Fluctuations of Conserved Quantities in High Energy Nuclear Collisions at RHIC

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Ab initio approaches in many-body QCD confront heavy-ion experiments

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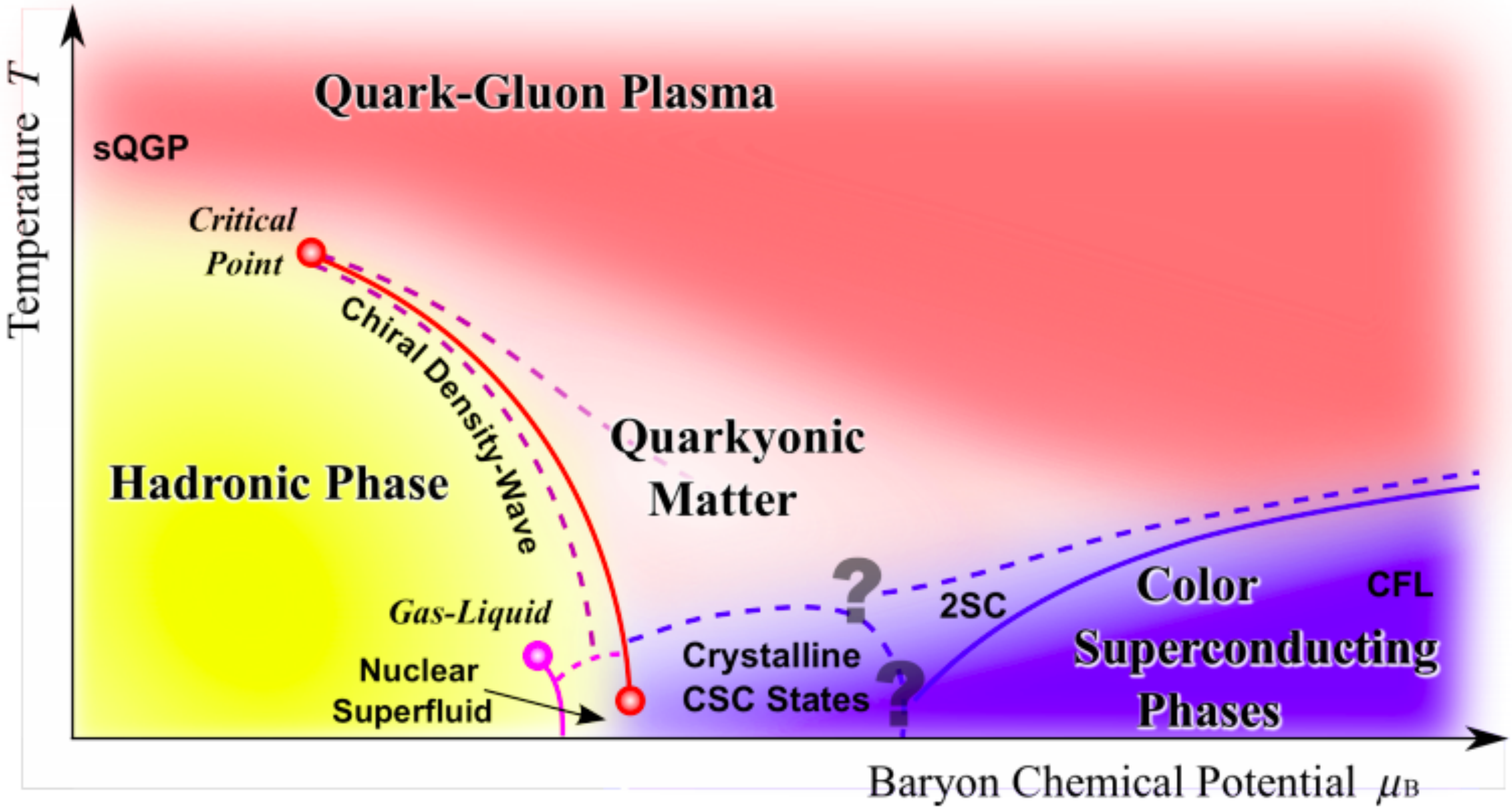
Outline

- Introduction
- Analysis Techniques
- Fluctuations for Net-proton and Net-charge in heavy-ion collisions.
- Summary and Outlook

QCD Phase Diagram (Conjectured)



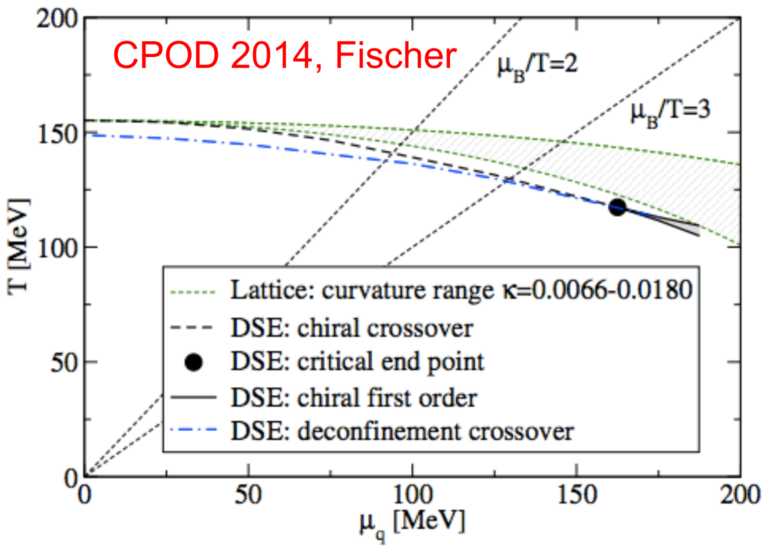
Hatsuda and Fukushima

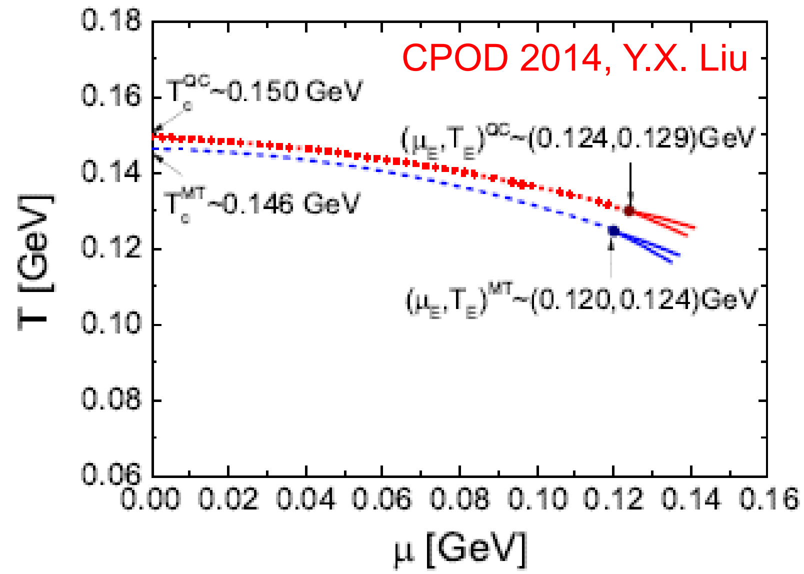
Very rich phase structure in the QCD phase diagram.

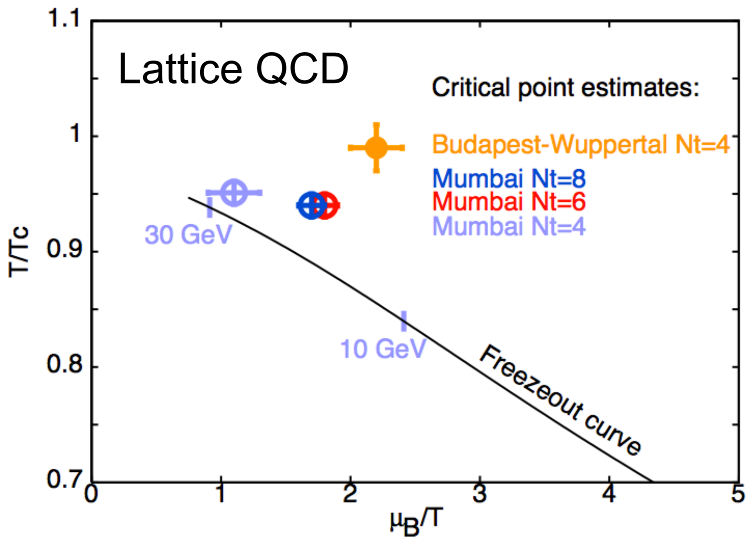
Fluctuations of conserved quantities, such as net-baryon (B), net-charge (Q) and net-strangeness (S), can be applied to explore the QCD phase structure, such as phase boundary (phase transition) and QCD critical point.

Search for the QCD Critical Point (CP)

DSE:







1) S. Datta, R. Gavai, S. Gupta, PoS (LATTICE 2013), 202.
$\mu^E_B/T^E \sim 1.7 \Rightarrow \sqrt{s_{NN}} \sim 20$ GeV

2) Y. X. Liu, et al., PRD90, 076006 (2014).
$\mu^E_B/T^E \sim 2.88 \Rightarrow \sqrt{s_{NN}} \sim 8$ GeV

3) C. S. Fischer et al., PRD90, 034022 (2014).
$\mu^E_B/T^E \sim 4.4 \Rightarrow \sqrt{s_{NN}} \sim 6$ GeV

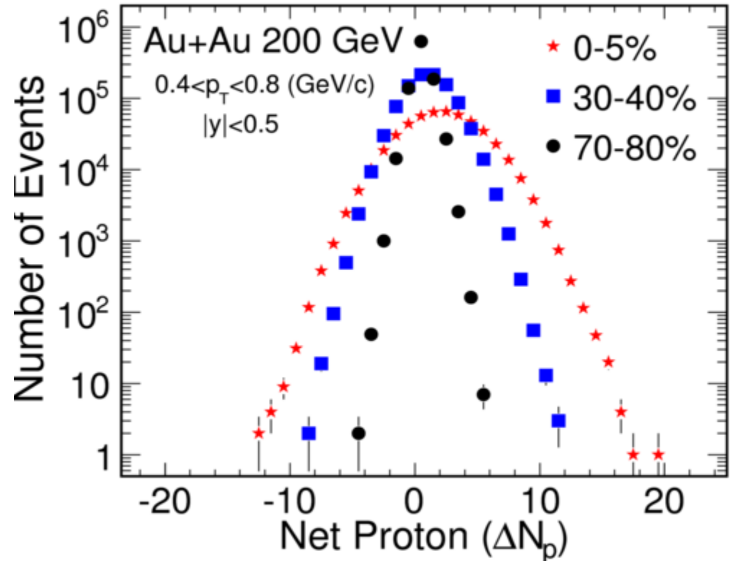
Different theoretical calculations give very different CP locations.

Higher Moments

Experimental Observables: Higher Moments of Conserved Quantities (q=B, Q, S).

1): **Sensitive to the correlation length (ξ):**

$$\left\langle (\delta N)^2 \right\rangle_c \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle_c \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle_c \approx \xi^7$$



2): **Direct comparison with calculations:**

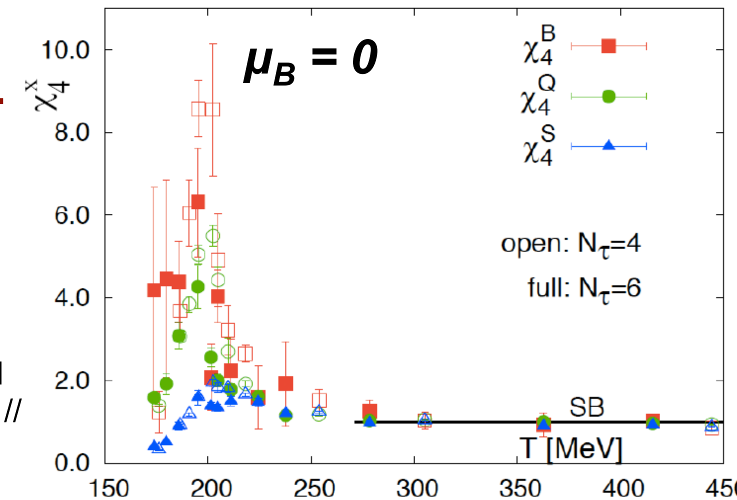
$$S\sigma \approx \frac{\chi_q^3}{\chi_q^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_q^4}{\chi_q^2}$$

χ_q^n

nth order susceptibility for conserved quantity q.

3): **Extract chemical freeze-out parameters.**

An independent/important test of thermal equilibrium in heavy-ion collisions.



M. Cheng, et. al., PRD79, 074505 (2009).

References:

- STAR: *PRL105*, 22303(10); *PRL112*, 032302 (14). *PRL113*, 092301 (14).
- M. Stephanov: *PRL*102, 032301(09) // M. Akasawa, et al., *PRL103*,262301 (09).R.V. Gavai et al., *PLB696*, 459(11) // F. Karsch et al,*PLB695*,136(11) // S.Ejiri et al, *PLB633*, 275(06) , PBM et al., *PRC84*, 064911 (11).
- A. Bazavov et al., *PRL109*, 192302(12) // S. Borsanyi et al., *PRL111*, 062005(13) //S. Gupta, et al., *Science*, 332, 1525(12).

RHIC Beam Energy Scan–Phase I

In the first phase of the RHIC Beam Scan (BES), seven energies were surveyed in 2010 and 2011.

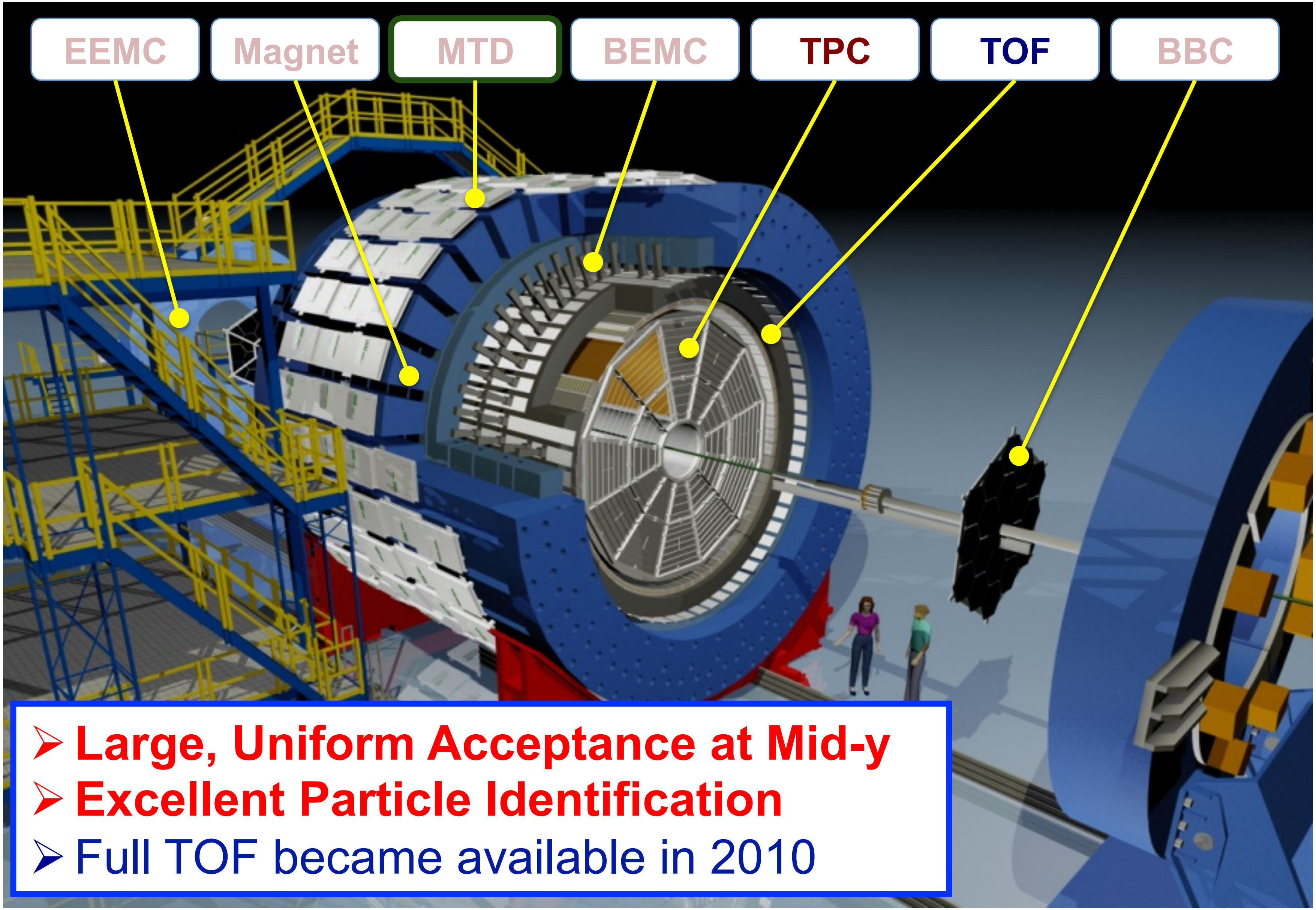
$\sqrt{s}$ (GeV)	Statistics(Millions) (0-80%)	Year	μ_B (MeV)	T (MeV)	μ_B /T
7.7	~3	2010	422	140	3.020
11.5	~6.6	2010	316	152	2.084
14.5	~10	2014	264	156	1.692
19.6	~15	2011	206	160	1.287
27	~32	2011	156	163	0.961
39	~86	2010	112	164	0.684
62.4	~45	2010	73	165	0.439
200	~238	2010	24	166	0.142

Chemical freeze-out $\mu_{B,}$ T : J. Cleymans et al., Phys. Rev. C 73, 034905 (2006).

The main goals of BES program:

- **Search for Onset of Deconfinement.**
- **Search for QCD critical point.**
- **Map the first order phase transition boundary.**

STAR Detector System



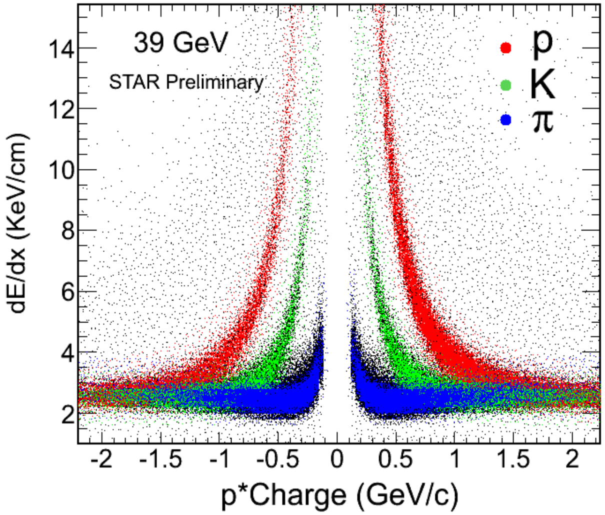
- **Large, Uniform Acceptance at Mid-y**
- **Excellent Particle Identification**
- Full TOF became available in 2010

Extend Phase Space Coverage with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.

TPC PID:

STAR, PRL 112, 032302 (2014).



$0.4 < p_T < 0.8$ (GeV/c)

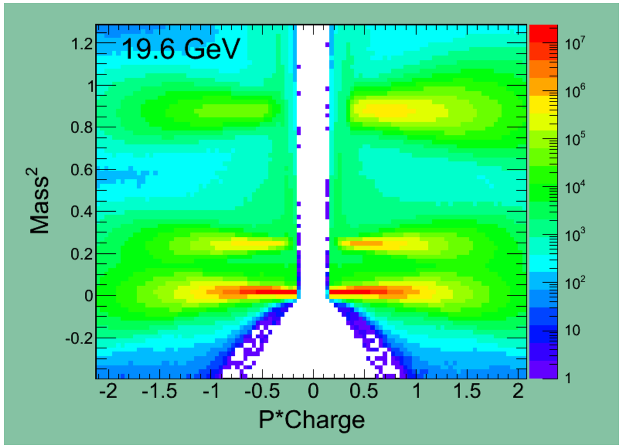
TPC PID

~ Doubled the accepted number of proton/anti-proton.

$0.4 < p_T < 2$ (GeV/c)

TPC+TOF PID

TOF PID:



1) Sufficiently large acceptance is important for fluctuation analysis and critical point search, ***but***

2) Efficiency corrections change dramatically between TPC and (TPC+TOF)

Efficiency Corrections

1) In **TPC ($|y| < 0.5$, $0.4 < p_T < 0.8$ GeV/c):**
ε_{TPC} changes as a function of transverse momentum, $\langle\varepsilon_{TPC}\rangle \sim 0.8$.
Centrality dependence is relatively small.
TPC efficiencies for 200 and 62.4 GeV are taken from 39 GeV results.

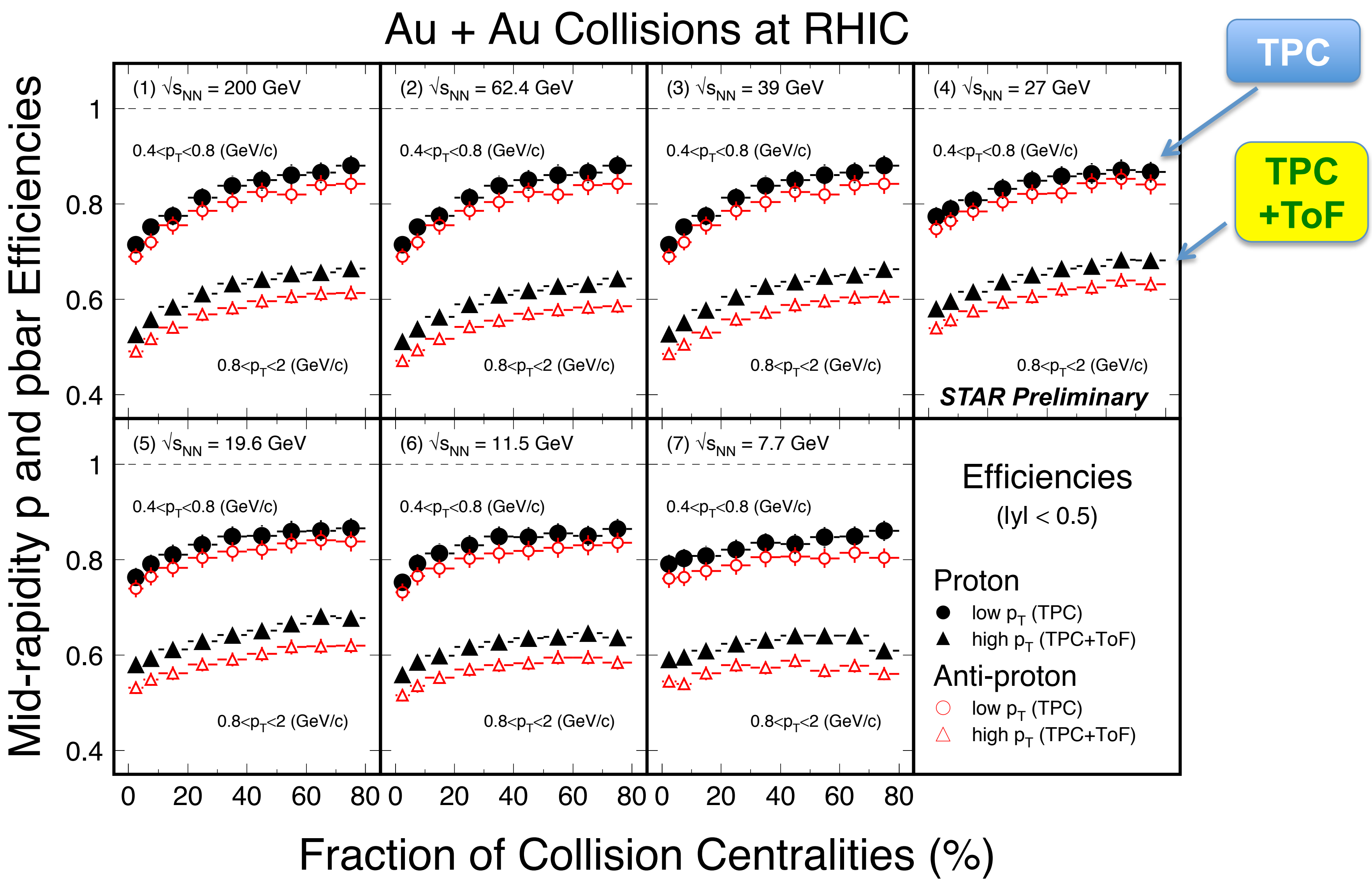
2) In **TPC+TOF ($|y| < 0.5$, $0.8 < p_T < 2$ GeV/c) :**
TOF matching efficiency $\varepsilon_{ToF} \sim 0.7$. Fairly constant vs. p_T
$\varepsilon_{TPC+ToF} = \varepsilon_{TPC} * \varepsilon_{ToF} \sim 0.5$ with small centrality variation.

3) Efficiency corrections are important not only for the values in the higher moments (fluctuations) analysis, but also the statistical errors since, e.g. for the n^{th} order Cumulants C_n

$$error \propto O\left(\frac{\sigma^n}{\varepsilon^n}\right)$$

Systematic error analysis is under way.

Efficiencies for Protons and Anti-protons



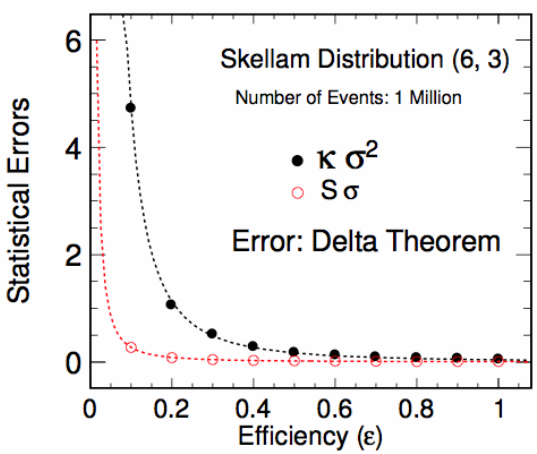
Efficiency Correlation and Error Estimation

We provide a unified description of efficiency correction and error estimation for higher moments analysis in heavy-ion collisions.

X. Luo, arXiv: 1410.3914

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

Error Estimation: MC simulation



Fitting formula: $f(\varepsilon) = \frac{1}{\sqrt{n}}\frac{a}{\varepsilon^b}$

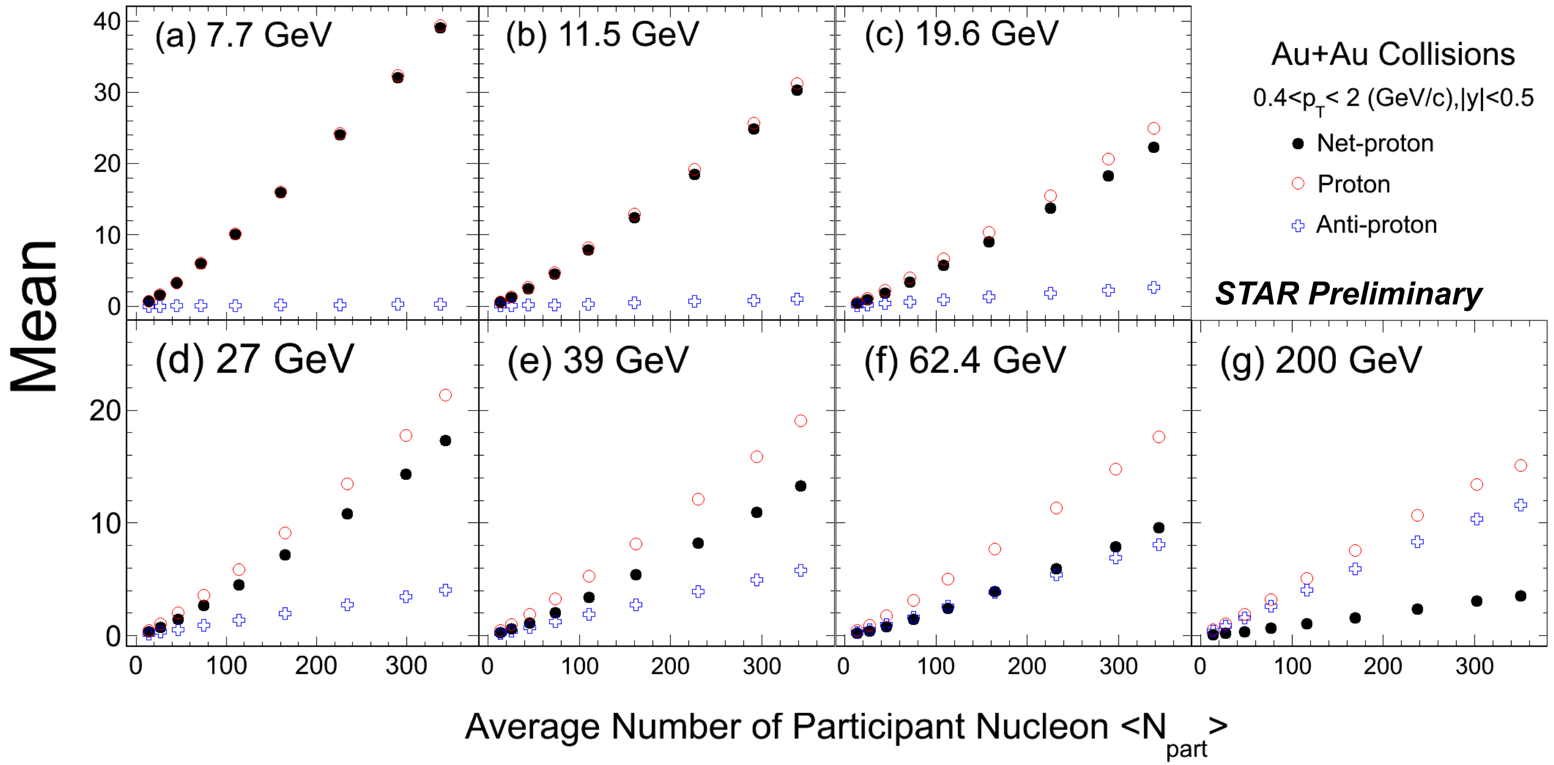
We can express the moments and cumulants in terms of the factorial moments, which can be easily efficiency corrected.

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

One can also see:
A. Bzdak and V. Koch,
arXiv: 1313.4574,
PRC86， 044904(2012).

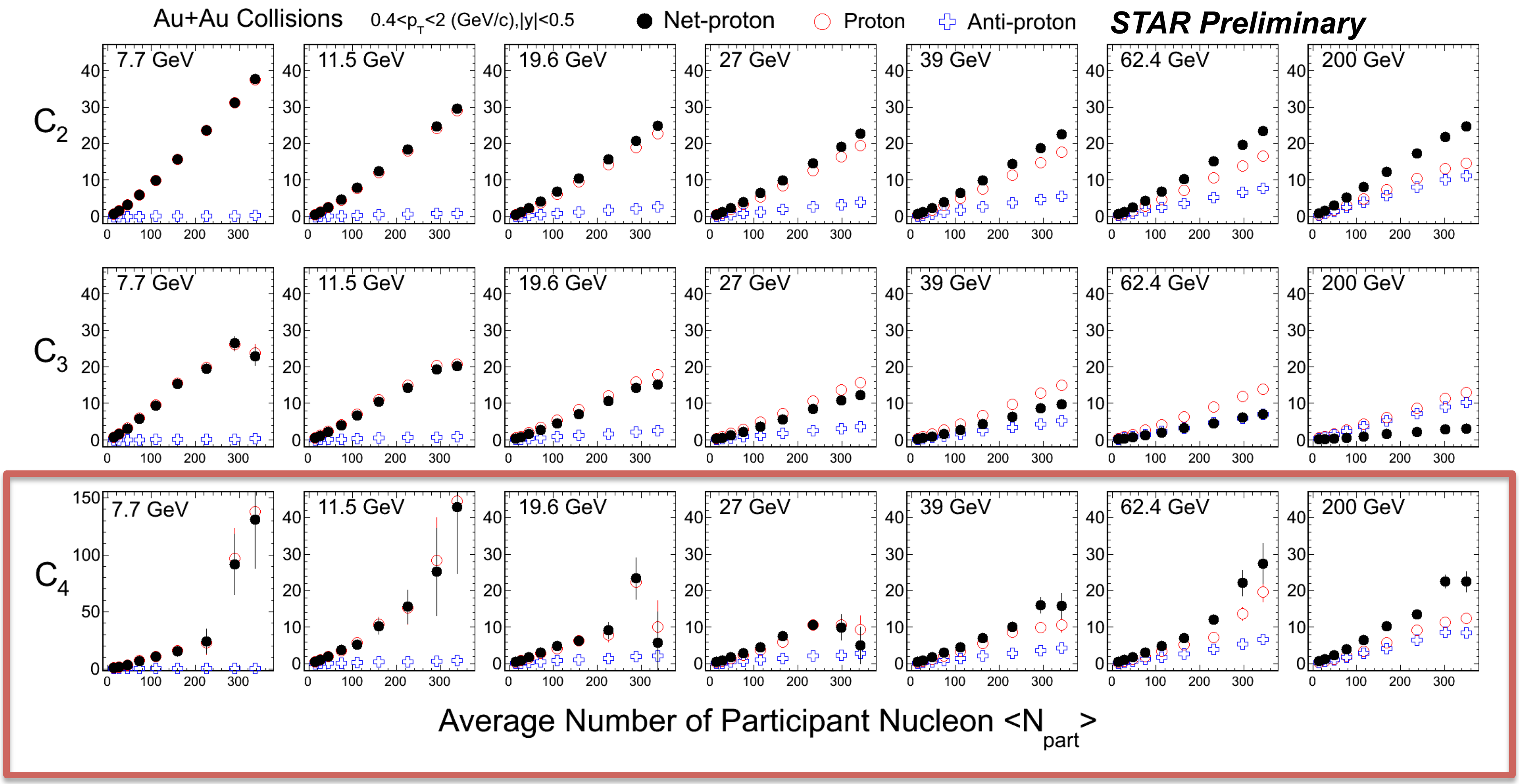
For other analysis techniques, see: STAR, PRL112, 032302 (2014); PRL113, 092301 (2014).

Results: Mean Net-p, p and pbar



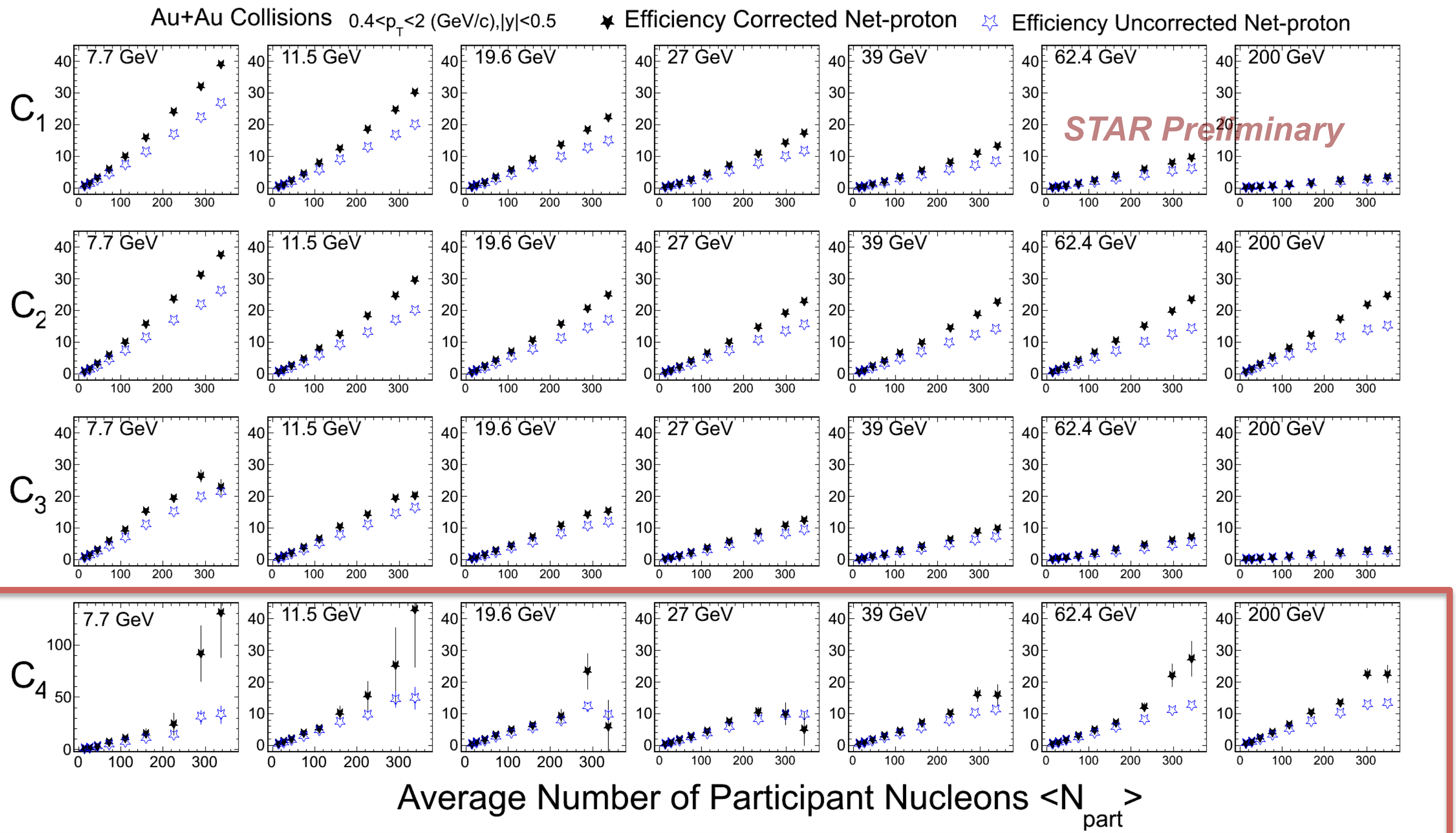
- Mean Net-proton, proton and anti-proton number increase with $\langle N_{part} \rangle$
- Net-proton number is dominated by protons at low energies and increases when energy decreases.
  (Interplay between baryon stopping and pair production)

Higher Order Cumulants for Net-p, p, pbar



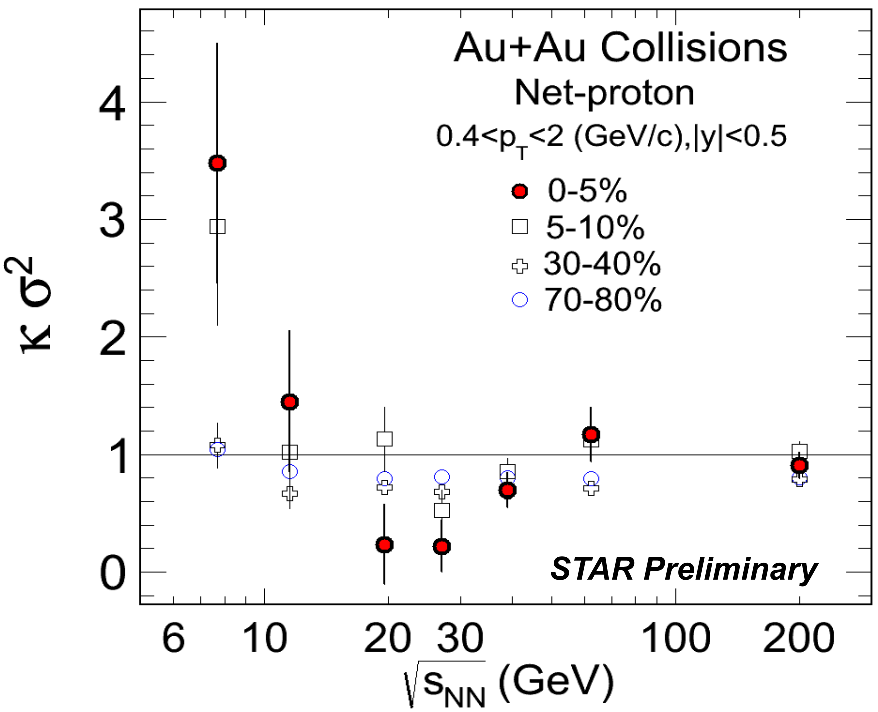
- In general, cumulants of Net-p, p and pbar are increasing with $\langle N_{part} \rangle$.
- At energies below 39 GeV, proton and net-proton cumulants are similar.

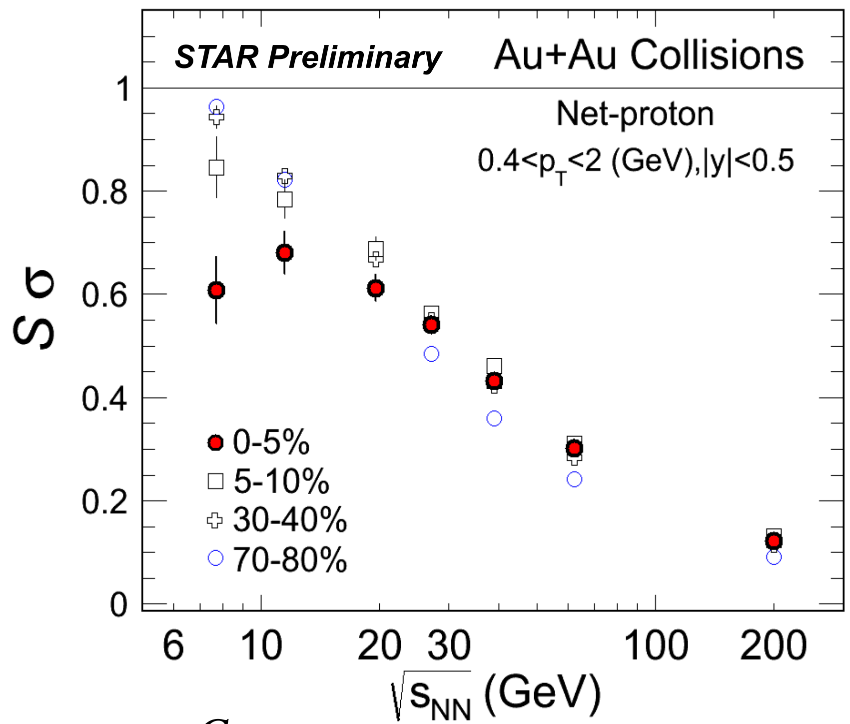
$C_{n=1-4}$ vs. Energy and Centrality



Efficiency corrections are important not only for the values in the higher moments analysis, but also the statistical errors since, e.g. error ~ $O(\sigma^n/\varepsilon^n)$ for C_n.

Energy Dependence of Cumulants Ratios



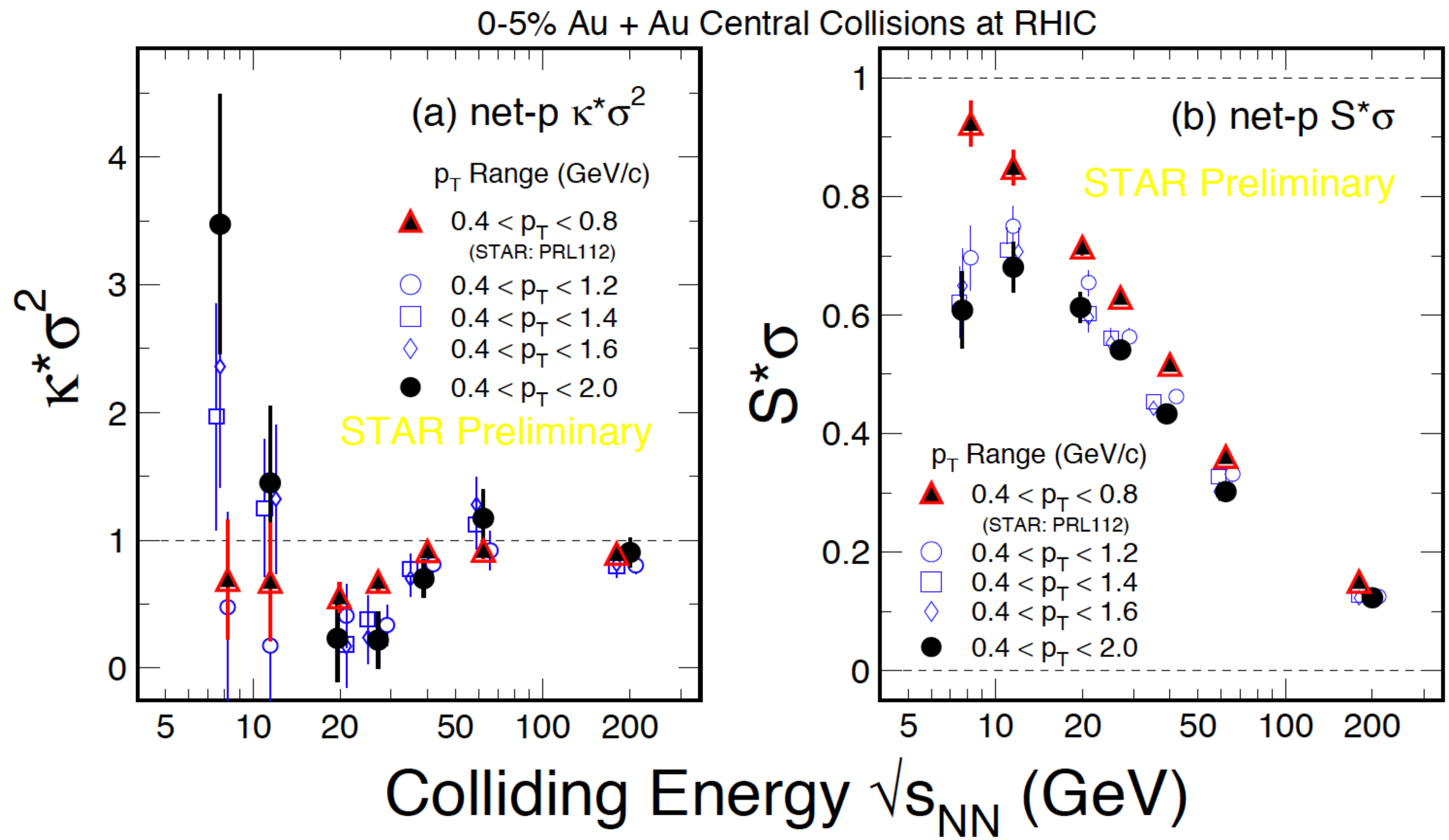


$$\kappa\sigma^2 = \frac{C_4}{C_2}, \qquad S\sigma = \frac{C_3}{C_2}$$

1) Error bars are statistical only. Systematic errors estimation underway. Dominant contributors: a) efficiency corrections b) PID;

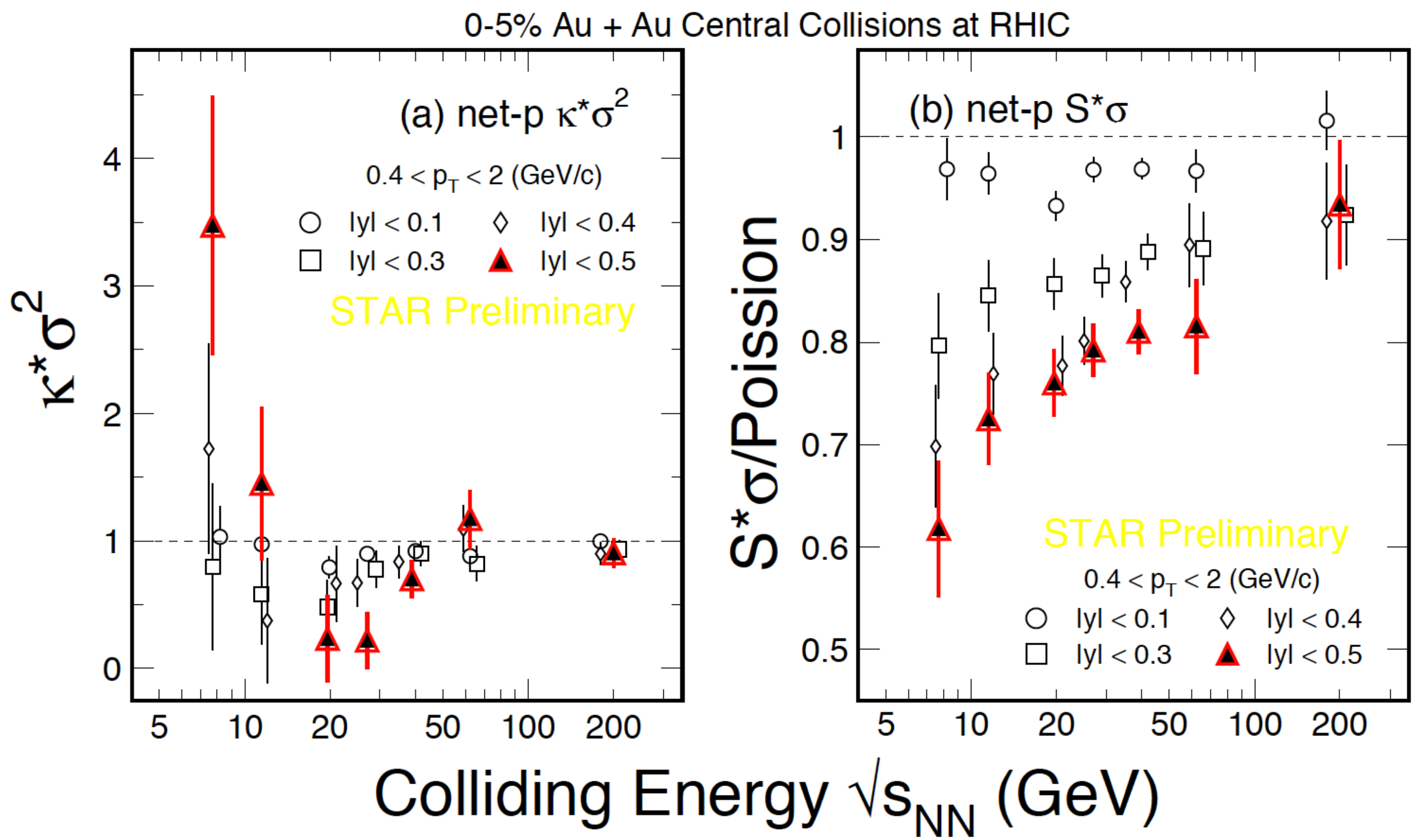
2) Non-monotonic behavior is observed at the most central collisions (0-5%).

Acceptance Study (I): p_T



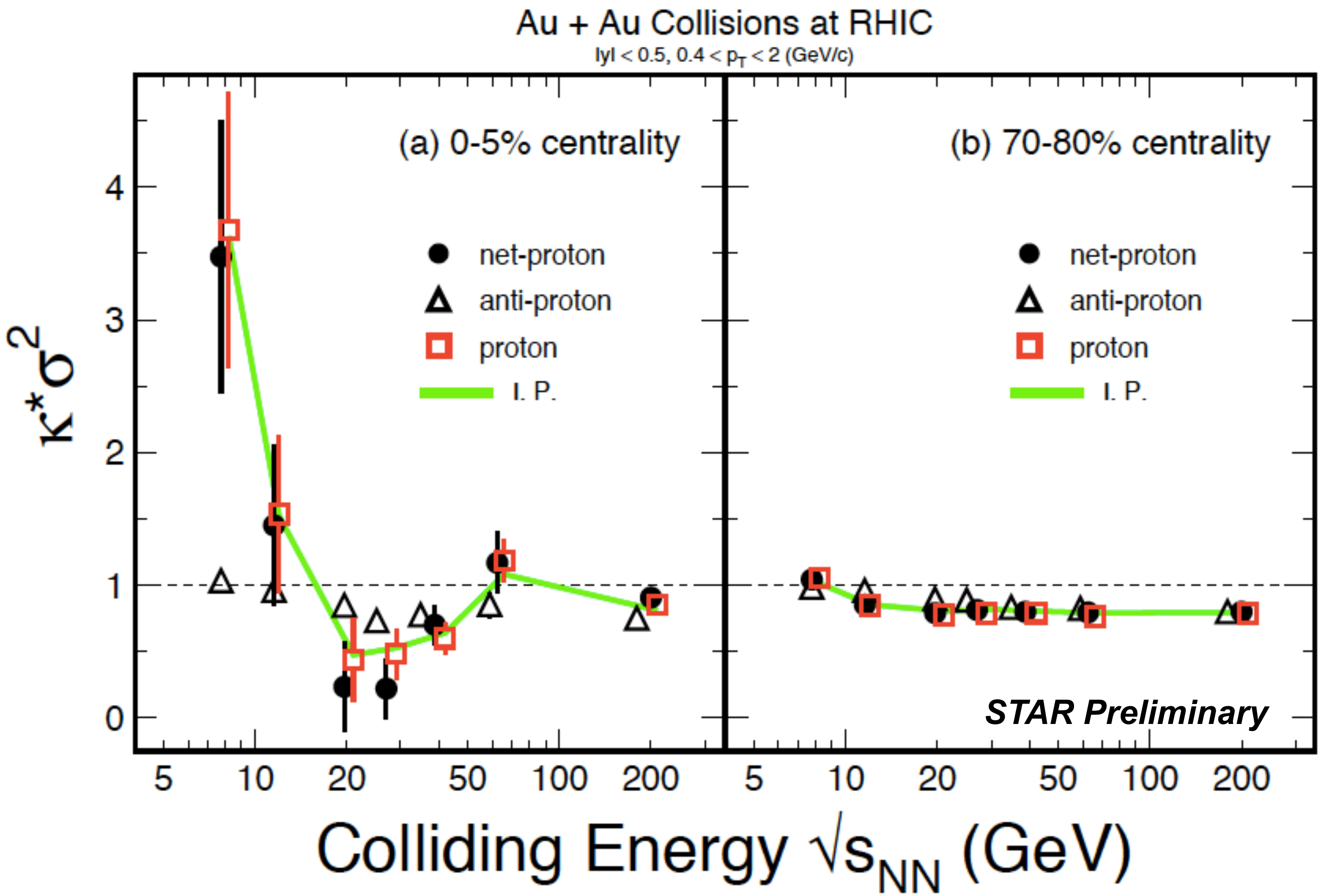
- $K*\sigma^2$: the energy dependence tends to be more pronounced with wider p_T acceptance, relative to published results.
- $S*\sigma$: the values are smaller for wider p_T acceptance.

Acceptance Study (II): Rapidity



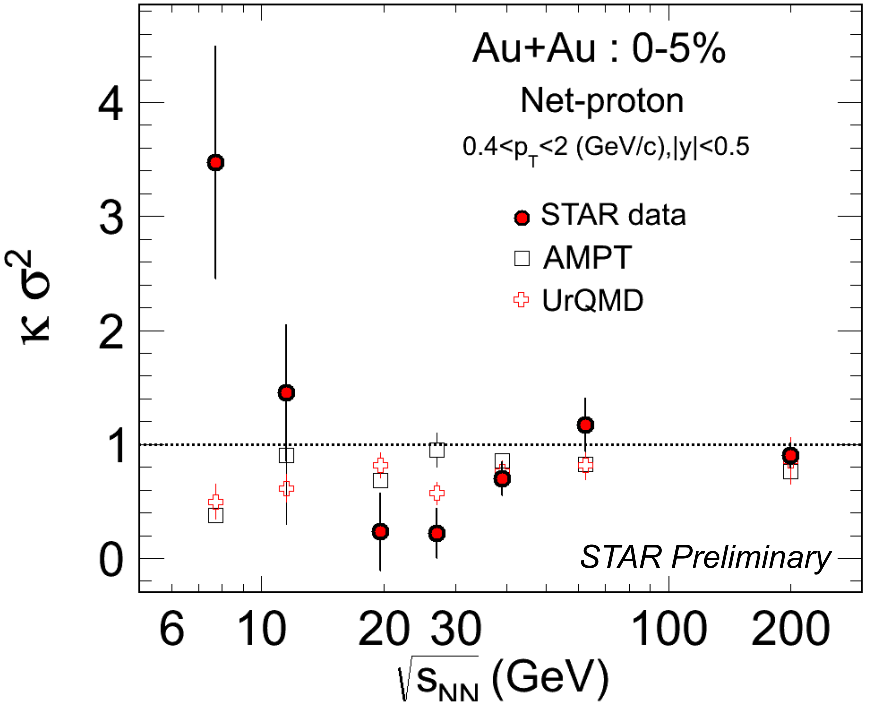
- The smaller the rapidity window the closer to the Poisson values.
- The acceptance needs to be large enough to capture the dynamical fluctuations. The related systematic errors should be carefully addressed.

Independent p, pbar Production Test

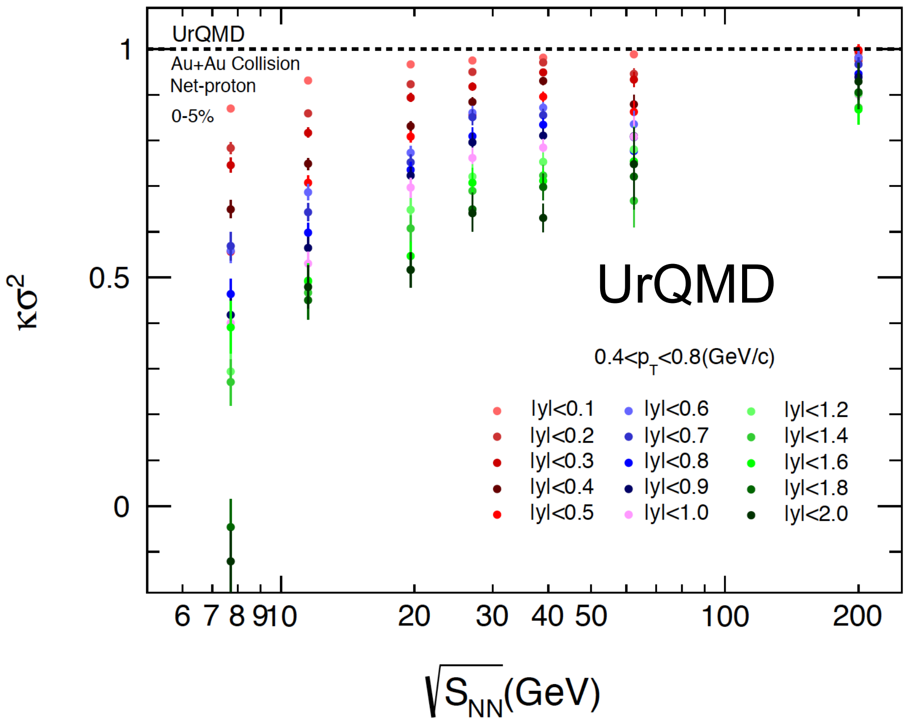


1) I.P. means de-correlation between protons and anti-protons.
2) I.P. closely traces proton and net-proton moments.
3) Anti-proton $K*\sigma^2$ also show minimum around $\sqrt{s_{NN}}$ = 27 GeV .

Transport Model Calculations: UrQMD and AMPT

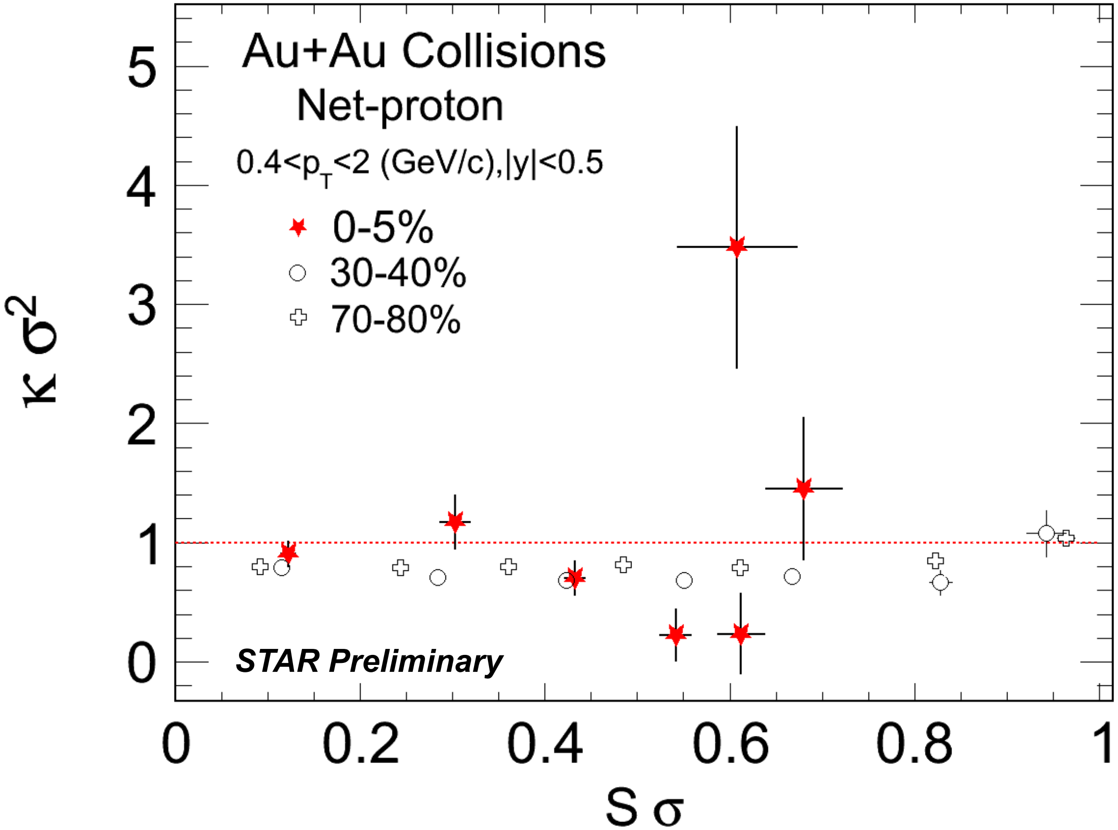


Rapidity Acceptance Study



- The non-monotonic structure in the data cannot be reproduced by UrQMD and AMPT models.
- In UrQMD calculation, wider rapidity acceptance, larger suppression. Consistent with baryon number conservation effects.

Big Dipper Plot



Taylor expansion in Lattice :

THERMO-meter :

$$\kappa\sigma^2 \sim \frac{\chi_B^4}{\chi_B^2}(T,0)$$

BARYO-meter :

$$S\sigma \sim \frac{\chi_B^3}{\chi_B^2}(T,\mu_B) \sim \tanh\left(\frac{\mu_B}{T}\right)$$

- A structure is observed for 0-5% most central data while it is flat for mid-central and peripheral collisions.
- Can be directly compared with theoretical calculations.

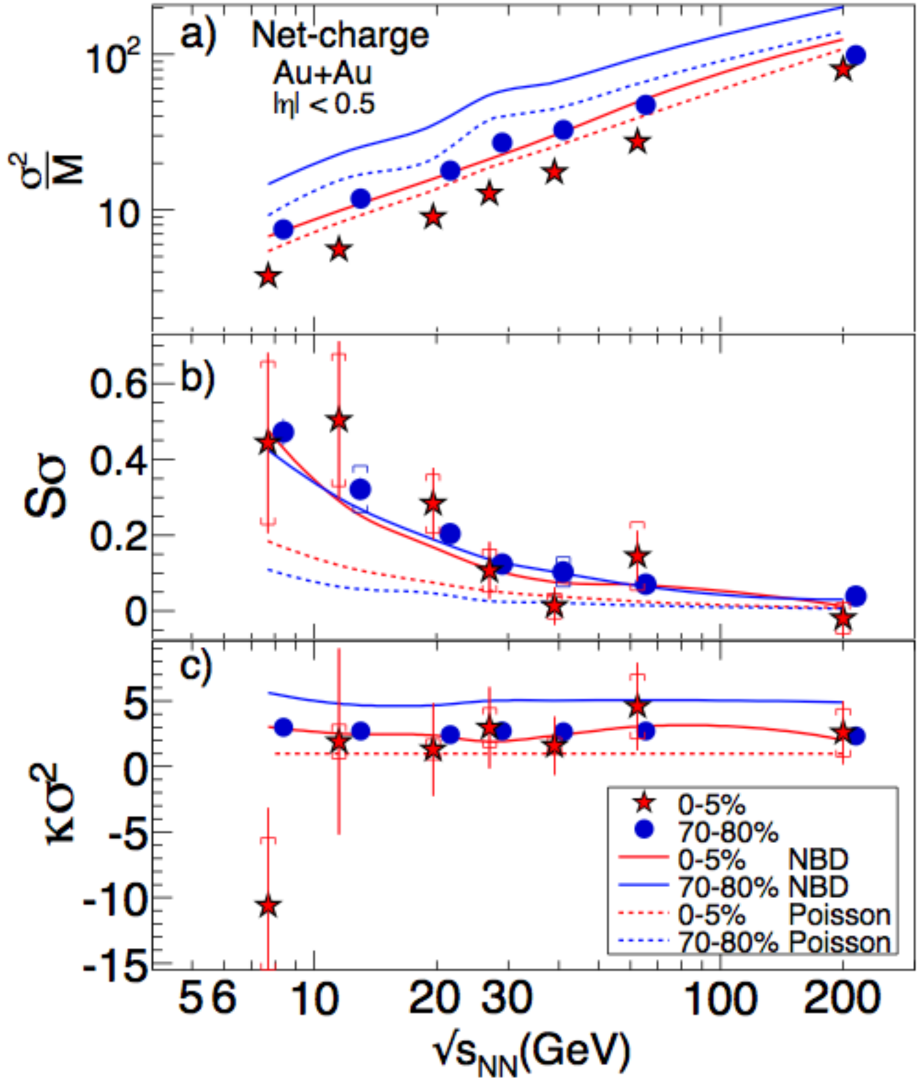
1) In strong interactions, net quantities of Q, S, and B are conserved quantities. STAR experiment has carried out analysis for fluctuations of net-protons (proxy for net-B), net-kaons (proxy for net-S), and net-charge (Q).

2) Different measurements are affected by kinematic cuts, resonance decays,and other dynamical effects differently. In search for the QCD critical point, careful studies are called for.

Reference:

Experimental Data: STAR, PRL112, 032302 (2014). PRL113, 092301 (2014). PRL105, 022302 (2010).
HRG model studies: P. Garg, et al, PLB 726, 691 (2013). J. Fu, PLB722, 144 (2013). F. Karsch and K. Redlich , PLB695, 136 (2011). Marlene Nahrgang et al, arXiv: 1402.1238. P. Alba et al., arXiv:1403.4903
Transport model studies: X. Luo et al., JPG 40, 105104 (2013). N.R. Sahoo, et al., PRC 87, 044906 (2013).

Moments of Net-charge Distribution at RHIC



STAR results:
PRL**113** 092301 (2014).

- Within the current statistics, smooth energy dependence is observed for net-charge distributions.
- NBD has better description than Poisson for net-charges.
- Net-kaon analysis is ongoing.

Summary and Outlook

- We present centrality and energy dependence of cumulants and their ratios for proton, antiproton and net-proton for the extended transverse momentum coverage [$|y|<0.5$, $0.4<p_T<2.0$ (GeV/c)] for Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7,11.5, 19.6, 27, 39, 62.4 and 200 GeV.

- A unified description of efficiency correction and error estimation is applied to the moments of net-proton distributions.

- Non-monotonic behavior is observed at the most central collisions (0-5%). Evaluation of the systematic error is on going.

- Higher statistics are needed at low energies to explore the QCD phase structure: STAR upgrade and RHIC BES-II (from 2018). Fixed target experiment, CBM@FAIR.

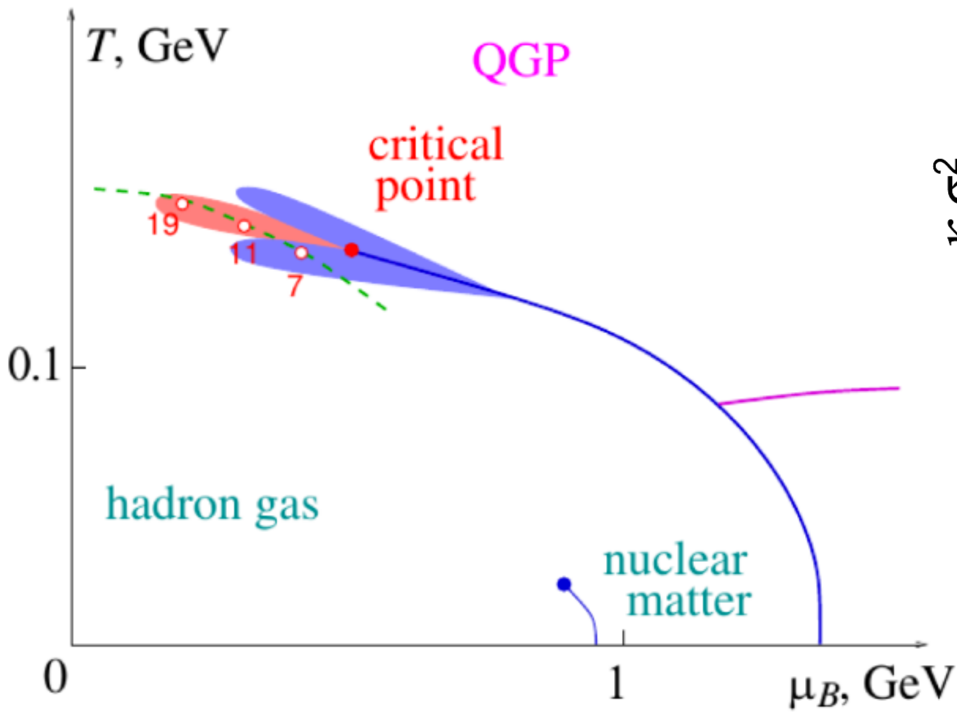
Future Critical Point Search:

- **Higher Luminosity**
- **Higher Baryon Density**
- **Large Acceptance**

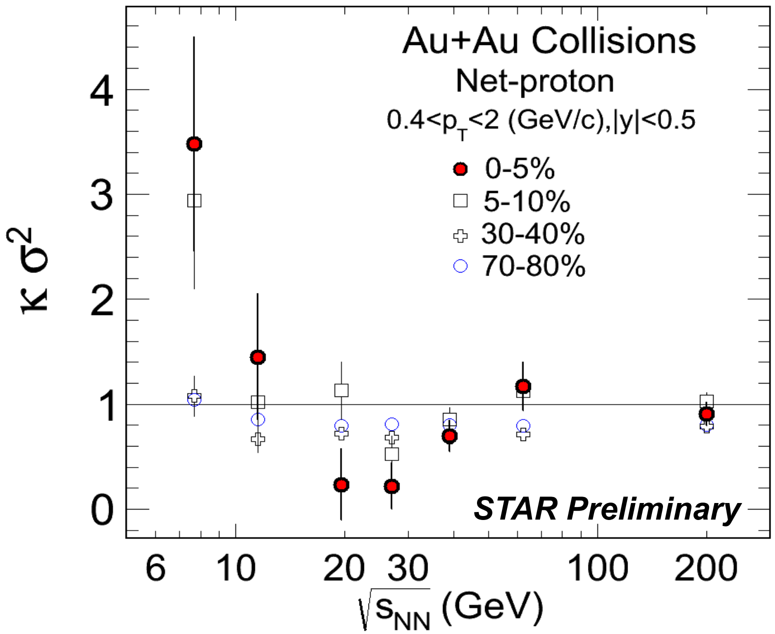
Thank you for your attention !!!

Signature of CP : Theoretical Expectations

CPOD 2014, Misha Stephnov

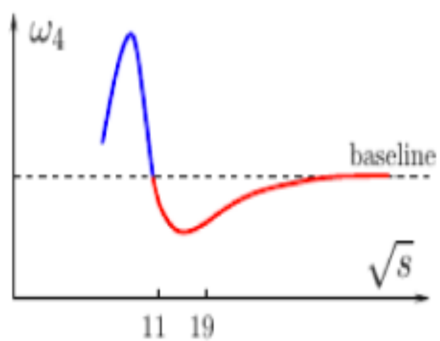


X. Luo, CPOD 2014



M.A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
, J. Phys. G: 38, 124147 (2011).

$$\kappa_4 \sim N^4.$$

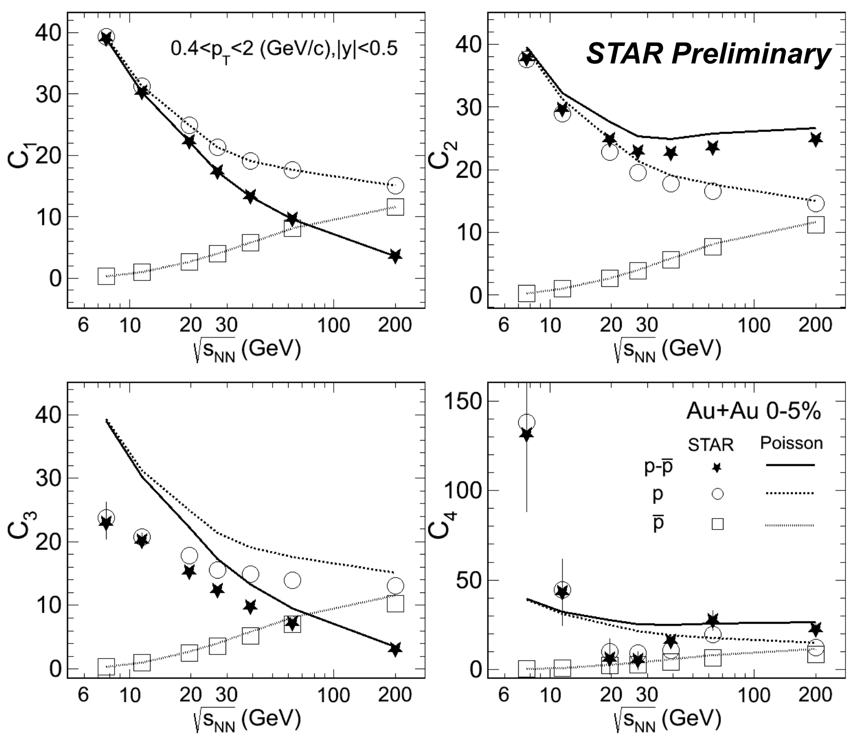


For Kurtosis, expecting a dip, then a significant increase with respect to the Poisson baseline near QCD Critical Point.

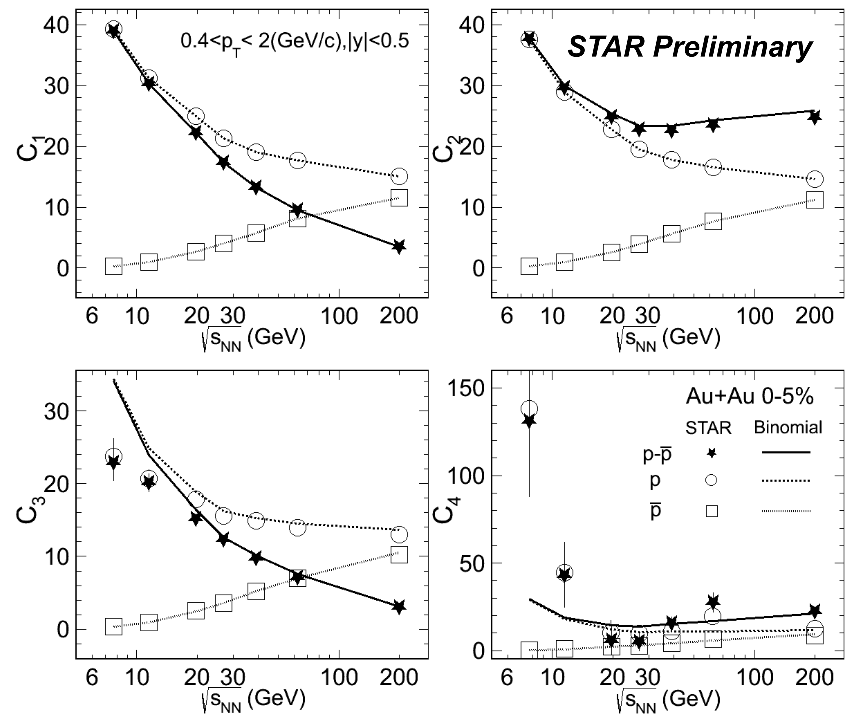
A similar calculation: J. Deng et al, arXiv: 1410.5454.

Cumulants vs. Baselines

Cumulants vs. Poisson



Cumulants vs. Binomial

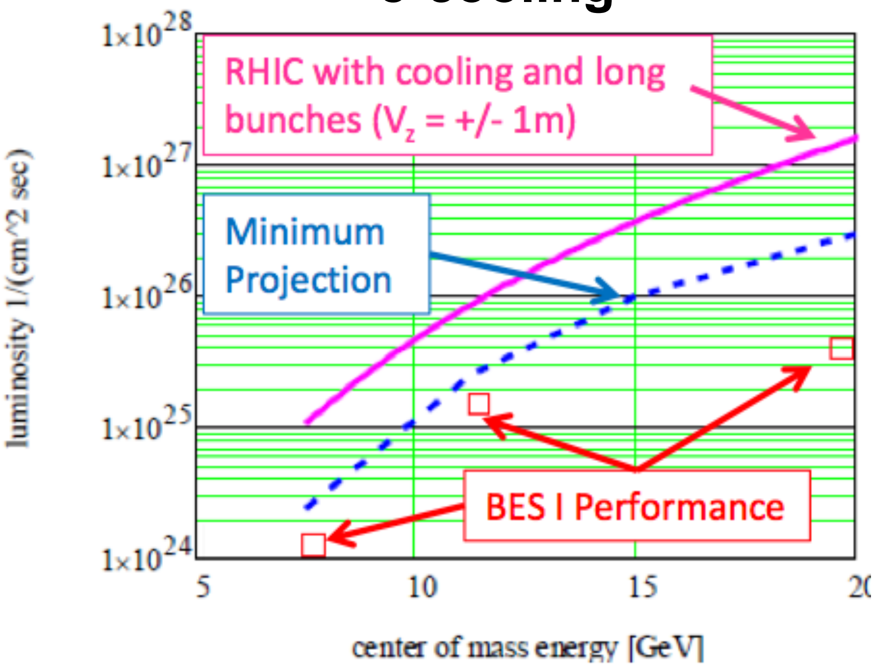


- The higher the order of cumulants the larger deviations from Poisson expectations for net-proton and proton.
- The binomial distribution (BD) better described the data than Poisson. But large deviations seen in C_3 and C_4 in central Au+Au collisions 7.7, 11.5, 19.6, 27 and 62.4 GeV.

STAR Upgrades and BES Phase-II

- Fine energy scan at $\sqrt{s_{NN}}$ <~ 20 GeV
- Electron cooling will provide increased luminosity ~ 3-10 times
- STAR iTPC upgrade extends mid-rapidity coverage – beneficial to many crucial measurements.
- Forward Event Plane Detector (EPD)： Centrality and Event Plane Determination.

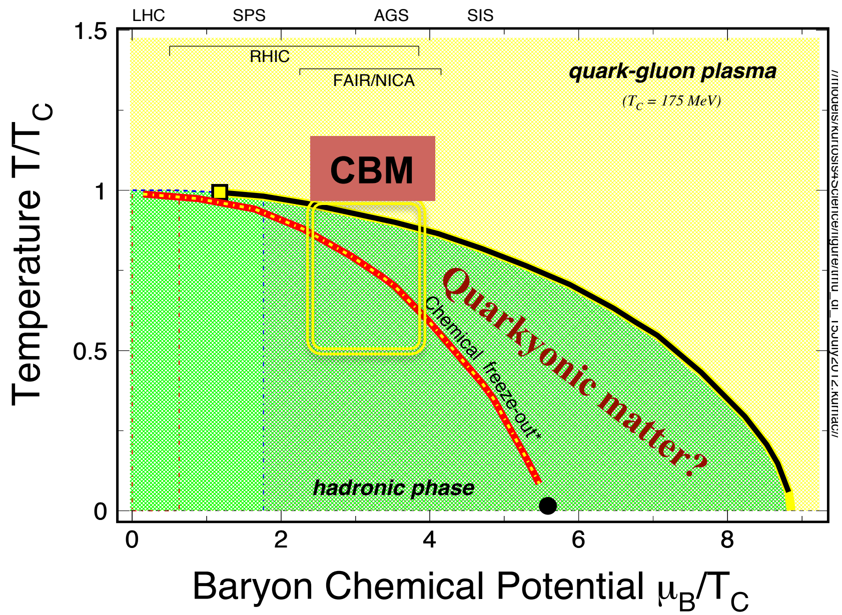
e-cooling



iTPC Upgrade

For moment analysis, iTPC upgrade will improve tracking efficiency and centrality resolution, EPD will provide centrality determination.

Experimental Study on Highly Compressed Baryonic Matter

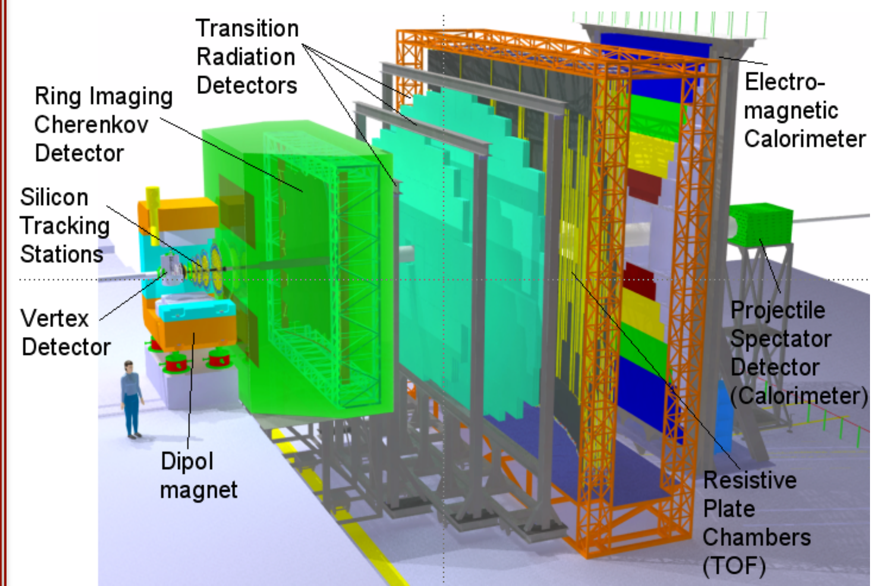


Exploring Phase Structure at High Baryon Density

（1） **QCD Critical Point**

（2） **Quarkyonic Phase/Phase Boundary**

Fixed Target Detector, CBM@FAIR



Center of Mass Energy $\sqrt{s_{NN}} \leqslant 8$ GeV per nucleon pair.

It allows us to explore the QCD phase structure at higher baryon density region with high precision !