# Study the QCD Phase Structure at RHIC

## Selected results from the RHIC Beam Energy Scan


Feng Liu

Xiaofeng Luo Shusu Shi Nu Xu

Institute of Particle Physics

Central China Normal University



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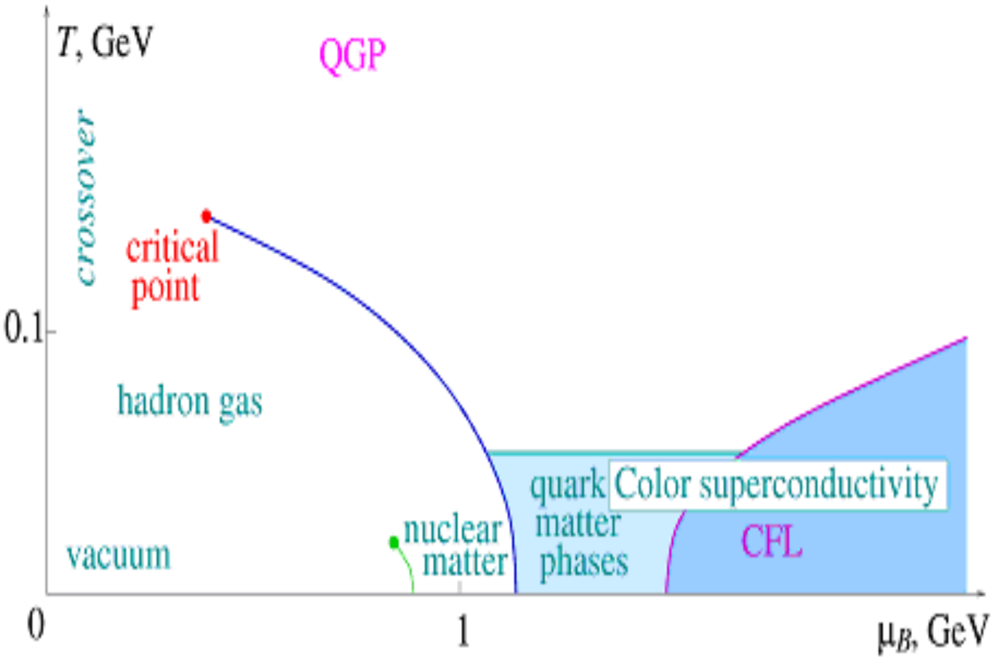
# Outline

- Introduction
- Experimental Observables
  - Elliptic flow
  - Higher Moments of Net-proton distributions
- Results and Discussion
- Summary and Outlook

# Explore the Phase Structure of Nuclear Matter




## Lattice QCD :

- Crossover at $\mu_B$ =0, 1st order phase transition at large $\mu_B$ .

Y. Aoki, et al., Nature 443, 675 ( 2006).
S. Gupta, et al. Science 332, 1525 (2011).
A. Bazavov et al, PRD 85, 054503 (2012).
Y. Aoki et al., JHEP 0906, 088 (2009) .

- QCD Critical Point (CP): The end point of first order phase transition boundary.

Z. Fodor, et al, JHEP04, 050 (2004) (hep-lat/0402006) M. A. Stephanov, Int. J. Mod. Phys. A 20, 4387 (2005) (hep-ph/0402115).

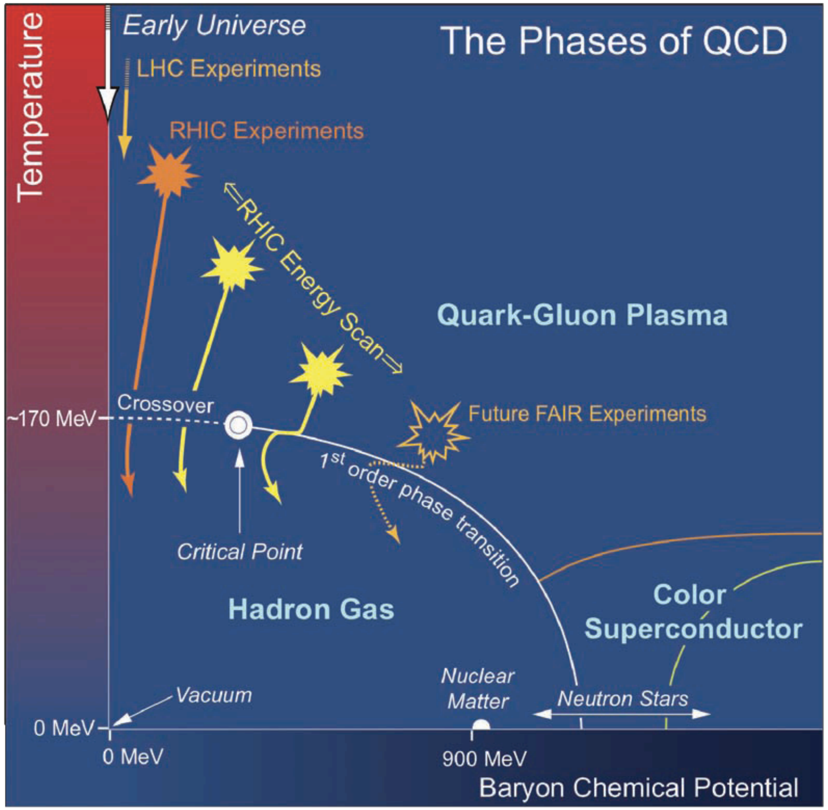
**Main Goals of Heavy Ion Collisions:**

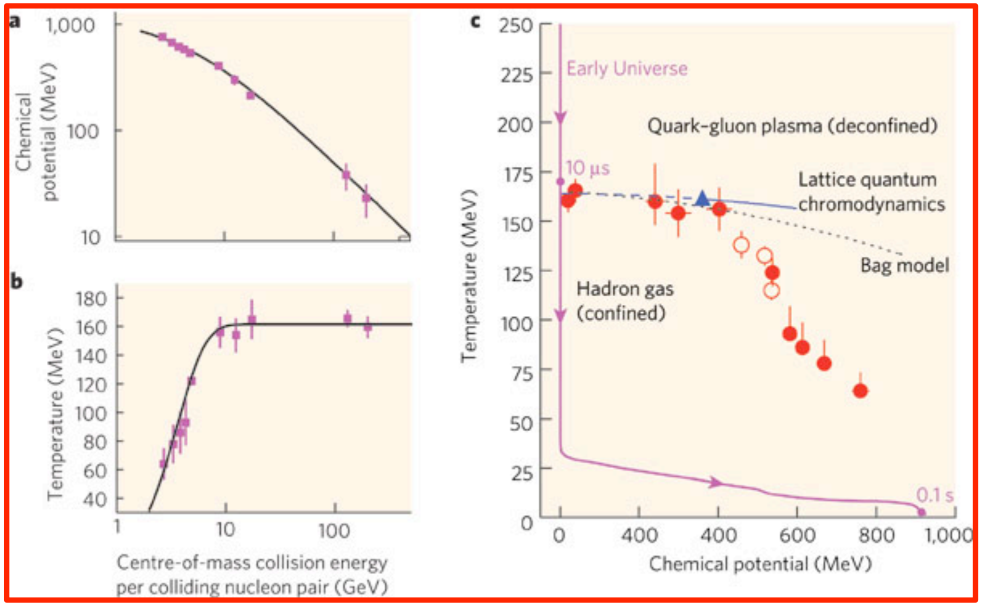
- Signals for phase transition/phase boundary.
- Search for Critical Point (CP).
- Bulk properties of QCD matter.

**Observables:**

1. Flucutations and correlations.
2. Collective flow: v1, v2…
3. Others…

# Access the QCD Phase Diagram-Experimental



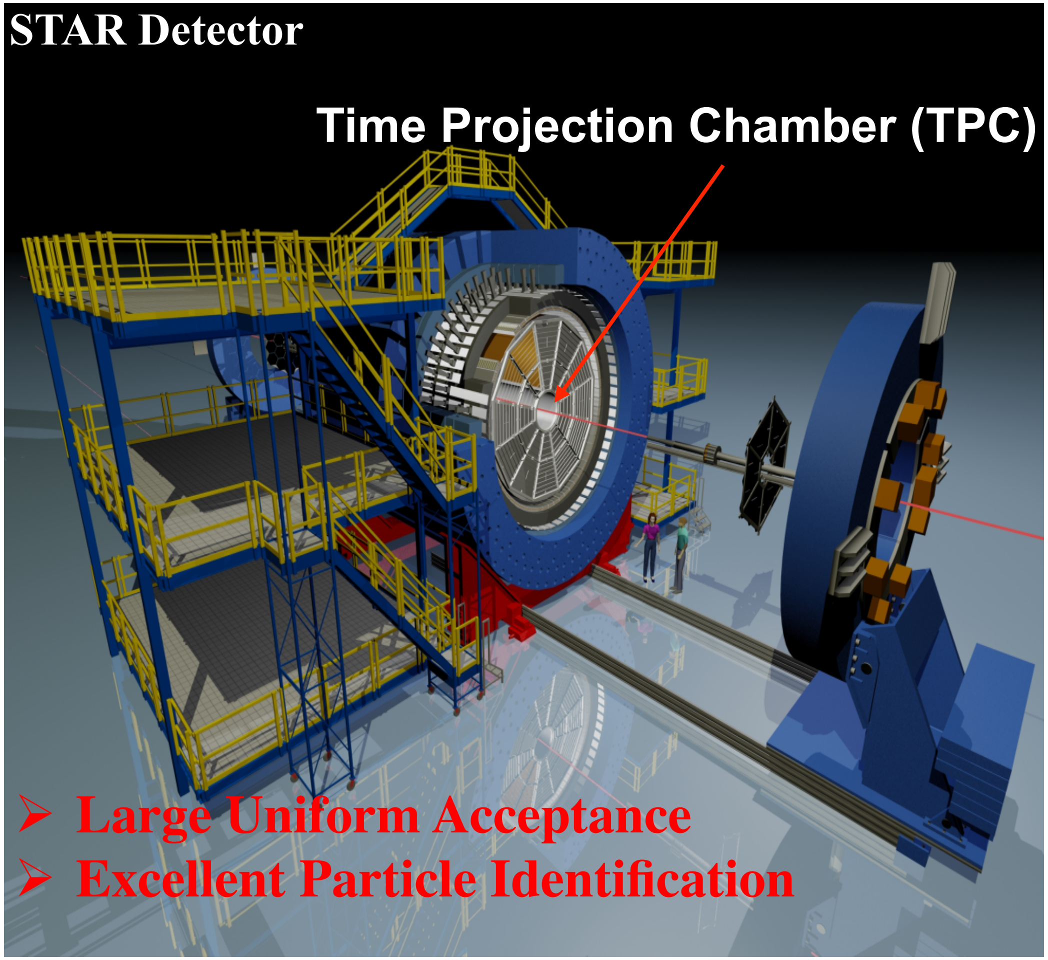

**Peter Braun-Munzinger and Johanna Stachel**
**Nature 448 (2007) 302**

**Vary beam energy to change T and $\mu_B$ .**

## Access the QCD phase diagram by varying beam energy !

# STAR Collaboration

# RHIC Beam Energy Scan-Phase I




**(RHIC BES-Phase I: Au+Au collisions at $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39, 62.4, 200 GeV)**

M. M. Aggarwal, arXiv:1007.2613 (2010).

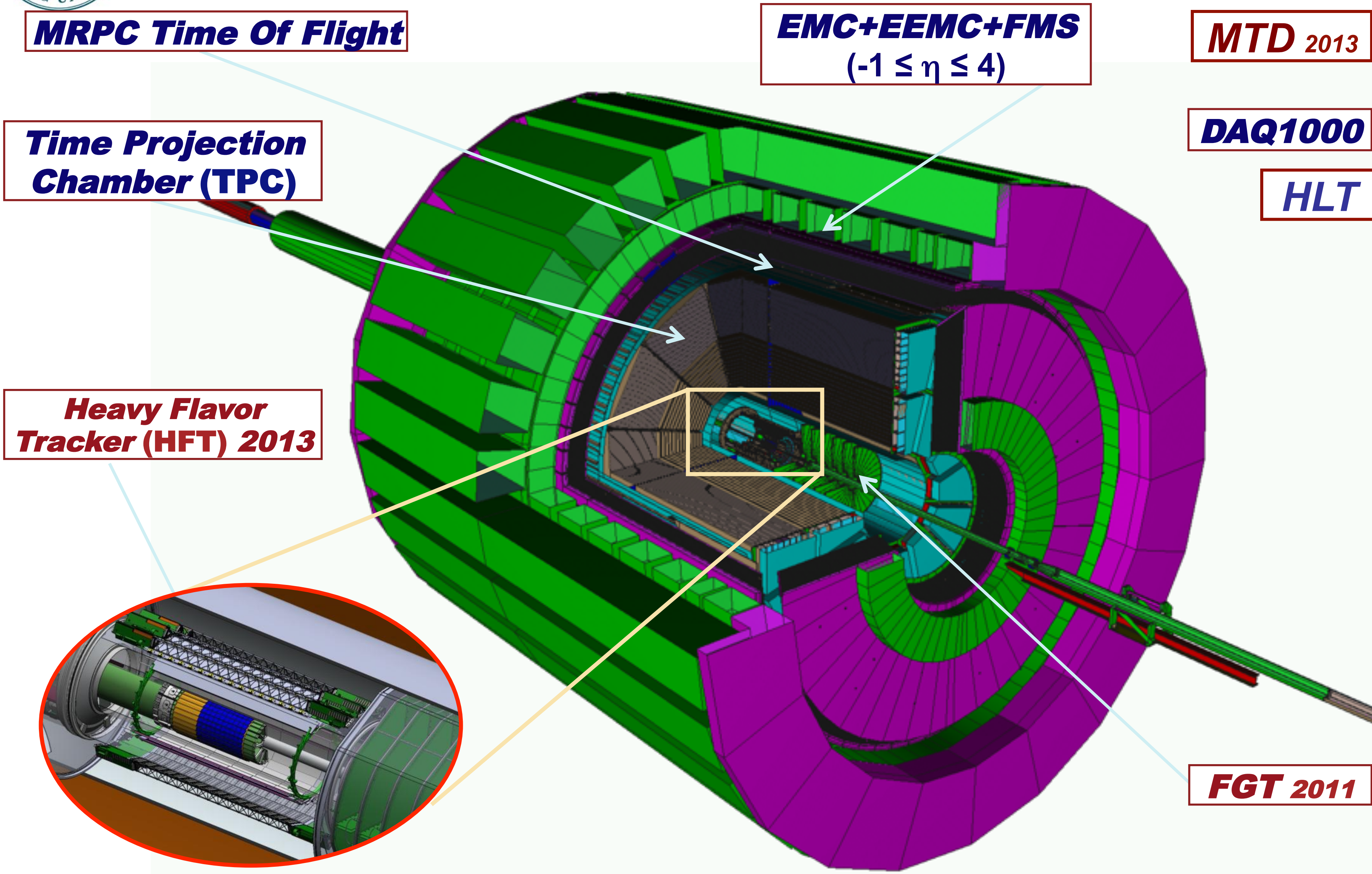
| $\sqrt{s}$ (GeV) | $\mu_B$ (MeV) | T (MeV) |
|---|---|---|
| 7.7 | 422 | 140 |
| 11.5 | 316 | 152 |
| 19.6 | 206 | 160 |
| 27 | 156 | 163 |
| 39 | 112 | 164 |
| 62.4 | 73 | 165 |
| 200 | 24 | 166 |

J. Cleymans et al., Phys. Rev. C 73, 034905 (2006)

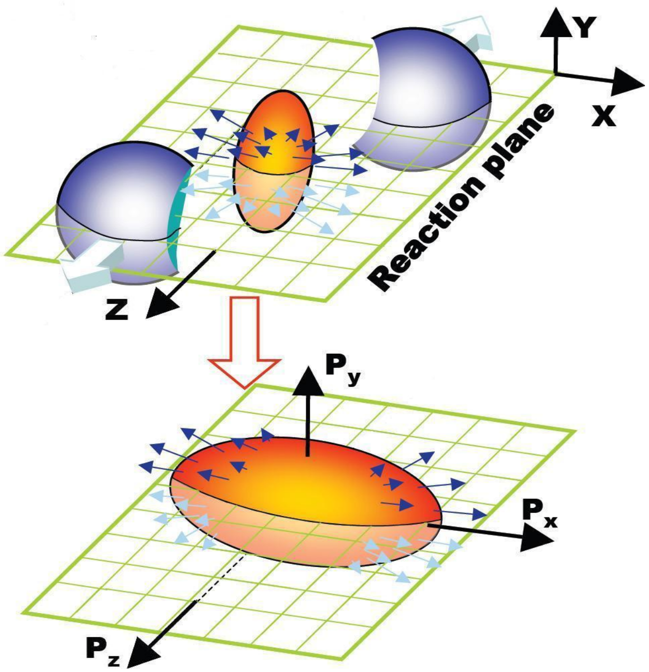
- ➢ **Access a broad region of QCD phase diagram by RHIC BES program.**

- ➢ **STAR is an ideal detector to perform correlation and fluctuation analysis to study the QCD phase diagram.**

# STAR Detector *Fast and Full azimuthal particle identification*



# Elliptic Flow ($v_2$)

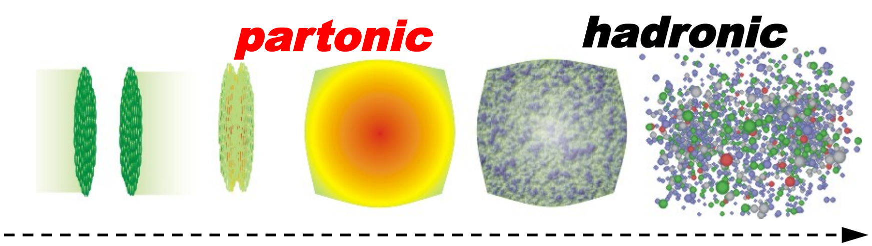



$$\varepsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}$$

$$v_2 = < \cos 2\varphi >, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- **Elliptic flow =>**
- Initial spatial anisotropy (eccentricity ε)
  ->final momentum anisotropy $v_2$
  - ➔ Interactions among constituents
  - Sensitive to degree of thermalization
- Self-quenching with time
  - Sensitive to the early stages of the system evolution
- **Strange hadron => less sensitive to late hadronic rescattering**

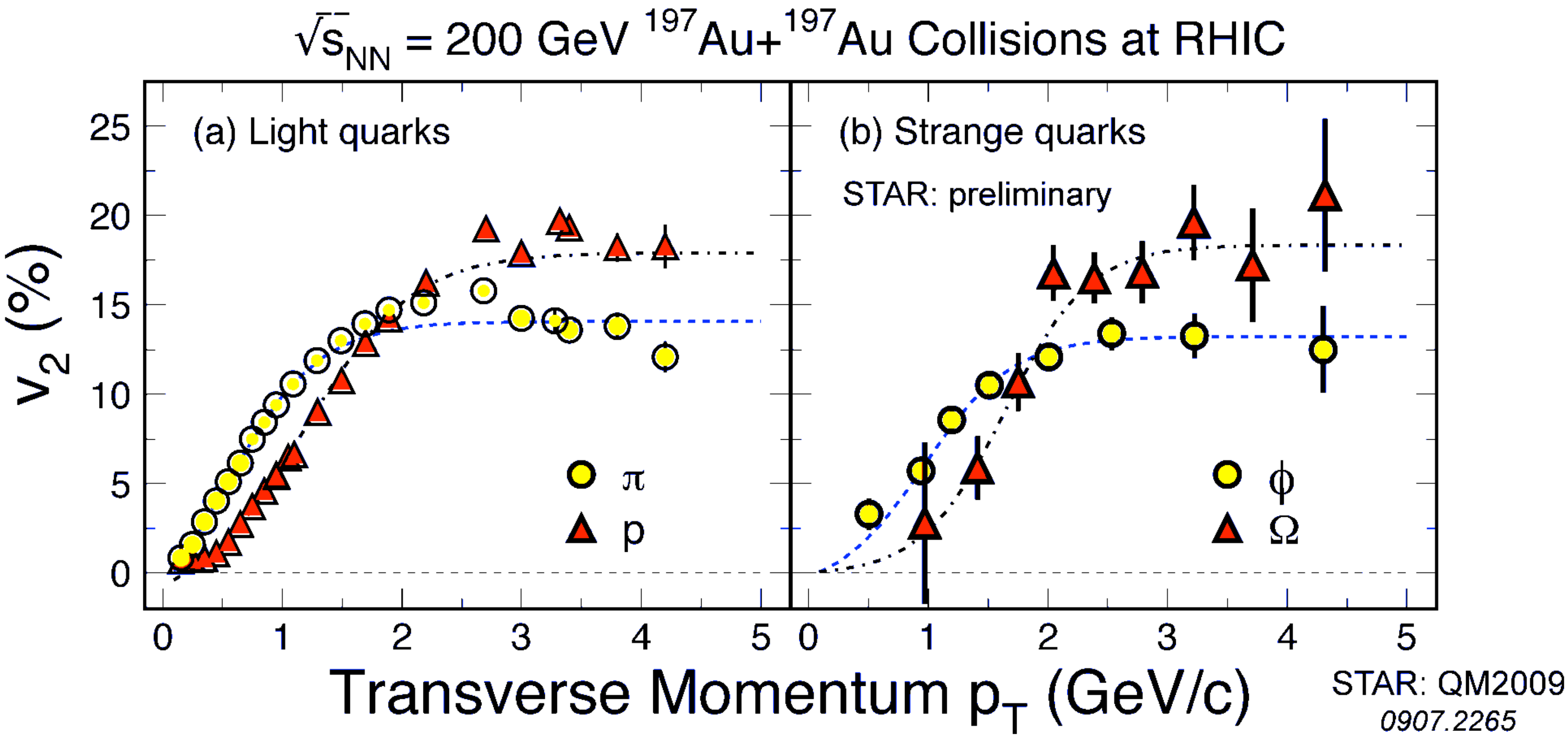
**Good probe of the early stage of the collision.**




**Experimental probes:**
**1) *Penetrating probes:* "jets" Energy loss**
**2) *Bulk probes* :Elliptic flow, radial flow,**
**3) *Fluactuation and correlation :* …**

D $\phi, \Omega, \Xi, \Lambda$ $\pi$, K, p

# Partonic Collectivity at RHIC



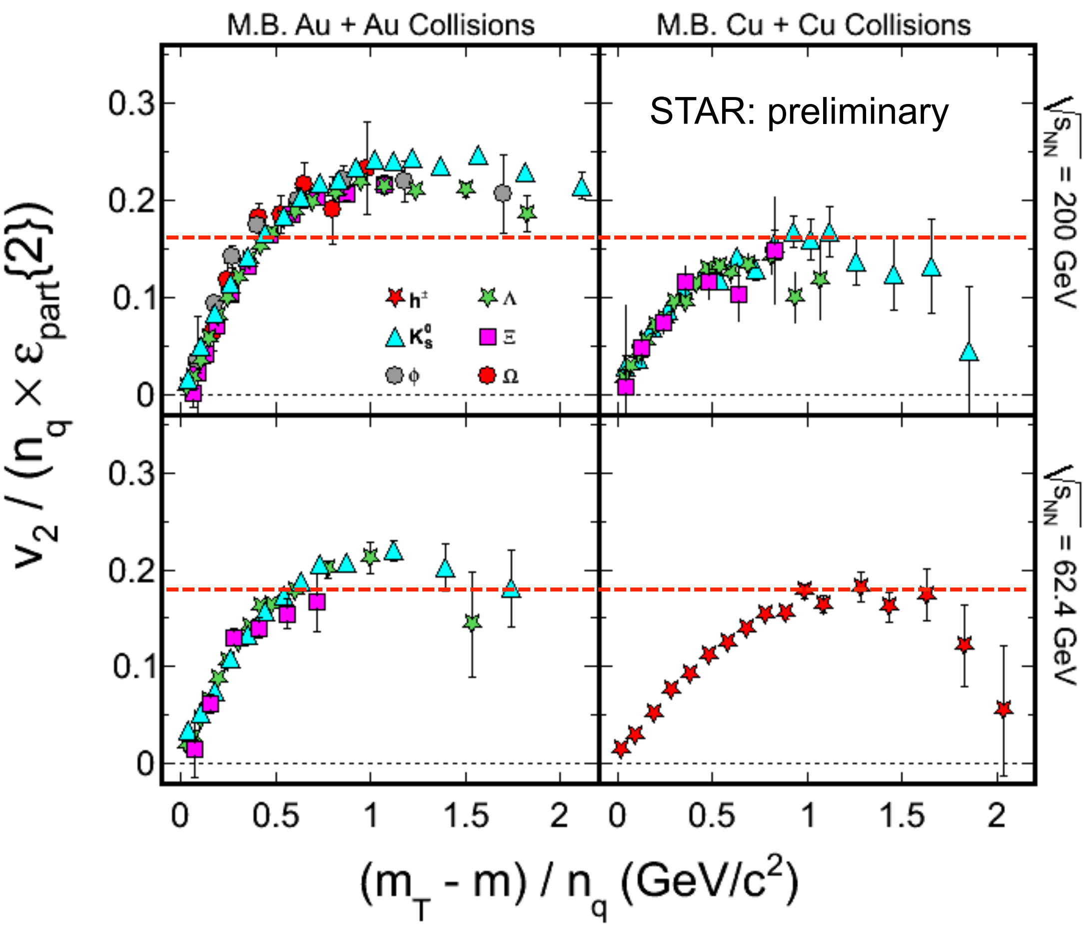

PHENIX π and p: nucl-ex/0604011v1

**STAR: Nucl. Phys.A830, 187c-190c (2009)**

- Low $p_T$ (≤ 2 GeV/c): mass ordering
- High $p_T$ (> 2 GeV/c): number of quarks ordering

***Collectivity developed at partonic stage!***

# System and Energy Dependence




**Au+Au and Cu+Cu**

- Minimum bias events
- 200 and 62.4 GeV

**Event plane**

- Au+Au: TPC
  Systematic: FTPC, 5%
- Cu+Cu: FTPC
  Systematic: $v_2\{AA\text{-}pp\}$, 5%

**NQ scaling**

- De-confinement at RHIC
- Partonic collectivity

**Scaled by eccentricity**

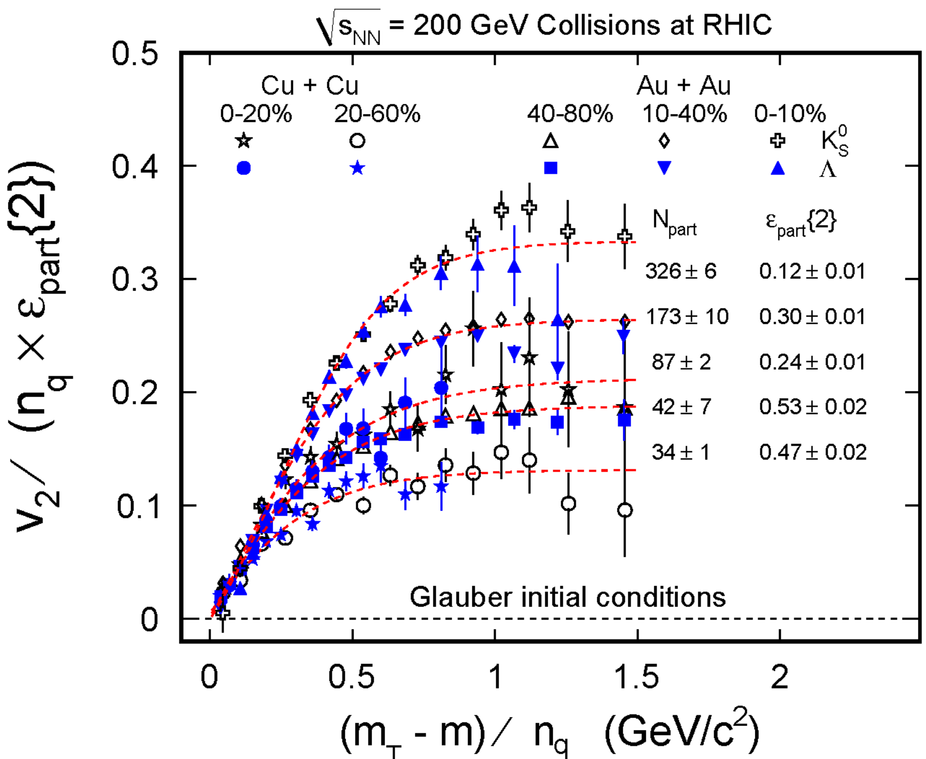
- Remove the initial geometry

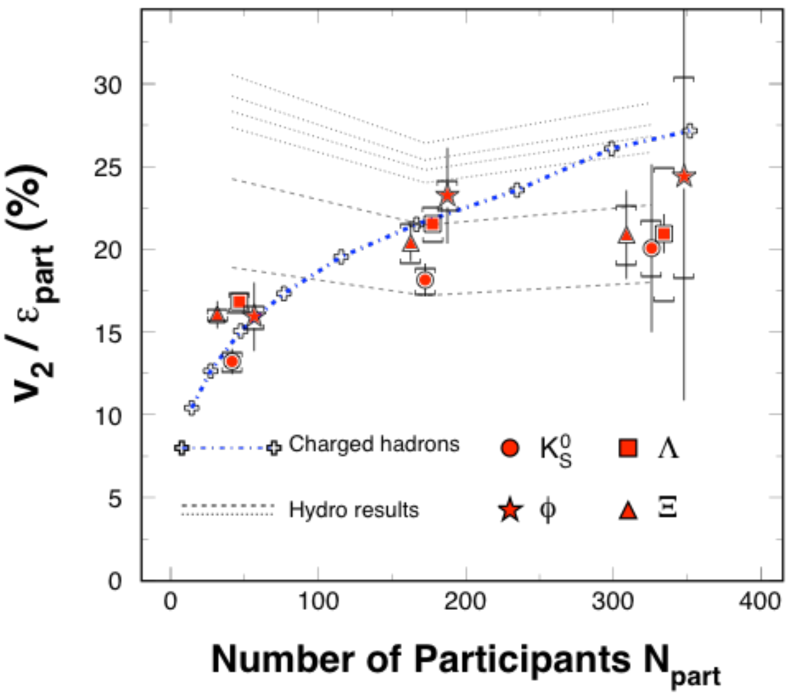
***Stronger collective flow in larger system***

STAR Au + Au 62.4 GeV : PRC75, 054906 (2007), PRC81, 044902 (2010),
$\varepsilon_{part}\{2\}$: J. Y. Ollitrault, A. M. Poskanzer and S. A. Voloshin, PRC80, 014904 (2009)

# Centrality Dependence

STAR Au + Au 200 GeV : PRC77, 054901 (2008)
Cu + Cu 200 GeV: ,PRC81, 044902 (2010),

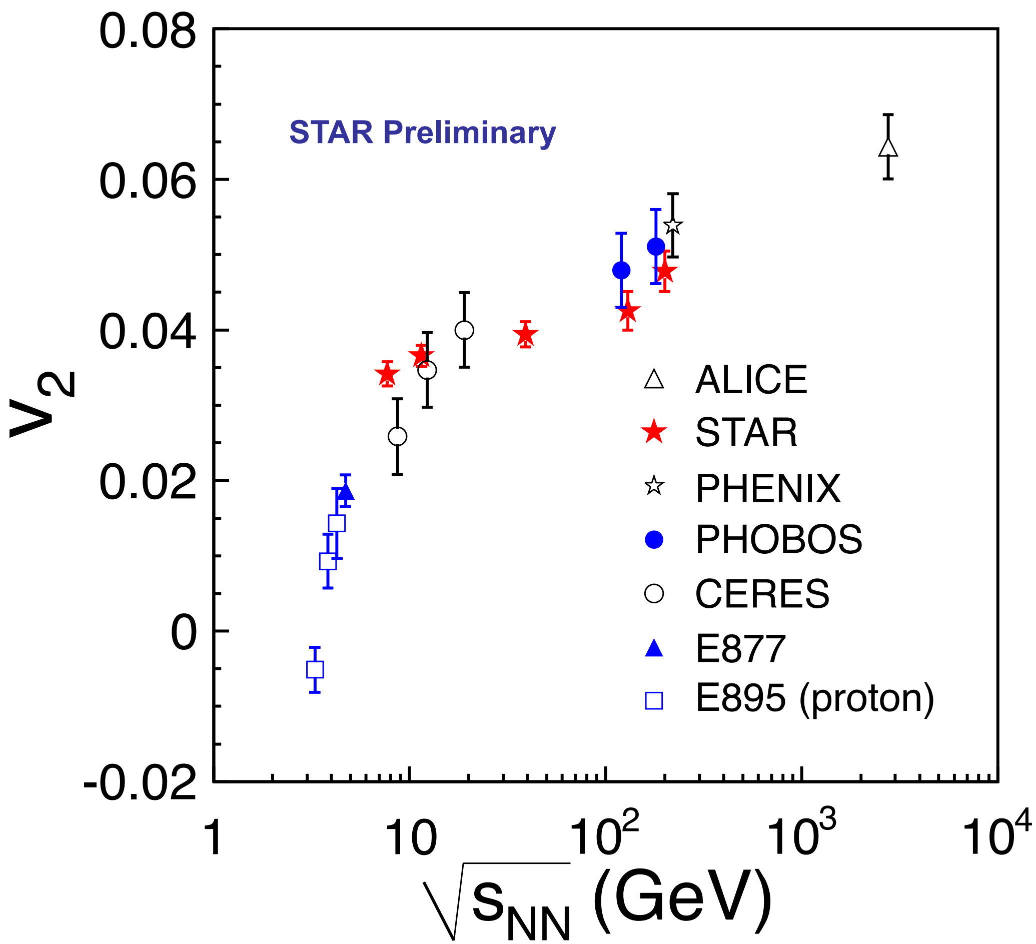



- Au+Au and Cu+Cu at 200 GeV
  - NQ scaling for each centrality bin
- Collective flow: depends on the number of participants
  - Larger $v_2/\varepsilon_{part}$ indicates stronger collective flow in more central collisions.

S. Voloshin, A. Poskanzer, PL B474, 27(00).
D. Teaney, et. al., nucl-th/0110037

# Energy Dependence

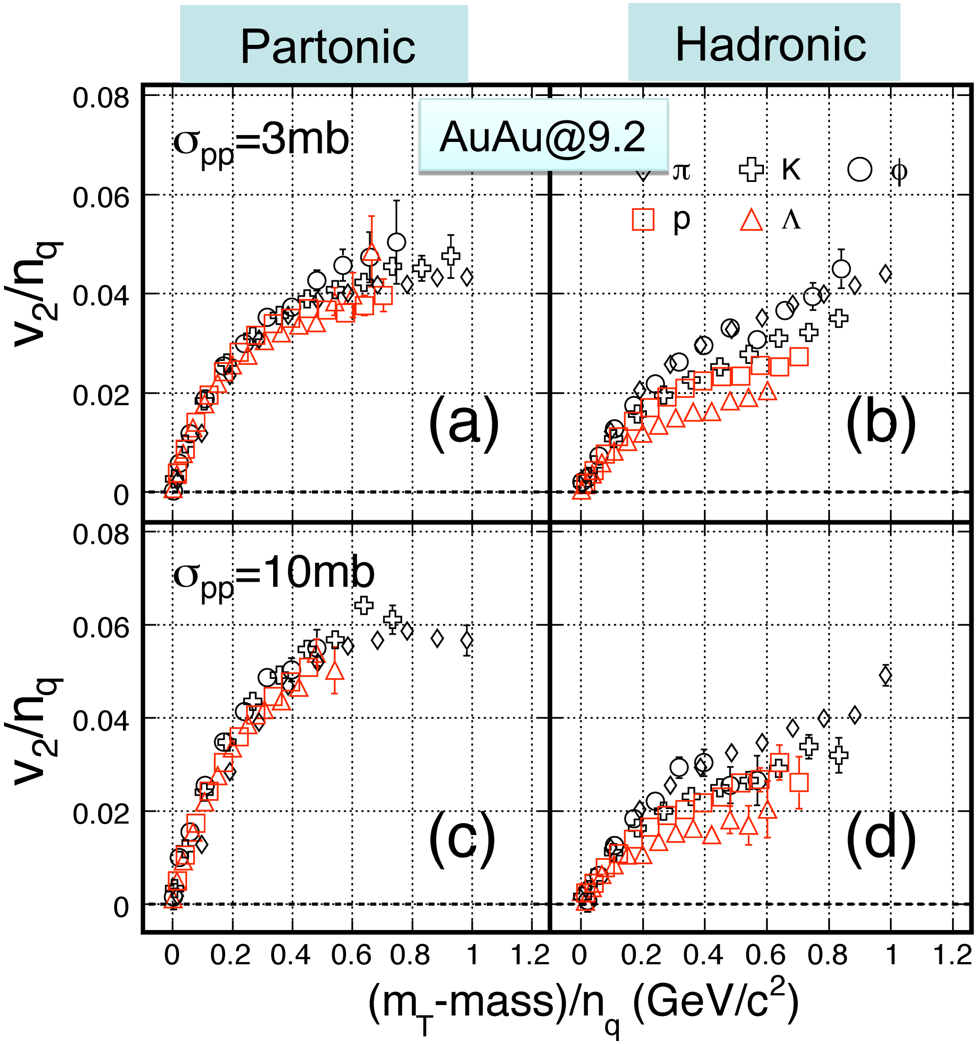



- **STAR, ALICE: $v_2\{4\}$ results**
  - **Centrality: 20-30%**

- **An increasing trend is observed for $p_T$ integrated $v_2$ from AGS to LHC**


ALICE: Phys. Rev. Lett. 105, 252302 (2010); PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
PHOBOS: Phys. Rev.Lett. 98, 242302 (2007). CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998). E895: Phys. Rev. Lett. 83, 1295 (1999).
STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005); QM2012,Nucl. Phys. A904-905(2013)895C=909C

# Energy Dependence of NCQ-scaling




**J.Phys.G,37-094029 (2010)**

**AMPT model results:**

➢Scaling in $v_2$: partonic dof dominant;
No scaling in $v_2$ : hadronic dof dominant

=>

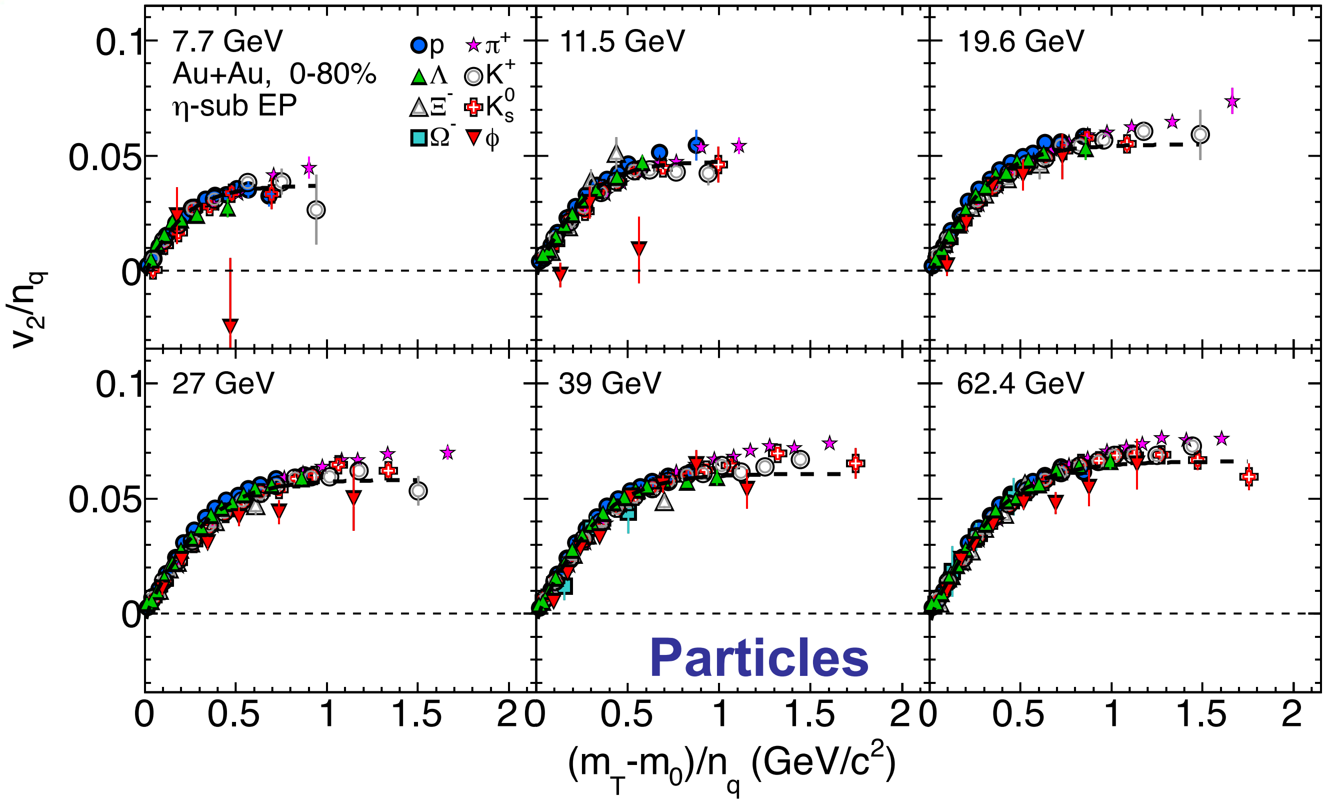
**A tool to search for the possible phase boundary!**

➢The beam energy dependence of the partonic cross sections will not affect the $v_2$ scaling argument.

=>

**Important for Beam Energy Scan program.**

# NCQ Scaling Test




STAR: Phys. Rev. Lett. 110 142301 (2013); arXiv:1301.2348

- Universal trend for most of particles and the corresponding anti-particles
- $\phi$ meson $v_2$ deviates from other particles ~ $2\sigma$ at the highest $p_T$ data in 7.7 and 11.5 GeV collisions

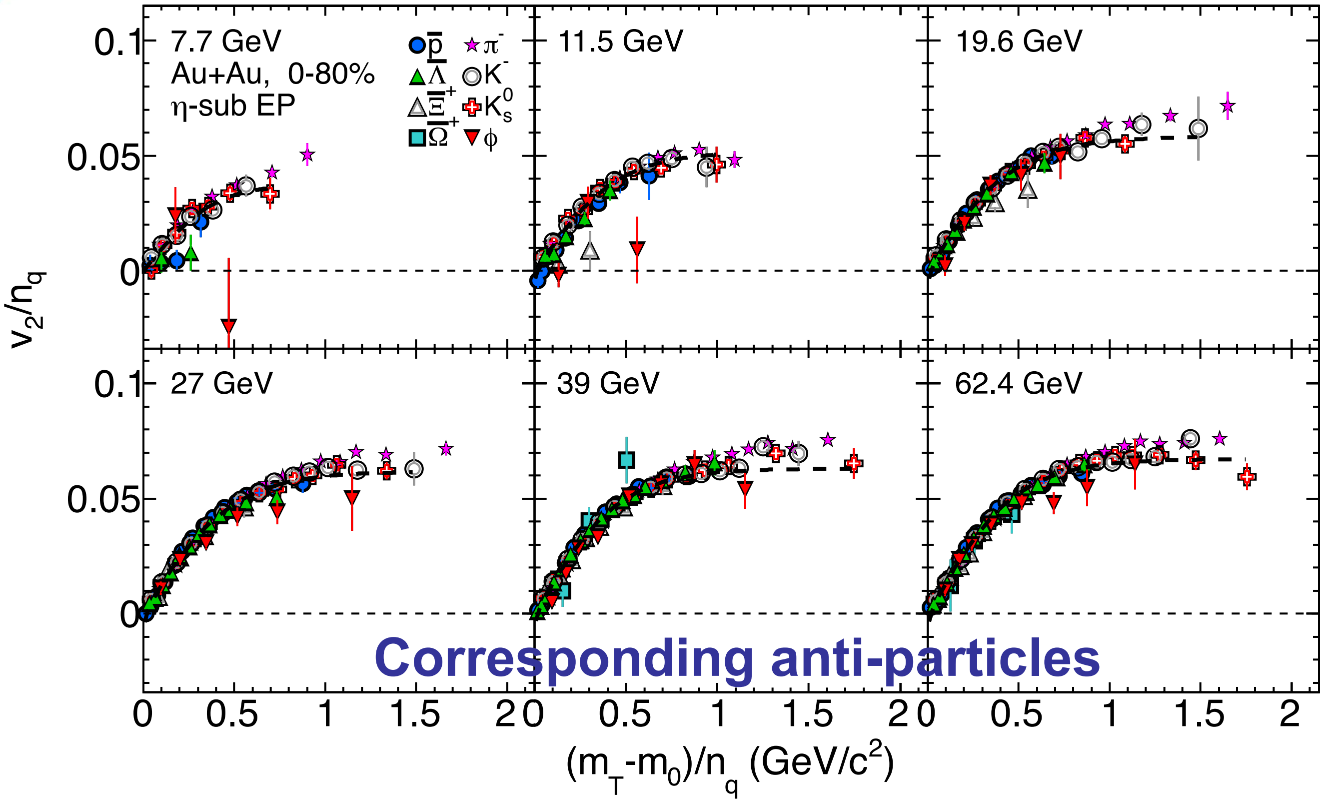
*Hadronic interactions are more important at lower energies*

*More data for 7.7 and 11.5 GeV are needed for clear conclusion*

*Small or zero $v_2$ for $\phi$ meson -> without formation of partonic matter*

**Ref: B. Mohanty and N. Xu: J. Phys. G 36, 064022(2009)**

# NCQ Scaling Test

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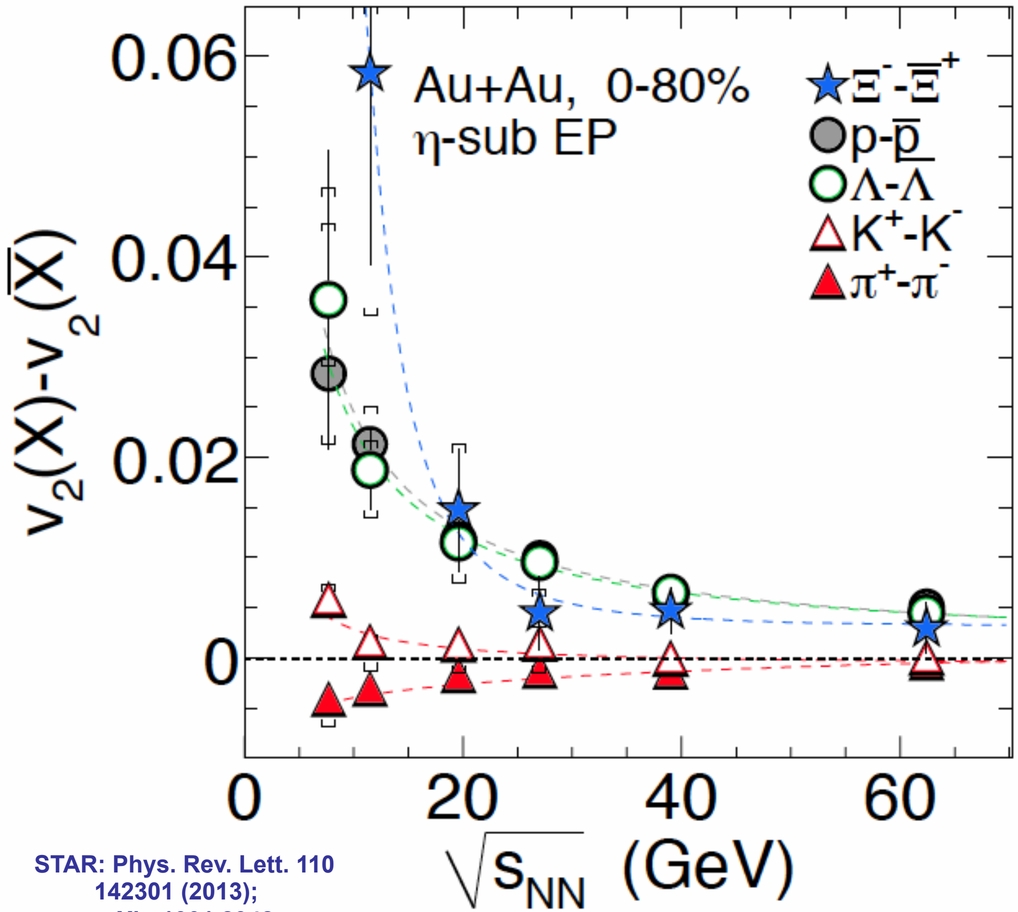
# Particles vs. Anti-particles

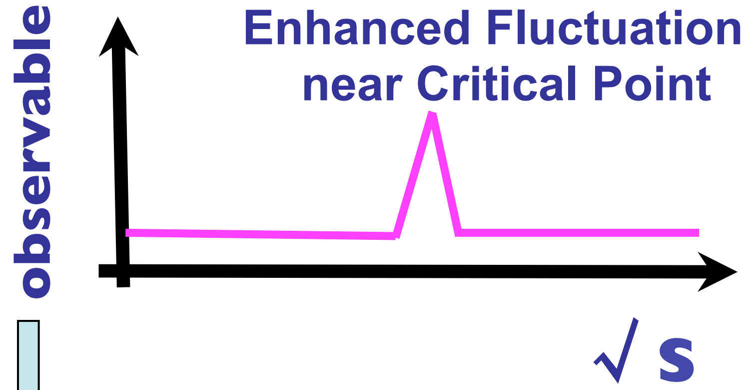



STAR: Phys. Rev. Lett. 110 142301 (2013); arXiv:1301.2348

- ➢ **Beam energy ≥ 39 GeV**
  - $\Delta v_2$ for baryon and anti-baryon within 10%
  - Almost no difference for mesons
- ➢ **Beam energy < 39 GeV**
  - The difference of baryon and anti-baryon $v_2$
    → *Increasing with decrease of beam energy*
  - $v_2(K^+)>v_2(K^-)$ at 7.7-19.6 GeV
  - $v_2(\pi^-) >v_2(\pi^+)$ at 7.7-19.6 GeV
- ➢ **Possible explanation**
  - Baryon transport to mid-rapidity?
    ref: J. Dunlop et al., PRC 84, 044914 (2011)
  - Hadronic potential?
    ref: J. Xu et al., PRC 85, 041901 **(2012)**

***The difference between particles and anti-particles is observed***

# Searching for QCD Critical Point




$CO_2$ near liquid-gas transition

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

- **Long wavelength fluctuations comparable with the light wavelength: Critical Opalescence.**

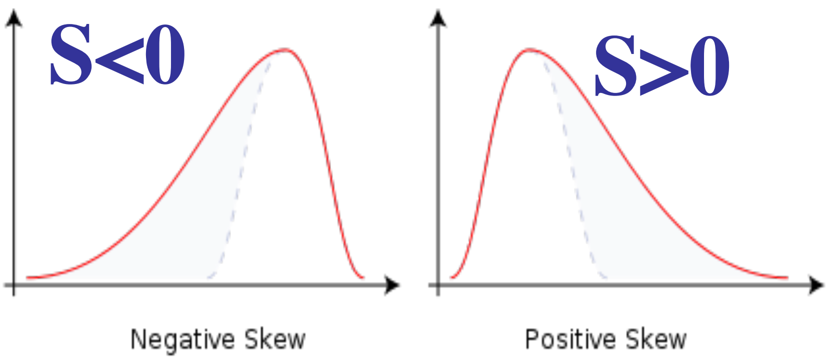
**✓Conserved number fluctuations**
**- Higher moments of net-protons, net-charge,..**

# Higher Moments : Sensitive to the Correlation Length

**Skewness:**

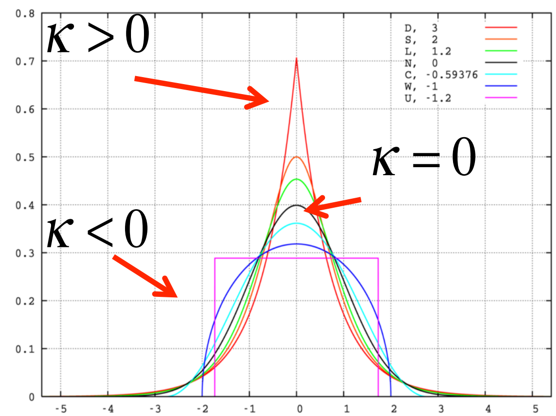
**$C_n$: $n^{th}$ order cumulants**

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{<(N-<N>)^3>}{\sigma^3}$$




**Kurtosis:**

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$




- **Ideal probe of non-gaussian fluctuations.**
  - **Sensitive to the correlation length (ξ).**

**Search for CP in Heavy Ion Collisions (ξ~2-3 fm)**

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

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

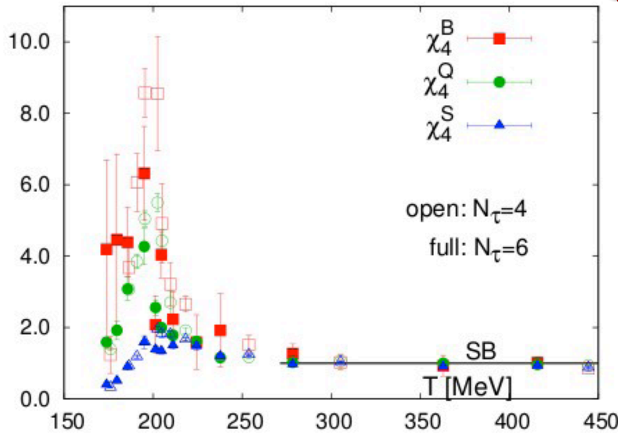
**M. A. Stephanov,**
**Phys. Rev. Lett. 102, 032301 (2009);**
**Phys. Rev. Lett. 107, 052301 (2011);**

# Higher Moments (II): Related to the Susceptibility

**Theory: Lattice QCD, HRG…** ⇔ **Experiment: Heavy Ion Collisions**

**Susceptibility:**

conserved quantum numbers: *Q, S, B*,




M. Cheng et al, *PRD79*, 074505(2009)

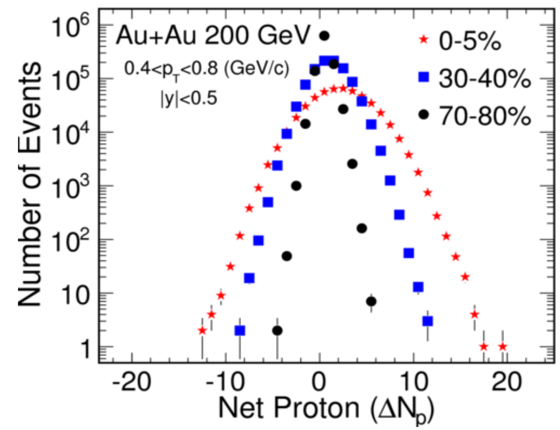
$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle, \chi_q^{(2)} = \frac{1}{VT^3}\langle (\delta N_q)^2 \rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\langle (\delta N_q)^3 \rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left( \langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2 \right)$$

A. Bazavov et al . PRL109, 192302 (2012)
B. F. Karsch et al, PLB 695, 136 (2011)
arXiv: 1203.0784; S. Borsanyi et al, JHEP1201,138(2011);

**STAR Experiment:** ***PRL105, 22303(2010).***




- **Susceptibility ⇔ Moments**

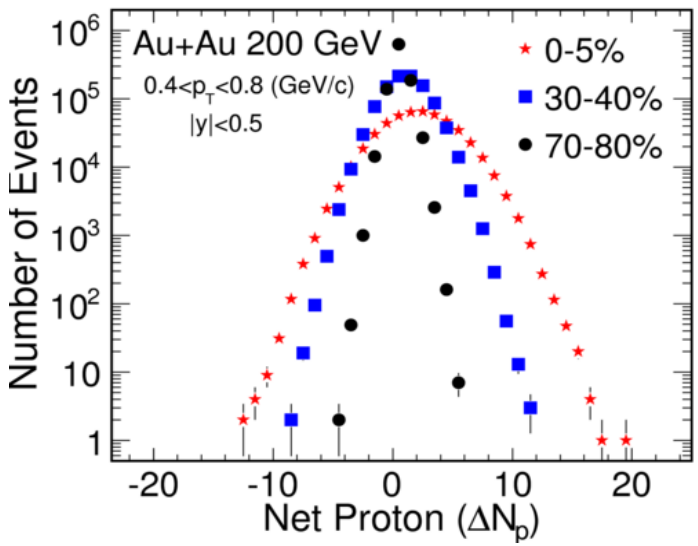
$$\kappa\sigma^2 \sim \frac{\chi^{(4)}}{\chi^{(2)}}, S\sigma \sim \frac{\chi^{(3)}}{\chi^{(2)}}, \frac{\sigma^2}{M} \sim \frac{\chi^{(2)}}{\chi^{(1)}}$$

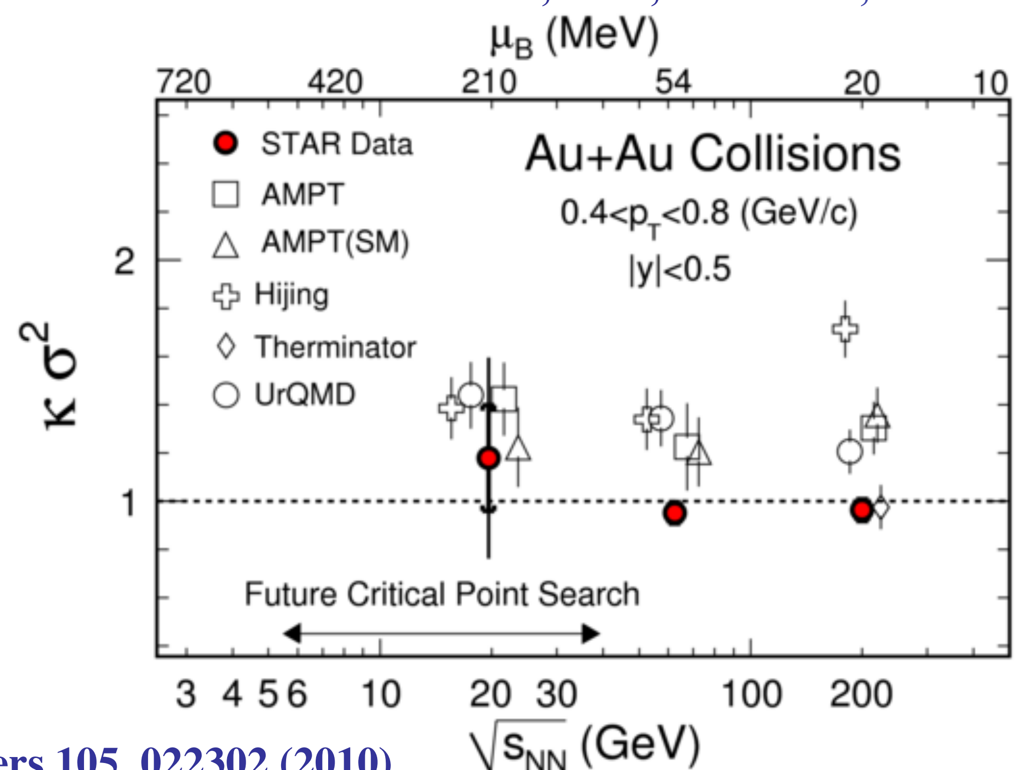
- **Study Phase Transition and Bulk properties of QCD matter.**

R.V. Gavai and S. Gupta, *PLB 696, 459 (2011).*
S. Gupta, et al., *Science, 332, 1525(2011).*
Y. Hatta, et al, *PRL. 91, 102003 (2003).*

# Observable: Higher Moments of Net-proton Distributions

**Net-proton fluctuations can reflect the diverges of baryon number fluctuations at CP and can be used to search for the CP.** Y. Hatta, et al., P.R.L. 91, 102003 (2003).

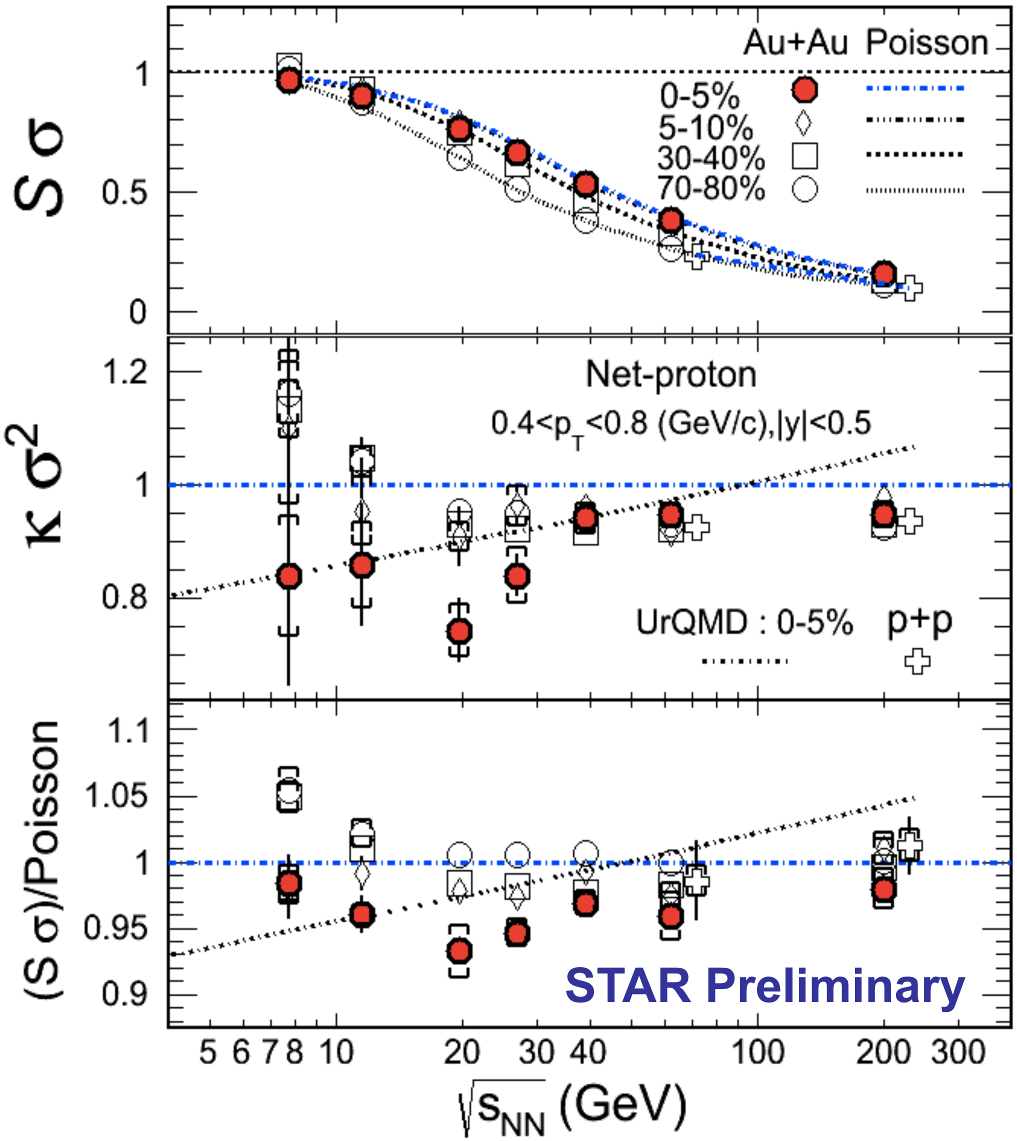



STAR: Physical Review Letters 105, 022302 (2010).

- First measurement of the higher moments of net-proton distributions at RHIC.
- There has no evidence for the existence of QCD critical point with $\mu_B$ <200 MeV.

# Net-proton Higher Moments in RHIC BES




STAR: X.F. Luo; QM2012
Nucl. Phy。A 904 911c（2013）

**STAR net-proton results:**

1) **All data show deviations below Poisson beyond statistical and systematic errors in the 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ at all energies.**

2) **UrQMD model show monotonic behavior**

3) **Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < *20 GeV***

# Summary

We present the elliptic flow and higher moments of net-proton distributions from RHIC Beam Energy Scan.

- **Multi-strange hadrons $v_2$ of $\phi$, $\Omega$ at 200 GeV:**
  **Partonic collectivity at RHIC!**
- **The difference in $v_2$ between particles and anti-particles increases with decrease of beam energy**
  **Partonic dominant for beam energy ≥ 39 GeV**
  **Hadronic dominant for beam energy ≤ 11.5 GeV**
- **$\phi$ meson deviates the trend of other particles ~ 2σ at highest pT data at 7.7 and 11.5 GeV**
- **The 0-5% most central results are smaller than Poisson baseline for all of the energies.**
- **More statistics are needed for low energies to see whether it has a dip for $S\sigma$ and $\kappa\sigma^2$ around 20 GeV.**

# Exploring the QCD Phase Structure

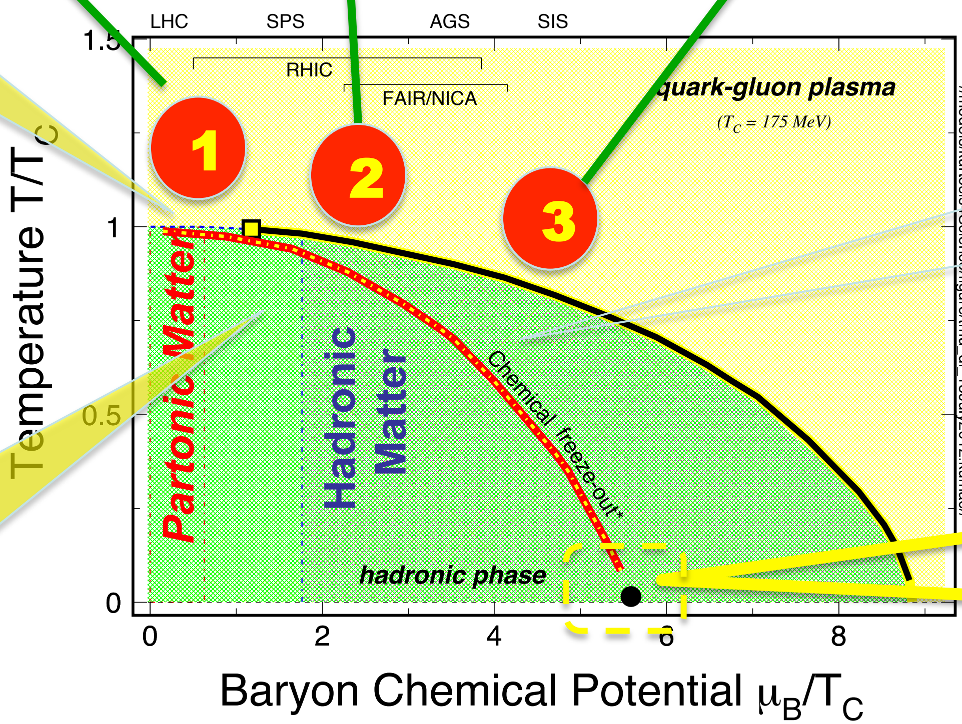
1 $T_{ini}$, $T_C$ **LHC, RHIC**

2 $T_E$ **RHIC, SPS**

3 Large $\mu_B$ **NICA, FAIR**

**LHC+RHIC**
**sQGP properties**
**$\sqrt{s_{NN}}$ ~ few TeV**

**RHIC BES-II**
**QCD phase structure and critical point**
**$\sqrt{s_{NN}} \leq 20$ GeV**



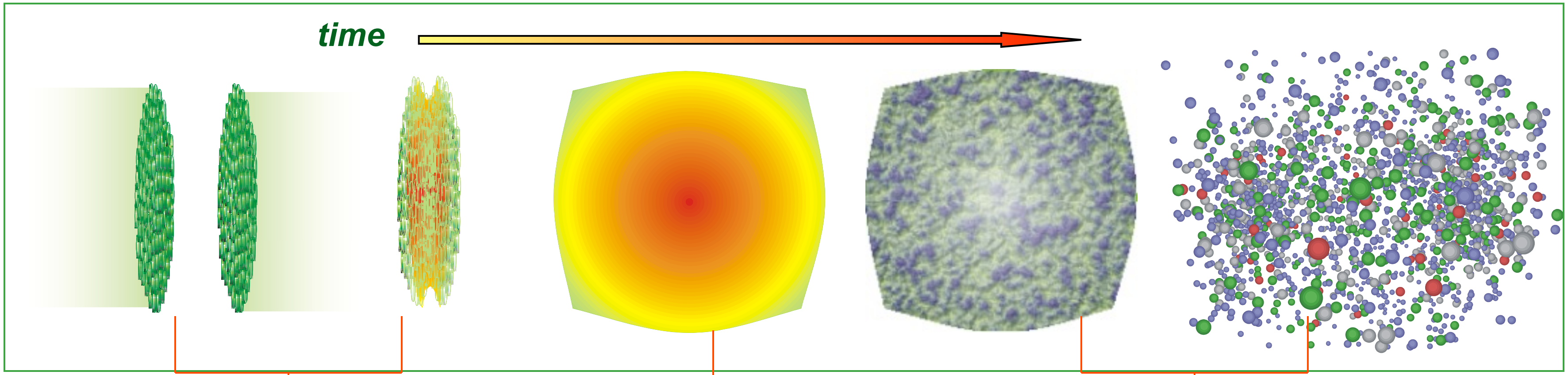

**NICA/FAIR**
**QCD phase structure**
**$\sqrt{s_{NN}} \leq 12$ GeV**

**Cold nuclear matter properties**
**e + ion collisions**

**Emergent properties of QCD matter**

# Thank you

# High-energy Nuclear Collisions




Initial conditions and interactions

Hot and Dense

Cooling down freezing out

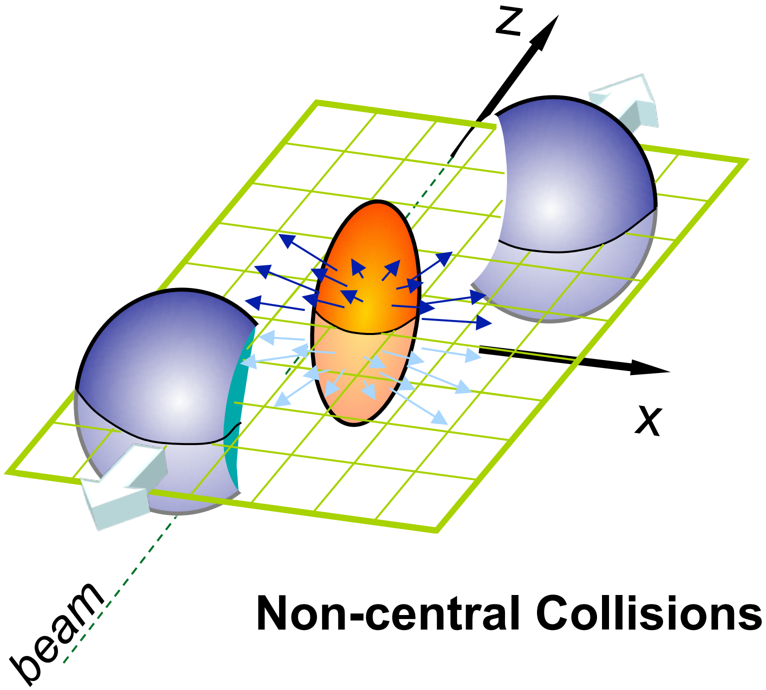
Experimental probes:

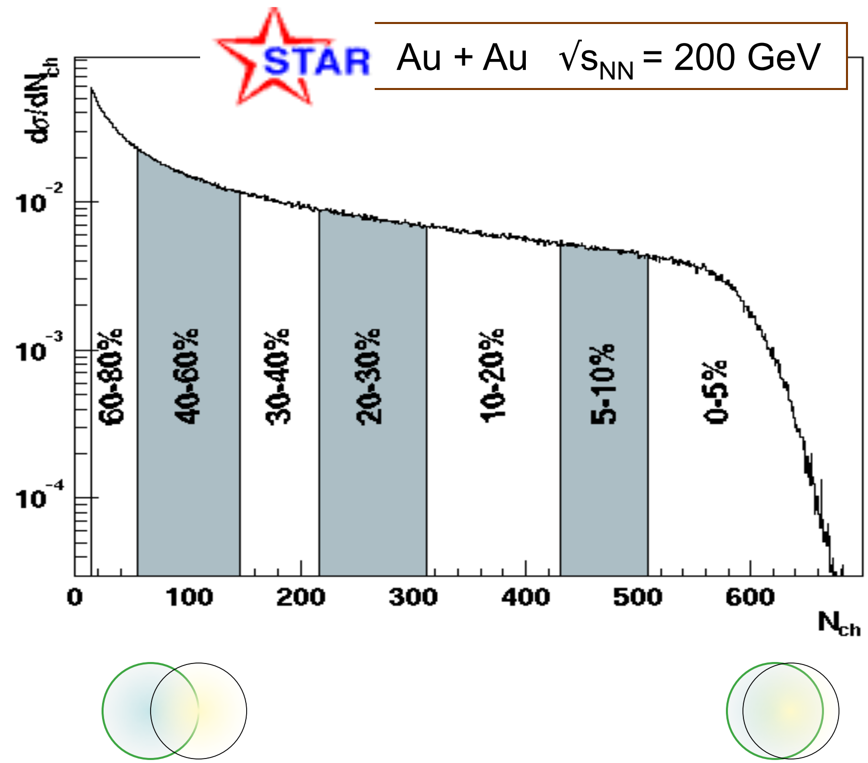
1) ***Penetrating probes:*** "jets" **Energy loss**

2) ***Bulk probes*** **:Elliptic flow, radial flow,**

3) ***Fluactuation and correlation :*** …

# Collision Geometry



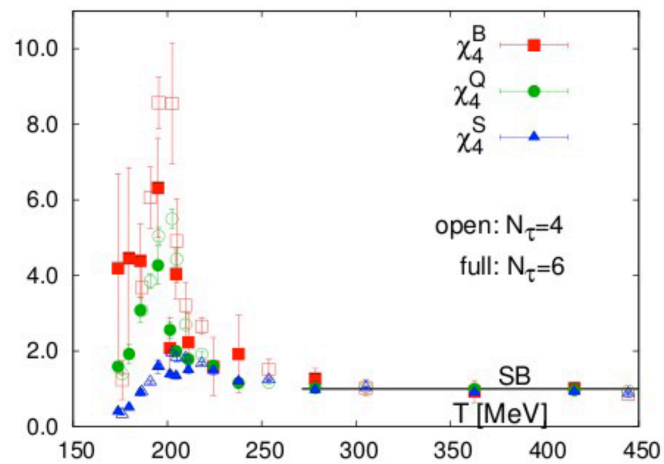




**Number of participants:** number of incoming nucleons in the overlap region
**Number of binary collisions:** number of inelastic nucleon-nucleon collisions

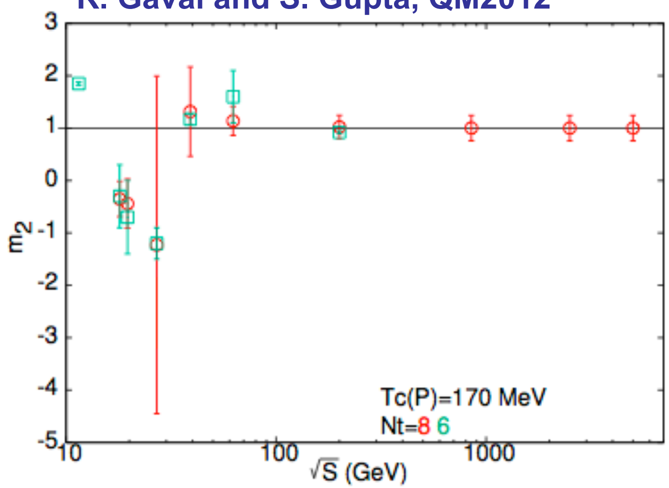
Charged particle multiplicity ⇔ collision centrality
Reaction plane: x-z plane

# Higher Moments

M. Cheng et al, *PRD79*, 074505(2009)




R. Gavai and S. Gupta, QM2012




1) High moments for conserved quantum numbers: ***Q*, *S*, *B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

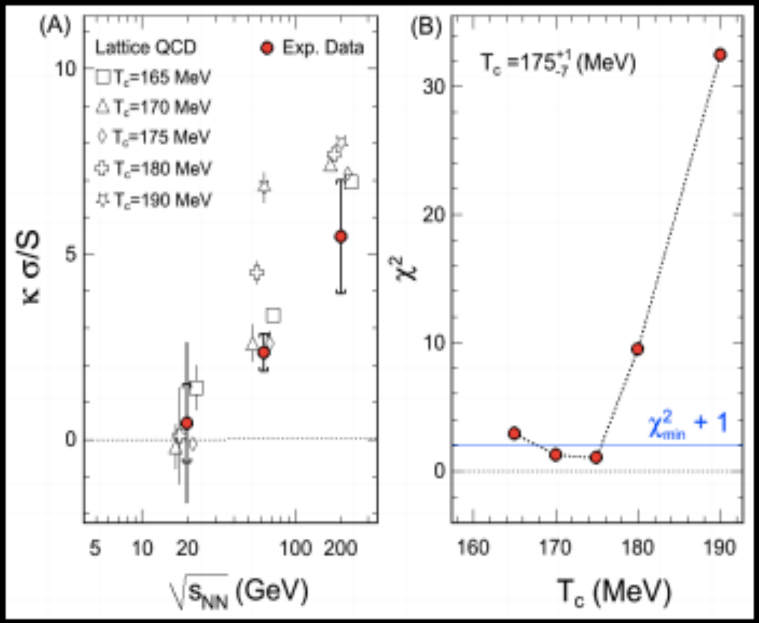
3) Direct comparison with Lattice results:

$$S * \sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa * \sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature. An independent/important test on thermal equilibrium in heavy ion collisions.


- A. Bazavov et al. *1208.1220* (NLOTE)
- STAR Experiment: *PRL*105, 22303(2010)
- M. Stephanov: *PRL*102, 032301(2009)
- R.V. Gavai and S. Gupta, *PLB696*, 459(2011)
- S. Gupta, et al., *Science*, 332, 1525(2011)
- F. Karsch et al, *PLB695*, 136(2011)
- M.Cheng et al, *PRD79*, 074505(2009)
- Y. Hatta, et al, *PRL91*, 102003(2003)

# Scale for the QCD Phase diagram




Science AAAS June, 2011

*"Scale for the Phase Diagram of Quantum Chromodynamics"*

***Science*, 332**, 1525(2011)

1) Central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption
2) Scale of LGT, determined with the data, is: $T_C=175^{+1}_{-7}$ (MeV)

STAR, *PRL105, 22303(2010);* S. Gupta, X.F. Luo, B. Mohanty, H.G. Ritter, N.Xu, *Science, 332, 1525(2011);* F. Karsch and K. Redlich, *PLB695, 136(2011);* R.V. Gavai and S. Gupta, *PLB696, 459(2011).*