Sequential Strangeness Freeze-out

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Thanks to: Paolo Alba, Livio Bianchi, Szabolcs Borsanyi, Zoltan Fodor, Anders, Knospe, Valentina Mantovani-Sarti, Jackie Noronha-Hostler, Paolo Parotto, Attila Pasztor, Claudia Ratti

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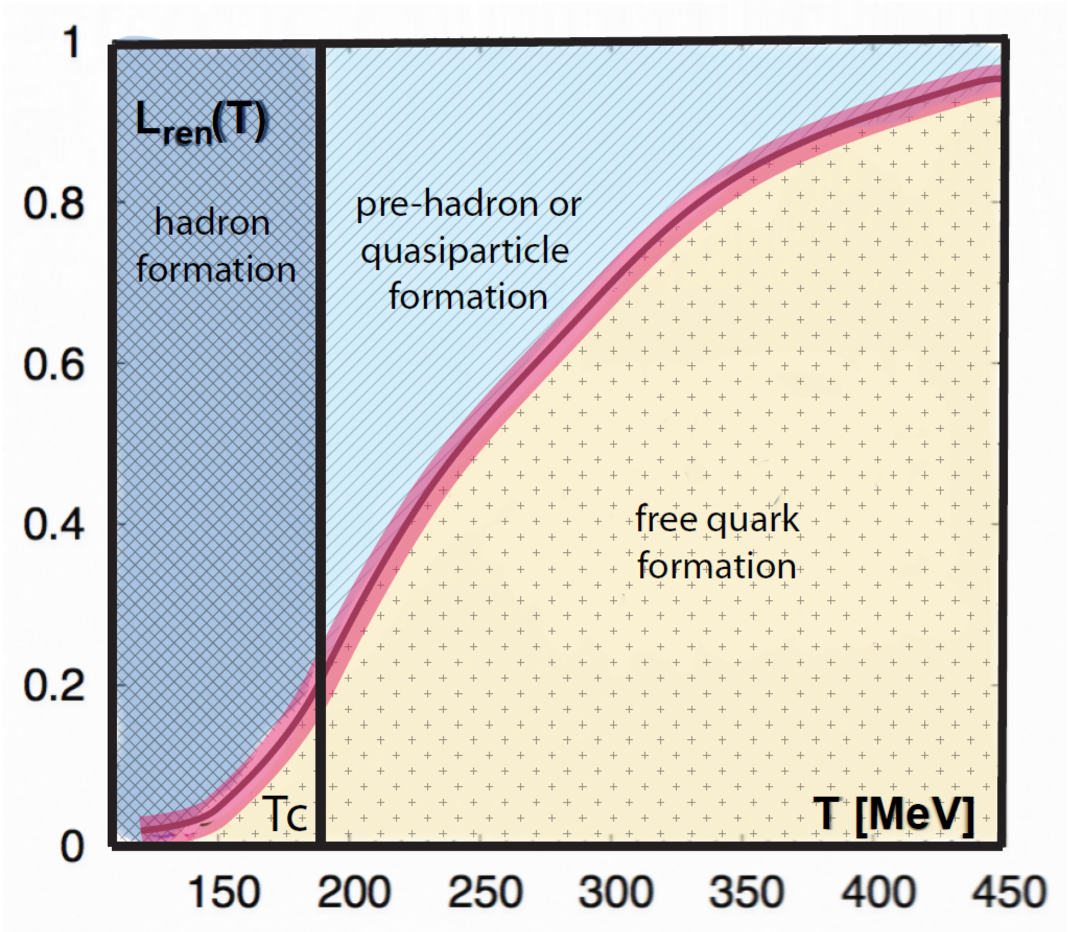
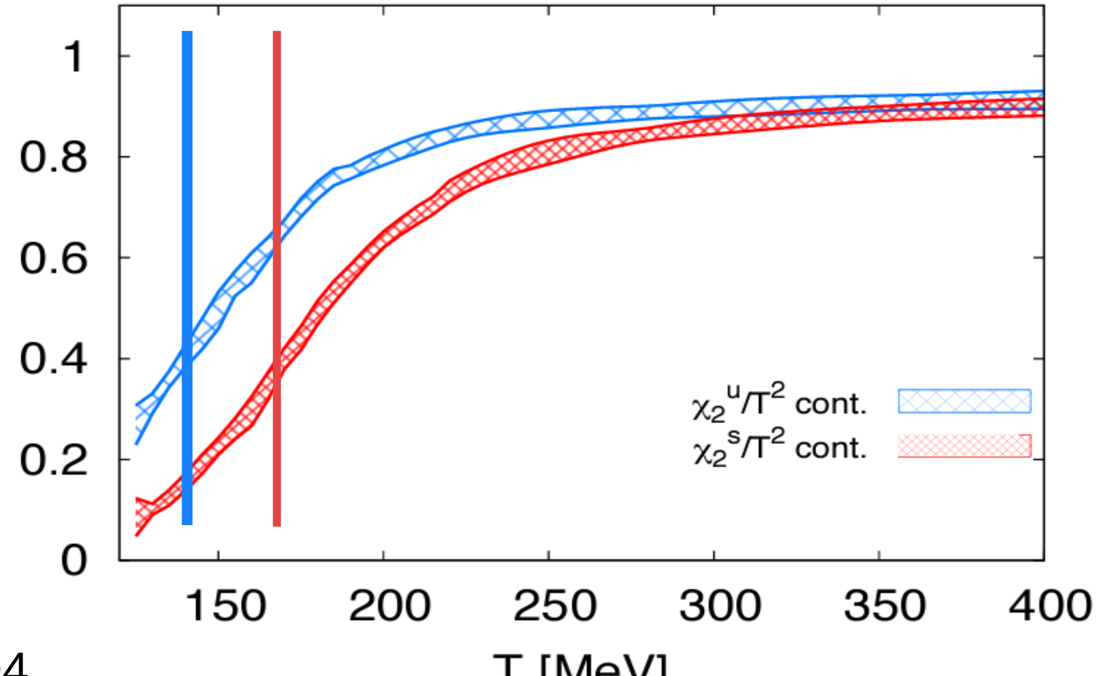
Lattice order parameters in the QCD cross-over

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



RB, C. Markert, PLB691 (2010) 208



C. Ratti et al., PRD 85 (2012) 014004

- In a regime where we have a smooth crossover and where quark masses (even for the s-quark) could play a role why would there be a single freeze-out surface ?

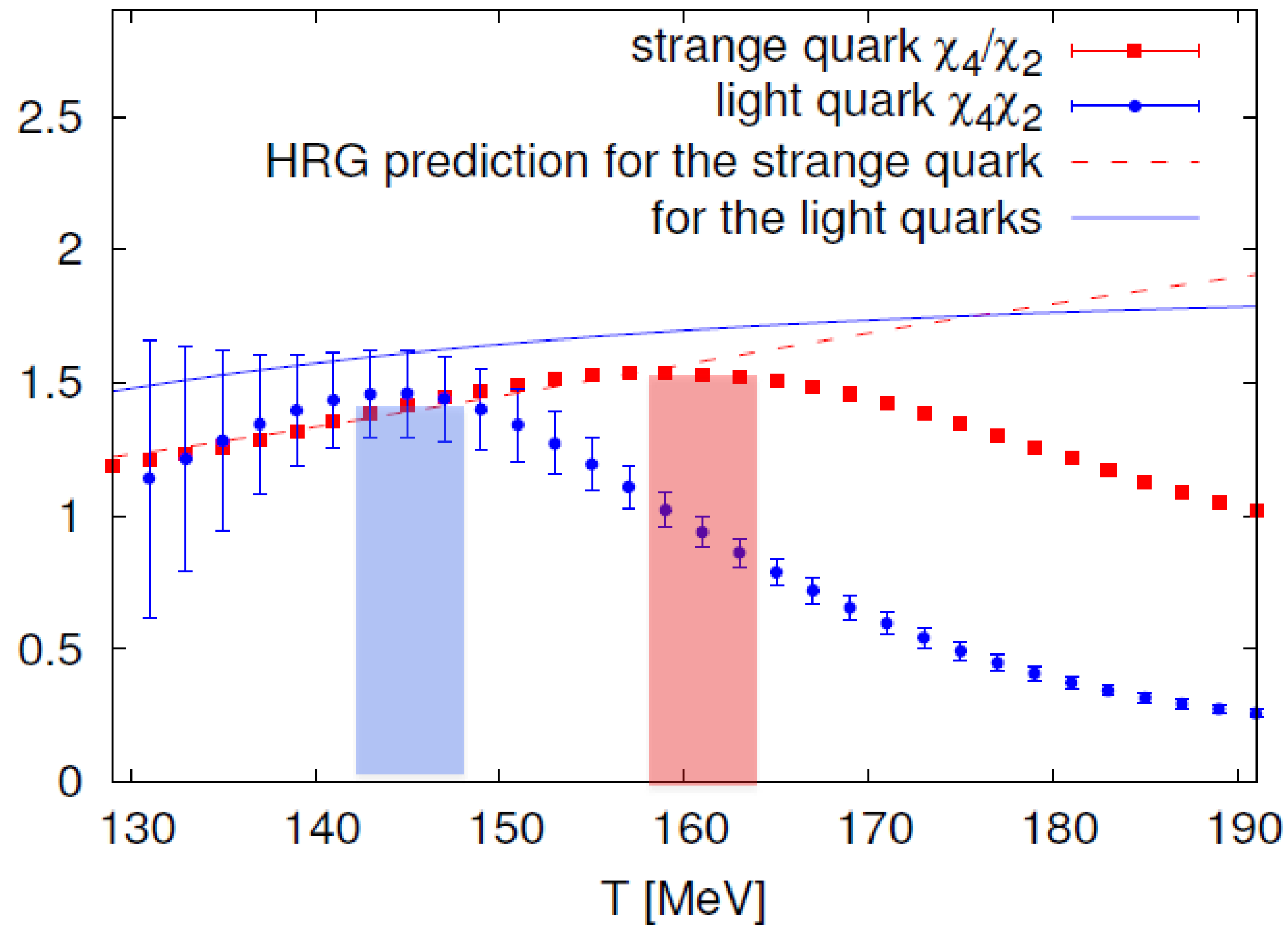
- We can calculate thermodynamic quantities for a static equilibrated system at a fixed temperature

- But are pseudo-critical temperatures extracted from flavor dependent susceptibilities as relevant for hadronization properties as chirality ?

Direct determination of freeze-out parameters from first principles (lattice QCD)

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

Susceptibility ratios are a model independent measure of the chemical freeze-out temperature near μ=0. (Karsch, arXiv:1202.4173)



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

Indication of sequential hadronization

Either based on the peak position in the lattice QCD calculation or on the point of deviation from the hadron resonance gas (HRG)

Needs experimental verification

Lattice QCD vs. HRG

The lattice calculations favor a flavor separation.

They use the proper pion and quark masses and they are continuum extrapolated.

Nothing can be changed or improved, except for the possibility that
a.) the action is not perfect
b.) the system is not in equilibrium.

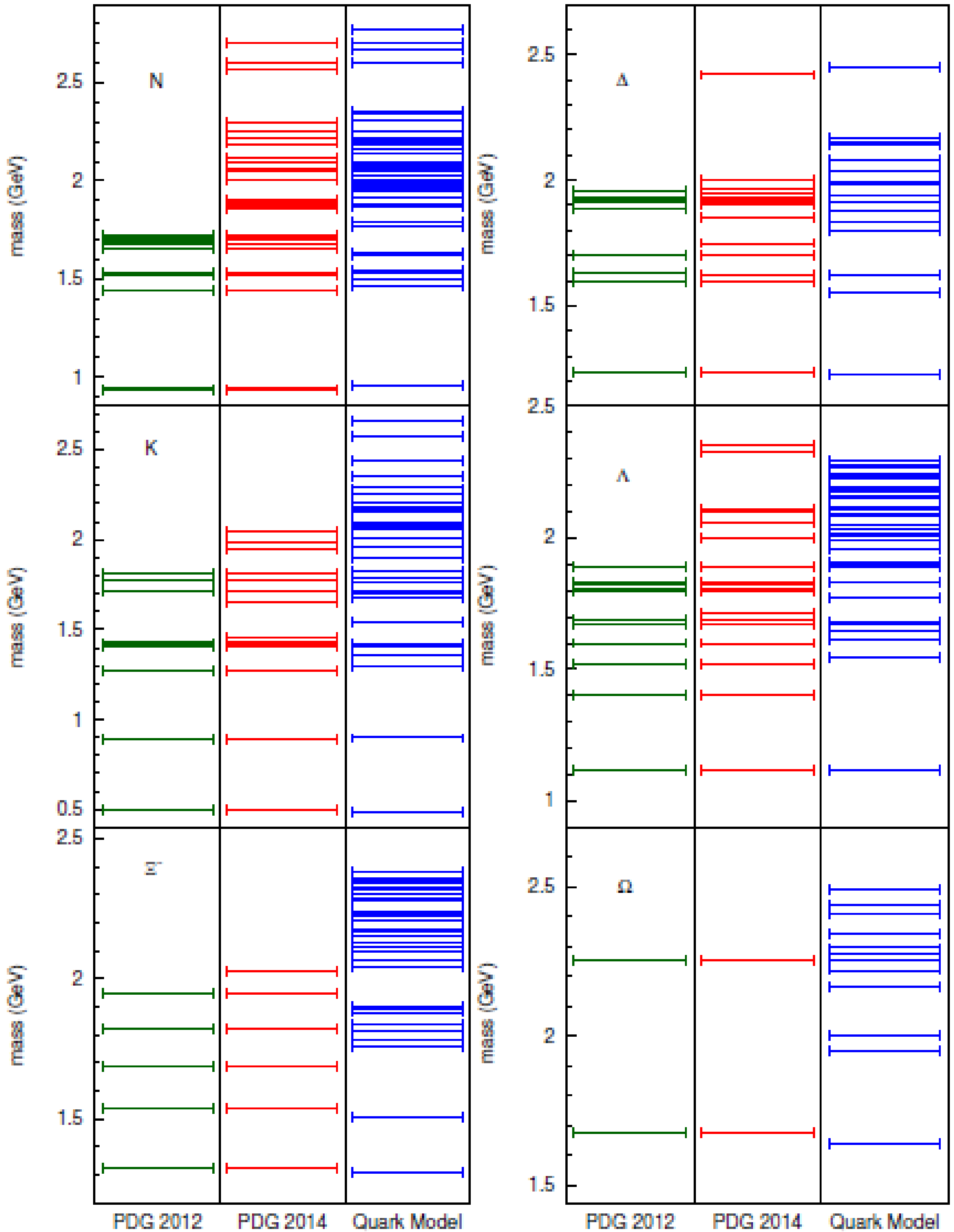
On the other hand the HRG comparison is subject to a lot of discussion in the recent past.

Two avenues have been pursued:

a.) a non-interacting HRG can only describe ‘reality’ if the resonance spectrum is complete.

b.) an interacting hadron gas is a better proxy as long as the interaction is properly modeled.

The incomplete HRG input spectrum

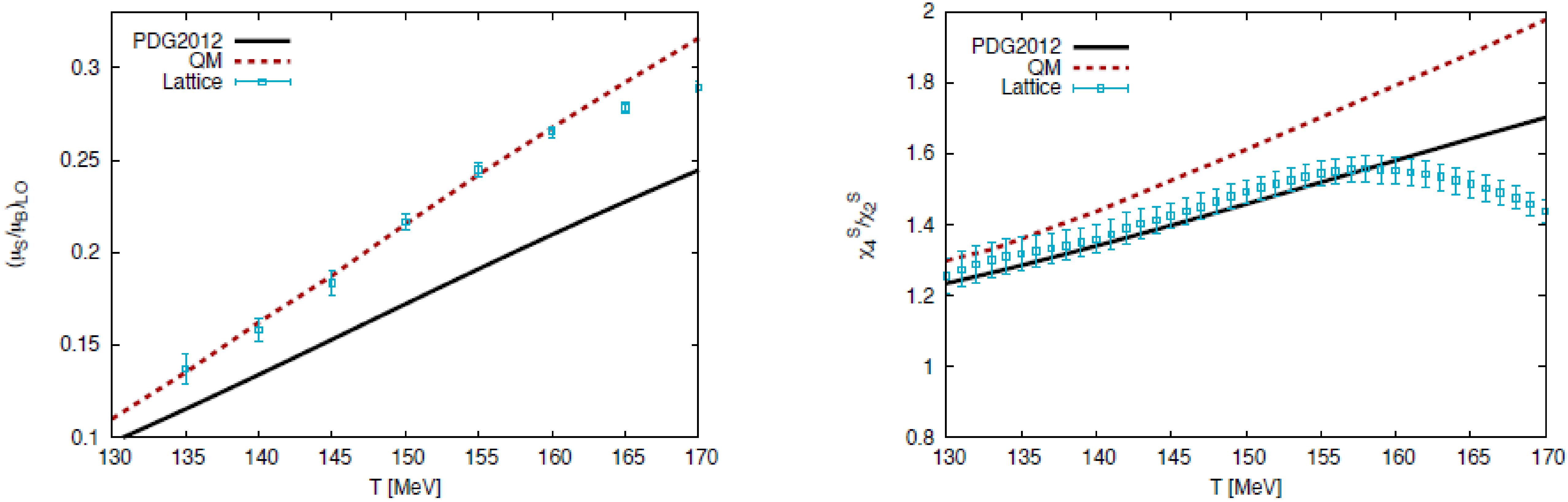


First suggested as a possible 'solution' to the different flavor surfaces by Bazavov et al. (PRL (2014), arXiv:1404.6511)

A more detailed study by P.Alba et al., arXiv:1702.01113)

See talk by C. Ratti on Wednesday

The problem: It impacts the comparison to different lattice parameters in different ways



Furthermore: there are many different Quark Models with different numbers of ‘extra states’ depending on the quark interaction

Best compromise seems to be PDG2016+ (incl. all 1-star resonances), see P.Alba et al., arXiv:1702.01113

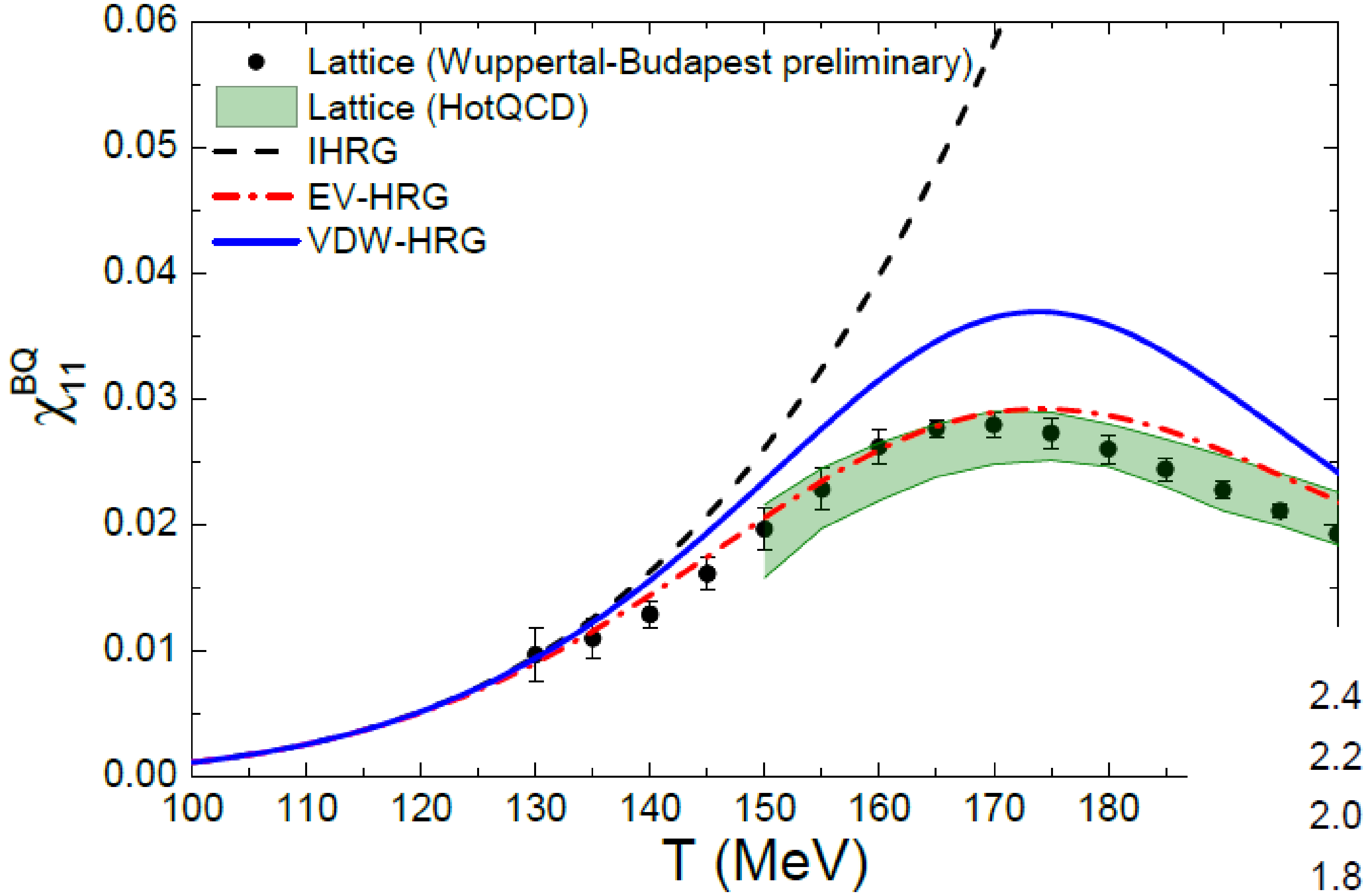
Conclusions for the experimental program

We need more experimental verification of higher mass baryonic resonances, especially in the S = 1 sector (higher level Λ and Σ resonances)

This is an interesting challenge for RHIC and LHC experiments, but also for the future JLab program

(new JLab experiment KLF was just proposed for this purpose, arXiv:1701.07346)

An alternative: the interacting hadron gas (excluded volume or van der Waals interaction), Vovchenko et al., PRL 2016, arXiv:1609.03975

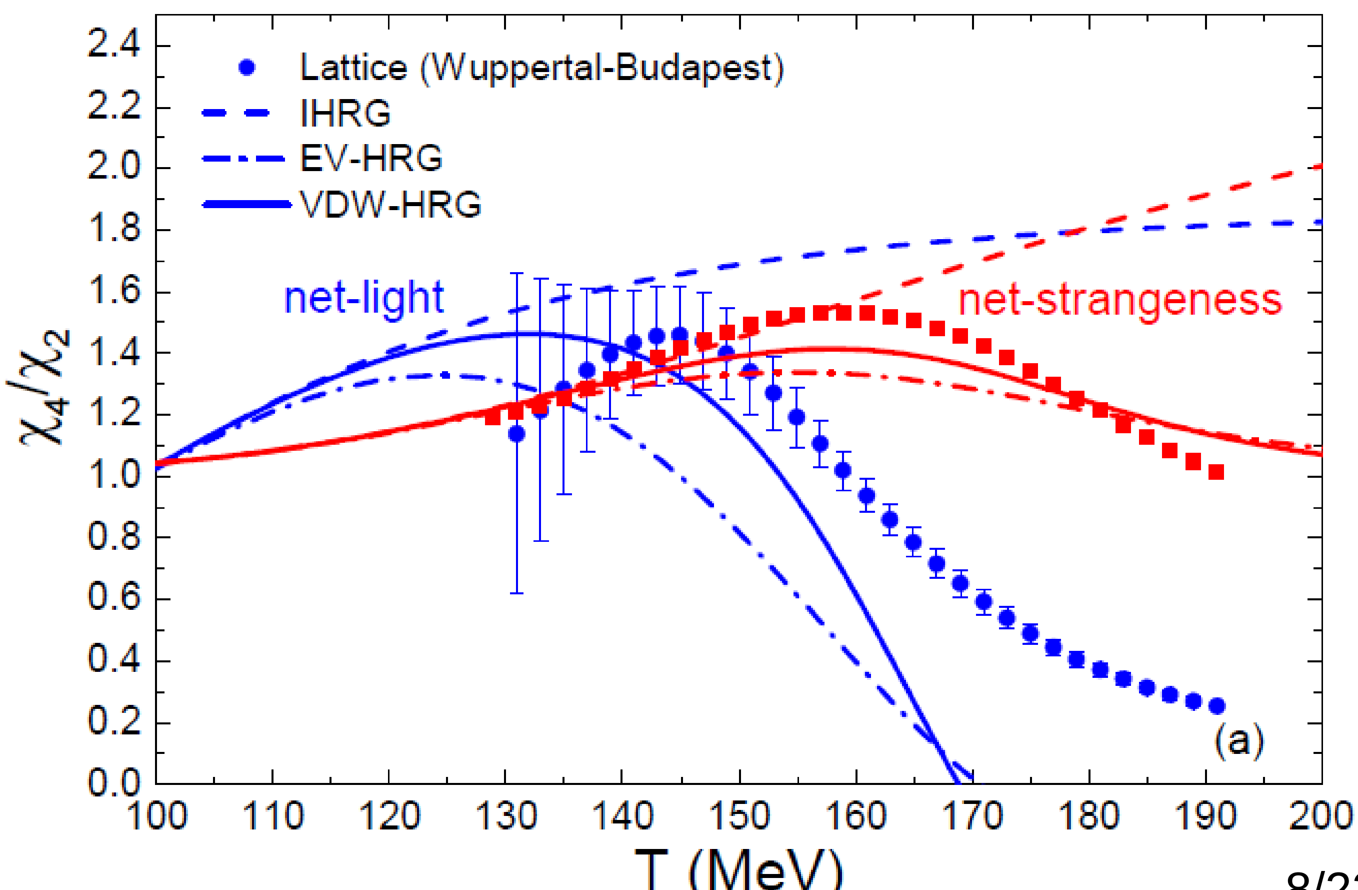


Seems to get some of the features right (peak structures in lattice susceptibility ratios)

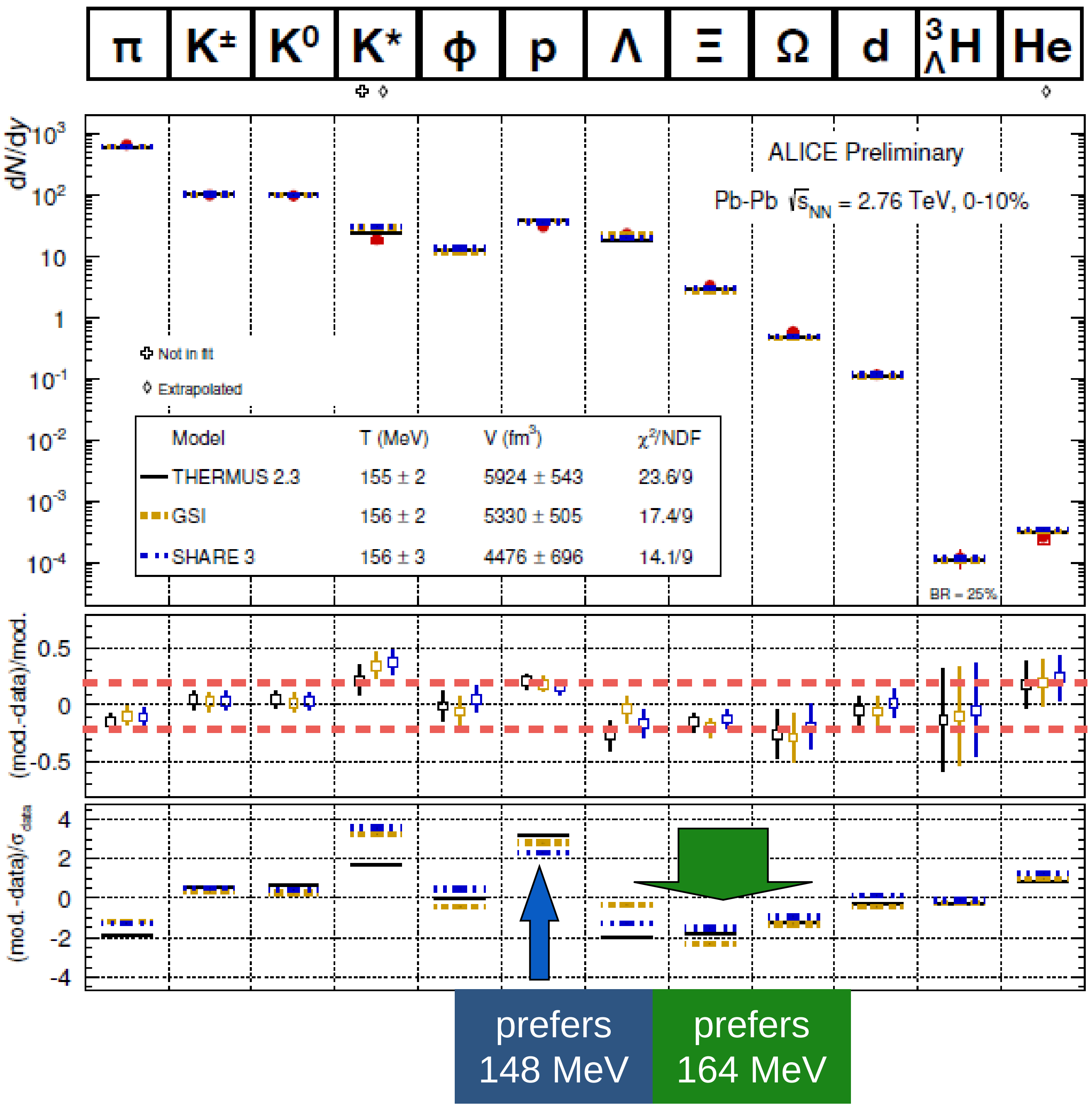
Problems:

-excluded volume calculation debatable

- pushes ‘agreement’ with lattice way beyond the pseudo-critical temperature



Experimental evidence: HRG (PDG 2010) model comparison based on yields



Data: ALICE, QM 2014, arXiv:1408.6403

This looks like a good fit, but it is not

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

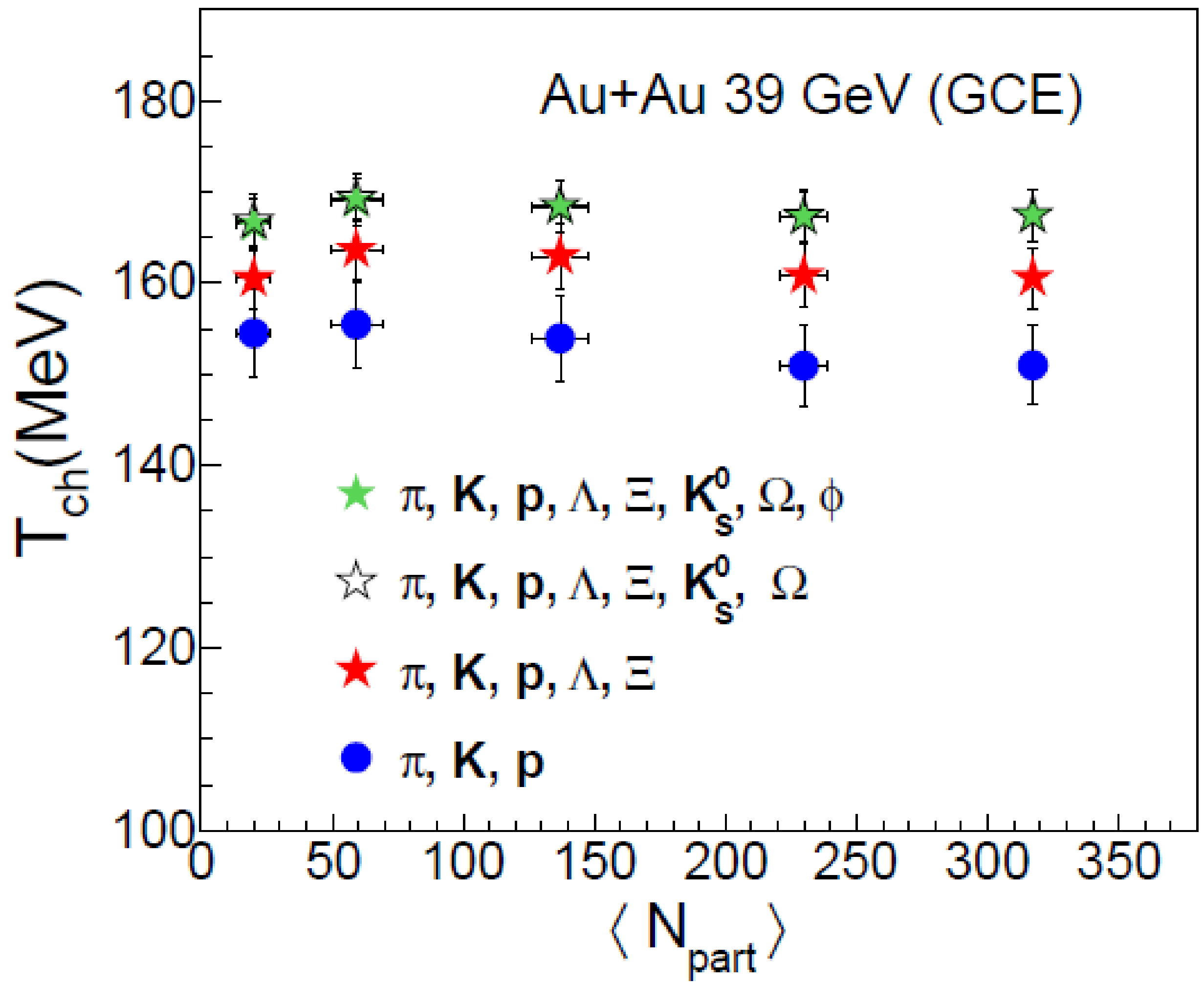
Fit to pions and protons alone yield a temperature of 148 MeV. Strange baryons yield 164 MeV

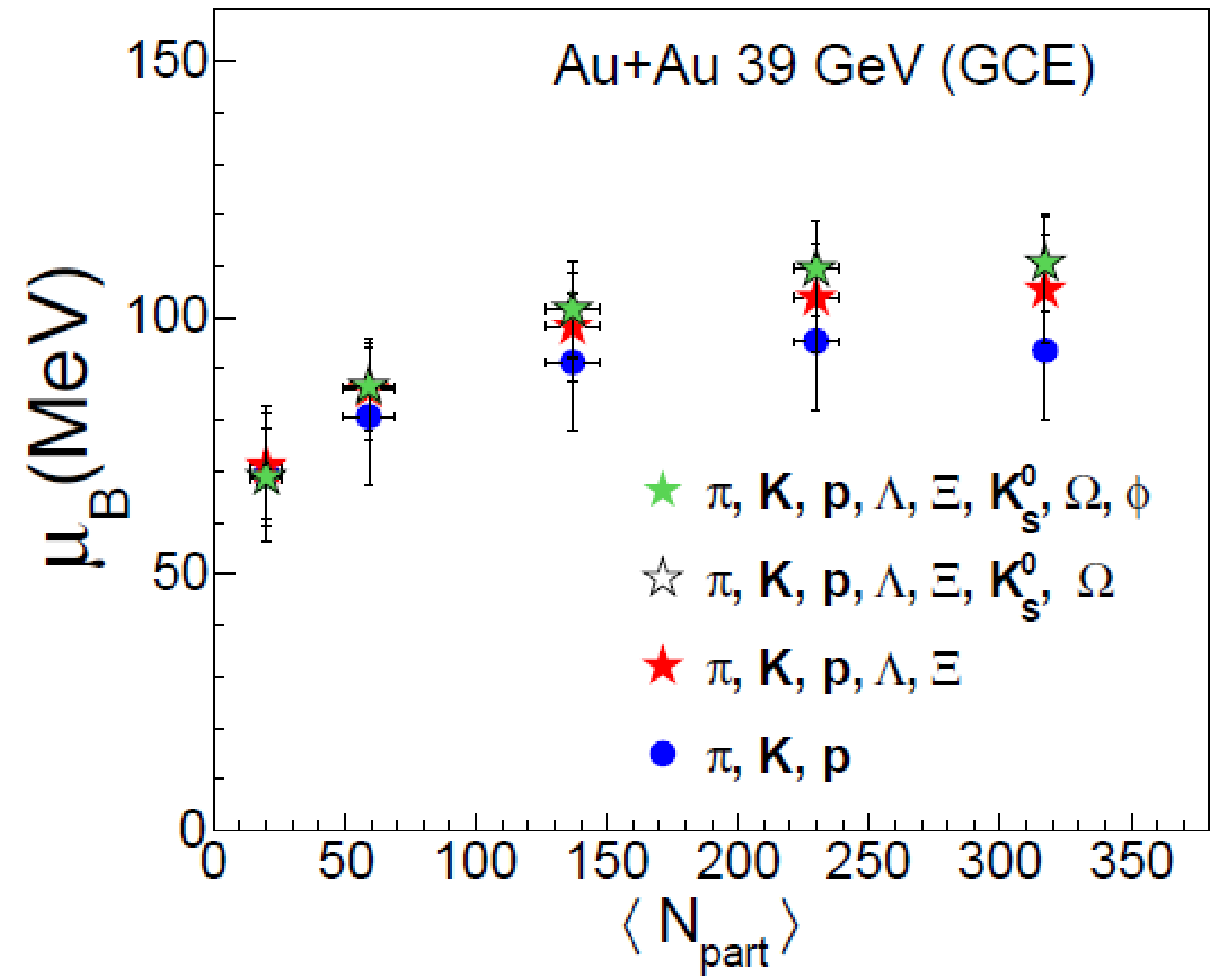
<u>Several alternate explanations:</u>

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

Experimental evidence from varying the input particles into the chemical fit

Latest example: Beam Energy Scan data from STAR (arXiv:1701.07065)

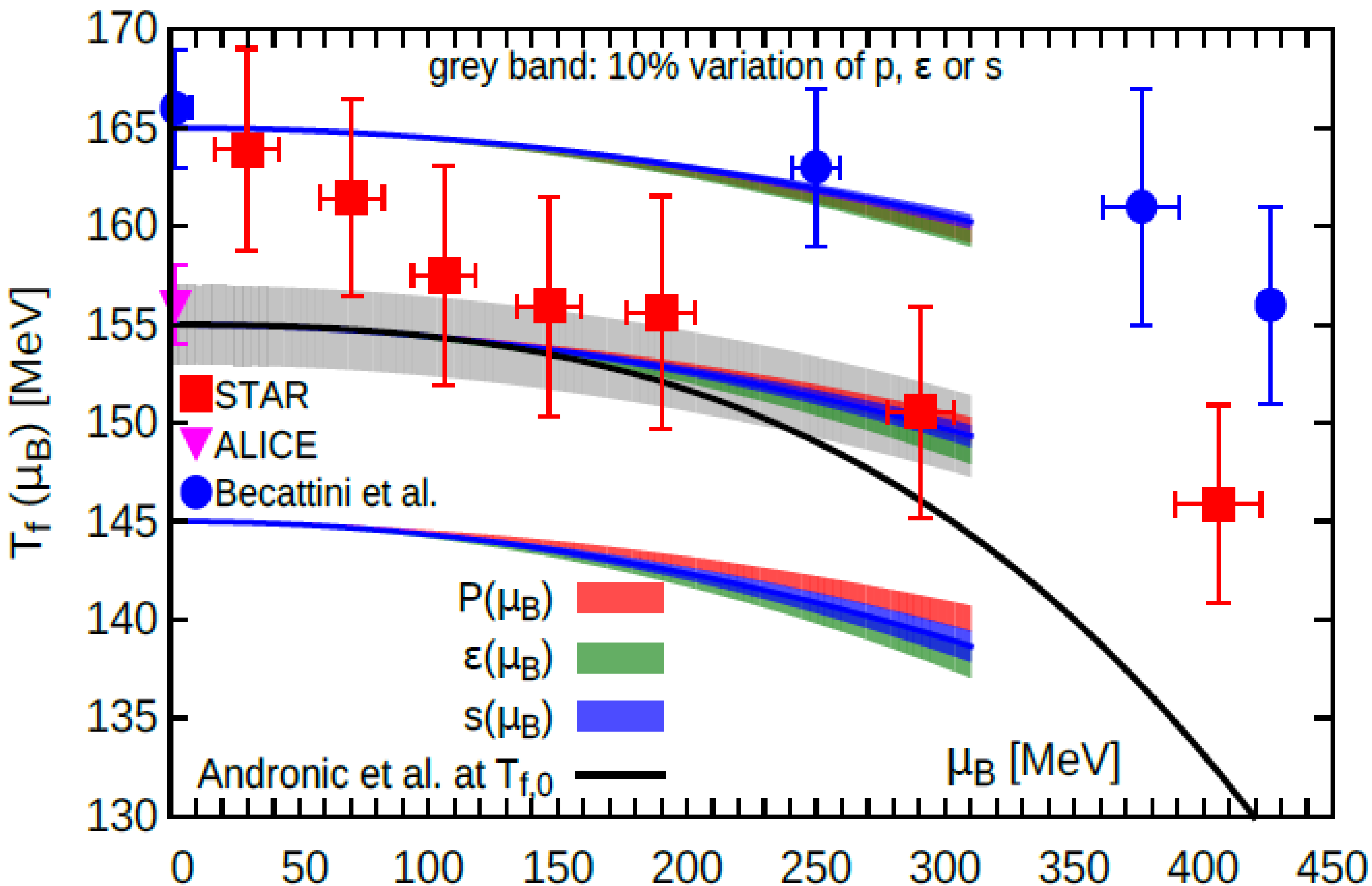




This is a long known fact in SHM, always argued as ‘the more states the better’, but all additional states (to π,k,p) are strange states

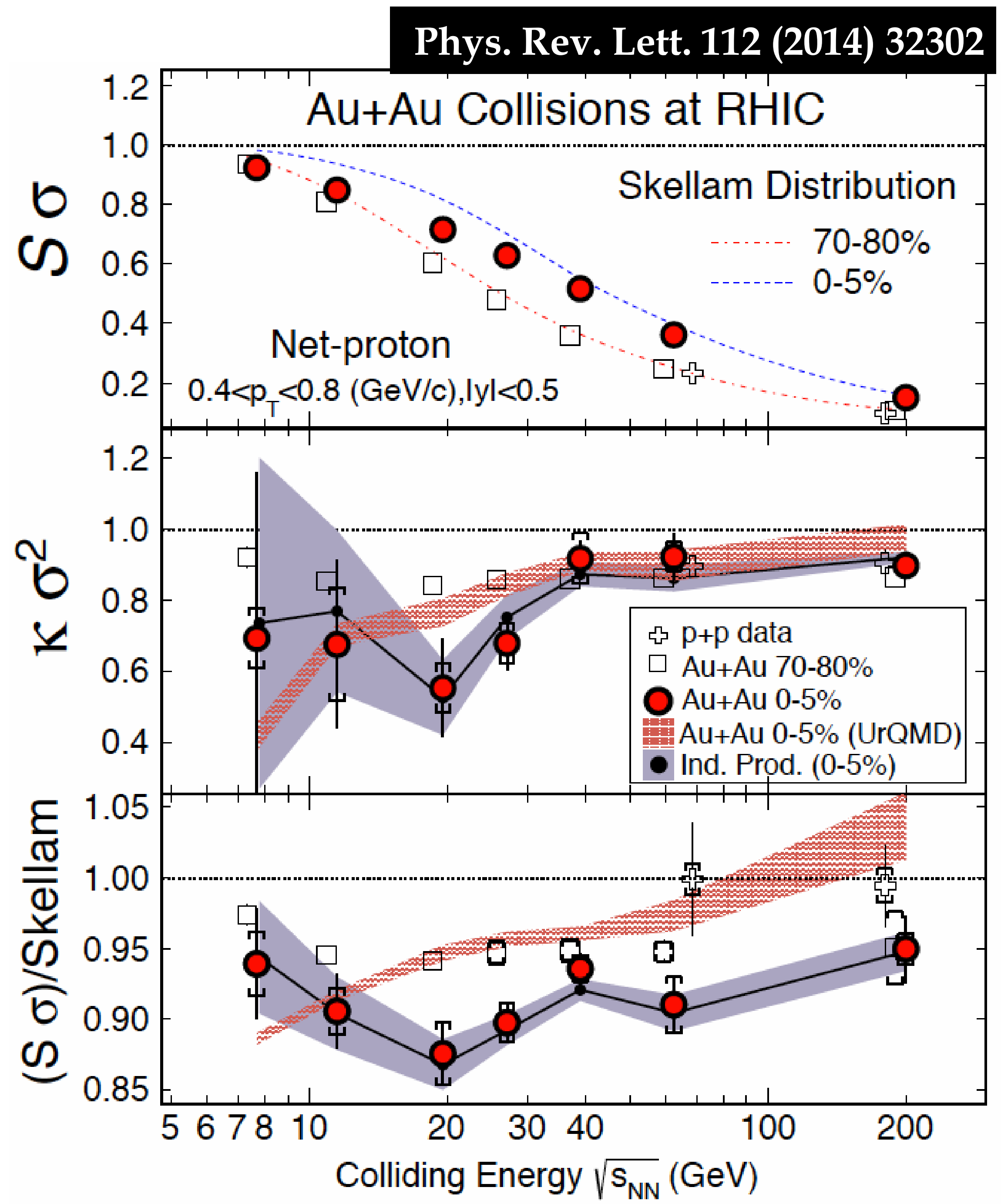
There is an upper limit……

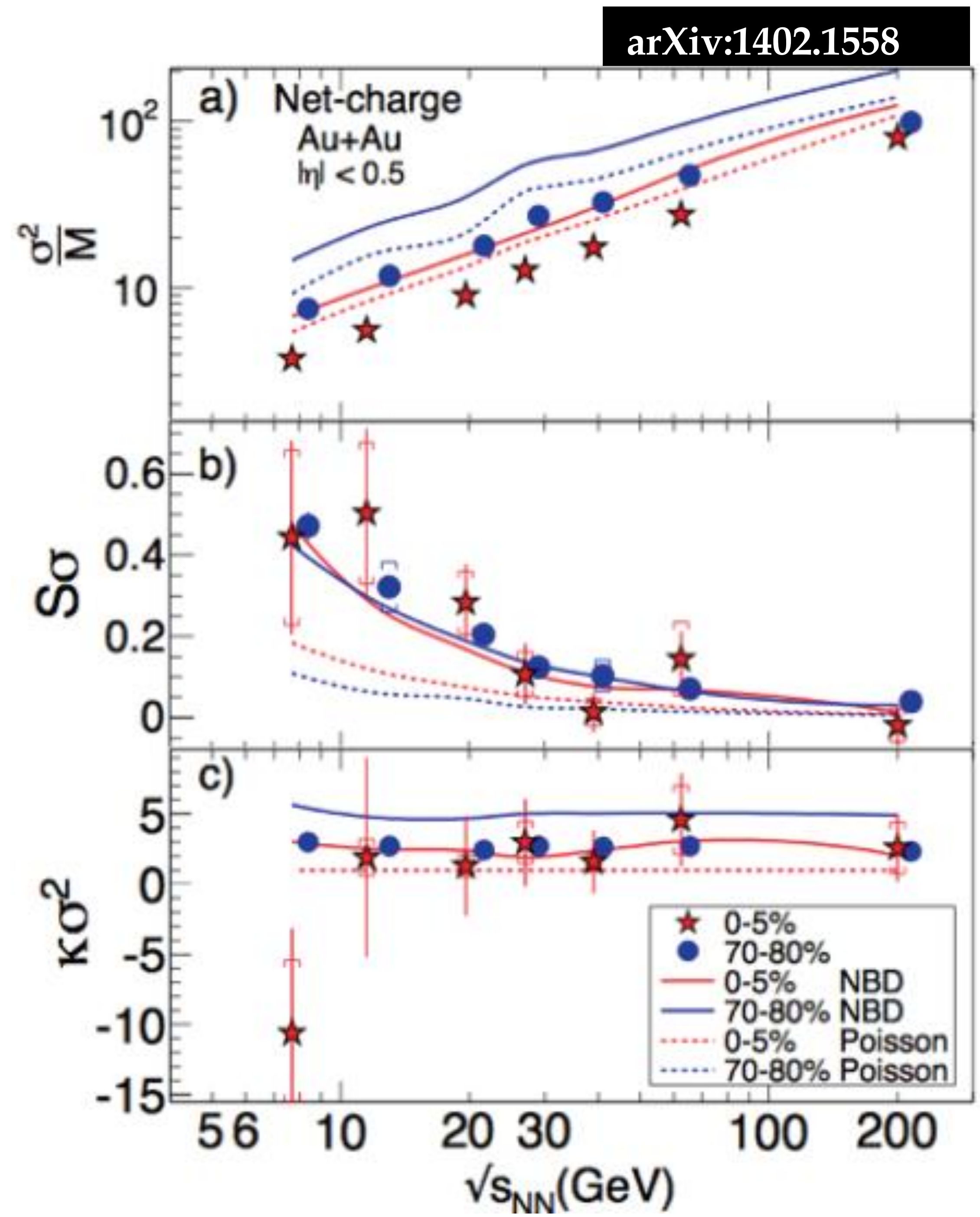
One important fact to remember: The chemical freeze-out surface cannot be above the pseudo-critical temperature from the lattice (154+-9 MeV) (both moved down over the years….)



F.Karsch, arXiv:1611.01973, SQM 2016
spread in T given by uncertainty in chiral pseudo-critical T, but also by difference between T from χ_u and χ_s

Higher moment ratios for net-charge and net-proton distributions (STAR 2014)





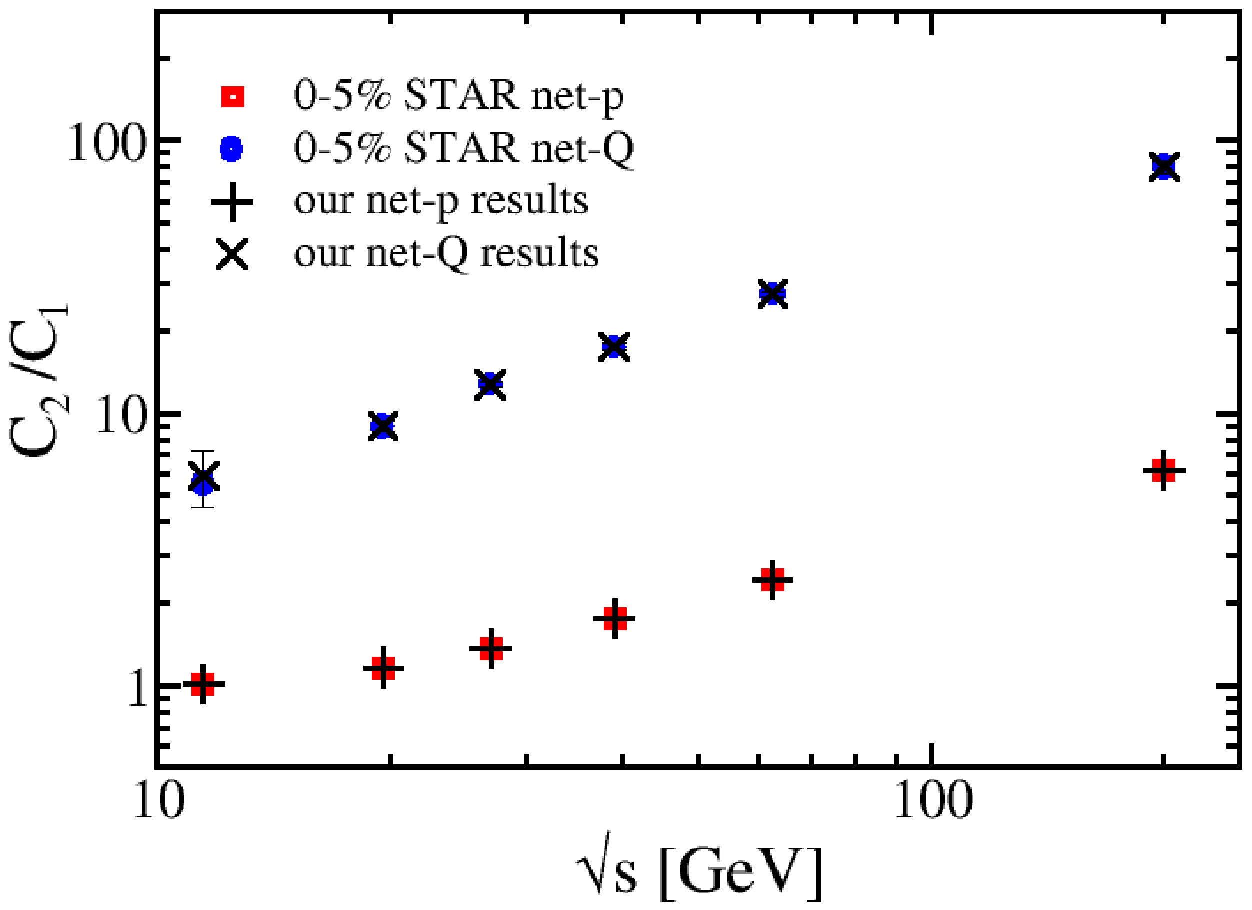
Fluctuations are more sensitive to chemical freeze-out as simple yields. They can be directly compared to susceptibilities on the lattice (P.Alba et al., PRC, (arXiv:1504.03262))

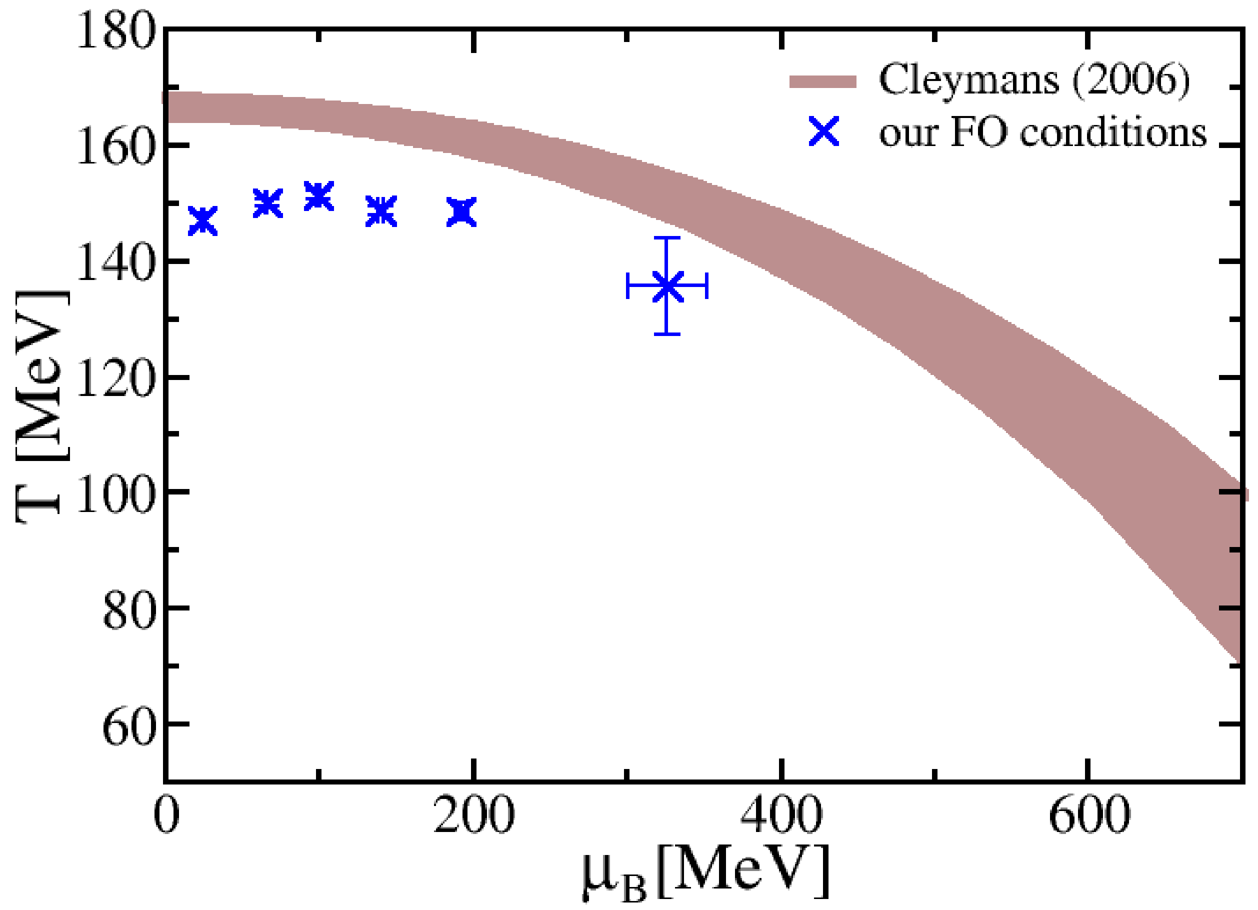
HRG (PDG 2008) analysis of STAR results (charge & proton)

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

HRG in partial chemical equilibrium: resonance decays for resonances up to 2 GeV/c^2 and weak decays taken into account), experimental cuts applied.

Use the lowest moments with the smallest errors and least 'criticality', i.e. σ^2/M



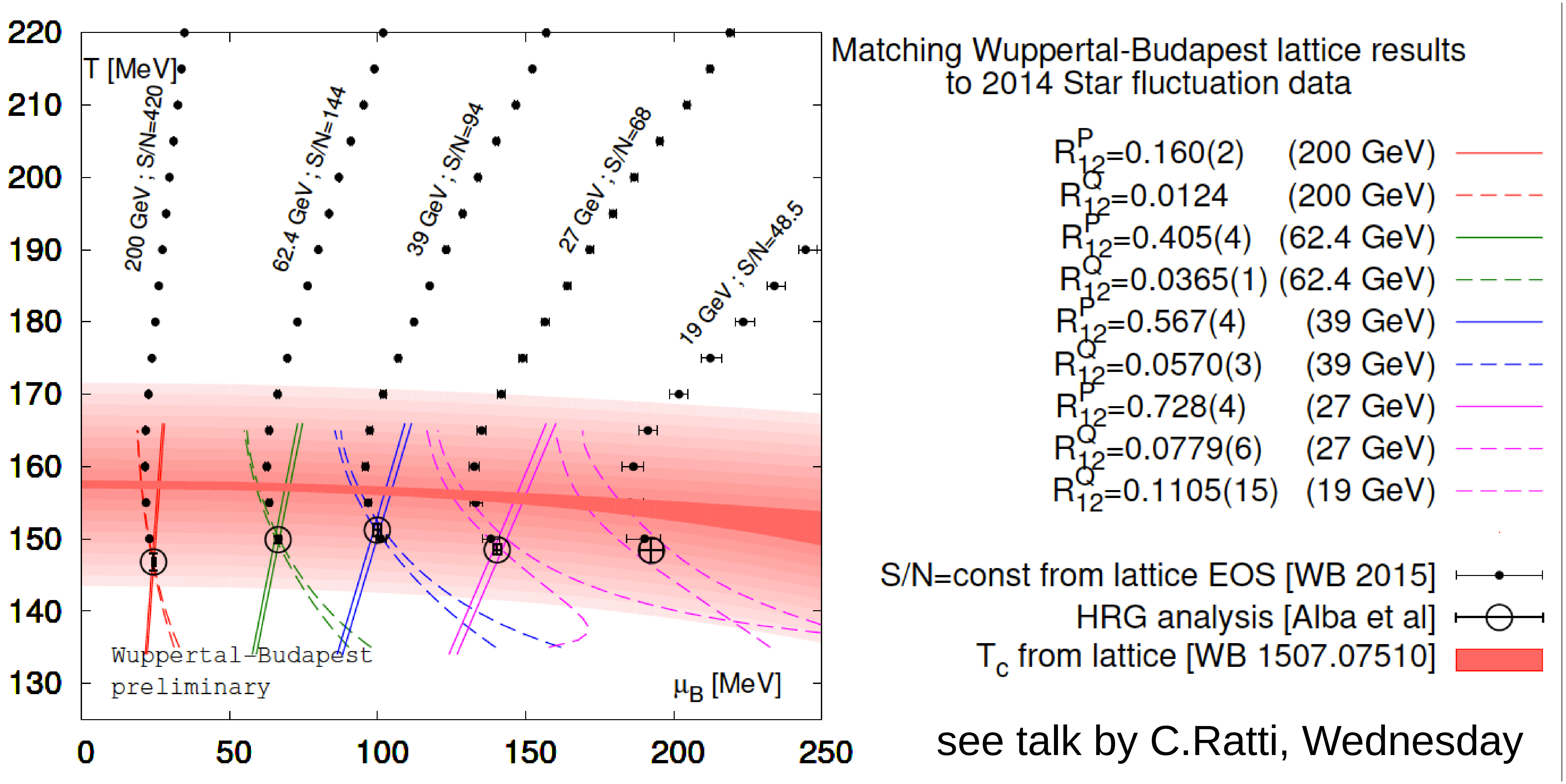


Result: intriguing 'lower' freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

The light quark freeze-out surface is well defined

Lattice: improved actions, realistic masses, continuum extrapolations – DONE

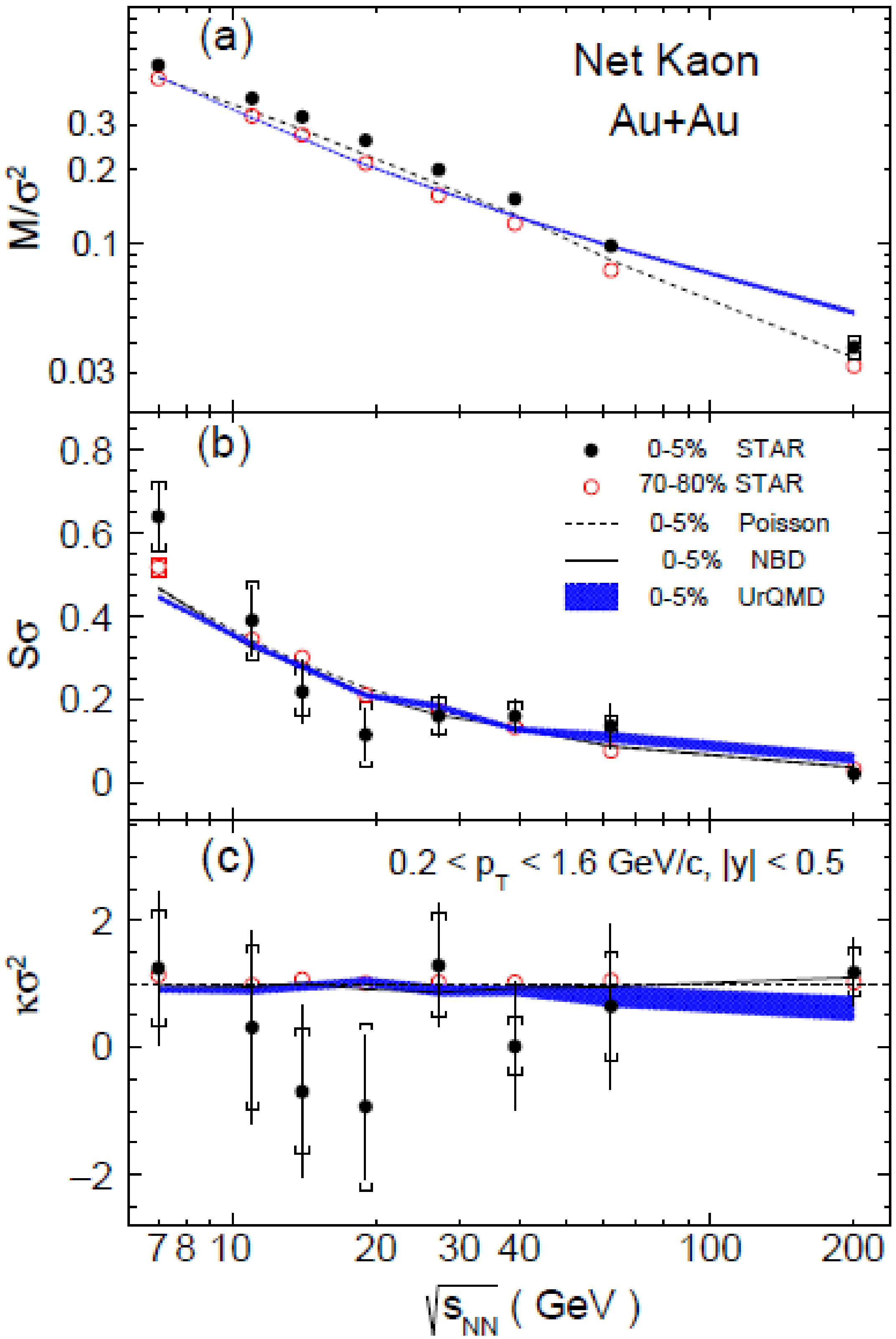
HRG: implementations improved, better PDG, more states – DONE

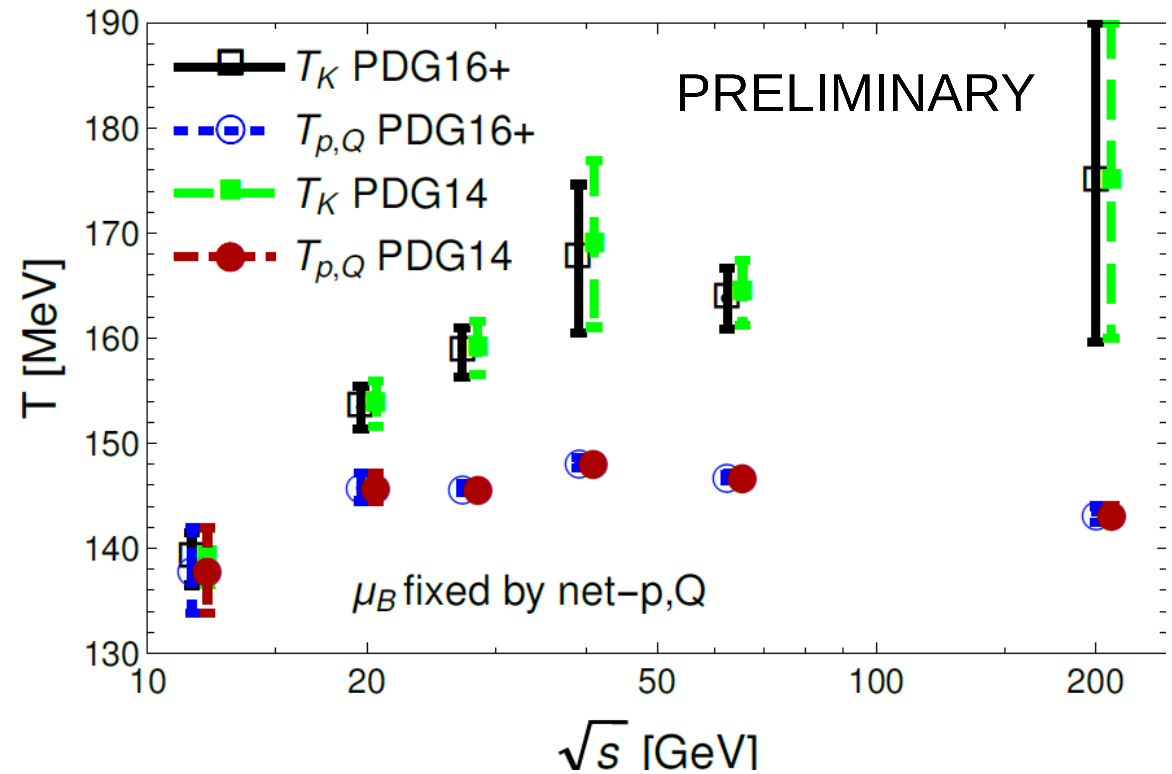


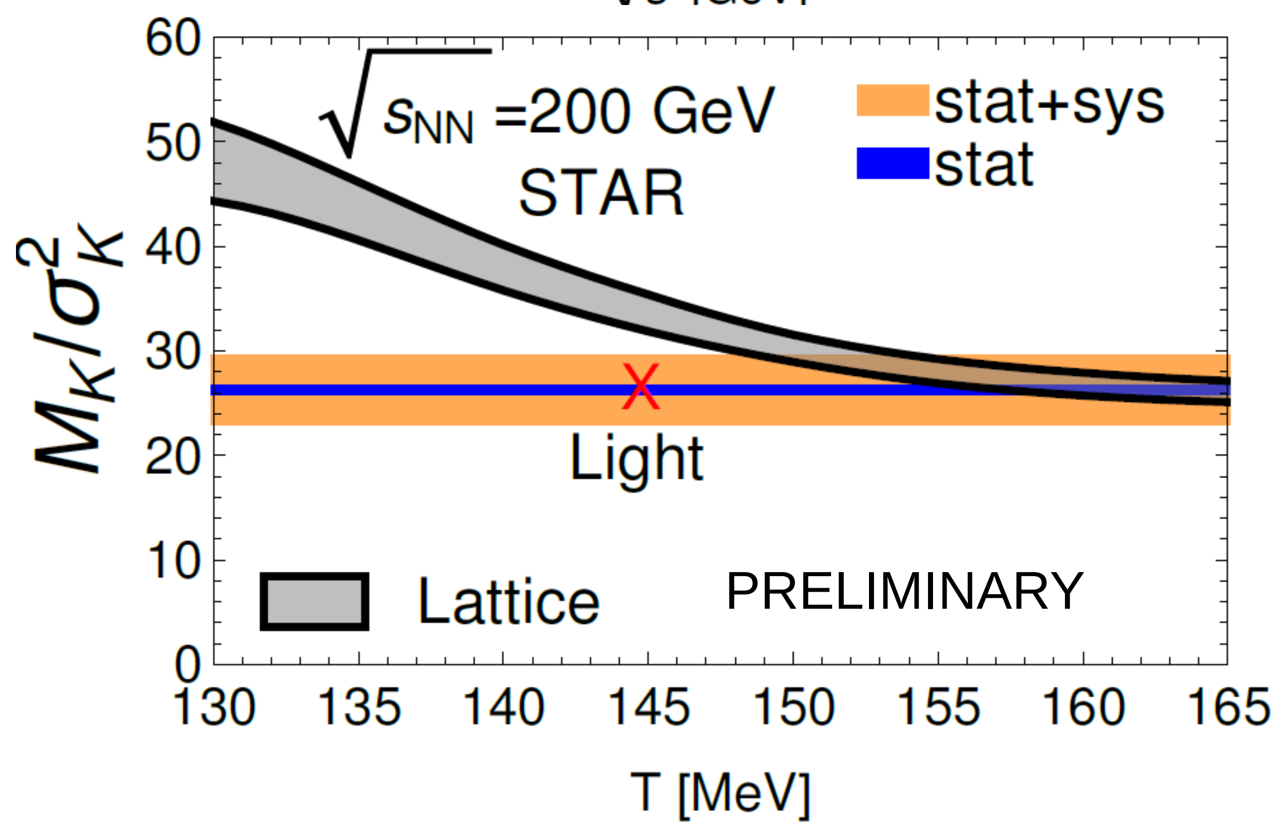
see talk by C.Ratti, Wednesday

The spread in the lattice range is effectively covered by the light vs strange quark susceptibilities

Fit σ^2/M for net-kaons in the same fashion than for net-proton and net-charge (Data: STAR, arXiv:1611.07132)







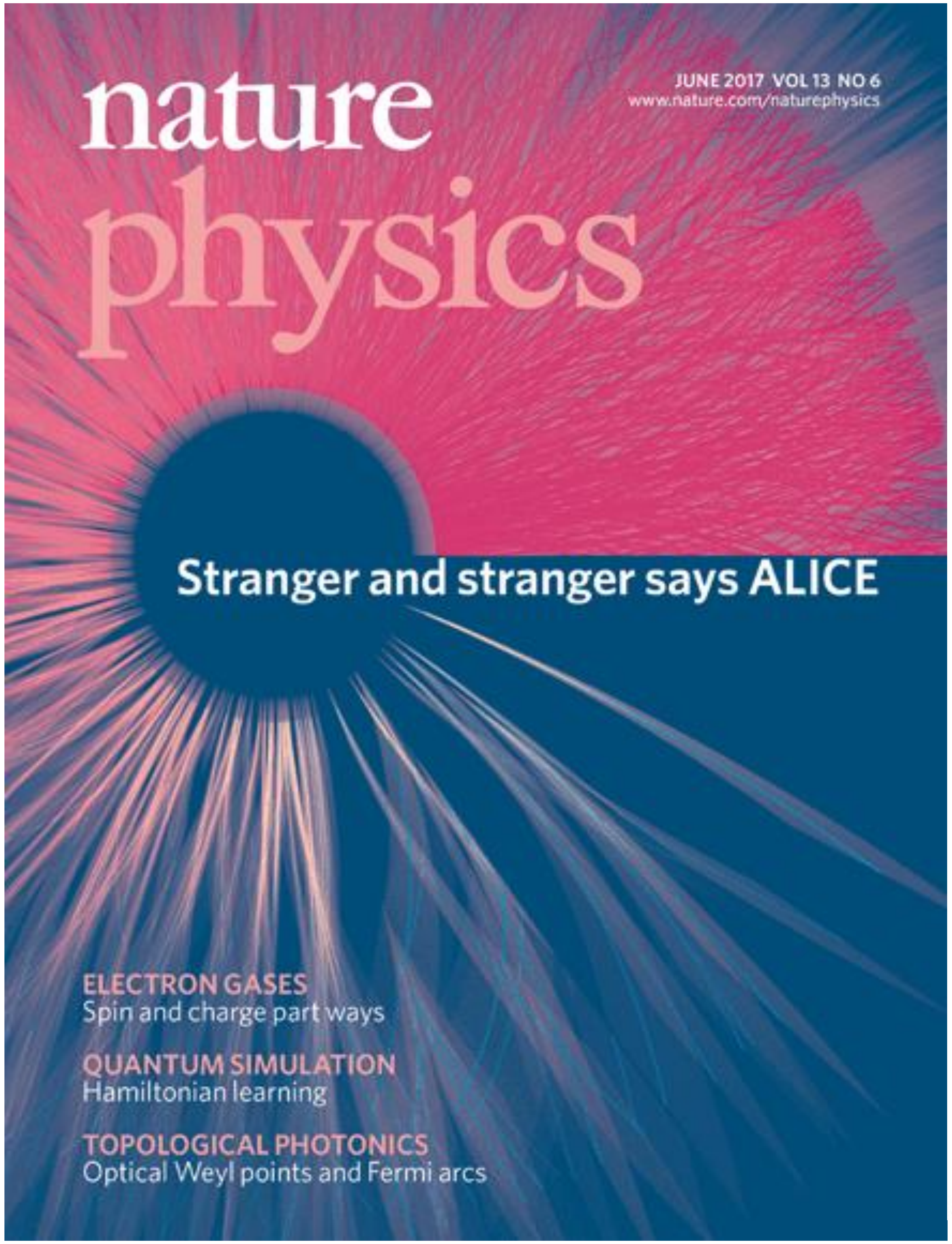
JNH, Ratti et al., arXiv:1607.02527

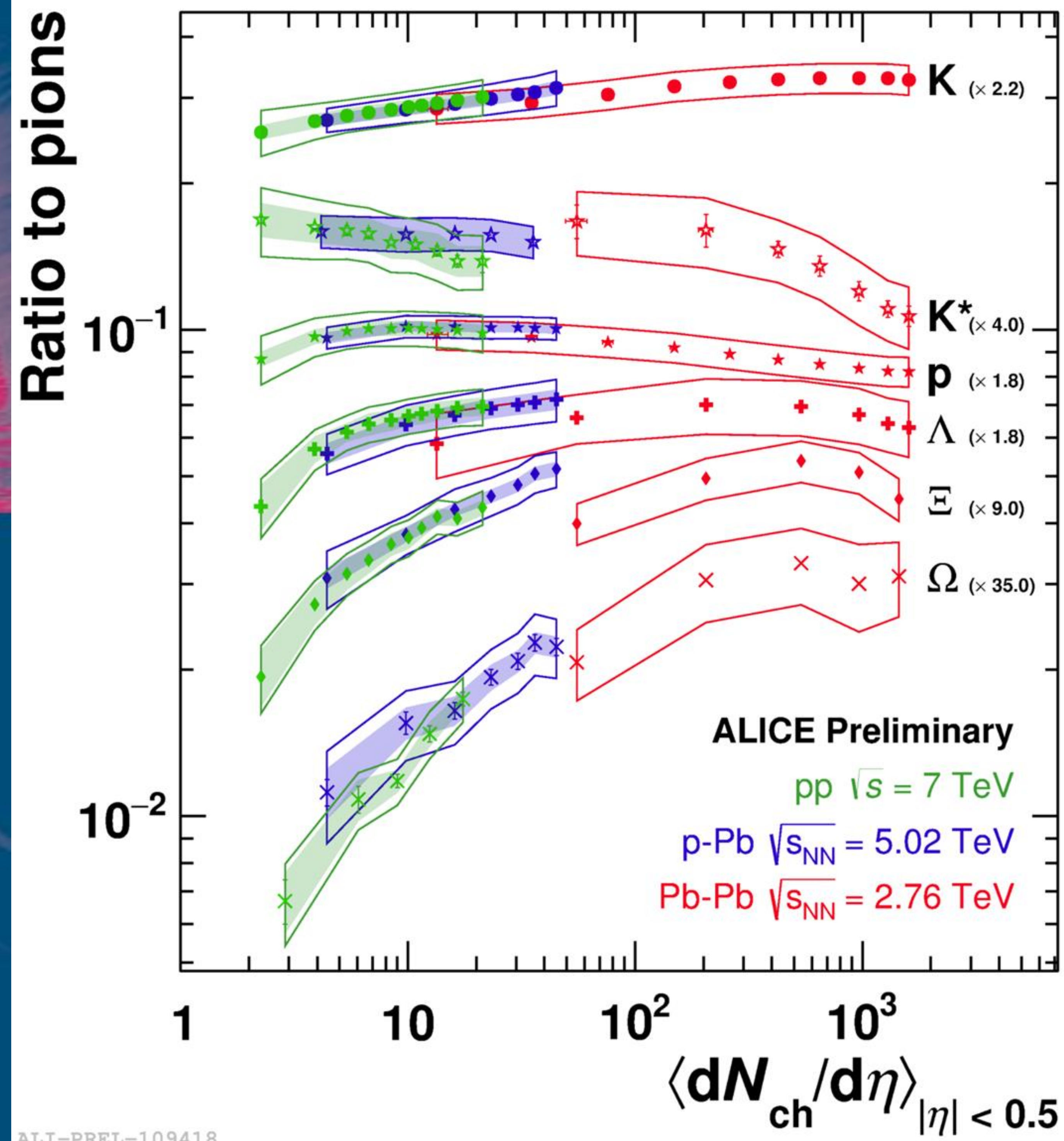
So let's assume there is a separate freeze-out hypersurface for strangeness – do we care ?

Strange matter creation ?:

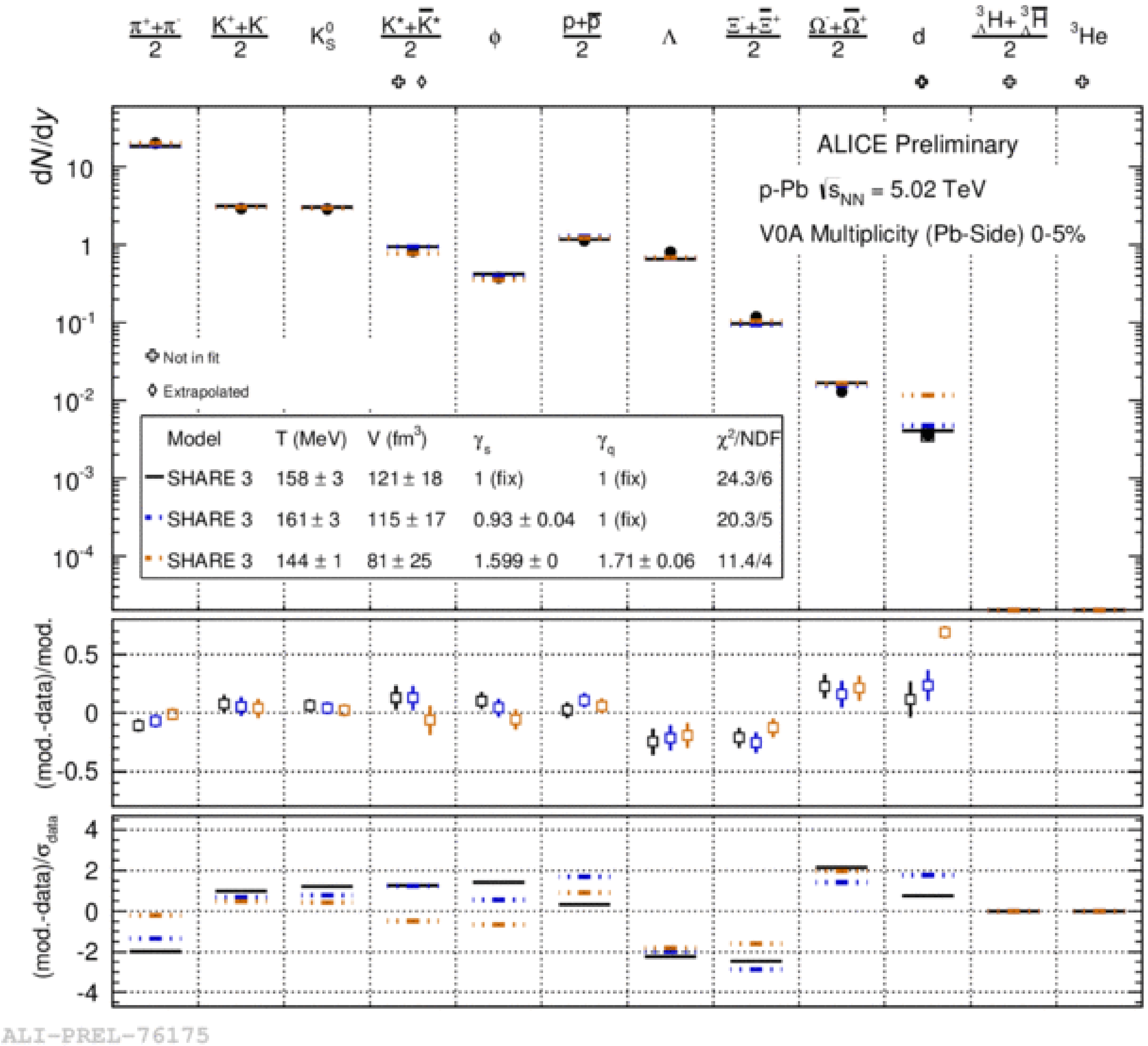
1.) strangeness enhancement vs. suppression
2.) strange resonance formation
3.) exotica

Stranger and stranger from small to large systems (ALICE, arXiv:1606.07424), see talk by L.Bianchi

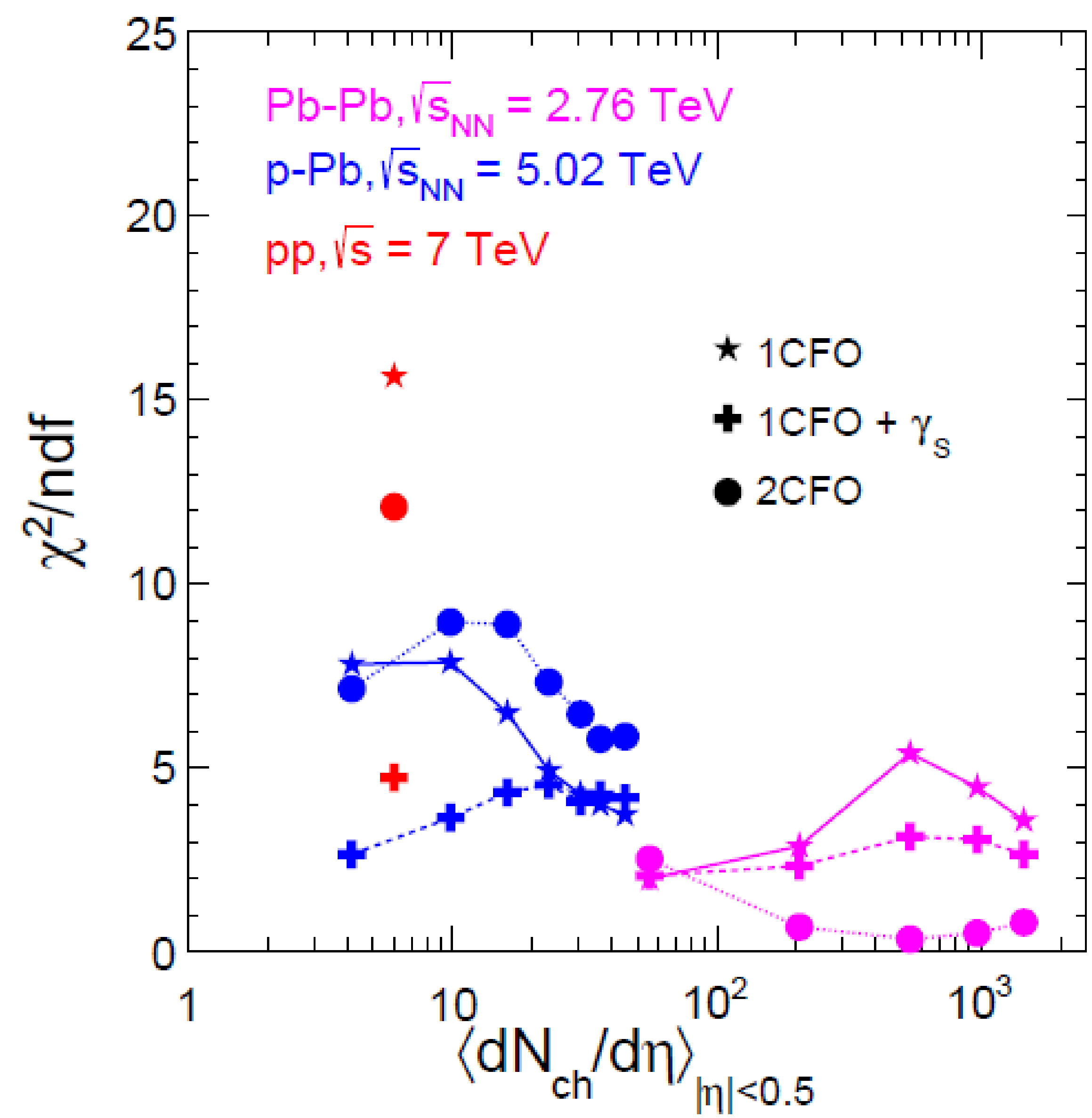




Small systems chemistry



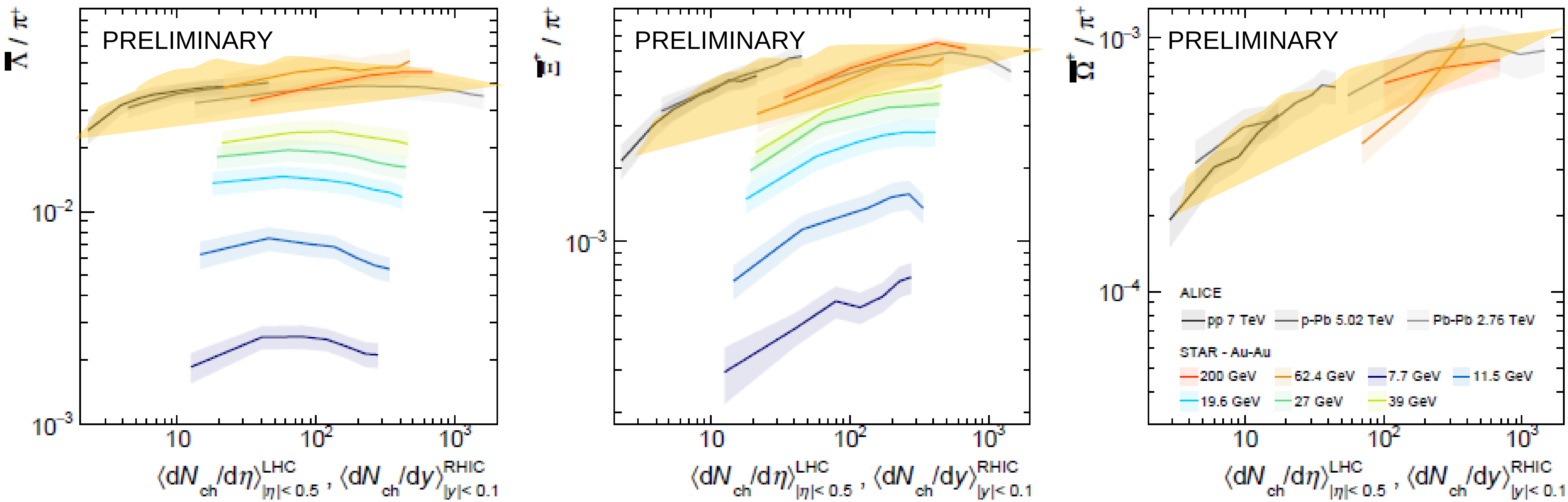
Model	T (MeV)	V (fm^3)	γ_s	γ_q	χ^2/NDF
SHARE 3	158 ± 3	121 ± 18	1 (fix)	1 (fix)	24.3/6
SHARE 3	161 ± 3	115 ± 17	0.93 ± 0.04	1 (fix)	20.3/5
SHARE 3	144 ± 1	81 ± 25	1.599 ± 0	1.71 ± 0.06	11.4/4



- HRG fit works rather well and yield similar T to PbPb fit (dependent on γ_S)
- Less evidence for flavor dependent freeze-out (Chatterjee, Dash, Mohanty, arXiv:1608.00643)

Is it time to re-evaluate strangeness suppression/enhancement ?

Canonical suppression reduces as a function of energy and as a function of system size (Tounsi, Redlich (2001)). Is suppression over at LHC energies ? Do we only see enhancement ? Can we distinguish ?

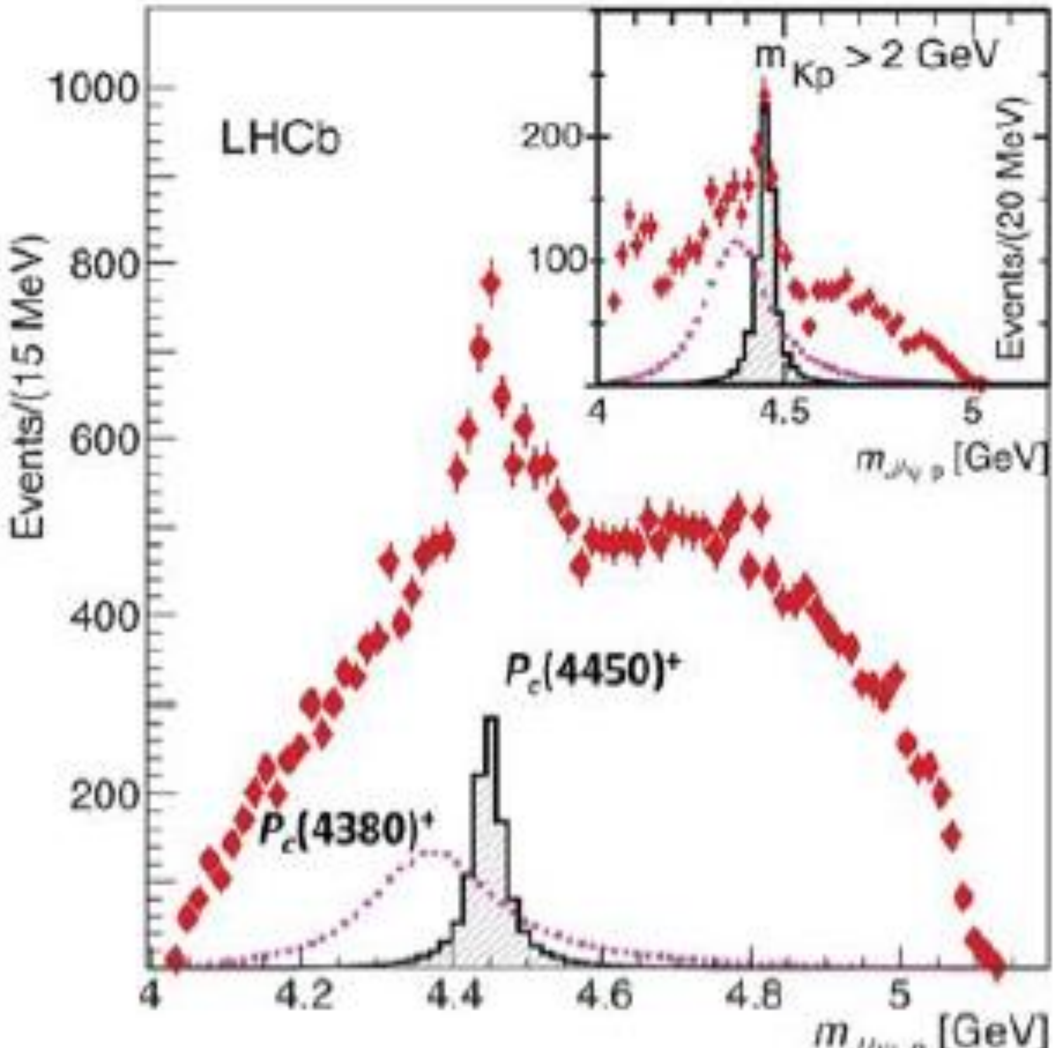


Above 39 GeV the curves seem to fall together, no more energy dependence. The volume dependence is still there (γ_s dependence ?). A higher T freeze-out surface in PbPb will lead to actual strangeness enhancement

Exotica:
Penta- and Tetra-quarks from LHCb

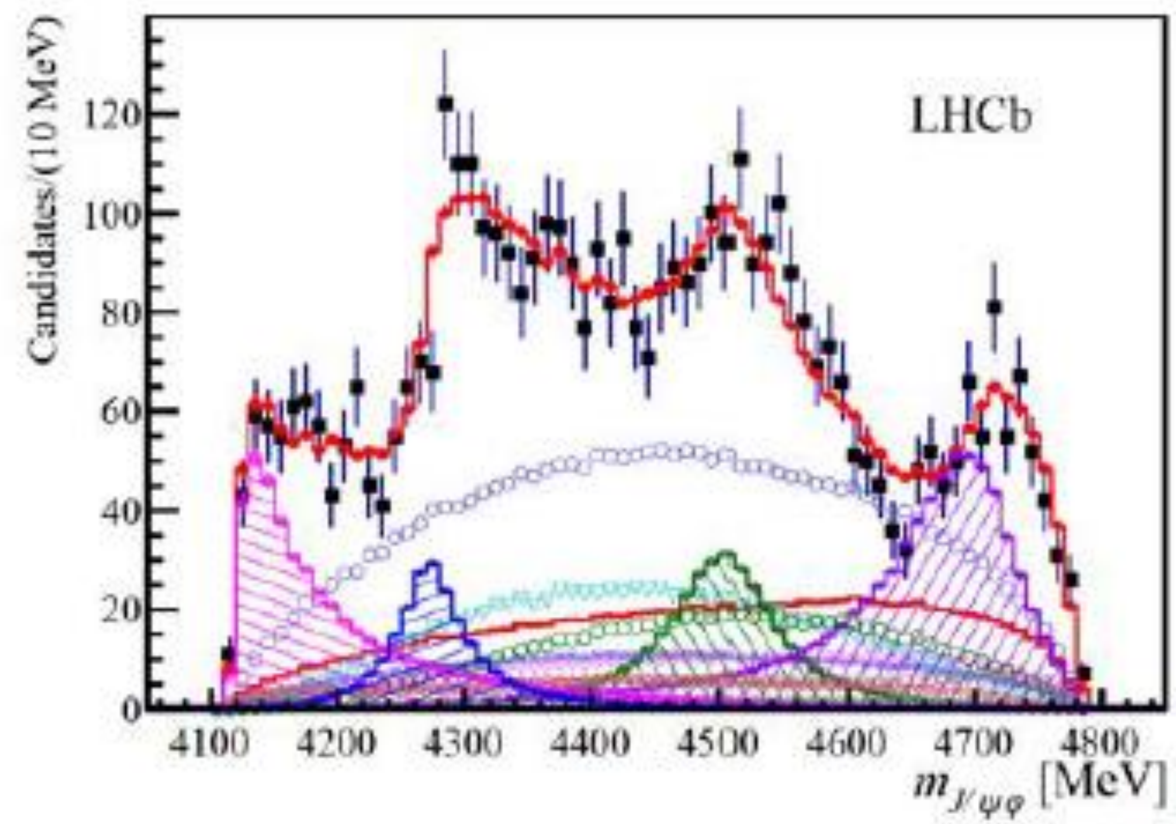
Penta-quark in 2015, 9σ evidence by 2016

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



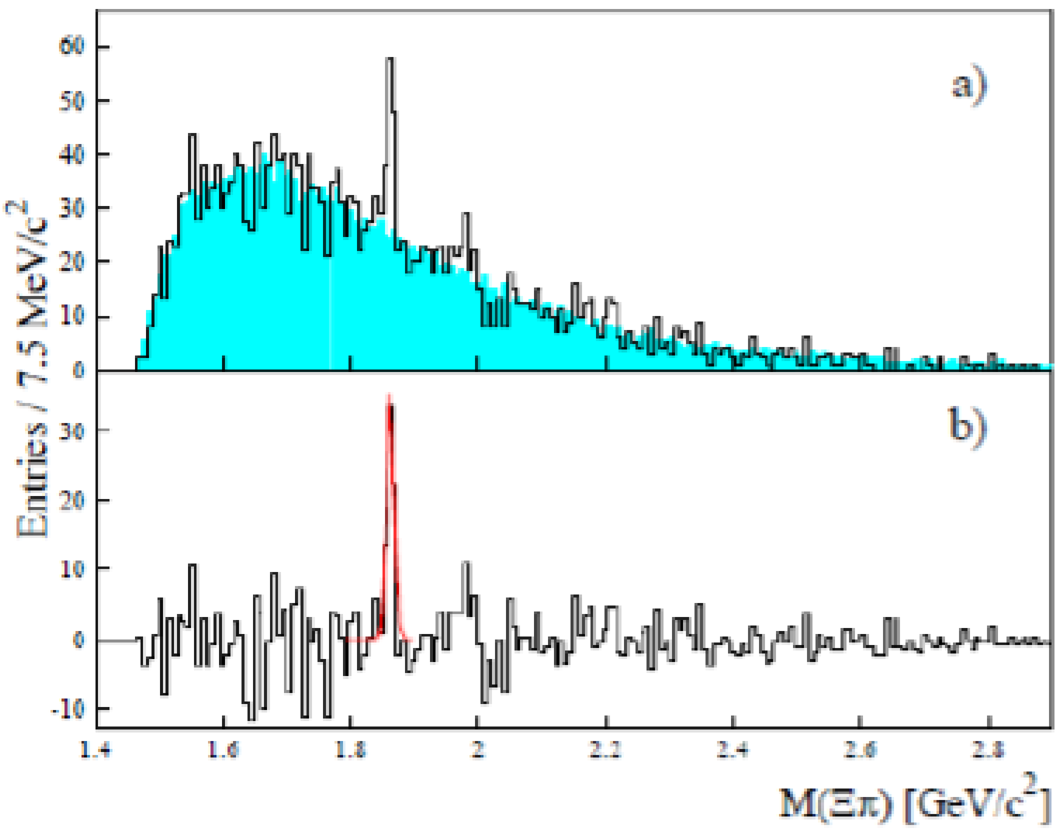
Tetra-quarks in 2016

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

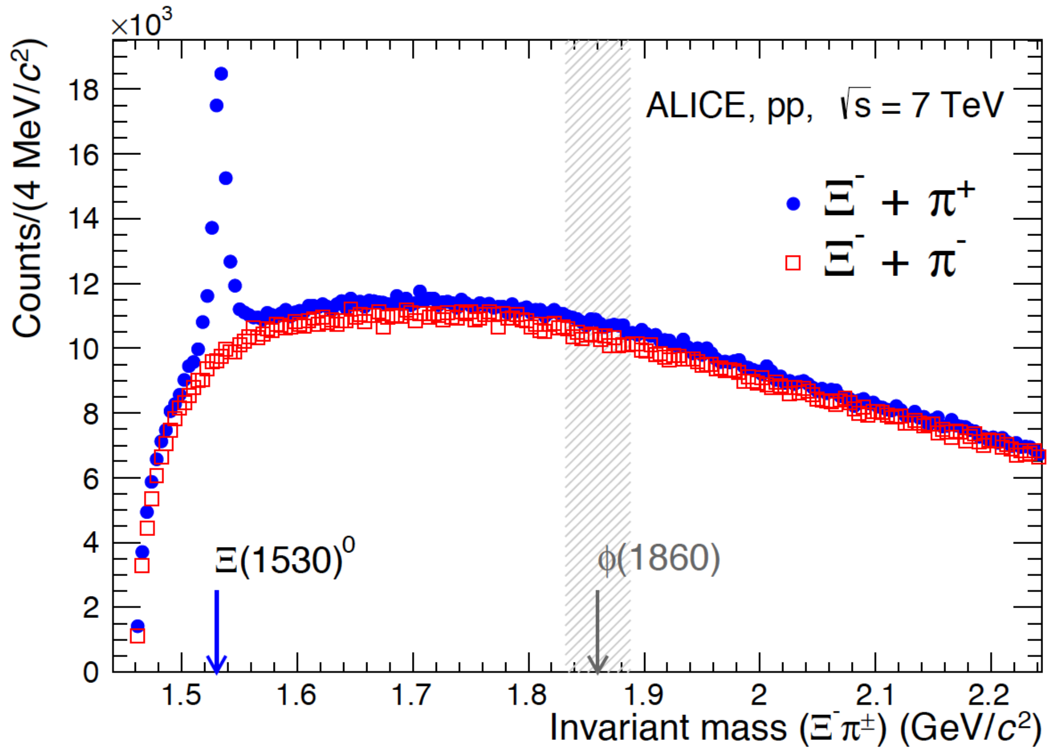


Why nothing in the strange sector ?

Exotica in strange sector ?



Famous pentaquark candidate from NA49 (2008) in $\Xi\pi$ channels (ϕ(1860)) (dsdsubar)
Never retracted, never confirmed



No evidence for H-dibaryon or ϕ(1860) in ALICE data.

Maybe we are looking in the wrong channels. In the charm sector all tetra- and penta-quarks seem to require closed charm components.

Keep looking !!

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 in which strange particle 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 Models).
- Dynamic quantities that evolve during the deconfined phase will be affected as long as the hadronization temperature plays a significant role, i.e. quark phase is shortened for heavier flavors, which could explain flavor effects in R_{AA} if energy loss builds up near Tc.

- Ongoing project (JNH, Ratti, Parotto): The phases can be linked in a hydrodynamic calculation by using a mixed EOS from lattice and HRG with varying flavor-dependent switching temperatures.