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# Study of the QCD Phase Diagram Using High Energy Nuclear Collisions

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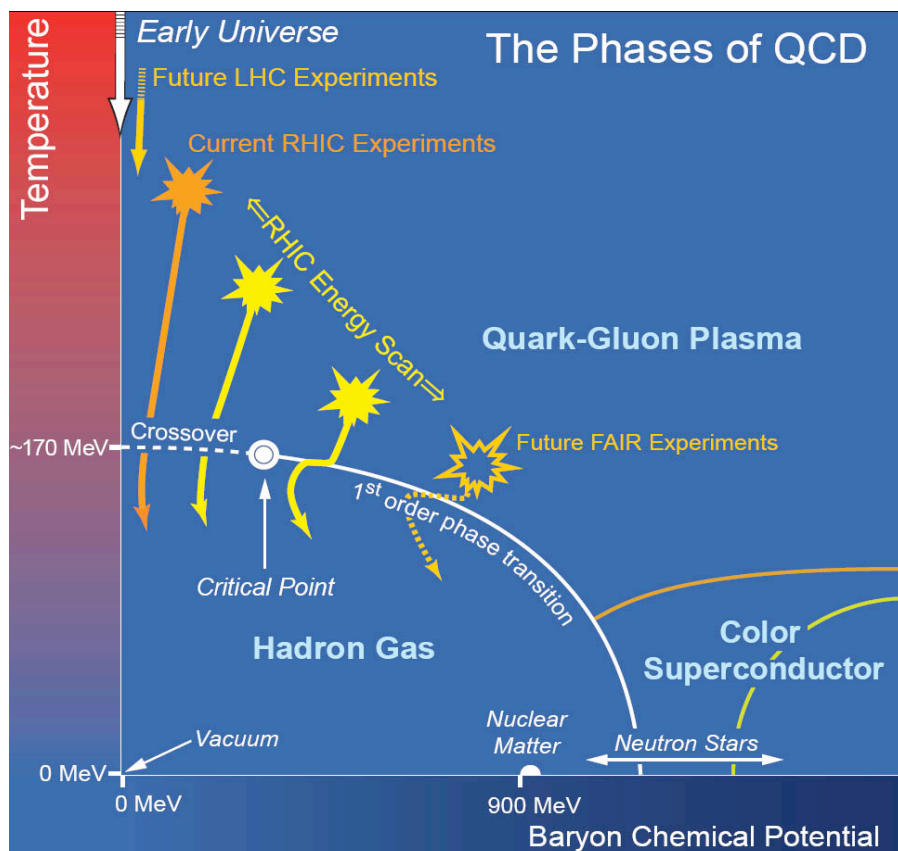
## Outline

- ❖ 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.

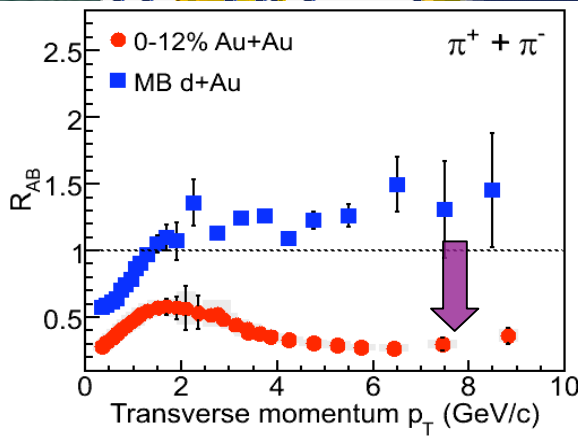
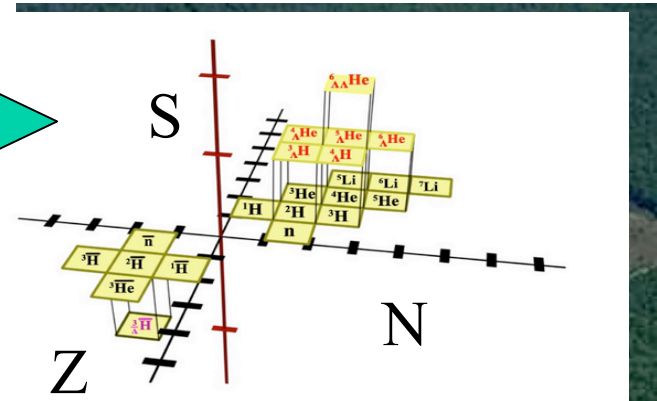
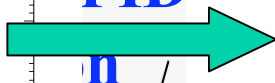
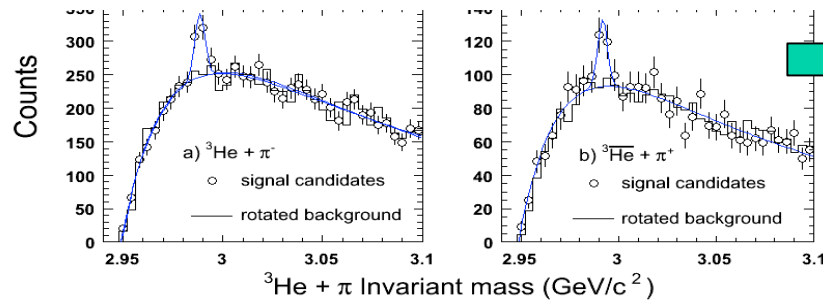
STAR: Nucl. Phys. A757, (2005) 102

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

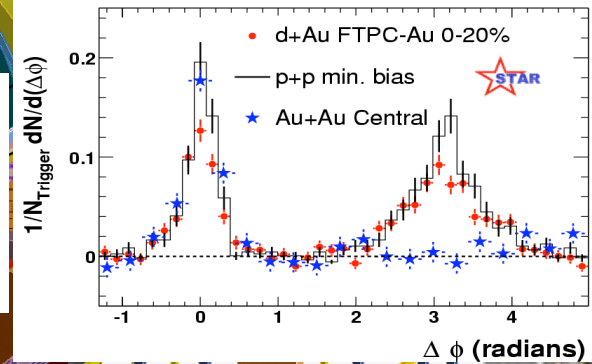
The only phase transition among those occurring in early universe to be accessible in laboratory.

# RHIC: Discovery Machine

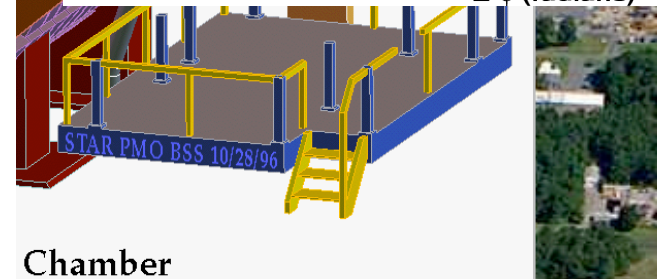
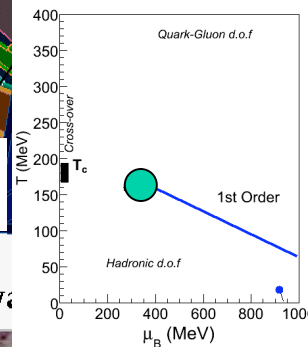
## First Observation of Anti-strange Matter



## Observation of Jet Quenching and Partonic matter



## QCD Critical Point ?



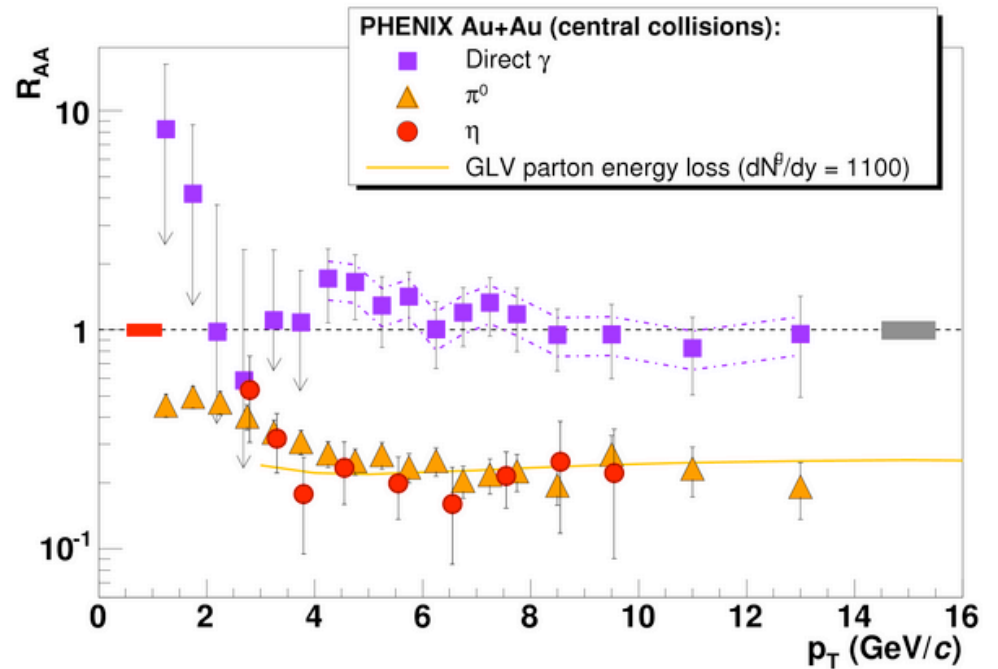
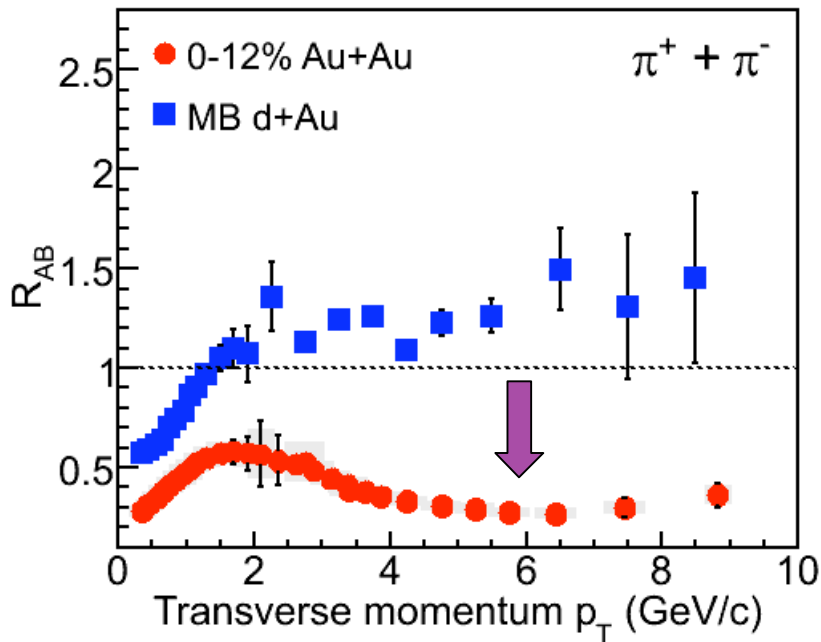
Dedicated facility for high energy nucleus-nucleus collisions

<http://www.bnl.gov/rhic>

# Partonic Matter at RHIC

Observations:

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



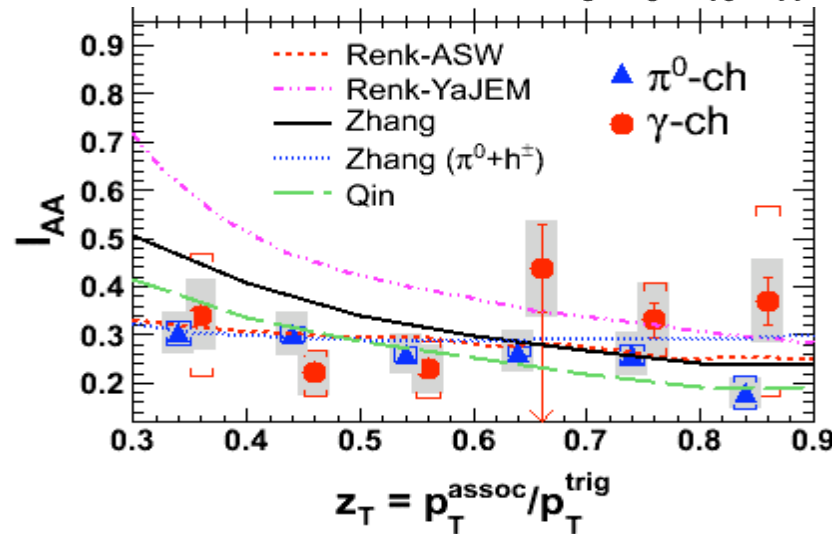
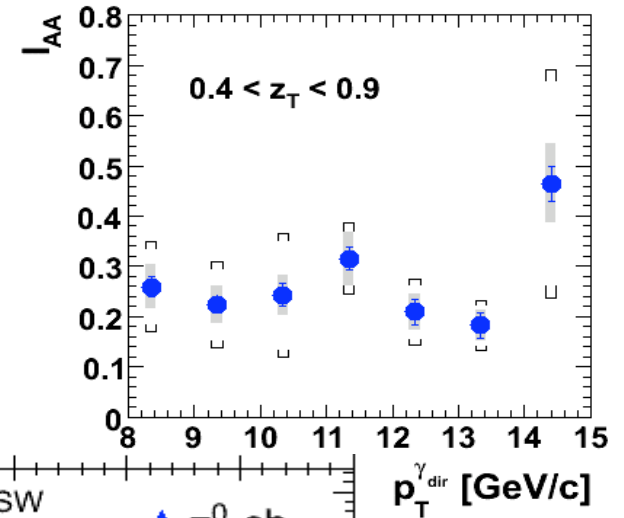
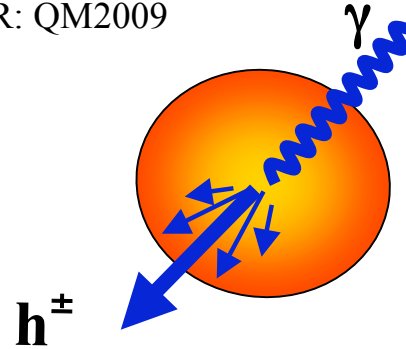
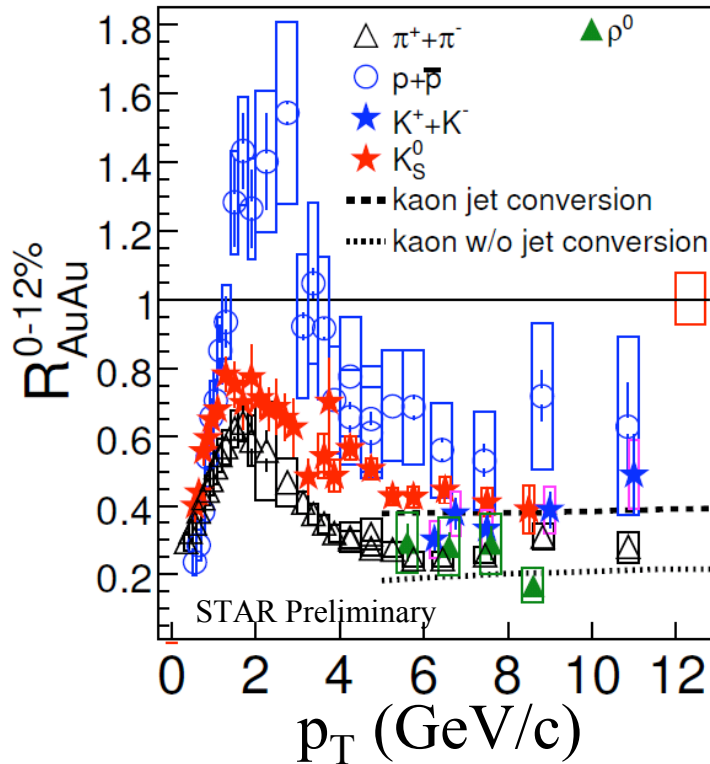
Interpretation : Energy loss of partons in a dense medium

$$\epsilon_{initial} > \epsilon_C \text{ (Lattice QCD)}$$

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

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

# Strong Interactions at RHIC



$E_{loss} \sim \text{Func}(\text{Color Factor}, \text{Path Length}, \text{Medium Density} \dots)$

q vs.g  $E_{loss}$ : Naïve expectations  $R_{AA}(pbar) < R_{AA}(\pi)$

q,g jet conversions: Model expectations  $R_{AA}(K) > R_{AA}(\pi)$

Path length dependence: Simple expectations  $I_{AA}(\gamma_{dir}) < I_{AA}(\pi^0)$

Dependence on initial parton energy: Study  $E_{loss}$  vs.  $E(\gamma_{dir})$

# Possible Local Parity Violation in Strong Interactions

P/CP invariance globally in strong interactions.

Experimentally: Neutron Electric Dipole Moment expts.

Pospelov, Ritz, PRL83 (1999) 2526

Baker et al., PRL97 (2006) 131801

Topological Structure of QCD Vacuum  $\implies$  Local Parity Violations

## Mechanism:

Mass less quarks can change Chirality  
by interacting with gluons

Causing  $N_L \neq N_R \implies$  P Violation

## Observable:

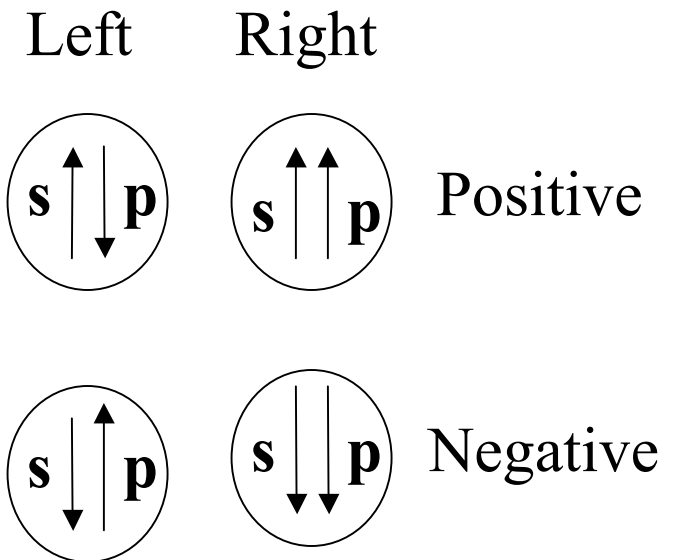
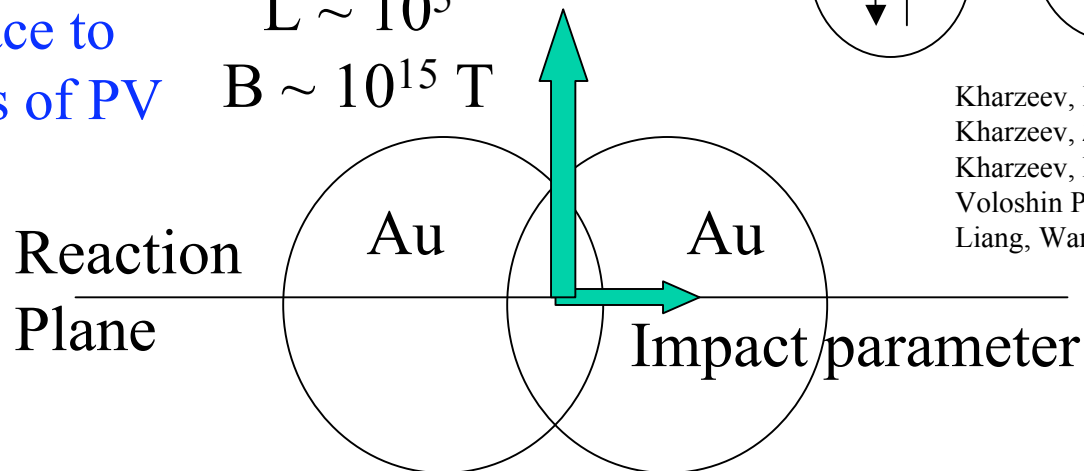
Magnetic field align quark spins

Causing charge separation along B

RHIC good place to  
look for signals of PV

$$L \sim 10^5$$

$$B \sim 10^{15} \text{ T}$$



Kharzeev, PLB633 (2006) 260

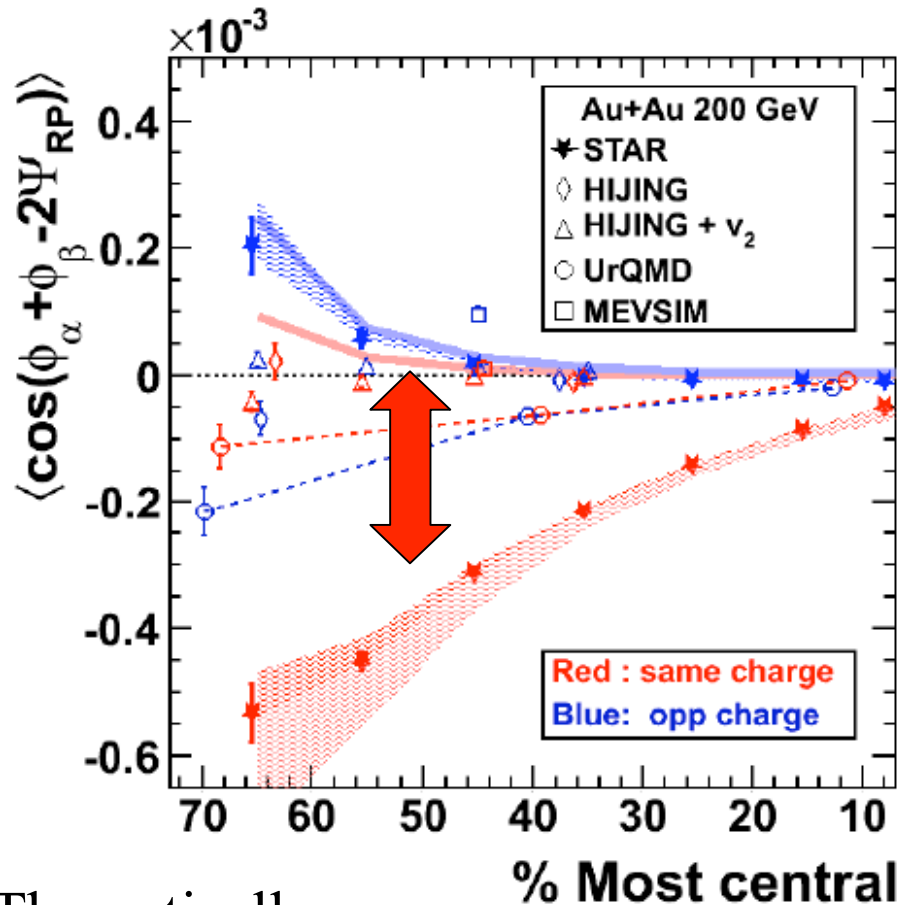
Kharzeev, Zhitnitsky, NPA797 (2007) 67

Kharzeev, McLerran, Warringa, NPA803 (2008) :

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

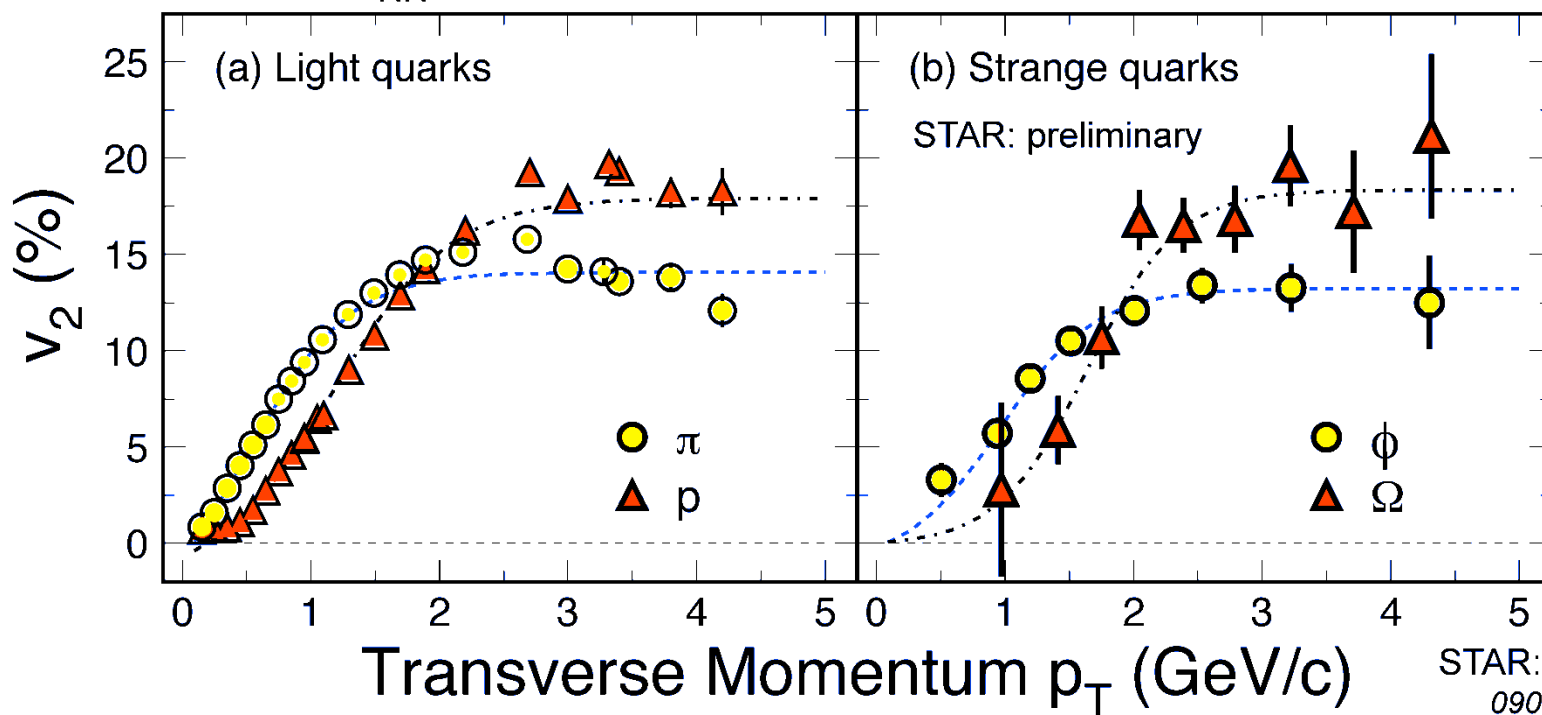
Theoretically:

- 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

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



PHENIX  $\pi$  and  $p$ : nucl-ex/0604011v1

- Low  $p_T$  : Heavier hadrons have lower  $v_2$  ( $\sim$  hydrodynamic pattern)
- High  $p_T$  : Collectivity grouped along baryon-meson lines  
( $\sim$  Hadronization by partonic recombination)
- All  $p_T$  : Collectivity similar for hadrons with strange and light quark  
( $\sim$  developed at partonic stage)

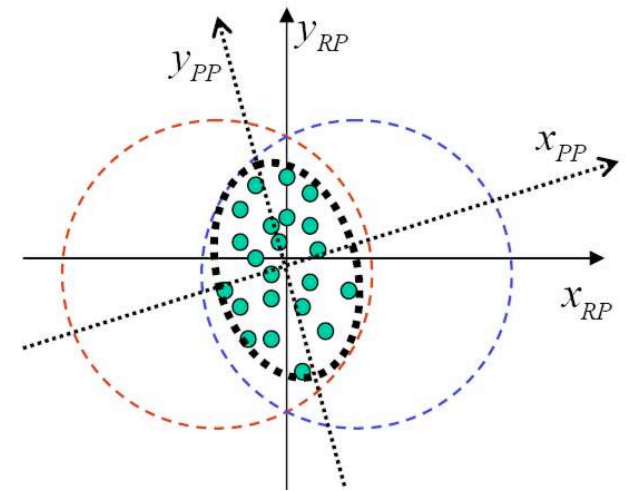
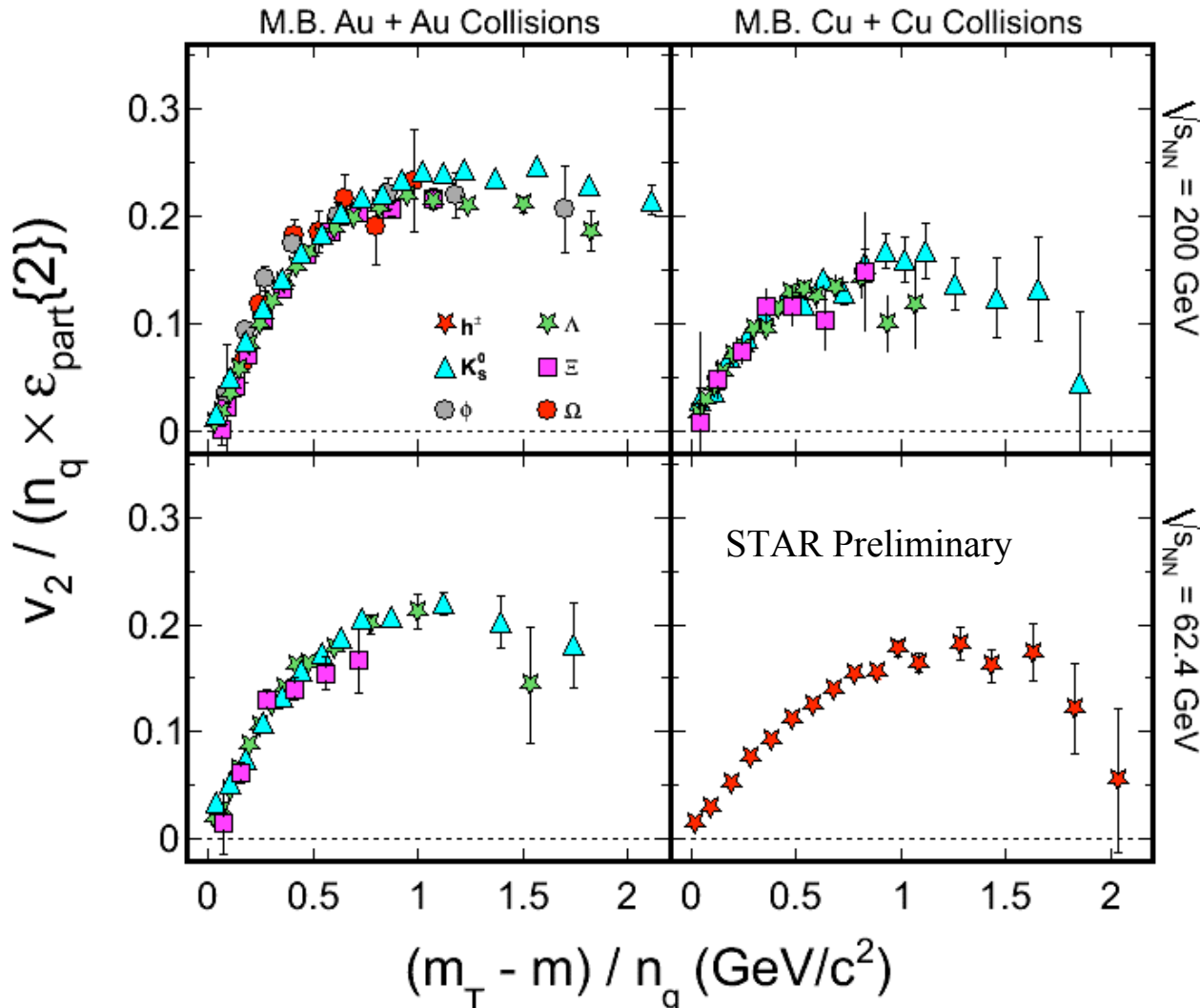


# Collectivity Developed at Partonic Stage

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

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

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



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

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

# Summary On Partonic Matter Formation At RHIC

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## 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

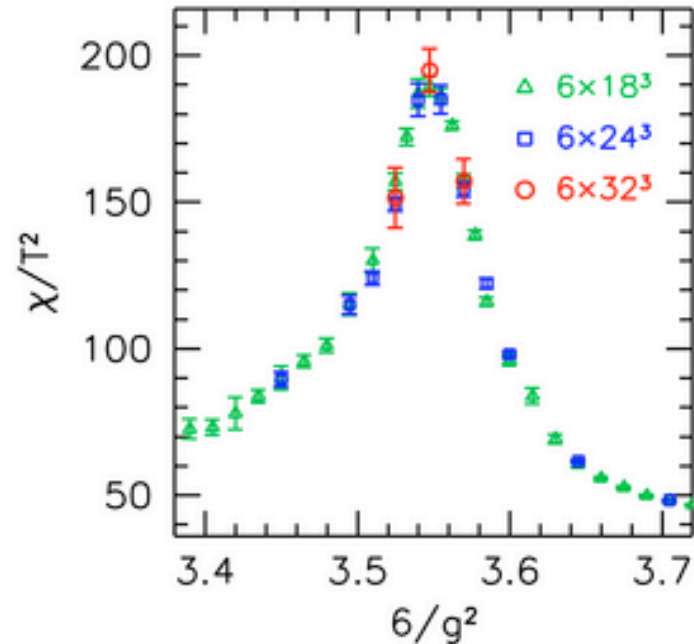
## Collectivity:

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

Future: heavy quark collectivity to experimentally study thermalization.

# Order Of The Quark-Hadron Transition

$$\mu_B = 0$$

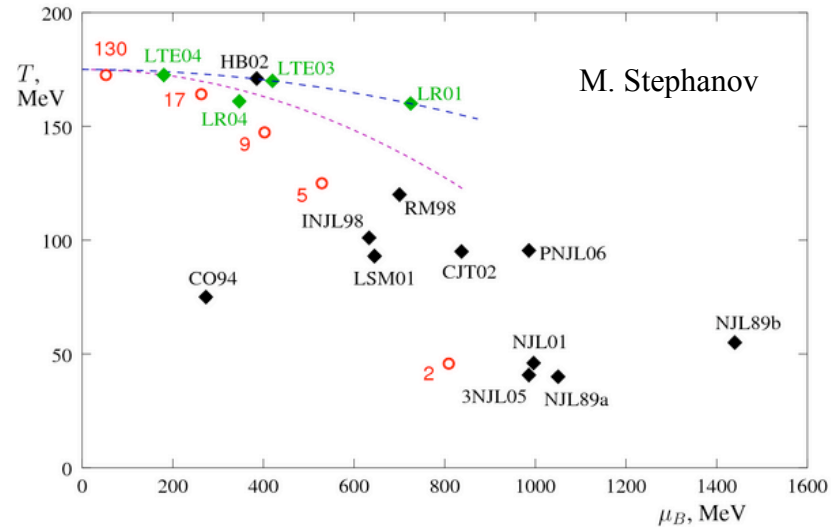


$$\chi(N_s, N_t) = \partial^2 / (\partial m_{ud}^2) (T/V) \cdot \log Z$$

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

$$\mu_B > 0$$

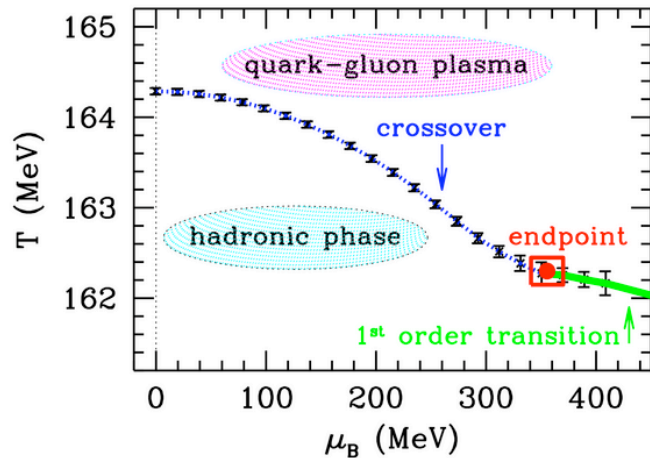


QCD models - 1<sup>st</sup> order phase transition, QCP location uncertain

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

Race between theory and experiment to locate QCP.

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



$$T_E = 162 \pm 2 \text{ MeV}$$

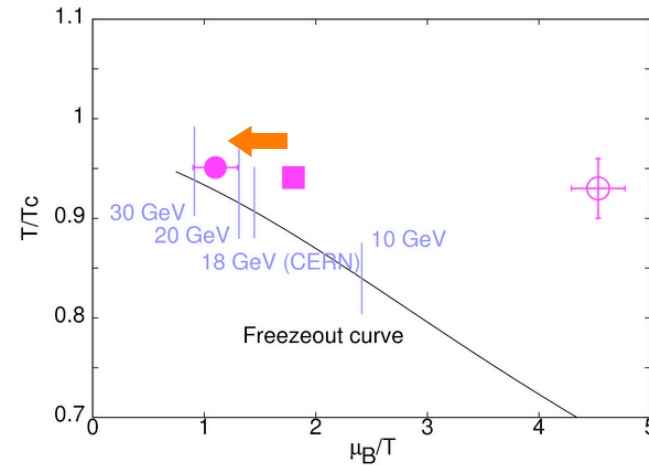
$$\mu_E = 360 \pm 40 \text{ MeV}$$

## 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  $N_t$ ?

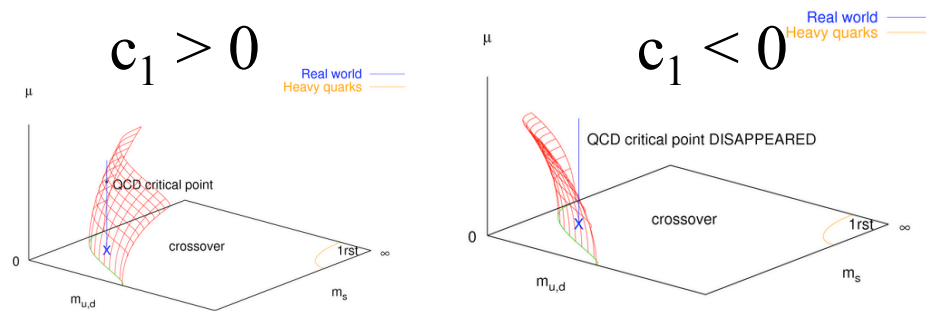
R. Gavai and S. Gupta Phys. Rev. D 78, 14503 (2008)



$$T_E/T_C = 0.94 \pm 0.01$$

$$\mu_E/T_E = 1.8 \pm 0.1$$

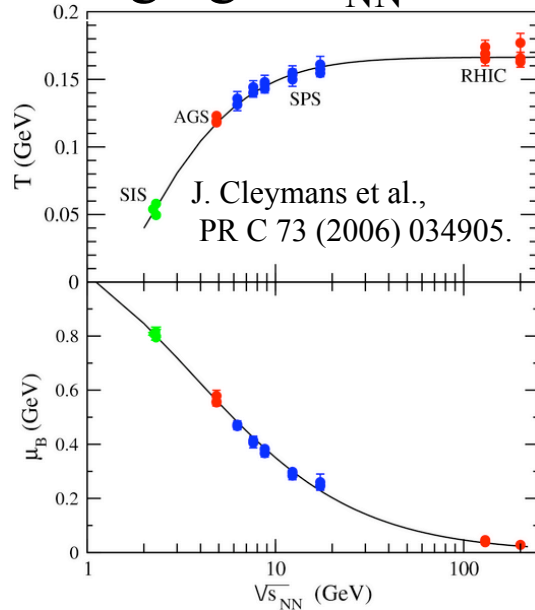
P. De Forcrand and O. Philipsen PoS LATTICE2008, 208 (2008)



# Experimental Search/Observable For QCP

## Experimental Plan:

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

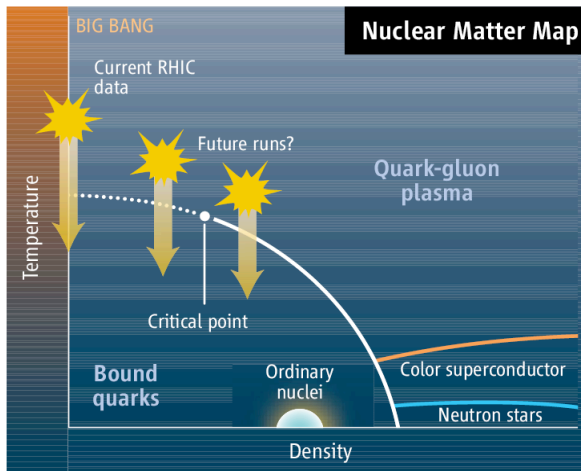
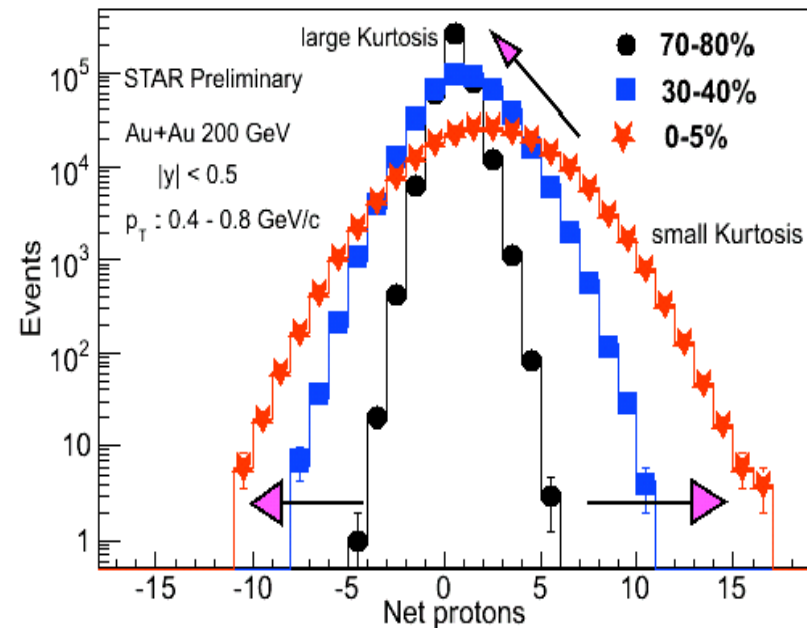


## One of the Observable:

High Moments of net-protons

Approximates Net-Baryons a conserved quantity.

Experimentally measurable



$$\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle} \quad s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

$$K = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$

# Higher Moments of Net-Protons

## Net-proton Number Fluctuations

~ Singularity in charge and baryon  
Number susceptibilities

$$Q = B/2 + I_3$$

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

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

## iso-spin blindness of $\sigma$ 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

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

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

R. Gavai & S. Gupta, arXiv:1001.3796

## Distributions non Gaussian at QCP

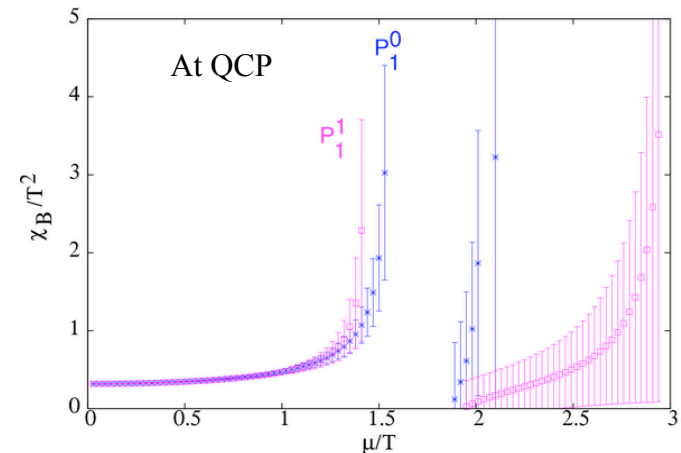
### Moments and Correlation length ( $\xi$ )

$$\langle (\delta N)^2 \rangle \sim \xi^2 \quad \langle (\delta N)^3 \rangle \sim \xi^{4.5}$$

$$\langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \sim \xi^7$$

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



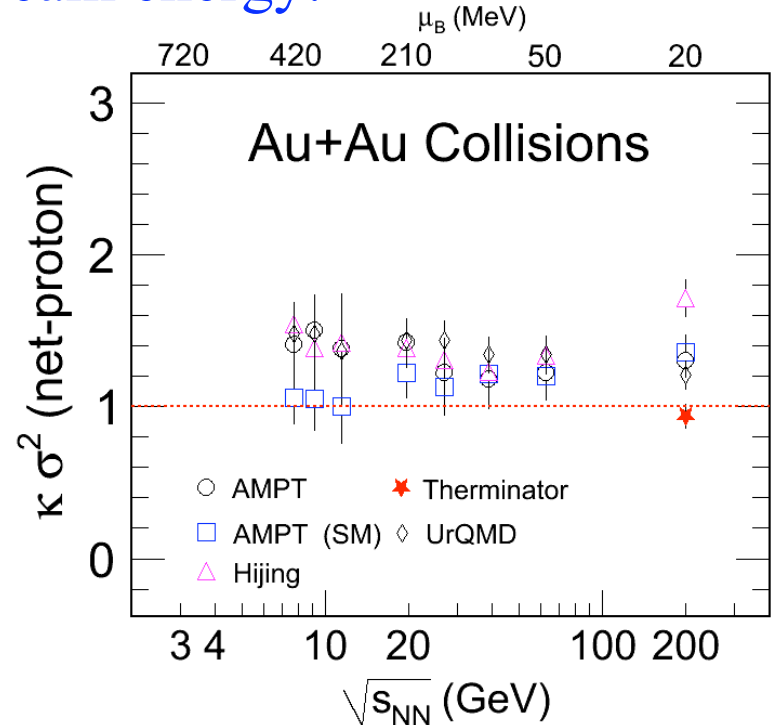
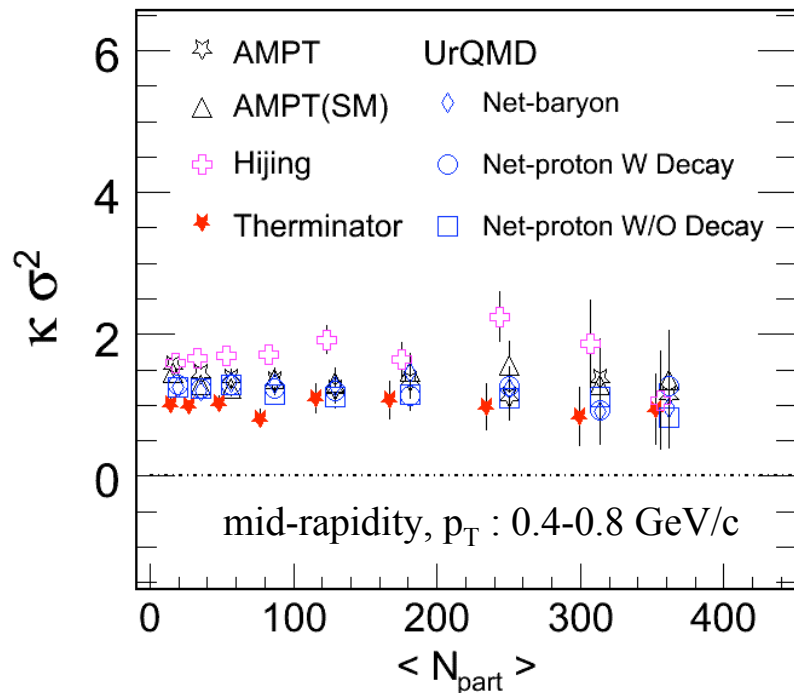
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Non monotonic variation of products of higher moments with beam energy

# Observable: Net-protons & Non QCP Physics

Collision centrality: Au+Au 200 GeV

Beam energy:



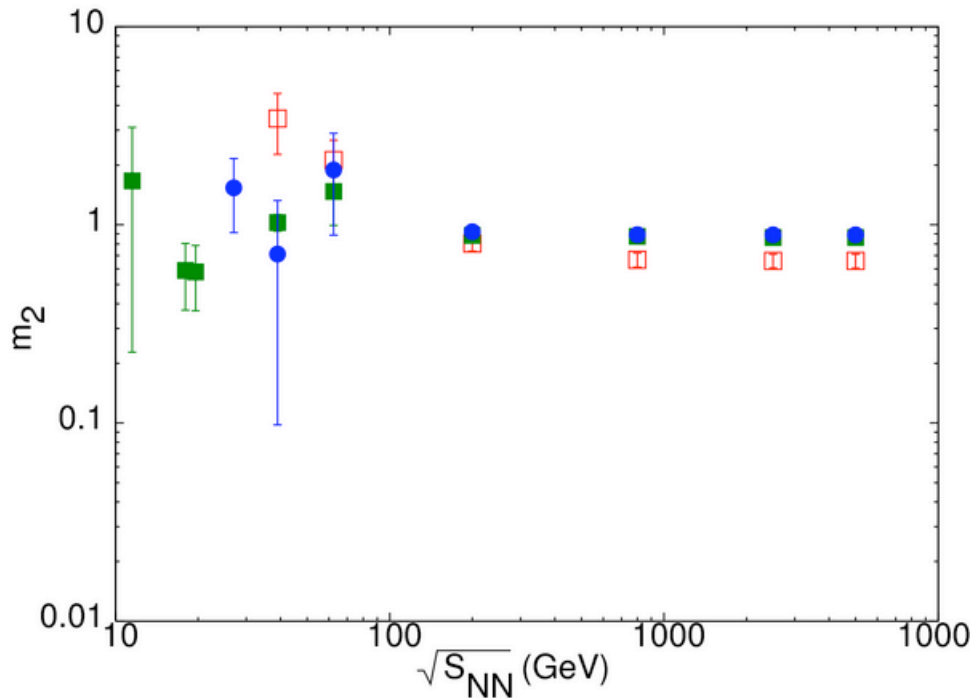
## Kurtosis x Variance: (Desirable features for QCP Search)

- 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)

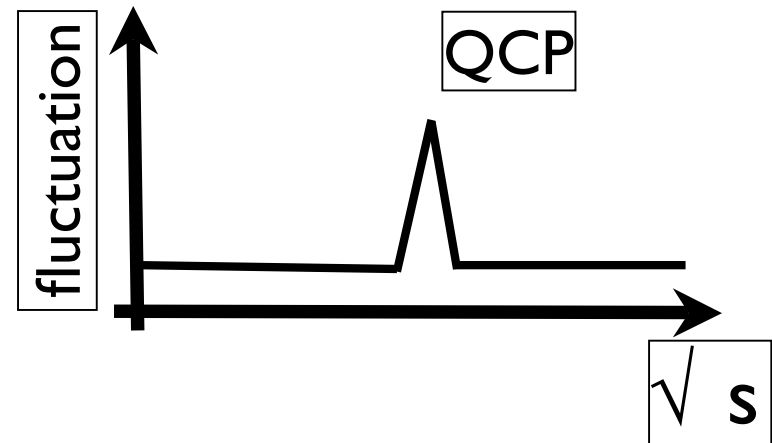


$m_2$  equivalent to Kurtosis x Variance  
 At QCP : Systems falls out of equilibrium will lead to deviations from Lattice QCD

## QCP Model:

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

Beam Energy (GeV)	Kurtosis x Variance (net protons) with $\xi \sim 3\text{fm}$ and QCP (No QCP $\sim 1$ )
200	$\sim 2.5$
62	$\sim 35$
19	$\sim 3700$
7.7	$\sim 29600$

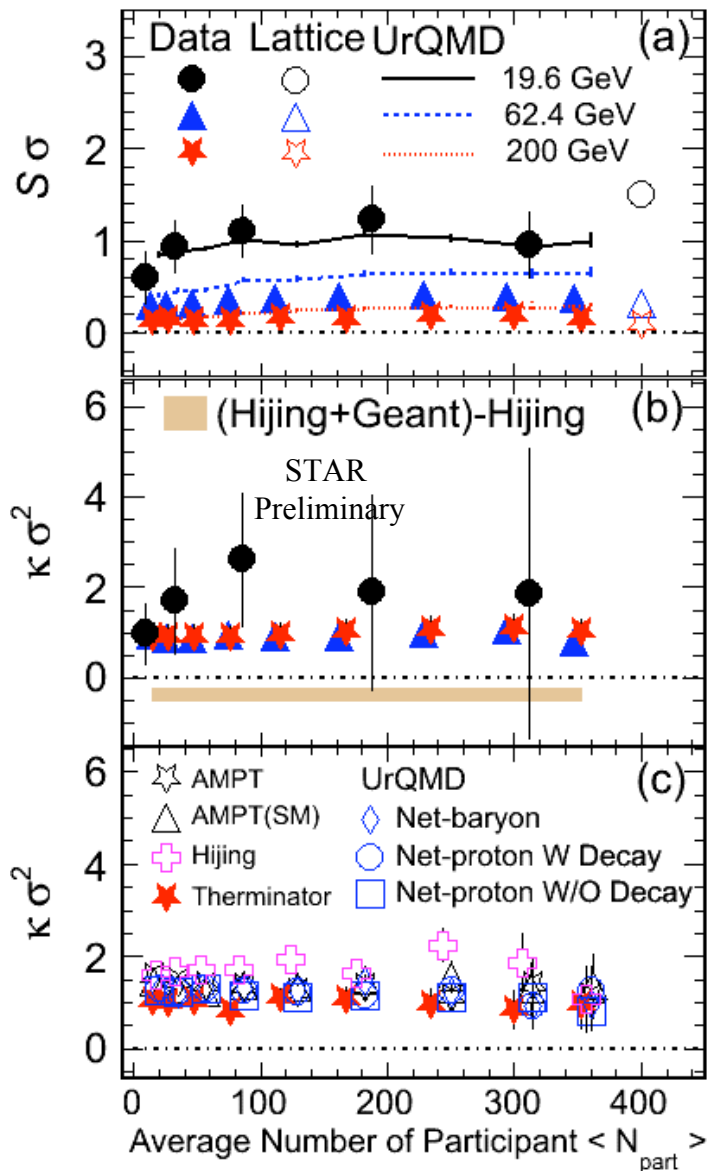




# Products of Moments of Net-proton Distributions

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

Observations: ( $\mu_B : 20 - 200$  MeV)

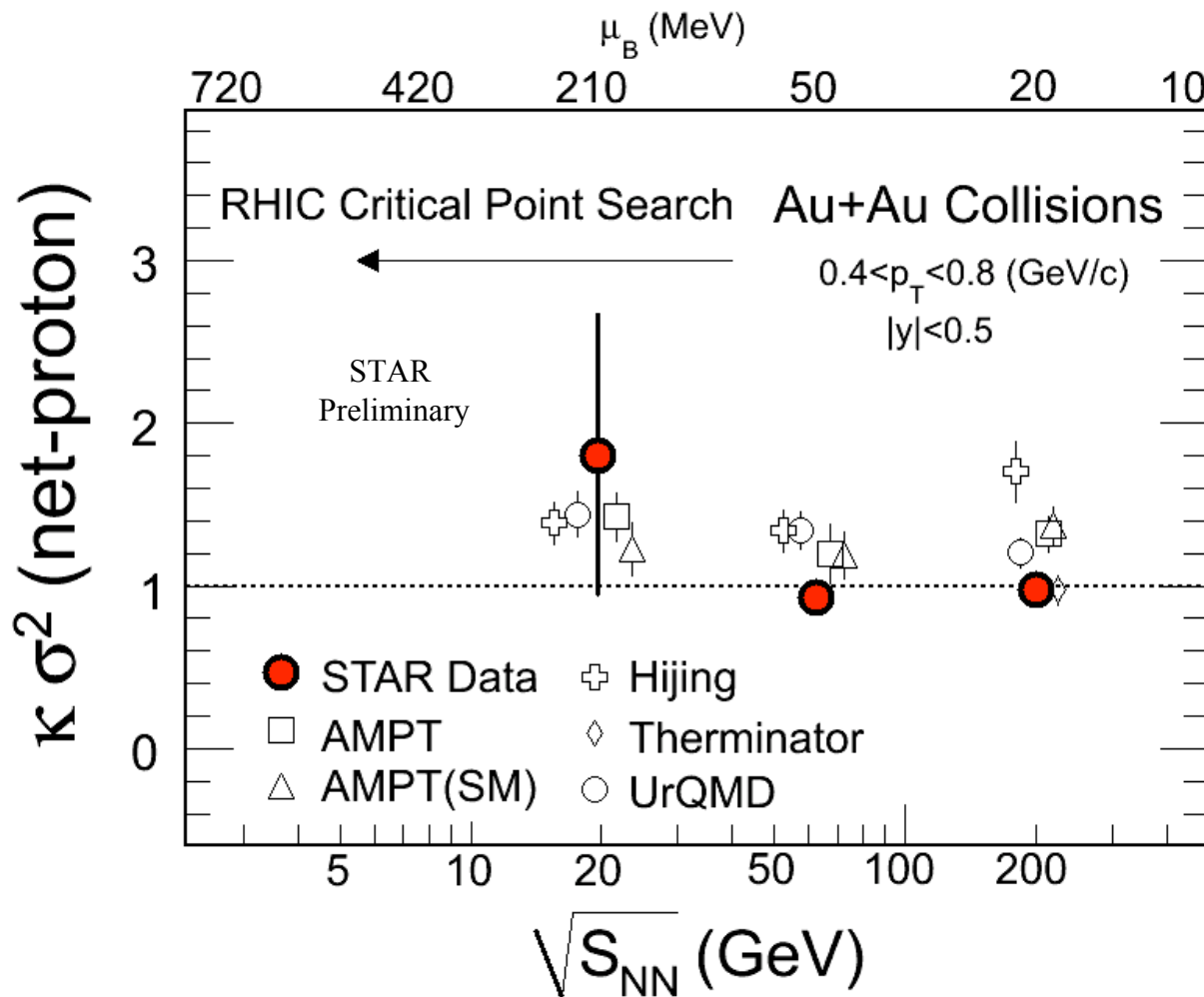


- o Products of moments constants a function of collision centrality, expected from Central Limit Theorem (CLT)
- o Good Agreement with non-QCP models
- o With large errors, values comparable to Lattice QCD (R. Gavai & S. Gupta arXiv:1001.3796)
- o Values lower than predicted by QCP models
- o Detector 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:

- κσ<sup>2</sup> constant as function of beam energy
- Good agreement with non-QCP model
- QCP models predict values of κσ<sup>2</sup> at least factor of 2 times more than measurements

Current observations indicate QCP not located for  $\mu_B < 200$  MeV

# RHIC BES Program

Goals:

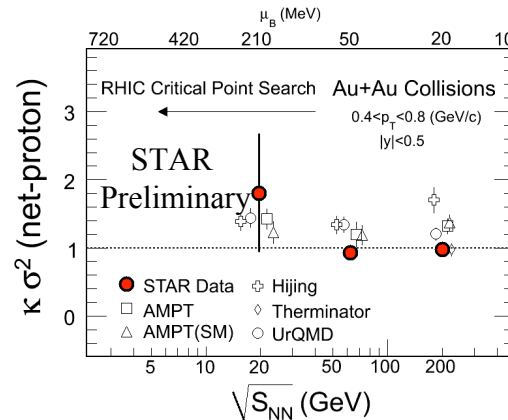
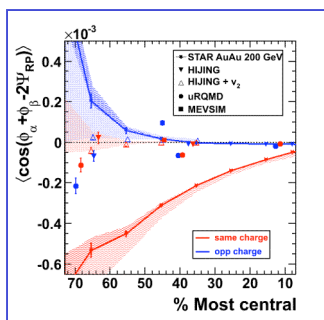
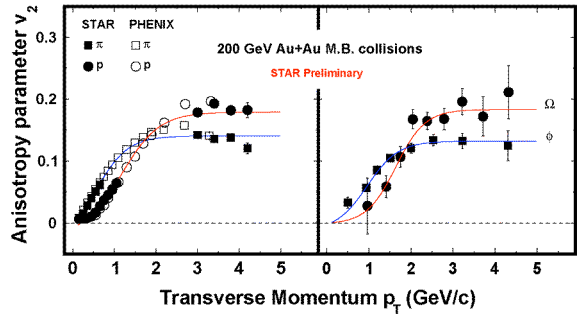
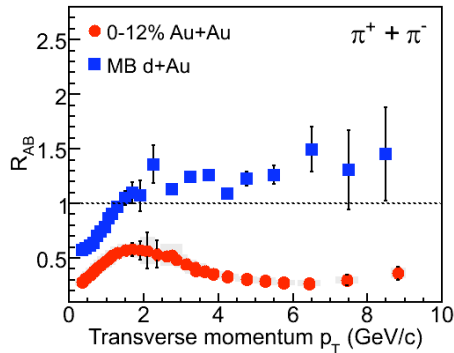
QCD Phase boundary  
QCD Critical Point

RHIC running below injection energy

$\mu_B \sim 100 - 550$  MeV

QCD Phase boundary

Onset of various observations: Examples



QCD Critical Point: **non-monotonic energy dependence of Fluctuations**

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

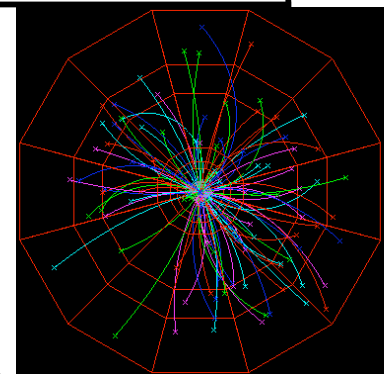
Capabilities:

Demonstrated by Collider and Experiment

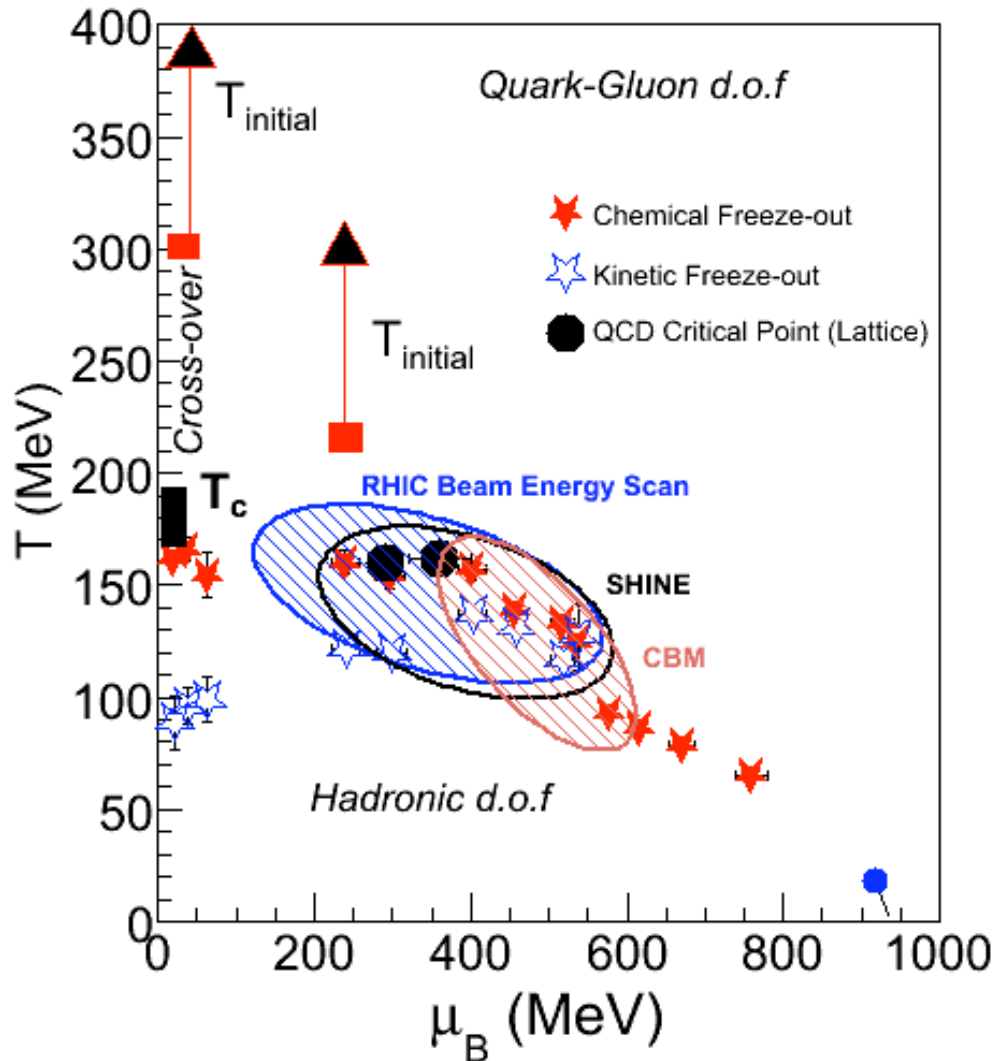
-9.2 GeV, 2008 -

-Results published in PRC

- arXiv:0909.4131



# Summary: QCD Phase Diagram



*LHC: ALICE talk by T.K. Nayak*

Lattice and other QCD based models :

$\mu_B = 0$  - Cross-over ( $\sim$  LHC)

$T_c \sim 170-195$  MeV

$\mu_n > 160$  MeV - QCD critical point

Experiments :

Relevant d.o.f are quark and gluons

[ $T_{\text{initial}}$  (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 <sup>20</sup>