55th Rencontres de Moriond 2021

QCD Critical Point and Net-Proton Number Fluctuations at RHIC-STAR

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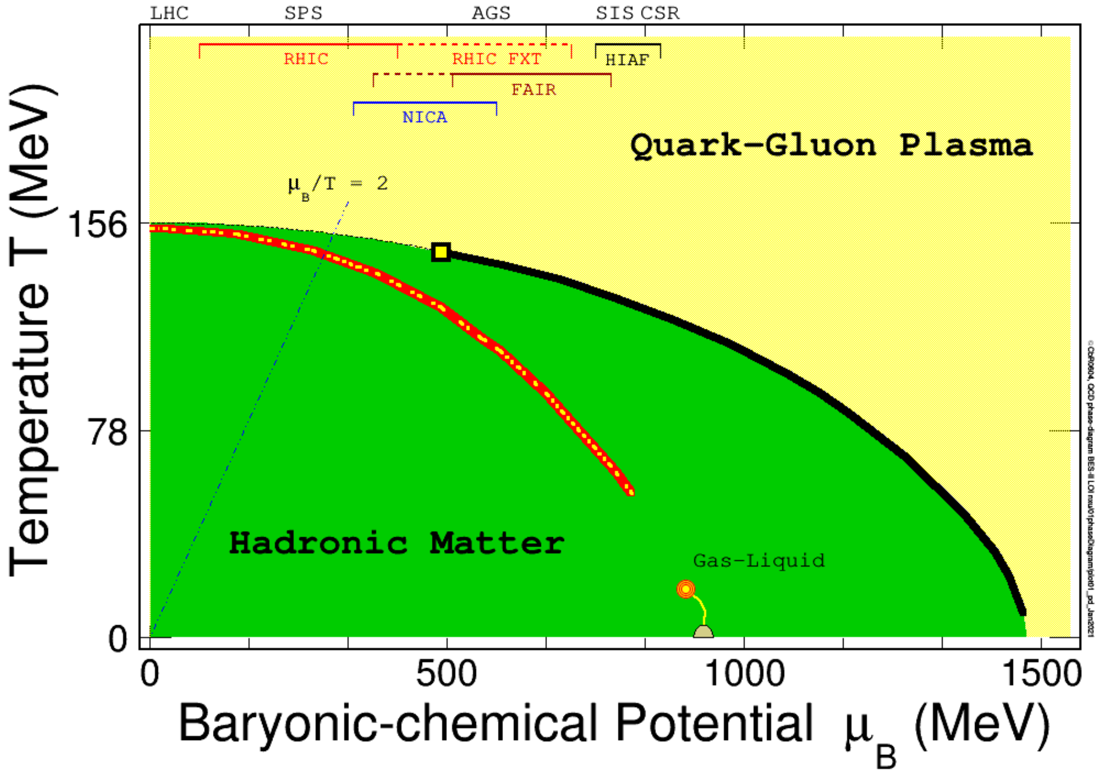
Outline

- Introduction
- Net-proton number fluctuations:
  - Beam Energy Scan-I Au+Au collisions
  - 200 GeV p+p collisions
- Summary and Outlook

QCD Phase Diagram

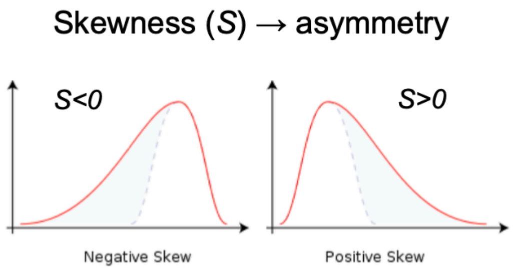


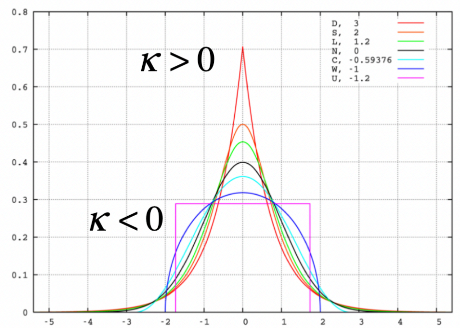
- Crossover at $\mu_B = 0$ *Y. Aoki et al, Nature 443, 675(2006)*
- Model predict 1st order phase transition at non-zero μ_B
- Possible QCD critical point?
- Scan the QCD phase diagram by varying collision energy

Higher moments of conserved quantities

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

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





- Sensitive quantities to correlation length ξ

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

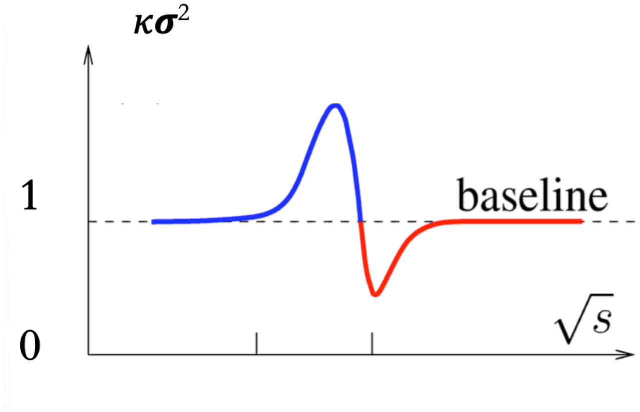
M. A. Stephanov Phys. Rev. Lett. 102, 032301
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

- directly related to susceptibility χ of the system.

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

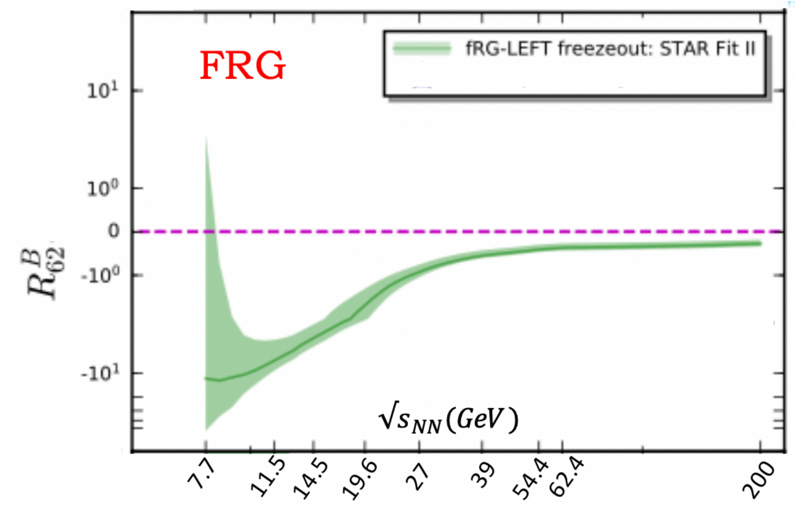
Higher moments and ratios are sensitive to QCD phase structure.

Theoretical Expectations

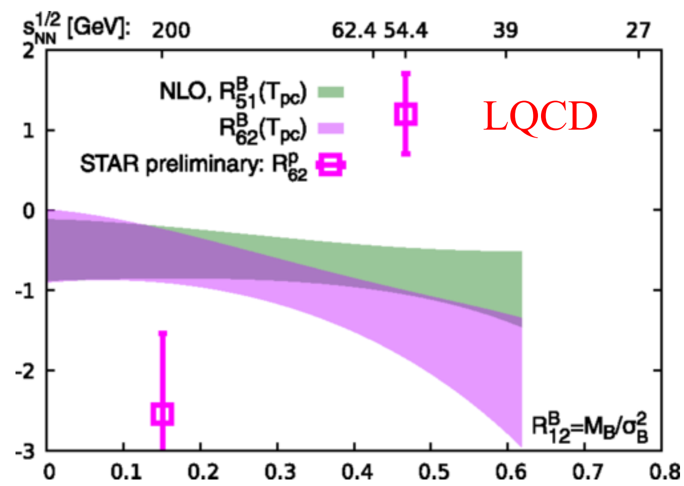


$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

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



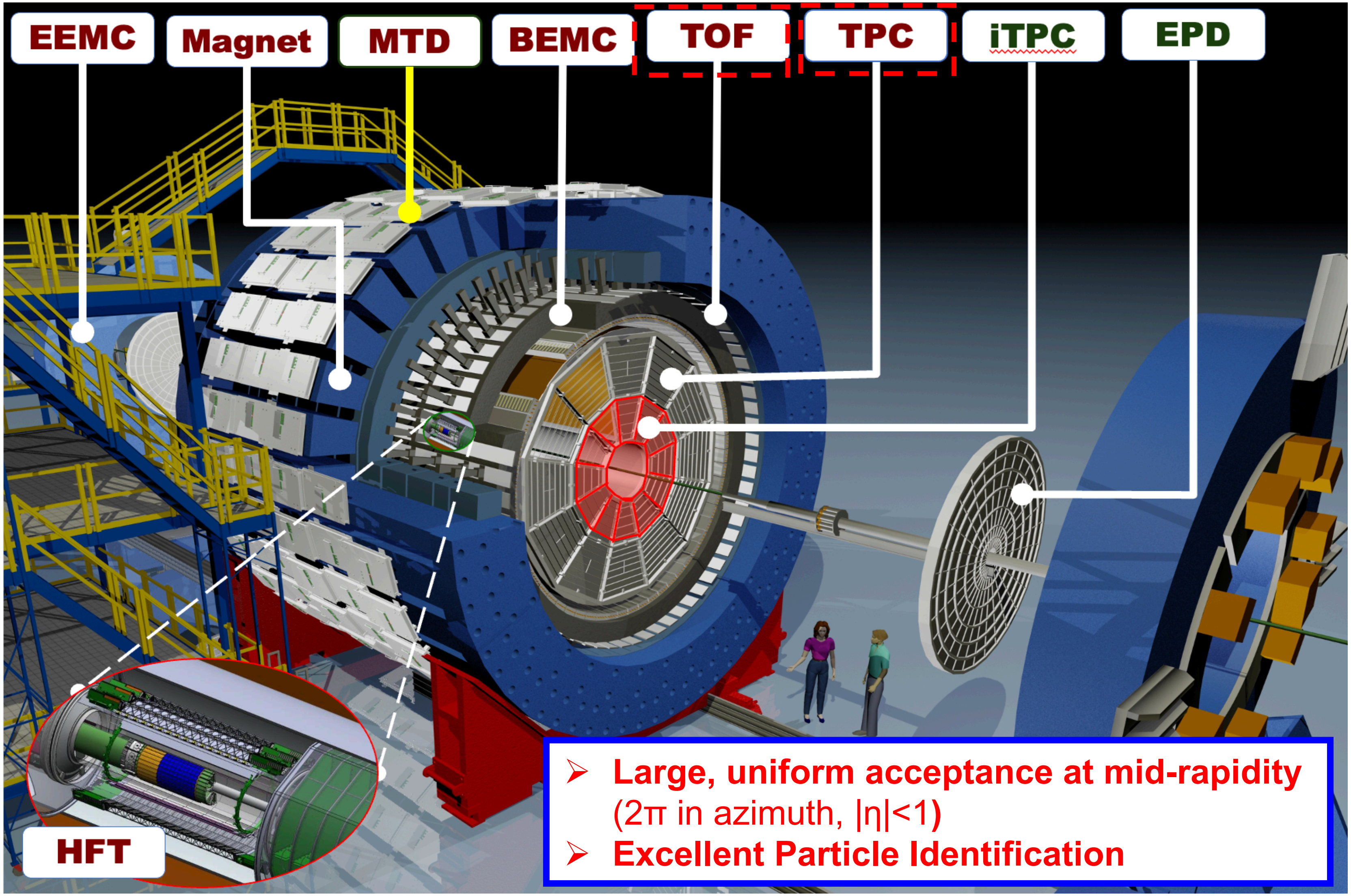
Wei-jieFu et.Al,arXiv:2101.06035



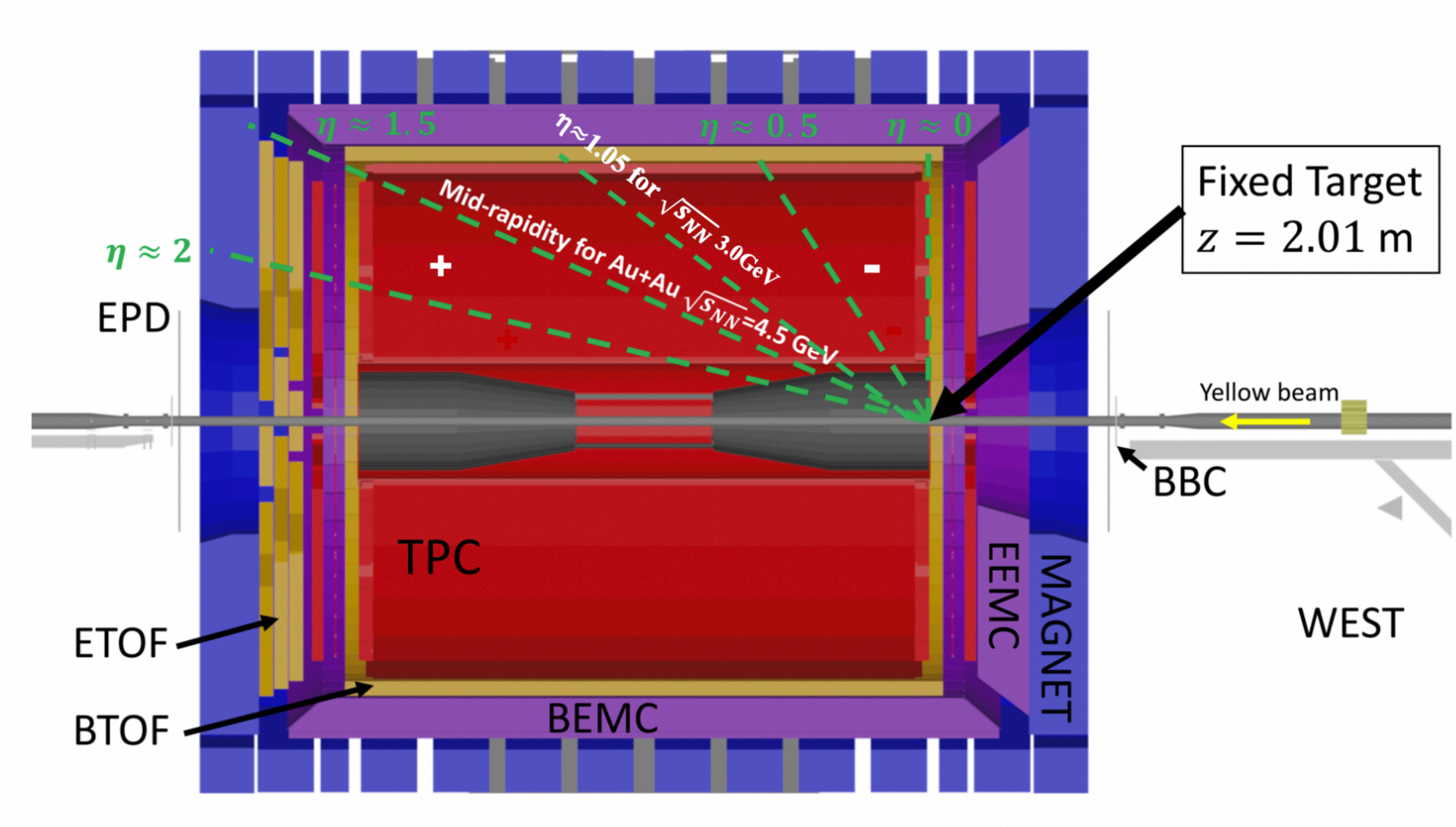
A. Bazavov et al. Phys. Rev. D **101**, 074502

- 4^{th} order cumulant ratio shows non-monotonic energy dependence because of contribution from critical point
- Predicted to be negative by lattice QCD from 200 to 39 GeV(25< μ_B < 112 MeV).
- Positive for UrQMD and HRG model without QCD phase transition

STAR Detector System



STAR Fixed-target Experiment Setup



Extend the coverage of baryon chemical potential to 720 MeV !

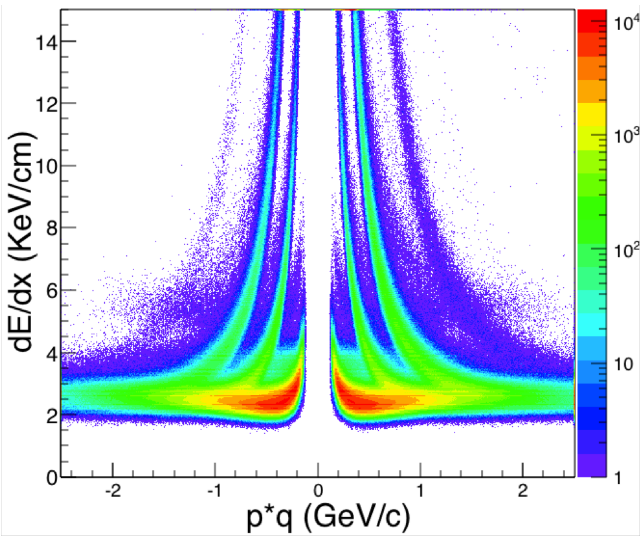
RHIC Beam Energy Scan Phase I (2010-2017) and Fixed-target Experiment

$\sqrt{s_{NN}}$ (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	~721	~100

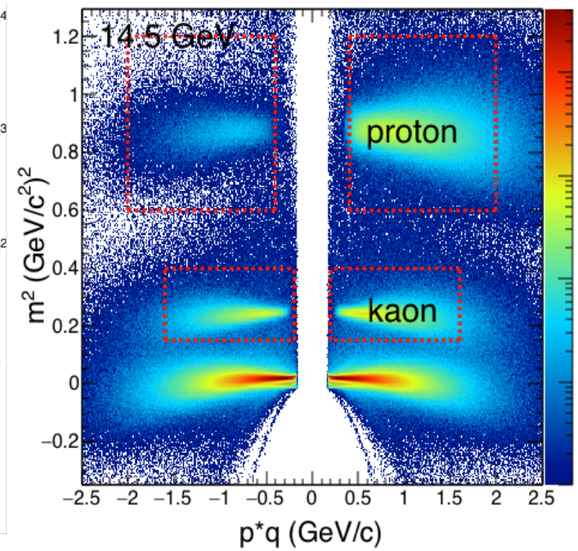
μ_B,T: J. Cleymans et al., PRC73, 034905(2006)

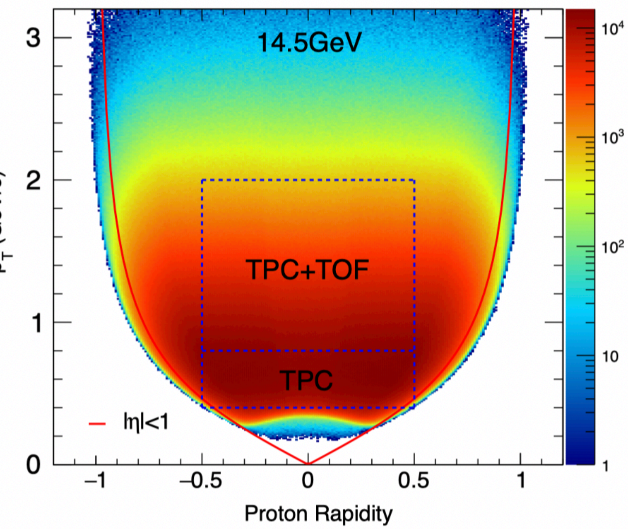
Proton Identification (Collider Mode)

TPC PID



TOF PID



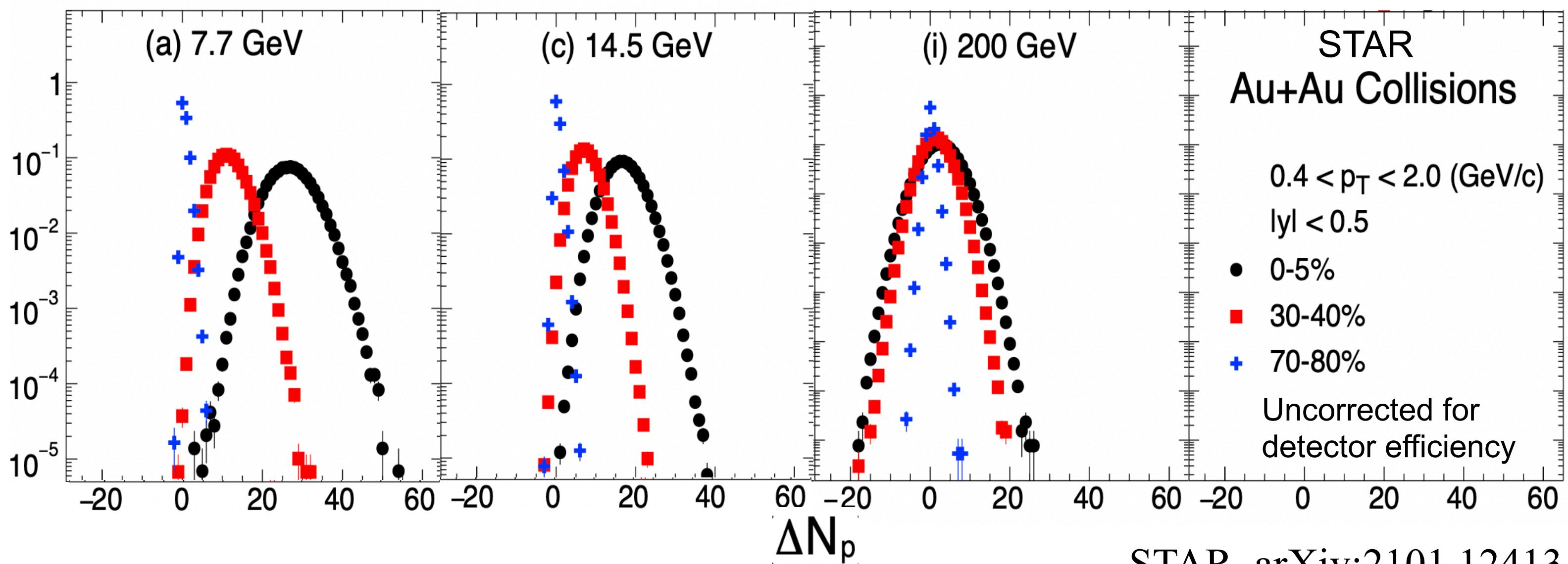


Kinematics cuts: $0.4 < p_T < 2.0$ GeV/c, |y| < 0.5

Proton identification: $0.4 < p_T < 0.8$ GeV/c → TPC

$0.8 < p_T < 2.0$ GeV/c → TPC+TOF

Analysis Detail



STAR, arXiv:2101.12413

1. Detector efficiency correction: TPC tracking + TOF matching

    Xiaofeng Luo Phys. Rev. C 91, 034907
    Phys. Rev. C 95, 064912 Toshihiro Nonaka, Masakiyo Kitazawa, and ShinIchi Esumi
    Phys. Rev. C 99, 044917 Xiaofeng Luo, Toshihiro Nonaka

2. Statistical error estimation: Delta method and bootstrap method

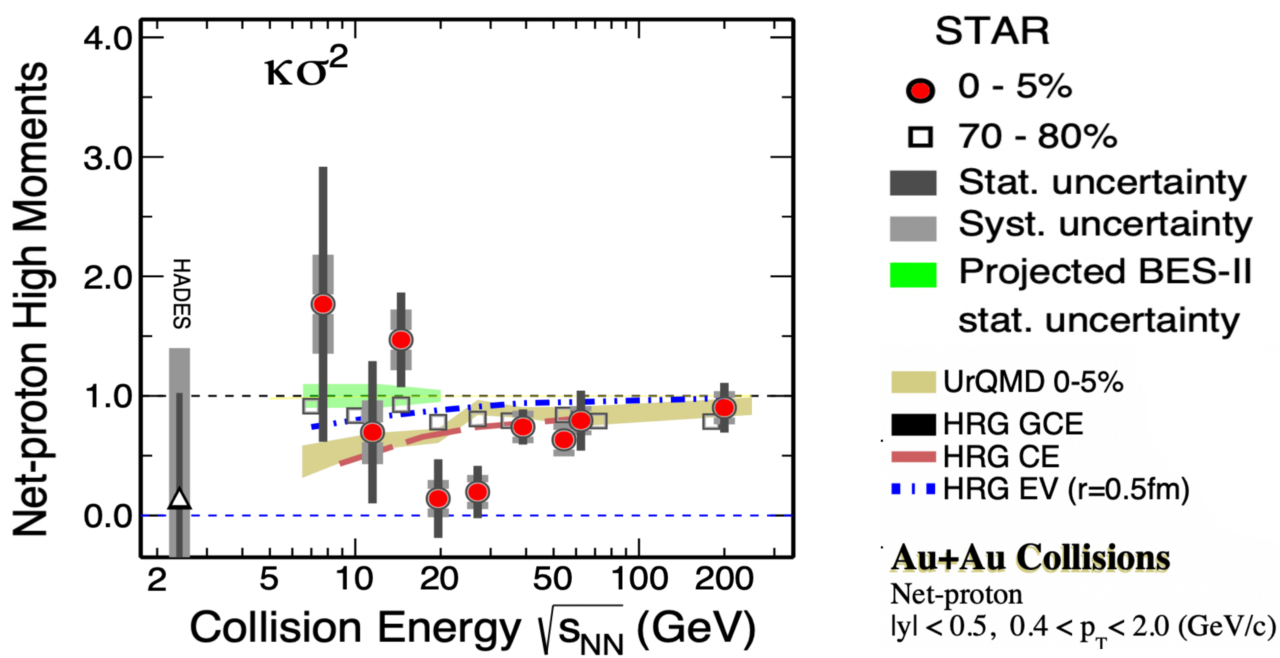
    Xiaofeng Luo 2012 J. Phys. G: Nucl. Part. Phys. 39 025008

3. Centrality bin width correction: suppress initial volume fluctuation

    Xiaofeng Luo et al 2013 J. Phys. G: Nucl. Part. Phys. 40 105104

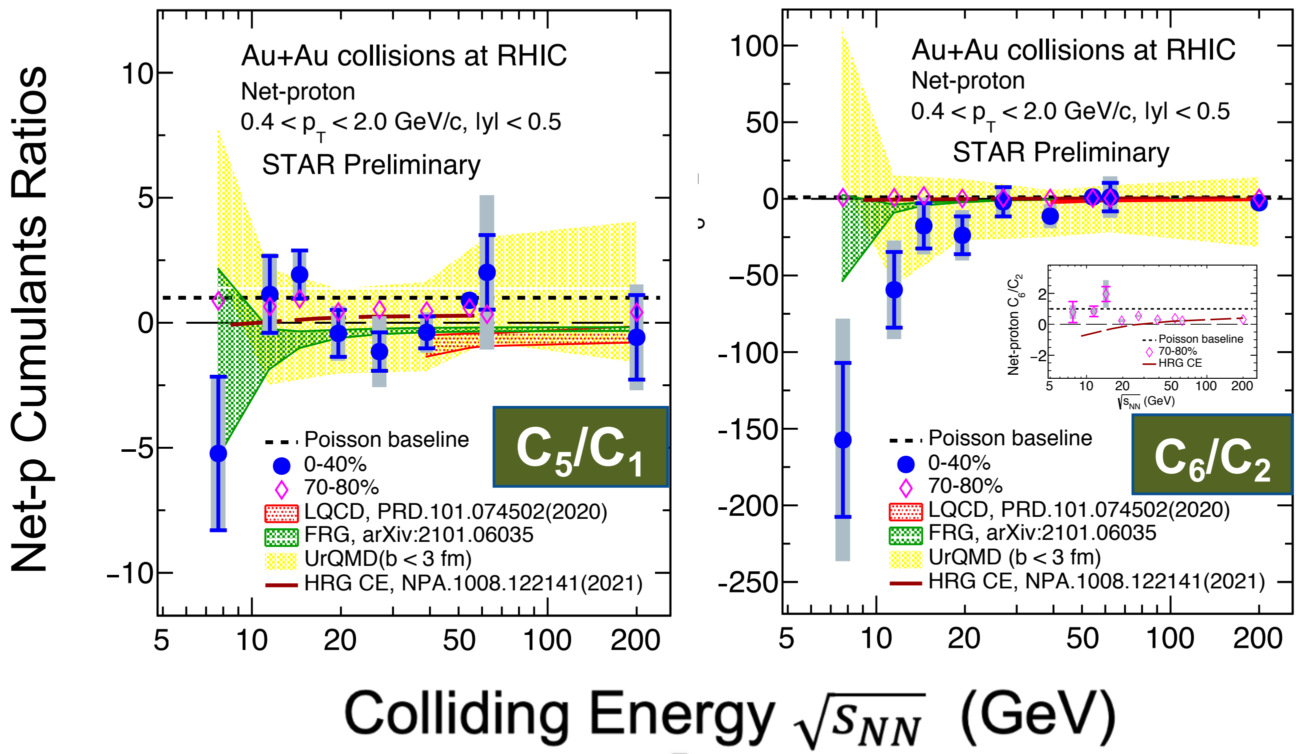
Result 1: Net-proton C_4/C_2 from BES-I

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



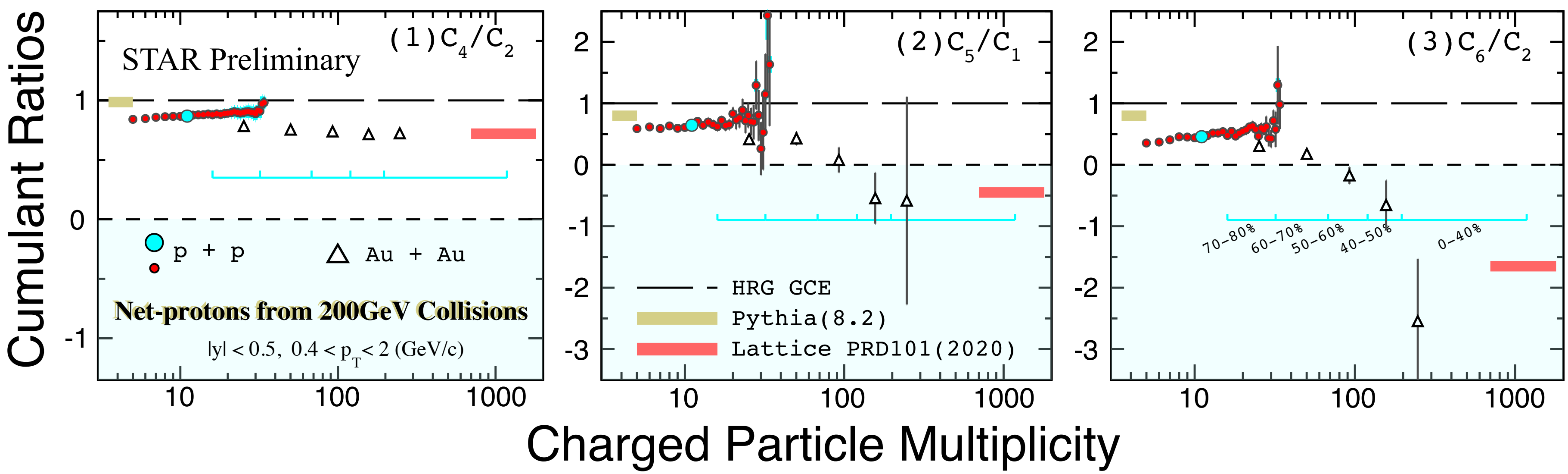
- Non-monotonic energy dependence of net-proton $\kappa\sigma^2$ is shown in top 5% from BES-I data which is not reproduced by various models.
- More statistics below 20 GeV are needed to confirm the non-monotonic trend.
- Measurement from new dataset in fixed target experiment at $\sqrt{s_{NN}} = 3$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

Result 2: Net-proton C_5/C_1 and C_6/C_2 from BES-I



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

Result 3: Net-proton from 200 GeV p+p collisions



1) Results of the net-p high moment 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 phase

Summary

1) Beam Energy Scan-I:

- C_4/C_2 : Non-monotonic energy dependence is observed in top 5% and is not reproduced by various models
- C_5/C_1, C_6/C_2 : Negative values in Au+Au central collisions while positive values in peripheral collisions

2) 200 GeV p+p:

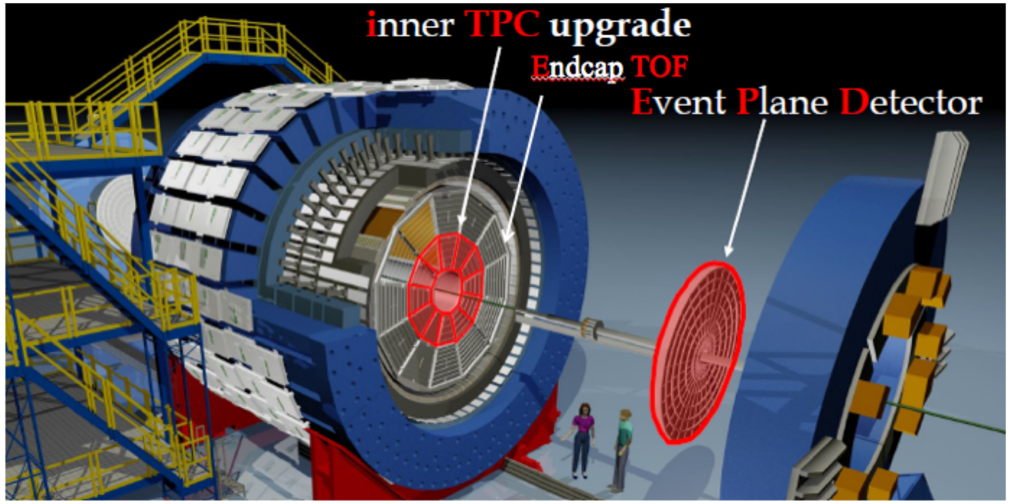
- C_4/C_2 , C_5/C_1 and C_6/C_2 : Results from 200 GeV p+p collisions fit in the centrality dependence of results from 200 GeV Au+Au collisions

After comparing to LQCD, FRG, and UrQMD calculations, it supports: "**Deconfined QCD matter created in central 200 GeV Au+Au collisions**".

High statistics data is needed to confirm the observations.

Outlook: Beam Energy Scan-II at RHIC

BES-II	
$\sqrt{s_{NN}}$ (GeV)	Requested Events (x10^6)
19.6	~400
17.1	~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)	~260+300



- 10-20 times larger statistics than BES-I
- Cover low energy range 3-20 GeV
- Upgraded iTPC, ETOF and EPD
  - Larger rapidity coverage $|\eta| < 1.5$
  - Better dE/dx resolution
  - Centrality determination

Thank you!