High-Energy Nuclear Collisions and the QCD Phase Structure

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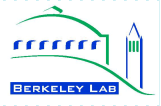
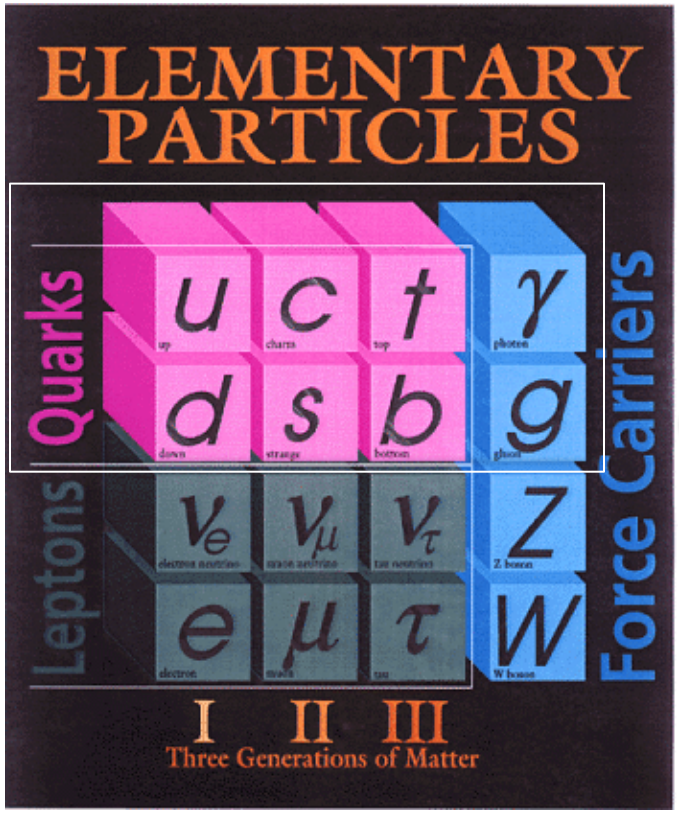
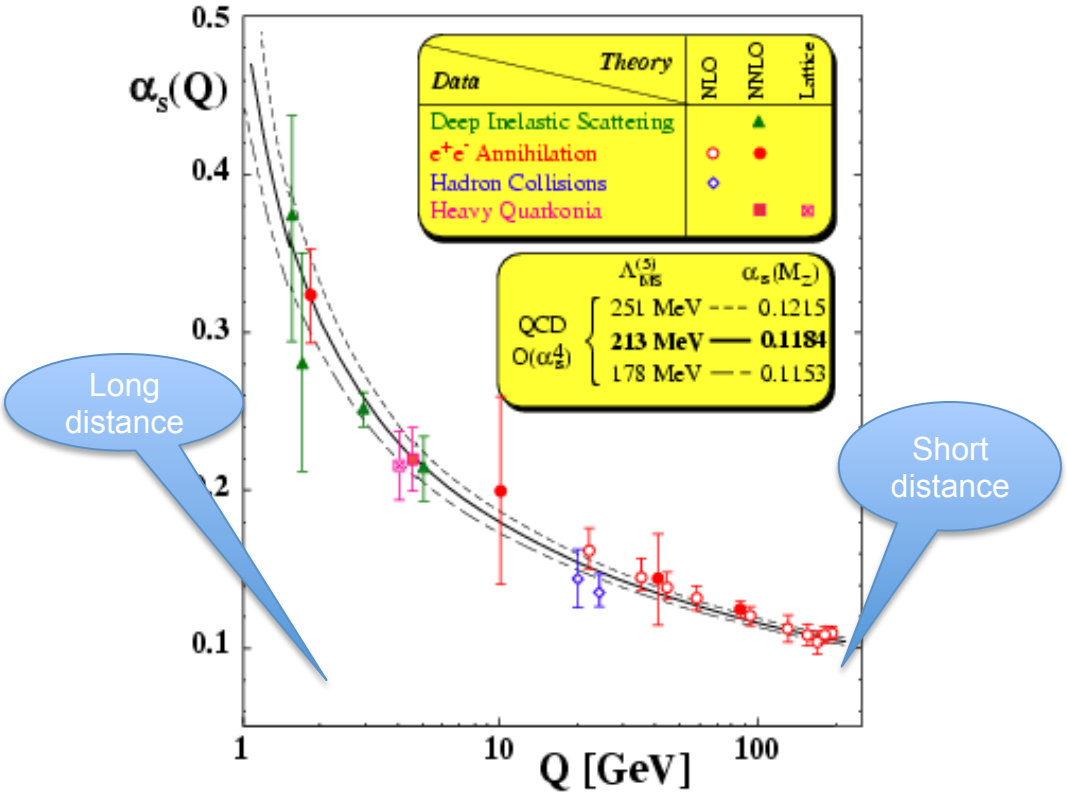


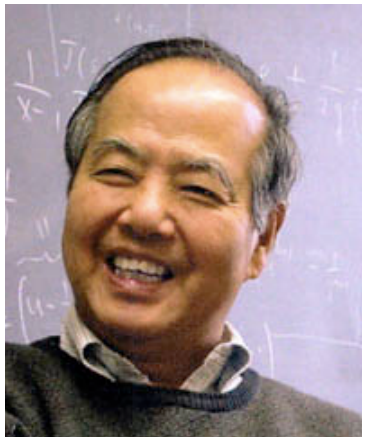
Quantum ChromoDynamics





1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
2) Little is known regarding the dynamical structures of matter that made from ***q, g***. *E.g. the confinement*, *nucleon spin*, the ***QCD phase structure***... Large α_S and strong coupling – QCD at long distance.

An Approach to Address the Problem



T.D Lee, 1970

- The confinement:

  Quarks are the basic building blocks of matter.

  No free quarks are seen, confined within hadron:

  $\Delta v_0 \sim 1\ fm^3$, $\rho_0 \sim 0.16\ fm^{-3}$, $\varepsilon_0 \sim 0.15\ GeV/fm^3$

- Heavy ion collisions: Large, hot, and dense system

  $\Delta v \sim 1000\ fm^3 = 1000\ v_0$

  $\rho >> 3\ fm^{-3} \sim 20\ \rho_0$

  $\varepsilon >> 3\ GeV/fm^3 \sim 20\ \varepsilon_0$

  $\Rightarrow$ **Quark Gluon Plasma (QGP)**

- ***QGP: Quarks and gluons are 'freely' moving in a large volume***

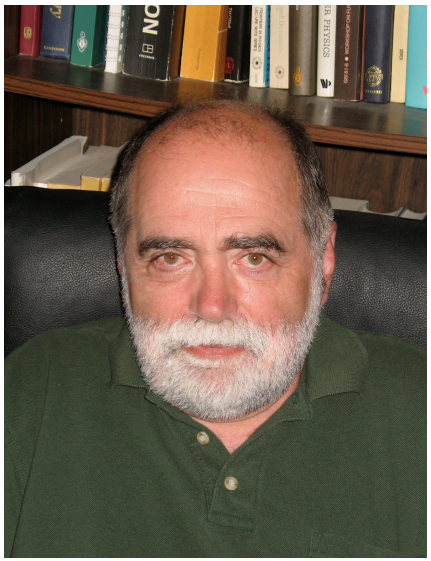
  New form of ***matter with partonic degrees of freedom.***

  Done!

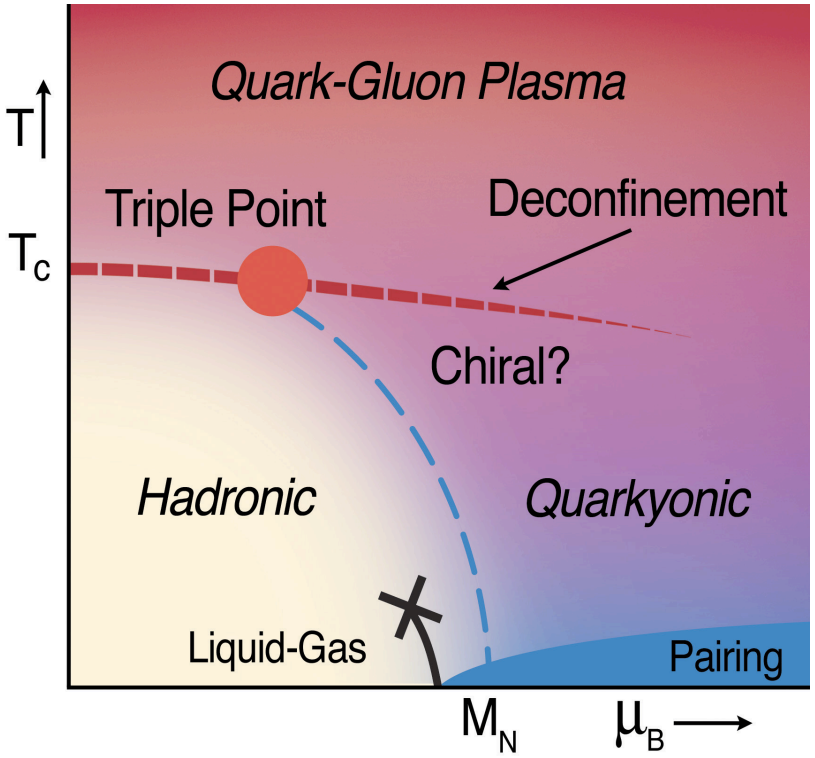
- ***Study the QCD Phase Structure:***

  - Fine structure of the Phase Boundary
  - Possible Critical Point

QCD Phase Diagram (2009)



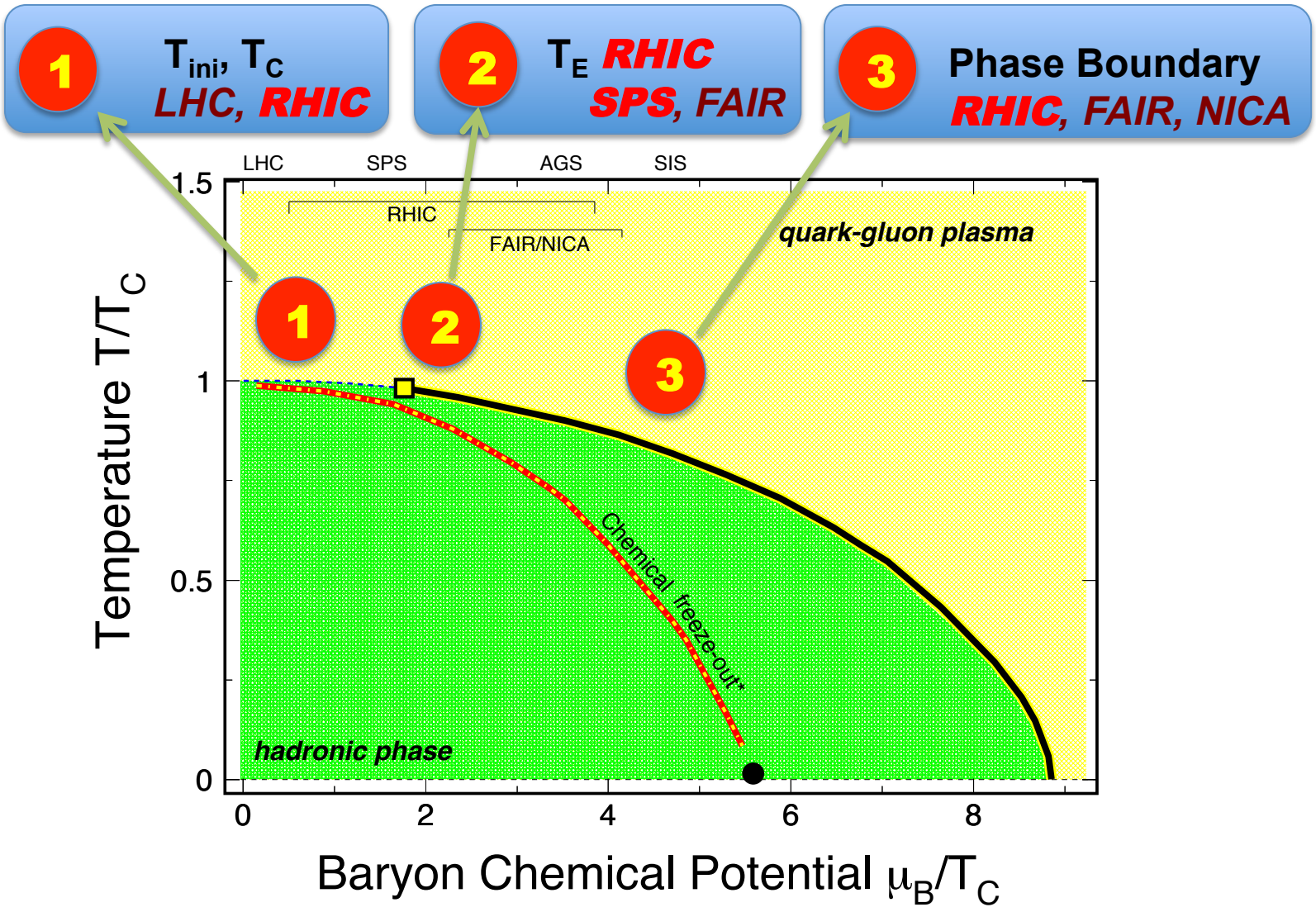
Larry McLerran



nucl-th: 0907.4489, NPA830.709(09) *L. McLerran*
nucl-th 0911.4806: *A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel*

Experiments: Systematic measurements (E_{beam}, A_{size}) : to extract **numbers** that are related to the ***phase diagram***!

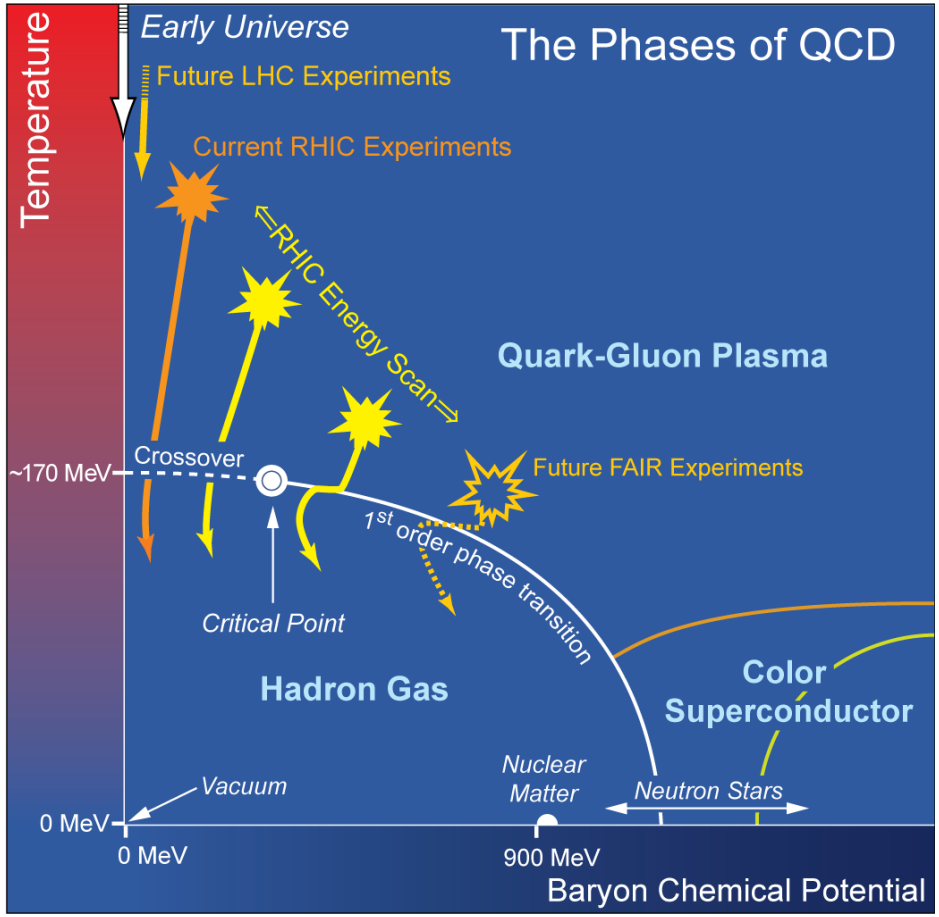
The QCD Phase Diagram and High-Energy Nuclear Collisions



Beam Energy Scan at RHIC

Study QCD Phase Structure

- Signals of phase boundary
- Signals for critical point



Observations:

(1) v_2 - NCQ scaling:
partonic vs. hadronic dof

(2) Dynamical correlations:
partonic vs. hadronic dof

(3) Azimuthally HBT:
1st order phase transition

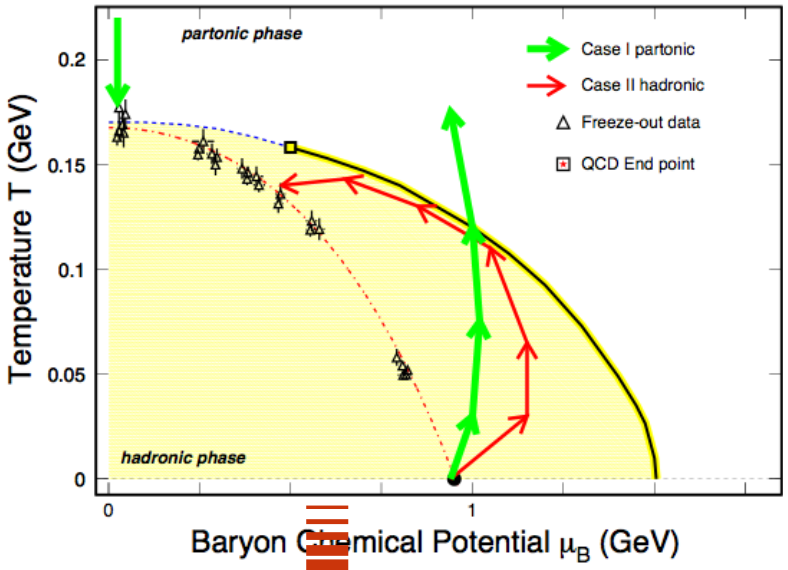
(4) Fluctuations:
Critical point, correl. length

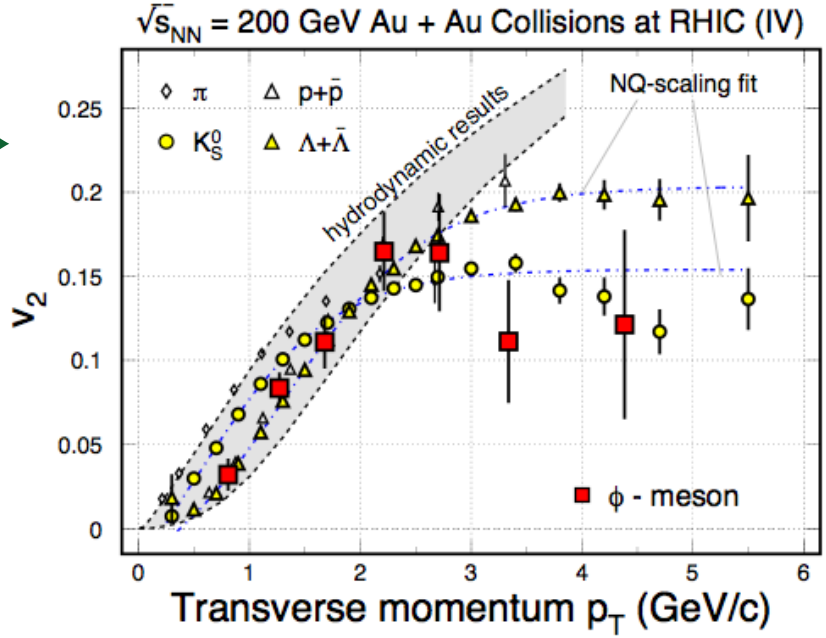
(5) Directed flow v_1
1st order phase transition

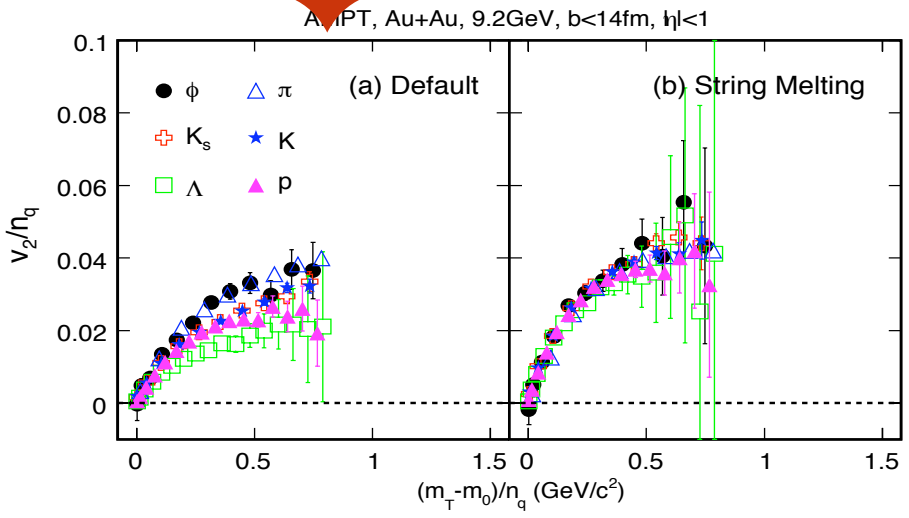
- *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493*

- *arXiv:1007.2613*

Observable*: NCQ Scaling in v_2







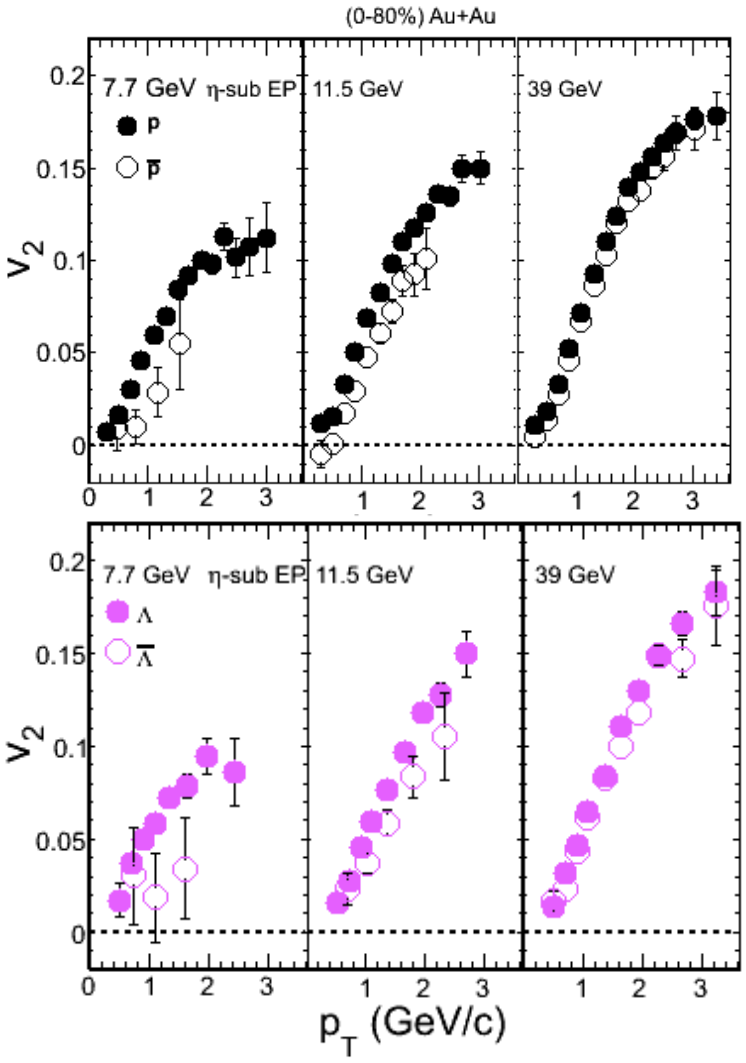
STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

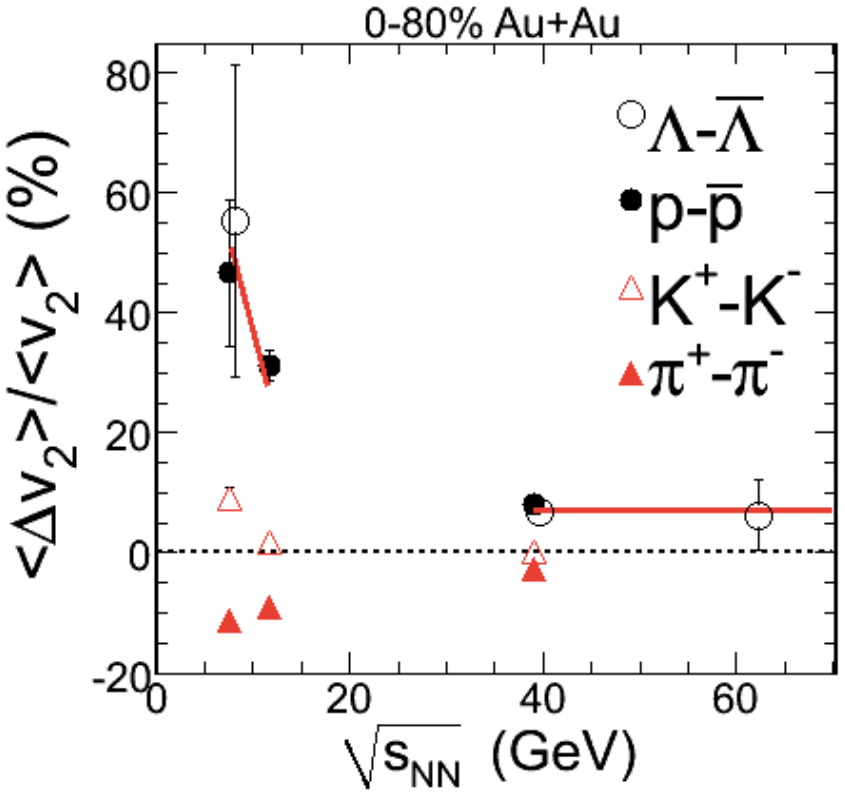
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Particle and Anti-Particle v_2 vs. $\sqrt{s_{NN}}$





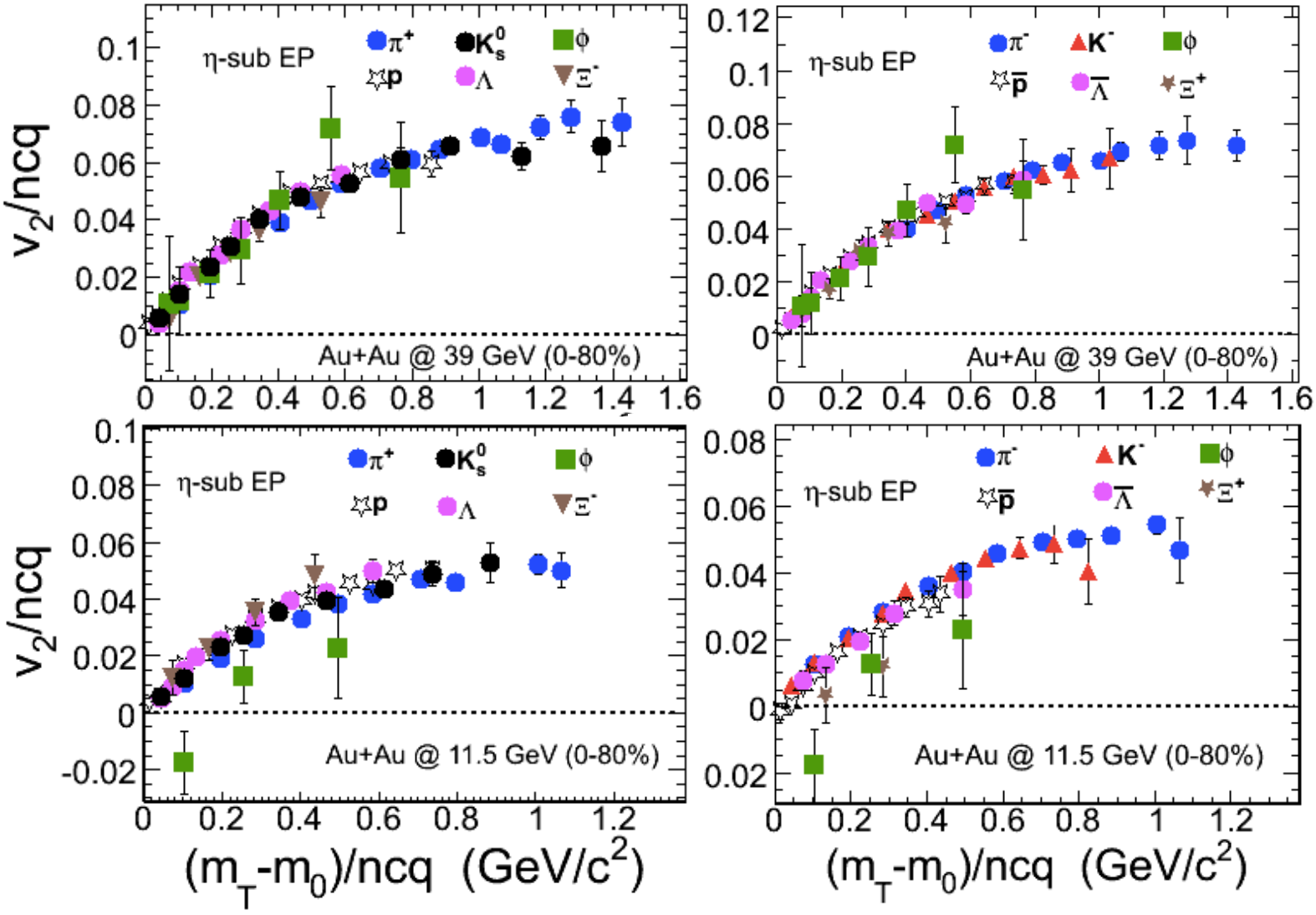
At $\sqrt{s_{NN}} \leq$ *11.5 GeV:*

- v_2(baryon) > v_2(anti-baryon)
- v_2(π^+) < v_2(π^-)
- v_2(K^-) < v_2(K^+)

STAR: Quark Matter 2011

Hadronic interactions are dominant

ϕ-meson v_2



The φ v_2 falls off trend from other hadrons at 11.5 GeV

Summary: NCQ-Scaling in v_2

1) Partonic collectivity in 200 GeV collisions

2) At $\sqrt{s_{NN}} \leq 11.5$ GeV
- v_2(baryon) > v_2(anti-baryon)
- $v_2(\phi) < v_2$(hadron)

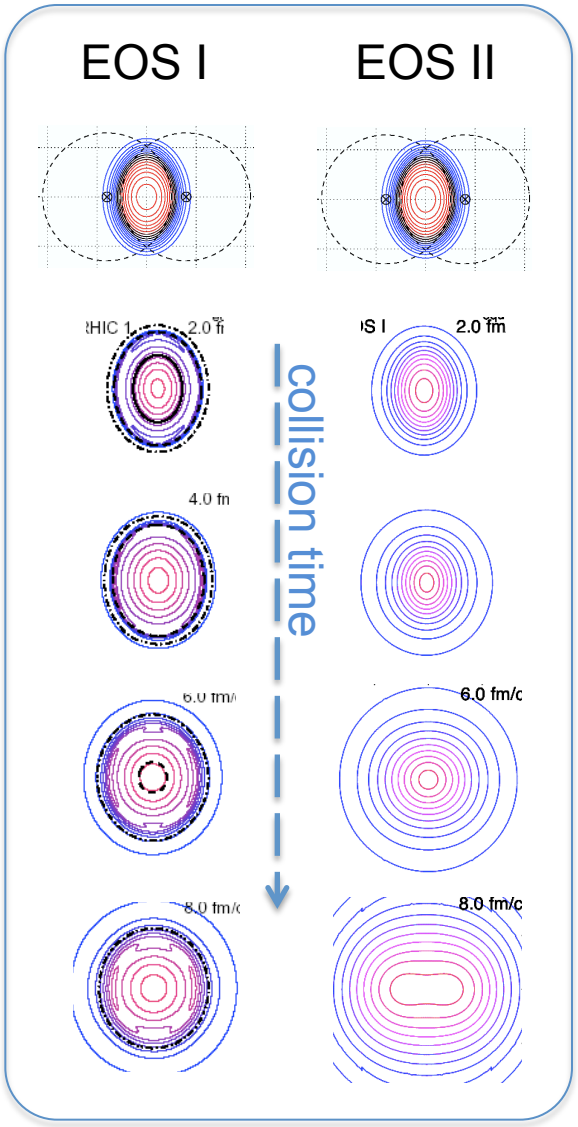
➔ v_2-NCQ-scaling broken

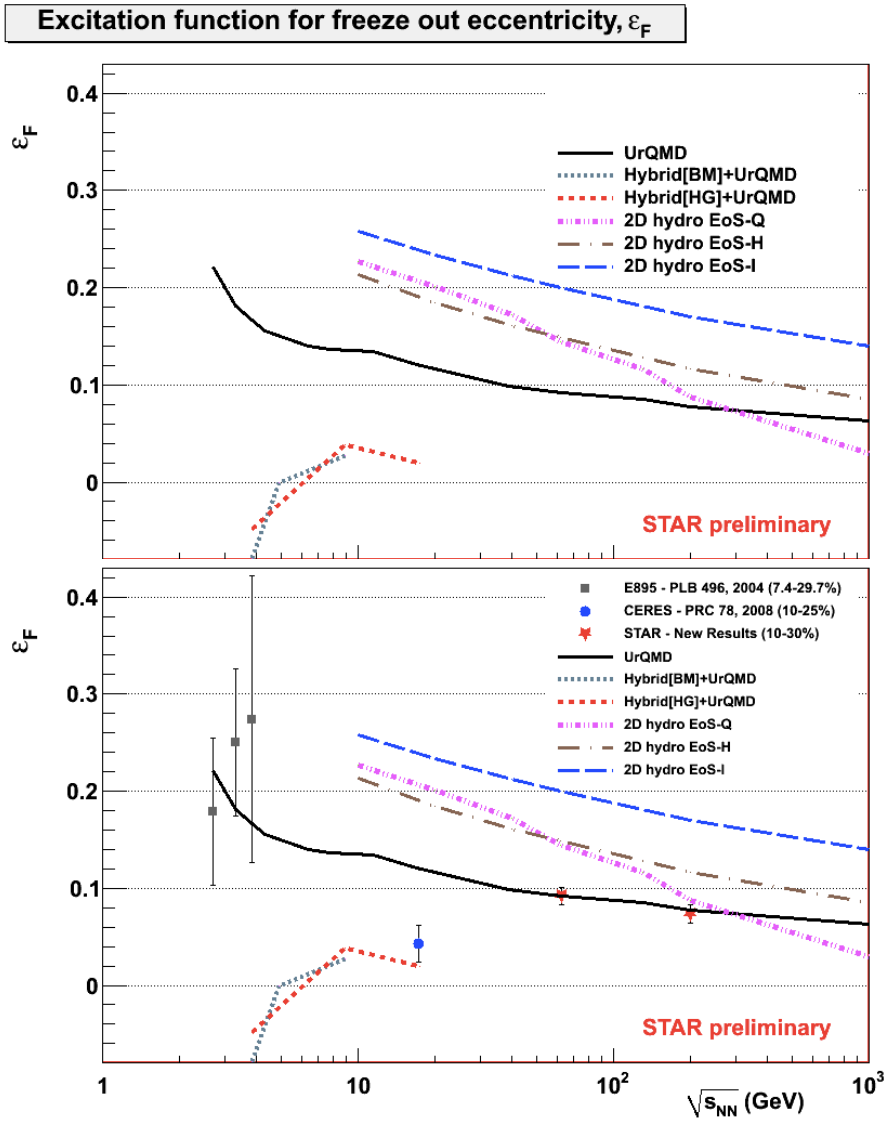
➔ **[hadronic]** ⌫ $\sqrt{s_{NN}} \leq 11.5$ GeV

[partonic] ⌫ $\sqrt{s_{NN}} \geq 39$ GeV

Where is the critical point?

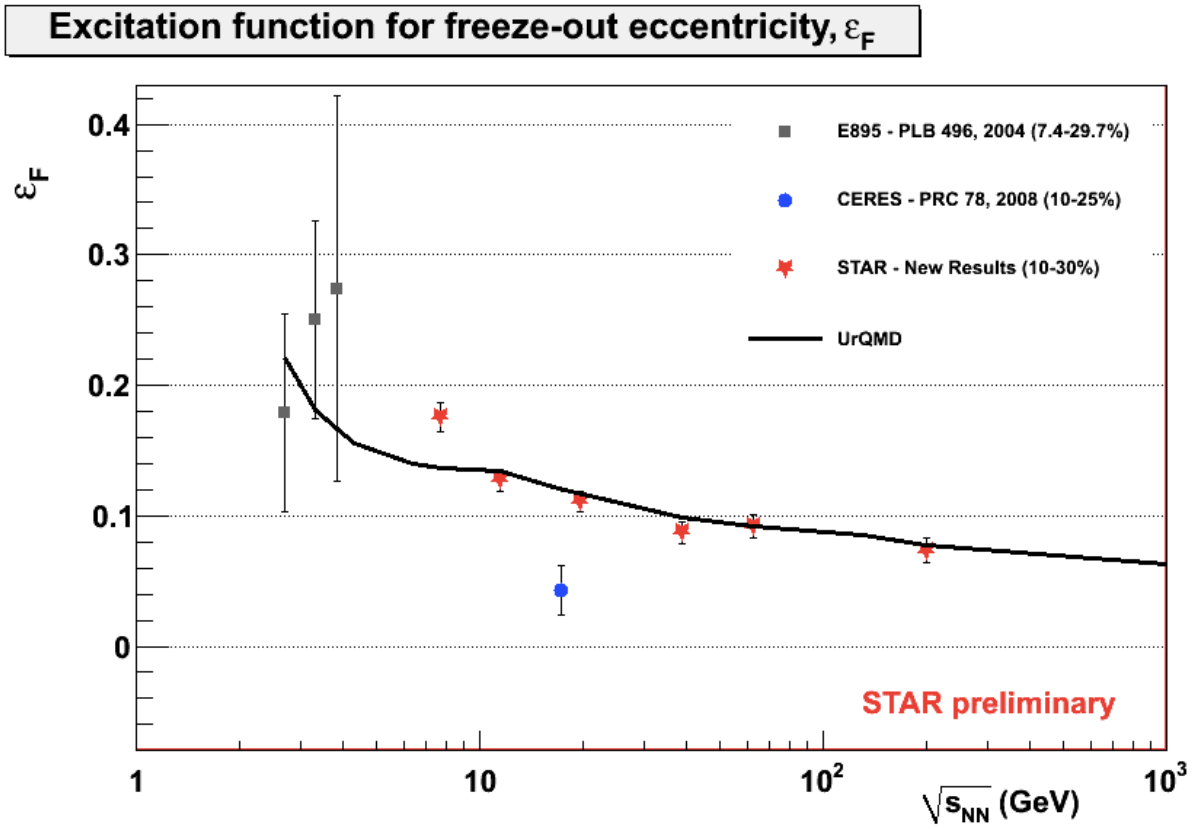
Azimuthal Dependence of HBT Parameters





Azimuthal Dependence of HBT Parameters

Exp.	Centrality
E895	7.5-30%
NA45	10-25%
STAR	10-30%



1) RHIC BES HBT results show a smooth decreasing as beam energy increasing.
2) uRQMD model predicts similar trend
3) NA45 result is not reproduced

Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i/T)^2 K_2(m_i/T)\cosh[(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_C}, \frac{\mu_q}{T}\right)\Big|_{T/T_C}, \qquad q = B, Q, S$

Conserved Quantum Number

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

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

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

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

$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

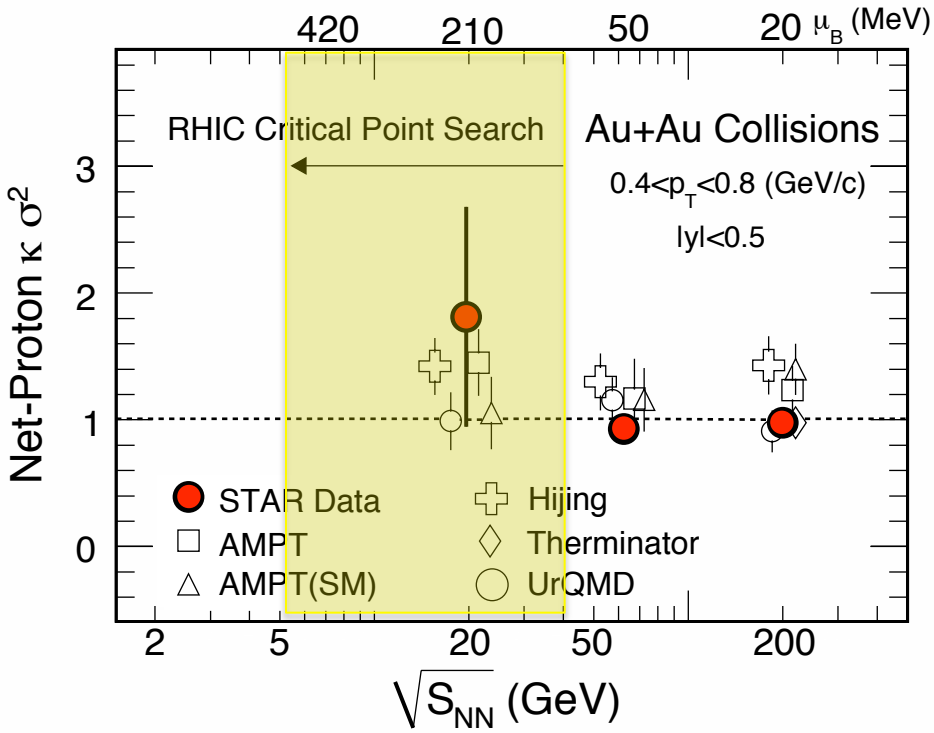
$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

Model calculations, *e.g.* LGT, HRG ⇔ Measurements

First Results from RHIC

STAR: *PRL, **105**, 22302(2010)*



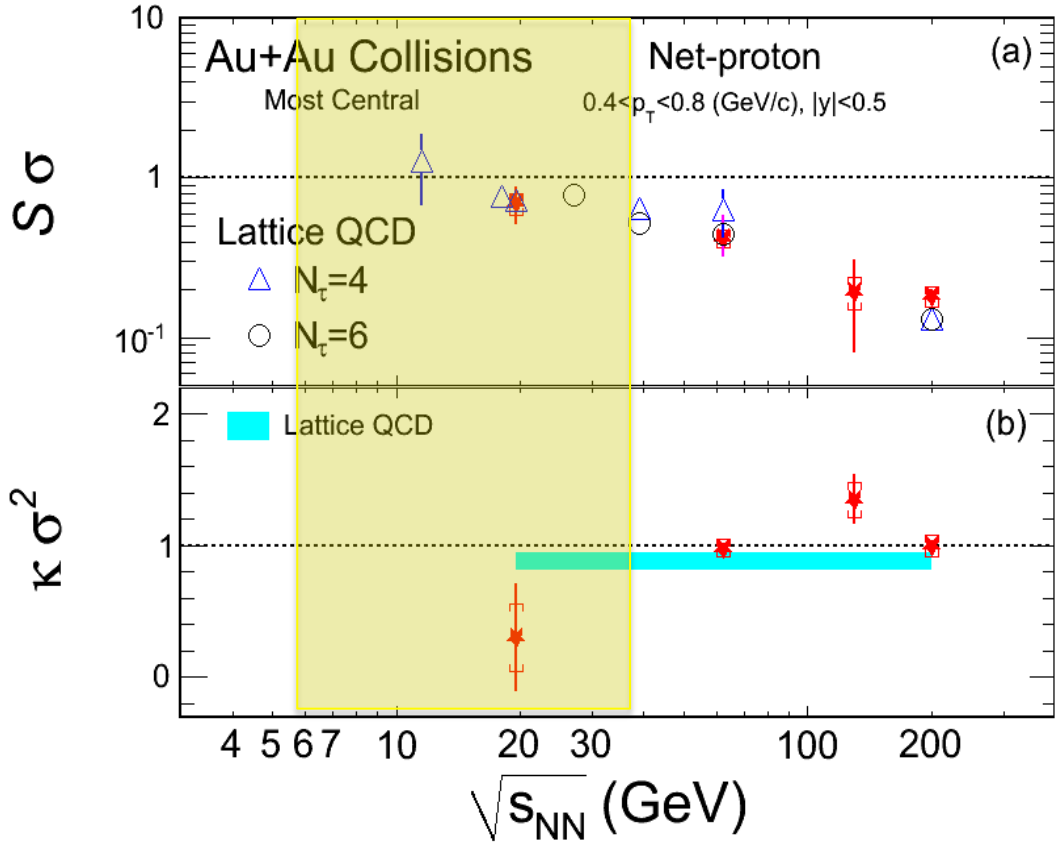
Energy Scan in Au+Au collisions:

Run 10: 7.7, 11.5, 39 GeV
Run 11: 19.6, 27 GeV

1) Centrality averaged events. In this analysis, effects of volume and detecting efficiencies are all canceled out.
2) ALL transport model results values are higher than unity, except the Theminator result at 200GeV. LGT predicted values around 0.8-0.9, due to finite chemical potential effect.
3) Test of thermalization with higher moments.
4) **Critical point effect**: non-monotonic dependence on collision energy.

• STAR: PRL105, 22302(2010).
• F. Karsch and K. Redlich, arXiv:1007.2581

Comparing with LGT Results



References:
- STAR, *PRL105, 22303(10)*
- F. Karsch and K. Redlich, *PLB695, 136(11)*
- R.V. Gavai and S. Gupta: *PLB696, 459(11)*

Assumptions:

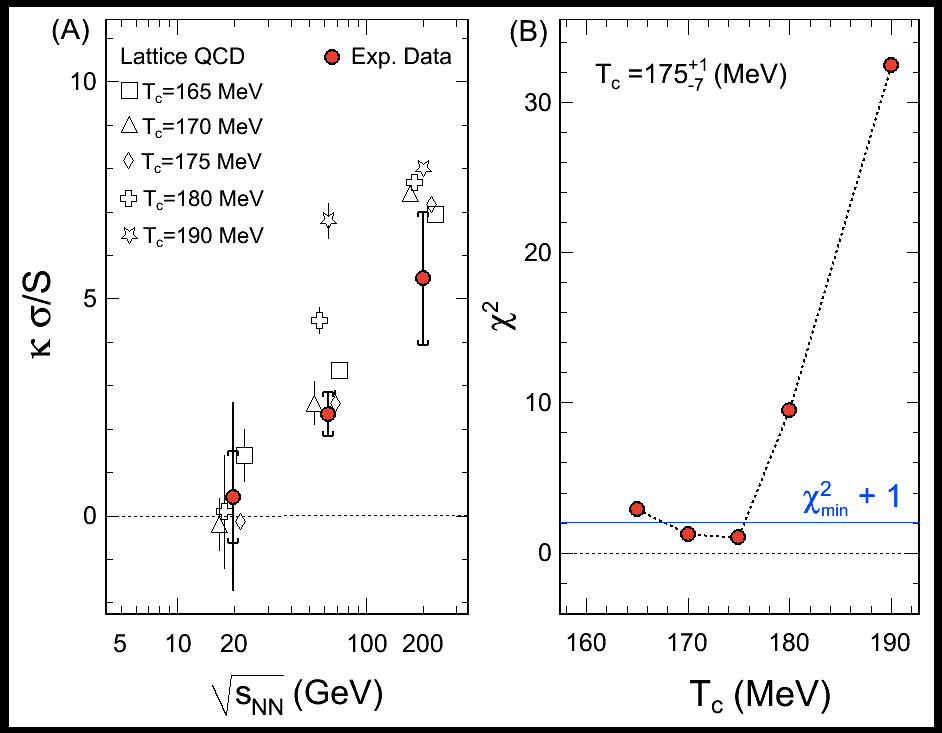
(a) Freeze-out temperature is close to LGT T_C

(b) Thermal equilibrium reached in central collisions

(c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

➔ **Lattice results are consistent with data for 60 < $\sqrt{s_{NN}}$ < 200 GeV**

Scale of Hot/Dense Matter on LGT



Science
AAAS

June, 2011

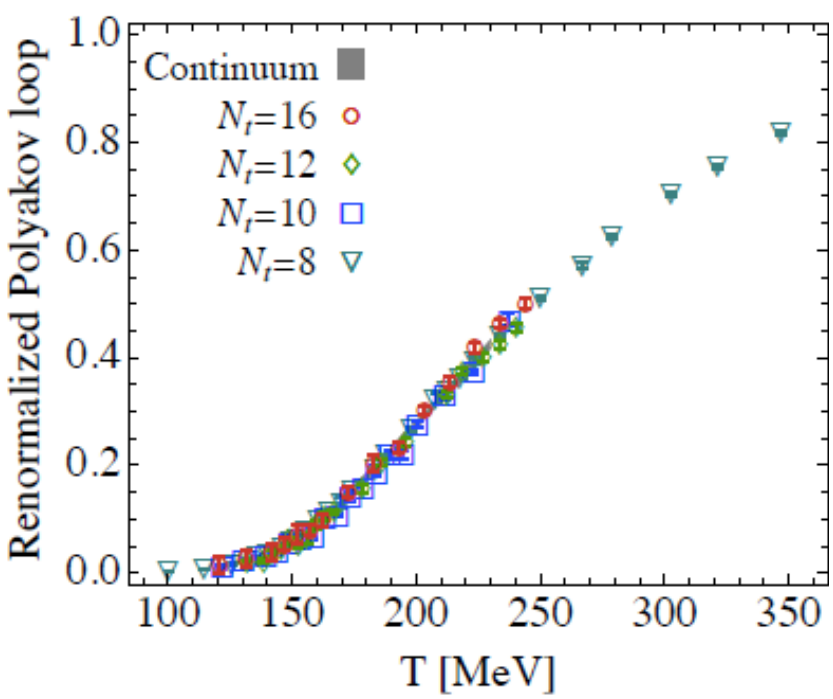
"Scale for the Phase Diagram of Quantum Chromodynamics"

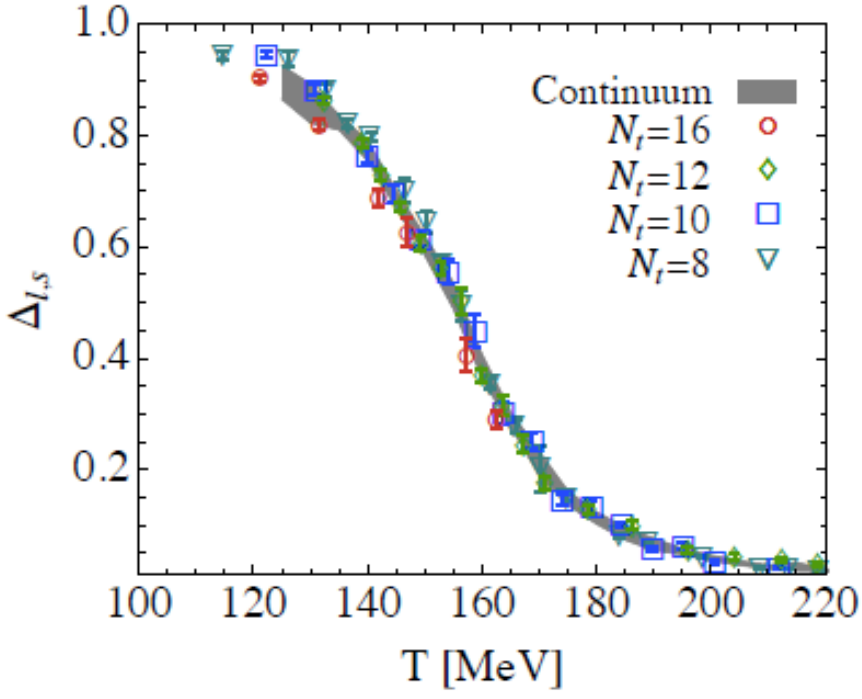
Science, 332, 1525(2011)

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)

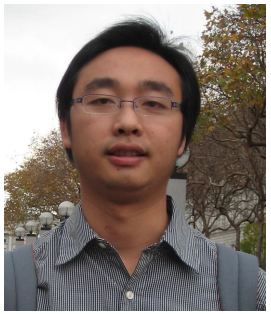
STAR, ***PRL****105, 22303(2010);* S. Gupta, X.F. Luo, B. Mohanty, H.G. Ritter, NX, ***Science****, 332, 1525(2011);* F. Karsch and K. Redlich, ***PLB****695, 136(2011);* R.V. Gavai and S. Gupta, ***PLB****696, 459(2011).*

Lattice: Phase Transition Temperature

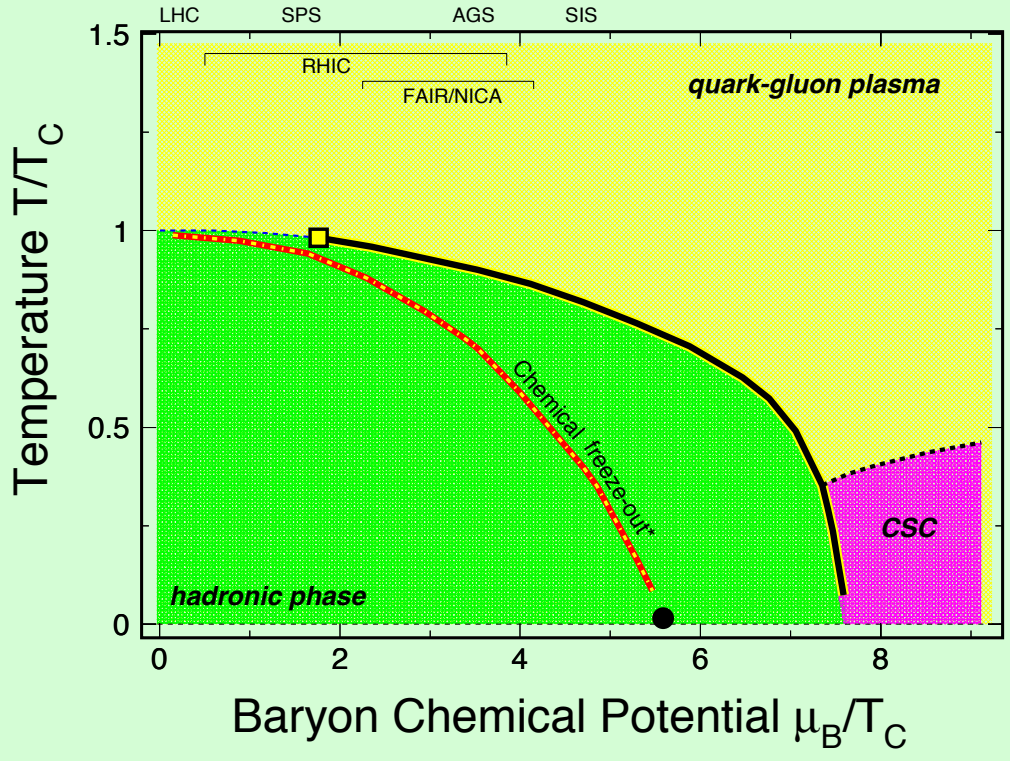




Action	Temperature
Polyakov Loop	$T_c^{conf} \sim 170$ MeV
Chiral Operator	$T_c^{chiral} \sim 160$ MeV
RHIC Data	$T_c^{Exp} \sim 175^{+1}_{-7}$ MeV



Sourendu Gupta, Xiaofeng Luo, Bedanga Mohanty, Hans-George Ritter, NX, ***Science**, 332, 1525(2011).*



Science
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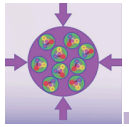
June, 2011

"Scale for the Phase Diagram of Quantum Chromodynamics"

$T_c = 175^{+1}_{-7}$ (MeV)

Science*, *332, 1525(2011)



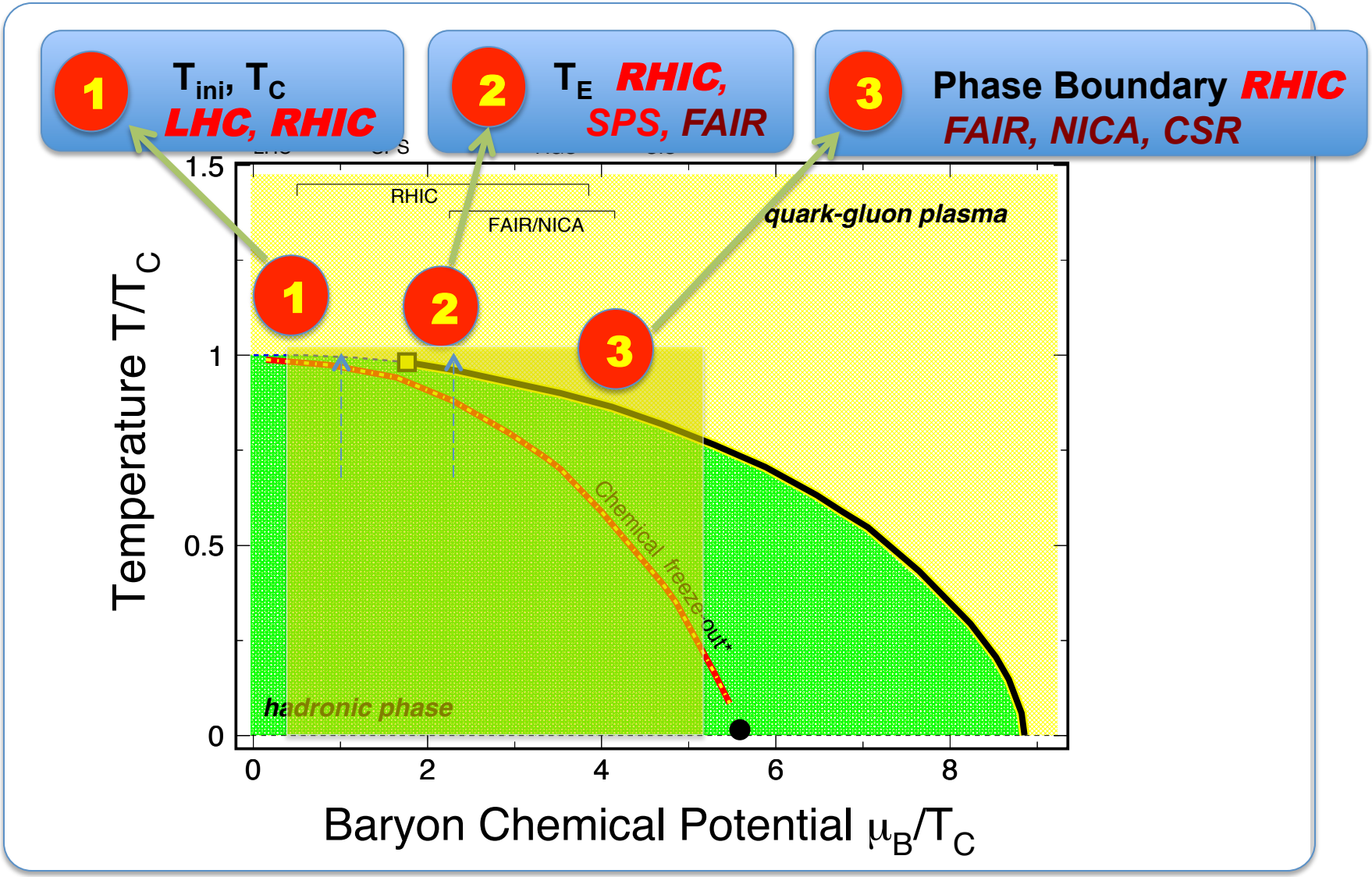
Summary

(1) In high-energy nuclear collisions, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

(2) **[partonic dominant]**
< μ_B ~*110–320* (MeV) <
[hadronic dominant]

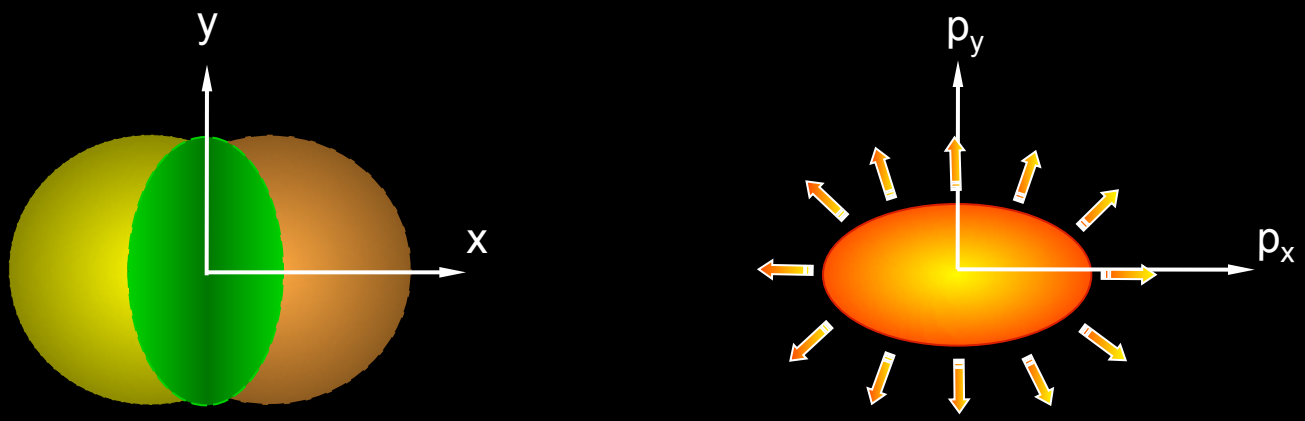
(3) Net-proton distributions are consistent with LGT results. QCD Scale: $T_c = 175^{+1}_{-7}$ **(MeV)**

BES: (5400, 200, 62.4, 39, 27, 19.6, 15.5, 11.5, 7.7: 8 – 1 GeV)



Anisotropy Parameter v_2

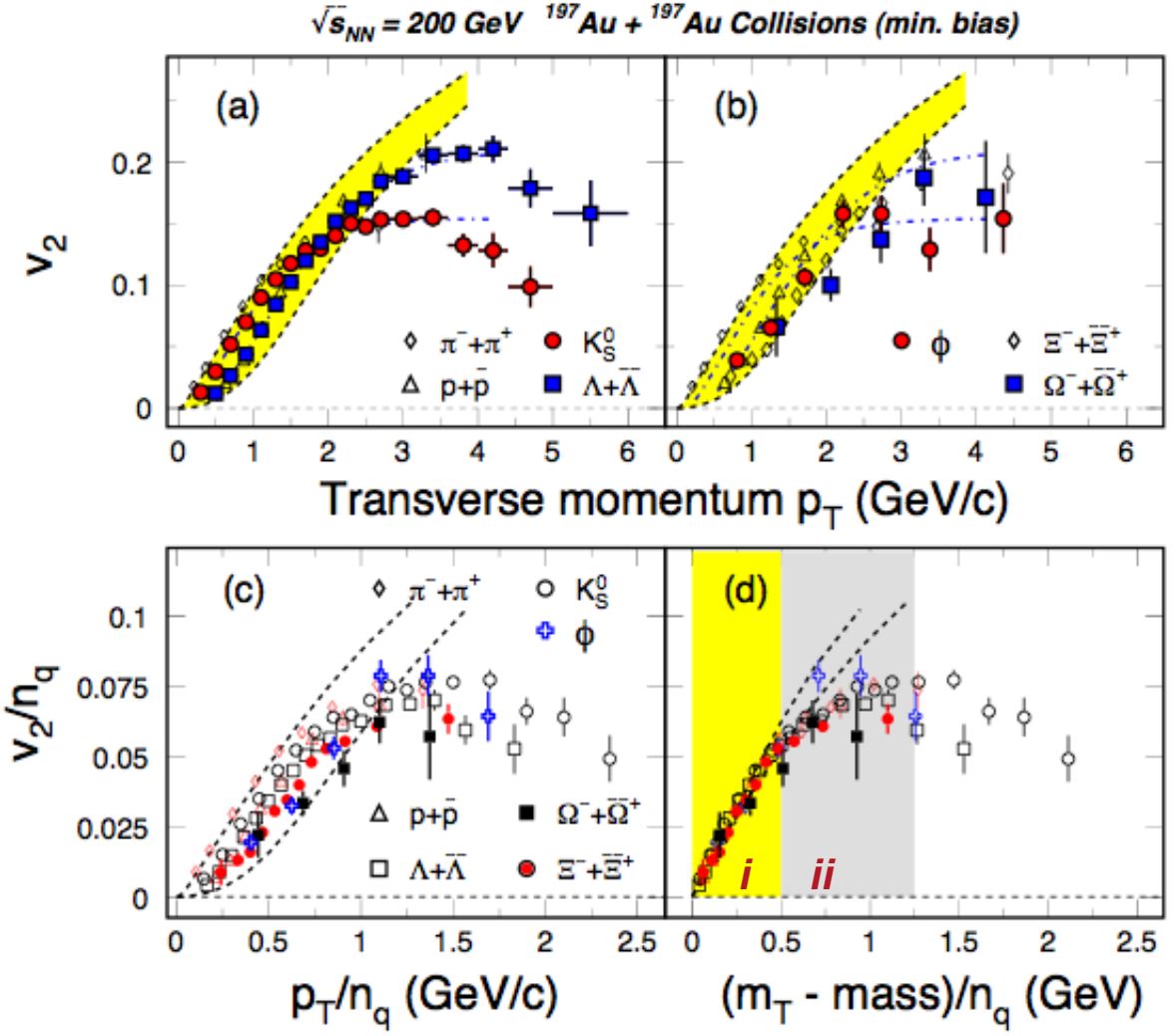
coordinate-space-anisotropy ⇨ momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

➪ **m_T - NQ scaling**

➪ **De-confinement**

*PHENIX: PRL **91**, 182301(03)*
*STAR: PRL **92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

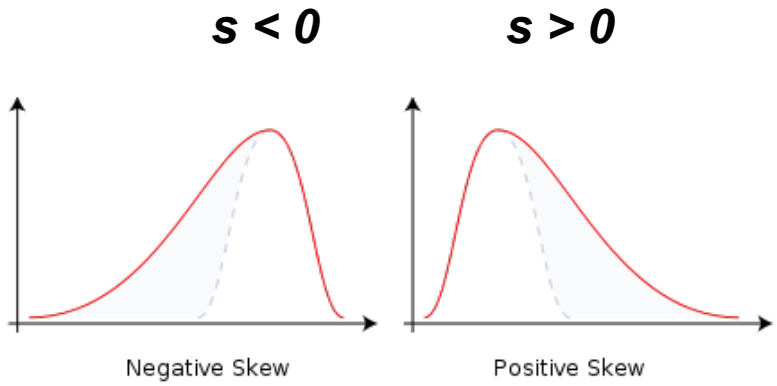
S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

Non-Gaussian Fluctuations

N: event by event multiplicity distribution

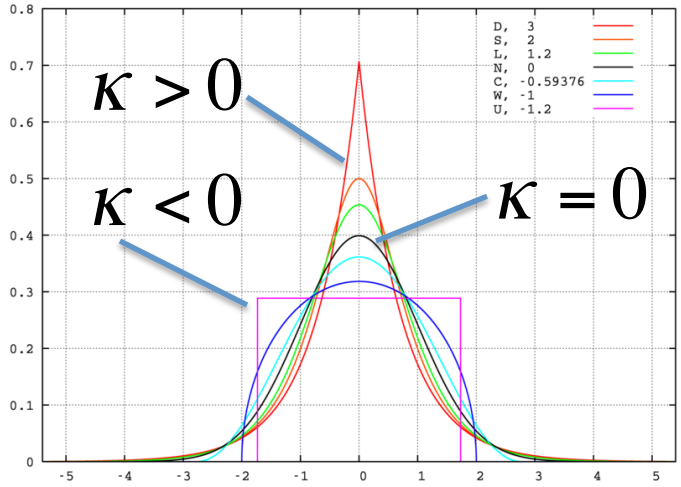
$$m = \langle N \rangle \qquad s = \frac{\left\langle \left(N - \langle N \rangle\right)^3 \right\rangle}{\sigma^3}$$

$$\sigma = \sqrt{\left\langle \left(N - \langle N \rangle\right)^2 \right\rangle} \qquad \kappa = \frac{\left\langle \left(N - \langle N \rangle\right)^4 \right\rangle}{\sigma^4} - 3$$

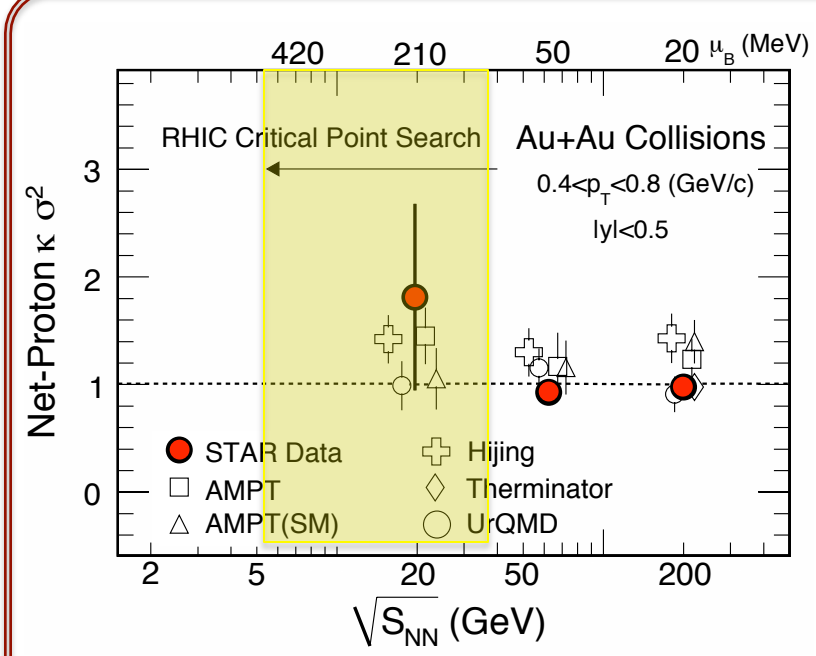


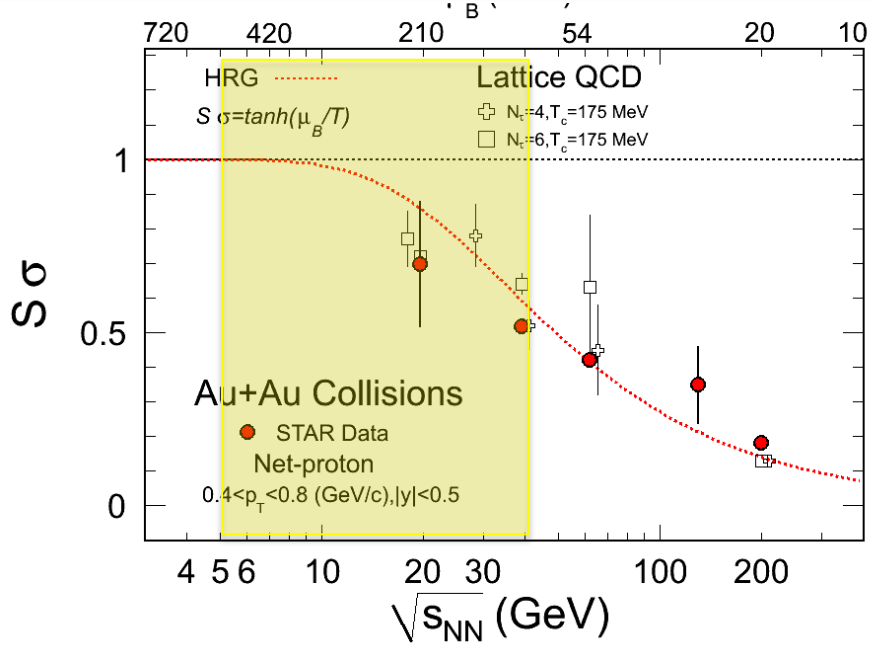
For a Gaussian distribution, the *s=0, κ=0.* **Ideal probe of the non-Gaussian fluctuations at critical point.**

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena**.
Price: large number of events required.



High Moments: Critical Point Search





- Measure conserved quantities, ***B, s, and Q***.
- **First:** High order fluctuation results consistent with thermalization.
- **First:** Tests the *long distance QCD* predictions in hot/dense medium.

Caveats: (a) static vs. dynamic; (b) net-B vs. net-p; (c) potential effects of freeze-out…

- R. Gavai, S. Gupta, 1001. 3796 / F. Karsch, K. Redlich, 1007.2581 / M. Stephanov, 0911.1772.
- STAR: PRL105, 02232(2010) and references therein.