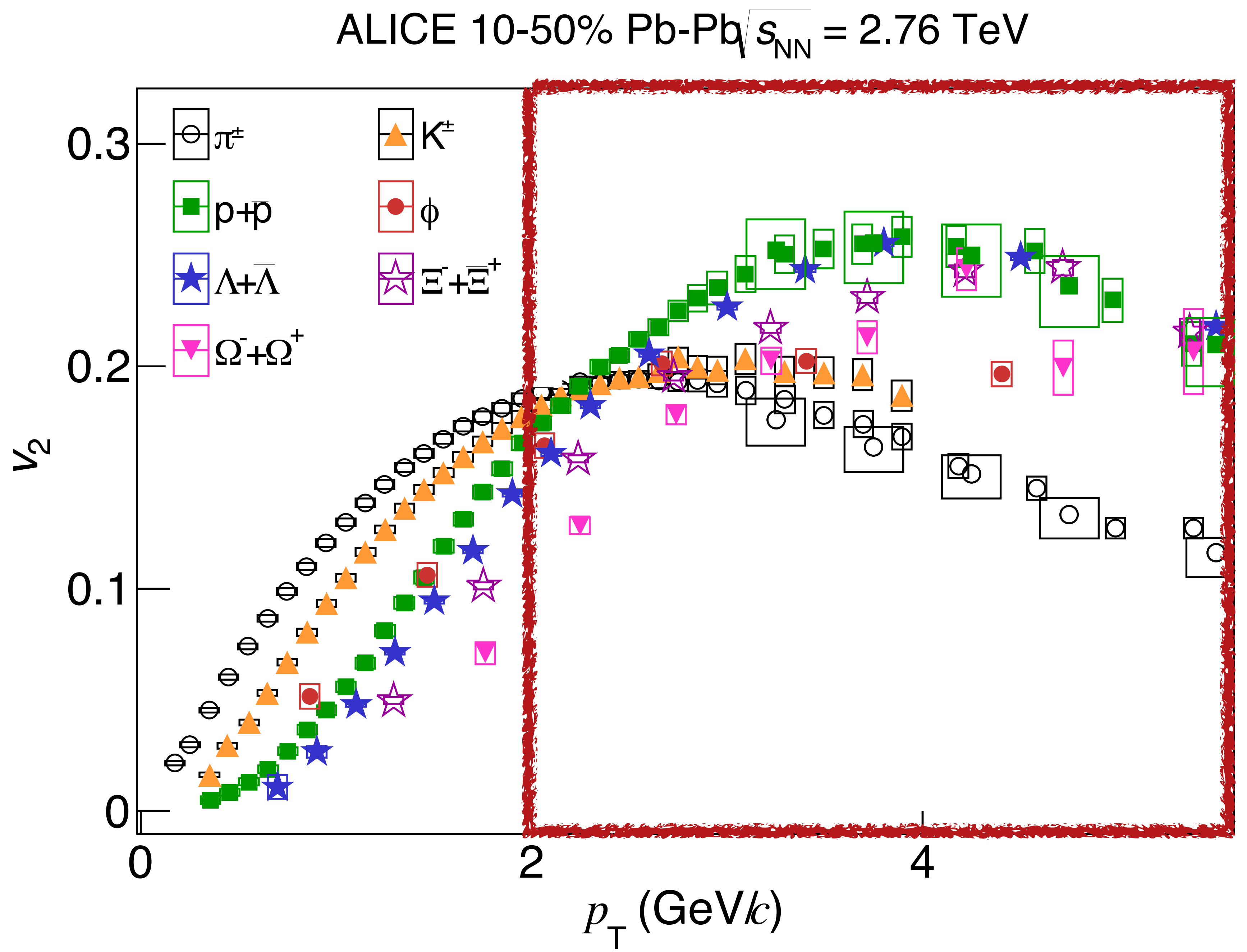


- Number of constituent quark (NCQ) scaling holding with good accuracy at RHIC
  - quarks coalesce forming hadrons?
  - NCQ scaling was considered as "evidence" of partonic degrees of freedom

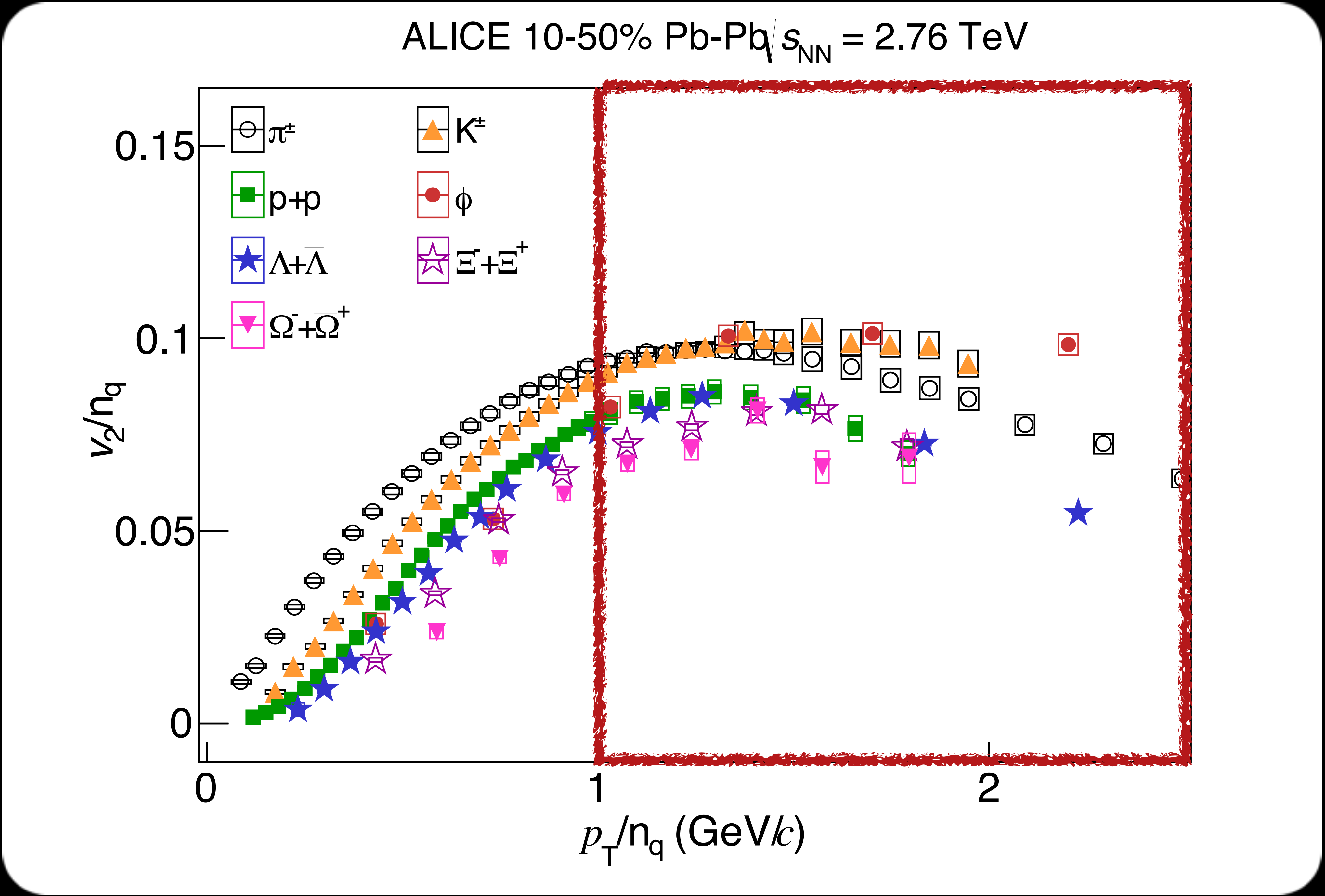


J. Adams *et al.*, (STAR Collaboration), Nucl.Phys. **A757** (2005) 102
K. Adcox *et al.*, (PHENIX Collaboration), Nucl. Phys. **A757**, (2005) 184

NCQ scaling at the LHC

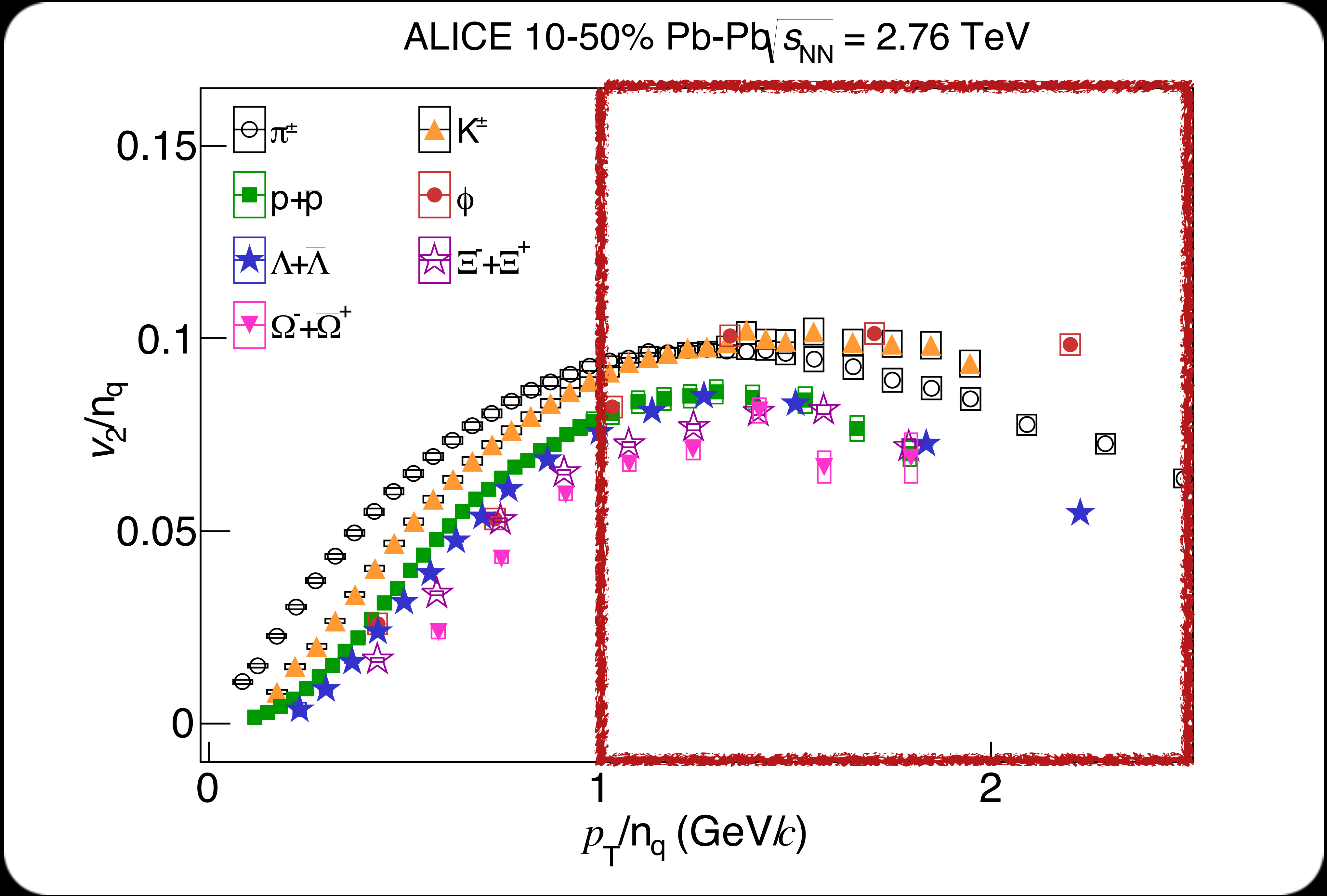


Scaling properties at the LHC



Intermediate p_T : scaling at an approximate level

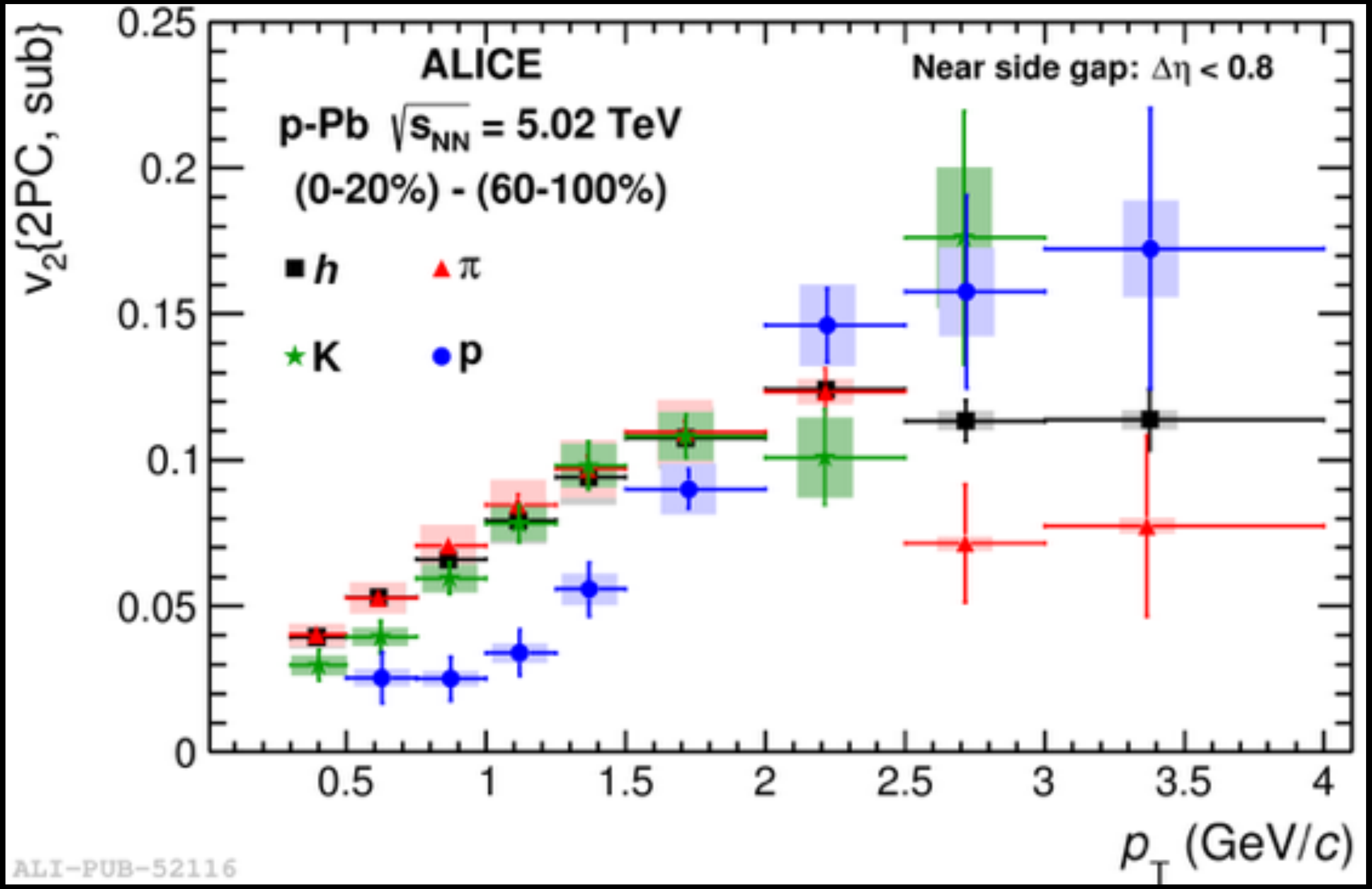
Scaling properties at the LHC



Theory was already based on approximations → need for refinement (e.g. how does hadronic rescattering affect the scaling?)

And there is more…: collective effects in small systems?

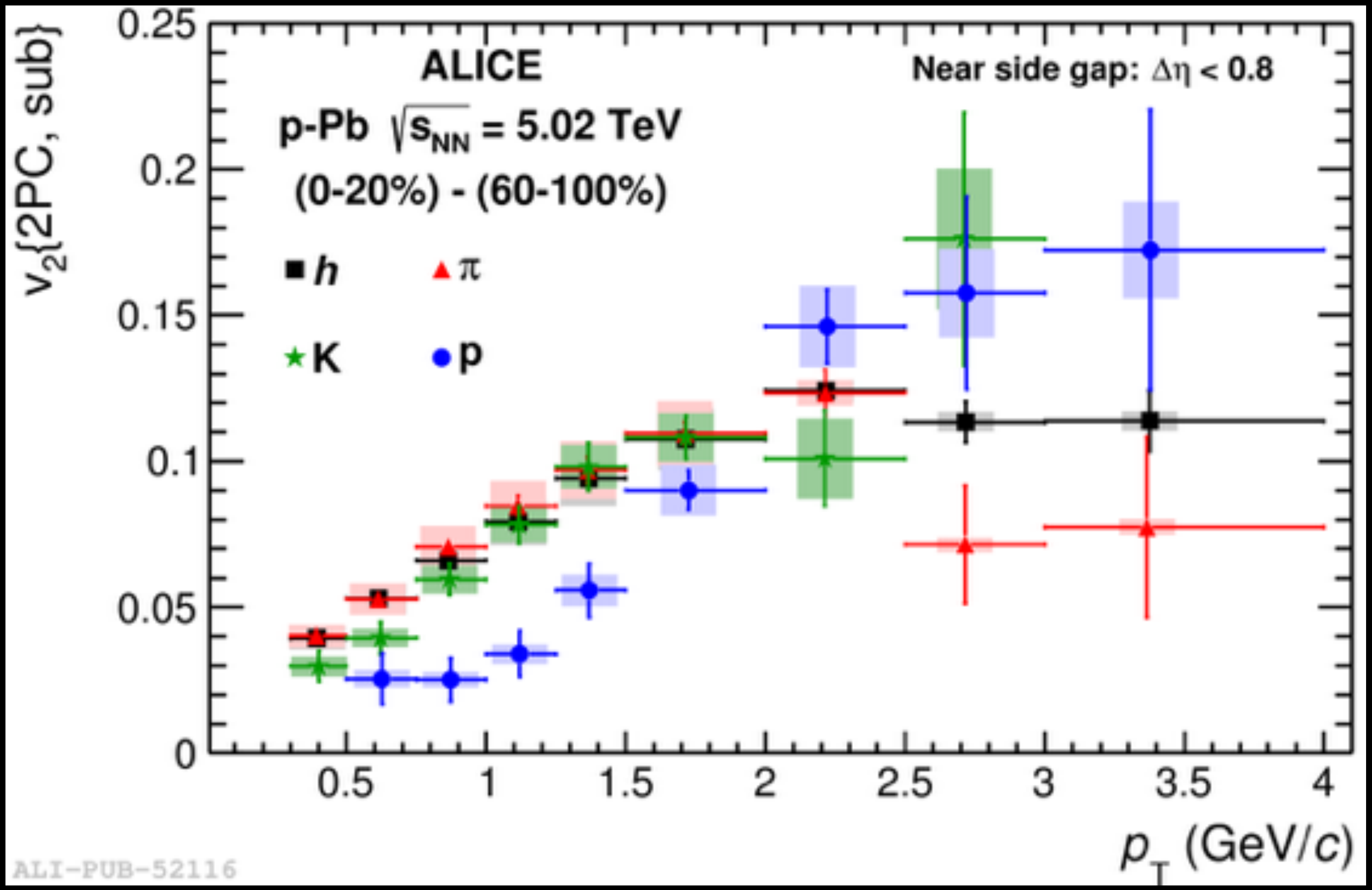
B. Abelev *et al*. (ALICE Collaboration: Phys. Lett. **B726**, (2013) 164



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

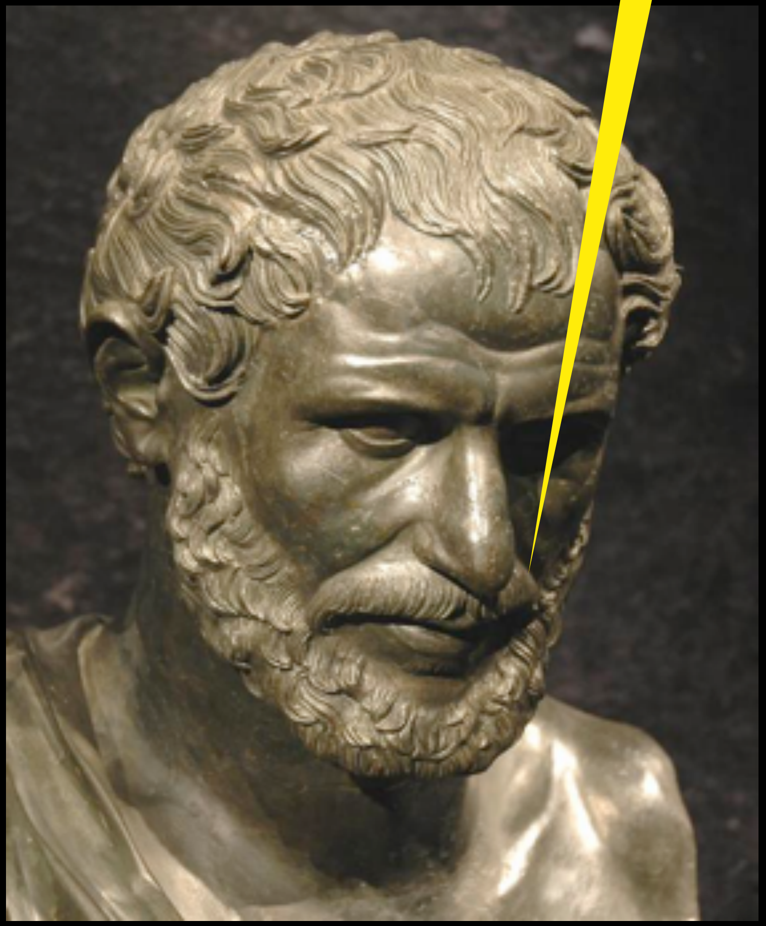
And there is more…: collective effects in small systems?

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



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

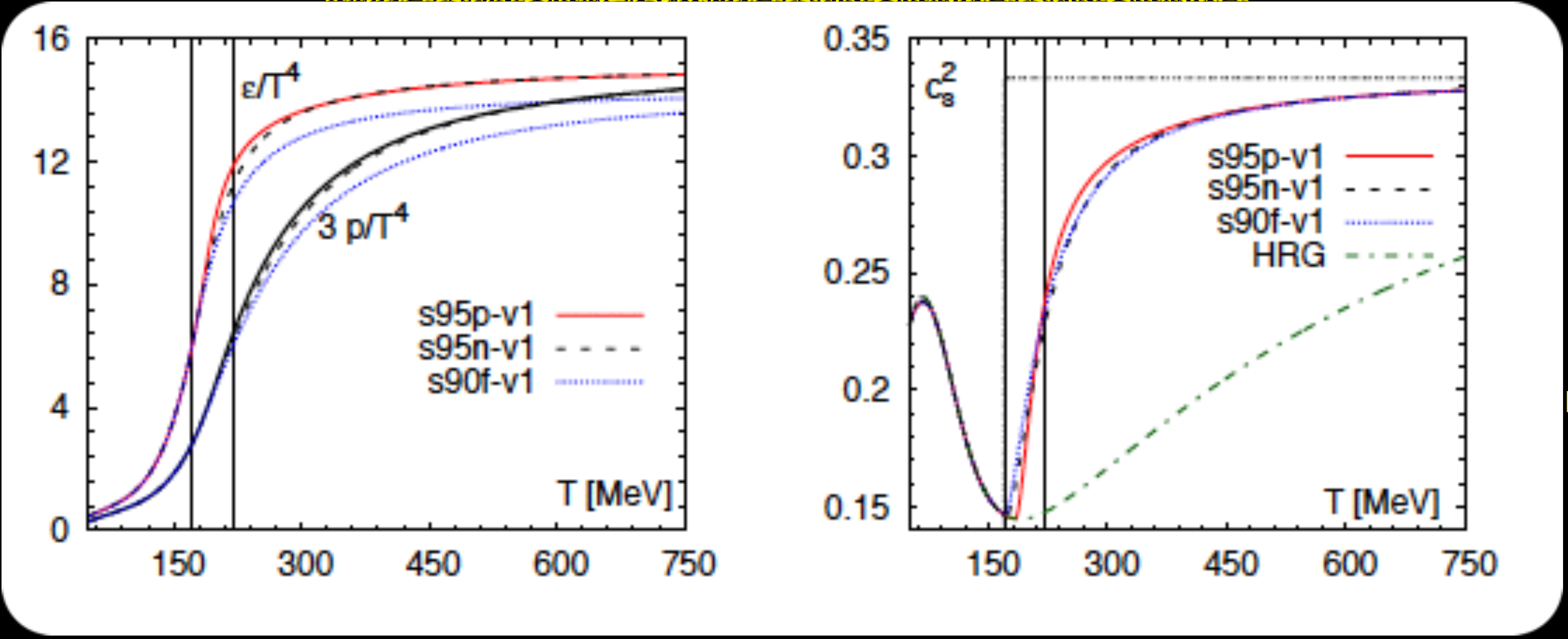
Τα πάντα ρει



Ηράκλειτος (Heraclitus) ~535 - 475 BC

QCD on the lattice and phase transition

P. Huovinen, P. Petreczky, Nucl.Phys. **A837**, (2010) 26-53



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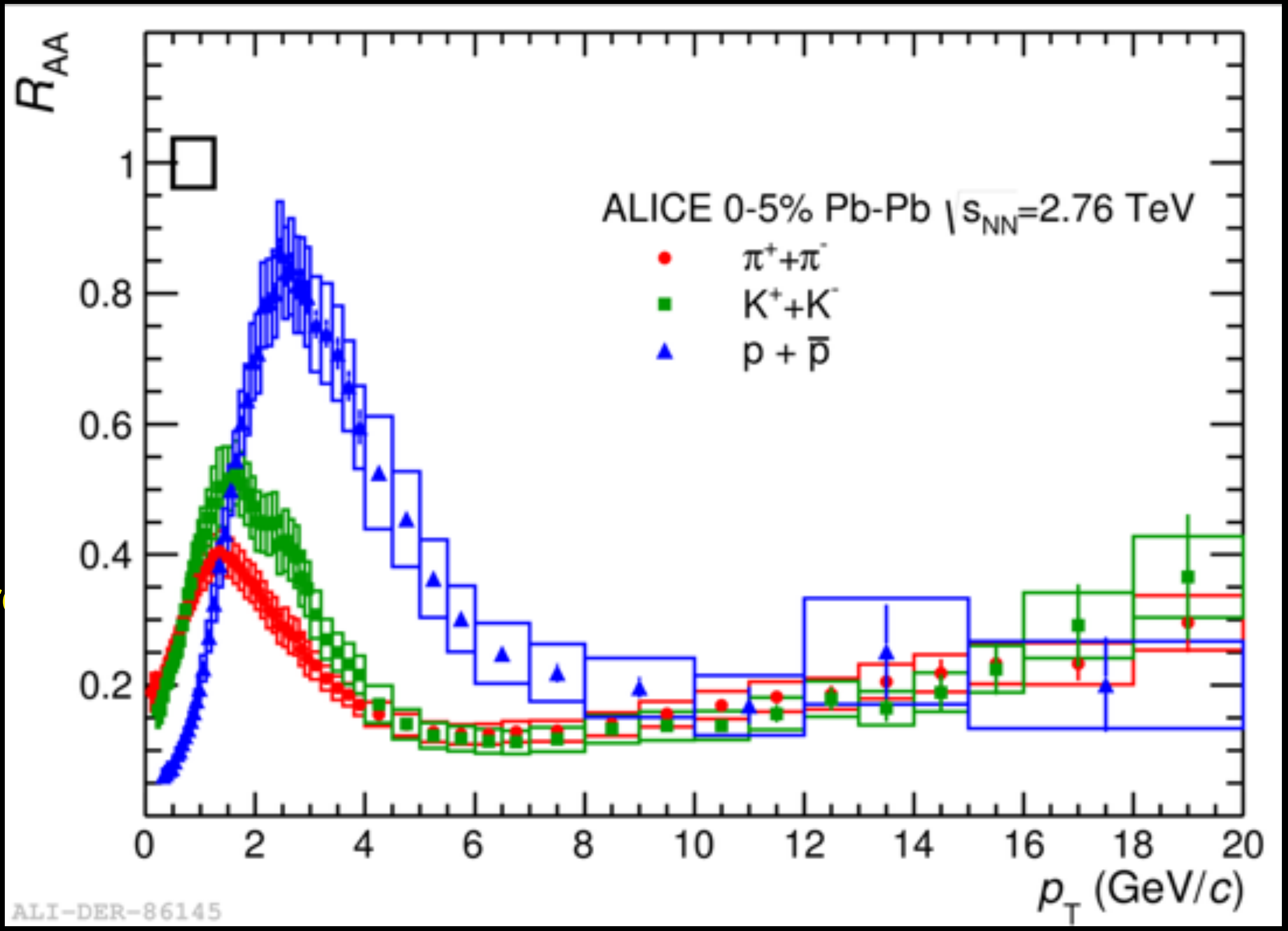
★ Need observables that are sensitive to the EOS

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
- Suppr