Sequential Hadronization and the opportunities it presents

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in collaboration with

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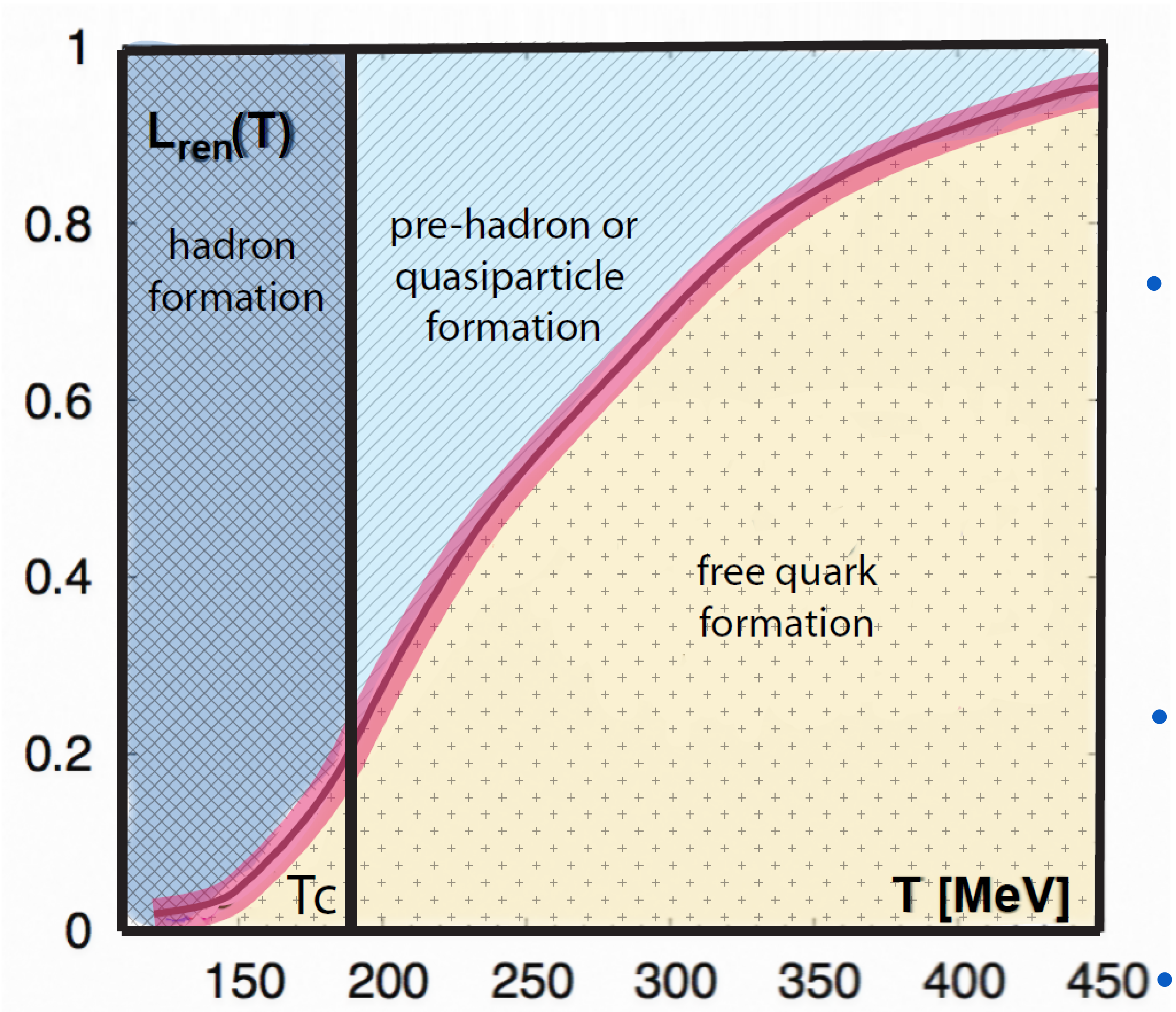
Outline

- Recent input from lattice QCD on the issue of hadronization
- The role of flavor during the transition
- Evidence for sequential hadronization
- Opportunities for exotic state formation and cosmology
- Opportunities for dynamic quantities (v_2 and R_{AA})

Lattice order parameters in the QCD cross-over

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

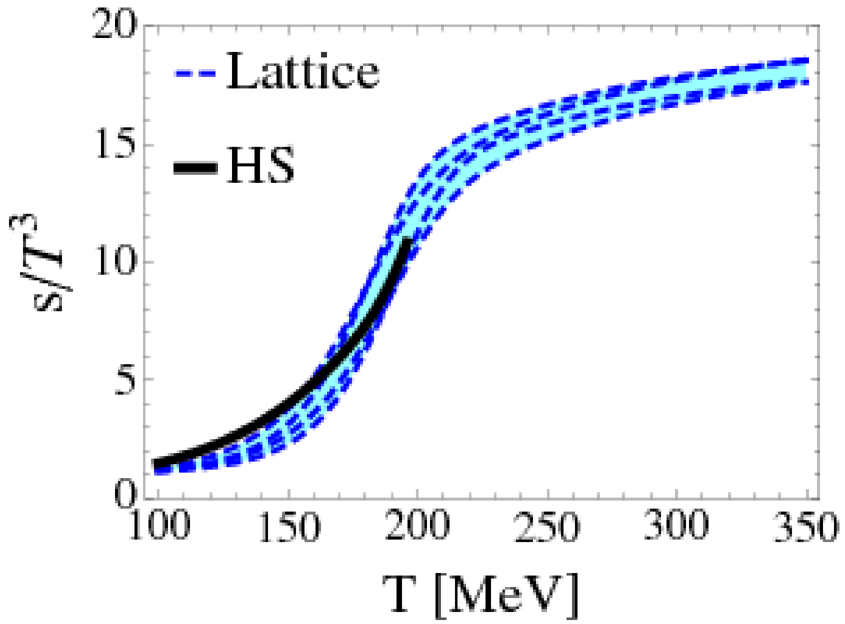


RB et al., PLB691 (2010) 208
Data: Bazavov et al., arXiv:1105:1131

- T_c based on average of all order parameters in lQCD: 154+-9 MeV
- What are the degrees of freedom between T_c and 400 MeV ?
- 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 ?
- Lattice can calculate thermodynamic quantities for a static equilibrated system at fixed T
- Generally: a HRG which includes all possible states (PDG) should describe lattice order parameters up to T_c

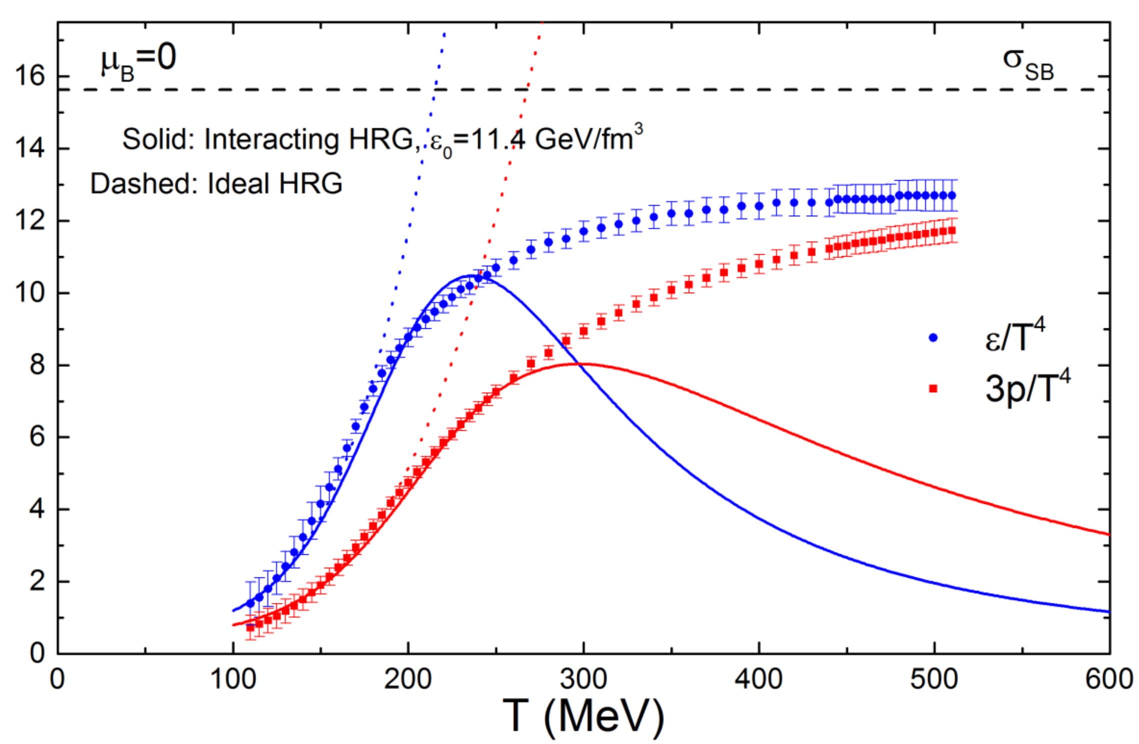
Interesting approaches to extending the HRG range at this conference

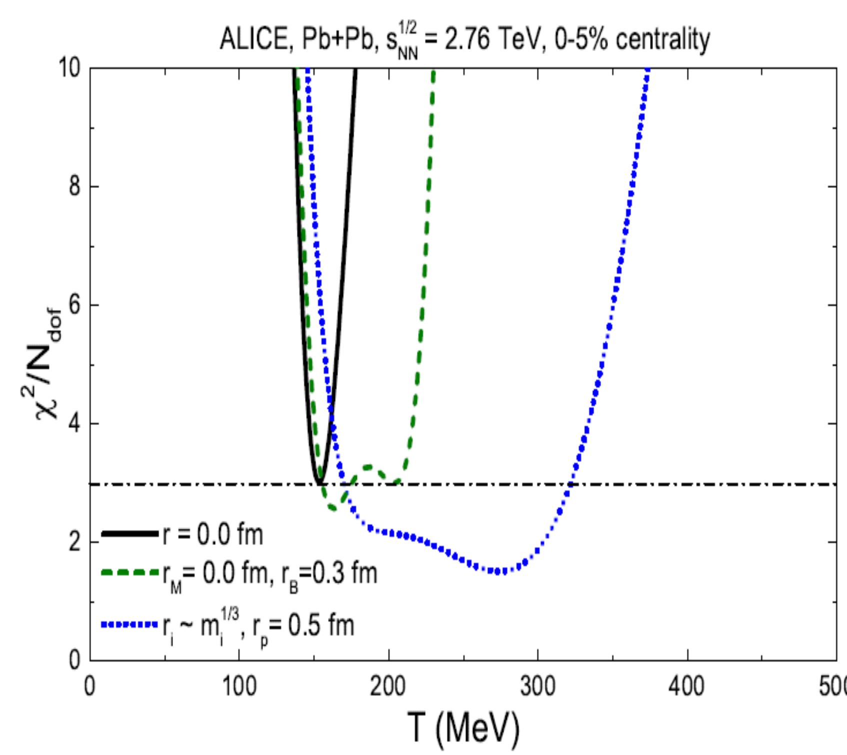
1.) Hagedorn states extend the hadronic spectrum (C. Greiner, We morning)



	p-p	Pb-Pb	4 GeV	8 GeV
K^-/π^-	0.123(14)	0.149(16)	0.187	0.210
$\overline{p}/\pi^-$	0.053(6)	0.045(5)	0.043	0.066
Λ/π^-	0.032(4)	0.036(5)	0.021	0.038
$\Lambda/\overline{p}$	0.608(88)	0.78(12)	0.494	0.579
Ξ^-/π^-	0.003(1)	0.0050(6)	0.0023	0.0066
$\Omega^-/\pi^- \cdot 10^{-3}$	-	0.87(17)	0.086	0.560

2.) Eigenvolume in HRG needs to be taken into account (H. Stoecker, next)





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:

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

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:

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

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

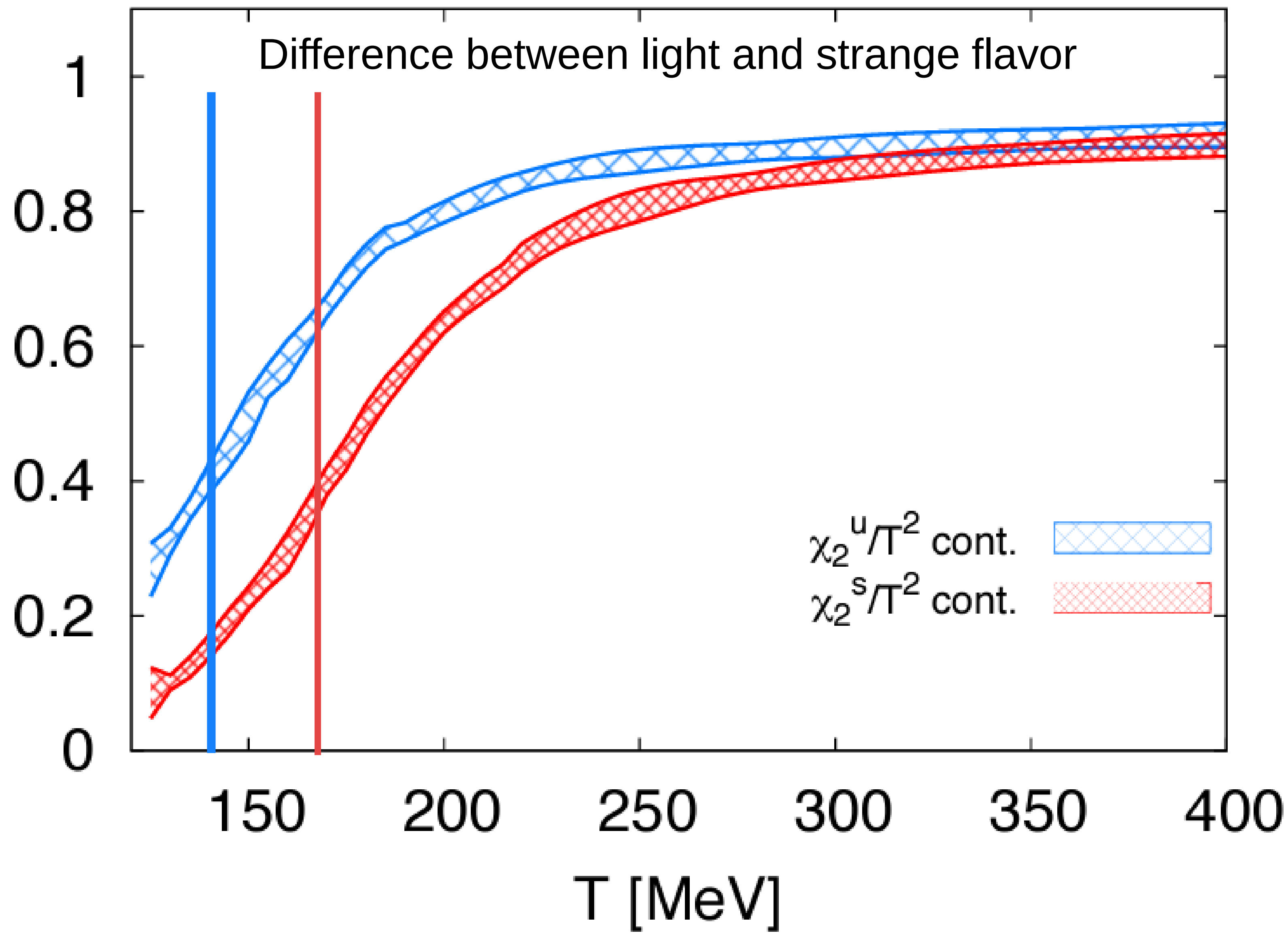
To measure μ_B:

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

To measure T:

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

Indication of flavor dependence in simplest diagonal susceptibility correlators (χ_2)



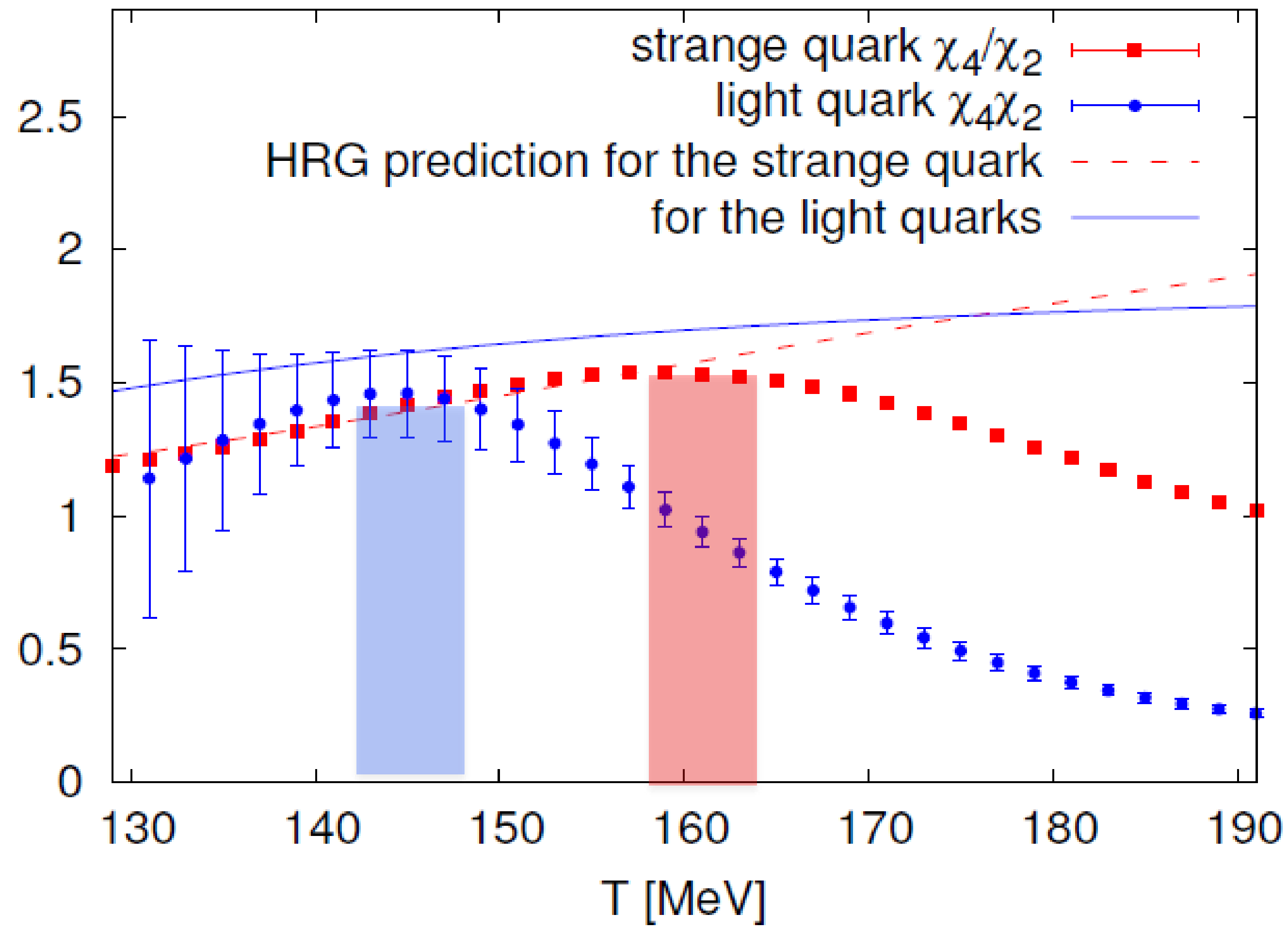
C. Ratti et al., PRD 85, 014004 (2012)
R. Bellwied, arXiv:1205.3625

- But is this just a simple mass effect, which cancels out when looking at ratios that relate to the chemical freeze-out ??

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

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

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



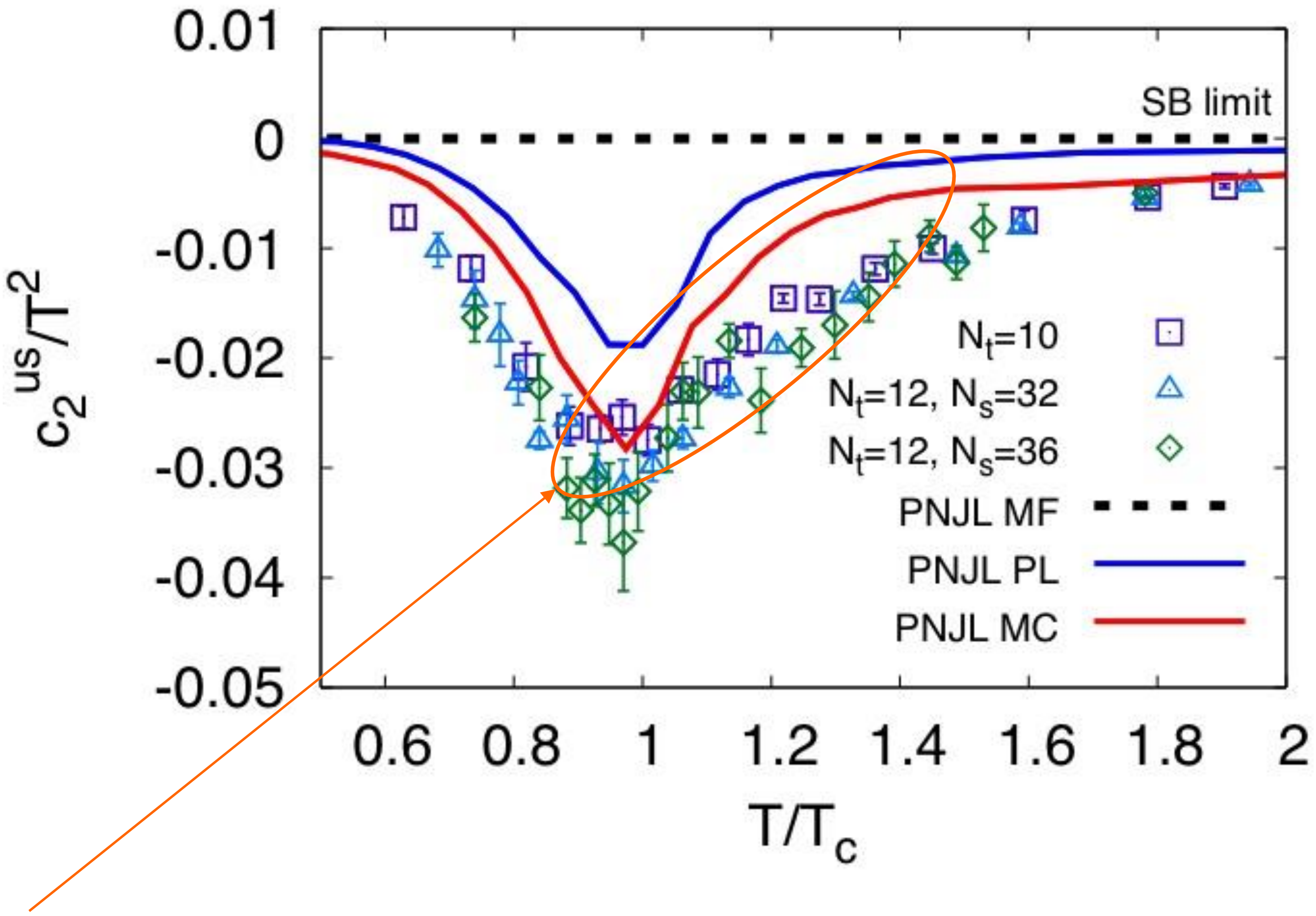
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

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

<u>Indication of sequential hadronization</u>

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

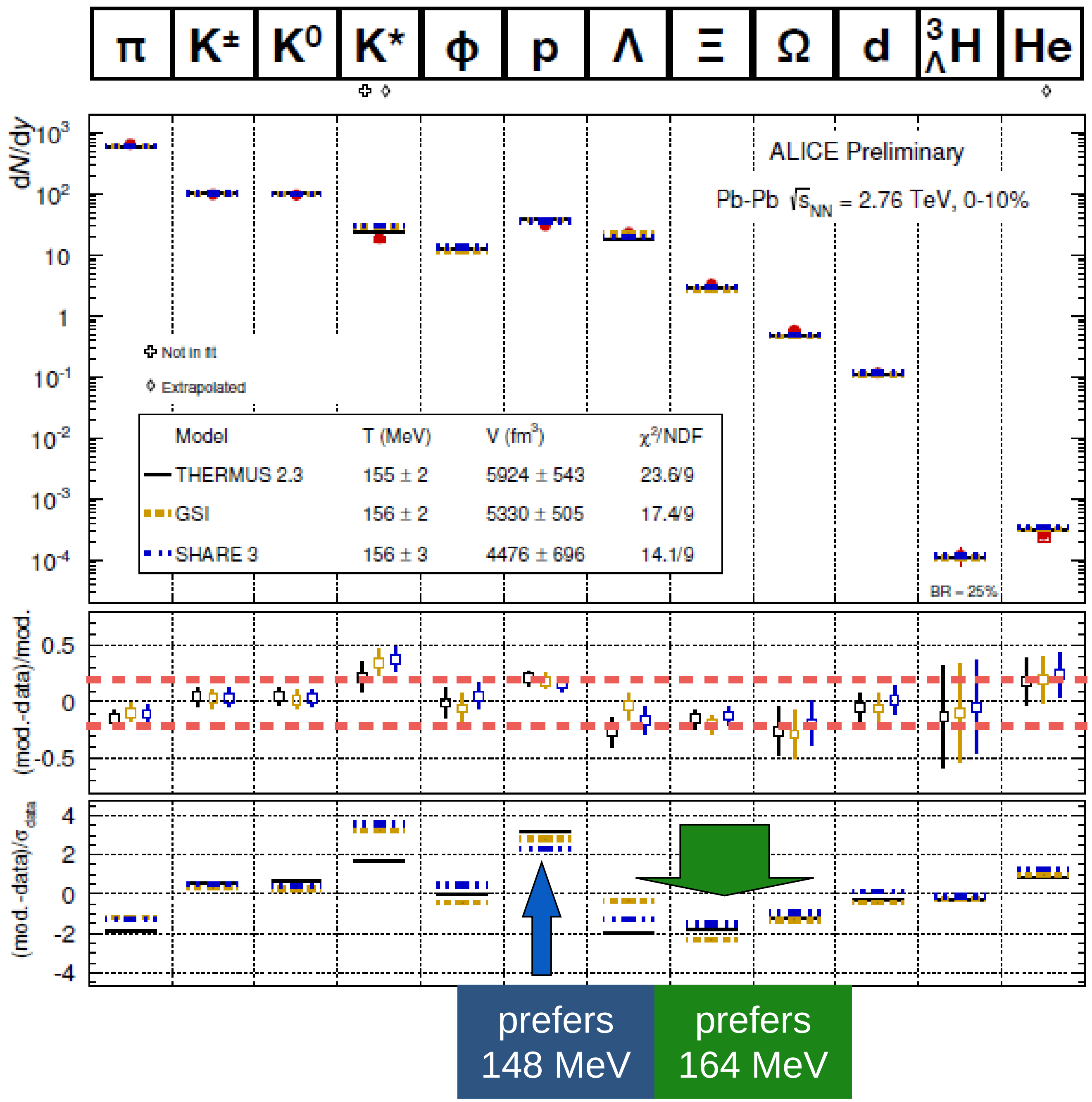
PNJL-PL:
mean field plus Polyakov loop fluctuations

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 (I): 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.

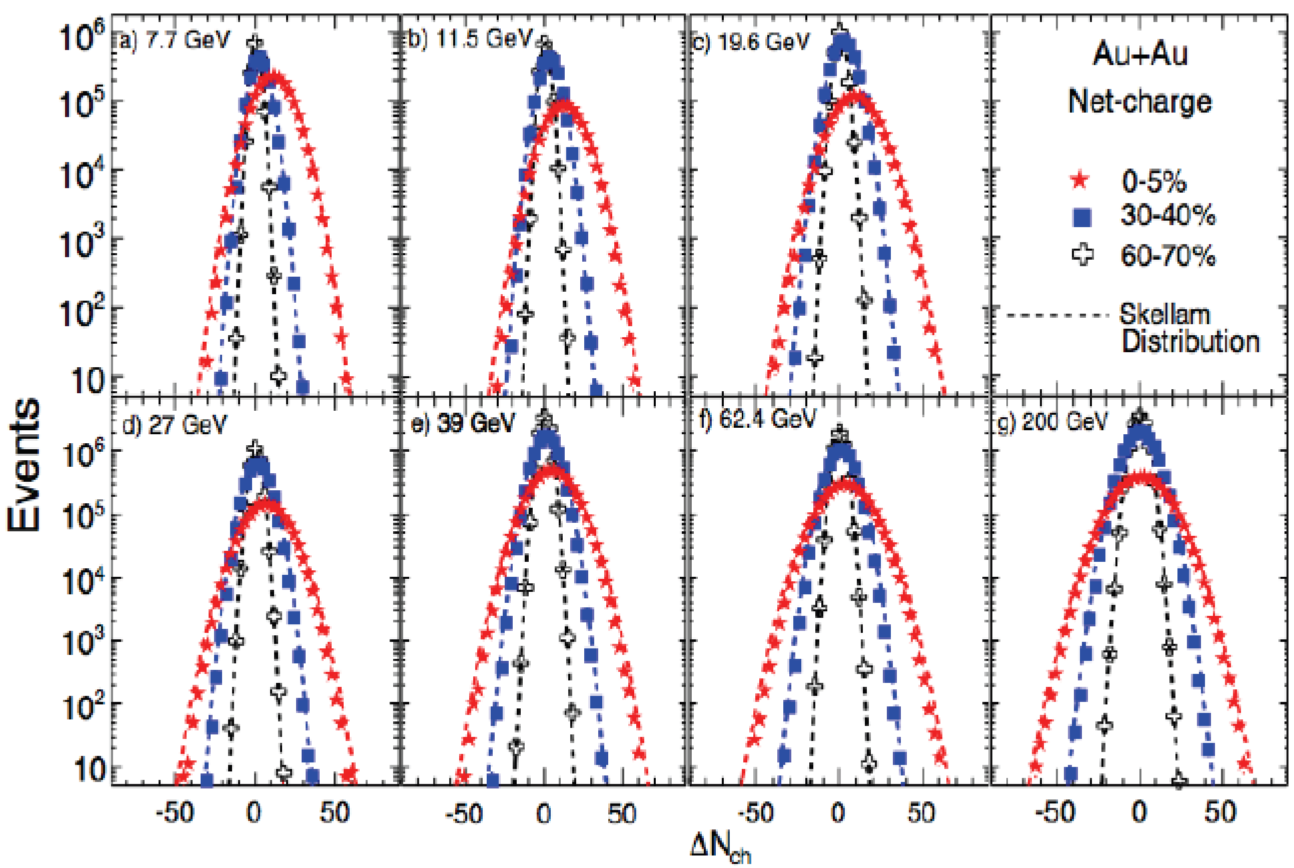
<u>Several alternate explanations:</u>

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

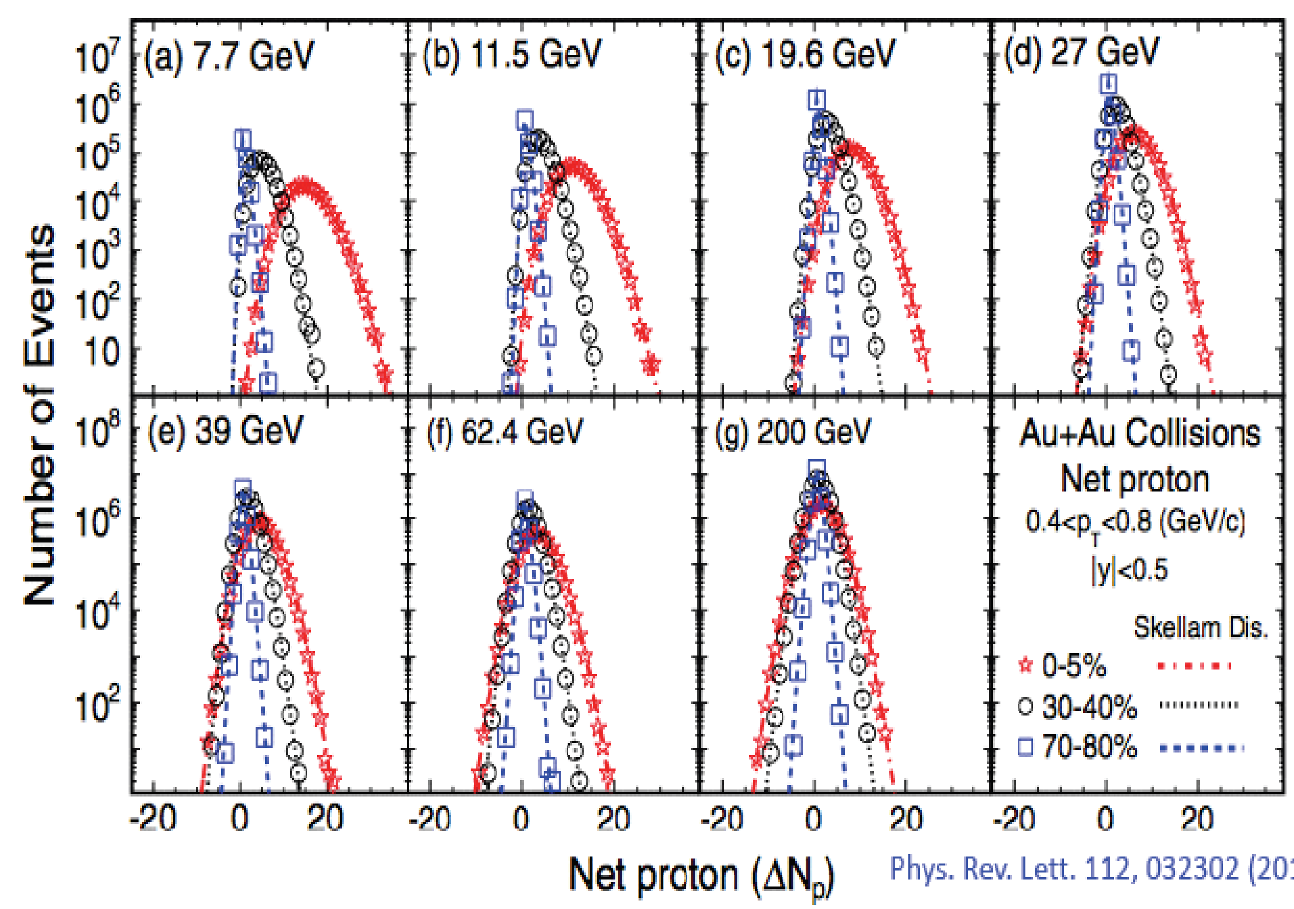
Is a common freeze-out surface that important ? Is it supported by lattice QCD ?

Measure net-distributions and calculate moments in STAR

Net-charge distribution



Net-Proton distribution

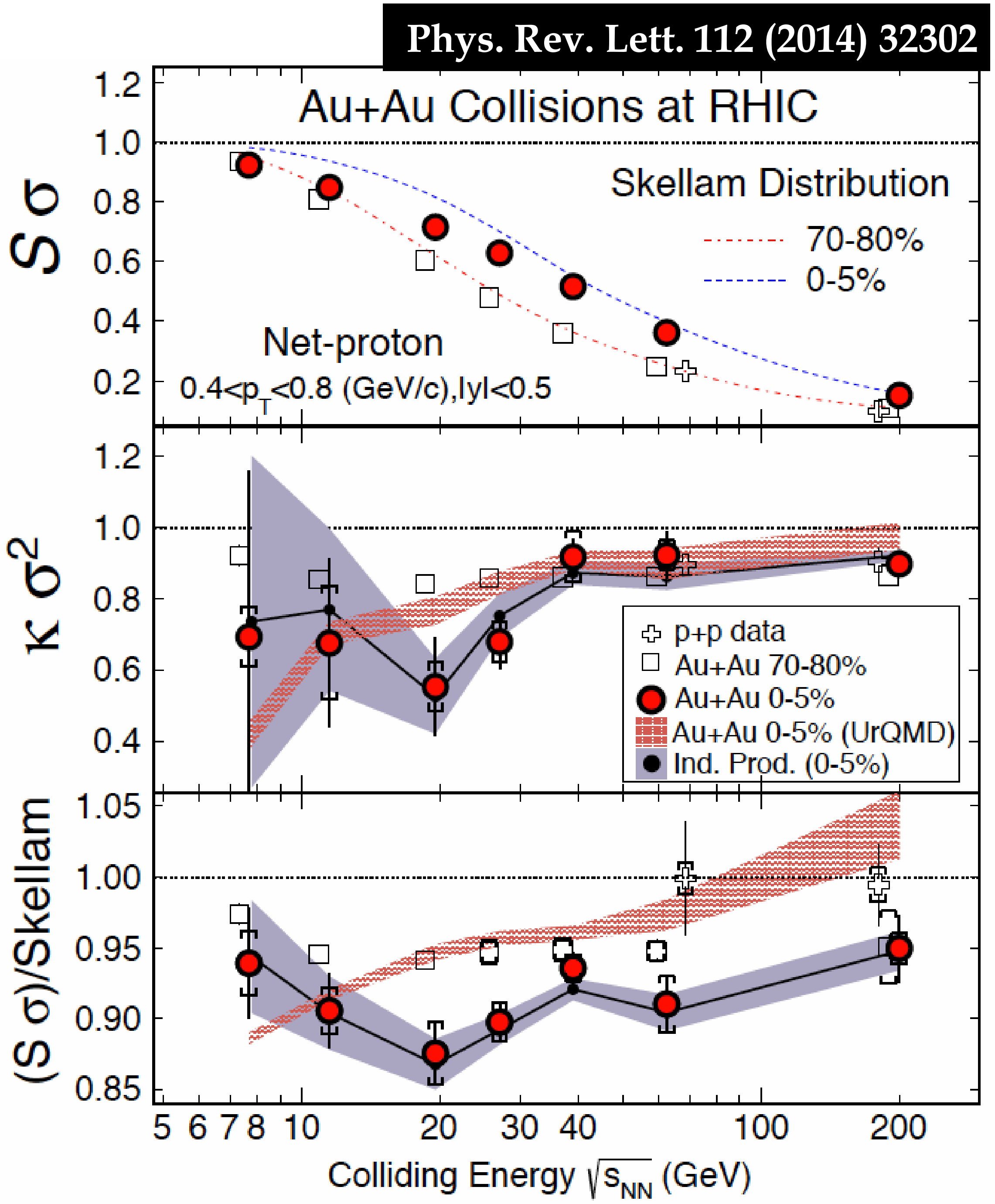


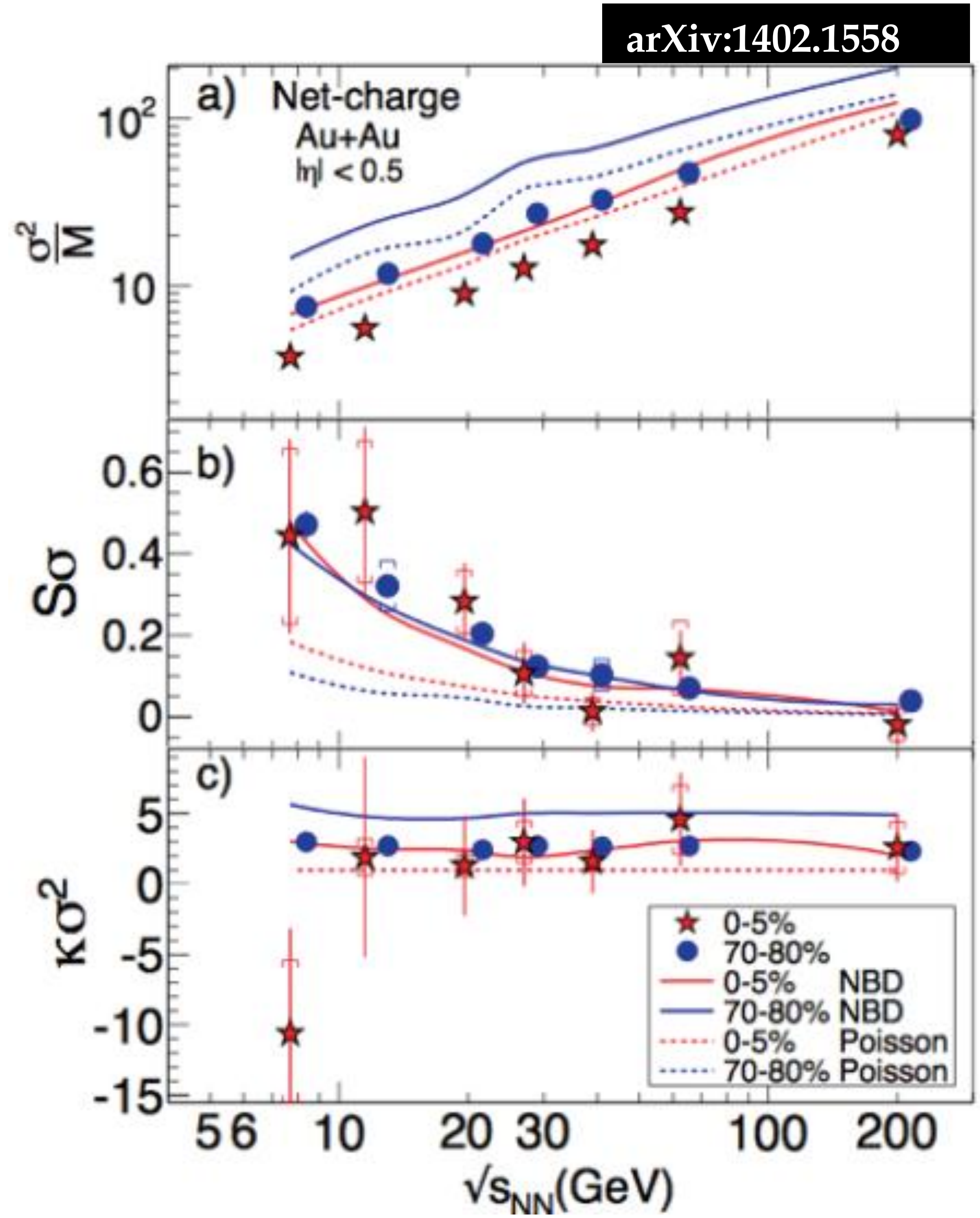
Phys. Rev. Lett. 112, 032302 (2014).

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

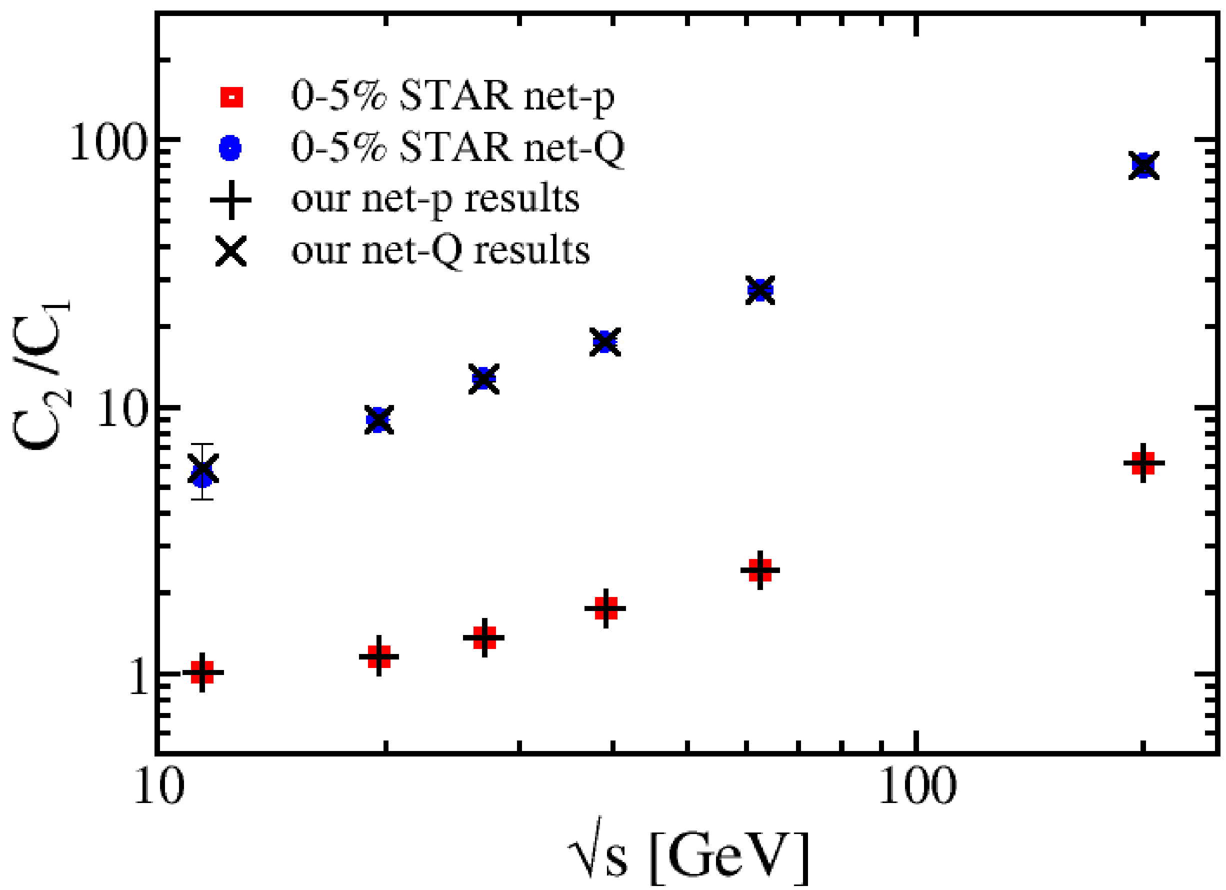


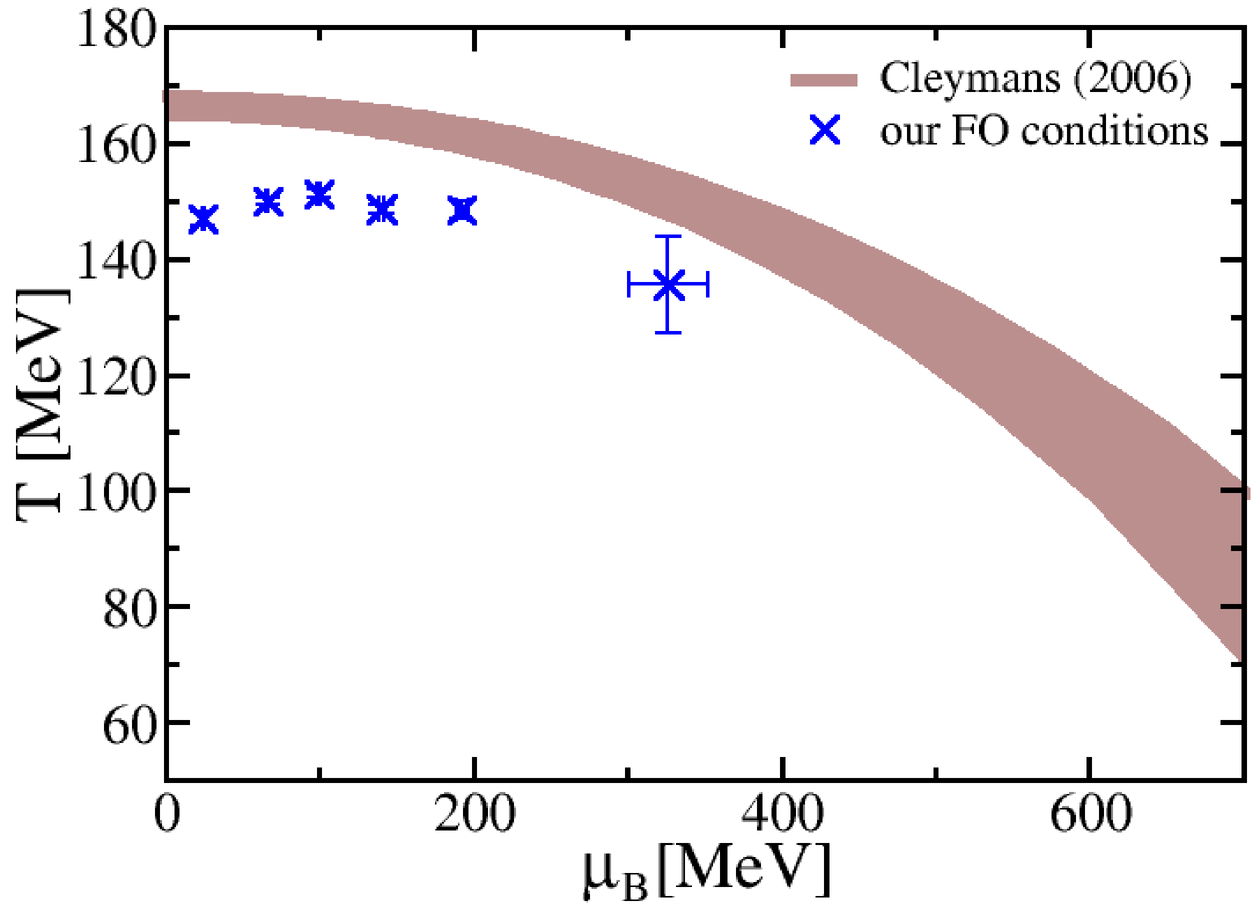


HRG analysis of STAR results (charge & proton)

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)

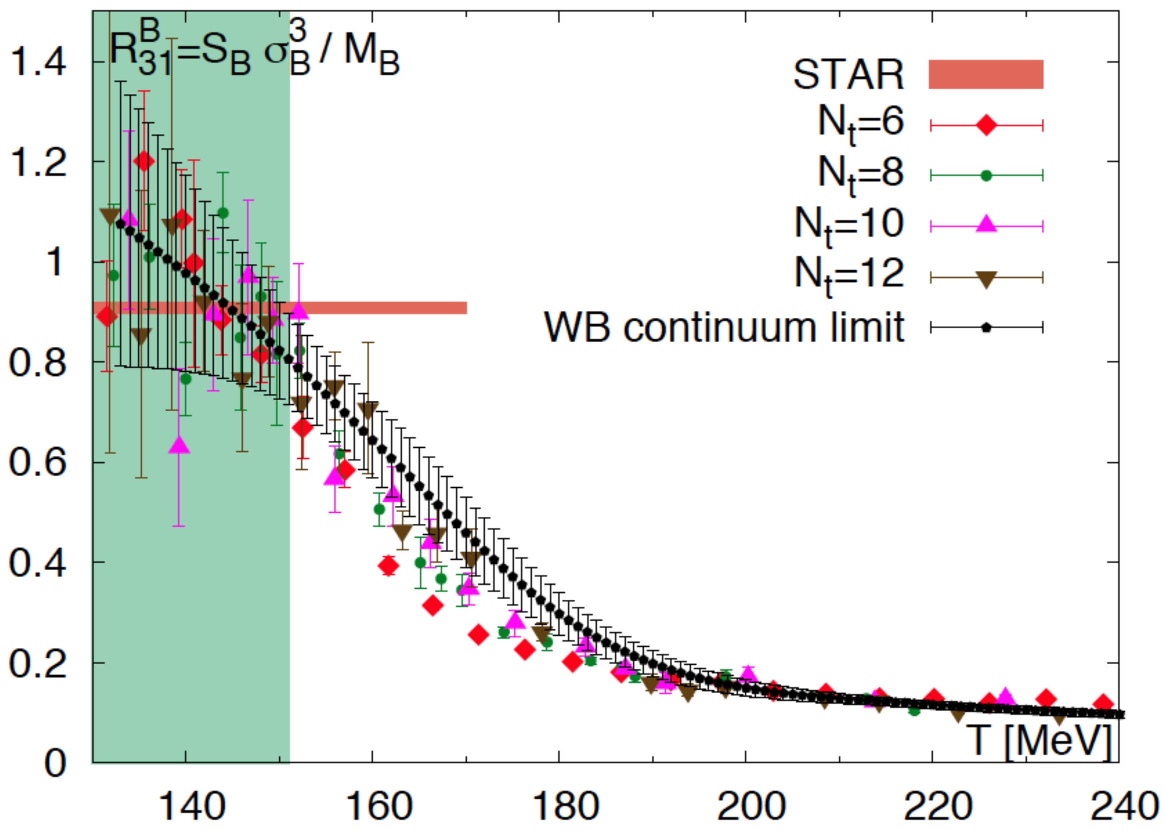


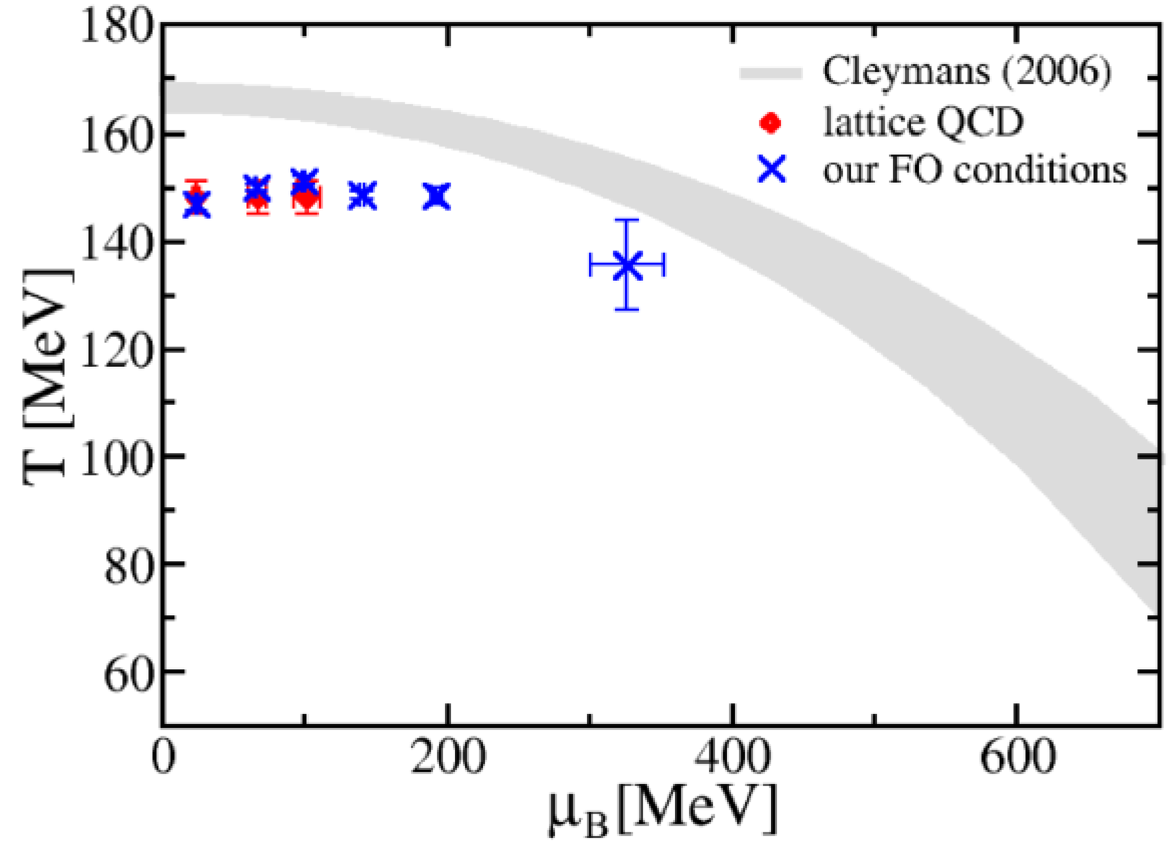


Result: intriguing ‘lower’ freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

Check consistency with lattice QCD

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





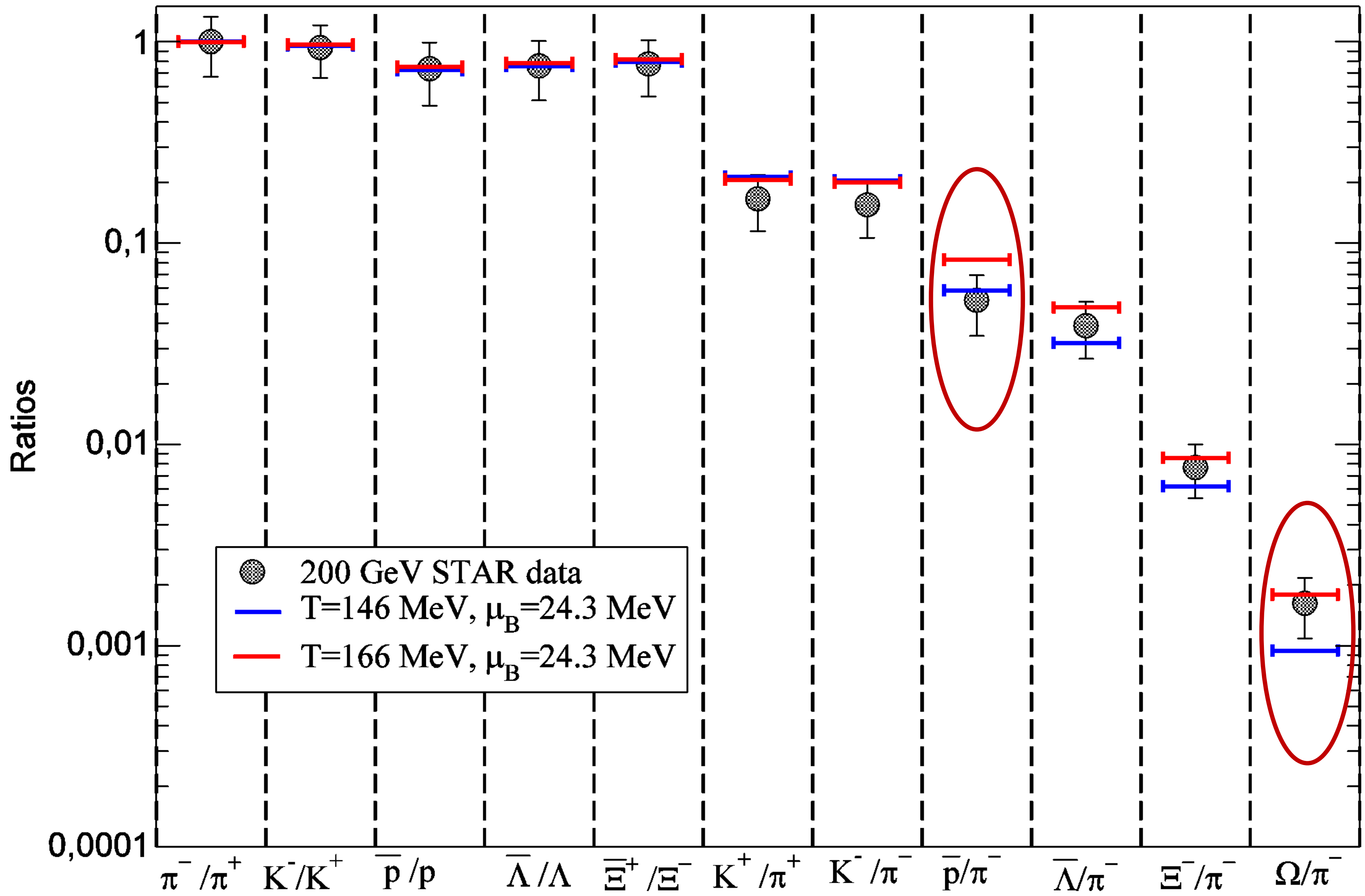
$\sqrt{s}$ [GeV]	$\mu_{B,ch}$ [MeV]	T_{ch} [MeV]
11.5	326.7±25.9	135.5±8.3
19.6	192.5±3.9	148.4±1.6
27	140.4±1.4	148.5±0.7
39	99.9±1.4	151.2±0.8
62.4	66.4±0.6	149.9±0.5
200	24.3±0.6	146.8±1.2

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

Maximum chemical freeze-out temperature:
151+-4 MeV (for sqrt(s) > 39 GeV),
recently verified by Karsch et al. (QM 2015)

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

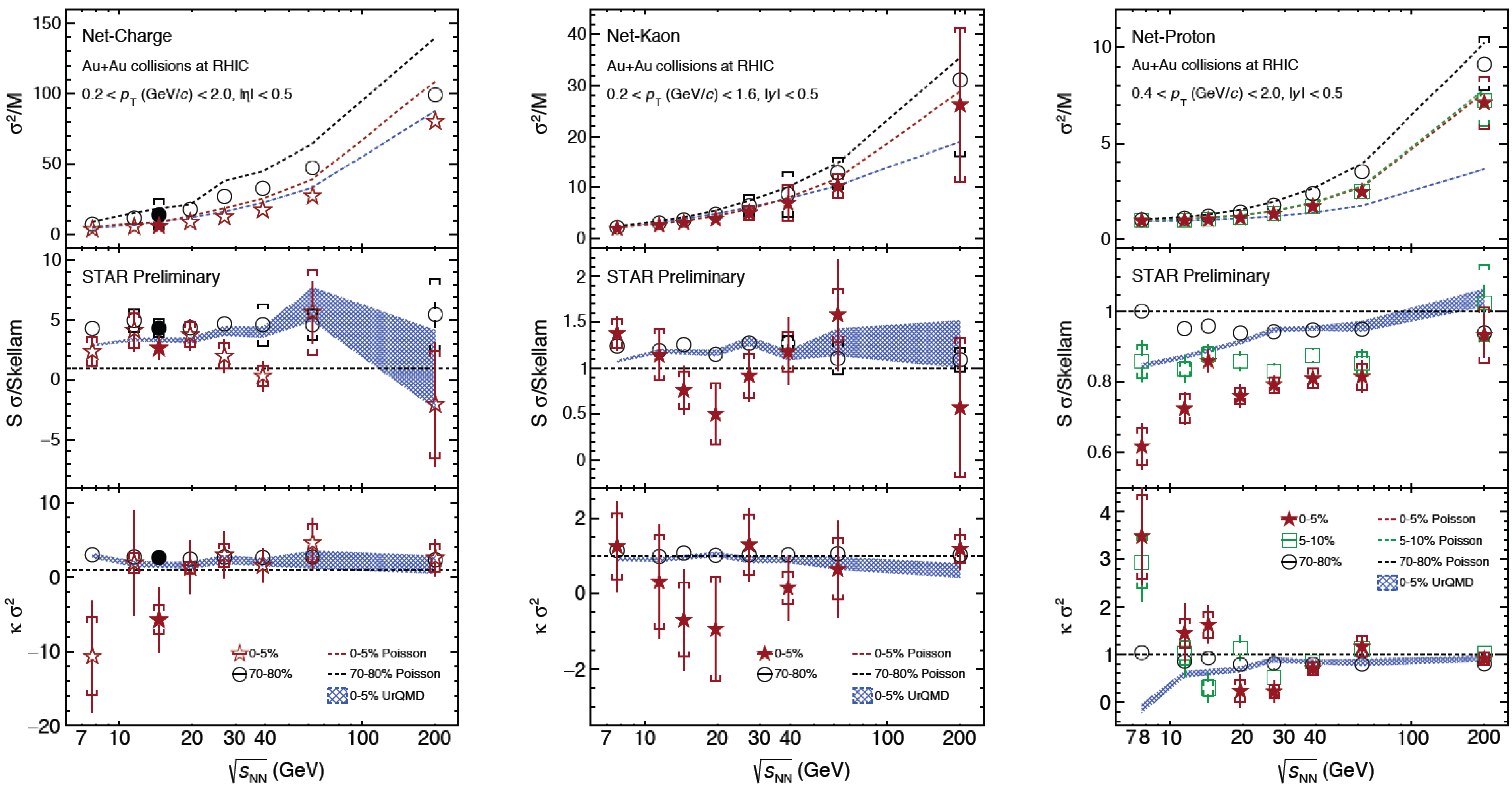


Main deviations in pure strange and light baryon state. Consistent with ALICE

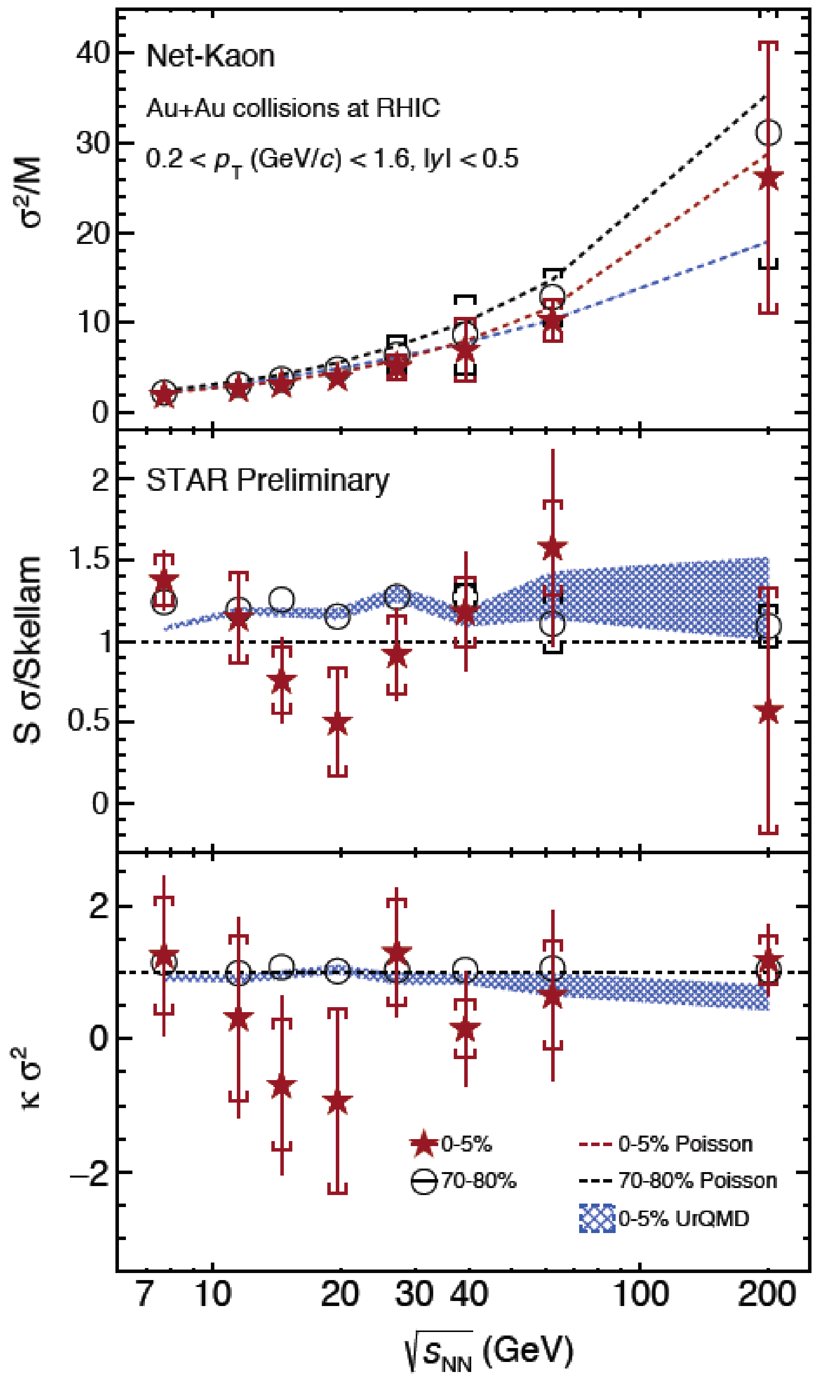
We need corrected net-strange fluctuations (kaons not sufficient ?)

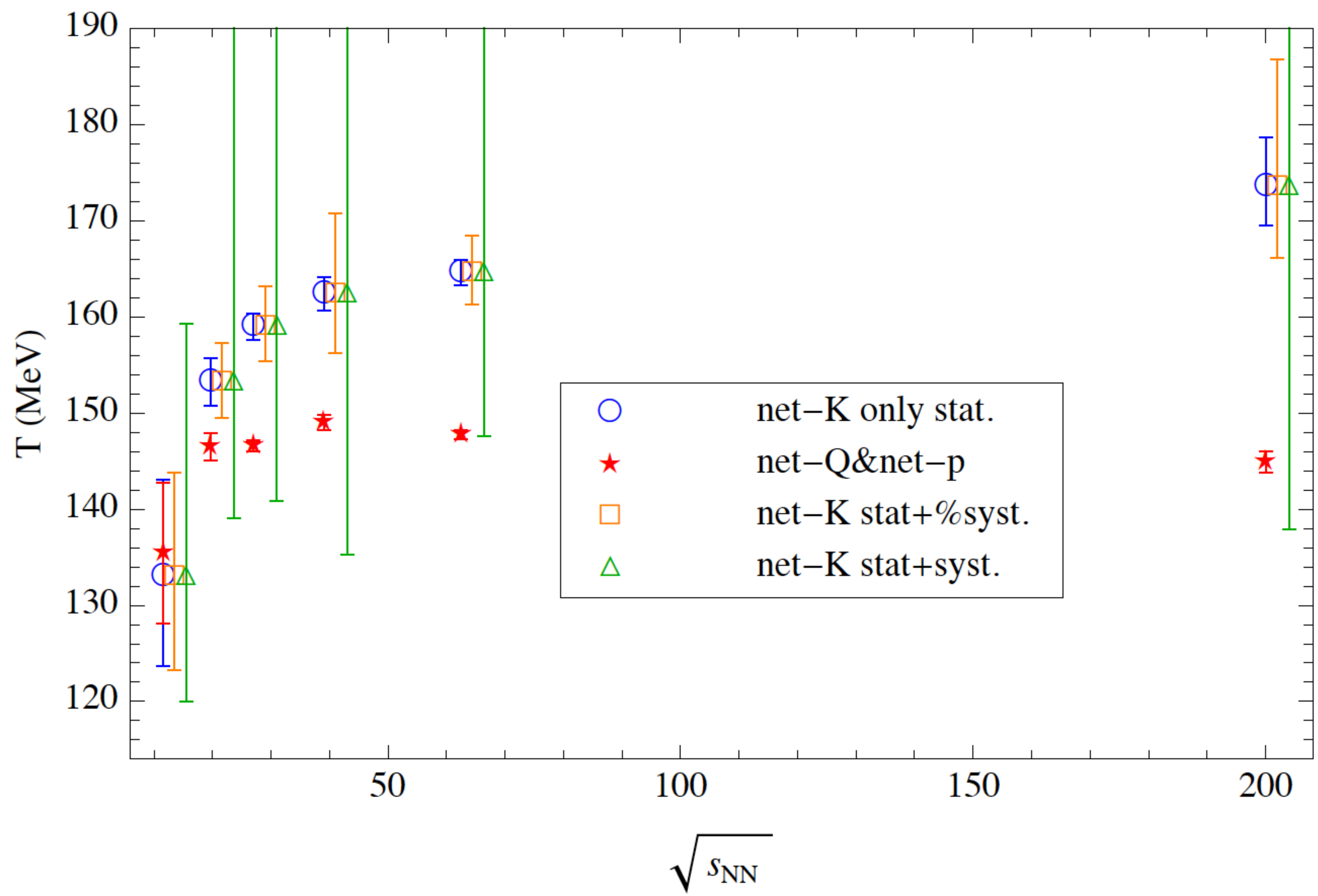
STAR has shown corrected kaons at QM 2015 (J. Xu and J. Thaeder)

Latest STAR results (see J.Xu's talk on Monday)



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



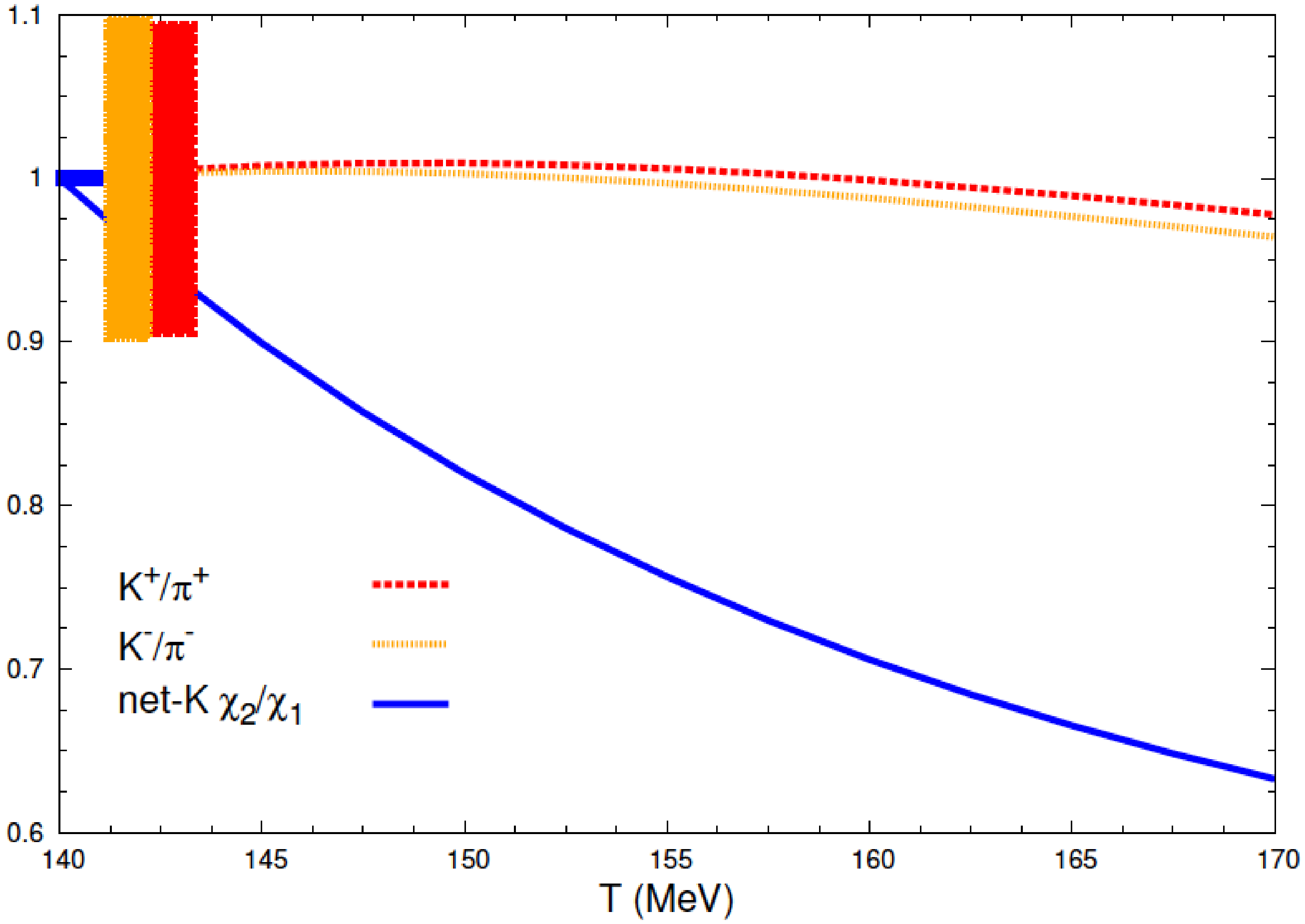


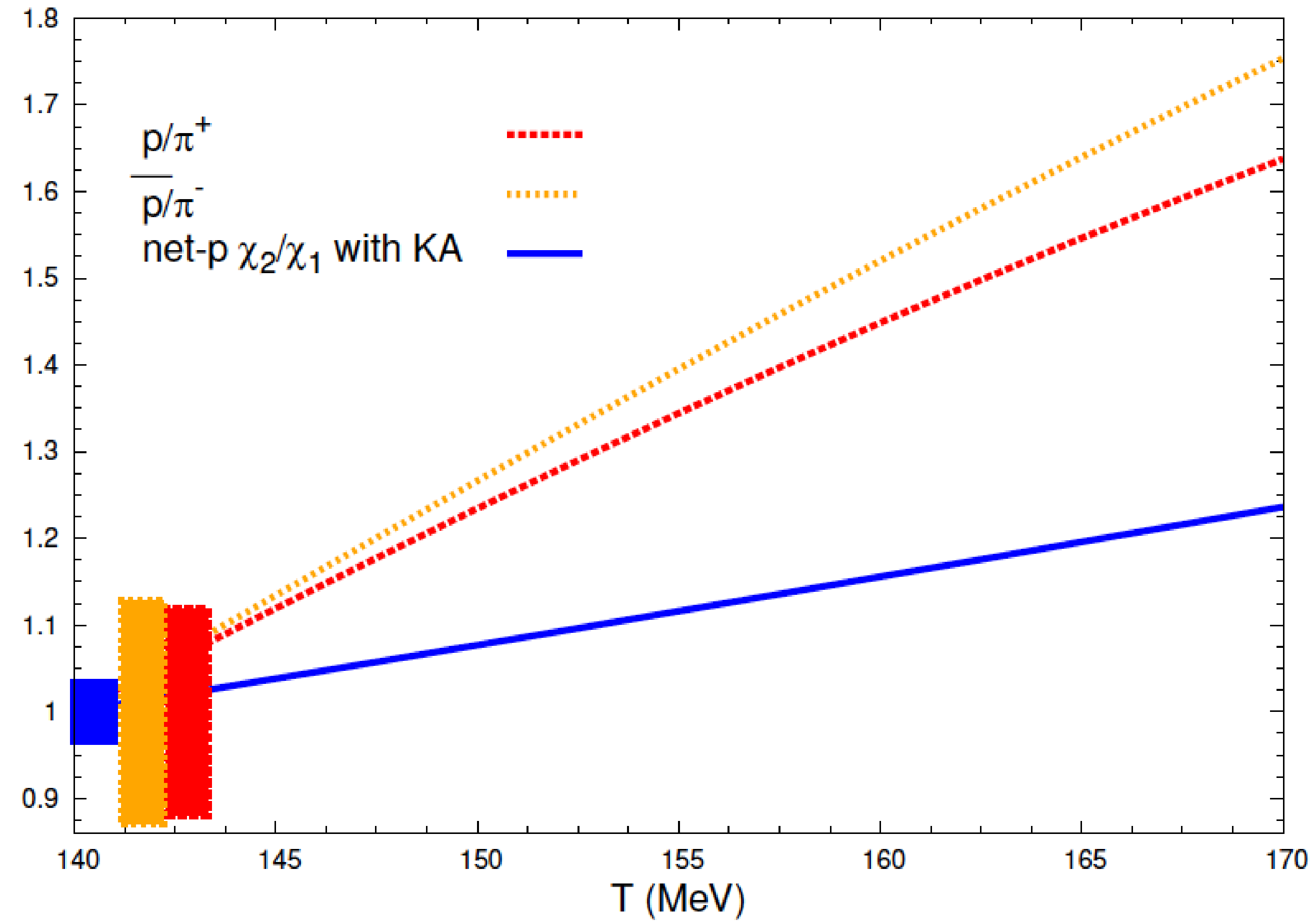
<u>Exciting result but presently hampered by systematic errors</u>

<u>(BES-II will help, analysis of neutral Kaons might help)</u>

Kaon fluctuations show a remarkable sensitivity to the chemical freeze-out temperature 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: P. Alba, RB et al. (PRC (2015), arXiv:1504.03262)

So what can happen between 148 and 164 MeV ?

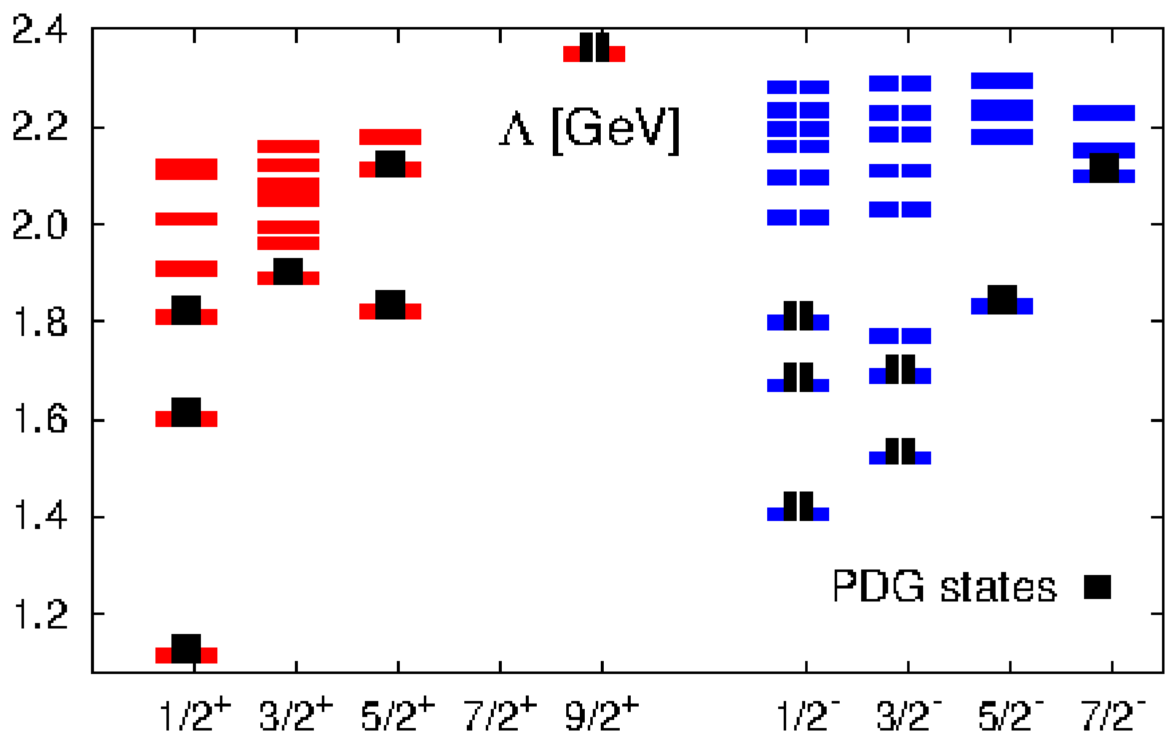
A 20 MeV drop can be translated into a 2 fm/c time window
Strangeness wants to freeze-out, light quarks do not

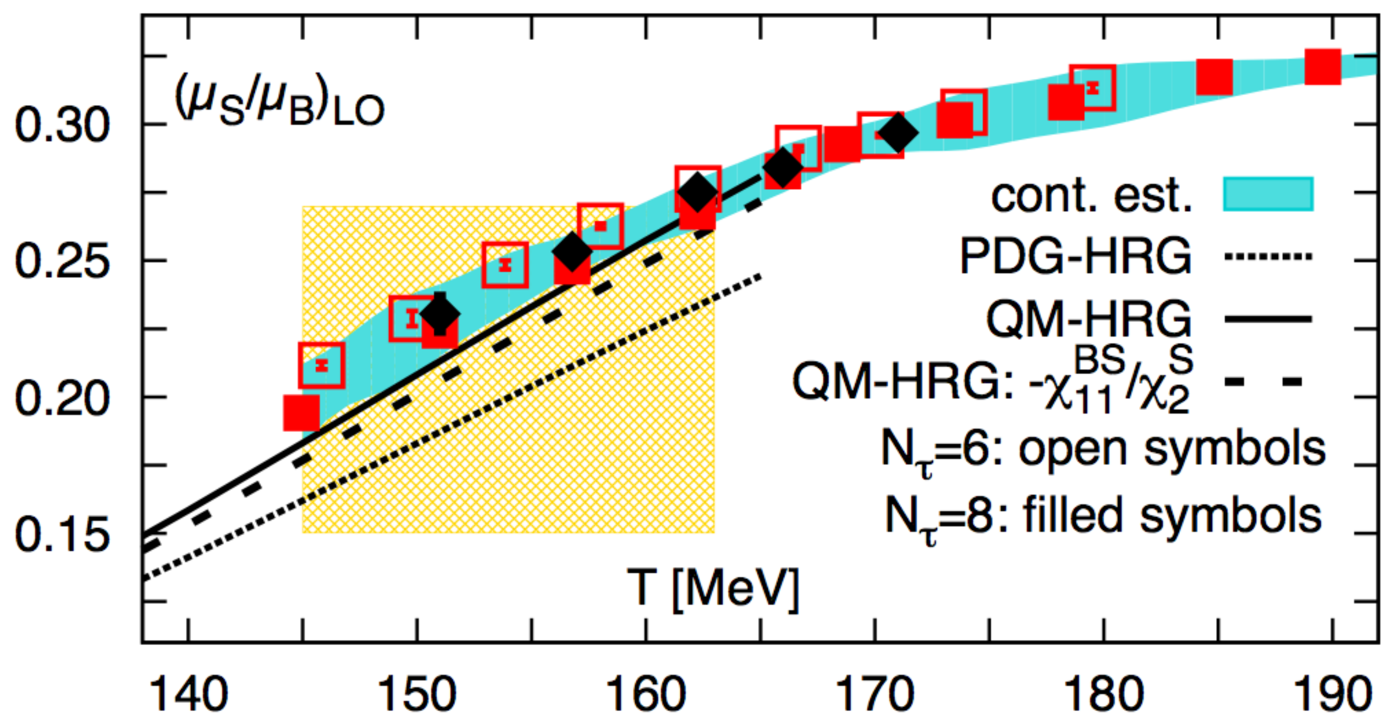
Can there be measurable effects ?
Can there be a mixed phase of degrees of freedom
Can there be implications for the cosmological evolution of matter ?

1.) exotic quark configurations with strangeness
2.) impact on dynamic quantities such as v_2 and R_{AA}

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)

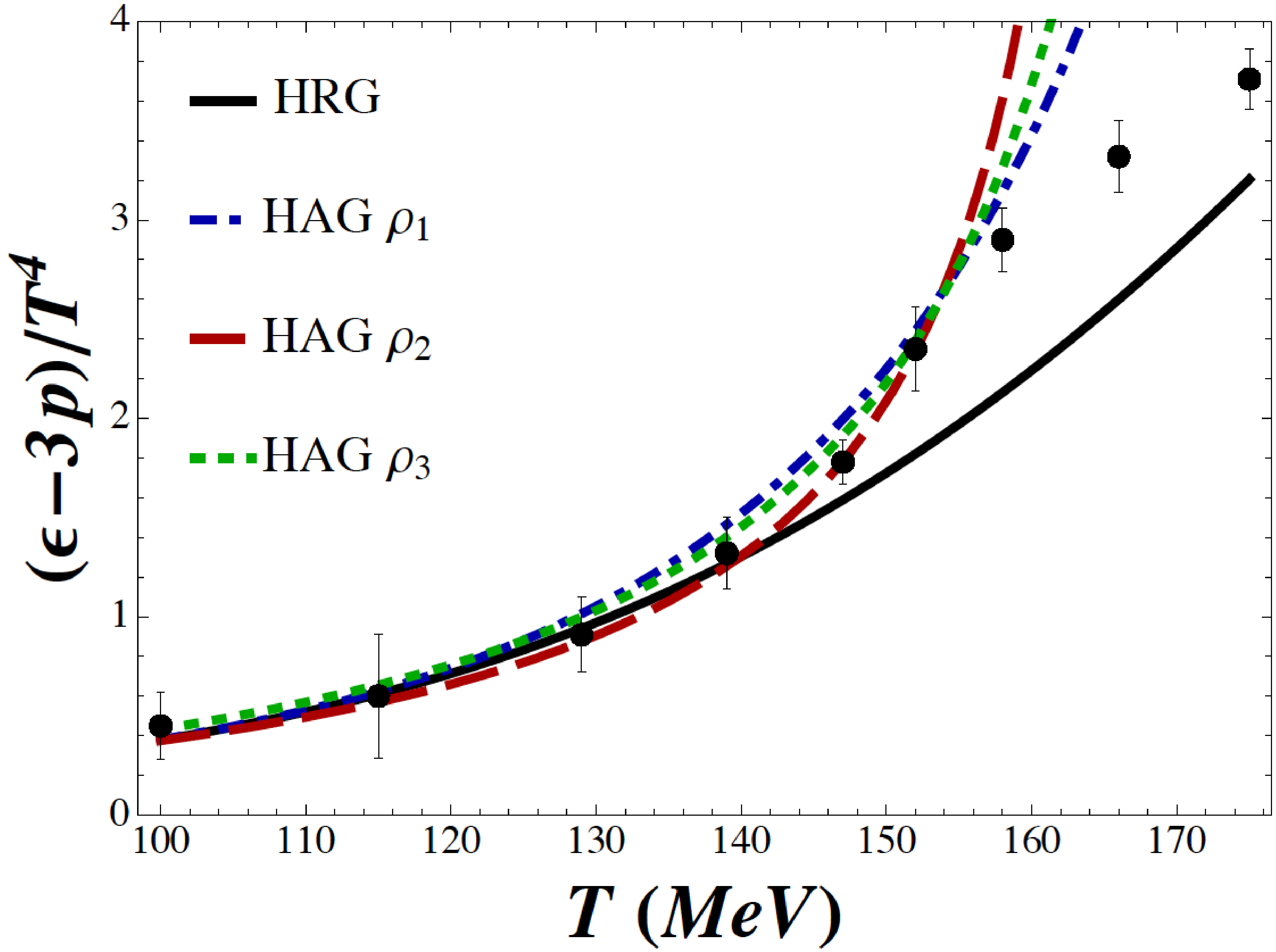




But those effects need to be consistently applied to all correlators that are possibly affected by higher lying strange states.

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

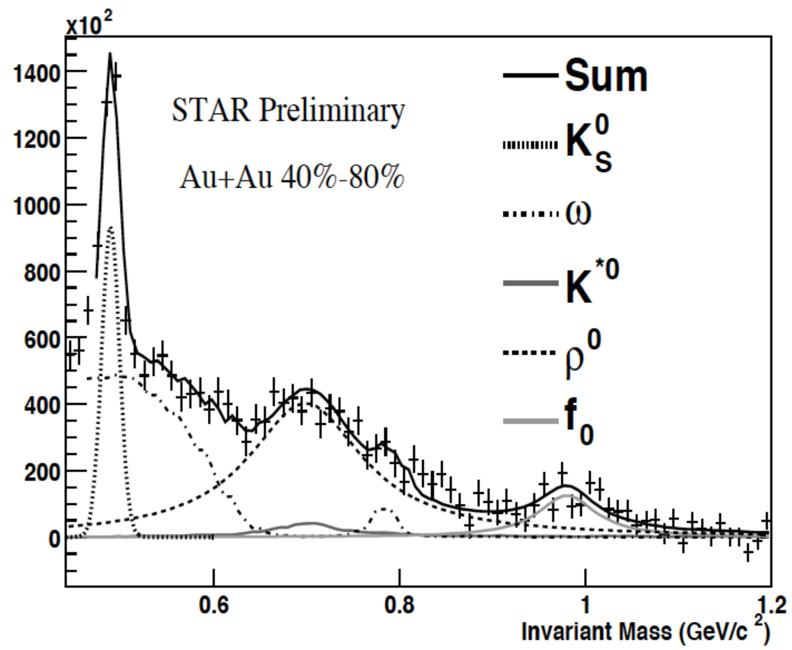
More evidence for exotic states: Comparison of trace anomaly from lattice to HRG spectrum expanded with Hagedorn States (J. Noronha-Hostler et al., PRC (2014), arXiv:1302.7038)

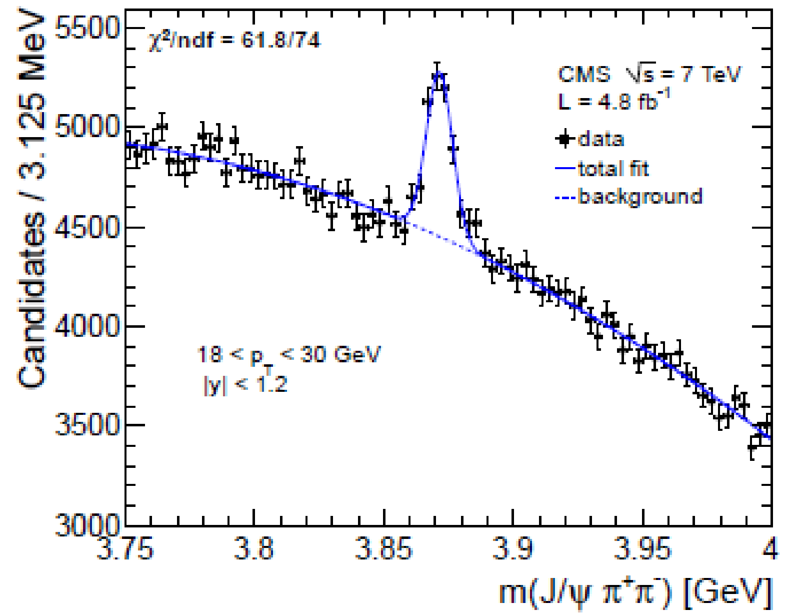


Inclusion of Hagedorn states seems to improve agreement with lattice near the transition temperature of 151+-4 MeV

Exotic states within the Standard Model

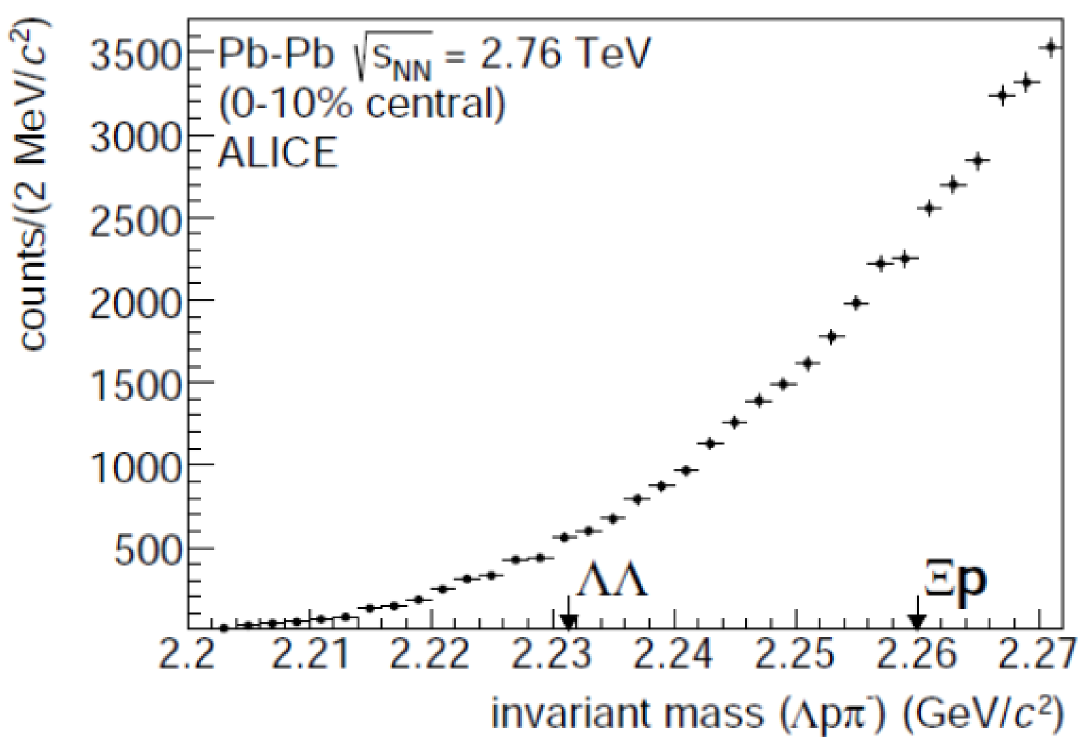
Exotic states measured at RHIC and the LHC (strange and charm sector)

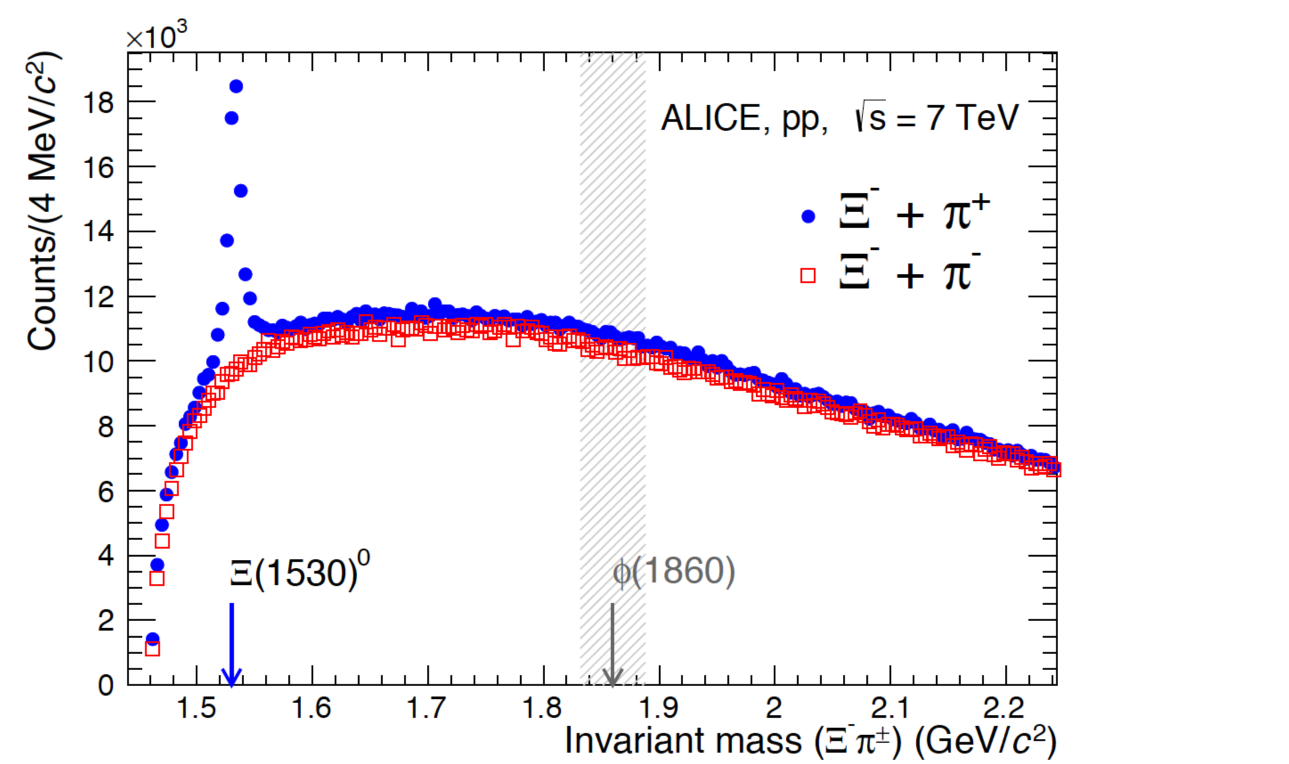




Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.
Mesons							
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$
$K(1460)$	1460	2	1/2	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$
$D_s(2317)$	2317	1	0	0^+	$c\bar{s}(L=1)$	$q\bar{q}c\bar{s}$	DK
T_{cc}^{1} [a]	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$
$X(3872)$	3872	3	0	$1^+, 2^-$ [c]	$c\bar{c}(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$
$Z^+(4430)$ [b]	4430	3	1	0^- [c]	—	$q\bar{q}c\bar{c}(L=1)$	$D_1\bar{D}^*$
T_{cb}^{0} [a]	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$
Baryons							
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqs(L=1)$	$qqqs\bar{q}$	$\bar{K}N$
$\Theta^+(1530)$ [b]	1530	2	0	$1/2^+$ [c]	—	$qqqq\bar{s}(L=1)$	—
$\bar{K}KN$ [a]	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}(L=1)$	$\bar{K}KN$
$\bar{D}N$ [a]	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$
$\bar{D}^*N$ [a]	2919	4	0	$3/2^-$	—	$qqqq\bar{c}(L=2)$	$\bar{D}^*N$
Θ_{cs} [a]	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}(L=1)$	—
BN [a]	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN
B^*N [a]	6226	4	0	$3/2^-$	—	$qqqq\bar{b}(L=2)$	B^*N
Dibaryons							
H [a]	2245	1	0	0^+	$qqqqss$	—	ΞN
$\bar{K}NN$ [b]	2352	2	1/2	0^- [c]	$qqqqqs(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$
$\Omega\Omega$ [a]	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$
H_c^{++} [a]	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$
$\bar{D}NN$ [a]	3734	2	1/2	0^-	—	$qqqqqq\,q\bar{c}$	$\bar{D}NN$
BNN [a]	7147	2	1/2	0^-	—	$qqqqqq\,q\bar{b}$	BNN

But little evidence for strange pentaquarks or dibaryons in ALICE data





How to get from a static equilibrium model (lattice QCD or HRG) to dynamic quantities in the QGP (v_2, R_{AA})

- The flavor difference in the chemical freeze-out temperature can be simulated by changing the switching temperature *in hydrodynamics*
- T_{sw} *= switch from quark to hadron phase =* T_{ch}

- Flavor effects would be manifested in static quantities (particle production)
- Switching temperature effects would be manifested in dynamic quantities (v_2, R_{AA})

- e.g. :
- Impact on v_2 in particular at high p_T = higher switching temperature yields less flow
- Less energy loss if quark phase is shorter due to higher switching temperature.

- *Both predictions depend strongly on the time/temperature dependence of flow generation and energy loss*

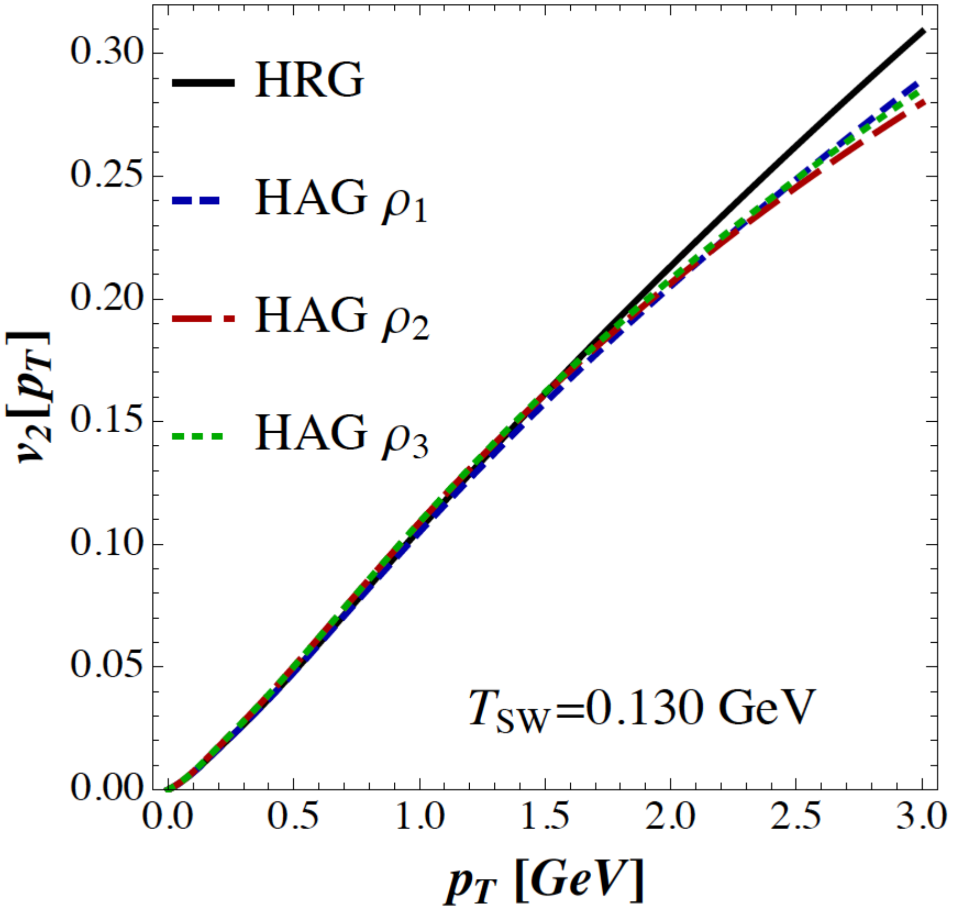
Effect on anisotropic flow

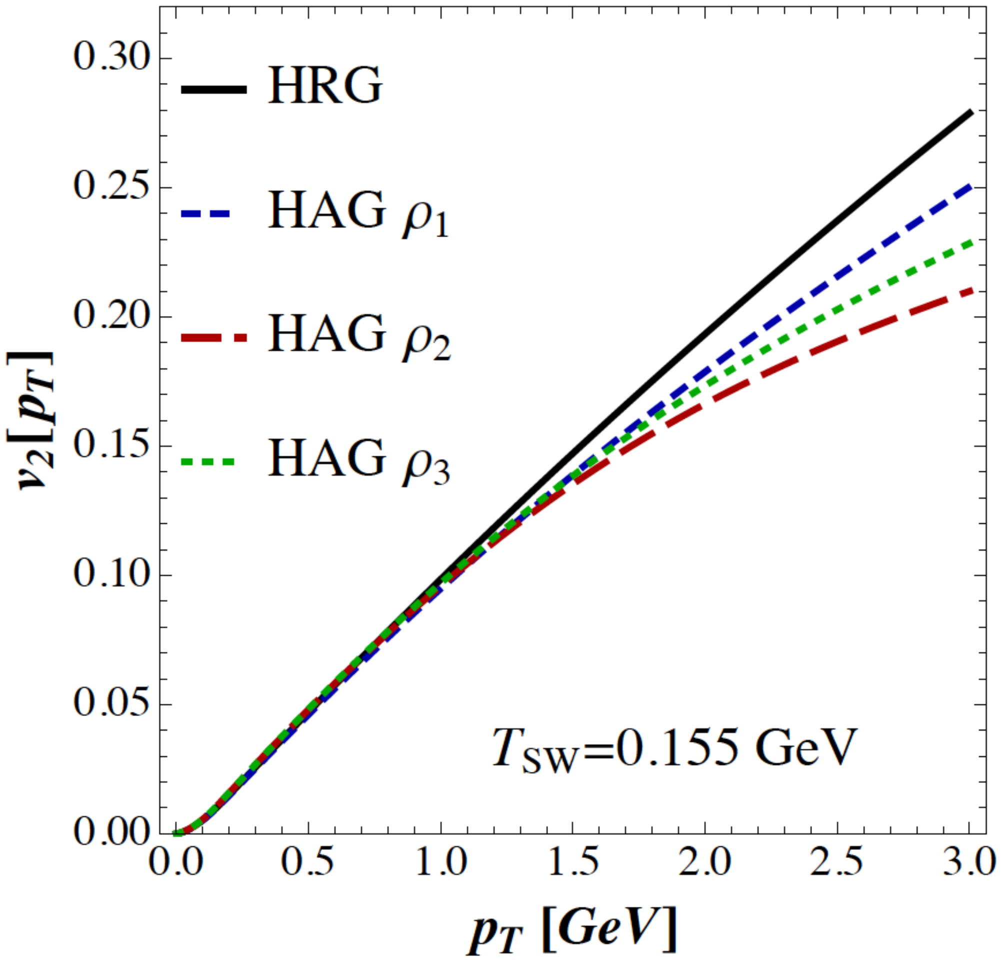
(J. Noronha-Hostler et al., PRC (2014), arXiv:1302.7038)

- *Approach: change the switching temperature in hydrodynamics*

  T_{sw} = *switch from quark to hadron phase* = T_{ch}

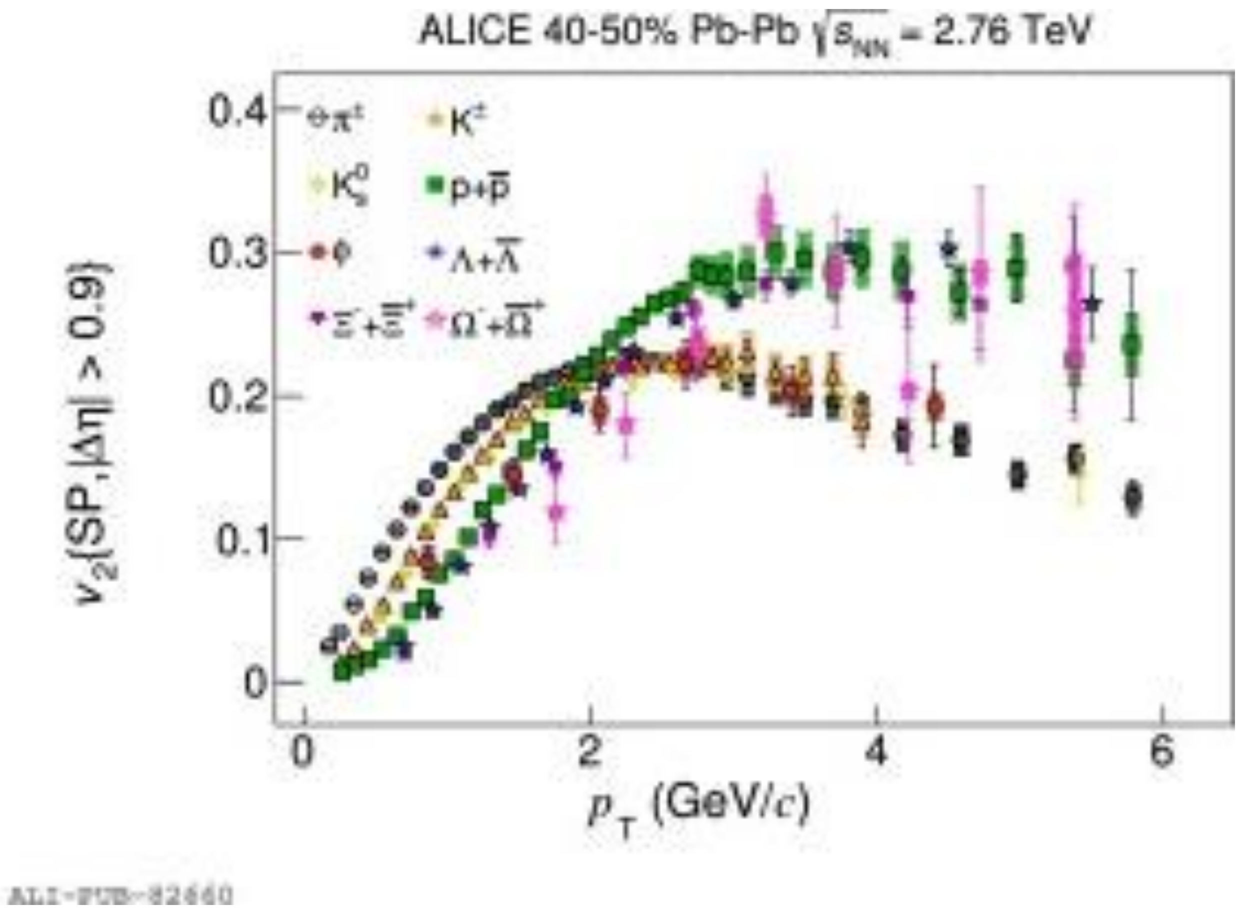
- *Impact on* v_2 *in particular at high* p_T = *higher switching temperature yields less flow and is more dependent on density of states*

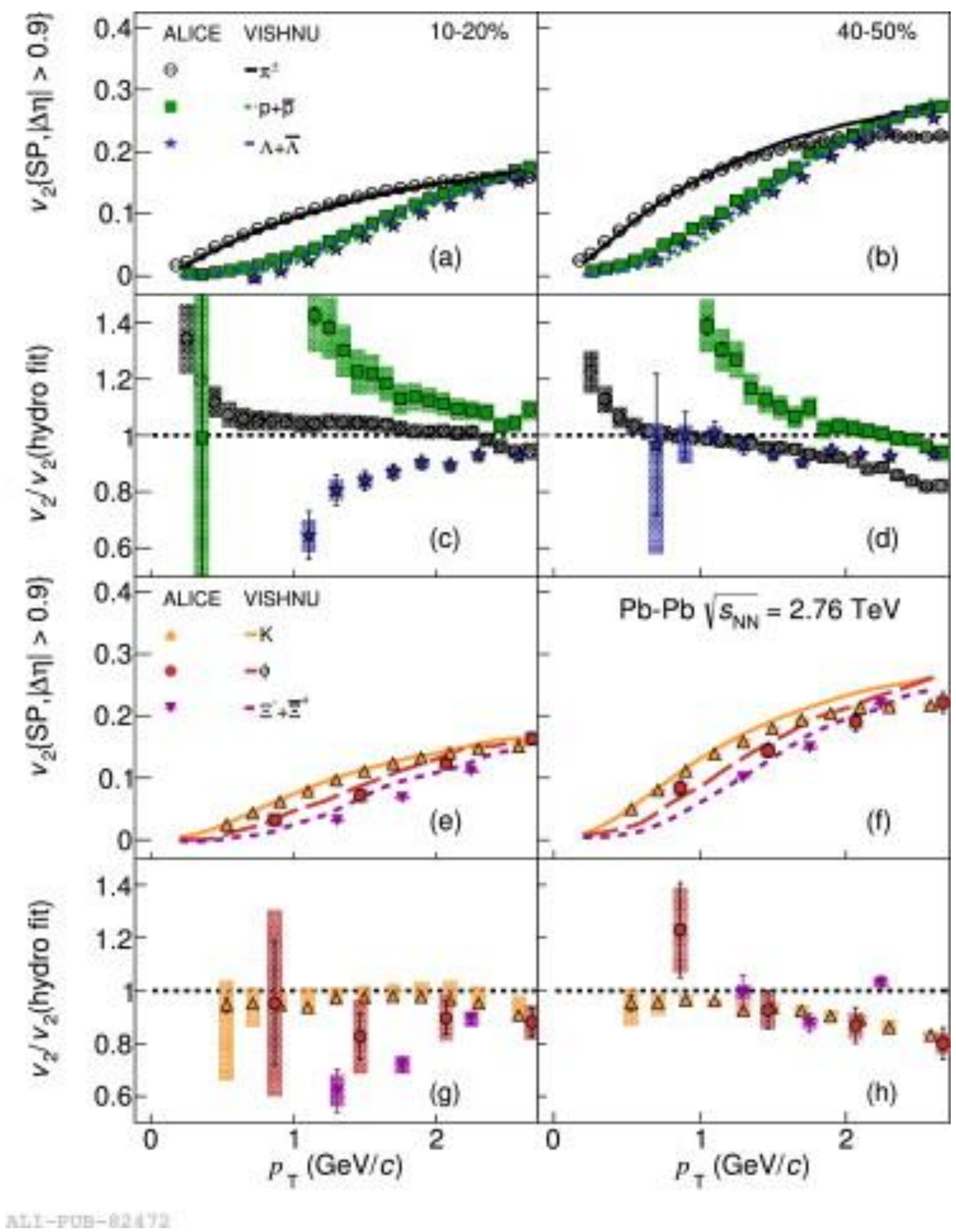




Small effect in v_2 based on existing ALICE data

ALICE data compared to VISHNU hydro (A.Dobrin for ALICE, QM 2014)

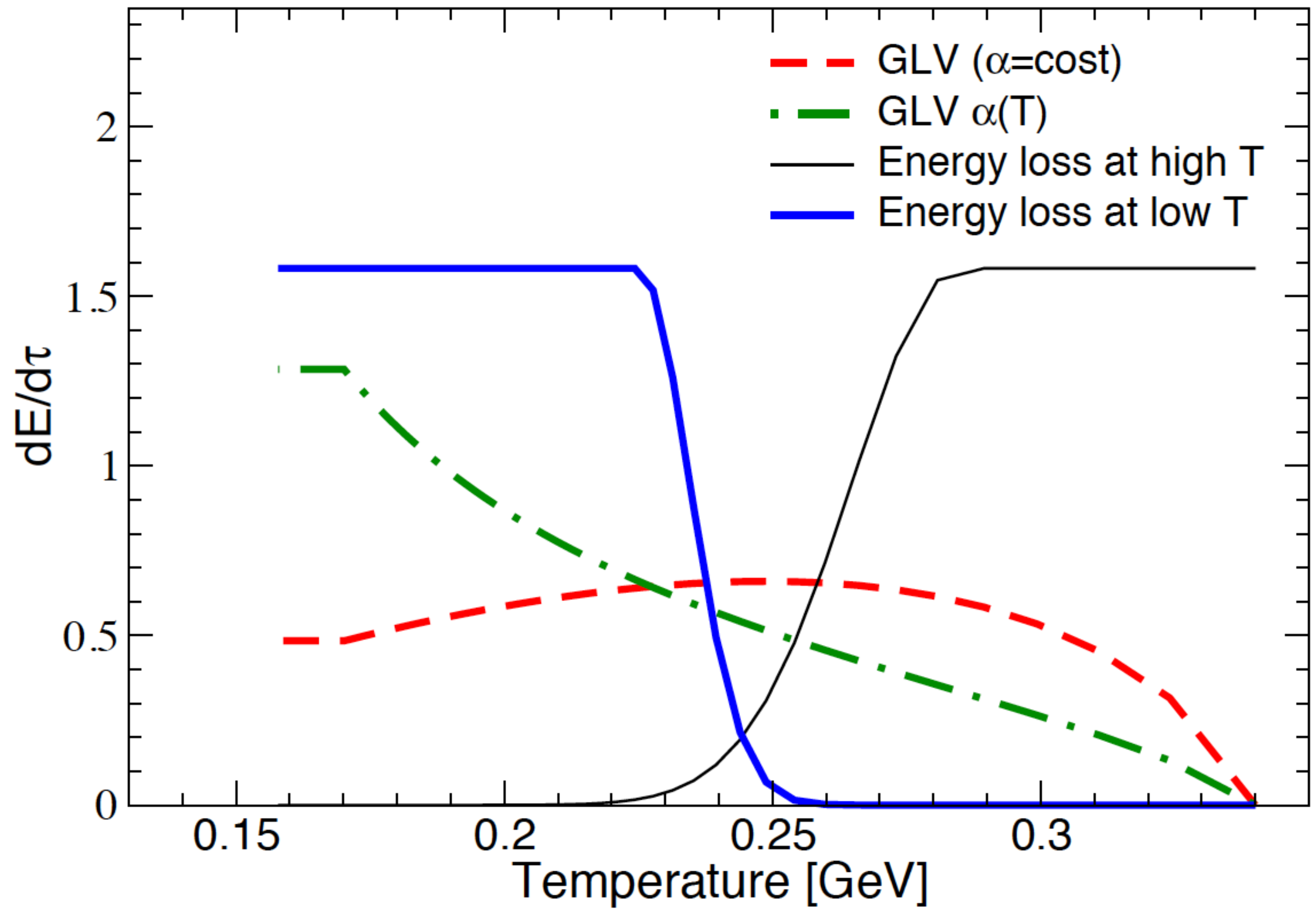




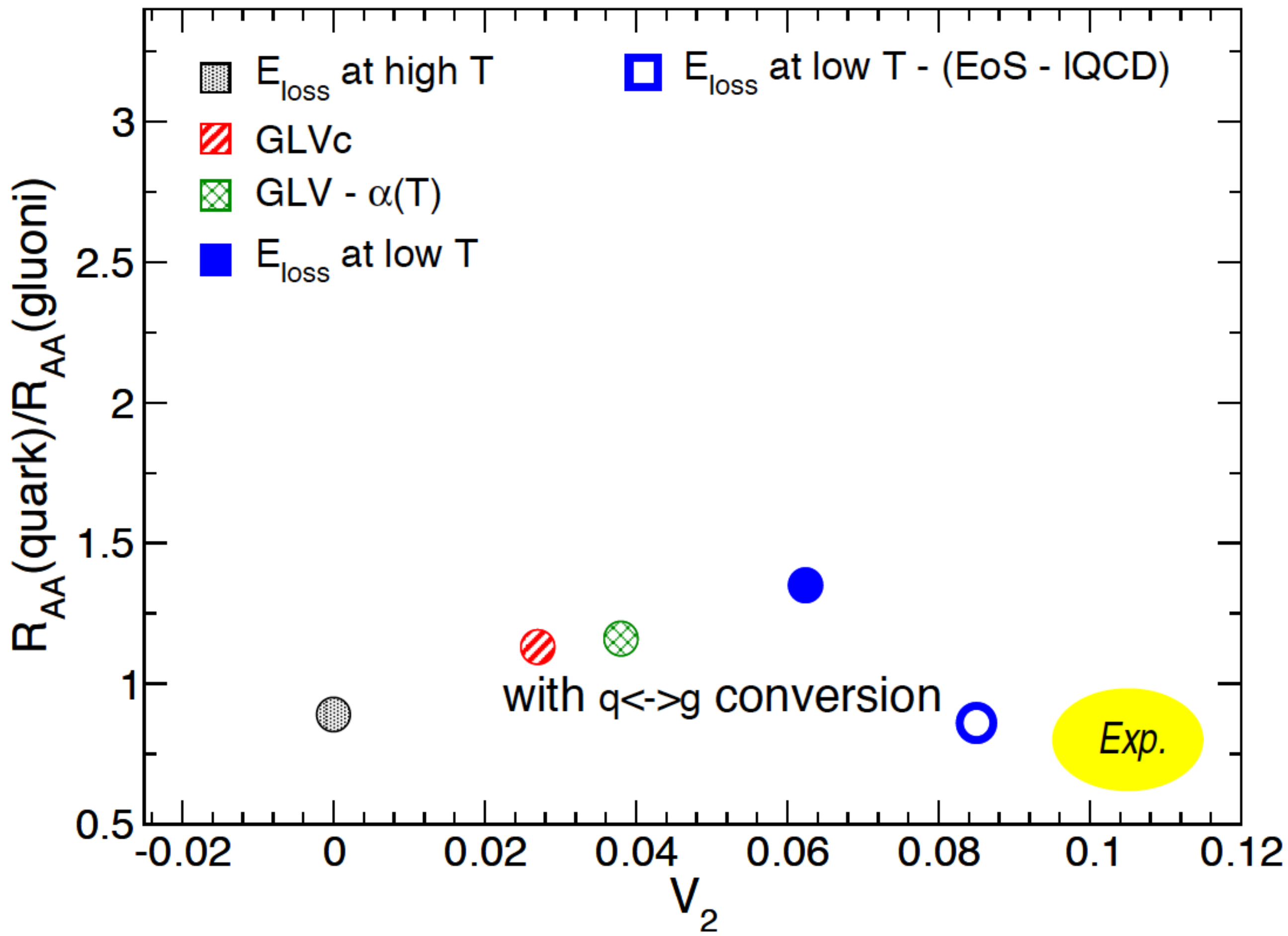
Some reduction of v_2 for strange states compared to hydro model (at high p_T), some increase of v_2 for light states compared to hydro model (at low p_T)

Can there be a strong effect on R_{AA} and a rather small effect on v_2 ?

Yes, if R_{AA} is generated late (near T_{sw}) and v_2 is generated early (Greco et al., PRC82 (2010) 054901): combined fit to R_{AA} and v_2



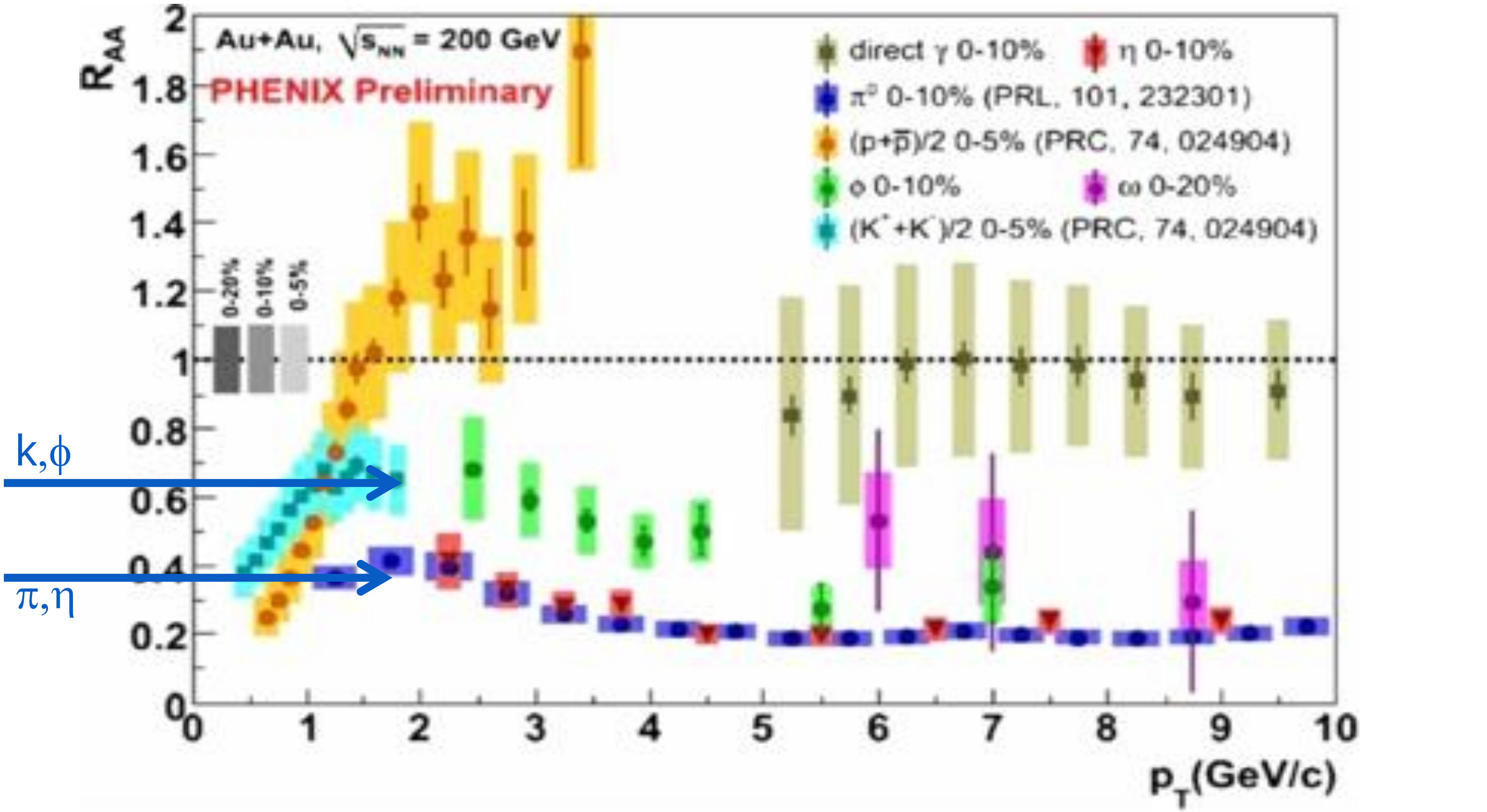
All curves describe R_{AA} at RHIC 200 GeV…..



…but only the energy loss at low T comes close to describing R_{AA} and v_2

Experimental evidence for energy loss effect

- Flavor effect in energy loss already between light and strange quarks ?
- *Higher switching temperature might yield less energy loss for strange flavor.*



More experimental evidence ?

(See D. Thomas talk on Tuesday)

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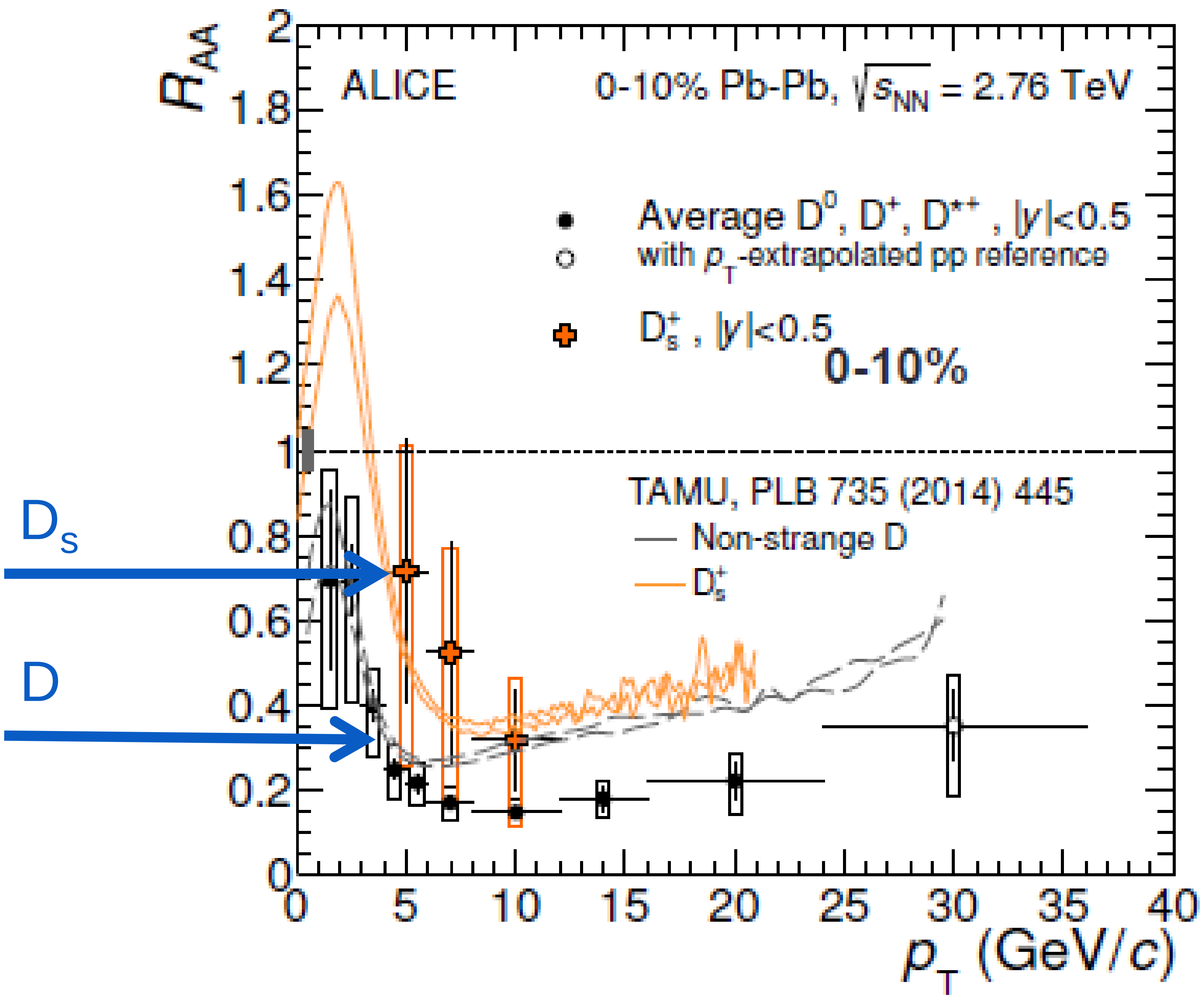


Conclusions / Outlook

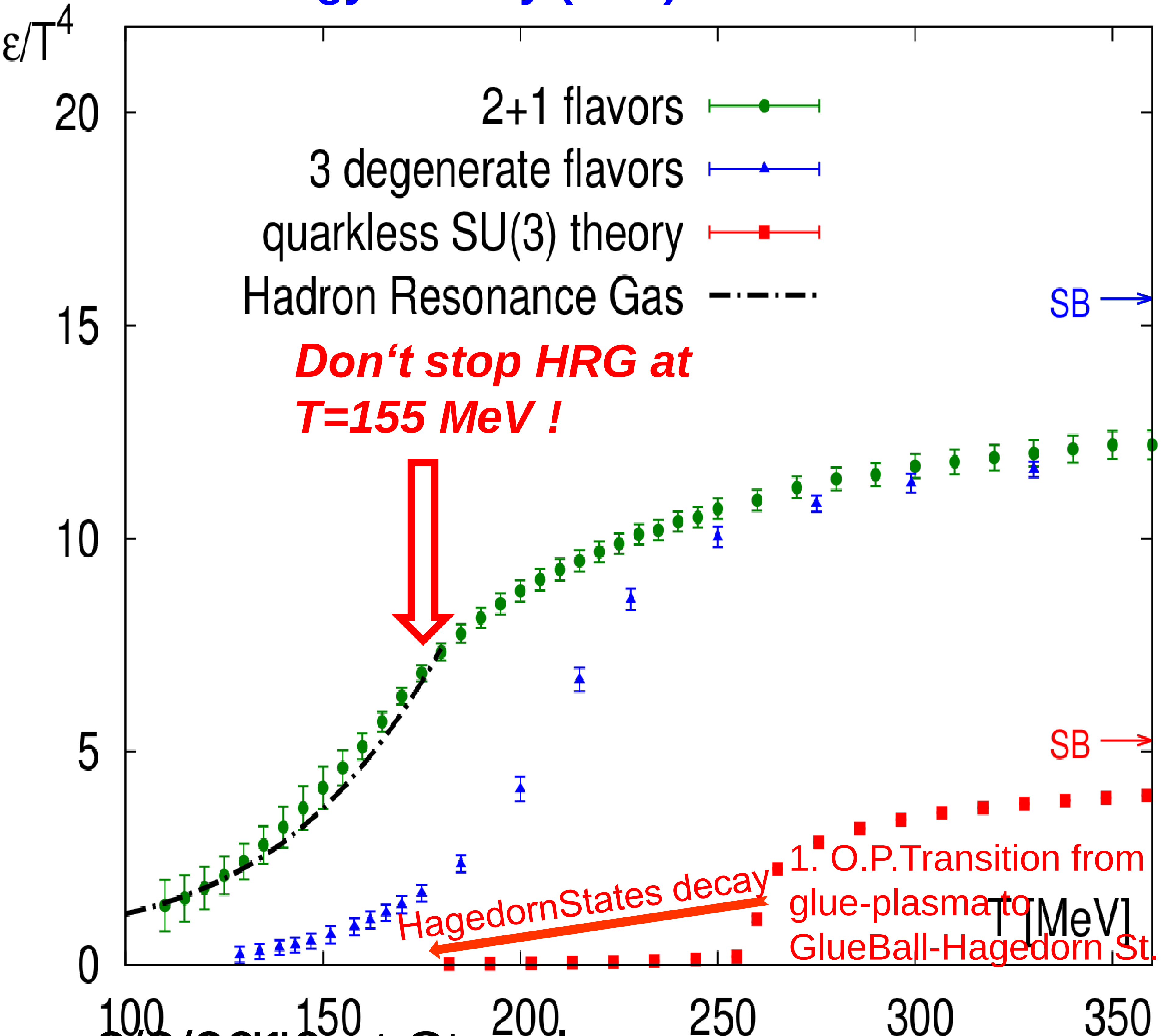
- High precision (continuum limit) lattice QCD susceptibility ratios indicate *flavor separation in the crossover from the partonic to the hadronic matter.*
- There are hints, when comparing to hadron resonance gas and PNJL calculations, that this could lead to a short phase during the crossover in which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

Backup slides

Pure YM LGT vs. 2+1 flavor Lattice QCD
Energy density (EoS) DIFFERENT for different quark masses



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

“physical point” 2+1
T_c.o. = 155 MeV

N_f = 3, $m_{u,d} = m_s$
T_c.o. = 220 MeV

pure gauge YM
T_c = 270 MeV

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