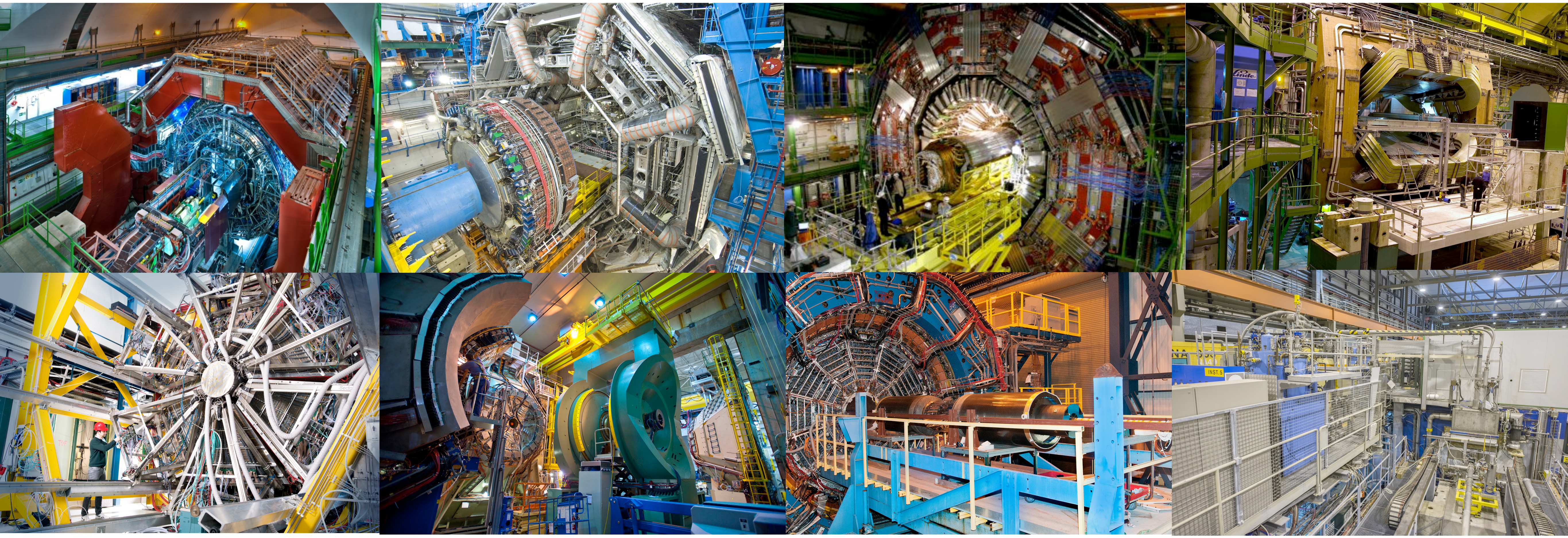
Strangeness production

Summary of experimental results



A. Kalweit, *CERN*

Introduction

- This talk tries to summarise the experimental findings of
  ➜ eight large experimental collaborations:

  ALICE, ATLAS, CMS, HADES, LHCb, NA-61, PHENIX, STAR

  ➜ covering a large range in beam energy.

- In total: 27 relevant talks! Strangeness is *the* topic of SQM.

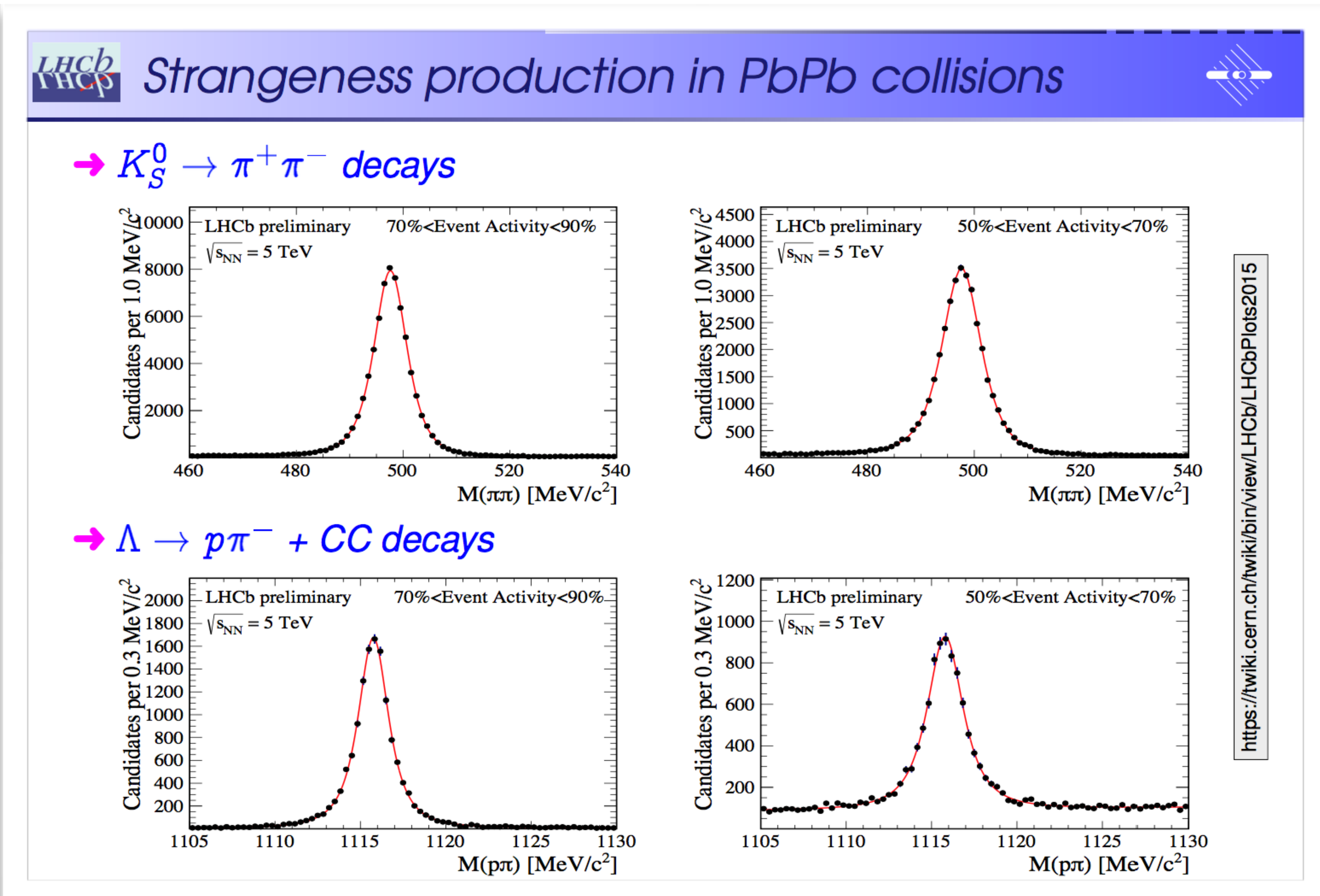
- Unfortunately, it is not possible to give justice to all the results in a single talk.

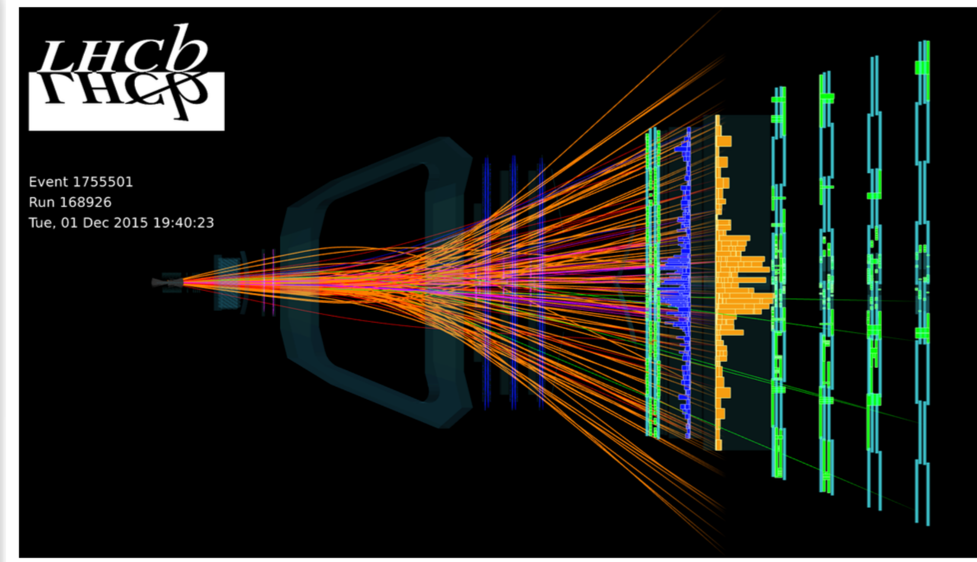
- Instead, this talk attempts to connect the experimental highlights from all the experiments and to point towards the questions which experimentalists need to address in the future.

LHCb

M. Schmelling
Mo., 12:00h

- The experimental heavy-ion community of strangeness physics is growing: **Welcome LHCb!**





- Looking forward to many interesting results on strangeness in a variety of collision systems and kinematic ranges with an impressive detector.

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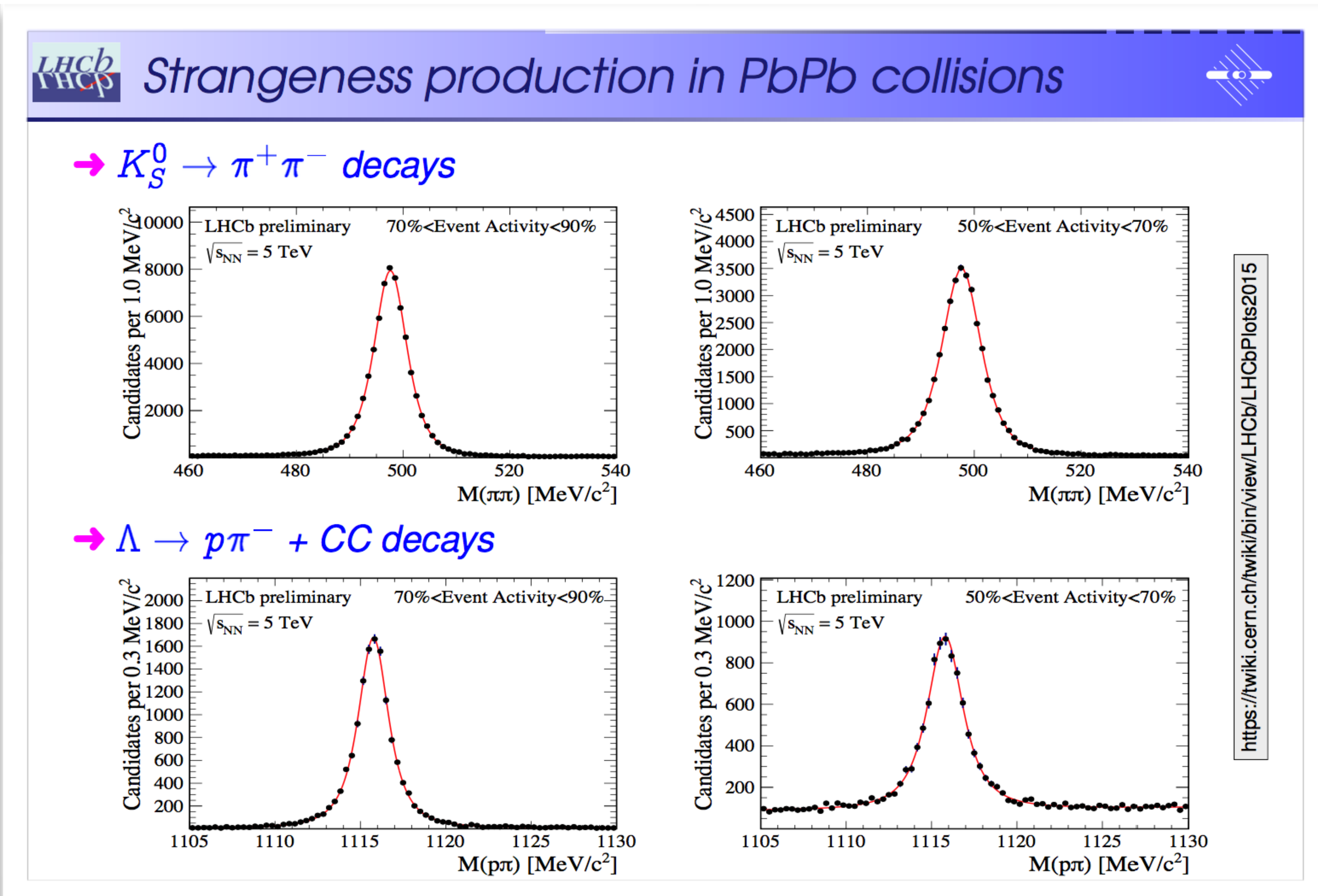
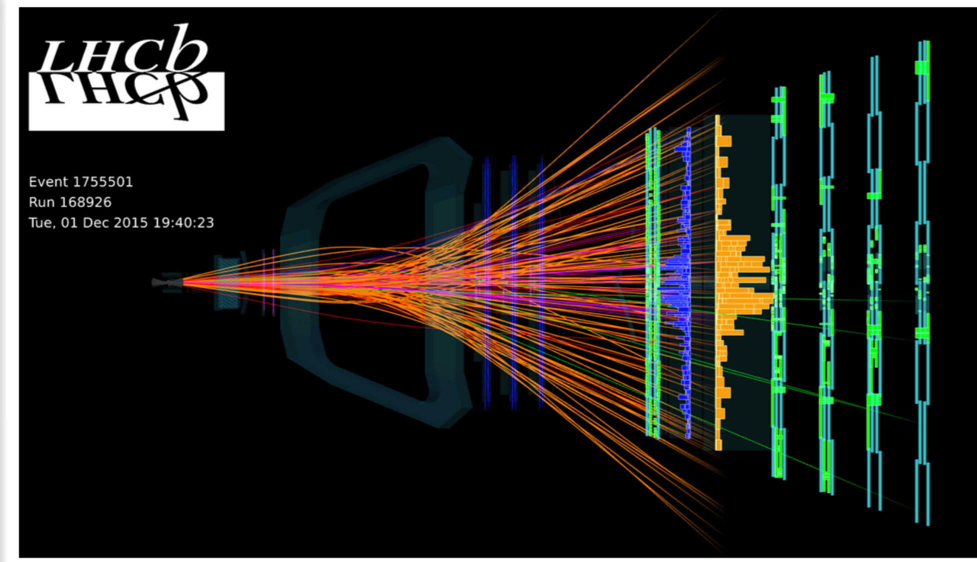




Experimental challenge:
make tracking working for as central collisions as possible!

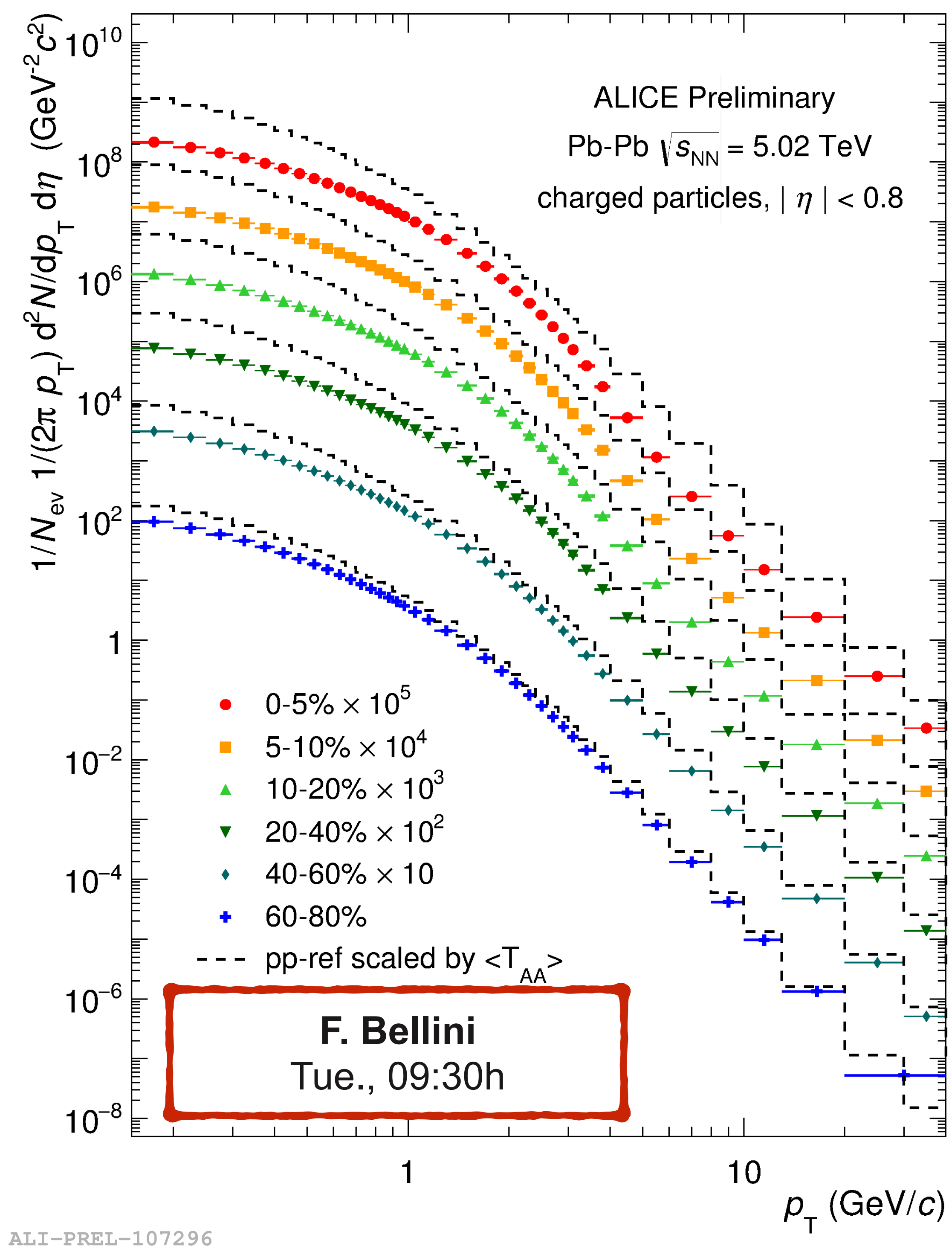
➔ tracking may be possible up to 15k VELO hits
➔ corresponds to 50-100% centrality.

- Looking forward to many interesting results on strangeness in a variety of collision systems and kinematic ranges with an impressive detector.

AA collisions at LHC and RHIC
statistical thermal model and hydrodynamics

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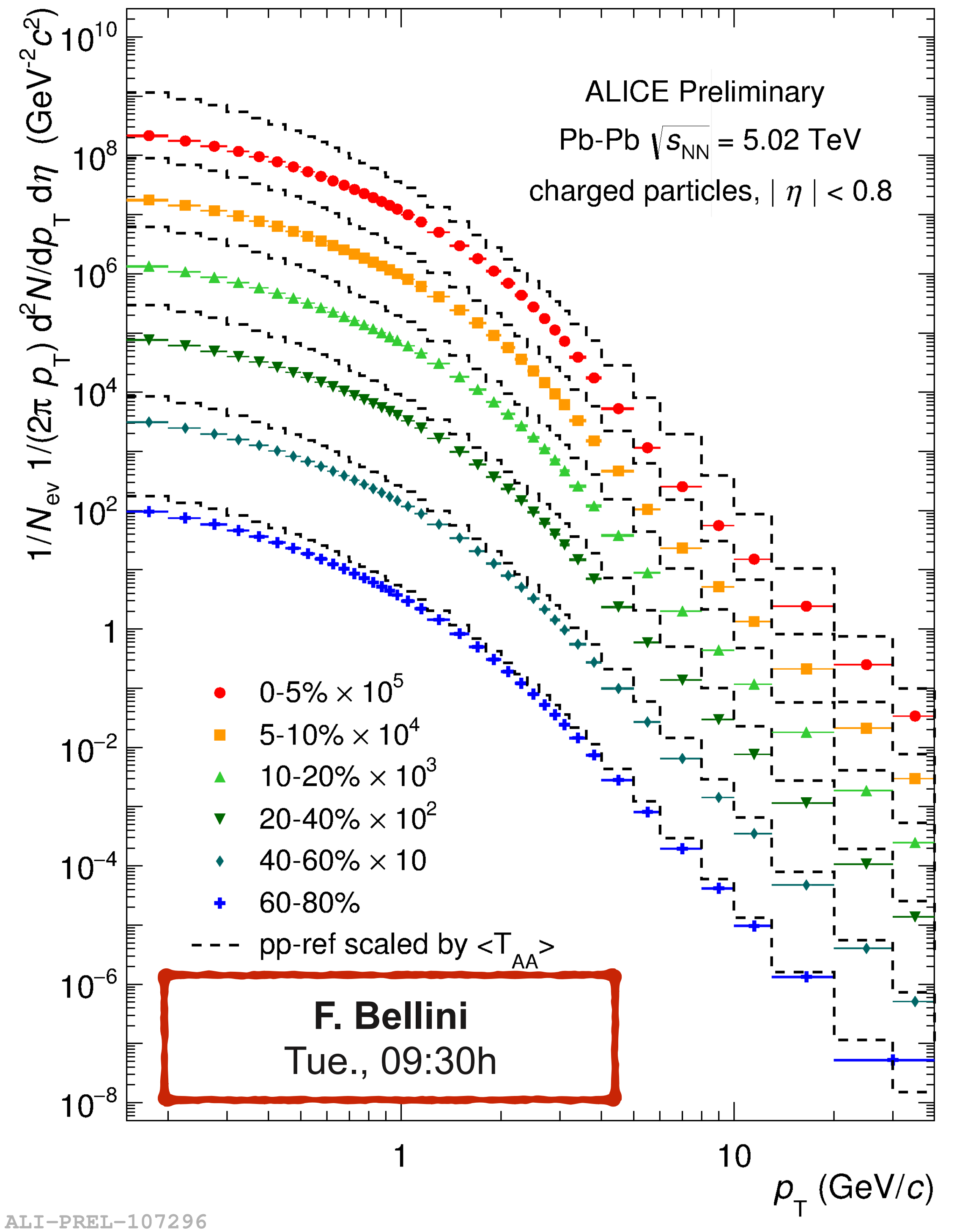
≈ 98% of all particles are produced with p_T < 2 GeV/c.



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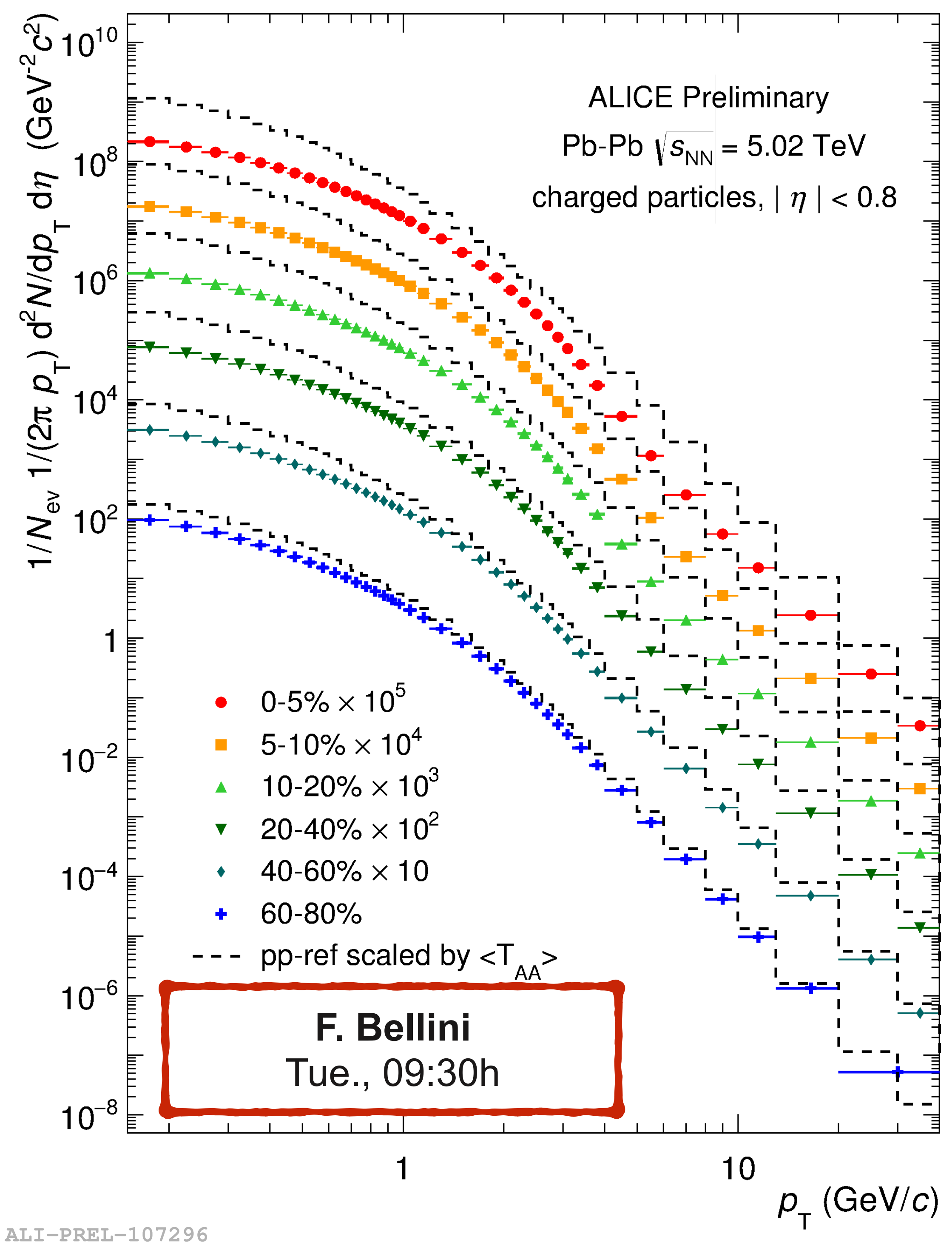

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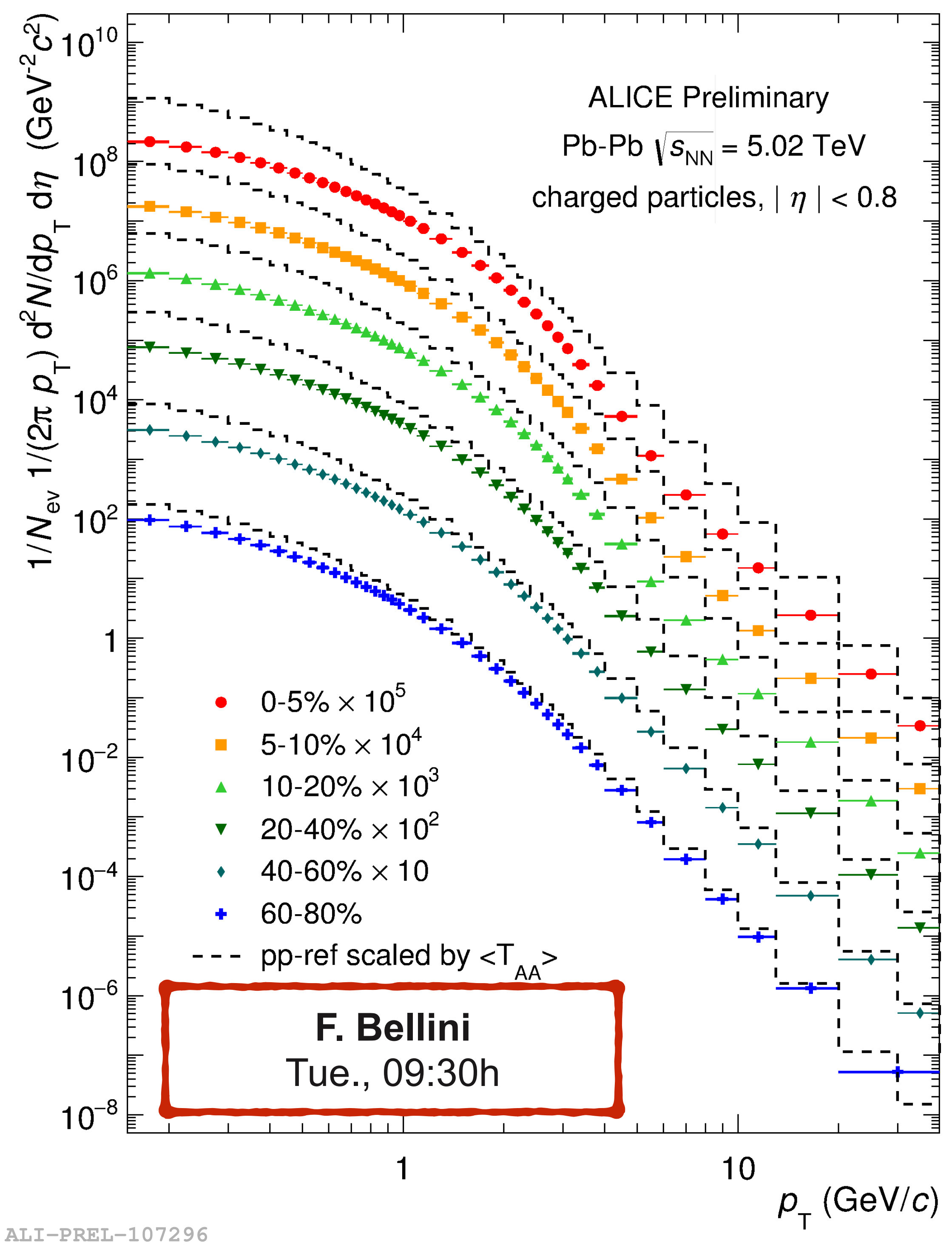


- "Standard model of heavy-ion physics"/ "Classical model of heavy-ion physics":

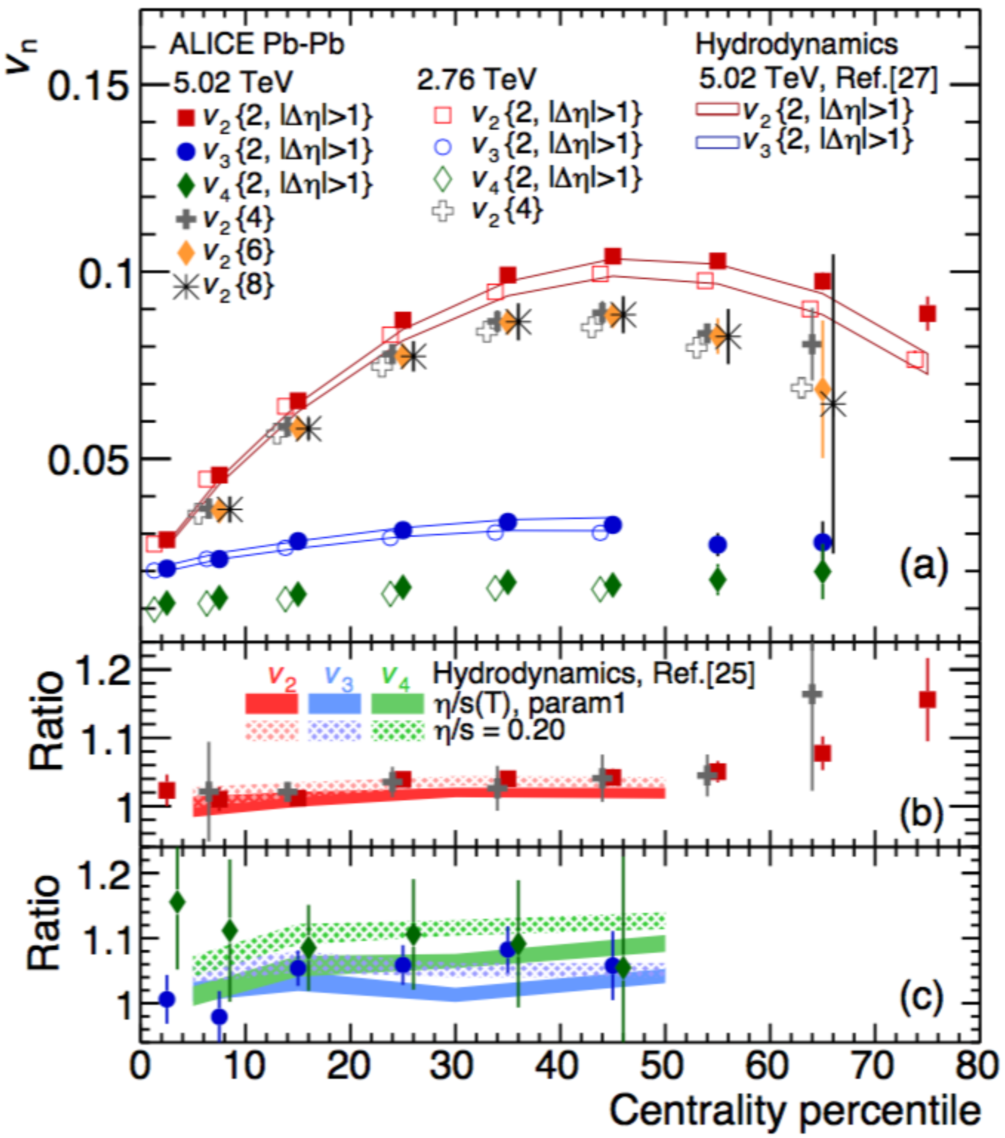
A fireball in *local thermodynamic equilibrium*:

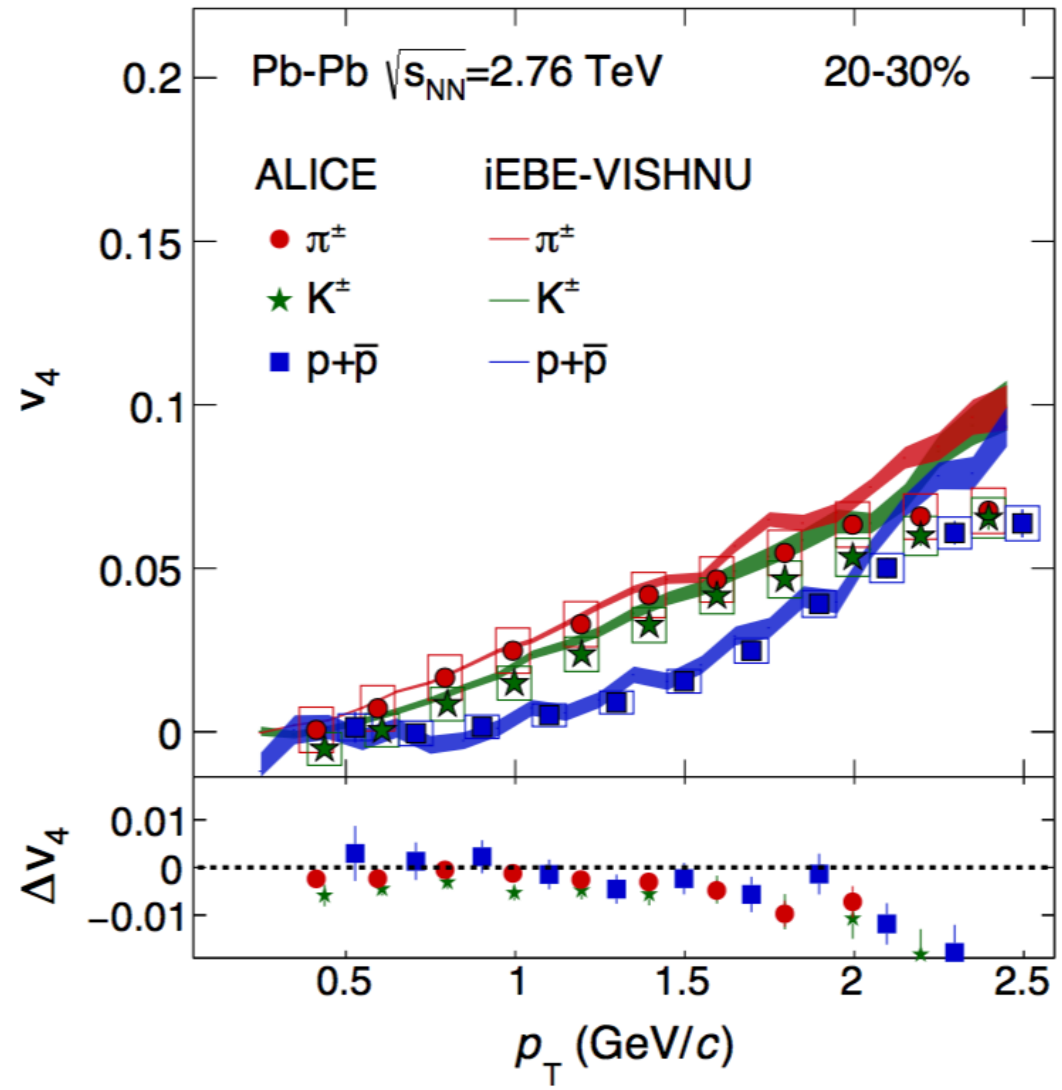
- particle chemistry in agreement with thermal model predictions
- p_T-spectra and v_2 measurements show patterns of radial and elliptic hydrodynamic flow.

Elliptic flow ALICE

Y. Zhou
Thu., 11:40h

N. Mohammadi
Thu., 09:00h





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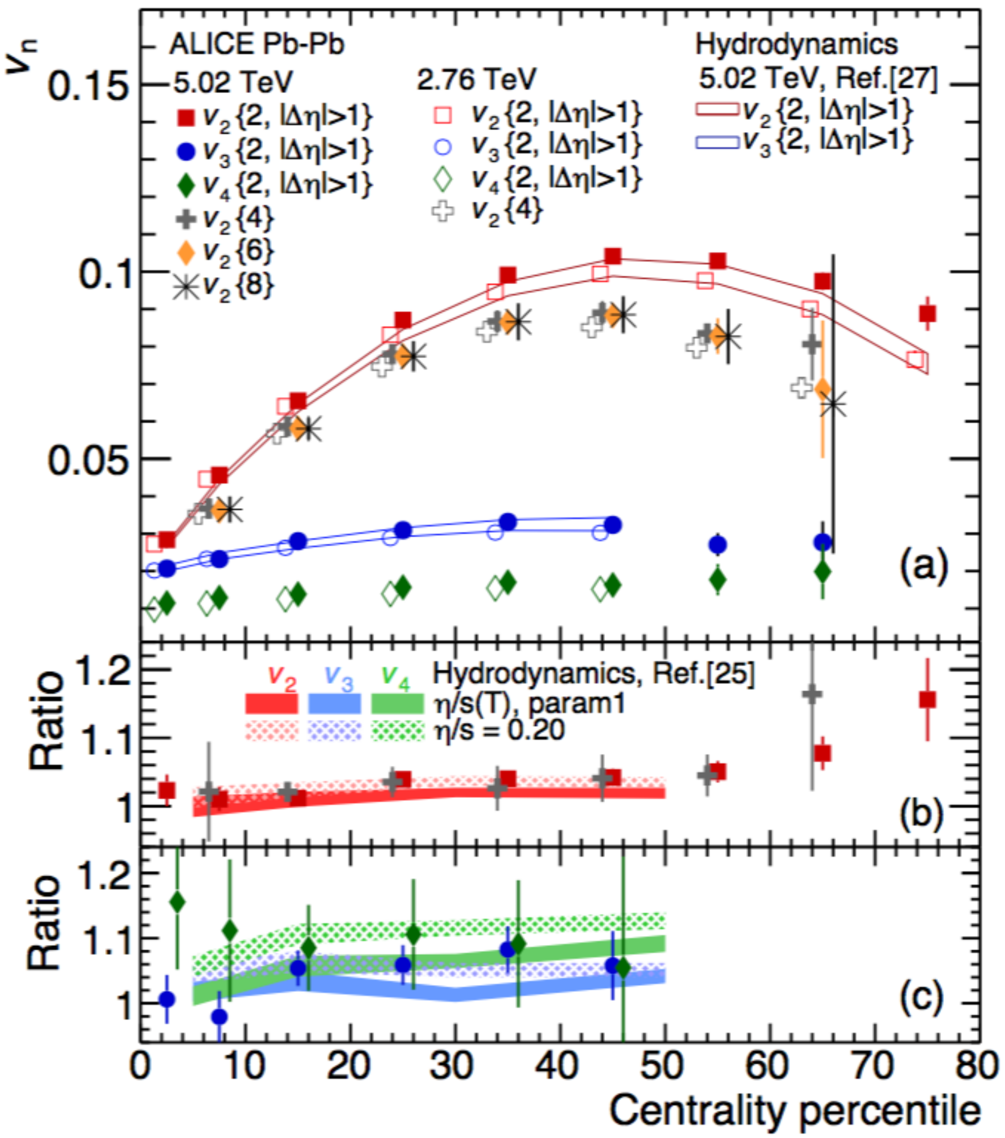

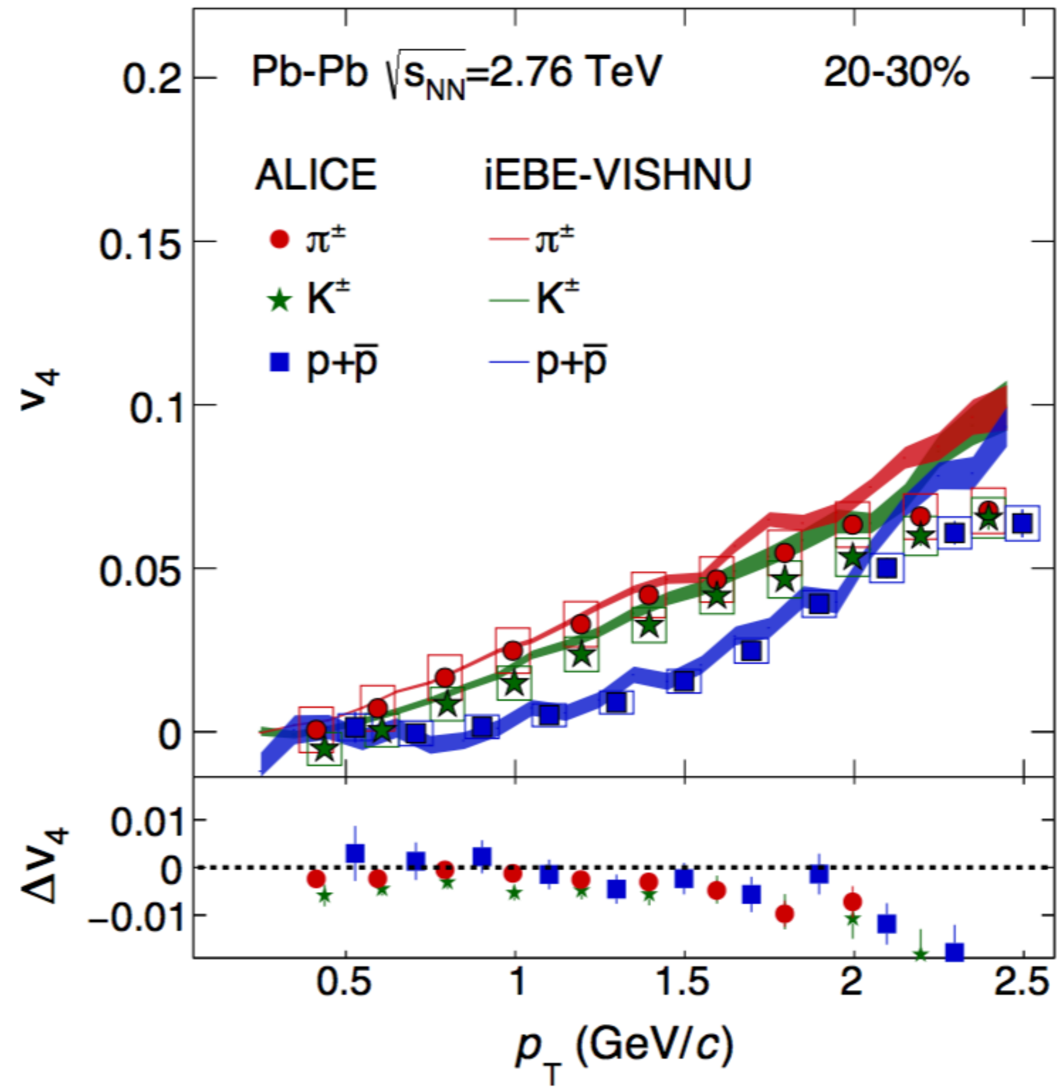

Validity of hydrodynamic description confirmed at the highest centre-of-mass energies available.

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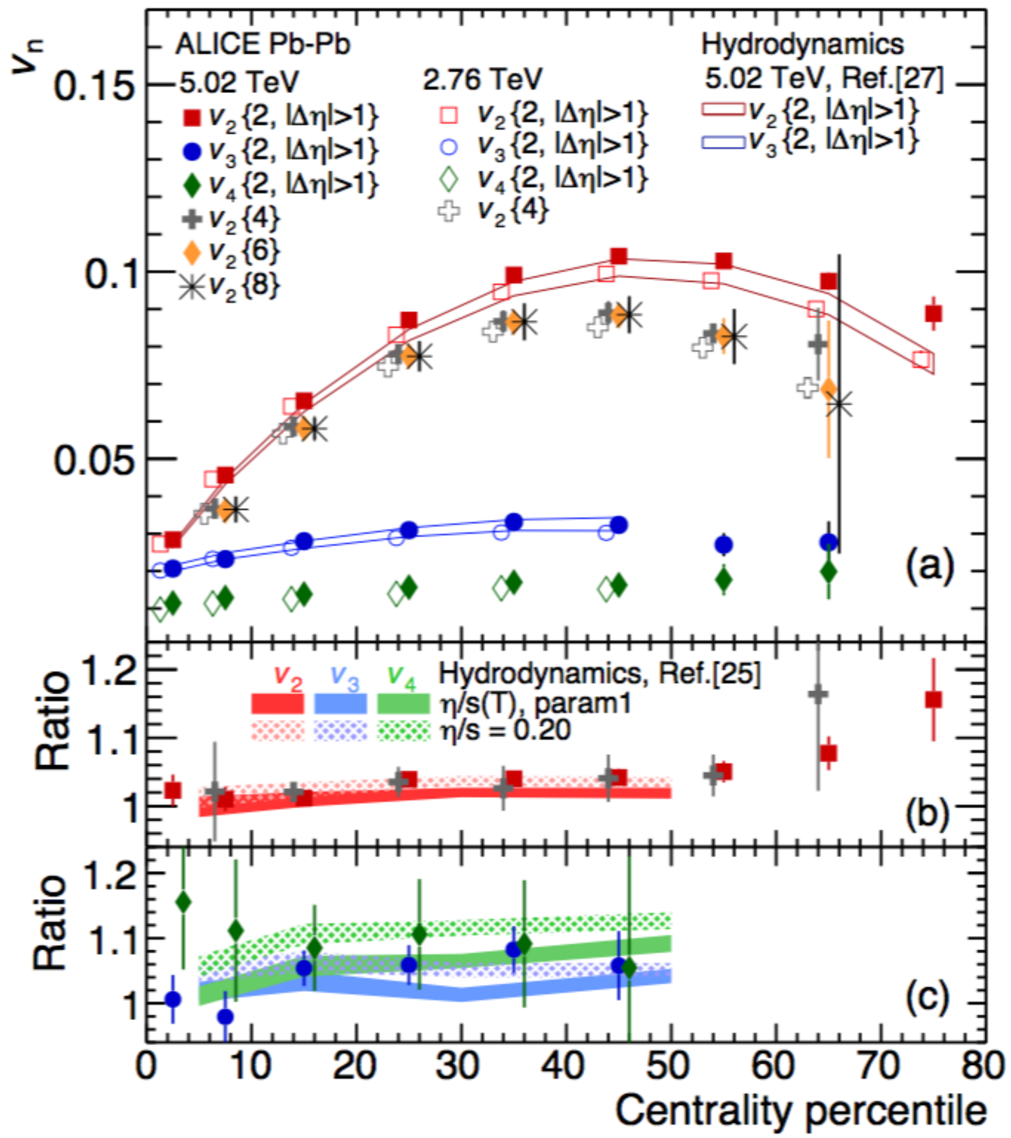

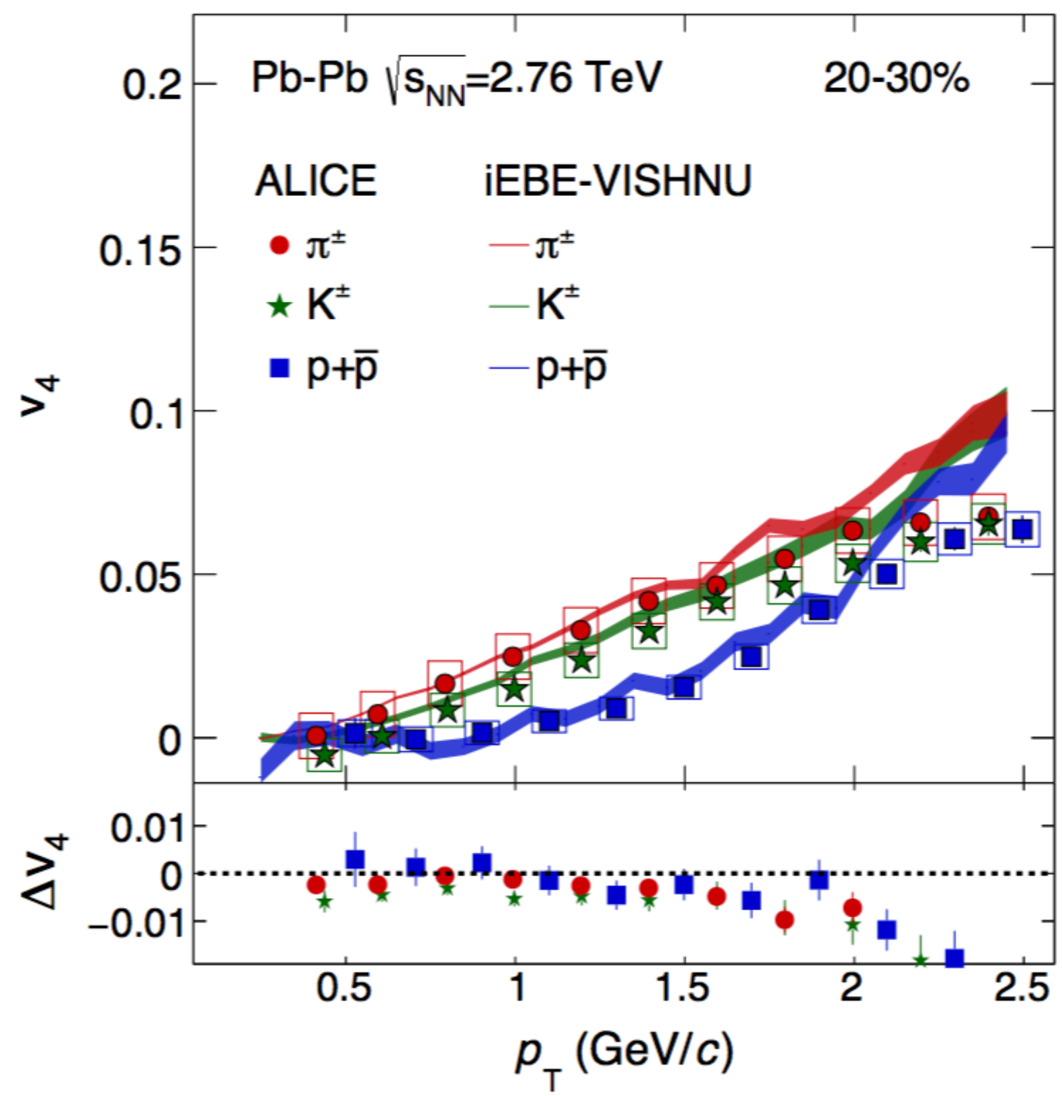

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Expected mass ordering
($p = \beta\gamma \cdot m$)
also observed in higher harmonic flow coefficients.

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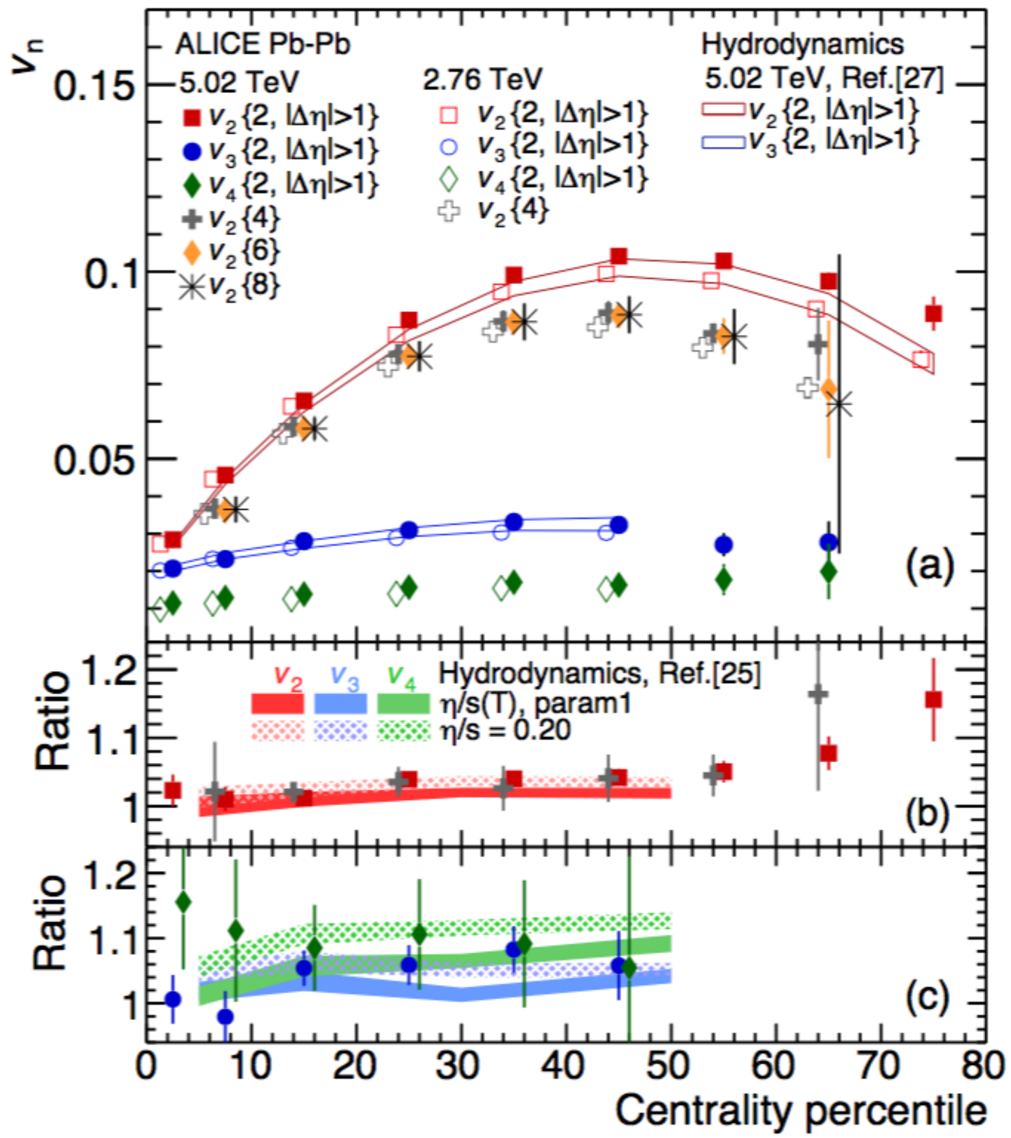

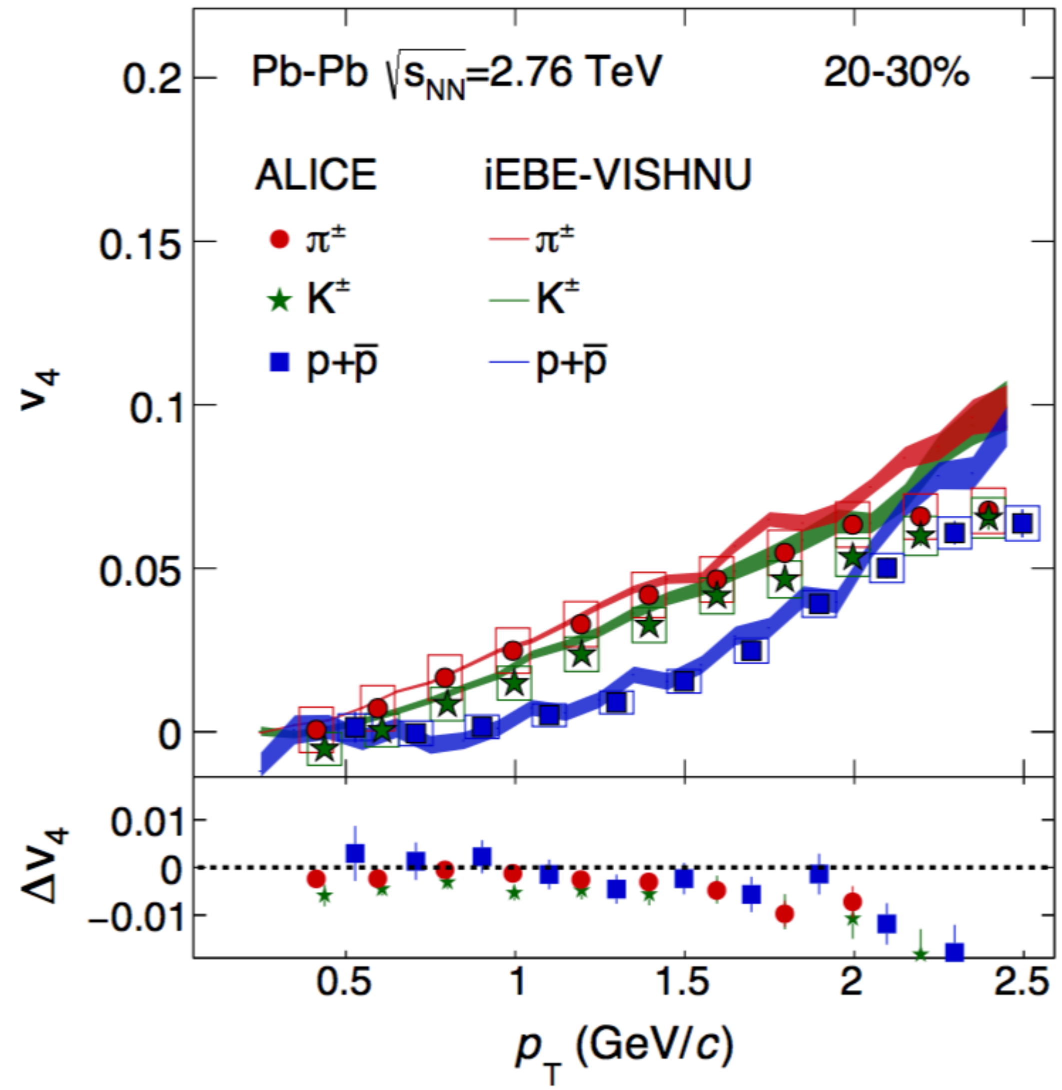

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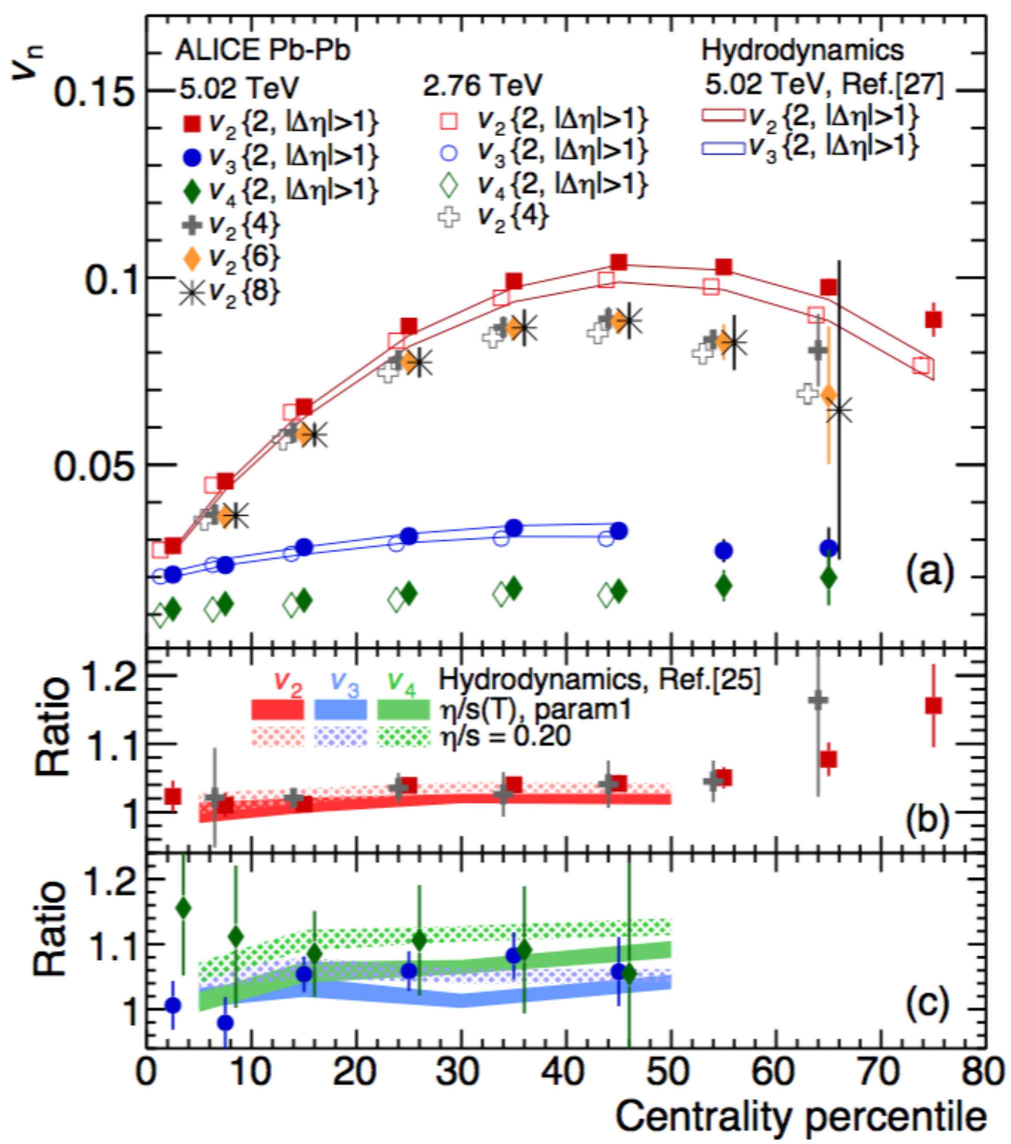

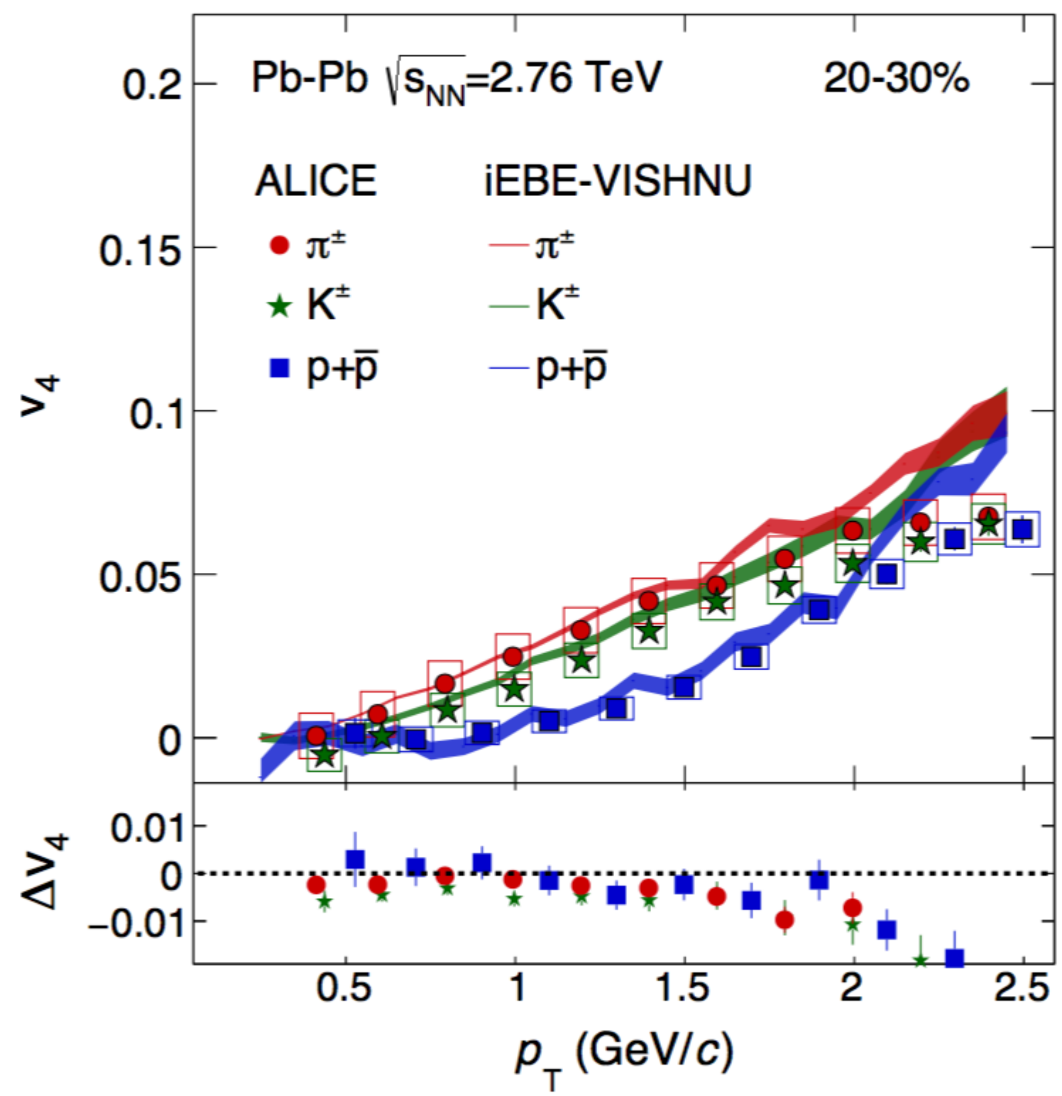

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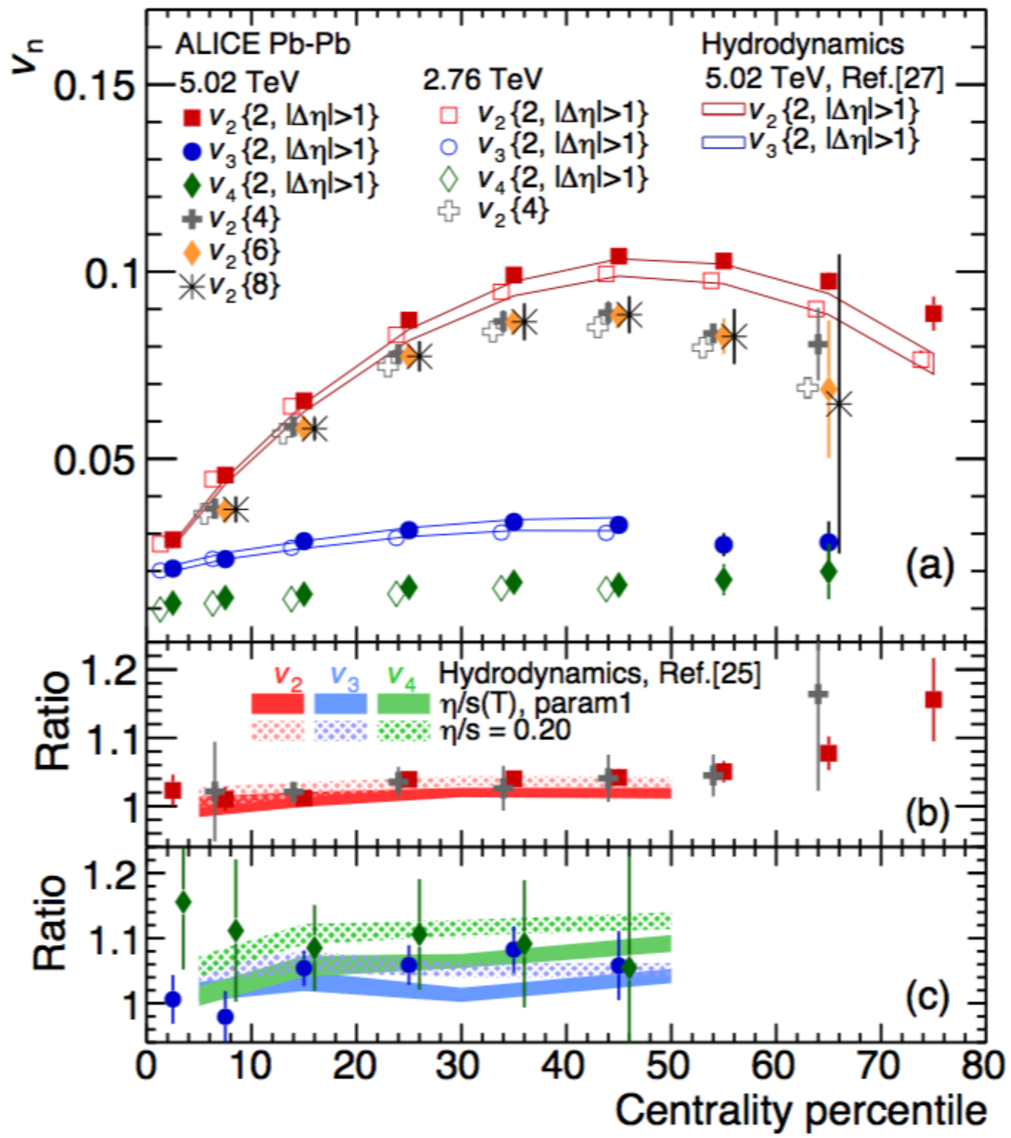

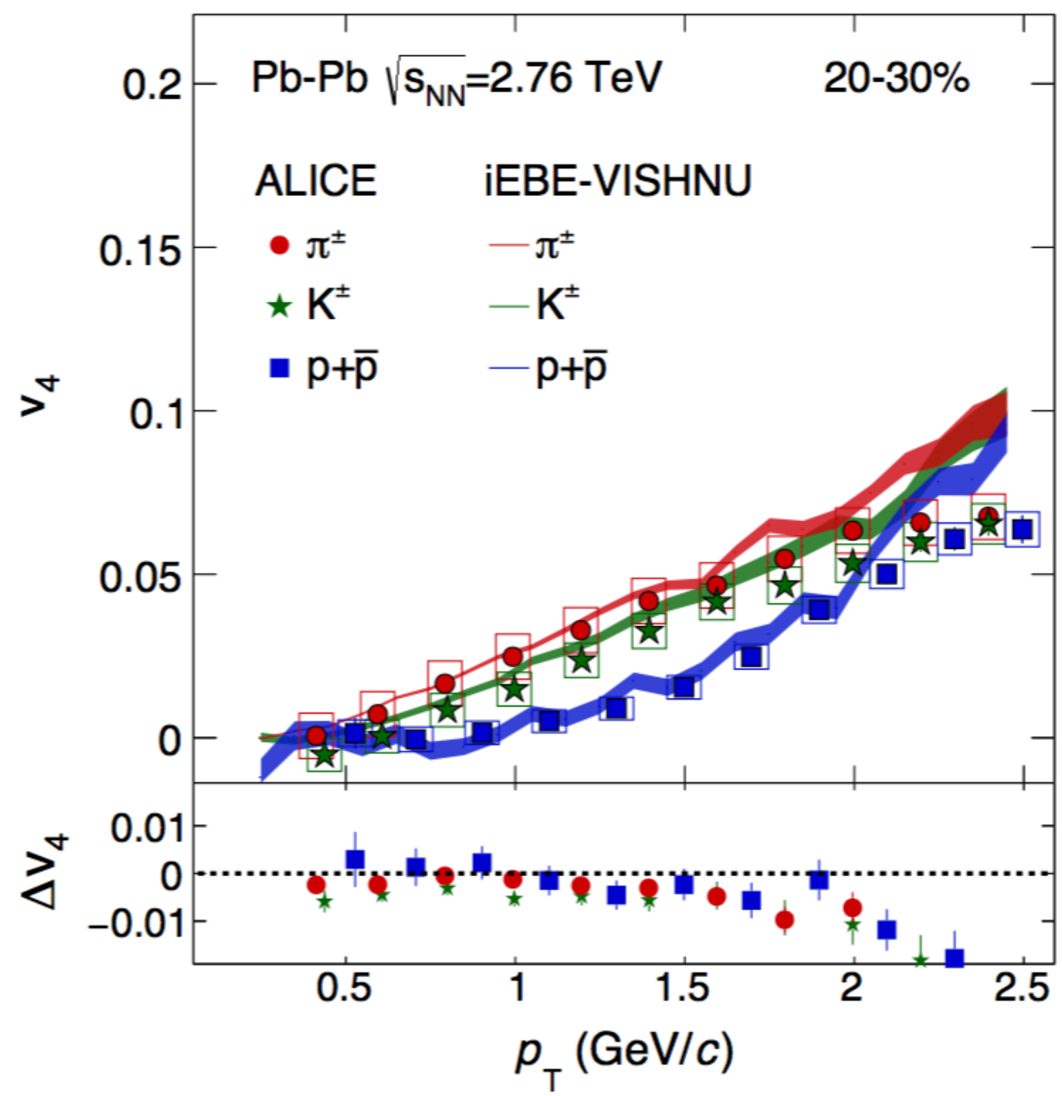

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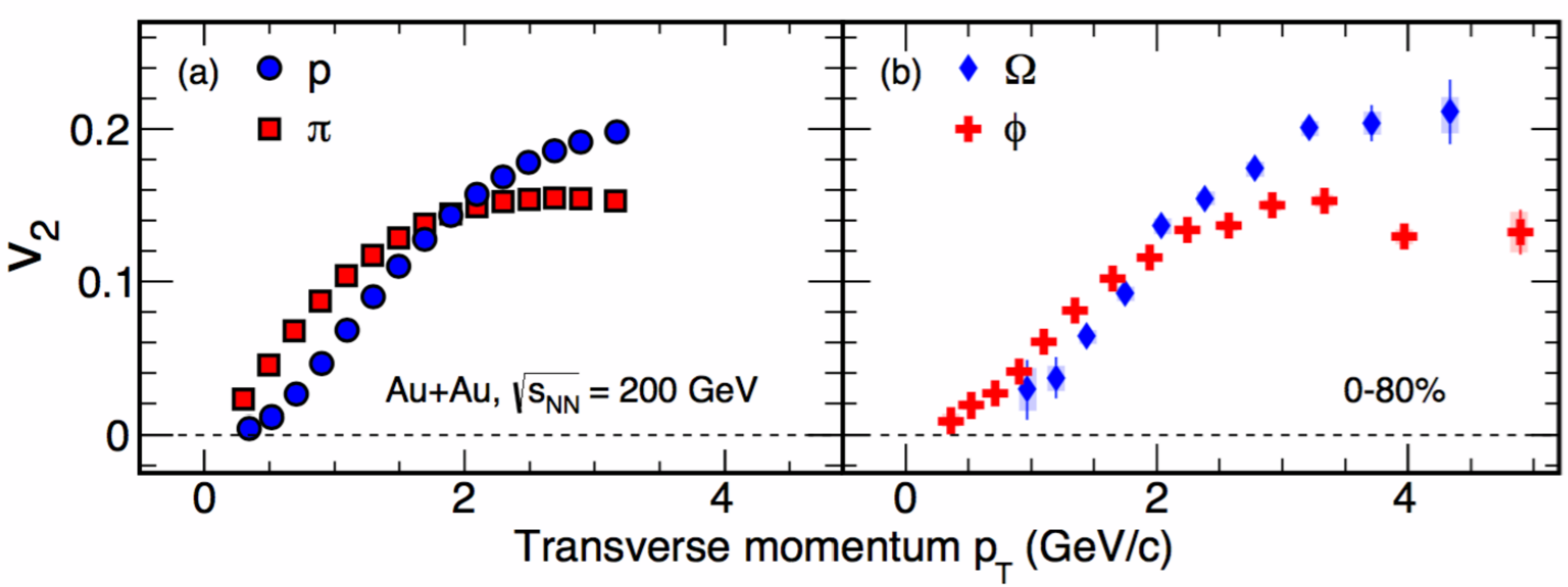
Elliptic flow STAR

S. Shi
Tue., 09:00h

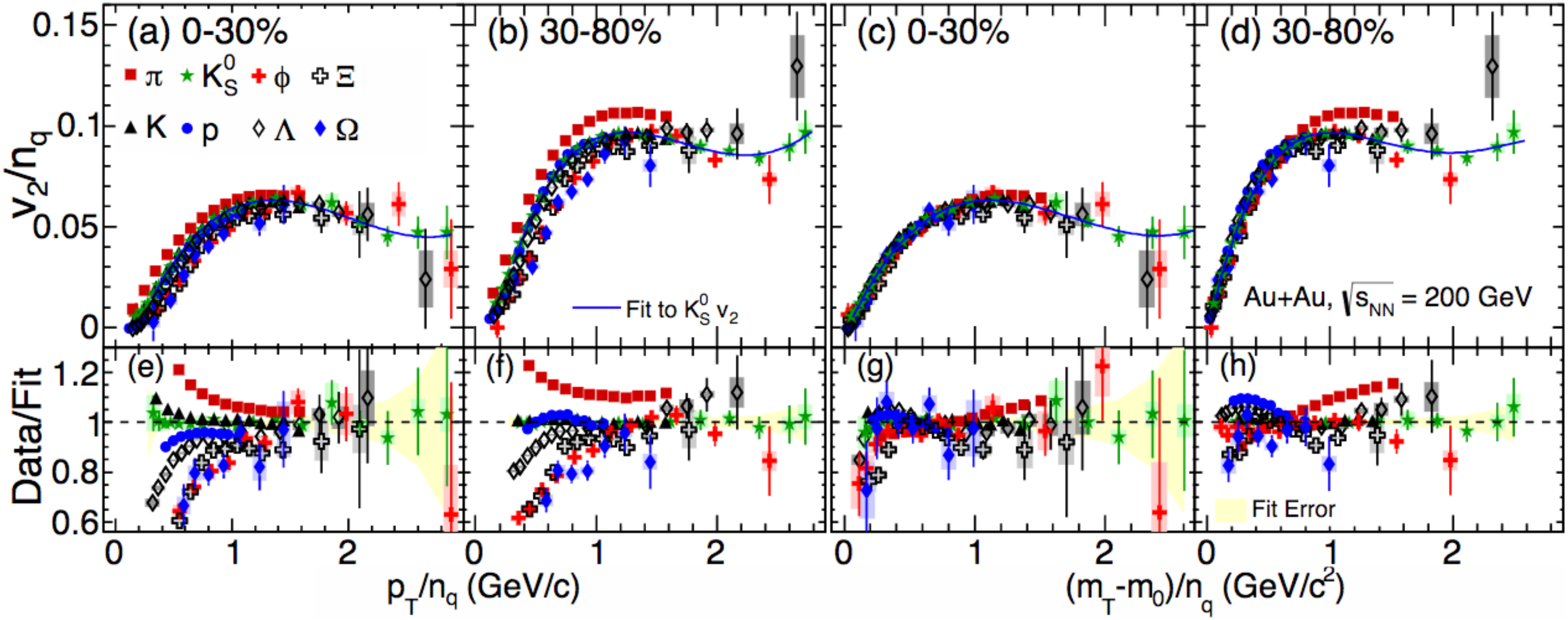


- Mass ordering also holds for multi-strange particles Ω(sss) and ϕ(ss-bar).
- Hadronic cross-sections for Ω and ϕ are significantly smaller than for the non-strange particles p and π.

  => The results indicate that a major part of the collectivity is already built up at the partonic stage.

STAR NCQ scaling

S. Shi
Tue., 09:00h



- v2 scaling with the number of constituent quarks holds on the 10% level at RHIC energies.

> ➢ Coalescence is the dominant hadronization mechanism at RHIC in the intermediate p_T range

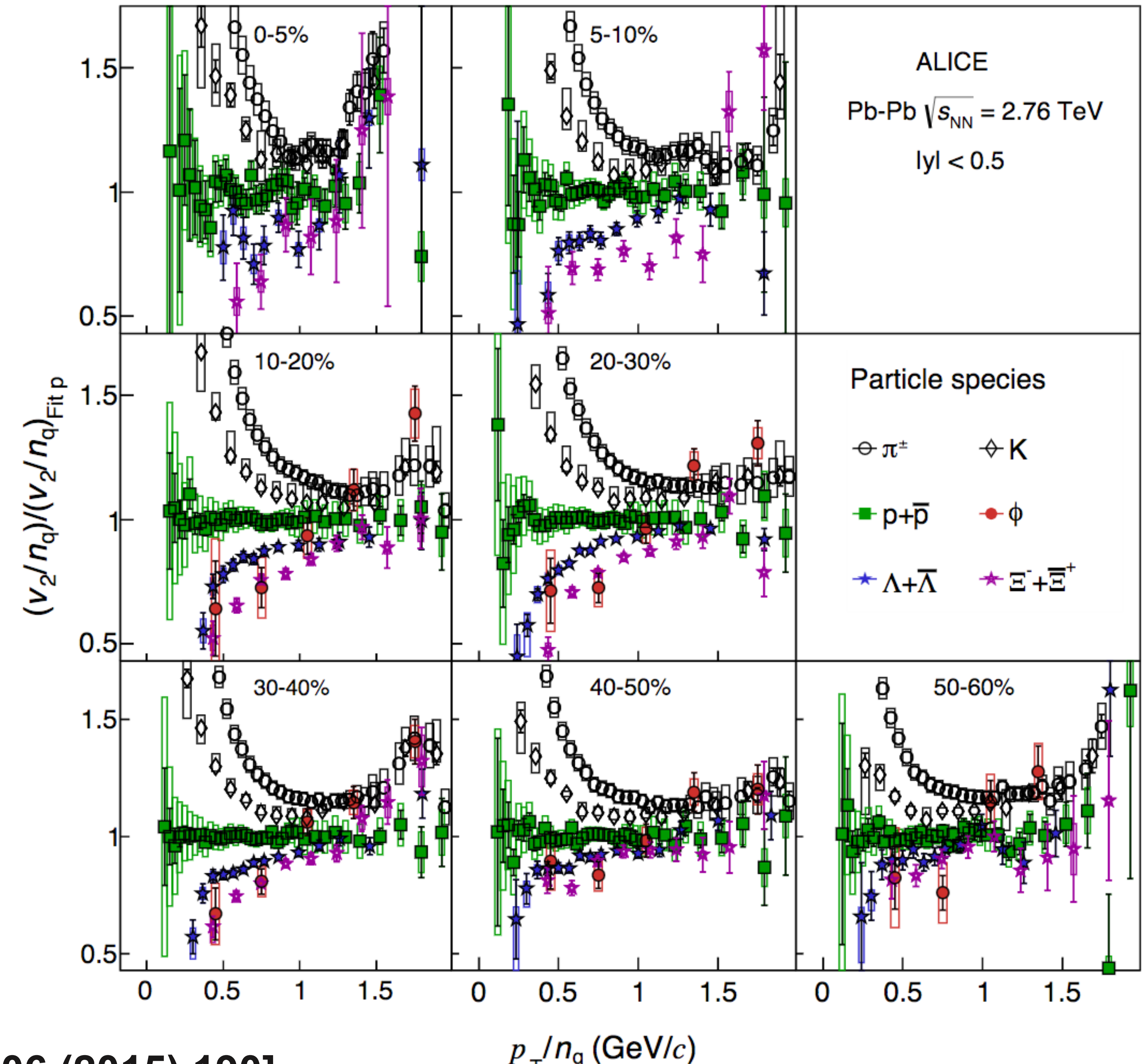
ALICE NCQ scaling

N. Mohammadi
Thu., 09:00h

- At LHC energies, constituent quark scaling is broken on the 20% level (also for higher order flow harmonics).

- N.B.: mesons (π,K) cluster above and baryons (p,Λ,Ξ) cluster below.

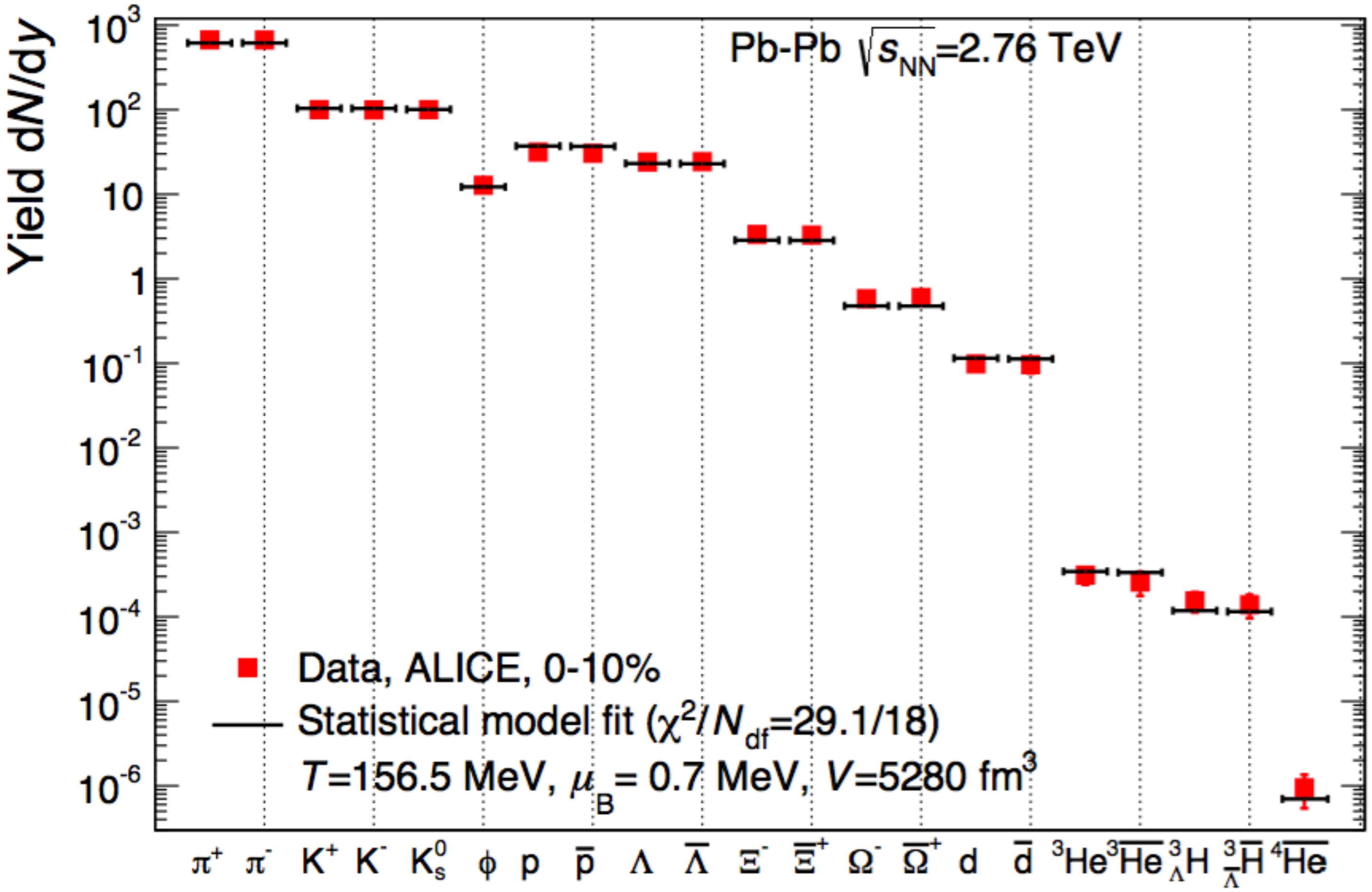
  => Better scaling would be achieved by dividing baryons by a factor smaller than 3 and mesons by a factor larger than 2.

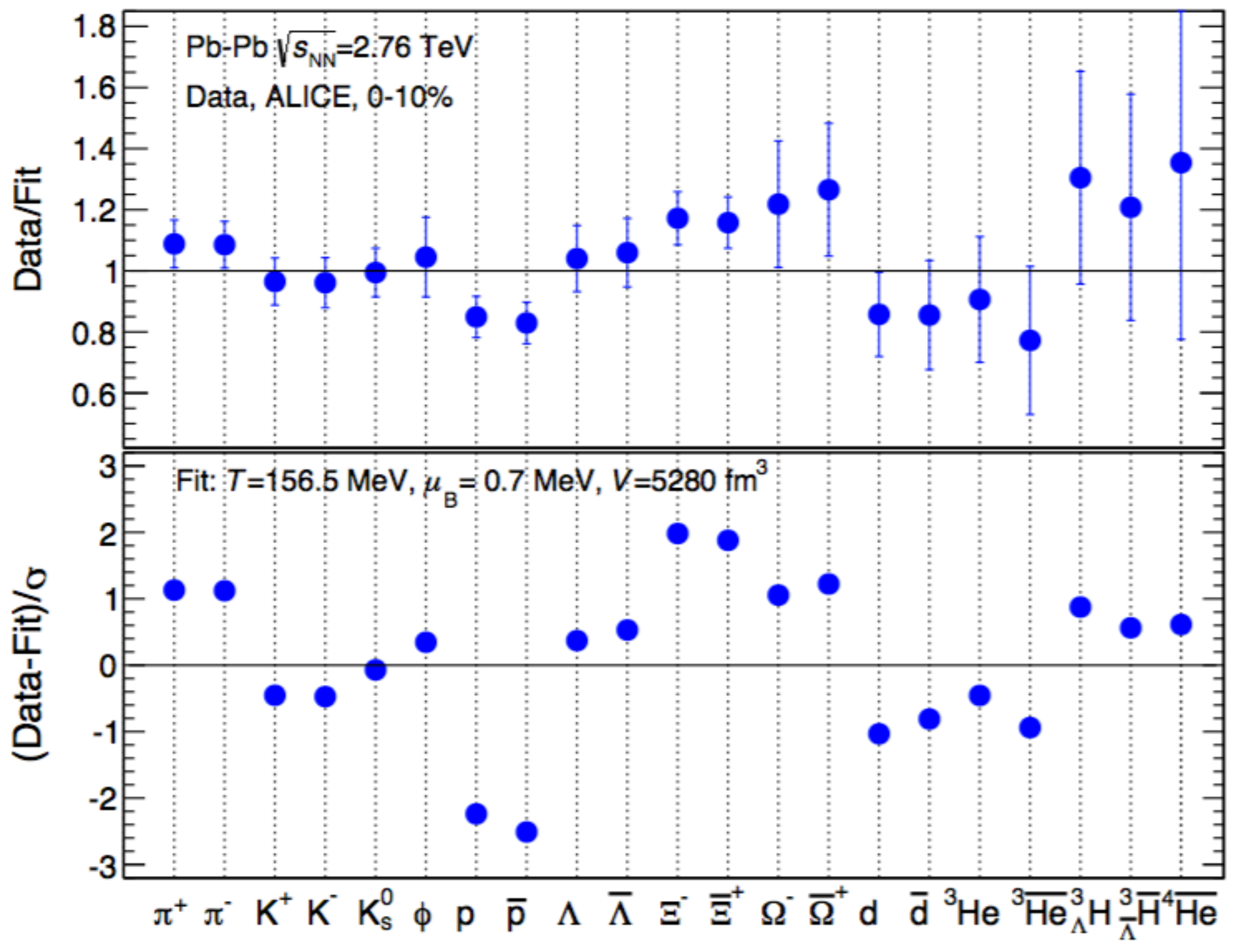


[JHEP 1506 (2015) 190]

Thermal model at the LHC

A. Andronic
Wed., 11:00h





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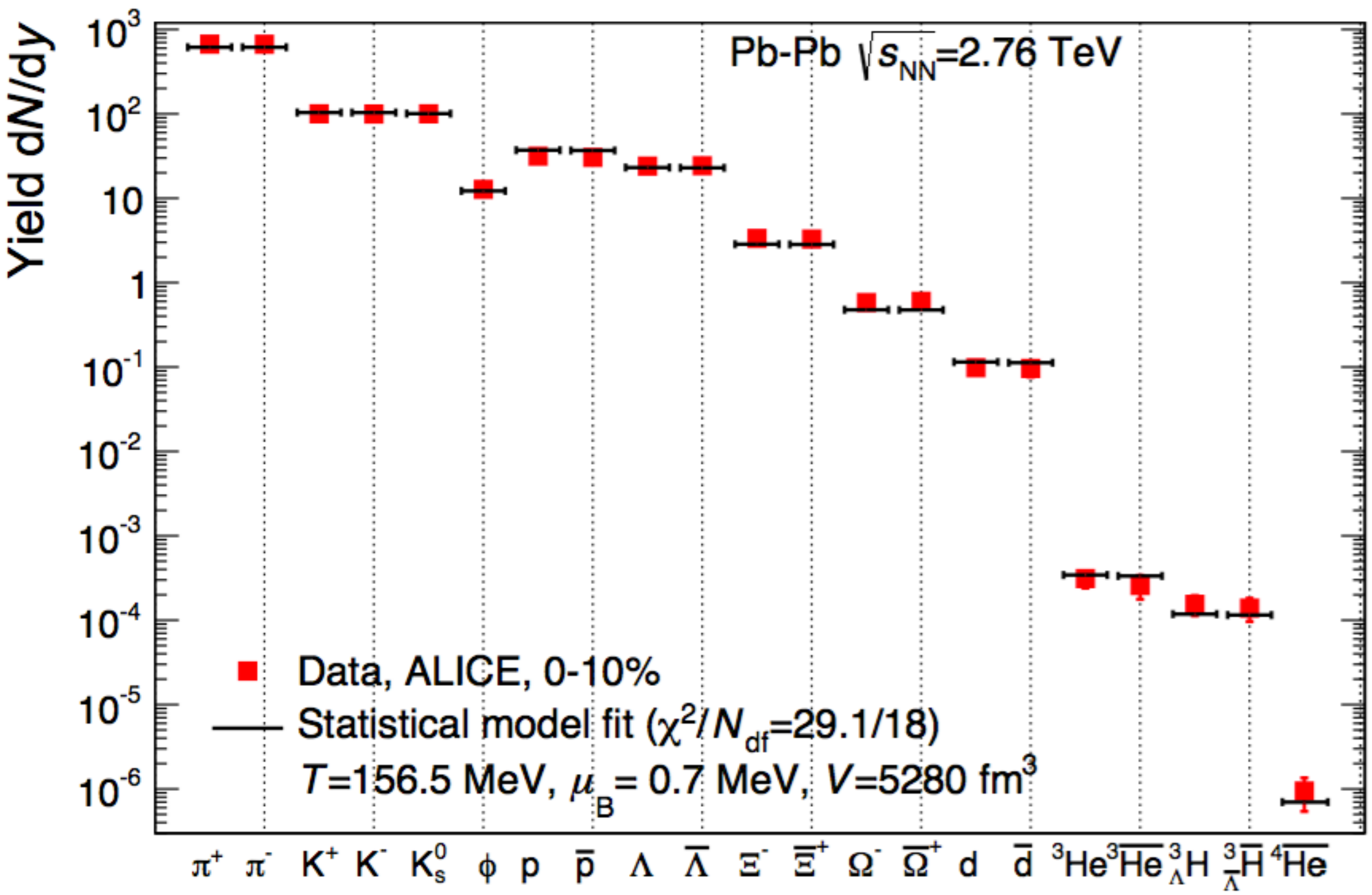

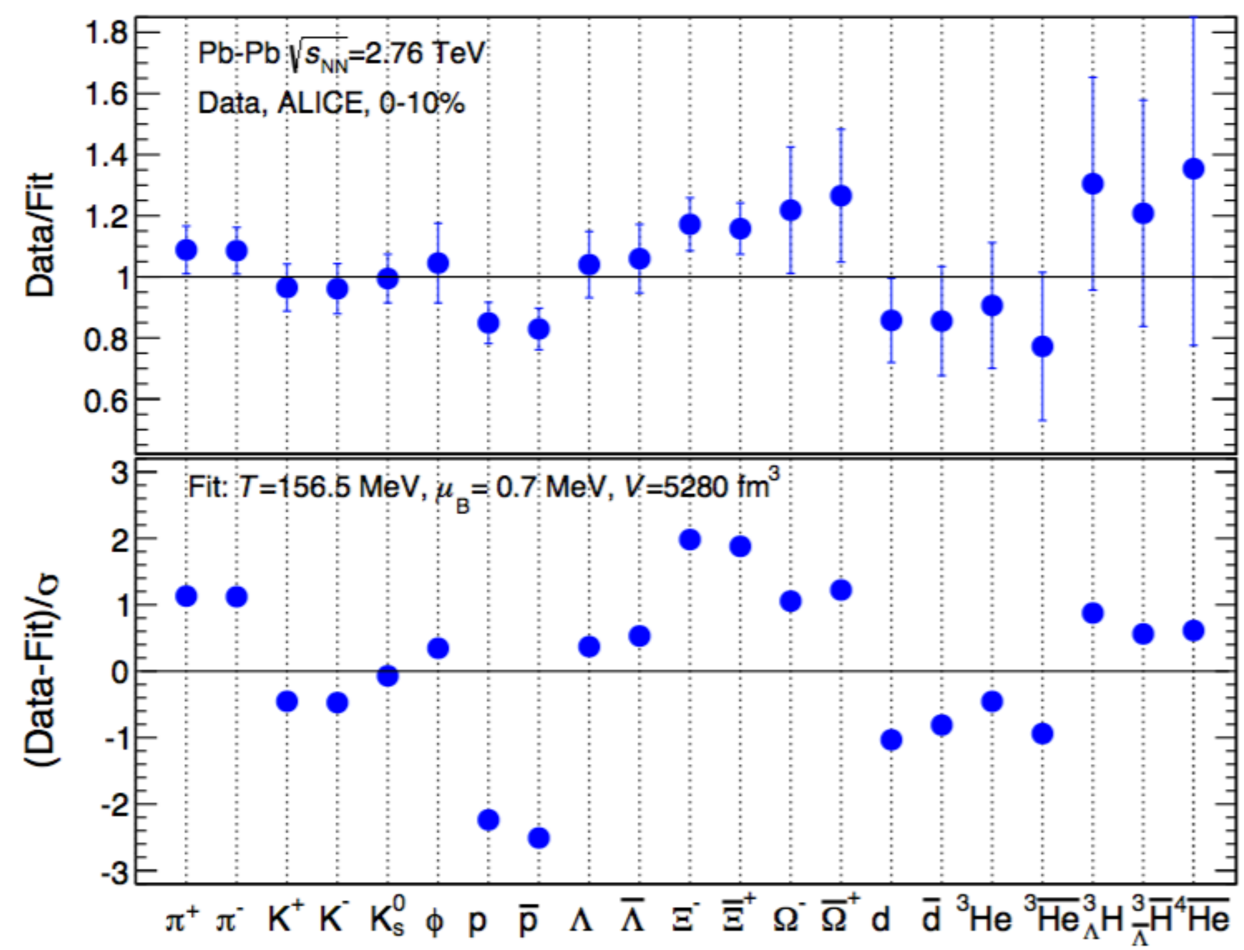

Particle yields of light flavour hadrons are described over 9 orders of magnitude within 20% with a common chemical freeze-out temperature of $T_{ch} \approx 156$ MeV.

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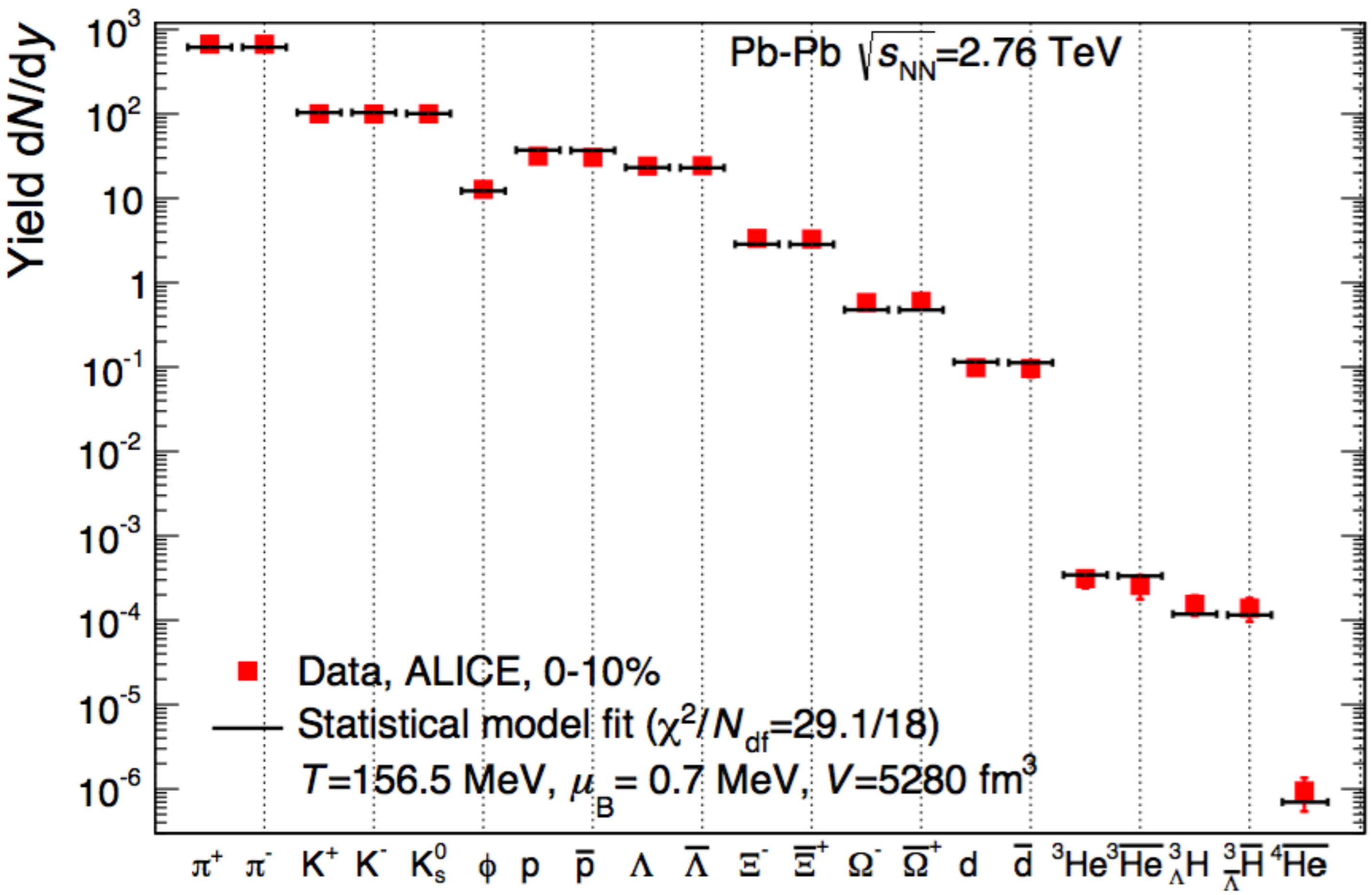

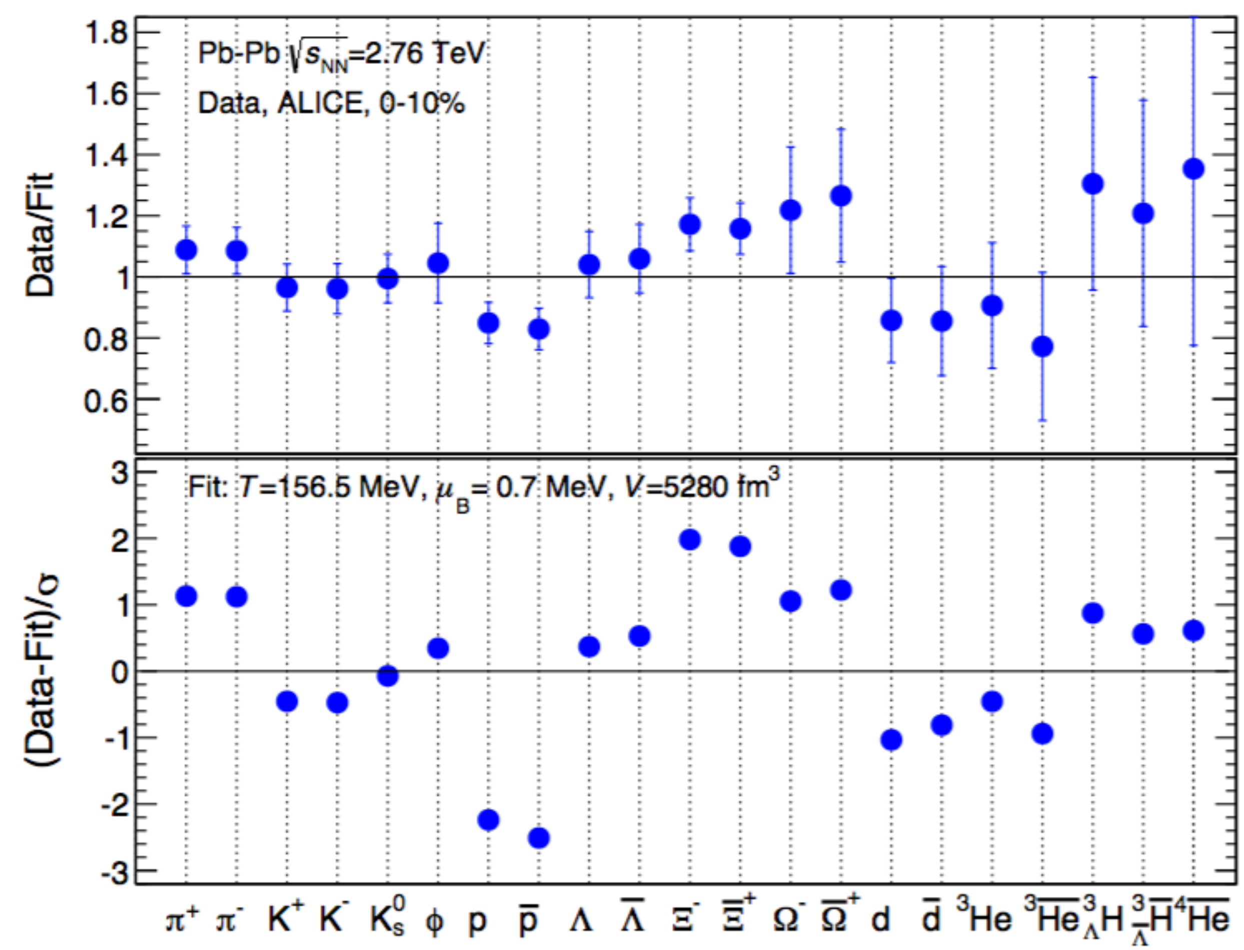

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Largest deviations observed for **protons** (would prefer lower T_{ch}) and for **Ξ** (would prefer higher T_{ch}).

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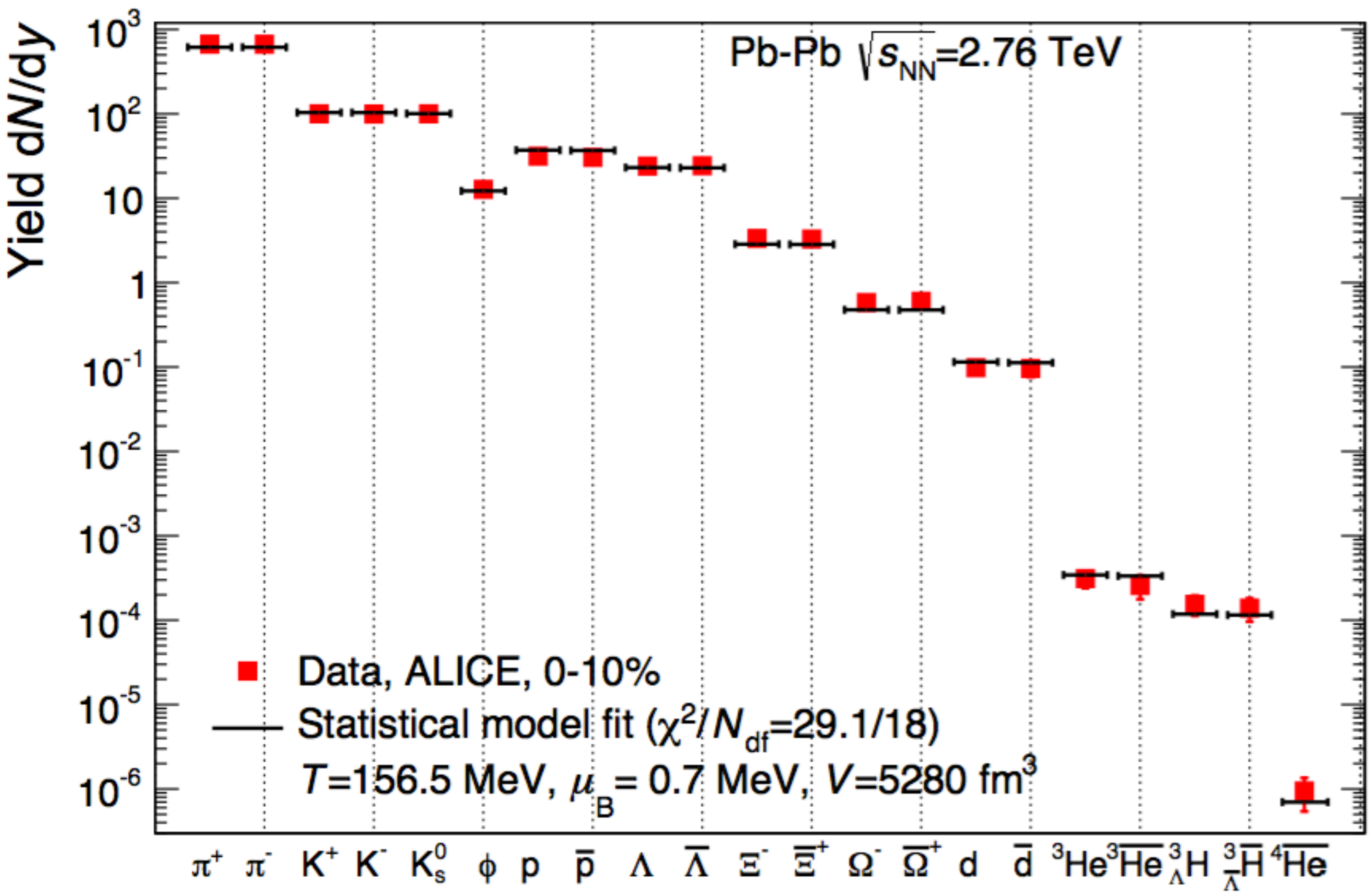

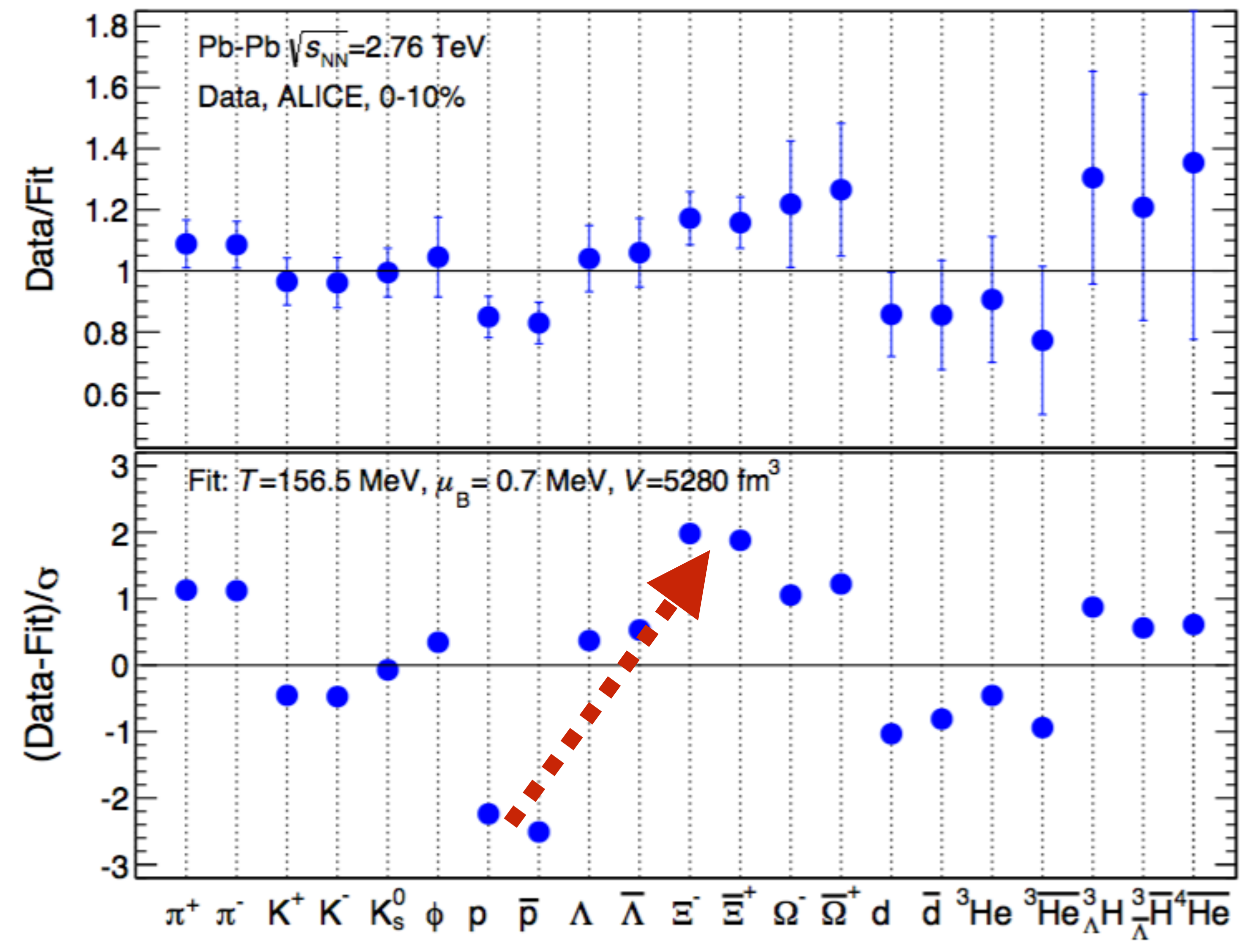

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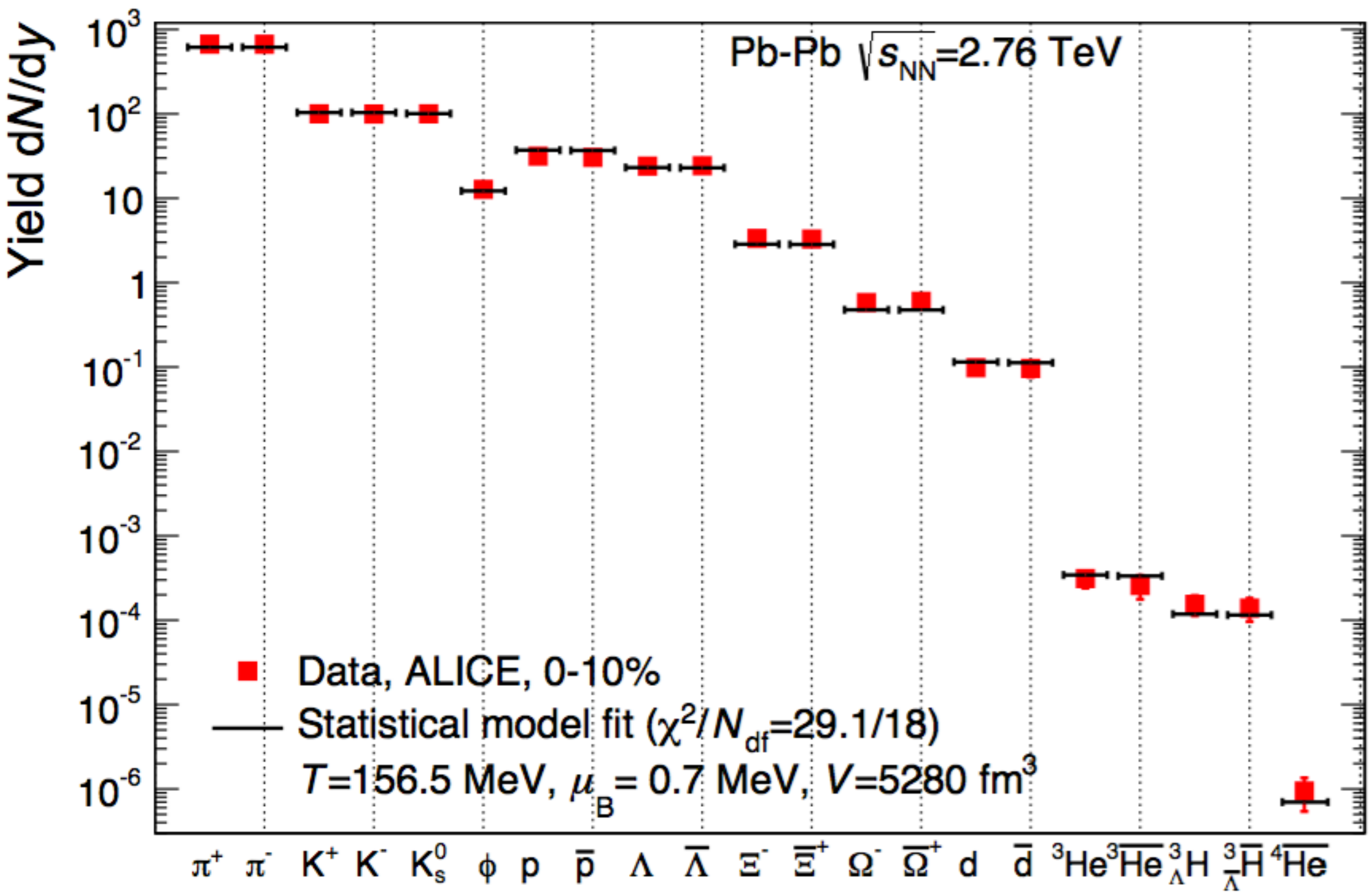

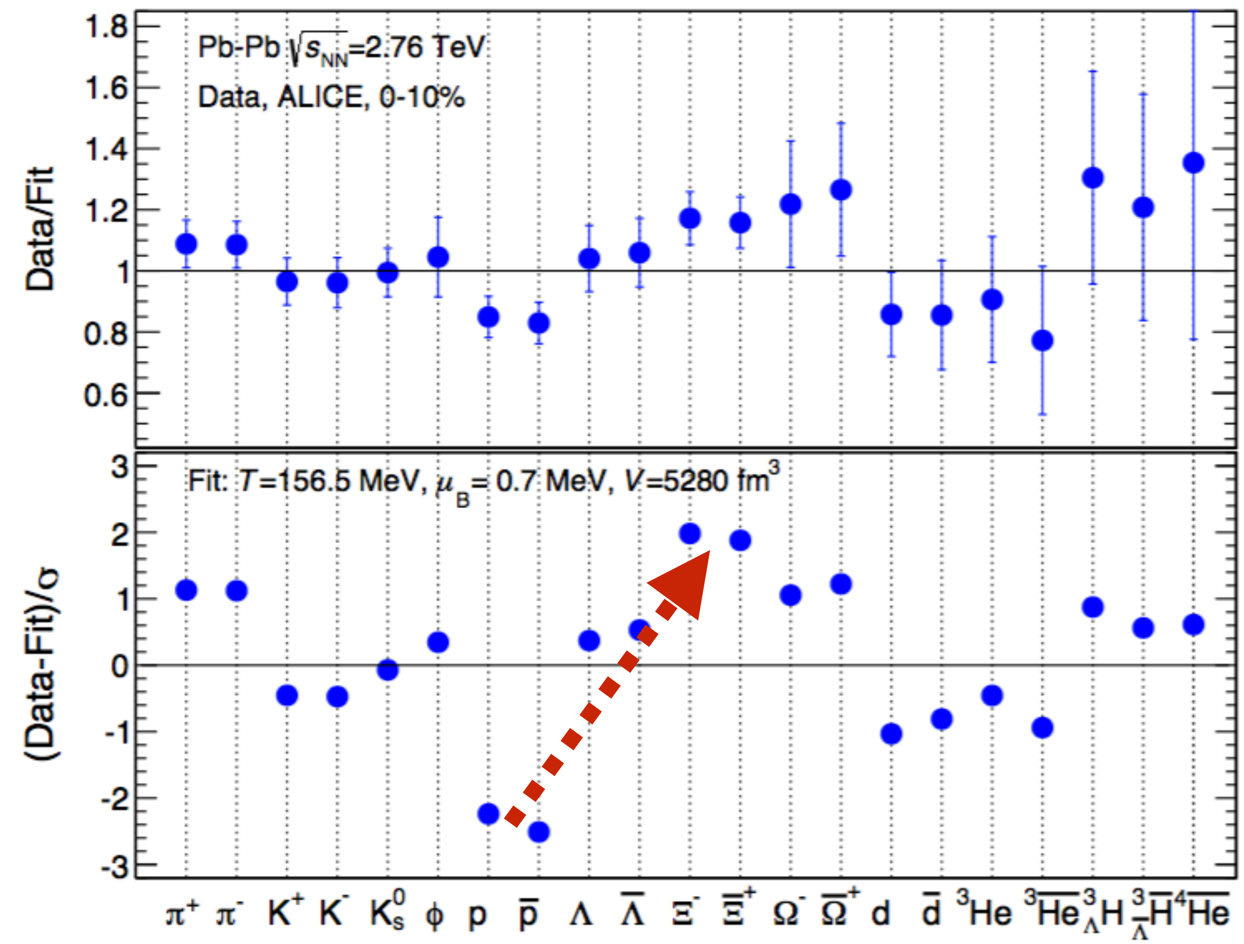

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Light (anti-)(hyper-)nuclei yields in agreement with equilibrium thermal model predictions: help in (a.) distinguishing equilibrium from non-equilibrium and (b.) stabilise the fit for different eigenvolume corrections.

Sequential freeze-out (1)

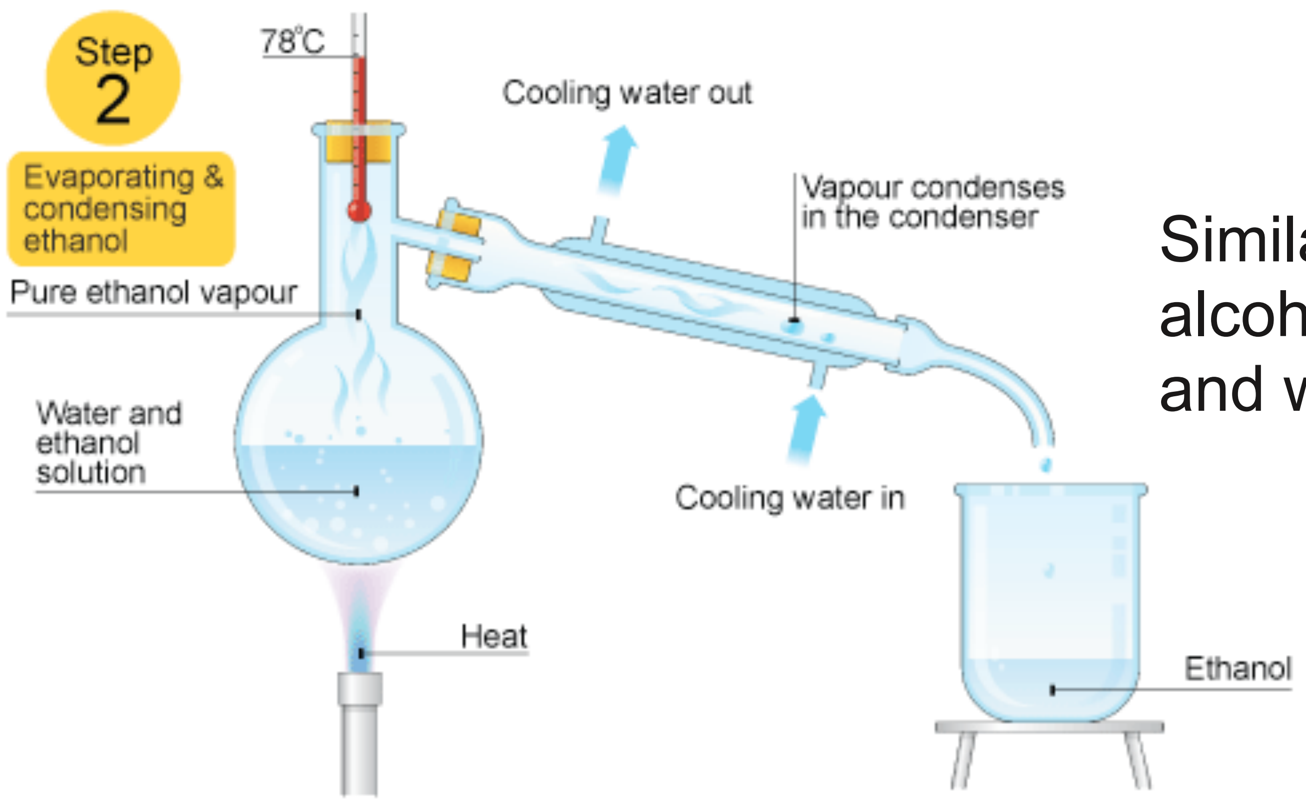
C. Ratti
Wed., 10:00h

B. Mohanty
Wed., 09:00h

- Are the deviations observed for p and Ξ due to physics? Or can it all be cut with Occam's razor?

- Two main ideas on the market:

  (1.) Different chemical freeze-out temperatures for *s* w.r.t. to *u,d* quarks.



Similar to heating a mixture of alcohol (boiling point 78,32 °C) and water (boiling point 100 °C).

  (2.) Inelastic collisions in the hadronic phase.

Sequential freeze-out (2)

C. Ratti
Wed., 10:00h

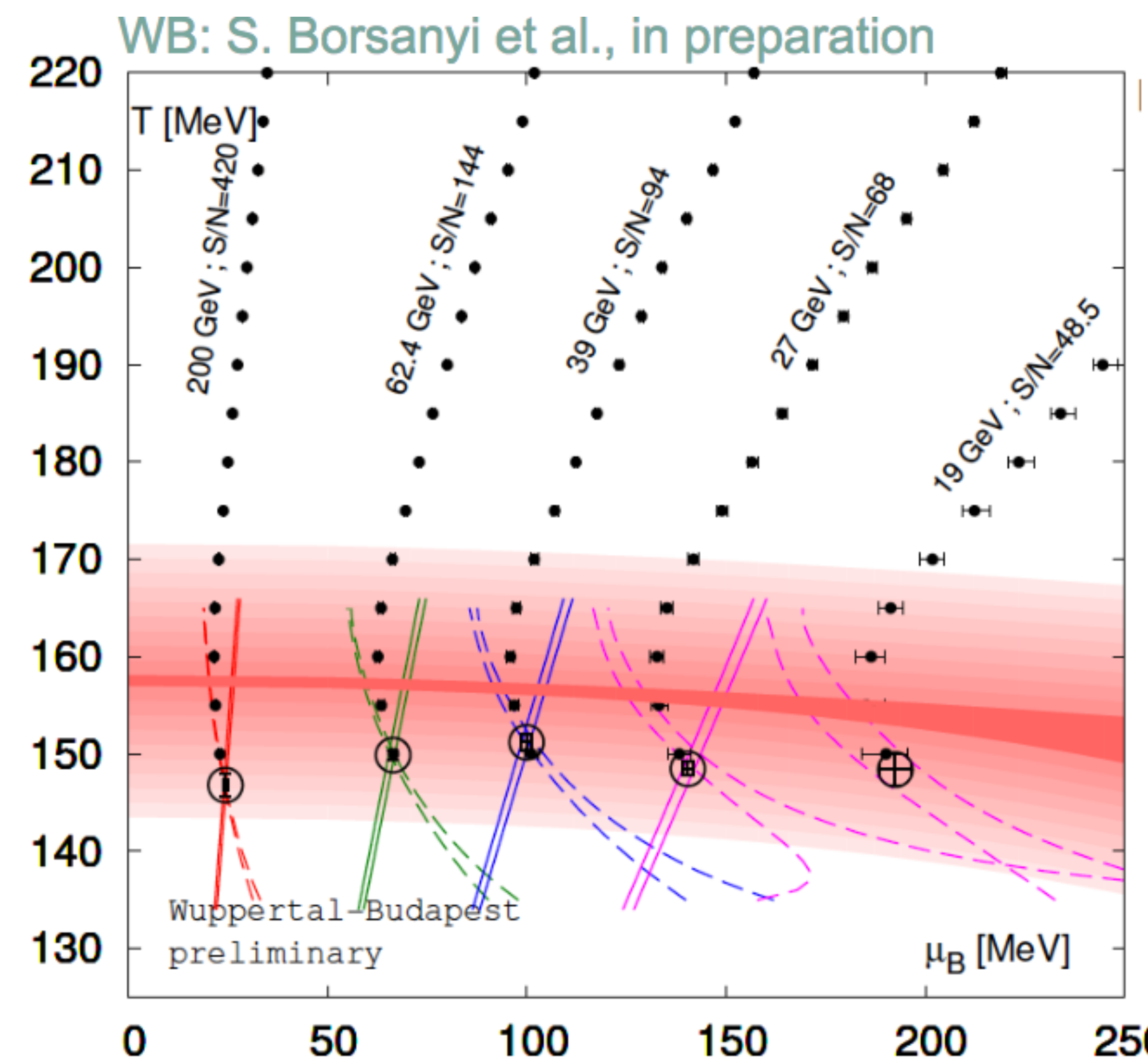
B. Mohanty
Wed., 09:00h

Different chemical freeze-out temperatures for (*s*) w.r.t. to (*u,d*) quarks:

- Motivated by LQCD results from Wuppertal-Budapest collaboration.
- Supported by chemical freeze-out conditions from net-charge fluctuations.
- However, no clear ordering
  Ω > Ξ or ϕ > Λ or K in the yields!

  => Needs to be re-addressed precisely from the experimental side (LHC Run 2, STAR with HFT): yields and fluctuations!

- What is the dynamical picture?



Sequential freeze-out (3)

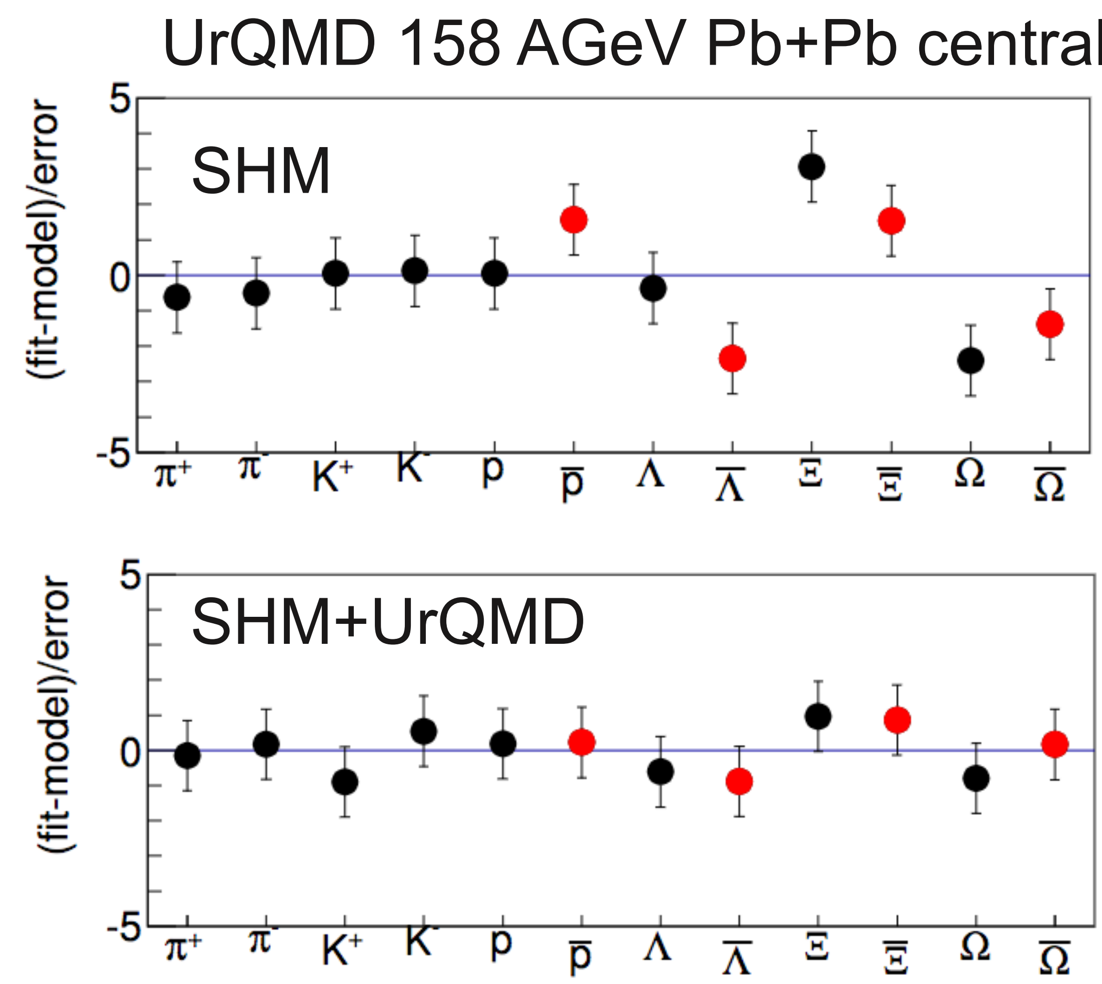
R. Stock
Tue., 16:20h

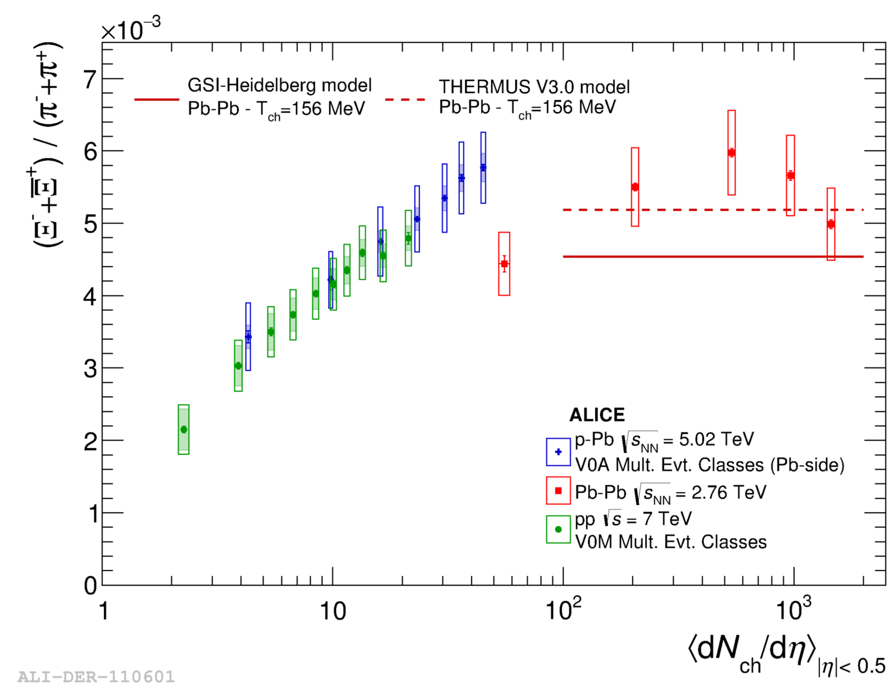
Inelastic collisions in the hadronic phase:

- Studied by UrQMD afterburner added to SHM fits (significant improvement of χ^2/n_{dof} and increase in freeze-out temperature → T_{ch} beyond region supported by Lattice?).

- Leads to centrality dependent effects which can be studied experimentally, but more precise data is needed to investigate significance of trends.

=> Needs to be re-addressed precisely from the experimental side (LHC Run 2, STAR with HFT).

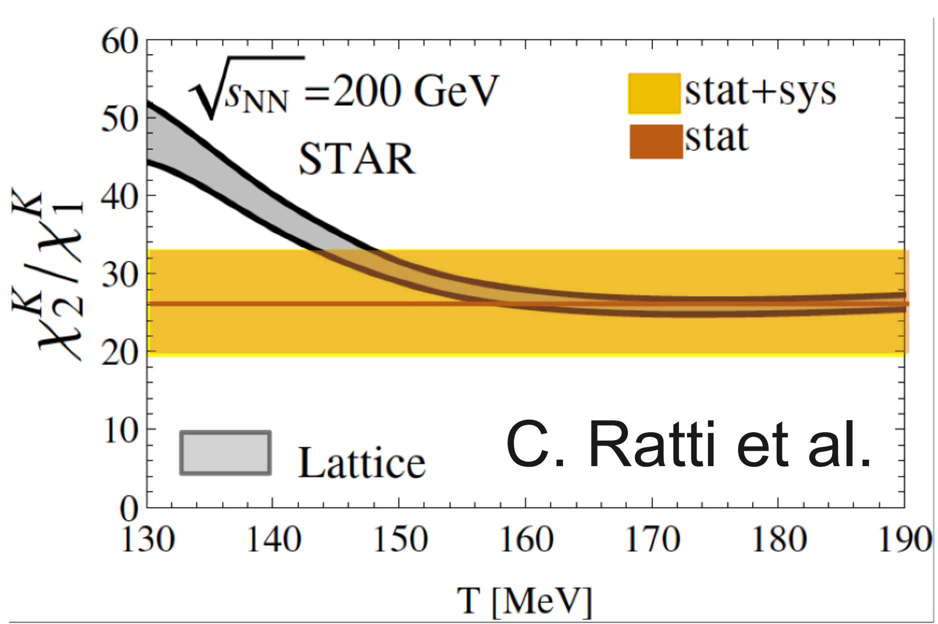


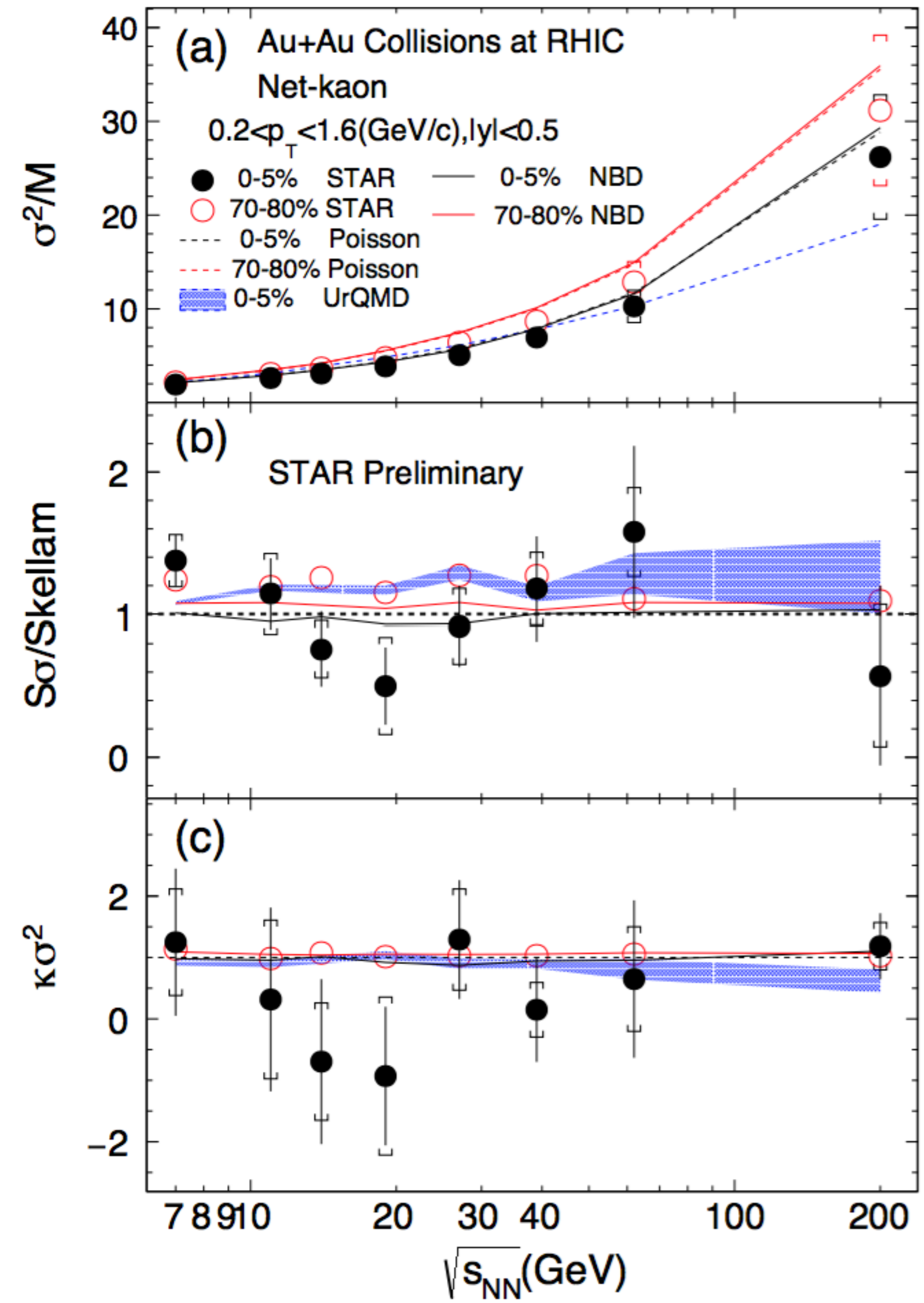


Net-kaon fluctuations

J. Xu
Tue., 09:20h

- New measurement of of net-Kaon cumulants for Au +Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 GeV.
- The values for $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with Poisson and negative binomial distribution baseline within errors.
- First attempts made for the extraction of freeze-out conditions, but need increased experimental precision:



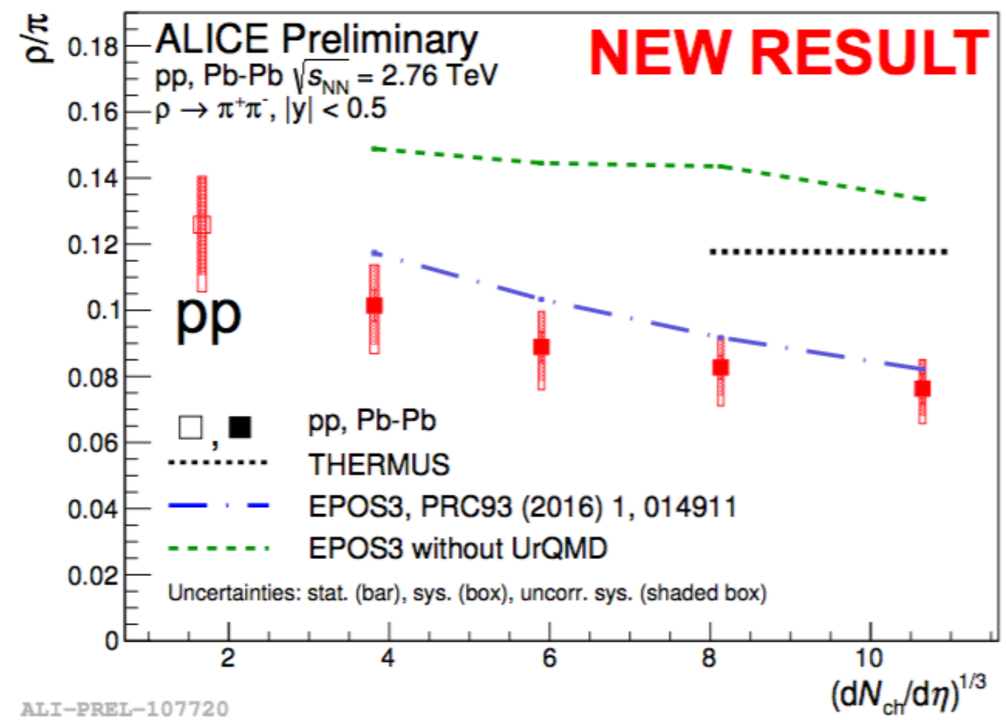


Resonances and (anti-)nuclei

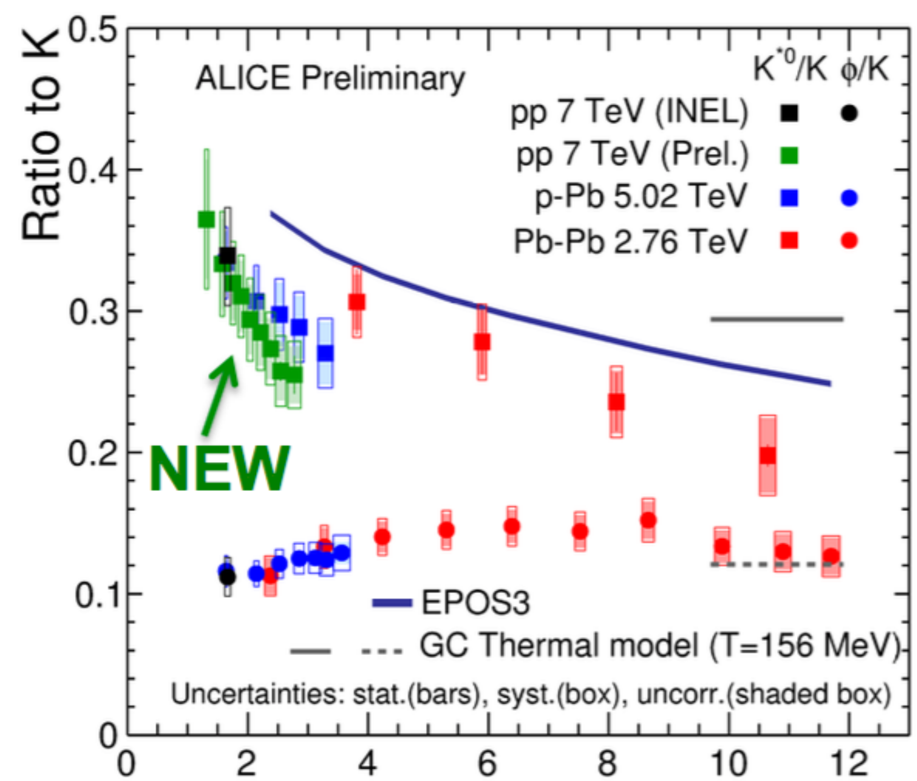
A. Knospe
Tue., 16:00h

B. Doenigus
Thu., 09:20h

- Already known before SQM: suppression of K^{*0}/K ratio with increasing centrality is consistent with re-scattering of the decay products in the late hadronic phase.
- New results for ρ/π ratio confirm this picture:
  [$\tau_{\rho} \approx 1.3$ fm/c < $\tau_{K^*} \approx 4$ fm/c << $\tau_{\varphi} \approx 45$ fm/c]



- No suppression observed for (anti-)nuclei despite their low binding energy ($E_B \approx 2.2$ MeV << 156 MeV):
  - yield in agreement with thermal model
  - p_T-spectra and elliptic flow pattern in agreement with hydrodynamic expansion and in contradiction with simple coalescence model



➔ Does this point to the non-existence of the hadronic phase?

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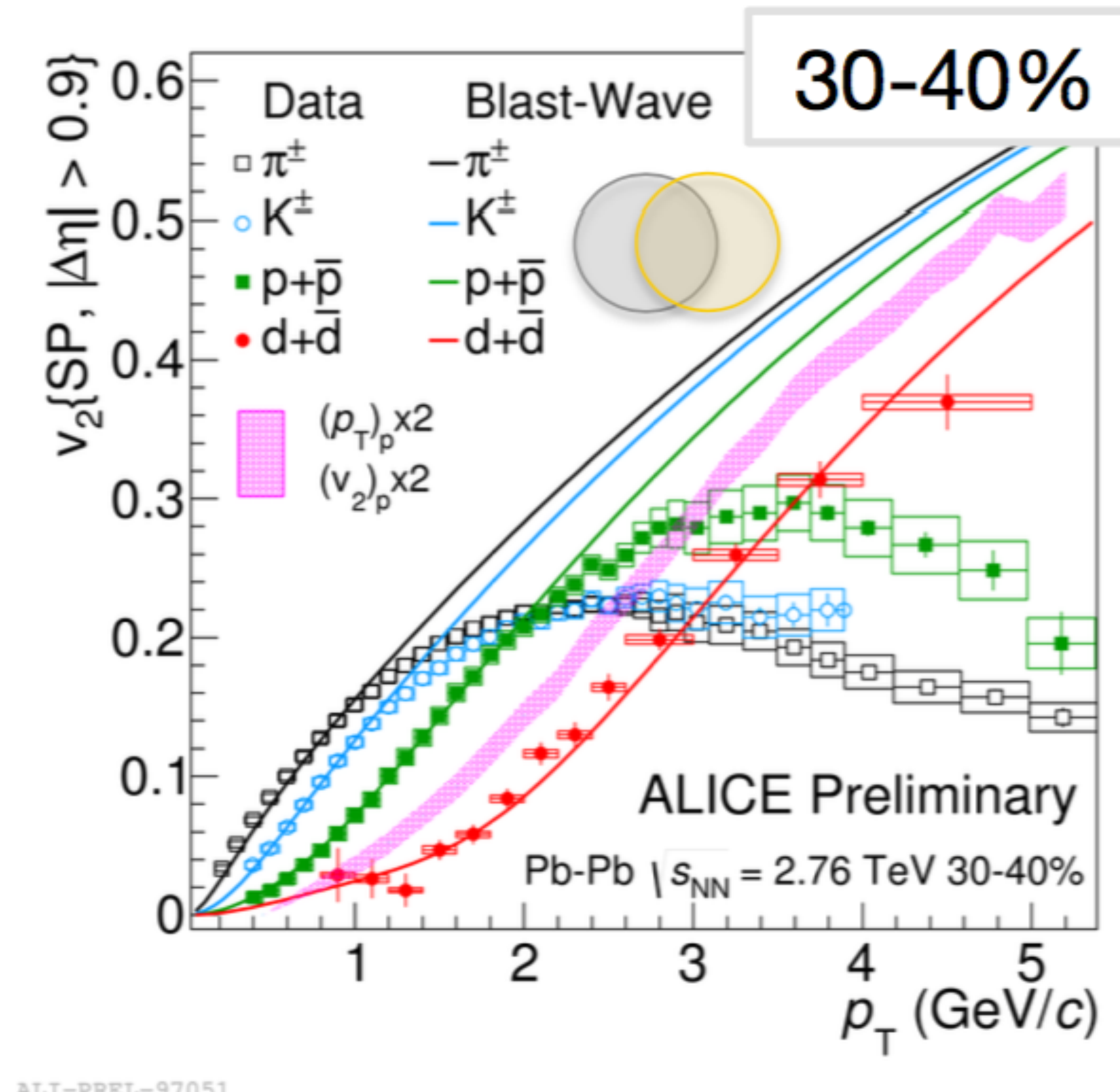
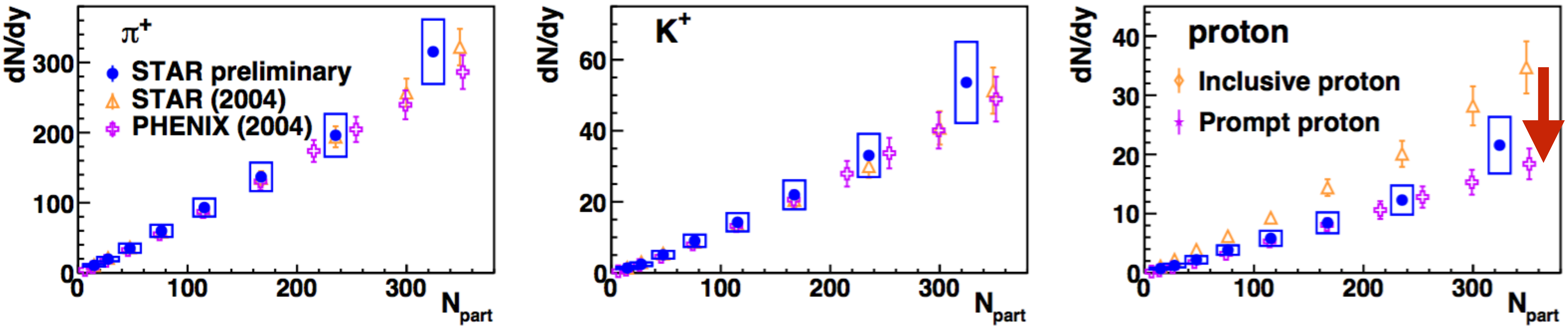
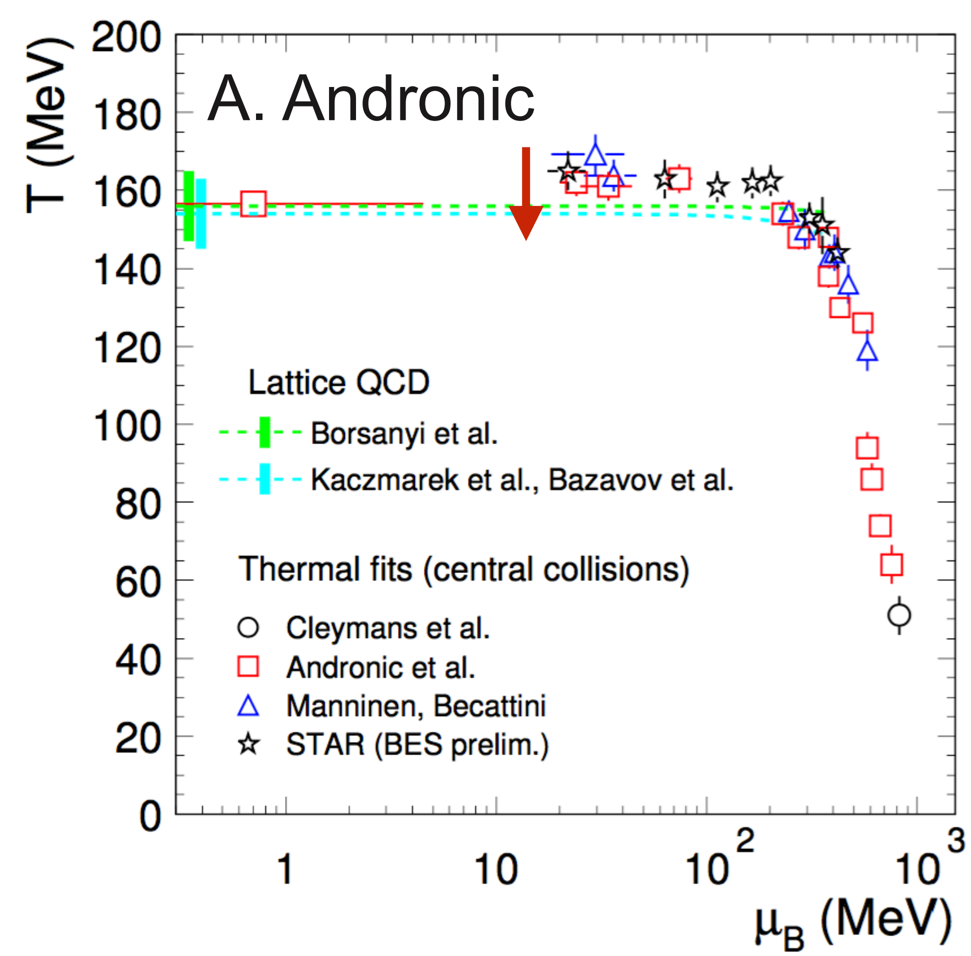


STAR p/π ratio

S. Mizuno
Tue., 16:20h



- STAR ***heavy*** flavour tracker allows to measure ***light*** favour hadrons much more precisely by separating primary protons from feed-down from weak decays.
- Change in π yield is small, but significant reduction for protons.
- The p/π ratio has significant influence on the temperature.
  => Update the thermal fit!
- Very important for the consistency with Lattice QCD!



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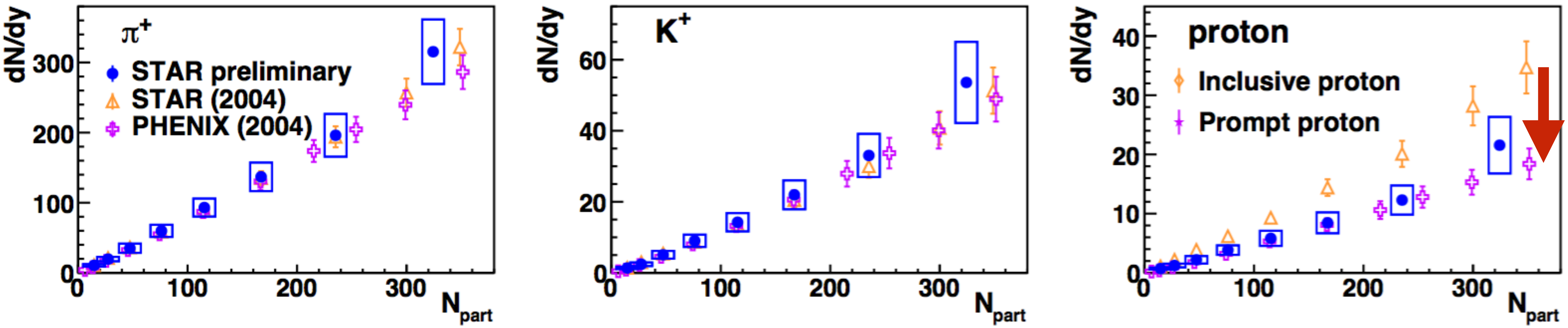

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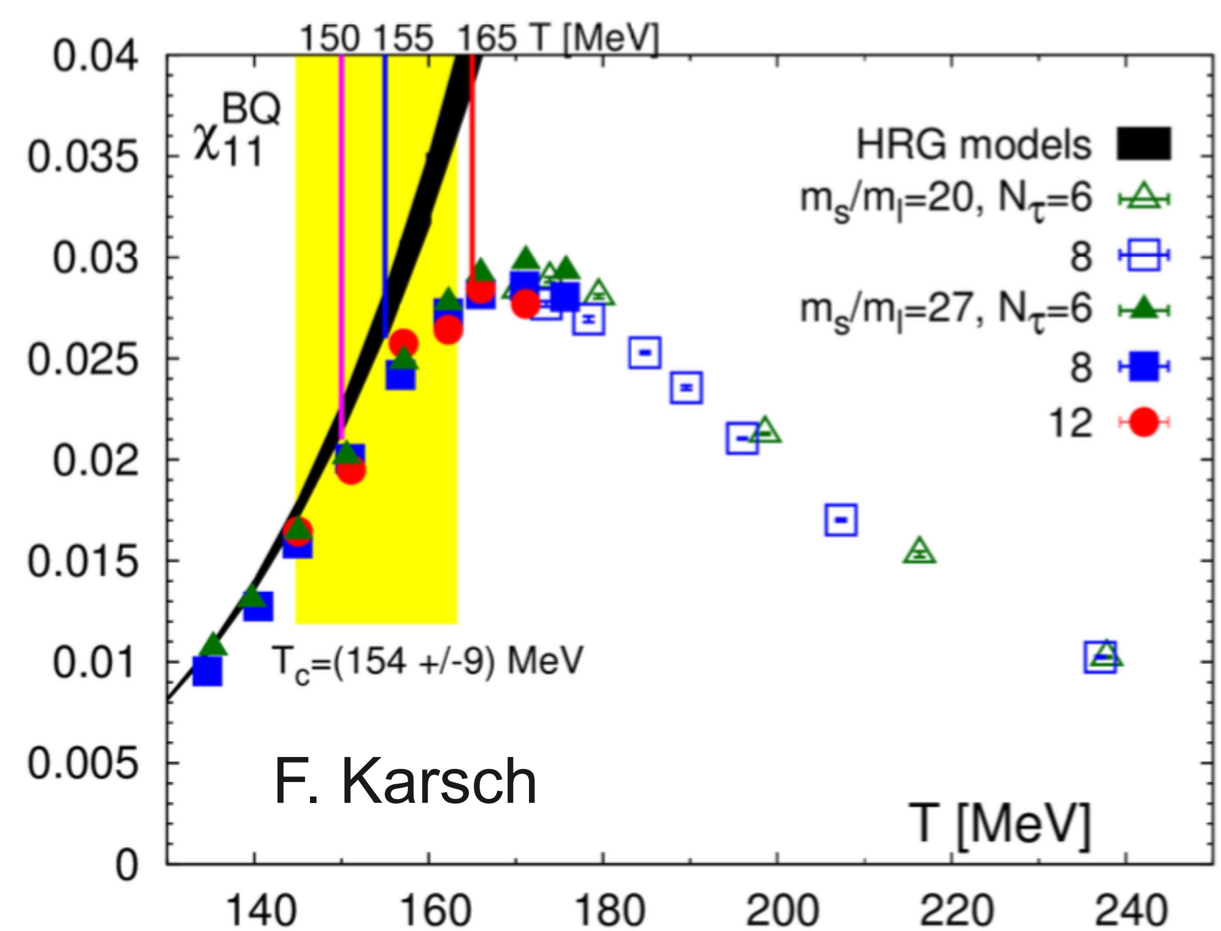
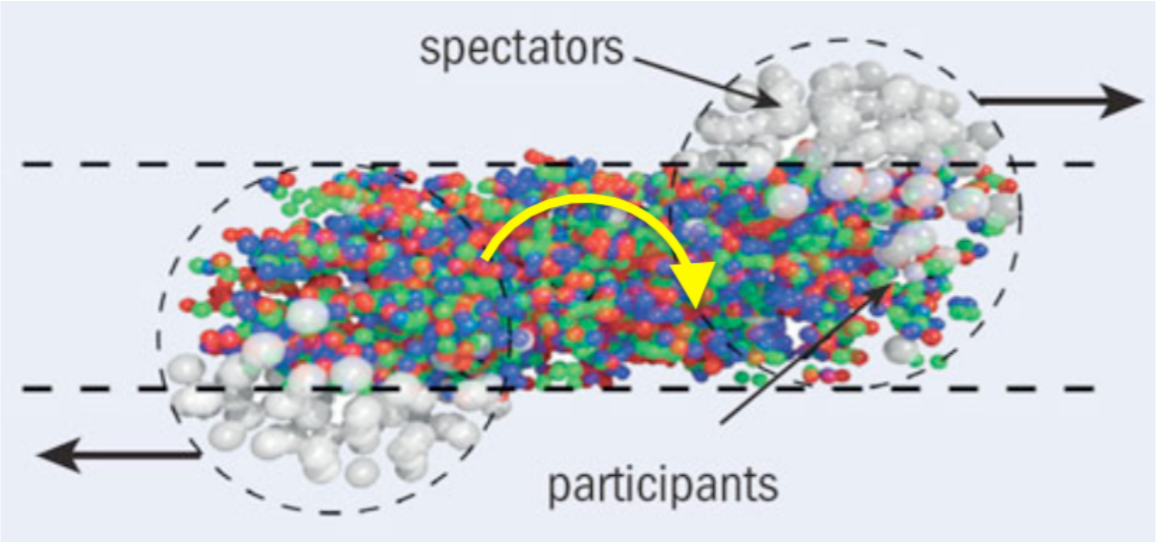
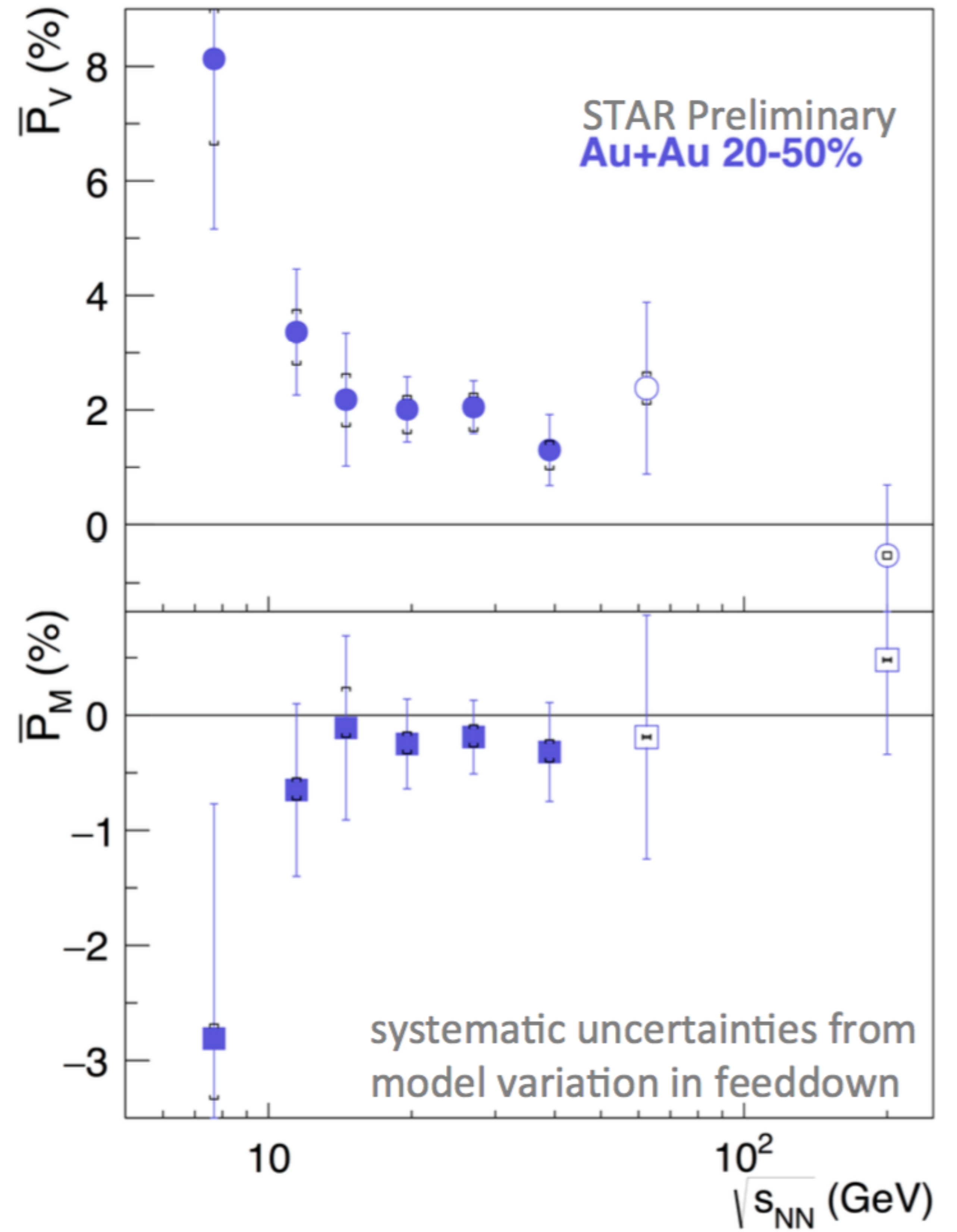


Λ polarisation

M. Lisa
Mon., 16:00h

- Global hyperon polarisation: unique probe of vorticity and B-field (non-exotic or chiral, input to calibrate chiral phenomena)
- 5-6 sigma effect is observed if results from several beam energies are averaged.
- BES-II: statistics and upgrades will allow further model discrimination.



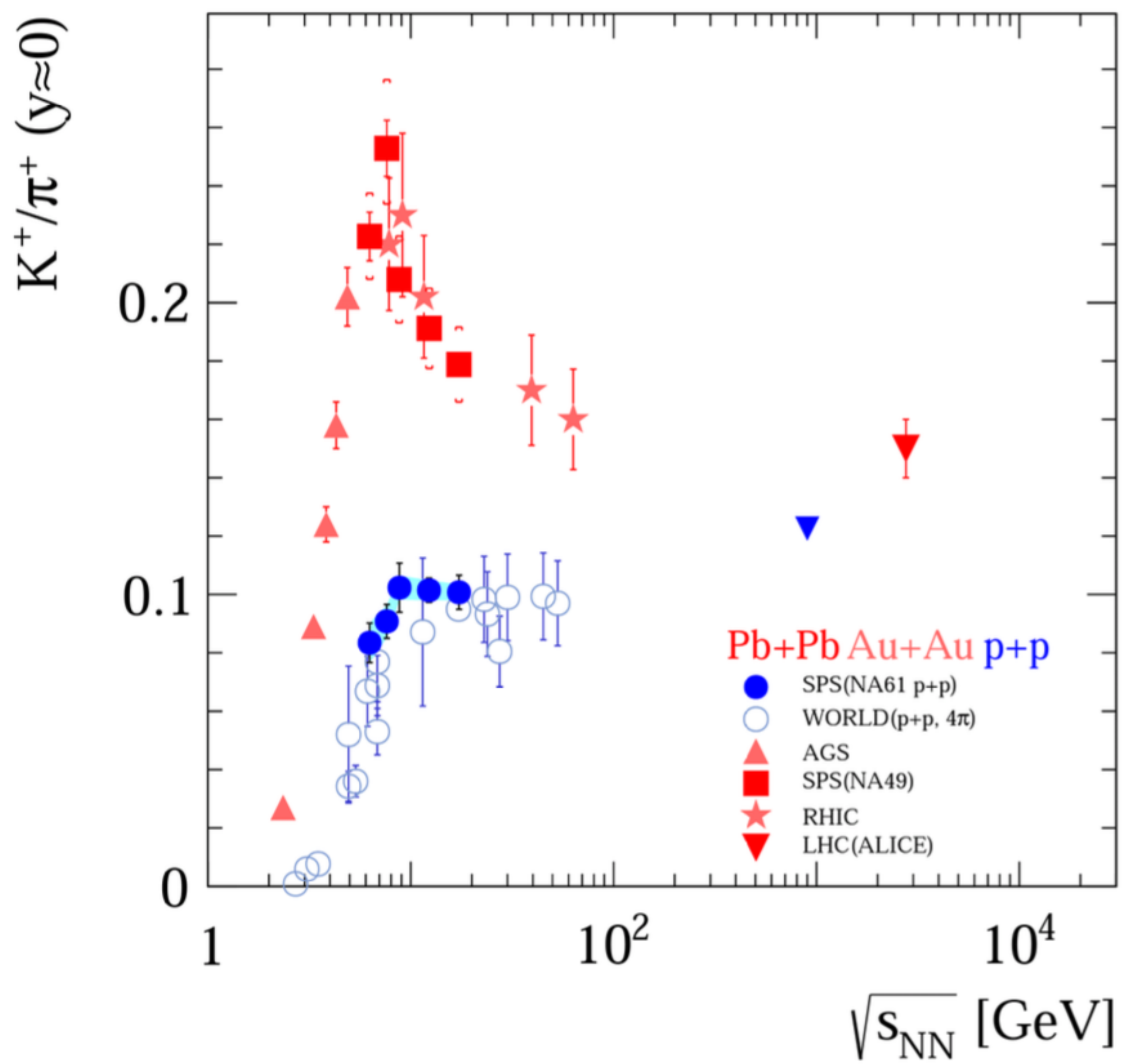


NA-61 and HADES:
Strangeness production at lower energies

NA-61/SHINE

H. Stroebele
Tu., 10:00h

- Excitation function of pp collisions nearly complete in the SPS energy range.
- Input for neutrino physics community: p+C target => π differential cross-section to calculate flux of decay neutrinos.
- Input for cosmic ray physics: π+C data to understand cosmic ray showers.
- NA-61/SHINE on the verge of reaching its goal with p+p results finalised, Ar+Sc being analysed, and Xe+La beam time being scheduled.



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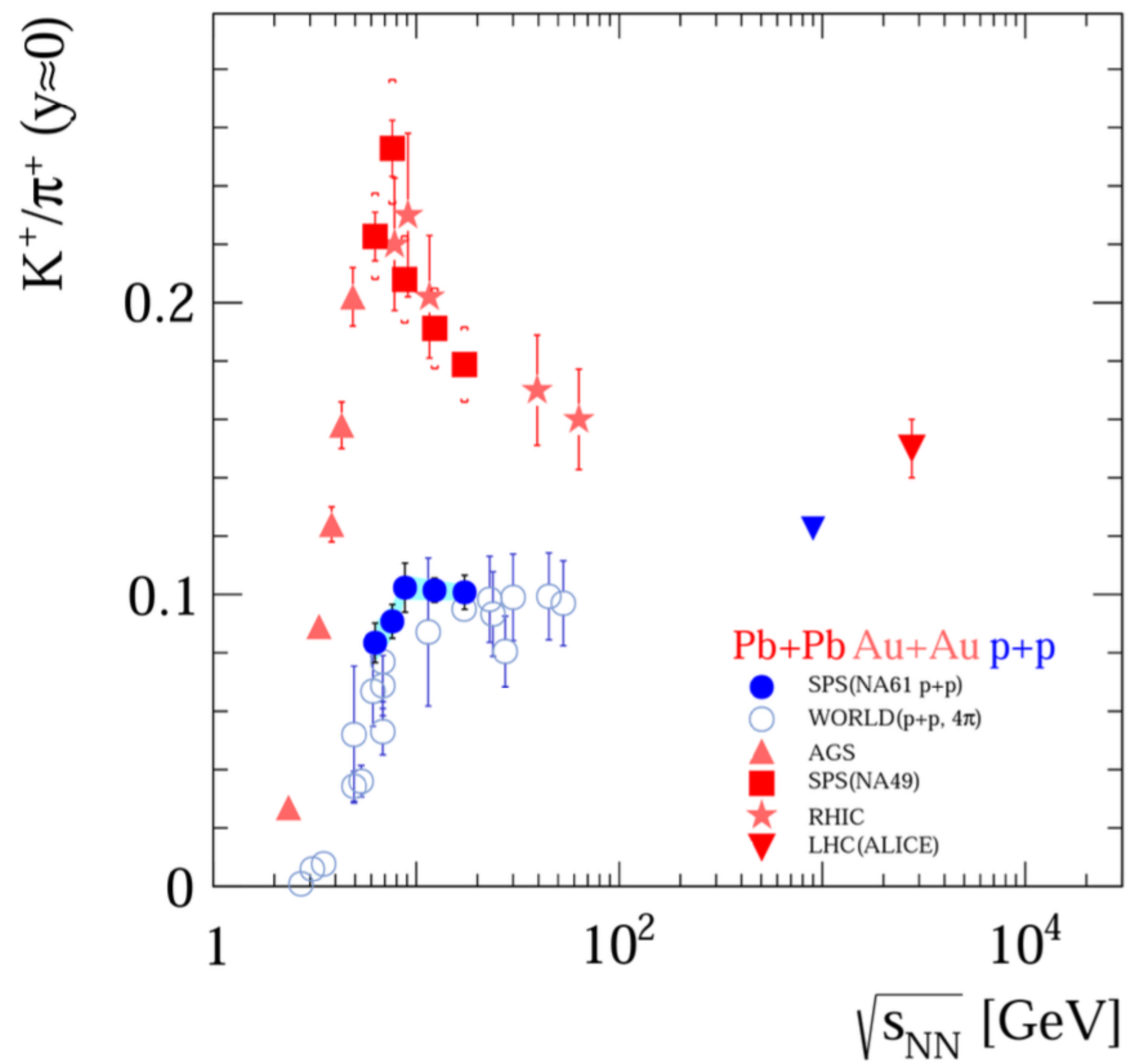
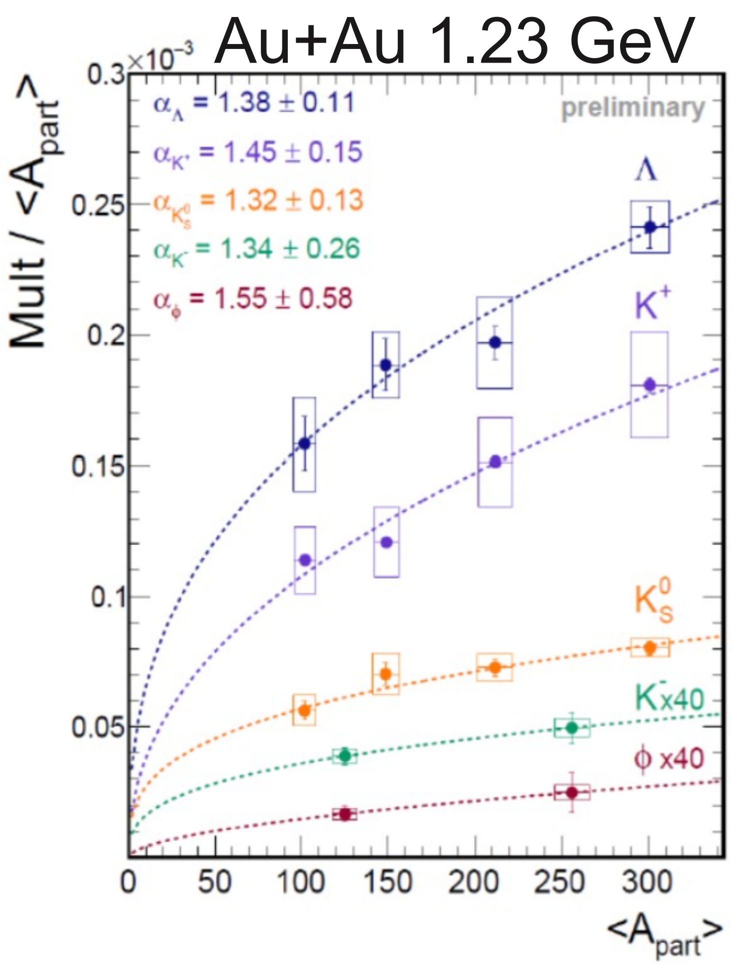


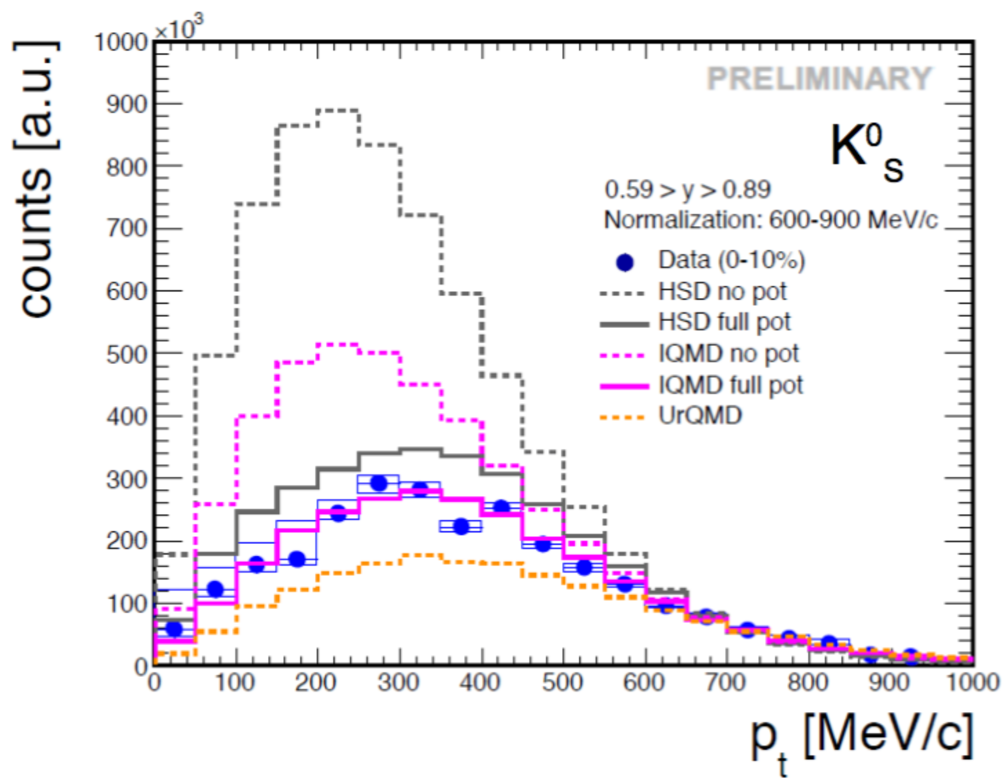
Horn is only observed in heavy-ions. Future data from intermediate collision systems will probe the onset.

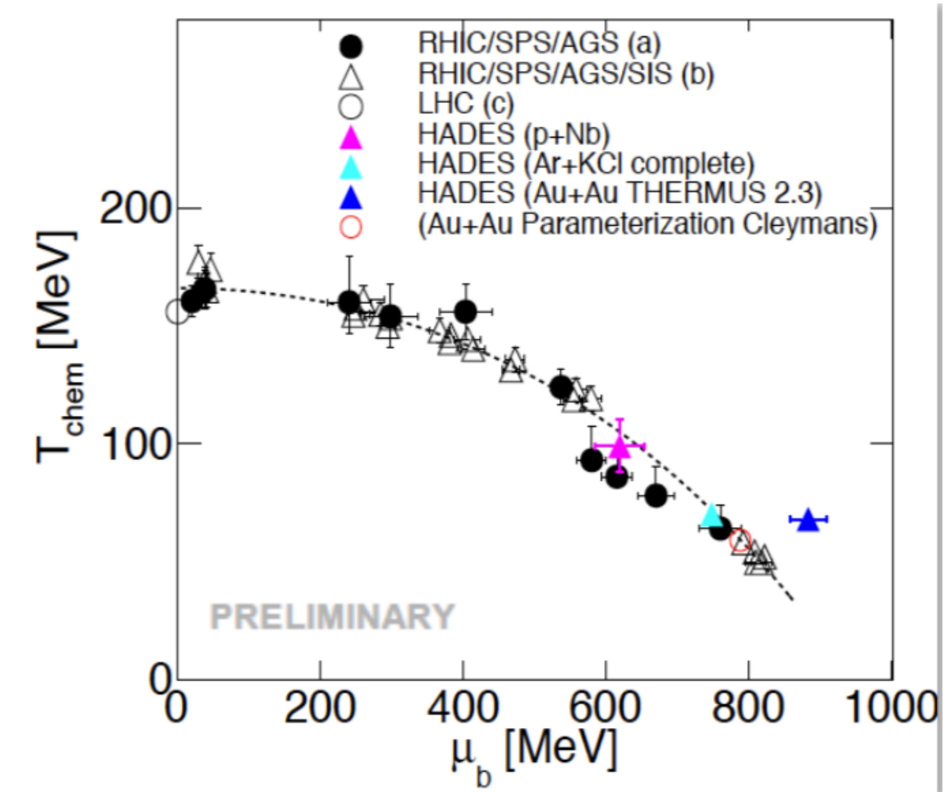
HADES strangeness

T. Scheib
Tue., 14:00h

- First comprehensive set of results on strange particle productions from the Au+Au run available.
- Feed-down from ϕ decays explains different slopes of K^+ and K^- spectra which were previously attributed to sequential freeze-out.







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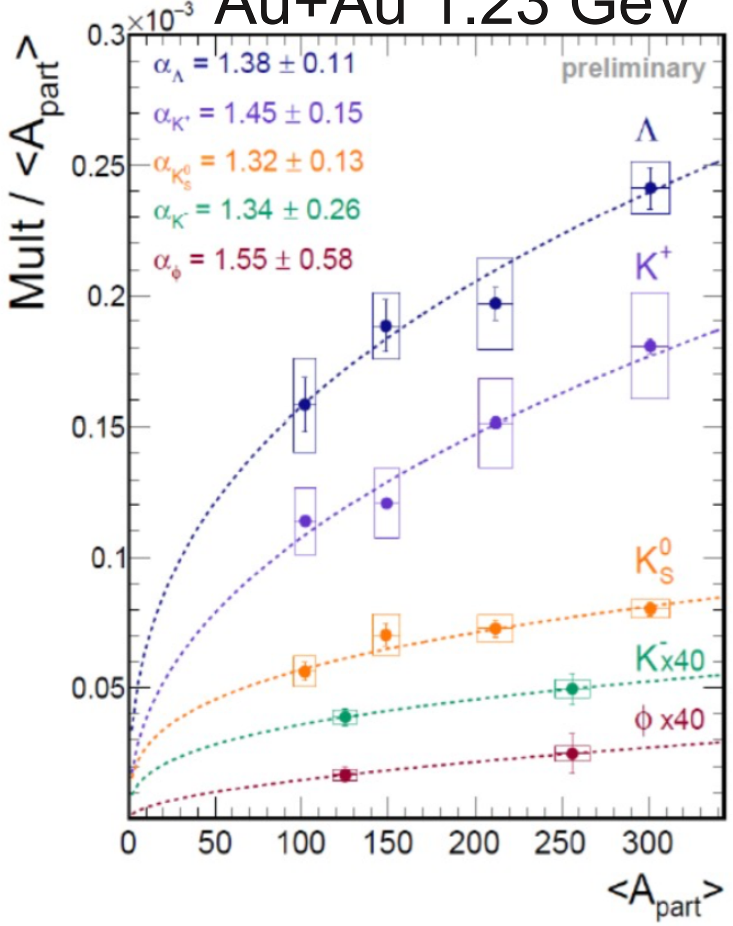
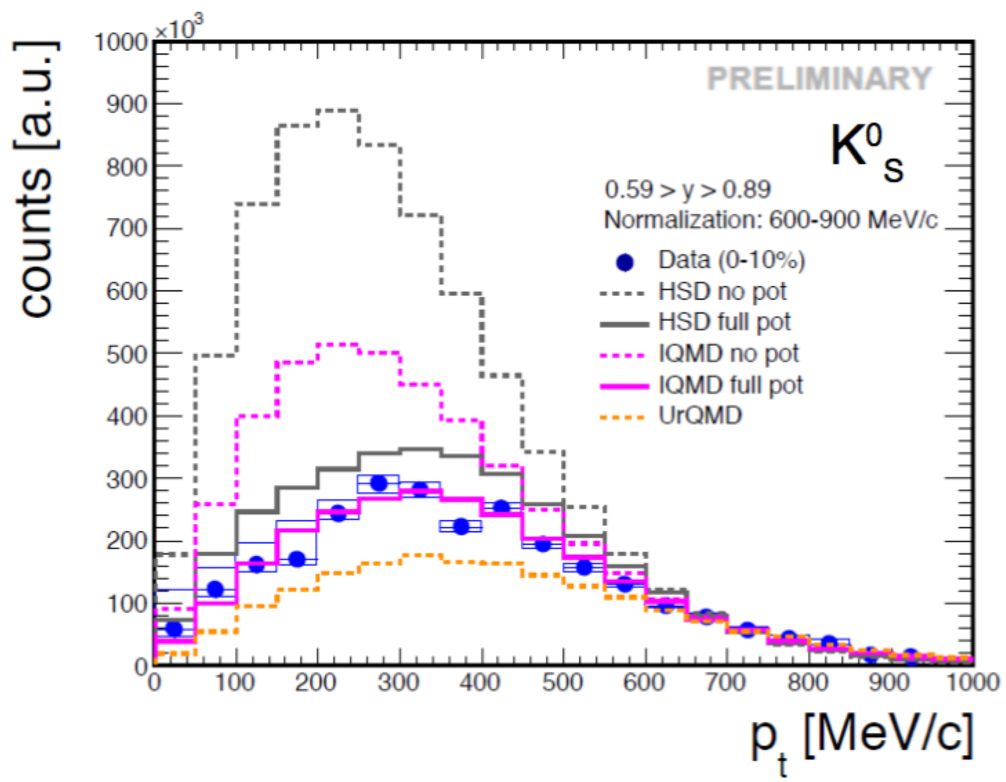
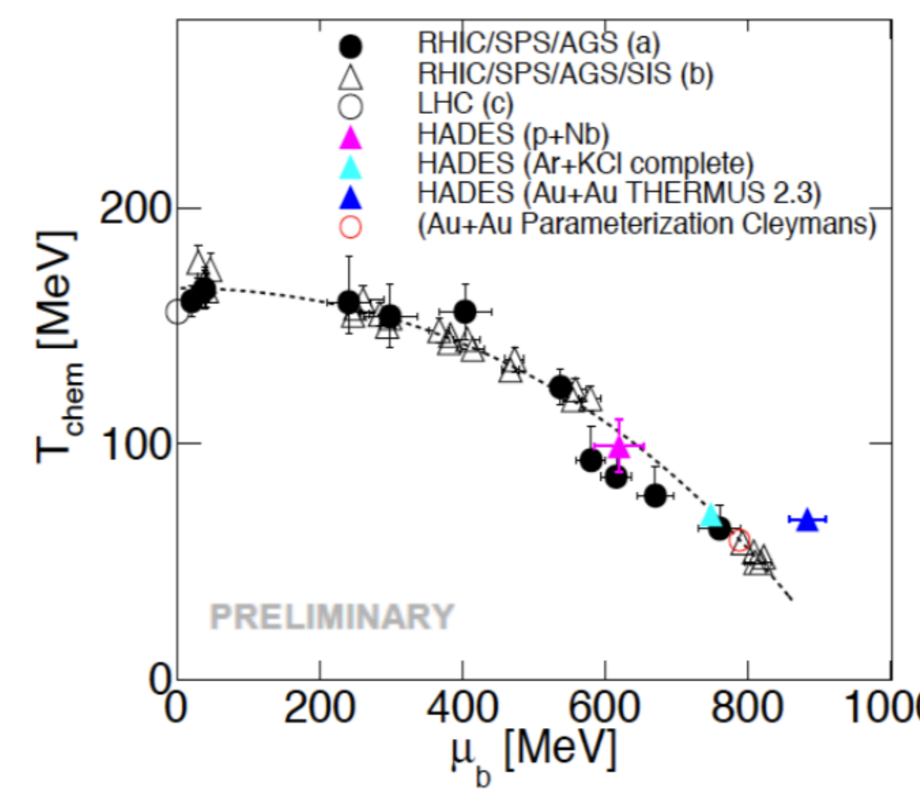
Au+Au 1.23 GeV







All strange particles produced below NN threshold ("infinite strangeness enhancement") -> strong sensitivity to medium effects and multi-particle collisions.

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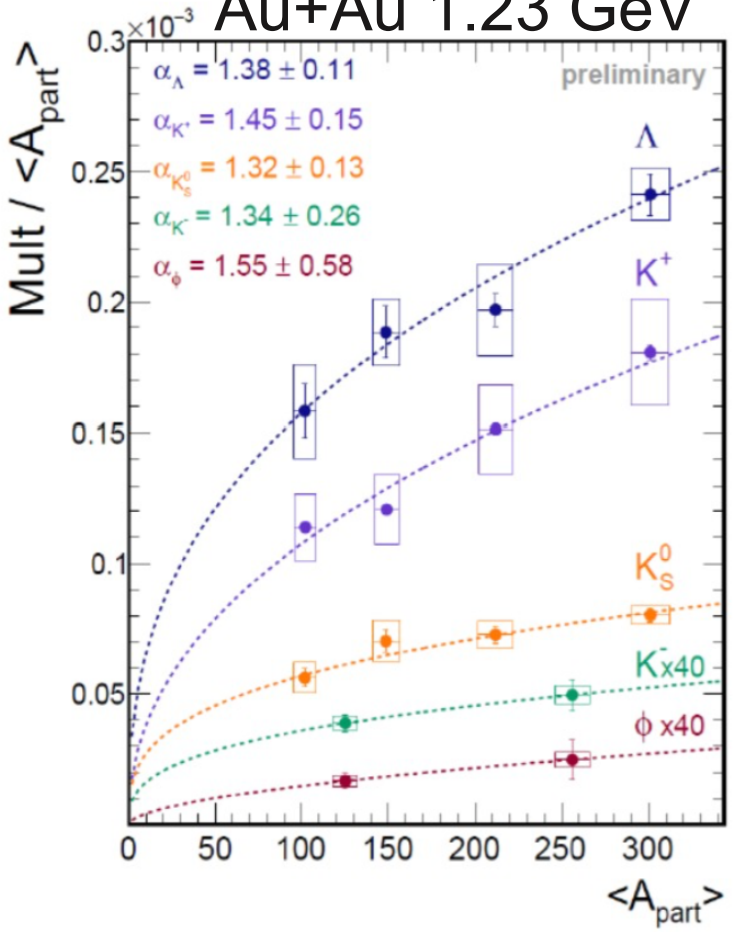

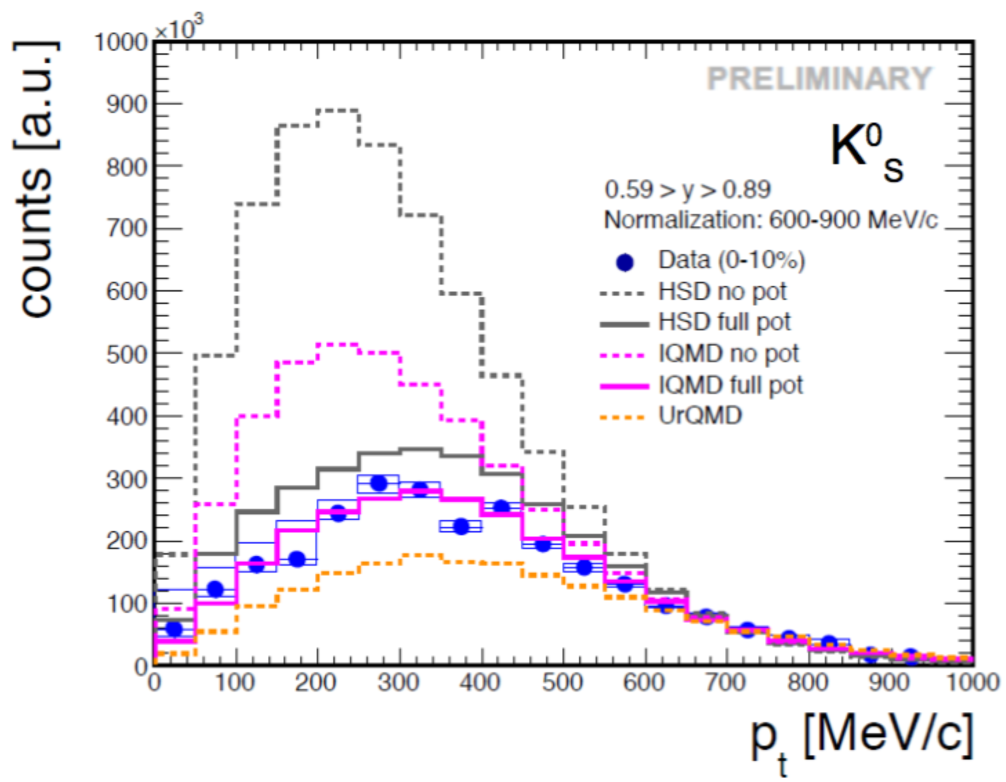

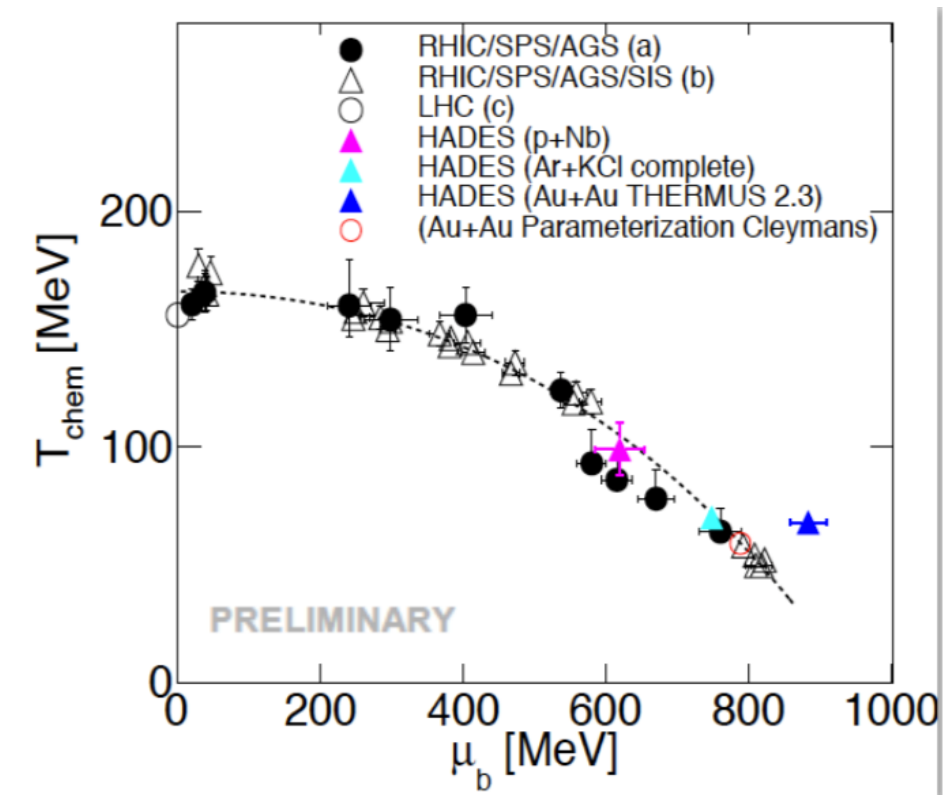

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Constraining better the poorly known kaon-nucleon potential by comparisons with transport codes.

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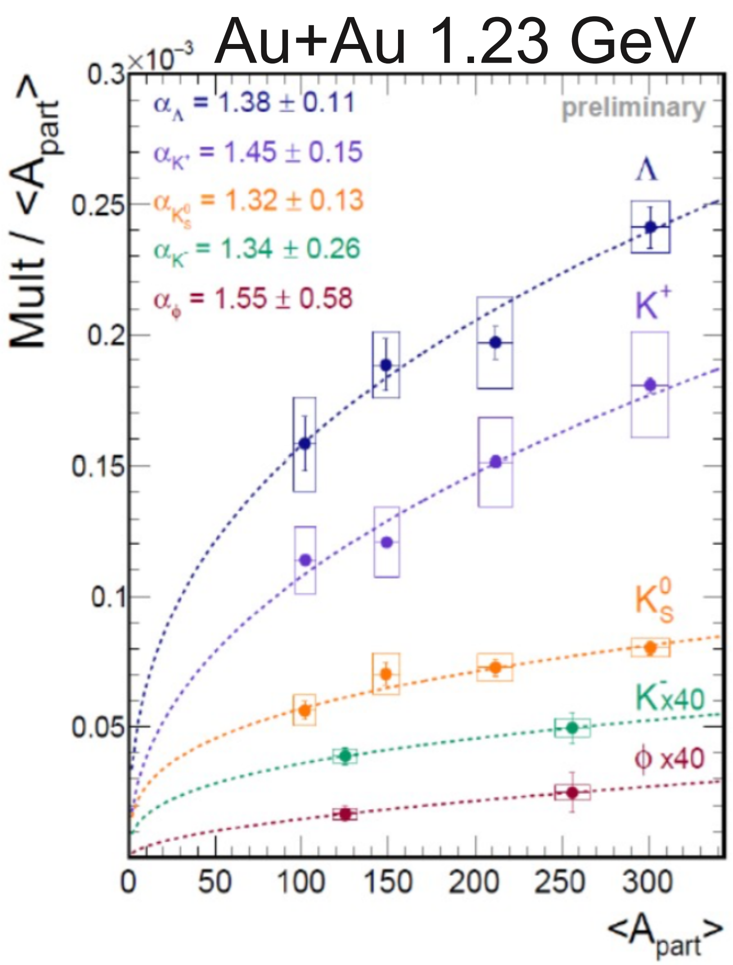

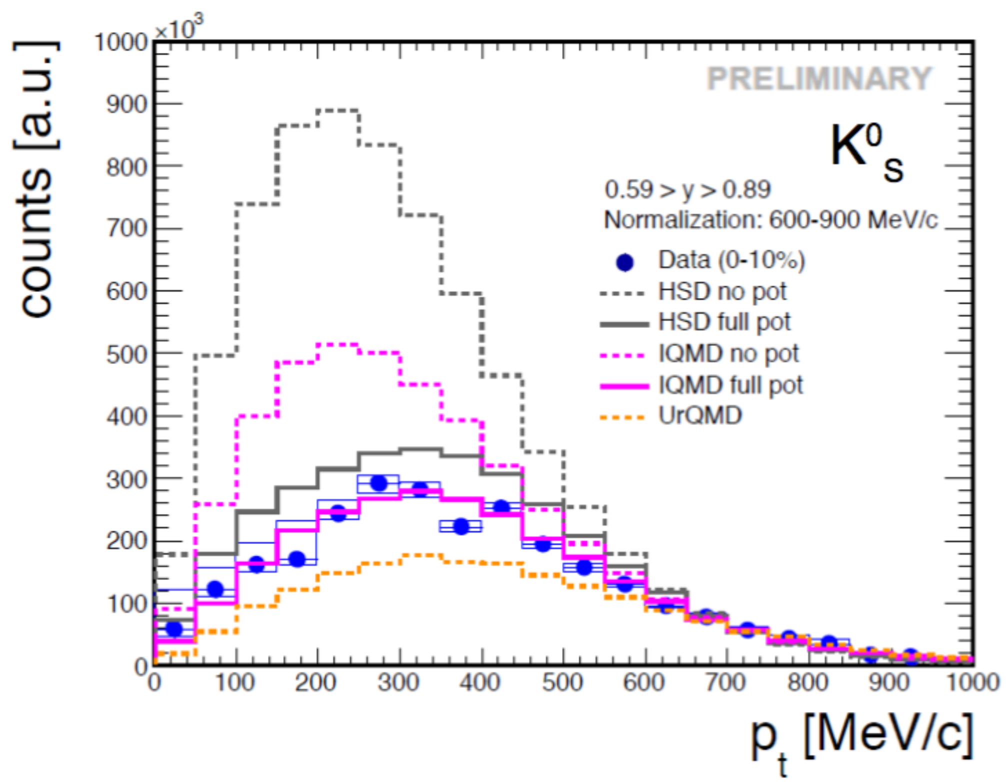

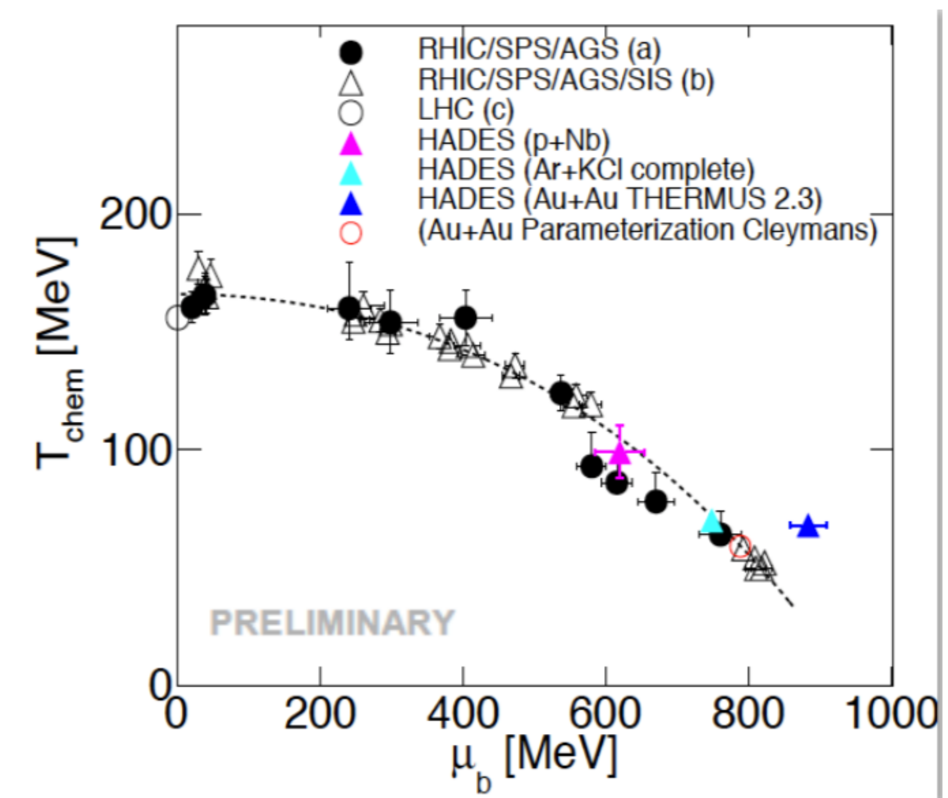

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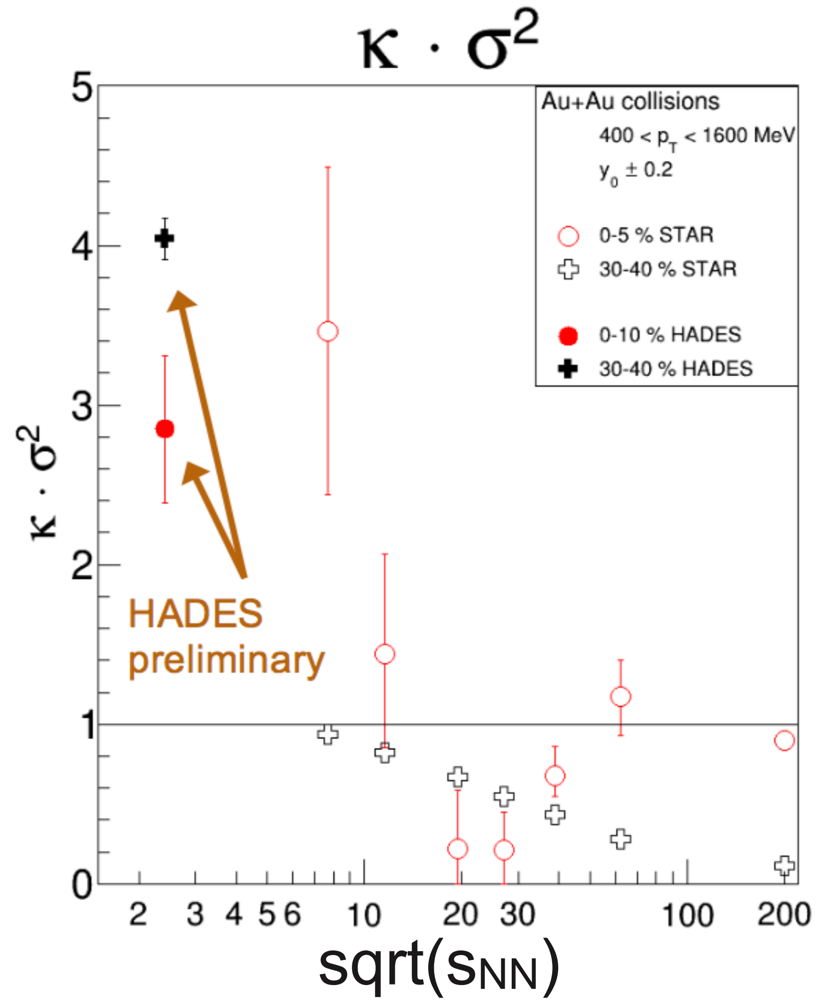
Constraining better the poorly known kaon-nucleon potential by comparisons with transport codes.

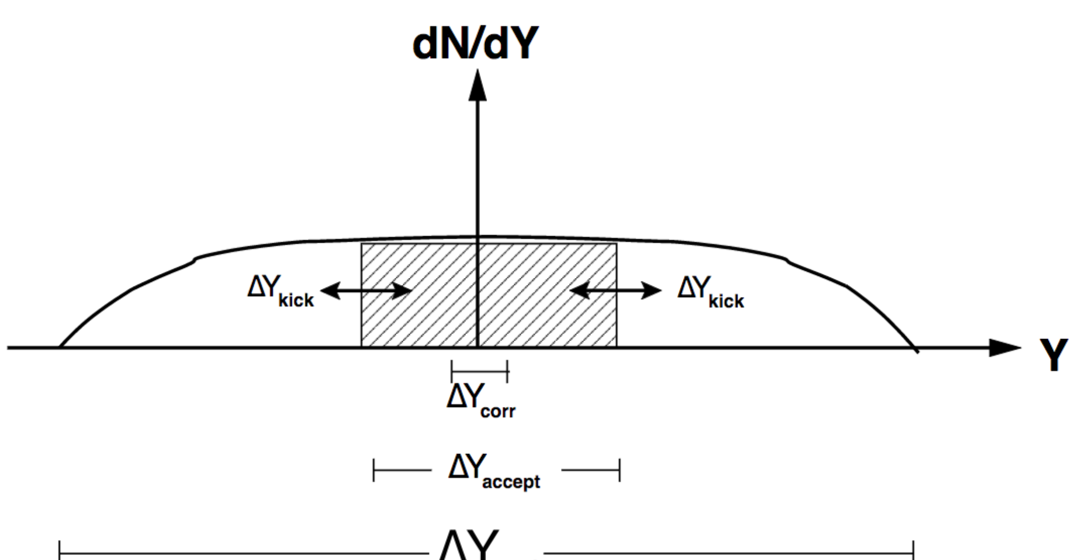
Chemical freeze-out: Smaller system (Ar+KCl) follows trend of freeze-out curve, larger system (Au-Au) does not. Looking forward to Ξ/π…

HADES net-proton

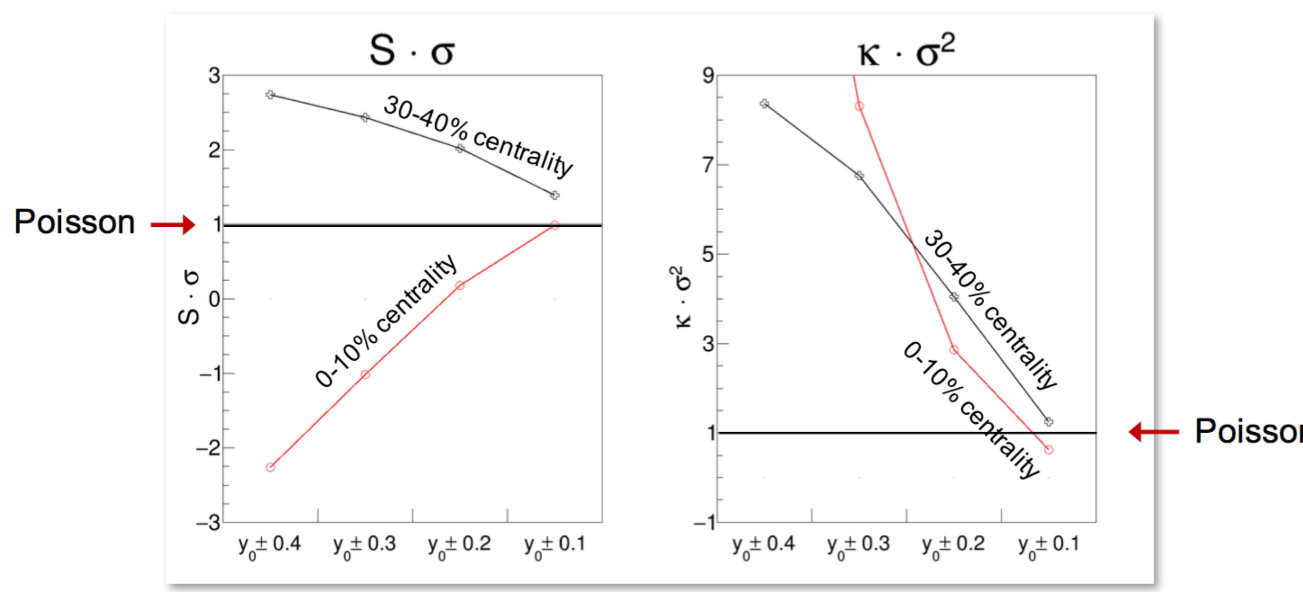
R. Holzmann
Tue., 11:00h

- HADES Au+Au data at sqrt(s_{NN}) = 2.41 GeV continues the trend of the STAR-BES data to even lower energies.
- Different rapidity window (Δy=0.2) with respect to STAR (Δy=0.5) in order to ensure large enough distance to beam rapidity.
- A strong dependence of the observable on the rapidity window is observed.





Sketch of rapidity distribution at *high* energies (LHC, top RHIC) from V. Koch.



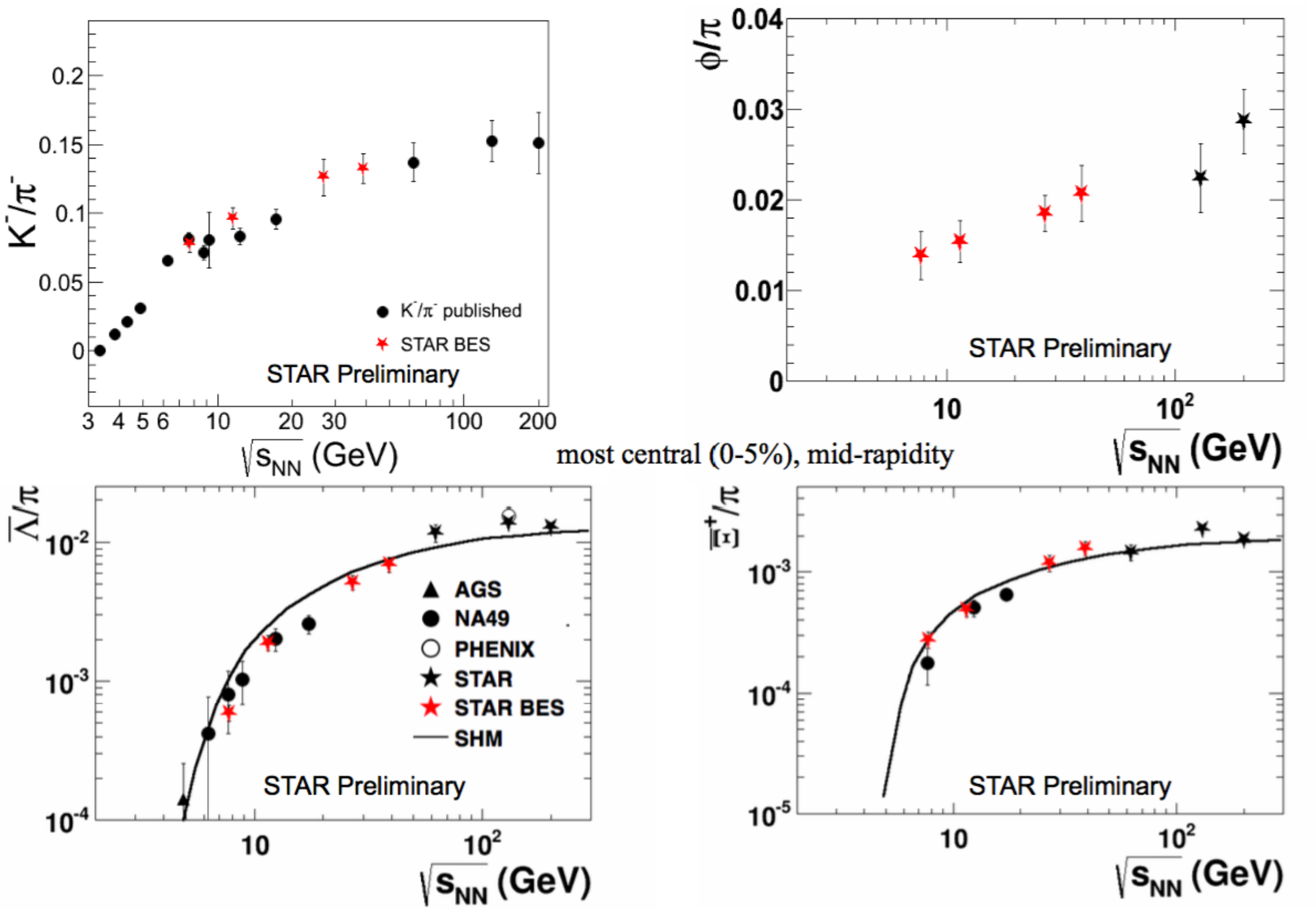
Strangeness production:
small systems at high energies and beam energy scan
(the continuous transition)

Strangeness production

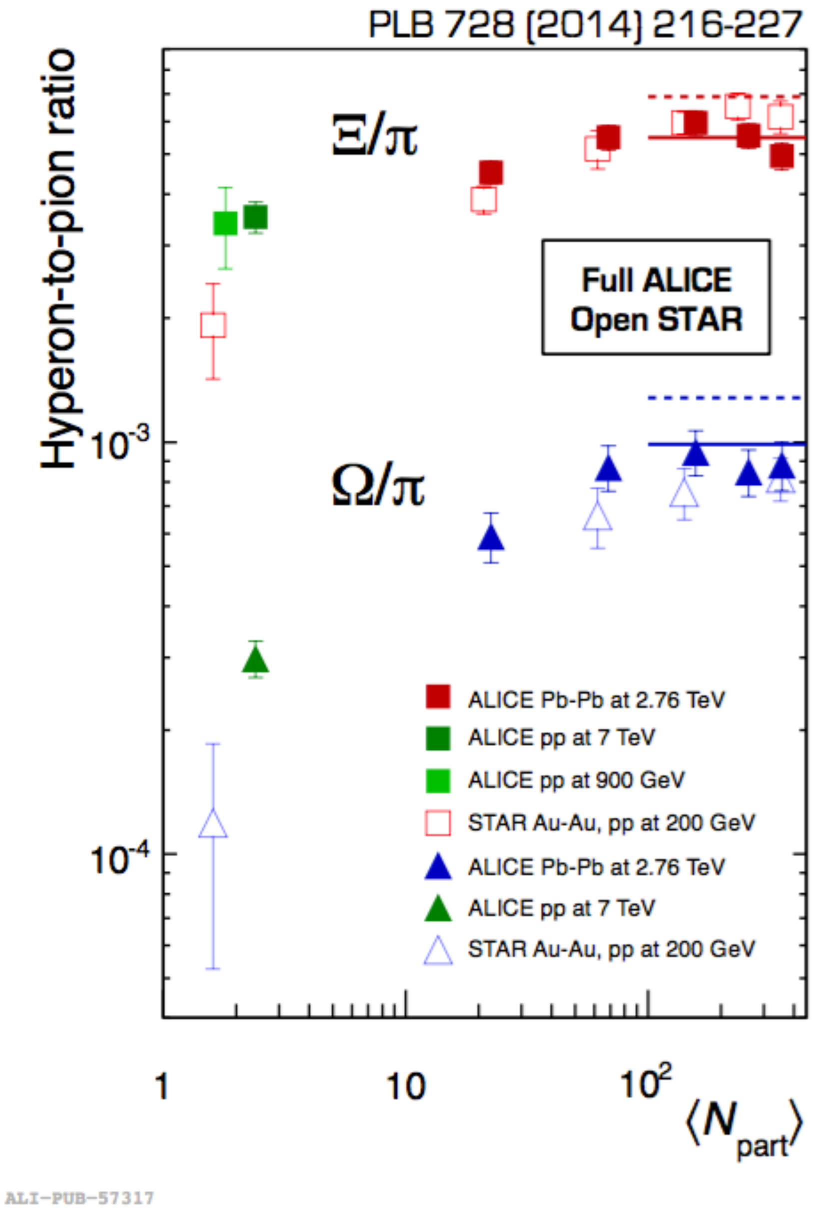
S. Shi
Tue., 09:00h

D. Colella
Tue., 14:40h

STAR - Beam energy scan



Statistical Hadron gas Model: A. Andronic et al., Nucl. Phys. A 772, 167 (2006)



- Smooth evolution of strangeness production (particle chemistry) across different **energies**.
- Smooth evolution of strangeness production (particle chemistry) across different **systems** *if multiplicity dependence is taken into account.*

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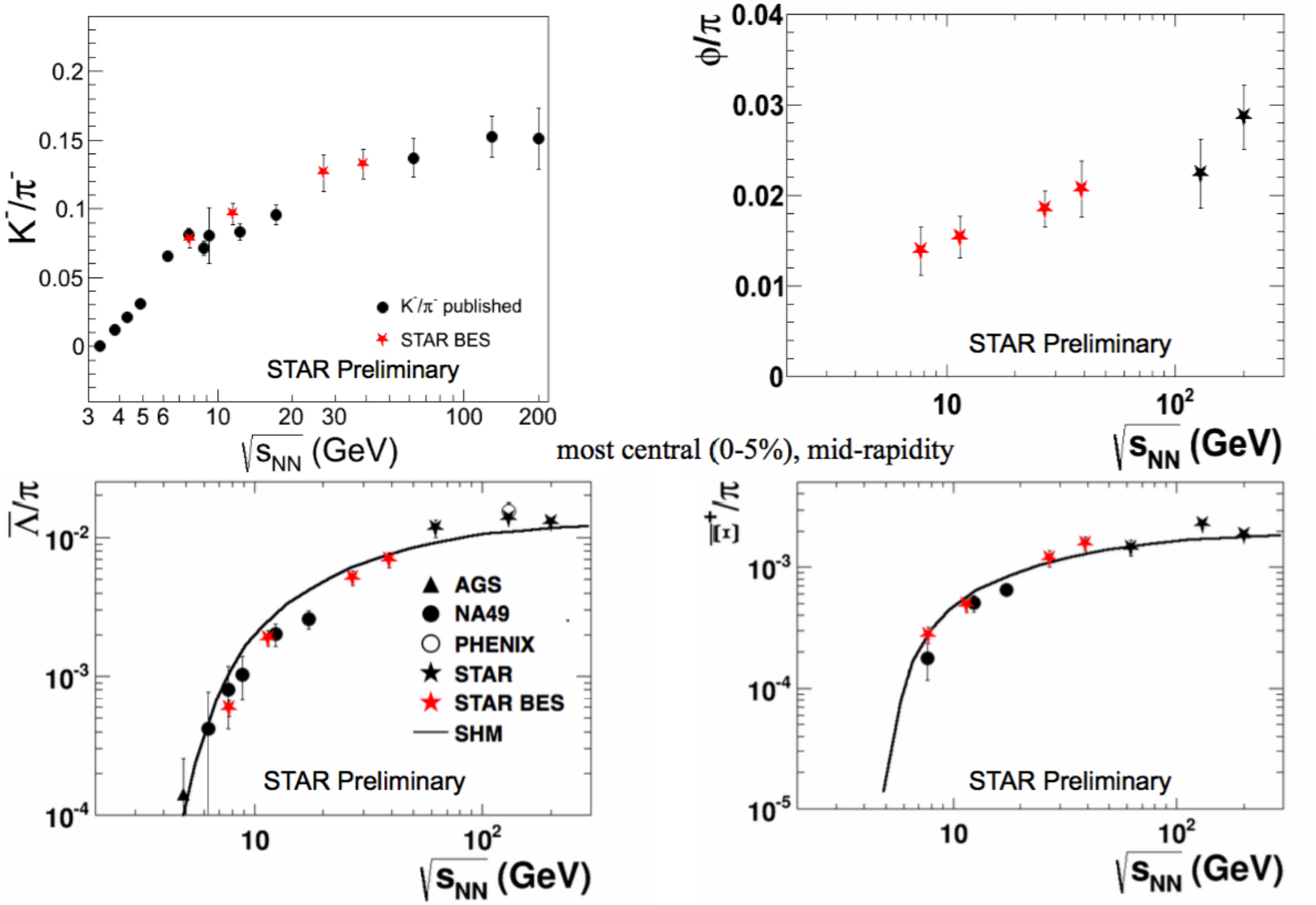

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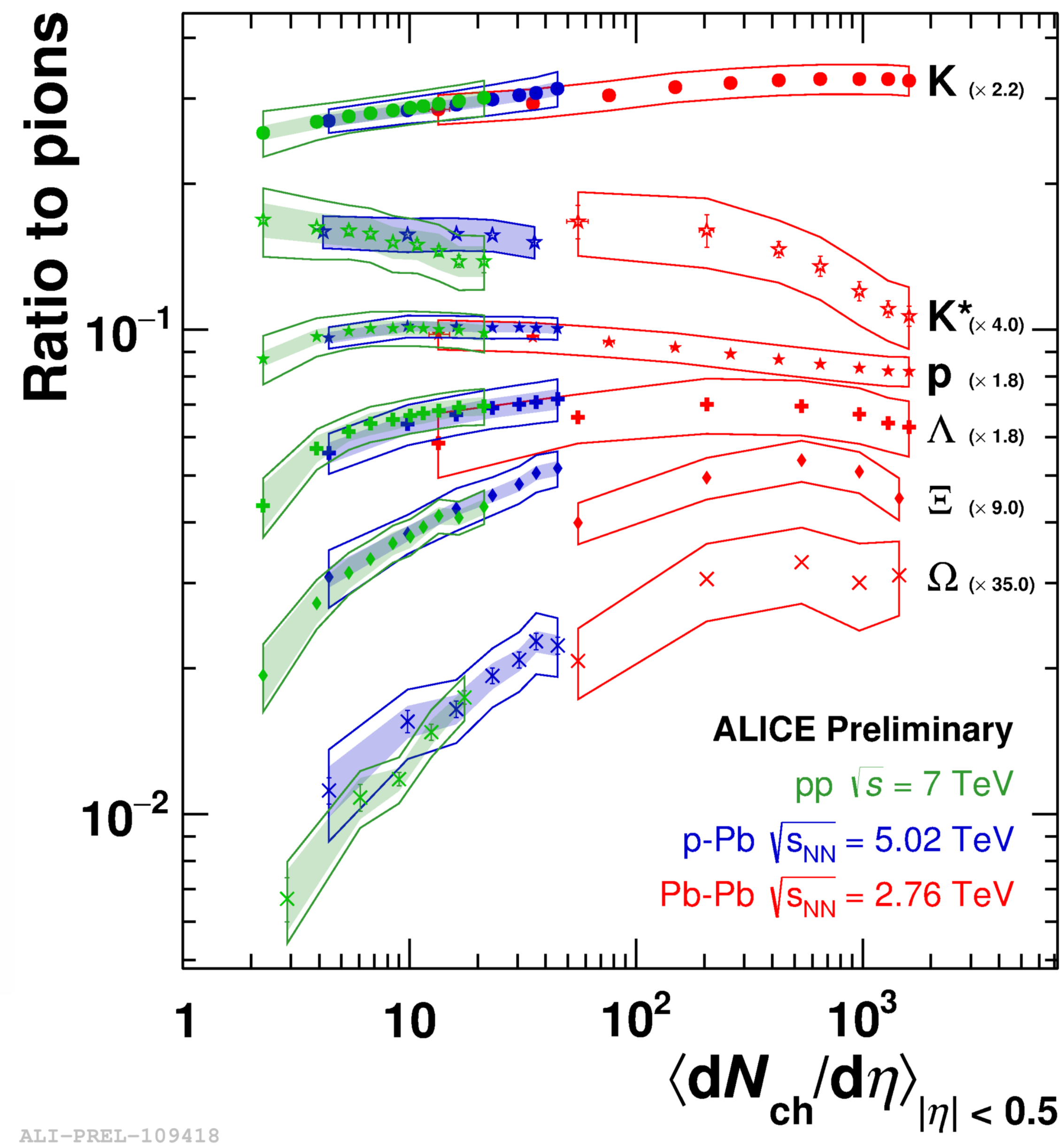
ALICE - System size scan



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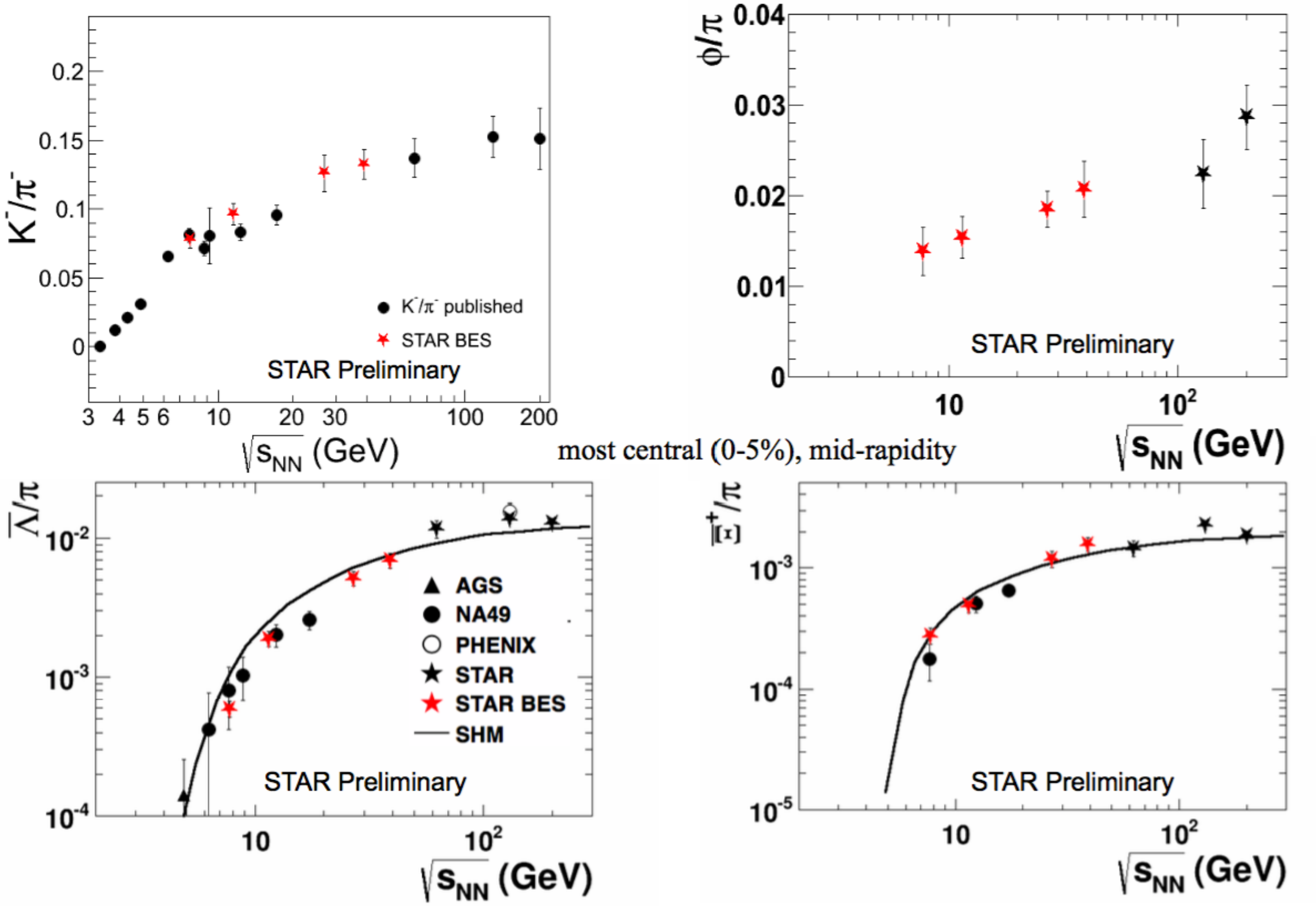

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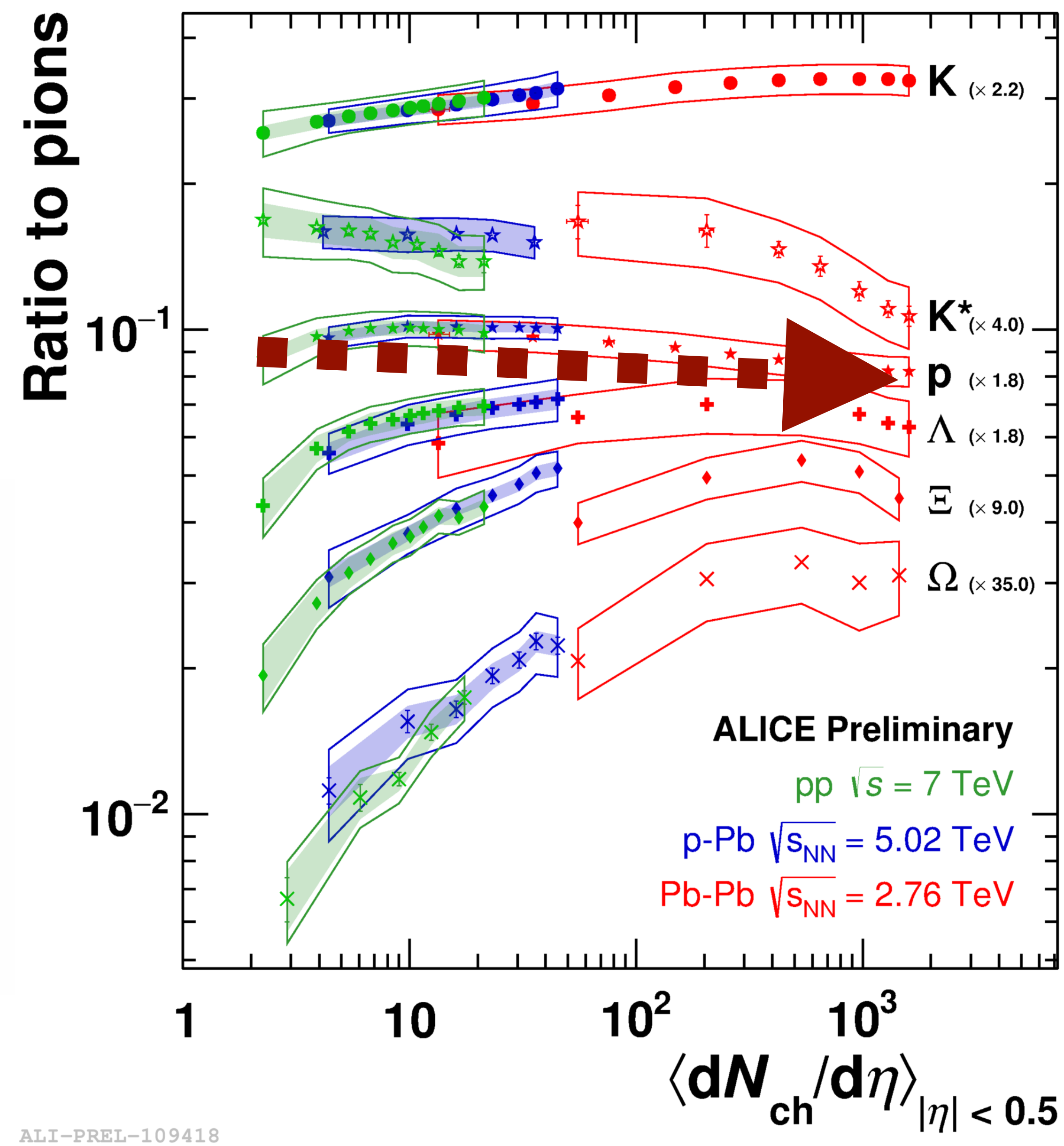

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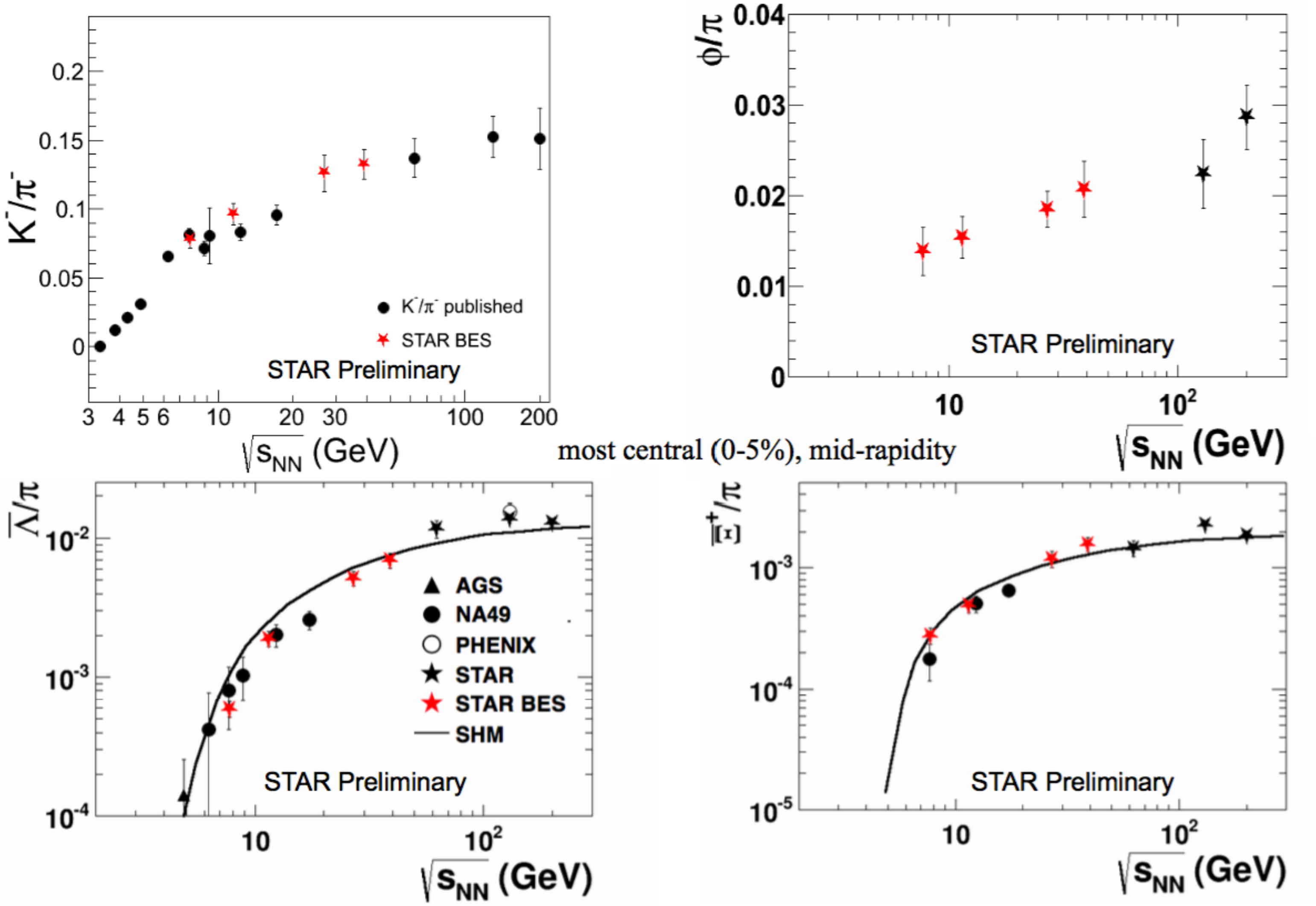

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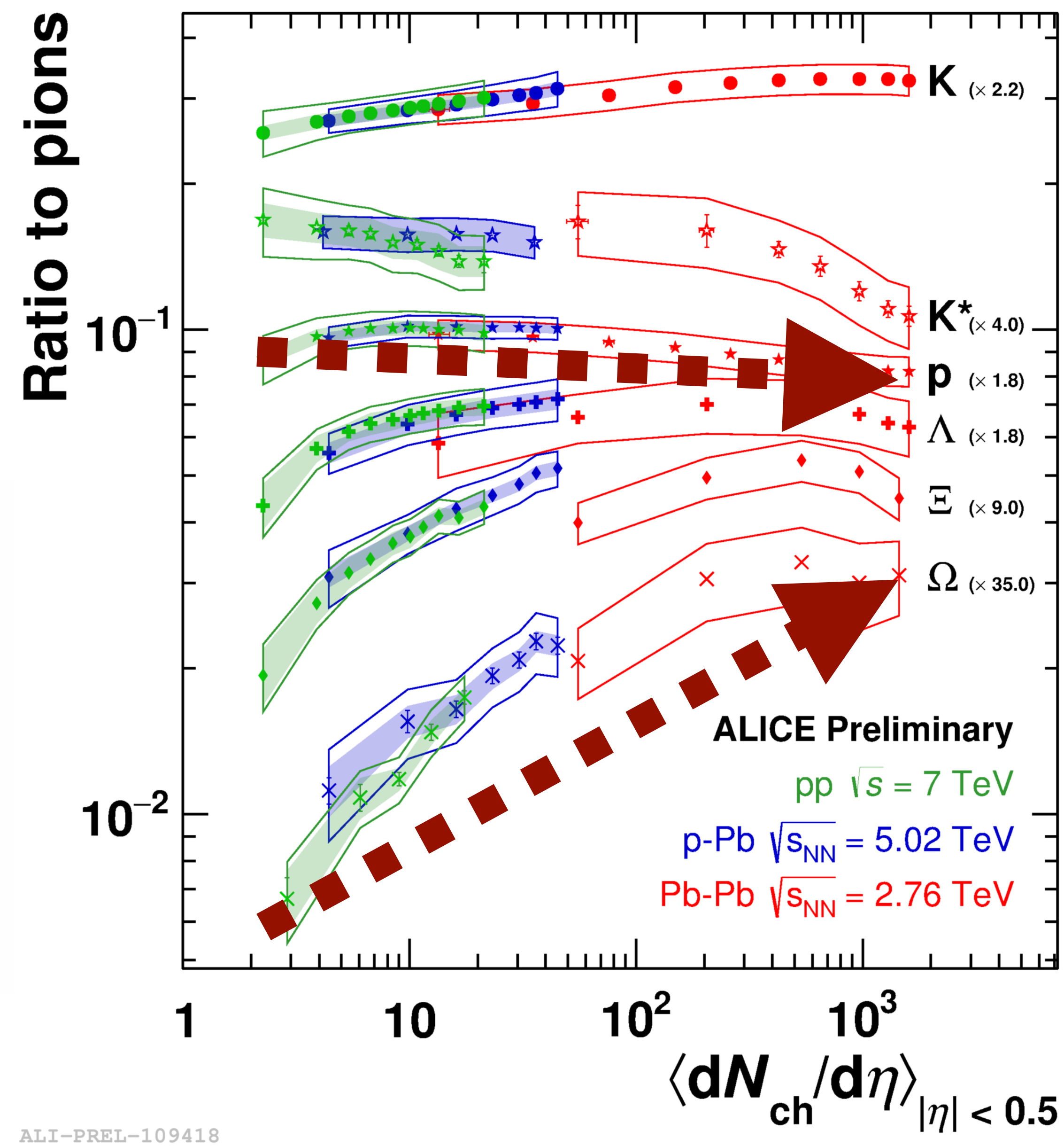

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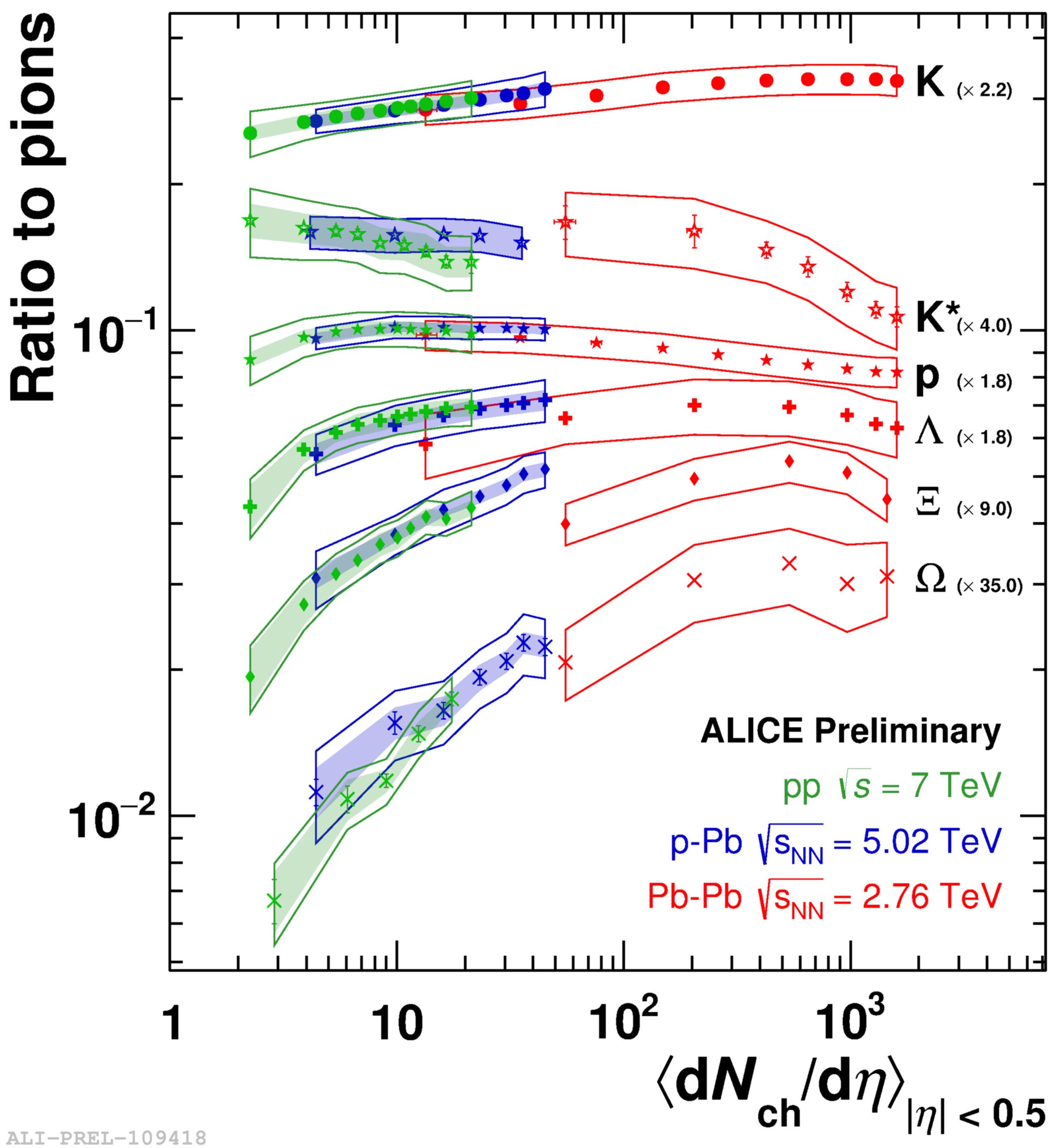
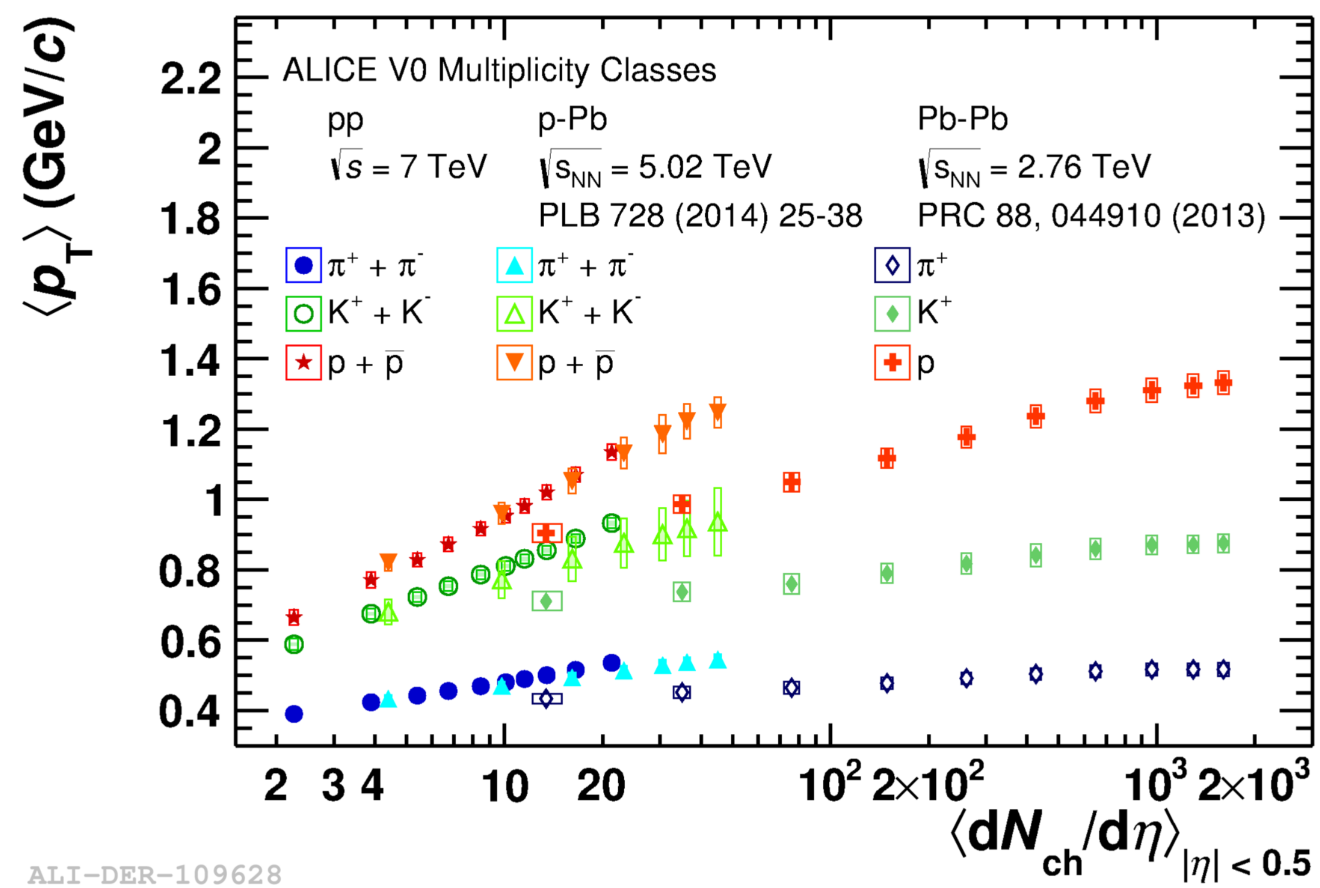
System size dependence

F. Bellini
Tue., 09:30h

R. Derradi
Tue., 17:00h

- Particle chemistry is smoothly evolving ("approach from canonical to grand-canonical equilibrium"). Spectral shapes are more sensitive to the centre-of-mass energy (power-law tail etc.).
- The ball is now on the theory side to describe the data quantitatively..



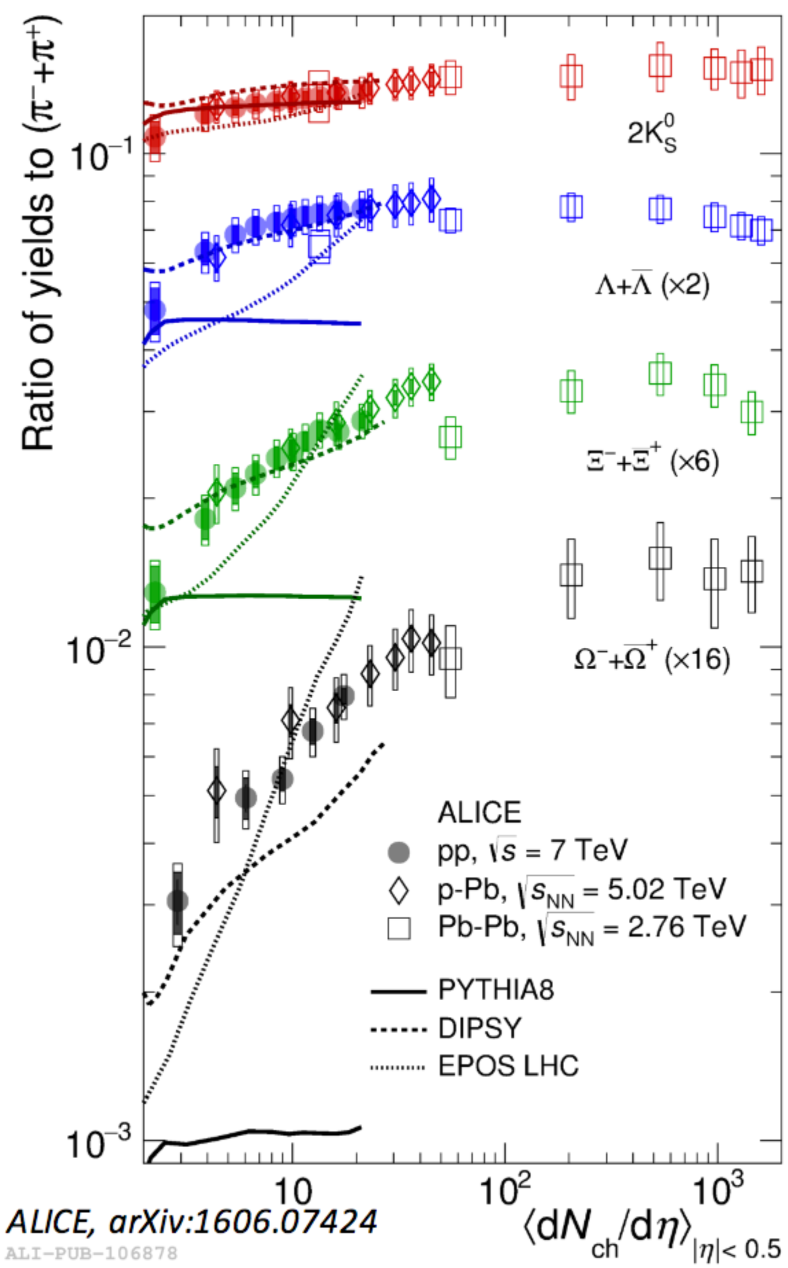


Thermal vs dynamical

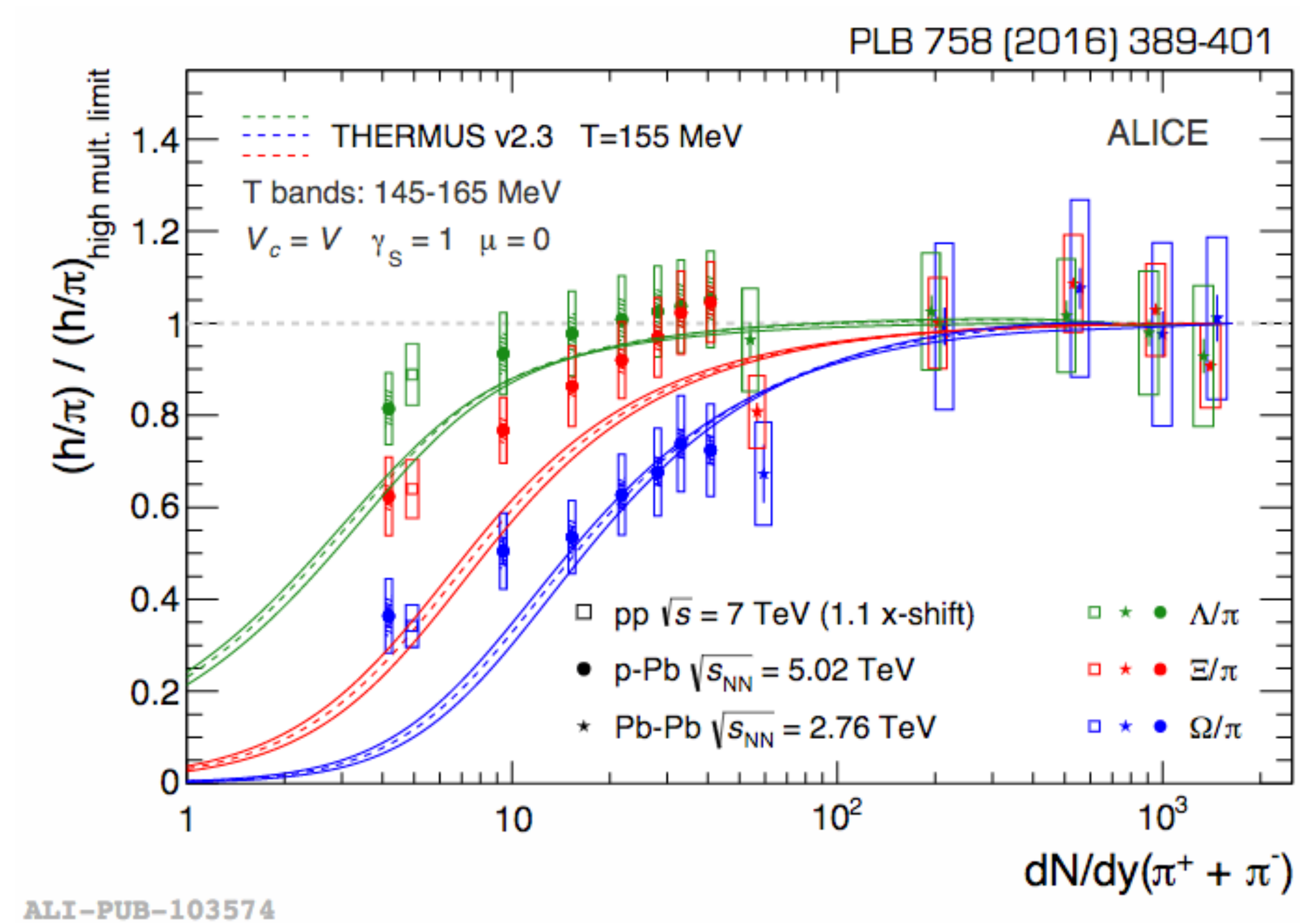
R. Derradi
Tue., 17:00h

D. Colella
Tue., 14:40h

- 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



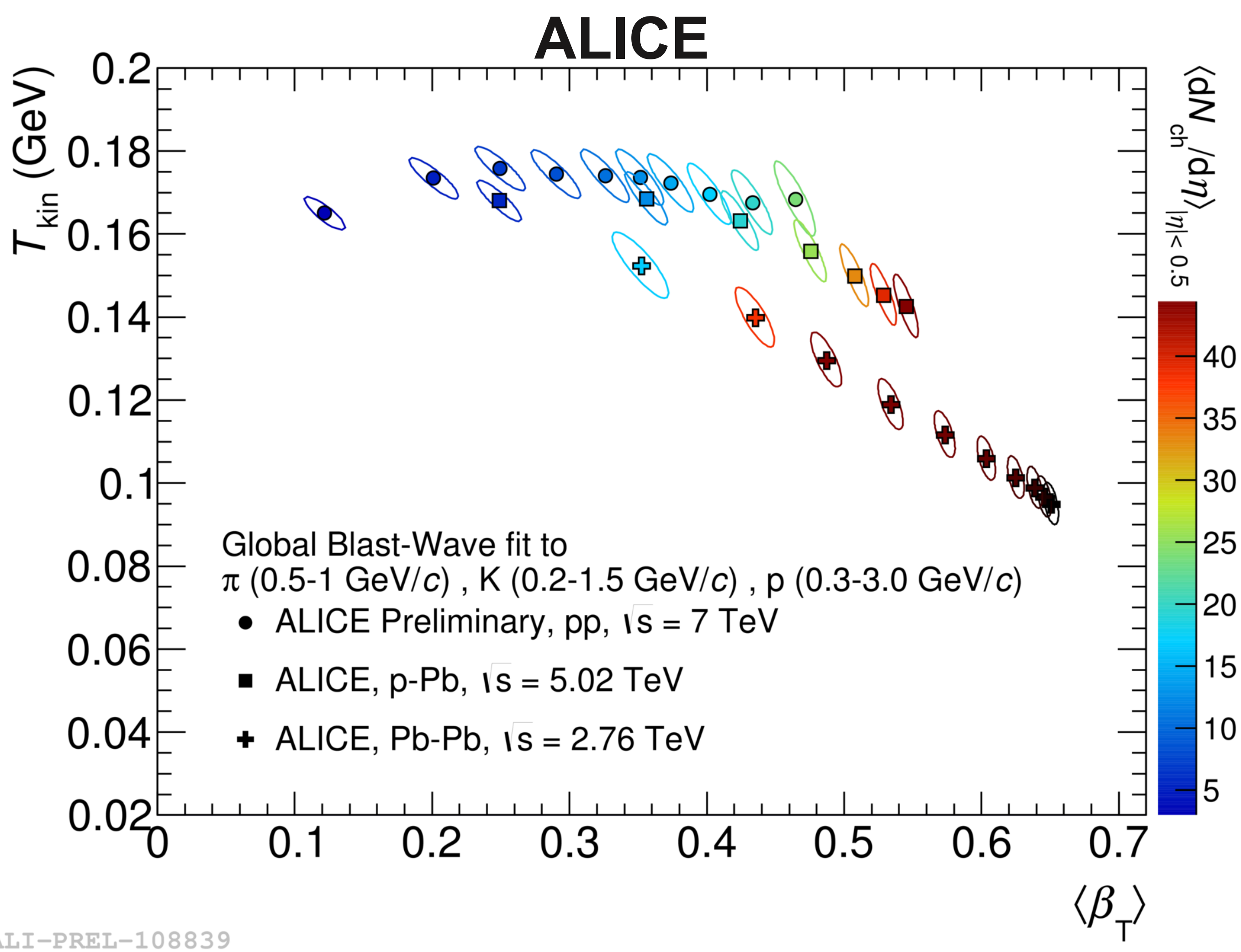
Blast-wave fits

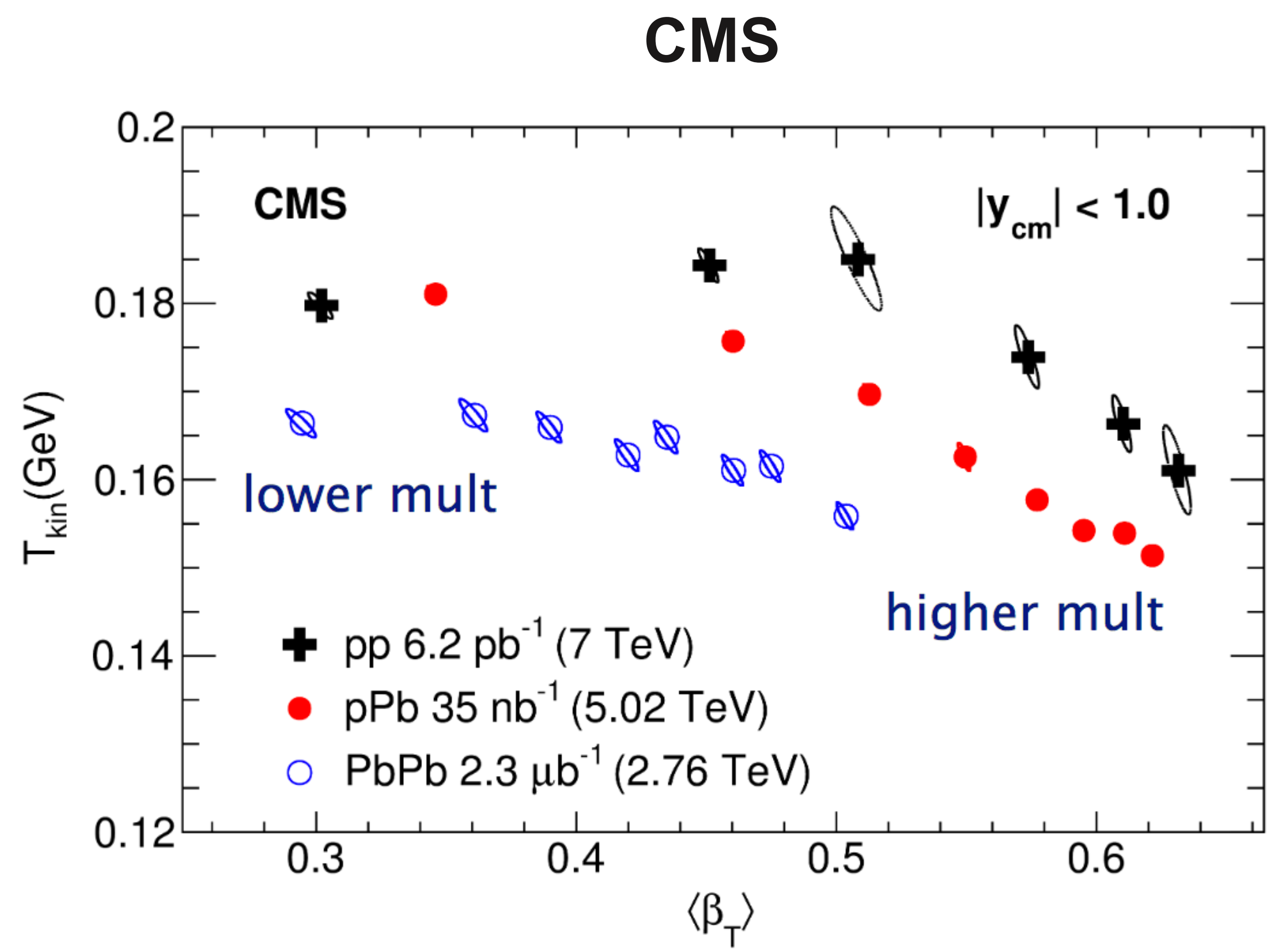
F. Belllini
Tue., 09:30h

R. Derradi
Tue., 17:00h

G. Stephens
Thu., 10:20h

- 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.
- Is there a difference in the freeze-out curves between pp and p-Pb?





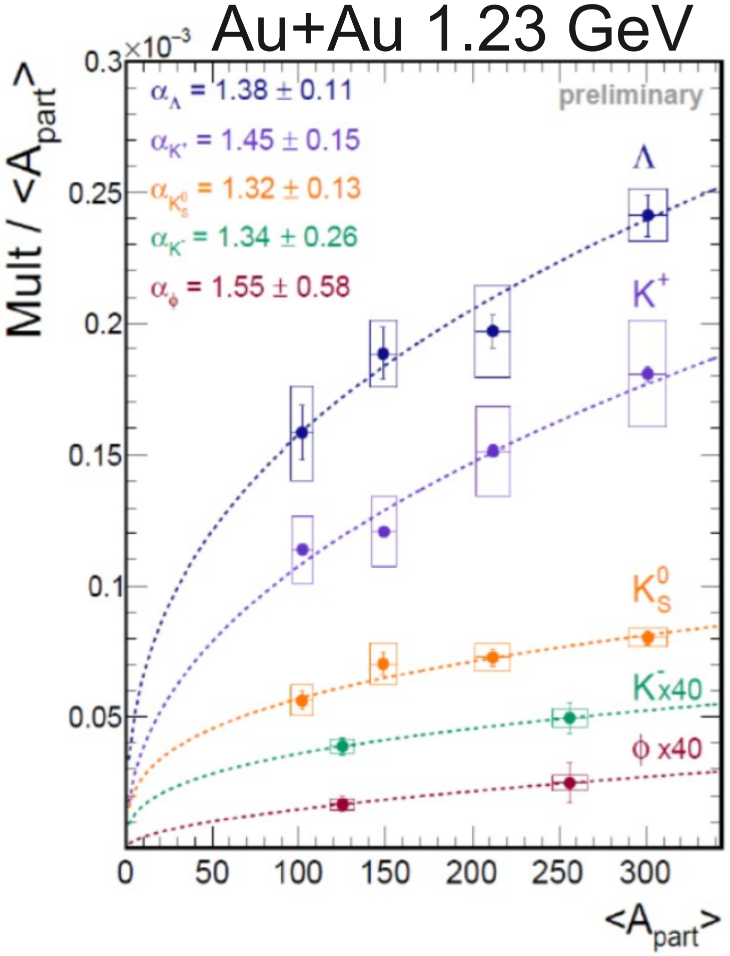
Summary & conclusion

Instead of a summary of the summary…

… an impressive set of data which spans strangeness production from the sub-threshold to the grand-canonical saturation regime

HADES

Au+Au 1.23 GeV



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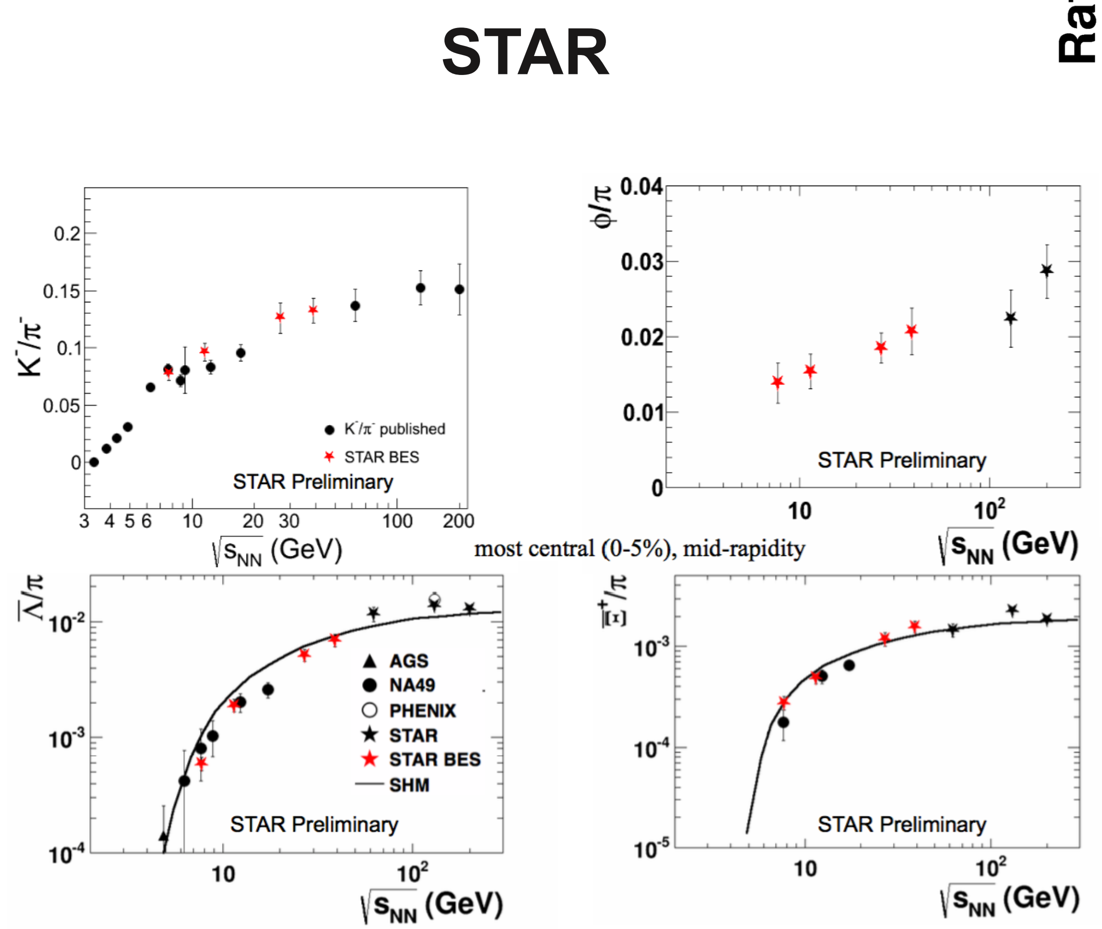

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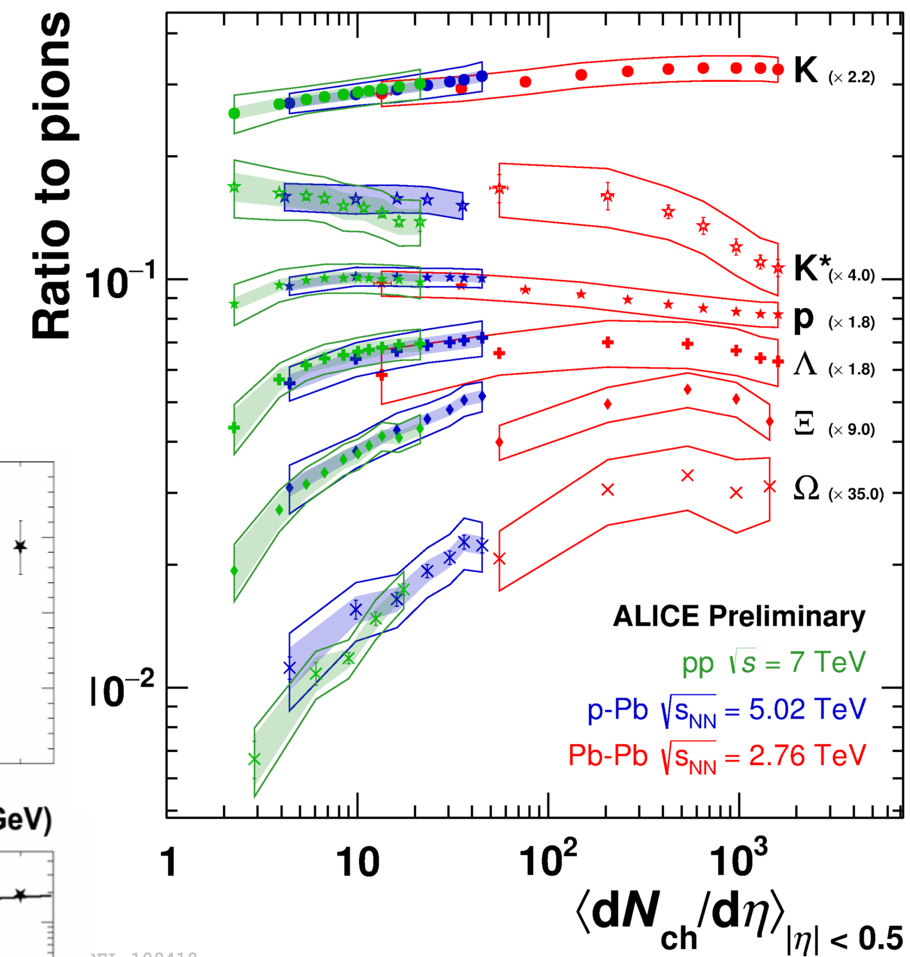

Acknowledgements

Many thanks to all my colleagues for inspiring discussion and for their help in the preparation of this talk:

S. Shi, A. Andronic, D. Chinellato, F. Bellini, R. Holzmann, H. Stroebele,
P. Braun-Munzinger, J. Schukraft, K. Safarik, B. Doenigus, R. Holzmann,
T. Scheib, J. Steinheimer, M. Schmelling, B. Mohanty, C. Ratti, F. Karsch,
A. Andronic, R. Bellwied, V. Begun, M. Lisa, H. Oeschler, Y. Zhou,…