Higher-order Cumulants of Proton Multiplicity Distributions in Au+Au Collisions at $\sqrt{s_{NN}}$ = 3 GeV from RHIC-STAR

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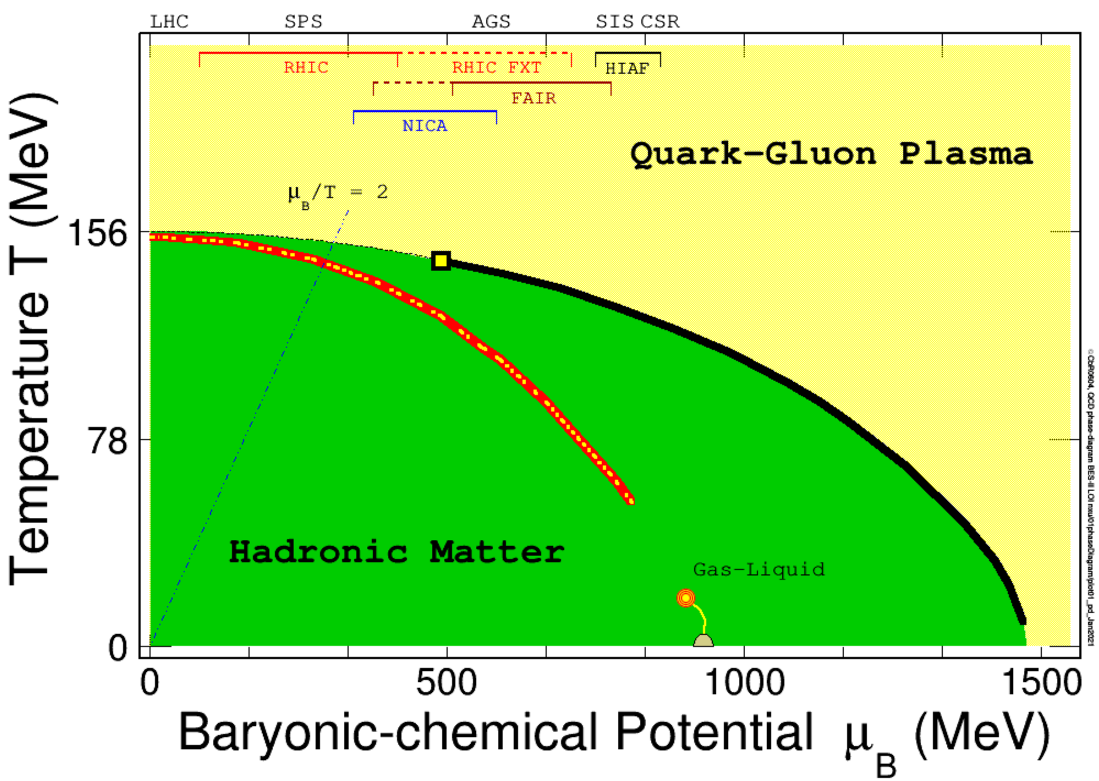
Supported in part by

Outline

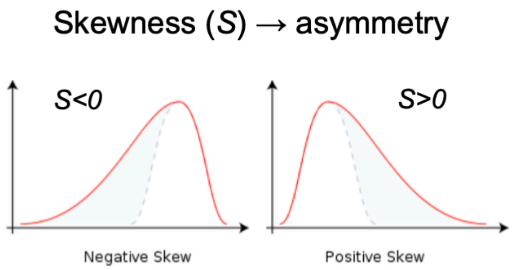
- Motivation
- STAR detector and fixed target program
- Analysis detail
  - Pileup effect
  - Volume fluctuation effect
- Summary

QCD Phase Diagram



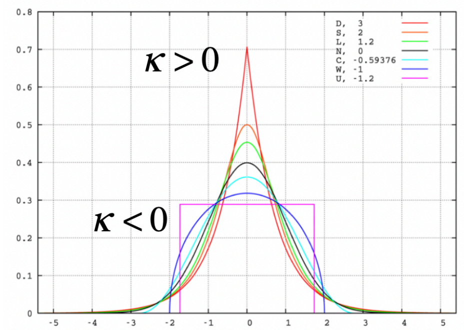
- Crossover at $\mu_B = 0$ *Y. Aoki et al, Nature 443, 675(2006)*
- Models predict 1st order phase transition at non-zero μ_B
- Possible QCD critical point?
- Change collision energy to scan phase diagram

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

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

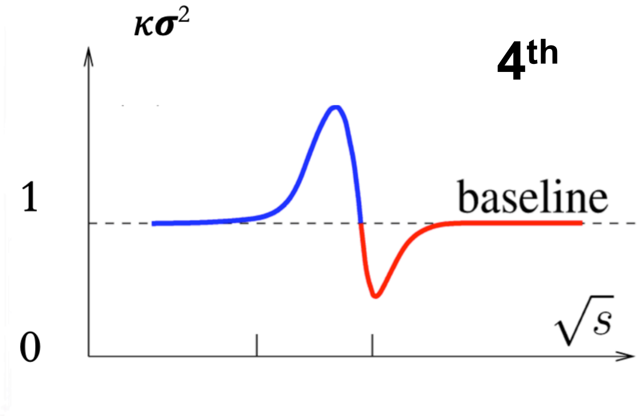
M. A. Stephanov Phys. Rev. Lett. 102, 032301
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).

- directly related to susceptibility χ of the system.

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

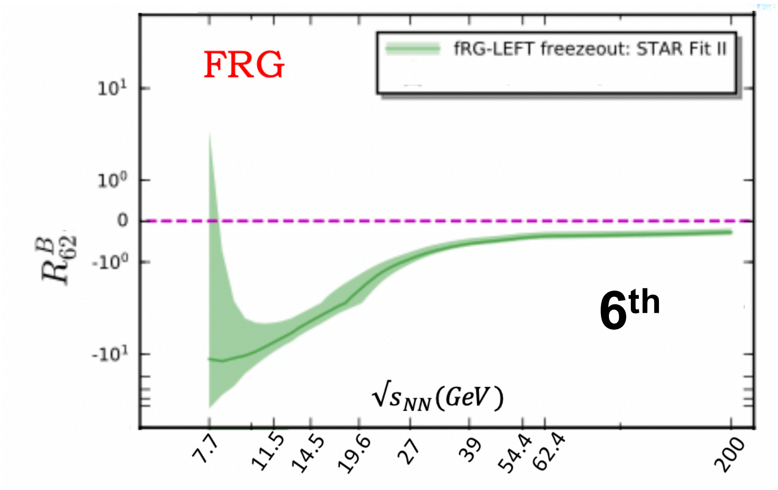
Higher moments and ratios are sensitive to QCD phase structure.

Theoretical Expectations

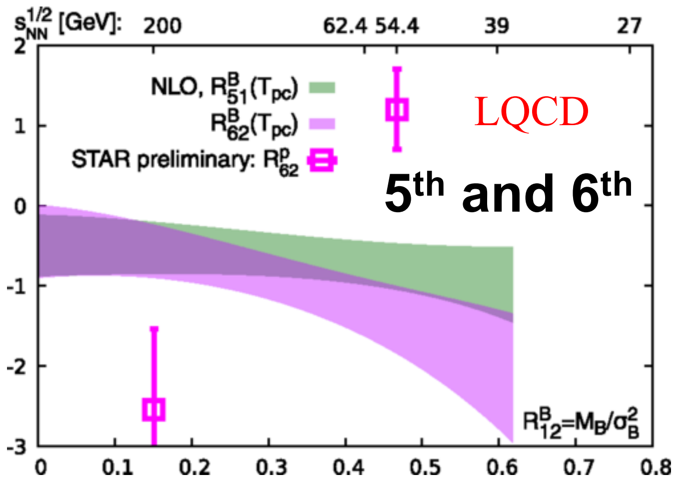


$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

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



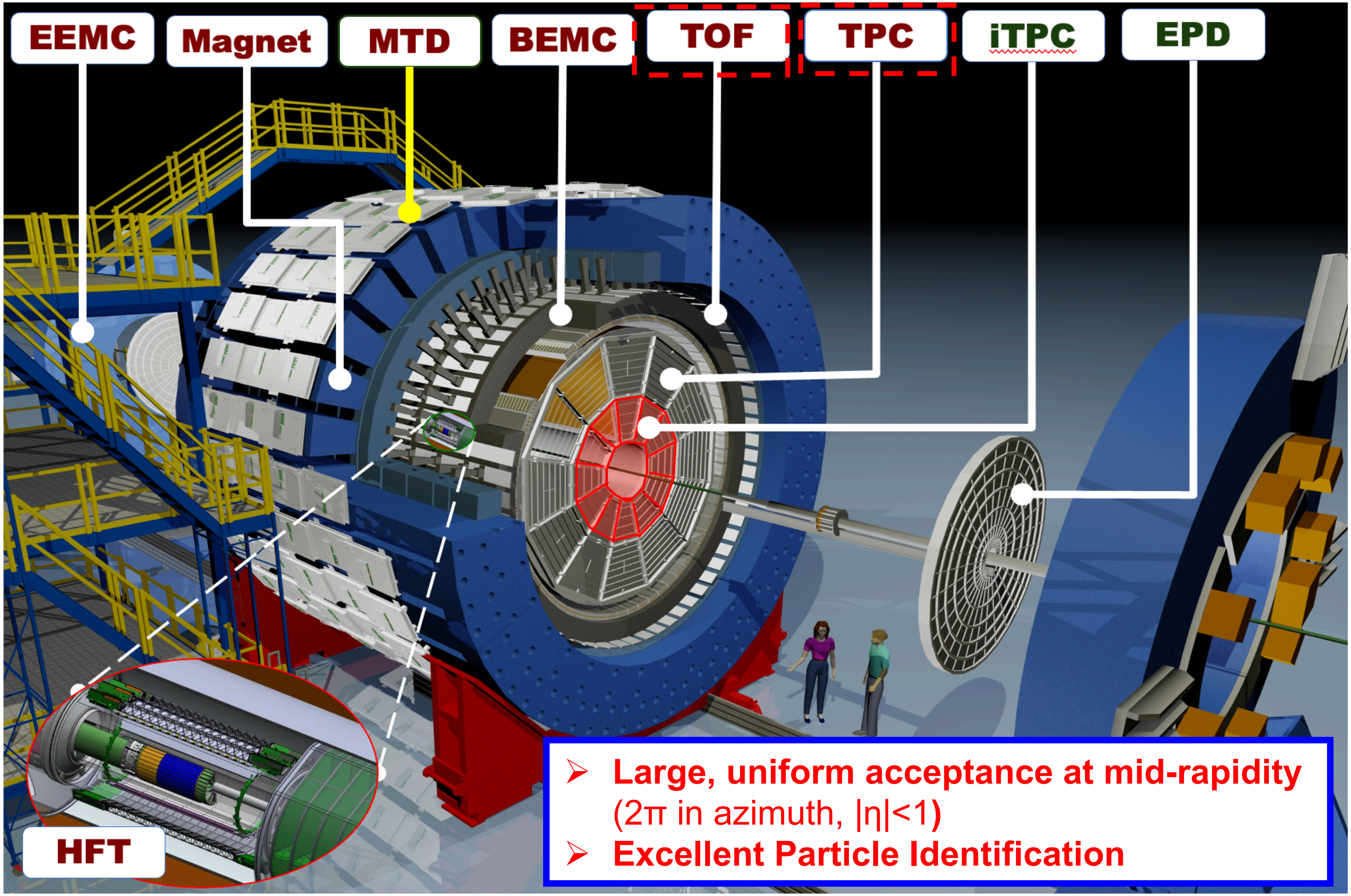
Wei-jieFu et.Al,arXiv:2101.06035



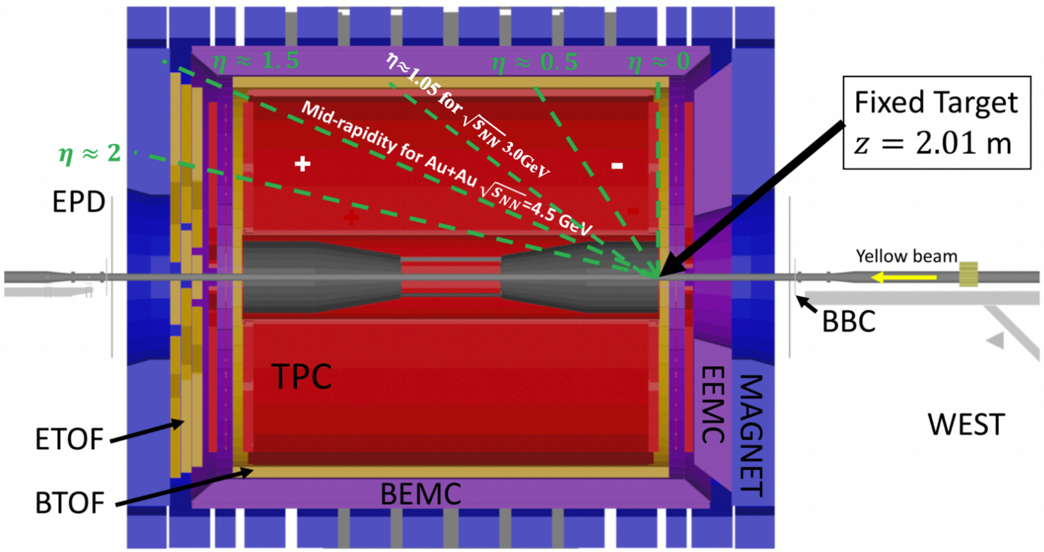
A. Bazavov et al. Phys. Rev. D **101**, 074502

- 4th order cumulant ratio shows non-monotonic energy dependence because of contribution from critical point
- 5th and 6th : 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 and BES-II

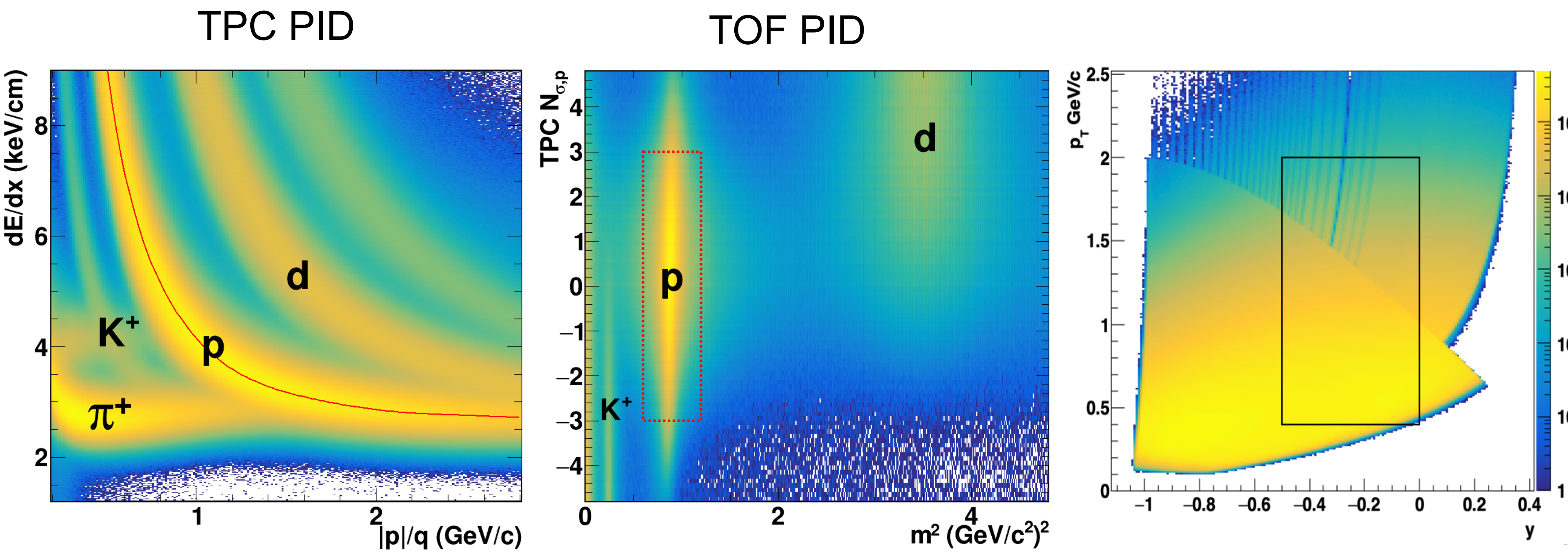


Extend the coverage of baryon chemical potential to 720 MeV !

Beam Energy Scan - II	
$\sqrt{s_{NN}}$ (GeV)	Events (x10^6)
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

Proton Identification (FXT Mode)

Fixed-target data at $\sqrt{s_{NN}} = 3$ GeV:



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

Proton identification: $0.4 < p_T < 2.0$ GeV/c → TPC

p > 2.0 GeV/c → TPC+TOF

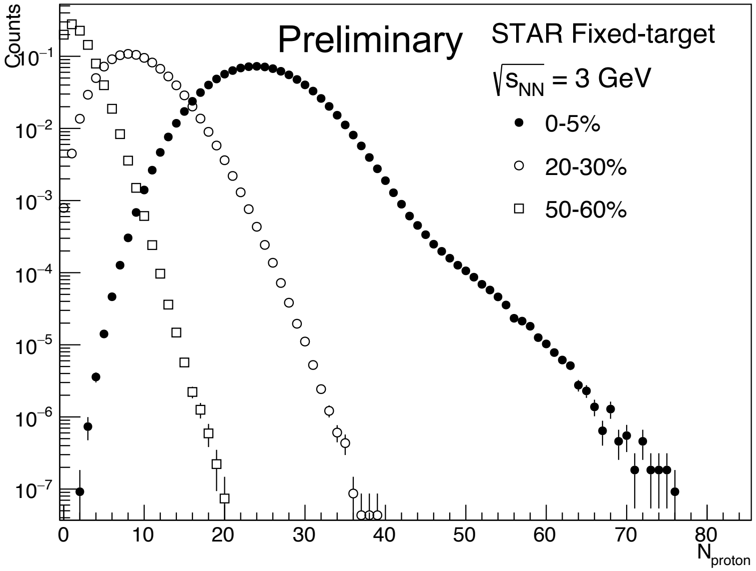
Analysis Detail

- Detector efficiency correction:
  TPC tracking efficiency + TOF matching

  Xiaofeng Luo Phys. Rev. C 91, 034907
  Phys. Rev. C 95, 064912 Toshihiro Nonaka,Masakiyo Kitazawa, ShinIchi Esumi
  Phys. Rev. C 99, 044917 Xiaofeng Luo, Toshihiro Nonaka
- Statistical error estimation:
  Delta method and bootstrap method
  Xiaofeng Luo 2012 J. Phys. G: Nucl. Part. Phys. 39 025008
- Centrality bin width correction:
  suppress initial volume fluctuation

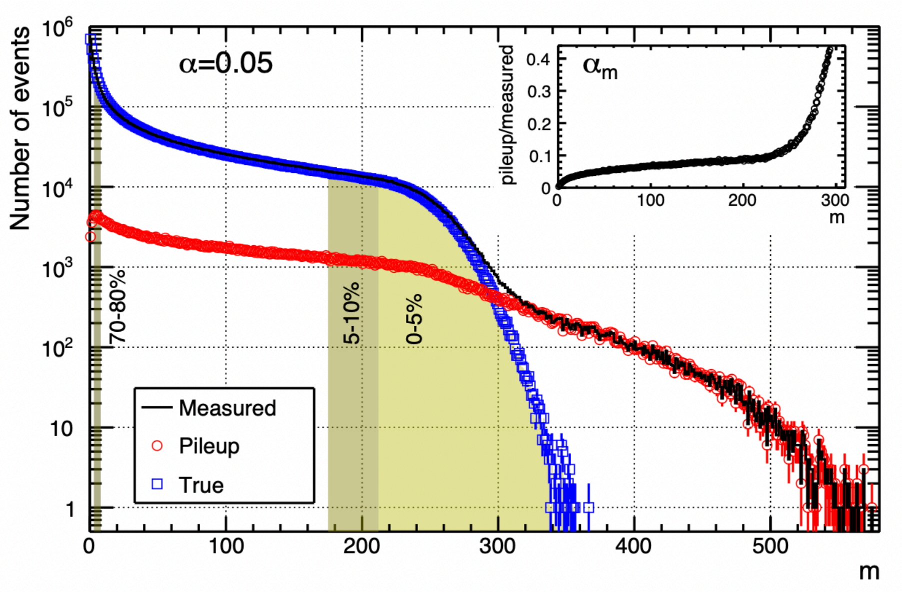
  Xiaofeng Luo et al 2013 J. Phys. G: Nucl. Part. Phys. 40 105104
- Pileup correction (at FXT $\sqrt{s_{NN}} = 3$GeV)

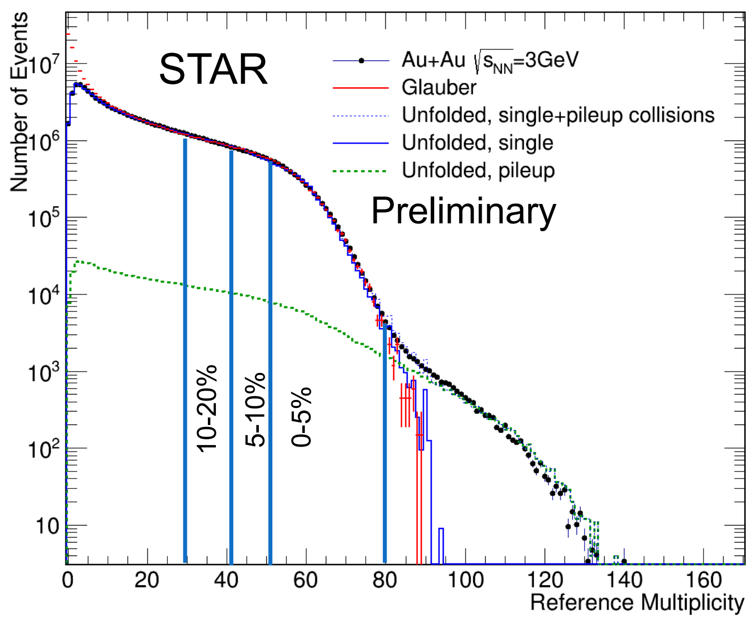
  Toshihiro Nonaka, Masakiyo Kitazawa, ShinIchi Esumi, J-PARC-TH-0220, arXiv:2006.15809
- Initial volume fluctuation correction
  P.Braun-Munzinger, A.Rustamov, J.Stachel, arxiv:1612.00702v1



Analysis Detail: Pileup Correction

Toshihiro Nonaka, Masakiyo Kitazawa, ShinIchi Esumi, arXiv:2006.15809





Probability distribution:

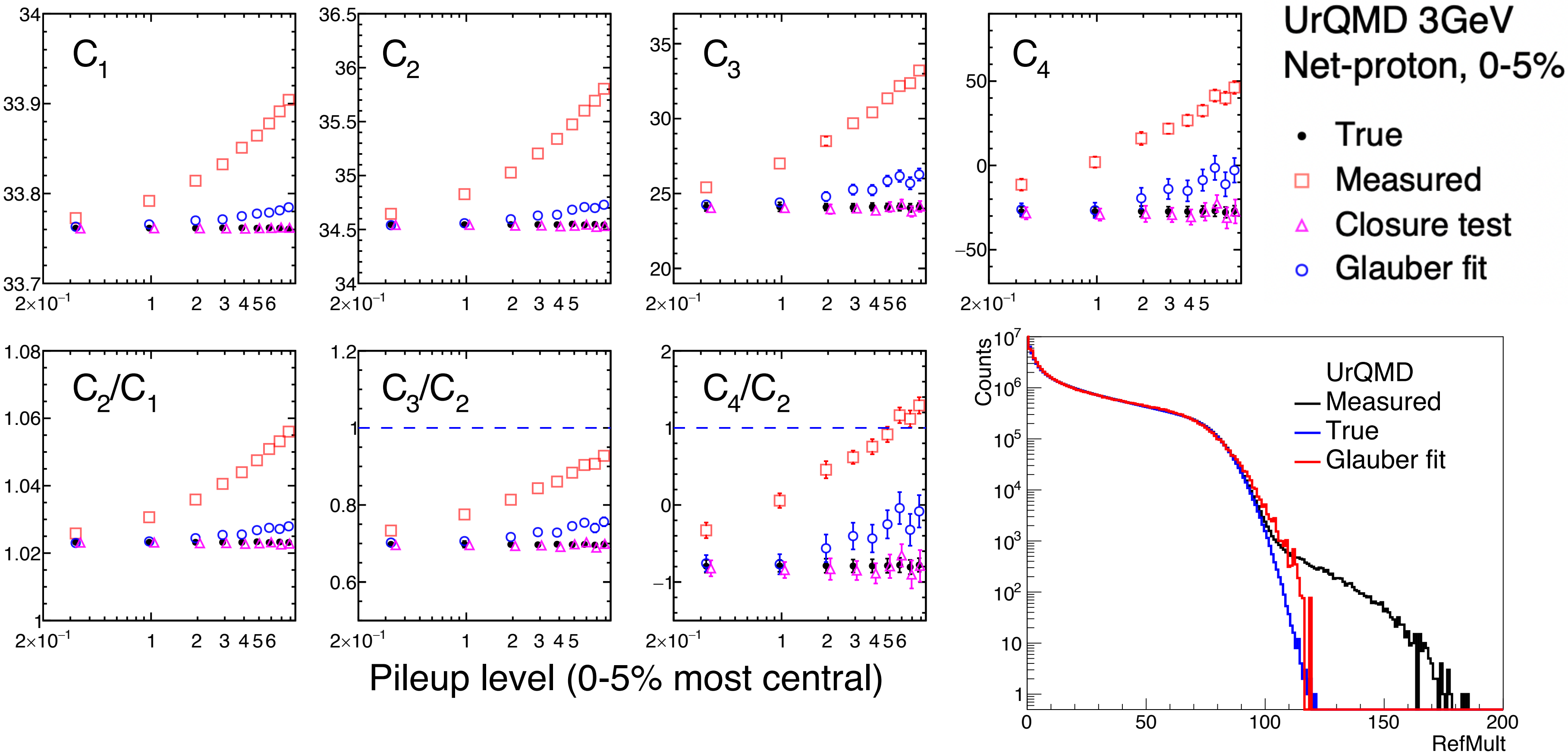
$$P_m(N) = (1-\alpha_m)P_m^{\rm t}(N) + \alpha_m P_m^{\rm pu}(N)$$

w/o pileup **pileup**

Unfolded single collision distribution at 3 GeV data

- Introduce pileup term in probability distribution
- With estimated pileup probability and single collision distribution, obtain pileup corrected cumulants analytically

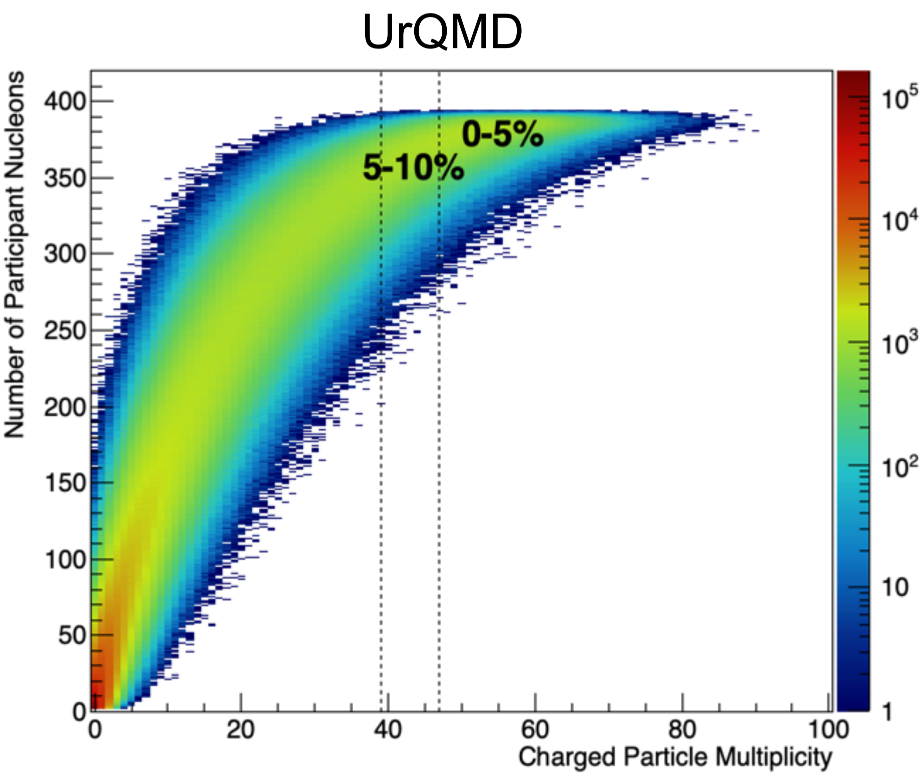
Pileup Correction closure test with UrQMD



- ➢ With well estimated pileup probability, cumulants can be well corrected
- ➢ The correction depends on the accuracy of estimation on pileup probability

Initial Volume Fluctuation and Correction

P. Braun-Munzinger, A. Rustamov, J. Stachel
arXiv:1612.00702



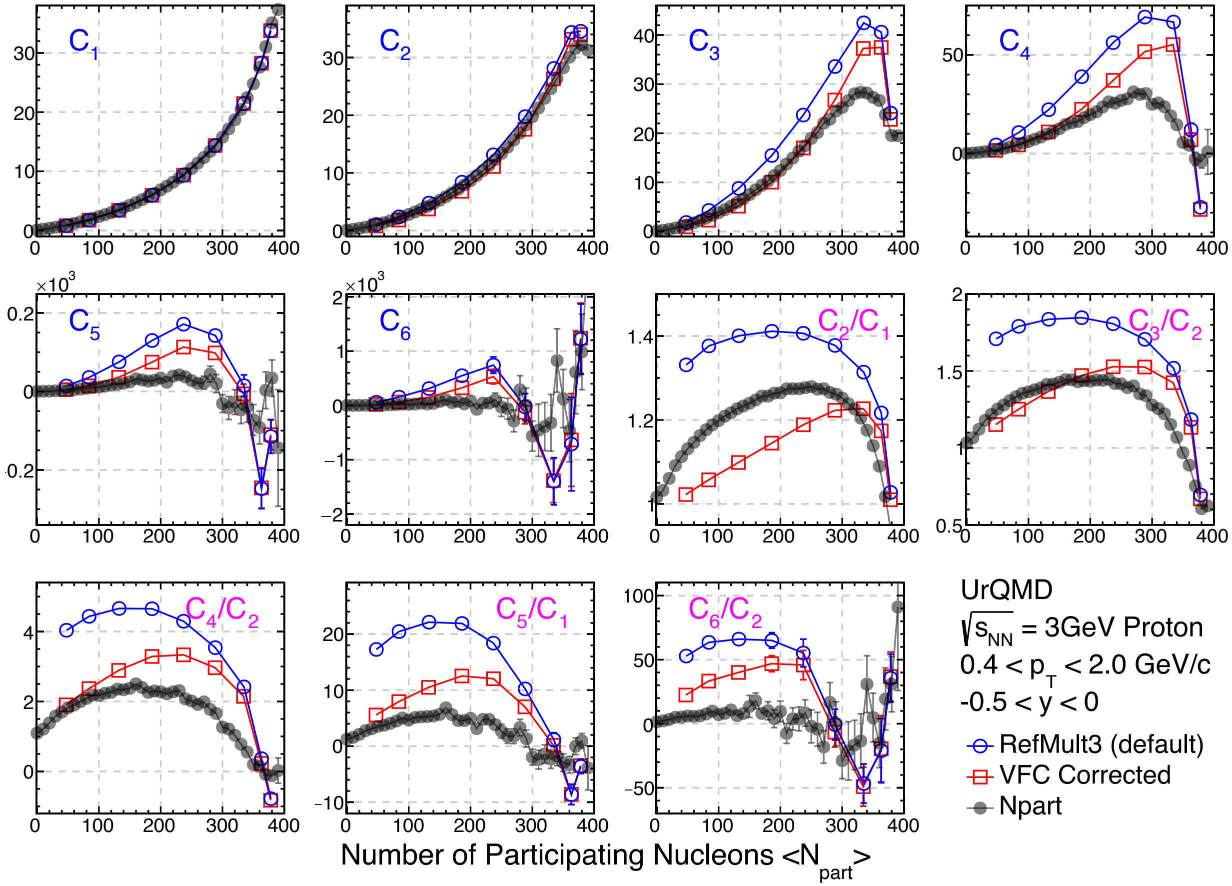
Assumption: wounded nucleon model: particle production is a superposition of **independent** contributions from wounded nucleons.

number of wounded nucleons

$$M_{\Delta N}(t) = \left[M_{\Delta n}(t)\right]^{N_W}$$

total moment generating function is then a product of generating function from **independent proton sources**

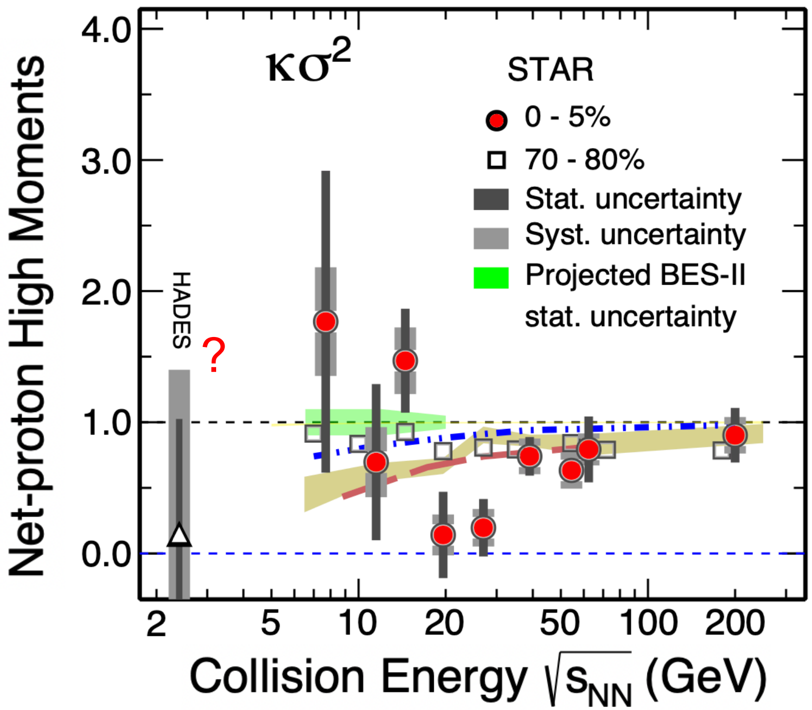
Volume fluctuation Correction (VFC) on UrQMD



- The correction strongly depends on input Npart distribution
- The assumption in VFC method might not be valid in data

Summary

1) Pileup correction and volume fluctuation correction tested on UrQMD; Application on data needs to be considered with caution.
2) Results from STAR $\sqrt{s_{NN}} = 3$ GeV are around the corner!



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

Thank you!