Measurement of the cumulants of net-proton multiplicity distribution in Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV

Roli Esha

(for the STAR Collaboration)

Fluctuation of Conserved Quantities

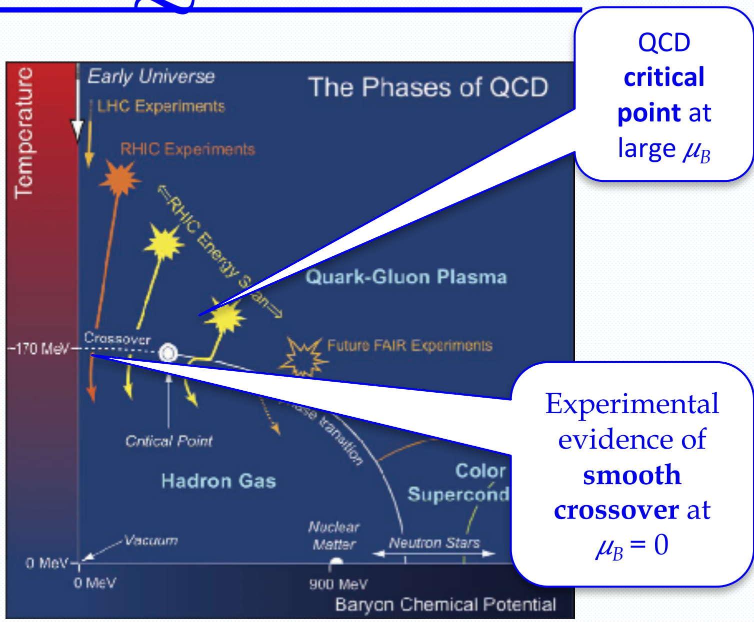
➢ Connection to the susceptibility of the system (χ)

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q/T)^n} \qquad q = B, Q, S$$

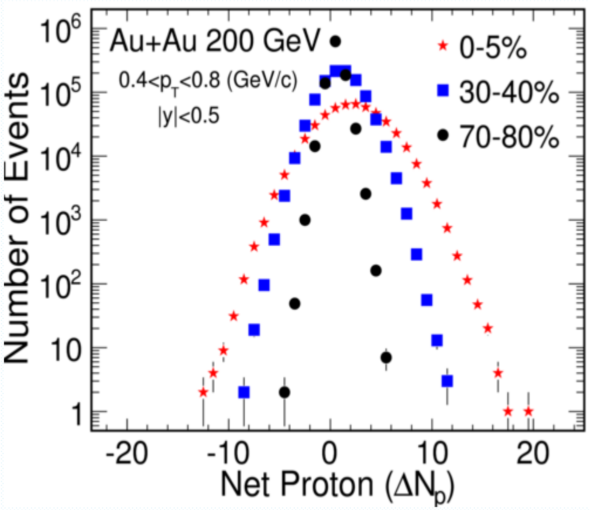
$$\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^{(6)}}{\chi_q^{(2)}} = \frac{C_{6,q}}{C_{2,q}}$$

➢ Higher order cumulants are more sensitive to the signatures of QCD phase transition

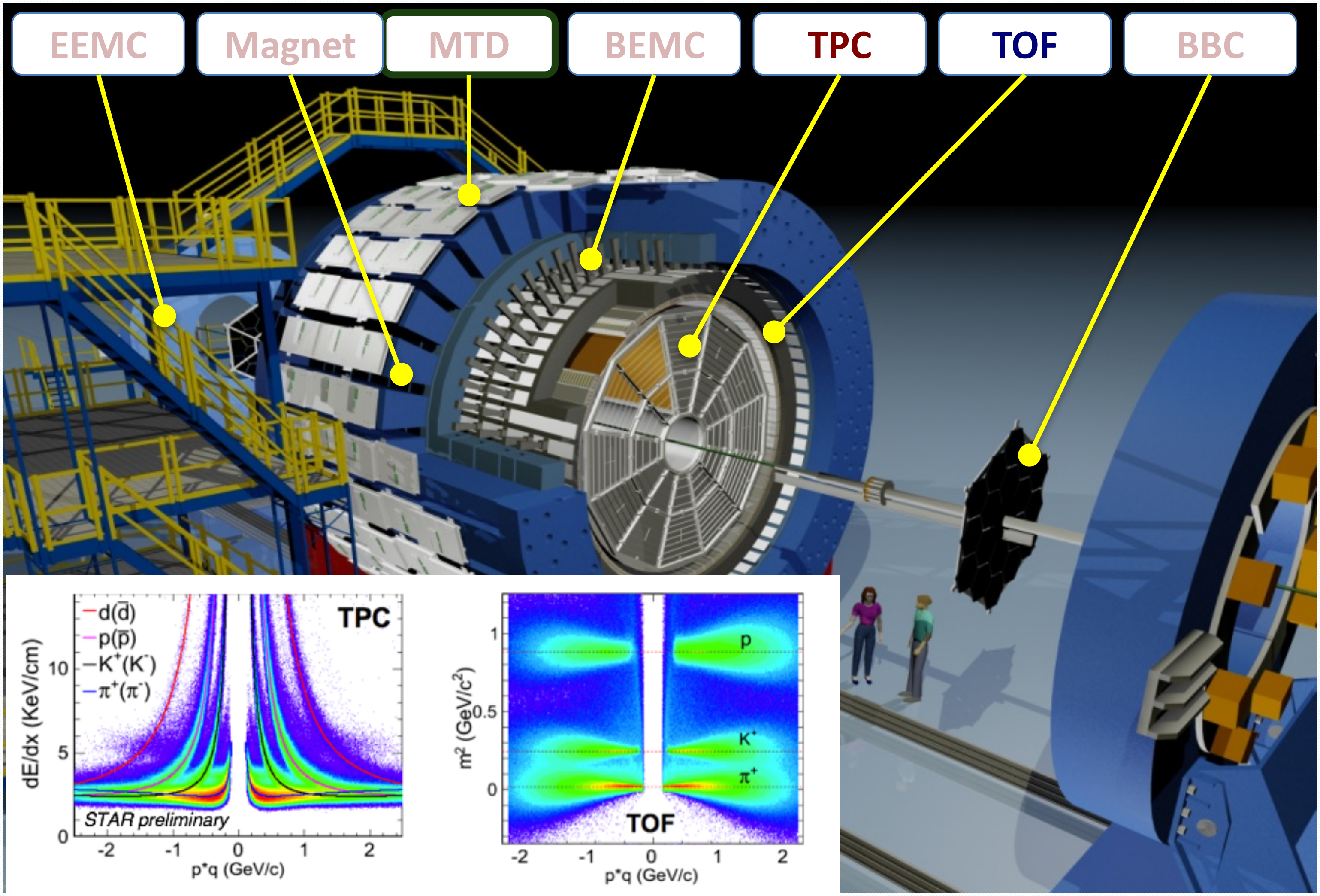
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).



STAR Collaboration, Phys.Rev.Lett. 105 (2010) 022302

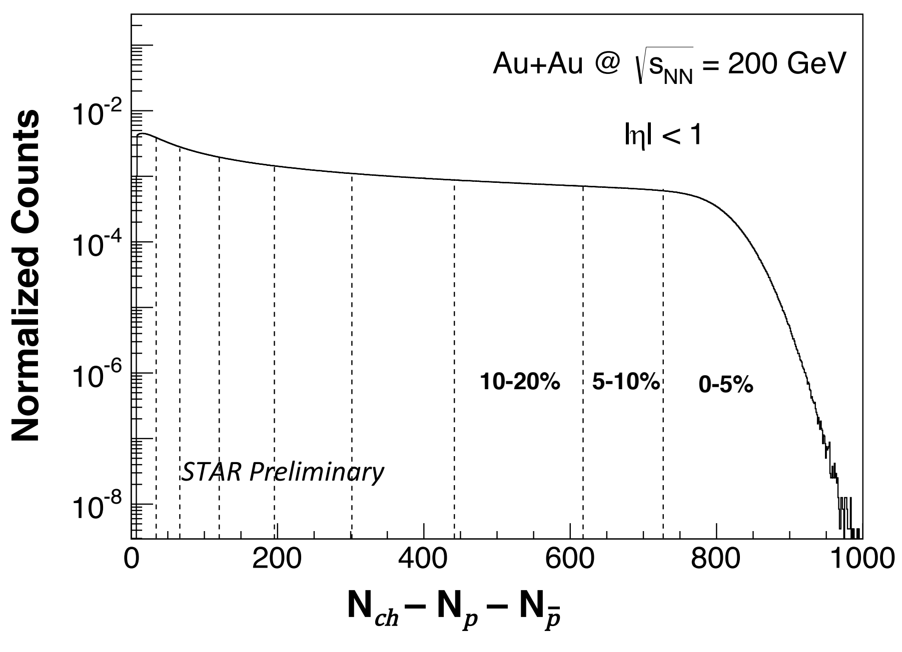


STAR Detector



Analysis Technique

- **Centrality determination**
  Use charged particles within $|\eta| < 1$, other than protons and anti-protons, to avoid **auto-correlations**



- **Centrality bin width correction**
  Evaluate cumulants for each centrality bin to suppress **volume fluctuations**

X. Luo and N. Xu, arXiv:1701.02105
STAR Collaboration, Phys.Rev.Lett. 105 (2010) 022302.
STAR Collaboration, Phys.Rev.Lett. 113 (2014) 092301 .

Analysis Technique

- **Error estimation**

Statistical errors are based on **Bootstrap technique** or the **Delta Theorem**.

$$Error\ (C_r) \propto \frac{\sigma^r}{\sqrt{n}}$$

$$Error\ (C_r/C_2) \propto \frac{\sigma^{r-2}}{\sqrt{n}}$$

σ : width of the distribution
n : Number of events

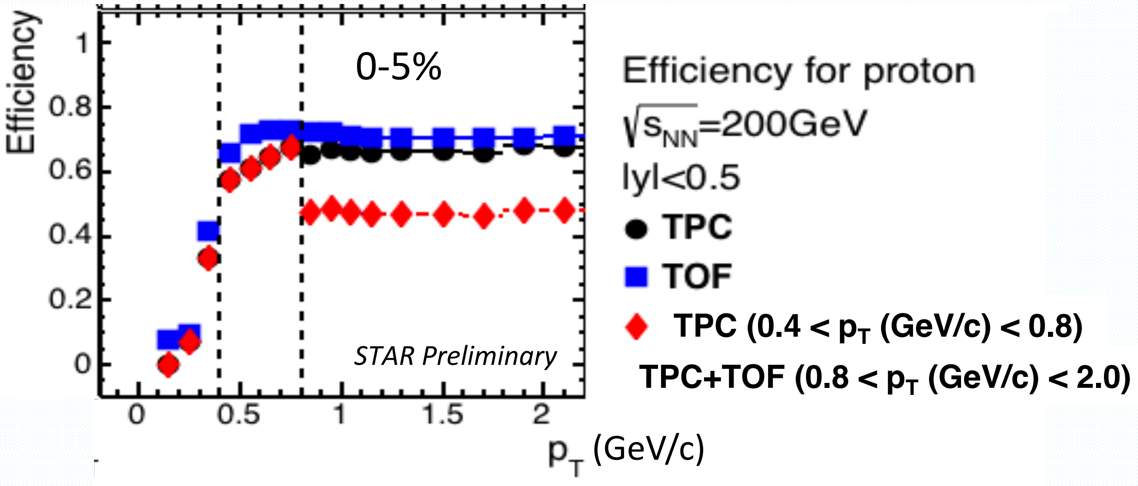
B. Efron et al. An Introduction to Bootstrap, Chapman & Hill (1993).
X. Luo, J. Xu, B. Mohanty, N. Xu, J. Phys. G 40, 105104 (2013)

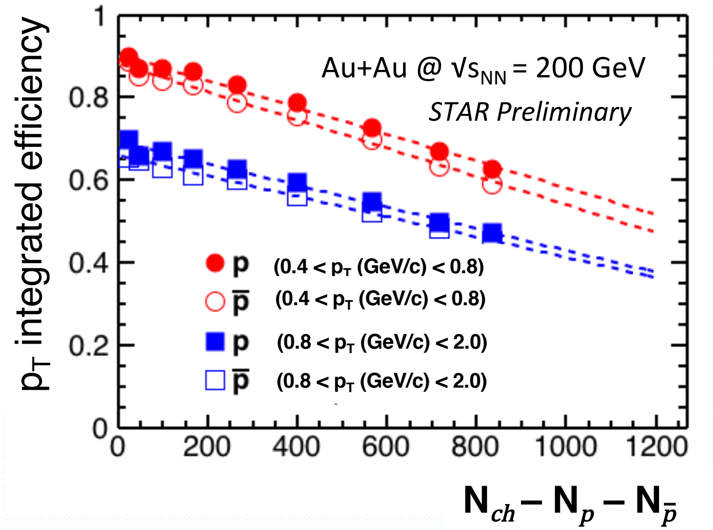
- **Efficiency correction**

Express the cumulants in terms of the factorial moments or factorial cumulants, which can be easily efficiency corrected by assuming **binomial response function for efficiency**.

Based on factorial cumulants: T. Nonaka, M. Kitazawa and S. Esumi, In preparation.
Based on factorial moments: A. Bzdak and V. Koch, PRC91, 027901 (2015). X. Luo, PRC91, 034907(2015). X. Luo and N. Xu, 1701.02105

Detector Efficiency





$$< \epsilon > = \frac{\int_{p_{T1}}^{p_{T2}} \epsilon(p_T)\, f(p_T)\, dp_T}{\int_{p_{T1}}^{p_{T2}} f(p_T)\, dp_T}$$

- p_T – integrated efficiency is calculated as a function of multiplicity
- Efficiency correction is applied at each multiplicity bin

Search for the QCD Critical Point

Cumulants and Correlation Function

- Higher order cumulants are more sensitive to the correlation lengths

$$C_2 = \langle(\delta N)^2\rangle \sim \xi^2; \; C_3 = \langle(\delta N)^3\rangle \sim \xi^{4.5}; \; C_4 = \langle(\delta N)^4\rangle \sim \xi^7 \quad \text{with} \quad \delta N = N - \langle N\rangle$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009); M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009); Y. Hatta, M. Stephanov, Phys. Rev. Lett. 91, 102003 (2003).

- Relation between cumulants (C_n) and correlation functions ($\hat{\kappa}_n$)

$$\hat{\kappa}_1 = C_1 \qquad C_1 =< N >$$

$$\hat{\kappa}_2 = C_2 - C_1 \qquad C_2 =< N > + \hat{\kappa}_2$$

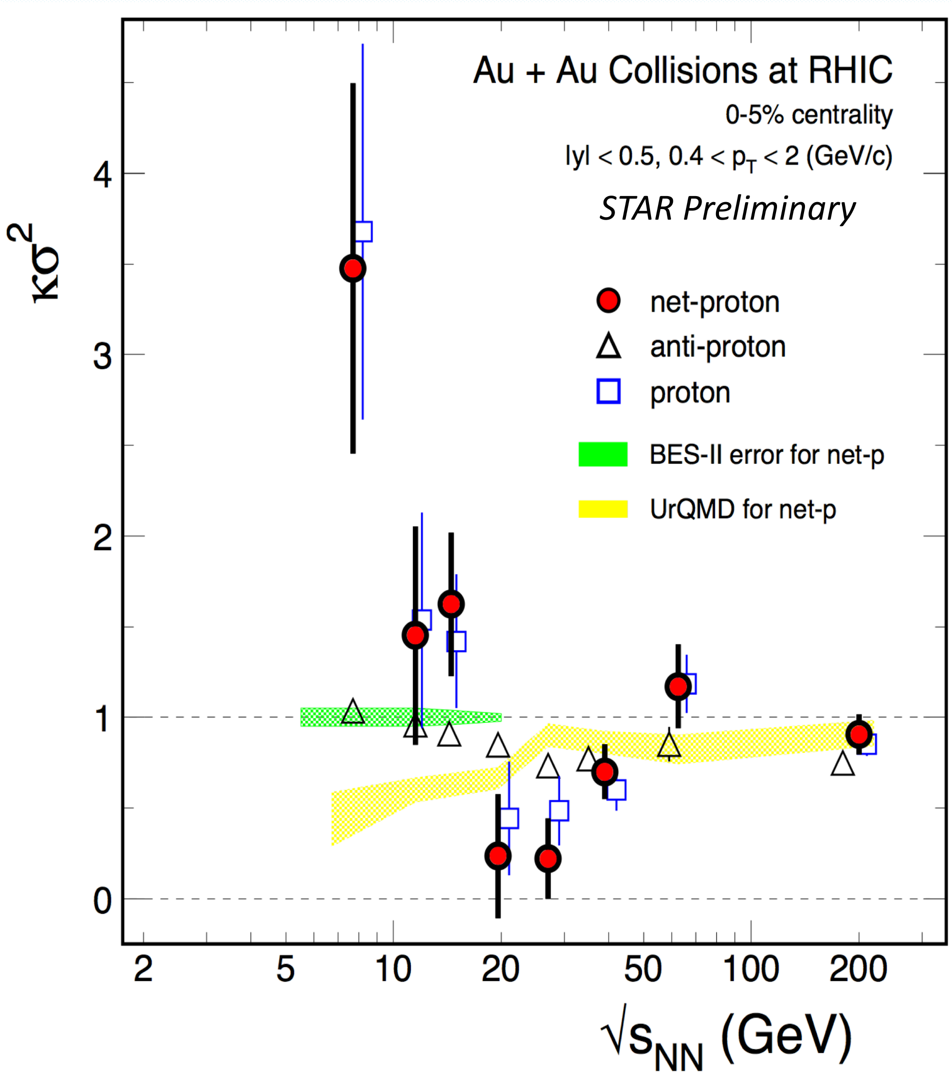
$$\hat{\kappa}_3 = C_3 - 3C_2 + 2C_1 \qquad C_3 =< N > + 3\hat{\kappa}_2 + \hat{\kappa}_3$$

$$\hat{\kappa}_4 = C_4 - 6C_3 + 11C_2 - 6C_1 \qquad C_4 =< N > + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

$$\hat{\kappa}_2 \propto \xi^2, \hat{\kappa}_3 \propto \xi^{4.5}, \hat{\kappa}_4 \propto \xi^7$$

B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016); A. Bzdak, V. Koch, N. Strodthoff, arXiv:1607.07375;
A. Bzdak, V. Koch, V. Skokov, arXiv:1612.05128

Fourth Order Net Proton Fluctuation

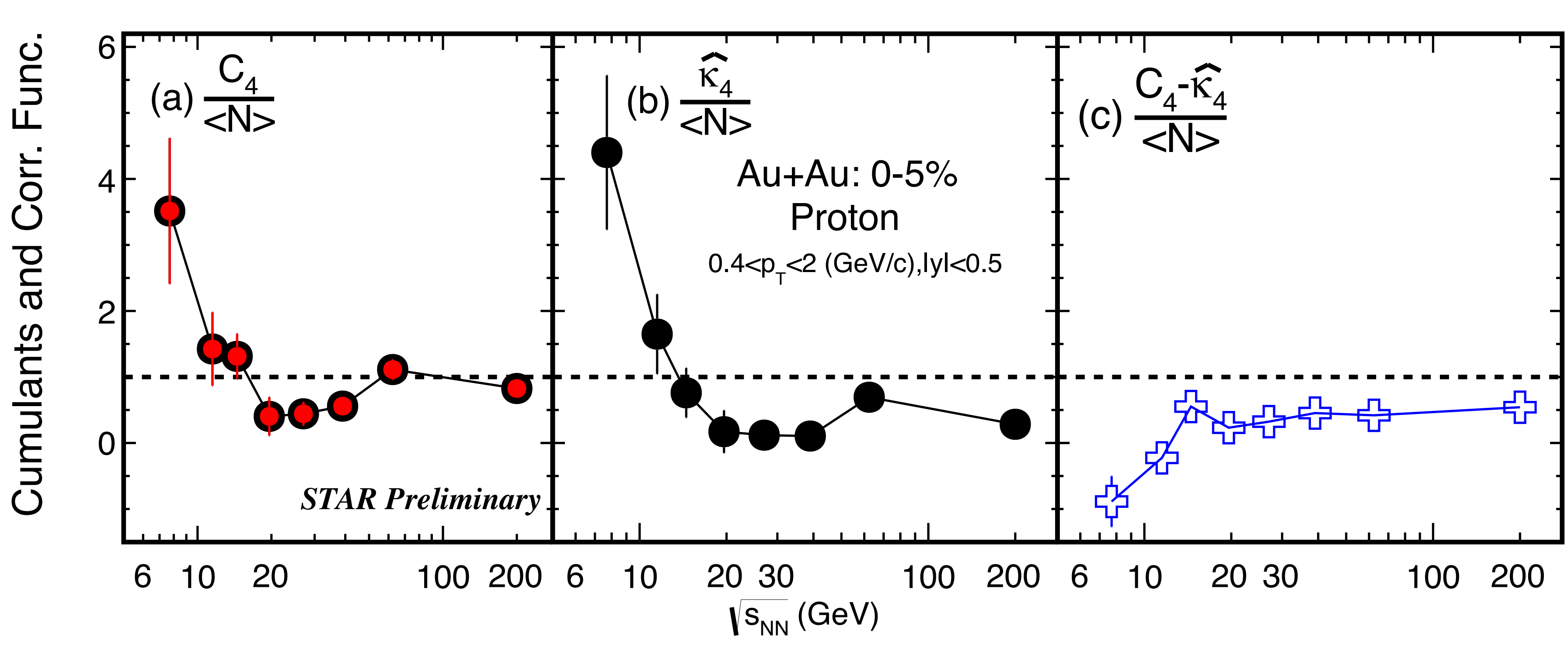


- Non-monotonic energy dependence is observed for 4th order net-proton, proton fluctuations in most central Au+Au collisions.

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

- UrQMD results show monotonic decrease with decreasing collision energy.

Contributions from Four-Particle Correlations



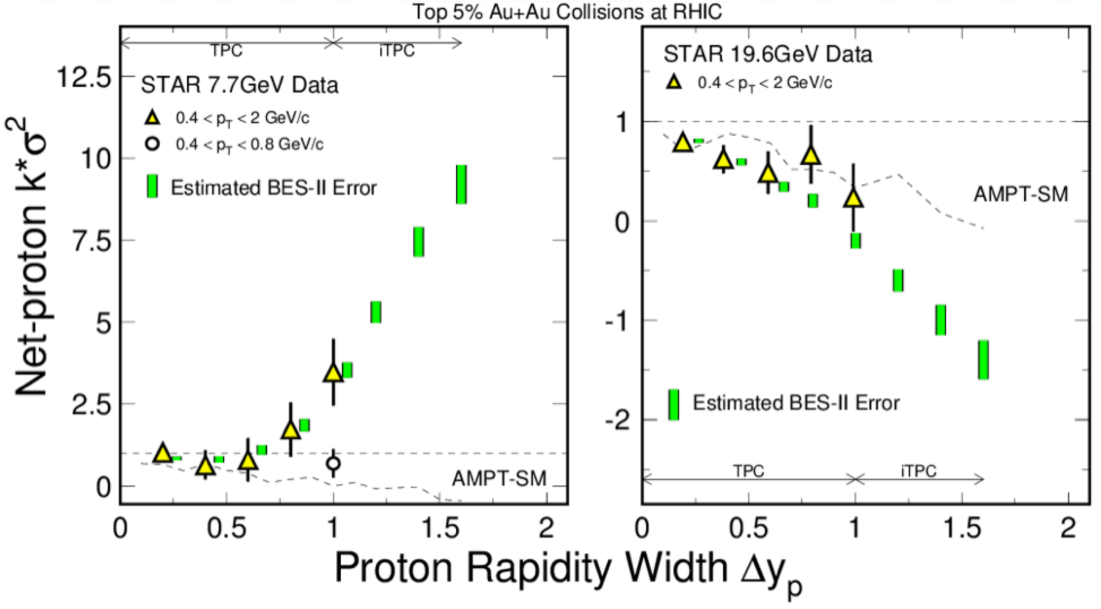
- Four-particle correlations contribute dominantly to the observed non-monotonicity.

Summary - I

- Non-monotonic energy dependence of net-proton and proton C_4/C_2 is observed for 0–5% central Au+Au collisions.

- Four-particle correlations contribute dominantly to the observed non-monotonicity.

- More data will be collected in BES-II at $\sqrt{s_{NN}}$ = 7.7 – 19.6 GeV in 2019–2020 with detector upgrades.



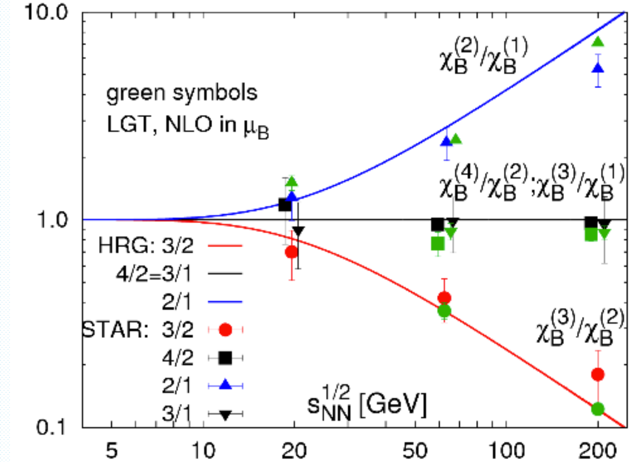
STAR Collaboration, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619

The measurement of net-proton sixth-order cumulant at small μ_B and its comparison to Lattice QCD

T. Nonaka
Poster ID 239

Connections with Lattice QCD

F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)
STAR Collaboration, Phys.Rev.Lett. 112 (2014) 032302.



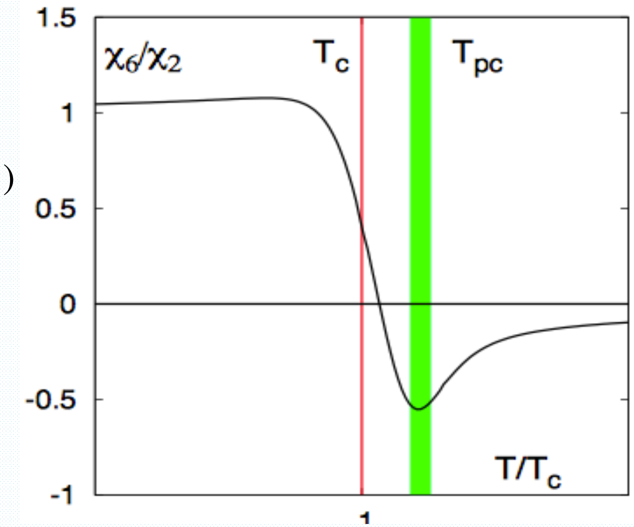
- LQCD predicts a "crossover" for $\mu = 0$
  Y. Aoki, Nature 443, 675(2006)

- No established approach to do QCD calculations at finite baryon chemical potential

- By putting $\mu_Q = \mu_S = 0$ and using Taylor expansion, the equation of state for finite μ_B:

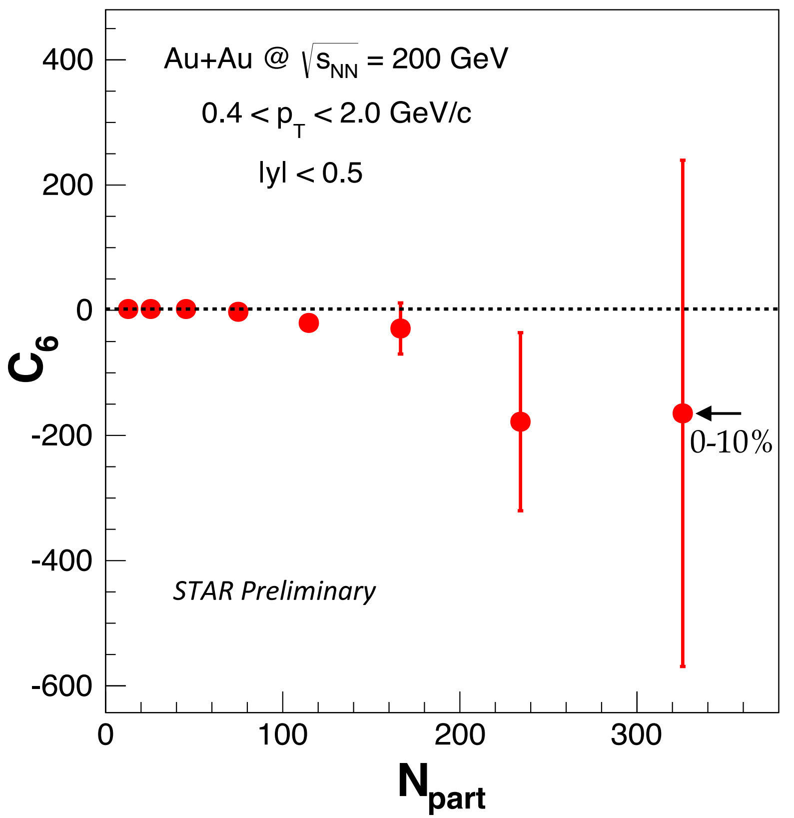
$$\frac{P(T,\mu_B)-P(T,0)}{T^4} = \frac{1}{2}\chi_2^B(T)\left(\frac{\mu_B}{T}\right)^2 \times \left[1+\frac{1}{4}\frac{\chi_4^B(T)}{\chi_2^B(T)}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{360}\frac{\chi_6^B(T)}{\chi_2^B(T)}\left(\frac{\mu_B}{T}\right)^4\right] + O(\mu_B^8)$$

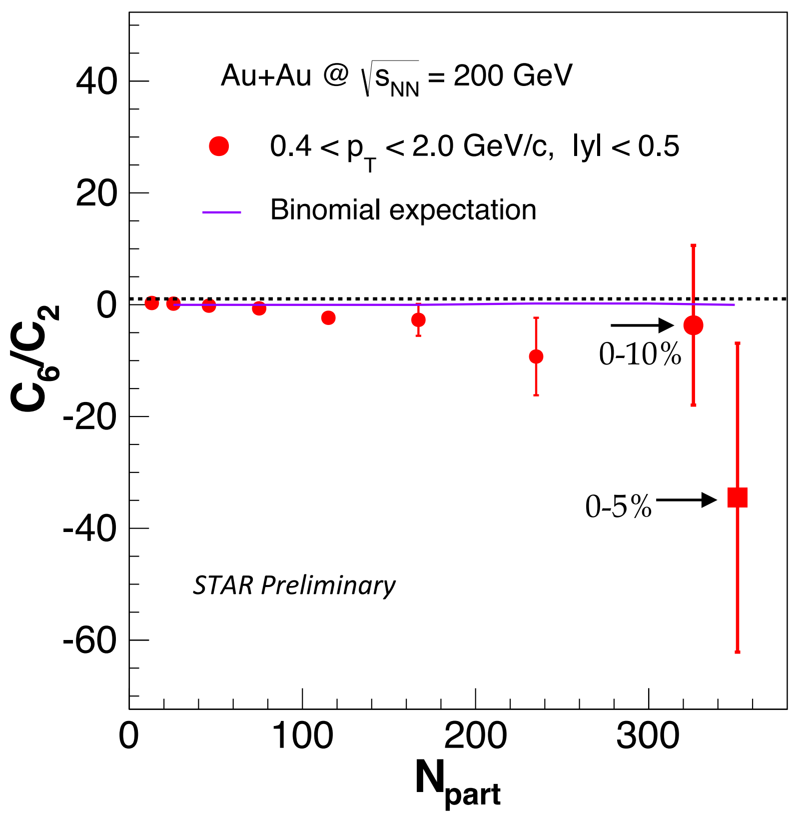
- The sixth order cumulants of baryon number is expected to be negative at chiral transition temperature



B. Friman, F. Karsch, K. Redlich, V. Skokov Eur. Phys. J. C 71, 1694 (2011)

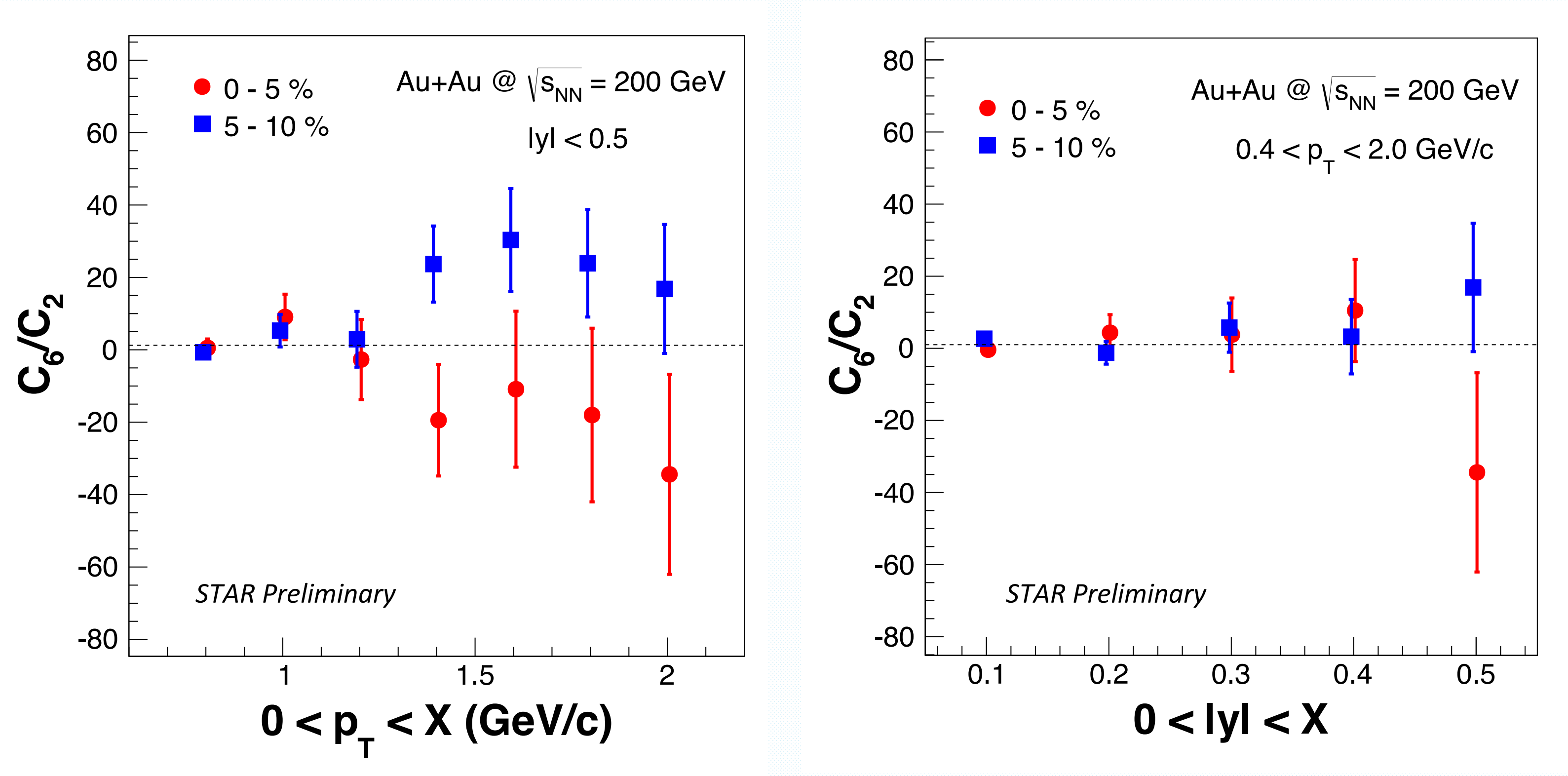
Net-Proton Sixth Cumulant





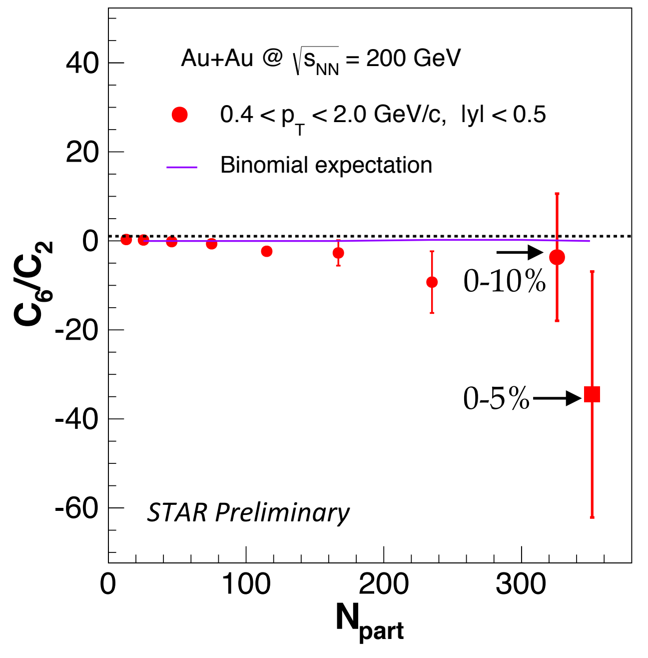
- Combined data of Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV from year 2010 and 2011: 200 M (0 – 10 %) and 650 M (10 – 80 %) events
- The C_6 and C_6/C_2 is negative for central collisions with large uncertainties

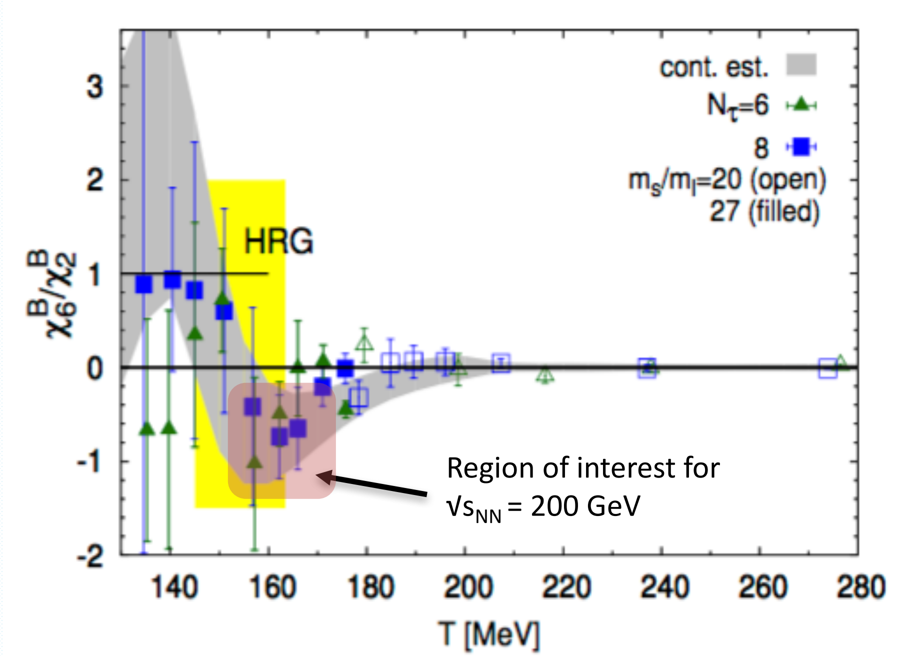
Acceptance Dependence



- Around 160 M events are analyzed for 0-10% central collisions for Au + Au at $\sqrt{s_{NN}}$ = 200 GeV with central trigger from year 2010

Comparison with LQCD





A. Bazavov et al, arXiv:1701.04325.

- C_6/C_2 for most central collisions is negative with large uncertainties
- Some differences between experiment and LQCD measurements:
  1. Net-proton is not equivalent to net-baryon
  2. Limited phase space
  3. $\mu_B \neq 0$ ($\mu_B \sim 20$ MeV at 200 GeV)

Summary - II

- We report the efficiency corrected sixth order cumulant of the net-proton multiplicity distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.
- Centrality, transverse momentum and rapidity dependence of the ratio C_6/C_2 are presented.
- C_6 and C_6/C_2 are negative for central collisions with large statistical uncertainty.
- Assessment of systematic errors is underway.
- Combining the data taken in year 2014 and 2016, with more than 2 billion events, we can get a better control on the statistical errors for C_6/C_2.

Thank you !

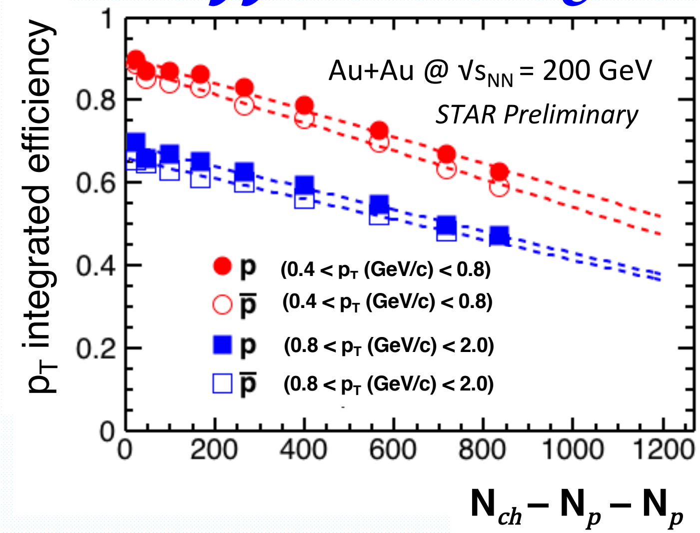
Back-up

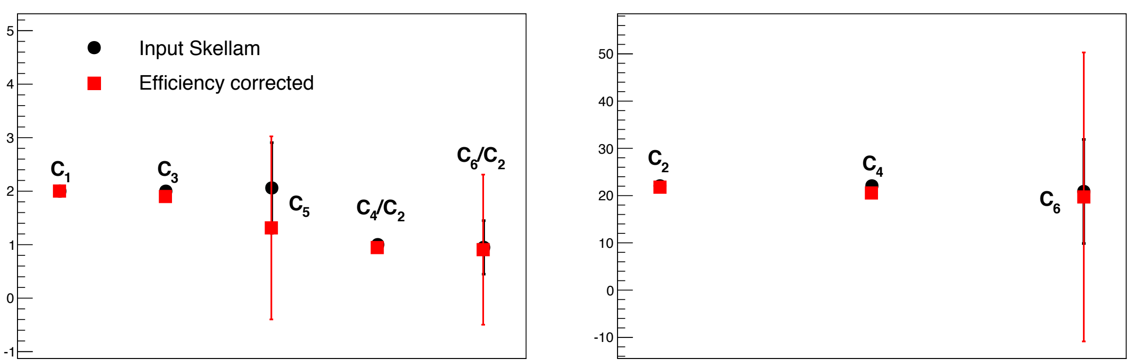
Multiplicity Dependent Efficiency

$$\varepsilon(N) = \varepsilon_0 + \varepsilon'(N - \langle N \rangle)$$

- ε_0: averaged
- ε': slope
- N: event by event
- $\langle N \rangle$: mean of Poisson

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





A. Bzdak et al Phys.Rev. C94, 064907 (2016) .

- Analyzed for 1B events
- Protons and anti-protons are sampled from Poisson distribution with Binomial efficiency
- Deviations for efficiency corrected higher order cumulants from the input Skellam are within statistical errors