Lattice QCD for RHIC and LHC:
from now to the next decade

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Lattice QCD for heavy ion collision experiments

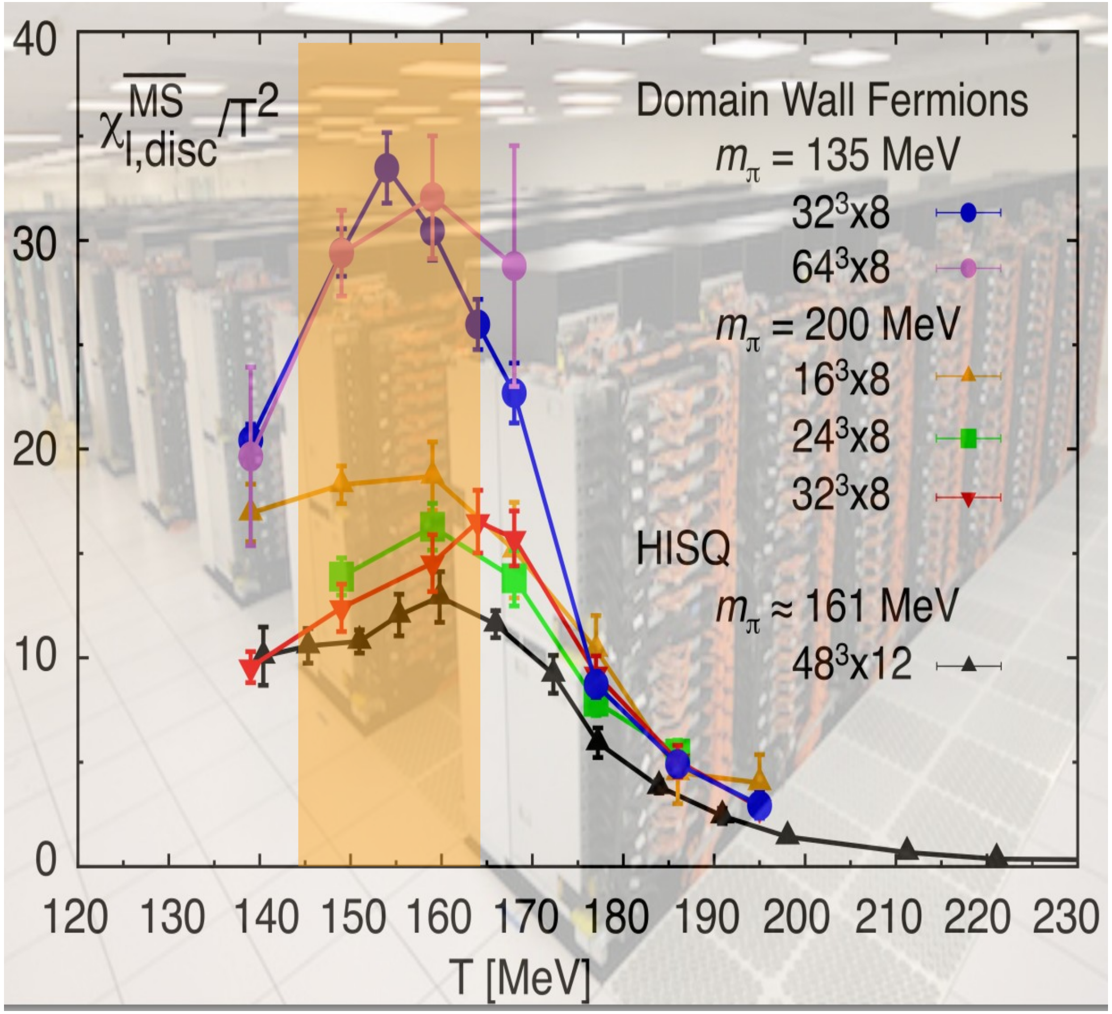
Lattice QCD provide QCD results for …

"… quantitative comparison of theory and experiment to determine the properties of the strongly interacting Quark-Gluon Plasma … and … exploration of the QCD phase diagram at non-zero baryon density …"

– Phases of QCD, 2007 Long Range Plan

- QCD: approximation-free, parameter-free
- results: equilibrium & near-equilibrium properties
  - as underlying inputs to dynamical modeling of HIC
  - for possible comparisons with HIC experiments
  - for providing qualitative guidance to HIC experiments

QCD transition at zero baryon density



$T_c = 154(9)$ MeV

physical quark masses
& continuum limit

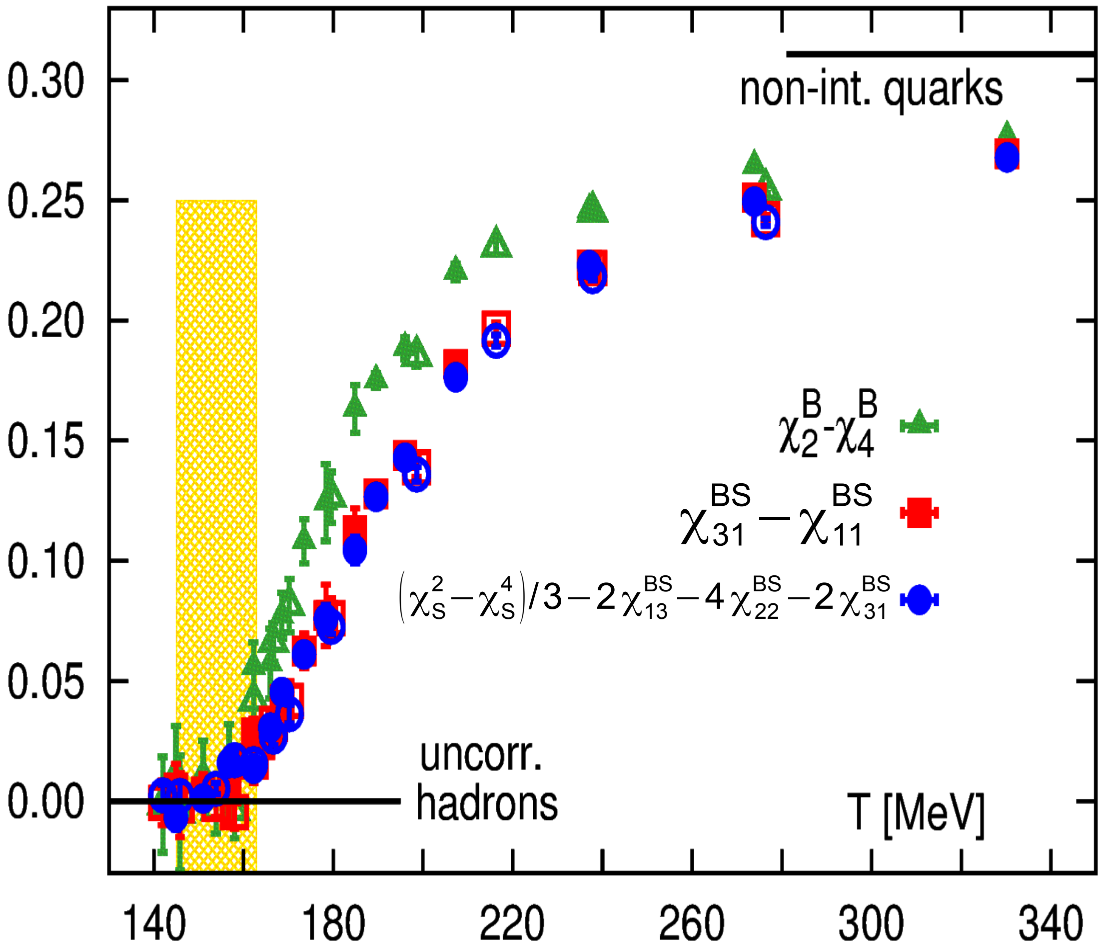
constrains 'switching' temperature of hydro calculations

chiral crossover with 3 physical pions

chiral fermion (domain wall)

HotQCD: Phys. Rev. Lett. 113 (2014) 082001

QCD transition at zero baryon density



$T_c = 154(9)$ MeV

physical quark masses
& continuum limit

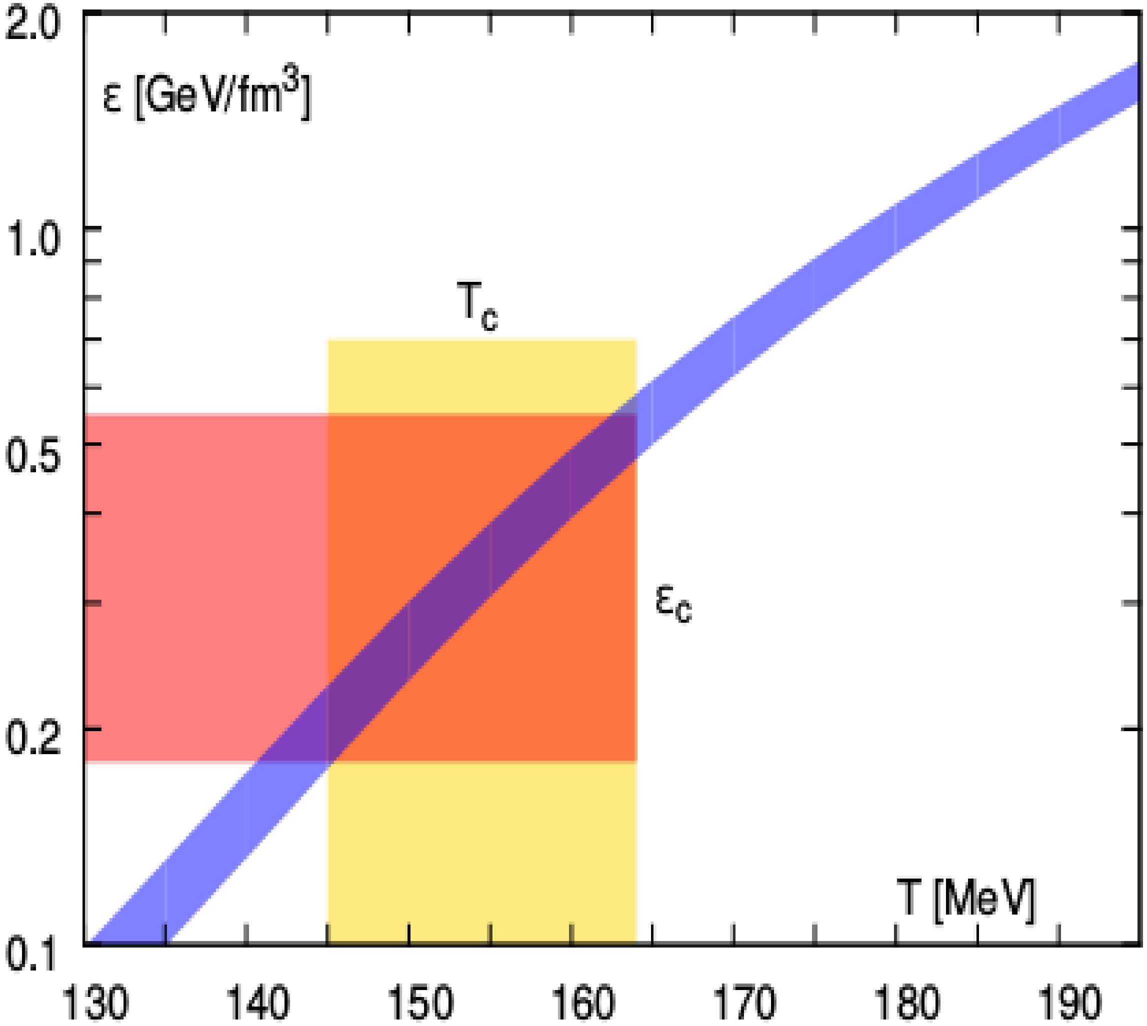
constrains 'switching'
temperature of hydro
calculations

deconfinement & chiral crossovers
in same temperature range

appearance of fractional charges

BNL-Bi: Phys. Rev. Lett. 111 (2013) 082301

QCD transition at zero baryon density



HotQCD: arXiv:1407.6387

critical energy density:

$$\epsilon_c = 0.18 - 0.50\ \mathrm{GeV/fm^3}$$

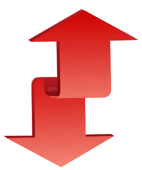
$$\epsilon_c = (1.2 - 3.3)\,\rho_{nuclear}$$

physical quark masses
& continuum limit

QCD equation of state at zero baryon density

how do we know the 'nearly perfect fluid' created in HIC is QGP?

hydrodynamics

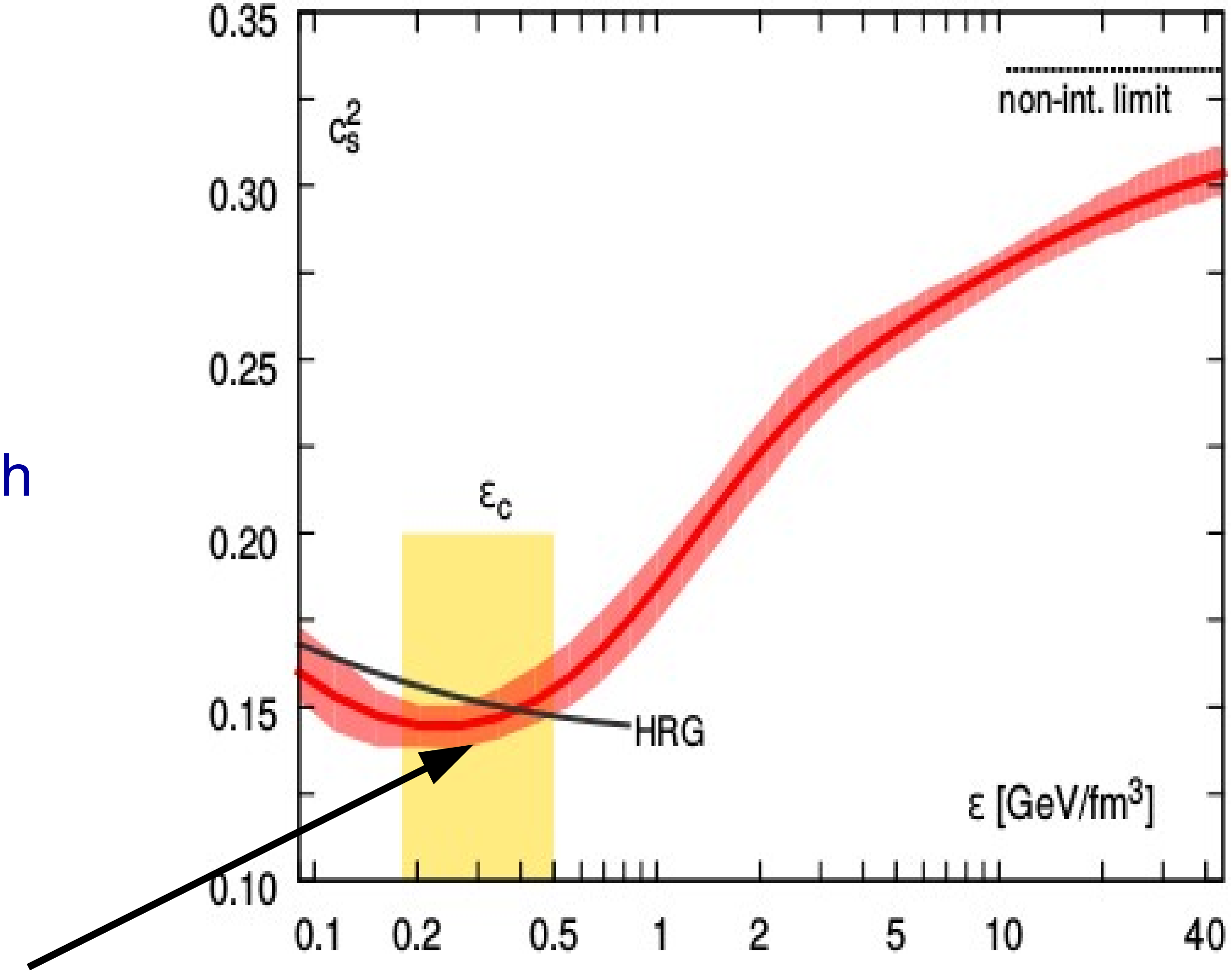


conservation laws

QGP enters only through equation of state

physical quark masses
& continuum limit

LQCD: speed of sound



softest point
of EoS

HotQCD: arXiv:1407.6387

Strongly-interacting and weakly-interacting regime of QGP

weakly-interacting quasi-quarks

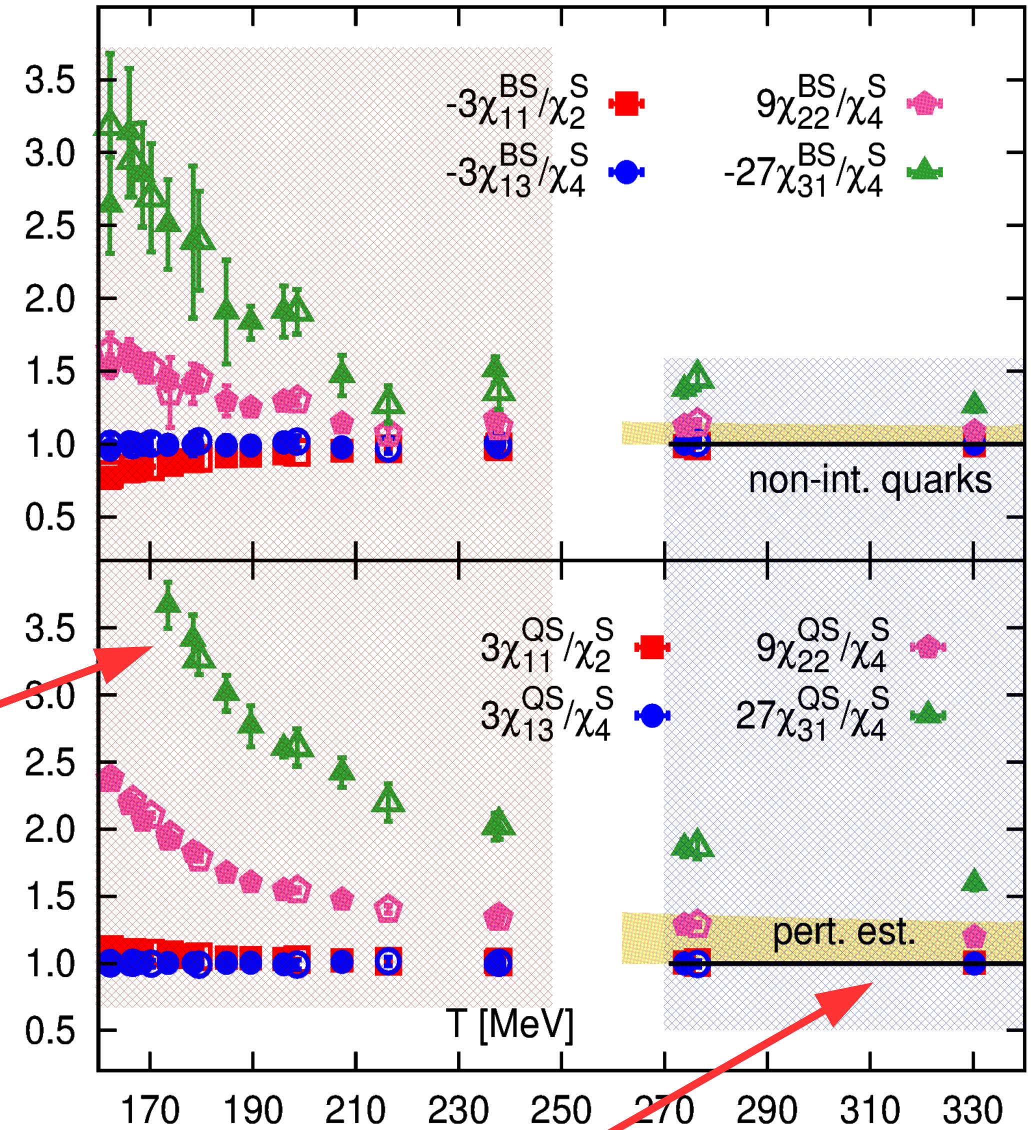
$S=-1,\ B=1/3,\ Q=-1/3$

baryon–strangeness correlations

$\chi^{BS}_{mn}/\chi^S_n = B^m S^n = (-1)^n/3^m$

charge–strangeness correlations

$\chi^{QS}_{mn}/\chi^S_n = Q^m S^n = (-1)^{m+n}/3^m$



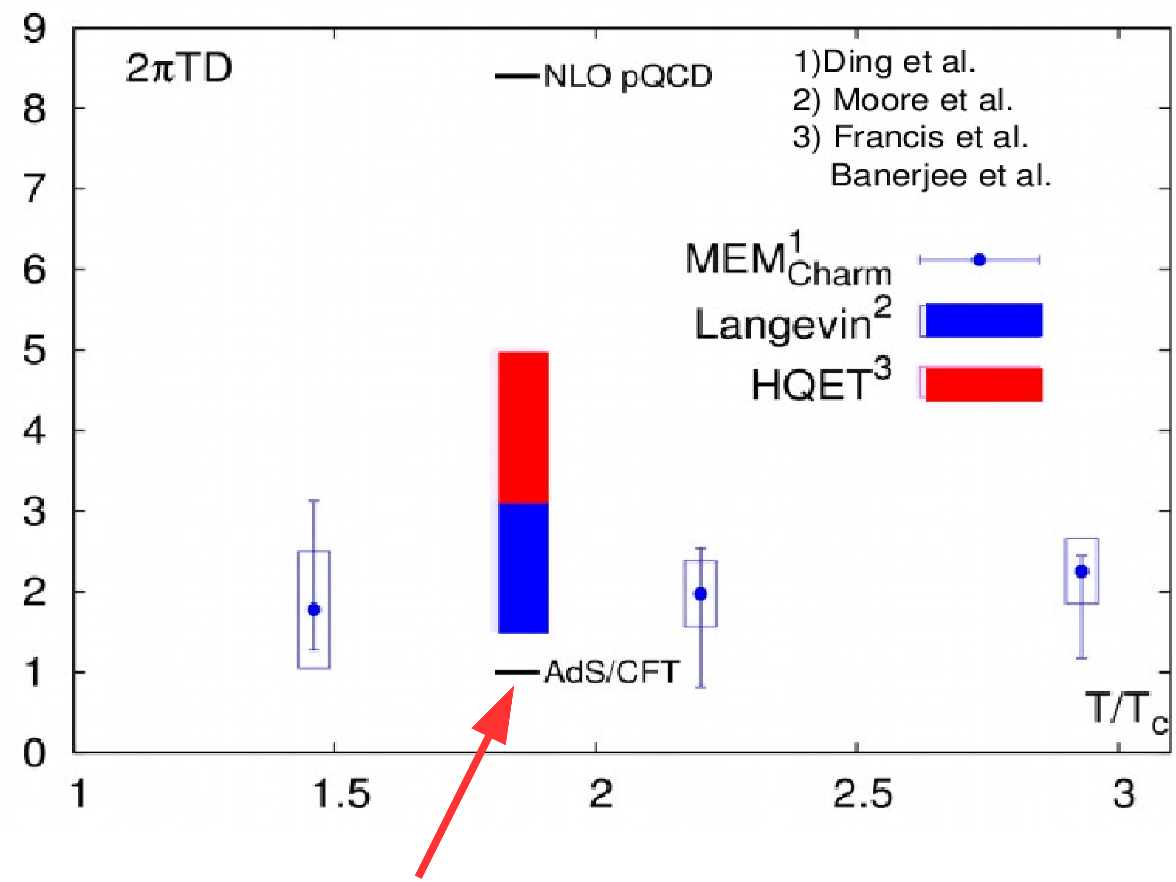
strongly interacting:
$T_c \lesssim T \lesssim 2T_C$

BNL-Bi: Phys. Rev. Lett. 111 (2013) 082301

weakly interacting:
$T \gtrsim 2T_C$

Transport properties of QCD

charm diffusion constant



QCD input for understanding thermalization and flow of heavy quarks

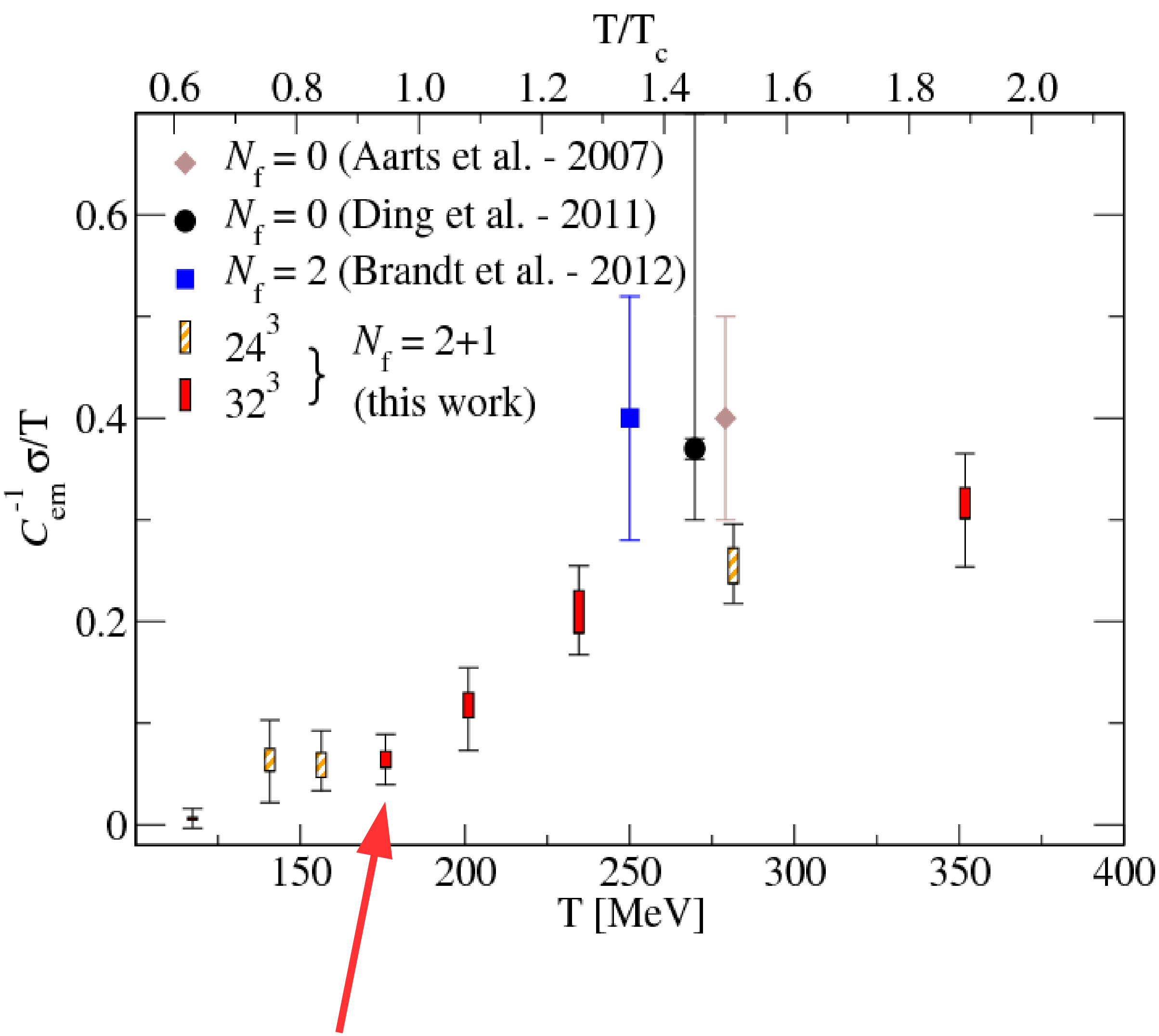
need to include light dynamical fermions

LQCD results are close to the strongly coupled AdS/CFT results

Ding et.al.: Phys. Rev. D86 (2012) 014509
Moore et.al.: Phys.Rev. C71 (2005) 064904
Francis et.al.: PoS LATTICE2011 (2011) 202
Banerjee et.al.: Phys.Rev. D85 (2012) 014510

Transport properties of QCD

electrical conductivity



decreases near the QCD crossover

ultra-soft photon emission rate is proportional to electrical conductivity

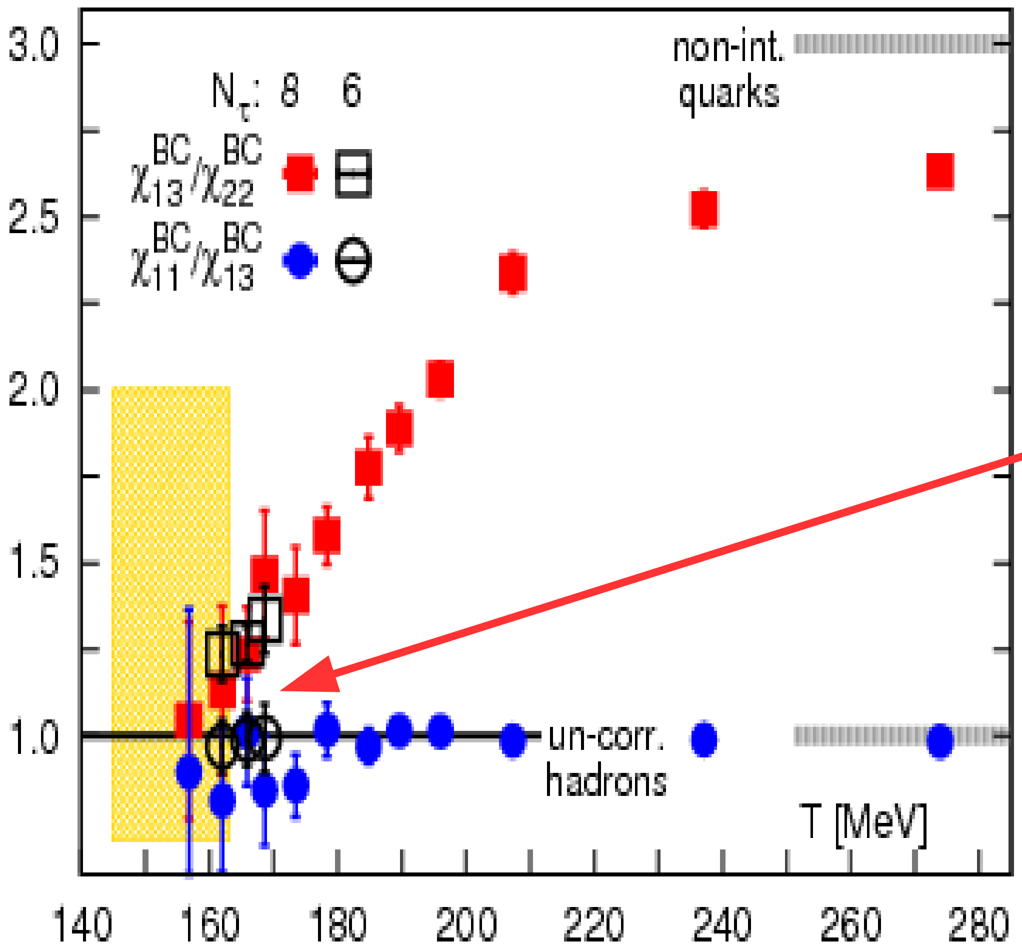
determines how fast initially produced magnetic field decays inside QGP

calculations needed for physical quark masses using large lattice sizes

Amato et.al: Phys. Rev. Lett. 111 (2013) 172001

Heavy quark bound states in QGP

melting of open charm hadrons



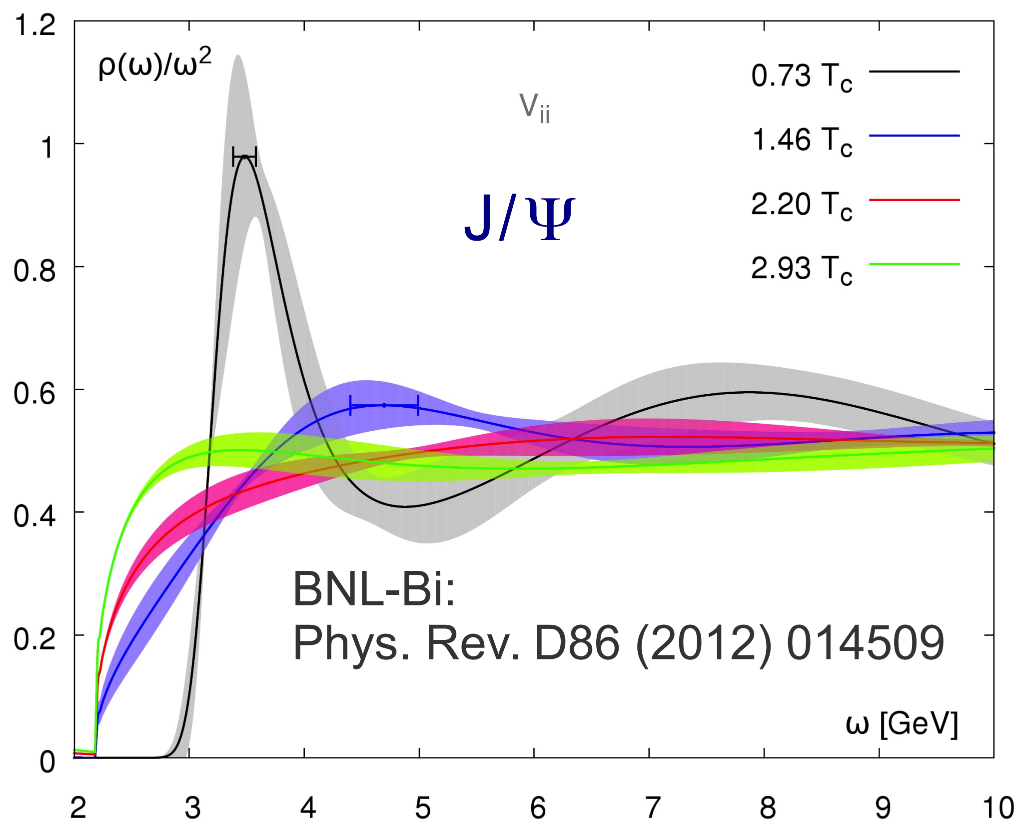
open charm bound states starts to melt in QCD crossover region

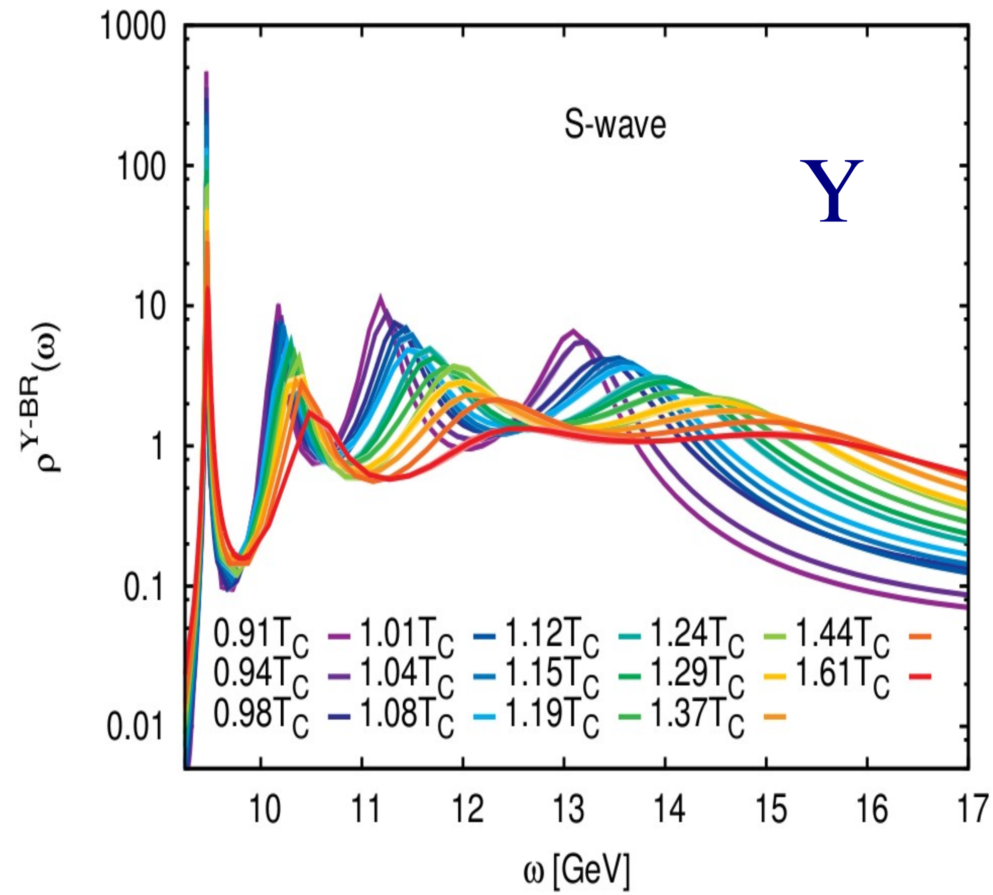
charm quarks associated with fractional baryon number starts to appear

BNL-Bi-CCNU: Phys. Lett. B737 (2014) 210

Heavy quark bound states in QGP

quarkonia melting



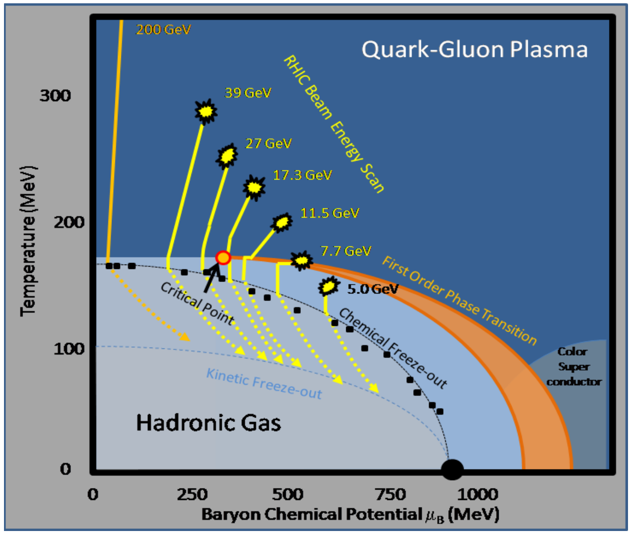


Rothkopf, Kim, Petreczky: to appear

no definitive answer yet
on meting temperatures
of quarkonium states

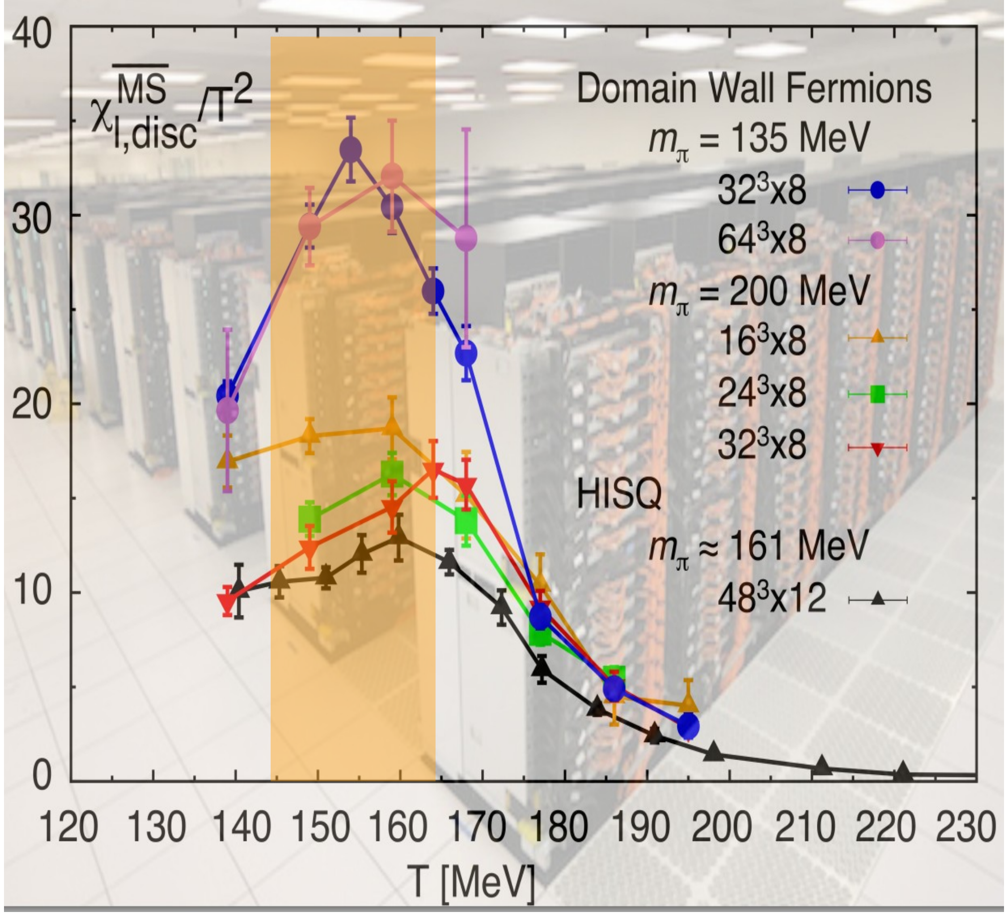
need even larger lattices
& inclusion of dynamical
quarks with physical masses

QCD phase diagram at non-zero baryon density



necessary condition for existence of QCD critical point: QCD transition is a crossover for $\mu_B \gtrsim 0$

crossover at $\mu_B = 0$



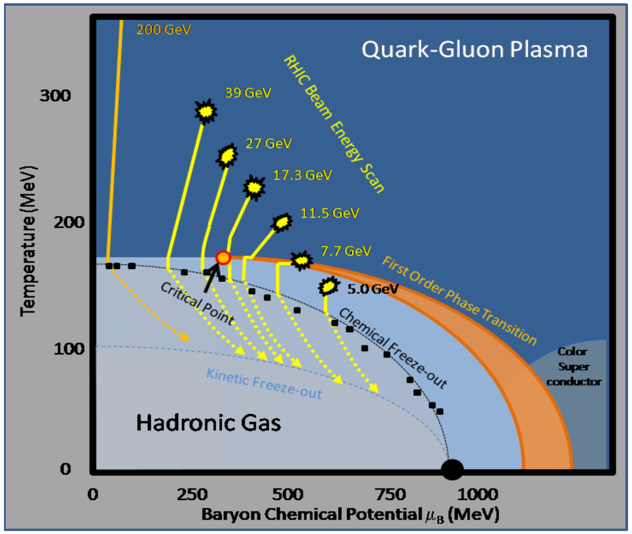
with exact chiral symmetry & chiral anomaly on the lattice

chiral fermion (domain wall)

practically no volume dependence of chiral susceptibility even with 8 times increased volume

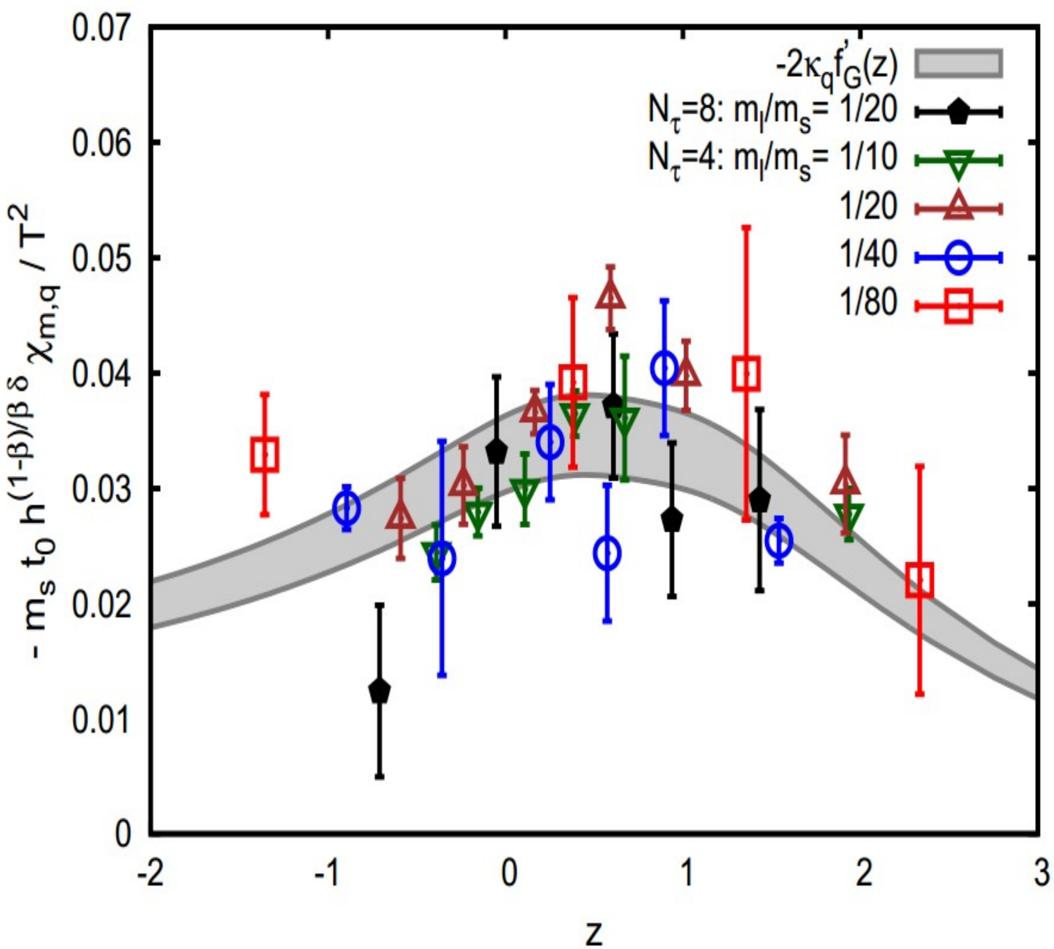
HotQCD: Phys. Rev. Lett. 113 (2014) 082001

QCD phase diagram at non-zero baryon density



necessary condition for existence of QCD critical point: QCD transition is a crossover for $\mu_B \gtrsim 0$

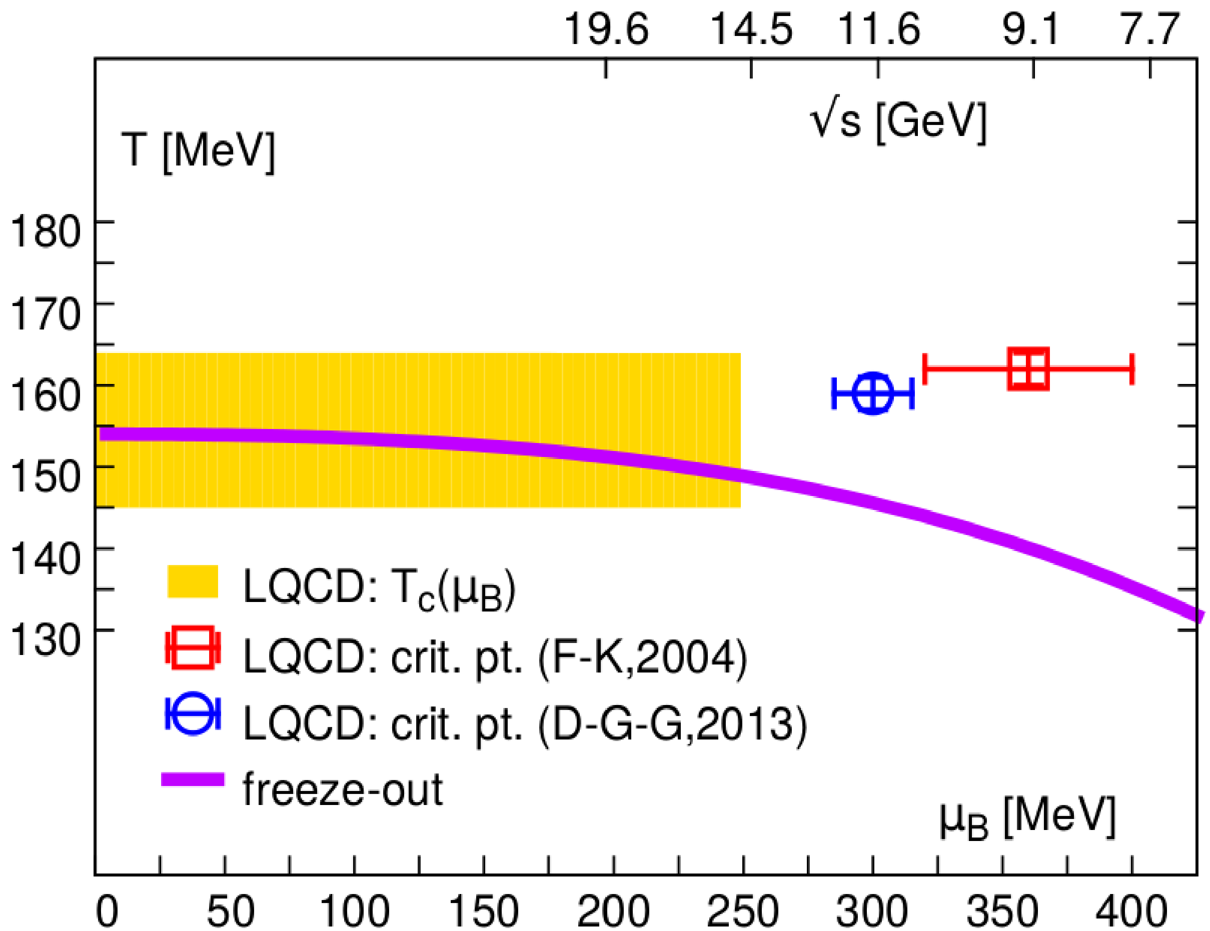
crossover for small $\mu_B \gtrsim 0$



2^{nd} order O(N) chiral scaling behavior of the order parameter for $\mu_B > 0$

BNL-Bi: Phys.Rev. D83 (2011) 014504

QCD phase diagram at non-zero baryon density



crossover $T_c(\mu_B)$

known up to $O(\mu_B^2)$

BNL-Bi: Phys.Rev. D83 (2011) 014504

W-B: JHEP 1104 (2011) 001

QCD critical point:

hints from two studies

Fodor-Katz: JHEP 0404 (2004) 050

Mumbai group:
PoS LATTICE2013 (2013) 202

existing LQCD predictions are within RHIC BES II scan range, but no consensus yet within the LQCD community on the robustness of these LQCD predictions

Equation of state at non-zero baryon density

essential for understanding
flow results from RHIC BES
talks by: D. Cebra & H. Petersen

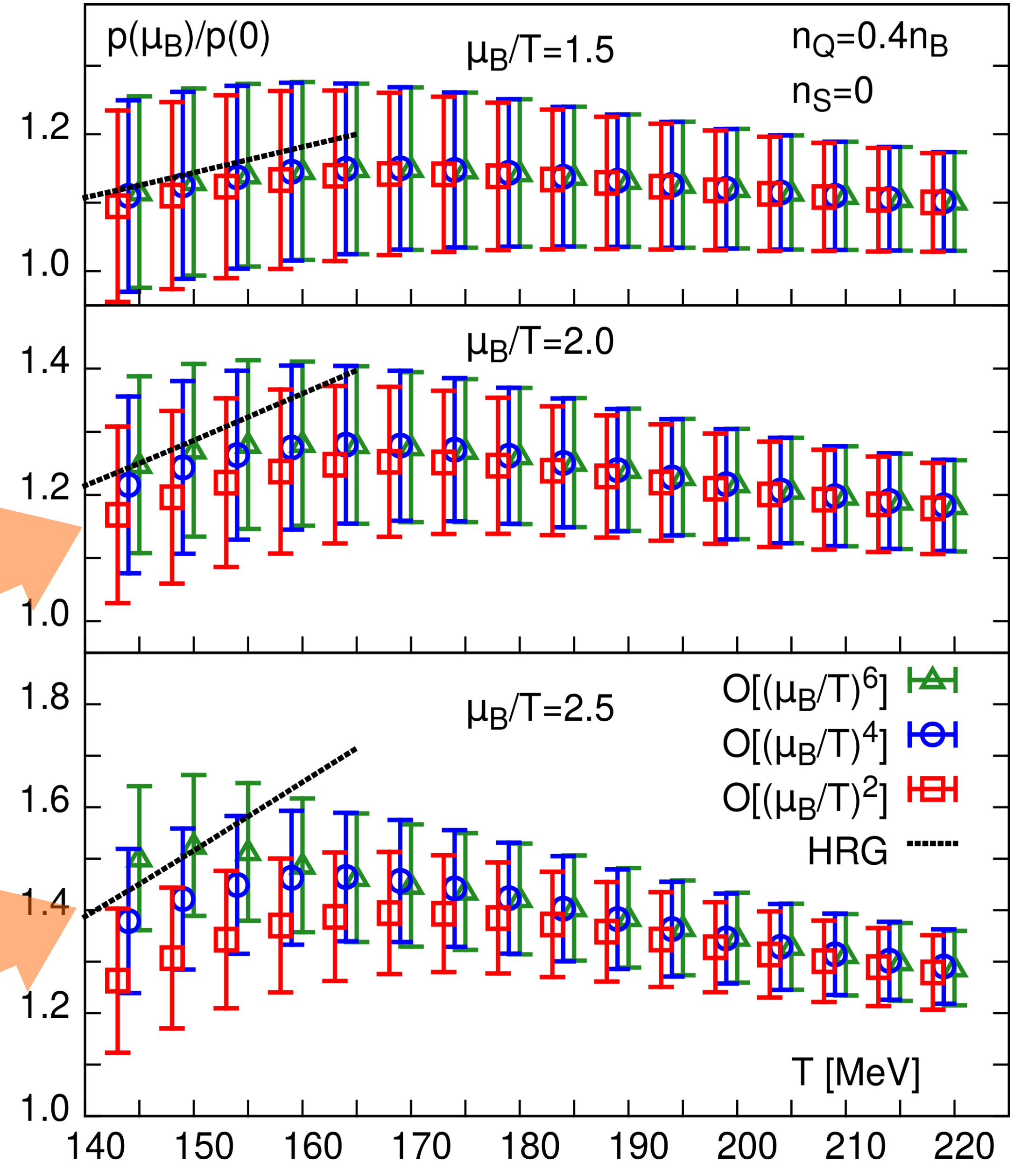
Taylor expansion method:

$$\frac{p(\mu_B, T)}{T^4} = \sum_n \frac{1}{n!} \chi_n^B(T) \left(\frac{\mu_B}{T}\right)^n$$

6^{th} order expansion is controlled for $\mu_B/T \lesssim 2$

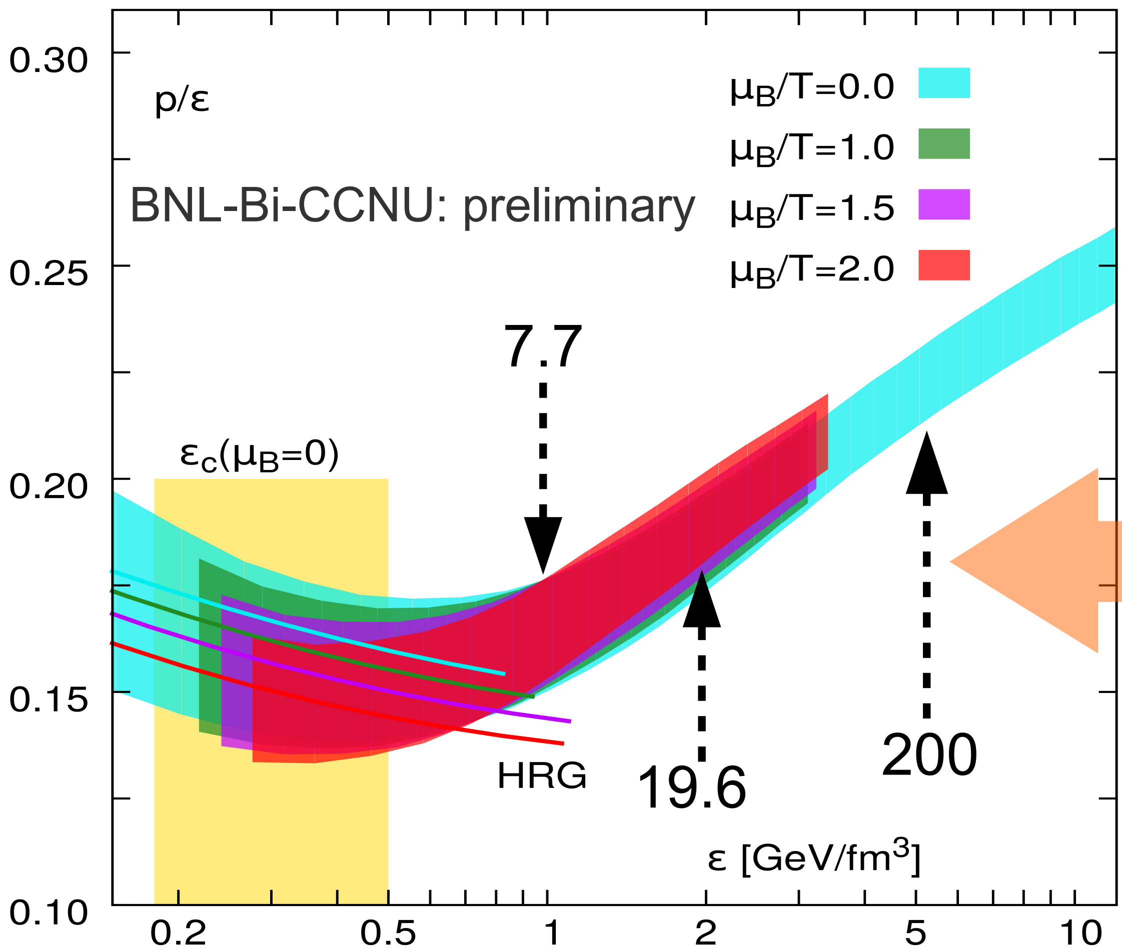
clear breakdown of the 6^{th} order expansion for T<Tc, T>Tc OK

need higher order expansion

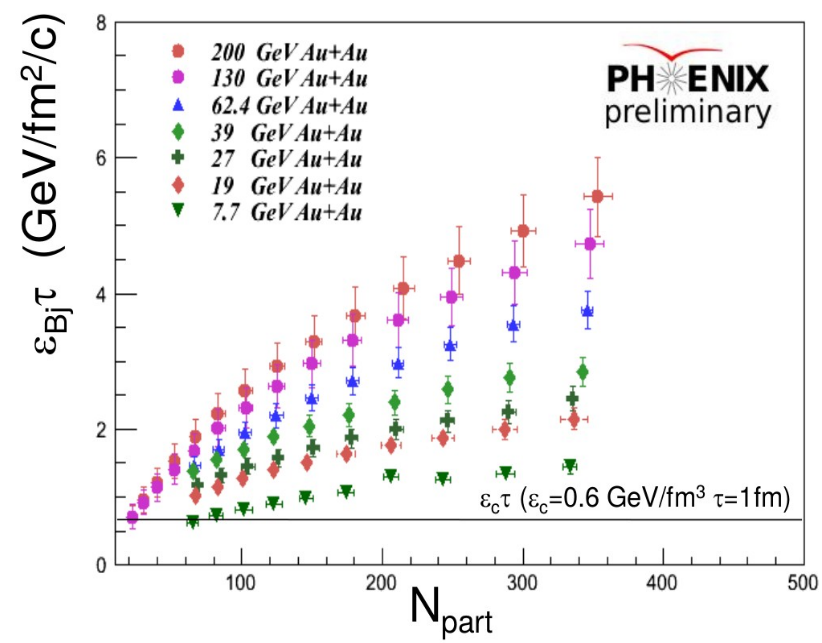


BNL-Bi-CCNU: preliminary

Equation of state at non-zero baryon density



Bjorken energy density ϵ_{BJ}
at $\tau=1$ fm



plausible QGP formation
even at $\sqrt{s}=7.7$ GeV

Cumulants of conserved charge fluctuations

LQCD: conserved charge susceptibilities

$$\chi_n^X(T,\mu_X) = \frac{\partial^n \left(p(T,\mu_X)/T^4\right)}{\partial(\mu_X/T)^n}$$

higher cumulants are more sensitive to critical fluctuations
talk by: M. Stephanov

$$\chi_n^X(T,\mu_X) = \sum_n \frac{1}{k!}\,\chi_{k+n}^X(T)\left(\frac{\mu_X}{T}\right)^n$$

can be compared directly with experimentally measured cumulants of charge fluctuations

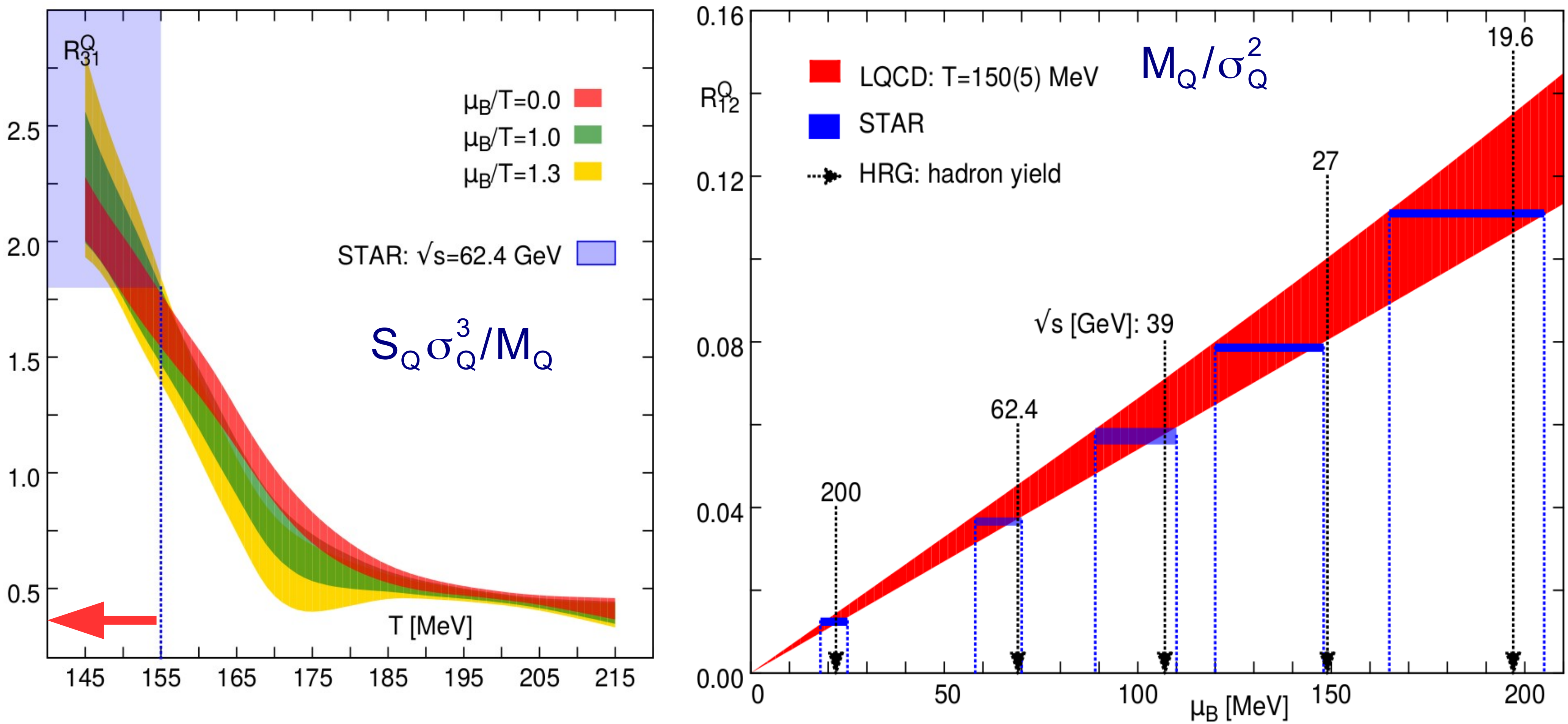
$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)} \qquad \frac{S_Q(\sqrt{s})\,\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)}$$

Expt.: mean: M_Q
variance: σ_Q^2
skewness: S_Q

can be used to extract freeze-out parameters

BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

Charge fluctuations, LQCD and freeze-out in HIC



thermometer: T^f

baryometer: μ_B^f

$T^f \leqslant 155$ MeV

need more precise measurements from BES-II

BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

SM: PoS CPOD2013, 039 (2013)

W-B: Phys. Rev. Lett. 113 (2014) 052301

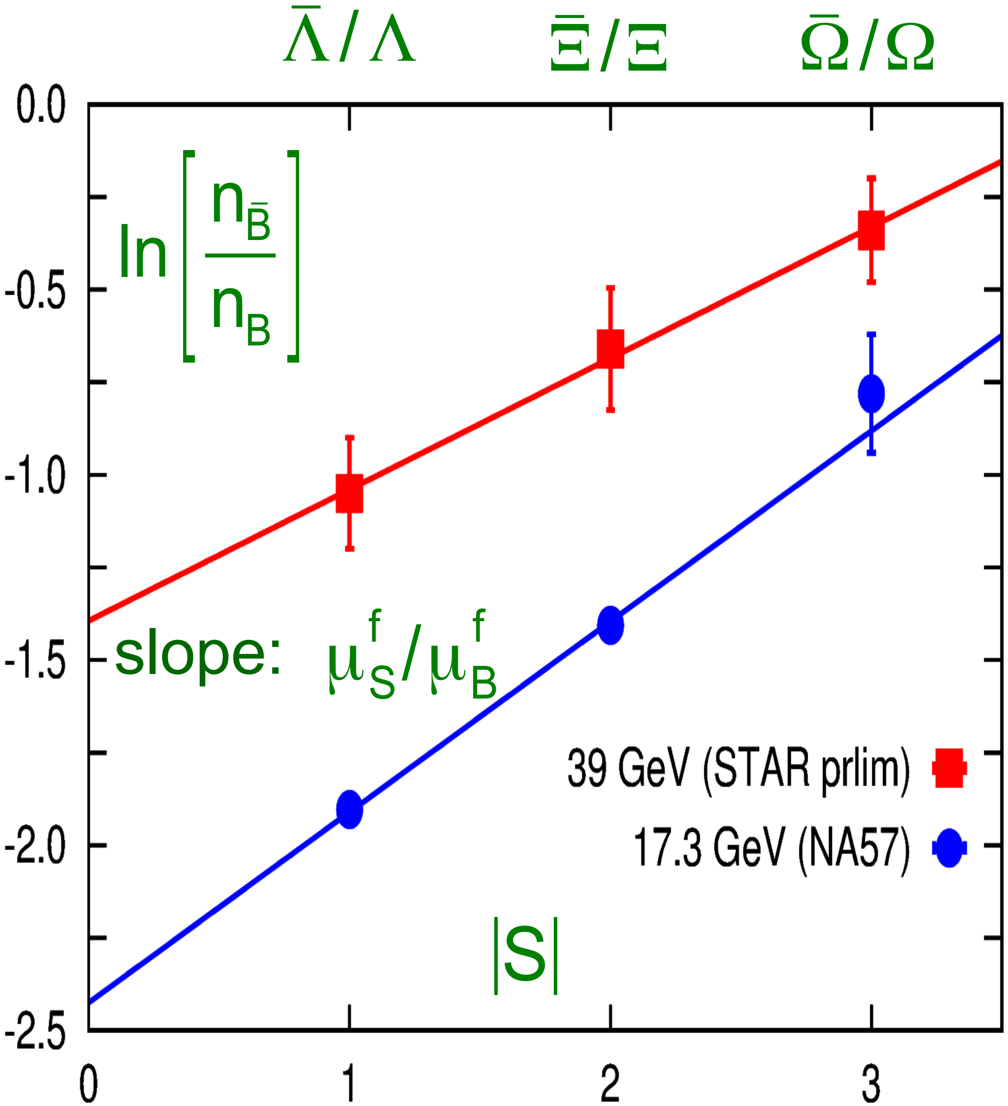
Strangeness, LQCD and freeze-out in HIC

medium formed in HIC is strangeness neutral:

$\langle n_S \rangle = 0 \Rightarrow \mu_S(T, \mu_B)$

$$\frac{\mu_S}{\mu_B}(T, \mu_B/T) \simeq \frac{\chi_{11}^{BS}(T)}{\chi_2^S(T)} + O[(\mu_B/T)^2]$$

can be calculated from LQCD



can be extracted from expt.:

$$\frac{n_{\bar{\Lambda}}}{n_\Lambda}, \frac{n_{\bar{\Xi}}}{n_\Xi}, \frac{n_{\bar{\Omega}}}{n_\Omega} = \exp\left[-\frac{2\mu_B^f}{T^f}\left(1 - \frac{\mu_S^f}{\mu_B^f}|S|\right)\right]$$

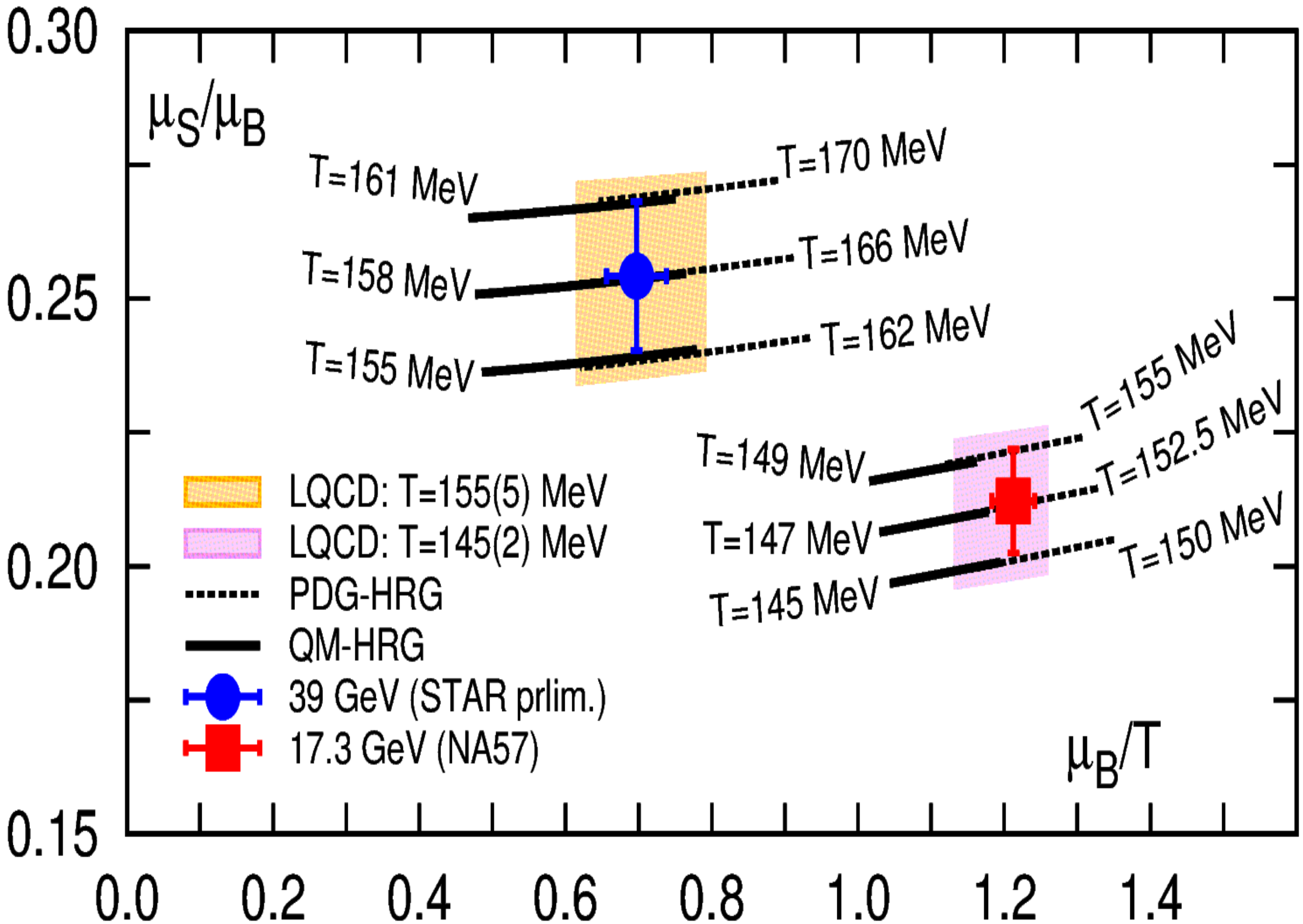
does not assume spectrum of hadron gas, only assumes hadron yields are thermal

freeze-out T by comparing (L)QCD and expt.

Strangeness, LQCD and freeze-out in HIC

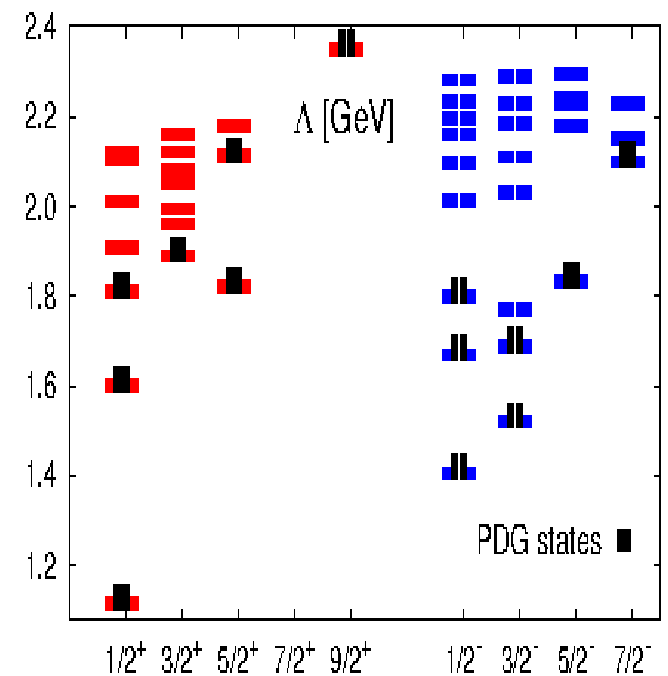
freeze-out T by comparing
μ_S/μ_B from LQCD and expt.

BNL-Bi-CCNU: Phys. Rev. Lett. 113 (2014) 072001



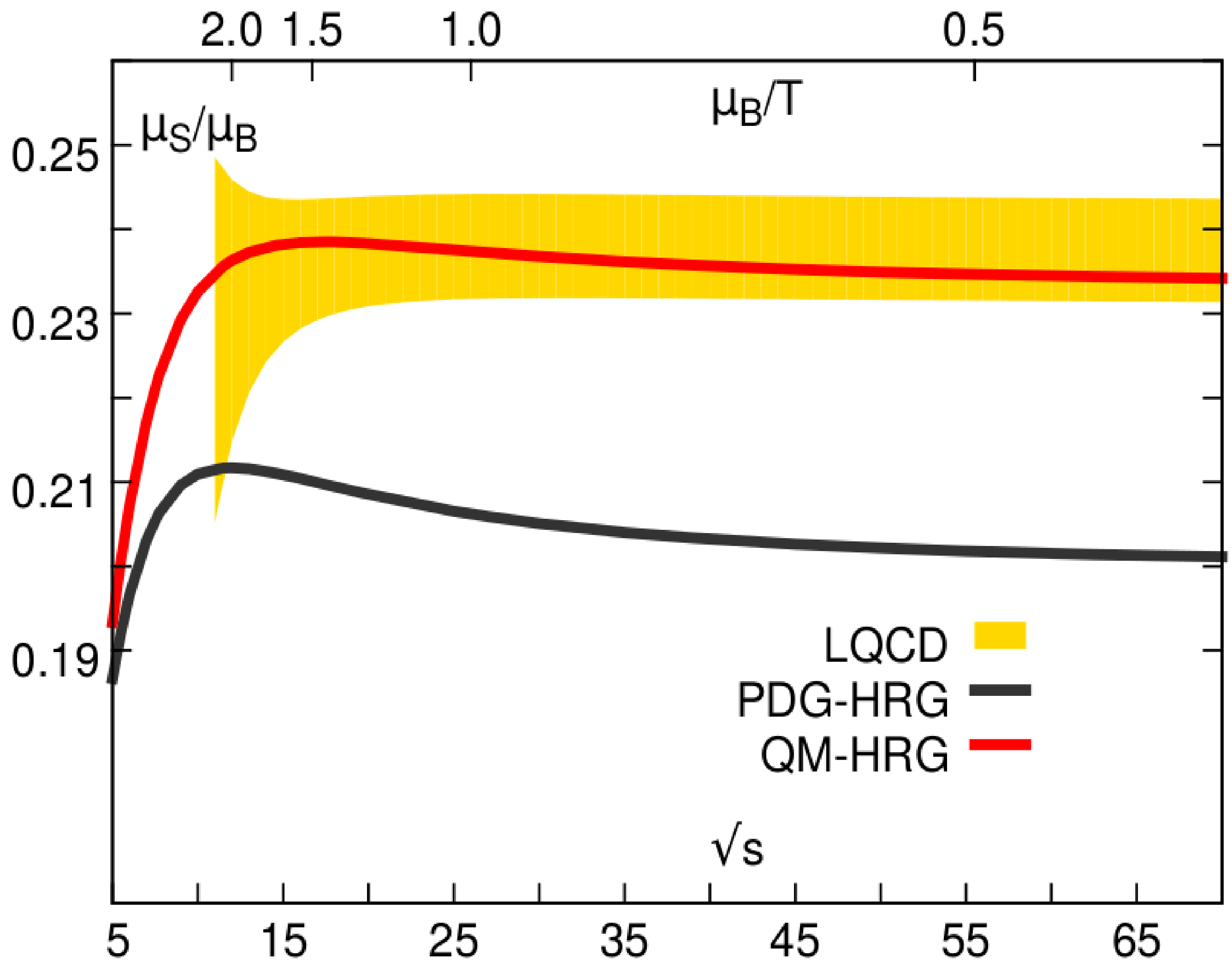
not reproduced by hadrons gas with only PDG states

reproduced when additional Quark Model (QM) predicted strange baryons are taken into account



indirect evidence for so-far undiscovered strange baryons at RHIC ?

Strangeness, LQCD and freeze-out in HIC



BNL-Bi-CCNU: preliminary

signature for unobserved strange baryons persists for RHIC BES-II

chosen:

$T^f(\sqrt{s} \to \infty) = 154$ MeV

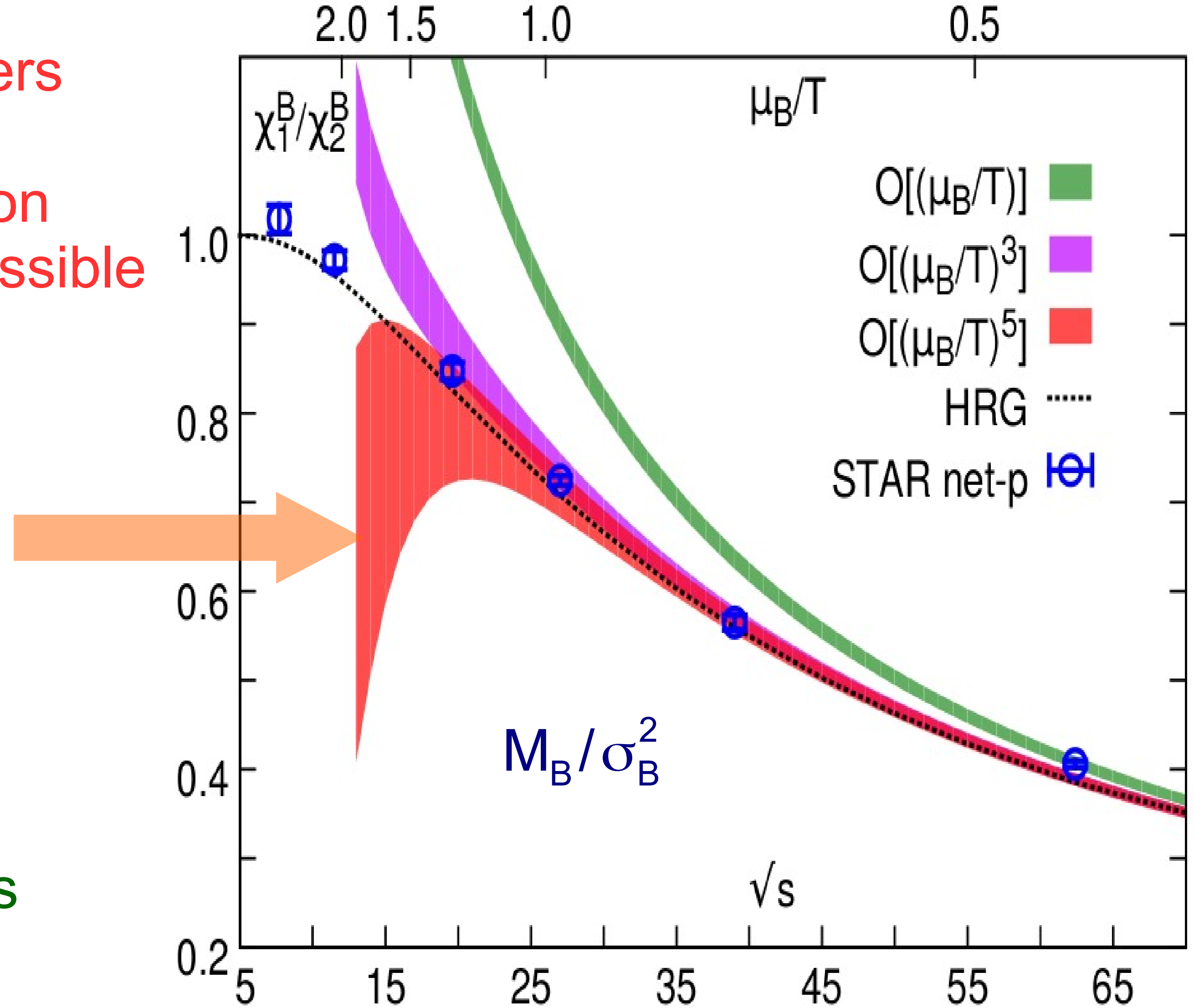
need accurate measurements of strange anti-baryon to baryon ratios

Cumulants of conserved charge fluctuations

once freeze-out parameters are fixed using QCD, parameter-free comparison with QCD calculations possible

hint for large baryon number fluctuation ?

need higher order corrections & improved statistics



BNL-Bi-CCNU: preliminary

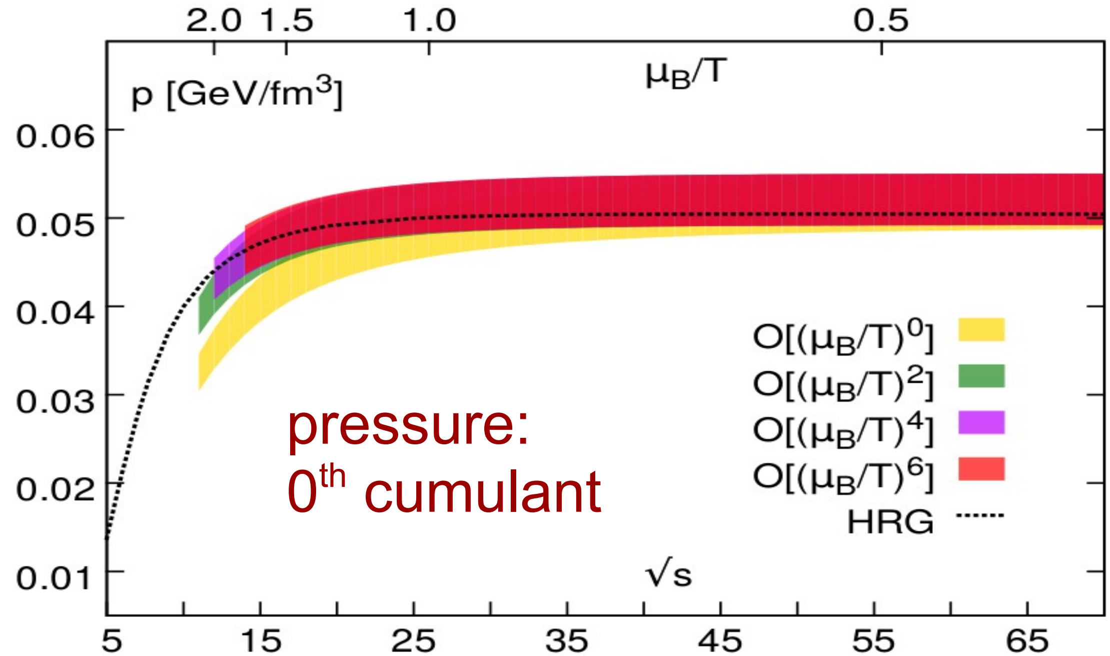
Cumulants of conserved charge fluctuations

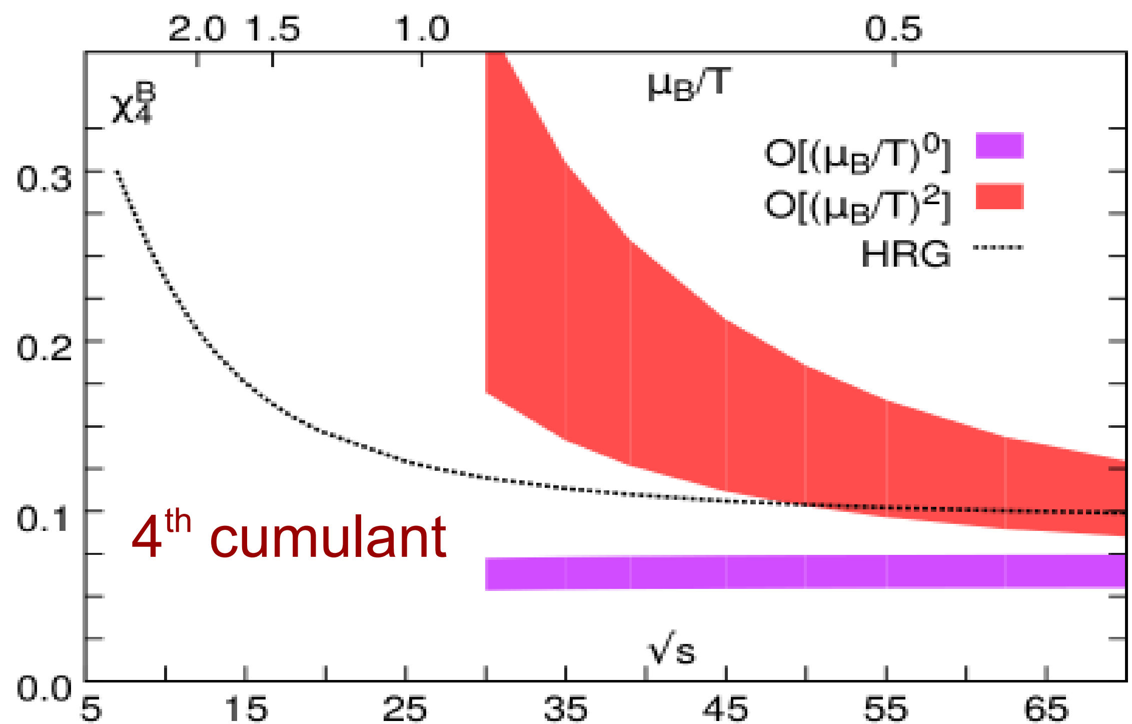
correction to higher cumulants starts at next higher order

presently, expansion of pressure up to $O(\mu_B^6)$

4^{th} order cumulant known only up to $O(\mu_B^2)$

for controlled calculation of 4^{th} order cumulant and to see possible break down of the expansion due to criticality, at least up to 10^{th} order susceptibilities are needed





Summary

QCD transition & EoS at zero baryon density:

✔ QCD calculations: physical quark masses, continuum limit

LQCD at non-zero baryon density:

✔ EoS controlled for $\mu_B/T \lesssim 2$

✔ direct comparison between (L)QCD calculations and HIC expt.
freeze-out parameters & more

✔ indirect evidence for unobserved strange baryons

✔ location of the QCD ciritical point remains a challenge

✔ need calculations of higher order cumulants: feasible in coming years

Transport, heavy quarks & other observables:

✔ observables calculated from fermionic correlation functions
have demonstrated to be feasible

✔ need inclusion of light dynamical fermions & very large lattices:
feasible in coming years

✔ observables involving gluonic correlation functions still challenging:
viscosities & jet-quenching parameter

Summary

extracting physics from heavy ion experiments
requires unambiguous theory inputs based on QCD

LQCD has made a big leap forward in providing
quantitative results for direct comparison with experiment