Nuclear Science Computing Center at CCNU

QCD phase diagram from Lattice QCD

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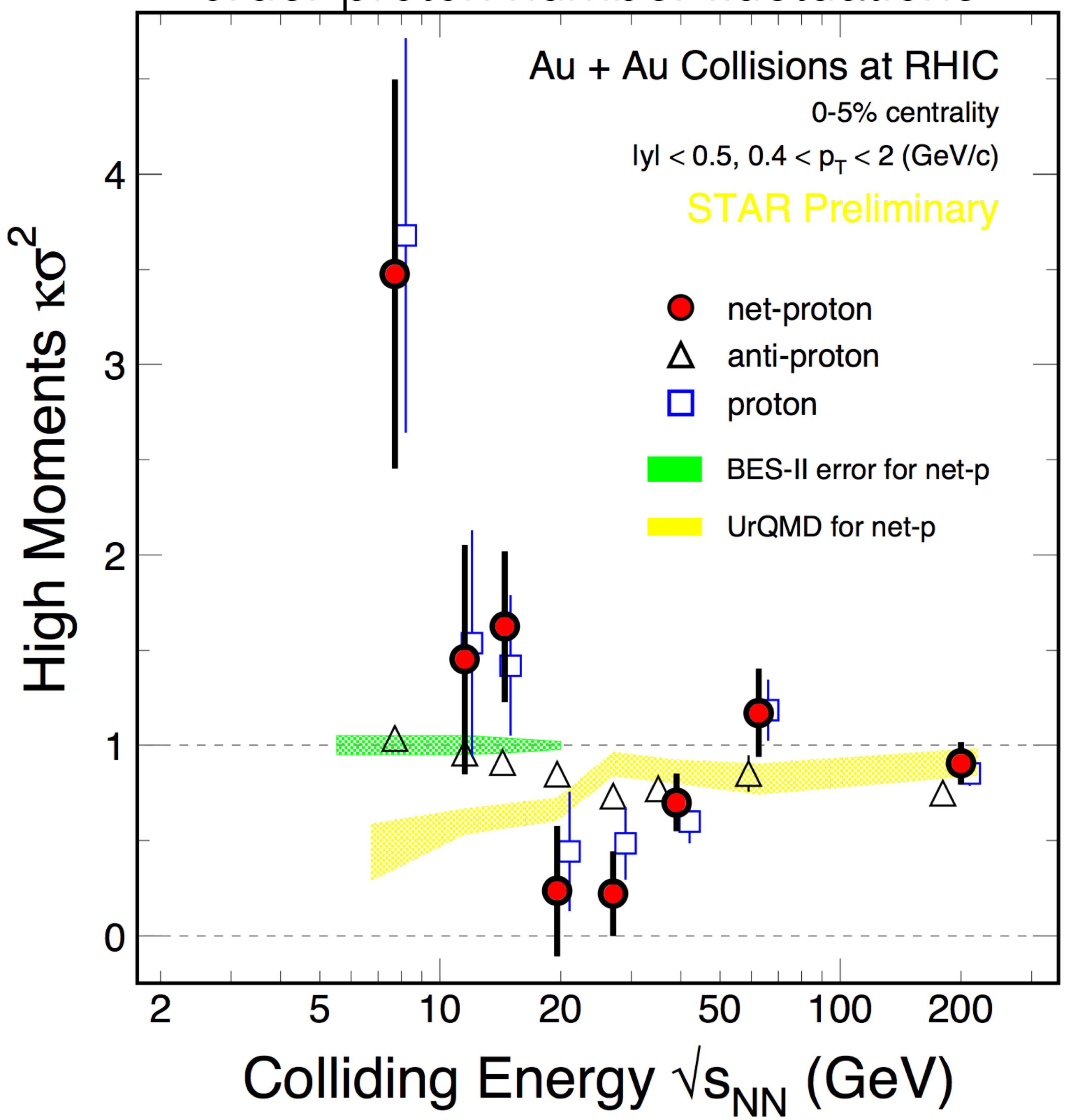
Central China Normal University

7th Asian Triangle Heavy-Ion Conference

3-6 Nov., 2018@USTC, Hefei

Search for the QCD critical point with fluctuations of conserved charges in HIC

Ratio of the 4th to 2nd order proton number fluctuations



Relation to QCD criticality?

STAR data: X.F. Luo, 1503.02558, X.F. Luo and N. Xu, 1701.02105

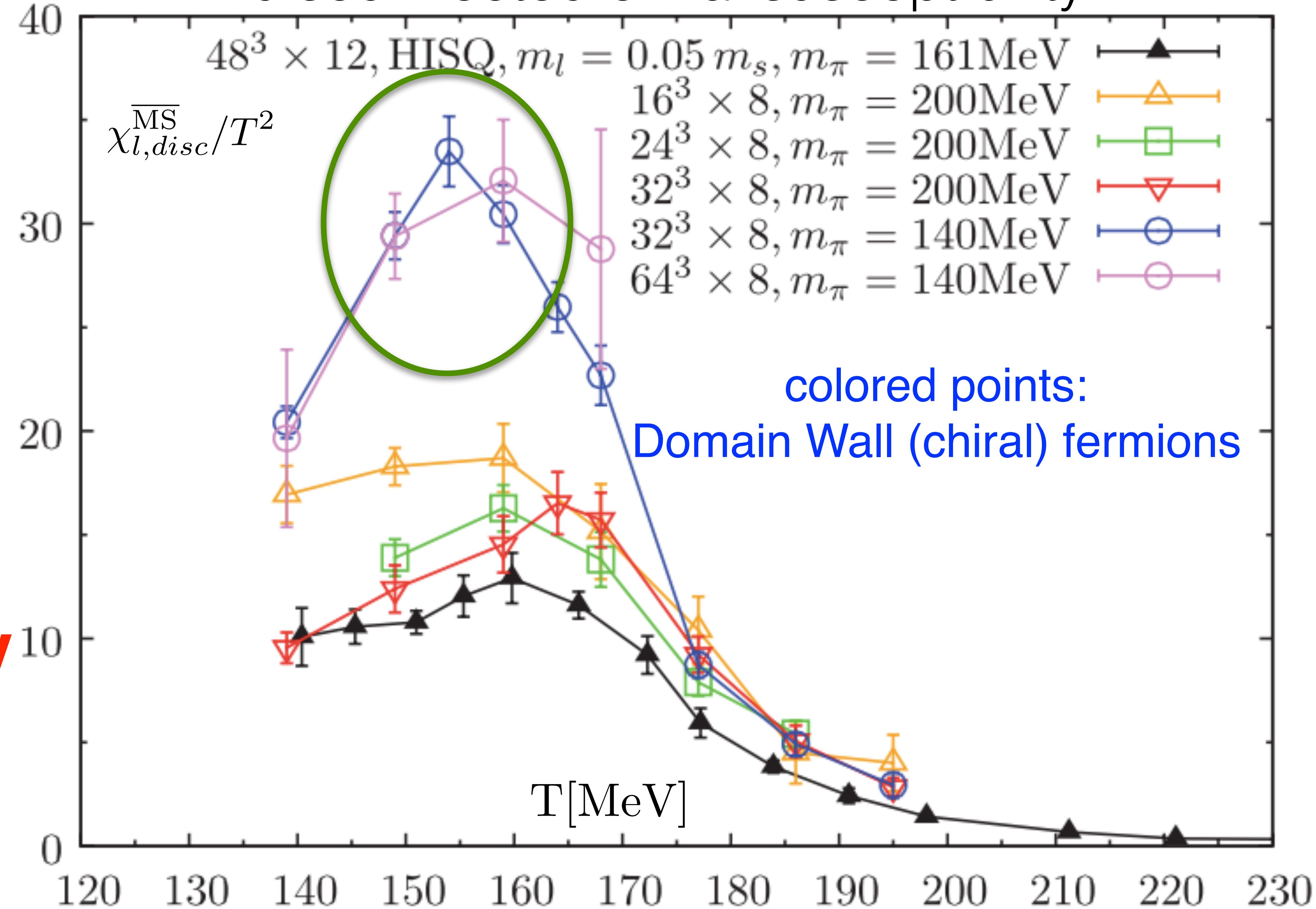
QCD transition with m_π =140 MeV at μ_B=0/$\sqrt{s_{NN}}$ ≳200 GeV

“cross over” type of transition

No true “PHASE transition”

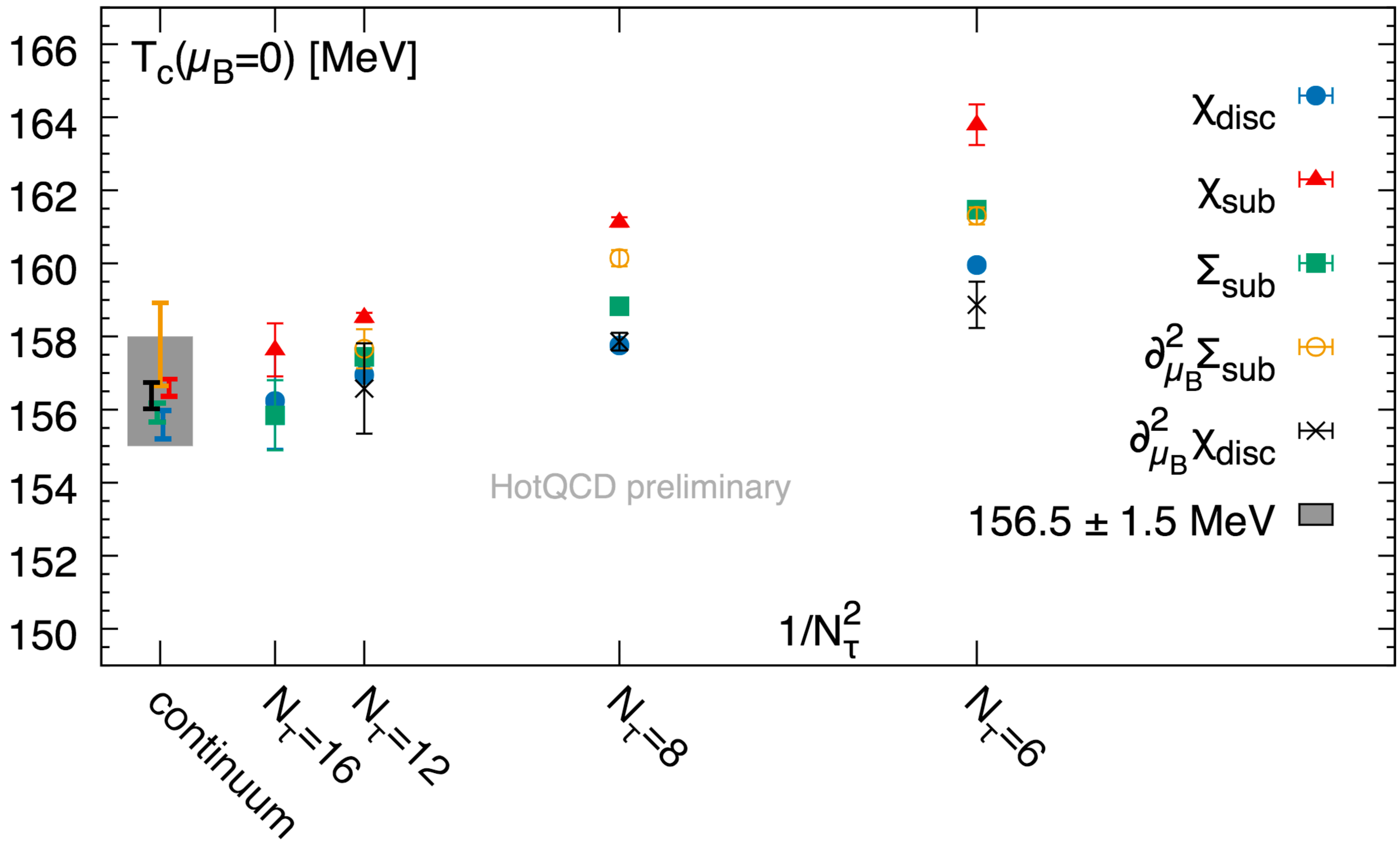
T_{pc} =155(1)(8) MeV

disconnected chiral susceptibility



T. Bhattacharya,…HTD,…et al. [HotQCD collaboration], Phys. Rev. Lett.,113(2014) 082001 (Editor’s suggestion)

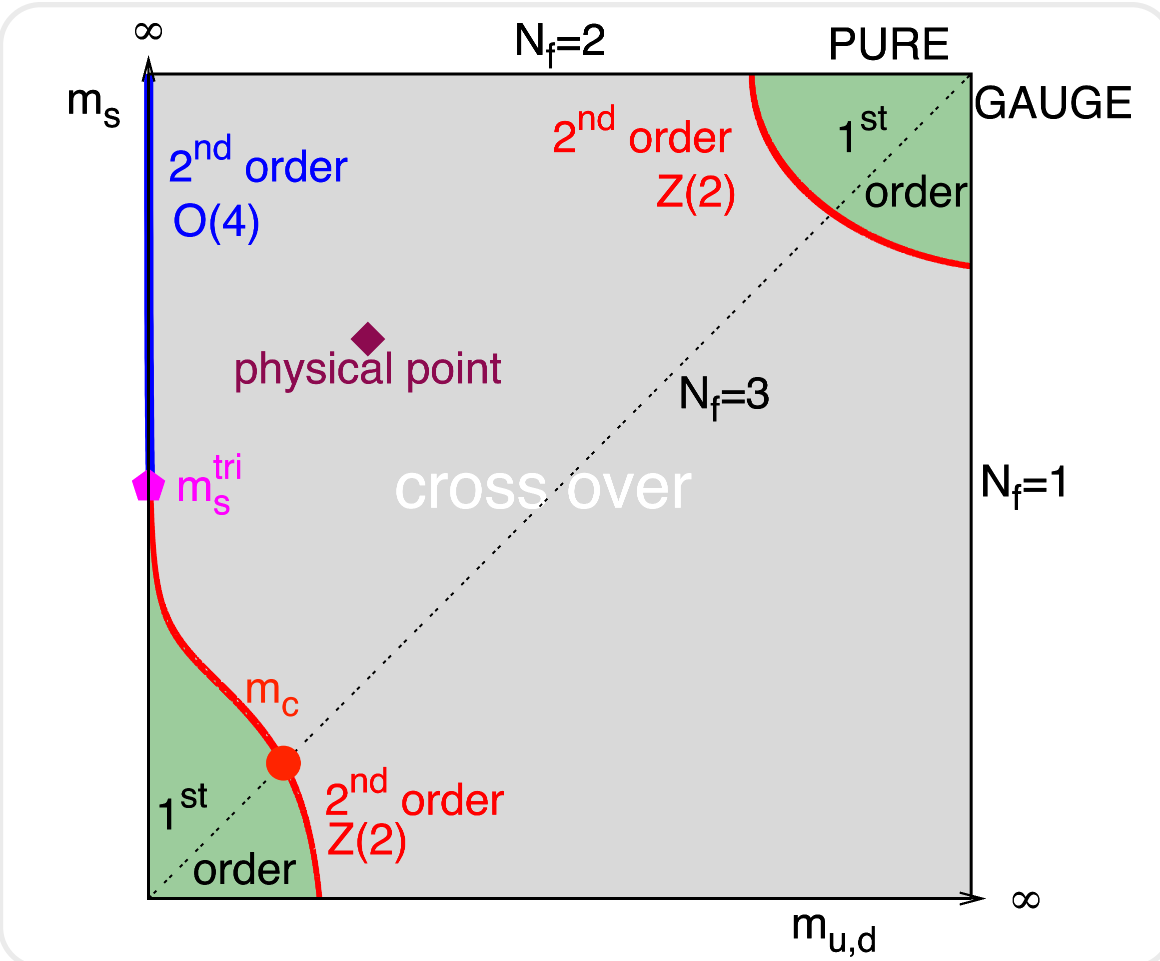
QCD transition with m_π =140 MeV at μ_B=0



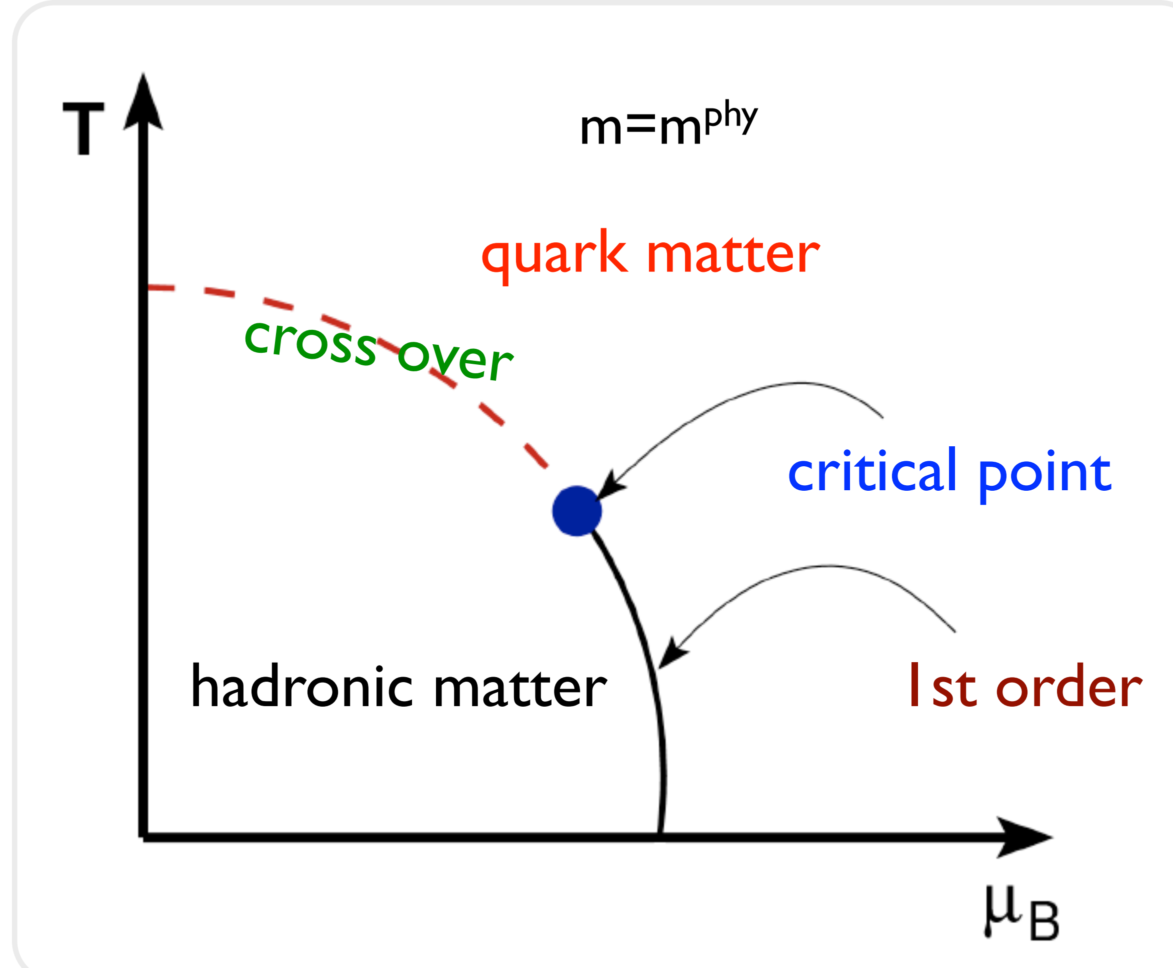
Higher precision in the continuum limit:

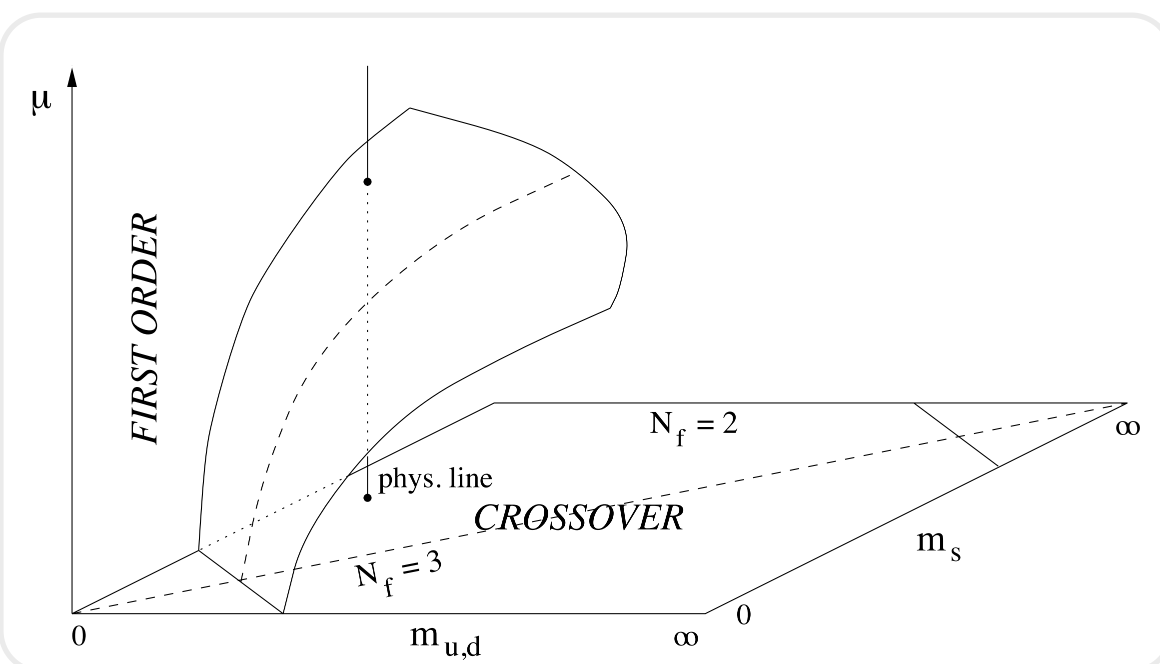
T_{pc} =156.5(1.5)MeV

QCD transitions at the physical point

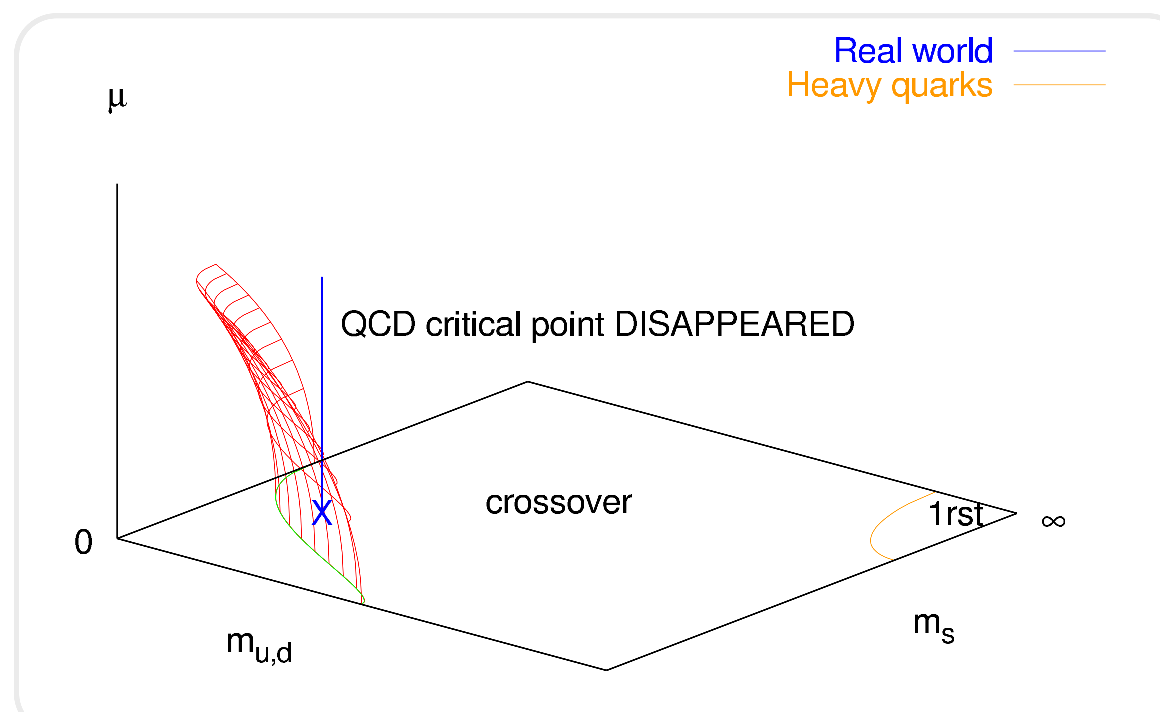


HTD, F. Karsch, S. Mukherjee, arXiv:1504.05274



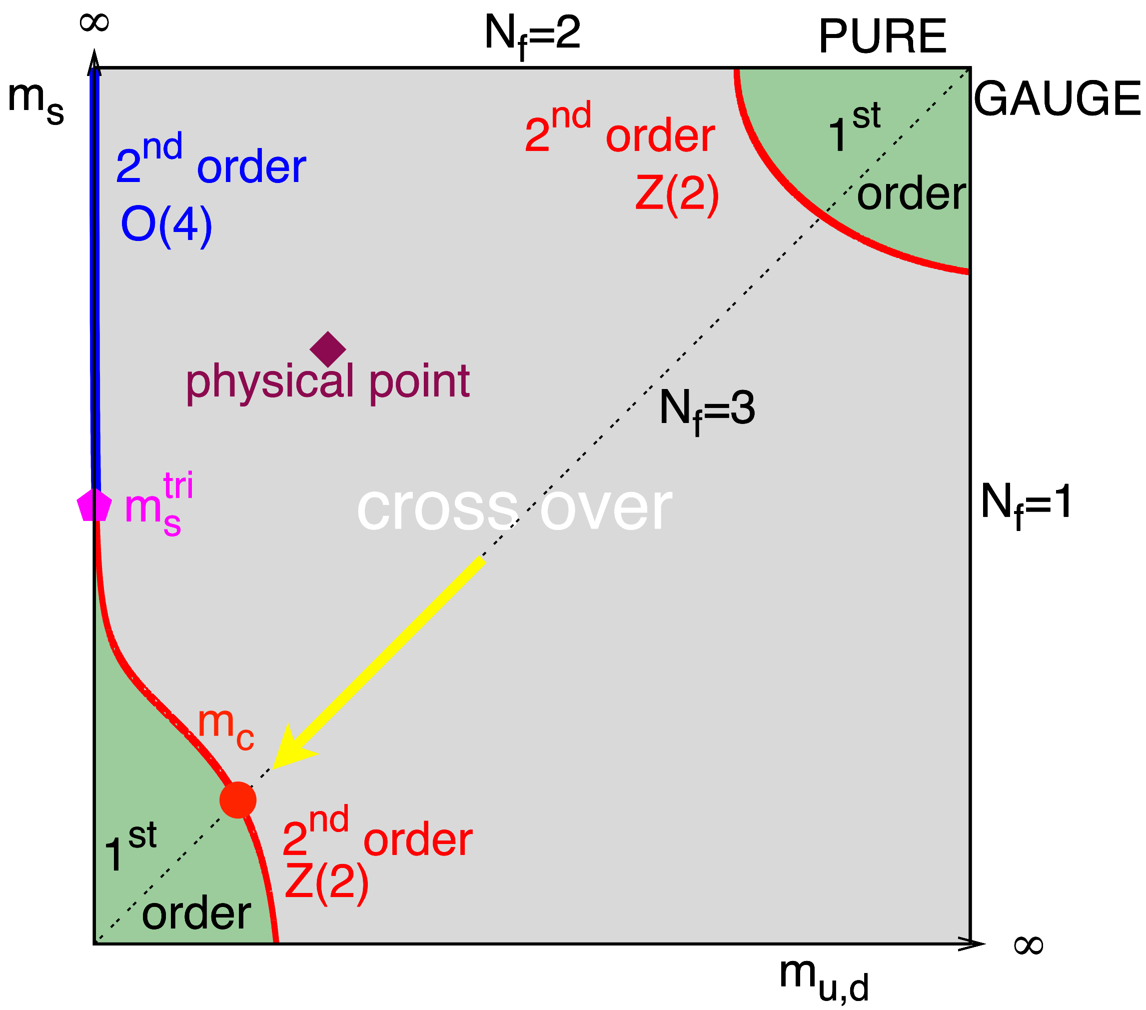


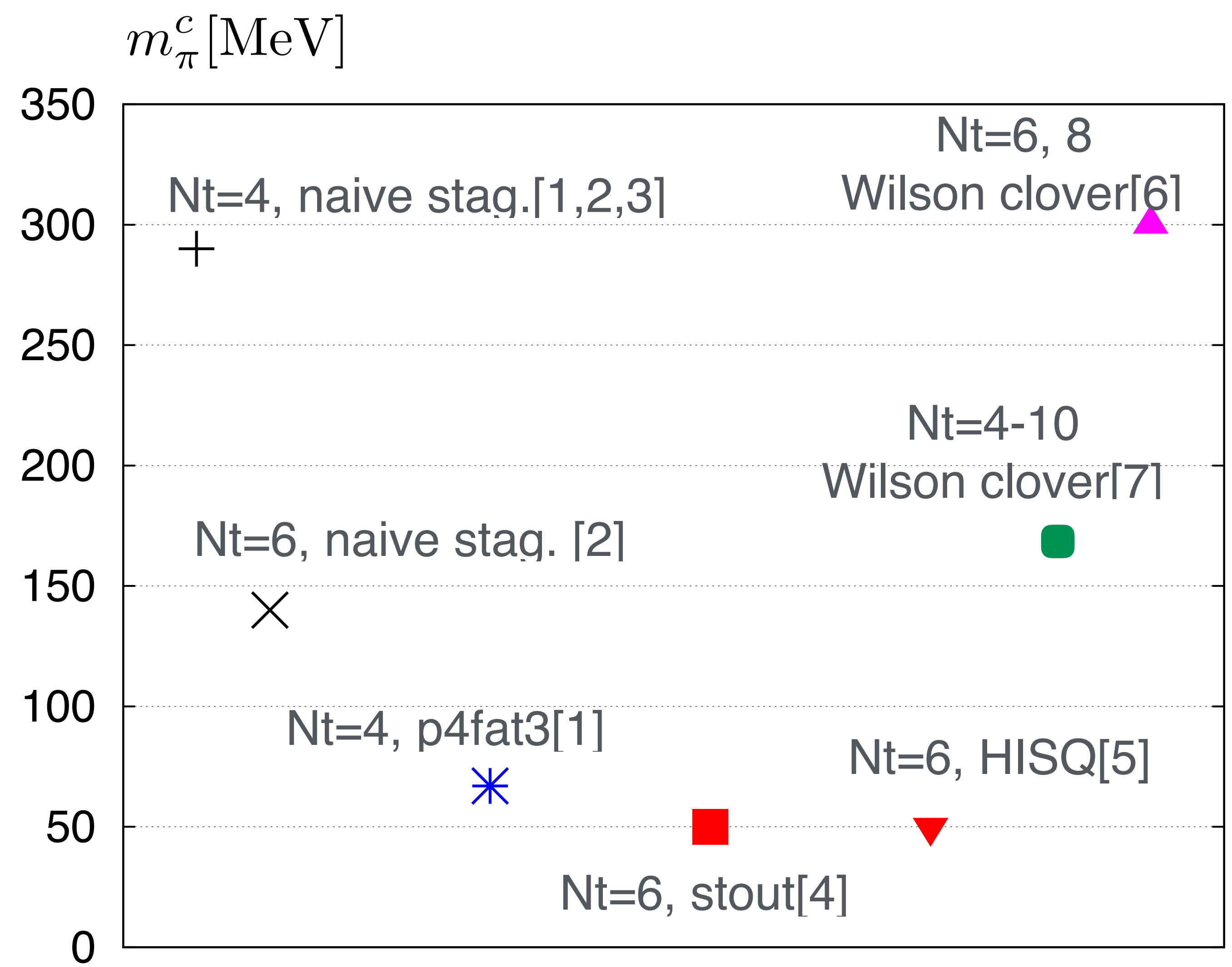
Karsch et al., '03, X.-Y. Jin et al., '15



de Forcrand & Philipsen, '07

1st order chiral phase transition region

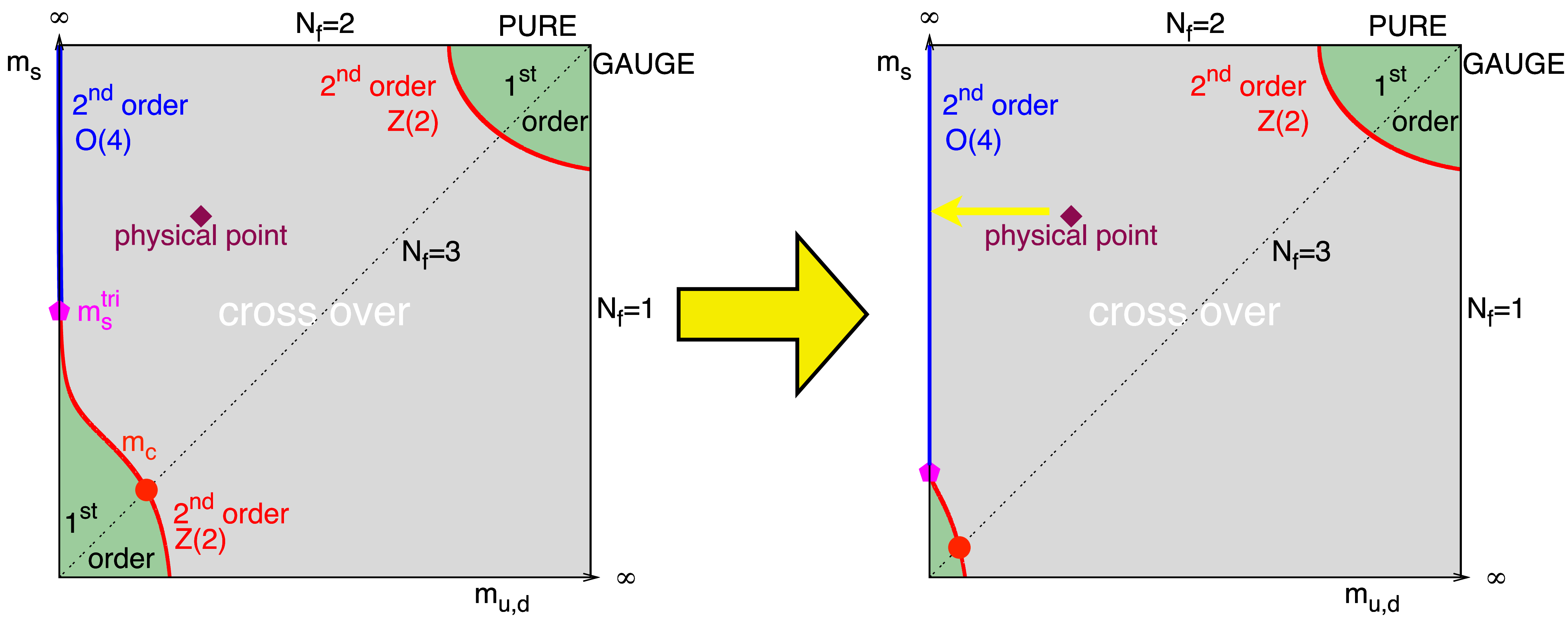




[1]F. Karsch et al., Nucl.Phys.Proc.Suppl. 129 (2004) 614
[2] P. de Forcrand et al, PoS LATTICE2007 (2007) 178
[3]D. Smith & C. Schmidt, Lattice 2011, arXiv:1109.6729
[4]G. Endrodi et al., PoS LAT2007 (2007) 228
[5] Bazavov, HTD et al., Phys.Rev. D95 (2017) no.7, 074505
[6]Y. Nakamura, Lattice 15',PRD92 (2015) no.11, 114511
[7] Jin et al., PRD96 (2017) no.3, 034523

The region shrinks from LQCD results
with improved actions and finer lattices

Chiral phase transition region in Nf=3 QCD at μB=0



1st order chiral phase transition seem to be not much relevant for thermodynamics at the physical point

How about the 2nd order O(4) transition line?

Nuclear Science Computing Center at CCNU

计算决定未来!

N: Nuclear **S**: Science **C³**: Color 3 -> QCD

“道生一，一生二，二生三，三生万物。” — 《道德经》老子 600 BC

”Tao gives birth to One, One gives birth to Two, Two gives birth to Three, Three gives birth to everything.“- Lao Tzu

18 computing nodes
(144 V100 GPUs)
Peak performance:
1 PFlops/s
Storage:
1 PB

June, 2018

TOP 500 The List.

The GREEN 500

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On 1-single GPU:
64^3x16, 72^3x12

8 GPUs in each node

8 nodes in each rack

18 computing nodes
(144 V100 GPUs)

Peak performance:
1 PFlops/s

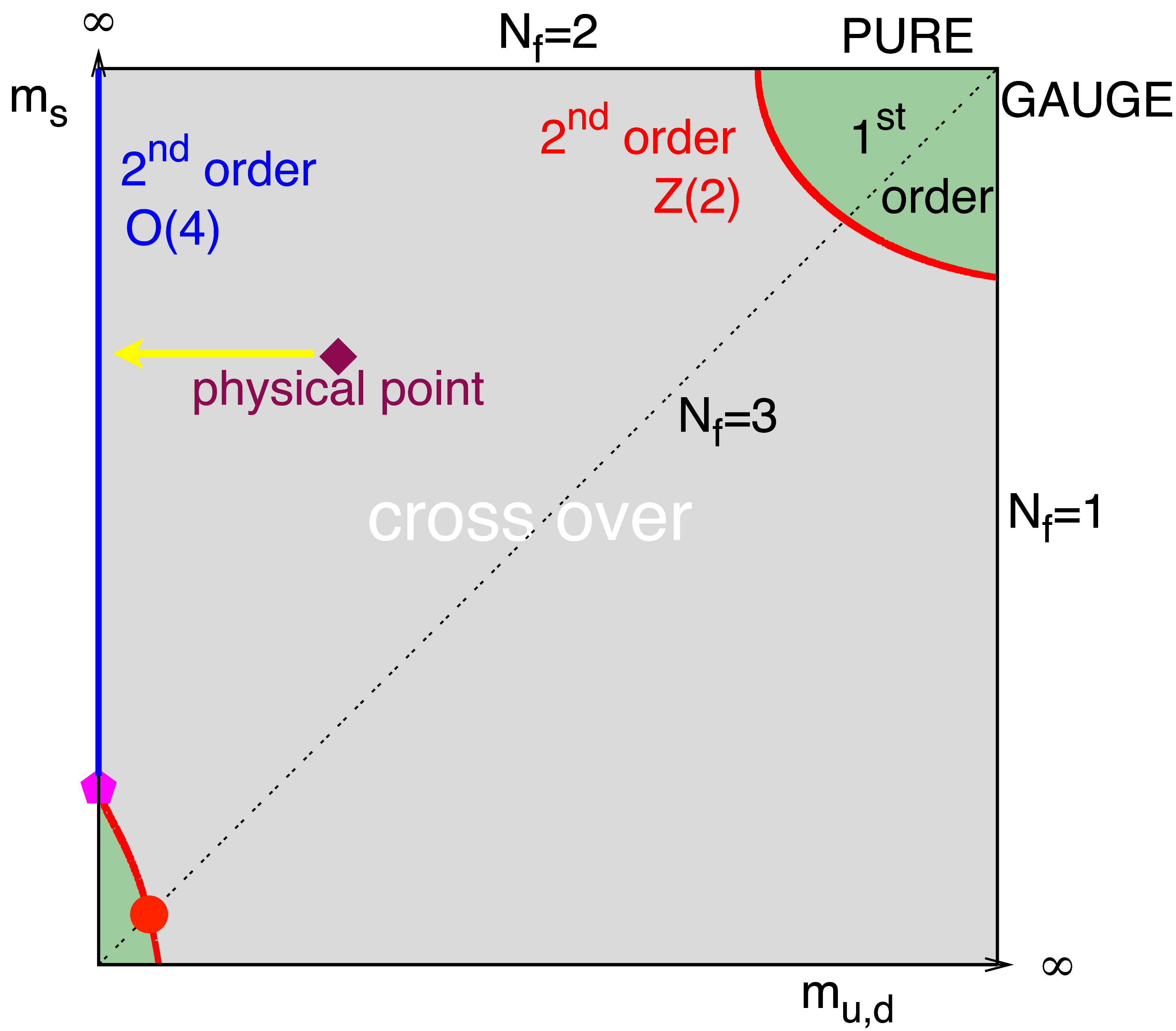
Storage:
1 PB

June, 2018

TOP 500 The List.

The GREEN 500

Towards chiral limit of (2+1)-flavor QCD

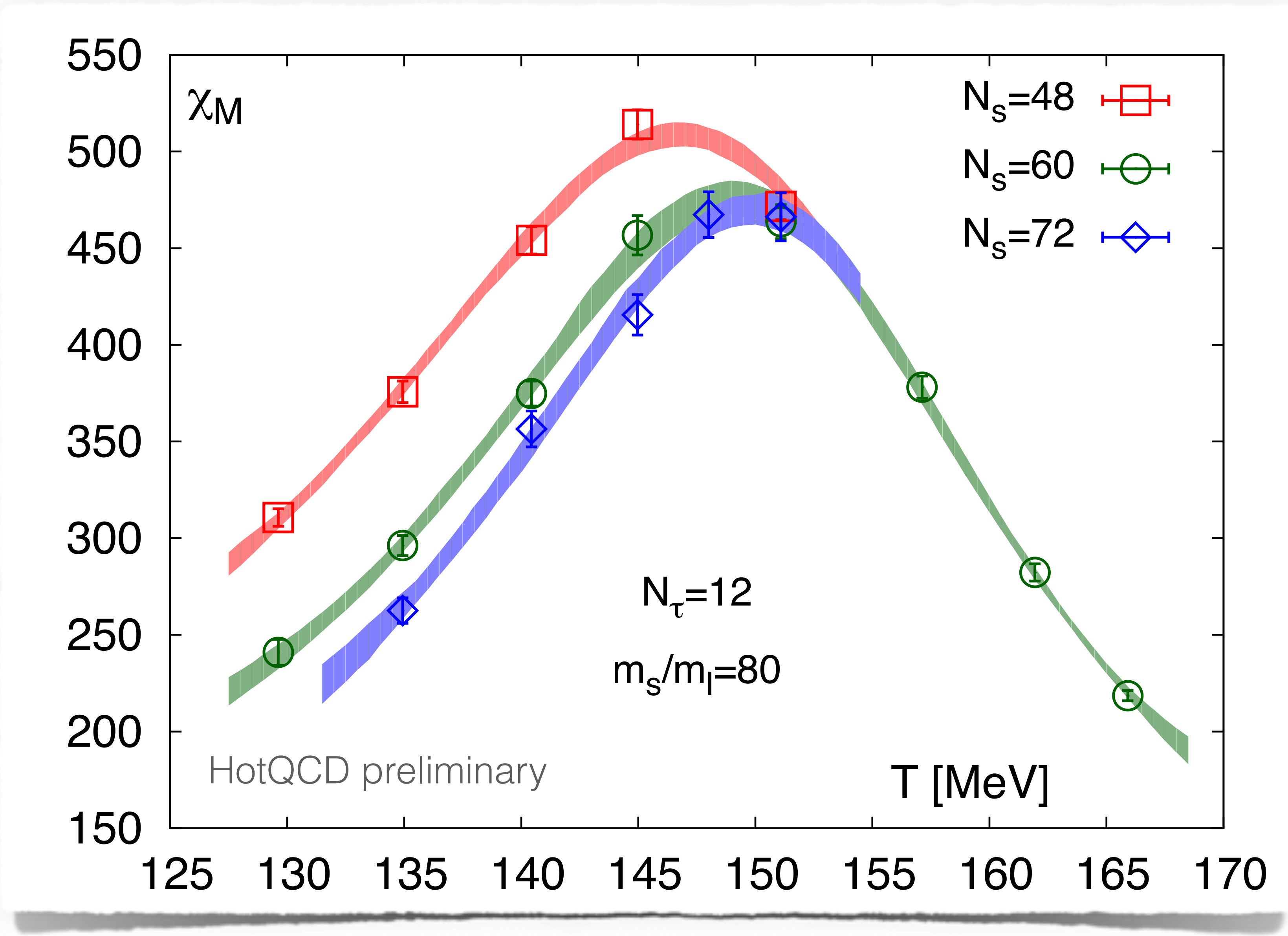


$m_u = m_d \rightarrow 0$

$m_s = m_s^{phy}$

Volume dependence of chiral susceptibility

m_π=80 MeV



No direct evidence of 1^{st} order phase transition down to m_π =80 MeV

hot from the machine

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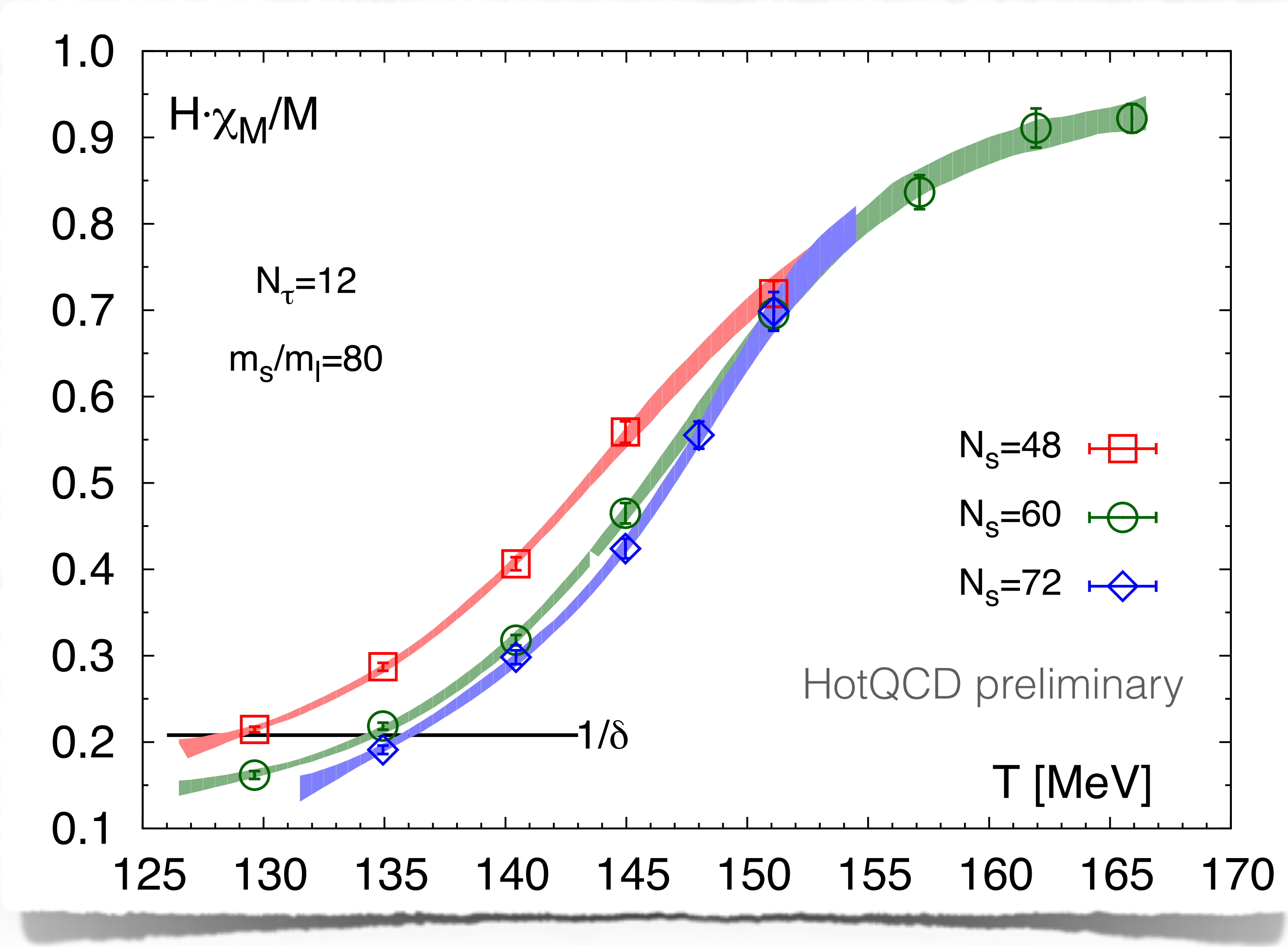
Chiral phase transition temperature T_c

$H\chi_M/M \to 1/\delta$ @ T_c^0

H: m_l/m_s
M: chiral condensate
χ_M: chiral susceptibility



hot from the machine

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A novel approach to estimate T_c^0

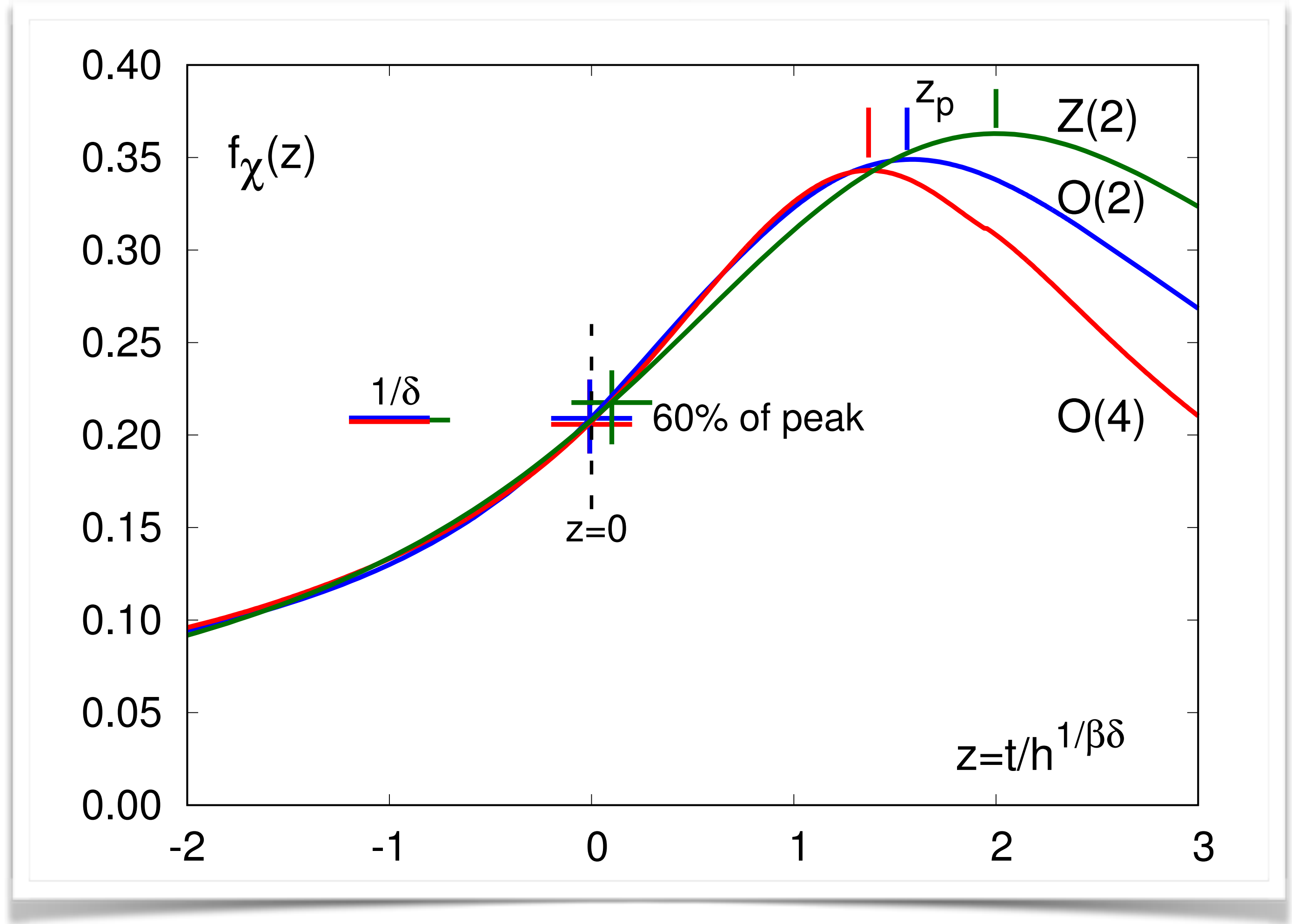
- Pseudo-critical temperature at H

$$T_{pc}(H) = T_c^0 \left(1 + \frac{z_p}{z_0} H^{\frac{1}{\beta\delta}}\right)$$

- Estimate of the chiral transition T_c^0

$$T_{60\%}^{-}(H) = T_c^0 \left(1 + \frac{z_{60\%}^{-}}{z_0} H^{\frac{1}{\beta\delta}}\right)$$

- ☑ small quark mass dependence
- ☑ small variations among universality classes

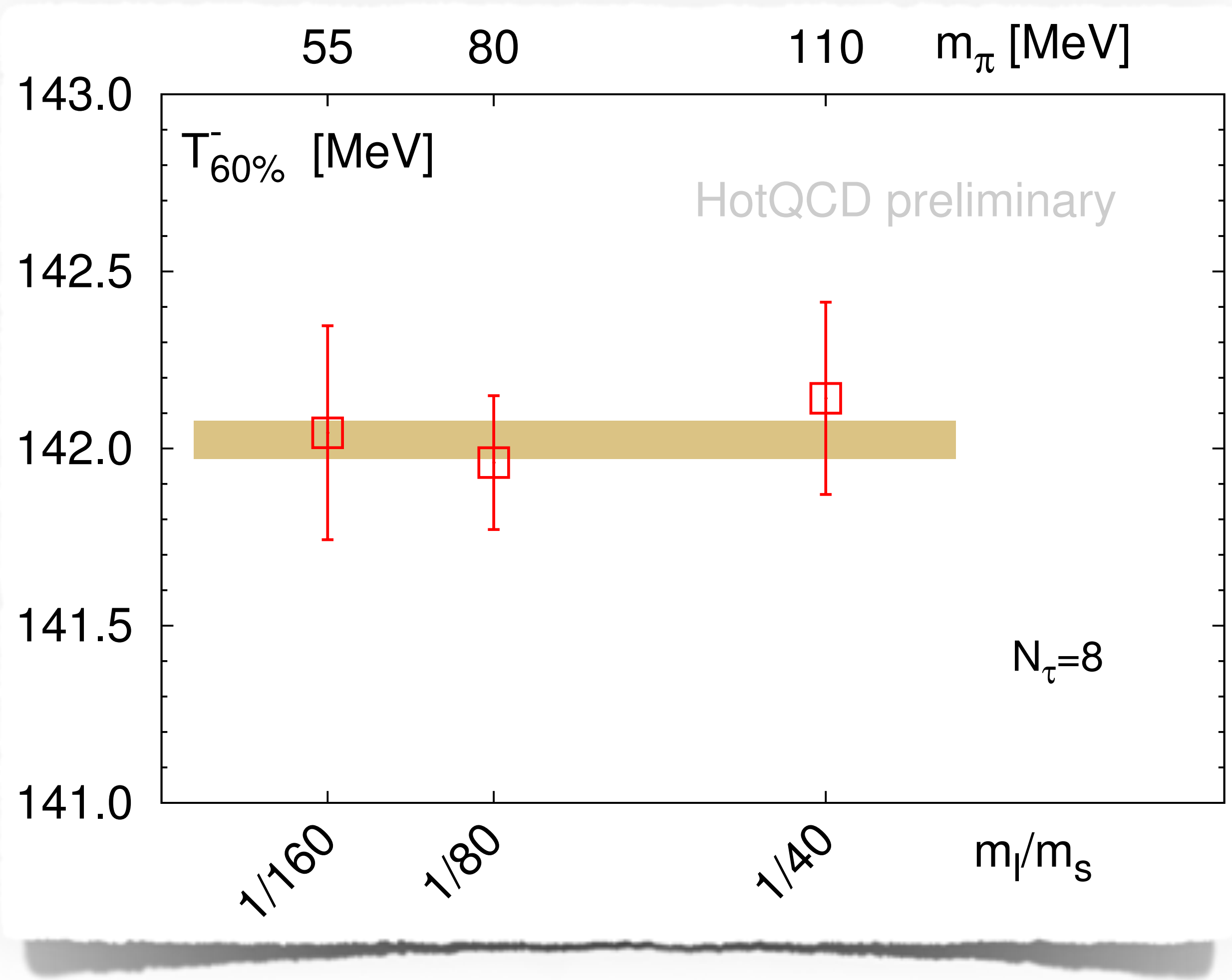


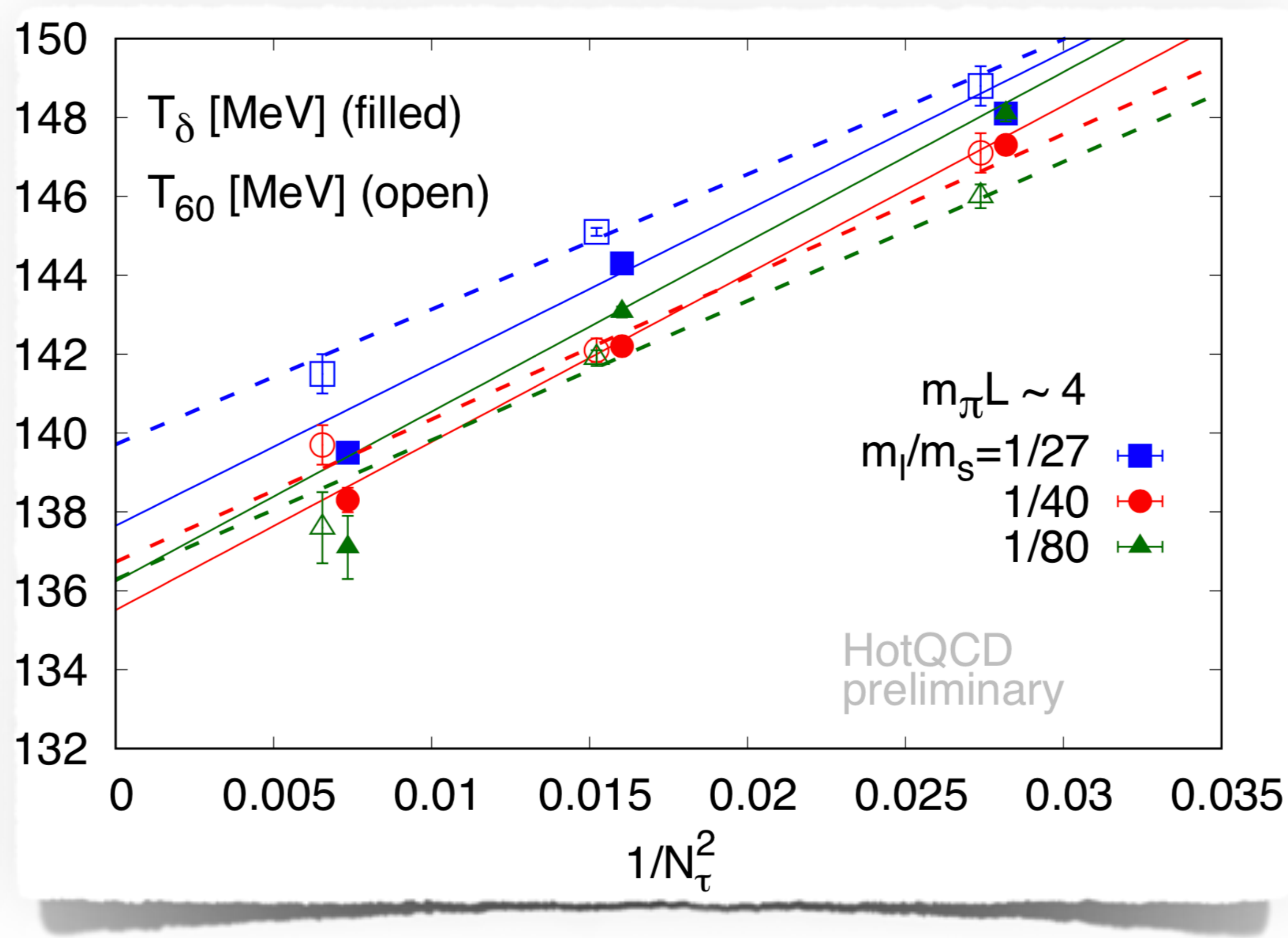
z_p: peak location of the susceptibility

$z_{60\%}^{-}$: location of 60% of peak height from left

	δ	z_p	z_{60}^{-}
Z(2)	4.805	2.00(5)	0.10(1)
O(2)	4.780	1.58(4)	-0.005(9)
O(4)	4.824	1.37(3)	-0.013(7)

Estimate of chiral phase transition T_c

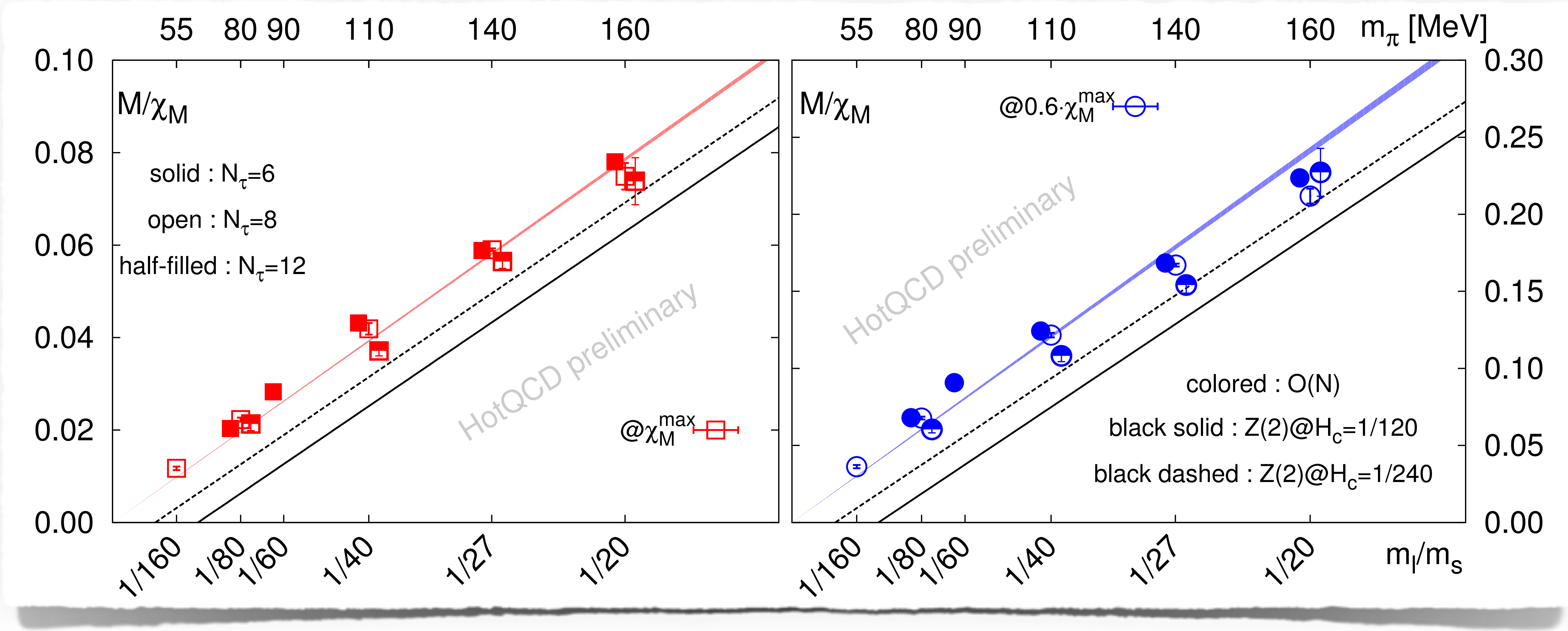




S.-T. Li, Lattice 2018, A. Lahiri, QM 2018

$T_c \approx 135$ MeV

Consistency of QCD chiral phase transition with O(N) universality class



S.-T. Li, Lattice 2018, A. Lahiri, QM 2018

$$M/\chi_M = \frac{m_l - m_l^{critical}}{m_s^{phys}} \frac{f_M}{f_{\chi_M}}$$

Taylor expansion coefficients of QCD pressure at μ_B =/=0

Allton et al., Phys.Rev. D66 (2002) 074507
Gavai & Gupta, Phys.Rev. D68 (2003) 034506

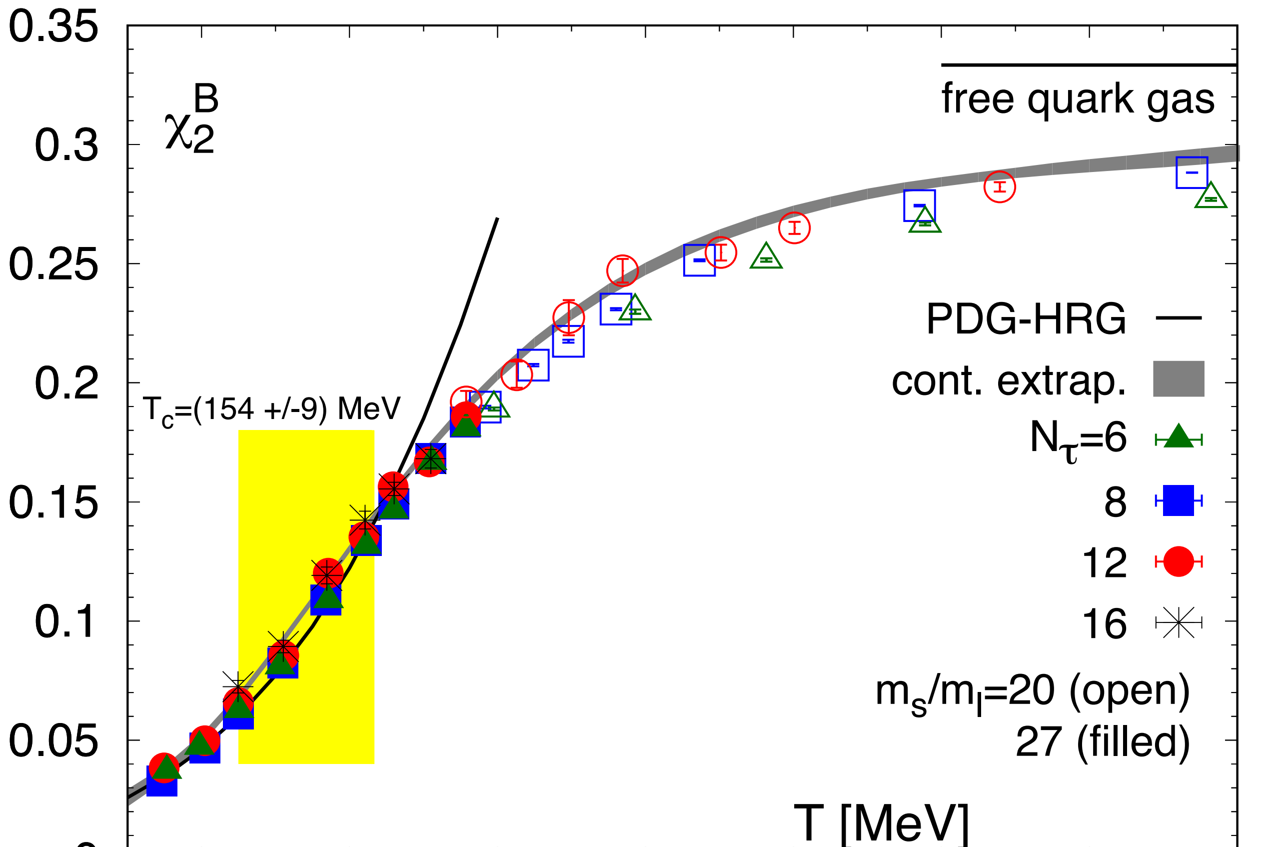
$\mu_Q=\mu_S=0$:

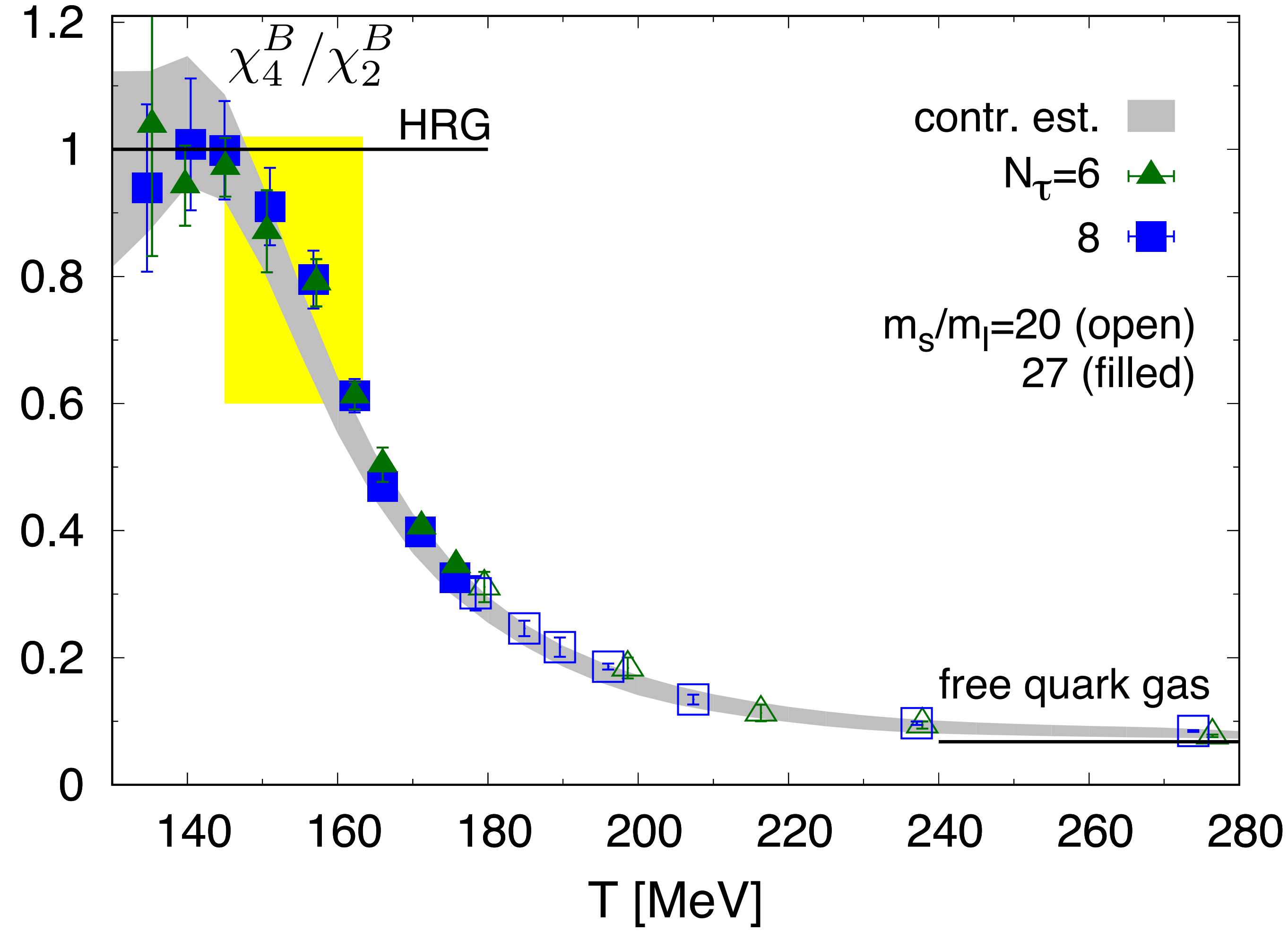
$$\Delta(P/T^4) = \frac{P(T,\mu_B)-P(T,0)}{T^4} = \sum_{n=1}^{\infty} \frac{\chi_{2n}^B(T)}{(2n)!}\left(\frac{\mu_B}{T}\right)^{2n}$$

$$= \frac{1}{2}\chi_2^B(T)\hat{\mu}_B^2\left(1+\frac{1}{12}\frac{\chi_4^B(T)}{\chi_2^B(T)}\hat{\mu}_B^2+\frac{1}{360}\frac{\chi_6^B(T)}{\chi_2^B(T)}\hat{\mu}_B^4+\cdots\right)$$

LO expansion coefficient
variance of net-baryon number distri.

NLO expansion coefficient
kurtosis * variance





Bielefeld-BNL-CCNU, Phys.Rev. D95 (2017) no.5, 054504

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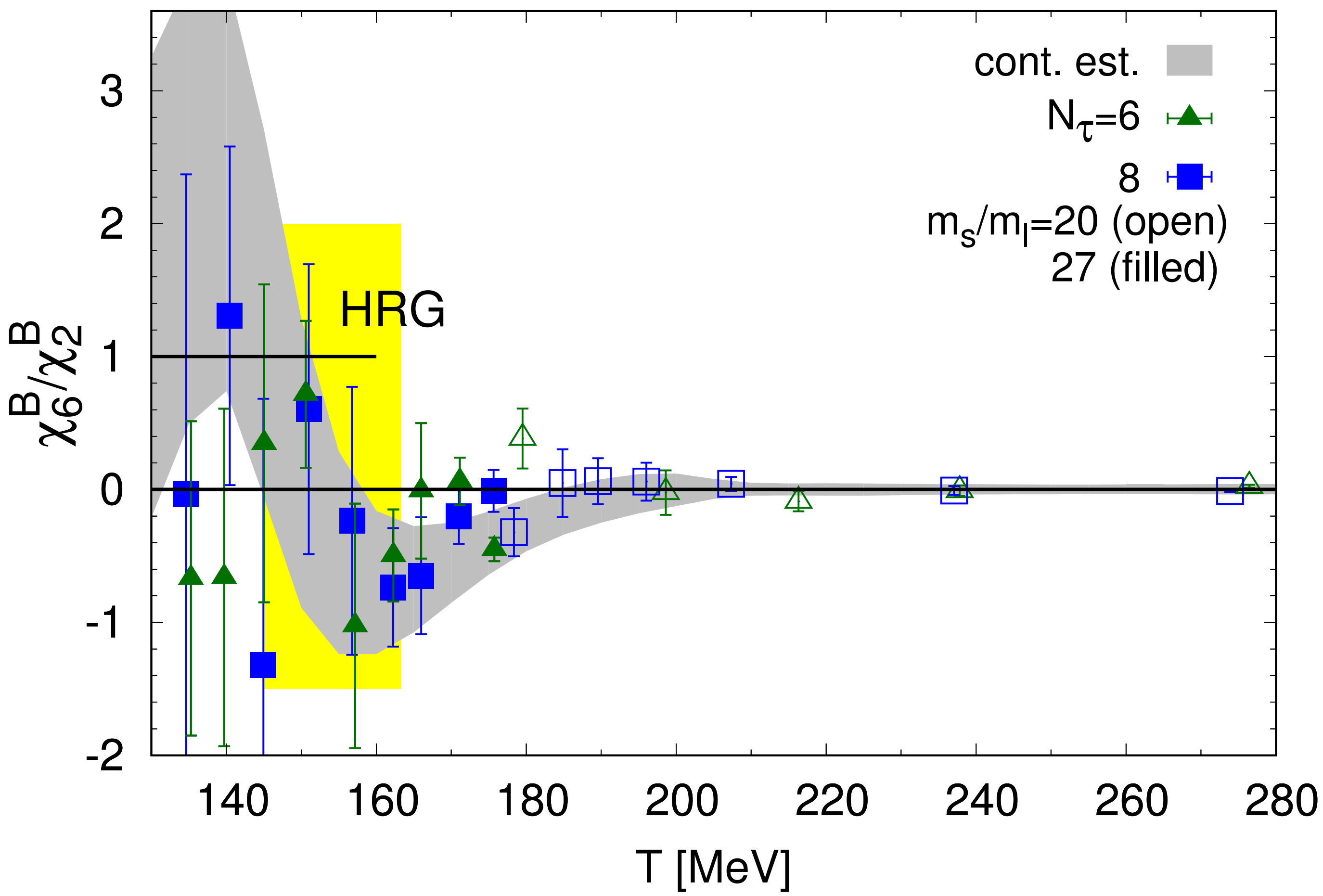
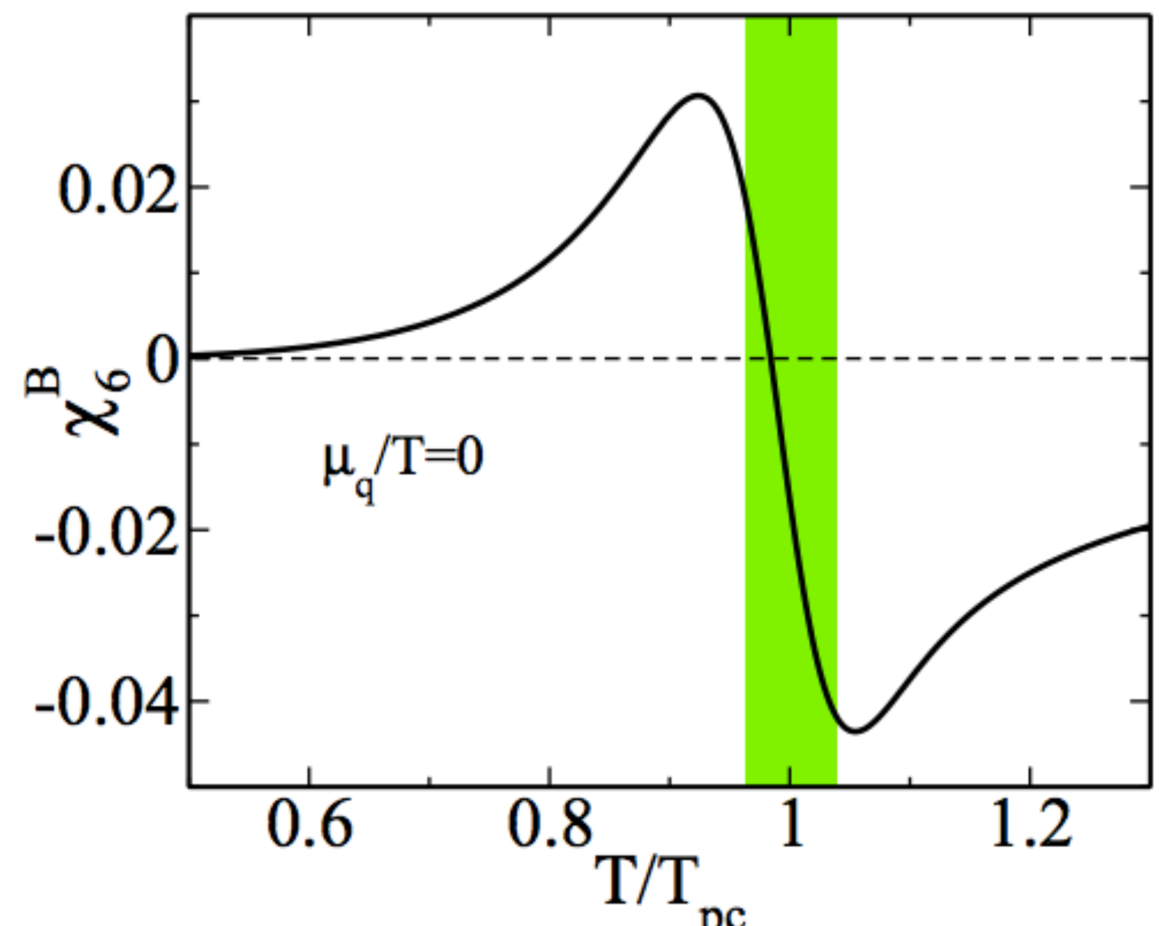
NNLO expansion coefficient



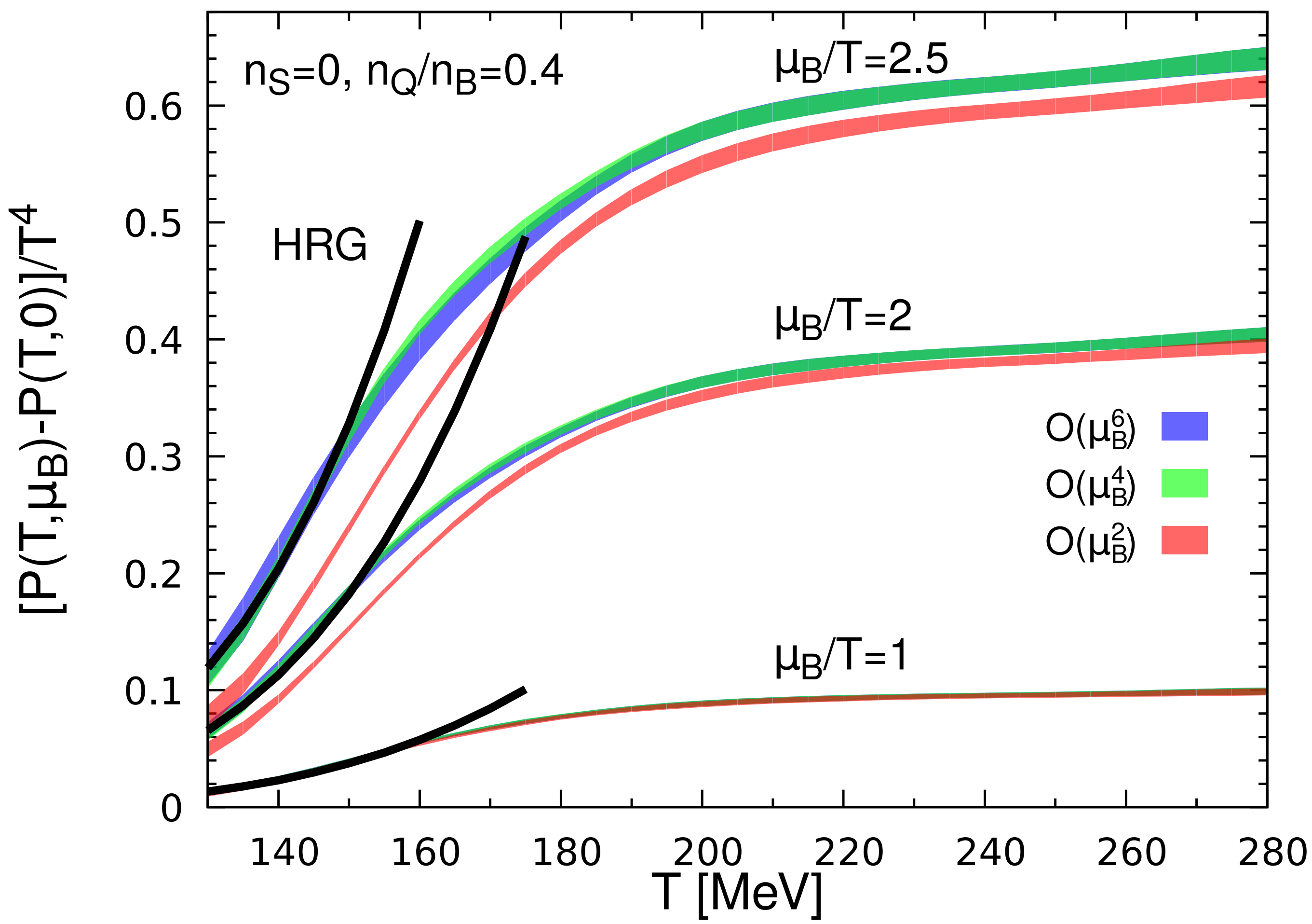
Bielefeld-BNL-CCNU, Phys.Rev. D95 (2017) no.5, 054504

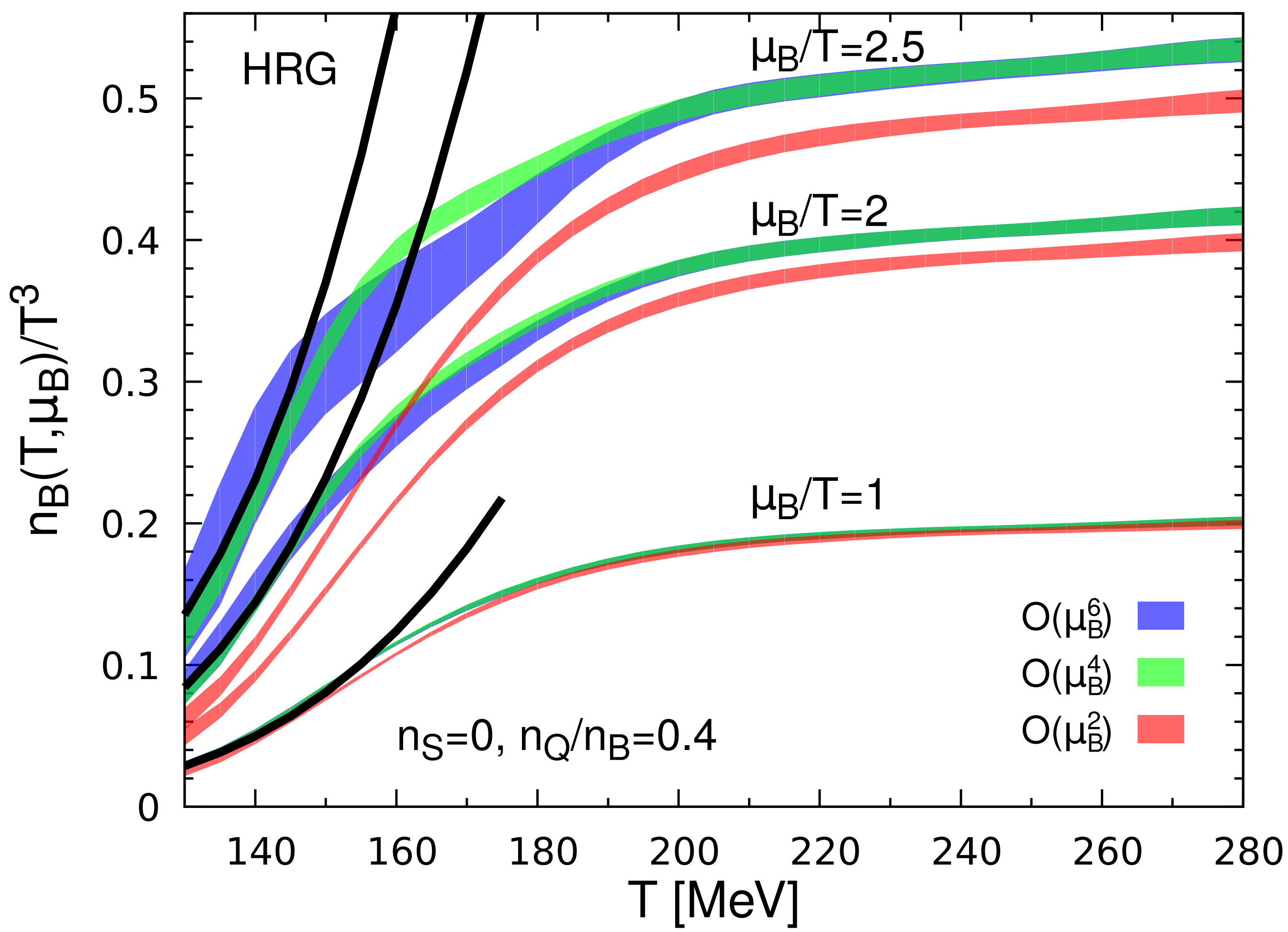
PQM with O(4) symmetry



B. Friman et al.,EPJC71 (2011) 1694

Pressure and baryon number density in the strangeness neutral case





Bielefeld-BNL-CCNU, Phys.Rev. D95 (2017) no.5, 054504

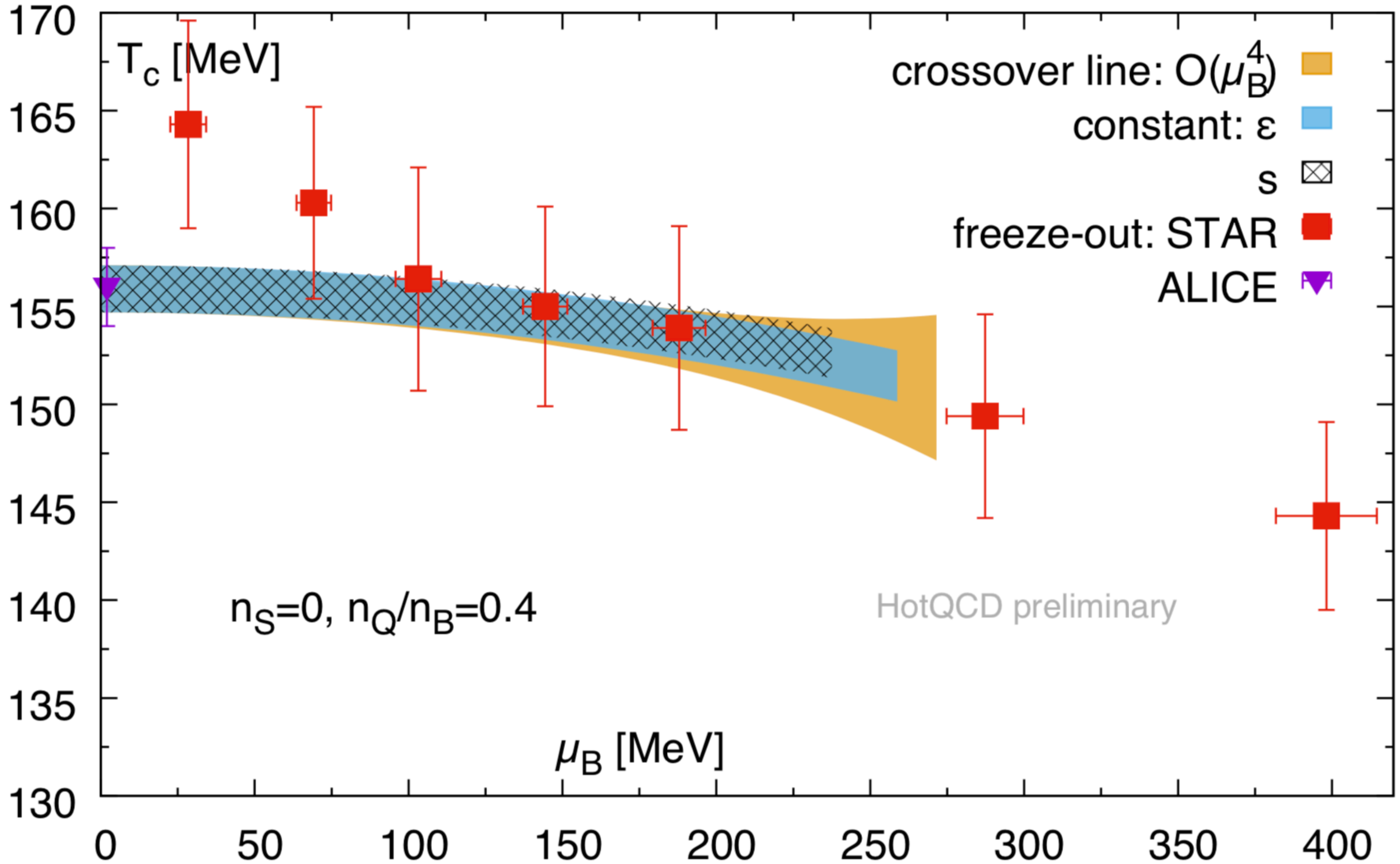
The EoS is well under control at $\mu_B/T \lesssim 2$ or $\sqrt{s_{NN}} \gtrsim 12$ GeV

Consistent results obtained using analytic continuations from the imaginary mu

Wuppertal-Budapest-Houston: EPJ Web Conf. 137(2017) 07008

Crossover, line of constant physics & freeze-out

$$T(\mu_B) = T(0)\left(1 - \kappa_2\left(\frac{\mu_B}{T}\right)^2 - \kappa_4\left(\frac{\mu_B}{T}\right)^4 + \mathcal{O}\left(\frac{\mu_B}{T}\right)^6\right)$$



curvature of crossover line

HotQCD preliminary

$$\kappa_2 = 0.0123 \pm 0.003$$

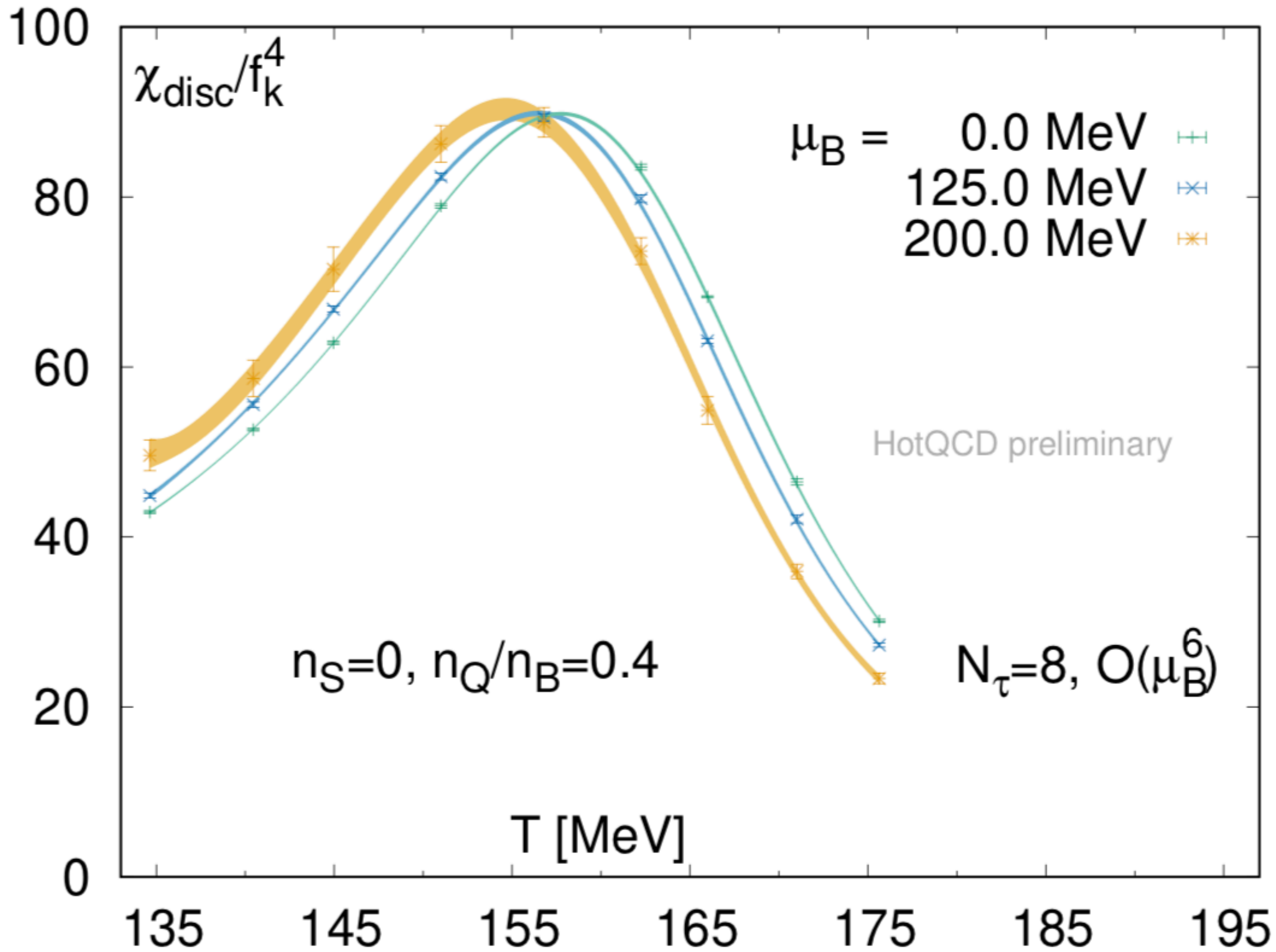
$$\kappa_4 = 0.000131 \pm 0.0041$$

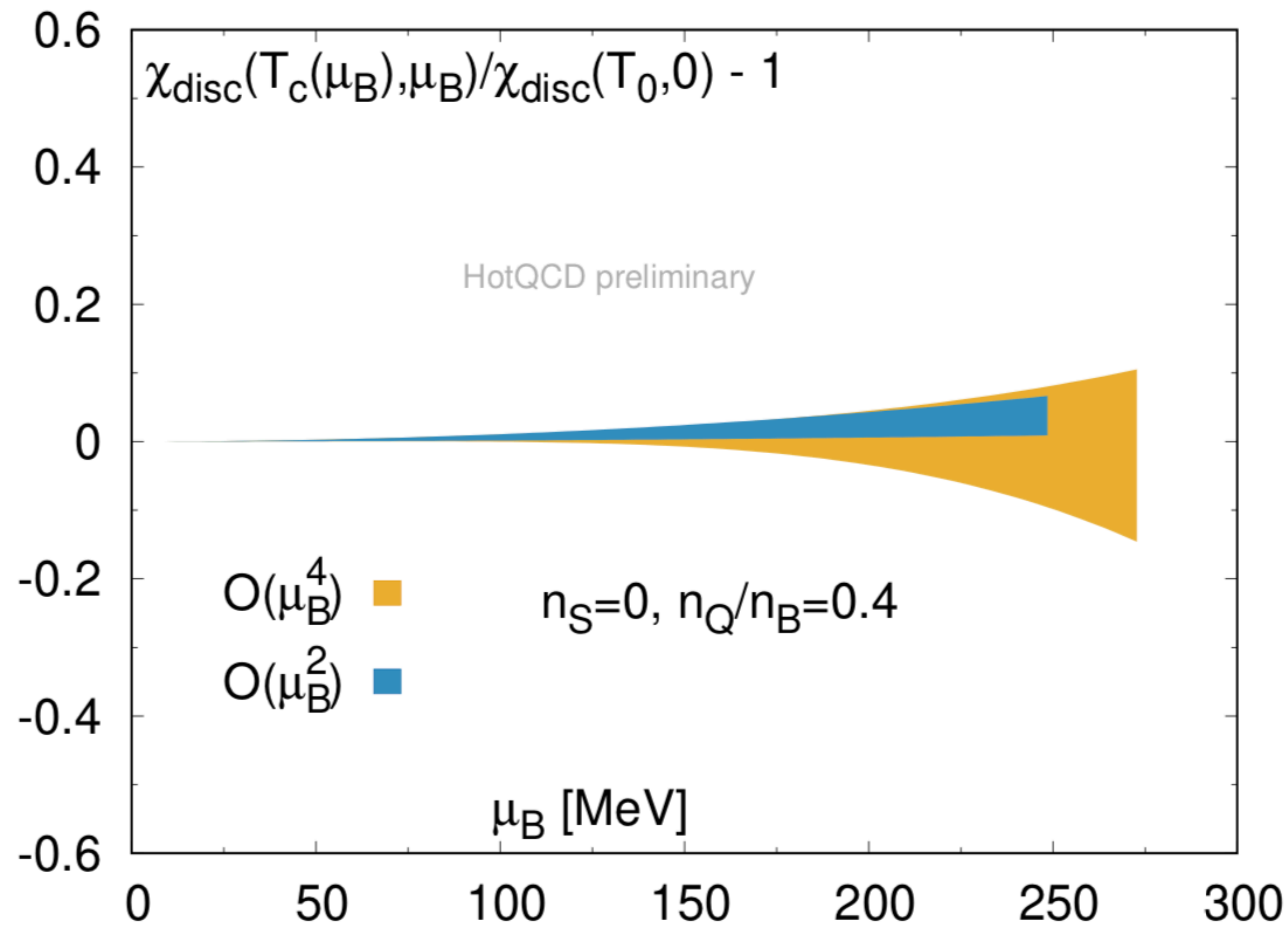
curvature at constant b:

$$0.006 \leq \kappa_2^b \leq 0.012, \quad b = P, \epsilon, s$$

Bielefeld-BNL-CCNU, PRD95 (2017) no.5, 054504

Order Parameter Susceptibility at μB=/=0

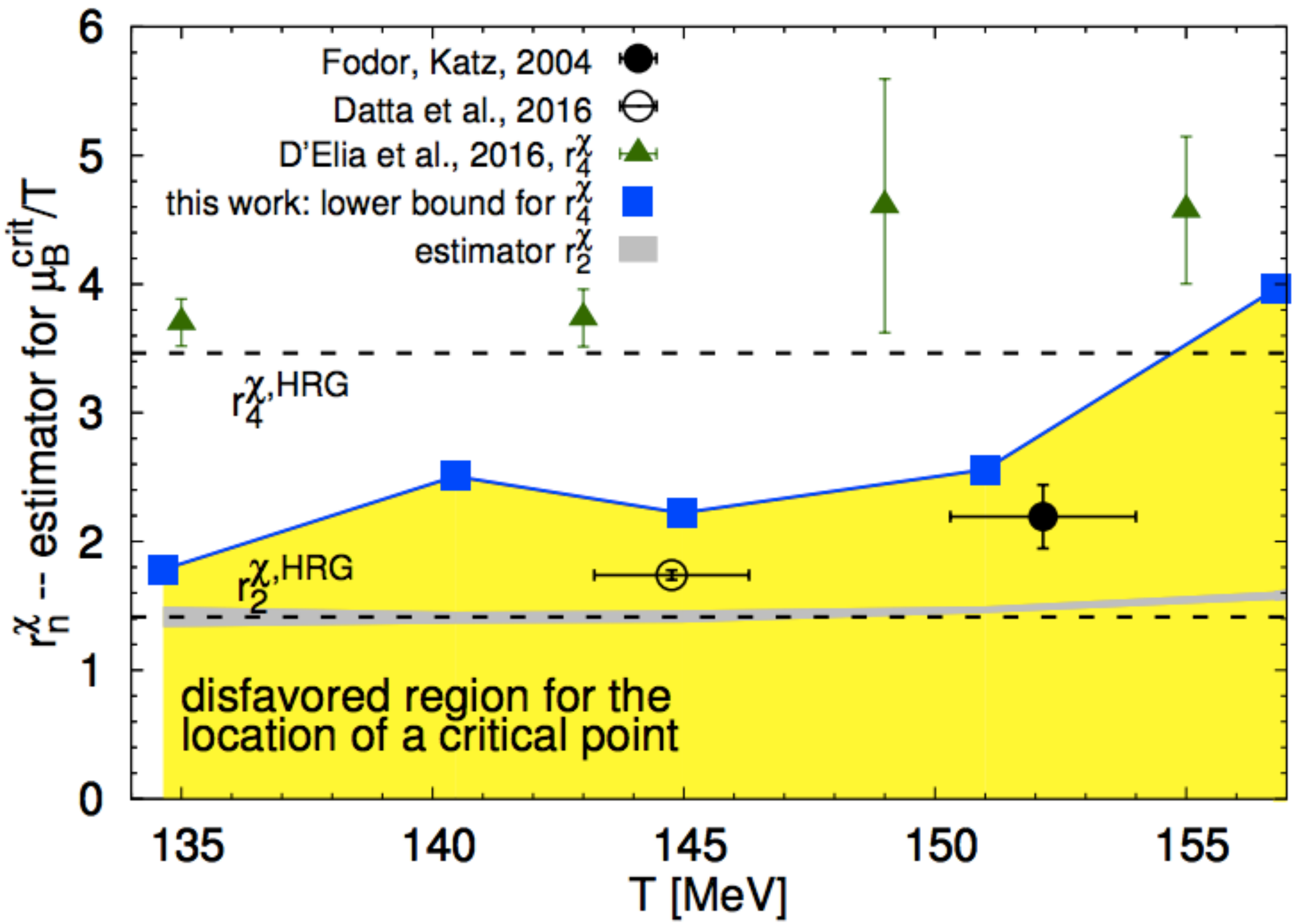




No indication of a stronger phase transition at larger μB

Estimates of the radius of convergence

radius of convergence = $\lim_{n\to\infty} r^{\chi}_{2n} = \lim_{n\to\infty} \left| \frac{2n(2n-1)\chi^B_{2n}}{\chi^B_{2n+2}} \right|^{1/2}$



HISQ + Taylor Exp. (this work):
Nf=2+1, Nt=8
Bielefeld-BNL-CCNU,
PRD 95 (2017) no.5, 054504

stout + Img. mu:
Nf=2+1,Nt=8
D'Elia et al., PRD 95 (2017) 094503

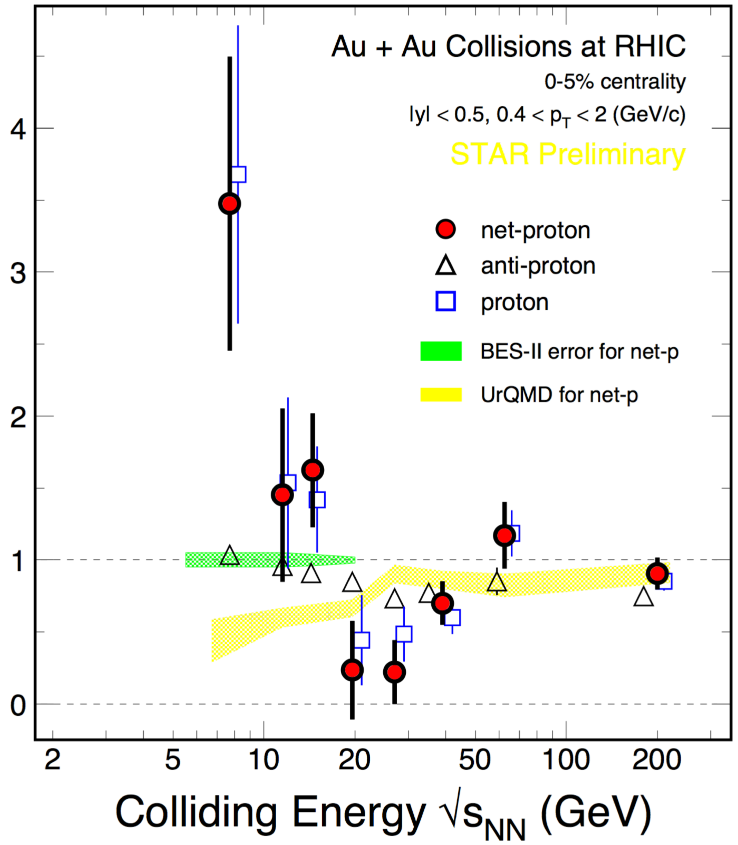
unimproved staggered + Taylor Exp.:
Nf=2, Nt=4,6,8
Datta et al., PRD 95 (2017) 054512

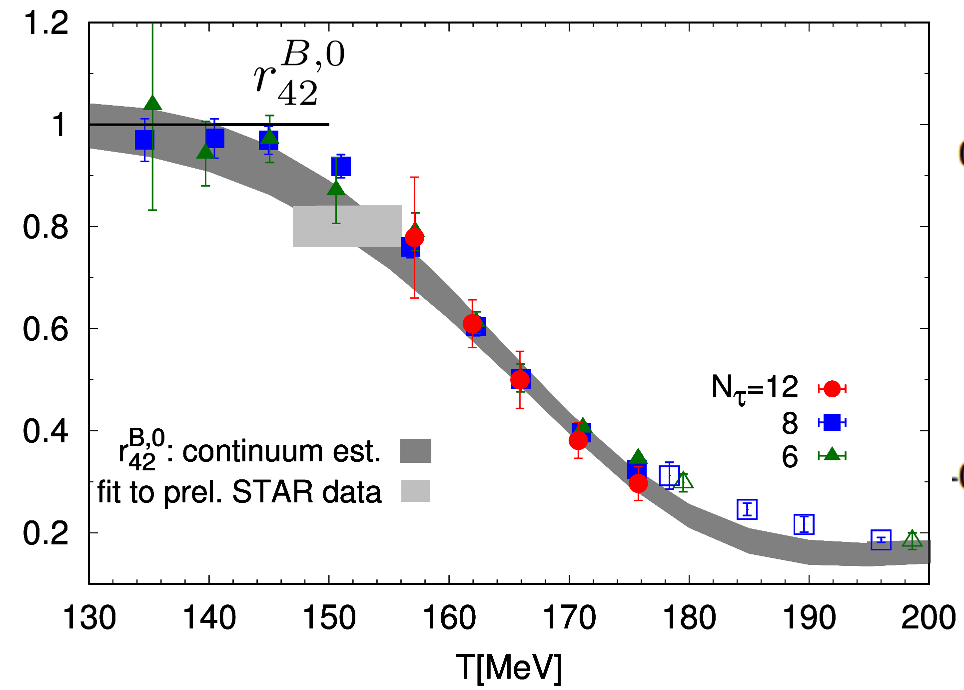
unimproved staggered + Reweighting:
Nf=2+1, Nt=4
Fodor and Katz, JHEP 0404 (2004) 050

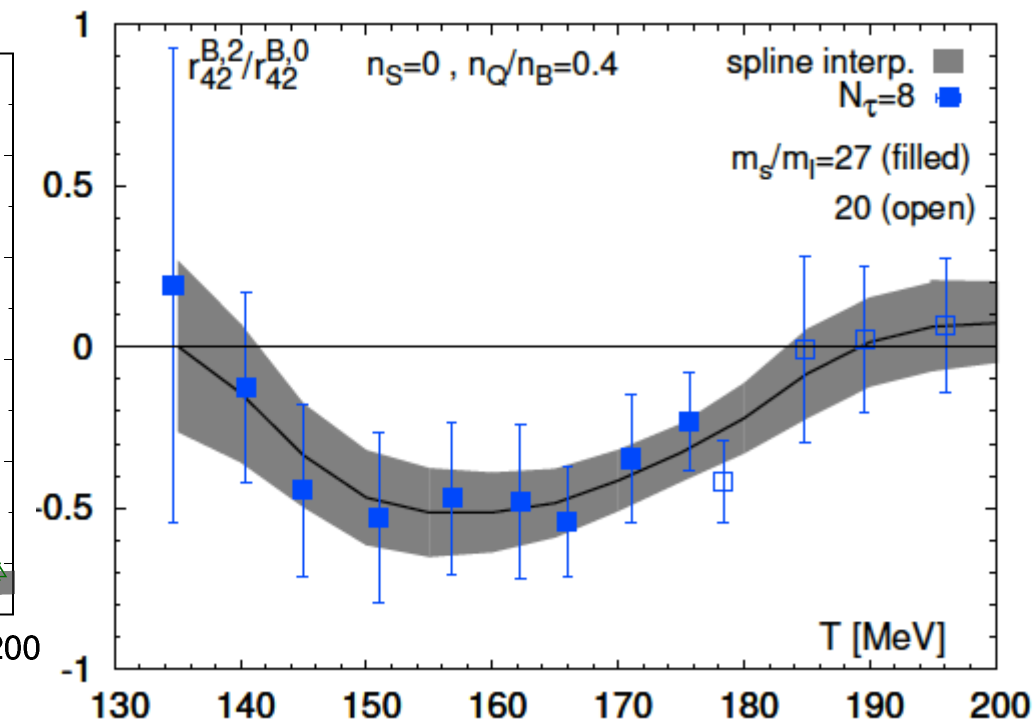
A QCD critical point is disfavored at $\mu_B/T \lesssim 2$ at T≳135 MeV

A. Bazavov, HTD et al., [Bielefeld-BNL-CCNU], Phys.Rev. D95 (2017) no.5, 054504

Cumulant ratios of proton (baryon) number fluctuations: HIC data v.s. Lattice results







Bazavov et al., [HotQCD], Phys.Rev. D96 (2017) no.7, 074510

strangeness neutral case:

$$(\kappa\sigma^2)_B = \frac{\chi_{4,\mu}^{B,\mathrm{SN}}}{\chi_{2,\mu}^{B,\mathrm{SN}}} = r_{42}^{B,0}\left[1 + \frac{r_{42}^{B,2}}{r_{42}^{B,0}}\left(\frac{\mu_B}{T}\right)^2 + \cdots\right]$$

$\sqrt{s_{NN}} \gtrsim 20$ GeV:

$\kappa\sigma^2$ is consistent with QCD in equilibrium

Conclusions

☑ The chiral Tc of Nf=2+1 QCD is ~135 MeV, and the O(N) universality class of the chiral phase transition is preferred

☑ EoS from Taylor expansions of QCD partition functions are now reliable in the region $\mu_B/T \lesssim 2$ or $\sqrt{s_{NN}} \gtrsim 12$ GeV

☑ Properties of cumulants measured in BES-I for $\sqrt{s_{NN}} \gtrsim 20$ GeV clearly differs from HRG thermodynamics but are consistent to QCD thermodynamics close to the transition region

☑ A QCD critical point is disfavored at $\mu_B/T \lesssim 2$ at $T \gtrsim 135$ MeV

Lattice 2019

37th series

June 16-22, 2019
Wuhan, China

like the role of
QM in HIC community

~ 400 participants annually

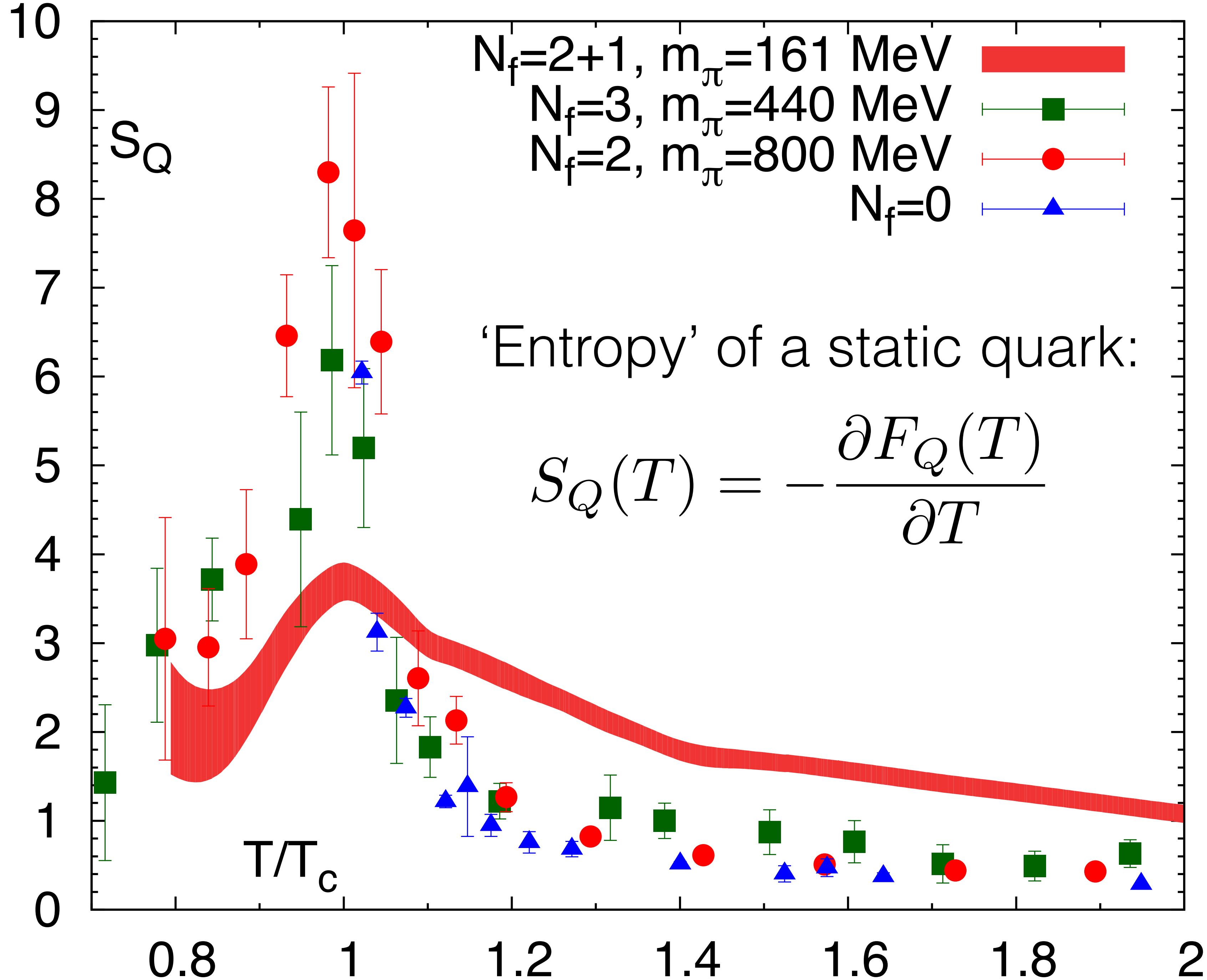
You are welcome
to join us!

Nuclear Science Computing Center at CCNU

谢谢！

Thanks for your attention!

Possible connections between deconfinement & chiral aspects of the cross over



A. Bazavov, N. Brambilla, HTD et al., PRD93 (2016) no.11, 114502

chiral phase transition and universal scaling

Behavior of the free energy close to critical lines

$$f(m,T)=h^{1+1/\delta} f_s(z) , \qquad z=t/h^{1/\beta\delta}$$

h: external field, t: reduced temperature, β,δ: universal critical exponents

$f_s(z)$: universal scaling function, O(N) etc.

$$h=\frac{1}{h_0}\frac{m_l}{m_s} \qquad t=\frac{1}{t_0}\frac{T-T_c}{T_c}$$

Magnetic Equation of State (MEoS):

$$M=-\partial f_s(t,h)/\partial H = h^{1/\delta} f_G(z) \qquad \chi_M = \partial M/\partial H = \frac{h^{1/\delta}}{H}\frac{1}{\delta}\left(f_G(z)-\frac{z}{\beta}\frac{df_G(z)}{dz}\right)$$