Study of the QCD Phase Diagram Using High Energy Nuclear Collisions

Bedanga Mohanty For STAR Collaboration
Variable Energy Cyclotron Centre, Kolkata

Prof. H. J. Bhabha

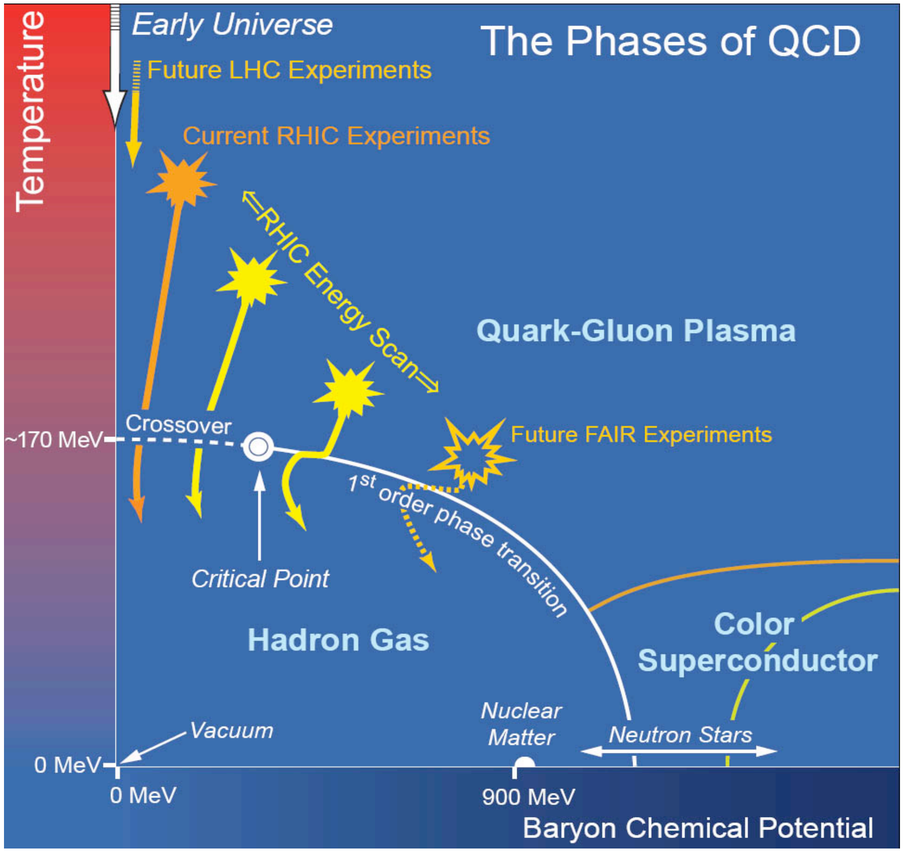
Outline

- QCD Phase Diagram
- Partonic Degrees of Freedom at RHIC
- QCD Critical Point
- RHIC Beam Energy Scan Program
- Summary

Strong Interaction In The 21st Century
Tata Institute of Fundamental Research, Mumbai
10-12 February, 2010

QCD Phase Diagram

One representation:



QCD predicted transitions:

✓Restoration of chiral symmetry

✓ De-confinement of quarks and gluons

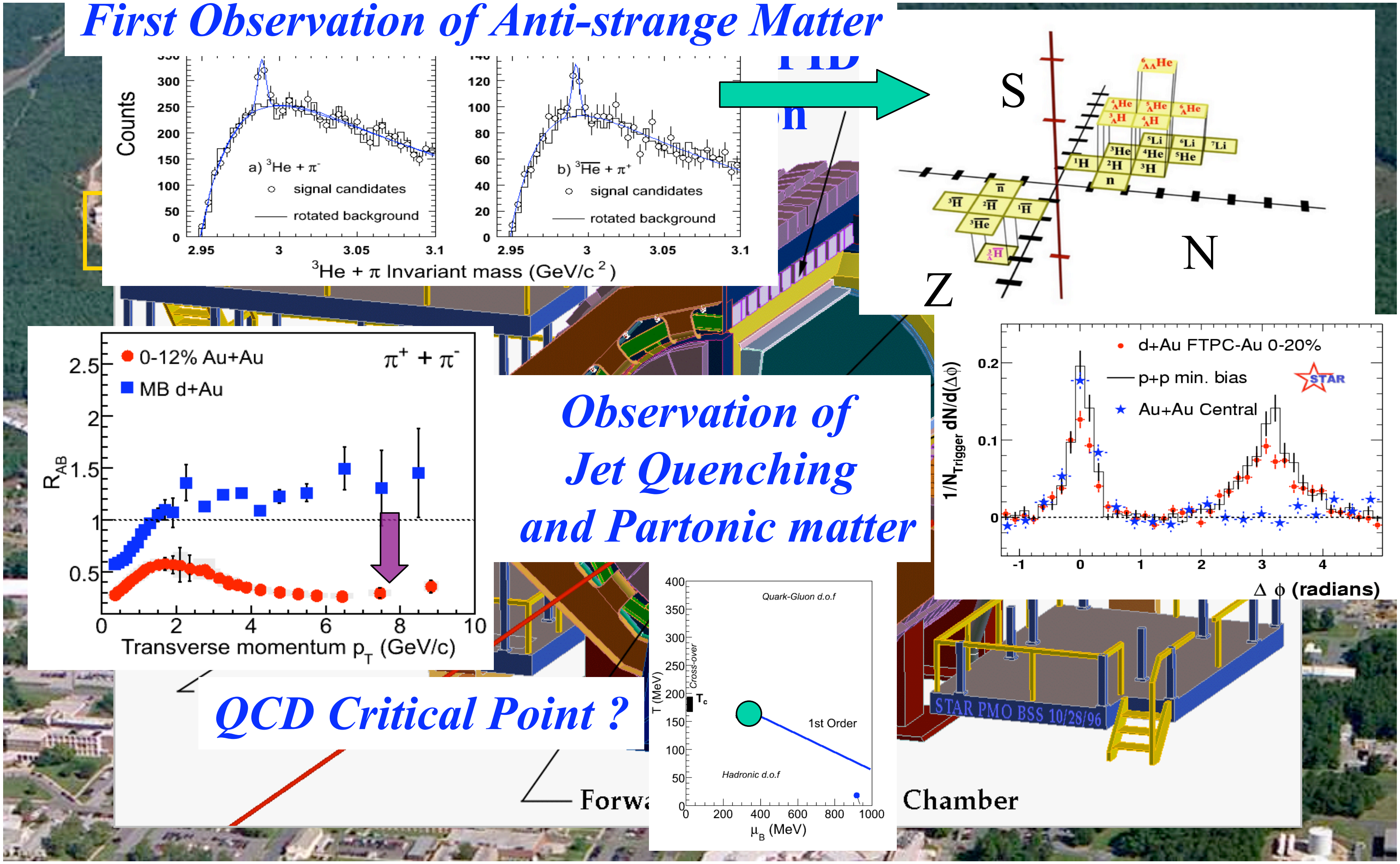
QGP ~ a (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes. Such a matter exhibits collectivity.

STAR: Nucl. Phys. *A757*, (2005) 102

Can we observe the QCD predicted transitions and the QCD Critical Point?

The only phase transition among those occurring in early universe to be accessible in laboratory.

RHIC: Discovery Machine



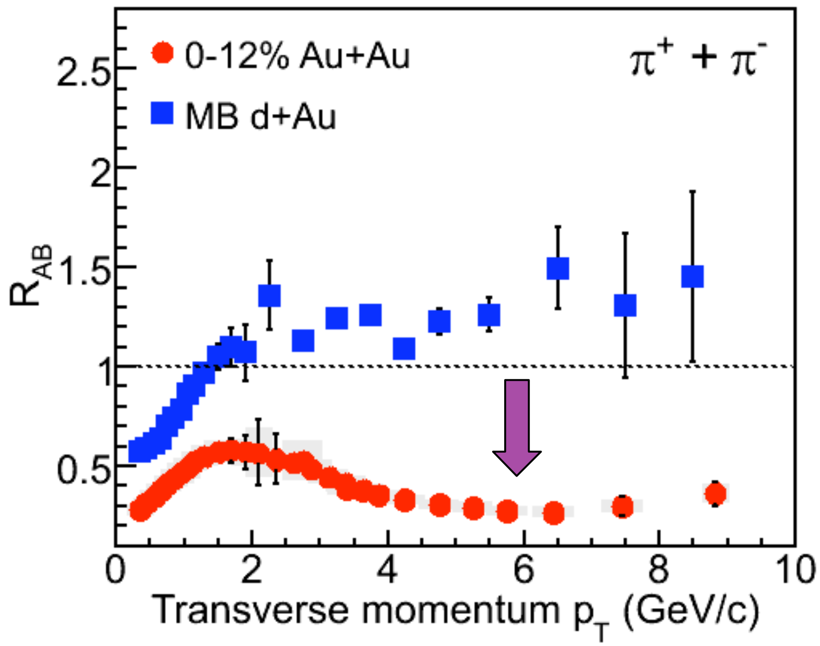
Dedicated facility for high energy nucleus-nucleus collisions

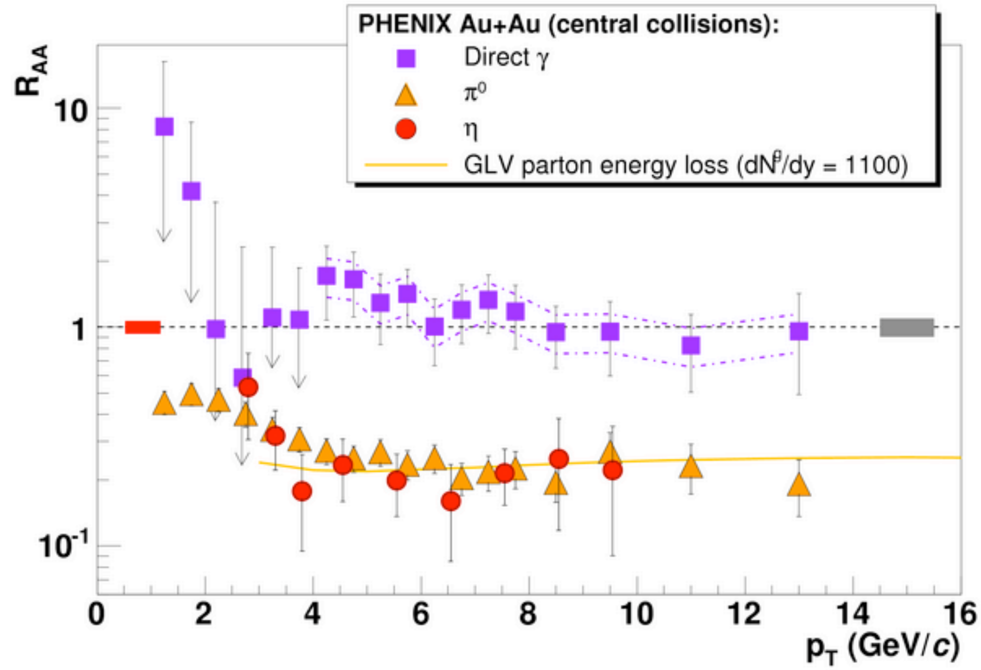
http://www.bnl.gov/rhic

Partonic Matter at RHIC

Observations:

$$R_{AB} = \frac{1}{N_{bin}} \frac{d^2 N^{AB} / dp_T\, d\eta}{d^2 \sigma^{pp} / dp_T\, d\eta}$$





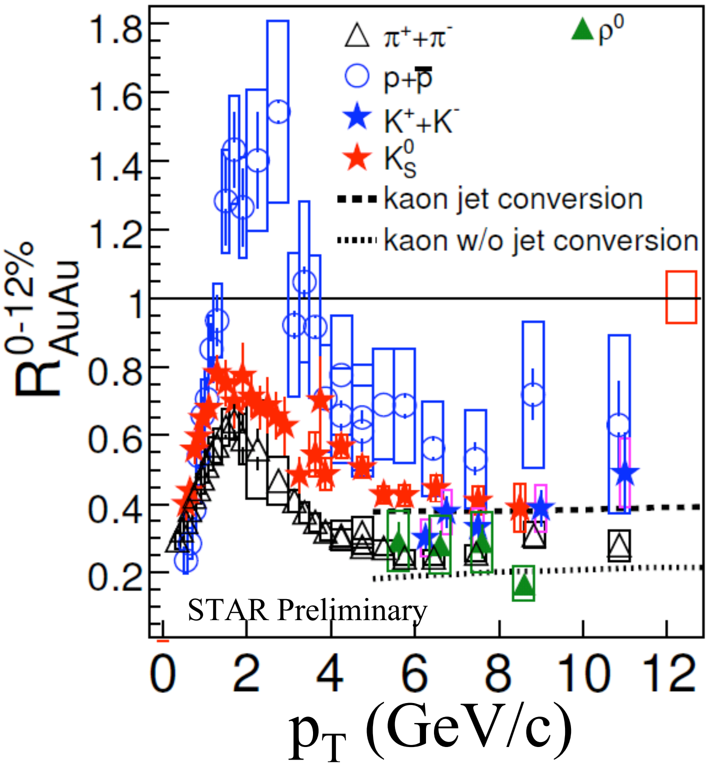
Interpretation : Energy loss of partons in a dense medium

$$\varepsilon_{initial} > \varepsilon_C \text{ (Lattice QCD)}$$

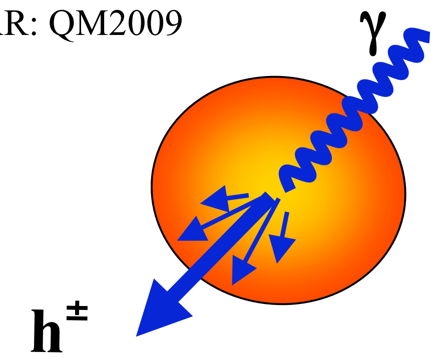
STAR : Phys.Rev.Lett.91:072304,2003
Phys.Lett.B655:104-113,2007

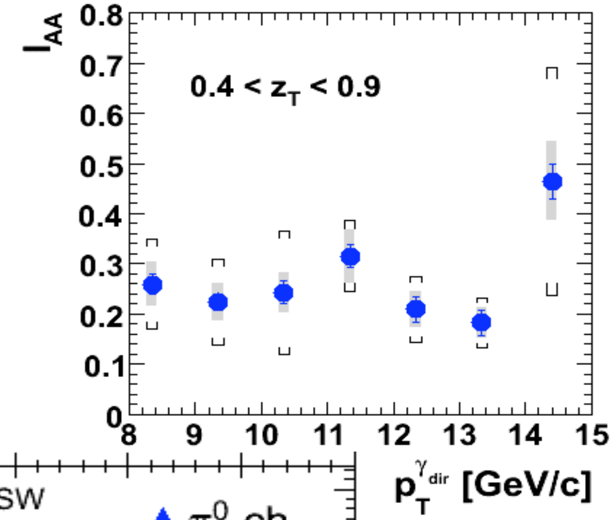
PHENIX : Phys.Rev.Lett.96:202301,2006

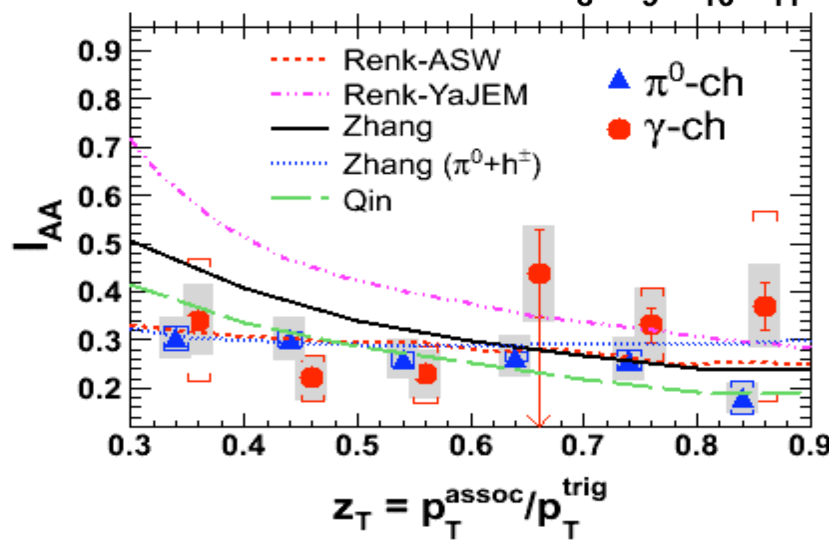
Strong Interactions at RHIC



STAR: nucl-ex/0912.1871
STAR: QM2009







E_{loss} ~ Func (Color Factor,
Path Length, Medium Density…)

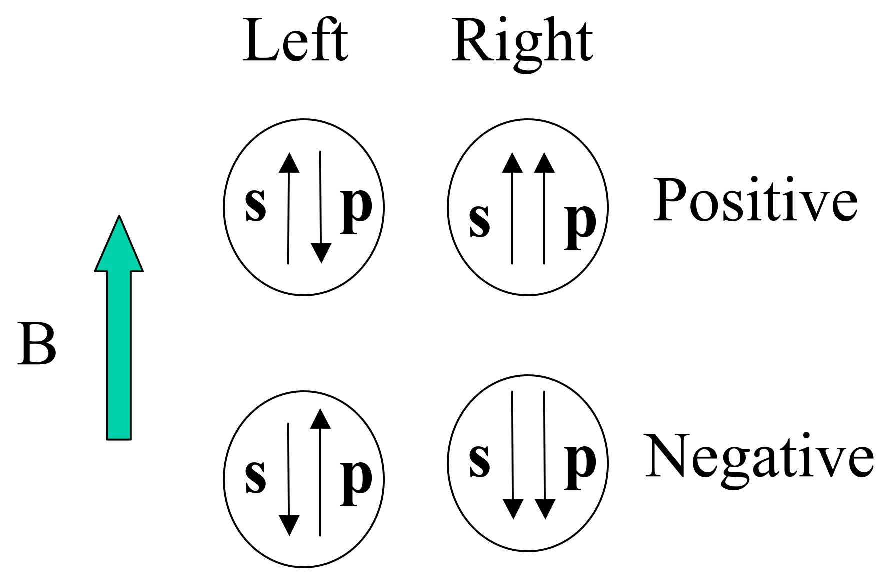
q vs.g E_{loss} : Naïve expectations R_{AA} (pbar) < R_{AA} (π)
q,g jet conversions: Model expectations R_{AA} (K) > R_{AA} (π)
Path length dependence: Simple expectations I_{AA} (γ_{dir}) < I_{AA} (π^0)
Dependence on initial parton energy: Study E_{loss} vs. E(γ_{dir})

Possible Local Parity Violation in Strong Interactions

P/CP invariance globally in strong interactions.
Experimentally: Neutron Electric Dipole Moment expts.
Topological Structure of QCD Vacuum ==> Local Parity Violations

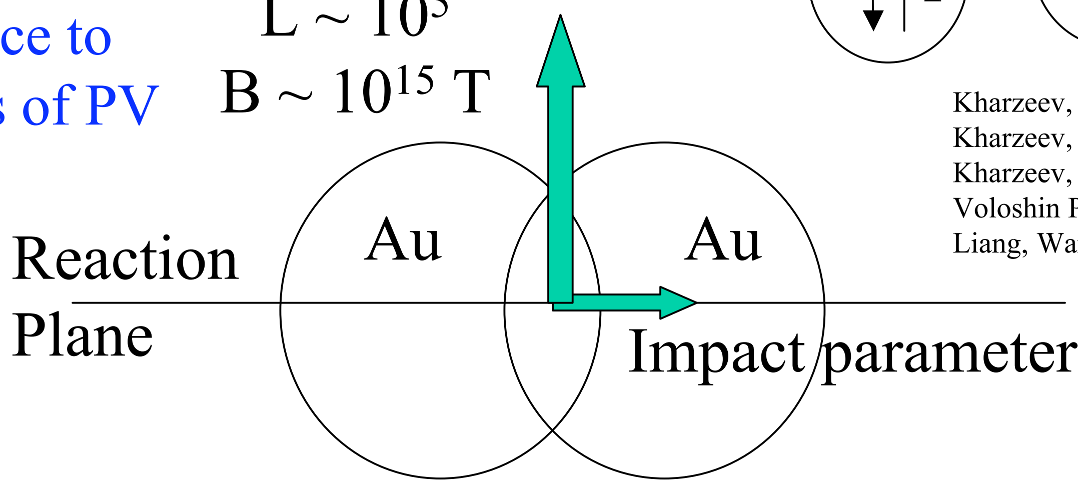
Pospelov, Ritz, PRL83 (1999) 2526
Baker et al., PRL97 (2006) 131801

Mechanism:
Mass less quarks can change Chirality by interacting with gluons
Causing $N_L \neq N_R$ ==> P Violation
Observable:
Magnetic field align quark spins
Causing charge separation along B



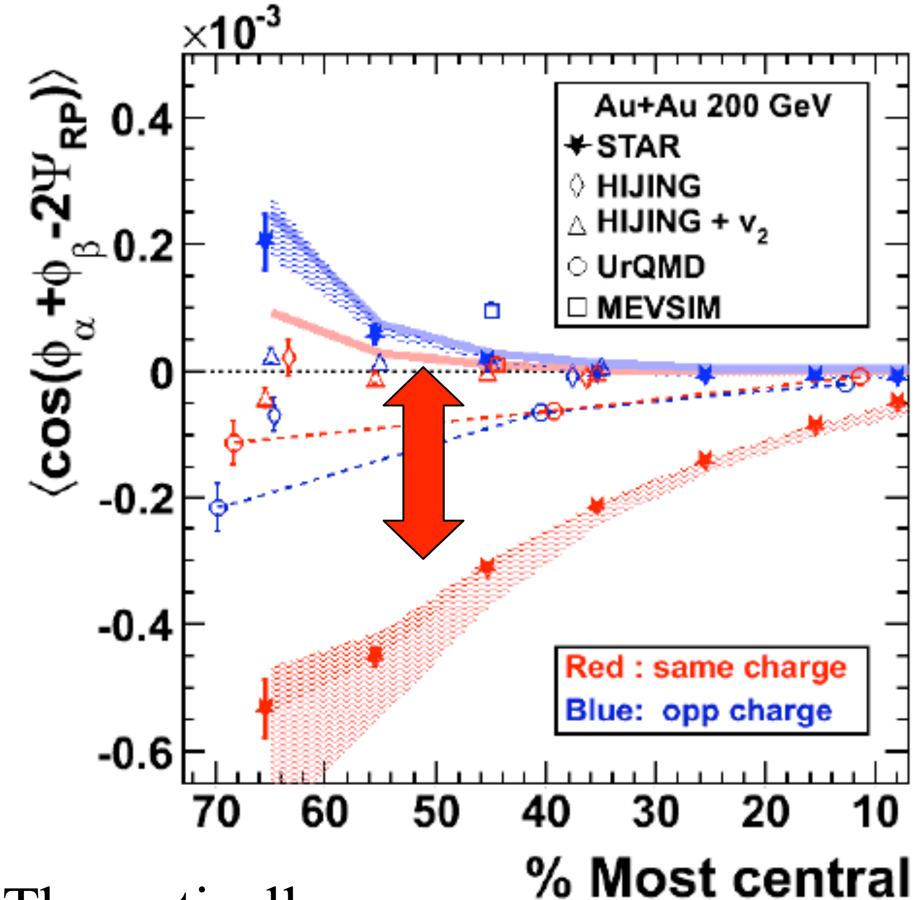
RHIC good place to look for signals of PV

$L \sim 10^5$
$B \sim 10^{15}$ T



Kharzeev, PLB633 (2006) 260
Kharzeev, Zhitnitsky, NPA797 (2007) 67
Kharzeev, McLerran, Warringa, NPA803 (2008) 2
Voloshin PRC 62 (2000)044901
Liang, Wang, PRL (2005) 102301

Possible Local Parity Violation in Strong Interactions



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.

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

Theoretically:

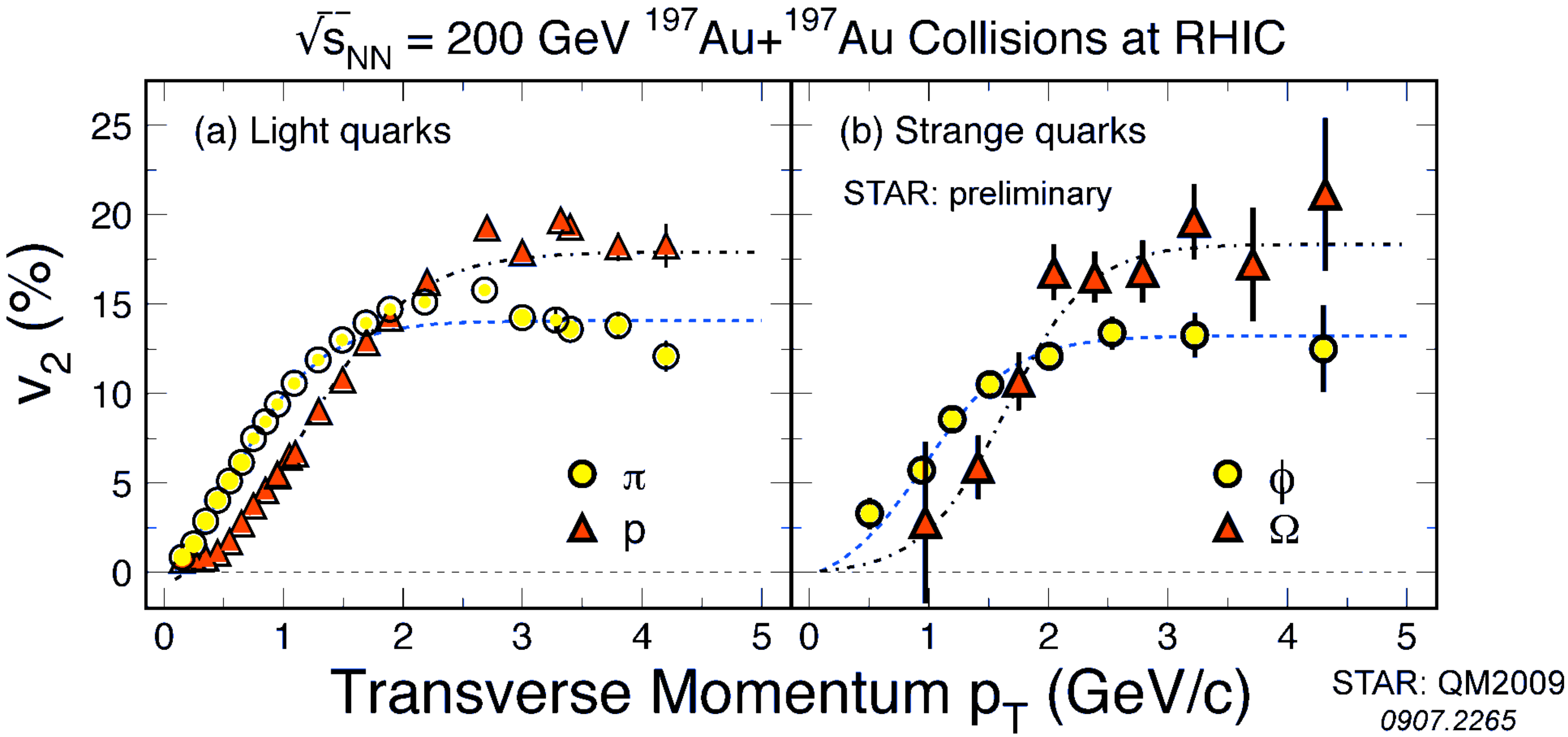
o Signal Consistent with expectations from Local Parity Violations in Strong Interactions.

o De-confined phase needed.

o Chirally symmetric phase needed.

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

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 grouped along baryon-meson lines

(~ Hadronization by partonic recombination)

All p_T : Collectivity similar for hadrons with strange and light quark

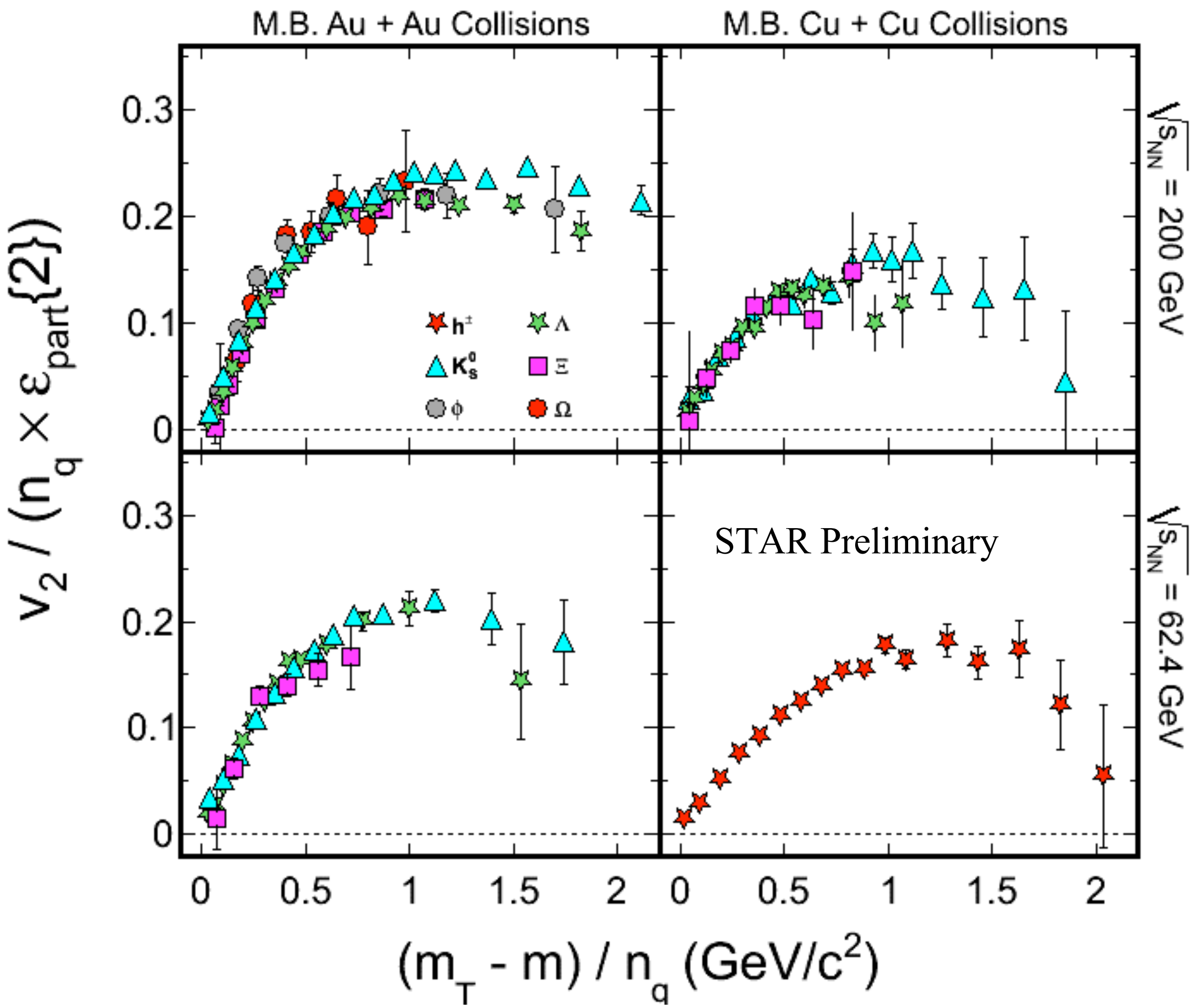
(~ developed at partonic stage)

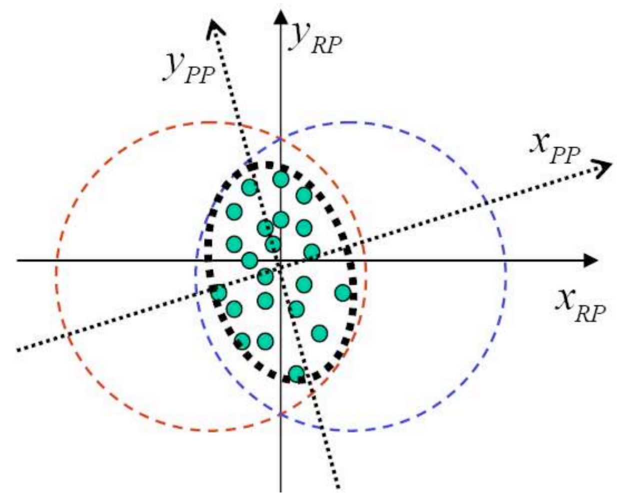
Collectivity Developed at Partonic Stage

n_q : Number of constituent quarks
= 3 for Baryons
= 2 for mesons

STAR: PRC77 (2008)054901;PRC75 (2007)054906

$$m_T^2 = p_T^2 + m^2$$





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

S. A. Voloshin, A. M. Poskanzer, A.Tang and G.Wang, PLB, 659 (2008), 537-541

Summary On Partonic Matter Formation At RHIC

Parton energy loss:

Observation: suppression in high transverse momentum hadron production in AA collisions relative to pp collisions.

Interpretation: parton energy loss in a hot and dense medium with color degrees of freedom.

Energy density: higher than predicted by Lattice QCD for transition

Partonic interactions in medium:

QCD predicted between quark and gluon energy loss ?

(Flavour dependence -- See STAR Talk by Wei Xei)

Quark and gluon jet conversions in the medium ?

Charge Asymmetry in particle production along magnetic field

Links to possible local parity violation - requires de-confinement and chiral symmetry restoration

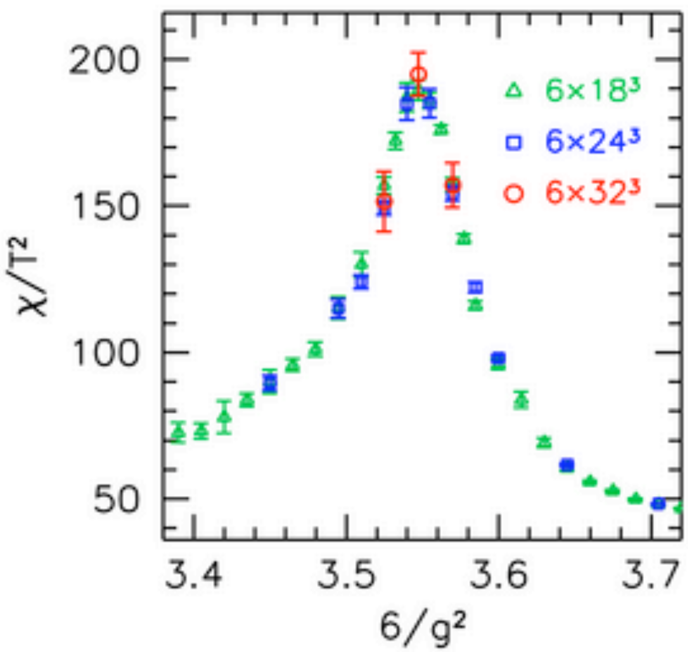
Collectivity:

Similar level for u,d,s constituent quark carrying hadrons.

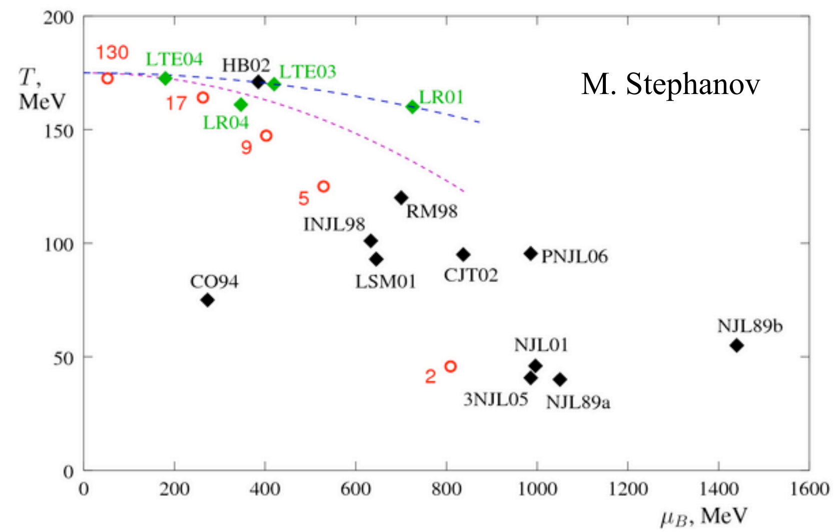
Future: heavy quark collectivity to experimentally study thermalization.

Order Of The Quark-Hadron Transition

$\mu_B = 0$



$\mu_B > 0$



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

No significant volume dependence (8 times difference in volumes). Transition at High T and $\mu_B = 0$ is a cross over.

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

QCD models - 1st order phase transition, QCP location uncertain

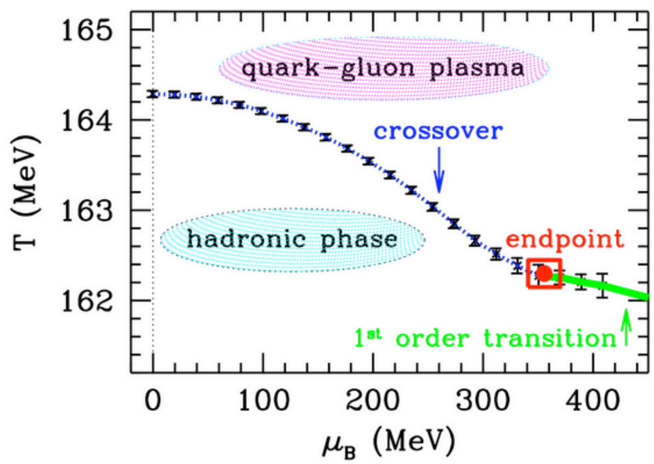
Lattice QCD - Issues with numerical computation (quark determinant being complex for non-zero μ). Ways to handle it exists. Results on QCP available.

Race between theory and experiment to locate QCP.

Theoretical Status of QCP

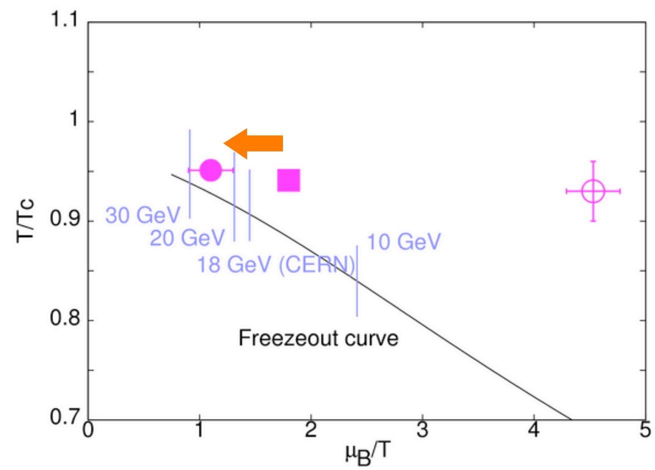
Reweighting | Taylor Expansion

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



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

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

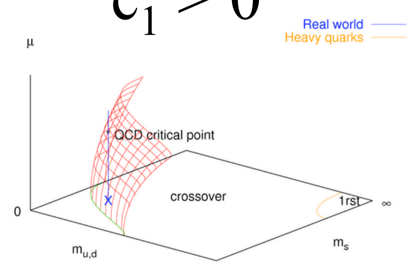
Imaginary Chemical Potential

$$\frac{m_c(\mu)}{m_c(0)} = 1 + \sum_{k=1} c_k \left(\frac{\mu}{\pi T}\right)^{2k}$$

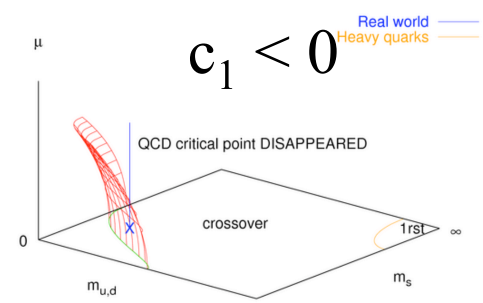
n_f = 2+1 continuum limit ?
Spatial volume, stable results for different N_t ?

P. De Forcrand and O. Philipsen PoS LATTICE2008, 208 (2008)

$c_1 > 0$



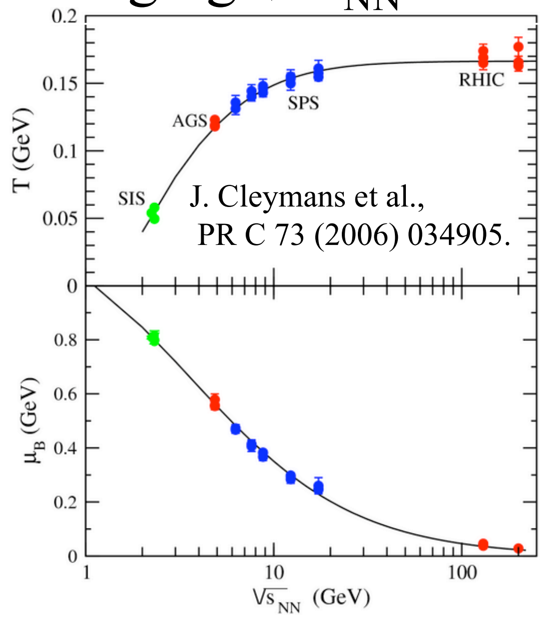
$c_1 < 0$

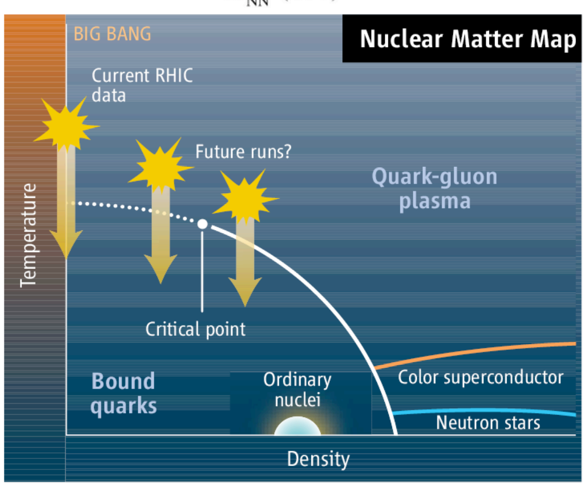


Experimental Search/Observable For QCP

Experimental Plan:

Changing $\sqrt{s_{NN}}$ varies T and μ_B





www.sciencemag.org SCIENCE VOL 312 14 APRIL 2006

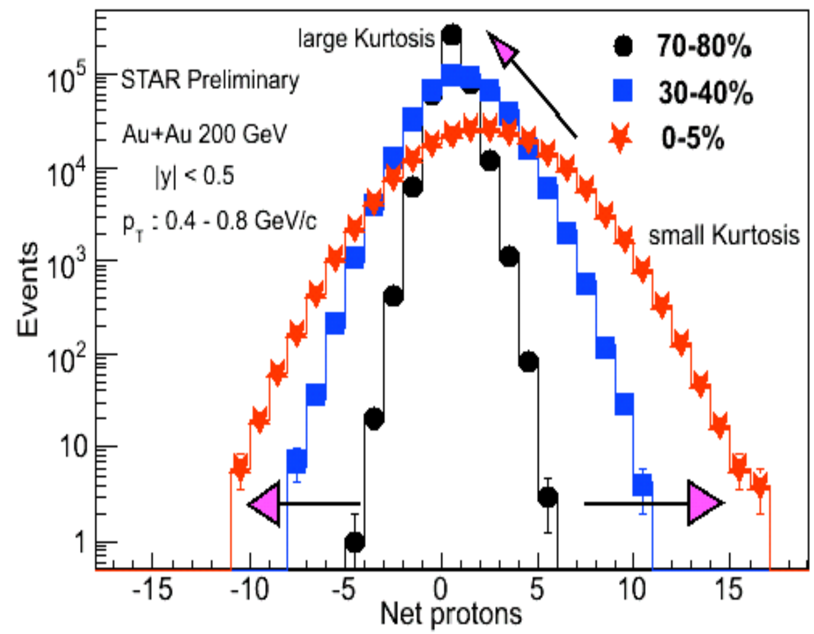
Published by AAAS

One of the Observable:

High Moments of net-protons

Approximates Net-Baryons a conserved quantity.

Experimentally measurable



$$\sigma = \sqrt{<(N-<N>)^2>} \qquad s = \frac{<(N-<N>)^3>}{\sigma^3}$$

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

Higher Moments of Net-Protons

Net-proton Number Fluctuations

~ Singularity in charge and baryon Number susceptibilities

$$Q = B/2 + I_3$$

$$\chi_Q \sim (1/VT) < (\delta Q)^2> = (1/4)\, \chi_B + \chi_I$$
$$\sim (1/VT) < \delta\, (N_{p\text{-}pbar})^2>$$

iso-spin blindness of σ field

Y. Hatta et al,PRL 91, 102003 (2003)
M. A. Stephanov, PRL 102, 032301 (2009)
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 ~ $\chi^{(4)}/ [\chi^{(2)}\, T^2]$

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

R. Gavai & S. Gupta, arXiv:1001.3796

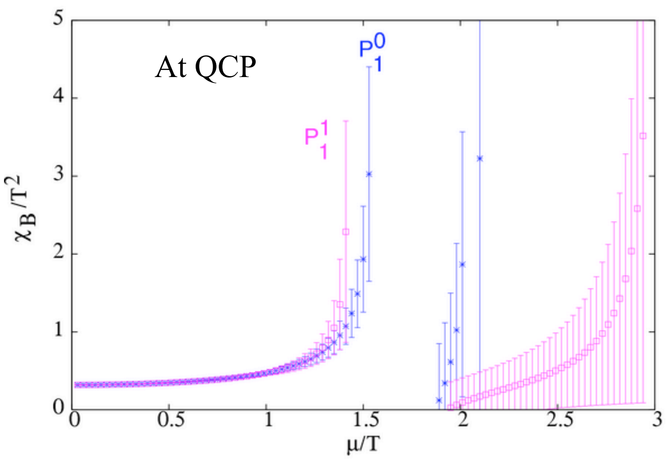
Distributions non Gaussian at QCP

Moments and Correlation length (ξ)

$$< (\delta N)^2> \sim \xi^2 \qquad < (\delta N)^3> \sim \xi^{4.5}$$
$$< (\delta N)^4> - 3 < (\delta N)^2>^2 \sim \xi^7$$

Value limited in heavy-ion collisions
Finite size effects ξ < 6 fm
Critical slowing down, finite time effects ξ ~ 2 - 3 fm

Higher moments higher sensitivity

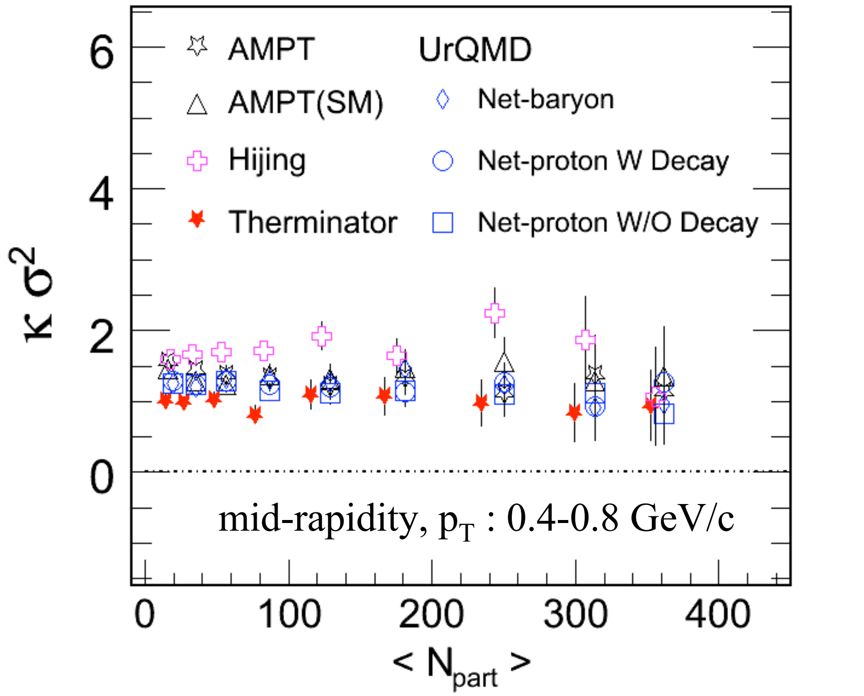


Non monotonic variation of products of higher moments with beam energy

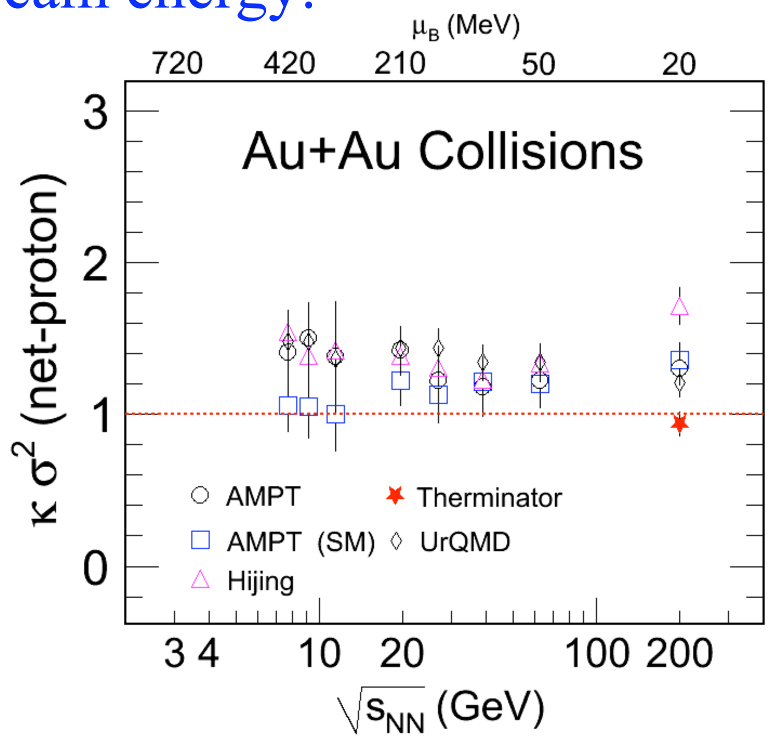
Observable: Net-protons & Non QCP Physics

Collision centrality:

Au+Au 200 GeV



Beam energy:



Kurtosis x Variance: (Desirable features for QCP 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

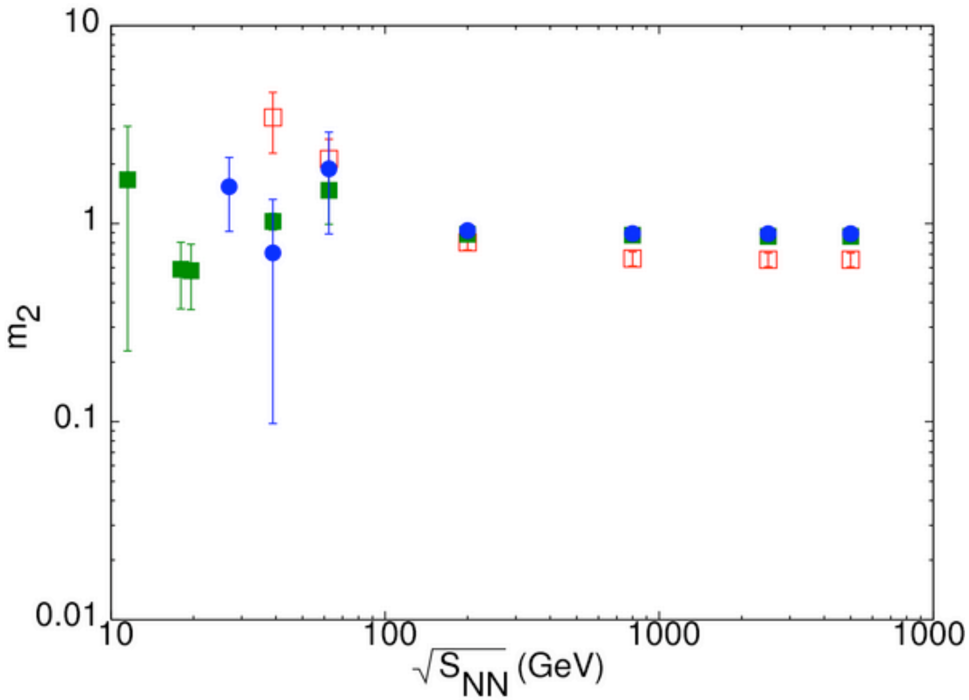
o Similar values for Transport, Mini-jets, Coalescence models

o Unity for Thermal model

Observable: Connection to QCD Calculations

Lattice QCD:

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



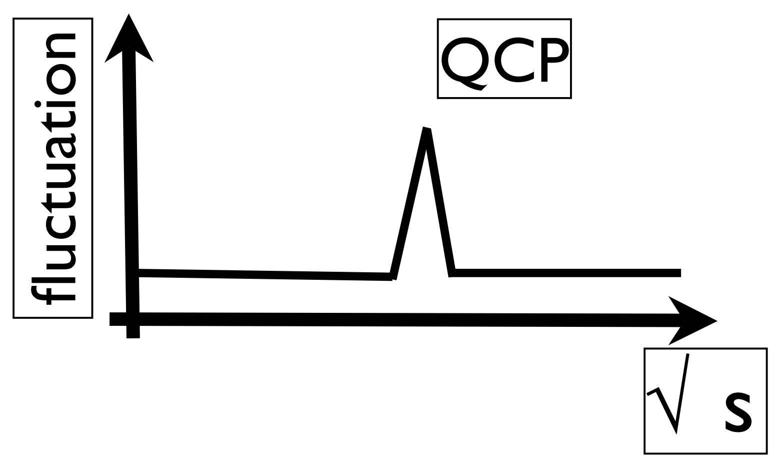
m_2 equivalent to Kurtosis x Variance

At QCP : Systems falls out of equilibrium will lead to deviations from Lattice QCD

QCP Model:

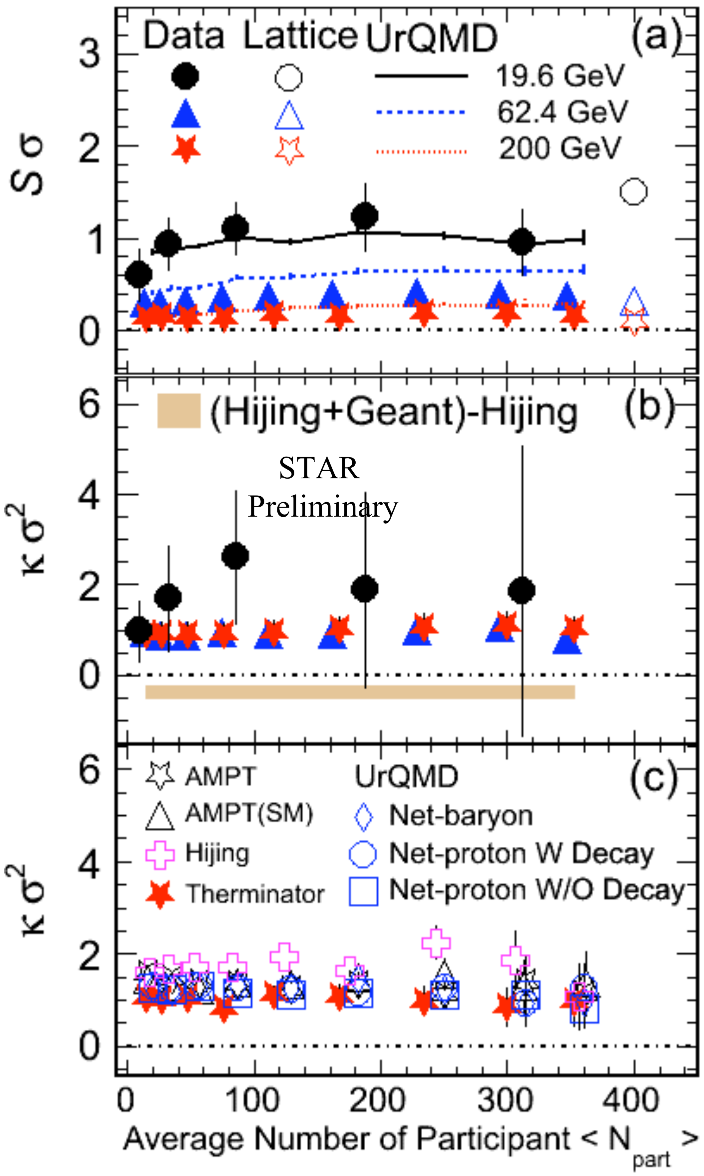
(C. Athanasiou,M. Stephanov, K. Rajagopal, PRL 102 (2009) 032301)

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



Products of Moments of Net-proton Distributions

STAR: Au+Au, mid-rapidity, p_T : 0.4-0.8 GeV/c



Observations: (μ_B : 20 - 200 MeV)

o Products of moments constants a function of collision centrality, expected from Central Limit Theorem (CLT)

o Good Agreement with non-QCP models

o With large errors, values comparable to Lattice QCD (R. Gavai & S. Gupta arXiv:1001.3796)

o Values lower than predicted by QCP models

o Detector effects small

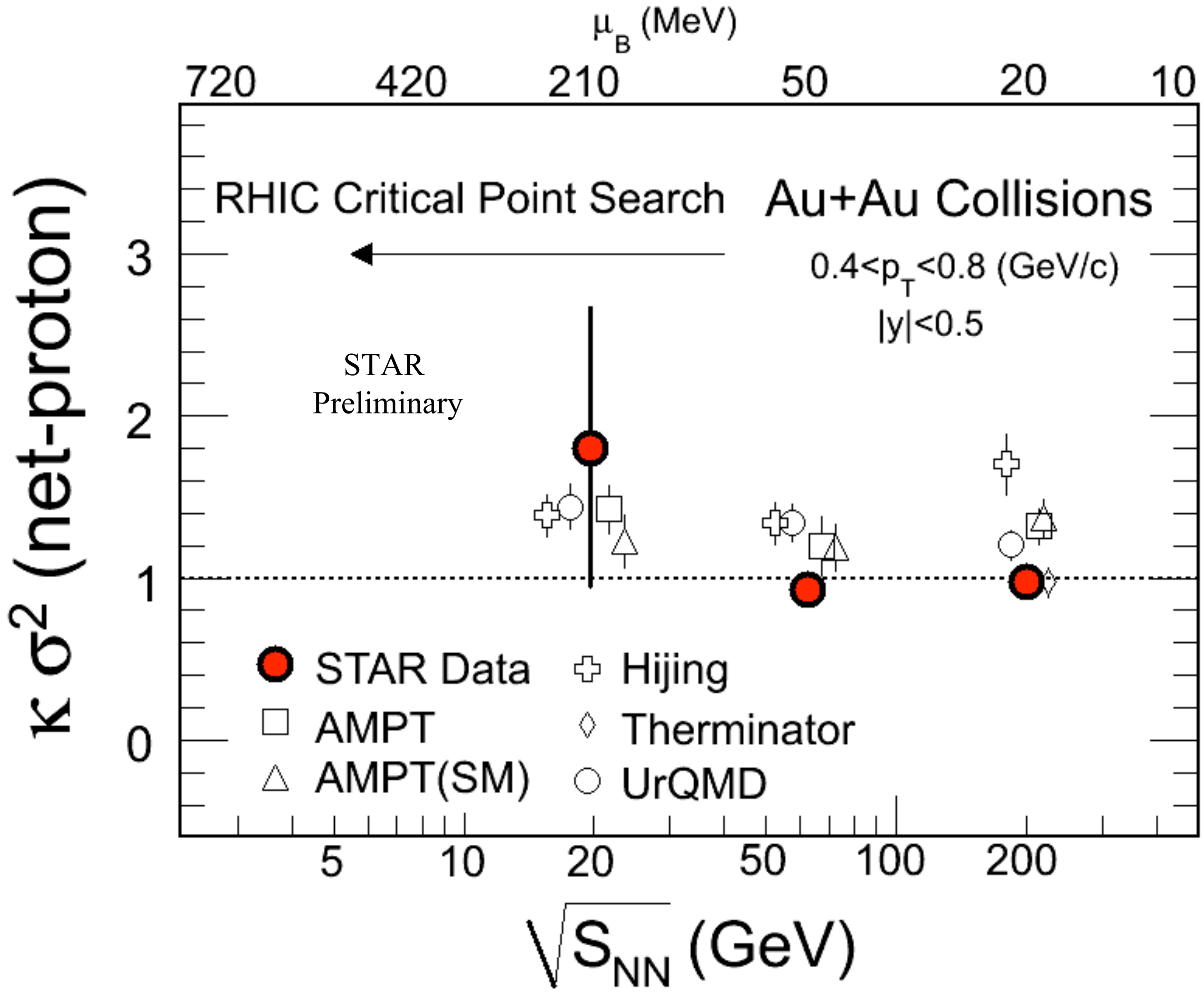
At QCP expect:

o Deviation from Lattice QCD values

o Close agreement with QCP Models

o Violation of N_{part} scaling

Where could be the QCD Critical Point ?



Observations:

- o $\kappa\sigma^2$ constant as function of beam energy
- o Good agreement with non-QCP model
- o QCP models predict values of $\kappa\sigma^2$ atleast factor of 2 times more than measurements

Current observations indicate QCP not located for μ_B < 200 MeV

RHIC BES Program

Goals:

QCD Phase boundary

QCD Critical Point

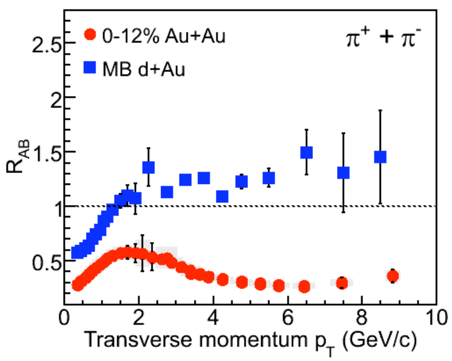
RHIC running below injection energy

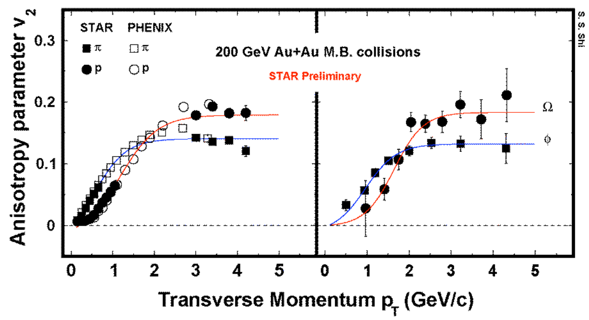
$\mu_B \sim 100 - 550$ MeV

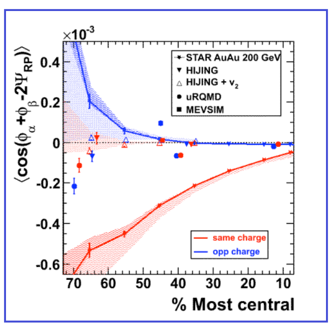
Energy (GeV)	Confirmed/ Expected
7.7	2010
11.5	2010
18	2011
27	2011
39	2011
62.4	2010
5	2010 (Test)

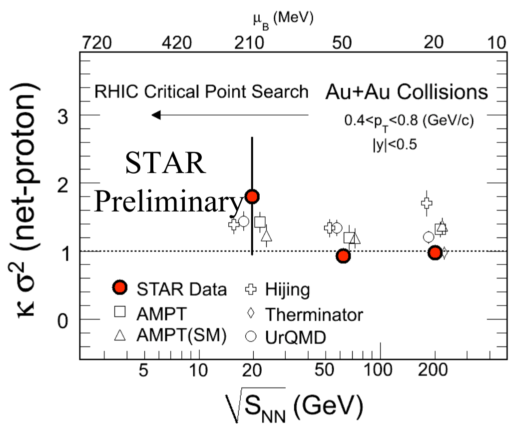
QCD Phase boundary

Onset of various observations: Examples









QCD Critical Point: non-monotonic energy dependence of Fluctuations

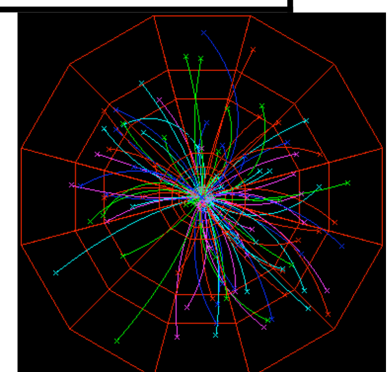
Capabilities:

Demonstrated by Collider and Experiment

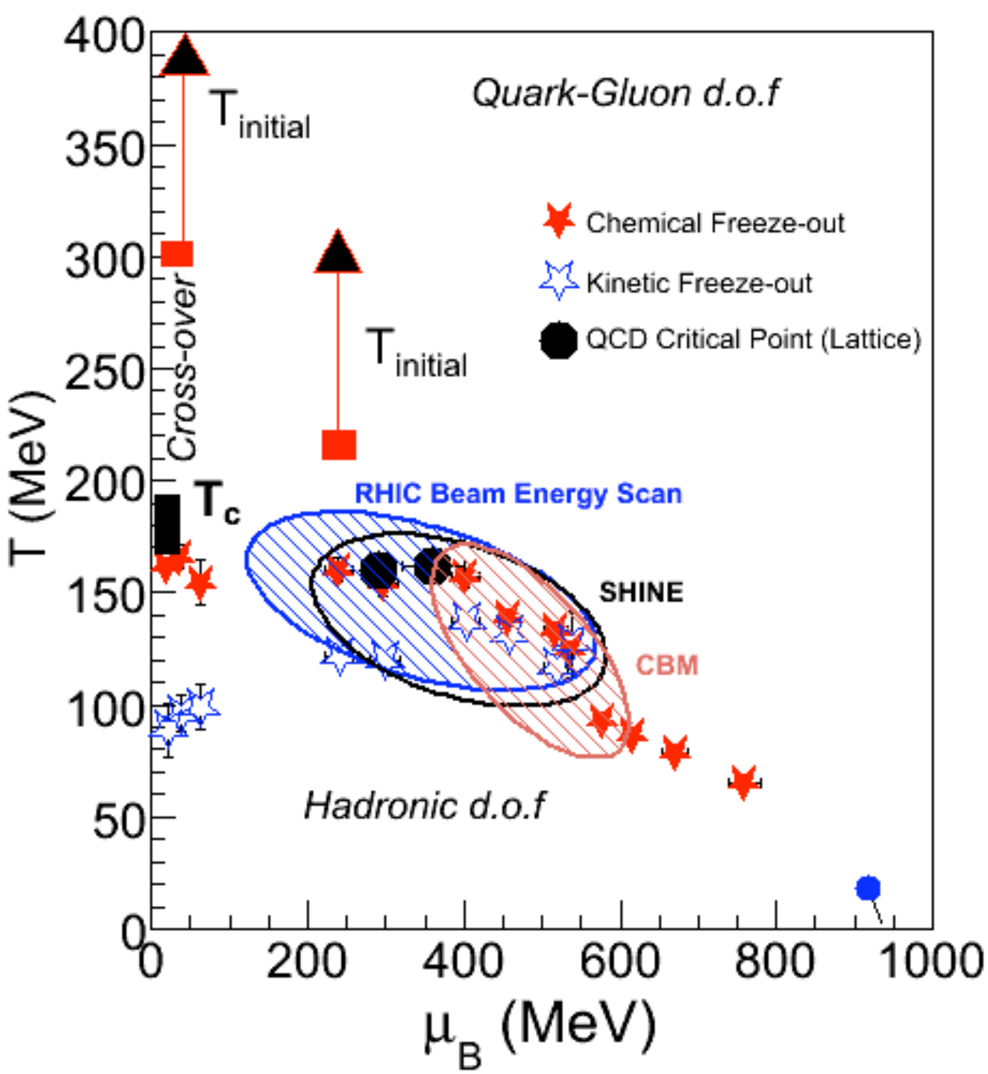
-9.2 GeV,2008 -

-Results published in PRC

- arXiv:0909.4131



Summary: QCD Phase Diagram



LHC: ALICE talk by T.K. Nayak

Lattice and other QCD based models :

μ_B = 0 - Cross-over (~ LHC)

T_C ~ 170-195 MeV

μ_B > 160 MeV - QCD critical point

Experiments :

Relevant d.o.f are quark and gluons

[$T_{initial}$(direct photons) > T_C(Lattice)]

(*Talk by D. K. Srivastava*)

Collectivity at partonic level observed

Measured the chemical and kinetic freeze-out points

Future programs@ RHIC, SPS, FAIR,NICA

Characterizing matter at varying baryon density

Finding QCD critical point

Locating QCD phase boundary

LHC: Detail properties of QGP and more closely resembles early universe