Exploring the QCD landscape with high-energy nuclear collisions

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Outline

- QCD Phase Diagram
- Experimental Study of QCD Phase Diagram
- Summary

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

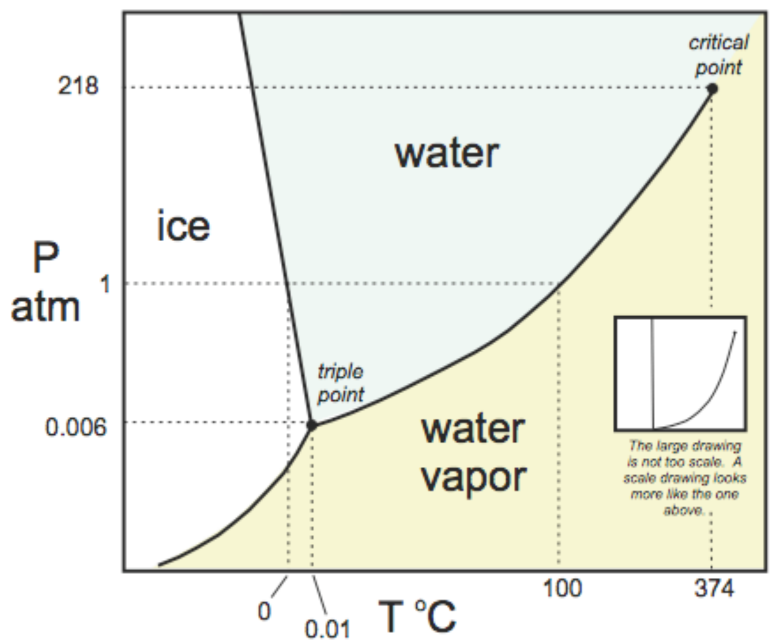
A simpler version : T vs. μ_B

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



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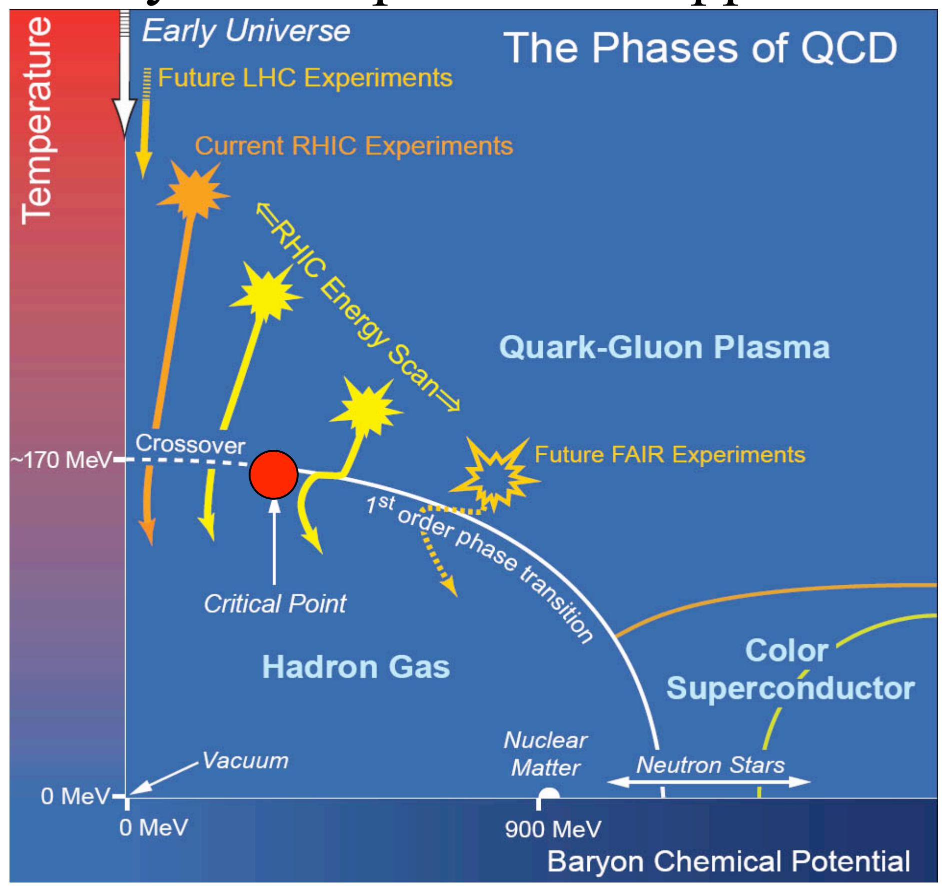
Establish the phase boundary
Find the QCD Critical Point

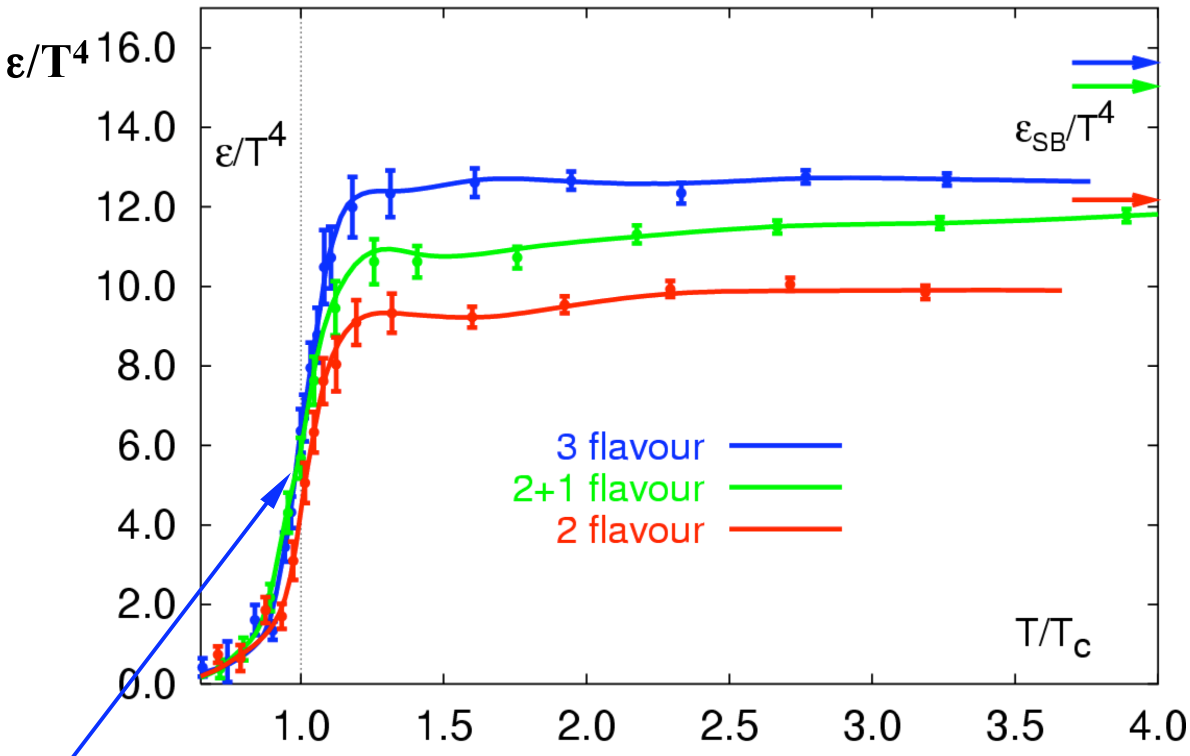
QCD (Hadrons -- Partons)

Theory and Experimental approaches



QCD: High Temperature

F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)



$g_{parton} \sim 47.5$

$\varepsilon/T^4 \sim g\,(\pi^2/30)$

$g_\pi \sim 3$

$T_C \approx 170 \pm 8$ MeV, $\varepsilon_C \approx 1$ GeV/fm^3

Lattice QCD predicts a transition to Quark Gluon Plasma at high temperature

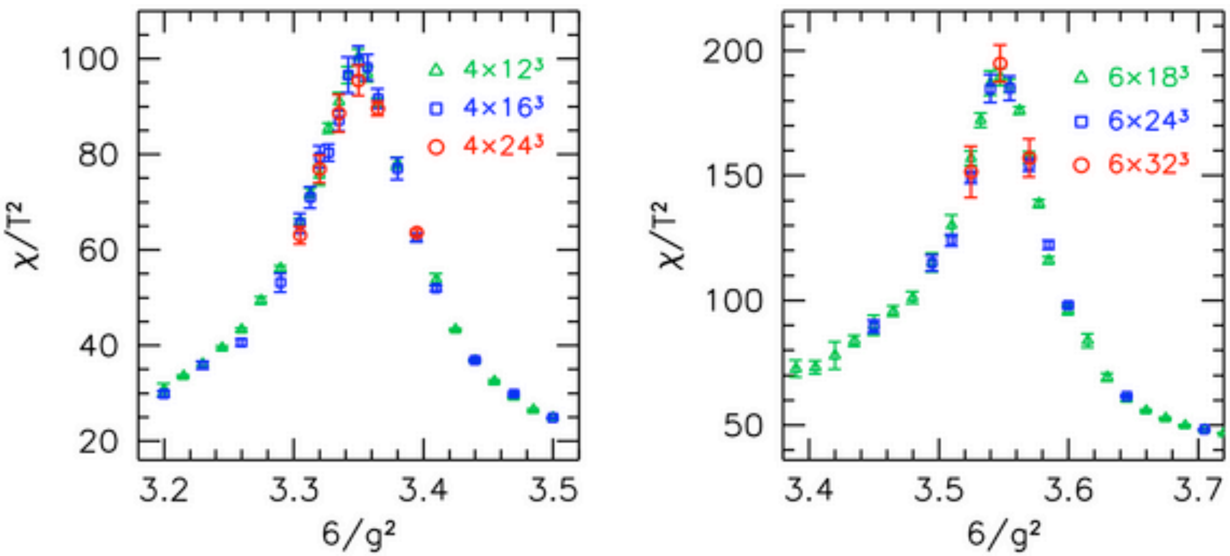
$$\varepsilon_{QCD} = \frac{\pi^2}{30}\left[2\times 8 + \frac{7}{8}2\times 2\times 3\times 3\right]T^4$$

gluon spin, color   quark spin, color, flavor

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



1st order :
- Peak height ~ V
- Peak width ~ 1/V

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

2nd order :
- Peak height ~ V^α

No significant volume dependence (8 times difference in volumes)
Phase 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:

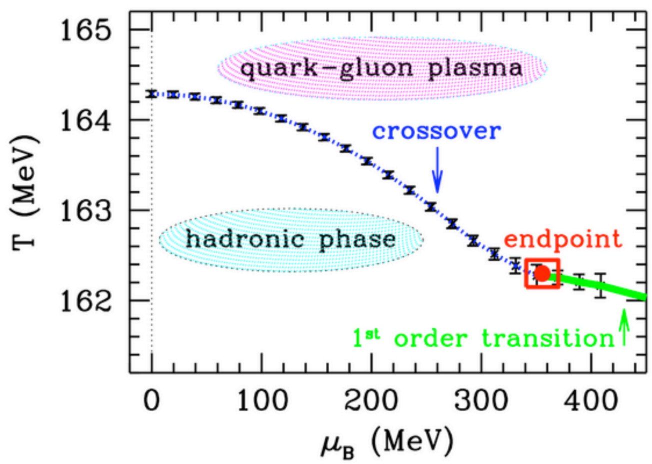
$$\langle\Theta(m_v)\rangle = \frac{\int DU \exp(-S_G)\Theta(m_v)\ \mathrm{Det}\ M(m_s)}{\int DU \exp(-S_G)\ \mathrm{Det}\ M(m_s)}$$

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)

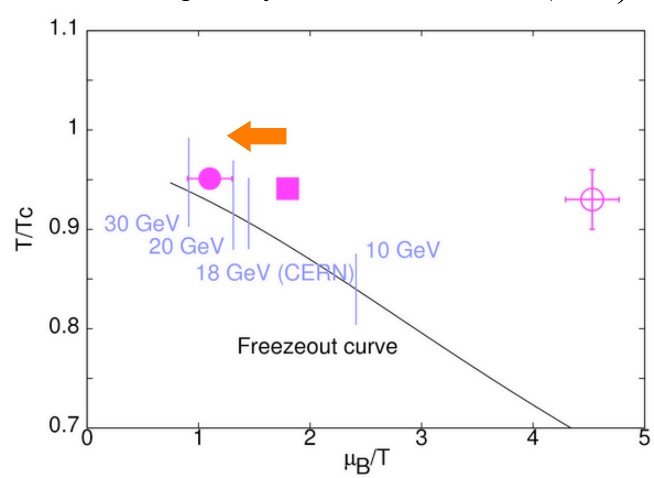


T_E = 162 +/- 2 MeV
μ_E = 360 +/- 40 MeV

CP exists
⇕
1st order transition at large μ_B

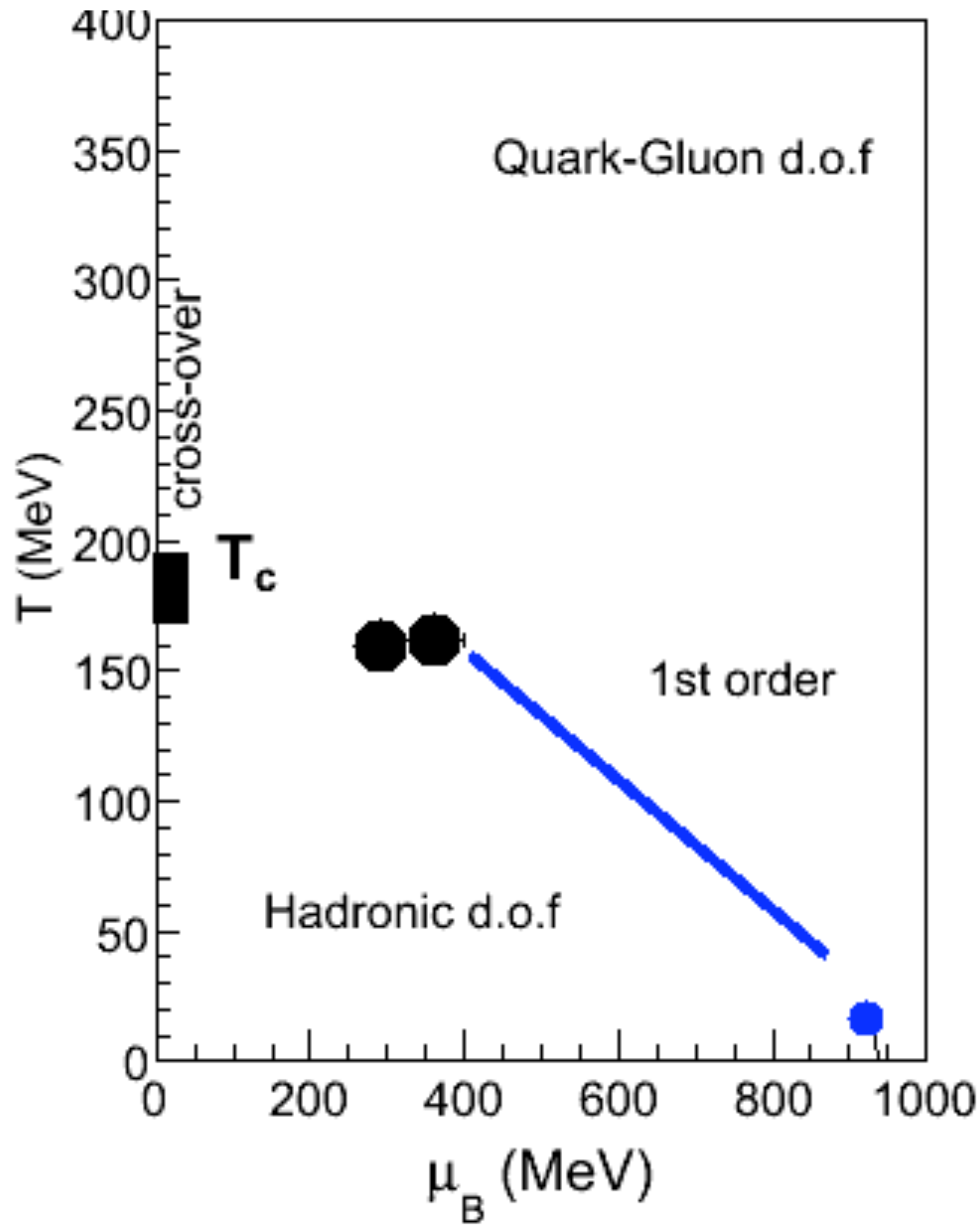
Taylor Expansion

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



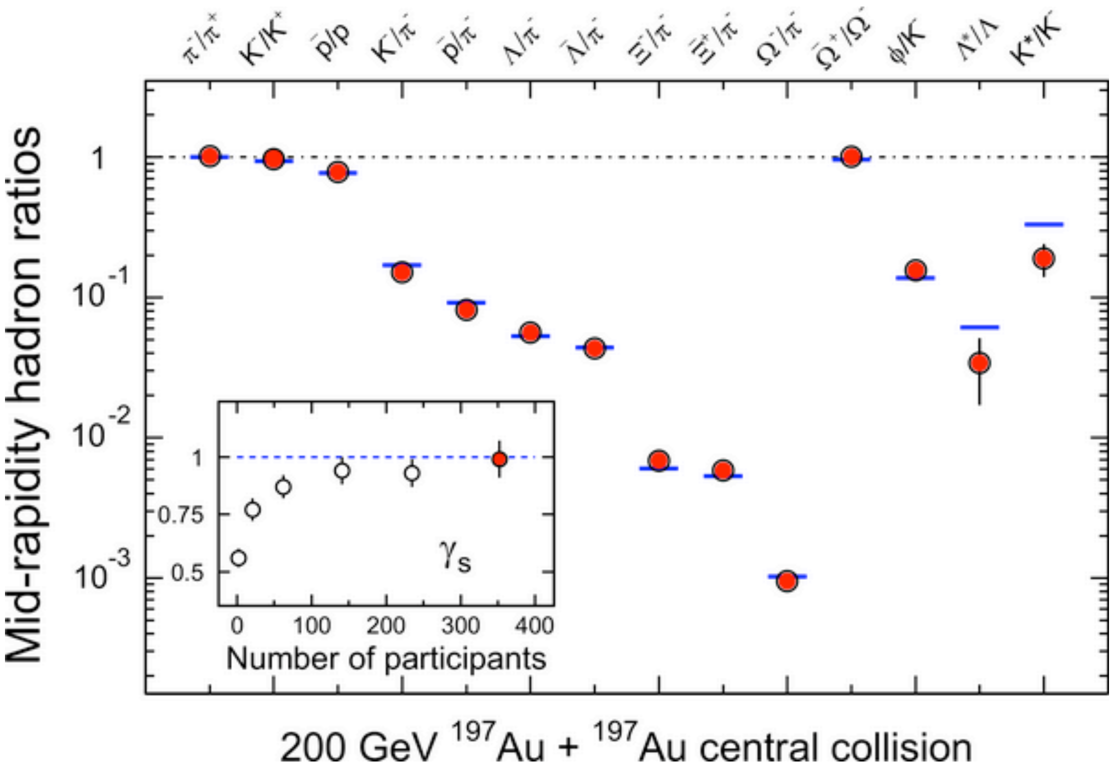
Lattice and other QCD based models :
μ_B = 0 - Cross-over
T_C ~ 170-195 MeV
μ_B > 160 MeV - QCD critical point

Experimental Study

(i) How to access PD
(ii) Establish Phase Boundary
(iii) Locate CP

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

Accessing Phase Diagram



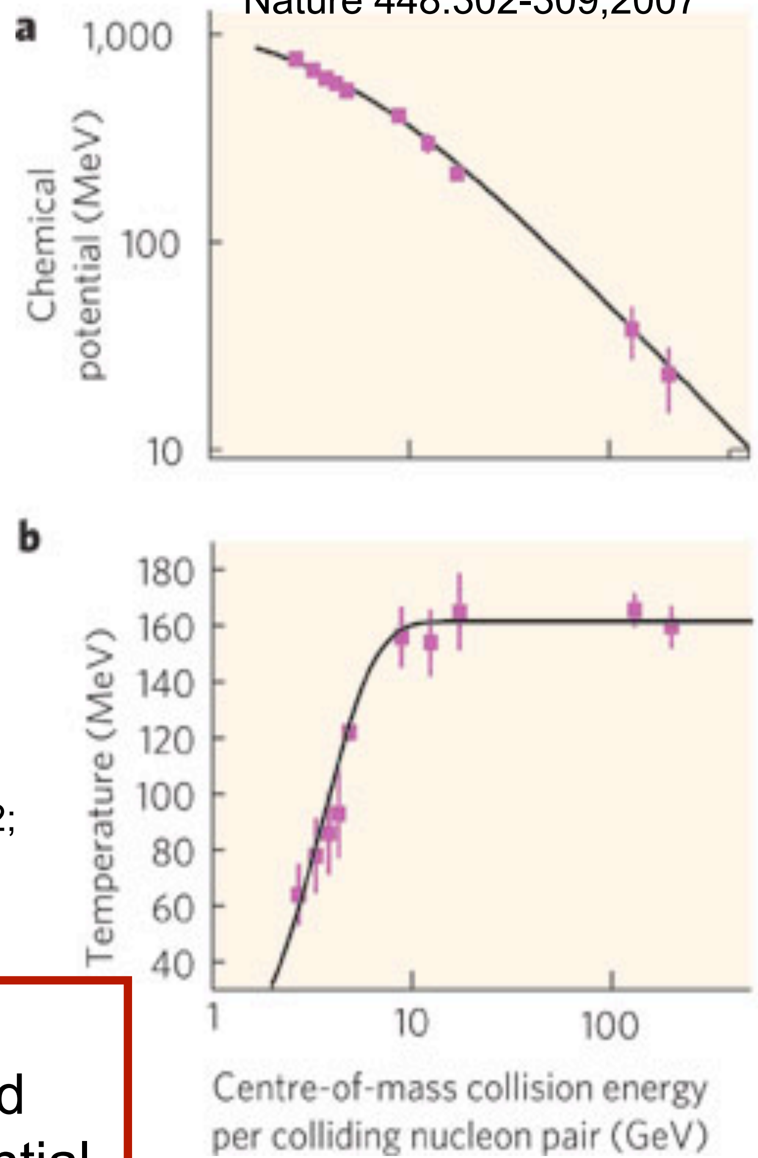
data

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
varies Temperature and
Baryon Chemical Potential

Establishing The Phase Boundary

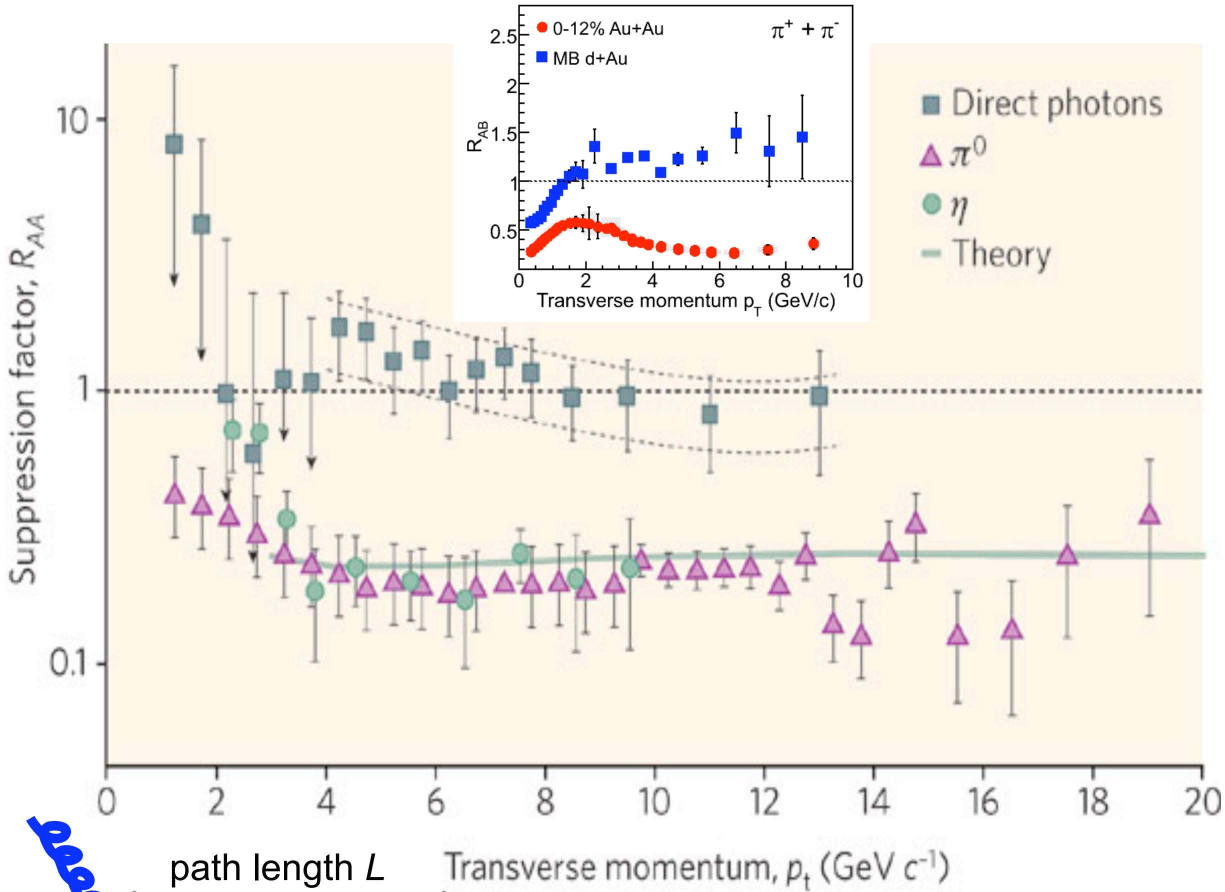
Strategy:

(I) Establish observables which give different values in the two phases (partonic and hadronic)

(II) Vary beam energy of collisions and look for transition in the observable

Jet Quenching

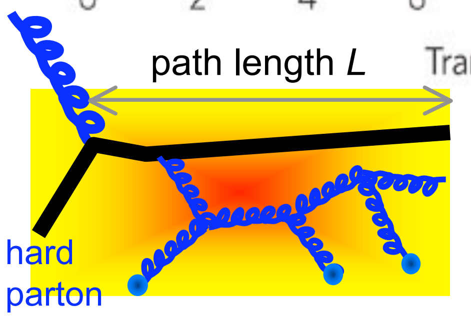
STAR : Phys.Rev.Lett.91:072304,2003
Phys.Lett.B655:104-113,2007
PHENIX : Phys.Rev.Lett.96:202301,2006



$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

- High p_T hadron prod. suppressed
- Photons prod. not suppressed
- No suppression in d+Au

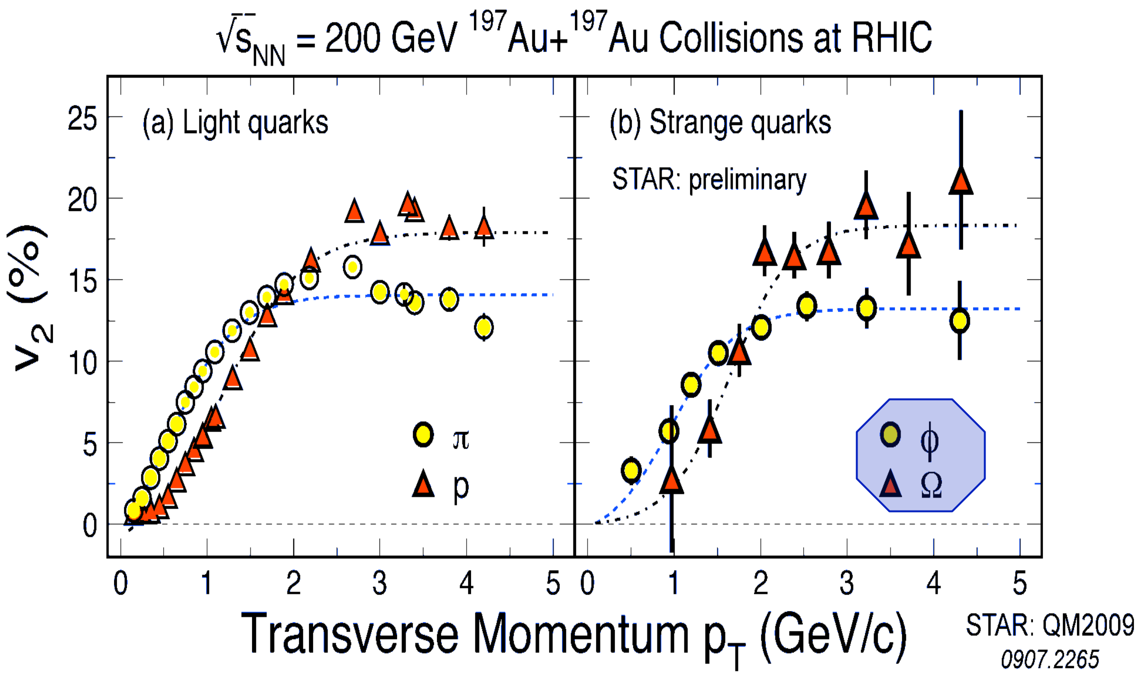
$\varepsilon_{initial} > \varepsilon_c$ (Lattice)

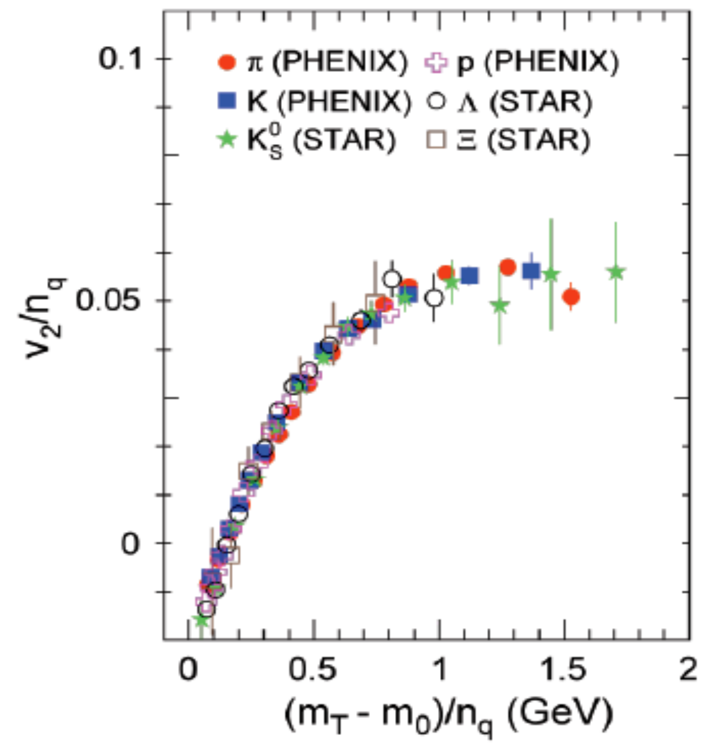


Interpretation : Energy loss of partons in a dense colored medium

Signature of QCD transition

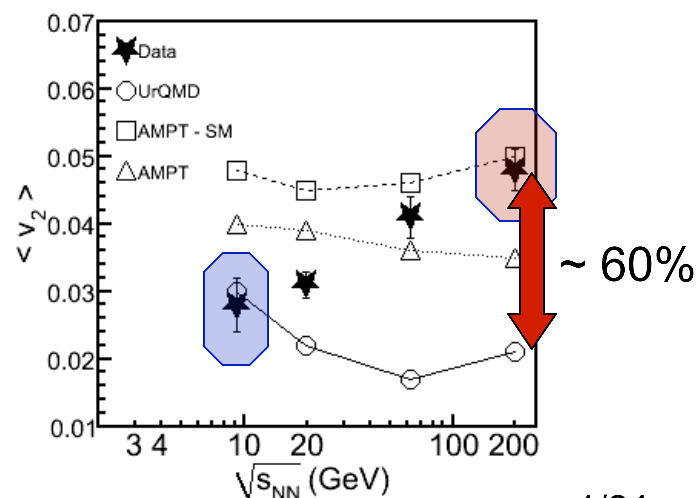
Strong Collectivity at RHIC





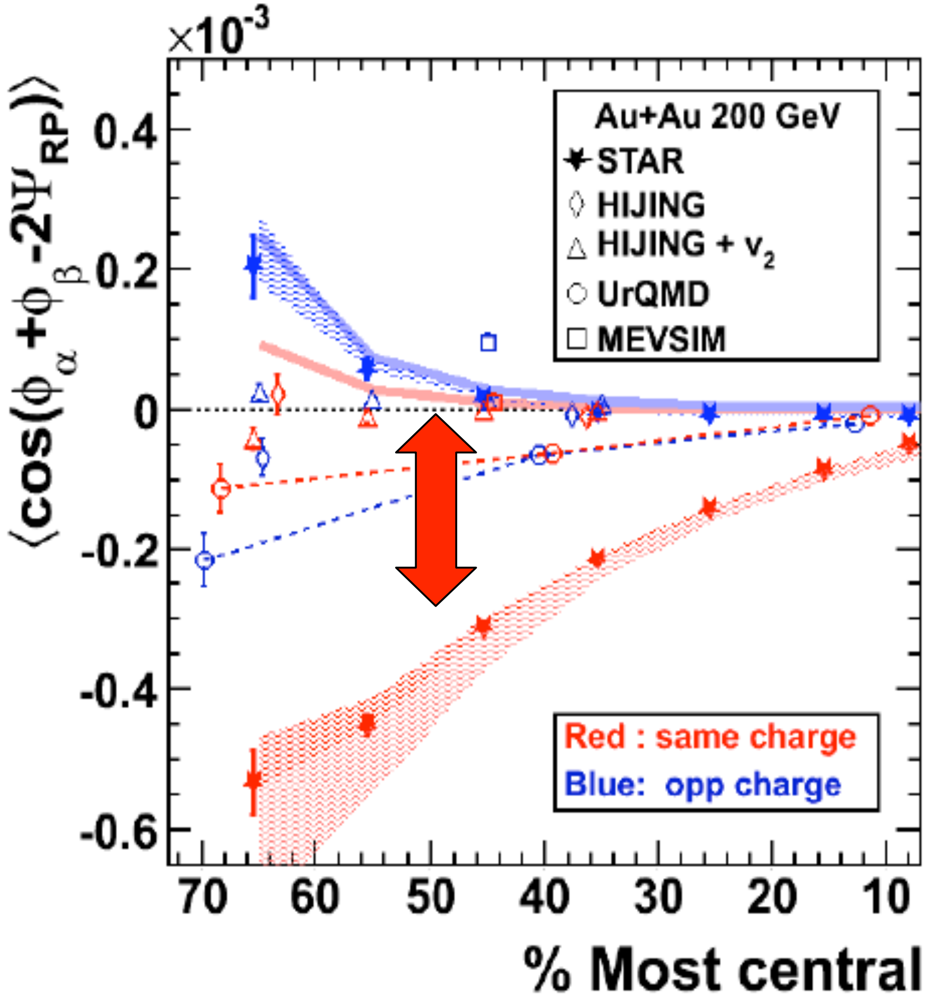
PHENIX π and p: nucl-ex/0604011v1

Low p_T : Heavier hadrons have lower v_2
(~ hydrodynamic pattern)
High p_T: Collectivity: baryon-meson
(~ Partonic recombination)
All p_T: Collectivity strange ~ light
(~ developed at partonic stage)



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

Dynamical Charge Correlations



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

Signature of QCD transition

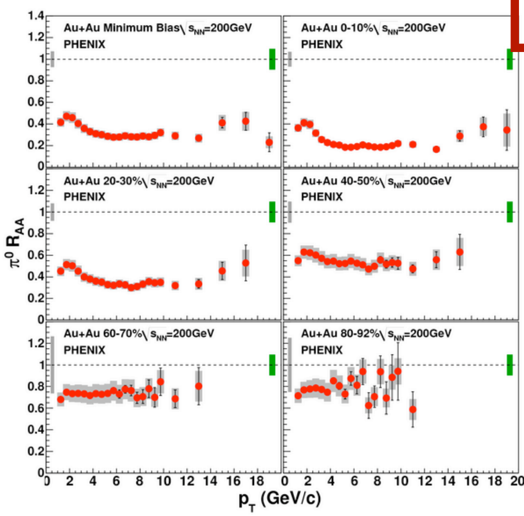
Experimentally:
- o Charge asymmetry observed in STAR experiment.
- o Parity even observable.
- o Physical background limited to studies with available models.
- o RHIC Beam Energy Scan program to be used to check the turning off of the signal.

Theoretically:
- o Consistent with Local Parity Violations in Strong Interactions
- o De-confined phase needed.
- o Chirally symmetric phase needed.

K. Fukushima et al, PRD 78, 074033 (2008)

Establishing The Phase Boundary

PHENIX : PRL 101, 232301 (2008)



Jet quenching

Turn-off
- Signature of QCD transition

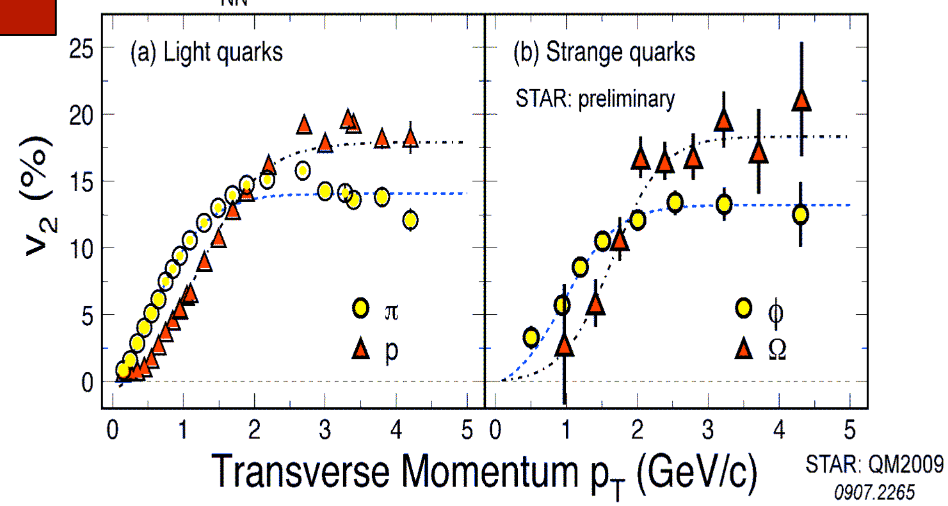
No Jet Quenching

No
NCQ Scaling
ϕ v_2 small

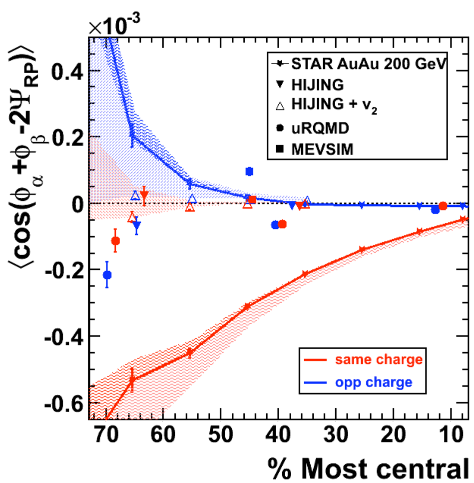
Partonic collectivity

STAR: Phys. Rev. Lett. 99 (2007)112301

$\sqrt{s_{NN}}$ = 200 GeV ^{197}Au+^{197}Au Collisions at RHIC



Chiral Magnetic effect



Au+Au
200 GeV
to
6 GeV

No Dynamical Charge Asymmetry

STAR: Phys. Rev. Lett. 103 (2009) 251601

Locating The QCD Critical Point

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

Strategy:

(I) Establish observables for critical point (CP) 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

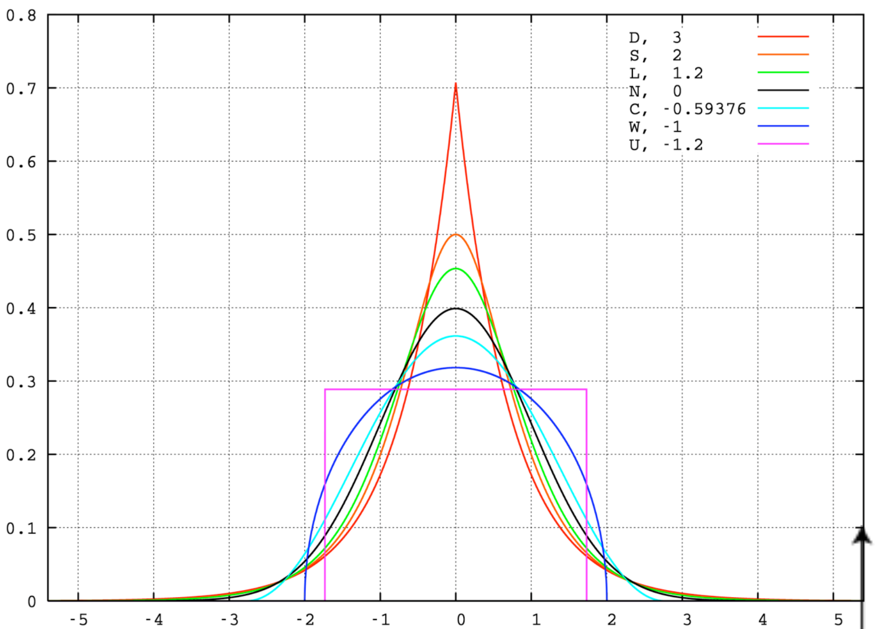
T. Andrews.
Phil. Trans. Royal Soc., 159:575, 1869

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

Measure Of Non-Gaussian Nature

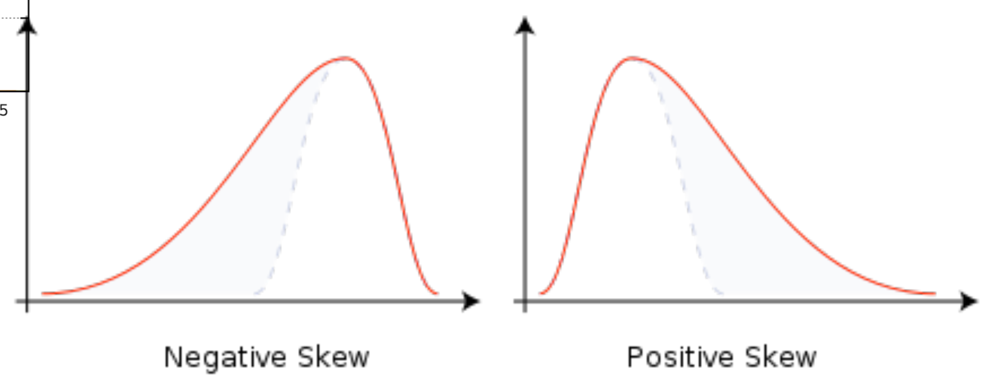
Deviation $\delta N = N - < N >$ Standard deviation, $\sigma = \sqrt{< (\delta N)^2 >}$

Skewness $= \dfrac{< (\delta N)^3 >}{(\sigma)^3}$ **Kurtosis** $= \dfrac{< (\delta N)^4 >}{(\sigma)^4} - 3$



D: Laplace distribution kurtosis = 3
S: hyperbolic secant distribution kurtosis = 2
L: logistic distribution kurtosis = 1.2
N: normal distribution kurtosis = 0
C: raised cosine distribution kurtosis = −0.59376
W: Wigner semicircle distribution kurtosis = −1
U: uniform distribution kurtosis = −1.2.

Skewness and Kurtosis are measures of non-Gaussian nature of the distribution.



Higher Moments of Net-Protons

Distributions non Gaussian at QCP

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)
B. Berdnikov, K. Rajagopal, Phys. Rev. D 61, 105017 (2000)
M. Cheng et al, PRD 79, 074505 (2009)
B. Stokic et al, PLB 91, 192 (2009)
R. Gavai & S. Gupta PRD 78, 114503 (2008)

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

$\sim$ Singularity in charge and baryon number susceptibilities

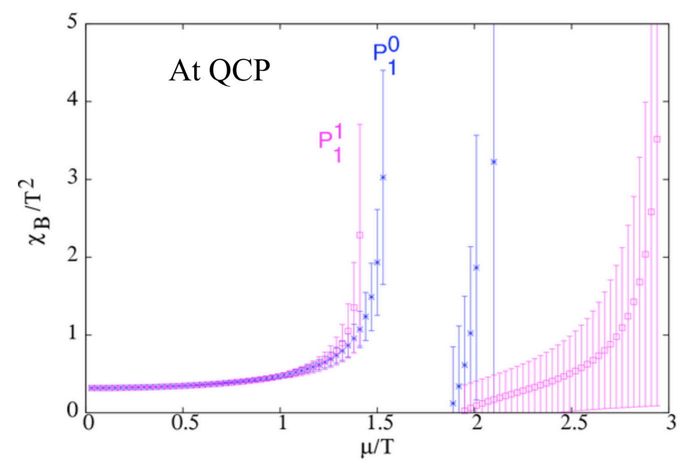
$Q = B/2 + I_3$

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

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

iso-spin blindness of σ field

Y. Hatta et al,PRL 91, 102003 (2003)

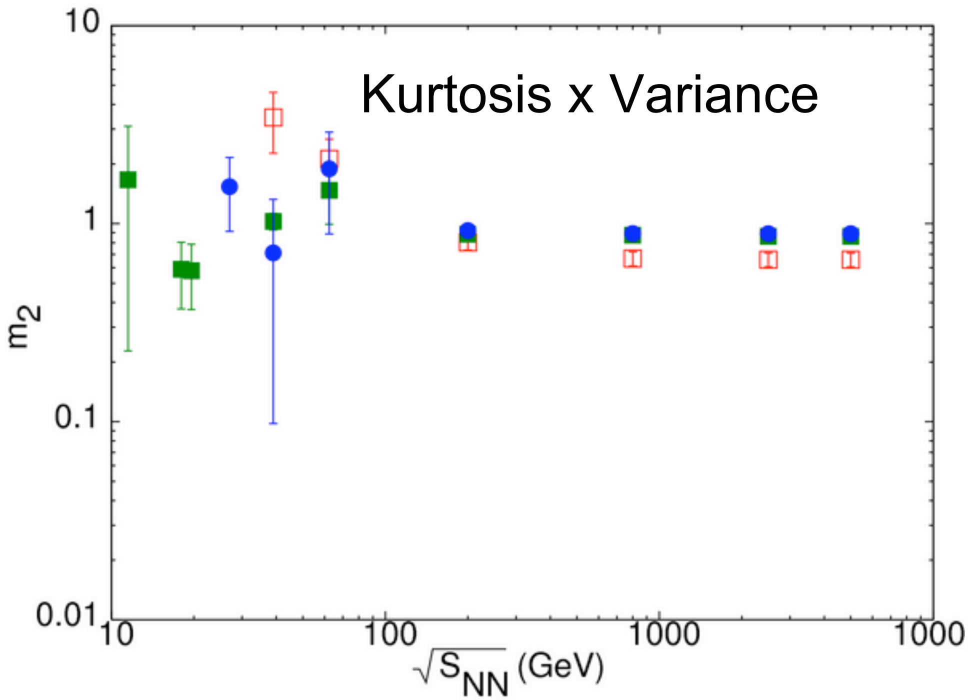


Non monotonic variation of products of higher moments with beam energy

Theory Expectations

Lattice QCD

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

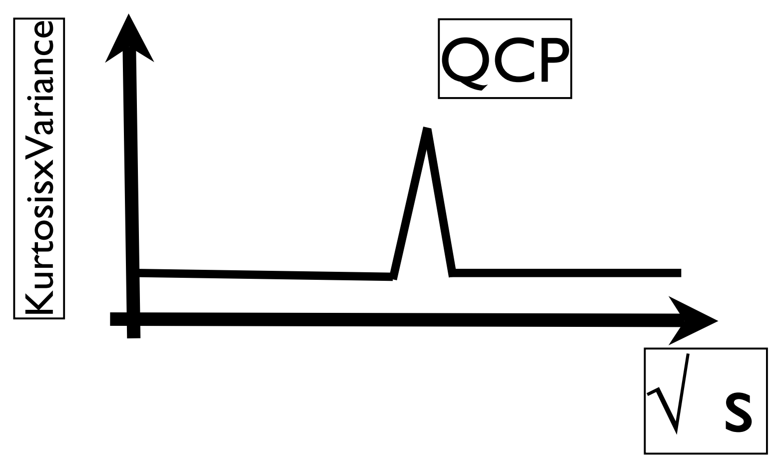


m_2 equivalent to Kurtosis x Variance
At CP : Systems falls out of equilibrium will lead to deviations from Lattice QCD

CP Model

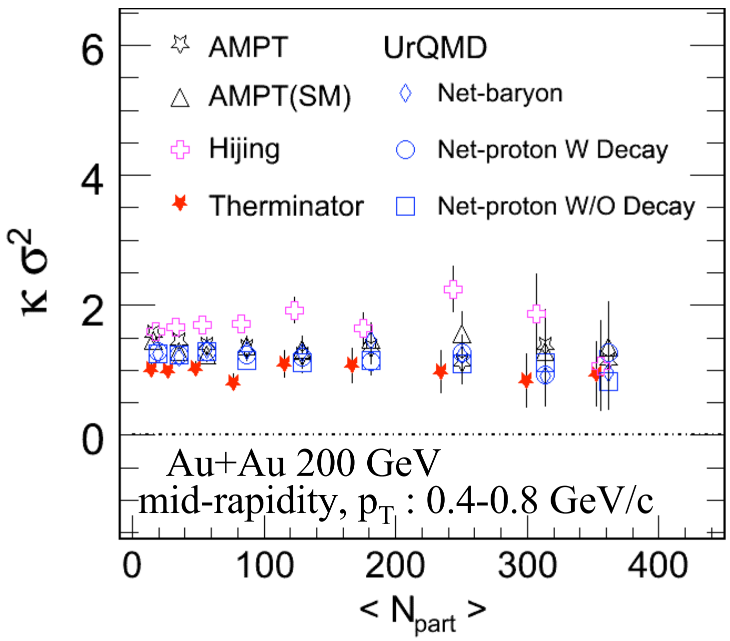
(C. Athanasiou,M. Stephanov, K. Rajagopal, arXiv:1006.4636 and PRL 102 (2009) 032301)

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

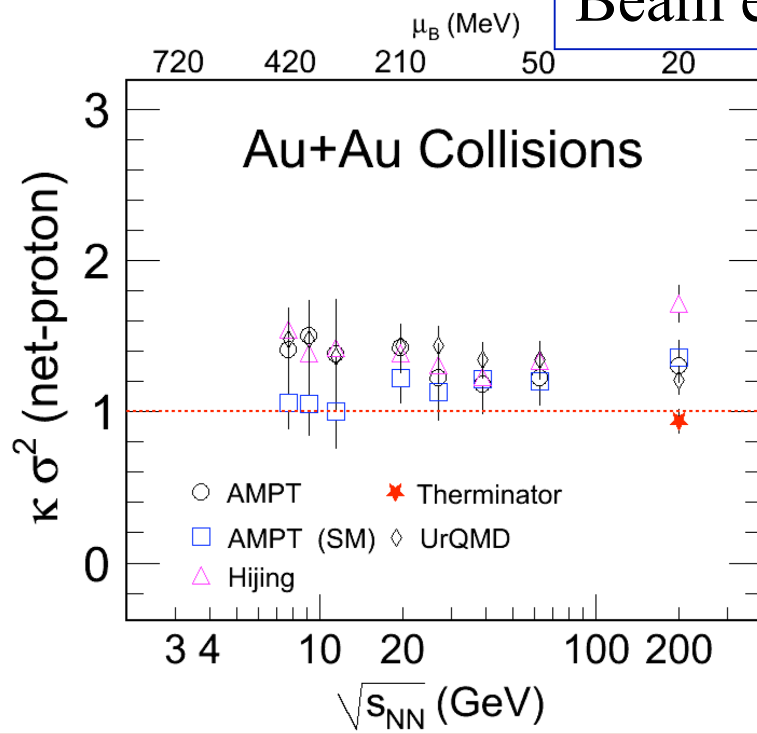


Observable and Non-CP Physics

Collision centrality



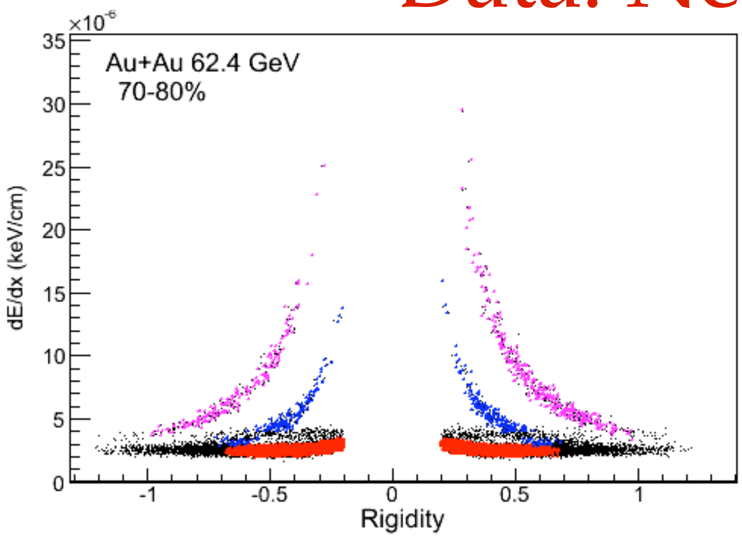
Beam energy



Kurtosis x Variance: (Desirable features for CP Search)

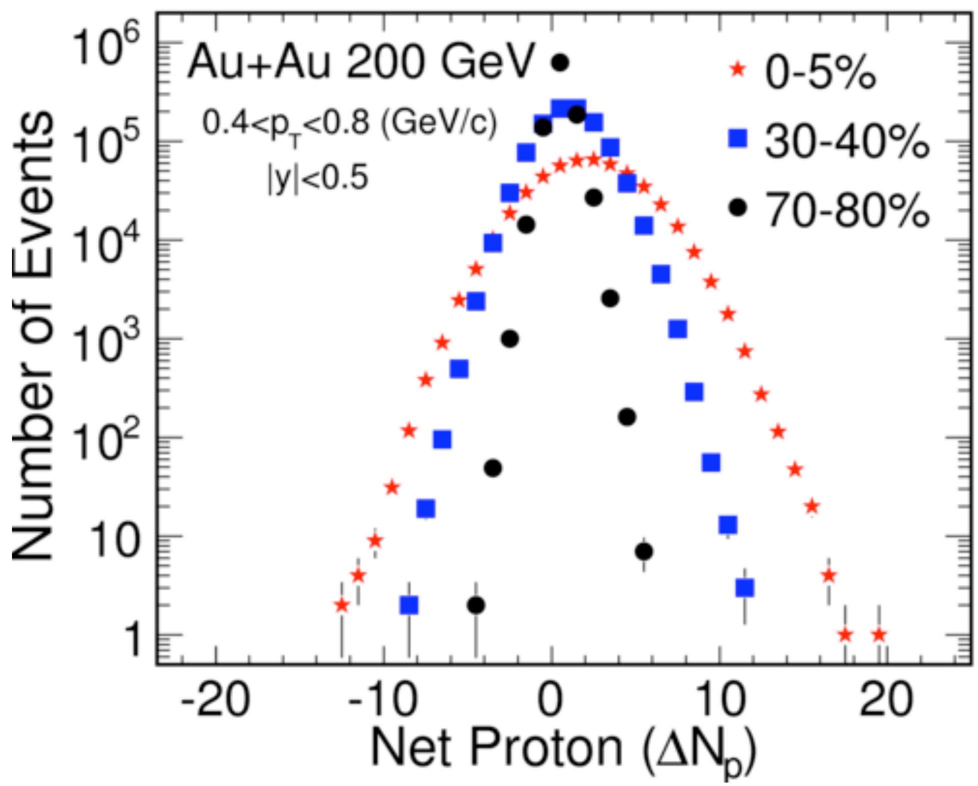
- o Constant as a function of beam energy
- o Constant as a function of collision centrality/impact parameter
- o No difference between net-baryon and net-proton
- o Effect of resonance decay small
- o Similar values for Transport, Mini-jets, Coalescence models
- o Unity for Thermal model

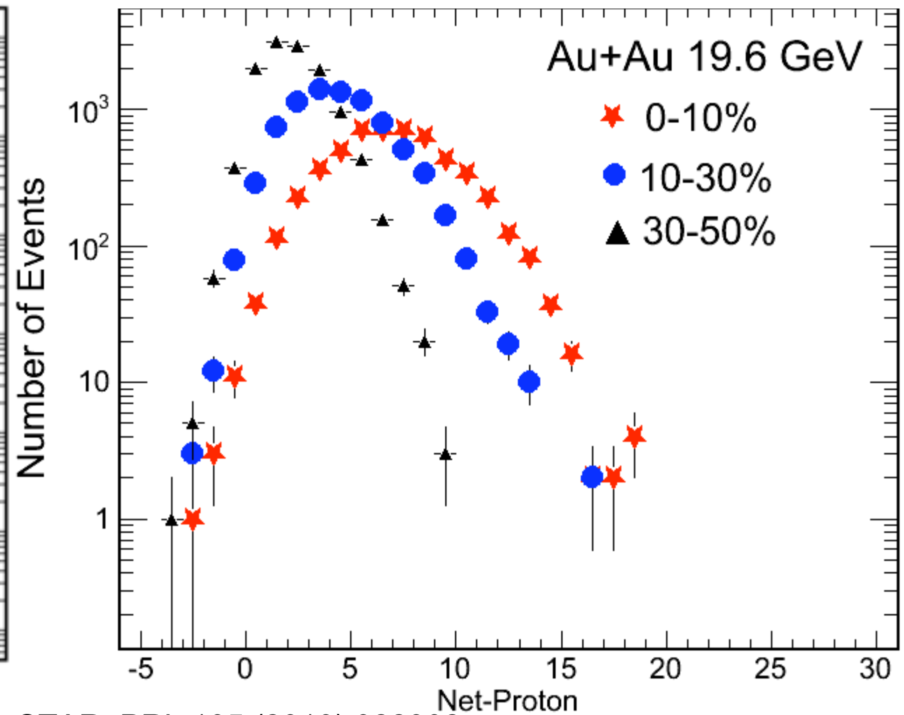
Data: Net-Proton Distribution



Clean identification of protons in STAR TPC for the transverse momentum range : 0.2 - 1 GeV/c.

All results for Au+Au collisions at 19.6, 62.4 and 200 GeV collisions

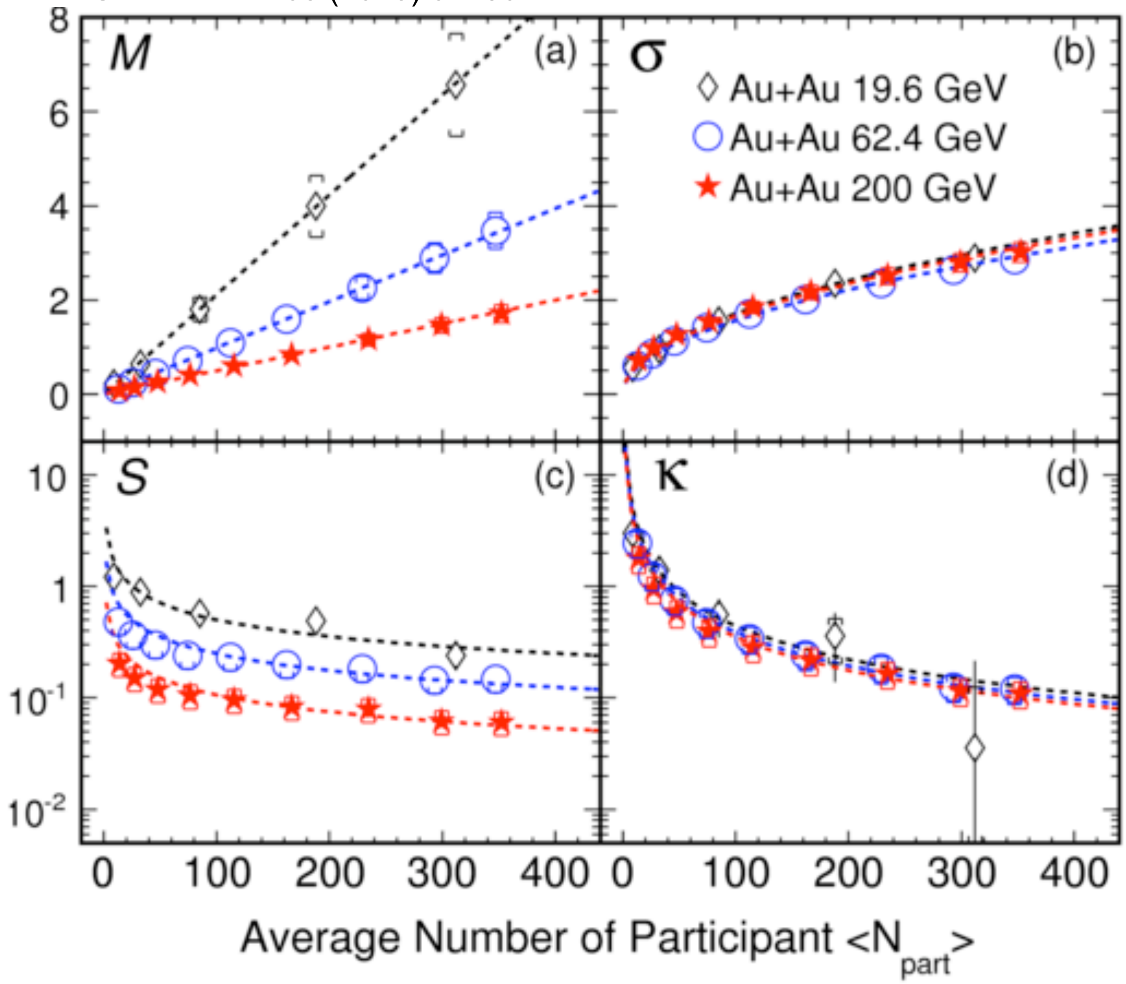




STAR: PRL 105 (2010) 022302

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:

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

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

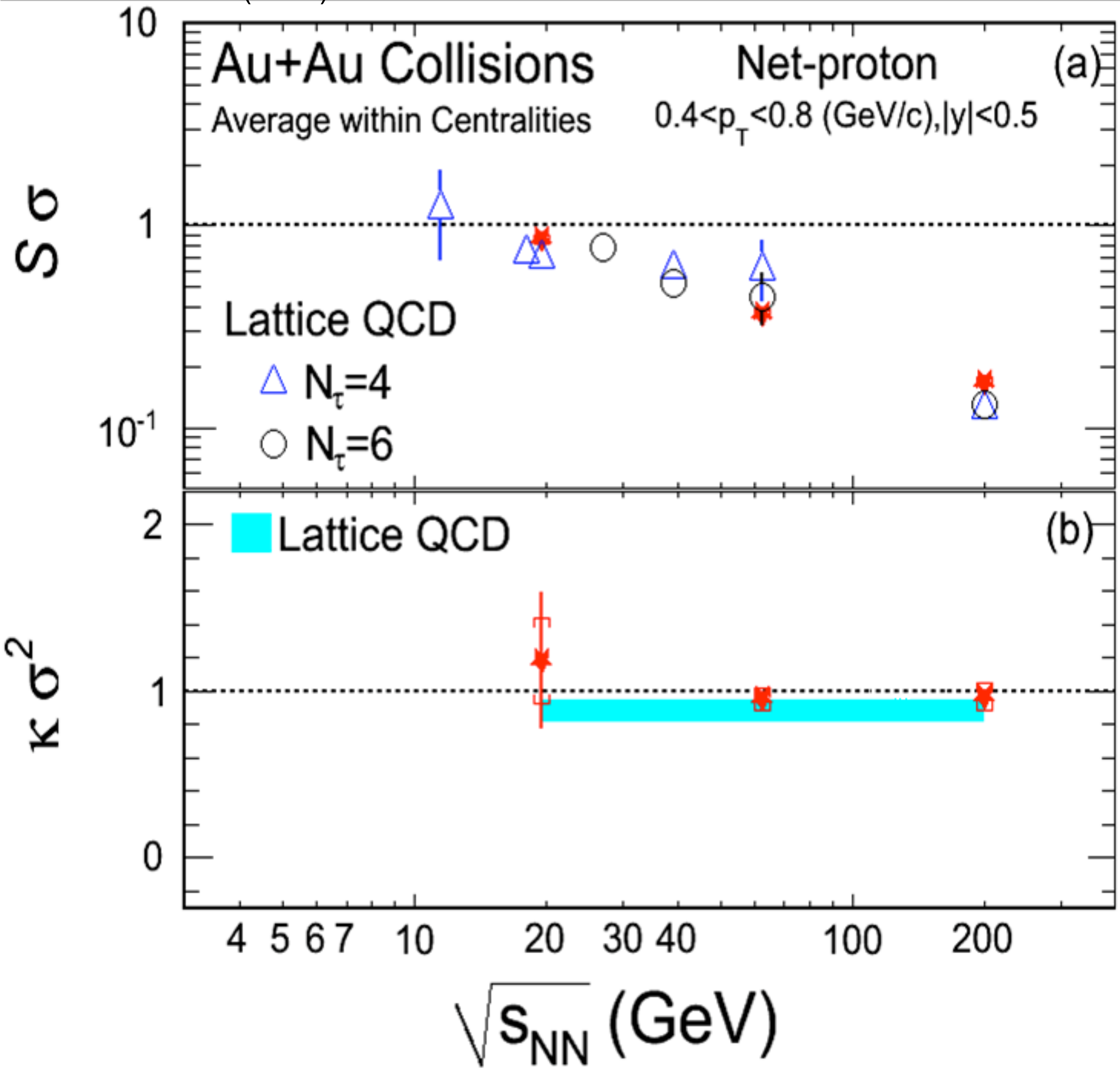
$S_i = S_x/\sqrt{[C <N_{part}>]_l}$

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

Consistent with CLT expectations (lines)

Data and Lattice QCD

STAR: PRL 105 (2010) 022302



$S\,\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}$

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

Assumptions:

Net-proton ~ net-Baryon

Thermalization

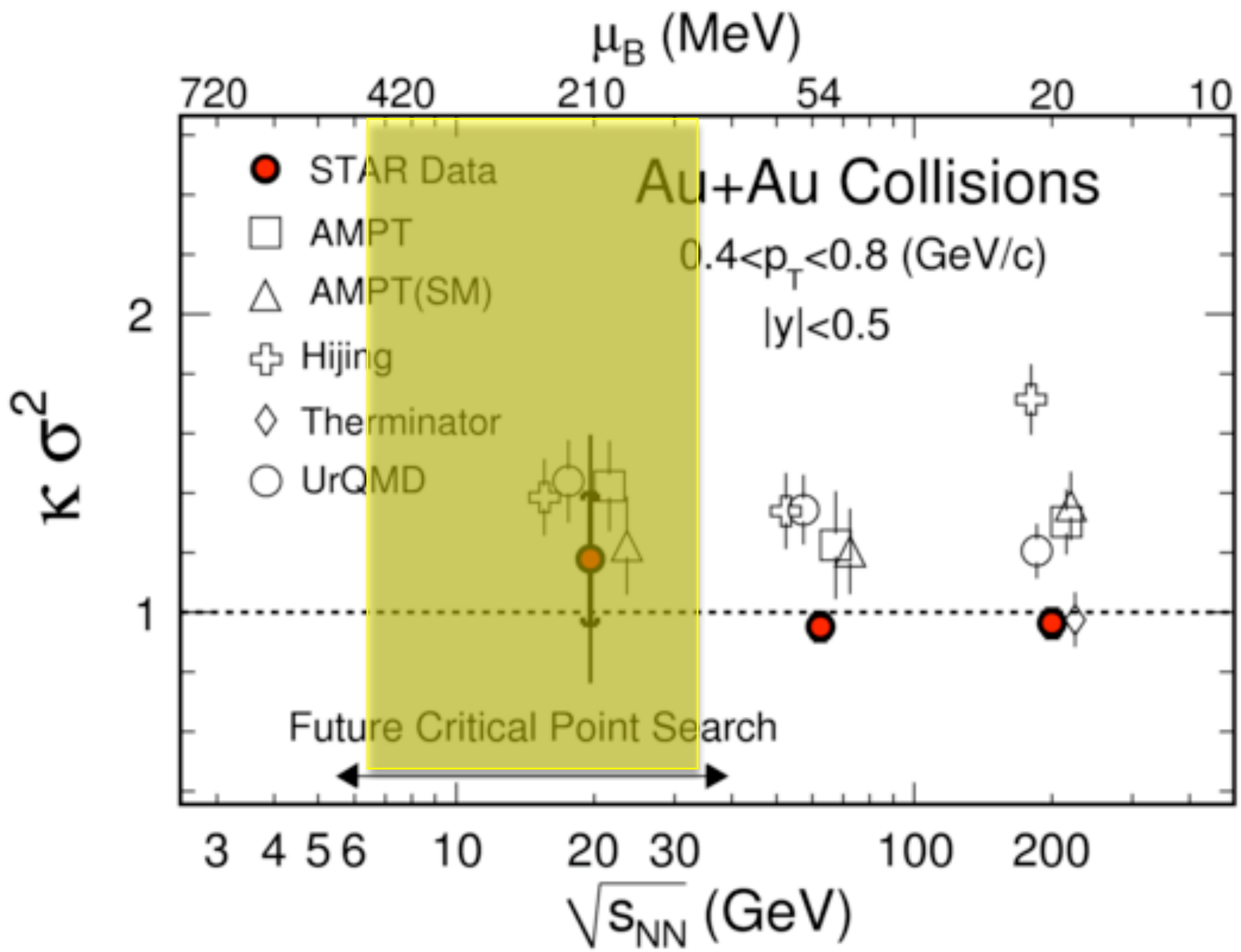
Modelling: Chemical Freeze-out

QCD Thermodynamics

Good agreement with Lattice QCD

R. Gavai & S. Gupta arXiv:1001.3796

Energy Dependence: $\kappa\sigma^2$



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

arXiv: 1006.4636;
PRL 102 (2009) 032301

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

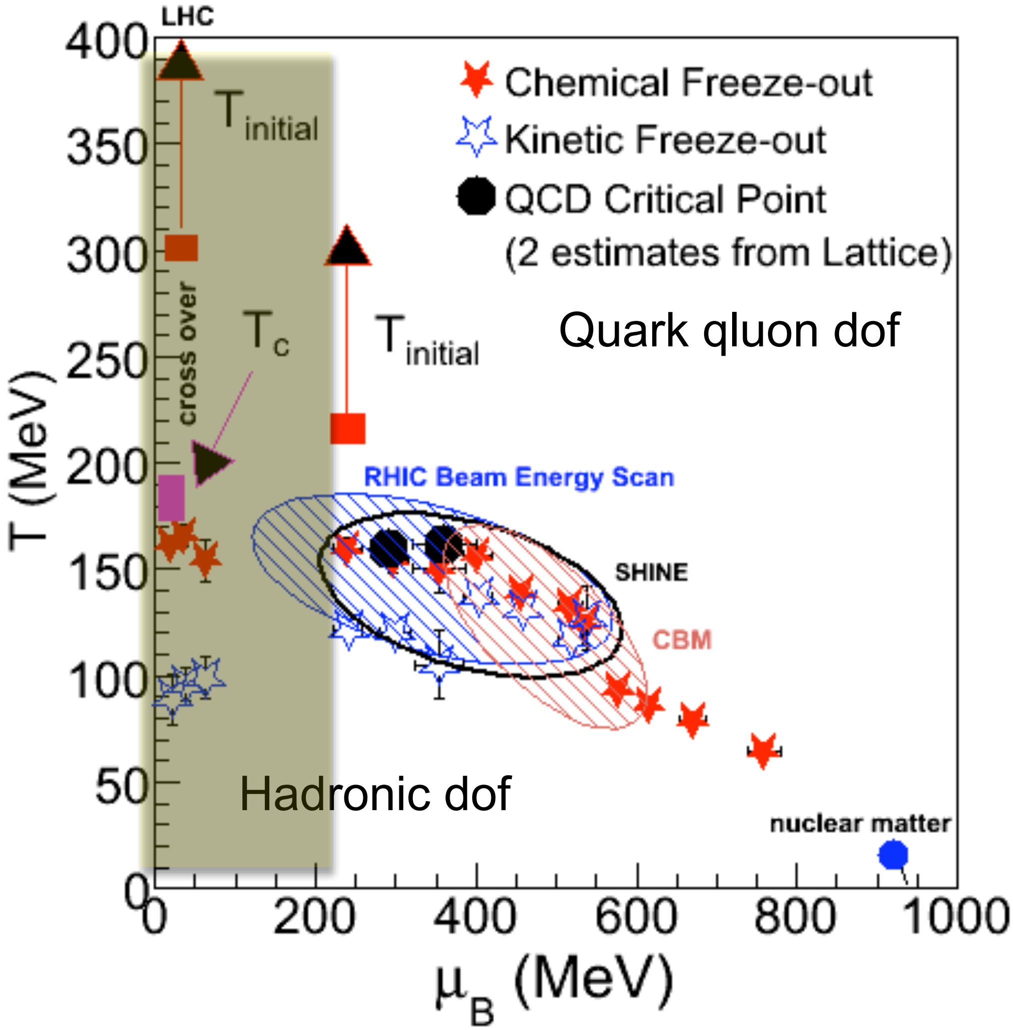
PRL 101 (2008) 122302;
PLB 647 (2007) 431
Eur. Phys. Lett. 86 (2009) 31001

STAR: PRL 105 (2010) 022302

Year 2010: 7.7, 11.5, 39 GeV
Year 2011: 18, 27 GeV

Observations indicate CP not located for $\mu_B < 200$ MeV

Summary



With the starting of LHC ($\mu_B \sim 0$) - 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:

- ✓ *characterization of quark-gluon matter at varying baryon density*
- ✓ *finding the QCD critical point and*
- ✓ *establishing the QCD phase boundary.*