QCD Critical Point : Synergy of Lattice & Experiments

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Introduction

Lattice QCD Results

Searching Experimentally

Summary

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♠ Many models & Approaches for QCD Phase Diagram

♠ QCD Critical Point in T-μ_B plane.

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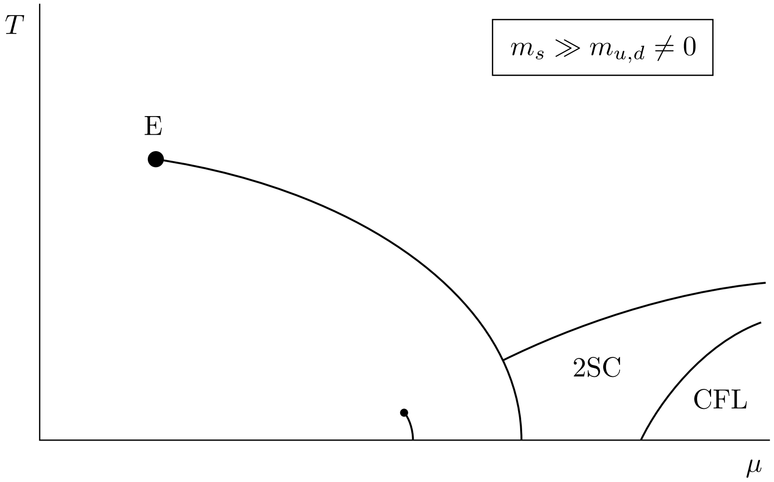

From Rajagopal-Wilczek Review

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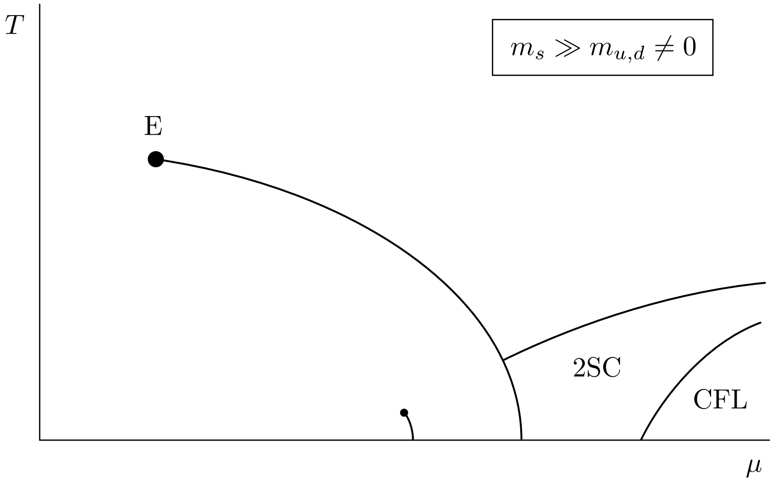

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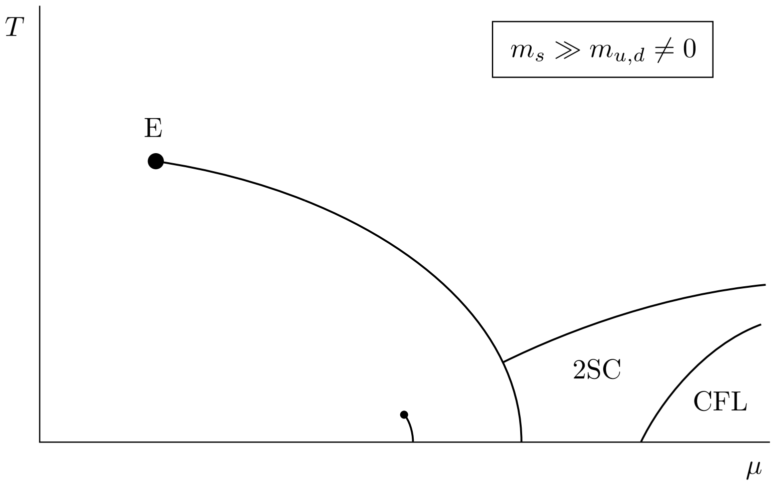

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- Search for its location using *ab initio* methods
- Search for it in the experiments RHIC, FAIR,...
- What hints can Lattice QCD investigations provide ?

The $\mu \neq 0$ problem : Quark Type

- Mostly staggered quarks used in these simulations. Broken flavour and spin symmetry on lattice. Moreover, NO flavour singlet $U_A(1)$ symmetry or anomaly. Critical point needs $N_f = 2$ and anomaly to persist by T_c.

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- Unfortunately BW-prescription breaks chiral symmetry ! (Banerjee, Gavai & Sharma PRD 2008; PoS (Lattice 2008); PRD 2009) Furthermore, anomaly for it depends on μ unlike in continuum QCD (Gavai & Sharma PRD 2010).

- Good News : Action with Continuum-like (flavour & spin) symmetries for quarks at nonzero μ and T proposed. (Gavai & Sharma , arXiv : 1111.5944).

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- Such chiral projections can be defined for the Overlap quarks. Use them to construct the action at nonzero μ. It does have the exact chiral invariance on the lattice ! Thus order parameter exists for the entire T-μ phase diagram. (Gavai & Sharma , arXiv : 1111.5944).

- We also showed why this is physically the right thing to do. Using Domain Wall formalism, we showed this action counts only the physical (wall) modes.

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Lattice Approaches in the past decade —

- Two parameter Re-weighting (Z. Fodor & S. Katz, JHEP 0203 (2002) 014).
- Imaginary Chemical Potential (Ph. de Forcrand & O. Philipsen, NP B642 (2002) 290; M.-P. Lombardo & M. D'Elia PR D67 (2003) 014505).
- Taylor Expansion (C. Allton et al., PR D66 (2002) 074507 & D68 (2003) 014507; R.V. Gavai and S. Gupta, PR D68 (2003) 034506).
- Canonical Ensemble (K. -F. Liu, IJMP B16 (2002) 2017, S. Kratochvila and P. de Forcrand, PoS LAT2005 (2006) 167.)
- Complex Langevin (G. Aarts and I. O. Stamatescu, arXiv:0809.5227 and its references for earlier work).

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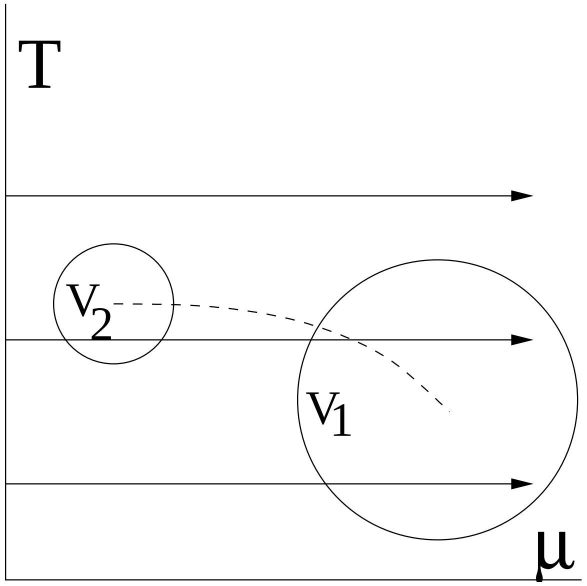

We study volume dependence at several T to i) bracket the critical region and then to ii) track its change as a function of volume.

How Do We Do This Expansion?

Canonical definitions yield various number densities and susceptibilities :

$$n_i = \frac{T}{V}\frac{\partial \ln \mathcal{Z}}{\partial \mu_i} \quad \text{and} \quad \chi_{ij} = \frac{T}{V}\frac{\partial^2 \ln \mathcal{Z}}{\partial \mu_i \partial \mu_j} \quad .$$

These are also useful by themselves both theoretically and for Heavy Ion Physics (Flavour correlations, $\lambda_s \ldots$)

Denoting higher order susceptibilities by χ_{n_u,n_d}, the pressure P has the expansion in μ:

$$\frac{\Delta P}{T^4} \equiv \frac{P(\mu,T)}{T^4} - \frac{P(0,T)}{T^4} = \sum_{n_u,n_d} \chi_{n_u,n_d} \frac{1}{n_u!}\left(\frac{\mu_u}{T}\right)^{n_u} \frac{1}{n_d!}\left(\frac{\mu_d}{T}\right)^{n_d} \tag{1}$$

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- We (Gavai-Gupta '05, '09) construct the series for baryonic susceptibility from this expansion. Its radius of convergence gives the nearest critical point.

- Successive estimates for the radius of convergence obtained from these using $\sqrt{\frac{n(n+1)\chi_B^{(n+1)}}{\chi_B^{(n+3)}T^2}}$ or $\left(n!\frac{\chi_B^{(2)}}{\chi_B^{(n+2)}T^n}\right)^{1/n}$. We use both these definitions.

- All coefficients of the series must be POSITIVE for the critical point to be at real μ, and thus physical.

- We use up to 8^{th} order. Need 20 inversions of $(D+m)$ on $\sim$ 500 vectors for a single measurement.

- 10th & even 12th order may be possible : Ideas to extend to higher orders are emerging (Gavai-Sharma PRD 2010) which save up to 60 % computer time.

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Lattice QCD Results

- Staggered fermions with $N_f = 2$ of $m/T_c = 0.1$; R-algorithm used.
- $m_\rho/T_c = 5.4 \pm 0.2$ and $m_\pi/m_\rho = 0.31 \pm 0.01$ (MILC)
- m_π = 230 MeV (Gavai-Gupta, PRD 2005, 2009).
- Earlier Lattice : 4 $\times N_s^3$, N_s = 8, 10, 12, 16, 24 (Gavai-Gupta, PRD 2005)

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- Earlier Lattice : 4 $\times N_s^3$, $N_s = 8$, 10, 12, 16, 24 (Gavai-Gupta, PRD 2005)
- Finer Lattice : 6 $\times N_s^3$, $N_s = 12$, 18, 24 (Gavai-Gupta, PRD 2009). We determined β_c. Our result ($\beta_c = 5.425(5)$) well bracketed by MILC for $m/T_c = 0.075$ and 0.15.
- Our Simulations made for 0.89 $\leq T/T_c \leq$ 1.92. Typical stat. 50-200 in autocorrelation units.

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- Even finer Lattice : 8 $\times 32^3$ going on.

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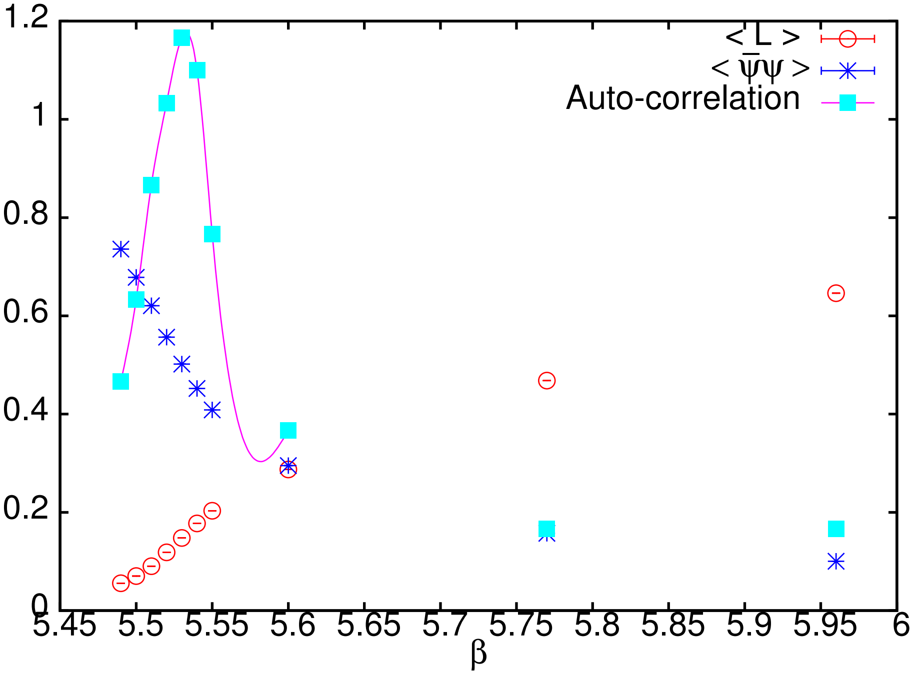
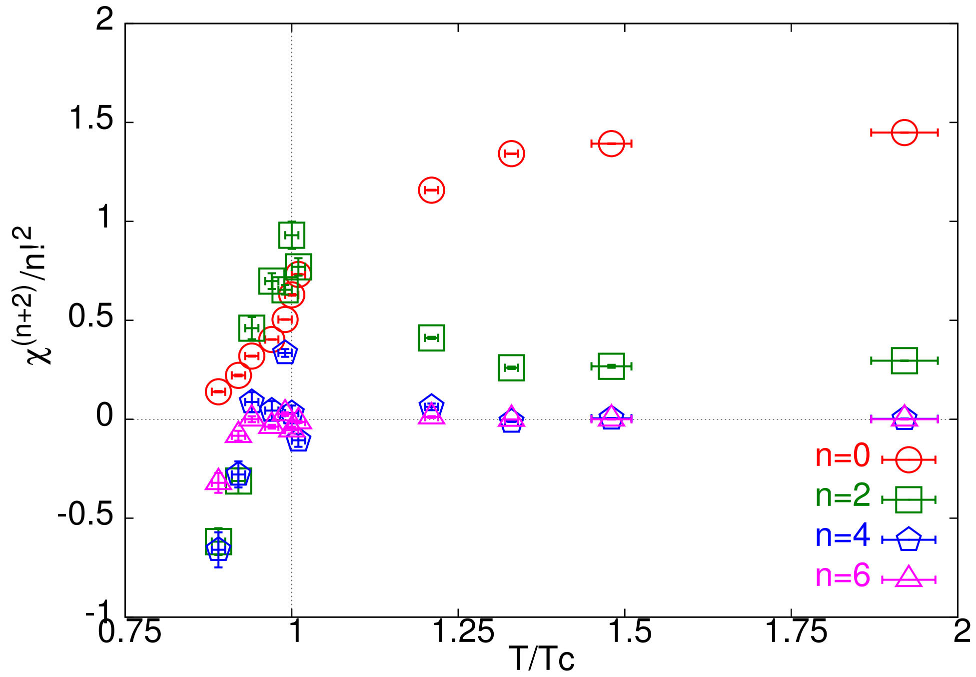


Datta-Gavai-Gupta, 2012

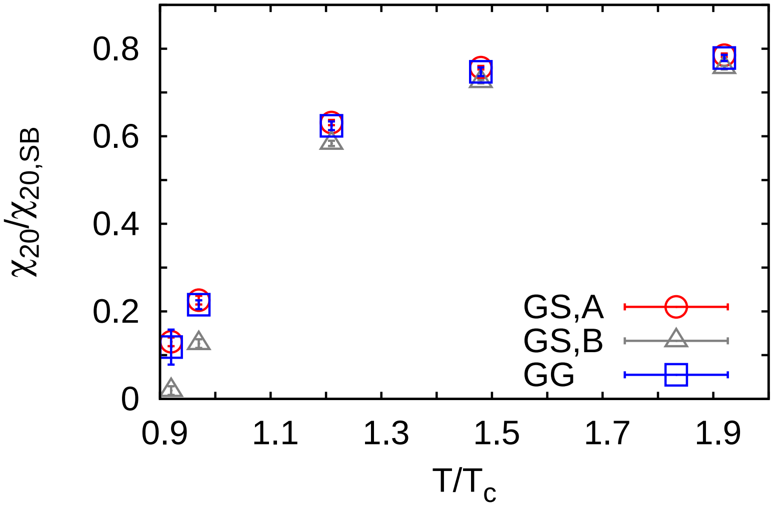
- Check for positivity: $N_t = 6$



Window of positivity just below T_c

Results with μN-idea

- ♠ Using our proposed μN term (Gavai-Sharma PRD 2010) to evaluate (Gavai-Sharma, arXiv 1111.5428, PRD 2012) the baryon susceptibility at $\mu = 0$,



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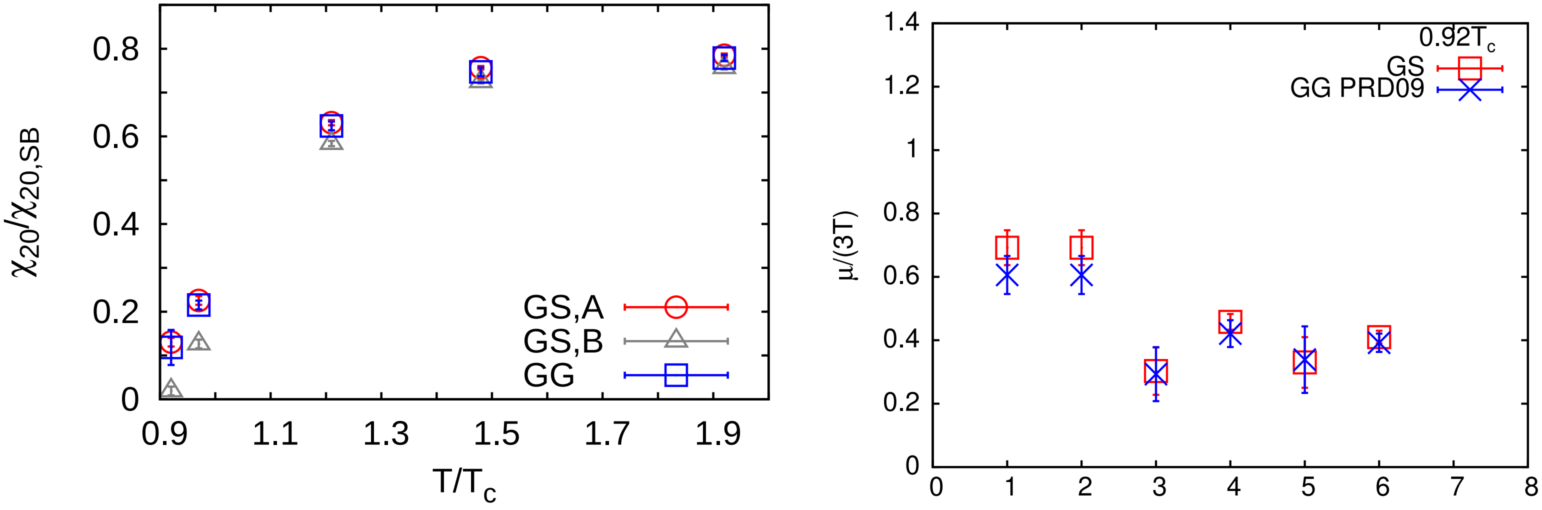
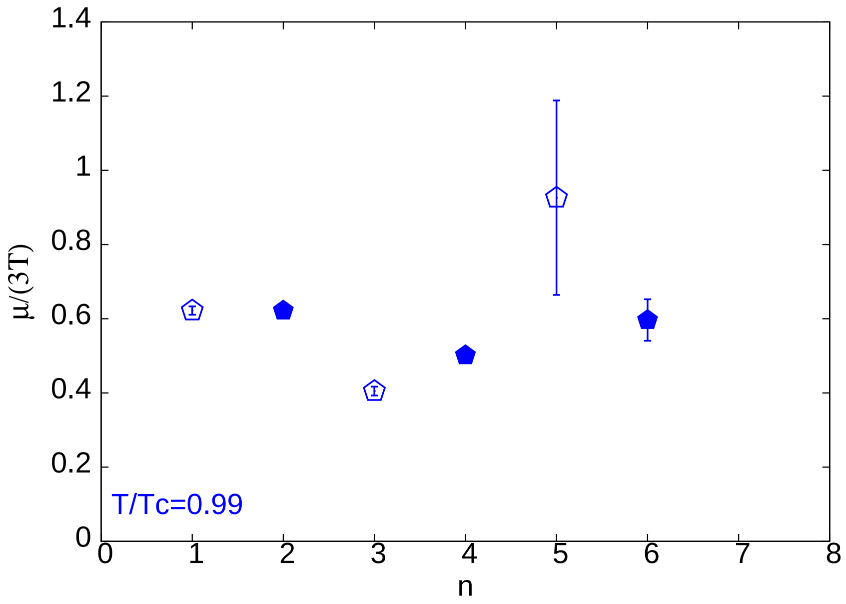


♡ ALL NLS Coefficients do have the same sign for the new method.

♠ The estimates for radius of convergence are comparable as well.


1.4
1.2
1
0.8
0.6
0.4
0.2
0
μ/(3T)
0
1
2
3
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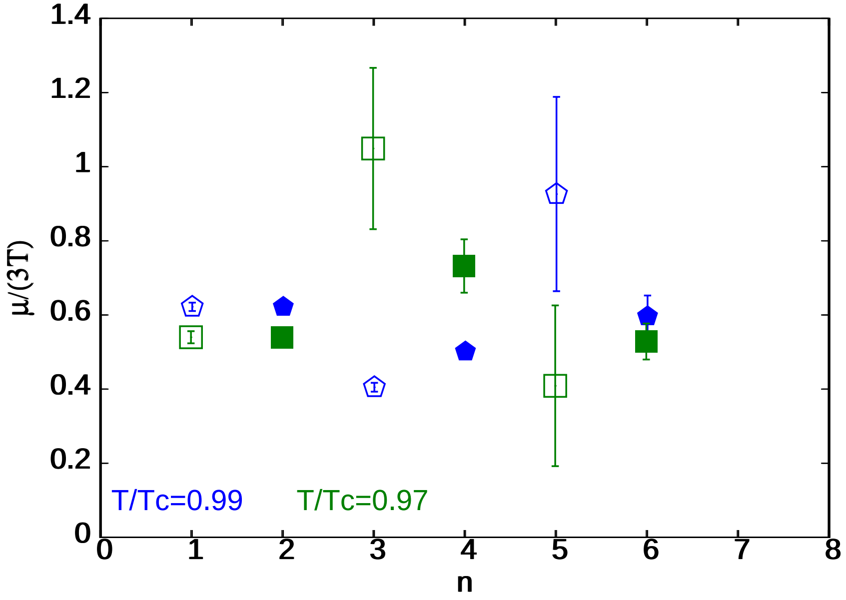
n
T/Tc=0.99


μ/(3T)
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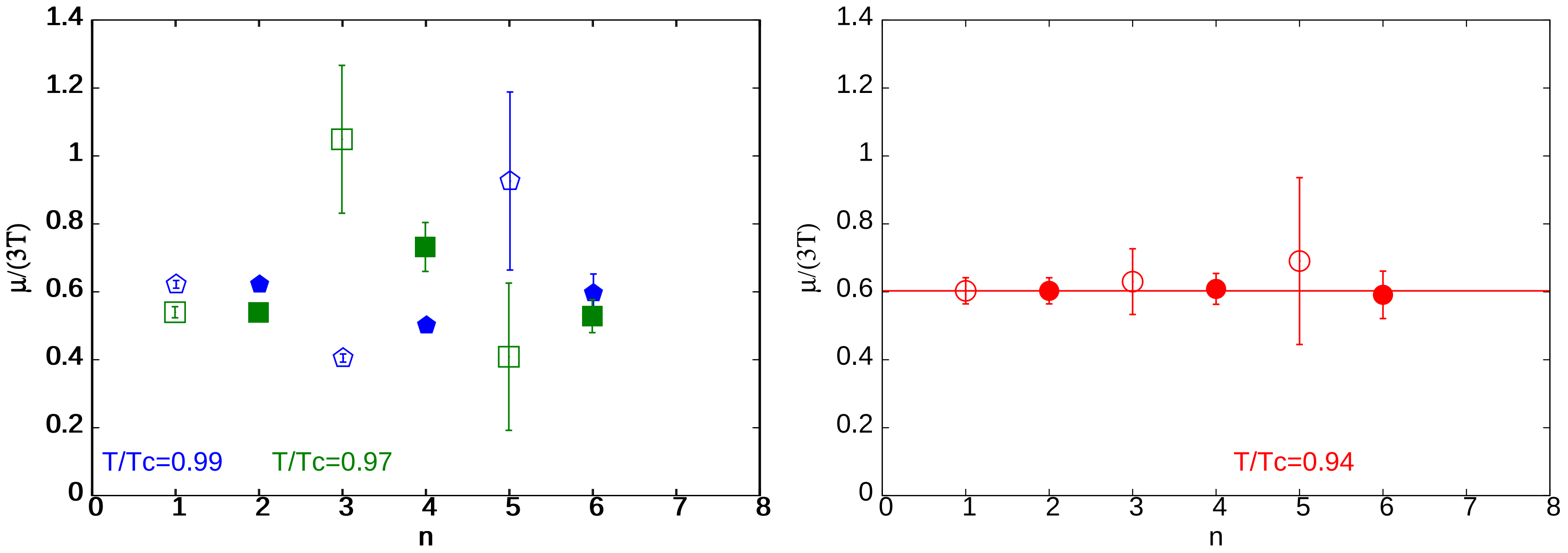
n
T/Tc=0.99
T/Tc=0.97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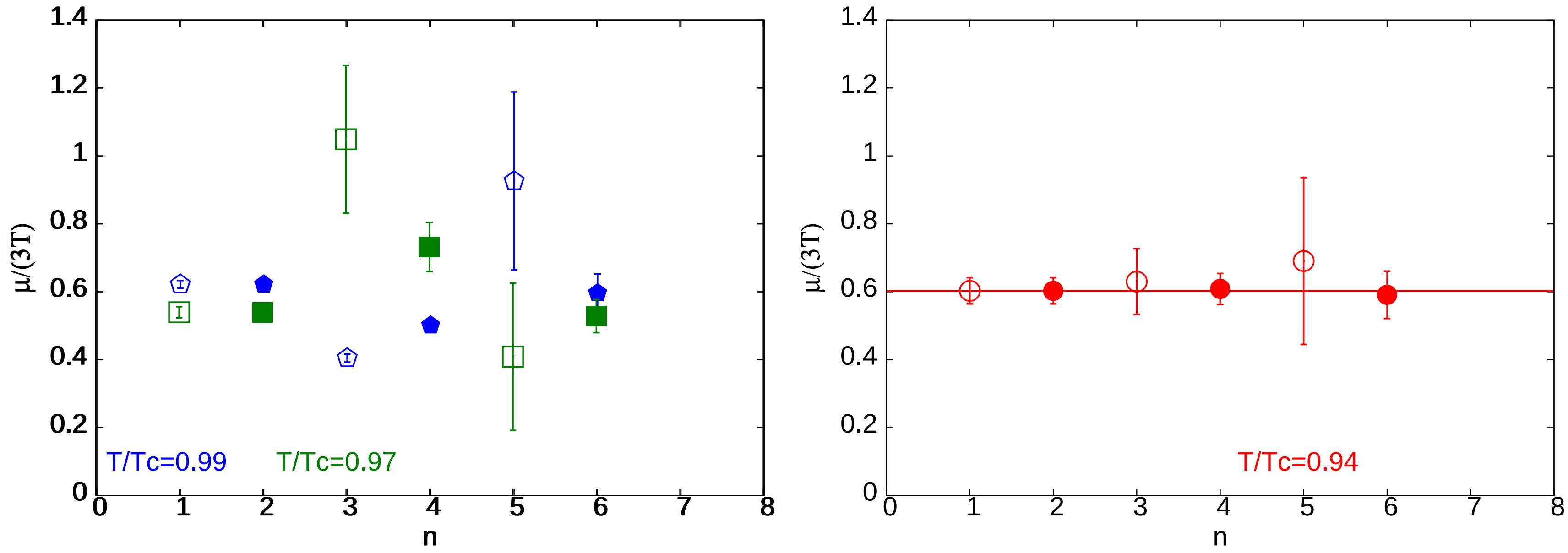
T/Tc=0.99
T/Tc=0.97
T/Tc=0.94

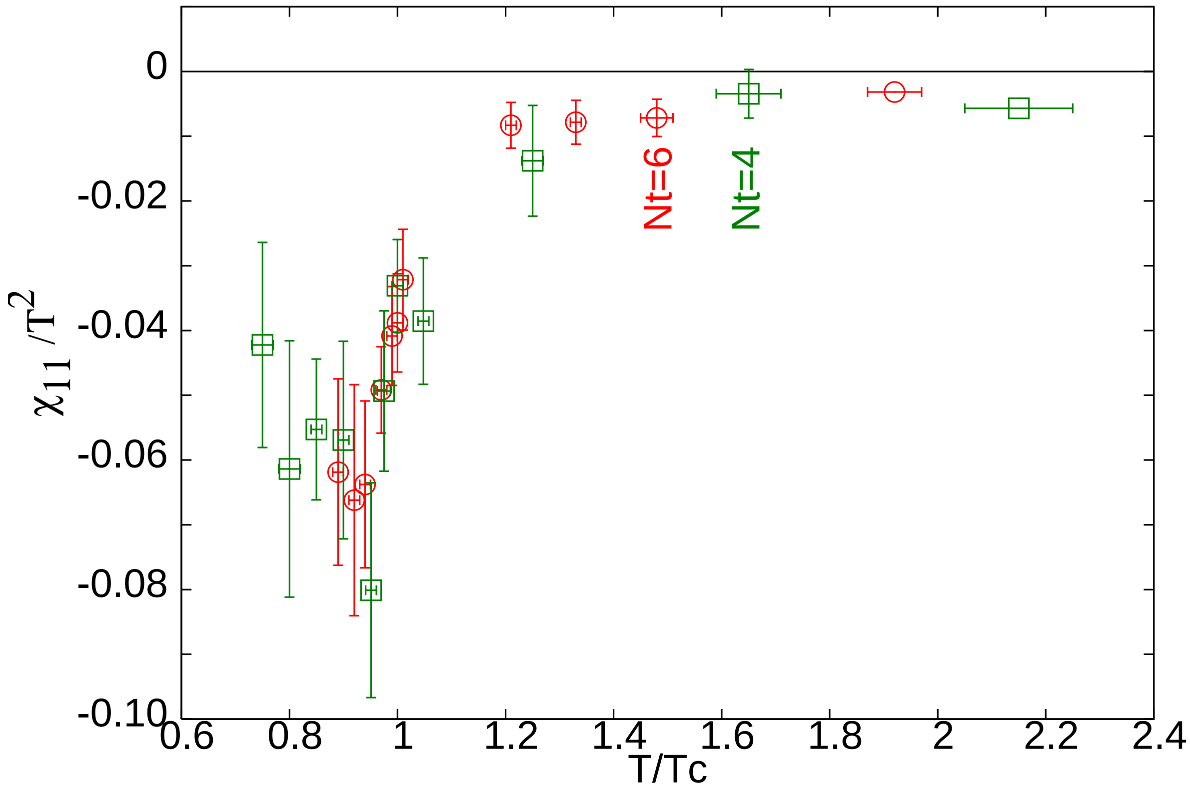


- $\frac{T^E}{T_c} = 0.94 \pm 0.01$, and $\frac{\mu_B^E}{T^E} = 1.8 \pm 0.1$ for finer lattice: Our earlier coarser lattice result was $\mu_B^E/T^E = 1.3 \pm 0.3$. Infinite volume result: ↓ to 1.1(1)

- Critical point at $\mu_B/T \sim 1 - 2$.

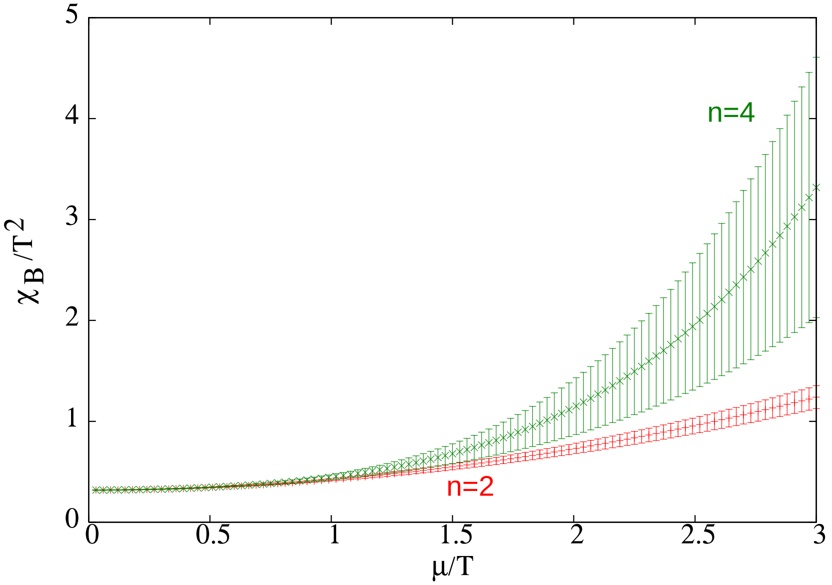
More Details

Measure of the seriousness of sign problem : χ_{11}; $N_t = 4$ & 6 agree.



Cross Check on μ^E/T^E

♠ Use the series directly to construct χ_B for nonzero μ $\longrightarrow$ smooth curves with no signs of criticality.



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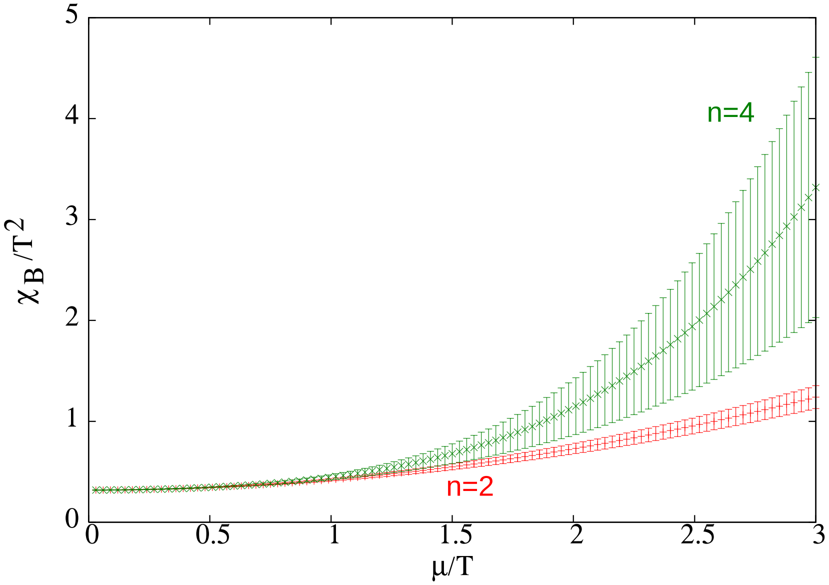
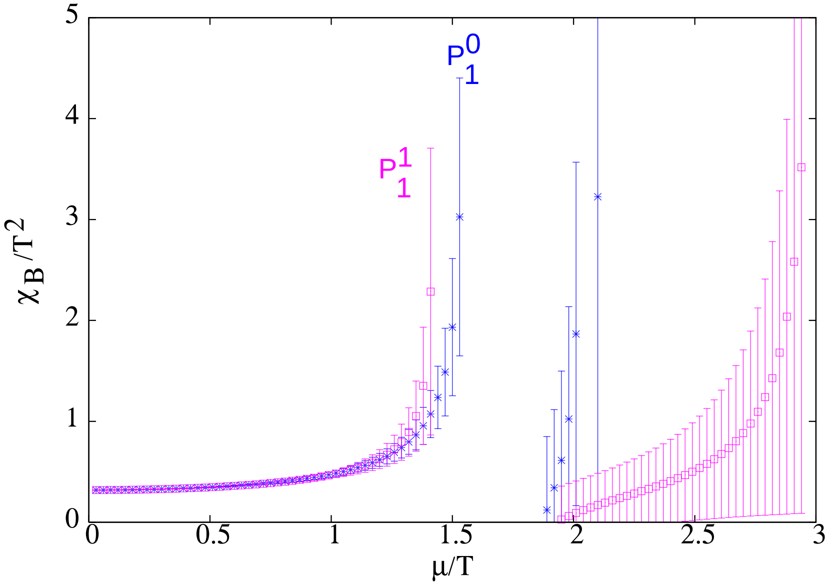


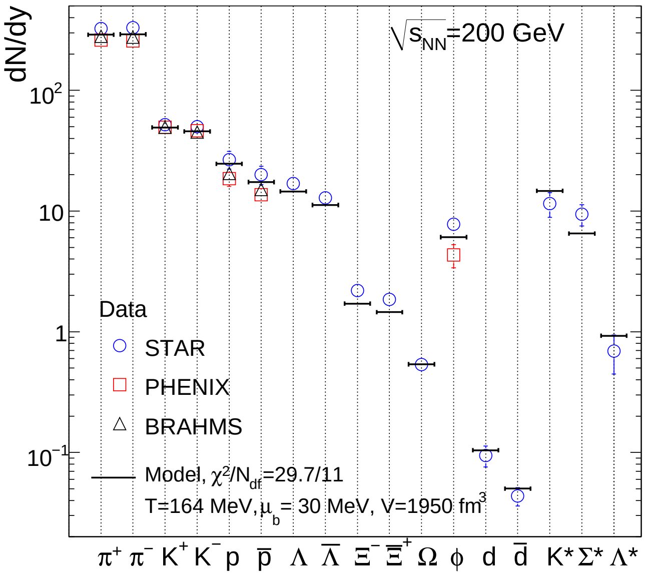


♠ Use Padé approximants for the series to estimate the radius of convergence.

♡ Consistent Window with our other estimates.

Lattice predictions along the freezeout curve

- Hadron yields well described using Thermodynamical Models, leading to a freezeout curve in the T-μ_B plane. (Andronic, Braun-Munzinger & Stachel, PLB 2009 ; Oeschler, Cleymans, Redlich & Wheaton, 2009)



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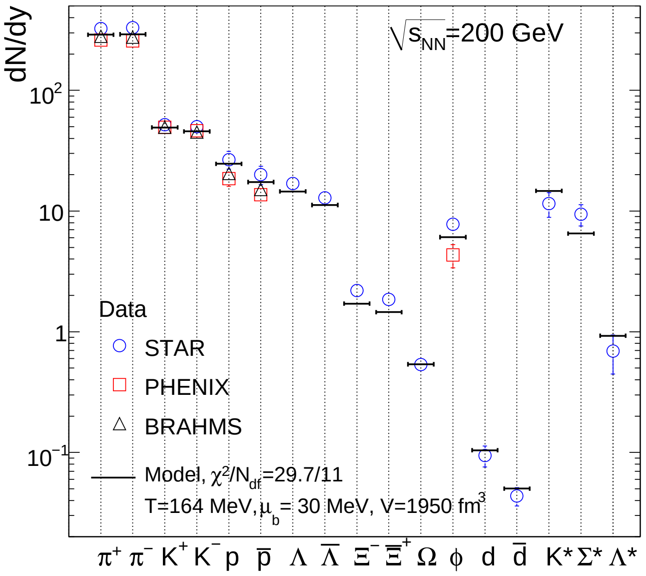
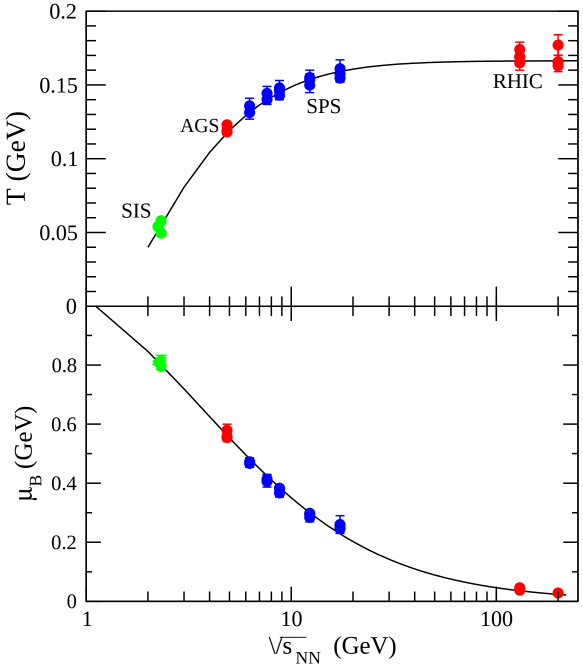
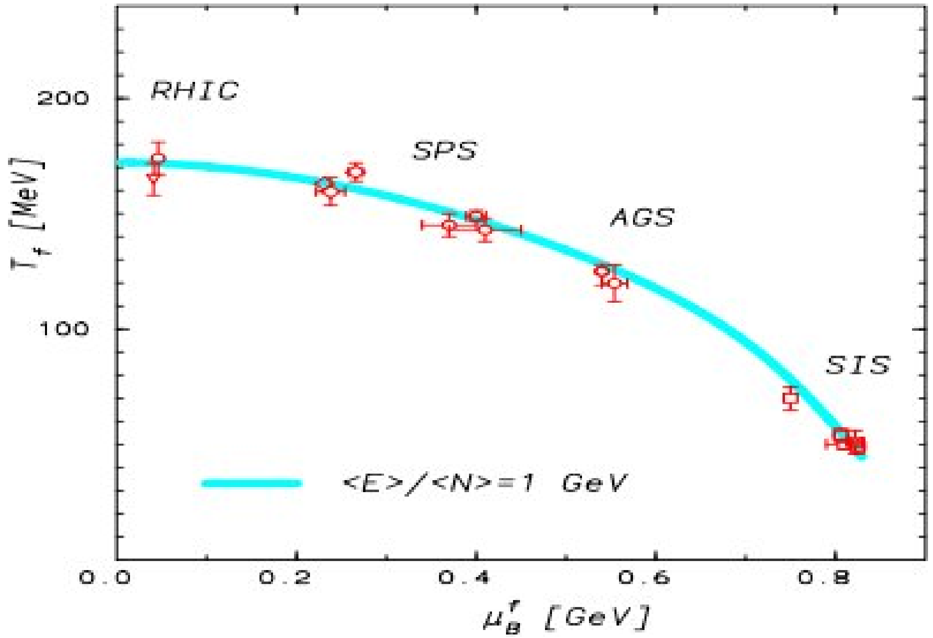


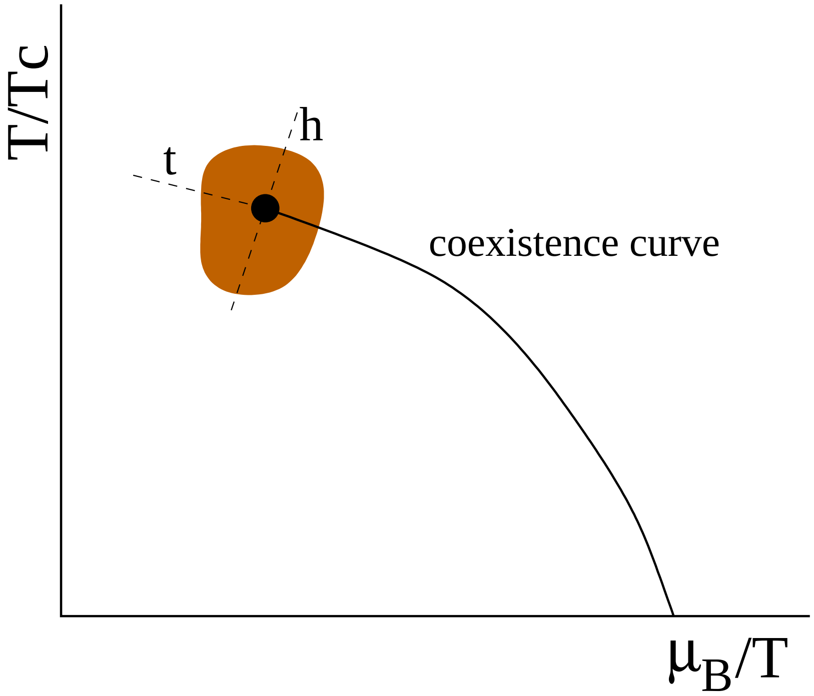


- Plotting these results in the T-μ_B plane, one has the freezeout curve, which was shown to correspond the $\langle E\rangle/\langle N\rangle \simeq 1$. (Cleymans and Redlich, PRL 1998)



(From Braun-Munzinger, Redlich and Stachel nucl-th/0304013)

- Our Key Proposal : Use this freezeout curve to relate $(T, \mu_B)$to $\sqrt{s}$ and employ lattice QCD predictions for fluctuations along it. (Gavai-Gupta, TIFR/TH/10-01, arXiv 1001.3796)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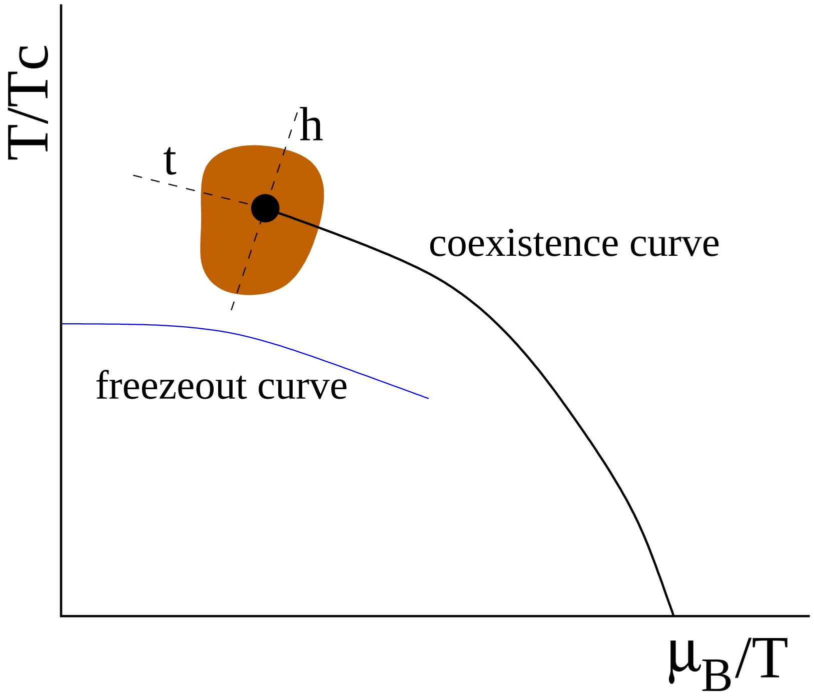
coexistence curve
μ_B/T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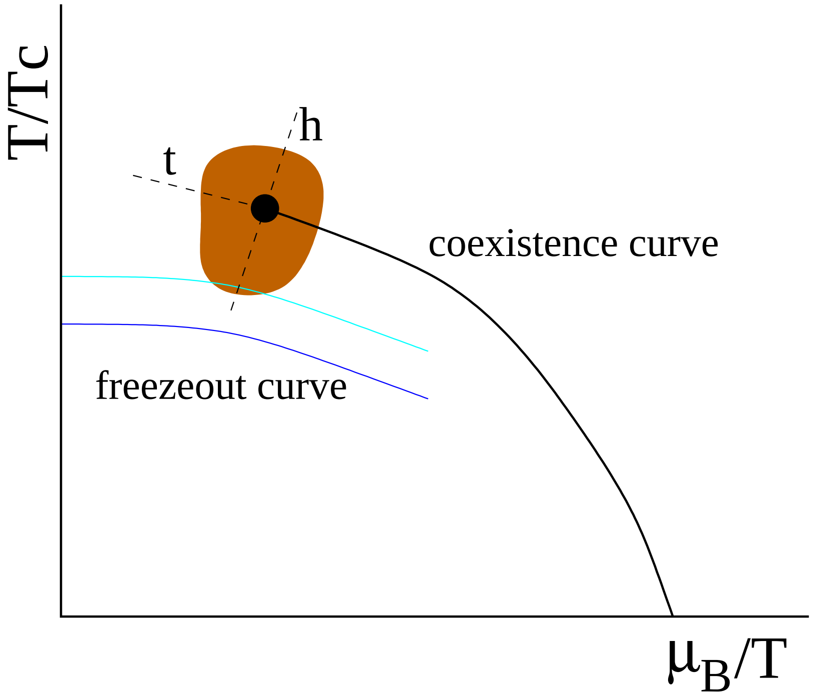
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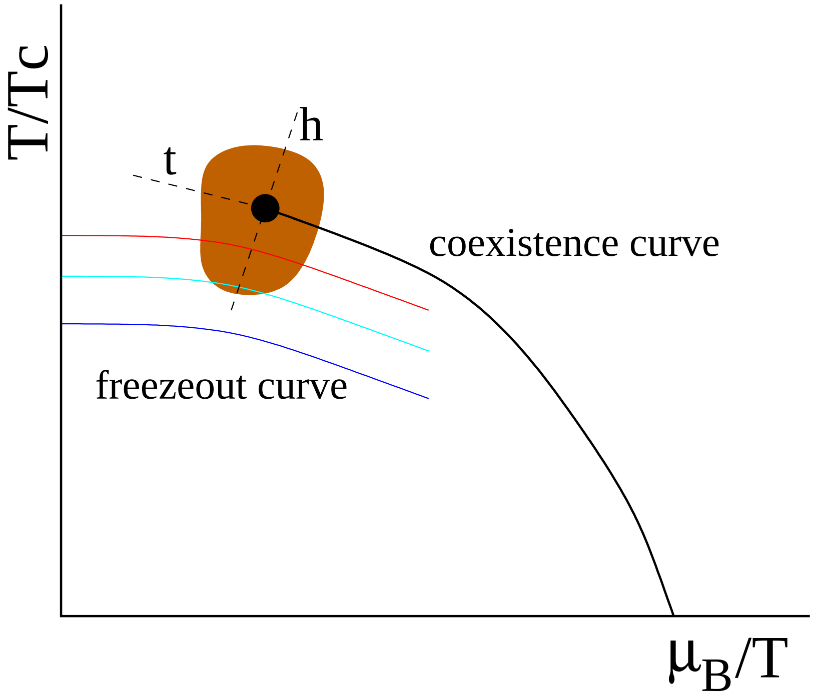
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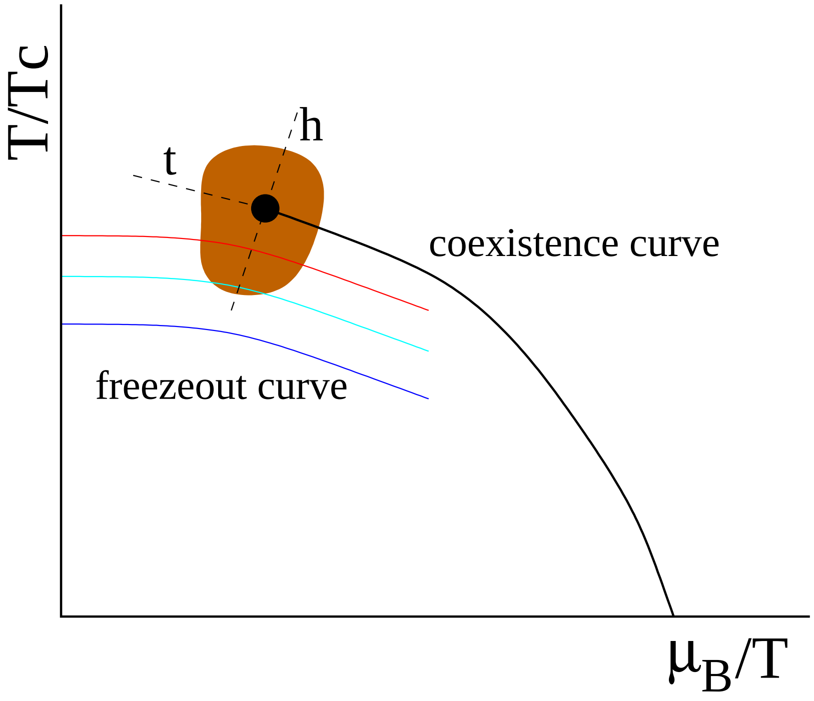
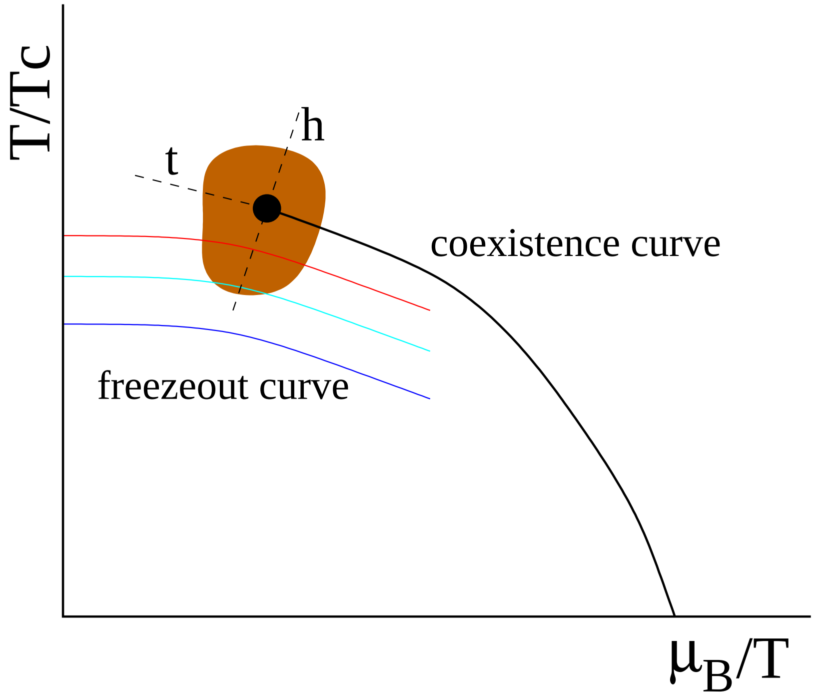


- Define $m_1 = \frac{T\chi^{(3)}(T,\mu_B)}{\chi^{(2)}(T,\mu_B)}$, $m_3 = \frac{T\chi^{(4)}(T,\mu_B)}{\chi^{(3)}(T,\mu_B)}$, and $m_2 = m_1 m_3$ (Gupta, arXiv : 0909.4630) and use the Padè method to construct them.



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- Near the critical point, $\chi_B \sim |\mu - \mu_E|^\delta$. Thus the ratios, m_i, should diverge in the critical region as well.

- m_i are dimensionless, and are computed as functions of T/T_c. $\Longrightarrow$ expect small lattice spacing corrections.

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- Defining $z = \mu_B/T$, and denoting by r_{ij} the estimate for radius of convergence using χ_i, χ_j, one has

$$m_1 = \frac{2z}{r_{24}^2}\left[1 + \left(\frac{2r_{24}^2}{r_{46}^2} - 1\right)z^2 + \left(\frac{3r_{24}^2}{r_{46}^2 r_{68}^2} - \frac{3r_{24}^2}{r_{46}^2} + 1\right)z^4 + \mathcal{O}(z^6)\right] .$$

- Similar series expressions for m_2 and m_3. Resum these by Padè ansatz :

$$m_1 = zP_1^1(z^2; a, b), \qquad m_3 = \frac{1}{z}P_1^1(z^2; a', b')$$

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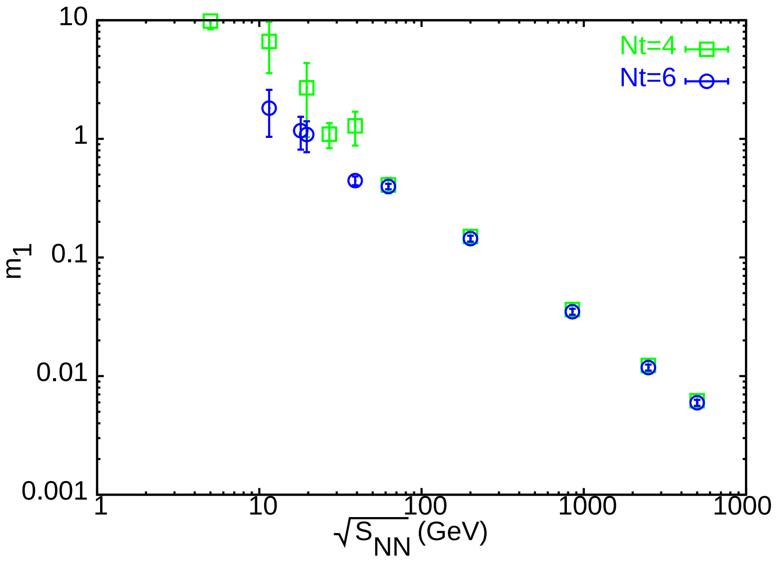
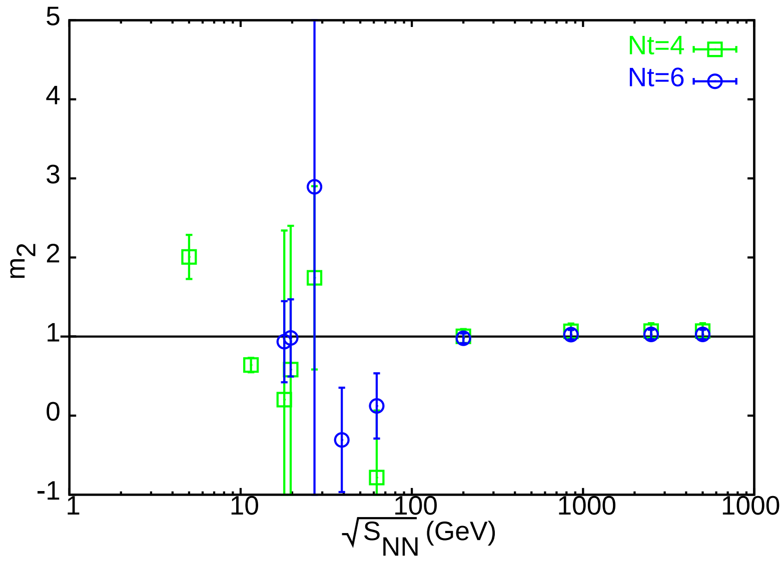
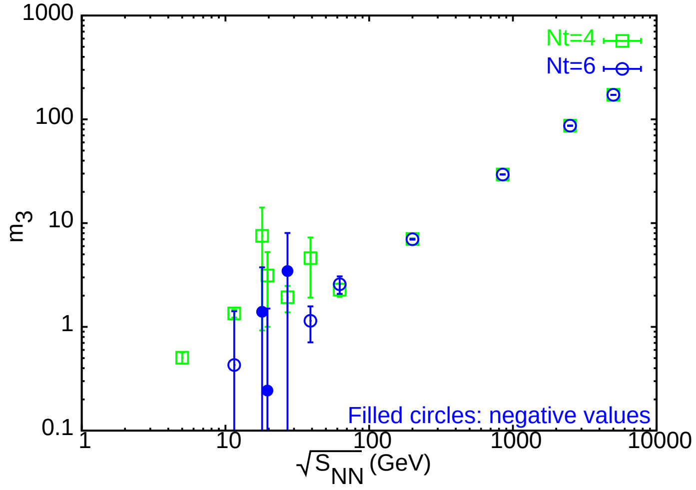
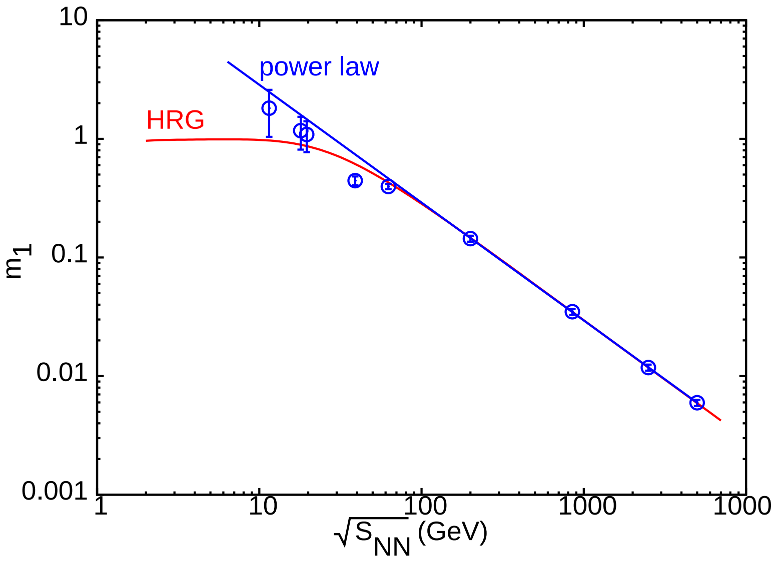
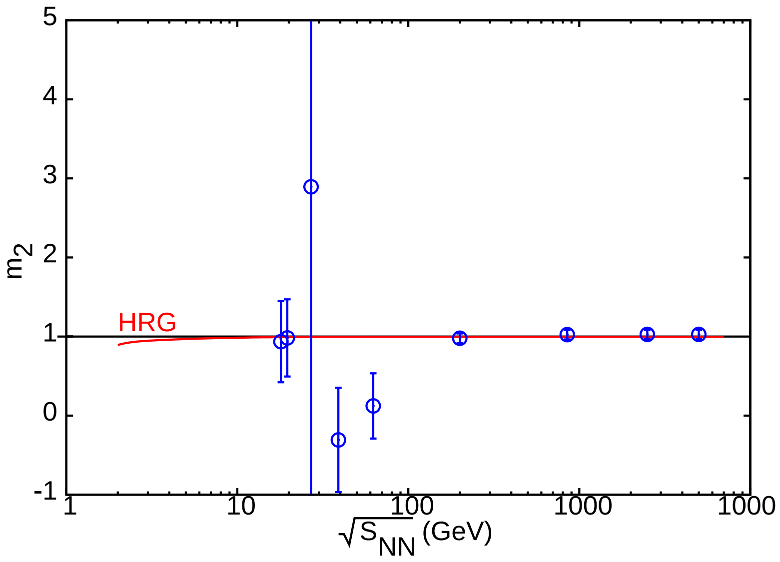


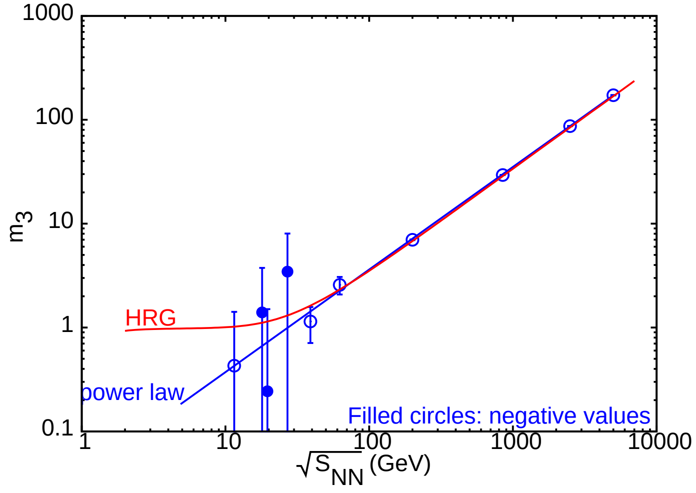




♠ Gavai & Gupta, arXiv: 1001.3796.







♠ Used $T_c(\mu = 0) = 175$ MeV (Gavai & Gupta, arXiv: 1001.3796).

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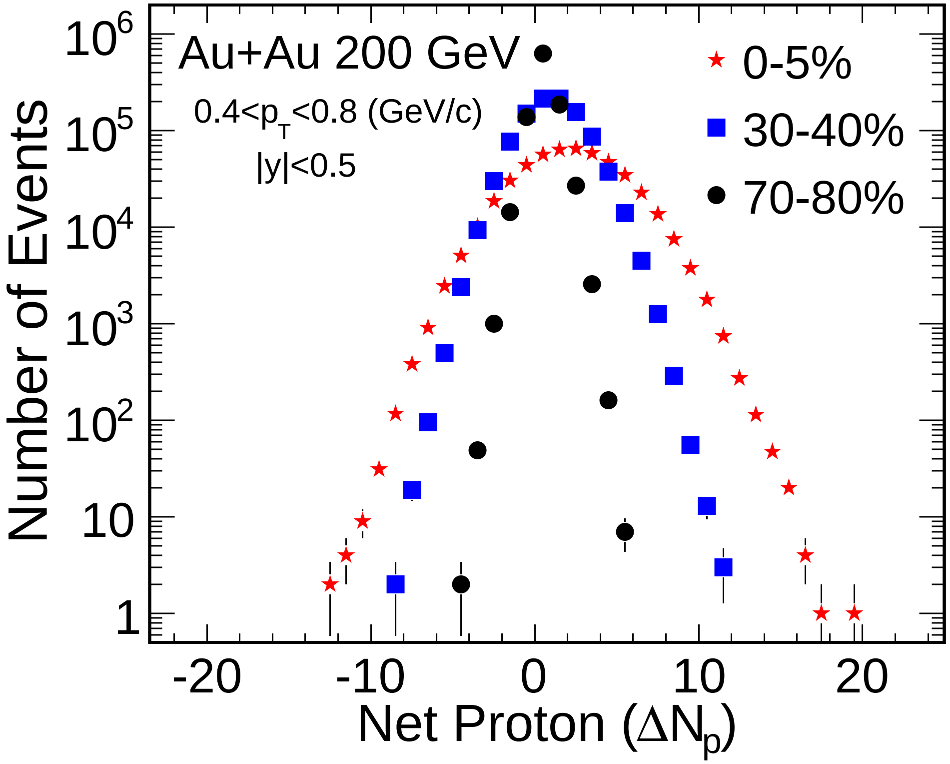
- Proton number fluctuations suffice (Hatta-Stephenov, PRL 2003).

- These are linked directly to the baryonic susceptibility which ought to diverge at the critical point.

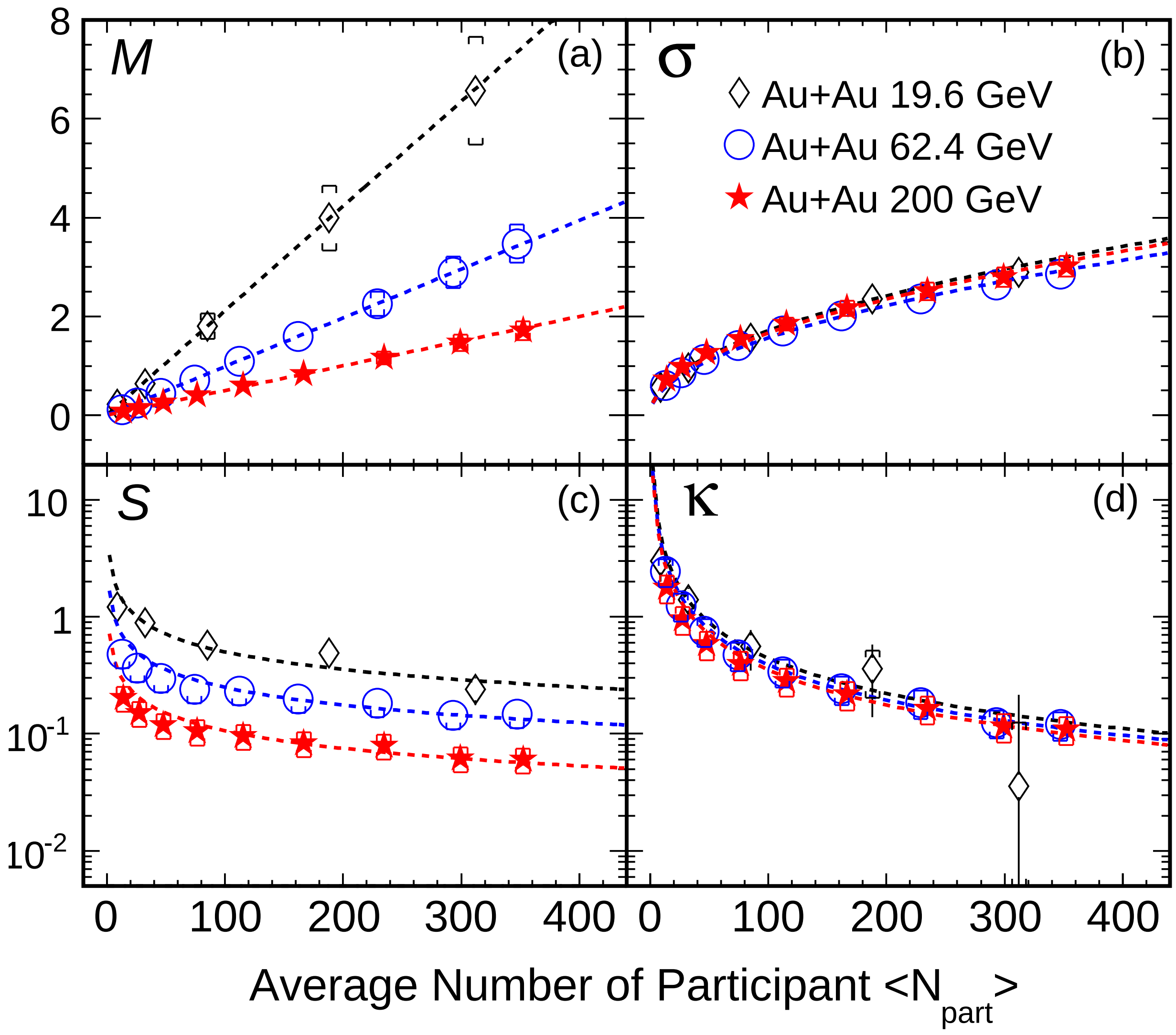
- Since diverging ξ is linked to σ mode, which cannot mix with any isospin modes, expect χ_I to be regular.

- Leads to a ratio χ_Q:χ_I:χ_B = 1:0:4

- STAR has recently used this idea and constructed the ratios m_1 and m_2 from net proton distributions : (Aggarwal et al., arXiv : 1004.4959).



Aggarwal et al., STAR Collaboration, arXiv : 1004.4959



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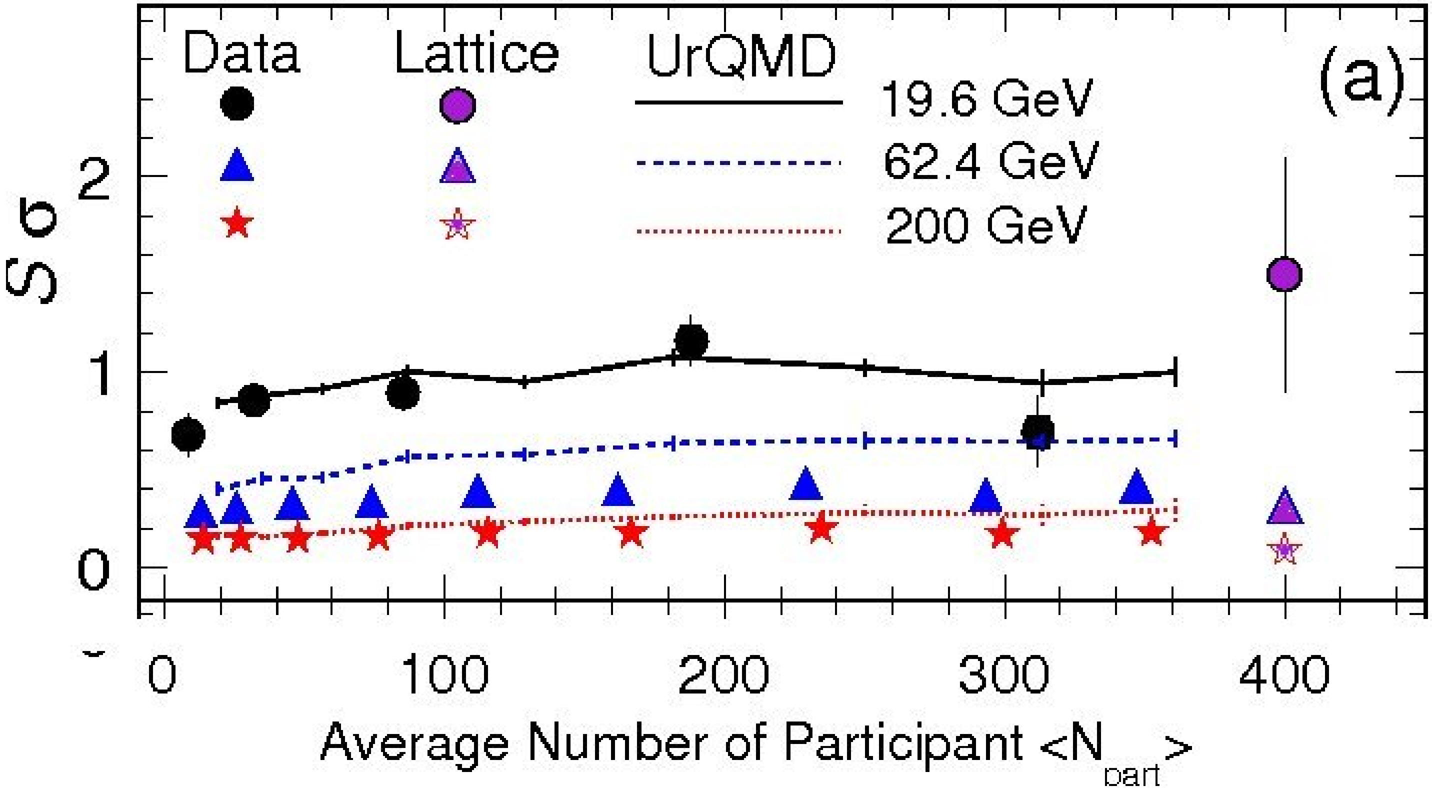
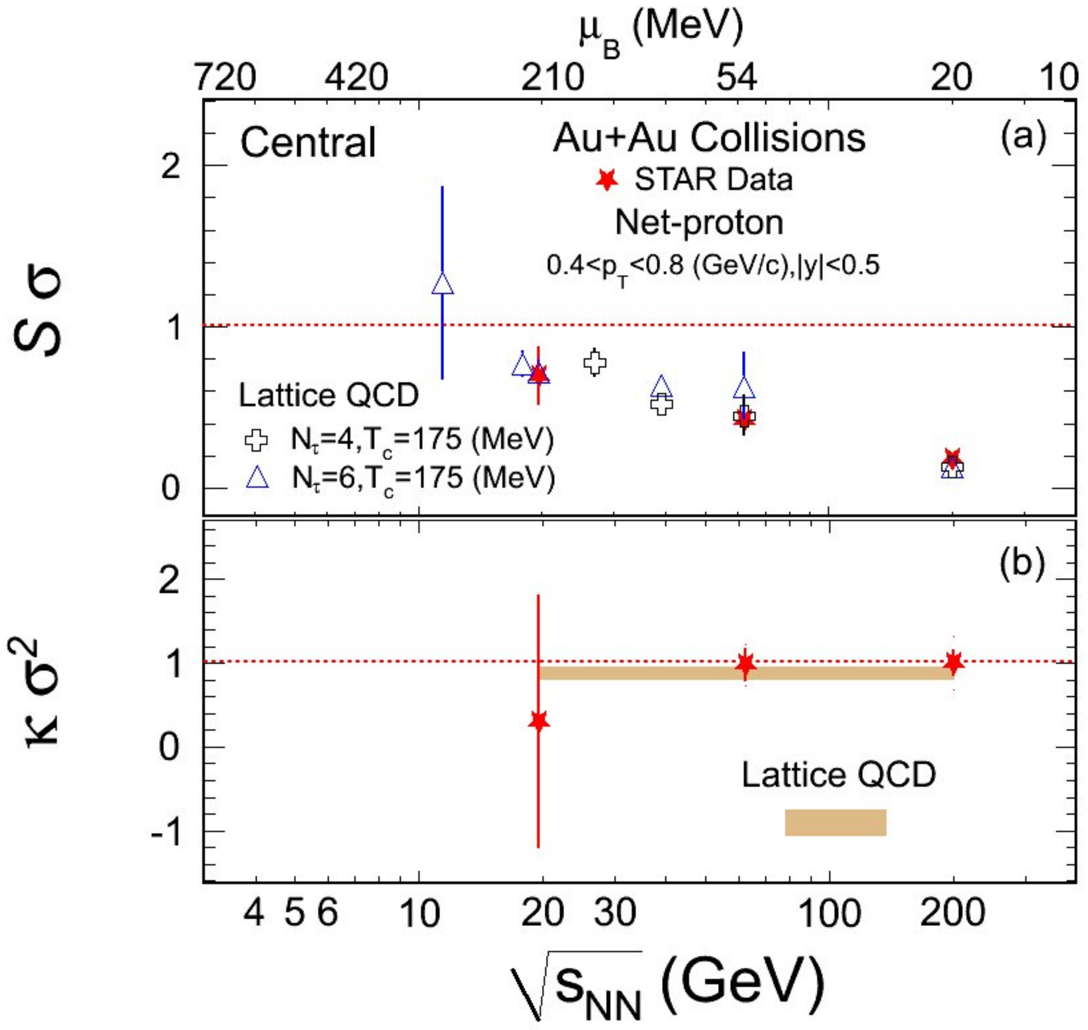


Aggarwal et al., STAR Collaboration, arXiv : 1004.4959

- Reasonable agreement with our lattice results. Where is the critical point ?



Private communication from STAR Collaboration

Summary

- Phase diagram in $T - \mu$ has begun to emerge: Different methods, $\rightsquigarrow$ similar qualitative picture. Critical Point at $\mu_B/T \sim 1 - 2$.

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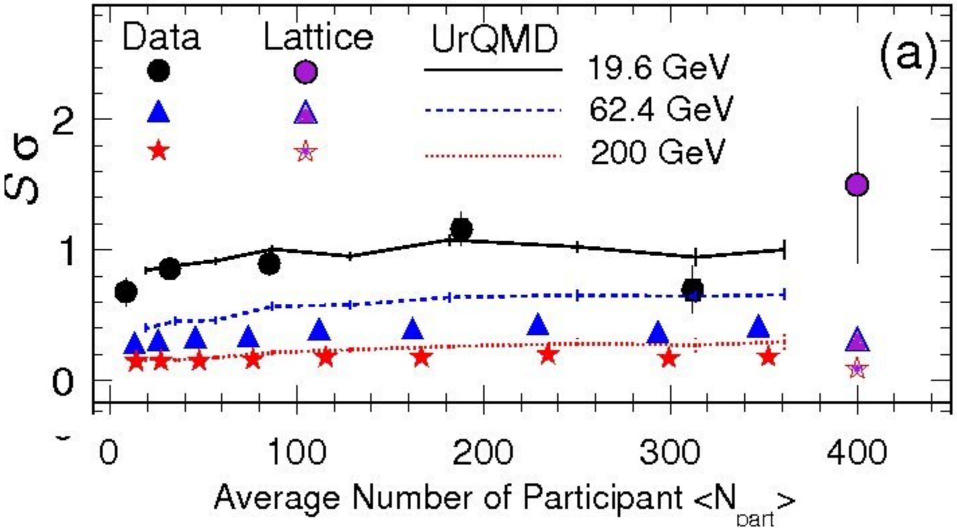

Summary

- Phase diagram in $T - \mu$ has begun to emerge: Different methods, $\rightsquigarrow$ similar qualitative picture. Critical Point at $\mu_B/T \sim 1 - 2$.
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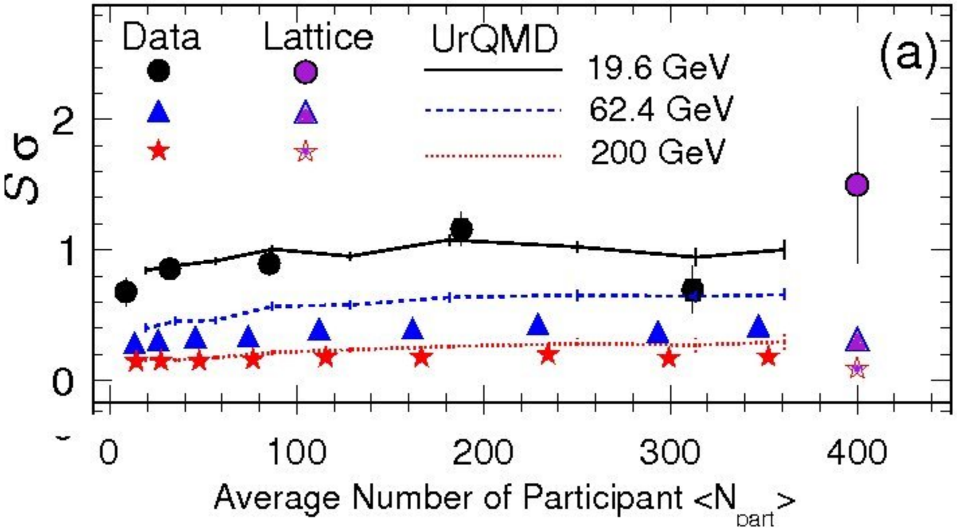
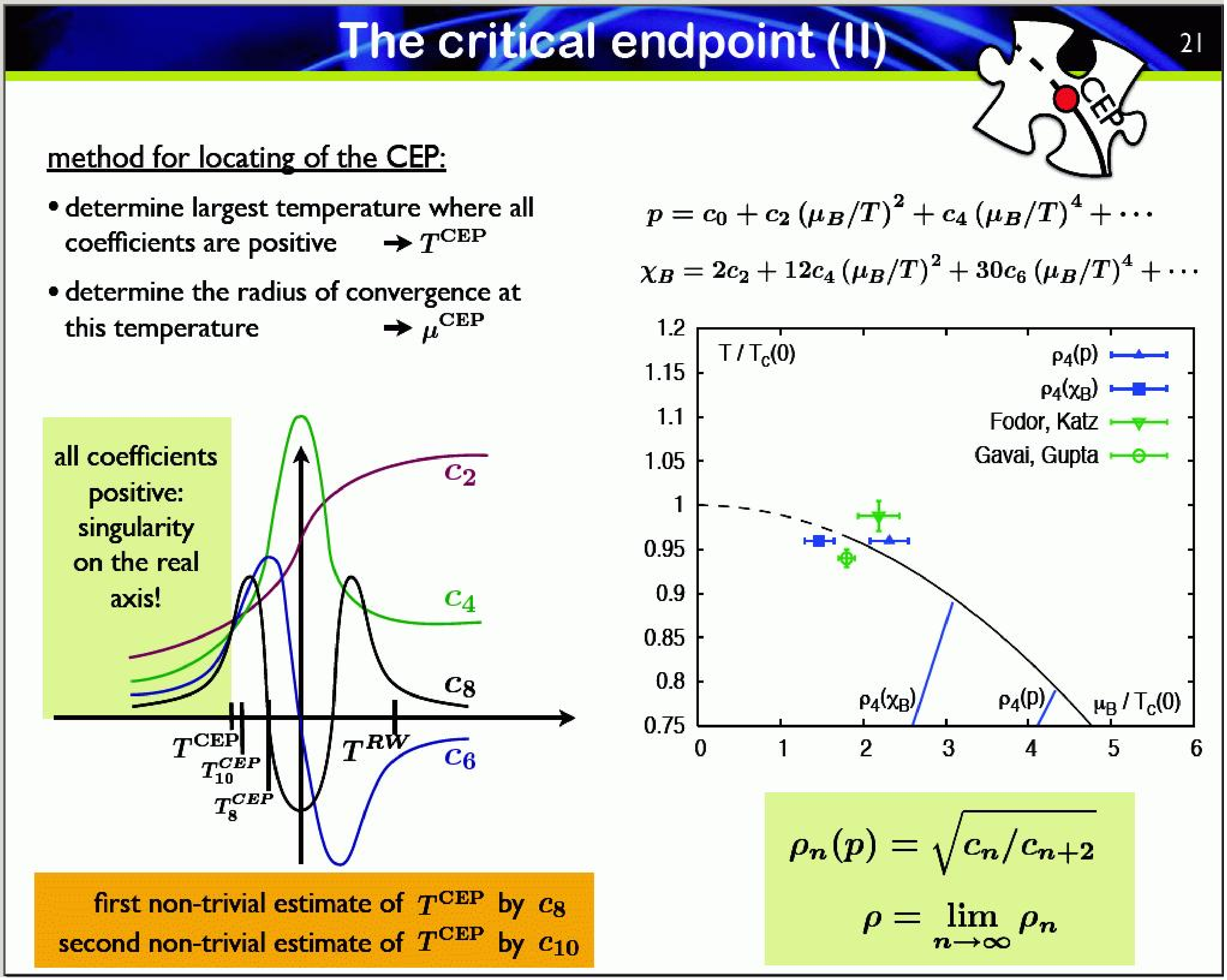


So far no signs of a critical point in the experimental results at CERN. Will RHIC energy scan deliver it for us ? and/or Will it be FAIR ?



The critical endpoint (II)

method for locating of the CEP:

- determine largest temperature where all coefficients are positive → T^{CEP}
- determine the radius of convergence at this temperature → μ^{CEP}

$$p = c_0 + c_2\,(\mu_B/T)^2 + c_4\,(\mu_B/T)^4 + \cdots$$

$$\chi_B = 2c_2 + 12c_4\,(\mu_B/T)^2 + 30c_6\,(\mu_B/T)^4 + \cdots$$

all coefficients positive: singularity on the real axis!

first non-trivial estimate of T^{CEP} by c_8
second non-trivial estimate of T^{CEP} by c_{10}

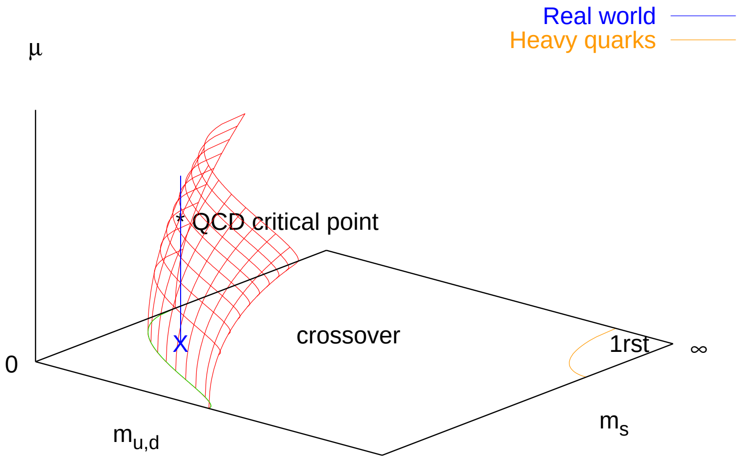
$$\rho_n(p) = \sqrt{c_n/c_{n+2}}$$

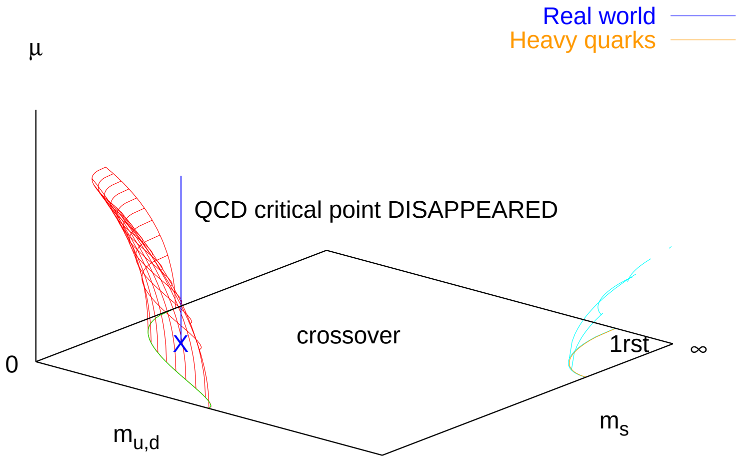
$$\rho = \lim_{n\to\infty} \rho_n$$

(Ch. Schmidt FAIR Lattice QCD Days, Nov 23-24, 2009.)

Imaginary Chemical Potential

deForcrand-Philpsen JHEP 0811





For $N_f = 3$, they find $\frac{m_c(\mu)}{m_c(0)} = 1 - 3.3(3)\left(\frac{\mu}{\pi T_c}\right)^2 - 47(20)\left(\frac{\mu}{\pi T_c}\right)^4$, i.e., m_c shrinks with μ.

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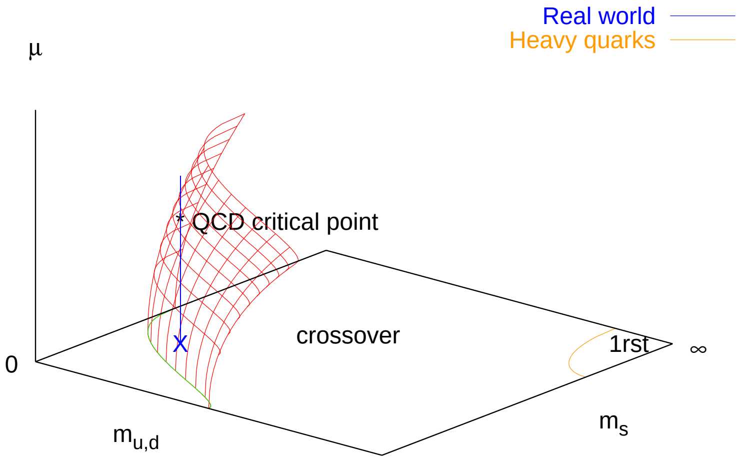

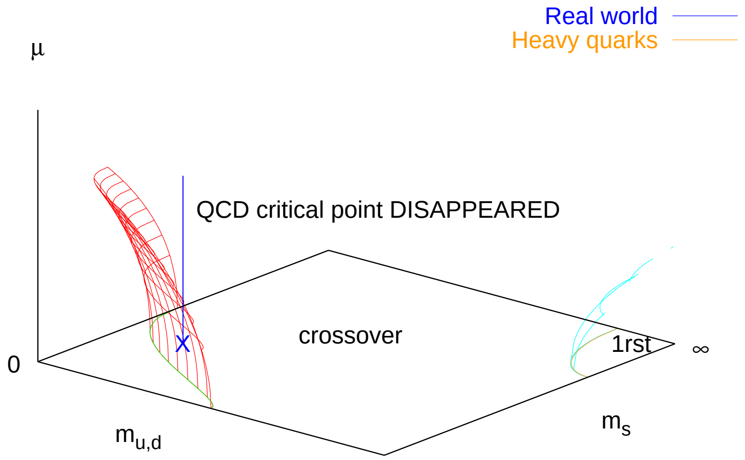

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Problems : i) Positive coefficient for finer lattice (Philipsen, CPOD 2009), ii) Known examples where shapes are different in real/imaginary μ, "The Critical line from imaginary to real baryonic chemical potentials in two-color QCD", P. Cea, L. Cosmai, M. D'Elia, A. Papa, PR D77, 2008