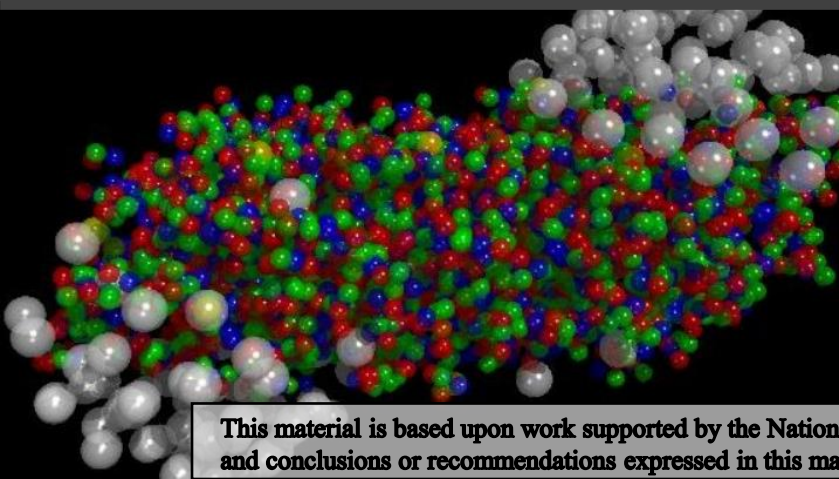
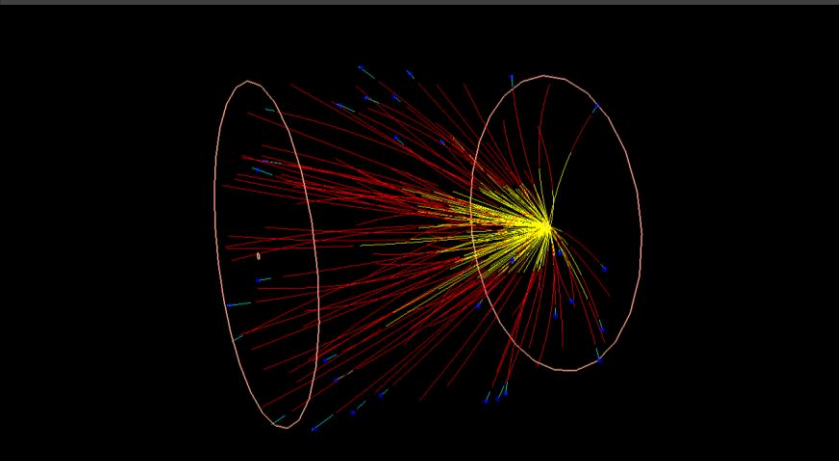
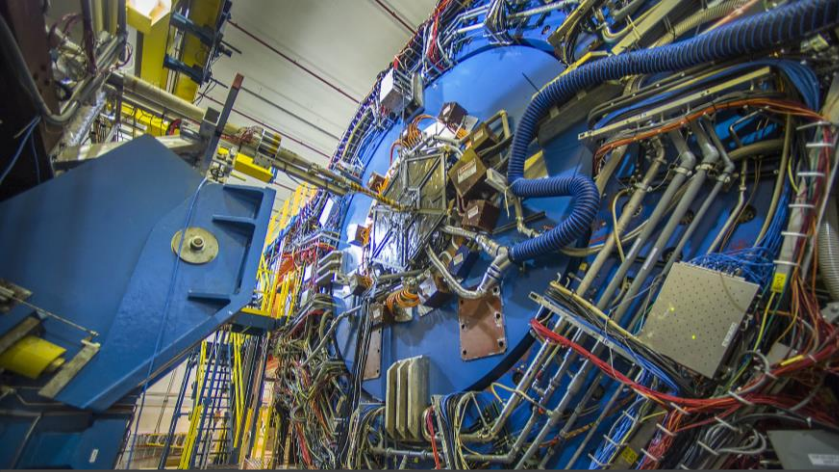




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# Higher Order Cumulants of Proton Multiplicity Distributions in Au+Au at $\sqrt{s_{NN}} = 3.0$ GeV

Samuel Heppelmann

For the STAR Collaboration

**UC DAVIS**  
UNIVERSITY OF CALIFORNIA

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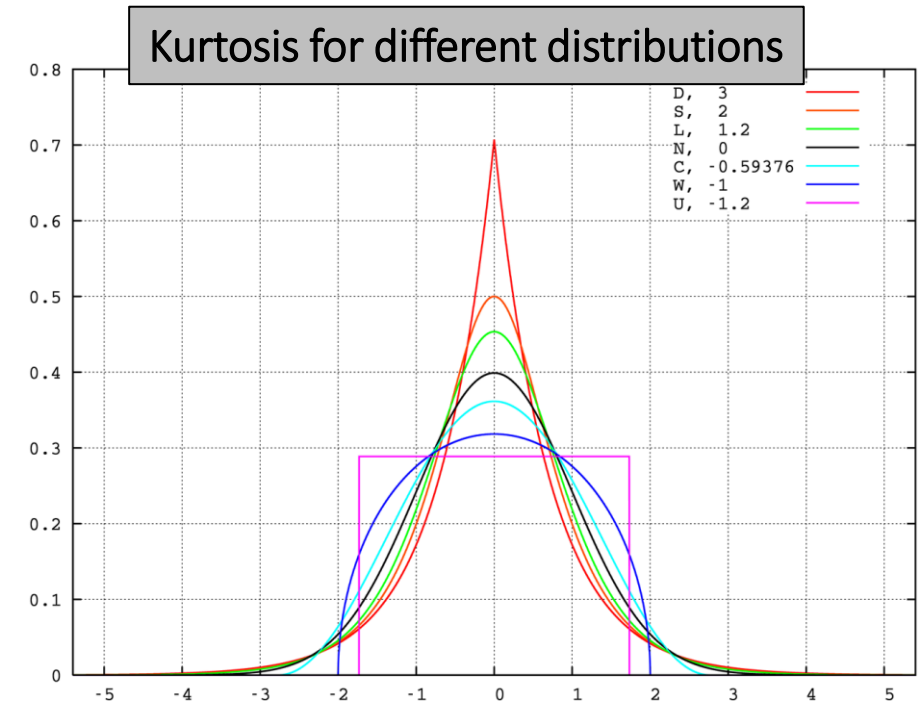
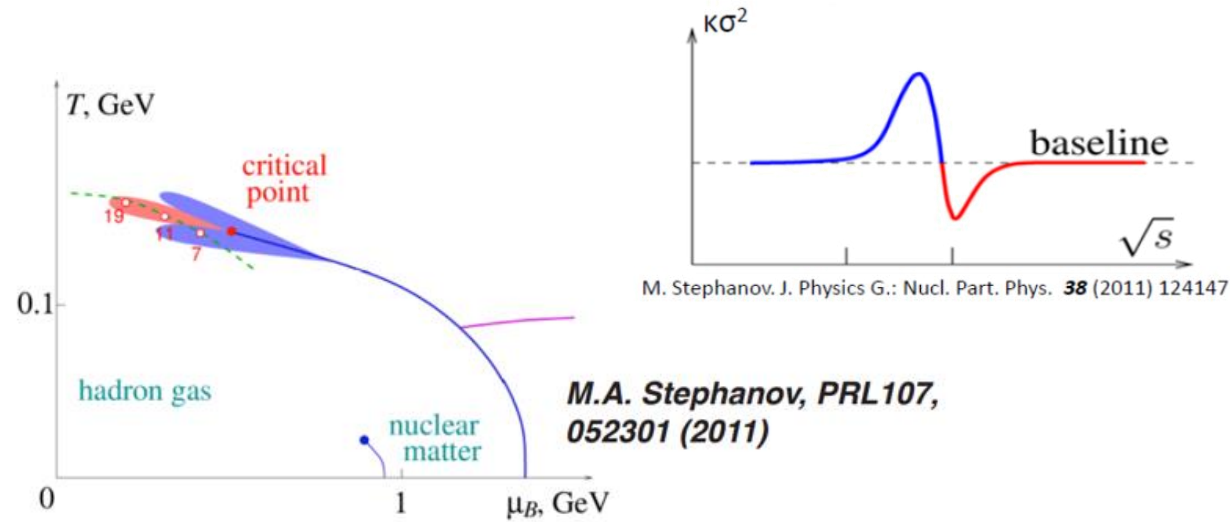


- Introduction
- Search for QCD critical point,  $C_4/C_2$
- Data Analysis Methods
  - Centrality Determination
  - Cumulant Corrections
  - Pile Up
- Results
- Summary

# Moments & Cumulants



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



**Cumulants** are algebraic combinations of moments:

Cumulant generating function:

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

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

1<sup>st</sup> raw moment  $m_1 = C_1$

2<sup>nd</sup> central moment  $\mu_2 = C_2$

3<sup>rd</sup> central moment  $\mu_3 = C_3$

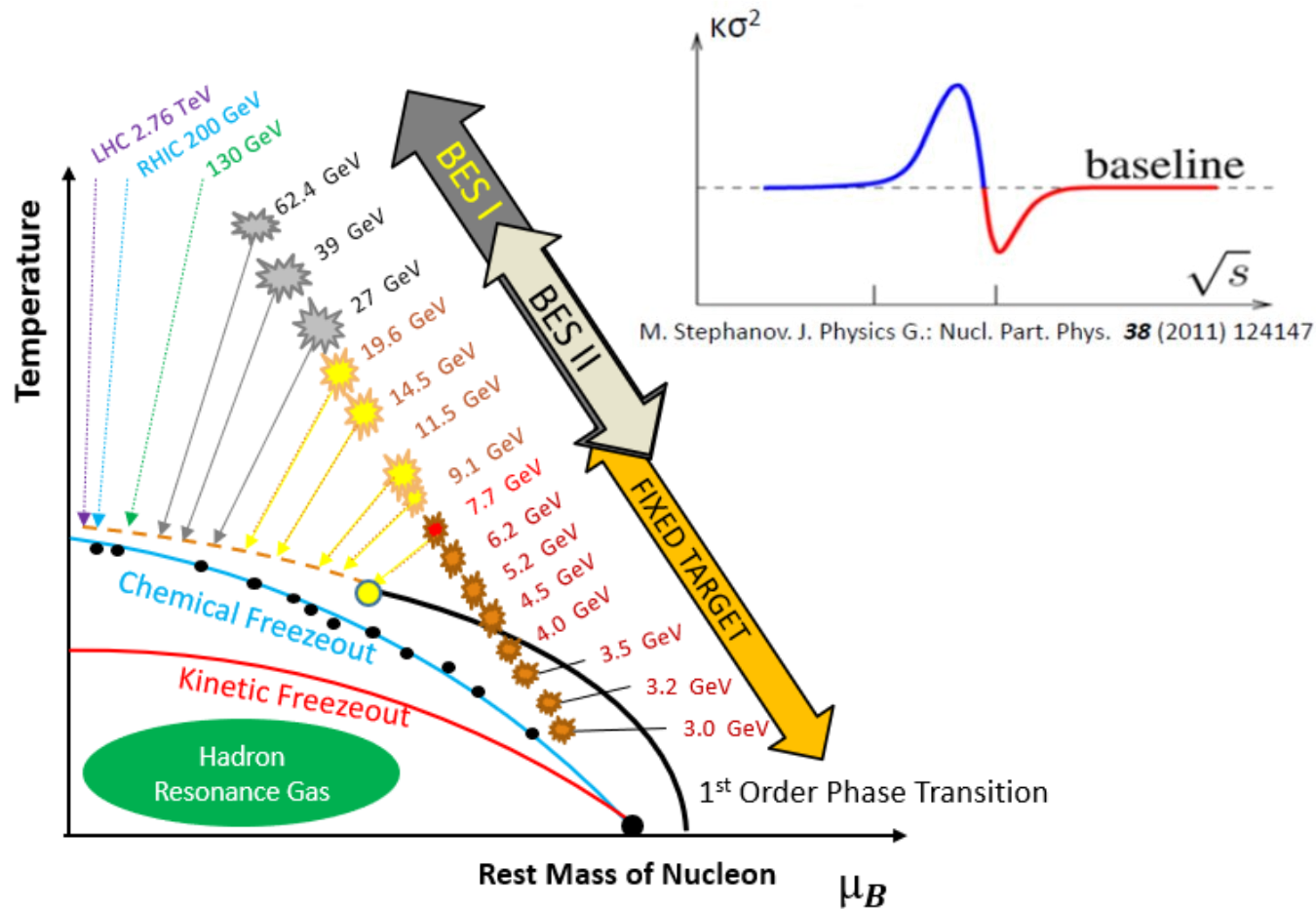
4<sup>th</sup> central moment  $\mu_4 = C_4 + 3 C_2^2$

**Normalized Moments** (*Volume dependence is cancelled*):

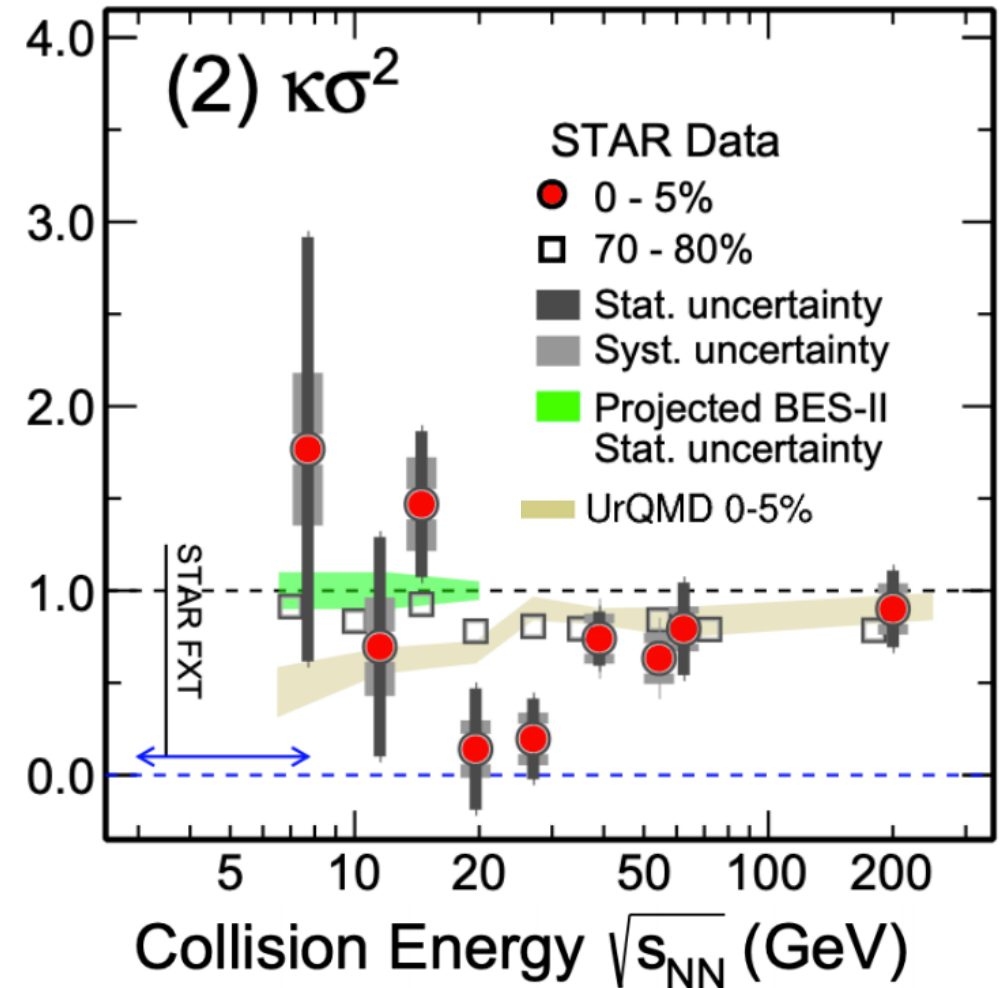
$$\frac{\chi_q^4}{\chi_q^2} = \frac{C_4}{C_2} = \kappa\sigma^2$$

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

# STAR Proton Measurements



STAR Collaboration, arXiv:2001.02852



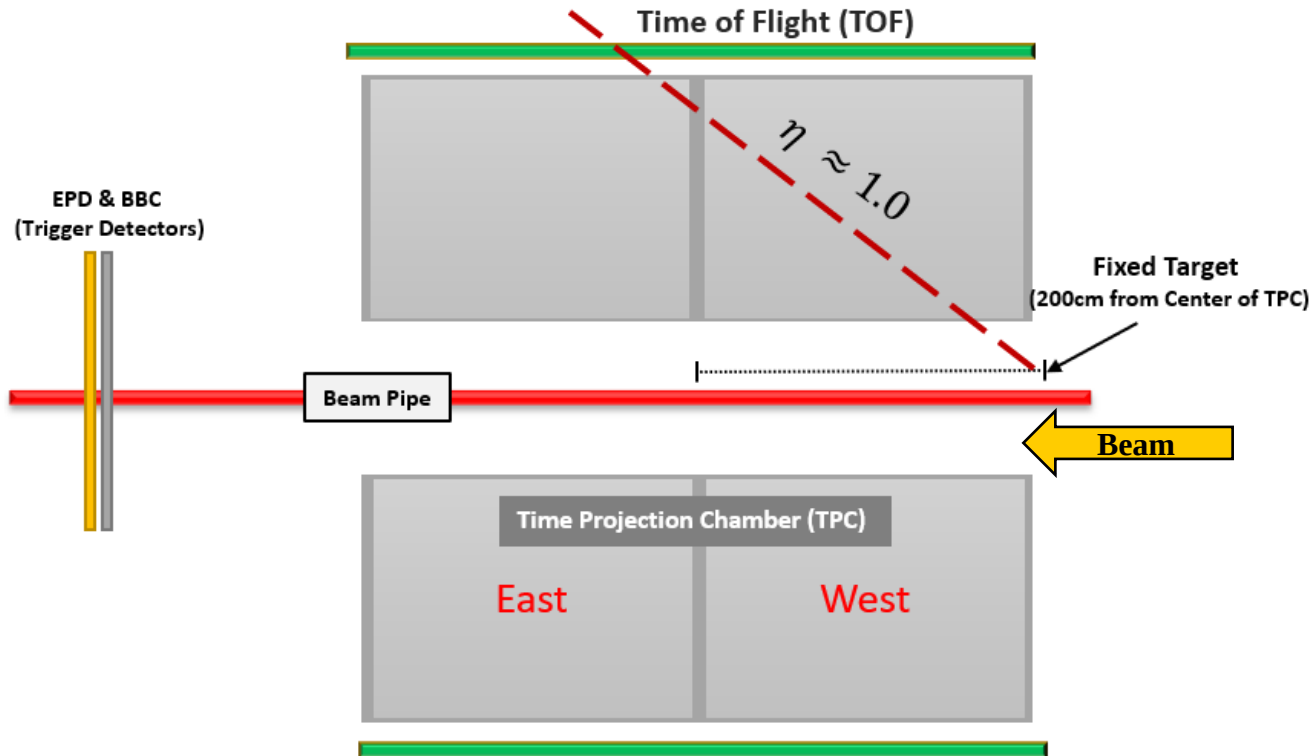
STAR measurements of net-proton  $\kappa\sigma^2$  show a rising trend below 19.6 GeV

$\sqrt{s_{NN}} = 3.0$  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

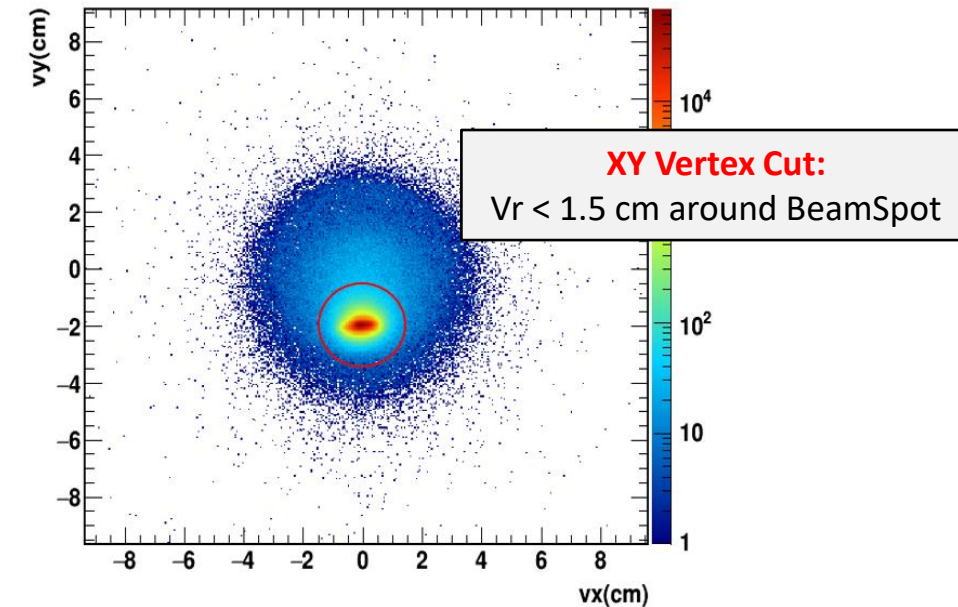
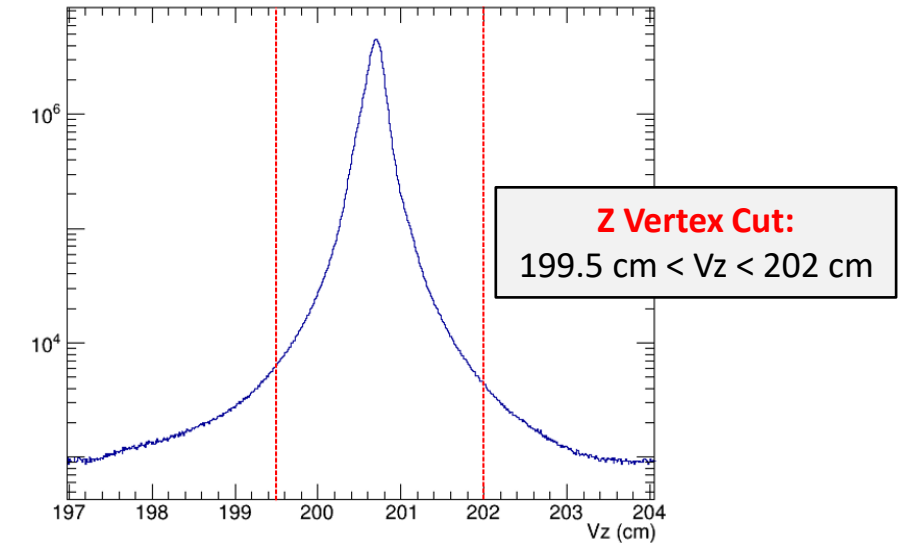


Events/Triggers (Taken in 2018):

| No Cuts | After Event & Run Cuts |
|---------|------------------------|
| 320M    | 140M                   |

Beam direction indicates positive rapidity

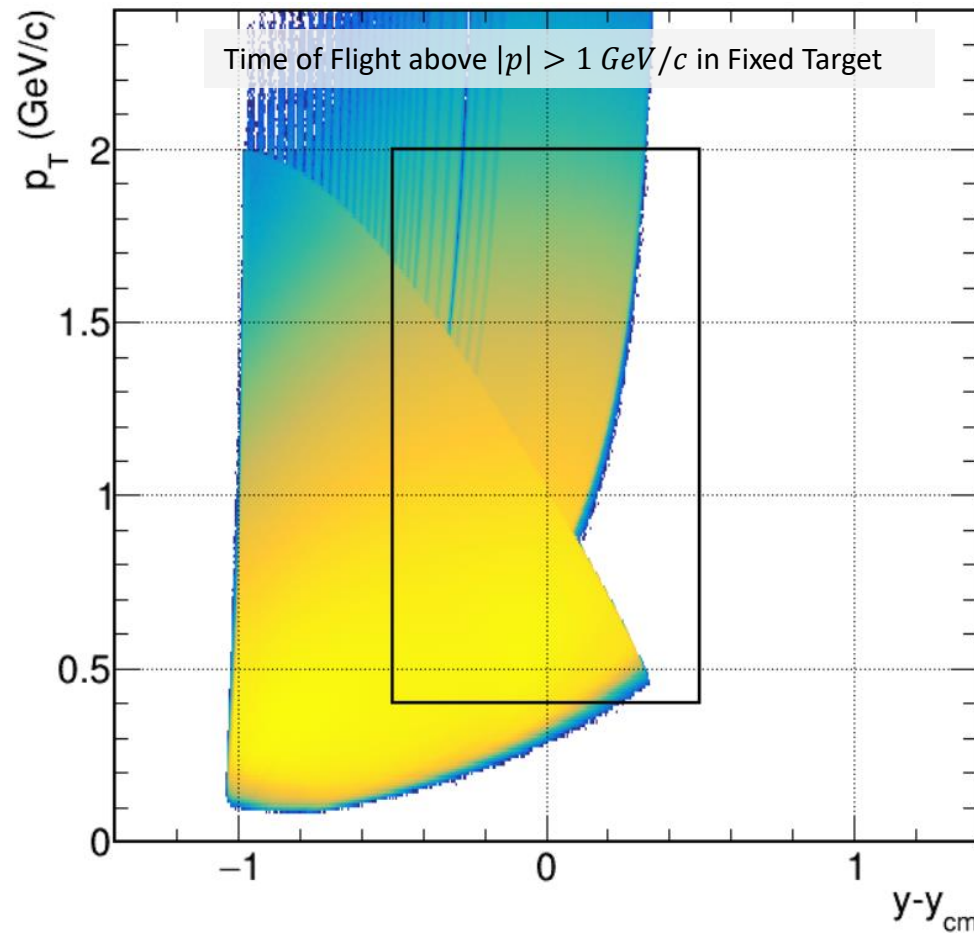
Fixed Target rapidity is reversed from typical collider running conditions



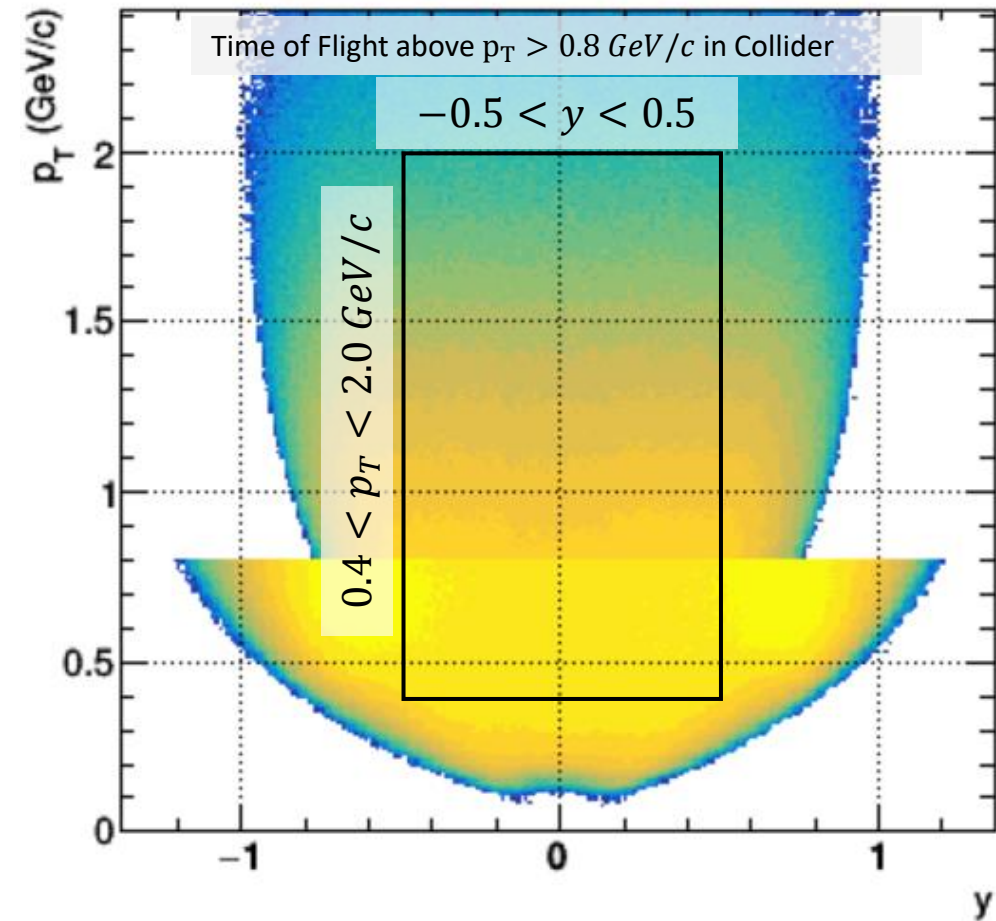
# Acceptance Comparison with STAR Collider $\sqrt{s_{NN}} = 7.7$ GeV



$\sqrt{s_{NN}} = 3.0$  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:**

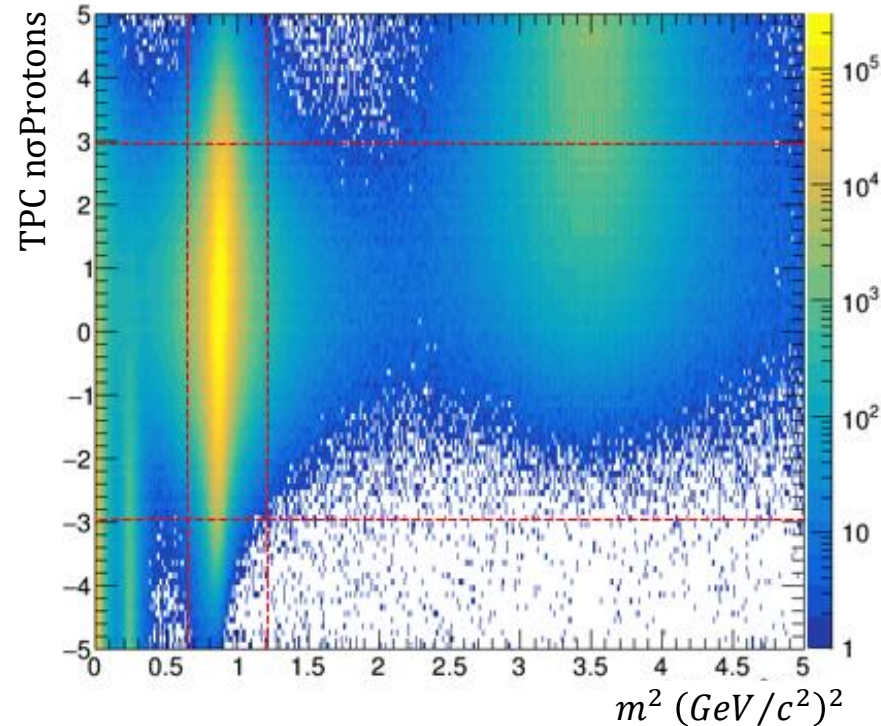
$$-0.5 < y < 0$$

$$0.4 < p_T < 2.0 \text{ (GeV/c)}$$

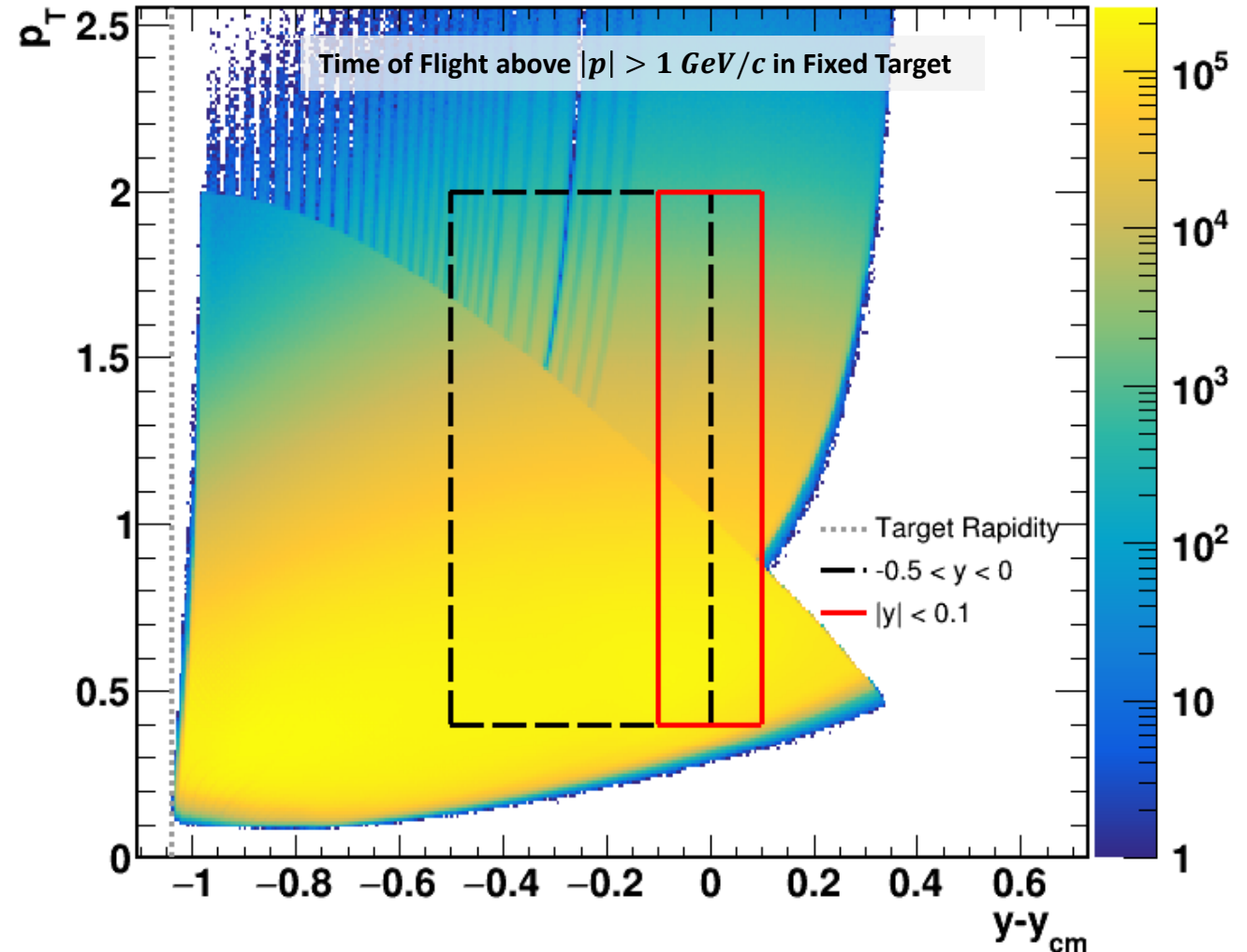
**Symmetric Window:**

$$|y| < 0.1$$

$$0.4 < p_T < 2.0 \text{ (GeV/c)}$$



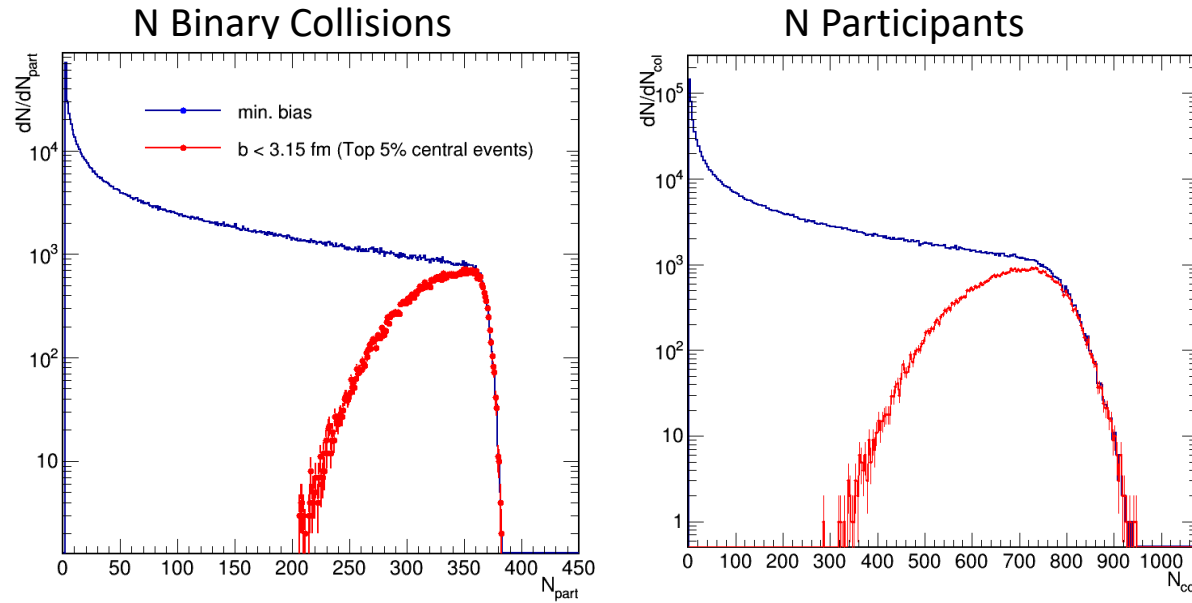
**Particle ID:**  $0.6 < m^2 < 1.2 \text{ (GeV/c}^2\text{)}^2$   
 $|\text{noProtons}| < 3$



**TPC + TOF analysis cuts provide ~97% proton purity**

# Centrality Determination

## MC Glauber Model Simulation



**Use TPC particle multiplicity (excluding protons) to determine centrality**

Exclude protons tracks to decrease auto-correlation in proton signal

### **FxtMult**

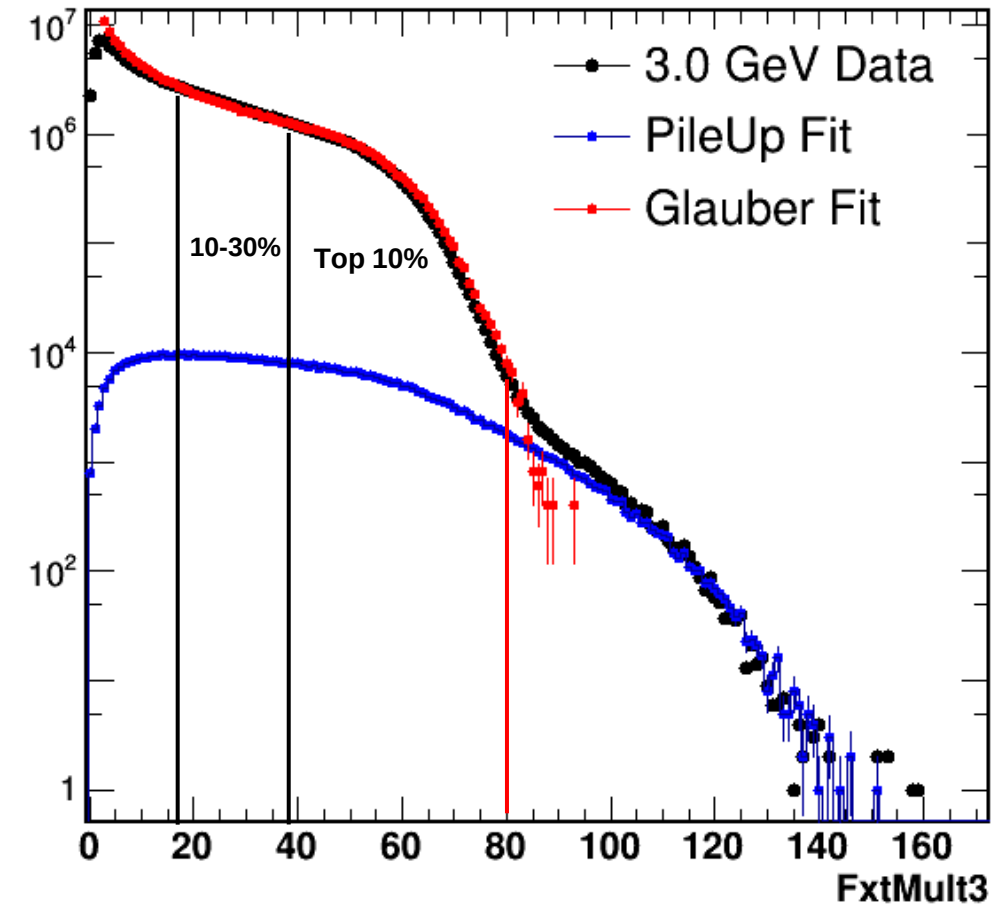
All TPC tracks in the Fixed Target acceptance ( $\eta \sim [0,2]$ )

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

### **FxtMult3**

All TPC tracks in the Fixed Target acceptance excluding protons

*Exclude Multiplicities above 80 to exclude pile up.*



Fit FxtMult3 with MC Glauber Sim. + Negative Binomial Fit



## 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

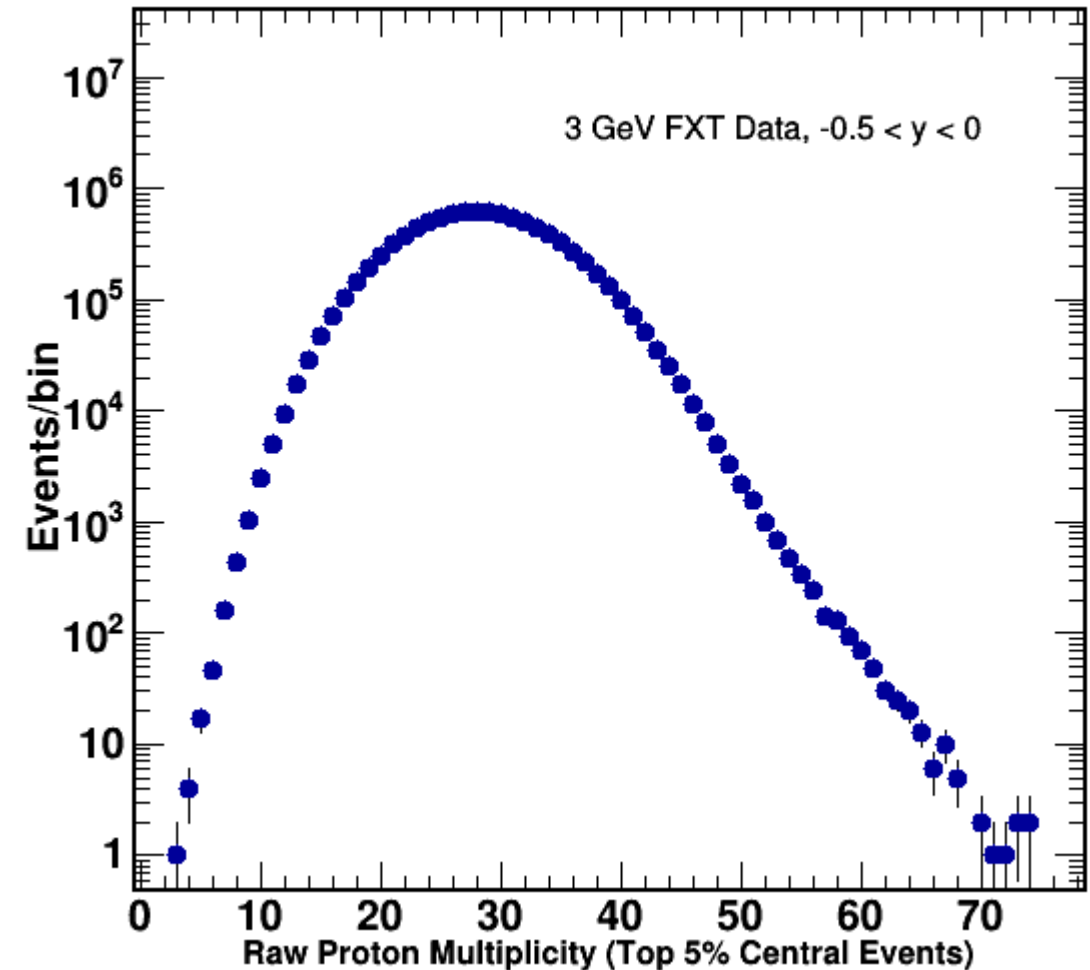
Reduce the effect of volume fluctuations by using a weighted average:

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

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

## Pile Up Correction (following slides)

## Uncorrected Proton Multiplicity in the TPC



## 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  $\tilde{P}(N)$ .

$$\tilde{P}(N) = \sum_N P(N) B_{p,N}(n)$$

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,  $\varepsilon_i$  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

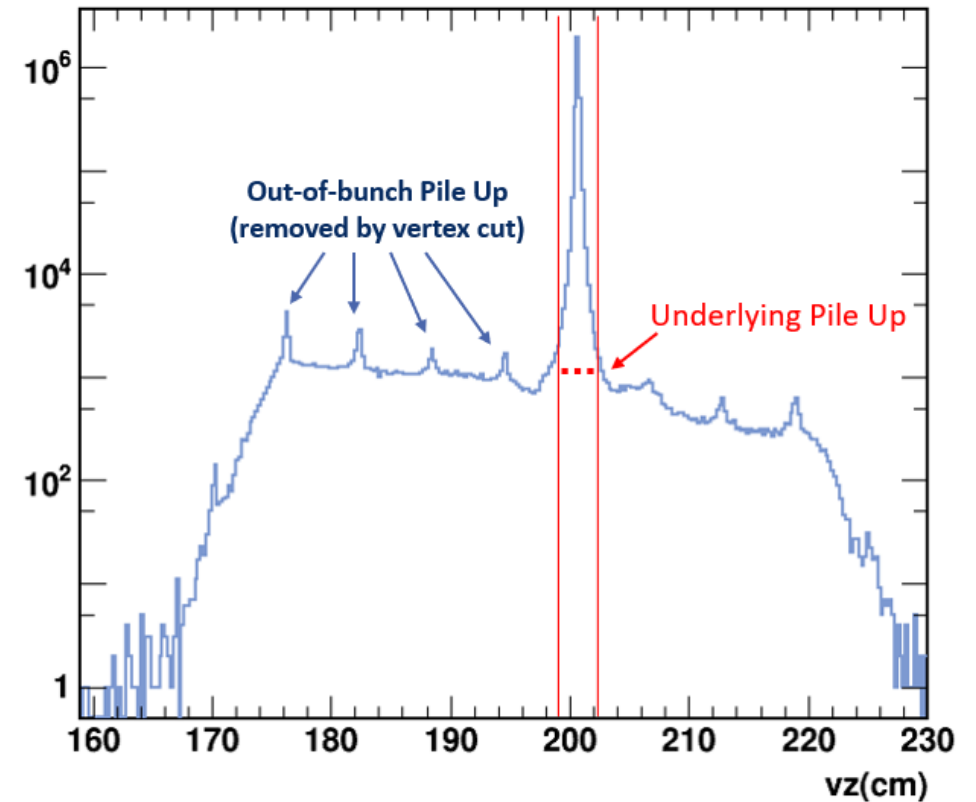
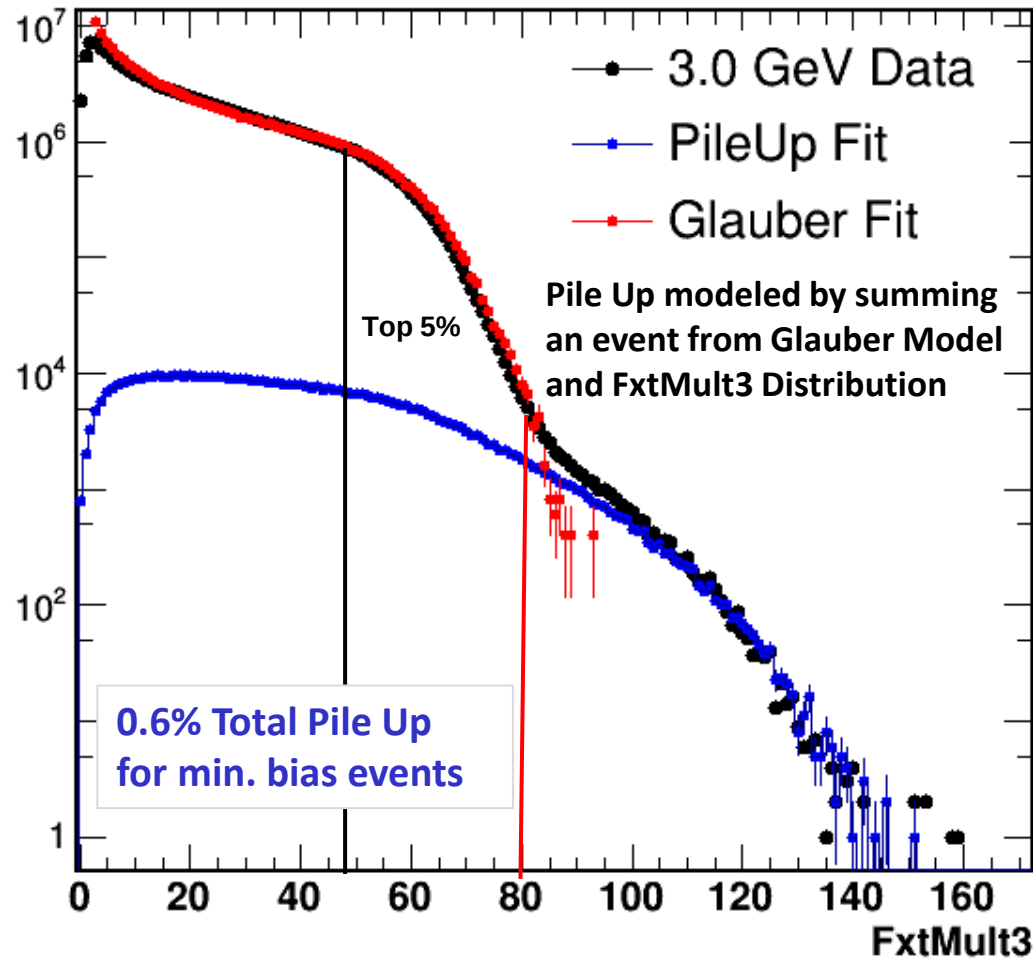
Statistical errors are calculated with a bootstrap method. Analysis is resampled ~200 times, and standard deviation of the sample provides statistical error.



# 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

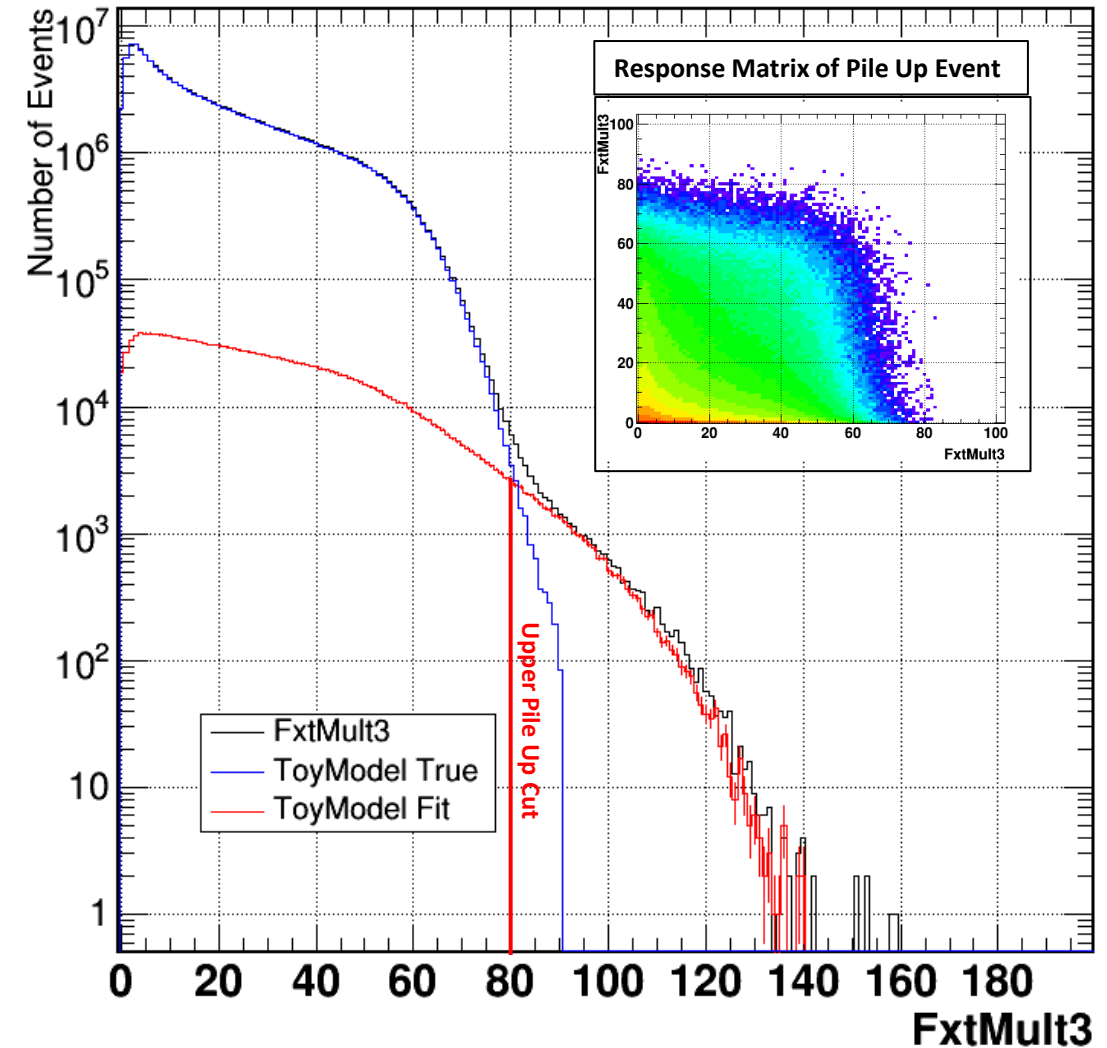
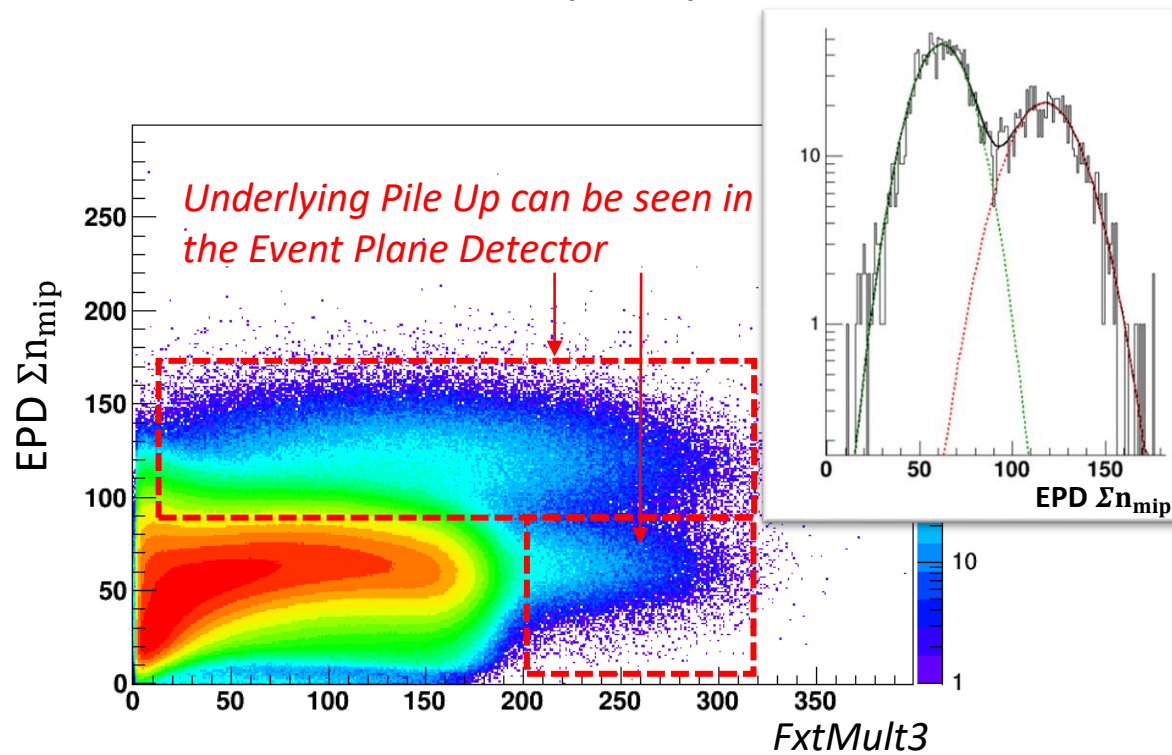


- Pile Up from the different bunches can be significantly reduced by vertex cuts
- Pile Up from the same bunch is more difficult to remove without altering the true proton moments

# 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



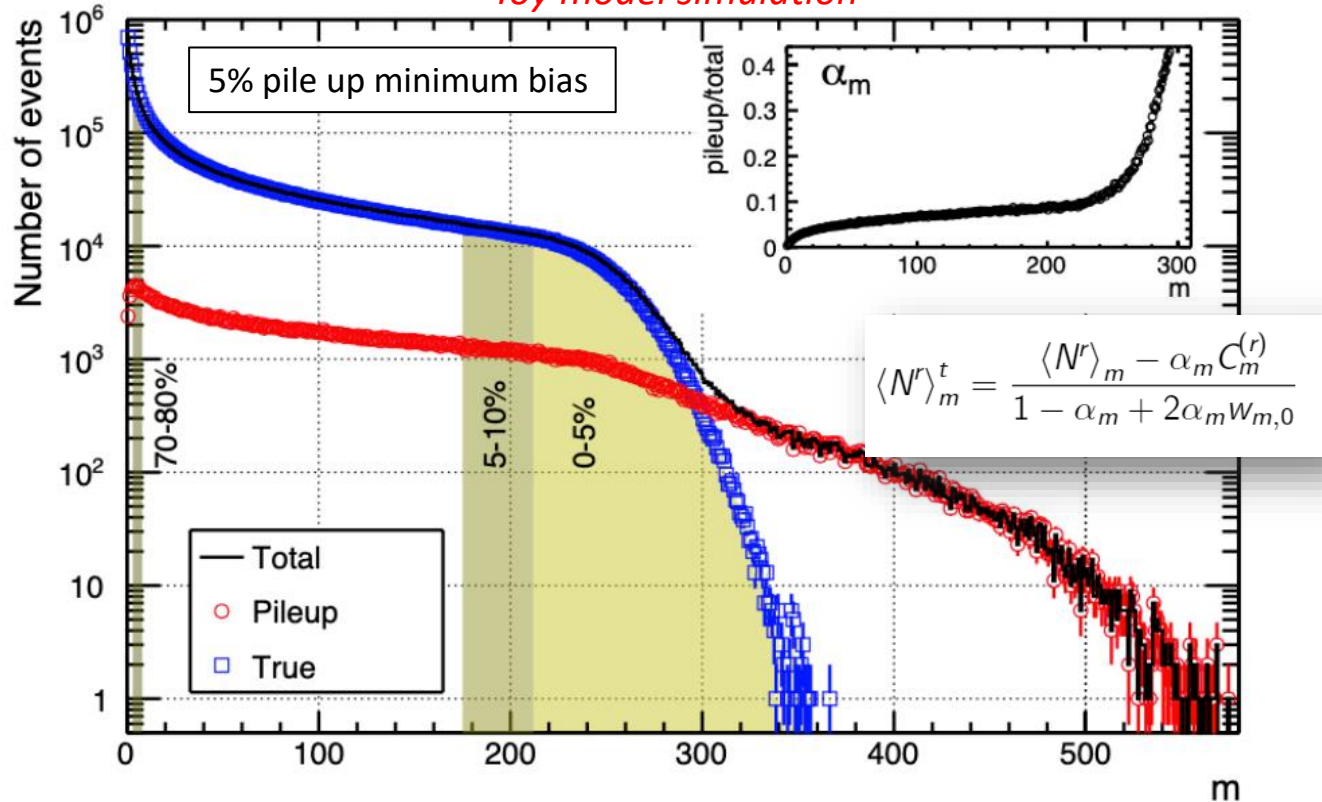
Compare to UrQMD pileup estimate for Systematic Uncertainty of Correction

# Pile Up Correction

Data driven approach to correct for pile up.

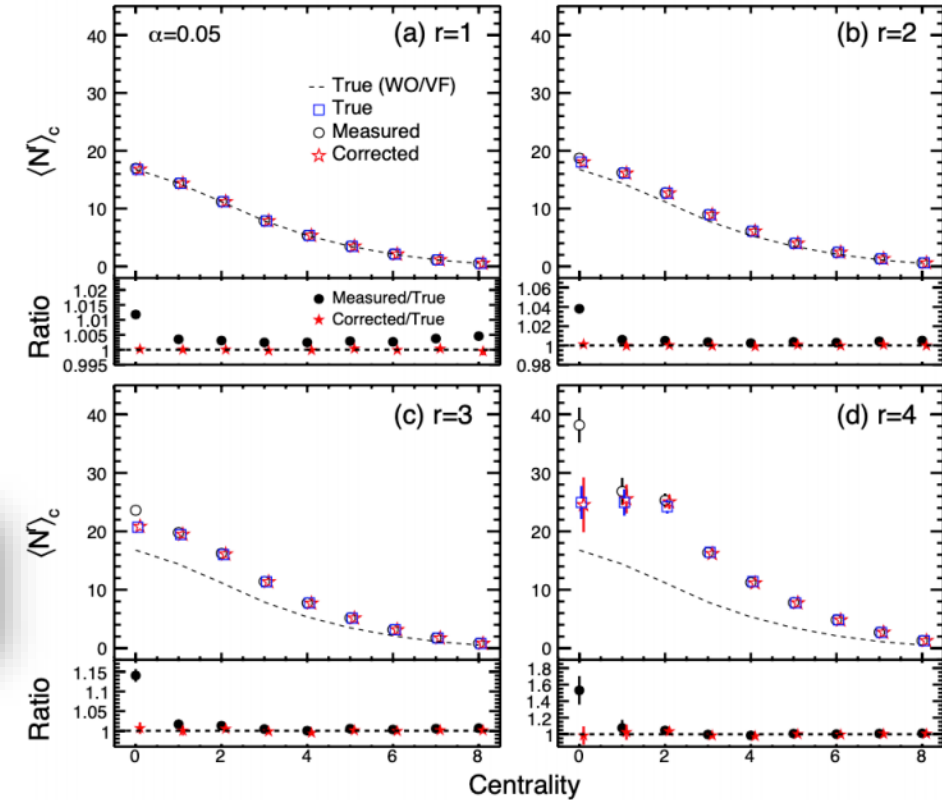
Account for pile up (sum of two events) and remove pileup cumulants from true cumulants.

*Toy model simulation*



*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:

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

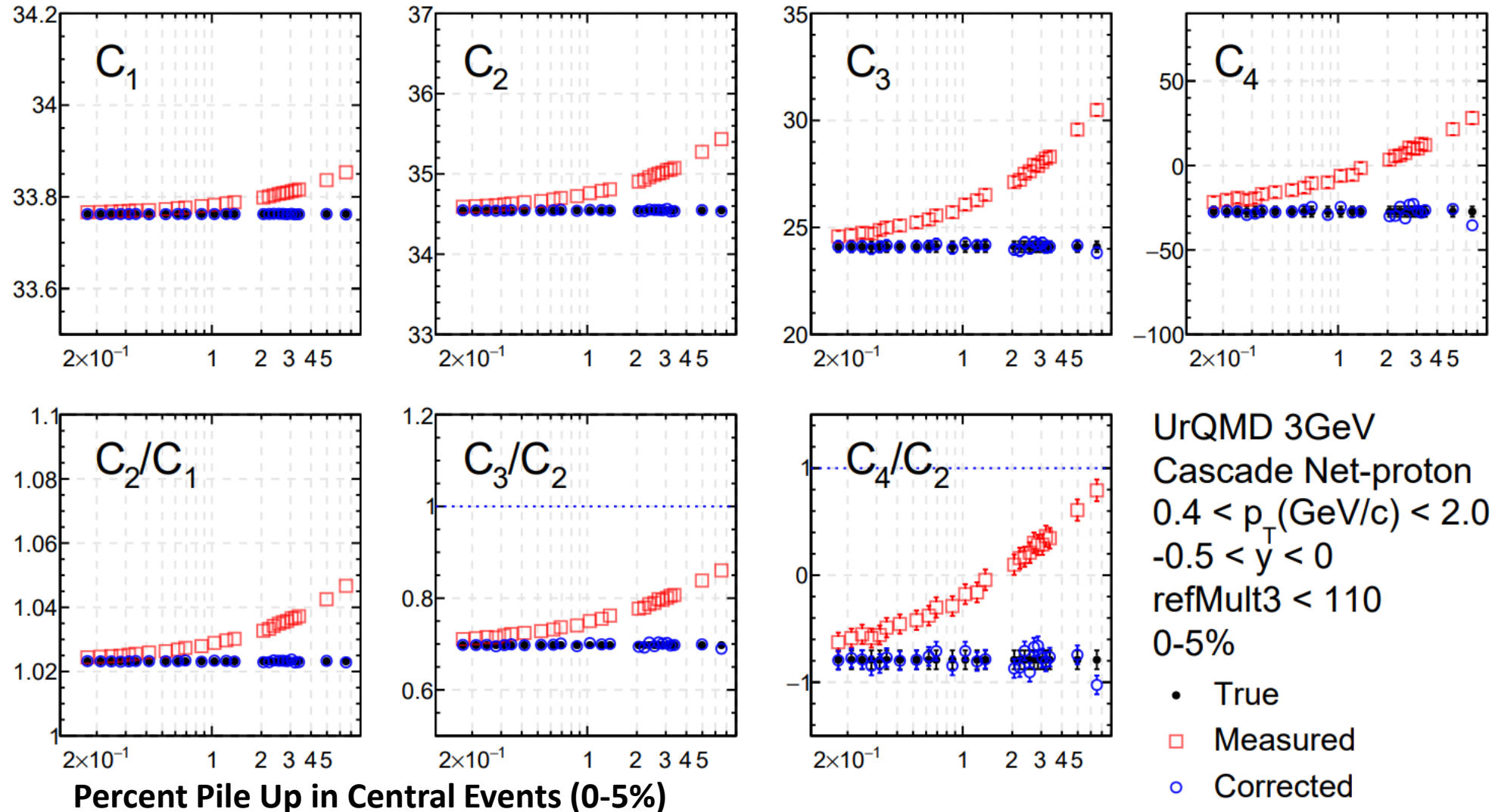
where  $\alpha$  is the pileup fraction,  $P_m^t(N)$  is the true proton distribution and  $P_m^{pu}(N)$  is the pileup proton distribution.

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



# UrQMD Pile Up Correction

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



# Net Proton Cumulants

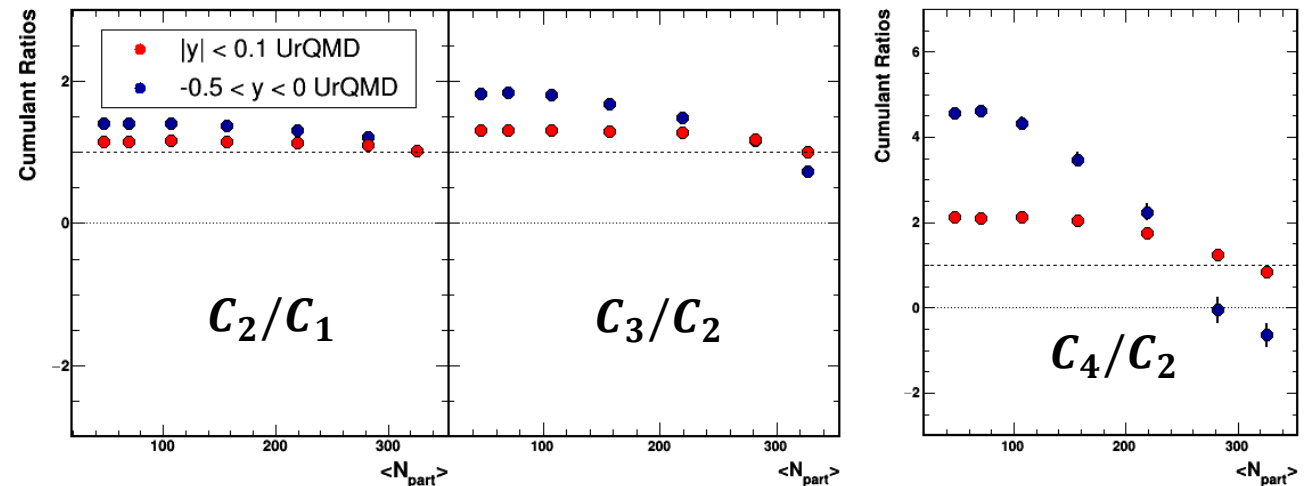
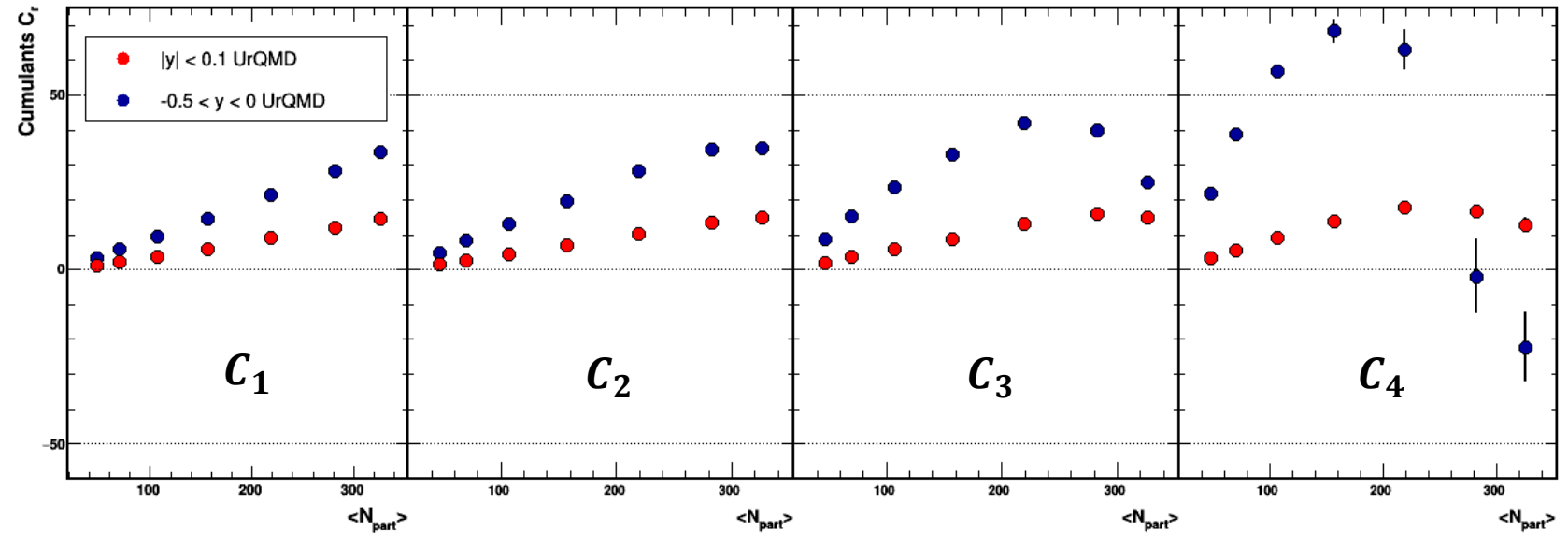


UrQMD  $C_4/C_2$  suggests large suppression is caused by baryon conservation

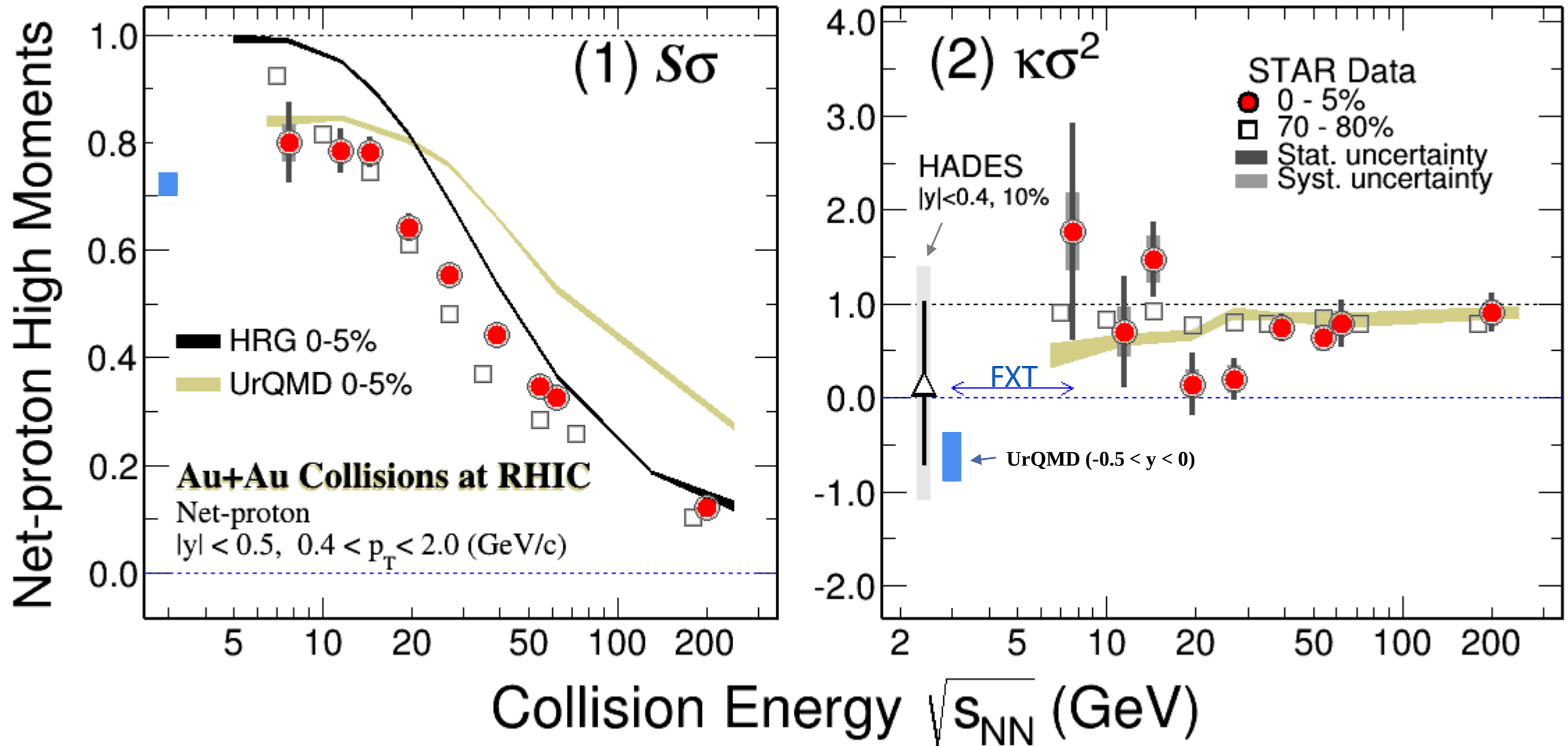
Signal returns to Poisson baseline when rapidity window is reduced to  $|y| < 0.1$

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:

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

