Interpreting BES fluctuation data using lattice QCD and phenomenological models

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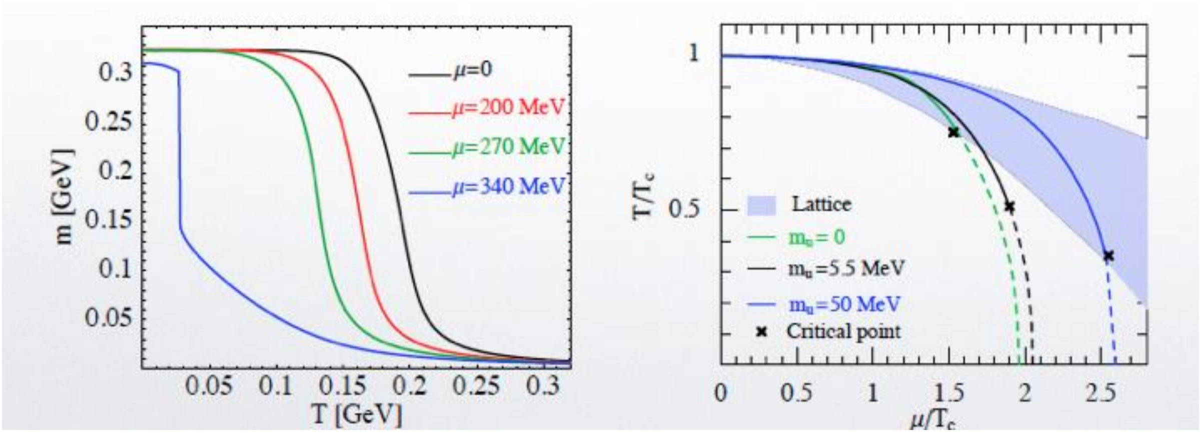
(and in collaboration with: P.Alba, W. Alberico, M. Bluhm, V. Mantovani, M. Nahrgang, C. Ratti)

Two main issues from theory which need to be addressed through the measurements of multiplicity fluctuations with the Beam Energy Scan

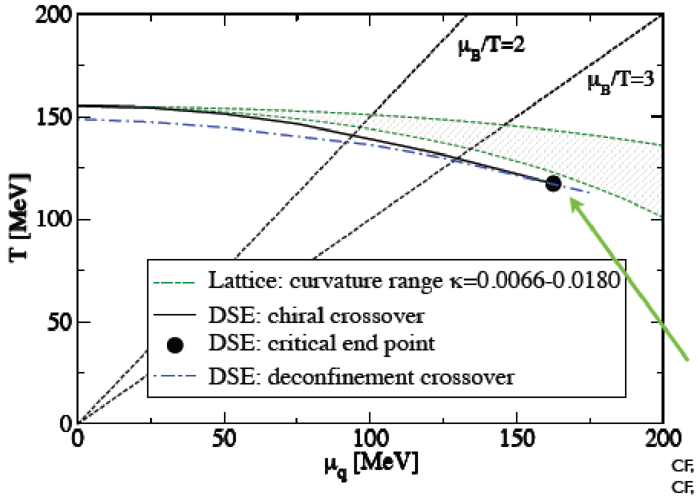
Critical point search on the basis of
fluctuating conserved quantum numbers
(Stephanov, Rajagopal, Shuryak, hep-ph/9903292)

Chemical freeze-out determination on the basis of fluctuating conserved quantum numbers
(F. Karsch, CPOD 2011, arXiv:1202.4173)

Effective Models predict critical point



PNJL, e.g. C. Ratti et al., CBM Physics Books, nucl-th/0604025



Extrapolated curvature from lattice

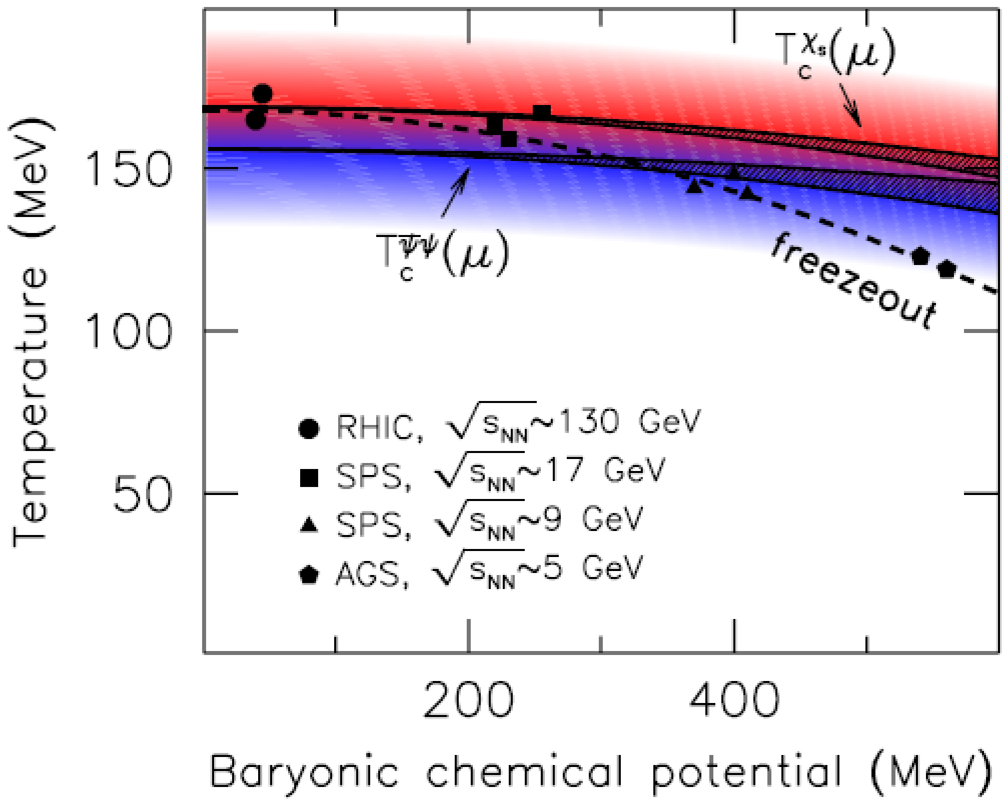
Kaczmarek at al. PRD 83 (2011) 014504,
Endrodi, Fodor, Katz, Szabo, JHEP 1104 (2011) 001
Cea, Cosmai, Papa, PRD 89 (2014) 074512

CEP at large μ

CF, Luecker, PLB 718 (2013) 1036,
CF, Fister, Luecker, Pawlowski, PLB in press, arXiv:1306.6022
CF, Luecker, Welzbacher, arXiv:1405.4762

The latest from QM-2014: Dyson-Schwinger approach, C. Fischer

… lattice QCD calculations do not necessarily



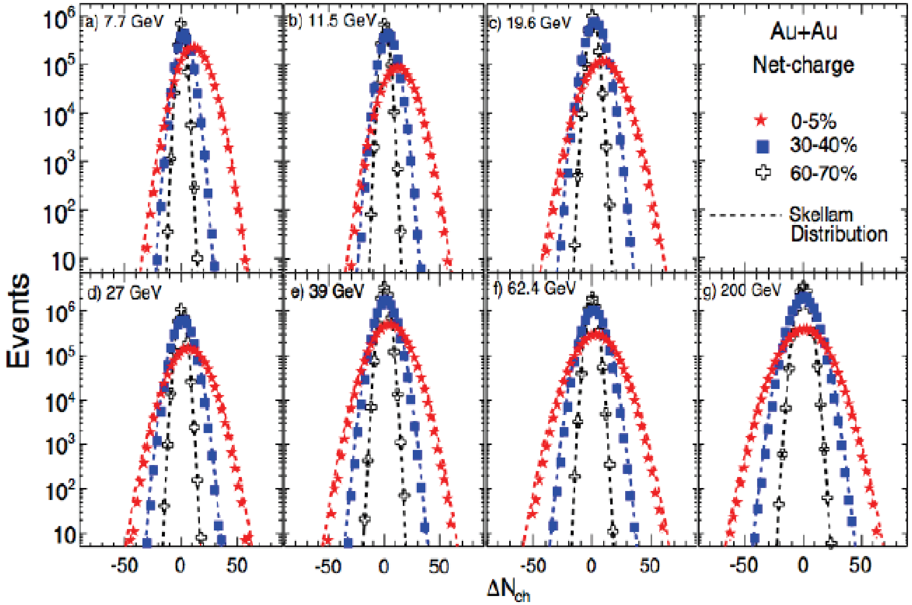
G. Endrodi et al. (WB coll.), JHEP 1104:001 (2001), arXiv:1102.1356

Caveat/ Problem: extension to finite μ_B is problematic (sign problem)

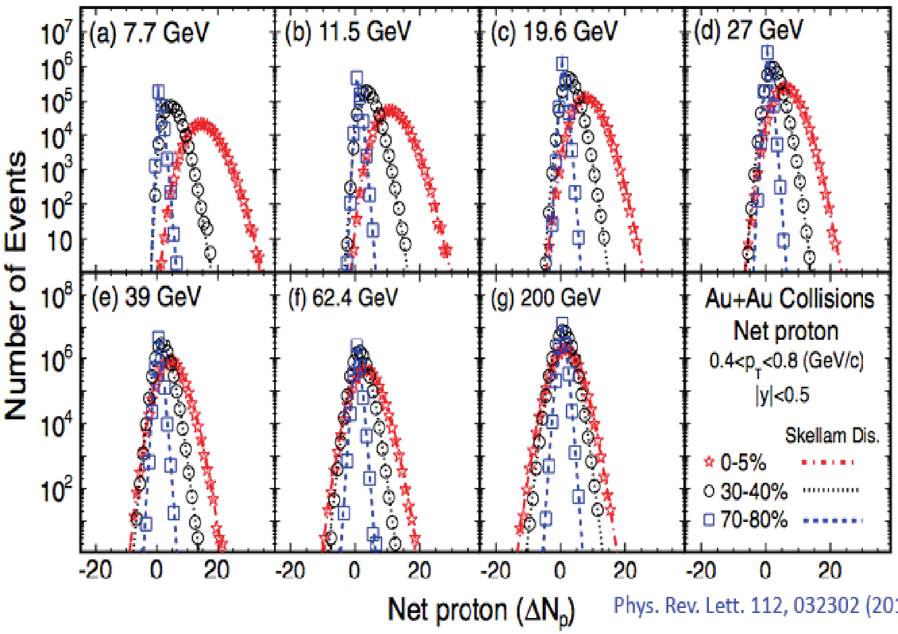
This is based on Taylor expansion

The STAR results:
measure net-distributions and calculate moments

Net-charge distribution



Net-Proton distribution



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

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

For further inspection: calculate moments

(c_1-c_4: mean, variance, skewness, kurtosis)

Moment definitions and their relation to lattice QCD

In a thermally equilibrated system we can define susceptibilities χ as 2^{nd} derivative of pressure with respect to chemical potential (1^{st} 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: $k = \frac{\langle(\delta N)^4\rangle}{\sigma^4} - 3 = \frac{VT^3\chi_4}{(VT^3\chi_2)^2};$

Moment definitions and their relation to lattice QCD

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:

Taking ratios of these fluctuations we obtain simple quantities related to the moments of the distributions, avoiding any volume dependence

$$\sigma^2/M = \chi_2/\chi_1 \qquad k\sigma^2 = \chi_4/\chi_2$$

$$S\sigma = \chi_3/\chi_2 \qquad S\sigma^3/M = \chi_3/\chi_1$$

F.Karsch, Central Eur.J.Phys. (2012)

Non-Linear Sigma Model: Key Predictions (I)

•For a Gaussian distribution: skewness and kurtosis are zero.

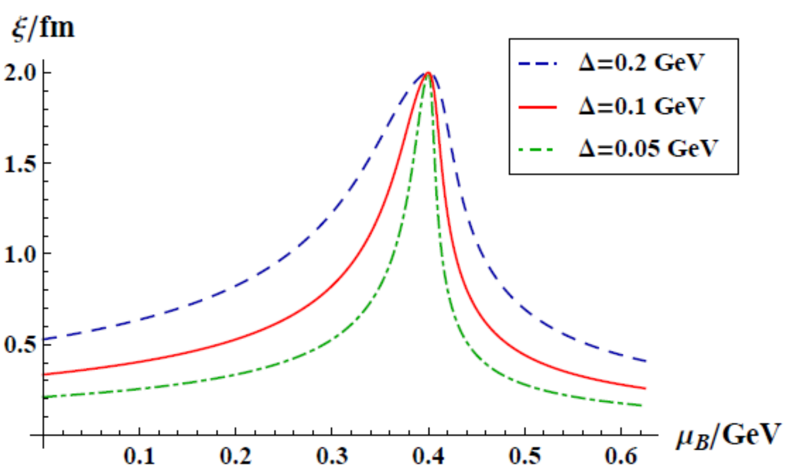
•Look for non-Gaussian distribution near critical point

•Baseline for net-quantitites: Skellam (folded Poissonians)

•Fluctuations depend on correlation length

Correlation length and fluctuations diverge at critical point

The higher the moment the larger the dependence on correlation length



Example calculation of correlation length ζ dependence on critical point (set to μ_B=400 MeV). ζ_{max}=2 fm.
Δ estimates different diffusion strengths near critical point

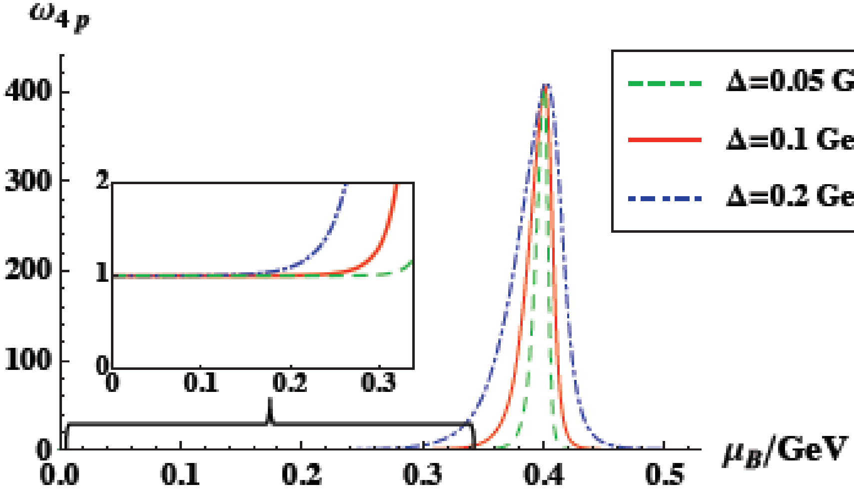
Dependence of moment on correlation length:
$c_2 \sim \zeta^2$, $c_3 \sim \zeta^{9/2}$, $c_4 \sim \zeta^7$

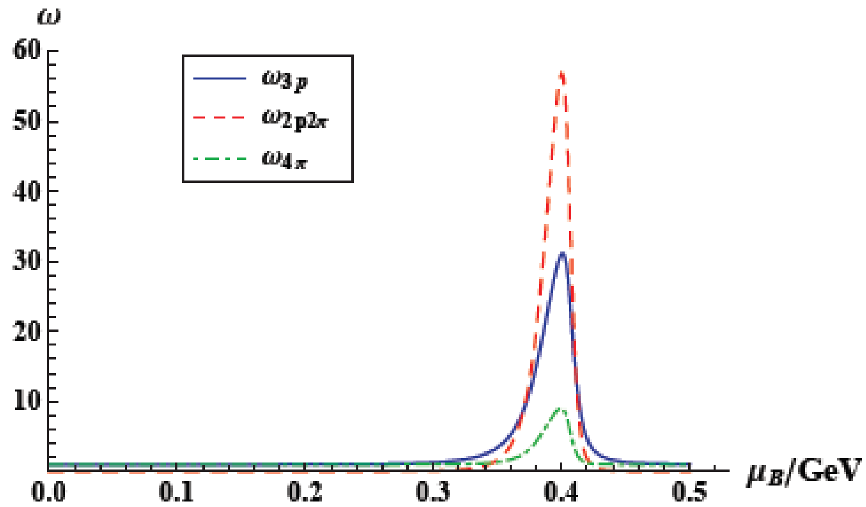
(Athanasiou et al., arXiv:1006.4636)

Non-Linear Sigma Model: Key Predictions (II)

•**The sigma field is isospin blind and its coupling can be applied to each particle species** (net-baryon = net-proton = proton distribution)

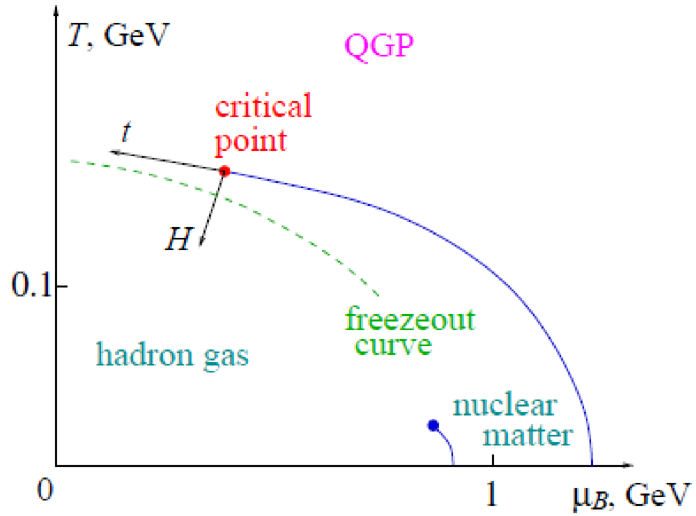
•**The coupling strength depends on the particle mass ($\omega_p > \omega_K > \omega_\pi$)**: protons should show the strongest fluctuations, pions should not show much fluctuations (net-charge might be flat, net-protons need to show strongest fluctuations)

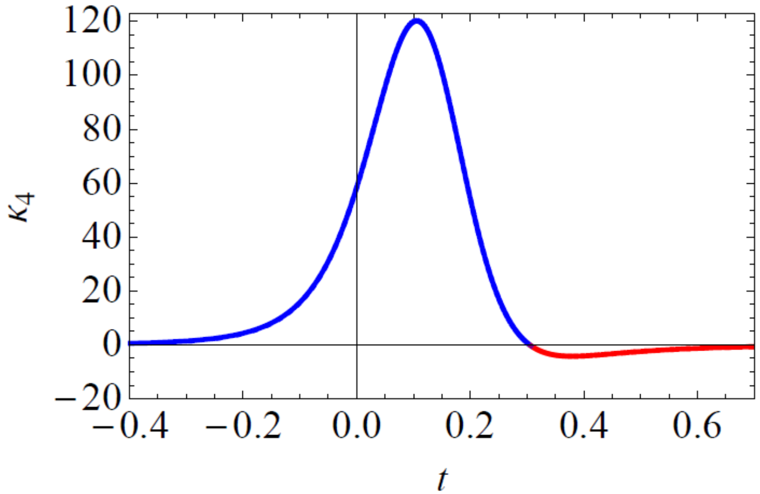


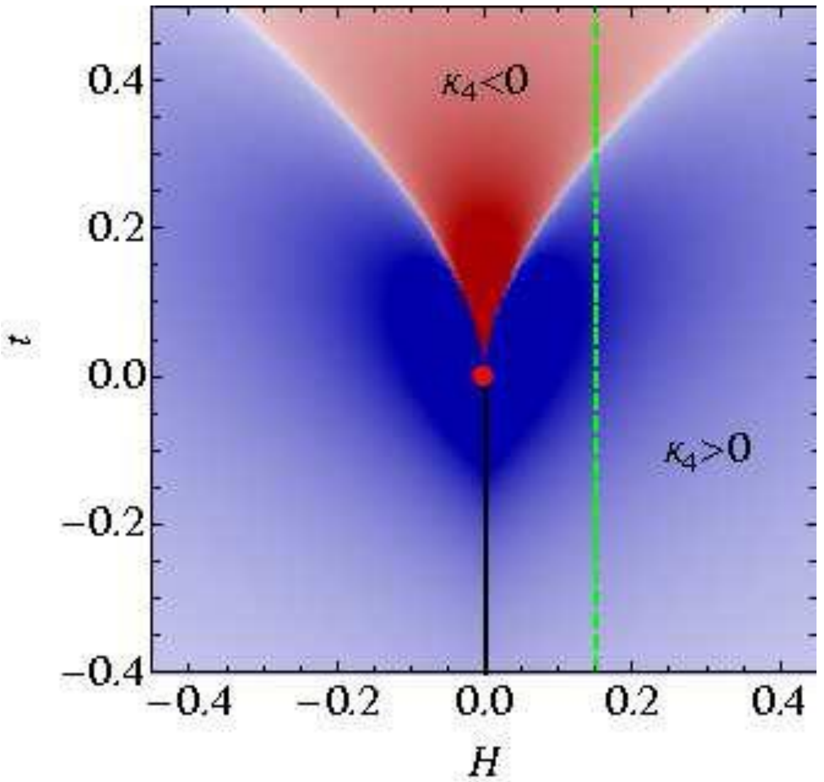


Non-Linear Sigma Model: Key Predictions (III)

- Kurtosis should change its sign near critical point



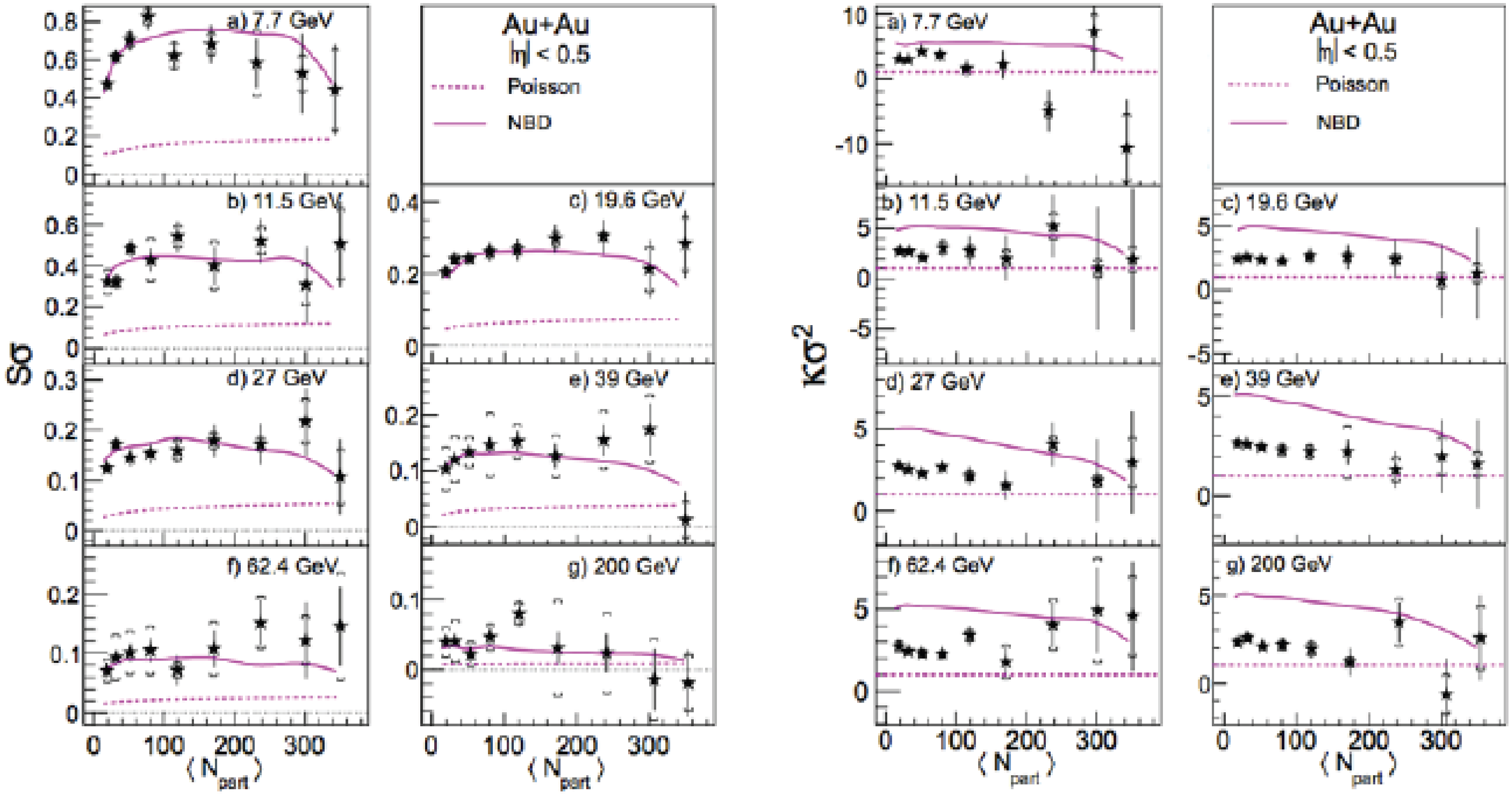




M. Stephanov,
arXiv:1104.1627

Efficiency corrected net-charge higher moments

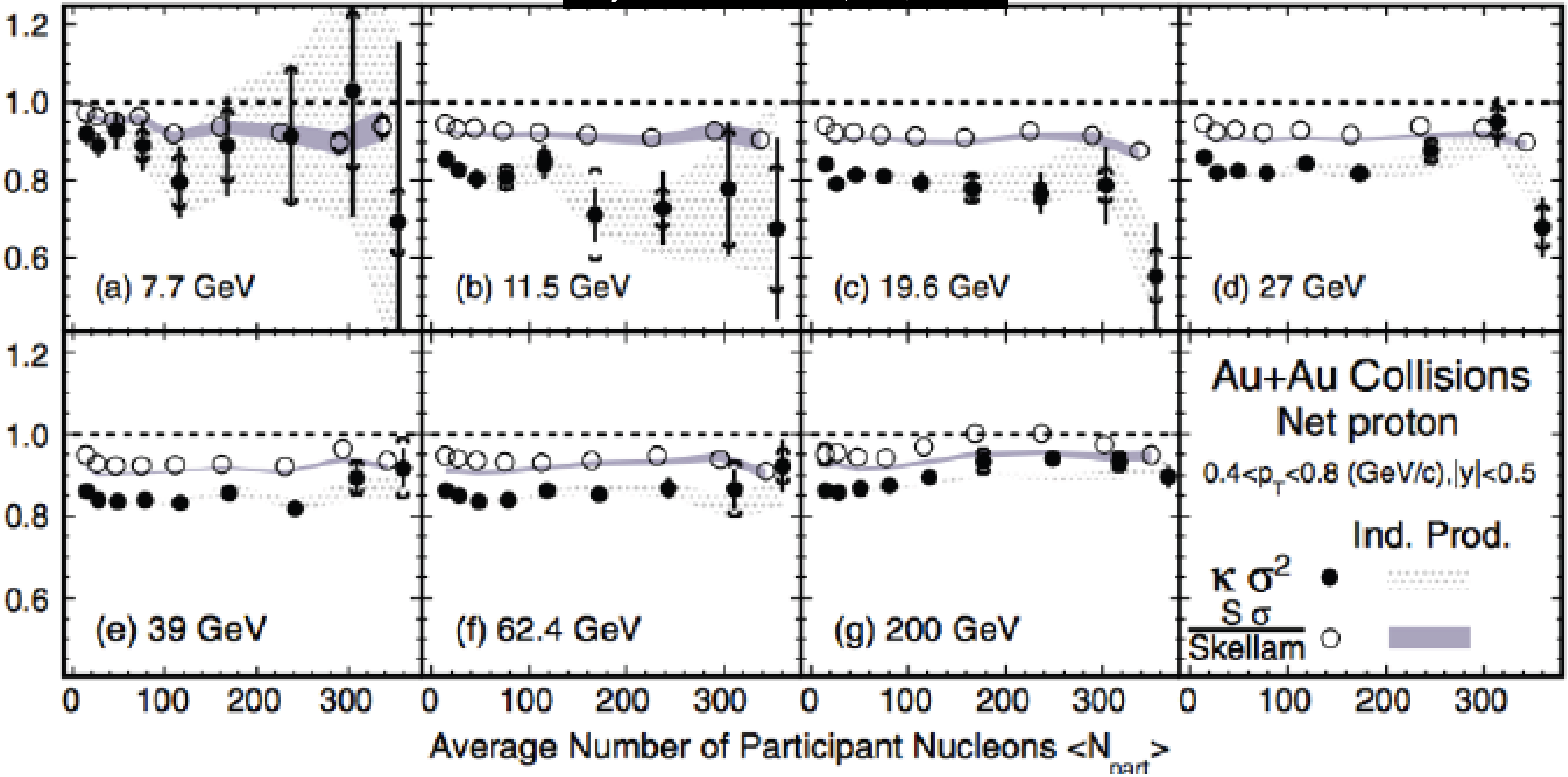
arXiv:1402.1558



Little centrality or collision energy dependence

Efficiency corrected net-proton higher moments

Phys. Rev. Lett. 112 (2014) 32302

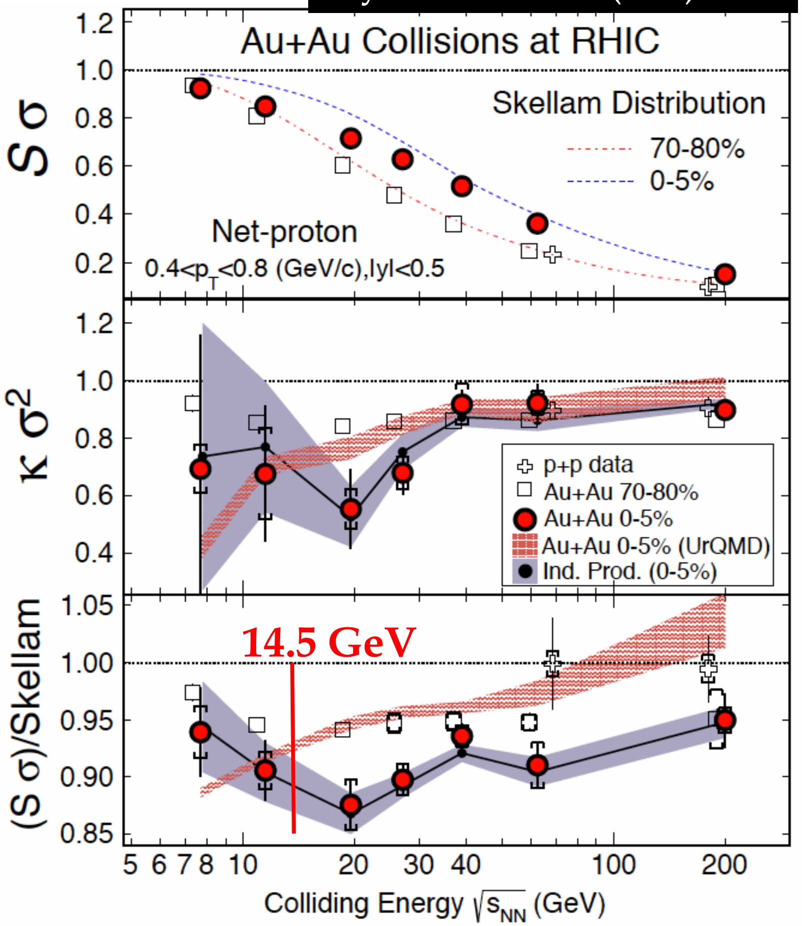


Some collision energy dependence in kurtosis measurement

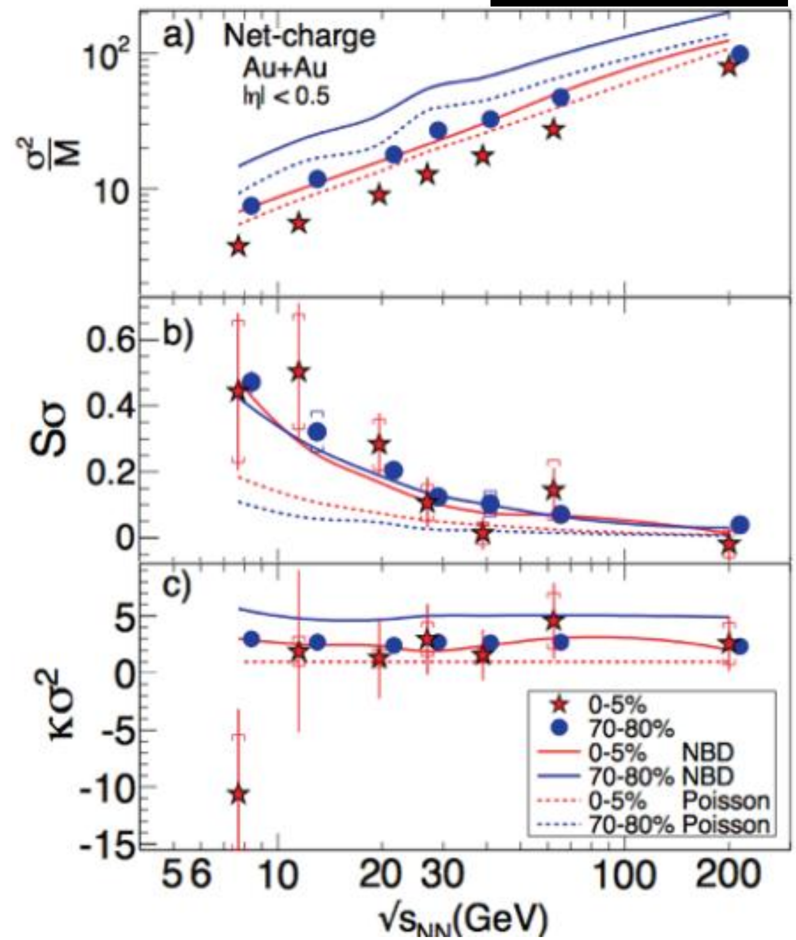
Searching for the critical point

Measuring higher moments of net-charged and net-protons (STAR)

Phys. Rev. Lett. 112 (2014) 32302



arXiv:1402.1558



Independent production (what does it mean ?)

STAR describes the data with 'independent production': The data apparently do not require that the proton and anti-proton production is correlated. Data can be described when using the measured proton and anti-proton distributions separately.

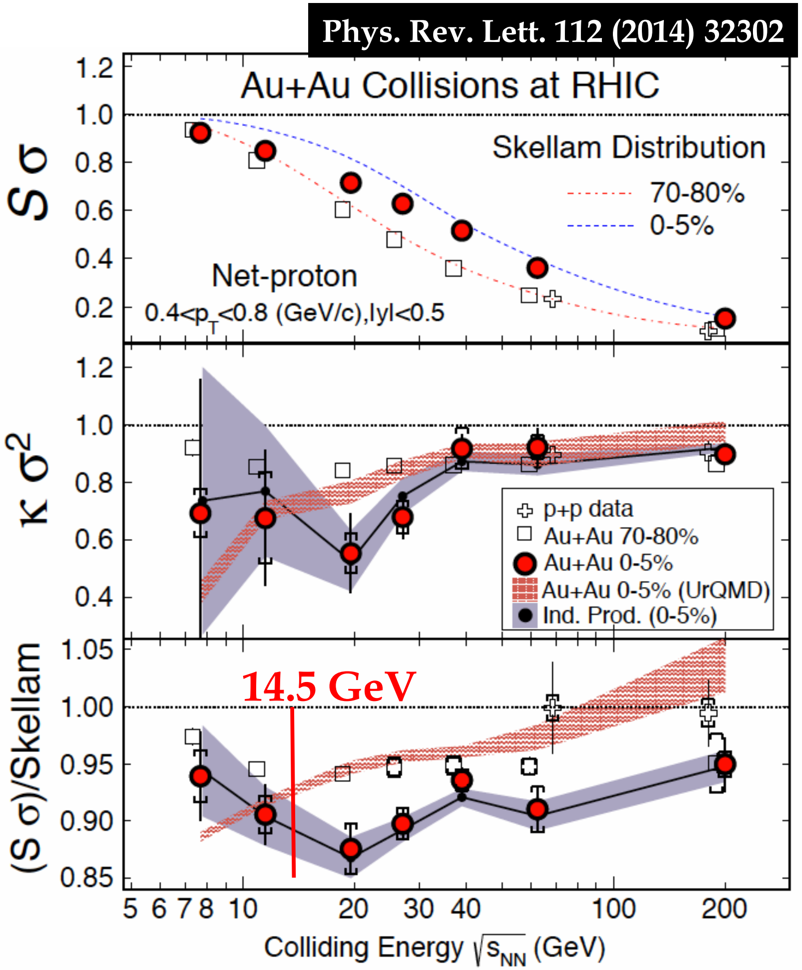
Remember: at low energies the net-proton fluctuations are dominated by the the primordial protons. Almost no anti-proton production, pbar/p < 10%.

Non-Linear Sigma Model (NLSM) : The conserved quantum number argument can still survive since according to the single particles couple to Sigma field (like quarks coupling to Higgs field). The larger the mass the stronger the coupling ($p>k>\pi$) .

Caveat 1: Single particle fluctuations might be affected by rescattering in hadronic phase (Kitazawa, QM 2014). The critical fluctuations wash out in the hadronic phase if the final (kinetic) freeze-out occurs sufficiently far from the critical point (more likely at higher temperatures). The exchange particle in the rescattering causes the fluctuations in the first place (Stephanov & Hatta)

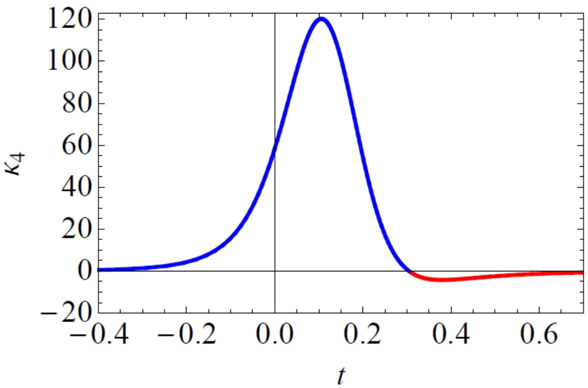
Caveat 2: Most of the measured protons are due to the baryon stopping of the colliding system and are not 'produced'. Therefore any fluctuation in the baryon stopping will be a fluctuation in the final number of protons and is not related to the quantum number conservation during particle production from the deconfined phase.

What goes down must come up….



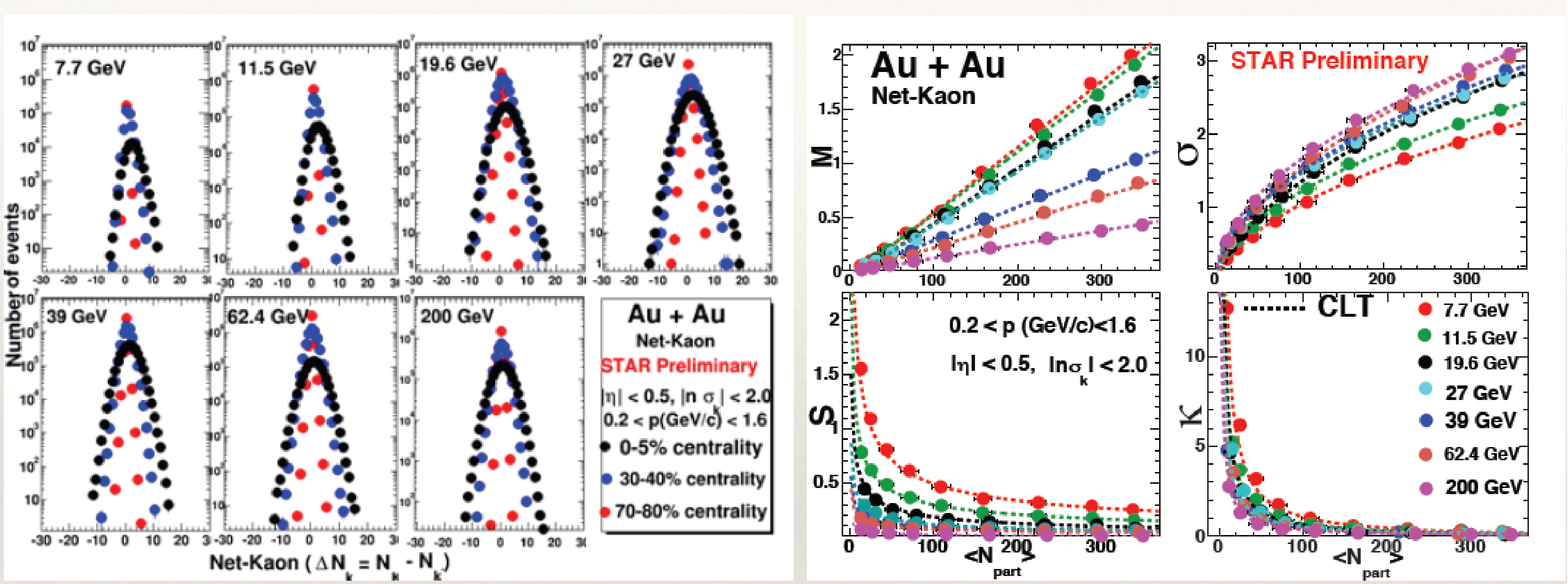
The lack of structure in the net-charge compared to the net-protons can be understood by the different coupling of specific species to the sigma field

But the negatvie kurtosis that might cause the dip near 20 GeV needs to be followed by a strong enhancement (positive kurtosis) at lower energies. The trends in the 14.5 GeV data provide a crucial test.



Future of critical point search w. fluctuations

1.) we need efficiency corrected strangeness data (Kaons first)



First uncorrected results (D. McDonald, QM 2012, A. Sarkar, QM 2014)

2.) we need data at 14.5 GeV/c (should the data point lie on the present trend in the net-proton kurtosis plot ?)

Chemical freeze-out determination

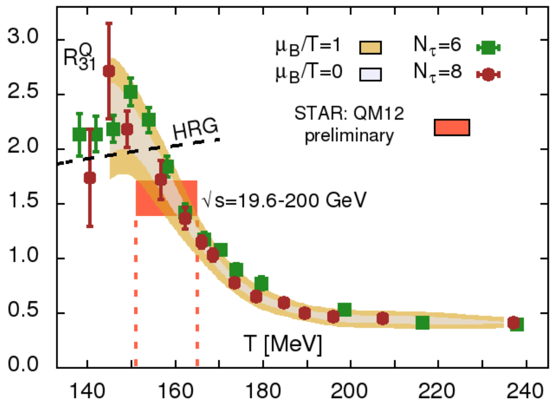
Lattice QCD susceptibility ratios –
A measure of chemical freeze-out based on first principles

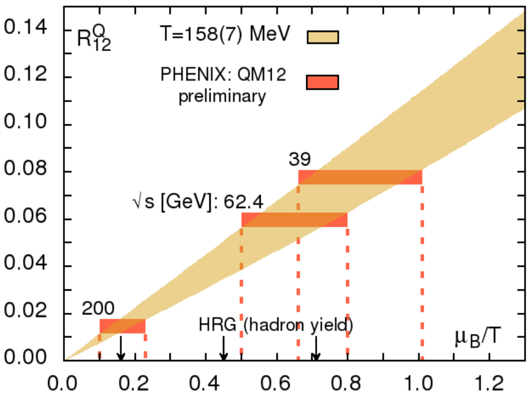
Karsch, arXiv:1202.4173: $$\kappa_B \sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)} \left[\frac{1 + \frac{1}{2}\frac{\chi^B_6(T)}{\chi^B_4(T)}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi^B_4(T)}{\chi^B_2(T)}(\mu_B/T)^2 + \ldots} \right]$$

At μ=0 the higher order expansion terms are zero, therefore χ2 ~ c2, χ4 ~ c4, χ6 ~ c6, etc.
Experimentally: susceptibility ratios = higher moment ratios of net multiplicity distributions

Early implementation by HotQCD and WB groups:

Use several ratios as baryonometer ($\mu_{B,ch}$)and thermometer (T_{ch})for chemical freeze-out.
Results based on uncorrected STAR / PHENIX net-charge results for skewness and variance





HotQCD, arXiv:1307.6255, confirmed by WB, arXiv: 1305.5161 (PRL)

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)

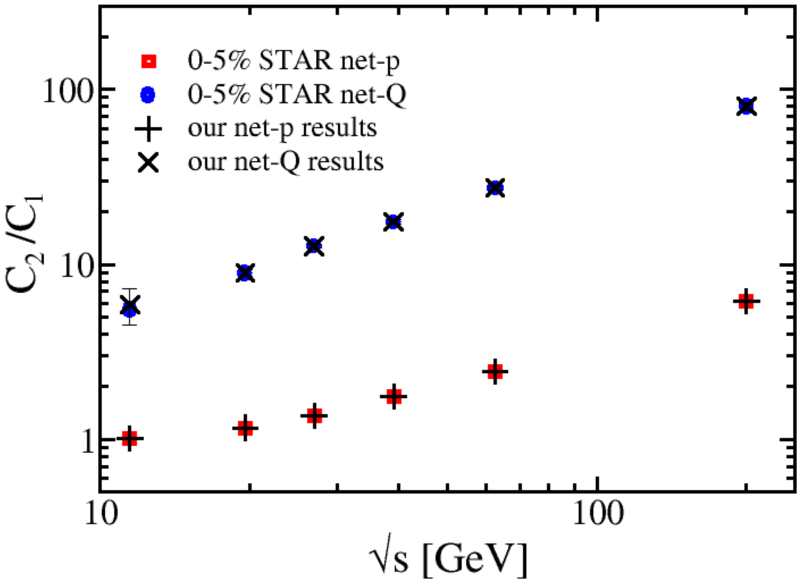
Experimental constraints and how to deal with them in the HRG

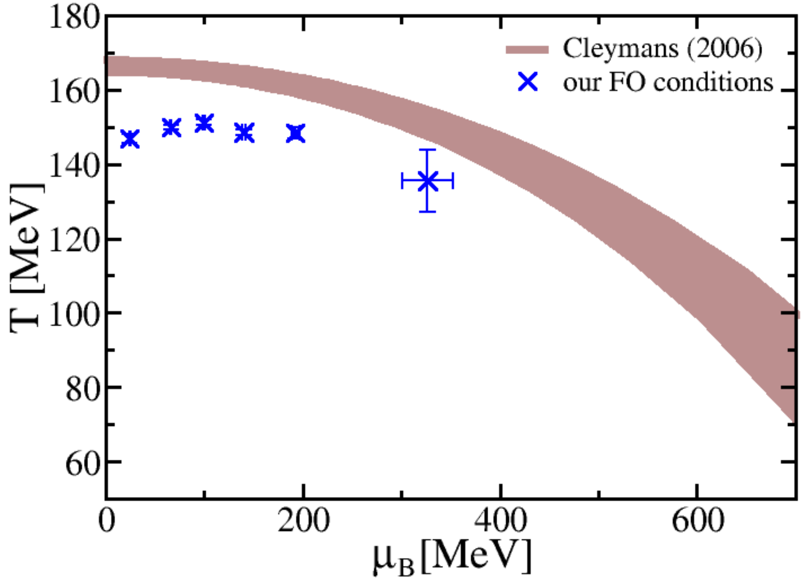
- Effects due to volume variation because of finite centrality bin width
  - → Experimentally corrected by centrality-bin-width correction method
- Finite reconstruction efficiency
  - → Experimentally corrected based on binomial distribution A. Bzdak, V. Koch, PRC (2012)
- Spallation protons
  - → Experimentally 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

HRG analysis of STAR results (charge & proton)

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

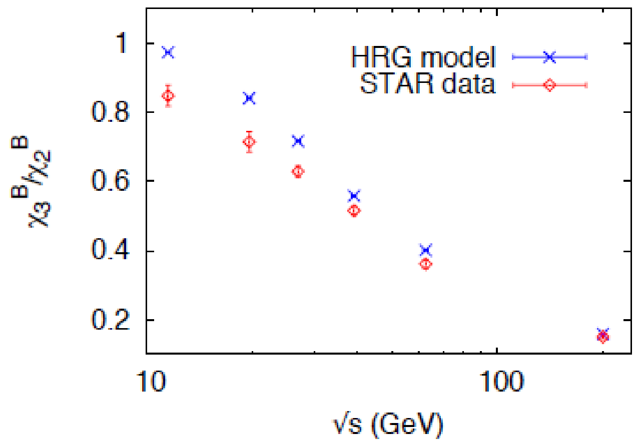
HRG in partial chemical equilibrium (resonance decays and weak decays taken into account).
Hadrons up to 2 GeV/c^2 mass taken into account (PDG), experimental cuts applied.
For protons full isopsin randomization taken into account (Nahrgang et al., arXiv:1402.1238)

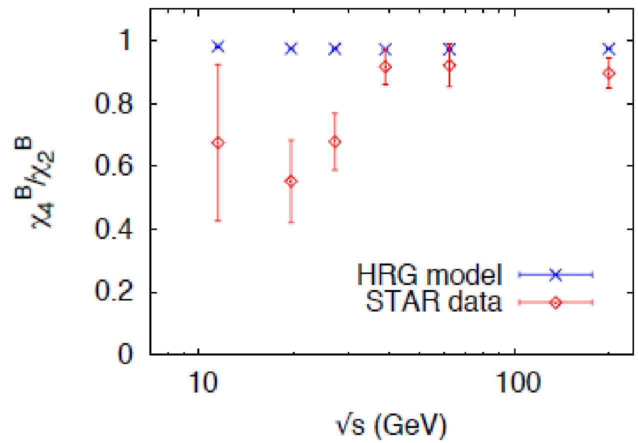


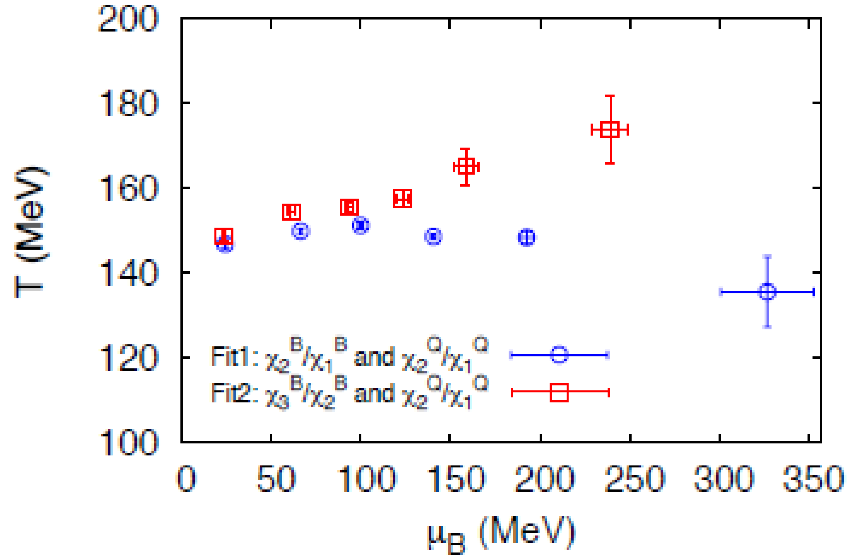


Result: intriguing 'lower' freeze-out temperature (compared to SHM yield fits) with very small error bars (due to good determination of c_2/c_1)

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:

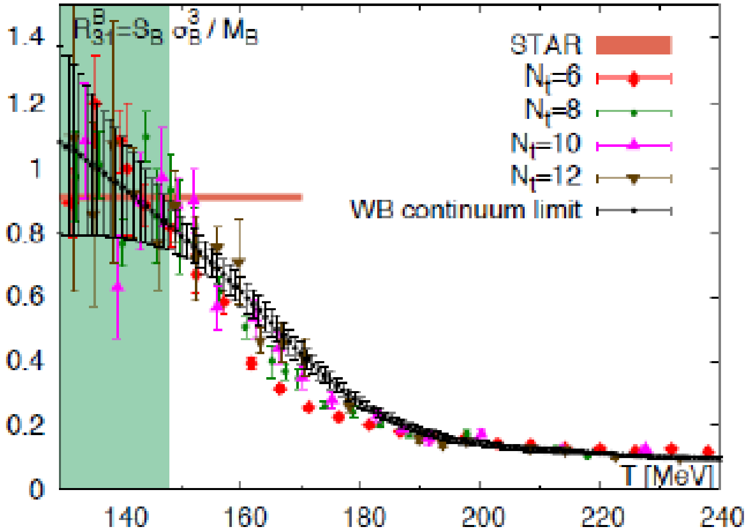
a.) overestimate of isospin randomization

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

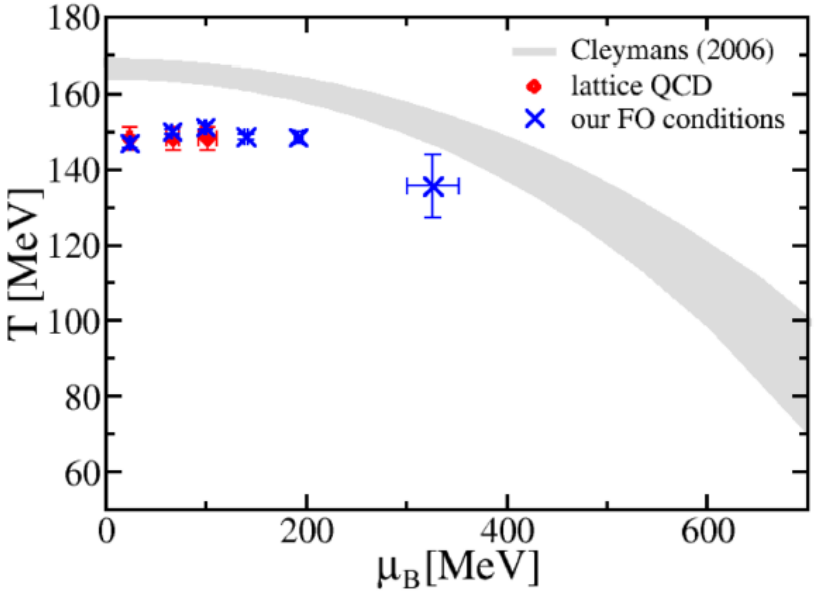
Important lesson: lower moments carry significant information with much smaller error bar (might be already sufficient)

Check consistency with lattice QCD

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



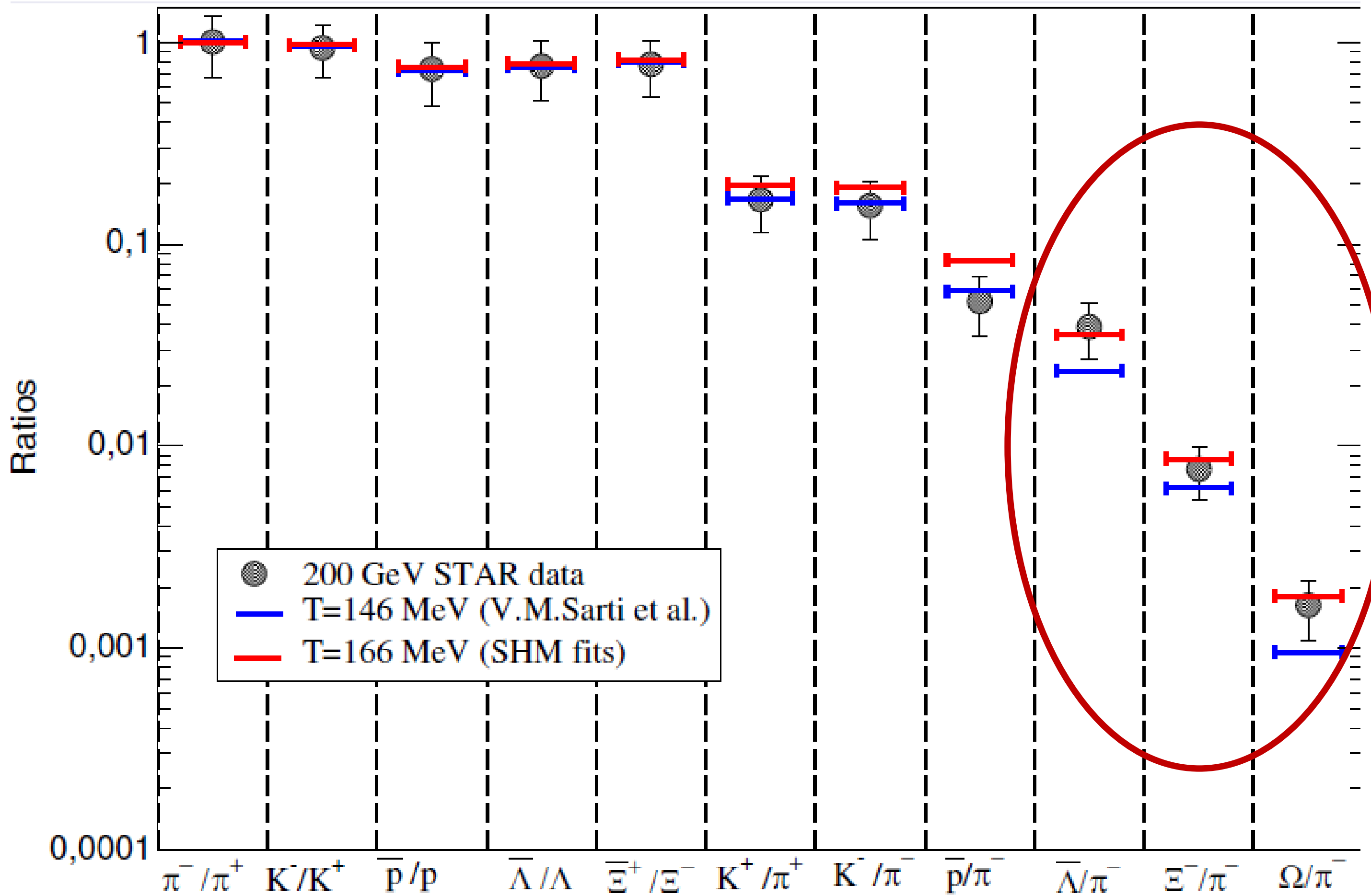
lattice QCD : S. Borsanyi et al., arXiv:1403.4576



$\sqrt{s}$ [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)

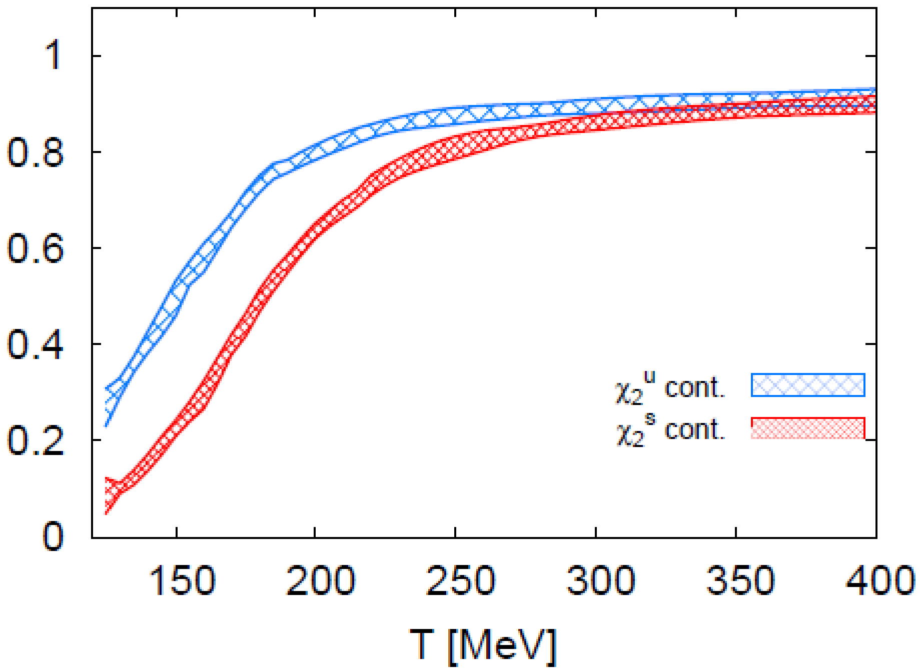
Difference to SHM yield fits - Yield fits with HRG temperatures: where does it go wrong ?



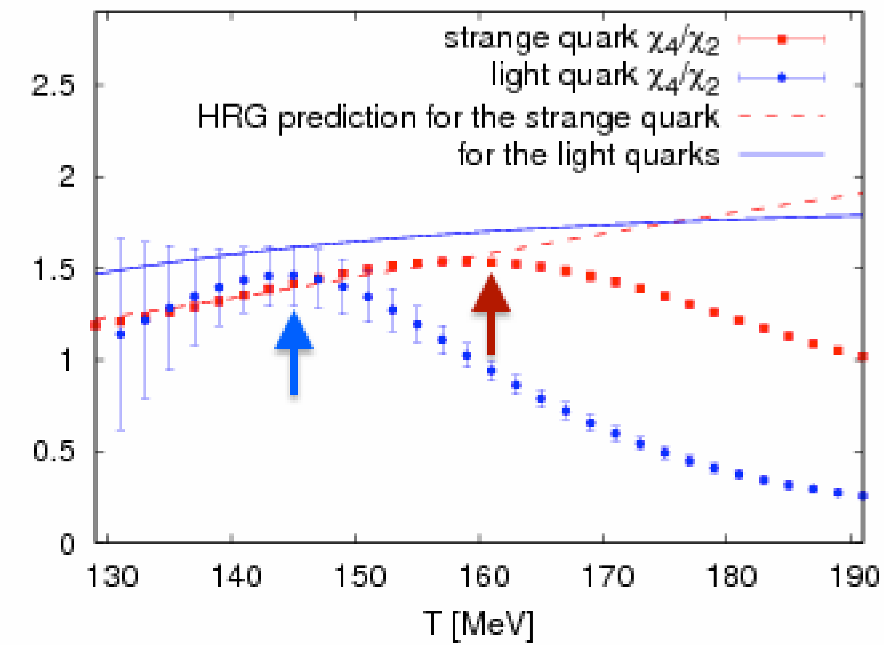
Main deviations in the strange quark sector (Ratti et al., to be published).
Consistent with ALICE ‘proton anomaly’

A possibility: strange / light freeze-out separation

C. Ratti et al., arXiv:1109.6243 (PRD)



R. Bellwied et al., arXiv:1305.6297 (PRL)



Evidence in lattice QCD in $\chi 2$ and in $\chi 4/\chi 2$

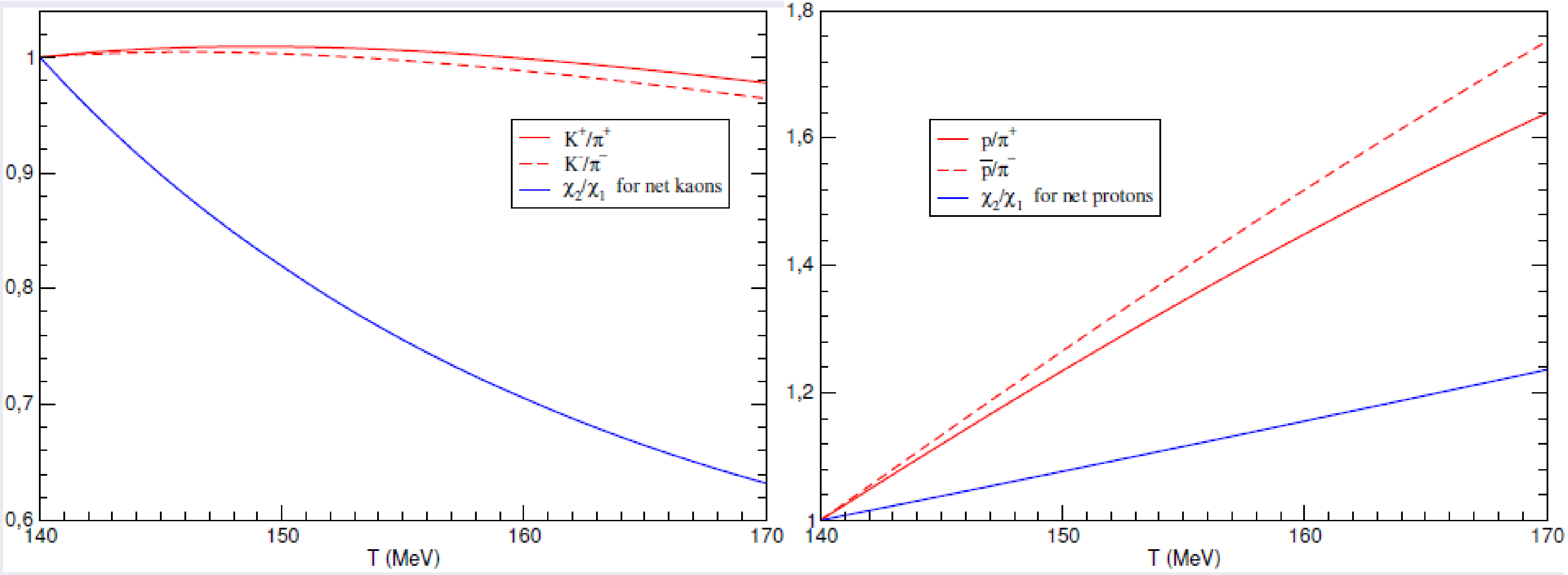
Alternative for $\chi 2$: impact of strange Hagedorn states (C. Schmidt, QM2014)

Conclusion: we need corrected net-strange fluctuations (kaons first, but not sufficient)

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

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

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



HRG model calculation: Mantovani, Ratti et al., to be published

Conclusions

Regarding the critical point search:

•Higher moments have proven to be a viable option to search for the critical point.

•*Some of the results, especially in the net-proton sector, can be interpreted to carry the predicted signatures, in particular from the NLSM*.

•*The 14.5 GeV data might show deviations from the established trend (for a narrow kurtosis peak at the critical point).* If not, the region between 5 and 20 GeV/c requires more statistics in BES-II.

Regarding chemical freeze-out determination

•Significant experimental and theoretical work has gone into making fluctuations in experiment and susceptibilities on the lattice comparable.

•*A common chemical freeze-out temperature can be established in HRG and lattice QCD based on net-charge and net-proton results*. The temperature, which is governed by light quark particles shows a temperature that is 15-20 MeV lower than the one established by SHM models based on particle yields.

•A different behavior of the strange sector compared to the light sector in the QCD crossover region could be the reason. *Corrected net-strangeness fluctuation measurements are needed.*

•Net kaons are a good first step, but the strange baryon sector needs to be investigated as well.