The 19th International Conference on Strangeness in Quark Matter

May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York

SQM2021

STAR

Higher-Order Cumulants of Net-Proton Multiplicity Distributions from RHIC-STAR

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for the STAR Collaboration

2021/5/18

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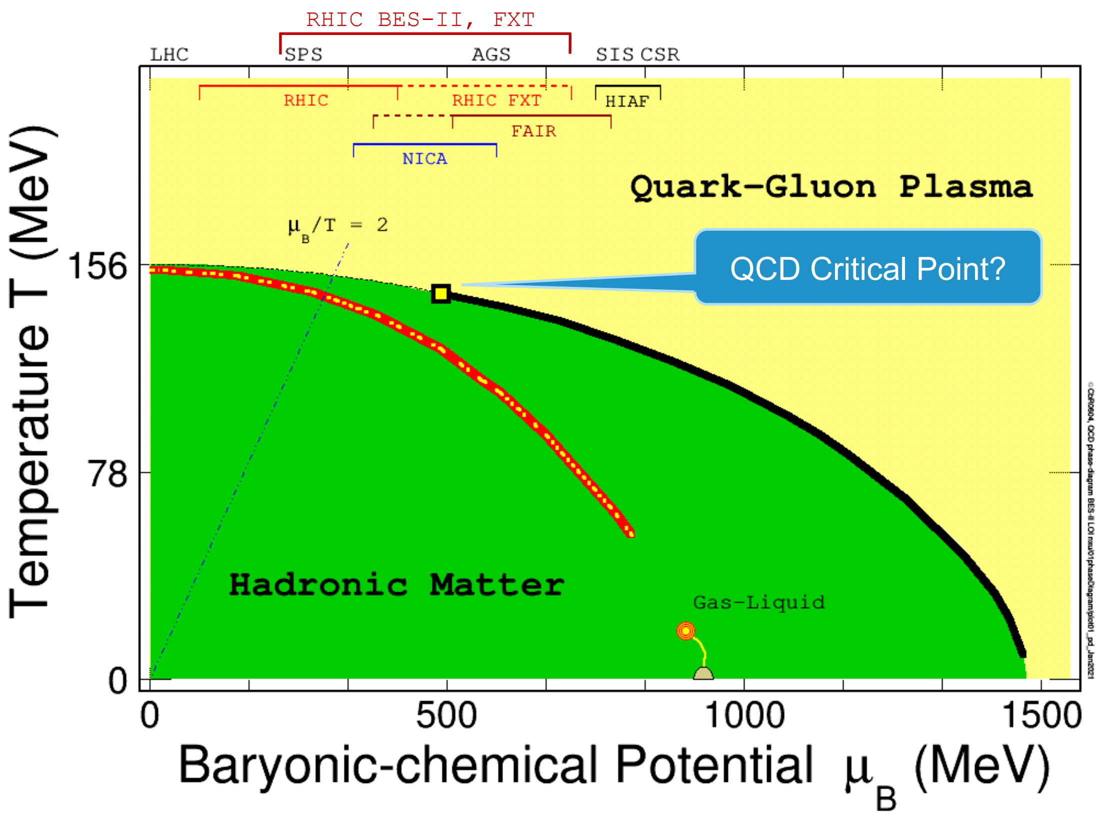
Strangeness in Quark Matter — May 17-21 2021

Outline

- Motivation
- Analysis Details
  - Particle Identification
  - Correction Methods
- Results
  - BES-I Au+Au collisions
  - 200 GeV p+p collisions
- BES-II Outlook
- Summary

QCD Phase Diagram



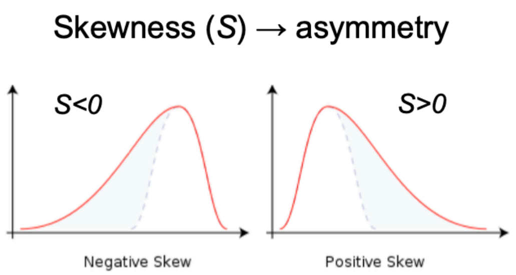
- **Crossover at $\mu_B = 0$** ***Y. Aoki et al, Nature 443, 675(2006)***
- **Models predict 1st order phase transition at large μ_B**
- **Possible QCD critical point and 1st-order phase boundary**
- **Change collision energy to scan phase diagram**

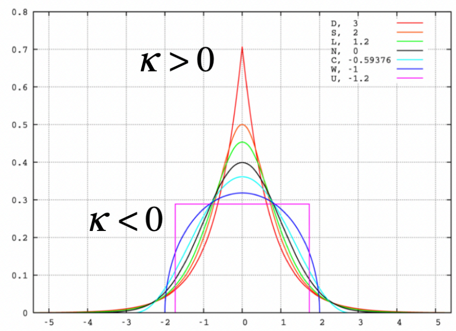
Higher-order Cumulants of Conserved Quantities

- Cumulants of conserved quantities (B, Q, S) are extensive variables (intensive when taken ratio)

net-proton: proxy for net-baryon
net-kaon: proxy for net-strangeness

$$M = \langle N \rangle,\ \delta N = N - \langle N \rangle$$
$$C_1 = \langle N \rangle,\ C_2 = \langle (\delta N)^2 \rangle,\ C_3 = \langle (\delta N)^3 \rangle$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$
$$S = C^3/(C^2)^{3/2},\ \kappa = \frac{C^4}{(C^2)^2},$$
$$\frac{C_2}{C_1} = \frac{\sigma^2}{M},\qquad \frac{C_3}{C_2} = S\sigma,\qquad \frac{C_4}{C_2} = \kappa\sigma^2$$





- Sensitive quantities to correlation length ξ

$$C_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 \sim \xi^7$$

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

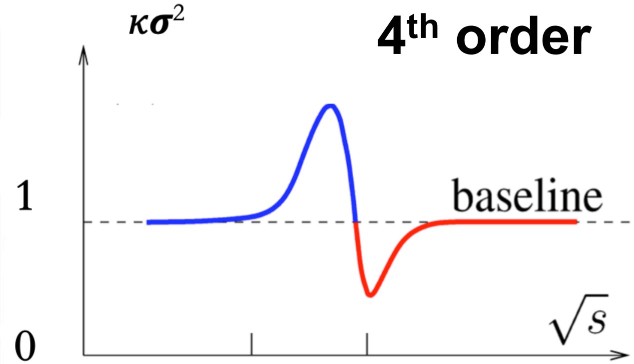
- Directly related to susceptibility χ of the system.

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

Higher-order cumulants and ratios are sensitive to QCD phase structure.

Theoretical Expectations

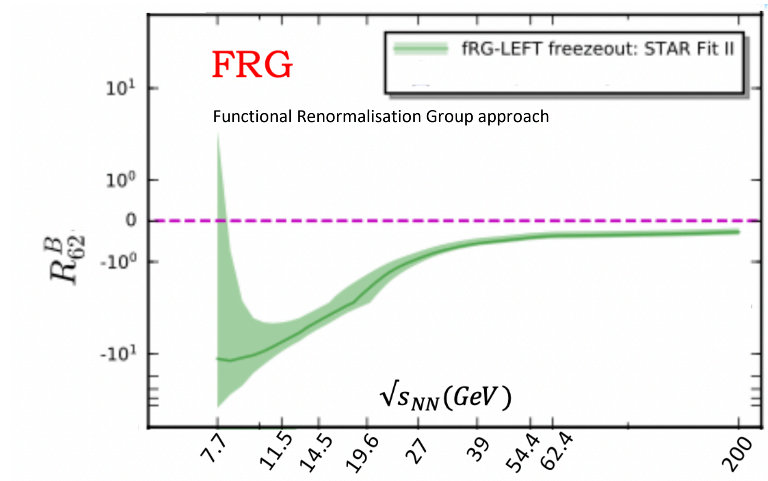
4^{th} order



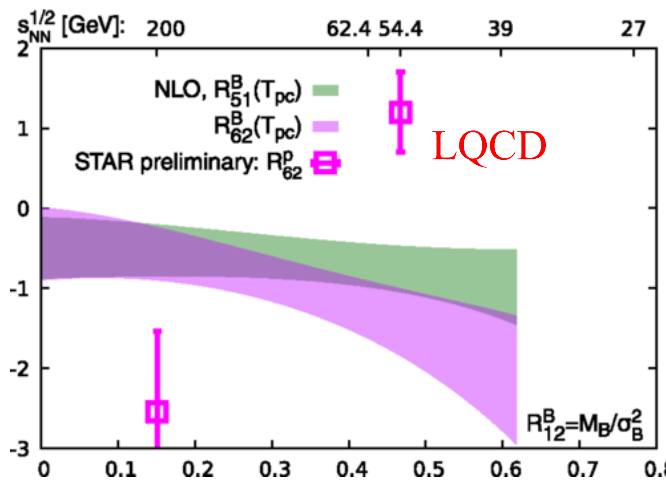
$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

M.A.Stephanov,PRL107,052301(2011).
Schaefer, Wanger,PRD 85, 034027 (2012)
JW Chen et al., PRD93, 034037 (2016); PRD95, 014038 (2017).

5^{th} and 6^{th} order



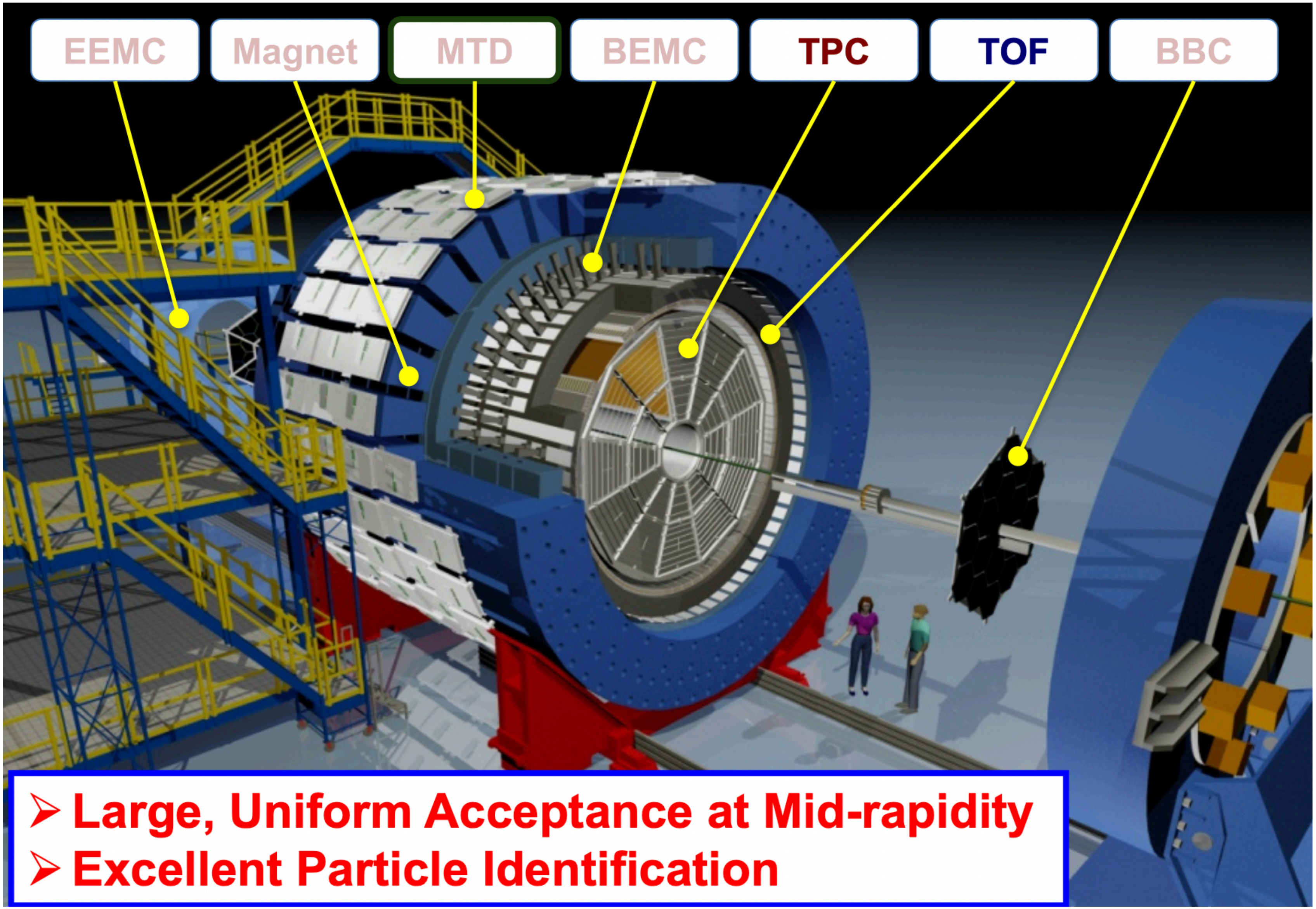
Wei-jieFu et.Al,arXiv:2101.06035



A. Bazavov et al. Phys. Rev. D **101**, 074502

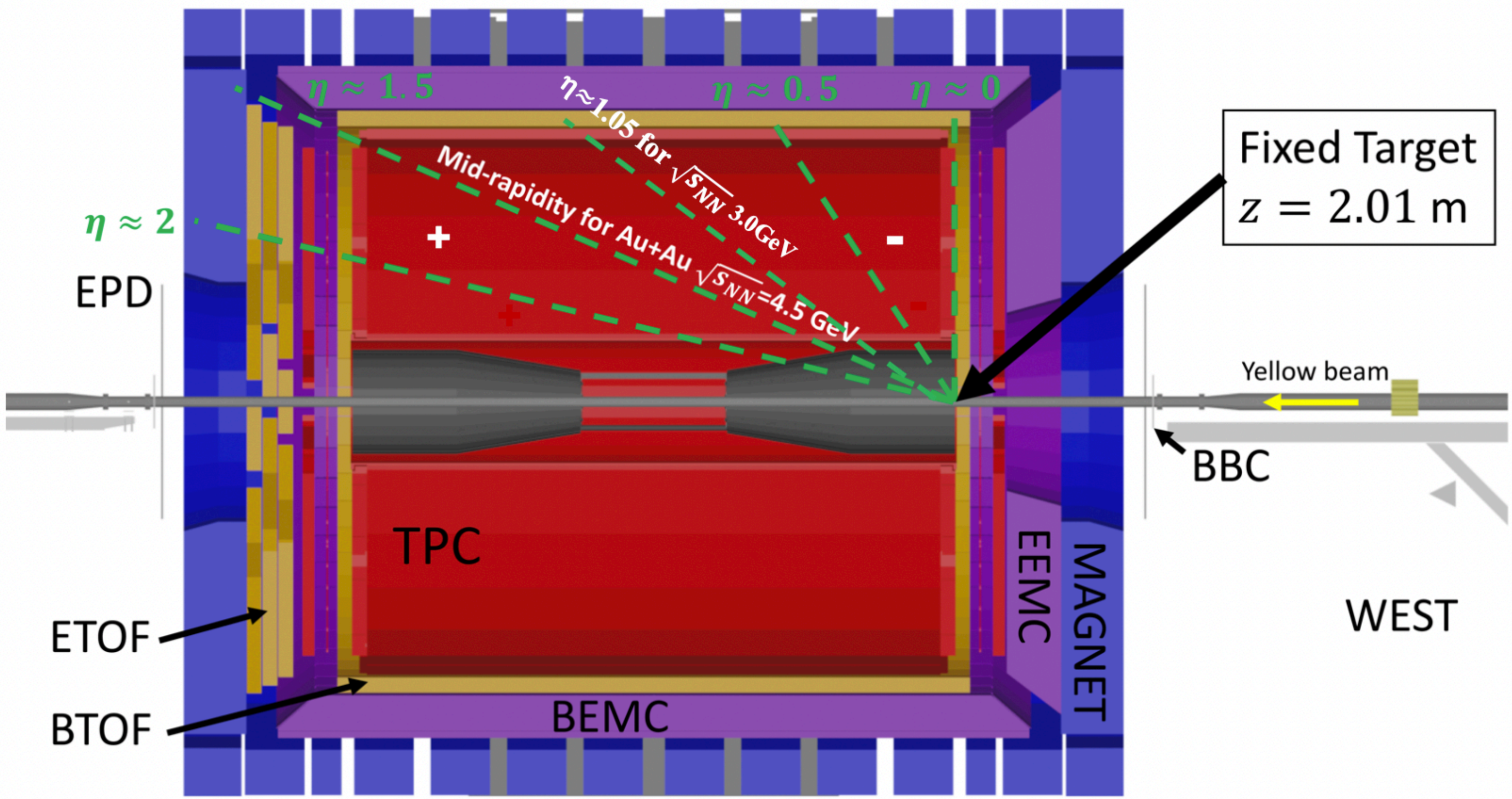
- **4^{th} order:** predicted a non-monotonic energy dependence due to contribution from QCD critical point
- **5^{th} and 6^{th}** : Predicted to be negative by lattice QCD from 200 to 39 GeV($25 < \mu_B < 112$ MeV) and FRG model; Positive for UrQMD and HRG model with no critical or phase transition physics implemented

STAR Detector System



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

STAR Fixed-target Experiment Setup



Extend the coverage of baryon chemical potential to 720 MeV !

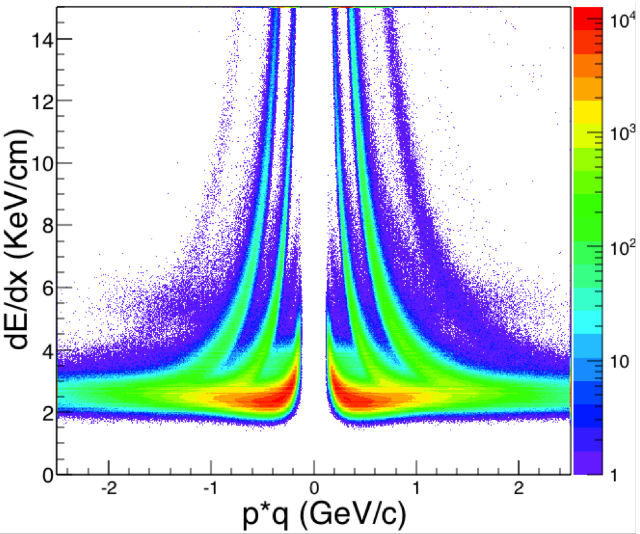
RHIC Beam Energy Scan Phase I (2010-2017) and Fixed-target Experiment (used in analysis)

$\sqrt{s_{NN}}$ (GeV)	Events ($x10^6$)	Year	μ_B (MeV)	T (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	~500	2017	83	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140
3 (FXT)	150	2018	~720	~100

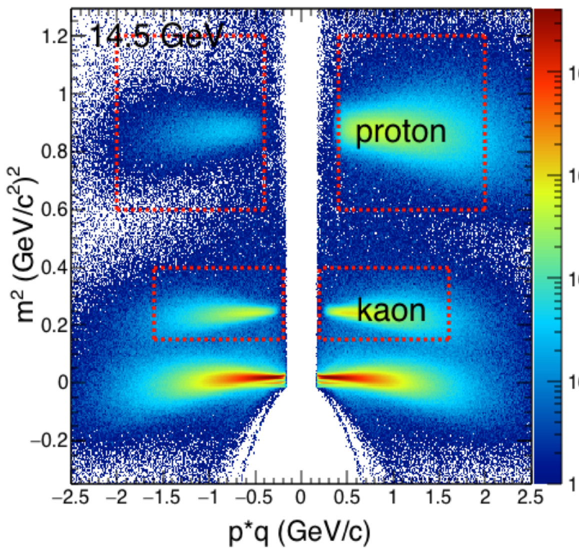
μ_B,T from *J. Cleymans et al., PRC73, 034905(2006)*

Proton Identification (Collider Mode)

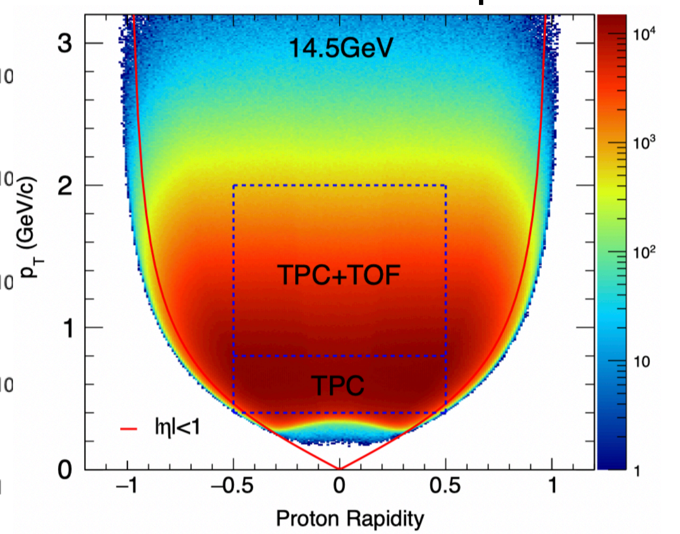
TPC PID



TOF PID



Proton Phase Space



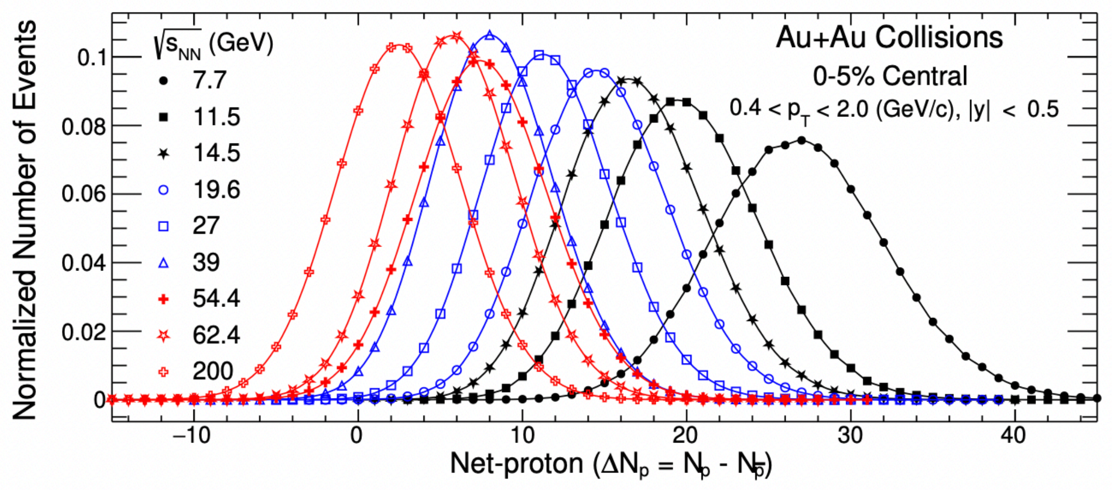
Analysis window:

$0.4 < p_T < 2.0$ GeV/c, $|y| < 0.5$

Proton identification:

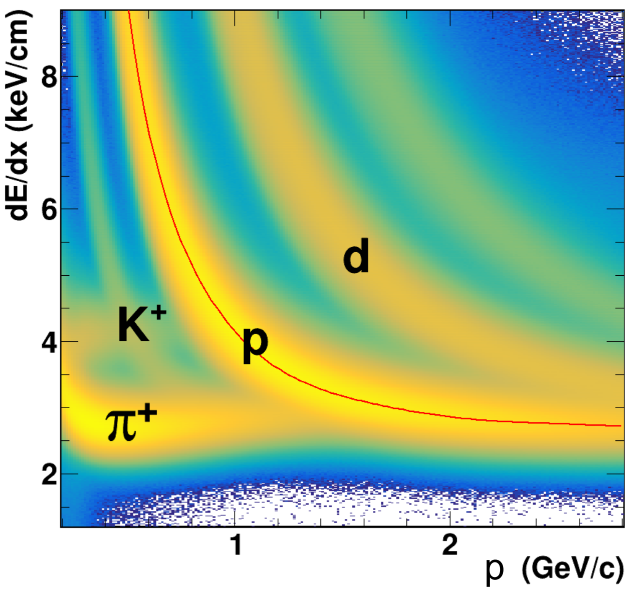
TPC (0.4 < p_T < 0.8 GeV/c)

TPC+TOF (0.8 < p_T < 2.0 GeV/c)

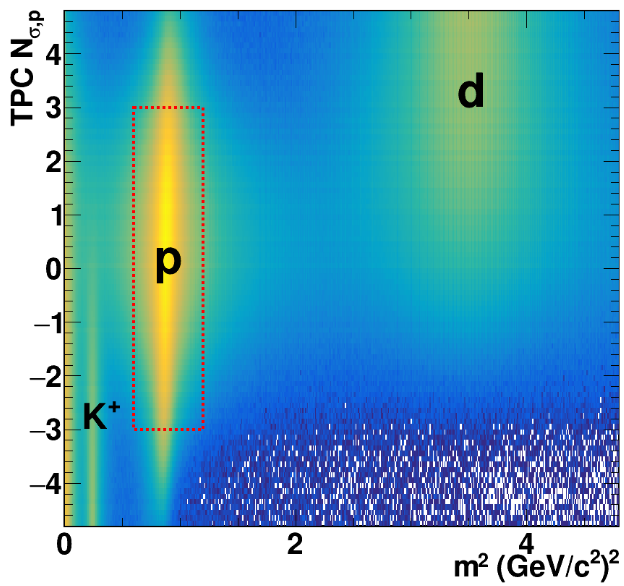


Proton Identification (FXT Mode)

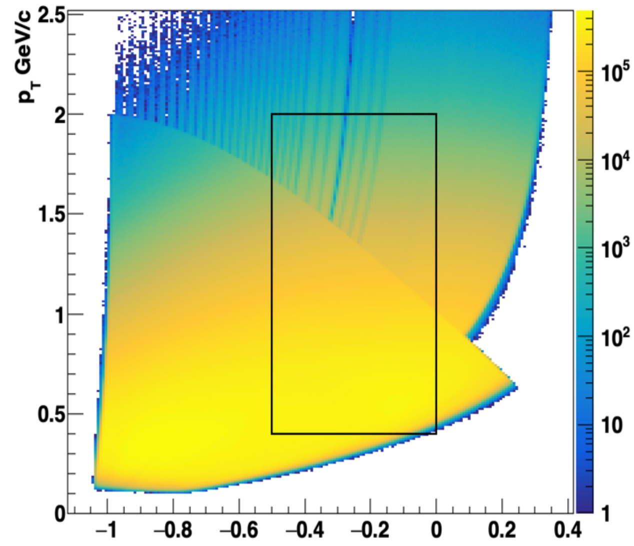
TPC PID

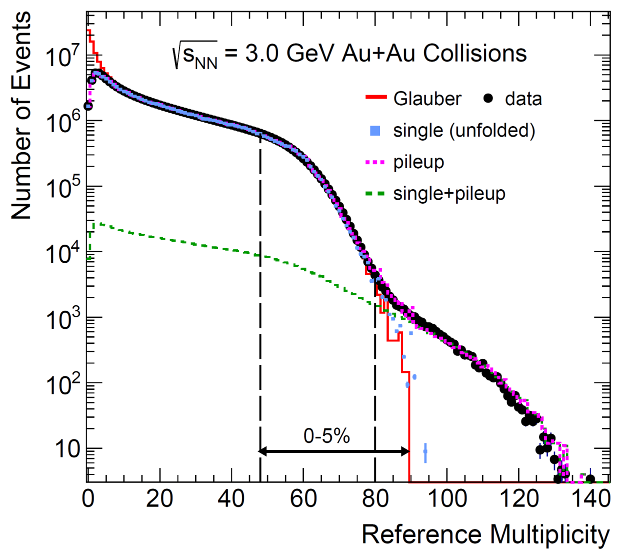


TOF PID



Proton Phase Space





Analysis window:

$0.4 < p_T < 2.0$ GeV/c, -0.5 < y < 0

Proton identification:

TPC when p < 2.0 GeV/c

TPC+TOF when p > 2.0 GeV/c

Analysis Methods

- **Detector efficiency correction:**

  TPC tracking efficiency + TOF matching

  X. Luo Phys. Rev. C **91**, 034907
  Phys. Rev. C **95**, 064912 T. Nonaka, M. Kitazawa, S. Esumi
  Phys. Rev. C **99**, 044917 X. Luo, T. Nonaka

- **Centrality bin width correction:**

  suppress initial volume fluctuation

  X. Luo et al 2013 J. Phys. G. Nucl. Part. Phys. **40** 105104

- **Statistical error estimation:**

  Delta method and bootstrap method

  X. Luo 2012 J. Phys. G: Nucl. Part. Phys. **39** 025008

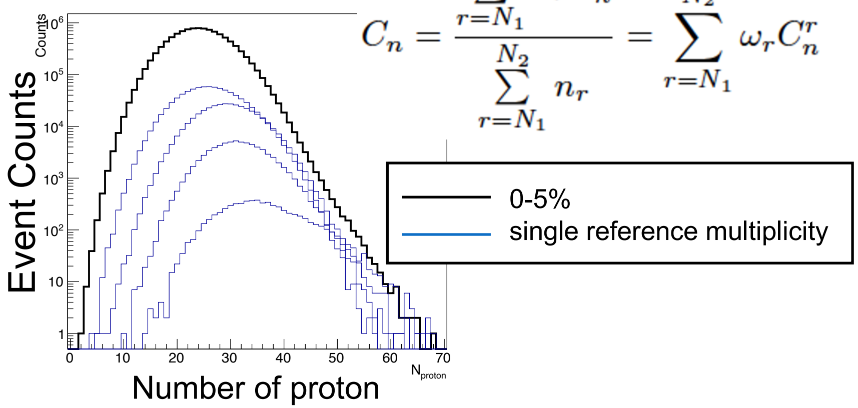
- **Pileup correction** (for fixed-target energy)

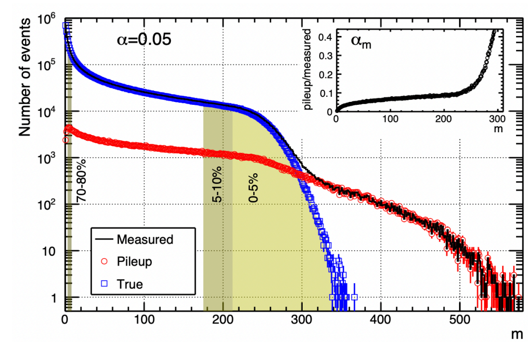
  T. Nonaka et al, Nucl. Inst. Meth. A **984** 164632, arXiv:2006.15809

$$p(n) = \sum_{N} Binomial(n; N, \varepsilon) \times P(N)$$

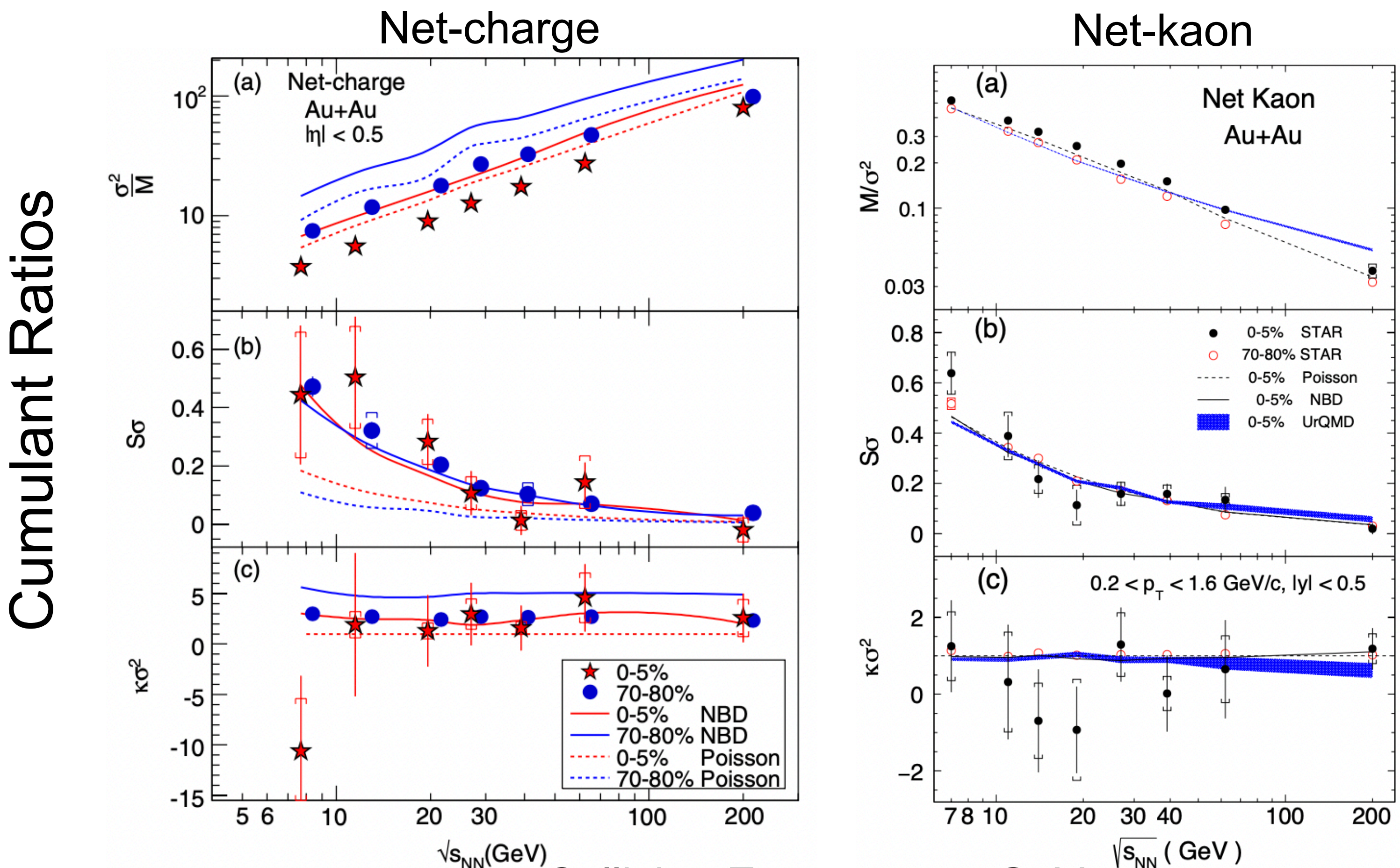
Measured — Detector Response — Actual dist.

$$C_n = \frac{\sum_{r=N_1}^{N_2} n_r C_n^r}{\sum_{r=N_1}^{N_2} n_r} = \sum_{r=N_1}^{N_2} \omega_r C_n^r$$





Net-charge and Net-kaon Cumulants from BES-I



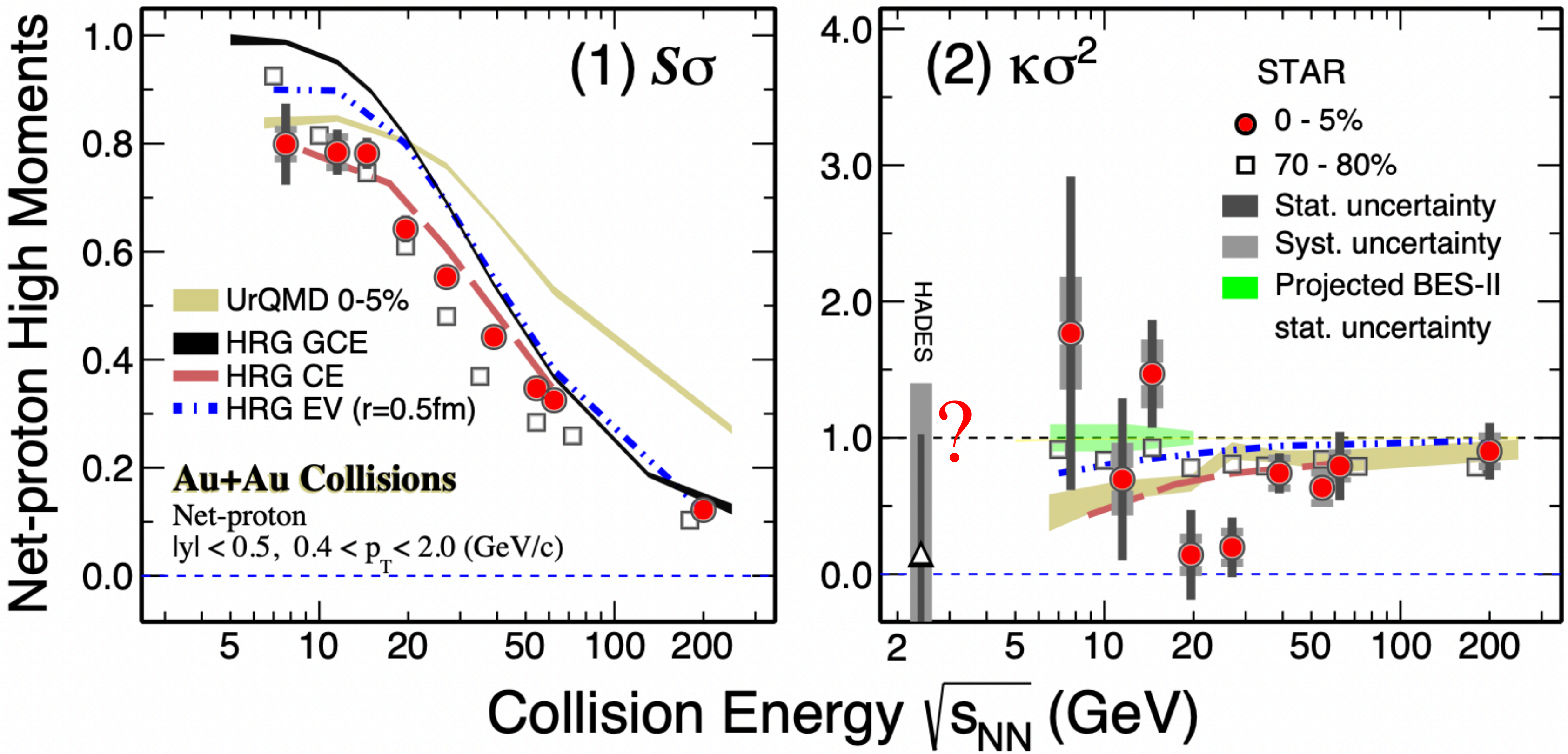
Collision Energy $\sqrt{s_{NN}}$ GeV

Phys. Rev. Lett. 113 092301 (2014).
Phys. Lett. B 785, 551 (2018).

1) Within statistical error, $\kappa\sigma^2$ of net-Q and net-kaon show flat energy dependence.
2) More statistics are needed, especially at low energies (BES-II will help).

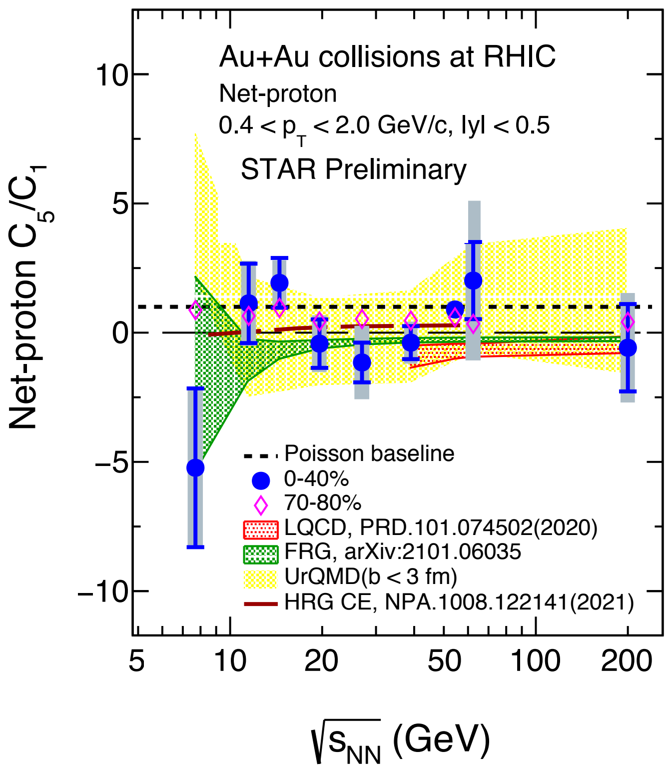
Net-proton Cumulants from BES-I

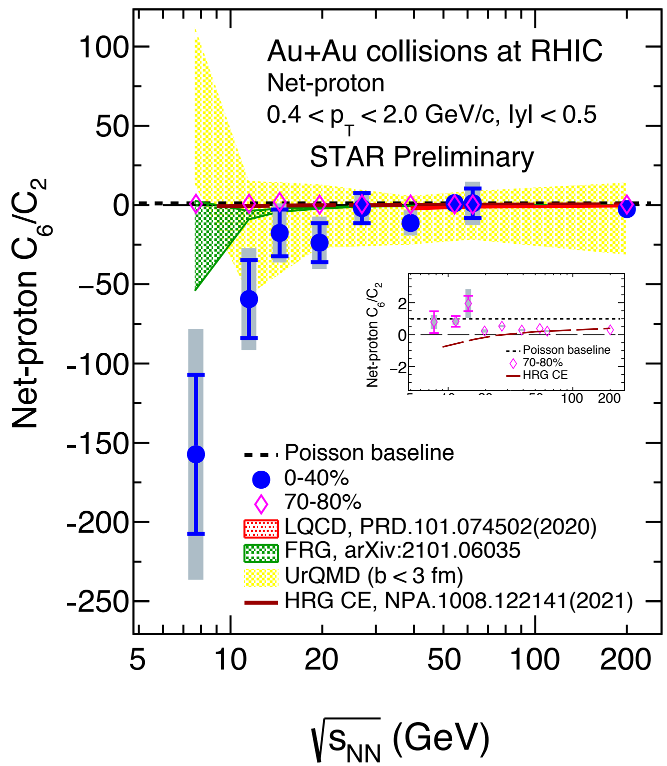
J. Adam et al. (STAR Collaboration) Phys. Rev. Lett. ***126****, 092301; arXiv:2101.12413*



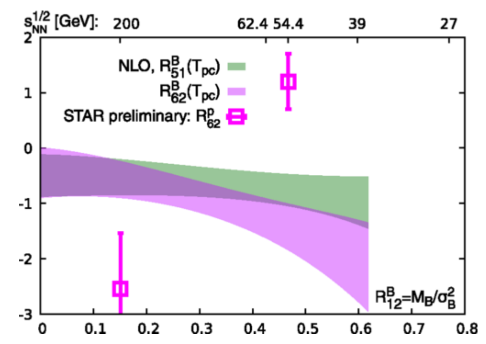
- Non-monotonic energy dependence of net-proton $\kappa\sigma^2$ is shown in top 5% from BES-I data which is not reproduced by various models.
- More statistics below 20 GeV are needed to confirm the non-monotonic trend.
- Measurement from new dataset in fixed-target experiment at $\sqrt{s_{NN}} = 3$ GeV is on the way!

Net-proton C_5/C_1 and C_6/C_2 from BES-I





Recent lattice QCD result



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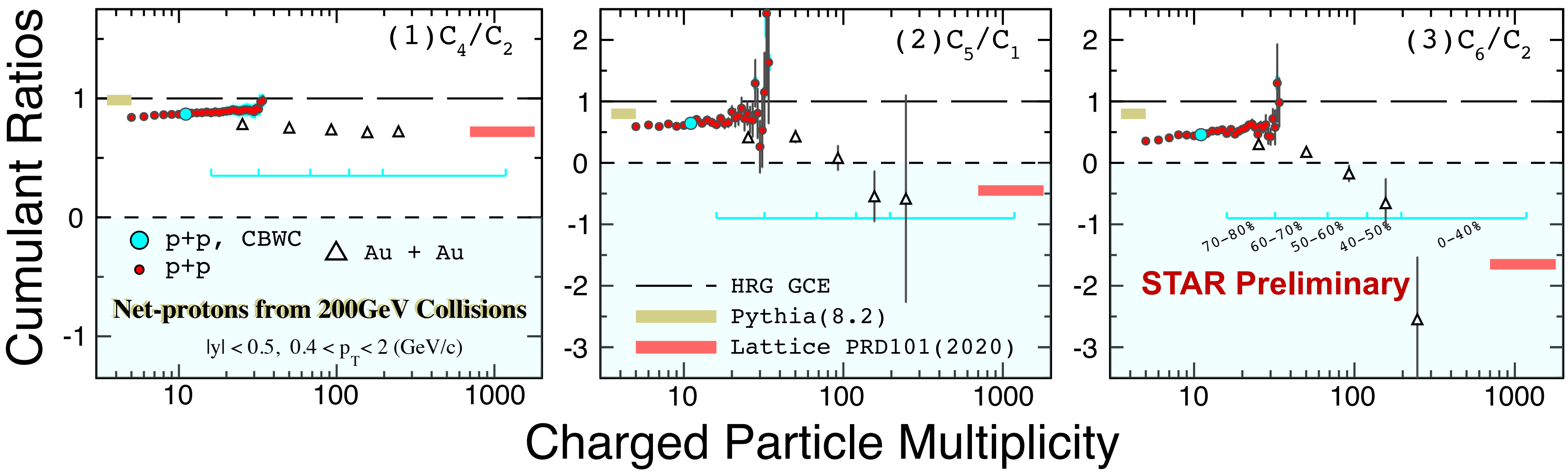
Phys. Rev. D **101**, 074502

1) LQCD and FRG calculations predict **< 0** due to the transition between partonic and hadronic phases
2) C_5/C_1 and C_6/C_2 data: (i) **> 0** for 70-80% peripheral collisions; (ii) **< 0** some for C_5/C_1 and mostly for C_6/C_2 in 0-40% central Au+Au collisions

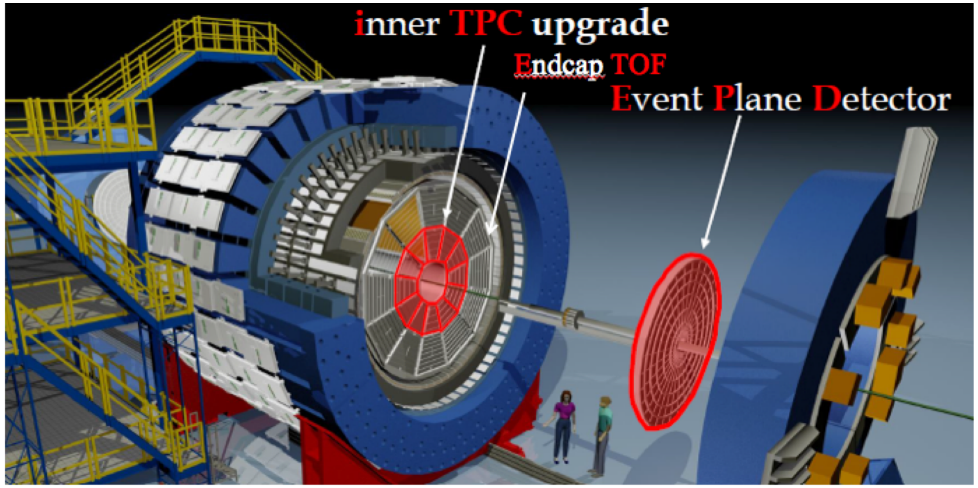
Net-proton Cumulants from 200 GeV p+p collisions



1) Results of the net-p cumulant ratios from p+p collisions fit in the multiplicity dependence of C_4/C_2, C_5/C_1 and C_6/C_2 in Au+Au collisions
2) C_5/C_1 and C_6/C_1 are found to be **negative in central** Au+Au collisions
3) LQCD calculations predict **< 0** due to the transition between partonic and hadronic phases

Higher-Order Cumulants Analysis on BES-II Overview

BES–II	
$\sqrt{s_{NN}}$ (GeV)	Events ($\times 10^6$)
19.6	~400
17.3	~250
14.5	~300
11.5	~230
9.1	~160
7.7	~100
7.7(FXT)	~160
6.2(FXT)	~120
5.2(FXT)	~100
4.5(FXT)	~100
3.9(FXT)	~120
3.5(FXT)	~120
3.2(FXT)	~200
3 (FXT)	2000



- **10 to 20** times larger statistics than BES-I
- Cover low energy range **3 to 20 GeV** and extend $\boldsymbol{\mu_B}$ **to ~720 MeV**
- Upgraded iTPC, ETOF and EPD:
  - Larger rapidity coverage $|\eta| < 1.5$
  - Better dE/dx resolution for particle identification
  - New method for centrality determination

* BES-II also have FXT data at $\sqrt{s_{NN}}$ = 9.2, 11.5, 13.7 GeV, ~50M for each.

Summary

1. Measurement of net-proton C_4/C_2 from BES-I data shows a non-monotonic energy dependence in 5% most central Au+Au collisions at RHIC
2. Measurements of net-proton C_5/C_1 and C_6/C_2 from BES-I data show negative deviation from zero with a level of $\leq 2\sigma$ while both ratios are positive at peripheral collisions.
3. Measurements of net-proton C_5/C_1 and C_6/C_2 from 200 GeV Au+Au and p+p collision suggest: deconfined QCD matter created in central 200 GeV Au+Au collisions
4. Exciting results at high baryon density region from BES-II are coming!

Thank you for your attention!