Overview of Lattice QCD Calculations on QCD Thermodynamics

relevance for heavy ion experiments and phenomenology

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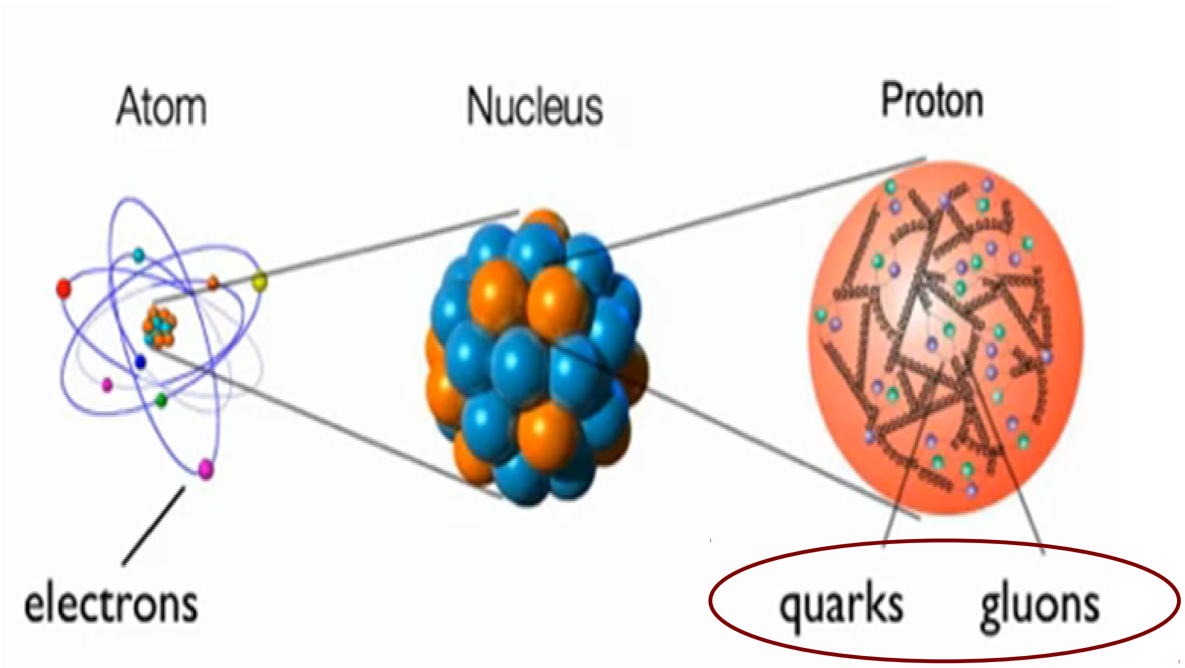
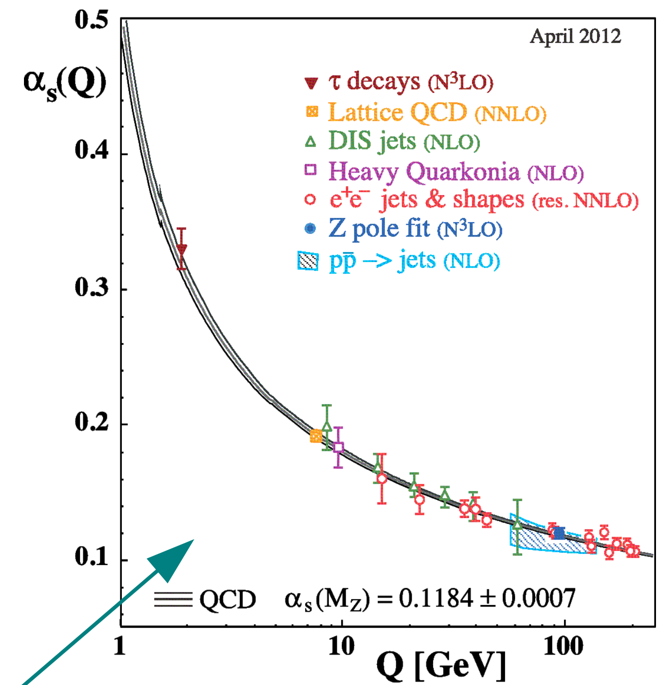
BROOKHAVEN NATIONAL LABORATORY

April 2013, LQCD workshop, ORNL

Quarks, Gluons and QCD





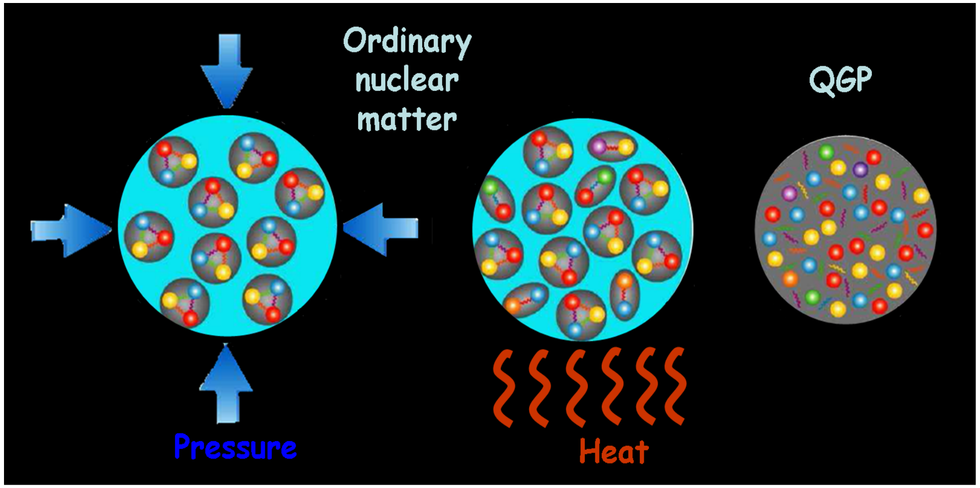
strong interaction

Quantum Chromo Dynamics

asymptotically free

coupling strength decrease with increasing energy

QGP: a new state of matter

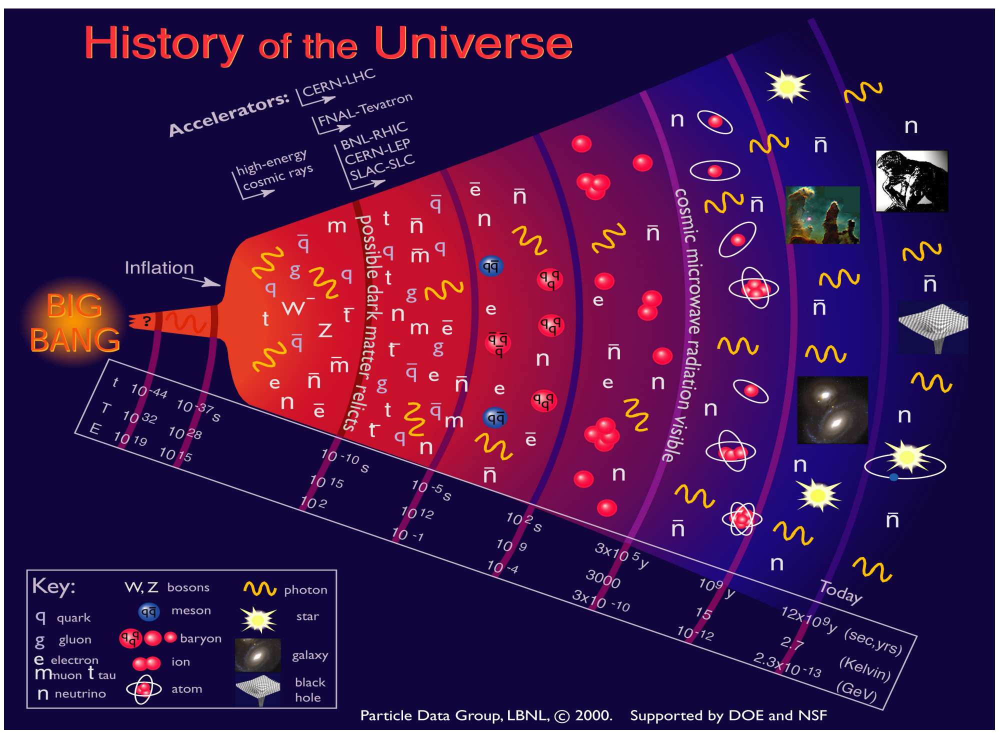


$T \gg \mu_B \gg \lambda_{QCD}$

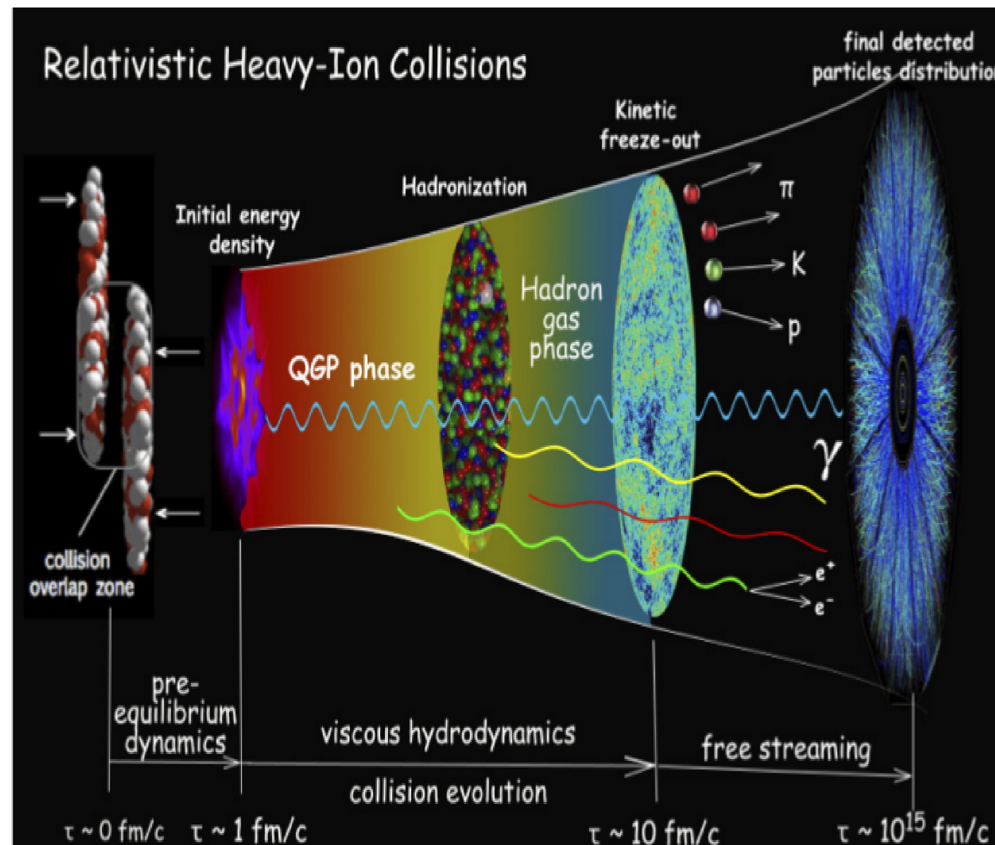
Quark Gluon Plasma

a new state of matter

quarks & gluons get liberated from nucleons



early universe



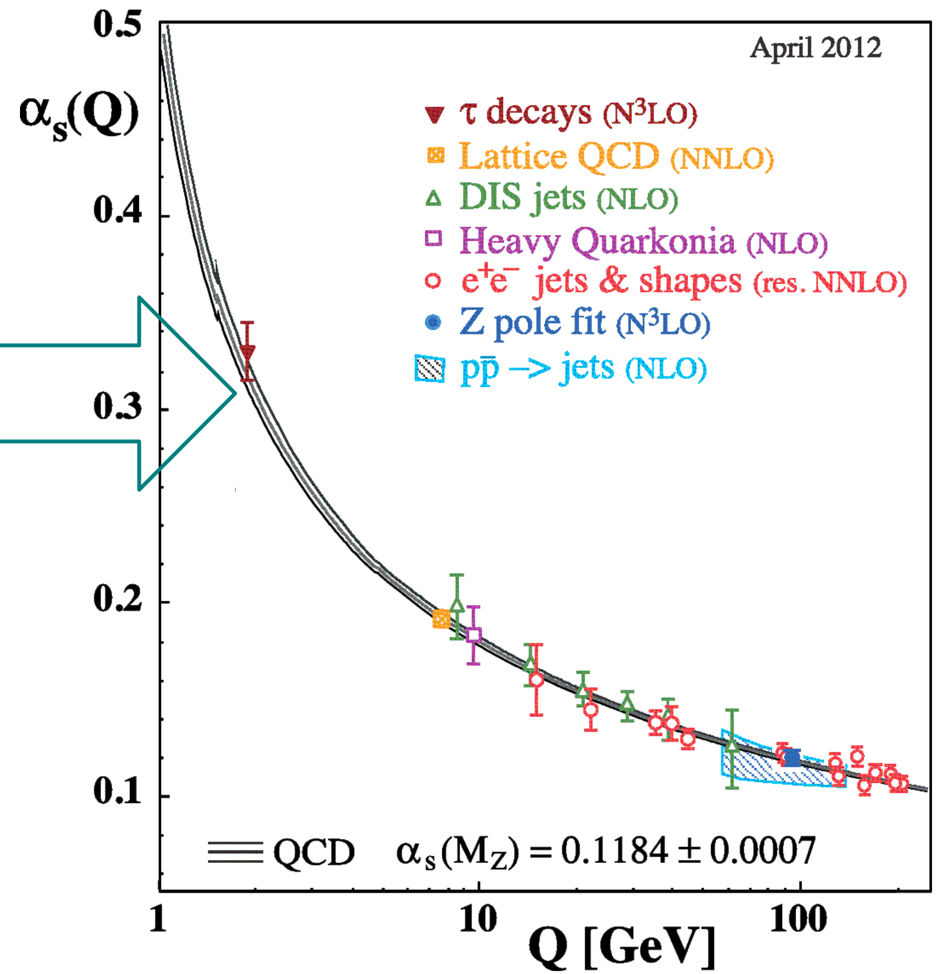
heavy-ion collision expt.

QGP from first principle QCD

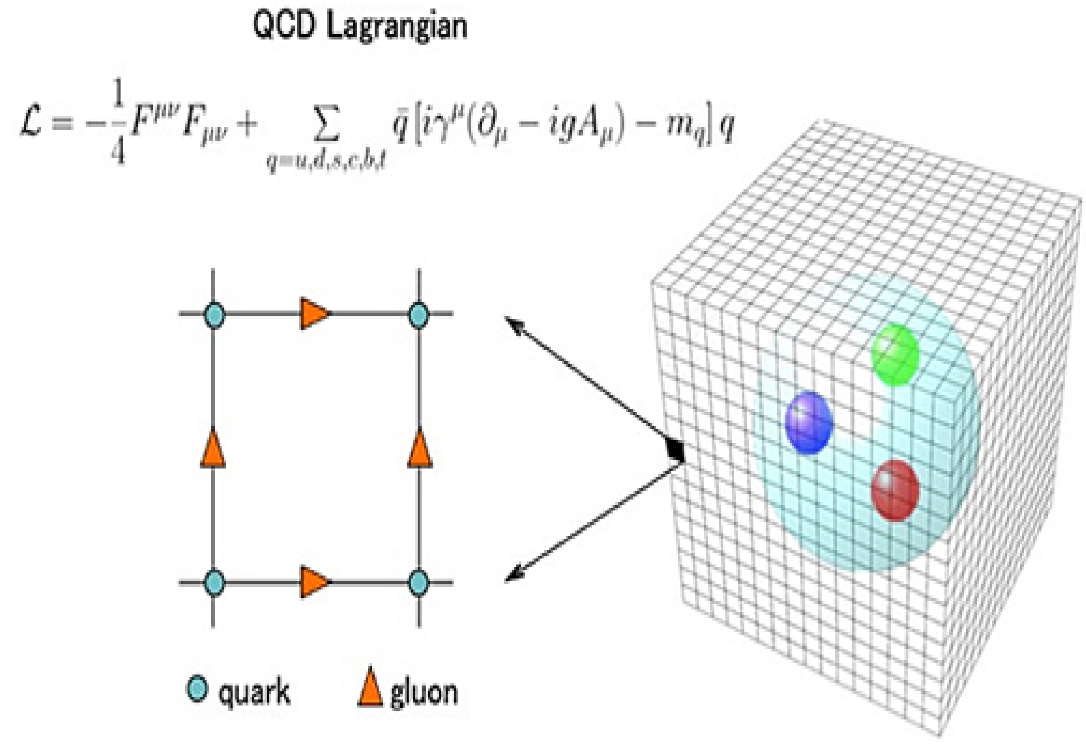
need non-perturbative technique

$\alpha_s(\lambda_{QCD})$ is not small

Lattice QCD



Lattice QCD



QCD on a discretized
(Euclidean) space-time lattice

ab-initio and non-perturbative

equilibrium & near-equilibrium
properties of QCD

temperature: space =/= time
(breaking Lorentz symmetry)

density: chemical potential
in QCD Lagrangian

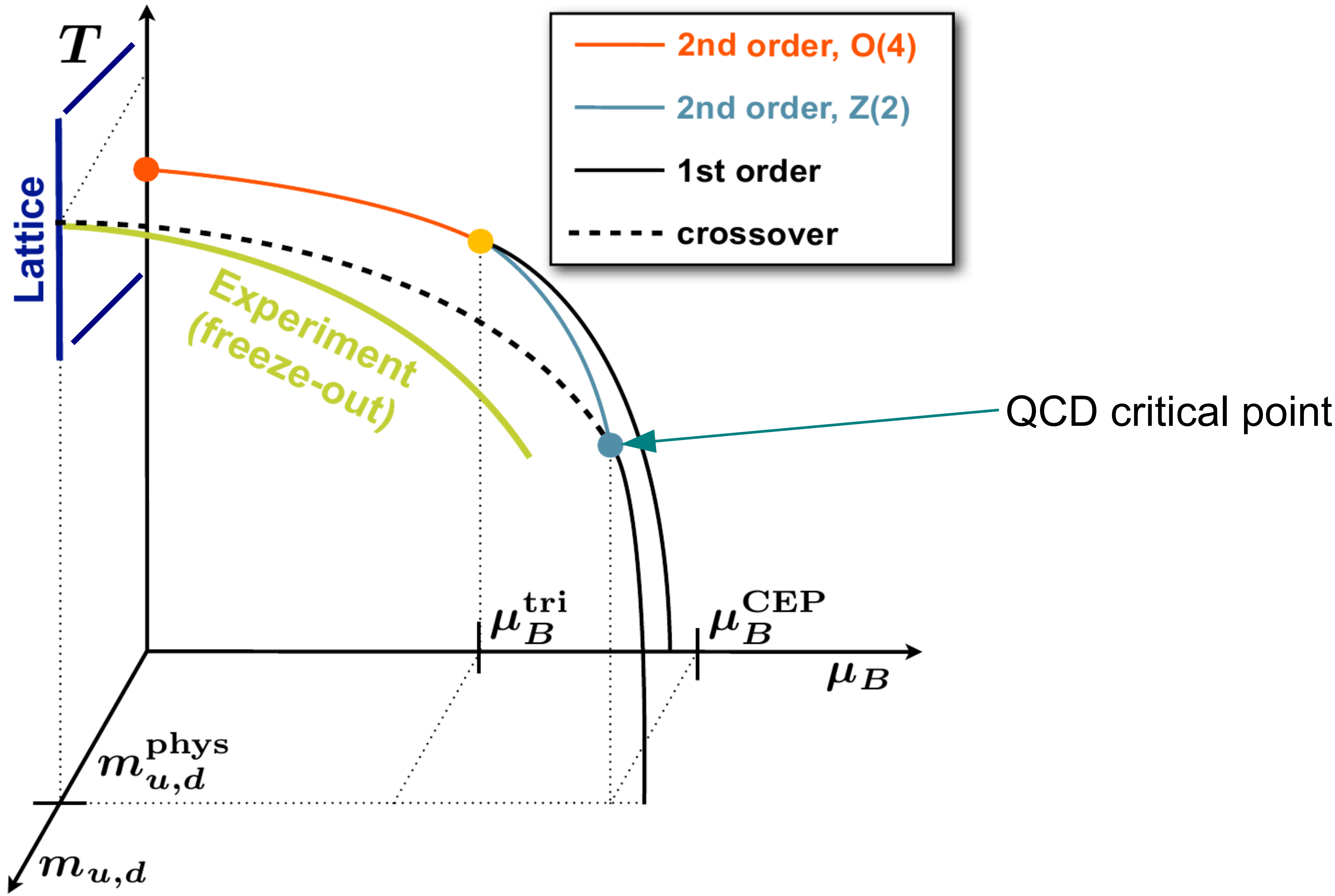
no free parameter
bare parameters of QCD Lagrangian
fixed by reproducing physics at T=0

perform path integral numerically
using Monte-Carlo technique

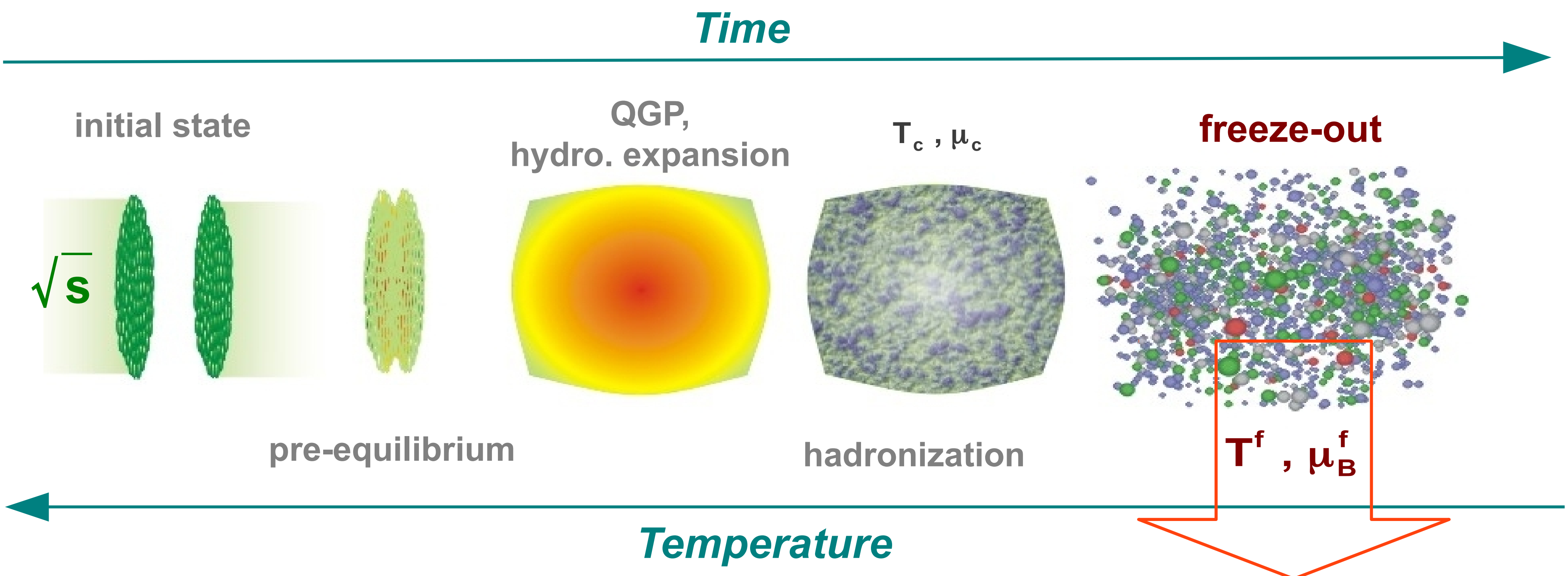
numerous inversions of
very large fermion matrices

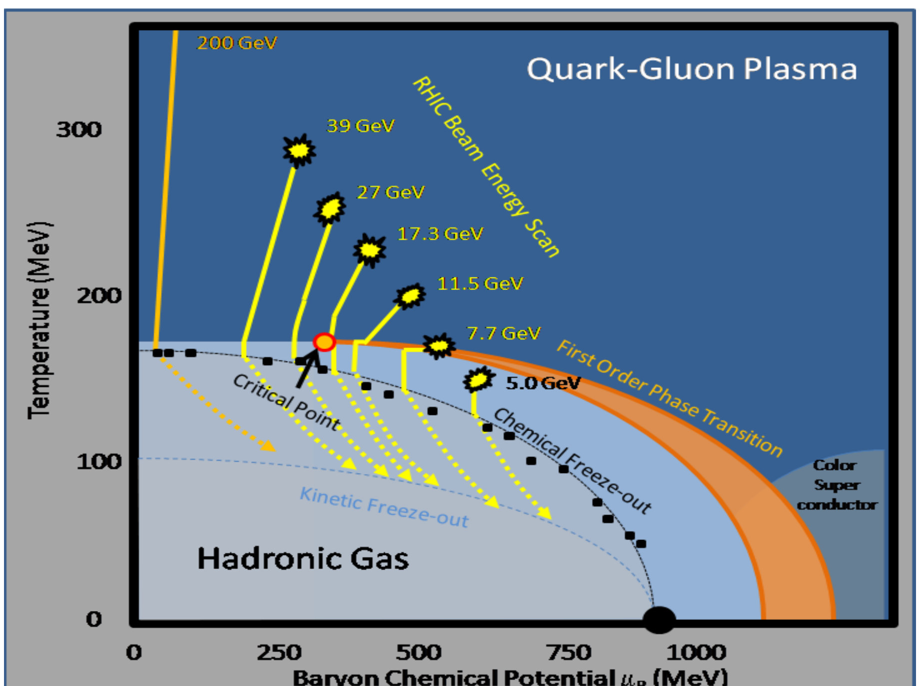
computationally intensive
need large scale supercomputing

Exploring QCD phase diagram



Exploring QCD phase diagram in HIC





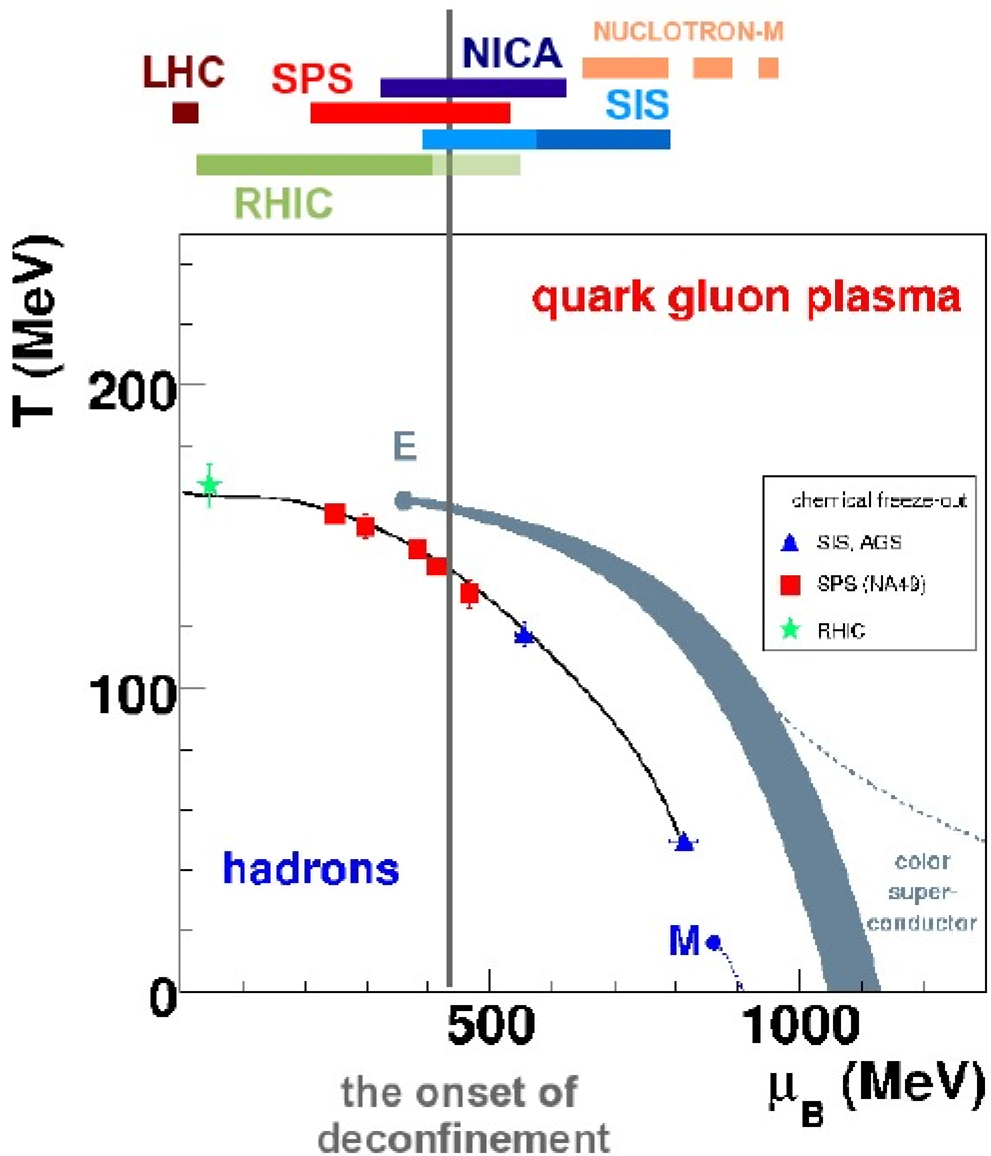
freeze-out: $\left(T^{f,ch}, \mu_B^{f,ch}, \mu_Q^{f,ch}, \mu_S^{f,ch}\right)$

"observed" in HIC

scan by changing colliding energies and species

to come closer to the phase boundary

Exploring QCD phase diagram in HIC



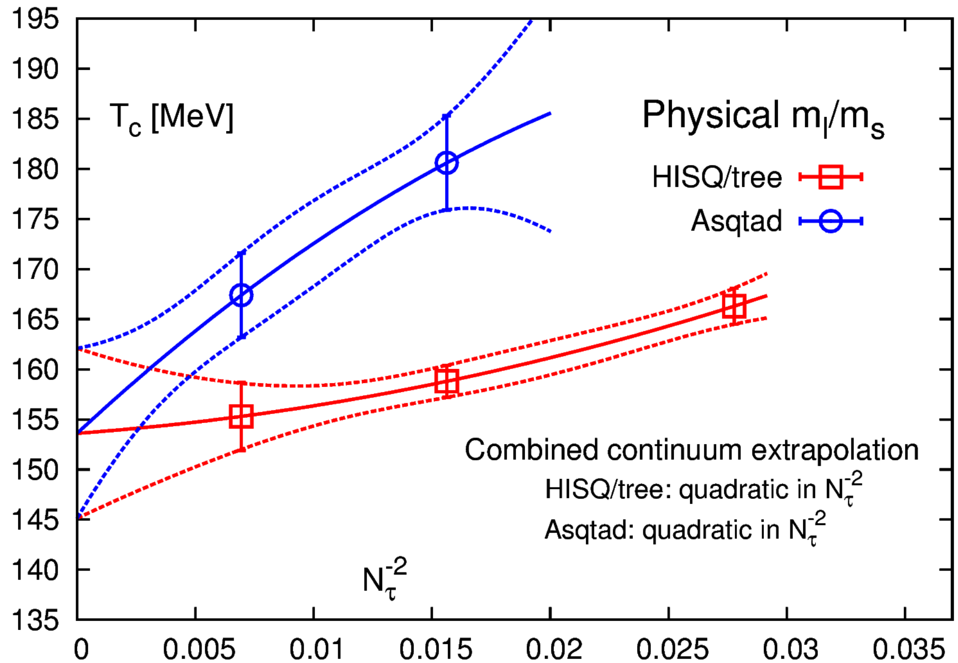
present and future HIC expt. for the exploration of the QCD phase diagram

CERN **SPS** (**NA61**)
BNL **RHIC** (**STAR, PHENIX**)
JINR **NICA** (**MPD**)
GSI **FAIR SIS-100/300**
(**HADES+CBM, CBM**)
JINR **NUCLOTRON-M** (**BM@N**)

2009(11) ↗
2010 ↗
2017 ↗
2017(19) ↗
2009 ↗
2015 ↗

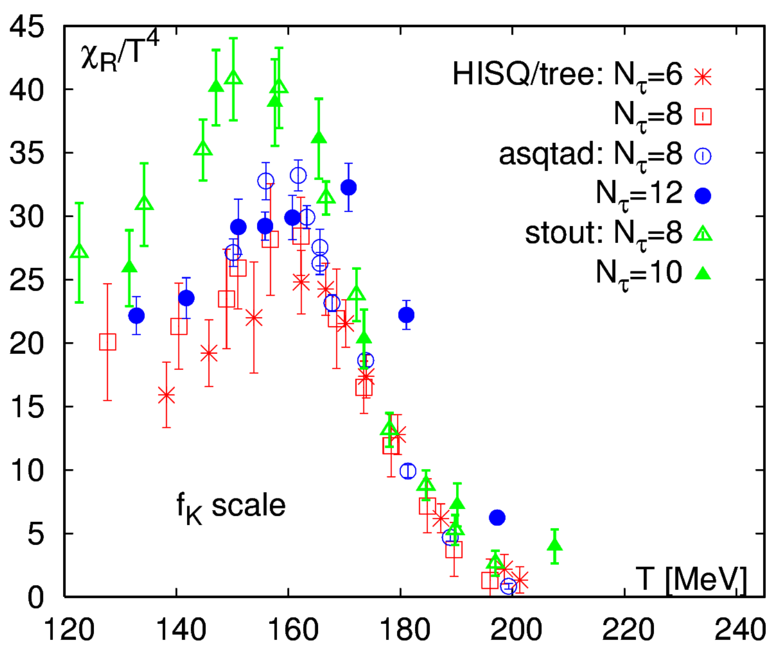
62

Phase boundary: chiral crossover



$$T_c(0) = 154(9)\ \text{MeV}$$

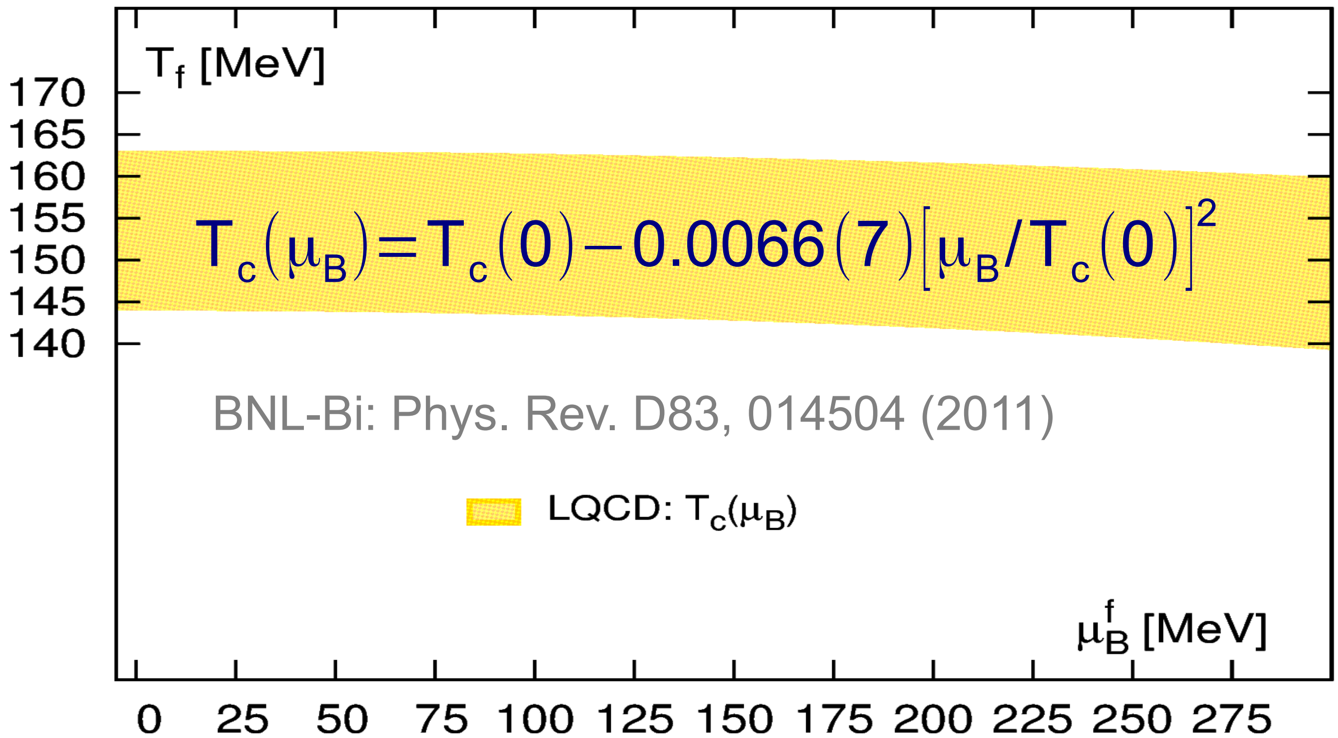
HotQCD: Phys. Rev. D85, 054503 (2012)

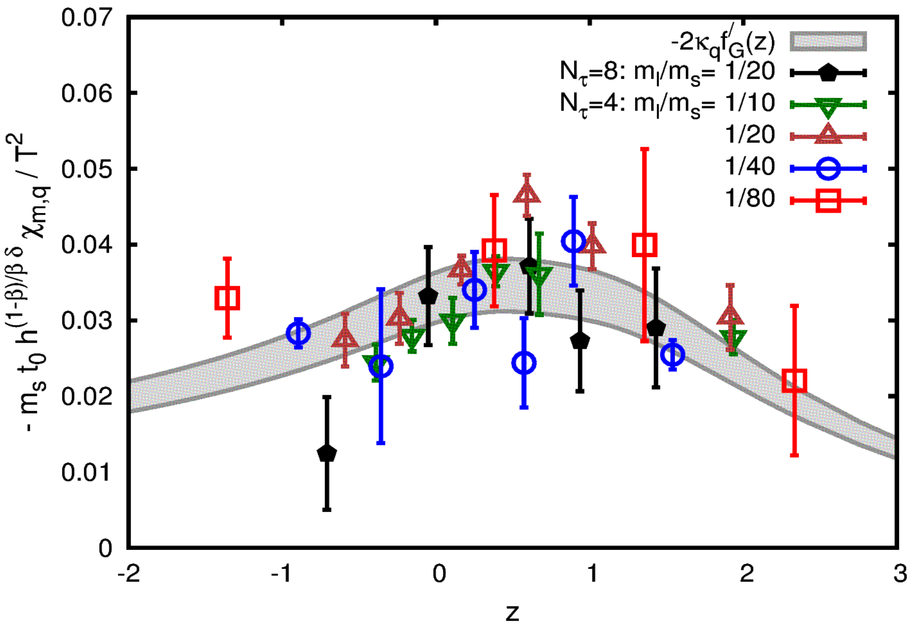


chiral susceptibility

fluctuations of chiral condensate

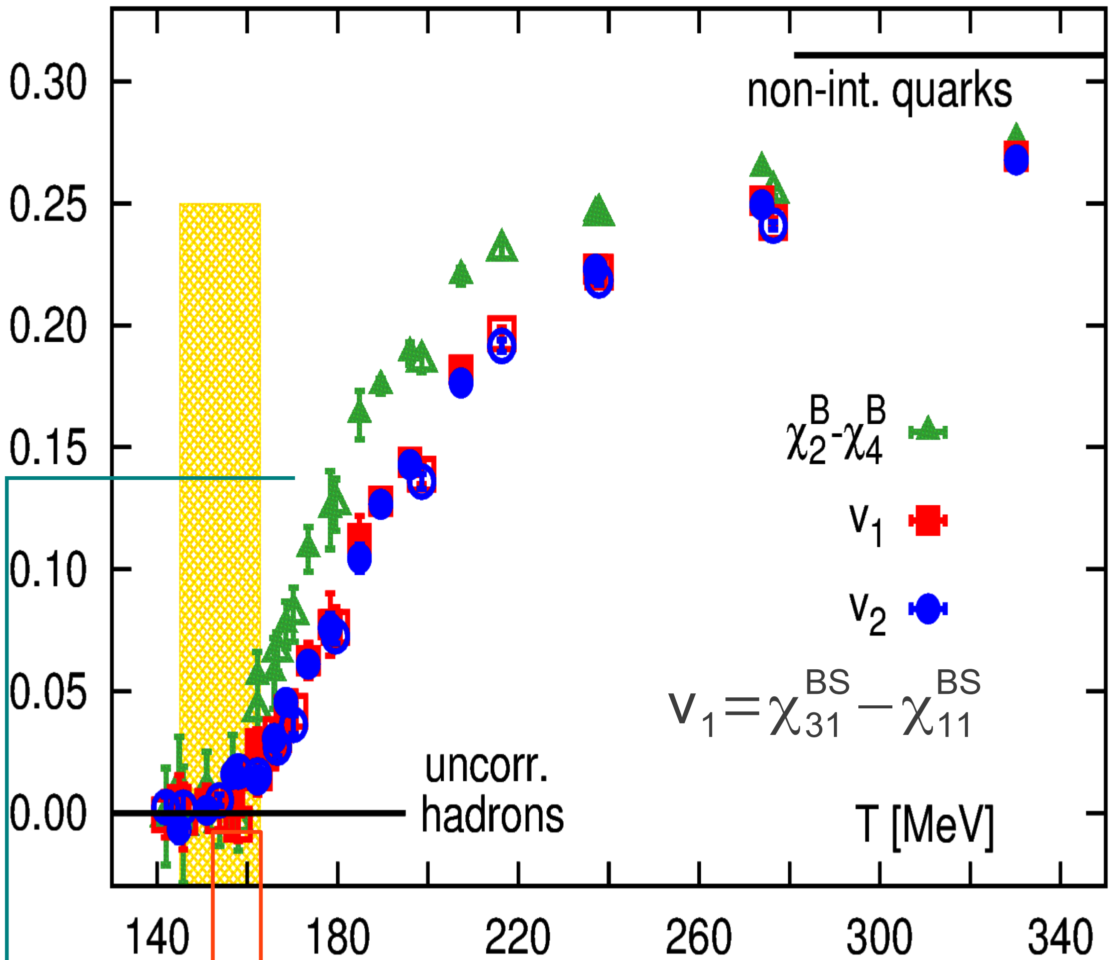
Phase boundary: chiral crossover





response of chiral condensate
to non-zero chemical potential

Phase boundary: deconfinement



deconfinement seems to takes place in the chiral crossover region

BNL-Bi: arXiv:1304.7220

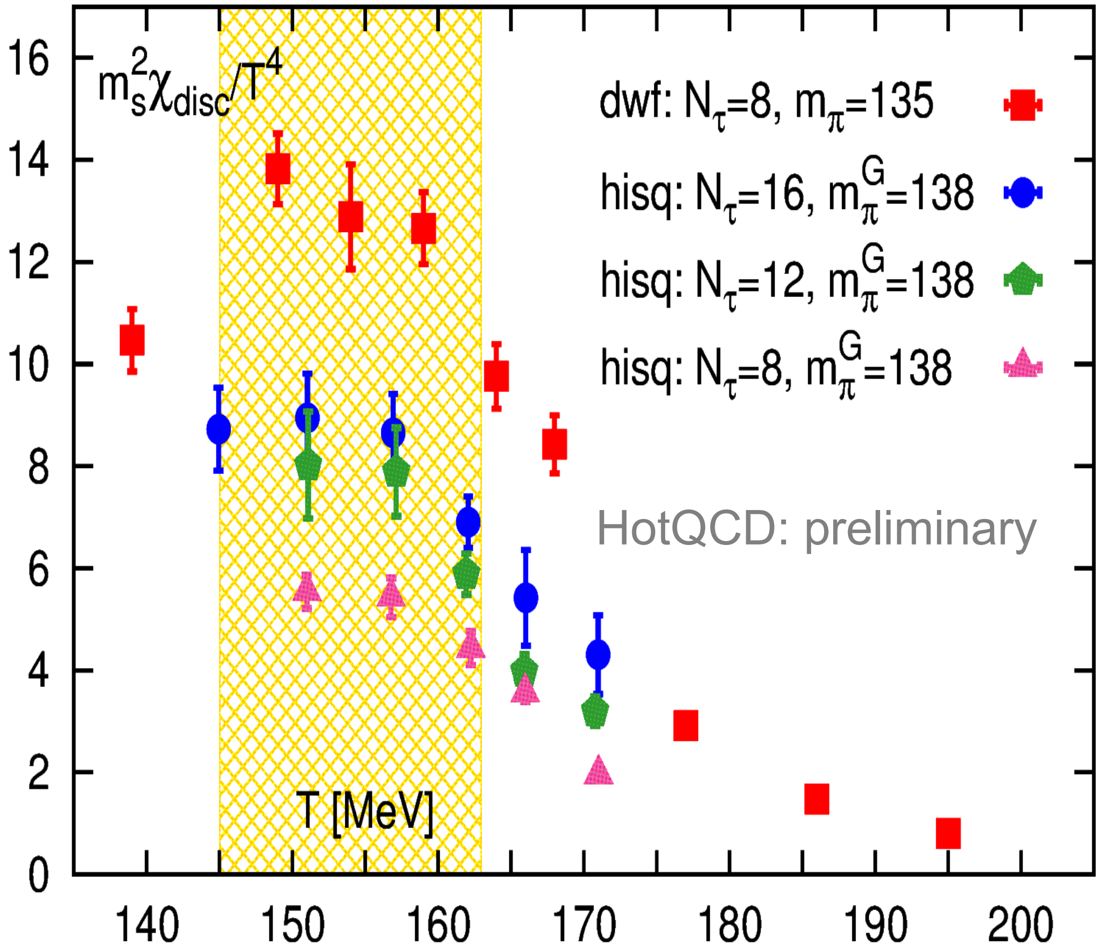
$T \lesssim T_c$: strangeness carrying DoF are associated with |B|=0,1 & |S|=0,1,2,3

but not above the chiral crossover

irrespective of the hadron masses

strange DoF behave similarly as the light quark DoF

Phase boundary: towards chiral (domain wall) fermions



extremely costly

Sequoia@LLNL

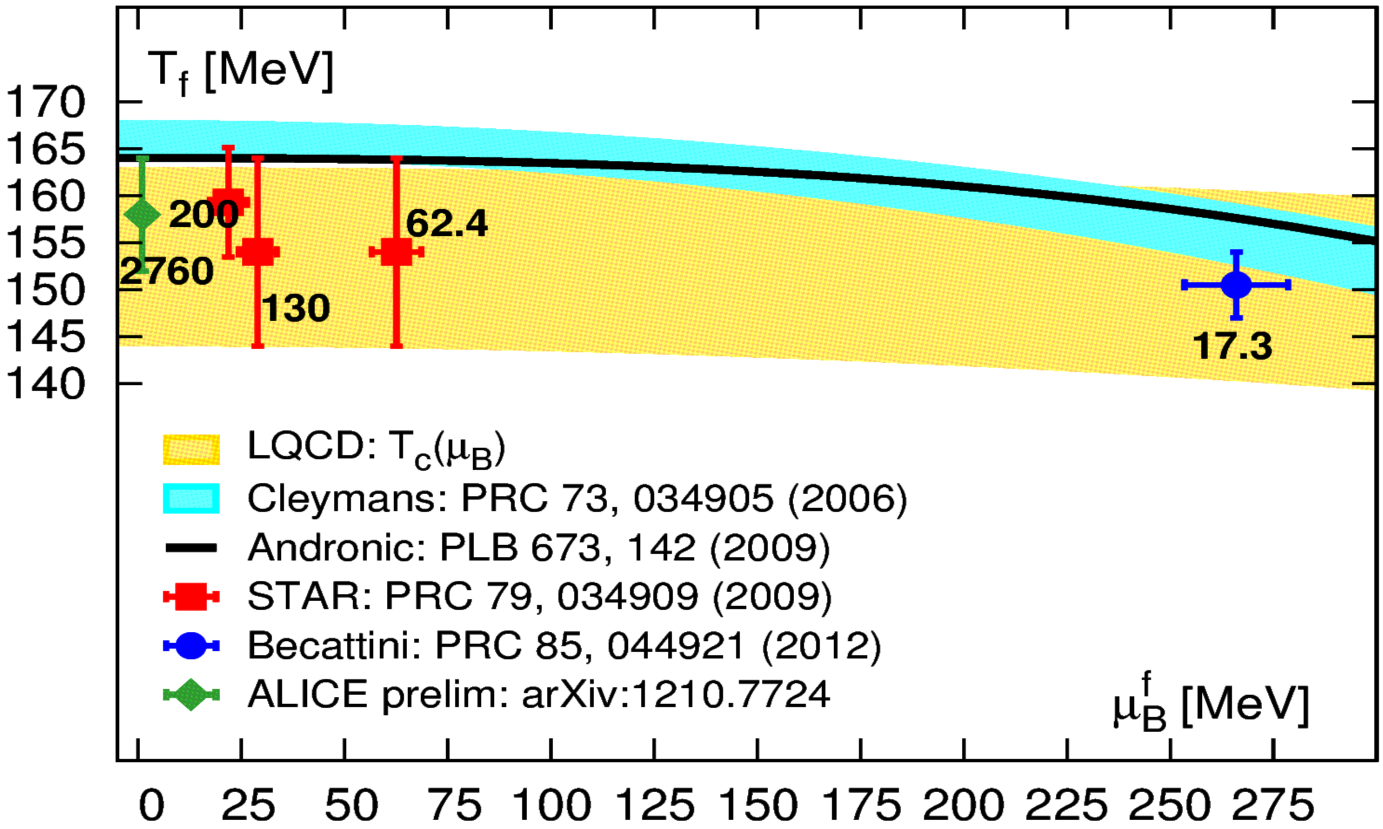
Mira@ALCF

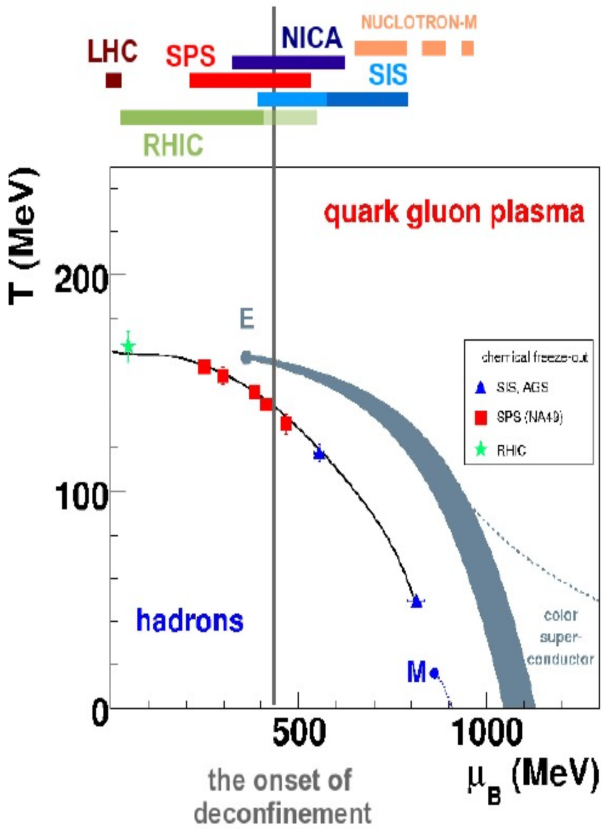
crosscheck using chiral fermions

program just started

Domain Wall Fermions: exact chiral symmetry & correct anomaly even at non-zero lattice spacings

Phase boundary and freeze-out in HIC





freeze-out: $\left(T^{f,ch}, \mu_B^{f,ch}, \mu_Q^{f,ch}, \mu_S^{f,ch}\right)$

"observed" in HIC

freeze-out in HIC from first-principle LQCD ?

traditionally determined by fitting experimental hadron yields using hadron resonance gas model

Freeze-out in HIC from LQCD

$\left(T^{f,ch}, \mu_B^{f,ch}, \mu_Q^{f,ch}, \mu_S^{f,ch}\right)$: by comparing experimentally measured higher order cumulants of electric charge fluctuations

$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\langle N_Q \rangle}{\langle (\delta N_Q)^2 \rangle} = \frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)} = R_{12}^Q(T,\mu_B)$$

$$\frac{S_Q(\sqrt{s})\,\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\langle (\delta N_Q)^3 \rangle}{\langle N_Q \rangle} = \frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)} = R_{31}^Q(T,\mu_B)$$

HIC

mean: M_Q

variance: σ_Q^2

skewness: S_Q

$\delta N_Q = N_Q - \langle N_Q \rangle$

LQCD

generalized charge susceptibilities:

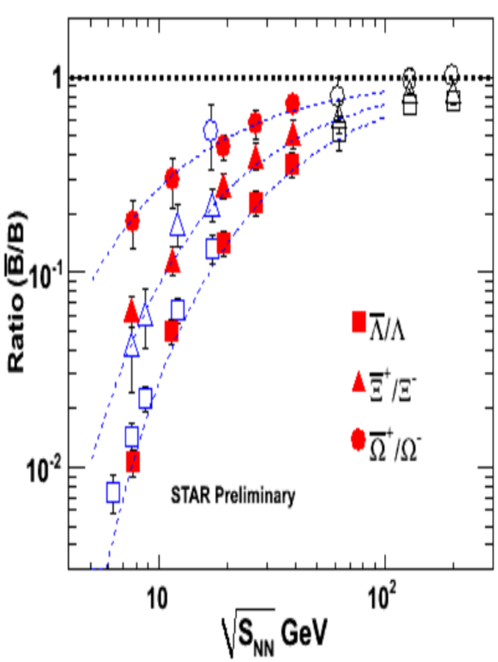
$$\chi_n^Q(T,\vec{\mu}) = \frac{1}{VT^3} \frac{\partial^n \ln \mathbb{Z}(T,\vec{\mu})}{\partial(\mu_Q/T)^n}$$

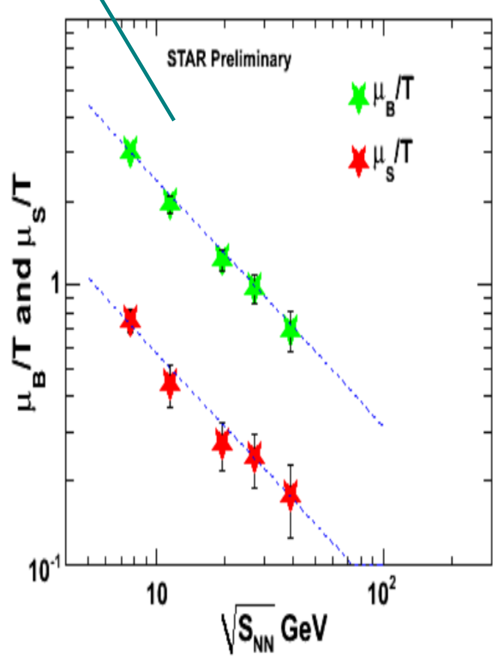
Freeze-out in HIC from LQCD

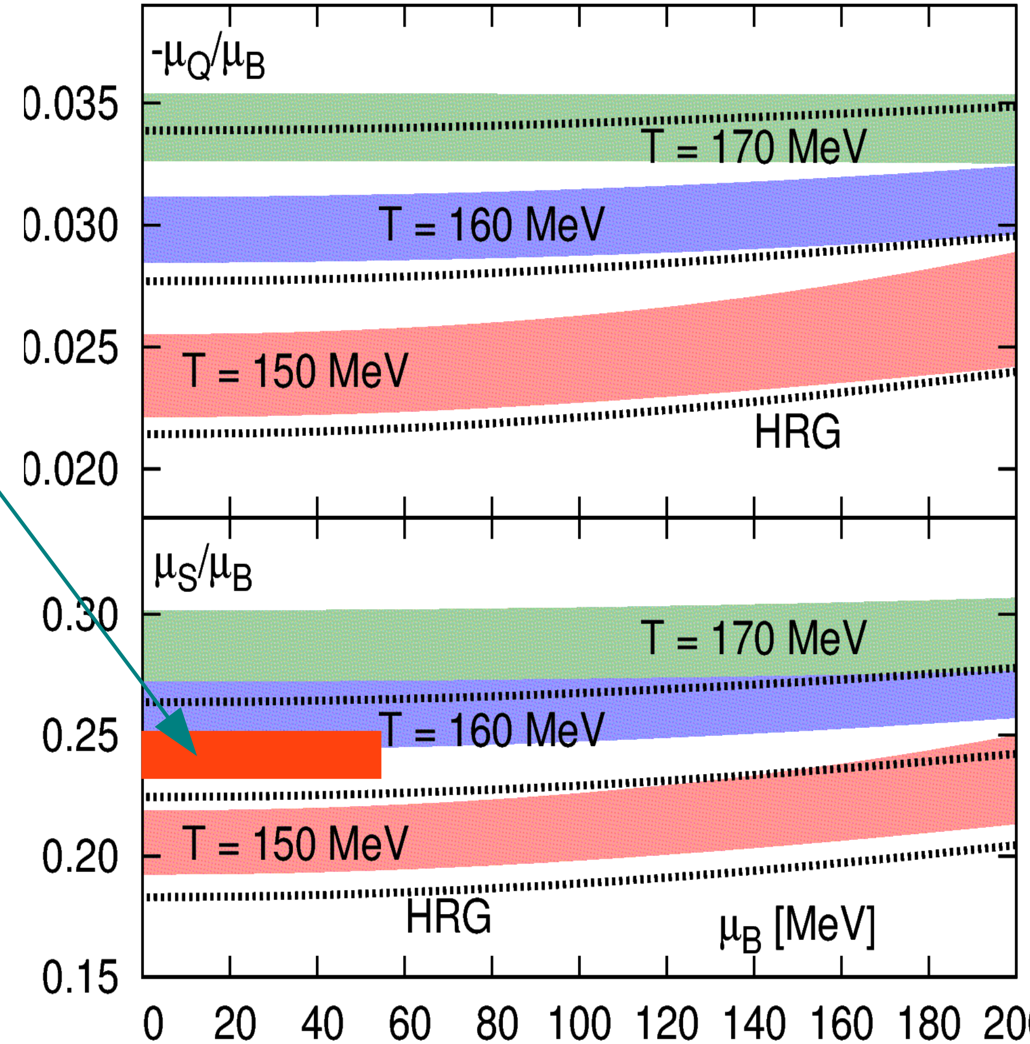
BNL-Bi: Phys. Rev. Lett. 109, 192302 (2012)

$\mu_S^f/\mu_B^f \approx 0.24(2)$

STAR preliminary





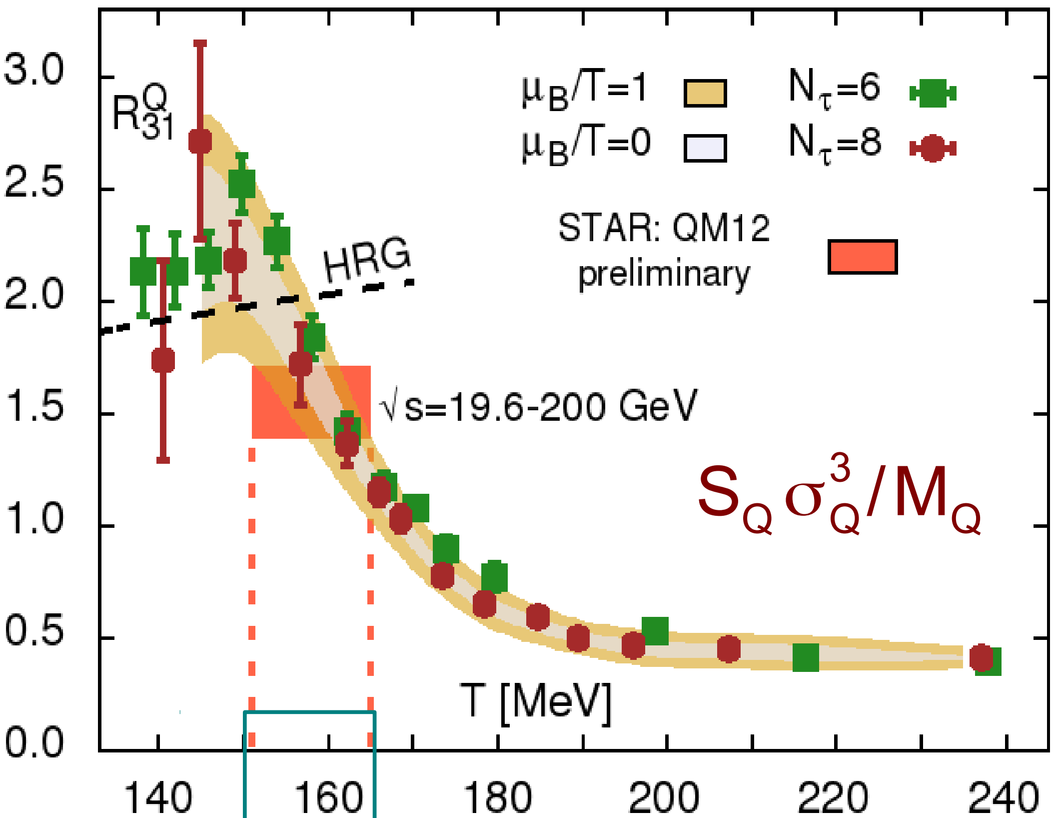


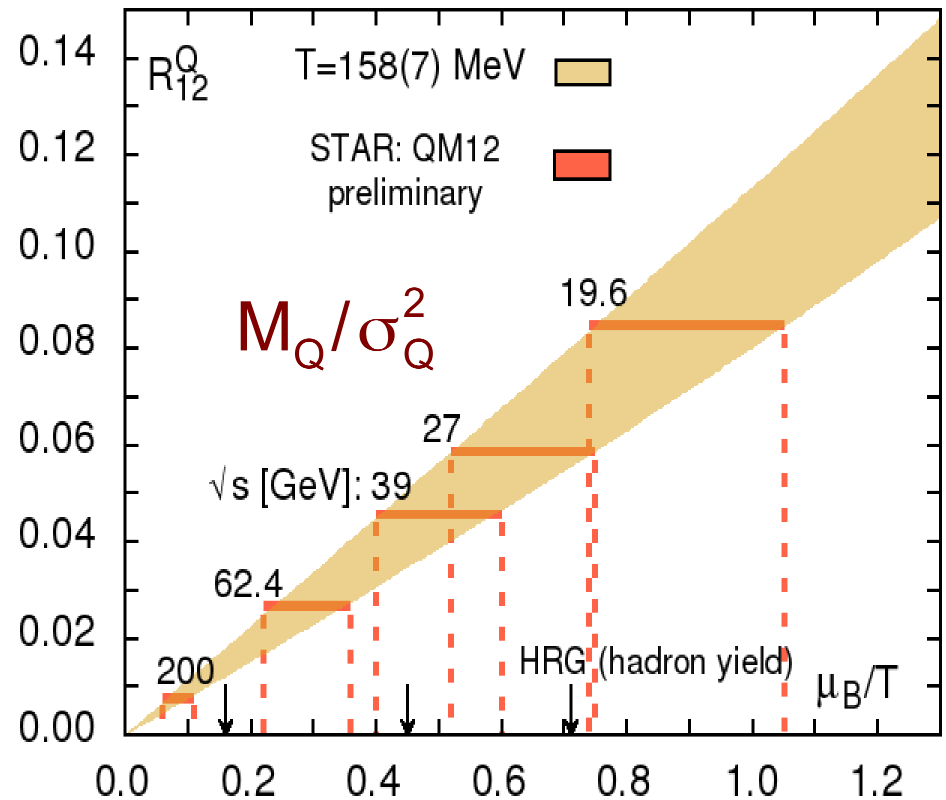
ratios of strange anti-baryon to baryon

F. Zhao, CPOD 2013

LQCD: electric charge, strangeness chemical potentials

Freeze-out in HIC from LQCD





thermometer
determines T^f

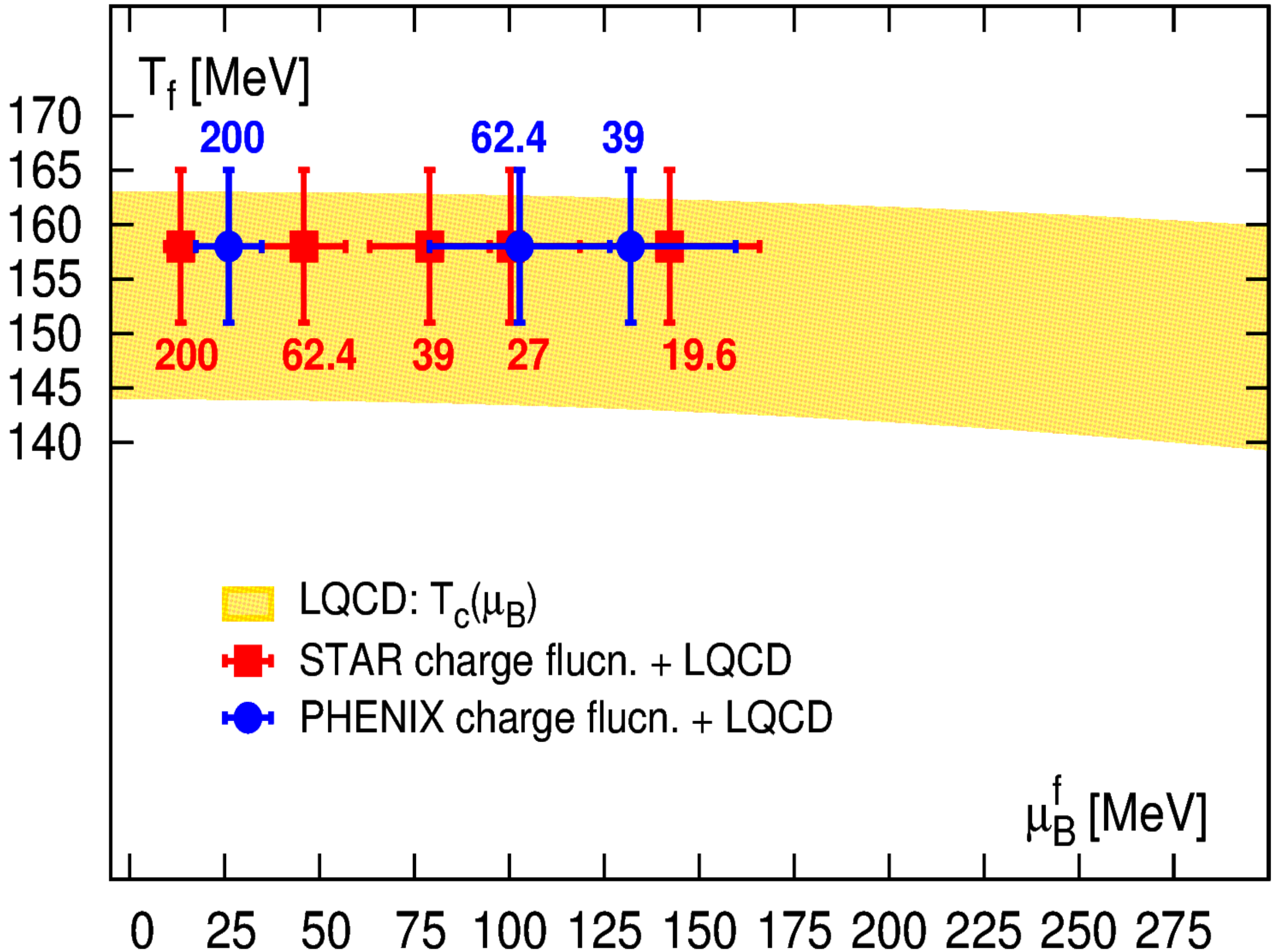
baryometer
determines μ_B^f

$T^f = 158(7)$ MeV

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

STAR preliminary: Quark Matter 2012

Freeze-out in HIC from LQCD



some tension between STAR and PHENIX preliminary (QM-12) data at present

large errors for both expt. & LQCD

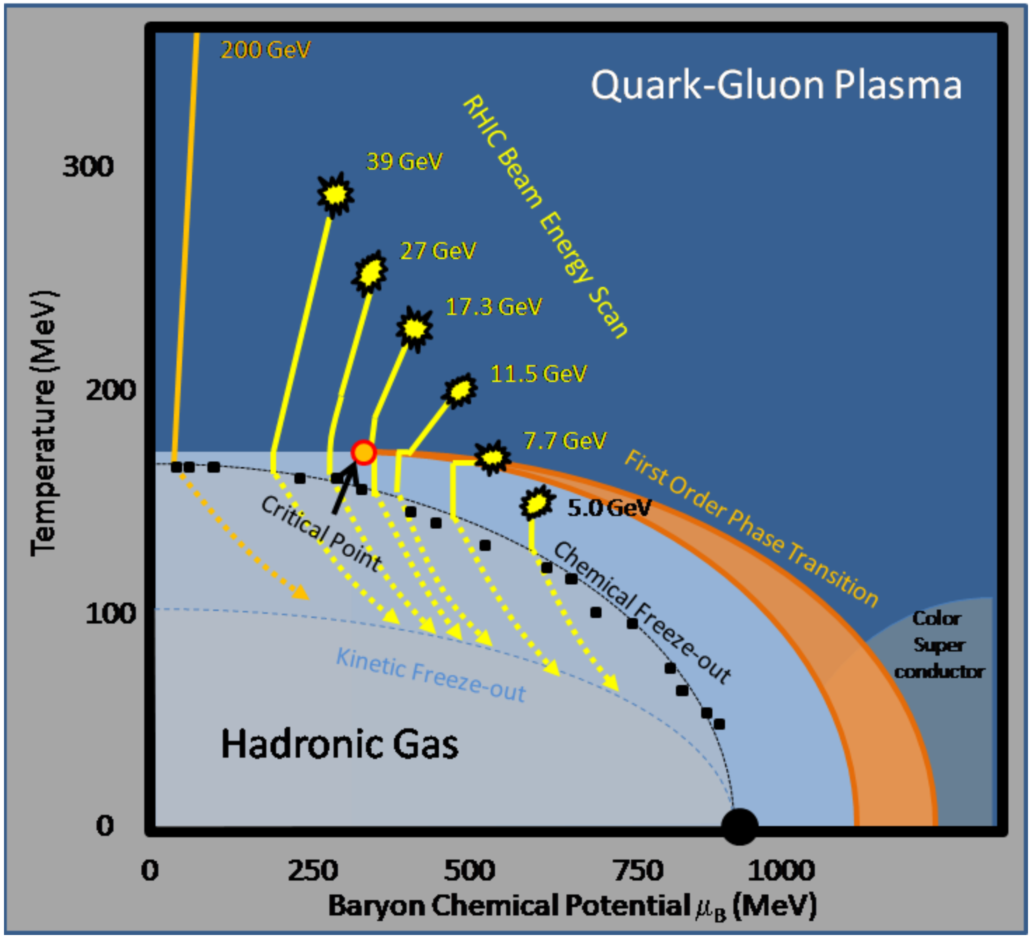
to do:
continuum extrapolations
extend to larger precision

required:
sarge lattices
higher order cummulnats
huge statistics

ideally suited for GPU

freeze-out on HIC takes place close to the phase boundary

Search for the QCD critical point



qualitatively different features from hadronic description

BES@RHIC

signature of criticality in QCD phase diagram,
higher order cumulants of conserved charge fluctuations

higher order cumulants are increasingly sensitive to the large correlation lengths encountered near criticality

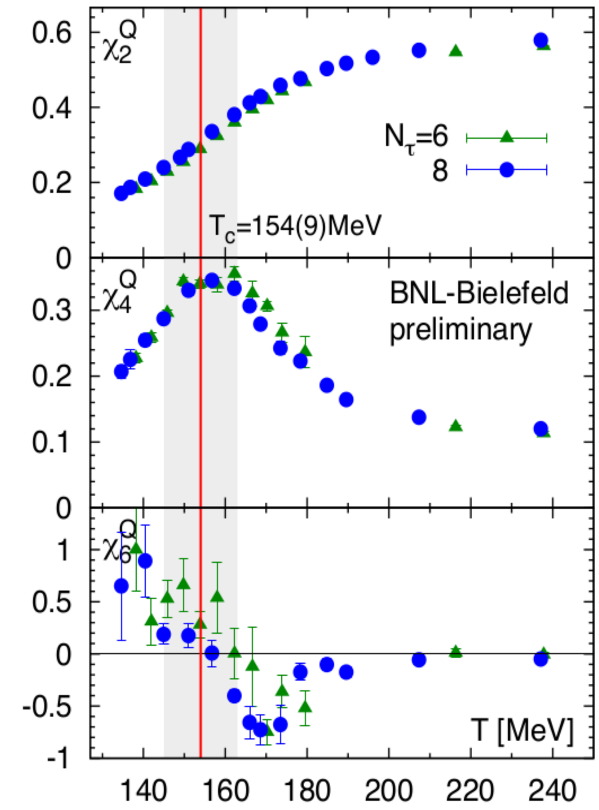
for example:
near the QCD ciritical point

variance $\sim \xi^2$
skewness $\sim \xi^{4.5}$
kurtosis $\sim \xi^7$

Search for the QCD critical point

LQCD $T \sim T_c$: $\chi_4(\mu_B) = \chi_4(0) + \chi_6(0)\mu_B^2/2 + \cdots$

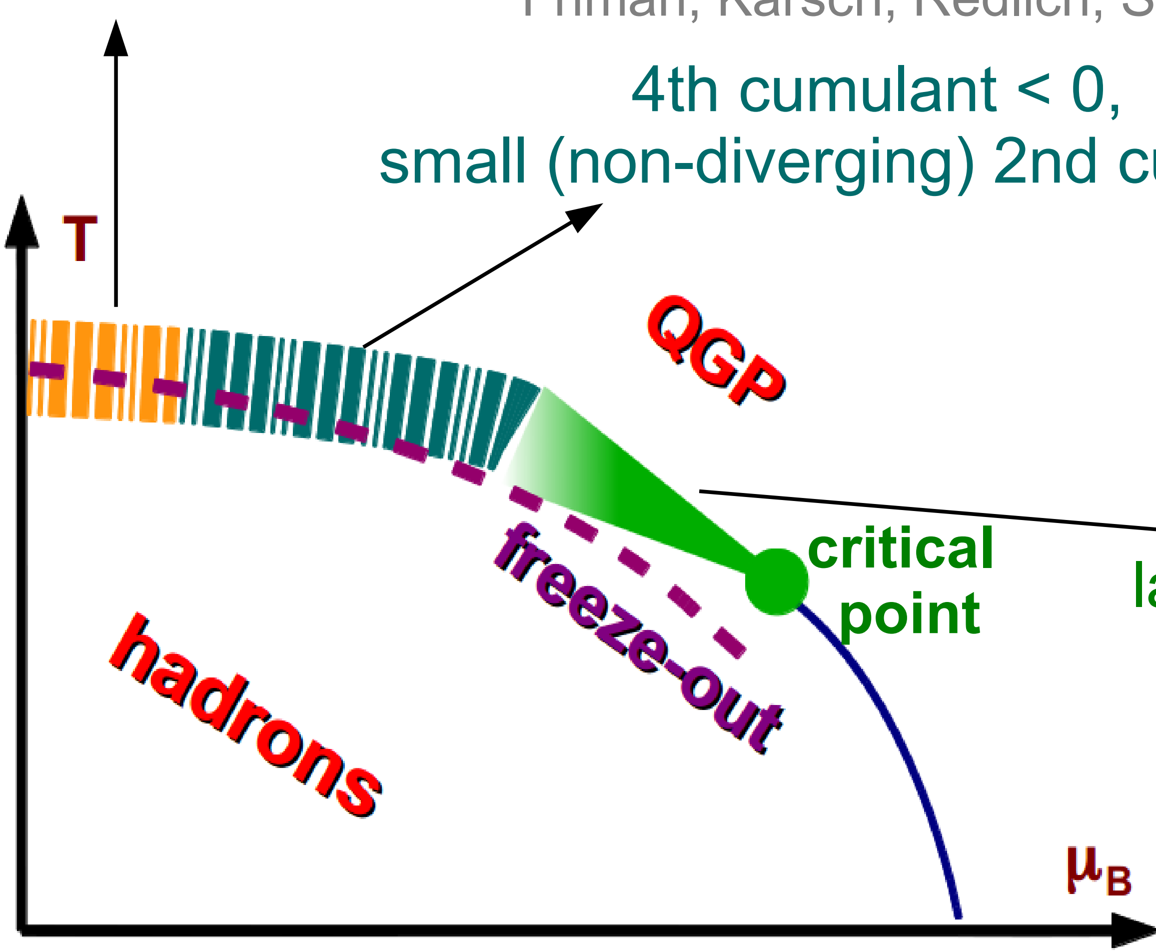
> 0 < 0



6th cumulant < 0

Friman, Karsch, Redlich, Skokov

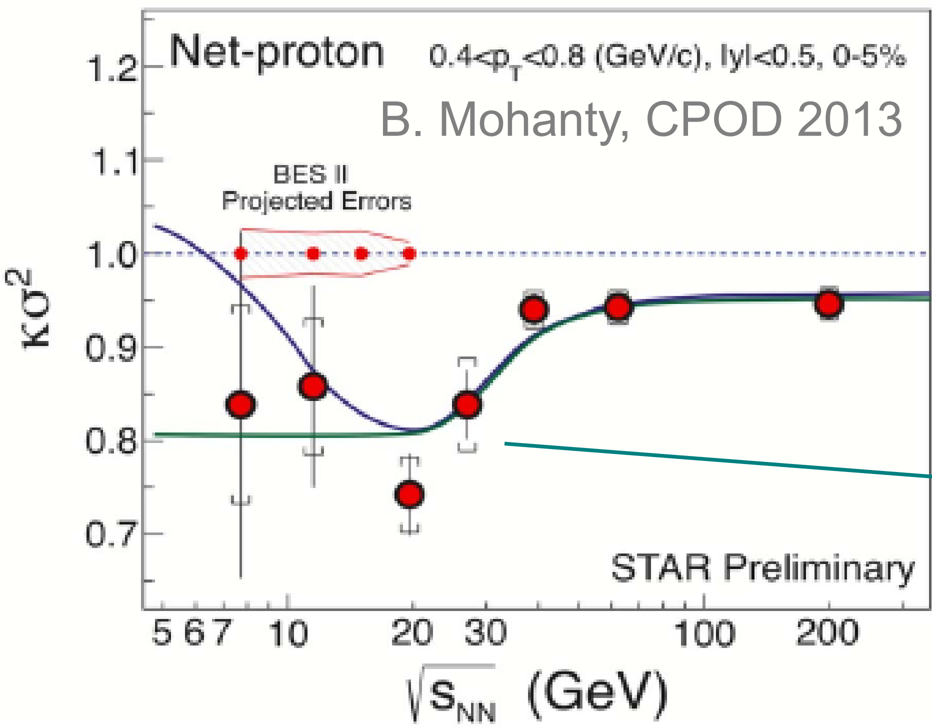
4th cumulant < 0,
small (non-diverging) 2nd cumulant



4th cumulant < 0,
large (diverging) 2nd cumulant

Stephanov

Search for the QCD critical point

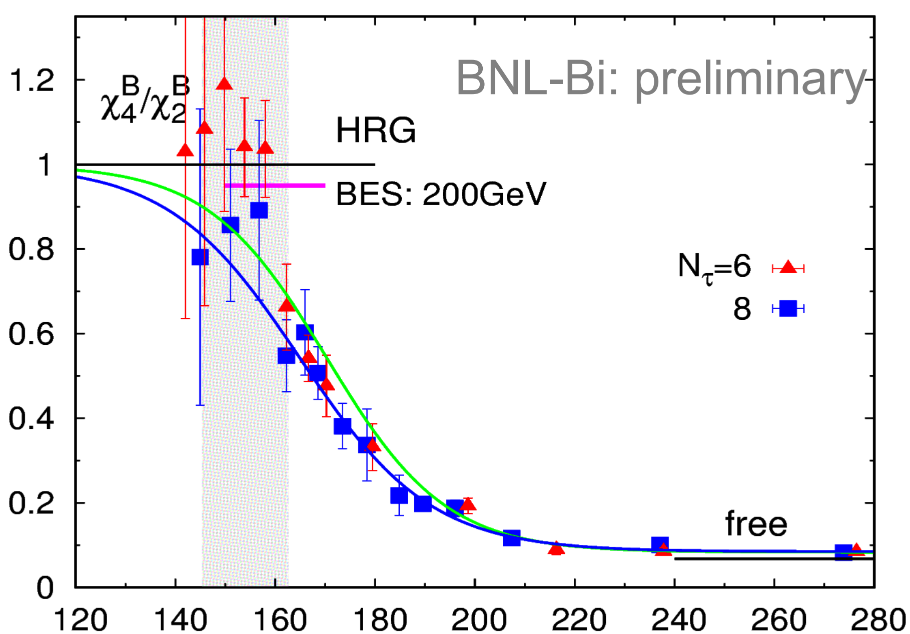


$$\kappa_B \sigma_B^2 = \chi_4^B(\mu_B)/\chi_2^B(\mu_B)$$
$$= \frac{\chi_4^B}{\chi_2^B}\left[1 + \left(\frac{\chi_6^B}{\chi_2^B} - \frac{\chi_4^B}{\chi_2^B}\right)\left(\frac{\mu_B}{T}\right)^2 + \cdots\right]$$

non-monotonic behavior ?

$\chi_B^6 < 0,\ T \sim T_c$

$\chi_B^6 > 0\,(\text{large}),\ T < T_c$

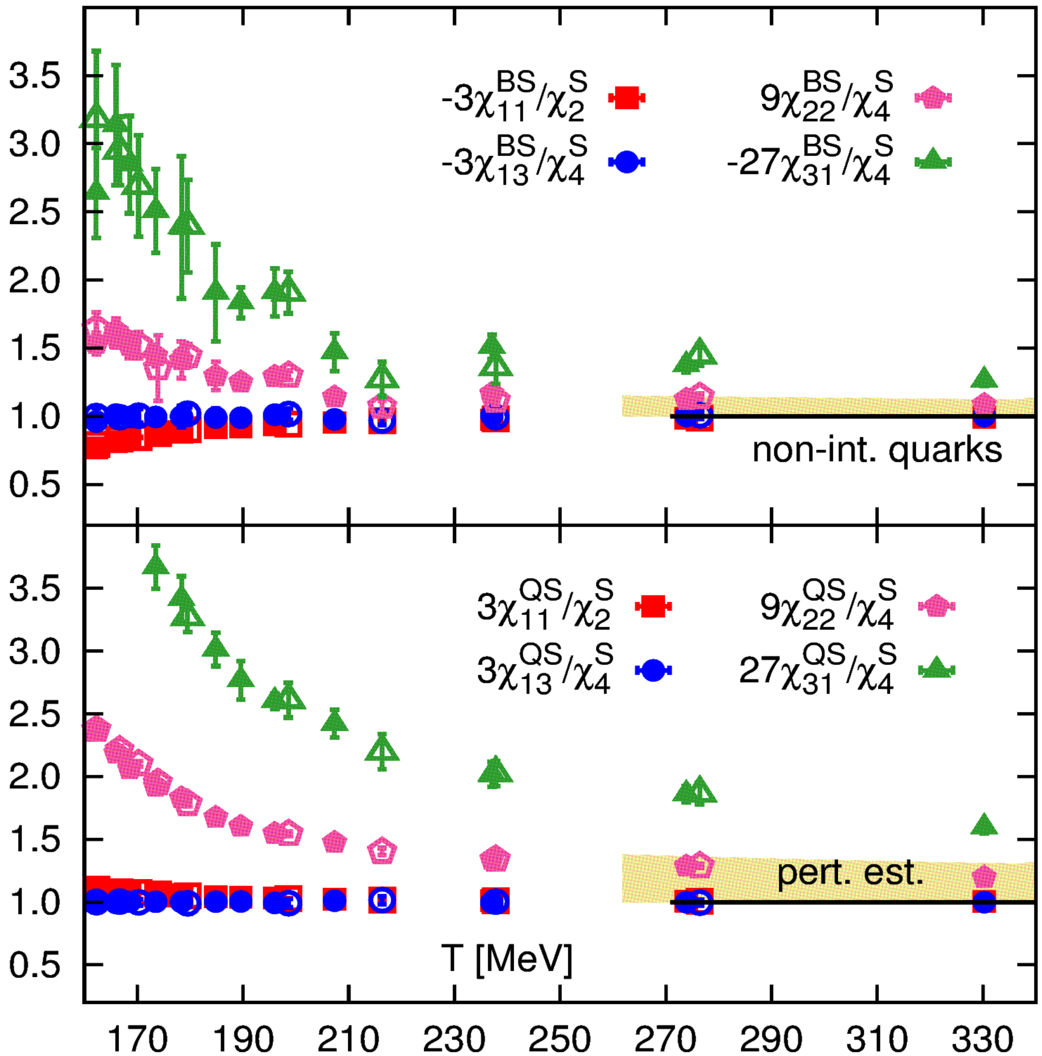


need precise determination of sixth order cumulant of baryon number fluctuations

ideally suited for GPU

Talk: C. Schmidt

Properties of QGP: a strongly coupled medium ?



BNL-Bi: arXiv:1304.7220

baryon-strangeness correlations

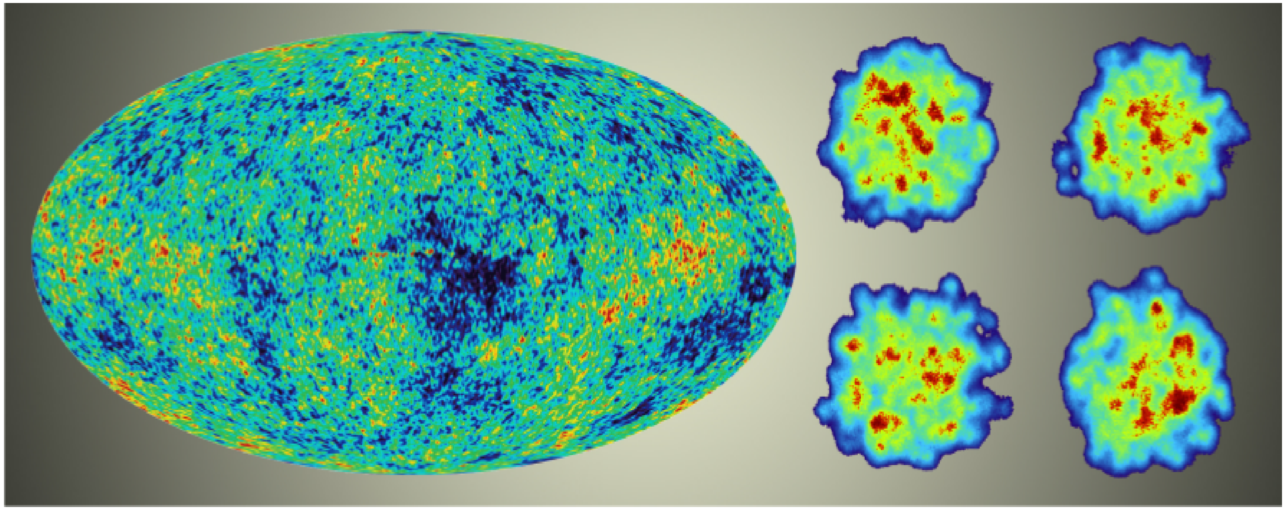
strangeness can be clearly associated with baryon number 1/3 and charge -1/3 only for $T \gtrsim 2T_c$

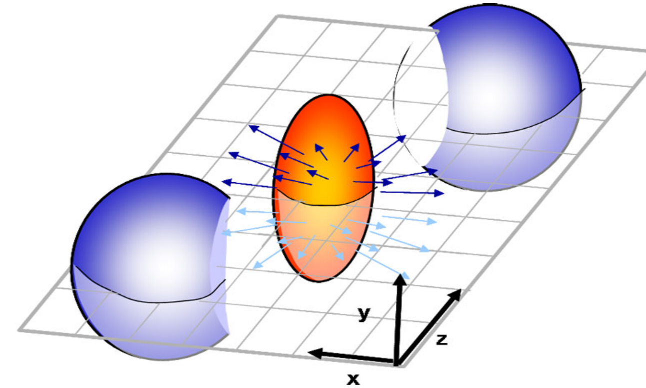
charge-strangeness correlations

$T_c \lesssim T \lesssim 2T_c$

a strongly coupled medium ?

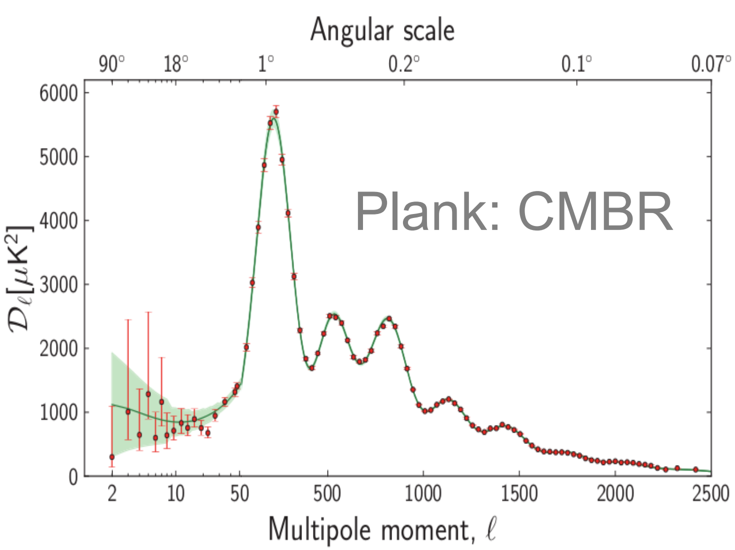
Collective flow: QGP a perfect fluid ?

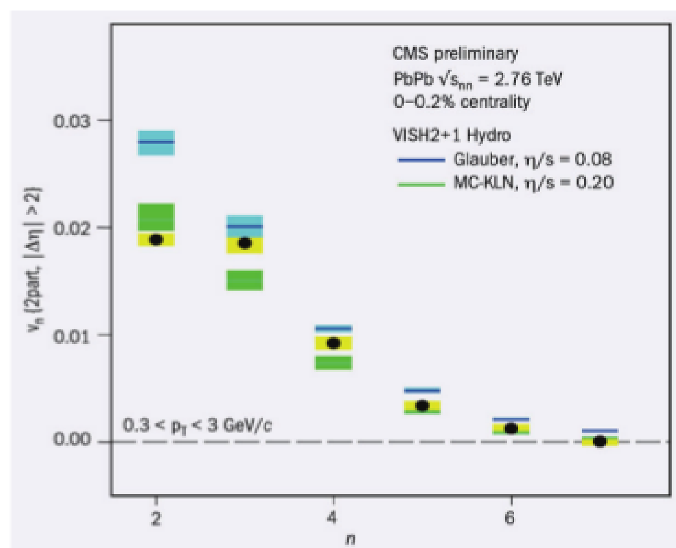




early universe

HIC



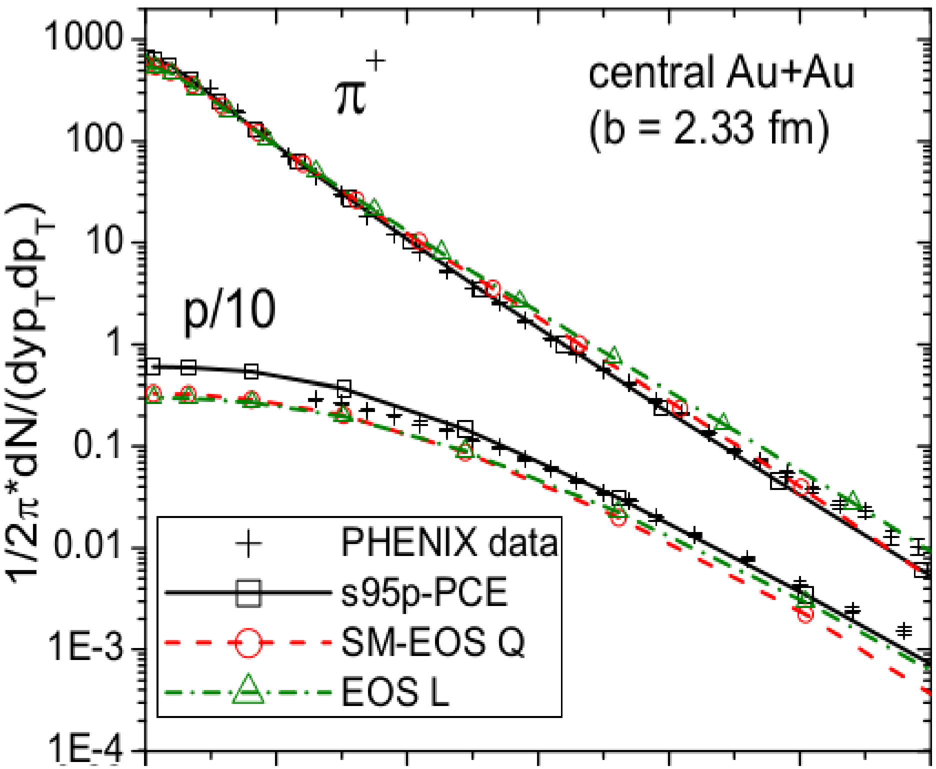


CMS @ LHC:
flow harmonics

initial momentum anisotropy 'carries' the initial fluctuations to the final state through collective flow of the medium

Heinz, arXiv:1304.3634

Collective flow: QGP a perfect fluid ?

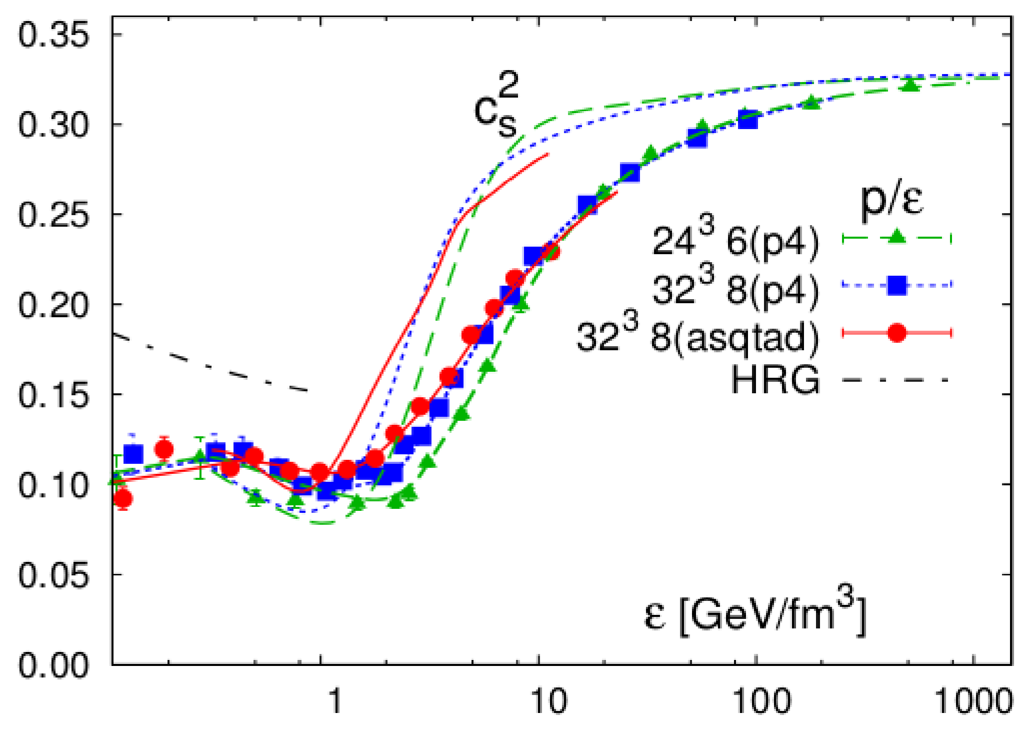


Shen et.al., Phys. Rev. C83, 054904 (2010)

collective flow in HIC is hydrodynamic

hydrodynamics: statements regarding conservation laws

QCD enters only through the Equation of State (EoS) of the medium

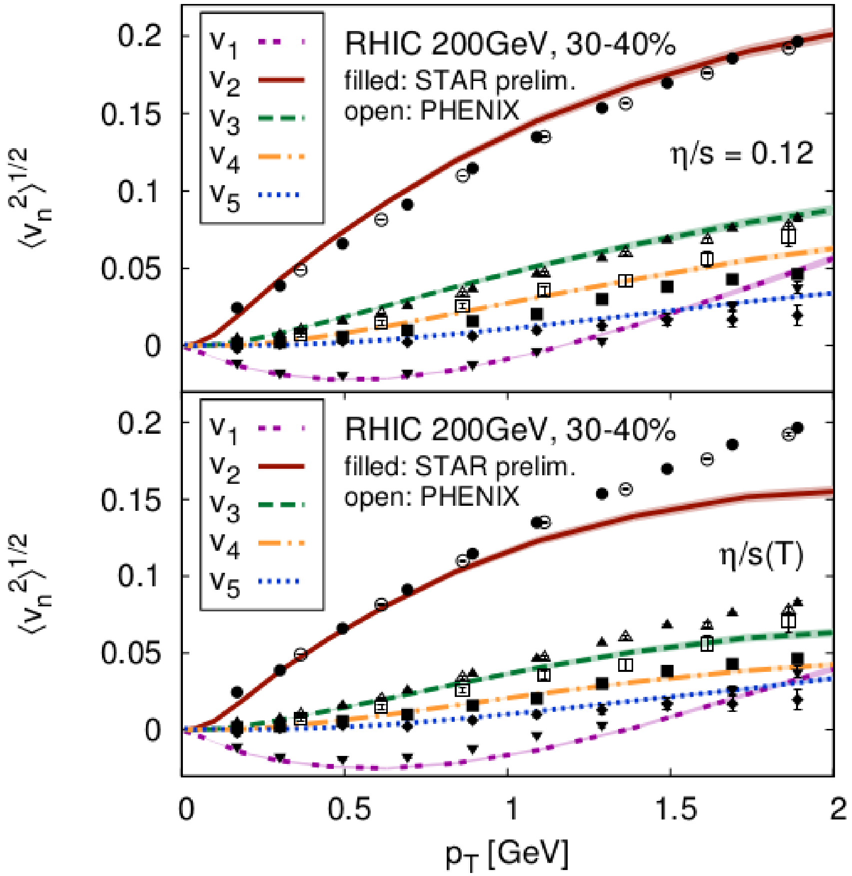


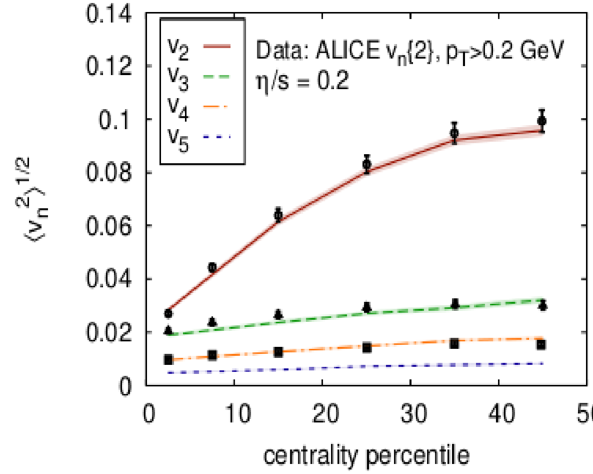
LQCD: speed of sound

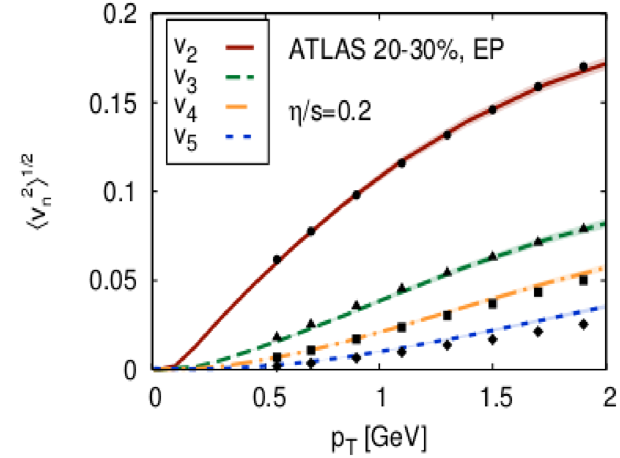
HotQCD: Phys. Rev. D80, 014504 (2009)

need continuum extrapolation and precision

Collective flow: QGP a perfect fluid ?

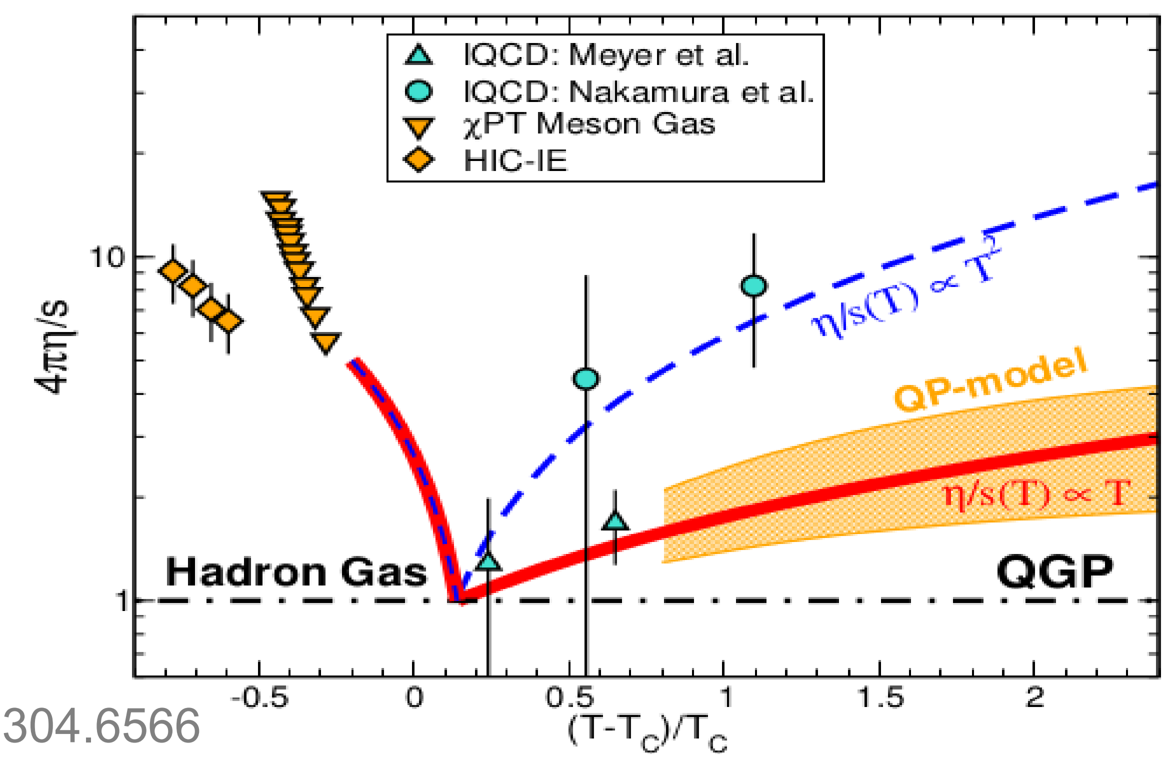






Gale et al, Phys. Rev. Lett. 110,012302 (2012)

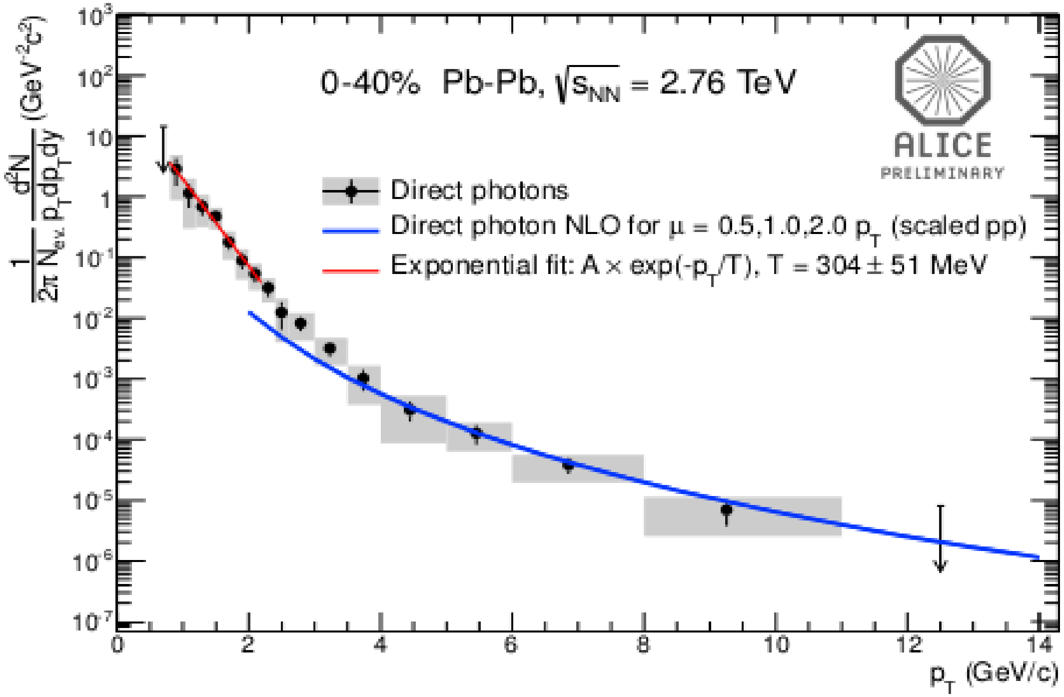
QGP a nearly perfect fluid ?



need realistic LQCD determination of the viscosity of QGP

Plumari et.al., arXiv:1304.6566

Hot QGP and flowing photons: photon/dilepton emissivity



RHIC: $T_{avg} = 221 \pm 19 \pm 19$ MeV

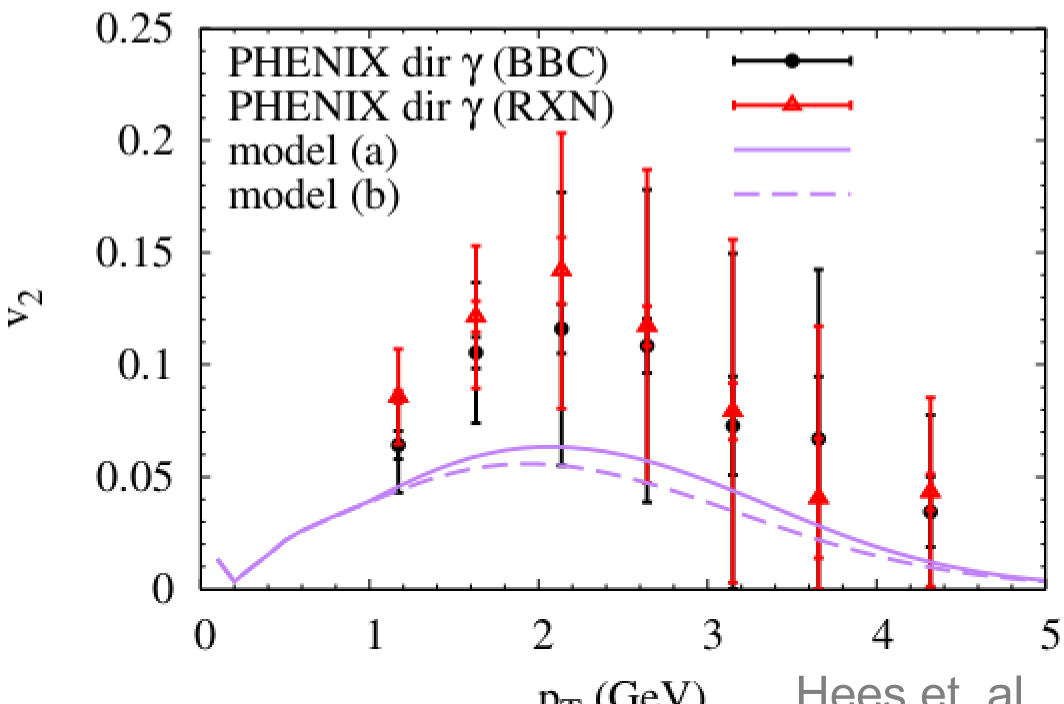
PHENIX: Phys. Rev. Lett. 104, 132301 (2010)

LHC: $T_{avg} = 305 \pm 52$ MeV

ALICE: arXiv:1212.3995

from photon emission spectra

photons are produced early early, before complete development of collective flow



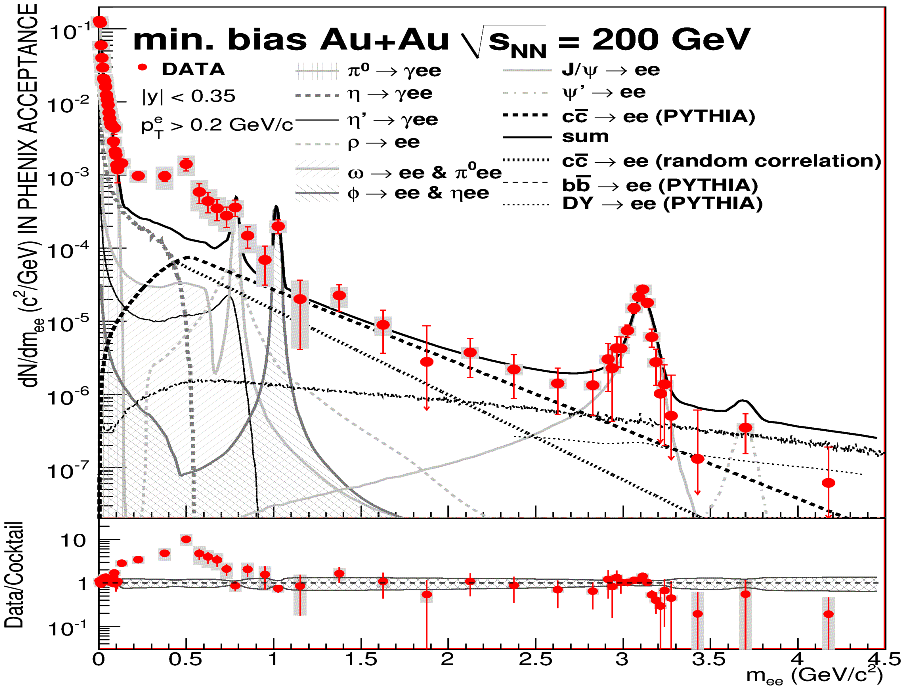
Hees et. al., Phys. Rev. C84, 054906 (2011)

but large photon (elliptic) flow

a puzzle !!

enhanced dilepton/photon emission at later states ?

Hot QGP and flowing photons: photon/dilepton emissivity

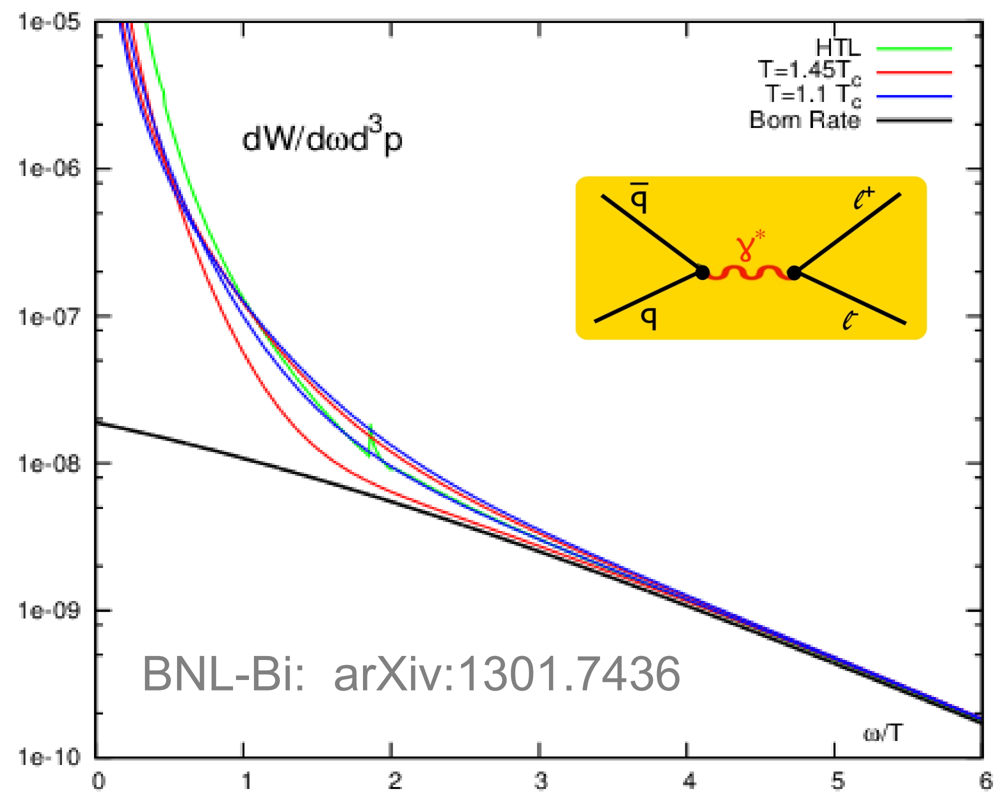


PHENIX @ RHIC:
dilepton enhancement

PHENIX: Phys. Rev. C81, 034911 (2010)

no evidence for enhancement so far, however were performed without taking into effects of dynamical quarks (quenched simuations)

LQCD: thermal dilepton emissivity

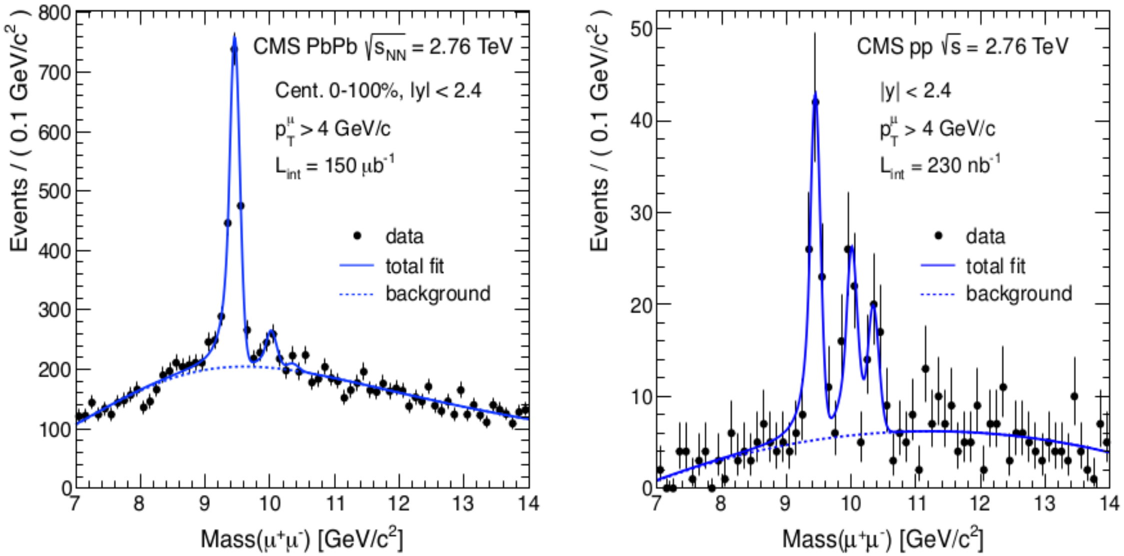


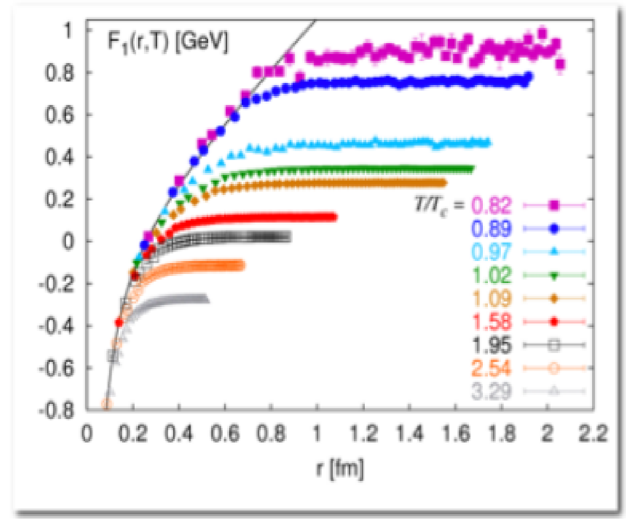
need full dynamical calculations

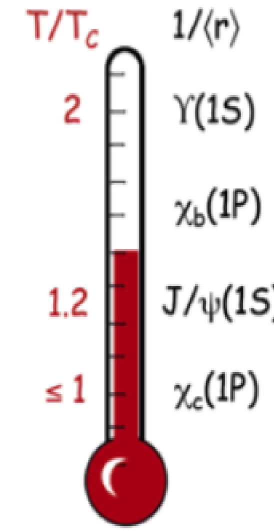
with large lattices required

Talk: P. Petreczky

Screened QGP: quarkonia melting







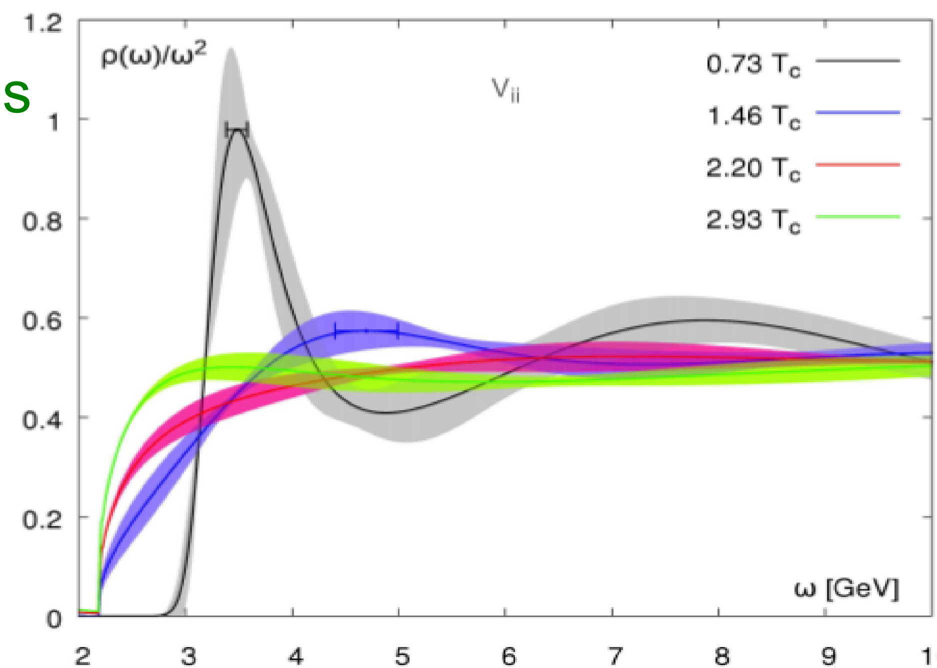
sequential melting of bottomonia in LHC

CMS: Phys. Rev. Lett. 109, 222301 (2012)

quarkonia are small objects, dissolve in the medium when the screening length of the plasma becomes comparable to the their radii

LQCD: charmonia spectral functions

BNL-Bi: Phys. Rev. D86, 014509 (2012)



need bottomonia spectral functions

require very fine but large lattices

Summary

LQCD is essential for understanding and interpretation of results from heavy-ion collision experiments