Exploring The QCD Phase Diagram With High Energy Nuclear Collisions

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Outline:

QCD Phase Diagram
Experimental Study of QCD Phase Diagram
Conclusions

Symposium on Charm, Dileptons and Deconfinement
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Phase Transitions

Physical systems undergo phase transitions when external parameters such as the temperature (T) or a chemical potential (μ) are tuned.

Systems following Quantum Chromodynamics (QCD) - No exception

Associated chemical potential

Conserved Quantities: Baryon Number ~ μ_B
Electric Charge ~ μ_Q ~ small
Strangeness ~ μ_S ~ small

In principle a four dimensional phase diagram

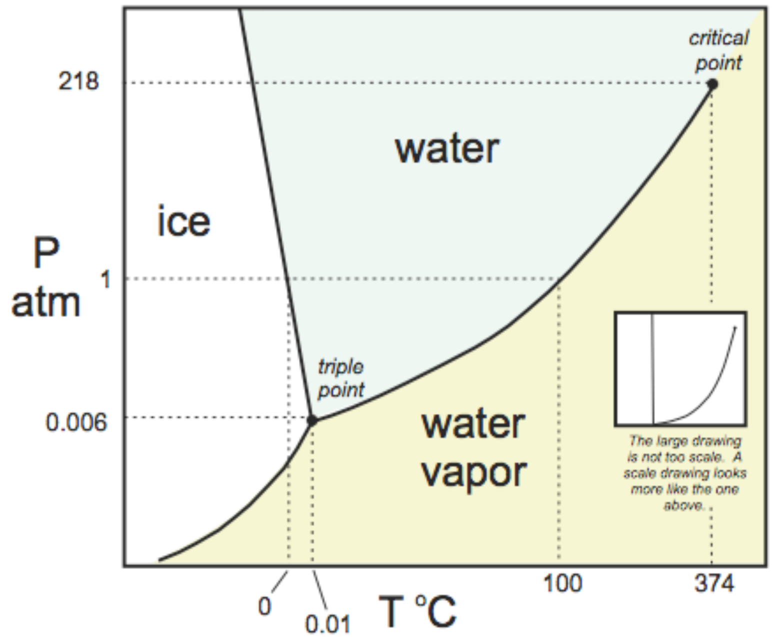
A simpler version : T vs. μ_B

QCD Phase Diagram

Phase diagram is a type of graph used to show the equilibrium conditions between the thermodynamically distinct phases

Water : Atomic

Precisely known

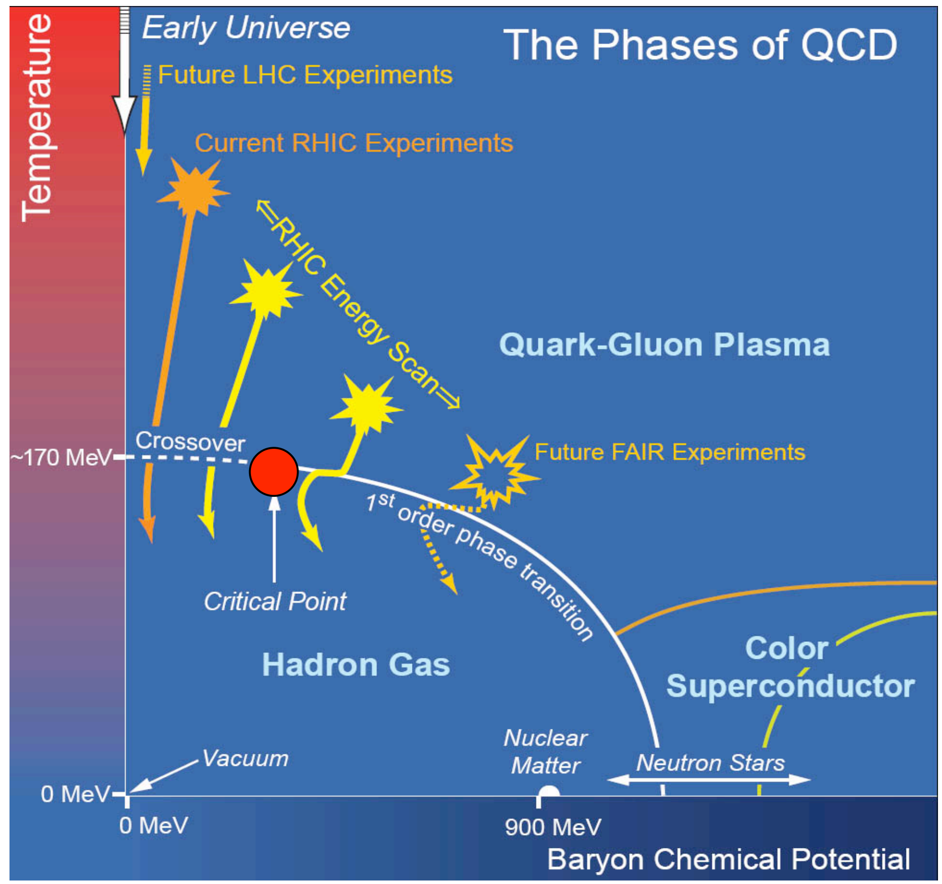


14 APRIL 2006 VOL 312 SCIENCE, Page 190

QCD phase diagram:
Thermodynamics of bulk strongly interacting matter

QCD (Hadrons -- Partons)

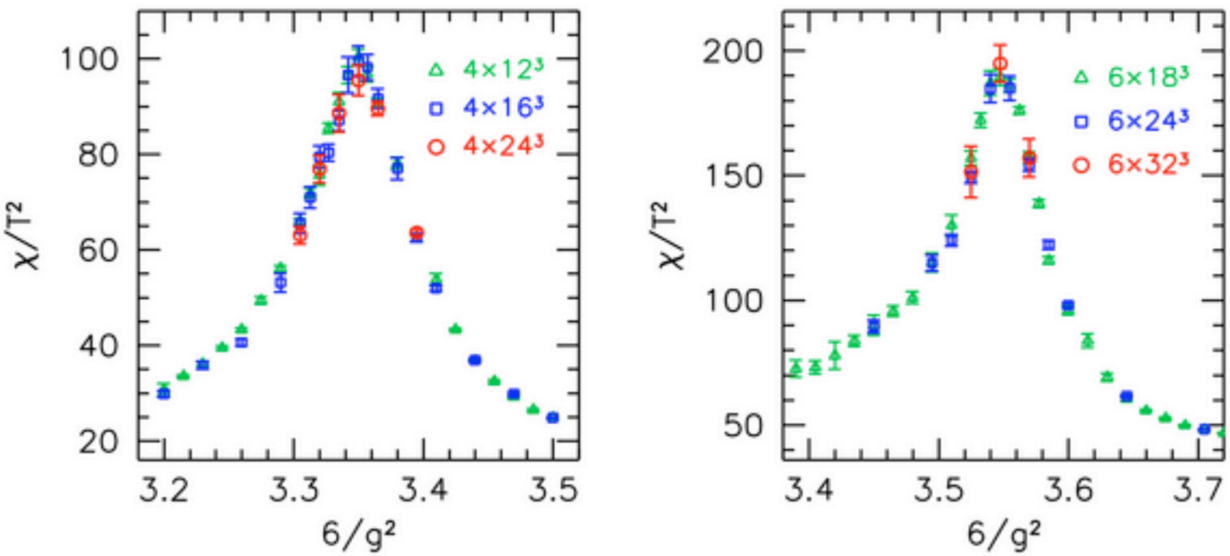
Theory and Experimental approaches



Order Of Phase Transition at $\mu_B \sim 0$

$$\chi(N_s, N_t) = \partial^2/(\partial m_{ud}^2)(T/V) \cdot \log Z$$

Y. Aoki et al., Nature443:675-678,2006



1^{st} order :
- Peak height ~ V
- Peak width ~ 1/V

Cross over :
- Peak height ~ const.
- Peak width ~ const.

2^{nd} order :
- Peak height ~ V^{α}

No significant volume dependence (8 times difference in volumes)
Transition at high T and μ_B = 0 is a cross over

Lattice results on electroweak transition in standard model is an analytic cross-over for large Higgs mass

K. Kajantie et al., PRL 77, 2887-2890,2006

QCD Critical Point

2nd order point in the PD,where the 1st order transition lines ends

First Principle QCD Calculations on Lattice:

$$\langle \Theta(m_v) \rangle = \frac{\int DU \exp(-S_G)\Theta(m_v)\ \mathrm{Det}\ M(m_s)}{\int DU \exp(-S_G)\ \mathrm{Det}\ M(m_s)}$$

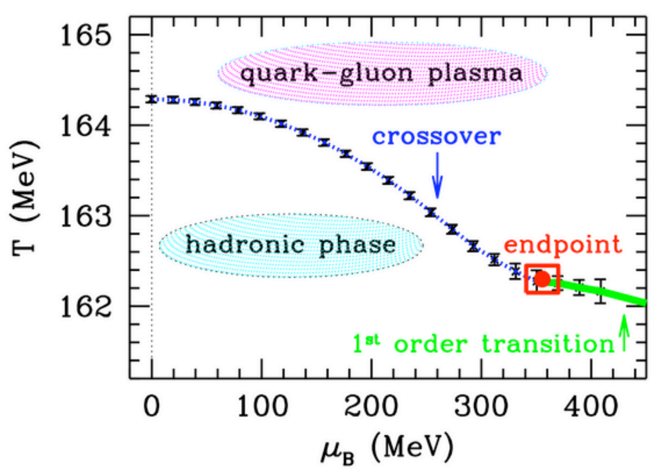
M : Dirac Matrix
S_G : Gluonic action

Issue for non zero μ, Det M is not positive definite

-- Sign problem

Reweighting

Z. Fodor and S.D. Katz JHEP 0404, 50 (2004)



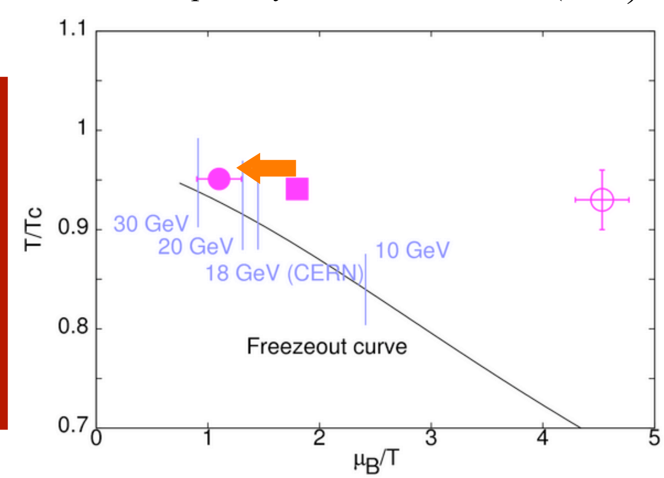
T_E = 162 +/- 2 MeV
μ_E = 360 +/- 40 MeV

CP exists
(in most QCD calculations)

1st order transition at large μ_B

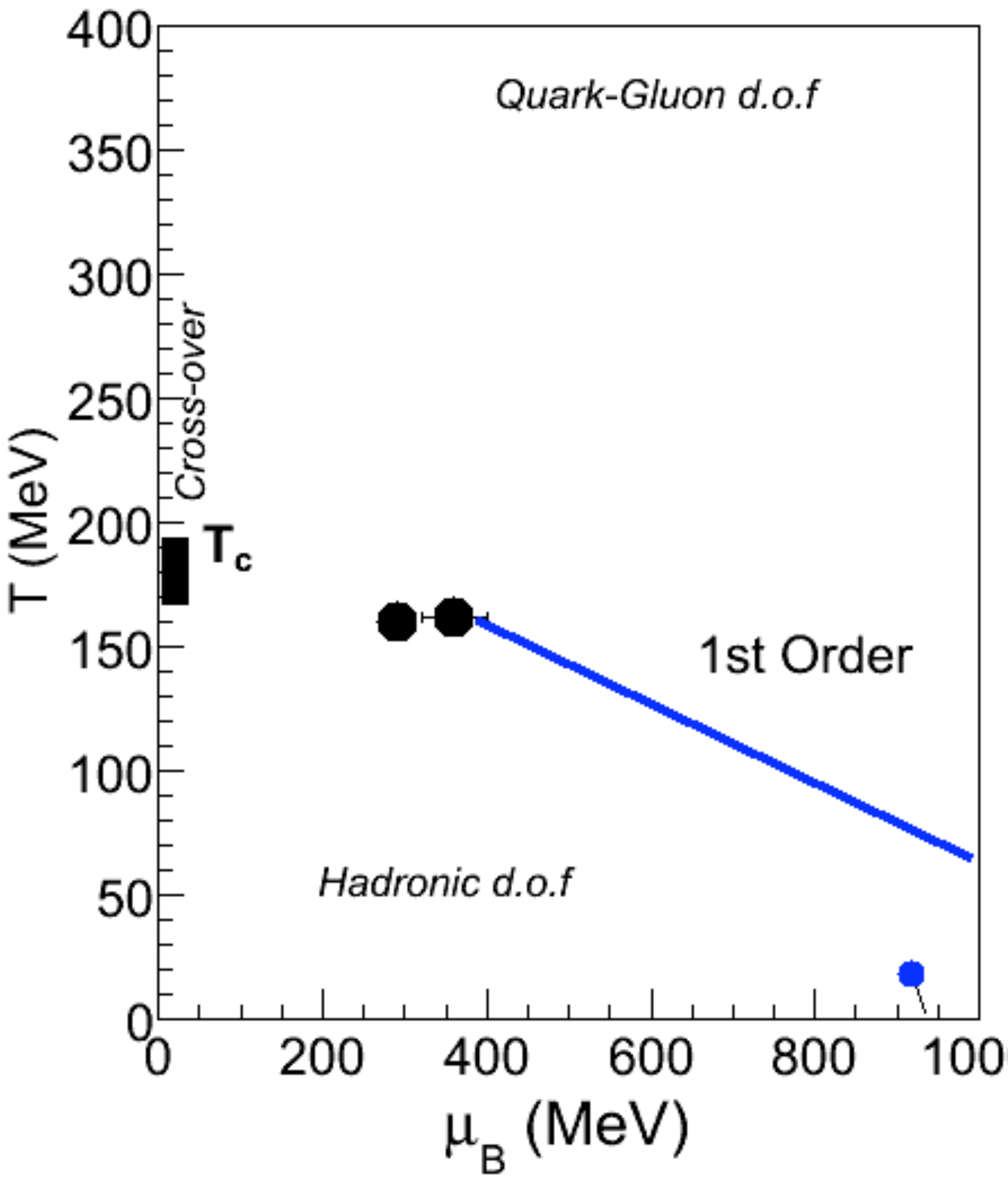
Taylor Expansion

R. Gavai and S. Gupta Phys. Rev. D 78, 14503 (2008)



T_E/T_C = 0.94 +/- 0.01
μ_E / T_E = 1.8 +/- 0.1

QCD Phase Diagram: Theoretical



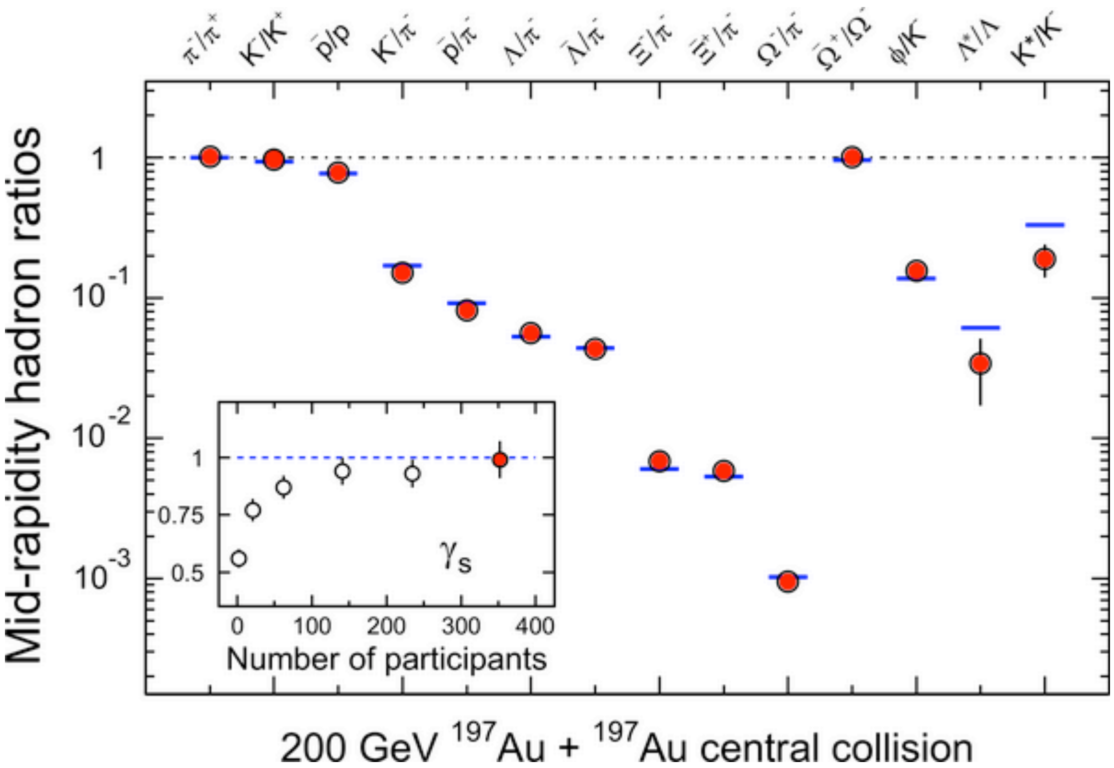
Tc: M. Cheng et al, Phys. Rev. D 74, 054507 (2006)
Y. Aoki et al, Phys. Lett. B 643, 46 (2006); 0903.4155

Lattice and other QCD based models :
μ_B = 0 - Cross-over
T_C ~ 170-195 MeV
μ_B > 160 MeV - QCD critical point

Experimental Study

(i) How to access PD
(ii) Tests of QCD
(iii) Scale of PD
(iv) Search Phase Boundary
(v) Search CP

Accessing Phase Diagram



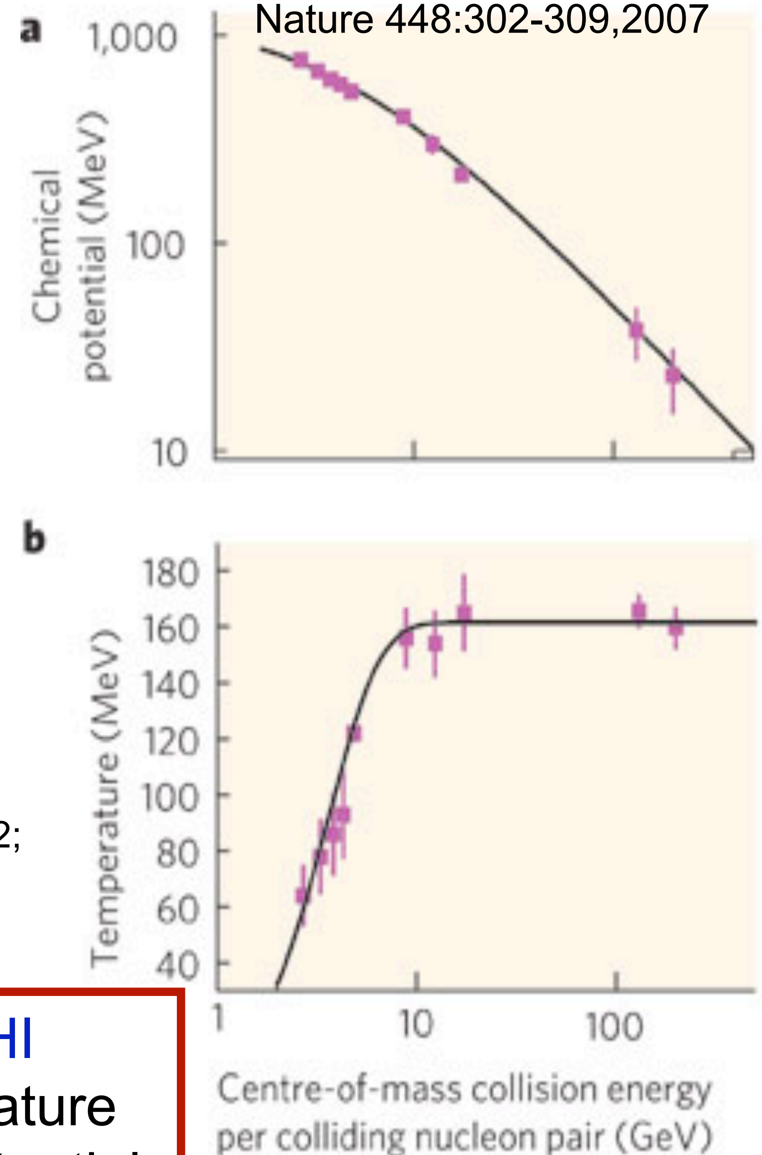
data

Thermal model fits

T_{ch} = 163 ± 4 MeV
μ_B = 24 ± 4 MeV

RHIC white papers - 2005, Nucl. Phys. *A757*, STAR: p102; PHENIX: p184.

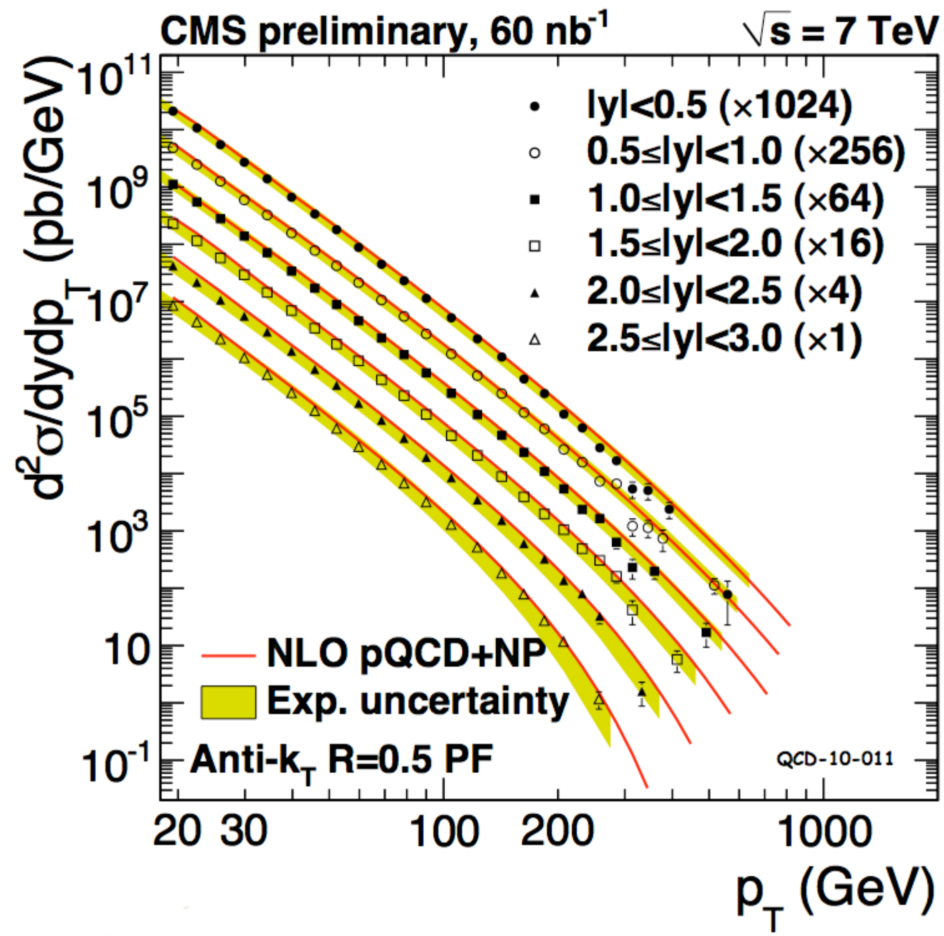
P. Braun-Munzinger, J. Stachel, Nature 448:302-309,2007



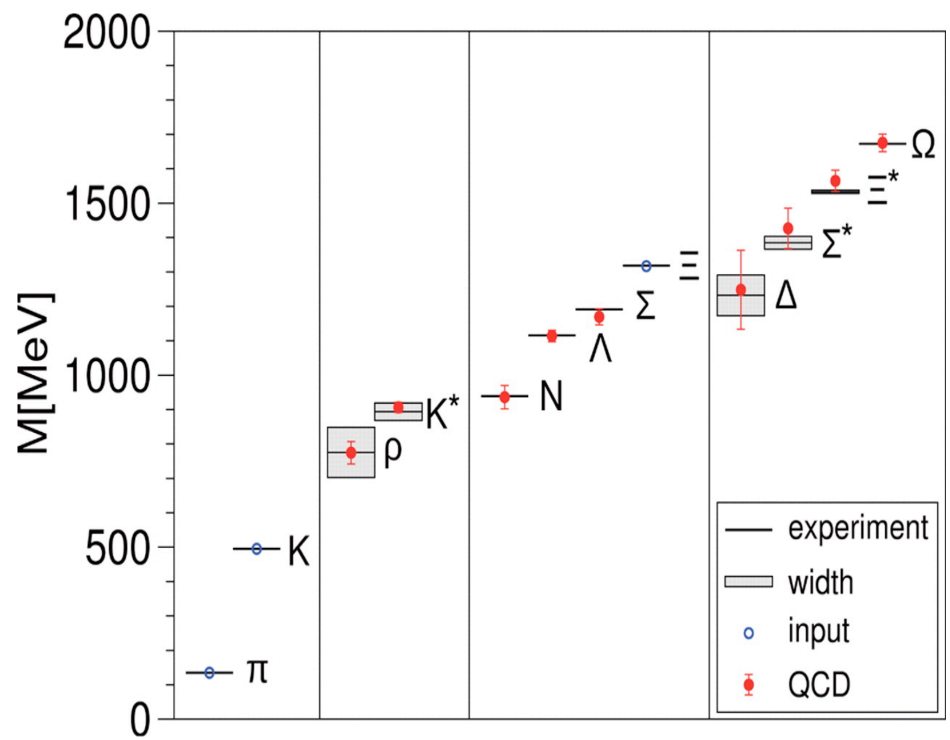
Varying beam energy in HI collisions varies Temperature and Baryon Chemical Potential

Tests of QCD

Short distance
perturbative regime



Long-distance
Non-perturbative regime



S. Durr et al, Science 322, 1224 (2008)

Can we test of the QCD thermodynamics of bulk strongly interacting mater

Tools for testing non-pQCD (T>0)

Theory

Lattice QCD

First principle QCD calculations
in non-perturbative regime

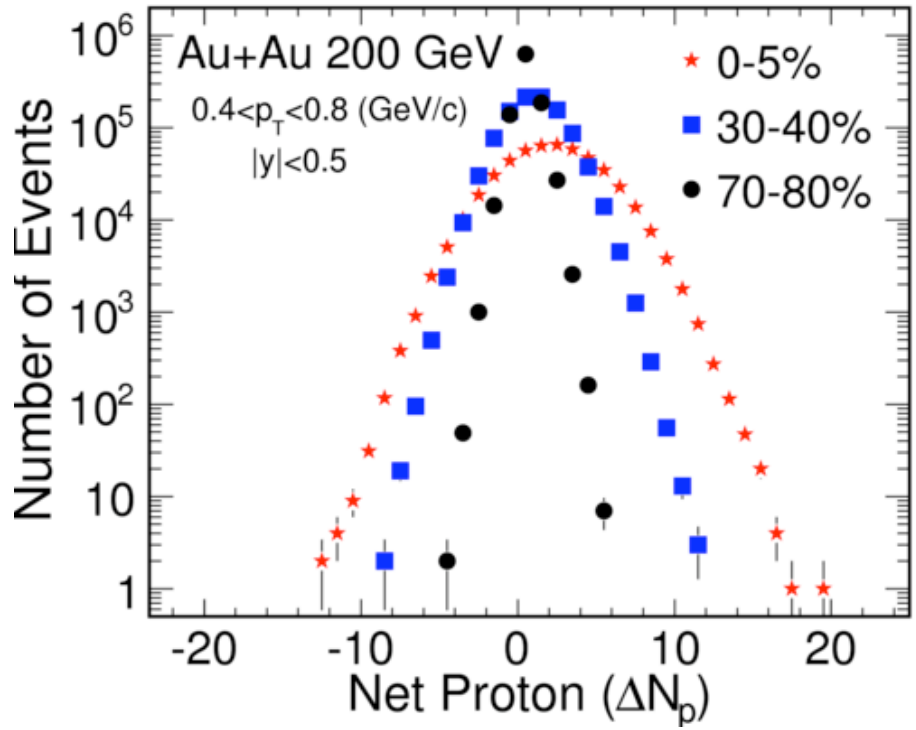
$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2 \rangle$$

$$\chi_4^X = \frac{1}{VT^3}\left(\langle N_X^4 \rangle - 3\langle N_X^2 \rangle^2\right)$$

$[\chi^{(3)} T] / [\chi^{(2)} T^2] \sim$ Skewness x σ
$\chi^{(4)} / [\chi^{(2)} T^2] \sim$ Kurtosis x σ^2
$\chi^{(4)} / [\chi^{(3)} T] \sim$ Kurtosis x σ/Skewness

Experiment

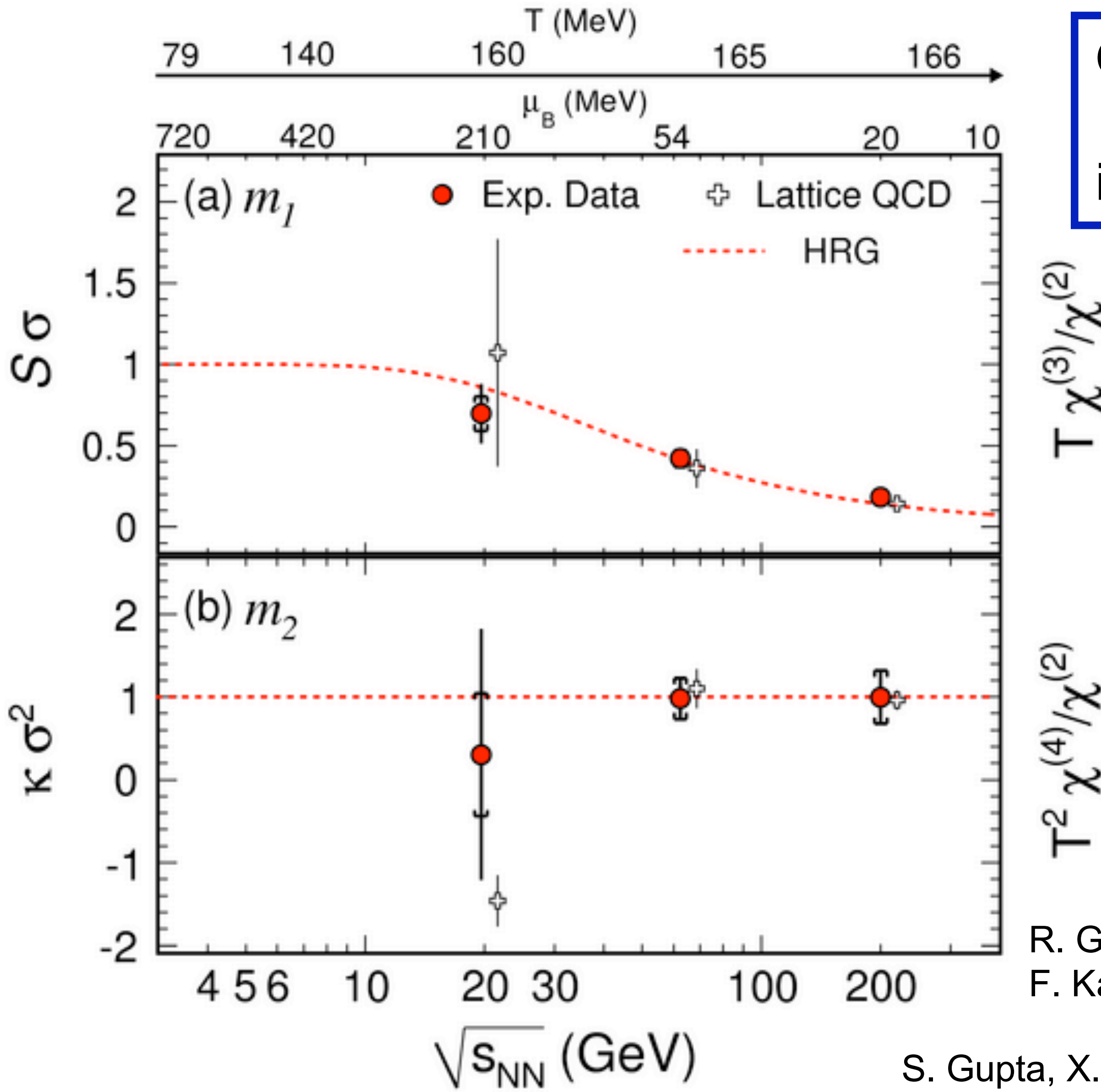
High Energy Heavy-ion collisions



Assumptions:

- Net-proton ~ Net-baryon
- Thermal Equilibrium and Grand Canonical Ensemble
- Freeze-out conditions
- Lattice Systematics

Test of QCD in non-perturbative regime



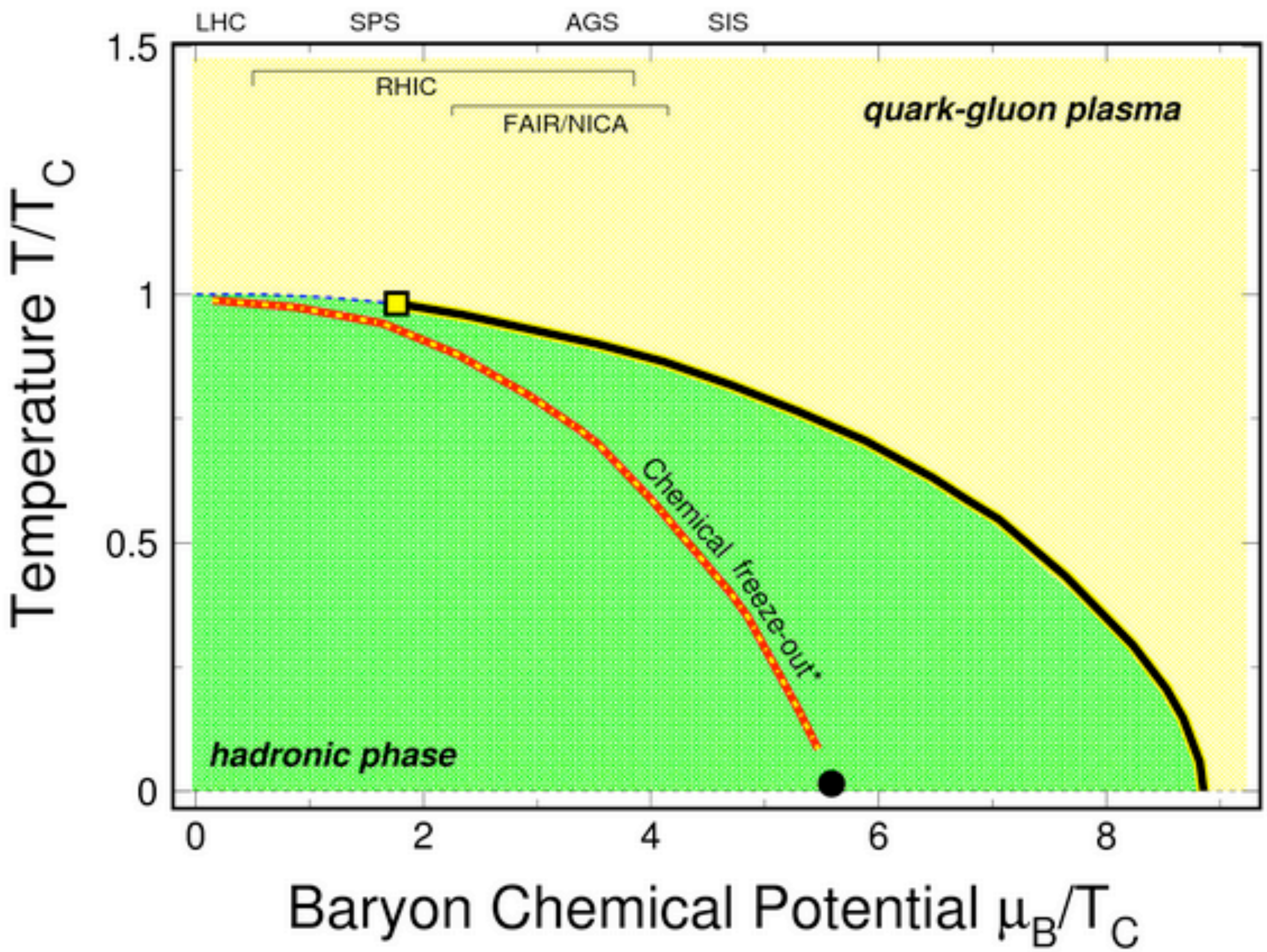
QCD vs. Expt. Data
(both T > 0)
in non-perturbative regime

Non-trivial indication (using fluctuations) that fireball produced in heavy-ion collisions attained thermal and chemical equilibrium at chemical freeze-out

R. Gavai & S. Gupta arXiv:1001.3796
F. Karsch & K. Redlich PLB 695, 136 (2011)

S. Gupta, X. Luo, H. G. Ritter, BM, N. Xu

Scale for the QCD phase diagram



T_c sets the scale of the QCD phase diagram

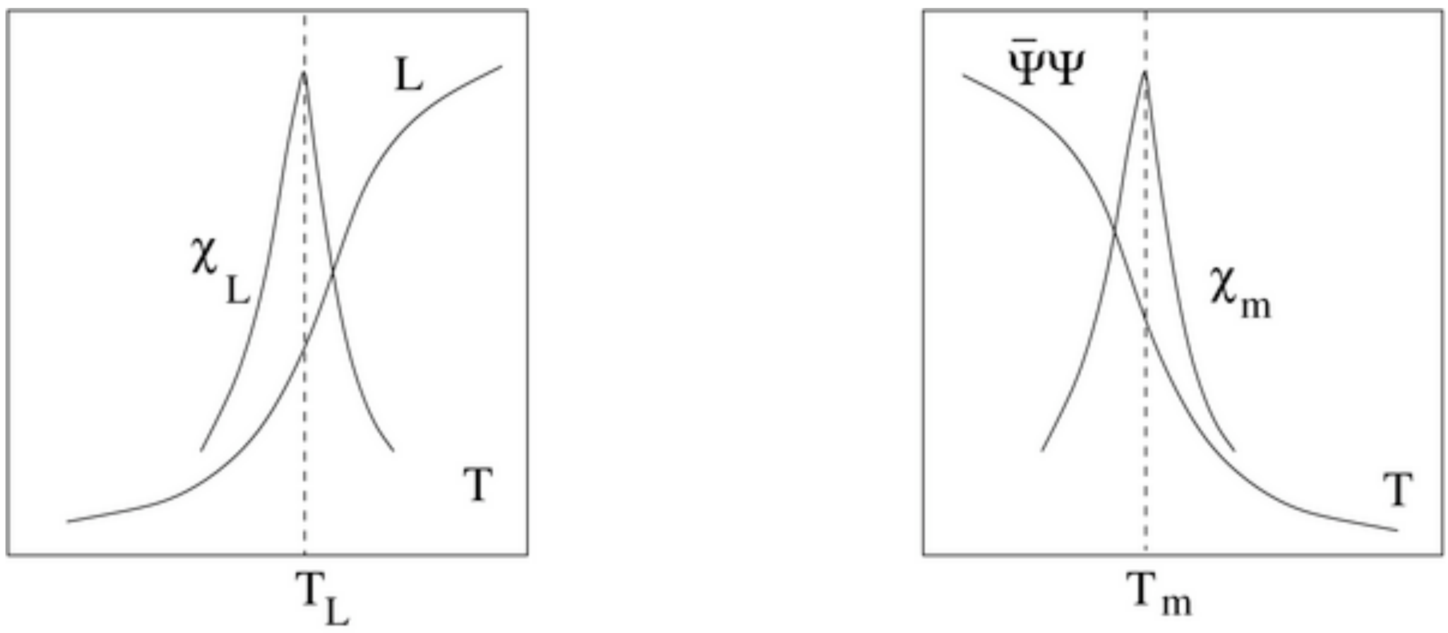
Definition of T_c

Polyakov Loop

$$L(T) \sim \lim_{r\to\infty} \exp\{-F(r)/T\}$$

Susceptibility

$$\chi_L(T) \sim \langle L^2\rangle - \langle L\rangle^2$$



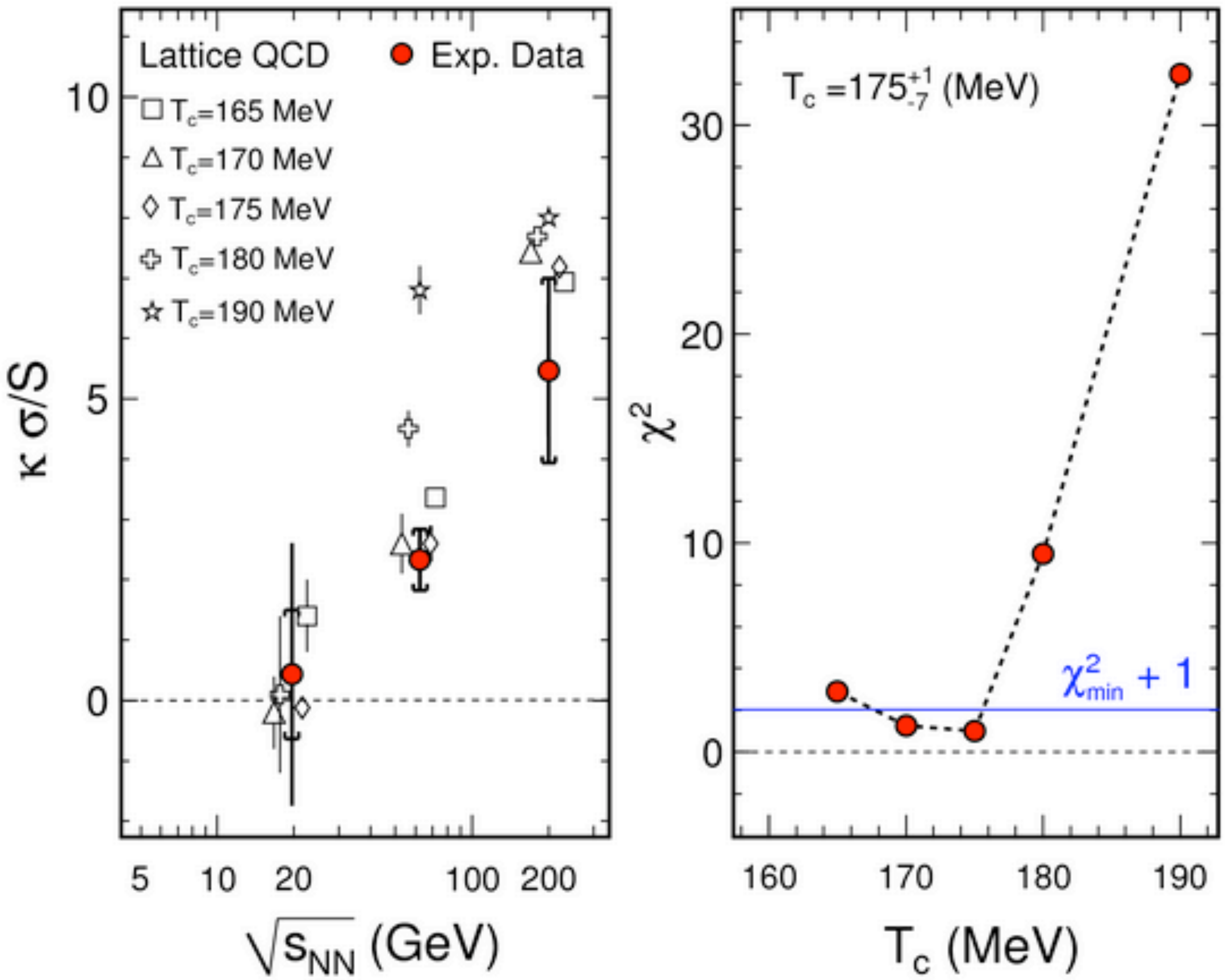
(a) (b)

It is the temperature at the peak of a susceptibility related to the confinement-deconfinement order parameter

Setting the scale of bulk QCD

$\chi^{(4)} / [\chi^{(3)} T] \sim$ Kurtosis x σ/Skewness

S. Gupta, X. Luo, H. G. Ritter, BM, N. Xu



$$\chi^2(T_c) = \sum_{\sqrt{s_{NN}}} \frac{[m_3^{\mathrm{expt}}(\sqrt{s_{NN}}) - m_3^{\mathrm{QCD}}(\sqrt{s_{NN}}, T_c)]^2}{\mathrm{Error}^2_{\mathrm{expt}} + \mathrm{Error}^2_{\mathrm{QCD}}}$$

T_c compatible with

✓Indirect estimates (Scale via Hadronic observables)

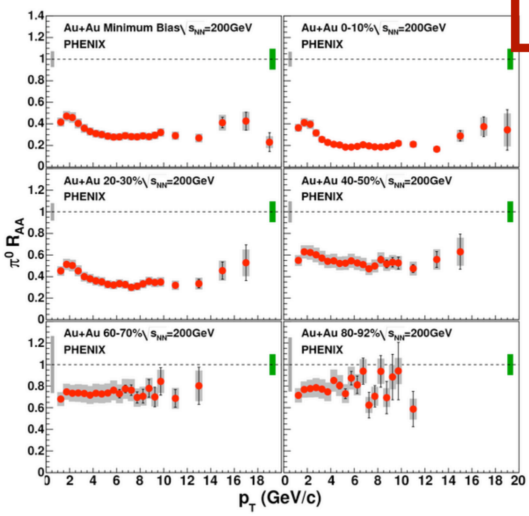
✓Temperature scales from resonance gas models

$$T_c = 175^{+1}_{-7} \;\; MeV$$

Searching the phase boundary

PHENIX : PRL 101, 232301 (2008)

Au+Au 200 GeV

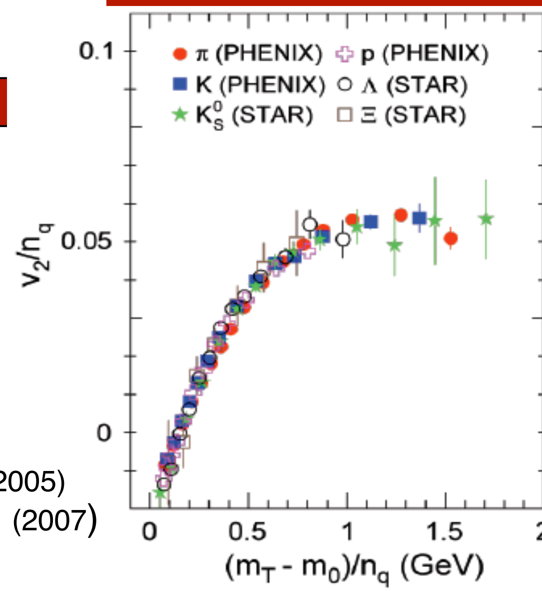


Jet quenching

No Jet Quenching

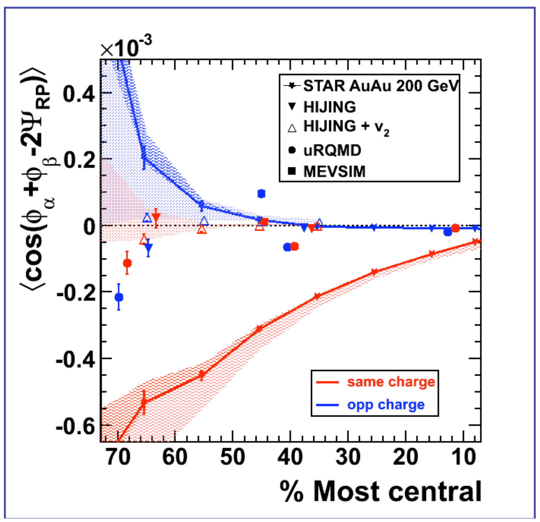
Partonic collectivity

No NCQ Scaling
ϕ v_2 small



STAR, PRL **95**, 122301 (2005)
PHENIX, PRL **98**, 162301 (2007)

Chiral Magnetic effect



No Dynamical Charge Asymmetry

STAR:PRL 103 (2009) 251601;
STAR: 0909.1717

Search For The QCD Critical Point

In the fields of observation chance favors only the prepared mind.
Louis Pasteur

Strategy:

(I) Establish observables for Critical Point which has sound theoretical basis and reflects the signatures at CP.

(II) Expectations from the observable from non critical point physics should be understood.

(III) Vary beam energy of collisions and look for non-monotonic dependence of the observable.

Signature Of Critical Point

$T > T_C$ $T \sim T_C$ $T < T_C$

Critical Opalescence as observed in CO_2 liquid-gas transition

T. Andrews.
Phil. Trans. Royal Soc., 159:575, 1869

- Distributions become non Gaussian
- Correlation length diverges
- Susceptibilities diverges
- Long wavelength fluctuations or low momentum fluctuations important

Deviation $\delta N = N - \langle N \rangle$

Standard deviation, $\sigma = \sqrt{\langle (\delta N)^2 \rangle}$

Skewness $= \dfrac{\langle (\delta N)^3 \rangle}{(\sigma)^3}$

Kurtosis $= \dfrac{\langle (\delta N)^4 \rangle}{(\sigma)^4} - 3$

Higher Moments of Net-Protons

Distributions non Gaussian at CP

Moments and Correlation length (ξ)

$< (\delta N)^2 > \sim \xi^2$ $< (\delta N)^3 > \sim \xi^{4.5}$

$< (\delta N)^4 > - 3 < (\delta N)^2 >^2 \sim \xi^7$

Value limited in heavy-ion collisions

Finite size effects $\xi < 6$ fm

Critical slowing down, finite time effects $\xi \sim 2$ - 3 fm

Higher moments higher sensitivity

M. A. Stephanov, PRL 102, 032301 (2009)
Y. Hatta et al,PRL 91, 102003 (2003)

Link to Lattice QCD and QCD Models

Kurtosis x Variance $\sim \chi^{(4)} / [\chi^{(2)} T^2]$

Skewness x Sigma $\sim [\chi^{(3)} T] / [\chi^{(2)} T^2]$

R. Gavai & S. Gupta, arXiv:1001.3796

Net-proton Number Fluctuations

~ Singularity in charge and baryon number susceptibilities

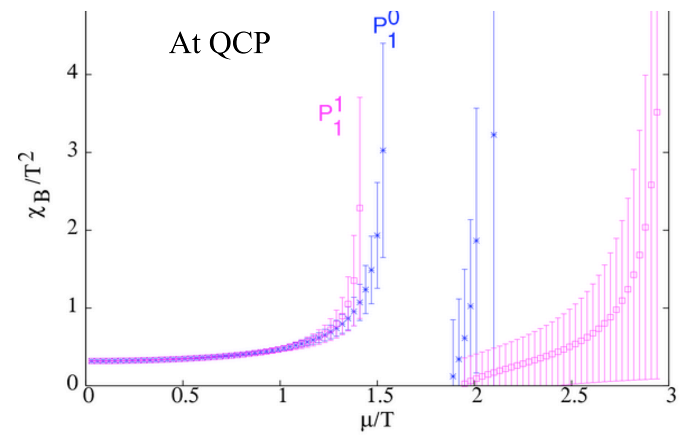
$Q = B/2 + I_3$

$\chi_Q \sim (1/VT) < (\delta Q)^2 > = (1/4) \chi_B + \chi_I$

$\sim (1/VT) < \delta (N_{p-pbar})^2 >$

iso-spin blindness of σ field

M. Cheng et al, PRD 79, 074505 (2009)
B. Stokic et al, PLB 91, 192 (2009)
R. Gavai & S. Gupta PRD 78, 114503 (2008)

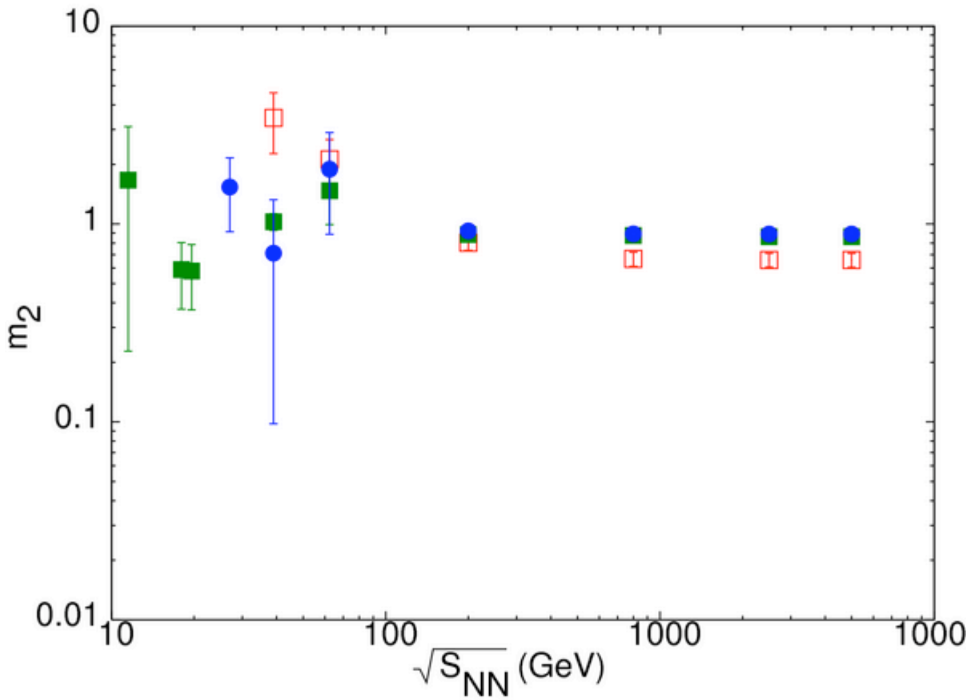


Non monotonic variation of products of higher moments with beam energy

Theory Expectations

Lattice QCD

(R. Gavai, S. Gupta, arXiv:1001.3796)

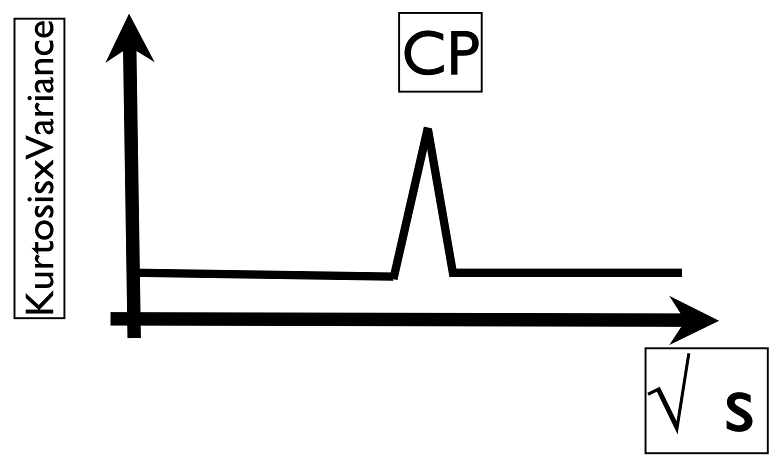


m$_2$ equivalent to Kurtosis x Variance
At CP : Kurtosis x Variance has large values

CP Model

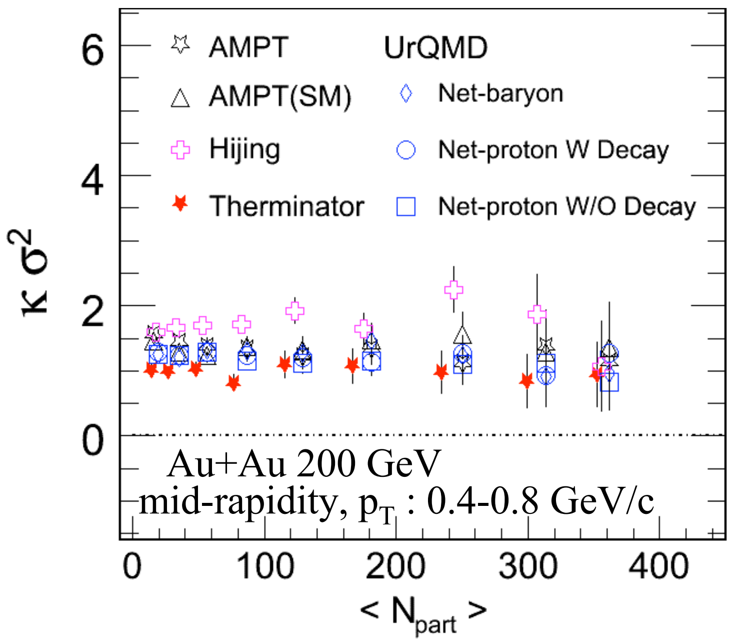
(C. Athanasiou,M. Stephanov, K. Rajagopal, arXiv:1006.4636 and PRL 102 (2009) 032301)

Beam Energy (GeV)	Kurtosis x Variance (net protons) with ξ ~ 3fm and CP (No CP ~ 1)
200	~ 2.5
62	~ 35
19	~ 3700
7.7	~ 29600

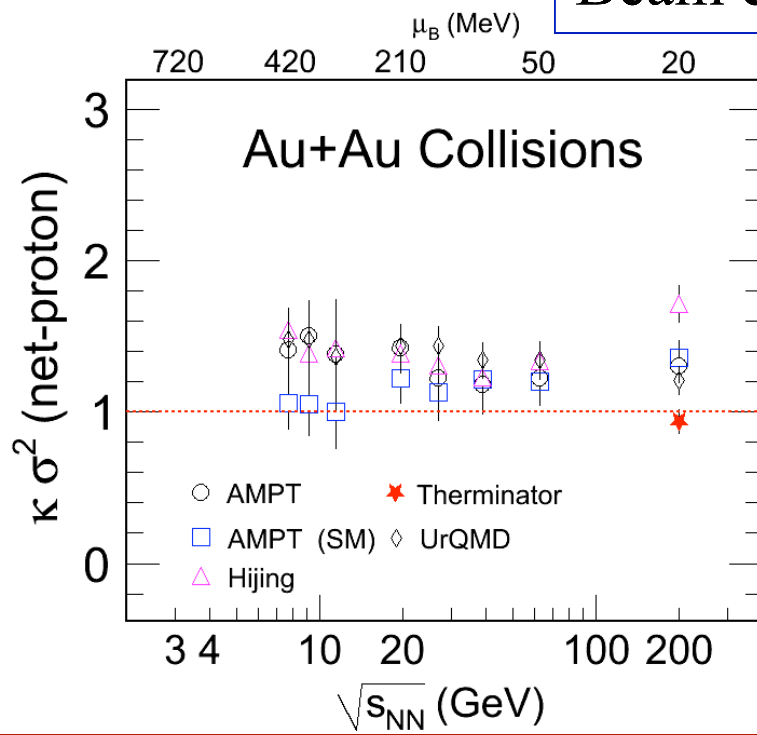


Observable: non-CP Physics

Collision centrality



Beam energy

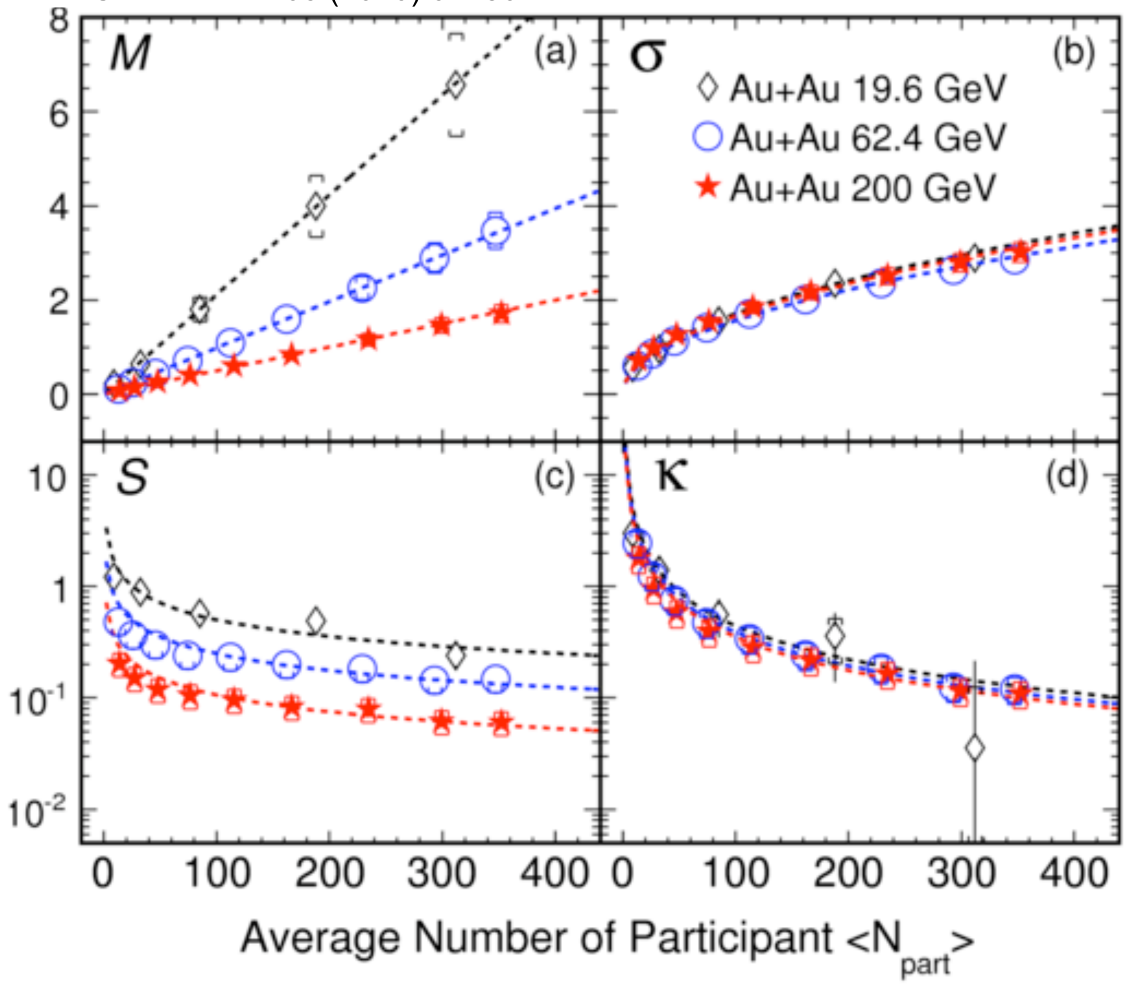


Kurtosis x Variance: (Desirable features for CP Search)

- o Constant as a function of beam energy
- o Constant as a function of collision centrality/impact parameter
- o No difference between net-baryon and net-proton
- o Effect of resonance decay small
- o Similar values for Transport, Mini-jets, Coalescence models
- o Unity for Thermal model

Moments: Net-Proton Distribution

STAR: PRL 105 (2010) 022302



Moments:

$$\sigma = \sqrt{<(N-<N>)^2>}$$

$$s = \frac{<(N-<N>)^3>}{\sigma^3}$$

$$\kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$

Central Limit Theorem:

$M_i = CM_x <N_{part}>_l$

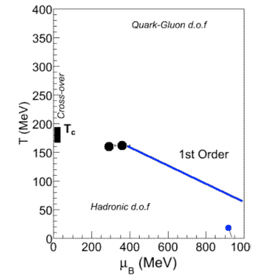
$\sigma^2_i = C\,\sigma^2_x <N_{part}>_l$

$S_i = S_x/\sqrt{[C <N_{part}>]_l}$

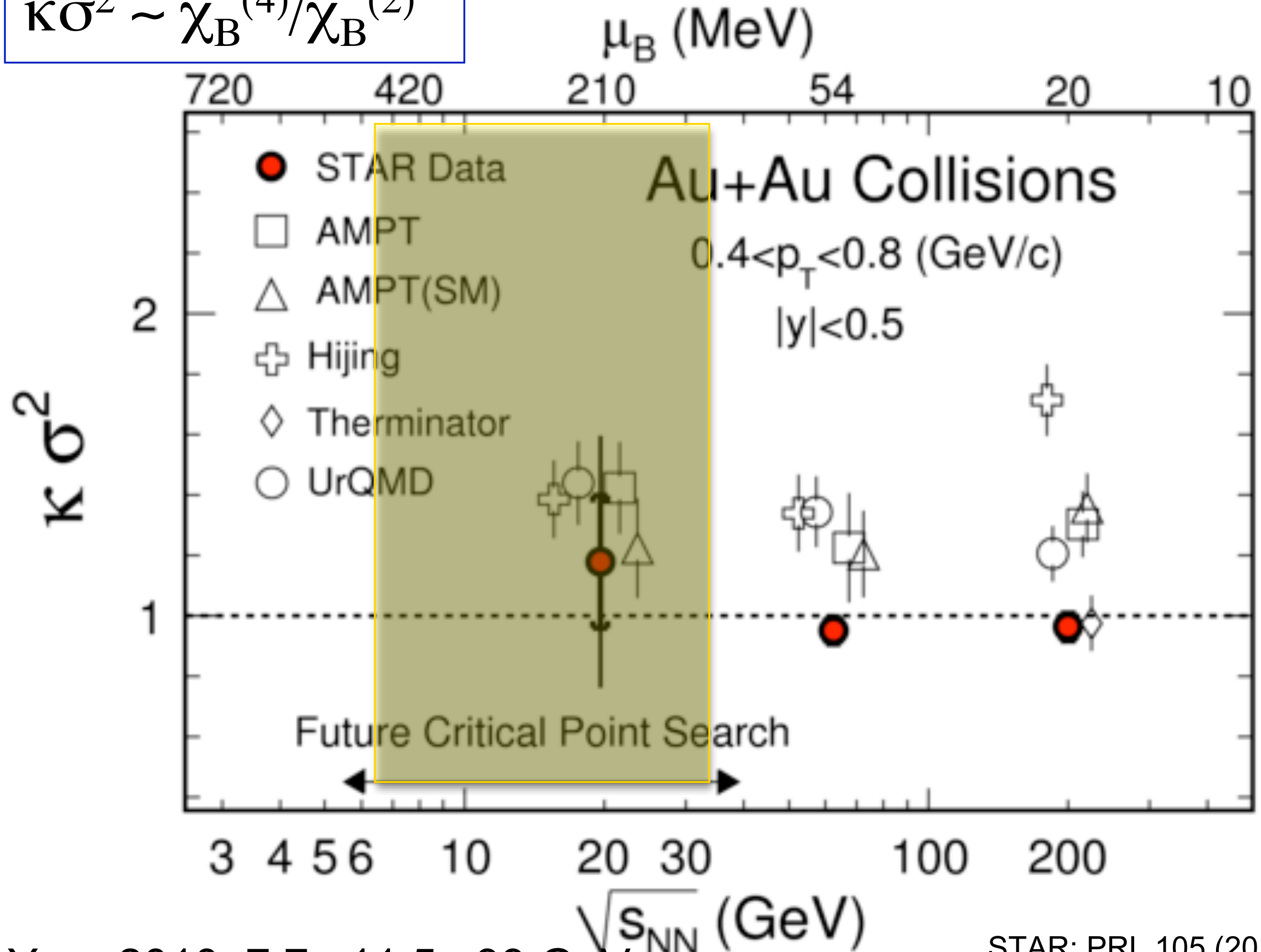
$\kappa_i = \kappa_x/[C <N_{part}>]_l$

Consistent with CLT expectations (lines)

Energy Dependence: $\kappa\sigma^2$



$\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}$



CP Model: $\kappa\sigma^2 > 2$

arXiv: 1006.4636;
PRL 102 (2009) 032301

Models:
$\Delta\mu^C_B \sim 100$ MeV

PRL 101 (2008) 122302;
PLB 647 (2007) 431
Eur. Phys. Lett. 86 (2009) 31001

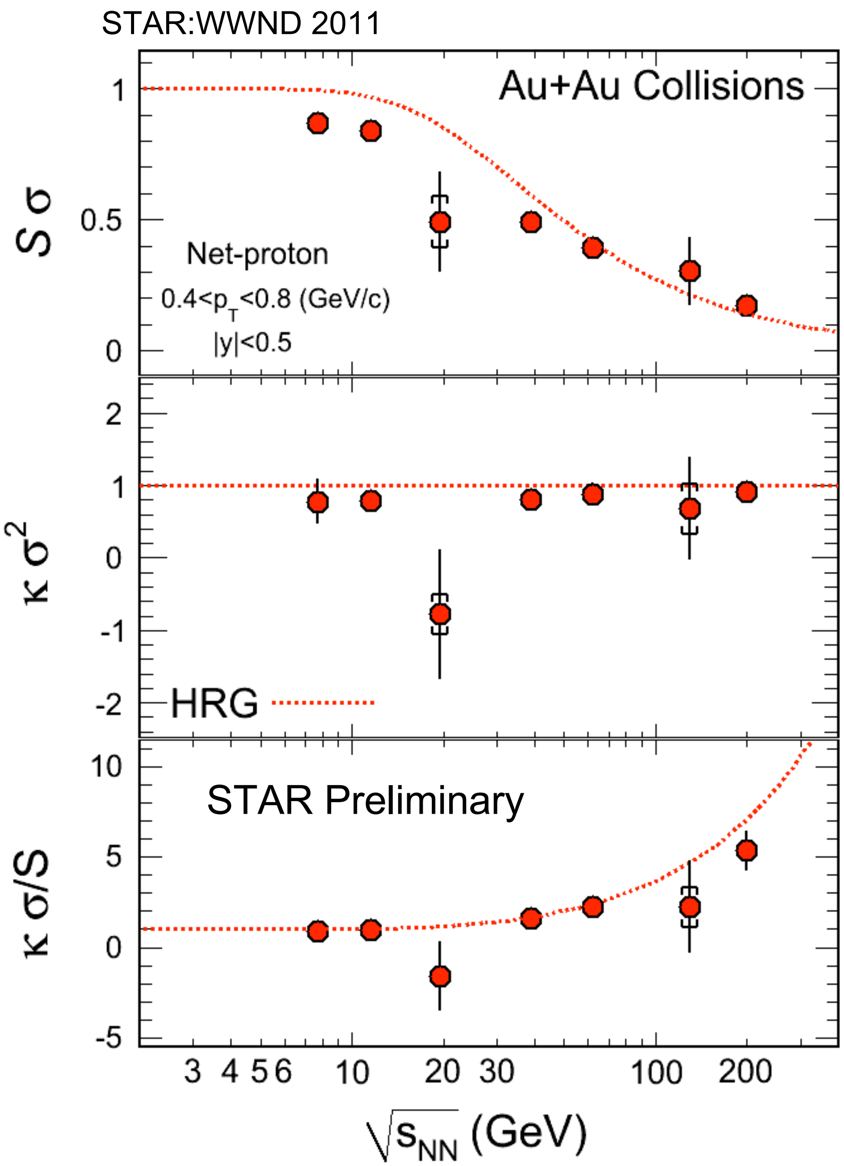
STAR: PRL 105 (2010) 022302

Year 2010: 7.7, 11.5, 39 GeV

Year 2011: 18, 27 GeV

Observations indicate CP not located for μ_B < 200 MeV

STAR: BES Results



Baryon number fluctuations:

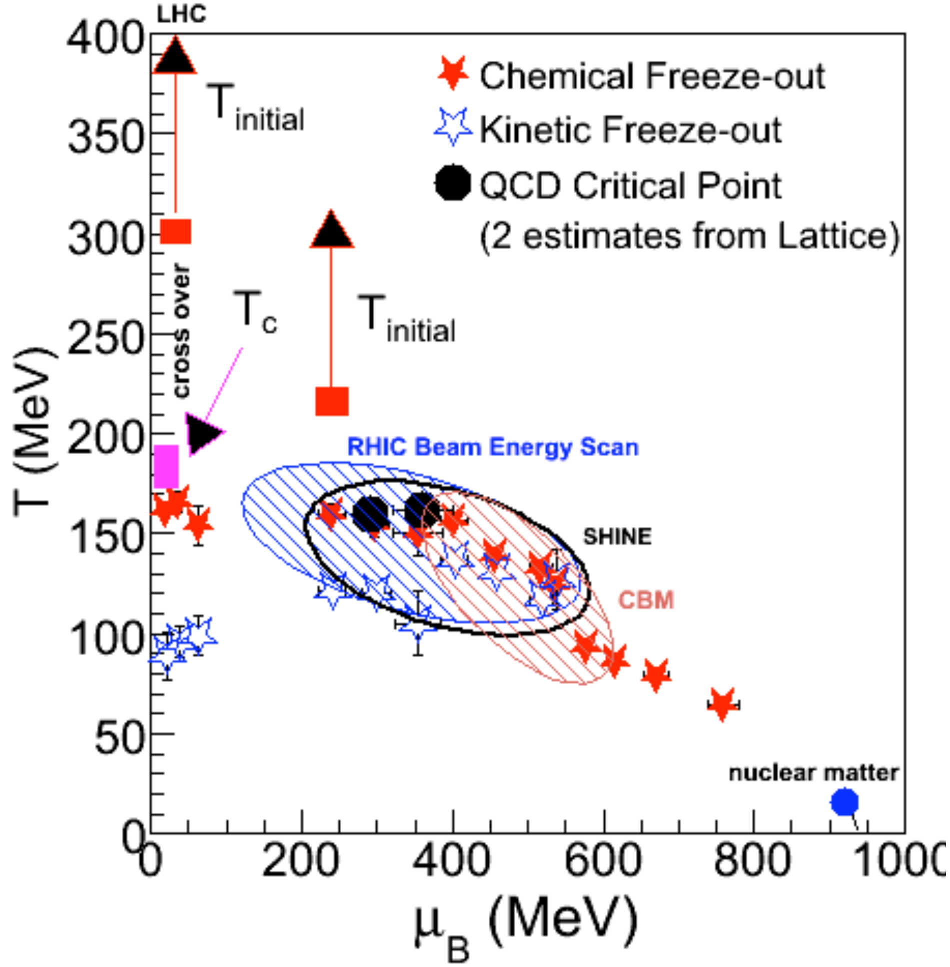
Thermalization
and/or
Deviation from Poisson fluctuations

Deviations from HRG from 39 GeV

Need high statistics run
at 18 GeV in context of CP search

HRG: F. Karsch & K. Redlich PLB 695, 136 (2011)

Summary and Outlook



With the starting of LHC (μ_B~ 0) - we have unique opportunity to understand the properties of matter governed by quark-gluon degrees of freedom at unprecedented initial temperatures achieved in the collisions.

To make the QCD phase diagram a reality equal attention needs to be given to high baryon density region.

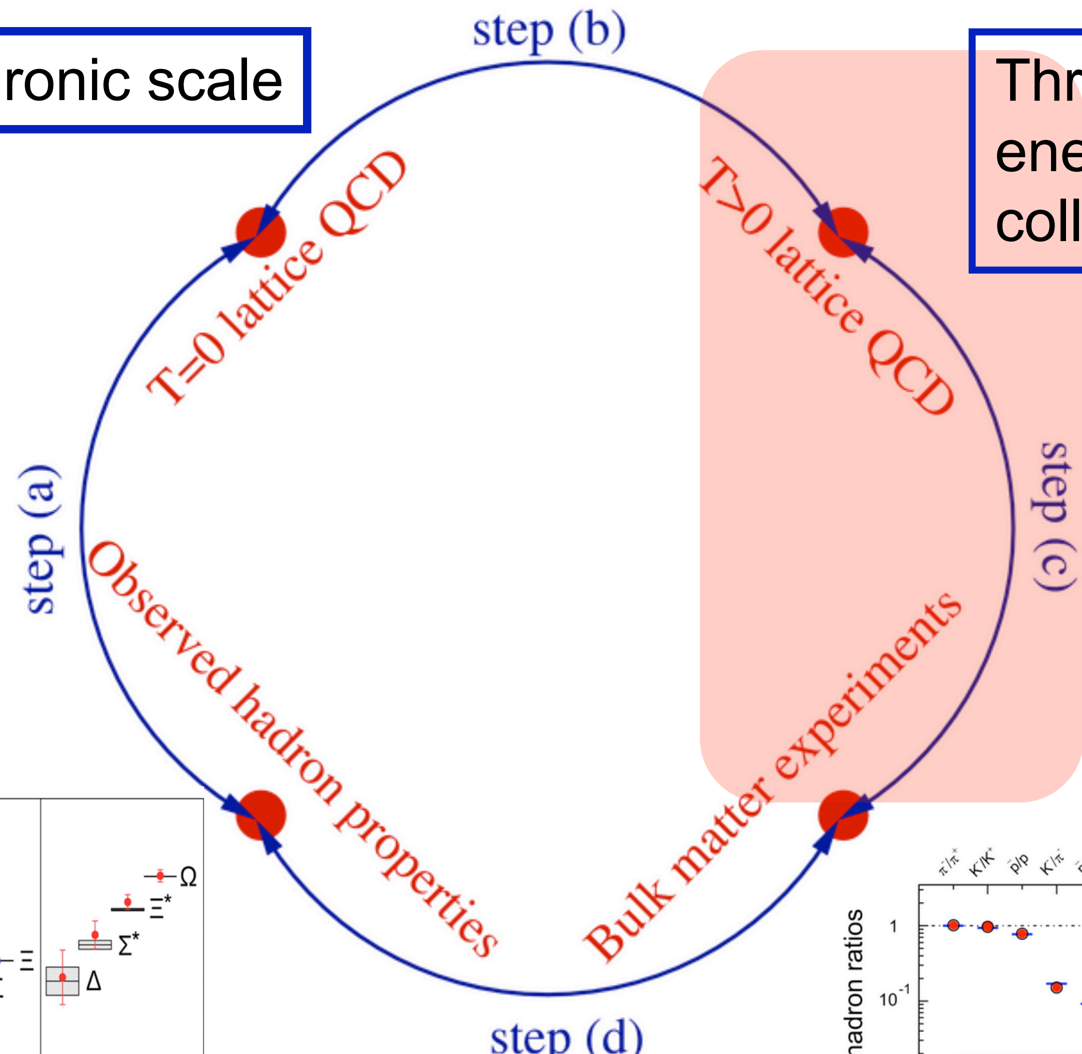
These two complementary programs will make our understanding clearer on:

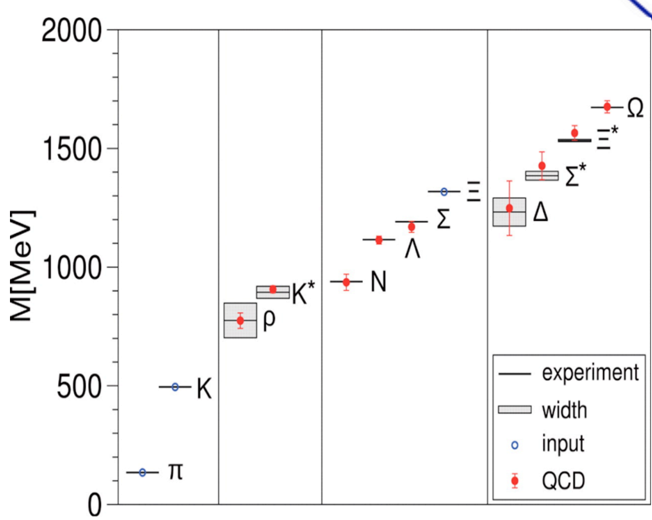
- ✓ *Test of QCD in non-peturbative regime*
- ✓ *characterization of quark-gluon matter at varying baryon density*
- ✓ *searching for the QCD critical point and*
- ✓ *searching for the QCD phase boundary*

Circle Of Reasoning

T_c / m; m = hadronic scale

Through high energy nuclear collisions





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