# Search for the QCD Critical Point -

# Conserved Charge Fluctuations and Light Nuclei Production at RHIC Beam Energy Scan


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Heavy Flavor Production and Forty Years of Quark-Gluon Plasma

10/08-10/11/2018

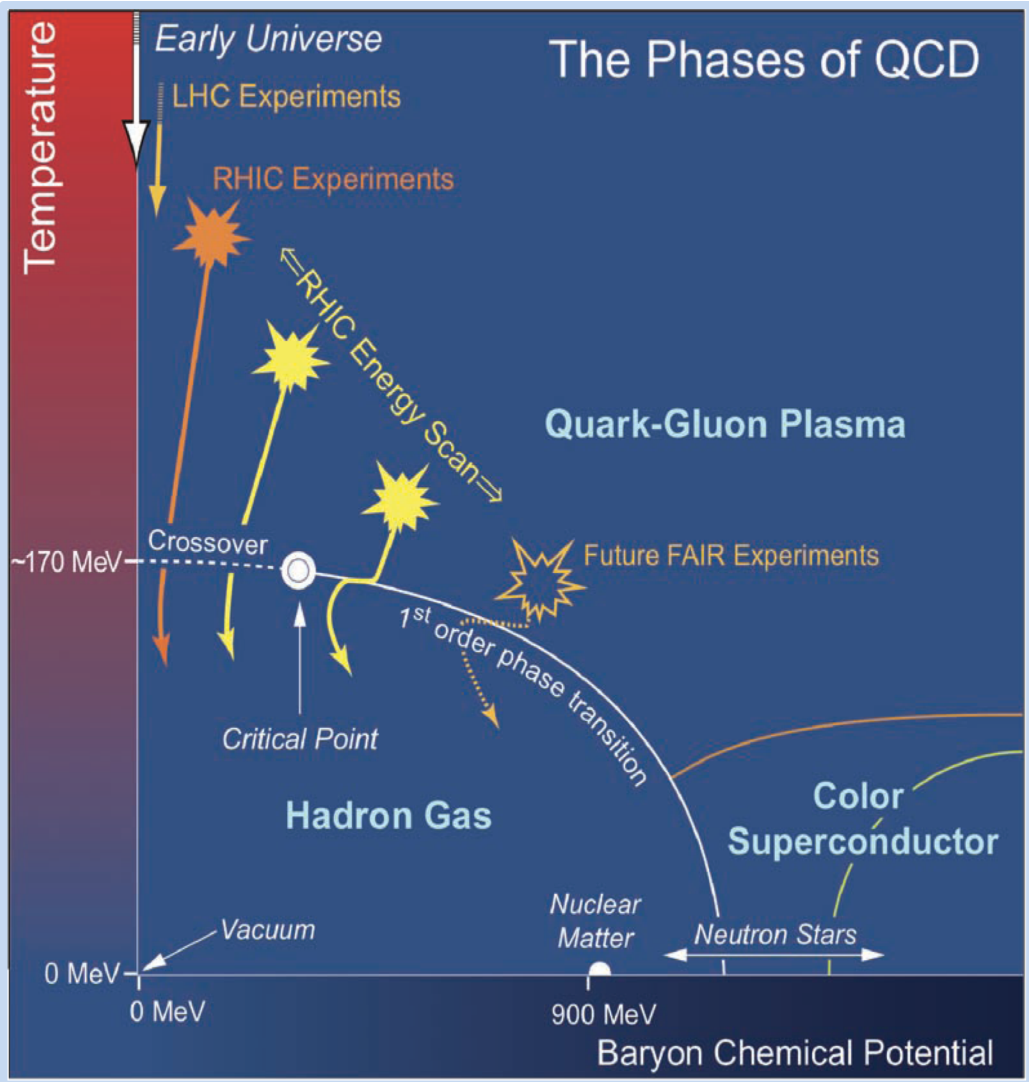
# *Happy Birthday to Edward*

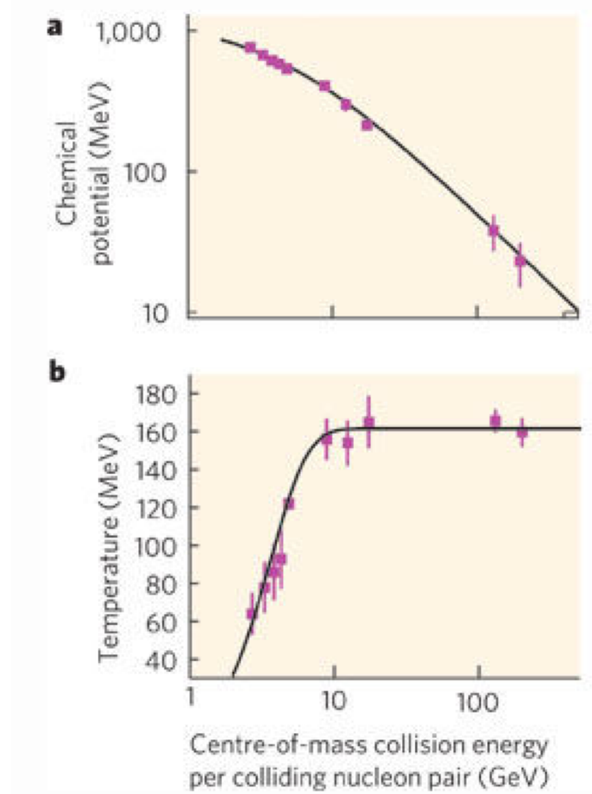
After giving seminar at Stony Brook University, April 30, 2015. (photo taken by Jiangyong Jia).

# Outline

1. Introduction
2. Conserved Charge Fluctuations
3. Light Nuclei (d, t) Production
4. Summary

# QCD Phase Structure and Beam Energy Scan




*PBM&Johanna, Nature* **448**, 302-309 (2007)

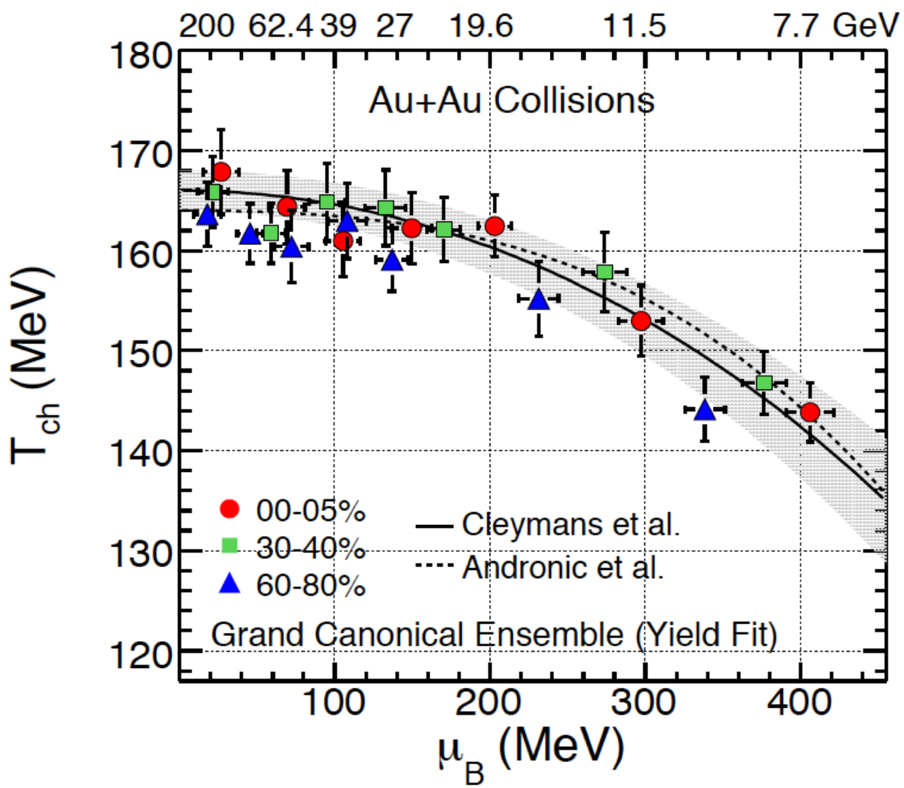
**Can we find signature of QCD phase transition in heavy-ion collisions ?**

1. **Crossover**
2. **Critical point**
3. **1st order phase transition (P.T.)**

# RHIC Beam Energy Scan I (2010-2014)

| $\sqrt{s_{NN}}$ (GeV) | Events ($10^6$) | Year | $^*\mu_B$ (MeV) | $^*T_{CH}$ (MeV) |
|---|---|---|---|---|
| 200 | 350 | 2010 | 25 | 166 |
| 62.4 | 67 | 2010 | 73 | 165 |
| 39 | 39 | 2010 | 112 | 164 |
| 27 | 70 | 2011 | 156 | 162 |
| 19.6 | 36 | 2011 | 206 | 160 |
| 14.5 | 20 | 2014 | 264 | 156 |
| 11.5 | 12 | 2010 | 316 | 152 |
| 7.7 | 4 | 2010 | 422 | 140 |

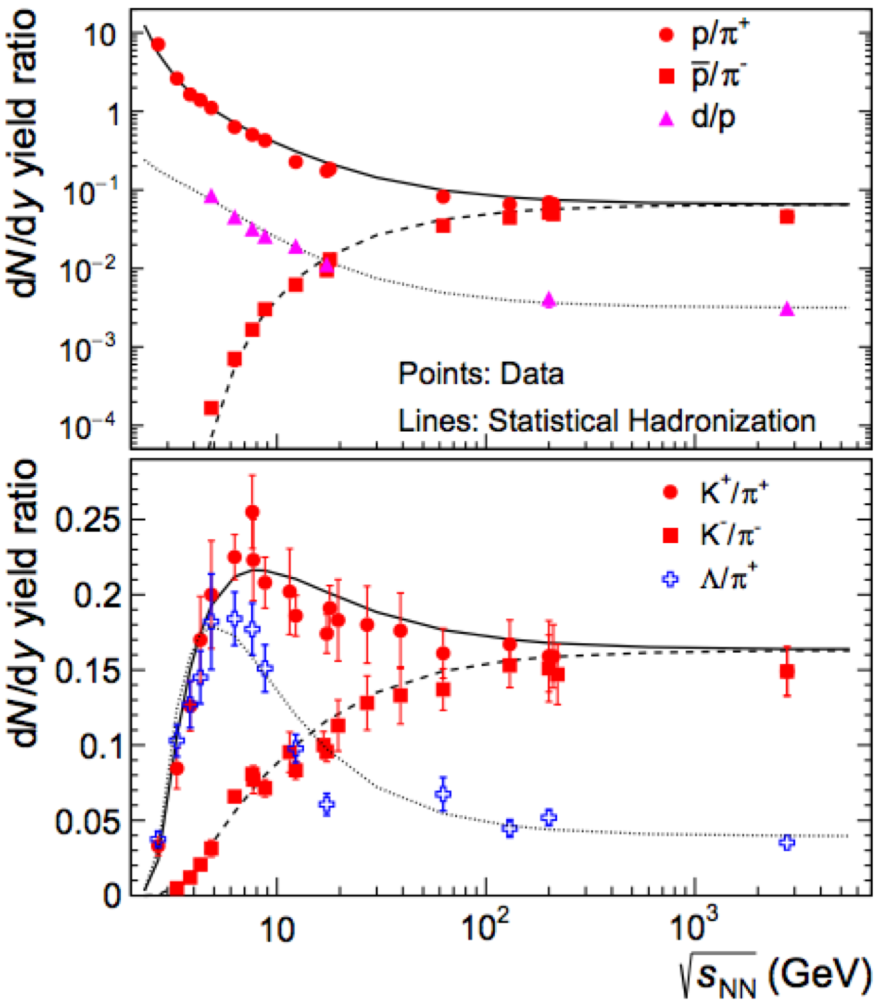
*($\mu_B$, $T_{CH}$) : J. Cleymans et al., PRC 73, 034905 (2006)

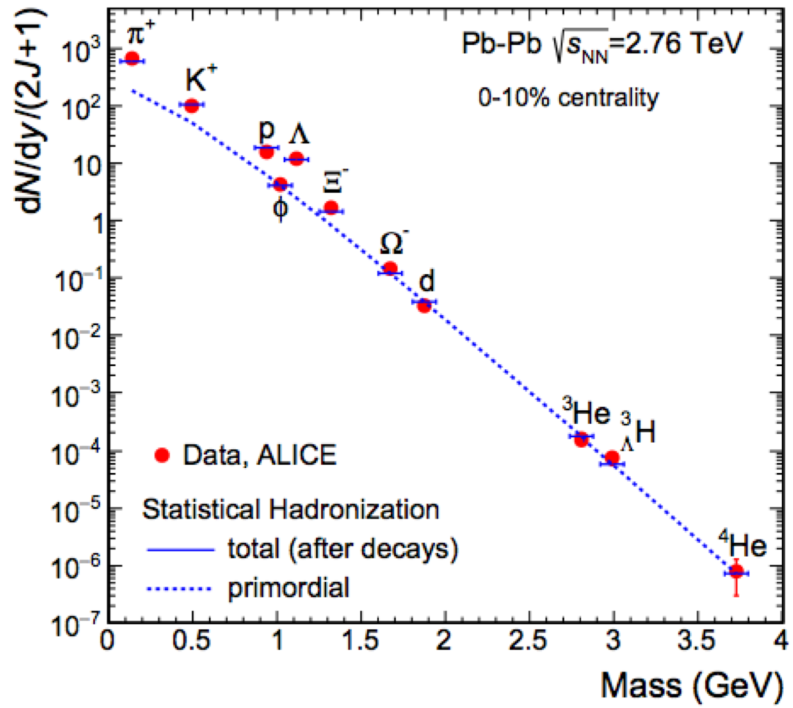



STAR: Phys. Rev. C 96, 044904 (2017).

Access the QCD phase diagram: vary collision energies/centralities.

# How to find the QCD phase transition signal ?




A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561, 321 (2018).

Does this mean the phase structures (or EoS) at high baryon density are the same as small baryon density ? All crossover ?

How to find 1st order P.T. or critical point signal ? need to look at: Fluctuation and Correlation

- Event-by-Event fluctuations.
- Baryon clustering: Light nuclei production

# Event-by-Event Fluctuations and QCD Critical Point

**20 years ago…**

PHYSICAL REVIEW D, VOLUME 60, 114028

**Event-by-event fluctuations in heavy ion collisions and the QCD critical point**

M. Stephanov
*Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794-3840*

K. Rajagopal
*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

E. Shuryak
*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800*
(Received 23 March 1999; published 10 November 1999)

**Citation:939**

**Signatures of the Tricritical Point in QCD**

M. Stephanov[1], K. Rajagopal[2] and E. Shuryak[3]
[1] *Institute for Theoretical Physics, State University of New York, Stony Brook, NY 11794-3840*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139*
[3] *Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800*
(June 1, 1998; ITP-SB-98-39, MIT-CTP-2748, SUNY-NTG-98-17)

Several approaches to QCD with two *massless* quarks at finite temperature $T$ and baryon chemical potential $\mu$ suggest the existence of a tricritical point on the boundary of the phase with spontaneously broken chiral symmetry. In QCD with *massive* quarks there is then a critical point at the end of a first order transition line. We discuss possible experimental signatures of this point, which provide information about its location and properties. We propose a combination of event-by-event observables, including suppressed fluctuations in $T$ and $\mu$ and, simultaneously, enhanced fluctuations in the multiplicity of soft pions.

**Citation:1113**

**Charged Particle Ratio Fluctuation as a Signal for QGP**

S. Jeon* and V. Koch†
*Nuclear Science Division*
*Lawrence Berkeley National Laboratory*
*Berkeley, CA 94720, USA*

letter we argue that the event-by-event fluctuations of the ratio of the positively charged gatively charged pions provides a signal of quark-gluon plasma. The fact that quarks ional charges is ultimately responsible for this distinct signal.

**Citation:515**

## Proposed experimental observables:

1. **Pion multiplicity fluctuations.**
2. **Mean $p_T$ fluctuations.**
3. **Particle ratio fluctuations**

**Scan T-μ Plane: Non-monotonic variation with energy,centrality or rapidity.**

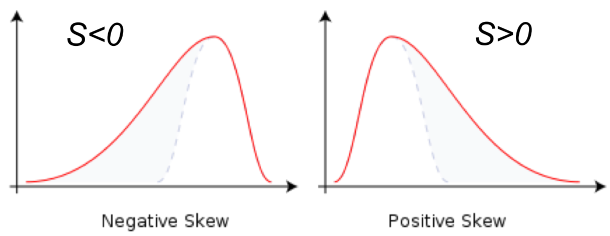
# Higher Moments of Conserved Quantities (B, Q, S)

1. Higher order cumulants/moments: describe the shape of distributions and quantify fluctuations. (sensitive to the correlation length (ξ))

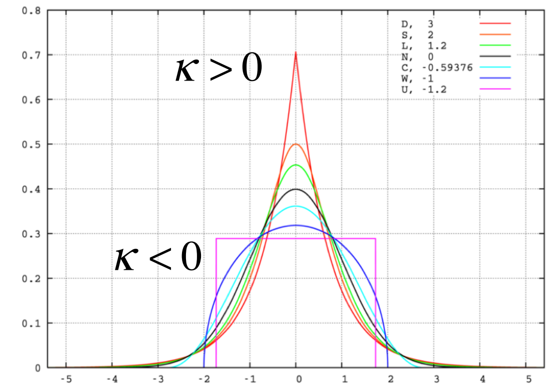
$$< \delta N >= N - < N >$$
$$C_1 = M =< N >$$
$$C_2 = \sigma^2 =< (\delta N)^2 >$$
$$C_3 = S\sigma^3 =< (\delta N)^3 >$$
$$C_4 = \kappa\sigma^4 =< (\delta N)^4 > -3 < (\delta N)^2 >^2$$

$$\left\langle (\delta N)^3 \right\rangle_c \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle_c \approx \xi^7$$

Skewness ($S$) → asymmetry




Kurtosis ($\kappa$) → Sharpness

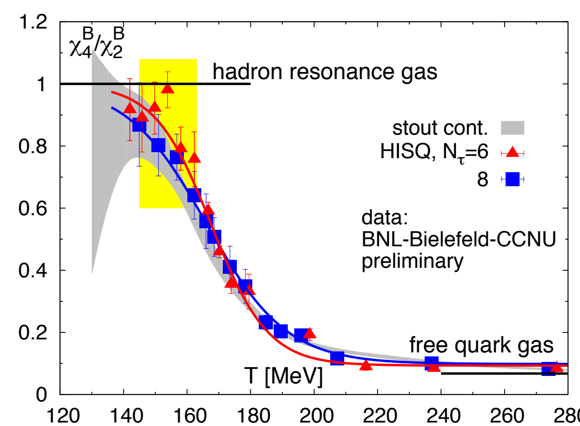



*M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).*
*M.Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).*
*M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).*

2. Direct connect to the susceptibility of the system.

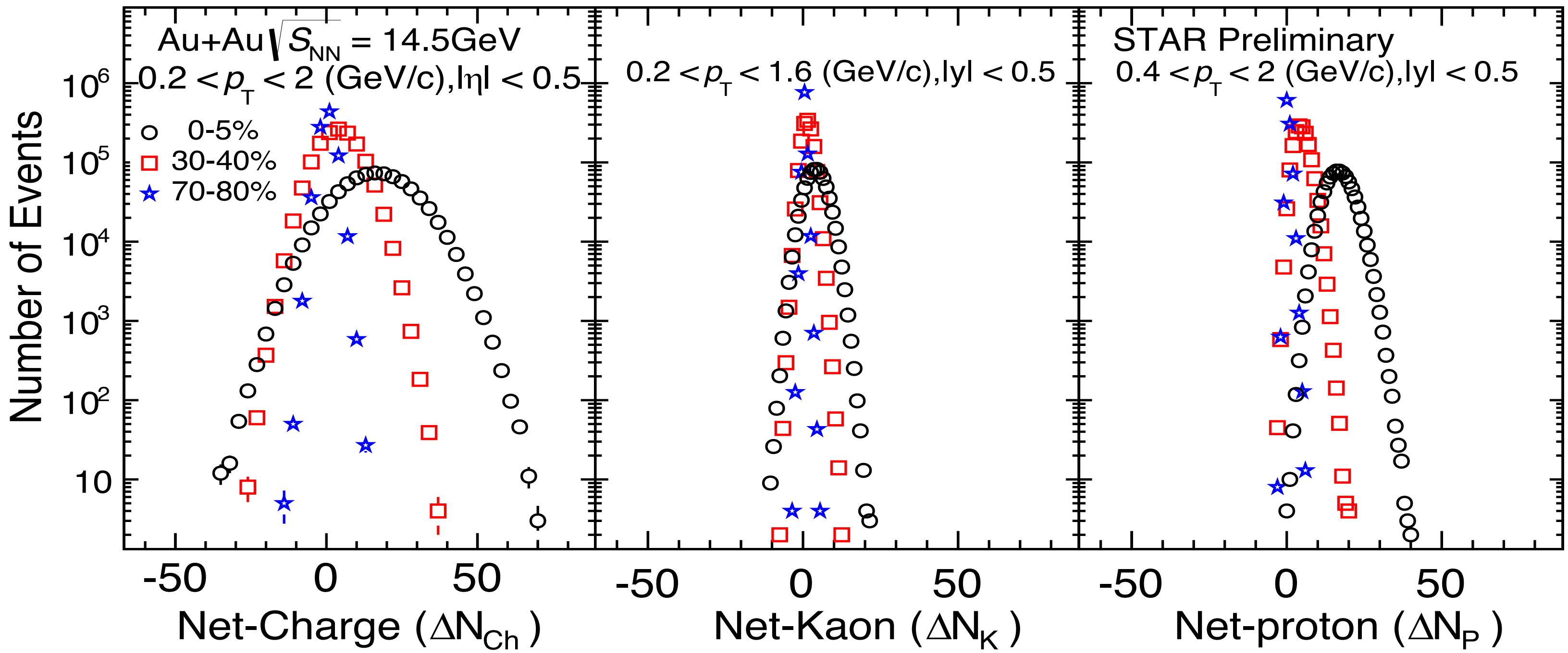
$$\frac{\chi_q^4}{\chi_q^2} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^3}{\chi_q^2} = S\sigma = \frac{C_{3,q}}{C_{2,q}},$$

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




*S. Ejiri et al,Phys.Lett. B 633 (2006) 275. Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694. F. Karsch and K. Redlich , PLB 695, 136 (2011).S. Gupta, et al., Science, 332, 1525(2012). A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903*

# Data Analysis Methods




Effects needed to be addressed to get final moments/cumulants:

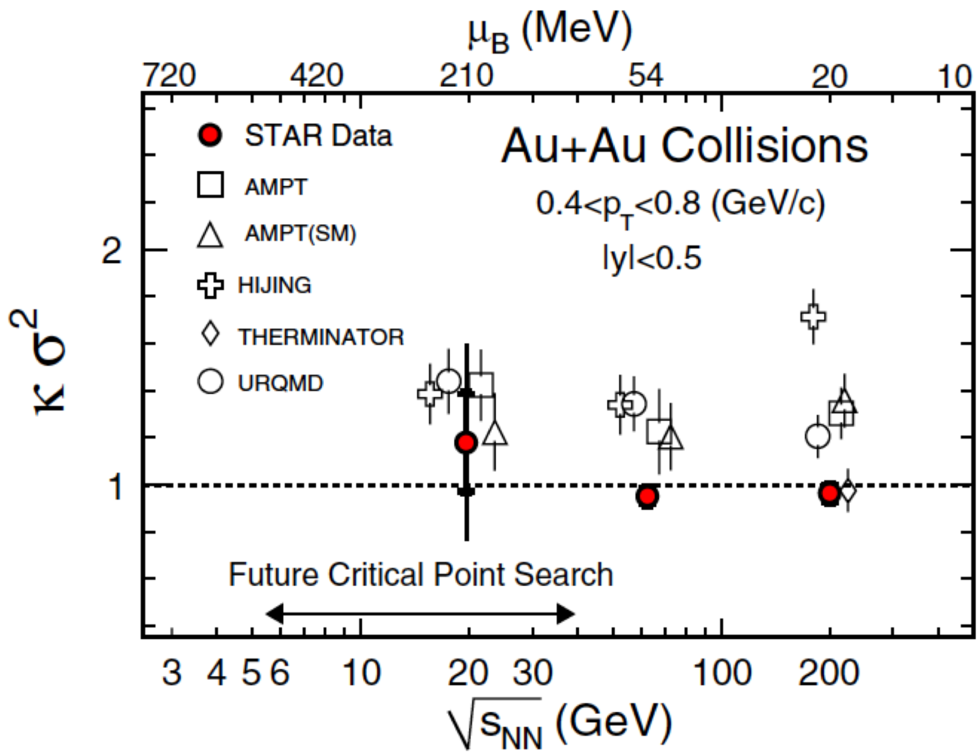
1. Statistical errors estimation : Delta theorem or bootstrap
2. Avoid auto-correlation effects: New centrality definition.
3. Suppress volume fluctuation：Centrality bin width correction
4. Finite detector efficiency correction (binomial response func.)

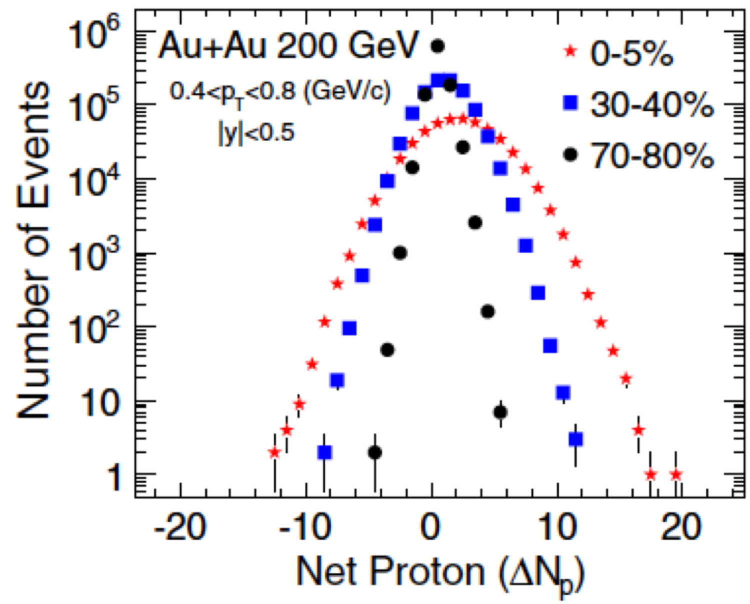
*X.Luo, et al. J. Phys. G39, 025008 (2012); A. Bzdak and V. Koch, PRC86, 044904 (2012); X.Luo, et al. J. Phys. G40,105104(2013); X.Luo, Phys. Rev. C 91, 034907 (2015); A . Bzdak and V. Koch, PRC91, 027901 (2015). T. Nonaka et al., PRC95, 064912 (2017). M. Kitazawa and X. Luo, PRC96, 024910 (2017). X. Luo and N. Xu, Nucl. Sci. Tech. 28, 112 (2017).*

# First measurement of high moments of net-proton distributions

Only TPC used for proton/anti-proton PID.

$p_T$ coverage : $0.4<p_T<0.8$ GeV/c

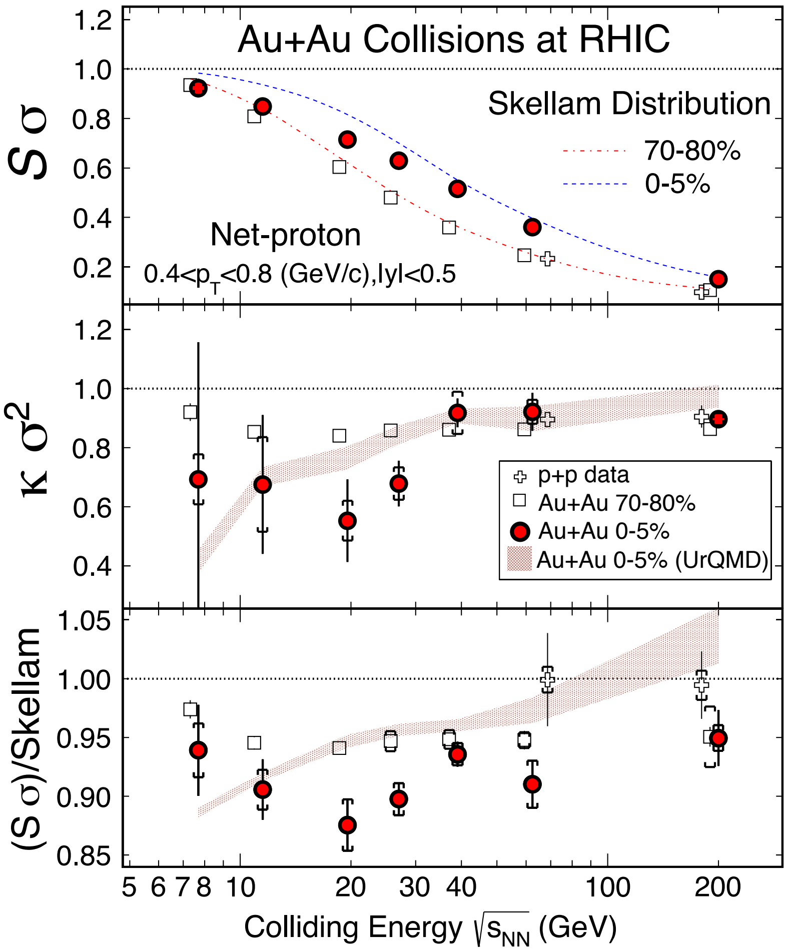



STAR: Phys. Rev. Lett. 105, 022302 (2010).

No critical point signature is observed at $\mu_B$ < 210 MeV.

# Net-proton fluctuations from BES-I at RHIC




STAR: Phy. Rev. Lett. 112, 032302 (2014).

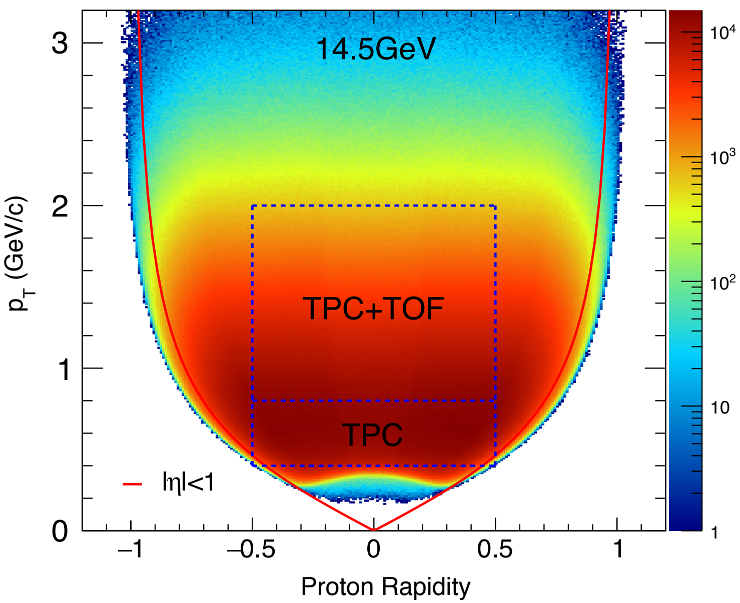
$p_T$ coverage : $0.4<p_T<0.8$ GeV/c

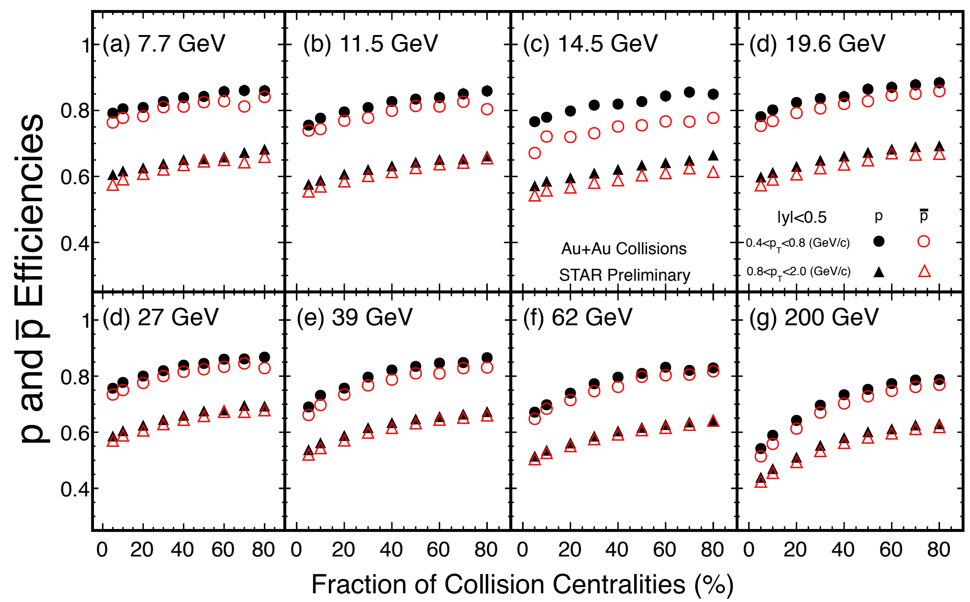
1. Deviation below Poisson baseline (unity).
2. A minimum shows at 19.6 GeV.

# (Anti-) Proton Acceptance and Efficiencies

TOF PID can extend the phase space coverage

$|y|<0.5$, $0.4<p_T<0.8$ (TPC PID only)
$0.8<p_T<2$ (TPC+TOF PID)

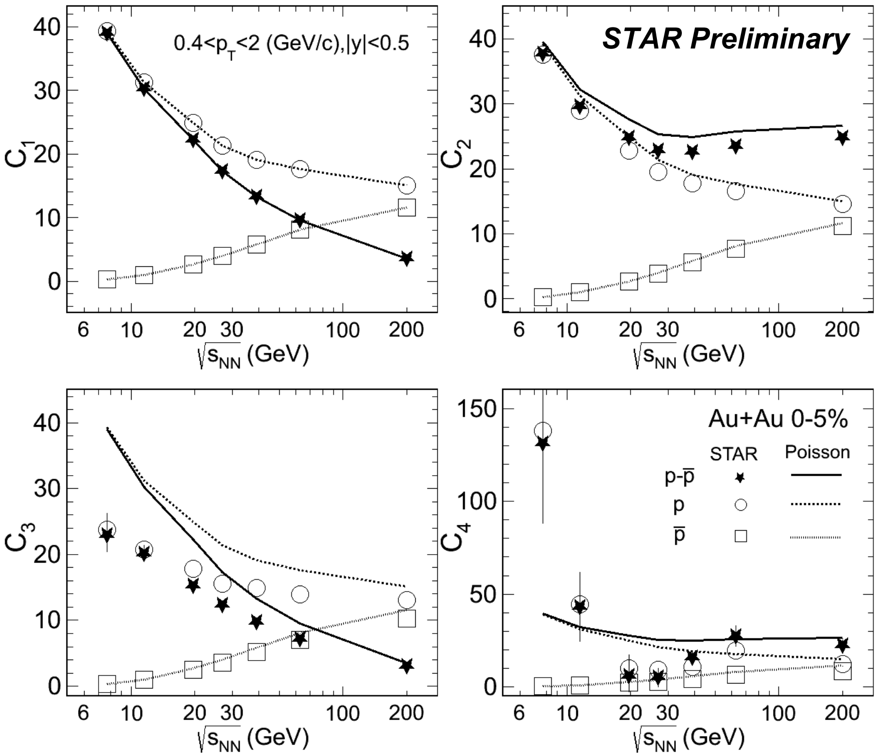


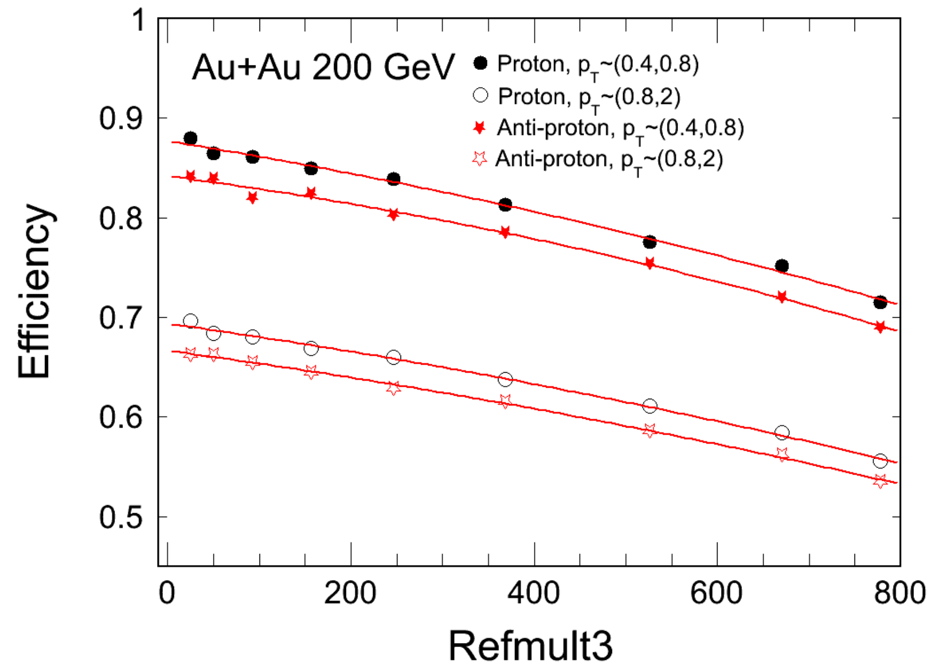




Doubled the accepted number of proton/anti-proton

- Sufficiently large acceptance is important for fluctuation analysis and critical point search.
- Efficiency : Proton> Anti-proton, Low $p_T$ > High $p_T$ , low energy > High Energy, Peripheral > Central

# Net-Proton Cumulants vs. Collision Energy

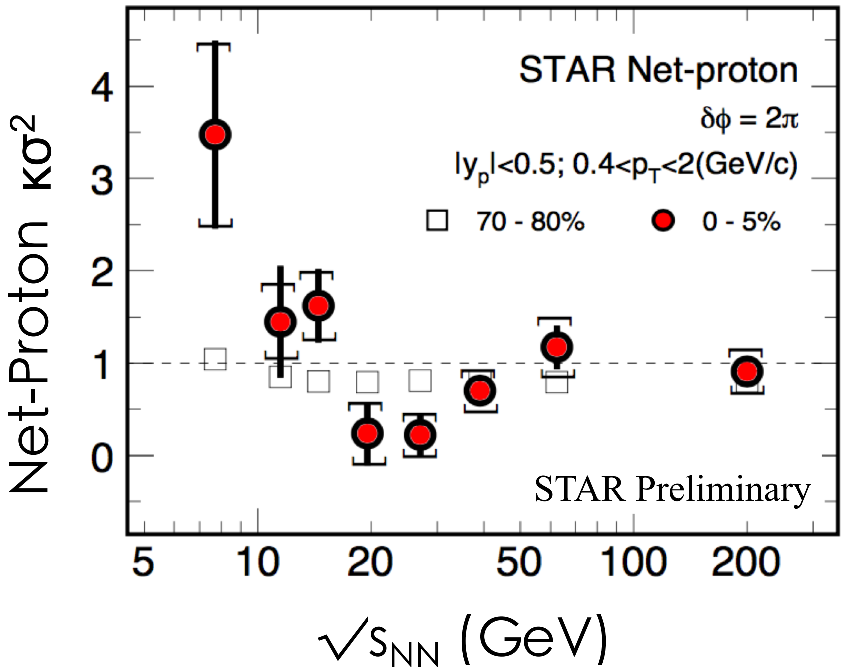



- Net-proton number is dominated by protons at low energies and increases when energy decreases. (Interplay between baryon stopping and pair production)
- The higher the order of cumulants the larger deviations from Poisson expectations for net-proton and proton.

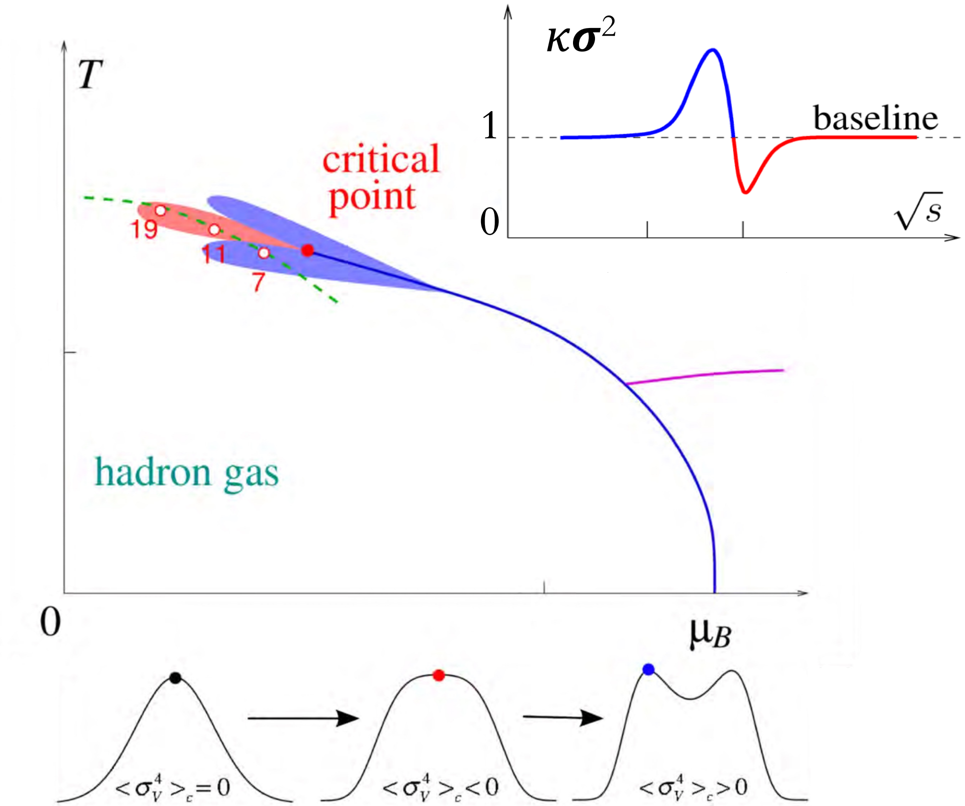
# Net-Proton Fluctuations

## Experimental Measure




STAR: PoS CPOD2014 (2015) 019.

## Theoretical calculations

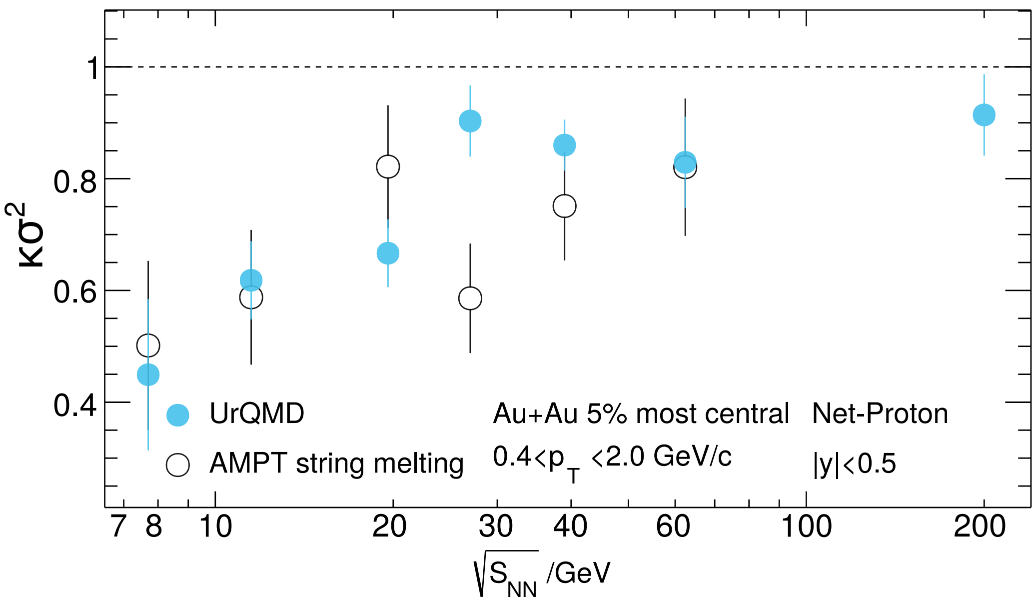



M. Stephanov, PRL107, 052301(2011)
J. Phys. G: 38, 124147 (2011).

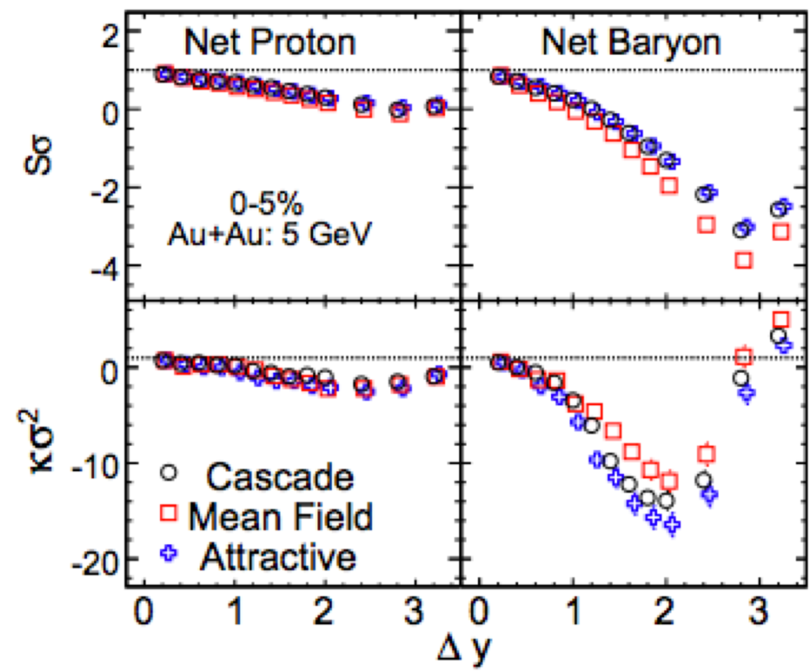
Observe non-monotonic energy dependence in 0-5% most central Au+Au collisions. A hint of entering the critical region.

# Non-critical Contributions: Transport Model Studies

## UrQMD and AMPT models




## JAM model

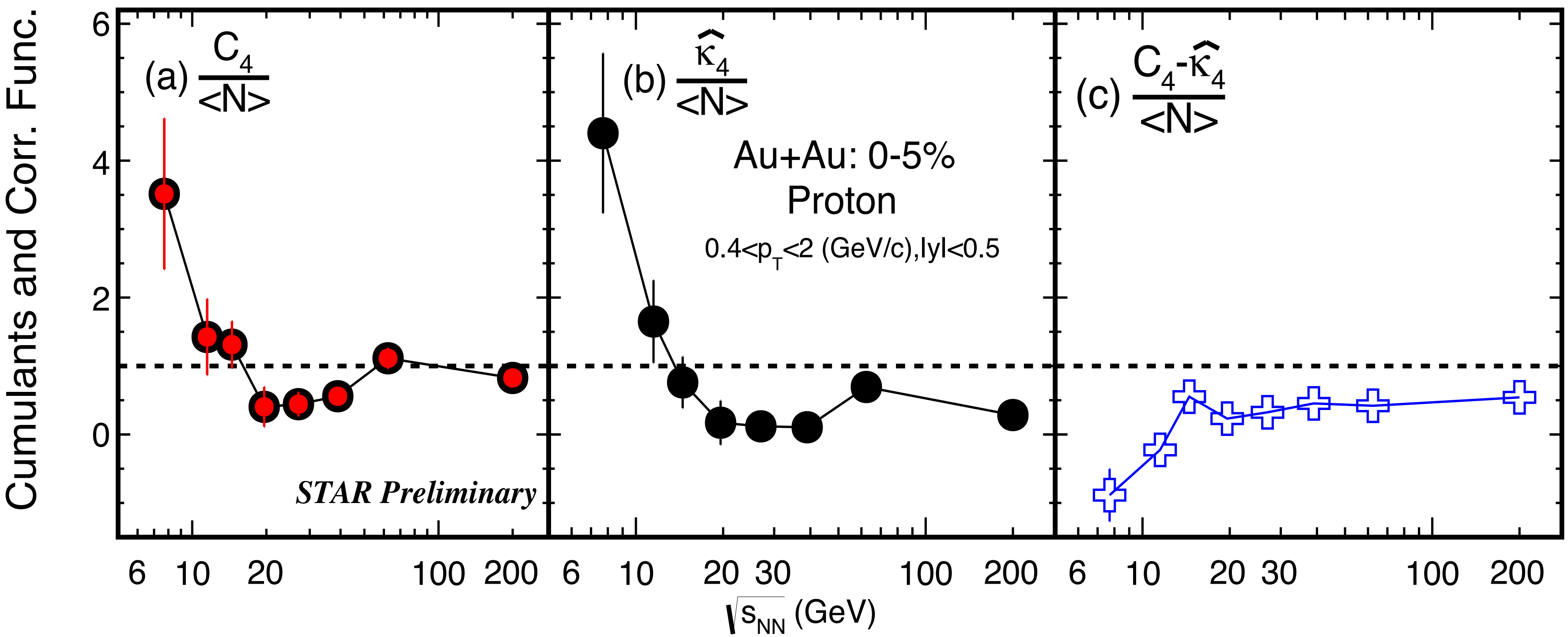



At $\sqrt{s_{NN}} \leq 10$ GeV: Data: **$\kappa\sigma^2 > 1$** Model: **$\kappa\sigma^2 < 1$**

➢ Model simulation : *suppress the net-proton fluctuations.*

*Z. Feckova, et al., PRC92, 064908(2015). J. Xu, et. al., PRC94, 024901(2016). X. Luo et al., NPA931, 808(14), P.K. Netrakanti et al. 1405.4617, NPA947, 248(2016), P. Garg et al. PLB 726, 691(2013). S. He, et. al., PLB762, 296 (2016). S. He, X. Luo, PLB 774, 623 (2017).*

# Proton Cumulants and Correlation Functions




Four-particle correlation dominated the non-monotonic behavior observed in forth order net-proton fluctuations.

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

$$C_3 = <N> + 3\hat{\kappa}_2 + \hat{\kappa}_3$$

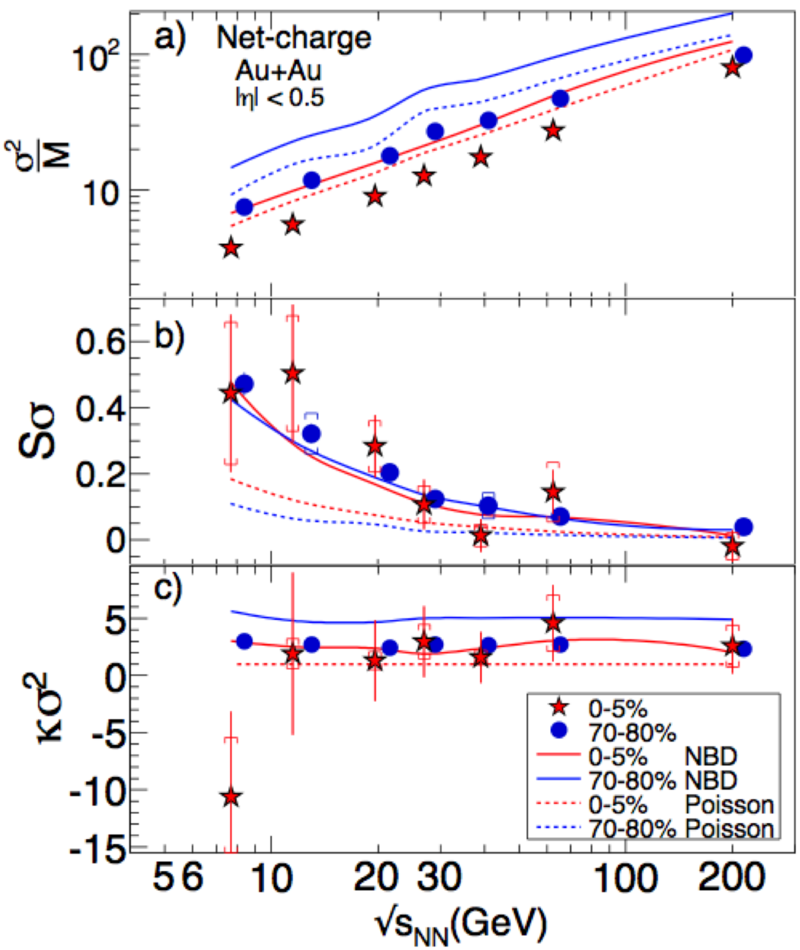
$$C_4 = <N> + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$$

$\hat{\kappa}_2, \hat{\kappa}_3, \hat{\kappa}_4$ : 2,3,4-particle correlation function

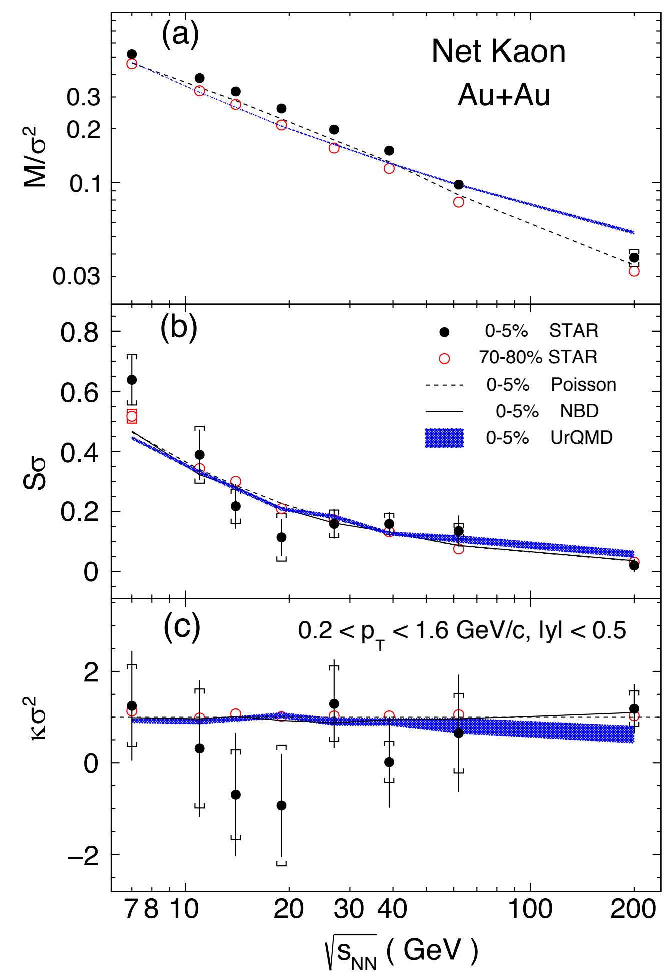
# Net-charge and Net-kaon fluctuations from BES-I

$$error(\kappa\sigma^2) \propto \frac{\sigma^2}{\varepsilon^2}\frac{1}{\sqrt{N_{evts}}}$$

Large statistical errors, need more data




STAR : Phys. Rev. Lett. 113 092301 (2014).




STAR : Phys. Lett. B 785, 551 (2018).

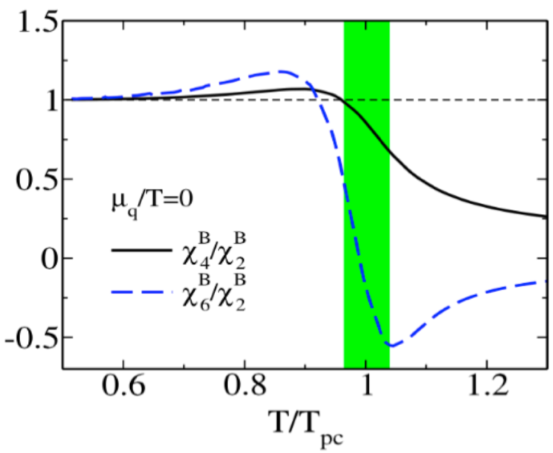
# The sixth-order ($C_6$) fluctuation measurement

- The sixth-order cumulants of net-charge and net-baryon distributions are predicted to be negative if the chemical freeze-out is close enough to the phase transition.

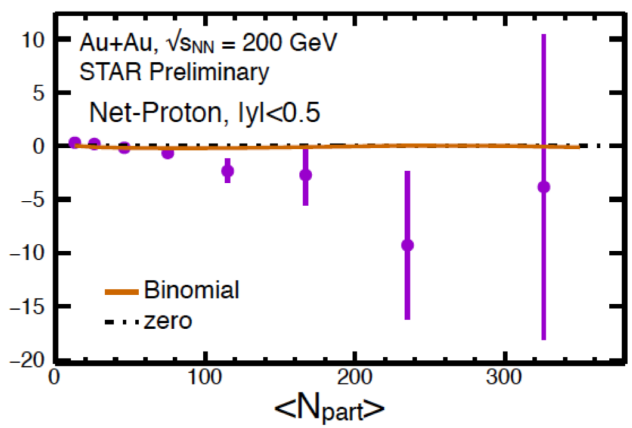
- In Au+Au collisions at 200 GeV, negative values are observed in net-proton $C_6/C_2$ systematically from peripheral to central. Results of net-charge $C_6/C_2$ are consistent with zero within large statistical errors.

$$error(C_n/C_2) \propto \frac{\sigma^{n-2}}{\sqrt{N_{evts}}}$$

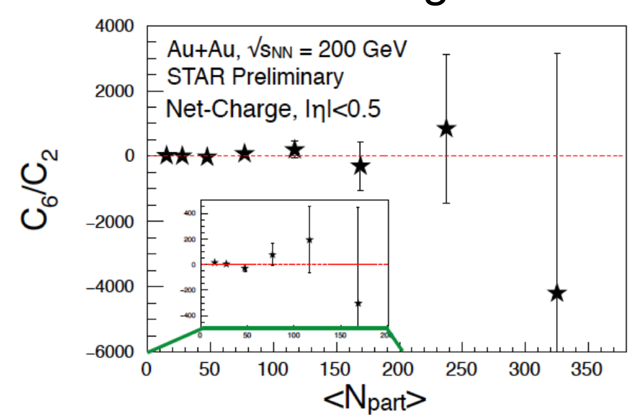
PQM model




Net-proton



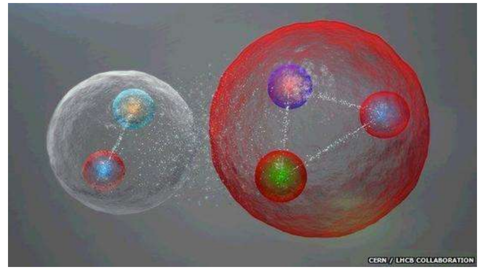

Net-charge




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

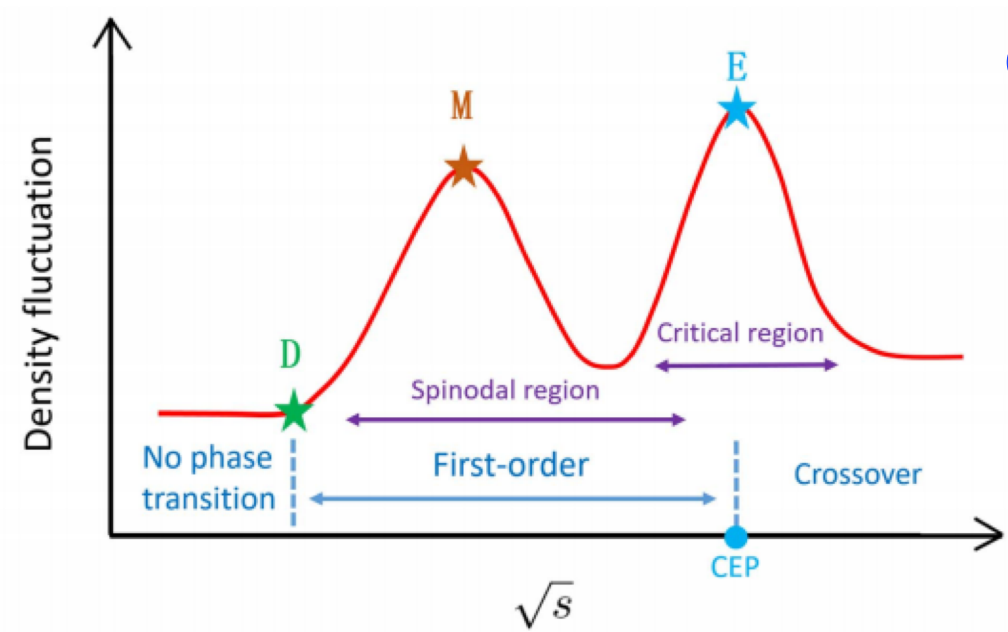
# Light nuclei production probes the QCD phase structure

**Near CP or 1st order phase transition, baryon density fluctuation become large.**



**Light nuclei production**

**(Baryon Clustering)**




Coalescence + nucleon density flu.

$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3/2} N_p\langle n\rangle(1+\alpha\Delta n),$$

$$N_{^3H} = \frac{3^{3/2}}{4}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3} N_p\langle n\rangle^2[1+(1+2\alpha)\Delta n],$$

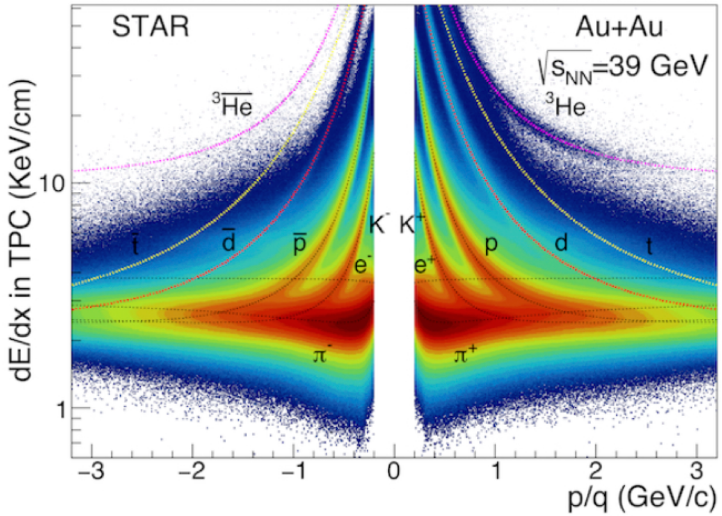
$$N_t \cdot N_p / N_d^2 \approx g(1+\Delta n)$$

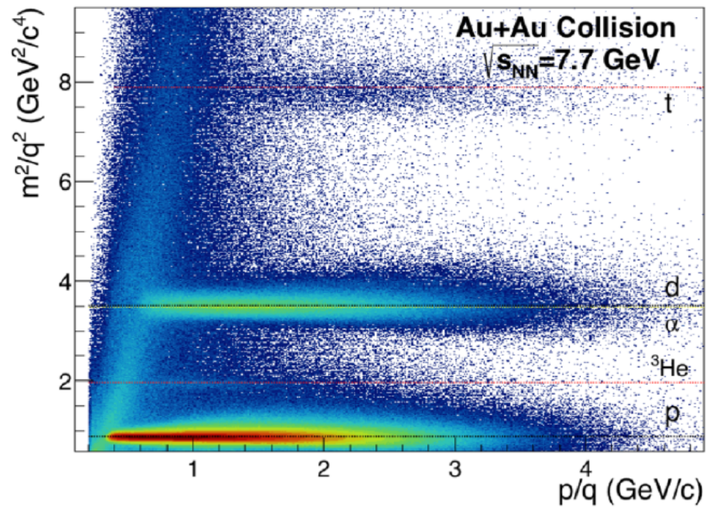
Neutron density flu.

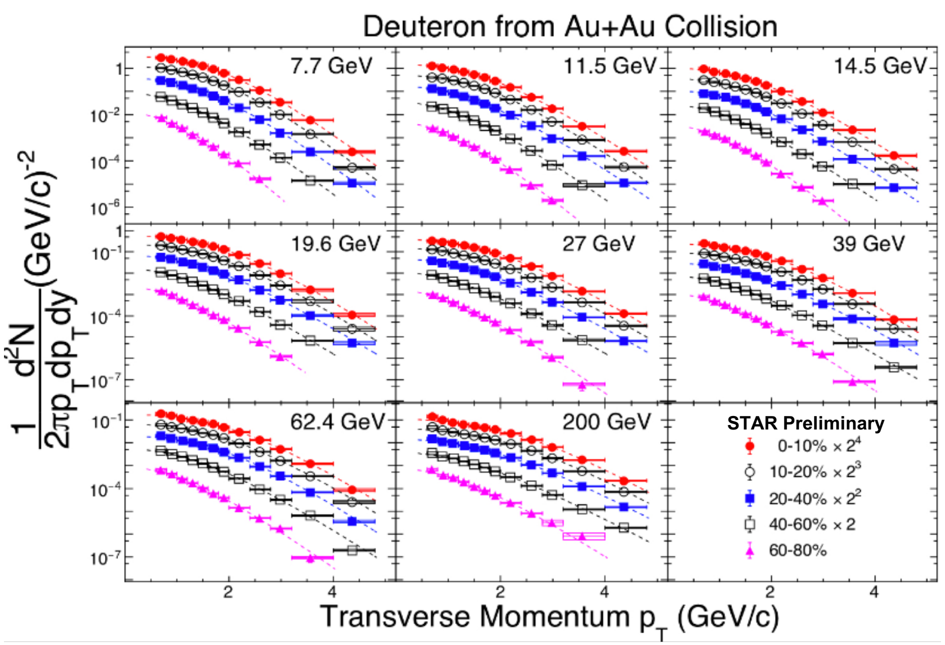
$$\Delta n = \langle(\delta n)^2\rangle / \langle n\rangle^2$$

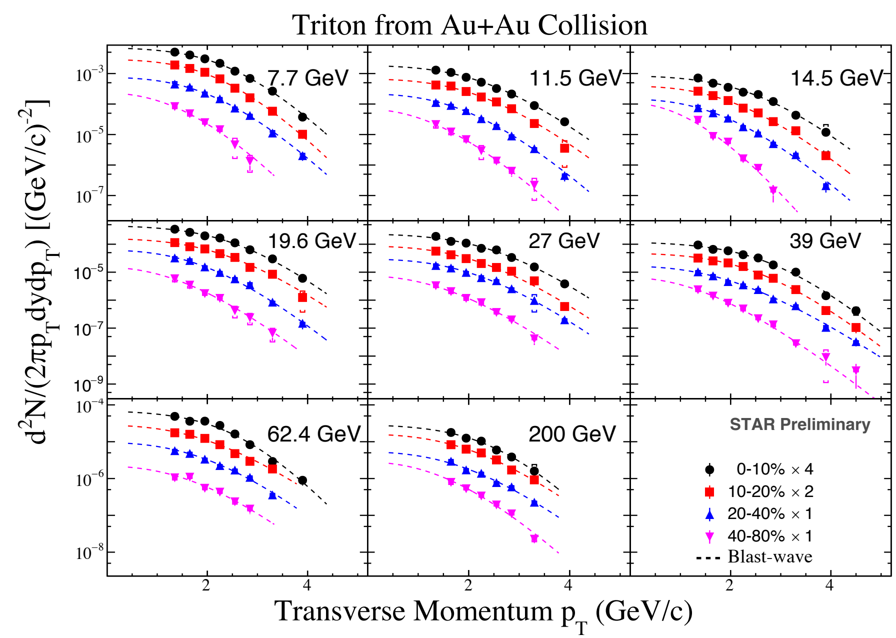

K. J. Sun, L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, arXiv:1805.04444

# Deuteron and triton production from BES-I at RHIC



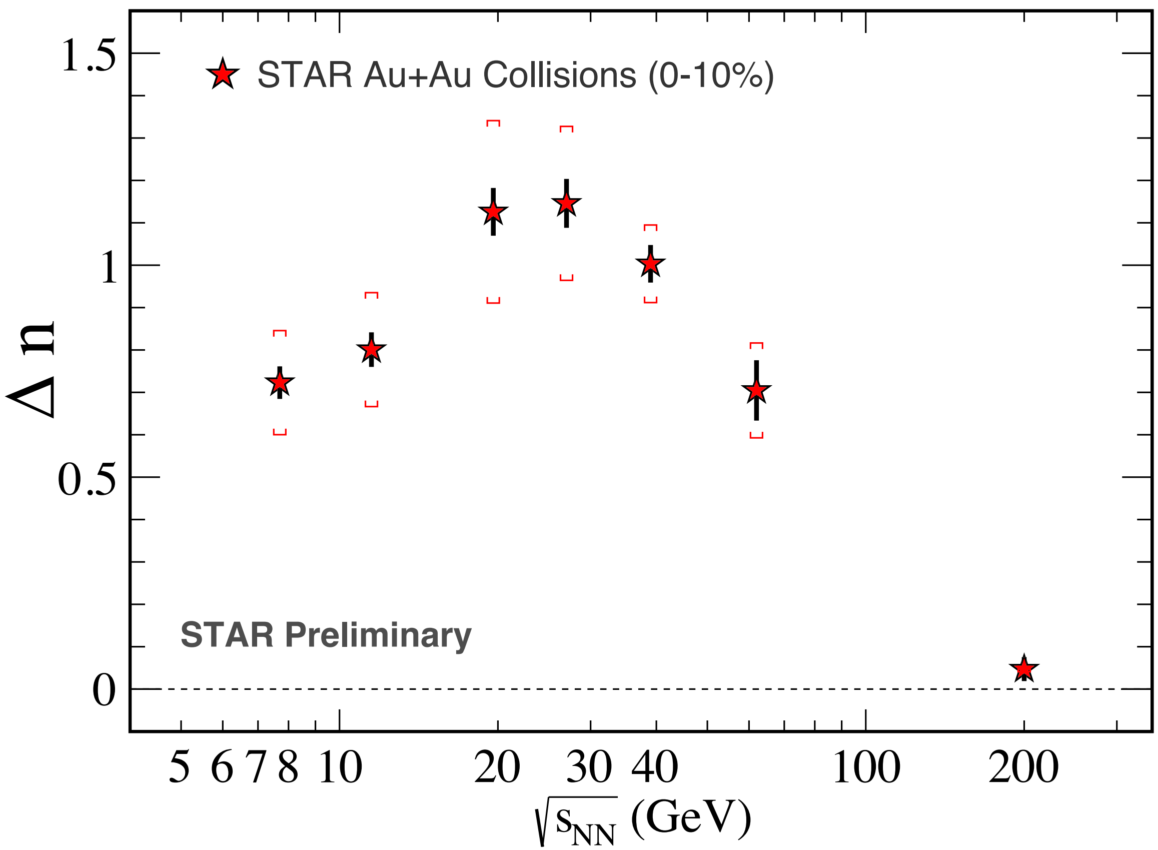



# Neutron Density Fluctuations : Energy Dependence

STAR， QM2018




$$\Delta n = \langle(\delta n)^2\rangle / \langle n \rangle^2$$

$$N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)$$

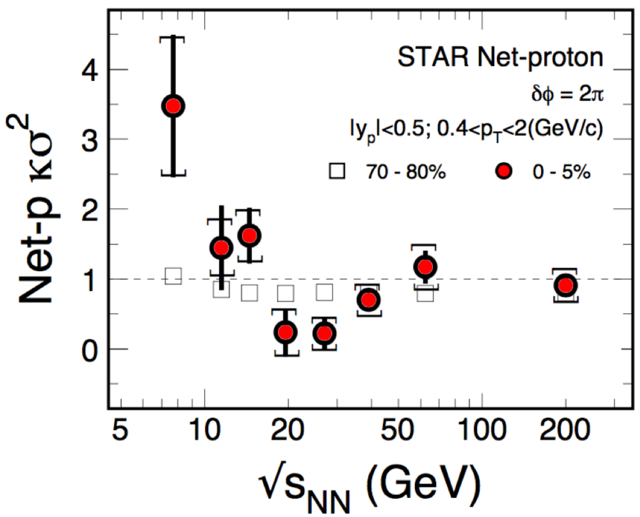
g=0.29.

$N_t$ : Triton yield
$N_d$ : Deuteron yield
$N_p$ : Proton yield

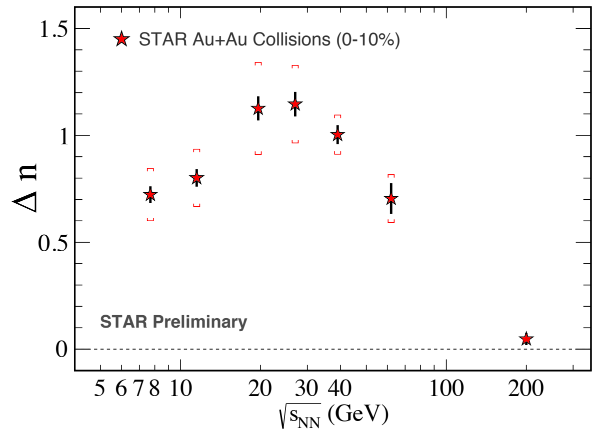
Observe non-monotonic energy dependence of neutron density fluctuation in 0-10% central Au+Au collisions with a peak around 20-30 GeV.

# Non-monotonic structures observed by STAR experiment

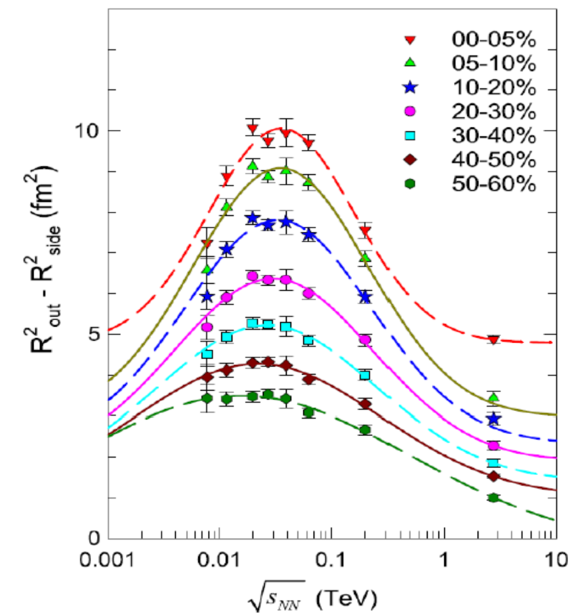
Net-p flu.



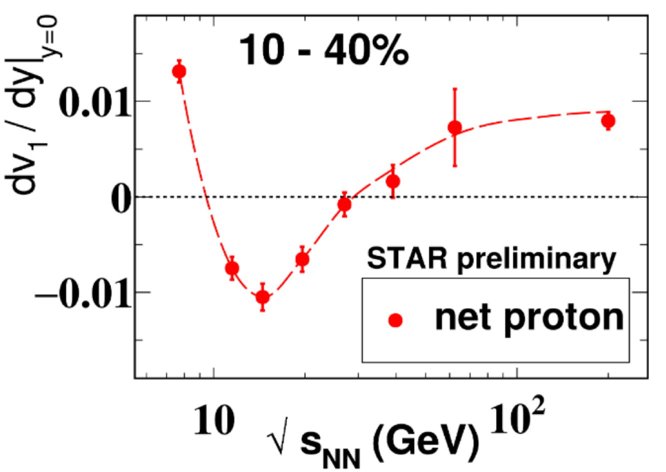

Neutron density flu.




HBT radii



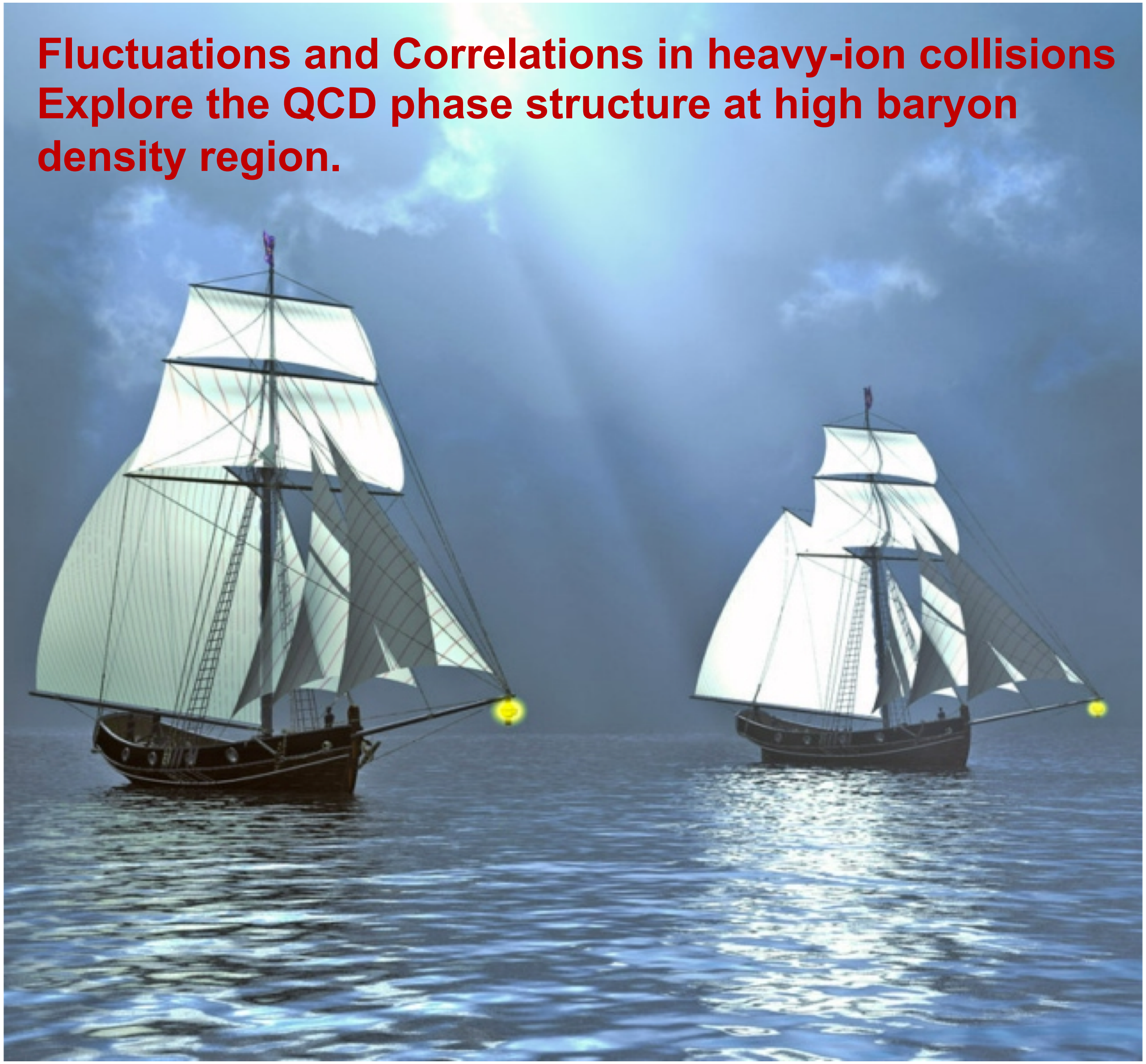

Slope of Directed flow vs y.




Peak and/or dip structures observed
at common energy ranges : 20-30 GeV !!

Hard to believe those are driven by different physics.

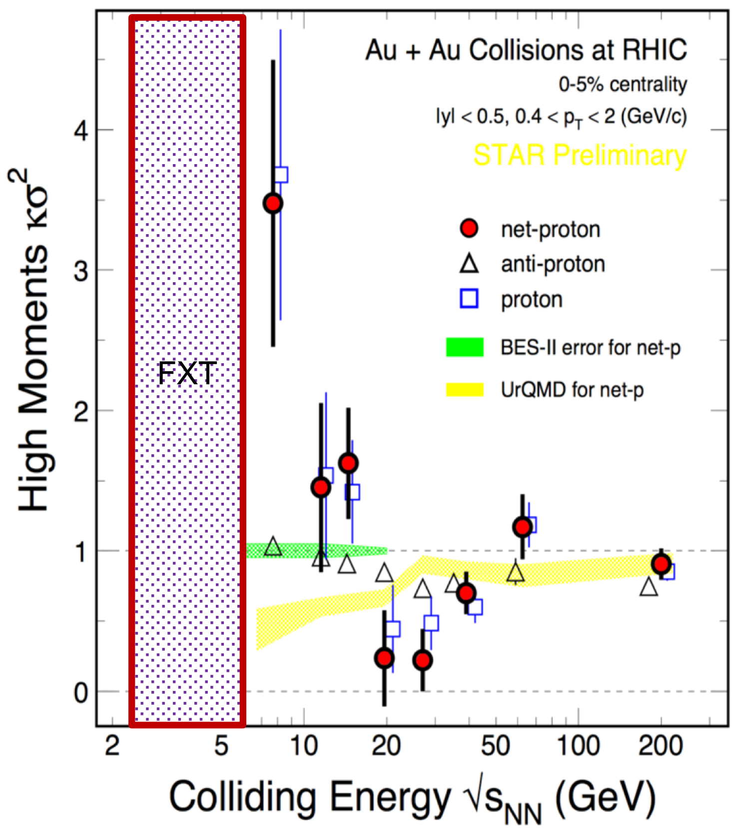
# Search for New Lands….



# BES-II at RHIC (2019-2020)

10-20 times higher statistics than BES-I

| $\sqrt{s_{NN}}$ (GeV) | Events ($10^6$) | BES II / BES I |
|---|---|---|
| 200 | 350 | 2010 |
| 62.4 | 67 | 2010 |
| 54.4 | 1200 | 2017 |
| 39 | 39 | 2010 |
| 27 | 70 | 2011 |
| 19.6 | **400** / 36 | **2019-20** / 2011 |
| 14.5 | **300** / 20 | **2019-20** / 2014 |
| 11.5 | **230** / 12 | **2019-20** / 2010 |
| 9.2 | **160** / 0.3 | **2019-20** / 2008 |
| 7.7 | **100** / 4 | **2019-20** / 2010 |




- BES-II : Precise mapping the QCD phase diagram **$200 < \mu_B < 420$ MeV**
- FIX-target mode : $\sqrt{s_{NN}}$ = 3-7.7 GeV (2018-2020)

# Summary

- Non-monotonic energy dependence is observed in net-proton $C_4/C_2$ at most central Au+Au collisions. *A hint of entering the critical region.* *Need to confirm with more statistics and lower energy data.*

- Within current uncertainties, net-charge and net-kaon fluctuations show flat energy dependent. *Need more statistics.*

- Observe non-monotonic energy dependence of neutron density fluctuations in 0-10% central Au+Au collisions with a peak around 20-30 GeV.

- Study the QCD phase structure with high precision: BES-II at RHIC (2019-2020, both collider and fixed-target mode).

***Happy Birthday to Edward***

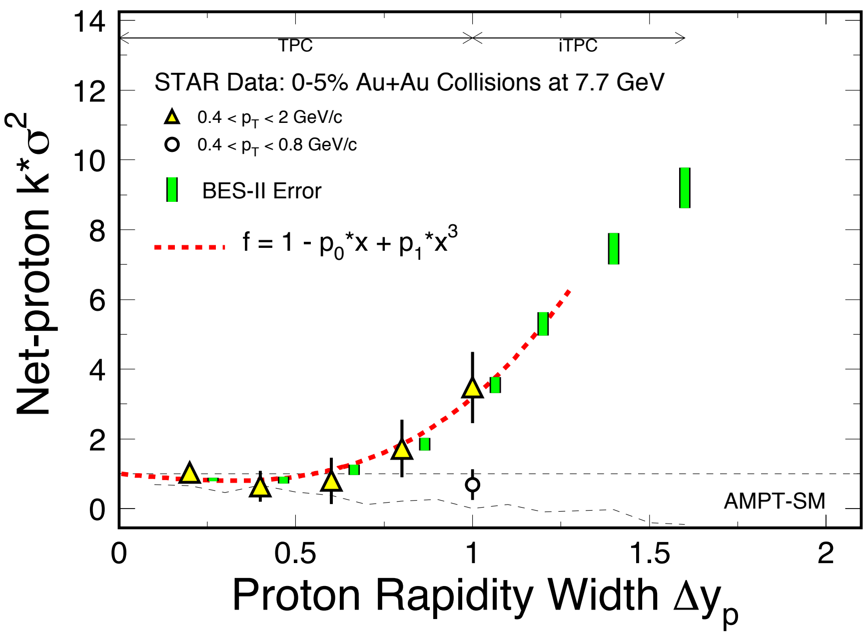
*Thank you !*

# *Back up slides*

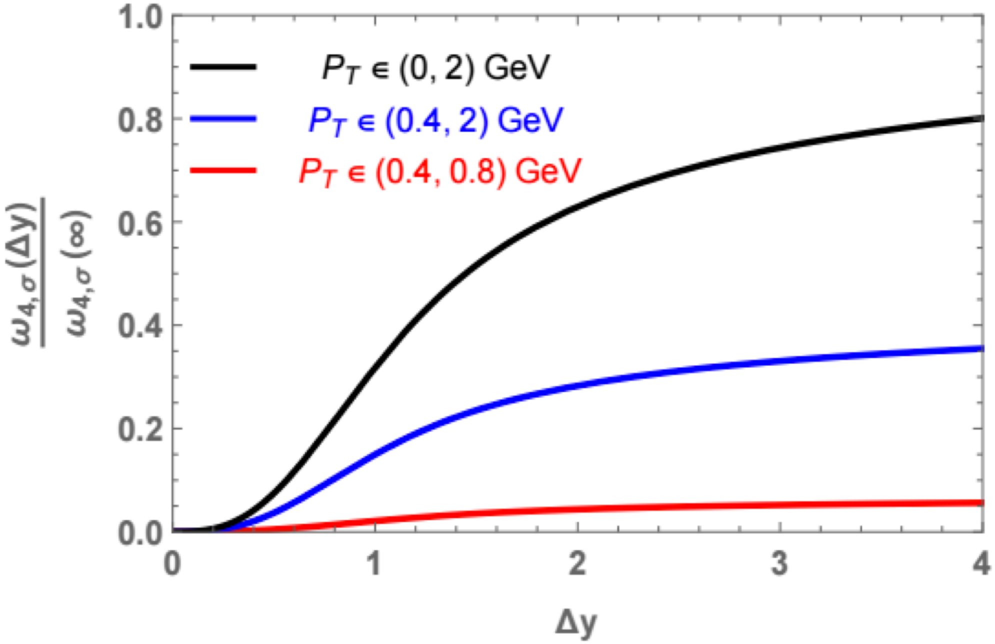
# Acceptance Dependence

Acceptance dep. near CP

**STAR Data**



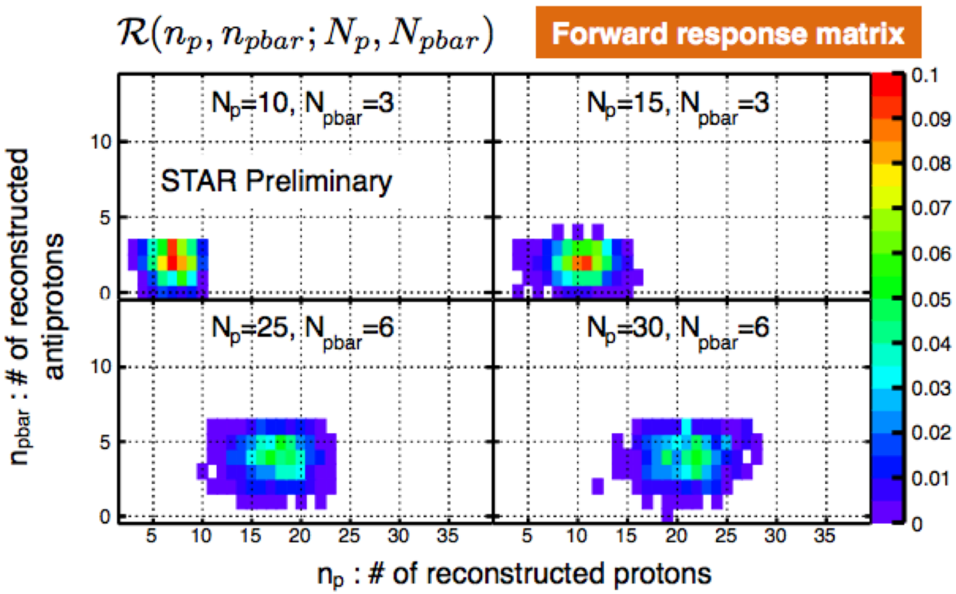

**Model**

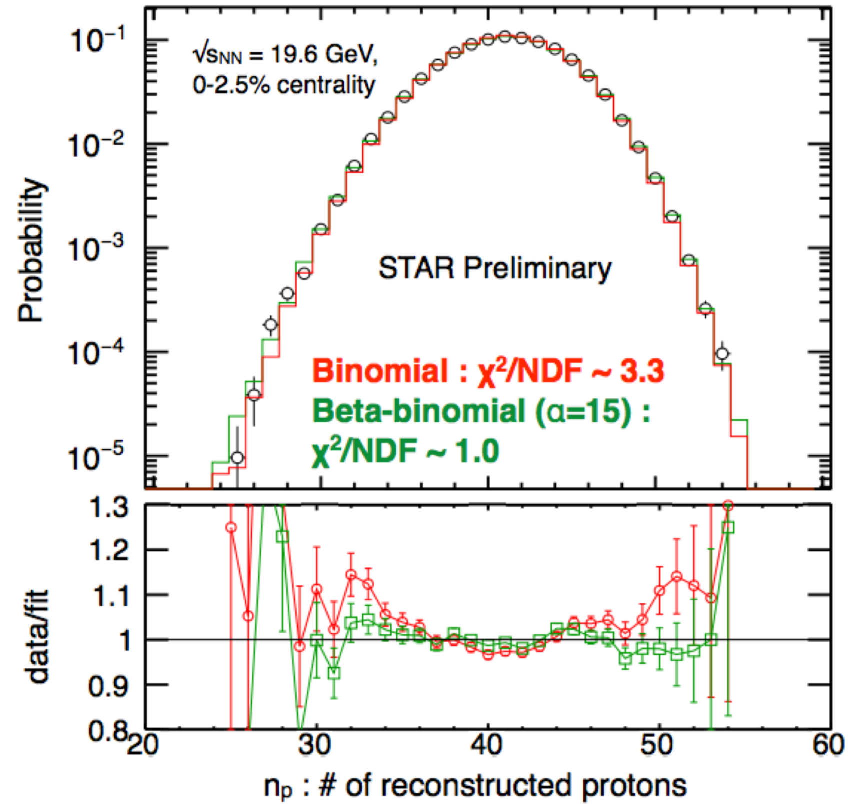



Signals can be enhanced by enlarging the acceptance.

*B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016).*
*A. Bzdak, V. Koch, Phys.Rev. C95, 054906 (2017)*
*M. Kitazawa, X. Luo, PRC96, 024910 (2017).*

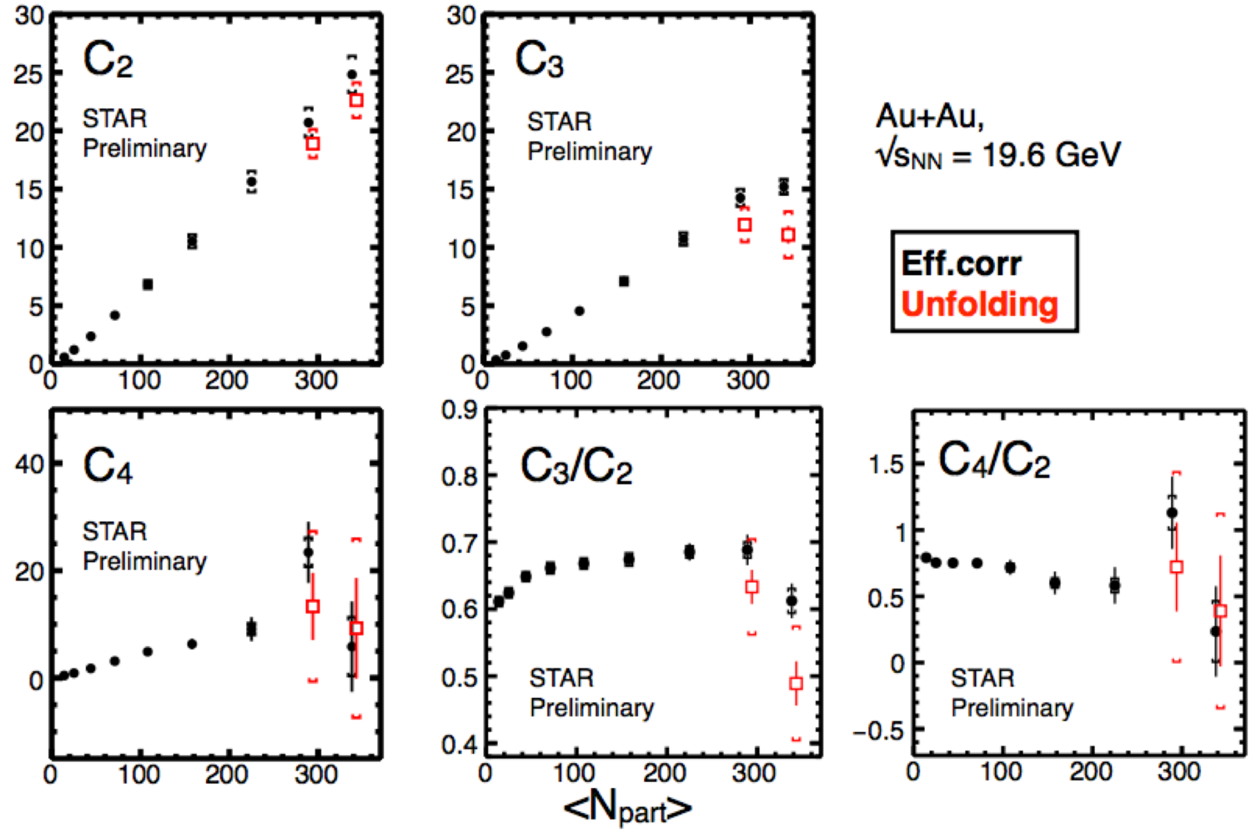
# Study Non-Binomial Effects from Embedding Simulation




- We perform simulation to construct response matrix by embedding MC tracks of protons and antiprotons into real events, which will be used for unfolding.
- When embed 60 protons (an extreme case), the response matrix is close to beta-binomial, which is wider than binomial (right plot). The deviation from binomial would depend on the # of embedded protons and antiprotons.

# Results of Unfolding




- For unfolding, 2.5% centrality width averaging has been done.
- Systematic suppression is observed for $C_2$ and $C_3$ with respect to the results of efficiency correction assuming binomial efficiencies.
- $C_4$, $C_3/C_2$ and $C_4/C_2$ are consistent within large systematic uncertainties limited by embedding samples.