Excited Hyperon Possibilities in Relativistic Heavy Ion Collisions

R. Bellwied (University of Houston)

YSTAR Workshop
November 16-17, 2016
Jefferson National Laboratory

YSTAR 2016 Excited Hyperons in QCD Thermodynamics at Freeze-Out

YSTAR 2016 Excited Hyperons in QCD Thermodynamics at Freeze-Out

Outline

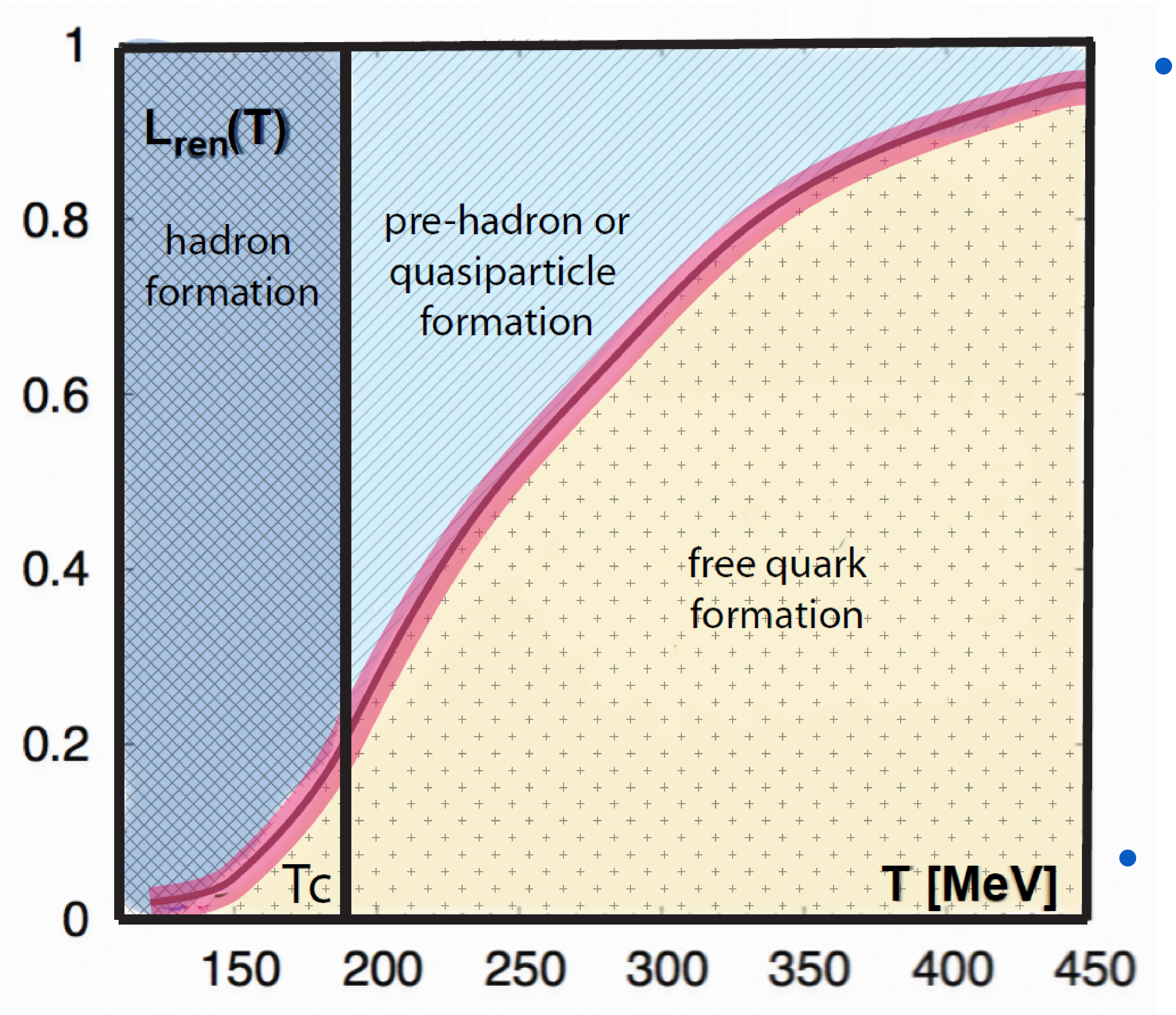
- Theoretical motivation in a nutshell
  - The role of flavor during the QCD transition
  - Evidence for sequential hadronization
  - Clusters, Hagedorn States, Resonances, Quasi-particles

- 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

- In a regime where we have a smooth crossover why would there be a single freeze-out surface ?
- In a regime where quark masses (even for the s-quark) could play a role why would there be single freeze-out surface ?
- We can calculate thermodynmic quantities for a static equilibrated system at a fixed temperature

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:

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

Measurable ratios:

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

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

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

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

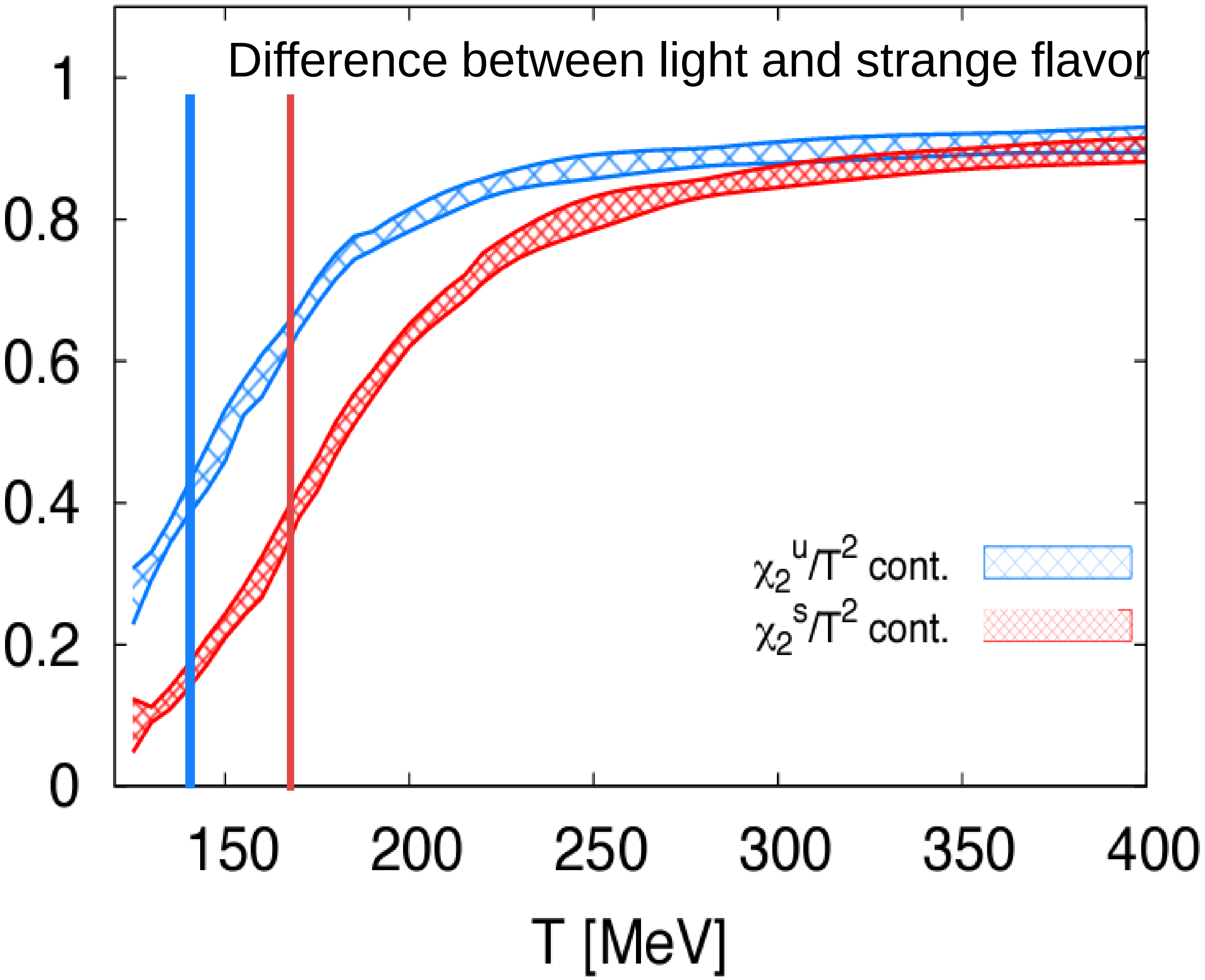
To measure μ_B:

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

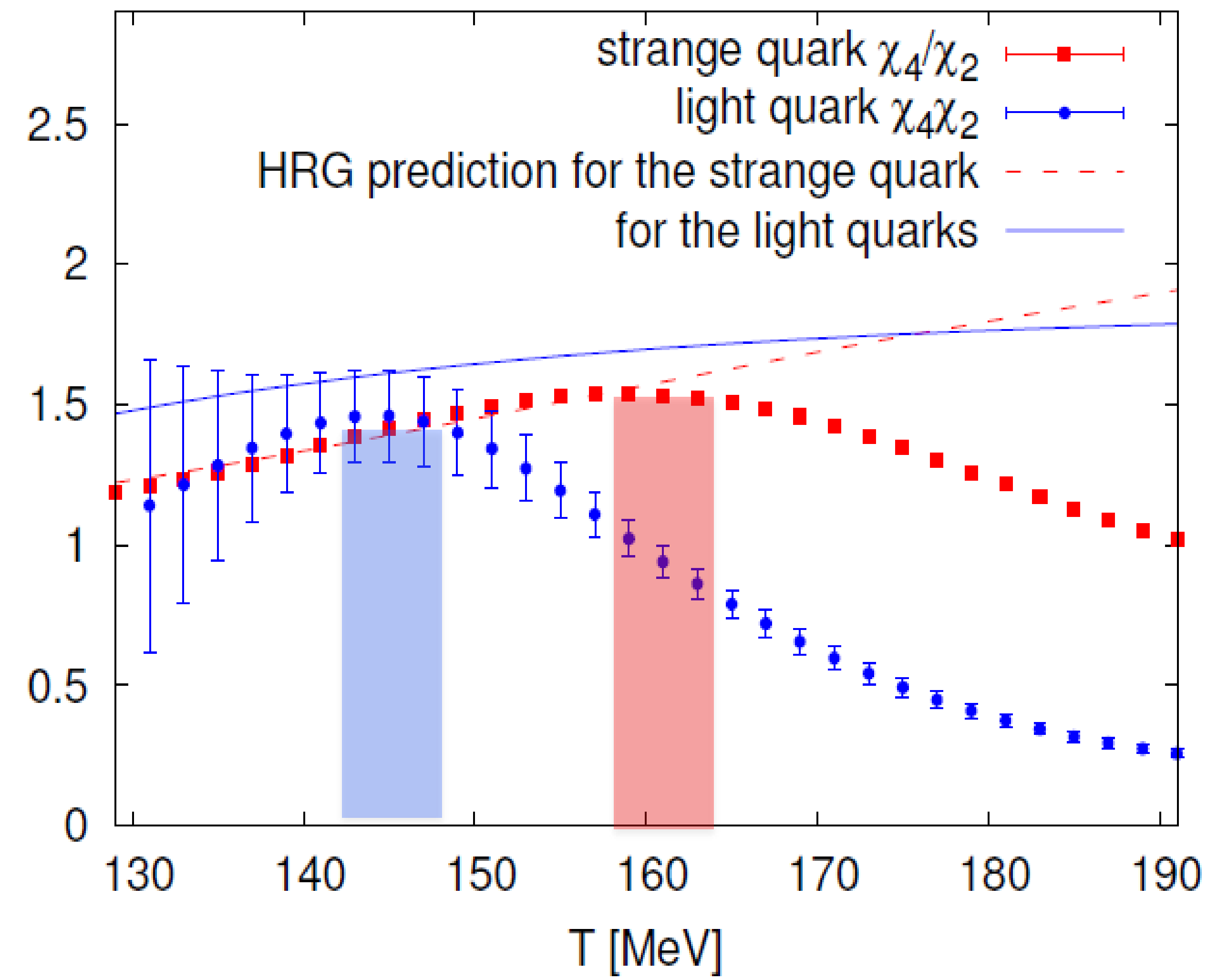
To measure T:

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

Indication of flavor dependence in susceptibilities and susceptibility ratios



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



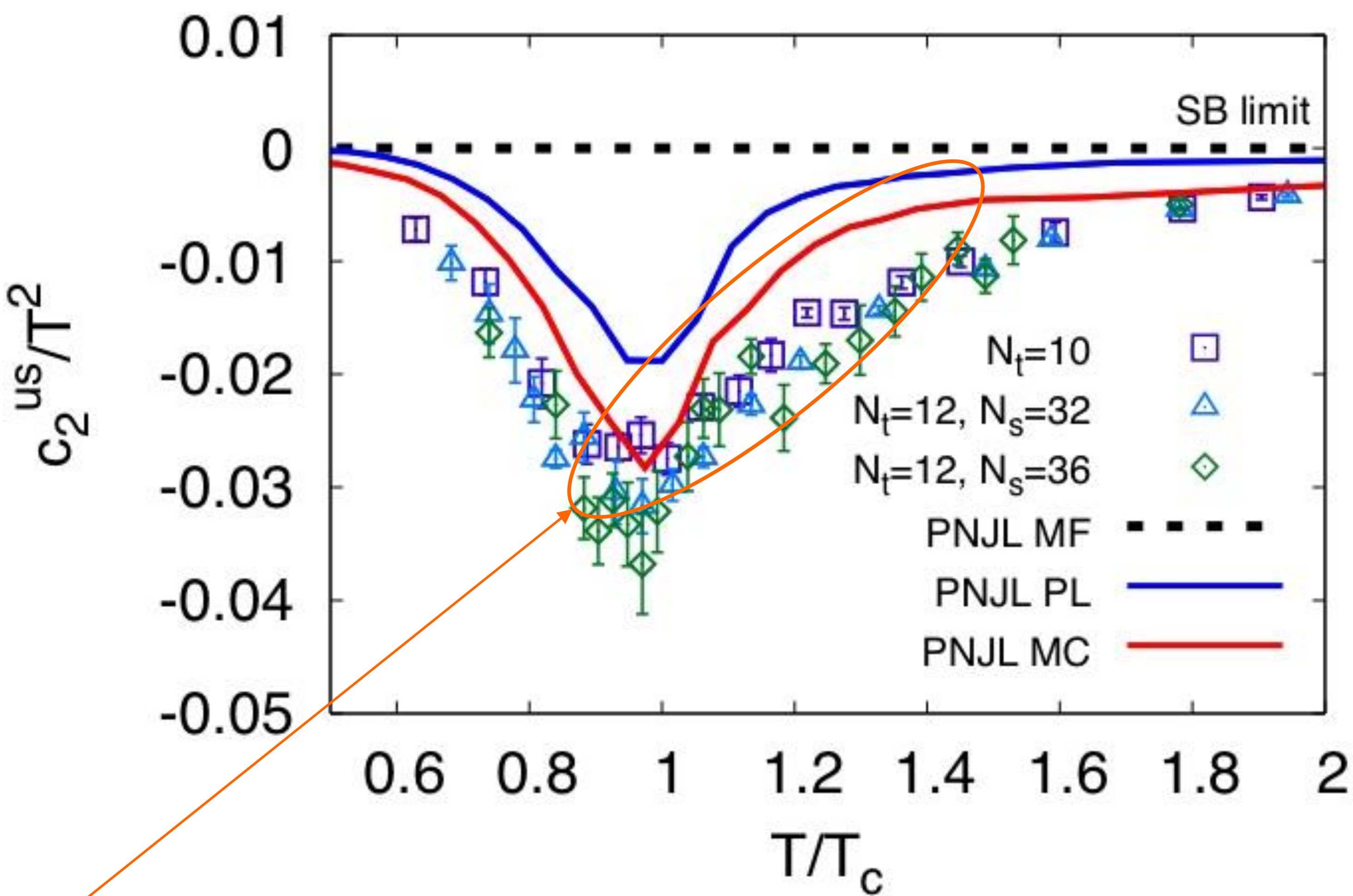
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

Indication of sequential hadronization ?

$$\kappa_B \sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)} \left[\frac{1 + \frac{1}{2}\frac{\chi^B_6(T)}{\chi^B_4(T)}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi^B_4(T)}{\chi^B_2(T)}(\mu_B/T)^2 + \ldots} \right]$$

Indication of bound states in non-diagonal susceptibility correlators *(C. Ratti et al., PRD 85, 014004 (2012))*

Comparison of lattice to PNJL

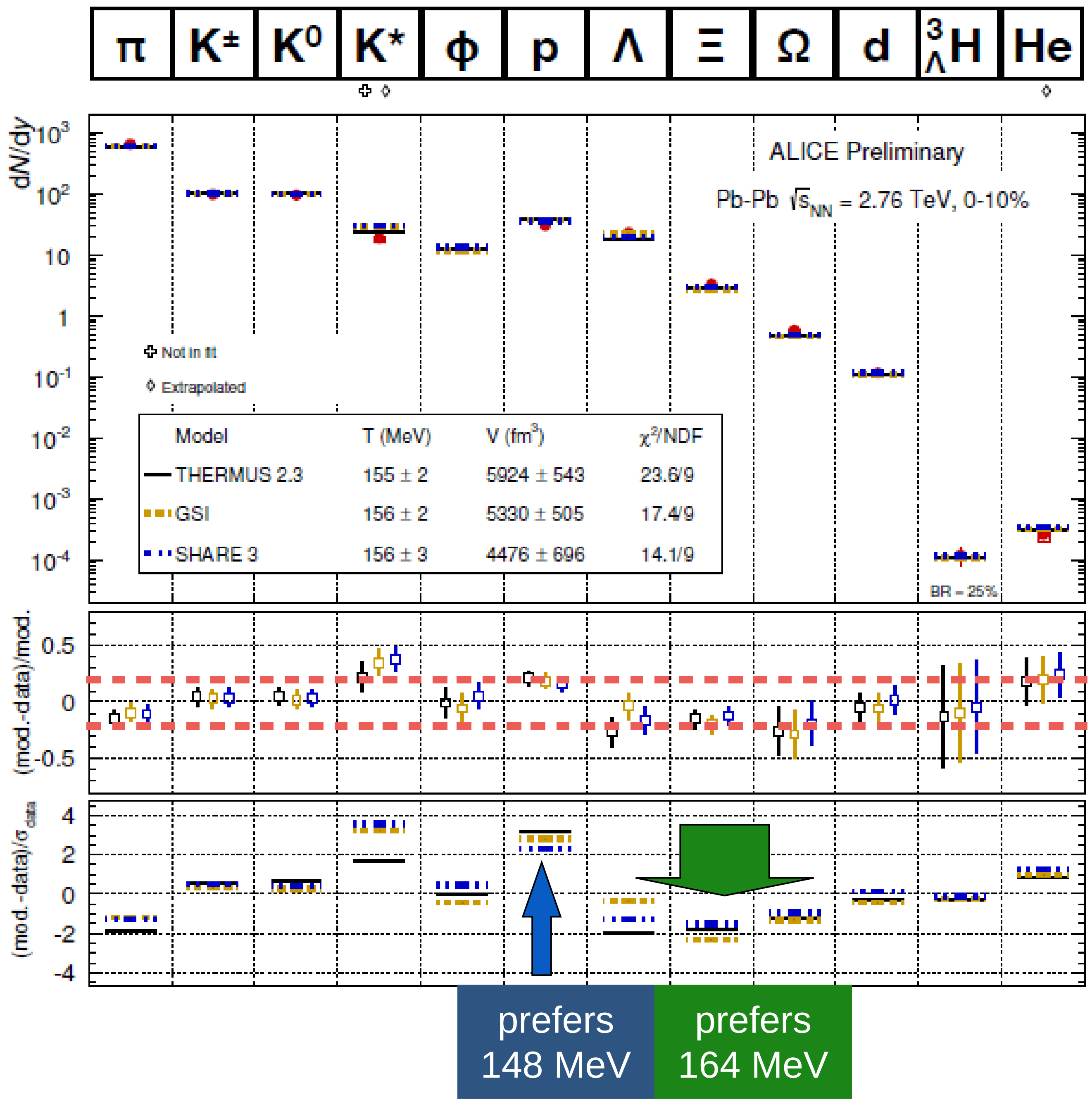


<u>PNJL variations</u>

PNJL-MF:
pure mean field calculation
PNJL-PL:
mean field plus Polyakov loop fluctuations
PNJL-MC:
mean field plus all fluctuations (incl. chiral and Kaon condensate fluctuations)

Conclusion: even the inclusion of *all possible flucutations* is *not sufficient* to describe lattice data above Tc.
<u>There has to be a contribution from bound states</u>

Experimental evidence:
SHM model comparison based on yields



This looks like a good fit, but it is not

χ^2/NDF improves from 2 to 1 when pions and protons are excluded.

Fit to pions and protons alone yield a temperature of 148 MeV.

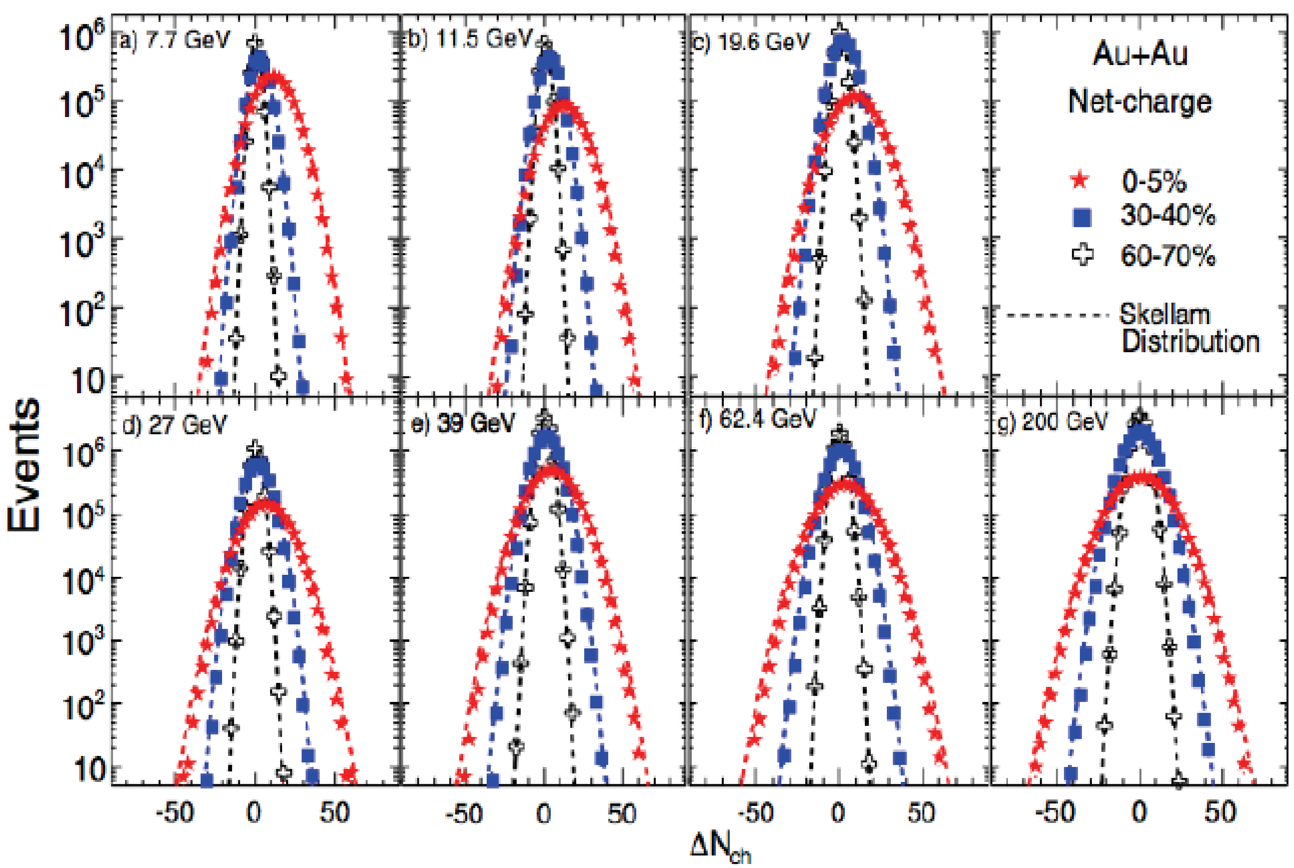
<u>Several alternate explanations:</u>

- Inclusion of Hagedorn states
- Non-equilibrium fits
- Baryon annihilation
- <u>*Different T_{ch} for light and strange*</u>

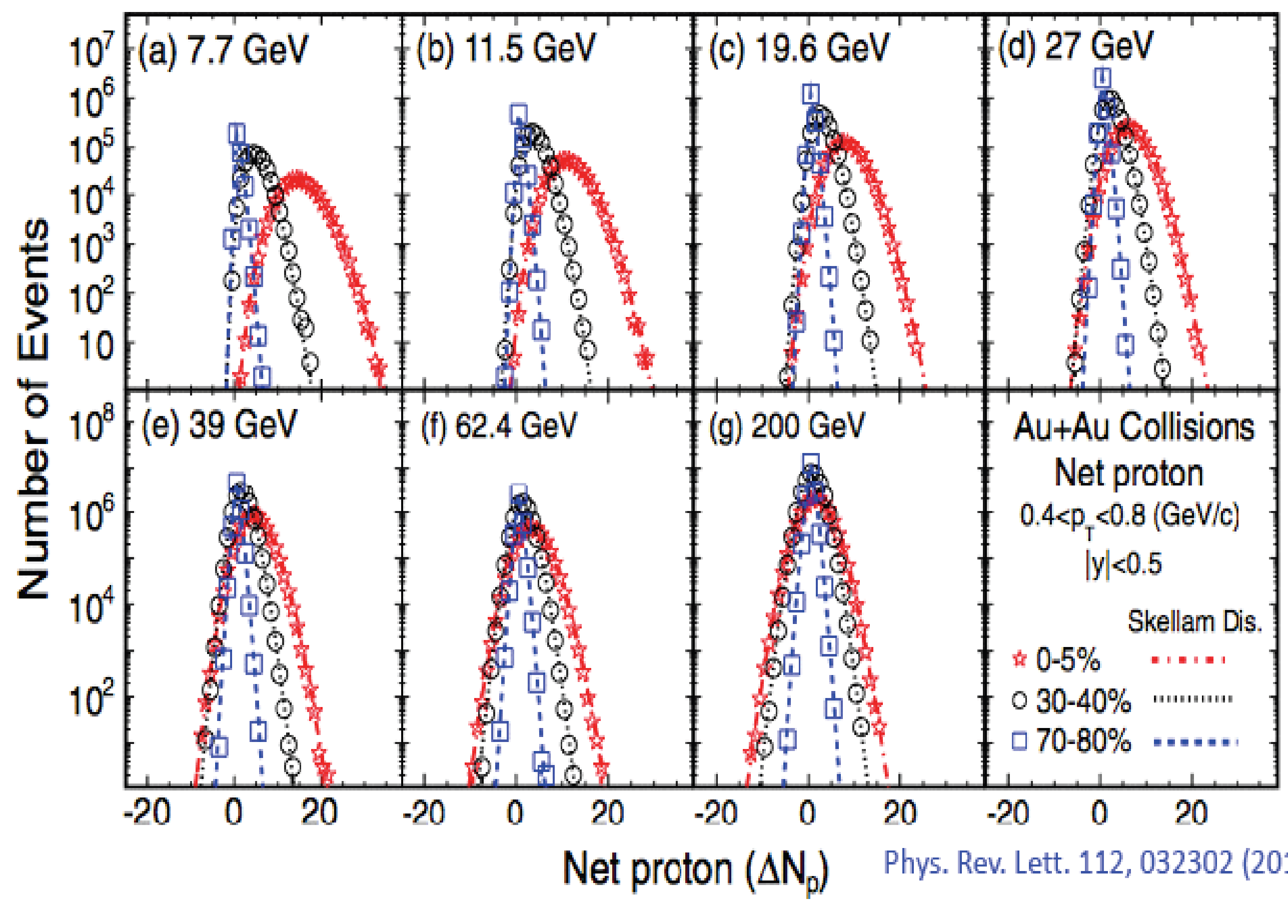
Is a common freeze-out surface that important ? Is it supported by lattice QCD ?

Measure net-distributions and calculate moments in STAR

Net-charge distribution



Net-Proton distribution



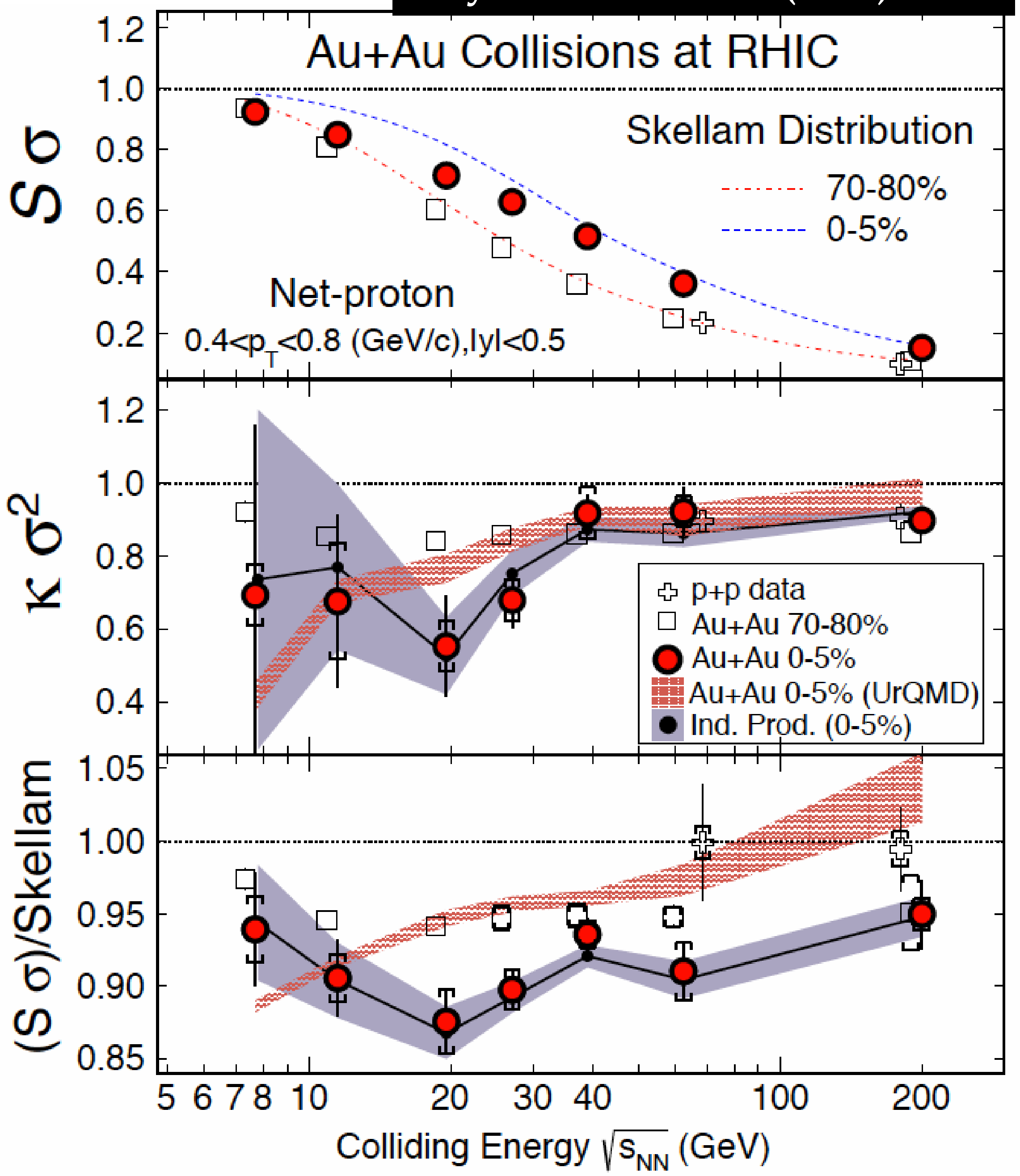
Phys. Rev. Lett. 112, 032302 (2014).

STAR distributions: the means shift towards zero from low to high energy

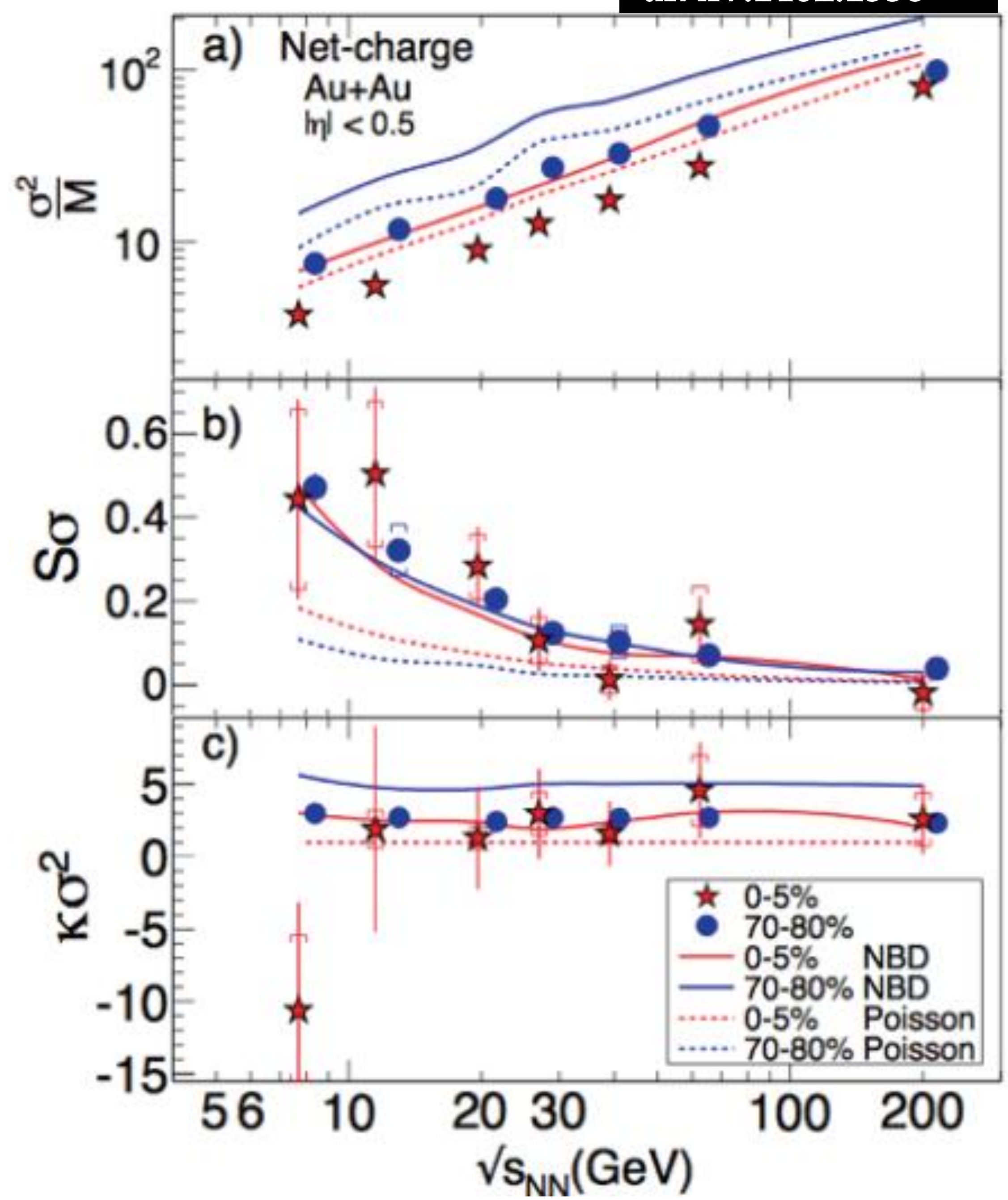
Then: calculate moments (c1-c4: mean, variance, skewness, kurtosis)

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

Phys. Rev. Lett. 112 (2014) 32302



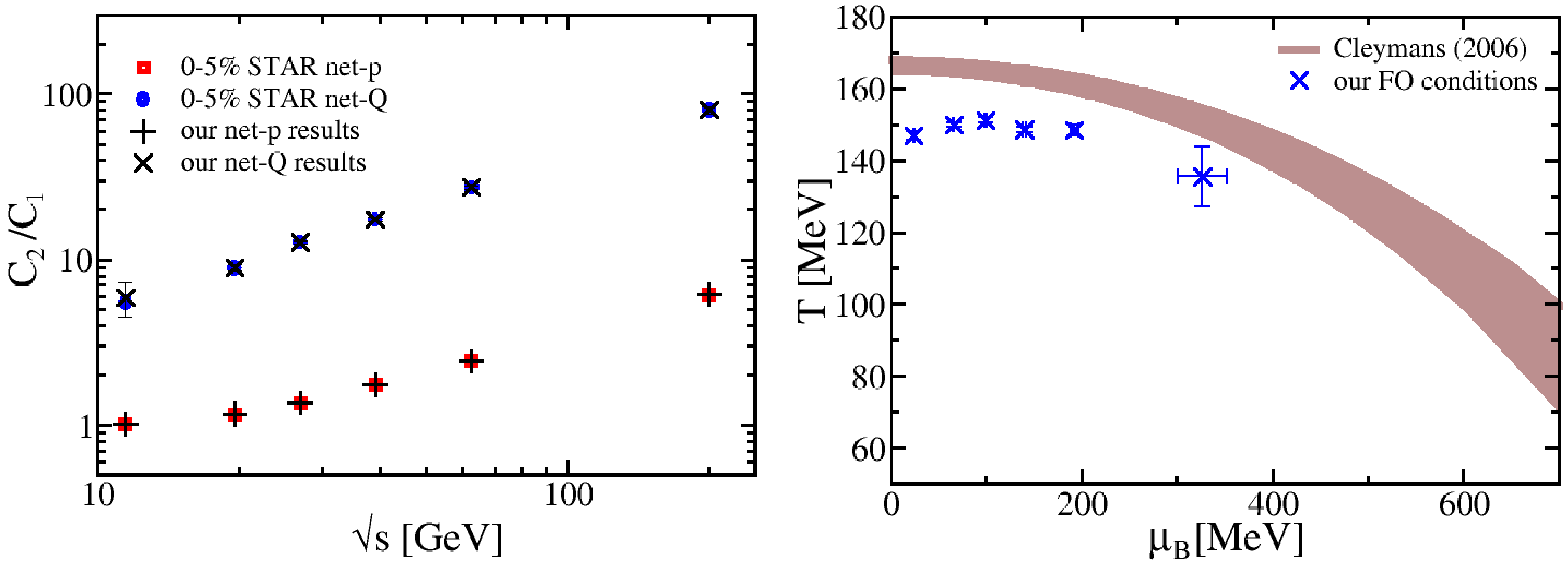
arXiv:1402.1558



HRG analysis of STAR results (charge & proton)

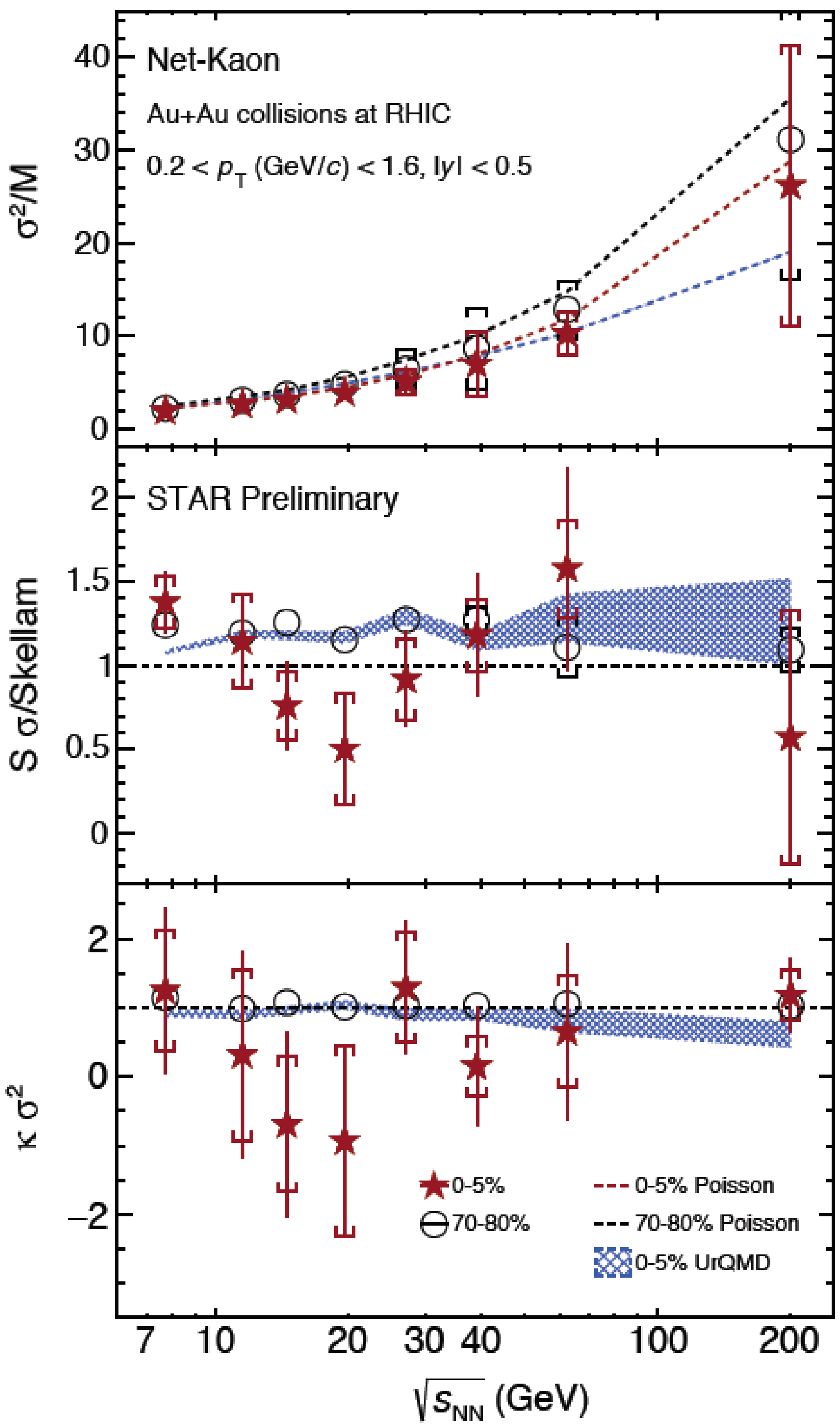
Alba, Bellwied, Bluhm, Mantovani, Nahrgang, Ratti (PLB (2014), arXiv:1403.4903)

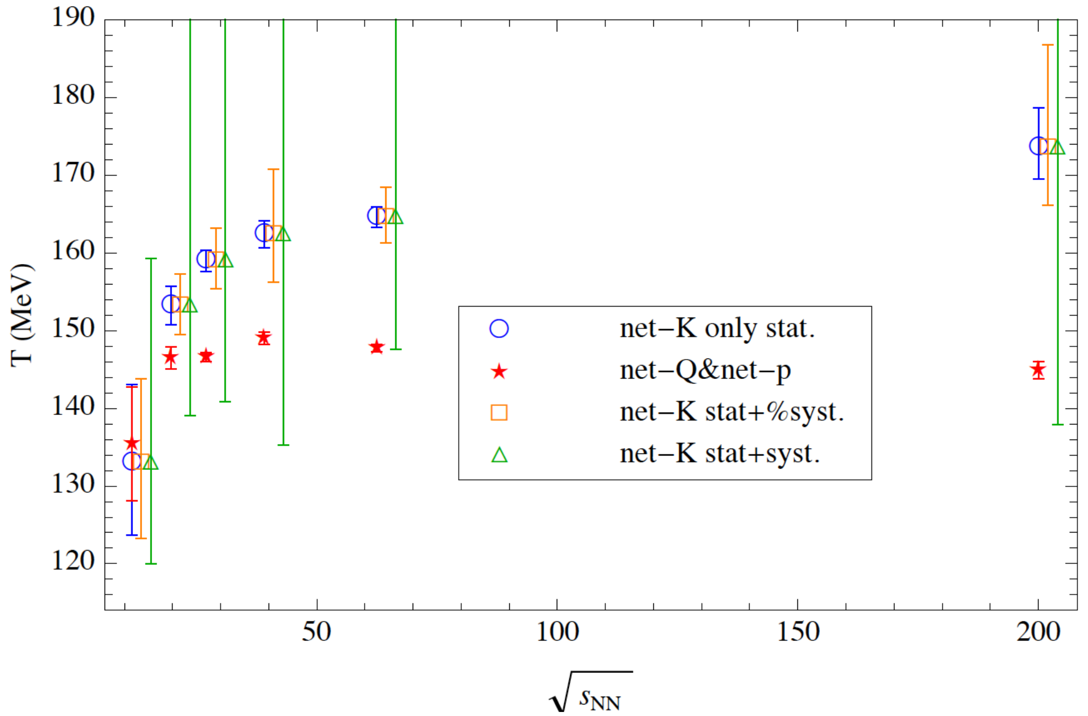
HRG in partial chemical equilibrium (resonance decays and weak decays taken into account).
Hadrons up to 2 GeV/c^2 mass taken into account (PDG), experimental cuts applied.
For protons full isospin randomization taken into account (Nahrgang et al., arXiv:1402.1238)

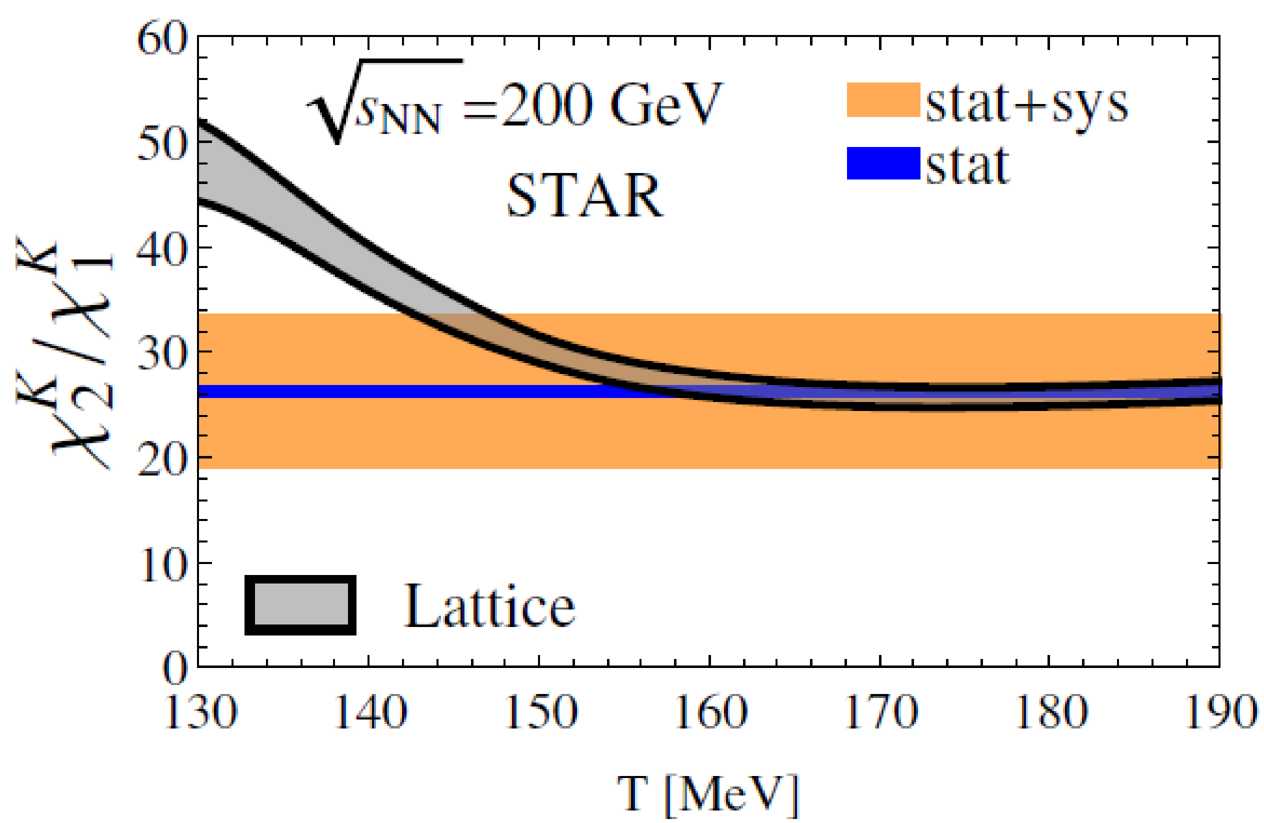


Result: intriguing 'lower' freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

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

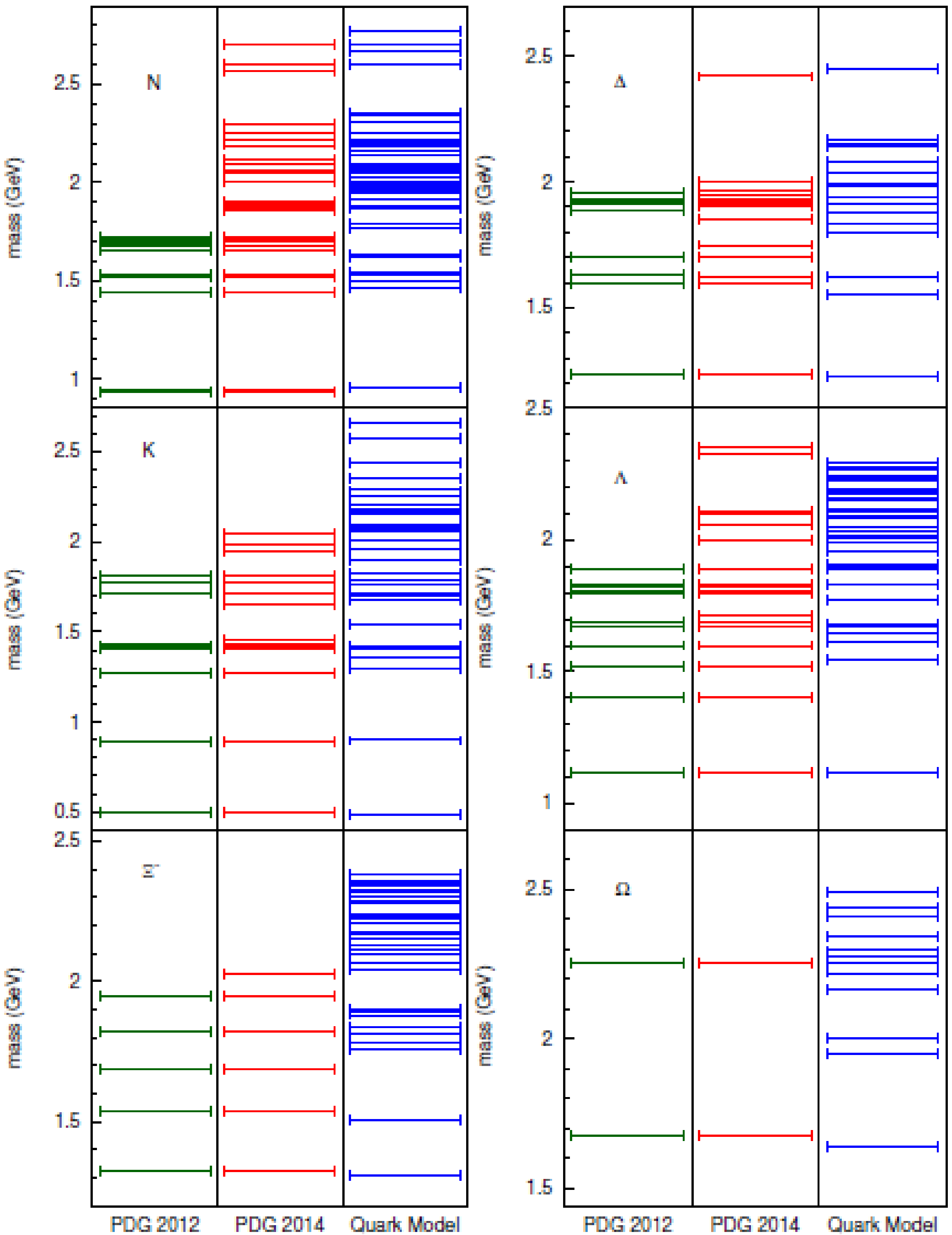






Noronha-Hostler et al., arXiv:1607.02527

So what can happen between 148 and 164 MeV ?



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

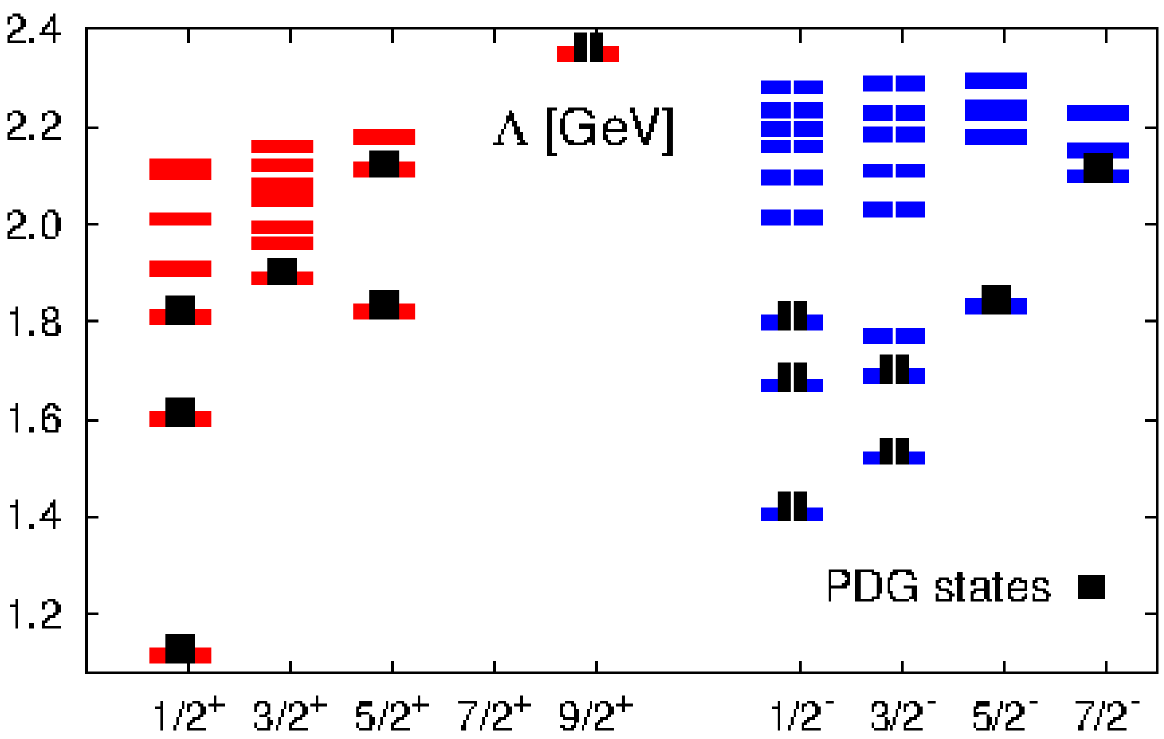
Strangeness wants to freeze-out, light quarks do not

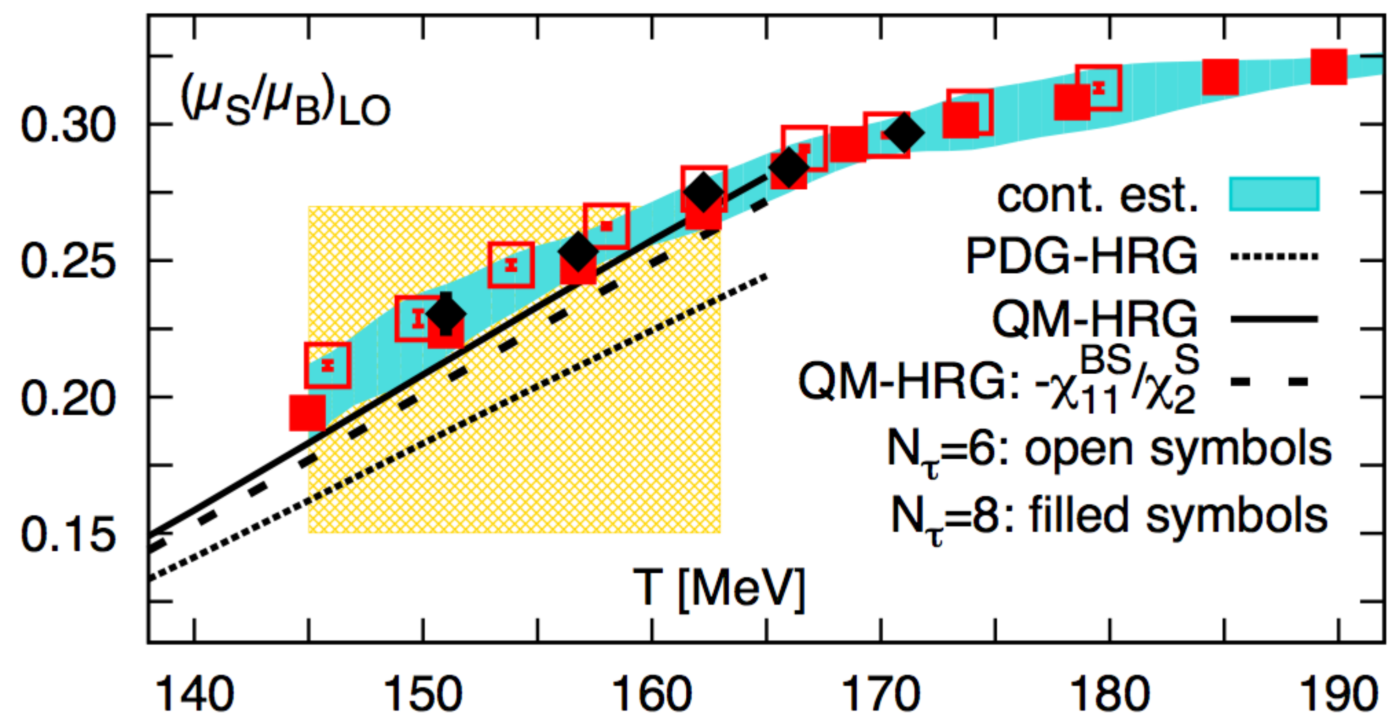
Can there be measurable effects ?

Simple strangeness enhancement of the strange ground states or additional strange hadronic resonances or exotic quark configurations with strangeness ?

Excited states within the Quark Model

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)



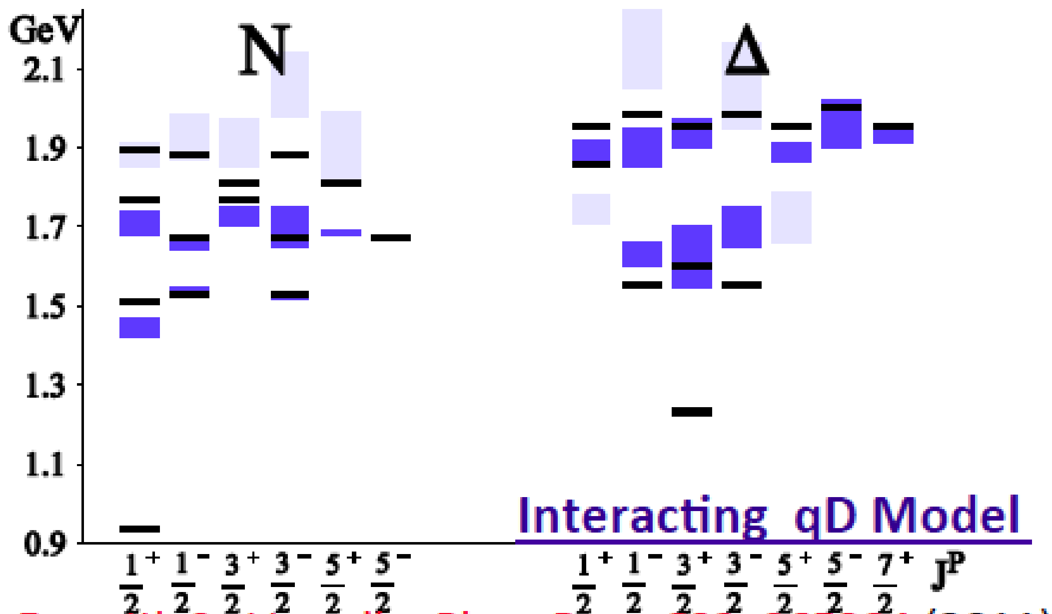


But those effects need to be consistently applied to all correlators that are possibly affected by higher lying strange states and they need to take into account all possible decay **modes (see talk by C. Ratti)**

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 ?)

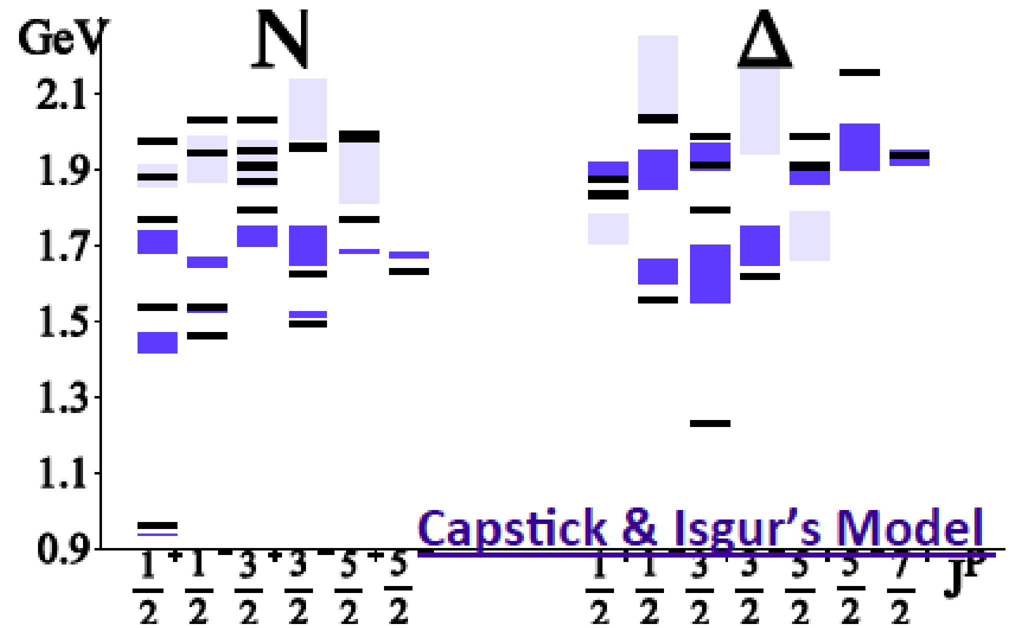
Plot from Elena Santopinto

Non-strange baryons. Complete spectrum



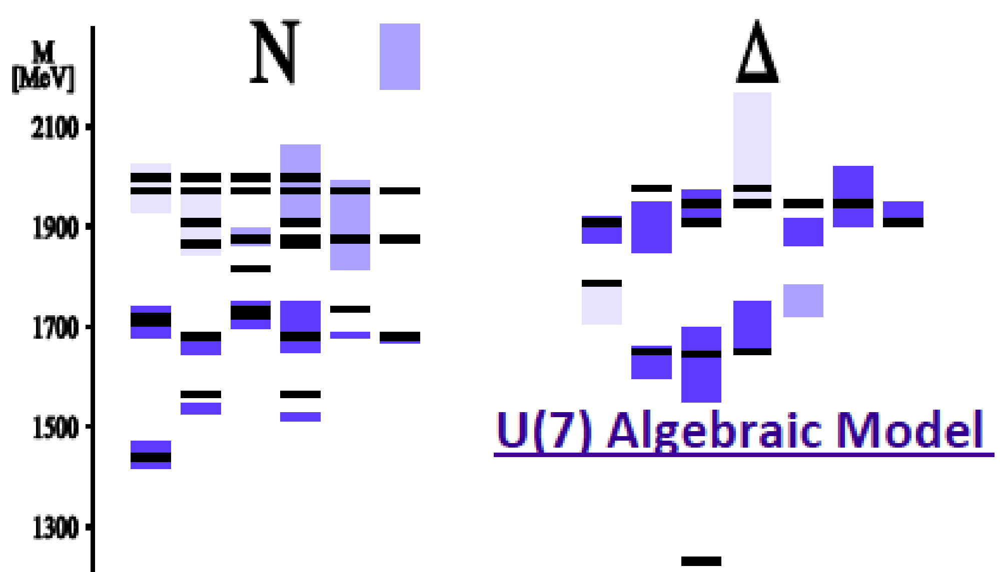
Ferretti, S., Vassallo ,Phys. Rev.. C83, 065204 (2011)
E.S.,Phys. Rev. C 72, 022201(R) (2005).

0 missing resonances



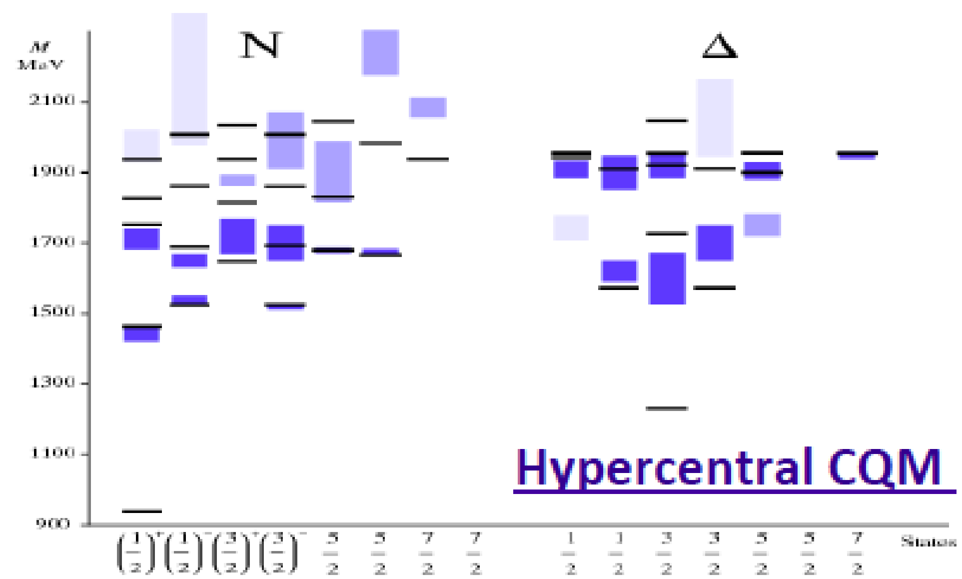
Capstick and Isgur, *Phys. Rev. D34, 2809.*

8 missing resonances



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

18 missing resonances



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

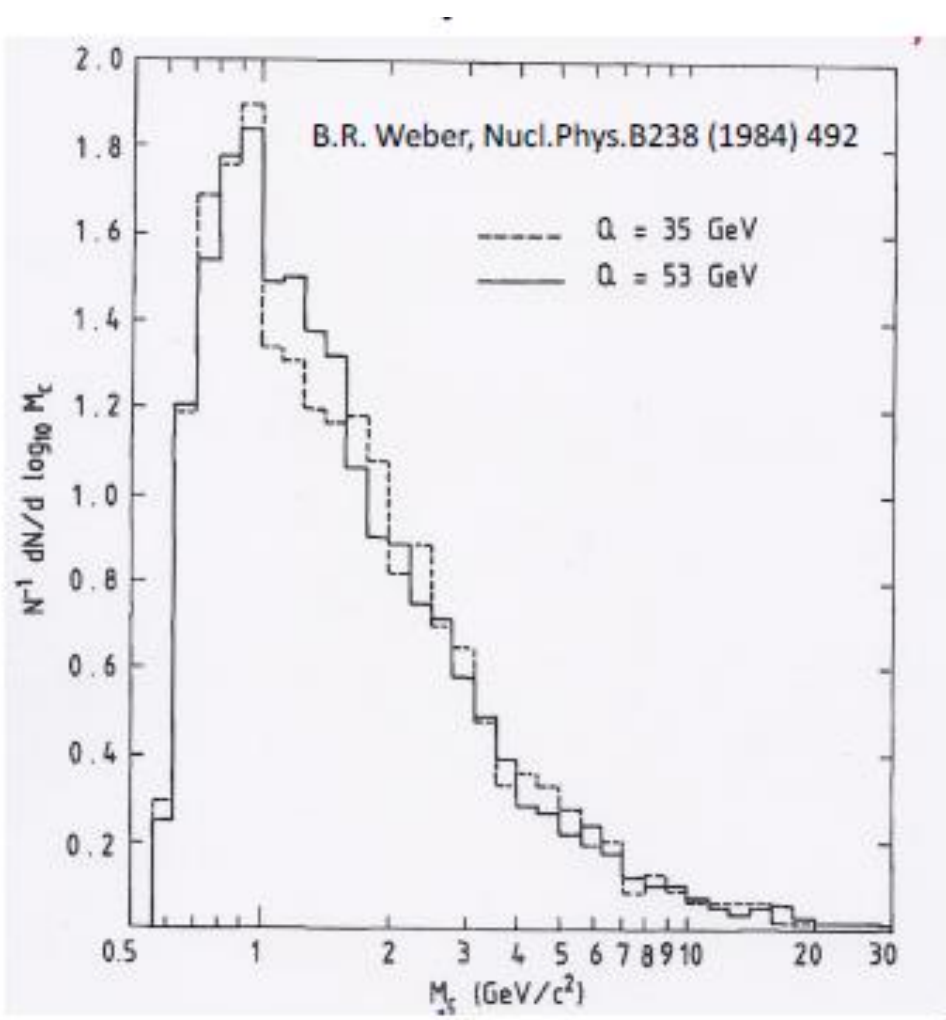
9 missing resonances

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

Color-neutral configurations in different phases

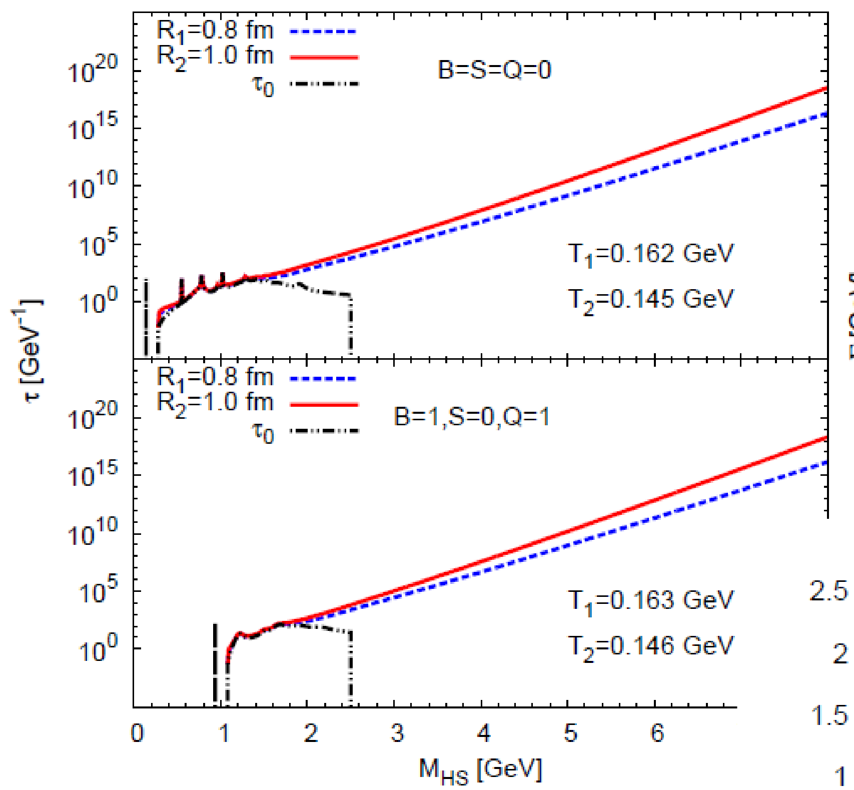
In the deconfined phase:

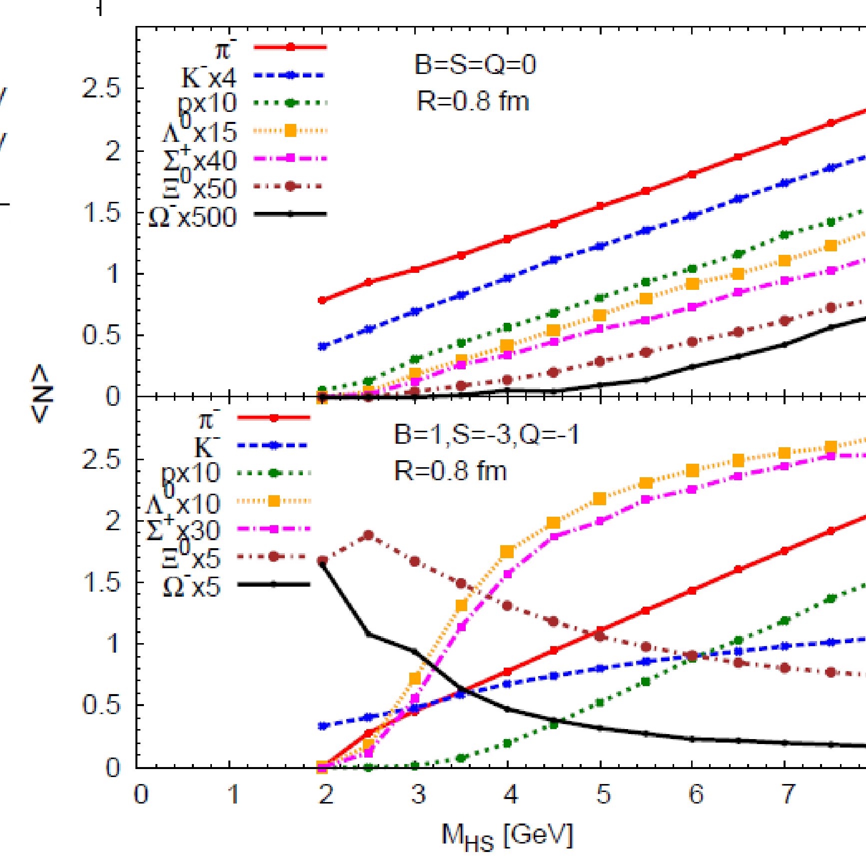
Veneziano / Webber model: cluster formation in deconfined phase = HERWIG event generator (color neutral clusters)



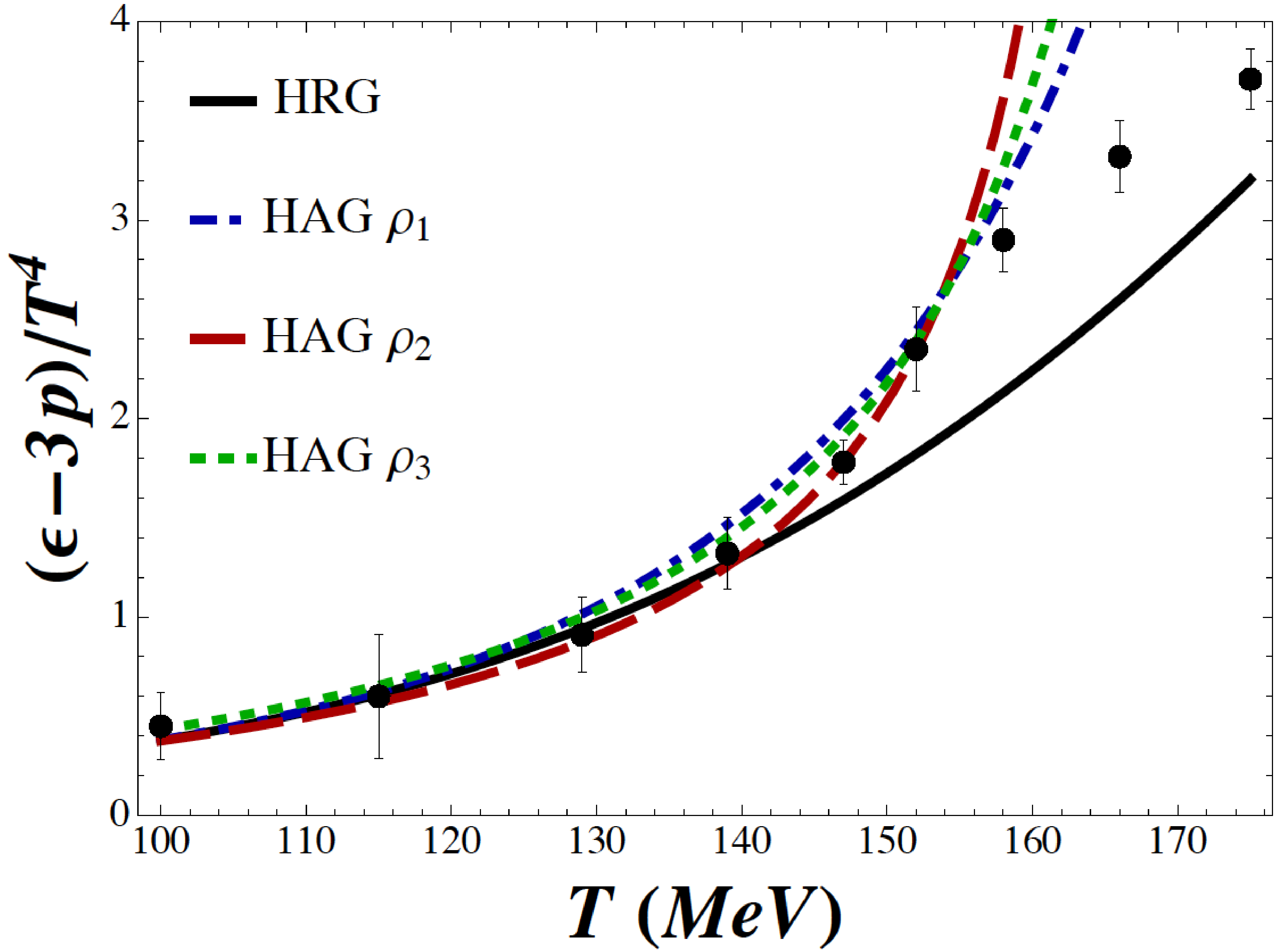
In the hadronic phase:

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)

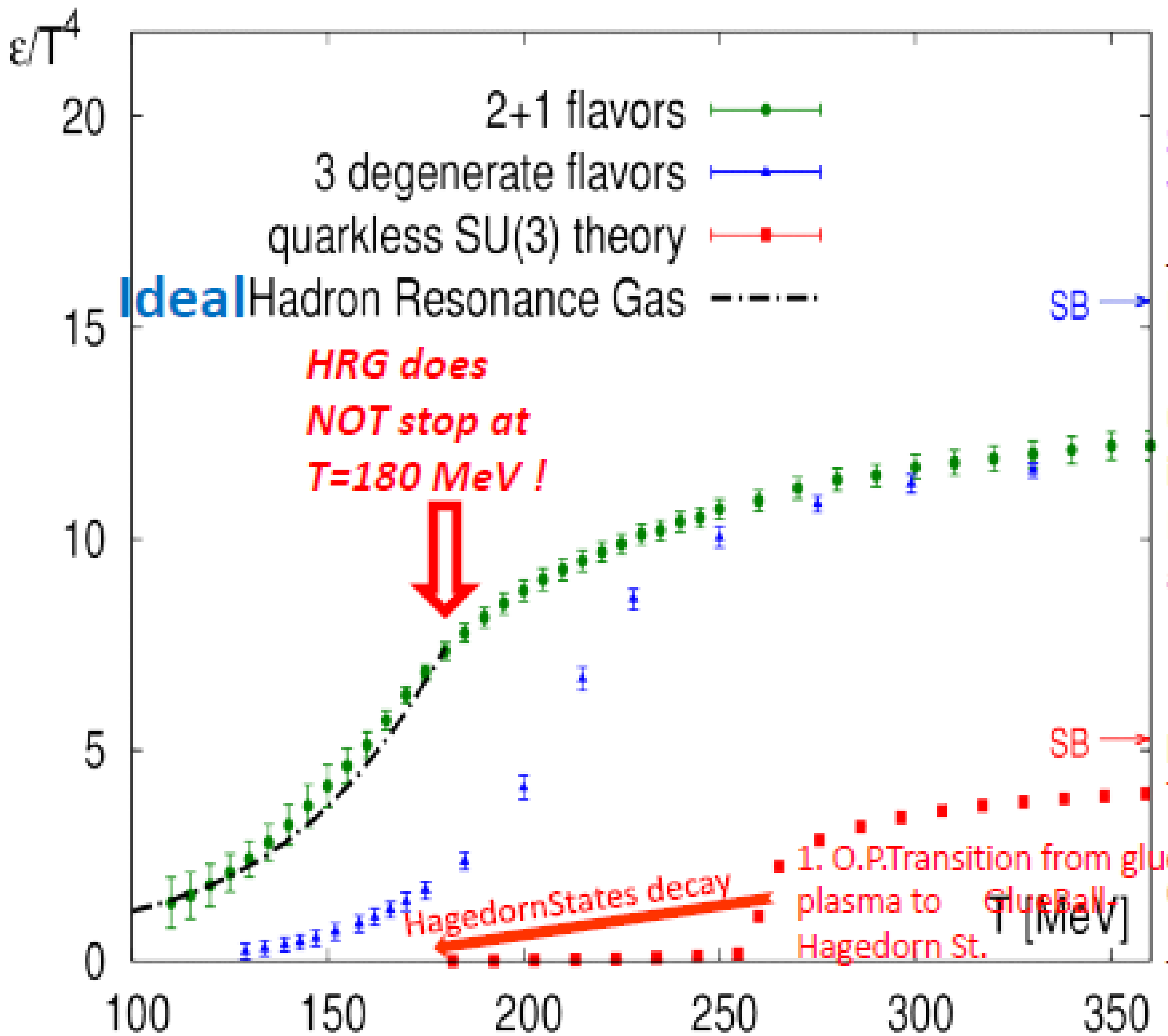


Inclusion of Hagedorn states seems to improve agreement with lattice near the transition temperature of 151+-4 MeV **(see talk by J. Noronha-Hostler)**

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

(see talk by Paolo Alba).



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

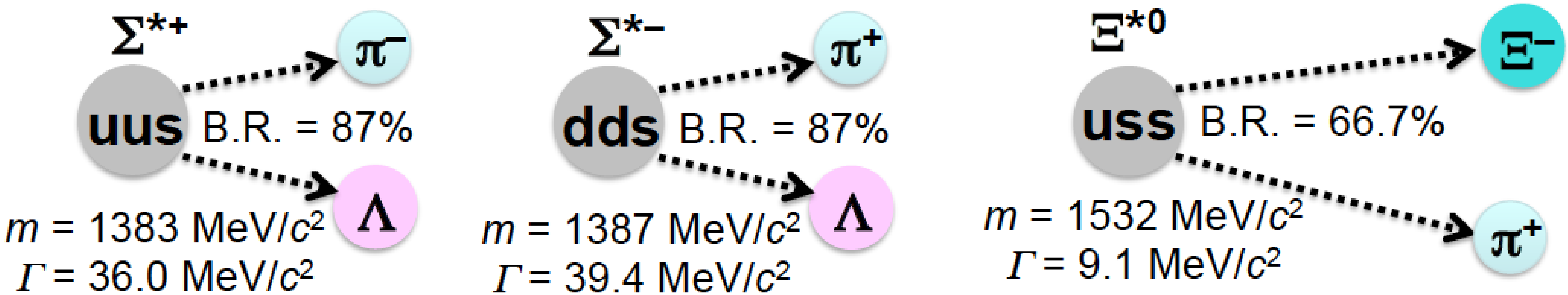
Relevant data from ALICE (see Benjamin's talk)

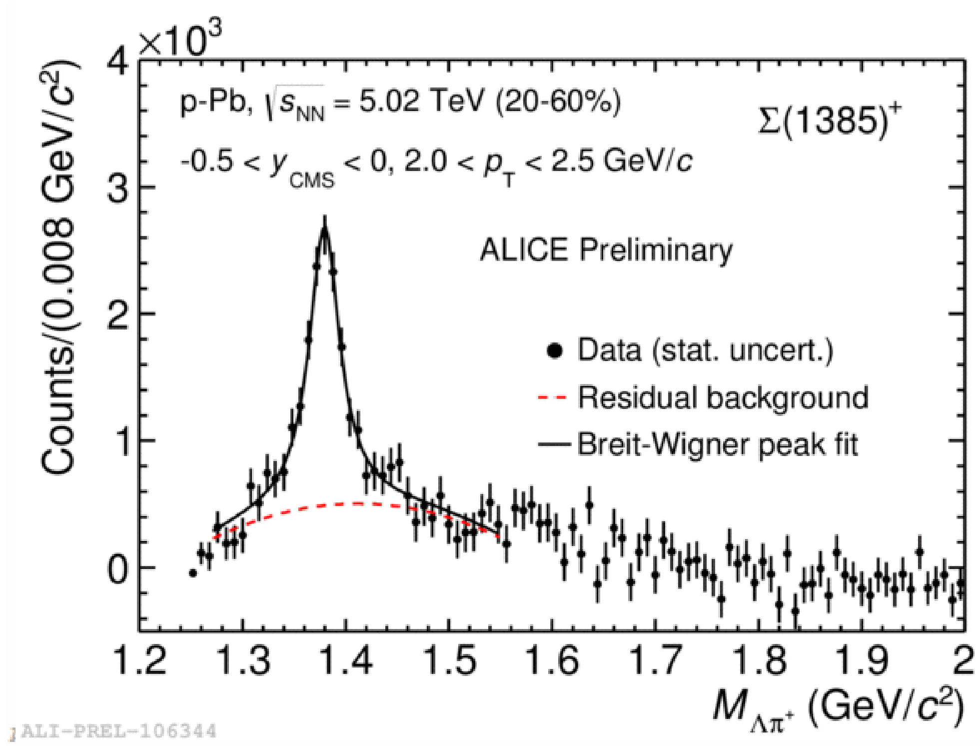
Resonances measured in pp (0.9, 2.76, 7, 13 TeV) , p–Pb (5.02 TeV), and Pb–Pb (2.76, 5.02 TeV) collisions

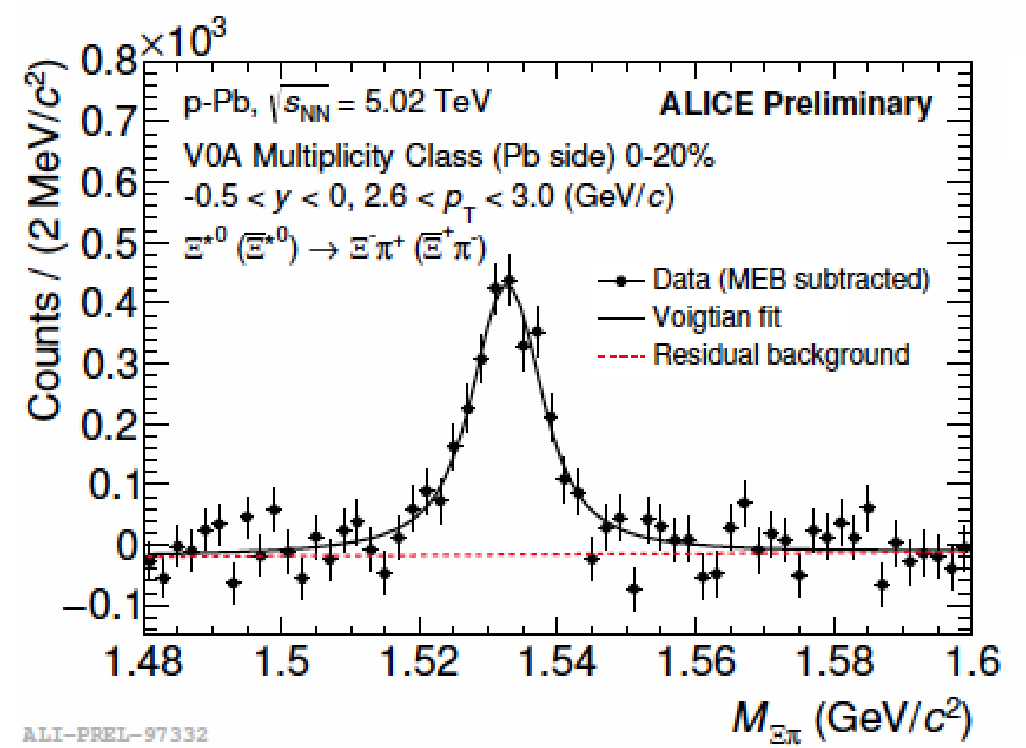
Particle	**Mass (MeV/c^2)**	**Width (MeV/c^2)**	**Decay**	**Branching Ratio (%)**
ρ^0	770	150	$\pi^-\pi^+$	100
K^{*0}	896	47.4	π^-K^+	66.7
ϕ	1019	4.27	K^-K^+	48.9
Σ^{*+}	1383	36.0	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

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})

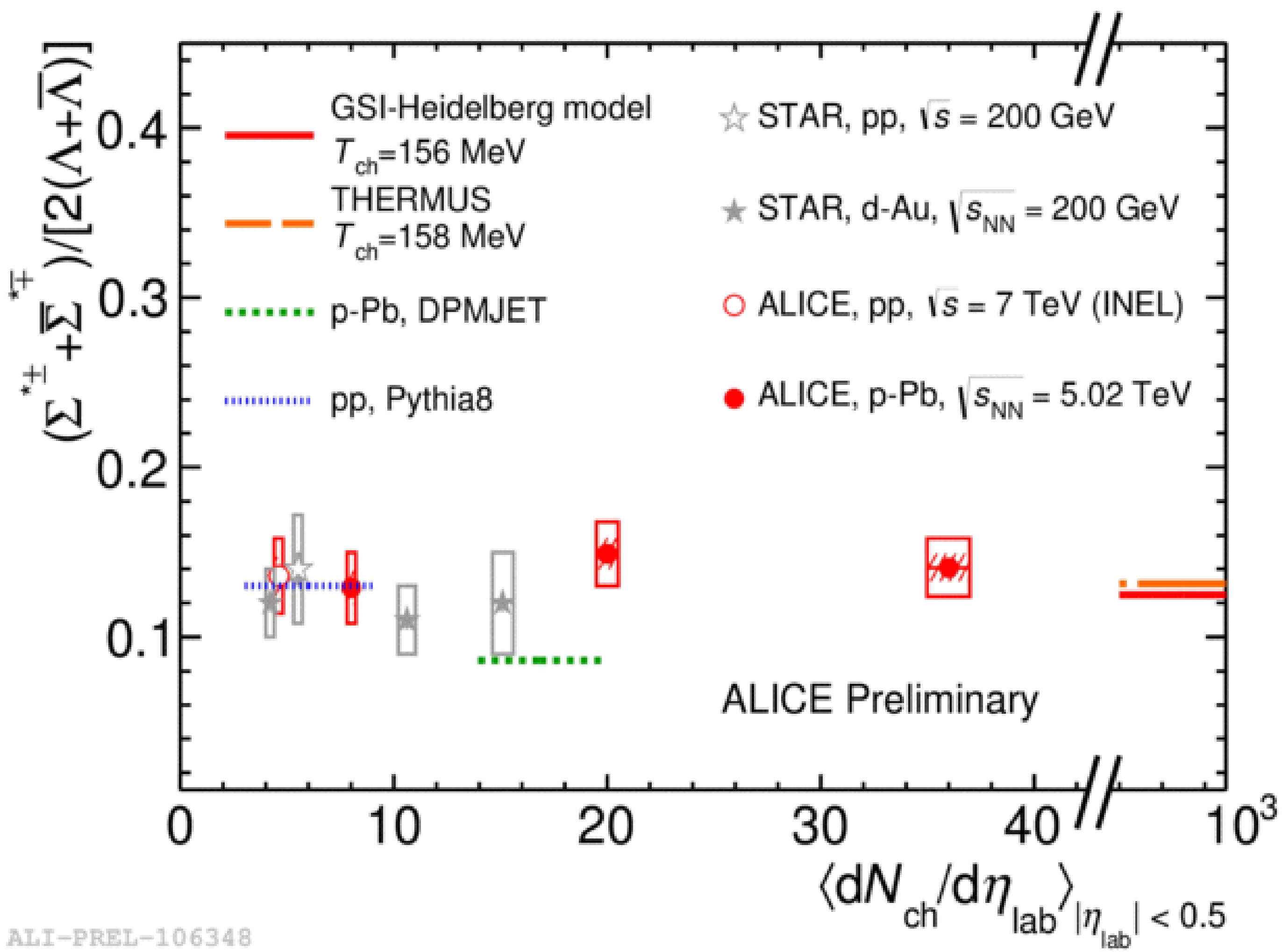


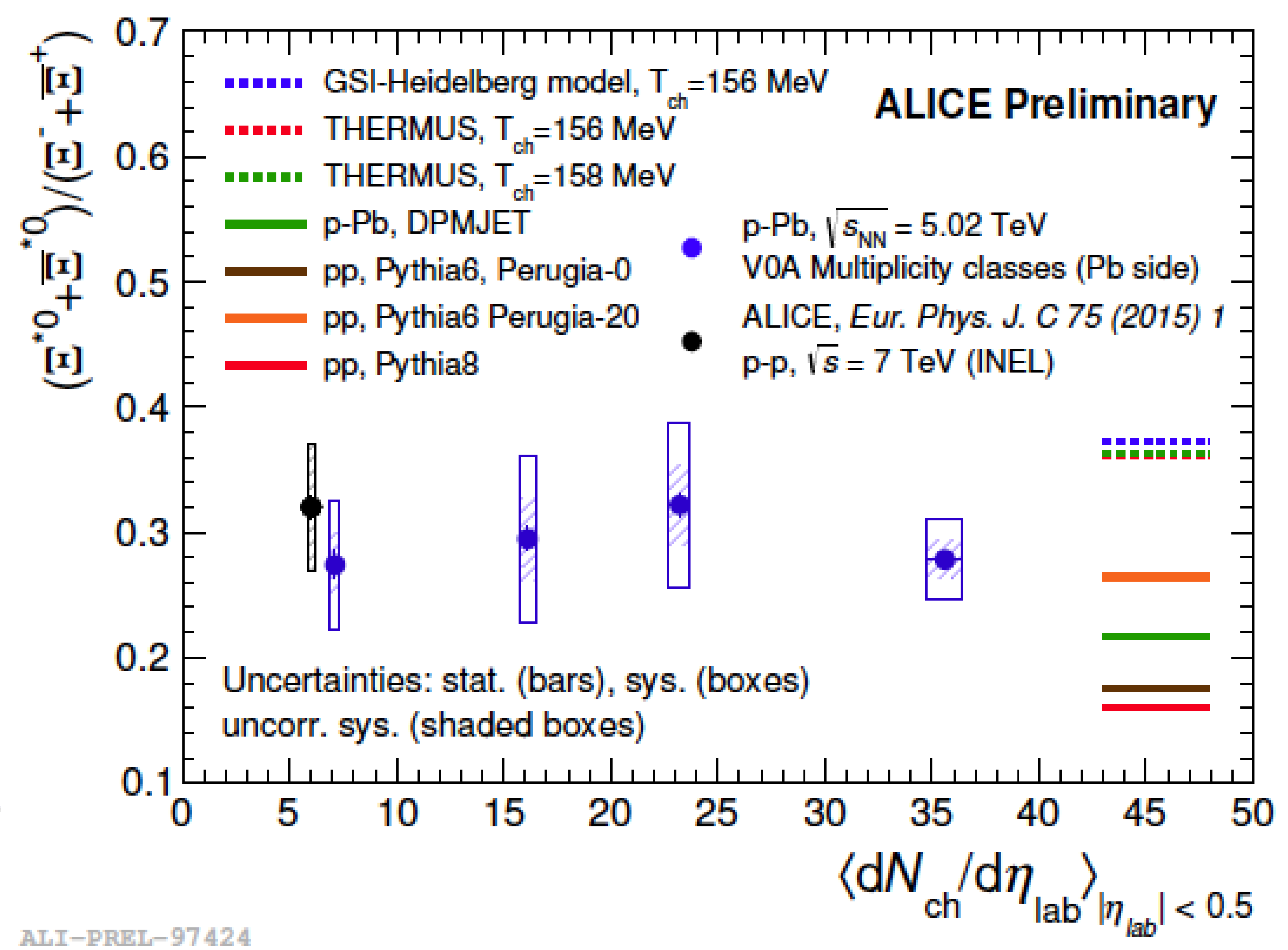




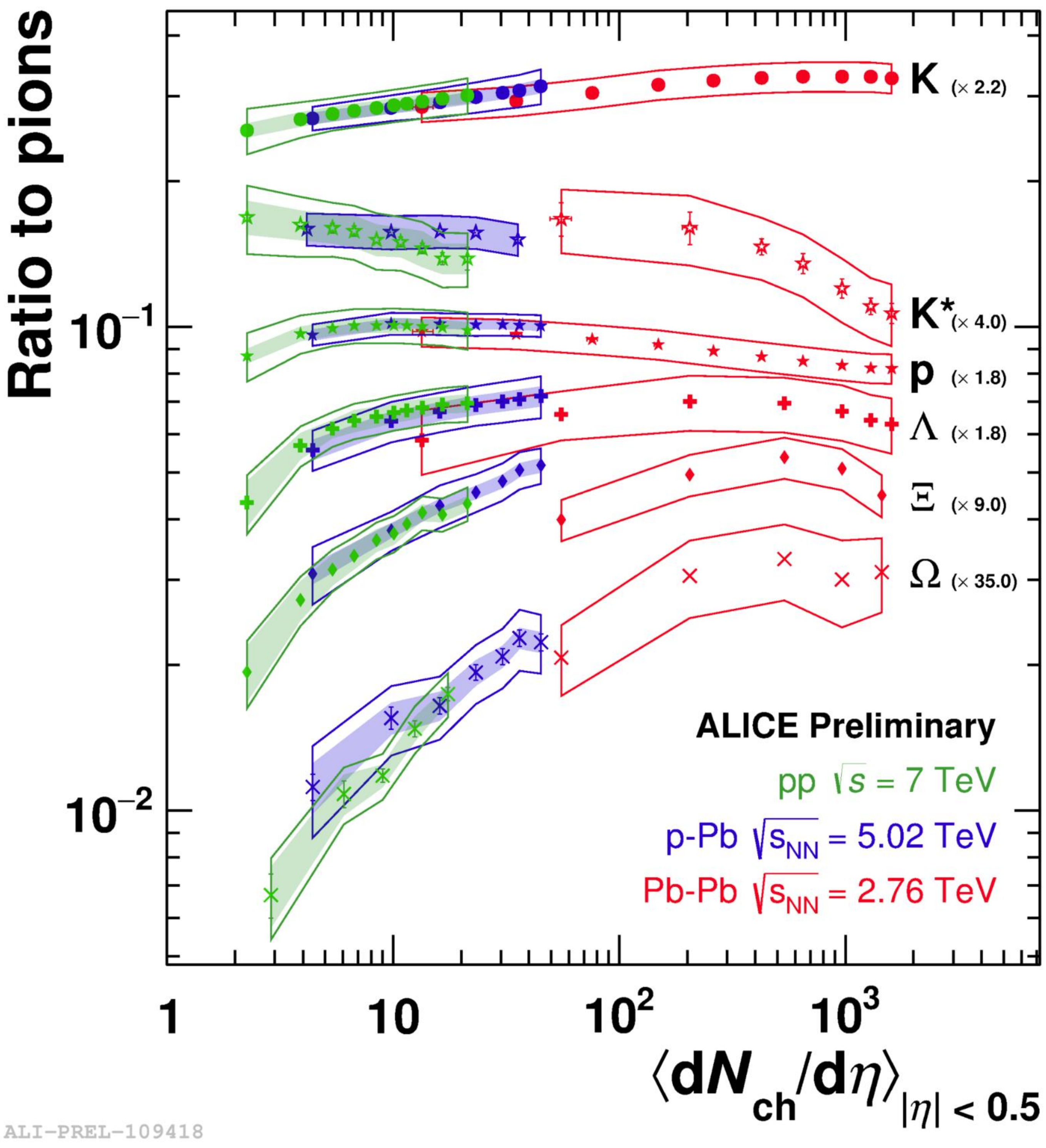
Ratios to stable hadrons

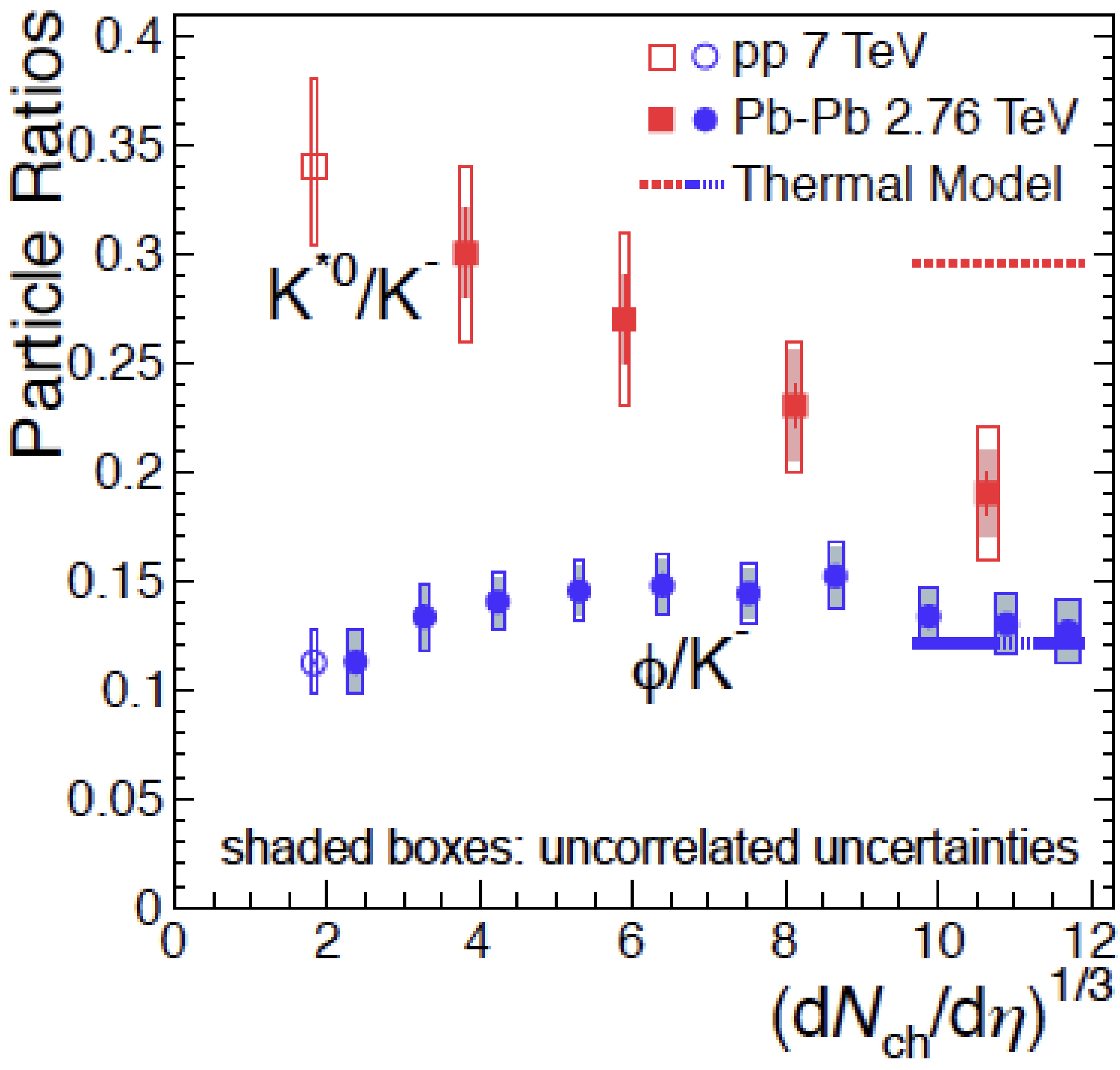
- New measurements of $\Sigma^{*\pm}$ and Ξ^{*0} in p–Pb collisions at 5.02 TeV
  - Measurements in progress for Pb–Pb collisions at 2.76 TeV
- No strong dependence of $\Sigma^{*\pm}/\Lambda$ on energy or system size from RHIC to LHC
  - Values consistent with thermal model and PYTHIA predictions
- No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





What about heavy ion collisions ?





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 systemnear the QCD phase transition (it is presently not clear whether heavy ions are a pre-requisite for such conditions).

Evidence for thermalized system in pp at LHC

Simultaneous **Blast-Wave model** fit to the π, K, p spectra

- In **Pb-Pb**: increase of radial flow with centrality

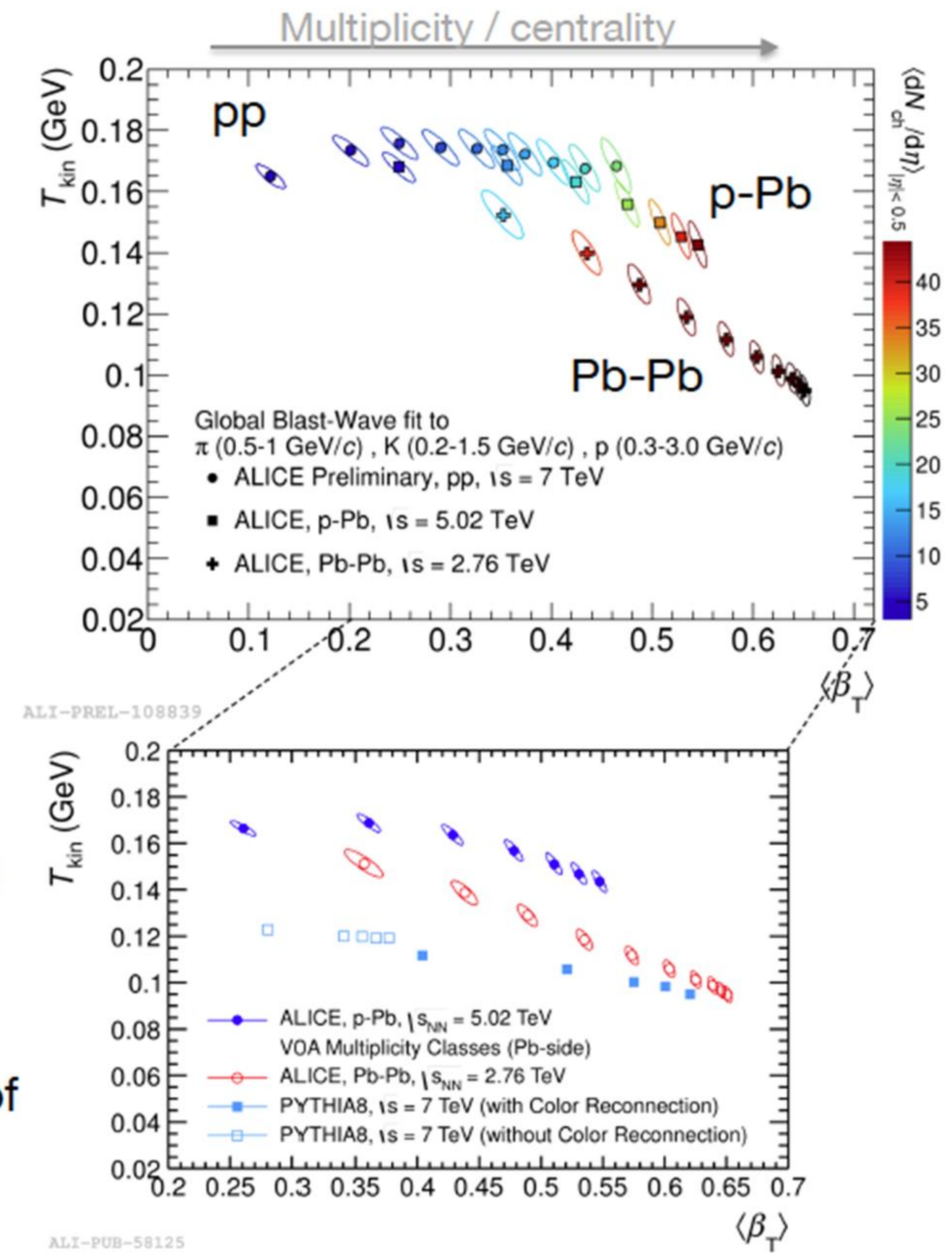
- In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity

- **Stronger <β_T> for smaller systems at similar multiplicity**

… but mind:

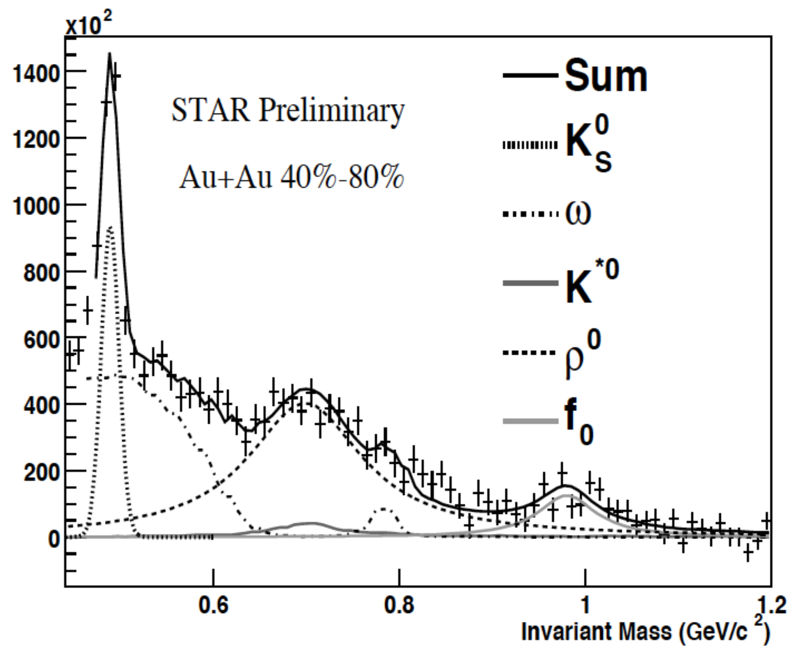
- Sensitivity to **fit range** and the set of **particles included in the fit**

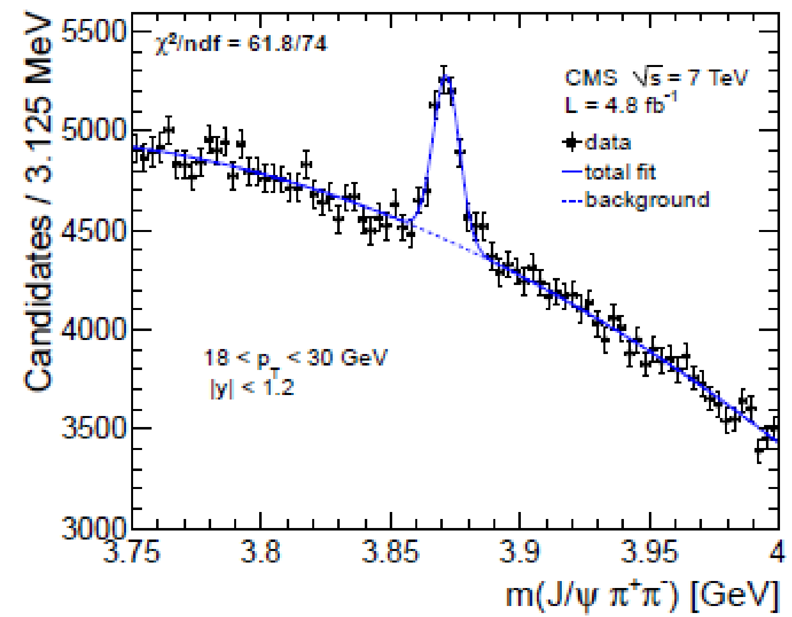
- Mechanisms such as color reconnection in models of pp collisions can mimic the effects of radial flow



Exotic states within the Standard Model

Exotic states measured at RHIC and the LHC (strange and charm sector)





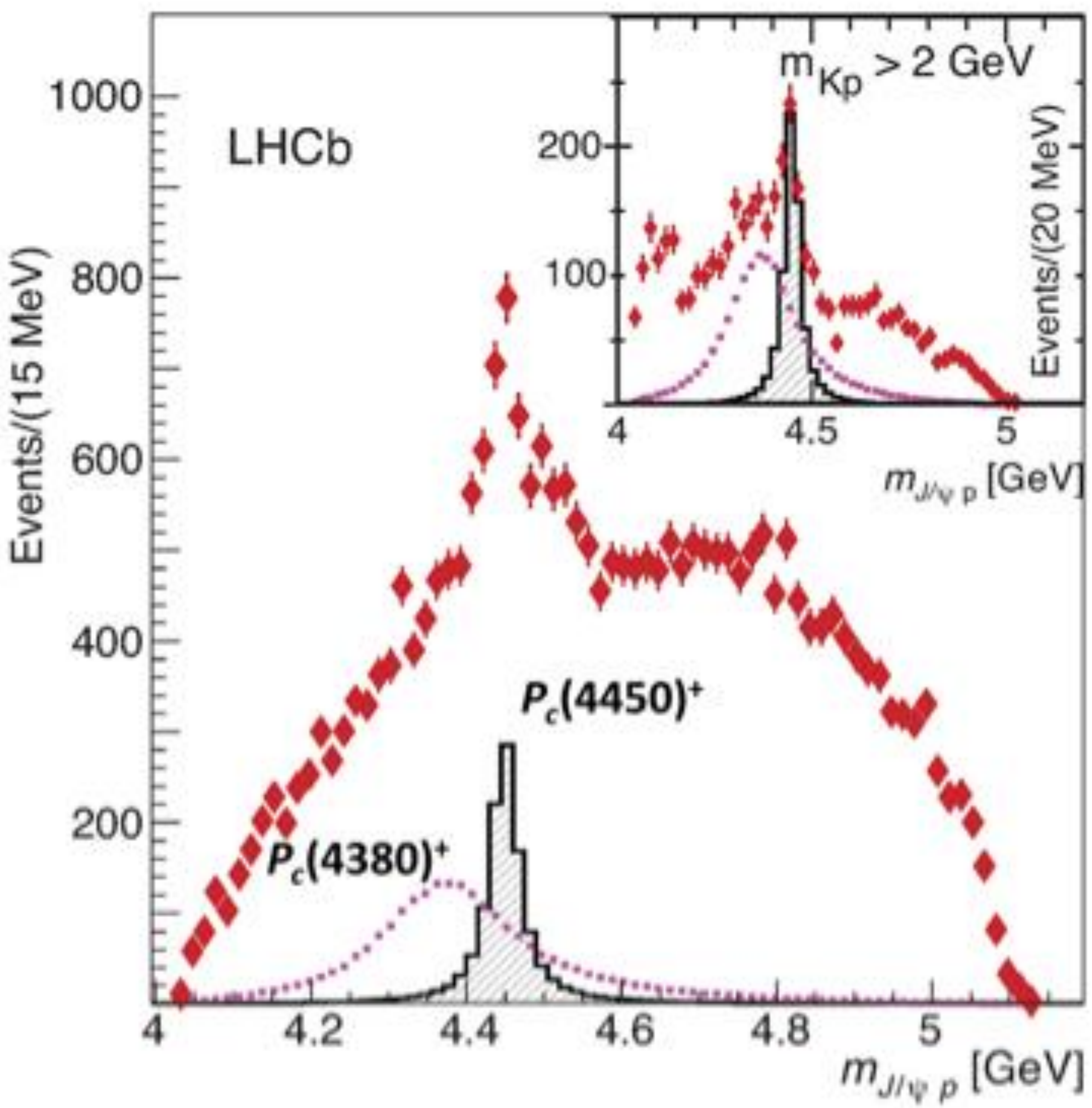
ExHIC Collaboration (2011):

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	RHIC $2q/3q/6q$	RHIC $4q/5q/8q$	RHIC Mol.	RHIC Stat.	LHC $2q/3q/6q$	LHC $4q/5q/8q$	LHC Mol.	LHC Stat.
Mesons															
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	3.8, 0.73($s\bar{s}$)	0.10	13	5.6	10, 2.0 ($s\bar{s}$)	0.28	36	15
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	11	0.31	40	17	31	0.83	1.1×10^2	46
$K(1460)$	1460	2	1/2	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$	—	0.59	3.6	1.3	—	1.6	9.3	3.2
$D_s(2317)$	2317	1	0	0^+	$c\bar{s}(L=1)$	$q\bar{q}c\bar{s}$	DK	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
T^{1}_{cc}[a]	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	3872	3	0	$1^+, 2^-$[c]	$c\bar{c}(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$Z^+(4430)$[b]	4430	3	1	0^-[c]	—	$q\bar{q}c\bar{c}(L=1)$	$D_1\bar{D}^*$	—	1.3×10^{-5}	2.0×10^{-5}	1.4×10^{-5}	—	2.1×10^{-4}	3.4×10^{-4}	2.4×10^{-4}
T^{0}_{cb}[a]	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	—	6.1×10^{-8}	1.8×10^{-7}	6.9×10^{-7}	—	6.1×10^{-6}	1.9×10^{-5}	6.8×10^{-5}
Baryons															
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqs(L=1)$	$qqqs\bar{q}$	$\bar{K}N$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
$\Theta^+(1530)$[b]	1530	2	0	$1/2^+$[c]	—	$qqqq\bar{s}(L=1)$	—	—	2.9×10^{-2}	—	1.0	—	7.8×10^{-2}	—	2.3
$\bar{K}KN$[a]	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}(L=1)$	$\bar{K}KN$	—	1.9×10^{-2}	1.7	0.28	—	5.2×10^{-2}	4.2	0.67
$\bar{D}N$[a]	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	—	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	—	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{D}^*N$[a]	2919	4	0	$3/2^-$	—	$qqqq\bar{c}(L=2)$	$\bar{D}^*N$	—	7.1×10^{-4}	4.5×10^{-2}	1.0×10^{-2}	—	4.7×10^{-3}	0.27	6.2×10^{-2}
Θ_{cs}[a]	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}(L=1)$	—	—	5.9×10^{-4}	—	7.2×10^{-3}	—	3.9×10^{-3}	—	4.5×10^{-2}
BN[a]	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	—	1.9×10^{-5}	8.0×10^{-5}	3.9×10^{-5}	—	7.7×10^{-4}	2.8×10^{-3}	1.4×10^{-3}
B^*N[a]	6226	4	0	$3/2^-$	—	$qqqq\bar{b}(L=2)$	B^*N	—	5.3×10^{-6}	1.2×10^{-4}	6.6×10^{-5}	—	2.1×10^{-4}	4.4×10^{-3}	2.4×10^{-3}
Dibaryons															
H[a]	2245	1	0	0^+	$qqqqss$	—	ΞN	3.0×10^{-3}	—	1.6×10^{-2}	1.3×10^{-2}	8.2×10^{-3}	—	3.8×10^{-2}	3.2×10^{-2}
$\bar{K}NN$[b]	2352	2	1/2	0^-[c]	$qqqqqs(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026 – 0.54	3.7×10^{-2}
$\Omega\Omega$[a]	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	3.2×10^{-5}	—	1.5×10^{-5}	6.4×10^{-5}	8.6×10^{-5}	—	4.4×10^{-5}	1.9×10^{-4}
H_c^{++}[a]	3377	3	1	0^+	$qqqqsc$	—	Ξ_cN	3.0×10^{-4}	—	3.3×10^{-4}	7.5×10^{-4}	2.0×10^{-3}	—	1.9×10^{-3}	4.2×10^{-3}
$\bar{D}NN$[a]	3734	2	1/2	0^-	—	$qqqqqq\,q\bar{c}$	$\bar{D}NN$	—	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	—	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}
BNN[a]	7147	2	1/2	0^-	—	$qqqqqq\,q\bar{b}$	BNN	—	2.3×10^{-7}	1.2×10^{-6}	2.4×10^{-7}	—	9.2×10^{-6}	3.7×10^{-5}	7.6×10^{-6}

Penta- and Tetra-quarks from LHCb

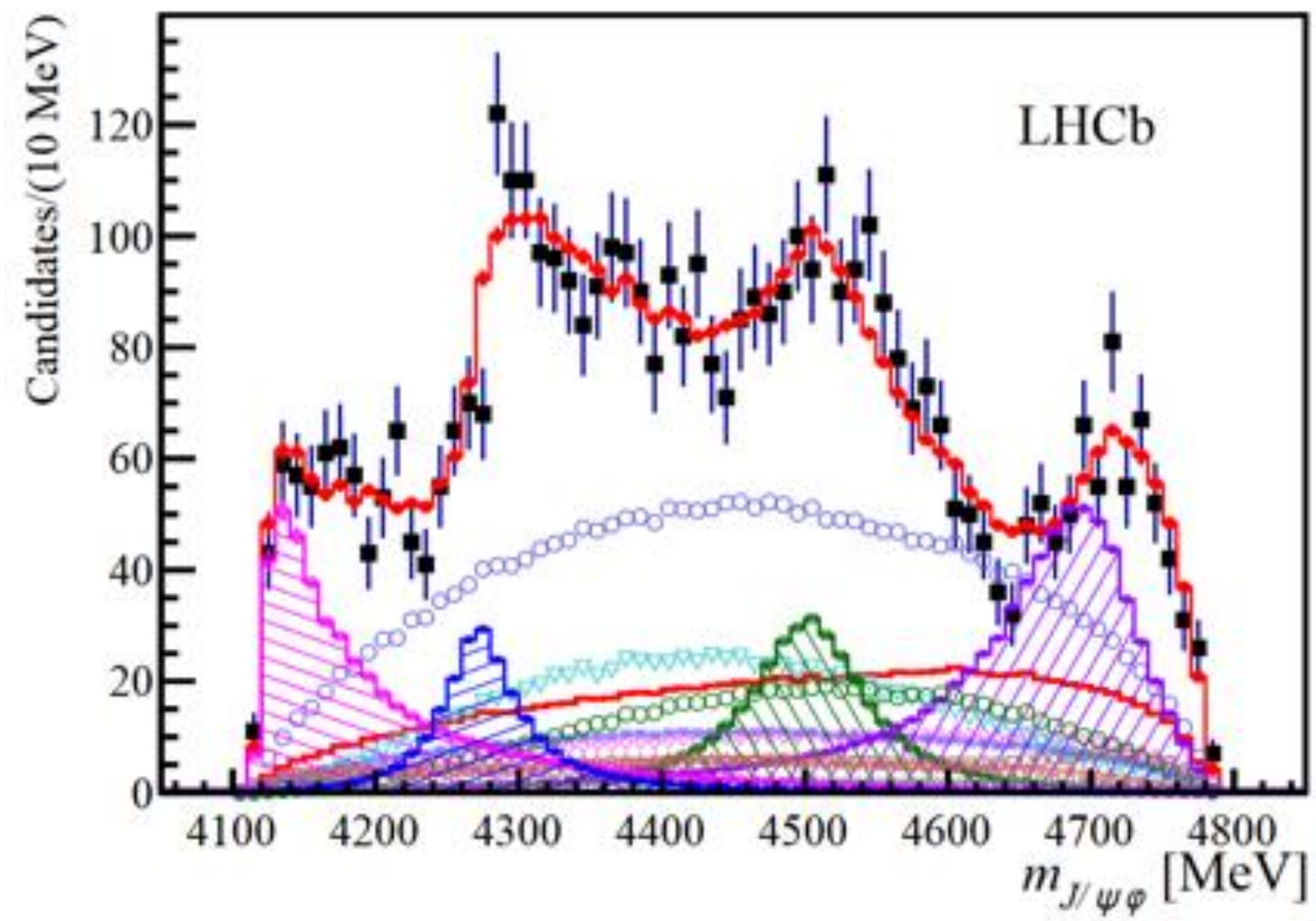
Penta-quark in 2015, 9σ evidence by 2016

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 $\Xi\pi$ channels, quark content: d s d s ubar, m = 1860 Mev/c^2

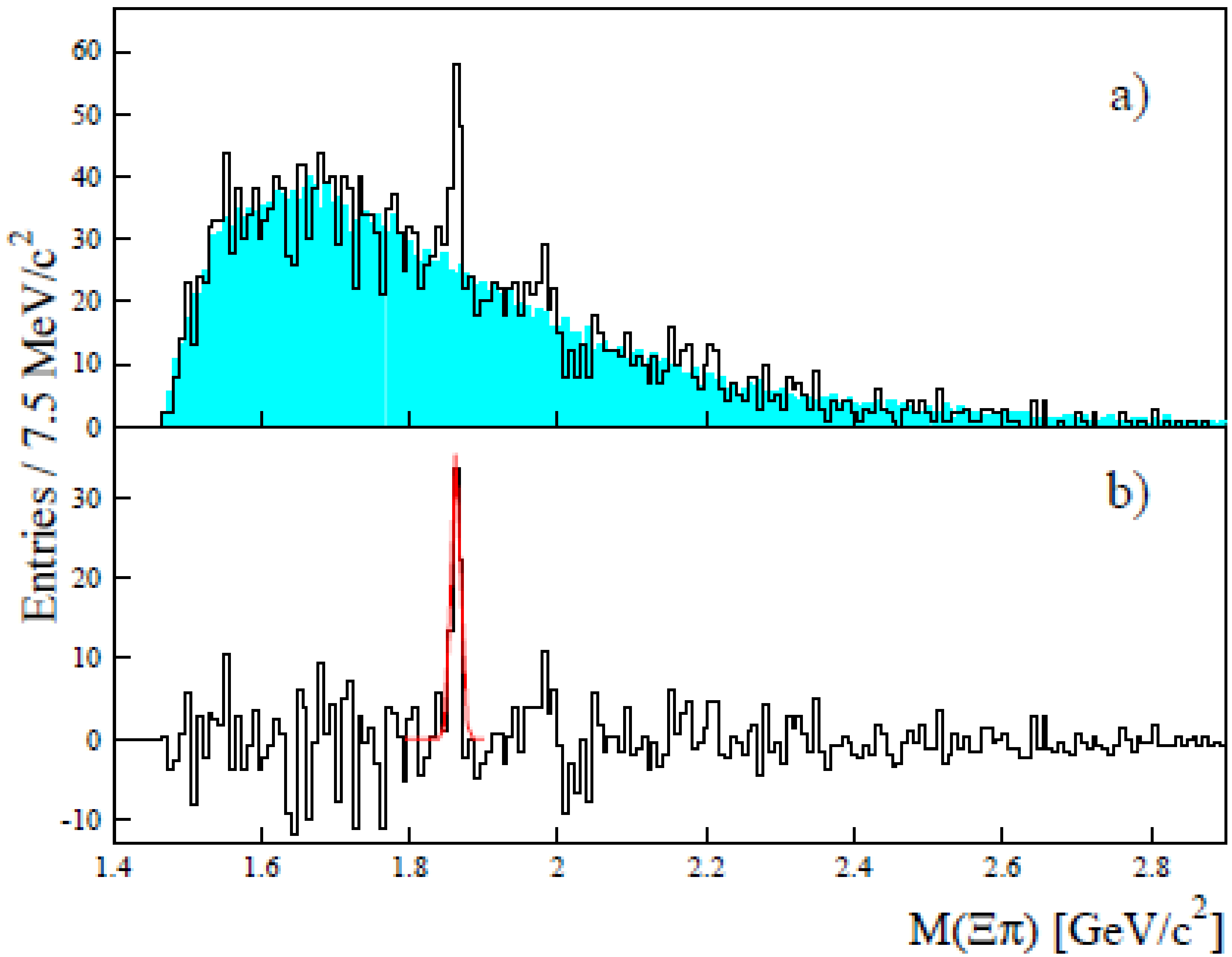
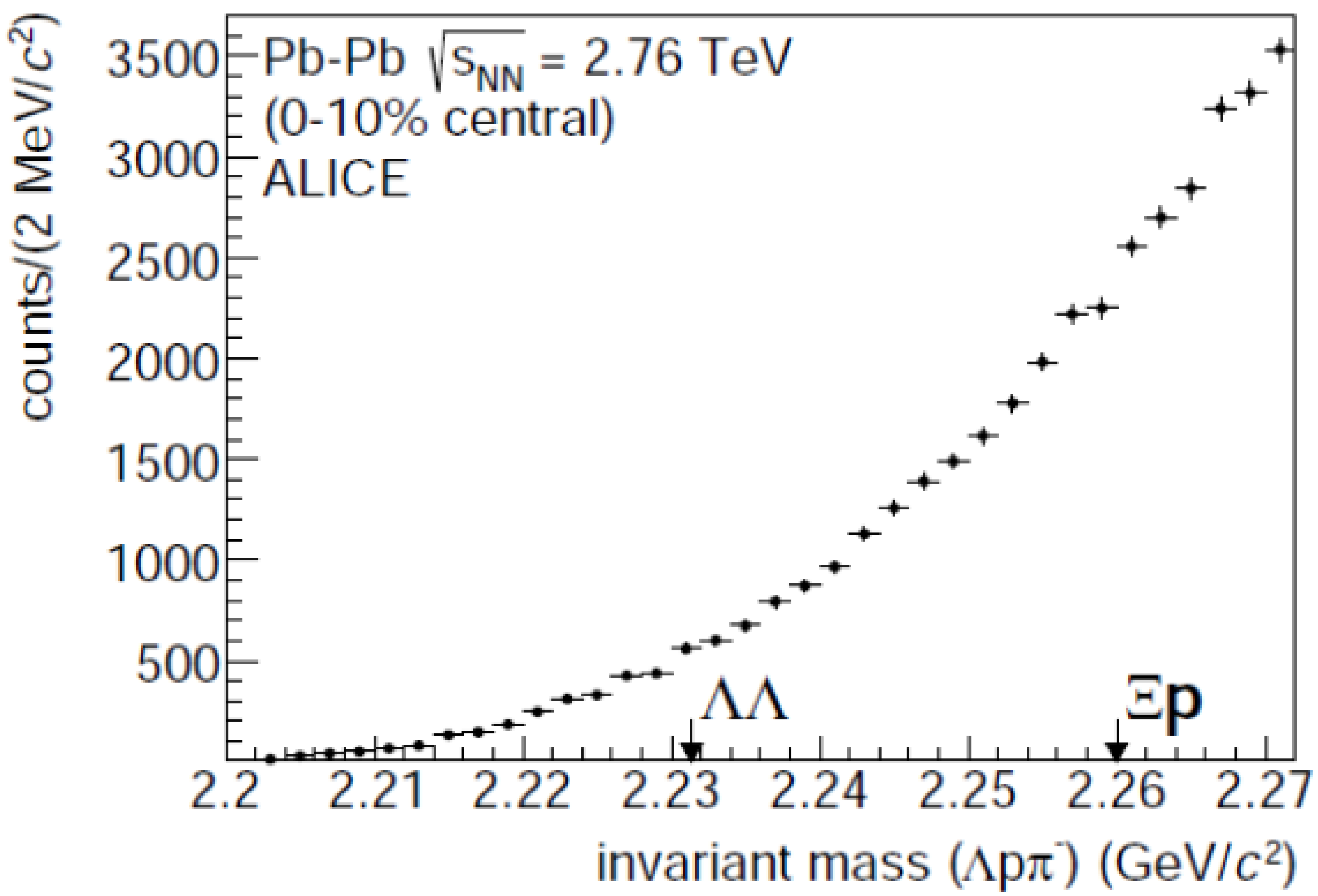


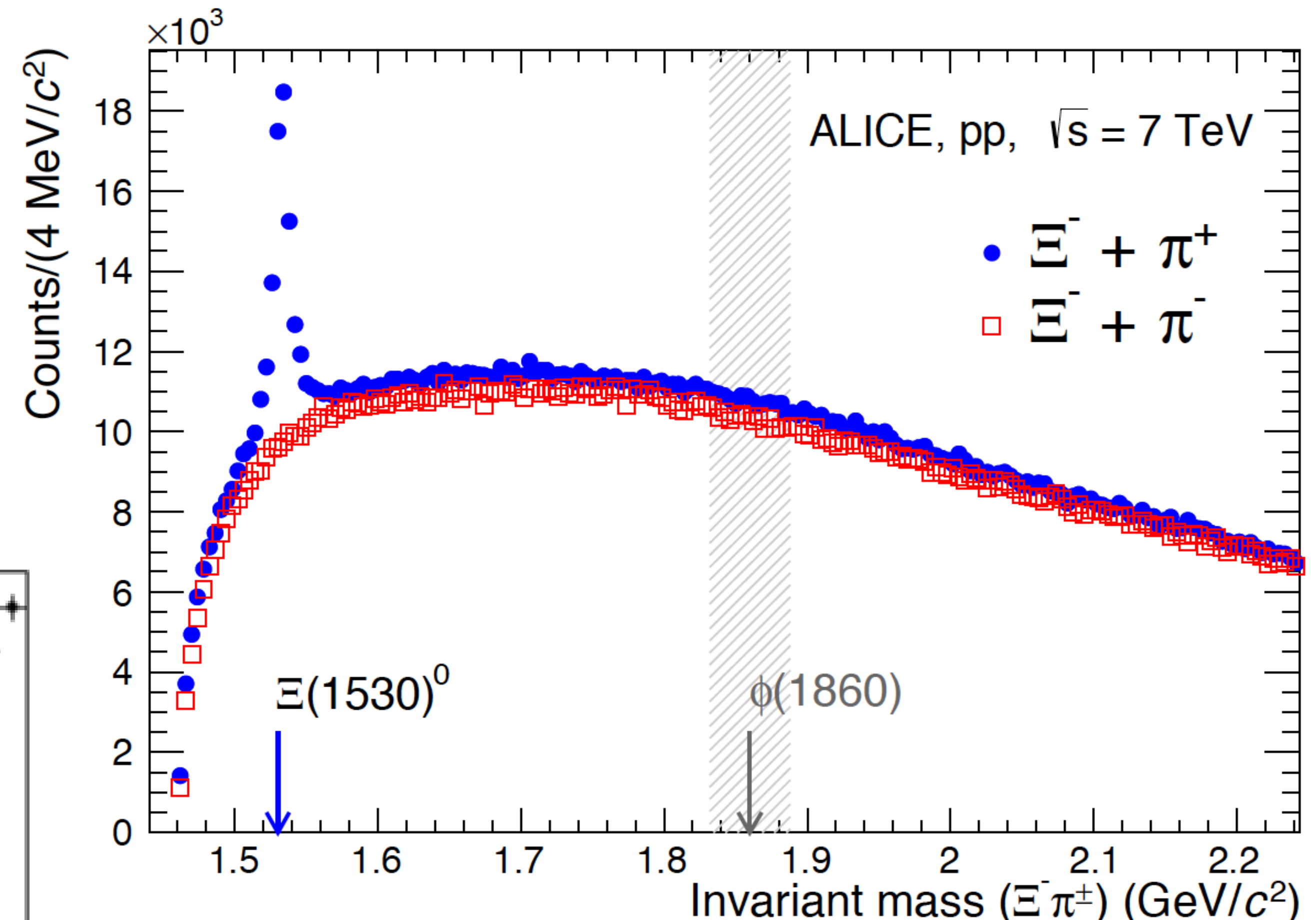
FIG. 3: (Color online) (a) The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$ and $\overline{\Xi}^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalised mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.

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.

Backup

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 $N\pi$ channel. In general at most half of the predicted resonant states have been found.

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.

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*.

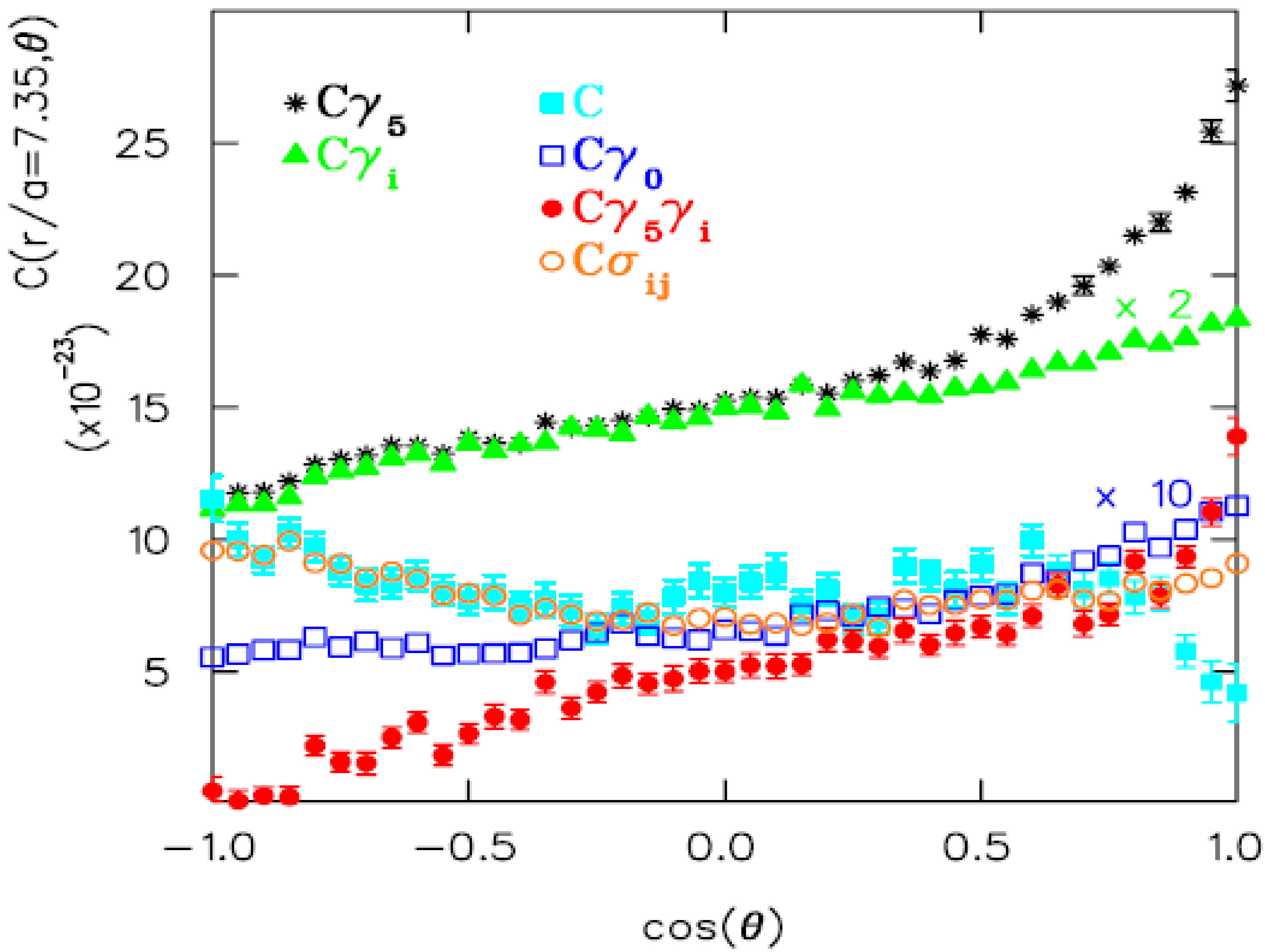
Lattice QCD baryon spectroscopy

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))



The most conservative approach for adding QM states to the HRG might be the states from the di-quark model