Centrality and Acceptance Dependence of Sixth Cumulant of Net-Proton Multiplicity Distribution at $\sqrt{s_{NN}}$ = 200GeV from the STAR Experiment

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JPS spring meeting @Osaka

- ✓ Motivation and Introduction
- ✓ STAR Detector and Proton Identifications
- ✓ Results and Summary

Motivation

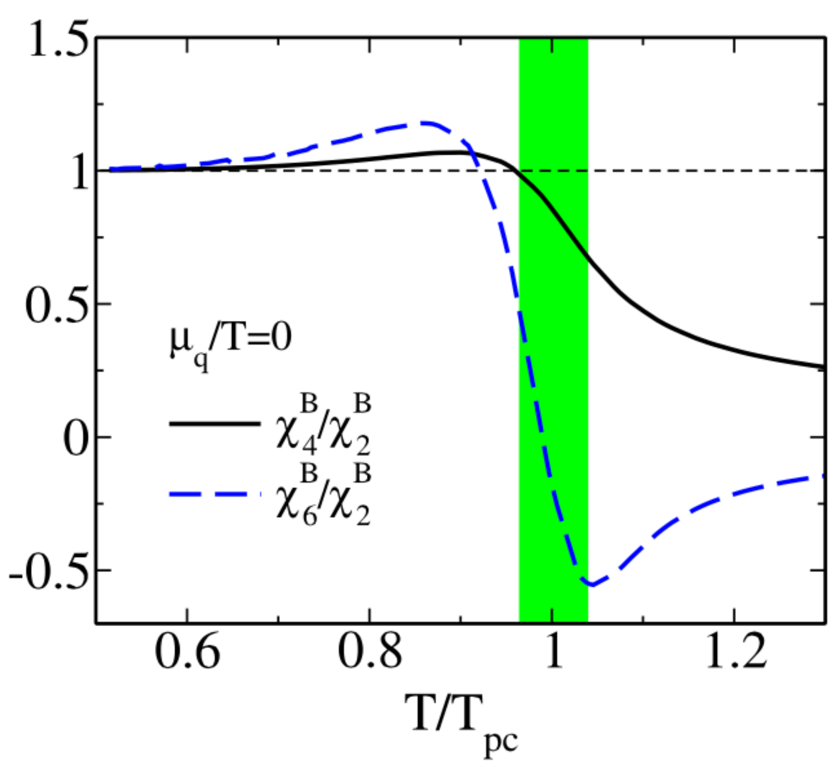
- ✓ **Lattice calculations predict a "smooth crossover" at μ_B=0.**

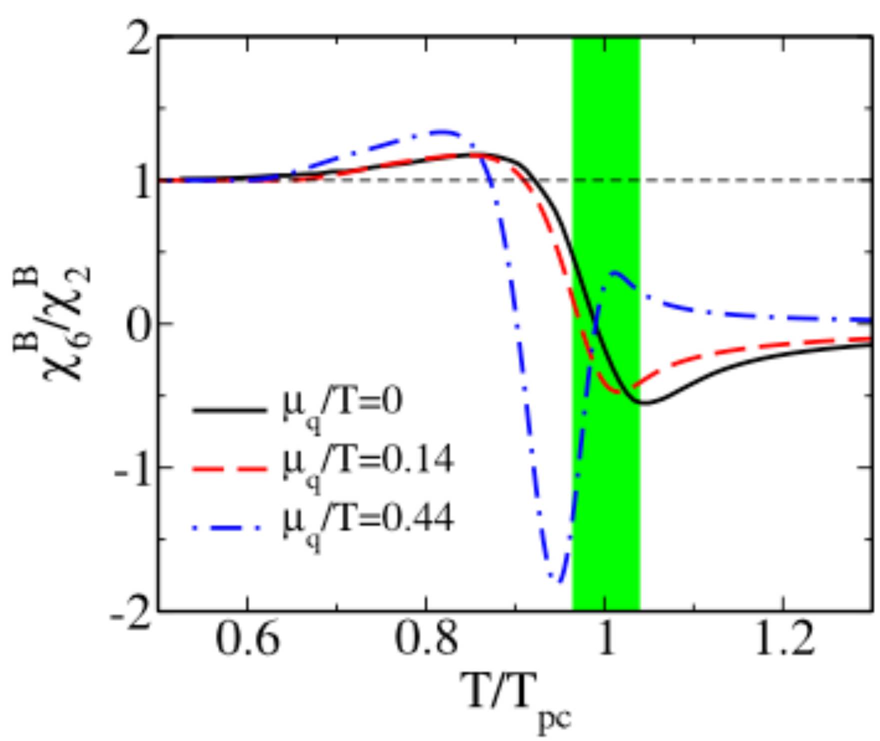
  Y. Aoki, Nature 443, 675(2006)

- ✓ **Theoretically the six order cumulant of net-baryon and net-charge fluctuation change sign near the chiral phase transition.**

  Friman et al, Eur. Phys. J. C (2011) 71:1694

- ✓ **Find an experimental evidence for the phase transition with measurement of the sixth order cumulant at the STAR experiment.**





✦ **Can we observe the negative value?**

$$\frac{C_6}{C_2} = \frac{\chi_6}{\chi_2}$$

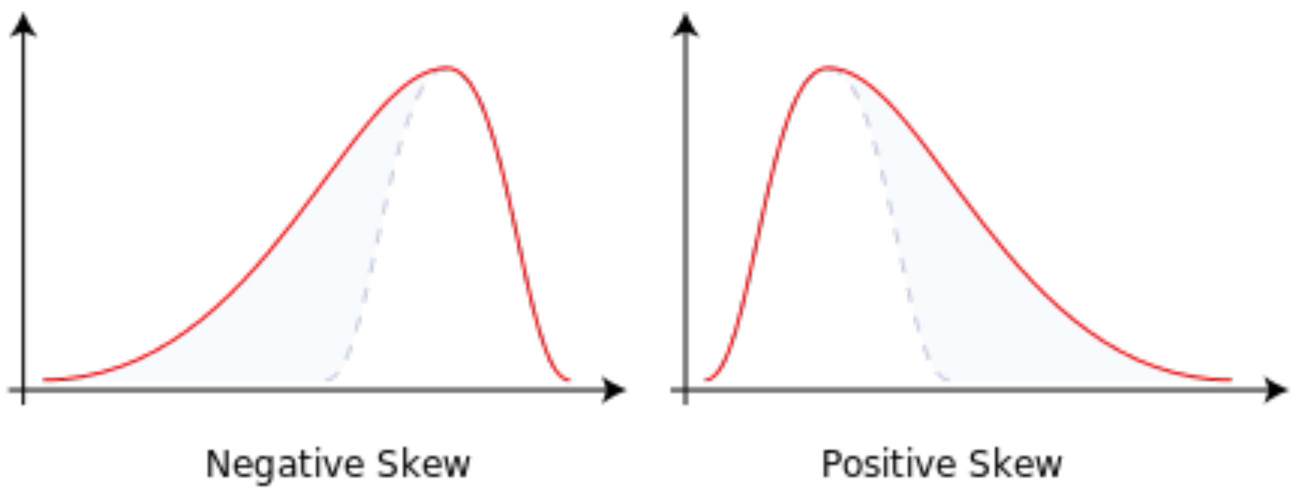
Friman et al, Eur. Phys. J. C (2011) 71:1694

Higher order fluctuations

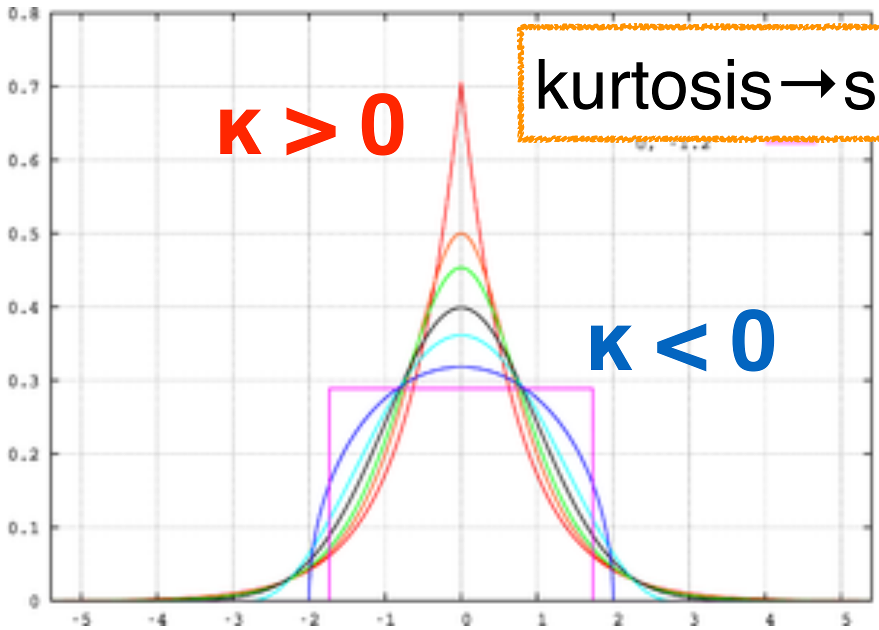
✦ **Moments and Cumulants are mathematical measures of "shape" of a histogram which probe the fluctuation of observables.**

- ✓ **Moments : Mean(*M*), sigma(*σ*), skewness(*S*) and kurtosis(κ).**
- ✓ ***S and κ are non-gaussian* fluctuations.**

skewness→asymmetry



kurtosis→sharpness



from wikipedia

✓ **Cumulant ⇄ Moment**

$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

✓ **Cumulant : additivity**

$$C_n(X+Y) = C_n(X) + C_n(Y)$$

➡ **Volume dependence**

Fluctuations of conserved quantities

✦ Net-baryon, net-charge and net-strangeness

X. Luo, CiRfSE workshop 2016 @Tsukuba University

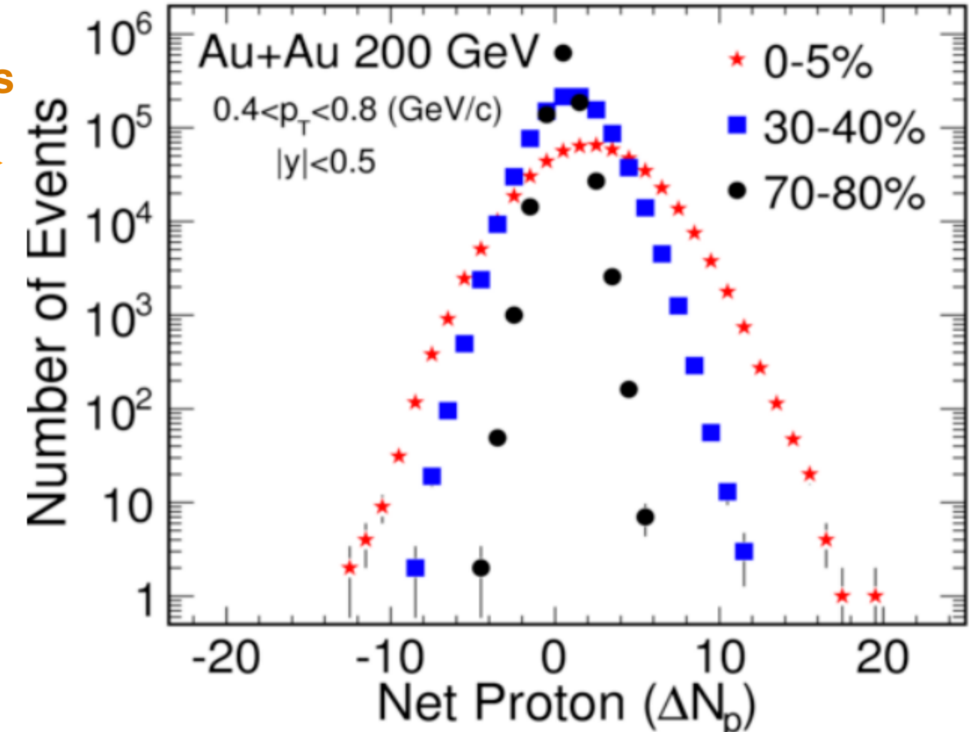
"Net" : positive - negative

$$\Delta N_q = N_q - N_{\bar{q}}, \quad q = B, Q, S$$

No. of positively charged particles in one collision

No. of negatively charged particles in one collision

Fill in histograms over many collisions



→neutrons cannot be measured

(1) Sensitive to correlation length

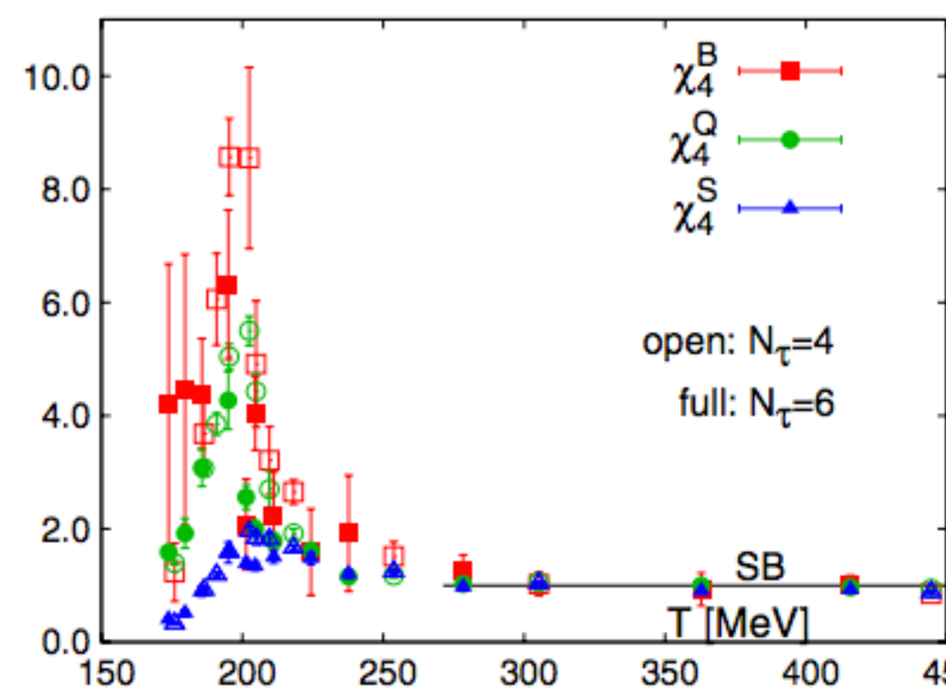
$$C_2 = <(\delta N)^2>_c \approx \xi^2$$

$$C_3 = <(\delta N)^3>_c \approx \xi^{4.5}$$

$$C_4 = <(\delta N)^4>_c \approx \xi^7$$

(2) Direct comparison with susceptibilities.

M. Cheng et al, PRD 79, 074505 (2009)

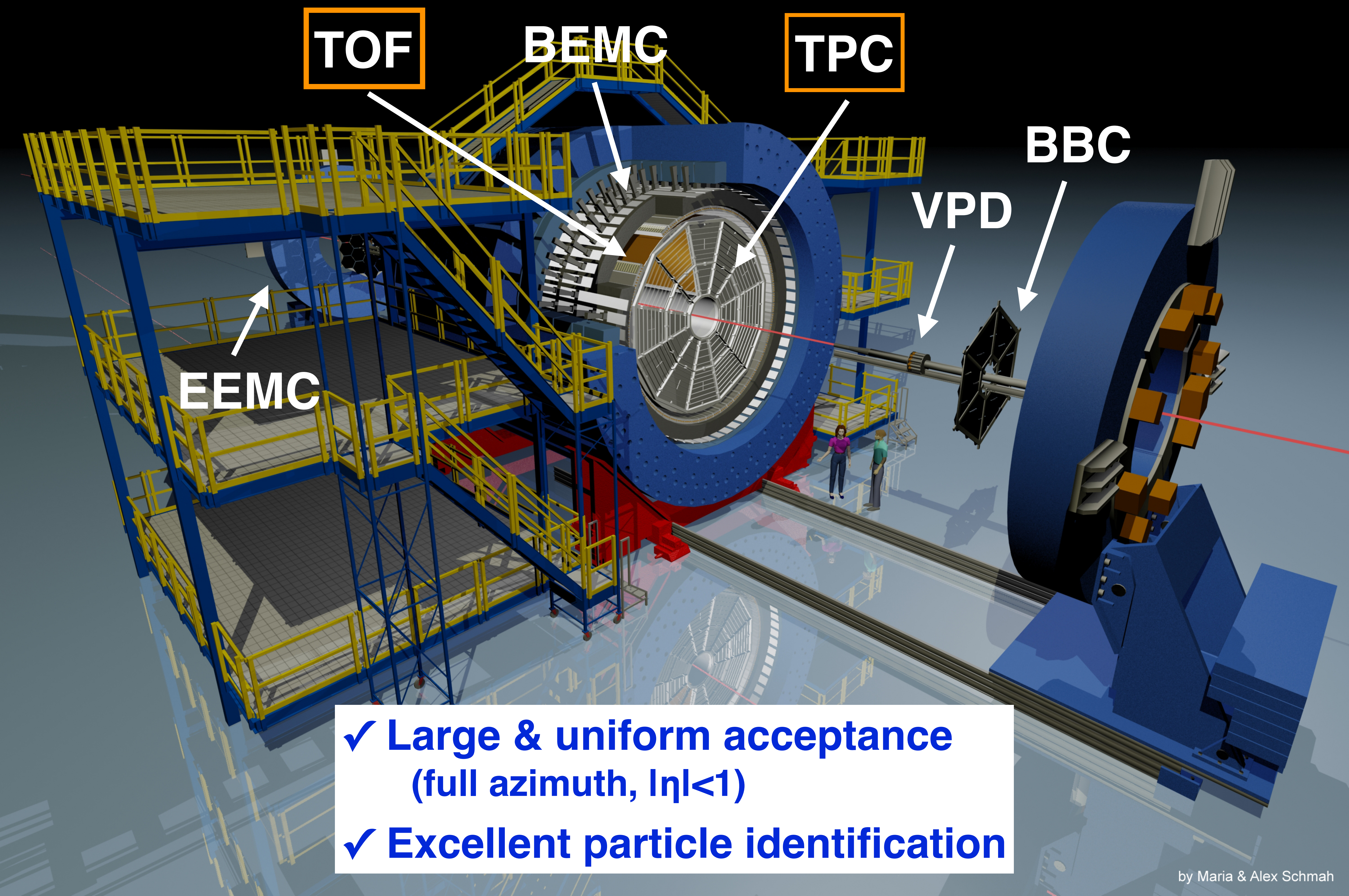


$$S\sigma = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \qquad \kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2}$$

$$\chi_n^q = \frac{1}{VT^3} \times C_n^q = \frac{\partial^n p/T^4}{\partial \mu_q^n}, \quad q = B, Q, S$$

Volume **dependence can be canceled by taking ratio.**

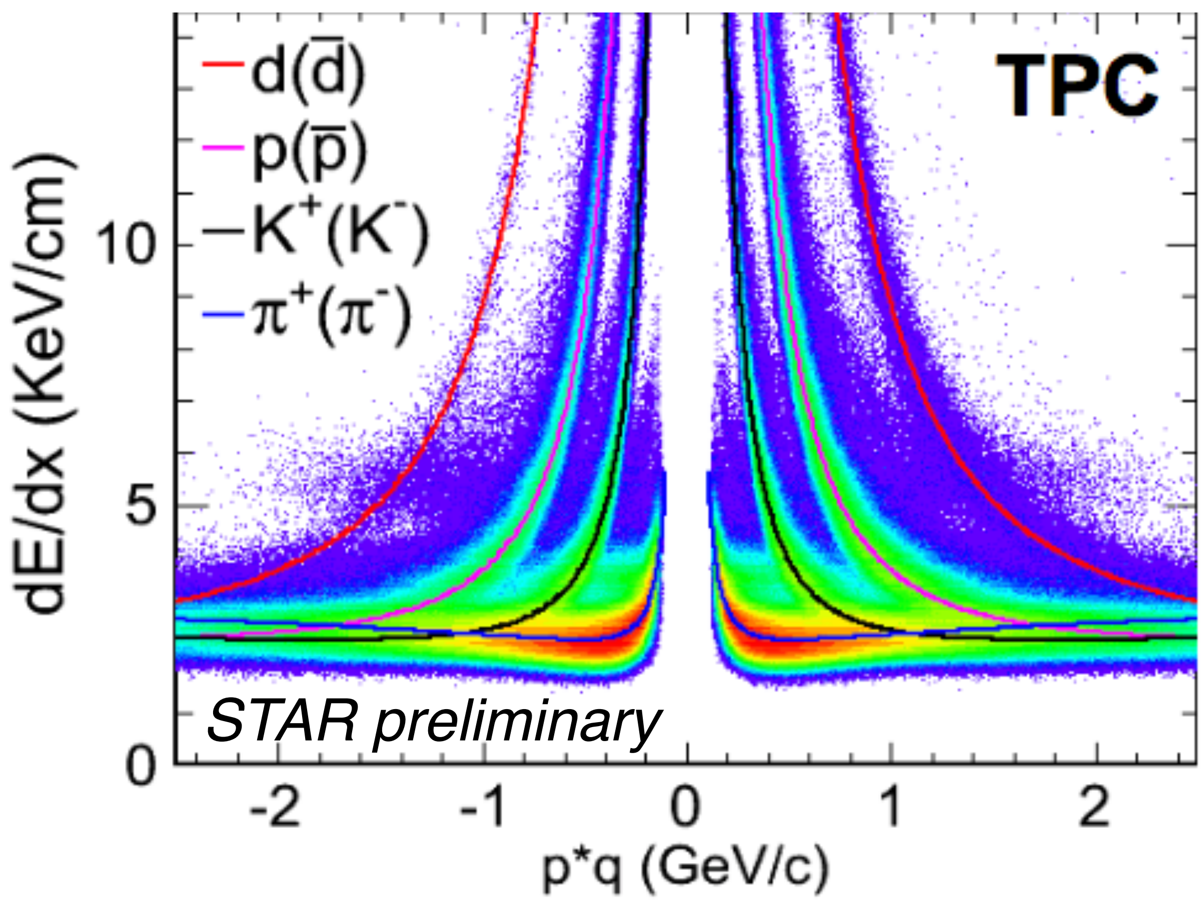
Solenoidal Tracker At RHIC

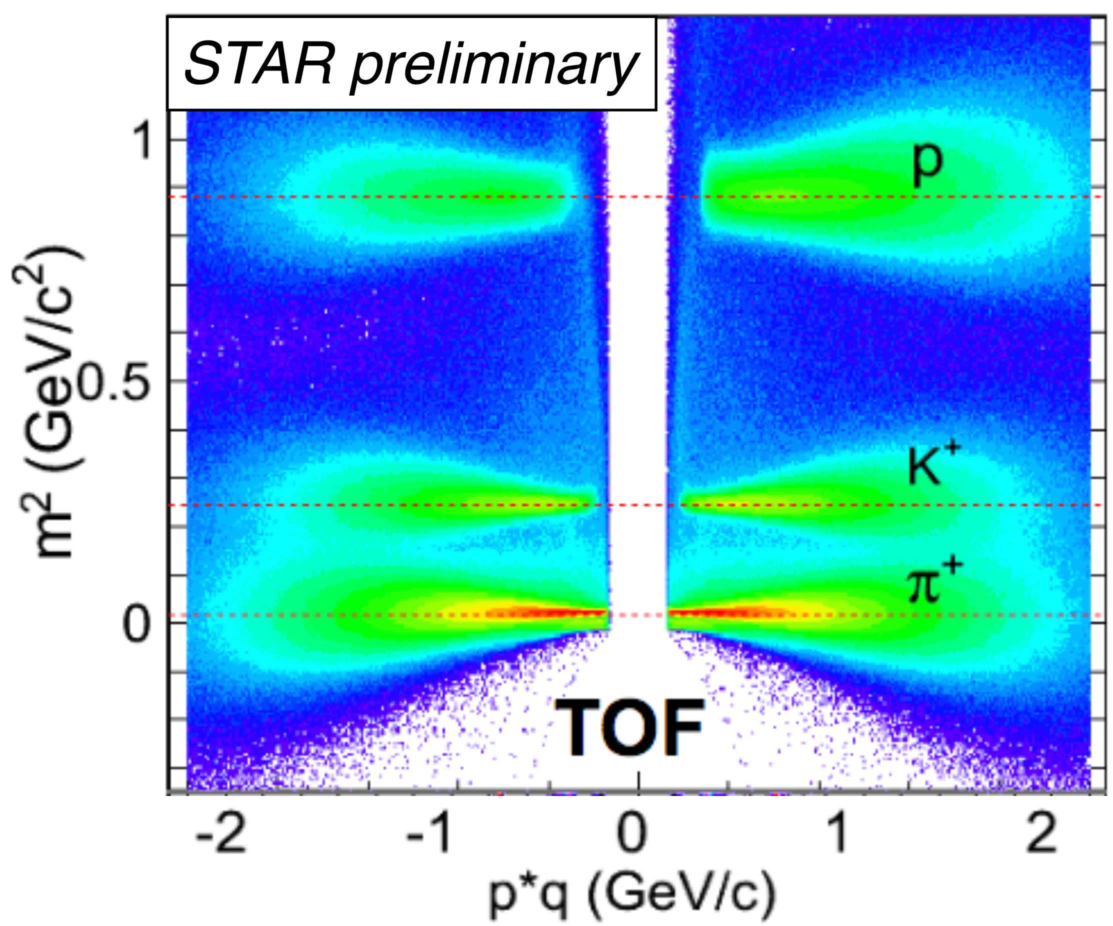


- ✓ **Large & uniform acceptance**
  (full azimuth, |η|<1)
- ✓ **Excellent particle identification**

Proton identification

- ✓ dE/dx measured with TPC is used for proton identification at $0.4<p_T<0.8$ GeV/c
- ✓ The combined PID with m^2 from TOF is used at $0.8<p_T<2.0$ GeV/c.





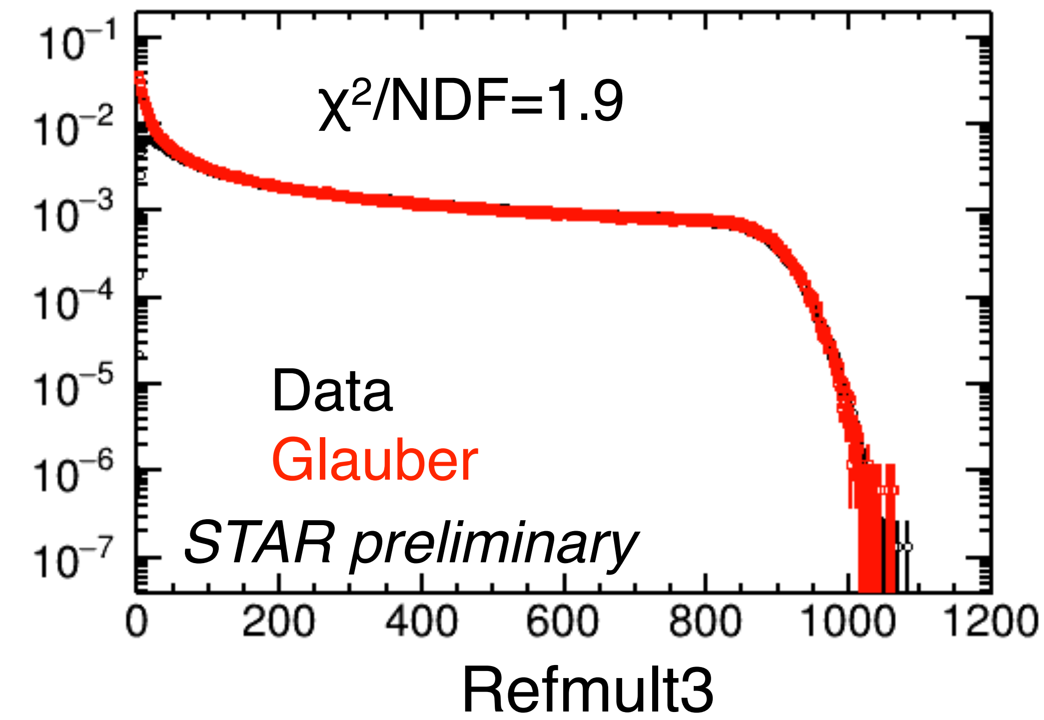
Analysis technique

X. Luo and N. Xu, arXiv: 1701.02105

1. Centrality determination

Use charged particles except protons in order to minimize the autocorrelation.

Analysis : lyl<0.5, p and pbar
Centrality : lηl<1.0, exclude p and pbar



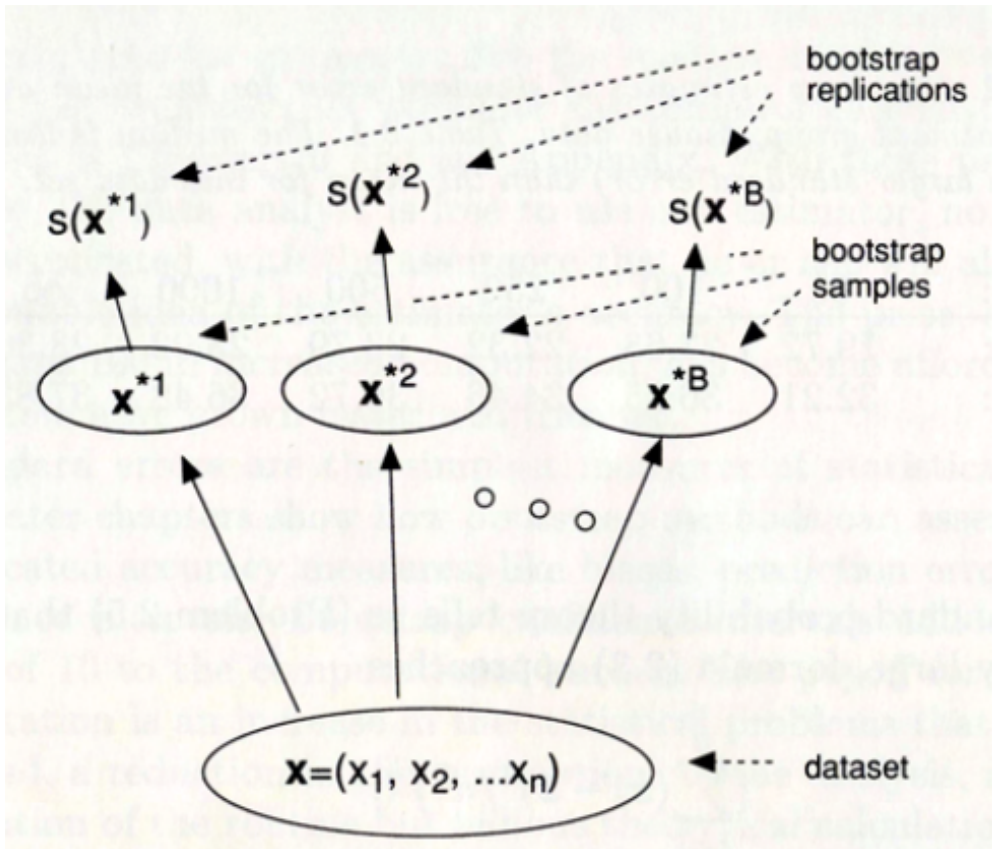
2. Centrality Bin Width Correction

Calculate cumulants at each multiplicity bin in order to suppress the volume fluctuation.

X.Luo et al. J. Phys.G40,105104(2013)

3. Statistical error calculation

- ✓ **Bootstrap**
- ✓ Delta theorem



B. Efron,R. Tibshirani, An introduction to the bootstrap, Chapman & Hall (1993).

Efficiency correction

✓ **Formulas derived via simple relationships between cumulants and factorial cumulants, which can drastically reduce calculation cost compared to usual formulas using factorial moments.**

$$q_{(r,s)} = q_{(a^r/p^s)} = \sum_{i=1}^{M} (a_i^r / p_i^s) n_i.$$

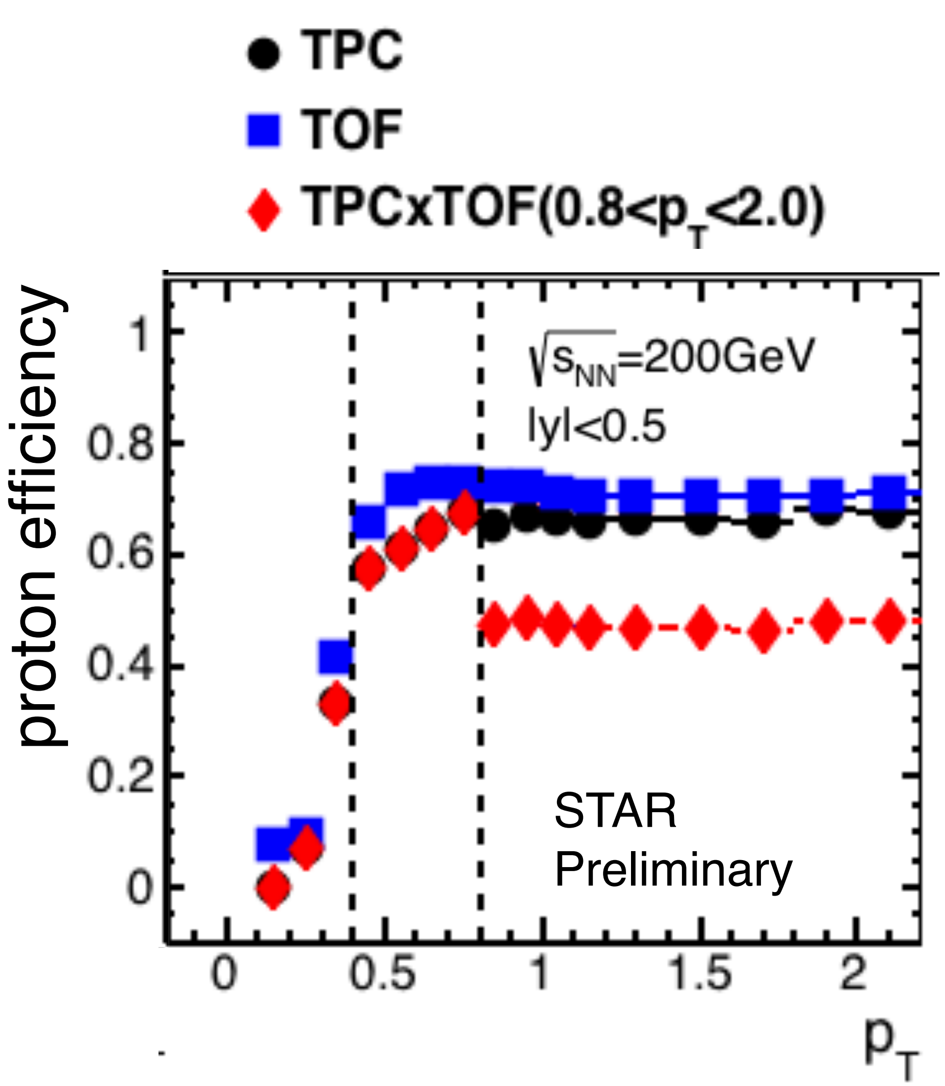
M : # of efficiency bins
n : # of particles
p : efficiency
a : electric charge

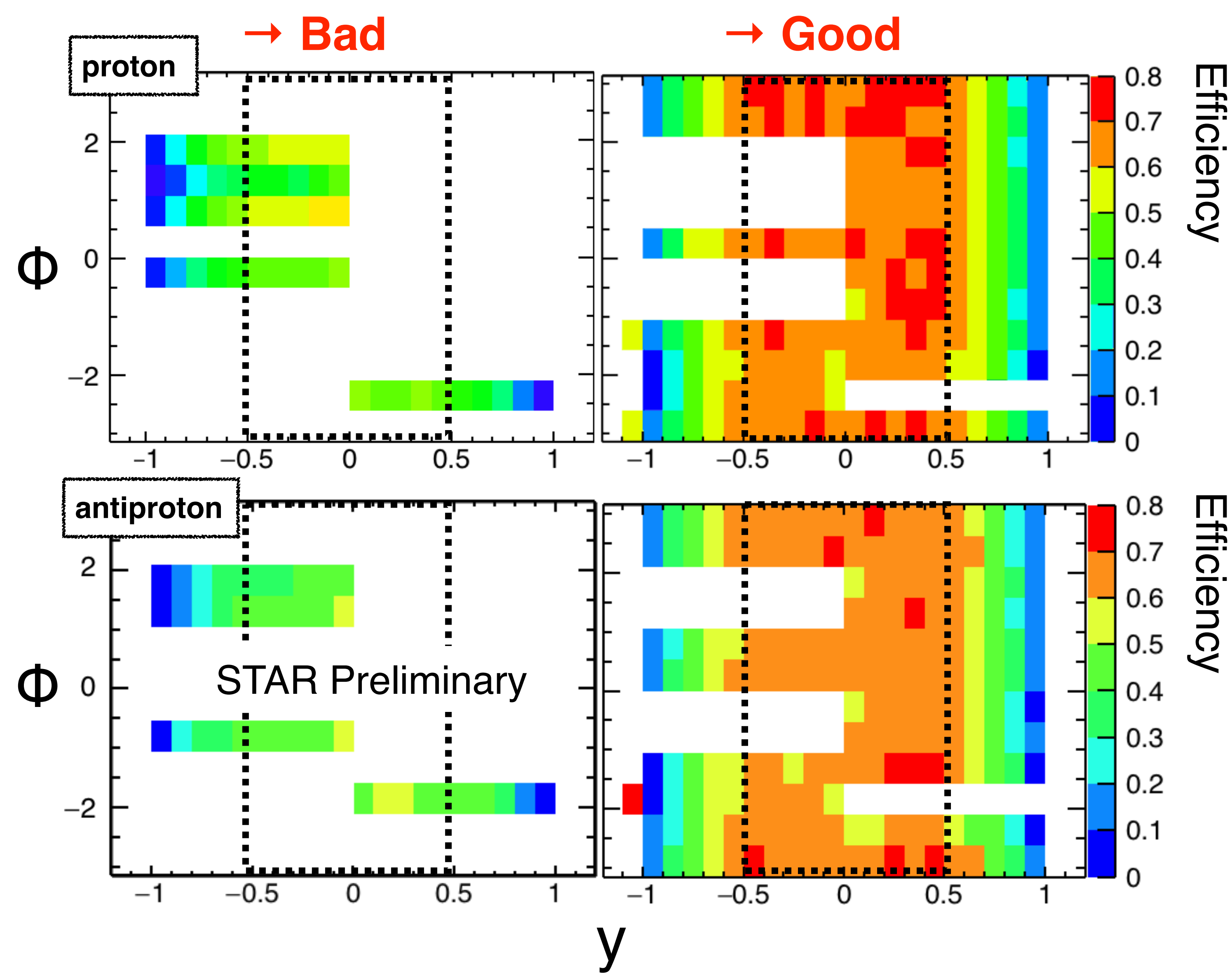
$$\begin{aligned}
\langle Q^6 \rangle_c = {} & \langle q_{(1,1)}^6 \rangle_c + 15\langle q_{(1,1)}^4 q_{(2,1)} \rangle_c - 15\langle q_{(1,1)}^4 q_{(2,2)} \rangle_c + 20\langle q_{(1,1)}^3 q_{(3,1)} \rangle_c - 60\langle q_{(1,1)}^3 q_{(3,2)} \rangle_c \\
& + 40\langle q_{(1,1)}^3 q_{(3,3)} \rangle_c - 90\langle q_{(1,1)}^2 q_{(2,2)} q_{(2,1)} \rangle_c + 45\langle q_{(1,1)}^2 q_{(2,1)}^2 \rangle_c + 45\langle q_{(1,1)}^2 q_{(2,2)}^2 \rangle_c \\
& + 15\langle q_{(2,1)}^3 \rangle_c - 15\langle q_{(2,2)}^3 \rangle_c + 15\langle q_{(1,1)}^2 q_{(4,1)} \rangle_c - 105\langle q_{(1,1)}^2 q_{(4,2)} \rangle_c + 180\langle q_{(1,1)}^2 q_{(4,3)} \rangle_c - 90\langle q_{(1,1)}^2 q_{(4,4)} \rangle_c \\
& - 45\langle q_{(2,1)}^2 q_{(2,2)} \rangle_c + 45\langle q_{(2,2)}^2 q_{(2,1)} \rangle_c + 60\langle q_{(1,1)} q_{(2,1)} q_{(3,1)} \rangle_c - 180\langle q_{(1,1)} q_{(2,1)} q_{(3,2)} \rangle_c \\
& + 120\langle q_{(1,1)} q_{(2,1)} q_{(3,3)} \rangle_c - 60\langle q_{(1,1)} q_{(2,2)} q_{(3,1)} \rangle_c + 180\langle q_{(1,1)} q_{(2,2)} q_{(3,2)} \rangle_c - 120\langle q_{(1,1)} q_{(2,2)} q_{(3,3)} \rangle_c \\
& + 6\langle q_{(1,1)} q_{(5,1)} \rangle_c - 90\langle q_{(1,1)} q_{(5,2)} \rangle_c + 300\langle q_{(1,1)} q_{(5,3)} \rangle_c - 360\langle q_{(1,1)} q_{(5,4)} \rangle_c + 144\langle q_{(1,1)} q_{(5,5)} \rangle_c \\
& + 15\langle q_{(2,1)} q_{(4,1)} \rangle_c - 105\langle q_{(2,1)} q_{(4,2)} \rangle_c + 180\langle q_{(2,1)} q_{(4,3)} \rangle_c - 90\langle q_{(2,1)} q_{(4,4)} \rangle_c \\
& - 15\langle q_{(2,2)} q_{(4,1)} \rangle_c + 105\langle q_{(2,2)} q_{(4,2)} \rangle_c - 180\langle q_{(2,2)} q_{(4,3)} \rangle_c + 90\langle q_{(2,2)} q_{(4,4)} \rangle_c \\
& + 10\langle q_{(3,1)}^2 \rangle_c - 60\langle q_{(3,1)} q_{(3,2)} \rangle_c + 40\langle q_{(3,1)} q_{(3,3)} \rangle_c + 90\langle q_{(3,2)}^2 \rangle_c - 120\langle q_{(3,2)} q_{(3,3)} \rangle_c + 40\langle q_{(3,3)}^2 \rangle_c \\
& + \langle q_{(6,1)} \rangle_c - 31\langle q_{(6,2)} \rangle_c + 180\langle q_{(6,3)} \rangle_c - 390\langle q_{(6,4)} \rangle_c + 360\langle q_{(6,5)} \rangle_c - 120\langle q_{(6,6)} \rangle_c,
\end{aligned}$$

✦ **Nonaka, Kitazawa, Esumi : arXiv 1604.06212**

Efficiency correction

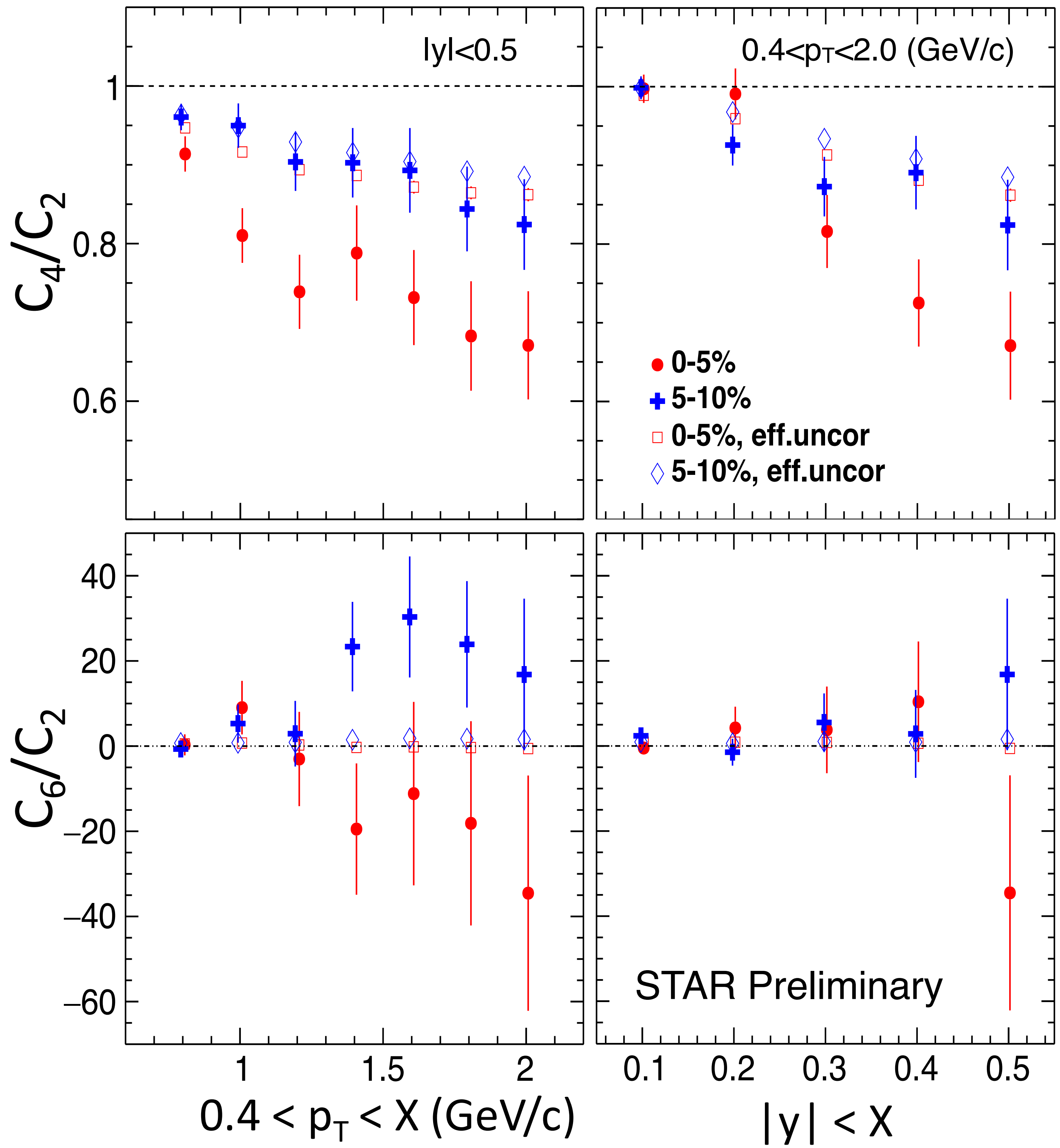
- ✓ It is important to apply efficiency correction with many efficiency bins in electric charge, p_T and phi.
- ✓ Using averaged efficiency would give wrong values for cumulants if there are different physics in different efficiency bins. arXiv 1604.06212
- ✓ Azimuthal dependence of efficiency as well as p_T dependence have been corrected.





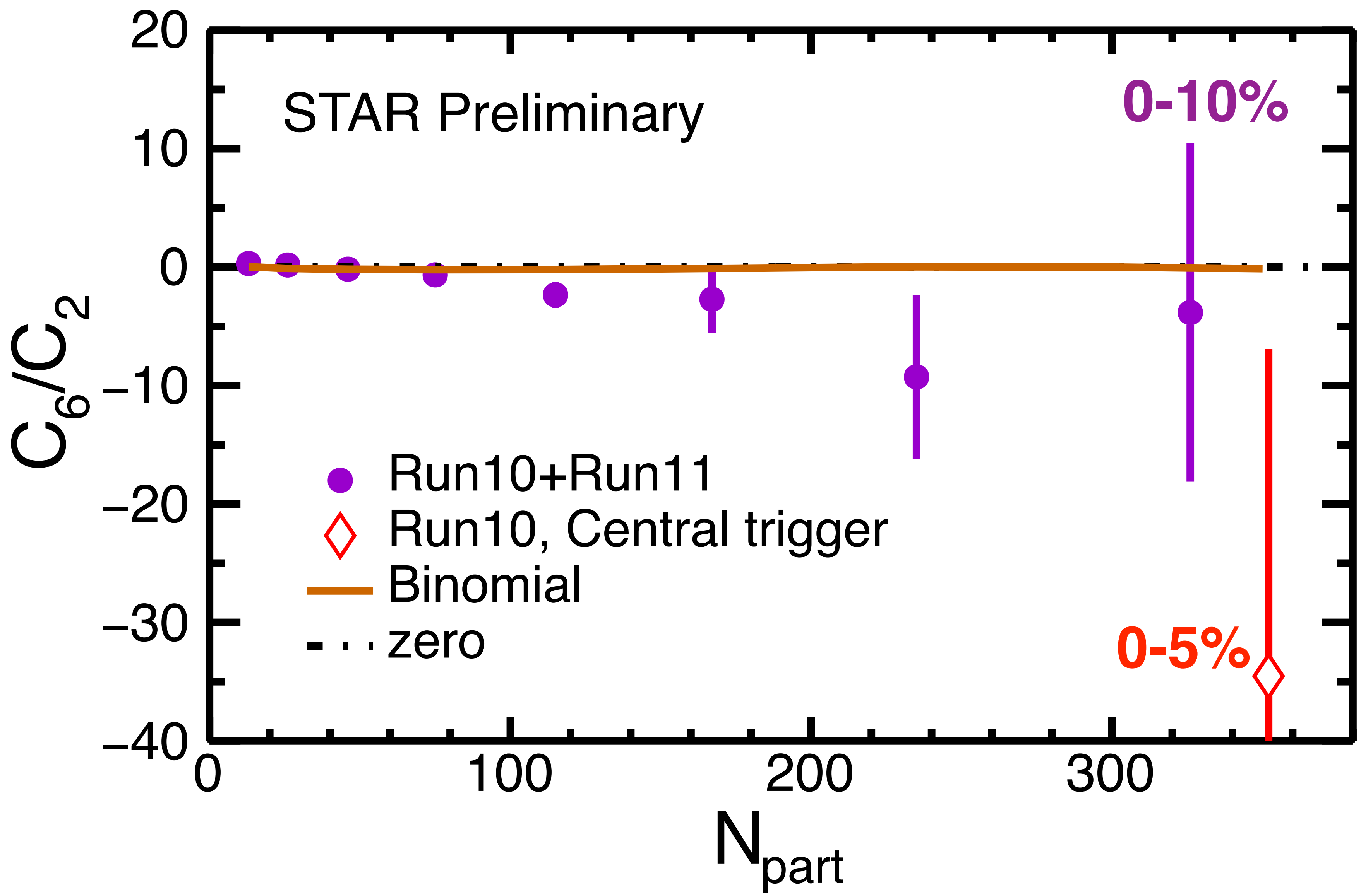
p_T and rapidity dependence

- ✓ ~160M events from the central trigger in Run10
- ✓ C_4/C_2 shows the monotonic decrease as a function of p_T and rapidity, which is predicted by baryon number conservation effect.
- ✓ C_6/C_2 shows opposite p_T dependence for 0-5% and 5-10% centralities, with large errors.
- ✓ C_6/C_2 shows no rapidity dependence within errors.



Centrality dependence

- ✓ Results from Run10 central trigger and Run11 minimum bias trigger are combined in order to reduce statistical errors.
- ✓ From peripheral to central collisions, the values of C_6/C_2 seem to decrease.
- ✓ Statistical uncertainties are large.



	0-10%	10-80%
Run10	160M	200M
Run11	50M	450M

➡ Number of events used in analysis. 0-10% in Run10 is from central trigger, while others are from minimum bias trigger.

Summary and Outlook

- We present the corrected results of C_6/C_2 of net-proton multiplicity distributions at $\sqrt{s_{NN}}$ = 200 GeV in Au+Au collisions as a function of centrality, p_T and rapidity.
- C_6/C_2 shows negative values from peripheral to central collisions systematically.
- STAR has collected a few billion event statistics in 2014 and 2016. Results from those data sets will also be merged to reduce statistical errors and derive more definite physics messages.

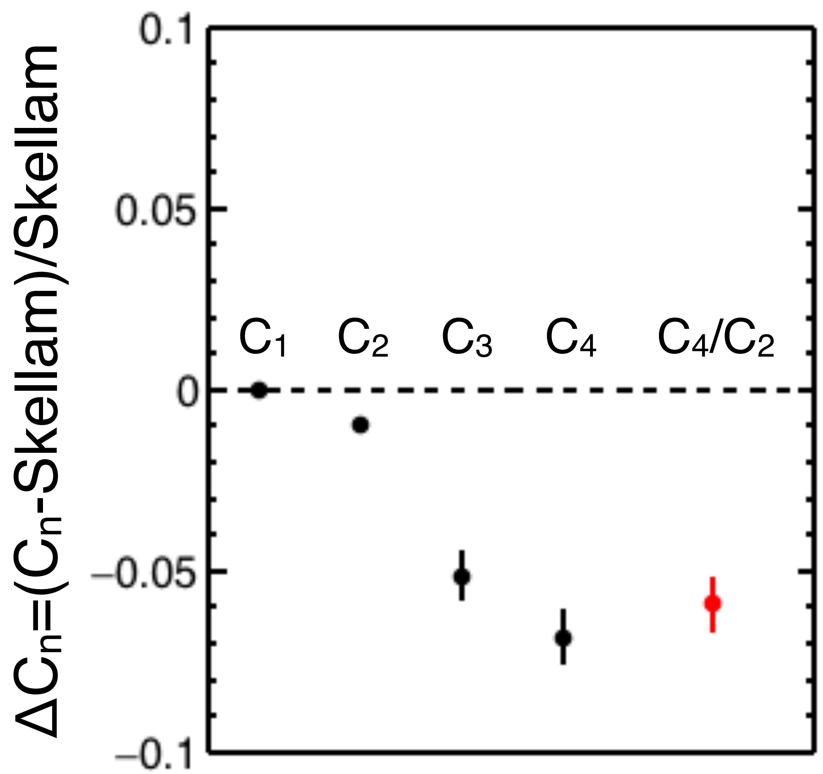
Multiplicity dependent efficiency

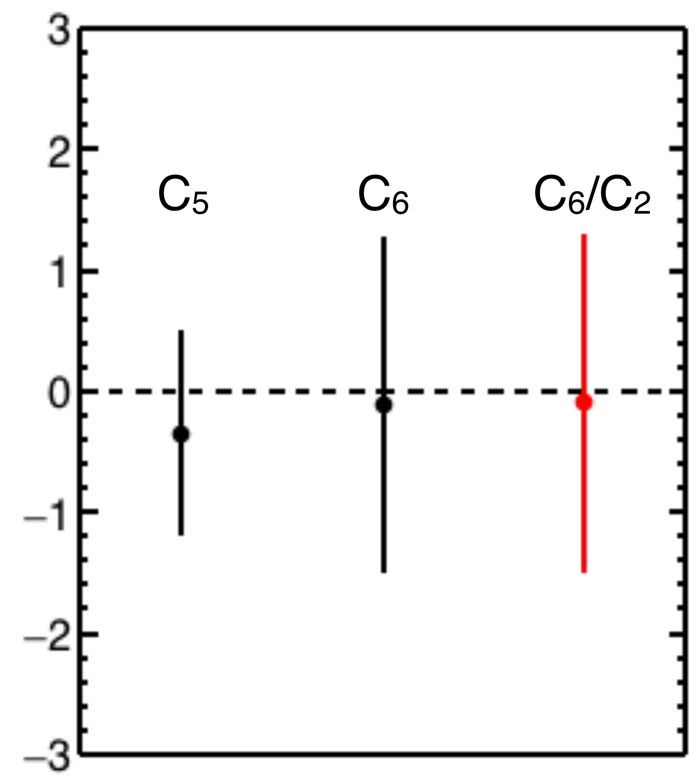
$$\underbrace{\varepsilon(N)}_{} = \varepsilon_0 + \varepsilon'(N - \langle N \rangle)$$

slope: ε'; event by event: $\varepsilon(N)$; averaged: ε_0; mean of Poisson: $\langle N \rangle$

	ε_0	ε'	<N>
proton	0.7	-0.0003	12
antiproton	0.68	-0.0003	10

- ✓ Two Poisson distributions are generated for p and pbar, and randomly sampled according to Binomial efficiencies.
- ✓ Efficiency is calculated event by event based on the equation above.
- ✓ Efficiency correction using averaged efficiency ε_0
- ✓ 1B events are proceeded. This is repeated with 30 times to estimate statistical errors.
- ✓ Relative deviation from Skellam expectation is shown.





- ✦ Finite deviation for 2nd to 4th cumulants and ratio.
- ✦ Deviations cannot be observed due to large errors for 5, 6 order cumulants and ratio.