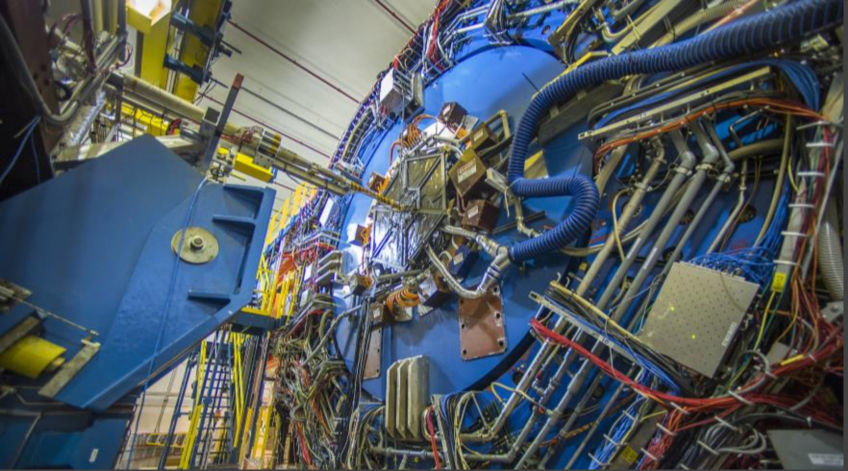
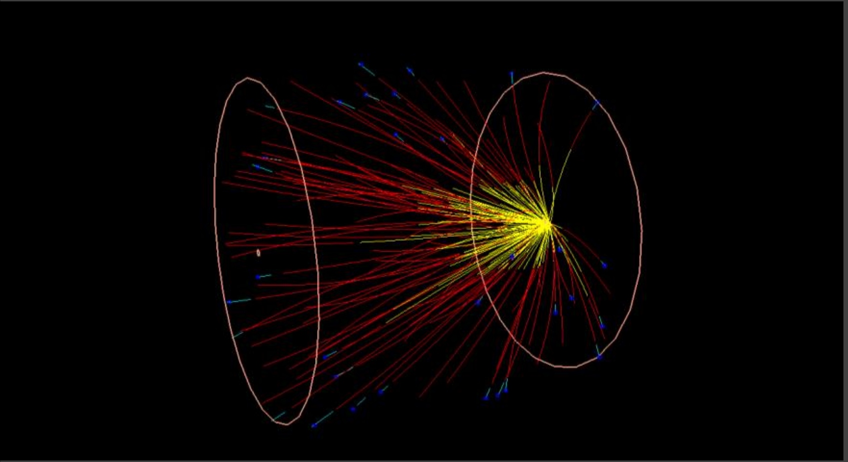
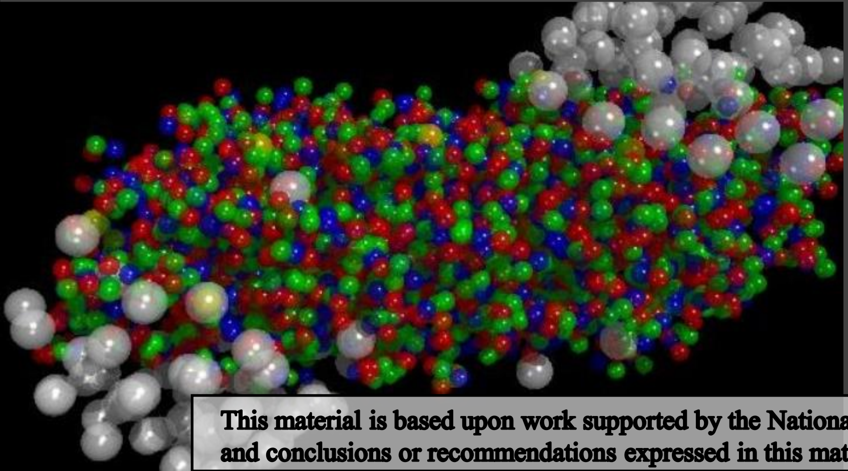
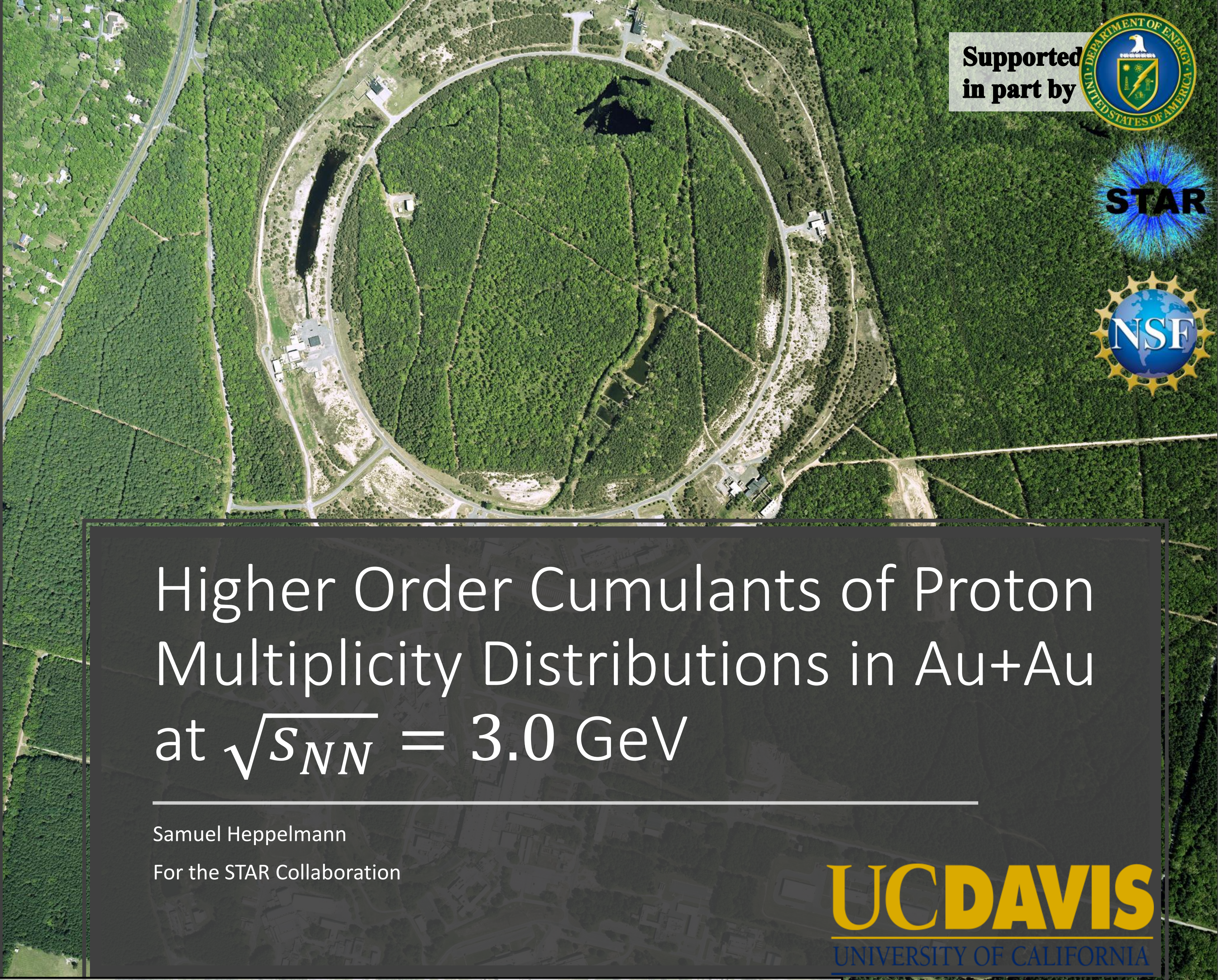








Higher Order Cumulants of Proton Multiplicity Distributions in Au+Au at $\sqrt{s_{NN}} = 3.0$ GeV

Samuel Heppelmann

For the STAR Collaboration

This material is based upon work supported by the National Science Foundation under Grant No. 1812398 (Cebra and Calderón de la Barca). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily represent the views of the National Science Foundation.

Outline

- Introduction
- Search for QCD critical point, C_4/C_2
- Data Analysis Methods

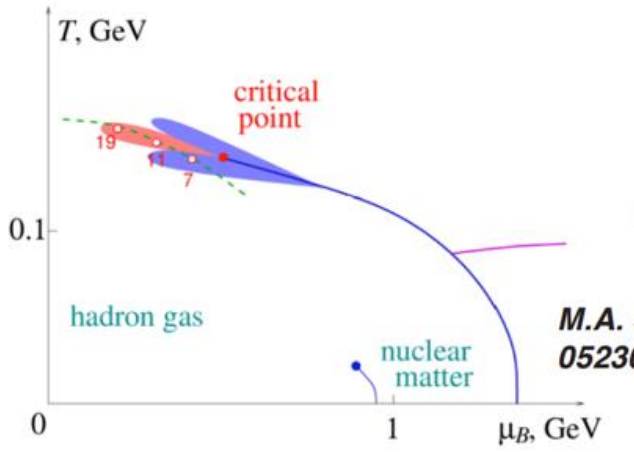
  Centrality Determination

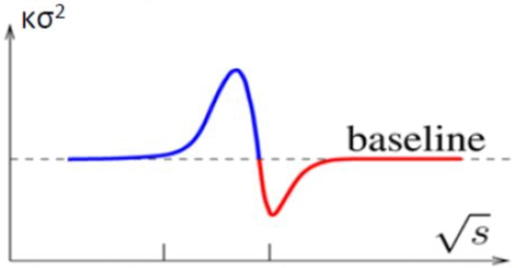
  Cumulant Corrections

  Pile Up
- Results
- Summary

Moments & Cumulants

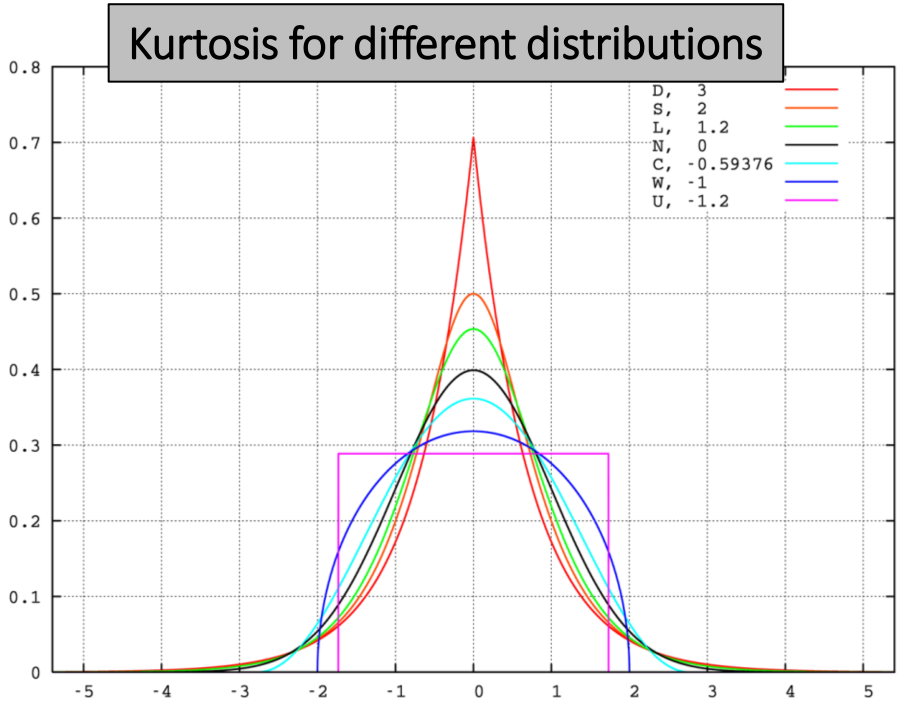
Look at the fluctuations of event-by-event observables:





M. Stephanov. J. Physics G.: Nucl. Part. Phys. ***38*** (2011) 124147

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



Cumulants are algebraic combinations of moments:

Cumulant generating function:

$$C(t) = \log E[e^{tX}]$$

where $E[e^{tX}]$ is the moment generating function

1st raw moment $m_1 = C_1$

2nd central moment $\mu_2 = C_2$

3rd central moment $\mu_3 = C_3$

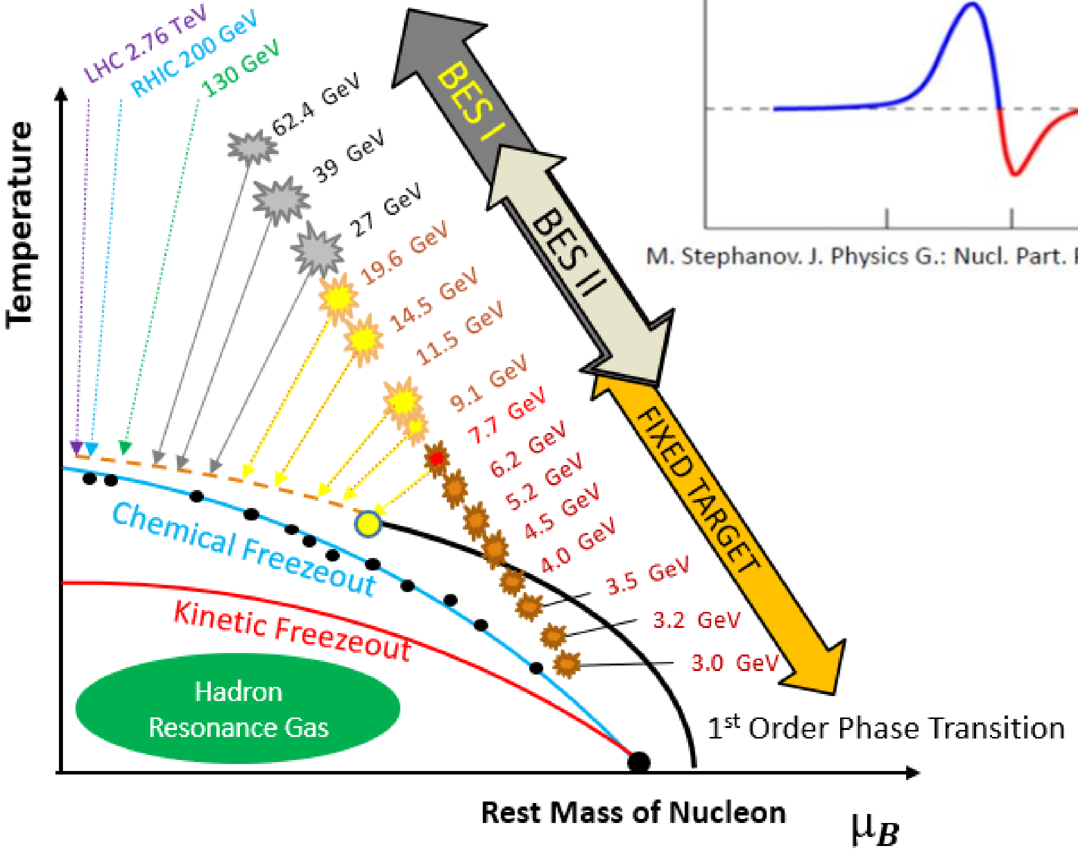
4th central moment $\mu_4 = C_4 + 3\,C_2^2$

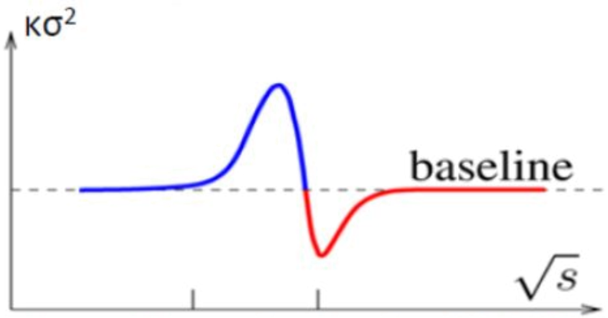
Normalized Moments *(Volume dependence is cancelled):*

$$\frac{\chi_q^4}{\chi_q^2} = \frac{C_4}{C_2} = \kappa\sigma^2$$

$$\frac{\chi_q^3}{\chi_q^2} = \frac{C_3}{C_2} = s\sigma$$

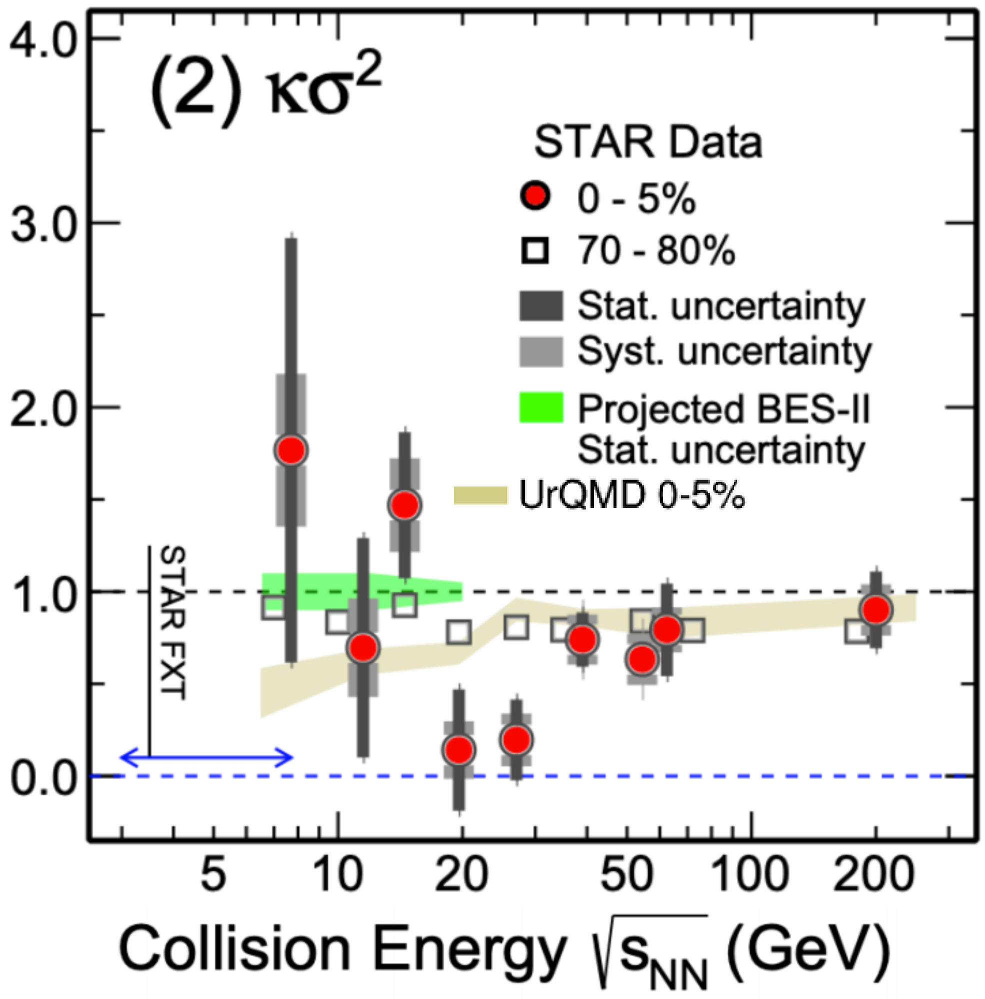
STAR Proton Measurements





M. Stephanov. J. Physics G.: Nucl. Part. Phys. ***38*** (2011) 124147

STAR Collaboration, arXiv:2001.02852



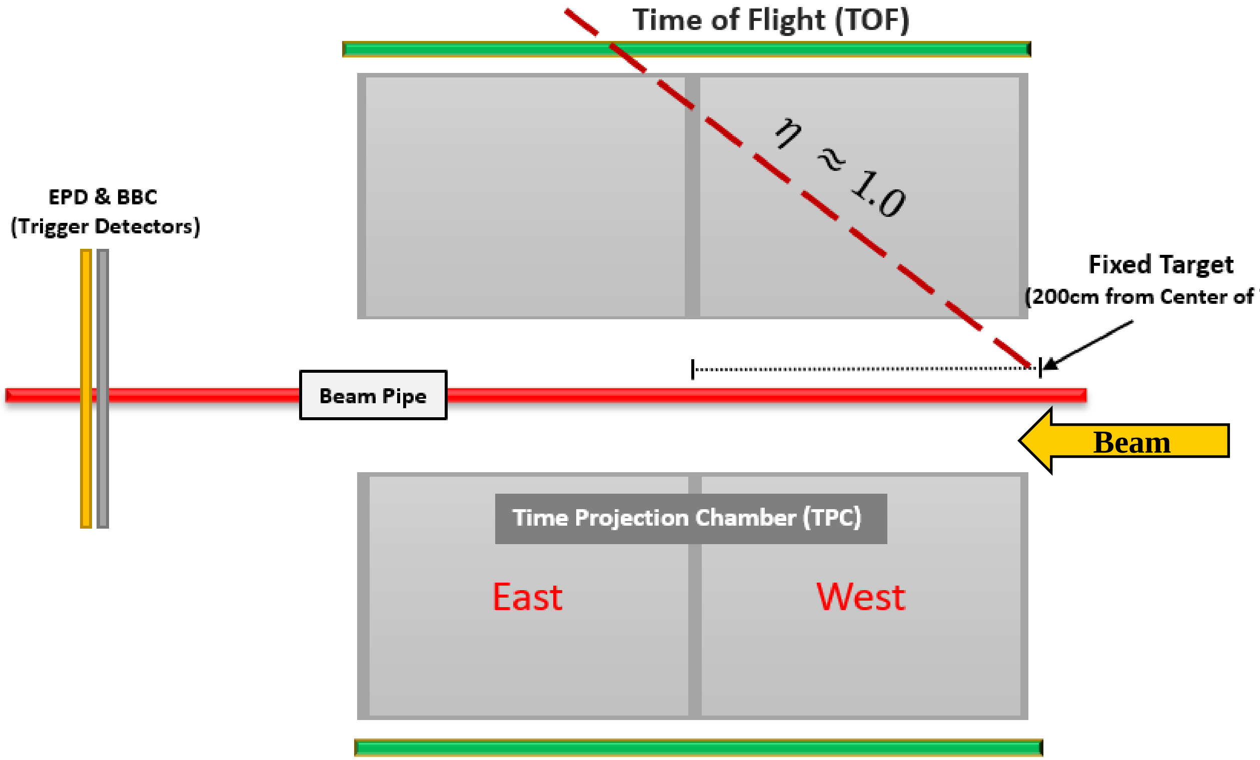
STAR measurements of net-proton $\kappa\sigma^2$ show a rising trend below 19.6 GeV

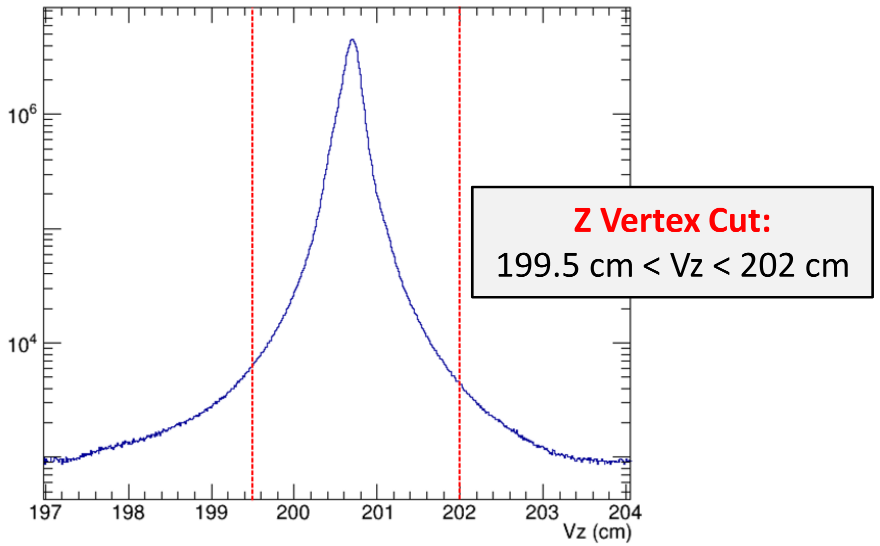
$\sqrt{s_{NN}}$ = 3.0 GeV is the lowest energy of the STAR Fixed Target Program

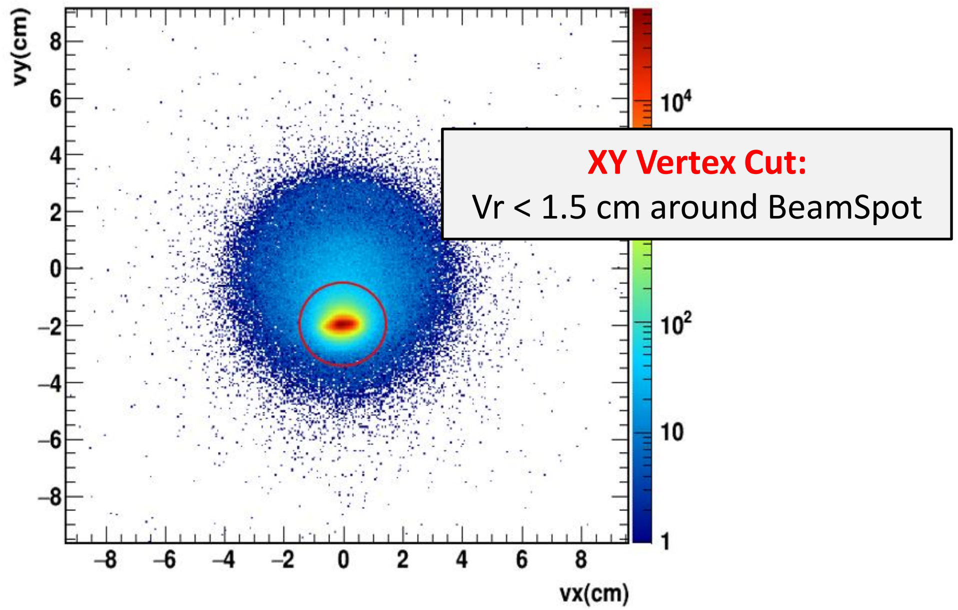
STAR Fixed Target

Mid-rapidity for $\sqrt{s_{NN}} = 3.0$ GeV is y = 1.049

Acceptance diagram of Detectors used in Higher Moments analysis for Fixed Target $\sqrt{s_{NN}} = 3.0$ GeV







Events/Triggers (Taken in 2018):

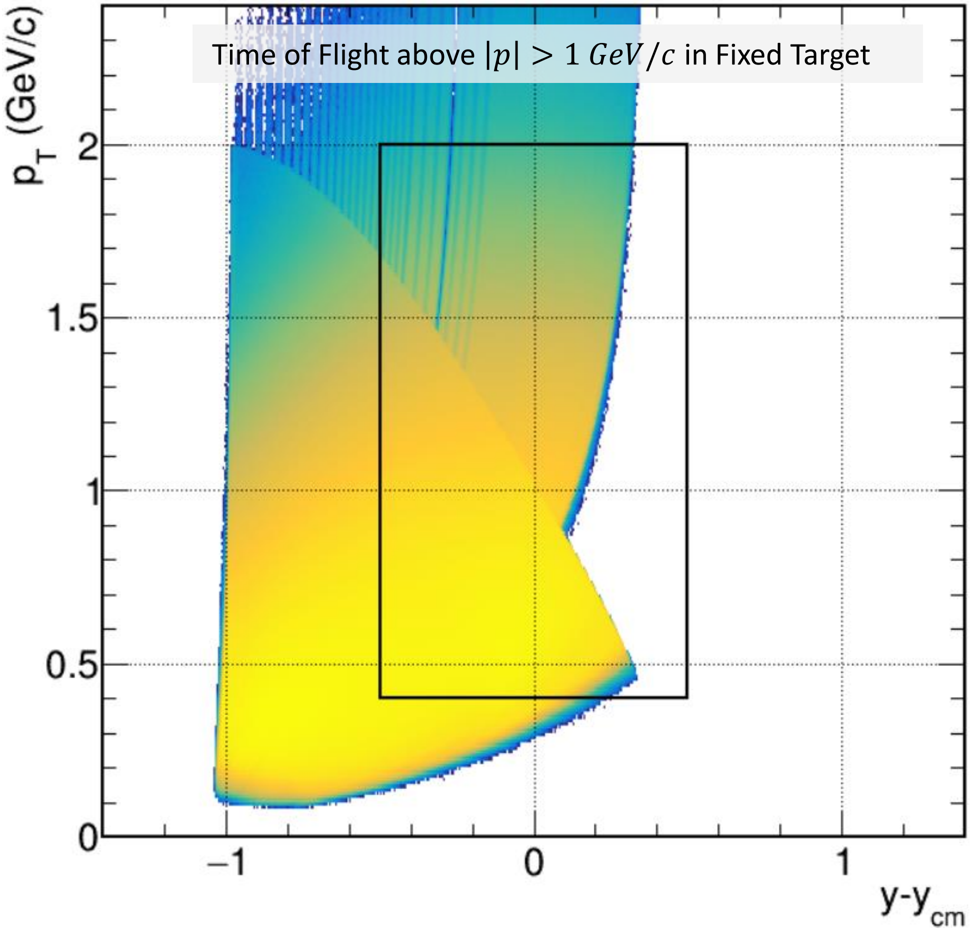
No Cuts	After Event & Run Cuts
320M	140M

Beam direction indicates positive rapidity

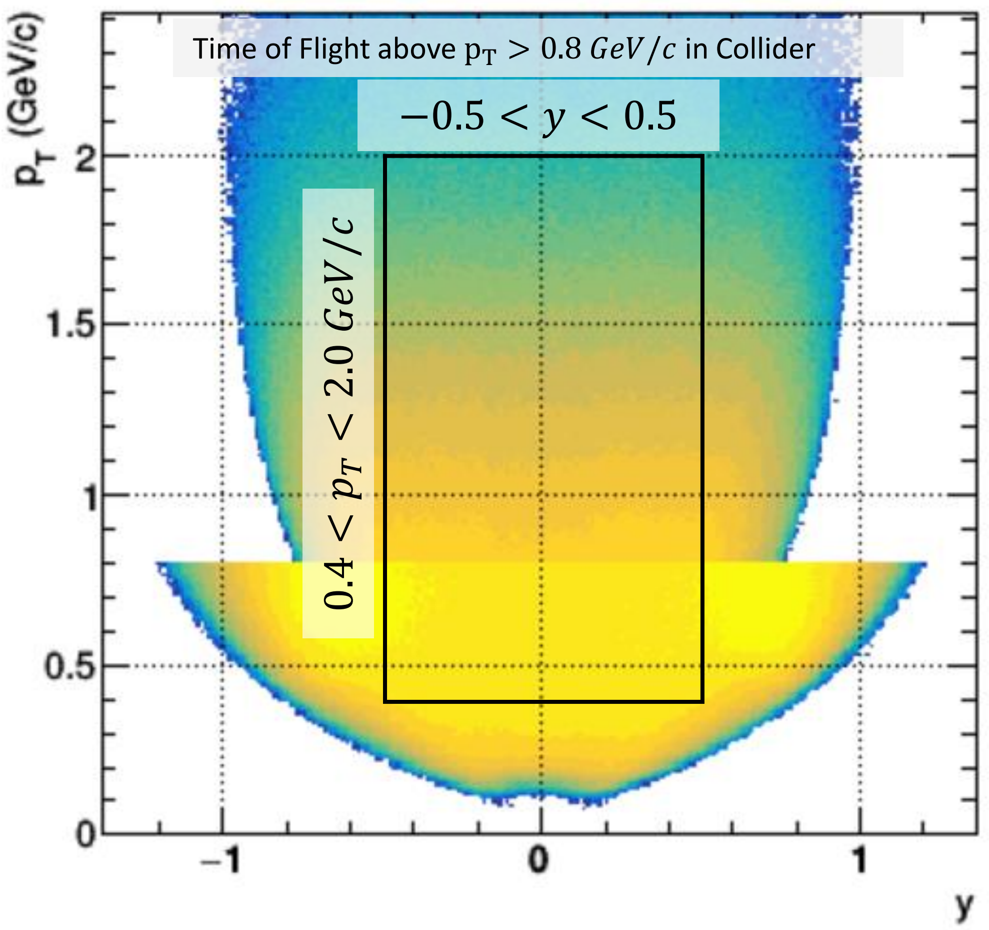
Fixed Target rapidity is reversed from typical collider running conditions

Acceptance Comparison with STAR Collider $\sqrt{s_{NN}} = 7.7$ GeV

$\sqrt{s_{NN}} = 3.0$ GeV Fixed Target Acceptance



$\sqrt{s_{NN}} = 7.7$ GeV Collider Acceptance



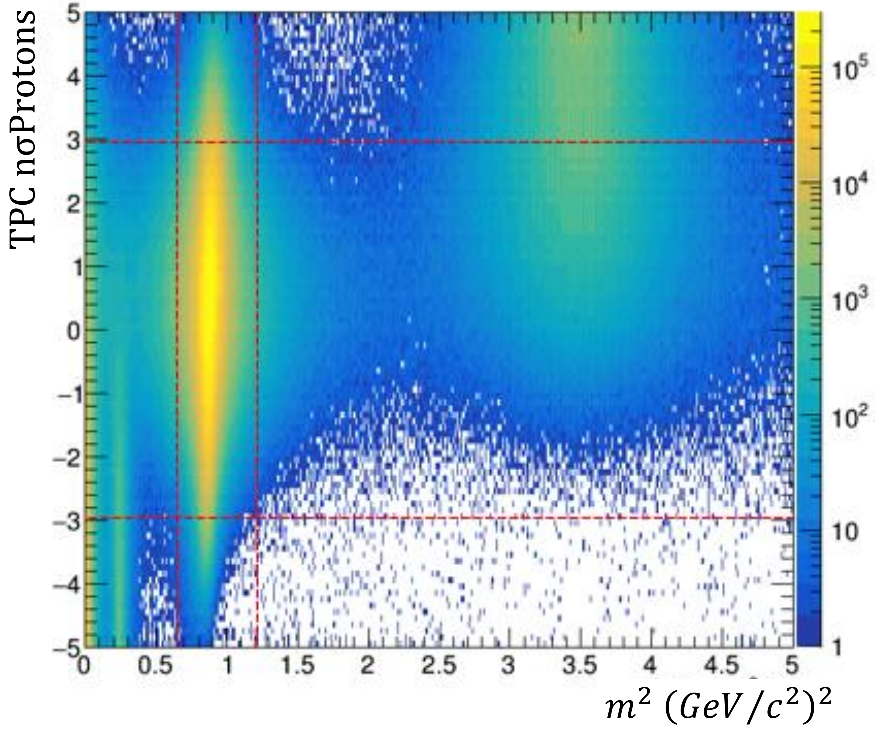
Black Box indicates analysis window of $\sqrt{s_{NN}} = 7.7$ GeV

Analysis Window

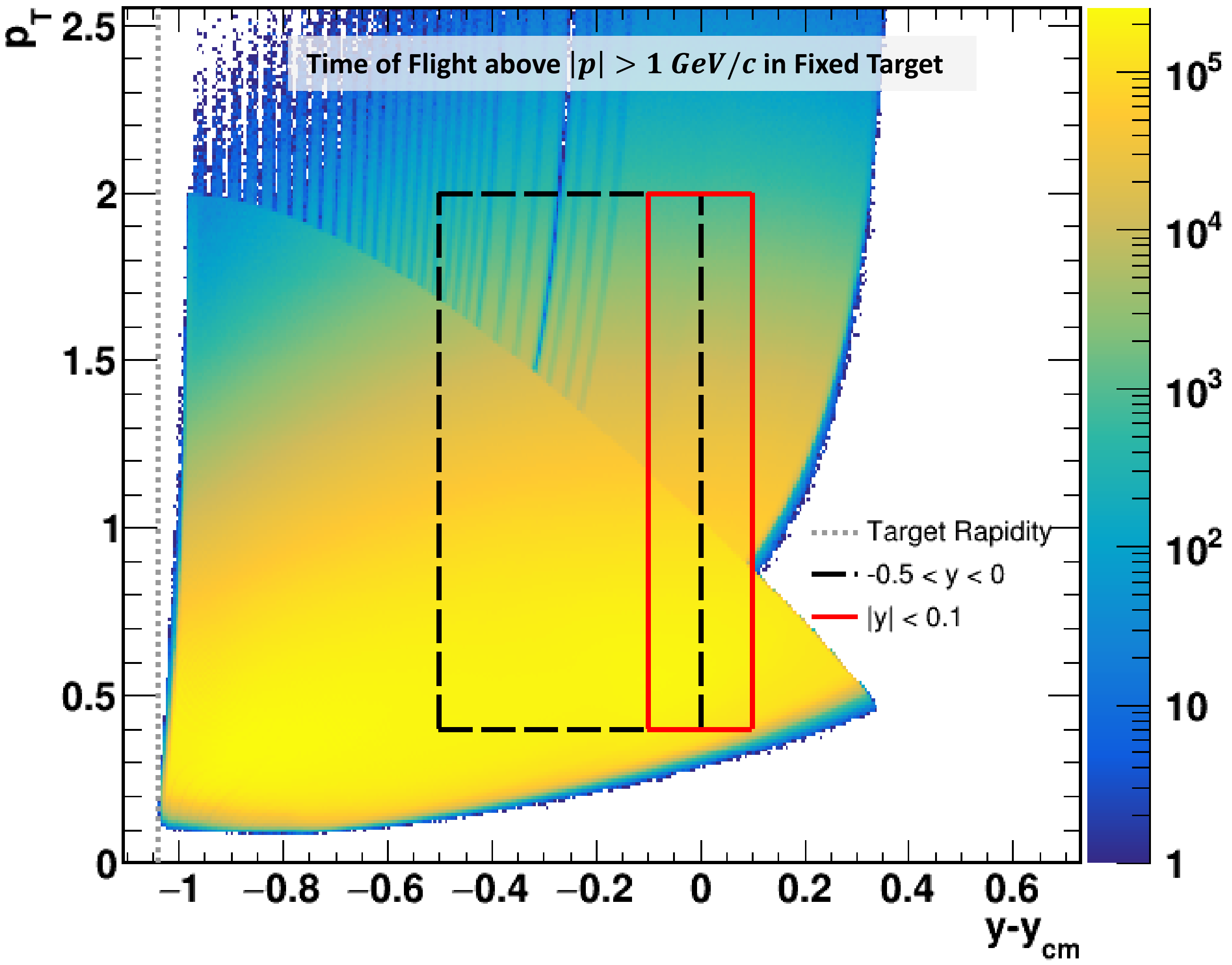
Previous STAR analysis: |y| < 0.5

Asymmetric window:
-0.5 < y < 0
$0.4 < p_T < 2.0\ (GeV/c)$

Symmetric Window:
|y| < 0.1
$0.4 < p_T < 2.0\ (GeV/c)$



Particle ID: $0.6 < m^2 < 1.2\ (GeV/c^2)^2$
$|n\sigma Protons| < 3$

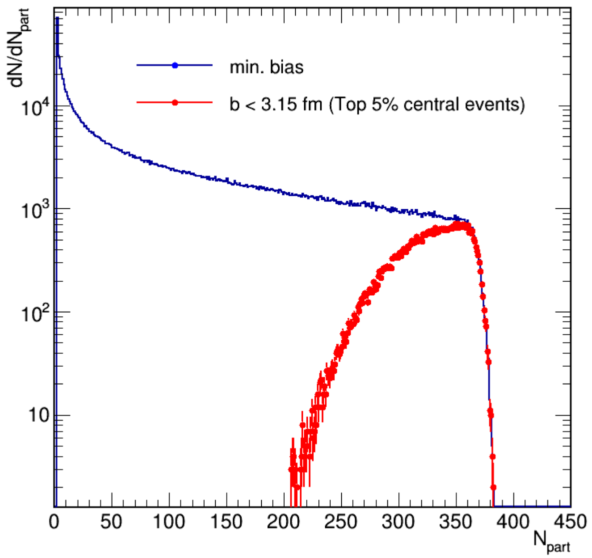


TPC + TOF analysis cuts provide ~97% proton purity

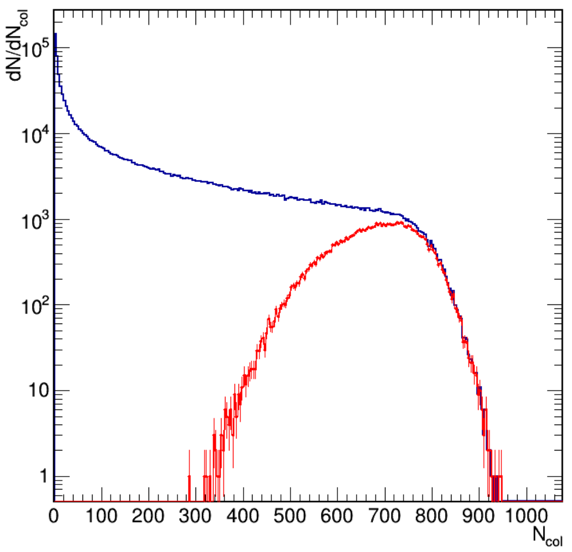
Centrality Determination

MC Glauber Model Simulation

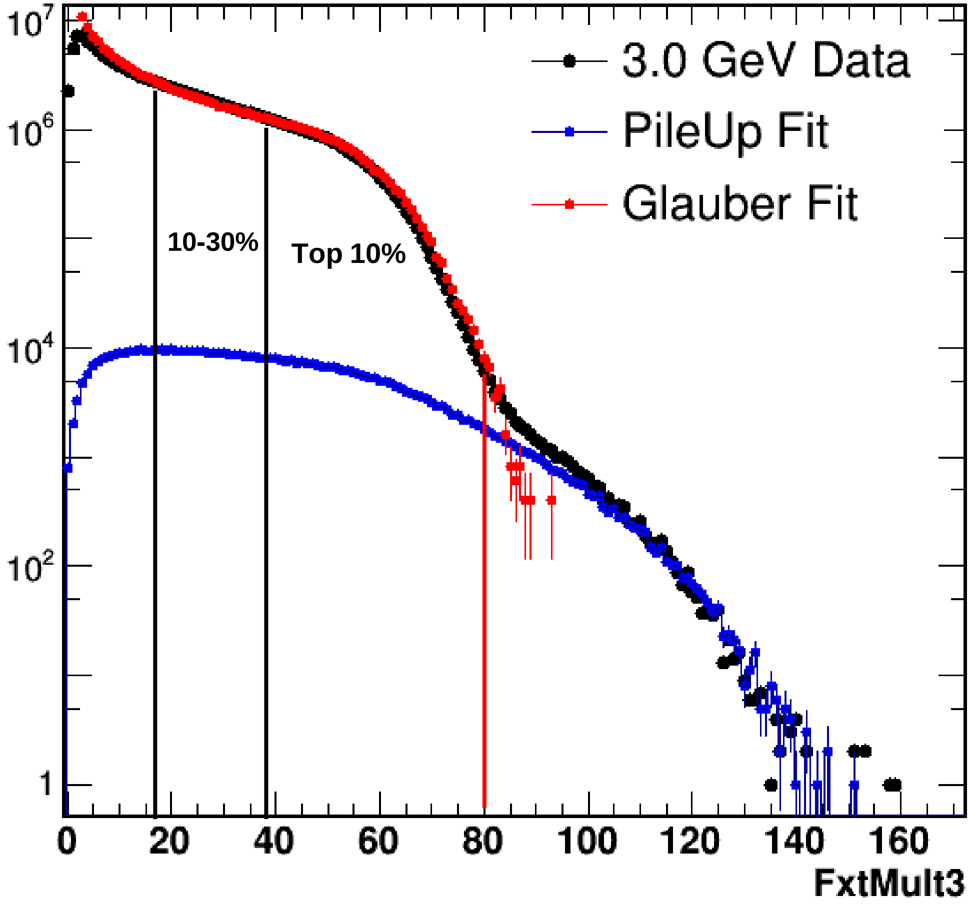
N Binary Collisions



N Participants



Exclude Multiplicities above 80 to exclude pile up.



Fit FxtMult3 with MC Glauber Sim. + Negative Binomial Fit

Use TPC particle multiplicity (excluding protons) to determine centrality

Exclude protons tracks to decrease auto-correlation in proton signal

FxtMult

All TPC tracks in the Fixed Target acceptance ($\eta \sim [0,2]$)

Typical STAR collider reference multiplicity, RefMult ($\eta \sim [-1,1]$)

FxtMult3

All TPC tracks in the Fixed Target acceptance excluding protons

Cumulant Analysis Corrections

Detector Efficiency Correction

Nonaka, Kitazawa, Esumi : PRC95 (2017) 064912

Xiaofeng Luo, Toshihiro Nonaka, PhysRevC.99.044917

Take binomial detector efficiency correction and assume infinite efficiency bins, the bivariate cumulant is:

$$q_{(r,s)} = \sum_{i=1}^{\infty} (a_i^r / \varepsilon_i^s) n_i$$

Centrality Bin Width Correction

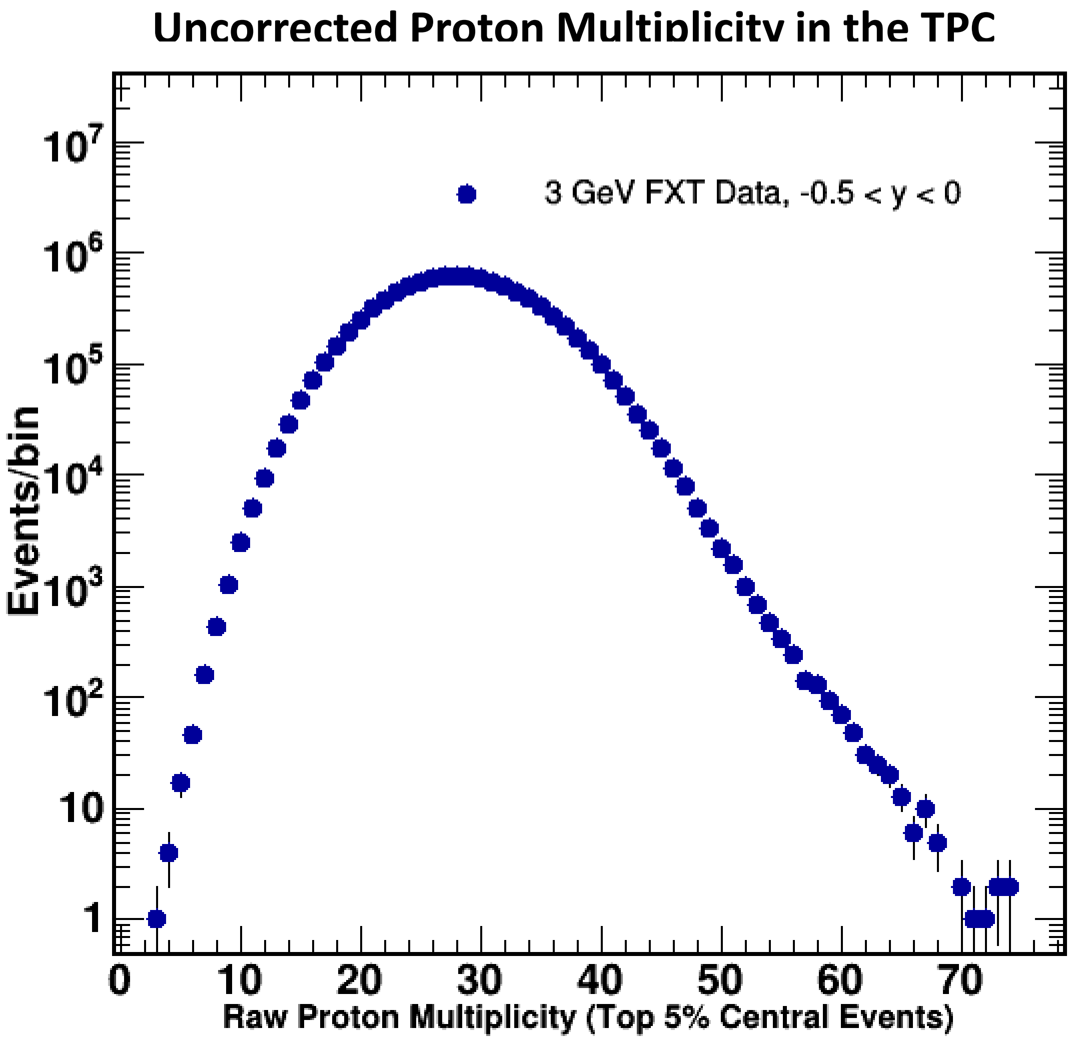
Xiaofeng Luo *et al* 2013 *J. Phys. G: Nucl. Part. Phys.* **40** 105104

Reduce the effect of volume fluctuations by using a weighted average:

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

$$\omega_r = \frac{n_r}{\sum n_r}$$ *bin weight*

Pile Up Correction *(following slides)*



Single Track Efficiency Correction

Binomial Detector Efficiency Correction

Assume a binomial efficiency $B_{p,N}(n)$ and a true net-proton distribution is $P(N)$ and the measured distribution is $\widetilde{P}(N)$.

$$\widetilde{P}(N) = \sum_{N} P(N) B_{p,N}(n)$$

With binomial detector response

$$B_{p,N}(n) = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n}$$

Can construct relation between measured factorial cumulants $\langle n^m \rangle_{fc}$ and true factorial cumulants

$$\langle n^m \rangle_{fc} = p^m \langle N^m \rangle_{fc}$$

Track-by-track Efficiency Correction

Xiaofeng Luo, Toshihiro Nonaka, PhysRevC.99.044917

Take binomial detector efficiency correction and assume infinite efficiency bins, the bivariate cumulant is:

$$q_{(r,s)} = \sum_{i=1}^{\infty} (a_i^r / \varepsilon_i^s) n_i$$

where i is the efficiency bin index, a_i is the charge of the particle, ε_i is the track's efficiency and n_i is the number of particles in the efficiency bin ($n_i = 1$ as efficiency bins $\rightarrow \infty$).

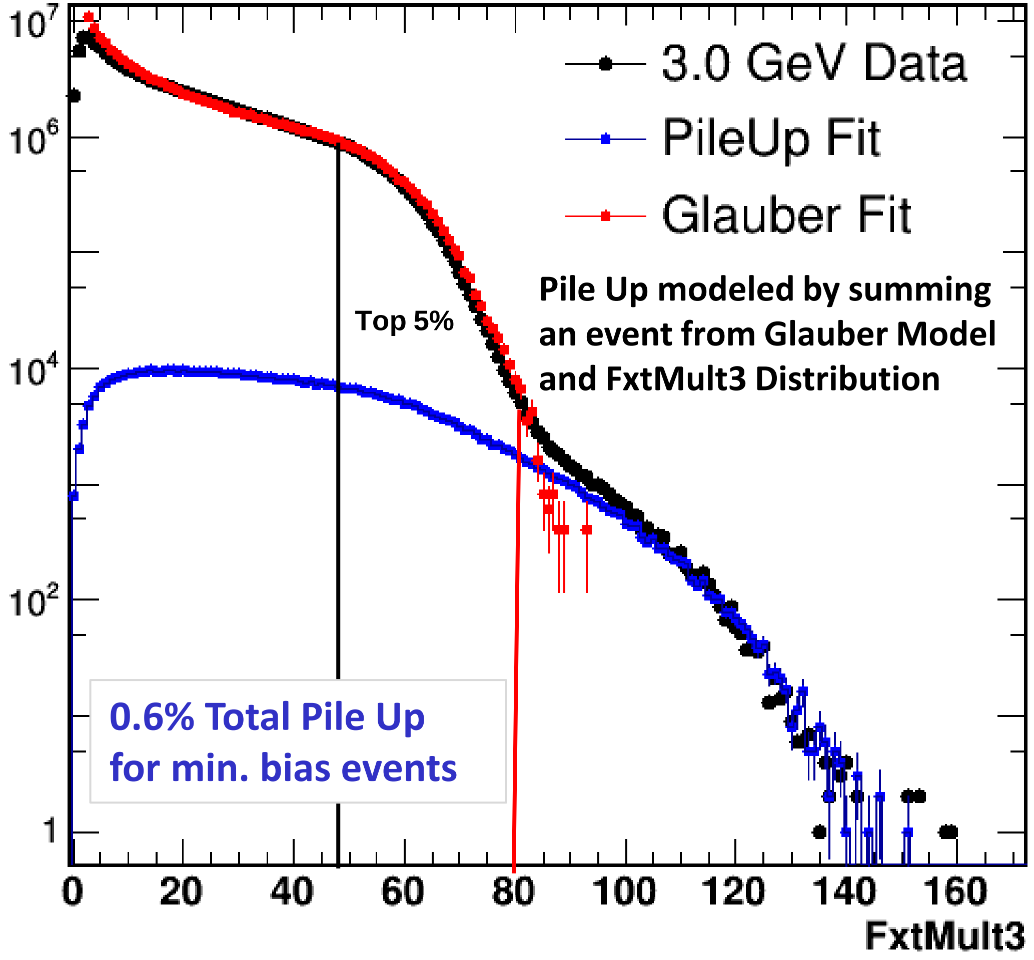
Statistical Errors

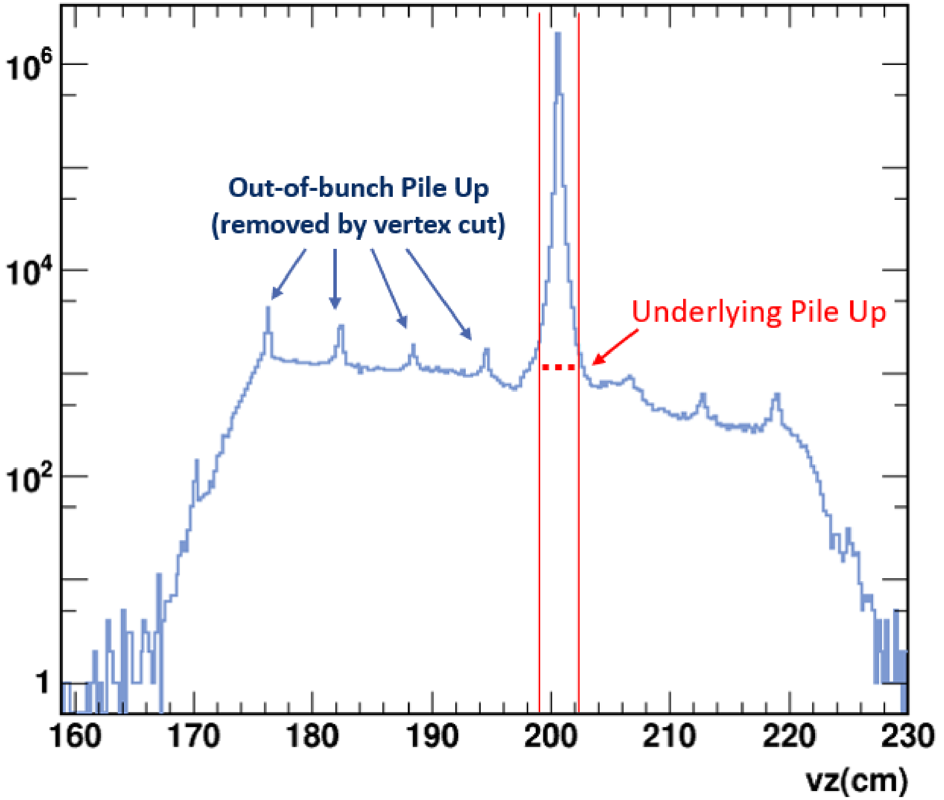
Statistical errors are calculated with a bootstrap method. Analysis is resampled ~200 times, and standard deviation of the sample provides statistical error.

Pile Up in the Fixed Target

Background Pile Up

- Two events reconstructed as one event
- Less than 1% Pile Up Background in STAR Fixed Target Run18



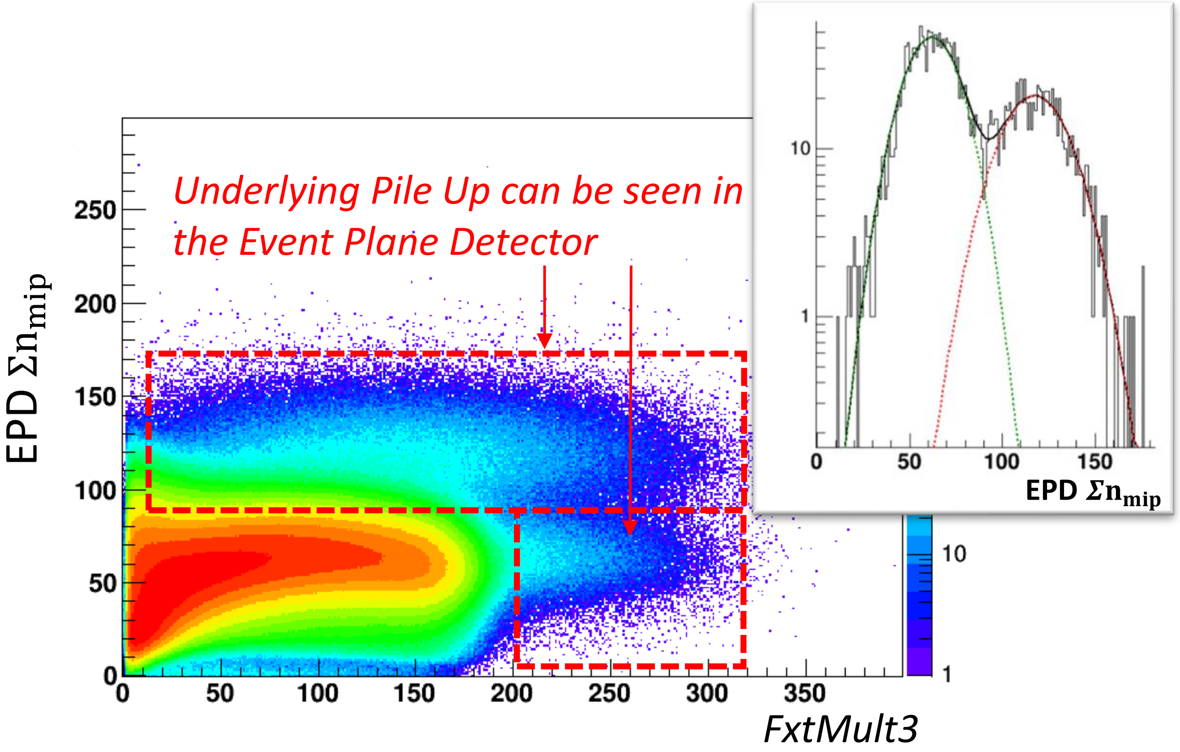


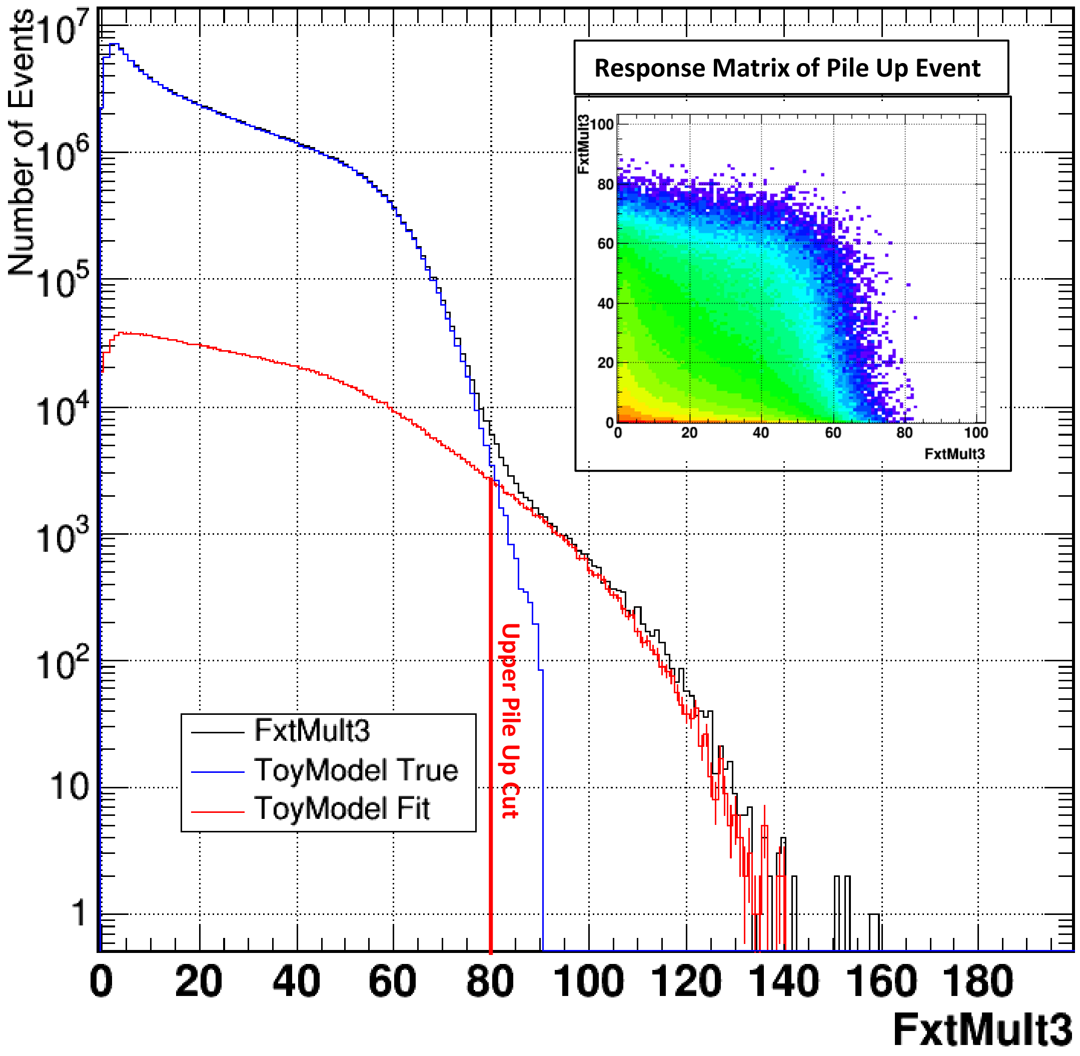
- Pile Up from the different bunches can be significantly reduced by vertex cuts
- Pile Up from the same bunch is more difficult to remove without altering the true proton moments

Pile Up Correction

Pile Up Correction requires underlying pileup distribution.

Rely on pile up fits in EPD (Event Plane Detector) and fits to FxtMult3 multiplicity distribution





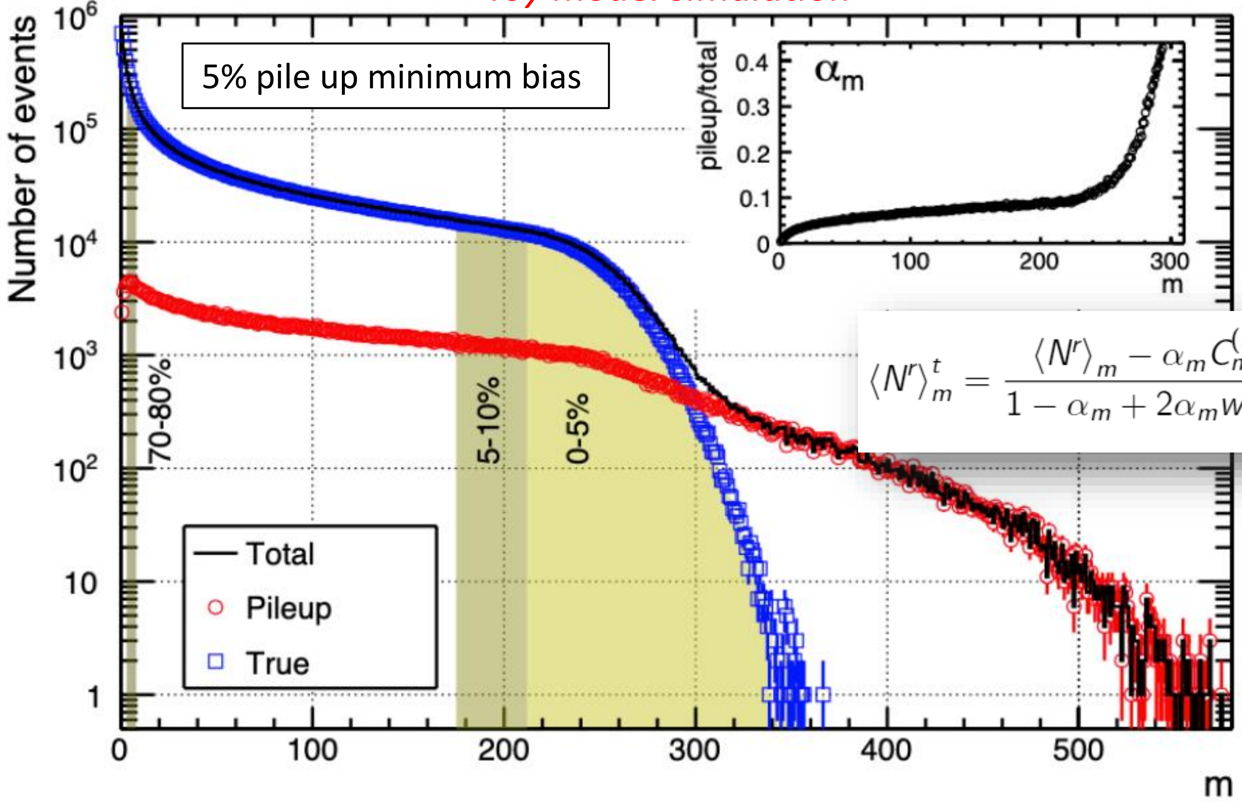
Compare to UrQMD pileup estimate for Systematic Uncertainty of Correction

Pile Up Correction

Data driven approach to correct for pile up.

Account for pile up (sum of two events) and remove pileup cumulants from true cumulants.

Toy model simulation

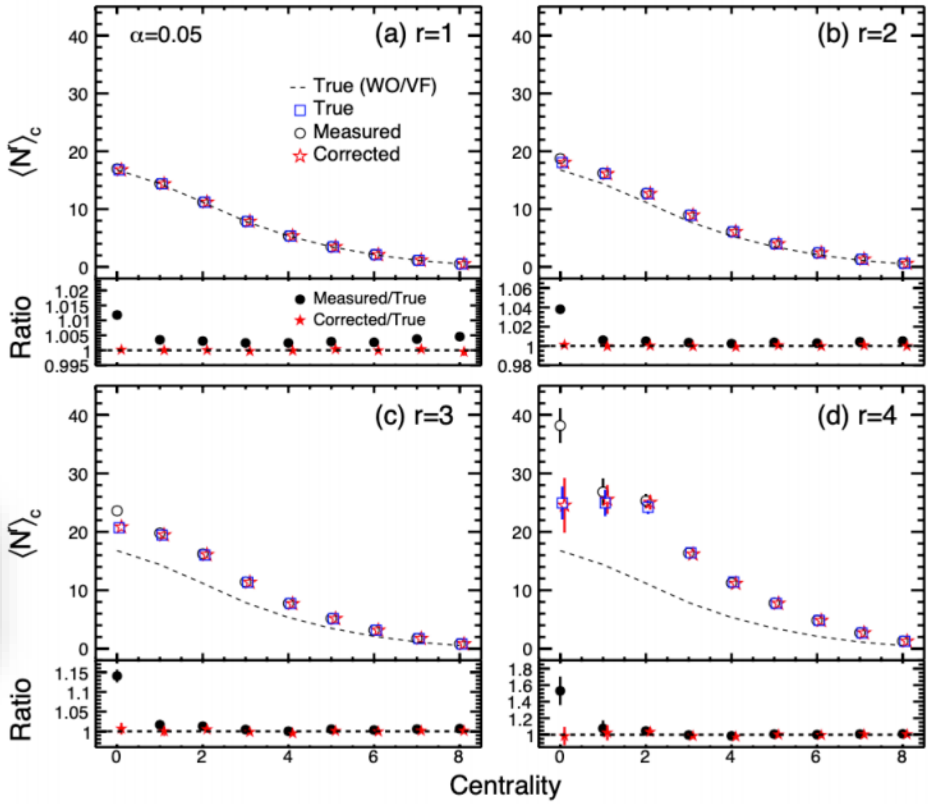


$$\langle N^r \rangle^t_m = \frac{\langle N^r \rangle_m - \alpha_m C^{(r)}_m}{1 - \alpha_m + 2\alpha_m w_{m,0}}$$

T. Nonaka, M. Kitazawa, S. Esumi,
Nucl. Instrumental. Meth. A 984, 164632 (2020)

Toy model simulation

Centrality bins, 0-5%,5-10%,10-20%,…,78-80% respectively indices x=0,1,…,8



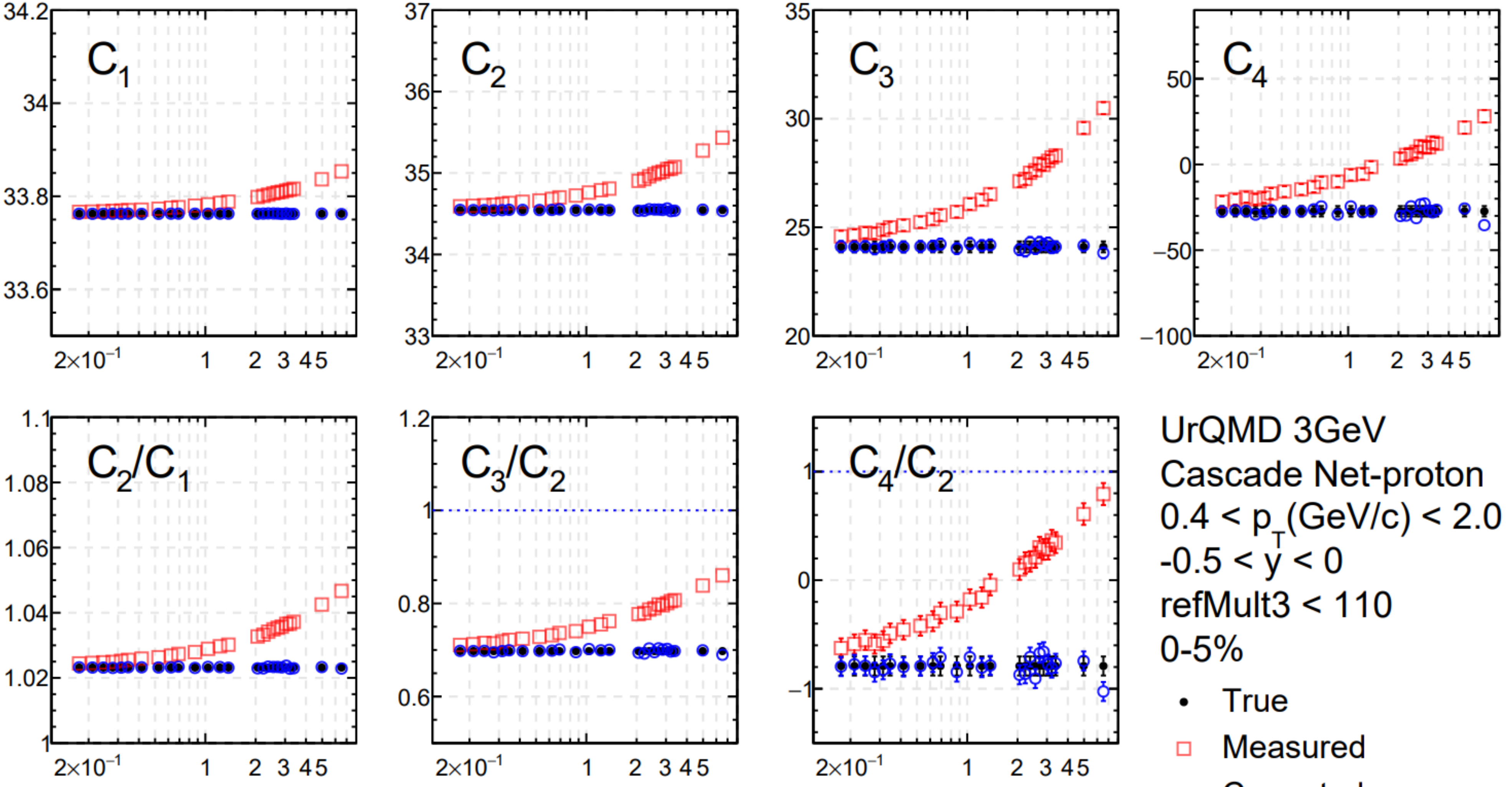
Measured proton distribution for a given multiplicity m is comprised of the true distribution and a pile up distribution:

$$P_m(N) = (1 - \alpha_m) P^t_m(N) + \alpha P^{pu}_m(N) \quad (1)$$

where α is the pileup fraction, $P^t_m(N)$ is the true proton distribution and $P^{pu}_m(N)$ is the pileup proton distribution.

UrQMD Pile Up Correction

UrQMD + Pile Up returns to true C_4/C_2 after pile up correction (reliable to 5% pile up)

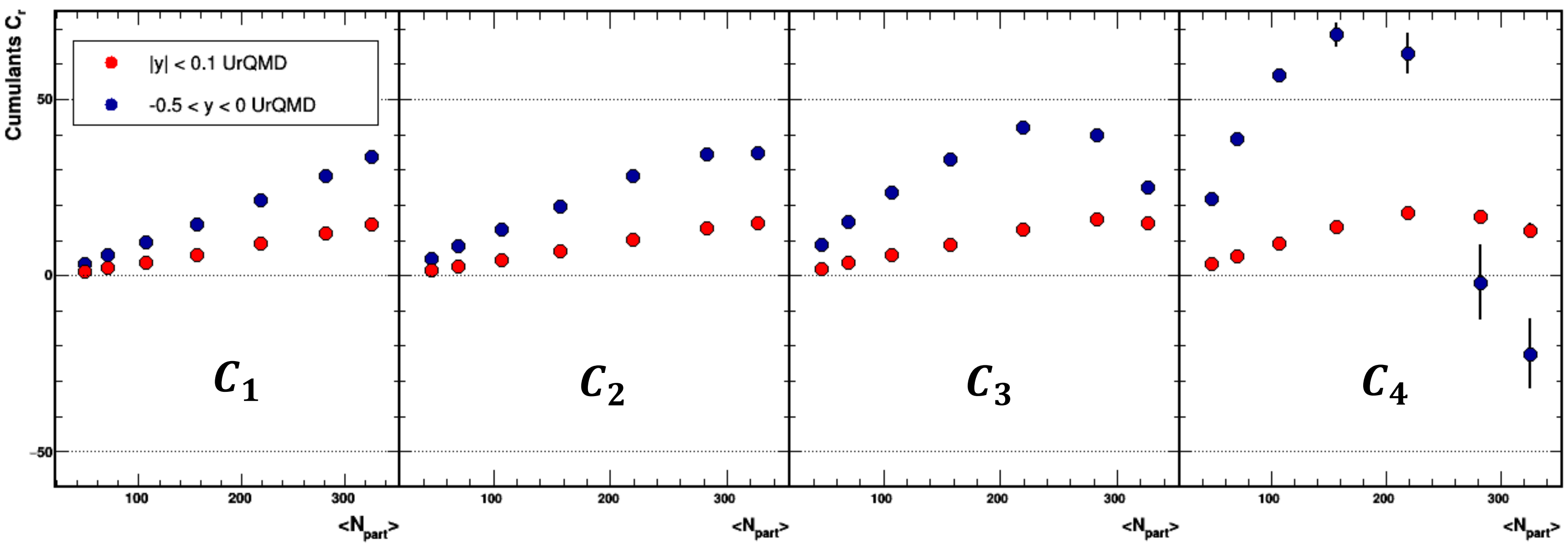


Percent Pile Up in Central Events (0-5%)

Net Proton Cumulants

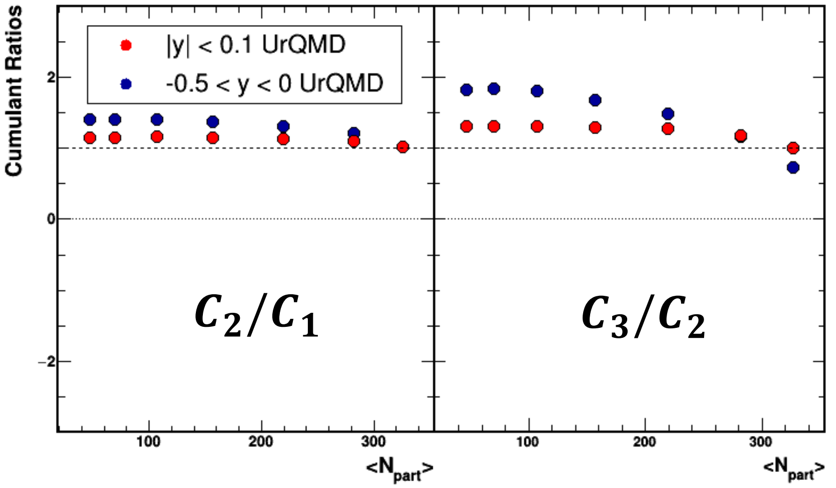
UrQMD C_4/C_2 suggests large suppression is caused by baryon conservation

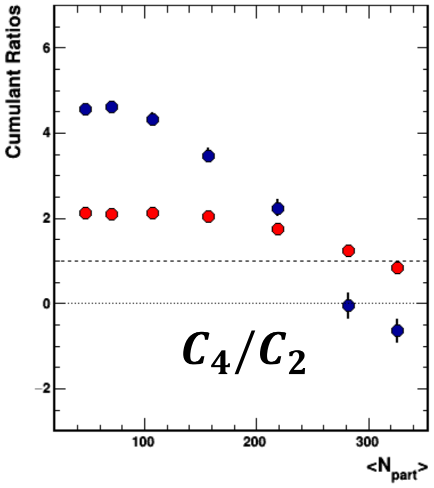
Signal returns to Poisson baseline when rapidity window is reduced to |y| < 0.1



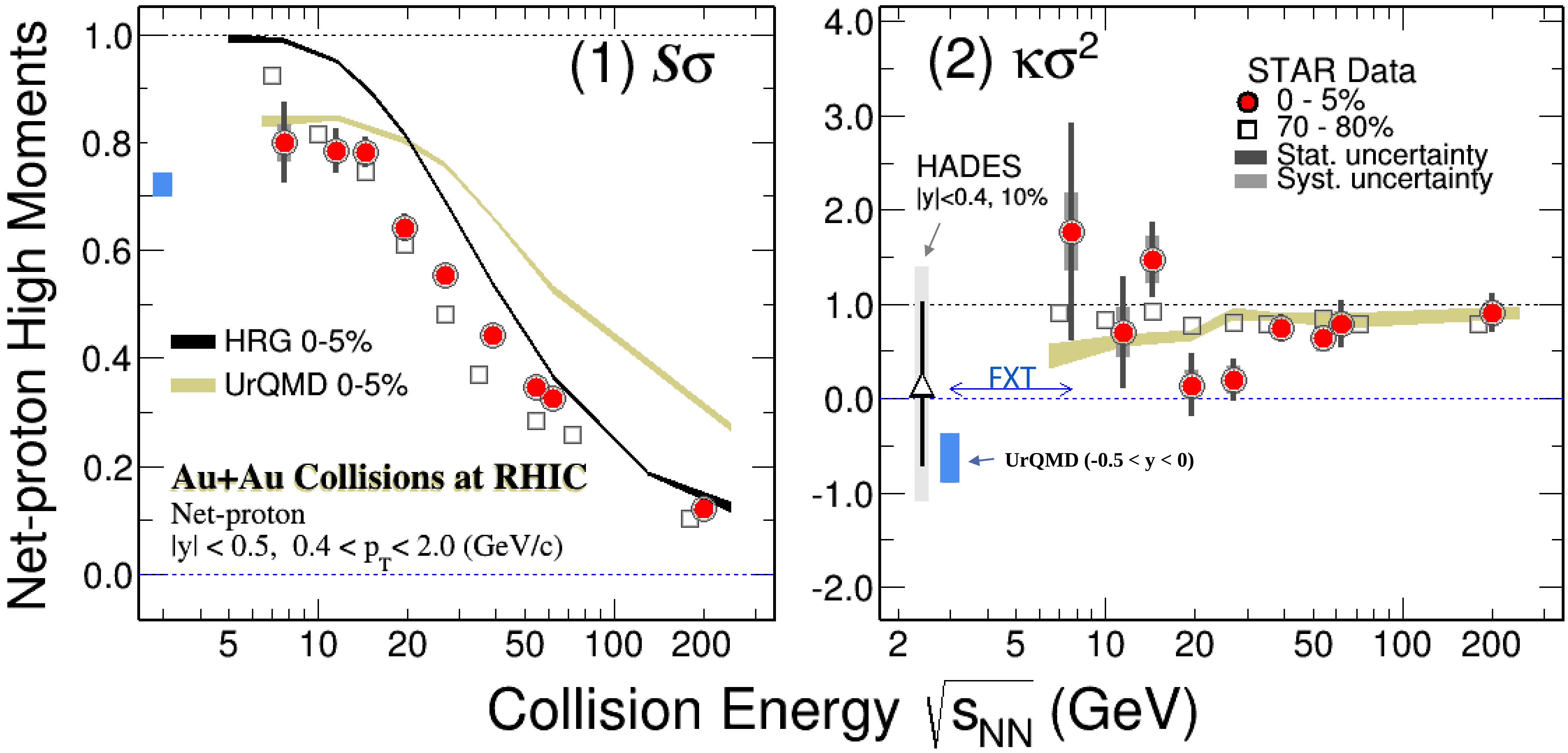
Non-Poisson signal could be sign of volume fluctuations in more peripheral centrality bins

Arghya Chatterjee, Yu Zhang, Hui Liu, Ruiqin Wang, Shu He, Xiaofeng Luo, arXiv:2009.03755 [nucl-ex]





STAR Net-Proton Energy Scan



BES I Data from $\sqrt{s_{NN}} = 7.7$ to 200 GeV in: STAR Collaboration, arXiv:2001.02852

Summary

Summary:
UrQMD suggests large suppression is caused by baryon conservation

UrQMD's $K\sigma^2$ supports the oscillation structure from the first STAR Beam Energy Scan.

Oscillation structure suggests critical behavior within the energy range.

OutLook:
The STAR Beam Energy Scan II and 2019 Fixed Target data will provide definite answer if critical behavior exists between $\sqrt{s_{NN}} = 3.0$ GeV and $\sqrt{s_{NN}} = 19.6$ GeV energy range