Exploring chiral symmetry restoration in heavy-ion collisions with fluctuation observables

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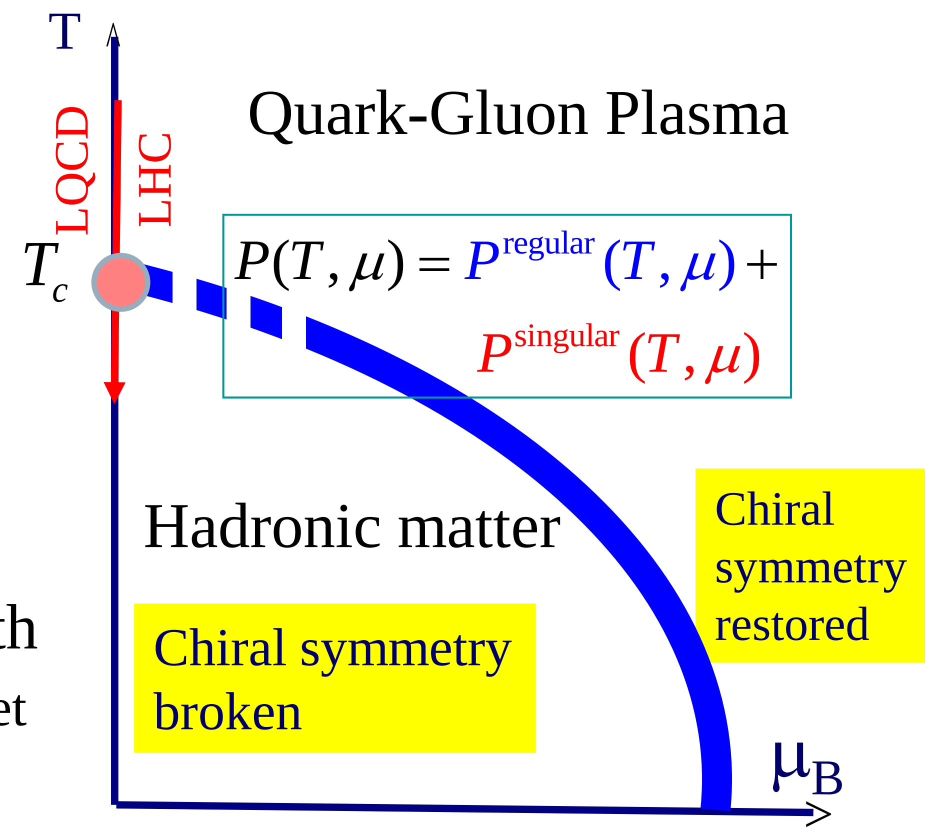
- Modelling regular part of pressure in hadronic phase: S-matrix approach:
  - charge-baryon correlations in LQCD
  - proton production yields at LHC
- Fluctuations of net-baryon charge:
  - probing chiral criticality systematics:
    FRG-PNJL model versus STAR data
  - decoding phase structure of QCD with a Fourier expansion coefficients of net baryon density



in collaboration with: Pok Man Lo, Kenji Morita, Chihiro Sasaki
Anton Andronic, Peter Braun-Munzinger, Johanna Stachel

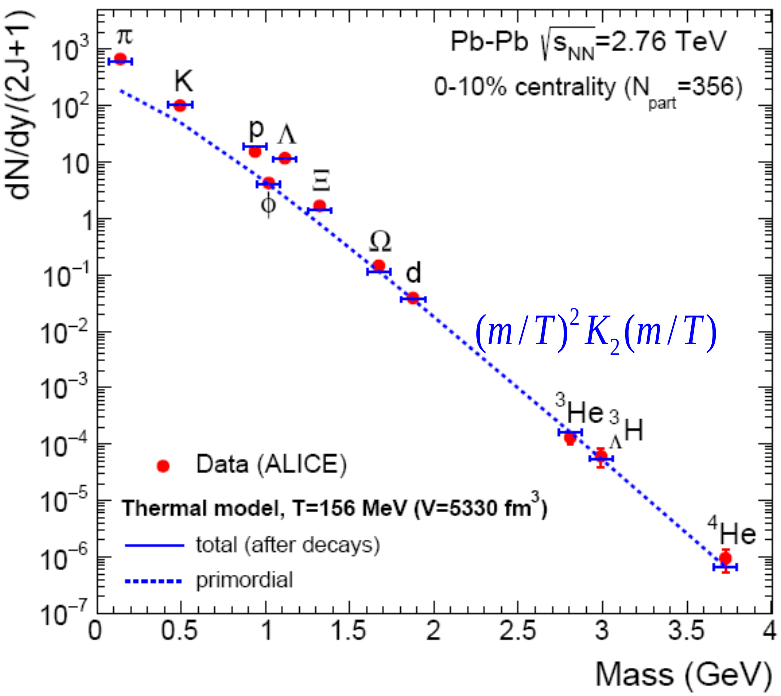
Statistical operator of HRG provides good approximation of QCD thermodynamics in hadronic phase

Hadron Resonace Gas (HRG):

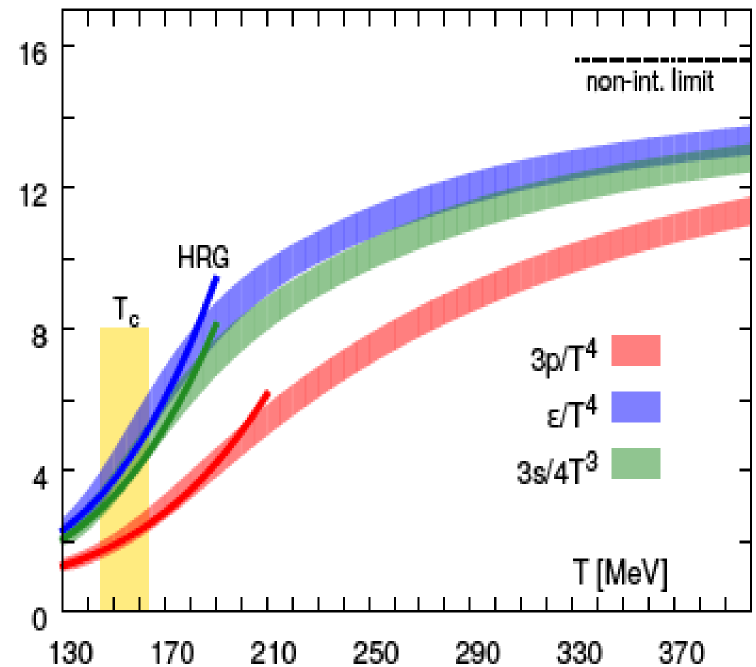
$$P^{regular}(T,\vec{\mu}) = \sum_H P_H^{id} + \sum_R P_R^{id}$$

- Good description of particle yields data and EqS from LQCD

A. Andronic, P. Braun-Munzinger, J. Stachel & K.R. arXiv:1710.0942



A. Bazavov et al. HotQCD Coll. Phys.Rev. D90 (2014) 094503



See also: P. Alba et al. arXiv:1711.05207

- HRG provides 1st approximation of QCD free energy in hadronic phase,

HRG in the S-MATRIX APPROACH

Pressure of an interacting, a+b ⇔ a+b, hadron gas in an equilibrium

$$\boxed{P(T) \approx P_a^{id} + P_b^{id} + P_{ab}^{\text{int}}}$$

The leading order interactions, determined by the two-body scattering phase shift, which is equivalent to the second virial coefficient

$$P^{\text{int}} = \sum_{I,j} \int_{m_{th}}^{\infty} dM \; B_j^I(M) P^{id}(T,M)$$

$$B_j^I(M) = \frac{1}{\pi} \frac{d}{dM} \delta_j^I(M)$$

R. Dashen, S. K. Ma and H. J. Bernstein, Phys. Rev. 187, 345 (1969)
R.Venugopalan, and M. Prakash, Nucl. Phys. A 546 (1992) 718.
W. Weinhold,, and B. Friman, Phys. Lett. B 433, 236 (1998).
Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533

Effective weight function $\downarrow$ $B_j^I(M)$ — *Scattering phase shift* $\downarrow$ $\delta_j^I(M)$

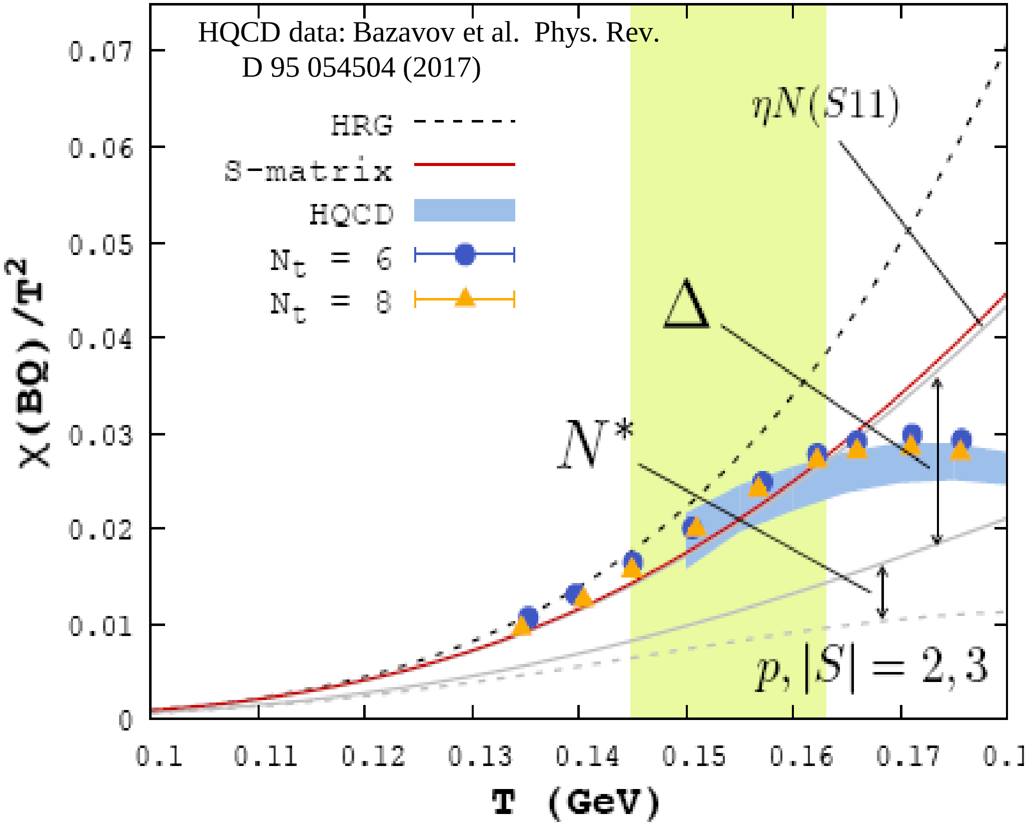
- Interactions driven by narrow resonance of mass M_R

$$B(M) = \delta(M^2 - M_R^2) \quad \Rightarrow \quad P^{\text{int}} = P^{id}(T, M_R) \;\Rightarrow HRG$$

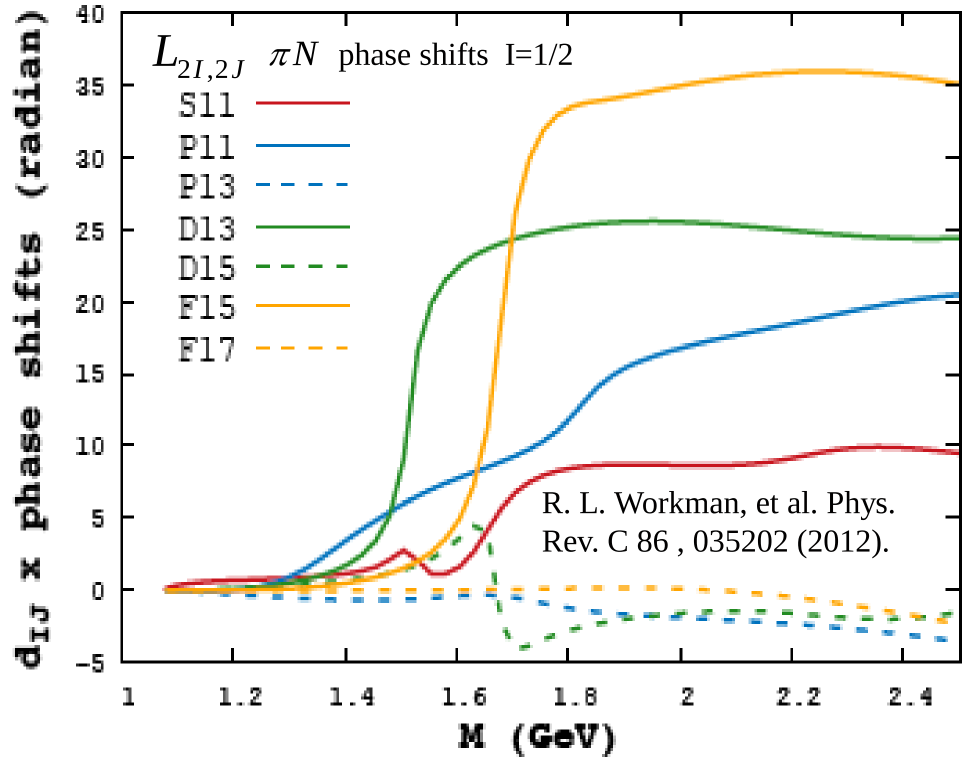
- For non-resonance interactions or for broad resonances the HRG is too crude approximation and $P^{\text{int}}(T)$ should be linked to the phase shifts

Probing non-strange baryon sector in πN- system

Pok Man Lo, B. Friman, C. Sasaki & K.R. , Phys.Lett. B778 (2018)



$$\chi_{BQ} = (\chi_{BB} - |\chi_{BS}|)/2$$

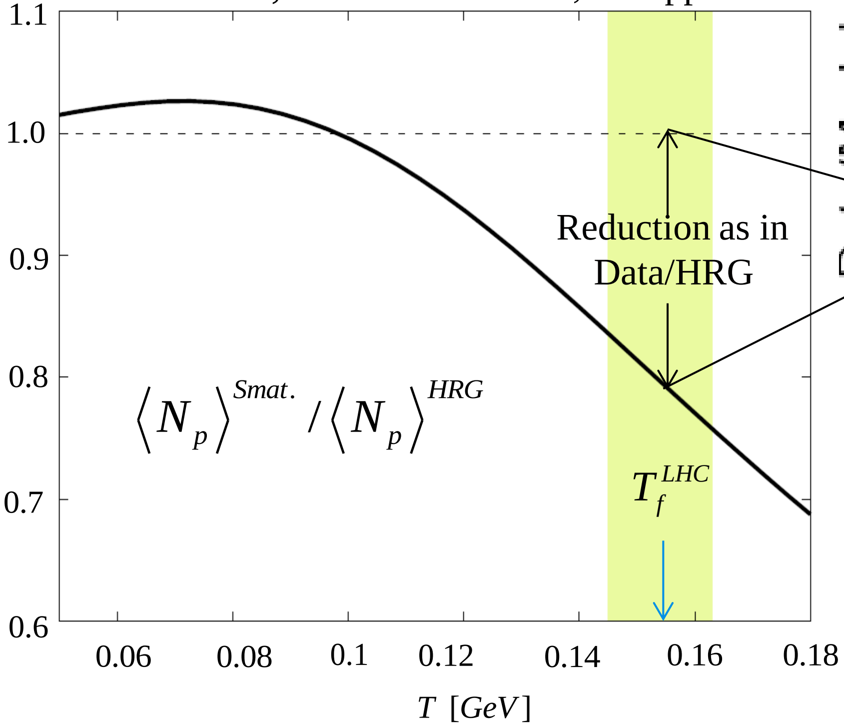


$$\Delta\chi_{BQ} \approx \sum_{I_z, j, B} d_j BQ \int dM \int d^3p \frac{1}{T} \frac{d\delta_j^I}{dM}$$
$$\times\ e^{-\beta\sqrt{p^2+M^2}} (1 + e^{-\beta\sqrt{p^2+M^2}})^{-2}$$

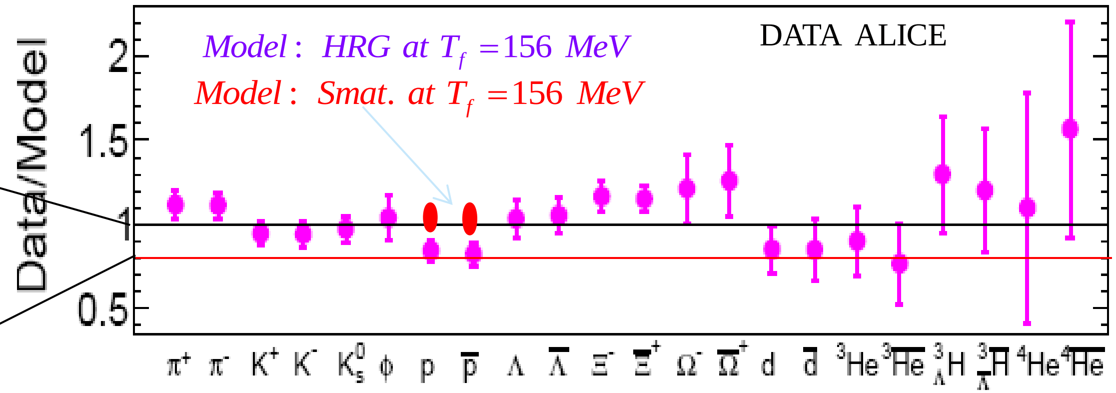
- Considering contributions of all πN $\delta_j^{I=(1/2),\ (3/2)}$ (N^*, Δ^*resonances) to χ_{BQ} within S-matrix approach, reduces the HRG predictions towards the LQCD in the chiral crossover $0.15 < T < 0.16\ GeV$

Phenomenological consequences: proton production yields

A. Andronic, P. Braun-Munzinger, B. Friman,
Pok Man Lo, J. Stachel & K.R., too appear.

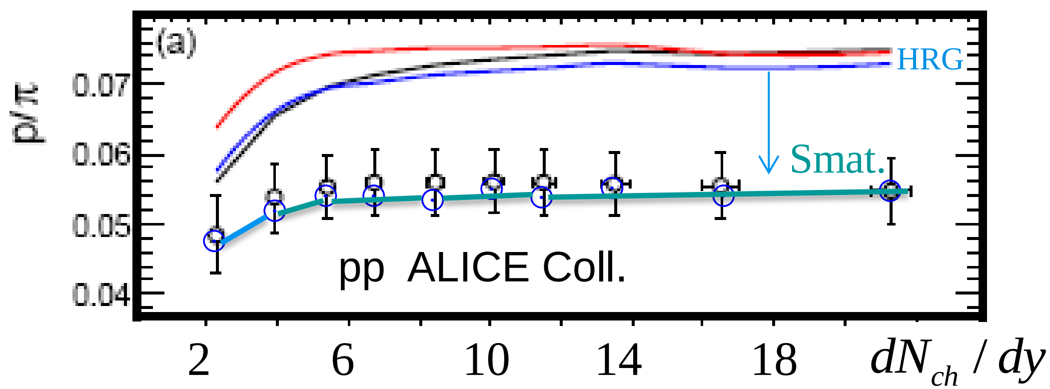


HRG: A. Andronic, P. Braun-Munzinger, J. Stachel & K.R.



- Yields of protons in AA collisions at LHC is consistent with S-matrix result within 1σ

HRG: N. Sharma, J. Cleymans, B. Hippolite, arXiv: 1803.05409



- S-matrix results well consistent with pp data

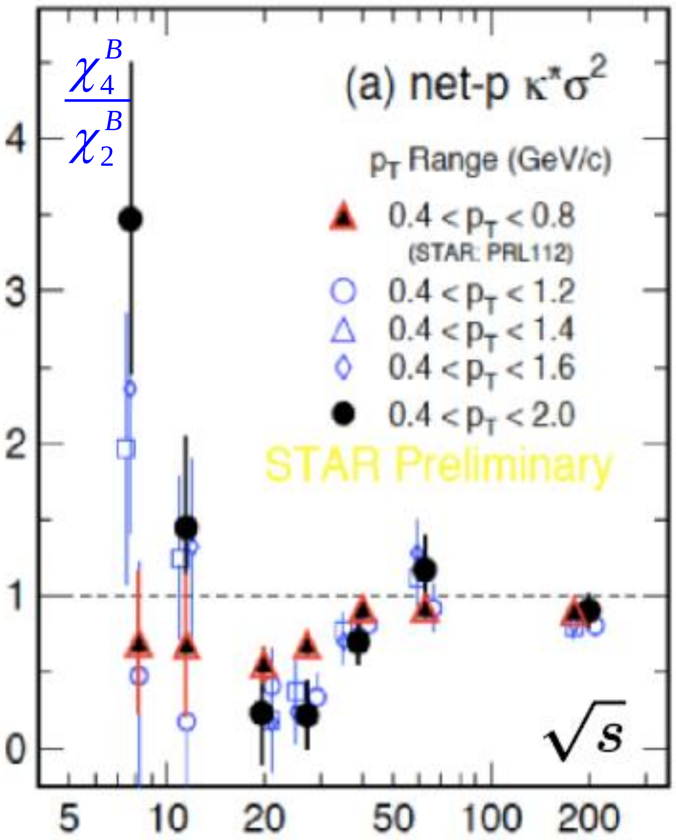
- Yields of protons in the S-matrix is suppressed relative to HRG

For further consequences of smat. See also: P. Huovinen, P. Petreczky Phys. Lett. B77 (2018) P. Huovinen, poster QM2018

Net-baryon fluctuations as a probe of chiral criticality

G. Almasi, B. Friman & K.R, Phys. Rev. D96 (2017) 014027

X. Luo et al. (2015), STAR Coll.



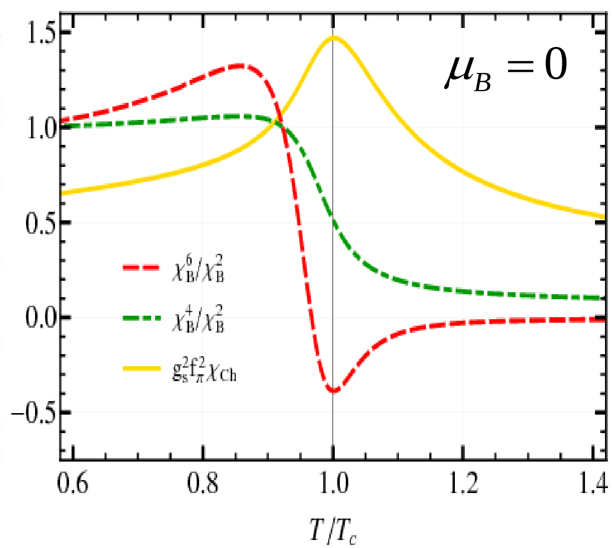
- An excellent observable of chiral criticality

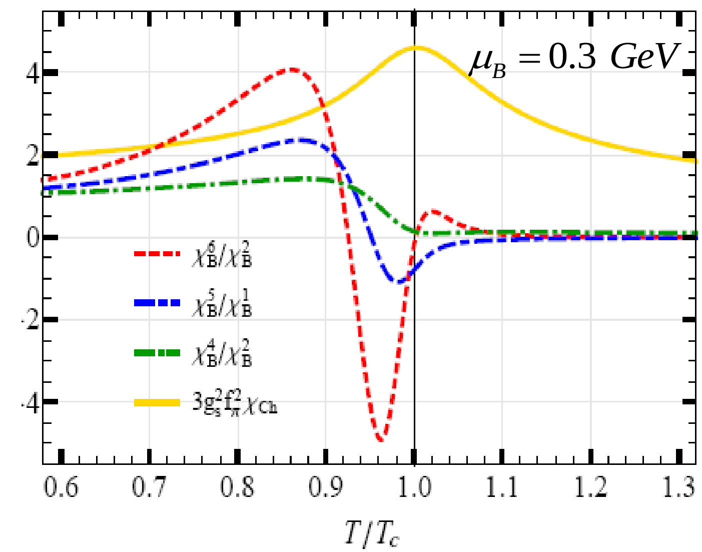
S. Ejiri, F. Karsch & K.R. Phys.Lett. B633 (2006) 275

S. Ejiri et al., Nucl.Phys.Proc.Suppl. 140 (2005) 505 , Phys.Rev. D71 (2005) 054508

$$\chi_n^B = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n} \quad \text{and} \quad R^{n,m} = \frac{\chi_n^B}{\chi_m^B}$$

- Modelling chiral properties of QCD in PNJL model within FRG approach.



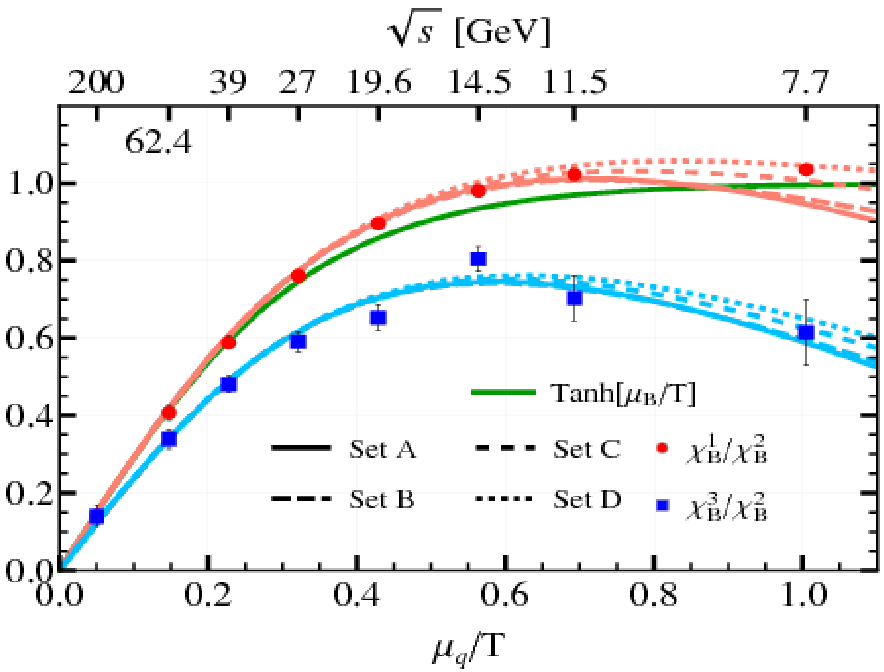


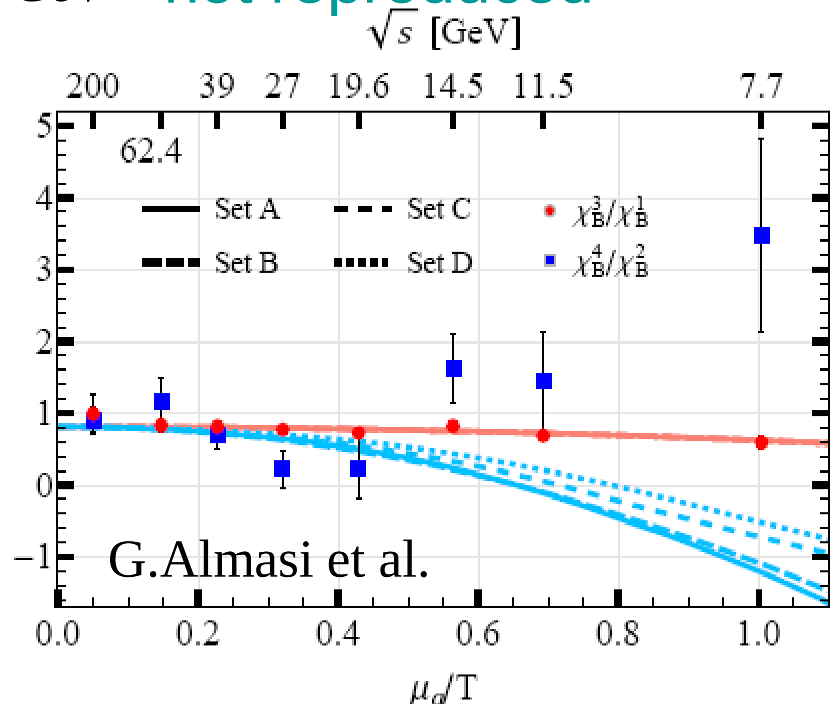
Are the above deviations an indication of the chiral criticality and the existence of the CEP?

Consider systematics of $R^{n,m}$ in relation to STAR data

Self - consistent freeze-out and STAR data

- Freeze-out line in $(T,\mu)-$ plain is fixed by χ_B^3/χ_B^1 to data
- Ratio $\chi_B^1/\chi_B^2 \approx \tanh(\mu/T)$ => further evidence of equilibrium and thermalisation at $7\ GeV \le \sqrt{s} < 5\ TeV$
- Ratio $\chi_B^1/\chi_B^2 \neq \chi_B^3/\chi_B^2$ expected due to critical chiral dynamics
- Enhancement of χ_B^4/χ_B^2 at $\sqrt{s} < 20\ GeV$ not reproduced

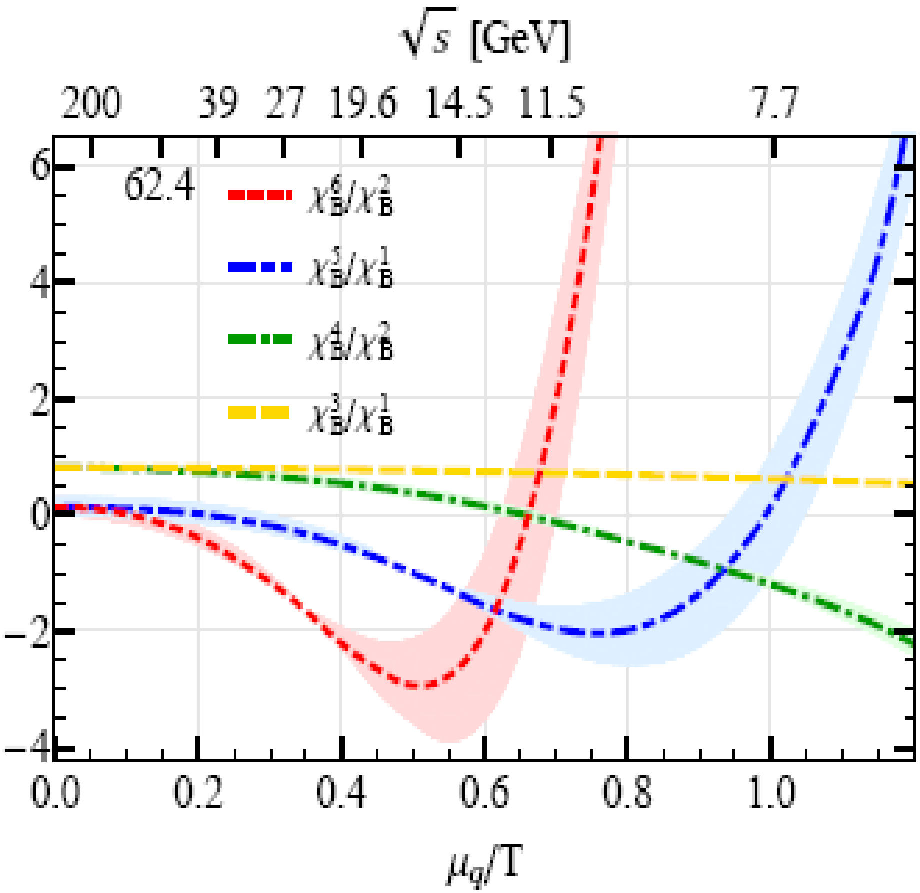




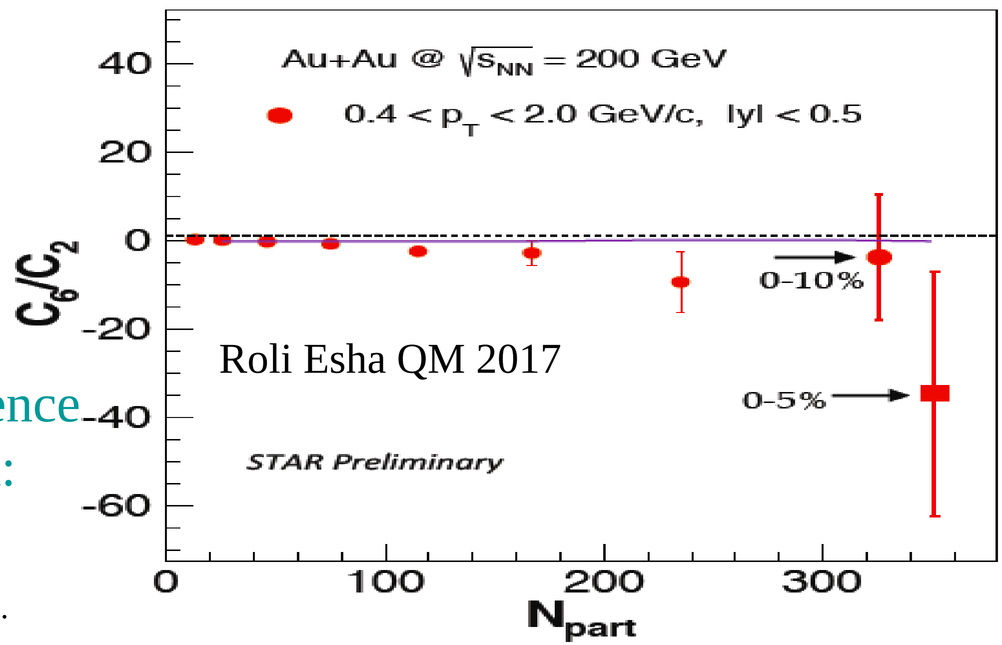
Similar conclusions as in the previous comparison of LQCD results with STAR data:

Frithjof Karsch J. Phys. Conf. Ser. 779, 012015 (2017)

Higher order cumulants - energy dependence



- Strong non-monotonic variation of higher order cumulants at lower $\sqrt{s}$
- Equality of different ratios excellent probes of equilibrium evolution in HIC
- At freeze-out , the ratio $\chi_B^6/\chi_B^2 \approx 0$ in agreement with preliminary STAR data, albeit within still very large error



Roli Esha QM 2017

However, to make final conclusions the influence of non-critical fluctuations must be analyzed:

See e.g. P. Braun-Munzinger, A. Rustamov and J. Stachel Nucl. Phys. A 960, 114 (2017),
A. Bzdak, V. Koch, V. Skokov, Eur.Phys.J. C77 (2017) 288.

Anar Rustamov, talk at this conference

Fourier coefficients of $\chi_B^1(T,\mu)$ and chiral criticality

G. Almasi, B. Friman, P.M. Lo, K. Morita & K.R. arXiv: **1805.04441**

- Considering the Fourier series expansion* of baryon density

$$\chi_B^1(T,\mu)=\sum_{k=1}^{\infty} b_k(T)\sinh(k\mu) \qquad \text{with} \qquad \boxed{b_k(T)=\frac{2}{\pi}\int_0^{\pi} d\theta[\mathrm{Im}\,\chi_B^1(T,i\theta)]\sin(k\theta)}$$

and $\mu=(\mu/T)$, $\theta=\mathrm{Im}\,\mu$

- At $\mu=0$,the susceptibility $\chi_B^n(T)$ expressed by Fourier coefficients

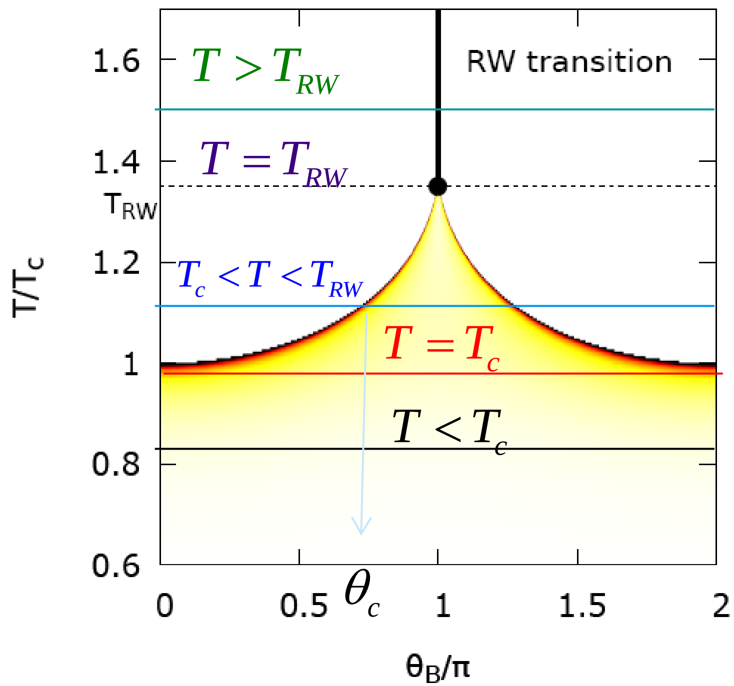
$$\chi_B^n(T,\mu)=\sum_{k=1}^{\infty} b_k(T)\frac{\partial^{n-1}}{\partial\mu^{n-1}}\sinh(k\mu), \qquad \text{thus} \qquad \boxed{\chi_B^n(T,\mu=0)=\sum_{k=1}^{\infty} k^{2n-1} b_k(T)}$$

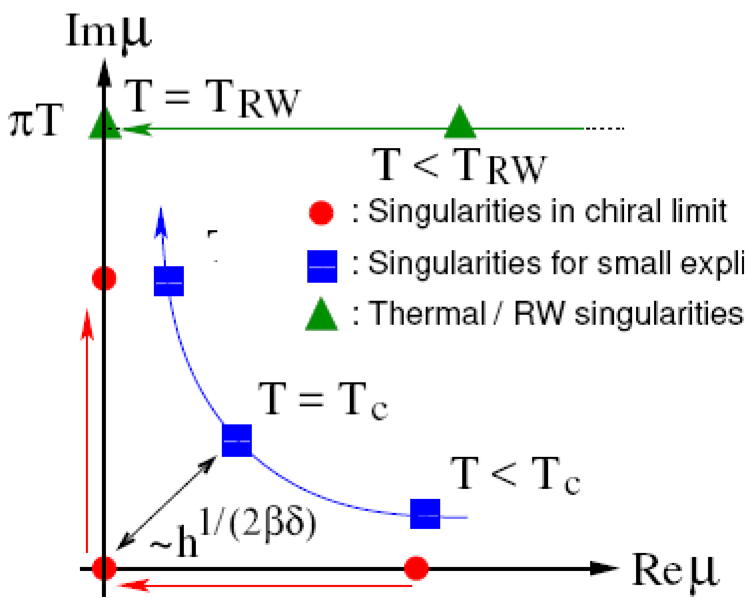
- Since $b_k(T)$ are carrying information on chiral criticality, thus their $T-$ and $k-$ dependence must inform about phase transition

* The first four $b_k(T)$ obtained recently in LQCD: V. Vovchenko, A. Pasztor, Z. Fodor, S. D. Katz, and H. Stoecker, Phys. Lett. B **775**, 71 (2017).

* see also K. Kashiwa and A. Ohnishi (2017) hep-1712.06220, for $b_k(T)$ properties related with deconfinement transition

Chiral limit: scaling of $b_k(T)$





- $T < T_c$, $P(T,\mu)$ dominated by

  $P(T,\mu) \approx f(m)\cosh(\mu)$, thus

  exponential damping $\Rightarrow$ $\boxed{b_k(T) \approx K_2(km)}$

- $T = T_c$, $P(T,\mu)$ dominated by $P^{\sin gular}$

  $\chi_1^B \approx \theta \left| \dfrac{T - T_c}{T_c} - \kappa\theta^2 \right|^{1-\alpha}$ $\Rightarrow$ $\boxed{b_k(T_c) \approx k^{2\alpha-4}}$

- $T_c < T < T_{RW}$

  $\Rightarrow$ $\boxed{b_k(T > T_c) \approx k^{\alpha-2}\sin(k\theta_c - \alpha\pi/2)}$

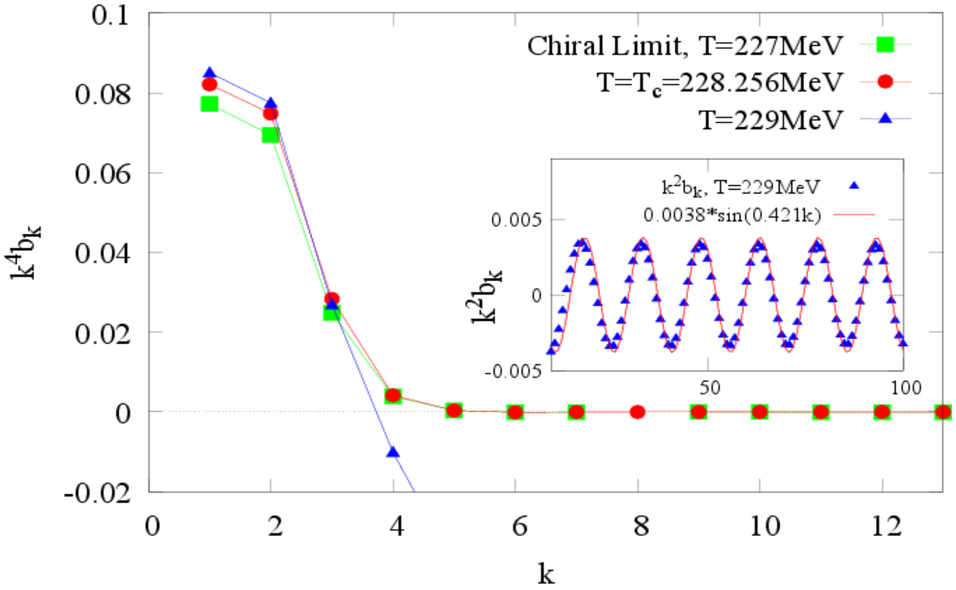
- $T = T_{RW}$, $P^{\sin gular}$ in Z(2) universality class

  $\chi_1^B \approx (\pi - \theta_B)^{1/\delta}$ $\Rightarrow$ $\boxed{b_k(T_{RW}) \approx (-1)^{k-1} k^{-1-1/\delta}}$

- $T > T_{RW}$, 1st order transition at $\theta = \pi$.

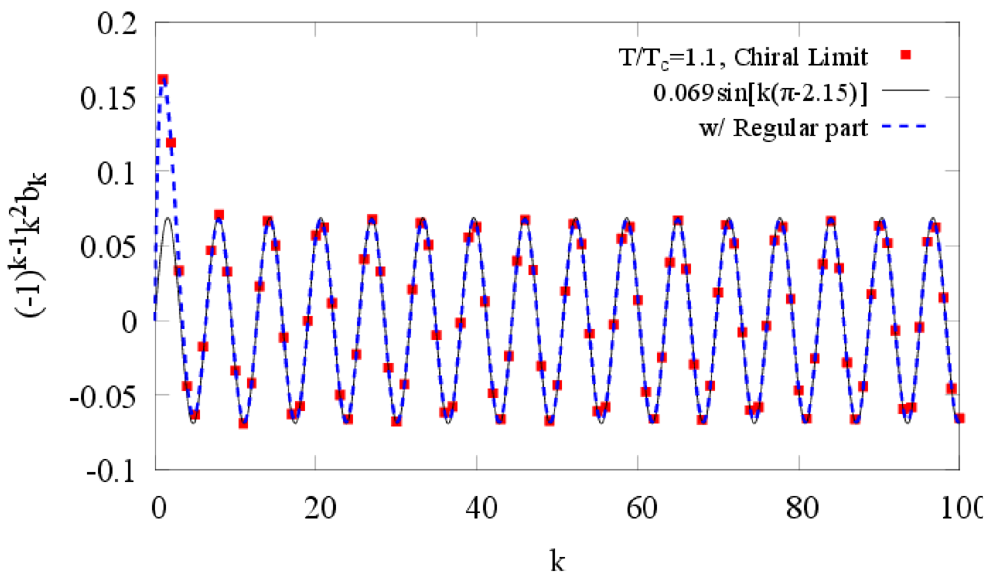
  $\Rightarrow$ $\boxed{b_k(T) \approx (-1)^{k-1} k^{-1}}$

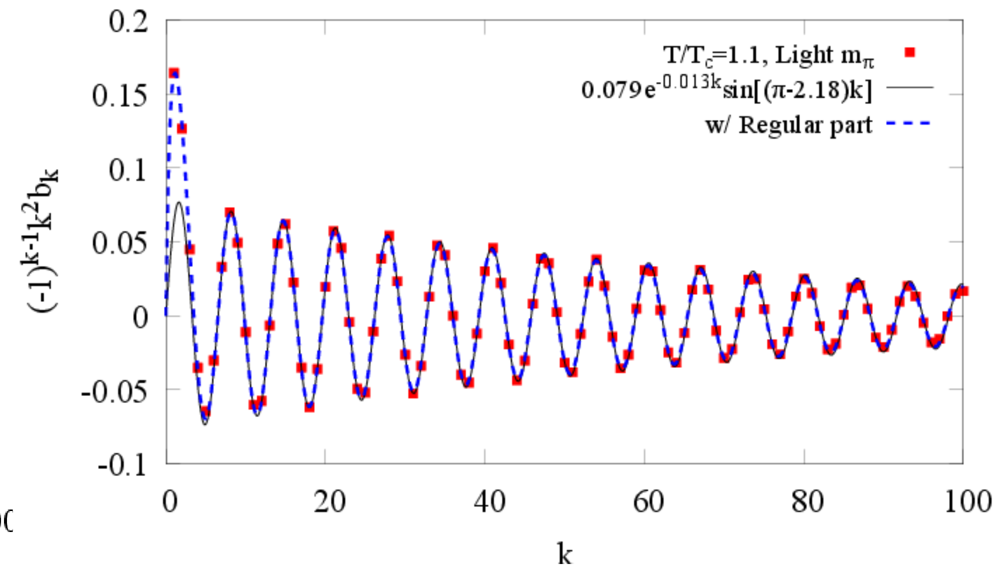
Scaling of Fourier coefficients: PNJL MF-results



- In the chiral limit, i.e. $m_\pi = 0$, the phase transition is signaled by oscillations of $b_k(T)$ just above T_c
- For $m_\pi > 0$ the singularity moves to the complex $\mu-$ plain resulting in an additional dumping of oscillations

$$b_k \simeq k^{-2} e^{-k\,\mathrm{Re}\,\mu_c(m_\pi,T)} \sin(k\theta_c)$$



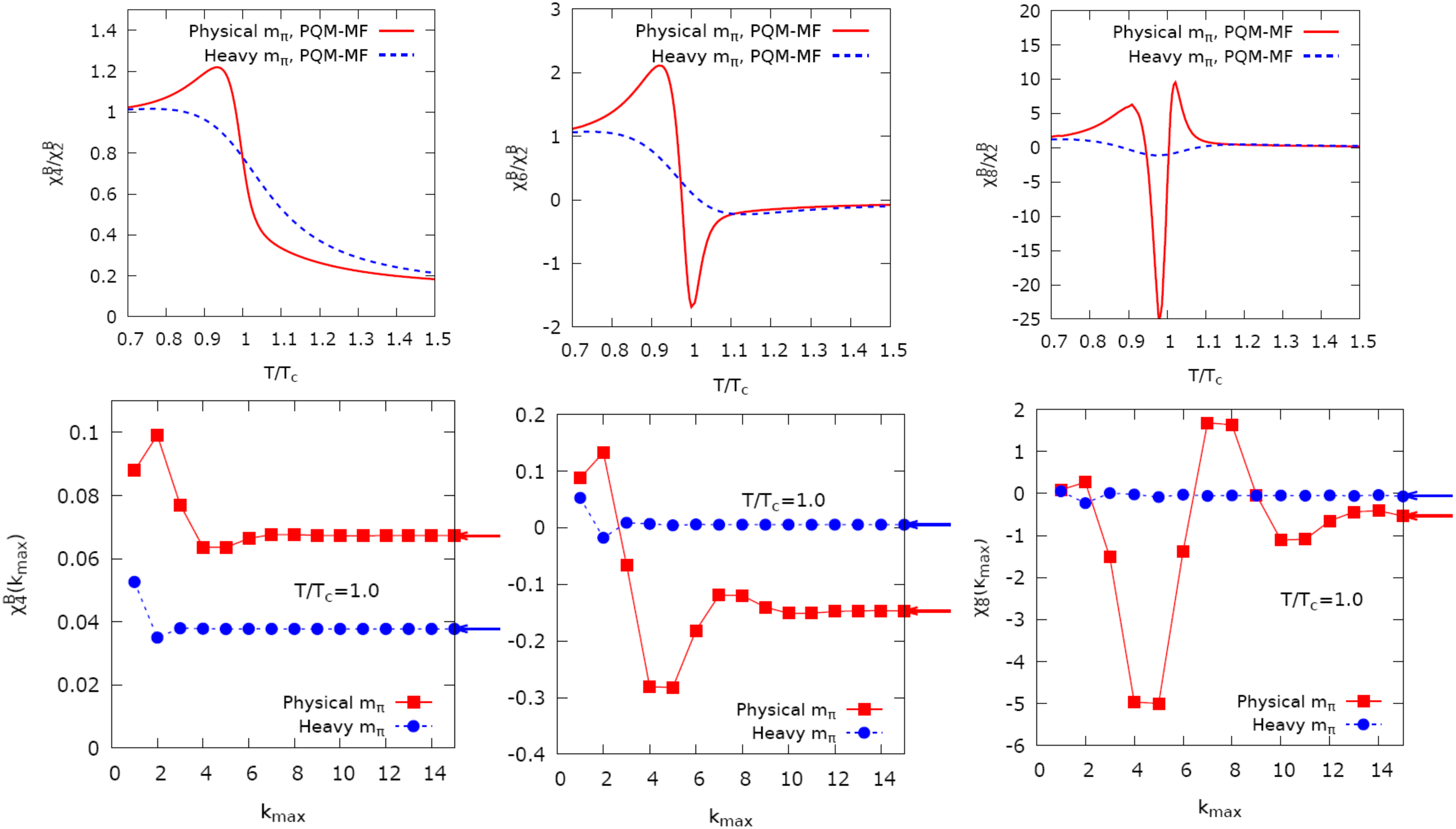


Conclusions:

- The S-matrix approach to hadron gas thermodynamics with empirical scattering phase shifts provides consistent description of LQCD results on (electric charge)-baryon correlations in the chiral crossover, and the proton production yields in AA and pp collisions at the LHC
- Systematics of net-proton number fluctuations at $\sqrt{s} > 20\ GeV$ measured by STAR in HIC at RHIC is qualitatively consistent with the expectation, that they are influenced by the critical chiral dynamics and deconfinement,

  however, possible contributions to fluctuation observables from effects not related to critical phenomena have to be understood
- The Fourier expansion coefficients of baryon density exhibit rich structure to probe the QCD phase diagram and chiral criticality in the complex chemical potential

Reconstructing: $\chi_B^n(T,\mu=0)=\sum_{k=1}^{k_{max}} k^{2n-1} b_k(T)$ with fixed k_{max}



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