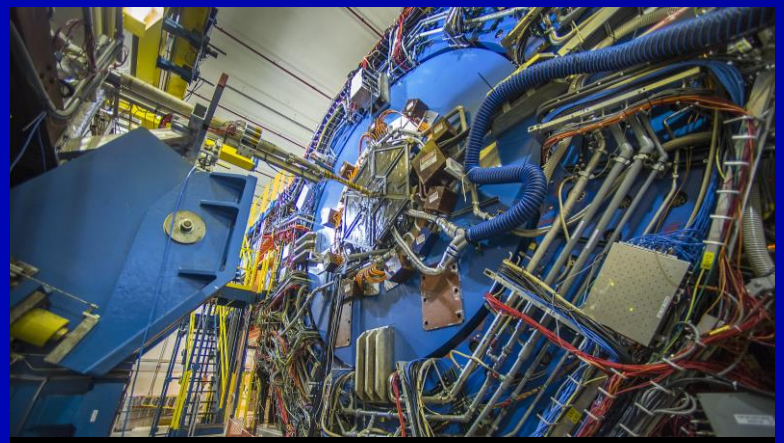
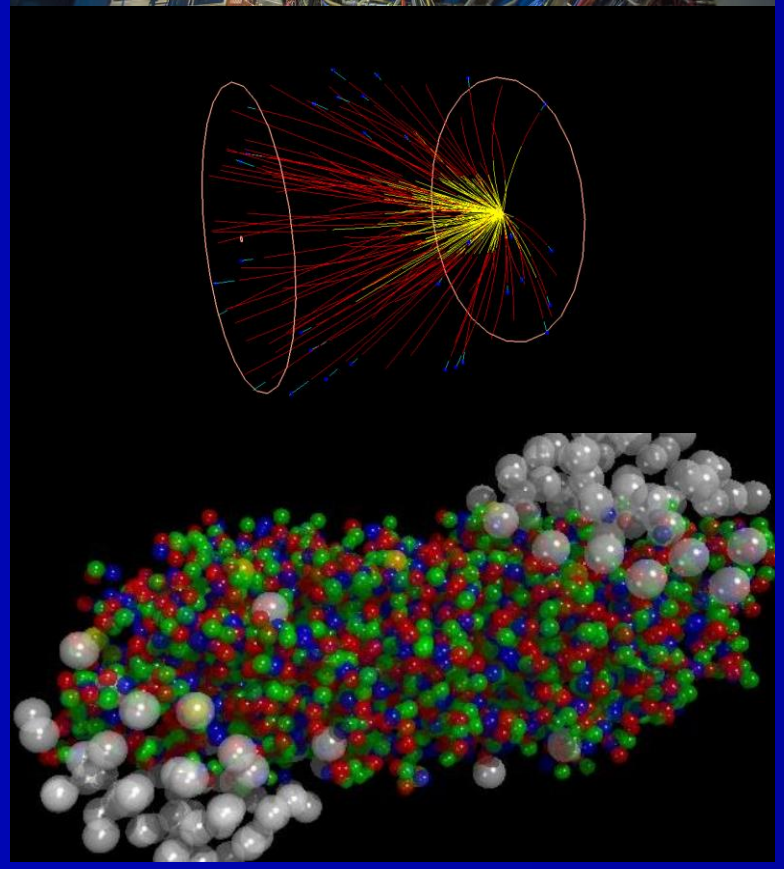




Higher-Order Proton Cumulants in Au+Au Collisions at $\sqrt{s_{NN}} = 3.0$ GeV in the Fixed-Target System and the Implications for a QCD Critical Point

Samuel Heppelmann on behalf of the STAR Collaboration

BNL Seminar

Outline:

Motivation

- QCD critical point
- Event-by-event observables
- Proton cumulants

Experimental Apparatus

- Kinematic acceptance
- TPC & TOF particle identification

Analysis Techniques

- "Track-by-track" efficiency correction
- Centrality determination
- Background corrections

Proton Cumulants at $\sqrt{s_{NN}} = 3.0$ GeV (new data!) arXiv:2112.00240 [nucl-ex]

Summary & Outlook

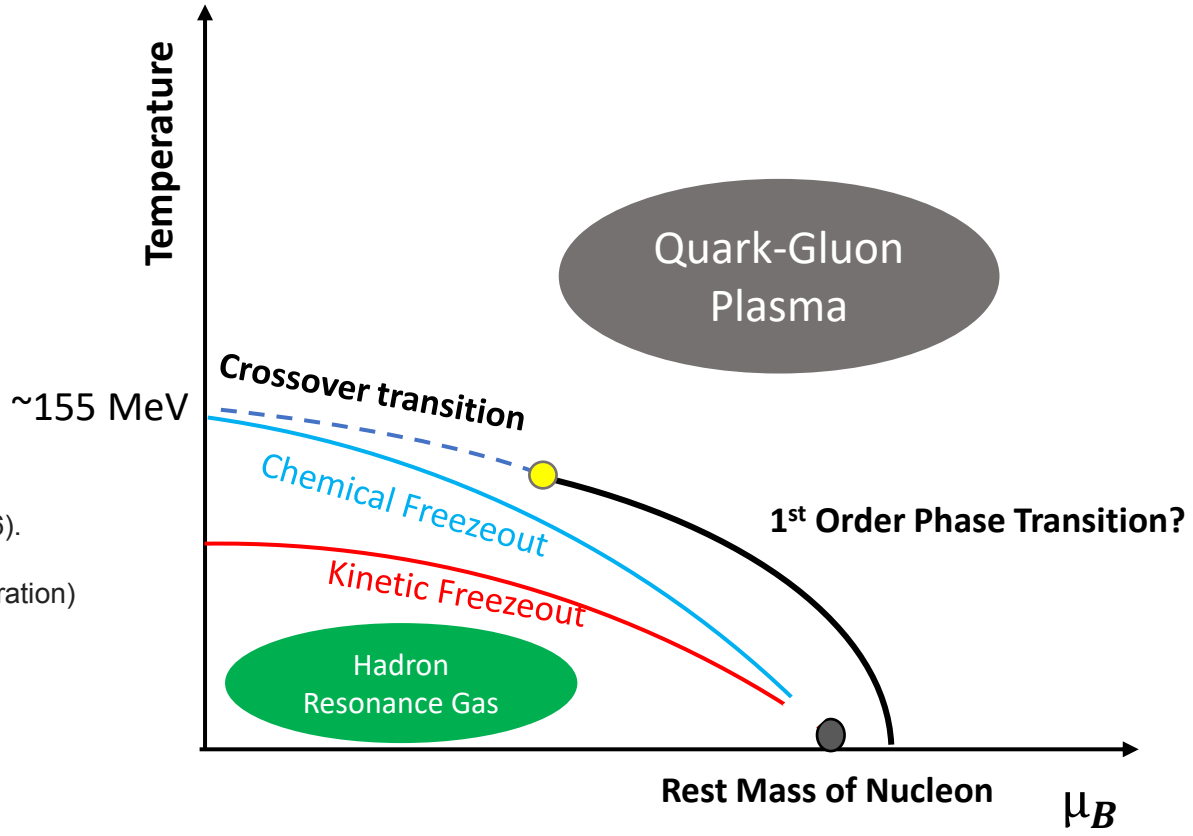
QCD Critical Point

Is there phase coexistence between the hadron gas and the QGP?

At μ_B=0, Lattice QCD predicts a continuous change of phase

Y. Aoki et al., Nature 443, 675 (2006).

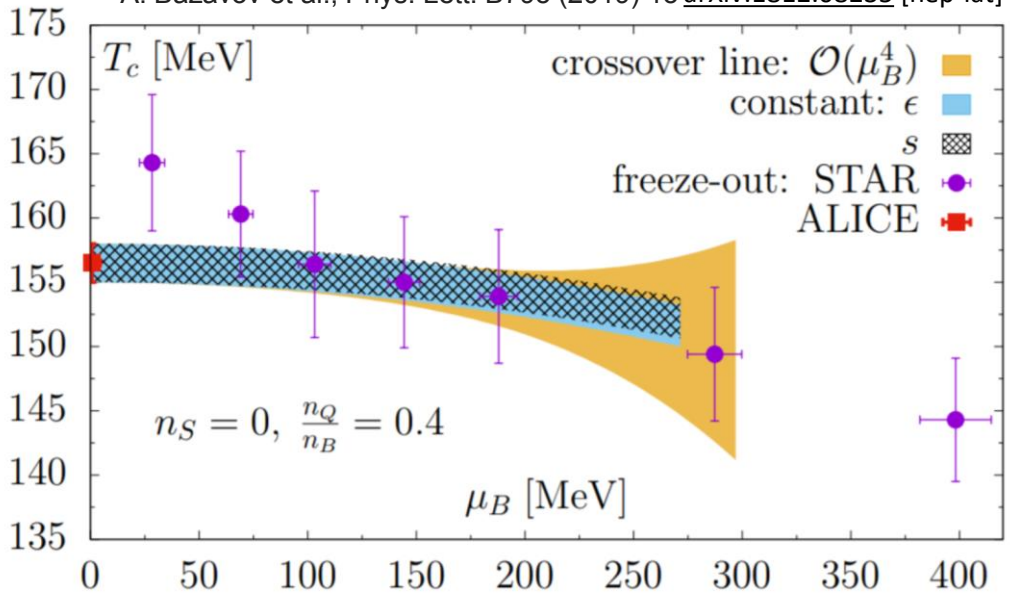
A. Bazavov et al., (HotQCD Collaboration) Phys. Rev. D 85, 054503 (2012).



QCD Critical Point

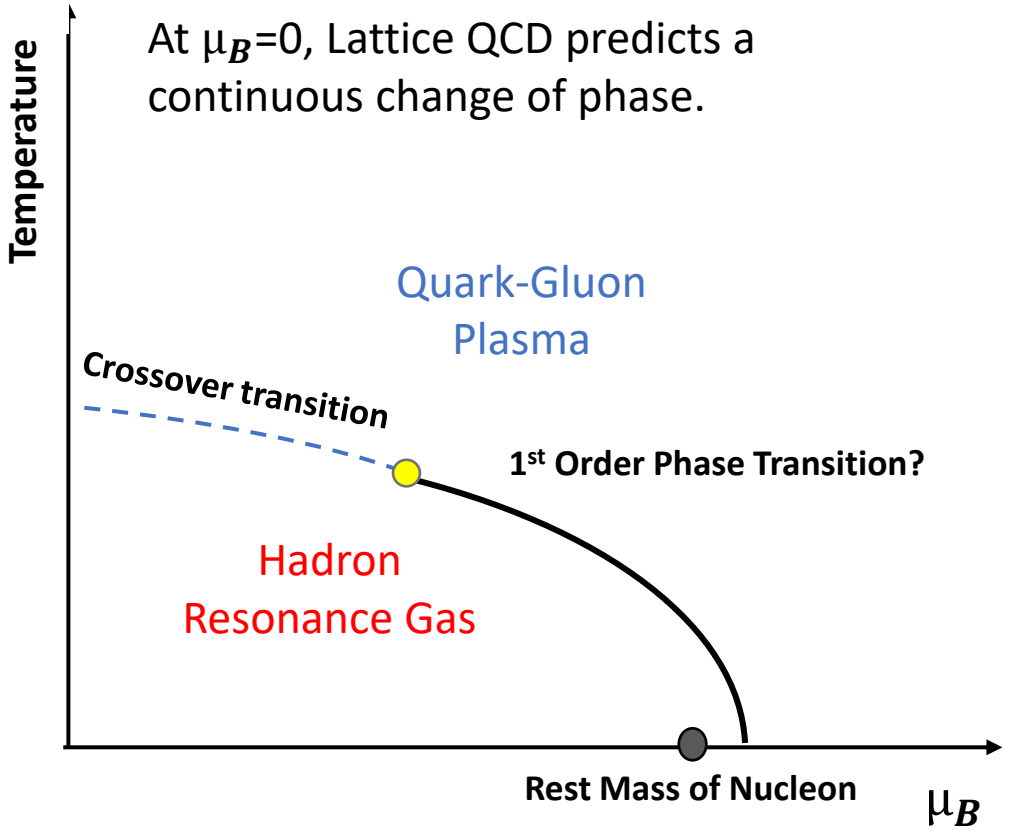
Is there phase coexistence between the hadron gas and the QGP?

A. Bazavov et al., Phys. Lett. B795 (2019) 15 arXiv:1812.08235 [hep-lat]



The pseudo-critical temperature in the $T - \mu_B$ plane for three different μ_B extrapolations for 2+1 flavor lattice QCD.

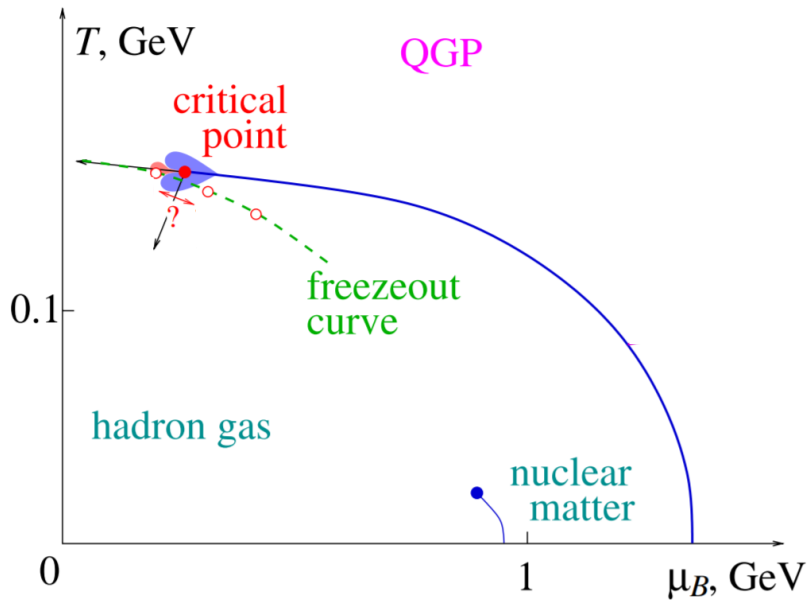
At μ_B=0, Lattice QCD predicts a continuous change of phase.

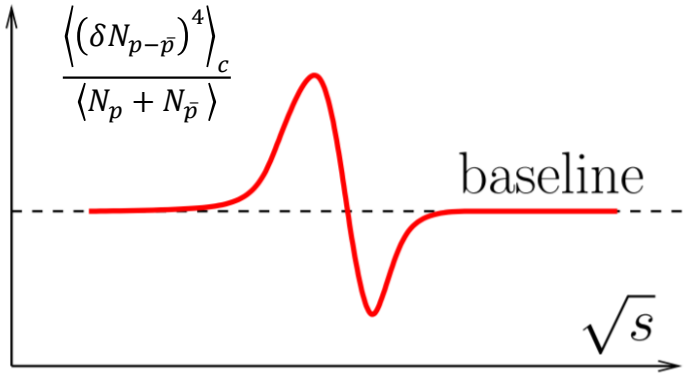


Event-by-event Fluctuations & Critical Behavior

Stephanov, M. A. "QCD critical point and event-by-event fluctuations". *J. Phys. G* 38 (2011)

Event-by-event variables may be sensitive to the divergence of the correlation length, ξ





$\xi^2 \sim \sigma^2$ (variance)

$\xi^{4.5} \sim C_3$

$\xi^7 \sim C_4$

To remove the volume dependence, we use the cumulant ratios:

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

$$\frac{C_3}{C_2} = s\sigma$$

In particular, the cumulants of conserved quantities (B,Q,S) are expected to be sensitive to the correlation length.

Event-by-event Fluctuations

Using the QCD Partition Function:

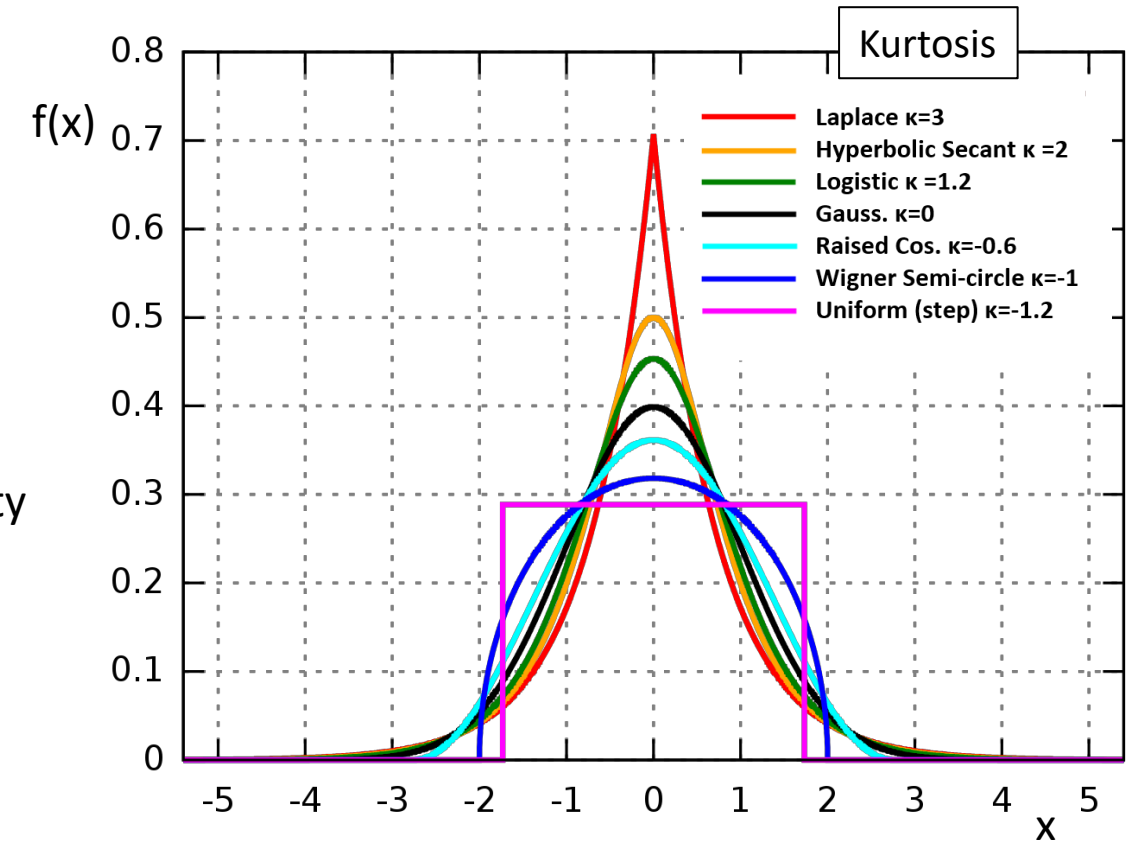
$$\frac{P}{T^4} = \frac{1}{VT^3}\ln\left[Z\left(V, T, \mu_B, \mu_Q, \mu_S\right)\right]$$

$$\chi_{ijk}^{BQS} = \frac{\partial^{i+j+k}[P/T^4]}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}$$

We can relate the ratios of cumulants to susceptibility

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

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

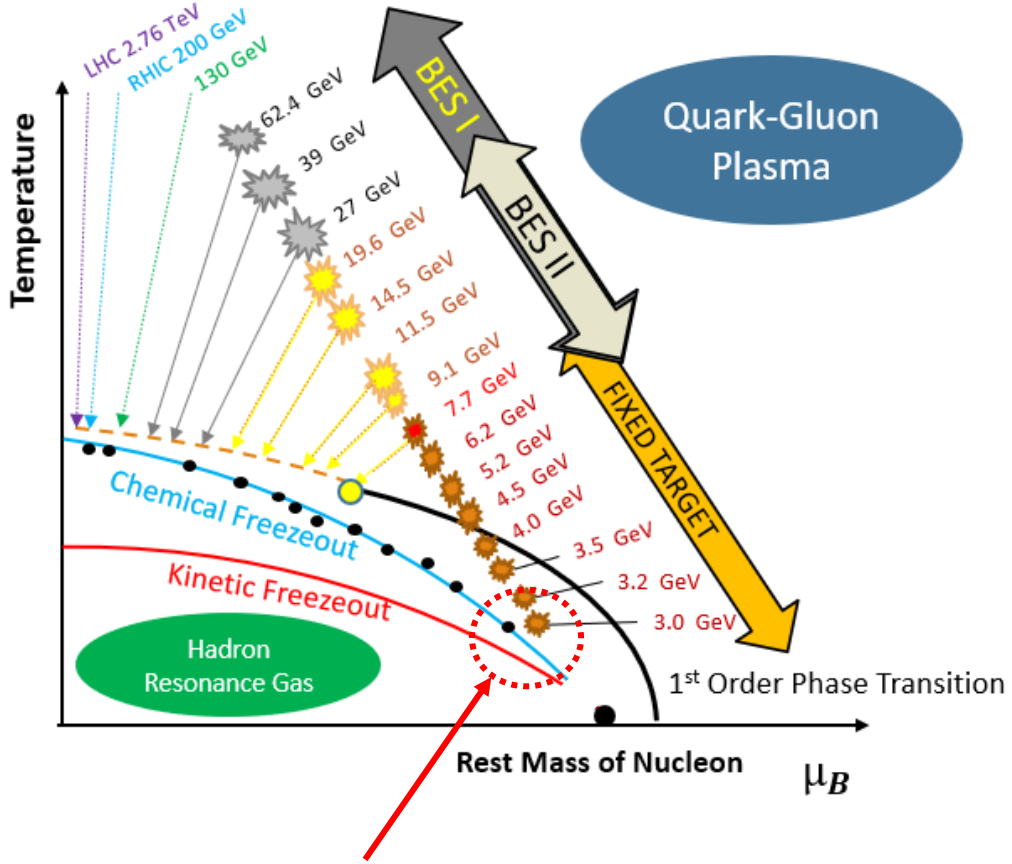


Probability density of various distributions

The susceptibility ratios can be calculated in Lattice QCD

Proton Fluctuations

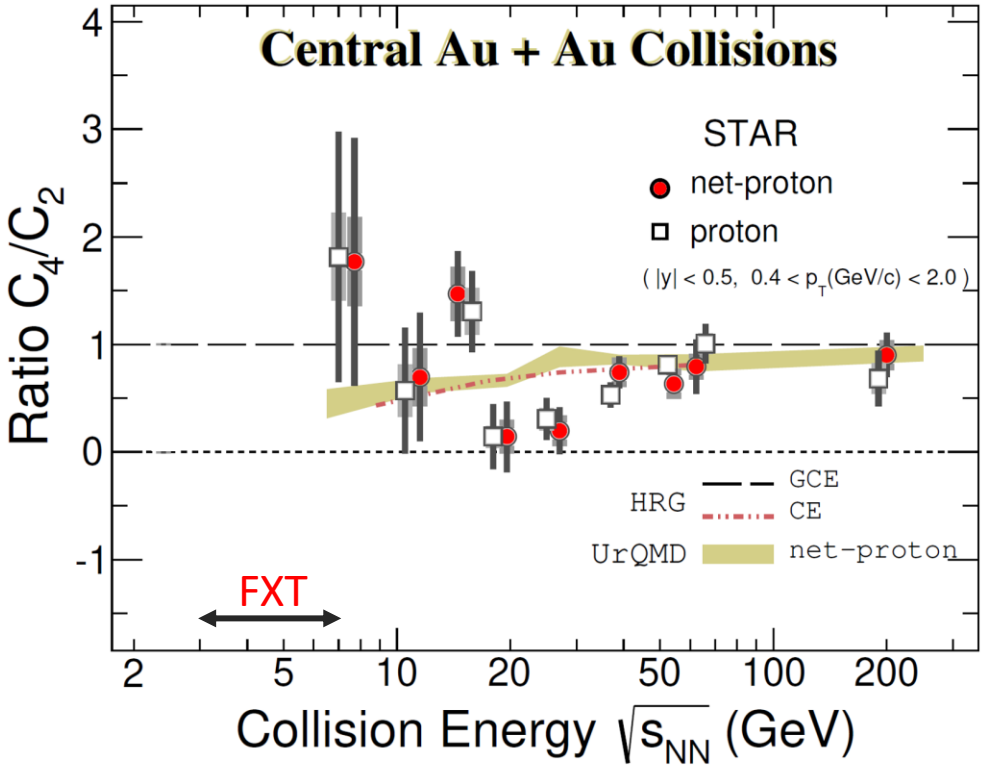
STAR collision energies



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

140 million $\sqrt{s_{NN}} = 3.0$ GeV events recorded in 2018.

We've seen interesting results in the fluctuations of net-protons

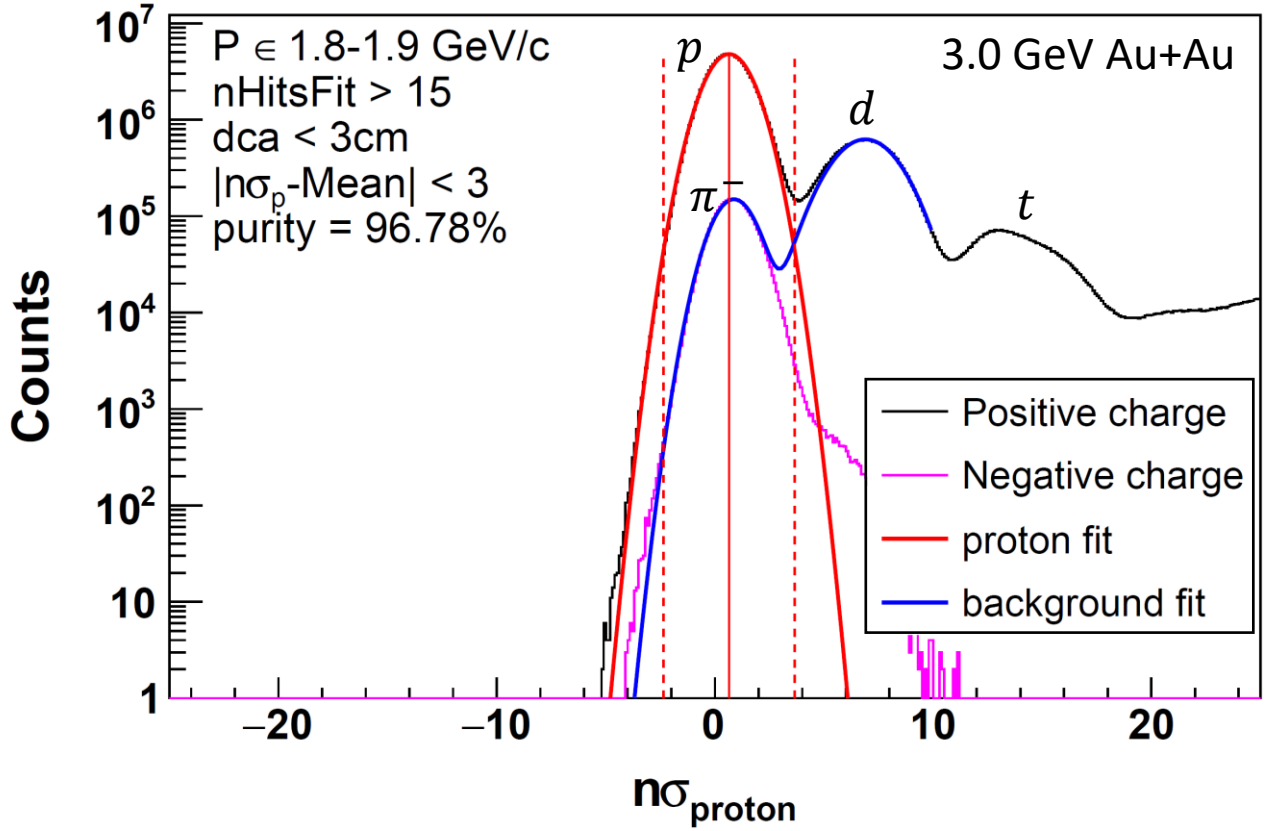


Non-monotonic variation of the BES-I result

Abdallah, Mohamed, et al. (STAR) *Phys. Rev. C* 104.2 (2021) arXiv:2101.12413

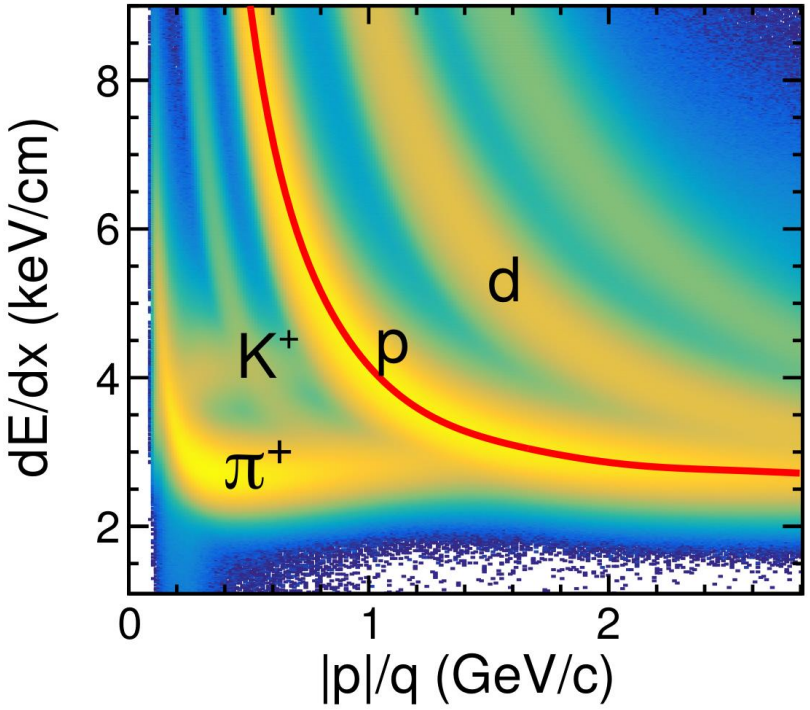
Particle Identification in the TPC

The proton purity is estimated by overlaying the π^- and K^- tracks onto the positively charged proton dE/dx distribution



Small measured offset in dE/dx calibration

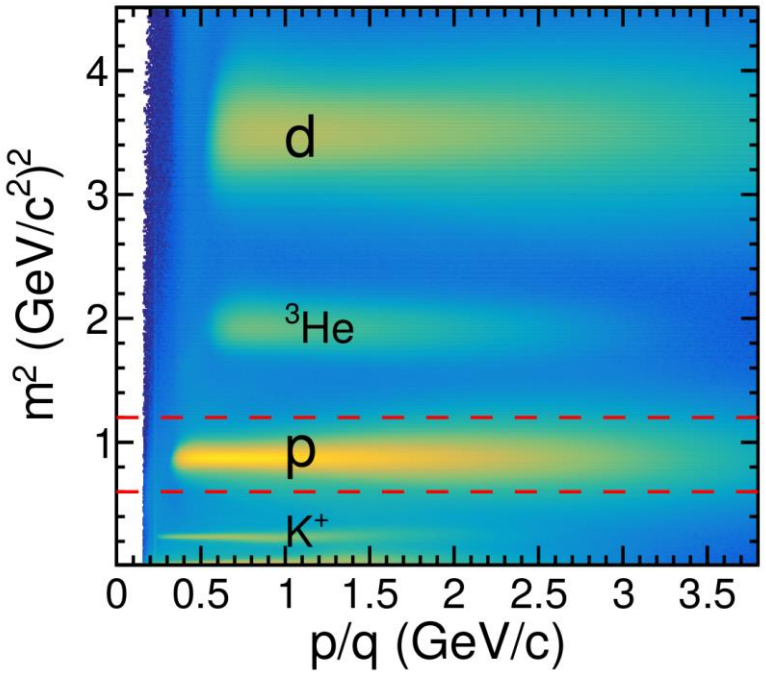
Deuteron band begins to merge above 2.0 GeV/*c*



The proton band is relatively clean (>95% purity) below |p|<2.0 GeV/*c*.

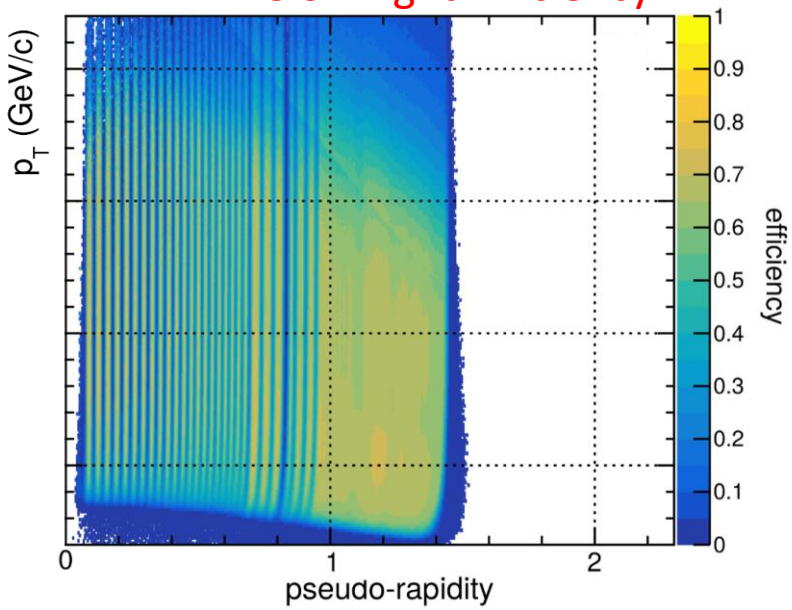
Particle Identification TOF

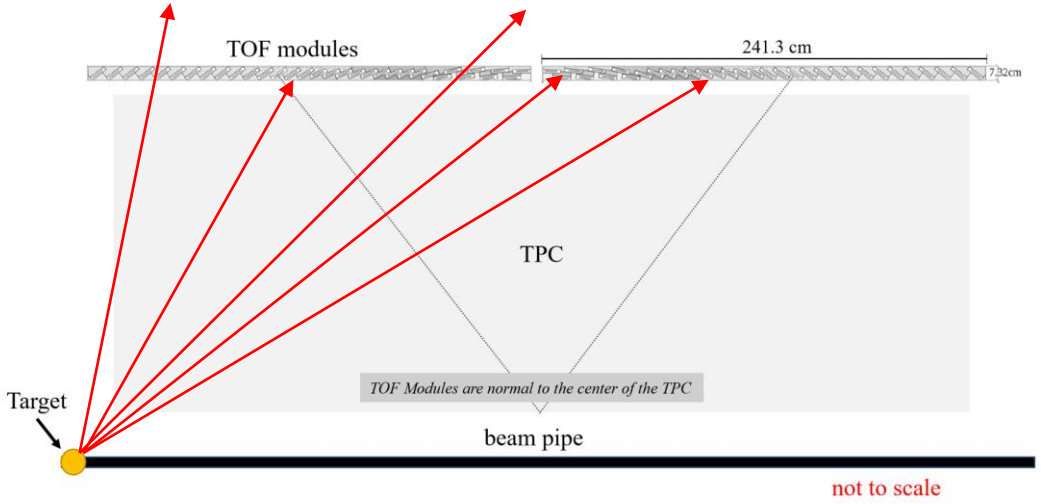
Time of Flight Detector (TOF modules placed around the barrel of the TPC)



Acceptance gap in the Time of Flight caused by module orientation with respect to the target

Time of Flight Efficiency





Mass-squared cut: $0.6 < m^2 < 1.2\ (GeV/c^2)^2$
for |p| > 2.0 GeV/c

TOF introduces a 60% matching efficiency

Kinematic Acceptance

Acceptance for comparison to BES-I:
-0.5 < y < 0
0.4 < pt < 2.0 GeV/c

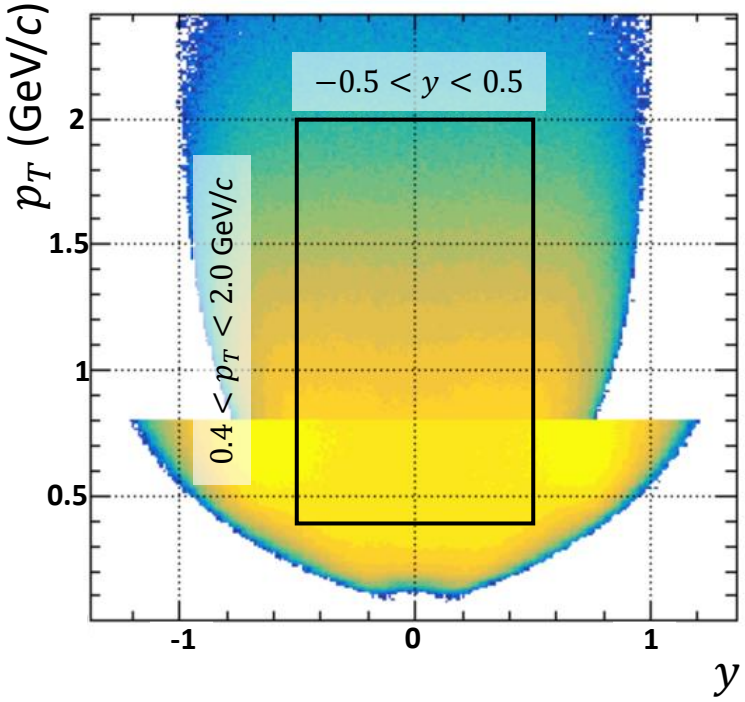
Proton PID:

dca < 3 cm
NFitsHit/NHitMax > 0.51
$|N_{\sigma,p}| < 3$ (with offset correction)
If |p| > 2.0 GeV, require TOF match

Mass cut:
$0.6 < m^2 < 1.2\ (GeV/c^2)^2$

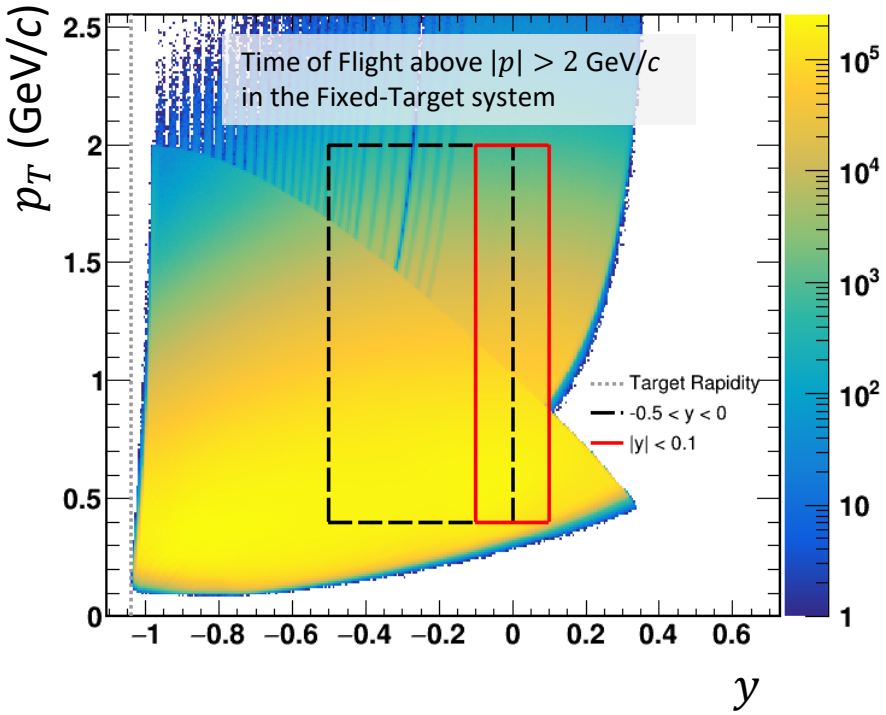
BES-I 2010

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



FXT 2018

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



Black Outline indicates analysis window of $\sqrt{s_{NN}} = 7.7$ GeV in the center of mass frame

“Track-by-Track” Efficiency Correction

BES-I correction method:

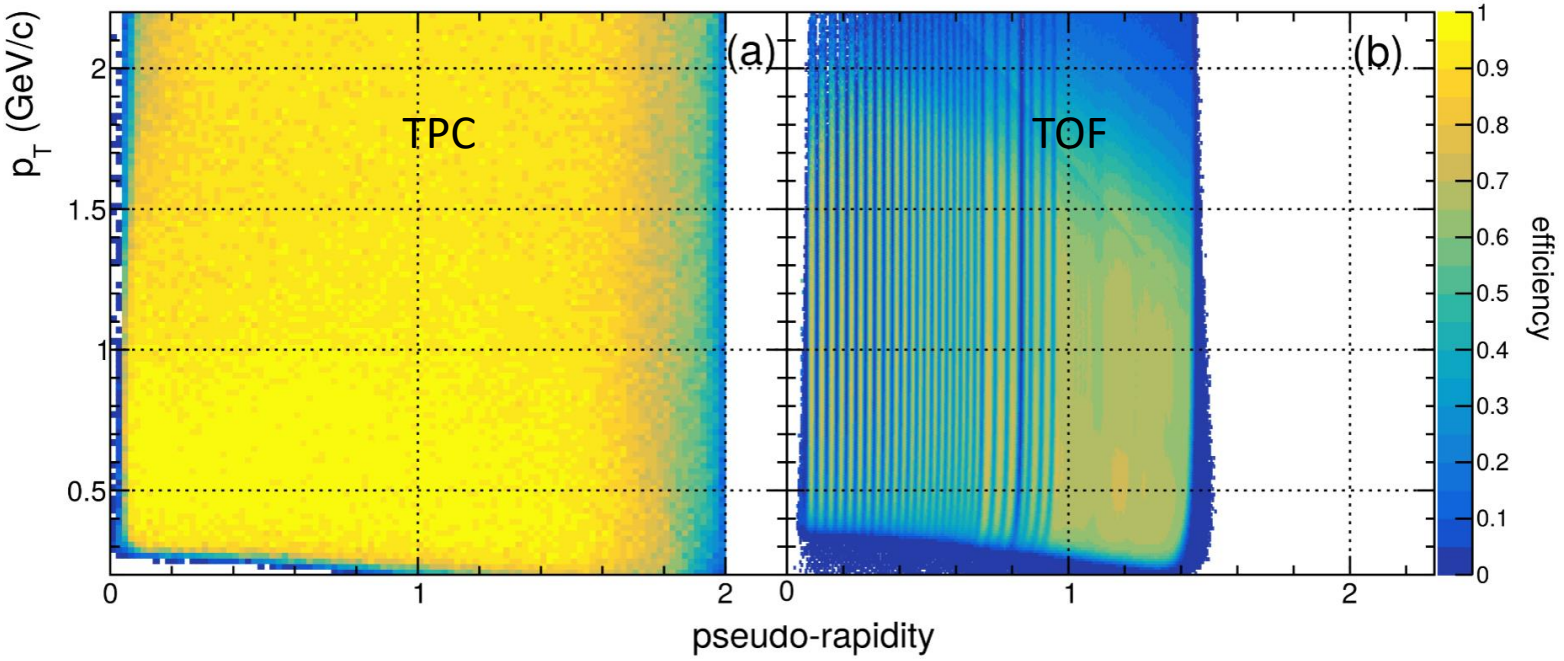
- Efficiency correction applied to the uncorrected cumulants
- Large averaged efficiency bins
- Efficiency bins weighted by the proton/anti-proton spectra

“Track-by-track” efficiency method:

- Efficiency correction as a function of rapidity and p_T is applied as a weight to proton tracks
- Allows for narrow efficiency bins
- Does not require proton spectra

X. Luo, T. Nonaka. *Physical Review C* 99.4 (2019) arXiv:1812.10303

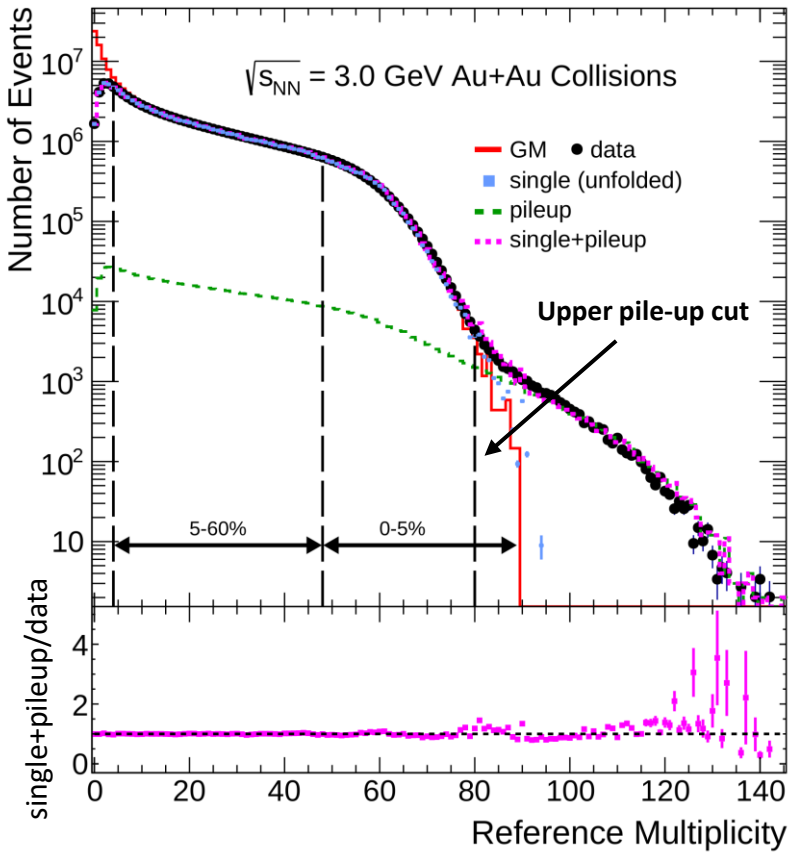
Track-by-Track Efficiency Correction



The efficiency correction assumes a binomial detector response

Centrality Determination

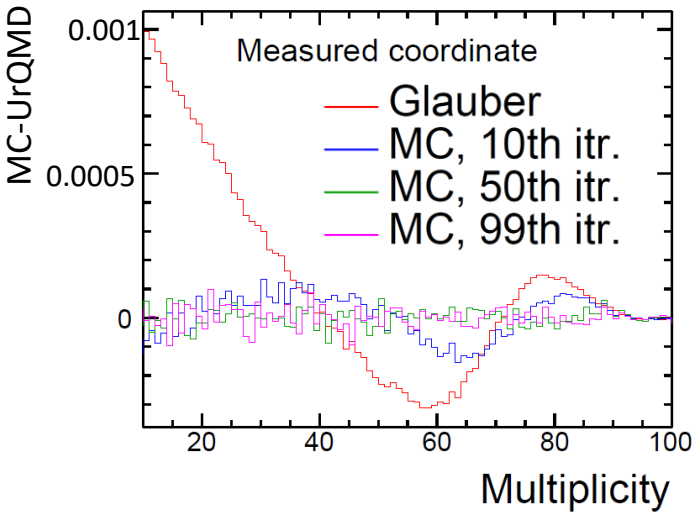
The reference multiplicity includes all pions, kaons, and electrons in the TPC acceptance



The centrality is determined by a Glauber model + two component model fit.

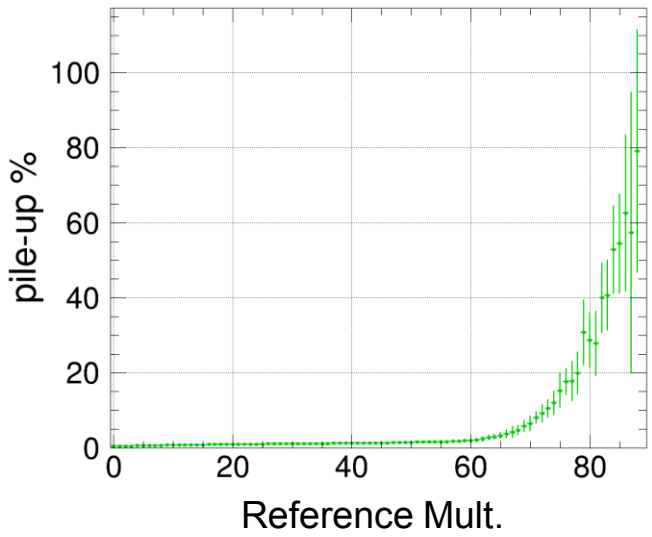
Pileup (double collisions)

Toy Model Test of unfolding procedure



0.46% total pile up probability

2.10% in top centrality class (0-5%)



The pile-up distribution is generated through an unfolding method

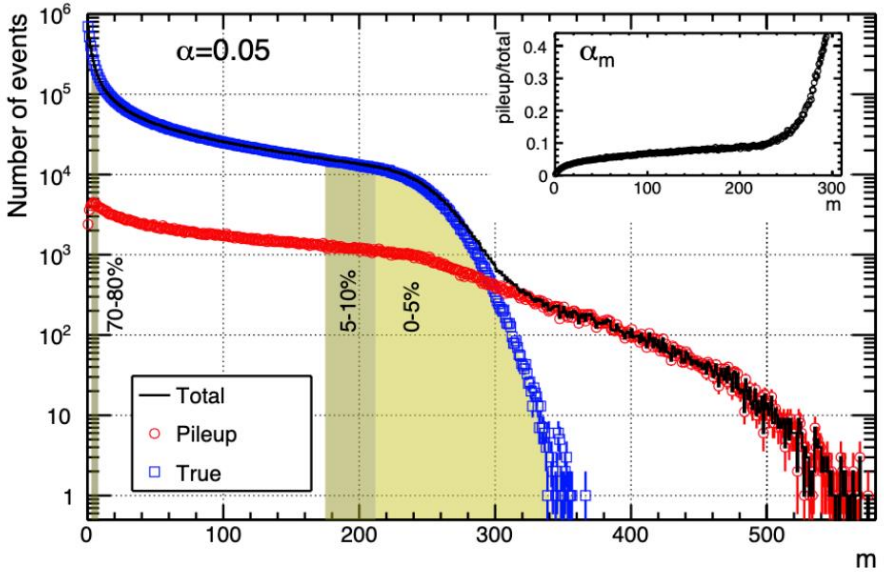
S. Esumi, K. Nakagawa, T. Nonaka. NIM 987 (2021)
arXiv:2002.11253

"Pileup Correction on Higher-order Cumulants with Unfolding Approach"
Y. Zhang, Y. Huang, T. Nonaka, X. Luo, arXiv : 2108.10134

Pile-up Correction

Pile-up correction assumes the pile-up distribution is a convolution of two single collision distributions

simulation

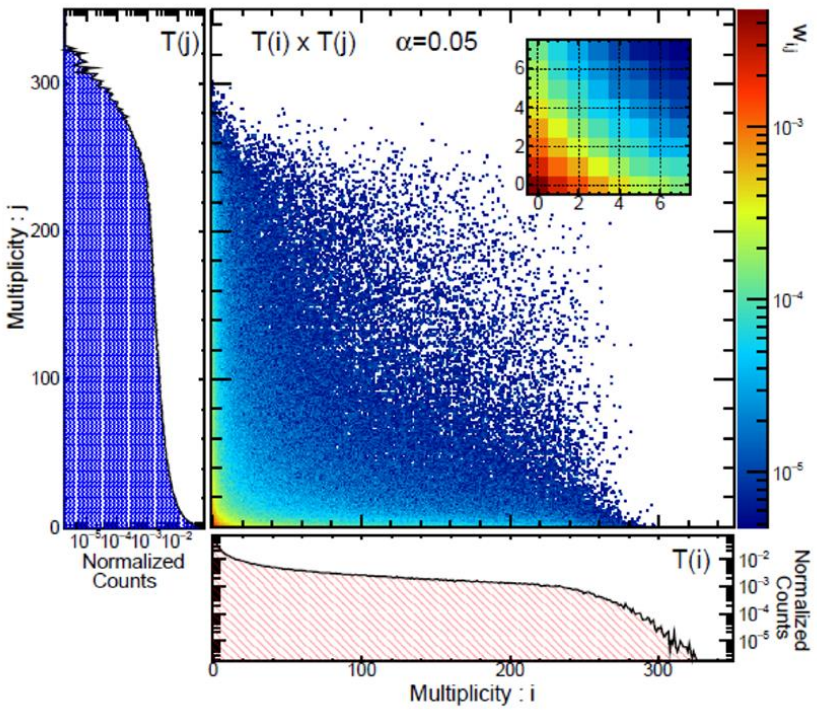


T. Nonaka, M. Kitazawa, S. Esumi, arXiv:2006.15809

$$\langle N^r \rangle_m^t = \frac{\langle N^r \rangle_m - \alpha_m C_m^{(r)}}{1 - \alpha_m + 2\alpha_m w_{m,0}}$$

With the pile-up fraction, the single collision and pile-up cumulants can be calculated

S. Esumi, K. Nakagawa, T. Nonaka. NIM 987 (2021)
arXiv:2002.11253

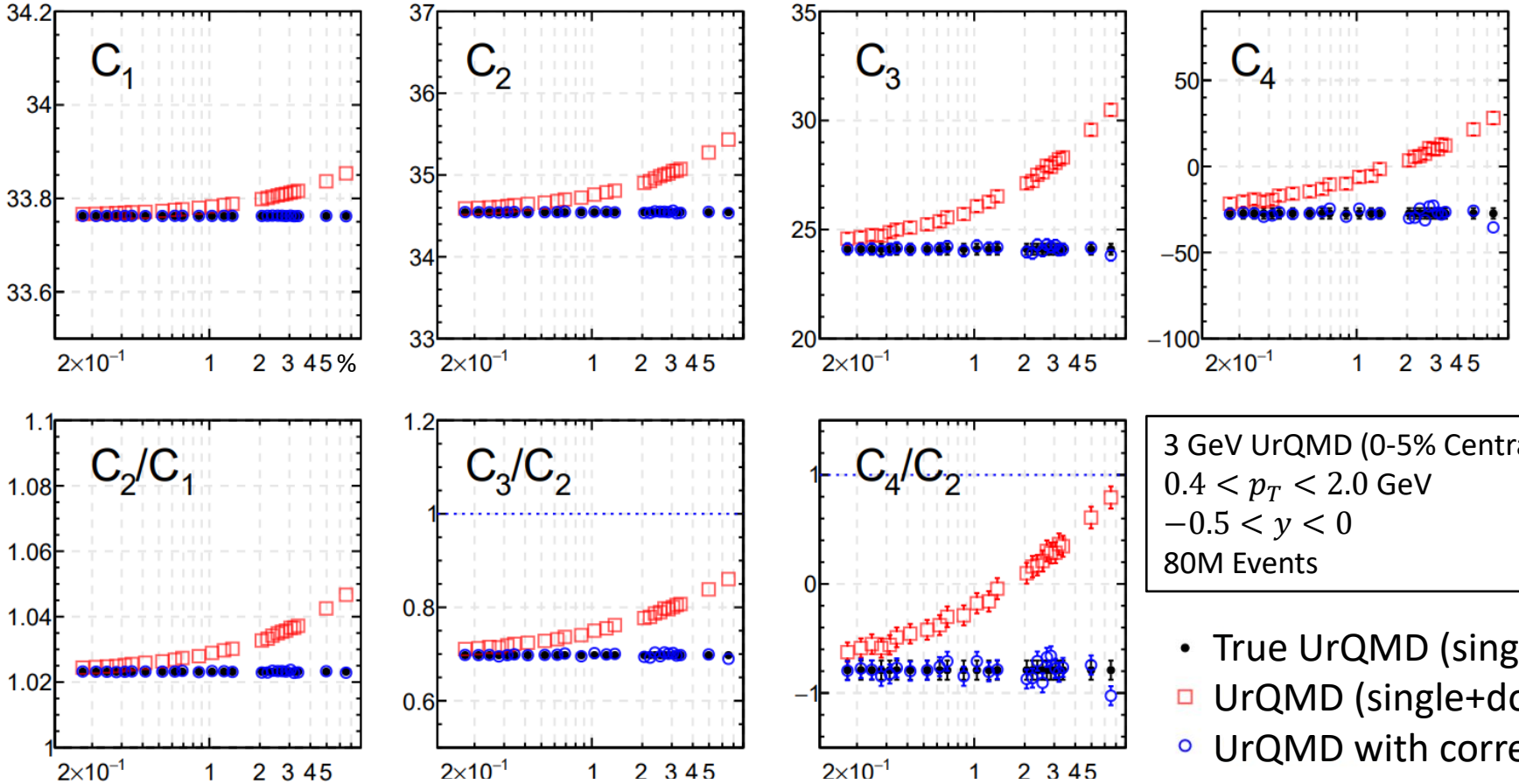


Response matrix of pile-up (double collision) events.

"Pileup Correction on Higher-order Cumulants with Unfolding Approach"
Y. Zhang, Y. Huang, T. Nonaka, X. Luo, arXiv : 2108.10134

Pile-up Correction Test on UrQMD

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



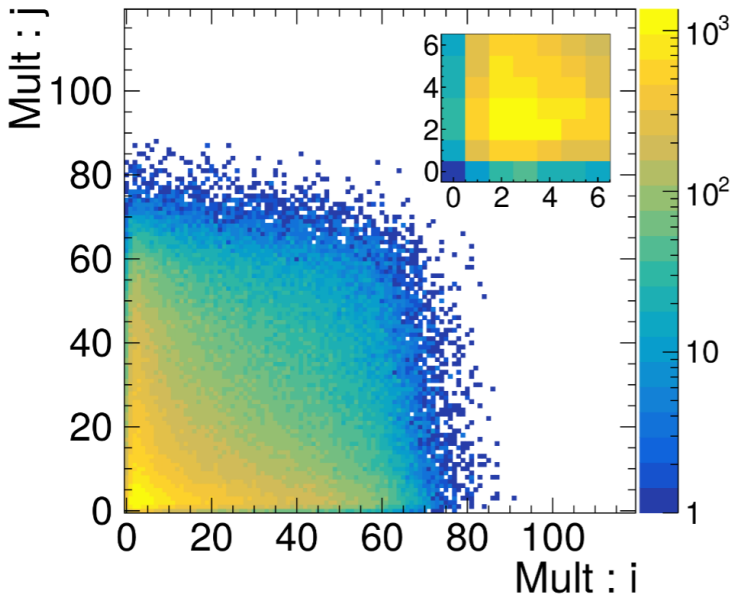
3 GeV UrQMD (0-5% Central)
$0.4 < p_T < 2.0$ GeV
$-0.5 < y < 0$
80M Events

- True UrQMD (single)
- UrQMD (single+double)
- UrQMD with correction

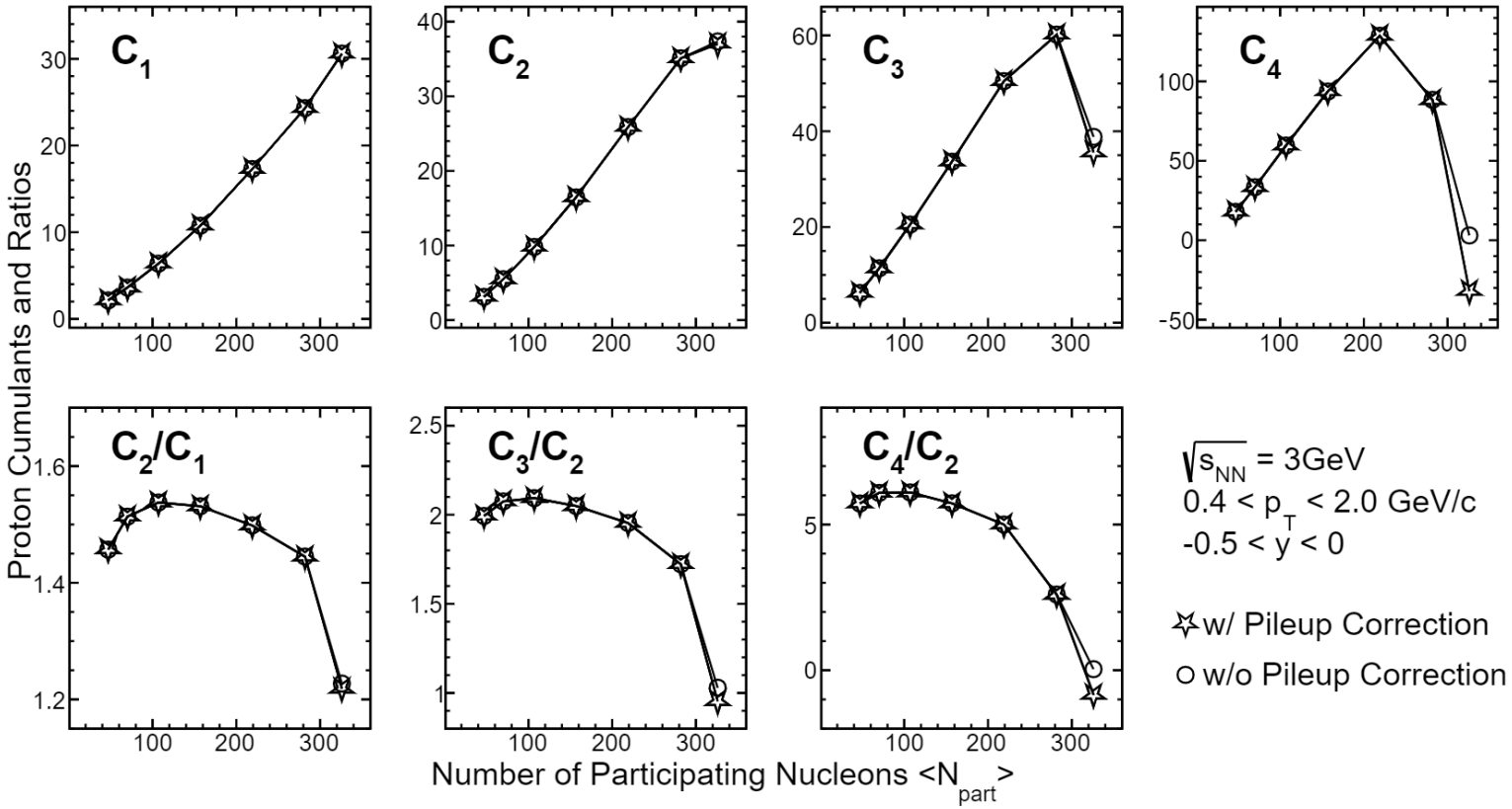
Pile-up Correction

Pile-up corrected cumulants as a function of multiplicity

Only the most central events are affected by the pile-up correction



Pile-up response matrix



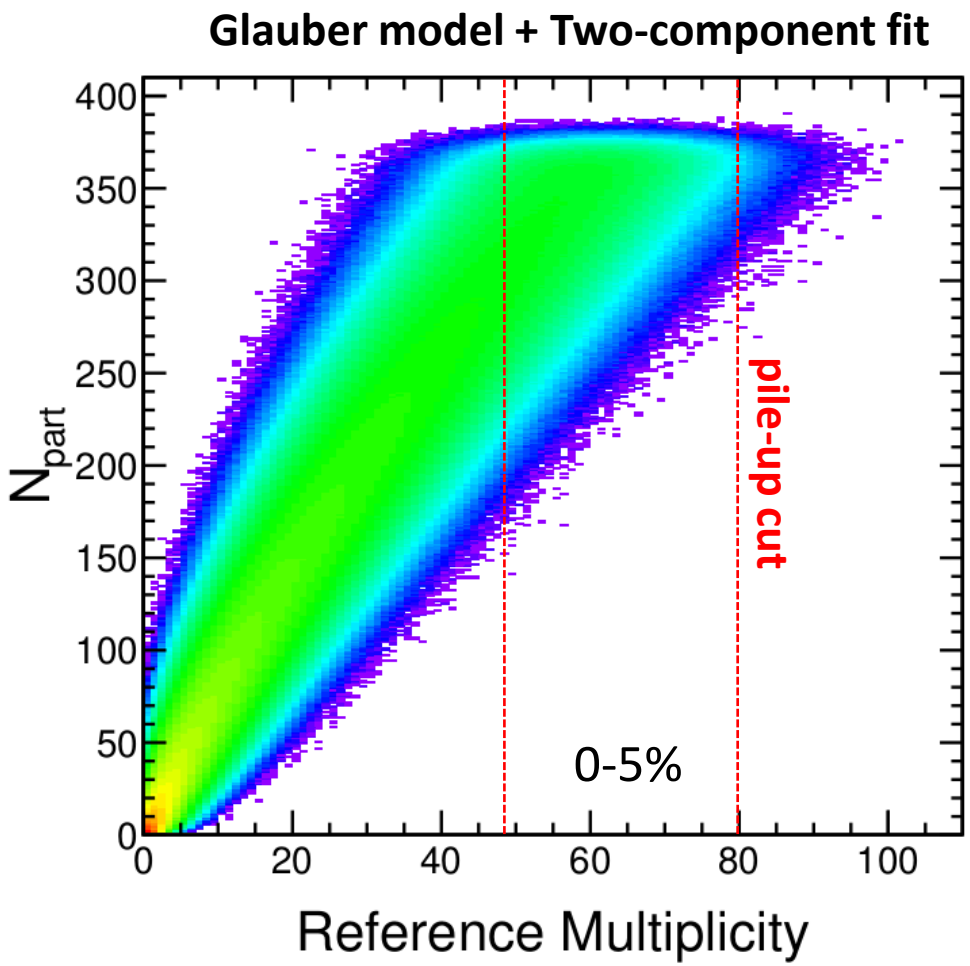
Volume Fluctuations

Fluctuations of the N_{part} distribution

The centrality class is determined by the reference multiplicity and not the underlying collision volume

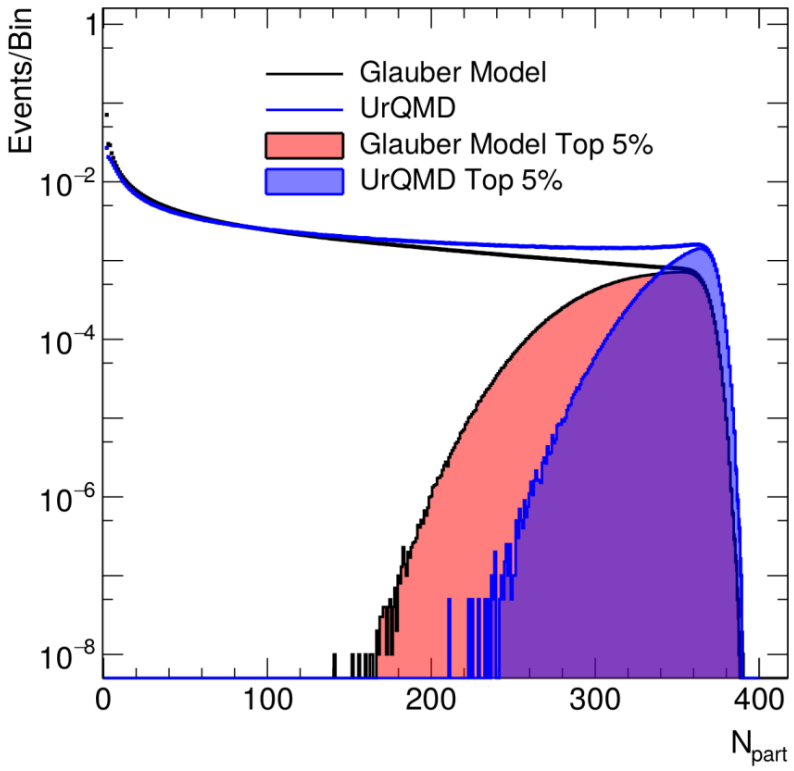
The collision volume is determined by the impact parameter or the number of participating nucleons N_{part}

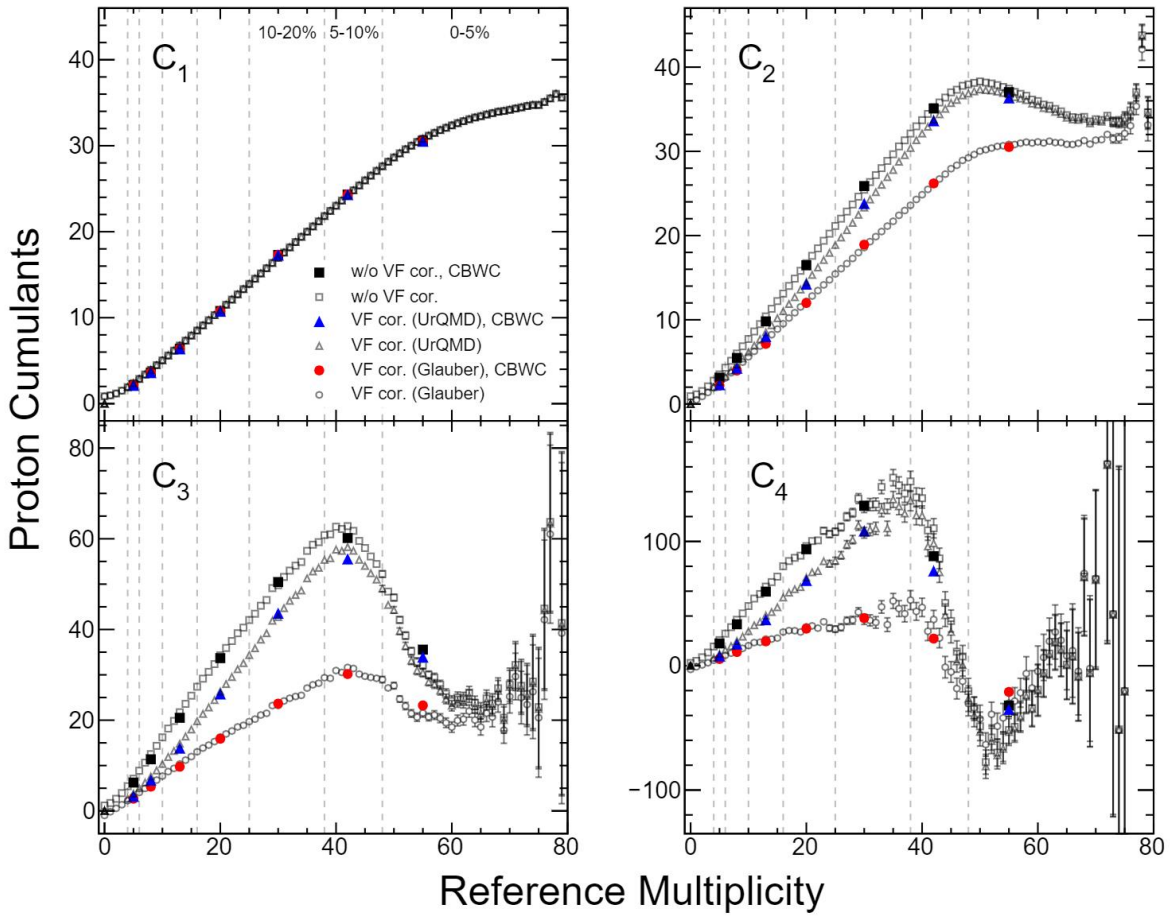
The underlying event-by-event N_{part} distribution in each centrality class can alter the proton cumulants



Volume Fluctuation Correction

N_{part} distributions from Glauber model and UrQMD



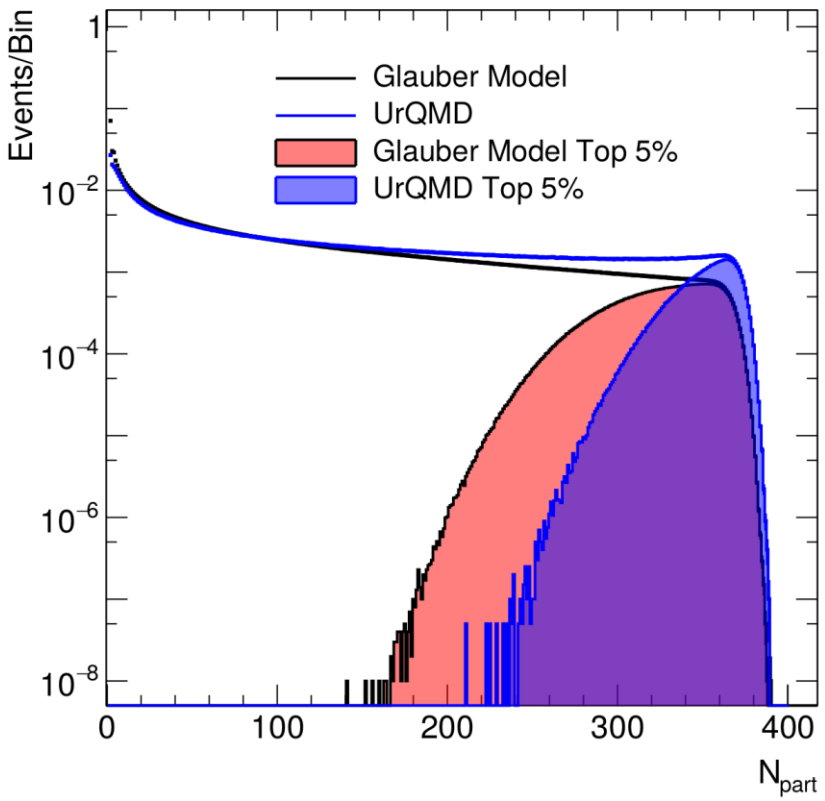


Model Dependent Volume Fluctuation Correction (VFC)

The cumulants are corrected using the underlying N_{part} distribution. The N_{part} is obtained from a model.

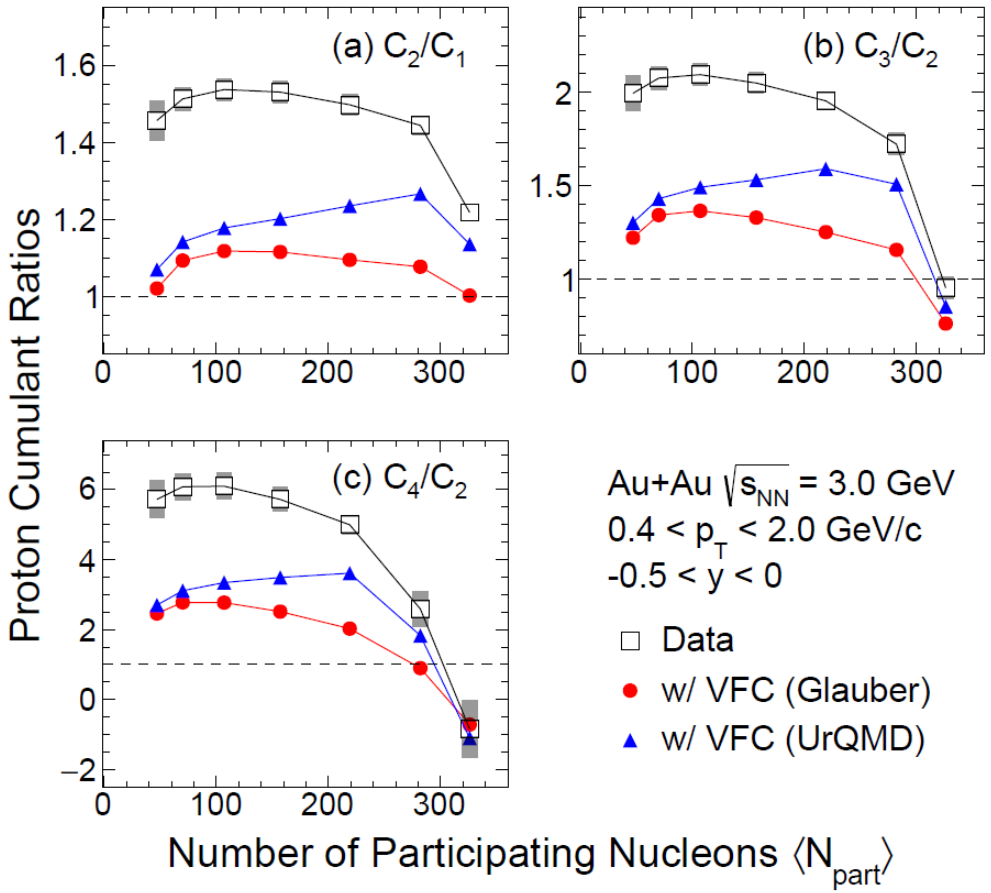
Braun-Munzinger, P., A. Rustamov, en J. Stachel. *Nuclear Physics A* 960 (2017) arXiv:1612.00702

Volume Fluctuation Correction



N_{part} distributions from Glauber model and UrQMD

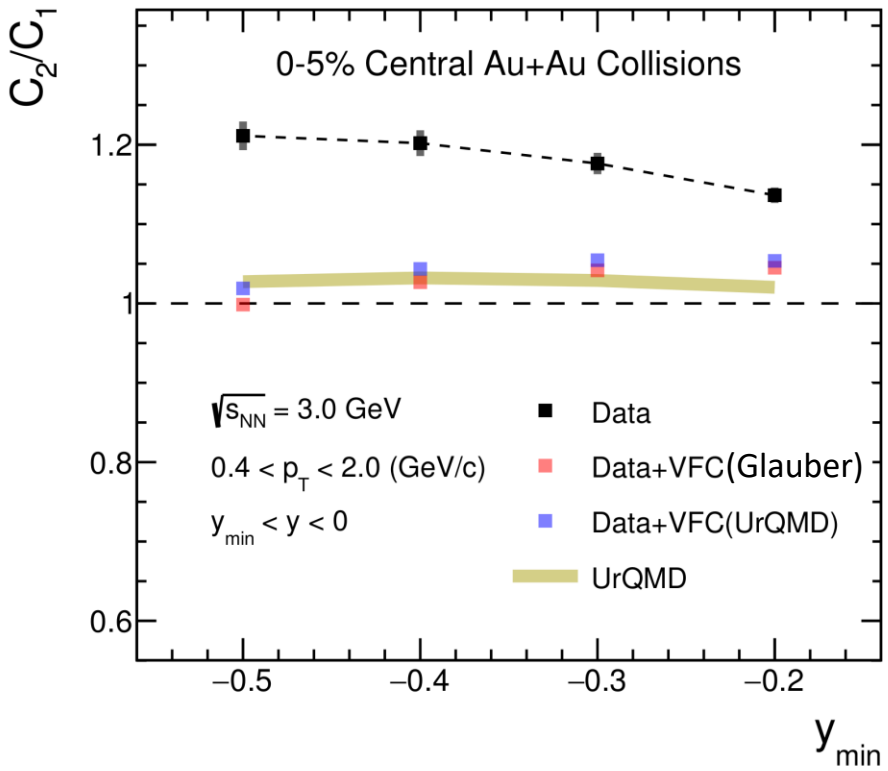
The volume fluctuations decrease for the most central events (0-5%)



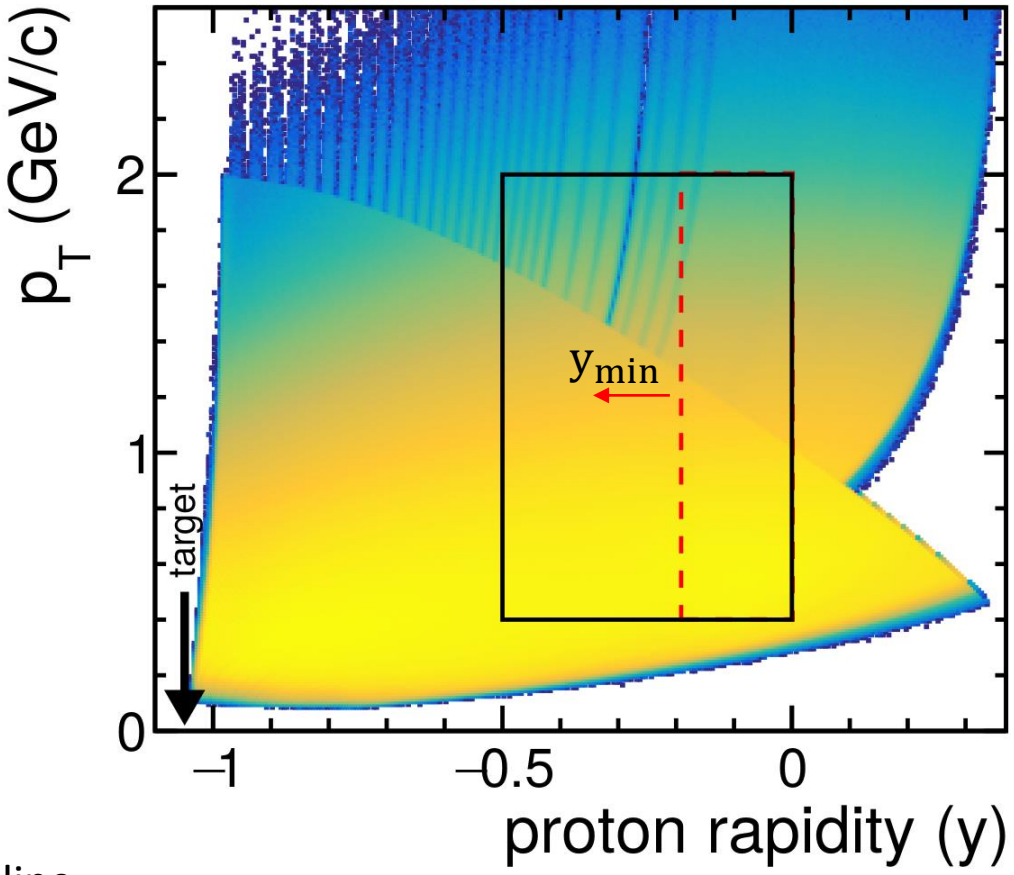
VFC for C_4/C_2 is negligible in central data

Proton Cumulants and Ratios Acceptance Scan

C_2/C_1 has a small rapidity dependence



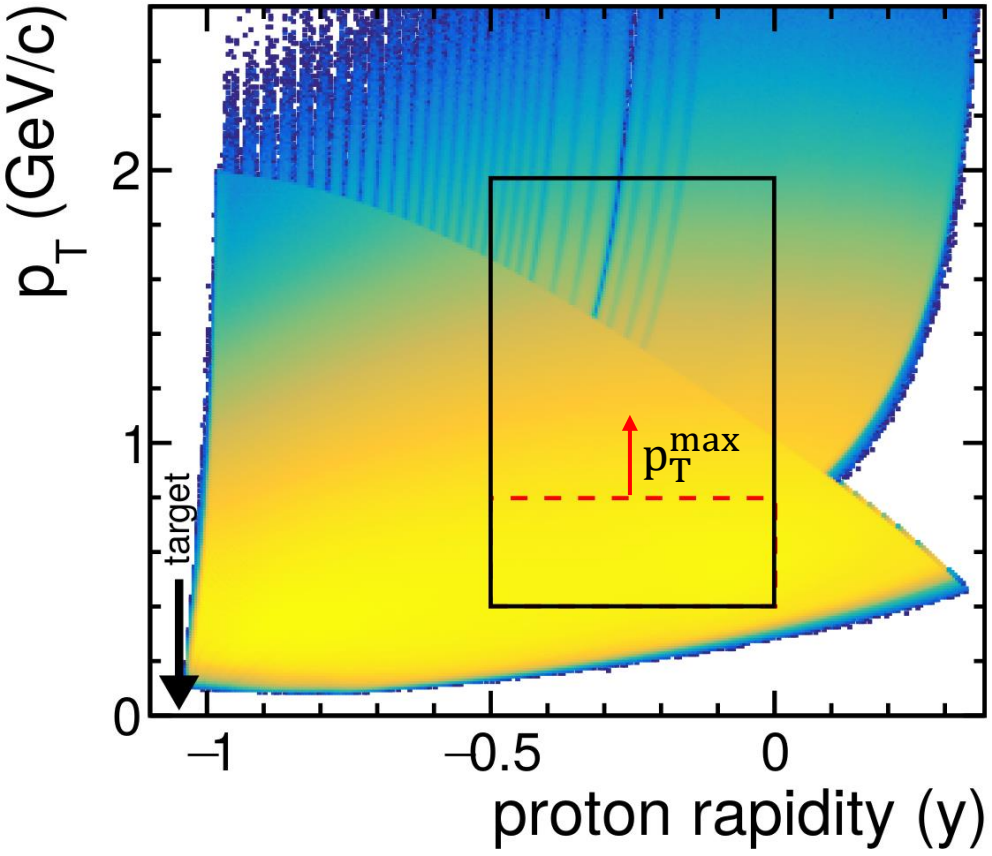
The rapidity is extended from -0.2<y<0 to -0.5<y<0

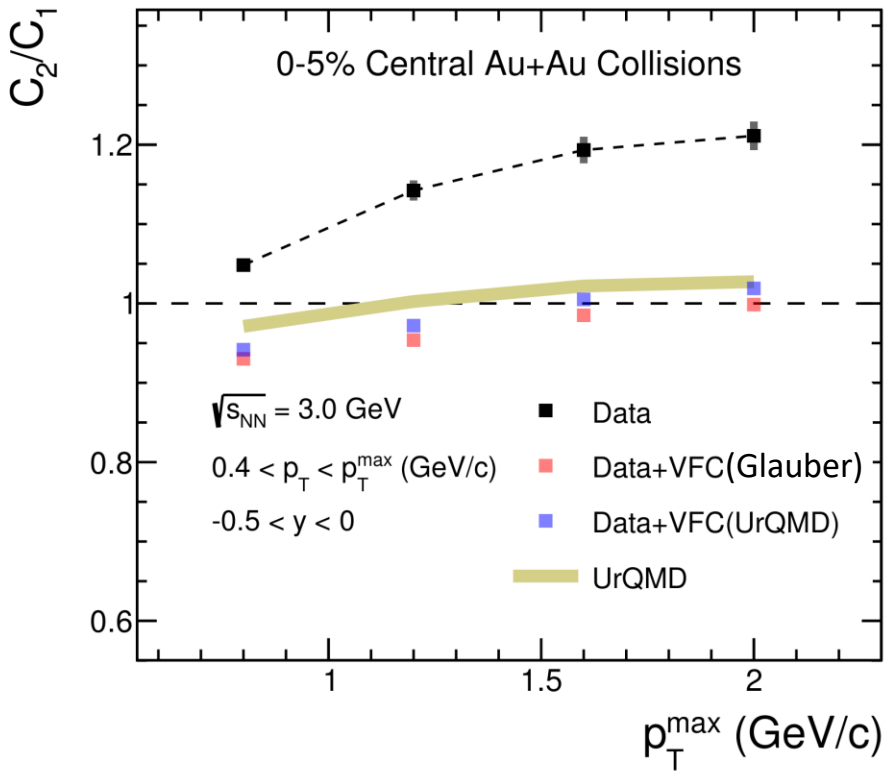


Applying VFC push C_2/C_1 to the Poisson baseline

Proton Cumulants and Ratios Acceptance Scan

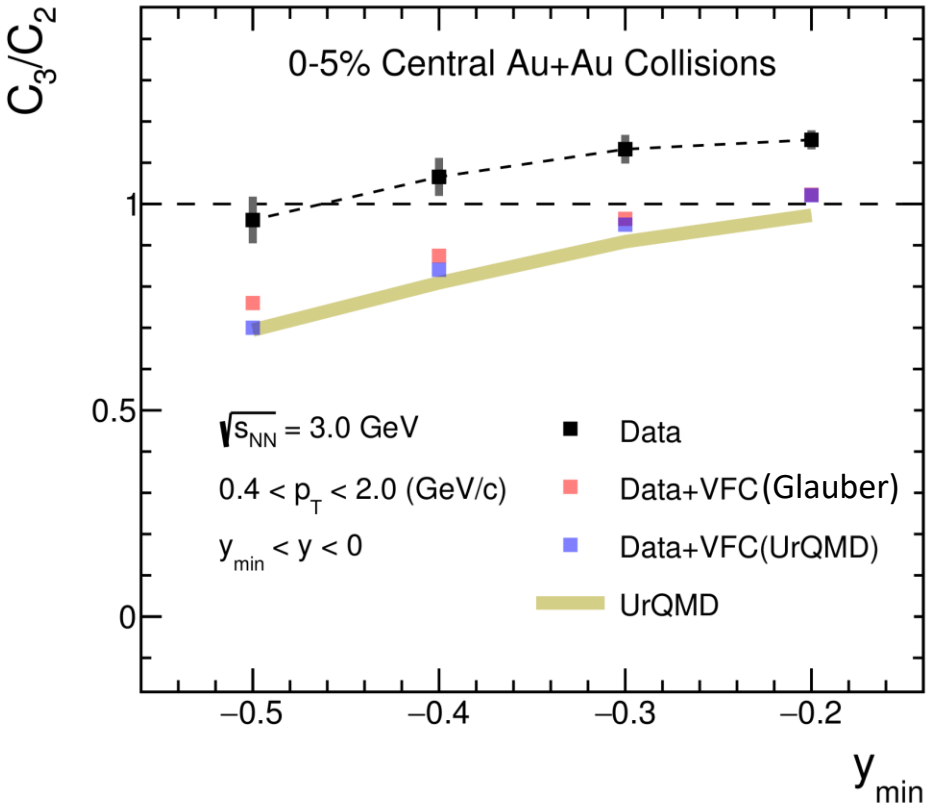
Expect the fluctuations to approach unity (Poisson baseline) as the acceptance window is decreased

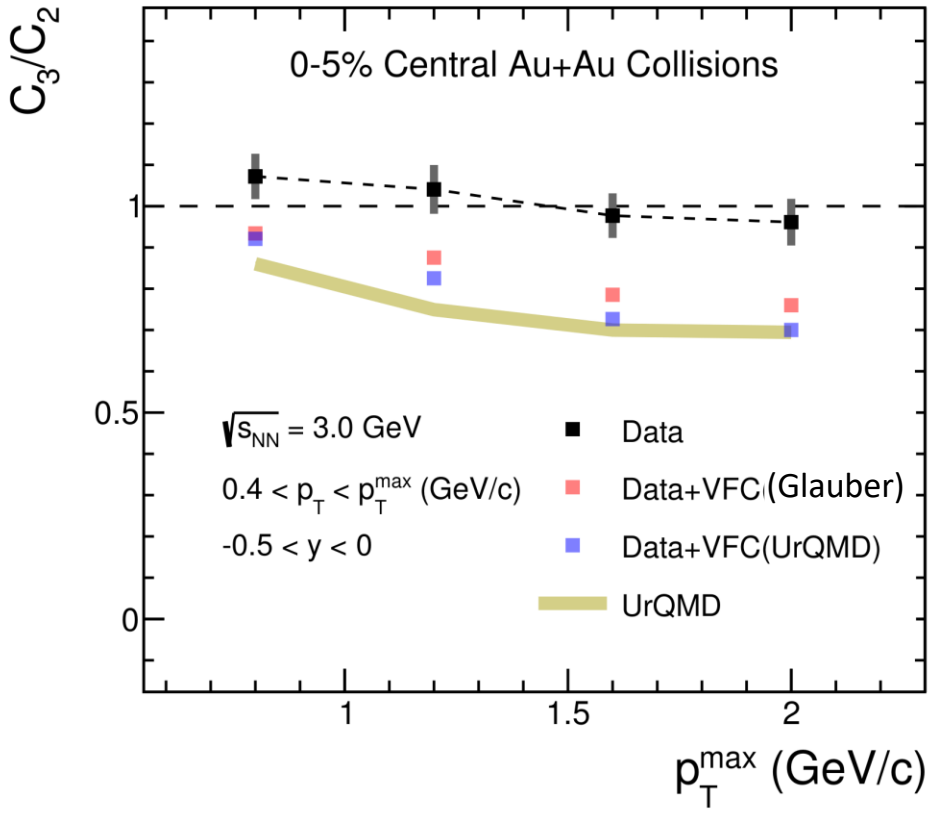




C_2/C_1 without correction approaches unity as the transverse momentum window is decreased

Proton Cumulants and Ratios Acceptance Scan

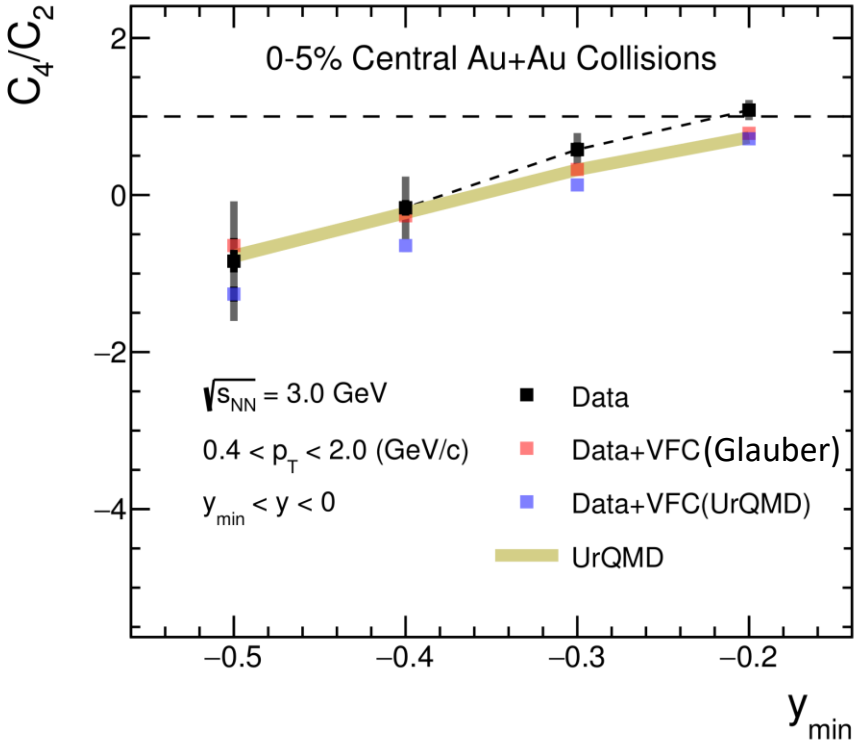


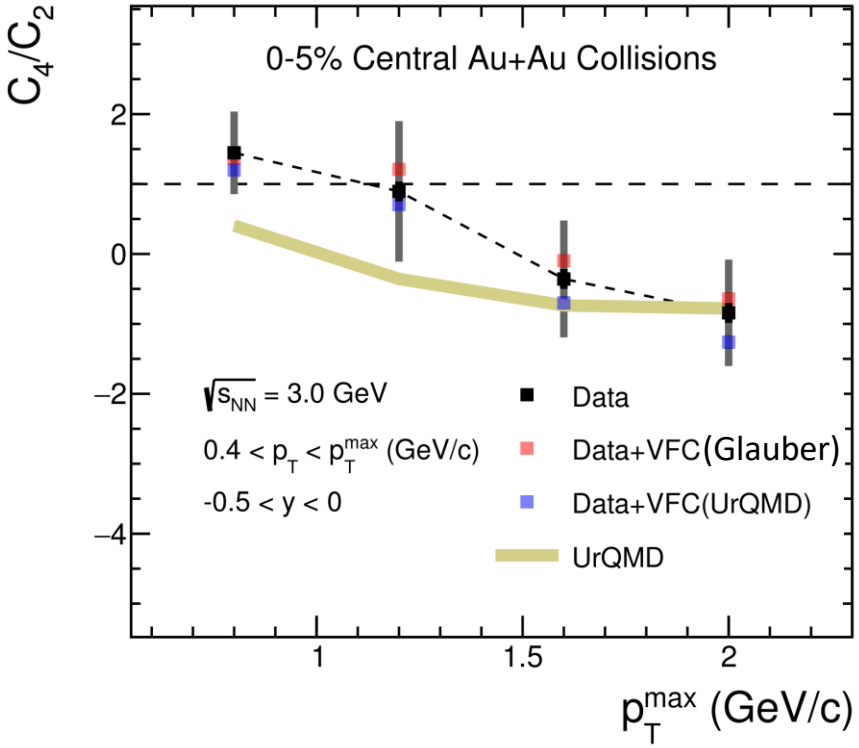


The trend in C_3/C_2 with respect to the Poisson baseline changes by applying volume fluctuation corrections

Proton Cumulants and Ratios Acceptance Scan

The C_4/C_2 is suppressed with respect to the Poisson baseline.





The suppression of C_4/C_2 vanishes and returns to the Poisson baseline as the acceptance window is decreased

This trend is seen in the transport model (UrQMD)

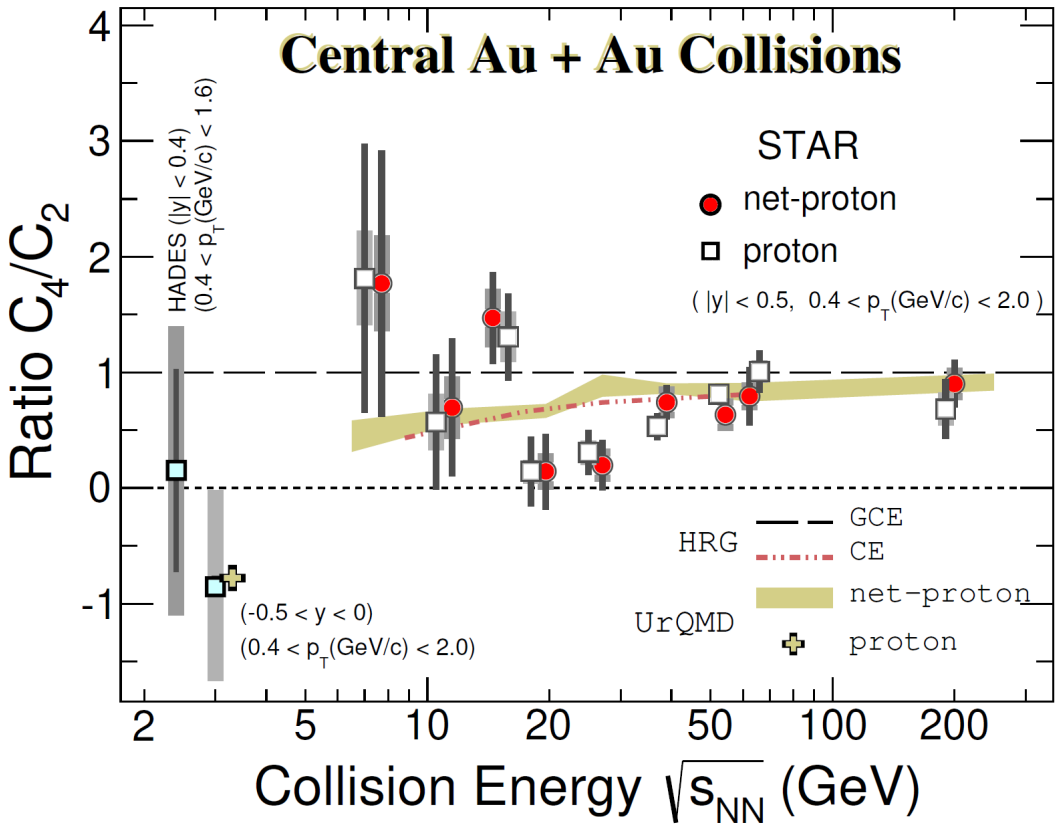
Cumulant Ratio Energy Scan

The suppression with respect to the Poisson baseline at $\sqrt{s_{NN}} = 3.0$ GeV is consistent with baryon number conservation.

The new result is consistent with the fluctuations in a region of high baryon density.

No evidence of critical fluctuations seen at $\sqrt{s_{NN}} = 3.0$ GeV.

These data imply that the QCD critical region, if created in heavy-ion collisions, could only exist at energies higher than 3 GeV.



Proton C_4/C_2 at $\sqrt{s_{NN}} = 3.0$ GeV (without correction) is consistent with the transport model

Summary & Outlook

Summary:

We report a C_4/C_2 = **-0.85 ± 0.09(stat.) ± 0.82(syst.)** in the kinematic acceptance -0.5 < y < 0 and 0.4 < p_T < 2.0 GeV/c for the top centrality class (0-5%) at 3 GeV.

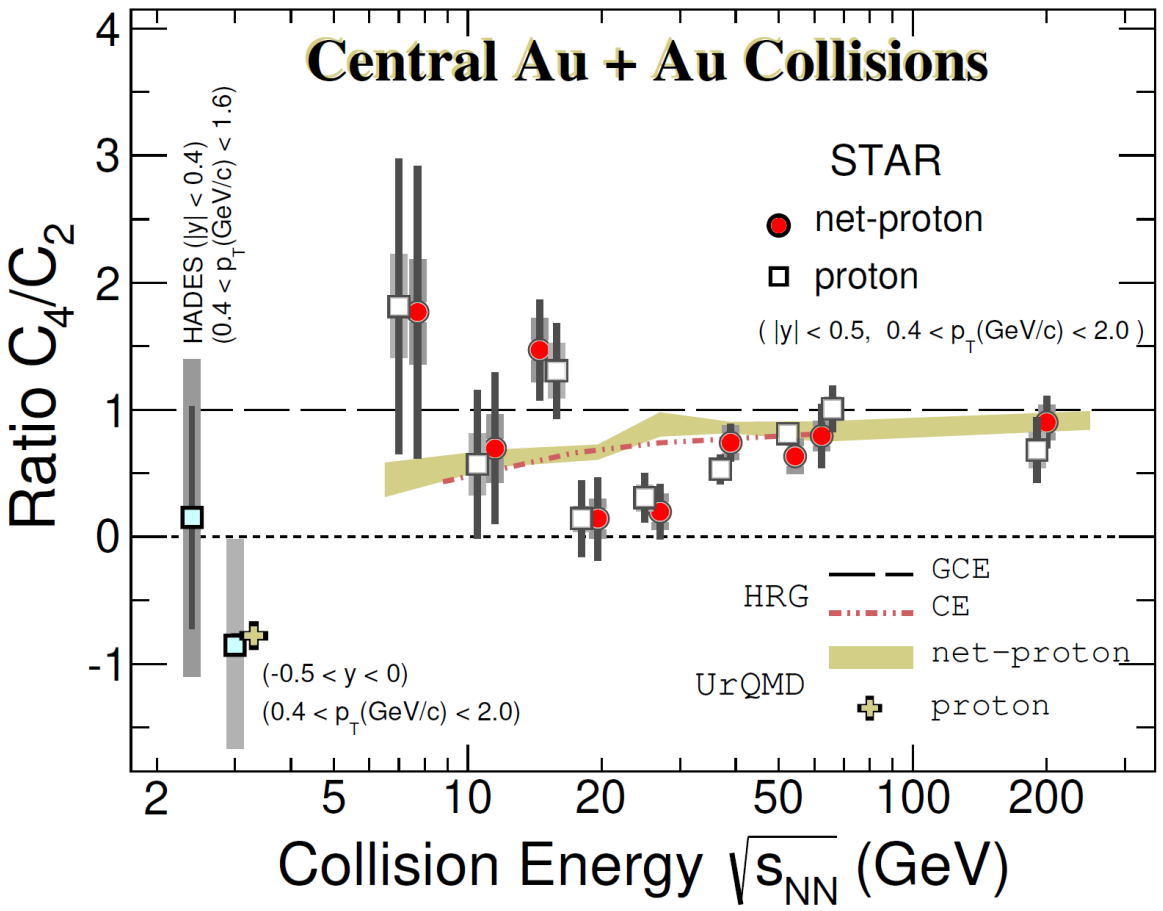
The uncertainty from VFC in the more peripheral data is large and needs more theoretical input.

The suppression in C_4/C_2 is consistent with fluctuations driven by baryon number conservation and indicates an energy regime dominated by hadronic interactions.

Outlook:

BES-II data from the 3 to 20 GeV region has been recorded. This result and the higher energies will be analyzed with higher statistics and detector upgrades.

This includes an overlap fixed-target/collider energy at 7.7 GeV.



Backup

Volume Fluctuations