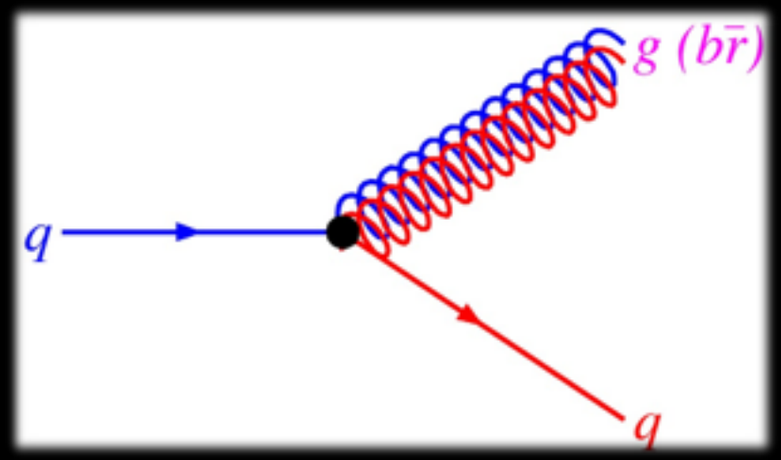
More than one mystery

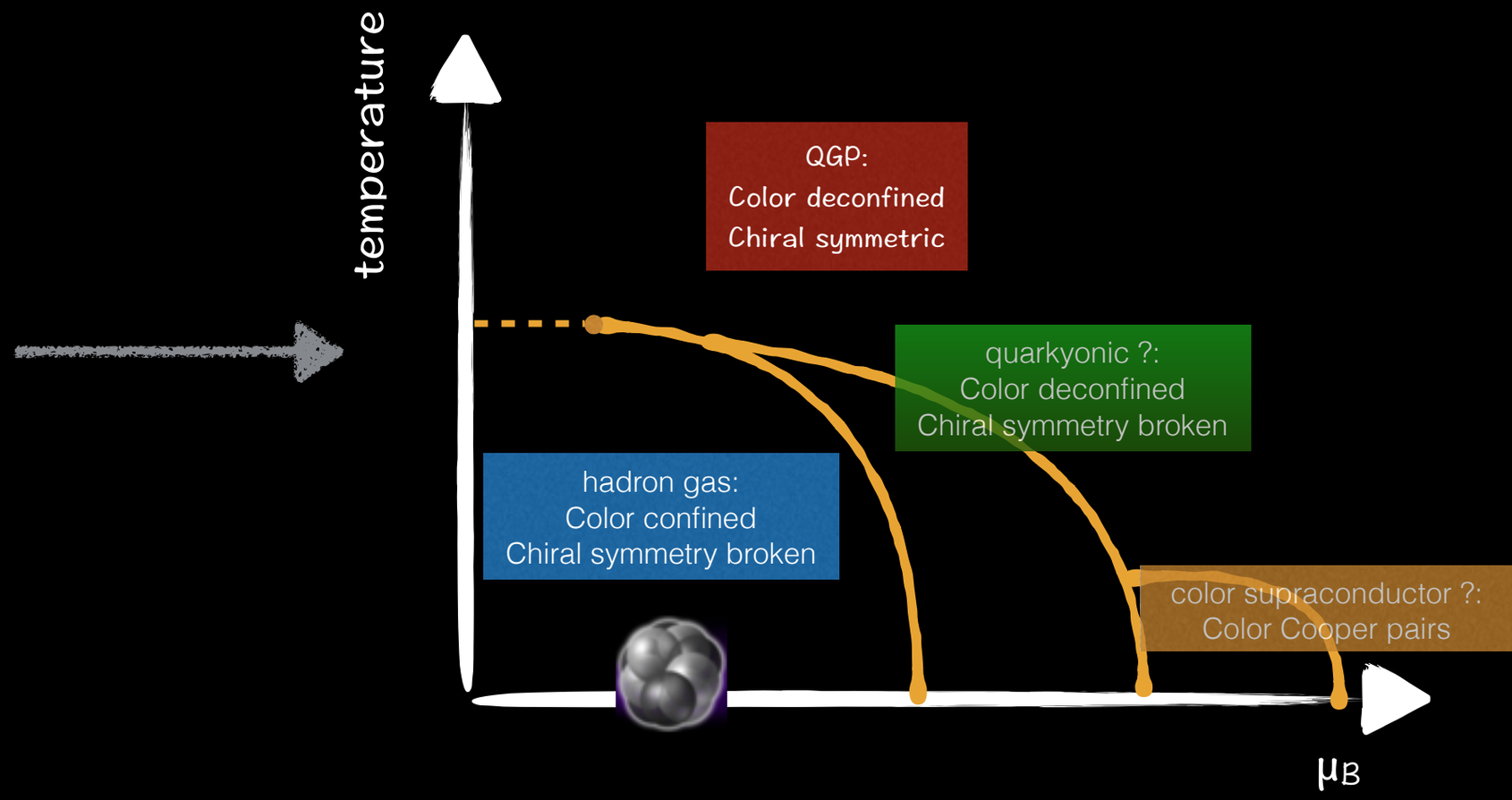
A personal assessment of ALICE results from RUN1 data

Reminder

The objectives of the LHC heavy-ion scientific program

Thermodynamics of strongly interaction matter





How does the complexity of matter emerge from the dynamics of the strong interaction

The ALICE core mandate

Establish the fundamental properties of strongly interacting matter through complete* precision measurement

* $p_t \sim T \oplus PID \oplus p_t \gg \Lambda_{QCD}$


MAGNET
TOF + TRD
ITS
ABSORBER
PHOS

Established facts: exp

- At LHC temperatures matter has the properties of a perfect* liquid**

The Quark-Gluon Plasma, a nearly perfect fluid

L. Cifarelli [1], L.P. Csernai [2] and H. Stöcker [3] - DOI: 10.1051/epn/2012206
[1] Dipartimento di Fisica, Universita di Bologna, 40126 Bologna, Italy;
[2] Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway;
[3] GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

We are living in interesting times, where the World's largest accelerator, the Large Hadron Collider, has its most dominant successes in Nuclear Physics: collective matter properties of the Quark-Gluon Plasma (QGP) are studied at a detail which is not even possible for conventional, macro scale materials.

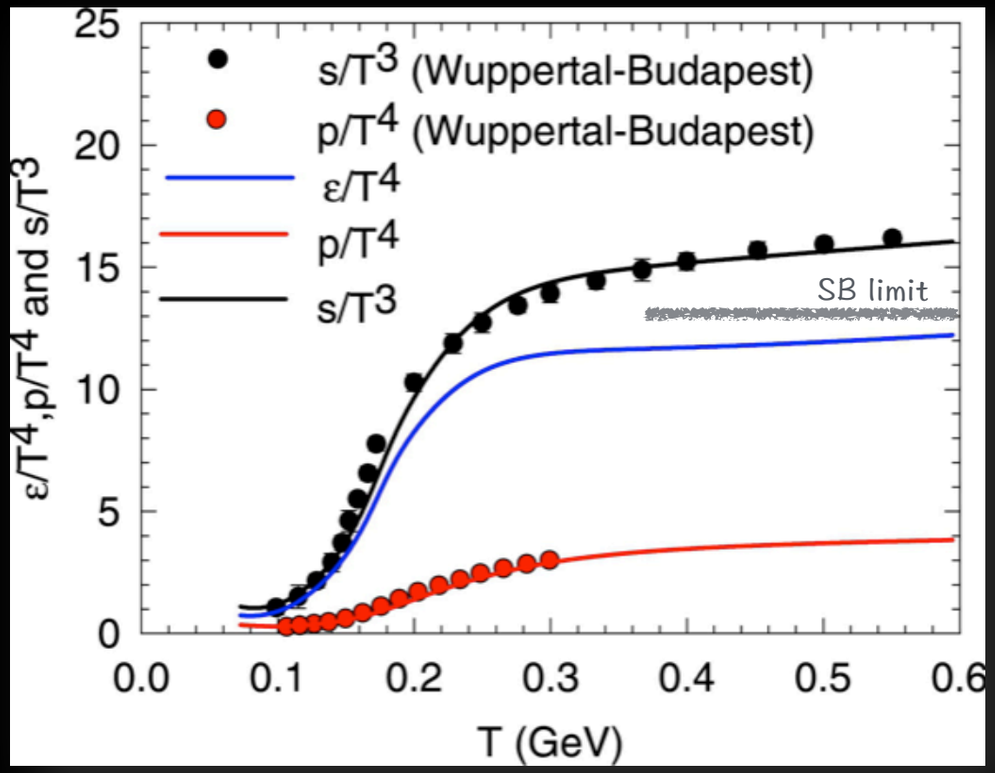
* non-dissipative

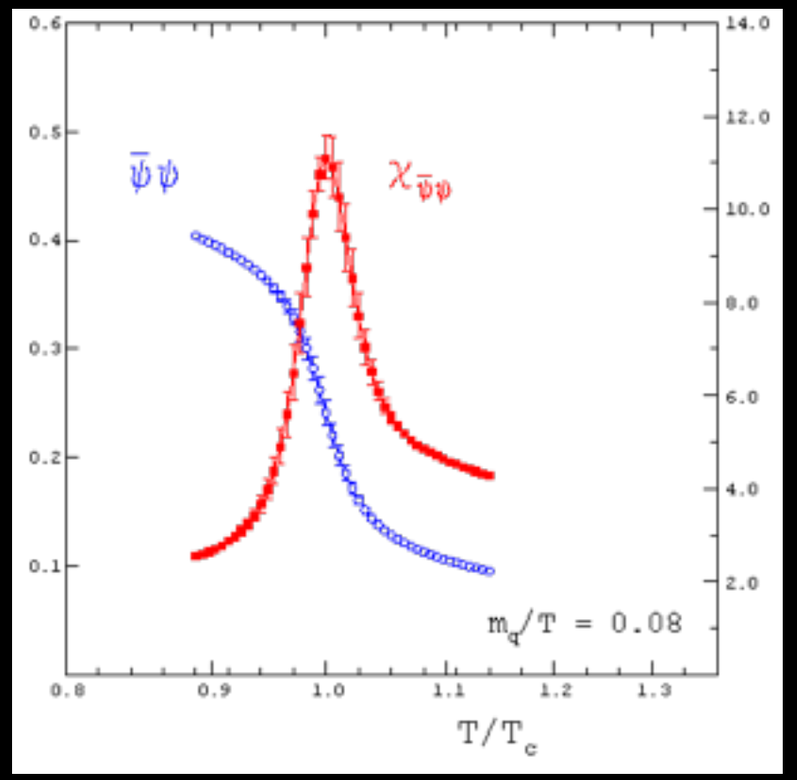
** strongly interacting


What is a liquid?
Gel, cream or paste
Make-up
Toiletries
Drinks
ELVIVE
hairspray

Established facts: theory

- smooth* transition from hadron gas to QGP, Z_3 symmetry restored
- Chiral symmetry restored**





* not a phase transition, not SB

** quark mass reverts to Higgs mass

Standard strategy

- Large and dense: heavy-ion physics

- Small and dilute: comparison measurement

Standard strategy

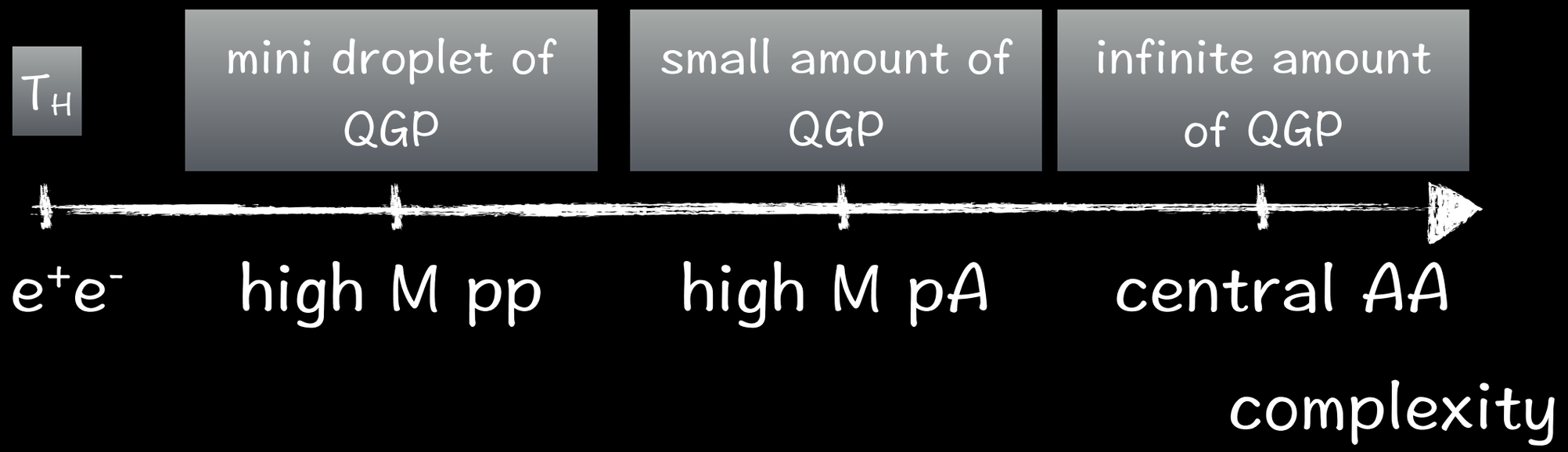
- Large and dense: heavy-ion physics
  - AA ➜ pQCD + Npdf + FF + collectivity
- Small and dilute: comparison measurement
  - pp ➜ pQCD + pdf + FF
  - pA ➜ pQCD + Npdf + FF

But … High M pp/pA

- particle production
- momentum spectra
- HBT radii
- Ridges
- Quarkonia suppression

Toward a new paradigm ?

- Collectivity everywhere !



- A coherent experimental and theoretical approach to statistical QCD from e^+e^- to AA

Mysteries

a personal assessment

questions for theory

- IS at LHC: classical gluon fields ? strongly or weakly coupled ?
- dynamics: from IS to an hydro liquid in 0.5 fm/c
- DoF: quasi-particle free medium ? just above T_H ? hadronization ?

questions for theory

- IS at LHC: classical gluon fields ? strongly or weakly coupled ?
- dynamics: from IS to an hydro liquid in 0.5 fm/c
- DoF: quasi-particle free medium ? just above T_H ? hadronization ?

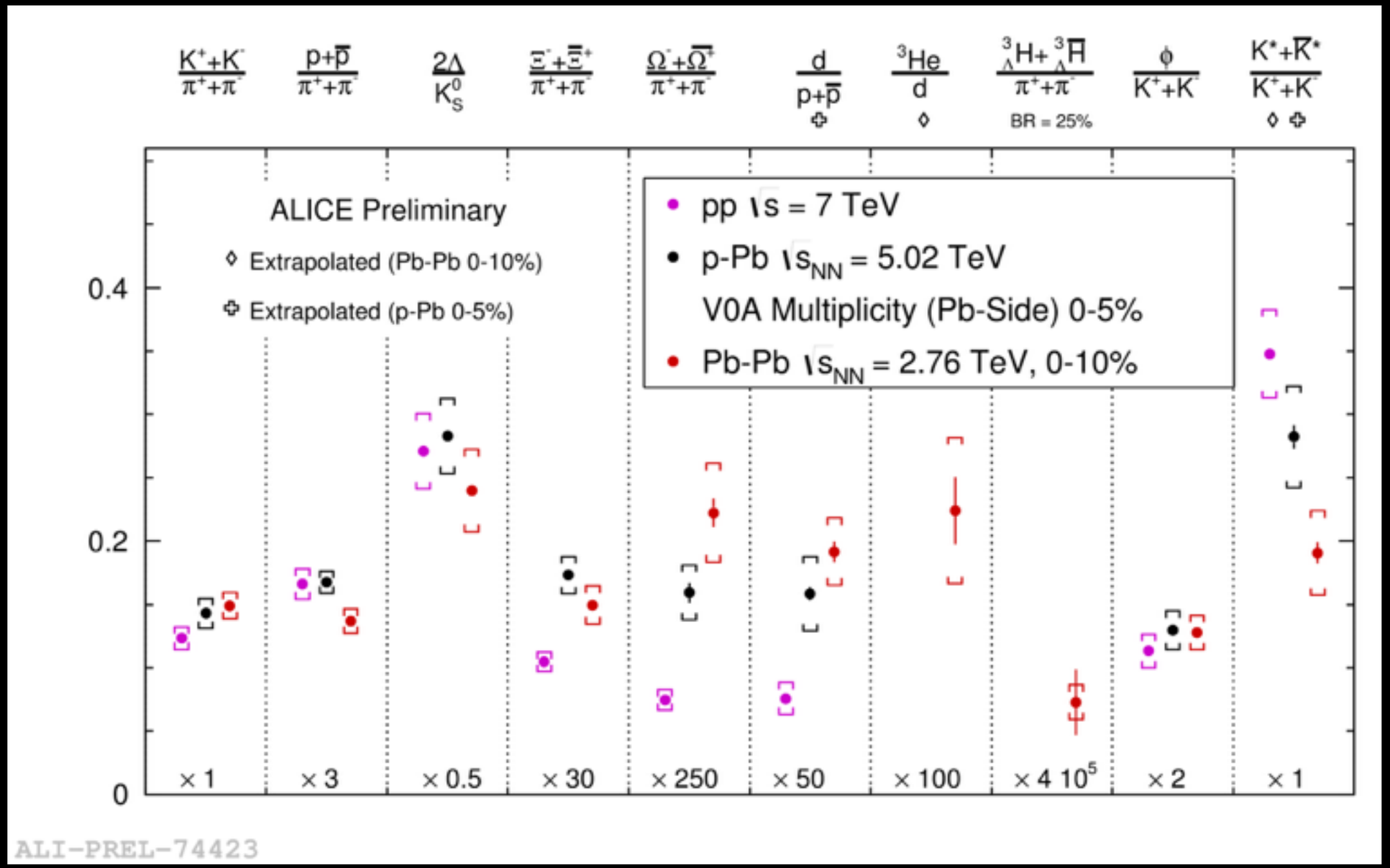
- How can experiment constrain this physics of equilibration in QCD ?
- LHC offers most favorable conditions
  - very low x
  - non dissipative medium

soft: $p_T \sim T, \Lambda_{QCD}$

probe the bulk

inclusive

hadrons production

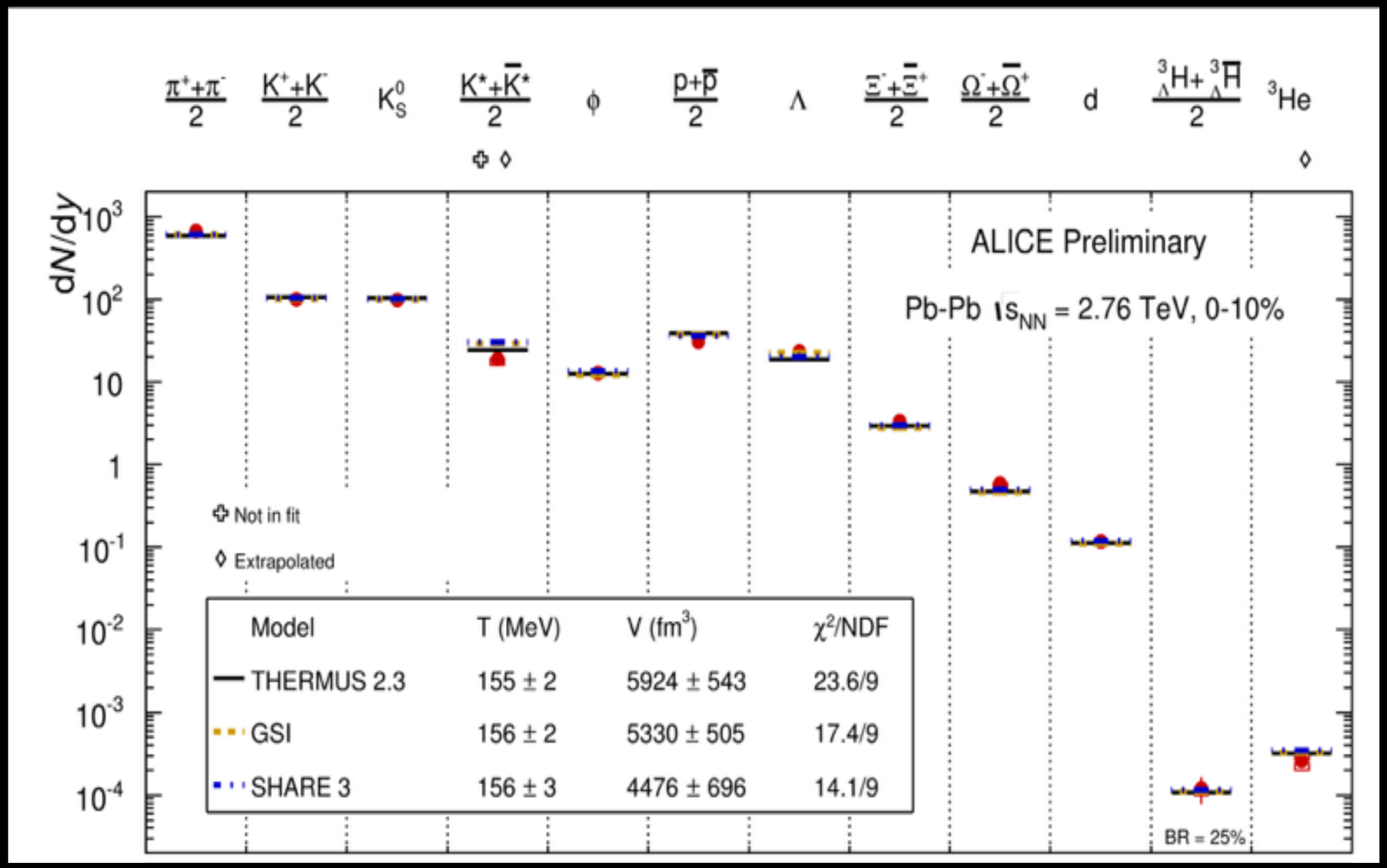


S enhancement,
K* suppression **OK**

p suppression,
d enhancement **!!!**

inclusive

hadrons production



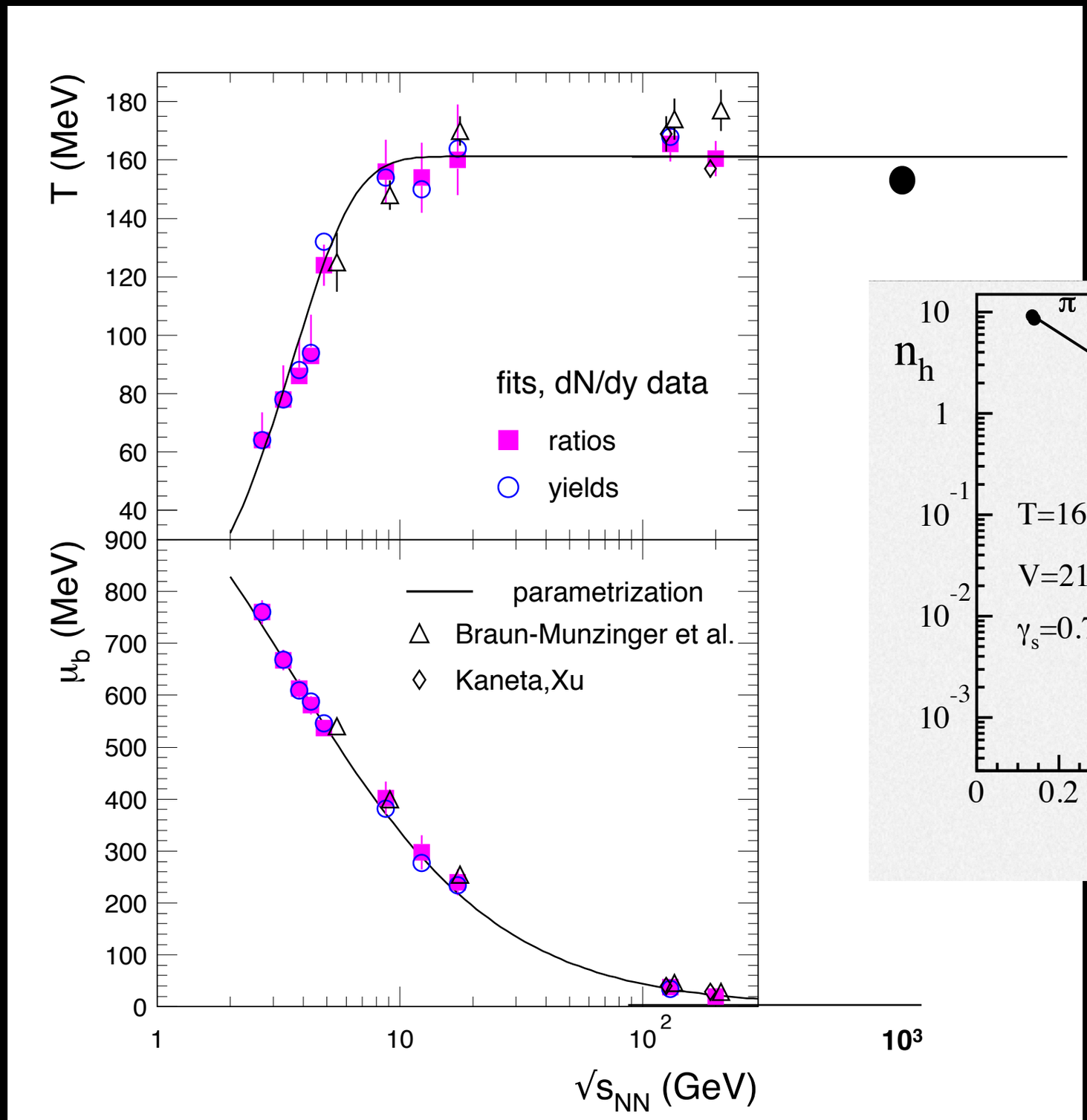
7 order of magnitude !

p, d, nuclei !!

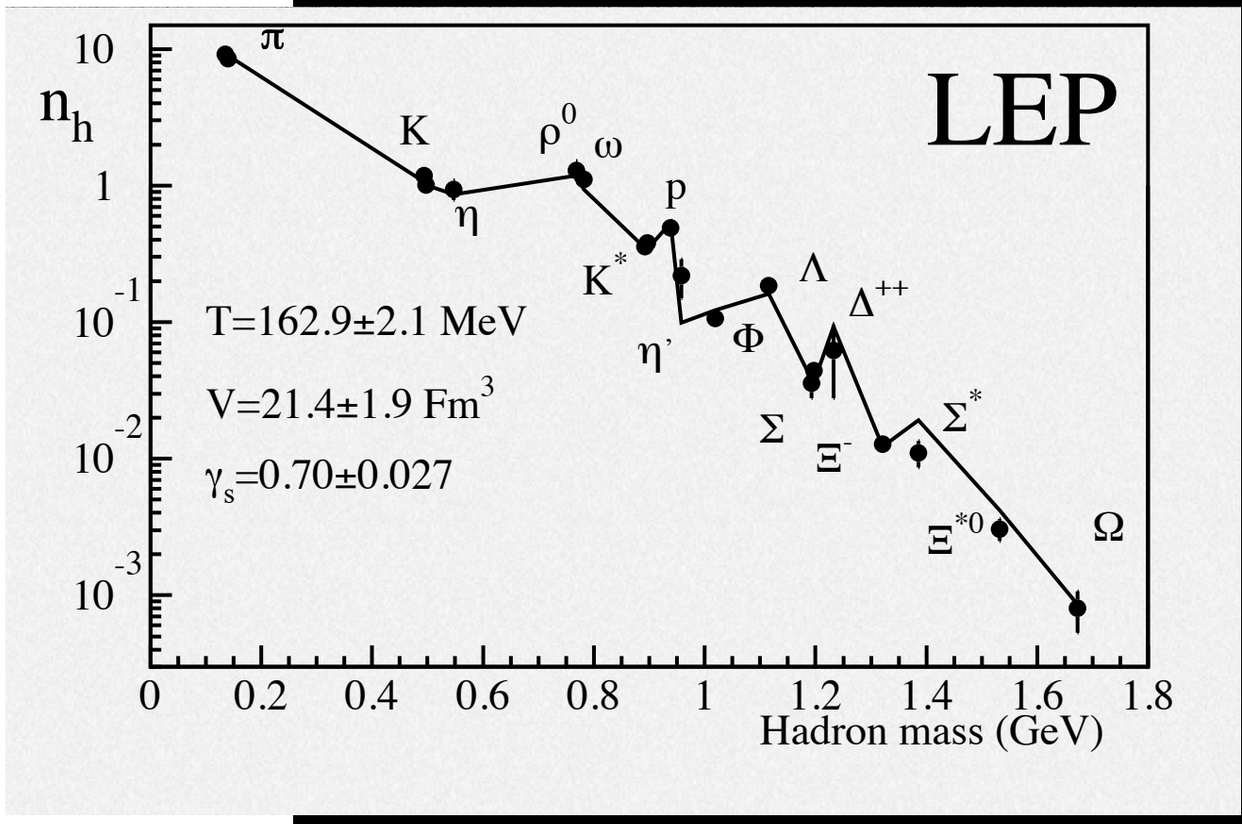
T_H = 155 MeV !!!

inclusive

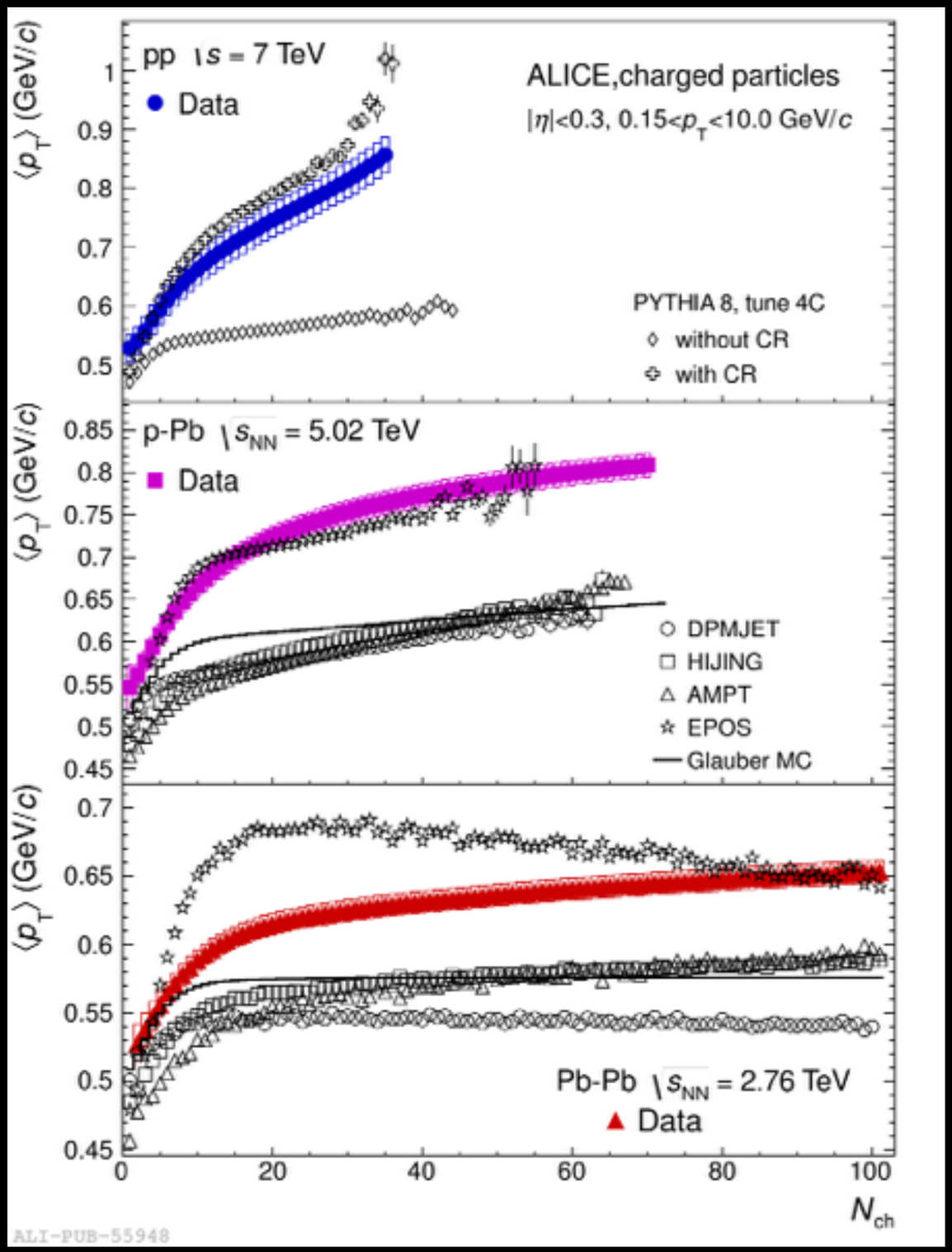
hadrons production



T_H = 155 MeV !!! !!!!
invisible hadrons ?



<p_t> vs M



pp: not an incoherent superposition of multi parton interactions (CR)

pA: not an incoherent superposition of NN collisions (EPOS + hydro)

Collectivity everywhere ?
Models !

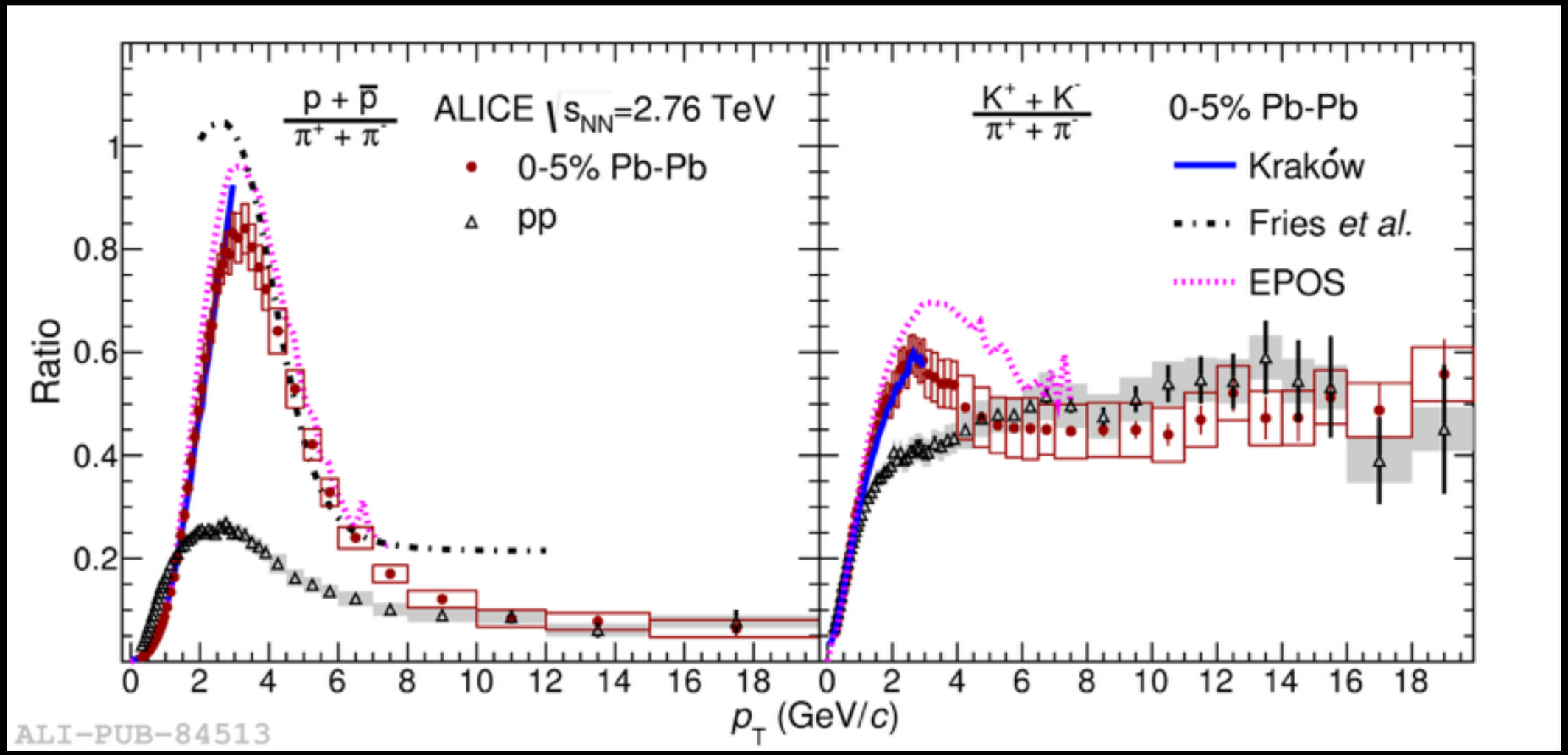
Heavy-ion collisions 4 Hydrodynamics

Back to Hydro Dynamics of QGP !

spectra + PID

Baryon & Meson

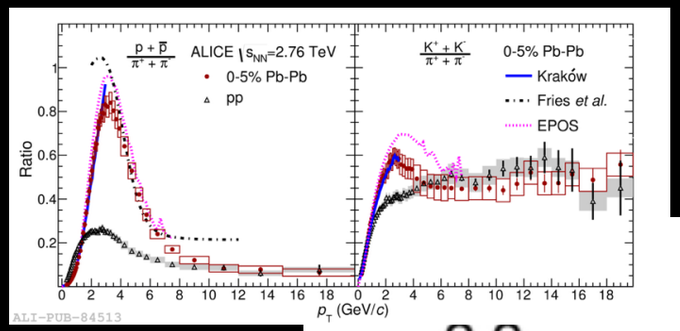
light

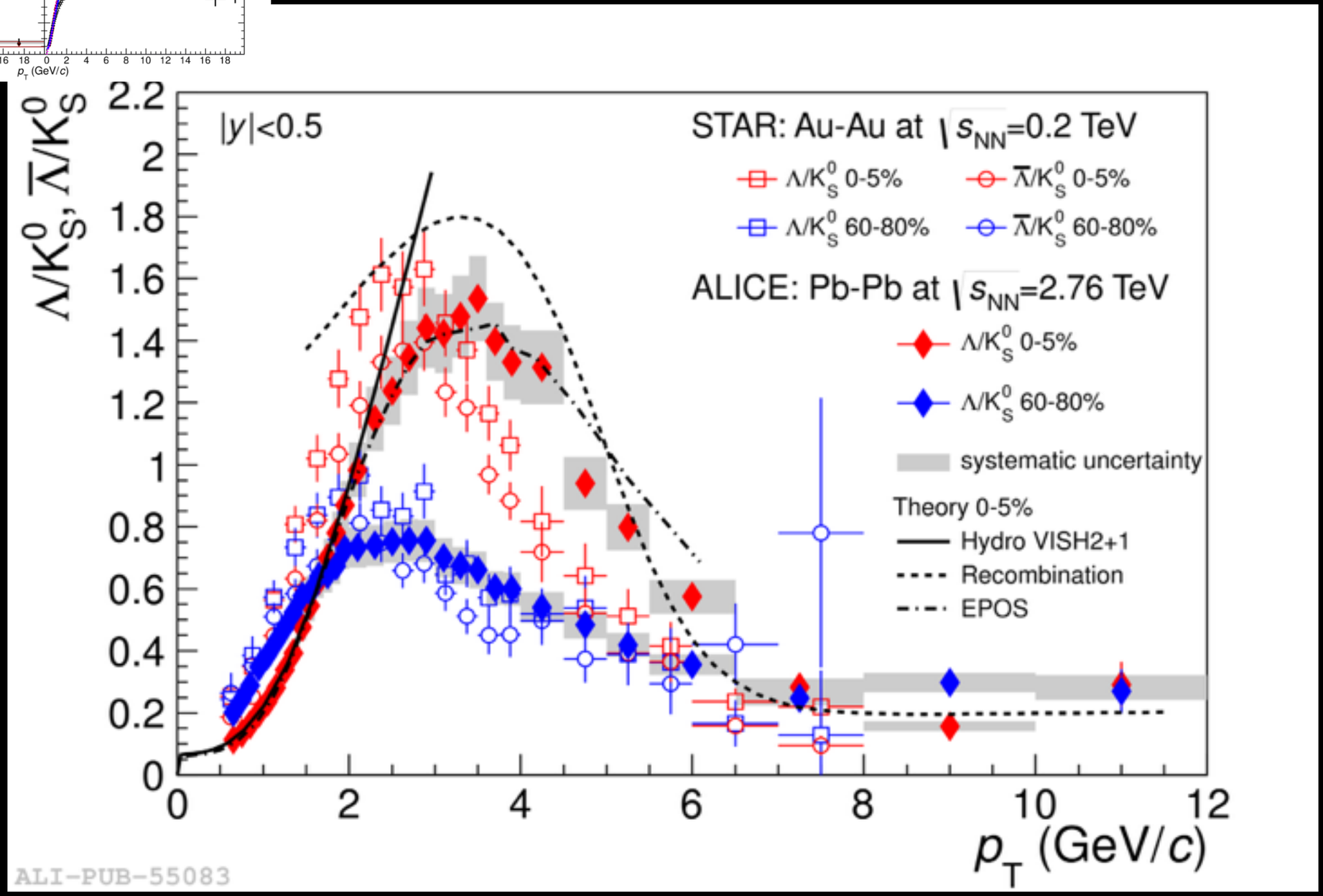


spectra + PID

Baryon & Meson

strange

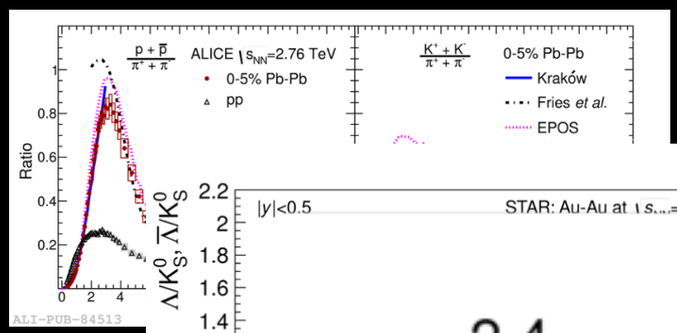


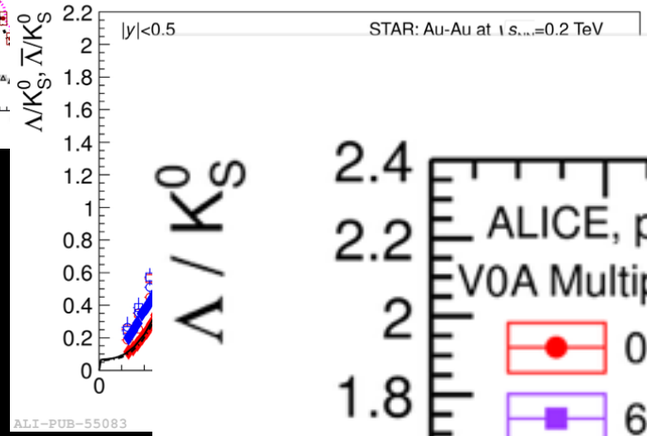


spectra + PID

Baryon & Meson

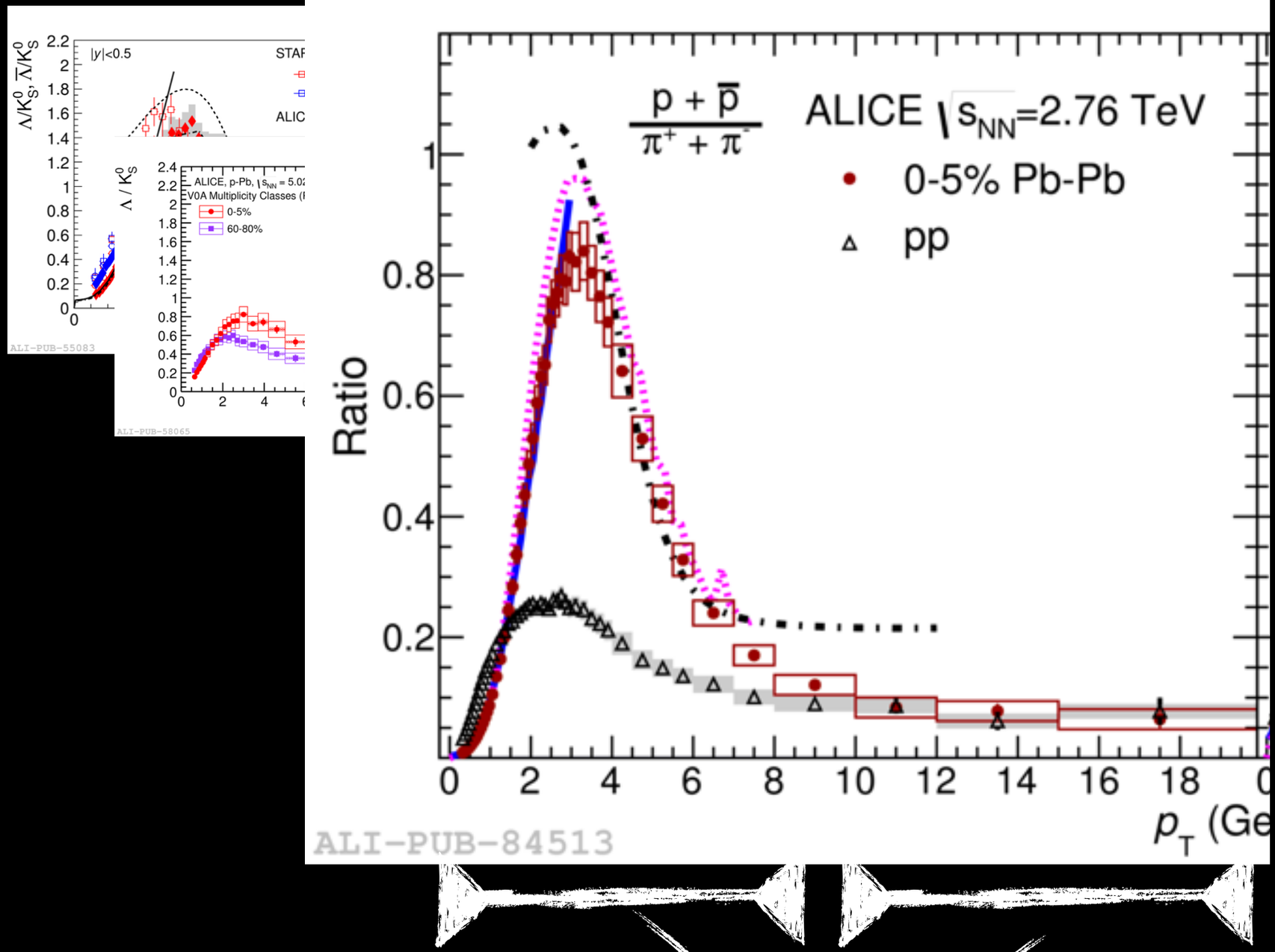
pPb as well !





spectra + PID

Baryon & Meson

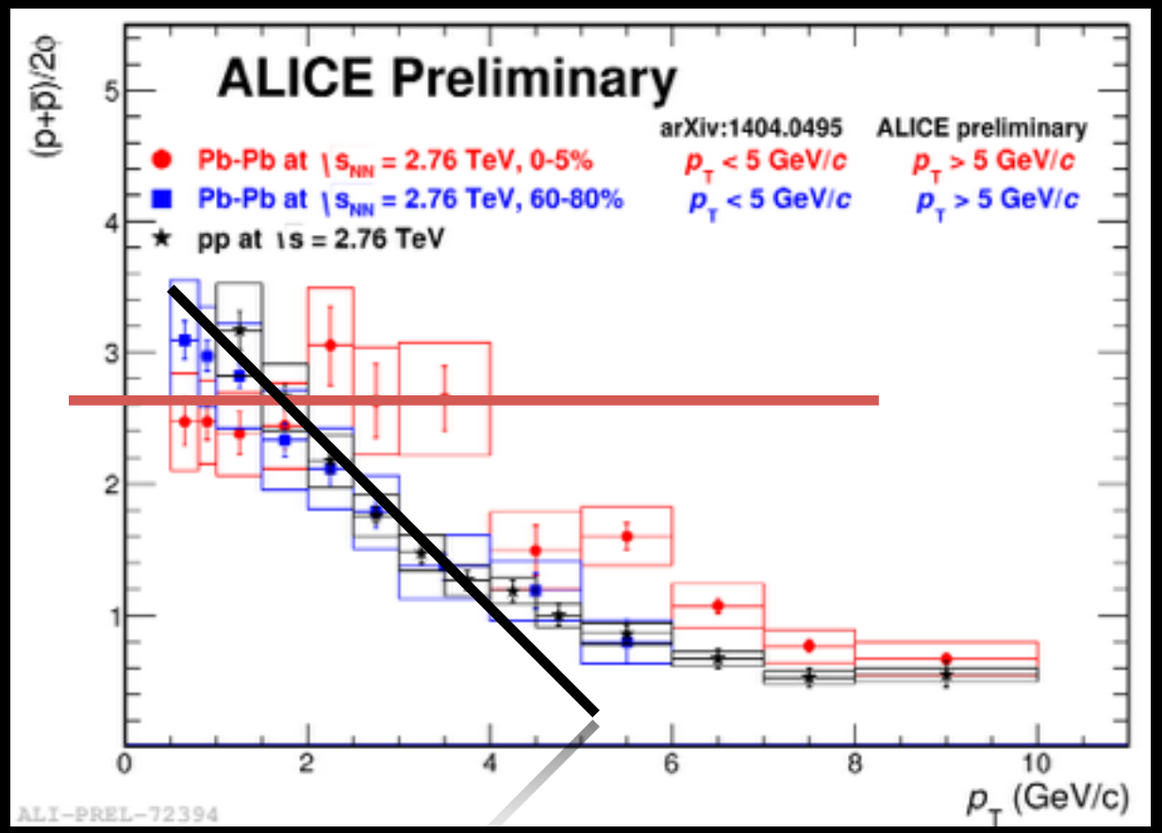


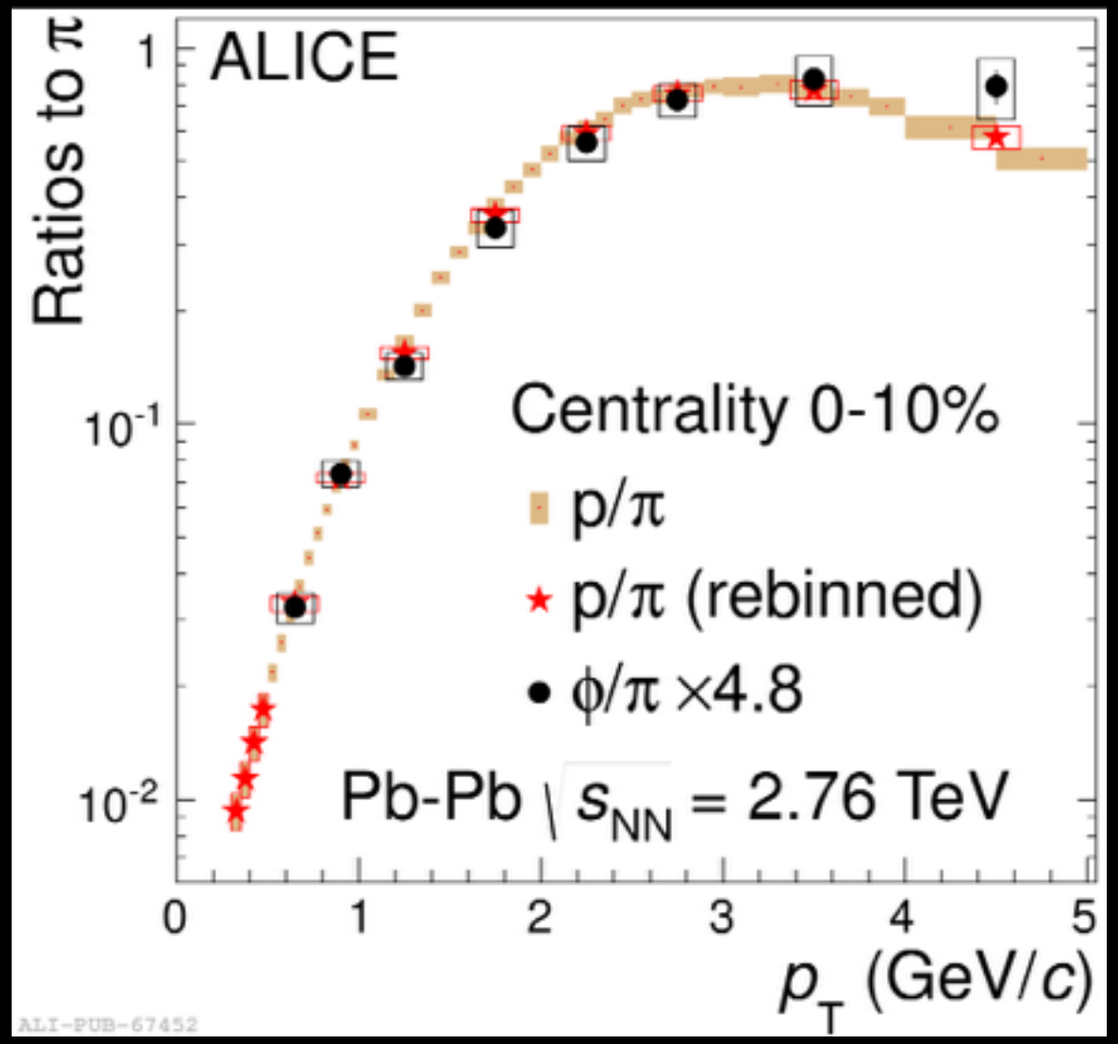
collective effects: radial flow + coalescence ?

vacuum jet fragmentation: pQCD

spectra + PID

Baryon & Meson



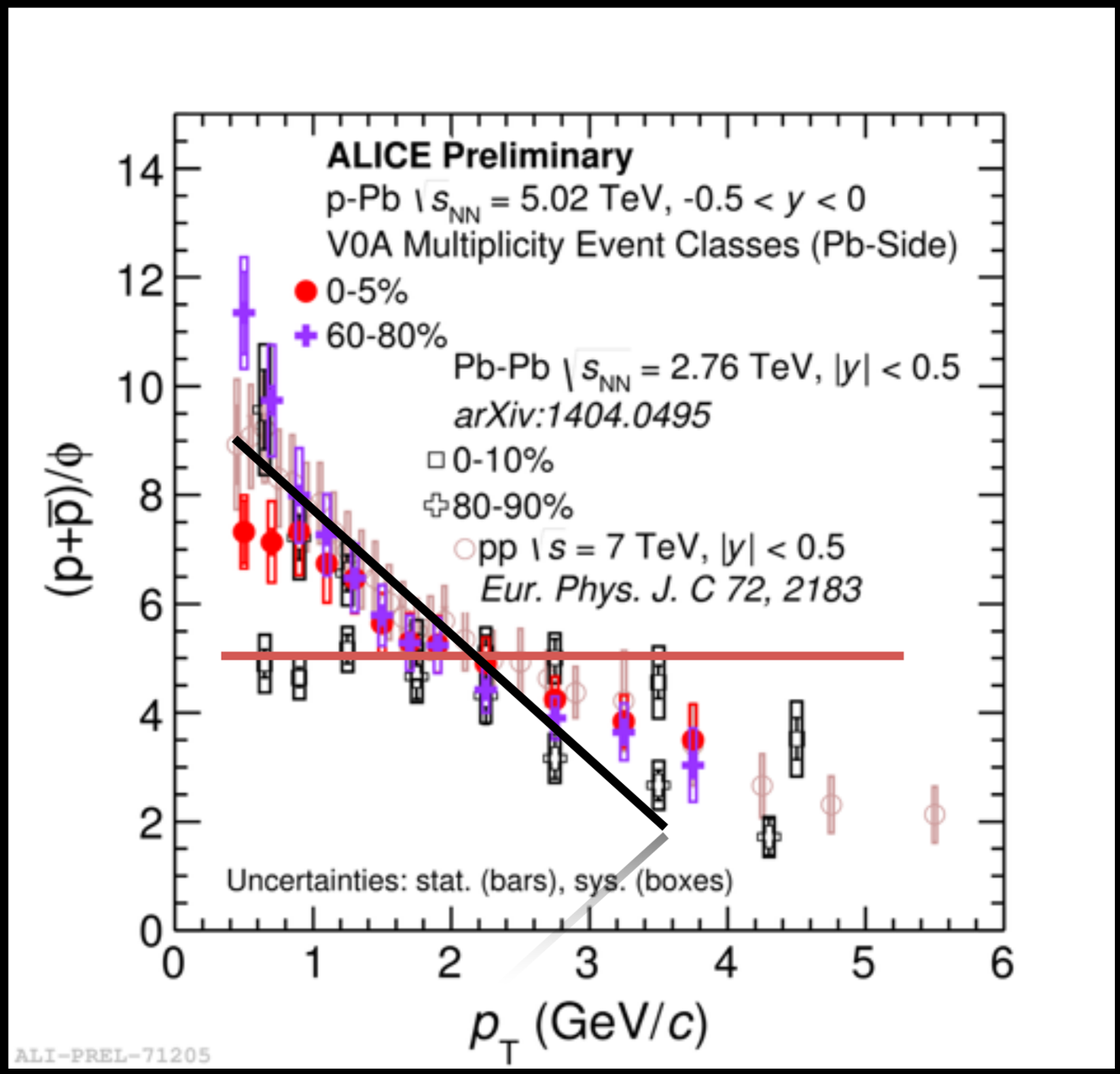


collective effects: radial flow + ~~coalescence ?~~

Mass rather than quark content

spectra + PID

Baryon & Meson

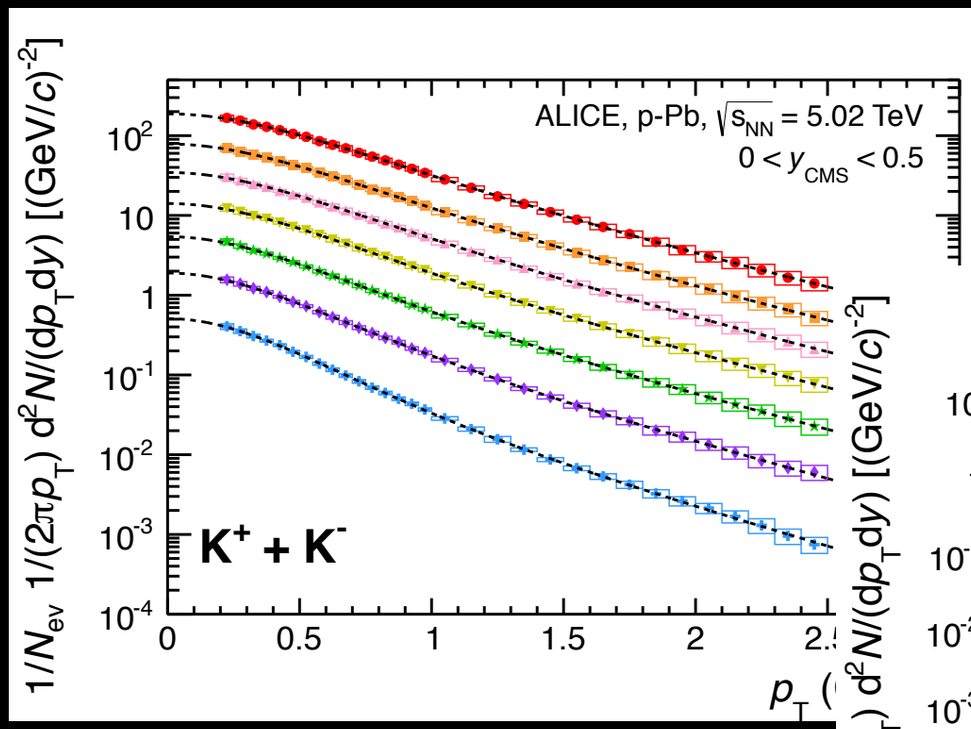


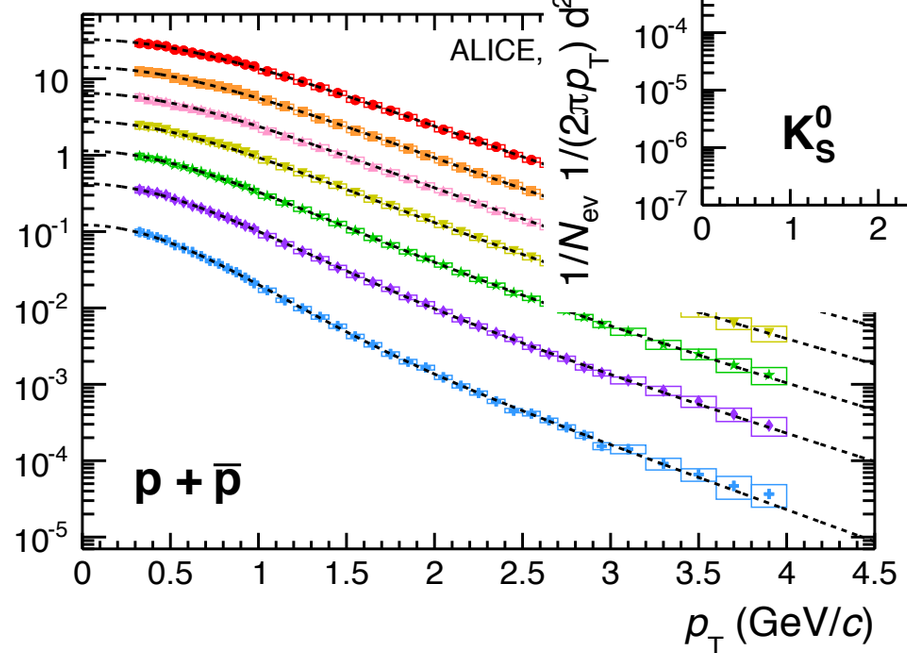
collective effects: radial flow + ~~coalescence ?~~

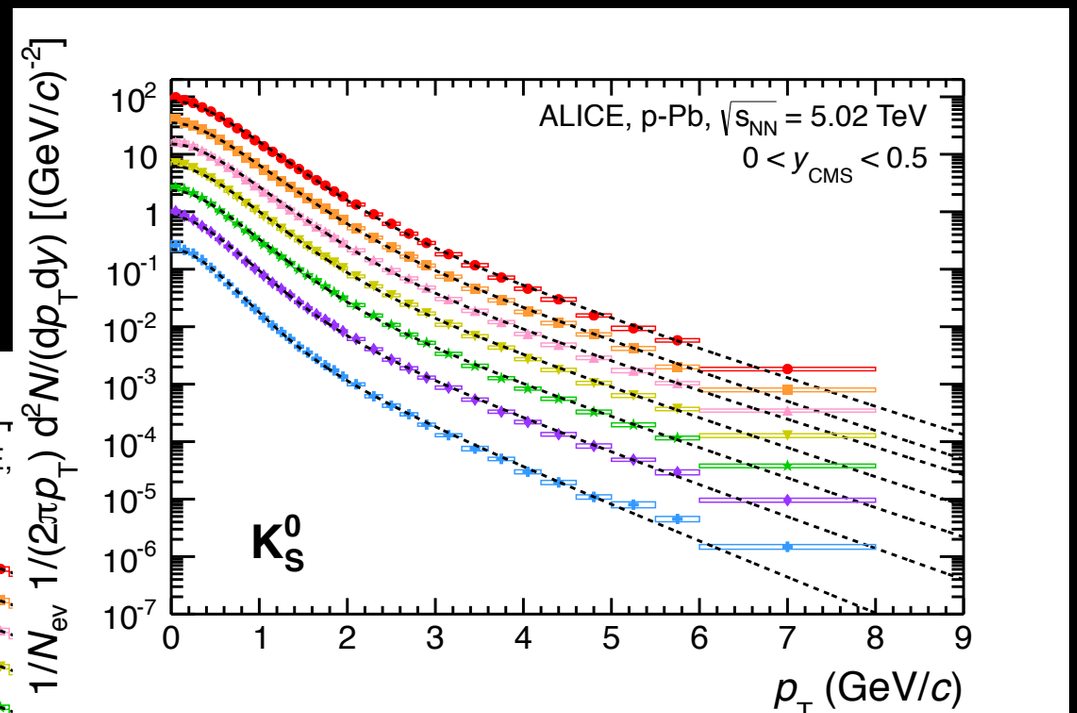
Mass rather than quark content

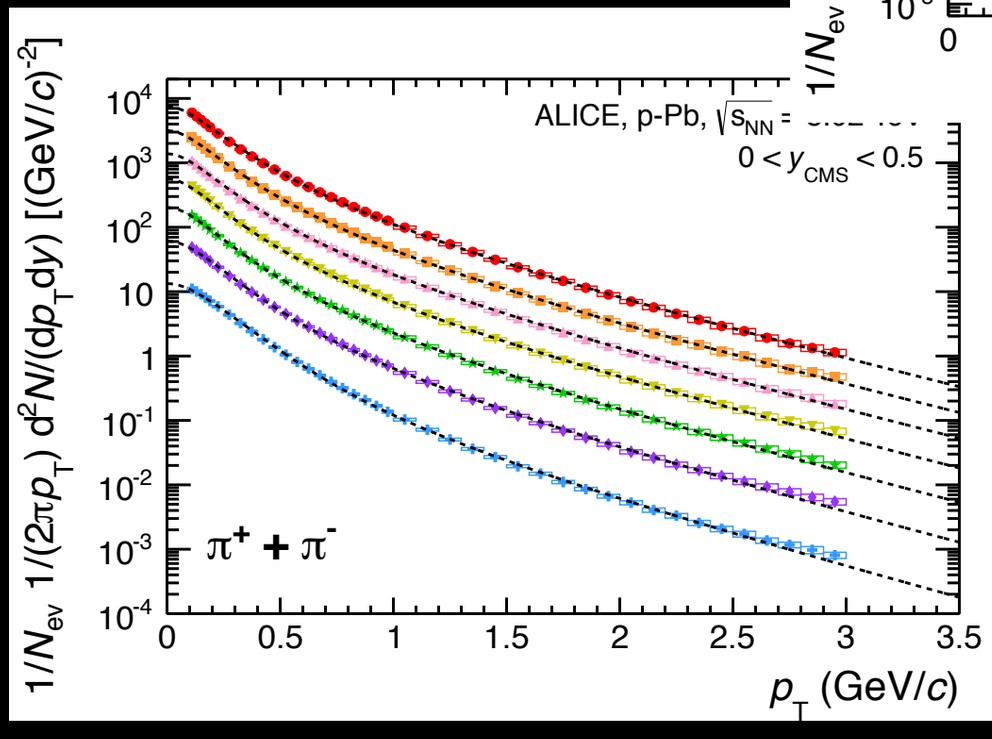
spectra + PID

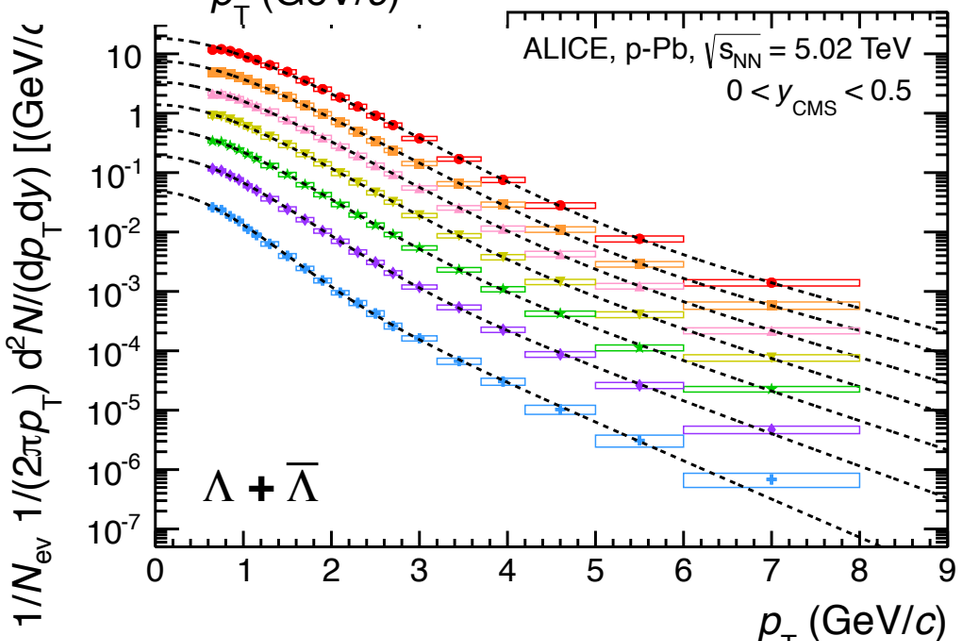
Blue shift





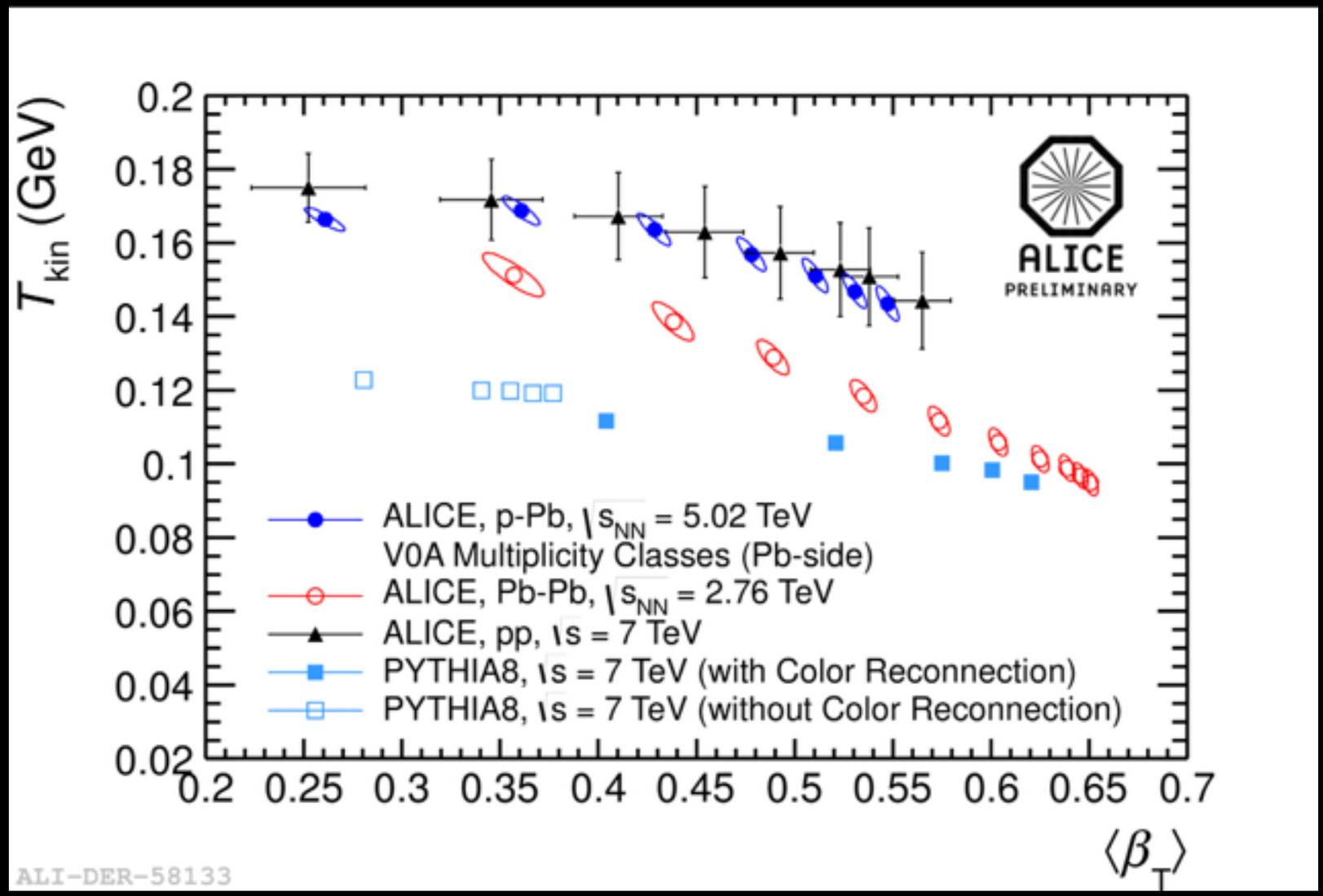






spectra + PID

Radial flow

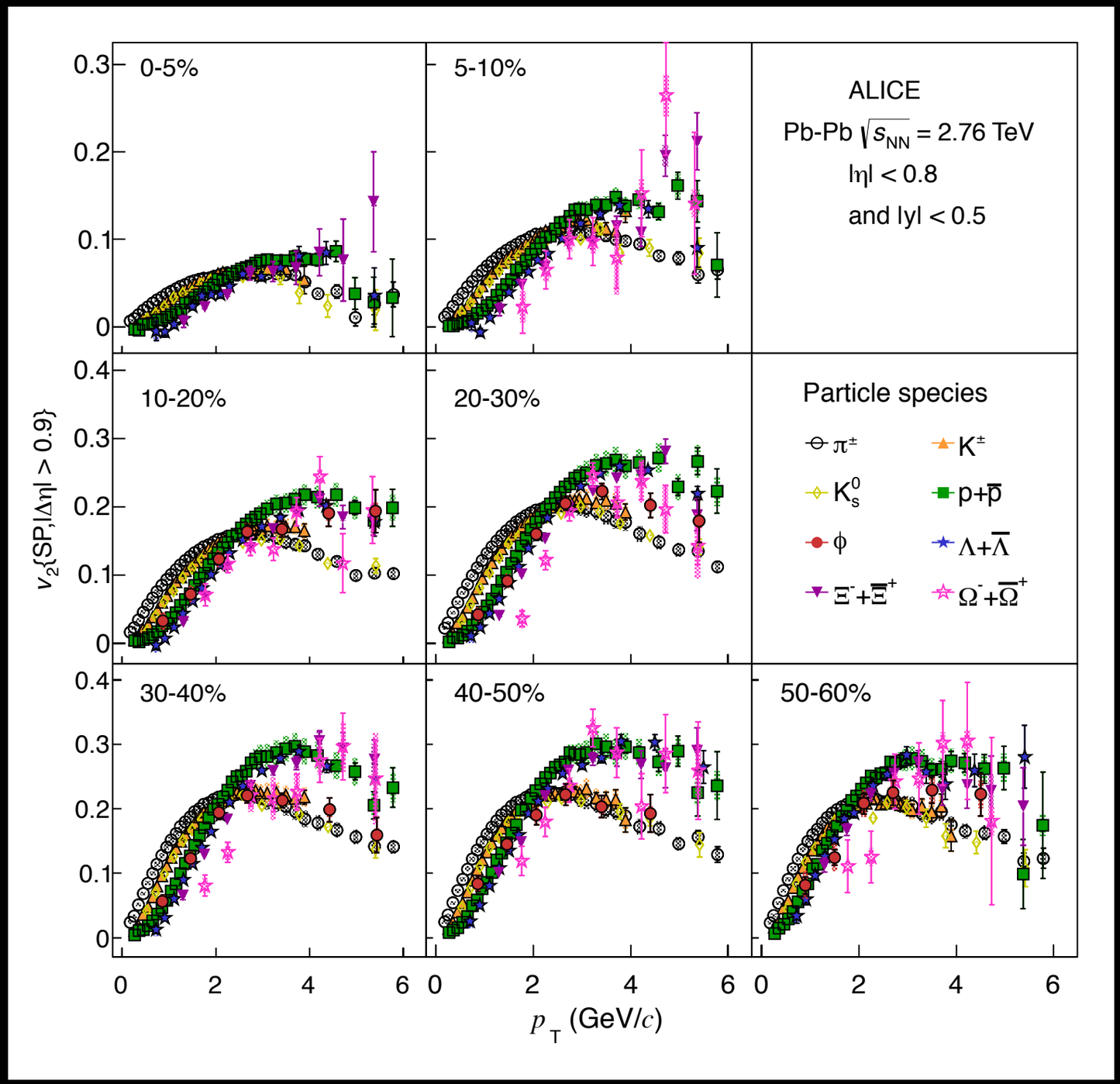


p-Pb and pp: (stronger) radial gradient !

p-p: FS mechanism that mimics radial flow !!

spectra + PID + v_2

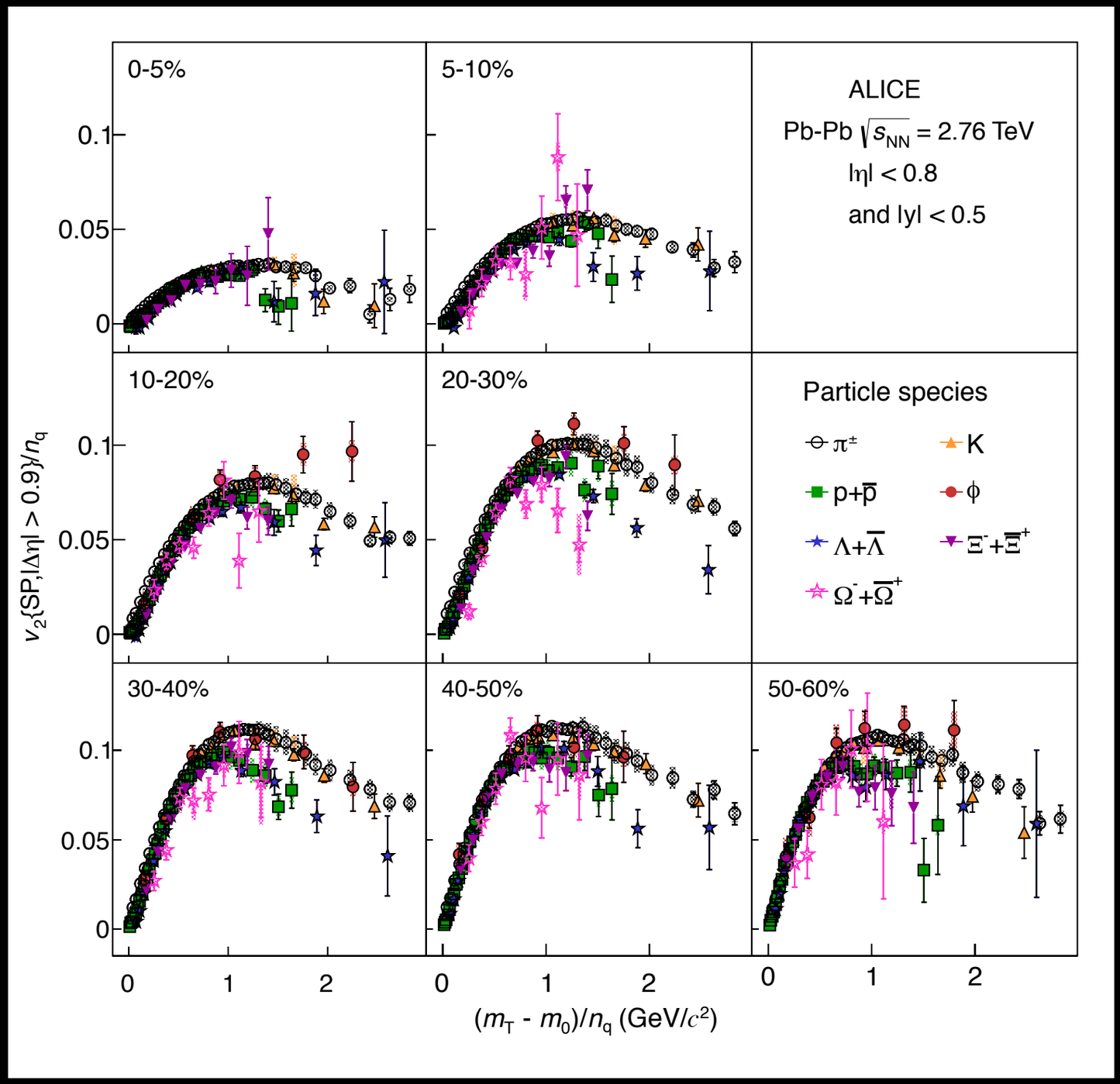
Elliptic flow



hadronization through q coalescence ➜ q DoF at $T > T_H$?

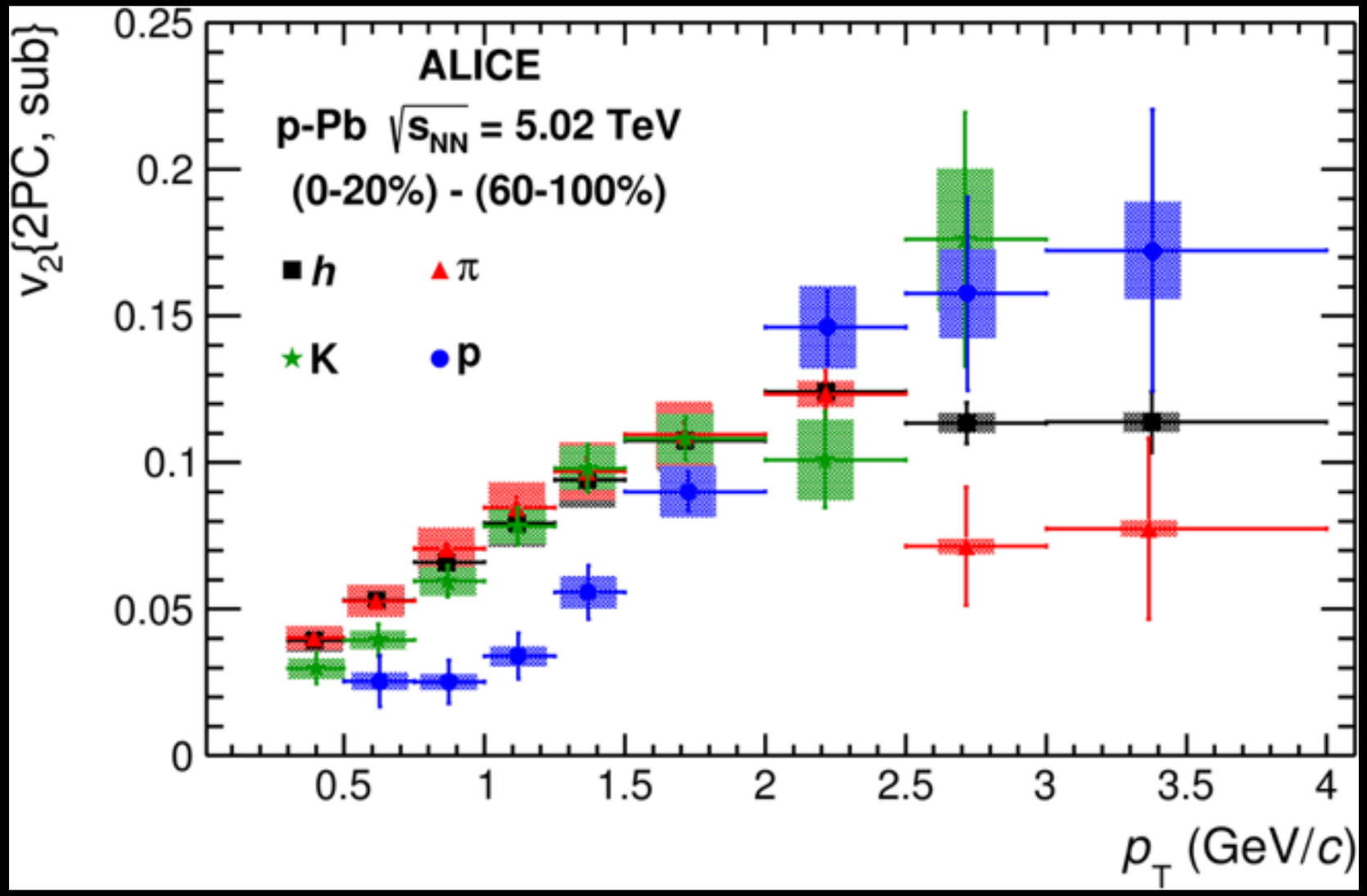
spectra + PID + v_2

Elliptic flow



~~hadronization through q coalescence~~ ➜ q DoF at $T > T_H$?

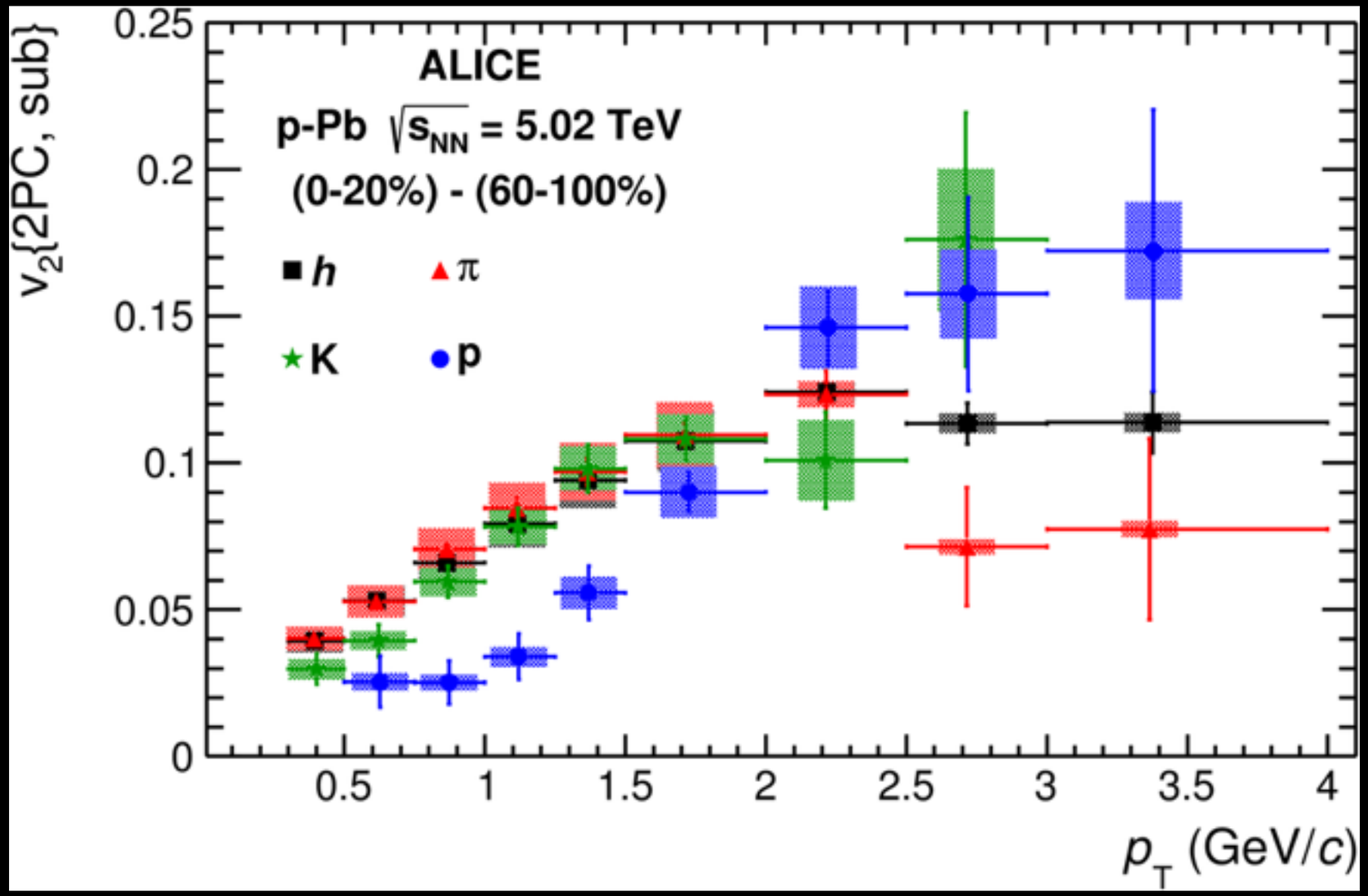
Elliptic flow



pp: hydro flow, as well ! the embarrassing success of hydro

spectra + PID + v_2

Elliptic flow

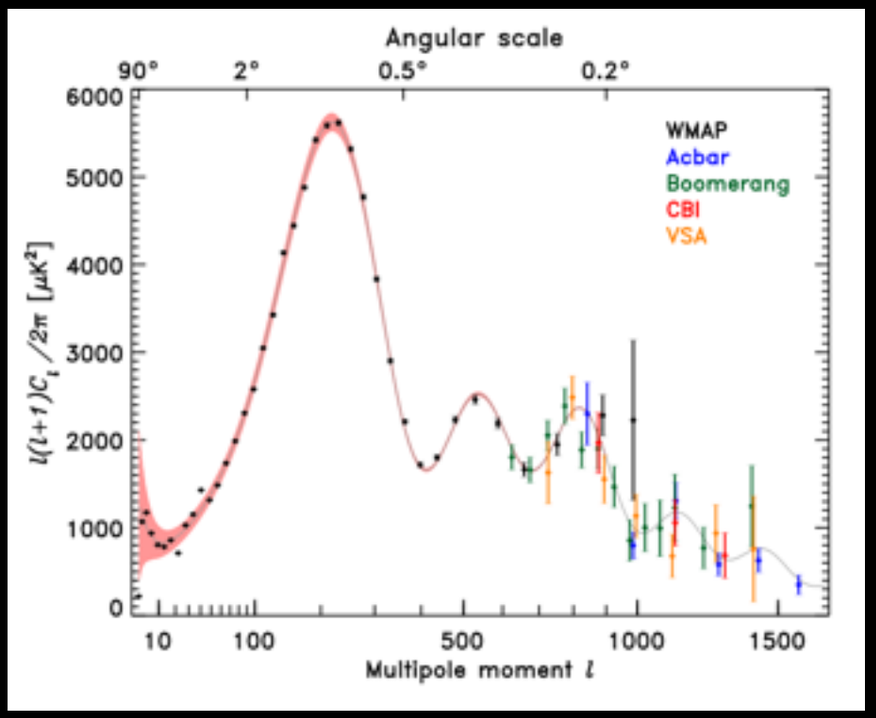


pp: hydro flow, as well ! the embarrassing success of hydro

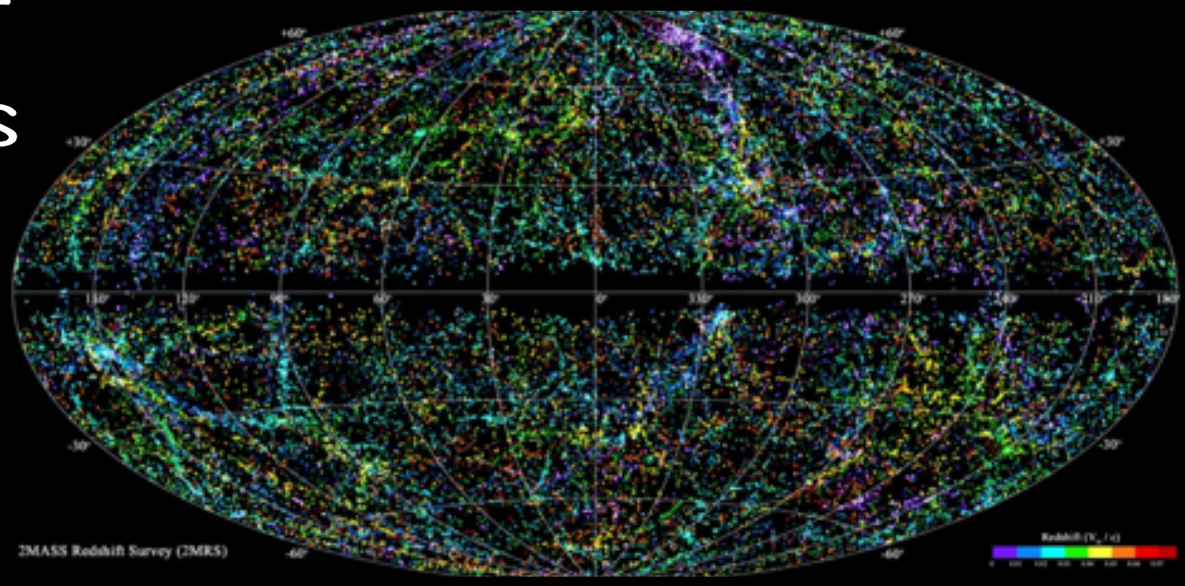
n flow

Dissipation in the perfect liquid is minimal:

The QGP is transparent to quantum fluctuations in the IS



BB model + parameters



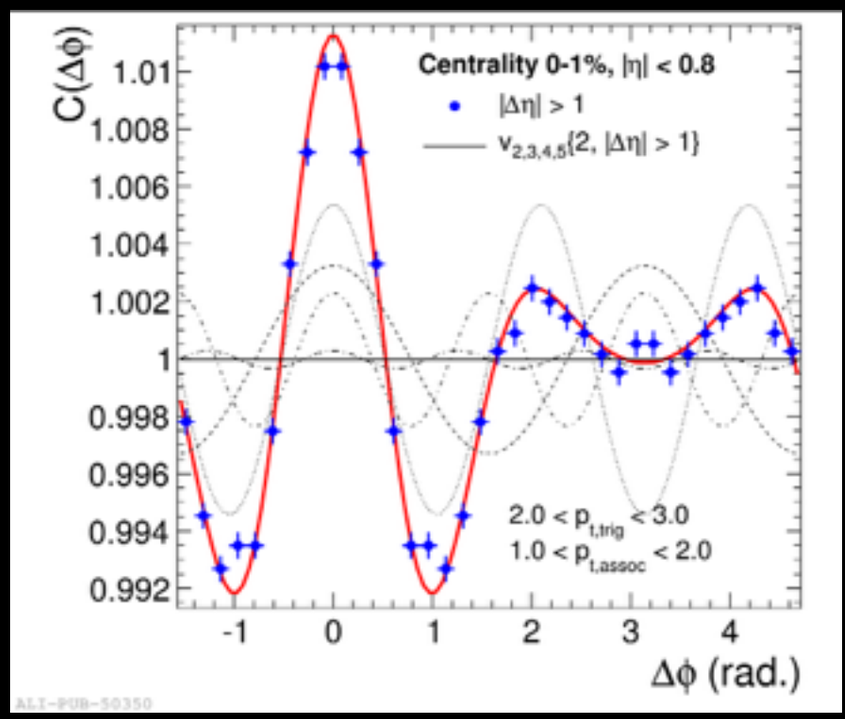
n flow

Dissipation in the perfect liquid is minimal:

The QGP is transparent to quantum fluctuations in the IS

non dissipatif
hydro + classical
field dynamics

IS: weakly coupled pure gauge field + quantum fluctuations

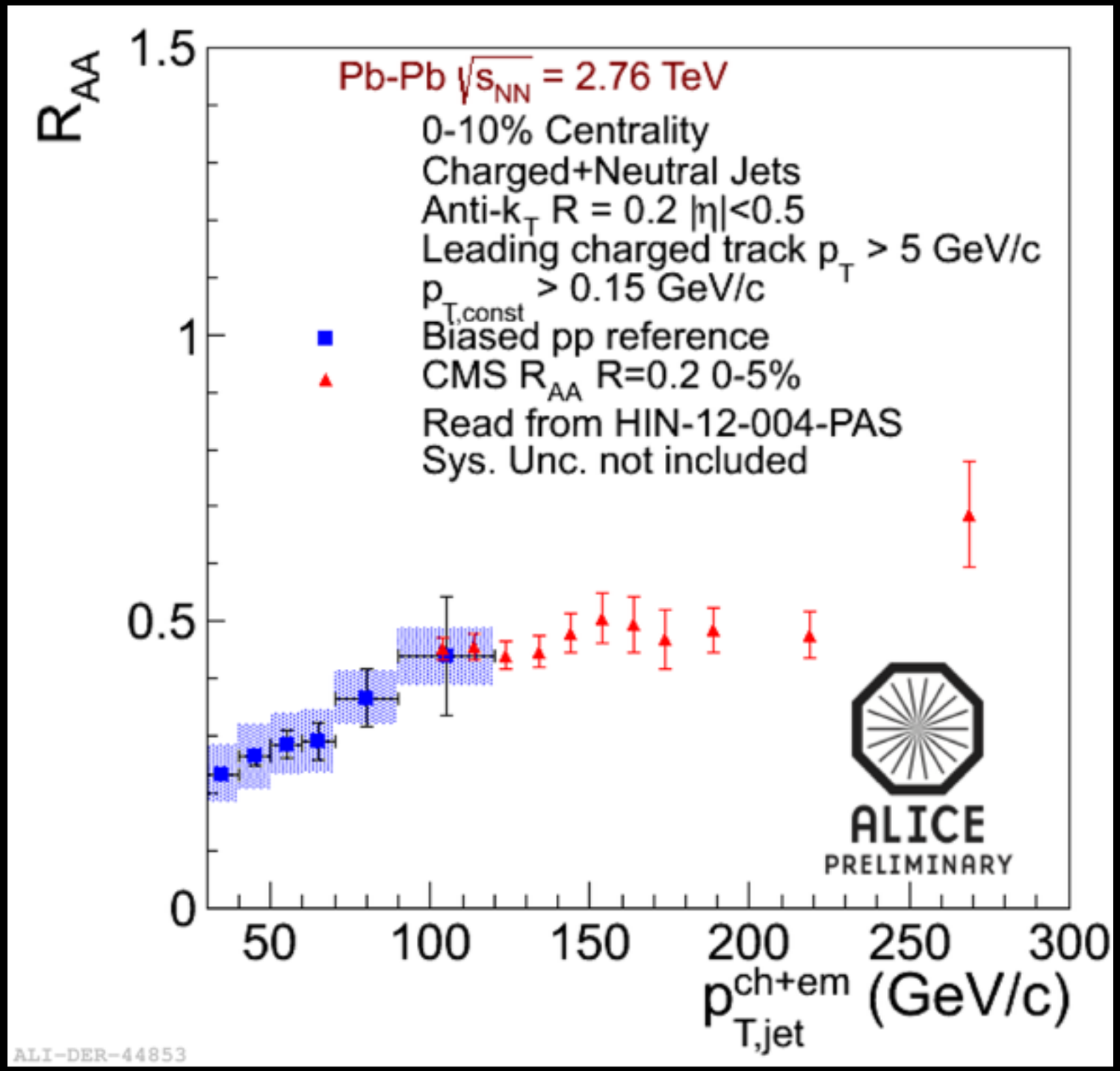


hard

hard: p_T, m_T ≫ T, Λ_{QCD}

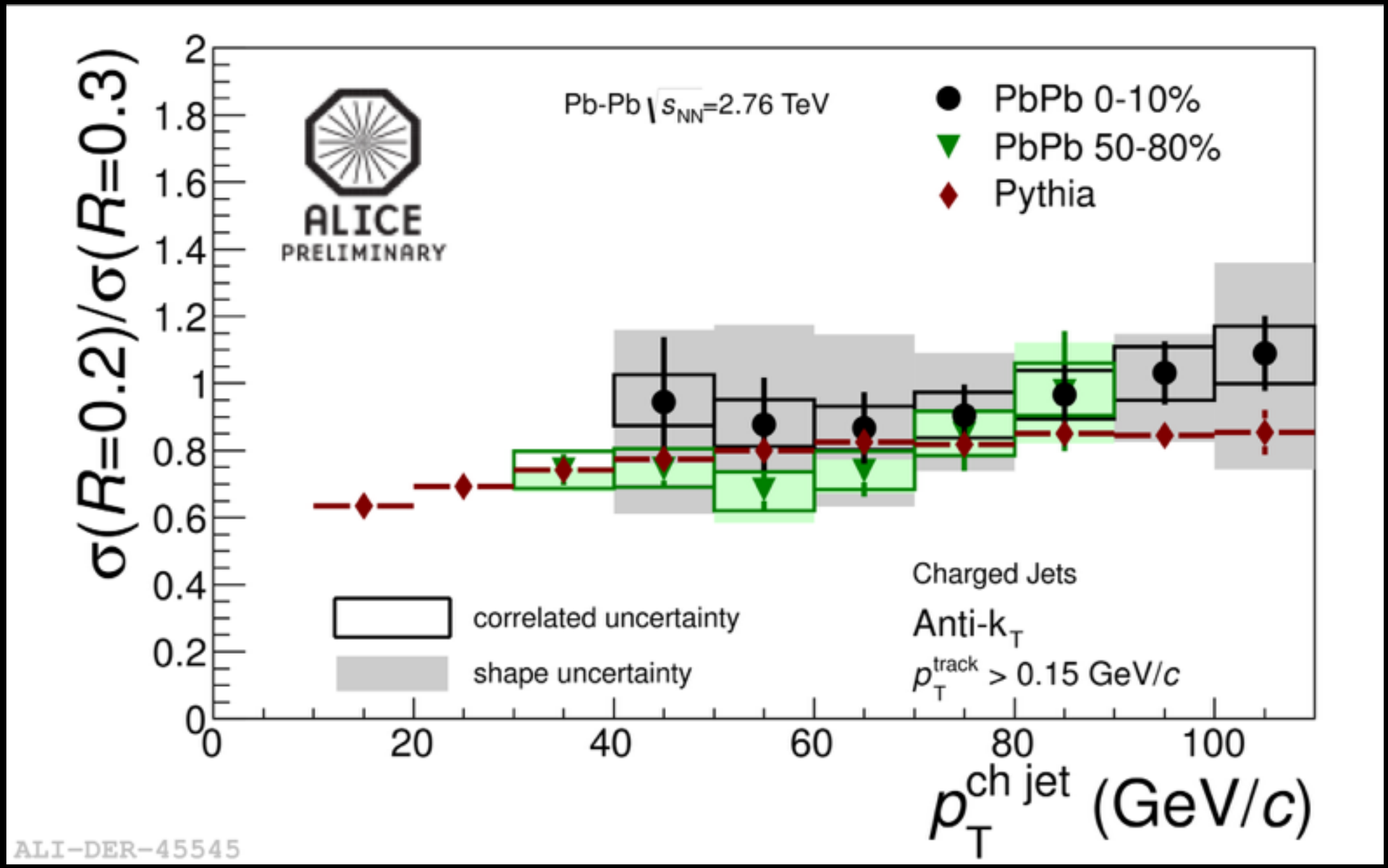
probe QGP at high resolution scale (DoF)

R_{AA}



jets follow trend of leading hadron

R_{AA}



Where is the lost energy radiated ?

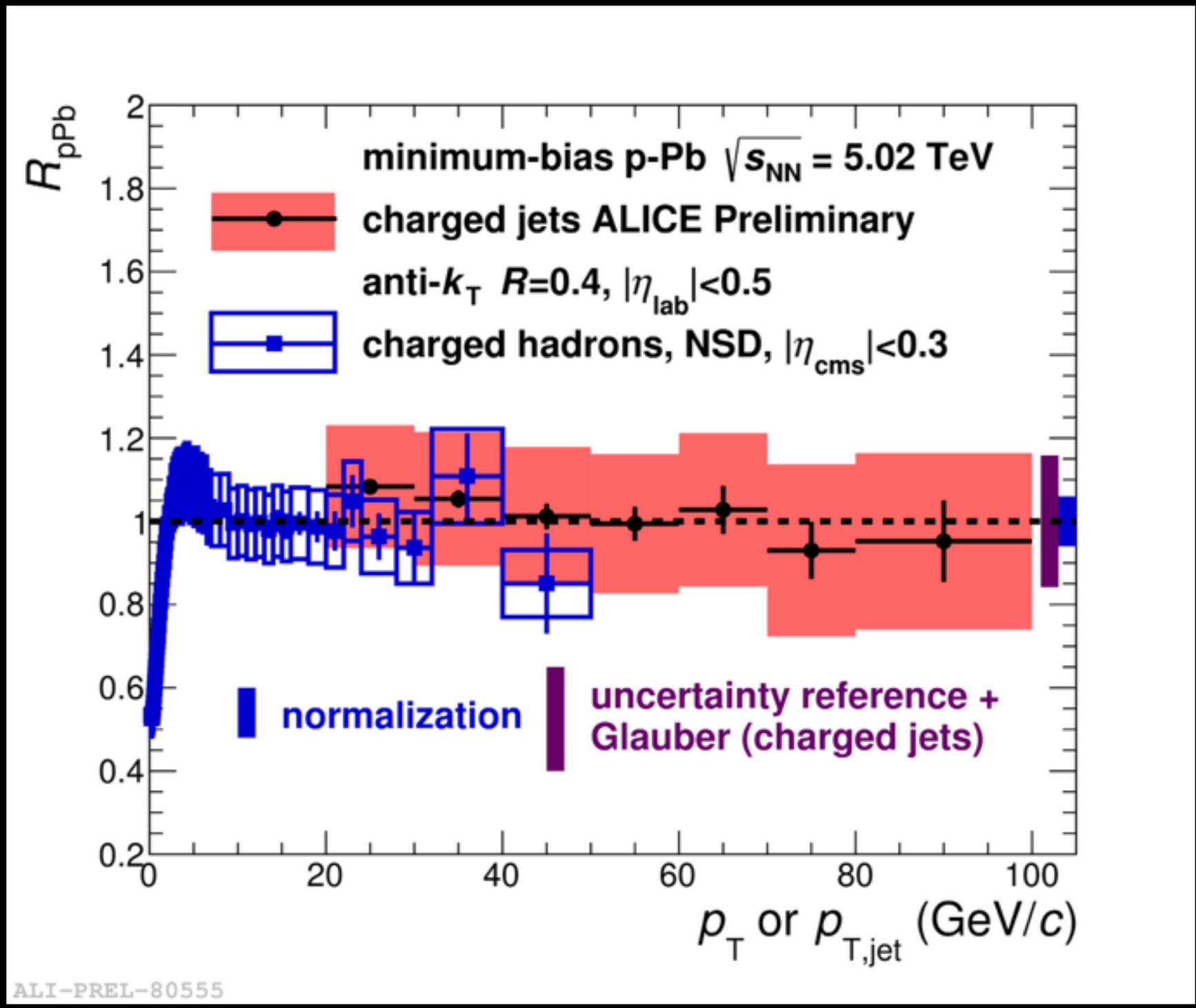
$$\hat{q} = f(\sqrt{s},\ T,\ E_{jet},\ L_{medium})$$

- How do these results constrain quantitatively the medium properties ?

- Do theory and experiment speak the same language ?

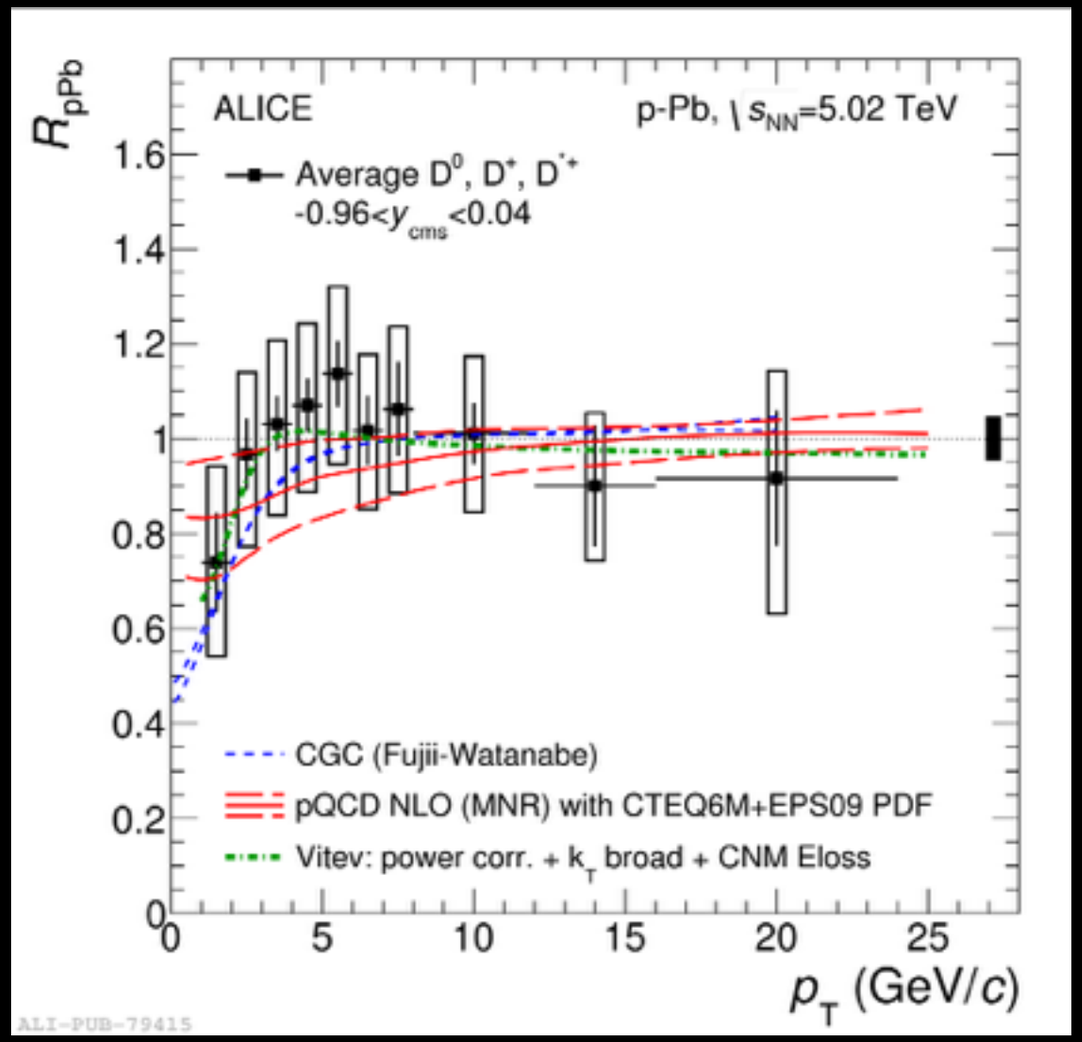
- Can we experimentally discriminate between perturbative and strongly coupled approaches ?

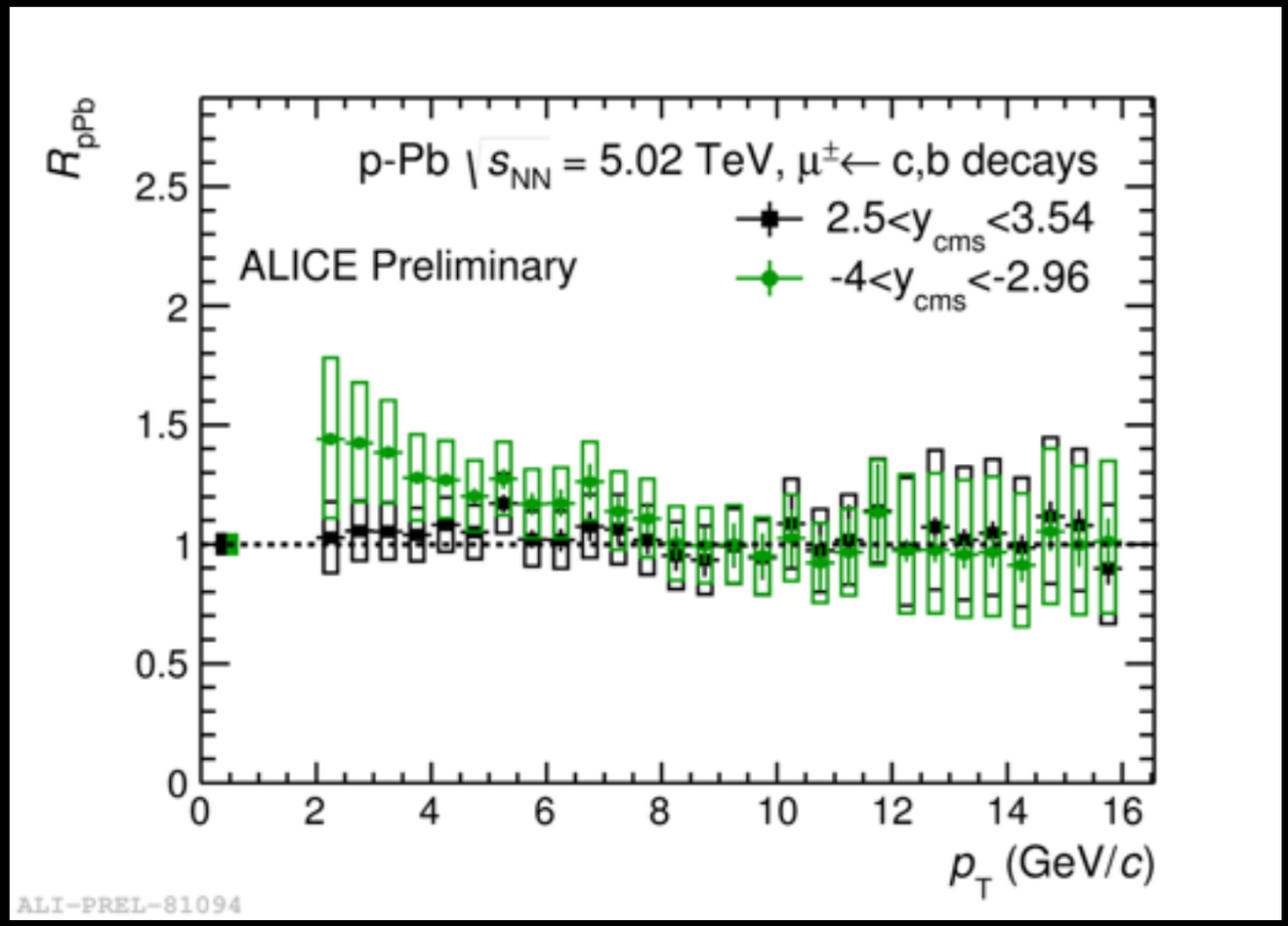
R_{pA}



No medium final state effect in pPb ??

R_{pA}





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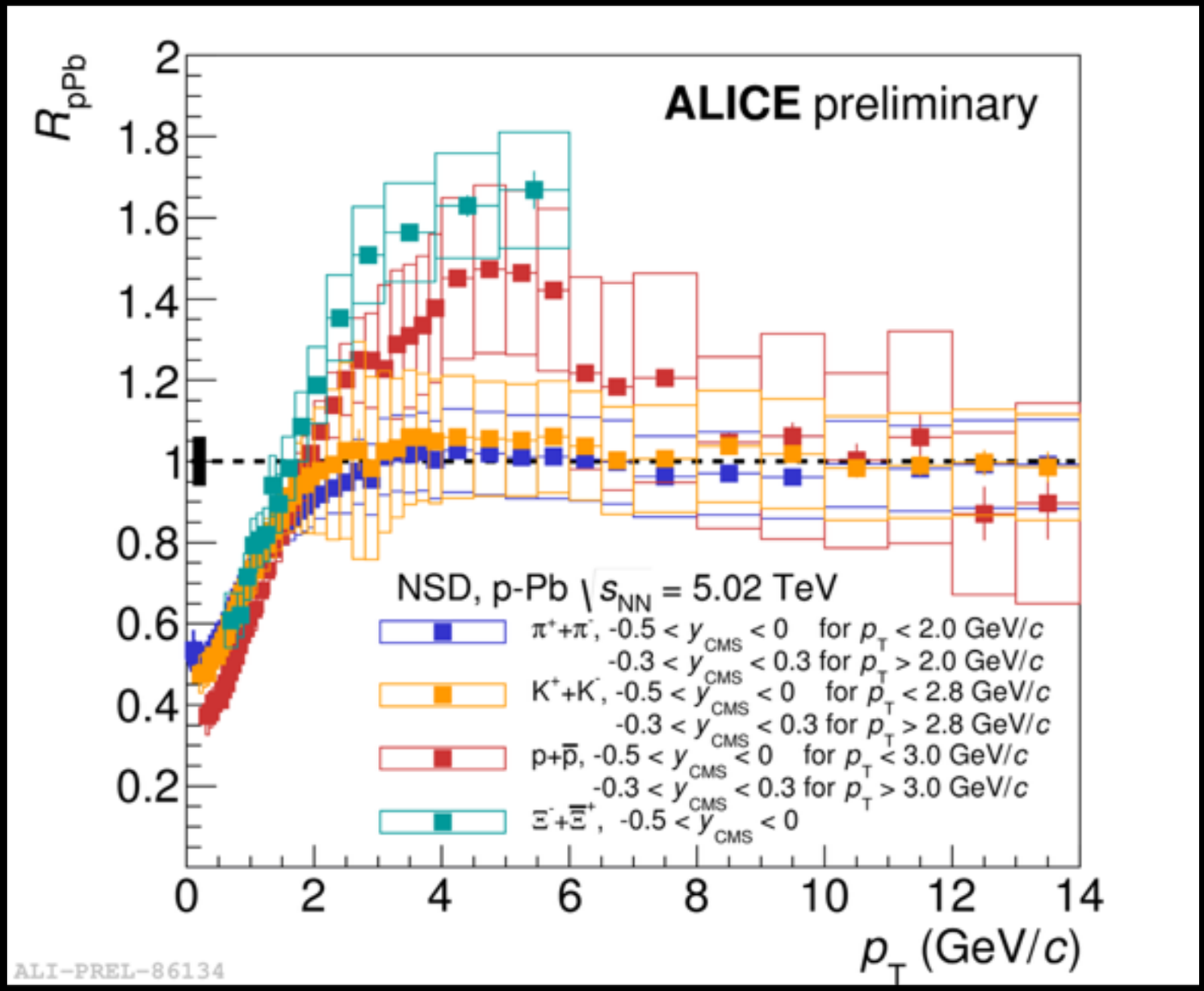
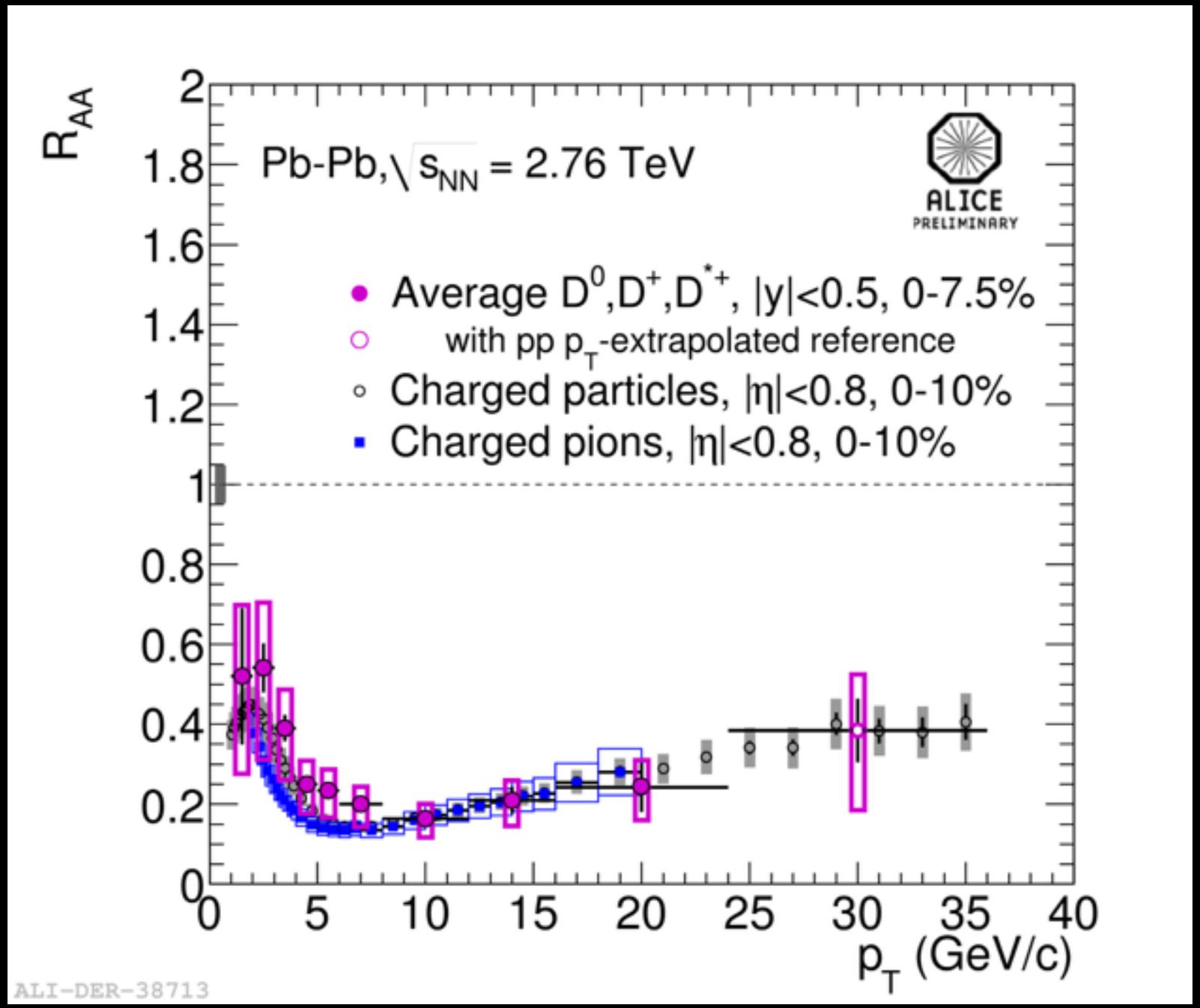


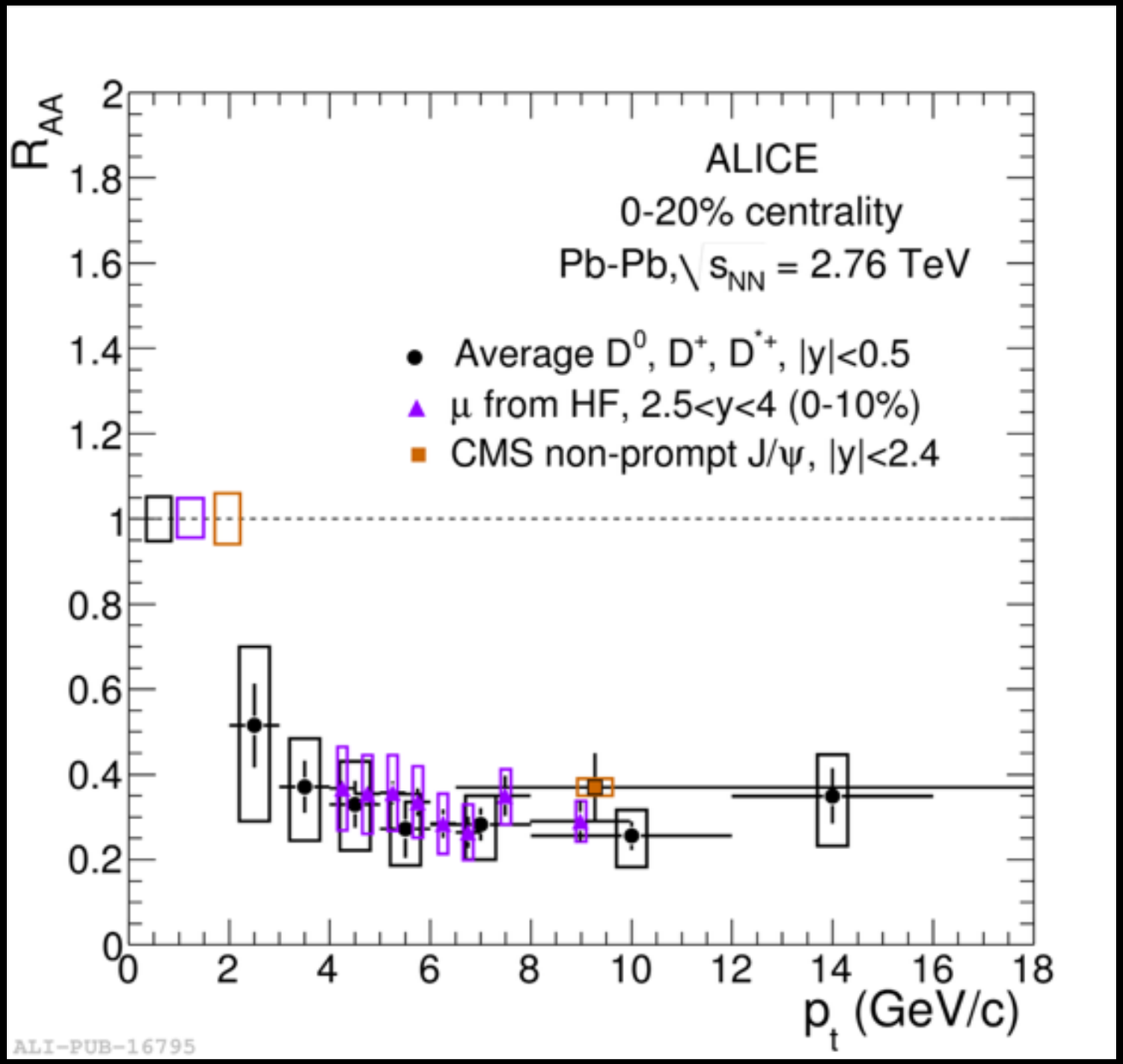
Another manifestation of transverse flow

R_{AA}: D vs π



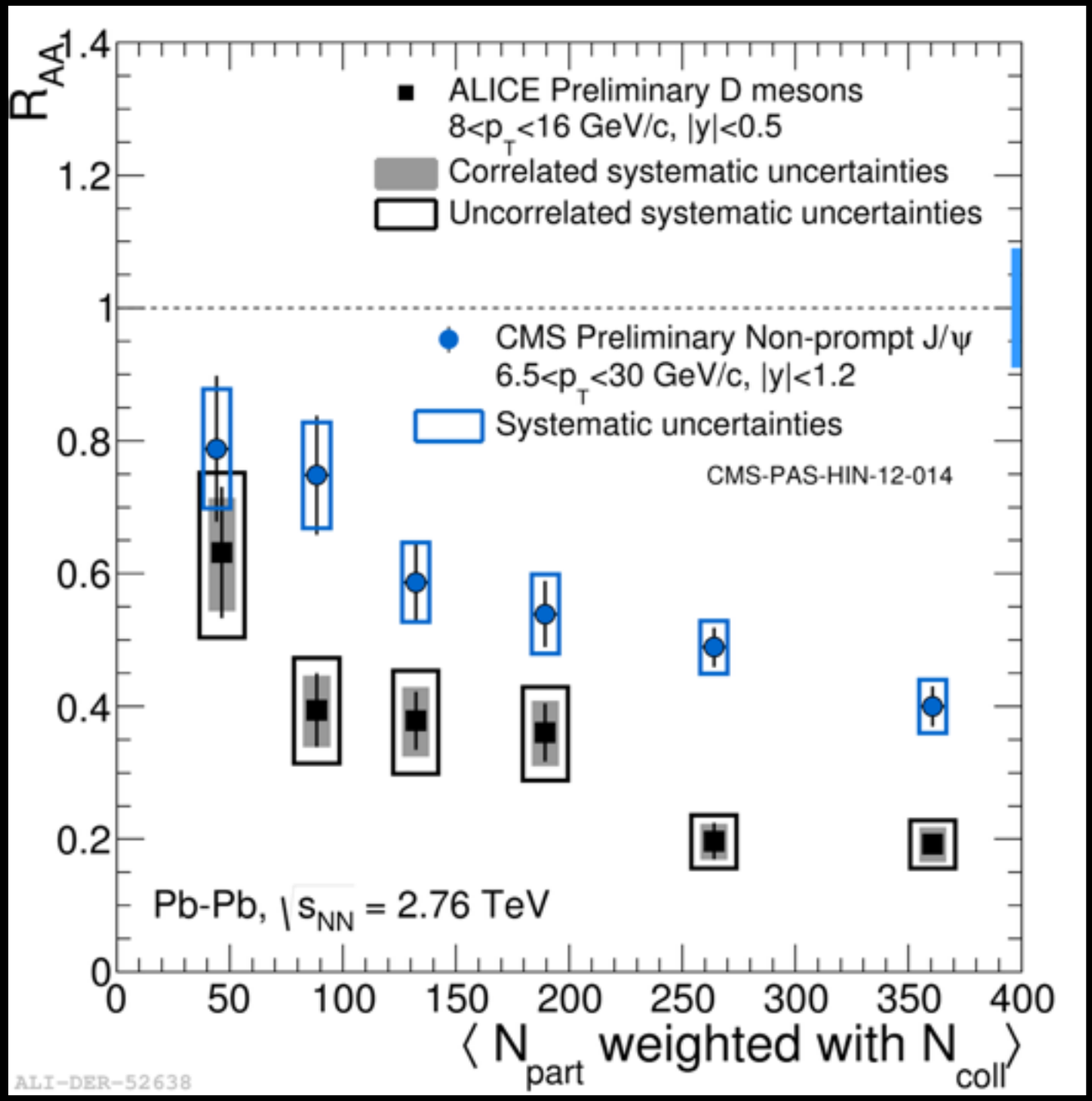
Color charge dependence (g vs q) ?

R_{AA}: D vs B



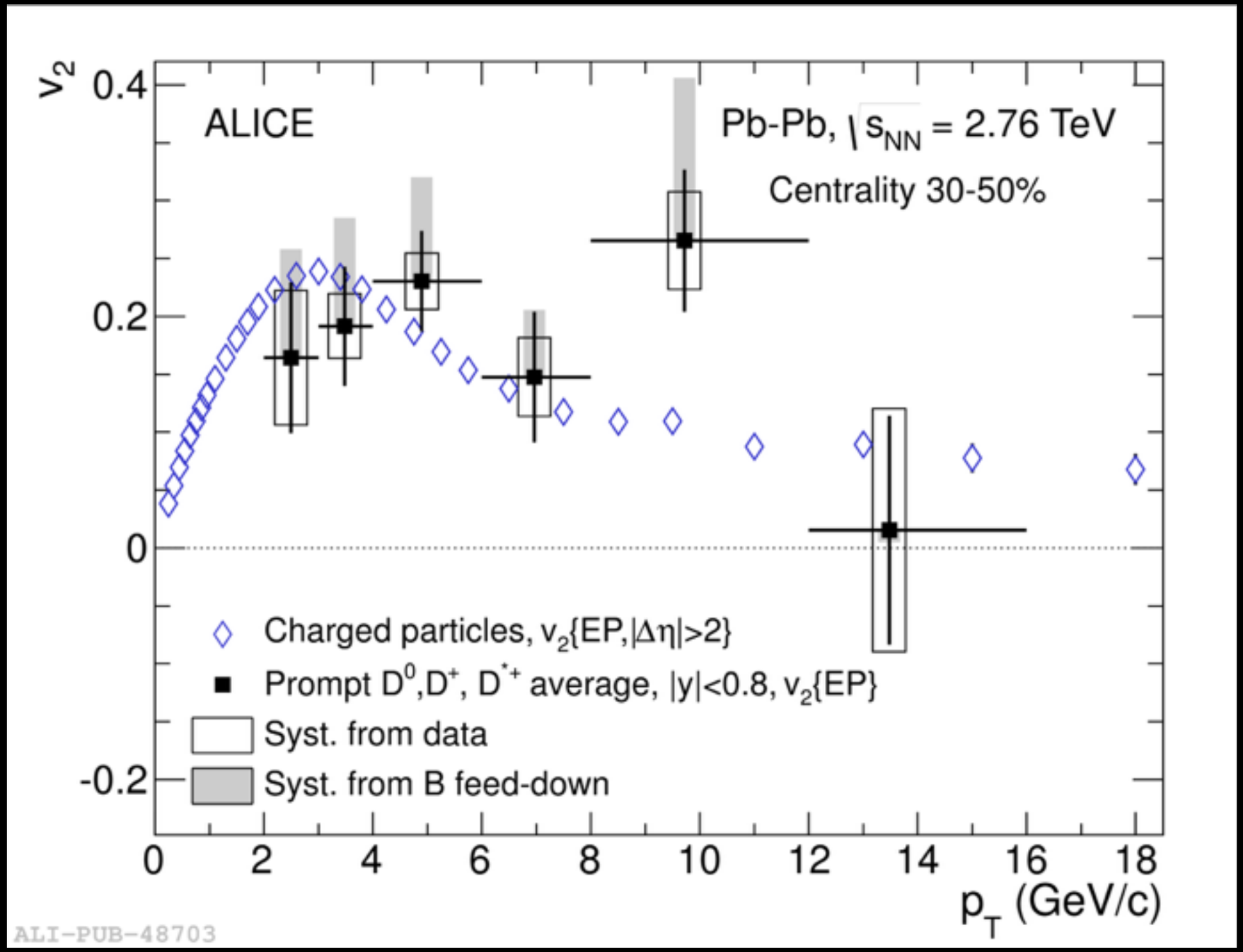
Mass dependence (c vs b) ?

R_{AA}: D vs B



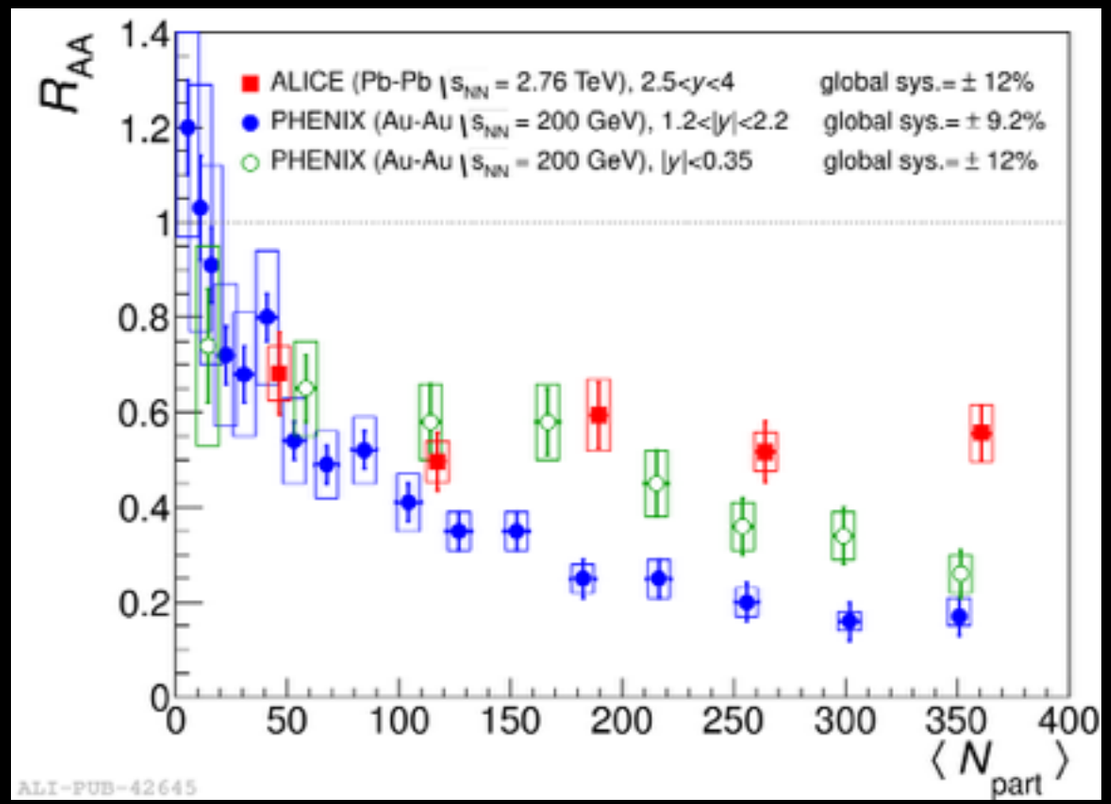
Radiative or collisional ? Flavor dependence ! But…

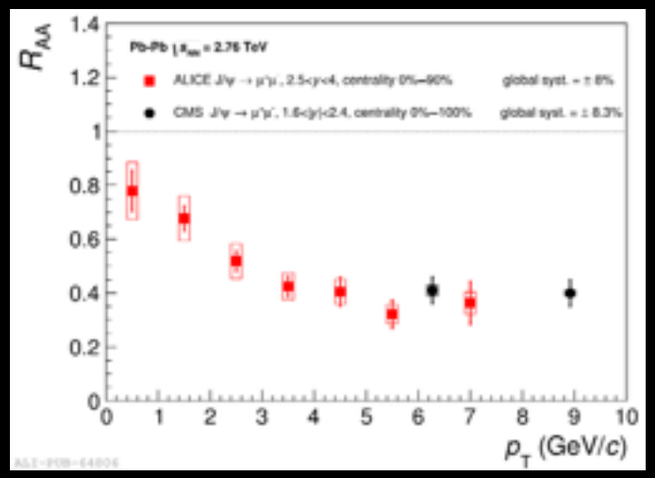
v_2

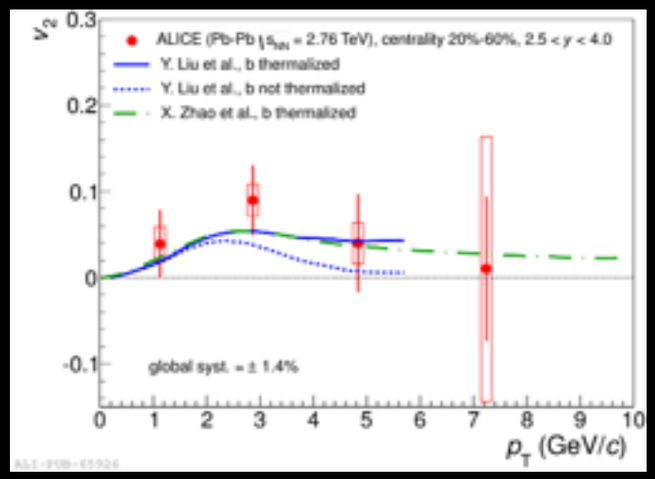


Flow ? coalescence ? dof ?

R_{AA} & v_2





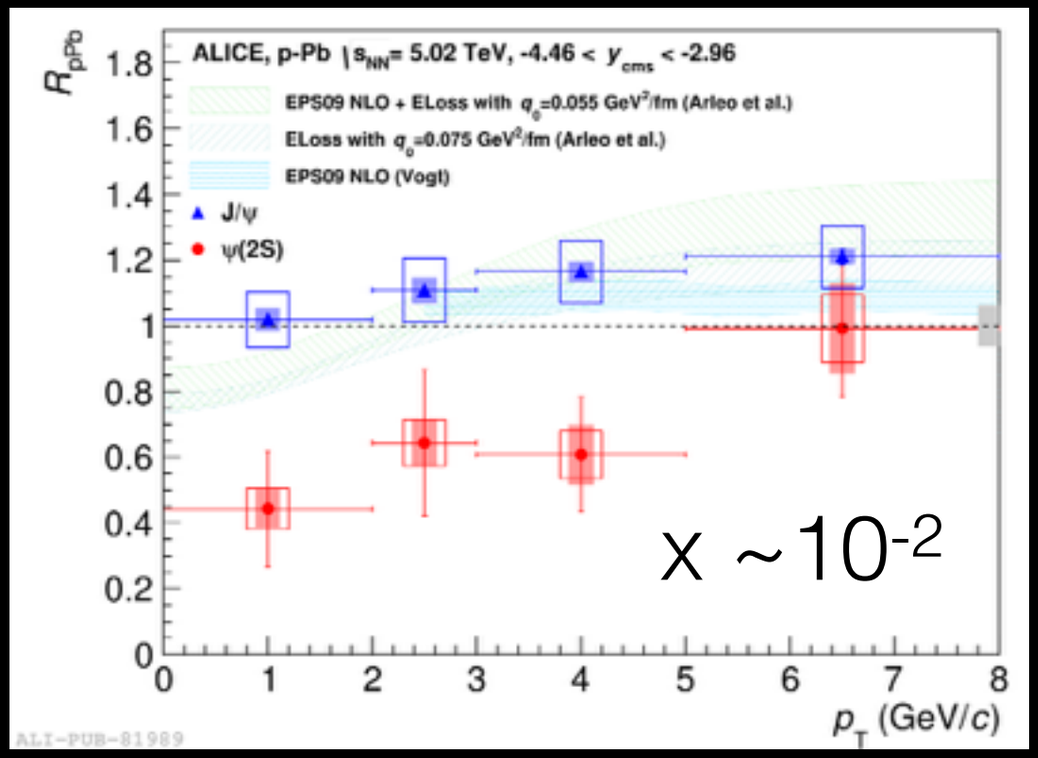


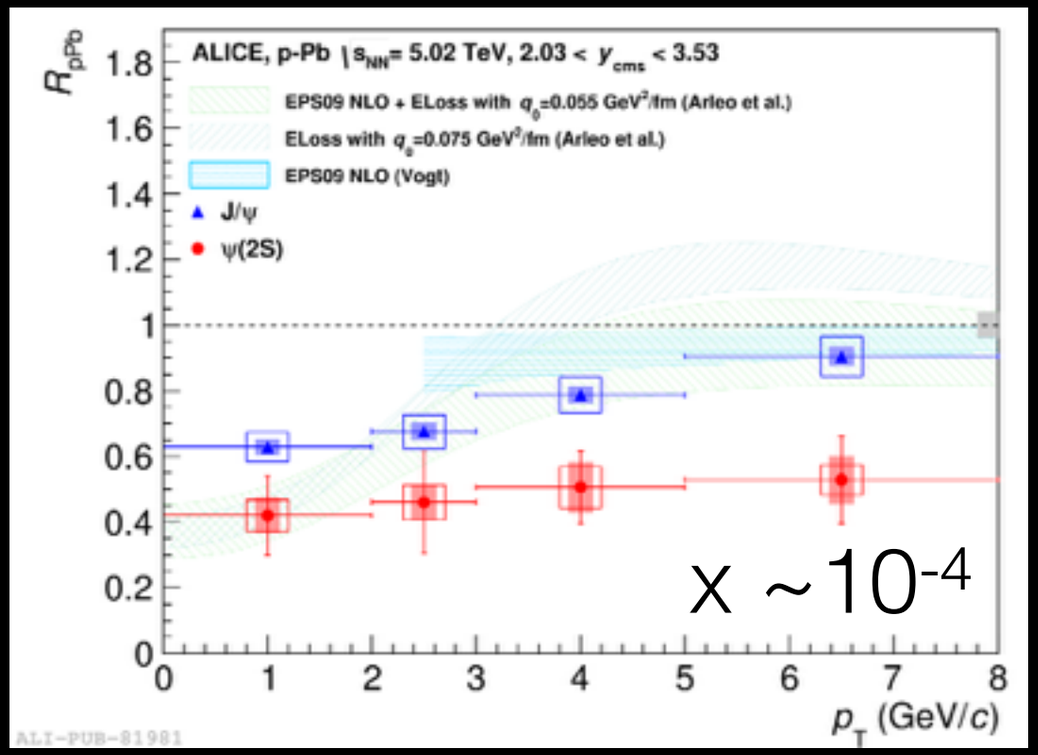
hard process ⊕ color screening ⊕ coalescence

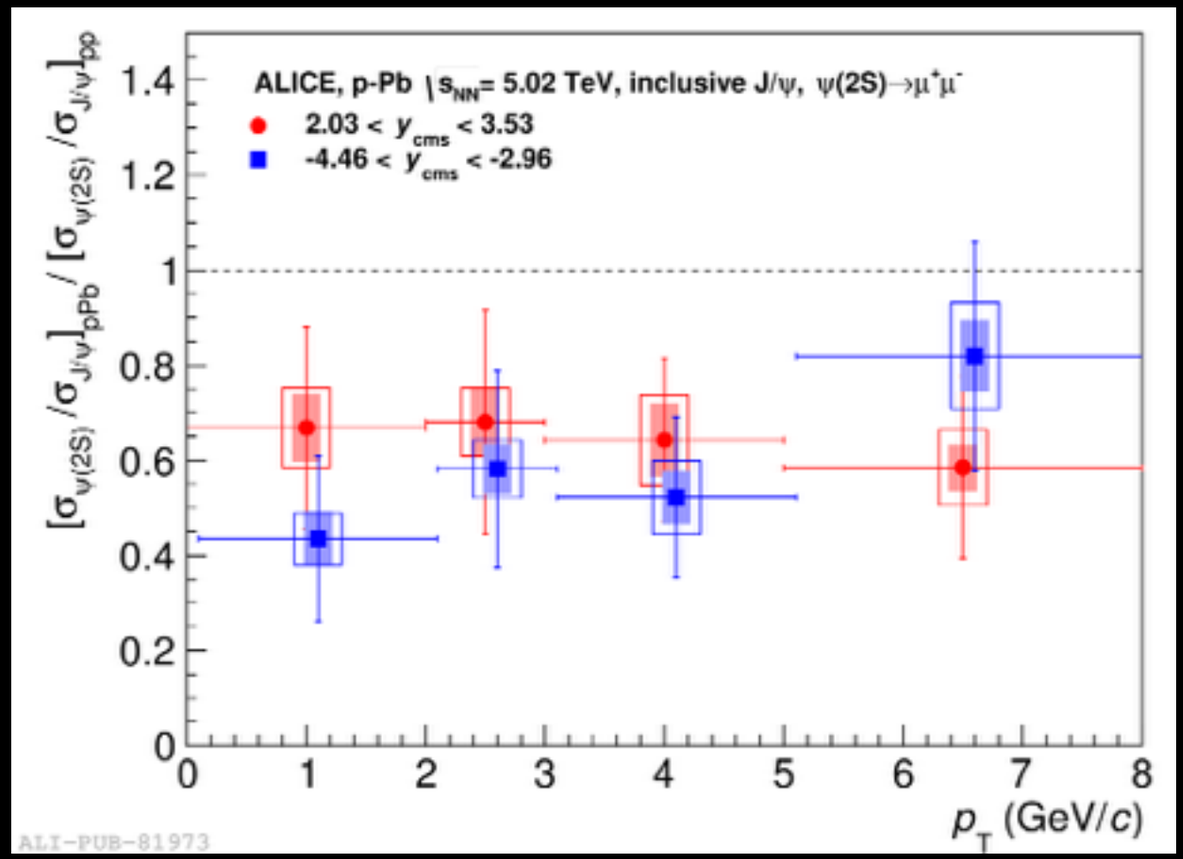
- deconfined c in **QGP** ➜ statistical hadronization ?
- continuous melting/creation in **QGP** ➜ freeze out ?

Quarkonia: c

R_{pA}







More than (anti-)shadowing for ψ(2S) ??

Time to conclude

A new chapter of QCD textbook

- What is the physics of equilibration in QCD ?
- How is minimal dissipation realized ?
- What is the QGP made of ?

« It is made of quarks and gluons ….»

- Frank Wilczek, QM2014 -