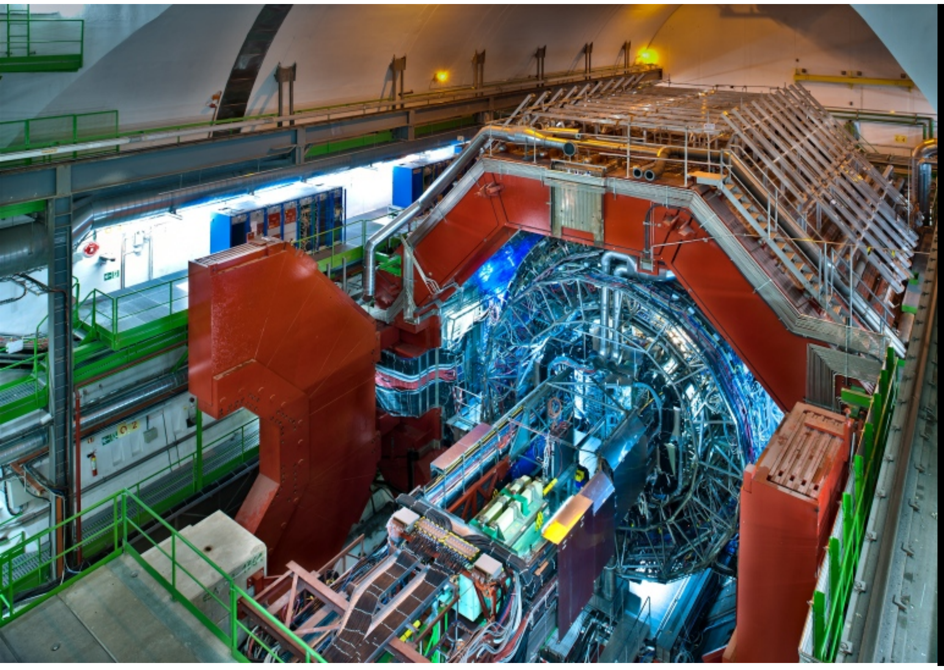
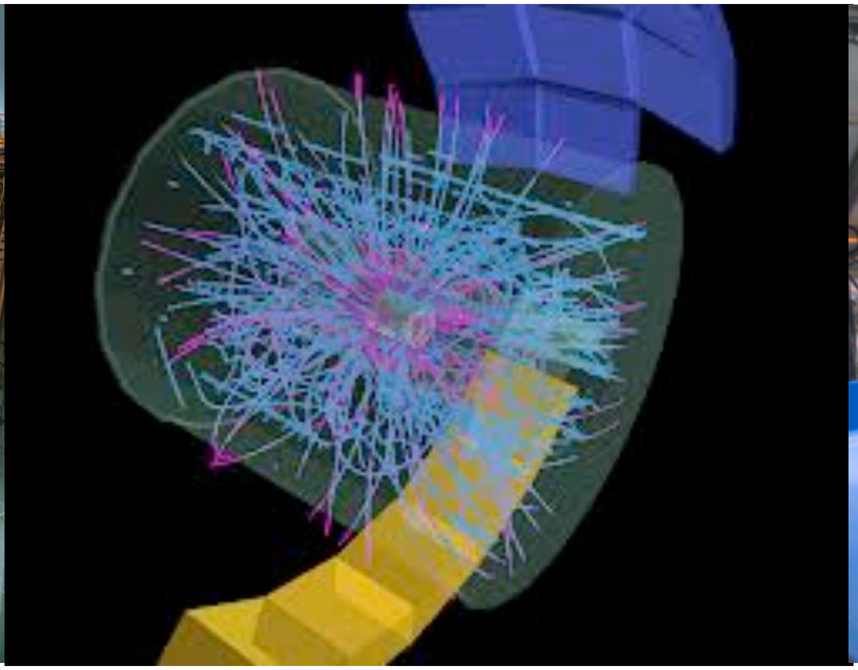
Light flavour physics at the LHC

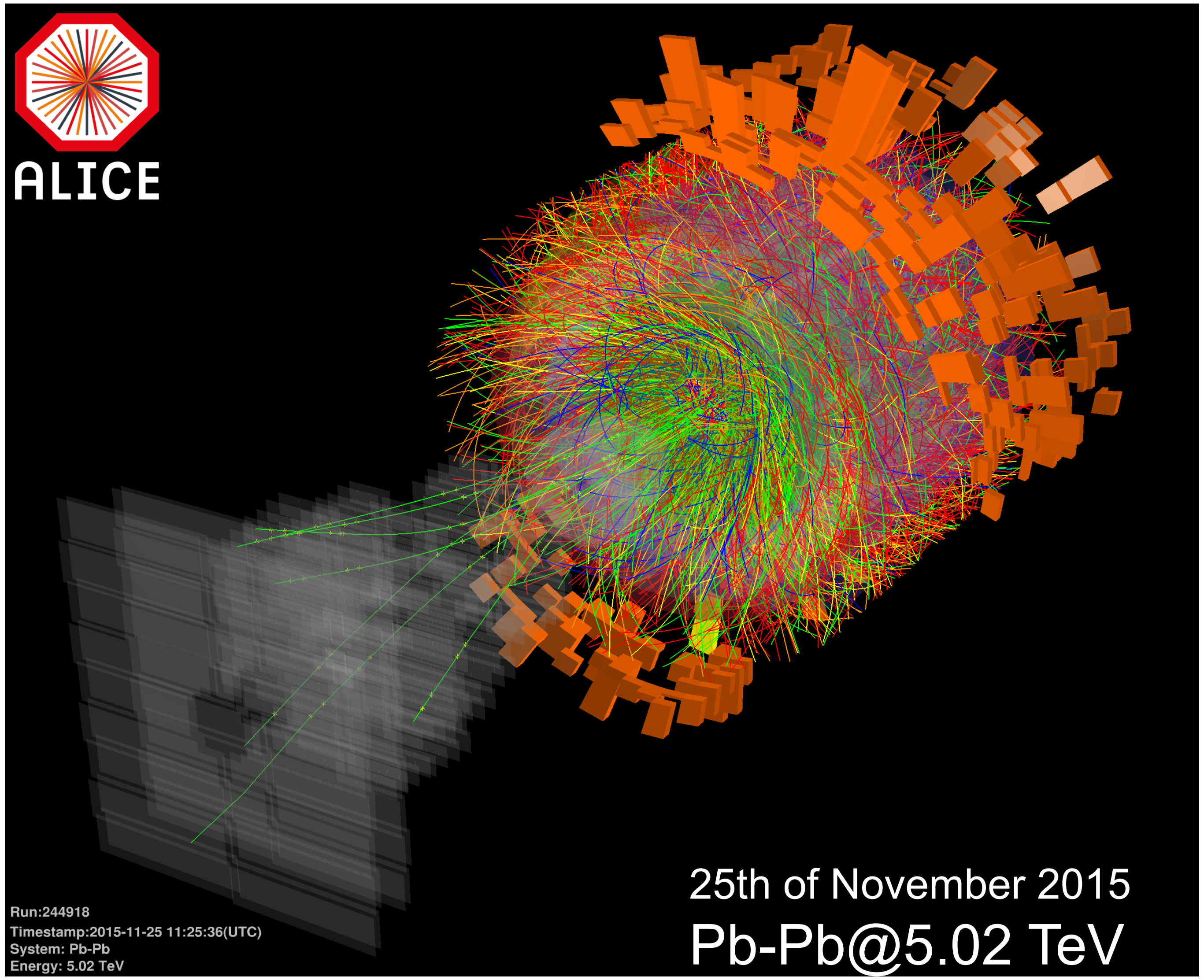
From equilibrium thermodynamics to chiral symmetry restoration


A. Kalweit, *CERN*

Introduction

- Production of light flavour hadrons in Pb-Pb collisions.
- Production of light flavour hadrons in small systems (pp,p-Pb).
- Event-by-event fluctuations in the production of light flavour hadrons.



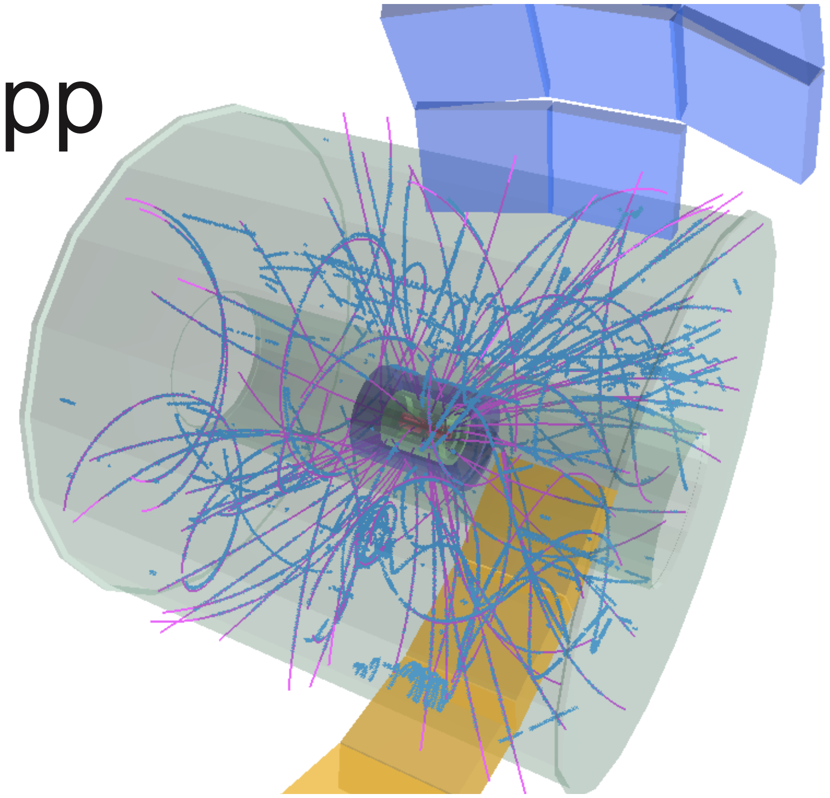
A fireball in thermal equilibrium

- It is important to distinguish between
  - a *system of individual particles* and
  - a *medium* in which individual degrees of freedom do not matter anymore and we can apply thermodynamic concepts.

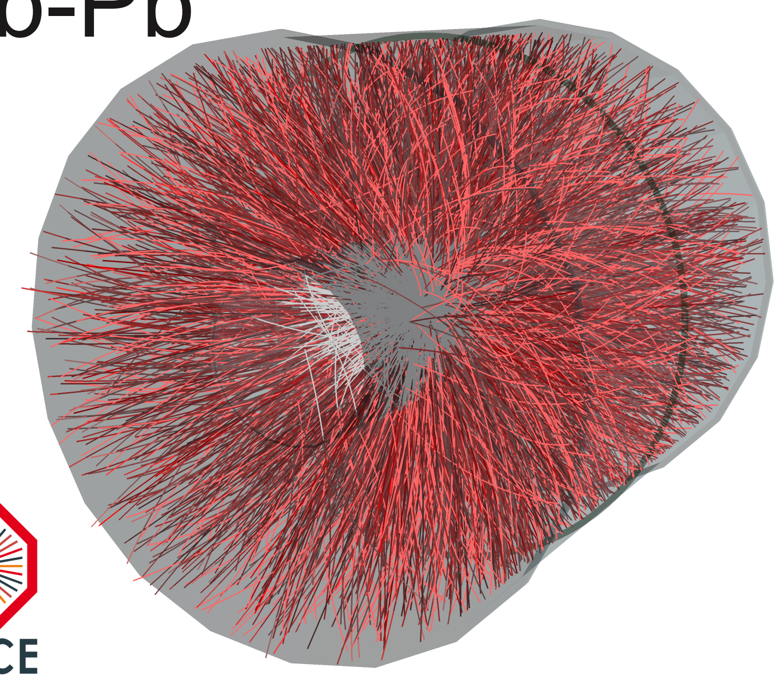
- Thermodynamic concepts are typically used for systems with 10^5-10^{23} particles in *local thermal equilibrium*.
  - central Pb-Pb collision 2.76 TeV (LHC): $dN_{ch}/d\eta \approx 1600$
  - high mult. p-Pb collision (LHC): $dN_{ch}/d\eta \approx 60$
  - pp collision 7 TeV (LHC): $dN_{ch}/d\eta \approx 6$

- Lifetime of the system must be long enough so that equilibrium can be established by several (simulations indicate 5-6) interactions between its constituents.

pp



Pb-Pb



ALICE
A JOURNEY OF DISCOVERY

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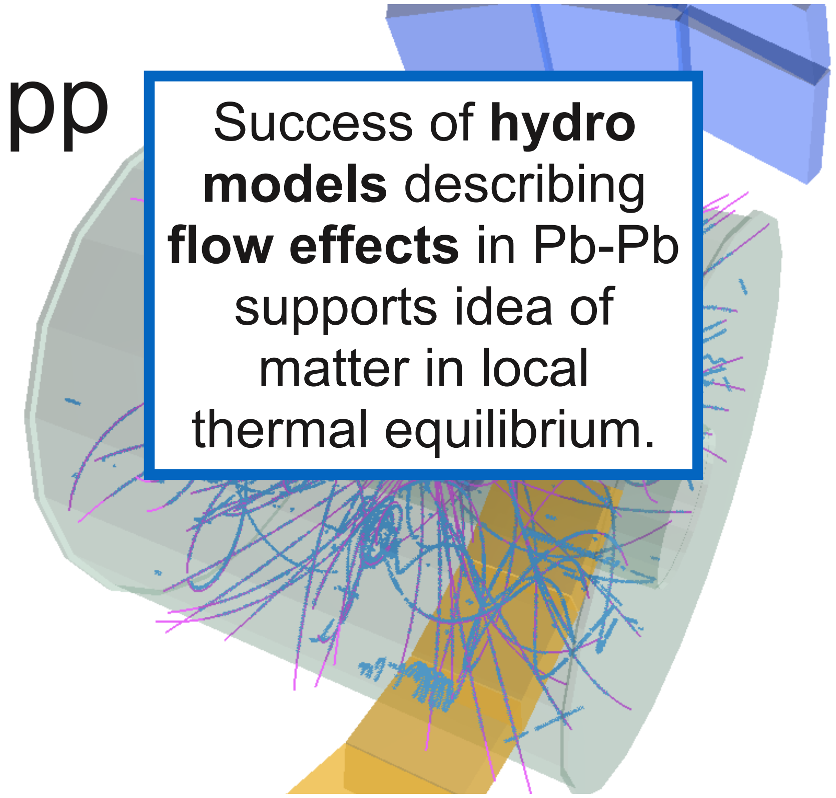

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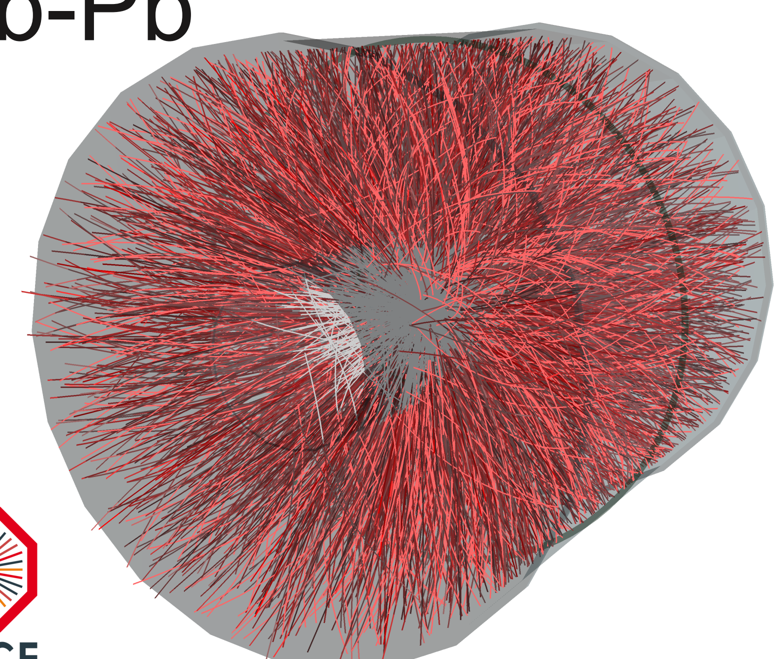

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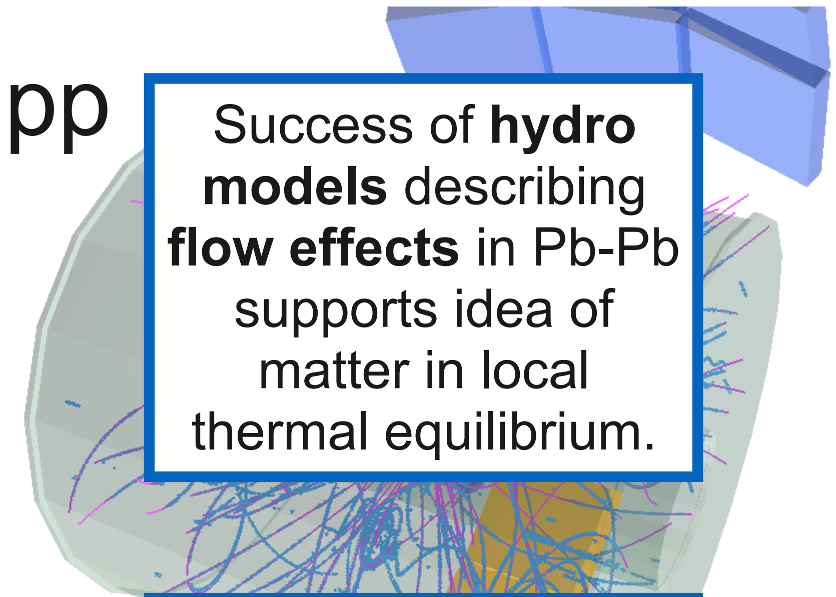

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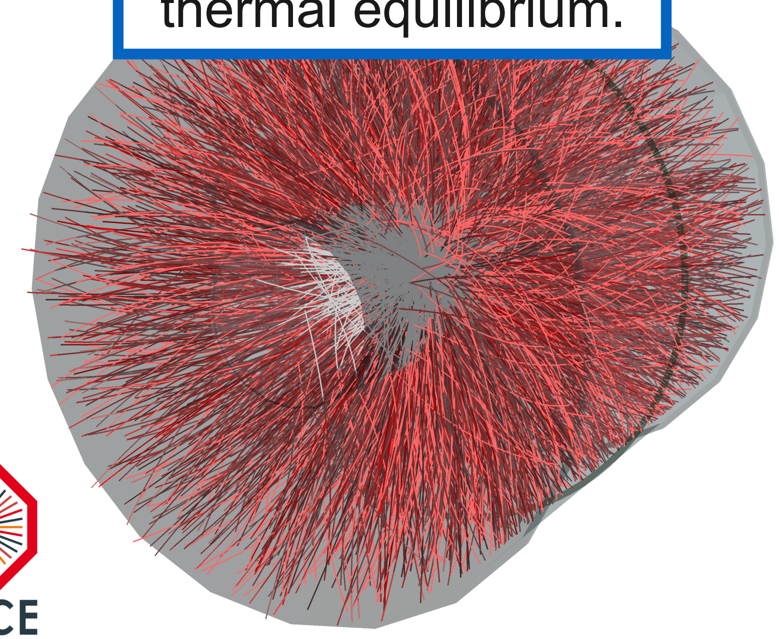
Pb-P



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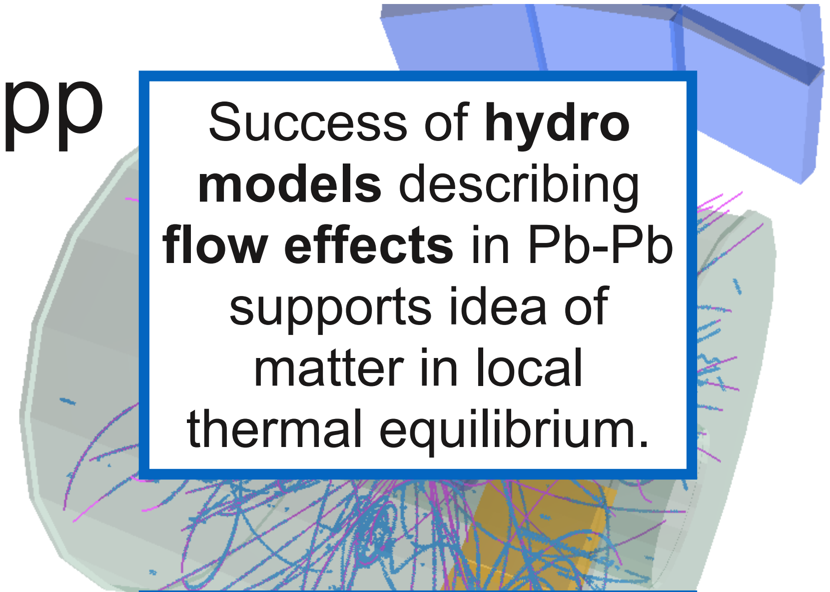

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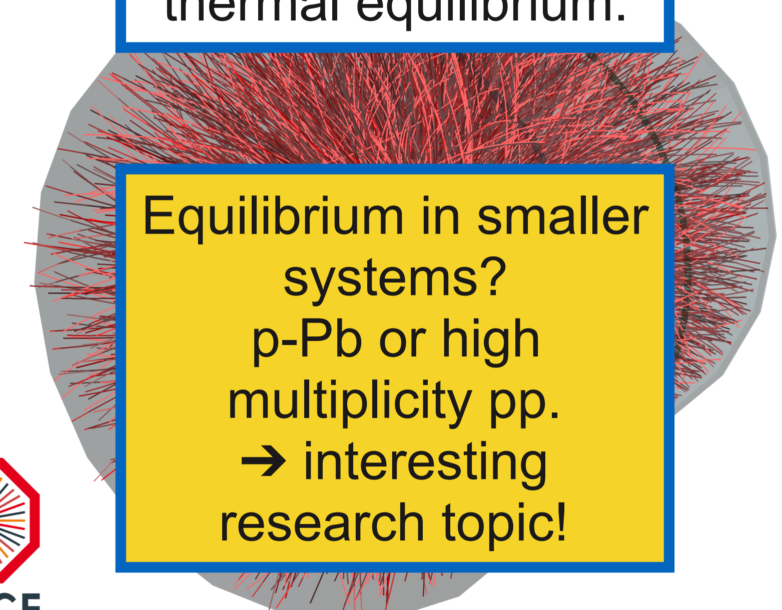
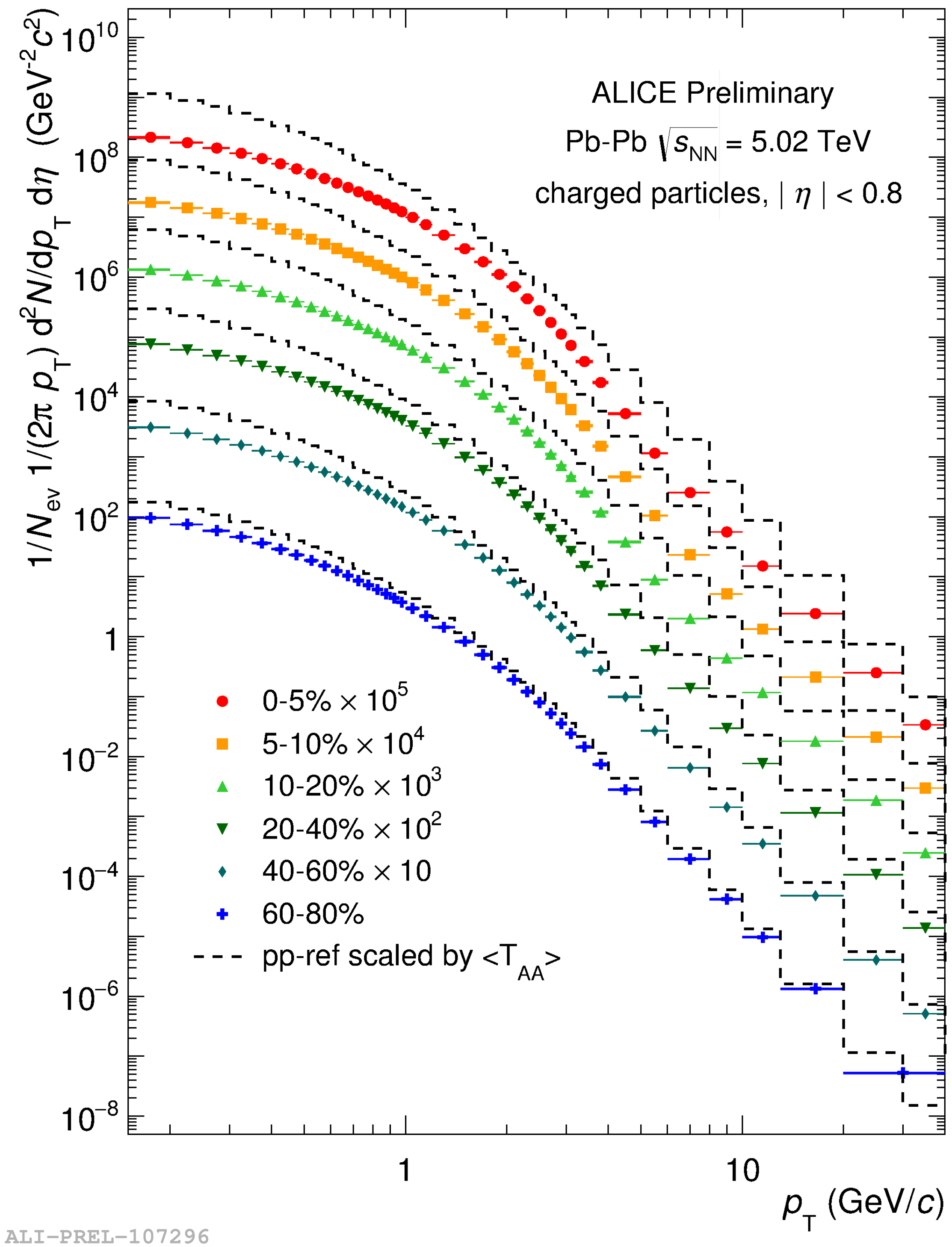


Equilibrium in smaller systems? p-Pb or high multiplicity pp. ➔ interesting research topic!

ALICE
A JOURNEY OF DISCOVERY

Bulk particle production and collectivity

- Low p_T hadrons composed of **(u,d,s)** valence quarks define the collective behaviour of the fireball.



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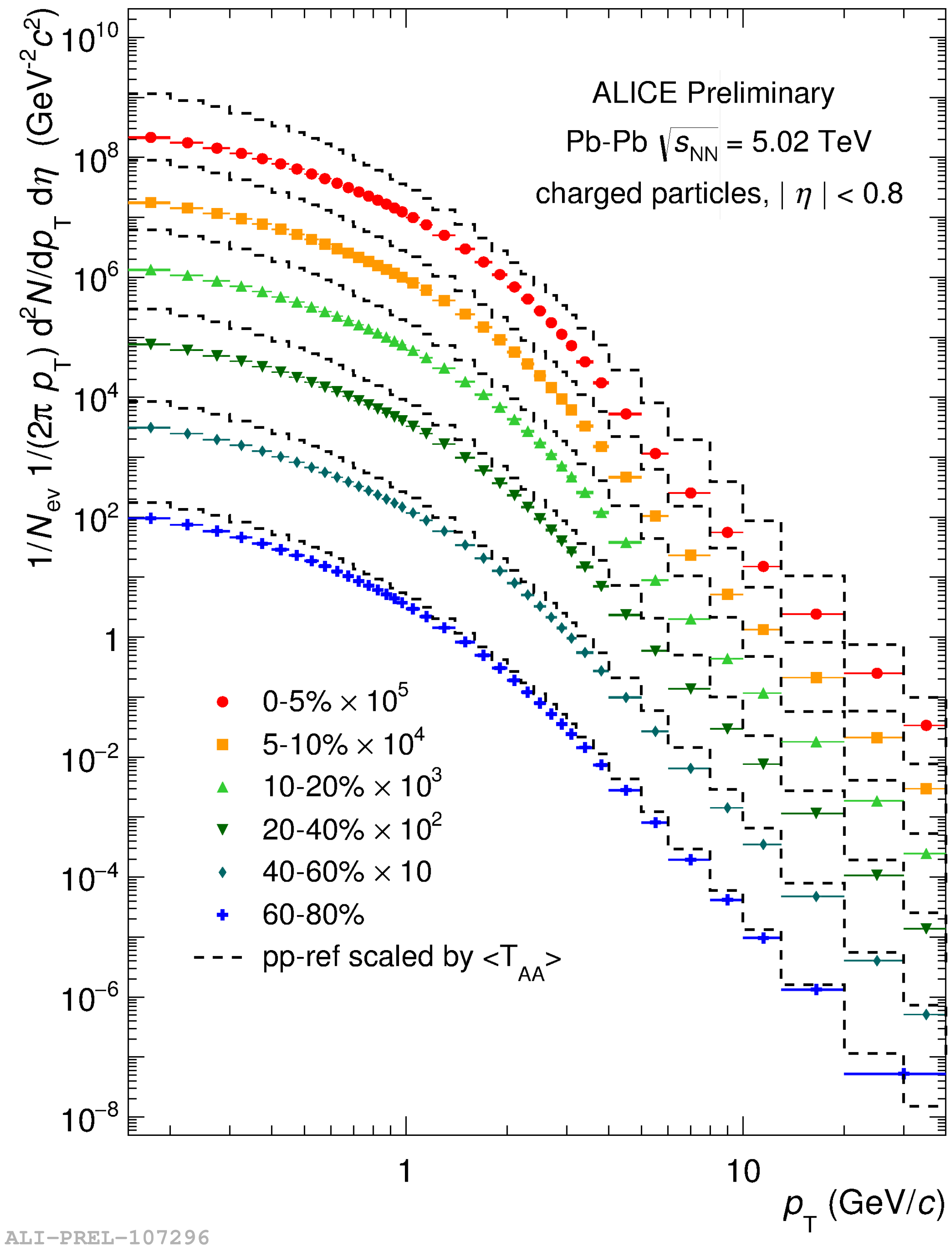
≈ 98% of all particles are produced with p_T < 2 GeV/*c*.



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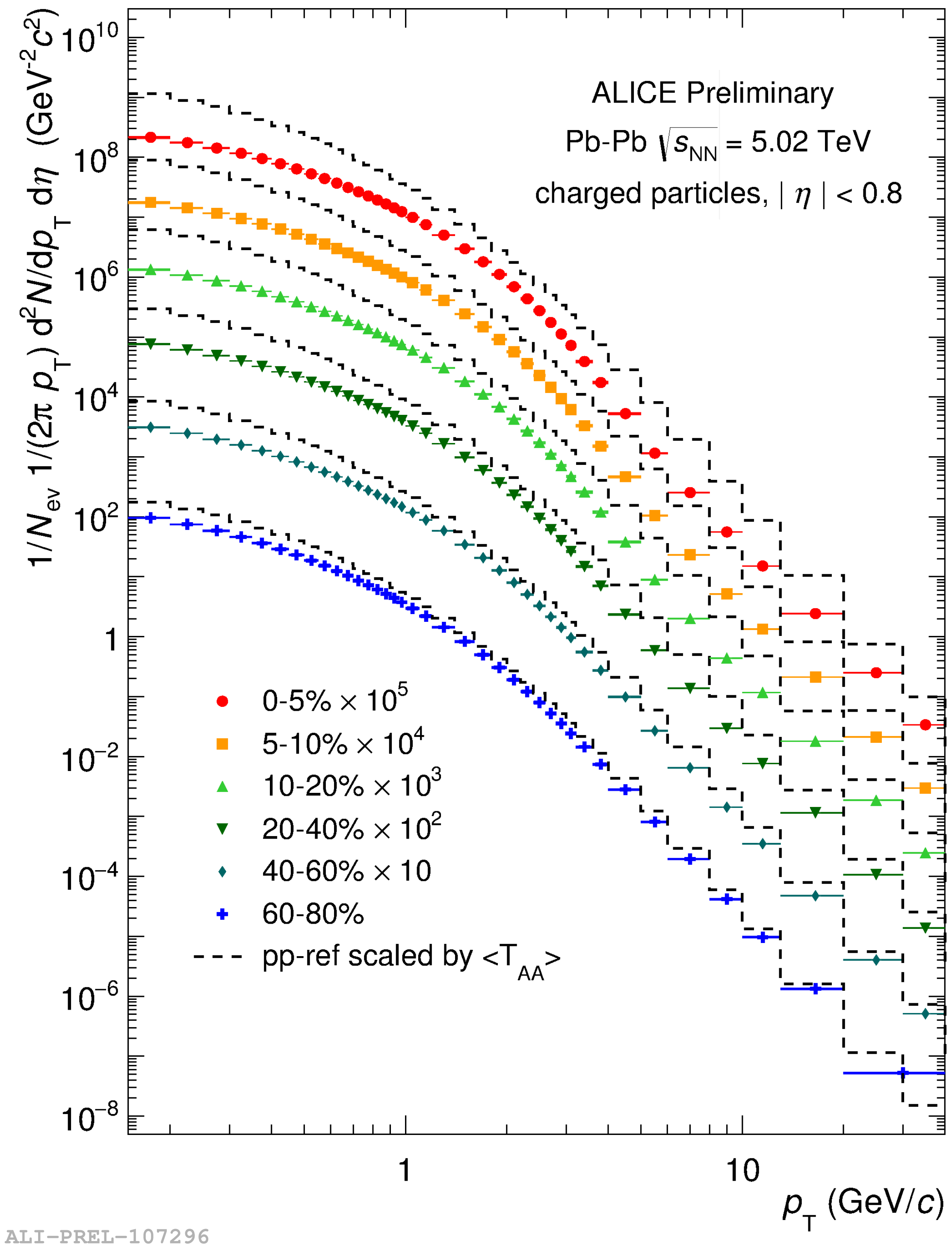

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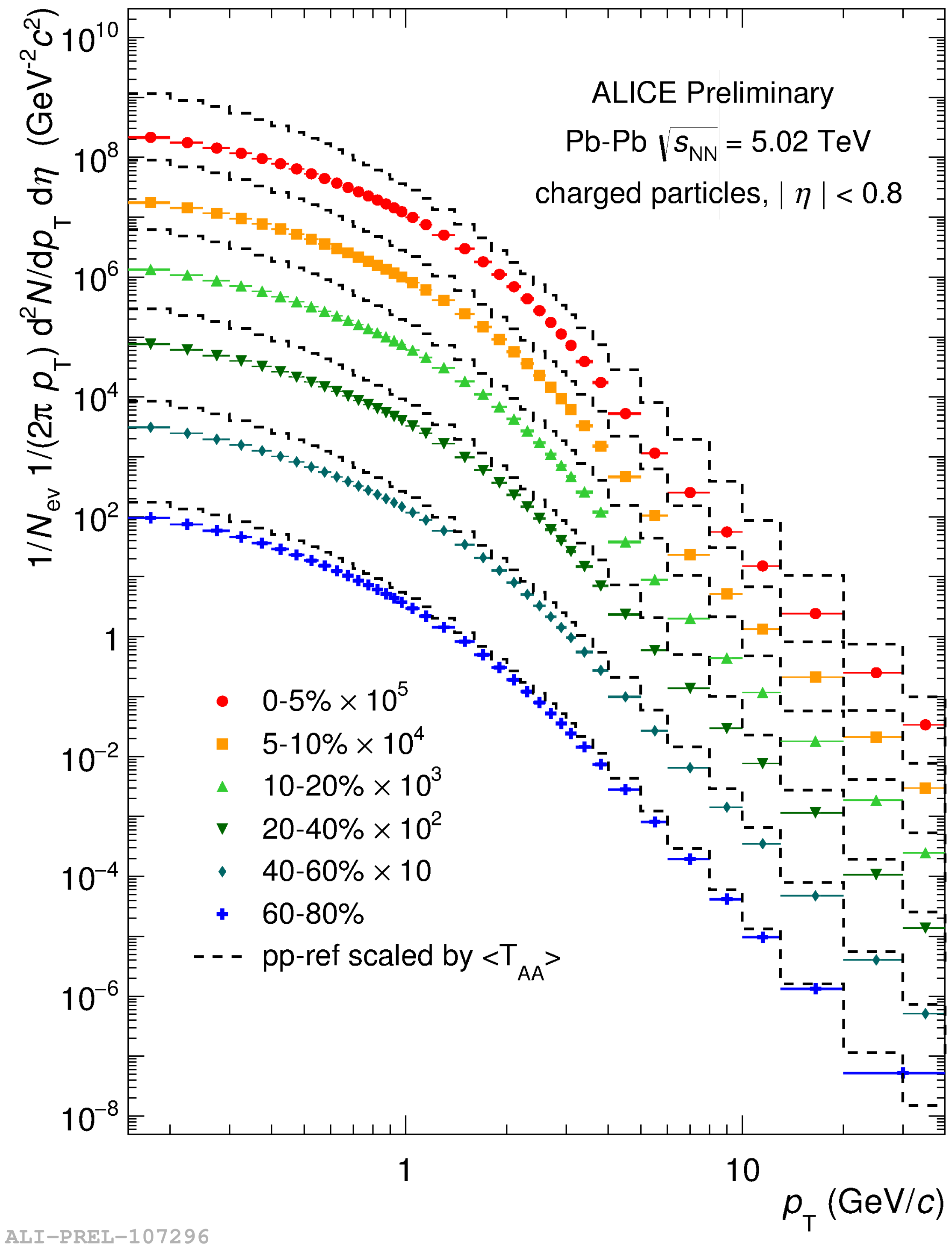
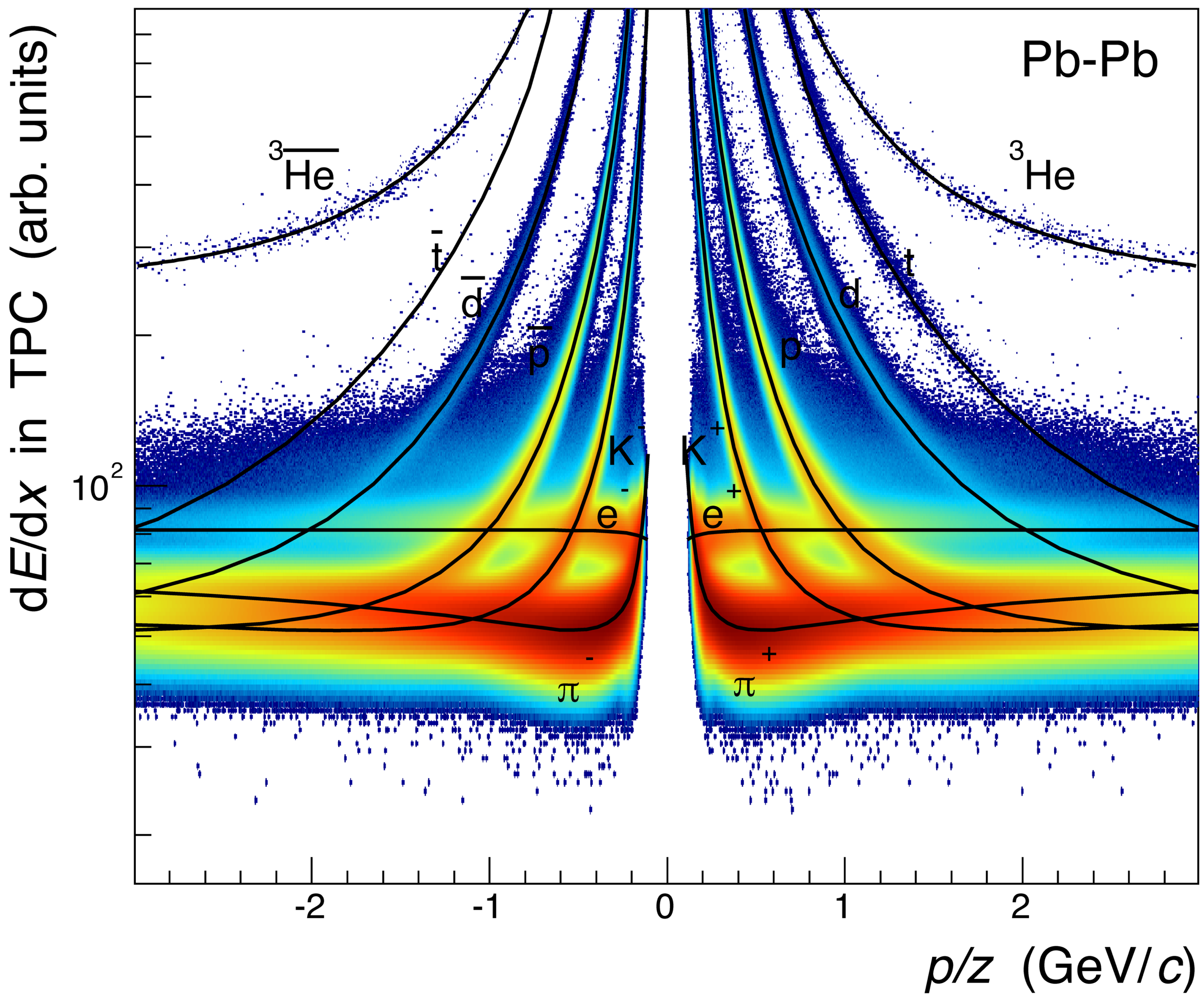


- "Standard model of heavy-ion physics"/ "Classical model of heavy-ion physics":

A fireball in *local thermodynamic equilibrium*:

- particle chemistry in agreement with thermal model predictions
- p_T-spectra and v_2 measurements show patterns of radial and elliptic hydrodynamic flow.

The physics defines the tools



[PRC 93 (2015) 024917]

- Soft particle production: rest mass of the particles is not negligible with respect to their momentum.

- Mass ordering:

  In hydrodynamics (roughly):

$$p = m \cdot \beta\gamma$$

  In statistical-thermal models (roughly):

$$dN/dy \propto \exp(-m/T_{them})$$

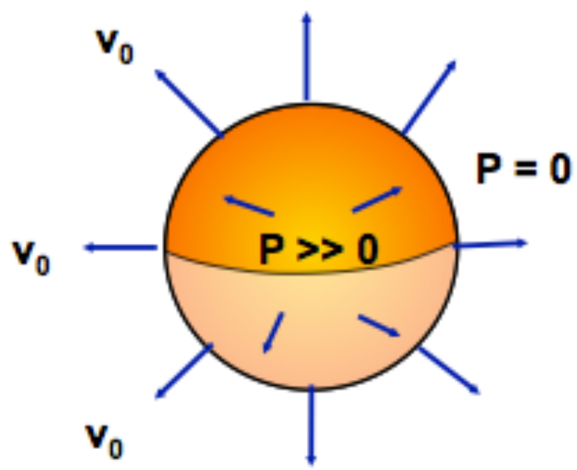
➜ Strong particle identification (PID) capabilities are required.

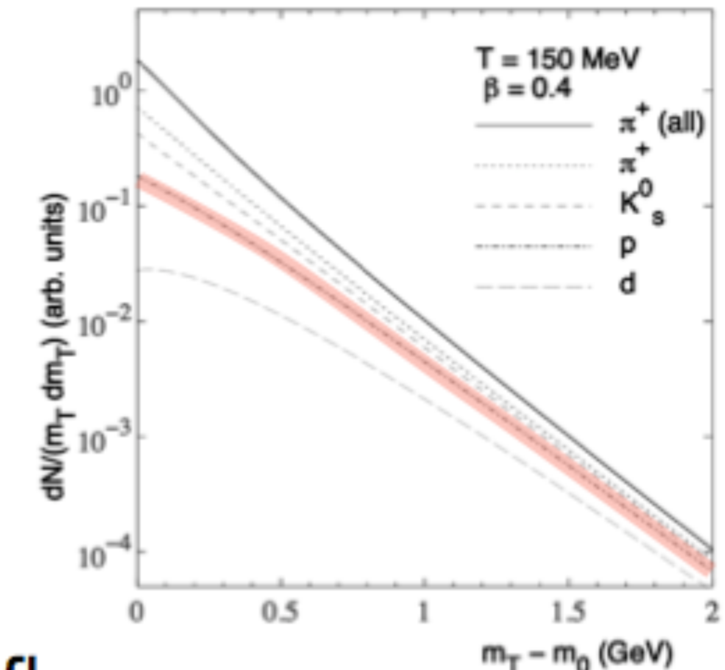
➜ ALICE experiment exploits all known techniques: dE/dx, TOF, Cherenkov, TRD, calorimetry, topological identification

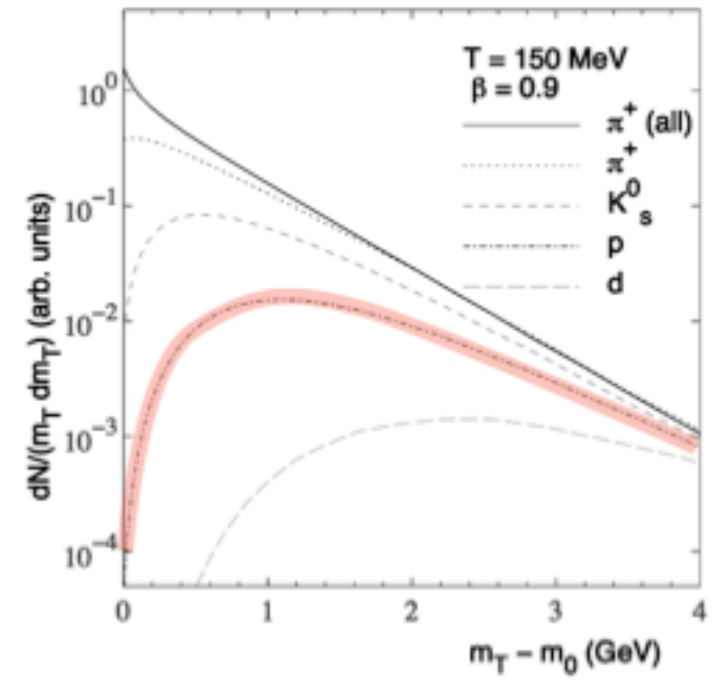
Pb-Pb collisions at LHC:
statistical thermal model and hydrodynamics

Radial and elliptic flow

Isotropic radial flow

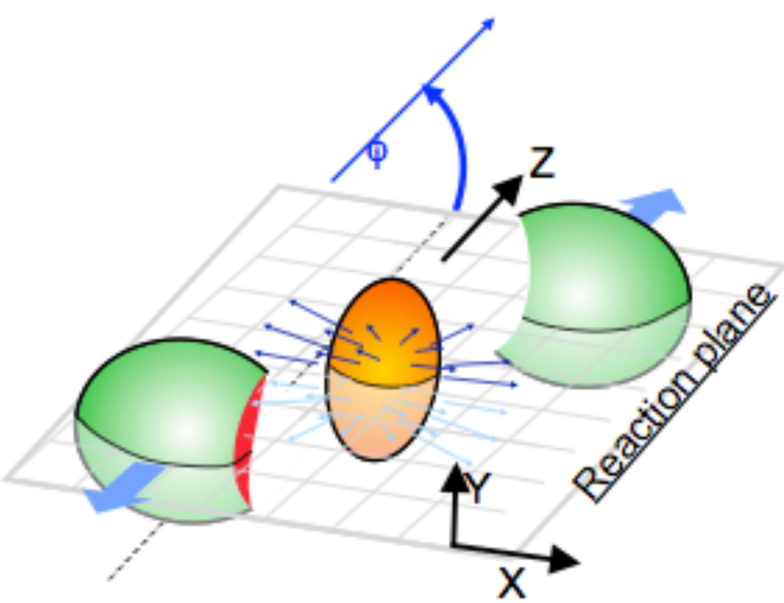




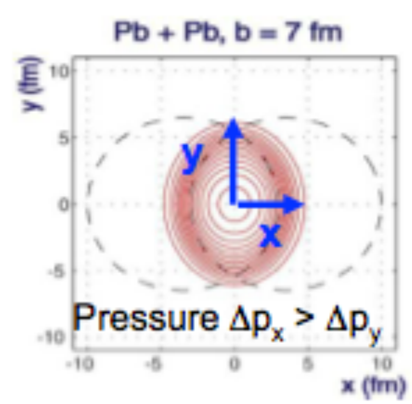


Anisotropic (elliptic) flow

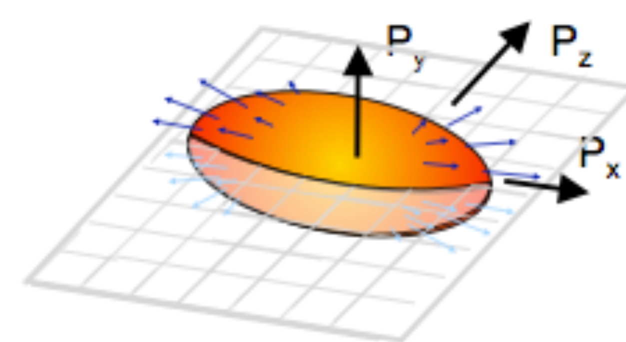
Spatial deformation



Azimuthal (φ) pressure gradients



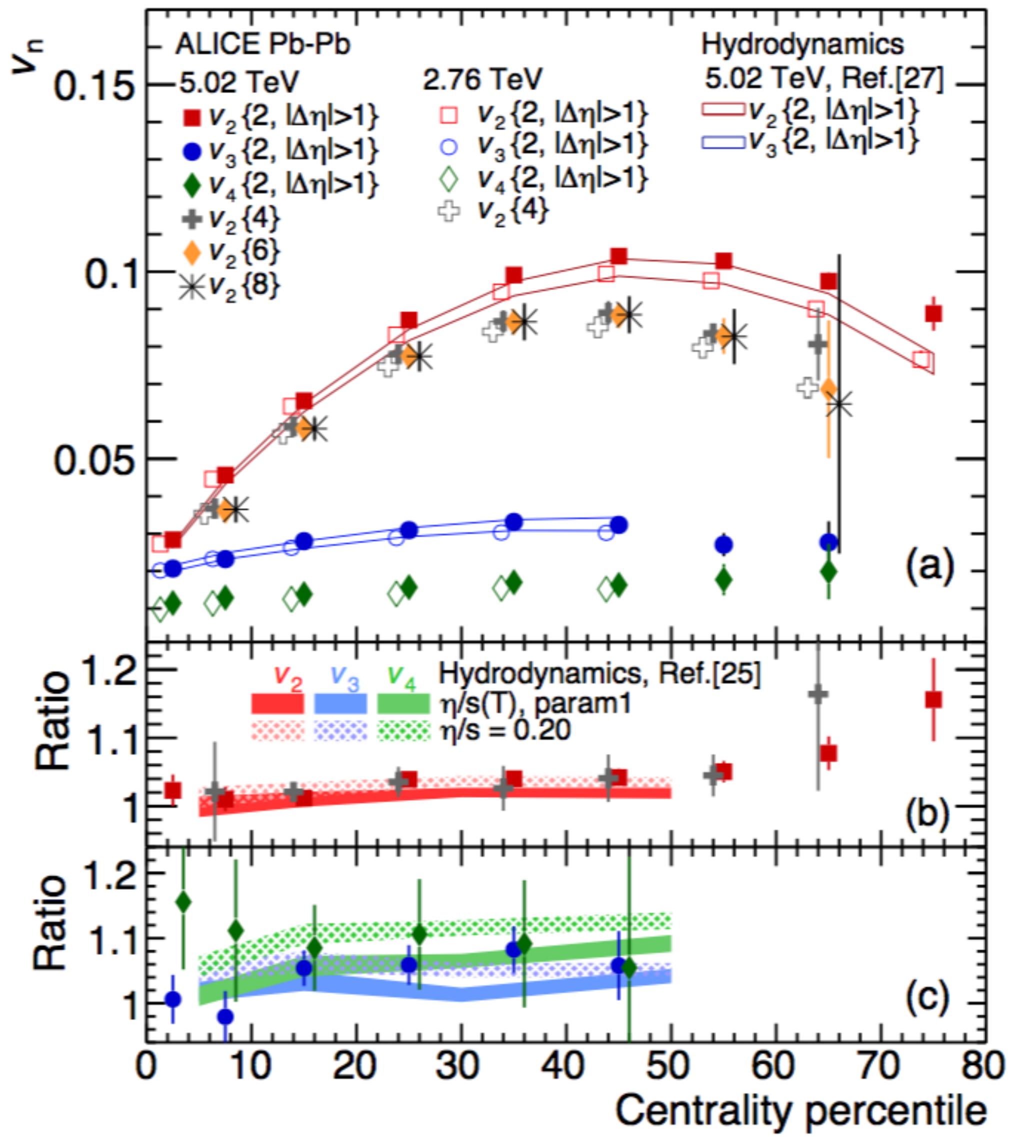
Anisotropic particle density



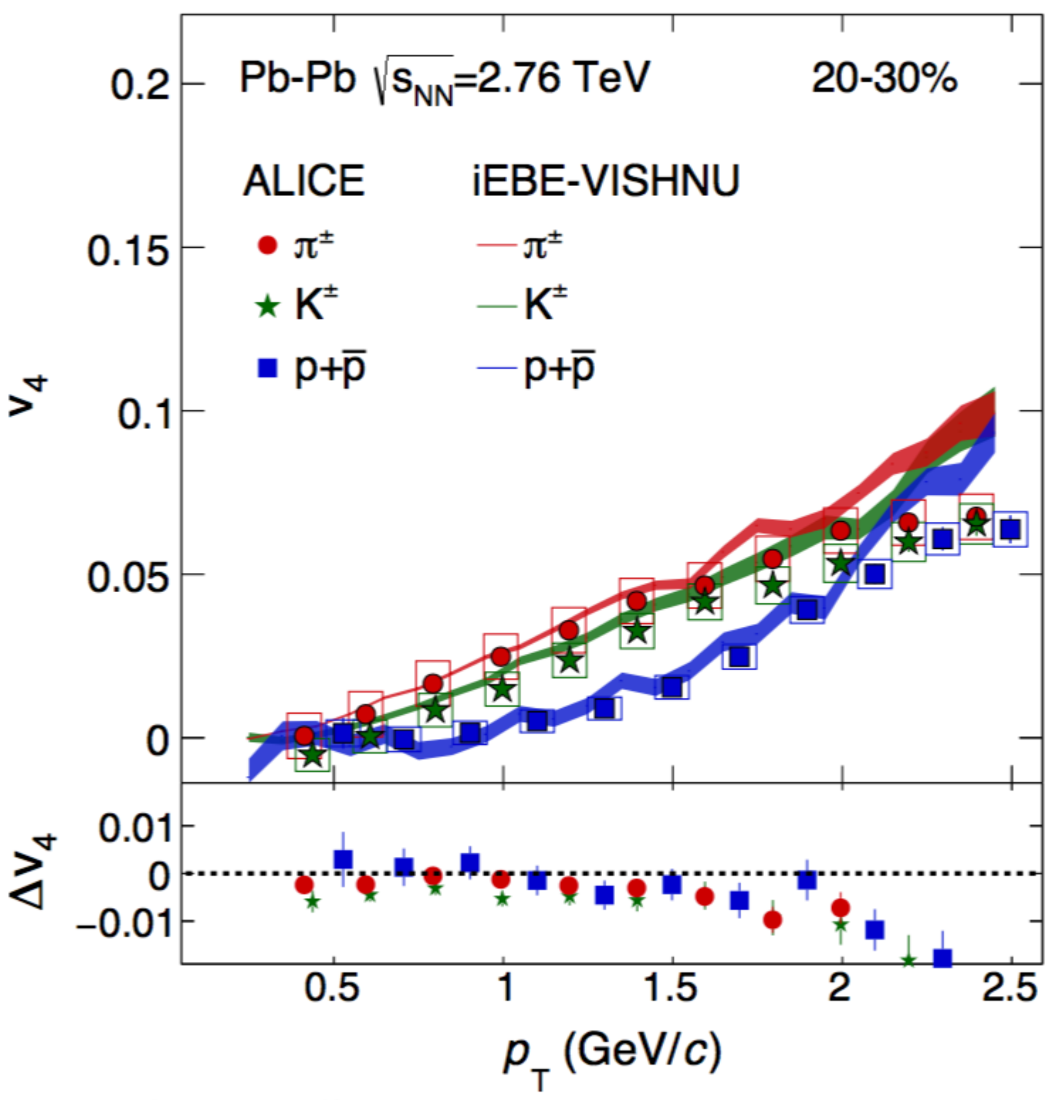
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

Elliptic flow at LHC energies

[PRL 116 (2016) 132302]



[arXiv:1606.06057]



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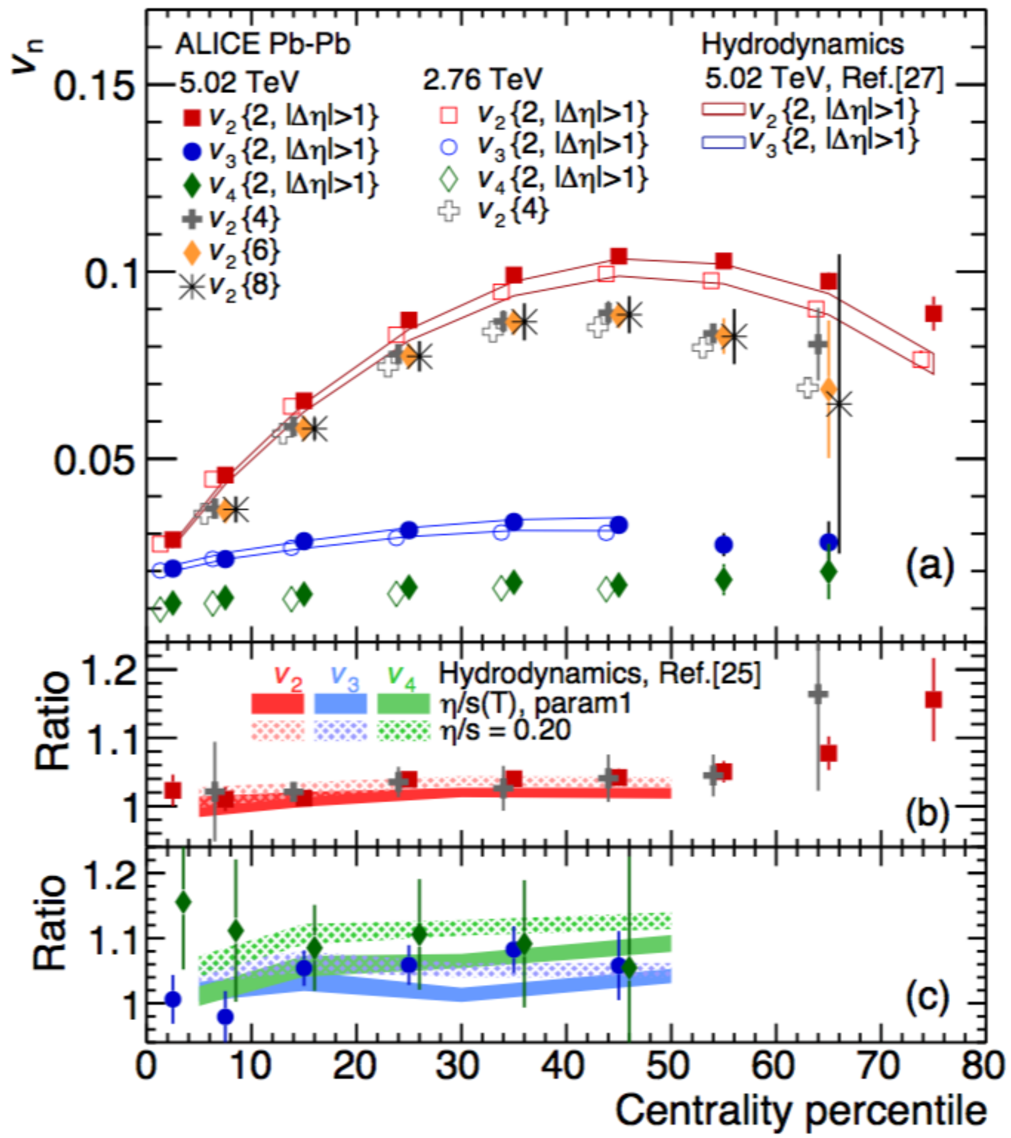

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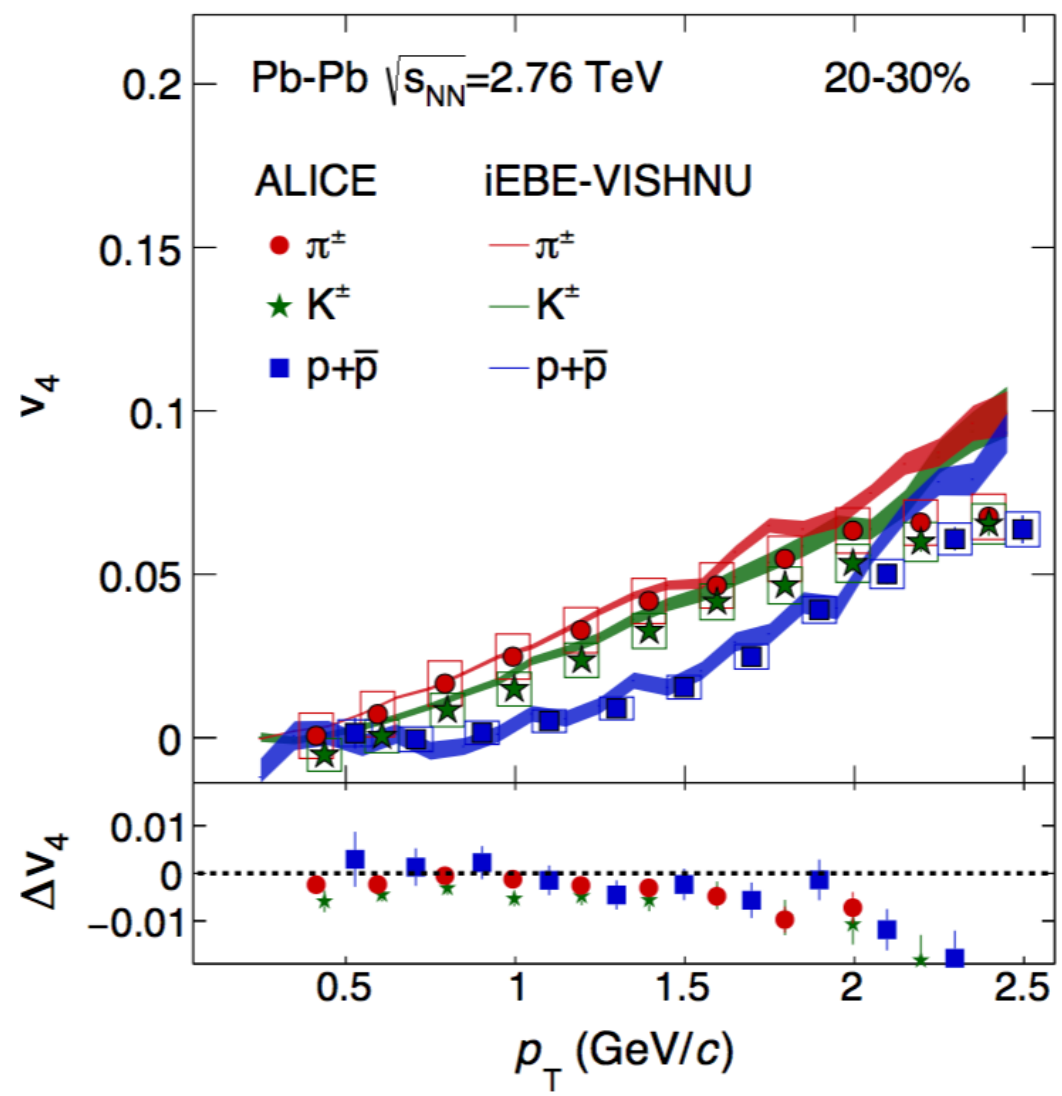

Validity of hydrodynamic description confirmed at the highest centre-of-mass energies available.

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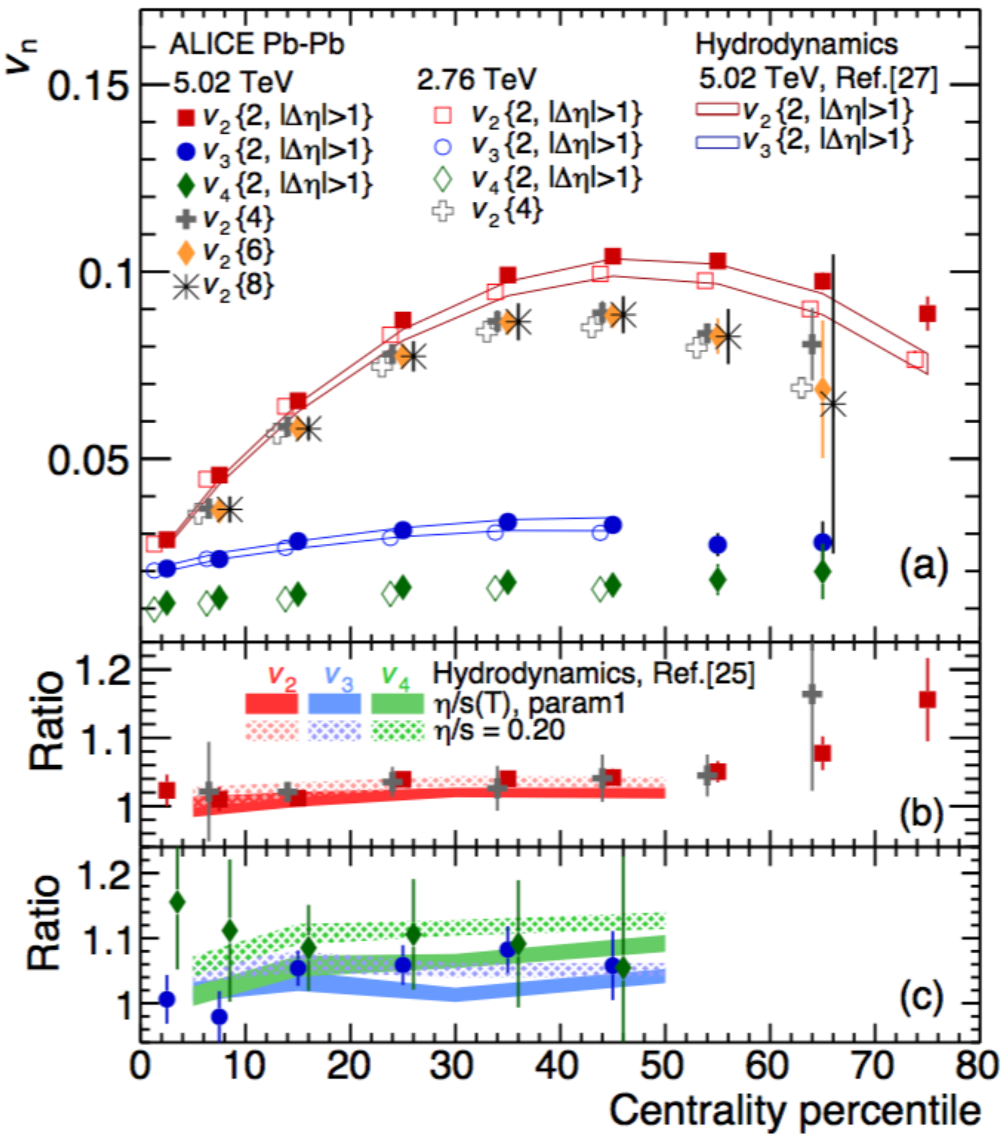

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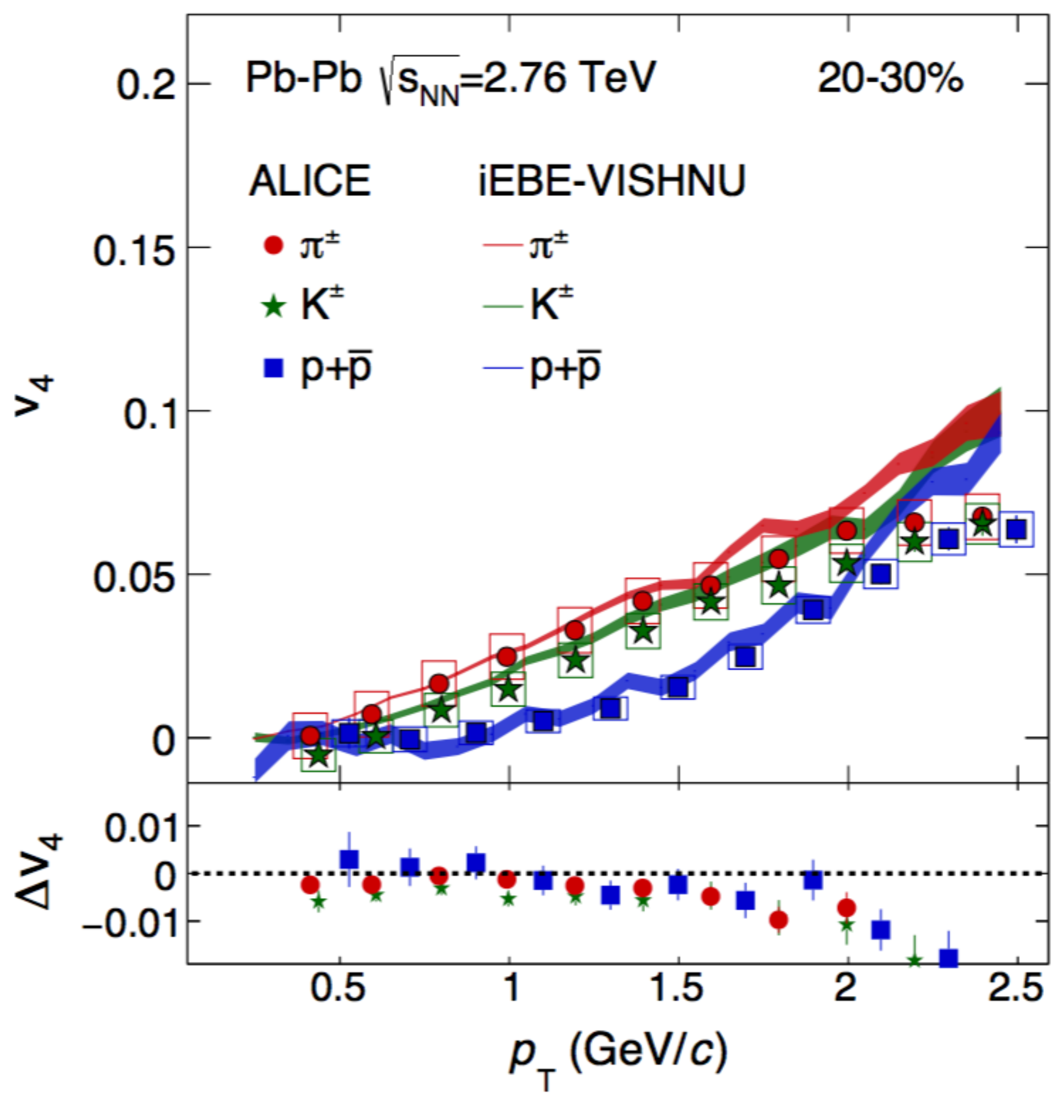
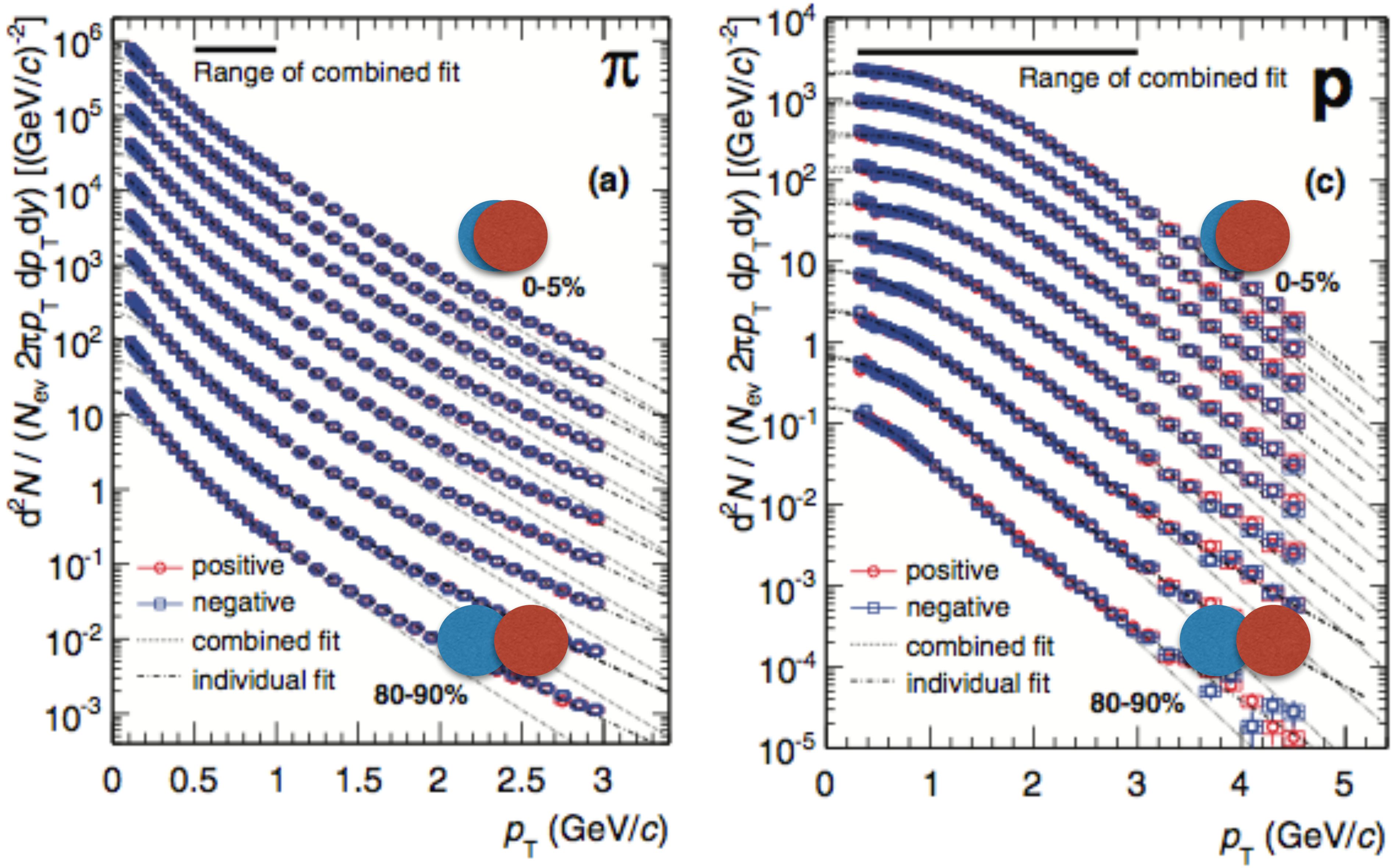


Validity of hydrodynamic description confirmed at the highest centre-of-mass energies available.

Expected mass ordering also observed in higher harmonic flow coefficients.

Radial flow in Pb-Pb



[Phys. Rev. C 88, 044910 (2013)]

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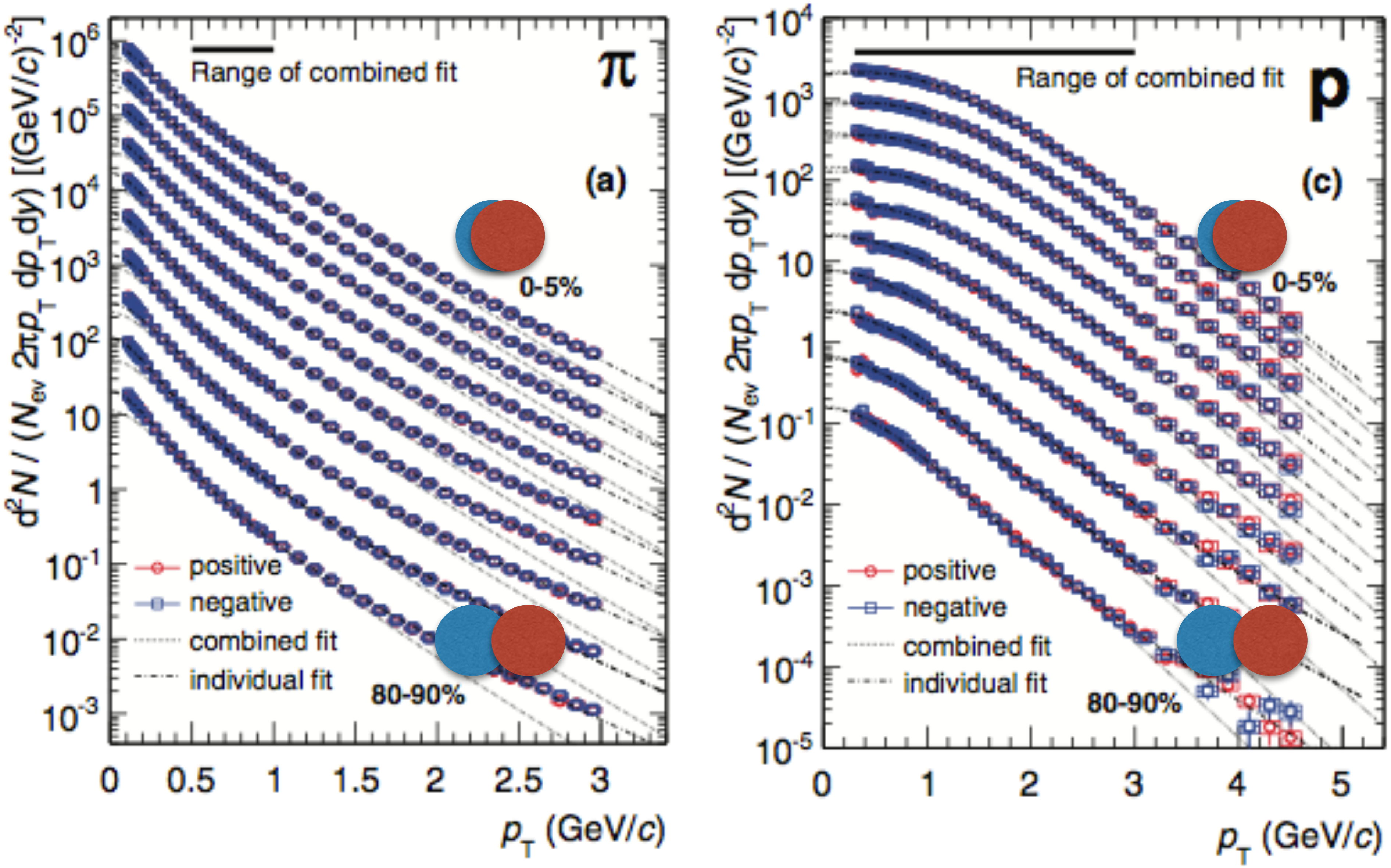

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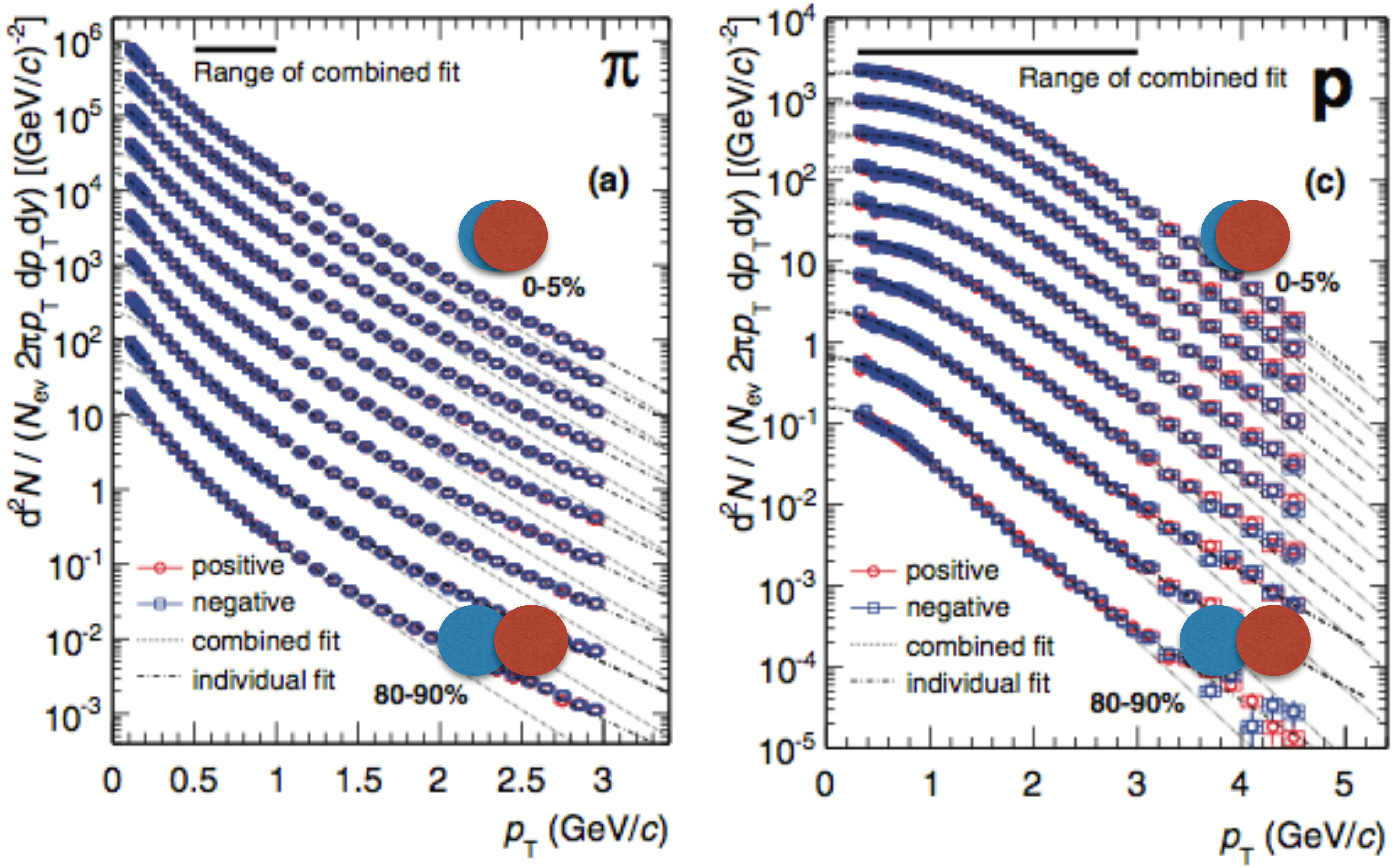

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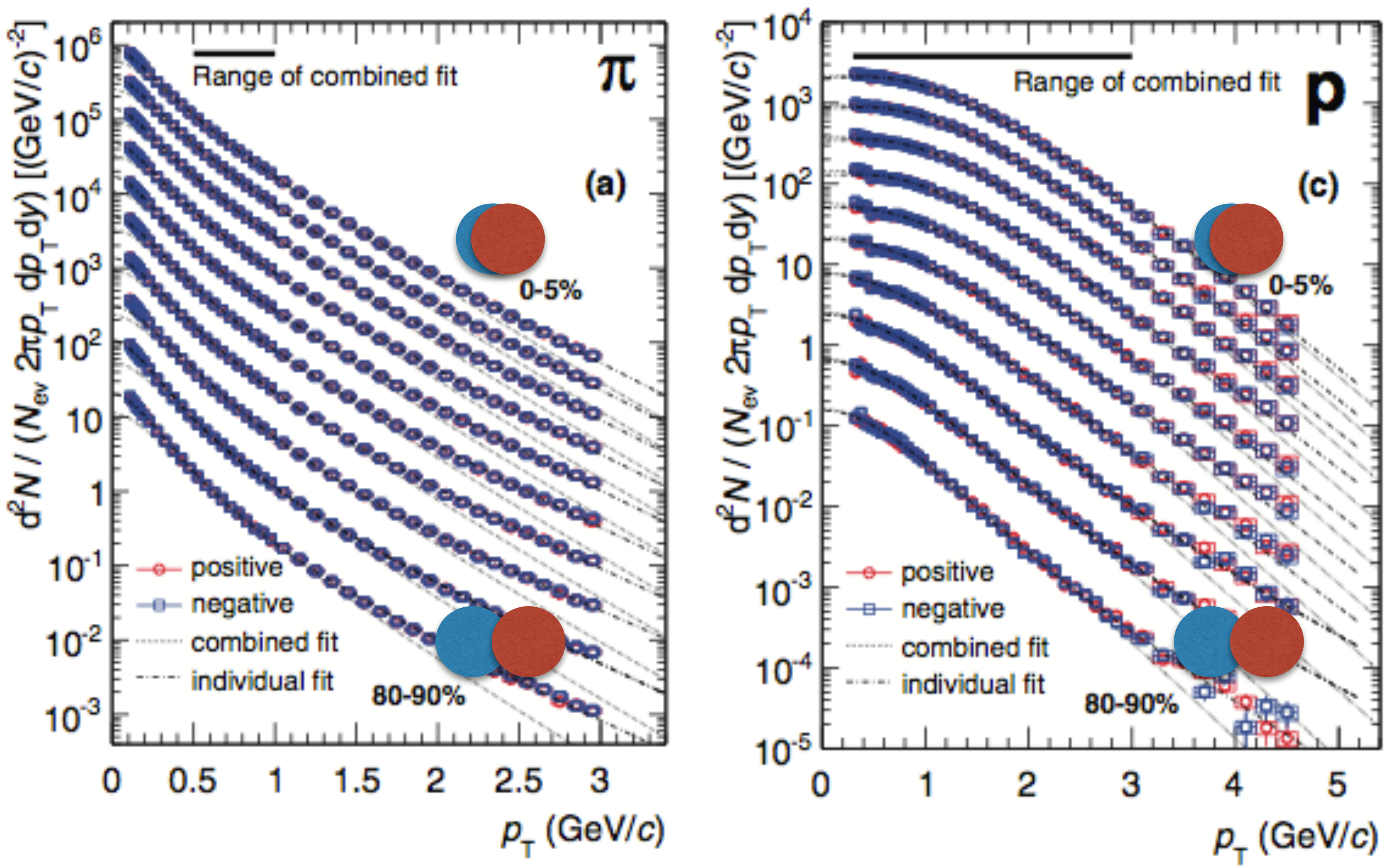

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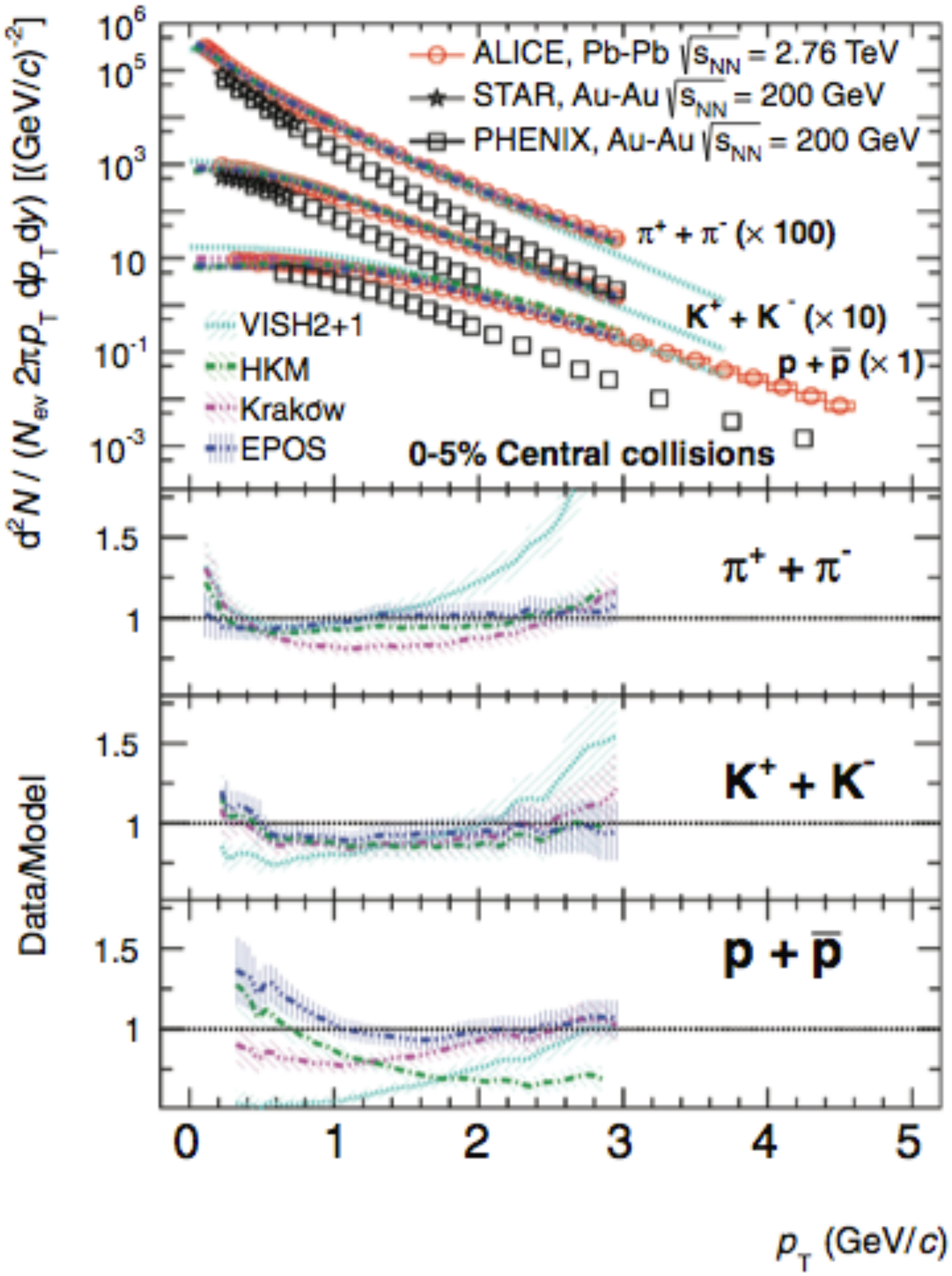

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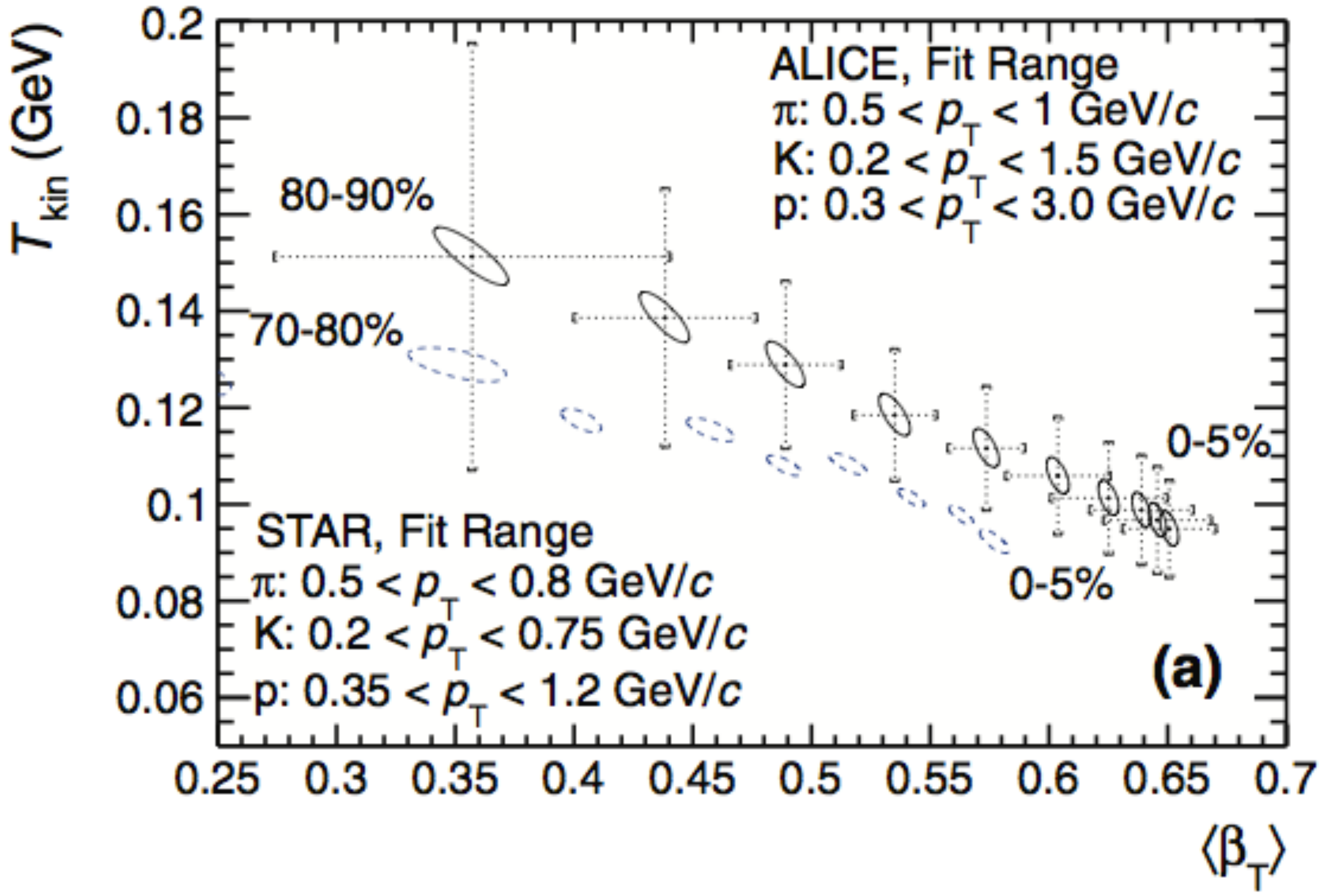

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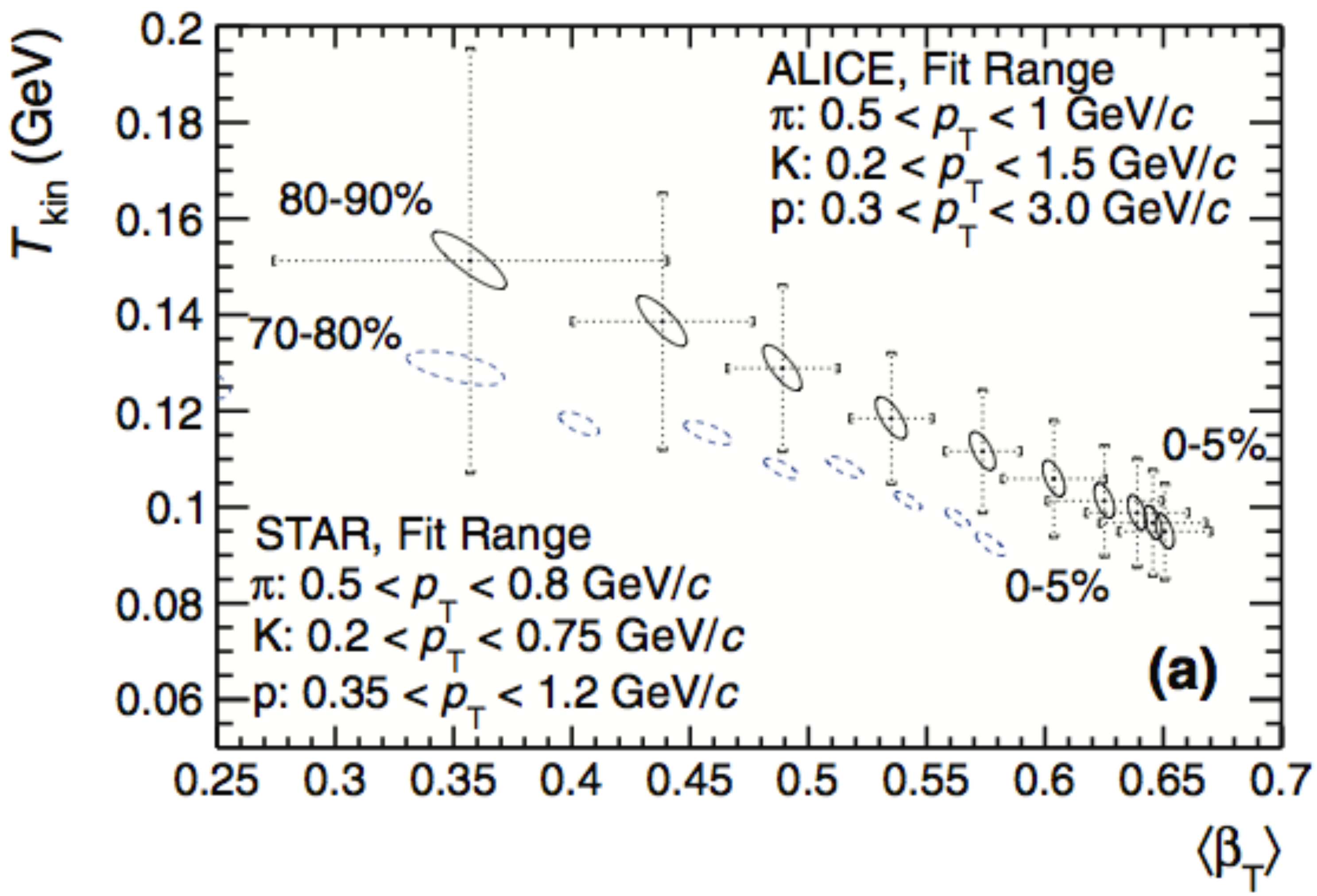

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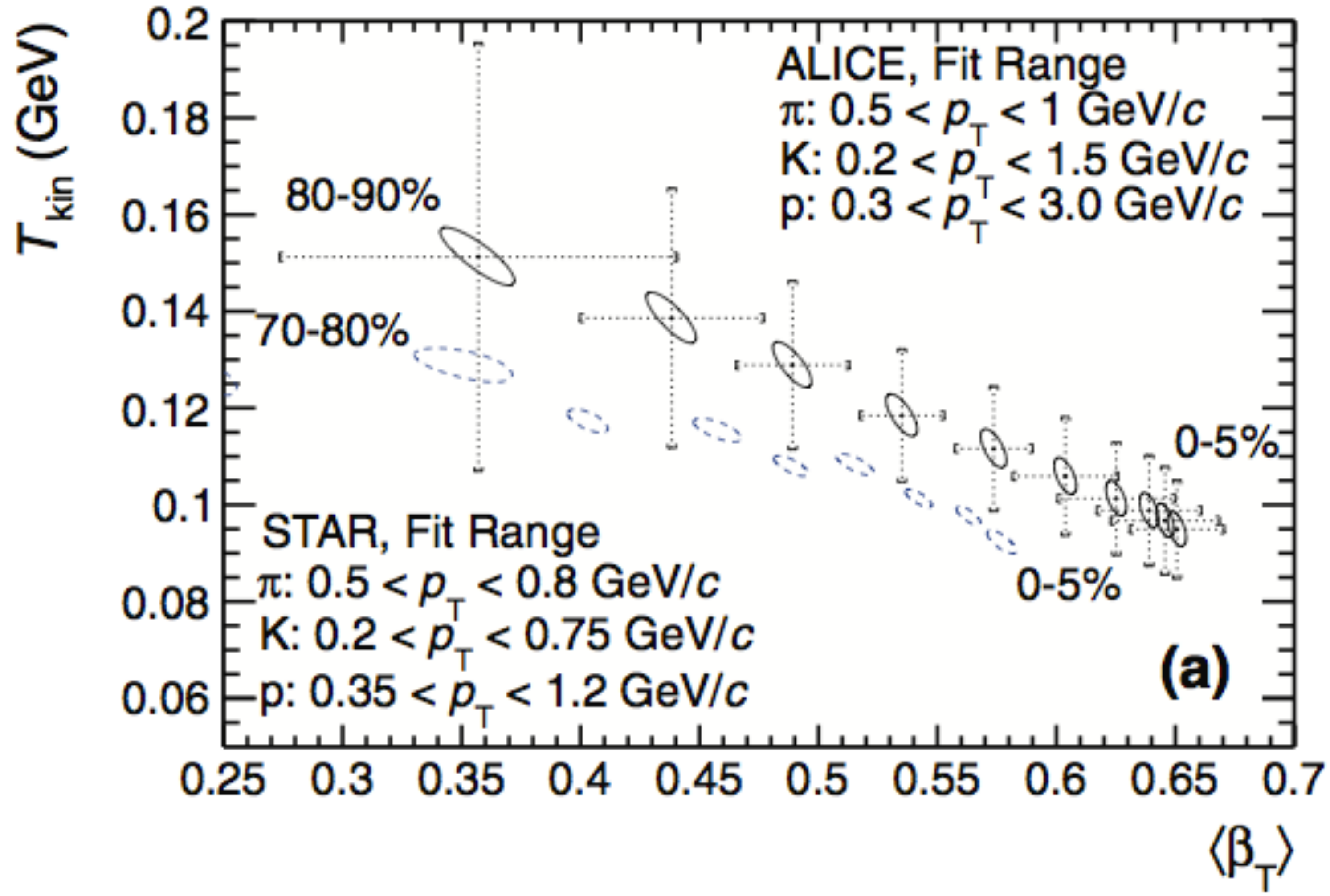

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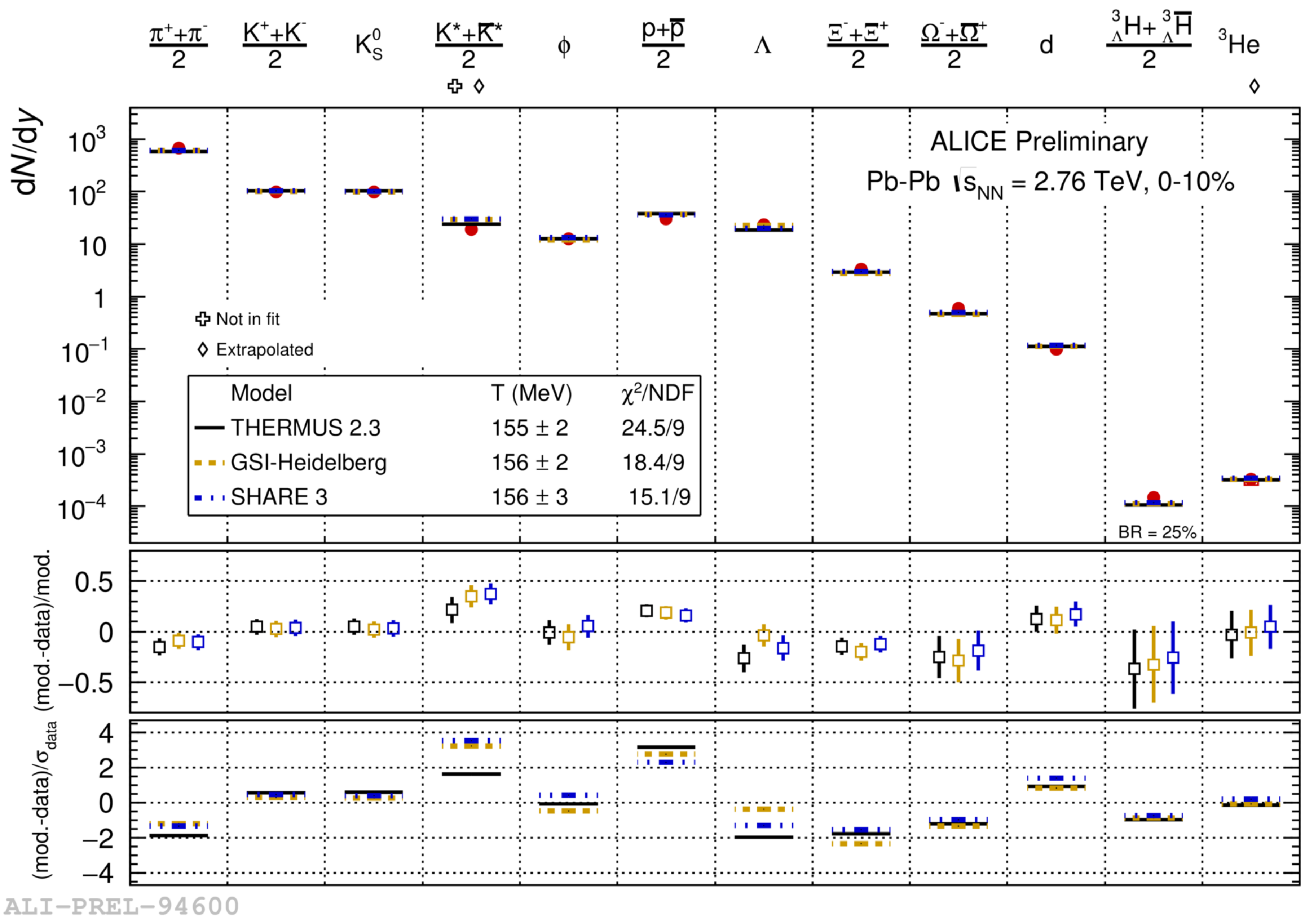
Within the severe limitations of the blast-wave model one finds: T_{kin} ≈ 100 MeV significantly smaller than T_{chem} ≈ 156 MeV and an average transverse expansion velocity around <β_T> 0.65 for most central Pb-Pb collisions.

Chemical equilibrium



Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% (except K^{*0}) with a common chemical freeze-out temperature of $T_{ch} \approx$ 156 MeV (prediction from RHIC extrapolation was ≈ 164 MeV).

Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC energies.

Light (anti-)nuclei yields in agreement with thermal model expectation.

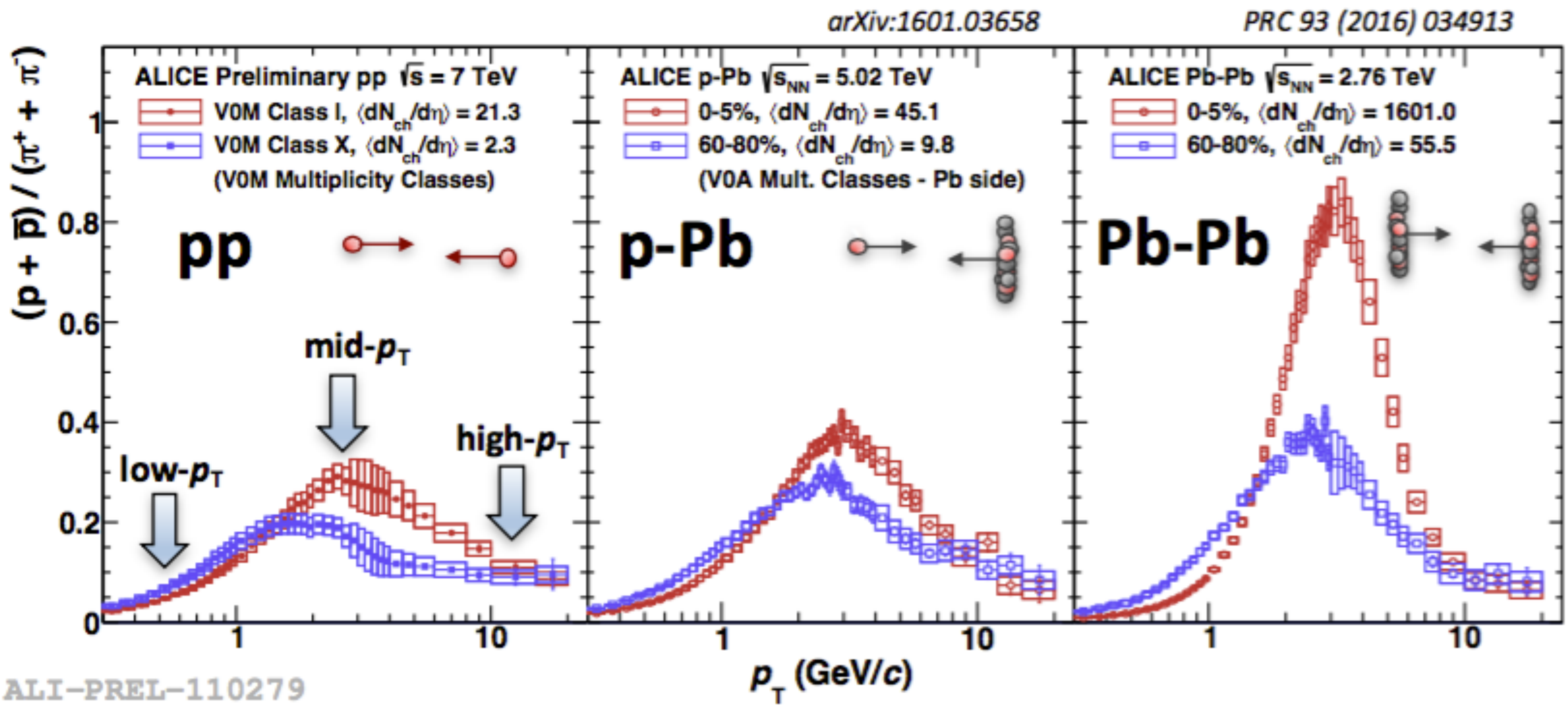
.. see also the other talks during this workshop.

[Wheaton et al, Comput.Phys.Commun, 180 84]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

Small systems at the LHC:
statistical thermal model and hydrodynamics?

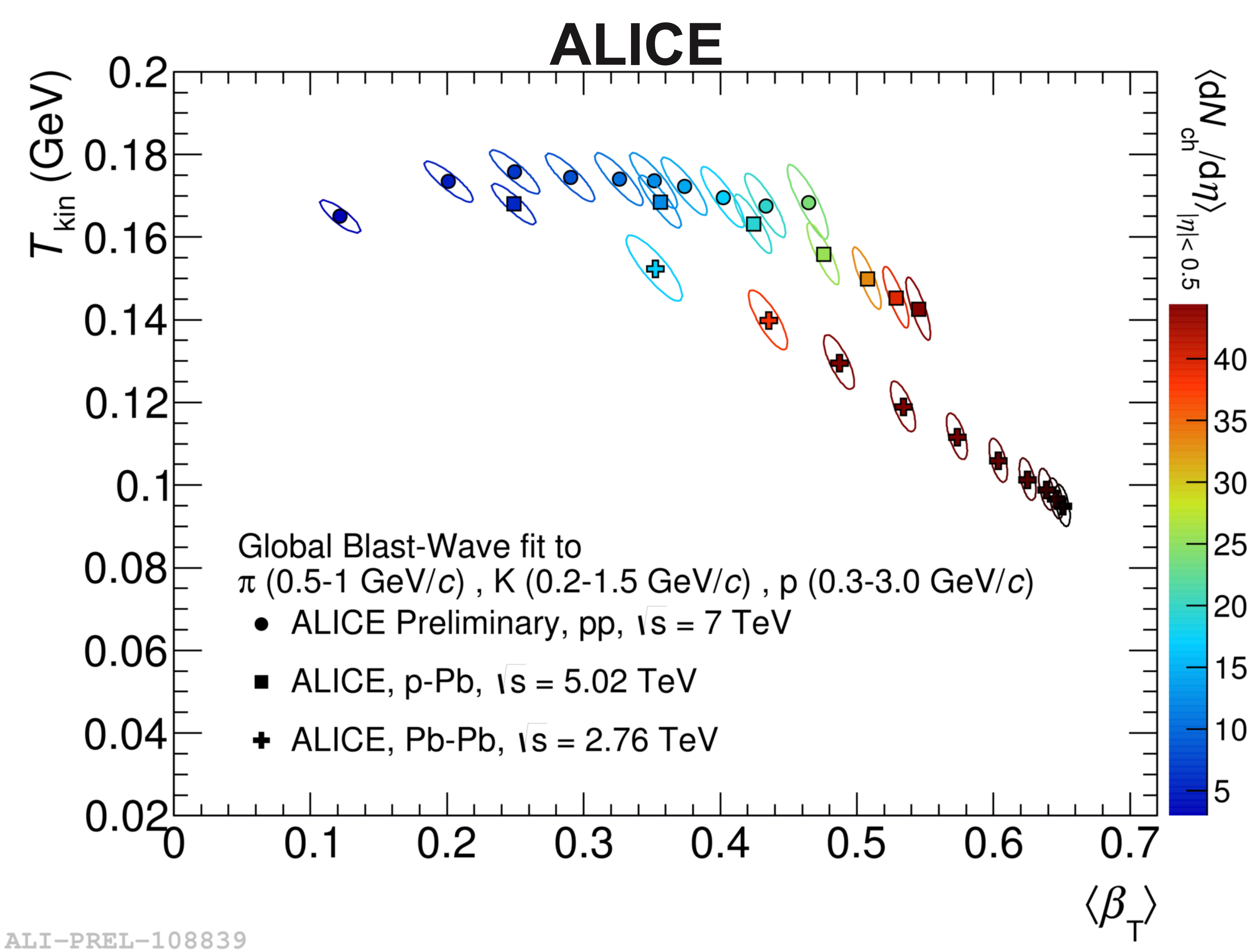
Baryon-to-meson ratios

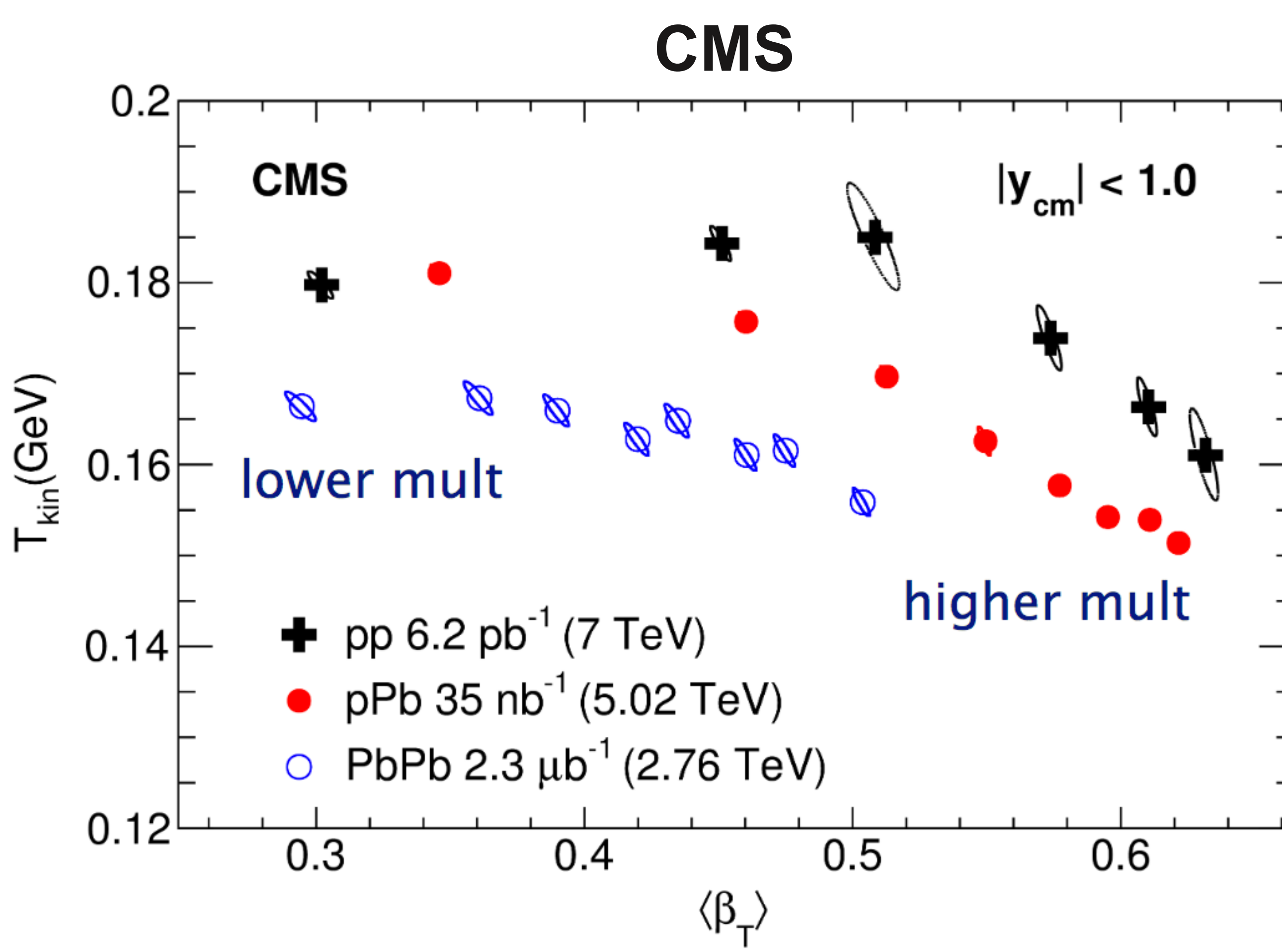
- Baryon-to-meson ratios as a function of event multiplicity behave qualitatively similar in all three collision systems.



Radial flow patterns in small systems

- Collectivity also in small systems?
  chemical equilibrium (particle yields) <=> kinetic equilibrium (radial flow)
- Check with a simplified hydro model and map the evolution as a function of multiplicity in all three systems.
- N.B.: non-hydro effects like color reconnection can mimic hydro patterns!
- Is there a difference in the freeze-out curves between pp and p-Pb?

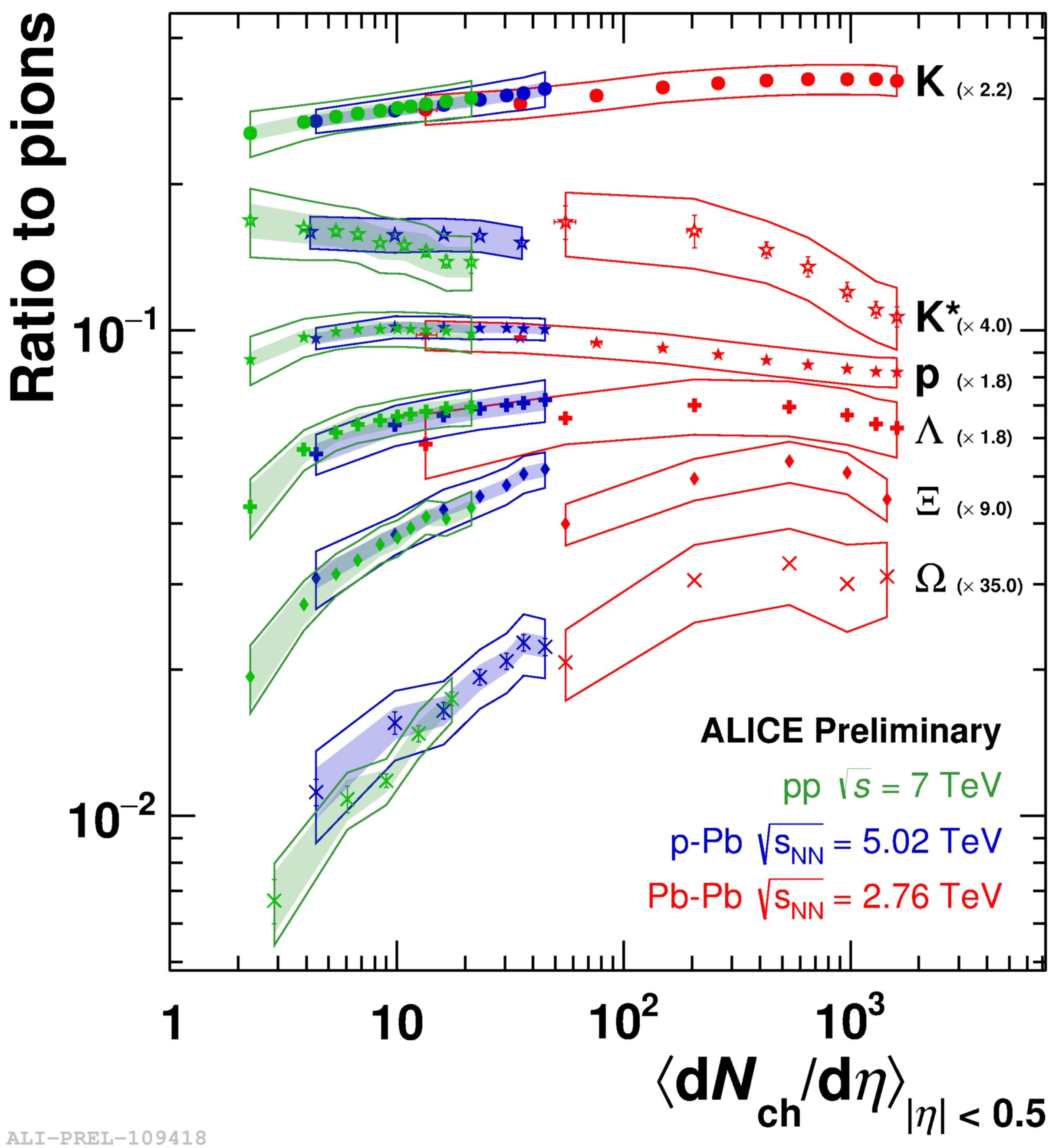


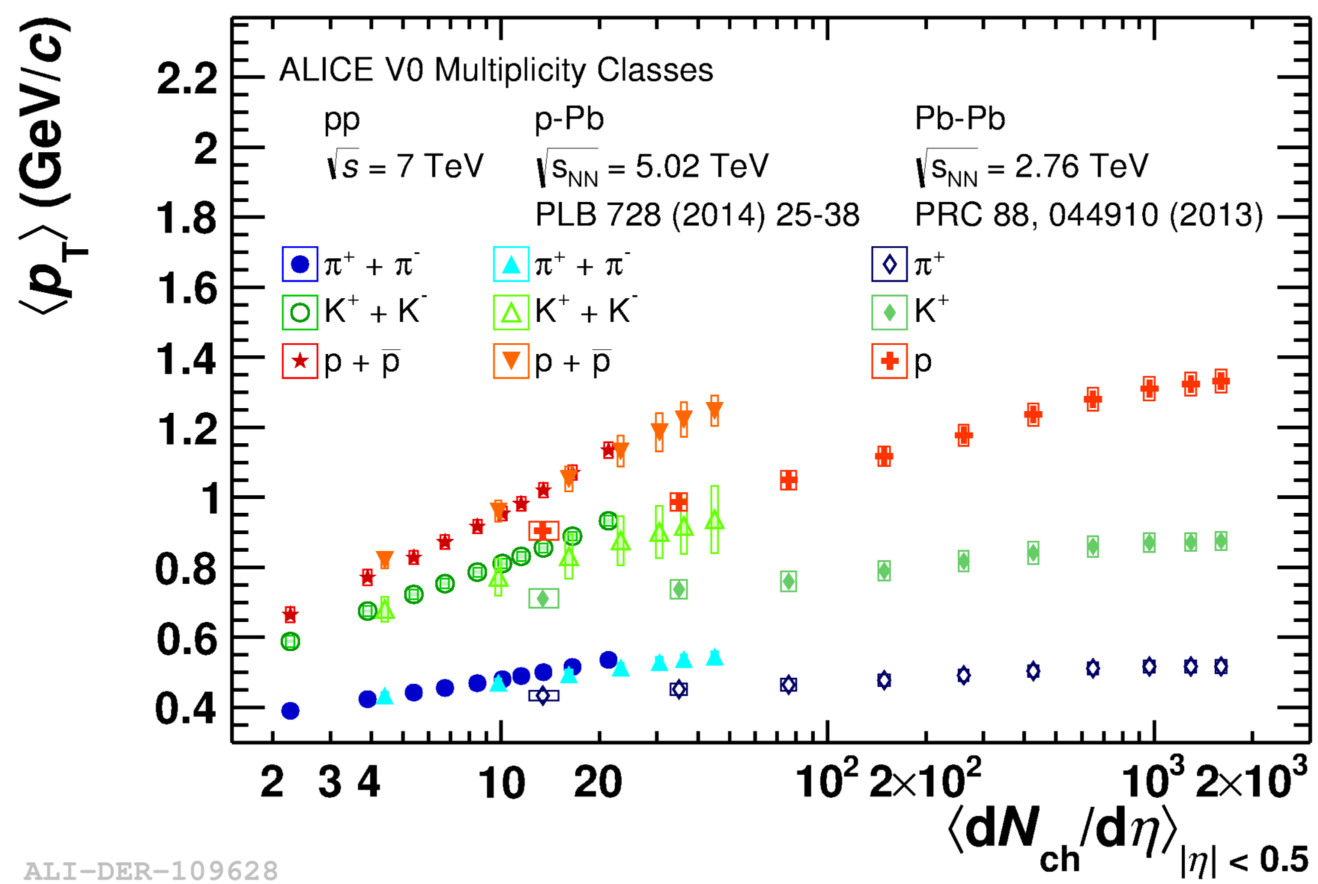


[arXiv:1605.06699]

Particle chemistry in small systems

- Particle chemistry is smoothly evolving. Spectral shapes are more sensitive to the centre-of-mass energy (power-law tail etc.).
- Strangeness production in small systems is clearly suppressed w.r.t. to the grand-canonical saturation value ➜ strangeness canonical suppression!

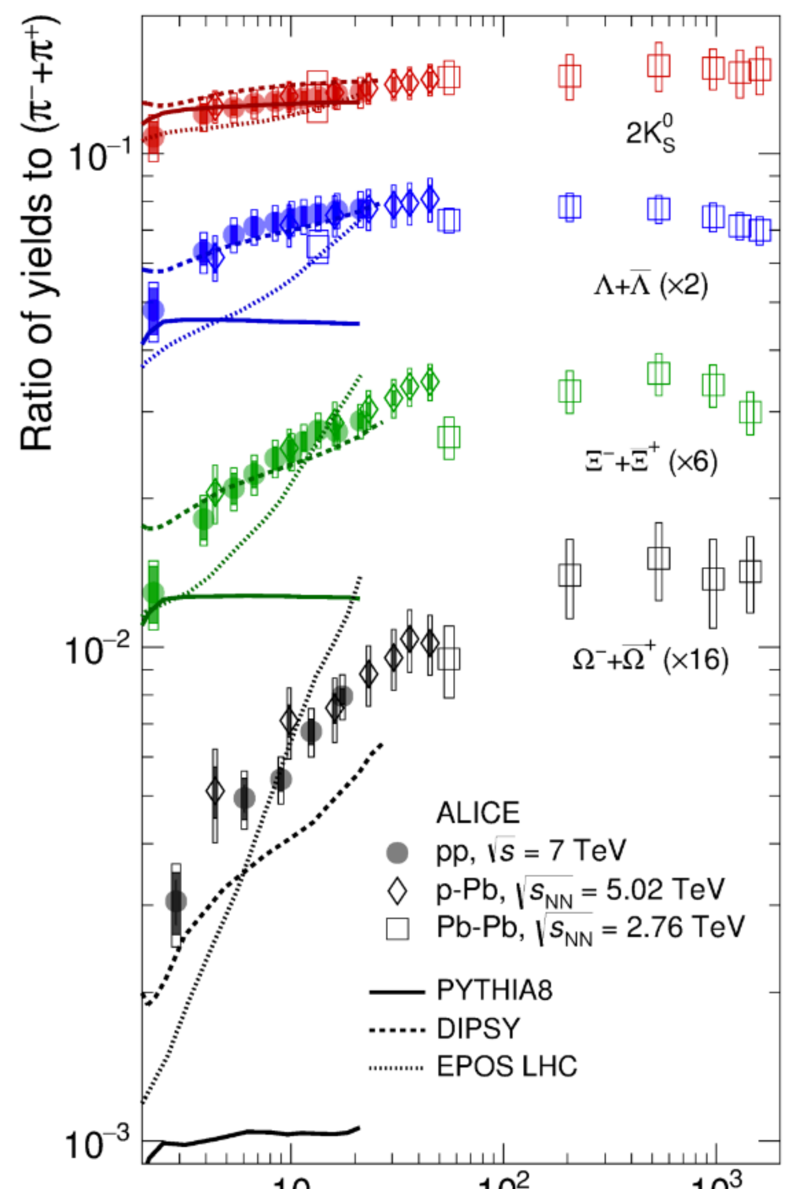




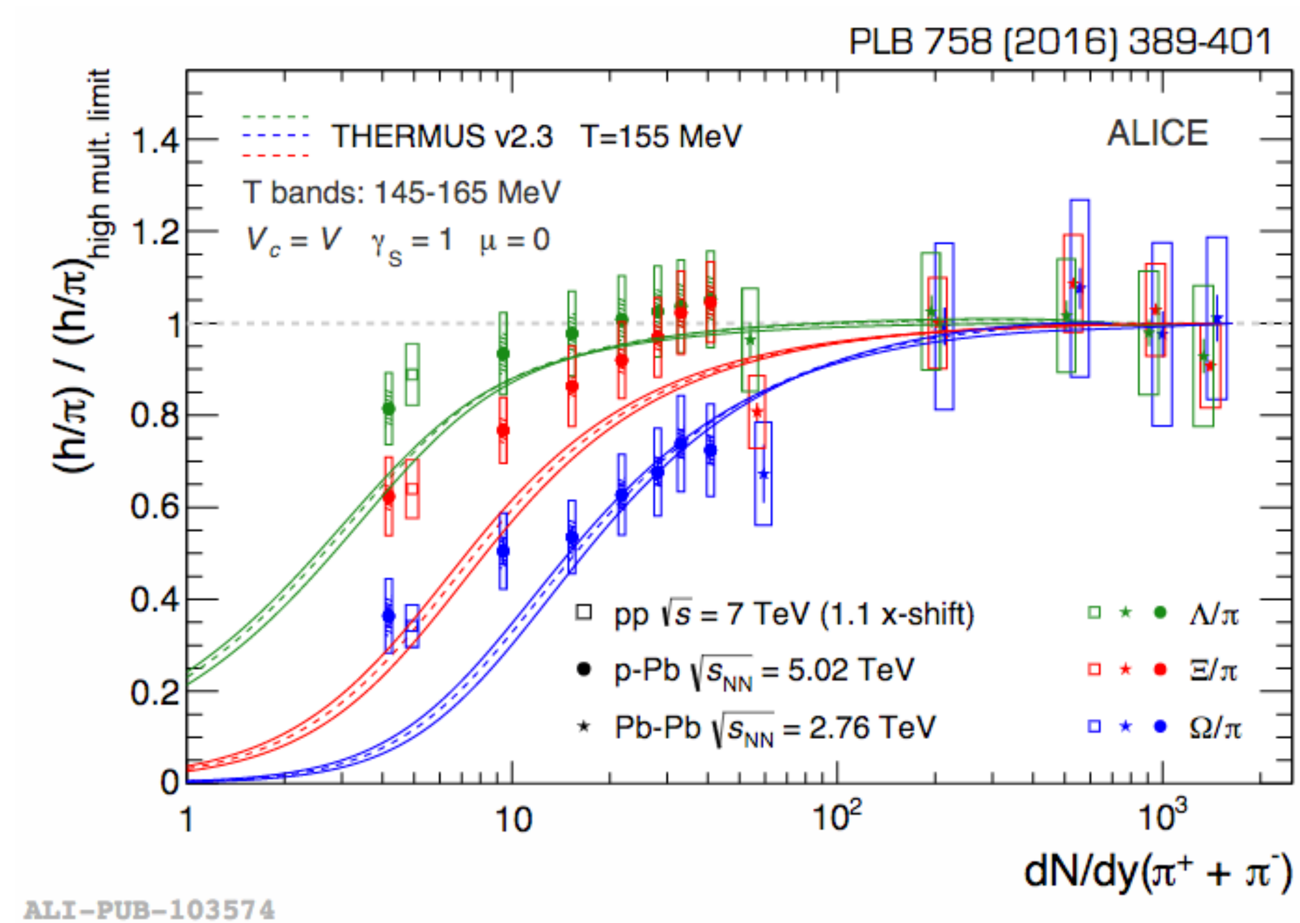
➜ Strangeness canonical suppression picture predicts a smooth transition as a function of $V_C = V$ <=> pion yield.

Thermal vs dynamical

- Opposite to the “classical model in heavy-ion physics”: QCD-inspired event generators to which we can compare now that multiplicity dependent data in pp collisions has become available.
- Which Ansatz will describe the data better? Can the dynamical models provide the underlying equilibration mechanism for the thermal models?



ALICE, arXiv:1606.07424
ALI-PUB-106878



➜ Does the strangeness canonical suppression picture still hold for pp collisions? Stay tuned..

Is there a more *direct experimental evidence* of the phase transition in the light flavour sector?

event-by-event fluctuations

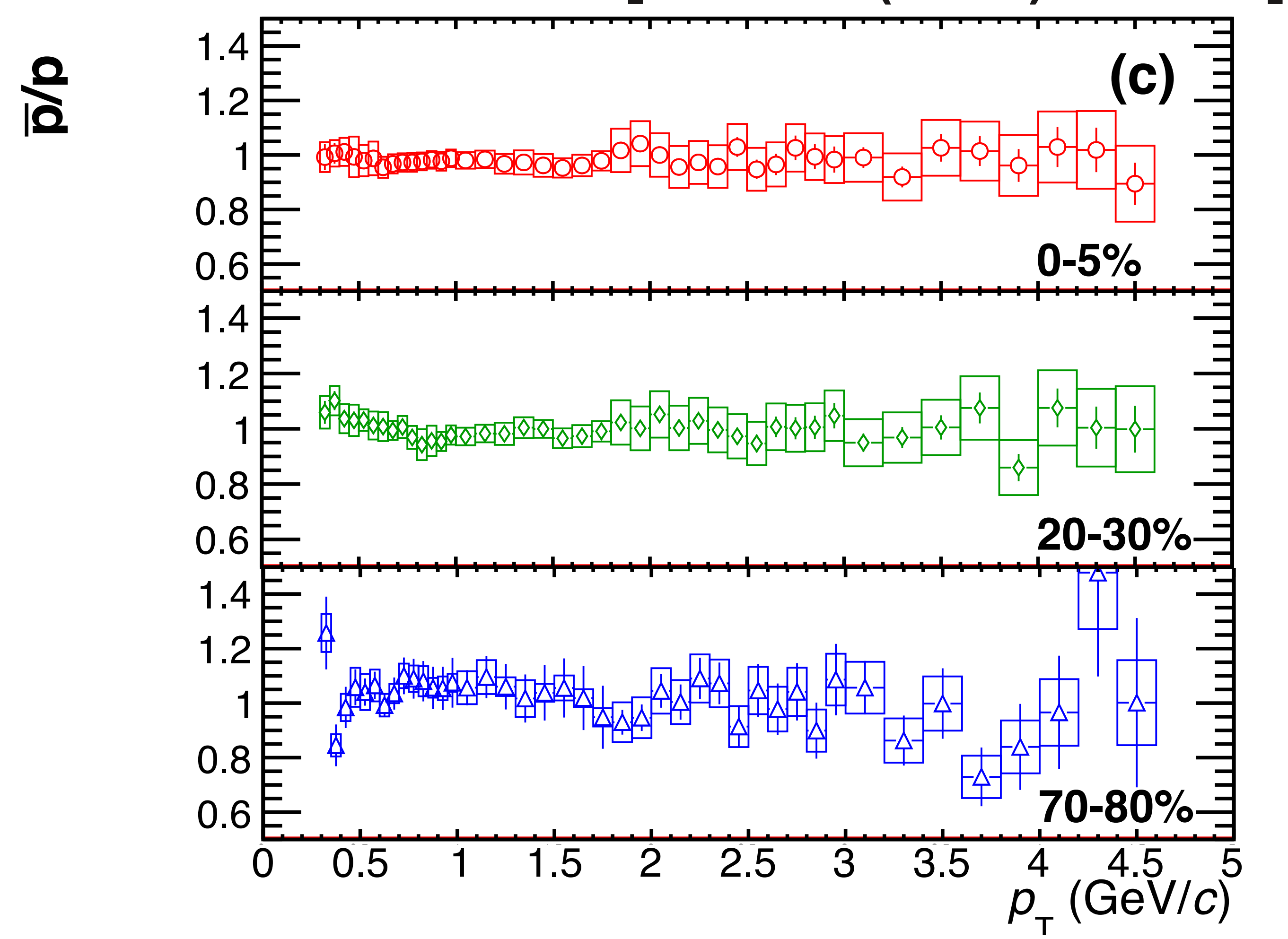
Event-by-event fluctuations

- If all is described by an ideal hadron resonance gas (or Van-der-Waals gas if finite volume corrections are considered) and hydrodynamic expansion, where is the phase transition and the related criticality?
- Event-by-event fluctuations of the conserved quantities in QCD (*charge Q*, *baryon number B*, *strangeness S*) correspond to thermodynamic susceptibilities χ of the system which can be directly calculated in Lattice QCD or in the Hadron Resonance Gas (HRG) model:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l\,\partial(\mu_S/T)^m\,\partial(\mu_S/T)^n}$$

- Statistical distribution of conserved quantities are quantified by their (central) moments or cumulants.

[PRC 88 (2013) 044910]



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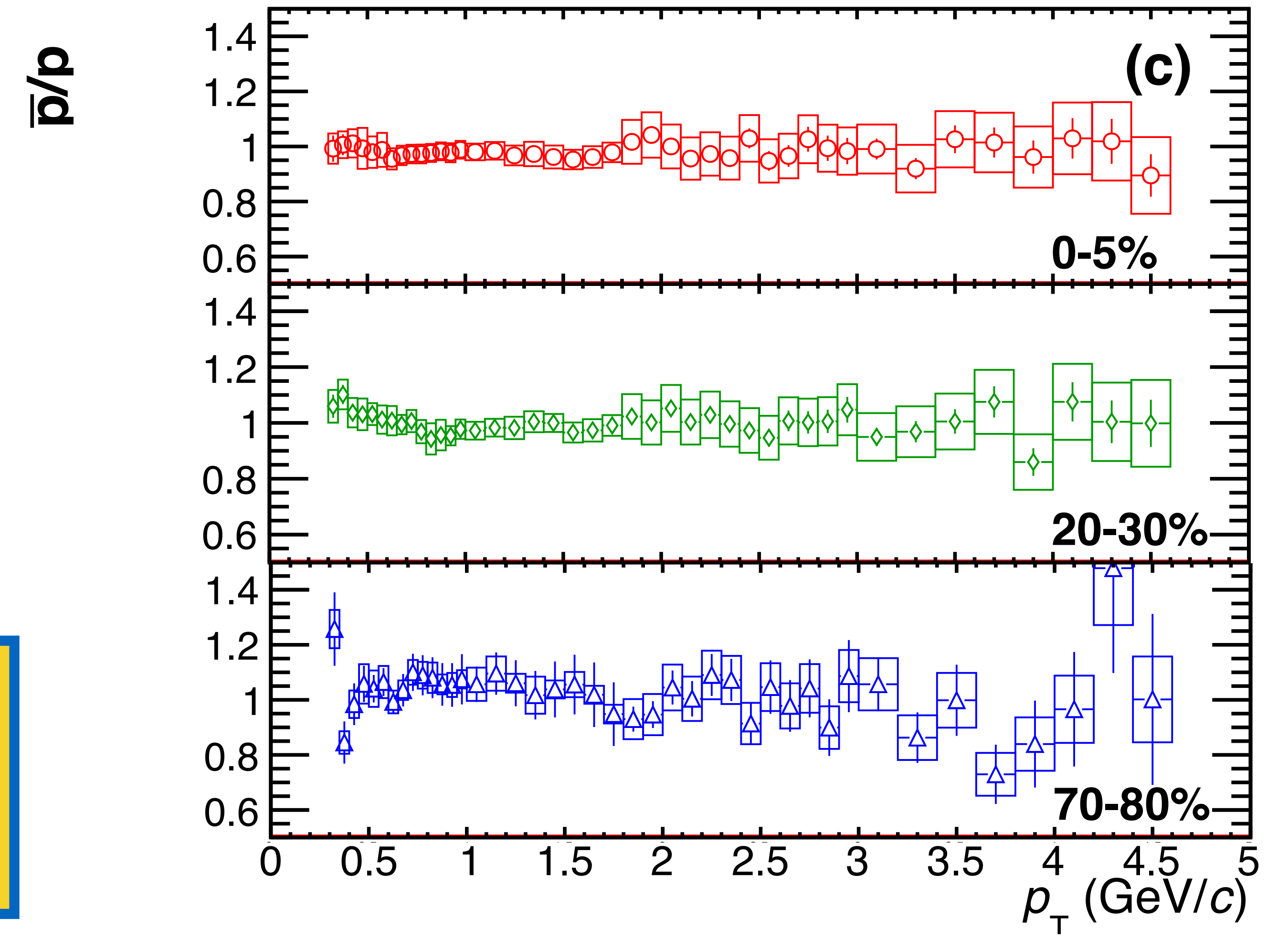
- Event-by-event fluctuations of the conserved quantities in QCD (*charge Q*, *baryon number B*, *strangeness S*) correspond to thermodynamic susceptibilities χ of the system which can be directly calculated in Lattice QCD or in the Hadron Resonance Gas (HRG) model:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n}(P/T^4)}{\partial(\mu_B/T)^l\,\partial(\mu_S/T)^m\,\partial(\mu_S/T)^n}$$

- Statistical distribution of conserved quantities are quantified by their (central) moments or cumulants.

LHC (ALICE) data allows the most direct comparison to Lattice QCD calculations which correspond to $\mu_B = 0$. No extrapolation needed at LHC energies!

[PRC 88 (2013) 044910]



Critical chiral dynamics

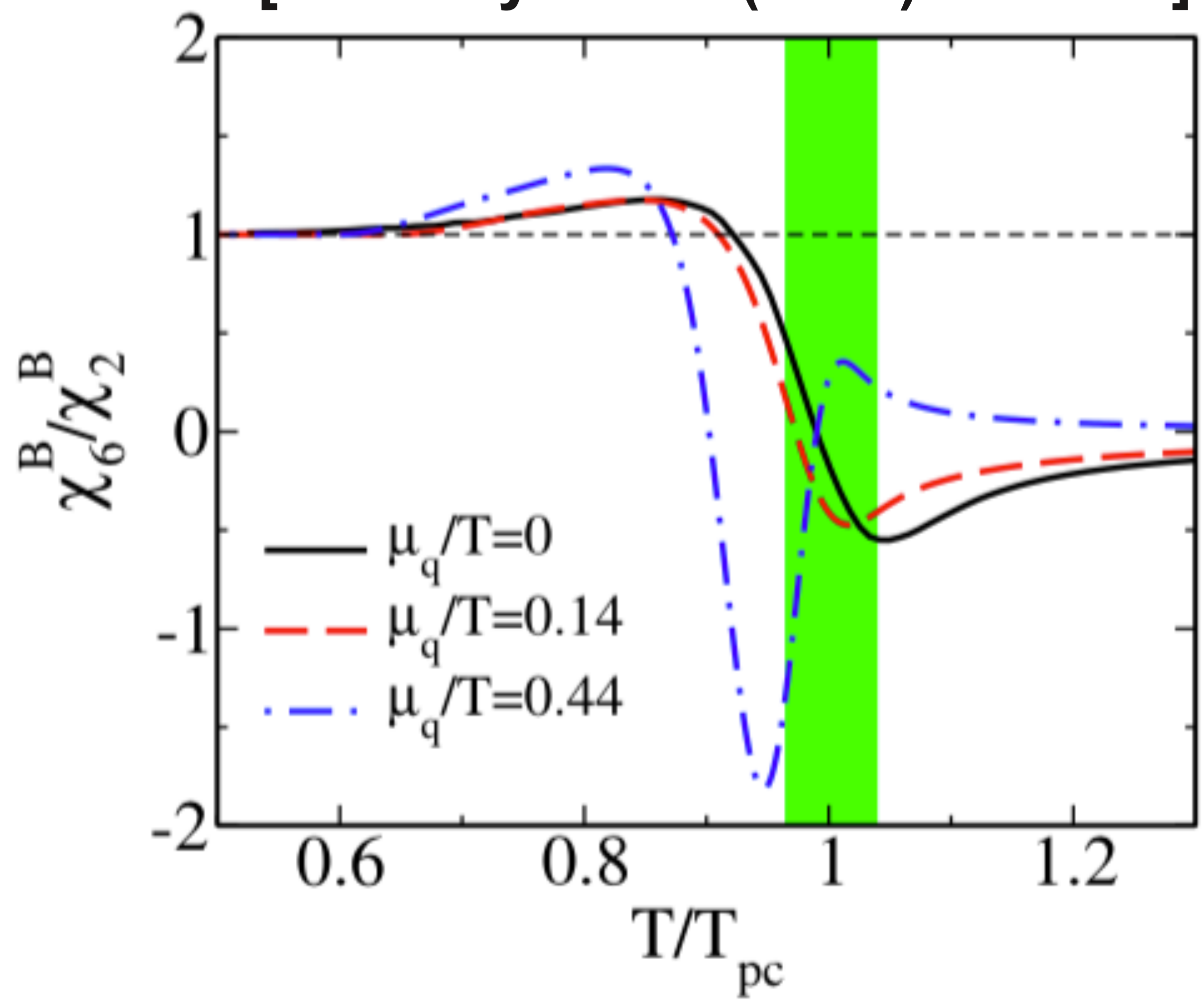
- Higher order thermodynamic susceptibilities are sensitive to remnants of chiral phase transition.

- Net-Baryon number fluctuations can be well approximated by net-proton measurements

  ➜ natural continuation of LF spectra measurements on an event-by-event basis!

- Sensitivity to this effects in heavy-ion collisions depends on how deep in the hadronic phase the chemical freeze-out takes place.

[Eur. Phys. J. C (2011) 71:1694]

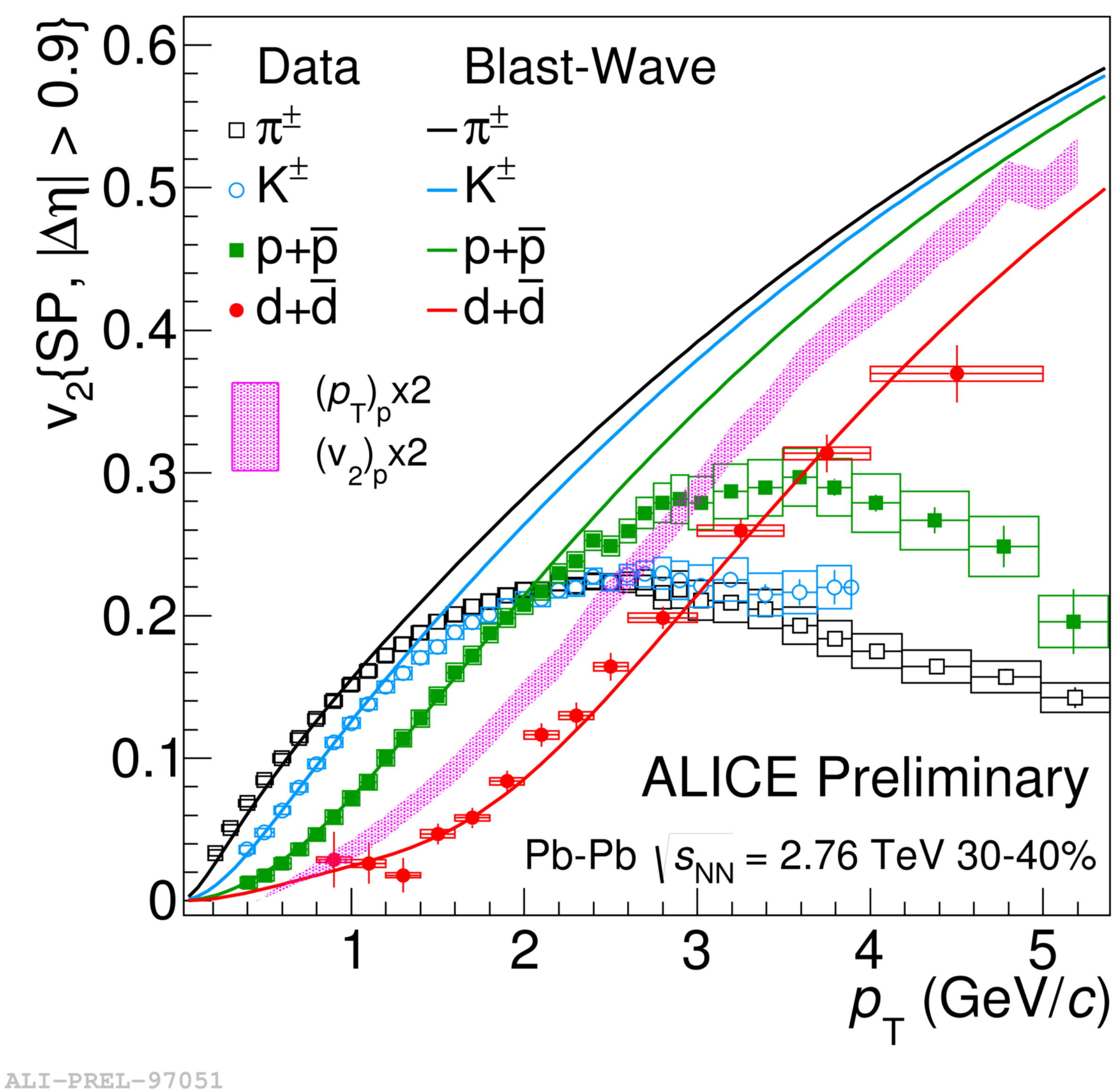


Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

Hadronic phase and (anti-)nuclei

- See the next talk by B. Doenigus: despite their low binding energy ($E_B \approx 2.2$ MeV for d), light (anti-)nuclei behave like non-composite objects:
  - Yields are in agreement with thermal expectations.
  - pT-spectra and azimuthal anisotropy follow hydrodynamic expectations.
  - Simple coalescence models do not describe the data.

- Isn't that a sign that the part of the hadronic phase in which inelastic collisions occur (**even with minimal energy transfer**) must be extremely short?



Summary & conclusion

Summary

- Light flavour hadron production in Pb-Pb collisions at the LHC are well described by particle emission from a QCD medium in chemical and kinetic equilibrium.
- This picture can be extended to small collisions systems (pp,p-Pb) if effects of strangeness suppression due to the exact conservation of the strangeness quantum number in small systems are taken into account.
- Natural next step: measurement of identified particle production on an event-by-event basis (see talk by A. Rustamov)!

Happy birthday..

.. and many thanks for the support during the last 11 years!

Nuclear Physics Course
Summer Semester 2005

Prof. Dr. Peter Braun-Munzinger
Dr. Dariusz Miskowiec, Dr. Christian Lippmann
Oliver Busch, Dr. Mario Babilon

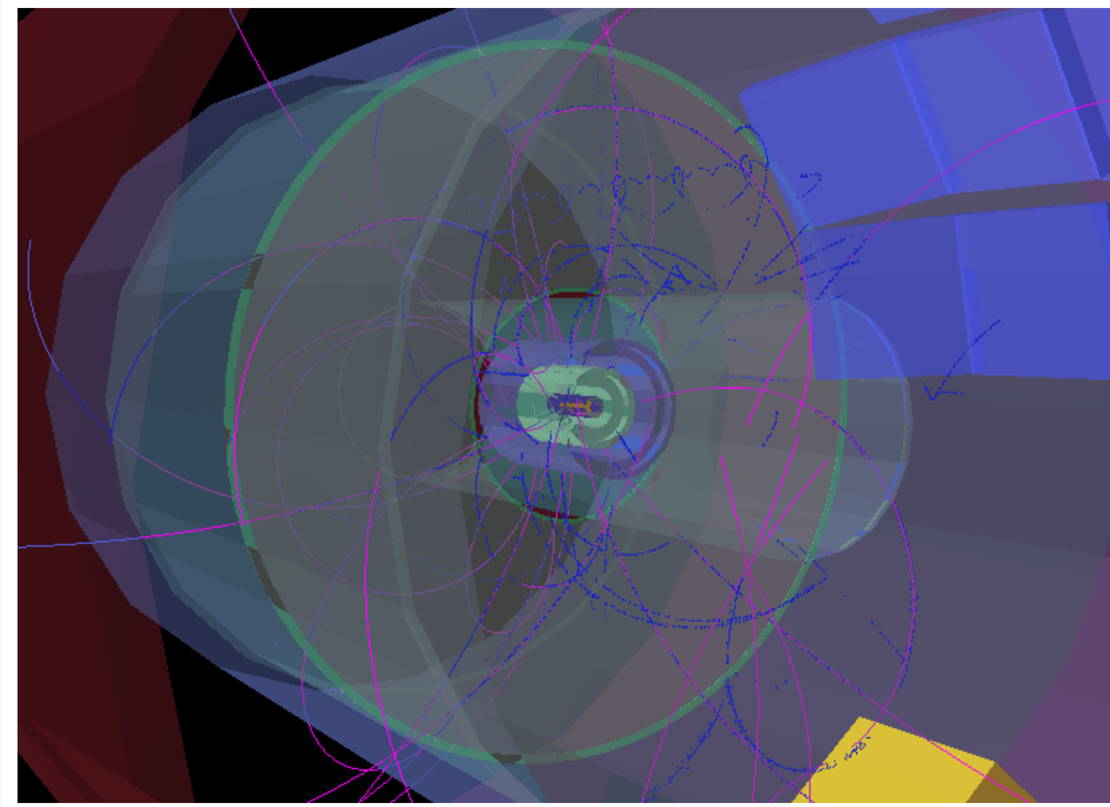
TECHNISCHE UNIVERSITÄT DARMSTADT

Problem Set #7

1. A proton beam of kinetic energy of 1 TeV is deflected in a 10 m long dipole magnet with homogeneous field $B = 10$ T. What is the angular deflection?

2. The maximum magnetic field that can be obtained in a magnet is about 10 T. Assume an accelerator that follows the equator and which is divided into several dipole magnets which sum up to 10% of the earth's circumference in total length and which are connected via straight pipes. What is its maximum energy for protons?

3. Compute the energy loss per turn due to synchrotron radiation for electrons of $p =$ 100 GeV in an accelerator of radius $r = 4.5$ km.



TPC records its first LHC collisions
2009-DEC-06

Supporting slides