Strangeness –
What is it still good for ?

R. Bellwied (University of Houston)

WWND 2017, January 8-15, 2017, Snowbird, Utah, USA

Outline

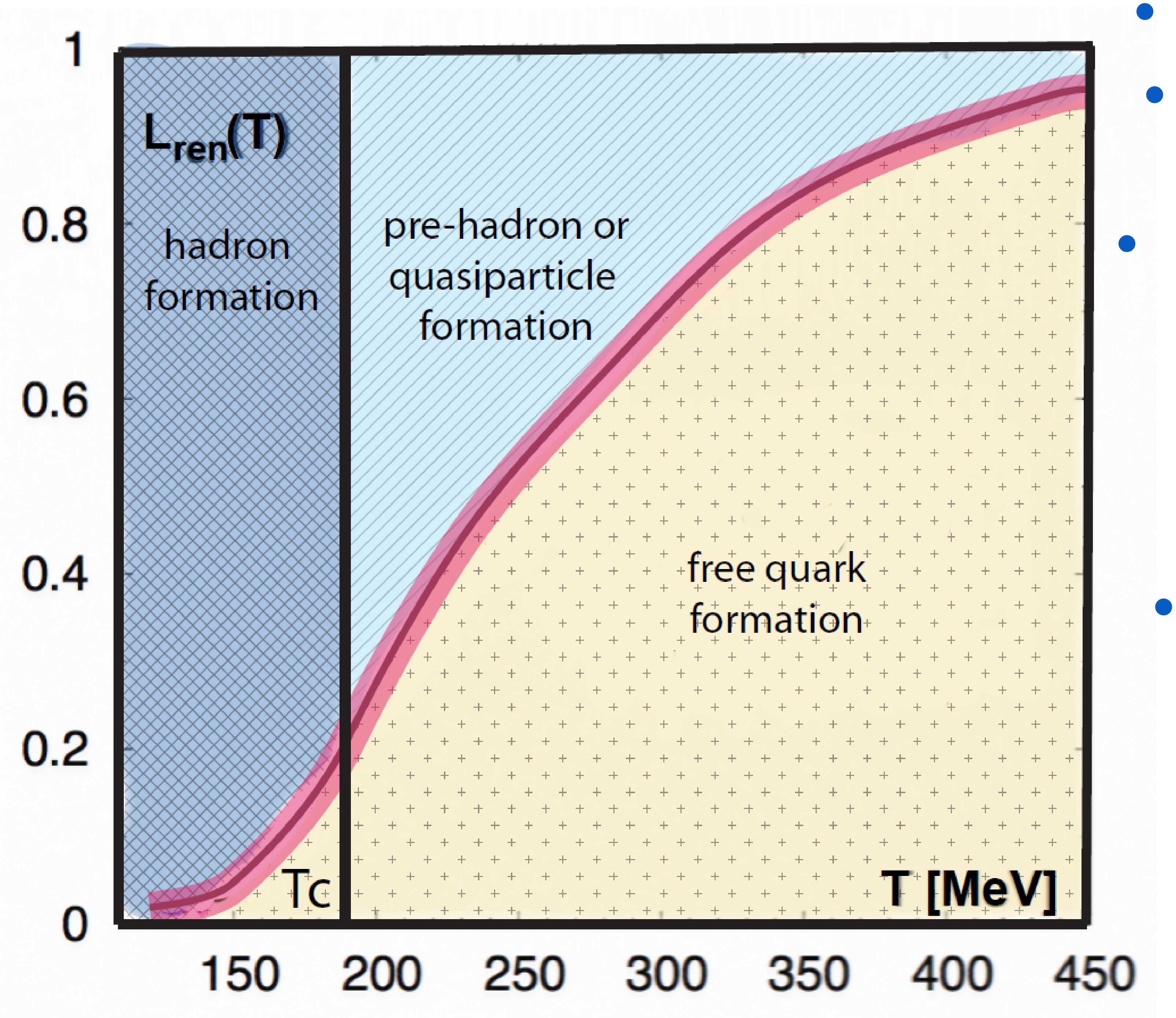
- Theoretical motivation in a nutshell
  - The role of flavor during the QCD transition
  - Evidence for sequential hadronization
  - Clusters, Hagedorn States, Resonances, Quasi-particles

- Experimental results from RHIC and LHC
  - Strange hadronic resonances
  - Hypermatter (not shown)
  - Multi-quark states (strangeness vs. charm)

- Where do we go from here
  - Fluctuation measurements to confirm sequential hadronization
  - Resonance and multi-quark states searches in pp, pA, AA

Lattice order parameters in the QCD cross-over

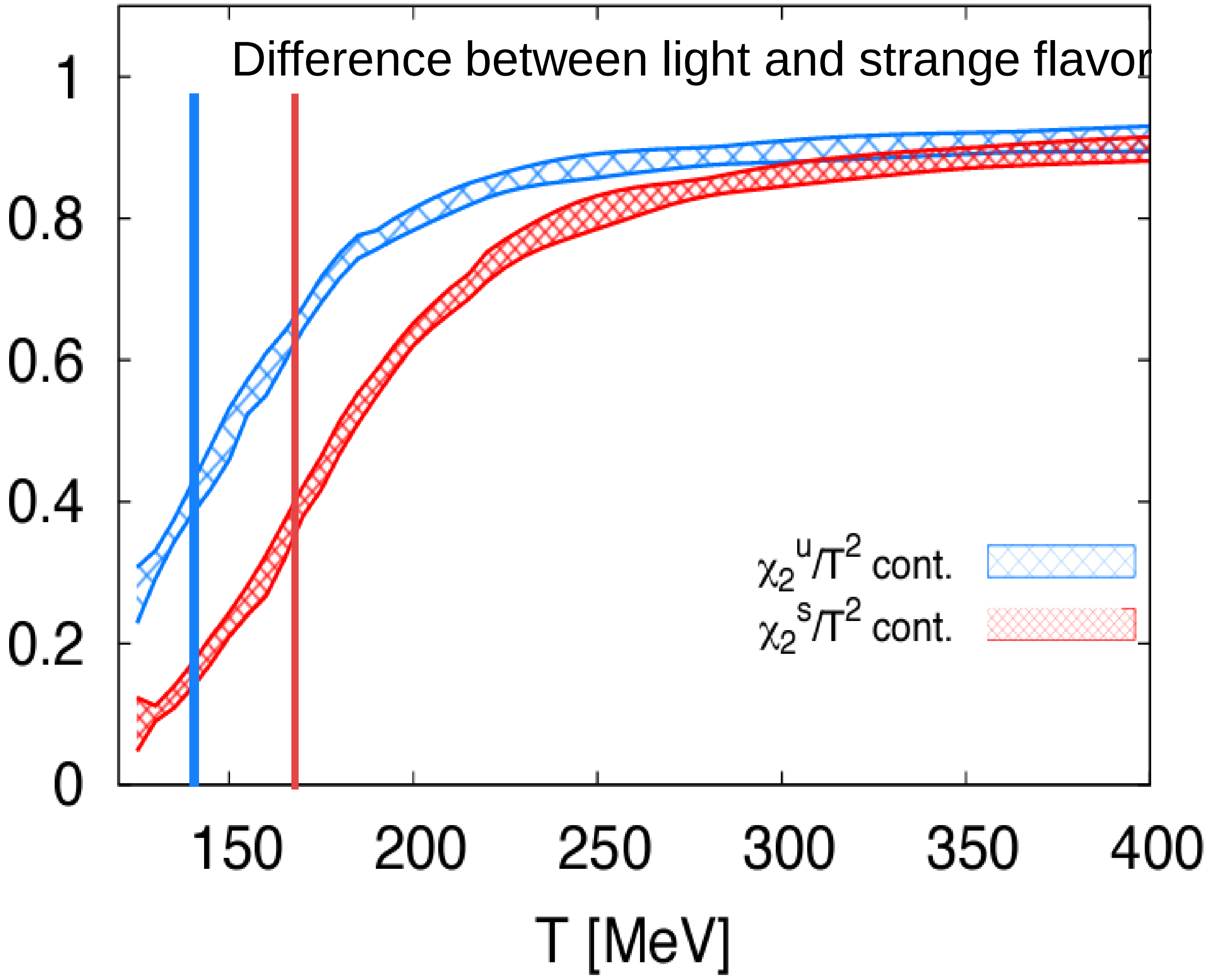
e.g. a re-interpretation of the Polyakov Loop calculation in lattice QCD



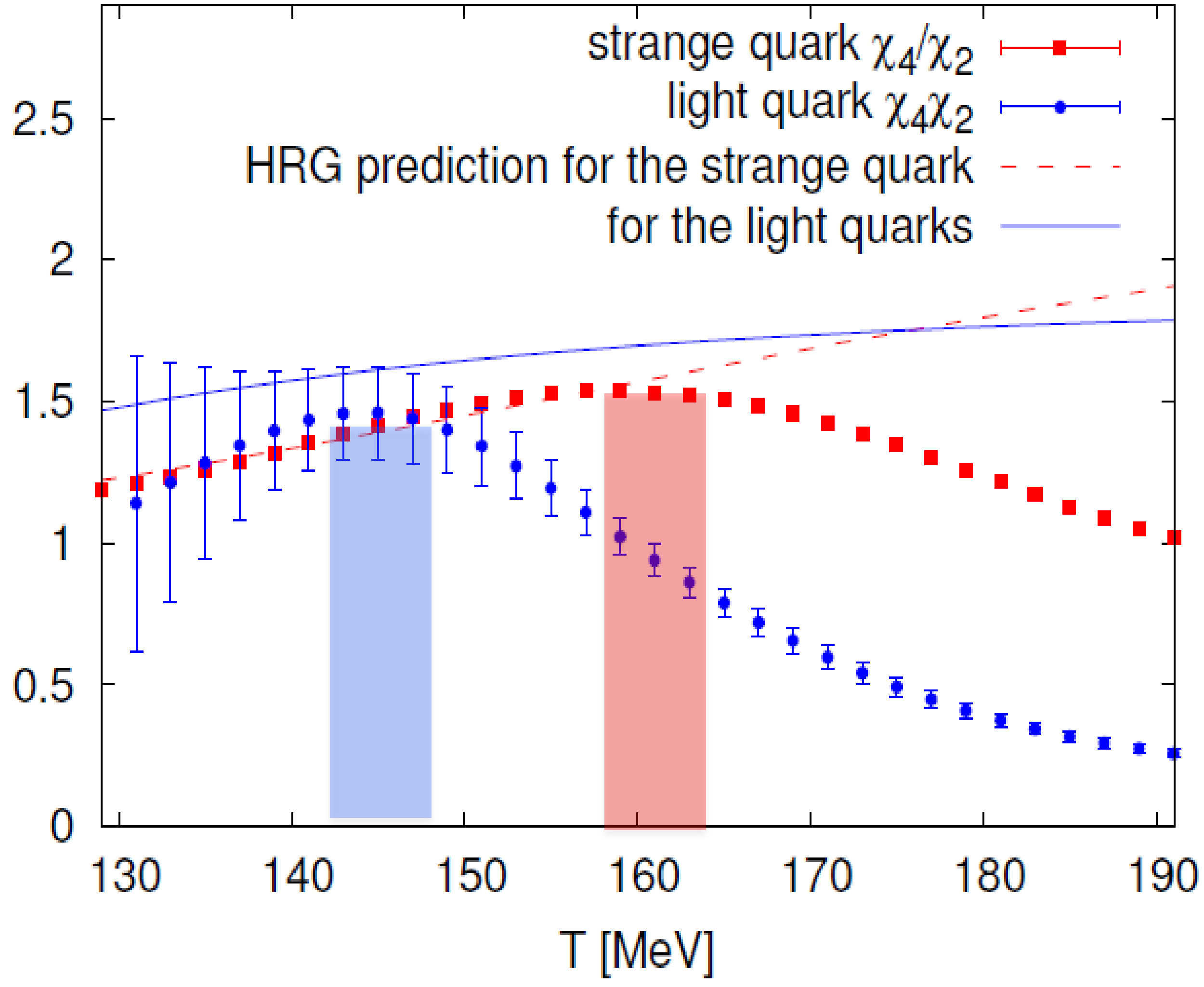
RB, C. Markert, PLB691 (2010) 208
Data: Bazavov et al., arXiv:1105:1131

- The semi-QGP (Pisarski et al.)
- Possible monopoles, possible bound states (Shuryak et al.)
- Contributions from bound states to partial pressure above T_c at least for charm states (Petreczky et al.)
- <u>In a regime where we have a smooth crossover why would there be a single freeze-out surface, if quark masses (even for the s-quark) play a role ?</u>
- We can calculate thermodynamic quantities for a static equilibrated system at a fixed temperature

Indication of flavor dependence in susceptibilities and susceptibility ratios



C. Ratti et al., PRD 85, 014004 (2012)
R. Bellwied, arXiv:1205.3625



R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

<u>Indication of</u>

<u>sequential hadronization ?</u>

$$\kappa_B\sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)}\left[\frac{1+\frac{1}{2}\frac{\chi_6^B(T)}{\chi_4^B(T)}(\mu_B/T)^2+\ldots}{1+\frac{1}{2}\frac{\chi_4^B(T)}{\chi_2^B(T)}(\mu_B/T)^2+\ldots}\right]$$

Susceptibilities on the lattice map to measureable moments of the multiplicity distribution

In a thermally equilibrated system we can define susceptibilities χ as 2nd derivative of pressure with respect to chemical potential (1st derivative of ρ).

Starting from a given partition function we define the fluctuations of a set of conserved charges as:

$$\frac{p}{T^4} = \frac{\ln \mathcal{Z}}{VT^3} \qquad \chi^{BSQ}_{lmn} = \frac{\partial^{l+m+n}\left(p/T^4\right)}{\partial\left(\mu_B/T\right)^l \partial\left(\mu_S/T\right)^m \partial\left(\mu_Q/T\right)^n}$$

The fluctuations of conserved charges are related to the moments of the multiplicity distributions of the same charge measured in HIC.

$$\delta N = N - \langle N \rangle$$

mean: $M = \langle N \rangle = VT^3\chi_1,$

variance: $\sigma^2 = \langle(\delta N)^2\rangle = VT^3\chi_2,$

skewness: $S = \dfrac{\langle(\delta N)^3\rangle}{\sigma^3} = \dfrac{VT^3\chi_3}{(VT^3\chi_2)^{3/2}},$

kurtosis: $k = \dfrac{\langle(\delta N)^4\rangle}{\sigma^4} - 3 = \dfrac{VT^3\chi_4}{(VT^3\chi_2)^2};$

Measurable ratios:

$$R_{32} = S\sigma = \frac{\chi_3^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

$$R_{42} = K\sigma^2 = \frac{\chi_4^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

To measure μ_B:

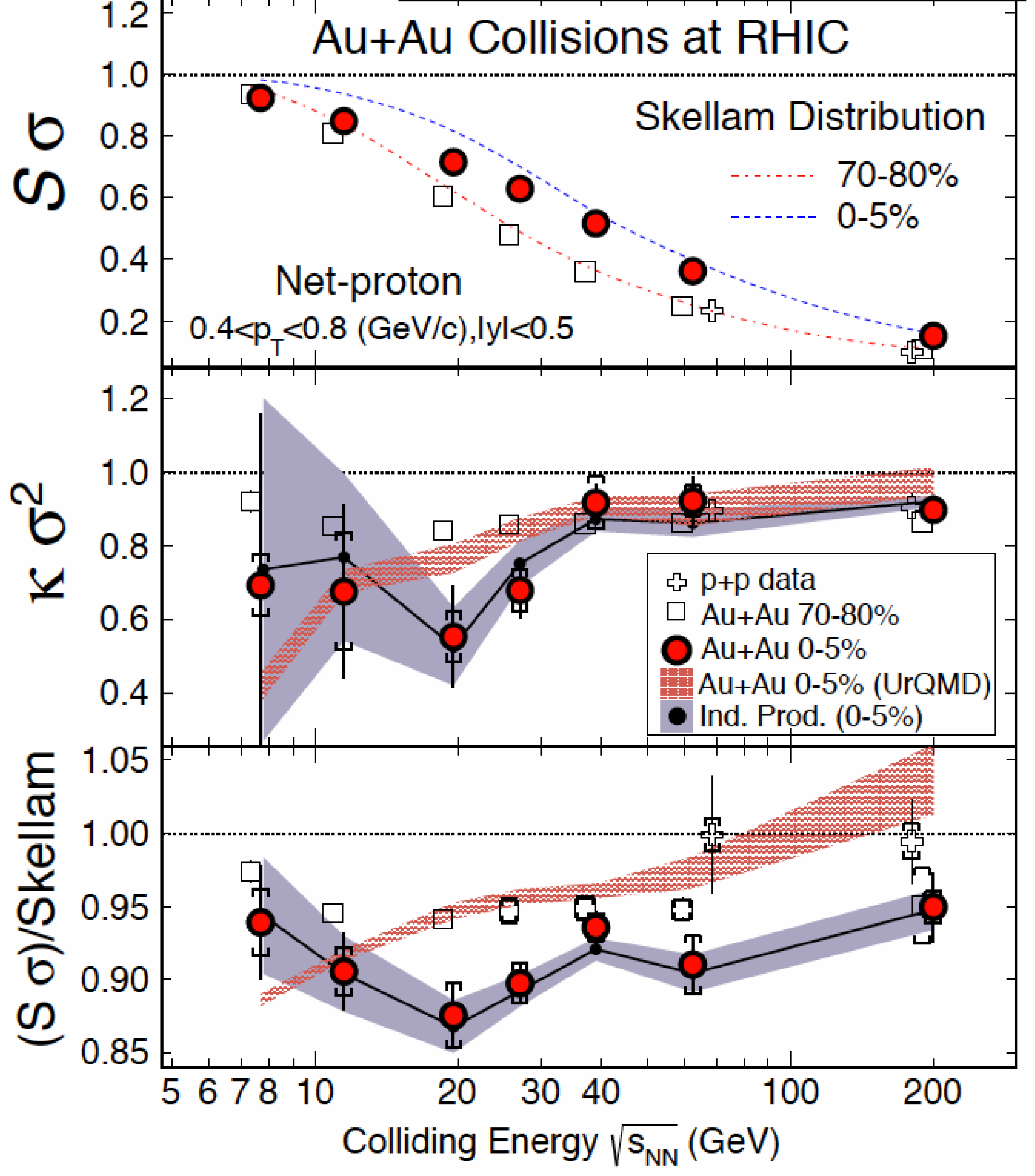
$$R_{12} = \frac{M}{\sigma^2} = \frac{\chi_1^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

To measure T:

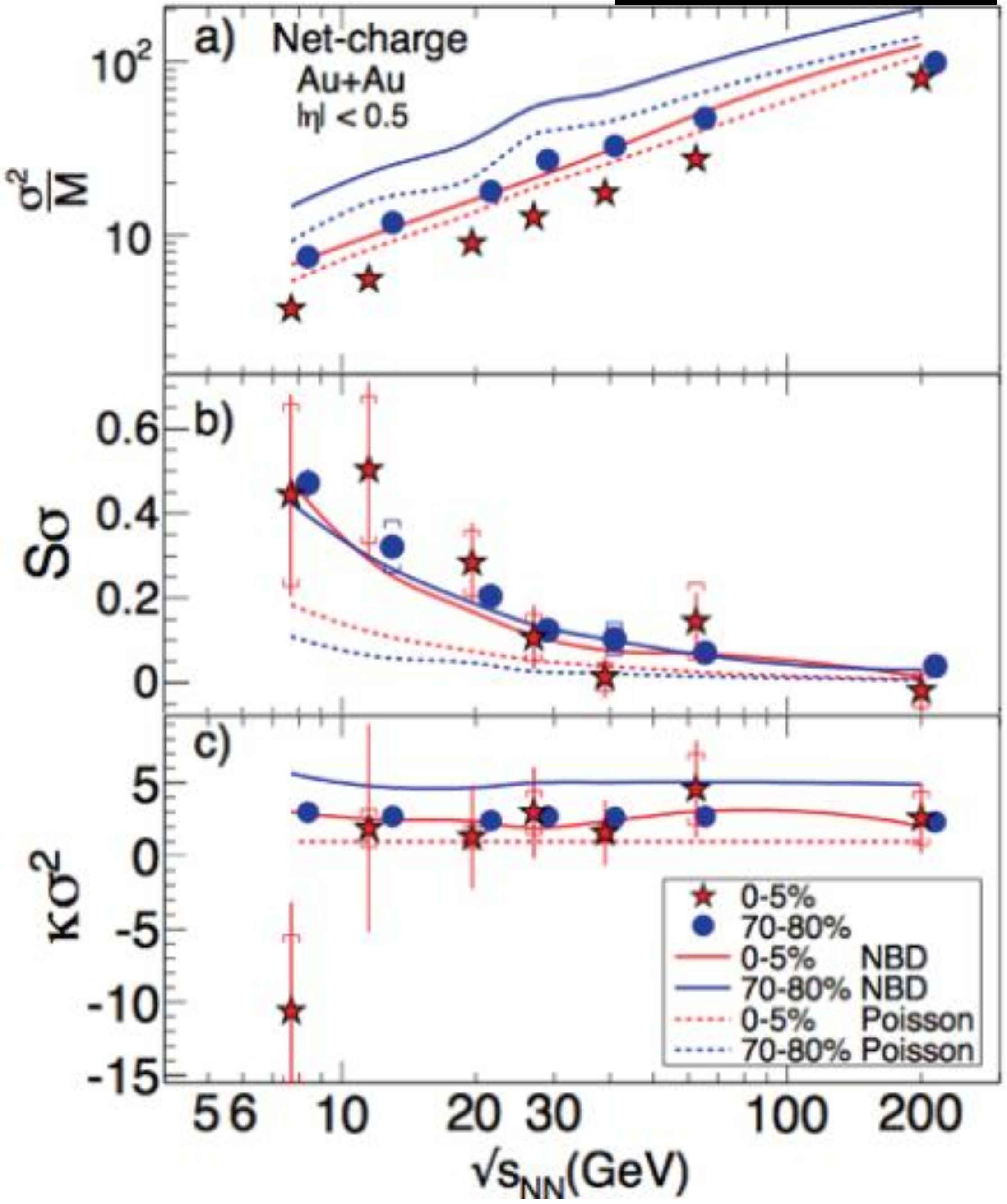
$$R_{31} = \frac{S\sigma^3}{M} = \frac{\chi_3^{(B,S,Q)}}{\chi_1^{(B,S,Q)}}$$

Higher moment ratios for net-charge and net-proton distributions

Phys. Rev. Lett. 112 (2014) 32302



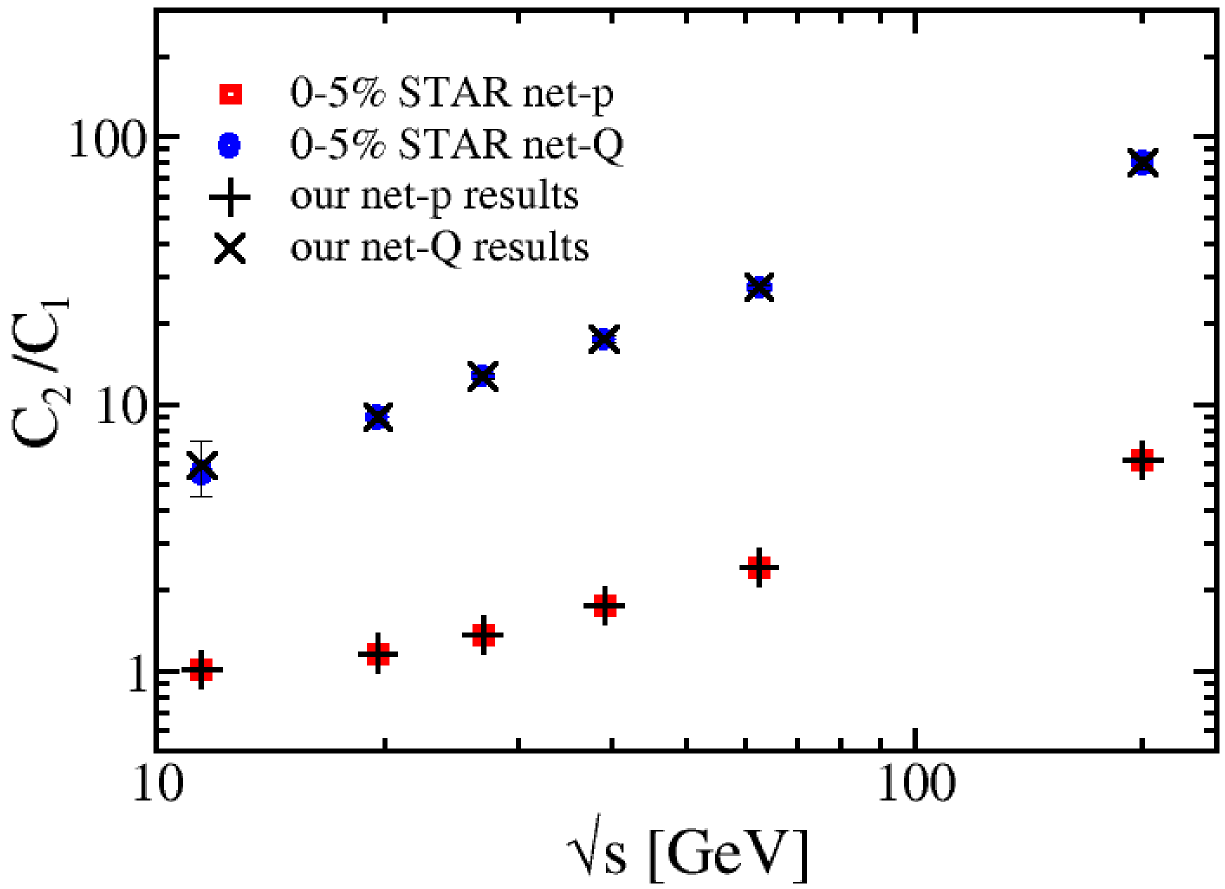
arXiv:1402.1558

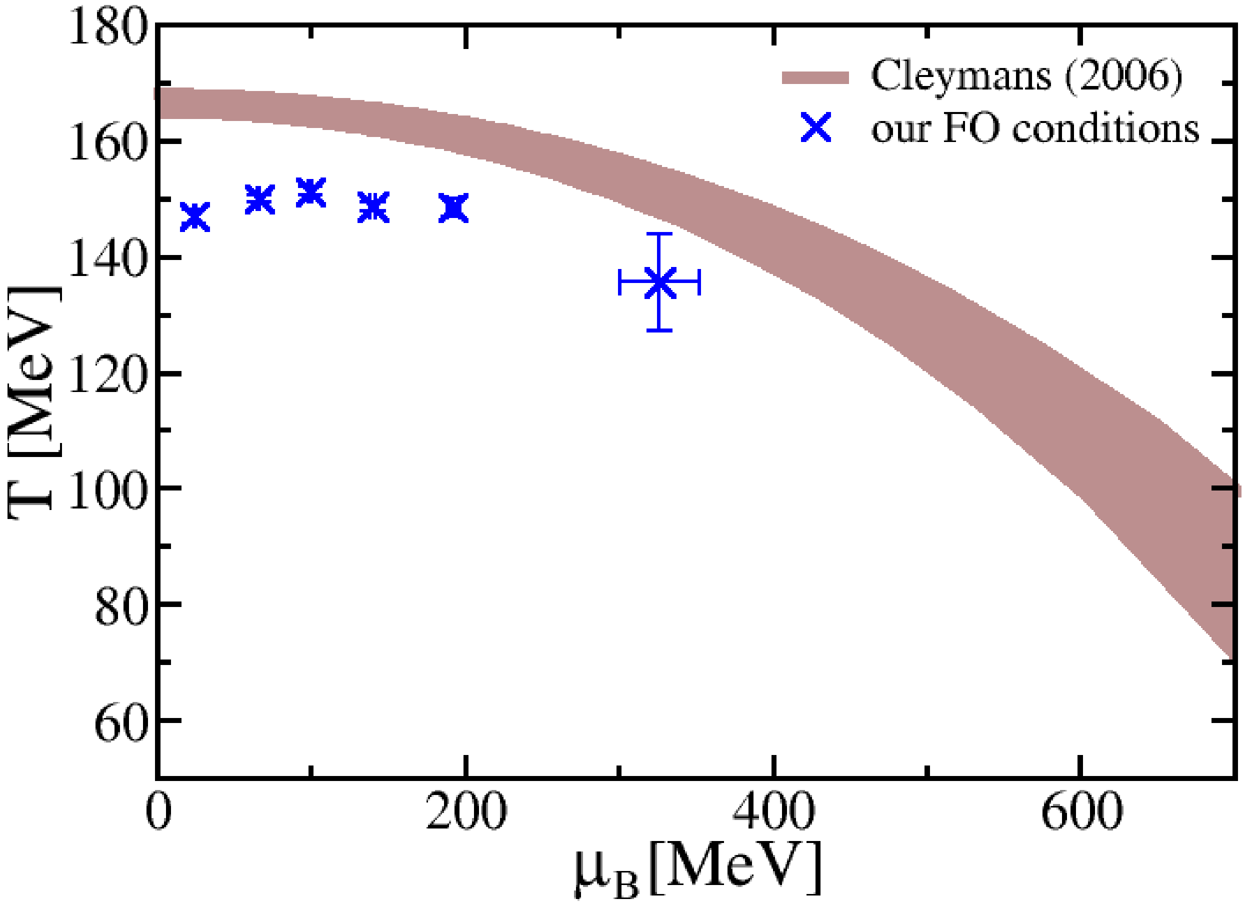


HRG analysis of STAR results (charge & proton)

Alba, Bellwied, Bluhm, Mantovani, Nahrgang, Ratti (PLB (2014), arXiv:1403.4903)

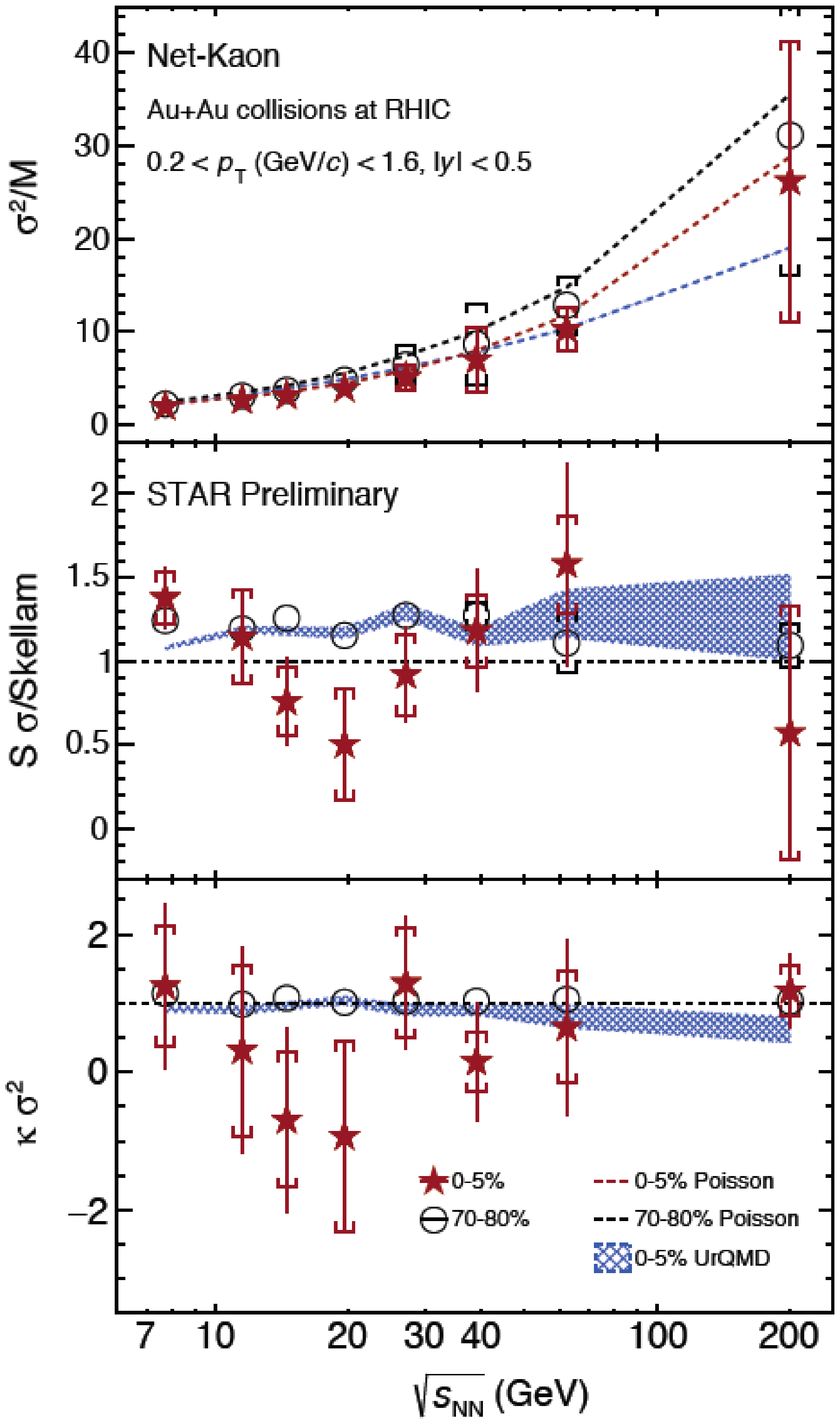
HRG in partial chemical equilibrium (resonance decays and weak decays taken into account).
Hadrons up to 2 GeV/c^2 mass taken into account (PDG), experimental cuts applied.
For protons full isospin randomization taken into account (Nahrgang et al., arXiv:1402.1238)

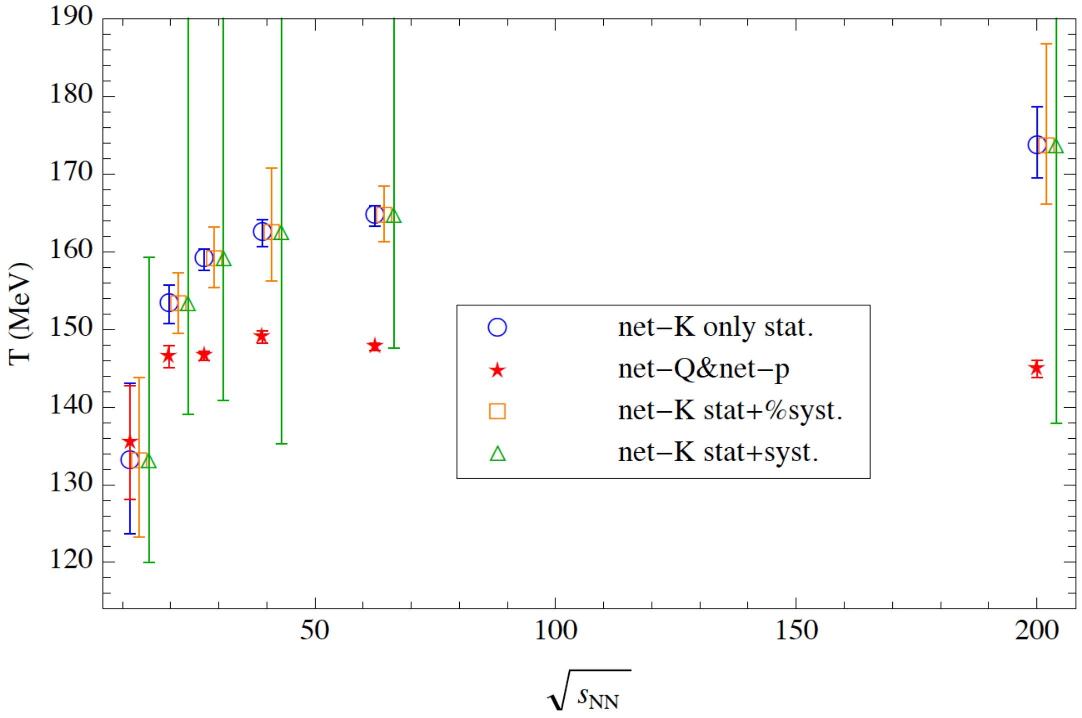


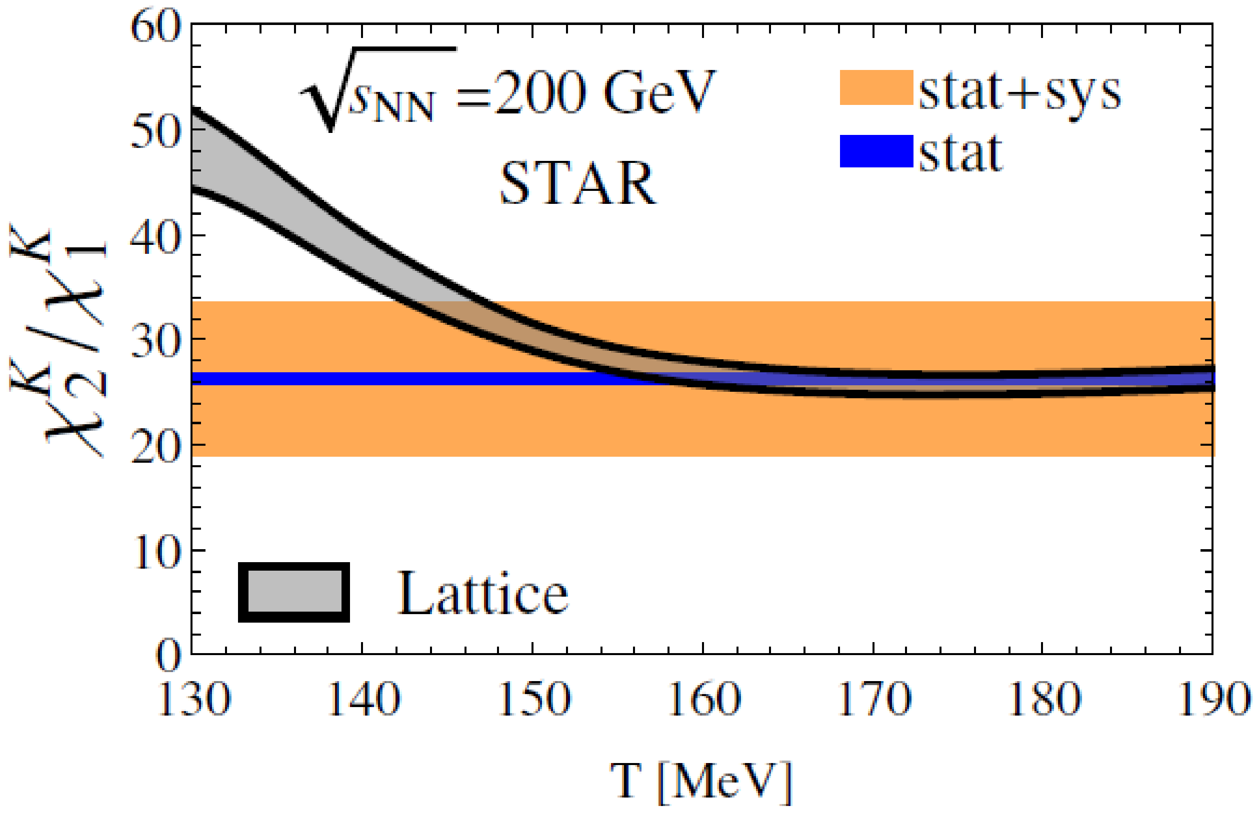


Result: intriguing 'lower' freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

Fit σ^2/M for net-kaons in the same fashion than for net-proton and net-charge (P. Alba et al. in prep.)







Noronha-Hostler et al., arXiv:1607.02527

So what can happen between 148 and 164 MeV ?

A 20 MeV drop can be translated into a 2 fm/c time window

Strangeness wants to freeze-out, light quarks do not

Can there be measurable effects ?

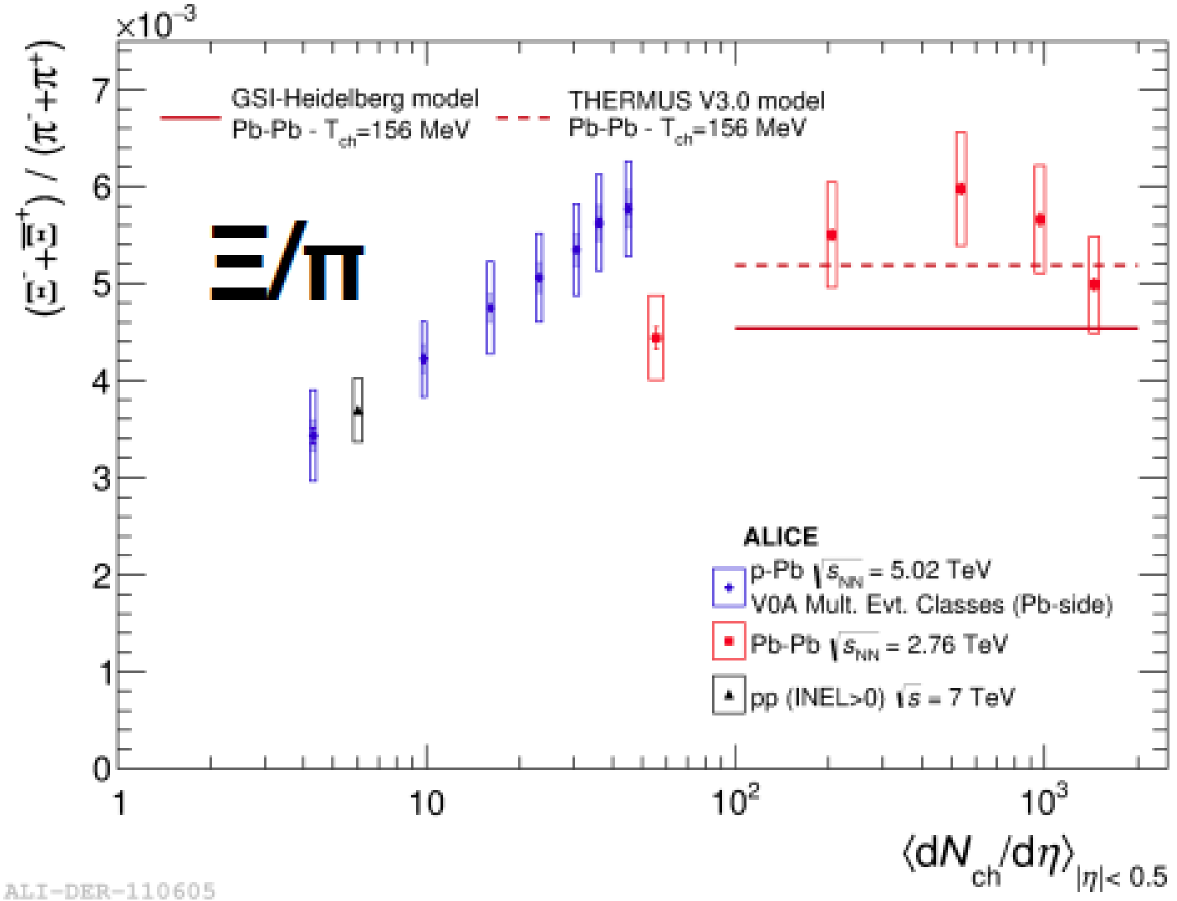
- Bellwied at WWND 2016: possible effect on dynamic quantities (v_2 and R_{AA}) if produced near T_c

- Simple strangeness enhancement of the strange ground states *(strangeness enhancement vs. canonical suppression)*

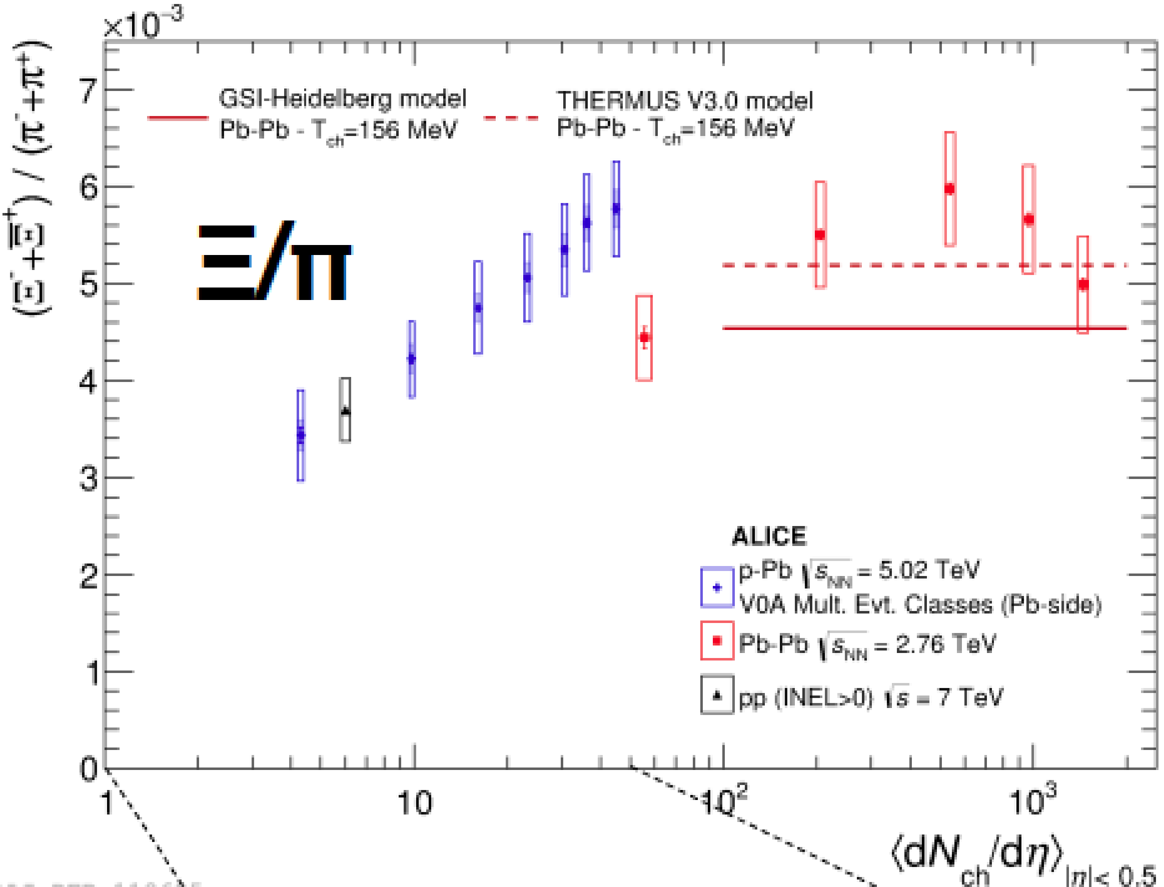
- or additional strange hadronic resonances *(quark model predictions vs. experimental evidence)*

- or exotic quark configurations with strangeness ? *(hypernuclei enhancement, multiquark states)*

Strangeness production in pPb



ALI-DER-110605



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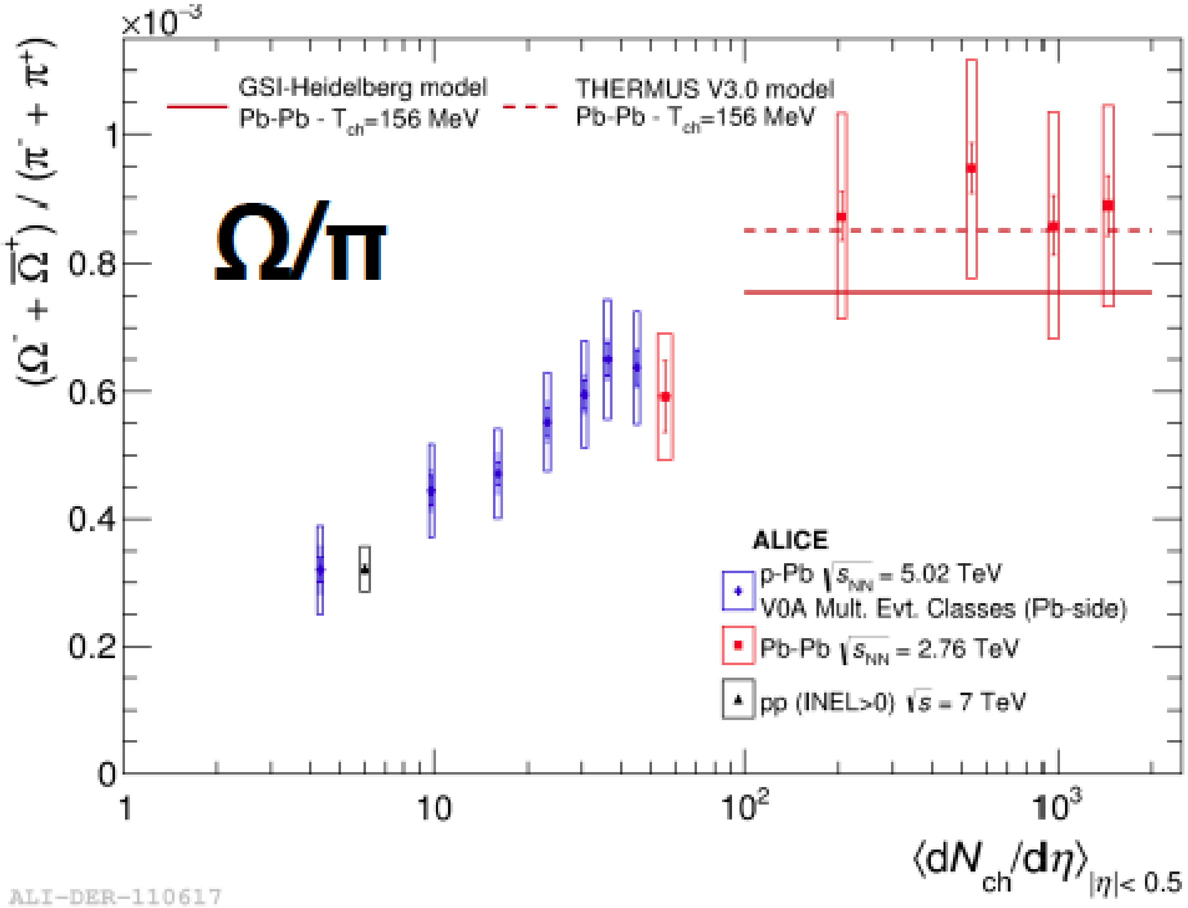

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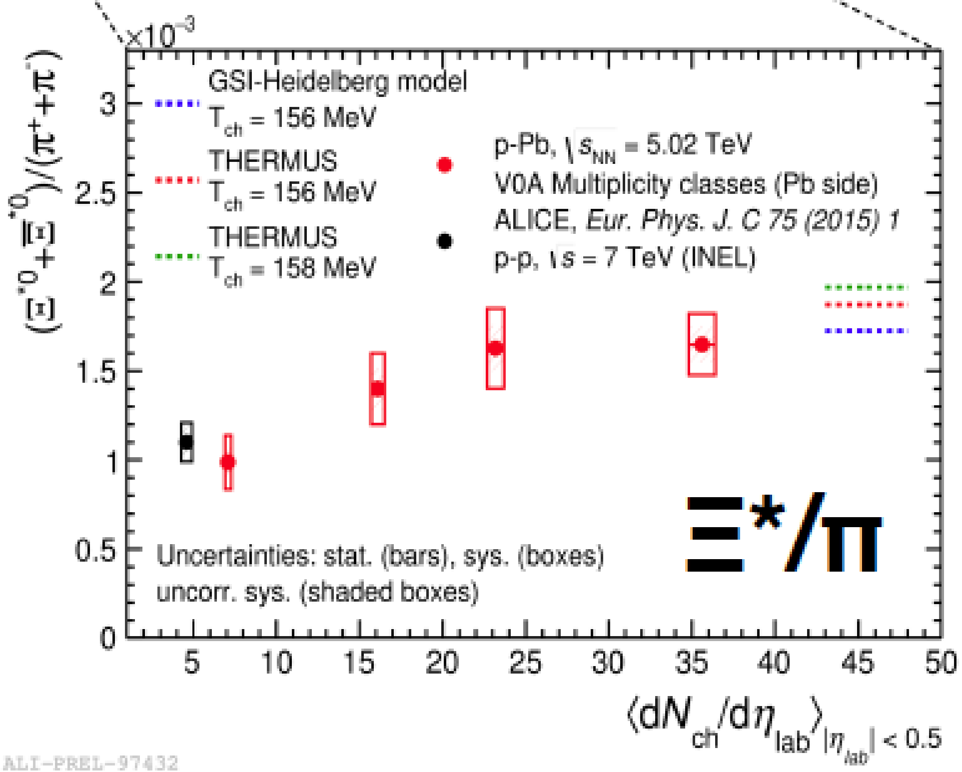
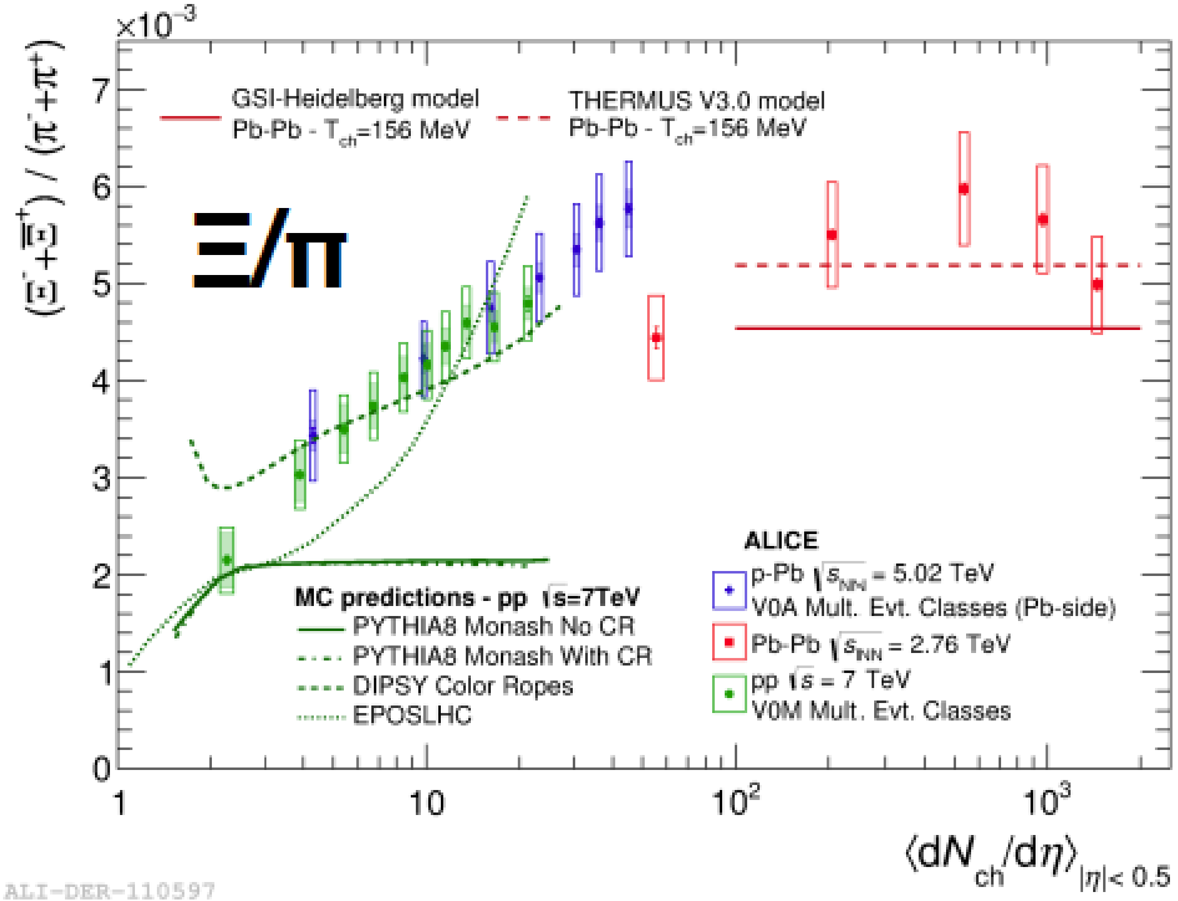
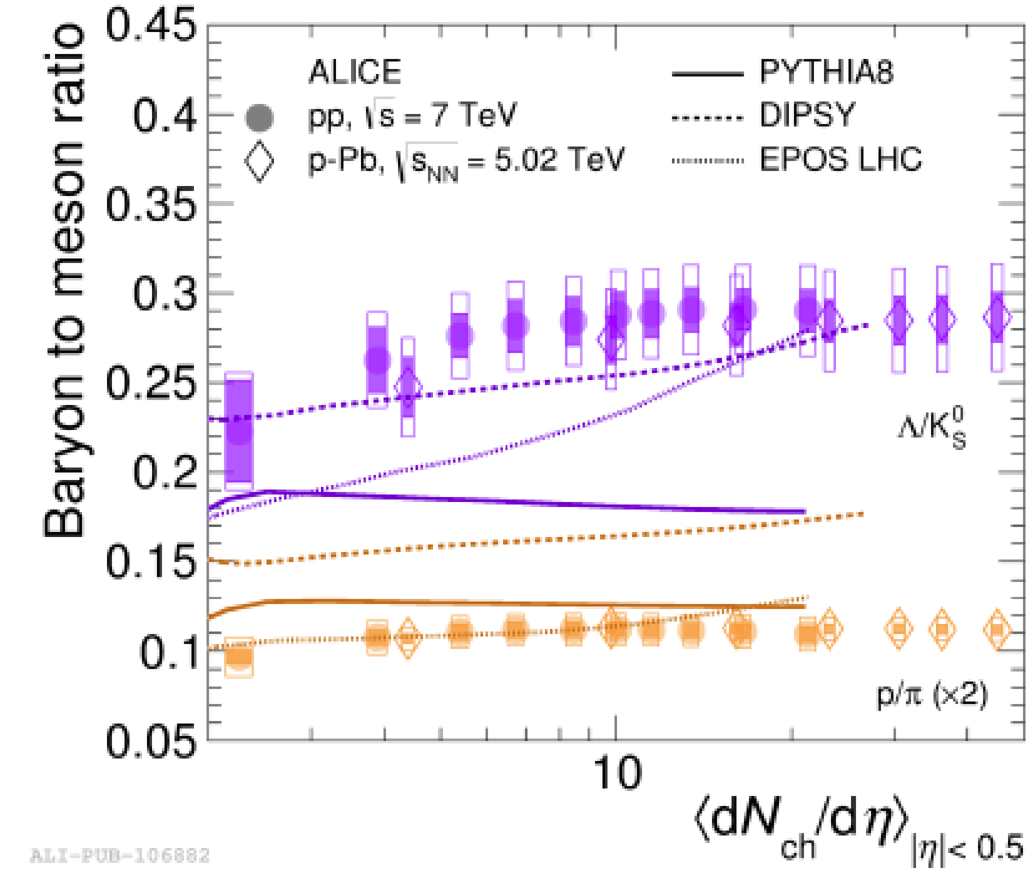


ALI-PREL-97432

Strangeness production in pp



ALI-DER-110597



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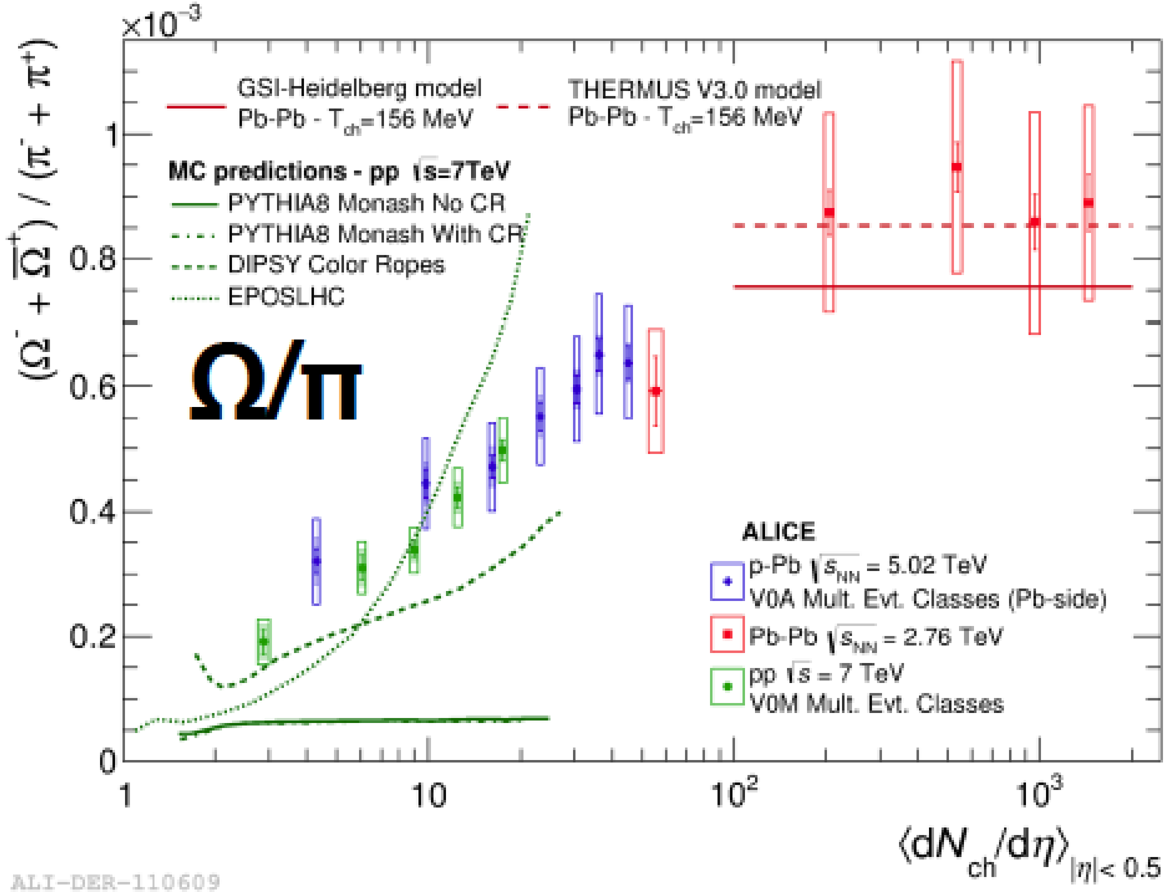
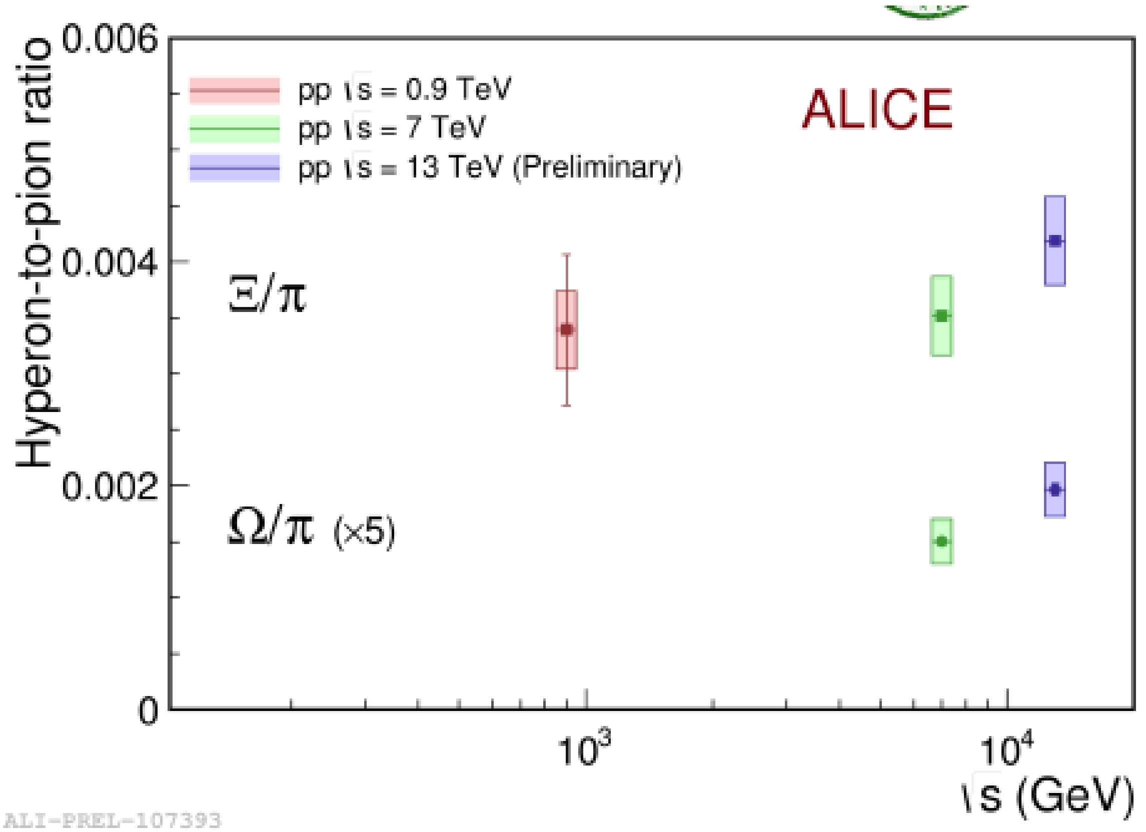
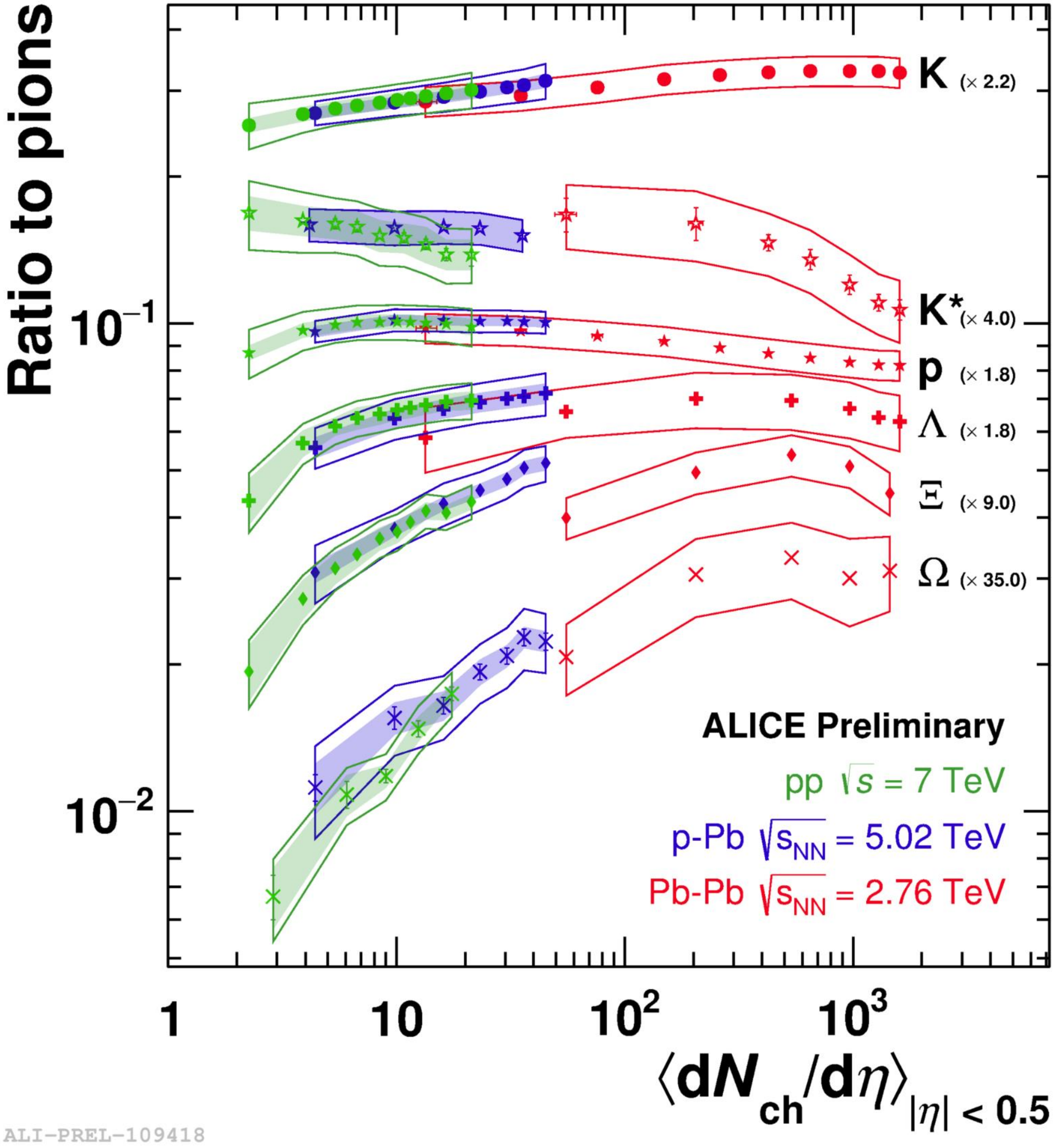


ALI-DER-110609



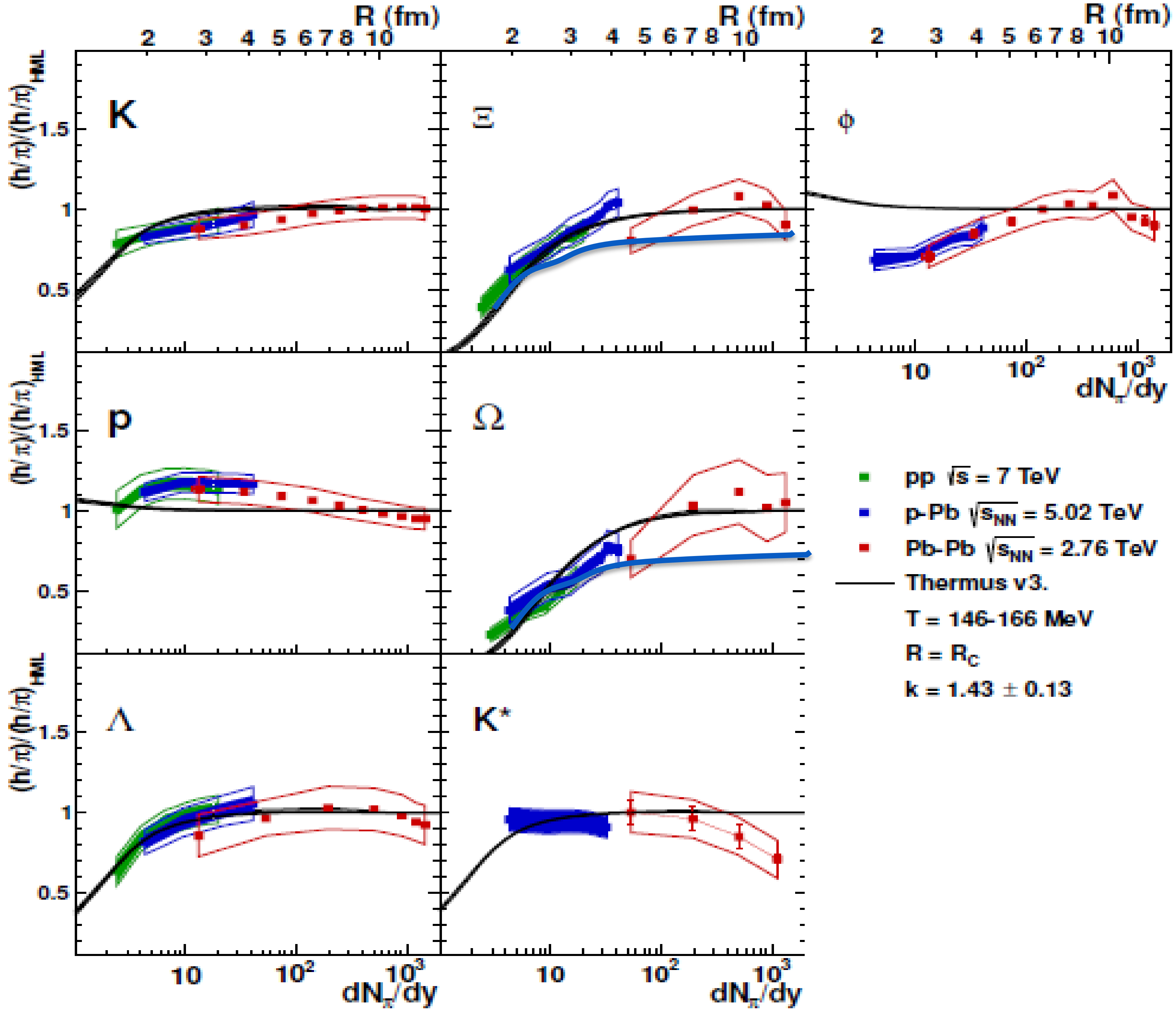
ALI-PREL-107393

What about heavy ion collisions ?



Canonical Suppression Model

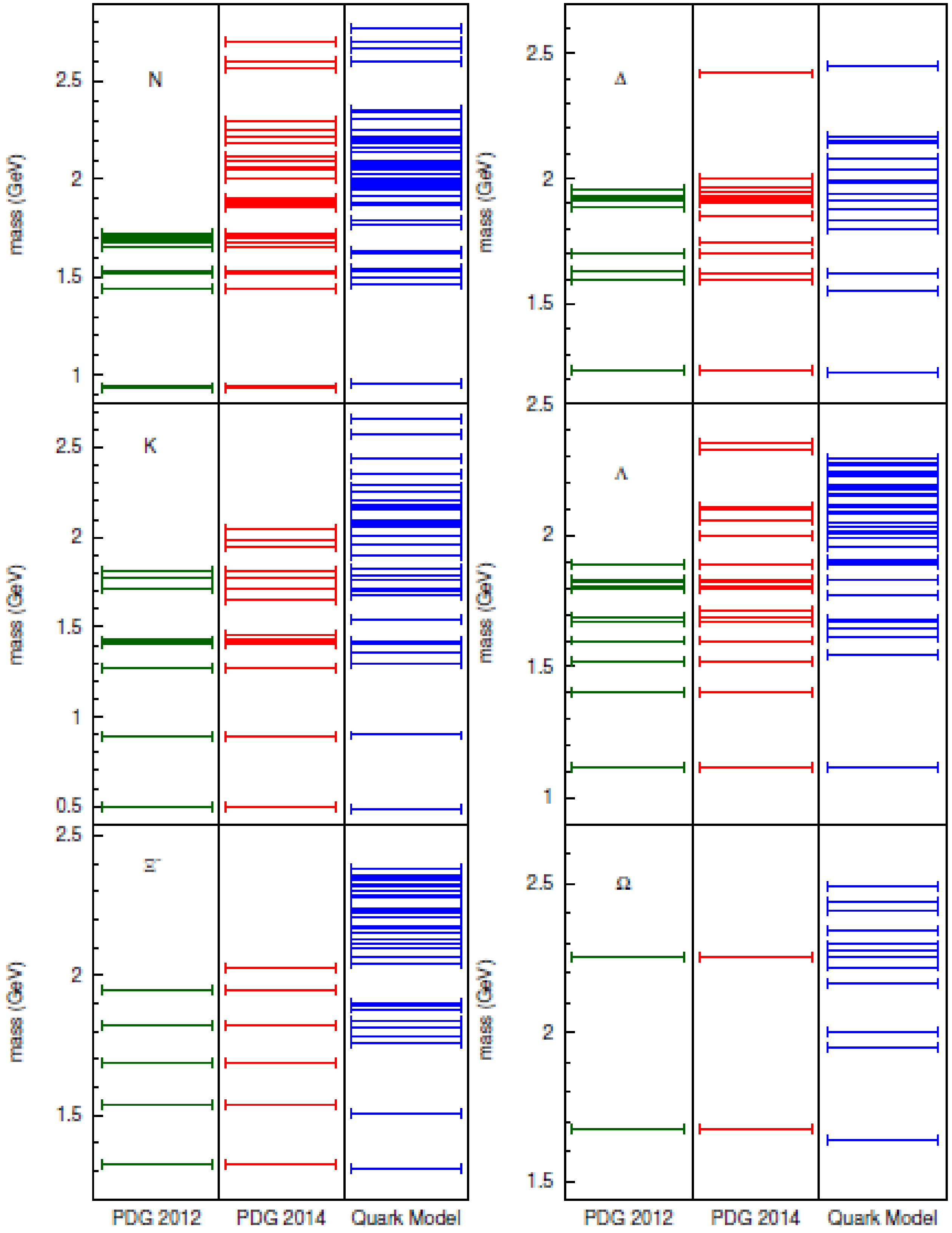
(Vislavicius, Kalweit, arXiv:1610.03001)



This seems to work but one needs to keep in mind that the saturation is fixed to the most central heavy-ion point.

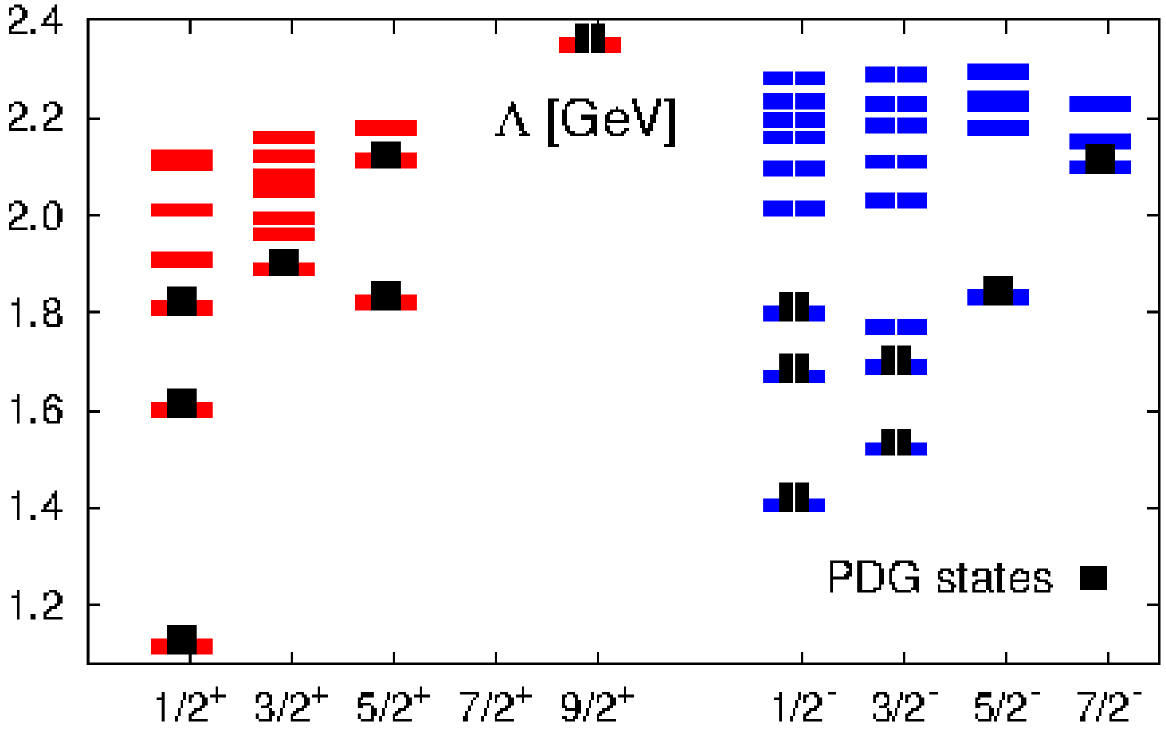
The model might also work if the saturation yield is reduced (blue line), which would leave room for genuine strangeness enhancement (see core-corona picture in K.Werner’s talk)

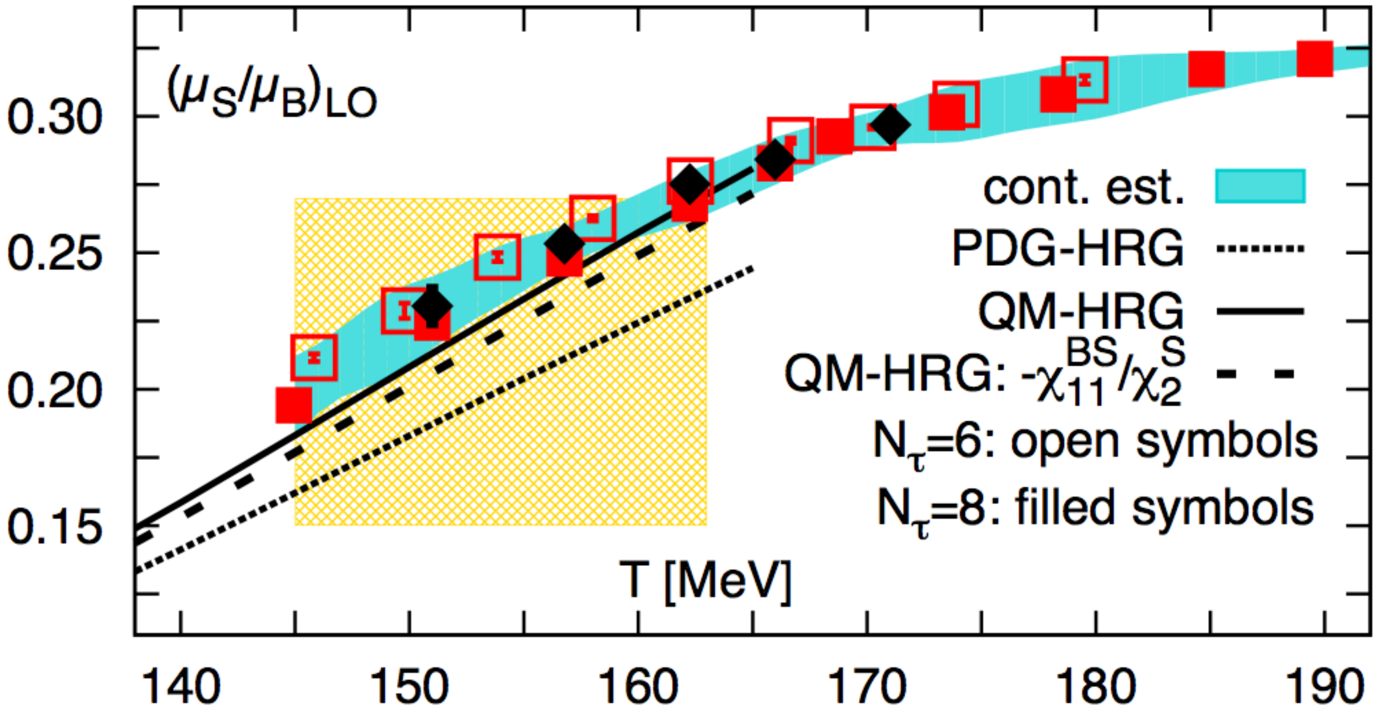
Enhanced resonance production - experimentally



Enhanced resonance production - theoretically

Not yet seen higher mass states from Quark Model calculations seem to improve agreement between HRG and lattice for the χ_{BS} correlator (Bazavov et al., PRL (2014), arXiv:1404.6511)





But those effects need to be consistently applied to all correlators that are possibly affected by higher lying strange states and they need to take into account all possible decay modes **(see talk by C. Ratti)**

Still, the idea of preferred strange bound state production in a particular temperature window is intriguing and could ultimately lead to the generation of exotic multi-quark configurations (pre-cursor to strange quark matter, core of neutron stars ?)

The missing resonance problem

The simplest predictions of additional hadronic states are based on the non-relativistic quark model, which assumes that every baryon is simply made of three constituent valence quarks using one-gluon exchange motivated, flavor independent color-magnetic interactions. This leads to a flavor-spin SU(6) basis.

The problem is that the number of predicted states is considerably larger than the number of observed states, which was already pointed out in the 70's by Isgur and Karl. The situation has not improved since then, although many detailed searches have been performed.

For example, up to E* = 2.4 GeV about 45 N* states are predicted, but only 14 are established and 10 more are tentative in PDG-2016. Even less couple to the basic Nπ channel. In general at most half of the predicted resonant states have been found (~700 listed in PDG, ~700 missing).

Possible solutions to the missing resonance problem

Degrees of freedom: In quark models the number of excited states is determined by the effective degrees of freedom. One possible solution to the problem is that any baryon consists only of two degrees of freedom, namely a valence quark and a tightly bound valence di-quark. That would *reduce the number of possible resonance configurations*.

An increase in the number in the number of possible states is expected in models that treat the quantum numbers in the baryon through junctions, string-like configurations or flux tubes, which can e.g. vibrate and lead to more excitations. Flux-tube models are motivated by lattice QCD and lattice therefore agrees with many excited states and disfavors di-quark clustering.

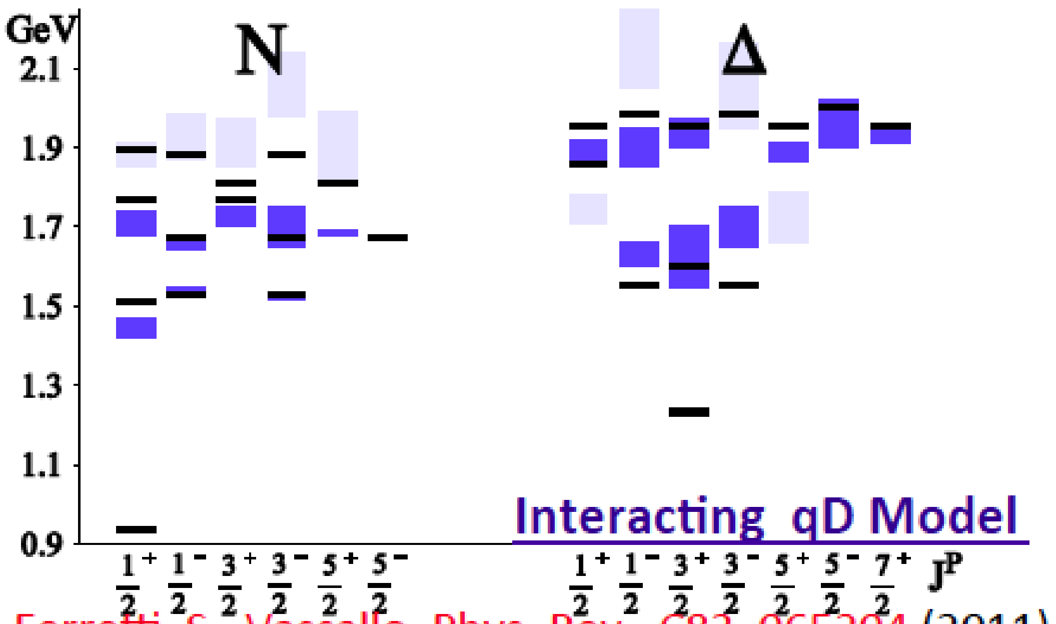
Input from lattice: Generally lattice QCD calculations agree with the simple NR Quark Model and disfavor di-quark clustering and/or parity doubling. Lattice QCD also assumes a flux tube type interaction between valence quarks and has no option of quark clustering. But density correlators show evidence for the production of di-quarks in the scalar positive parity channel

(Alexandru, deForcrand, Lucini (2006))

Chiral symmetry/parity doubling: at higher excitation energies there is some evidence of doubling or even full chiral multiplets of chiral partners in the light quark baryon resonances. That would mean that the mass generating mechanism for low and high mass states is different. Parity doublets would *reduce the number of additional states*.

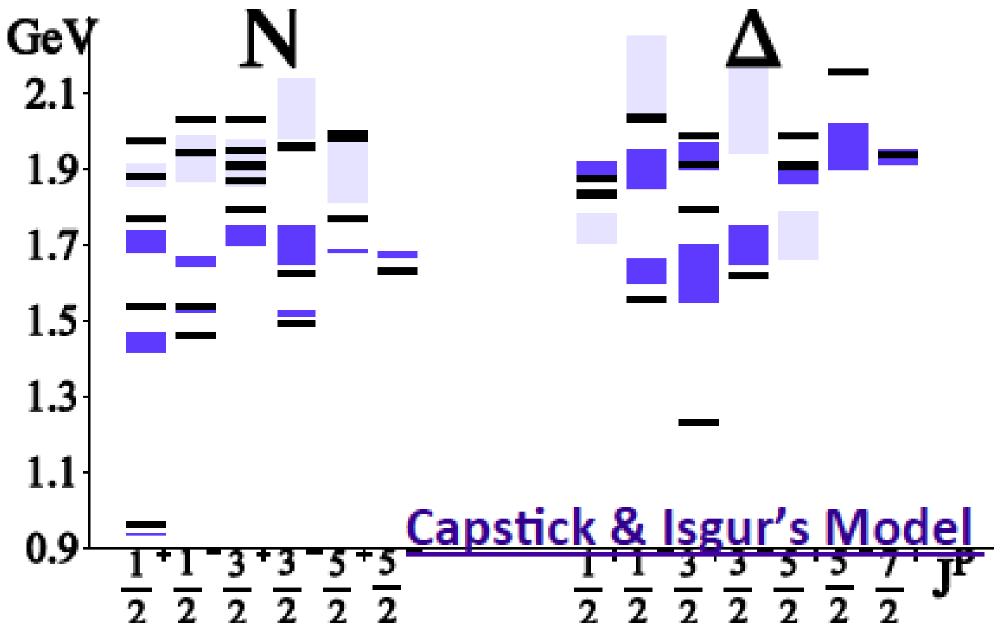
Plot from Elena Santopinto

Non-strange baryons. Complete spectrum



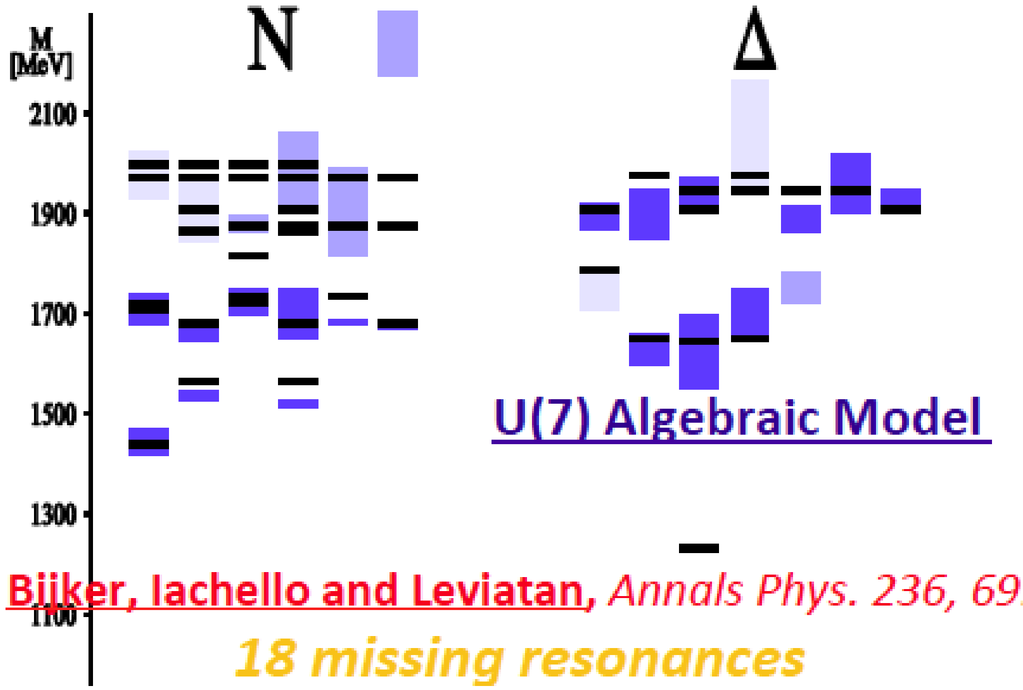
Ferretti, S., Vassallo ,Phys. Rev.. C83, 065204 (2011)
E.S.,Phys. Rev. C 72, 022201(R) (2005).

0 missing resonances



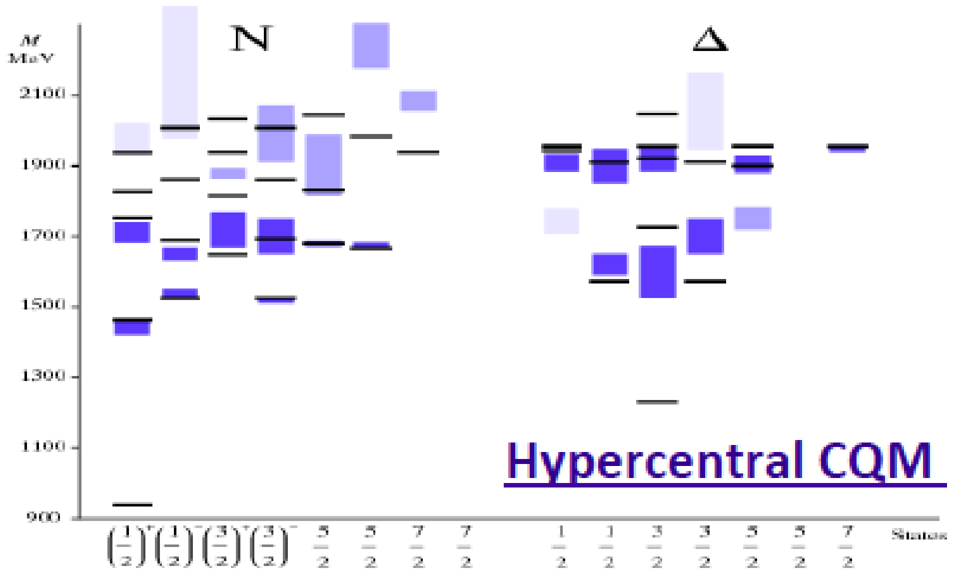
Capstick and Isgur, *Phys. Rev. D34, 2809.*

8 missing resonances



Bijker, Iachello and Leviatan, *Annals Phys. 236, 69.*

18 missing resonances



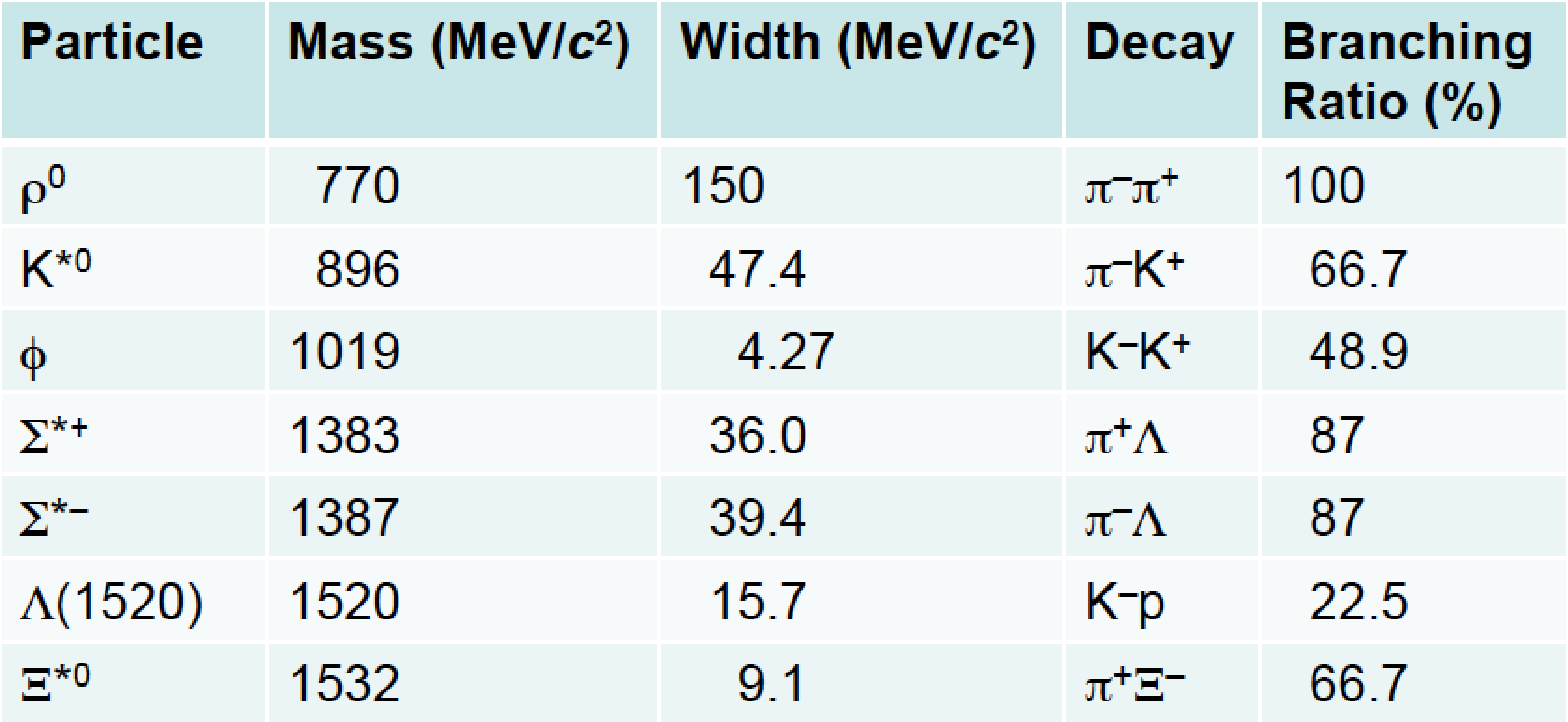
Giannini, Santopinto, Vassallo, *Eur. Phys. J .A12:447*

9 missing resonances

Similar in the strange sector, see arXiv:1412.7571 and arXiv:1510.00582

Relevant data from ALICE

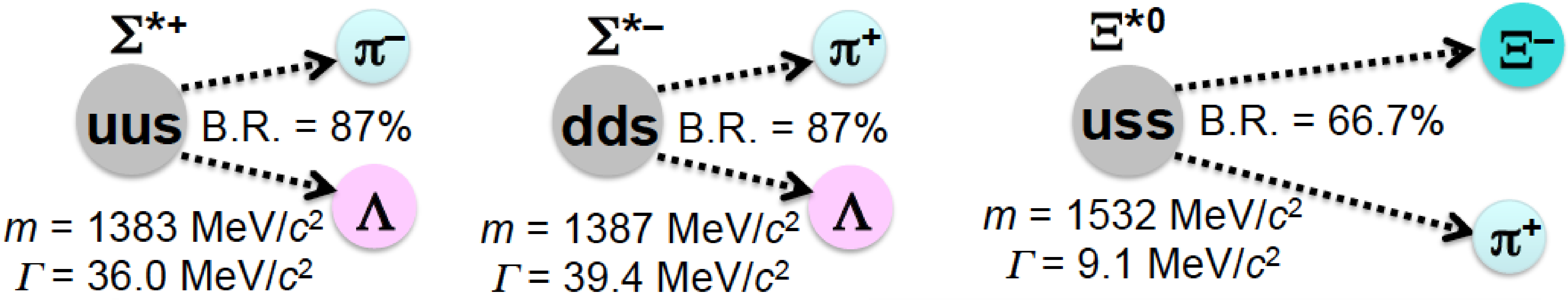
Resonances measured in pp (0.9, 2.76, 7, 13 TeV) , p–Pb (5.02 TeV), and Pb–Pb (2.76, 5.02 TeV) collisions



Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Decay	Branching Ratio (%)
ρ^0	770	150	$\pi^-\pi^+$	100
K^{*0}	896	47.4	π^-K^+	66.7
ϕ	1019	4.27	K^-K^+	48.9
Σ^{*+}	1383	36.0	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

Σ^* and Ξ^* reconstruction

- Measured in pp collisions at 7 TeV & p–Pb collisions at 5.02 TeV (Pb–Pb collisions at 2.76 TeV in progress)
- Subtract mixed-event combinatorial background
- Polynomial residual background
- Peaks: Breit-Wigner ($\Sigma^{*\pm}$) or Voigtian (Ξ^{*0})



Σ^{*+}

uus B.R. = 87%

π^- Λ

m = 1383 MeV/c^2

Γ = 36.0 MeV/c^2

Σ^{*-}

dds B.R. = 87%

π^+ Λ

m = 1387 MeV/c^2

Γ = 39.4 MeV/c^2

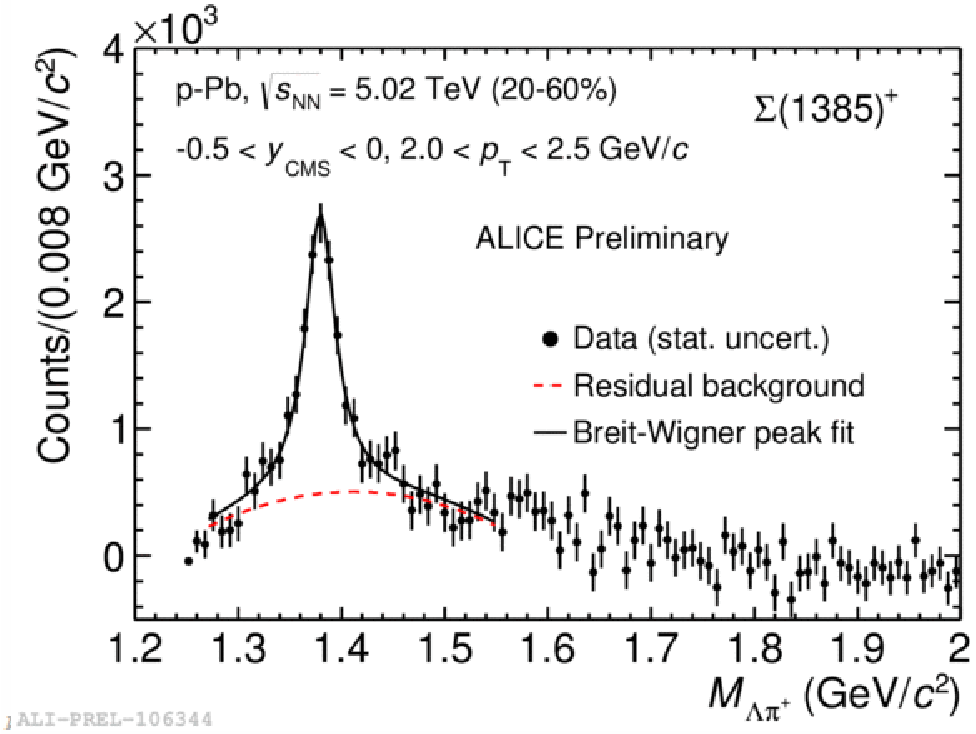
Ξ^{*0}

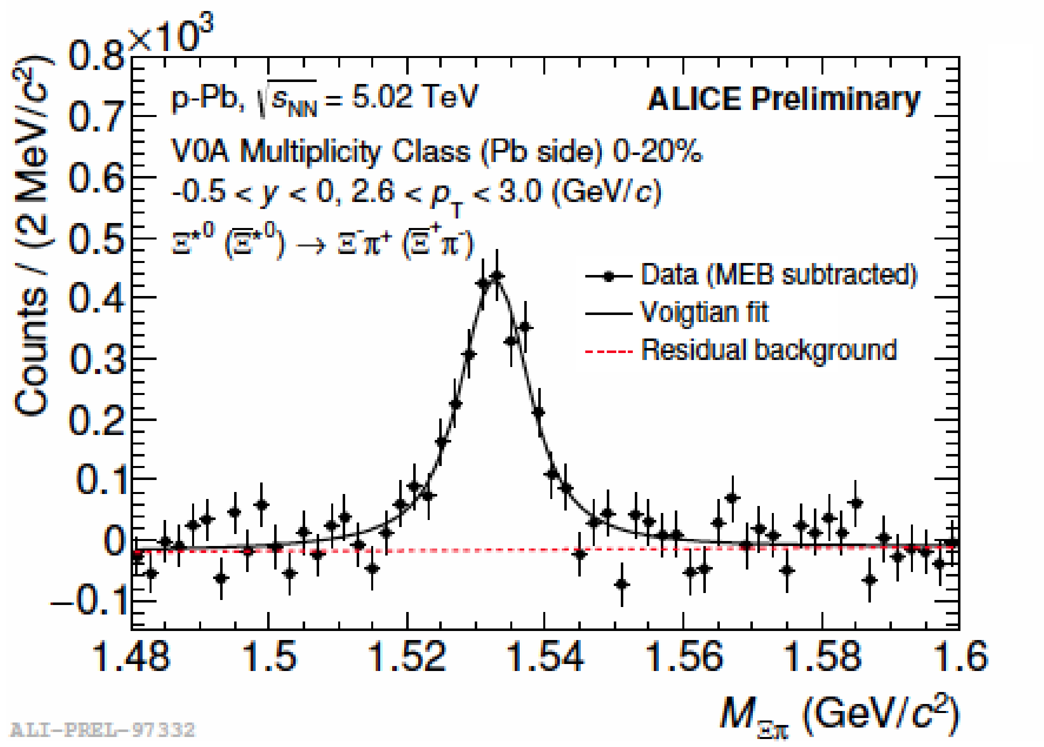
uss B.R. = 66.7%

Ξ^- π^+

m = 1532 MeV/c^2

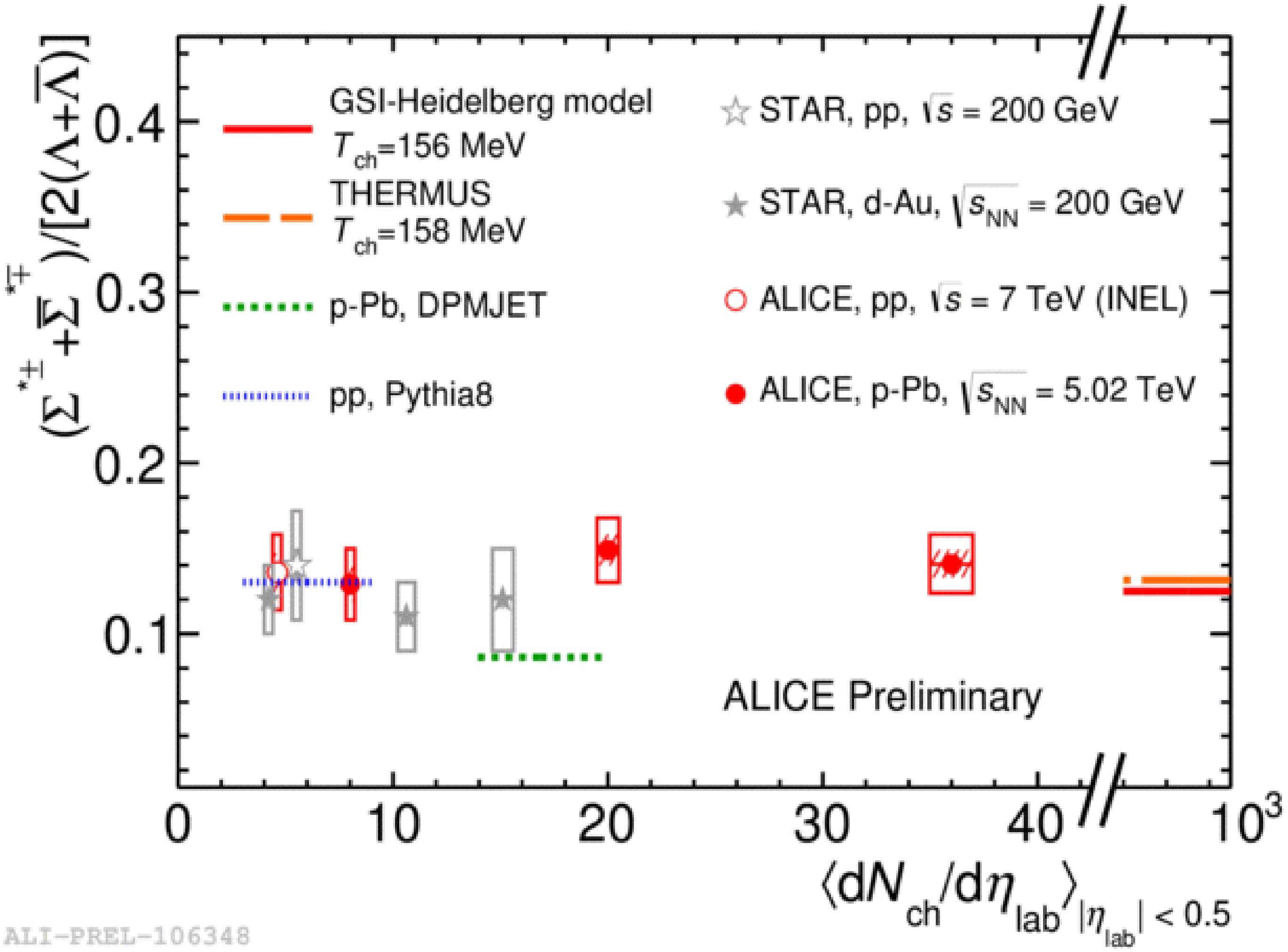
Γ = 9.1 MeV/c^2

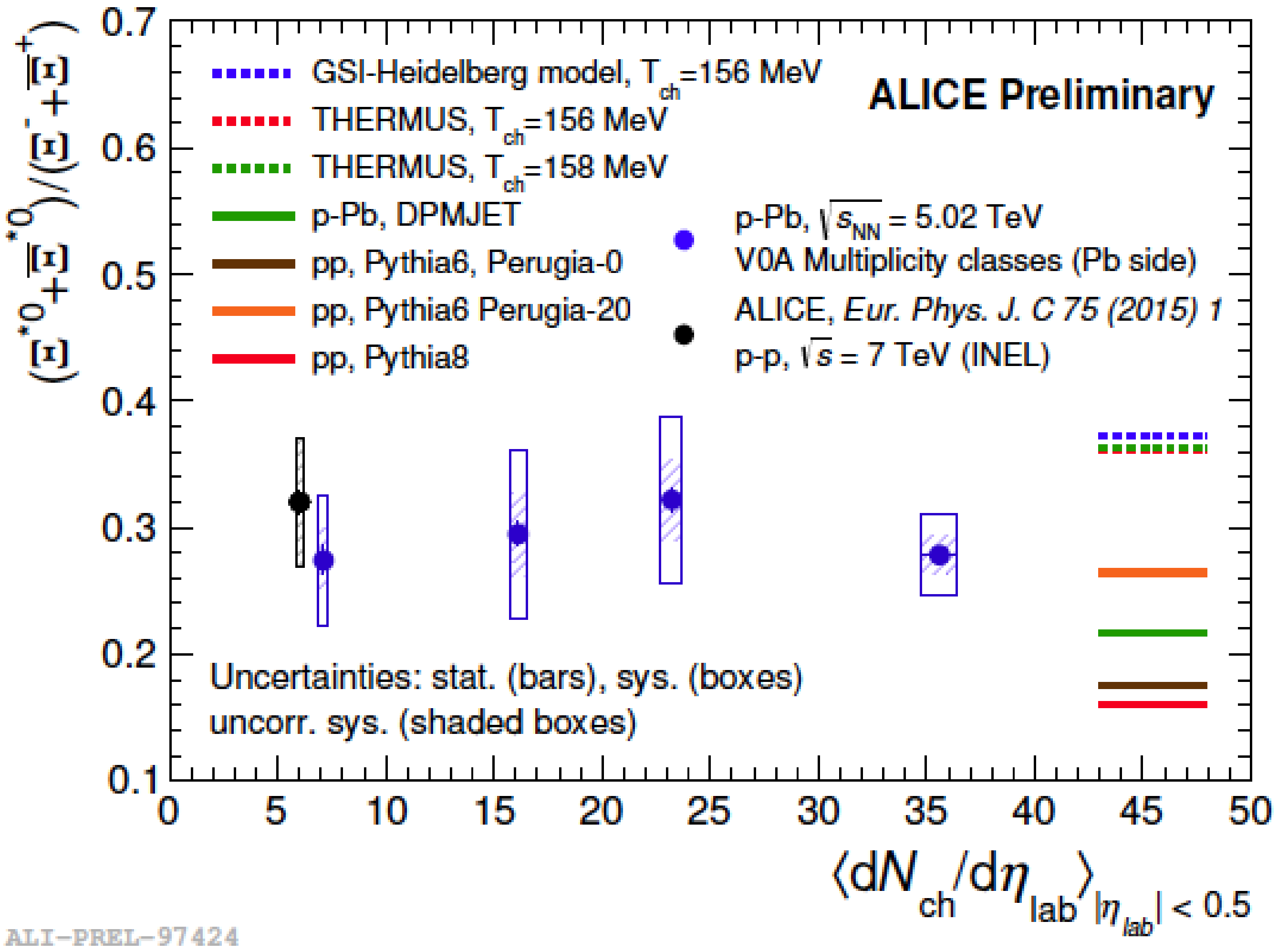




Ratios to stable hadrons

- New measurements of $\Sigma^{*\pm}$ and Ξ^{*0} in p–Pb collisions at 5.02 TeV
  - Measurements in progress for Pb–Pb collisions at 2.76 TeV
- No strong dependence of $\Sigma^{*\pm}/\Lambda$ on energy or system size from RHIC to LHC
  - Values consistent with thermal model and PYTHIA predictions
- No system size dependence of Ξ^{*0}/Ξ at LHC
  - Values in pp and p–Pb tend to be below thermal model predictions





General conclusions for heavy ion systems

- Strange baryons in heavy ion collisions are enhanced relative to their scaled yield in proton proton interactions

- The ratio of resonances to ground state particles is not enhanced, which means the resonances are enhanced just as much as the ground state hyperons

- For short-lived resonances the ratio is reduced, since resonances decay in the hadronic medium and some of the decay particles scatter so that the resonance cannot be reconstructed.

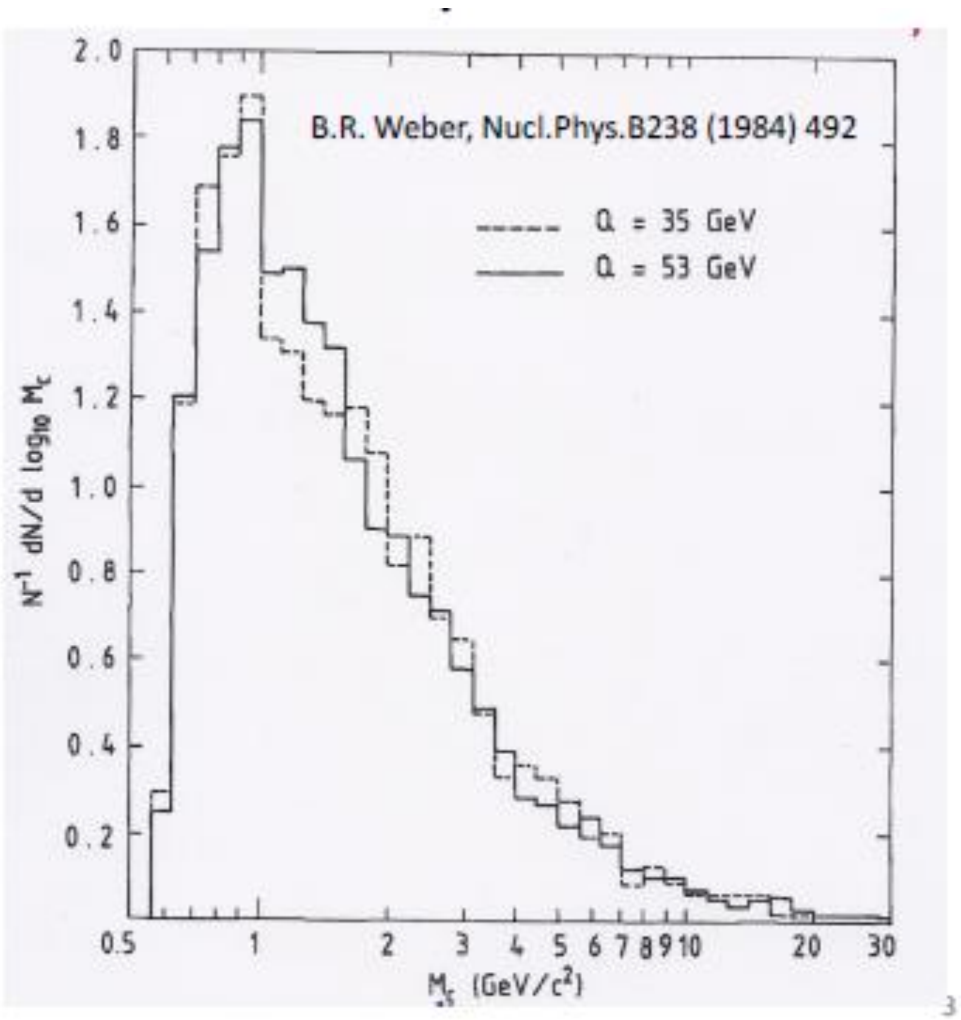
- So in general: the higher the strangeness content in the resonance the more its yield is enhanced (due to plasma formation and/or canonical suppression in the small system).

- But advantage relative to increase background in discovery measurement in heavy ion system is not clear. All HRG calculations of increased excited hyperon production require a thermalized system near the QCD phase transition (it is presently not clear whether heavy ions are a pre-requisite for such conditions).

Color-neutral configurations in different phases

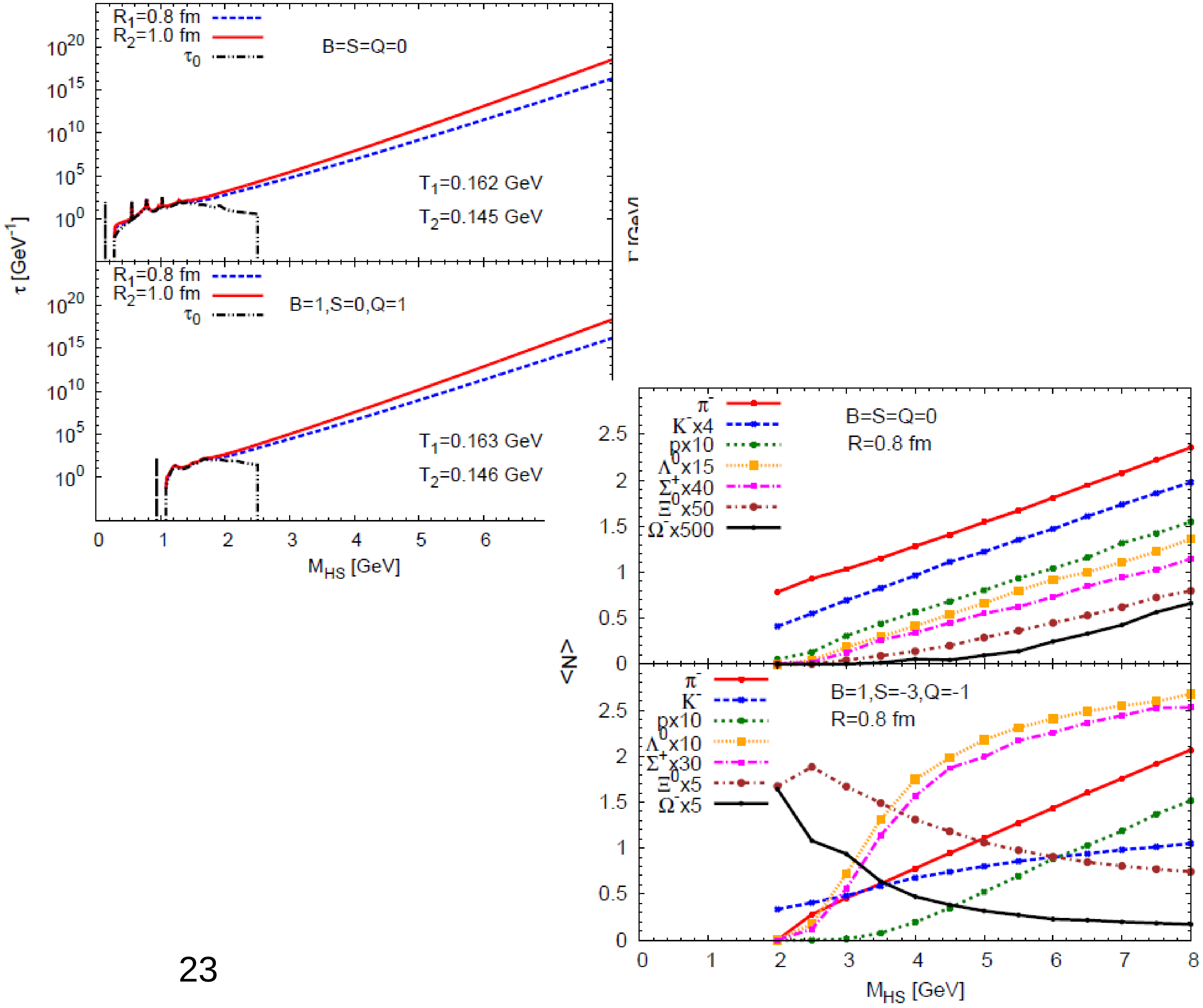
In the deconfined phase:

Veneziano / Webber model: cluster formation in deconfined phase = HERWIG event generator (color neutral clusters)

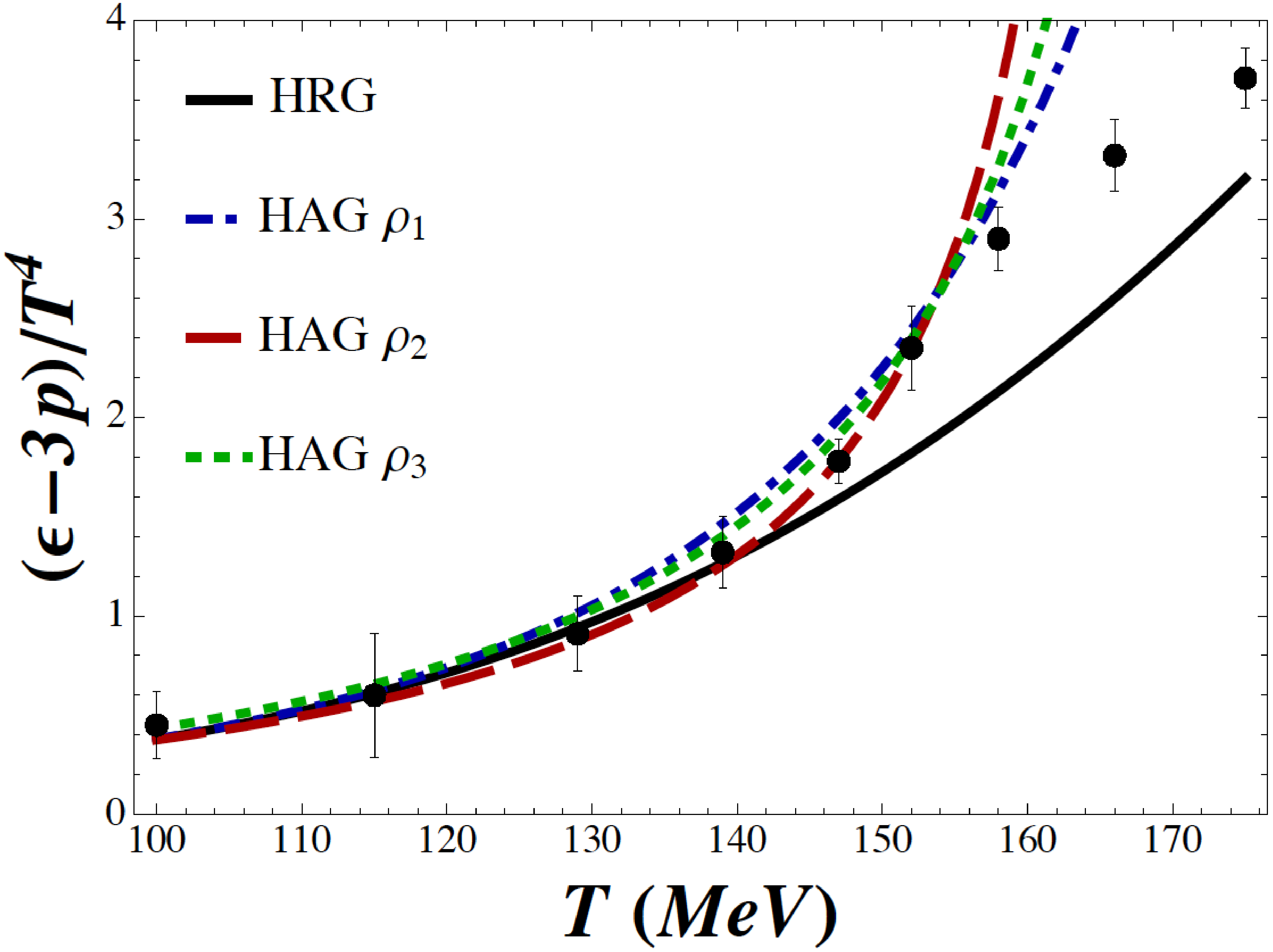


In the hadronic phase:

Hagedorn states: exponentially rising mass spectrum of color neutral very high mass resonances (e.g. Beitel et al., arXiv:1407.0565)



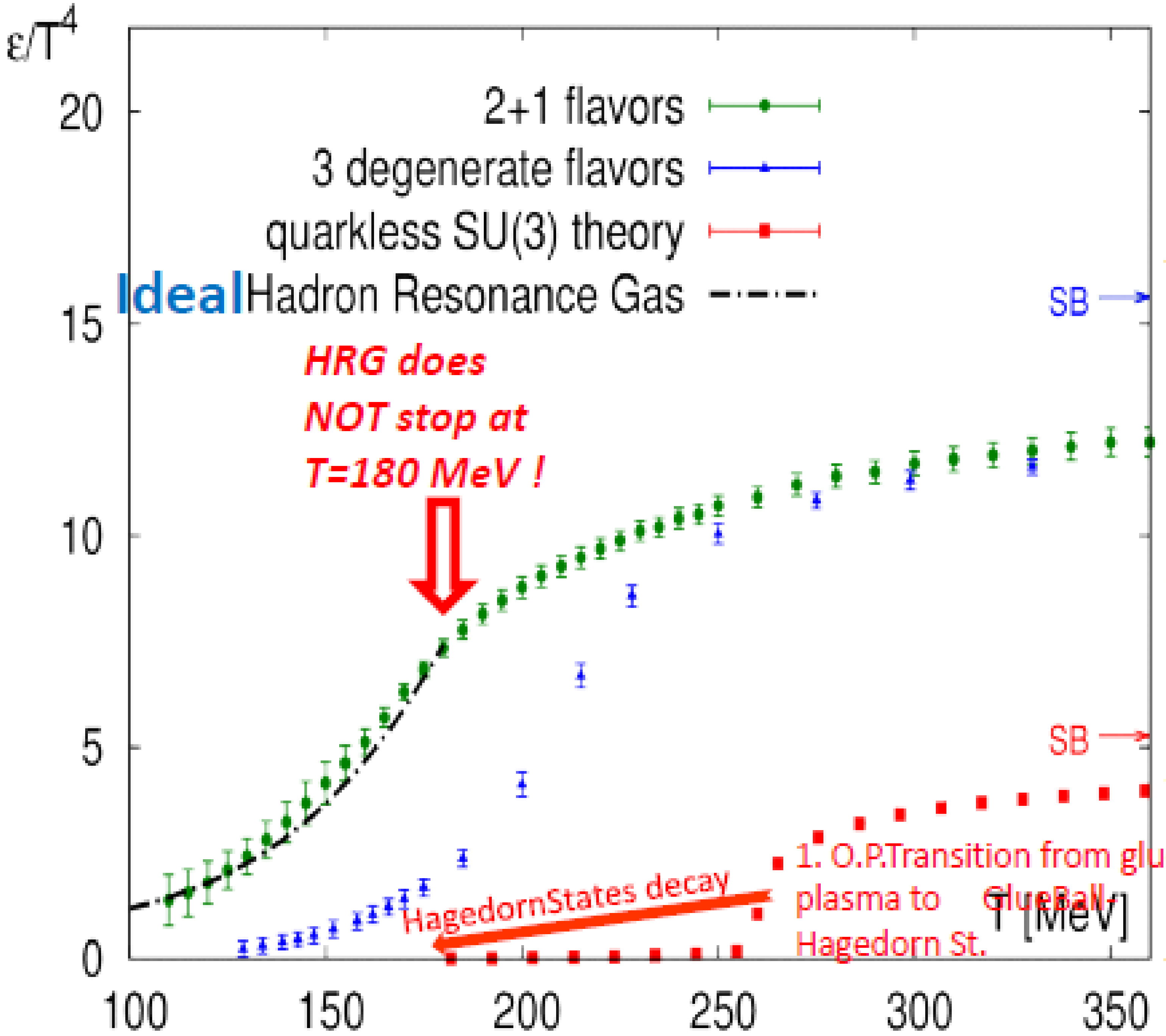
More evidence for exotic states: Comparison of trace anomaly from lattice to HRG spectrum expanded with Hagedorn States (J. Noronha-Hostler et al., PRC (2014), arXiv:1302.7038)



Inclusion of Hagedorn states seems to improve agreement with lattice near the transition temperature of 151+-4 MeV

Extreme: fully quenched lattice QCD spectroscopy

In a fully quenched lattice QCD approach, the system transitions at a much higher temperature (~270 MeV) directly from a pure Gluon Plasma potentially to Hagedorn states which subsequently decay into glue-balls, hadronic resonances and ground states



HRG does NOT stop at T=180 MeV !

HagedornStates decay

1. O.P.Transition from glue-plasma to GlueBall-Hagedorn St.

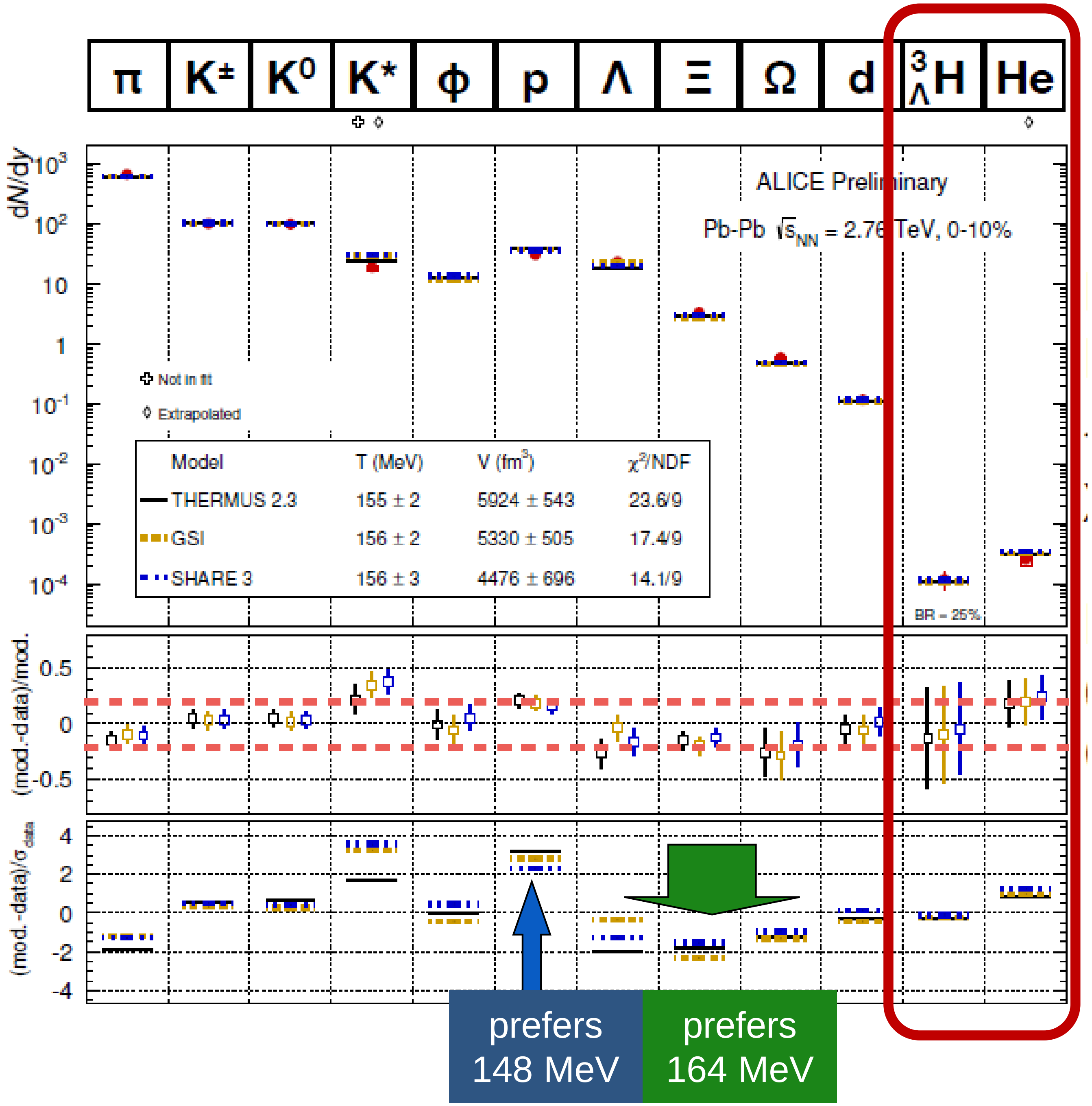
Energy density from Sz. Borsanyi et al.W.B. Wuppertal-Budapest coll
JHEP 1011, 2010,077;
PLB730, 2014, 99

(2+1)- flavor QCD is matched by $N\_f = 3, m_{u,d} = m_s$ at T = 250 MeV

pure gauge, YangMills T_c = 270 MeV

Quenched: W.B. coll.
JHEP 1207, 2012, 056

Hypernuclei are not enhanced relative to thermal model predictions



Model	T (MeV)	V (fm³)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	23.6/9
GSI	156 ± 2	5330 ± 505	17.4/9
SHARE 3	156 ± 3	4476 ± 696	14.1/9

prefers 148 MeV

prefers 164 MeV

Both hypernuclei and molecular states (deuteron, ^{4}He) are well described by a thermal model with a temperature around 156 MeV. Hypernuclei are dominated by light quark properties

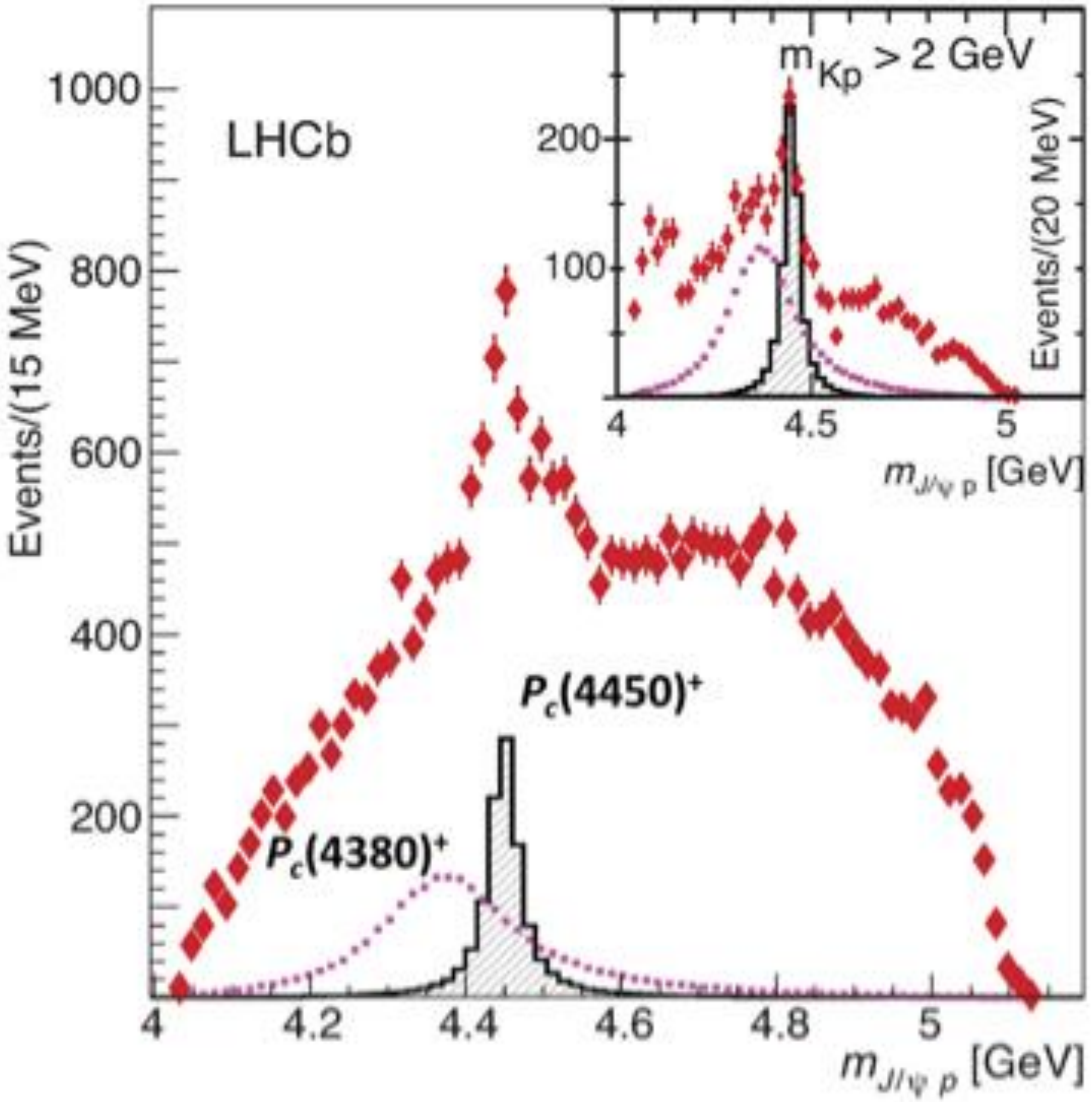
Bound states with binding energies in the keV range are described by thermodynamics frozen at 156 MeV ?

Is the entropy/baryon indeed fixed at freeze-out and the yields need to reflect the chemical yields even if the particle dissolves in the dense hadronic phase ?

Penta- and Tetra-quarks from LHCb

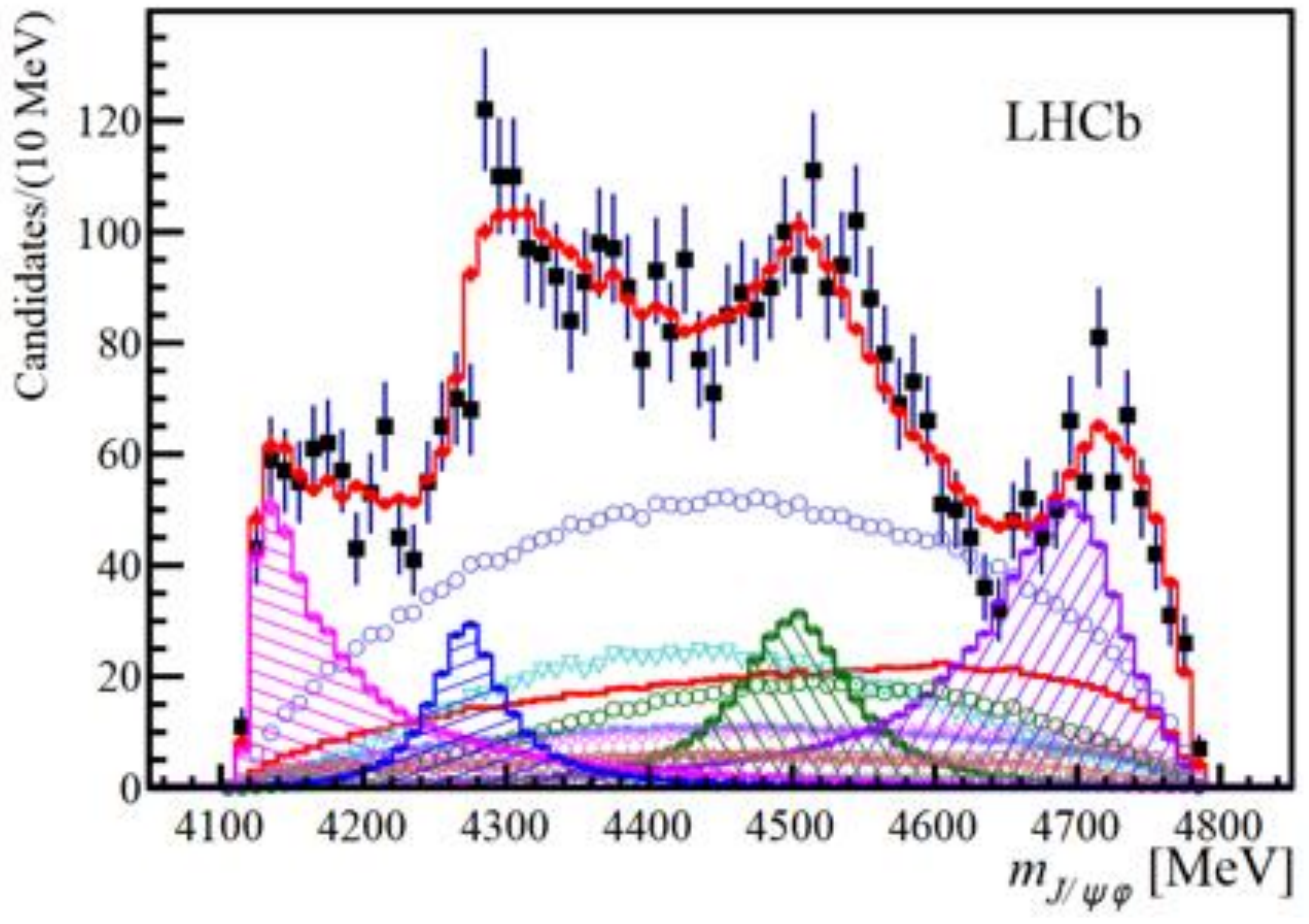
Penta-quark in 2015, 9σ evidence by 2016

In the charm sector: J/ψ p resonance
In Λ_b decays to J/ψ p K^-



Tetra-quarks in 2016

In the charm sector: J/ψ ϕ resonance
In B^+ decays to J/ψ ϕ K^+



Why nothing in the strange sector ?

Famous pentaquark candidate from NA49 at the CERN-SPS

in 2008, in the Ξπ channels, quark content: d s d s ubar, m = 1860 Mev/c^2

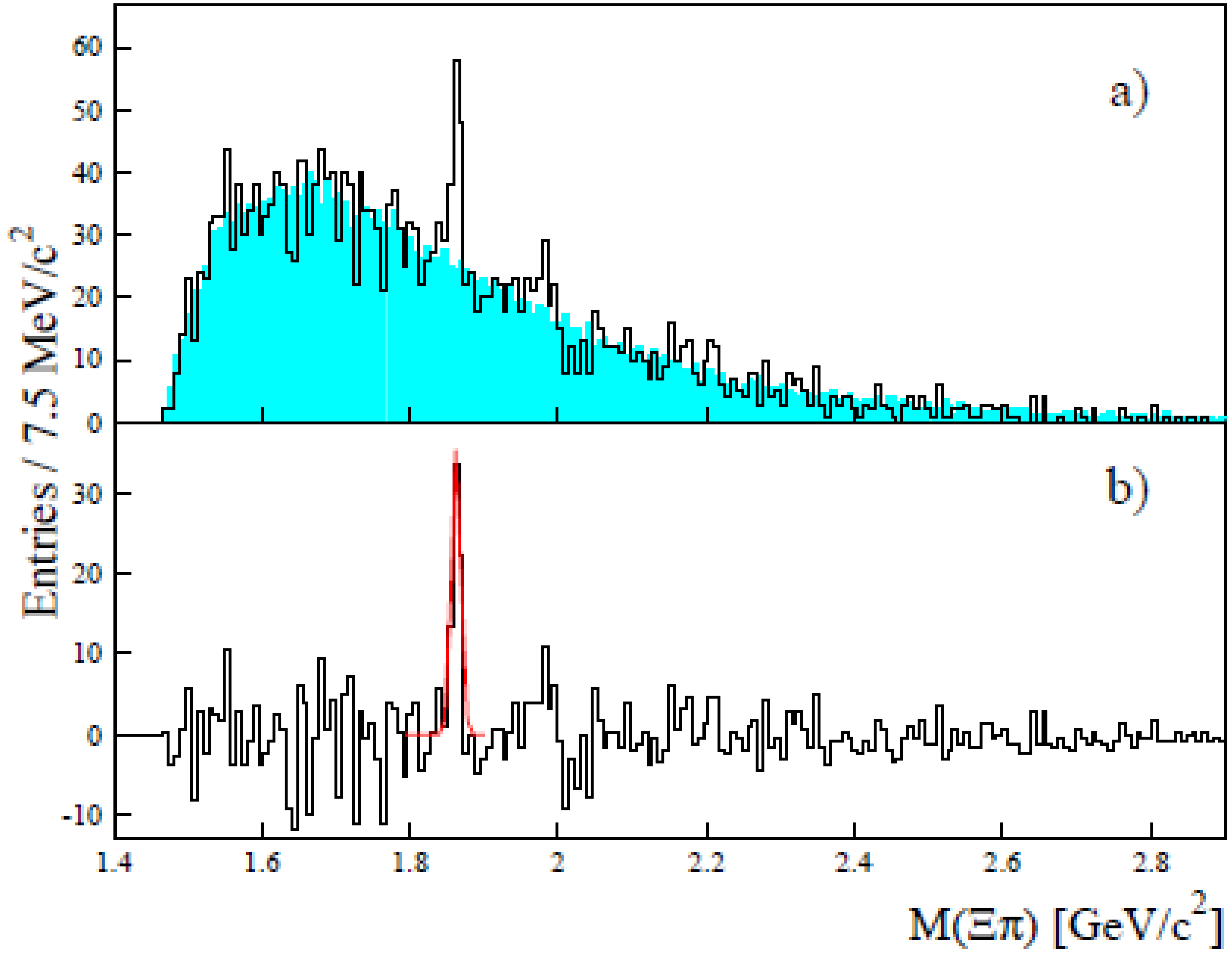
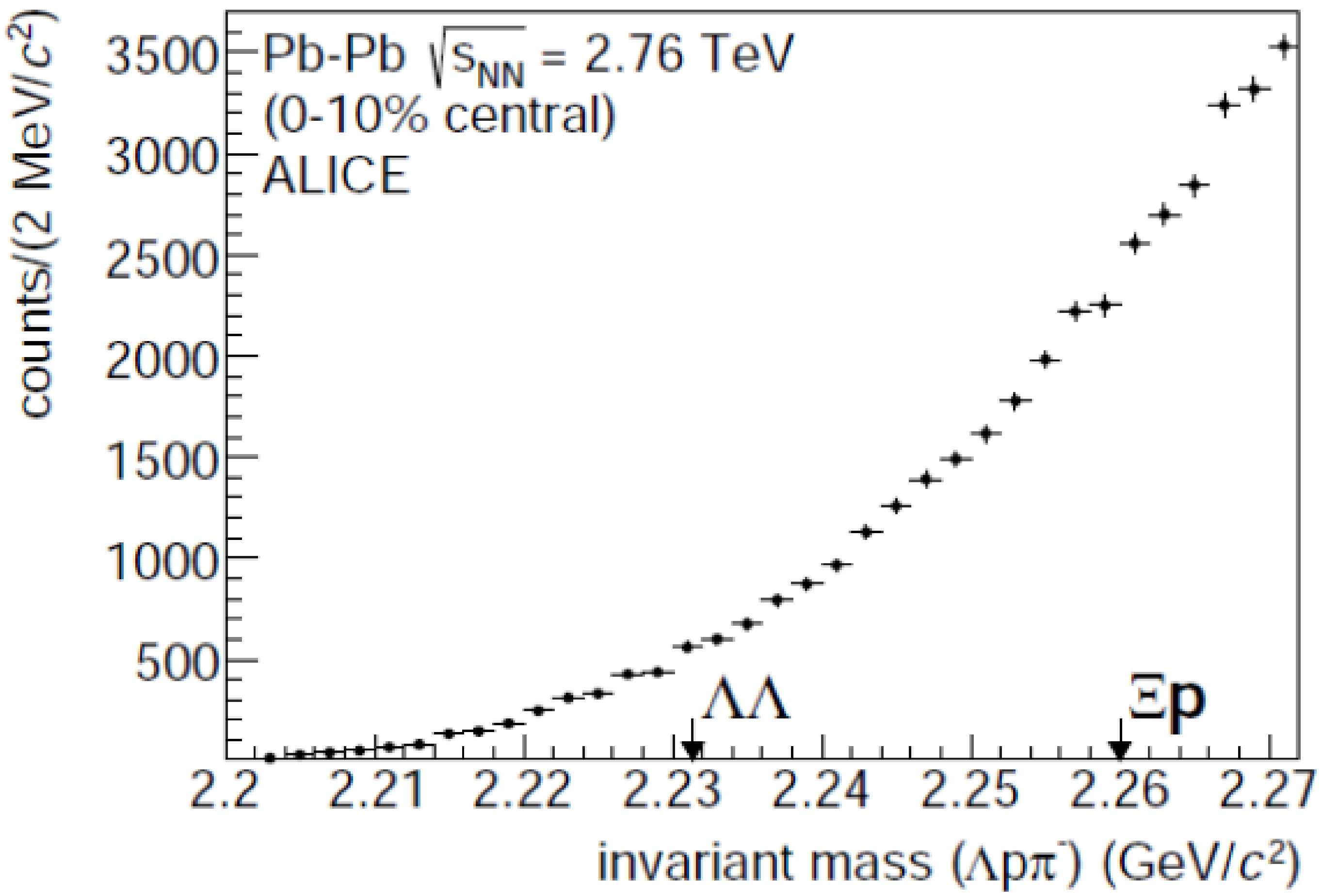


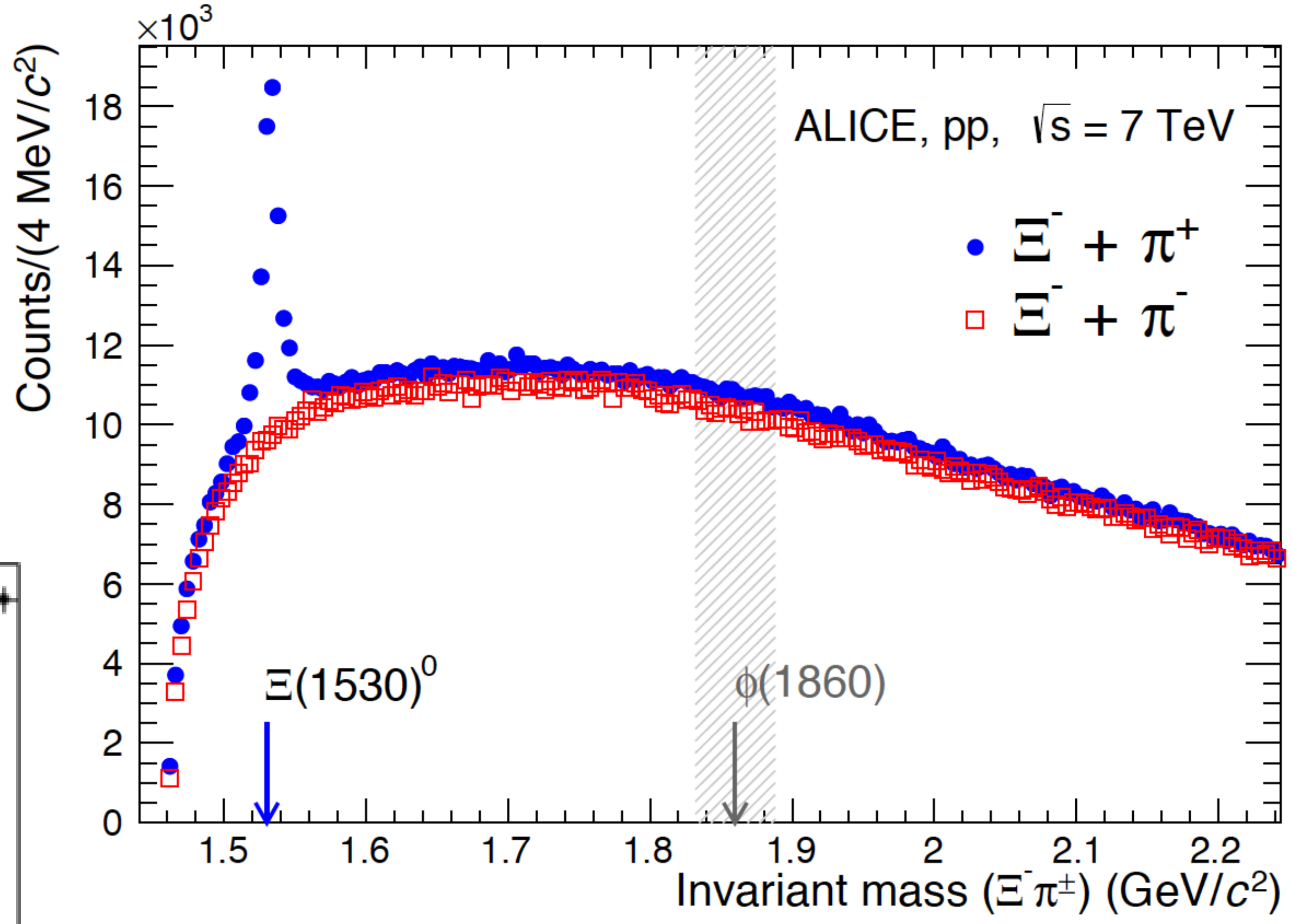
FIG. 3: (Color online) (a) The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$ and $\overline{\Xi}^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalised mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.

Never confirmed

No evidence in strange sector at the LHC

Search for strange penta-quarks or di-baryons in ALICE data





Conclusions / Outlook

- High precision (continuum limit) lattice QCD susceptibility ratios indicate *flavor separation in the crossover from the partonic to the hadronic matter.*
- There are hints, when comparing to hadron resonance gas and PNJL calculations, that this could lead to a short phase during the crossover where strange resonance formation is dominant.

- If the abundance of strange quarks is sufficiently high (LHC) this could lead to *enhancements in the strange hadron yields (evidence from ALICE)* and it could lead to *strangeness clustering (exotic states: dibaryons, strangelets)* or *higher mass strange Hagedorn states* (as predicted by Quark Model).

- Rare resonances in heavy ion experiments are better measured in pp reactions, but the underlying theory requires a deconfined thermalized system for the yields to be enhanced.
- There is evidence from the LHC that a thermal deconfined system has been formed in high multiplicity pp or pPb collisions.

- ALICE and STAR will continue to search for high mass resonances and multi-quark states in the strange sector.