Energy Dependence of Moments of Net-Proton, Net-Kaon and Net-Charge Multiplicity Distributions at STAR

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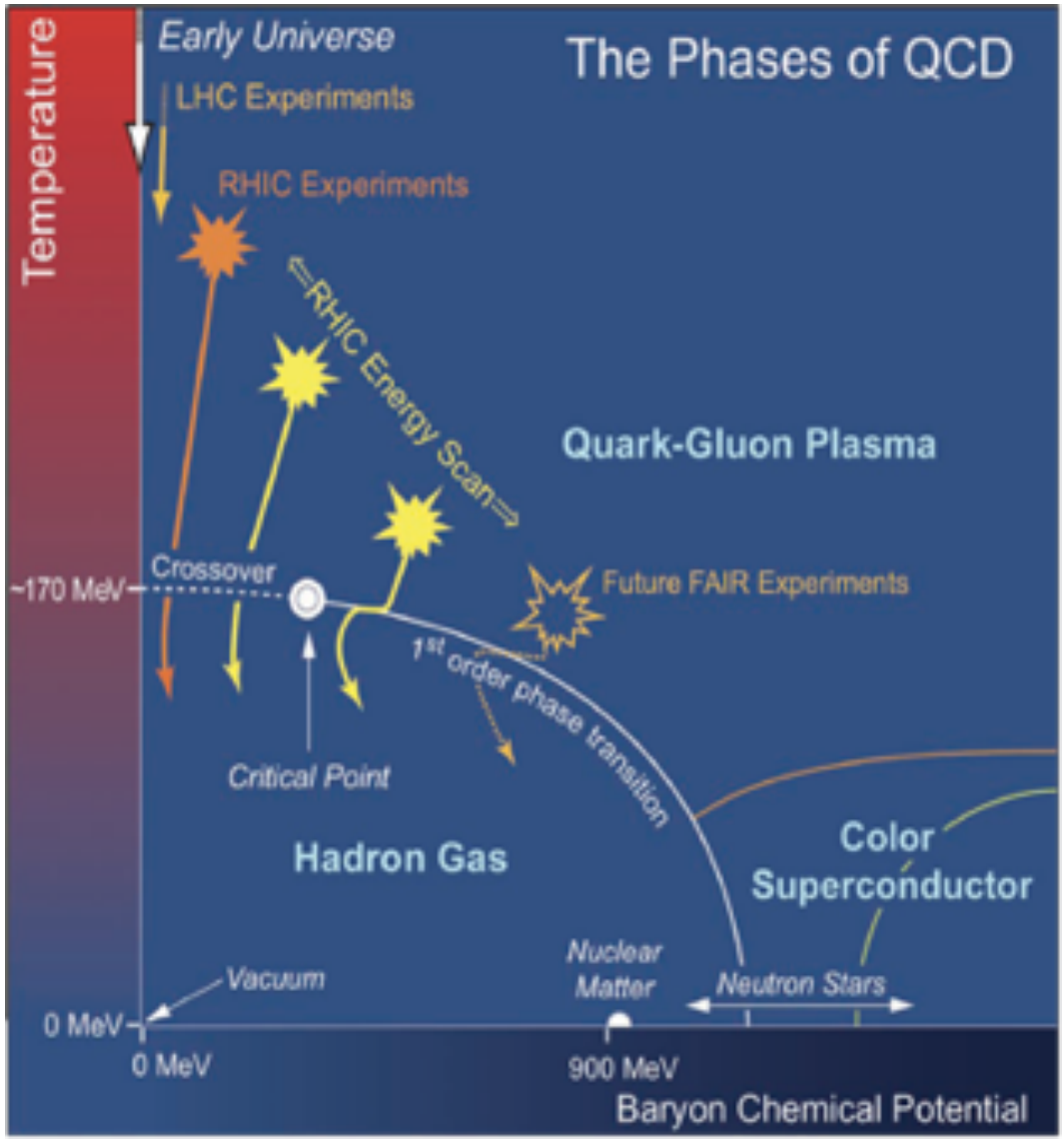
Outline

- Introduction
- Analysis Techniques and Details
- Results for Net-Proton, Net-Charge and Net-Kaon
- Summary

QCD Phase Diagram



- Crossover at μ_B=0.
- First order phase transition expected at large μ_B.
- QCD Critical Point: The end point of first order phase transition boundary.
- Does CP(Critical Point) exist? Where is it?

STAR Note 0598

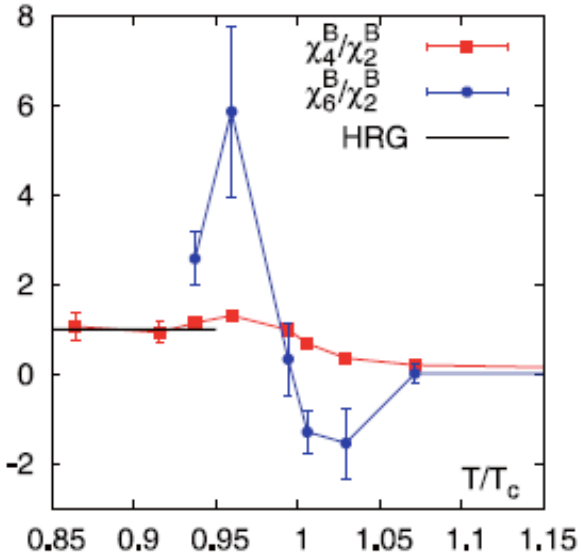
Fluctuations of Conserved Quantities(B,Q,S)

- Sensitivity to correlation length (ξ) and probe non-gaussian fluctuations near the Critical Point.

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

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

- Direct connection to the susceptibility of the system.



$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^{\wedge}4)}{\partial(\mu_q)^n}, q = B, Q, S$$

S. Ejiri et al, Phys.Lett. B 633 (2006) 275.
Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.
F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2012).
A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

Higher Moments (fluctuations)

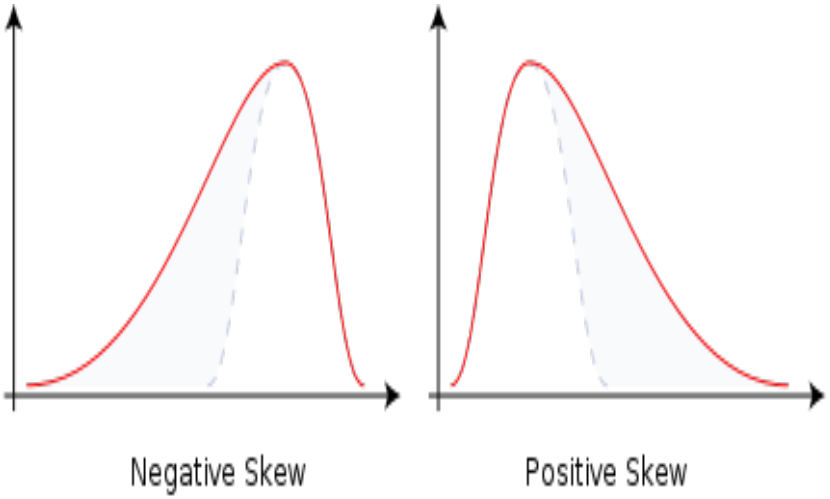
"Shape" of the fluctuations can be measured: non-Gaussian moments (cumulants):

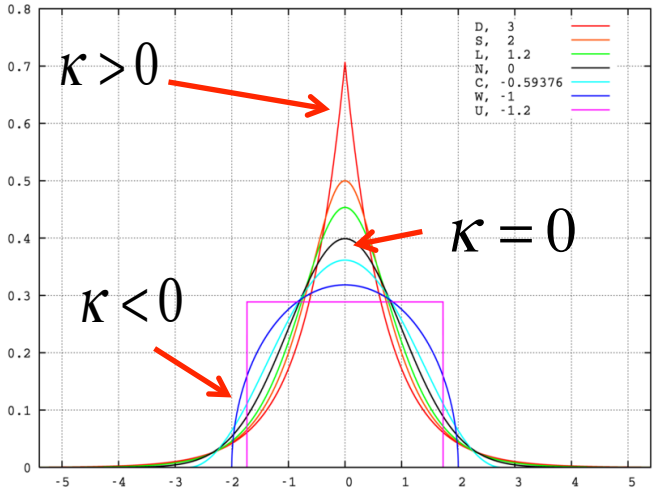
$$C_{1,x} = < x >, C_{2,x} = < (\delta x)^2 >,$$

$$C_{3,x} = < (\delta x)^3 >, C_{4,x} = < (\delta x)^4 > -3 < (\delta x)^2 >^2$$

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

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





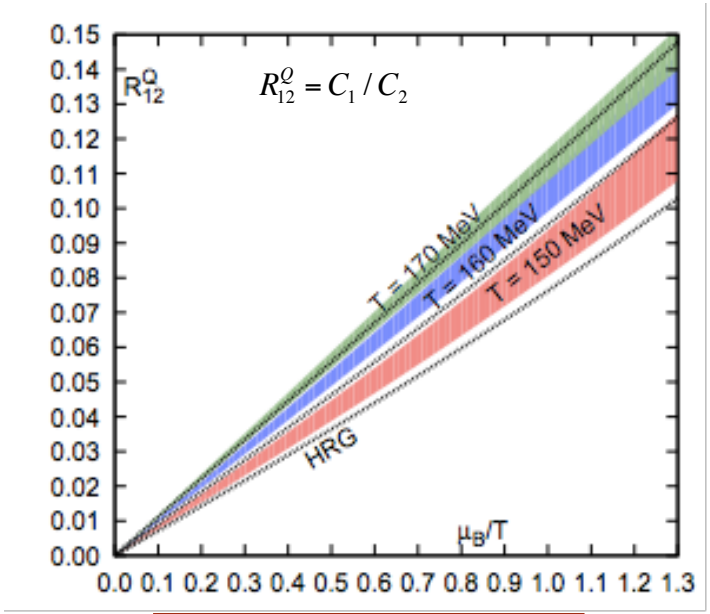
➢ **Susceptibility ratios ⇔ Cumulant Ratios (Cancel V dependence)**

$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

(q=B, Q, S)

Experiment Observable

- Experimentally, we measured the net-particle multiplicity fluctuations: net-charge, net-proton (proxy for net-baryon) , net-kaon (proxy for net-strangeness). The main observable is volume independent cumulant ratios.



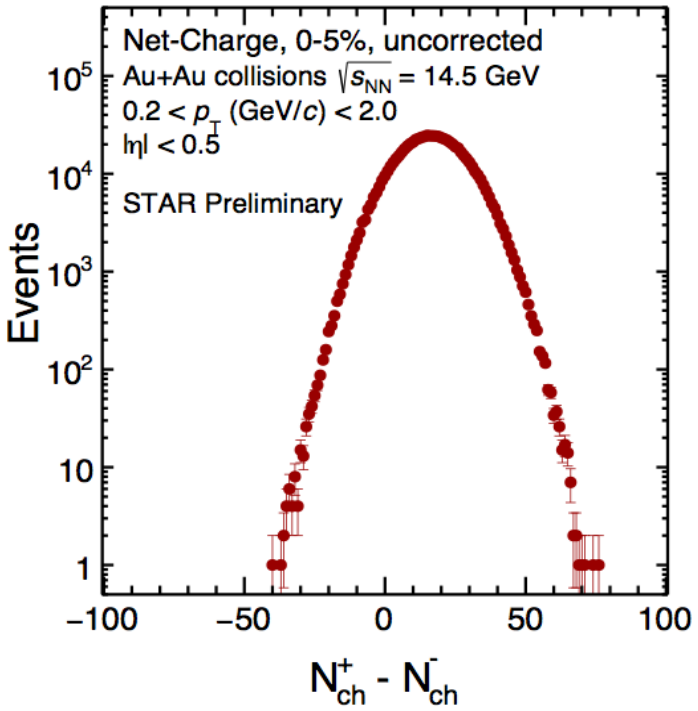
HotQCD, PRL109, 192302 (2012)
WB Group, PRL111, 062005 (2013)

$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

$$i = B, Q, S$$



Theory ⟺ **Experiment**

RHIC Beam Energy Scan Phase 1 (BES I)

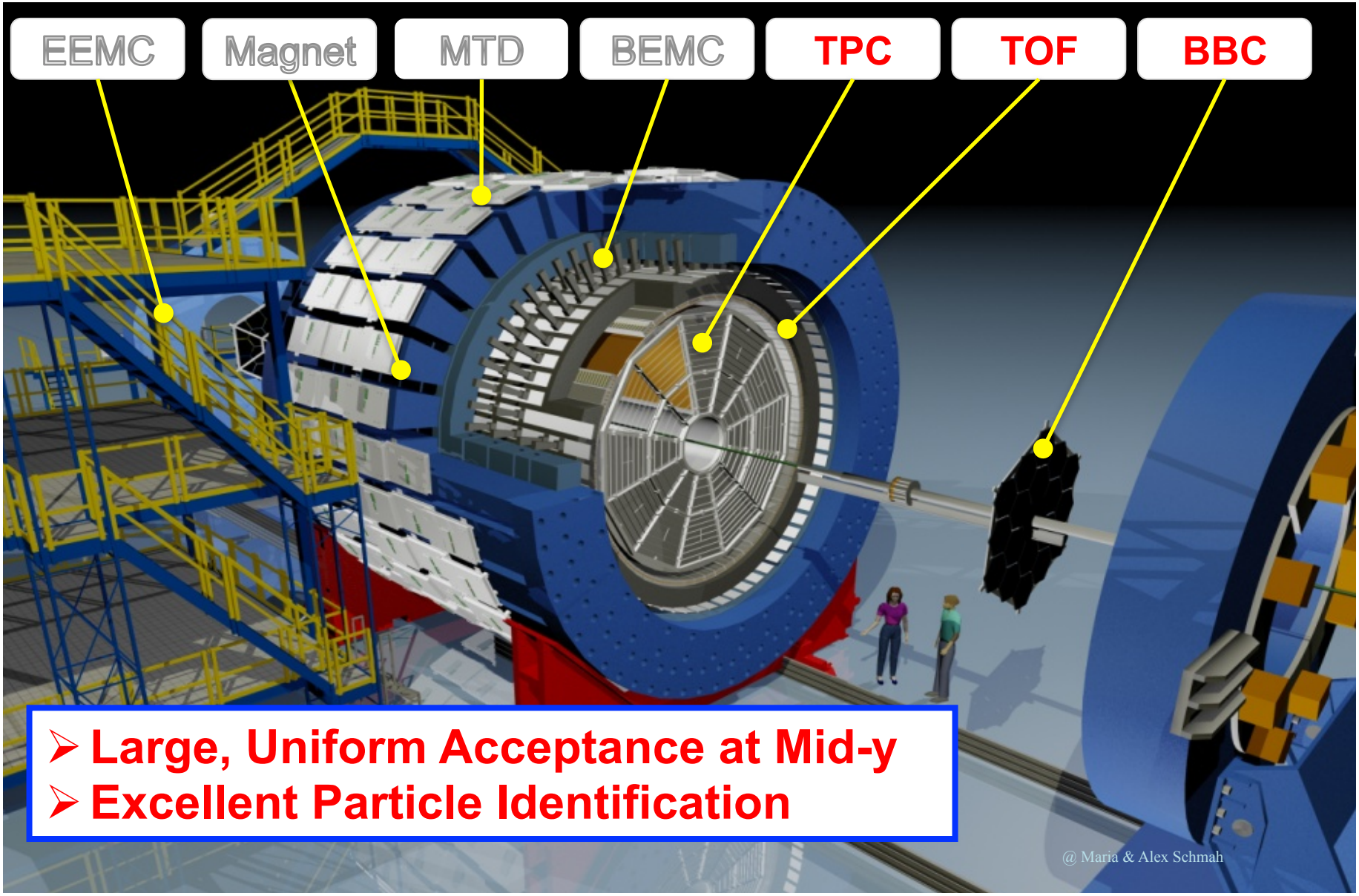
- In the first phase of the Beam Energy Scan (BES) program at RHIC, eight beam energies have already been analysized from $\sqrt{s_{NN}}$=7.7GeV to 200GeV.

√s (GeV)	Statistics (Millions)	Year	μ_B (MeV)	T (MeV)	μ_B /T
7.7	~4	2010	420	140	3.020
11.5	~12	2010	315	152	2.084
14.5	~ 20	2014	266	156	1.705
19.6	~36	2011	205	160	1.287
27	~70	2011	155	163	0.961
39	~130	2010	115	164	0.684
62.4	~67	2010	70	165	0.439
200	~350	2010	20	166	0.142

μB, T : J. Cleymans et al., PRC 73, 034905 (2006)

Study QCD Phase Structure
- Onset of sQGP
- Phase boundary and **critical point.**

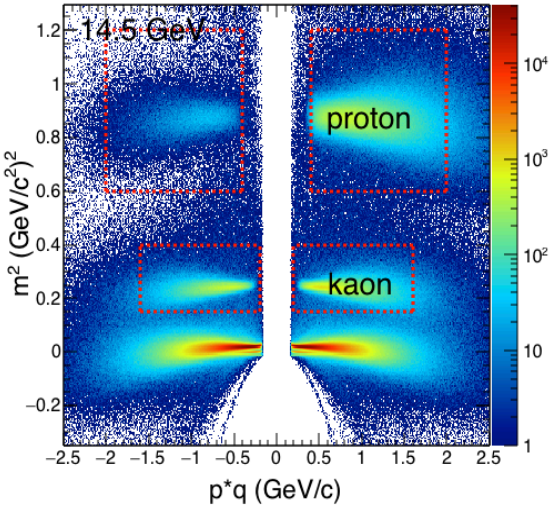
STAR Detector

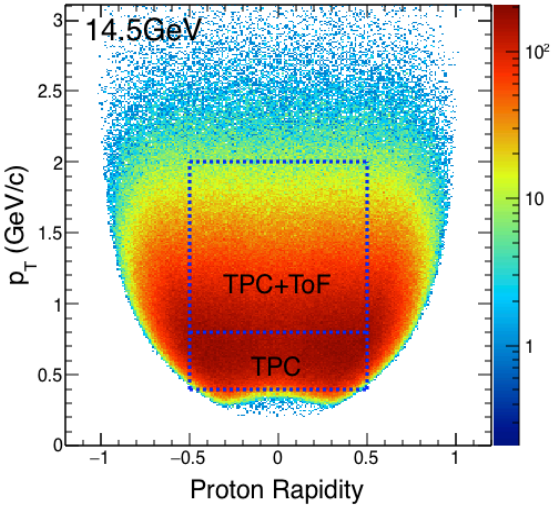


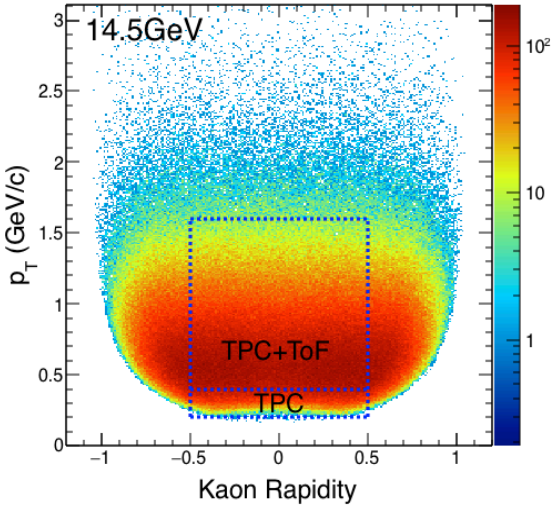
- Large, Uniform Acceptance at Mid-y
- Excellent Particle Identification

Analysis Details

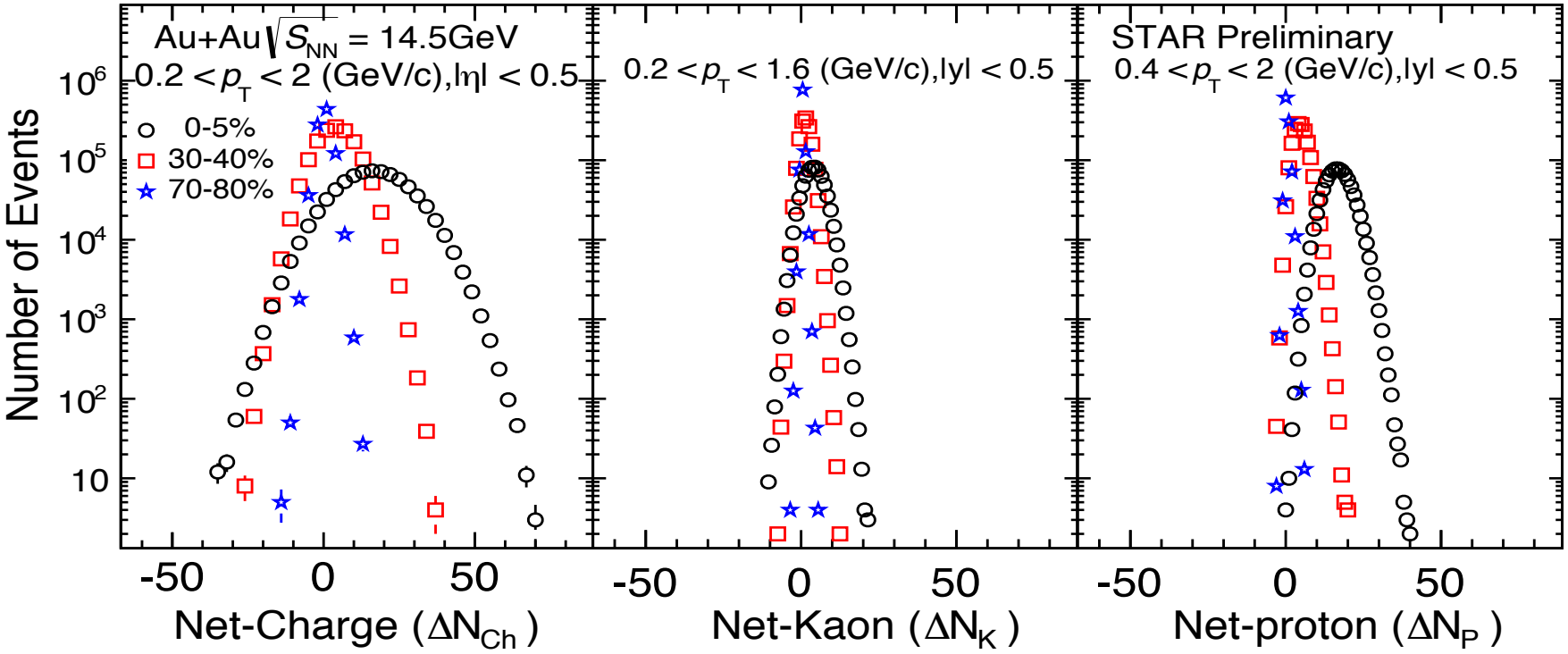
	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\|\eta\| < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\|y\| < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\|y\| < 0.5$
Particle Identification	Reject protons form spallation for $p_T < 0.4$ GeV/c	$0.4 < p_T$ (GeV/c) < 0.8 → TPC $0.8 < p_T$ (GeV/c) < 2.0 → TPC+TOF	$0.2 < p_T$ (GeV/c) < 0.4 → TPC $0.4 < p_T$ (GeV/c) < 1.6 → TPC+TOF
Centrality definition, → *to avoid auto-correlations*	Uncorrected charged primary particles multiplicity distribution	Uncorrected charged primary particles multiplicity distribution, without (anti-)protons	Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons
	$0.5 < \|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.0$







Raw Event-By-Event Net-Particle Multiplicity Distribution



Effects needed to be addressed to get final moments/cumulants:

1. Auto-correlation effects.
2. Effects of volume fluctuations.
3. Finite detector efficiency .

A. Bzdak and V. Koch, PRC86, 044904 (2012)
X.Luo, et al. J. Phys. G40,105104(2013)
X.Luo, Phys. Rev. C 91, 034907 (2015)
A . Bzdak and V. Koch, PRC91, 027901 (2015)

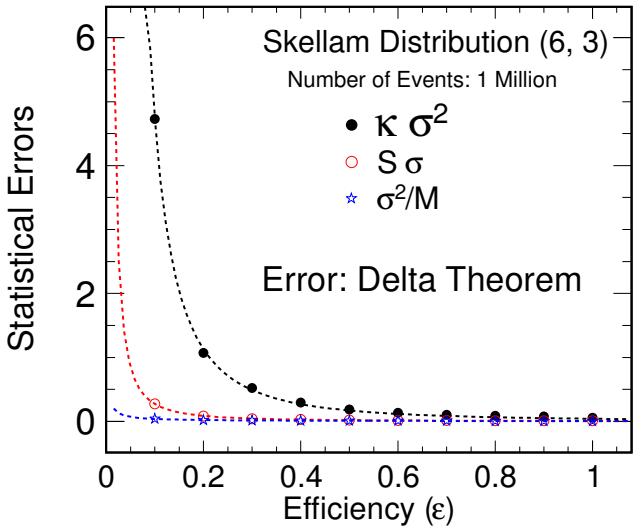
Efficiency Correlation and Error Estimation

- We can express the moments and cumulants in terms of the factorial moments, which can be easily efficiency corrected. X. Luo, PRC91, 034907 (2015); A. Bzdak and V. Koch, PRC91, 027901 (2015)

- Statistical Errors based on Delta Theorem. With same N events: error(net-charge) > error(net-kaon) > error(net-proton)

Au+Au 14.5GeV	Net-Charge	Net-Proton	Net-Kaon
Typical Width(σ)	12.2	4.2	3.4
Average efficiency(ε)	65%	75%	38%
σ^2/ε^2	355	32	82

numbers here not used in actual analysis

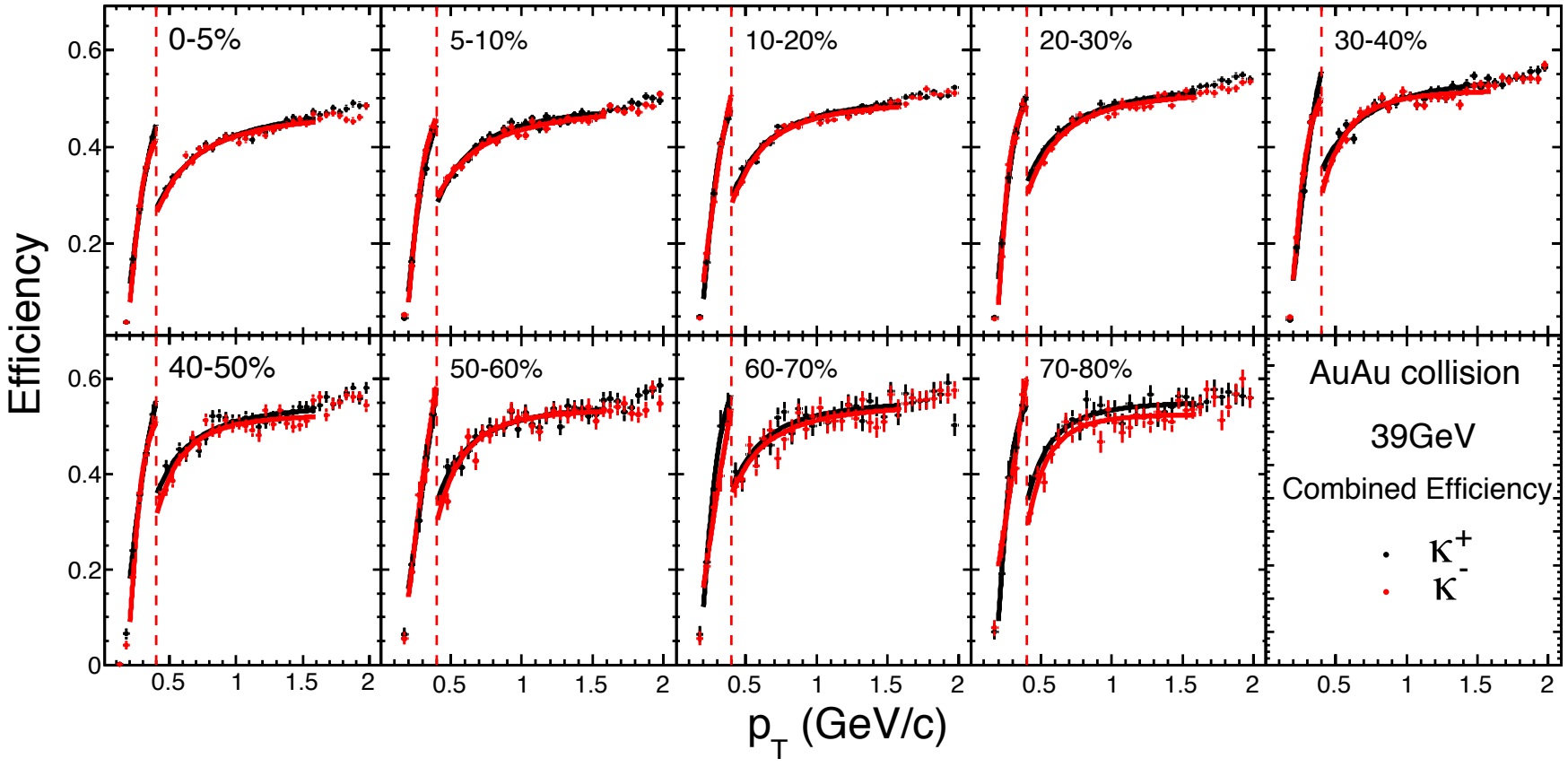


$$error(S\sigma) \propto \frac{\sigma}{\varepsilon^{3/2}}$$

$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}$$

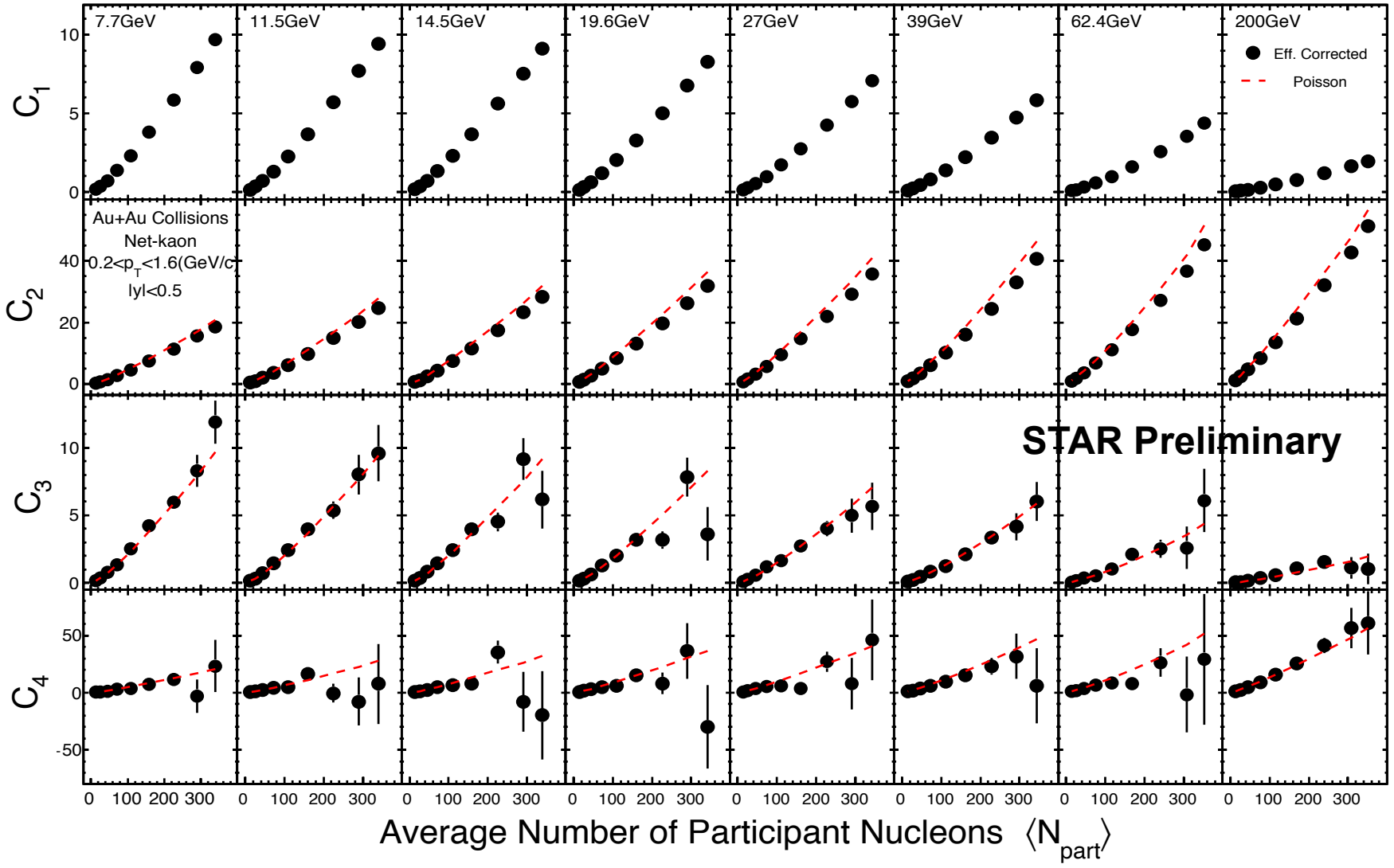
- Systematic error estimation
  - Includes uncertainties on efficiency and efficiency fluctuations
  - PID and track cuts

Combined Efficiency for K^+ and K^-



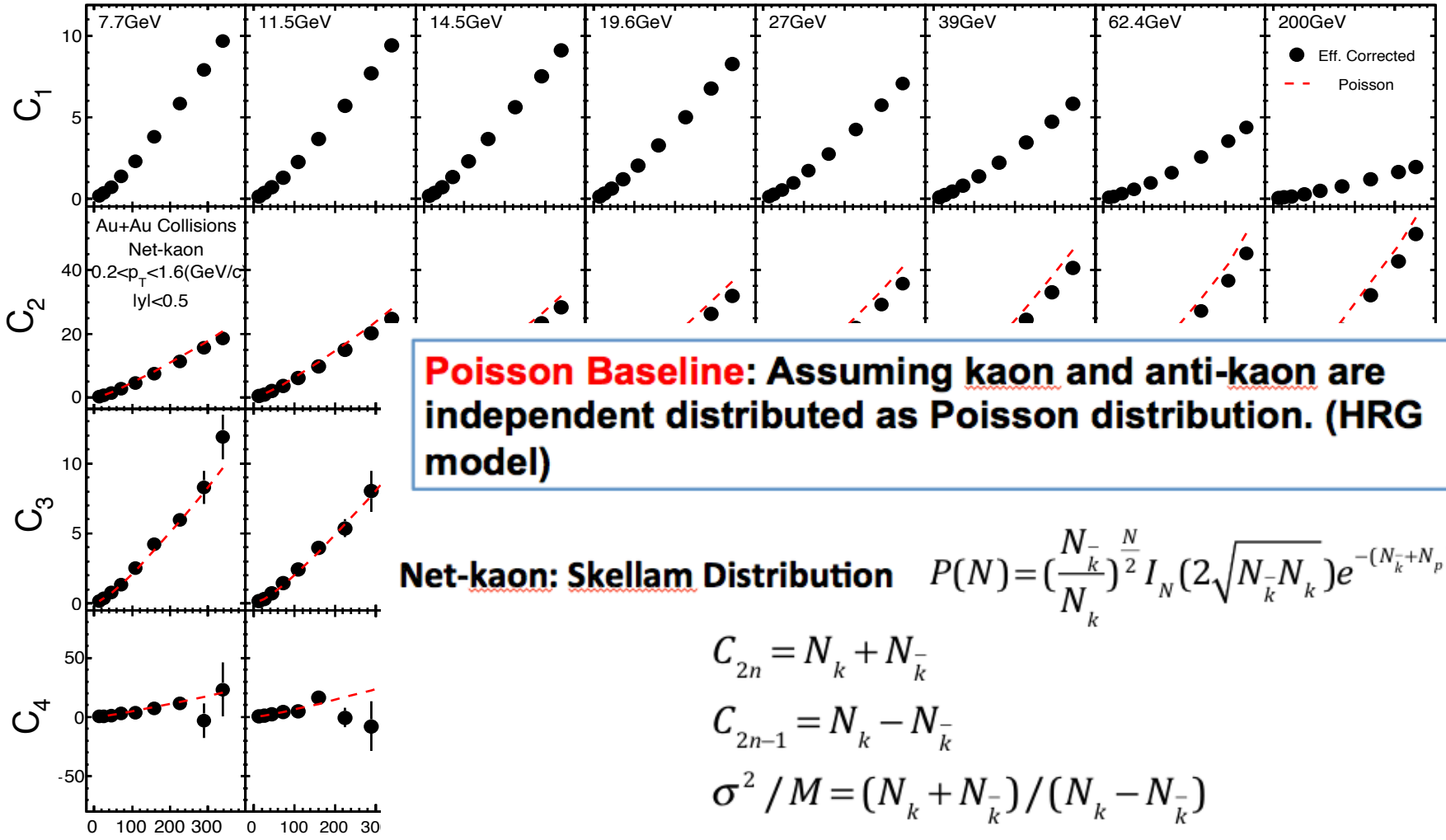
- $0.2 < p_T < 0.4$ (GeV/c), TPC only
- $0.4 < p_T < 1.6$ (GeV/c), TPC+TOF
  Efficiency=Efficiency(Tracking)*Efficiency(TOF match)
- The input number is the p_T weighted average efficiency.

Cumulants for Net-Kaon



C_3 and C_4 generally consistent with Poisson expectation.

Cumulants for Net-Kaon



Poisson Baseline: Assuming kaon and anti-kaon are independent distributed as Poisson distribution. (HRG model)

Net-kaon: Skellam Distribution $P(N)=(\frac{N_{\bar{k}}}{N_k})^{\frac{N}{2}} I_N(2\sqrt{N_{\bar{k}}N_k})e^{-(N_{\bar{k}}+N_p)}$

$$C_{2n}=N_k+N_{\bar{k}}$$

$$C_{2n-1}=N_k-N_{\bar{k}}$$

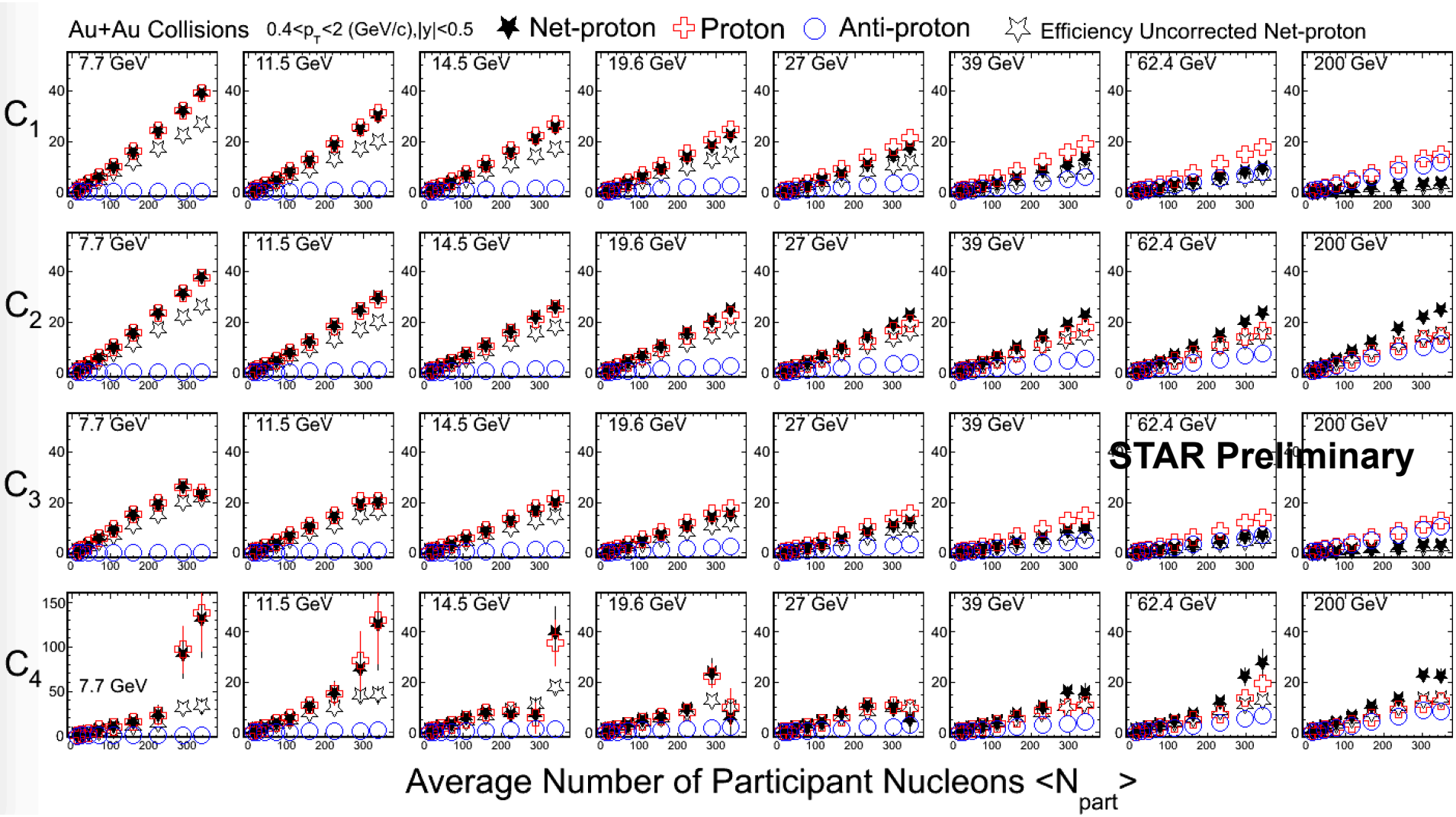
$$\sigma^2/M=(N_k+N_{\bar{k}})/(N_k-N_{\bar{k}})$$

$$S\sigma=(N_k-N_{\bar{k}})/(N_k+N_{\bar{k}})$$

$$\kappa\sigma^2=1$$

C_3 and

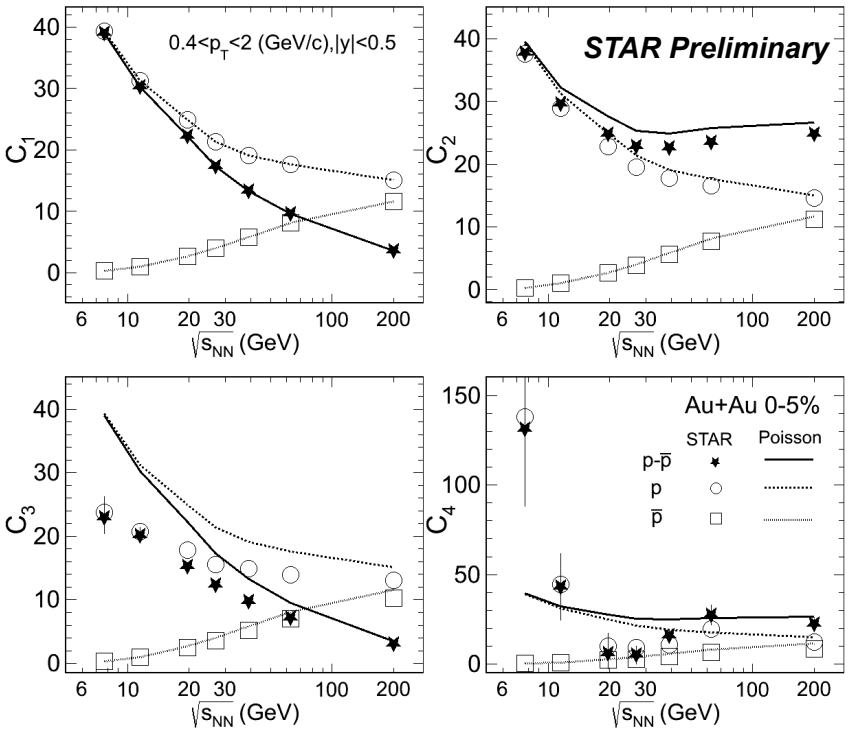
Cumulants for Net-P, P and Anti-P



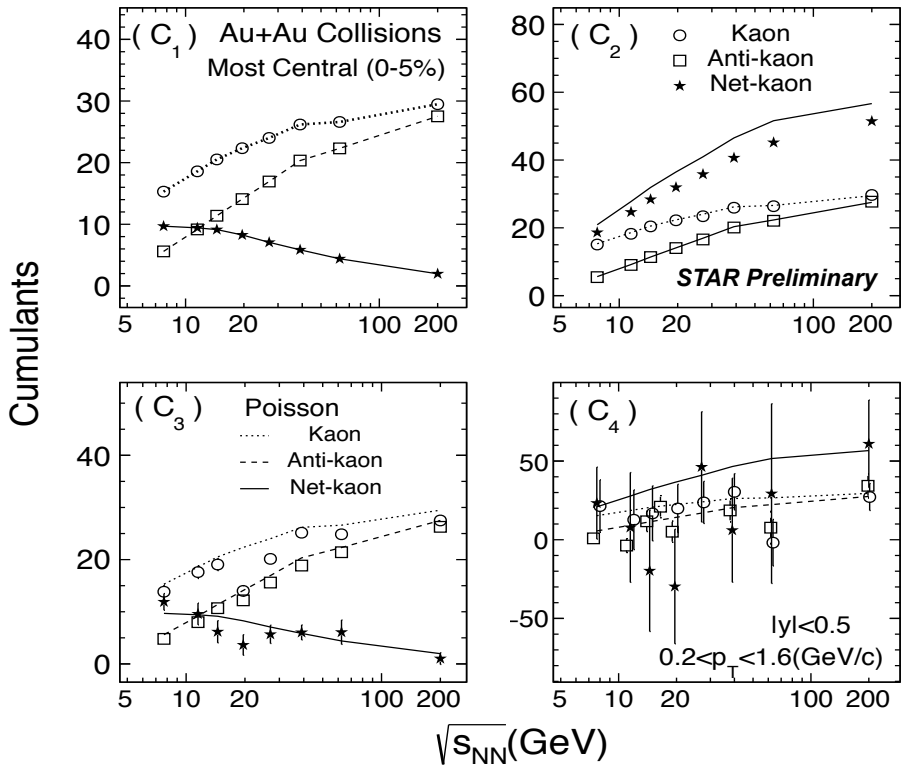
In general, cumulants are increasing with $\langle N_{part} \rangle$.

Cumulants vs. Baselines

Cumulants vs. Poisson (Protons)

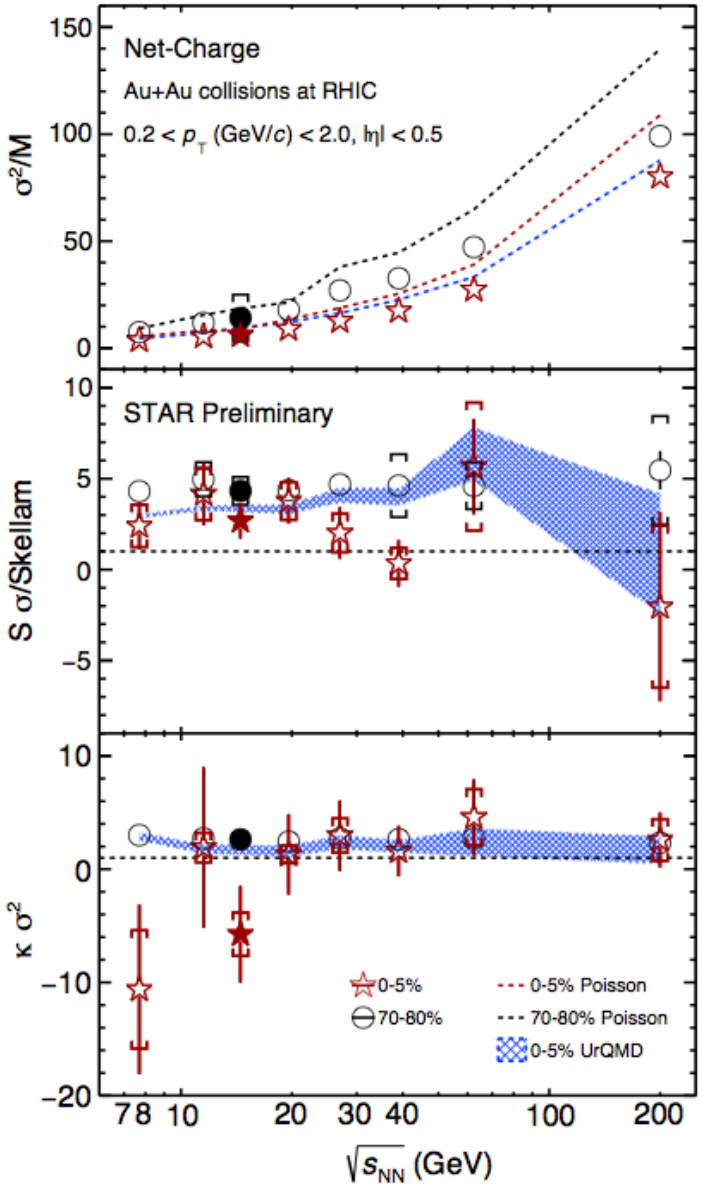


Cumulants vs. Poisson (Kaons)



- The higher the order of cumulants, the larger deviations from Poisson expectations for net-proton and proton.
- In general, the cumulants for net-kaon, kaon and antikaon are consistent with Poisson baseline within uncertainties.

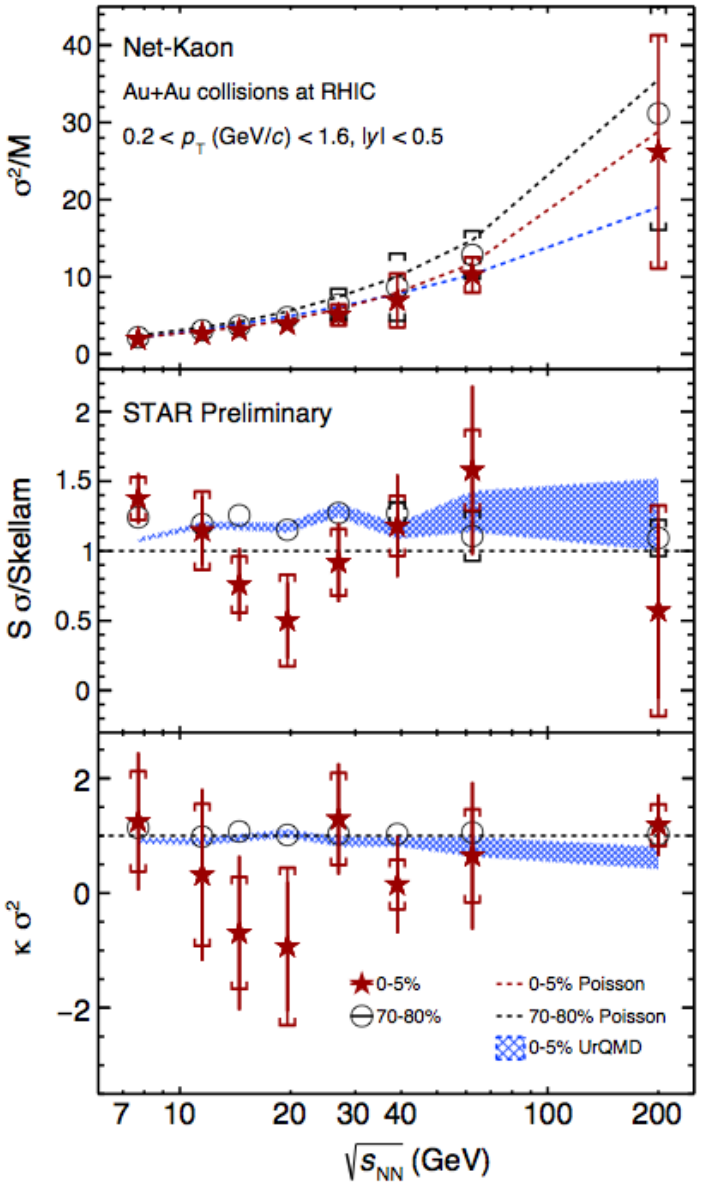
Energy Dependence of net-charge



- 14.5 GeV data-point added to the published data. Fits well into trends
- σ^2/M increases with increasing collision energy.
- $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with unity within uncertainties.
- UrQMD (no Critical Point), shows no energy dependence.

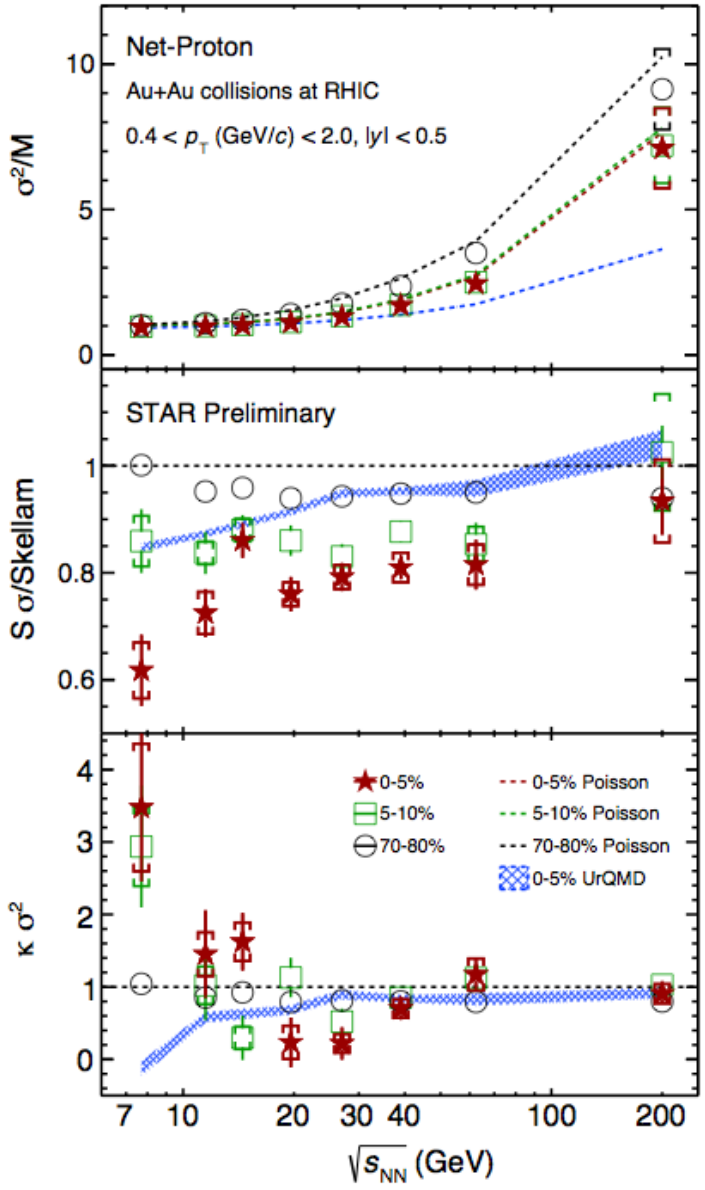
Phys. Rev. Lett. 113, 092301 (2014)

Energy Dependence of Net-kaon



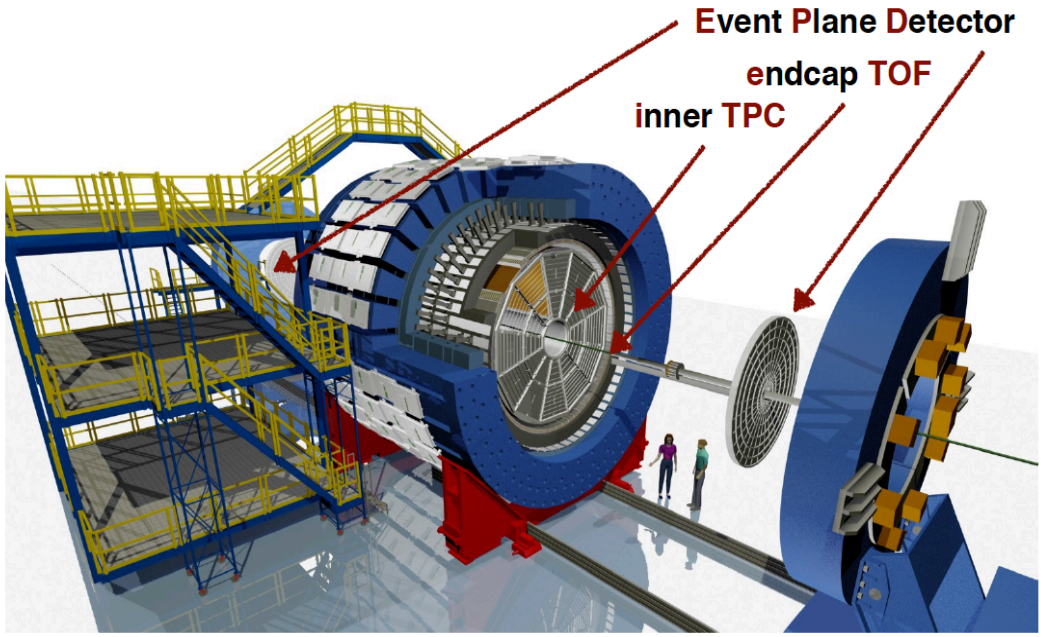
- The values of σ^2/M increase as the energy increases.
- The values of Sσ/Skellam are consistent with unity, within uncertainties.
- The values of $\kappa\sigma^2$ are consistent with unity within uncertainties.
- UrQMD (no Critical Point), shows no energy dependence.

Energy Dependence of Net-proton



- σ^2/M increases with increasing energy, consistent with Poisson expectation.
- $S\sigma$/Skellam increases with increasing energy.
- Non-monotonic behavior of net-proton $\kappa\sigma^2$ seen in 0-5% and 5-10% central collisions.
- Peripheral collisions show smooth trend.
- UrQMD (no Critical Point), shows suppression at lower energies - due to baryon number conservation.

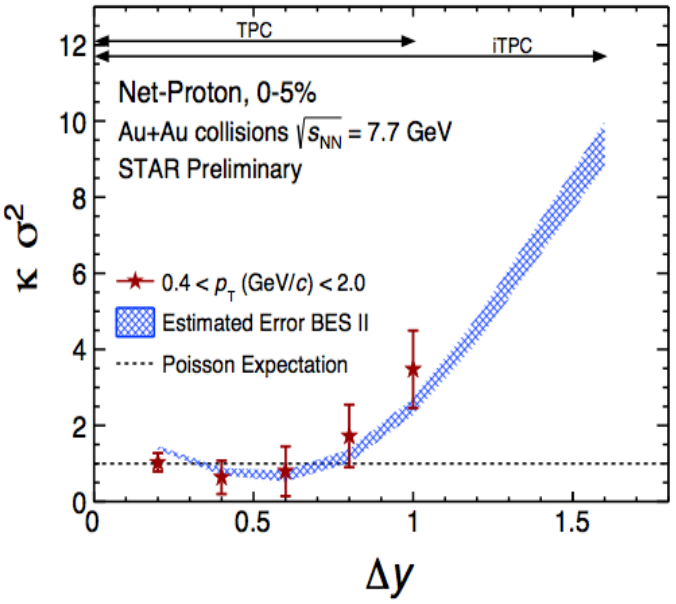
Beam Energy Scan II

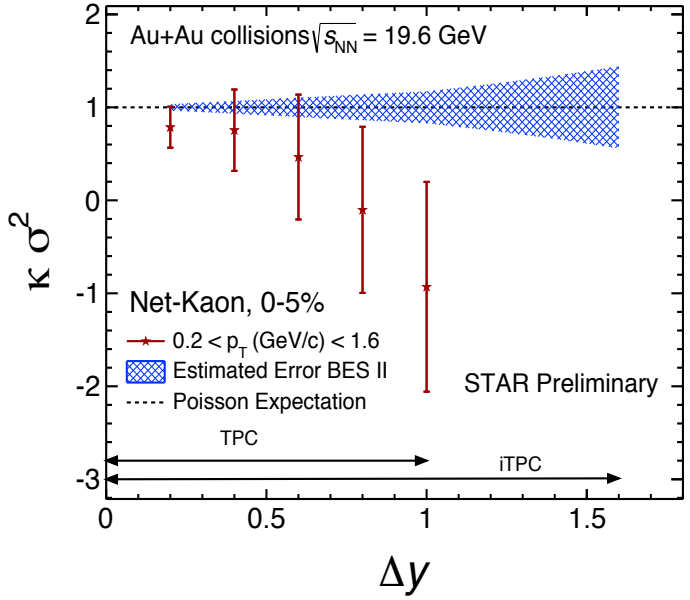


iTPC proposal: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
BES-II whitepaper: http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Errors estimate from: X. Luo, PHys. Rev. C91, 034907 (2015)
Δy trend from: Bo Ling, Misha Stephanov, arXiv: 1512.09125

- Inner TPC(iTPC) upgrade : |η| < 1 to | η |< 1.5, better dE/dx resolution.
- Forward Event Plane Detector (EPD): Centrality and Event Plane Determination. 1.8 < |η| < 4.5





Summary

- STAR results on collision energy dependence of net-Proton, net-Kaon and net-Charge cumulant ratios for Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV are presented.
- The values of net-Kaon's and net-Charge's $\kappa\sigma^2$ and $S\sigma$/ Skellam are consistent with Poisson distributions within errors.
- Non-monotonic behavior seen in net-Proton $\kappa\sigma^2$ in 0-5% and 5-10% central collisions.
- BES-II (2019-2020) will improve on:
  - rapidity coverage $|y| < 0.5 \Rightarrow |y| < 0.8$
  - purity and efficiency
  - statistical uncertainties for all collisions < 20 GeV

Thank You!