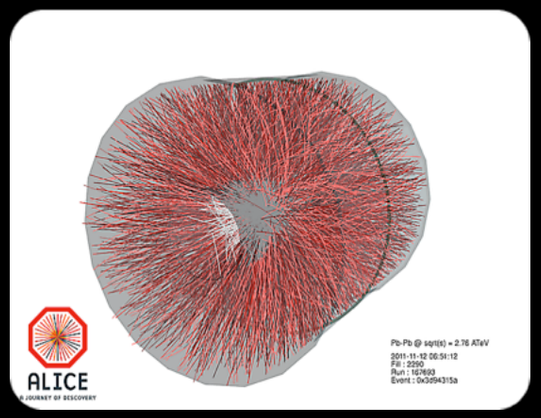
Elliptic flow of identified hadrons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

Results based on: arXiv:1405.4632 [nucl-ex]



Panos Christakoglou (Nikhef)

for the ALICE Collaboration

The “perfect liquid” at RHIC and LHC

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

News

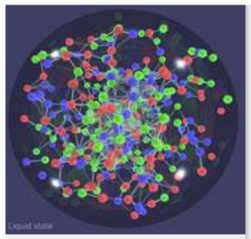
Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

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

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



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

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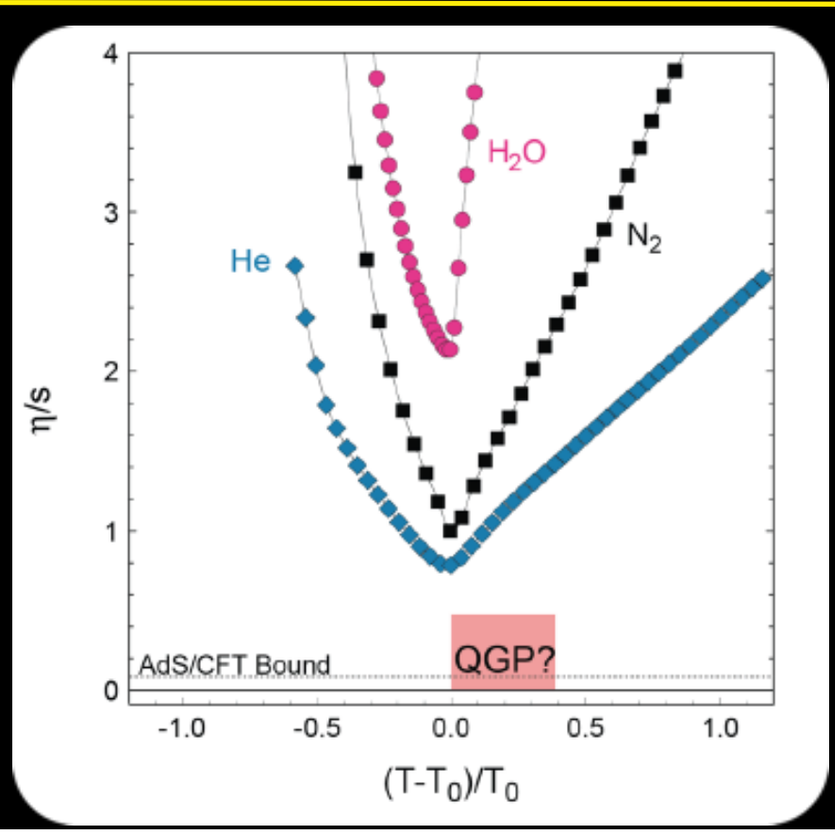

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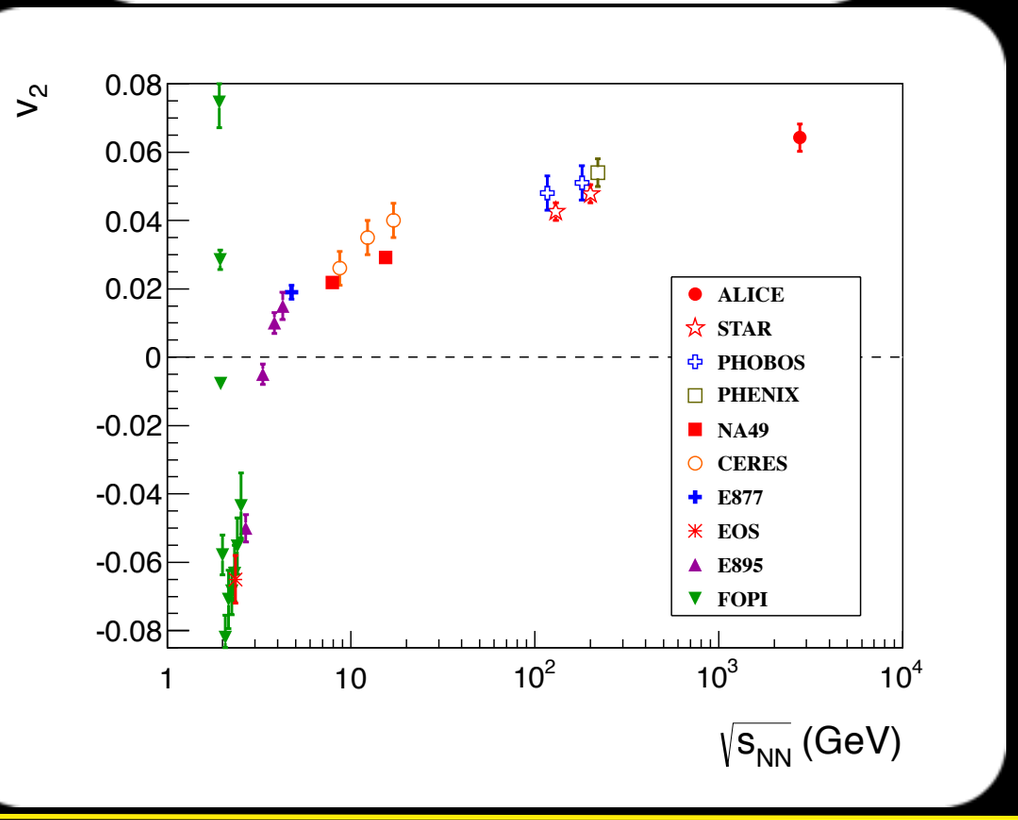
RHIC Scientists Serve Up "Perfect" Liquid

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

Monday, April 18, 2005

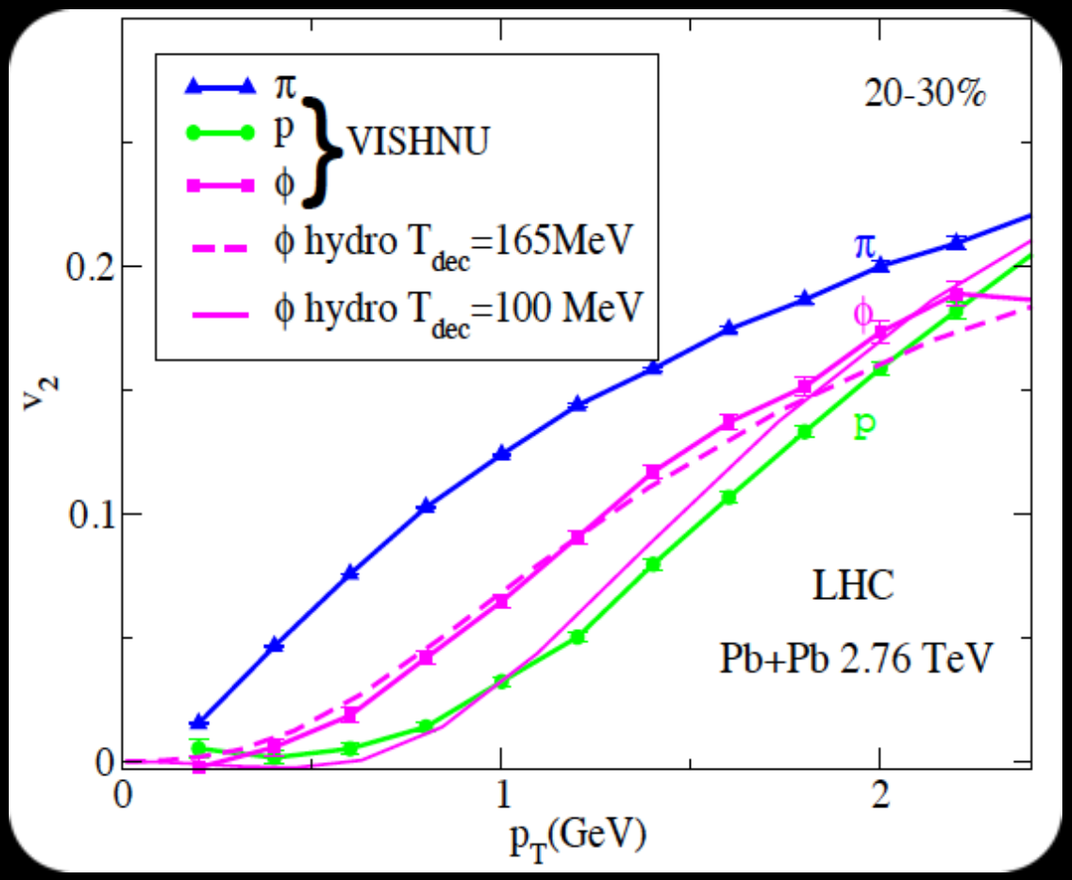
TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the 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'



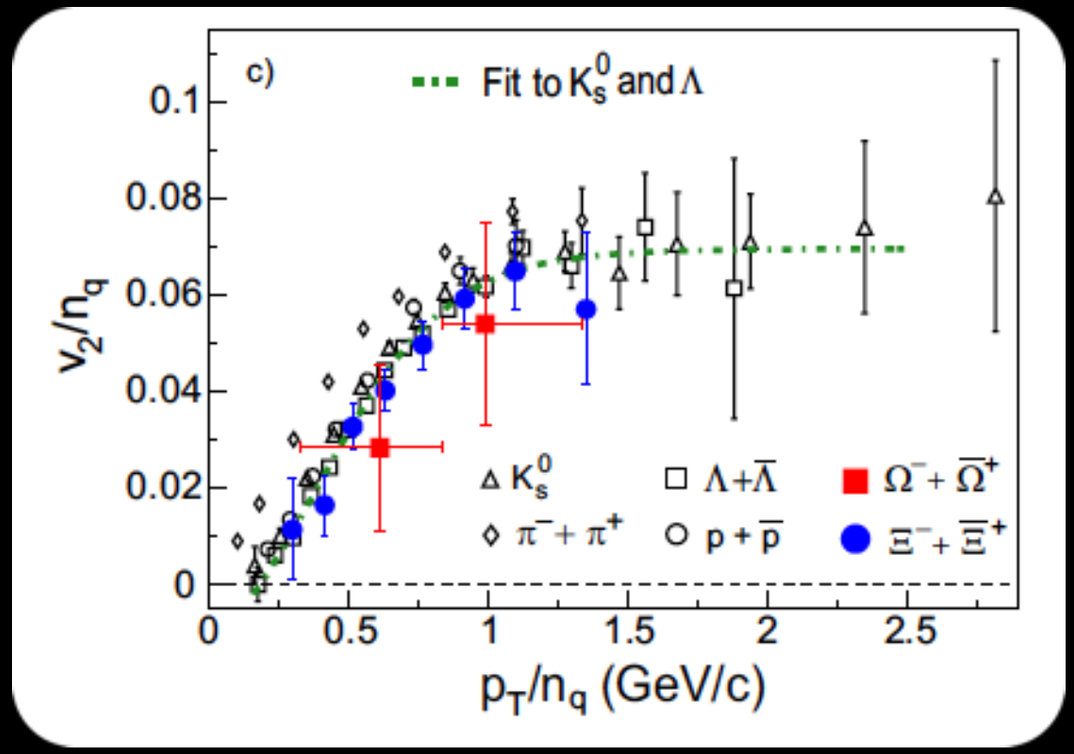
Motivation

- Mass ordering observed at low p_T at RHIC energies
  - ★ expected by hydrodynamic calculations
- New calculations expect the mass ordering to be violated



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

- 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

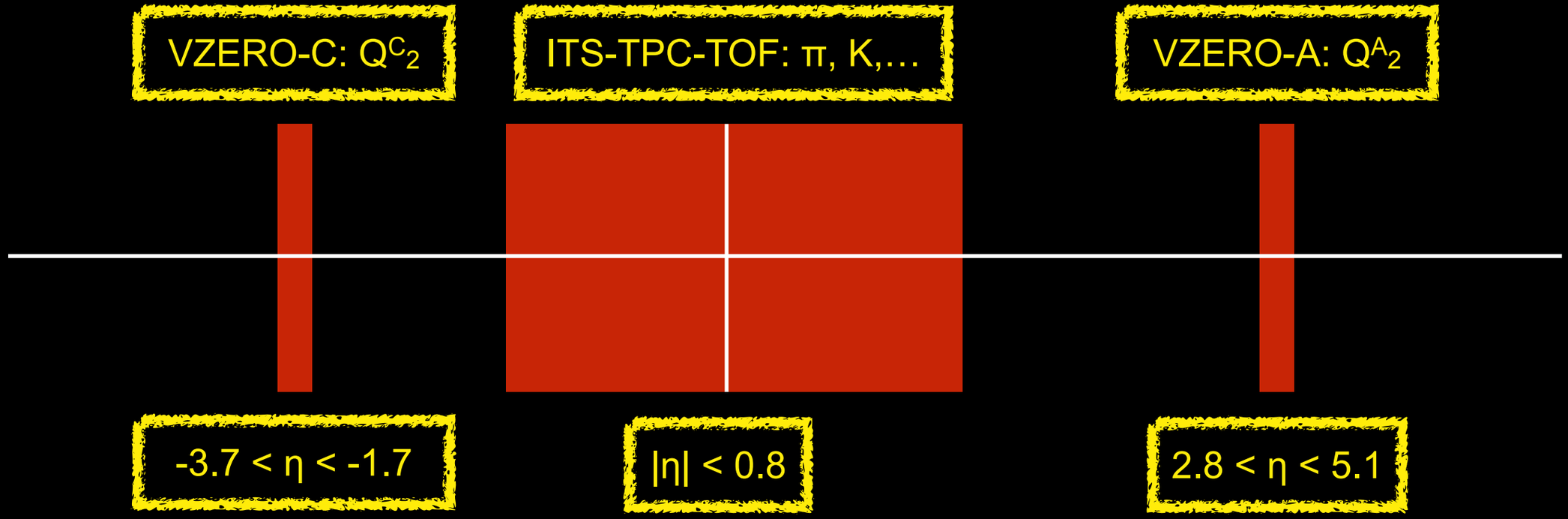


J. Adams *et al.*, (STAR Collaboration) Nucl.Phys. **A757** (2005) 102
K. Adcox *et al.*, (PHENIX Collaboration), Nucl. Phys. **A757**, (2005) 184

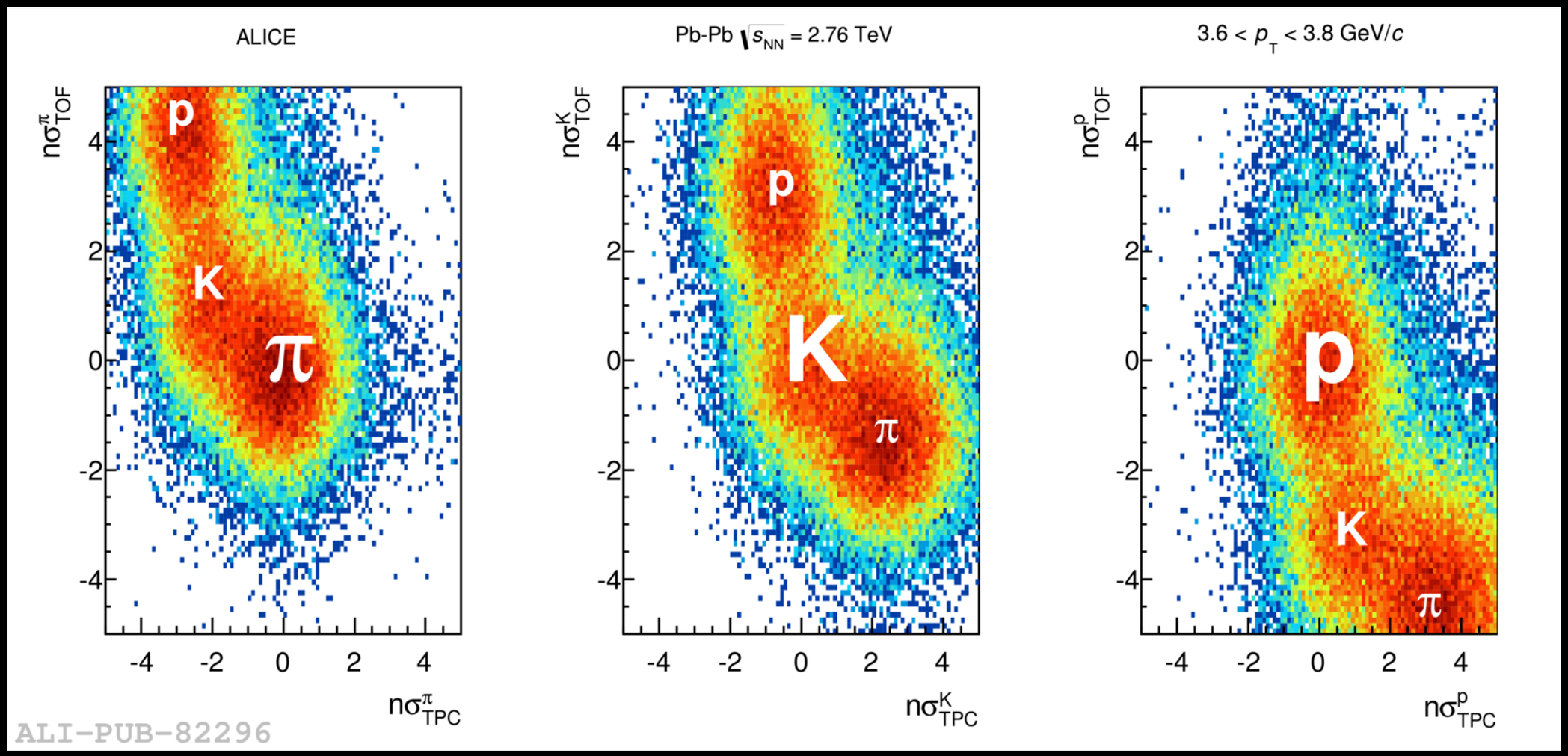
Analysis details

- Analysis of the 2010 Pb-Pb sample (~15M events analysed)
- Elliptic flow with the Scalar Product (SP) method with $|\Delta\eta| > 0.9$ (reduction of non-flow contribution)

$$v_2 = \sqrt{\frac{\langle\langle \vec{u}_2^{B} \cdot \frac{\vec{Q}_2^{A*}}{M_A} \rangle\rangle \langle\langle \vec{u}_2^{B} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \rangle\rangle}{\langle \frac{\vec{Q}_2^{A}}{M_A} \cdot \frac{\vec{Q}_2^{C*}}{M_C} \rangle}}$$

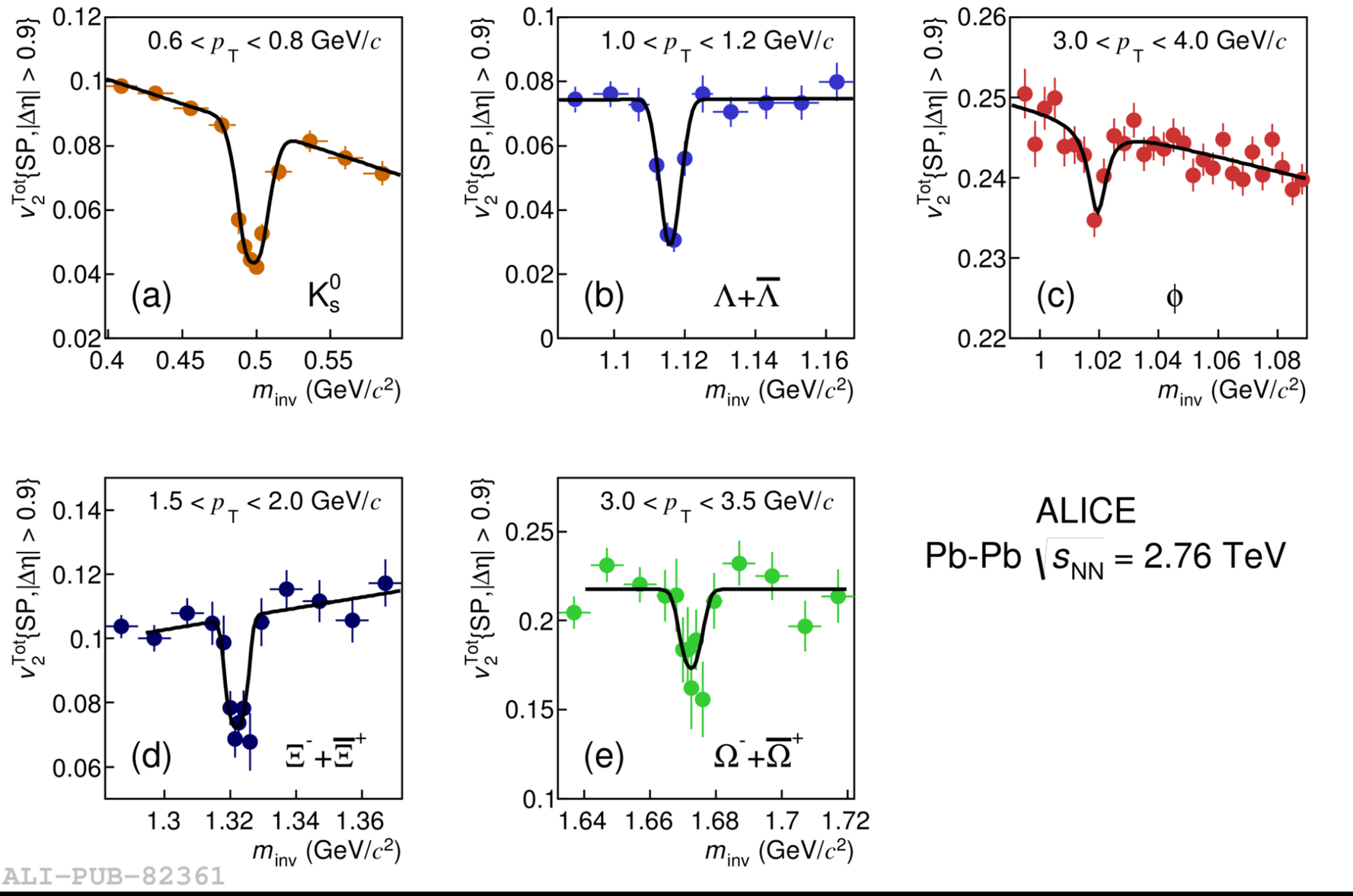


Identifying particles



- Combination of TPC and TOF information
  - number of standard deviations in a p_T dependent way
- Purity > 95% for all p_T bins

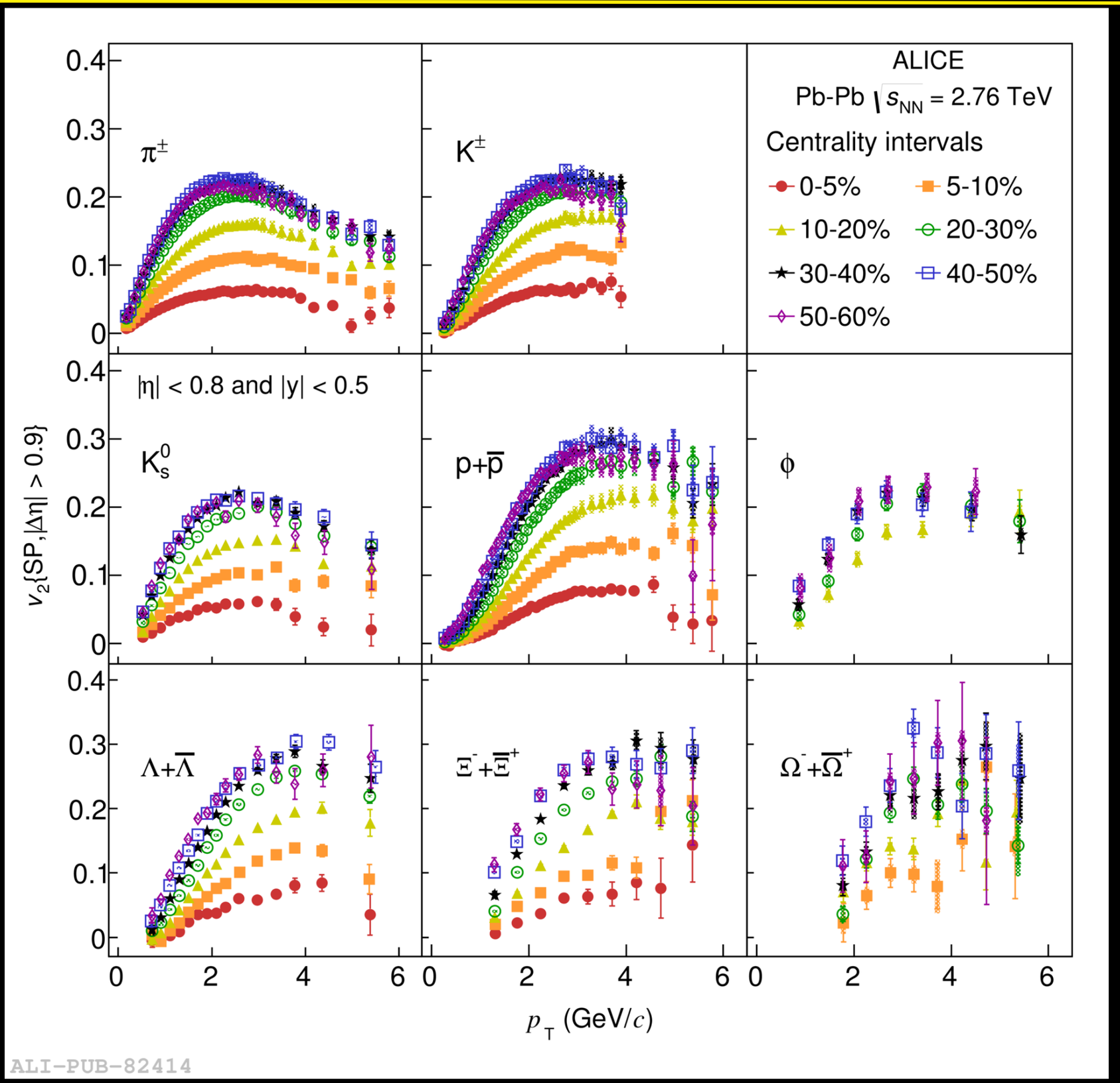
Measuring v_2 for decays



$$v_2^{\mathrm{Tot}}(m_{\mathrm{inv}}, p_{\mathrm{T}}) = v_2^{\mathrm{Sgn}}(m_{\mathrm{inv}}, p_{\mathrm{T}}) \frac{N^{\mathrm{Sgn}}(m_{\mathrm{inv}}, p_{\mathrm{T}})}{N^{\mathrm{Tot}}(m_{\mathrm{inv}}, p_{\mathrm{T}})} + v_2^{\mathrm{Bg}}(m_{\mathrm{inv}}, p_{\mathrm{T}}) \frac{N^{\mathrm{Bg}}(m_{\mathrm{inv}}, p_{\mathrm{T}})}{N^{\mathrm{Tot}}(m_{\mathrm{inv}}, p_{\mathrm{T}})}$$

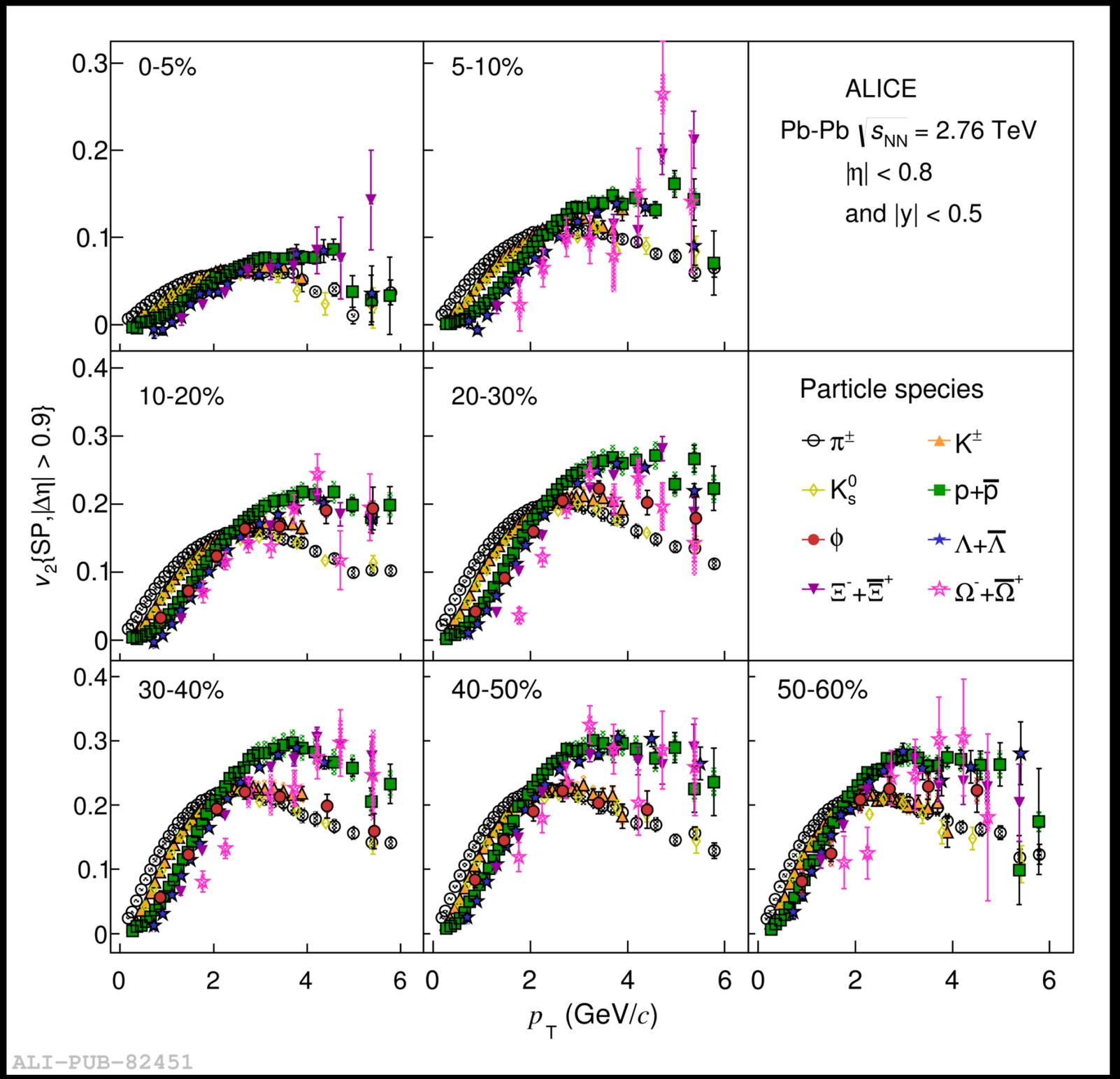
Results

p_T differential v_2 grouped by particle species

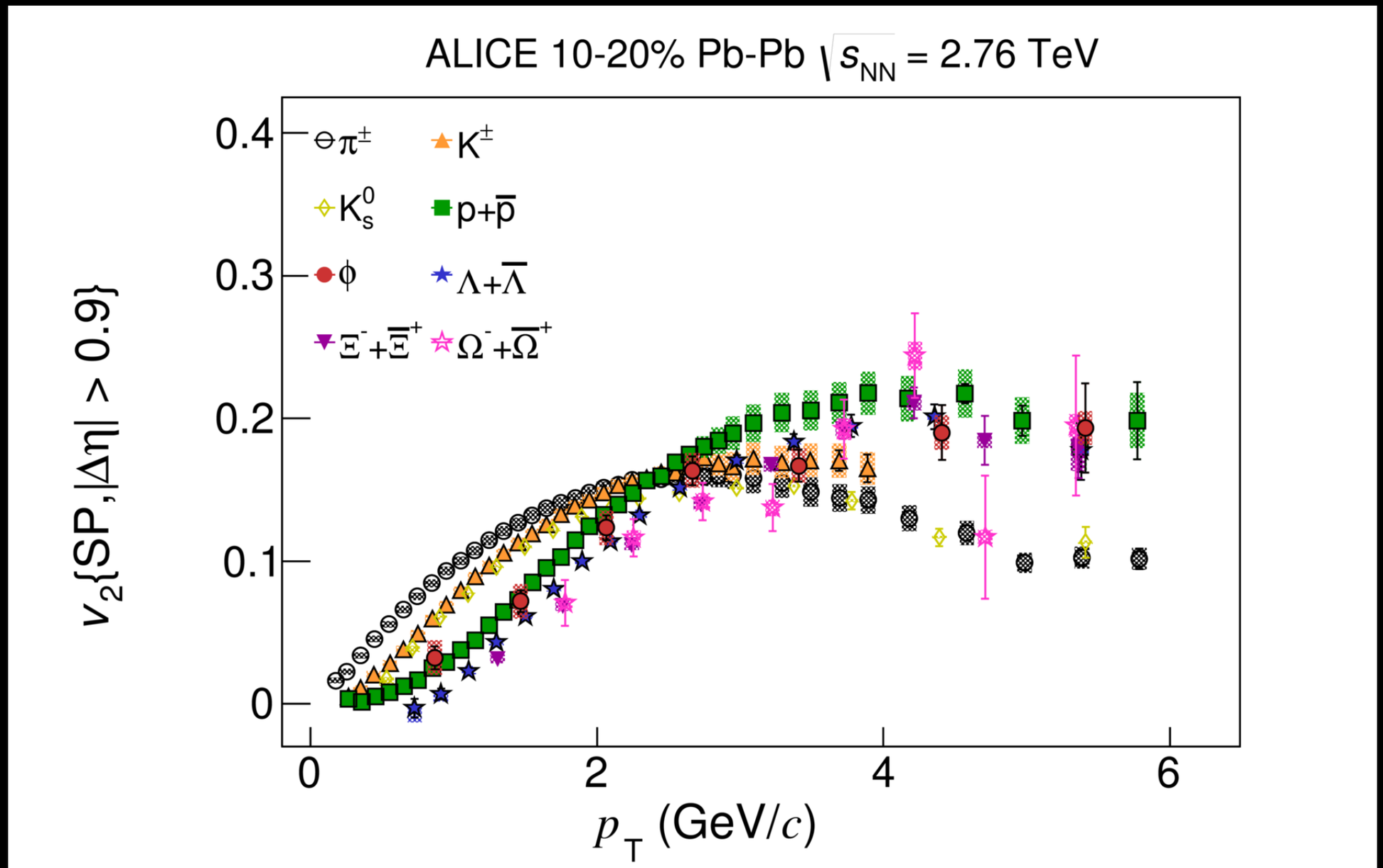


ALI-PUB-82414

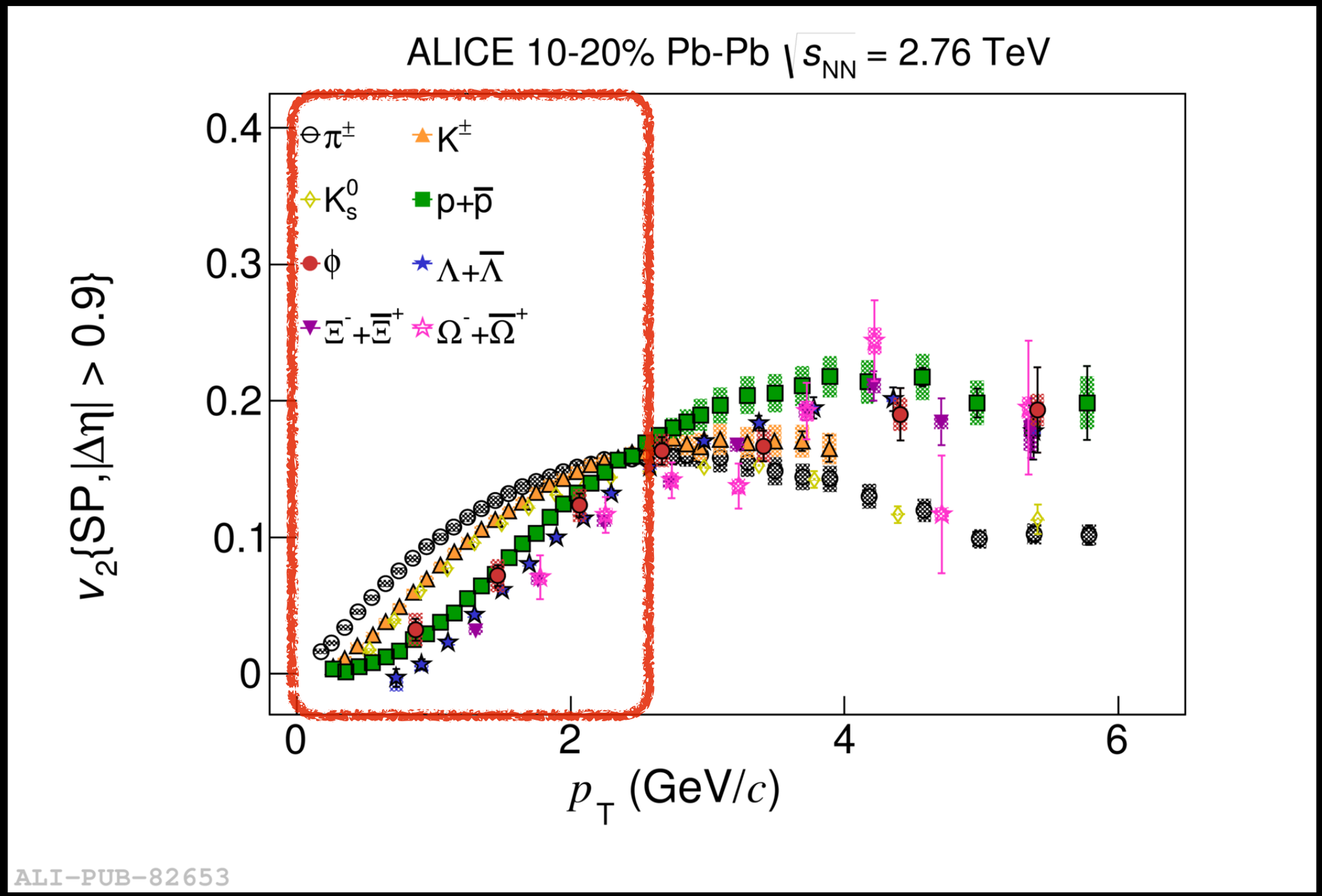
p_T differential v_2 grouped by centrality



p_T differential v_2 grouped by centrality

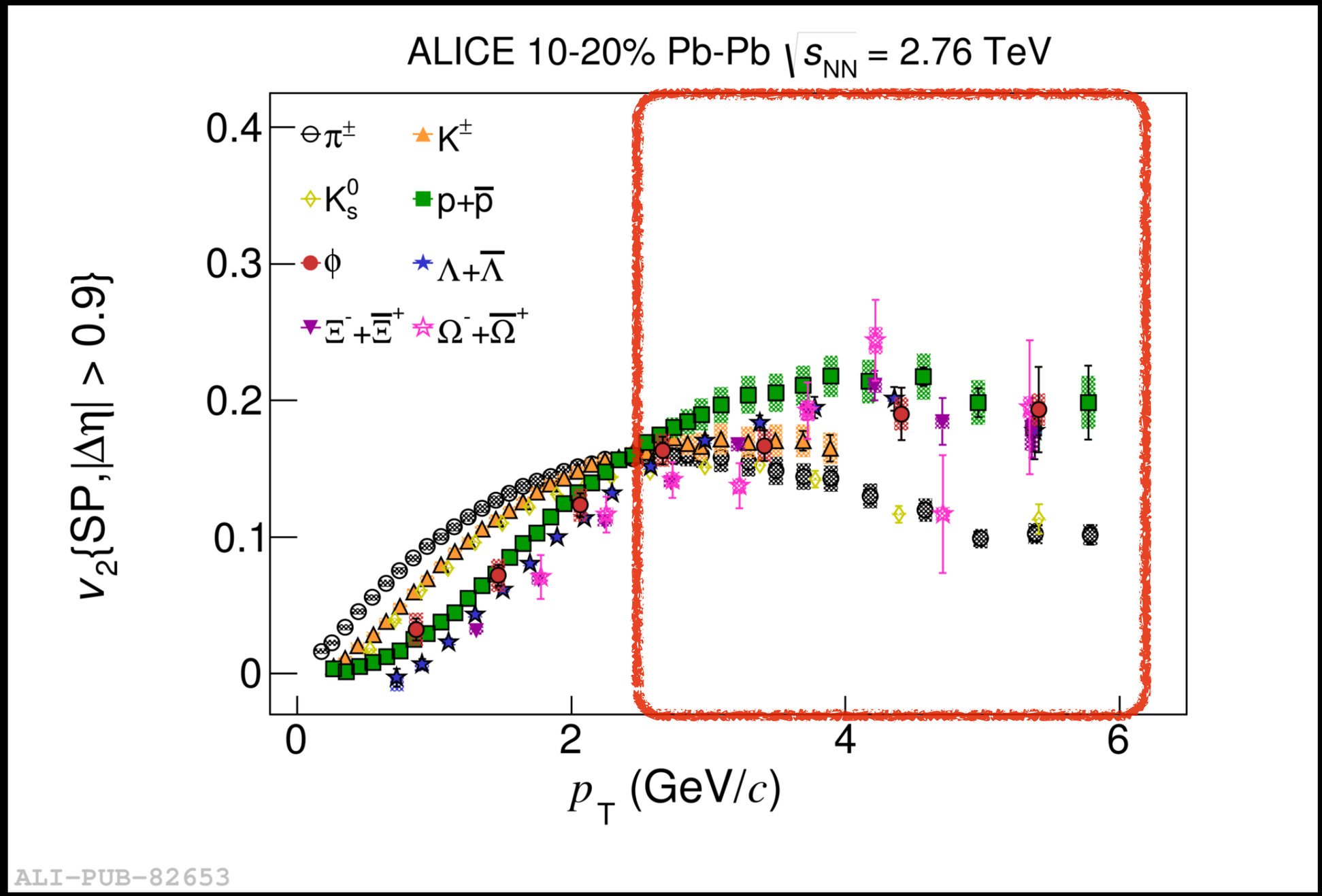


p_T differential v_2 grouped by centrality



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

p_T differential v_2 grouped by centrality



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

A careful look at the φ-meson…

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

A careful look at the φ-meson…

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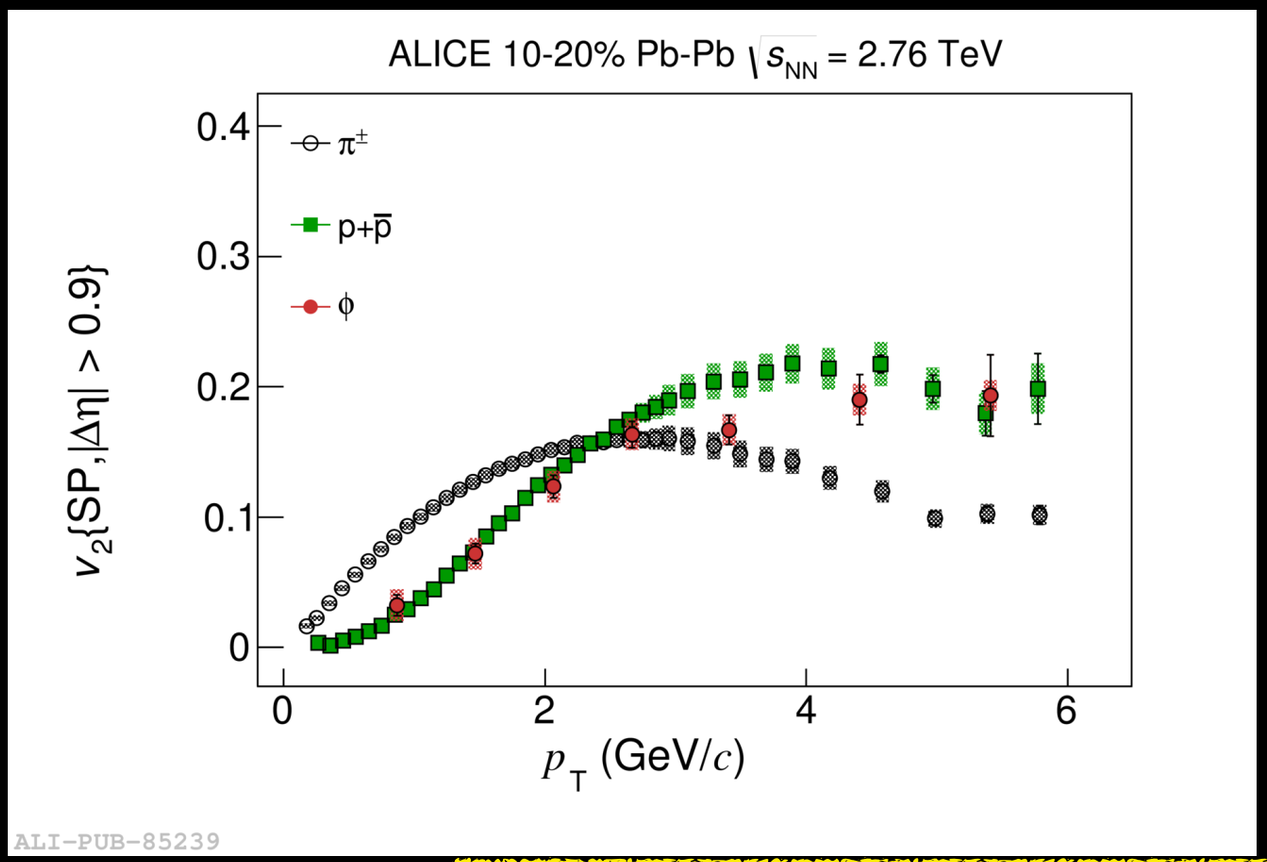
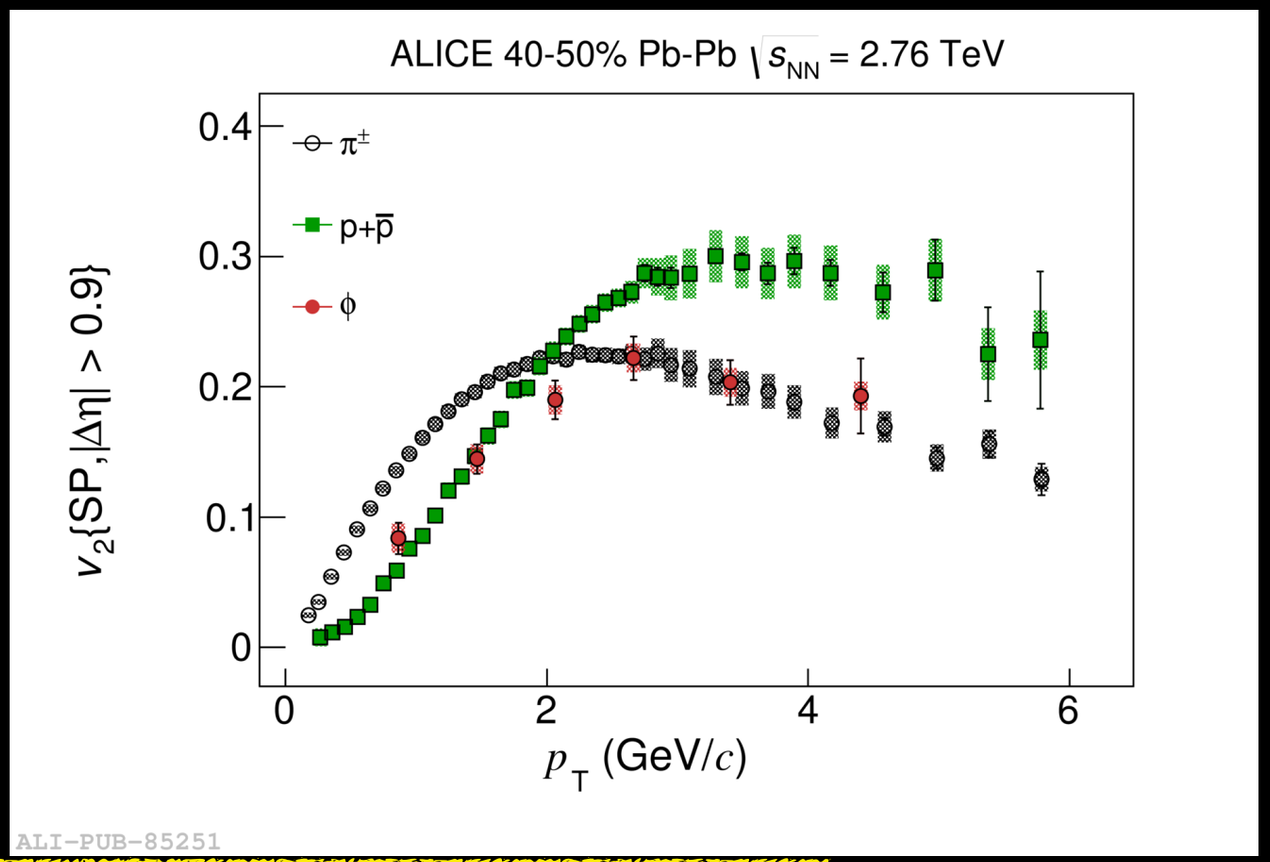


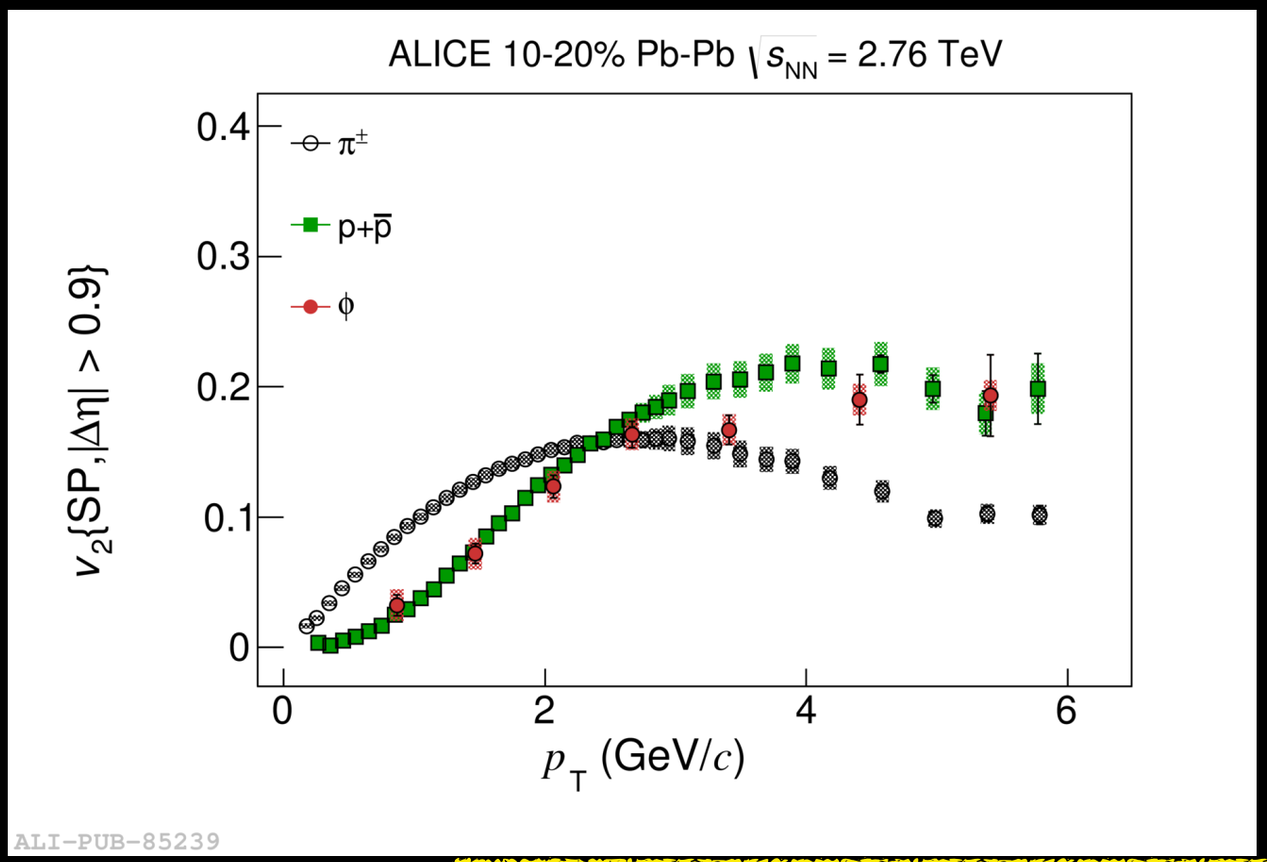


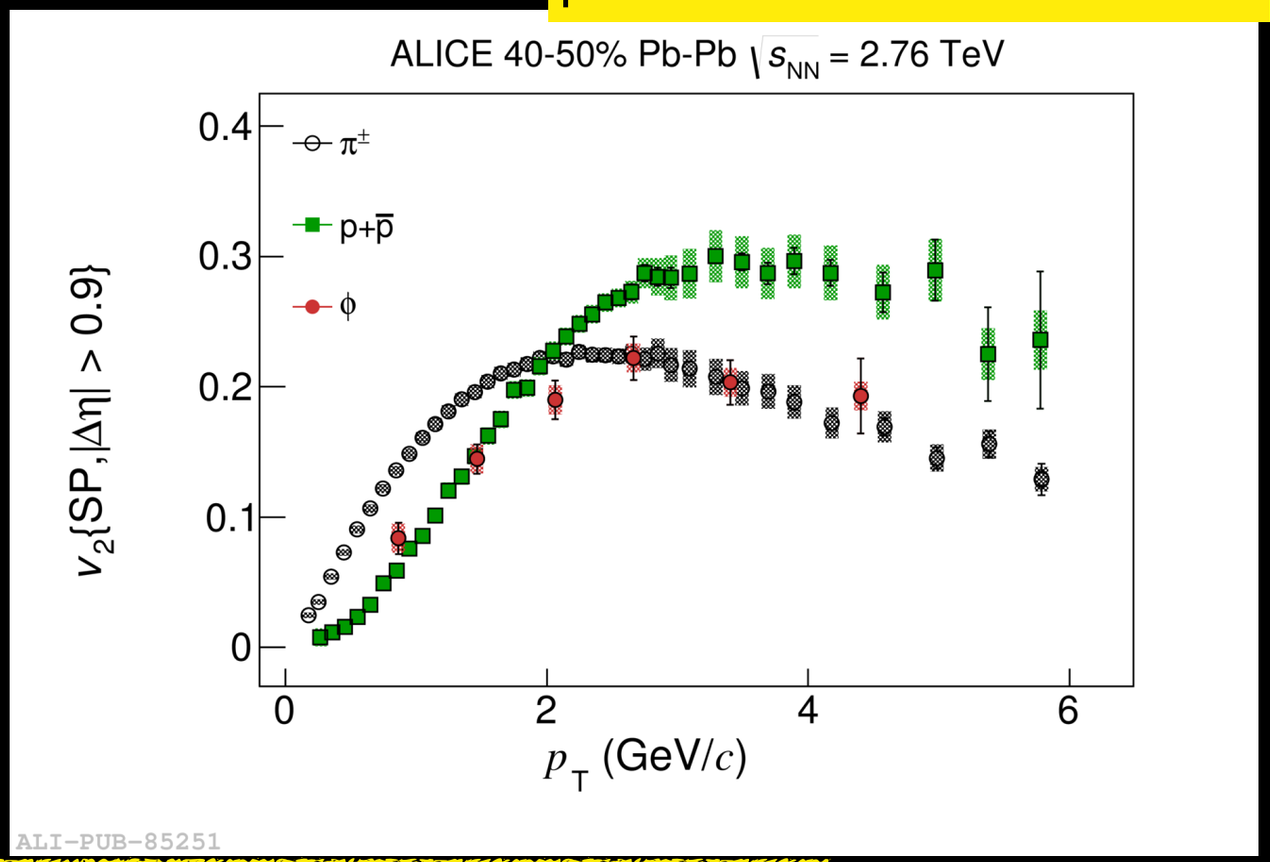
- At low p_T (p_T < 3 GeV/c): mass ordering ➜ elliptic/radial flow interplay
  - ★ First bins could hint to a different ordering? Still inconclusive…
- Intermediate p_T (3 < p_T < 6 GeV/c) the φ-meson follows
  - ★ the baryon band for central events
  - ★ the meson band for peripheral events

A careful look at 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
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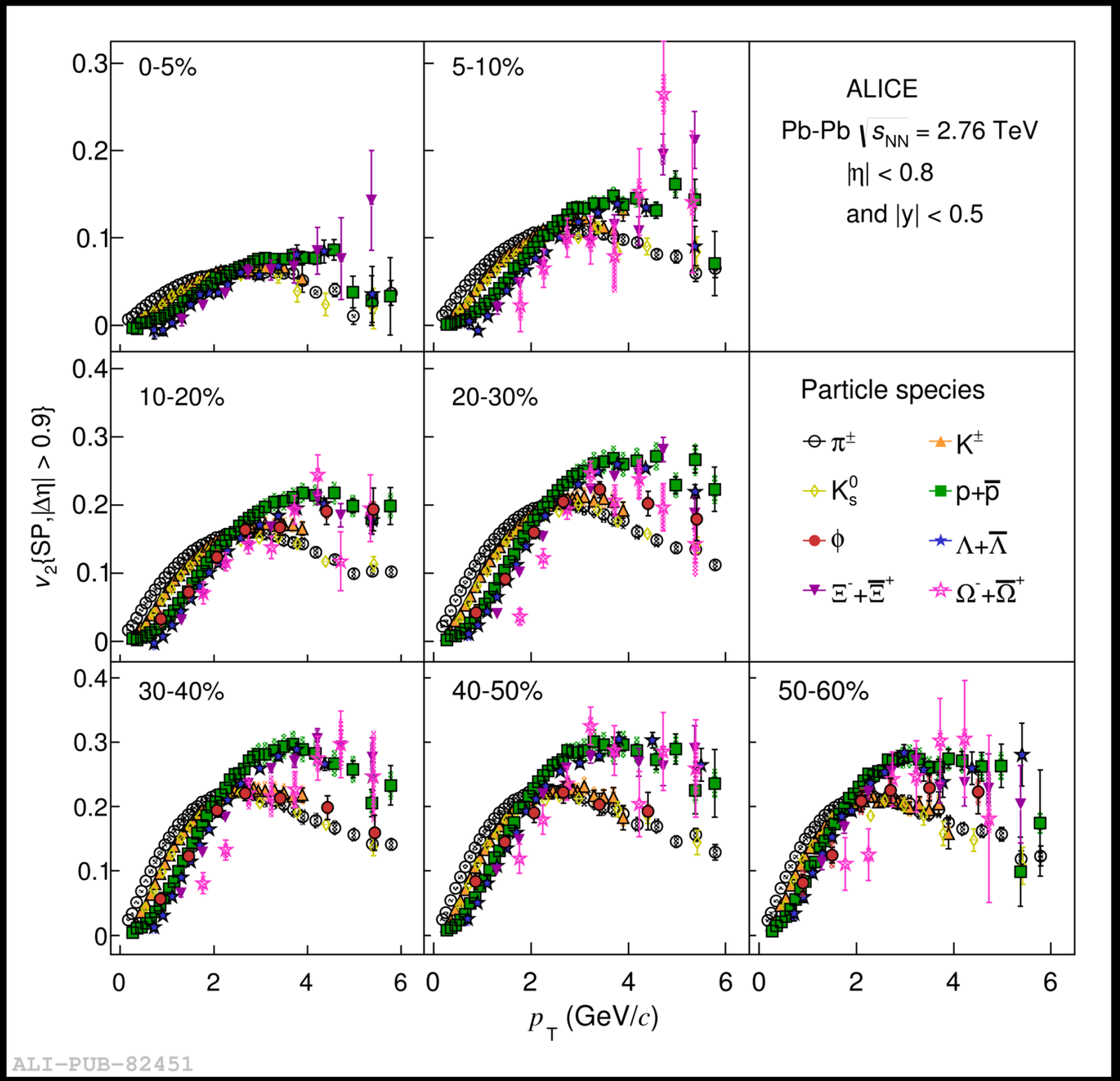
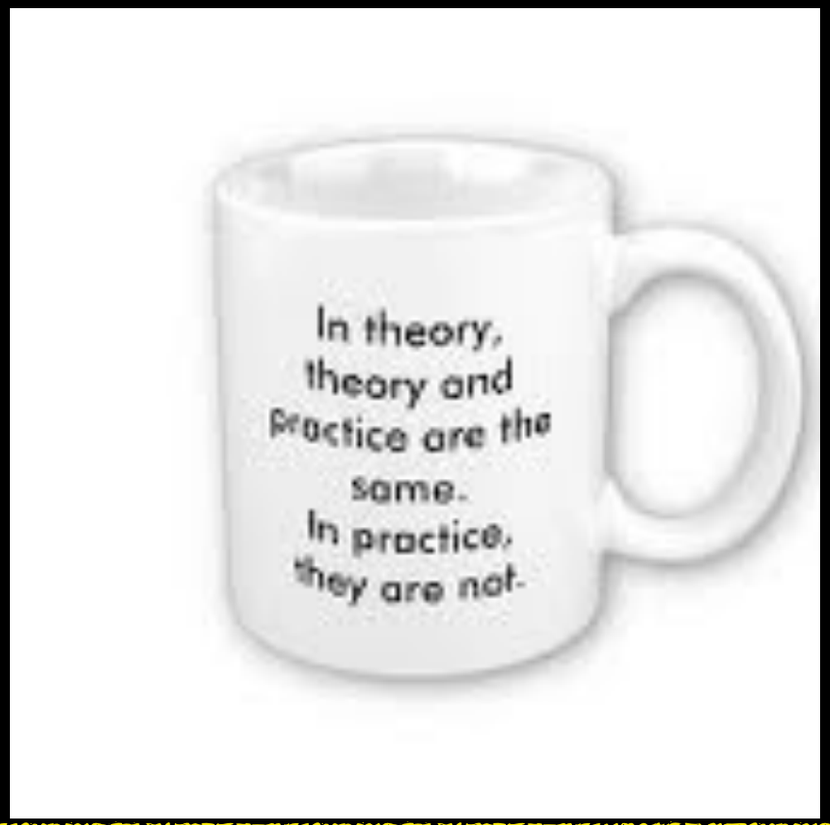
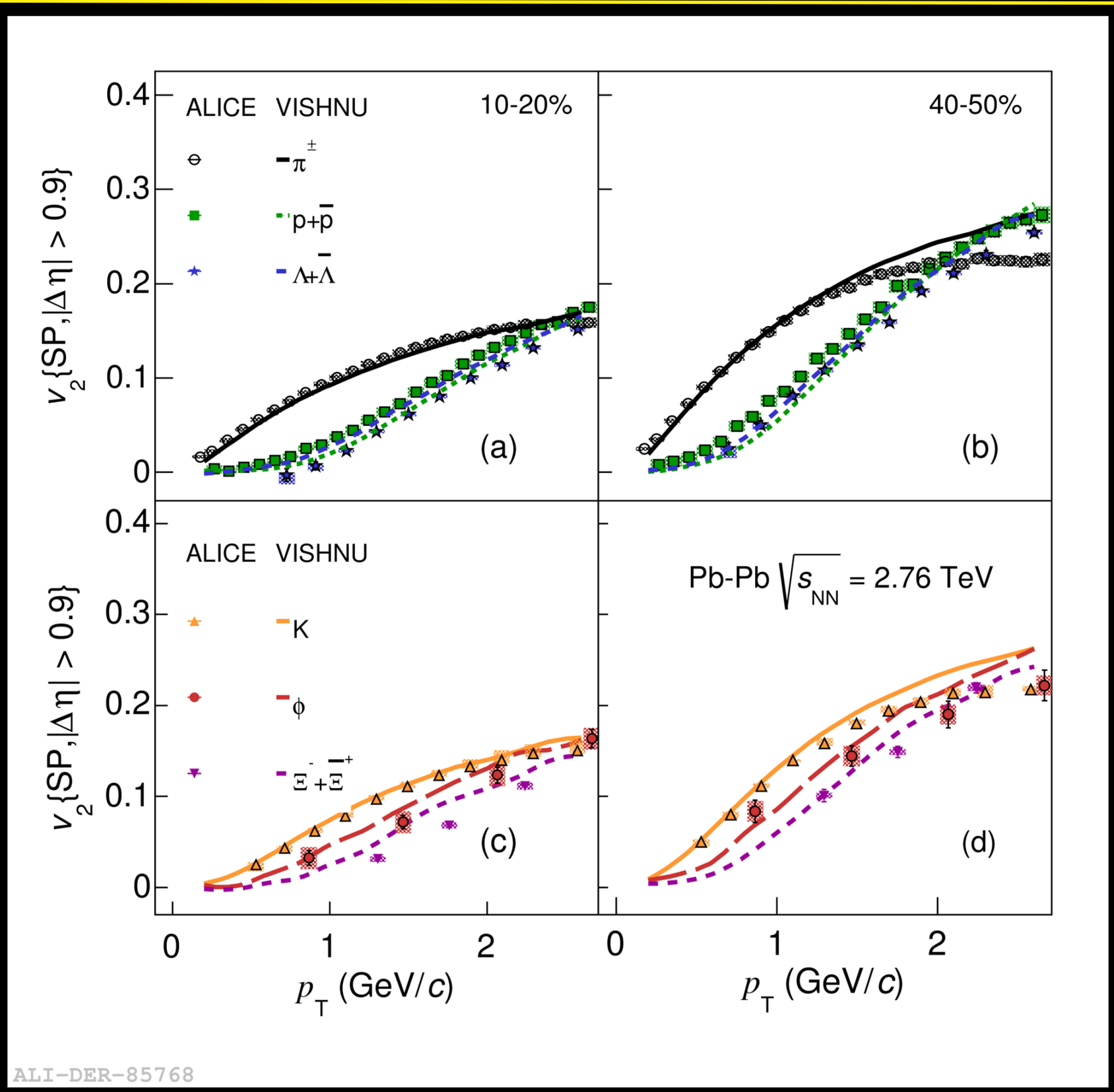

0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
ALICE
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
|η| < 0.8
and |y| < 0.5
Particle species
$\pi^{\pm}$
$K^{\pm}$
K^0_s
$p+\bar{p}$
ϕ
$\Lambda+\bar{\Lambda}$
$\Xi^-+\bar{\Xi}^+$
$\Omega^-+\bar{\Omega}^+$
$v_2\{SP,|\Delta\eta| > 0.9\}$
p_T (GeV/c)
ALI-PUB-82451

Comparison with hydrodynamic calculations



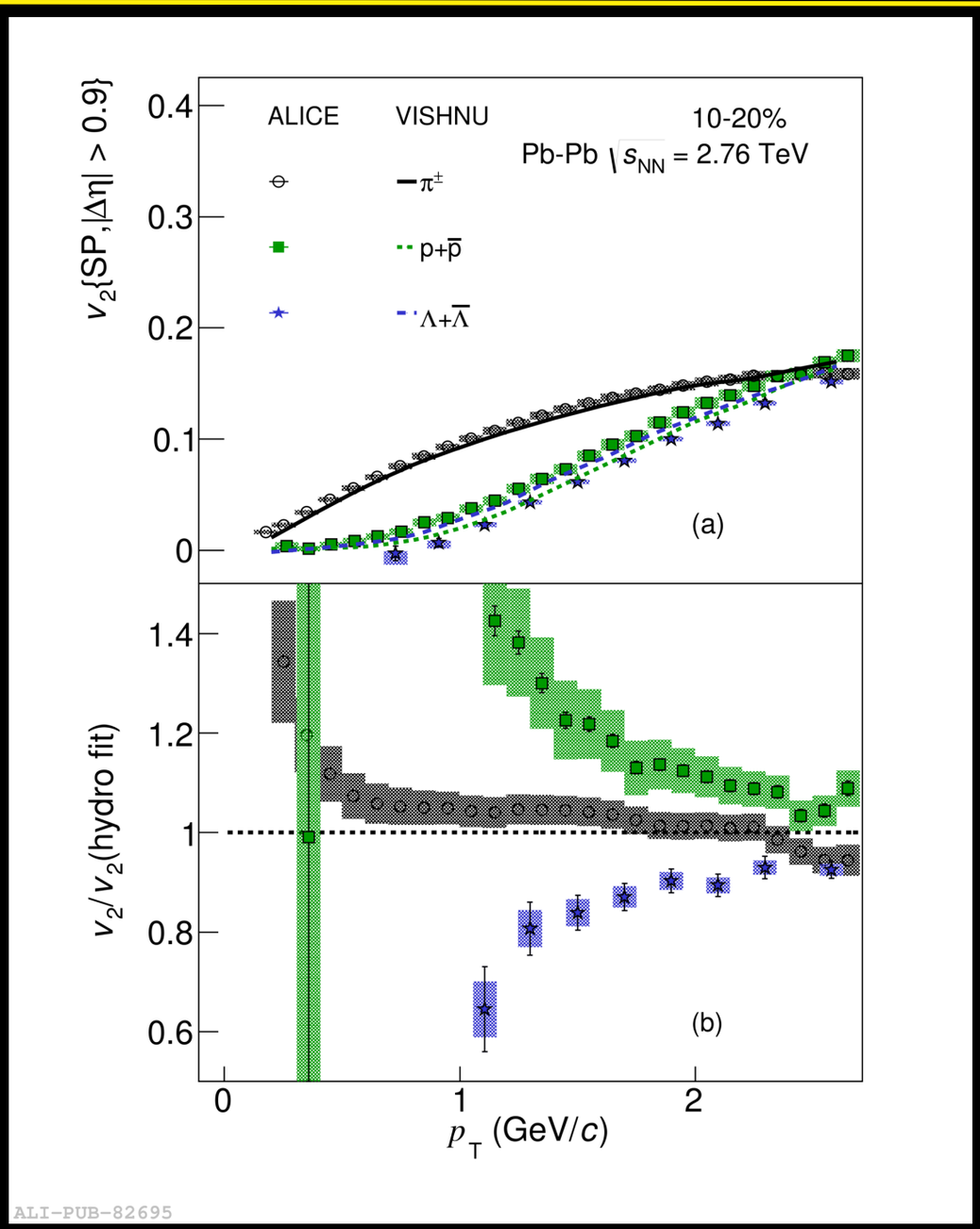
hydro curves from: H. Song, S. Bass and U. Heinz arXiv:1311.0157 [nucl-th]

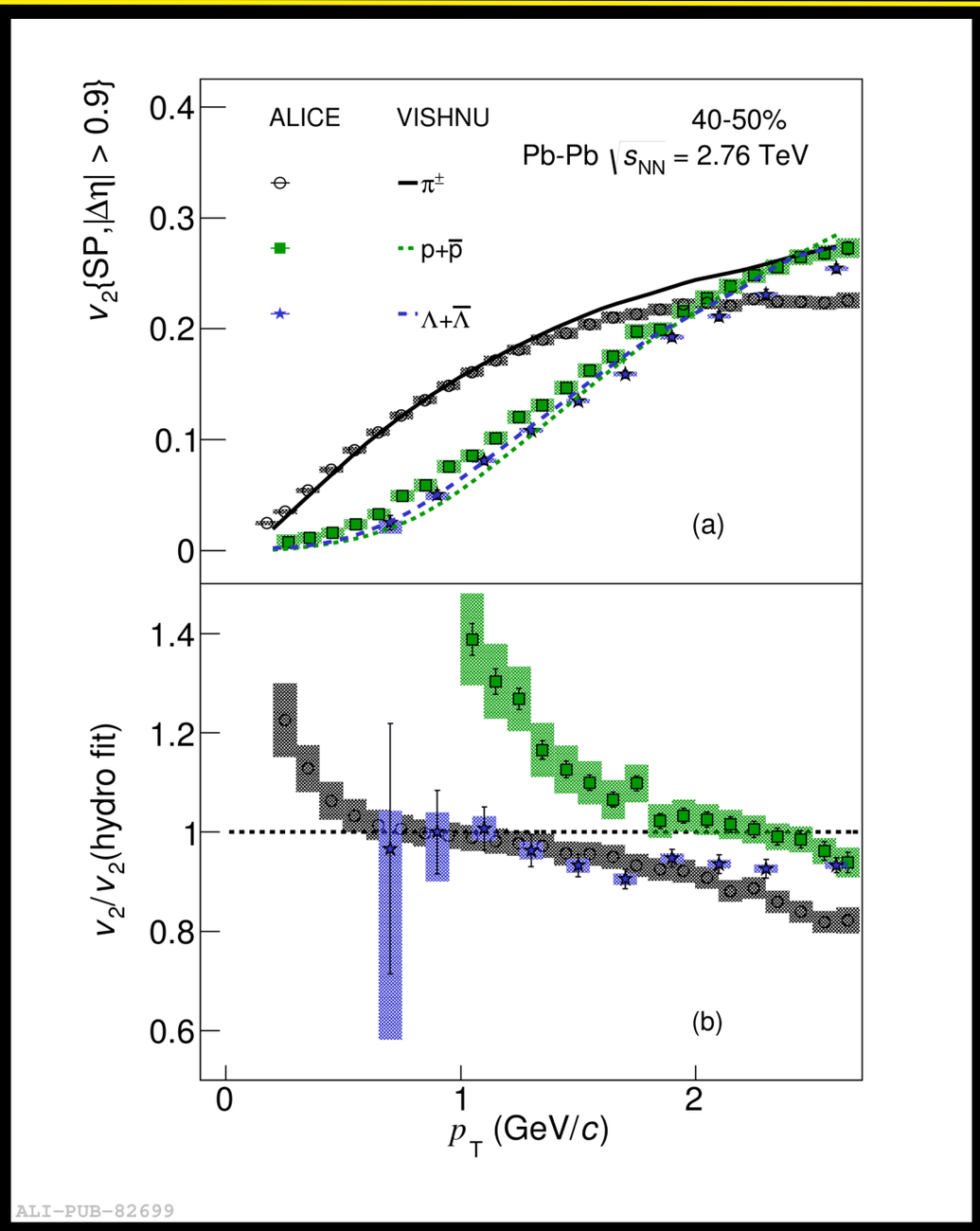
Comparison with VISHNU



ALI-DER-85768

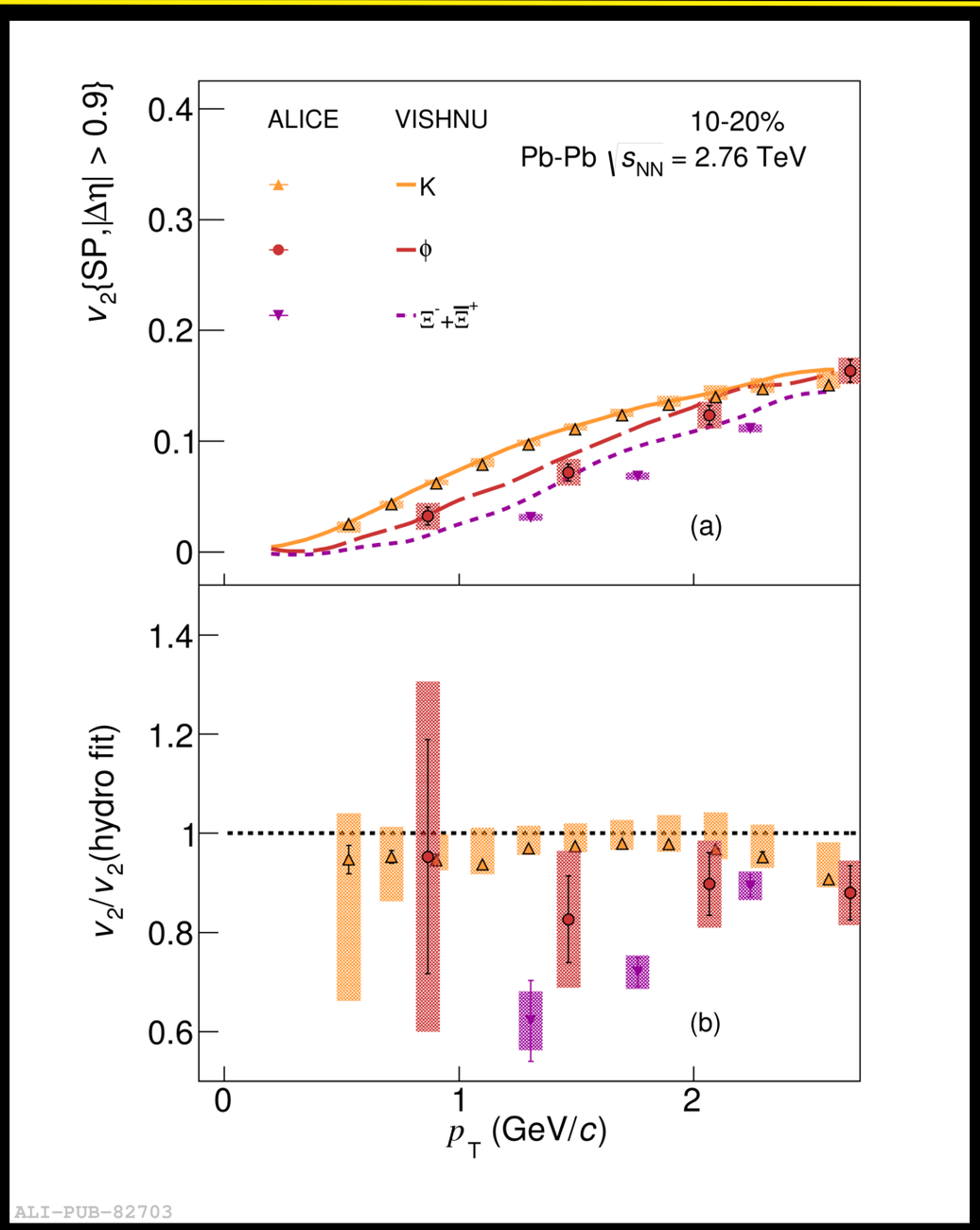
Looking at the details…: π, p, Λ

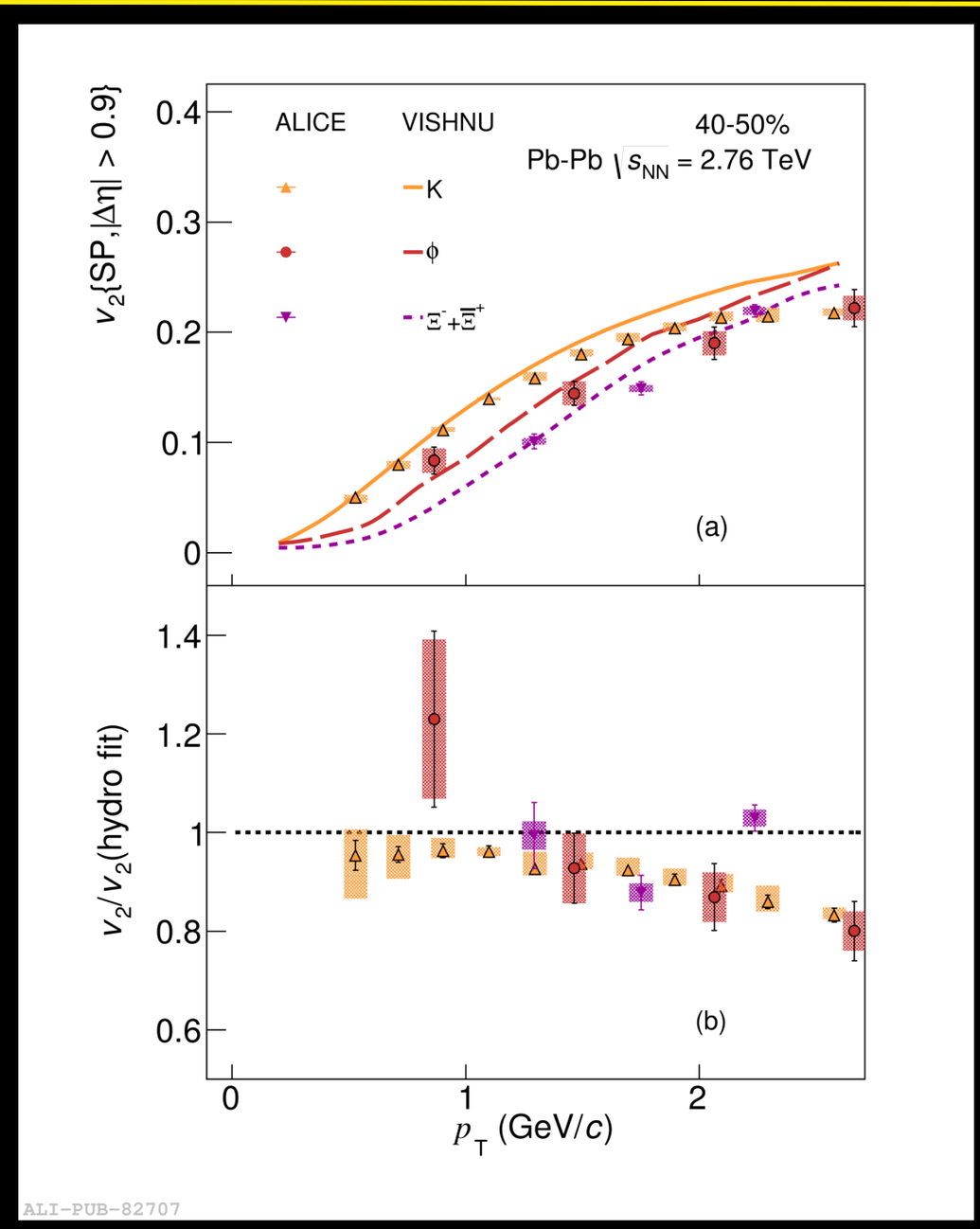




- Pion v_2 systematically underestimated for central events (for peripheral events the agreement is improved)
- Proton v_2 underestimated (i.e. extra push expected in hydro) for both centralities
- Λ v_2 overestimated (i.e. less push expected in hydro) for central events

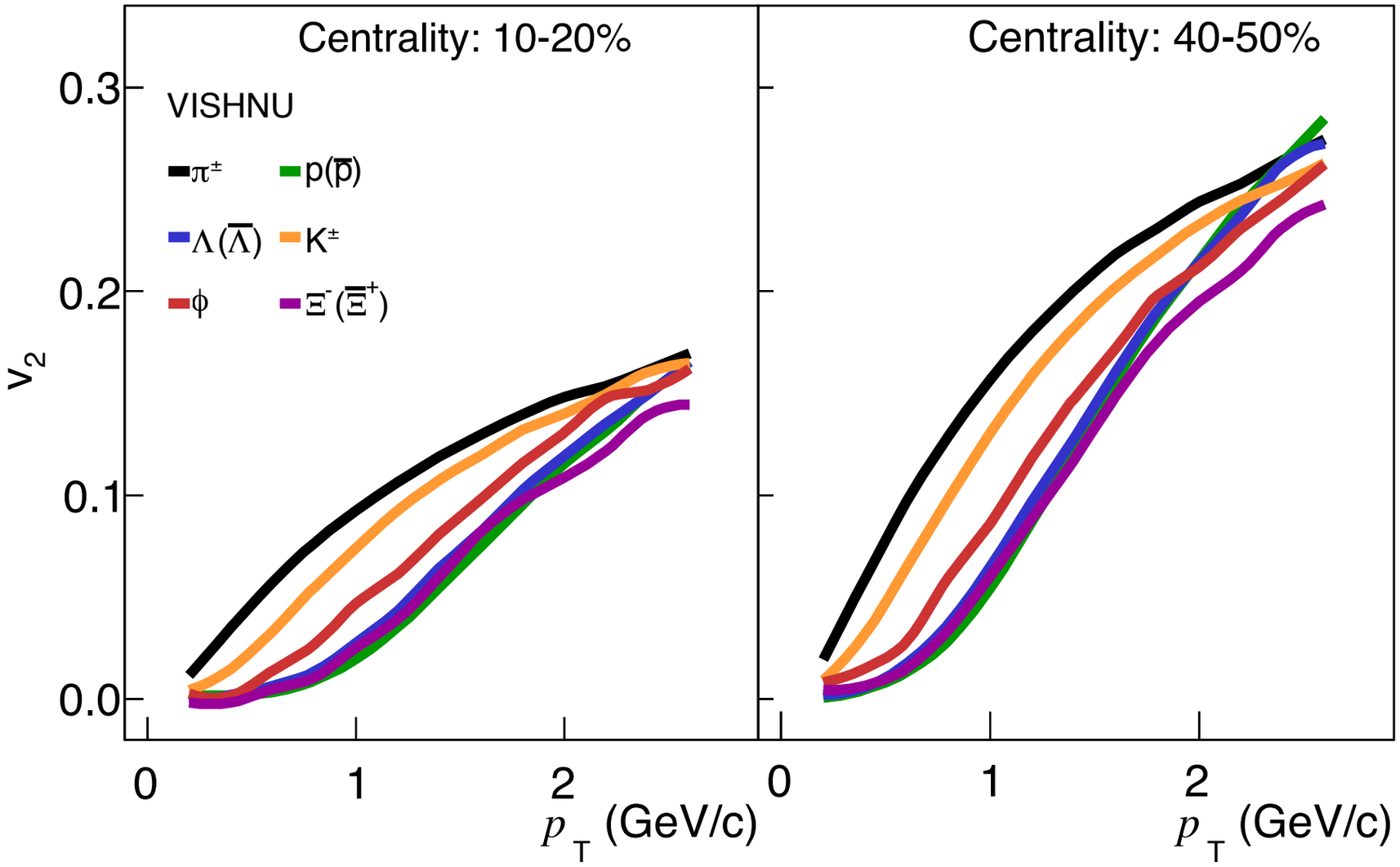
Looking at the details…: K, φ, Ξ





- 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

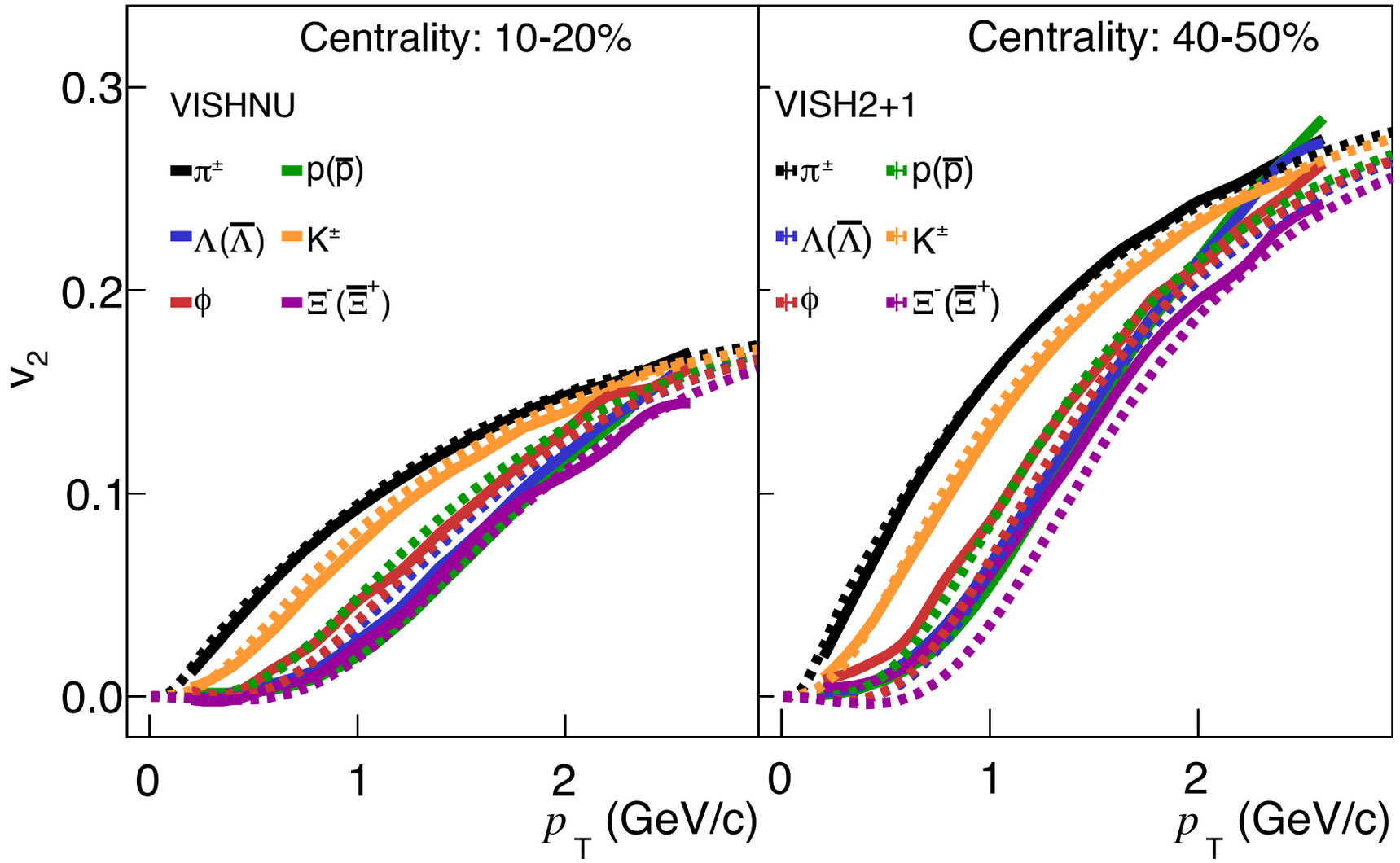
- 2+1 hydro without hadronic cascade
- Glauber density profiles
- $\eta/s = 0.08$
- $\tau_0 = 0.6$ fm/c

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]].

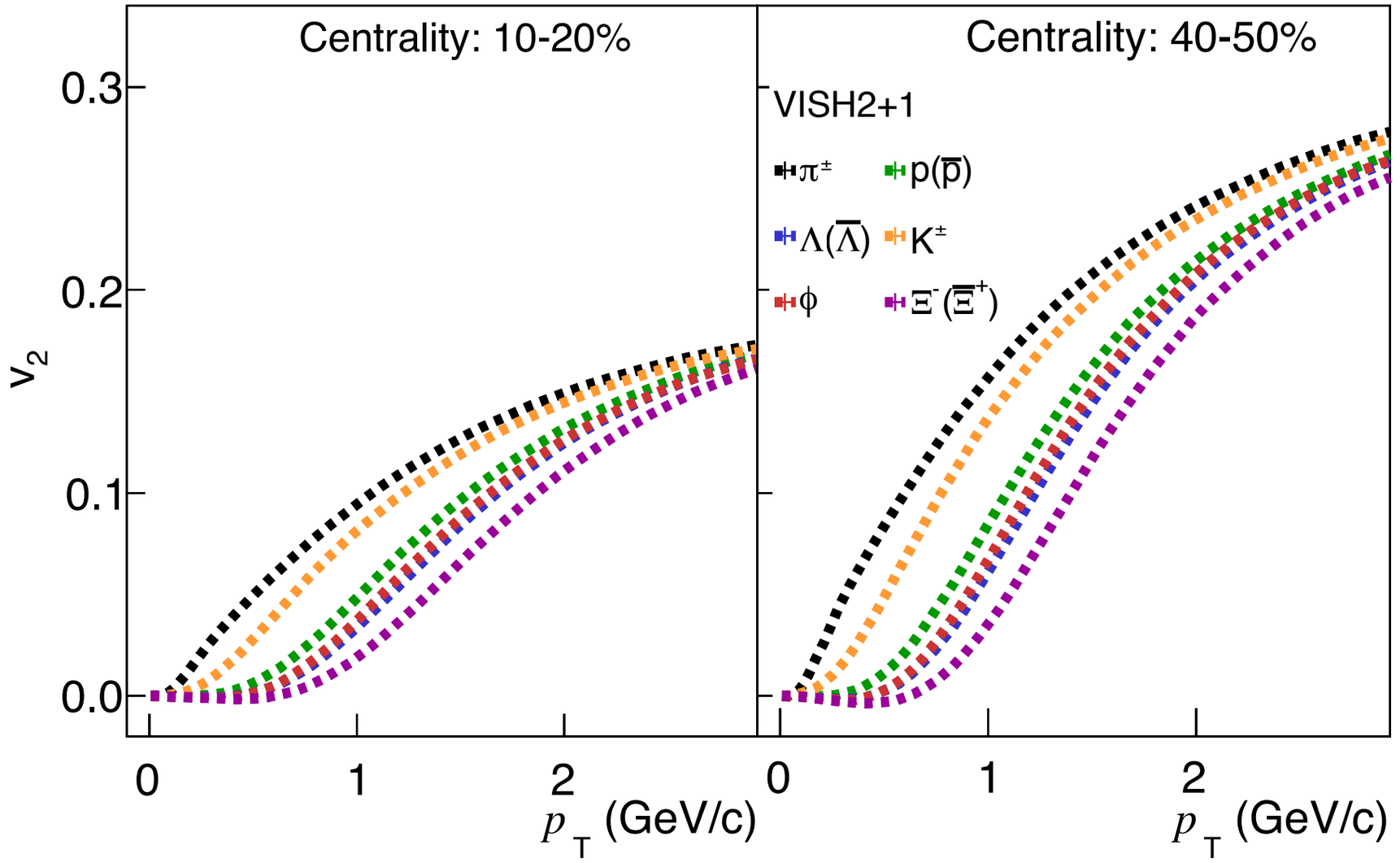
H. Song and U. W. Heinz, Phys. Rev. C 78 (2008) 024902 [arXiv:0805.1756 [nucl-th]].

VISHNU vs VISH2+1



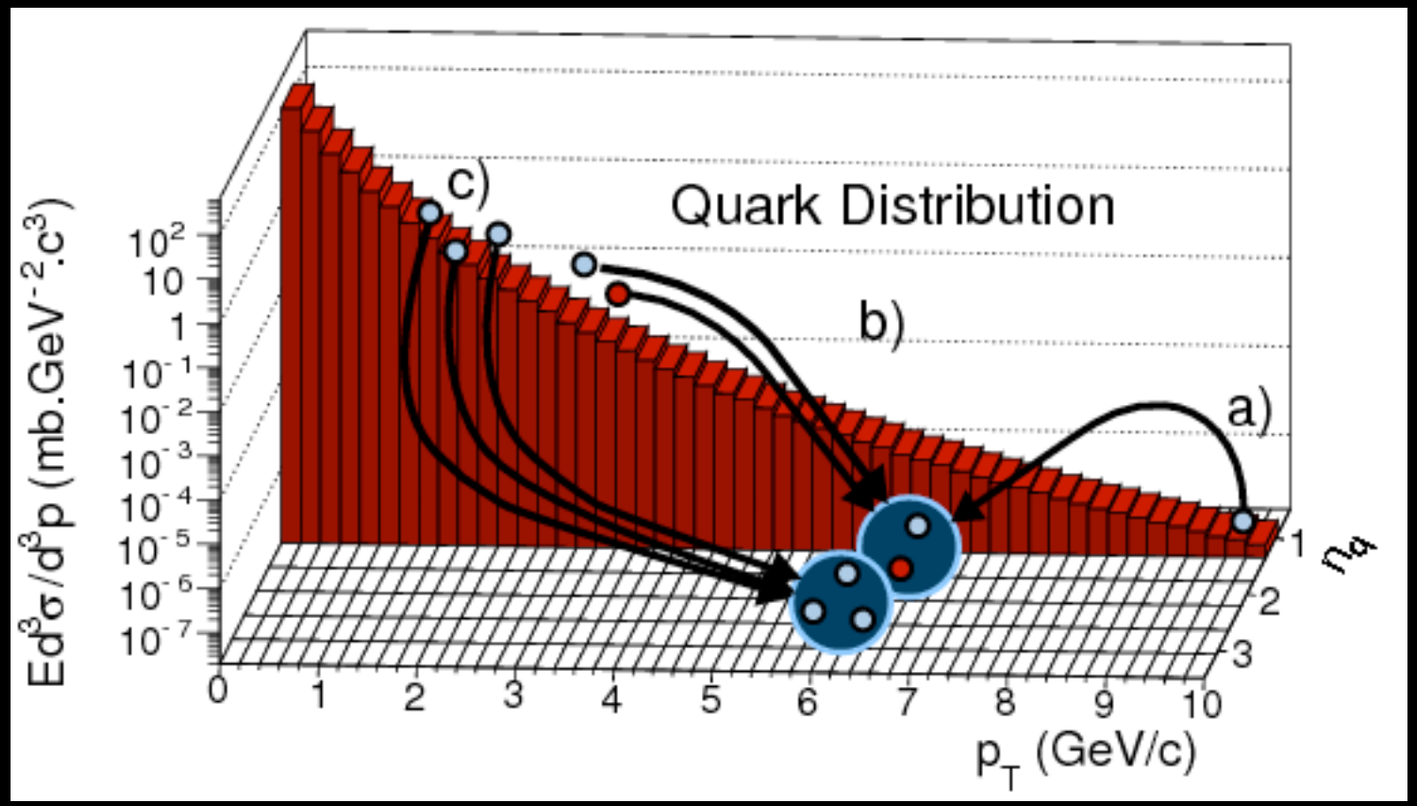
Not a clear trend: π, K similar for both centralities, φ similar for central events but different for peripheral, some baryons (e.g. p, Λ) "pushed" to higher p_T, while others (e.g. Ξ) to lower p_T

VISH2+1 in more detail

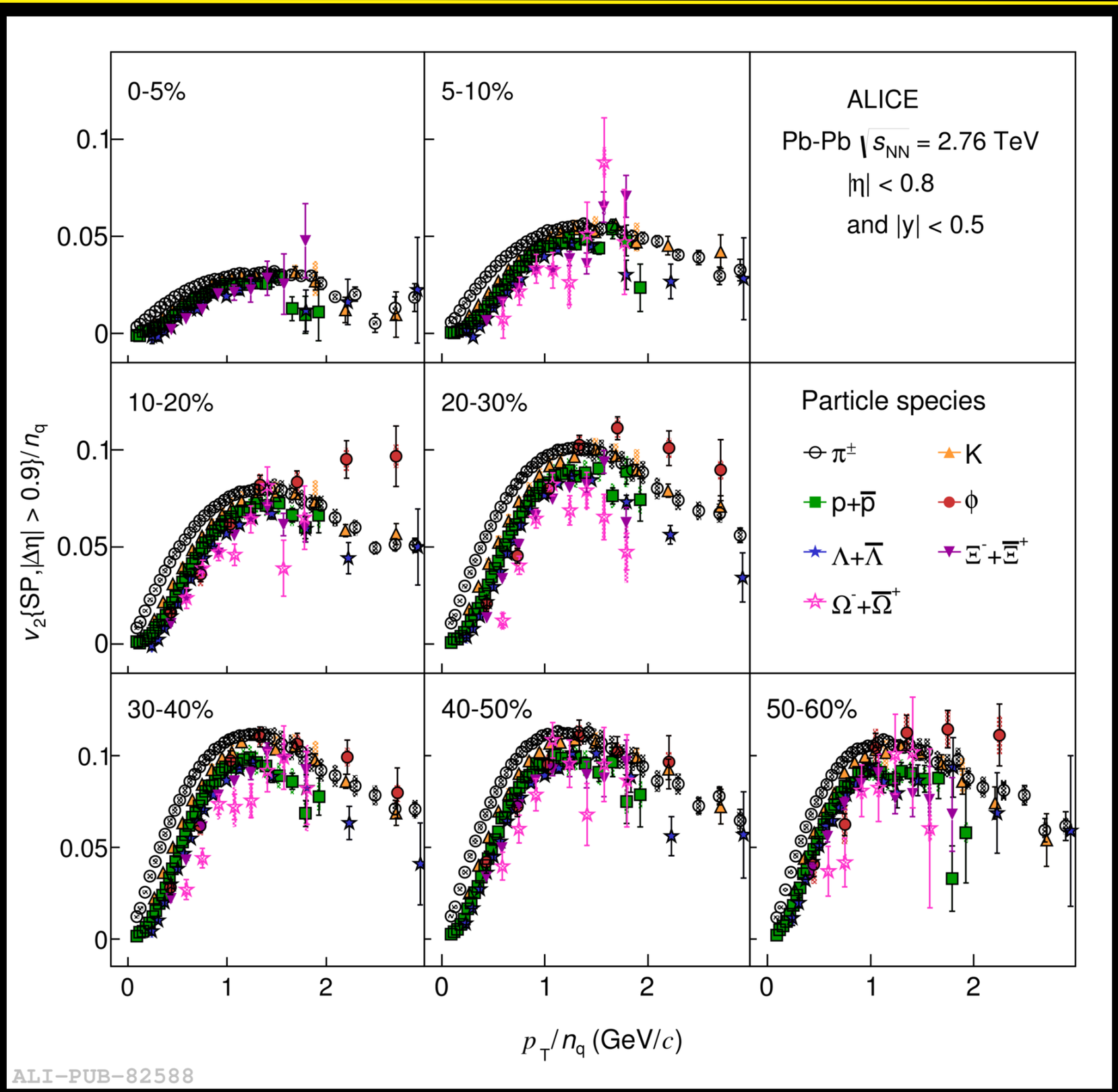


Mass ordering preserved

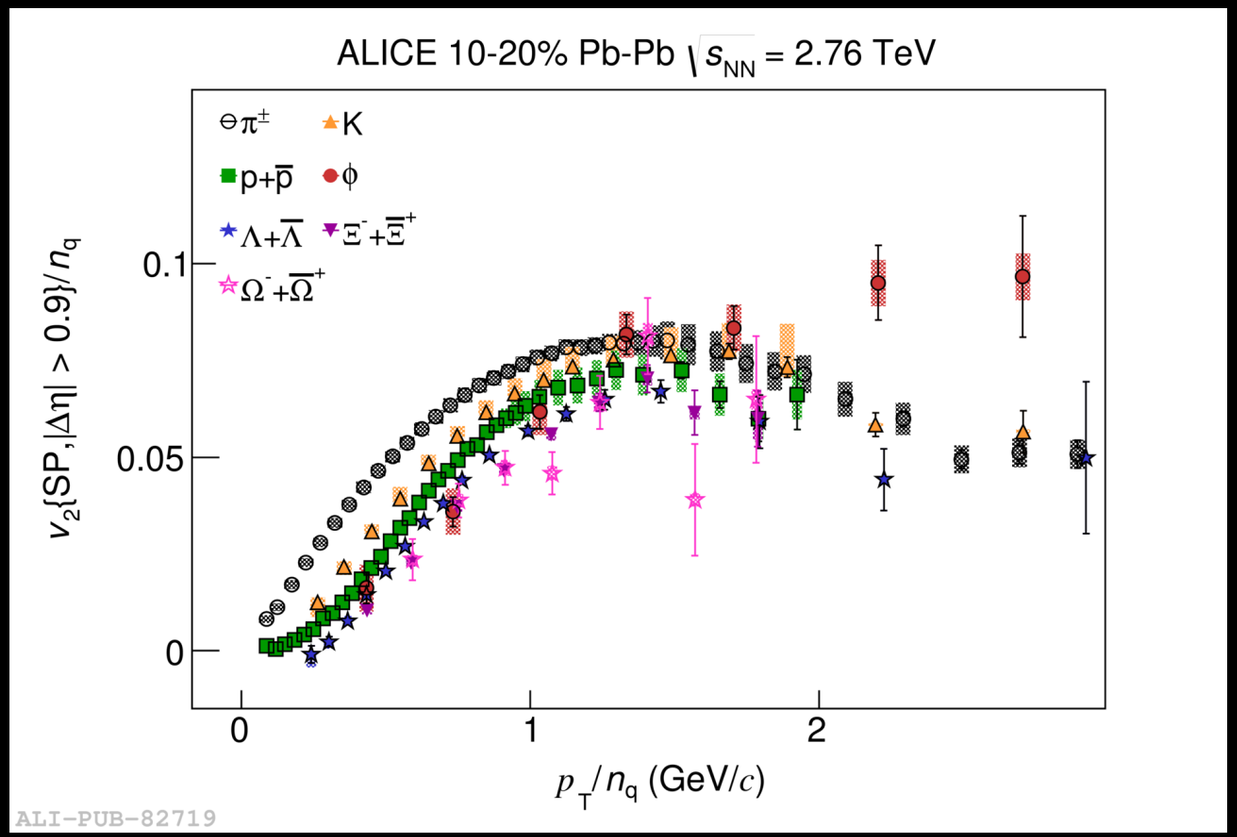
Number of constituent quark (NCQ) scaling

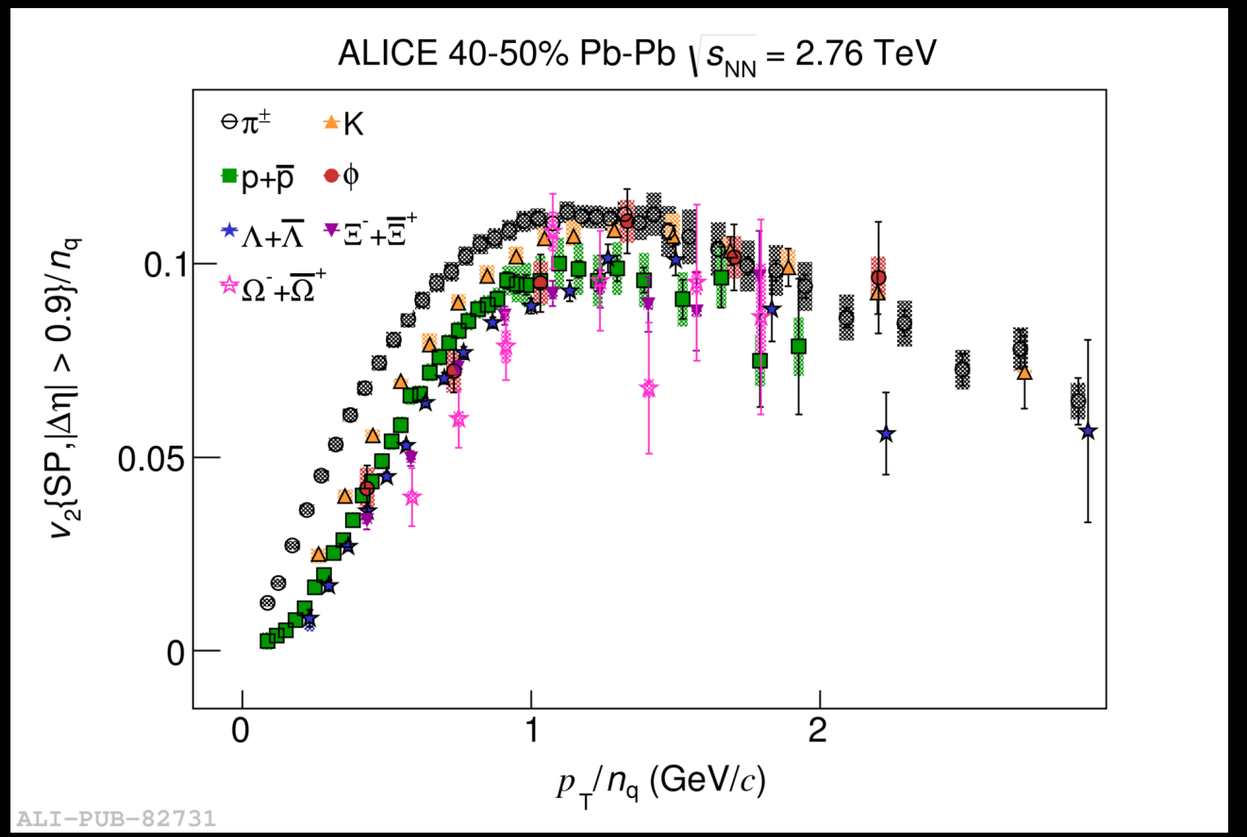


Number of constituent quark (NCQ) scaling in p_T/n_q



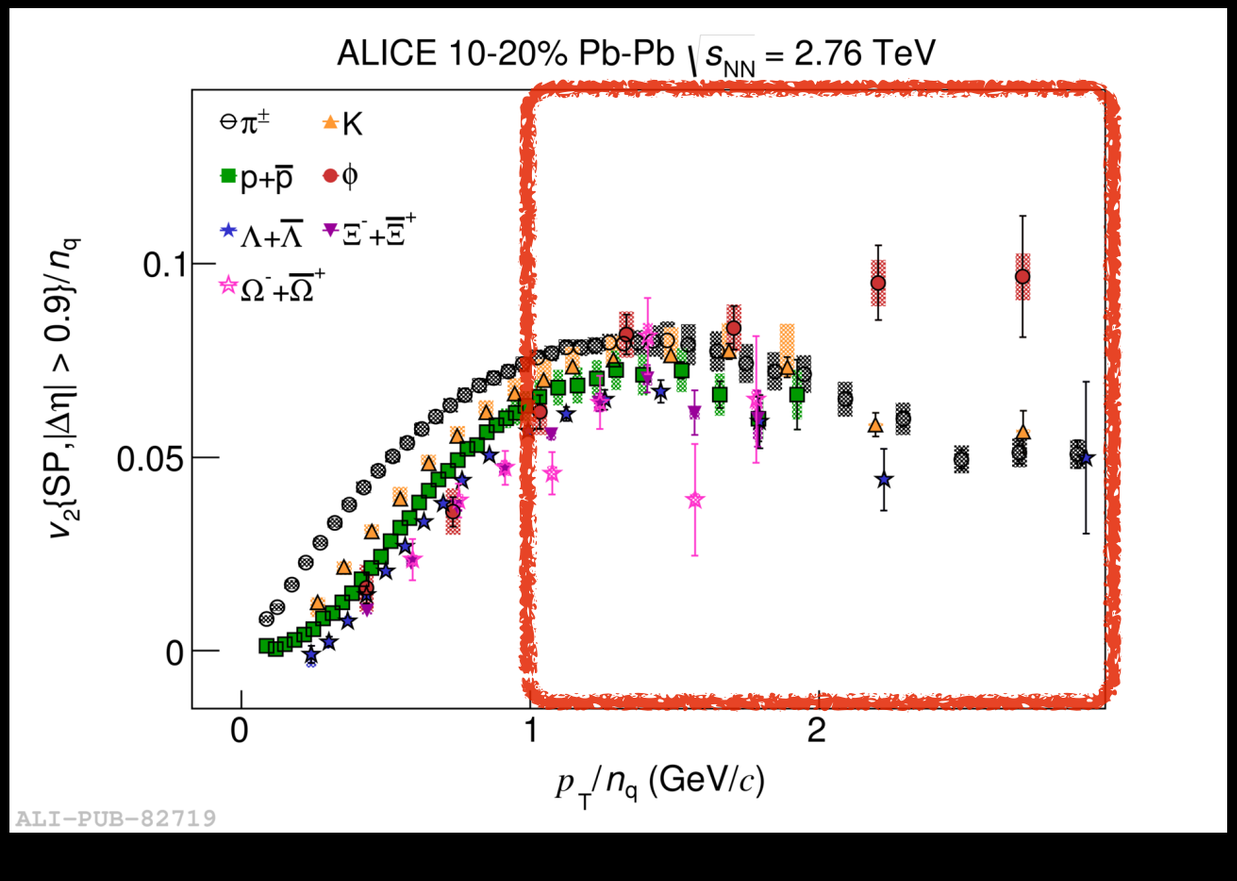
Number of constituent quark (NCQ) scaling in p_T/n_q

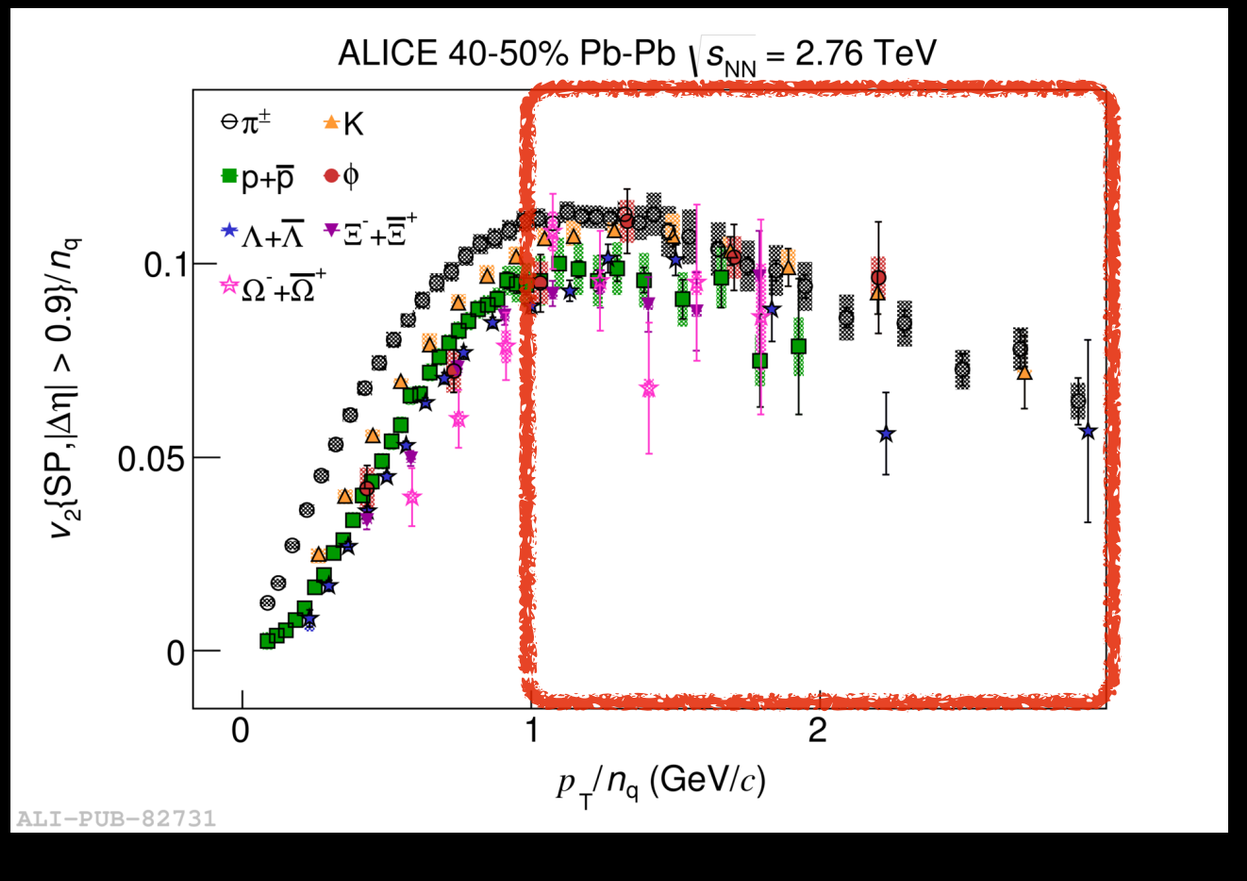




Relevant range: $p_T/n_q > 1$ GeV/c

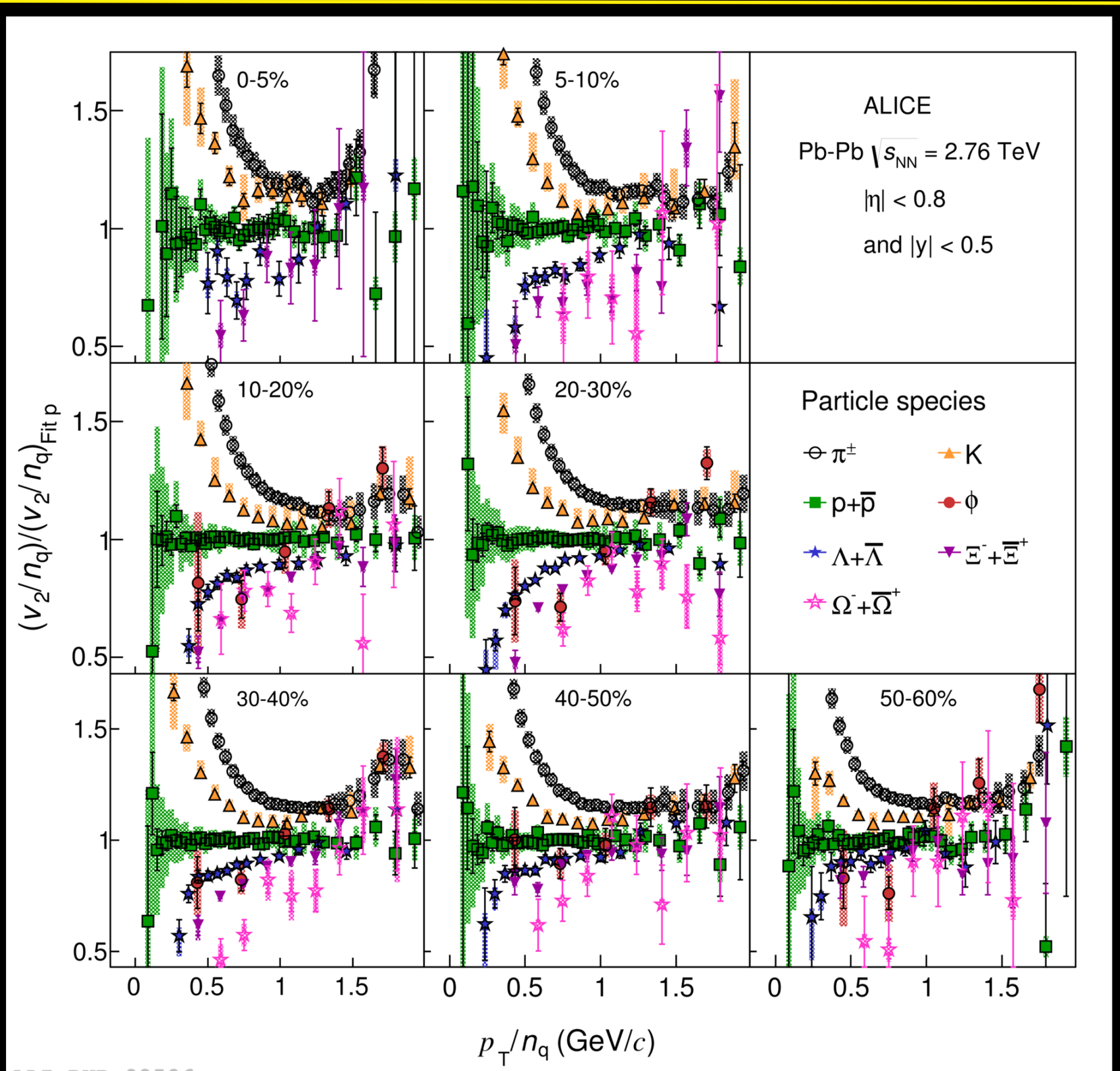
Number of constituent quark (NCQ) scaling in p_T/n_q



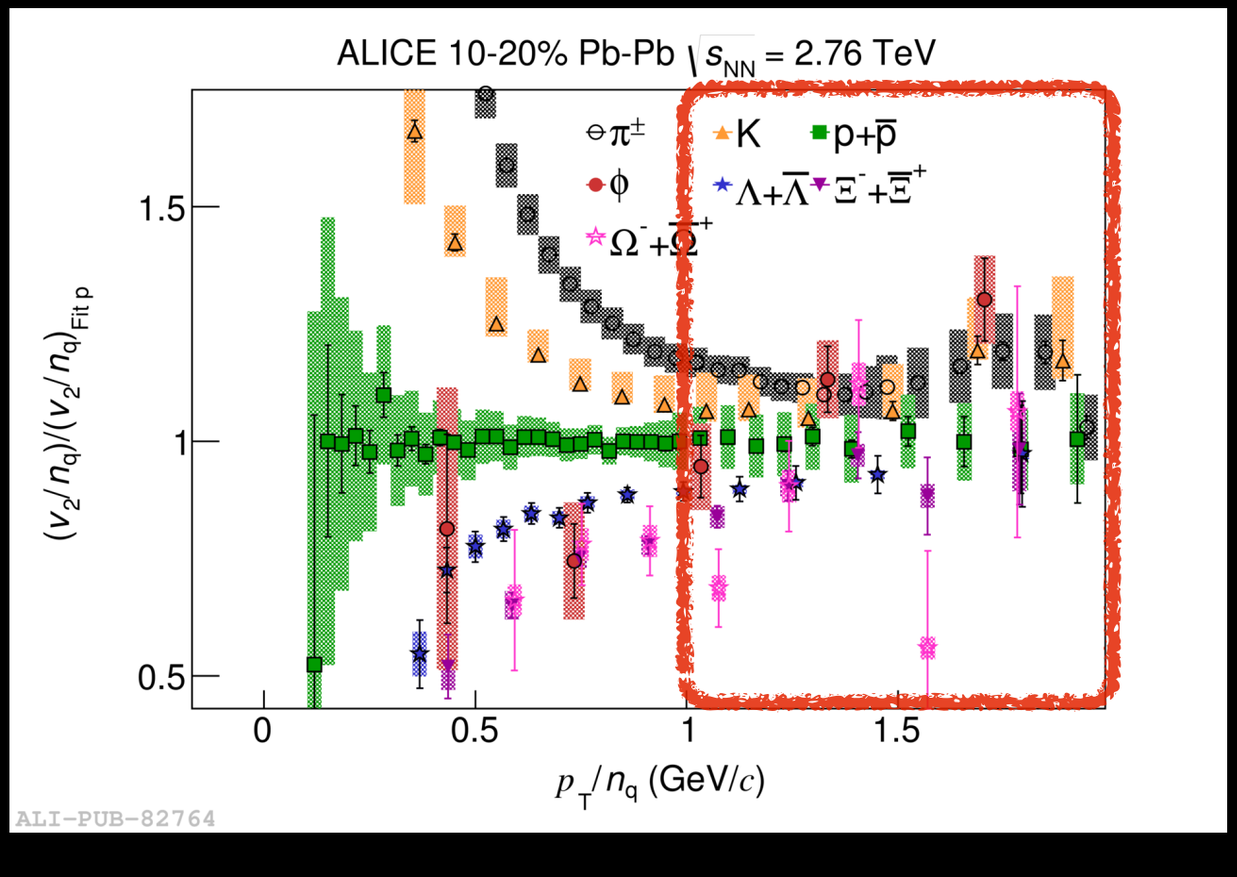


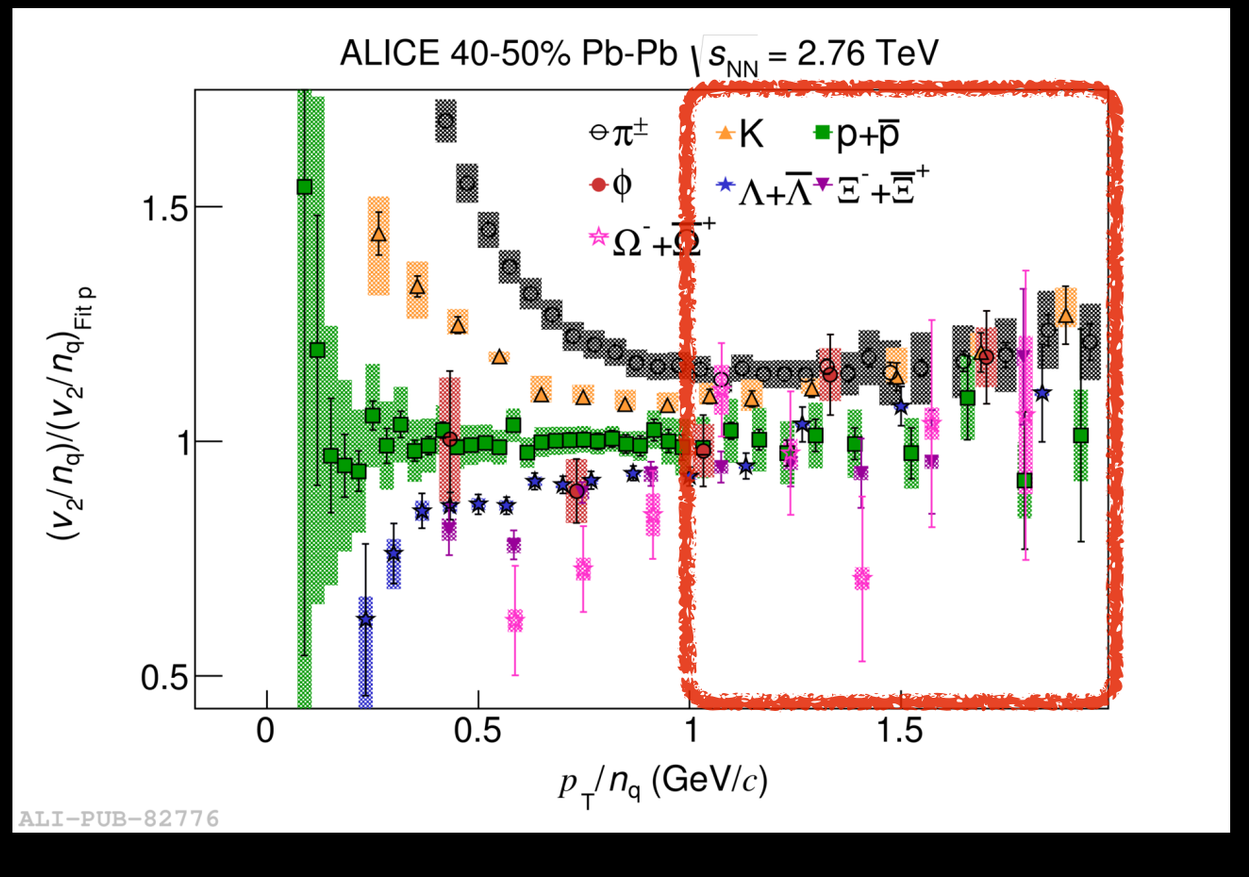
Scaling only approximate

NCQ scaling in p_T/n_q (double ratio)



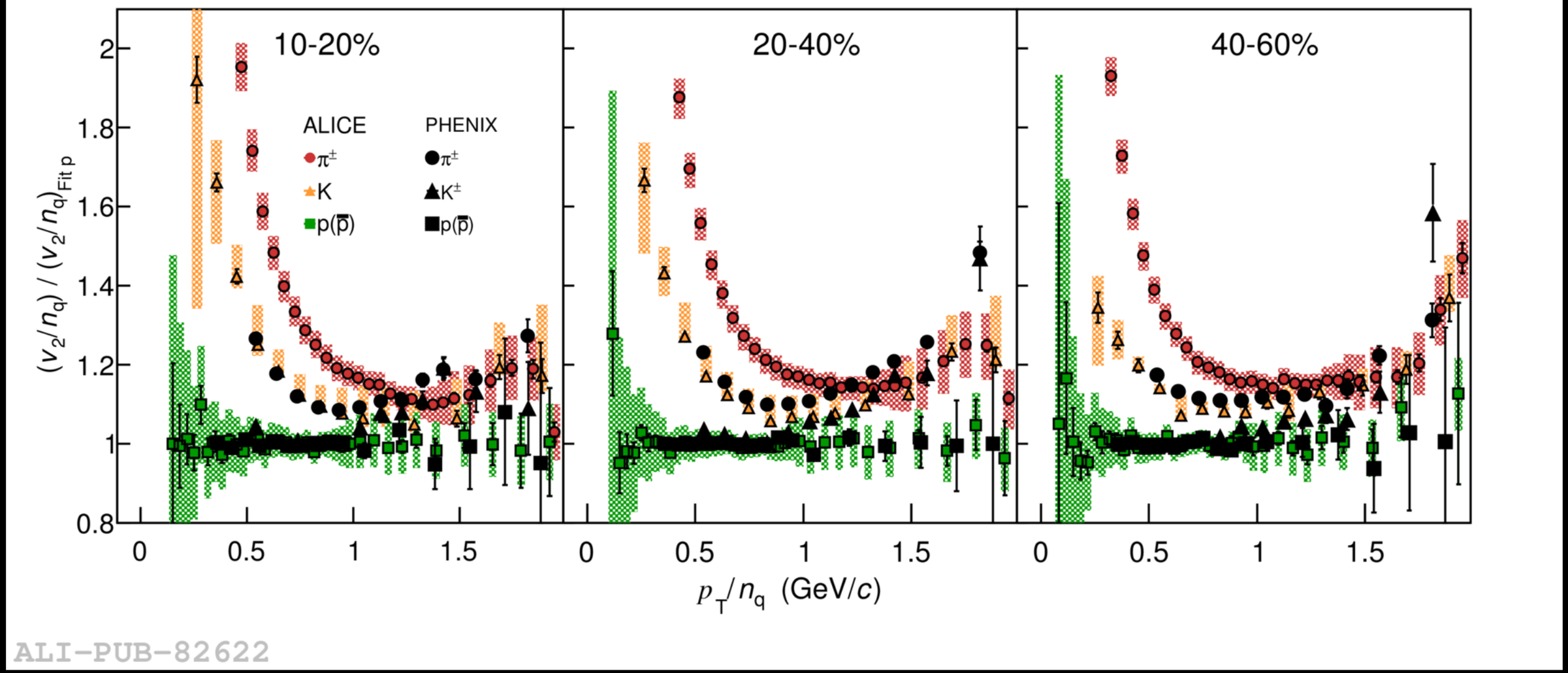
NCQ scaling in p_T/n_q (double ratio)





Scaling at the level of no better than ± 20%

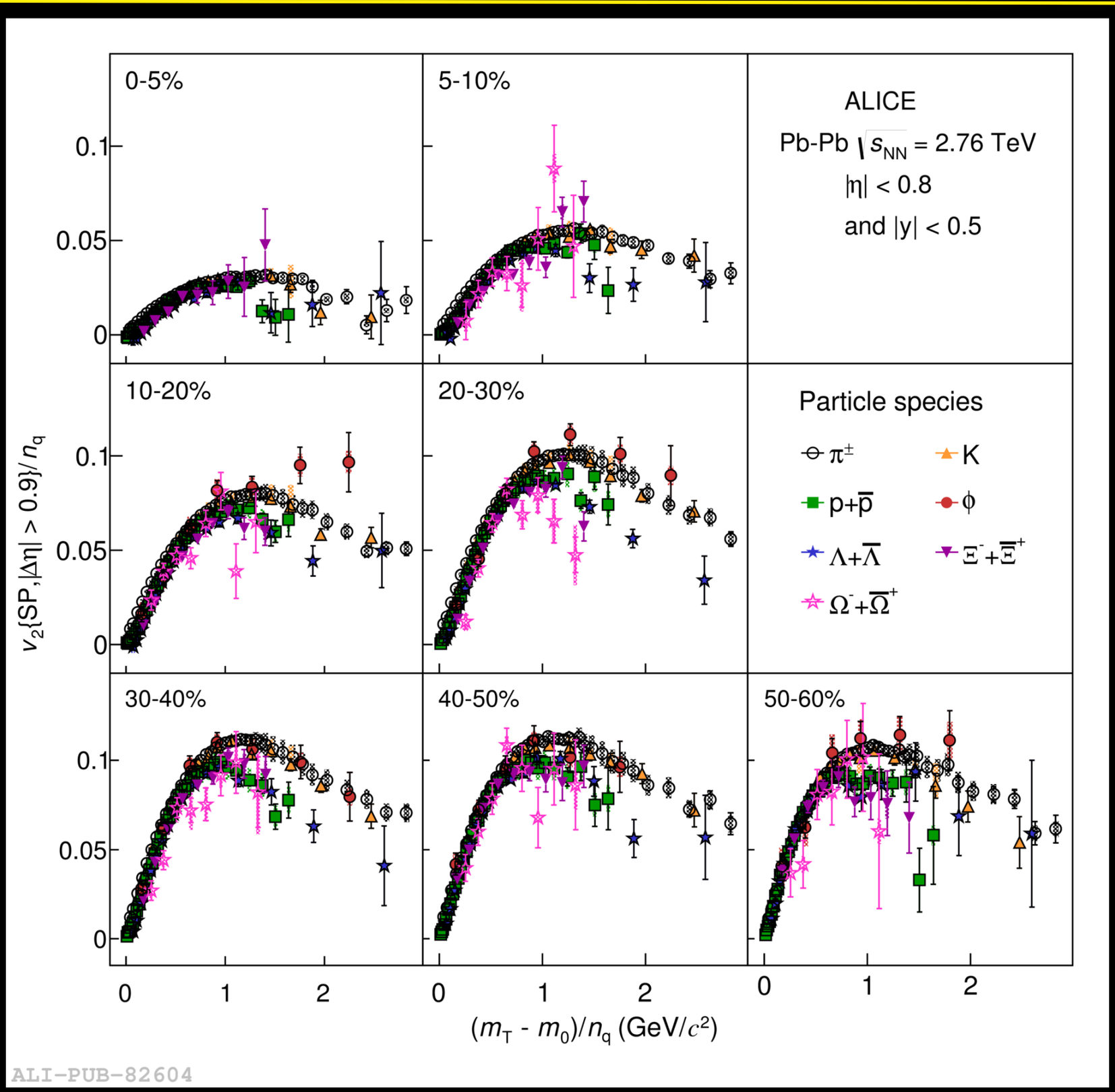
NCQ scaling in p_T/n_q (double ratio): evolution with energy



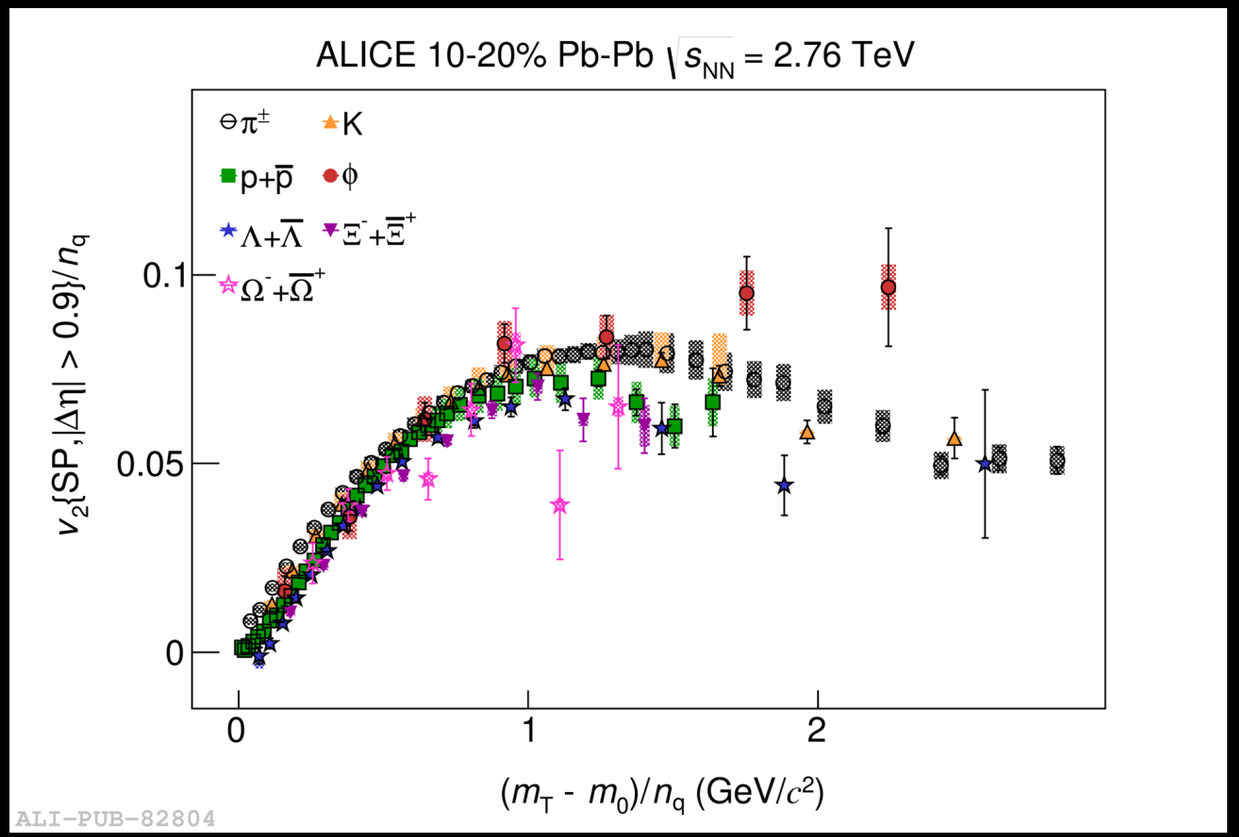
Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species

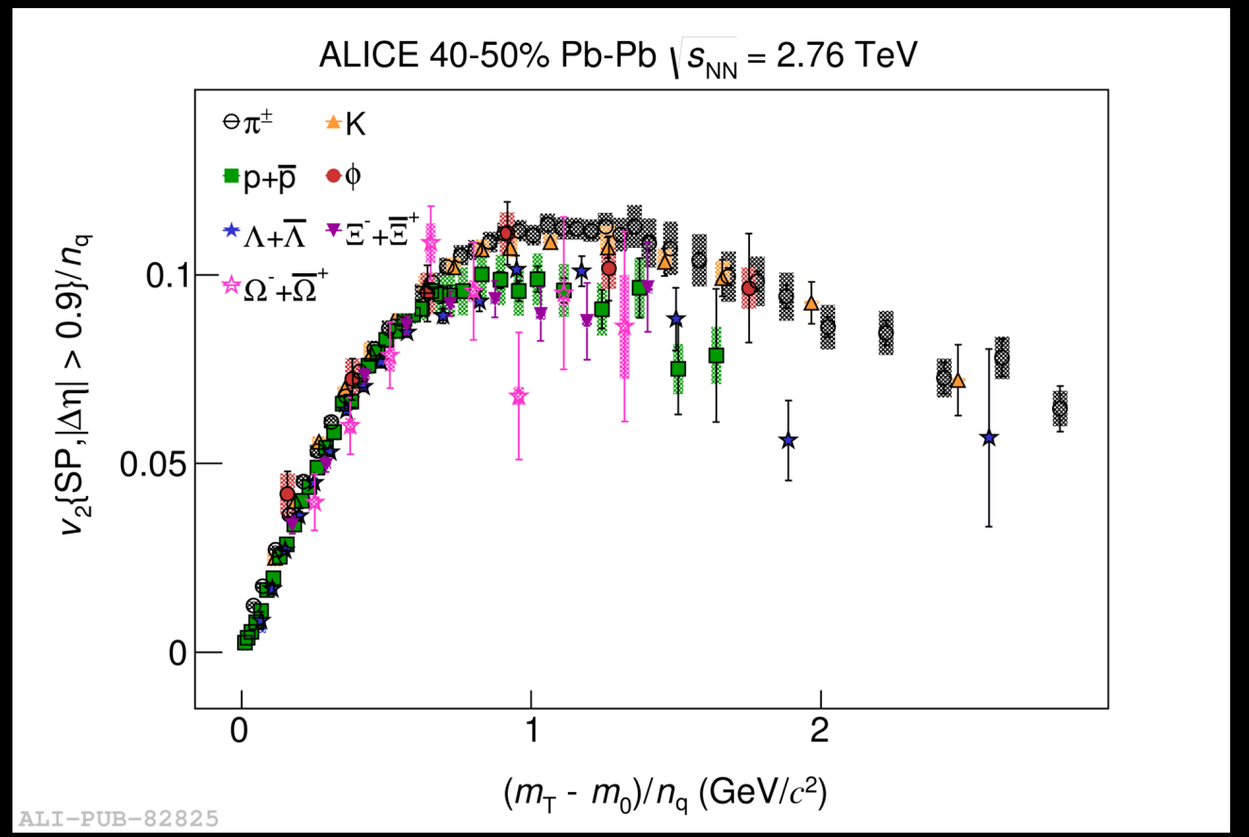
A. Adare *et al.,* [PHENIX Collaboration], Phys. Rev. **C85,** (2012) 064914, [arXiv:1203.2644 [nucl-ex]].

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



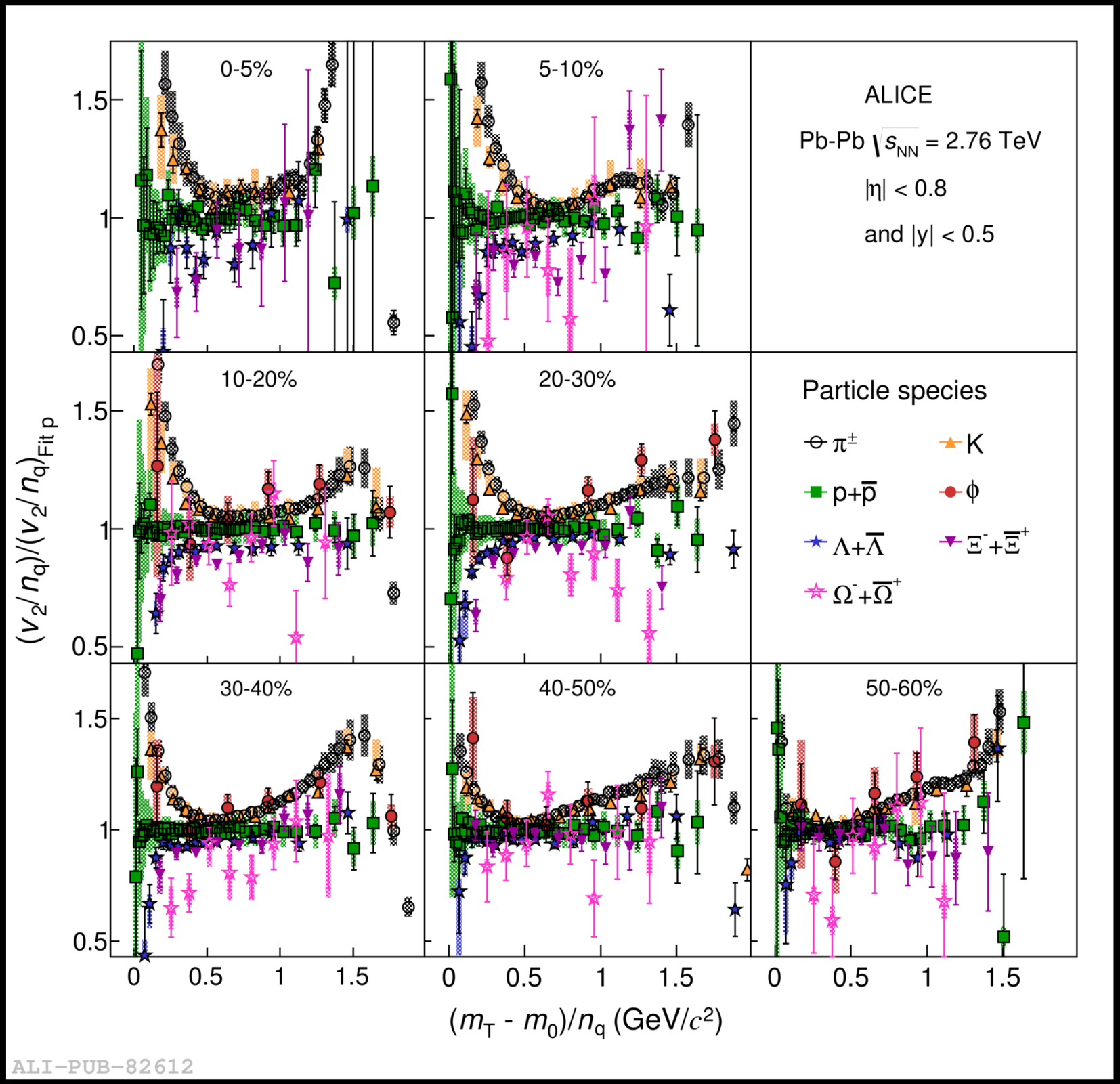
NCQ scaling in $(m_T - m_0)/n_q$



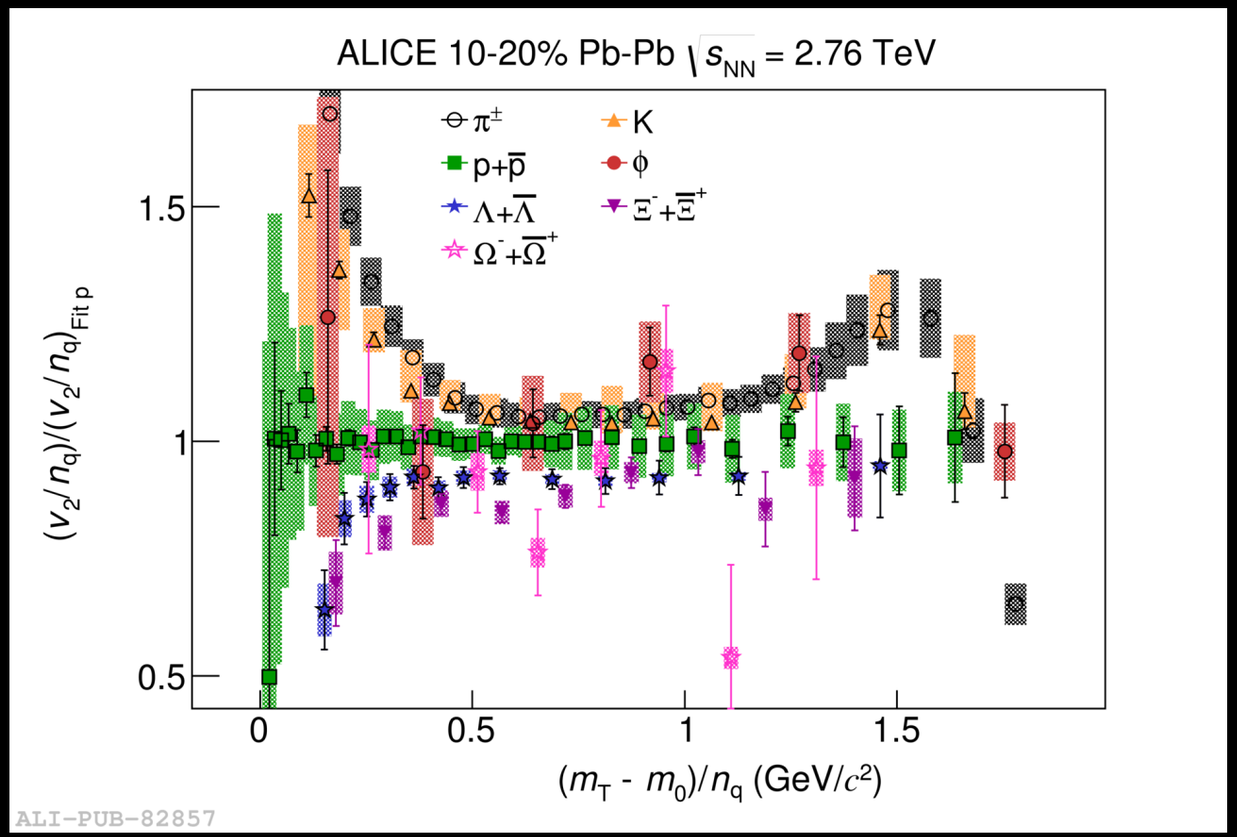


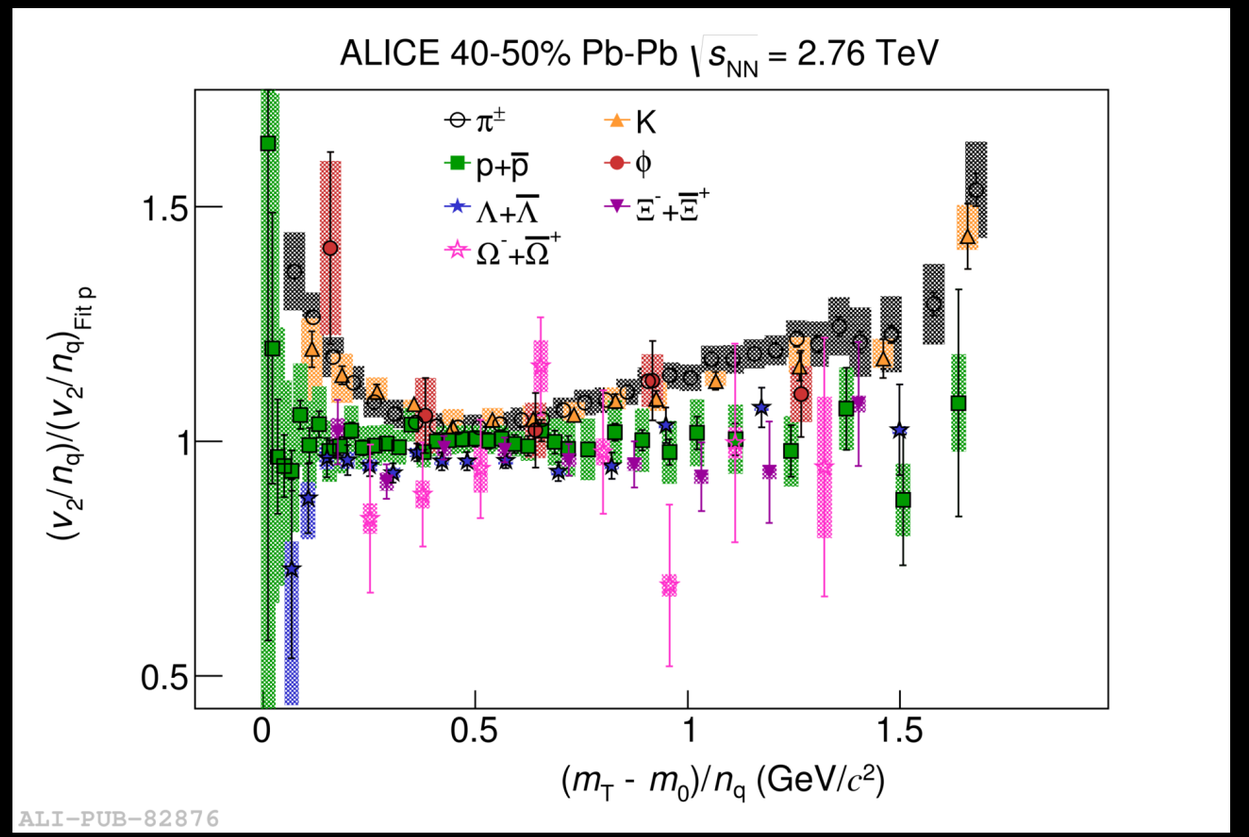
Introduced to extend the scaling to lower p_T

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



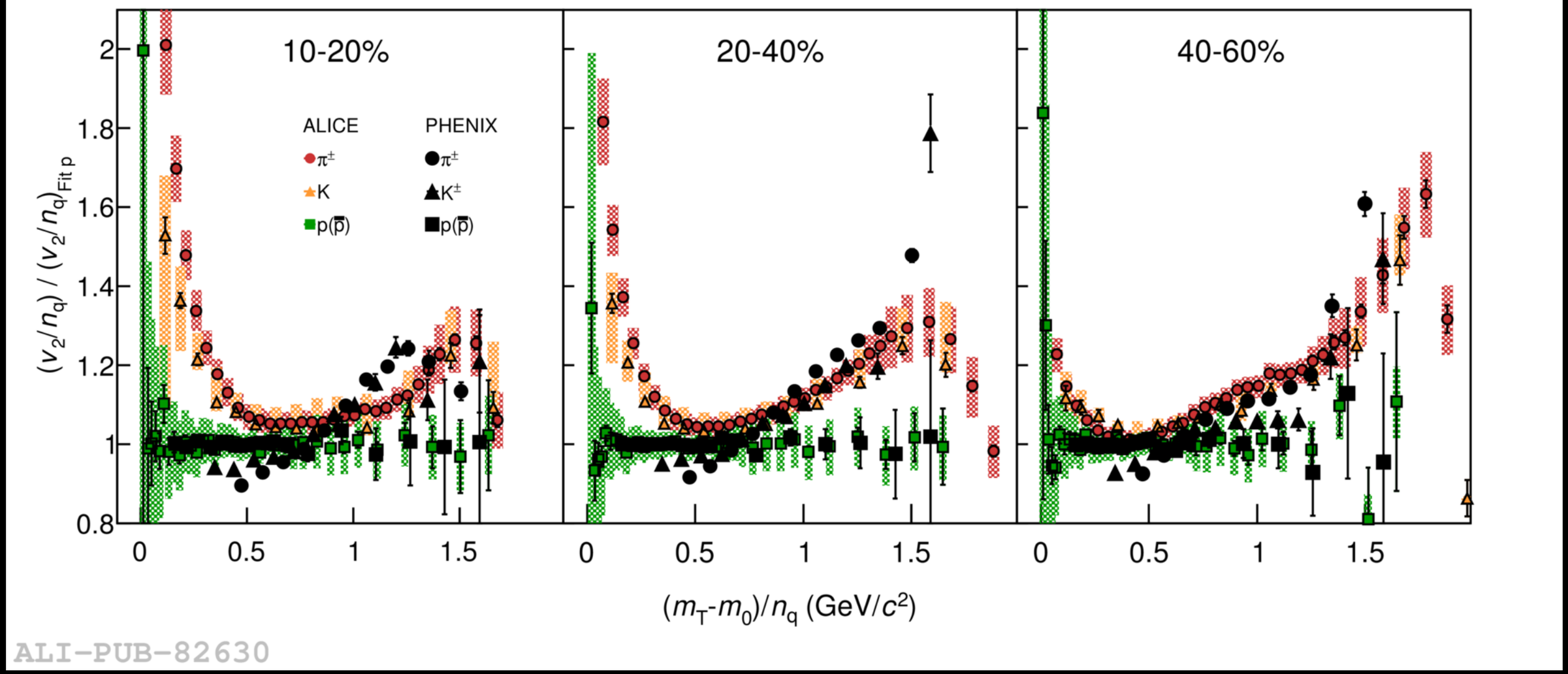
NCQ scaling in $(m_T - m_0)/n_q$ (double ratio)





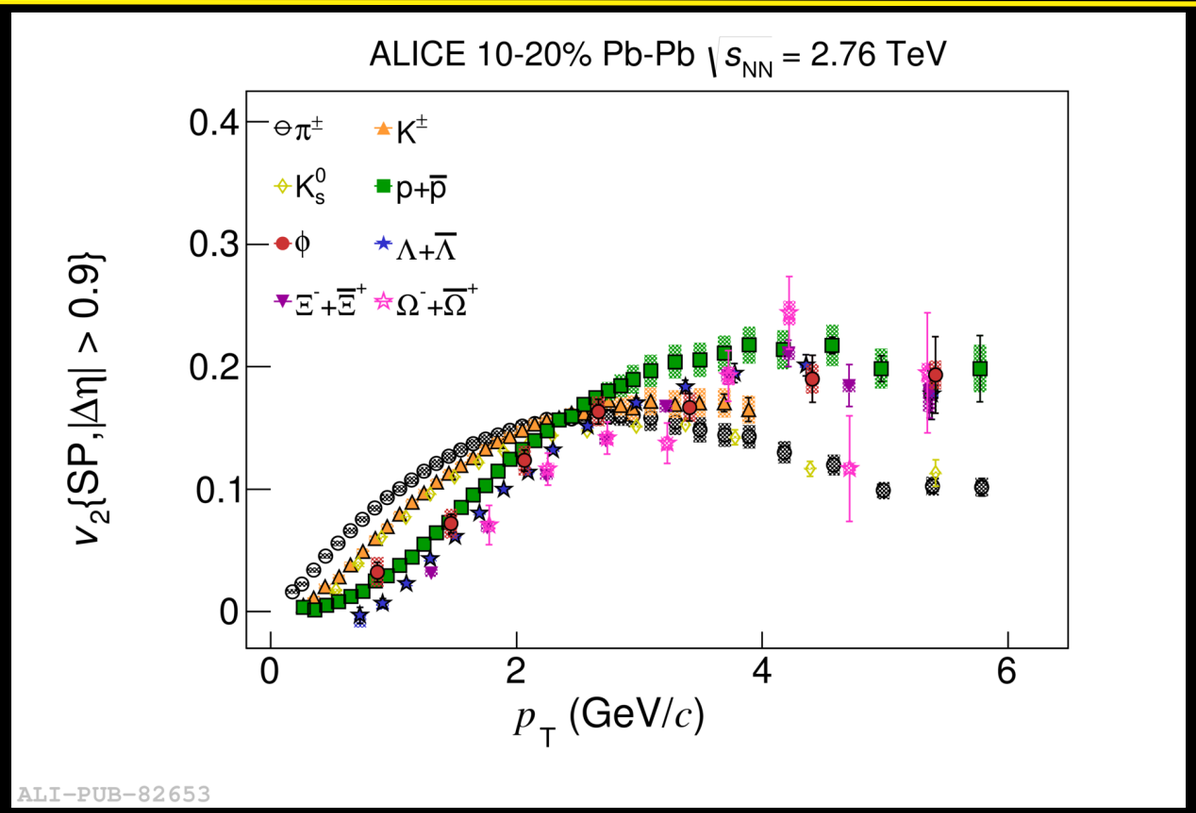
- For $(m_T - m_0)/n_q$ < 0.6 - 0.8 GeV/c^2: scaling is broken at the LHC
- For $(m_T - m_0)/n_q$ > 0.6 - 0.8 GeV/c^2: scaling is only approximate at the level of ± 20%

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

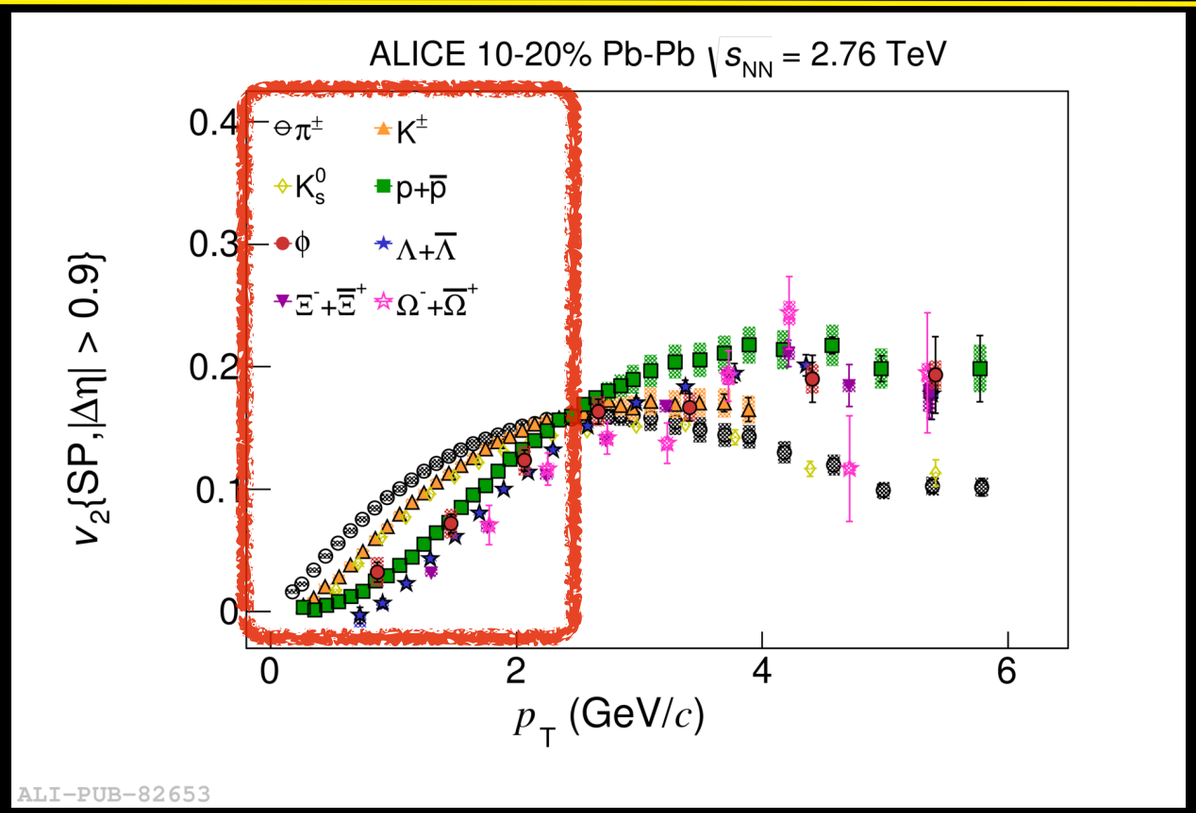


Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species

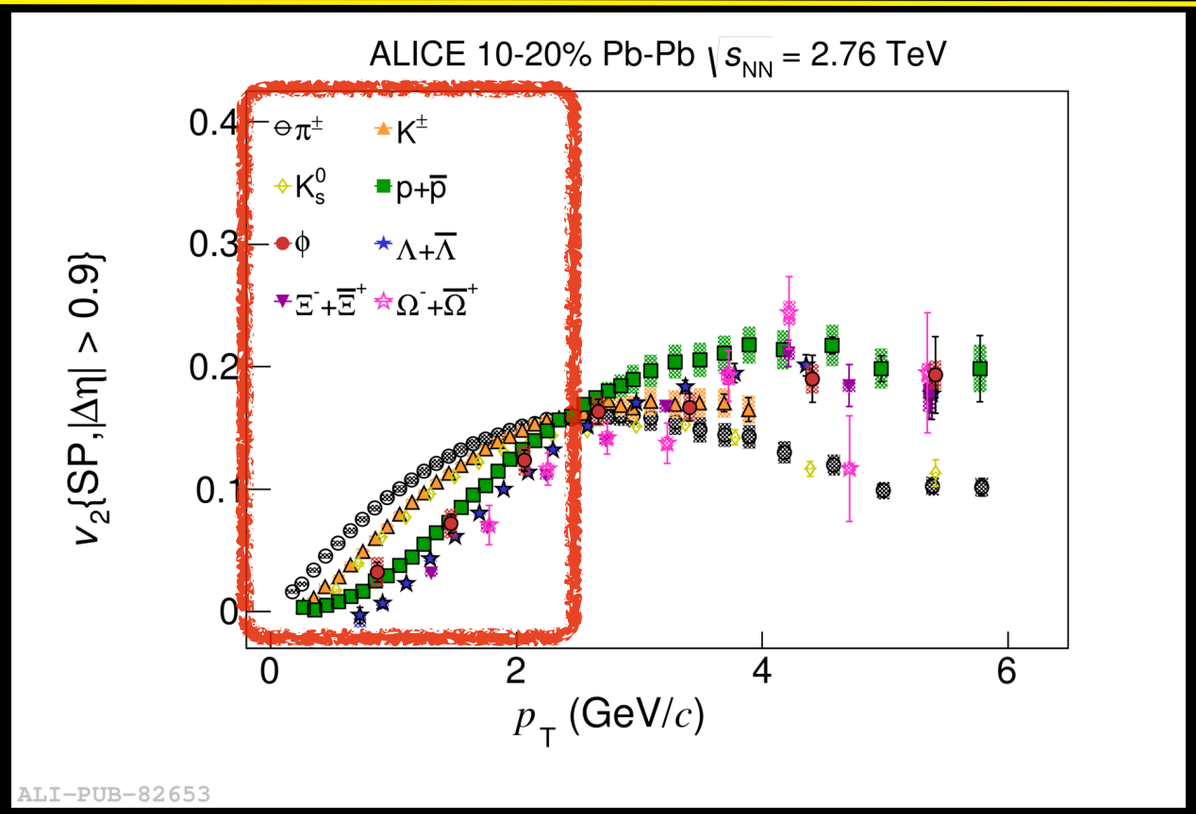
Instead of a summary…

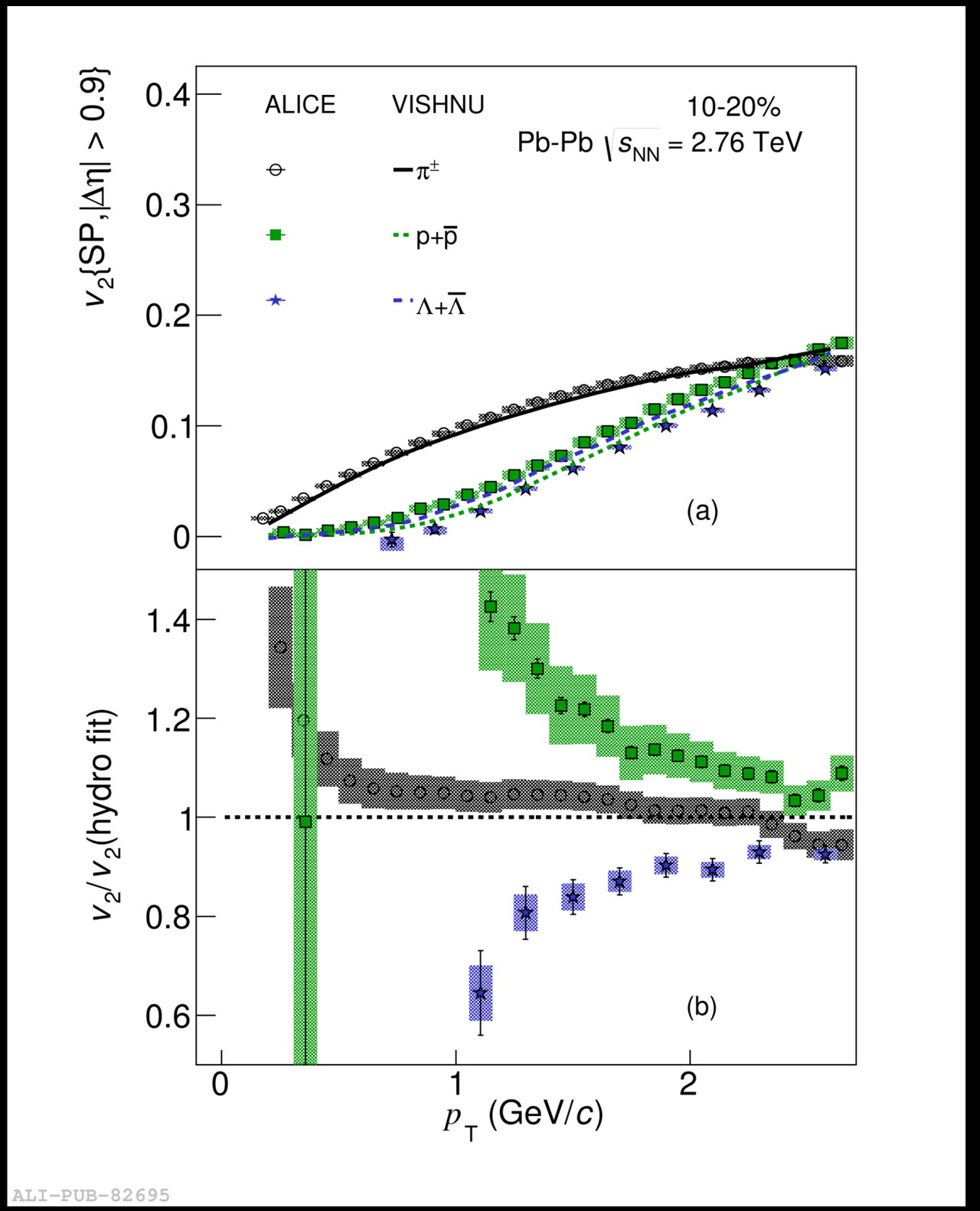


Instead of a summary…



Instead of a summary…





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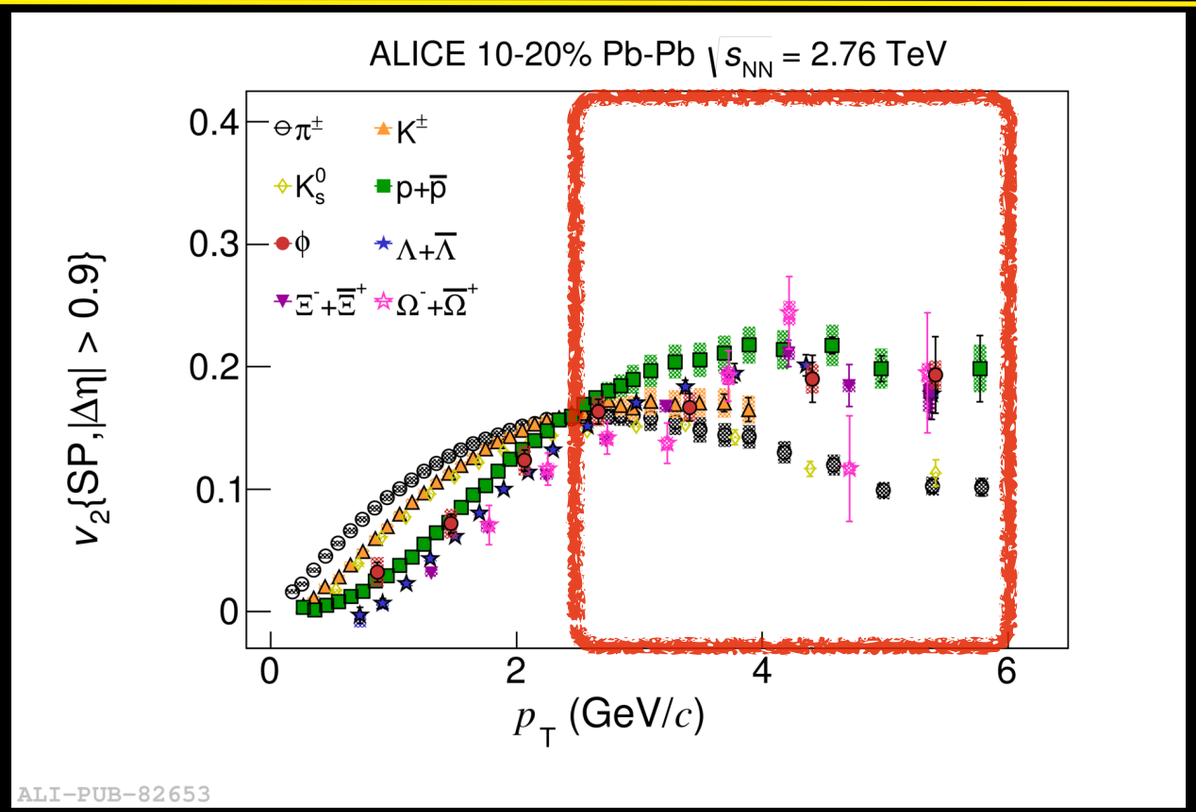
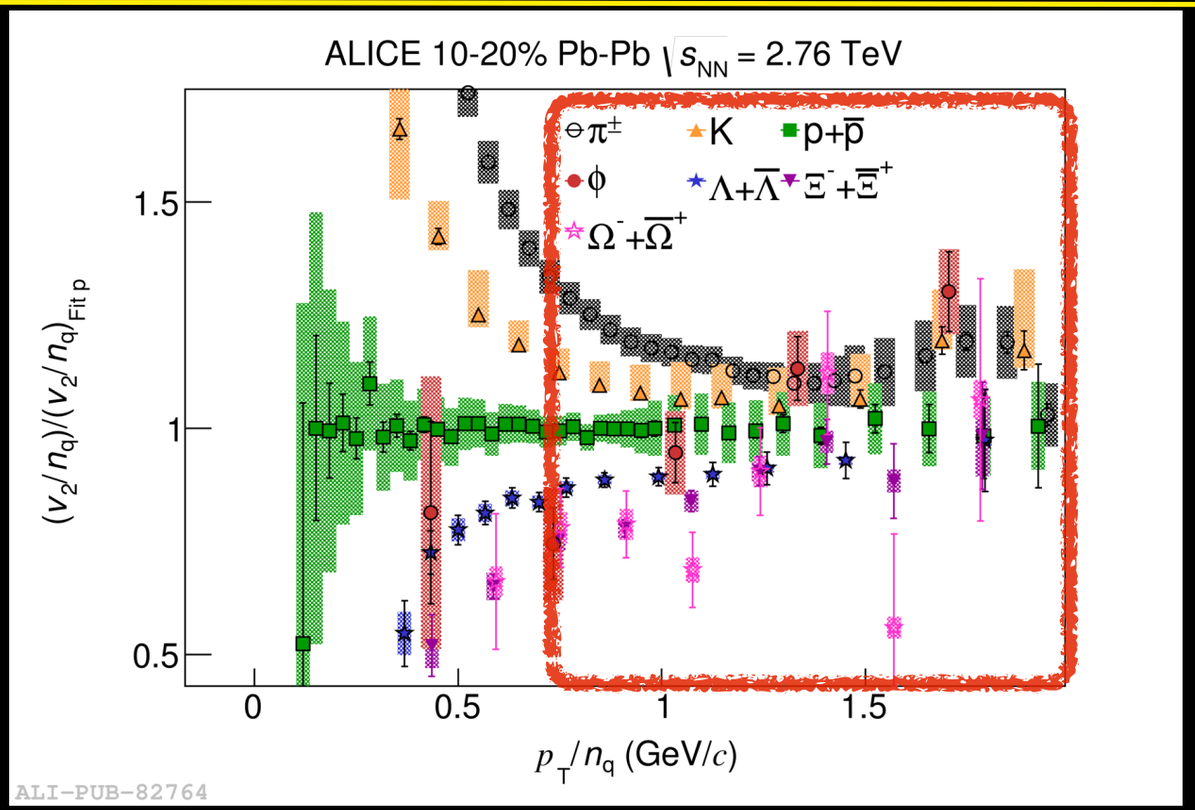
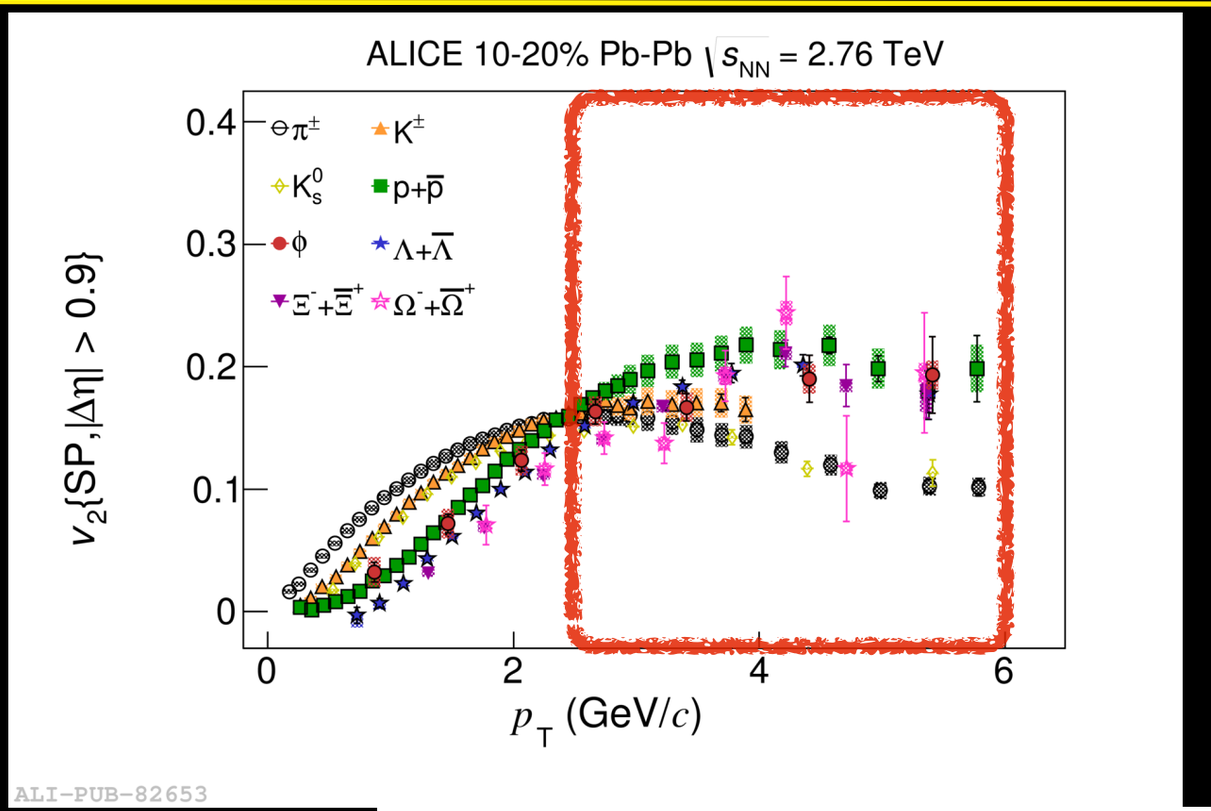
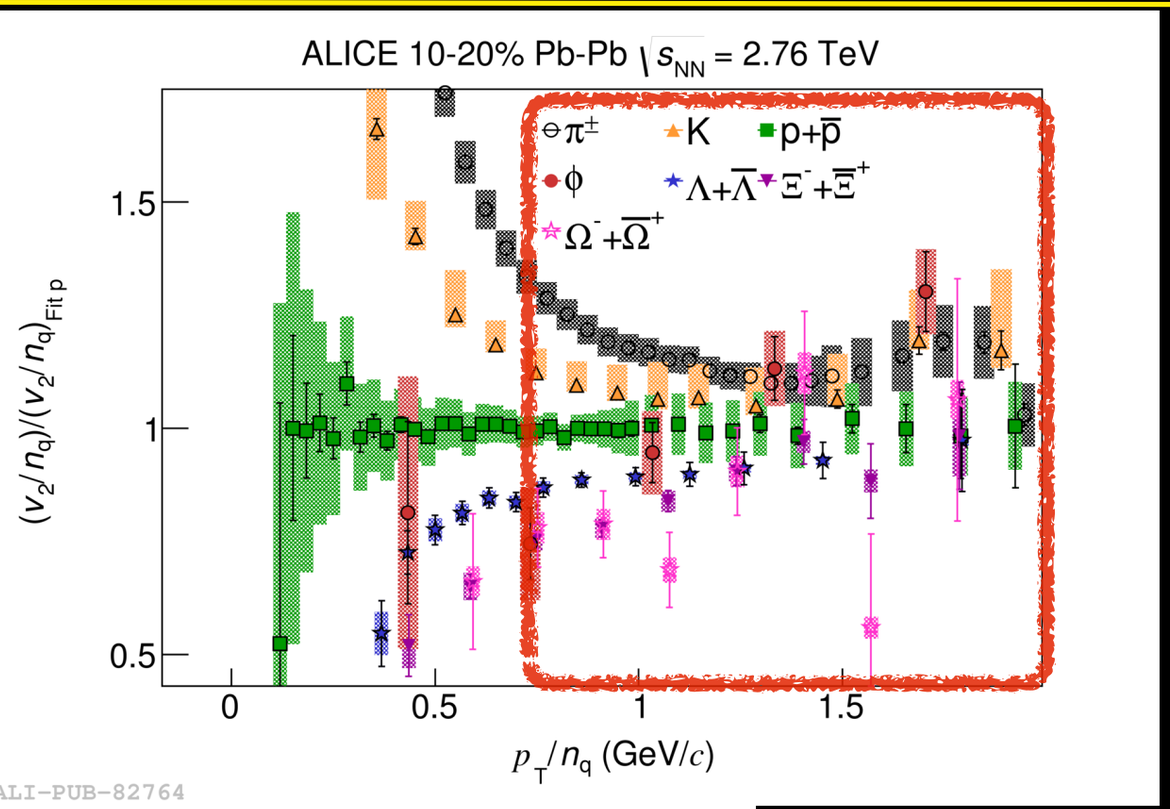
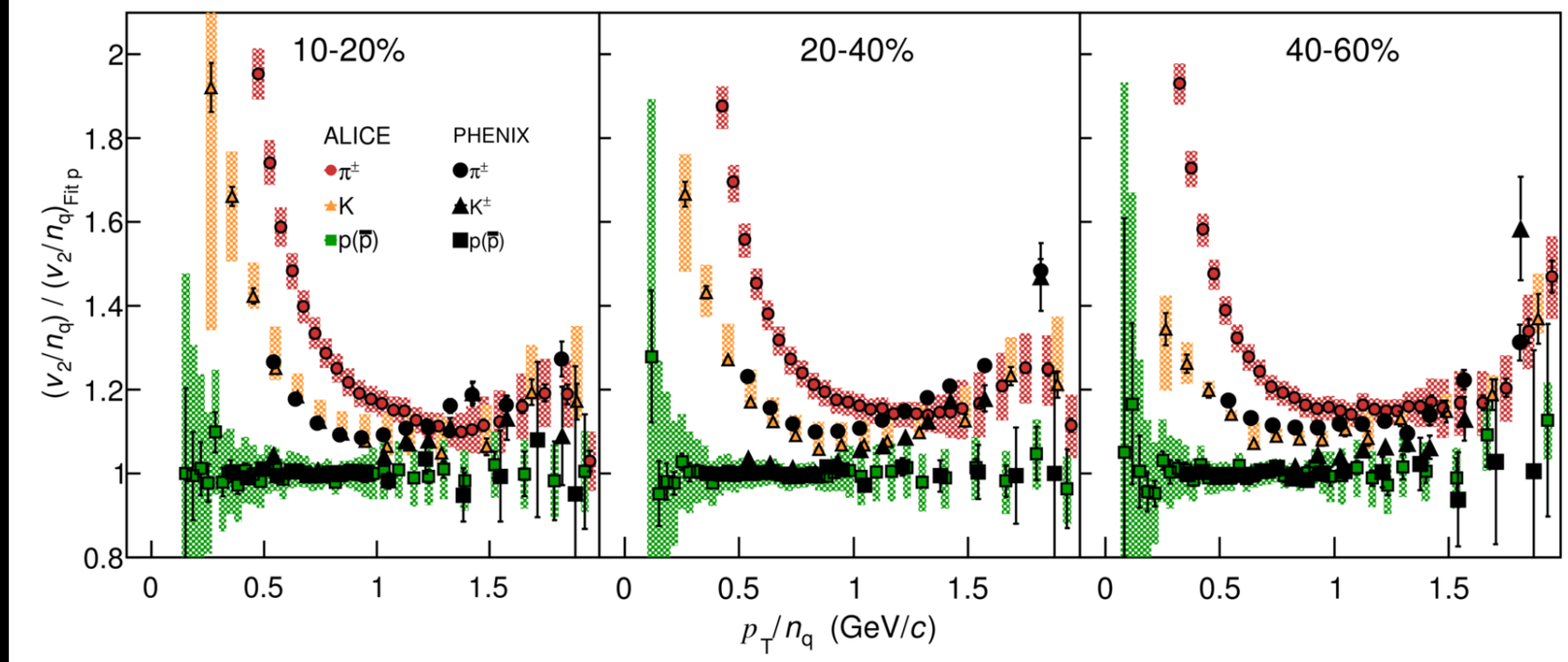




Instead of a summary…

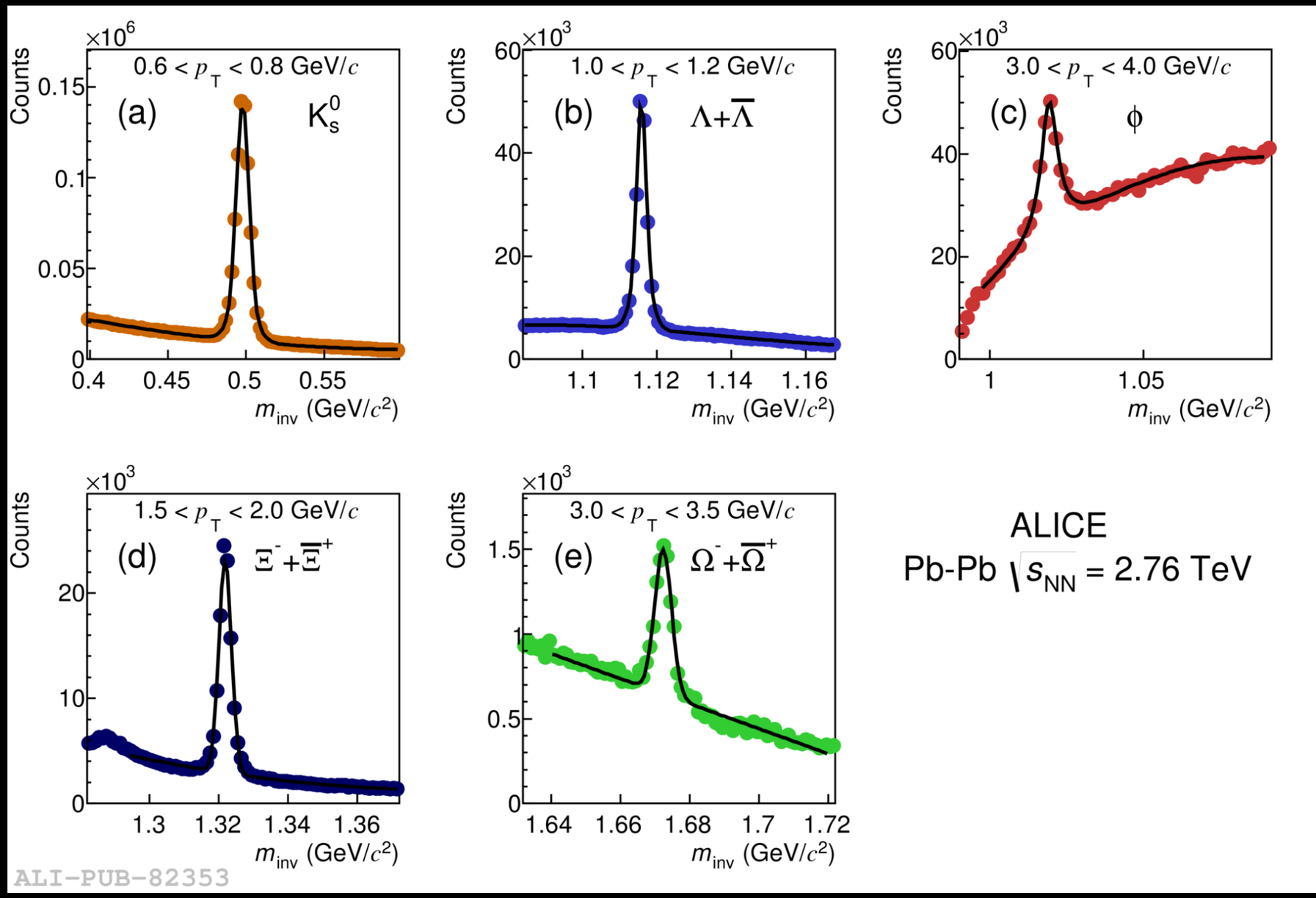






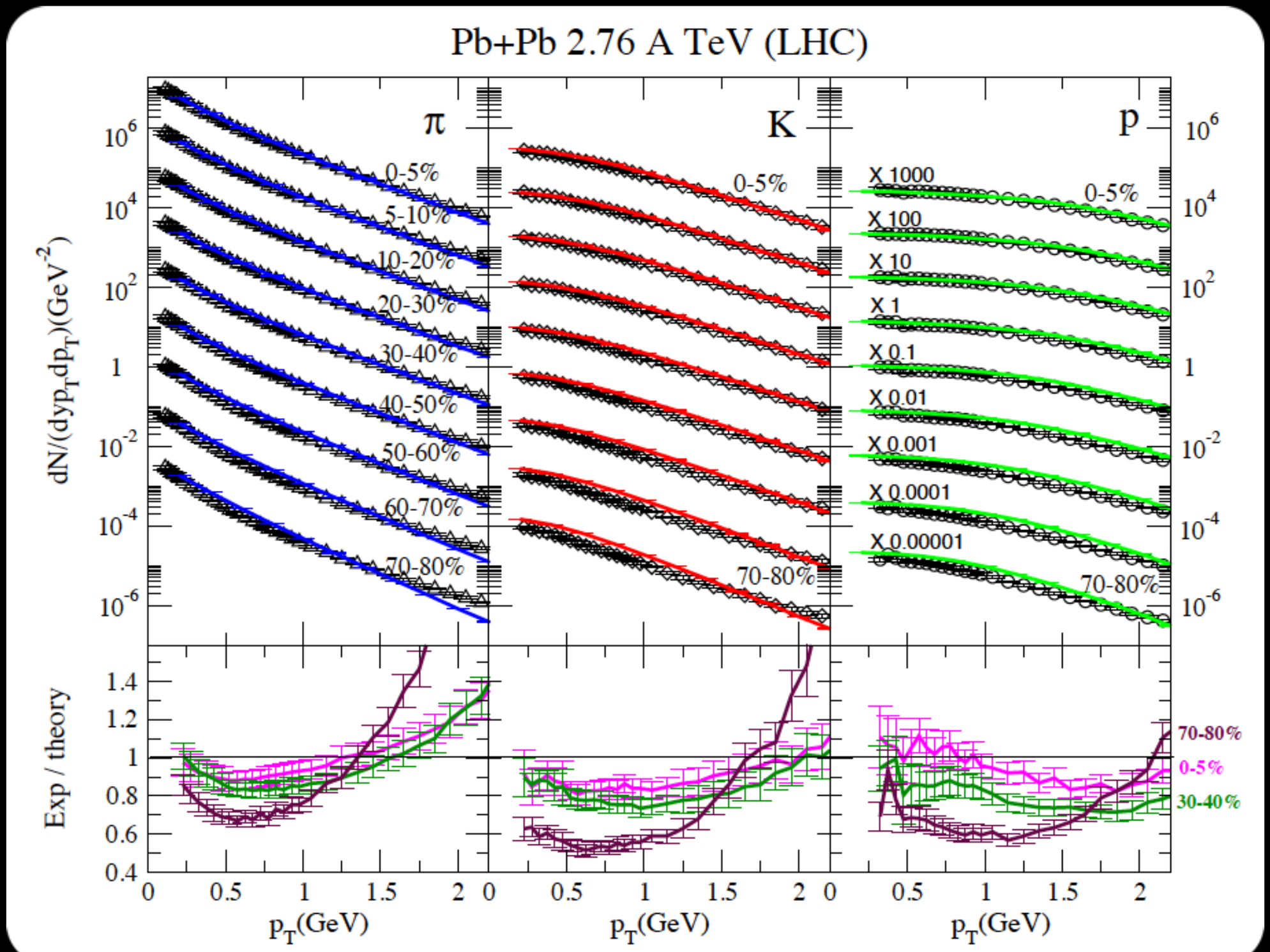
Backup

Reconstructing decays



Comparison with hydrodynamic calculations

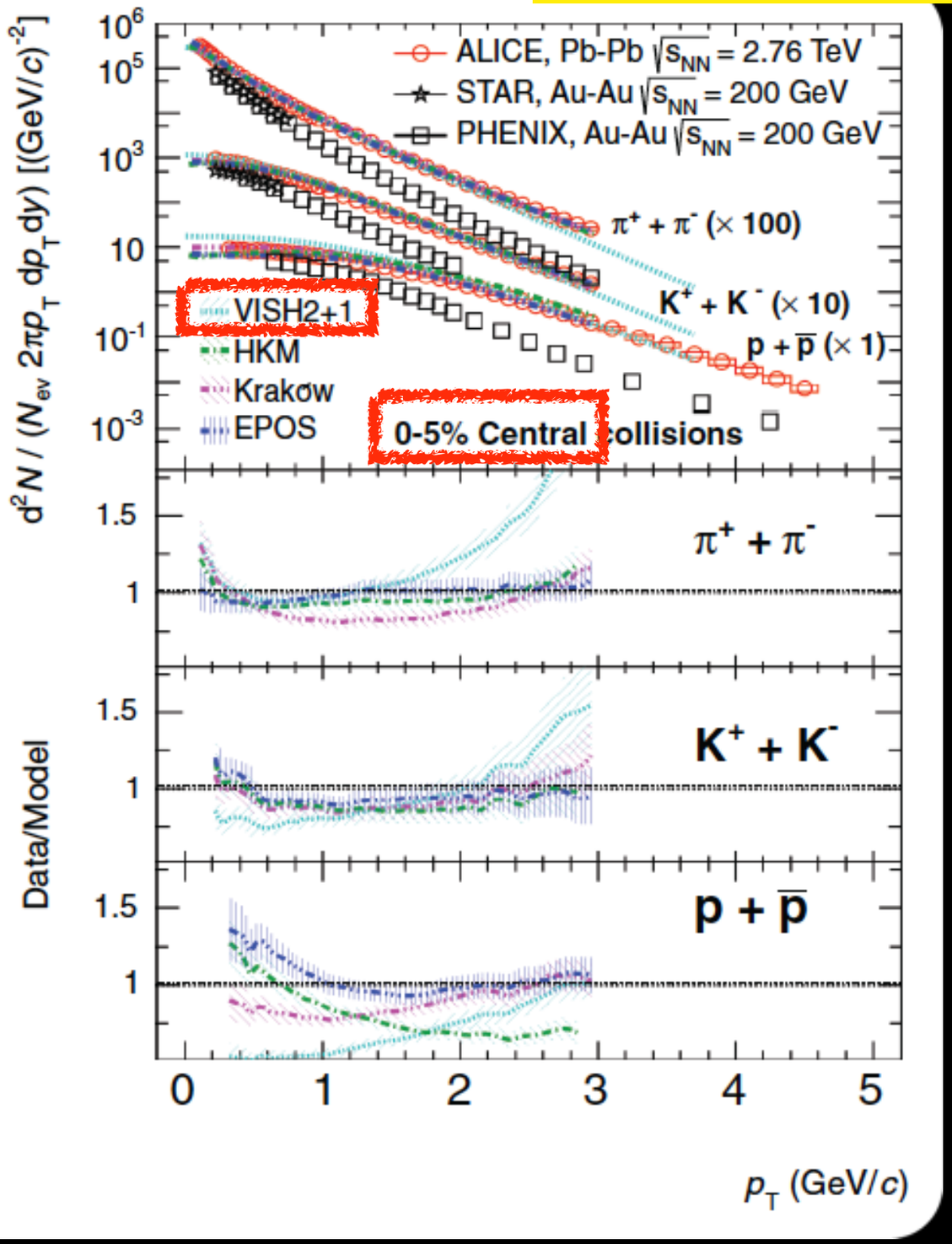
Spectra: How good is VISHNU doing?

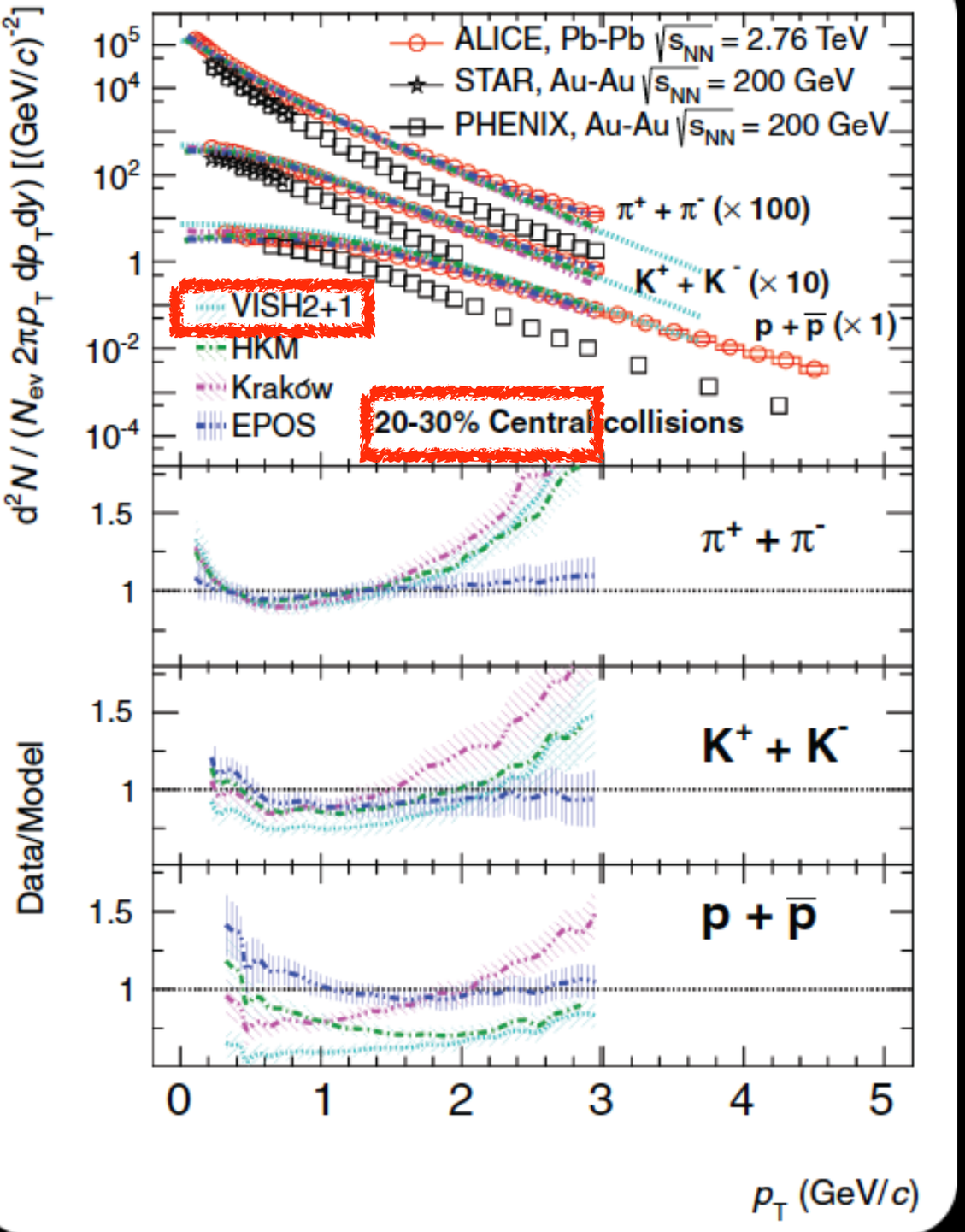


H. Song *et al.*, arXiv:1311.0157 [nucl-th]

VISH2+1: comparison to spectra

ALICE Collaboration: Phys. Rev. C 88, 044910 (2013)

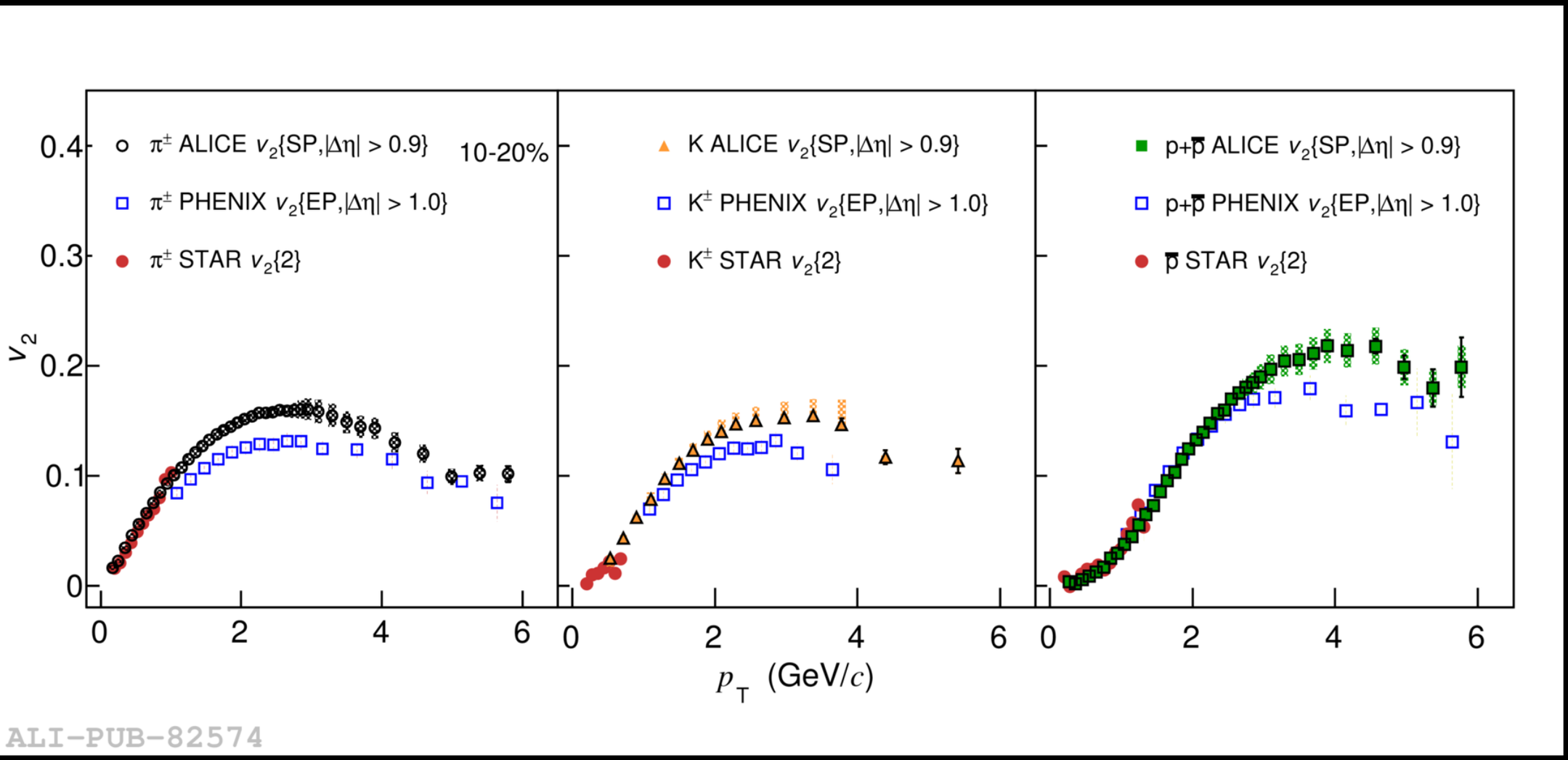




Discussion II

v_2 comparison to RHIC

Comparison with RHIC



- At low p_T (ALICE vs STAR)
  - ★ Hard to quantify the difference due to different non-flow treatment (STAR ⇒ v_2{2})
- At intermediate p_T (ALICE vs PHENIX)
  - ★ All particles at the LHC are higher than the RHIC points