

ALICE

past

present

future

ALICE

past: confirmation, questions, discovery

present

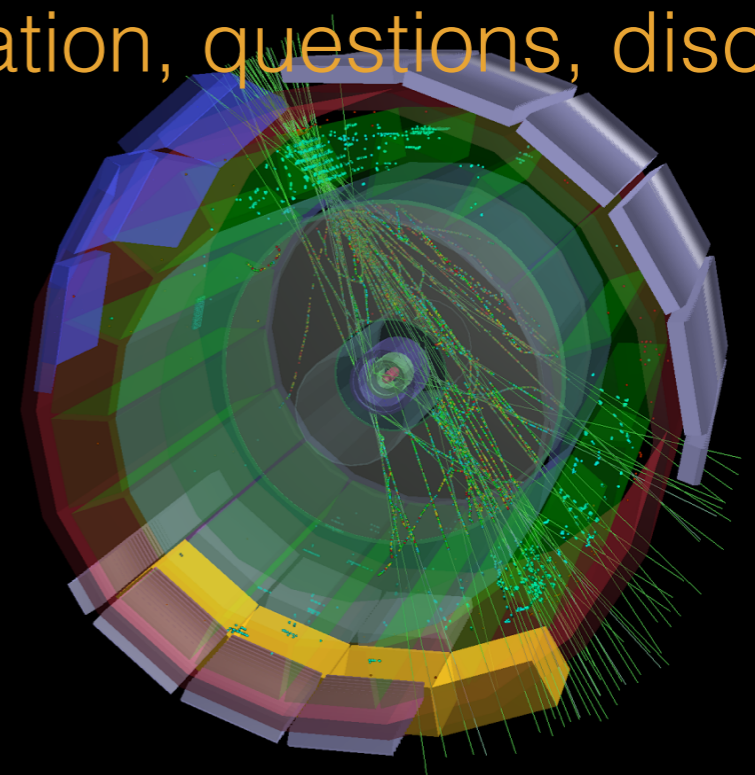
future

ALICE

past: confirmation, questions, discovery

present:

future



ALICE

past: confirmation, questions, discovery

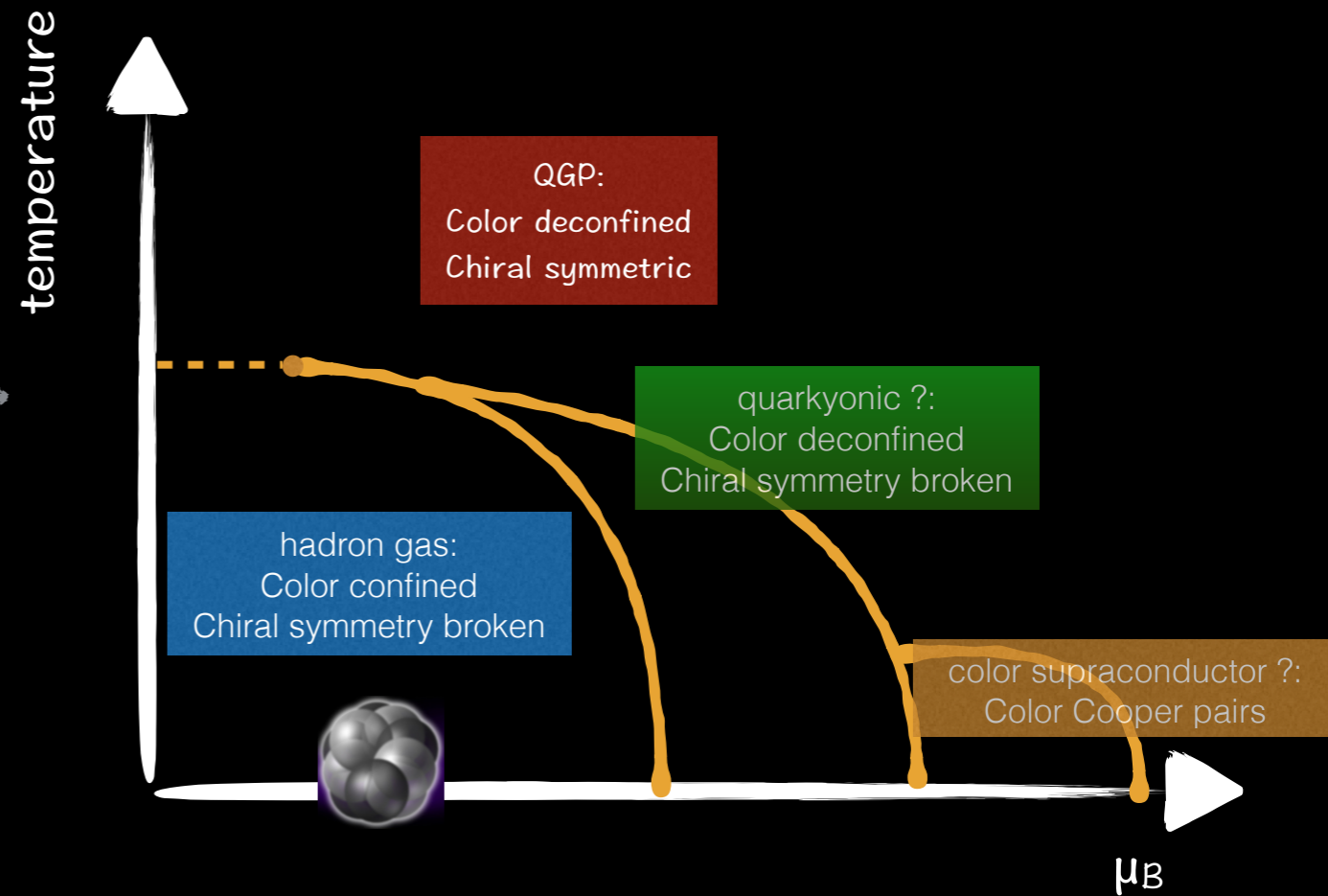
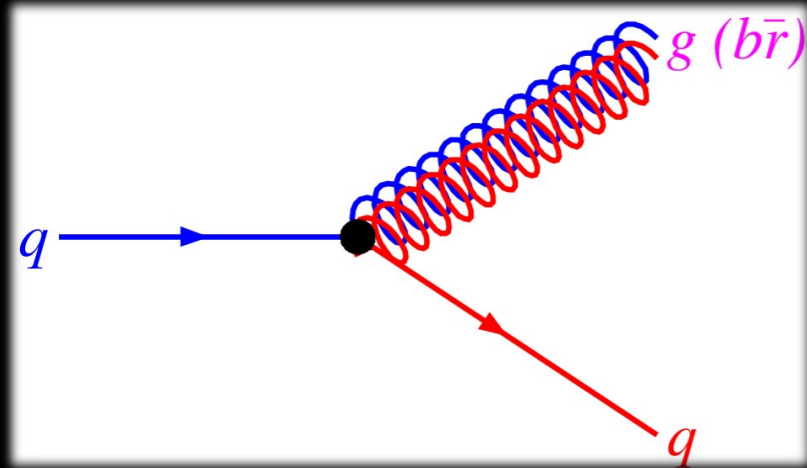
present: consolidation

future: precision

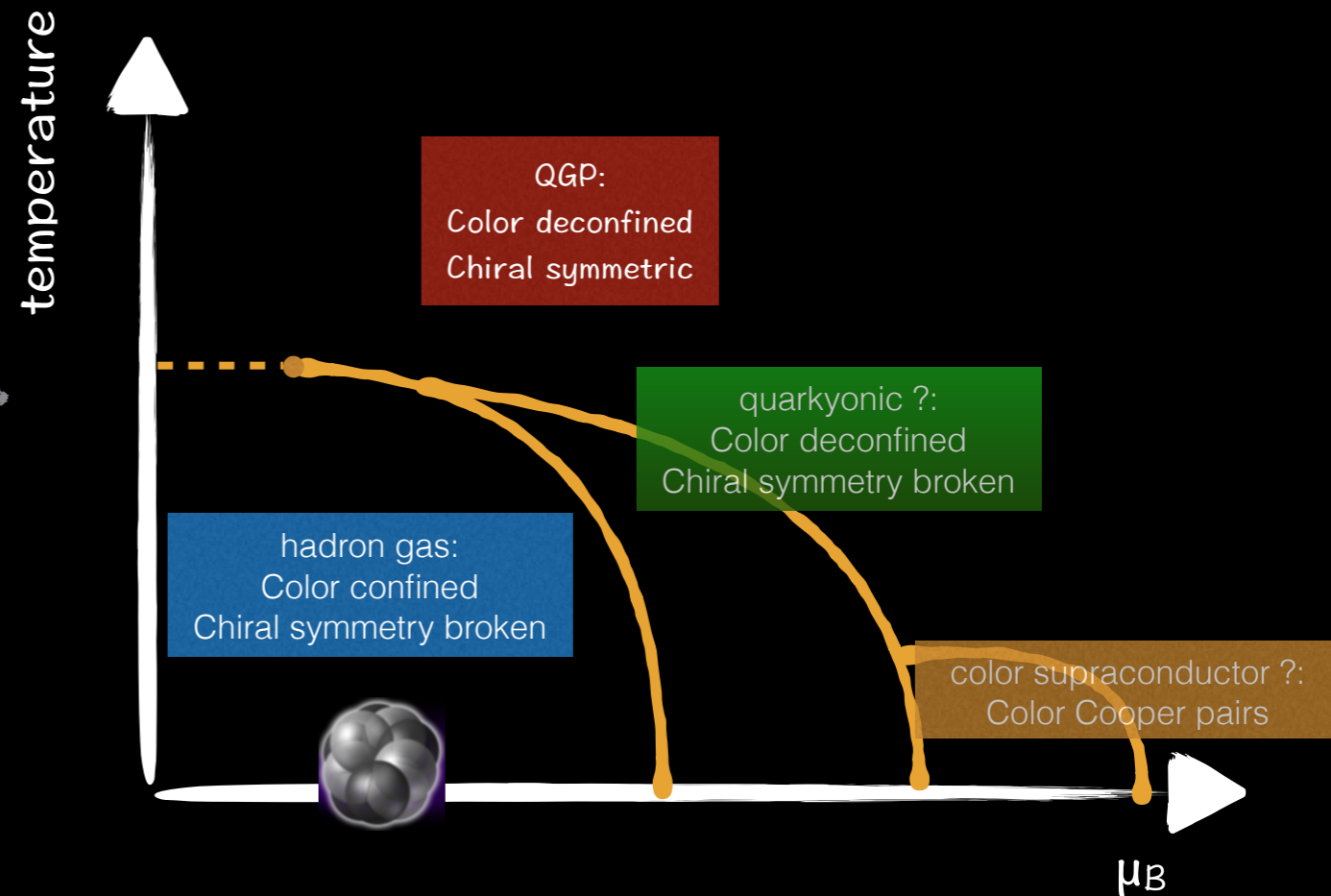
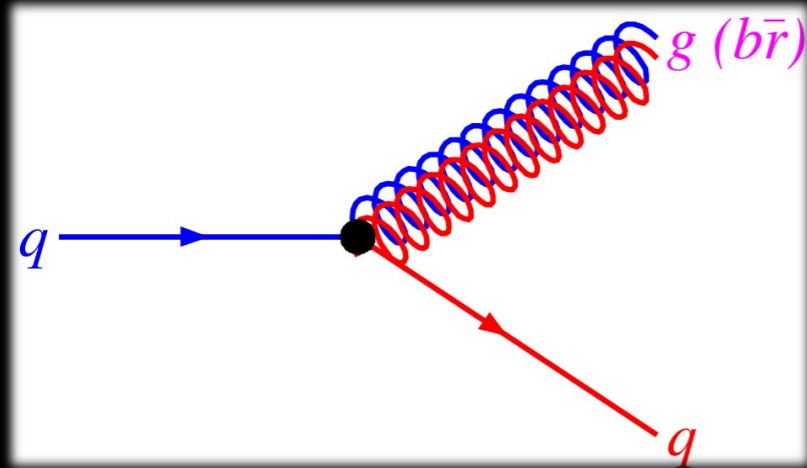
Reminder

The objectives of the LHC heavy-ion scientific program

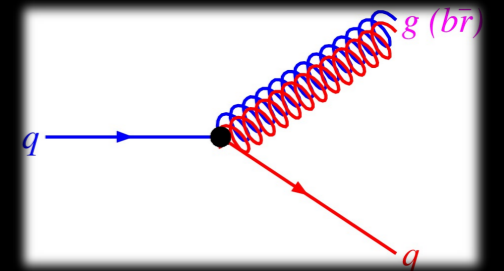
Thermodynamics of strongly interaction matter



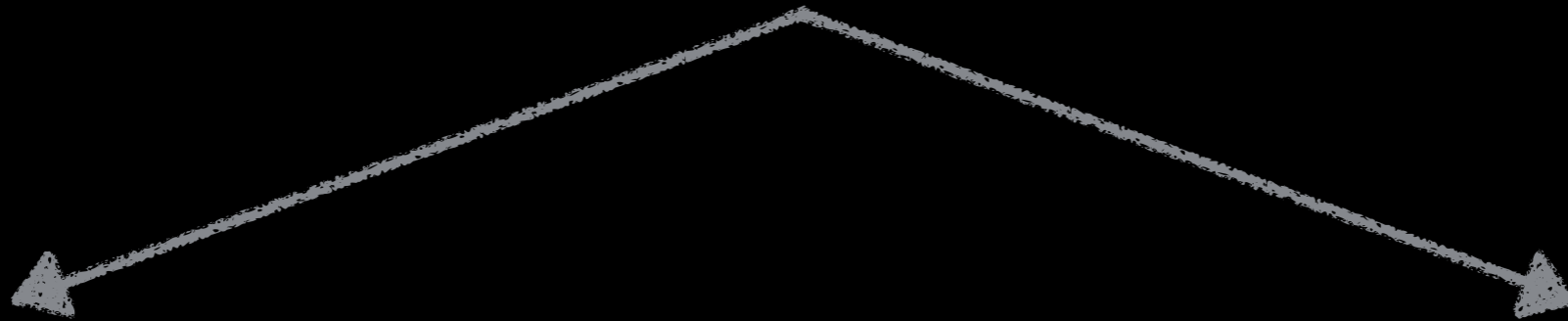
Thermodynamics of strongly interaction matter



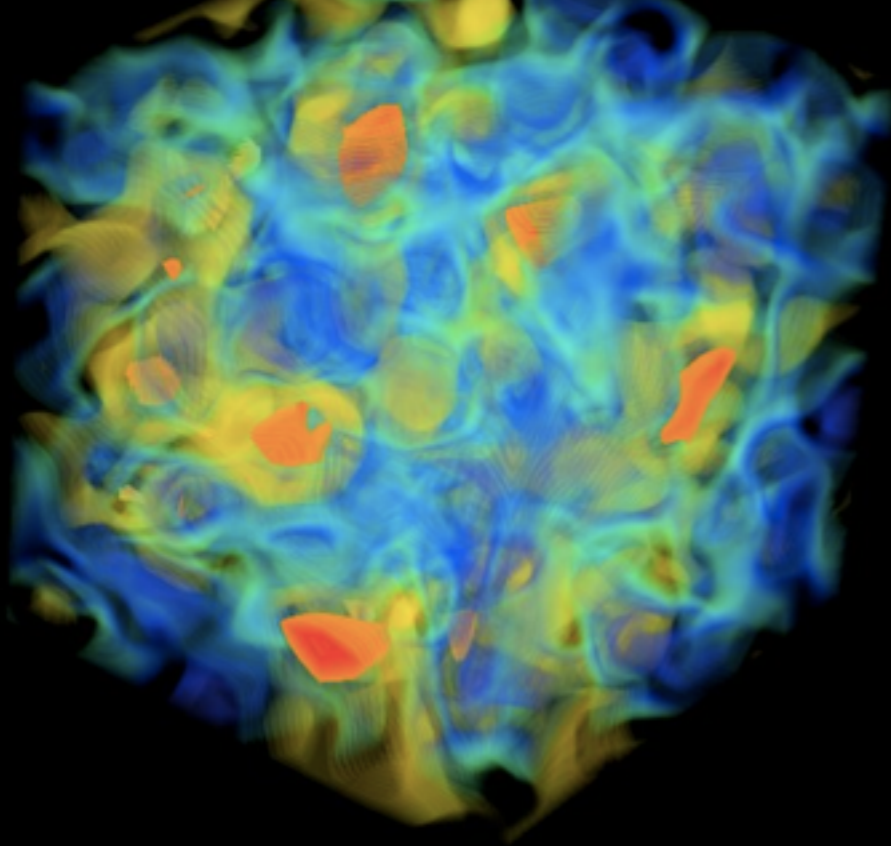
How does the complexity of matter emerge from the dynamics of the strong interaction



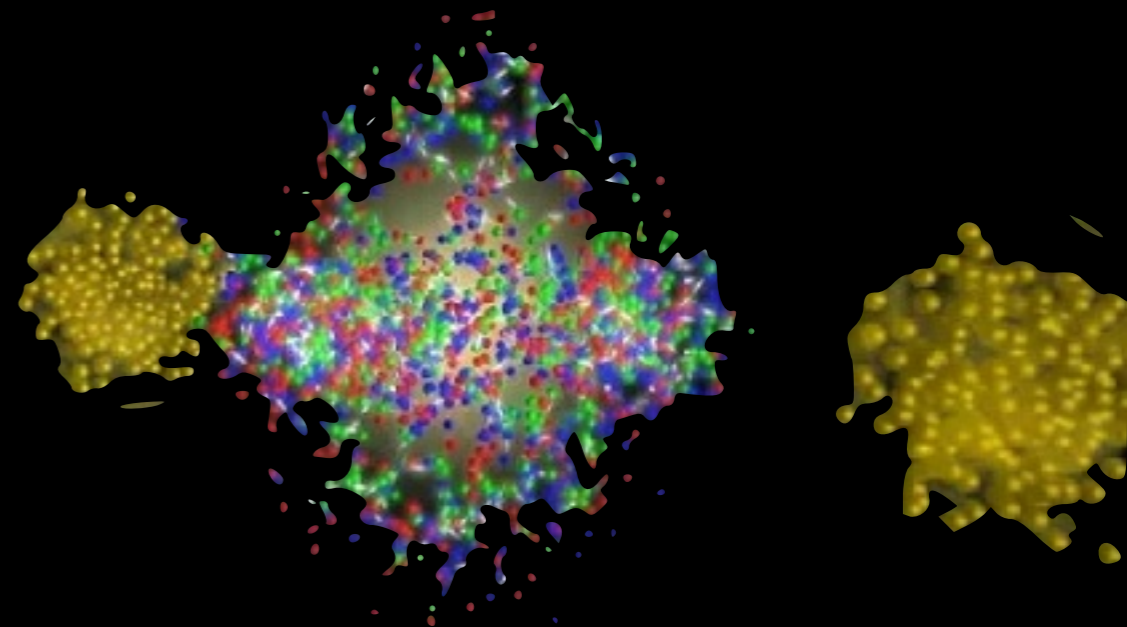
Thermodynamics of strongly interaction matter



statistical QCD



heavy-ion collisions



The ALICE core mandate

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

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



Established facts: exp

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

* non-dissipative

** strongly interacting

Established facts: exp

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

The Quark-Gluon Plasma, a nearly perfect fluid

■ L. Cifarelli¹, L.P. Csernai² and H. Stöcker³ - DOI: 10.1051/epn/2012206

■ ¹ Dipartimento di Fisica, Università 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.

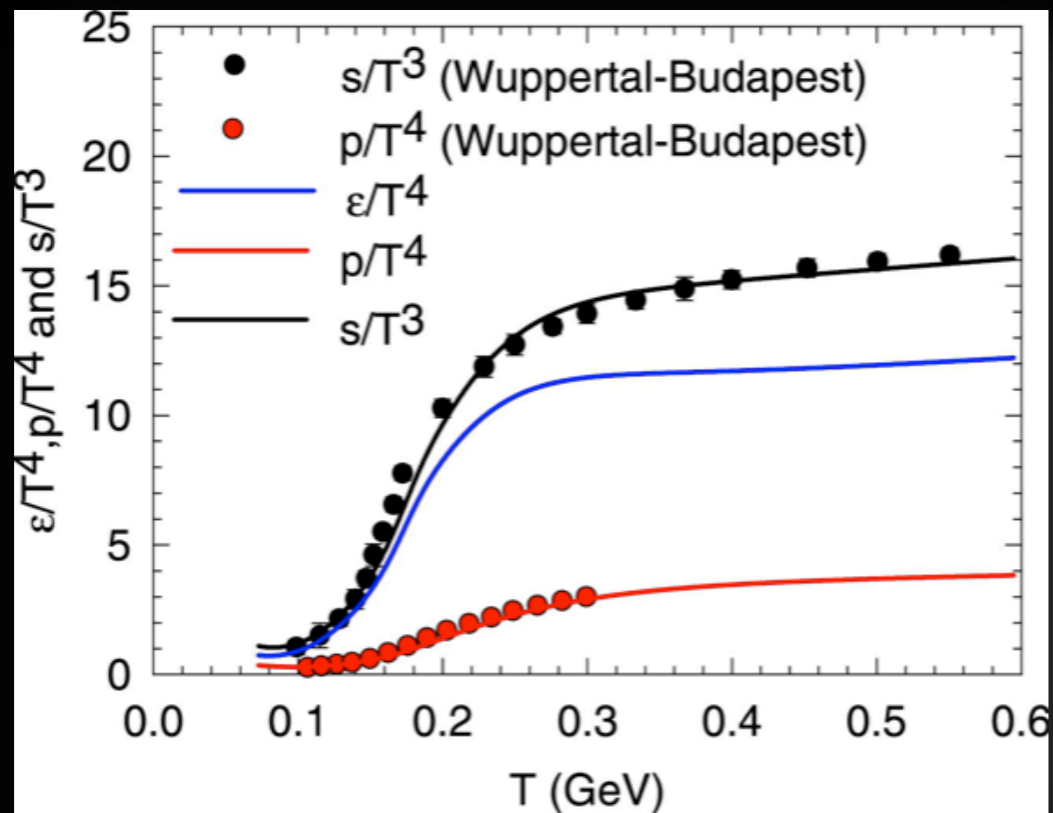
* non-dissipative

** strongly interacting

Established facts: theory

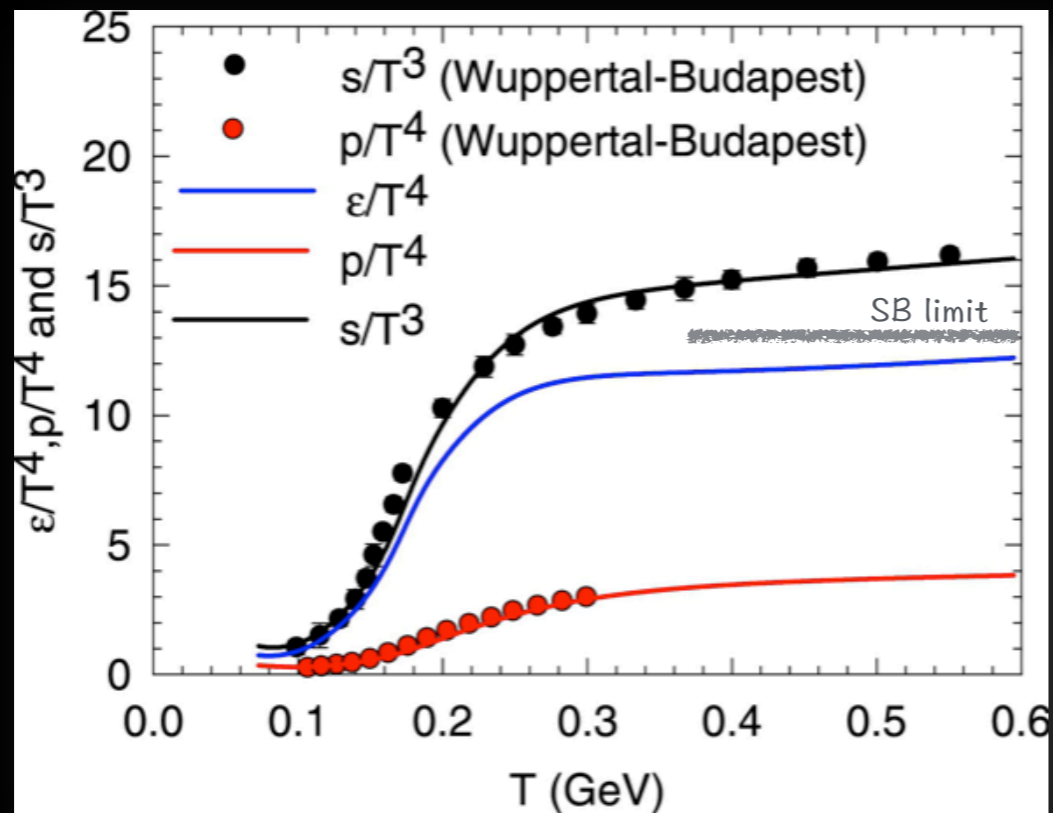
Established facts: theory

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



Established facts: theory

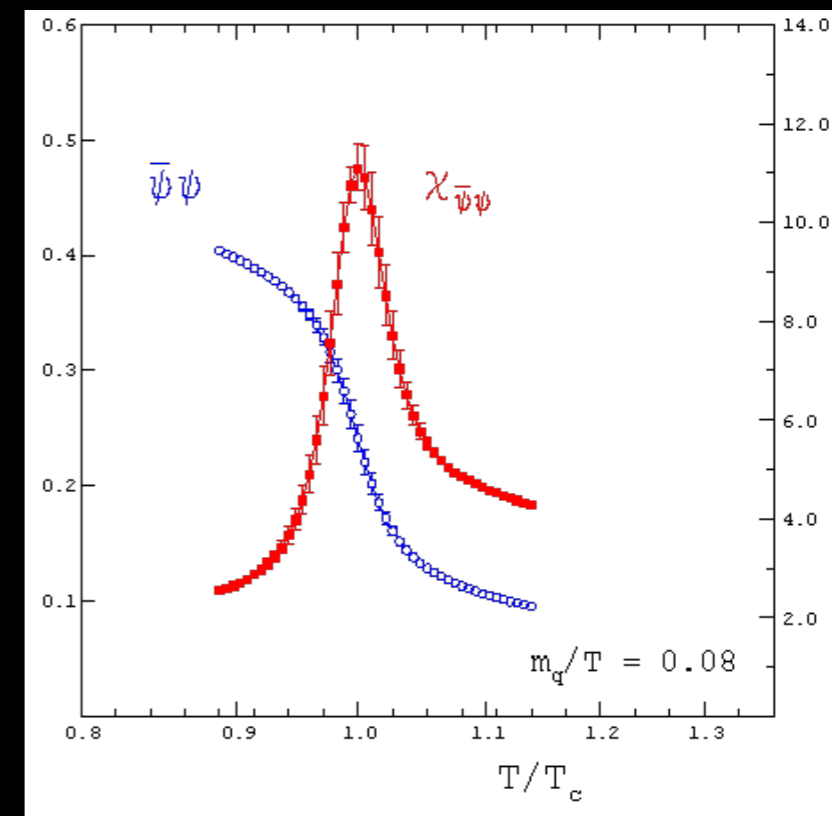
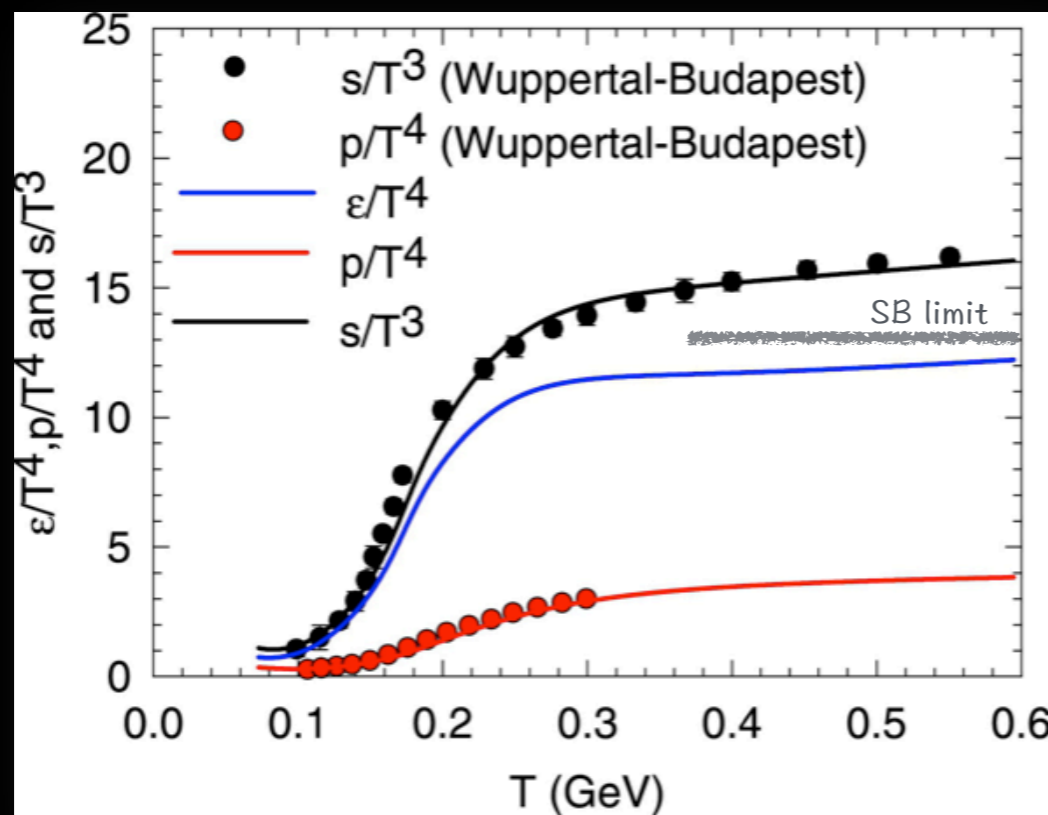
- **smooth*** transition from hadron gas to QGP, Z_3 symmetry restored



* not a phase transition, not SB

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

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Standard strategy

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- Small and dilute: comparison measurement
 - ▶ $pp \rightarrow p\text{QCD} + \text{pdf} + \text{FF}$

Standard strategy

- Large and dense: heavy-ion physics
- Small and dilute: comparison measurement
 - ▶ $pp \rightarrow p\text{QCD} + \text{pdf} + \text{FF}$
 - ▶ $pA \rightarrow p\text{QCD} + N\text{pdf} + \text{FF}$

Standard strategy

- Large and dense: heavy-ion physics
 - ▶ $AA \rightarrow p\text{QCD} + N\text{pdf} + FF + \text{collectivity}$
- Small and dilute: comparison measurement
 - ▶ $pp \rightarrow p\text{QCD} + \text{pdf} + FF$
 - ▶ $pA \rightarrow p\text{QCD} + N\text{pdf} + FF$

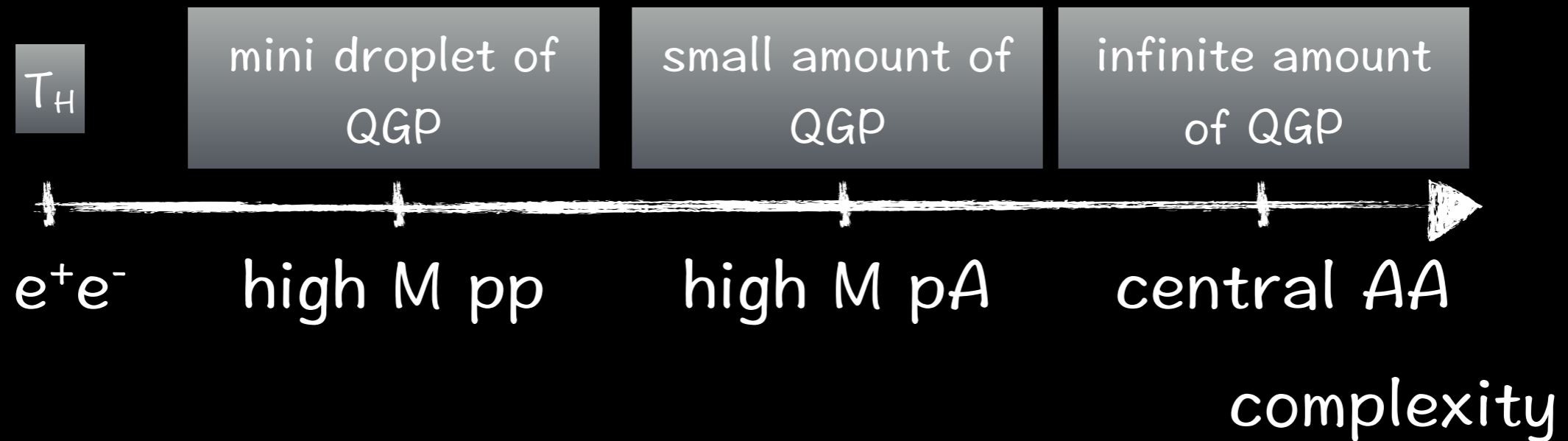
But ... High M pp/pA

But ... High M pp/pA

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

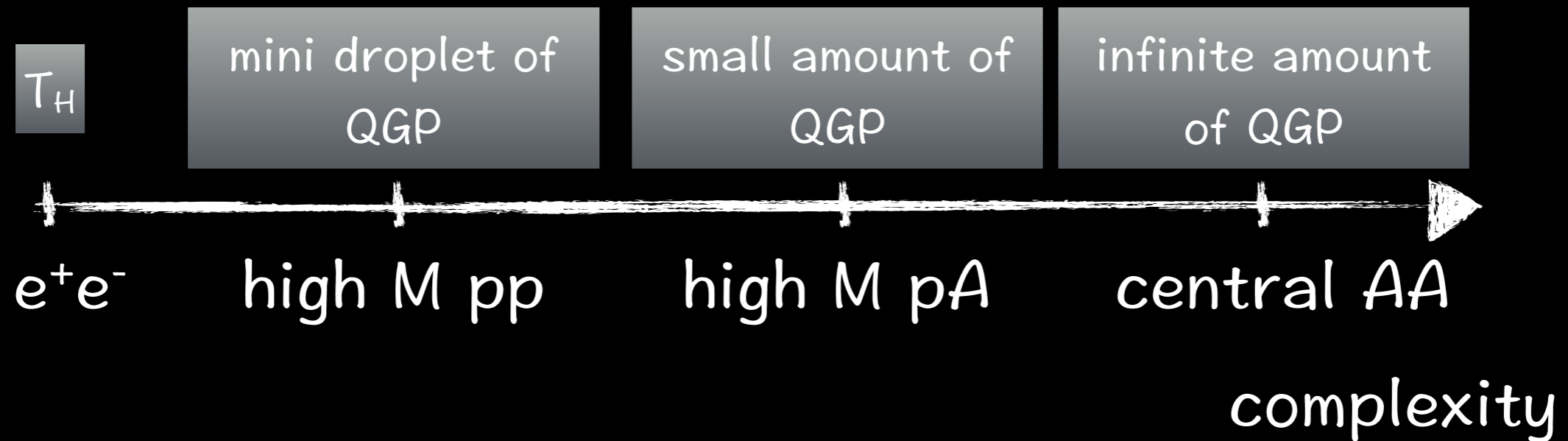
Toward a new paradigm ?

- Collectivity everywhere !



Toward a new paradigm ?

- Collectivity everywhere !



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

More than one mystery

A few ALICE results from RUN1 data ...

More than one mystery

A few ALICE results from RUN1 data ...

A few questions first !

Where do we start from ?

- IS at LHC: classical gluon fields ? strongly or weakly coupled ?
- dynamics: from IS to an hydro liquid in 0.5 fm/c
 - ▶ The physics of equilibration in QCD at LHC ?
 - ✓ very low x
 - ✓ non dissipative medium

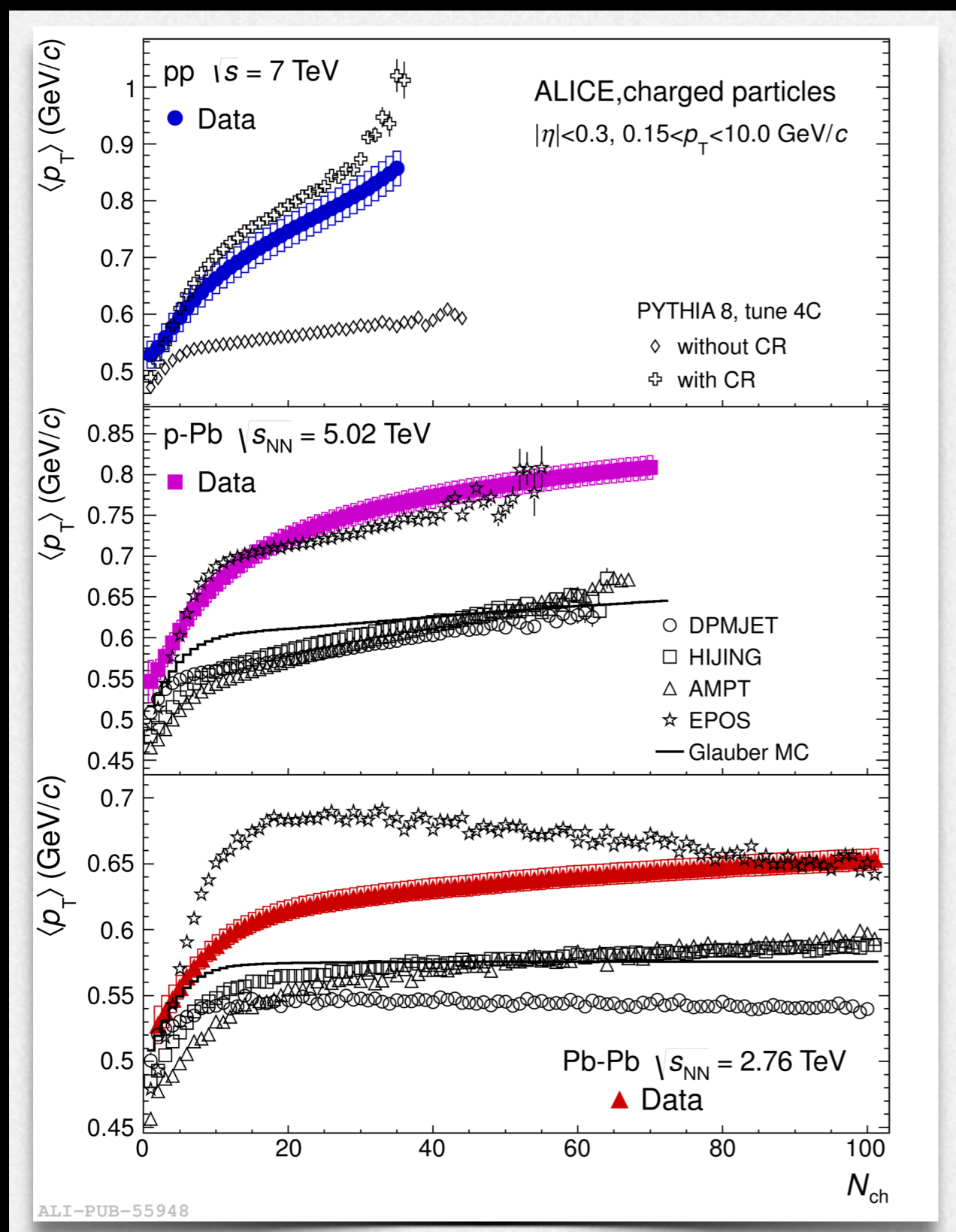
What is ...

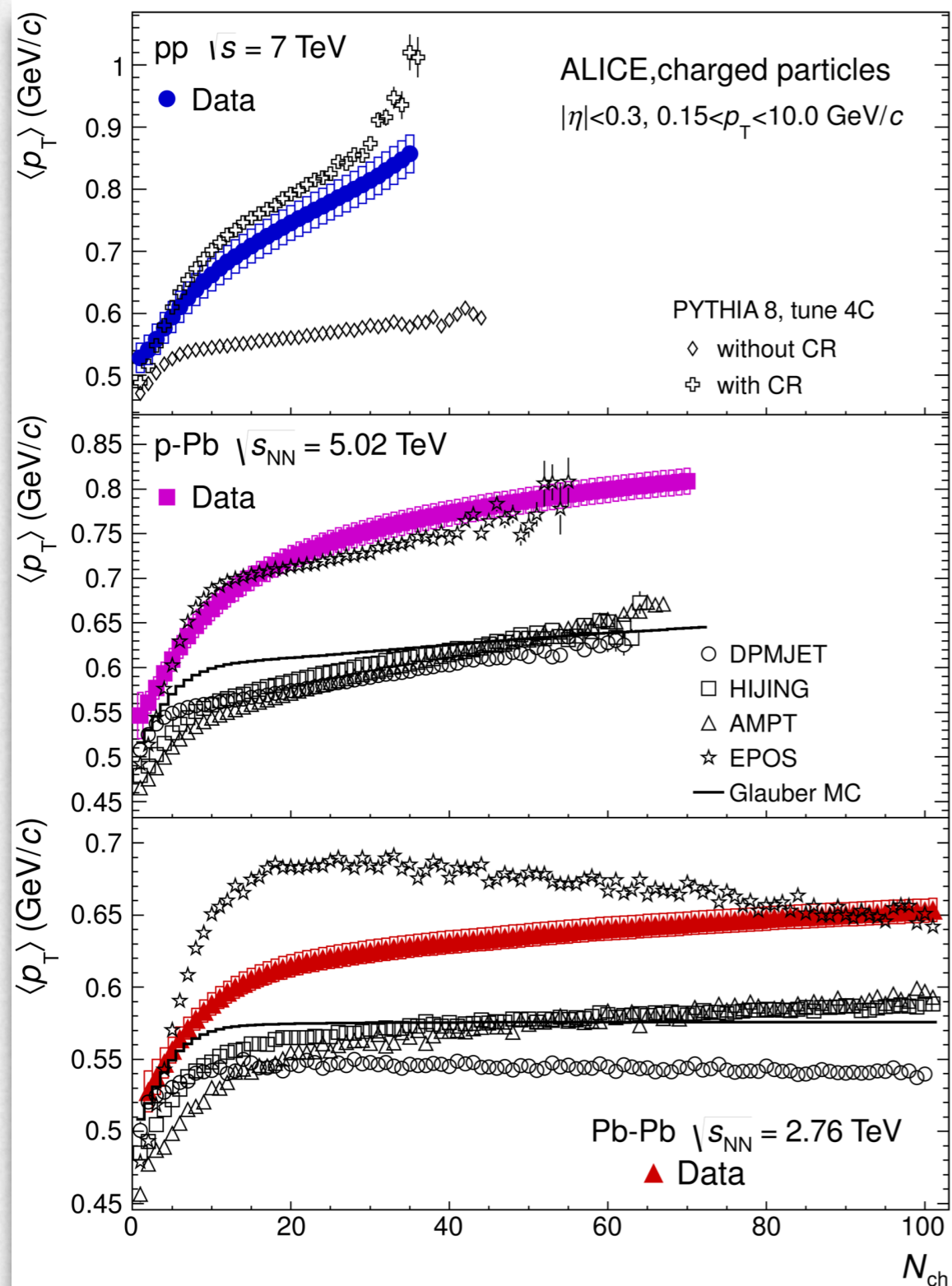
- ... the state of matter between the instant of an AA (pp, pA) collision and the final production of outgoing particles (FS)
 - ▶ a non viscous liquid
 - ▶ a quasi-particle free medium ? just above T_H ?
 - ▶ hadronization ?

soft: $p_T \sim T, \Lambda_{\text{QCD}}$
probe the bulk

Particle production: pp to AA

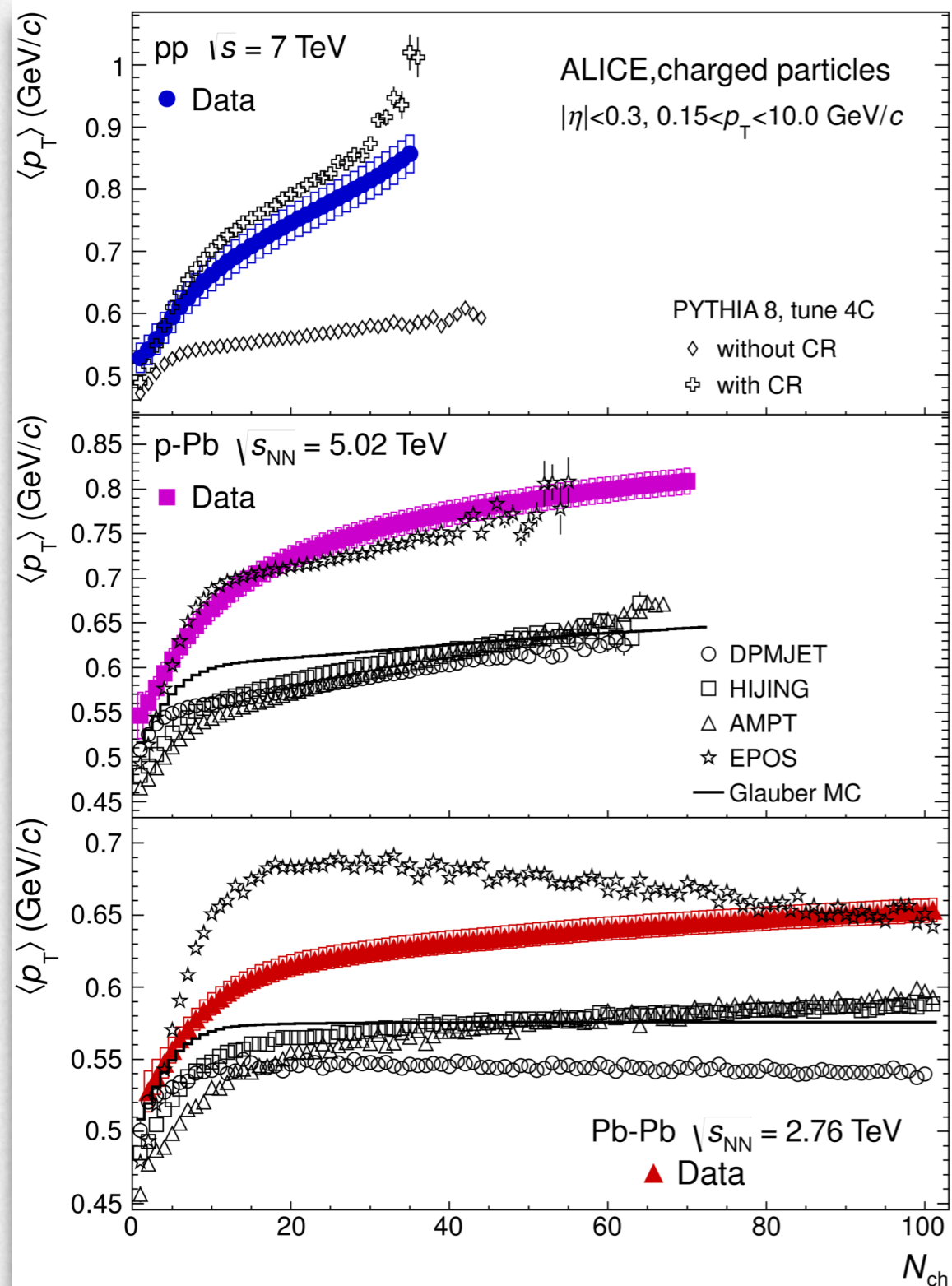
$\langle p_t \rangle$ vs M



$\langle p_t \rangle$ vs M 

ALI-PUB-55948

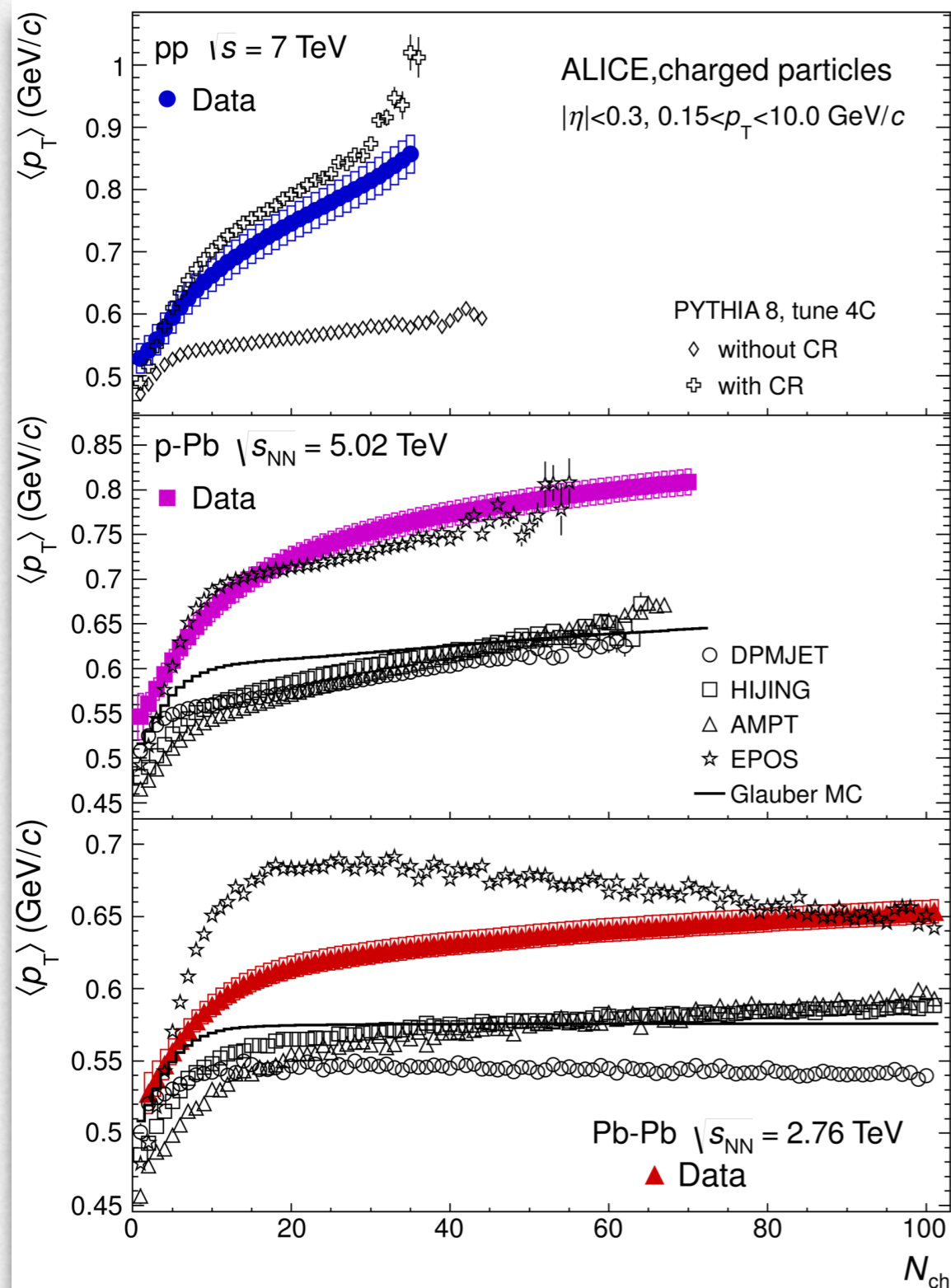
pp: not an incoherent superposition of multi parton interactions (CR)

$\langle p_t \rangle$ vs M 

ALI-PUB-55948

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

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

$\langle p_t \rangle$ vs M 

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

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

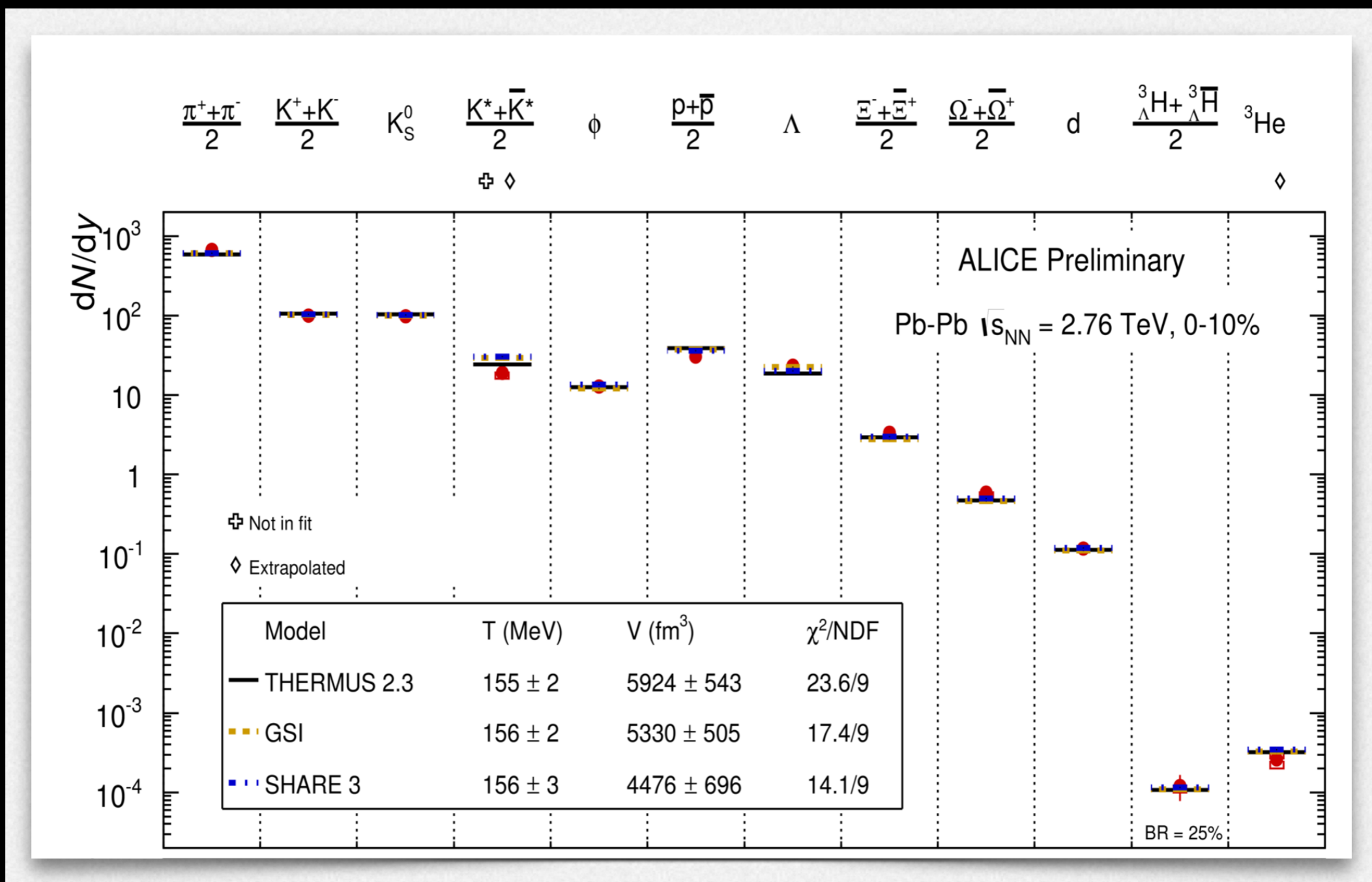
Collectivity everywhere ?
Models !

QGP-hadronisation, ... nucleosynthesis



Sarah Szabo

hadrons production



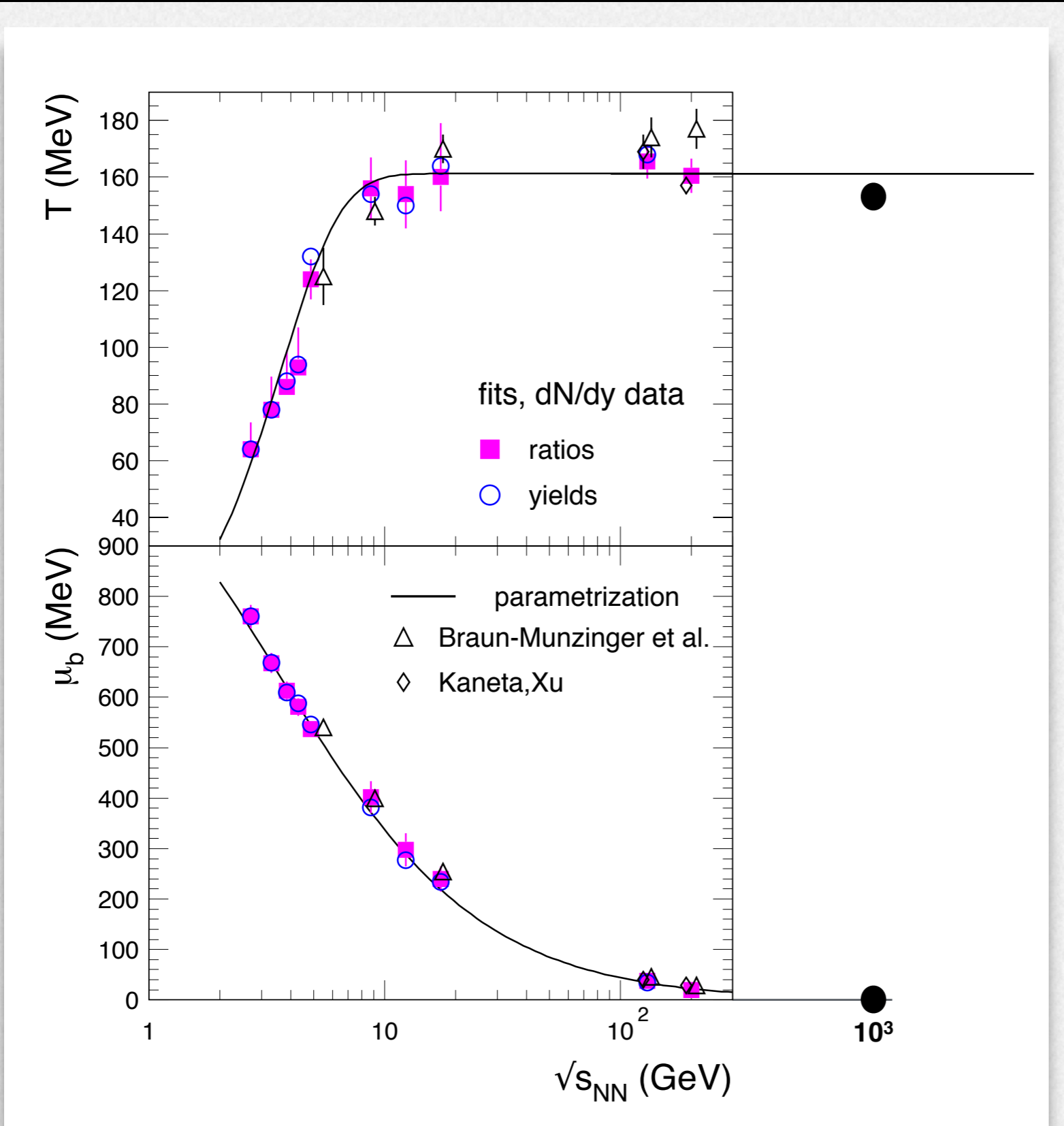
7 order of magnitude !

p, d, nuclei !!

$T_H = 155$ MeV !!!

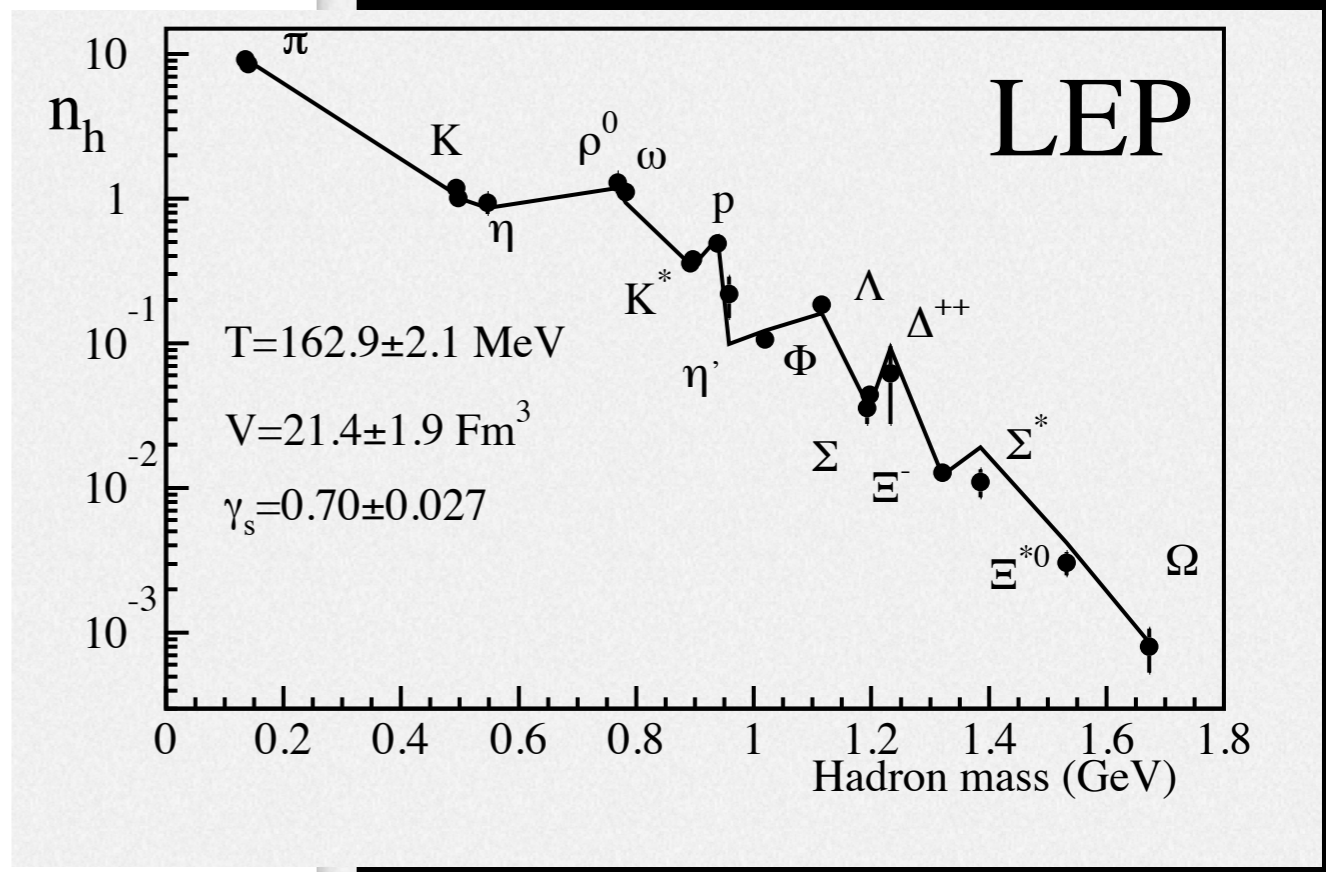
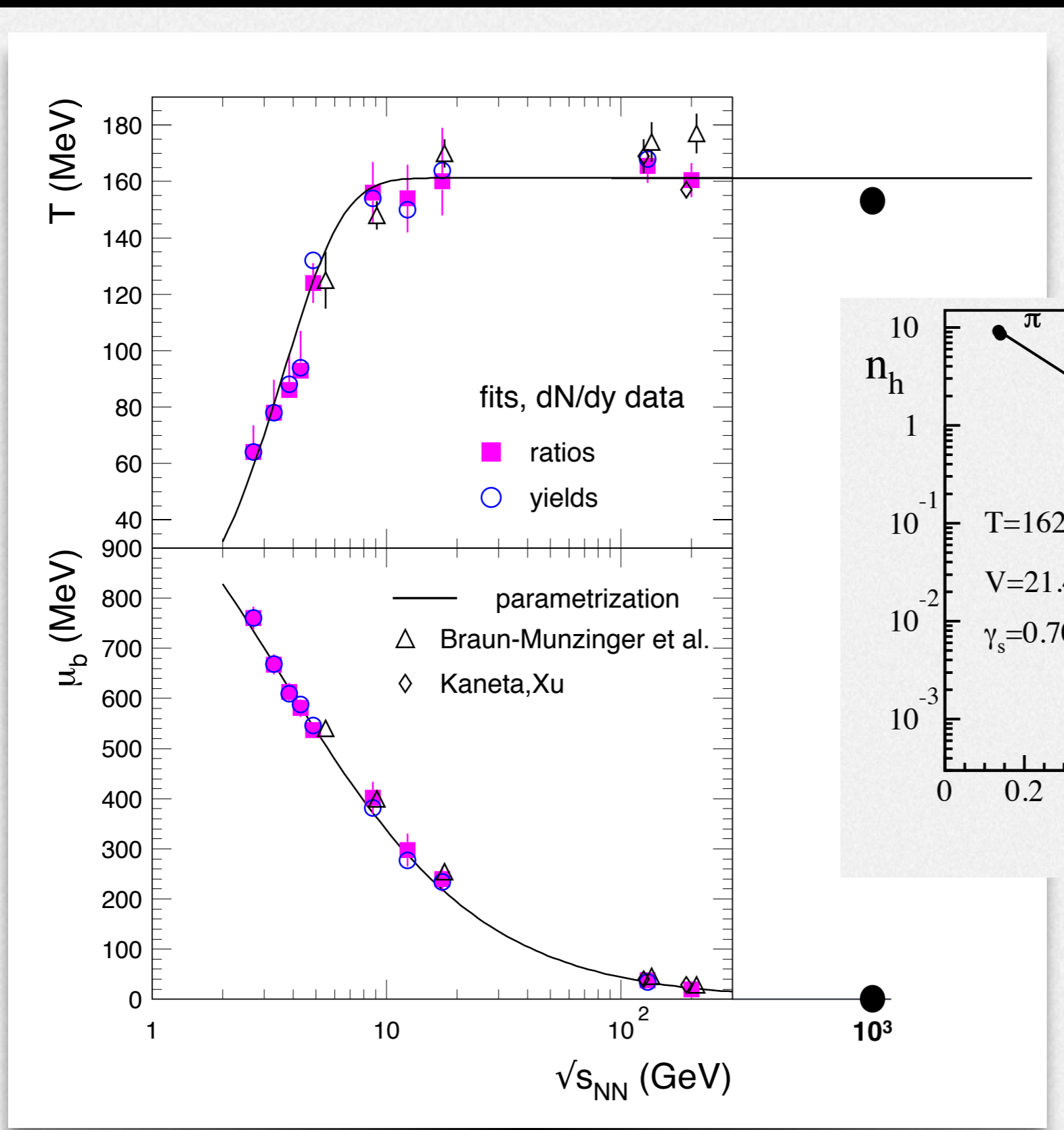
hadrons production

$T_H = 155 \text{ MeV} !!!$
invisible hadrons ?



hadrons production

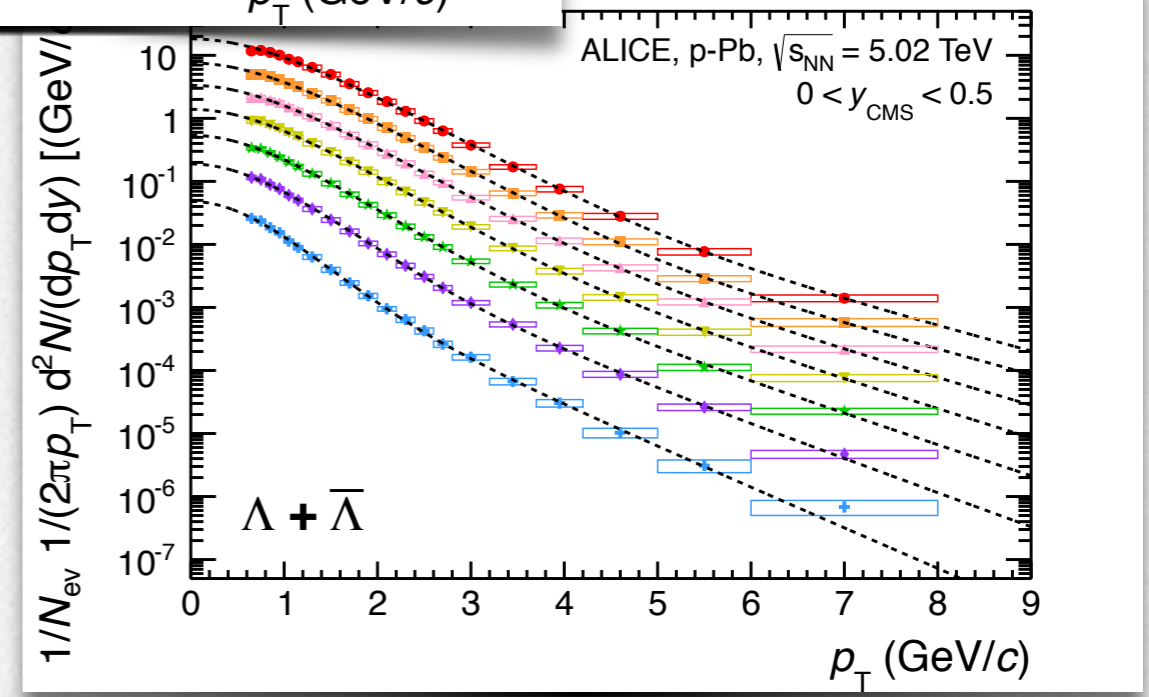
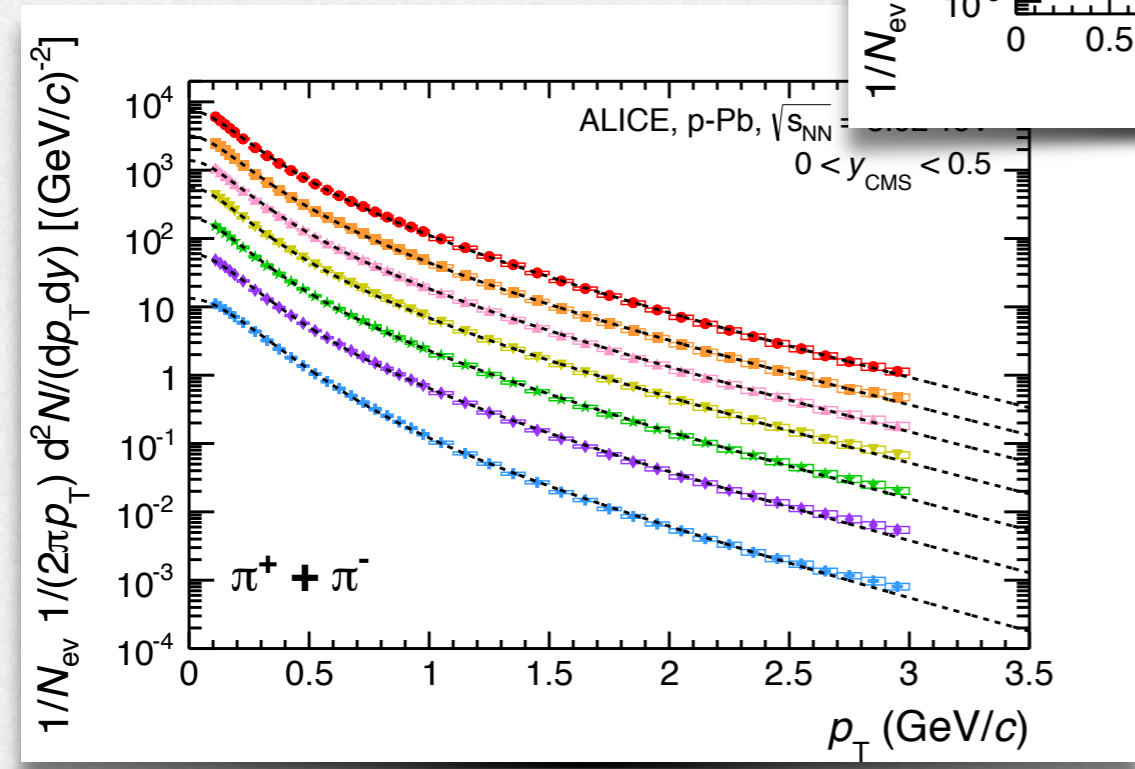
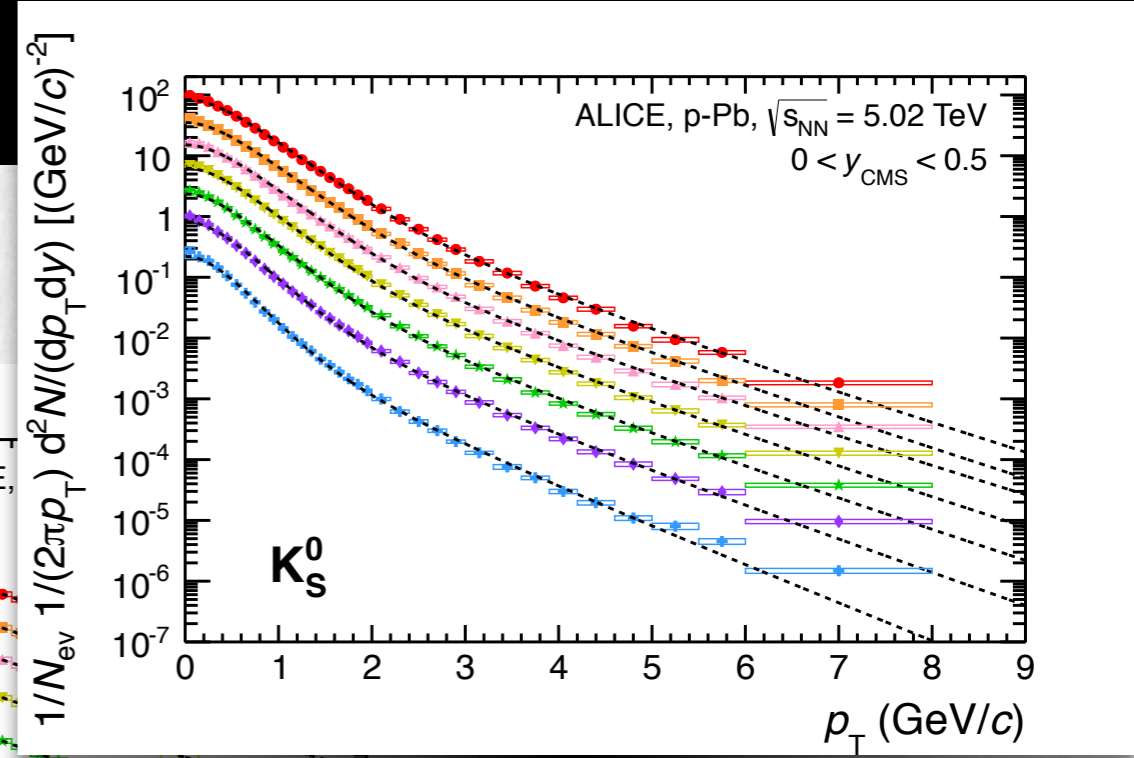
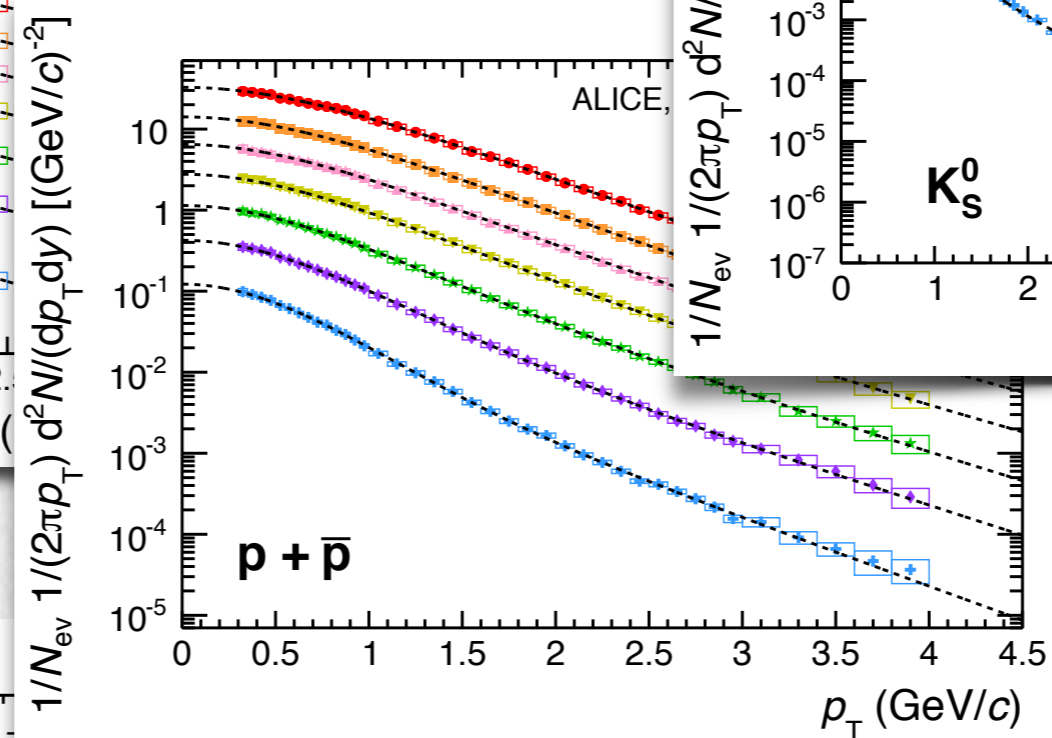
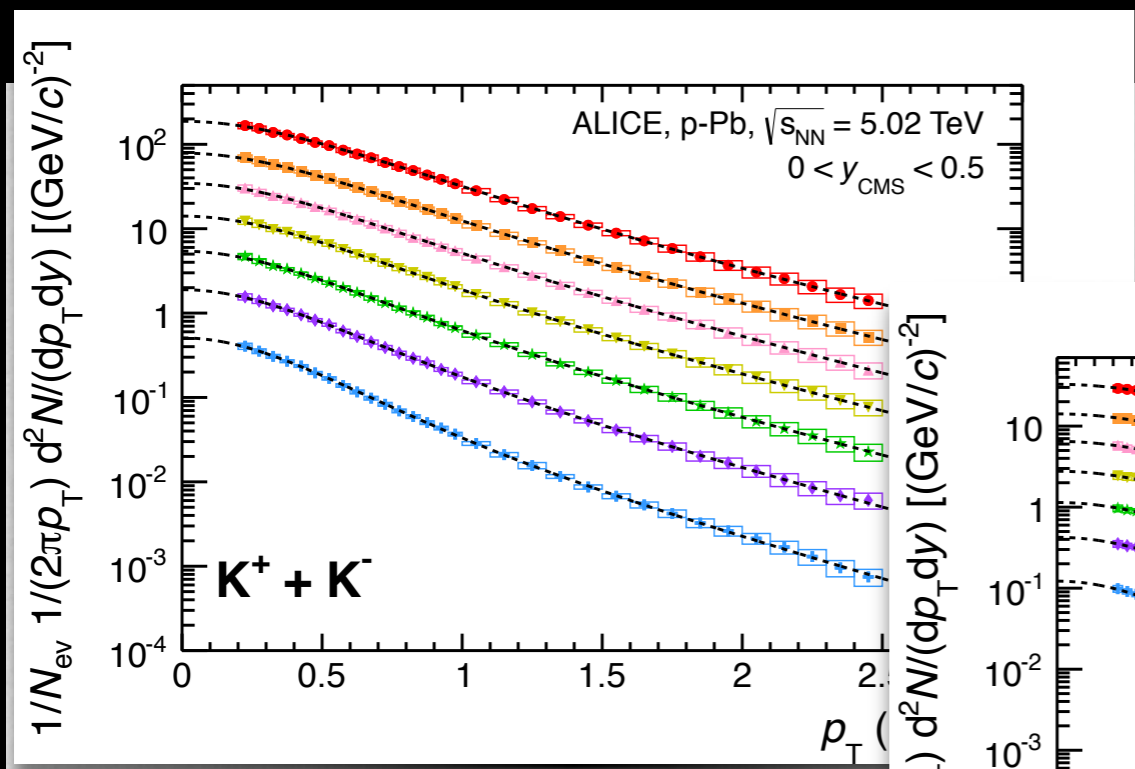
$T_H = 155 \text{ MeV} !!! !!!!!$
invisible hadrons ?



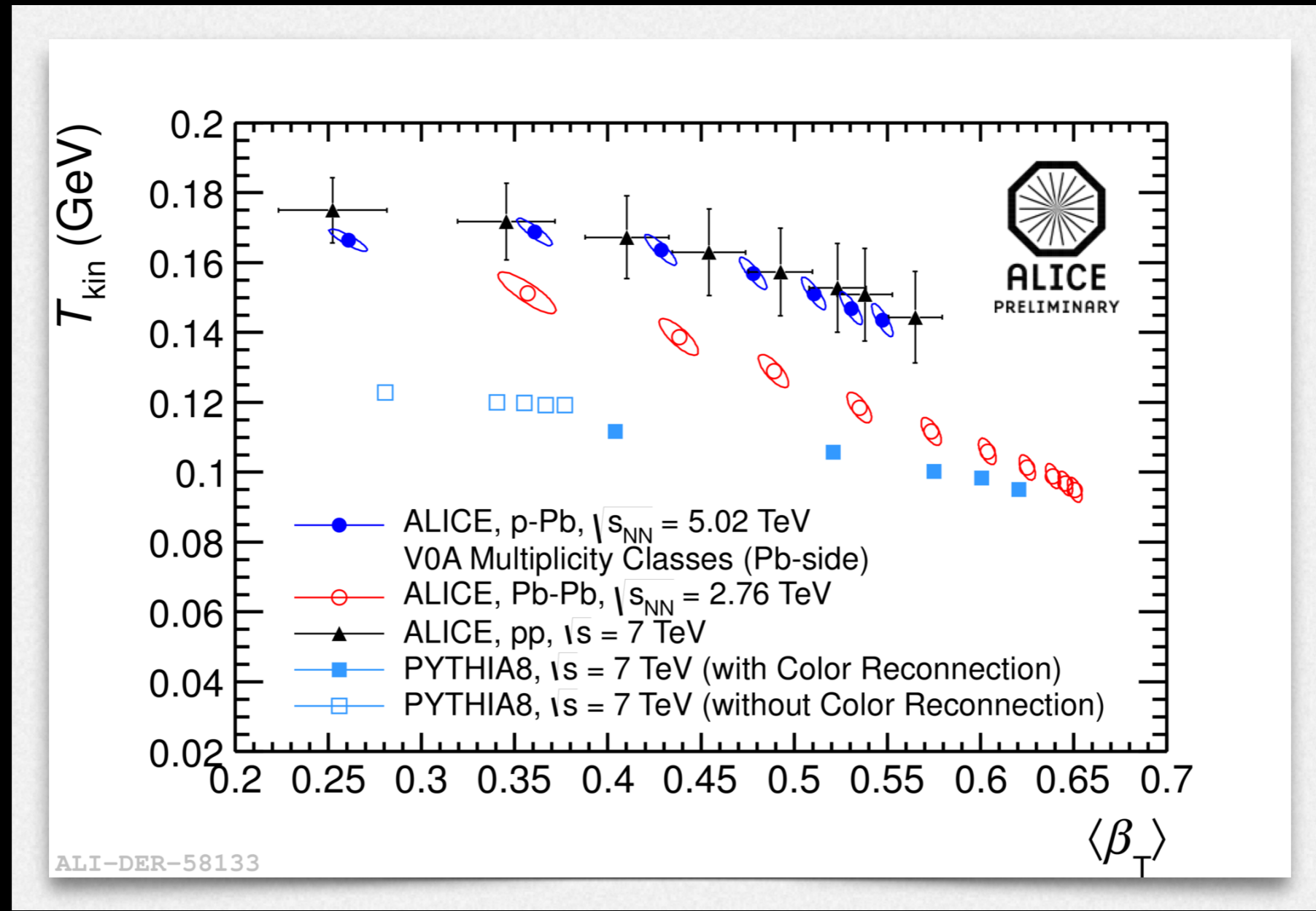
Collective flow (radial): AA to pp

Test the dynamics

Blue shift



Radial flow



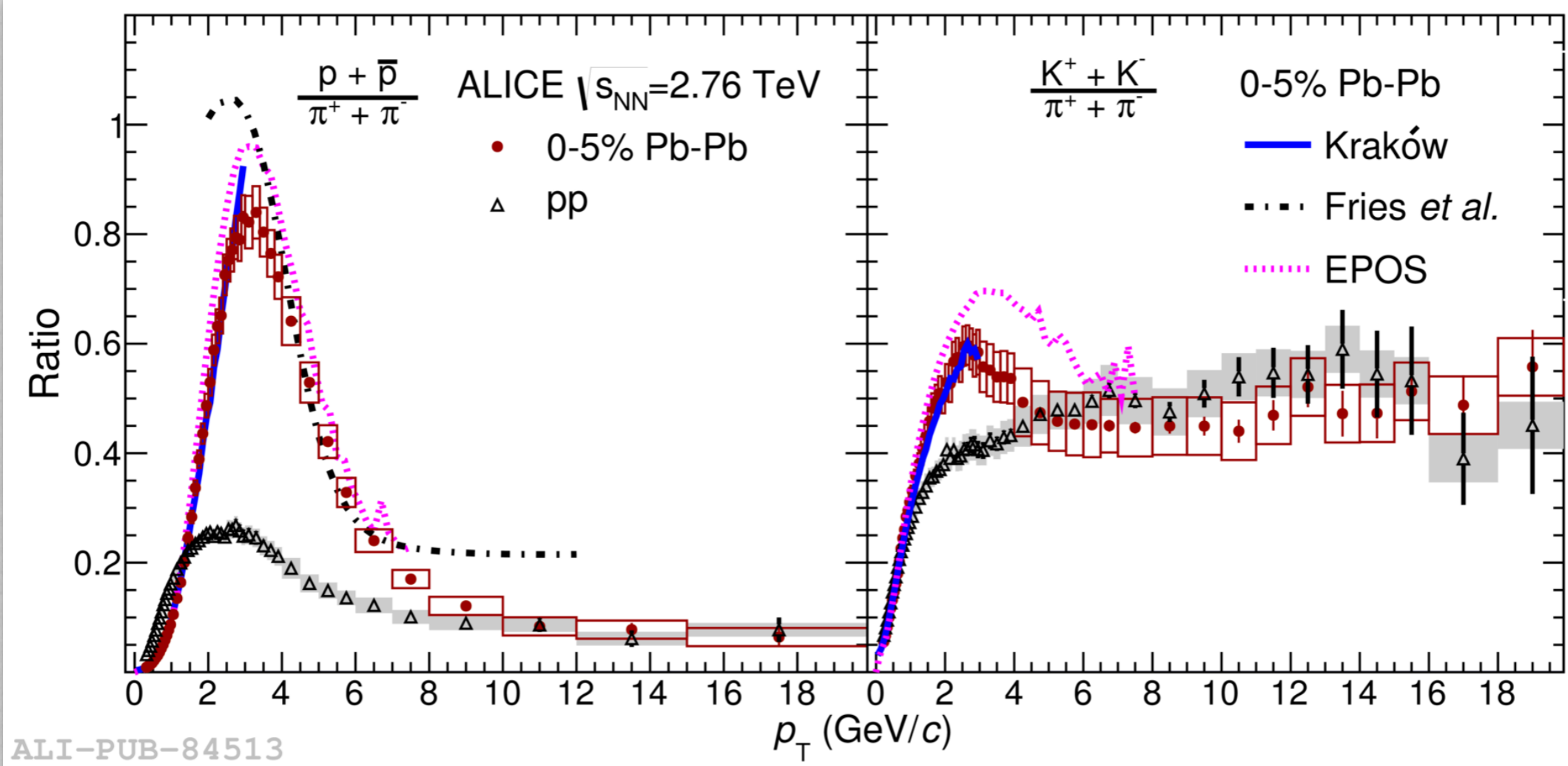
p-Pb and pp: (stronger) radial gradient !

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

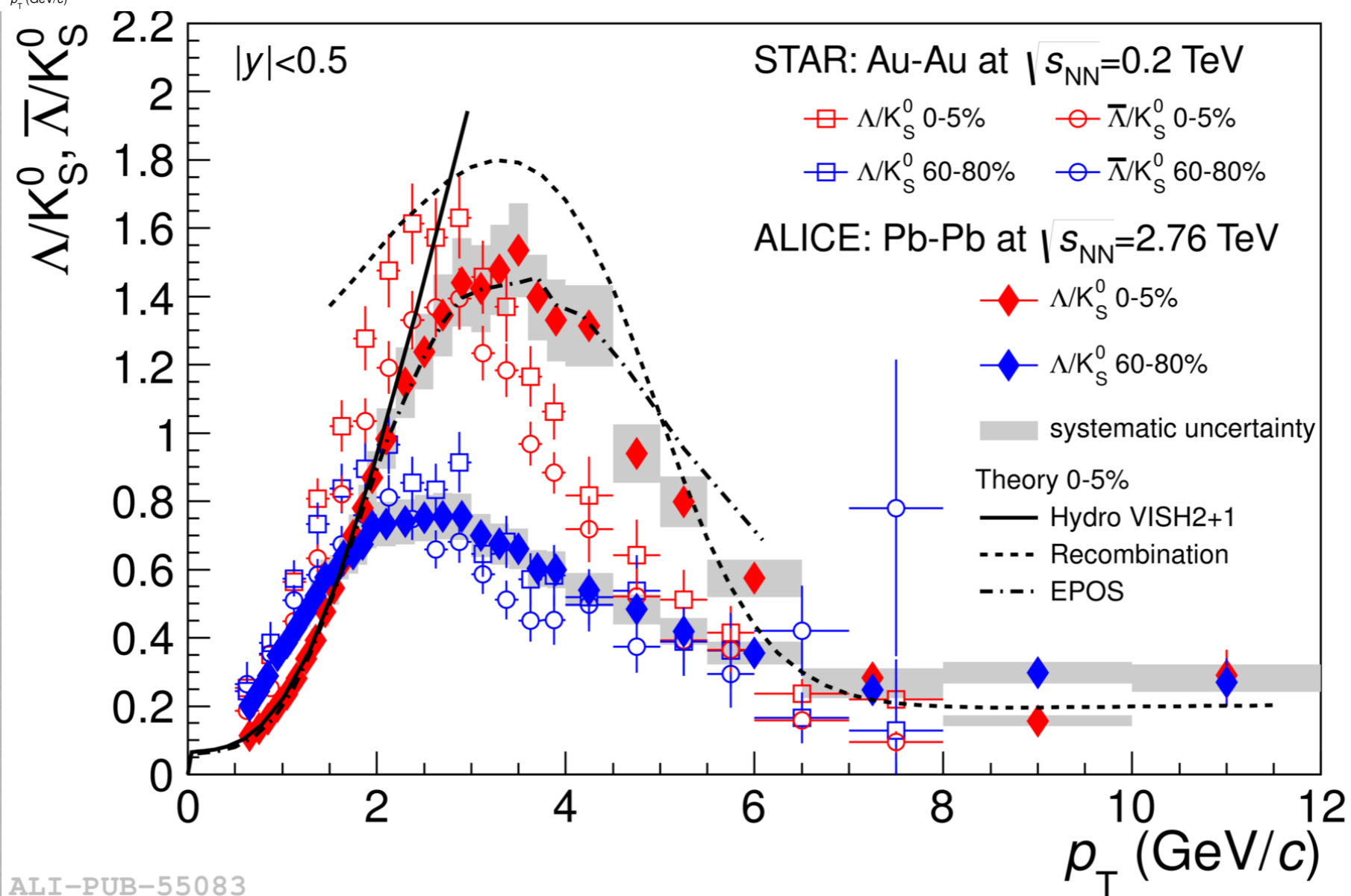
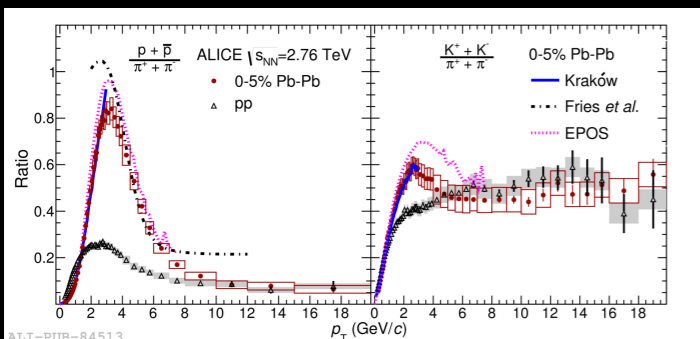
Collective flow (radial) and QGP- hadronisation

Test the DoF

Baryon & Meson light



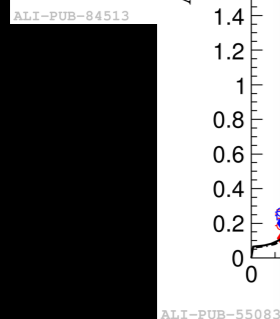
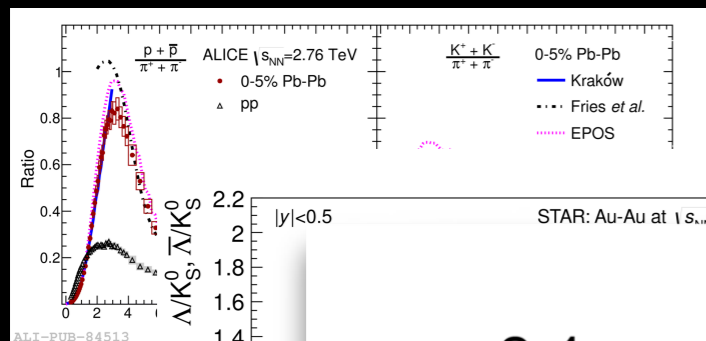
Baryon & Meson strange



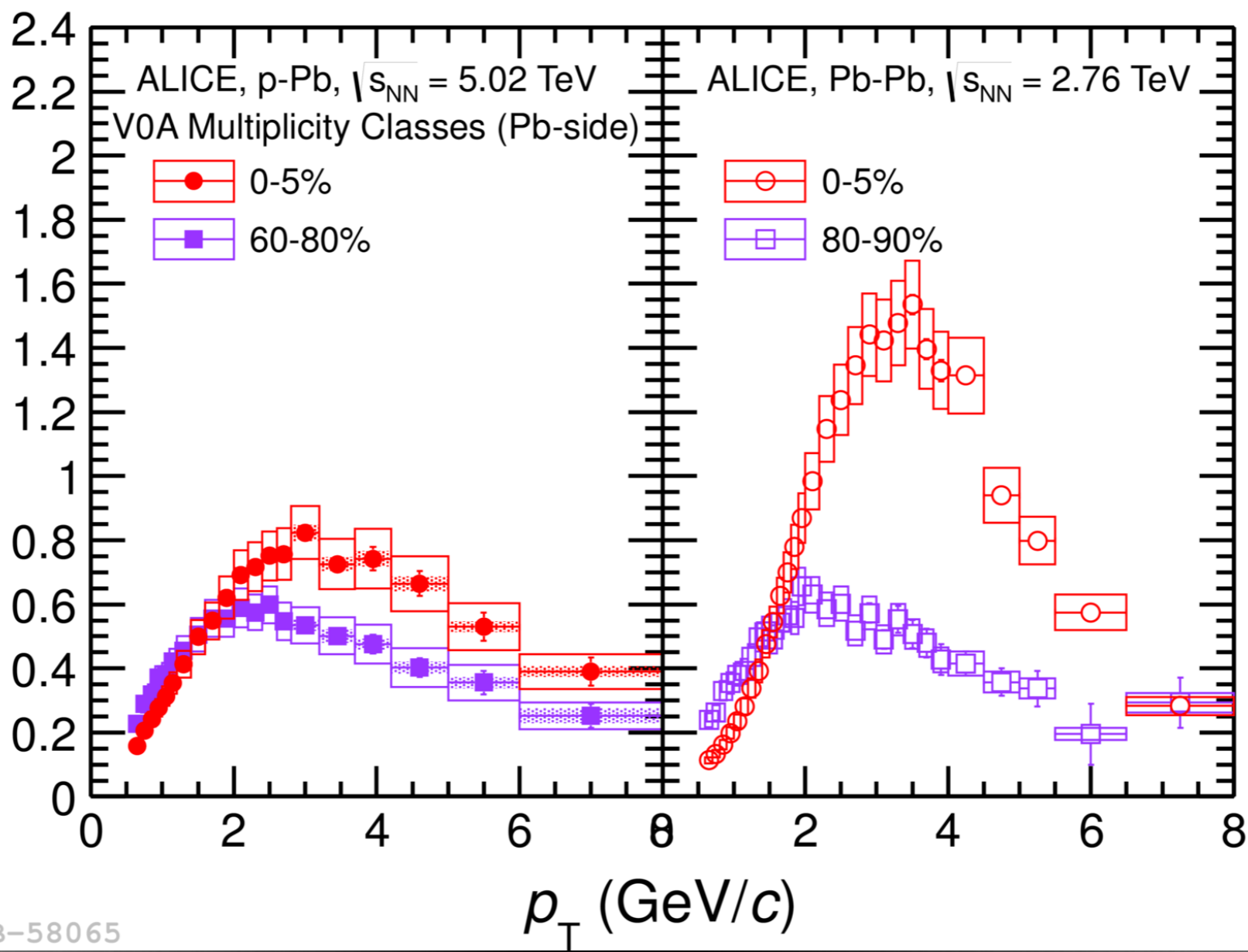
ALI-PUB-55083

Baryon & Meson

pPb as well !

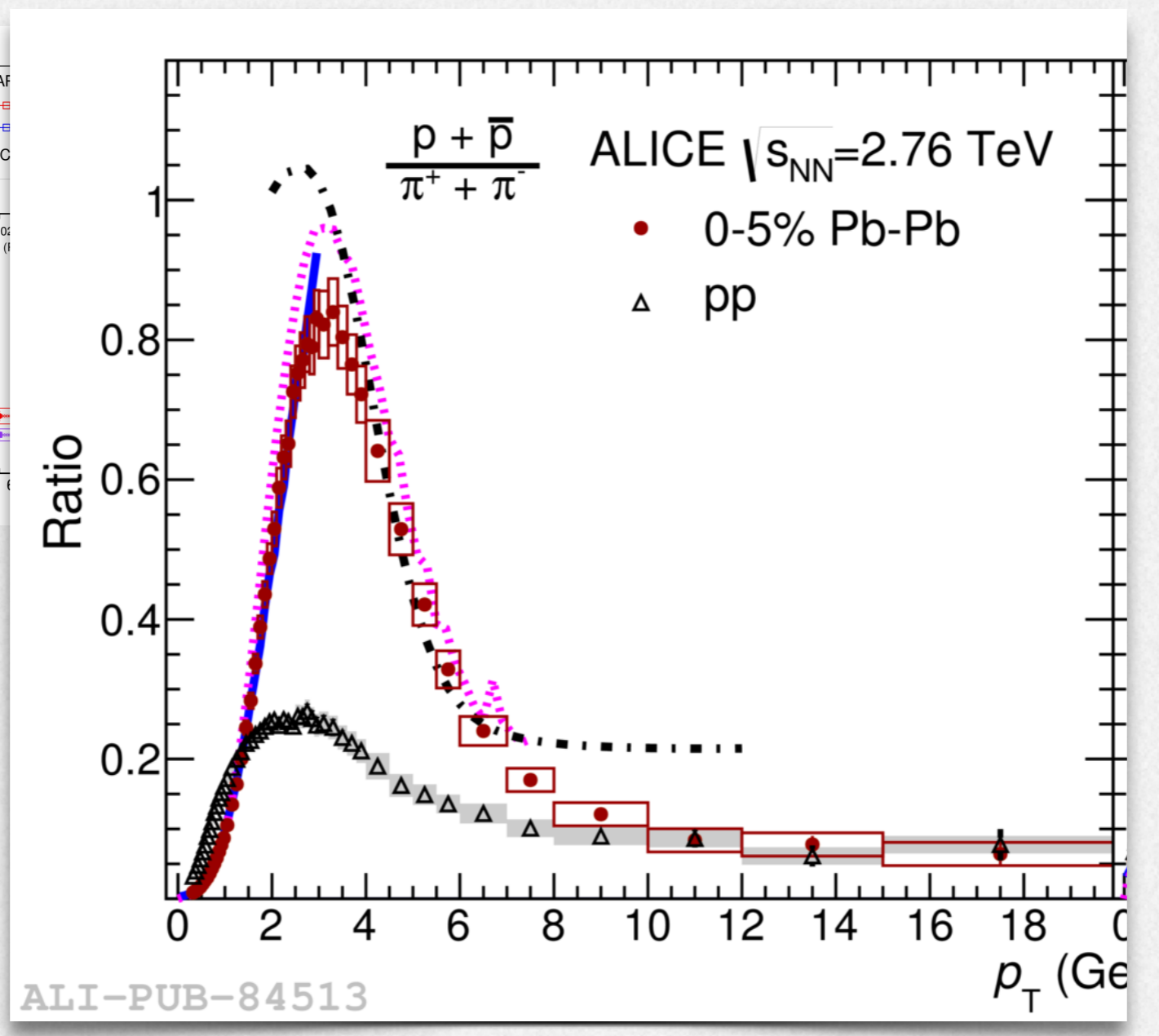
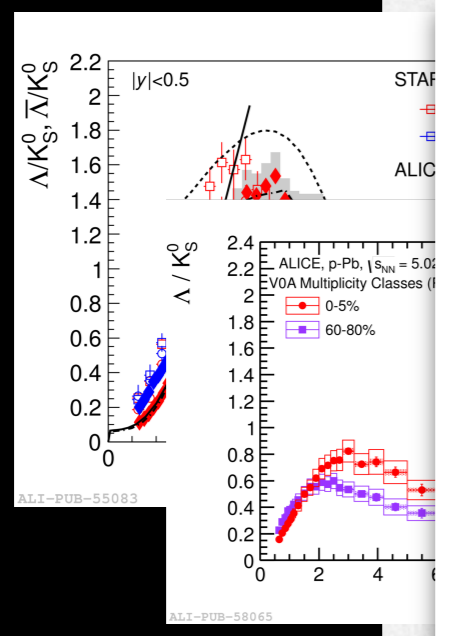


Λ / K_S^0



ALI-PUB-58065

Baryon & Meson

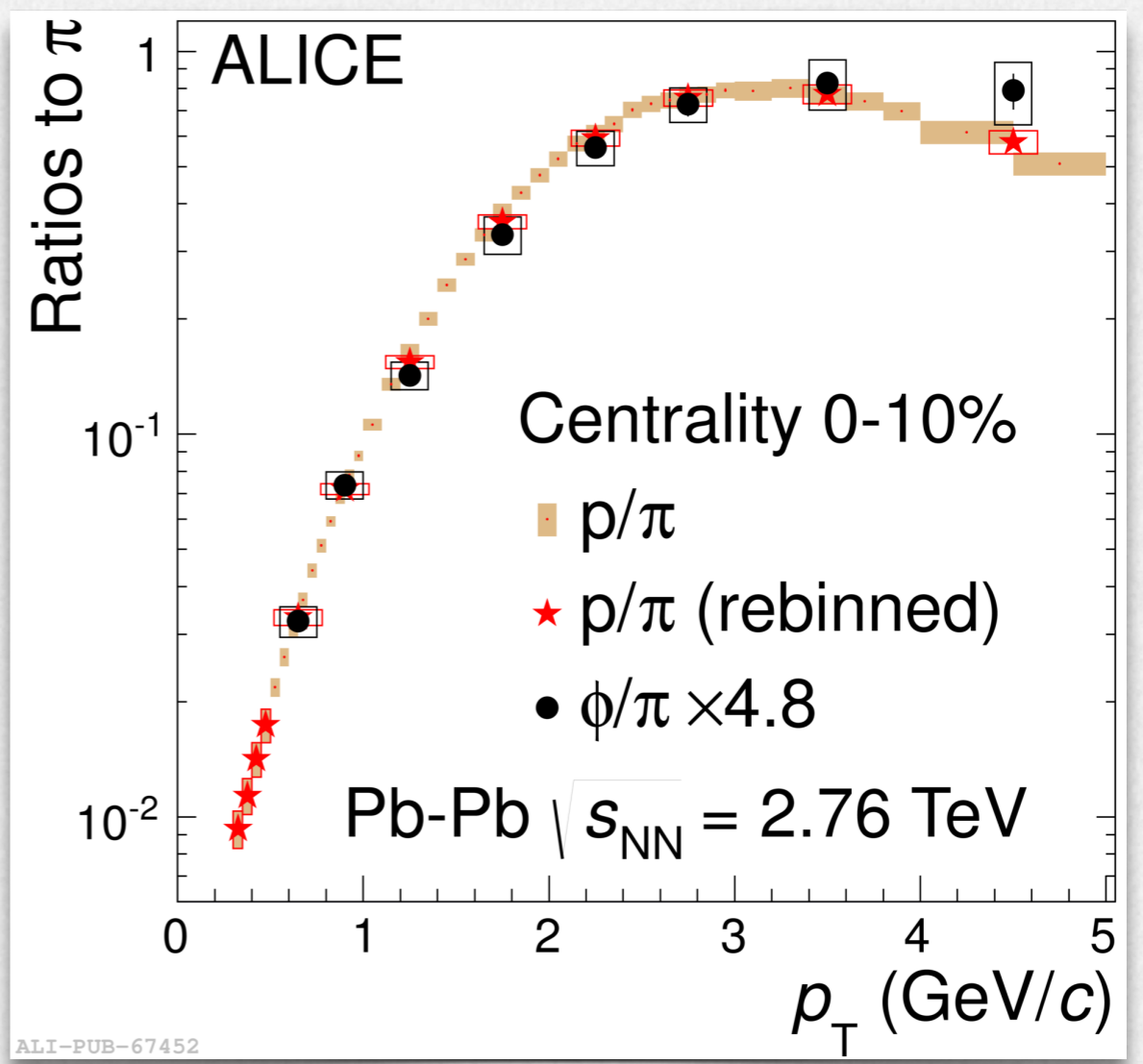
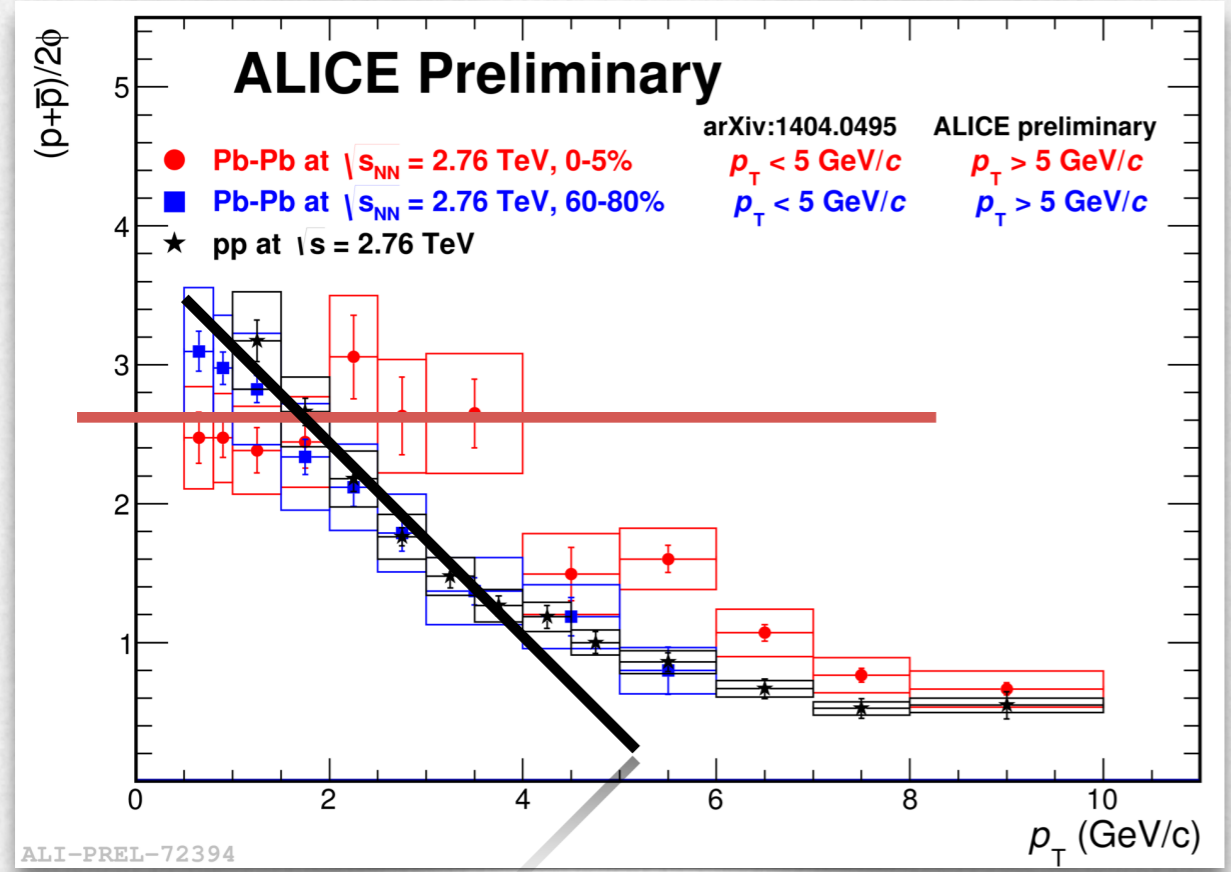


collective effects: radial flow + coalescence ?

vacuum jet fragmentation: pQCD

Baryon & Meson

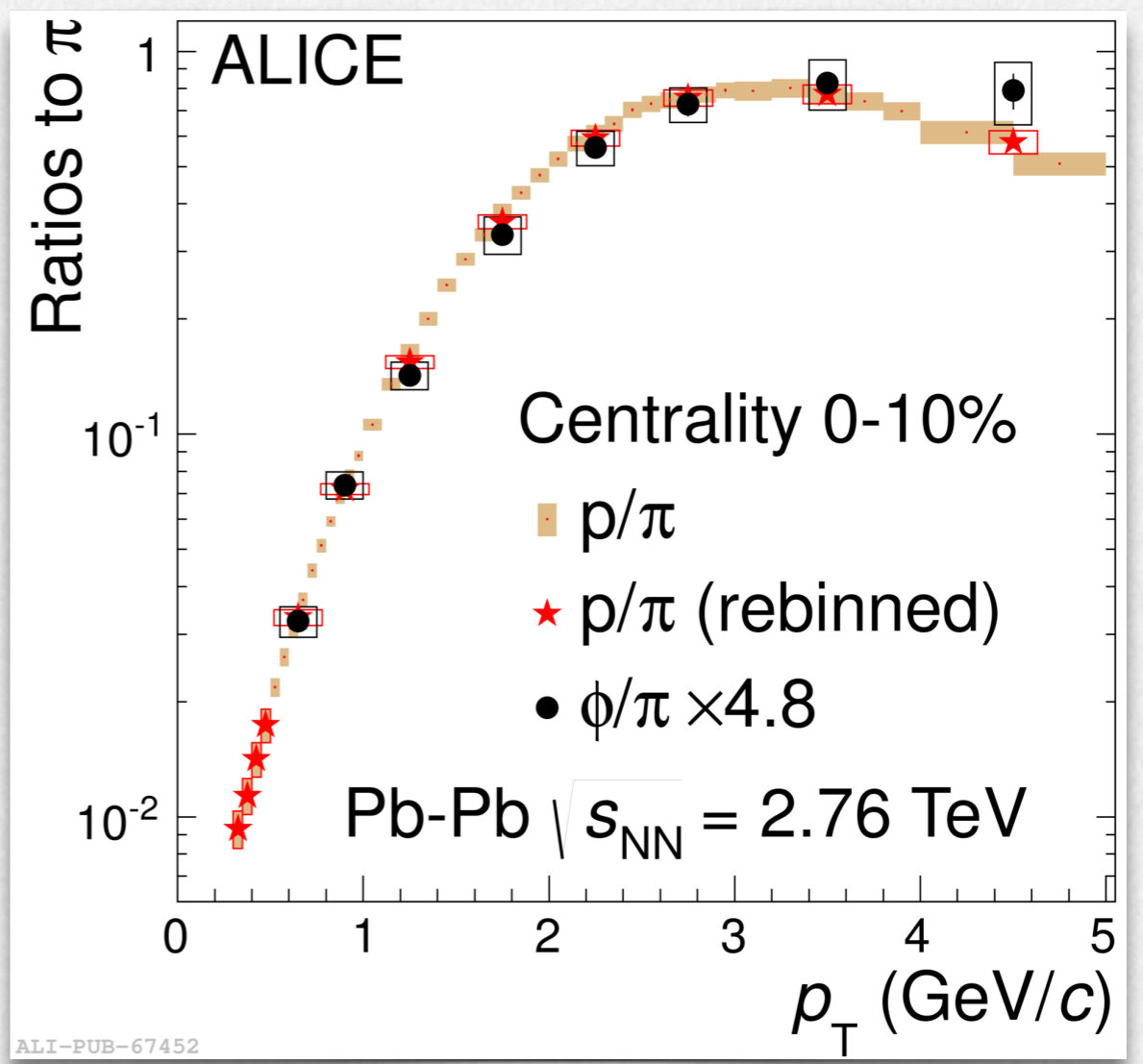
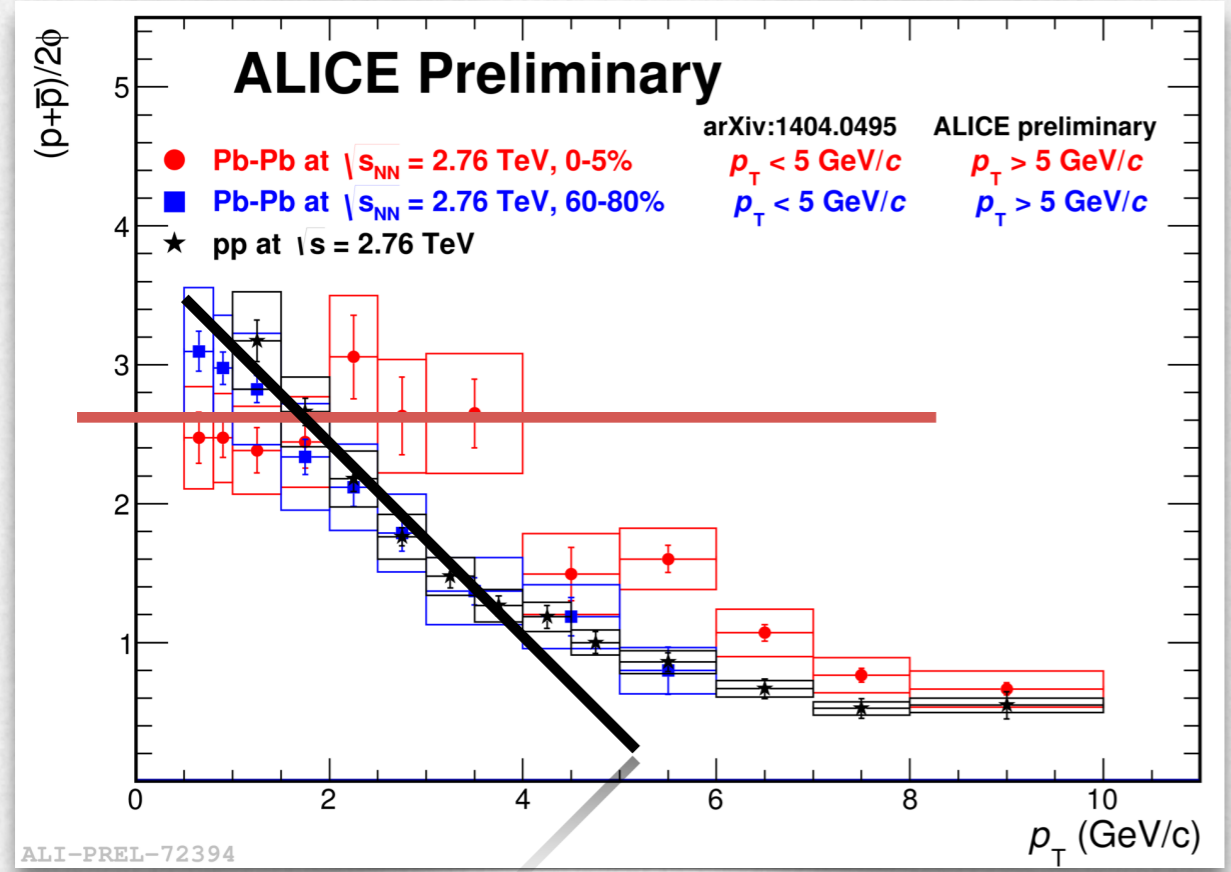
$$M_p \approx M_\phi$$



collective effects: radial flow + coalescence ?

Baryon & Meson

$$M_p \approx M_\phi$$



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

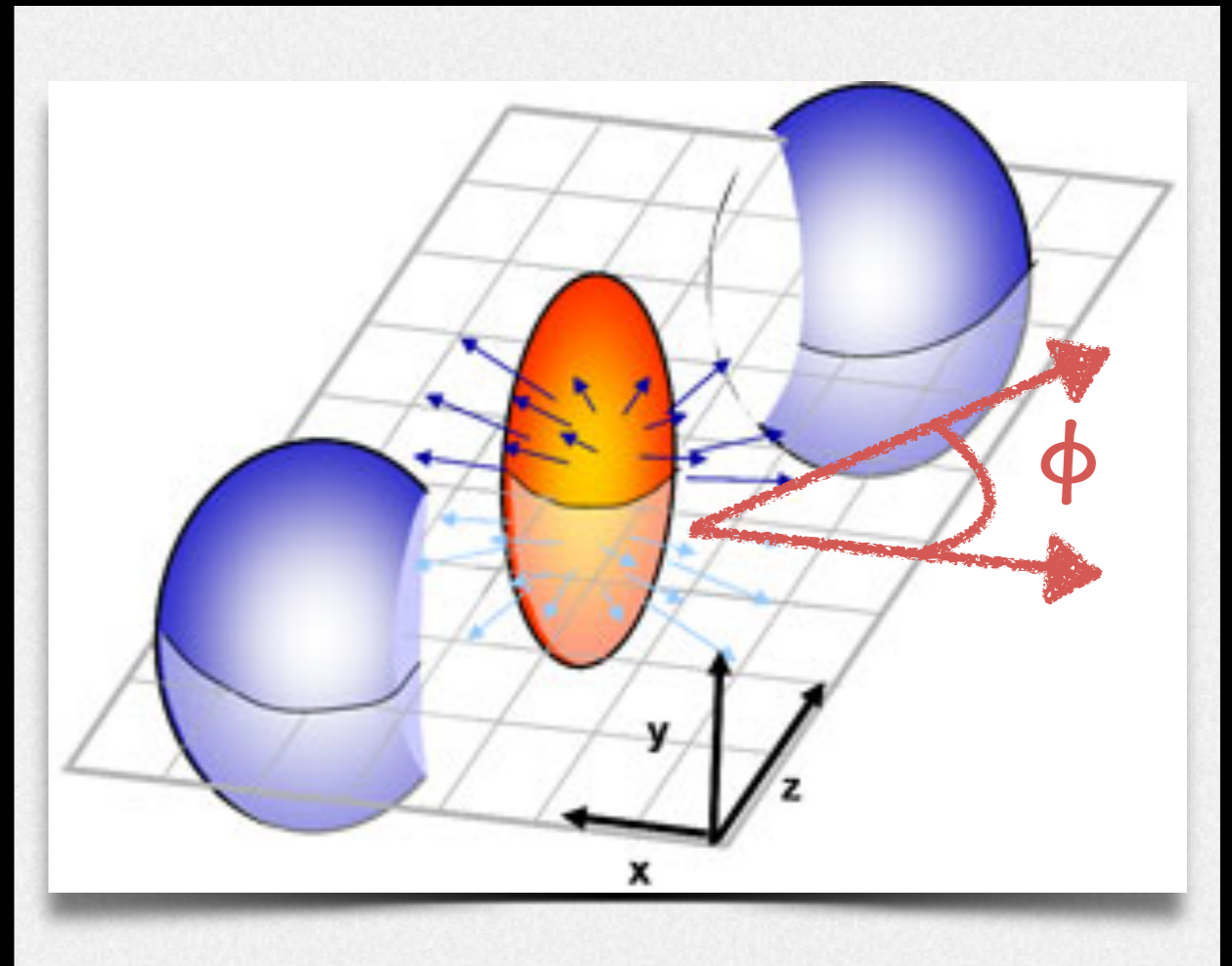
Mass rather than quark content

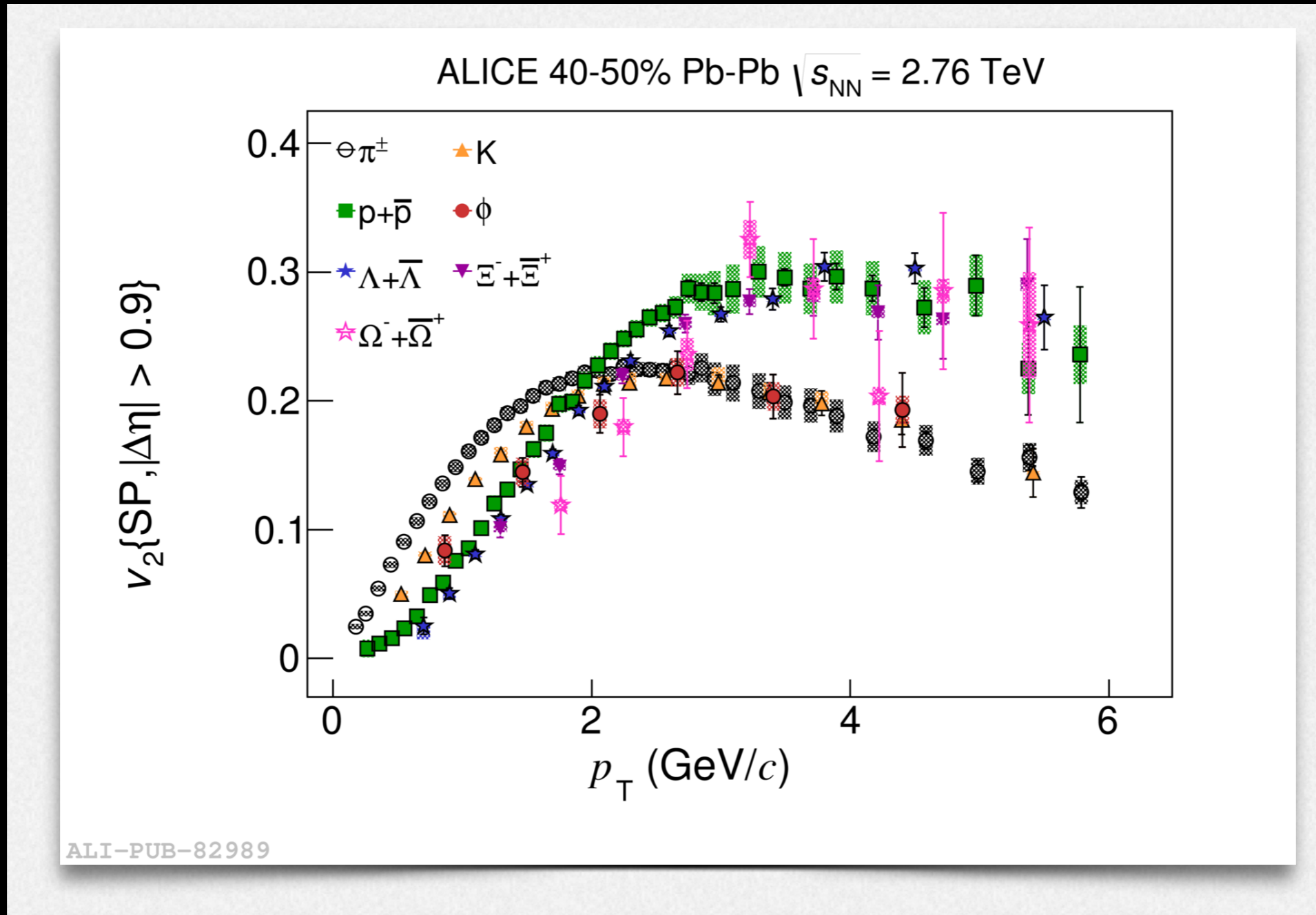
Collective flow (elliptic): AA to pp

ε_2 : overlap geometry
(impact parameter)

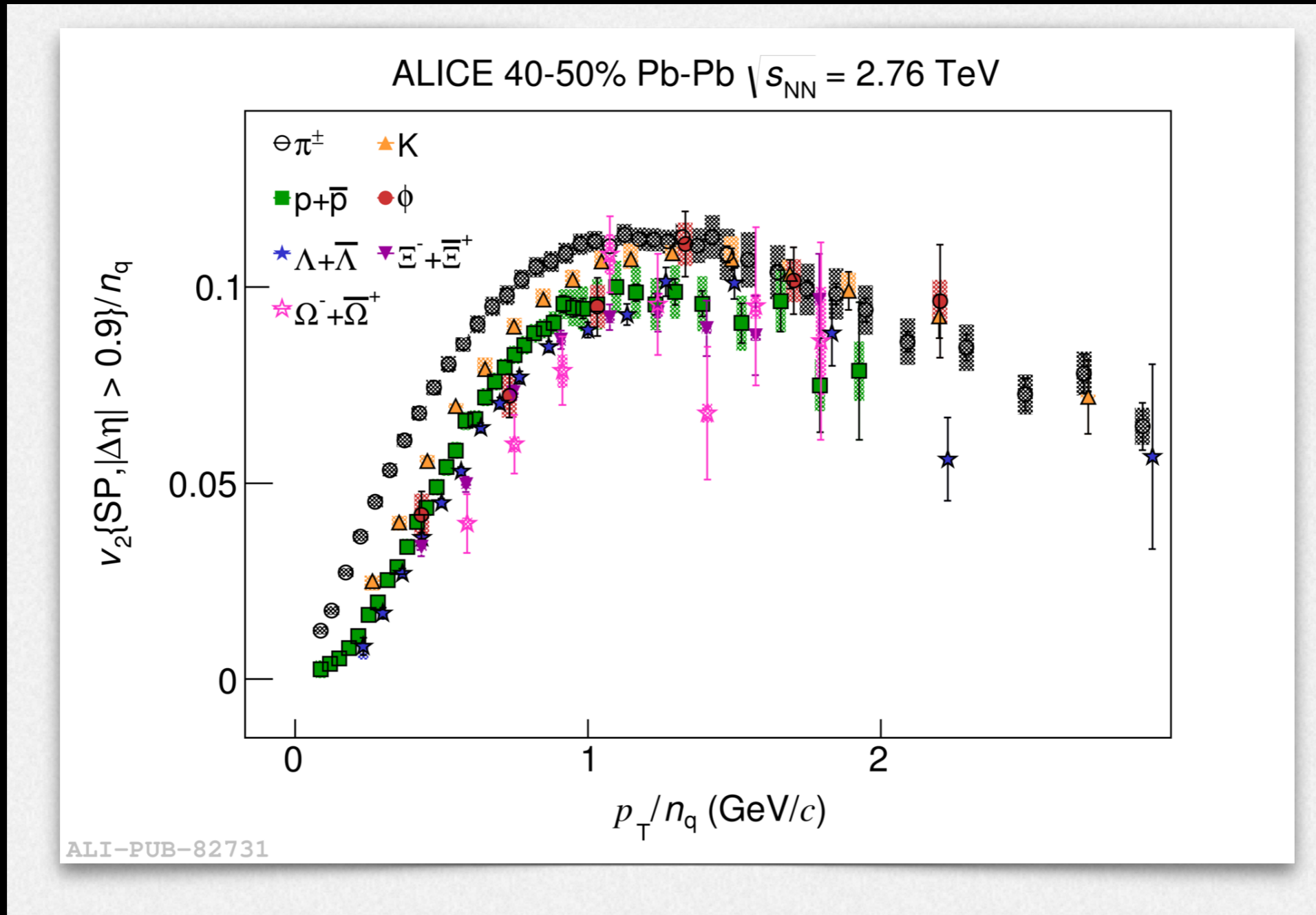
liquid + minimal
shear viscosity

v_2 : mapped into
momentum space



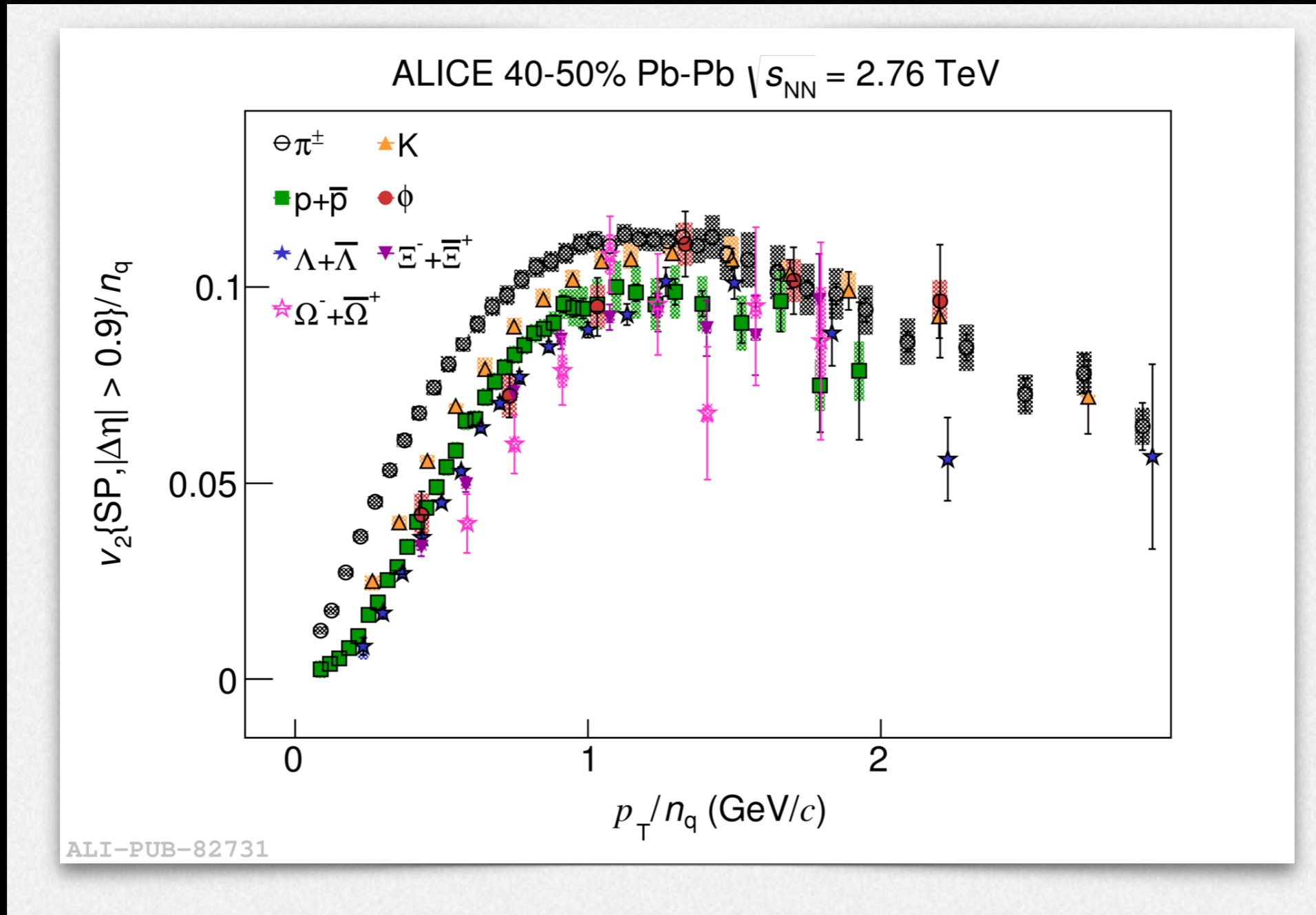


hadronization through q coalescence \rightarrow q DoF at $T > T_H$?



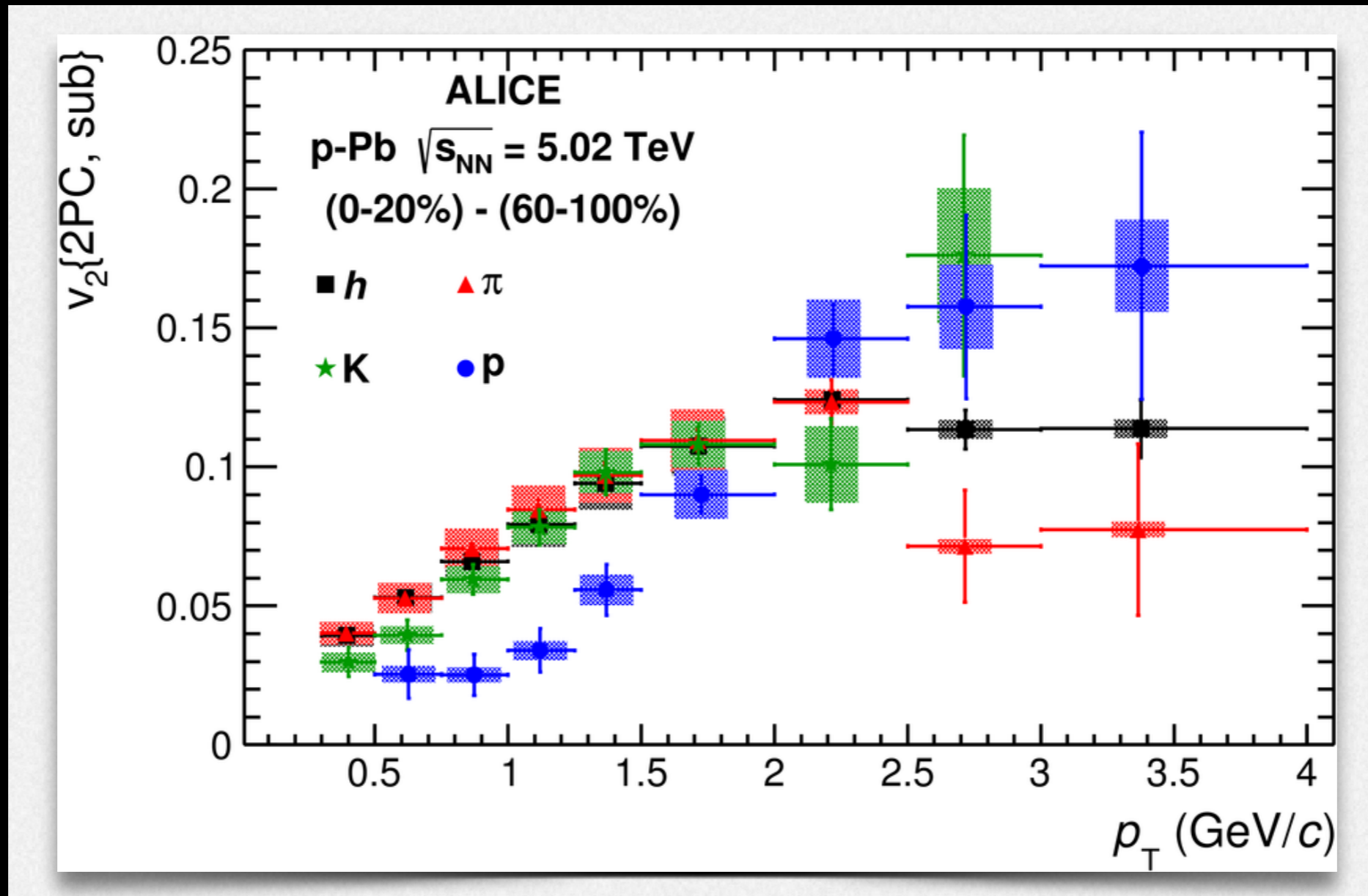
hadronization through q coalescence \rightarrow q DoF at $T > T_H$?

Elliptic flow



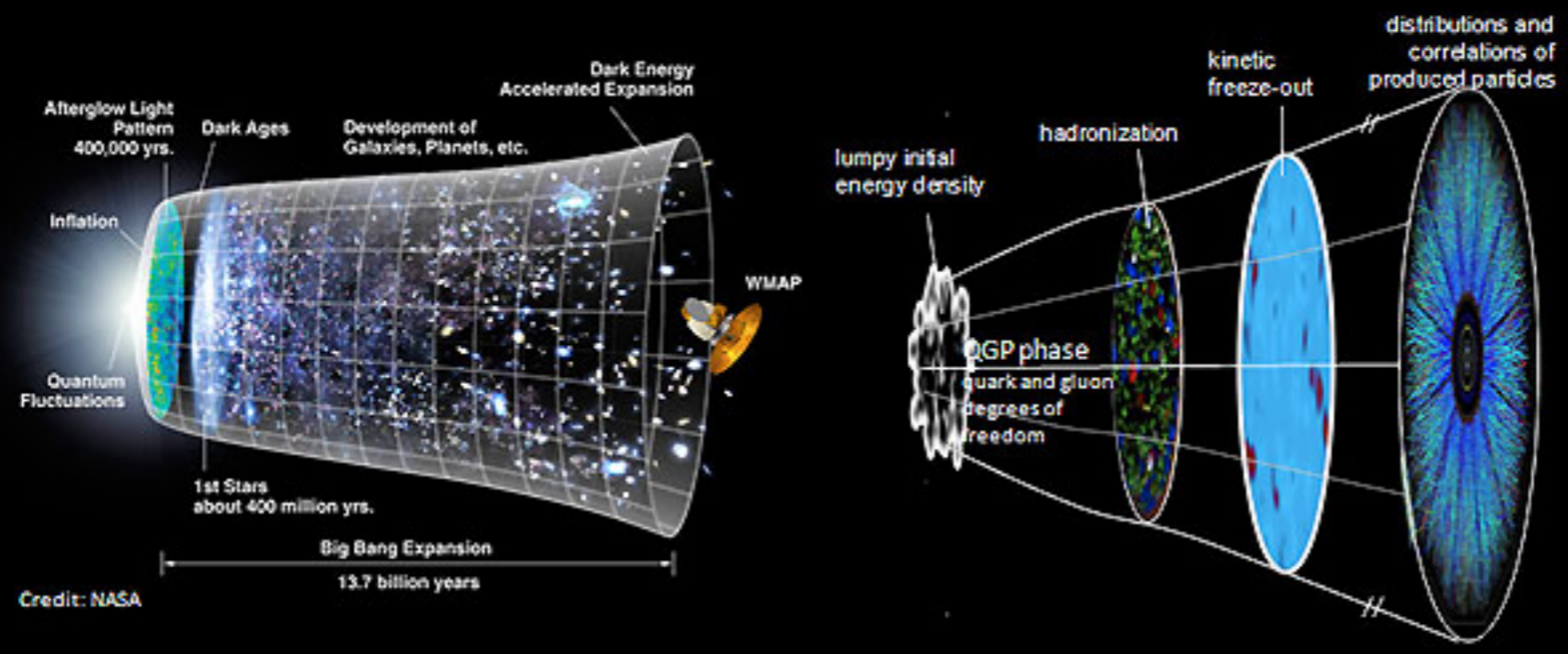
~~hadronization through q coalescence \rightarrow q DoF at $T > T_H$?~~

Elliptic flow



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

The Big (Bang) story



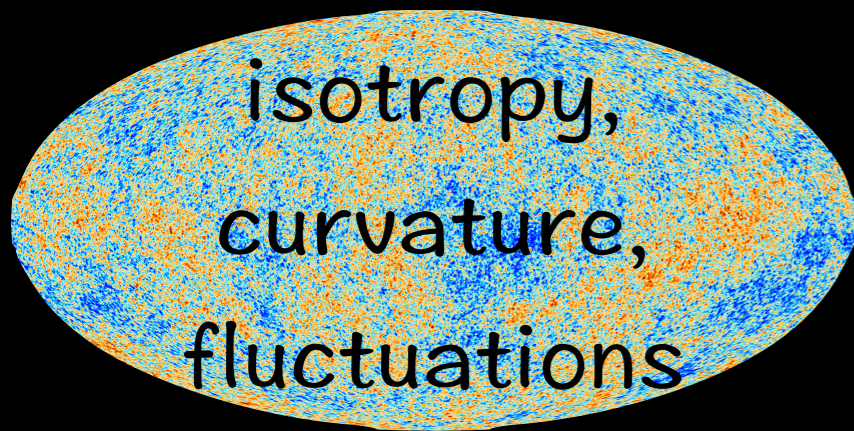
a parte

CMB - Big Bang - Universe

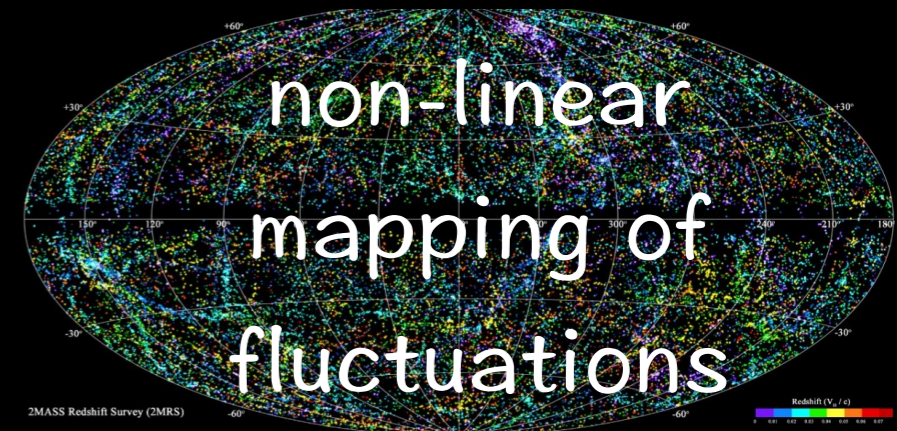
CMB

Big Bang model

Today's Universe



almost linear
time evolution



Big Bang time

IC (IS)

BB model*

FS (data)

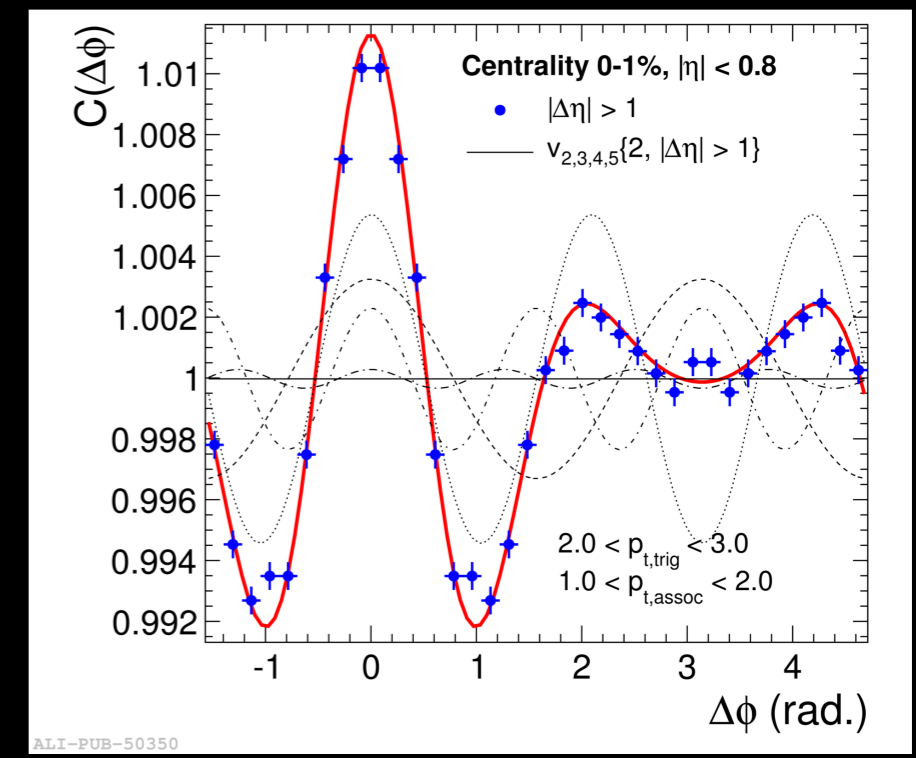
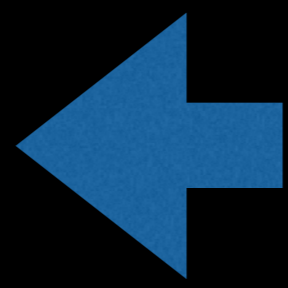
* a priori knowledge of initial conditions

Dissipation in the perfect liquid is minimal:

The QGP is transparent to quantum fluctuations in the IS

non dissipatif
hydro + classical
field dynamics

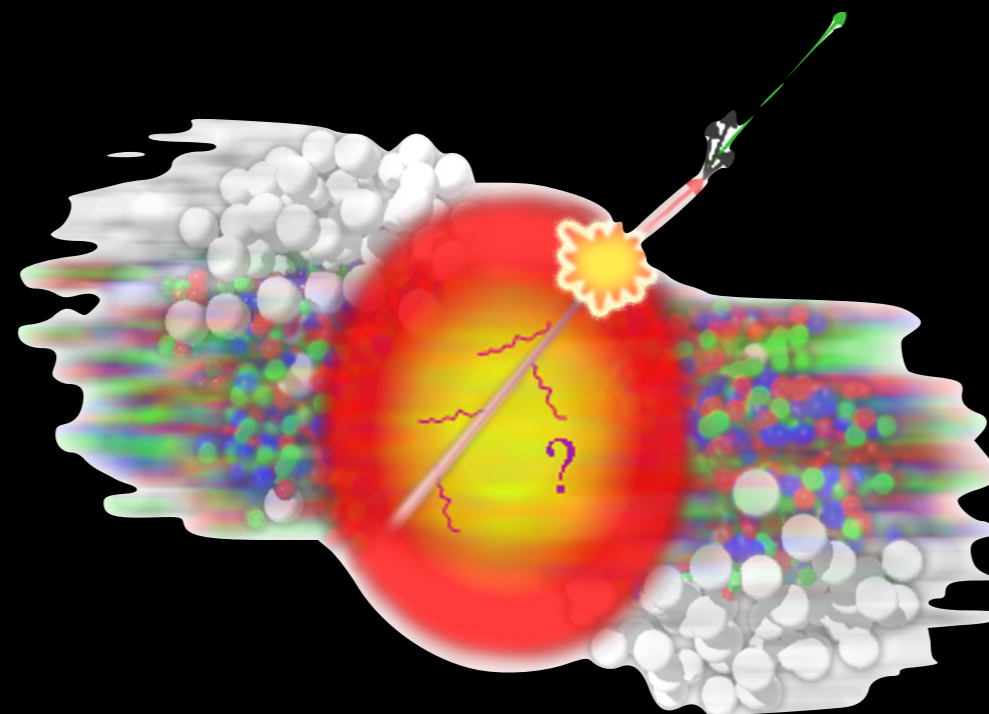
IS: weakly coupled
pure gauge field +
quantum
fluctuations

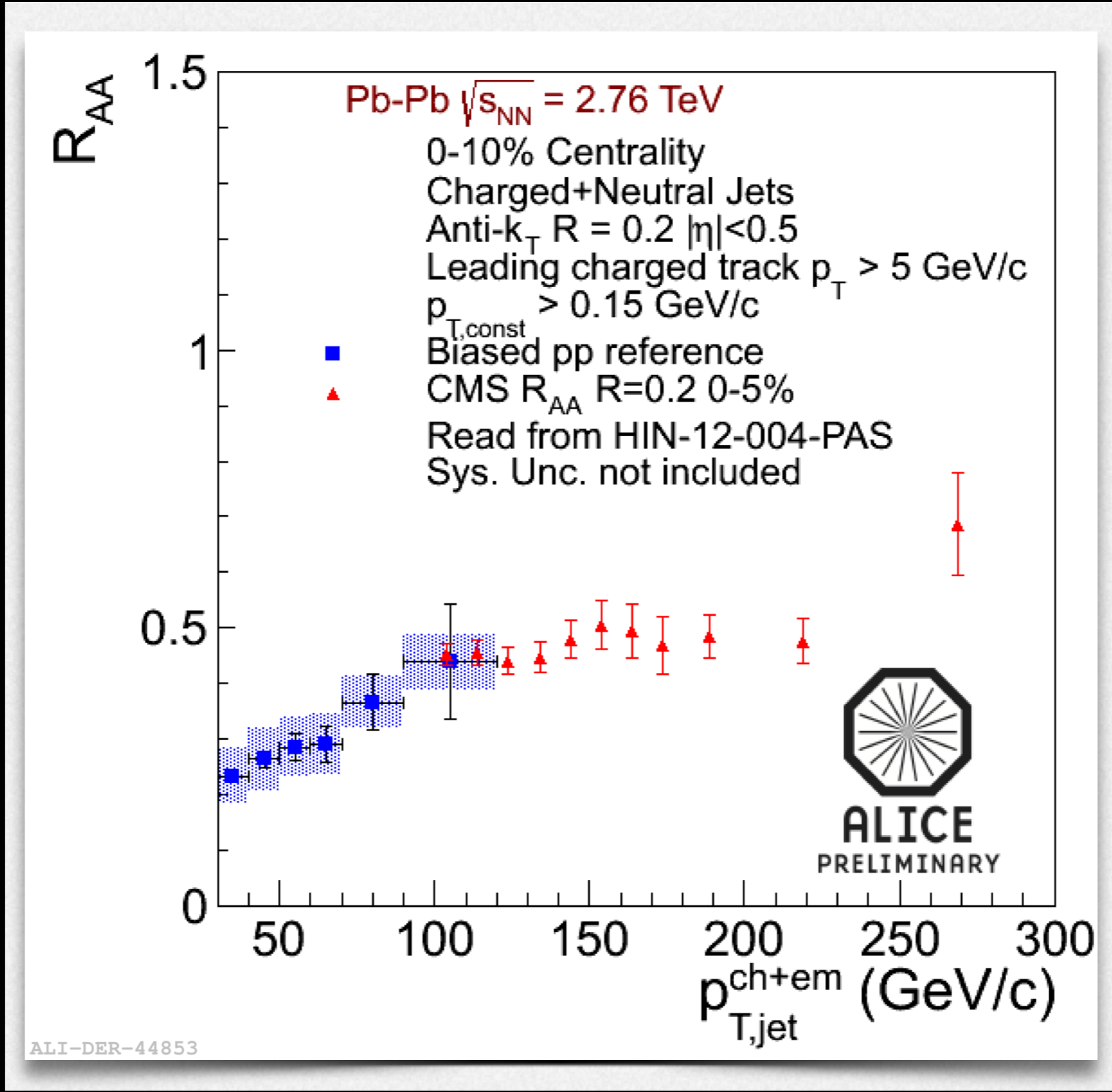


hard: $p_T, m_T \gg T, \Lambda_{\text{QCD}}$

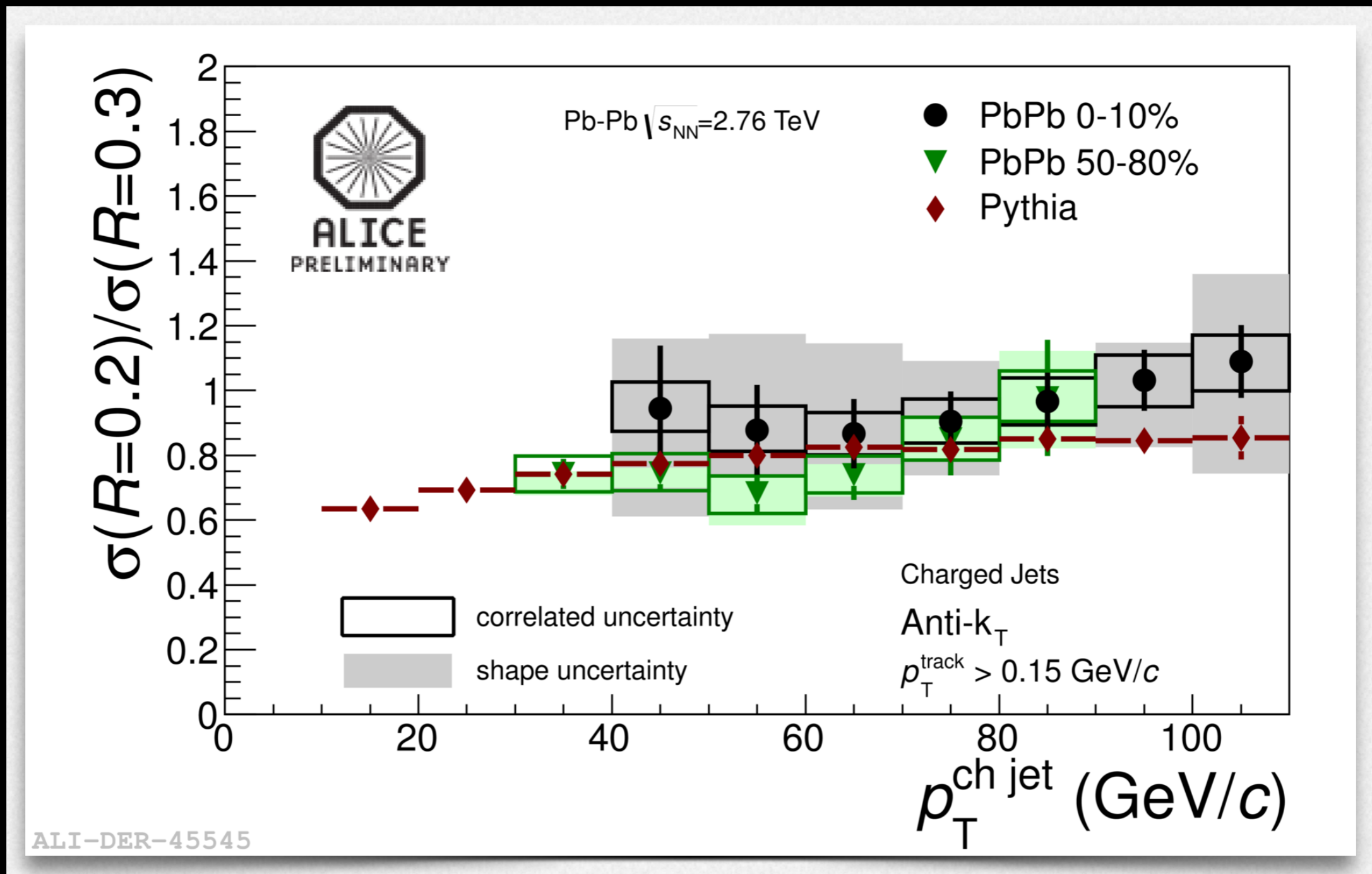
probe QGP at high resolution scale (DoF)

parton transport in QGP





jets suppressed → parton shower loses energy in QGP

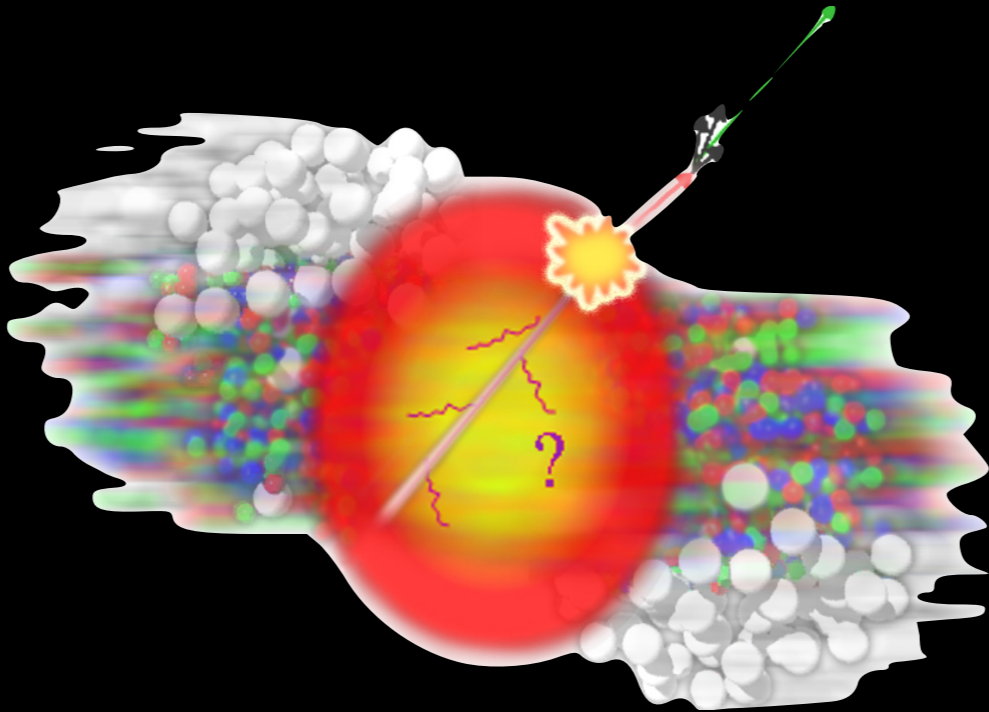


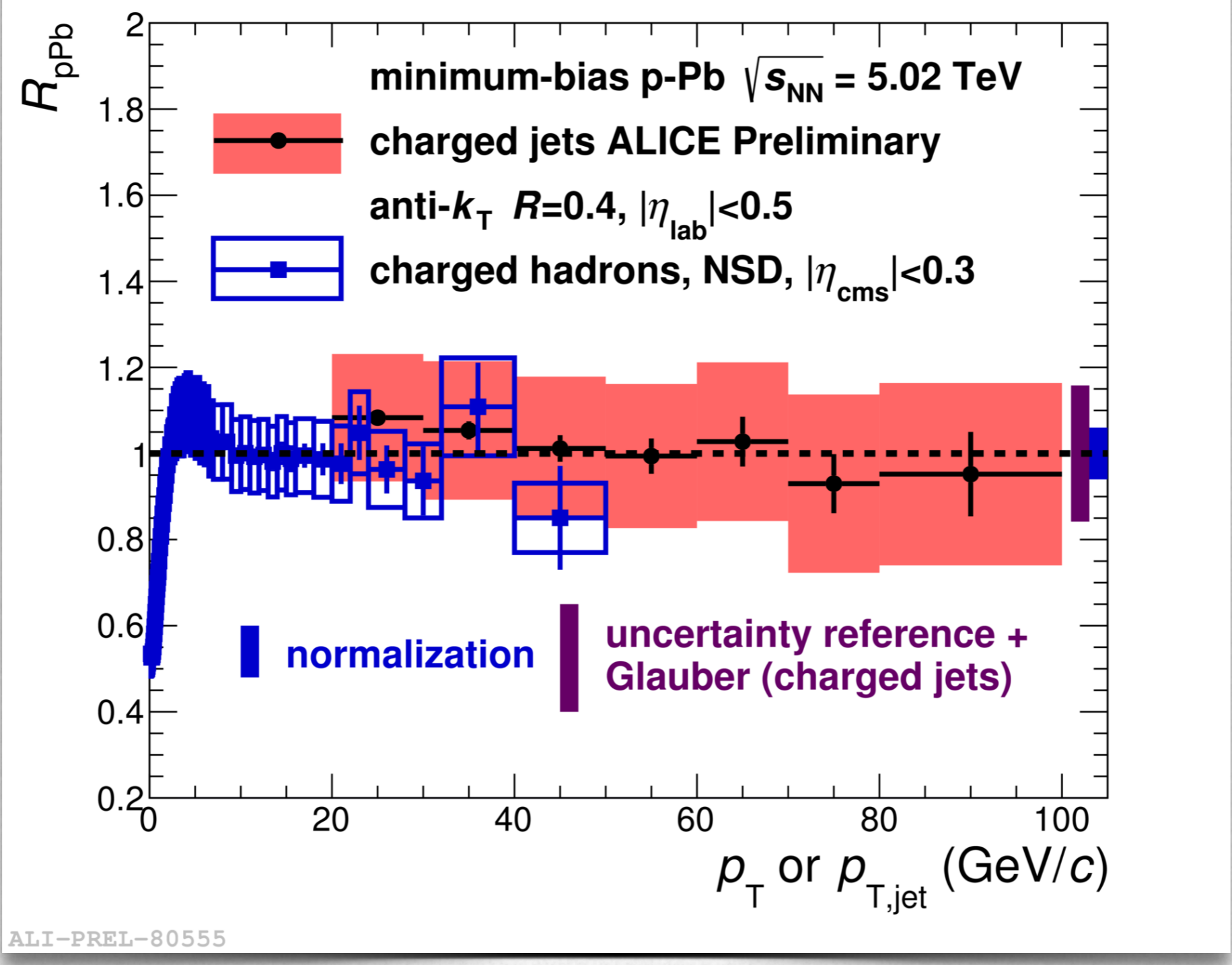
Jet structure same as in vacuum: Where is the lost energy radiated ?

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

- ▶ 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 ?

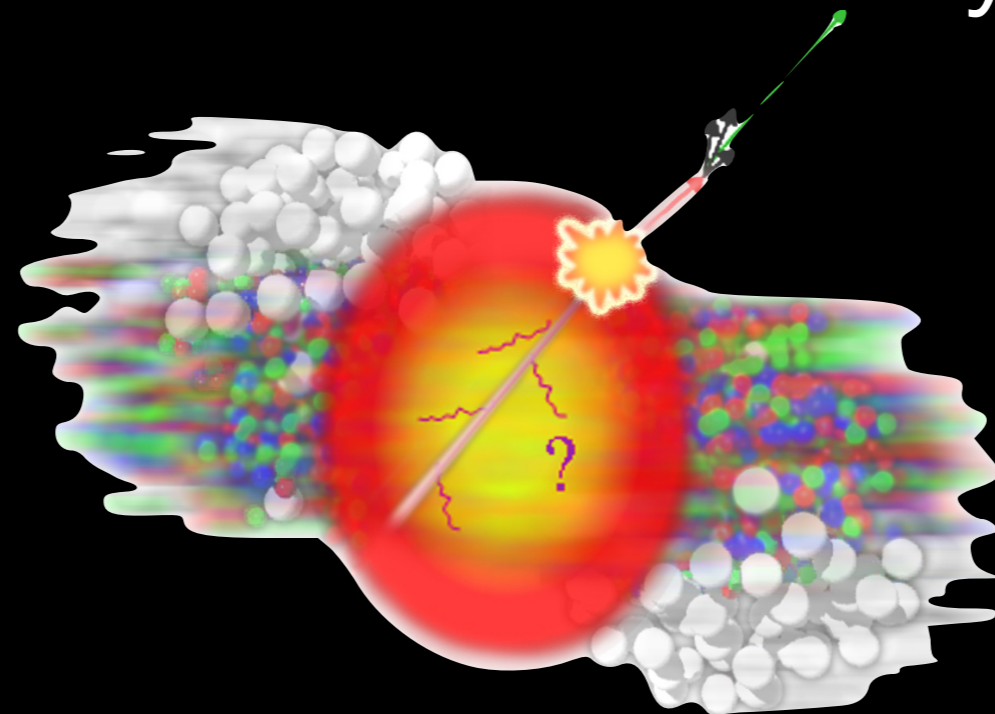
parton transport in QGP: not in pPb !

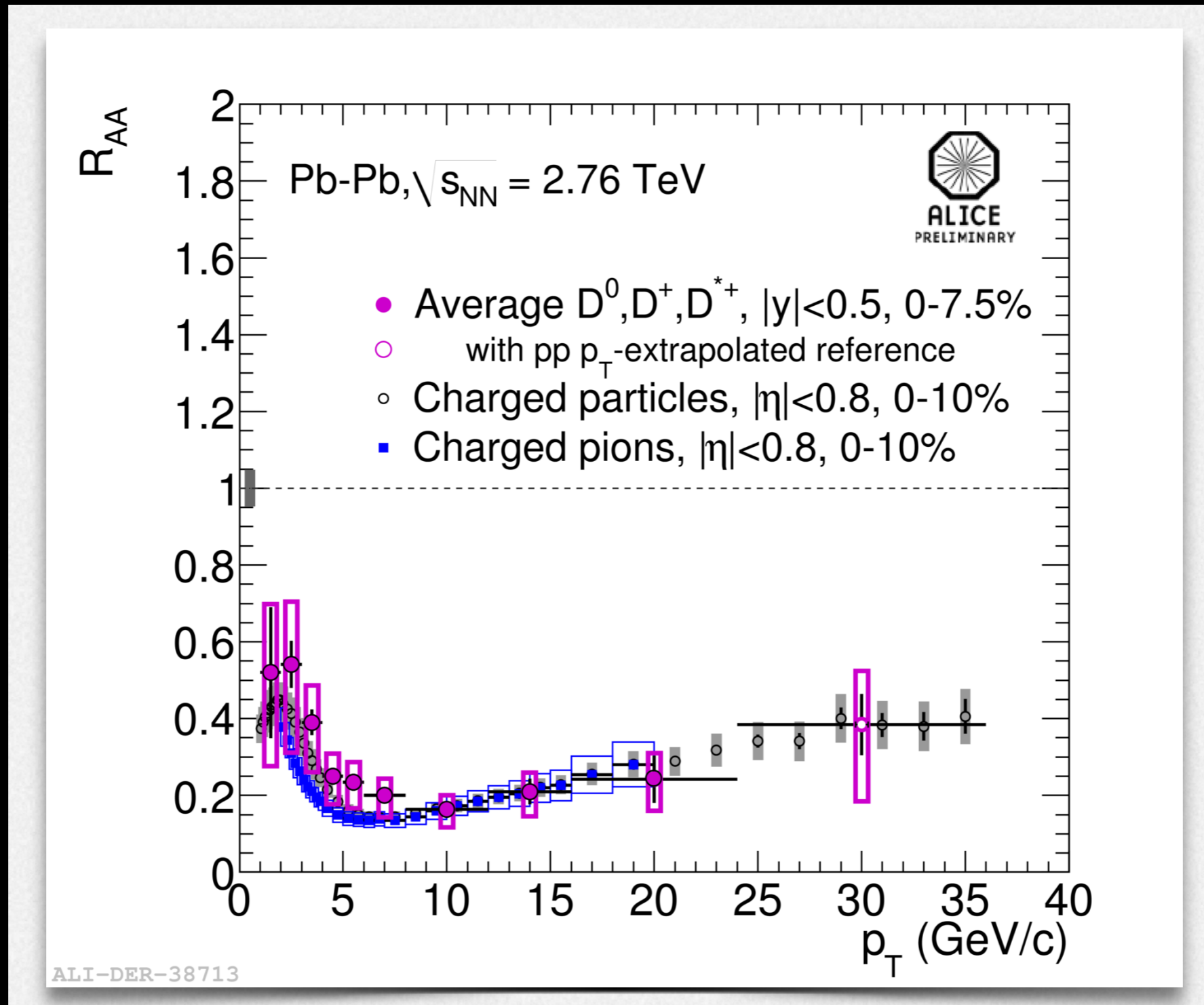




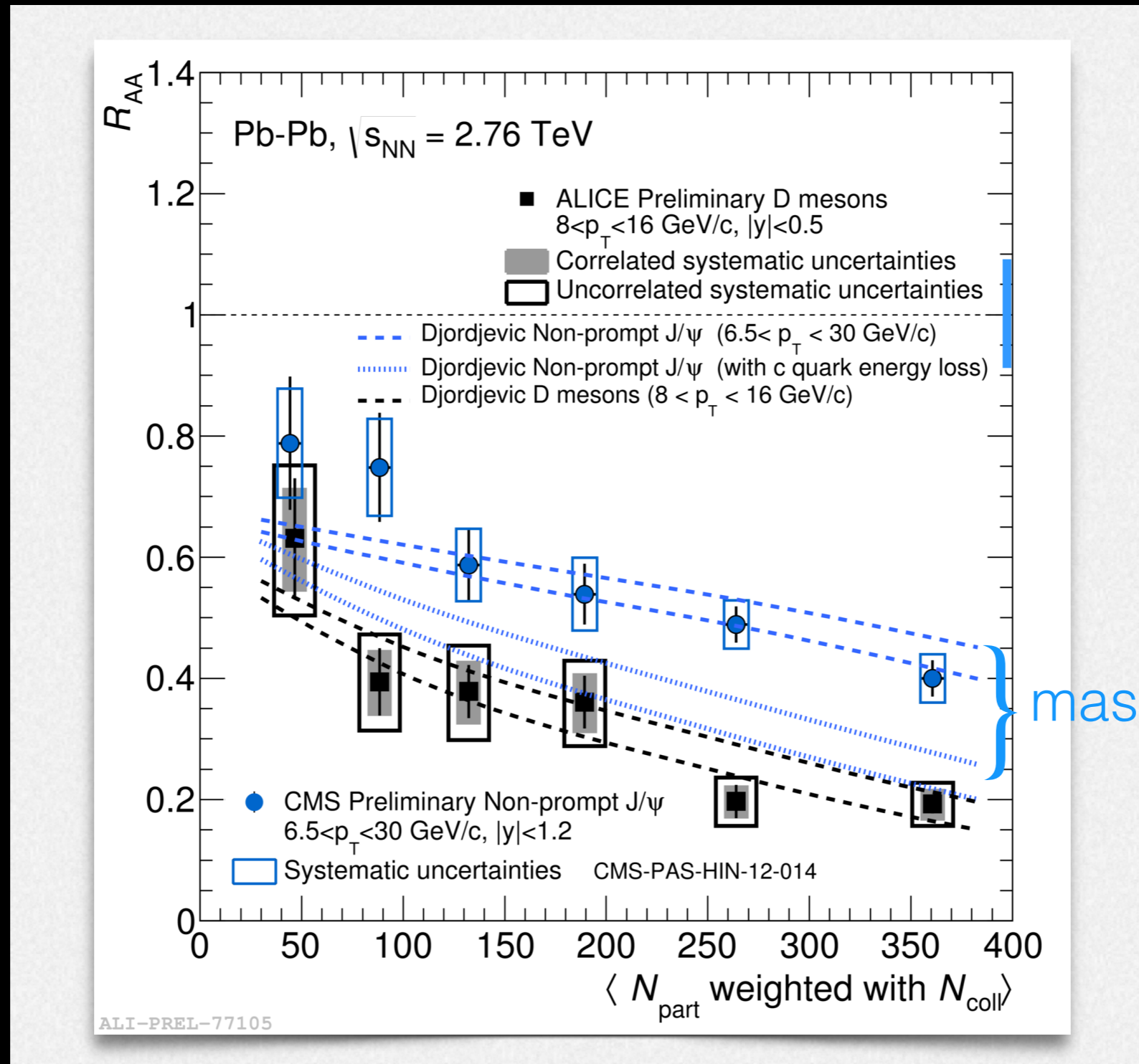
No medium final state effect in pPb ??

parton transport in QGP: color charge
and mass hierarchy ?

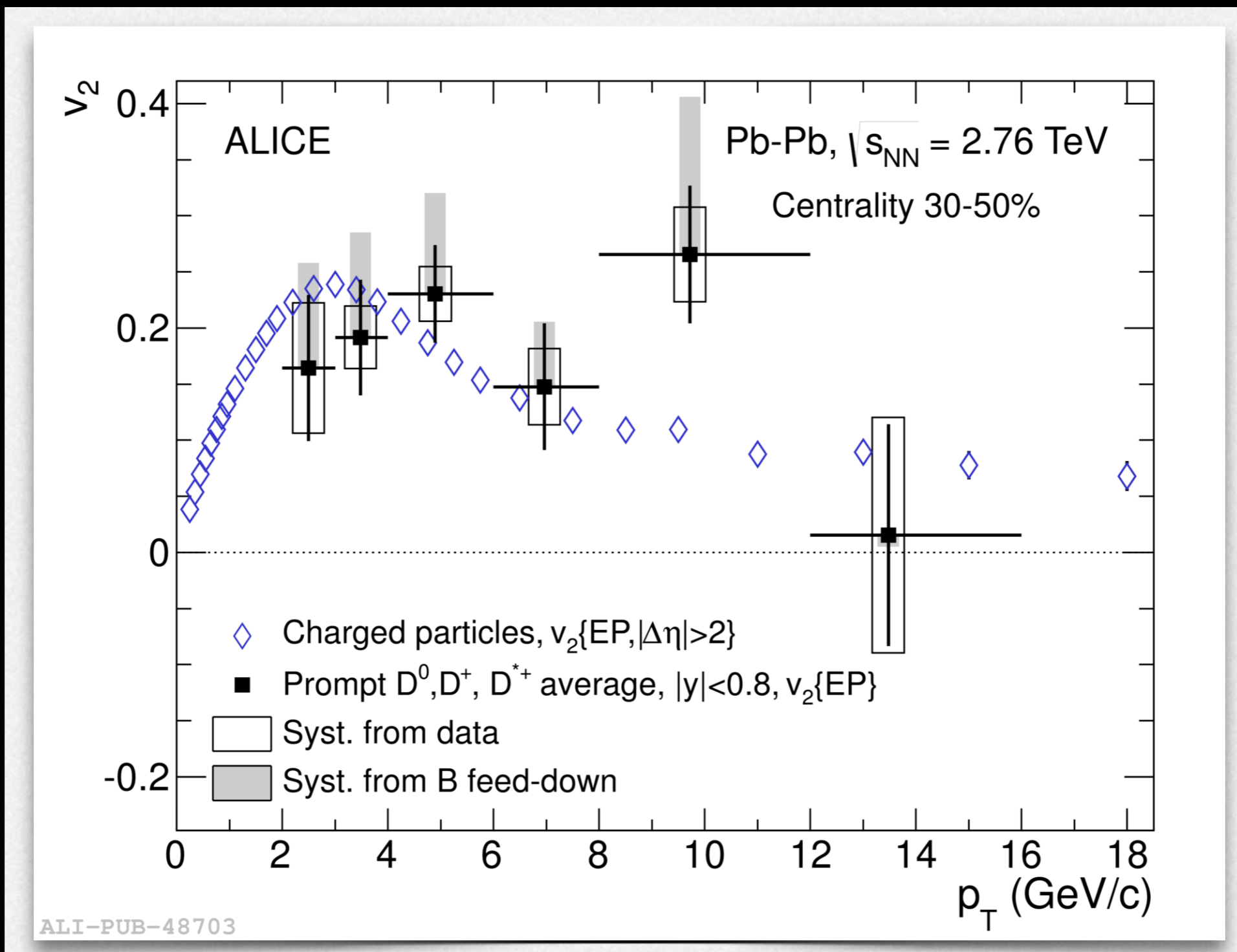




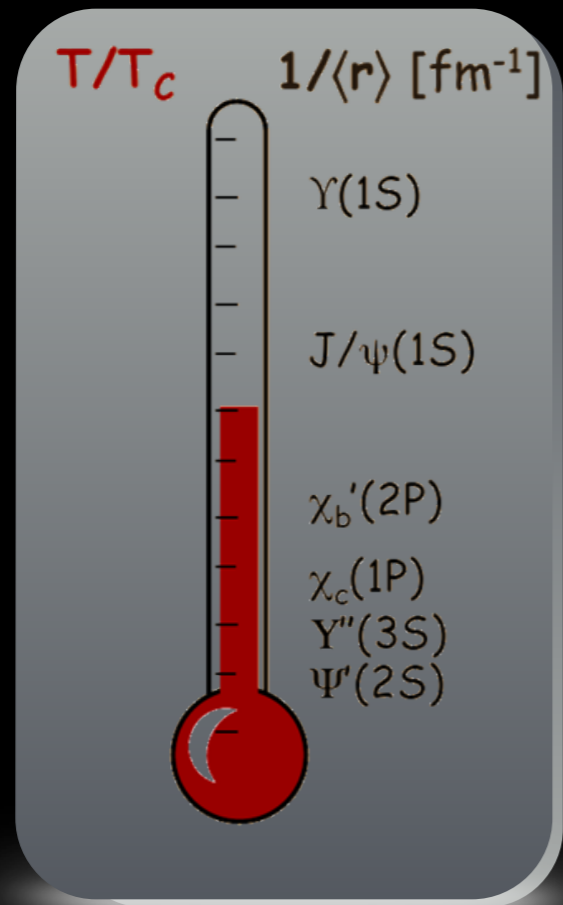
Color charge dependence (g vs q) ?



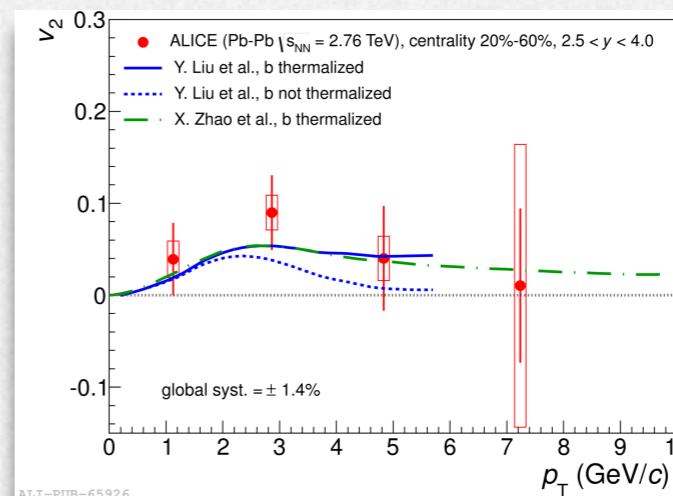
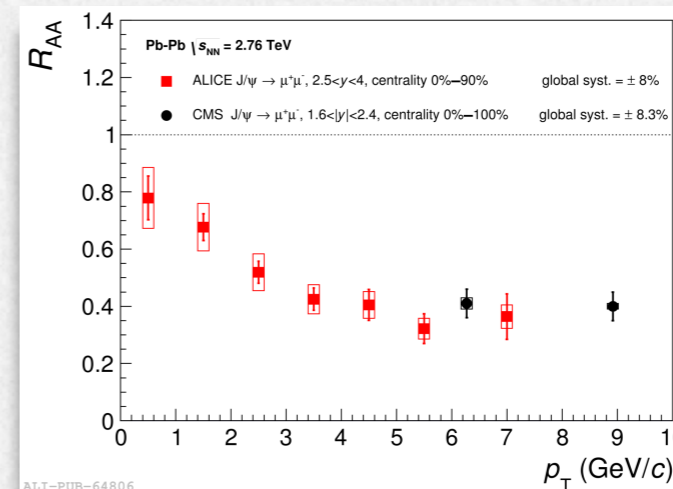
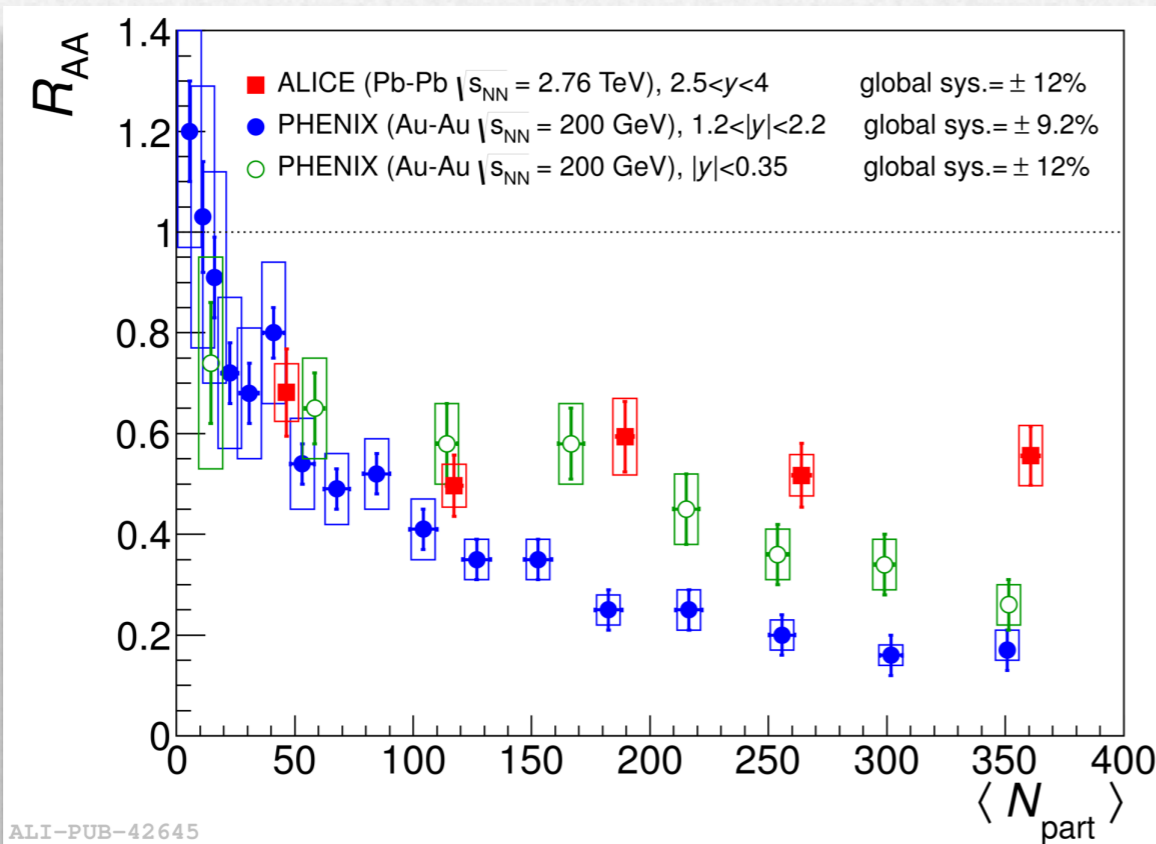
Radiative or collisional ? Flavor dependence ! But...



Deconfined HQ ? Flow ? coalescence ? dof ?



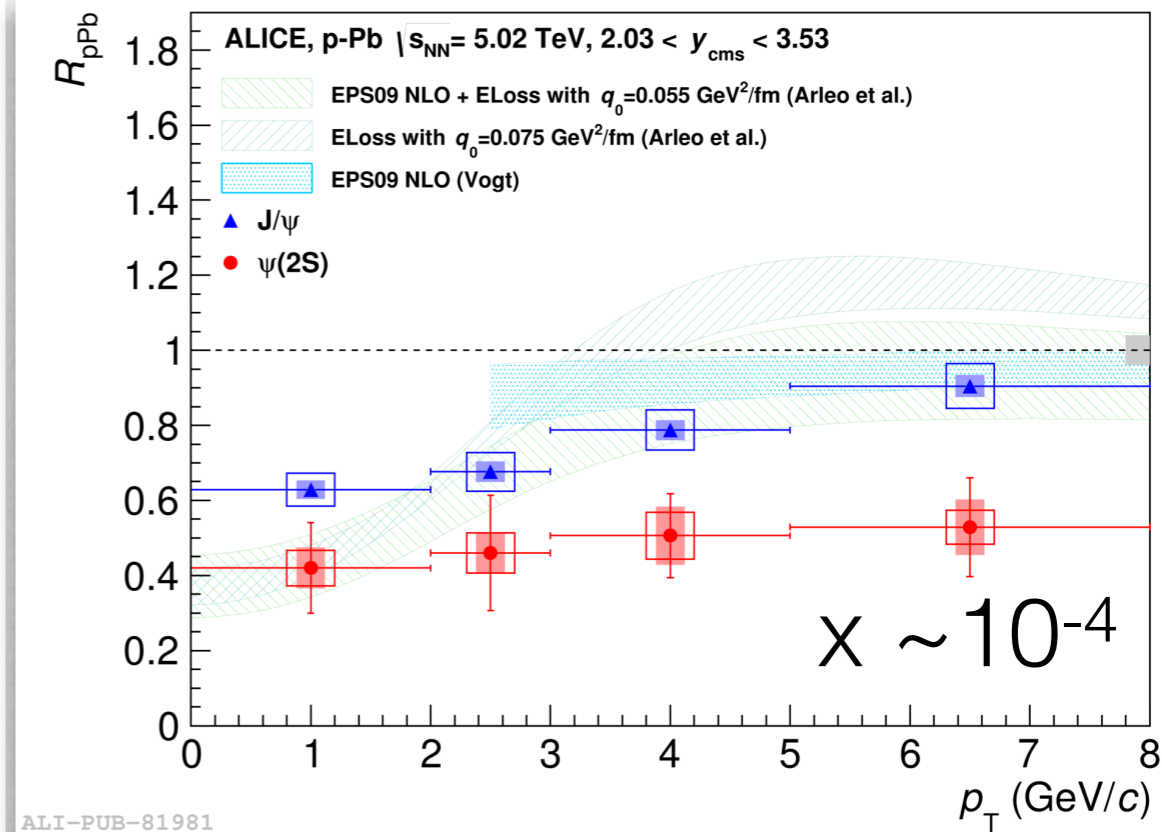
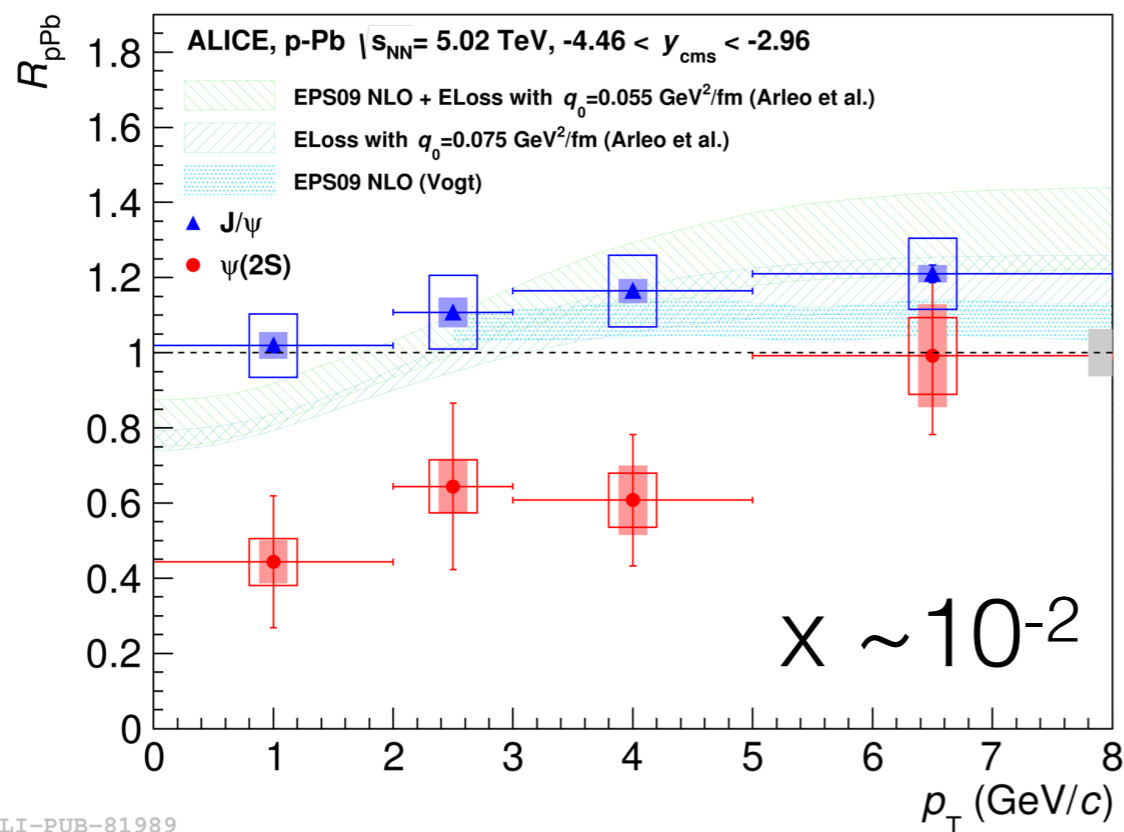
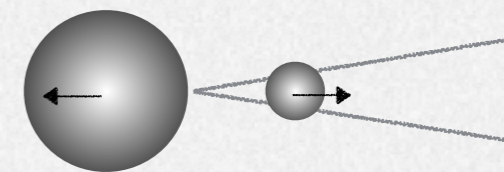
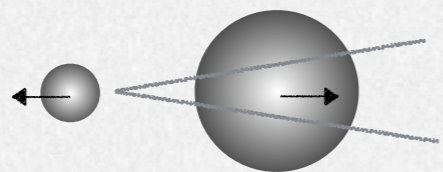
the quarkonia saga ...



hard process ⊕ color screening ⊕ coalescence

▶ deconfined c in **QGP** → statistical hadronization ?

▶ continuous melting/creation in **QGP** → freeze out ?



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 »

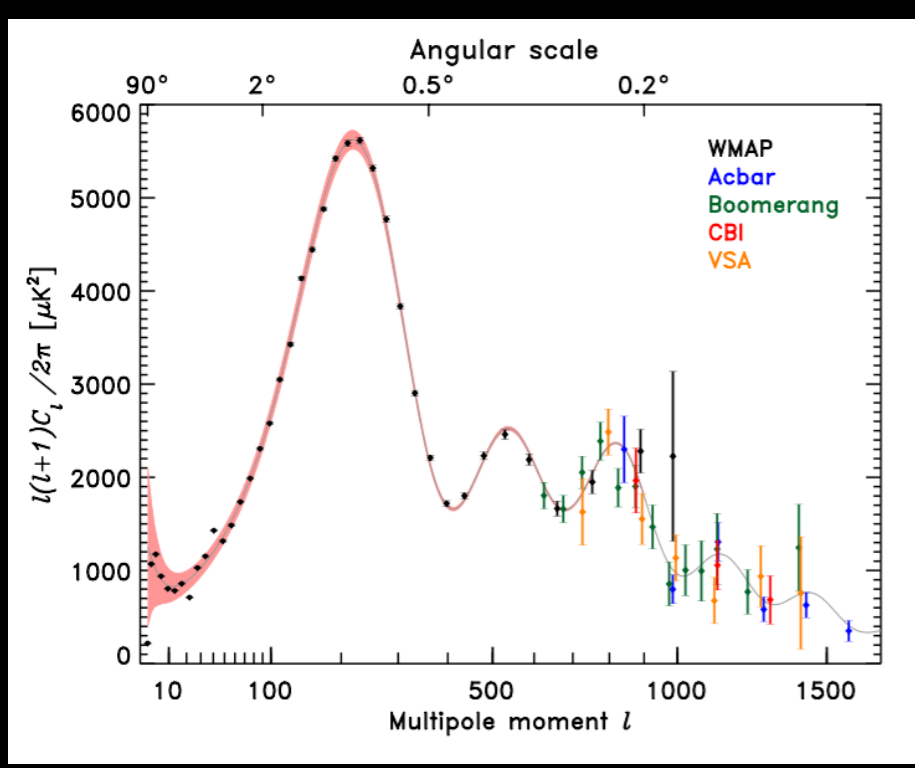
- *Frank Wilczek, QM2014* -

Heavy-ion collisions 4 Hydrodynamics

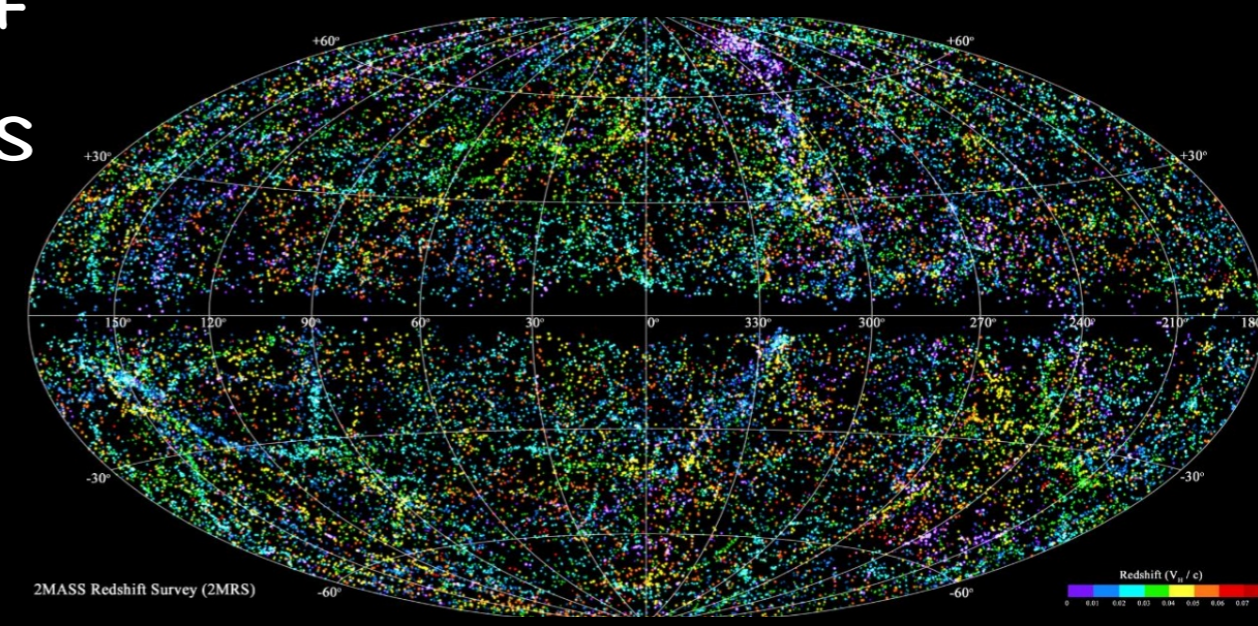
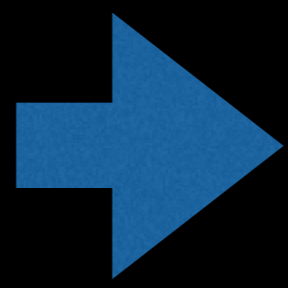
Back to Hydro Dynamics of QGP !

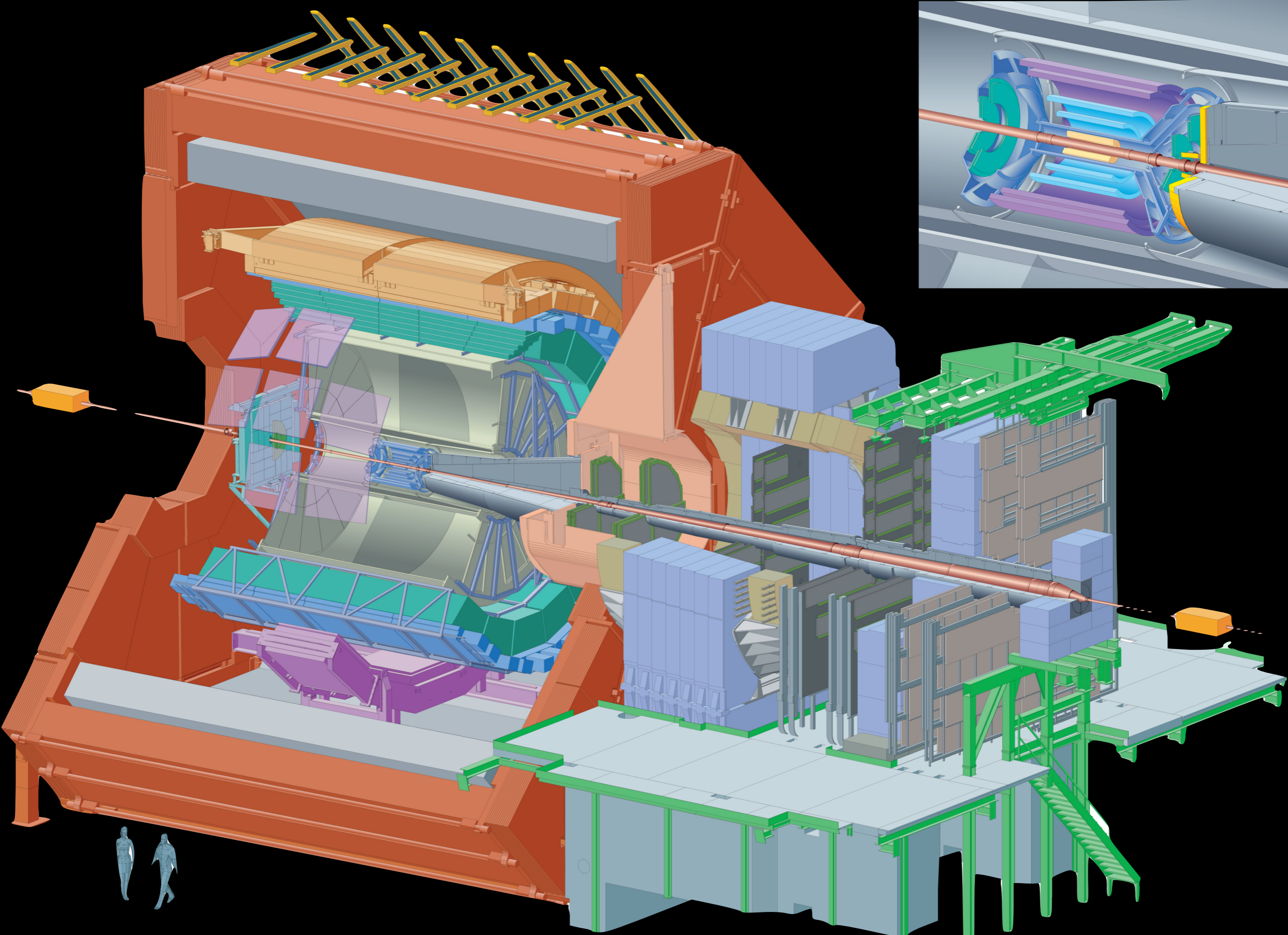
Dissipation in the perfect liquid is minimal:

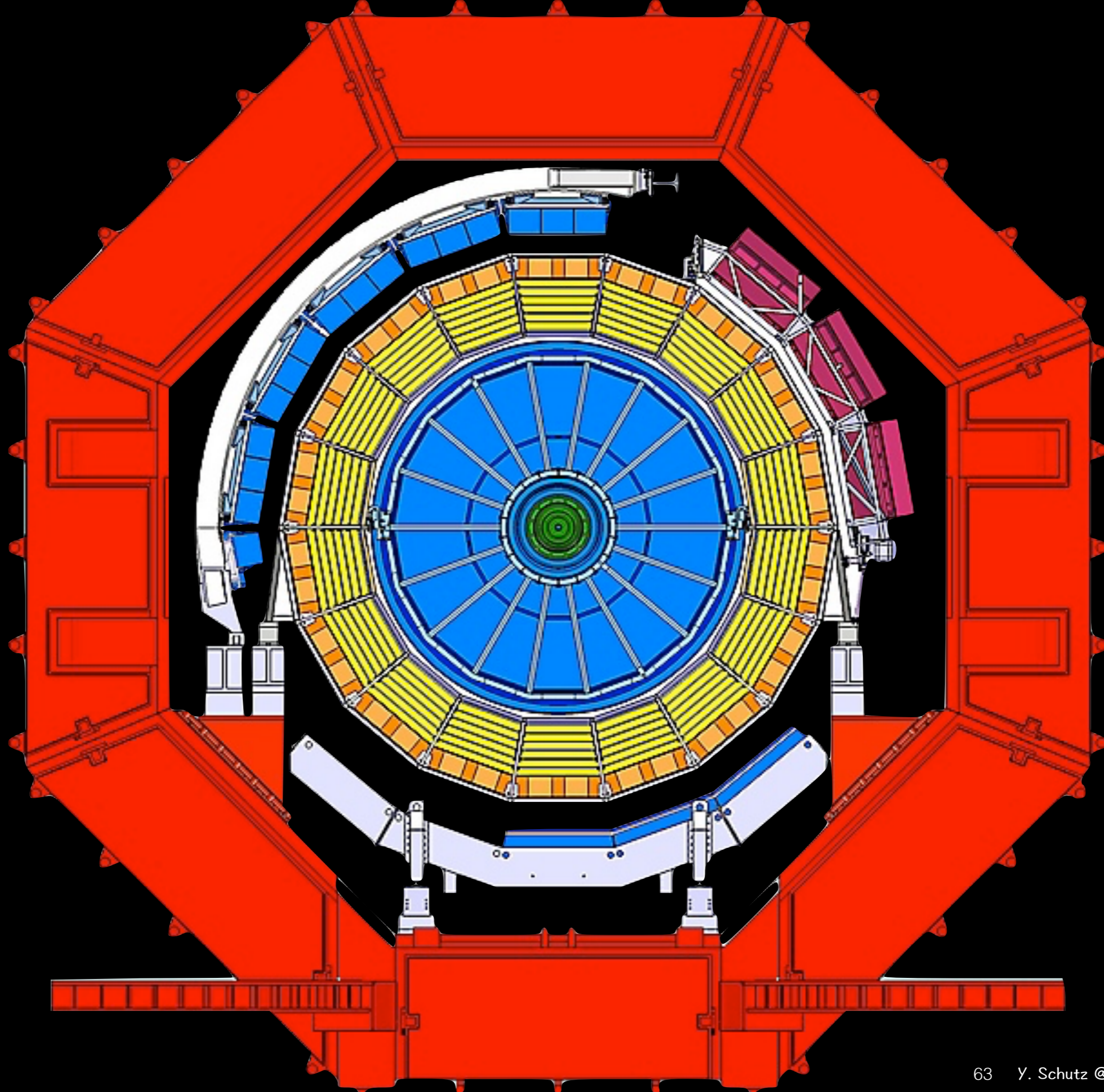
The QGP is transparent to quantum fluctuations in the IS

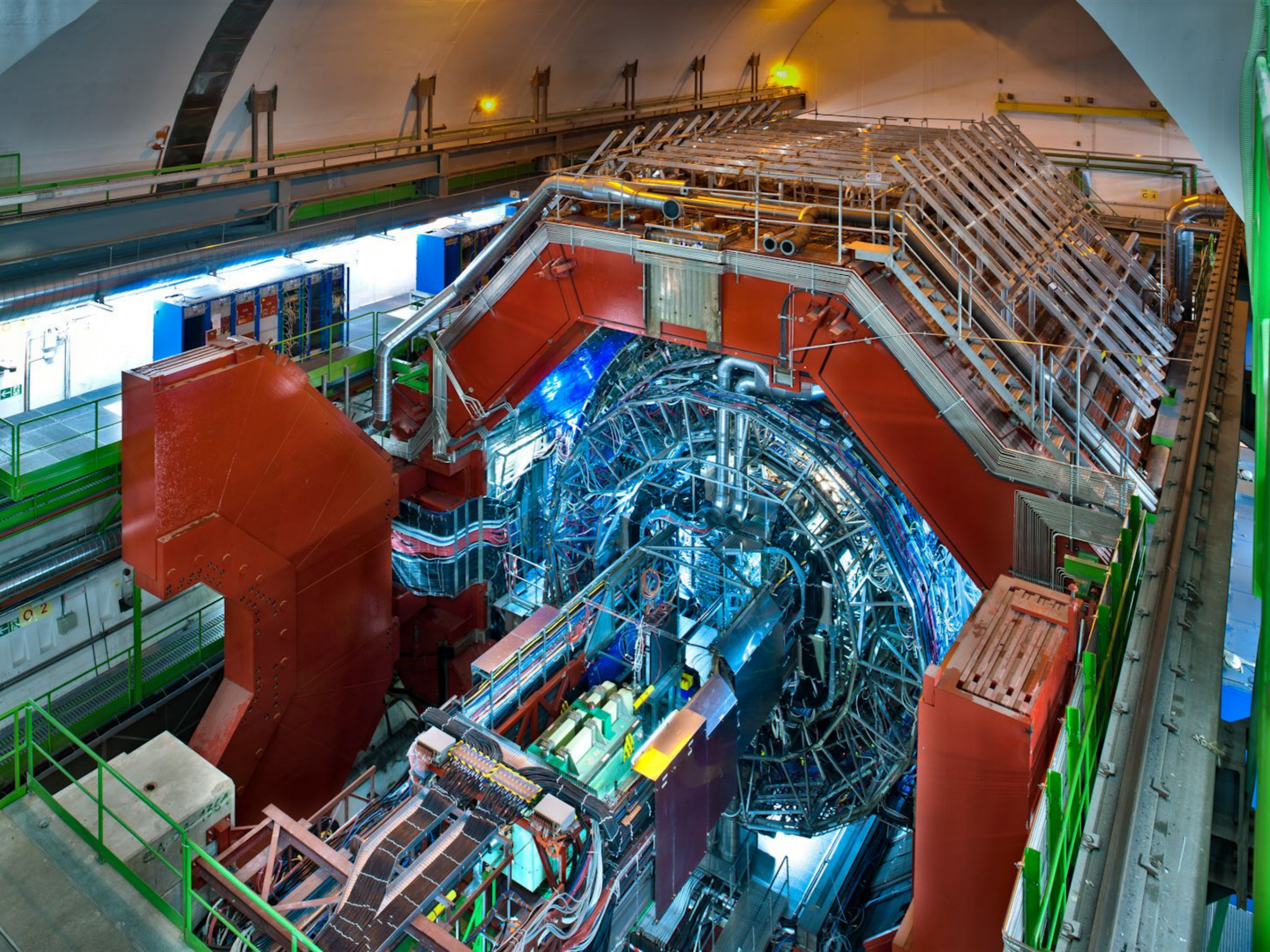


BB model + parameters









What is a liquid?

Gel, cream or paste



Make-up



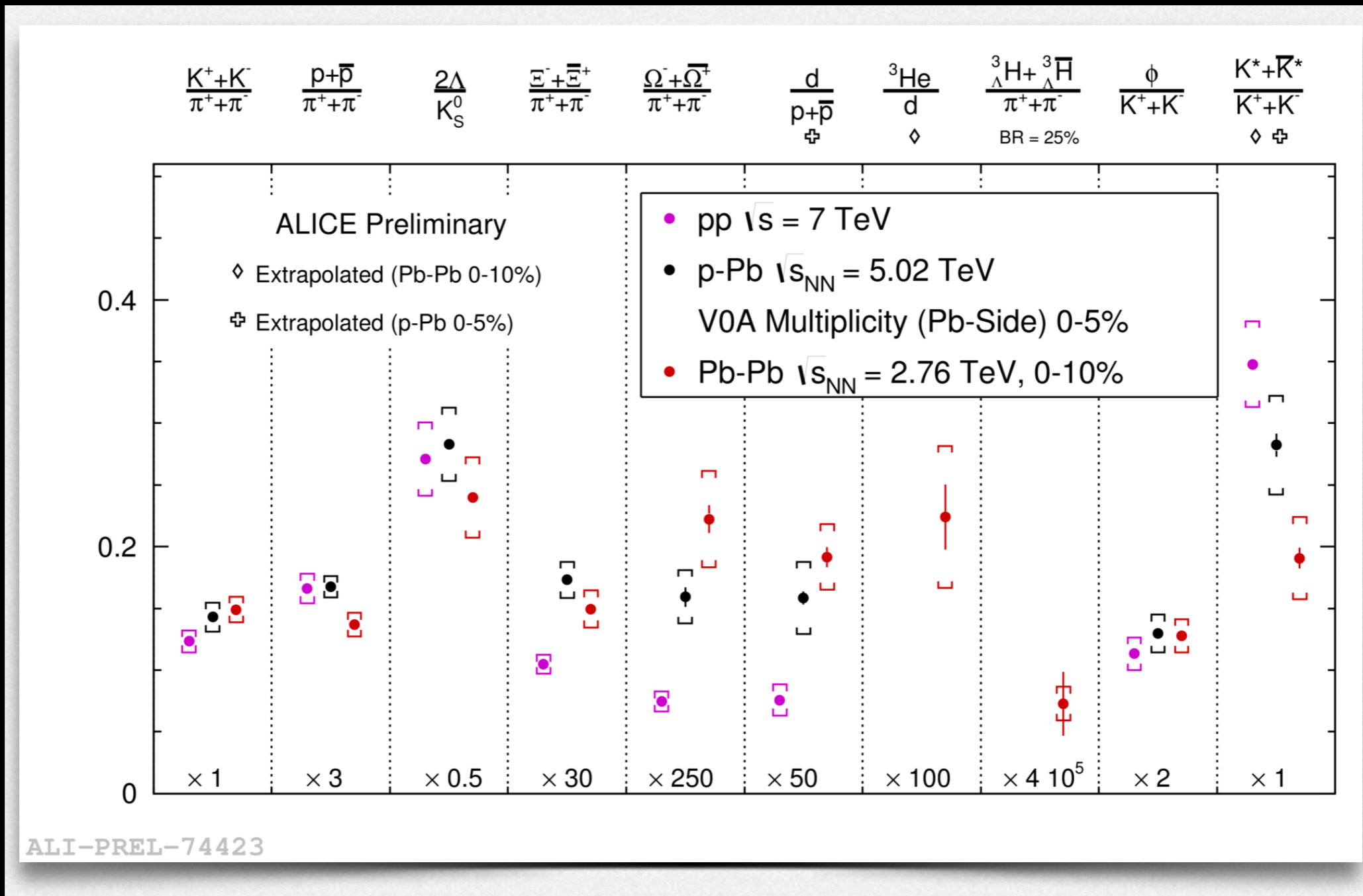
Toiletries



Drinks



hadrons production



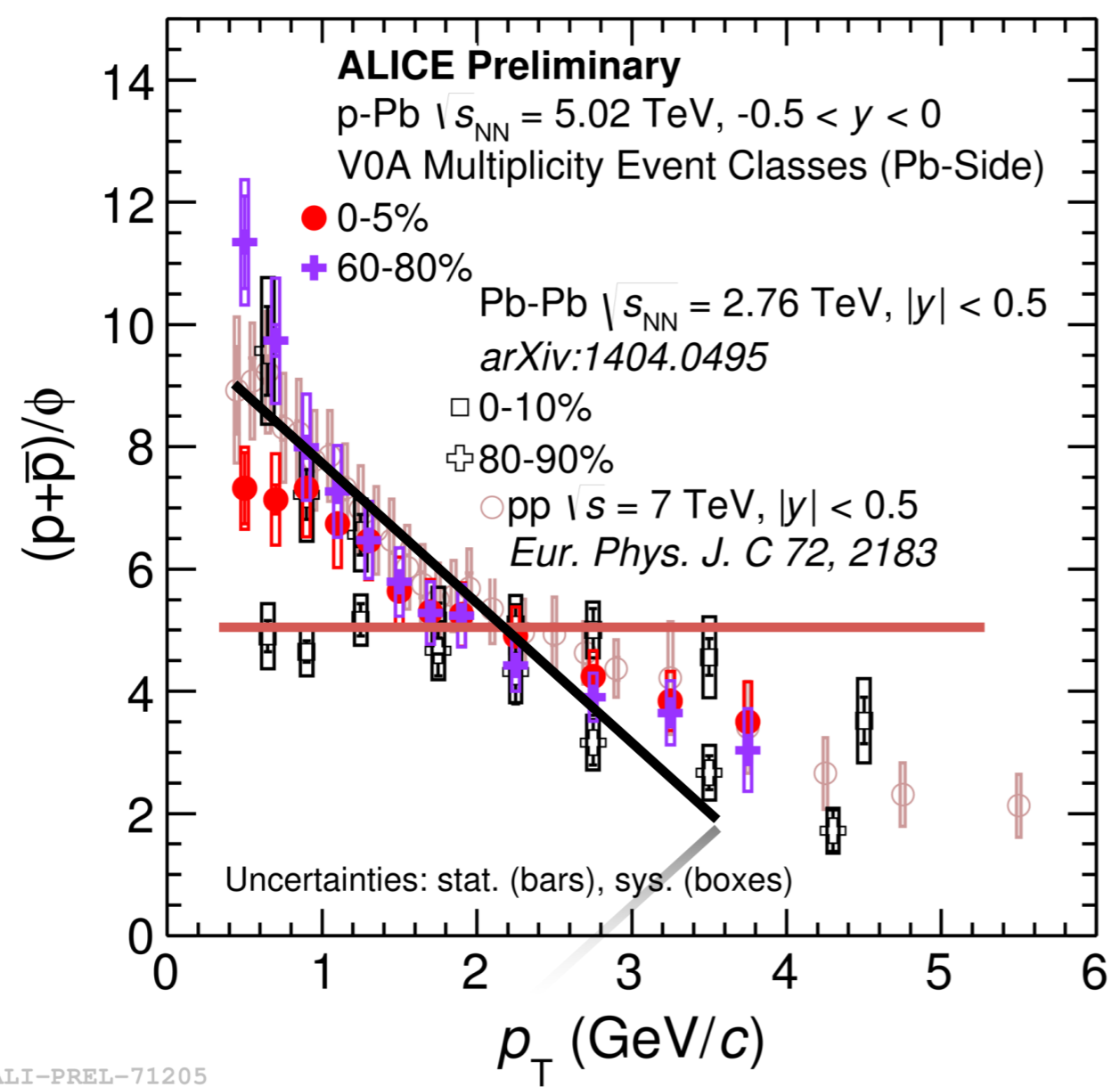
S enhancement,
K* suppression

OK

p suppression,
d enhancement

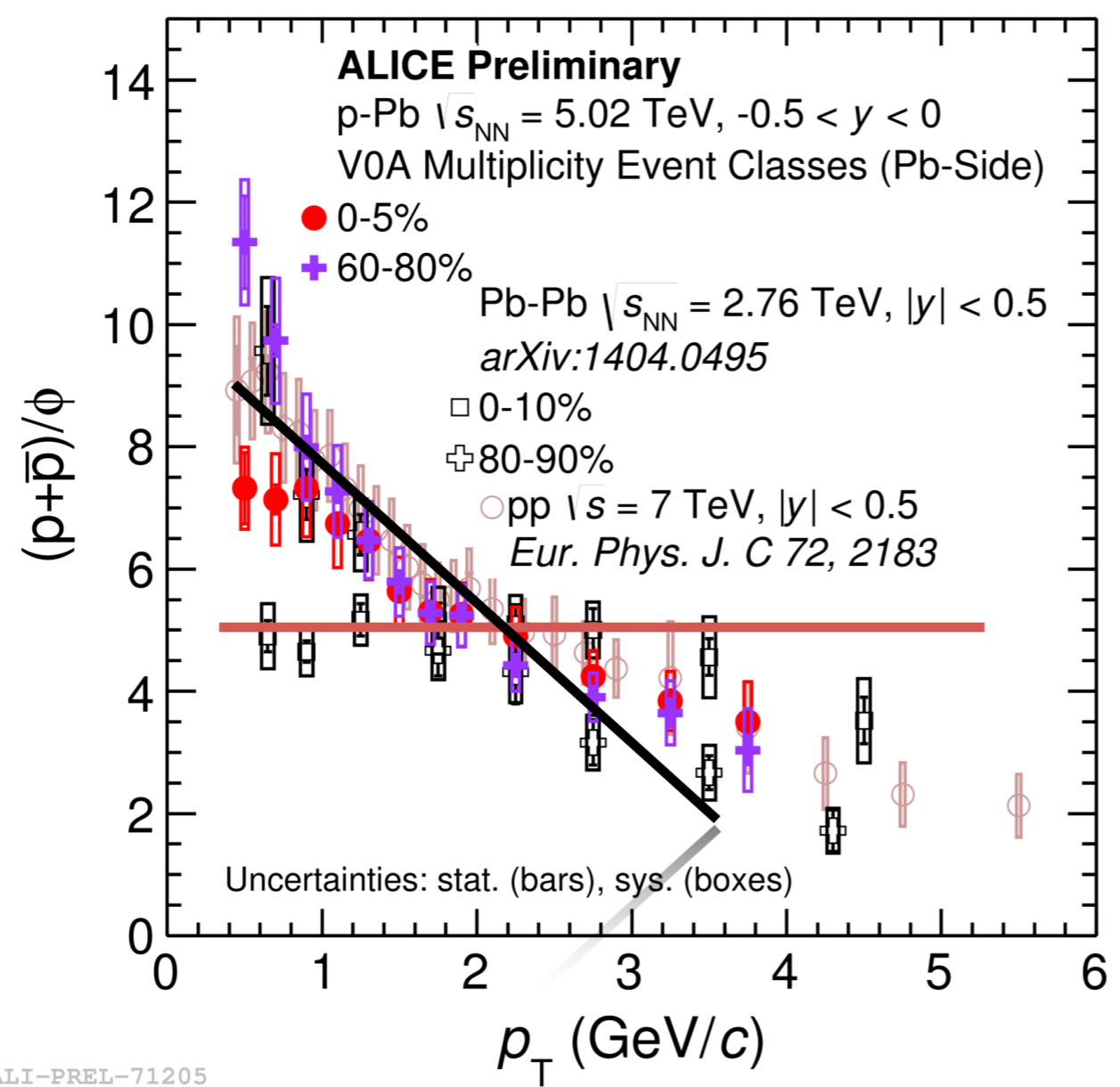
!!!

Baryon & Meson



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

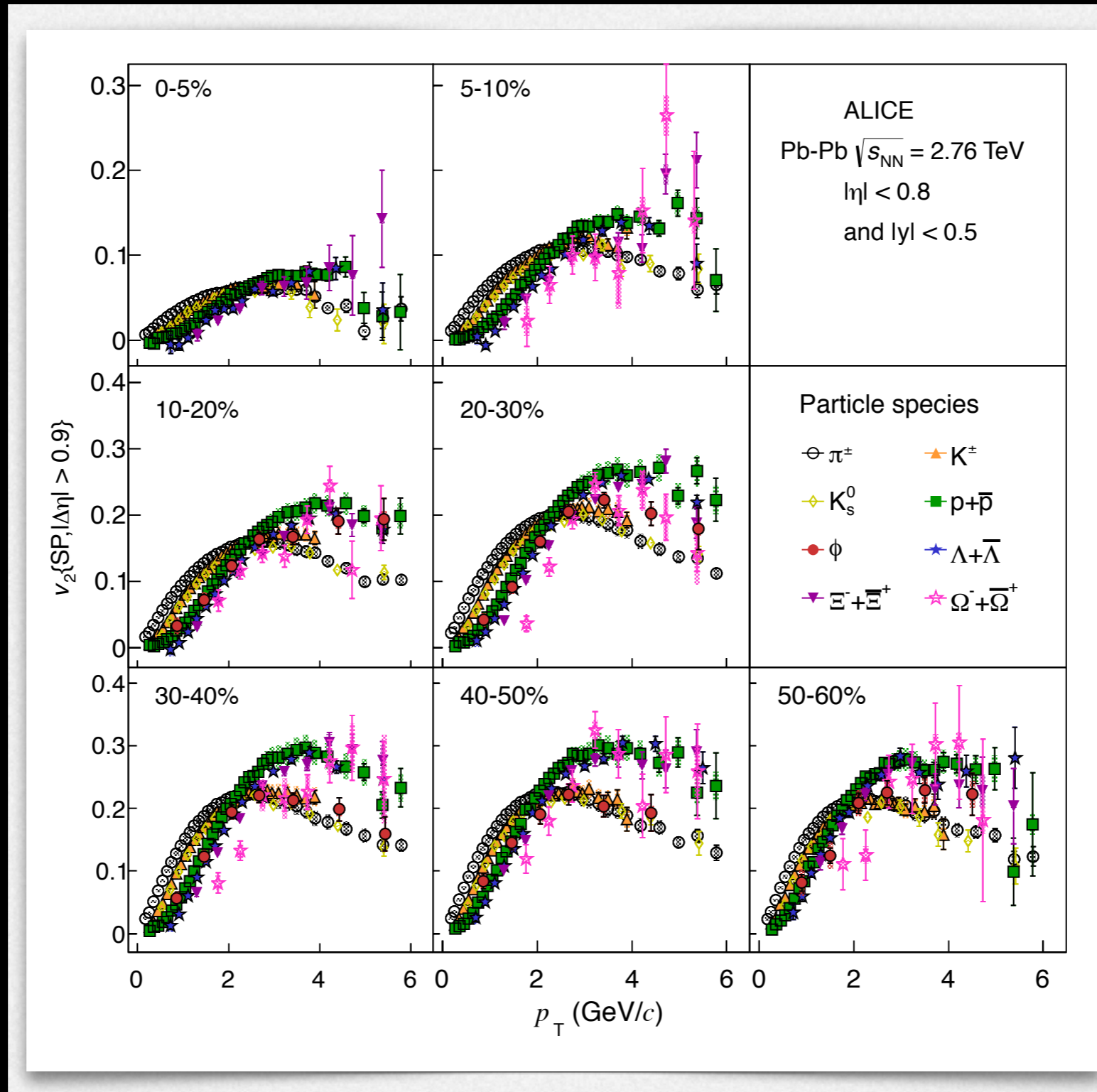
Baryon & Meson



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

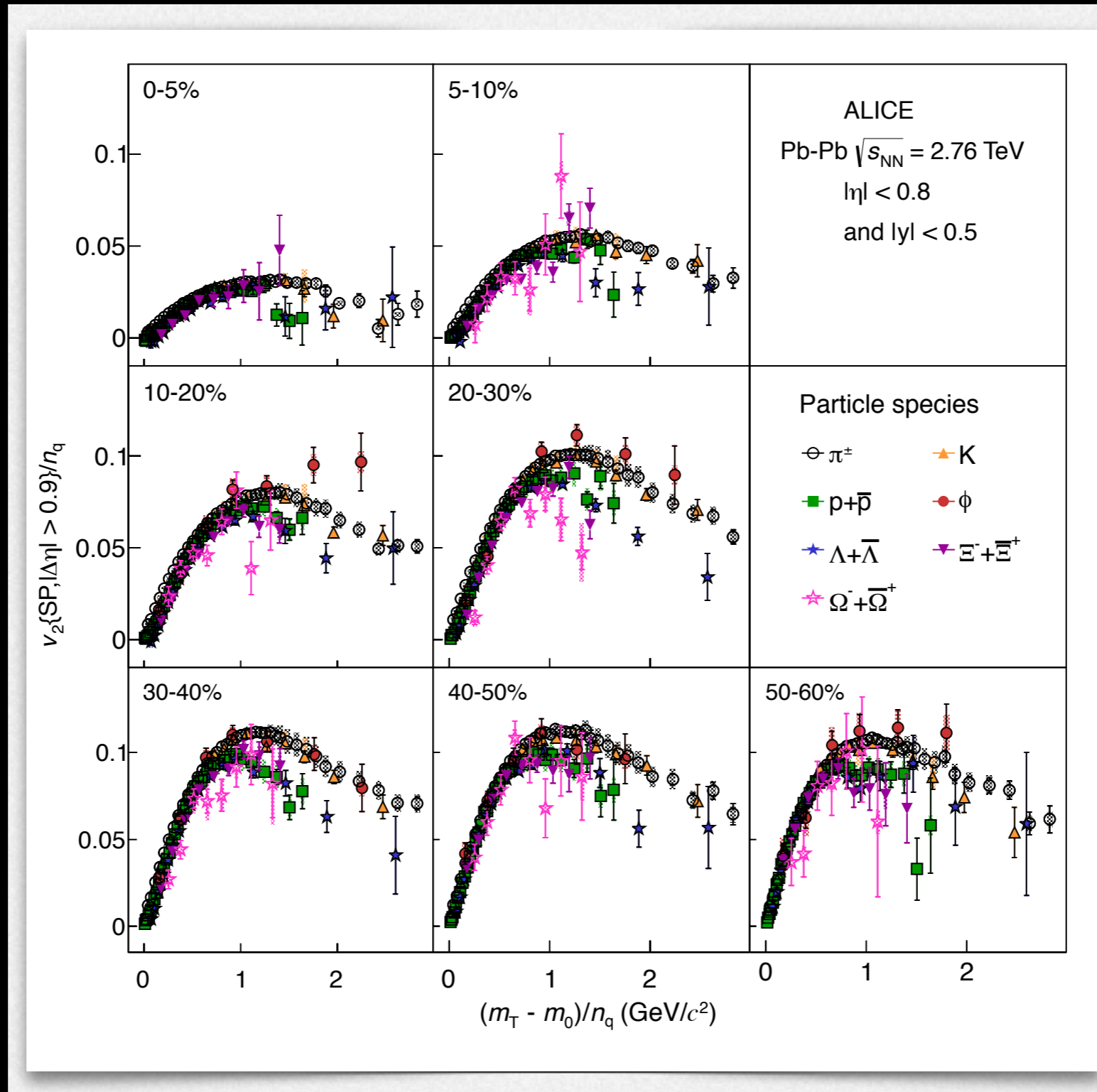
Mass rather than quark content

Elliptic flow



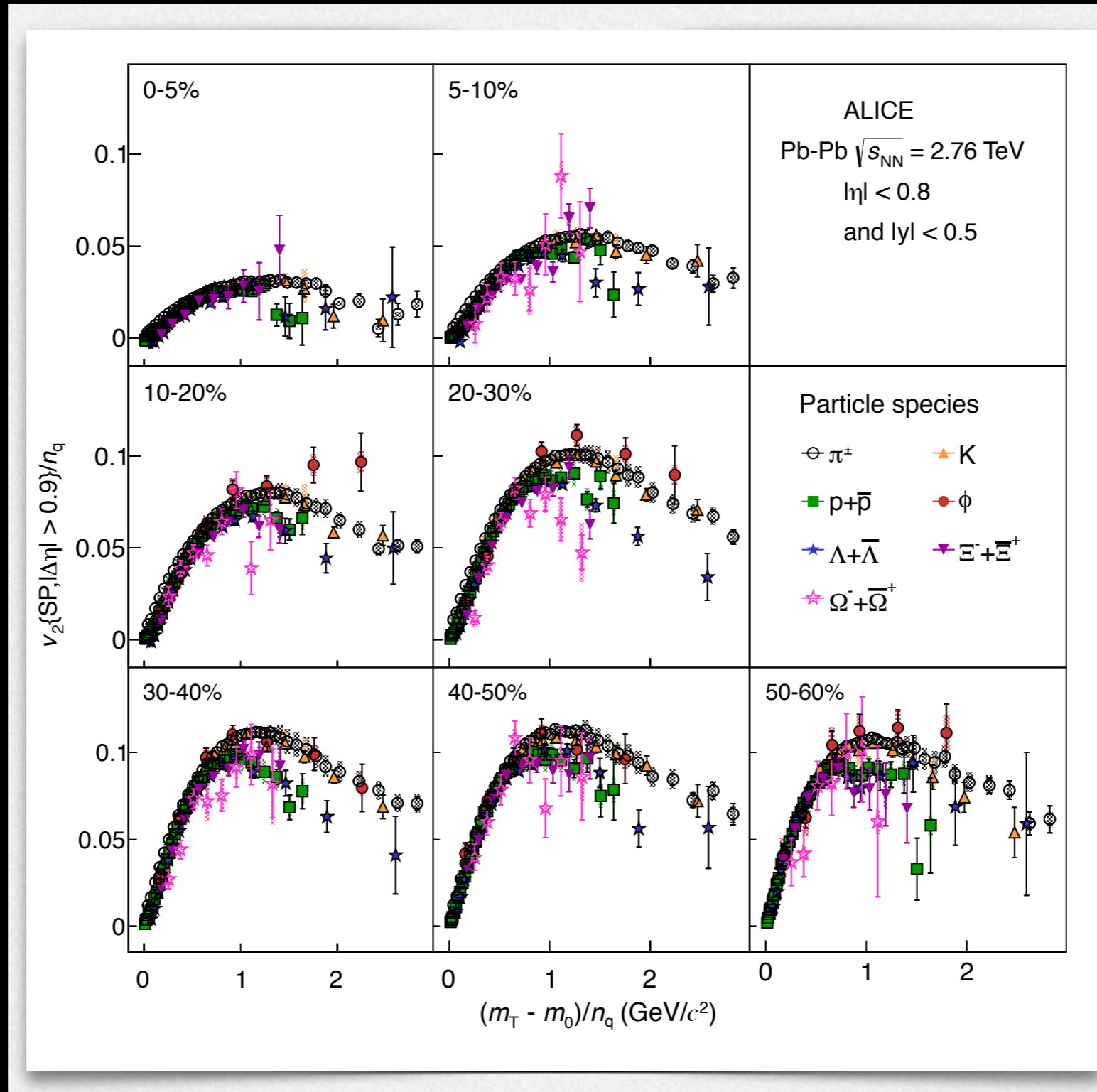
hadronization through q coalescence \rightarrow q DoF at $T > T_H$?

Elliptic flow

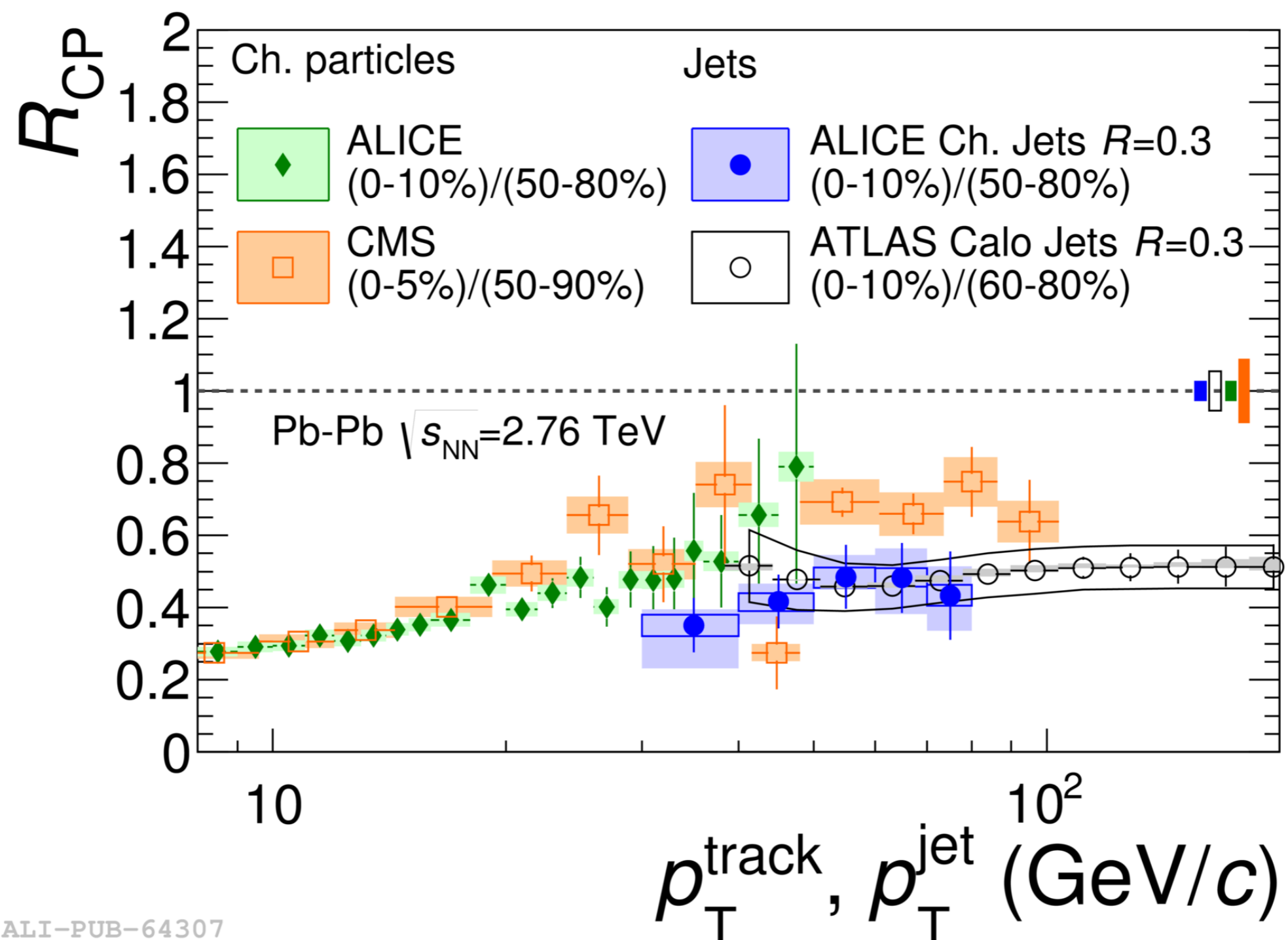


hadronization through q coalescence \rightarrow q DoF at $T > T_H$?

Elliptic flow



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

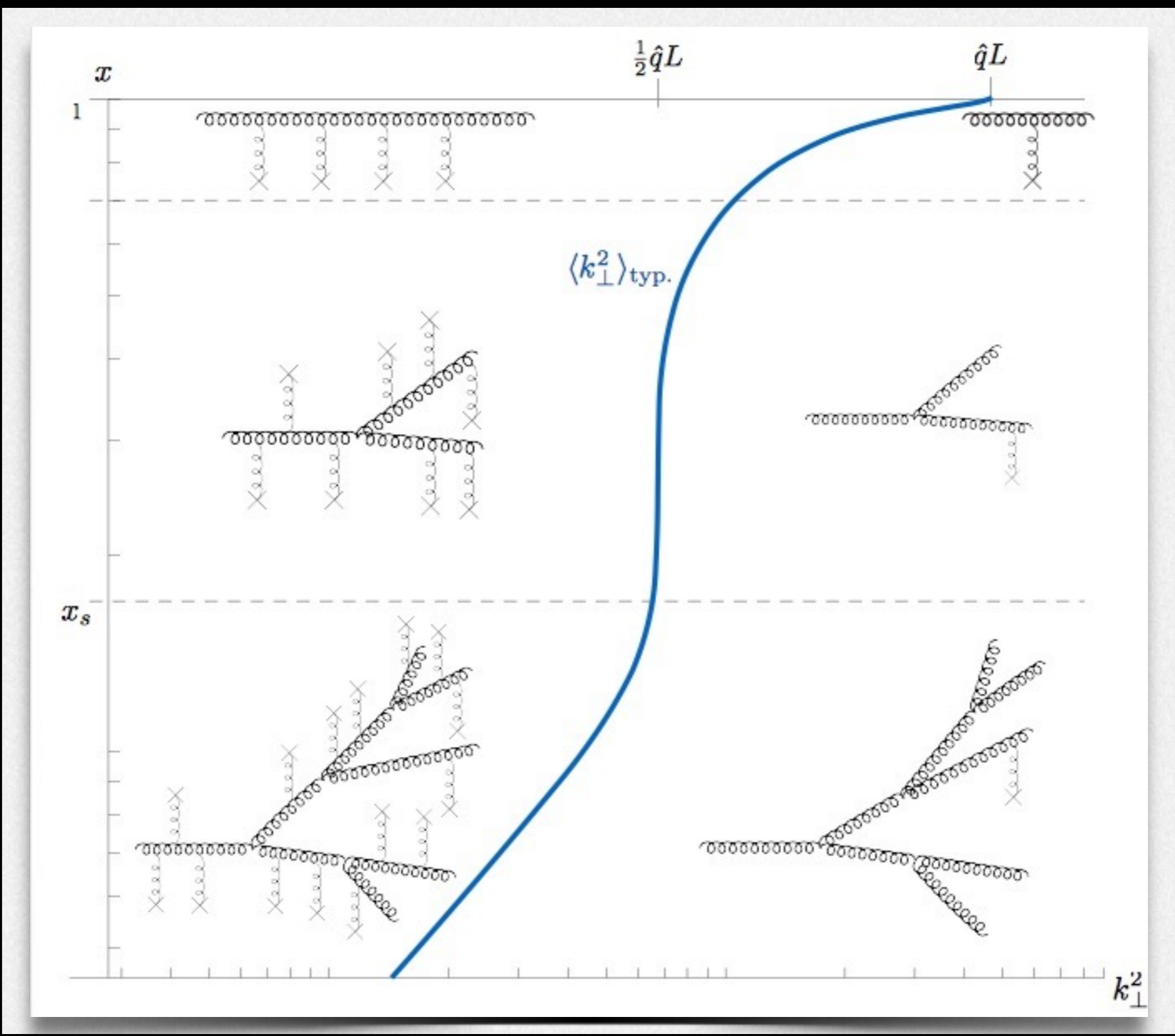


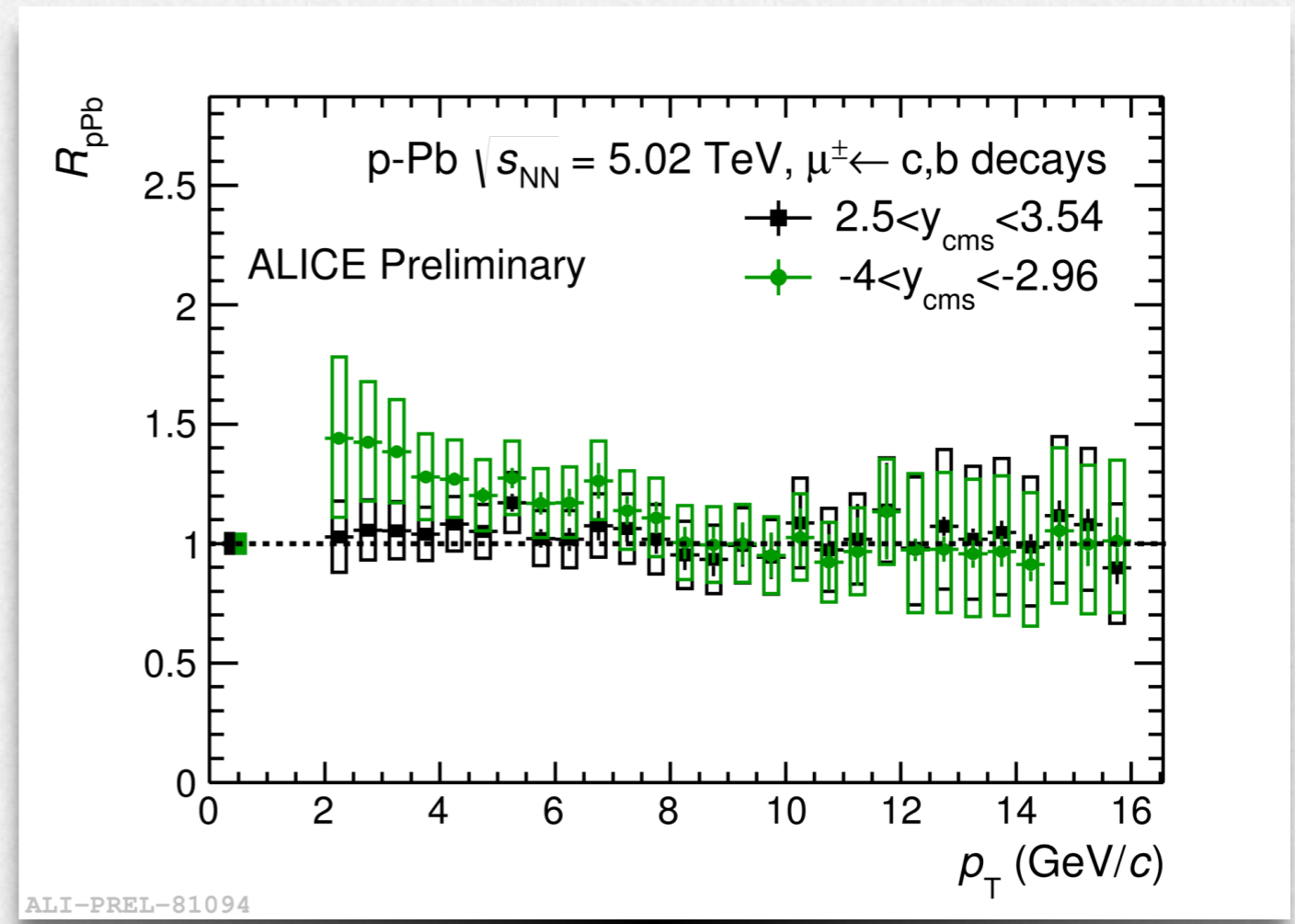
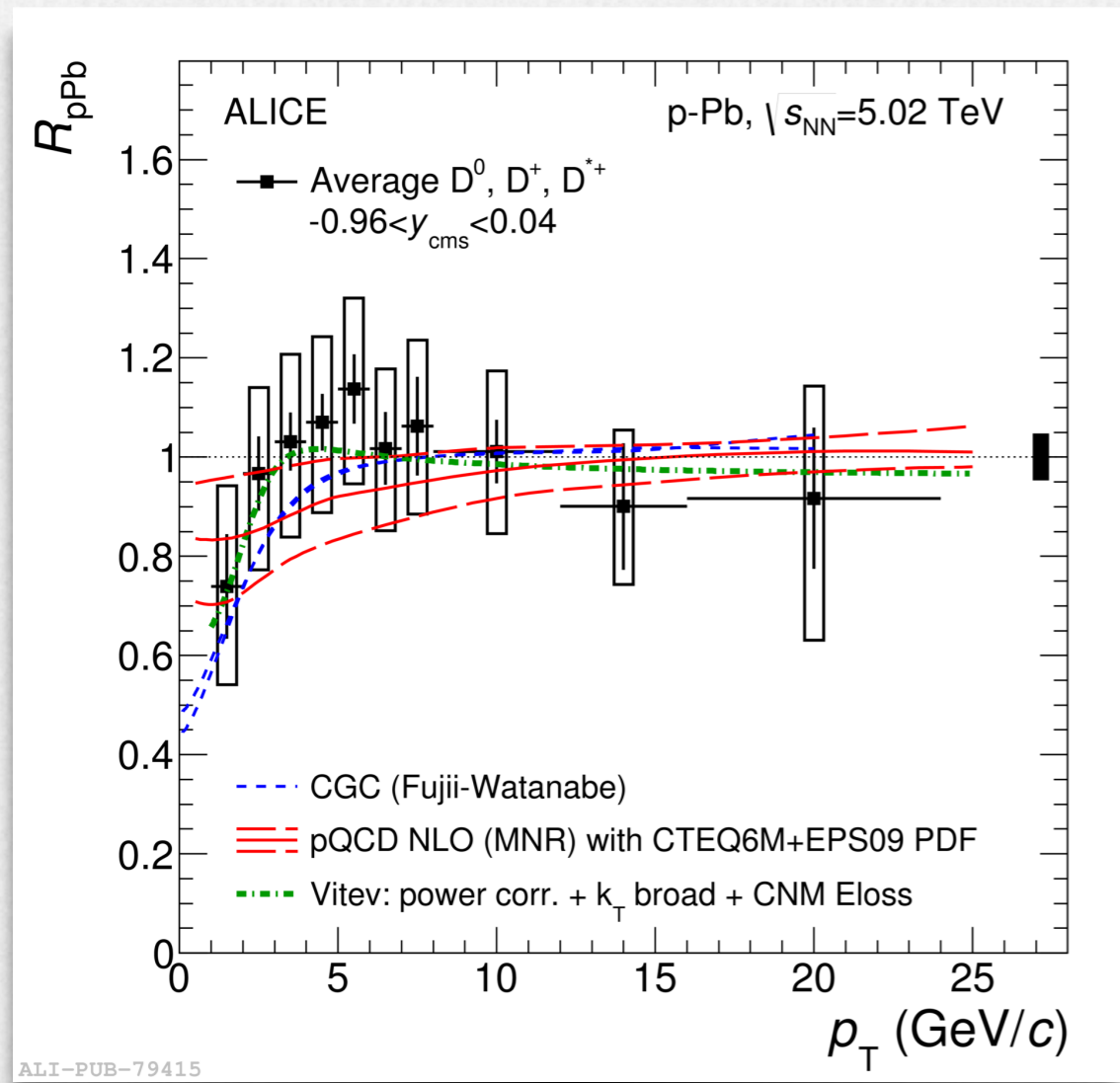
ALI-PUB-64307

jets follow trend of leading hadron

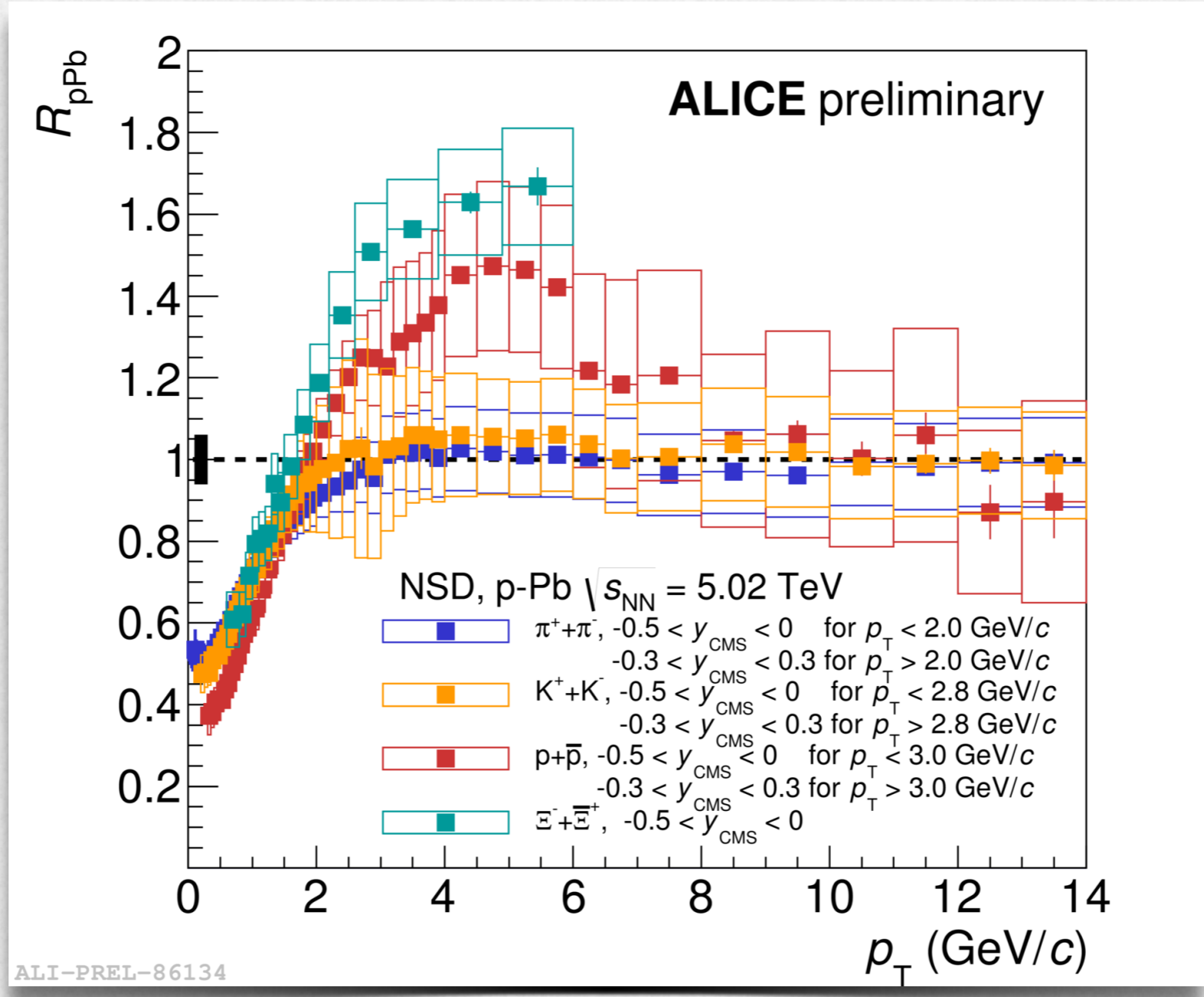
« Theorist's idealization of jet transport »

- Jean-Paul Blaizot, 2014 -





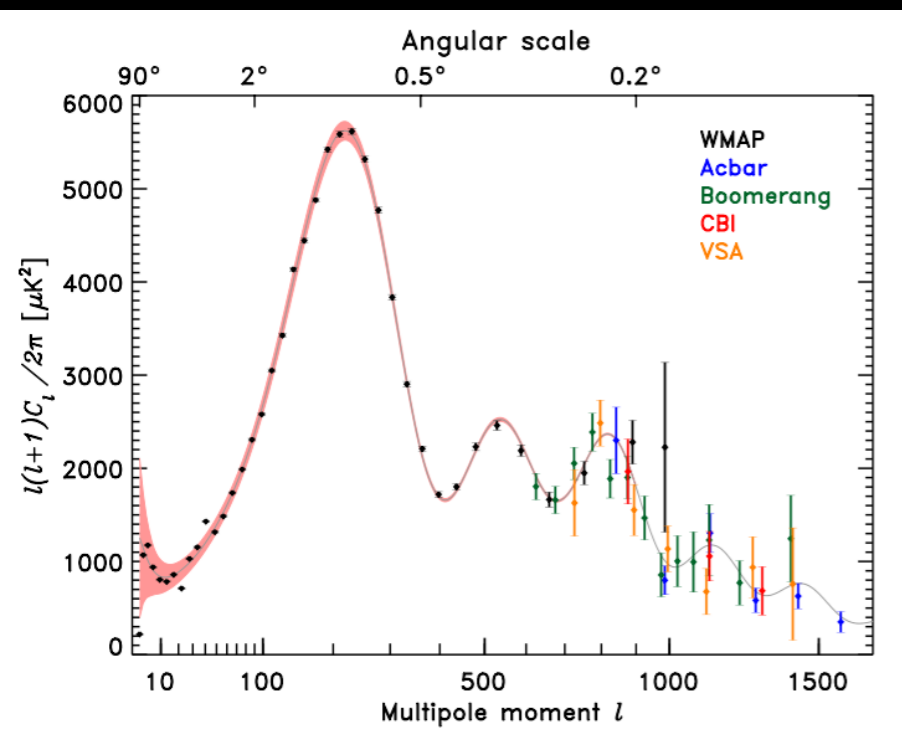
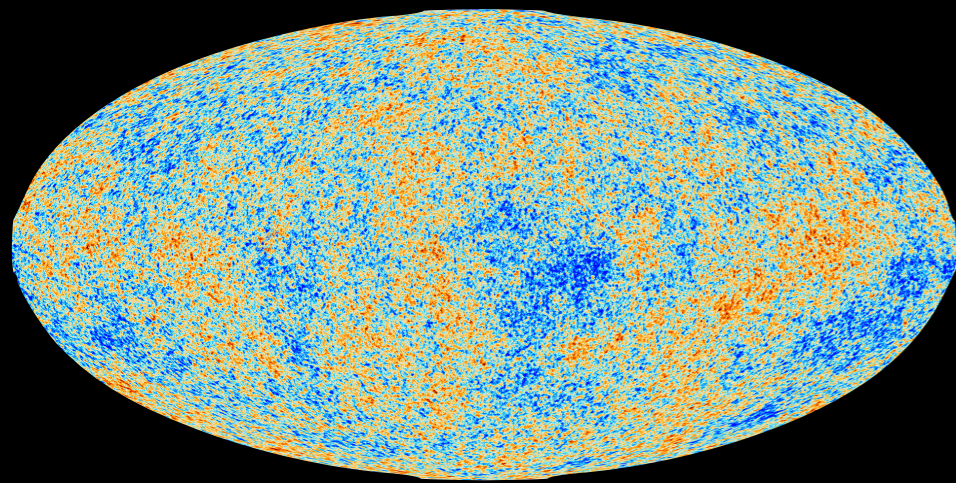
No medium final state effect in pPb ??



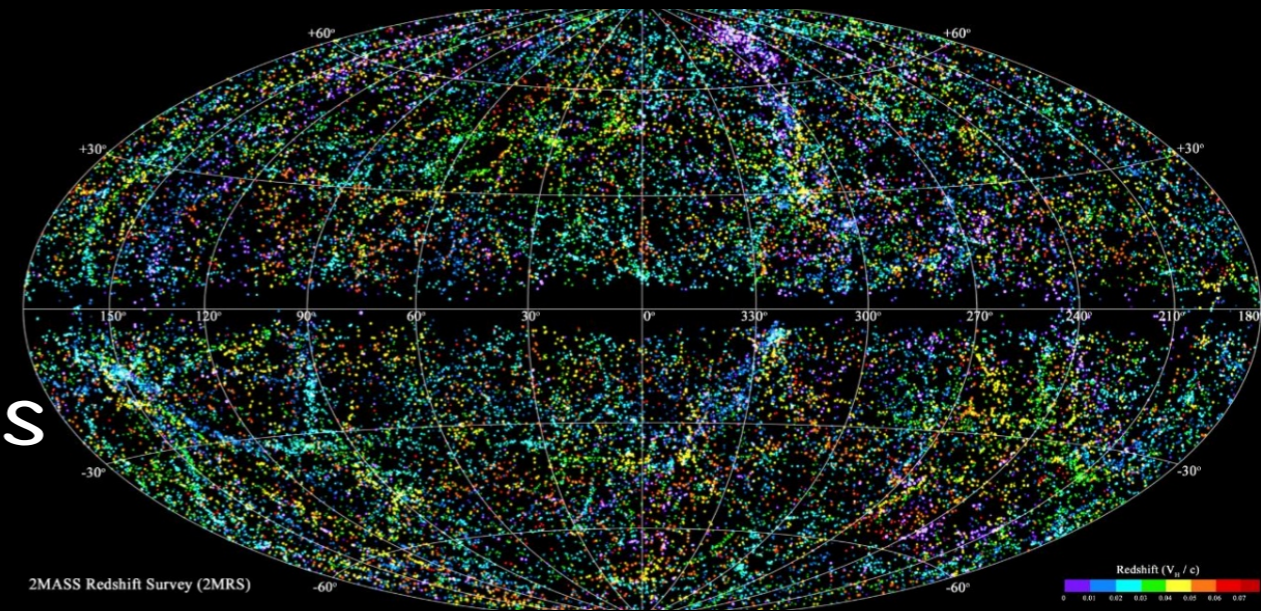
Another manifestation of transverse flow

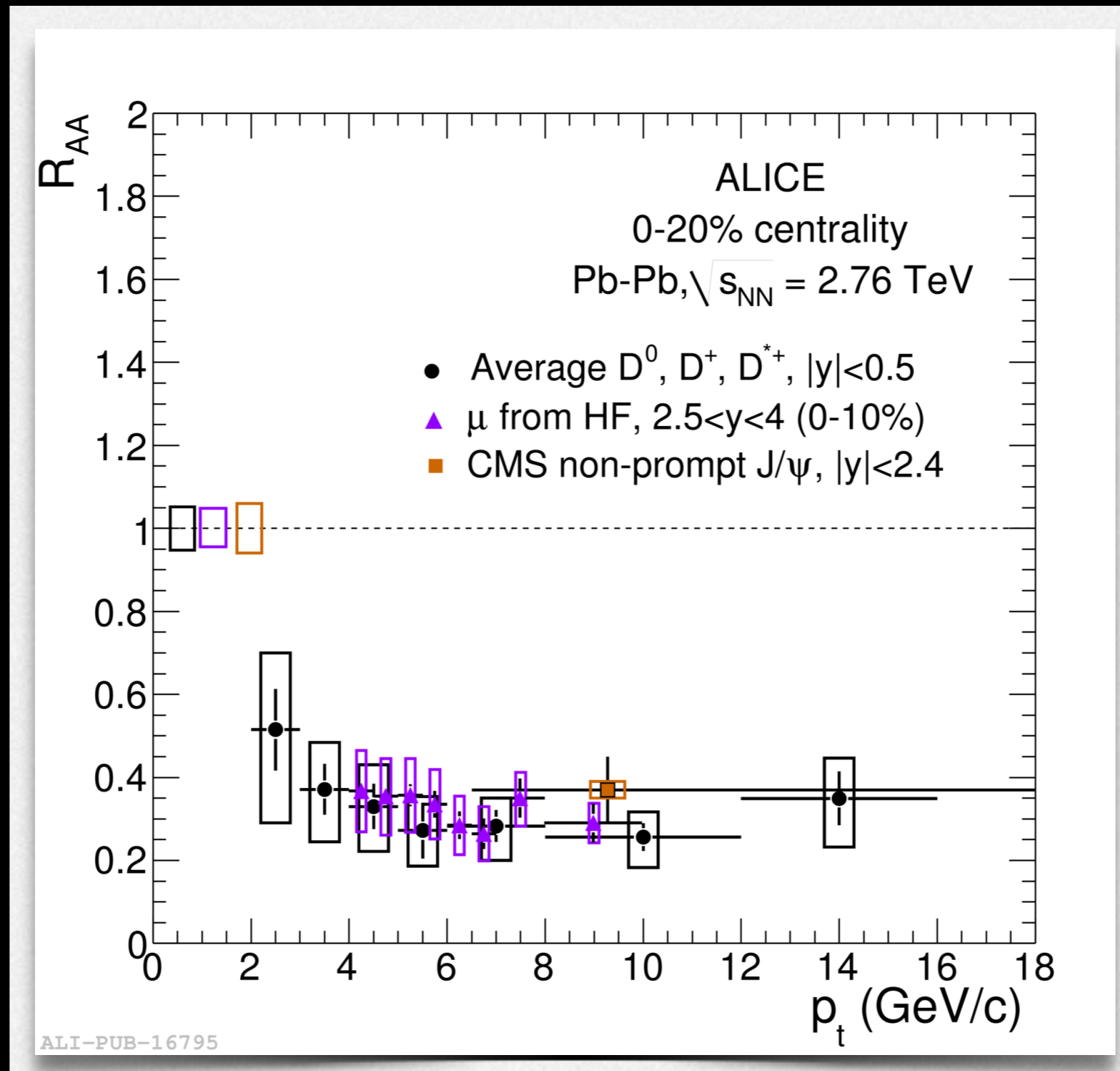
a parte

CMB - Big Bang - Universe

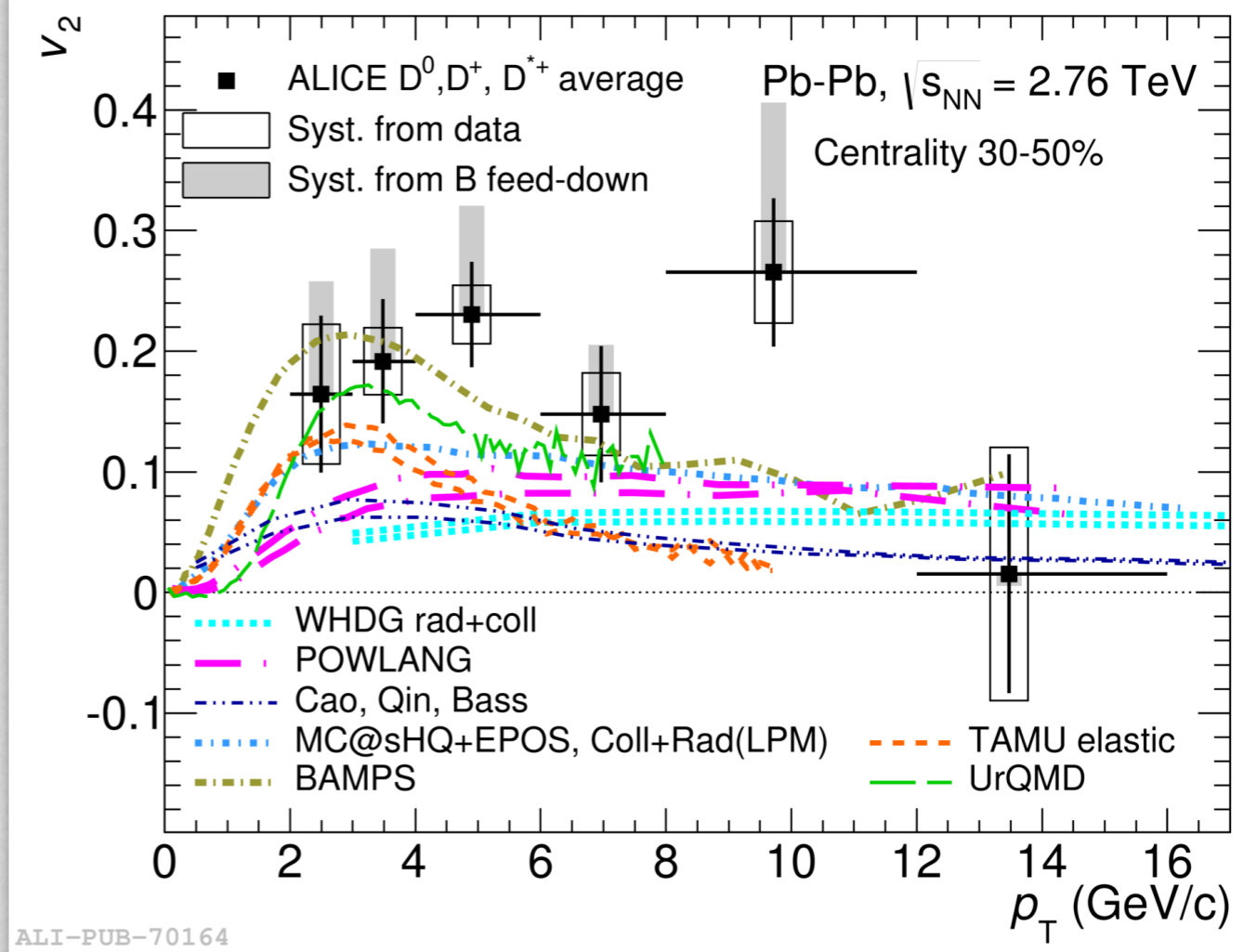
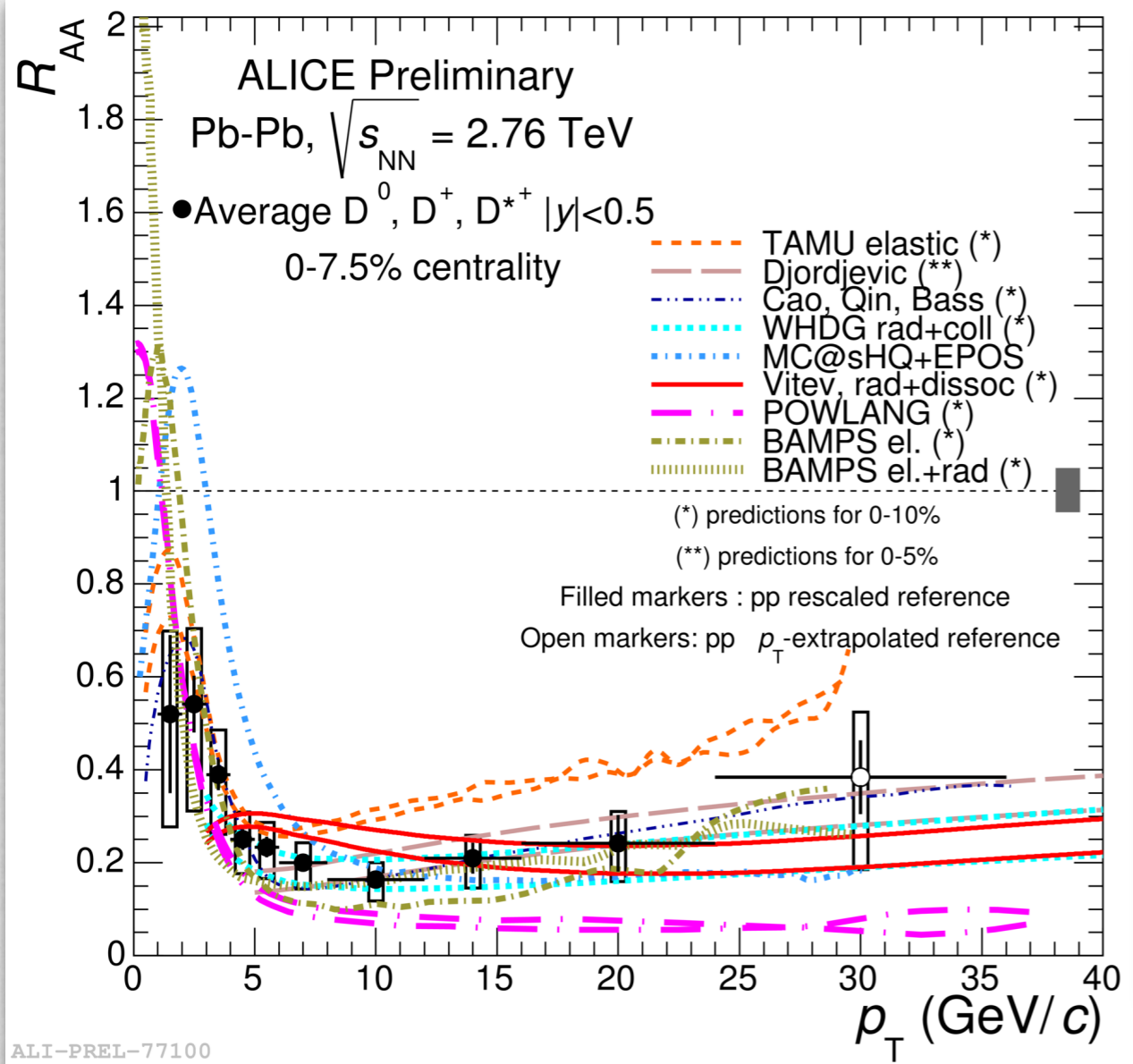


BB Model
+
parameters





Mass dependence (c vs b) ?



Challenging theory !