Measurements of corrected Net-Particle Distributions with STAR at RHIC

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Outline

- Motivation
- Observables and their experimental access
- Corrections / Error Estimation
- Results from Net-Proton Higher Moments
- Results from Net-Charge Higher Moments
- Outlook: Beam Energy Scan – Phase II

Motivation

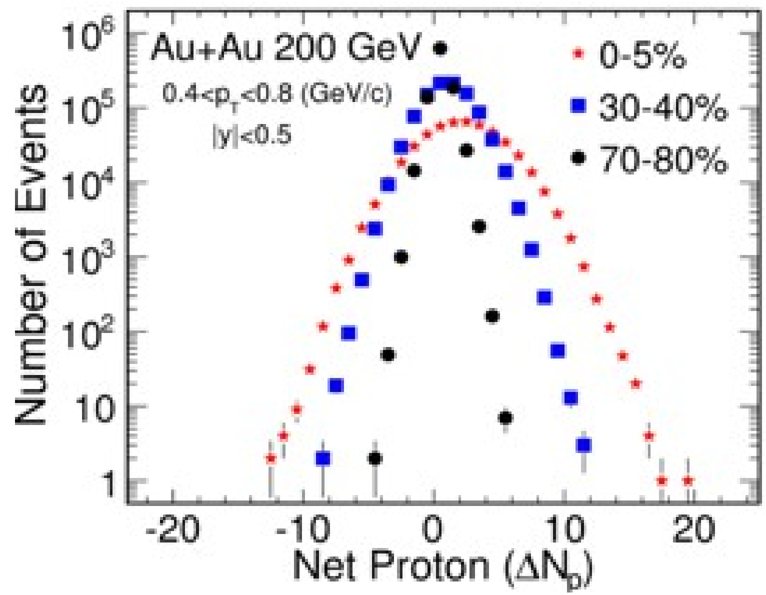
- Event-by-event fluctuations of conserved quantities have been proposed as most direct observables for the study of the phase transition between a quark-gluon plasma and hadronic matter
  - Net-charge / net-baryon (*net-proton*) / net-strangeness

Phys. Rev. Lett. 113 (2014) 092301 Phys. Rev. Lett. 112 (2014) 032302

- Evolution of fluctuations
  - Transition between high-T QGP phase and low-T hadronic phase occurs in small ΔT and leads to rapid change in entropy and energy density
  - It is expected that these transitions cause large fluctuations of conserved quantities.

→ Study tails of net-particle distributions

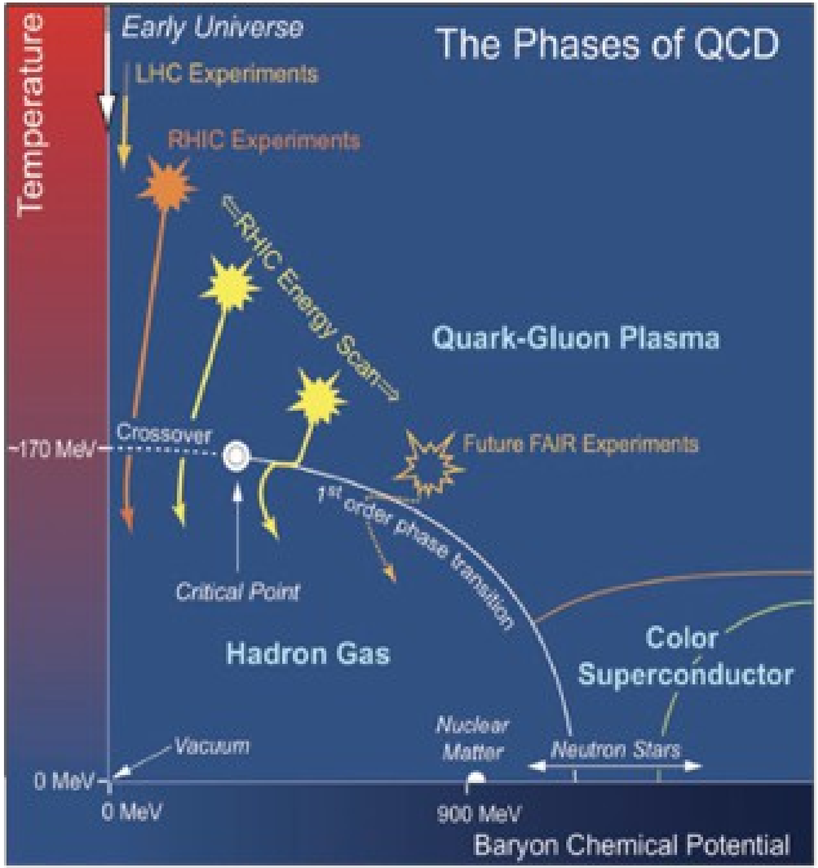
Phys. Rev. Lett. 112 (2014) 032302



Search for the QCD critical point

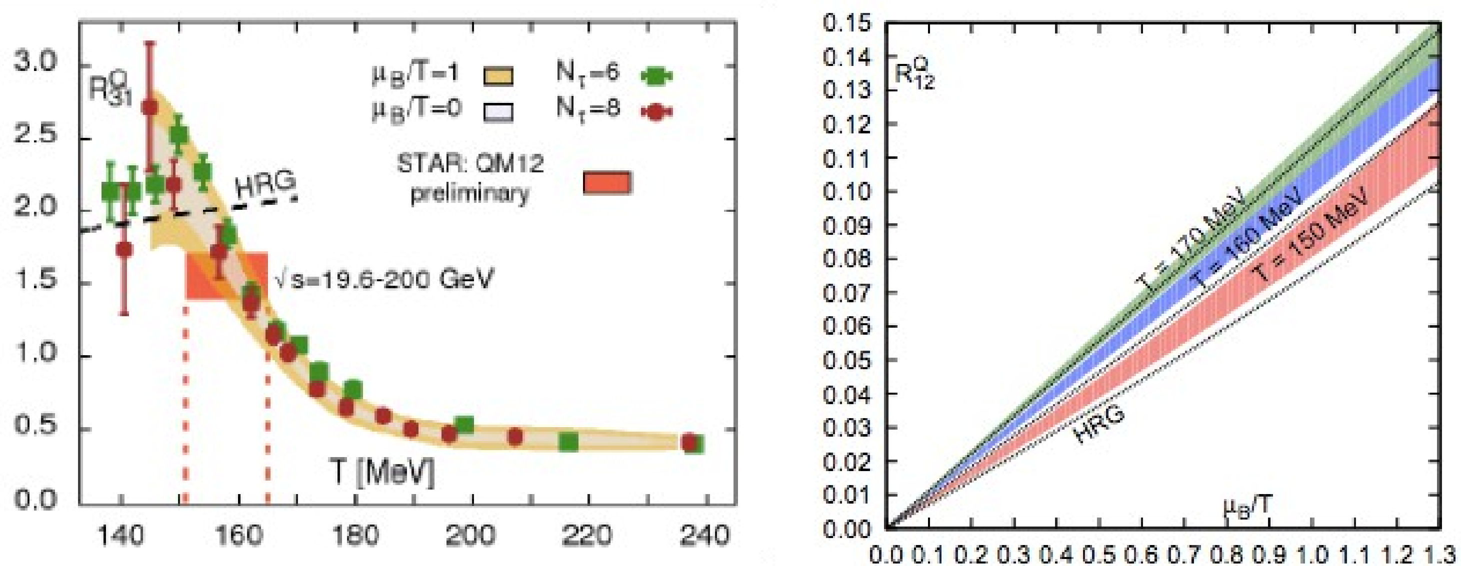
- Endpoint of the first order phase transition boundary.

- Experimental discovery of the QCD critical point will be
  - an excellent test of QCD theory in non-perturbative region
  - and a landmark of the exploring the QCD phase structure.



Freeze out parameters

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



Comparing first principal Lattice calculations with measured moments of conserved quantities (Net-Charge), one can extract the chemical freeze out parameter T and μ_B

Observables

- Higher order moments of conserved charges q
  - Charge (Q), Strangeness (S), Baryon number (B)
- Expressed by fluctuations of net-particle distributions ($\Delta N = N_{q+} - N_{q-}$)
  - Net-charge, net-kaon (proxy for S), net-proton (proxy for B)
  - Sensitive to correlation length (ξ) of the system

$$\langle(\Delta N)^2\rangle \approx \xi^2 \qquad \langle(\Delta N)^3\rangle \approx \xi^{4.5} \qquad \langle(\Delta N)^4\rangle \approx \xi^7$$

M.A.Stephanov, PRL107, 052301 (2011)

- Direct comparison with Lattice calculations via susceptibilities (χ^q_n) which are cumulants by assumption

$$\chi_1 = \frac{1}{VT^3}\langle(\Delta N_p)\rangle \qquad \chi_2 = \frac{1}{VT^3}\langle(\Delta N_p)^2\rangle$$

$$\chi_3 = \frac{1}{VT^3}\langle(\Delta N_p)^3\rangle \qquad \chi_4 = \frac{1}{VT^3}[\langle(\Delta N_p)^4\rangle - 3\langle(\Delta N_p)^2\rangle^2]$$

Susceptibilities **are calculable via Lattice QCD for small μ_B,** ***Cumulants*** **via experiment**

Experimental Observables

- Quantified via
  - higher order moments,
  - their cumulants c_k and
  - cumulant ratios
    - To cancel volume effects

$$Mean : M = \overline{x} = c_1$$

$$Variance : \sigma = \sqrt{\mu_2} = c_2$$

$$Skewness : S = \frac{\mu_3}{\mu_2^{3/2}} = \frac{c_3}{c_2^{3/2}}$$

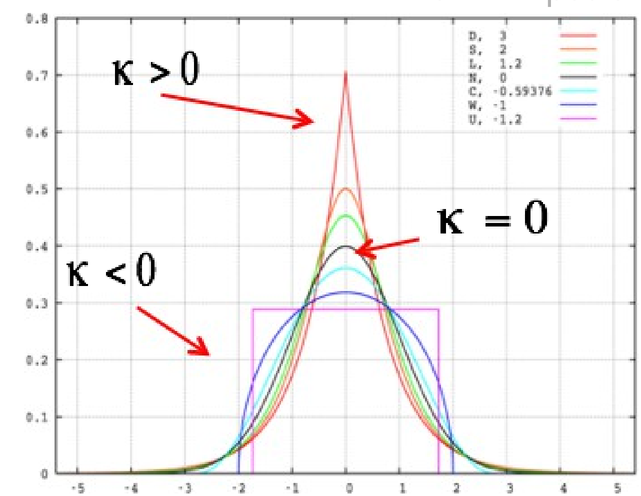
$$Kurtosis : \kappa = \frac{\mu_4}{\mu_2^2} - 3 = \frac{c_4}{c_2^2}$$

$$\sigma^2 / M = \frac{c_2}{c_1} \quad \text{better} \quad M / \sigma^2 = \frac{c_1}{c_2}$$

$$S \sigma^3 / M = \frac{c_3}{c_1}$$

$$S \sigma = \frac{c_3}{c_2} \qquad \kappa \sigma^2 = \frac{c_4}{c_2}$$

From wikipedia



Experimental Access

Naïvely: Measure number of particles and anti-particles per event - take the difference

- Higher order moments are extremely sensitive to
  - Detector or reconstruction/PID efficiencies
  - Event selection → avoid pile up events (more than one collision in TPC readout window)
  - Effects on both particles and anti-particles in the same way / in different ways / only particles or anti-particles
  - Limited acceptance (φ/η) coverage
  - Secondary particles from weak decays (mainly protons)
  - Non-perfect PID, misidentification
  - Absorption of anti-particles in the material (anti-protons)
  - Secondary particles from the material (mainly protons)

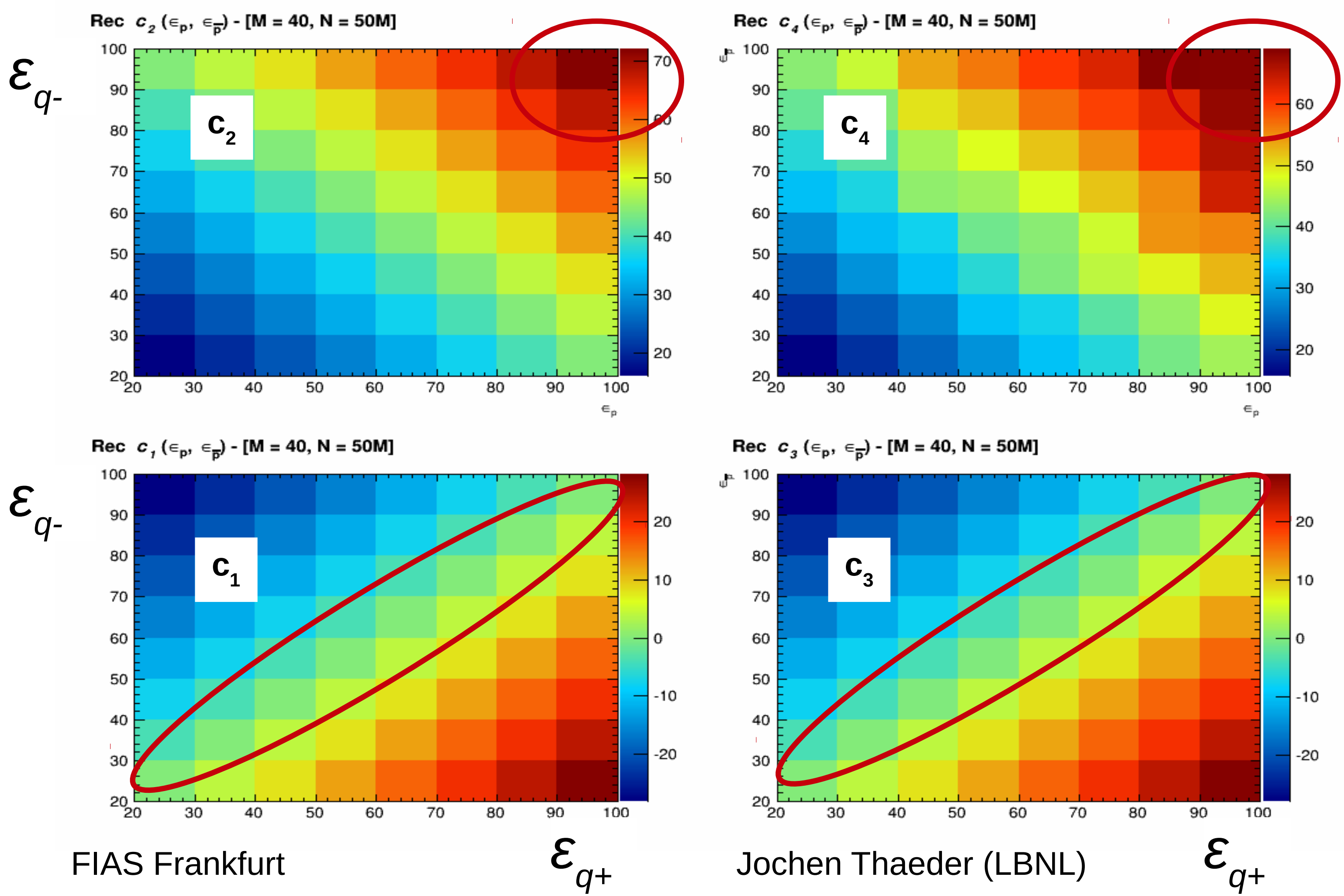
Therefore: Correct the higher order cumulants for those effects!

- But: a normal – on average – correction will only correct the mean.
- … need more sophisticated methods

Simple (Poissonian) Toy MC

Study efficiency dependence c_n for ε_{q+} vs ε_{q-}

→ Mean of number of particles/anti-particles per event (N_p / N_{pbar}): 40



Even cumulants:
the closer to 100%
the better
$c_2 = c_4 = N_{q+} + N_{q-}$

Odd cumulants:
equal efficiencies
preferred
$c_1 = c_3 = N_{q+} - N_{q-r}$

Efficiency correction

A. Bzdak and V. Koch, PRC86, 044904 (2012)

Factorial Moments

- Factorize out different orders of efficiencies

$$F_{ik} \equiv \left\langle \frac{N_1!}{(N_1-i)!}\frac{N_2!}{(N_2-k)!} \right\rangle = \sum_{N_1=i}^{\infty}\sum_{N_2=k}^{\infty} P(N_1,N_2)\frac{N_1!}{(N_1-i)!}\frac{N_2!}{(N_2-k)!},$$

$$f_{ik} \equiv \left\langle \frac{n_1!}{(n_1-i)!}\frac{n_2!}{(n_2-k)!} \right\rangle = \sum_{n_1=i}^{\infty}\sum_{n_2=k}^{\infty} p(n_1,n_2)\frac{n_1!}{(n_1-i)!}\frac{n_2!}{(n_2-k)!}.$$

- Apply "flat, average" efficiency for particle/anti-particles

$$f_{ik} = p_1^i \cdot p_2^k \cdot F_{ik}$$

- Extract cumulants:

$$c_1 = pK_1,$$

$$c_2 = p(1-p)N + p^2K_2,$$

$$c_3 = p(1-p^2)K_1 + 3p^2(1-p)(F_{20} - F_{02} - NK_1) + p^3K_3,$$

See talks of Adam and Volker

Efficiency correction

A. Bzdak and V. Koch, PRC91, 027901 (2015)
X. Luo, PRC91, 034907 (2015)

Local Factorial Moments

- Use local factorial moments
  - Allows for non-monotonic phase-spaced dependence
  - Arbitrary binning

$$A_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) = \langle N(x_1)[N(x_2)-\delta_{x_1,x_2}]\cdots[N(x_i)-\delta_{x_1,x_i}-\cdots-\delta_{x_{i-1},x_i}]$$
$$\bar{N}(\bar{x}_1)[\bar{N}(\bar{x}_2)-\delta_{\bar{x}_1,\bar{x}_2}]\cdots[\bar{N}(\bar{x}_k)-\delta_{\bar{x}_1,\bar{x}_k}-\cdots-\delta_{\bar{x}_{k-1},\bar{x}_k}]\rangle,$$
$$a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) = \langle n(x_1)[n(x_2)-\delta_{x_1,x_2}]\cdots[n(x_i)-\delta_{x_1,x_i}-\cdots-\delta_{x_{i-1},x_i}]$$
$$\bar{n}(\bar{x}_1)[\bar{n}(\bar{x}_2)-\delta_{\bar{x}_1,\bar{x}_2}]\cdots[\bar{n}(\bar{x}_k)-\delta_{\bar{x}_1,\bar{x}_k}-\cdots-\delta_{\bar{x}_{k-1},\bar{x}_k}]\rangle.$$

$$a_{i,k} = \epsilon(x_1)\cdots\epsilon(x_i)\bar{\epsilon}(\bar{x}_1)\cdots\bar{\epsilon}(\bar{x}_k)A_{i,k}.$$

$$F_{i,k} = \sum_{x_1,\ldots,x_i}\sum_{\bar{x}_1,\ldots,\bar{x}_k} A_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k),$$
$$f_{i,k} = \sum_{x_1,\ldots,x_i}\sum_{\bar{x}_1,\ldots,\bar{x}_k} a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k).$$

See talks of Adam and Volker

Efficiency correction

A. Bzdak and V. Koch, PRC91, 027901 (2015)
X. Luo, PRC91, 034907 (2015)

Local Factorial Moments

- STAR use case:
  - 2 p_T bins for particle and anti-particle

$$F_{u,v,j,k}(N_{p_1}, N_{p_2}, N_{\bar{p}_1}, N_{\bar{p}_2}) = \frac{f_{u,v,j,k}(n_{p_1}, n_{p_2}, n_{\bar{p}_1}, n_{\bar{p}_2})}{(\epsilon_{p_1})^u(\epsilon_{p_2})^v(\epsilon_{\bar{p}_1})^j(\epsilon_{\bar{p}_2})^k}$$

$$\begin{aligned}
&F_{r_1,r_2}(N_p, N_{\bar{p}}) = F_{r_1,r_2}(N_{p_1}+N_{p_2}, N_{\bar{p}_1}+N_{\bar{p}_2}) \\
&= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2} s_1(r_1,i_1)s_1(r_2,i_2) < (N_{p_1}+N_{p_2})^{i_1}(N_{\bar{p}_1}+N_{\bar{p}_2})^{i_2} > \\
&= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2} s_1(r_1,i_1)s_1(r_2,i_2) < \sum_{s=0}^{i_1}\binom{i_1}{s} N_{p_1}^{i_1-s}N_{p_2}^{s}\sum_{t=0}^{i_2}\binom{i_2}{t} N_{\bar{p}_1}^{i_2-t}N_{\bar{p}_2}^{t} > \\
&= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2}\sum_{s=0}^{i_1}\sum_{t=0}^{i_2} s_1(r_1,i_1)s_1(r_2,i_2)\binom{i_1}{s}\binom{i_2}{t} < N_{p_1}^{i_1-s}N_{p_2}^{s}N_{\bar{p}_1}^{i_2-t}N_{\bar{p}_2}^{t} > \\
&= \sum_{i_1=0}^{r_1}\sum_{i_2=0}^{r_2}\sum_{s=0}^{i_1}\sum_{t=0}^{i_2}\sum_{u=0}^{i_1-s}\sum_{v=0}^{s}\sum_{j=0}^{i_2-t}\sum_{k=0}^{t} s_1(r_1,i_1)s_1(r_2,i_2)\binom{i_1}{s}\binom{i_2}{t} \\
&\times s_2(i_1-s,u)s_2(s,v)s_2(i_2-t,j)s_2(t,k) \times F_{u,v,j,k}(N_{p_1}, N_{p_2}, N_{\bar{p}_1}, N_{\bar{p}_2})
\end{aligned}$$

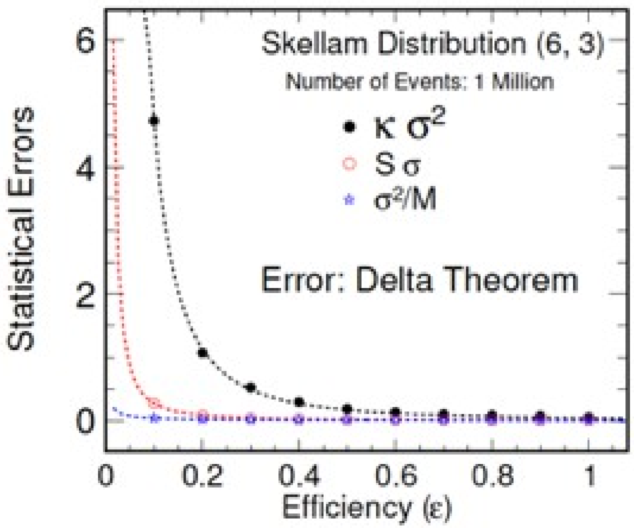
Rather involved formalism!

See talks of Adam and Volker

Statistical Error Estimation

X. Luo, PRC91, 034907 (2015)

Delta Theorem



$$error(c_n) \propto \frac{\sigma^n}{\epsilon^n} \qquad error\left(\frac{c_n}{c_2}\right) \propto \frac{\sigma^{n-2}}{\epsilon^{n/2}},\ for\ n>2$$

$$error(S\sigma) \propto \frac{\sigma}{\epsilon^{3/2}} \qquad error(\kappa\sigma^2) \propto \frac{\sigma^2}{\epsilon^2}$$

- Typical efficiencies
  - ε(proton) > ε(net-charged) > ε(kaon)
- Typical width
  - σ(net-charge) > σ(net-proton) > σ(net-kaon)
- **With same N events**
  - **error(net-charge) > error(net-kaon) > error(net-proton)**

Other Contributions

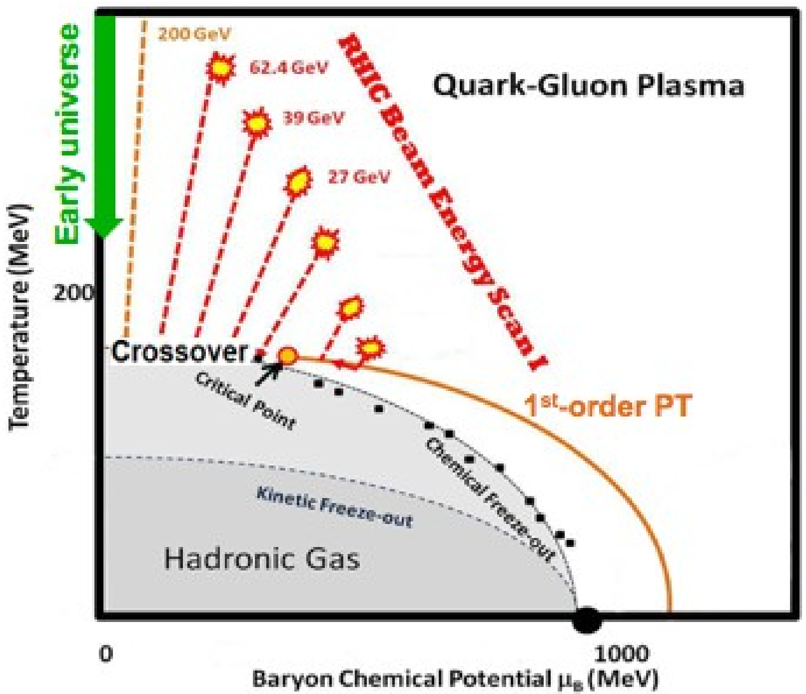
- Initial volume fluctuations
  - Improve centrality resolution
  - apply centrality-bin-width correction
- Remove auto-correlation
  - Particles used in the analysis are excluded in centrality definition
  - STAR uses TPC to extract event centrality

Further Reading
STAR, PRL 105, 022302 (2010)
STAR, PRL112, 032302 (2014)
X. Luo, J. Phys.: Conf. Ser. 316 012003 (2011)
X. Luo, JPG 39, 025008 (2012)
X. Luo,et al., JPG 40, 105104 (2013)
X. Luo, PRC 91, 043907 (2015)

RHIC Beam Energy Scan Phase I (BES I)

Search for the critical point

- Collide heavy-ions and vary beam (collision) energy to change Temperature & Baryon Chemical Potential
- Baryon stopping is the reason that we can achieve finite baryon chemical potential



- **2007**: STAR Beam Energy Scan (BES) Focus Group formed
- **2008**: Test run at √sNN = 9.2 GeV [PRC 81, 024911 (2010)]
- **2009**: Proposal for BES Phase-I [STAR Note SN0493 & arXiv:1007.2613]
- **2010**: BES-I data-taking began 39, 11.5 and 7.7 GeV
- **2011**: Two further energies 27 and 19.6 GeV
- **2012**: Test at 5 GeV
- **2014**: Final BES-I energy (14.5 GeV) and BES-II proposal

RHIC Beam Energy Scan Phase I (BES I)

Search for the critical point

- Map phase transition boundary
- Search for possible QCD critical point
- Scanning 8 collision energies form 7.7 – 200 GeV in 2011, 2011, and 2014

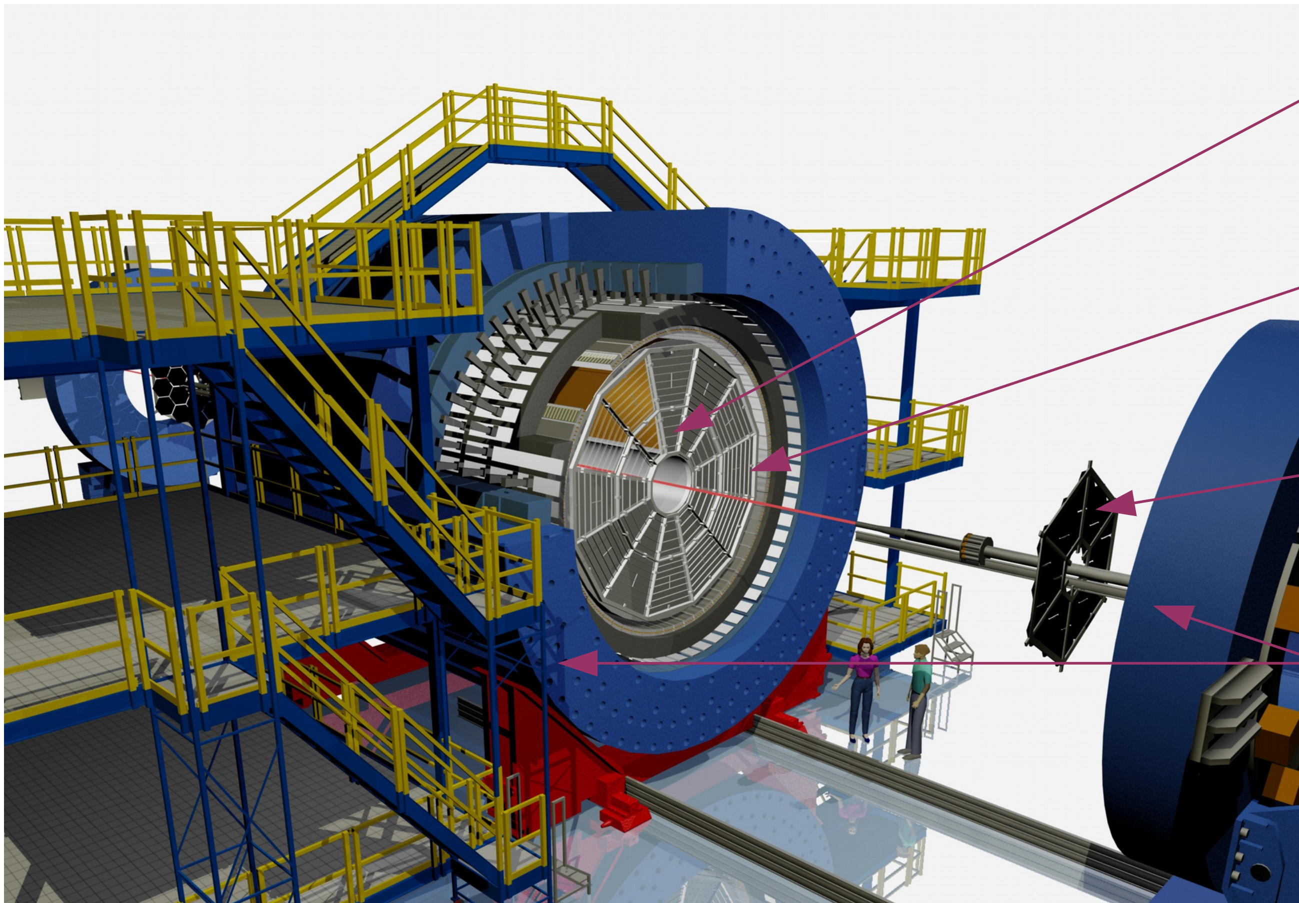
μ_B , T : J. Cleymans et al., PRC 73, 034905 (2006)

$\sqrt{s_{NN}}$ (GeV)	Statistics in 0-80% (M events)	Year	μ_B (MeV)	T (MeV)
7.7	~3	2010	422	140
11.5	~6.6	2010	316	152
14.5	~12.5	2014	264	156
19.6	~15	2011	206	160
27	~32	2011	156	162
39	~86	2010	112	164
62.4	~45	2010	73	165
200	~238	2010	24	166

QM '15

The STAR detector

Full azimuthal coverage, |η| < 1



Time Projection Chamber
Tracking, PID (dE/dx), vertexing
multiplicity

Time-Of-Flight detector
PID (time-of-flight)

Beam-Beam Counter
Min-bias trigger

Magnet

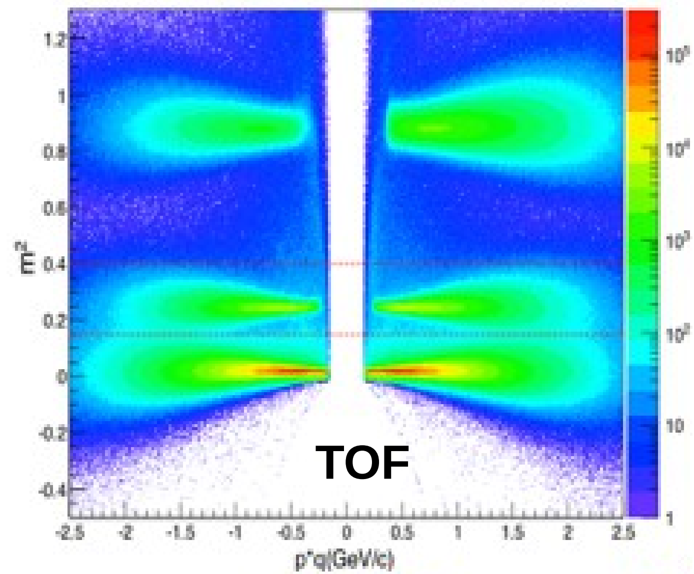
Analysis

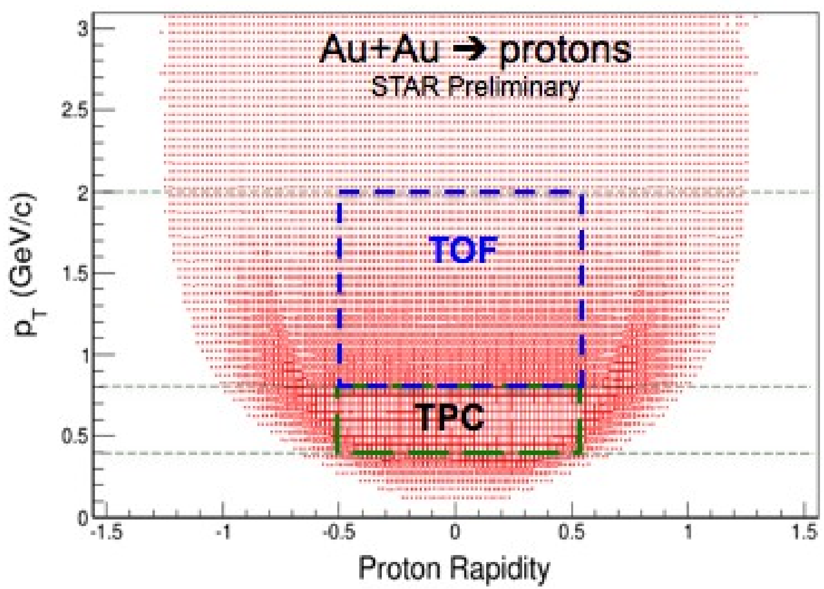
- Events QA: event quality cuts have been applied, bad run/events removed
- Net-Proton
  - $0.4 < p_T < 2.0$ (GeV/c) , $|y| < 0.5$
  - Primary track selection:
    - $DCA_r < 1$ cm, $nHits_{TPC} >= 20$, $nHits_{TPC}/nHitsPoss > 0.52$, $nHits_{dEdx} > 5$
  - Centrality definition: primary particles, <u>except protons</u> in $|y| < 0.5$
- Net-Charge
  - $0.2 < p_T < 2.0$ (GeV/c) , $|\eta| < 0.5$
  - Remove spallation protons for $p_T < 400$ MeV/c
  - Primary track selection:
    - $DCA_r < 1$ cm, $nHits_{TPC} >= 20$, $nHits_{TPC}/nHitsPoss > 0.52$, $nHits_{dEdx} > 10$
  - Centrality definition: primary particles in $0.5 < |\eta| < 1.0$
- Efficiency * acceptance corrections are done appropriately

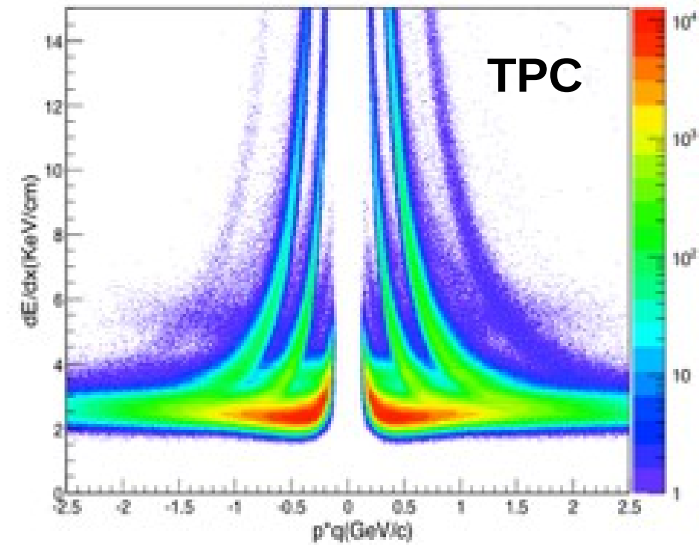
Particle Identification

Combined PID for Net-Proton (|y| < 0.5)

- TPC : $0.4 < p_T < 0.8$ (GeV/c)
- TPC+TOF $0.8 < p_T < 2.0$ (GeV/c)
  - New compared to published: *PRL 112, 032302 (2014)*
  - Doubles total multiplicity for (anti-)protons







Efficiencies (Tracking + PID)

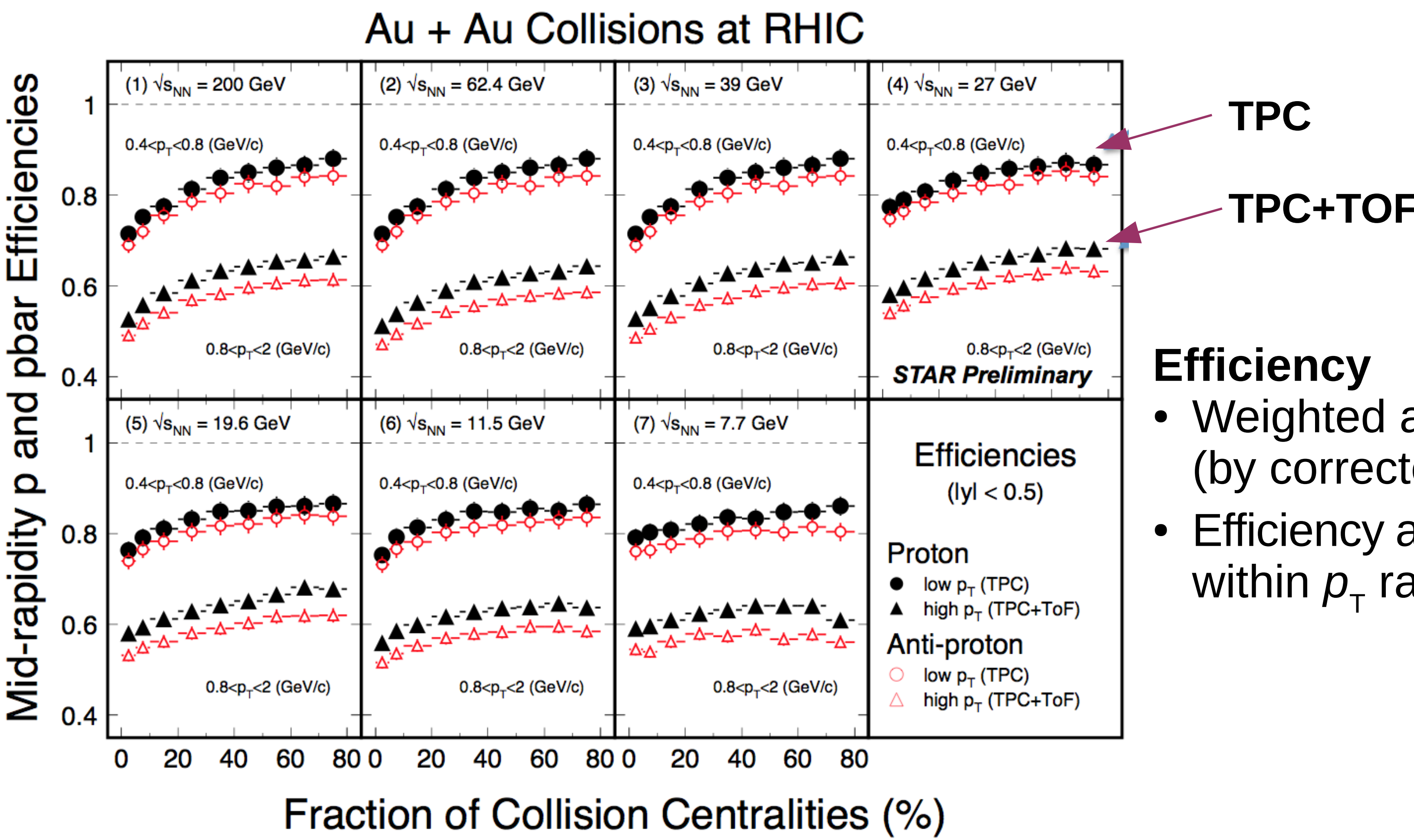
Combined PID for Net-Proton (|y| < 0.5)

- TPC : $0.4 < p_T < 0.8$ (GeV/c)
  - ε_{TPC} changes as a function of p_T, **$\langle\varepsilon_{TPC}\rangle \sim 0.8$**
  - Centrality dependence is relatively small
- TPC+TOF $0.8 < p_T < 2.0$ (GeV/c)
  - Significantly smaller efficiencies !
  - TOF overall efficiency $\langle\varepsilon_{TOF}\rangle \sim 0.7$
    - Fairly constant vs p_T
  - **$\langle\varepsilon_{TPC+TOF}\rangle$** $= \langle\varepsilon_{TPC}\rangle * \langle\varepsilon_{TOF}\rangle \sim$ **0.5**
    - small centrality variation

Efficiencies (Tracking + PID)

Combined PID for Net-Proton (|y| < 0.5)

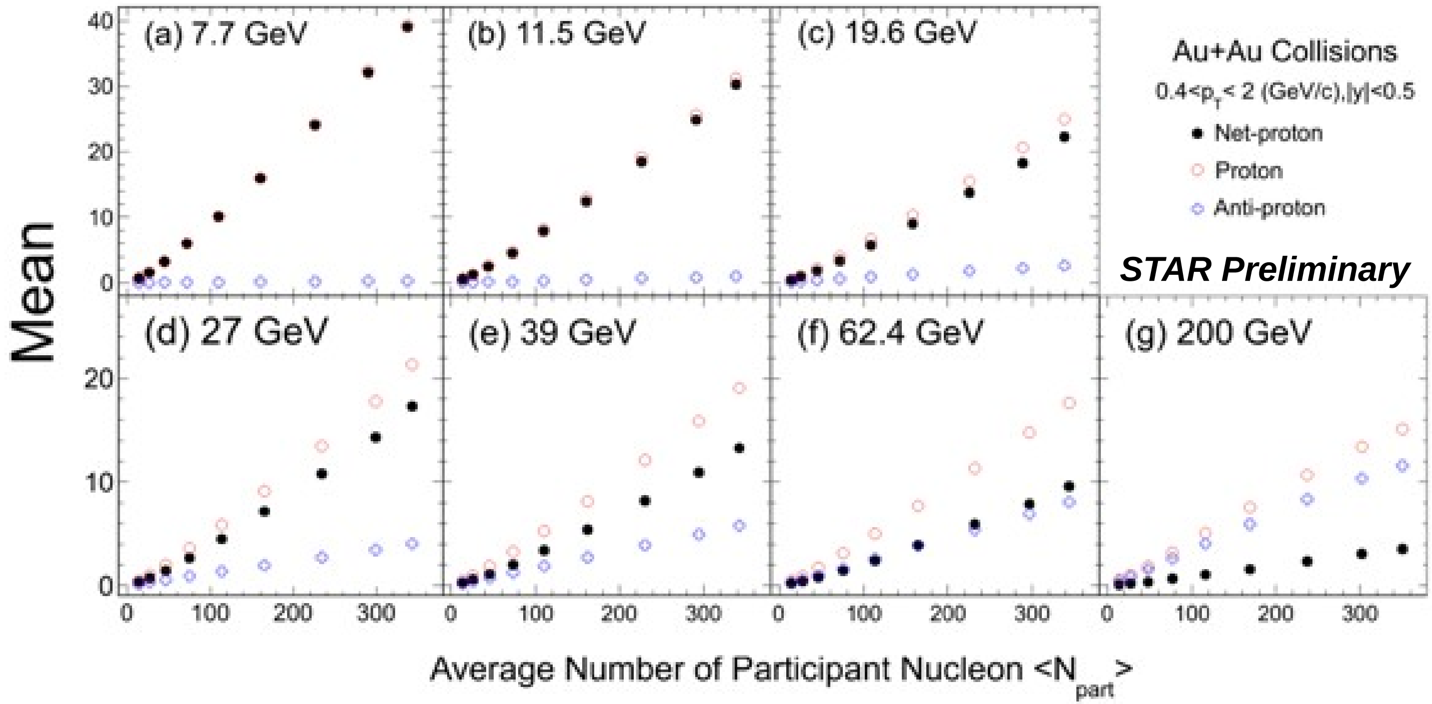
CPOD 2014



Efficiency

- Weighted average (by corrected p_T spectra)
- Efficiency almost flat within p_T range

Net-Proton / Protons / Anti-Protons

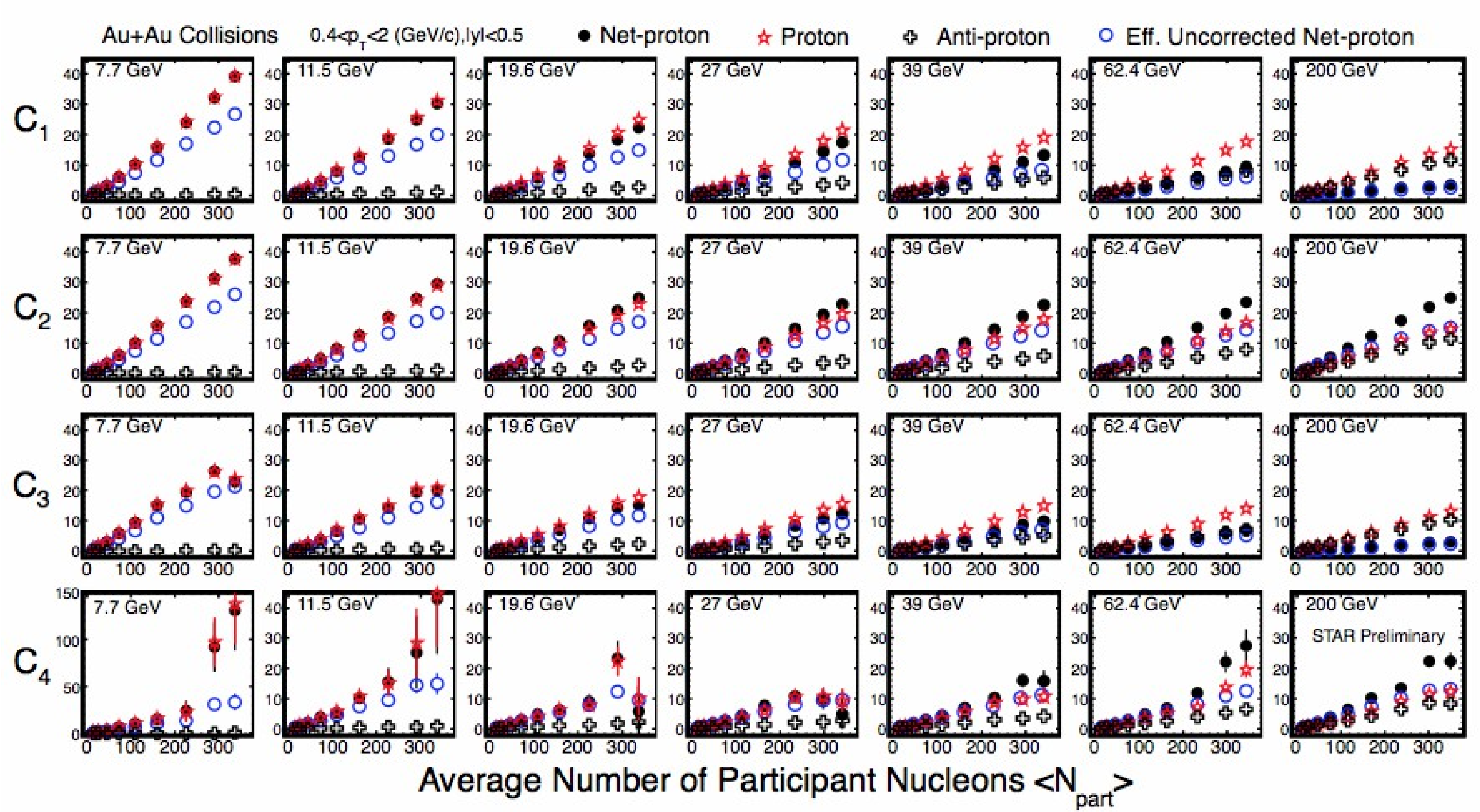


- Mean net-proton and (anti-)proton number increase with $\langle N_{part} \rangle$
- Net-proton number is dominated by protons at low energies and increases when energy decreases
  - (Interplay between baryon stopping and pair production)

Net-Proton Energy Dependence

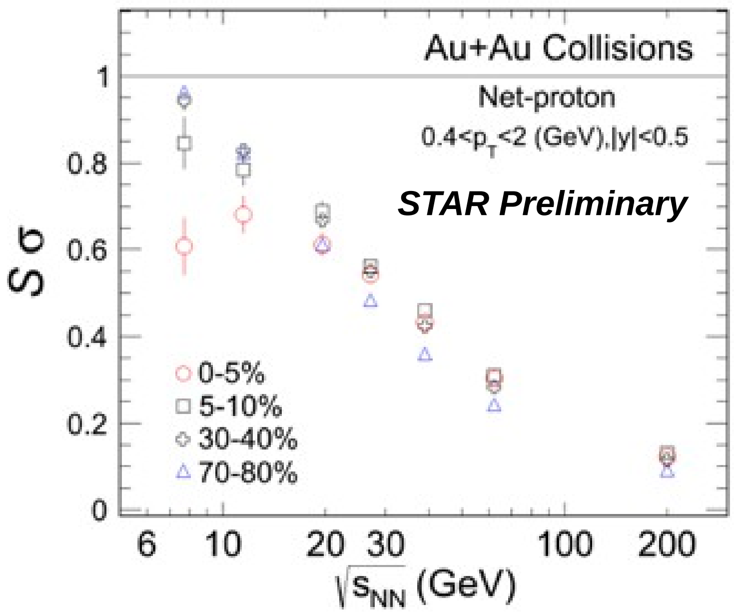
CPOD 2014

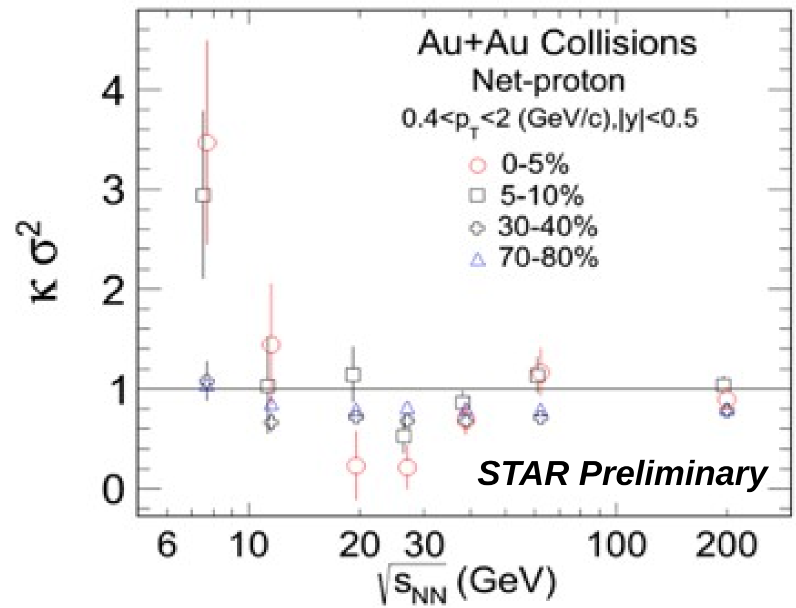
Cumulants



Net-Proton Energy Dependence

Cumulants Ratios – Centrality Dependence Study



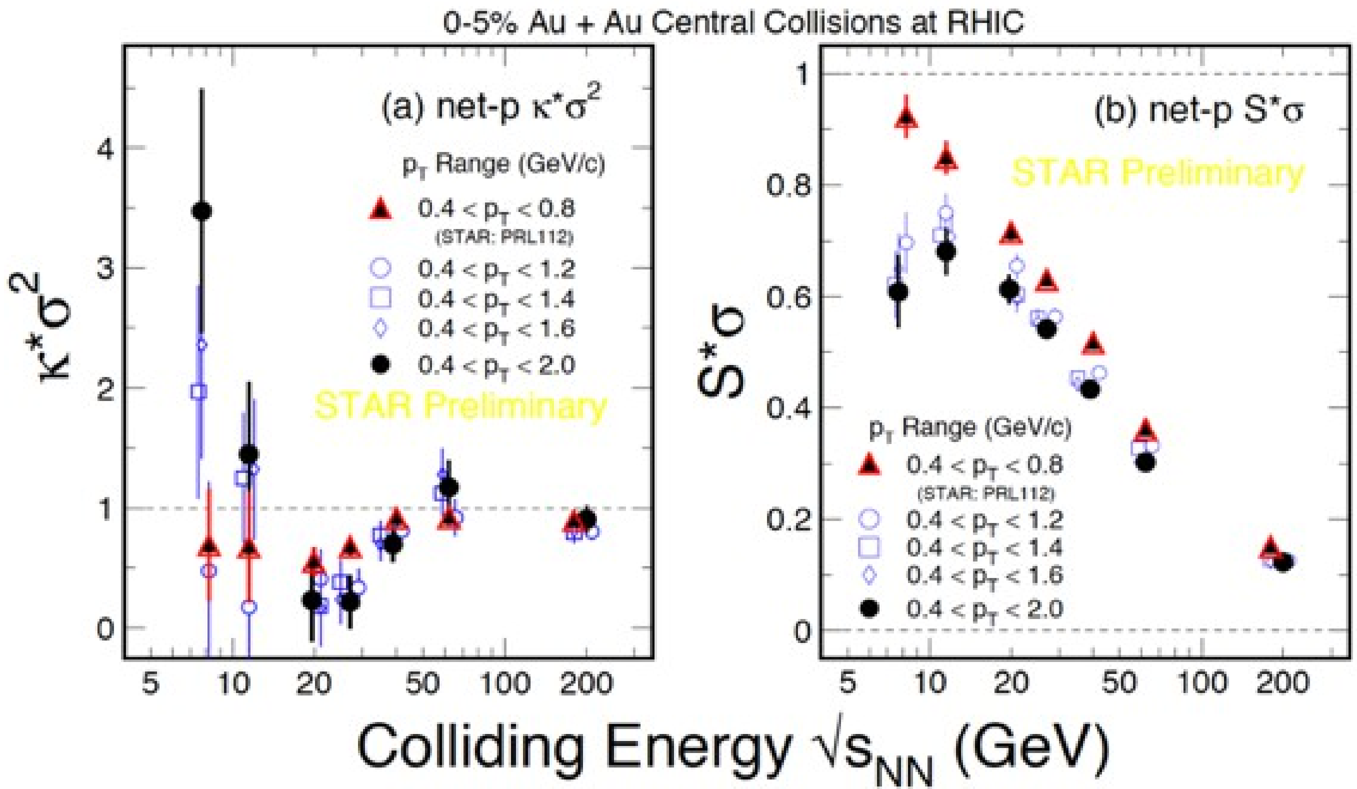


- Error bars are statistical only. Systematic errors estimation underway.
- Dominant contributors:
  - efficiency corrections / PID

Net-Proton Energy Dependence

CPOD 2014

Cumulants Ratios – Momentum Dependence Study



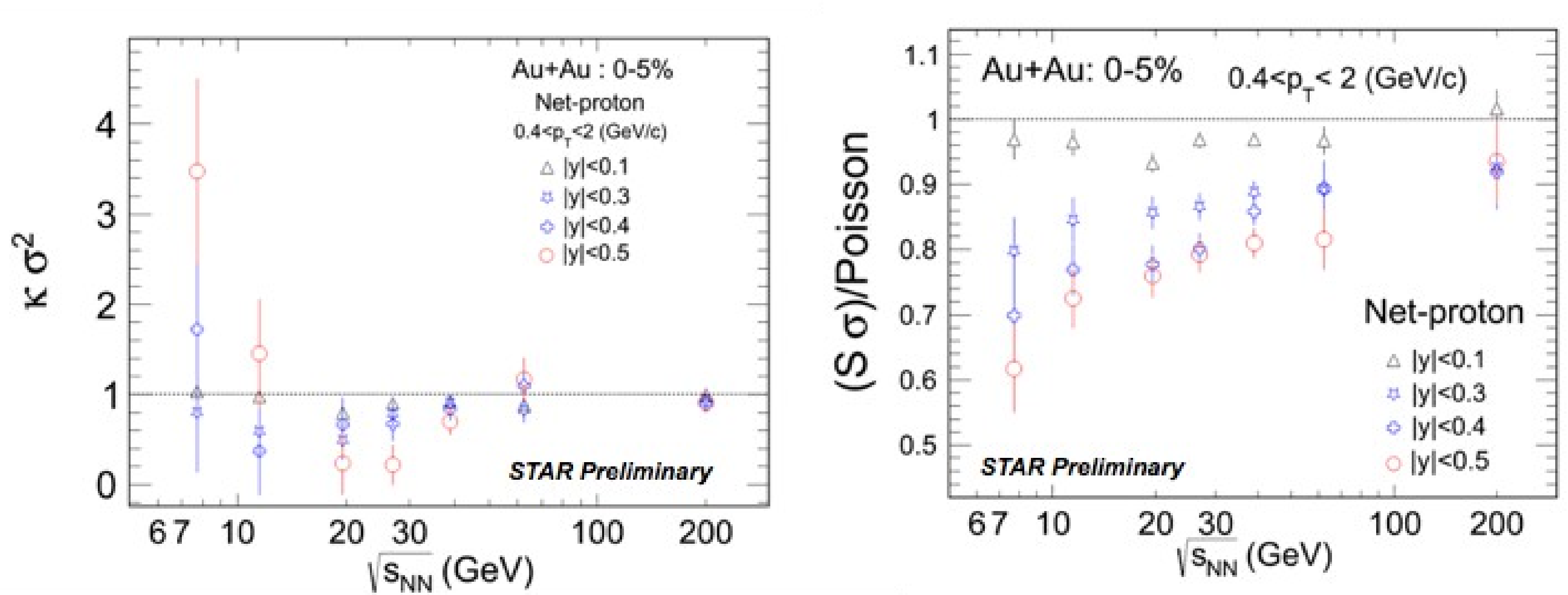
Kσ²: the energy dependence tends to be more pronounced with wider p_T acceptance, relative to published results

Sσ: the values are smaller for wider pT acceptance

Net-Proton Energy Dependence

CPOD 2014

Cumulants Ratios – Rapidity Dependence Study



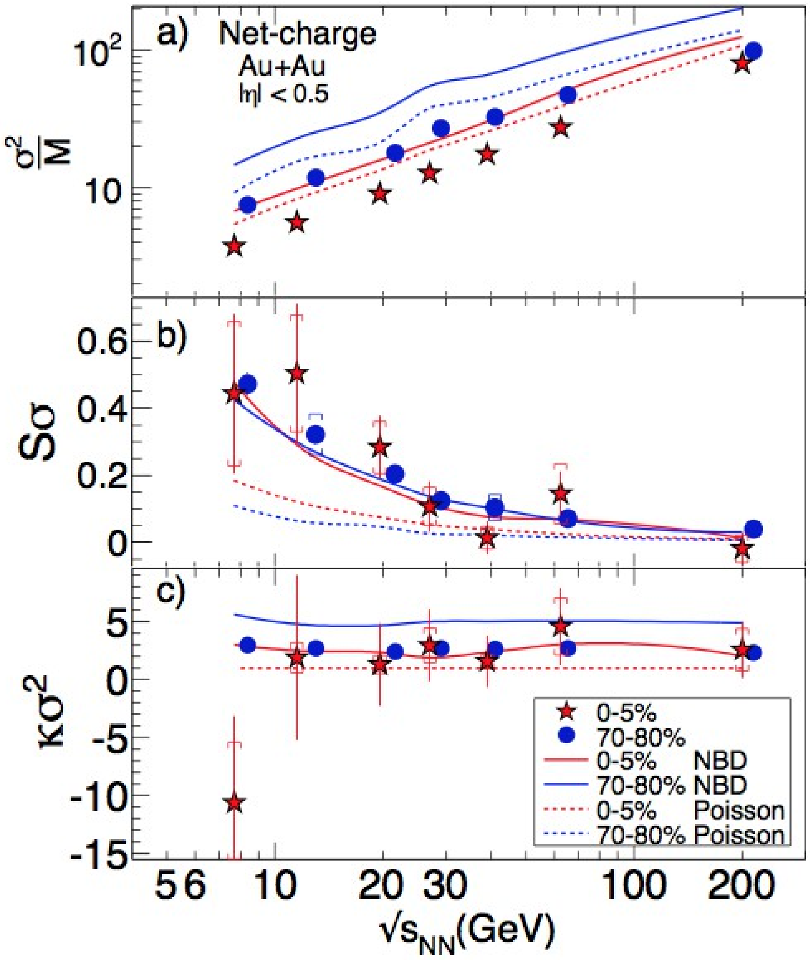
Decreasing |*y*| brings cumulant ratios closer to Poisson Expectation

- Both in p_T and *y* acceptance impact the values of moments.
- The acceptance needs to be large enough to capture the dynamical fluctuations.

The related systematic errors should be carefully addressed.

Net-Charge Energy Dependence

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

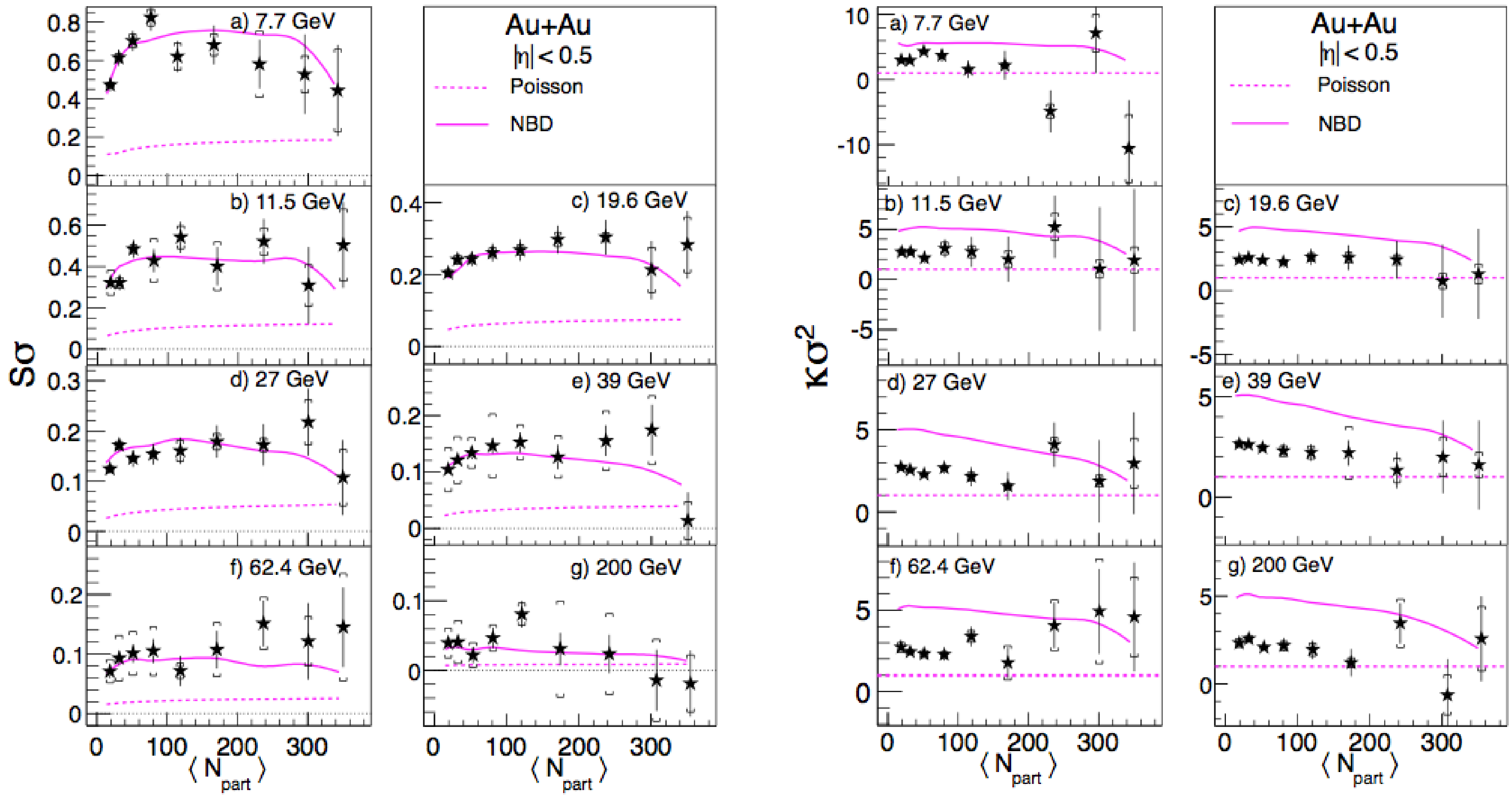


- σ^2/M values increase monotonically with increasing beam energy.
- $S\sigma$ values increase with decreasing beam energy.
- The values of $\kappa\sigma^2$ seem to be consistent with no beam energy dependence

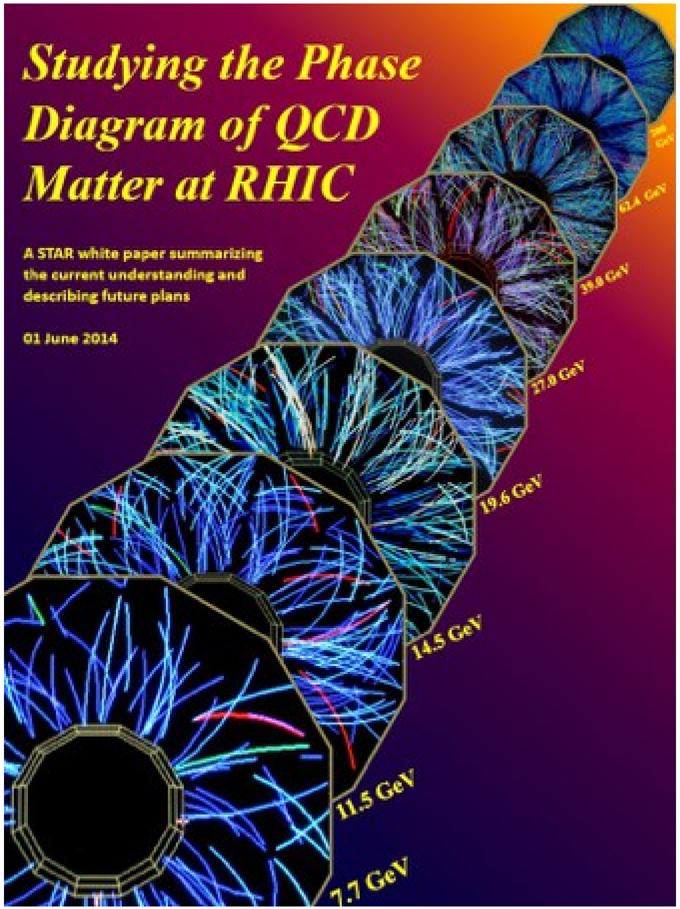
NBD: Negative Binomial Distribution

Net-Charge Centrality Dependence

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



Plans Beam Energy Scan Phase II
(2018-2019)



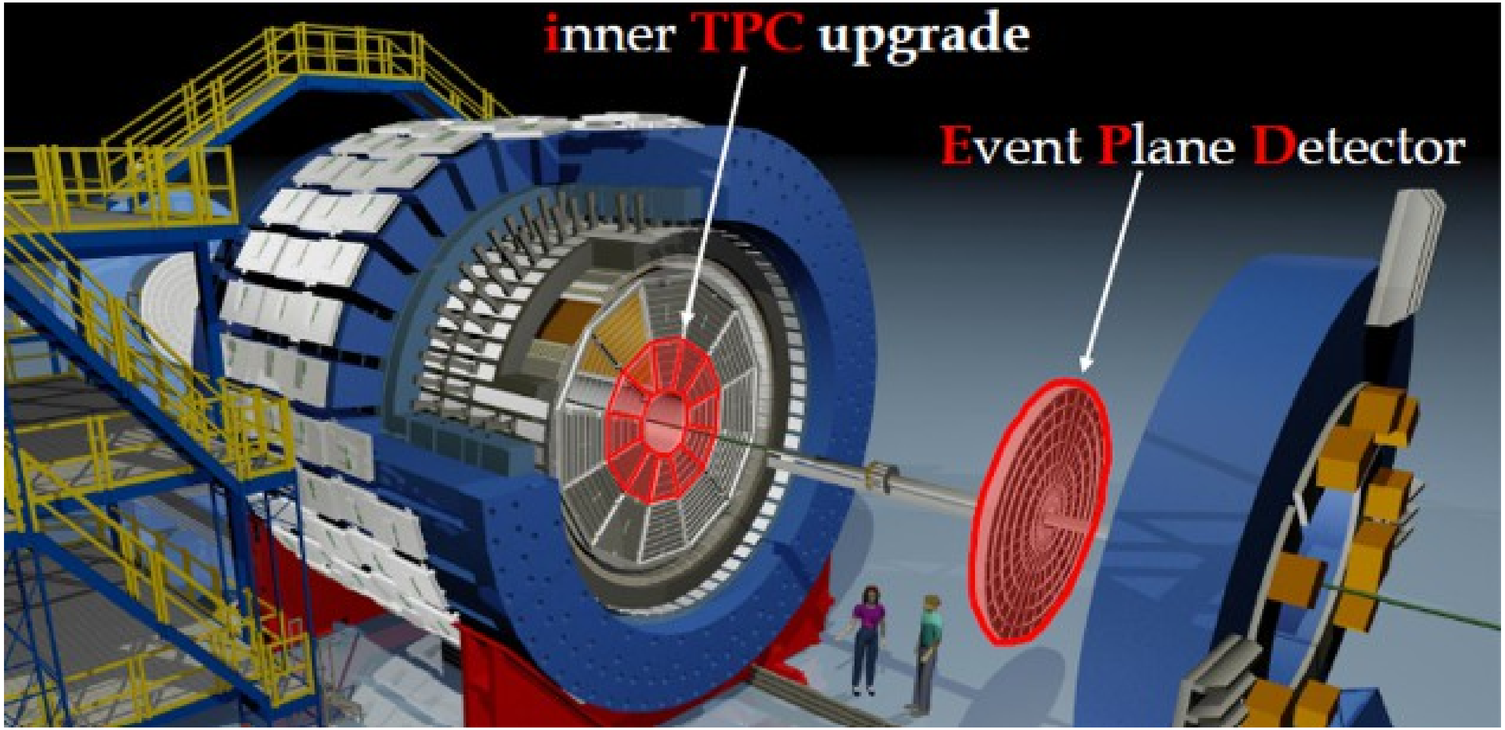
Fine energy scan
at $\sqrt{s}_{NN}$ <~ 20 GeV

Electron cooling
increased luminosity factor 3-10

STAR detector upgrades
Improved tracking
Pseudo-rapidity coverage
Centrality determination

Plans Beam Energy Scan Phase II

(2018-2019)



Improve
pseudo-rapidity coverage
and PID

iTPC upgrade:
Replace aging wires
Sparse pads → cover full area, better dE/dx
$-1.7 < \eta < 1.7$
$p_T > 60$ MeV/c

EPD Upgrade
Replaces aging BBC
Greatly improved Event Plane
Better trigger & b/g reduction
$-4.5 < \eta < -1.8$, $1.8 < \eta < 4.5$

Other
Hcal
Endcap TOF

Summary and Outlook

- STAR has measured higher order moments of Net-Charge and Net-Proton distribution for BES energies $\sqrt{s_{NN}}$ = 7.7 , 11.5, 19.6, 27, 39, 62.4 and 200 GeV
- Results are corrected for tracking and PID efficiencies, as well as the centrality-bin-width, auto-correlation effects from the centrality definition have been taken care of
- New results from $\sqrt{s_{NN}}$ = 14.5 GeV and Net-Kaons are in preparation, including study of rapidity dependence
- In the upcoming BES II, STAR will provide a larger rapidity and momentum coverage, improved PID and centrality estimation outside the central barrel

Stay tuned for Quark Matter