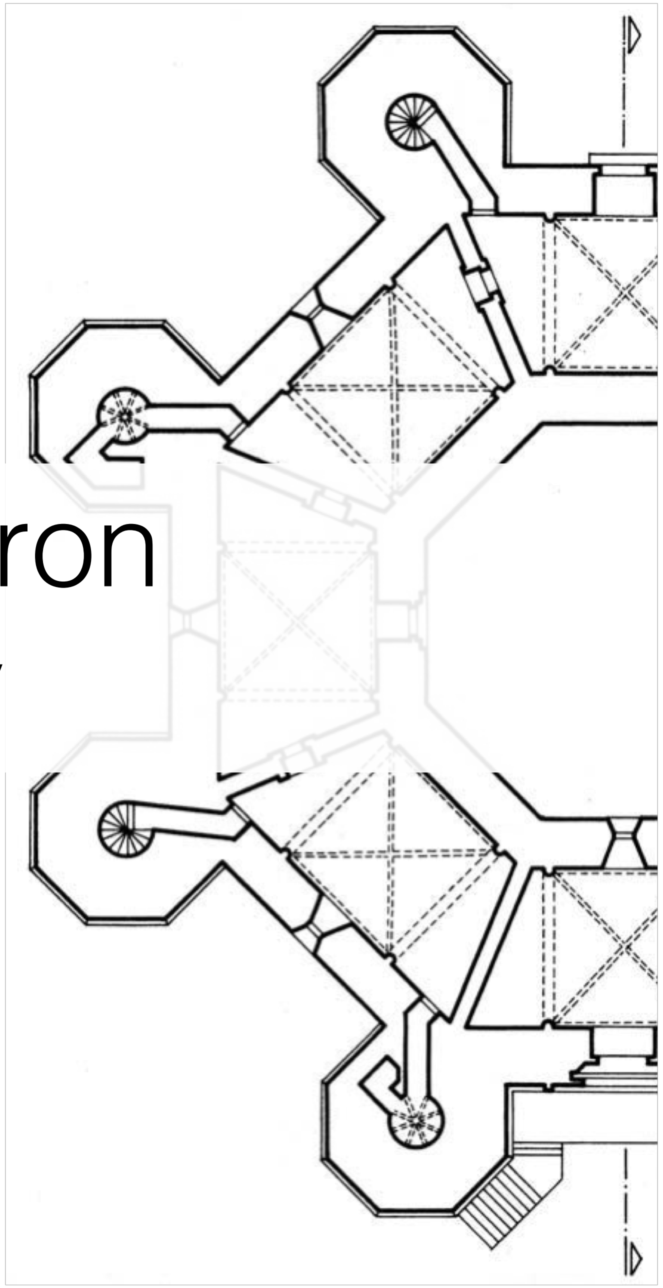
Strangeness and light flavor hadron production at low baryon density

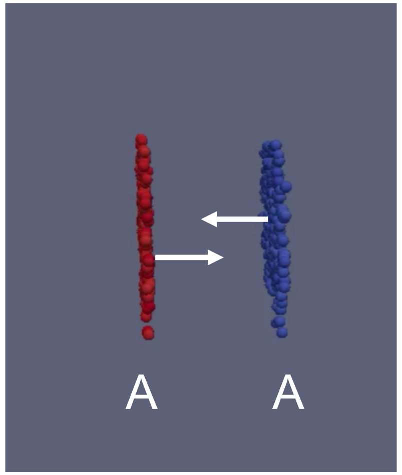


F. Bellini (CERN)

Strangeness in Quark Matter – Bari, 12th June 2019

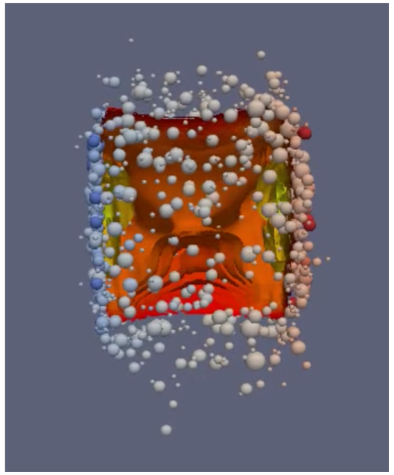
A song of hallmarks and anomalies

Heavy-nuclei
τ ~0

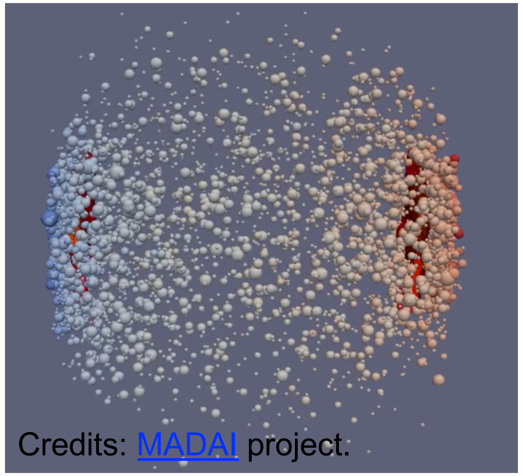


QGP
τ ~ 1 fm/*c*

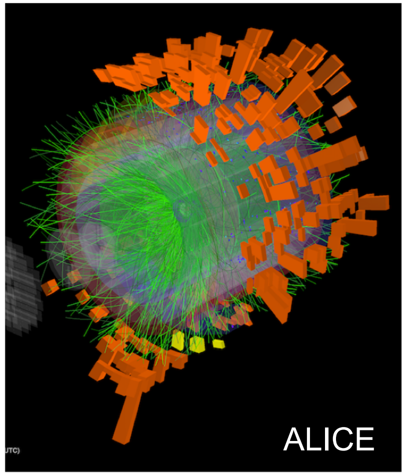
QGP
τ ~ 5 fm/*c*



Hadronic phase
τ > 10 fm/*c*



Detection
τ > 10 pm/*c*



Initial conditions

Collision energy dependence
System geometry dependence

Thermalization
Evolution of a thermalized system
Transport in dense colored medium

Energy loss and medium properties
Hydrodynamics

Hadronisation and freeze-out(s)
Interactions in the hadronic phase

Chemical composition and equilibrium
Hadron transport

The proton anomaly
The anti-(hyper-)nuclei puzzle
The unicity of the ϕ meson
The baryon anomaly

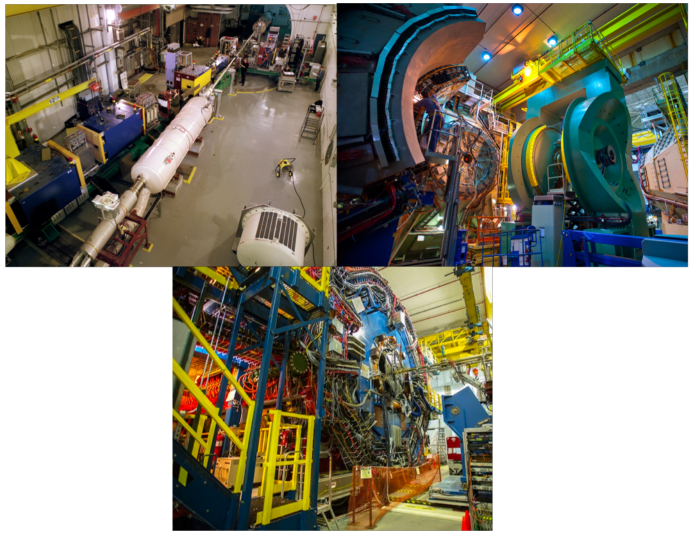
Focus on high-energy AA collisions

Properties of the bulk are being investigated with a comprehensive (and impressive) set of measurements of light flavor hadron production and flow.
Include: πKp, strangeness, resonances, light nuclei, antimatter, hypernuclei.

RHIC, Au-Au and Cu-Cu

Top energy $\sqrt{s_{NN}}$ = 200 GeV

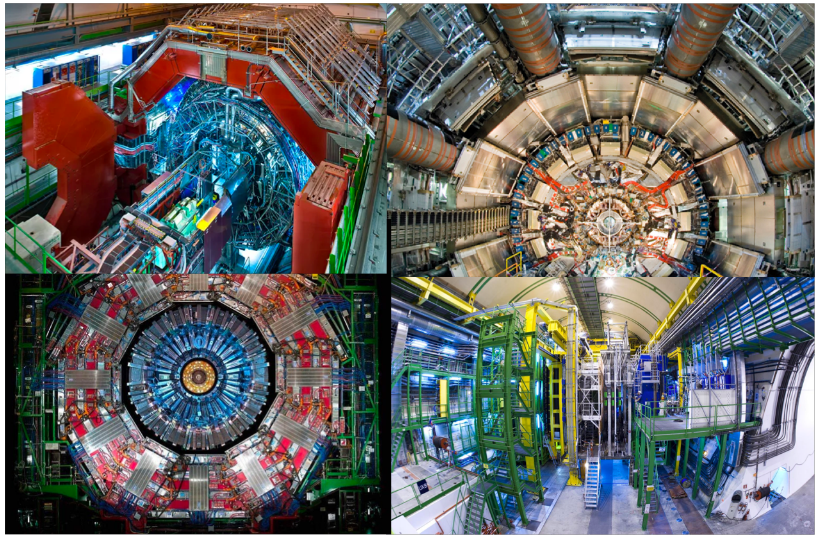
BRAHMS, PHENIX, STAR



LHC, Pb-Pb and Xe-Xe*

$\sqrt{s_{NN}}$ = 2.76 TeV, 5.02 TeV, *5.44 TeV

ALICE, ATLAS, CMS, LHCb

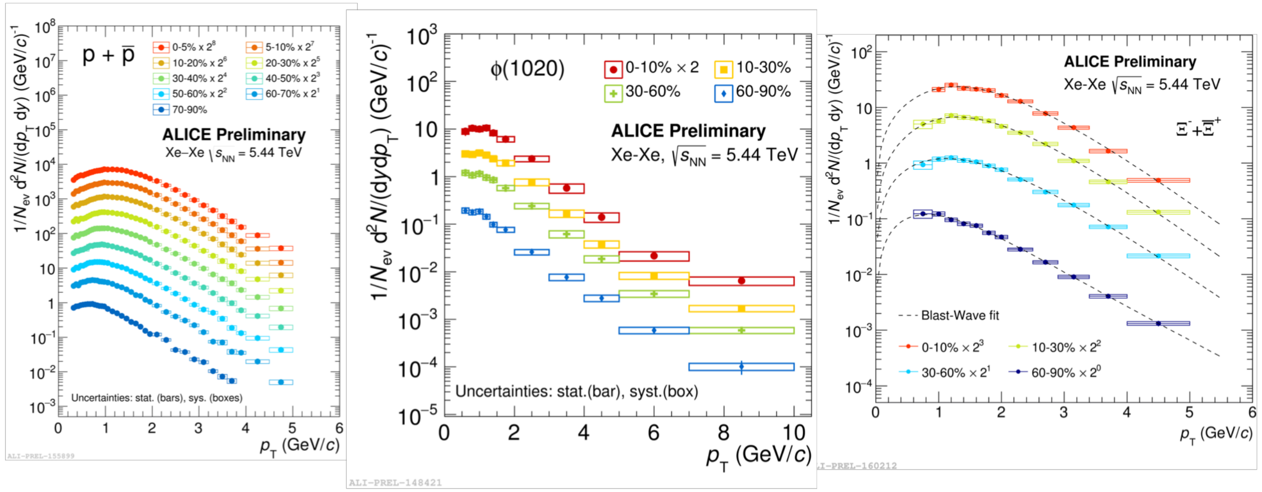


Plenty of data from RHIC and LHC!

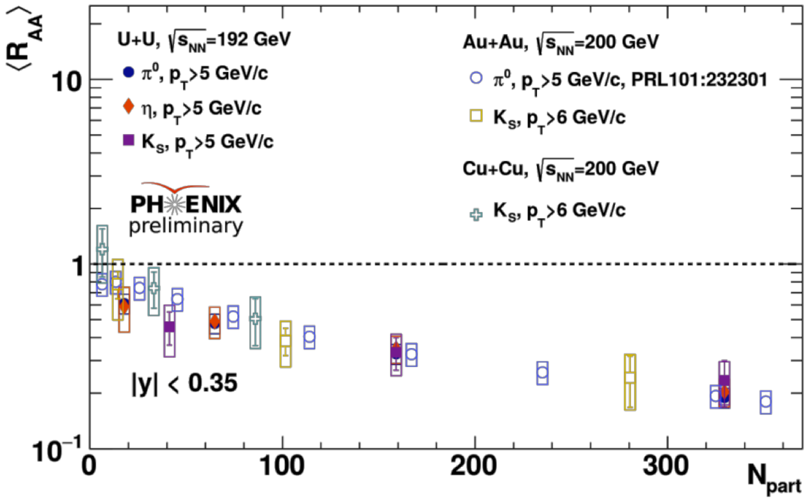
	RHIC		LHC		
Particle species	Au-Au 200 GeV	Cu-Cu 200 GeV	Pb-Pb 2.76 TeV	Pb-Pb 5.02 TeV	Xe-Xe 5.44 TeV
π, K, p					
Λ					
Ξ					
Ω					
ϕ					
d		-			-
$^{3}_{\Lambda}H$		-			-

Published or **Preliminary** results available for most light-flavor and strange hadron species.
Nota bene: not an exhaustive list!

I will necessarily focus on a selection of results – my apologies for omitting your favourite one!



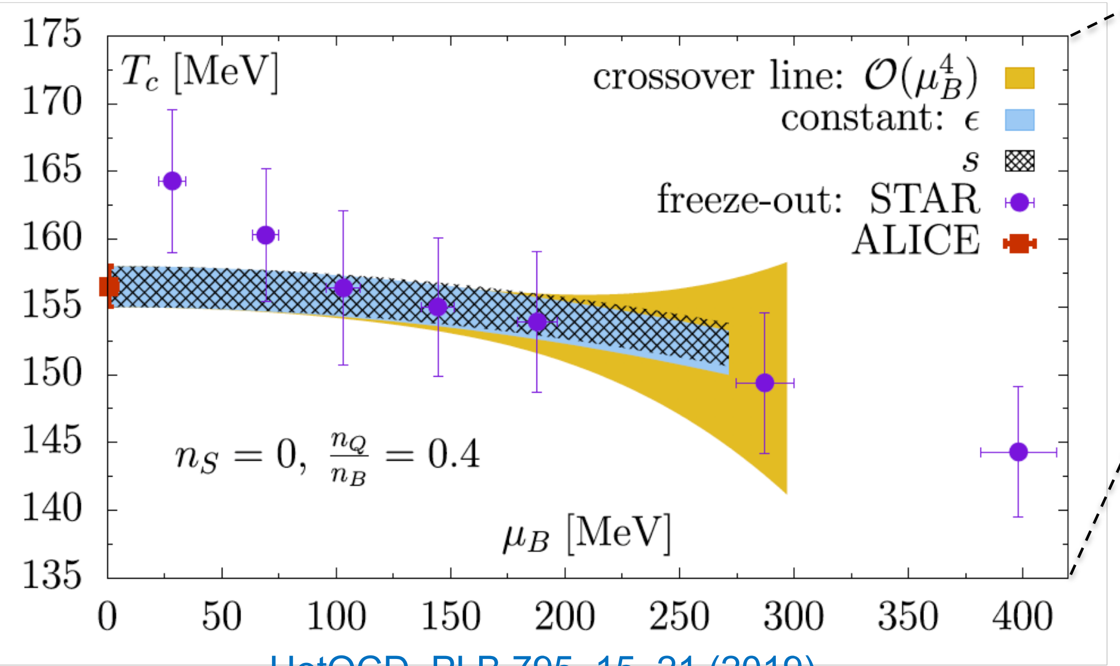
ALICE, QM2018



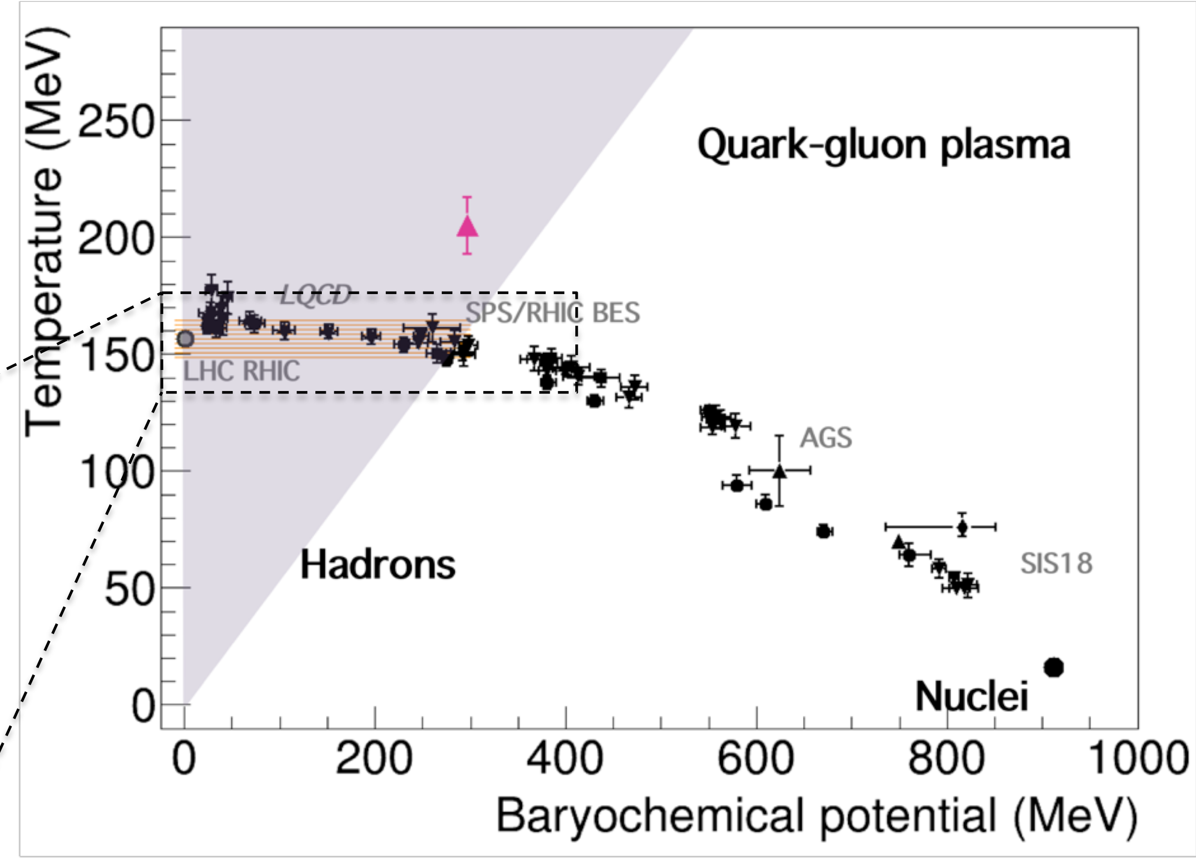
PHENIX, this conference

Experimental access to the QCD phase diagram

RHIC and LHC give experimental access to the region of the QCD phase diagram at zero and low μ_B, allowing direct comparison with state-of-the-art *ab initio* lattice QCD calculations.



HotQCD, PLB 795, 15–21 (2019)



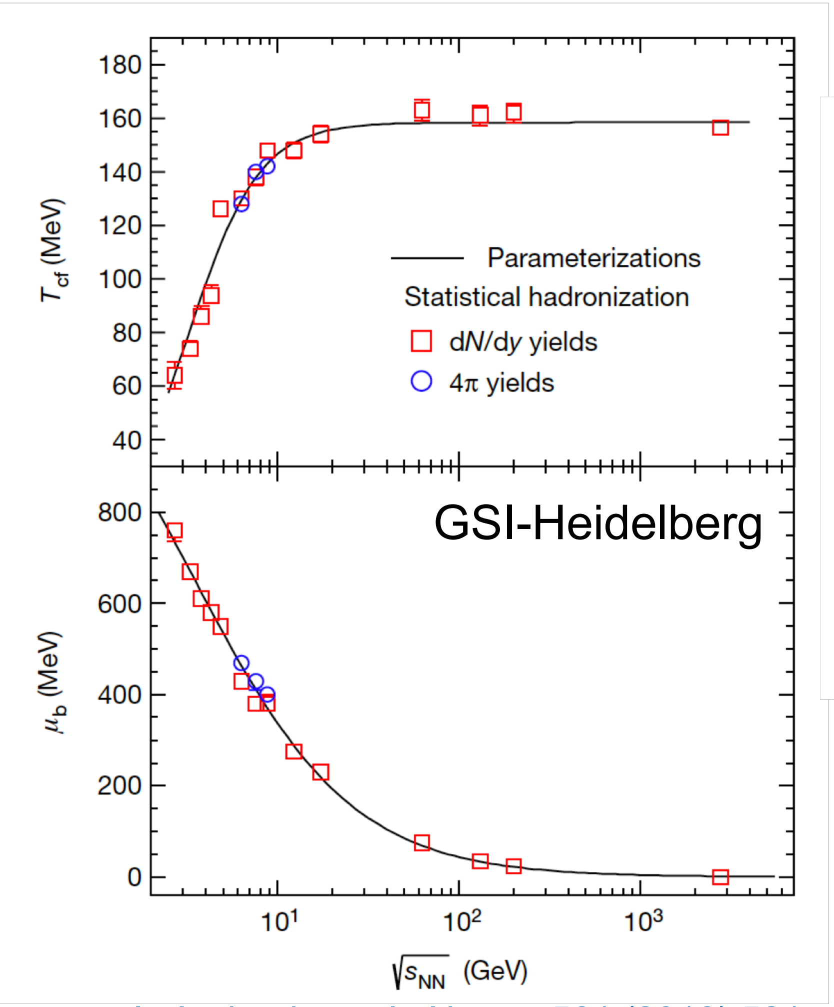
T. Galatyuk, QM 2018

Latest lQCD prediction for $T_c(\mu_B = 0) = (156.5 \pm 1.5)$ MeV

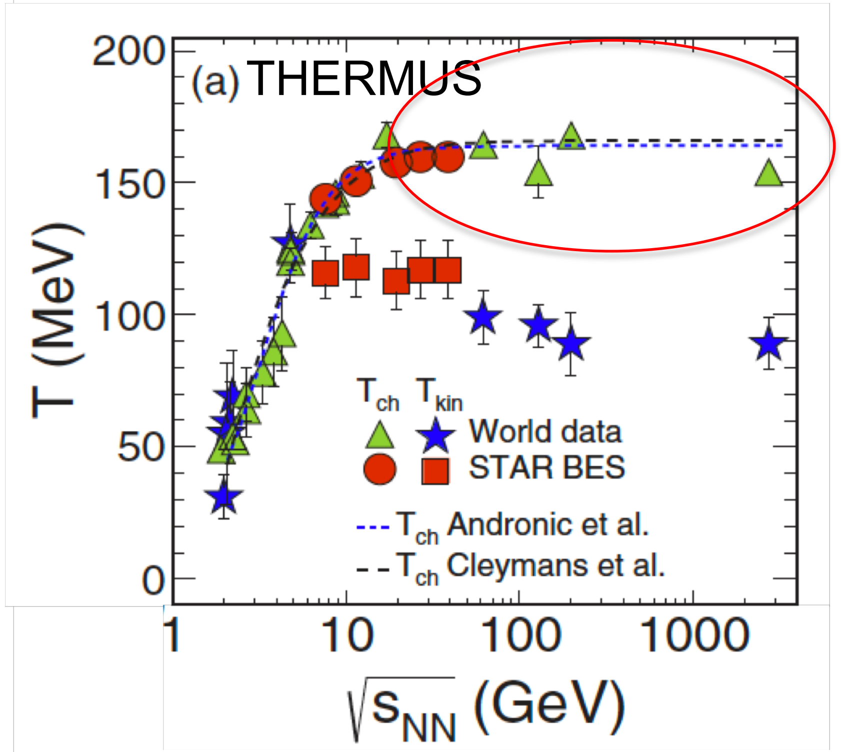
Energy dependence of T_{ch}, μ_B

The chemical freeze-out parameters can be extracted from statistical hadronisation analyses of hadron yields (or particle ratios).

At top RHIC energy and at the LHC, the chemical freeze-out occurs in the vicinity of the critical temperature, i.e. of hadronisation.



A. Andronic et al., Nature 561 (2018) 521



STAR, PRC 96 (2017) 044904

→ *more on BES in X. Zhu's talk*

Thermal model fits to RHIC data (200 GeV)

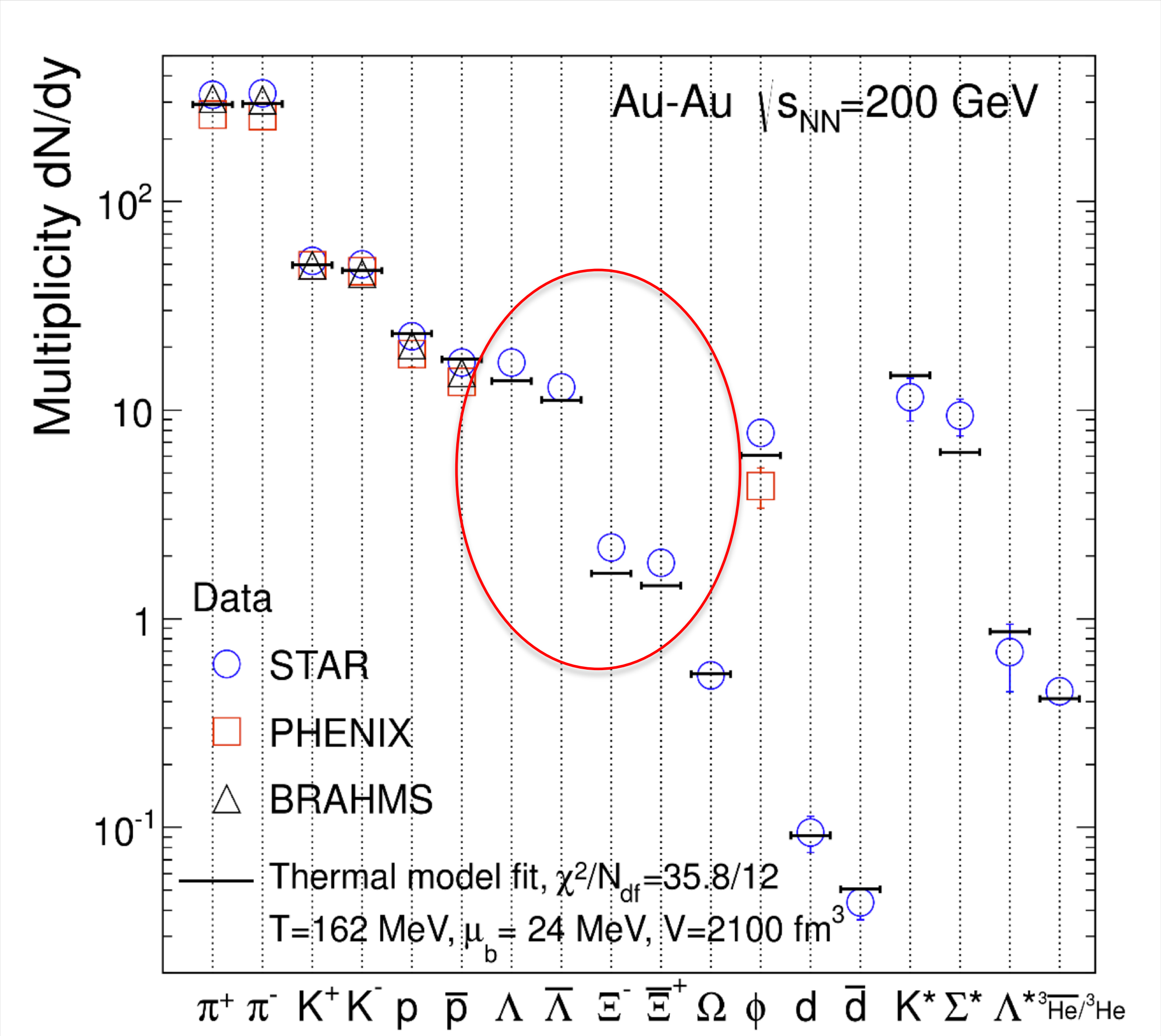
Grand-Canonical thermal model fit performed on STAR, PHENIX and BRAHMS data.

Most hadron abundances are in agreement with a thermally equilibrated system freezing out at

T_{ch} = 162 MeV at 200 GeV

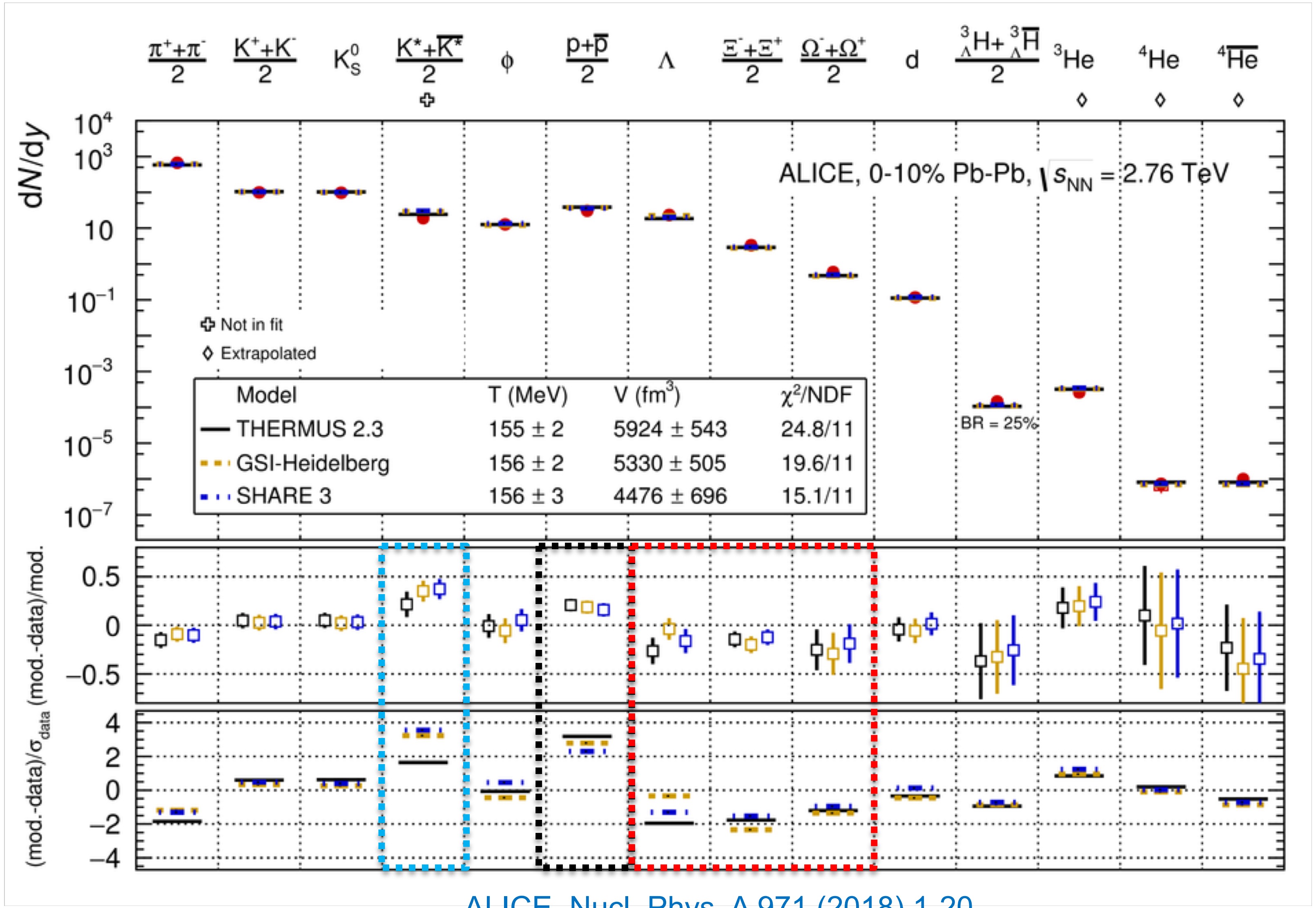
with indication for deviations in the strange baryon sector.

Fits performed also on STAR BES data.



A. Andronic, Nucl. Phys. A 904-905 (2013) 535

Thermal model fits to LHC data (2.76 TeV)



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11

ALICE, Nucl. Phys. A 971 (2018) 1-20

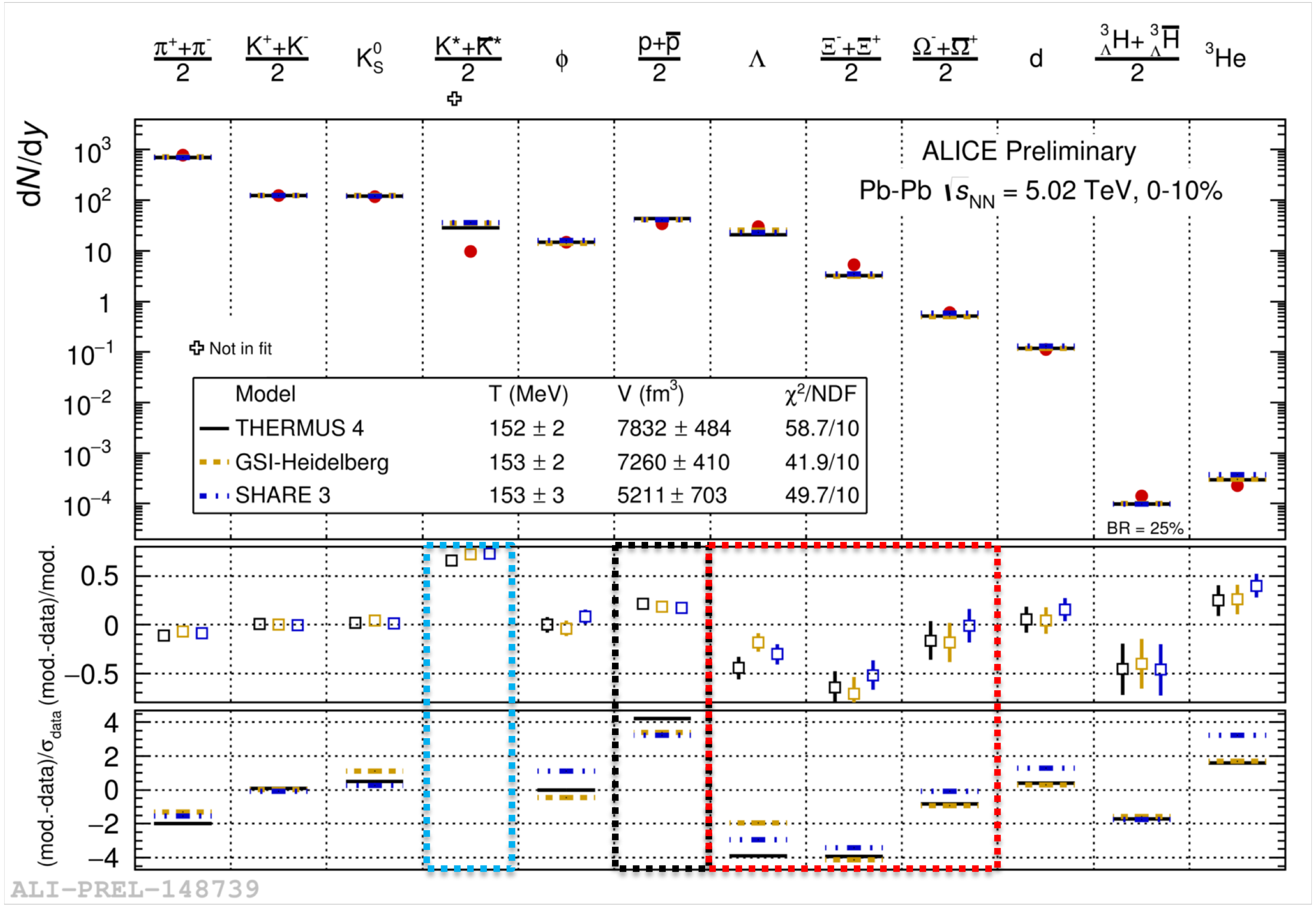
Production of (most) light-flavour hadrons in Pb-Pb at 2.76 TeV is described (χ^2/ndf ~ 2) by thermal models with a single chemical freeze-out temperature

$T_{ch} \approx$ 156 MeV at 2.76 TeV

Deviation for short-lived **K^{*0}**

Tensions between **protons** and **multi-strange baryons**

Thermal model fits to LHC data (5.02 TeV)



Preliminary data in 0-10% Pb-Pb at 5.02 TeV can be fitted with a slightly lower temperature and higher χ^2/ndf ~ 4-6

T_{ch} ≈ 153 MeV at 5.02 TeV

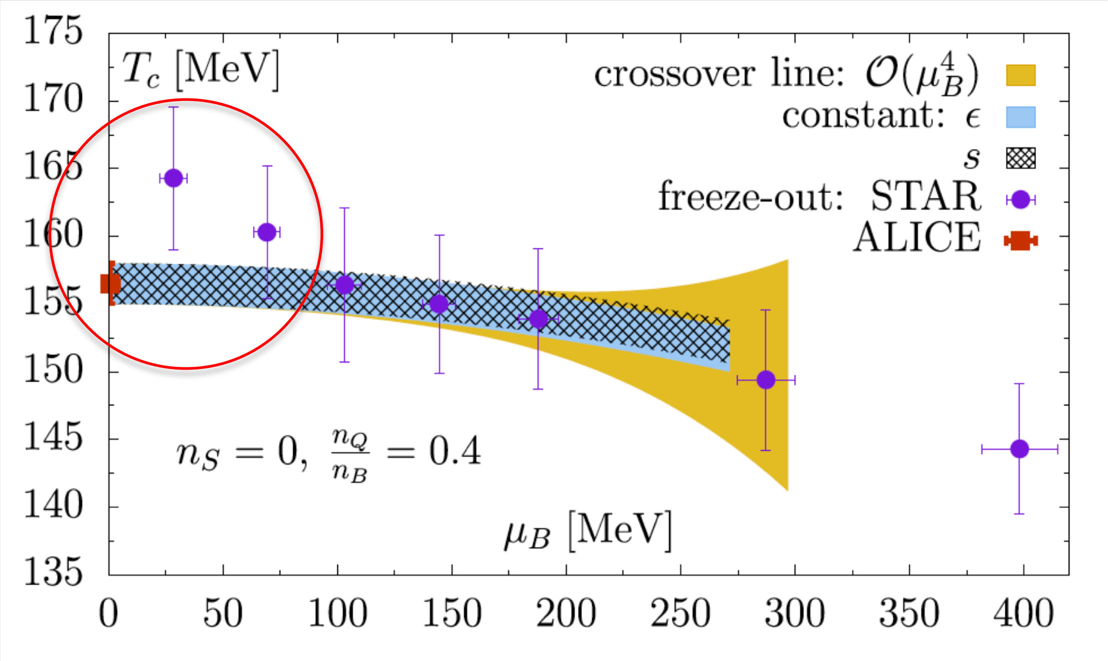
Tensions seen at 2.76 TeV are confirmed.

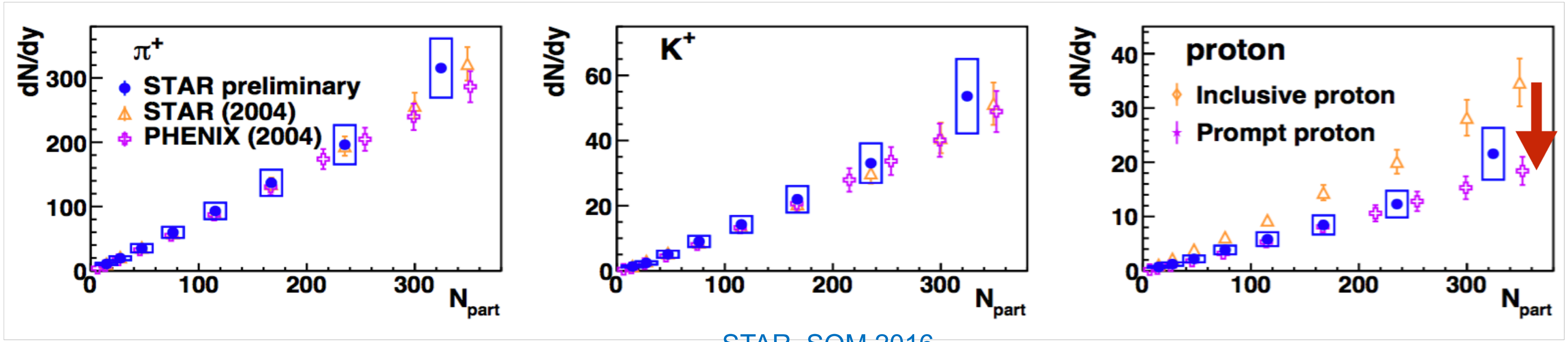
Proton-to-pion ratio

p/π drives the temperature in the thermal fit.

STAR measures inclusive proton production (no feeddown from weak decays).

⟶ Can this be at the origin of the larger T_{ch} obtained fitting the 200 GeV data?





STAR, SQM 2016

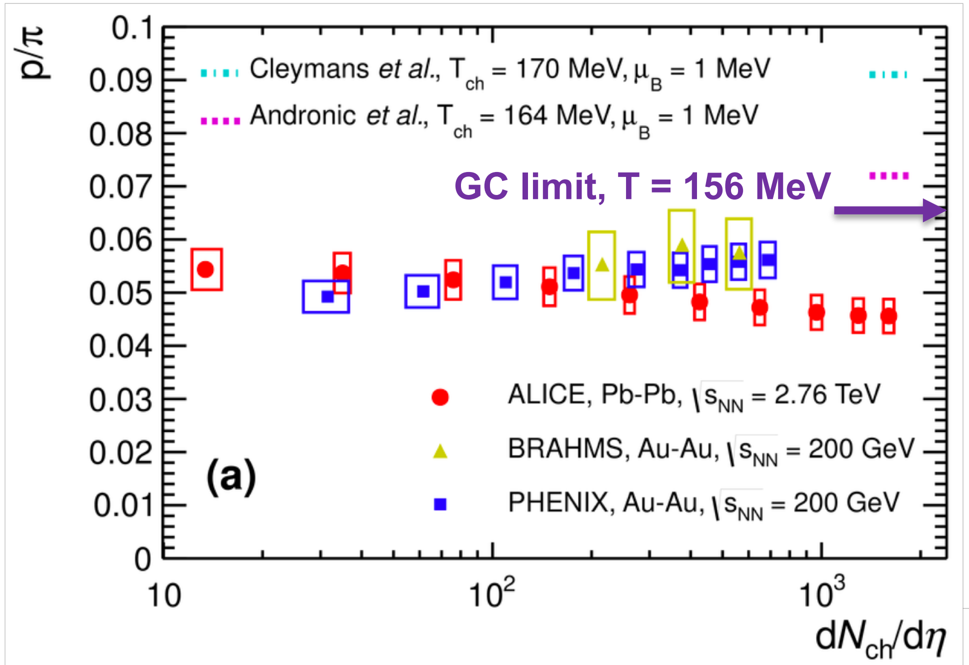
Proton-to-pion ratio

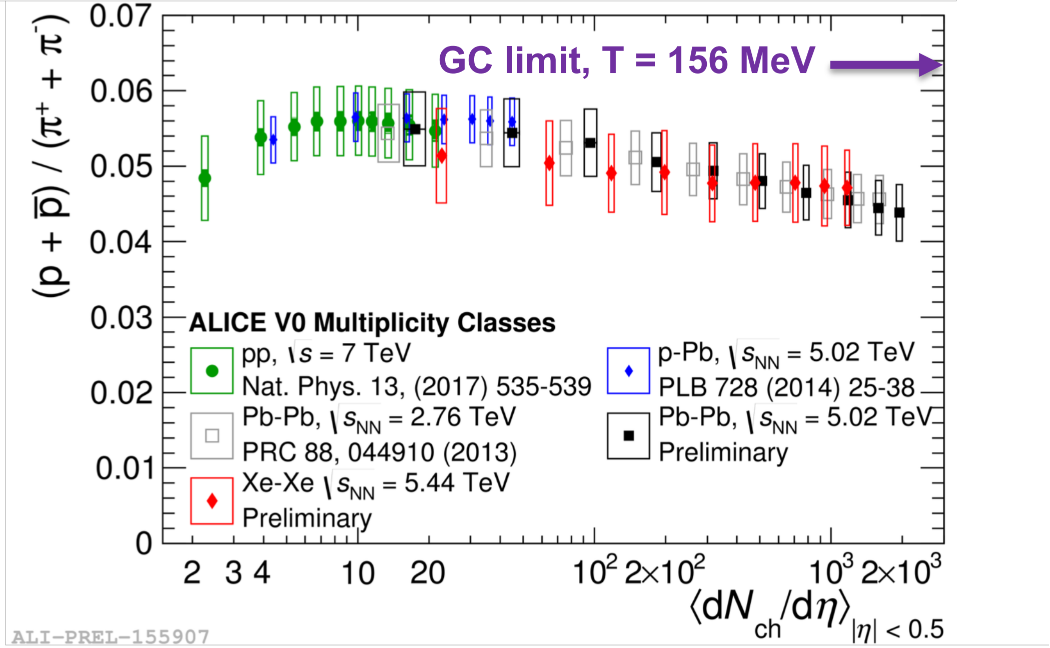
p/π drives the temperature in the thermal fit.

Indication for a decrease from peripheral to central Pb-Pb collisions in ALICE confirmed by Run II data.

⟶ How much of the experimental uncertainties is correlated across centrality?

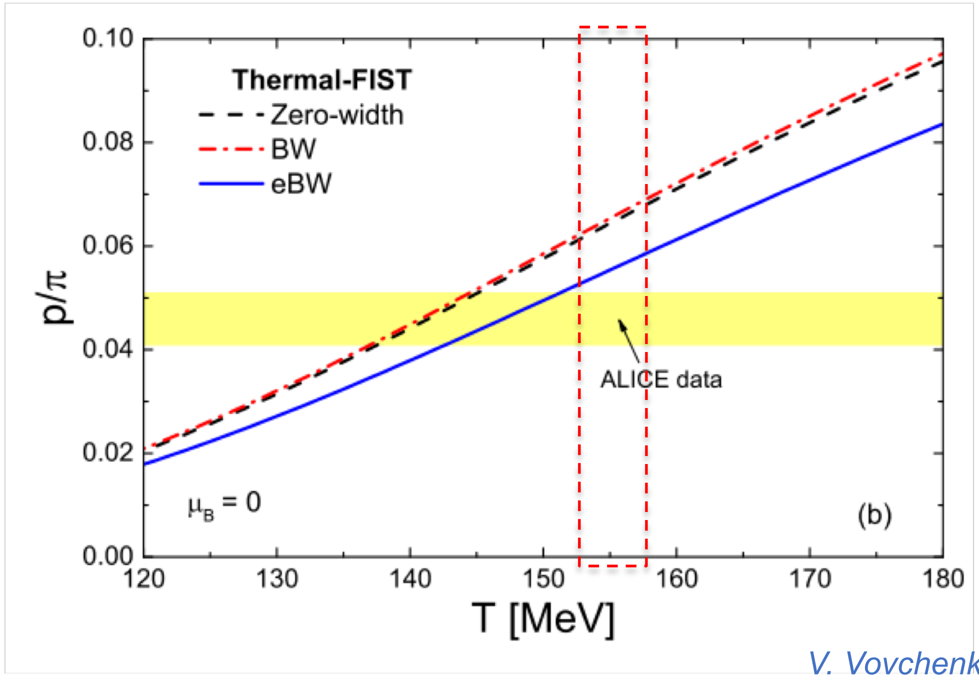
The proton anomaly: in central Pb-Pb collisions, p/π lies below the Grand Canonical limit for T_{ch} = 156 MeV
(~2.7σ considering 2.76 TeV data uncert.)

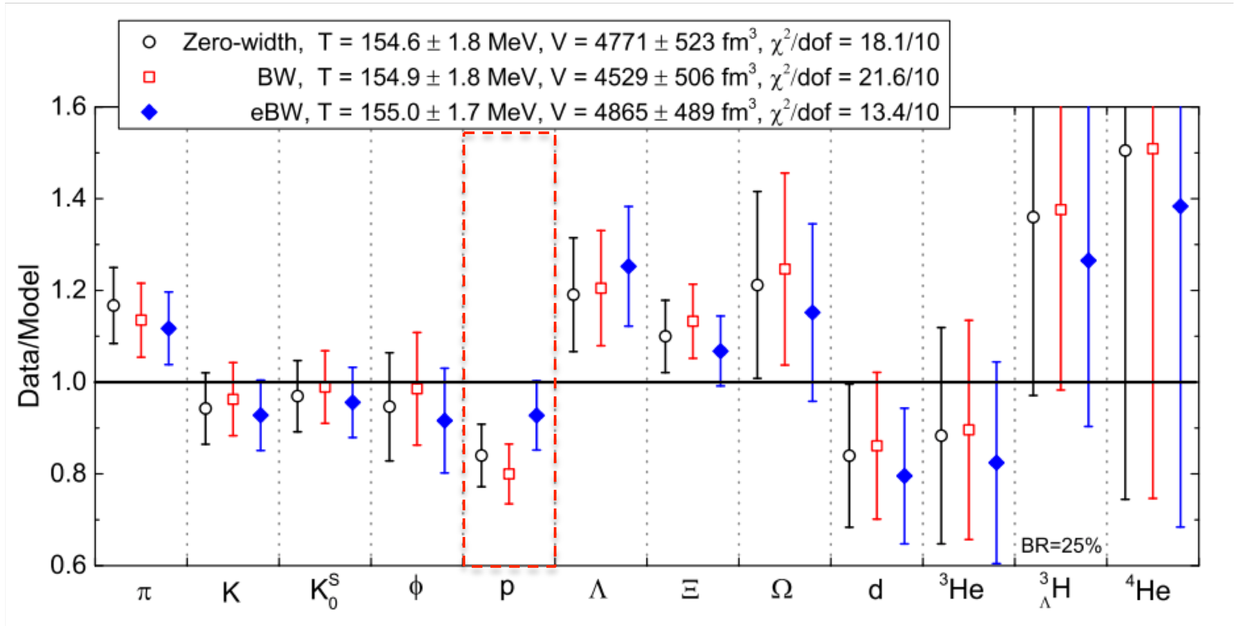




Towards understanding the thermal proton anomaly

The role of the finite resonance width



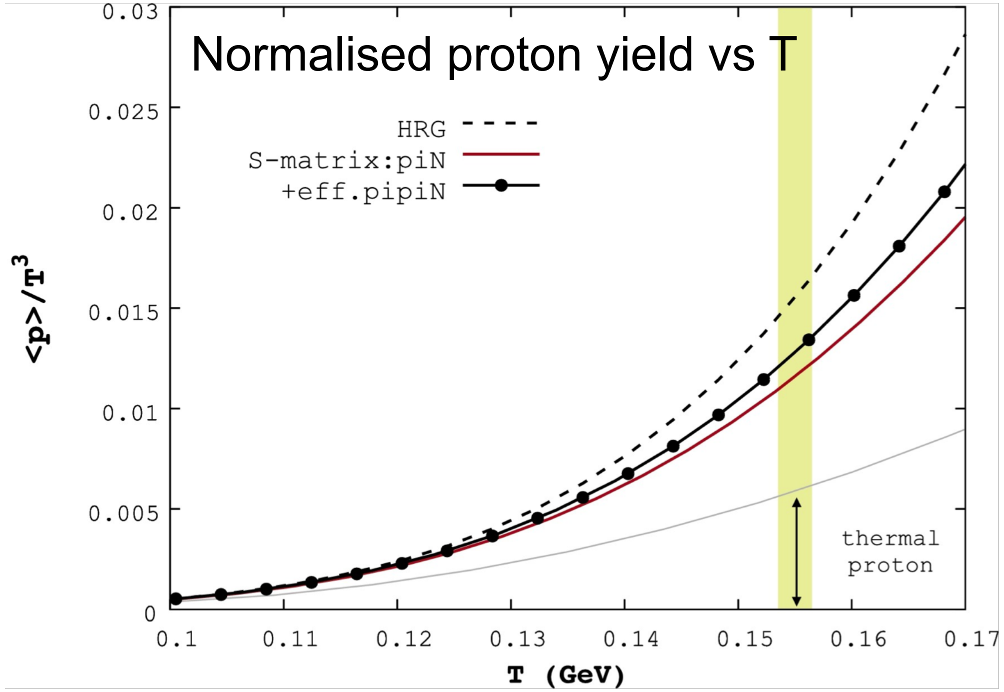


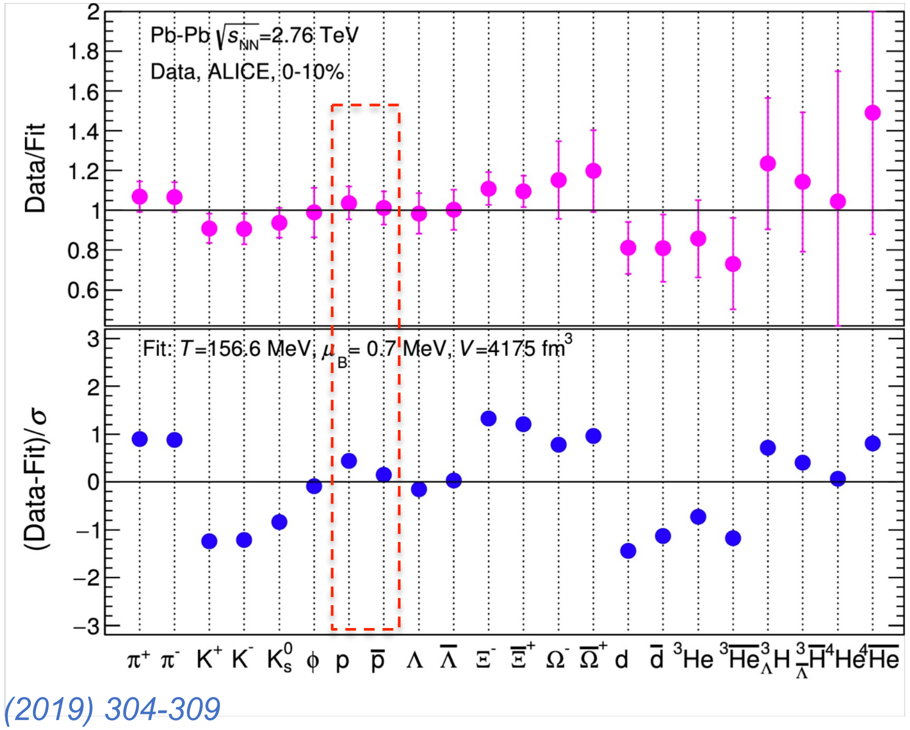
V. Vovchenko et al. PRC 98 (2018) 034906

The thermodynamical observables are sensitive to the low-mass tail of resonances, due the Boltzmann factor.
The application of the energy-dependent Breit-Wigner scheme helps the thermal model description of the p/π ratio by reducing the p feeddown from near-threshold *Δ*'s.

Towards understanding the thermal proton anomaly

The role of resonant and non-resonant πN and ππN interactions





A. Andronic et al., PLB 792 (2019) 304-309

The inclusion of the resonant and non-resonant πN and ππN interactions via the S-matrix formalism has the net effect of reducing by 17% (1%) the proton (pion) yield with respect the HRG case. More specifically, πN reduces the proton, ππN tends to increase it.

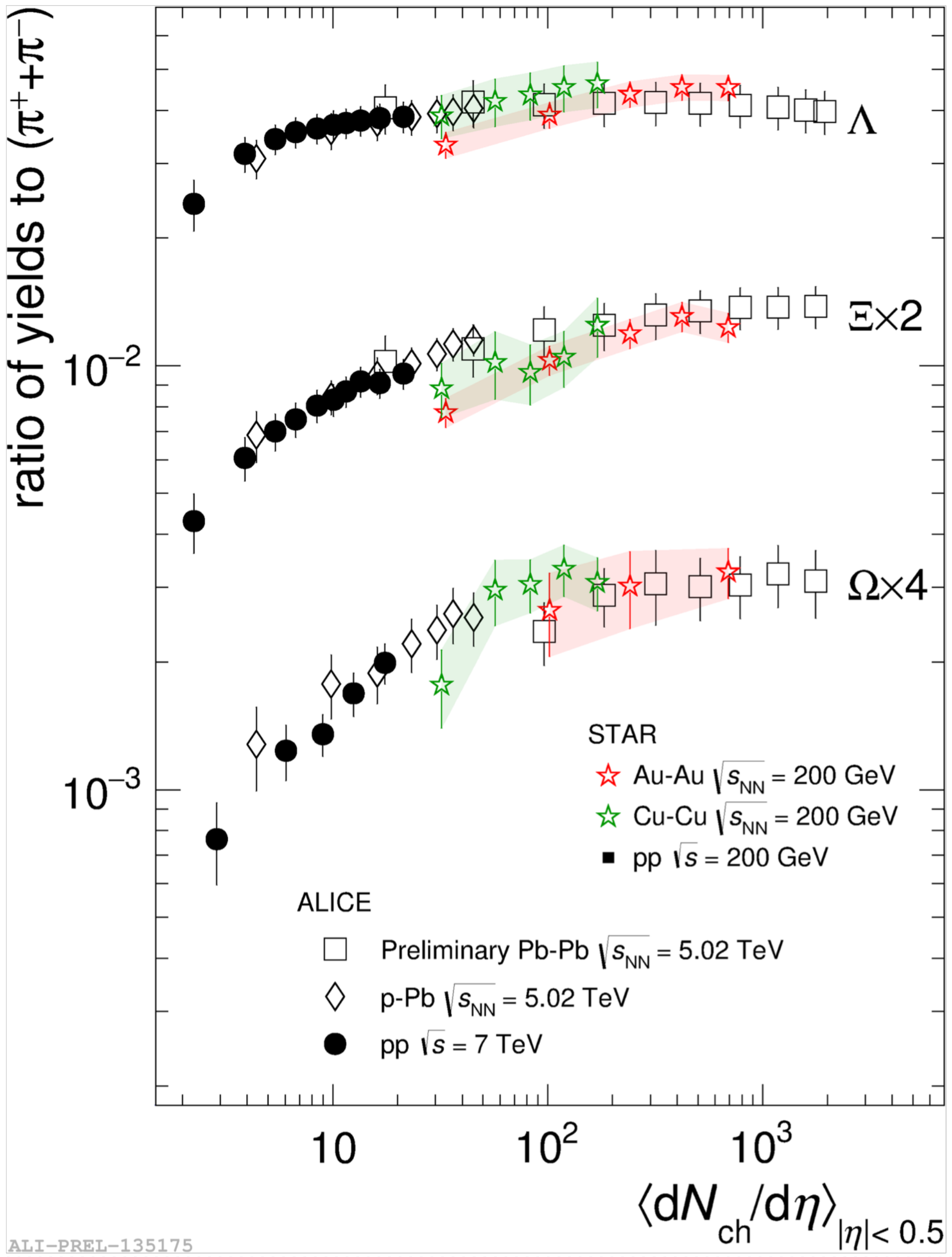
⟶ Improved agreement between p ALICE data and thermal model after this correction.

Strangeness enhancement

The modern way:
multiplicity dependence of yield relative to π

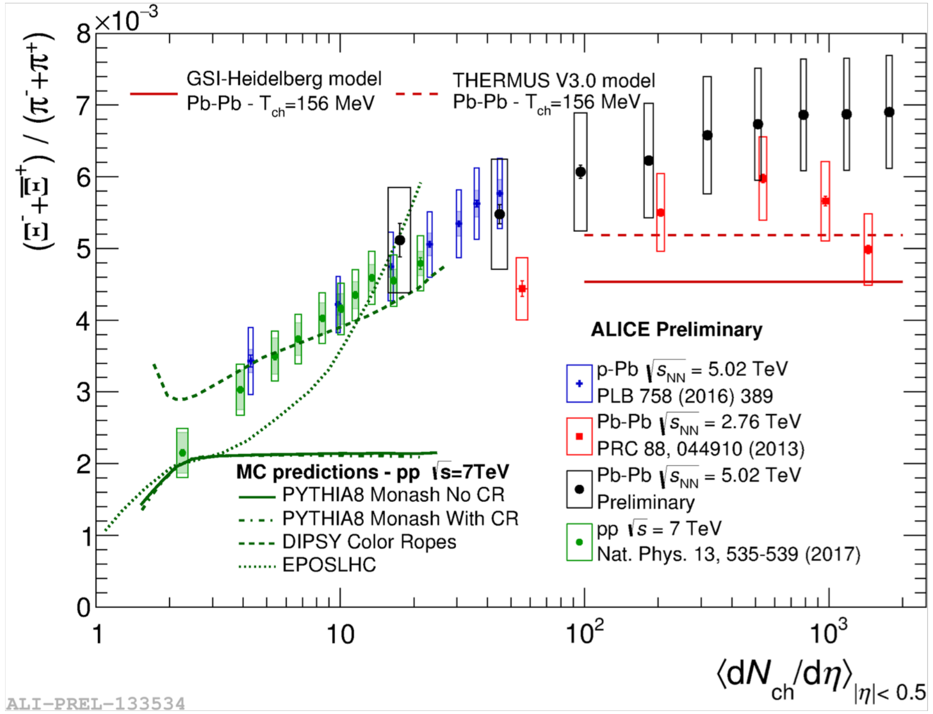
Strangeness enhancement from pp to p-Pb, to A-A depends on multiplicity.

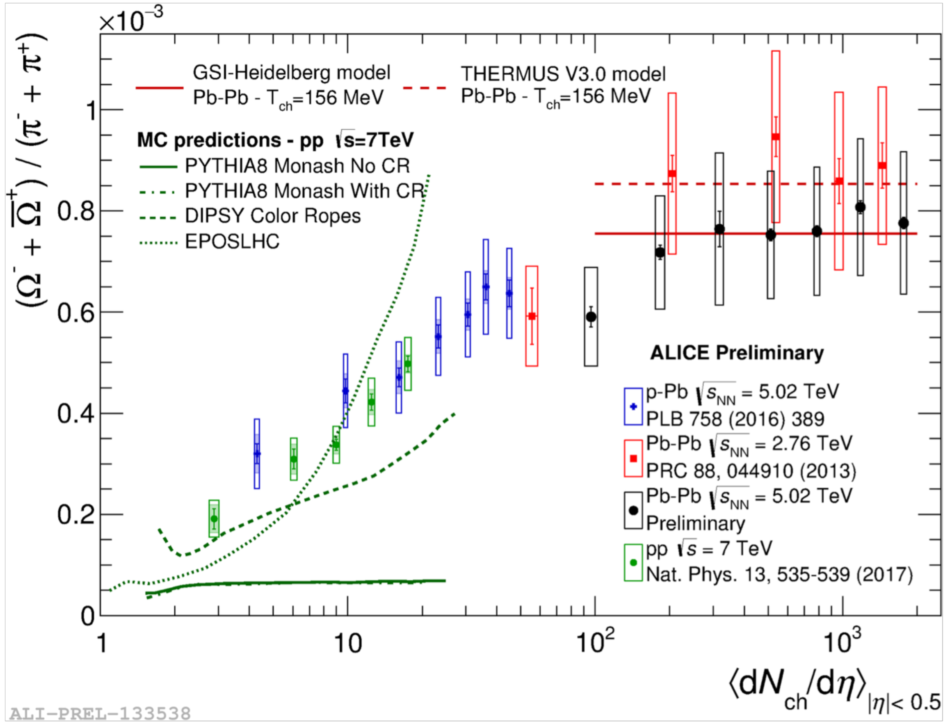
Do the RHIC BES measurements fit in this picture if plotted vs dN/dη?



pp 7 TeV: Nat. Phys. 13 (2017) 535-539
p-Pb 5 TeV: PLB 728 (2014) 25-38, PLB 758 (2016) 389-401
Au-Au 200 GeV: PRL 98 (2007) 62301
Cu-Cu 200 GeV: PRL 108, 072301

A closer look to strangeness in central AA



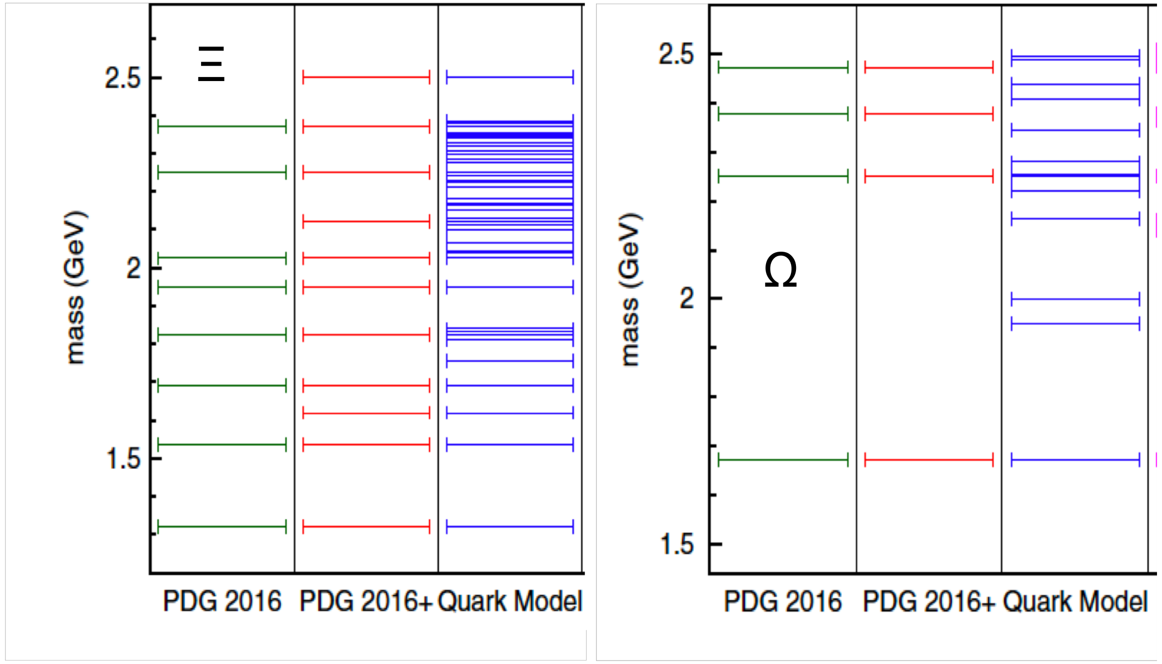


In central Pb-Pb collisions, most recent Ξ/π data lie above the GC plateau, while Ω/π is consistent with the thermal model expectations.

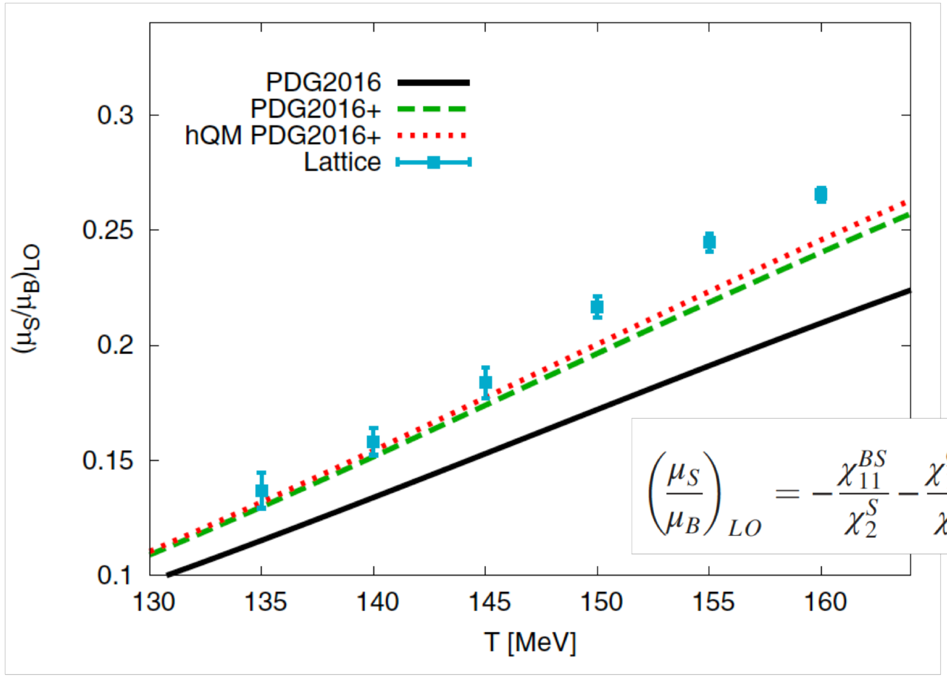
→ Difference between 2.76 TeV and 5.02 TeV for Ξ/π is being addressed by ALICE by means of a re-analysis of the data: stay tuned!

Towards understanding of multi-strange

The role of possible higher mass strange resonances in HRG



P. Alba at al. PRD 96, 034517 (2017)



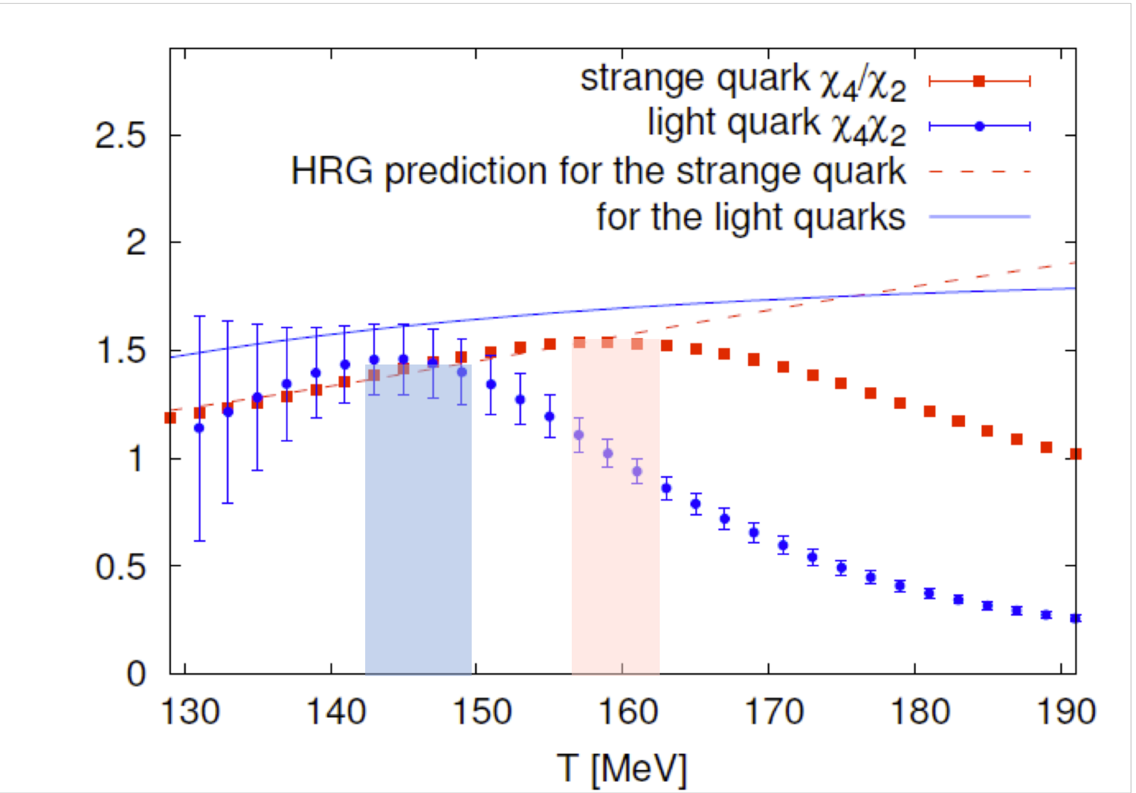
$$\left(\frac{\mu_S}{\mu_B}\right)_{LO} = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B}$$

A comparison between lQCD and the hadron resonance gas (HRG) model suggests the existence of missing strange resonances, i.e. not yet detected, or not yet fully established.

→ Higher mass baryonic states would need experimental verification with searches at RHIC and/or at LHC.

Towards understanding of multi-strange

Indication of sequential hadronisation from lQCD



R. Bellwied, PRL 111, 202302 (2013)

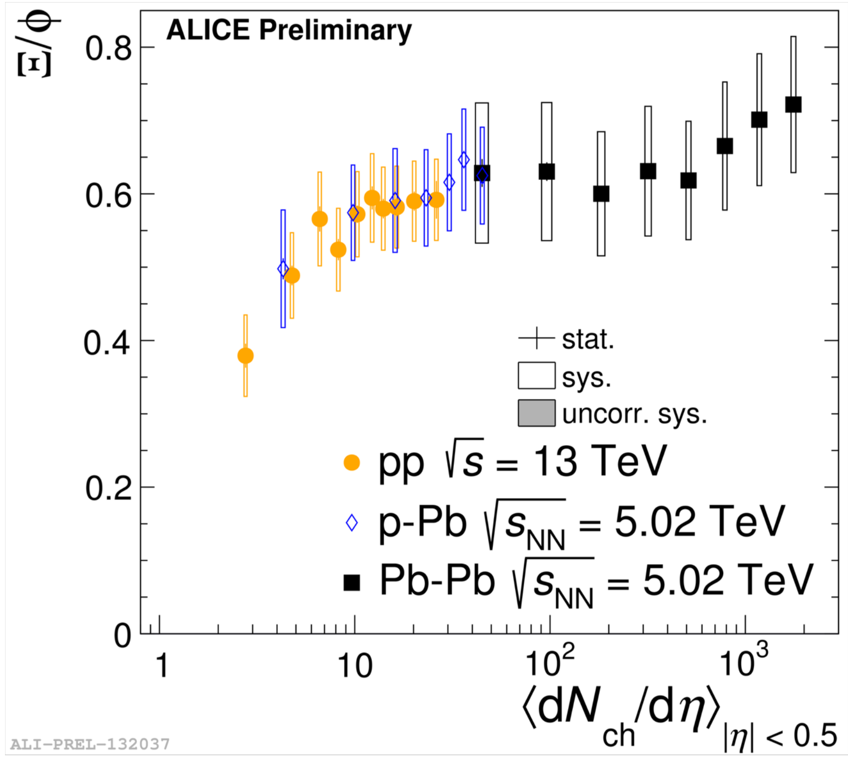
Indication of sequential hadronisation of light (u,d) and strange quarks comes from the ratio of even-even cumulants (which, at first order, is determined by the freeze-out temperature near $\mu_B = 0$).

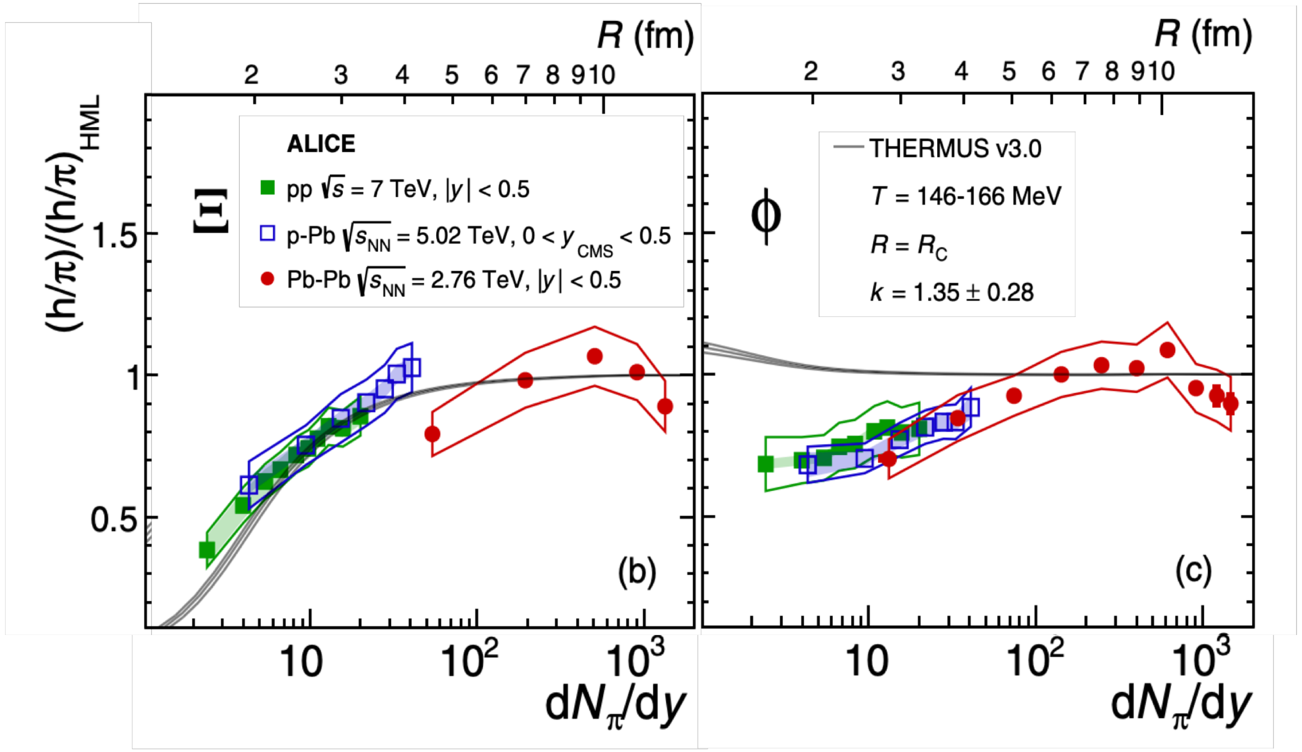
Light quarks would prefer a lower temperature, strange would prefer a higher temperature.

⟶ More measurements (net-kaon, net-lambda, …) needed to address this

⟶ More in the parallel sessions!

The pivotal role of ϕ meson



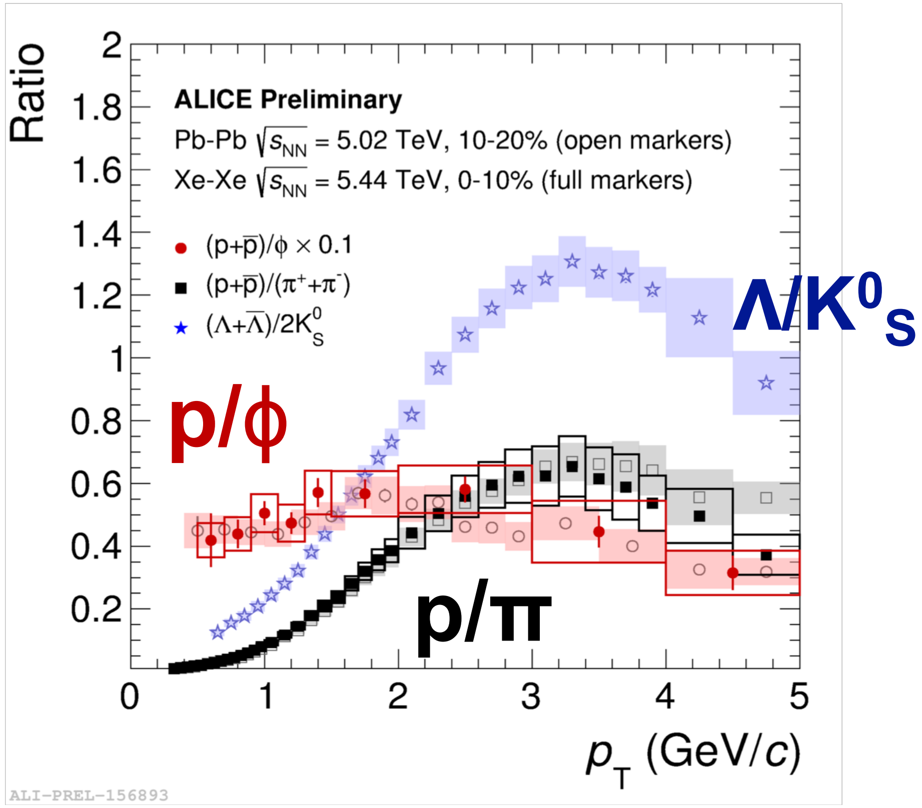


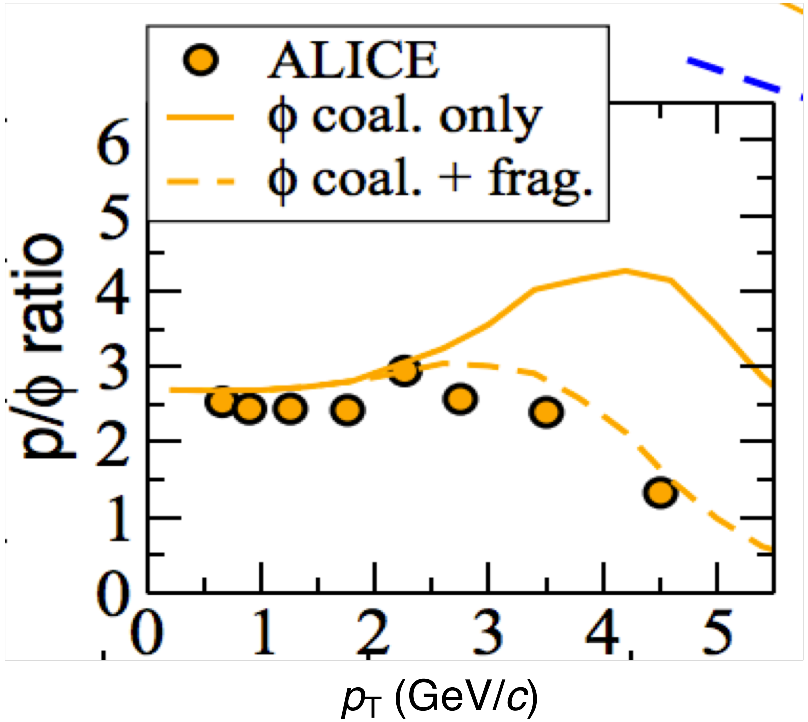
ALICE, PRC 99, 024906 (2019)

From the measured multiplicity-dependence of ϕ/π, the behavior of ϕ meson is between that of a S=1 and a S=2 particle.

ϕ is the exception that does not fit in the canonical suppression picture that describe all other measured LF and strange hadrons from small to large systems.

The pivotal role of ϕ meson



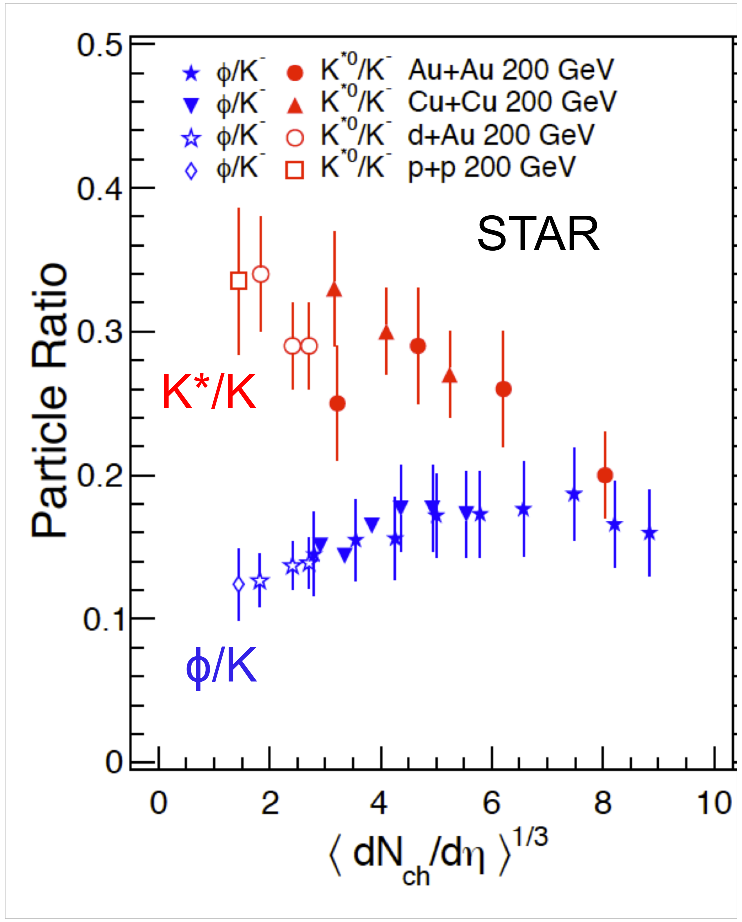


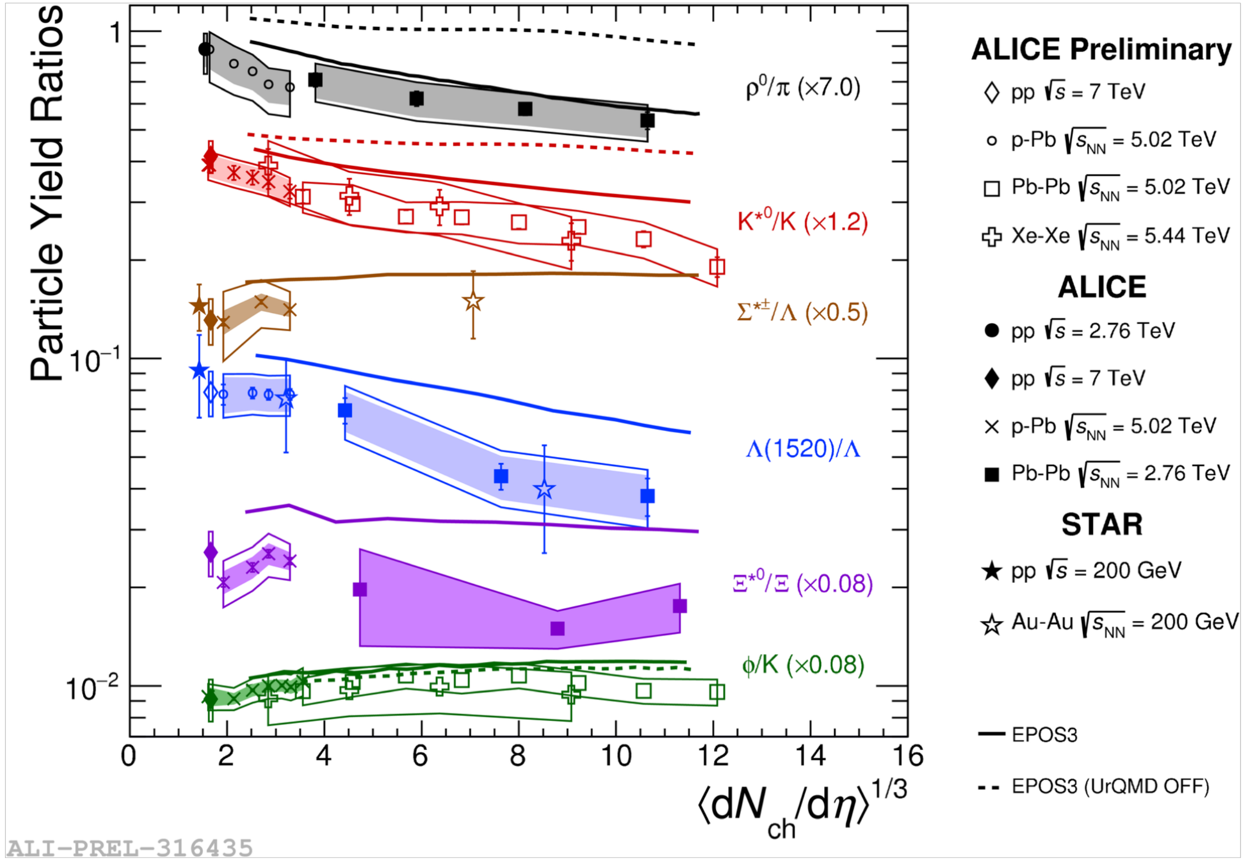
V. Greco at al, PRC 92 (2015) 054904

Having similar mass as the proton, the ϕ meson can be used to investigate the interplay of flow and recombination / fragmentation.

⟶ Still an open point on whether recombination or flow determine the spectral shape at intermediate p_{T}

Resonance suppression in central AA collisions



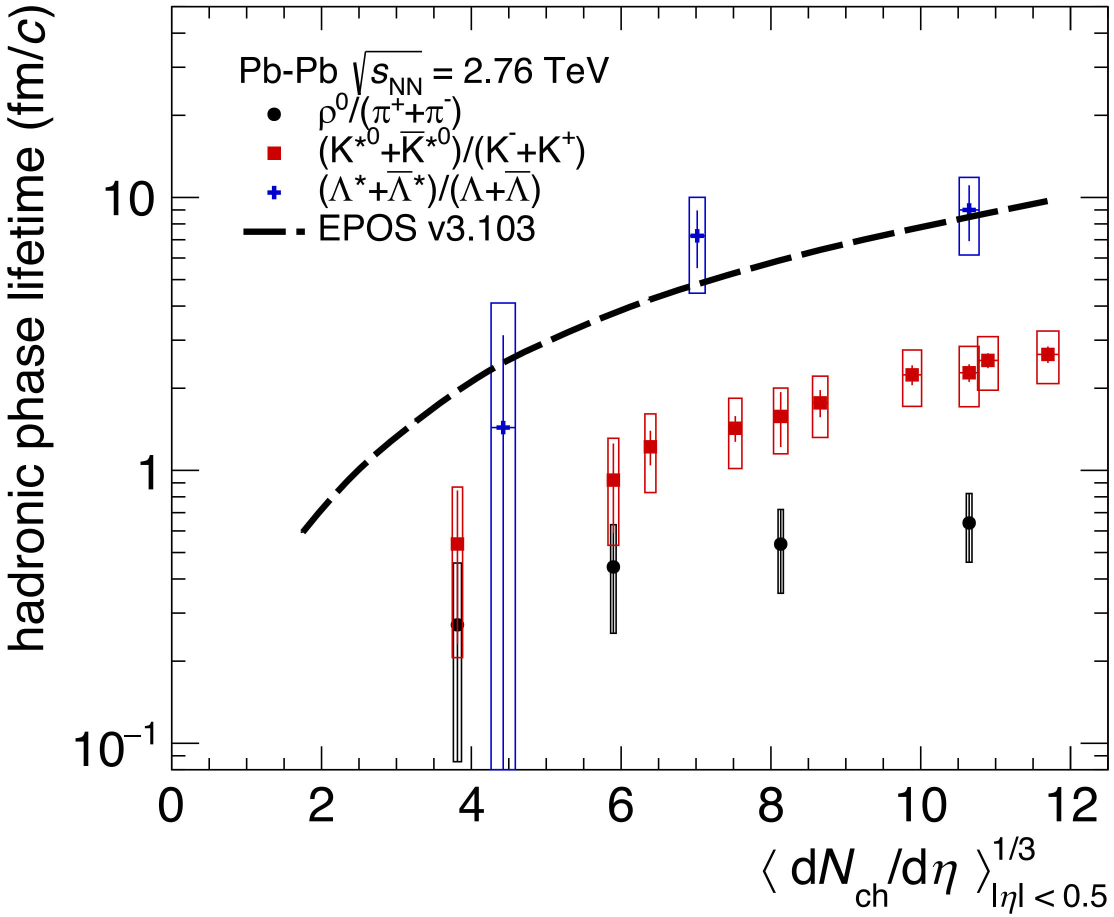


Consistent results on short-lived resonance suppression at RHIC and LHC provides evidence for long-lasting hadronic phase in central AA collisions.

⟶ More in A. Knospe's talk

Effect qualitatively reproduced by EPOS with UrQMD to model rescattering and regeneration.

Lifetime of the hadronic phase



ALICE: PRC 69, 064901 (2019), PRC 99, 024905 (2019), PRC 95, 064606 (2017), PRC 91, 024609 (2015)
EPOS: A. Knospe et al., PRC 93, 014911 (2016)

Rough estimate of the hadronic phase lifetime from ALICE data, ignoring regeneration:

$$ratio_{cent} = ratio_{pp} e^{-\frac{t}{\tau_x}} \qquad ratio_{cent} = \frac{dN_x/dy}{dN_{ll}/dy}$$

$\tau(\rho)$ = 1.3 fm/c < $\tau(K^*)$ = 4.5 fm/c < $\tau(\Lambda^*)$ = 12.5 fm/c

Consistent with the hadronic phase lifetime from UrQMD, which includes rescattering and regeneration.

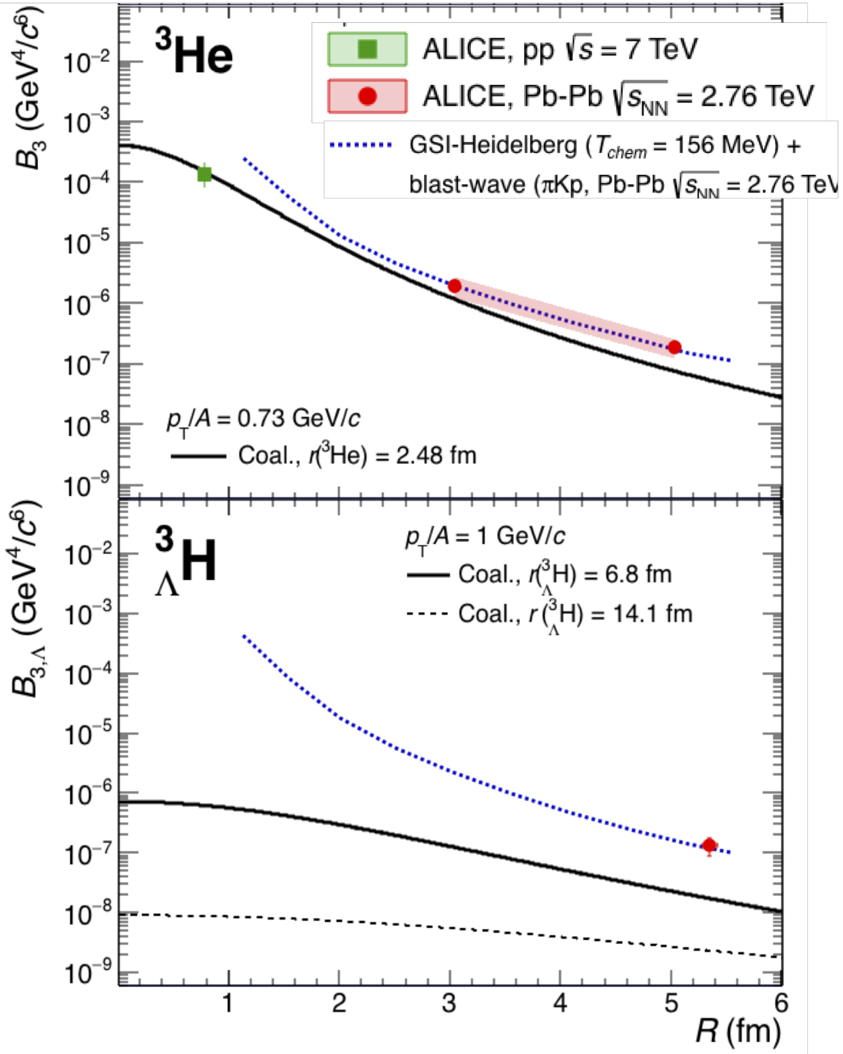
→ Measure Σ(1385), which is expected to undergo significant regeneration.

“Fragile” objects: production and survival

(Anti-)nuclei puzzle:
how can loosely-bound states (B_E ~ 1 MeV) produced at chemical freeze-out survive the hadronic phase (156 MeV < T < 100 MeV)?

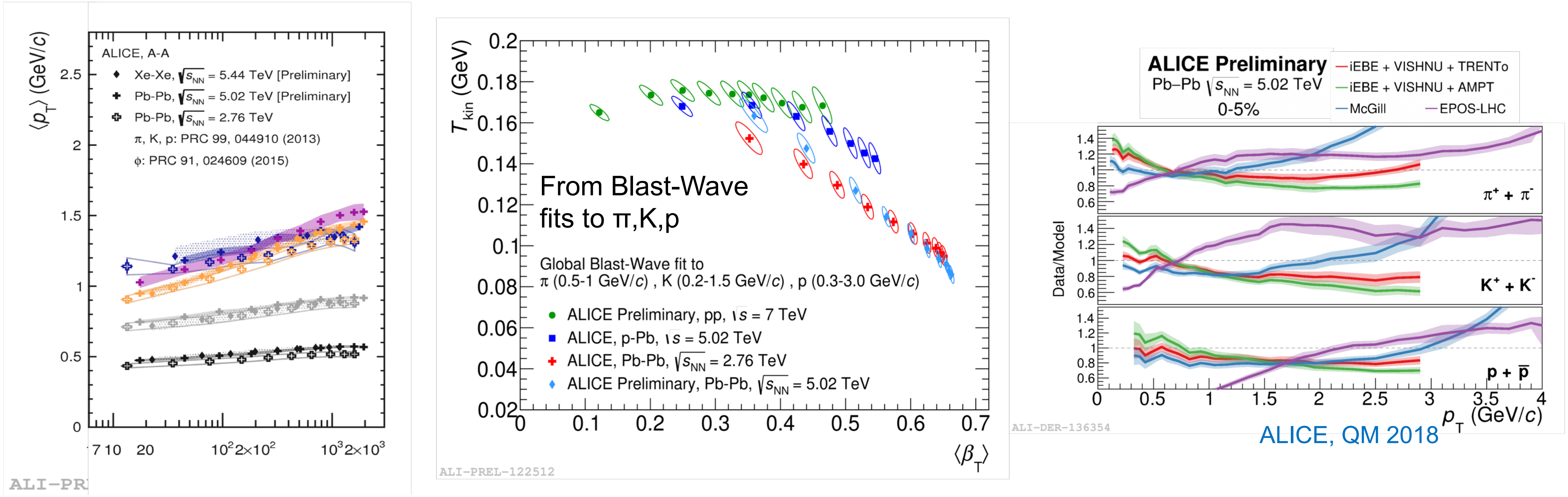
Production via coalescence of nucleons at kinetic freeze-out? Other explanations?
⟶ More in D. Ollinychenko’s talk

⟶ Experimentally to be addressed with multiplicity-dependent measurements of different nucleus species



FB, A. Kalweit, PRC 99, 054905 (2019)

Collectivity manifested by radial and elliptic flow



Larger radial flow velocity for central Pb-Pb collisions, centrality dependence and mass scaling of mean p_T are consistent with the hydrodynamic picture.

Direct comparison with “full-hydro” models and EPOS reveals a typical agreement within 20-30% with hydrodynamical predictions, which worsens towards more peripheral collisions.

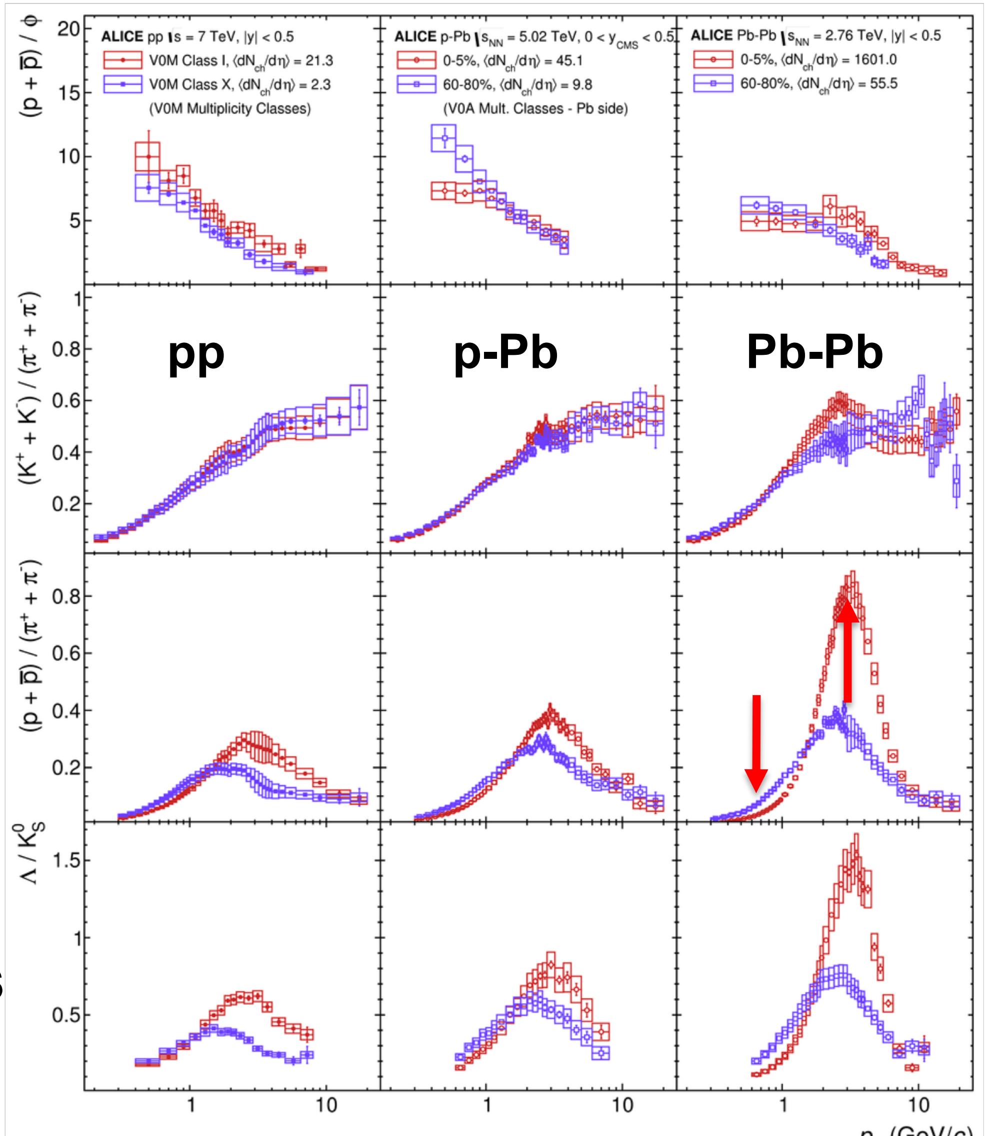
Radial flow affects baryon/meson production

p/ϕ

K/π

p/π

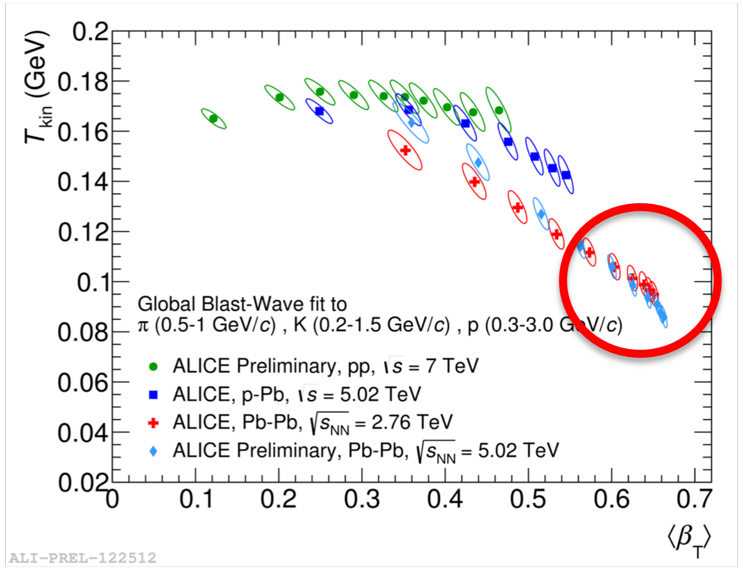
Λ/K^0_S



ALICE, PRC 99, 024906 (2019)

Baryon-to-meson (B/M) ratios evolve from **low multiplicity** to **high multiplicity** events similarly across collision systems.

Baryon anomaly:
enhancement of B/M at intermediate p_T and depletion at low p_T

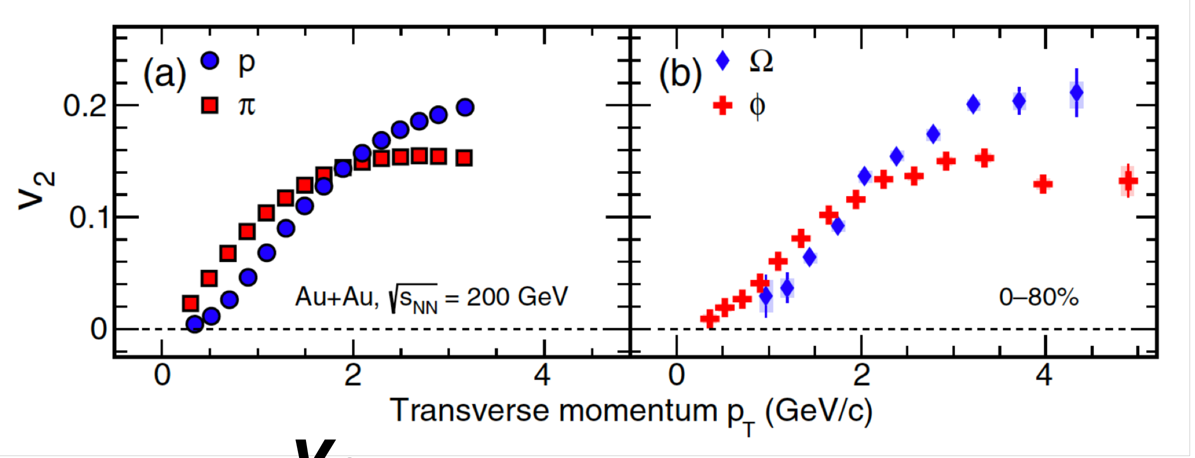


Strongest radial flow (β_T) in central Pb-Pb collisions

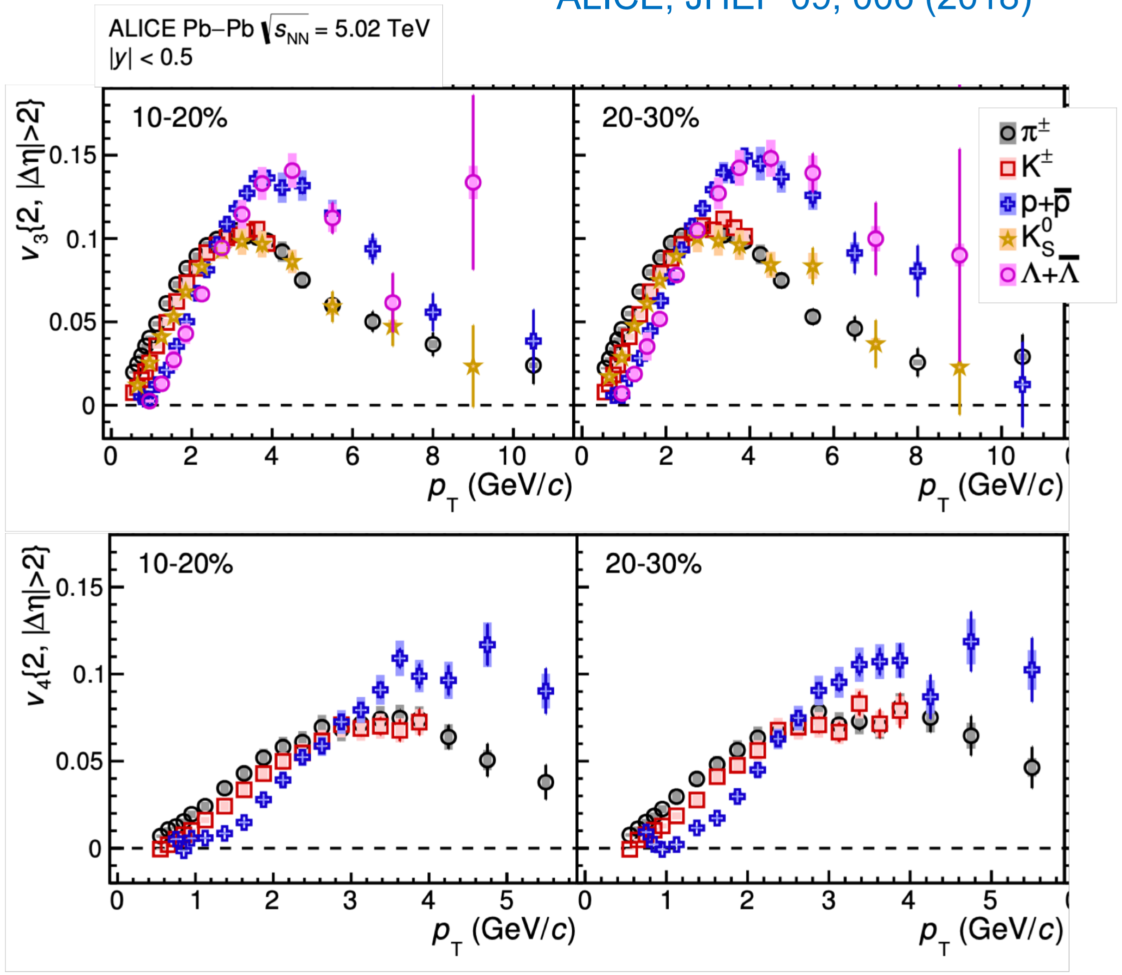
⟶ More in F. Prino's talk

Collectivity manifested by radial and elliptic flow

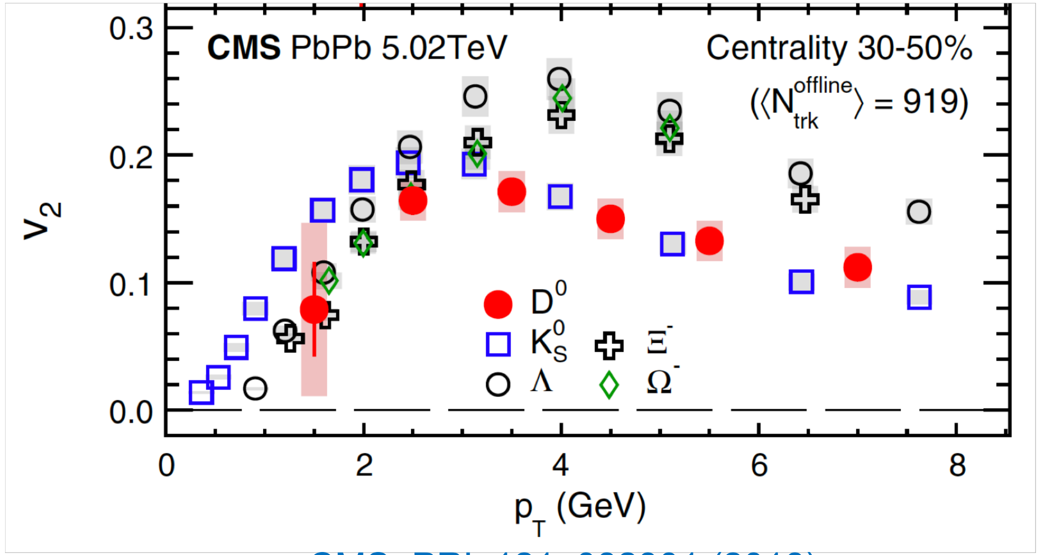
STAR, PRL 116, 062301 (2016)



ALICE, JHEP 09, 006 (2018)



v_2



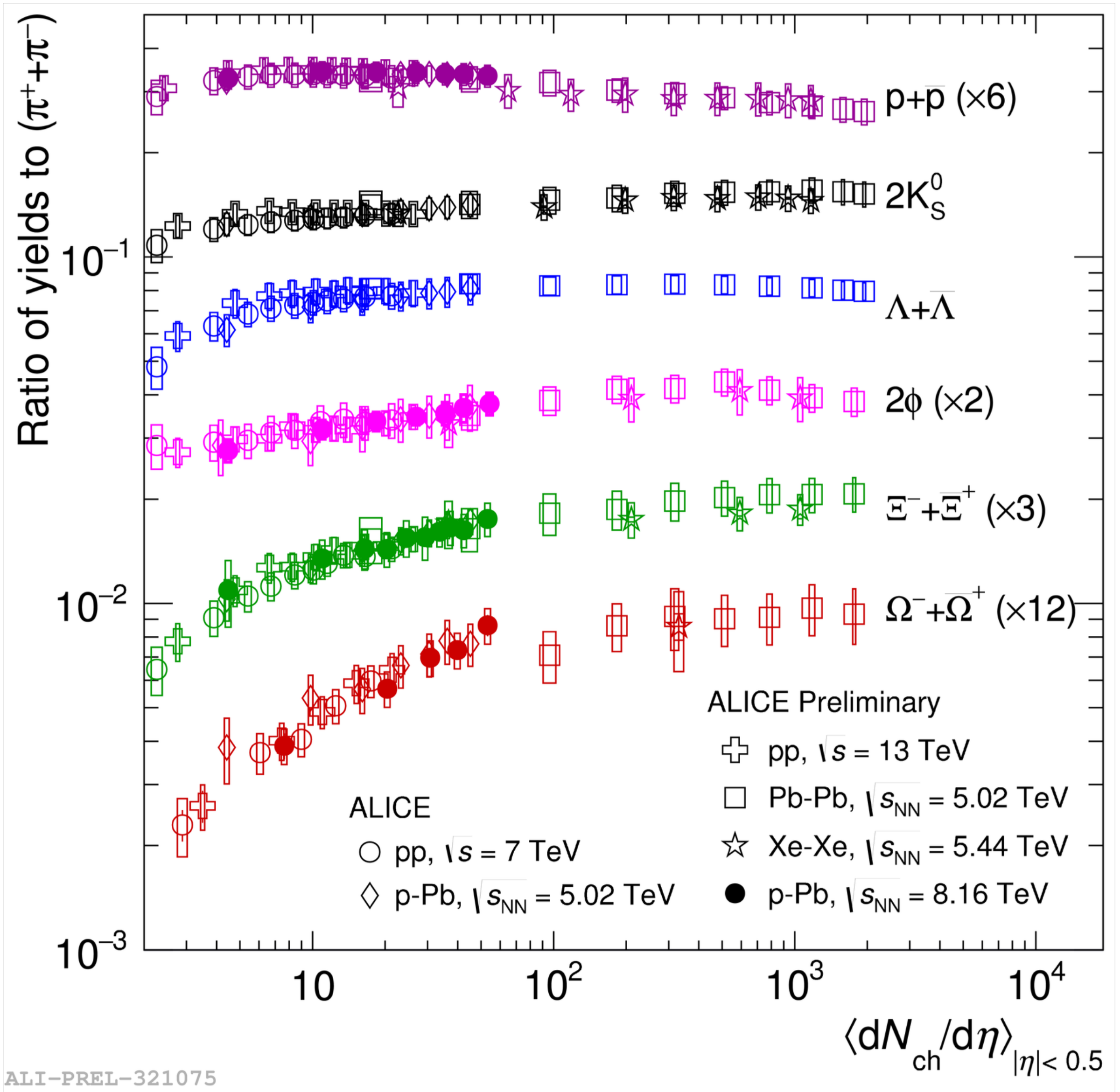
CMS, PRL 121, 082301 (2018)

Outlook to small systems

The smooth multiplicity-dependent evolution of particle chemistry (and signatures for collective behaviour) across systems might be pointing at a common hadron production mechanism.

Advocates for a unification of the theoretical description under a “small-to-large” or “large-to-small” paradigm.

A point of no return (?)



⟶ more in talk by R. Preghenella on Fri.

Instead of a summary of a selection, some open questions….

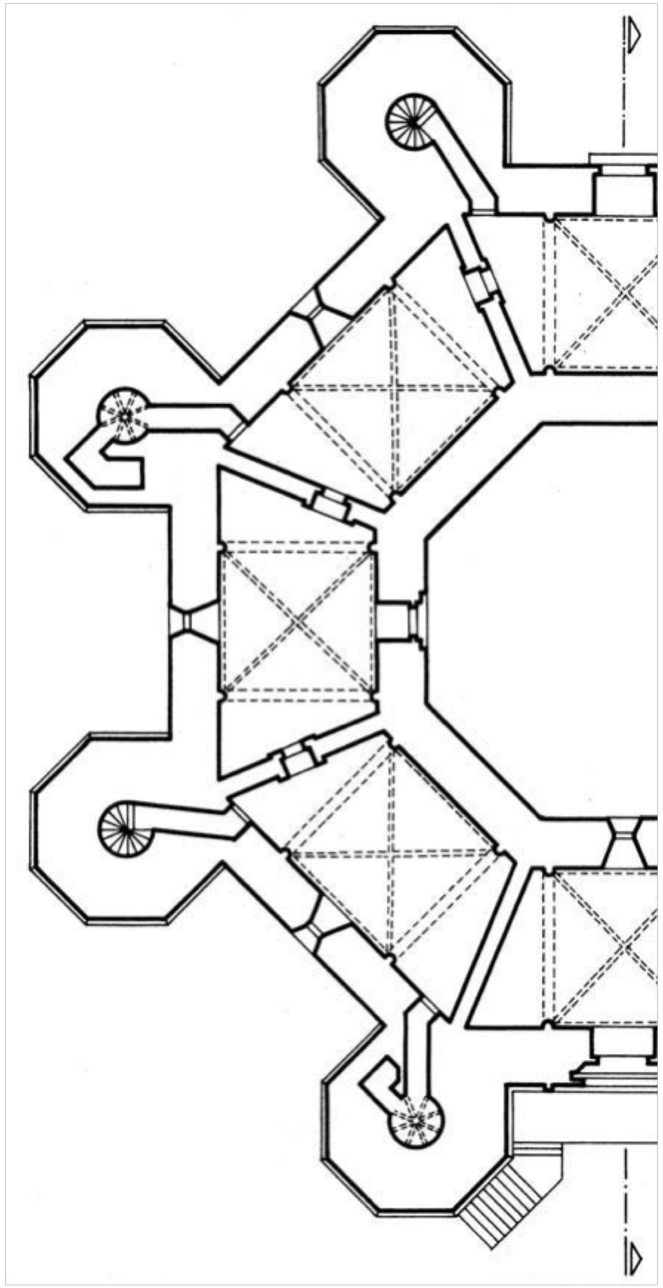
Chemical composition and equilibrium of particle species
⟶ Do we understand the deviations from the SHM?
Have we reached the limit of precision of the SHM?

"Strangeness enhancement" implies understanding the pp reference
⟶ Do we understand the multiplicity dependence?
MC generators, canonical suppression, two-component models…

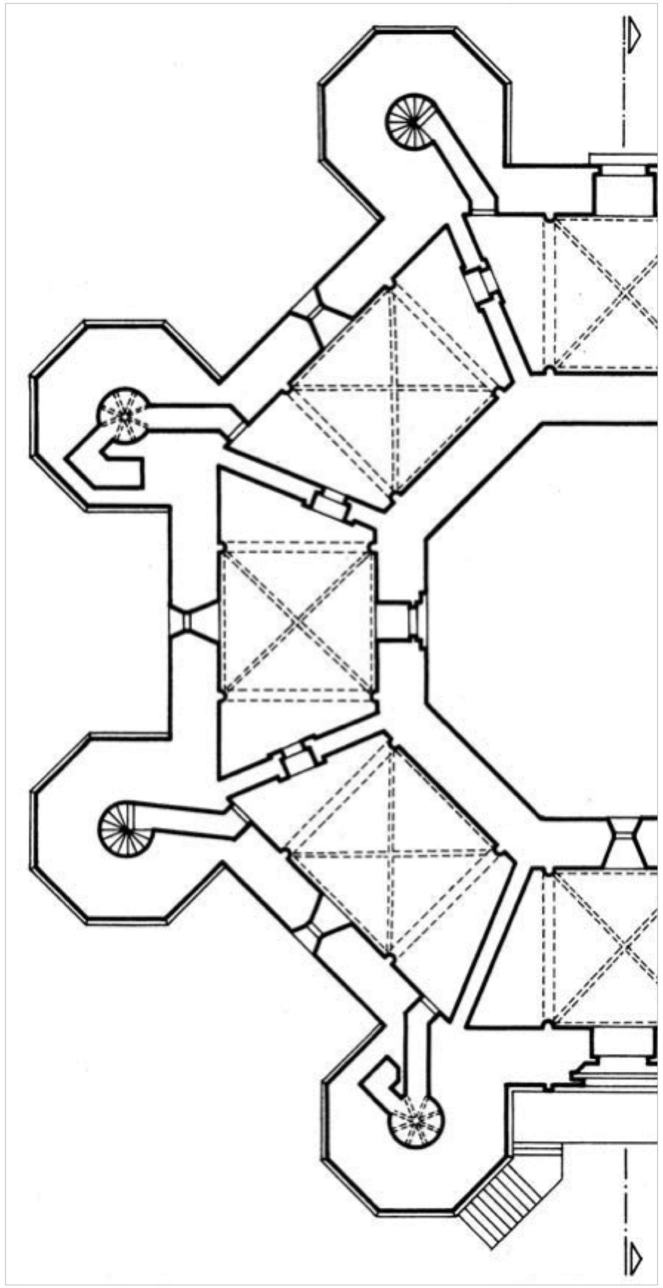
Collectivity and flow
⟶ Do these have the same origin in small and large systems?
How does the system reach equilibration?

Composite, fragile objects
⟶ How can they survive the hadronic phase?

Production mechanisms: baryon/meson
⟶ Have we settled the issue with recombination?



Thank you!



The 18th International Conference on

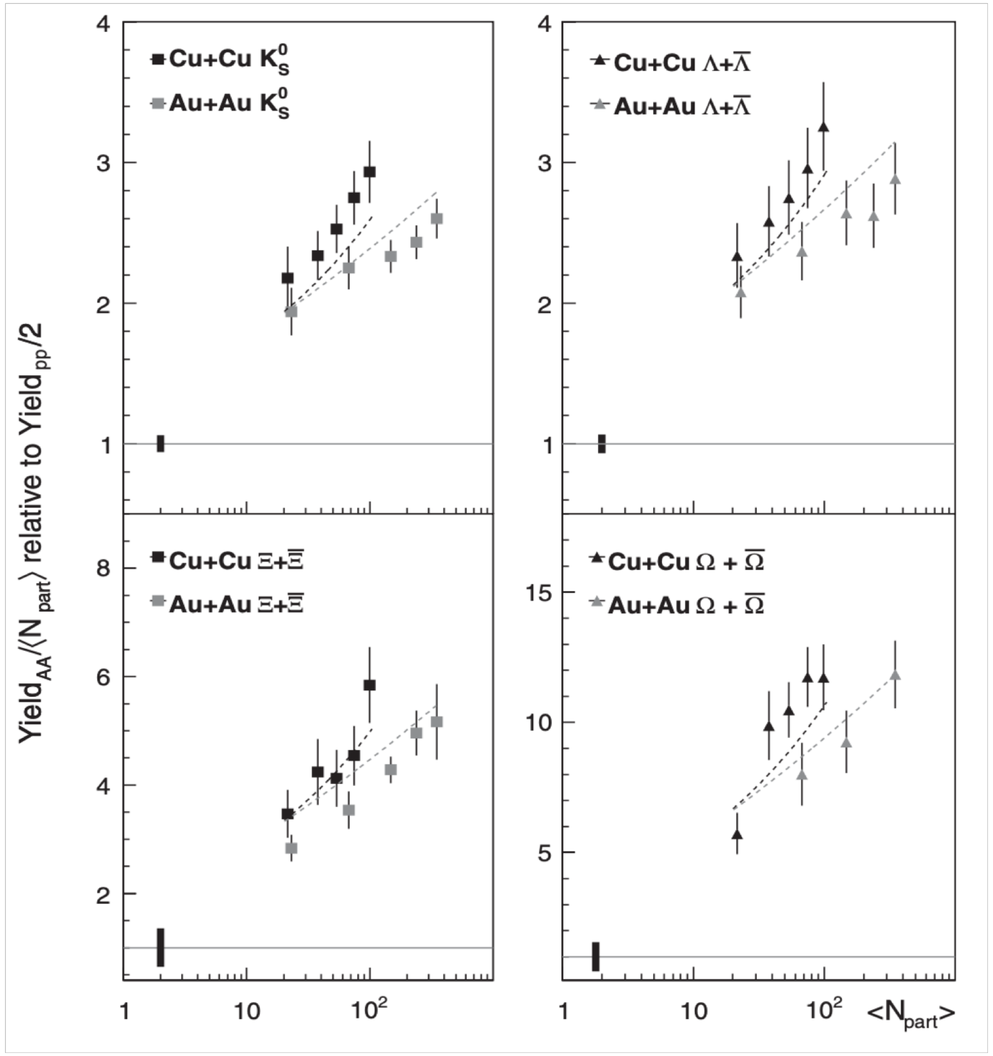
Strangeness in Quark Matter (SQM 2019)

10-15 June 2019, Bari (Italy)

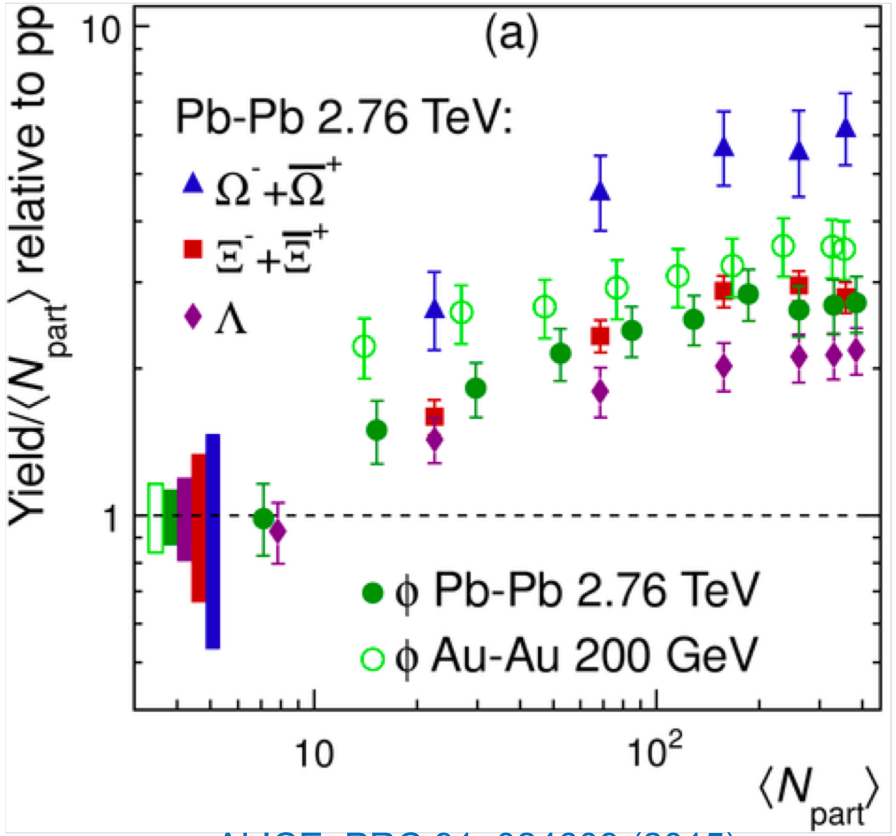
Contact: Francesca.Bellini@cern.ch

Strangeness enhancement

The historical way: yield in AA relative to pp

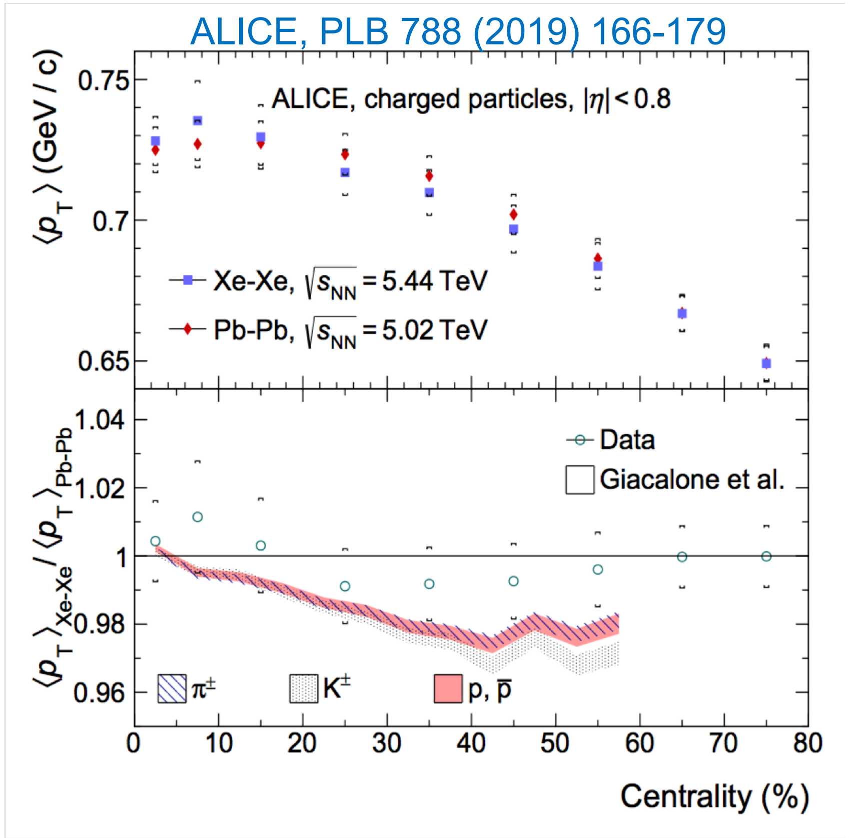


STAR, PRL 108, 072301 (2012)



ALICE, PRC 91, 024609 (2015)

System geometry dependence

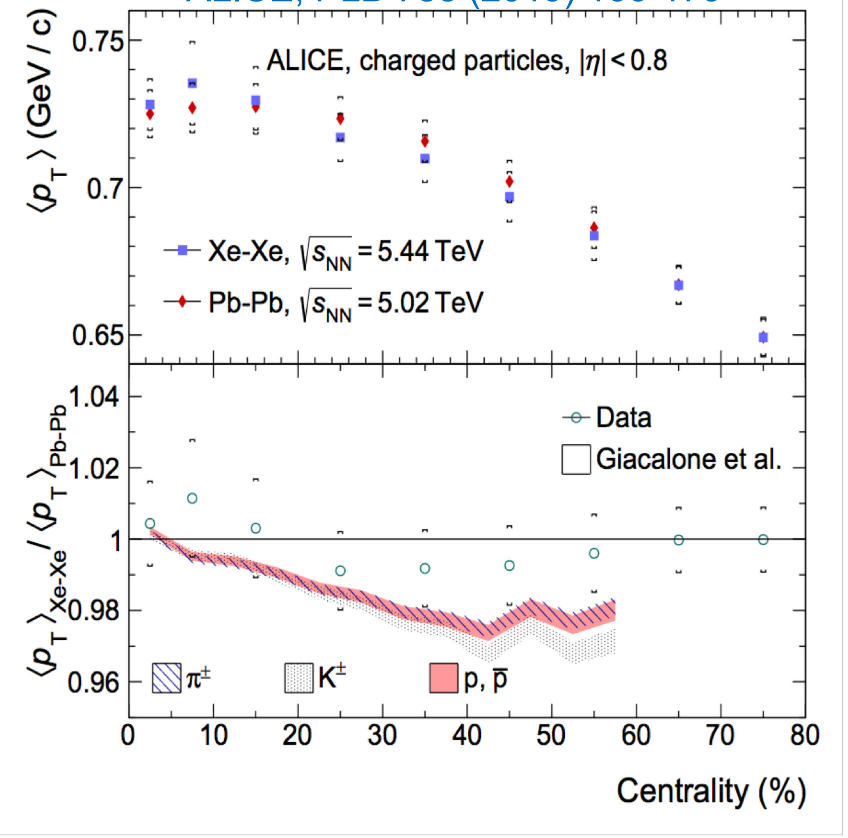


Weak dependence of $\langle p_T \rangle$ on centrality in AA collisions and mass scaling, but small (O(3%)) difference between Xe-Xe and Pb-Pb, as predicted by hydrodynamics.

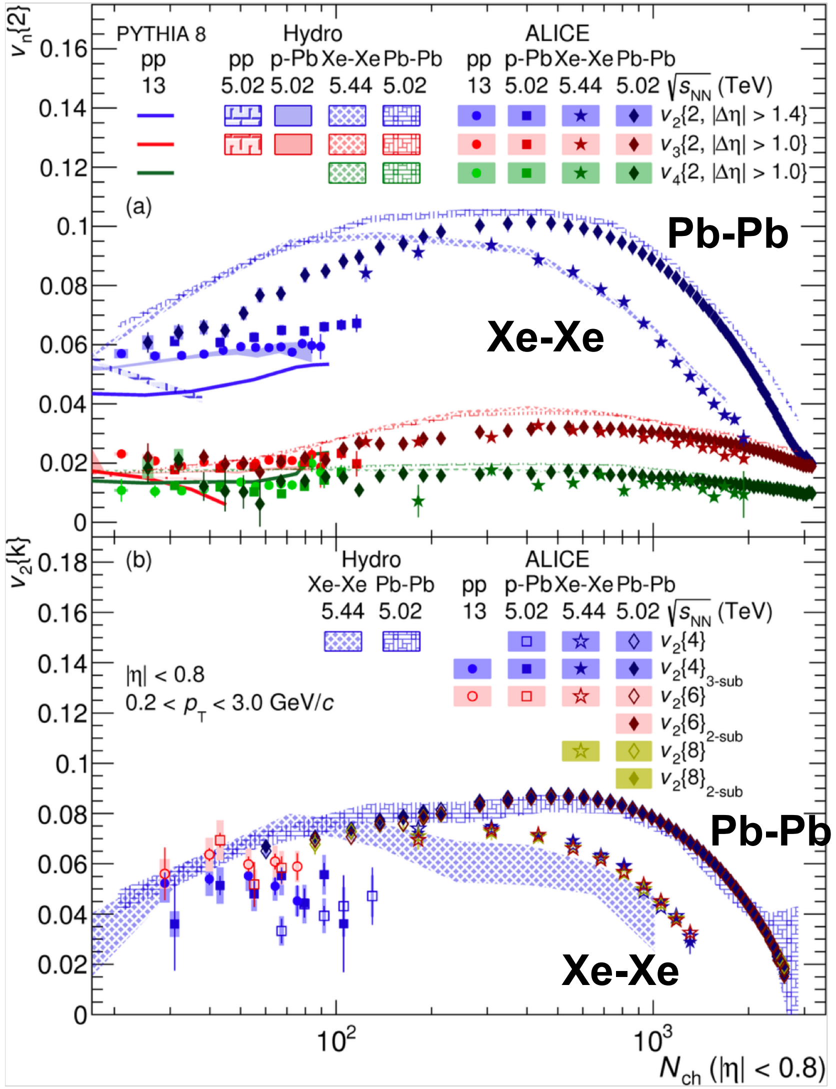
Hydro prediction from G. Giacalone et al., PRC 97, 034904 (2018)

System geometry dependence

ALICE, PLB 788 (2019) 166-179



ALICE, arXiv:1903.01790



The multiplicity and system-geometry dependence of v2{k} is captured by hydro (IP-Glasma+MUSIC+UrQMD) in AA collisions, but not in small systems.