Beam energy and centrality dependence of the statistical moments of the net-charge and net-Kaon multiplicity distributions in Au+Au collisions at STAR

Daniel McDonald for the STAR Collaboration
Rice University
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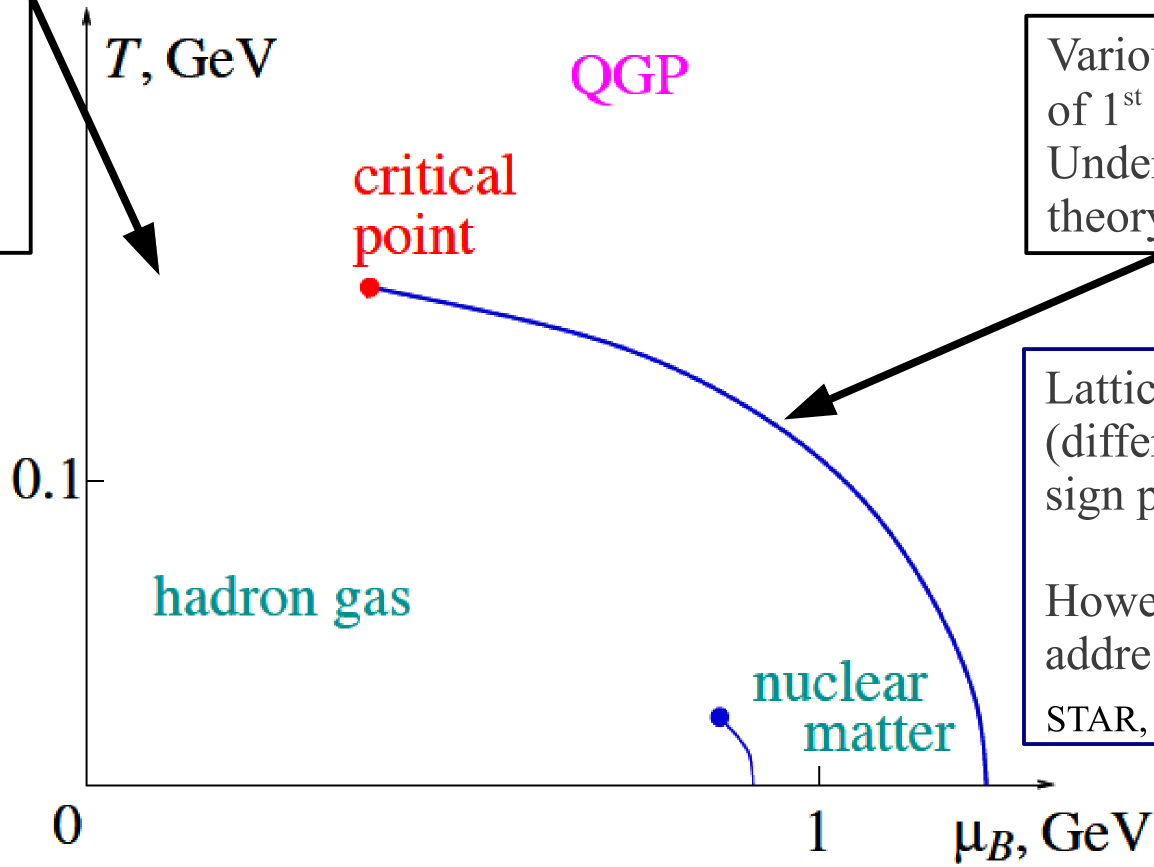
QCD phase diagram

- Top RHIC energies
- baryochemical potential is small
- crossover transition



Various indirect suggestions of 1st order phase transition. Under discussion in the theory community.

Lattice QCD is difficult (different actions, numerical sign problem).

However, this topic can be addressed experimentally!

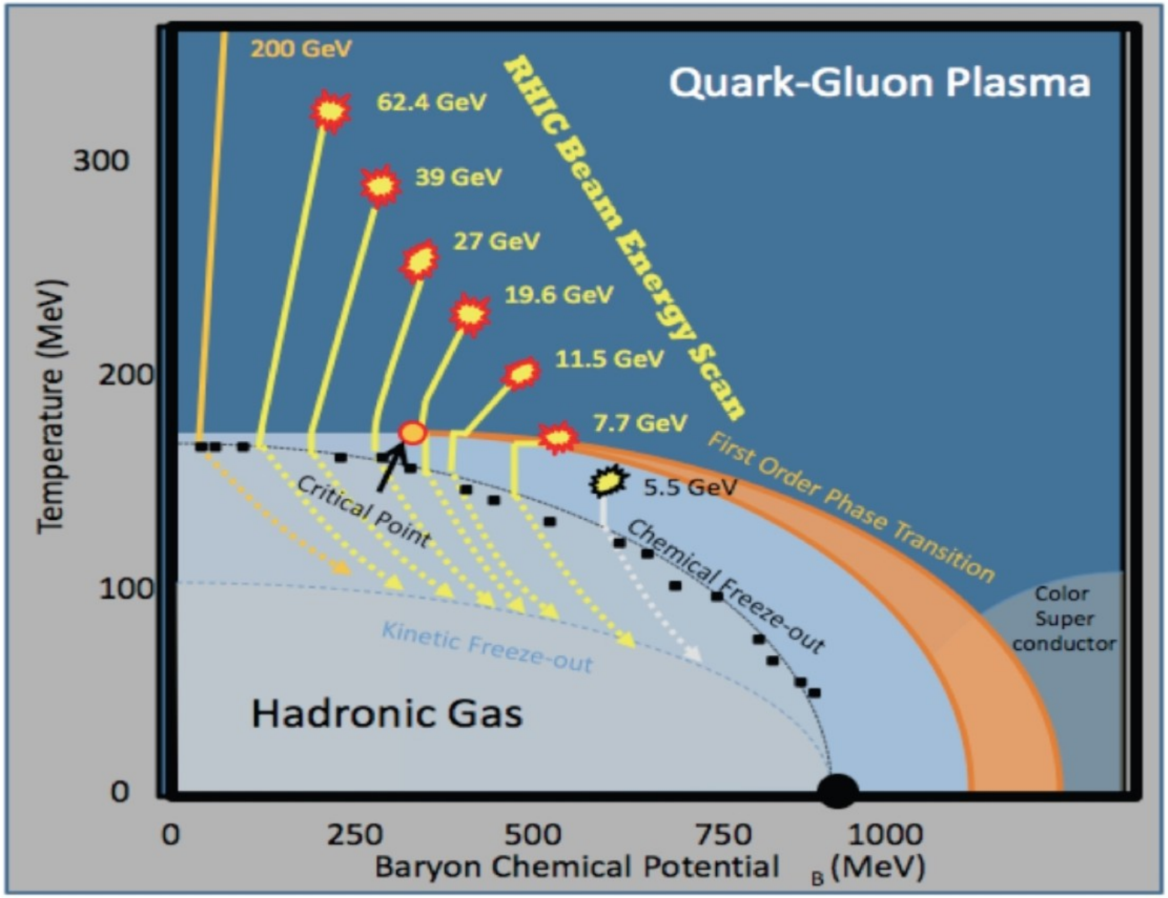
STAR, arXiv:1007.2613 [nucl-ex]

Thus, a critical point (CP) might exist somewhere in between these extremes at the end of the 1st order phase transition…

QCD phase diagram

STAR, arXiv:1007.2613 [nucl-ex]

- Varying the beam energy results in different trajectories through this space. Decreasing the beam energy results in larger μ_B values, as shown in the cartoon below.



STAR Beam Energy Scan (BES) data sets from RHIC Runs 10 and 11 (2010-2011)

$\sqrt{s_{NN}}$(GeV)	MB Events in 10^6	μ_B (MeV)
7.7	4.3	421
11.5	11.7	316
19.6	35.8	206
27	70.4	156
39	130.4	112
62.4	67.3	73
200	587	24

For the conversion from $\sqrt{s_{NN}}$ to μ_B, please see Cleymans et al. PRC **73**,034905 (2006)

- We will be describing data collected by the STAR experiment at:

$$\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4, 200 \text{ GeV}$$

Correlation length divergence near the critical point

At the critical point the correlation length, ξ, should diverge.

- "critical opalescence"

For T~Tc, substance becomes "cloudy," indicating long-range density fluctuations.

→

T. Andrews, Phil. Trans. Royal Soc., 159:575, 1869
A. Einstein, *Annalen der Physik,* 33 (1910) 1275-1298

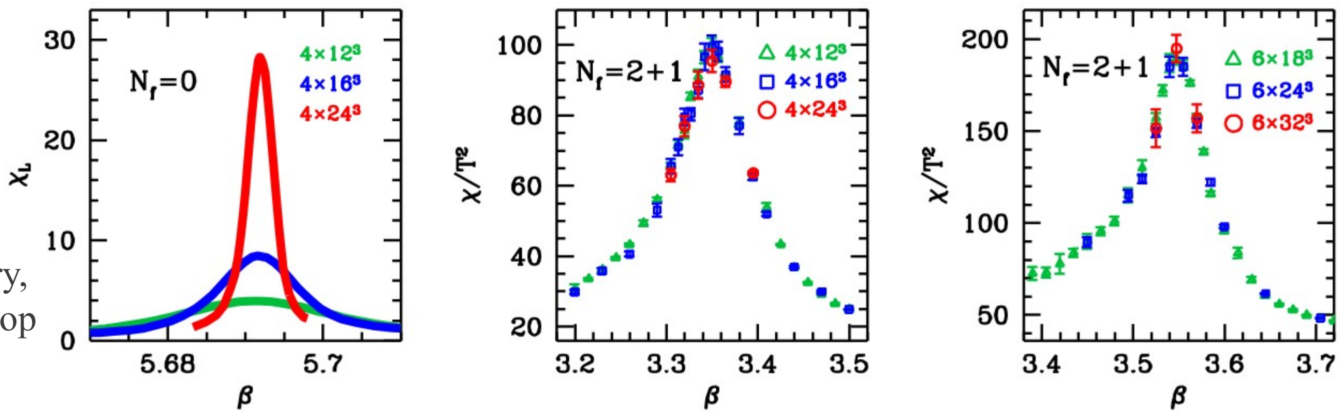
At the critical point, the susceptibility, χ, should diverge.

$$\chi_n^B = -\frac{1}{3^n}\frac{\partial^n f/T^4}{\partial \hat{\mu}_q^n}$$

← Susceptibility is the derivative of free energy vs. baryochemical potential

Susceptibilities
Z. Fodor, **PoS**, 11, 2007

Pure SU(3) Gauge Theory, Polyakov Loop



Full QCD, Lattice

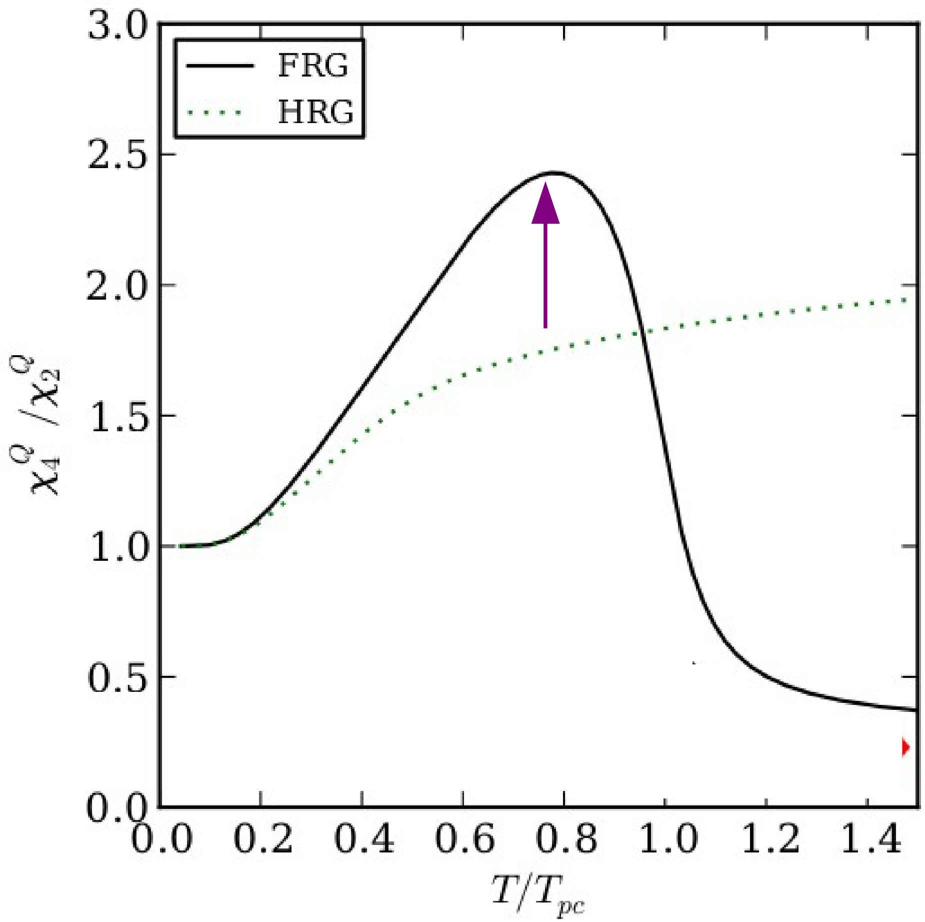
β ~ temperature

Different volumes (lattice sizes) in different colors

Electric charge susceptibility

Charge susceptibility, χ^Q, may be sensitive to the chiral phase transition.

Skokov et al, **PLB**, 708, 2012, 179-185.



HRG = Hadron Resonance Gas.
FRG = Functional Renormalization Group

Andronic et al. **PLB**, 571 (2003).

$$\chi_n^Q = \frac{1}{2^n}\left[\chi_n^B + \chi_n^I + \sum_{i=1}^{n-1}\binom{i}{n}\frac{\partial^n(p\beta^4)}{\partial(\beta\mu_I)^i\partial(\beta\mu_B)^{n-i}}\right]$$

Fluctuations of χ^Q are related to net-baryon (χ^B) and isospin (χ^I) fluctuations.

Charge susceptibility ratios are related to the correlation length, ξ:

$$\sim \quad \chi_3^Q/\chi_2^Q \sim \xi^{5/2}$$

$$\sim \quad \chi_4^Q/\chi_2^Q \sim \xi^{5}$$

Strong dependence on ξ, so may reflect long-range correlations near the critical point.

Gavai, Gupta. **PLB**, 696 (2011), 459-463

Experiment observables

We measure the multiplicity distributions of particles and the multiplicity cumulants.

number in an event

average number over an ensemble of events

"deviate" $\delta x \equiv x - \langle x \rangle$

"cumulants"

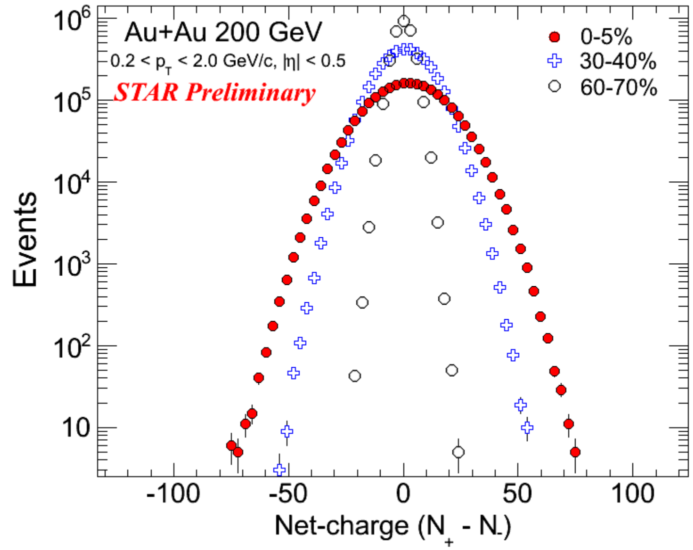
$$\kappa_{2x} \equiv \langle\langle x^2 \rangle\rangle \equiv \langle (\delta x)^2 \rangle$$

$$\kappa_{3x} \equiv \langle\langle x^3 \rangle\rangle \equiv \langle (\delta x)^3 \rangle$$

$$\kappa_{4x} \equiv \langle\langle x^4 \rangle\rangle \equiv \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2$$

$$\text{skewness} = \frac{\kappa_3}{\kappa_2^{3/2}}, \quad \text{kurtosis} = \frac{\kappa_4}{\kappa_2^2}$$

"S" "K"



Final observables

$S\sigma = \kappa_3/\kappa_2$ $K\sigma^2 = \kappa_4/\kappa_2$

These cumulants of conserved charge are related not only to ξ, but also to χ^Q:

$$\kappa_3/\kappa_2 \sim \chi_3^Q/\chi_2^Q \sim \xi^{5/2}$$

$$\kappa_4/\kappa_2 \sim \chi_4^Q/\chi_2^Q \sim \xi^{5}$$

Gavai, Gupta. **PLB**, 696 (2011), 459-463

Near the critical point, the cumulants will diverge with large powers of the correlation length (ξ). Higher moments scale with higher powers of the correlation length.

$$\kappa_{2x} = \langle(\delta x)^2\rangle \sim \xi^2 \qquad \kappa_{3x} = \langle(\delta x)^3\rangle \sim \xi^{9/2}$$

$$\kappa_{4x} = \langle(\delta x)^4\rangle - 3\langle(\delta x)^2\rangle^2 \sim \xi^7$$

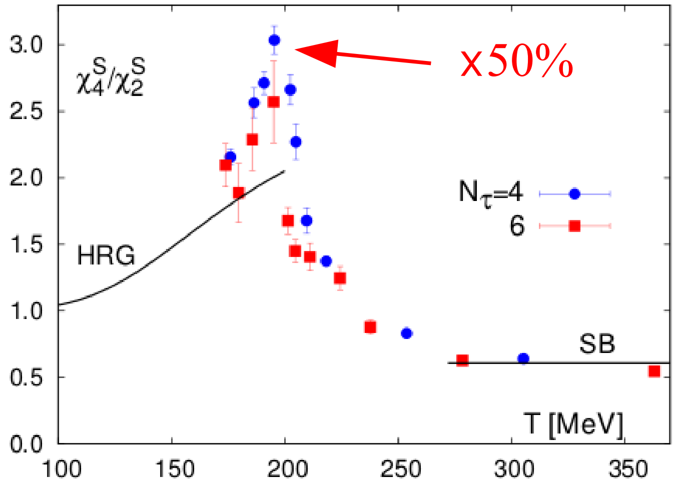
Stephanov PRL **102**, 032301 (2009)

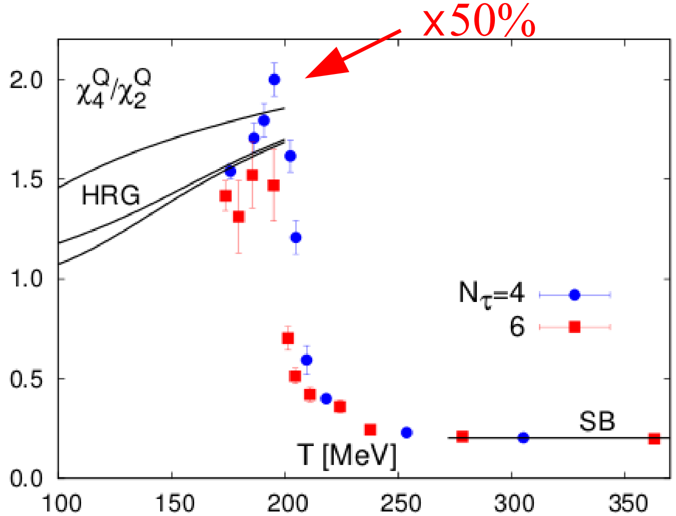
Sensitivity to critical phenomena

Lattice implies $K\sigma^2 = \chi_4^Q/\chi_2^Q$ and $K\sigma^2 = \chi_4^S/\chi_2^S$ increases by ~50%.

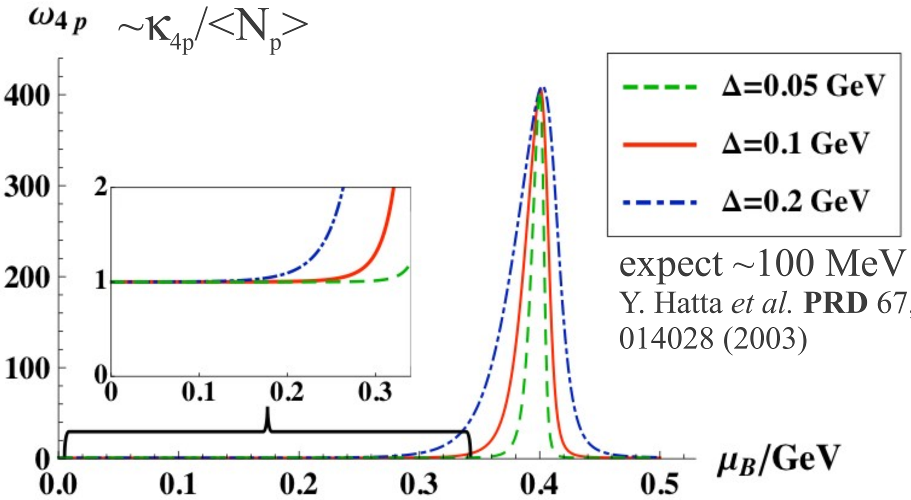
Non-linear sigma model predicts enhancements to the proton and pion cumulants of order 10-100.

Cheng, et al. **PhysRevD,**.79.074505



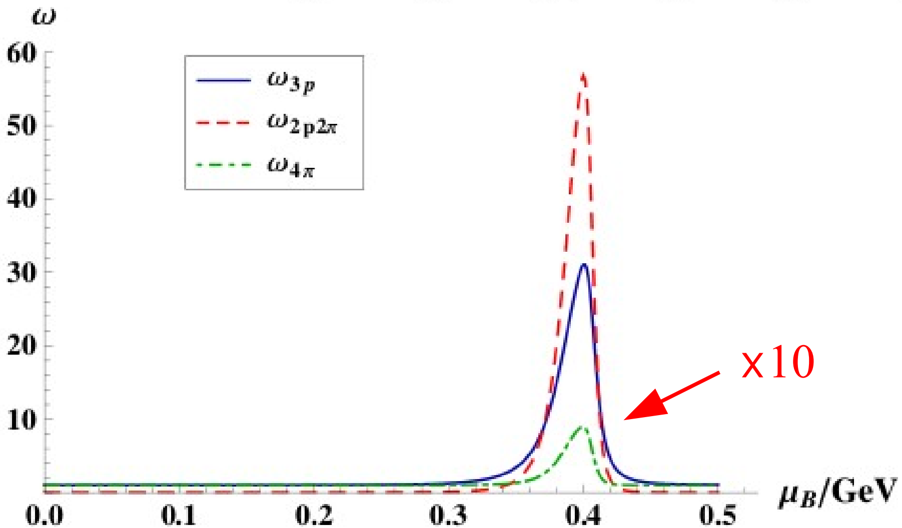


x400



expect ~100 MeV
Y. Hatta *et al.* **PRD** 67, 014028 (2003)

Athanasiou *et al.*
arXiv: 1006.4636v2 [hep-ph]

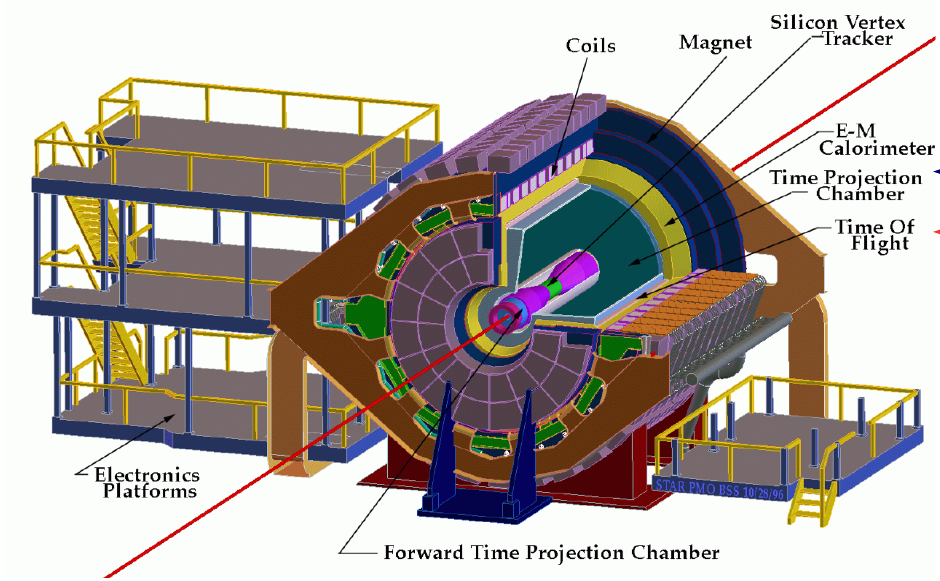


Both lattice and a phenomenological field theory model predict enhancements in κ_4 and $K\sigma^2$.

Analysis Details: Detectors and Cuts

Third and fourth moments may be very sensitive to possible critical fluctuations, but are also very sensitive to experiment effects (background, drift, etc). Care is made to remove these experimental effects via data QA and cuts.

Solenoidal Tracker at RHIC (STAR)



TPC (dE/dx PID)

TOF (TOF PID)

Only the most central 0-5% will be shown.

Error bars are statistical only and calculated using the Delta Theorem.

X. Luo, arXiv:1109.0593v1 [physics.data.an]

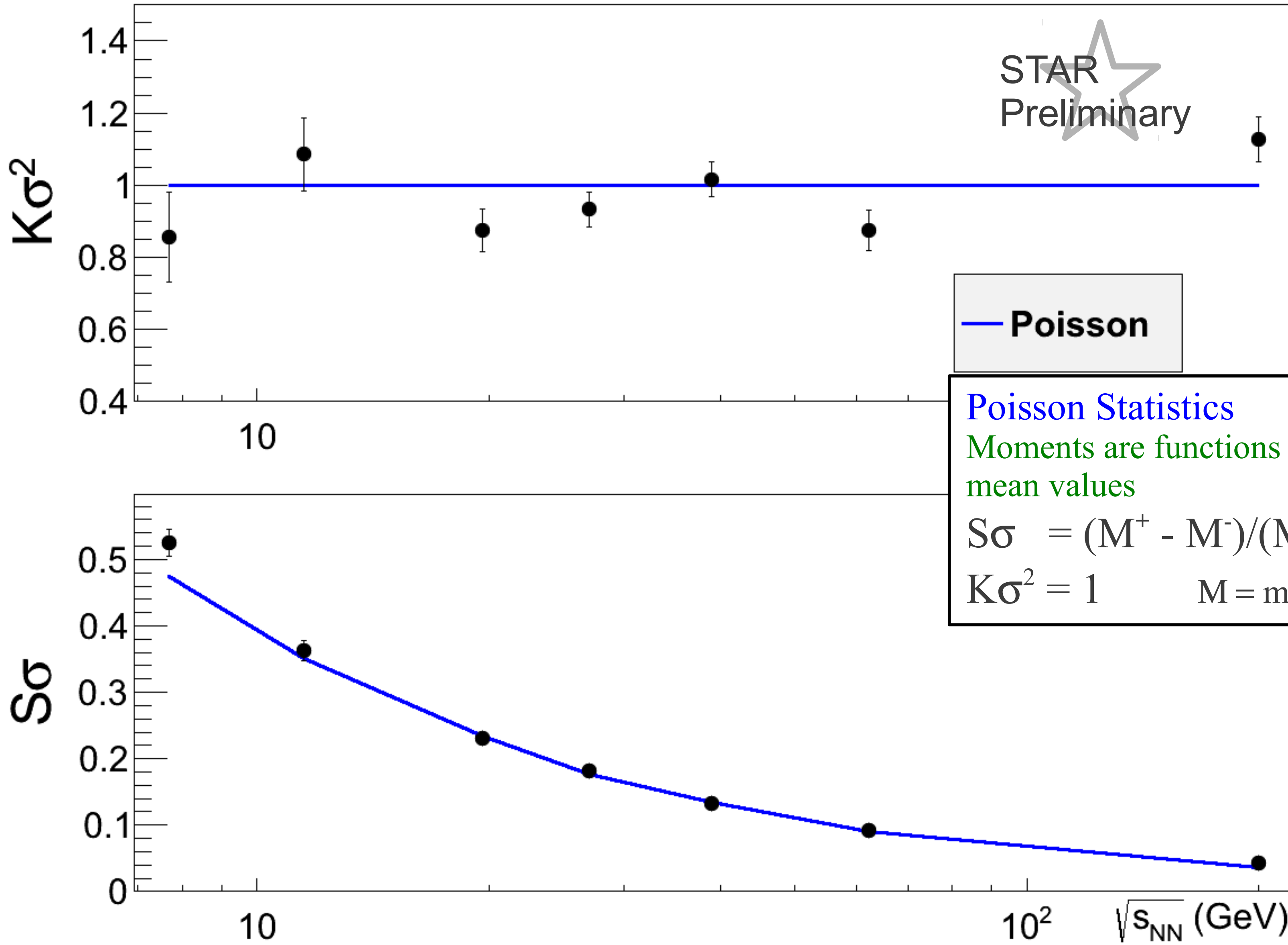
Will show moments products for 2 particle groups:

K^+-K^-	"net-Kaons"
pos-neg	"net-charge"

Numbers of events surviving cuts in the 0-80% centrality range

	7.7 GeV	11.5 GeV	19.6 GeV	27 GeV	39 GeV	62.4 GeV	200 GeV
# events	1.4 M	2.4 M	15.5 M	24.1 M	55.8 M	31.4 M	74.6 M

Sσ, Kσ² net-Kaons, 0-5% centrality



Poisson Statistics

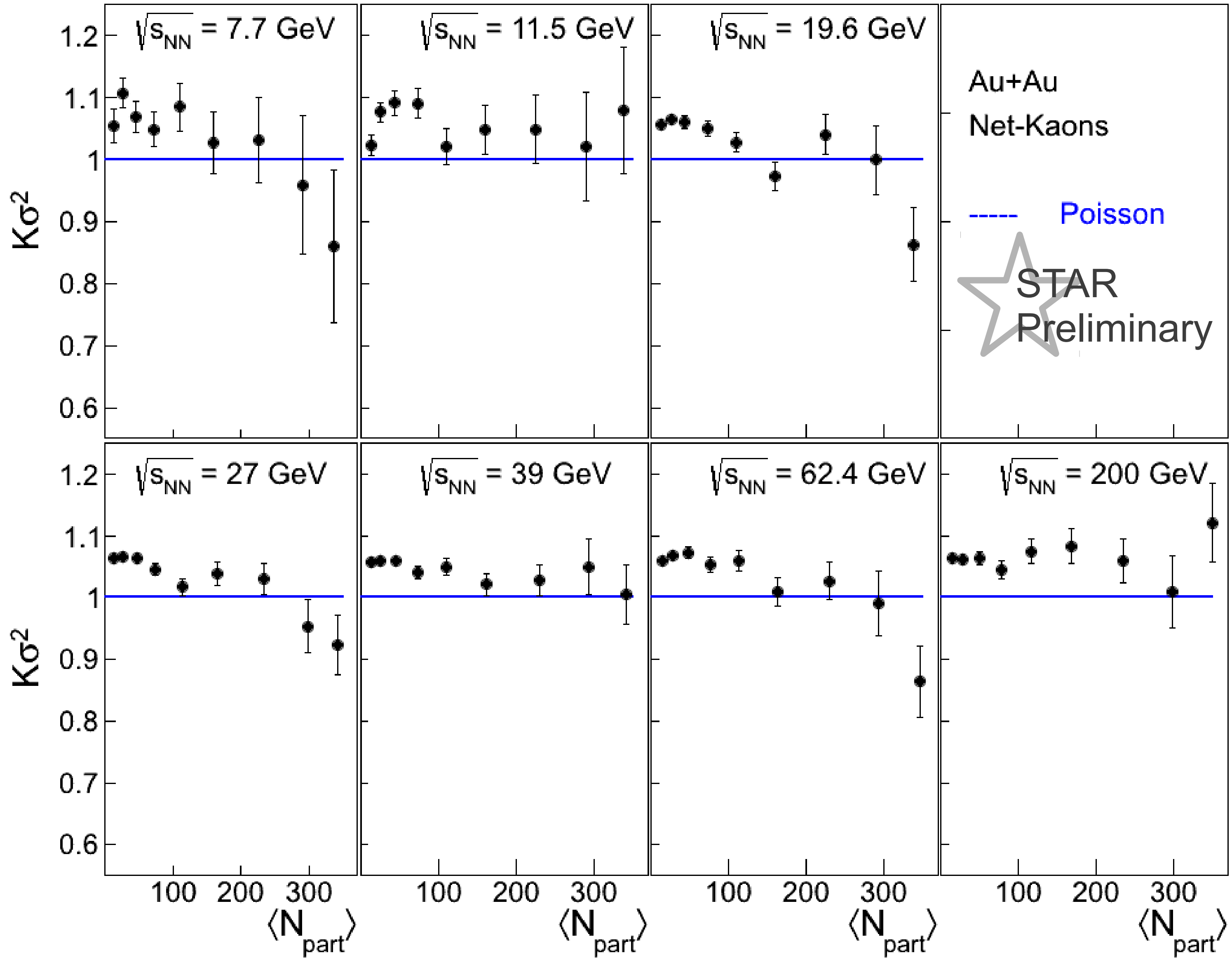
Moments are functions only of the mean values

$S\sigma = (M^+ - M^-)/(M^+ + M^-)$

$K\sigma^2 = 1$ M = mean value

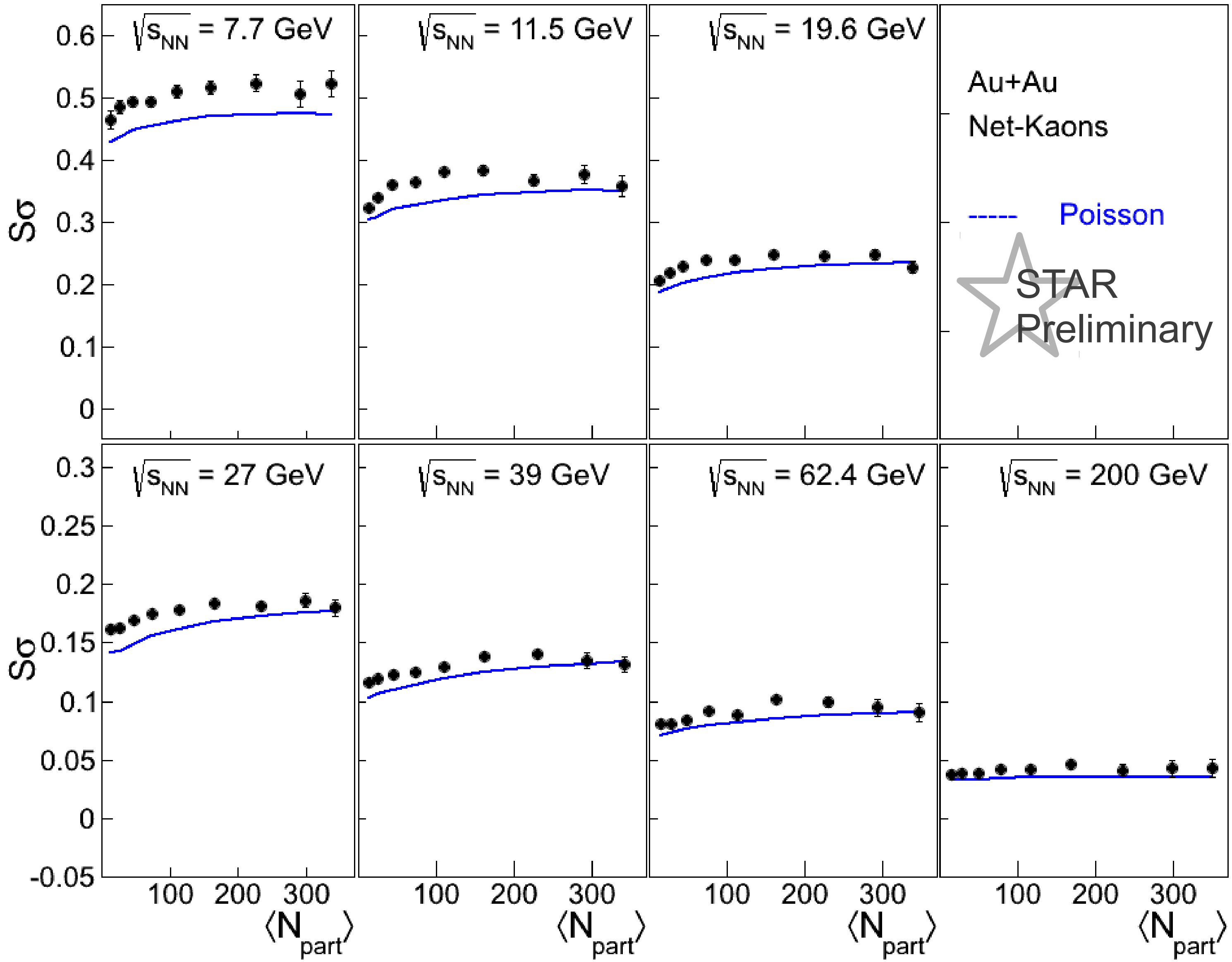
No significant enhancement relative to Poisson expectation observed.

$K\sigma^2$, net-Kaons, centrality dependence



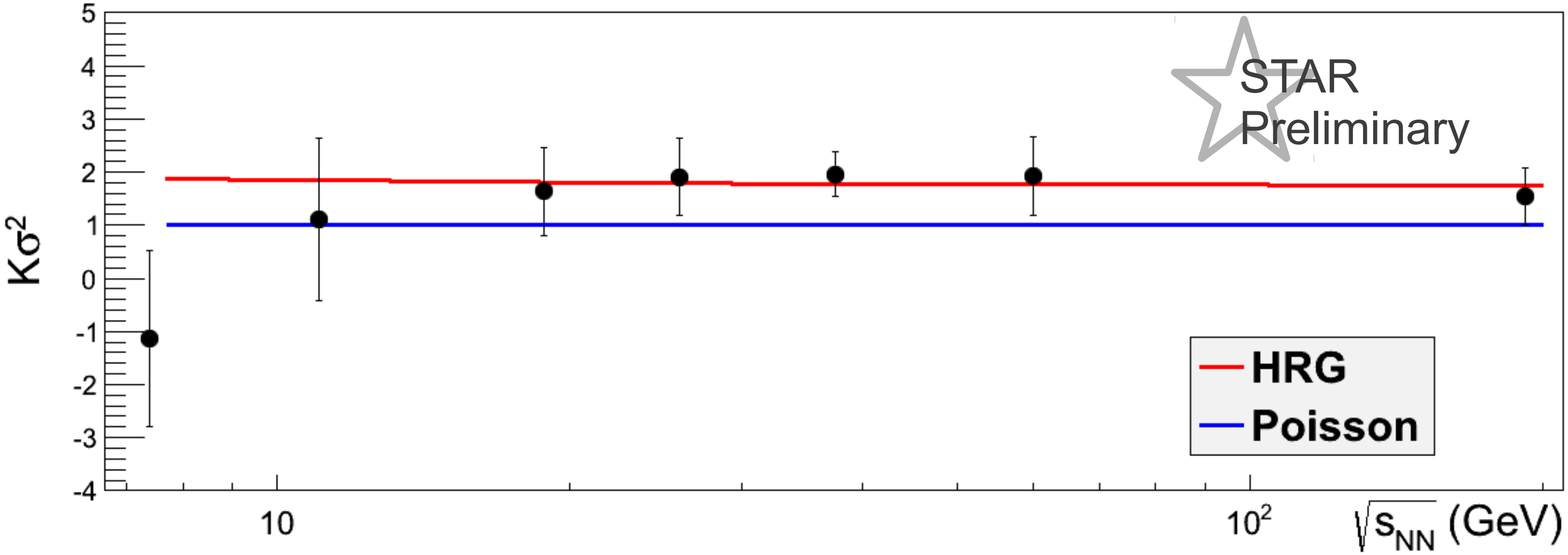
- $K\sigma^2$ is independent of centrality to within ~10%.
- $K\sigma^2$ is generally greater than the Poisson expectation.

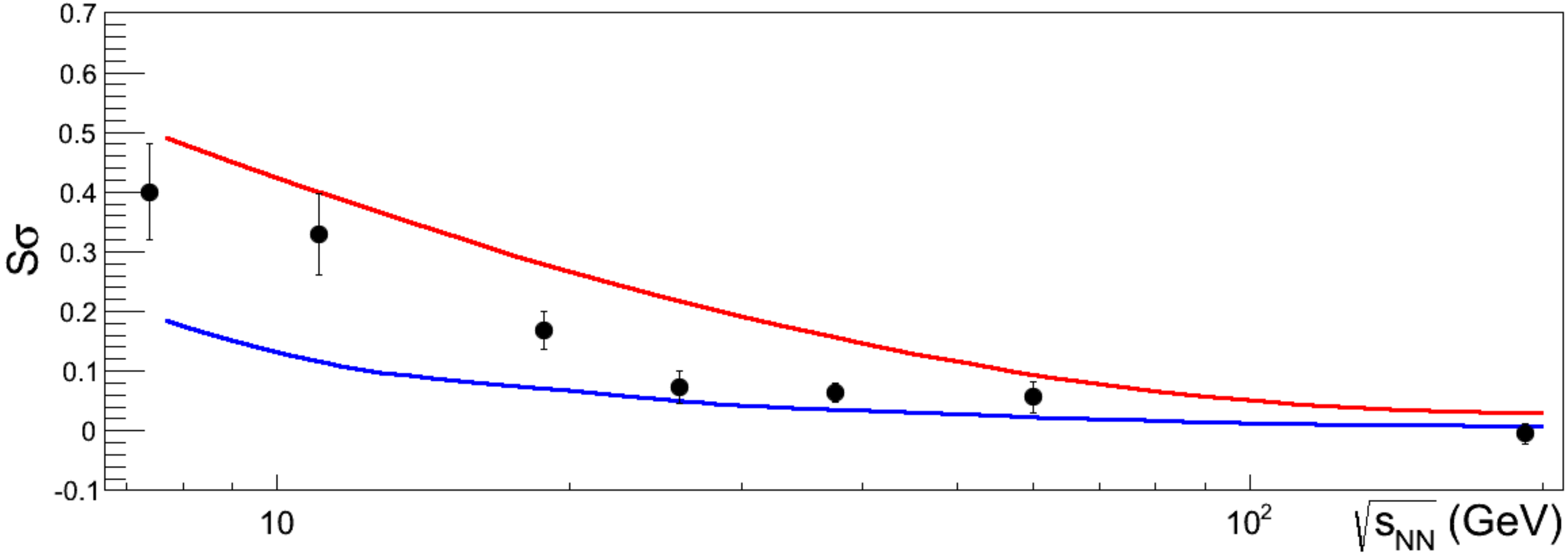
Sσ, net-Kaons, centrality dependence



- Sσ is independent of centrality to within ~15%.
- Sσ is greater than the Poisson expectation.

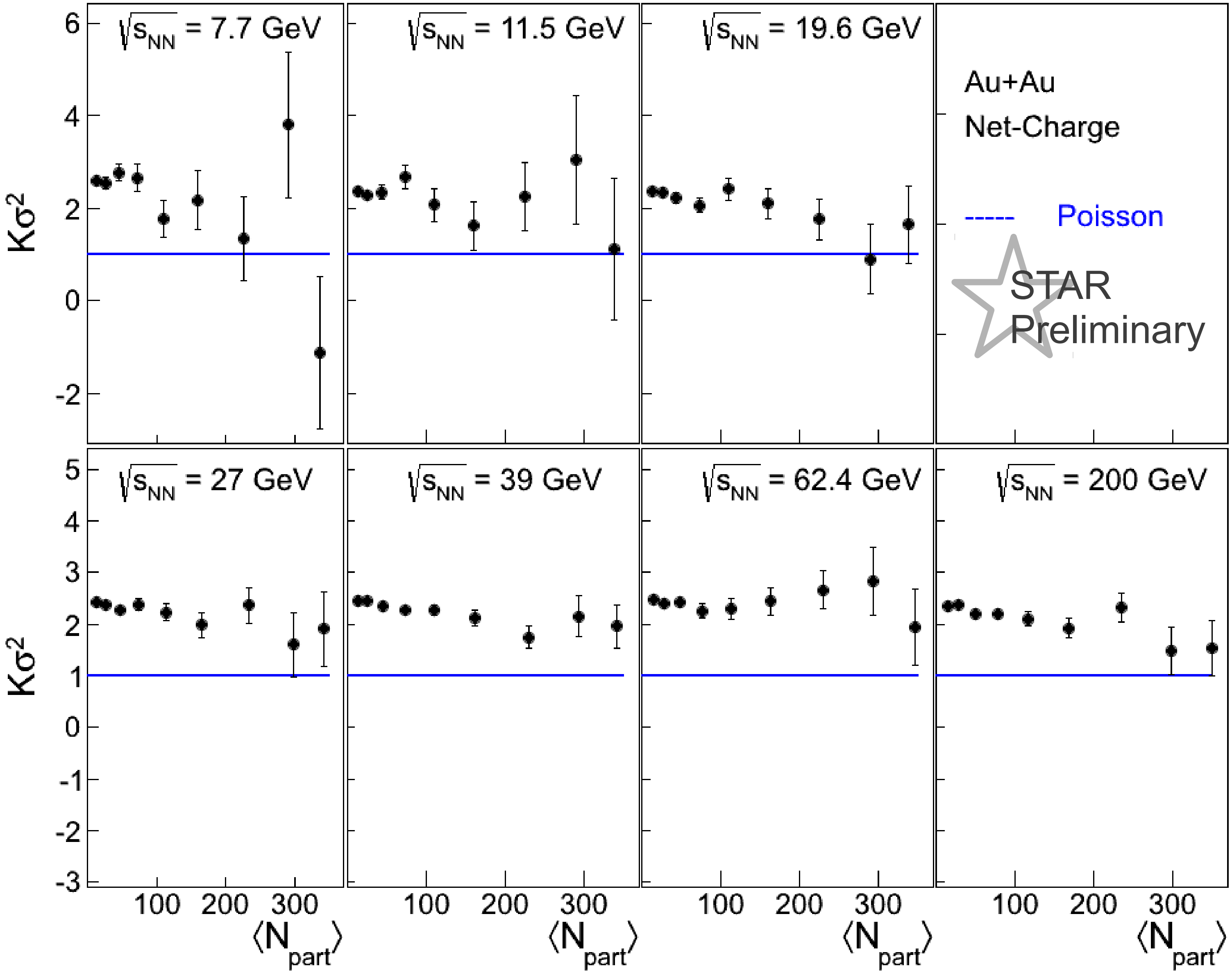
Sσ, $K\sigma^2$ net-charge, 0-5% centrality





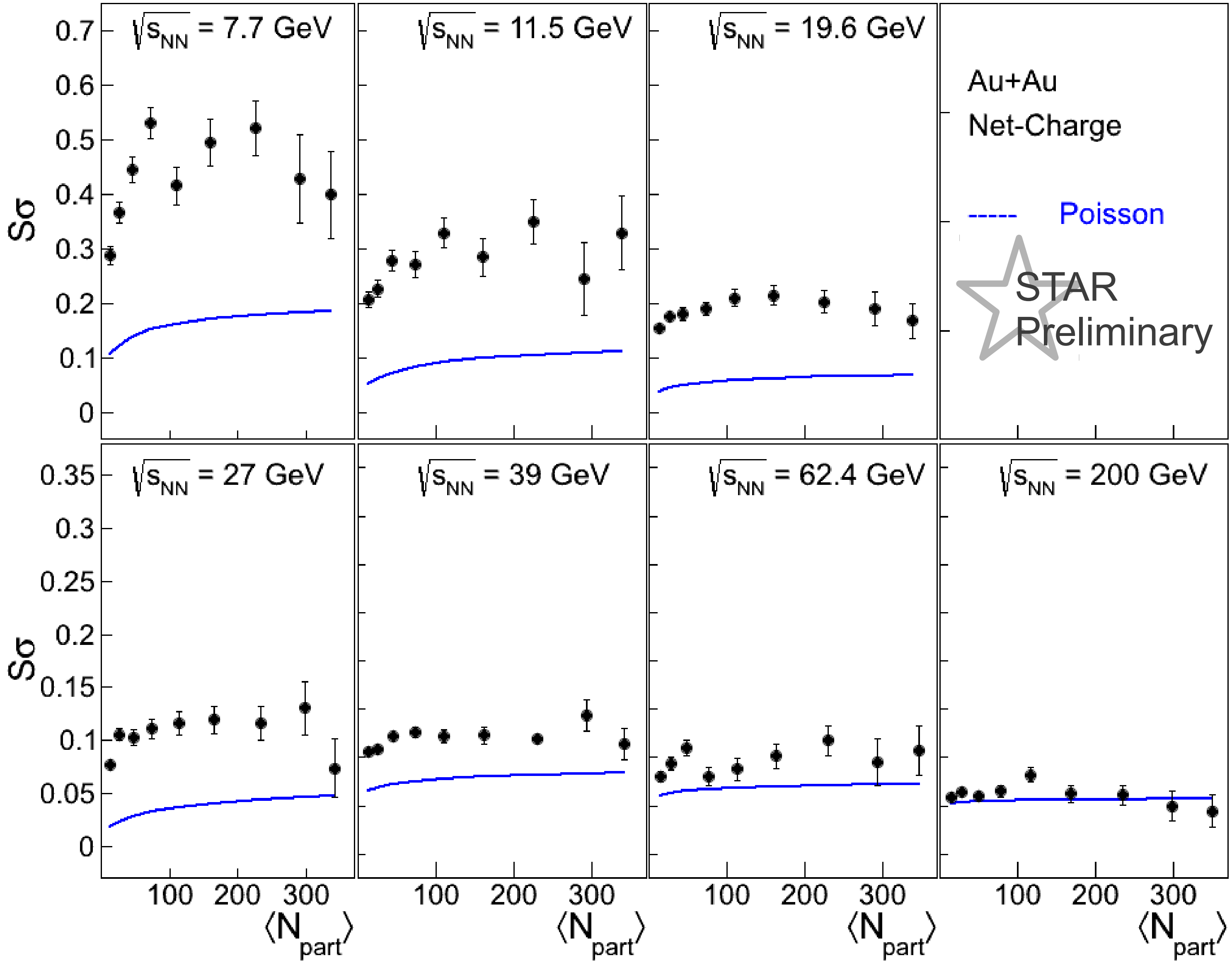
- In 0-5% central collisions, Sσ is greater than the Poisson expectation and less than the HRG prediction.

$K\sigma^2$ net-charge, centrality dependence



$K\sigma^2$ is generally independent of centrality and is above the Poisson expectation at all $\sqrt{s_{NN}}$.

Sσ, net-charge, centrality dependence



- Sσ is independent of centrality to within ~10%.
- Sσ is generally greater than the Poisson expectation.

Summary

- Critical point might result in non-monotonic changes to the statistical moments of the multiplicity distributions of specific groups of identified charged particles.

- Studied Au+Au collisions for beam energies, $\sqrt{s_{NN}}$, from 7.7 - 200 GeV ($\sim 420 > \mu_B > \sim 20$ MeV).
  - Care taken to obtain clean data and to avoid autocorrelations

- Showed moments products $S\sigma$ and $K\sigma^2$ for two particle groups: net-Kaons and net-charge.
  - Compared to Poisson expectation and the Hadron Resonance Gas model
  - Moments products do not depend significantly on the centrality of the collision
  - For both net-charge and net-Kaons, $S\sigma$ and $K\sigma^2$ are above or near the Poisson expectation
  - Net-charge $K\sigma^2$ values in central collisions are close to the HRG predictions
  - Net-charge $S\sigma$ values in central collisions are below the HRG predictions

- At the presently available beam energies, no beam-energy and centrality localized large enhancements of the net-charge or net-kaons moments products.

Thank you!