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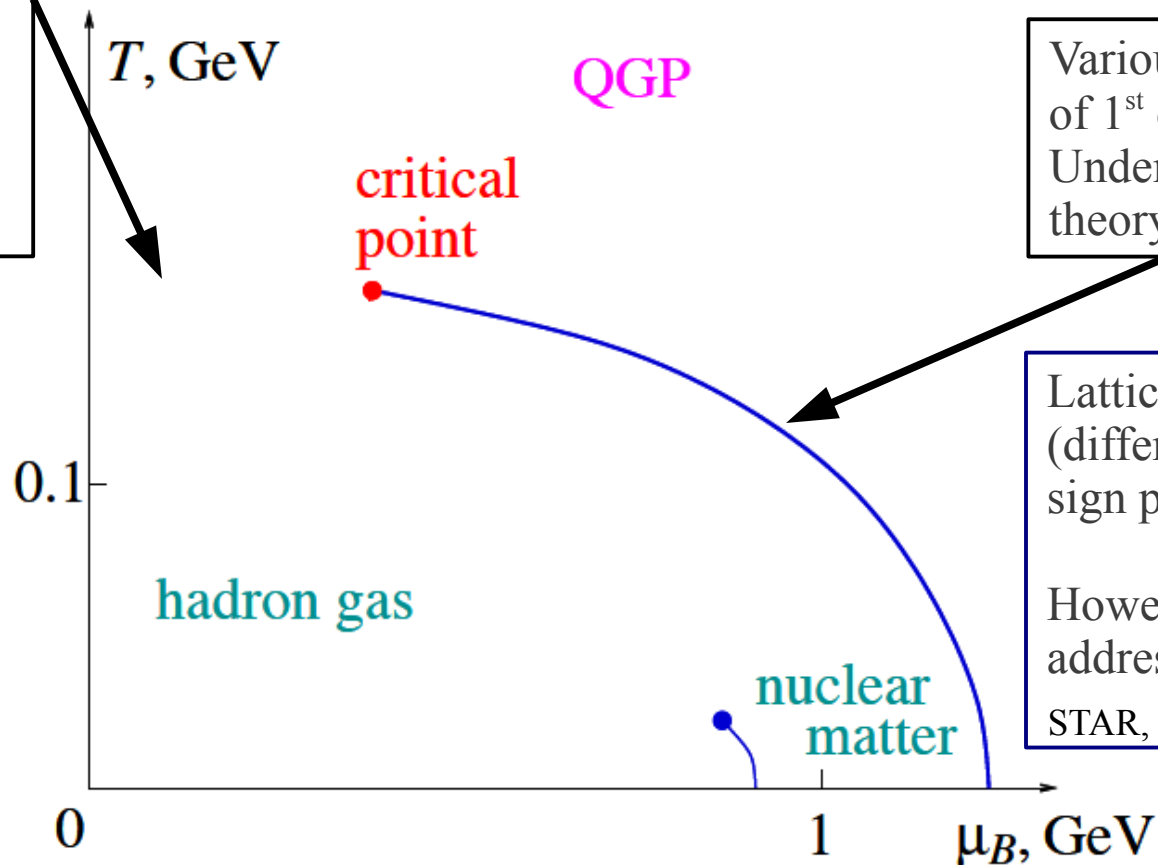
Daniel McDonald for the STAR Collaboration

Rice University
Quark Matter 2012
August 17, 2012

QCD phase diagram

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

T, GeV

QGP

critical point

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

0.1

hadron gas

nuclear matter

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

However, this topic can be addressed experimentally!

STAR, arXiv:1007.2613 [nucl-ex]

0

1

μ_B, GeV

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

QCD phase diagram

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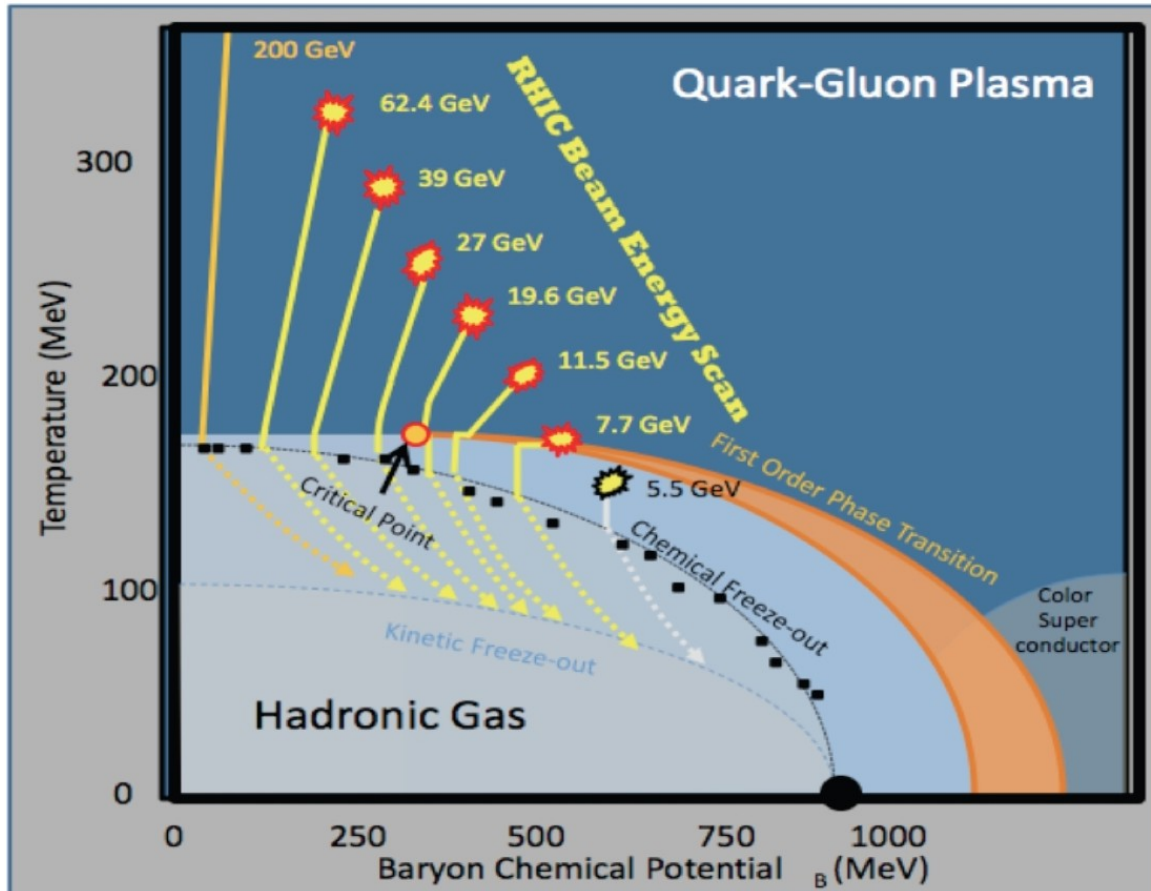
STAR Beam Energy Scan (BES) data sets from RHIC Runs 10 and 11 (2010-2011)

$\sqrt{s_{NN}}$ (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

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
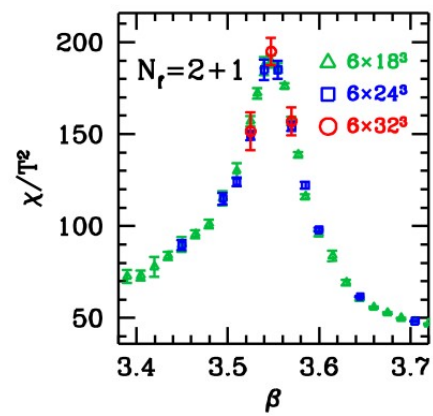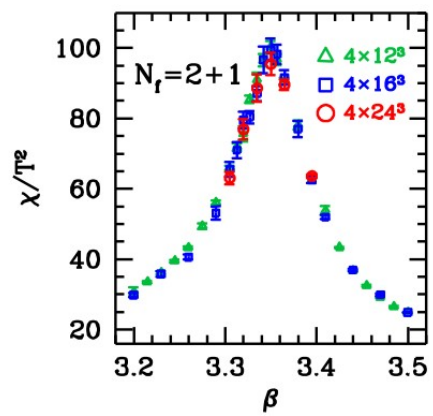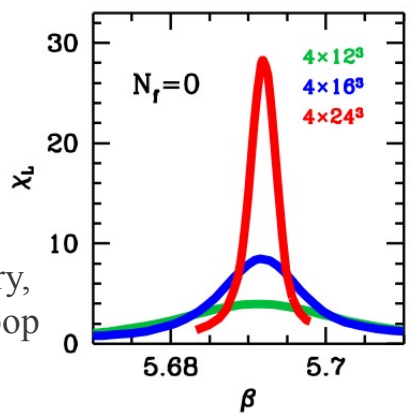A. Einstein, *Annalen der Physik*, 33 (1910) 1275-1298

CO_2

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

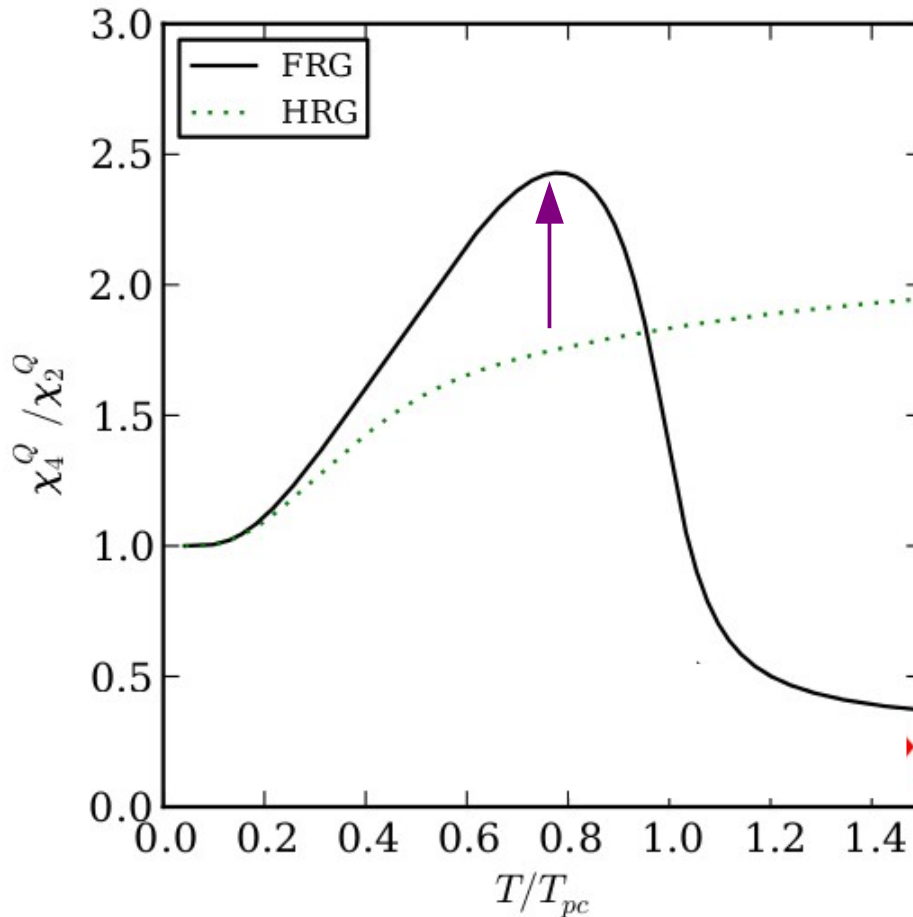Z. Fodor, **PoS**, 11, 2007

Pure SU(3) Gauge Theory, Polyakov Loop

$N_f=0$
4×12^3
4×16^3
4×24^3

$N_f=2+1$
△ 4×12^3
□ 4×16^3
○ 4×24^3

$N_f=2+1$
△ 6×18^3
□ 6×24^3
○ 6×32^3

Full QCD, Lattice

β ~ temperature

Different volumes (lattice sizes) in different colors

4

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.

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

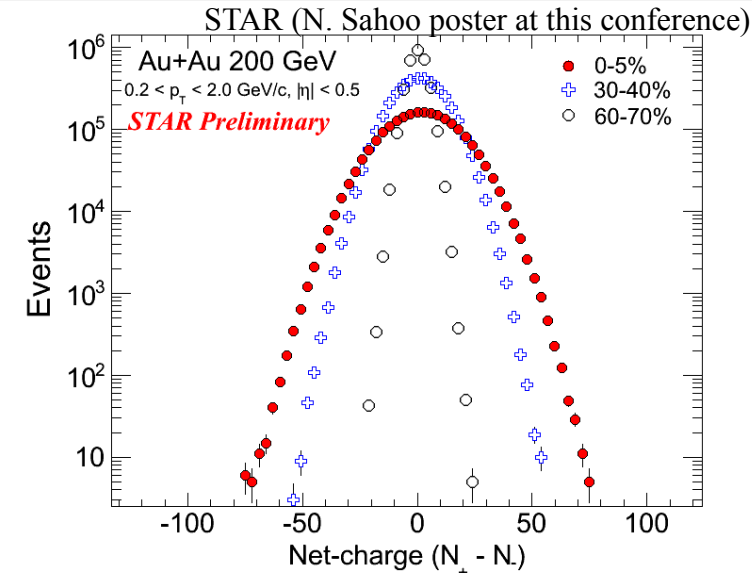Charge susceptibility ratios are related to the correlation length, ξ:

$$\sim \quad \chi_3^Q/\chi_2^Q \sim \xi^{5/2}$$
$$\sim \quad \chi_4^Q/\chi_2^Q \sim \xi^5$$

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

5

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"

"cumulants"

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

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

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

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

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

"S"   "K"

STAR (N. Sahoo poster at this conference)

Au+Au 200 GeV
$0.2 < p_T < 2.0$ GeV/c, $|\eta| < 0.5$
STAR Preliminary

- 0-5%
- 30-40%
- 60-70%

Events

Net-charge ($N_+ - N_-$)

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

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

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

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

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.

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

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

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

6

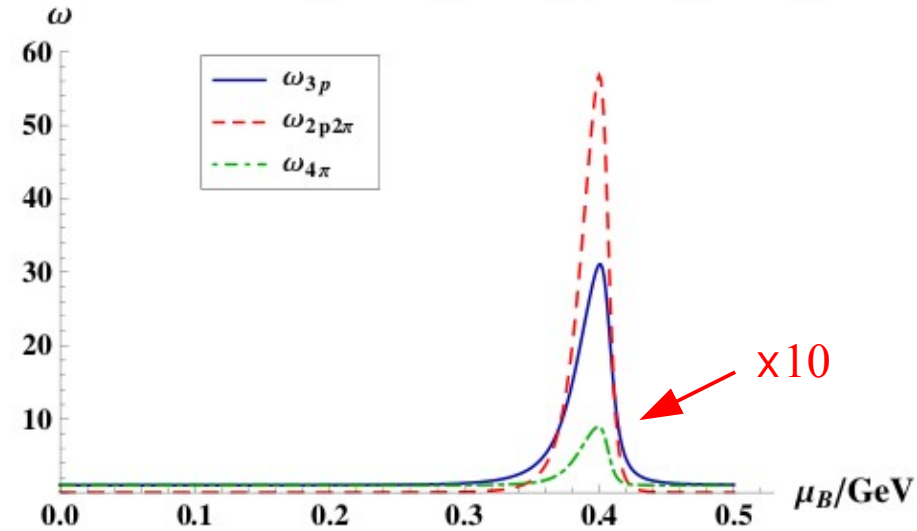# Sensitivity to critical phenomena

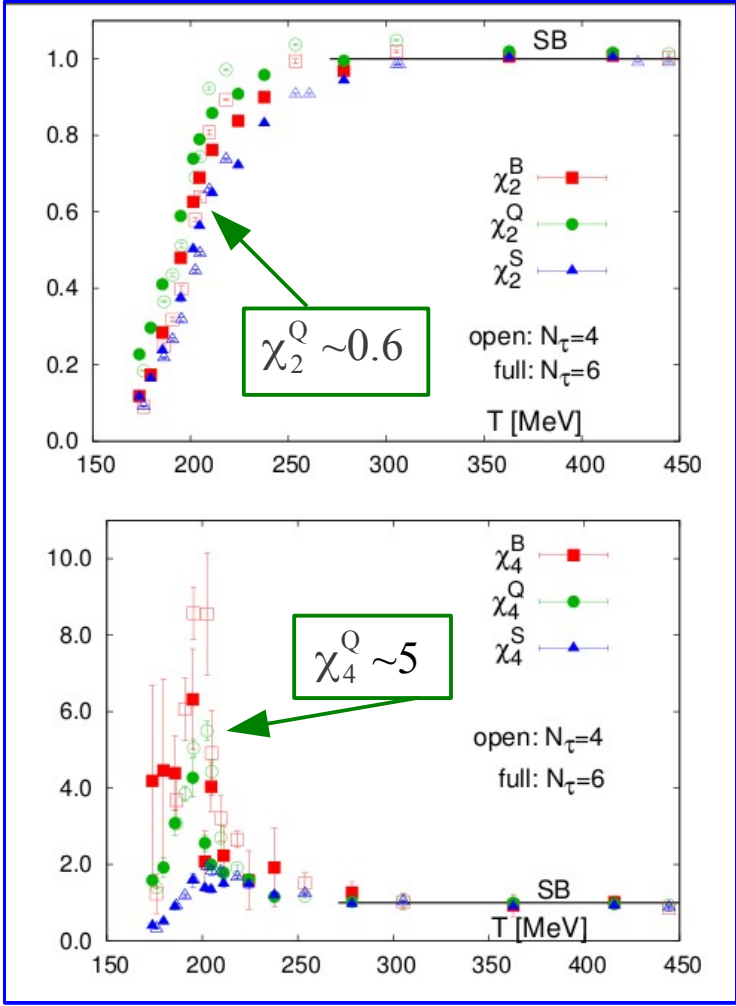Lattice implies $K\sigma^2 = \chi_4^Q / \chi_2^Q$ increases by an order of magnitude (~5/0.6).

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

$\omega_{4p} \sim \kappa_{4p}/\langle N_p \rangle$

x400

Δ=0.05 GeV
Δ=0.1 GeV
Δ=0.2 GeV

expect ~100 MeV
Y. Hatta *et al.* **PRD** 67, 014028 (2003)
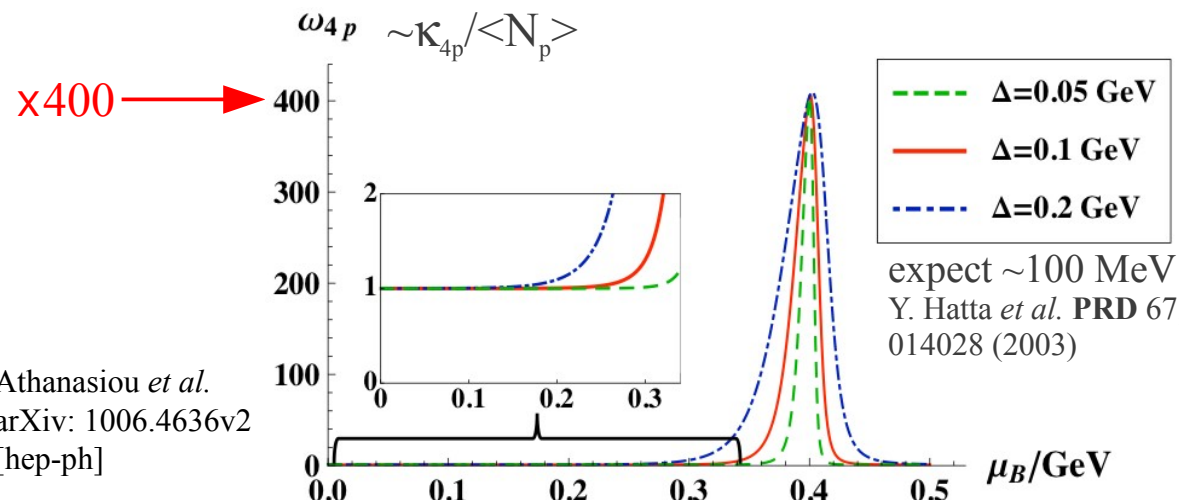
Athanasiou *et al.* arXiv: 1006.4636v2 [hep-ph]

$\chi_2^Q \sim 0.6$

open: $N_\tau=4$
full: $N_\tau=6$

χ_2^B
χ_2^Q
χ_2^S

SB

T [MeV]

$\chi_4^Q \sim 5$

χ_4^B
χ_4^Q
χ_4^S

open: $N_\tau=4$
full: $N_\tau=6$

SB

T [MeV]

ω

ω_{3p}
$\omega_{2p2\pi}$
$\omega_{4\pi}$

x10

Both lattice and a phenomenological field theory model predict factor > ~10 enhancements in κ_4 and $K\sigma^2$.

7

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). It is important to remove these experimental effects via careful data QA and cuts.

Solenoidal Tracker at RHIC (STAR)

TPC (dE/dx PID)
TOF (TOF PID)
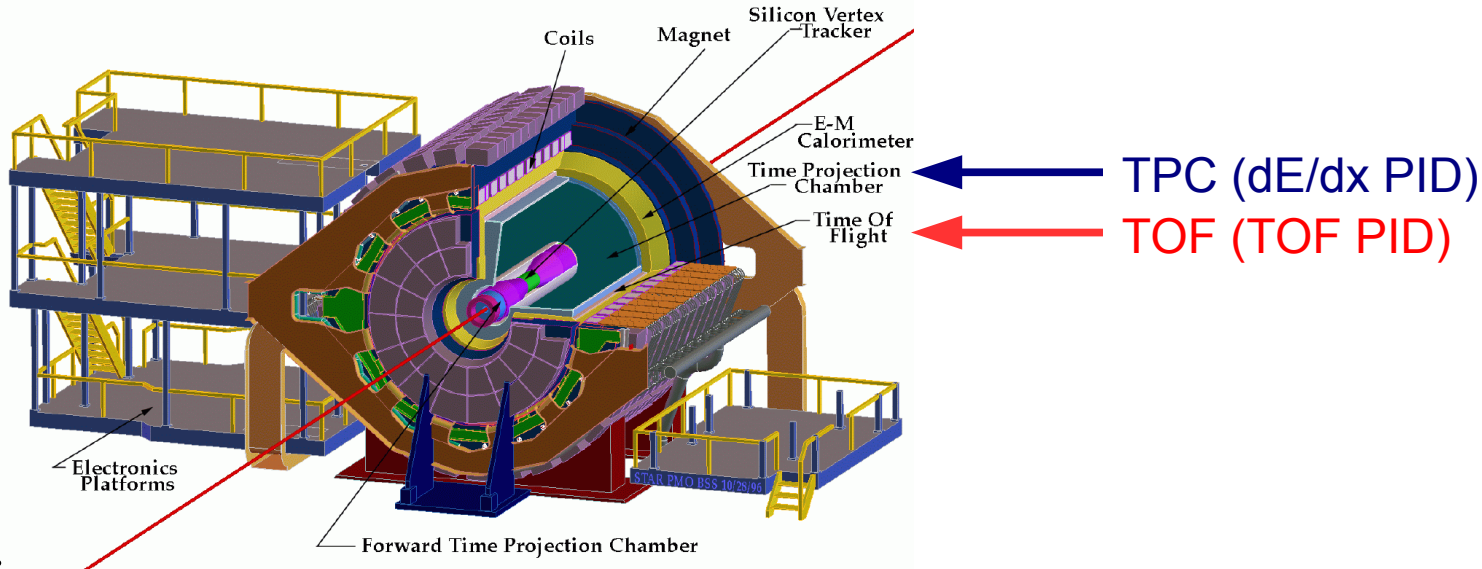
Good event cuts:
- all beam energies: |Zvtx| <30 cm, Rvtx < 2 cm, and other cuts on global observables
- careful bad run and bad event rejection performed

Good track cuts:
- Nhitsfit > 20, NhitsdE/dx >10, $|\eta|$ <0.5, globaldca <1.0 cm, Nhitsratio >0.52
  $0.2 < p_t < 2.0$ GeV, p < 1.6 GeV/c for K (TPC+TOF) $0.2 < p_t < 2.0$ GeV/c for 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

Analysis Details, continued

Moments are corrected for centrality bin-width effects by using track-multiplicity weighted average of the moments inside each centrality bin.

X. Luo arXiv: 1106.2926 [nucl-ex]

Centrality definition separated from analysis region to avoid autocorrelations between the centrality definition and the multiplicity moments.

Au+Au 19.6 GeV
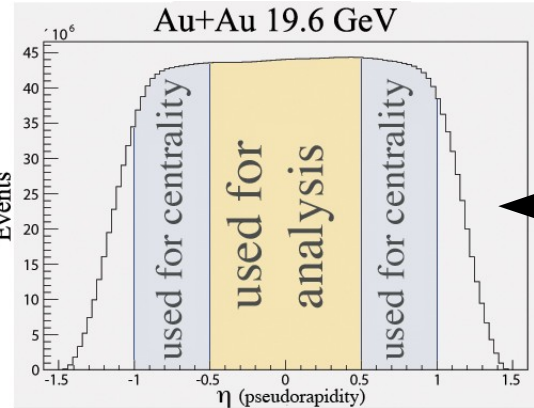
• analyze moments for $|\eta|<0.5$
• determine centrality using $0.5<|\eta|<1.0$

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"	...see also Amal Sarkar's poster
pos-neg	"net-charge"	...see also Nihar Sahoo's poster

Will compare to "baselines" from Poisson statistics and HRG model.

HRG model
Moments are functions of thermodynamic parameters.

$$S\sigma = \tanh(Q_i\mu_Q/T) \quad Q_i = \text{electric charge}$$

$$K\sigma^2 \sim 1.8 \quad \text{(very weakly dependent on } \sqrt{s_{NN}})$$

Karsch & Redlich, **PLB** 695, 136 (2011).
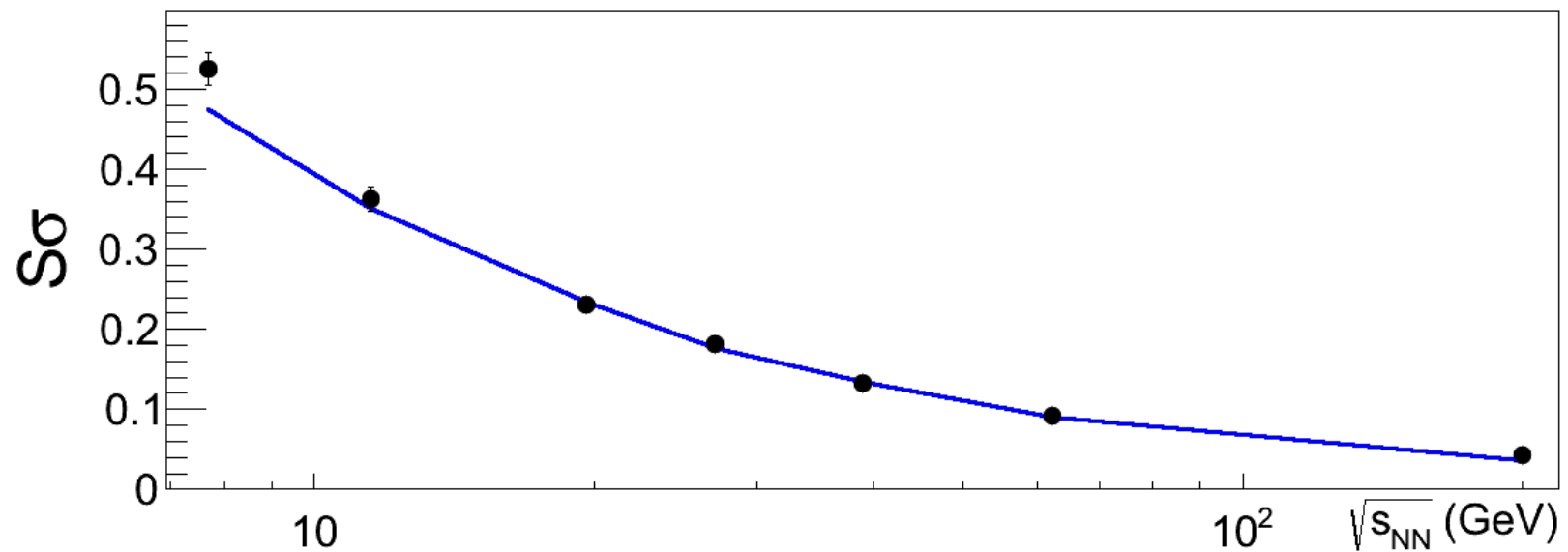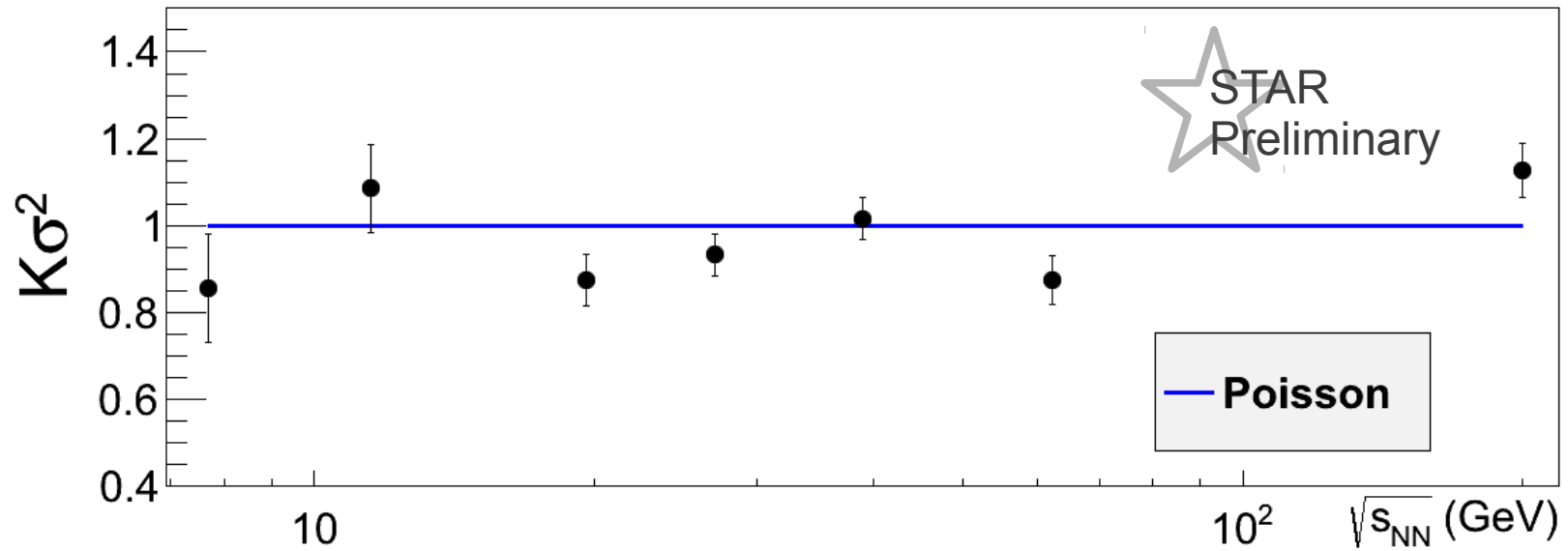A. Andronic, *et al*, Nucl. Phys. A 772 (2006) 167

Poisson Statistics
Moments are functions only of the mean values

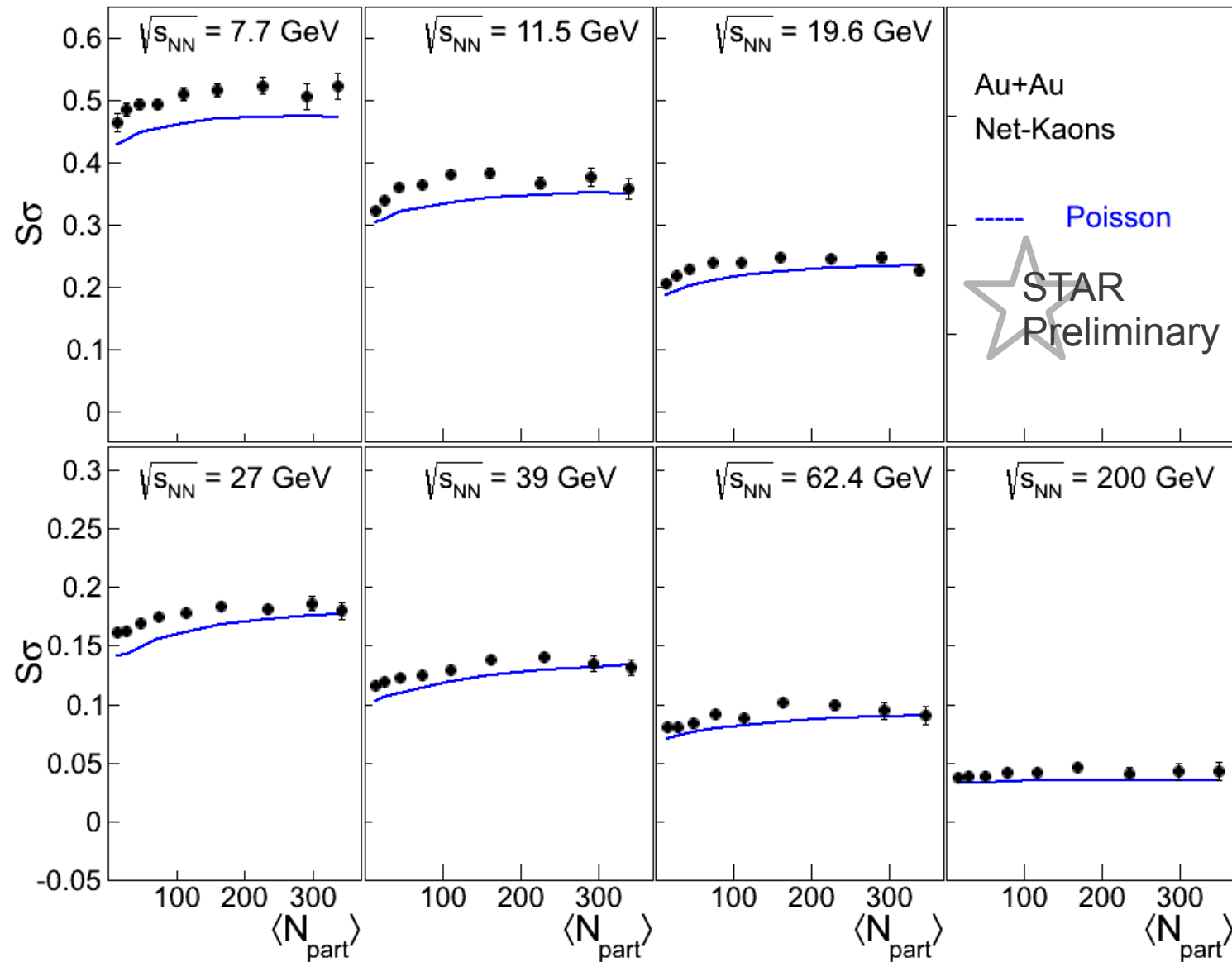$$S\sigma = (M^+ - M^-)/(M^+ + M^-)$$

$$K\sigma^2 = 1 \quad M = \text{mean value}$$
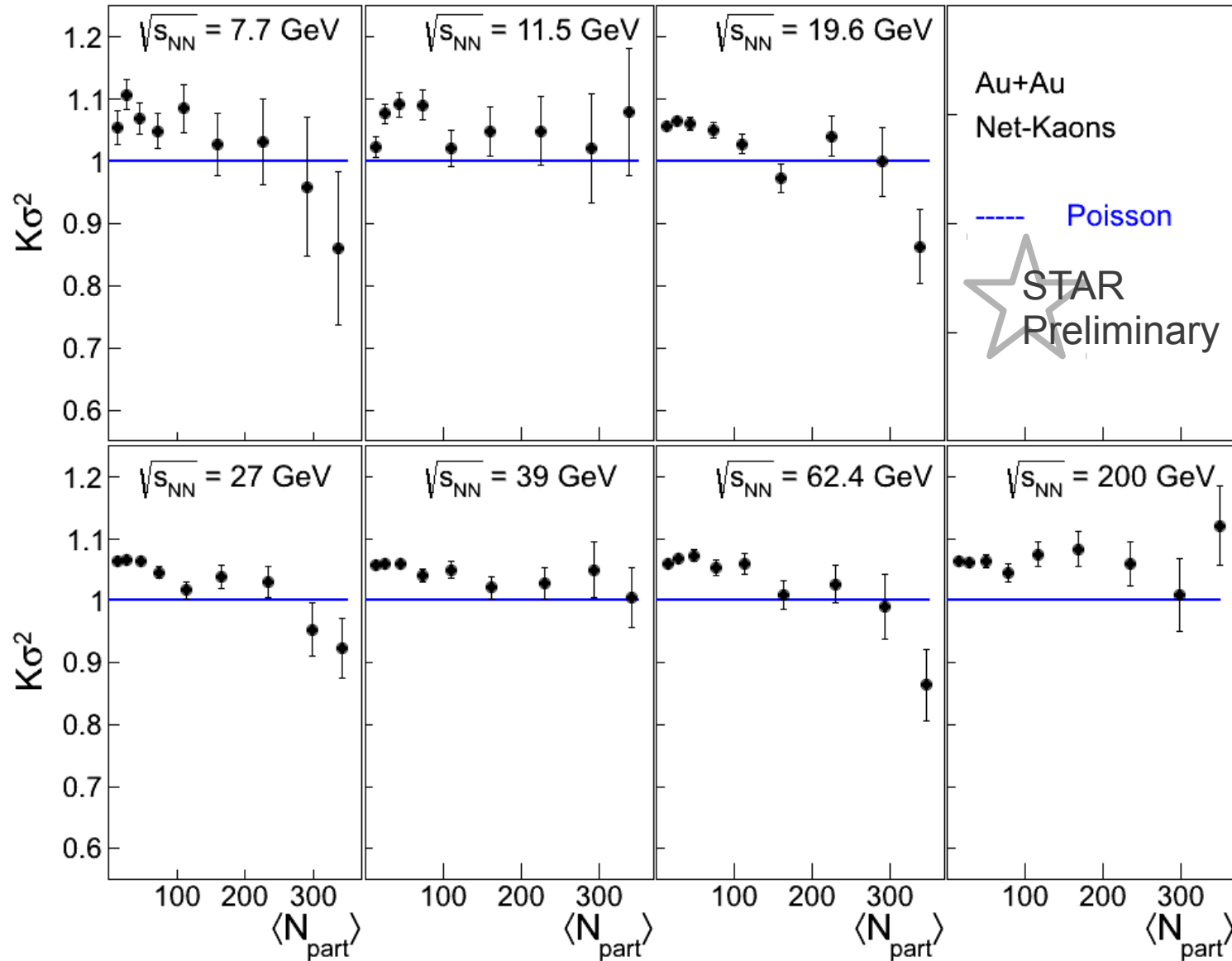
9

Sσ, Kσ² net-Kaons, 0-5% centrality

No significant enhancement relative to Poisson baseline observed.

Sσ, net-Kaons, centrality dependence

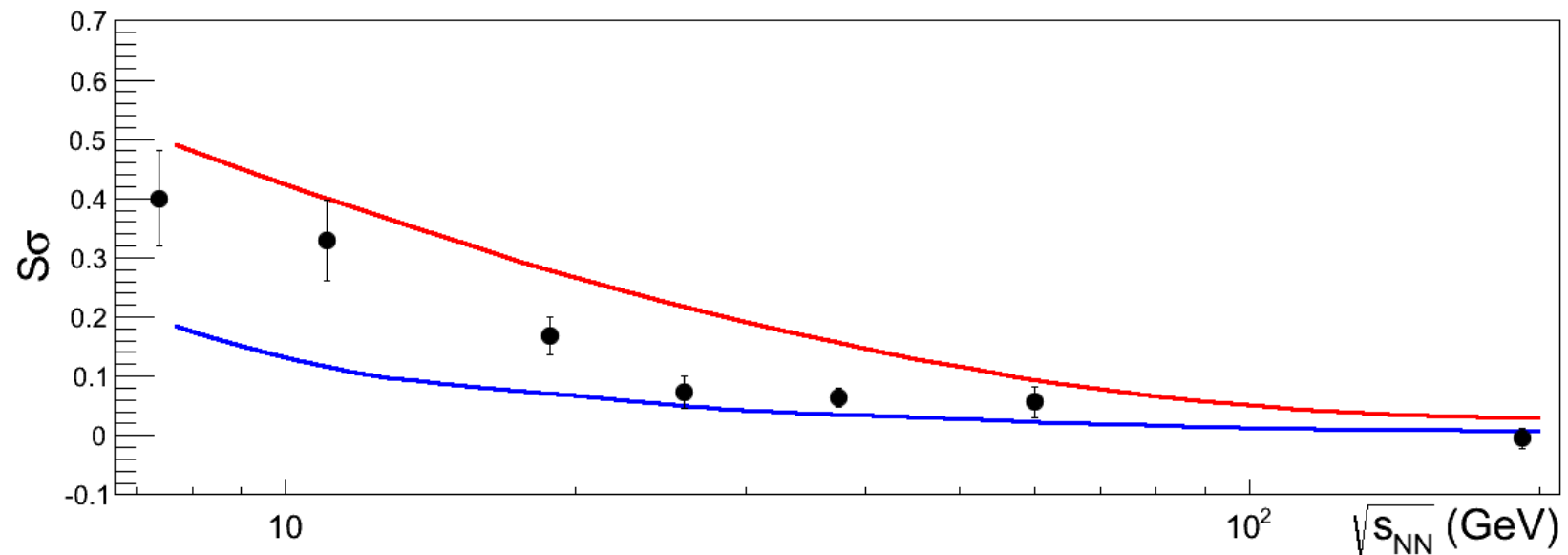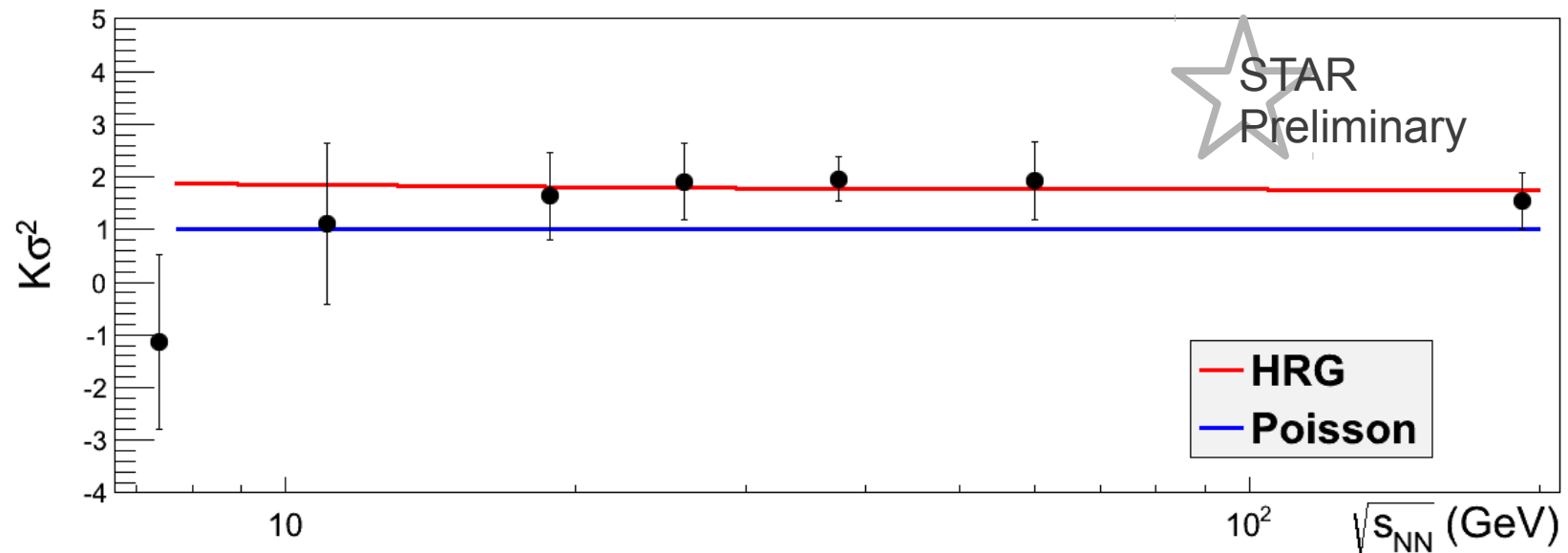- Sσ is independent of centrality to within ~15%.
- Sσ is greater than the Poisson baseline.

Kσ², net-Kaons, centrality dependence

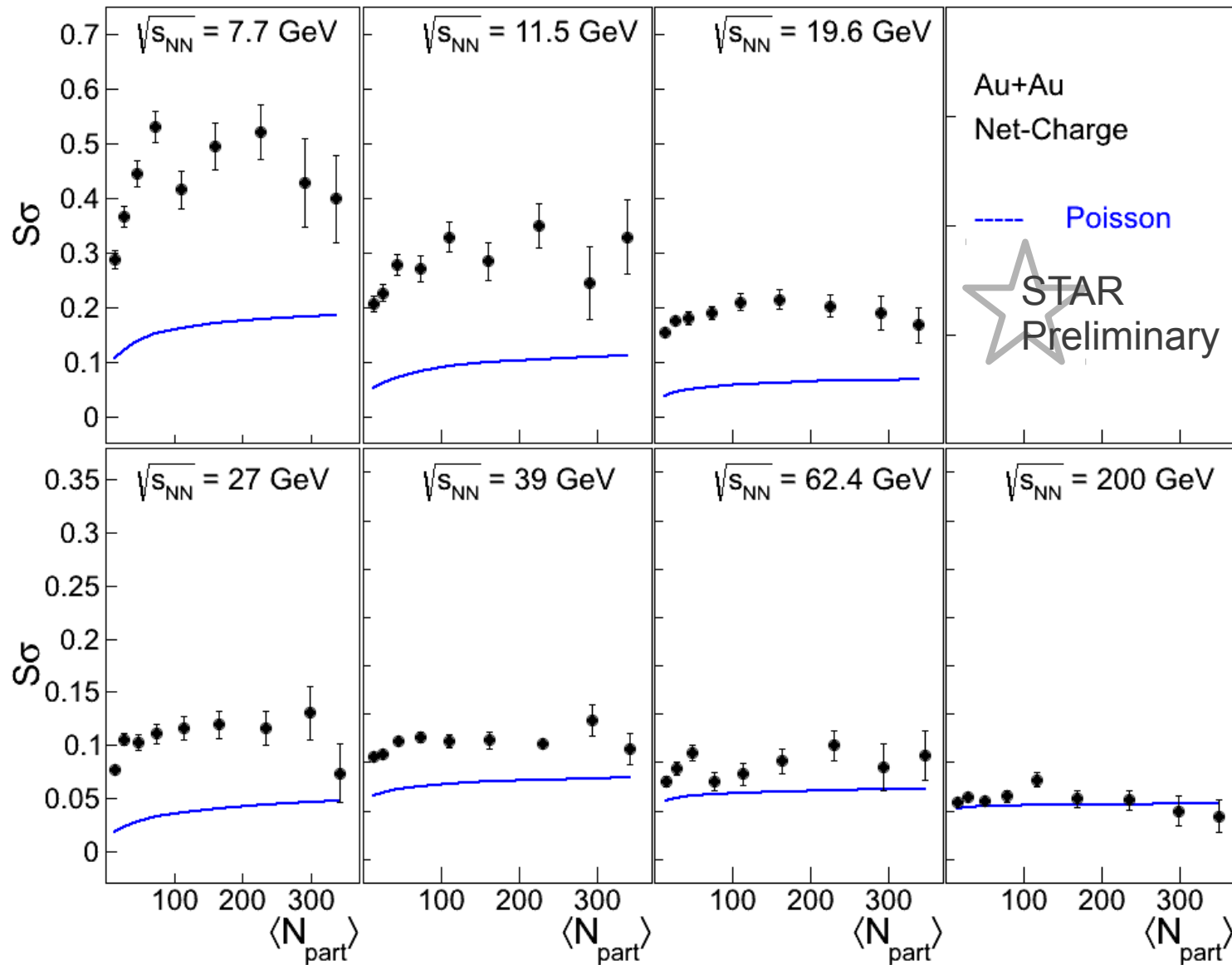- Kσ² is independent of centrality to within ~10%.
- Kσ² is generally greater than the Poisson baseline.

Sσ, Kσ² net-charge, 0-5% centrality
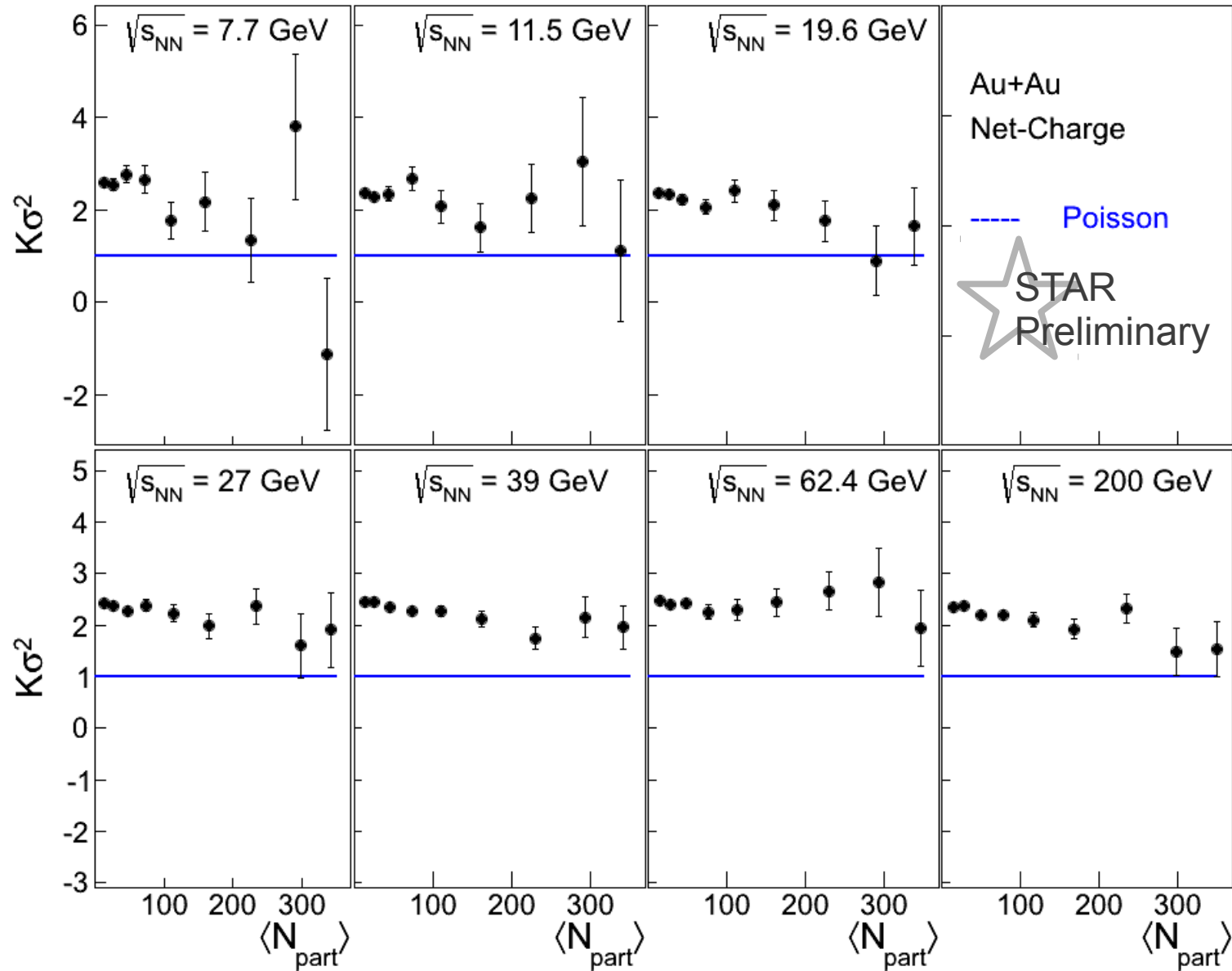

• In 0-5% central collisions, Sσ is greater than the Poisson baseline and less than the HRG prediction.

Sσ, net-charge, centrality dependence

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

Kσ² net-charge, centrality dependence

Kσ² is generally independent of centrality and is above the Poisson baseline at all √s$_{NN}$.

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 ($\sim 20 < \mu_B < \sim 420$ 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-charge and net-Kaons.
    - Compared to Poisson baselines 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 baseline
    - 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, of order 10-100 enhancements of the moments products was not observed.

Thank you!