Exotic Strange States Near the Phase Transition

R. Bellwied (University of Houston)

in collaboration with

C. Ratti, S. Jena, D. McDonald (University of Houston)

P. Alba, V. Mantovani (Torino University & INFN)

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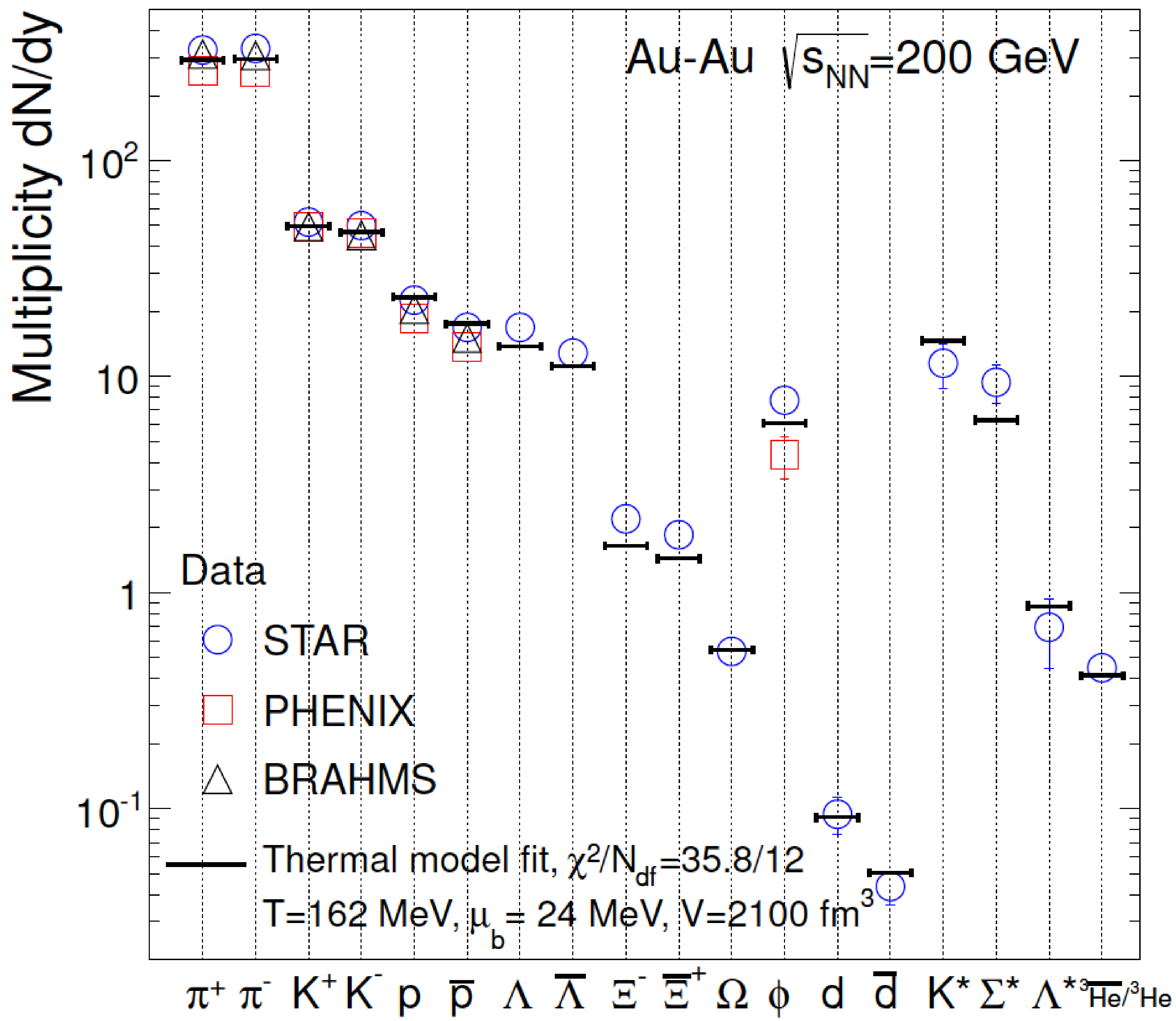
Outline

- SHM / HRG model input
- Recent input from lattice QCD on the issue of hadronization
- The role of flavor during the transition
- New measurements: fluctuations in addition to yields & ratios
- Experimental verification of lattice predictions
- Where do we go, what does it mean ?

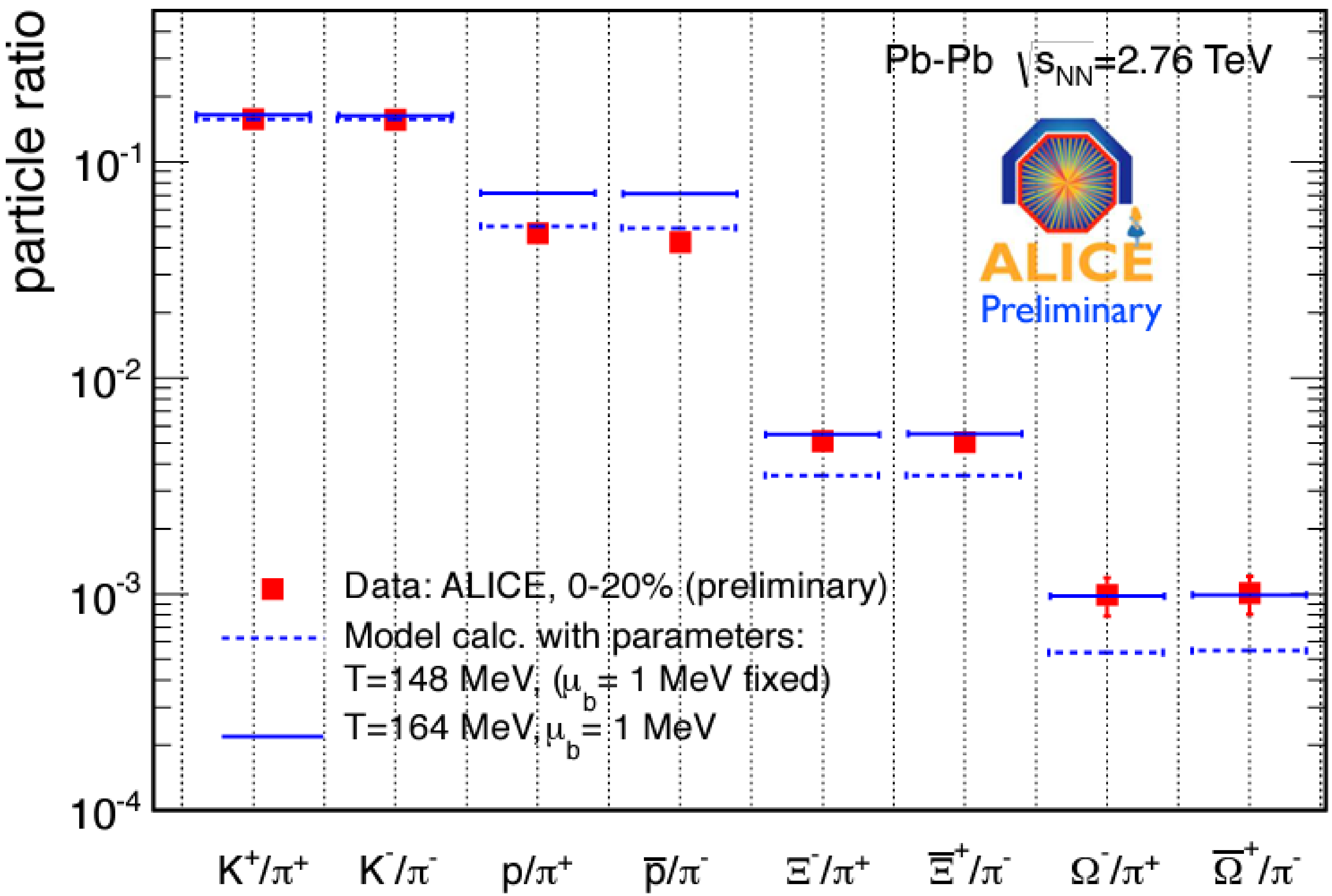
The impressive success of SHM

(the latest 200 GeV RHIC fits based on yields)



A. Andronic et al.,
QM 2012
arXiv:1210.7724

SHM model comparison based on ratios including multi-strange baryons



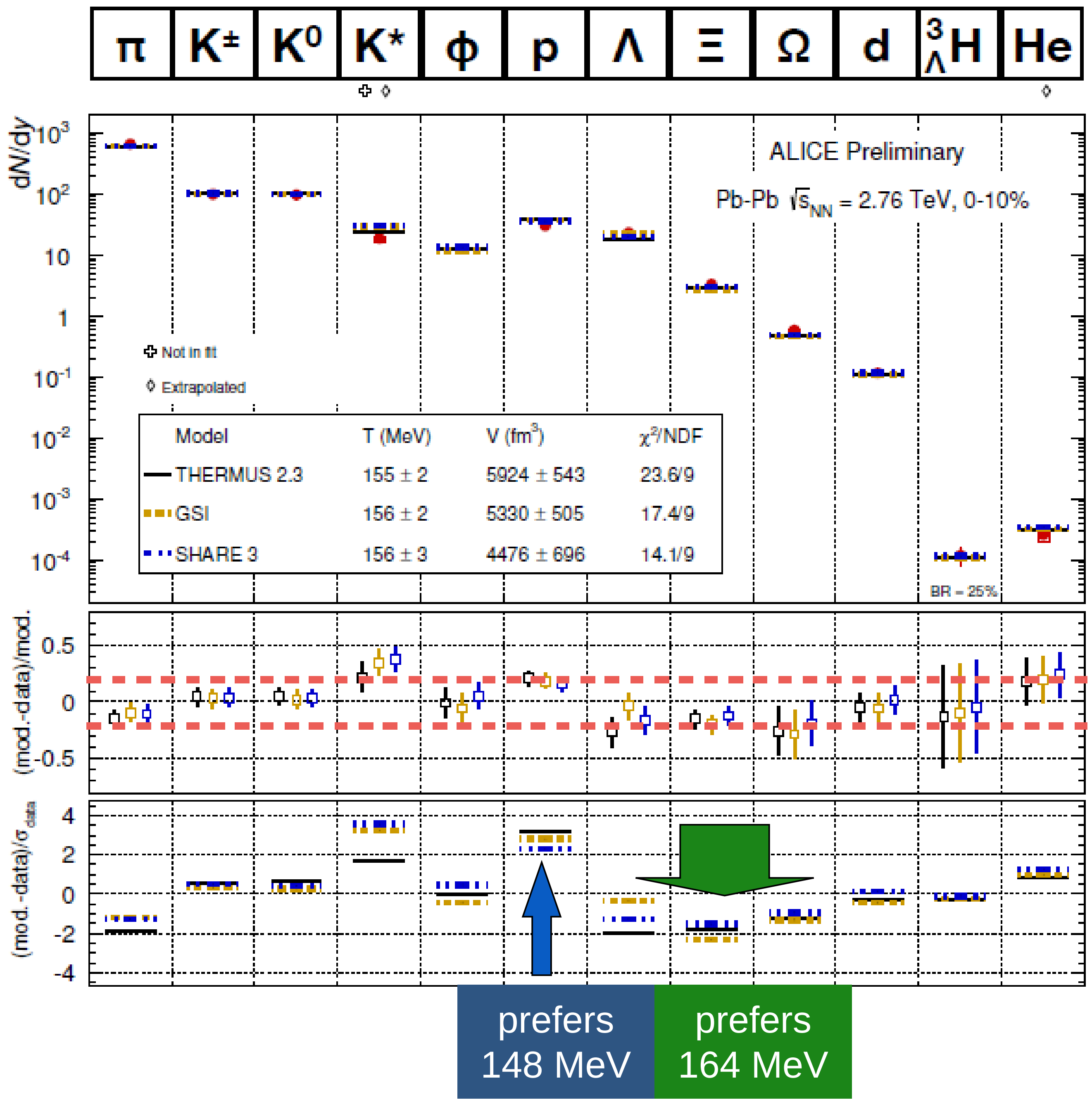
R. Preghenella
for ALICE
SQM 2012
arXiv:1111.7080
Acta Phys. Pol.

Ratios or Yields ?:

Ratios are less sensitive to biases and do not require the volume parameter

Yields might be more sensitive to determine freeze-out parameters

SHM model comparison based on yields including multi-strange baryons



This looks like a good fit, but it is not

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

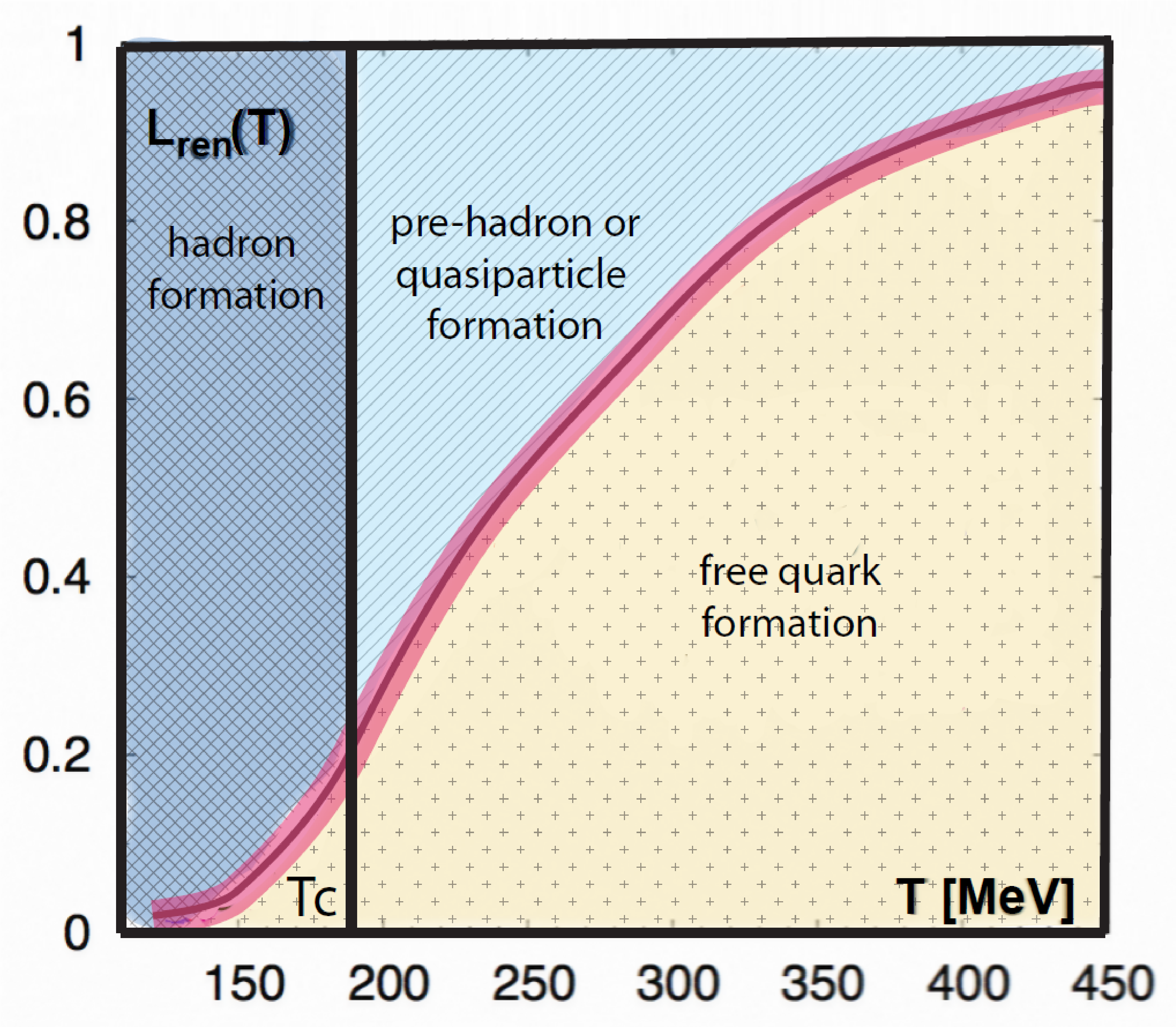
Fit to pions and protons alone yield a temperature of 148 MeV.

Several alternate explanations:
- Inclusion of Hagedorn states
- Non-equilibrium fits
- Baryon annihilation
- *Different T_{ch} for light and strange*

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

Does this make sense near the QCD phase transition ?

A re-interpretation of the Polyakov Loop calculation in lattice QCD



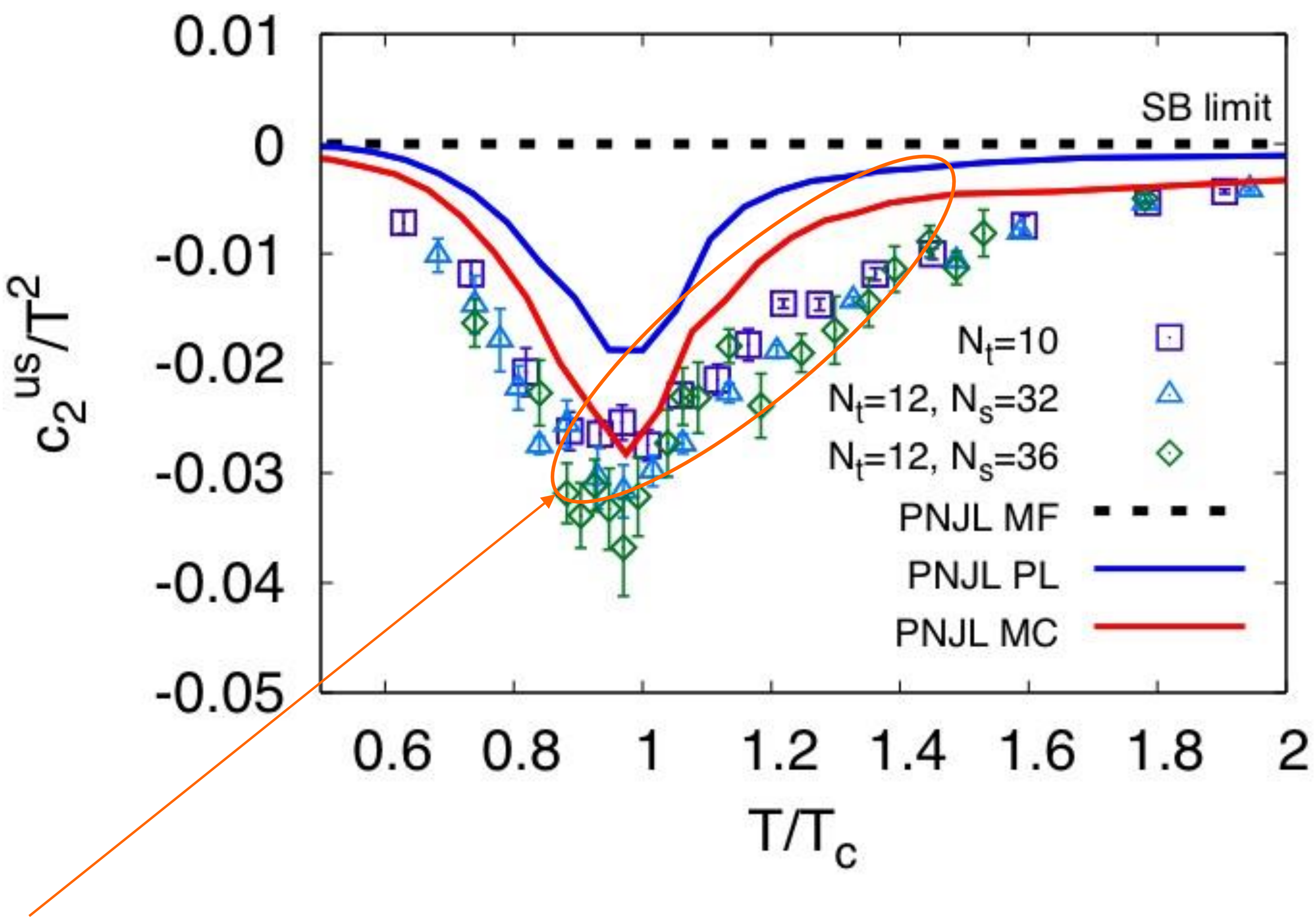
RB et al., PLB691 (2010) 208
Data: Bazavov et al., arXiv:1105:1131

- 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 ?

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

Comparison of lattice to PNJL



PNJL variations

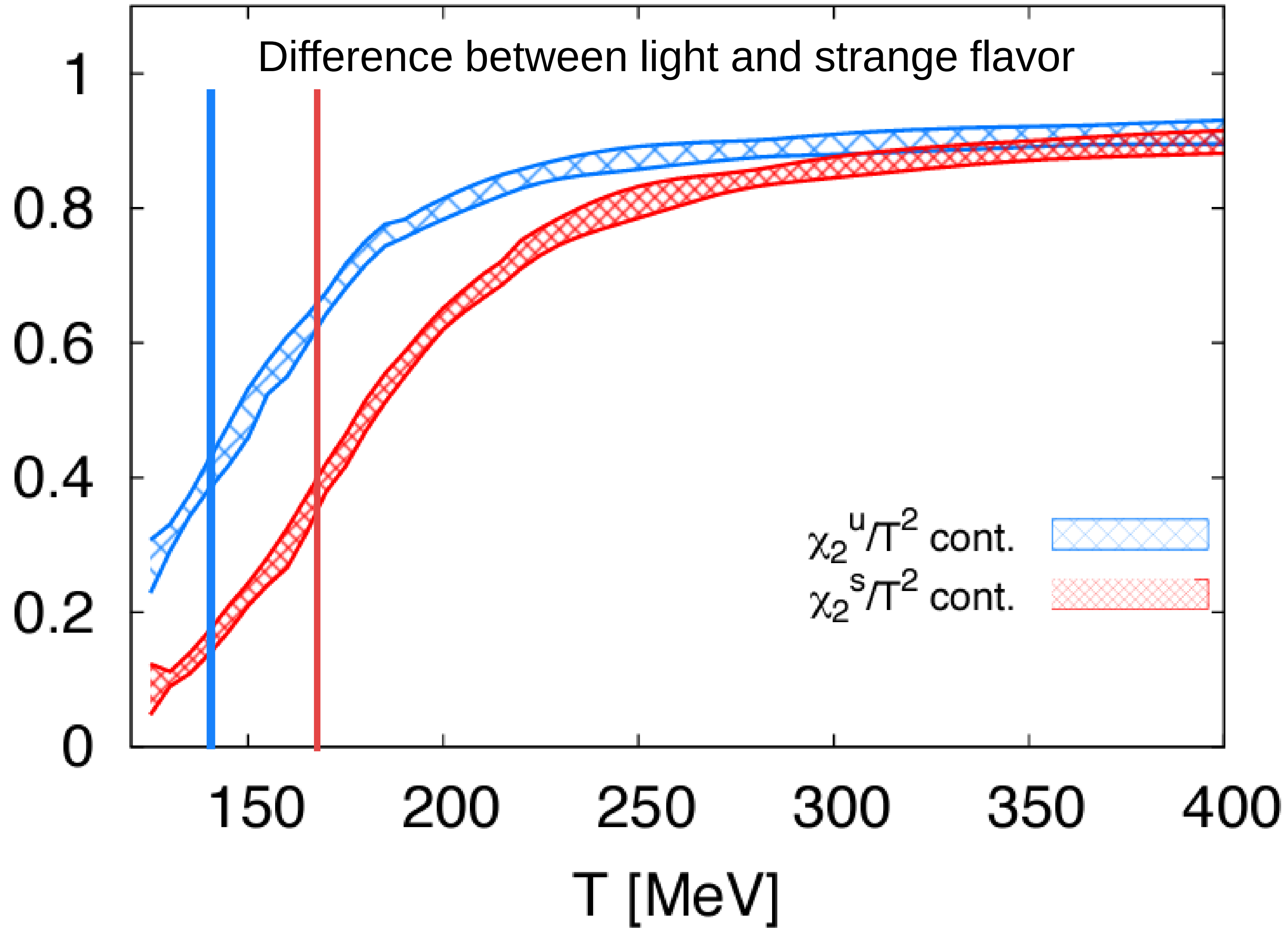
PNJL-MF:
pure mean field calculation

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.
There has to be a contribution from bound states

Indication of flavor dependence in diagonal susceptibility correlators

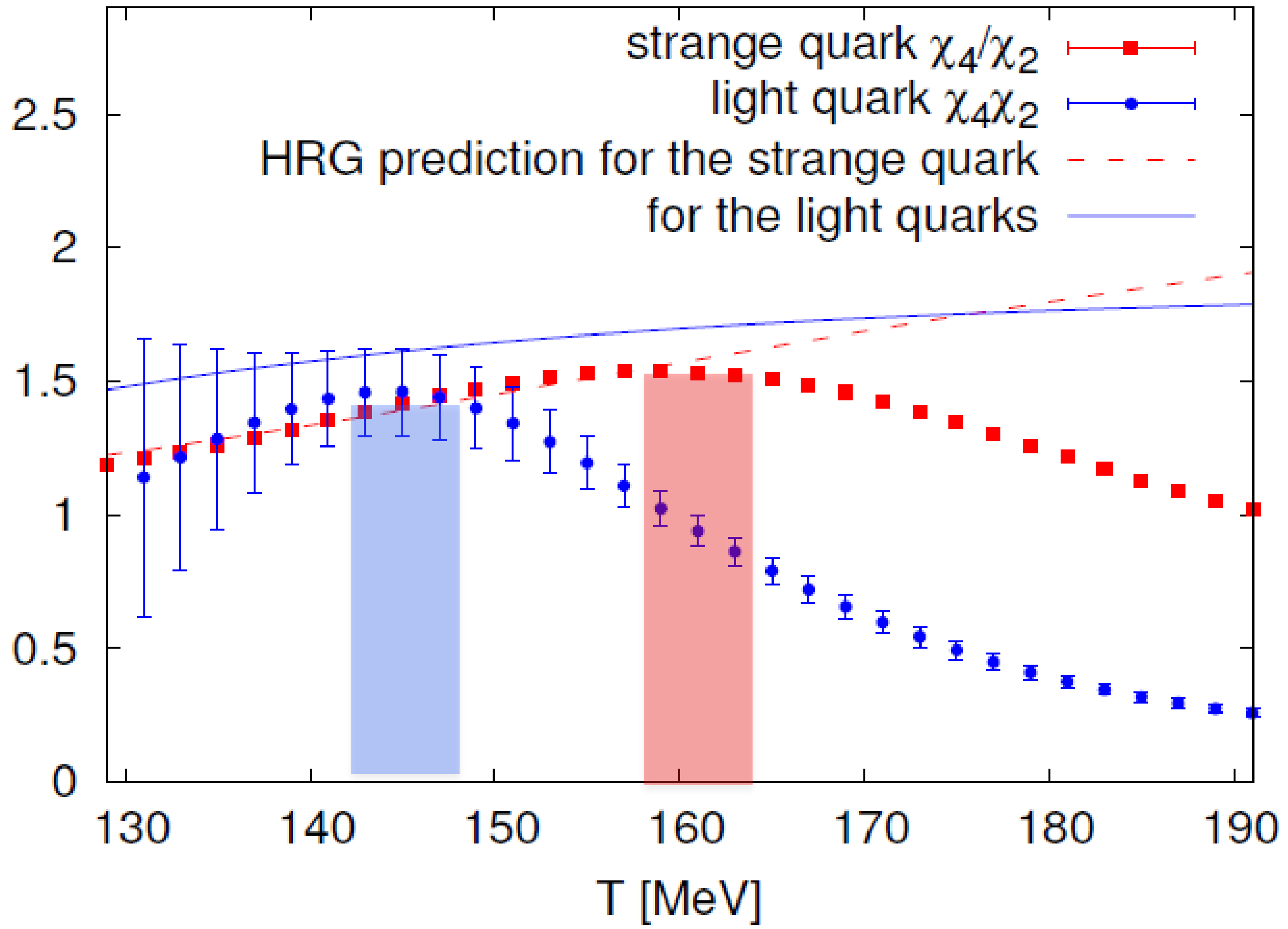


C. Ratti et al., PRD 85, 014004 (2012)
R. Bellwied, arXiv:1205.3625

And finally: 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

- In a regime where we have flavor (quark mass) dependent susceptibility ratios there might be no single freeze-out surface

Experimental verification

Yields of strange particles should be enhanced relative to yields of non-strange particles (the new strangeness enhancement)

Higher order fluctuations of conserved charges should be sensitive to the freeze-out temperature.

A closer look at RHIC measurements

Relating susceptibilities to moments

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:

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

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

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:

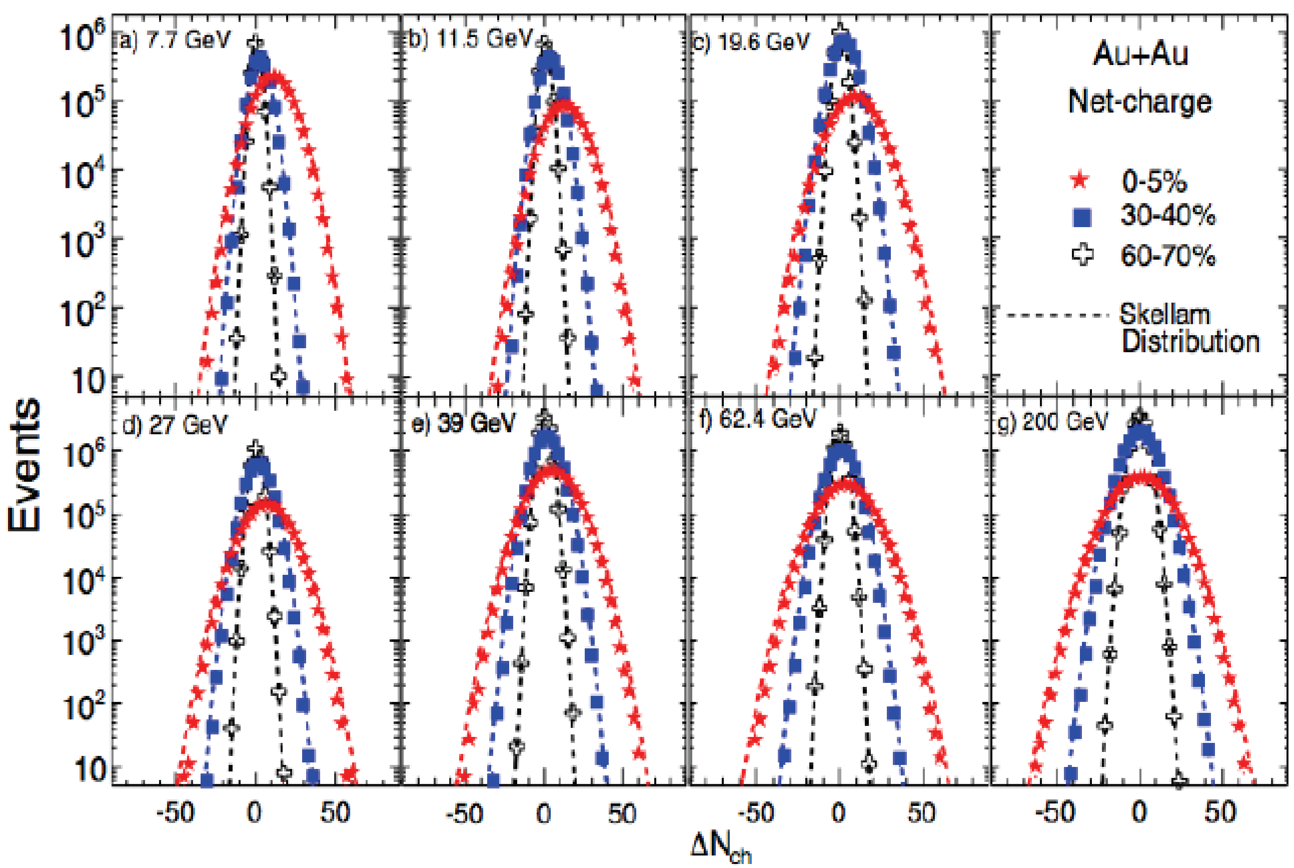
$$R_{12} = \frac{M}{\sigma^2} = \frac{\chi_1^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

To measure T:

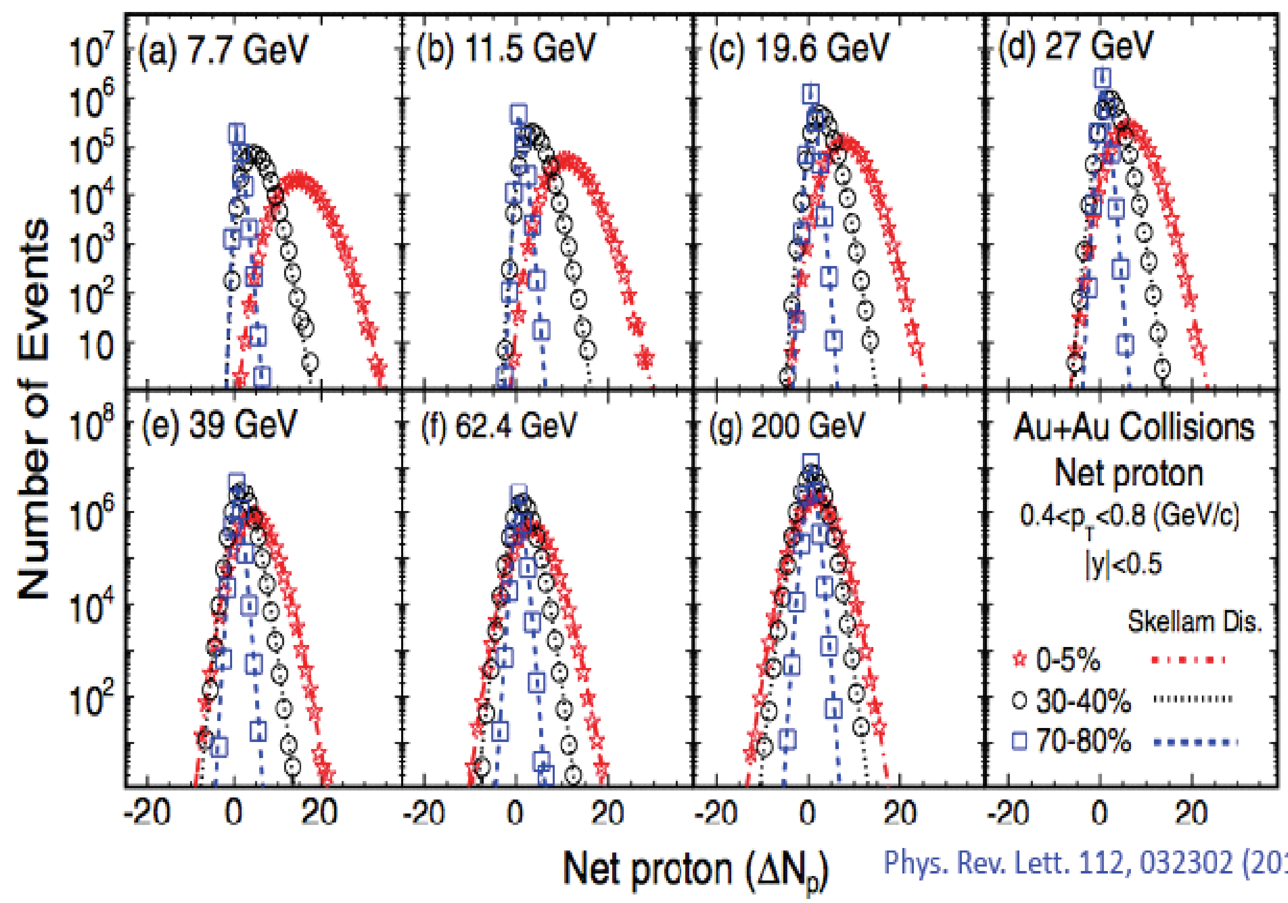
$$R_{31} = \frac{S\sigma^3}{M} = \frac{\chi_3^{(B,S,Q)}}{\chi_1^{(B,S,Q)}}$$

Measure net-distributions and calculate moments in STAR

Net-charge distribution



Net-Proton distribution



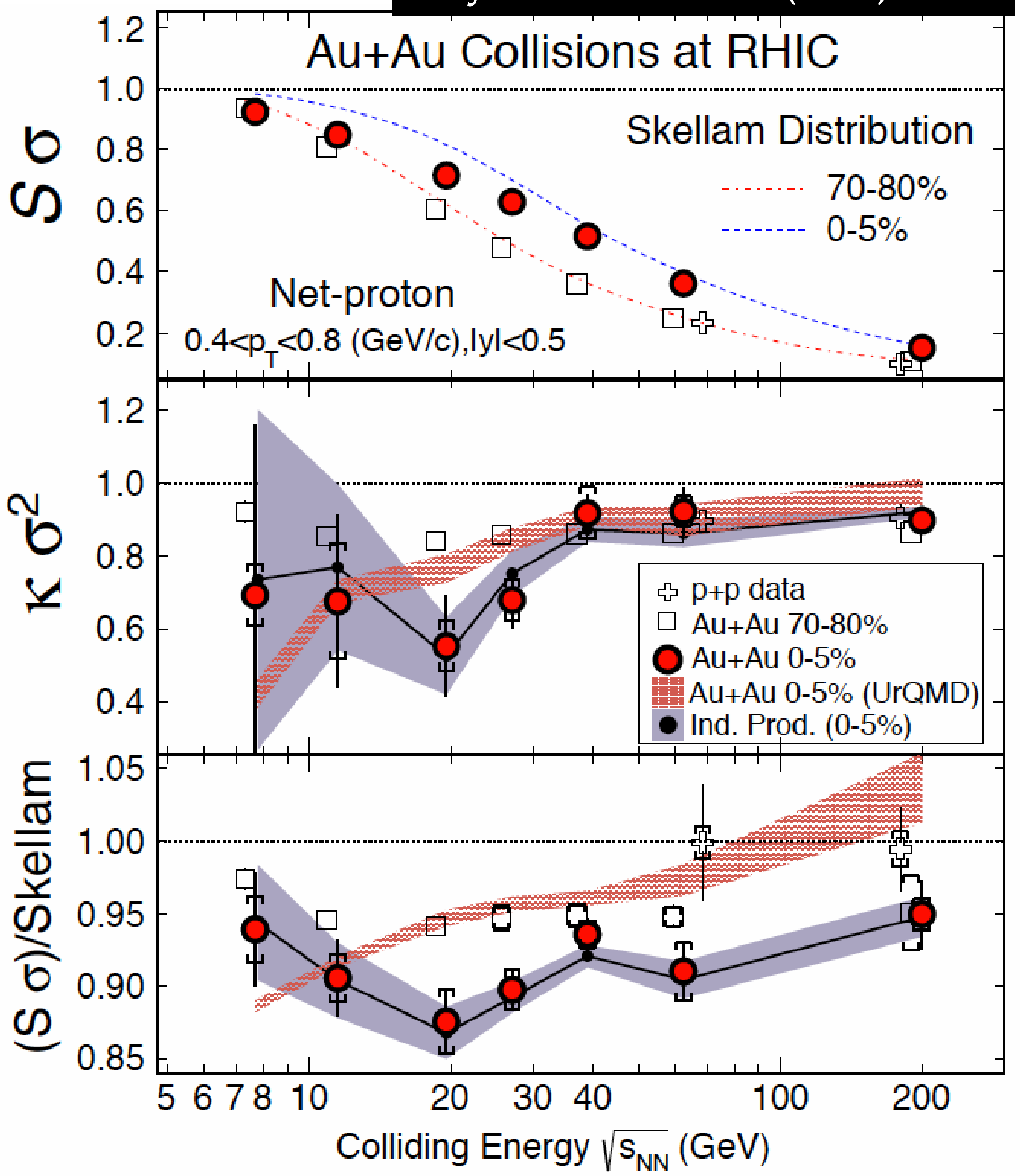
Phys. Rev. Lett. 112, 032302 (2014).

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

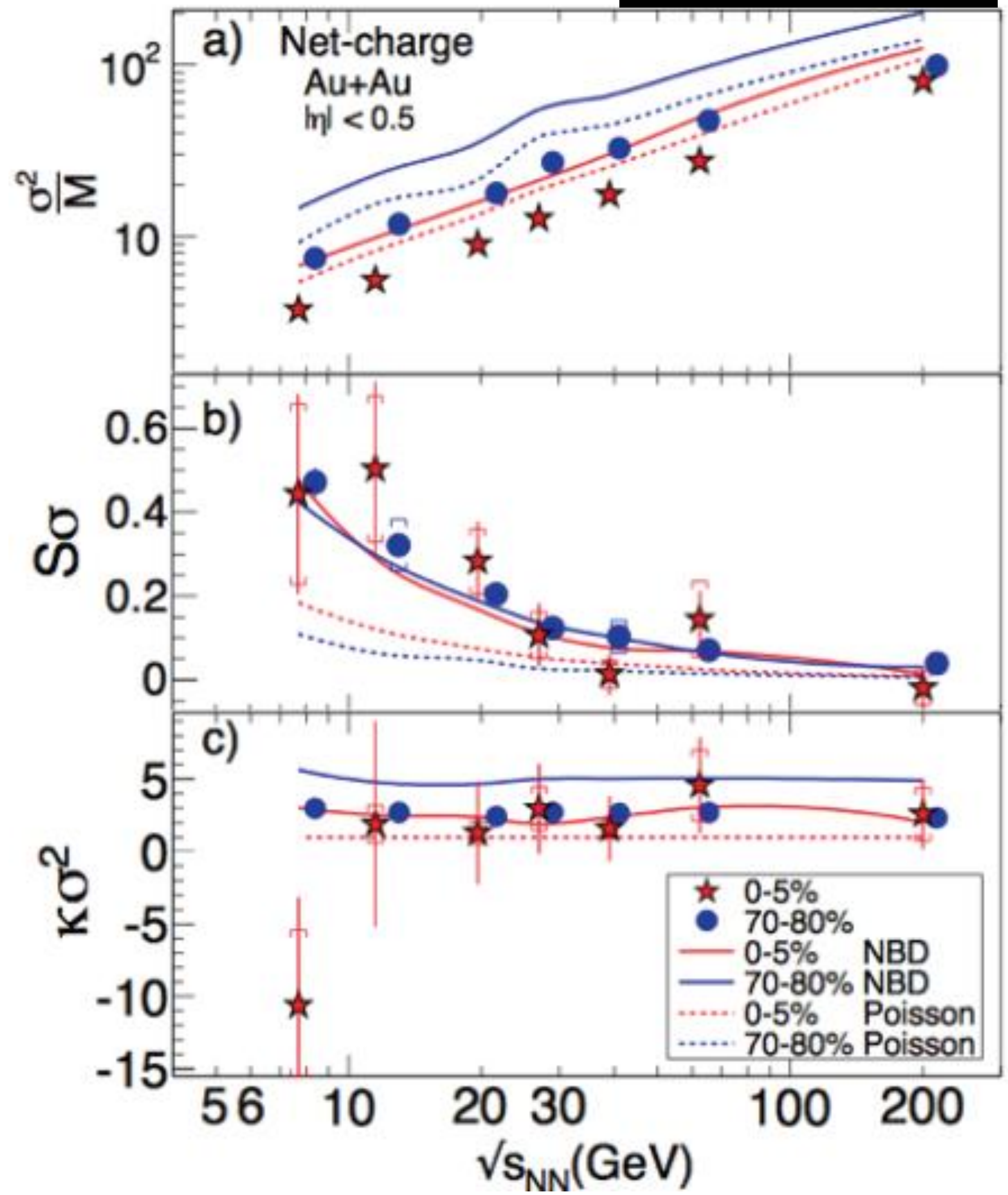
Then: calculate moments (c1-c4: mean, variance, skewness, kurtosis)

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

Phys. Rev. Lett. 112 (2014) 32302



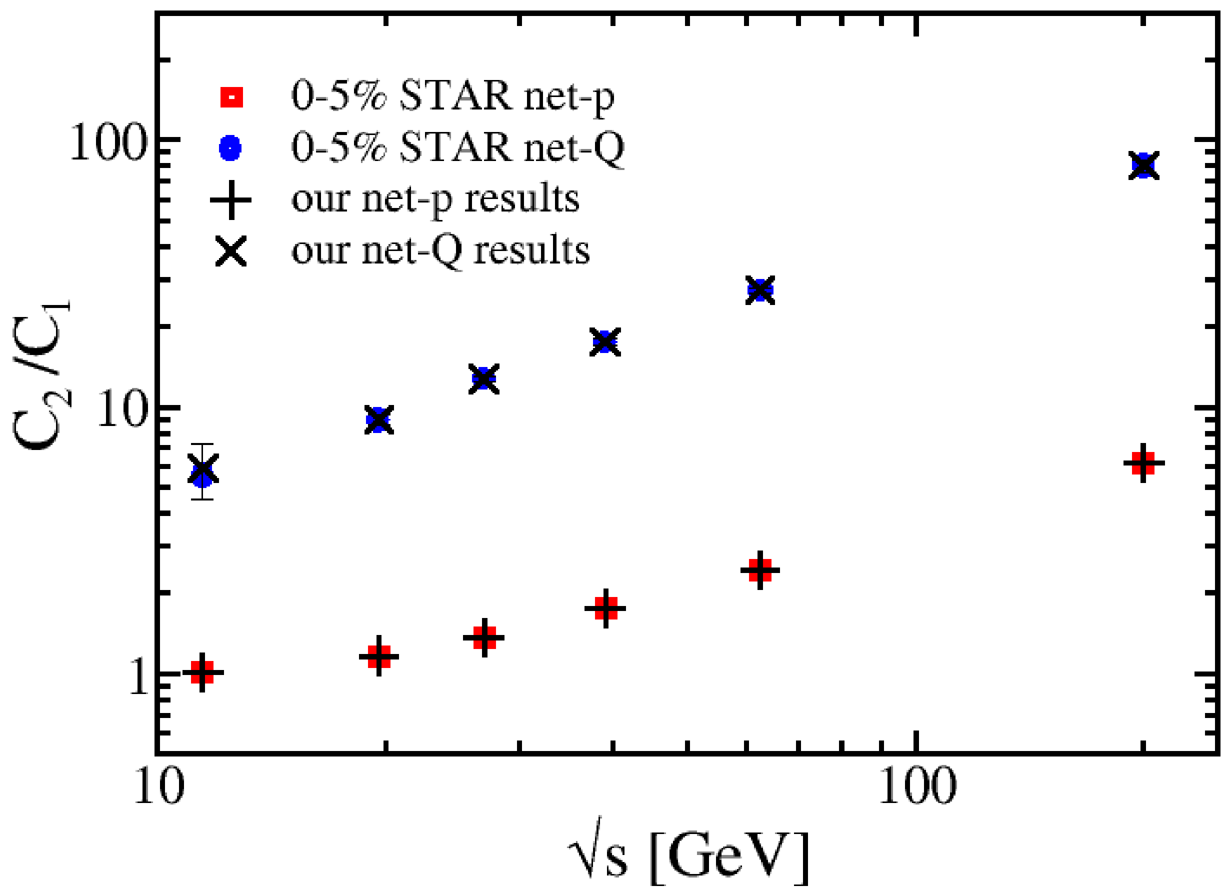
arXiv:1402.1558

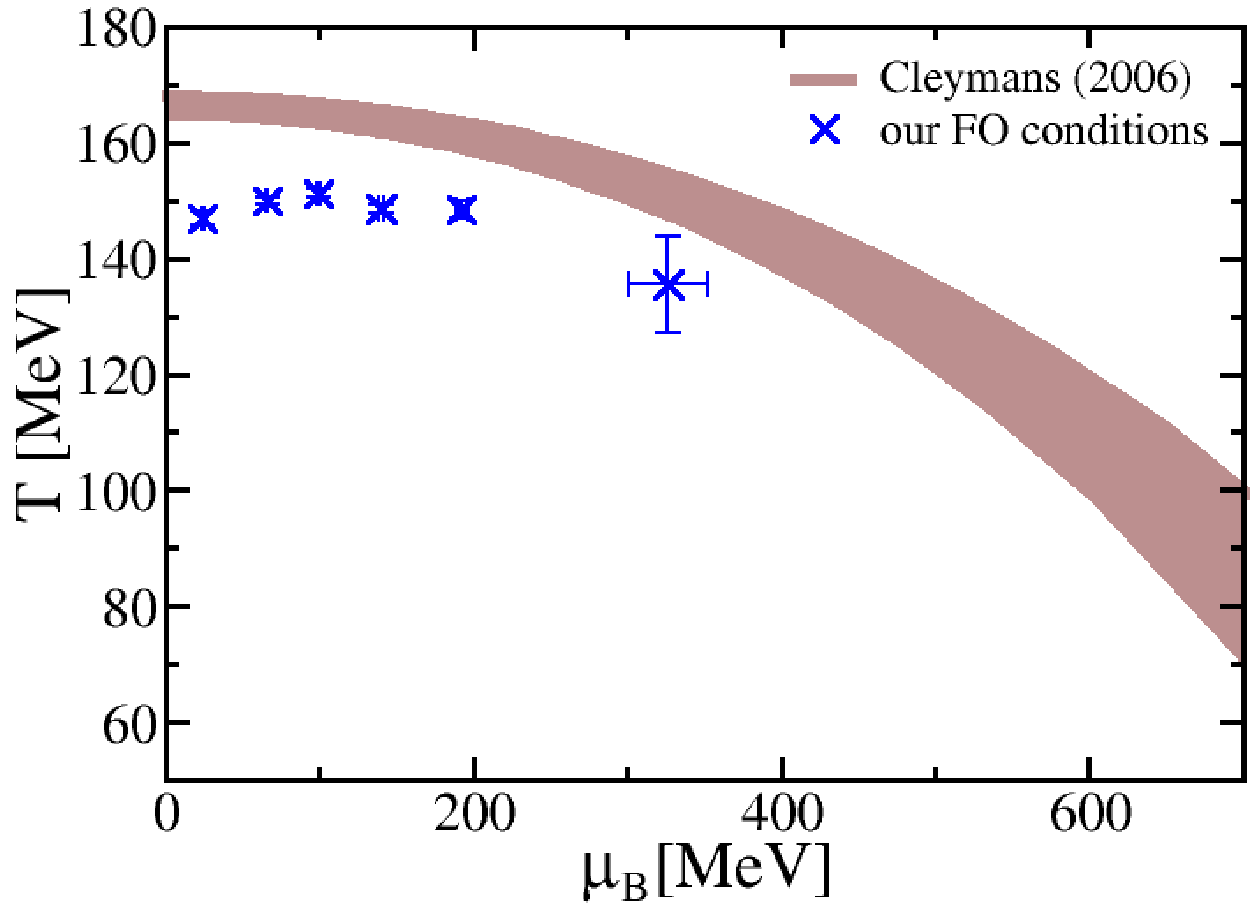


HRG analysis of STAR results (charge & proton)

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)

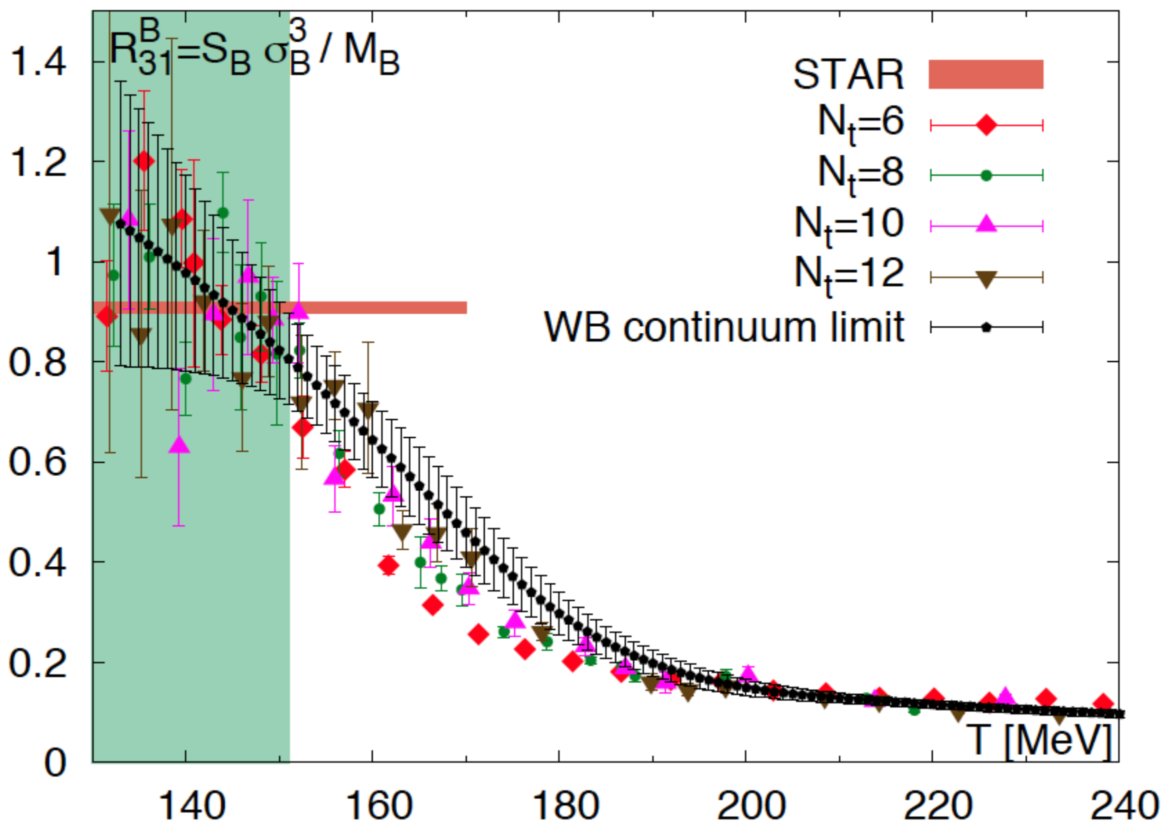


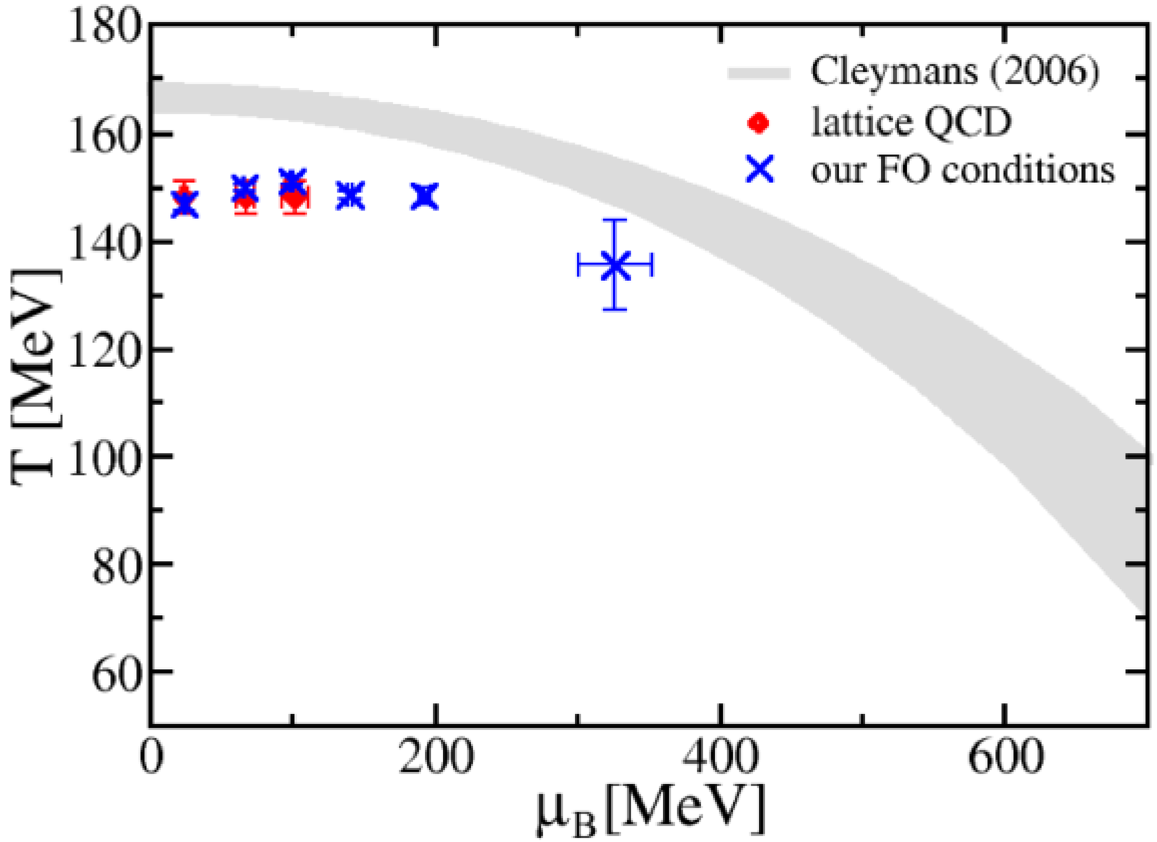


Result: intriguing 'lower' freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

Check consistency with lattice QCD

(lQCD result based on simultaneous net-charge and net-proton fit)



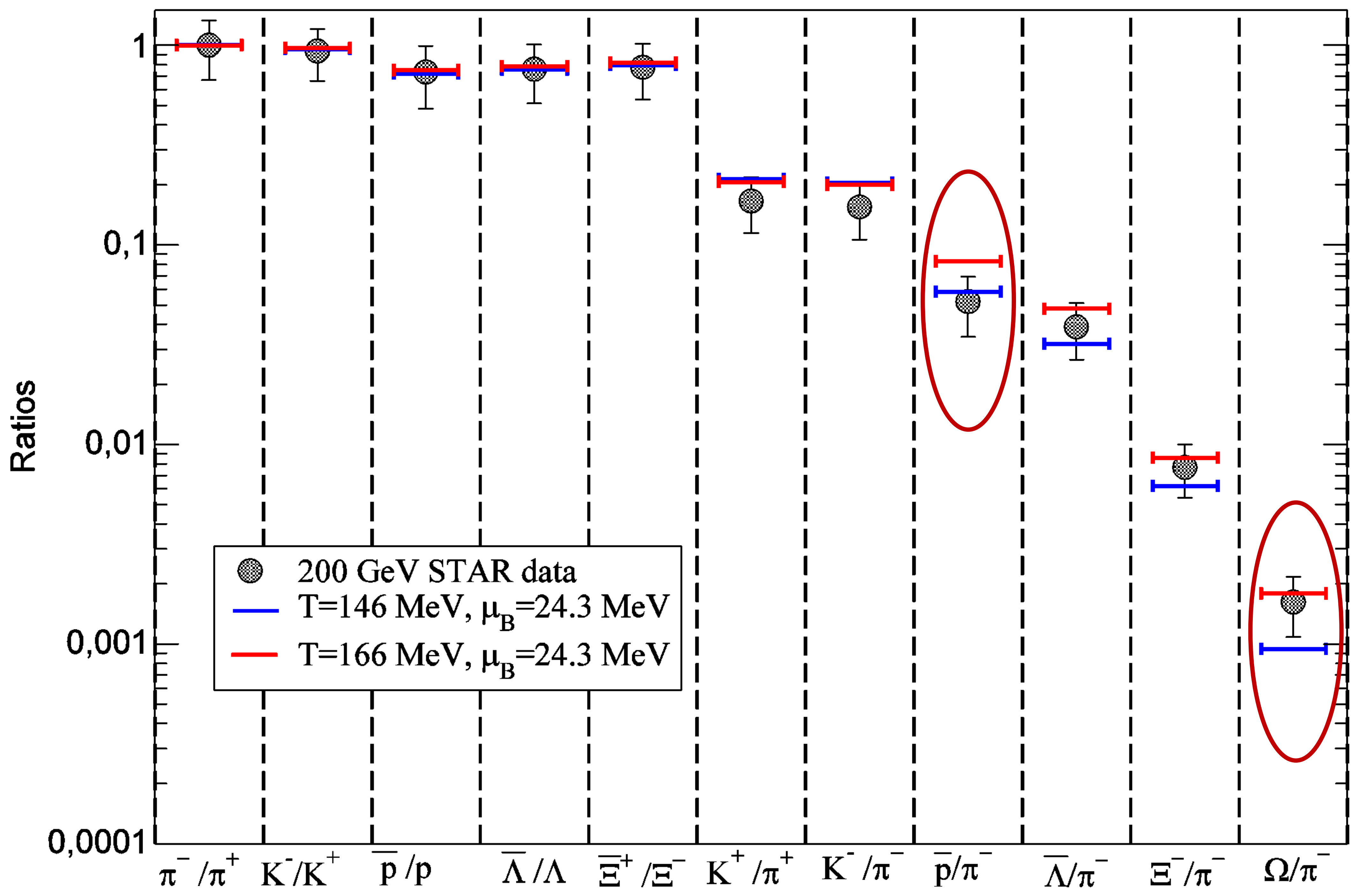


(WB collaboration, PRL (2014) arXiv:1403.4576)

$\sqrt{s}$ [GeV]	$\mu_{B,ch}$ [MeV]	T_{ch} [MeV]
11.5	326.7±25.9	135.5±8.3
19.6	192.5±3.9	148.4±1.6
27	140.4±1.4	148.5±0.7
39	99.9±1.4	151.2±0.8
62.4	66.4±0.6	149.9±0.5
200	24.3±0.6	146.8±1.2

Remarkable consistency, pointing to lower freeze-out temperature for particles governing net-charge (π,p) and net-protons (p)

Difference: SHM-T and HRG-T in particle ratio fits

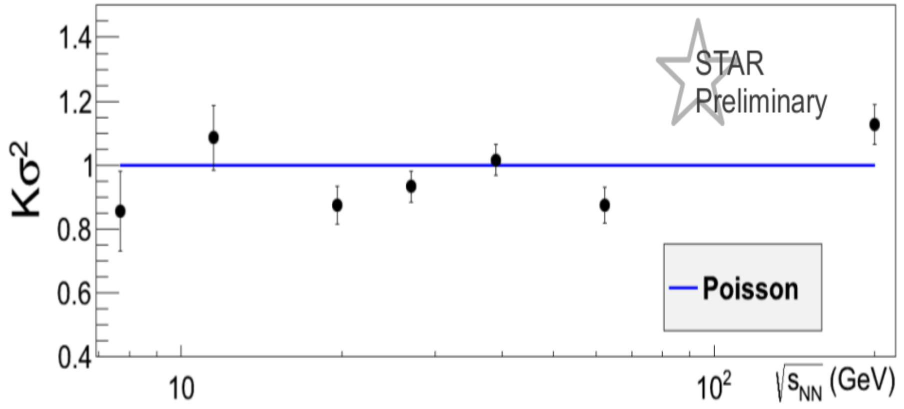


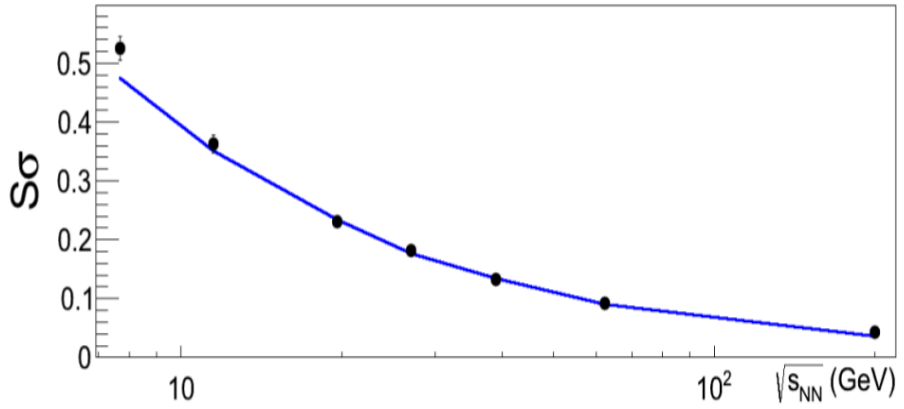
Main deviations in pure strange and light baryon state. Consistent with ALICE

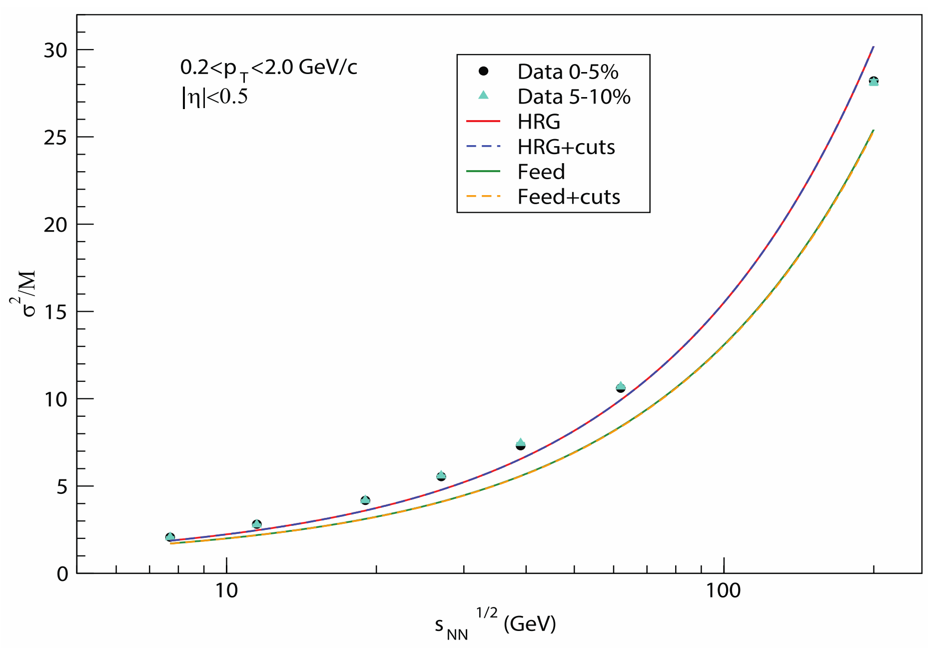
We need corrected net-strange fluctuations (kaons not sufficient ?)

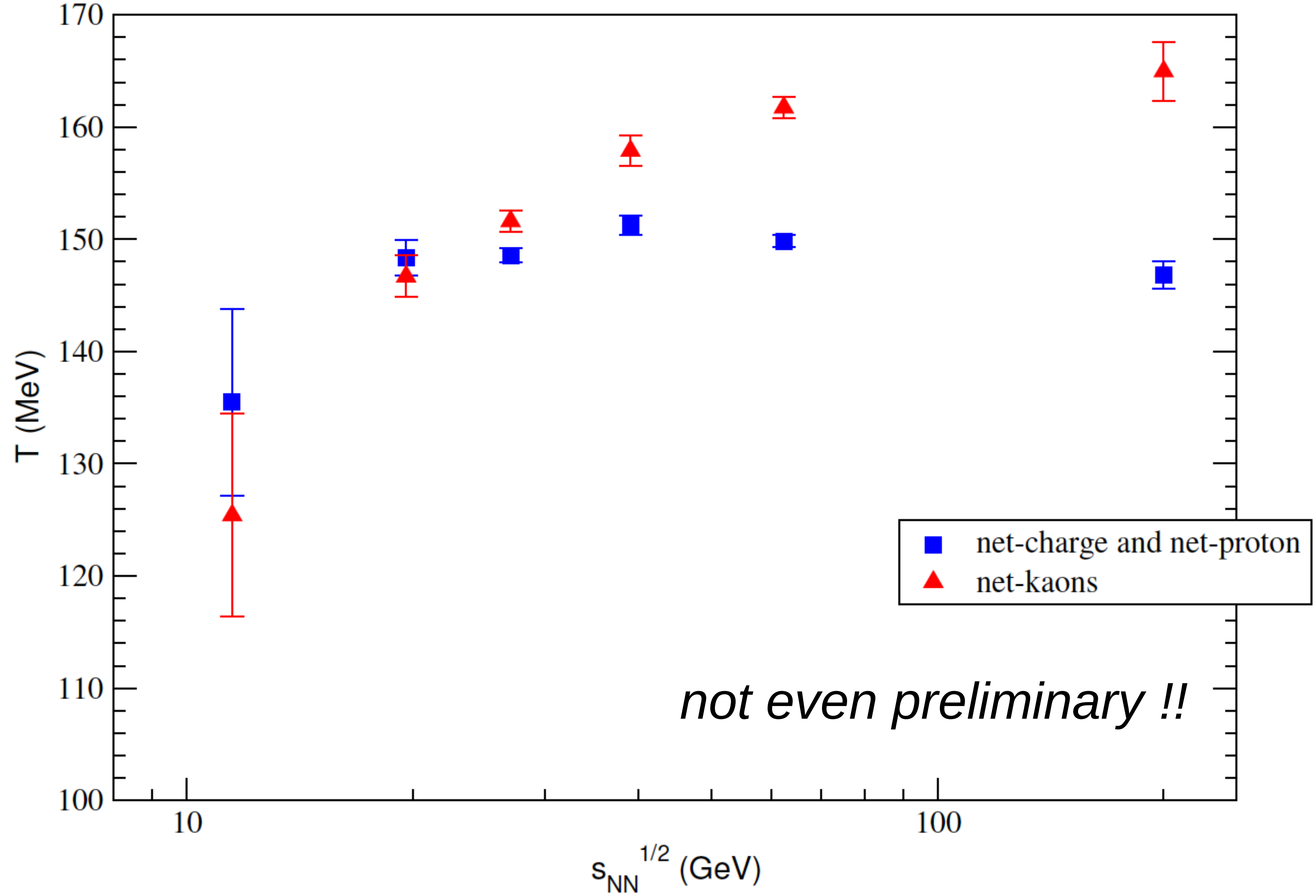
STAR has shown uncorrected kaons at QM (D. McDonald and A. Sarkar)

If we play with uncorrected data…….







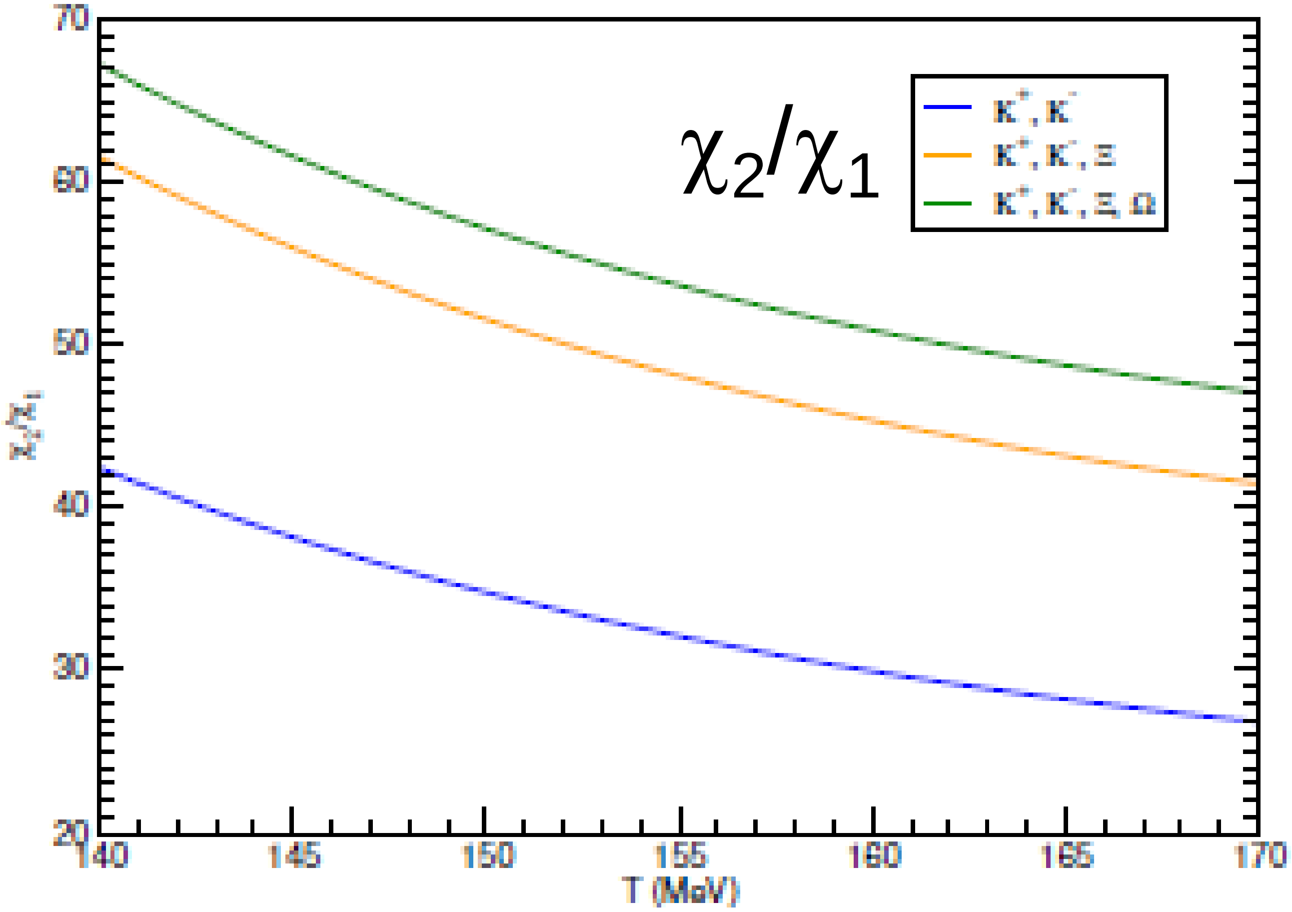


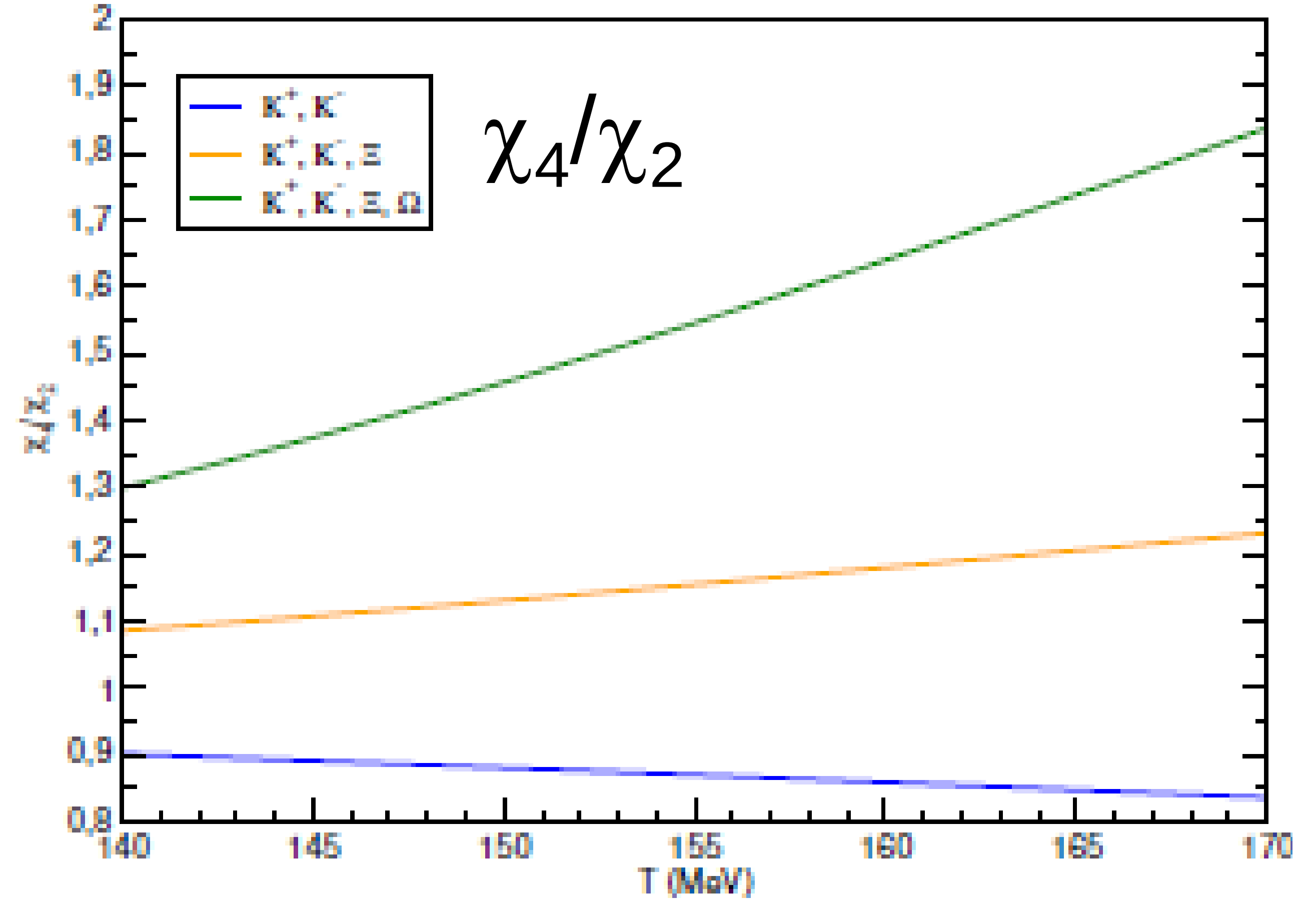
It only shows the sensitivity of the measurement

Do not conclude any relevant physics prior to efficiency corrections

Can we just measure a subset of states to determine strangeness freeze-out temperature ?

HRG calculations are very sensitive to particle composition





Temperature sensitivity varies for moment ratios

We need complete strange particle spectrum for χ_4/χ_2

For χ_2/χ_1 just kaons are sufficient

But we need even/even ratio to compare to lattice

Mantovani, Bellwied, Bluhm, Ratti et al.

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 ?

Can there be a mixed phase of degrees of freedom

Can there be implications for the cosmological evolution of matter ?

Three options *<u>from the mundane to the exotic:</u>*

1.) a new strangeness enhancement

Enhancement factors from 146 to 166 MeV:

(assuming V= 5570 fm^3 and V= 1760 fm^3, respectively)

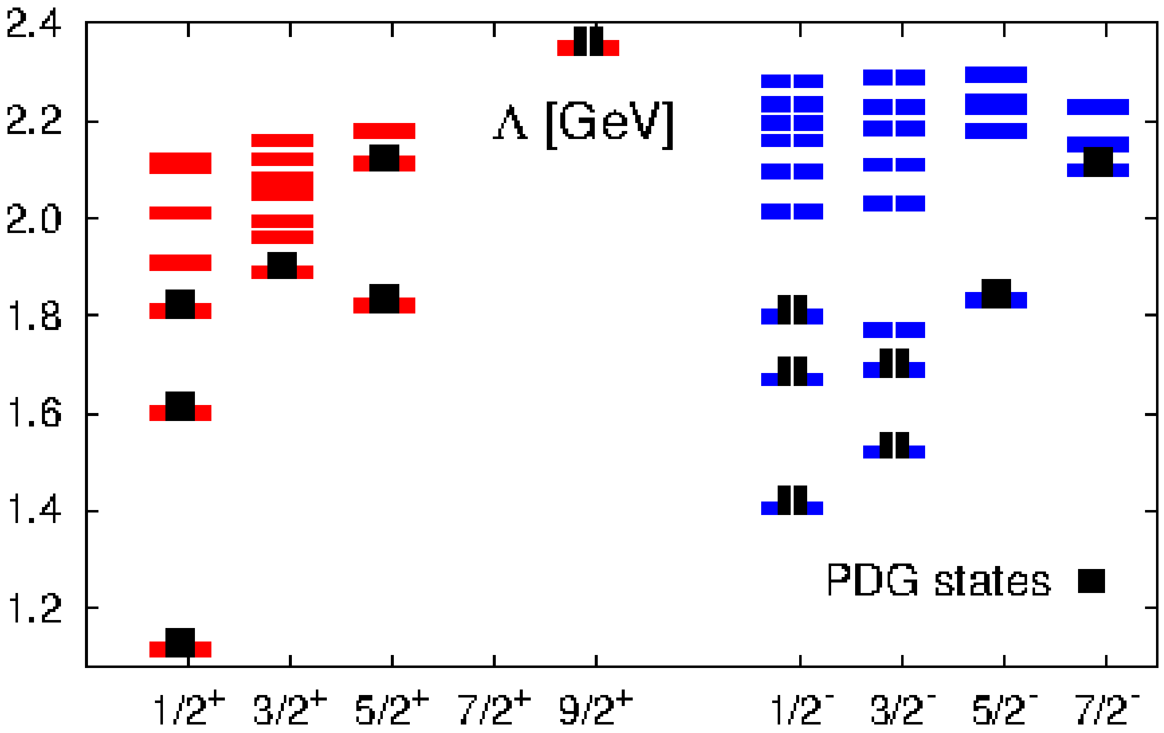
Λ yield increases by 20%, Ξ yield increases by 30%, Ω yield increases by 44%

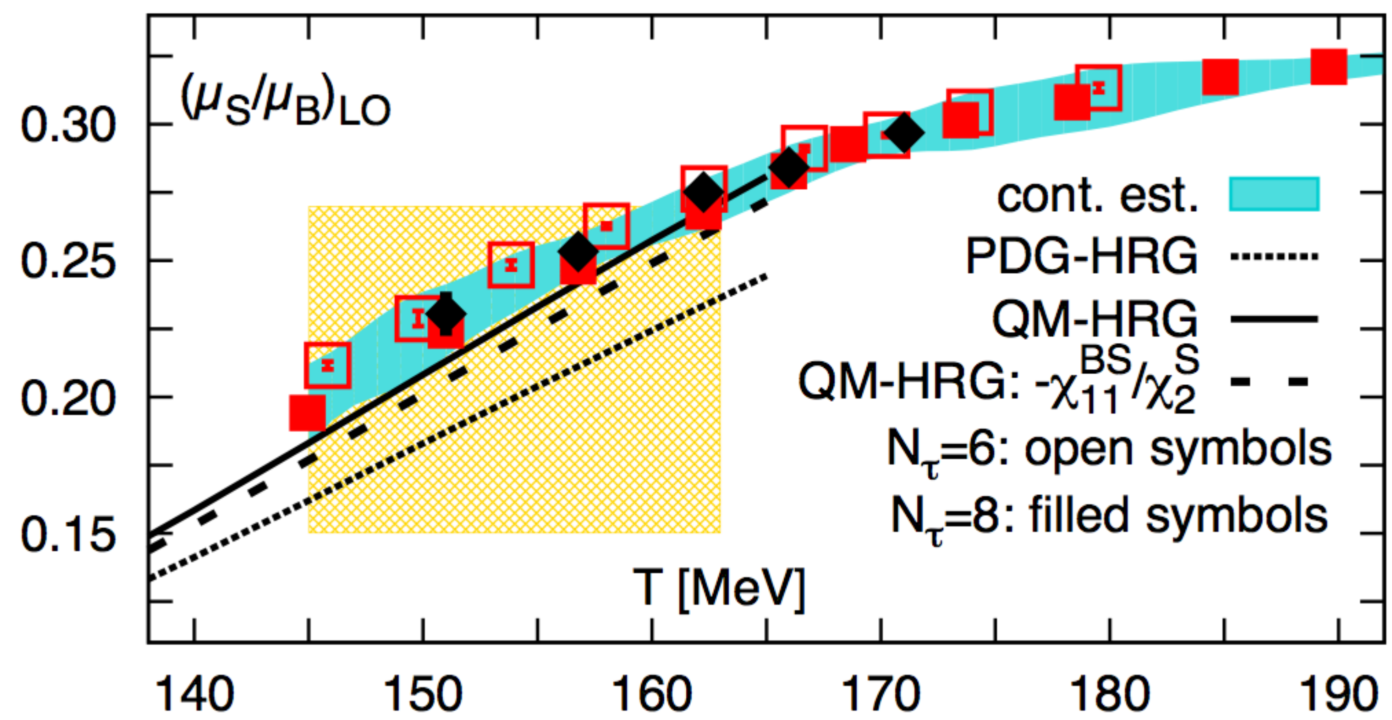
2.) higher strange states based on excited states in Quark Model

3.) exotic quark configurations

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)

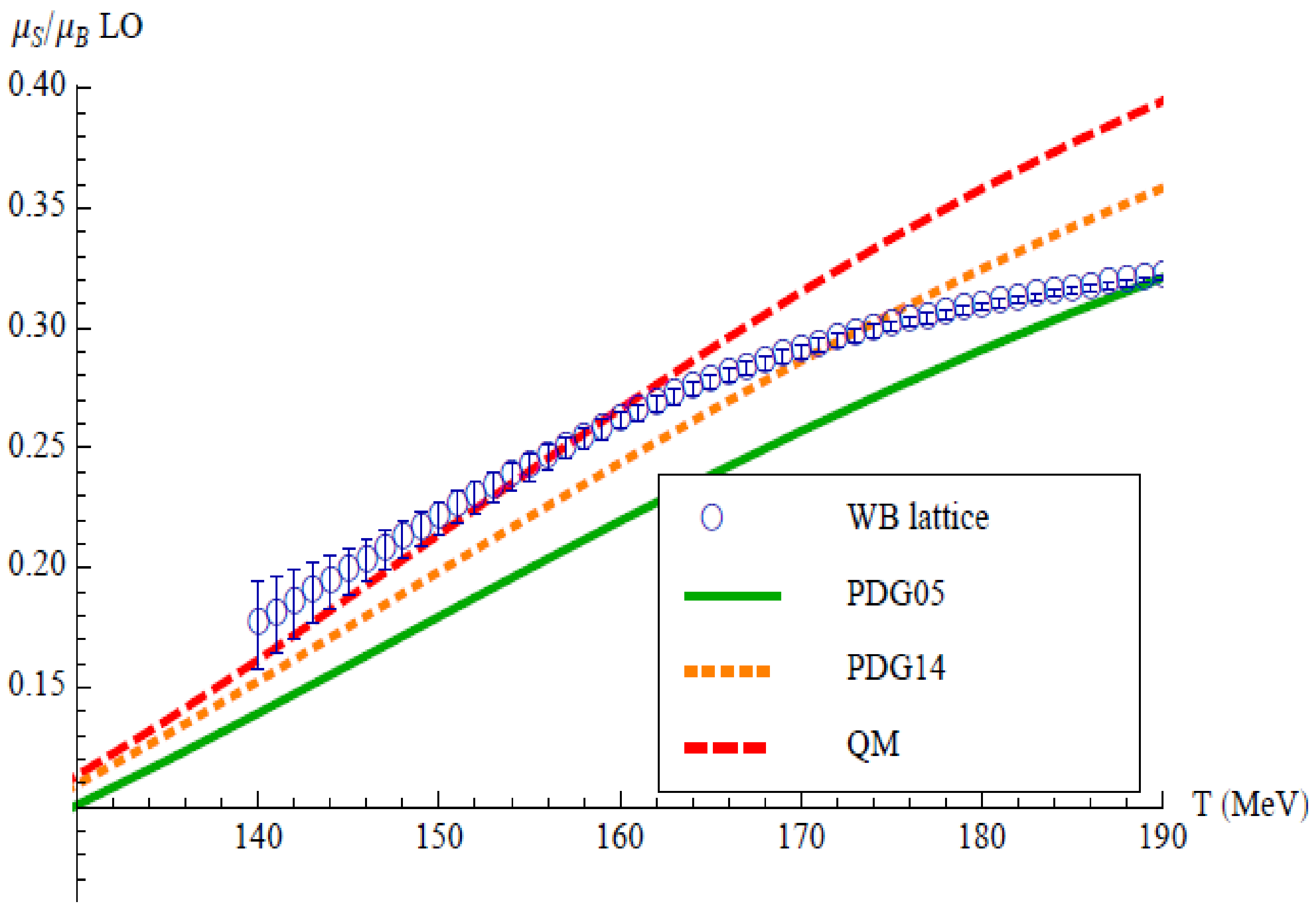


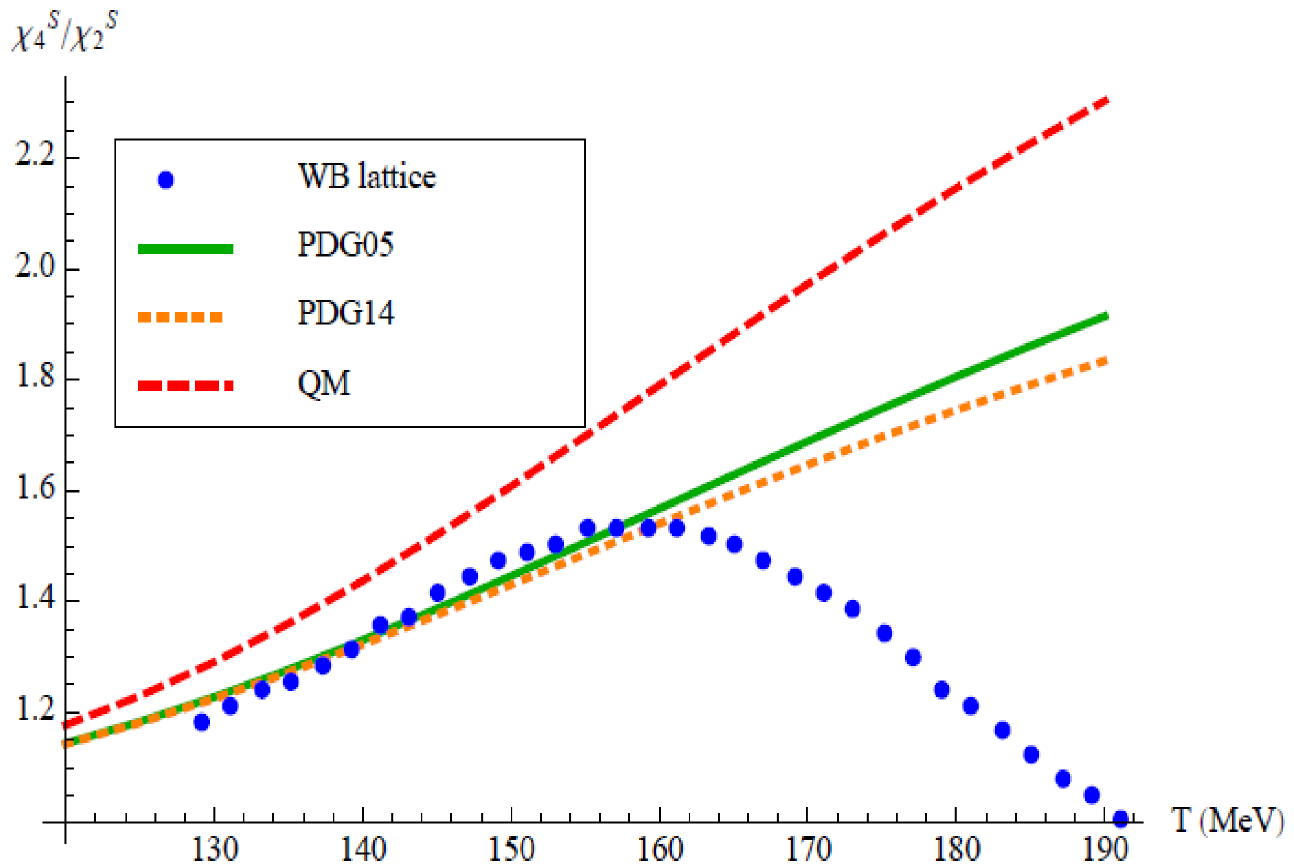


But those effects need to be consistently applied to all correlators that are possibly affected by higher lying strange states.

Still, the idea of preferred strange bound state production in a particular temperature window is intriguing and could ultimately lead to generation even of exotic multi-quark configurations

Do we really need not yet measured states ?
What happens from PDG-2008 to PDG-2014 ?



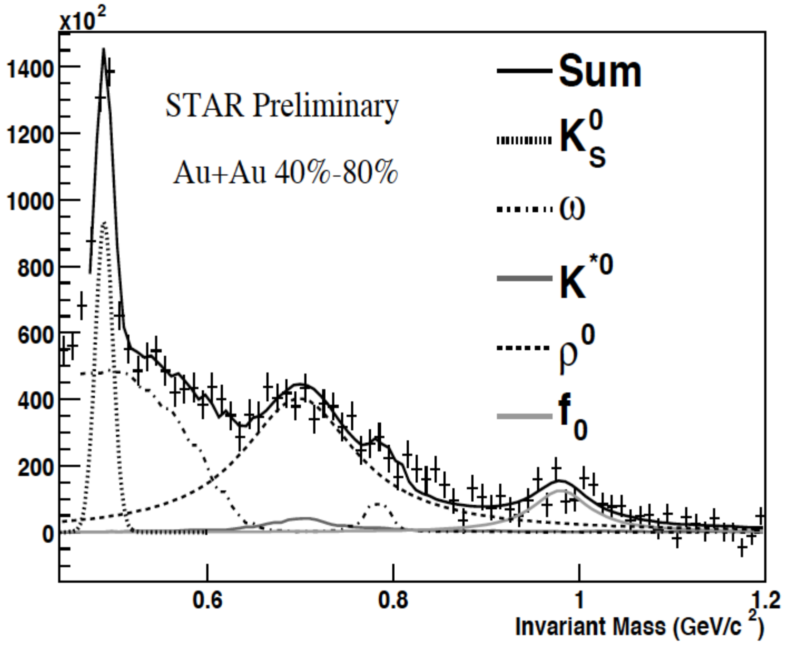


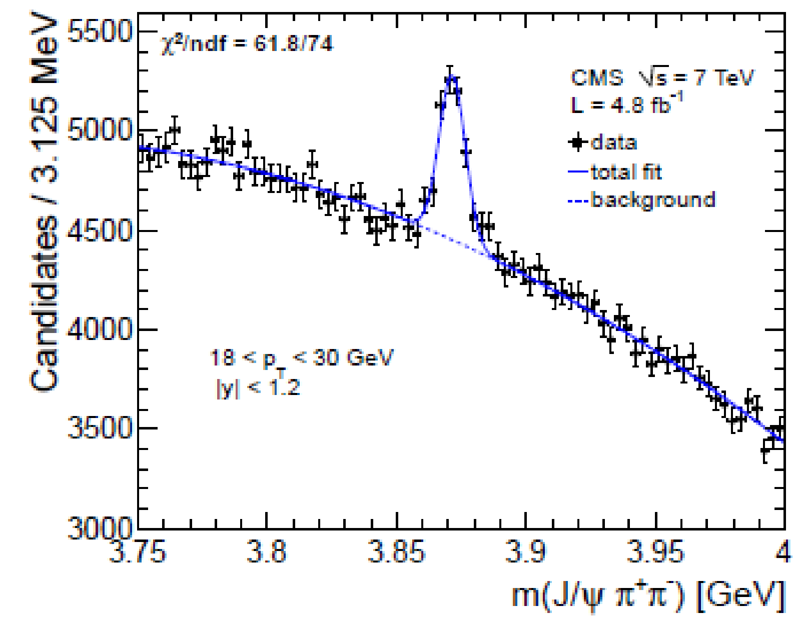
Although, new states from the Quark Model (QM) improve the leading order ratio, they worsen he agreement with the higher moment ratio on the lattice (c4/c2).

It is true that the states available in PDG-2005 are not sufficient to describe both ratios equally well, but the inclusion of newly measured higher mass strange resonances as listed in PDG-2014 seem to be sufficient to reach a good agreement between lattice and data.

Exotic states within the Standard Model

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



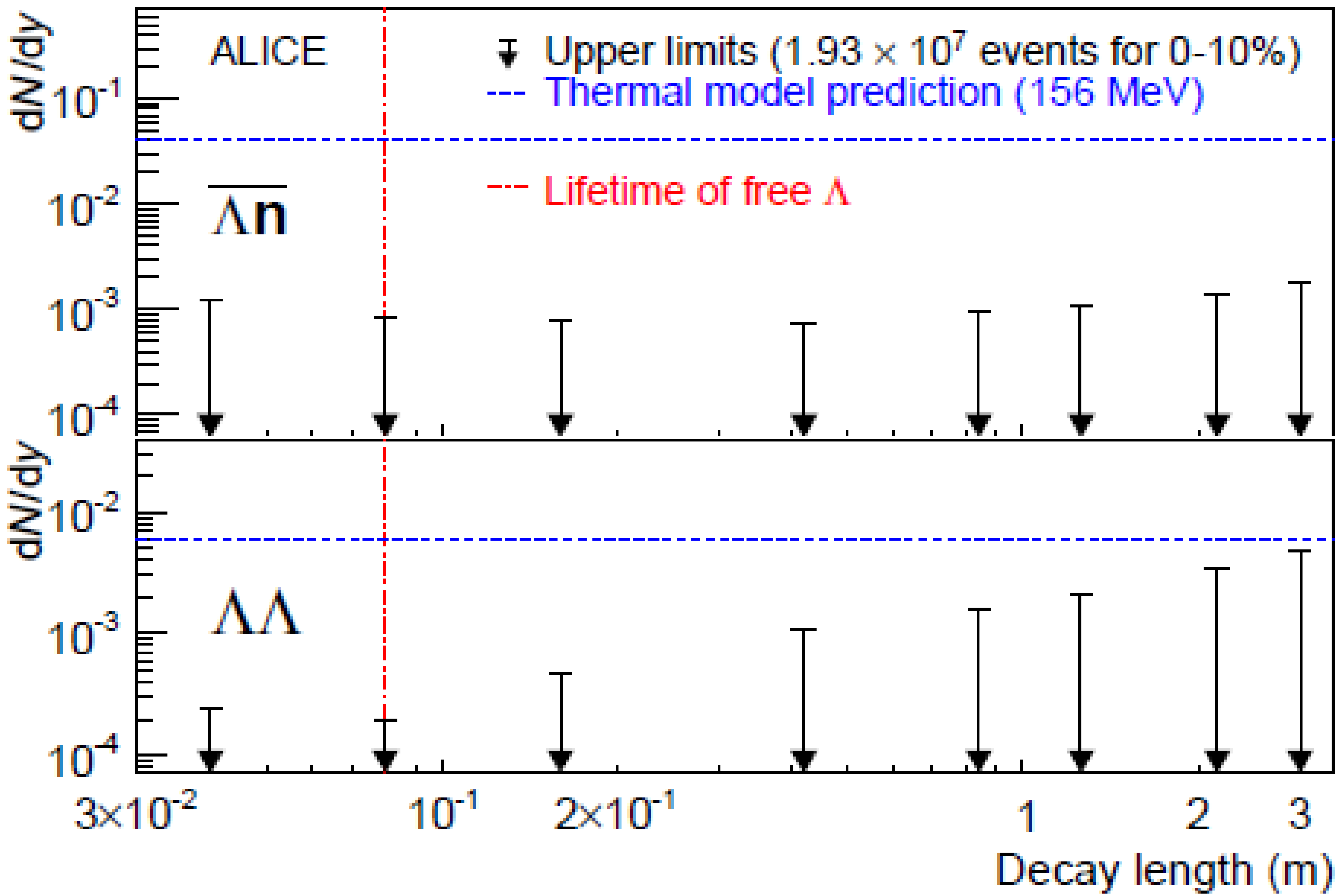


ExHIC Collaboration (2011):

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	RHIC				LHC			
								$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	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_{cc}^{1} [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_{cb}^{0} [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^+	$qqqqsc$	—	$\Xi_c N$	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}

Unfortunately little evidence for strange exotic states

Unsuccessful searches for H-Dibaryon and Λn states in ALICE



Summary / Conclusions

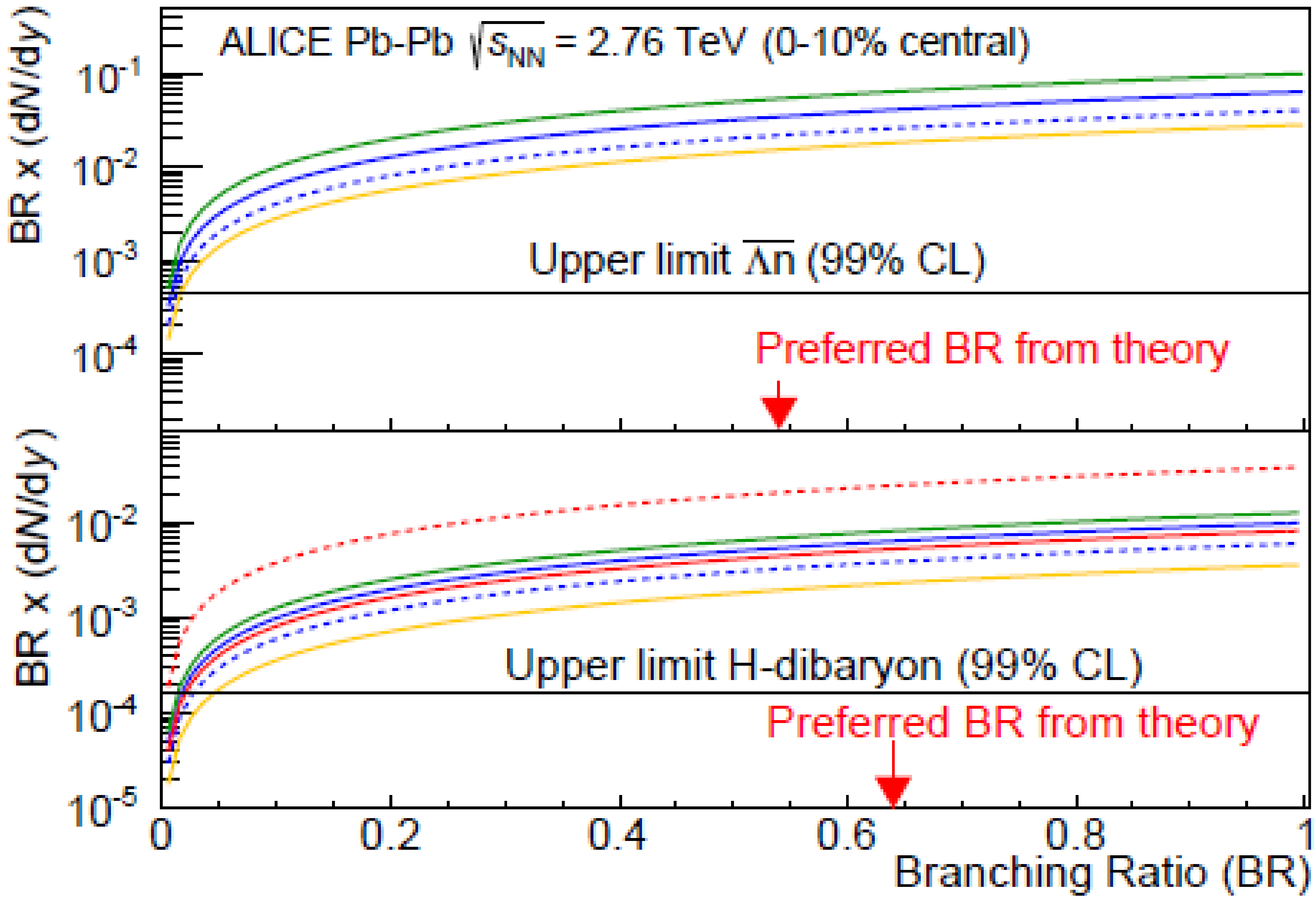
- High precision (continuum limit) lattice QCD susceptibility ratios indicate *flavor separation in the crossover from the partonic to the hadronic matter.*
- There are hints, when comparing to hadron resonance gas and PNJL calculations, that this could lead to a short phase during the crossover in which 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)*.
- It could also lead to evidence for *higher mass strange Hagedorn states* (as predicted by Quark Model (for the low mass part of the spectrum))

- A new experimental verification method for flavor separation can be devised by <u>measuring the higher moments of the strangeness production in comparison to light quark production</u>.
- The translation of lattice susceptibility ratios to higher moments of measured multiplicity distributions is not trivial but possible. It needs exact mapping of the measurable states.
- The question remains whether any separation of flavor hadronization requires pure flavor states (e.g. p vs. Ω), as indicated by HotQCD charm study

Backup slides

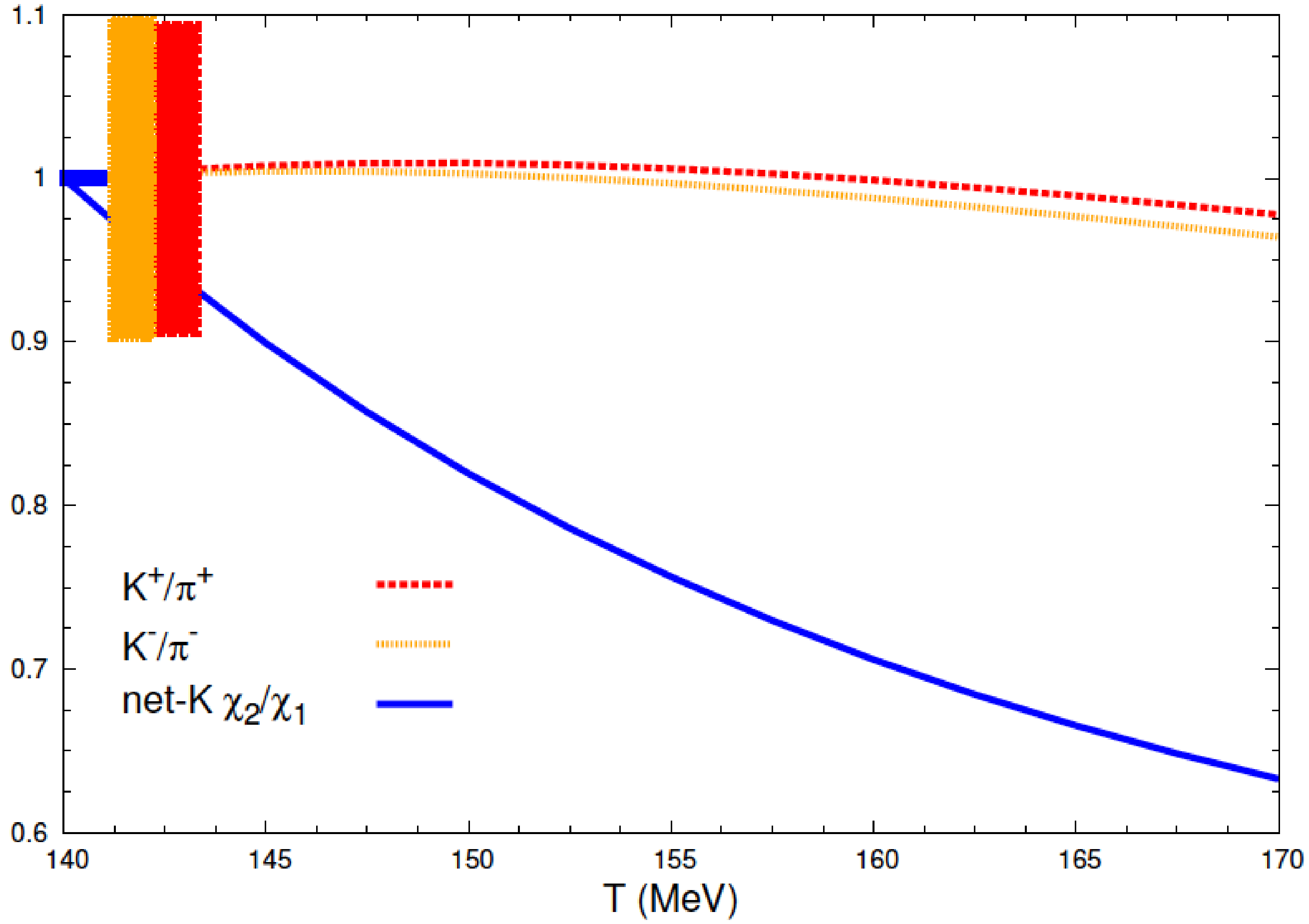
Unfortunately little evidence for strange exotic states

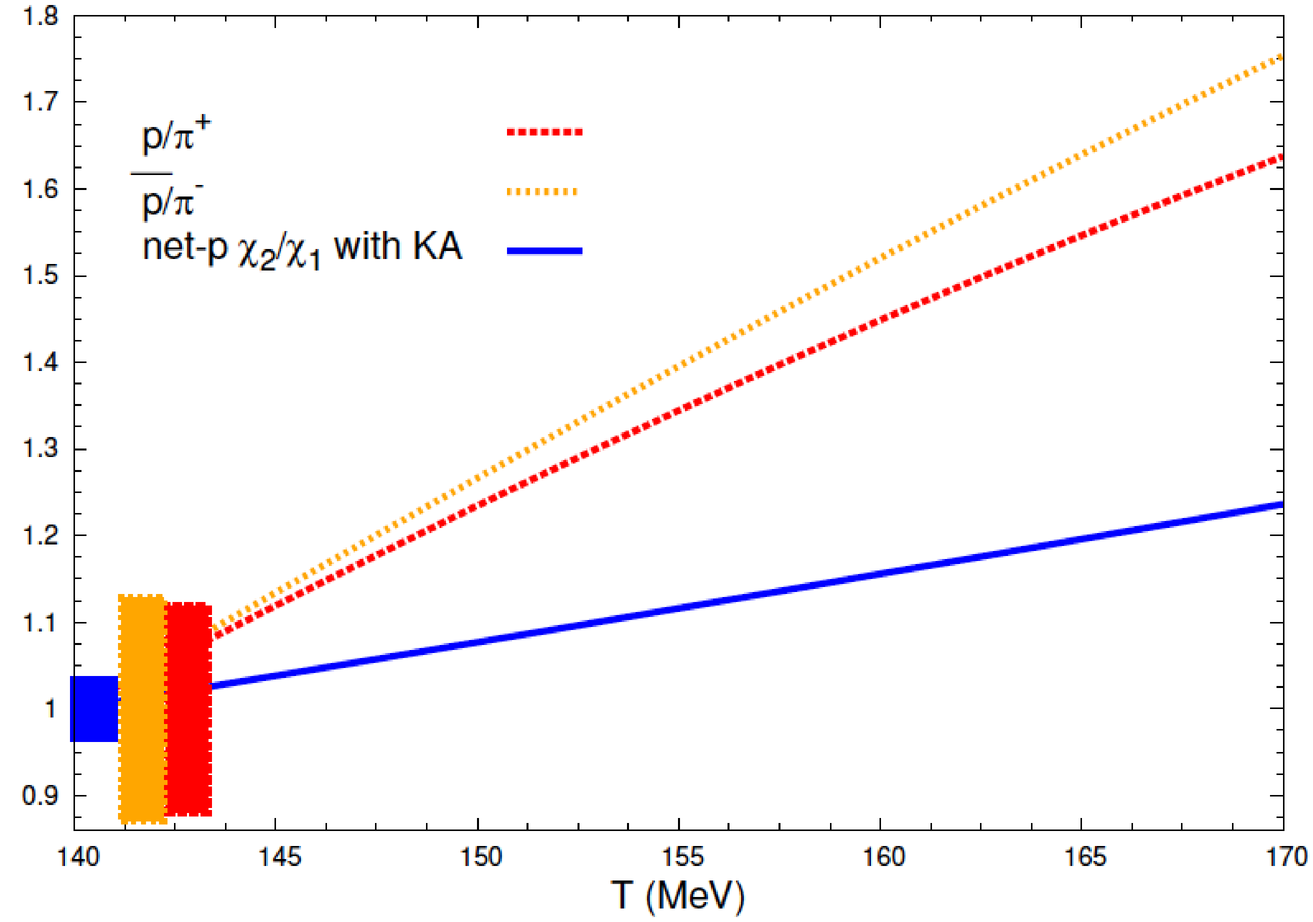
Unsuccessful searches for H-Dibaryon and Λn states in ALICE



Kaons are likely not sufficient, but their fluctuations show a remarkable sensitivity to T_{ch}

Comparing the temperature sensitivity of particle ratios and lower moment fluctuation ratios for kaons and protons in a HRG model





HRG model calculation: Mantovani, Alba, Bellwied, Ratti (to be published)

Experimental error bars on particle ratios

(are the too big and why are they bigger than the fluctuation uncertainties ?)

STAR has presented detailed uncertainty evaluations, separately for π,k,p and V0's:

For p,k,p PRC (2008), arXiv:0808.2041

For all strange baryons: PRL (2006), nucl-ex/0606014

Included in systematics for π,k,p:

PID uncertainties (all dE/dx and TOF cross check), small pT coverage, Fit function uncertainties

Not included for π,k,p:

Lambda feed-down correction (obtained from Andronic plot (points larger than error bars)), proton background uncertainty (spallation)

General uncertainty between 10-15%

Included in systematics for V0:

Feed-down correction, V0 cuts, magnetic field settings, pT dependence

Not included for V0:

Fit function variation (pT-coverage around 60-70%) yields probably an additional 10% uncertainty

General uncertainty: ~20%

<u>Since fluctuation measurements are not extrapolated their uncertainties can be smaller. Ultimately all uncertainties that were used are as published by STAR</u>

But can one simply compare lattice susceptibility results to experimental fluctuation measurements ?

The following criteria need to be met:

- one needs a grand-canonical ensemble (intrinsic in lattice QCD conditions, but only reached in limited acceptance in experiment). In full acceptance a conserved charge cannot fluctuate.

(very nice overview paper by V. Koch, arXiv: 0810.2520)

- one needs to take into account acceptance, efficiency, detector effects

- one needs to estimate the effect from measuring only a subset of the conserved charge (e.g. protons instead of baryon number)

The easiest method: build all caveats into a statistical hadronization model (HRG) and show equivalence between HRG and lattice QCD

Experimental constraints and how to deal with them in the HRG

- Effects due to volume variation because of finite centrality bin width

- Finite reconstruction efficiency

- Spallation protons

- Canonical vs Gran Canonical ensemble

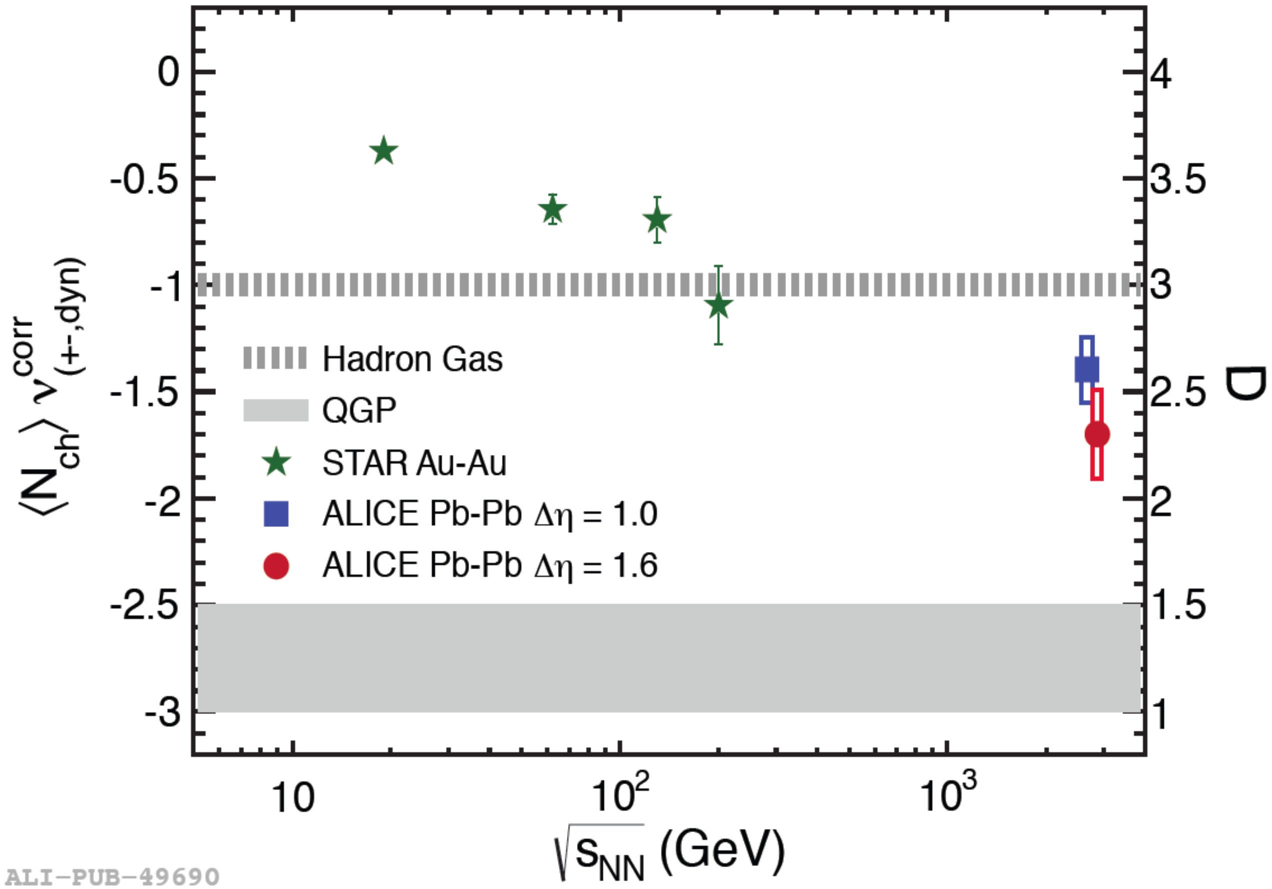
- Proton multiplicity distributions vs baryon number fluctuations

- Final-state interactions in the hadronic phase J.Steinheimer *et al.*, PRL (2013)

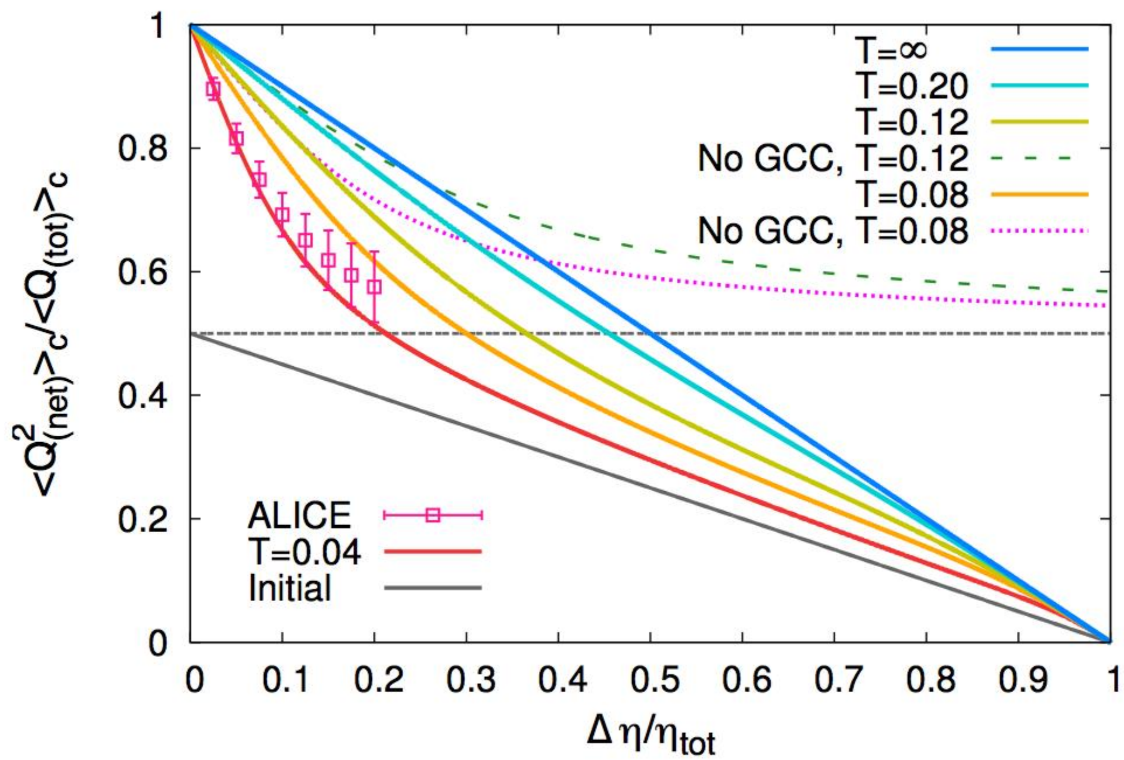
Experimental constraints and how to deal with them in the HRG

- Effects due to volume variation because of finite centrality bin width
  - → Experimentally corrected by centrality-bin-width correction method
- Finite reconstruction efficiency
  - → Experimentally corrected based on binomial distribution A. Bzdak, V. Koch, PRC (2012)
- Spallation protons
  - → Experimentally removed with proper cuts in p_T
- Canonical vs Gran Canonical ensemble
  - → Experimental cuts in the kinematics and acceptance V. Koch, S. Jeon, PRL (2000)
- Proton multiplicity distributions vs baryon number fluctuations
  - → Numerically very similar once protons are properly treated M. Asakawa and M. Kitazawa, PRC (2012), M. Nahrgang *et al.*, 1402.1238
- Final-state interactions in the hadronic phase J.Steinheimer *et al.*, PRL (2013)
  - → Consistency between different charges = fundamental test

On the issue of global charge conservation



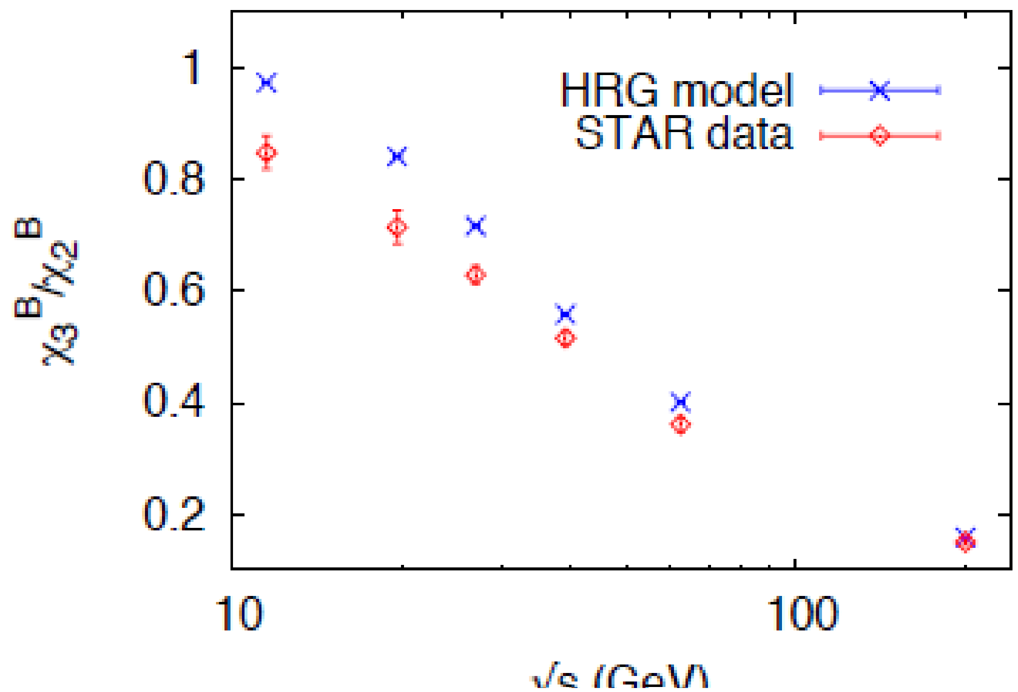
ALICE, PRL 110, 152310 (2013)

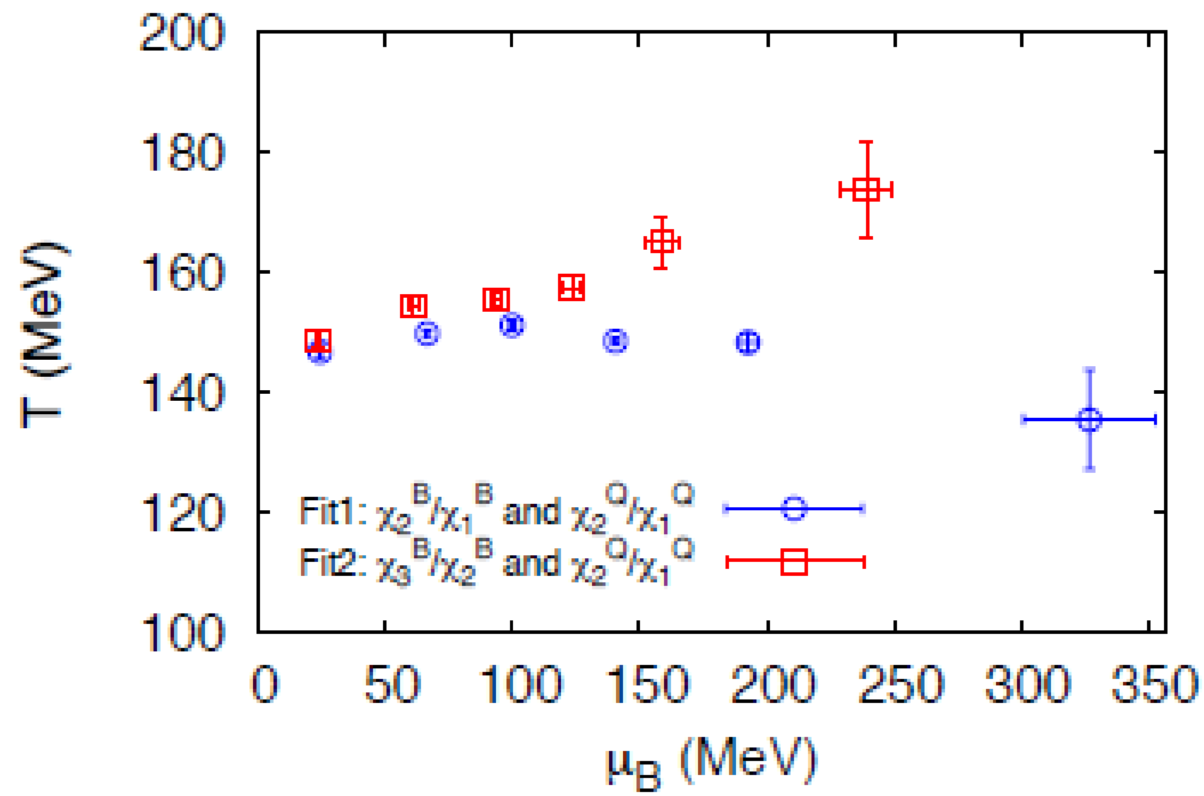


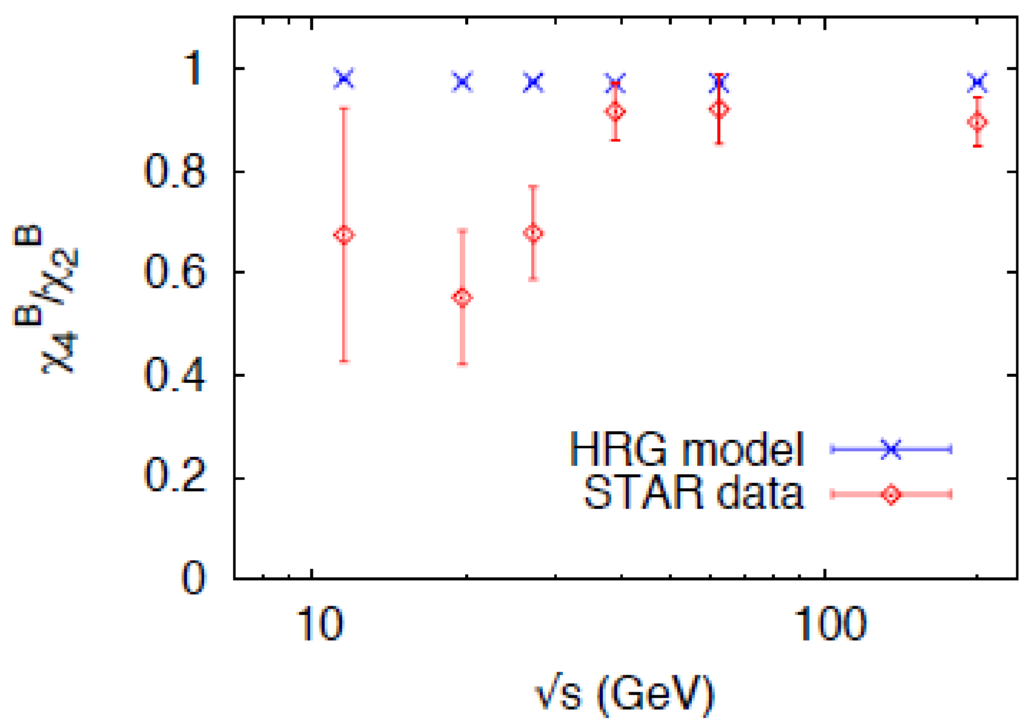
Sakaida, Asakawa, Kitazawa, arXiv:1409.6866

The pseudo-rapidity coverage in STAR and ALICE is such that GCC effect are negligible

Problems with higher moments







HRG overshoots the $\chi3/\chi2$ at lower energies and cannot explain the 'dip' in $\chi4/\chi2$. Temperature dependence on collision energy becomes 'unphysical'.

Possible reasons:

a.) overestimate of isospin randomization

b.) onset of critical behavior in $\chi3$ and $\chi4$

<u>Important lesson: </u>lower moments carry significant information with much smaller error bar (might be already sufficient)