Deuteron Number Fluctuations and Proton-deuteron Correlations in High Energy Heavy-ion Collisions in STAR Experiment at RHIC

QUARK MATTER KRAKÓW 2022

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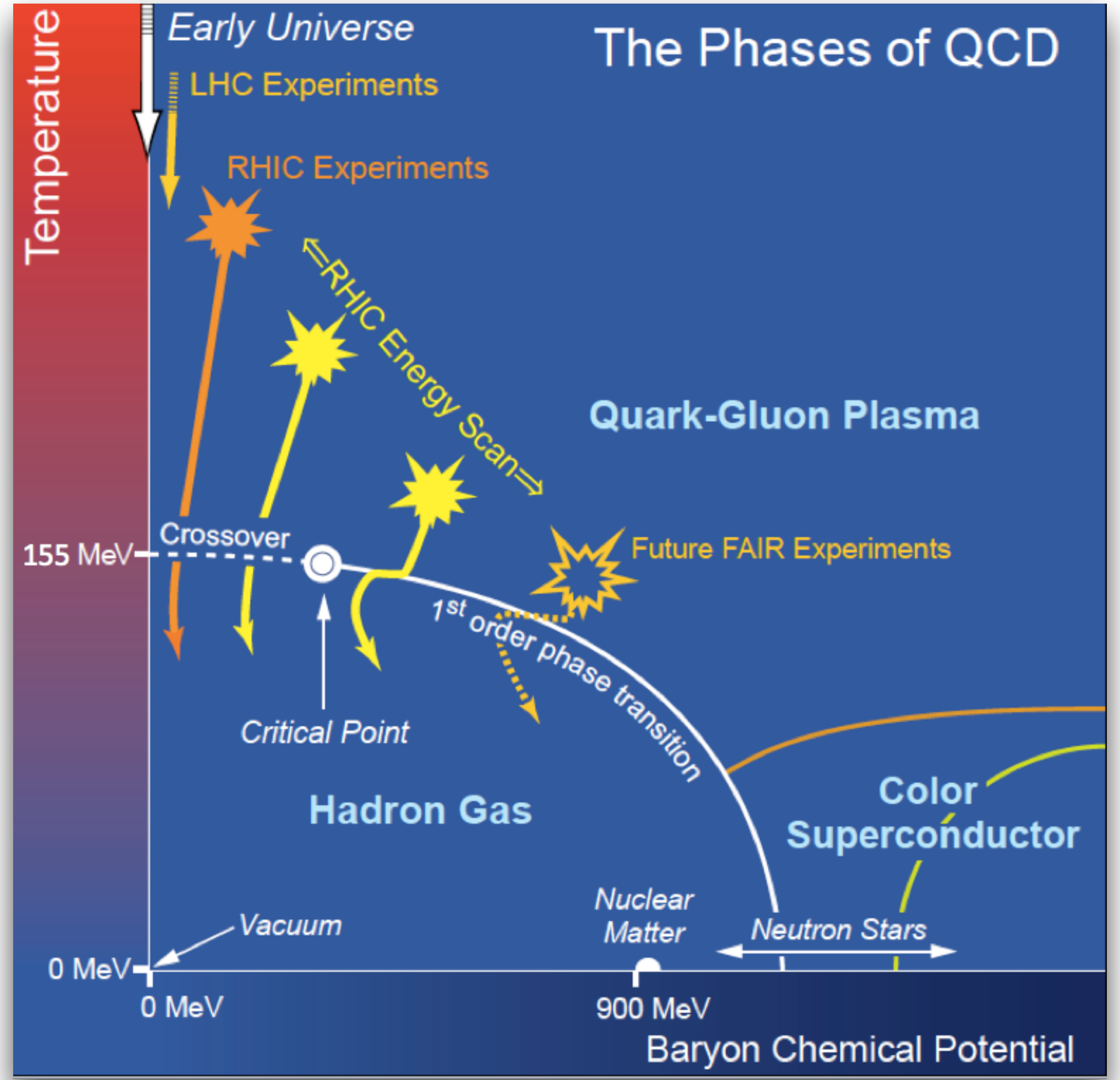
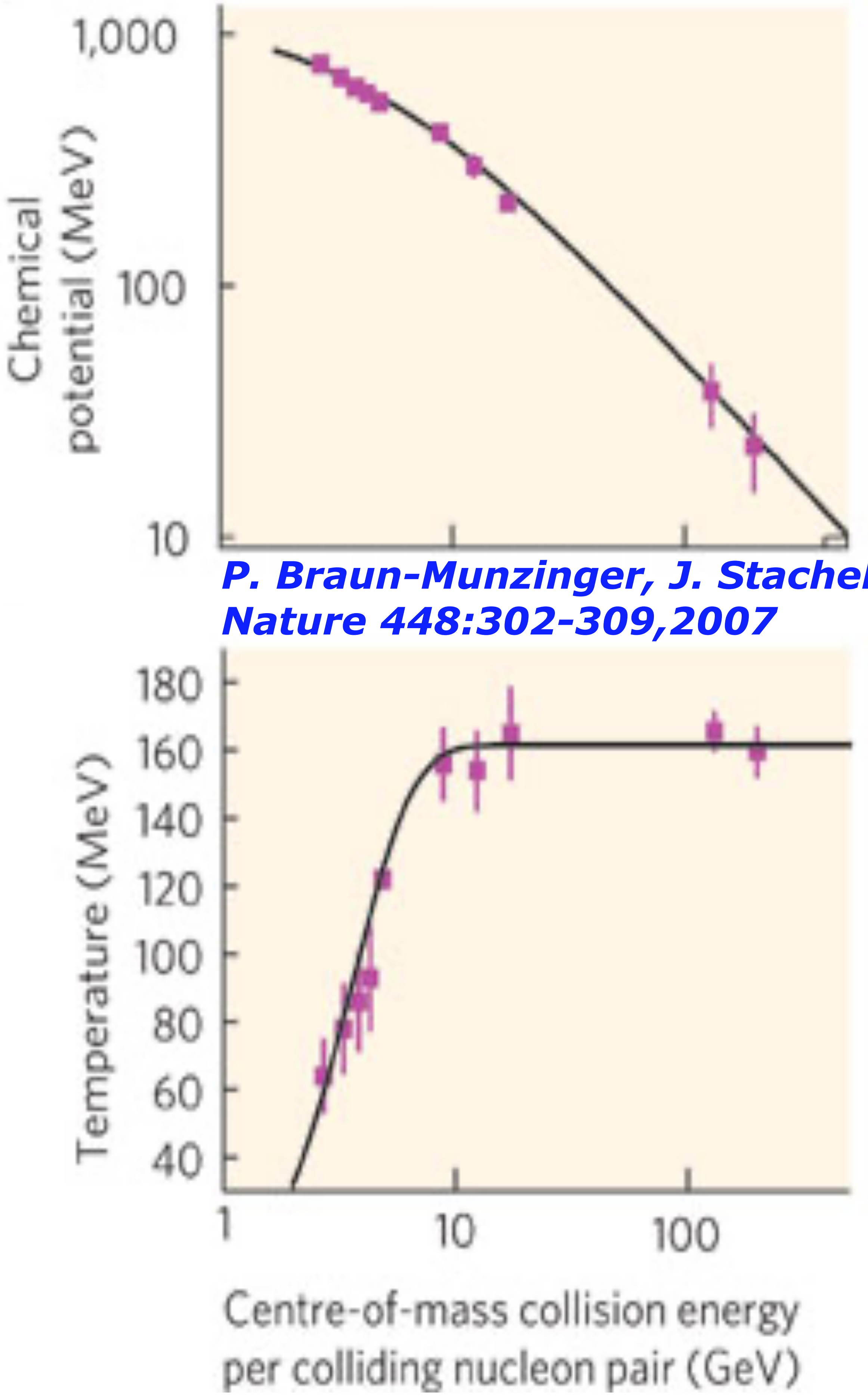
Jatni, India

Outline:
- Introduction
- Motivation and Observables
- STAR and Analysis Method
- Results
- Summary

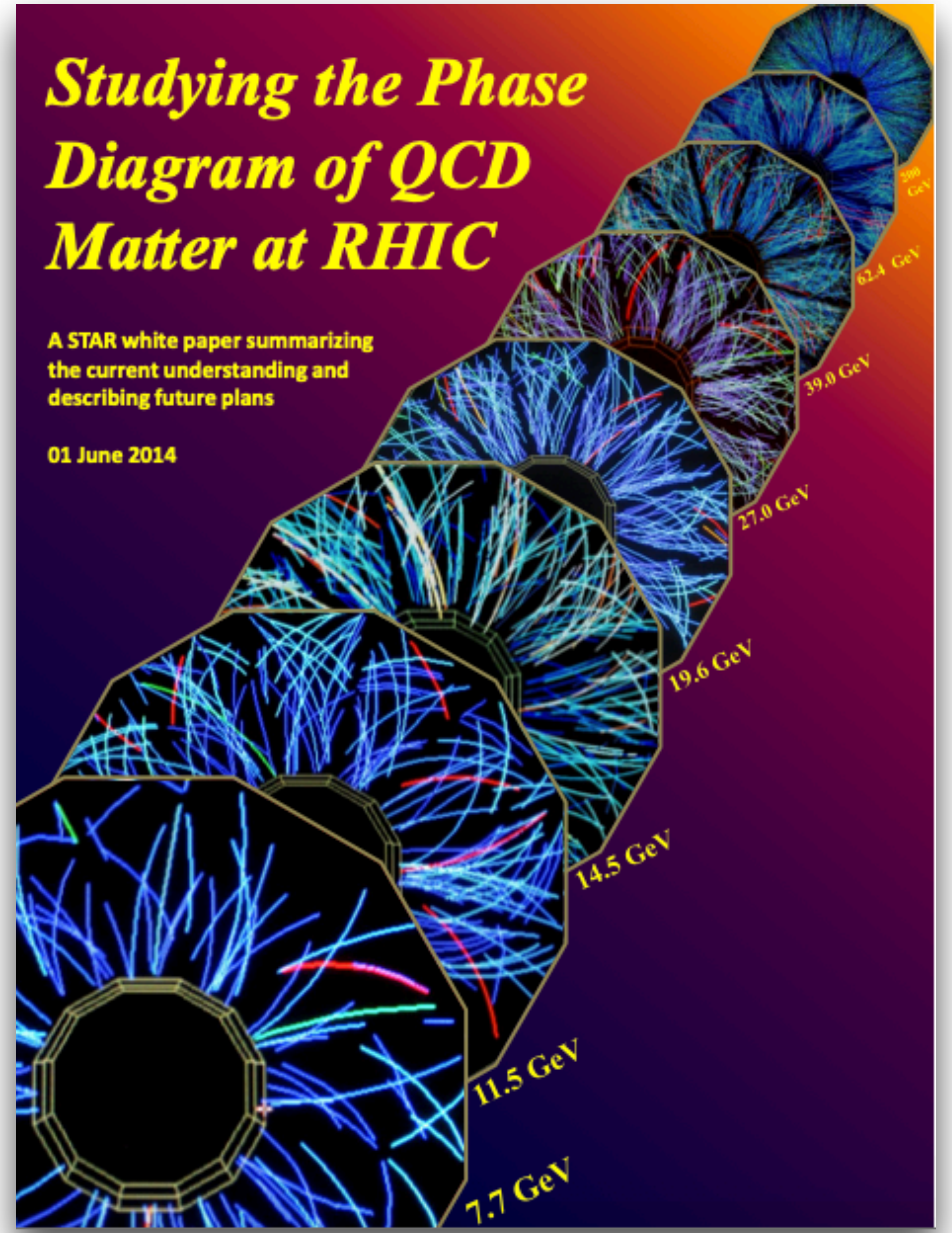
Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

Introduction





P. Braun-Munzinger, J. Stachel Nature 448:302-309,2007



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/files/BES_WPII_ver6.9_Cover.pdf

Goal: Study the phase diagram of QCD.
Beam Energy Scan (BES): Varying beam energy varies temperature (T) and baryon chemical potential (μ_B).
☑ Fluctuations in conserved quantities are sensitive to phase structure and critical point.

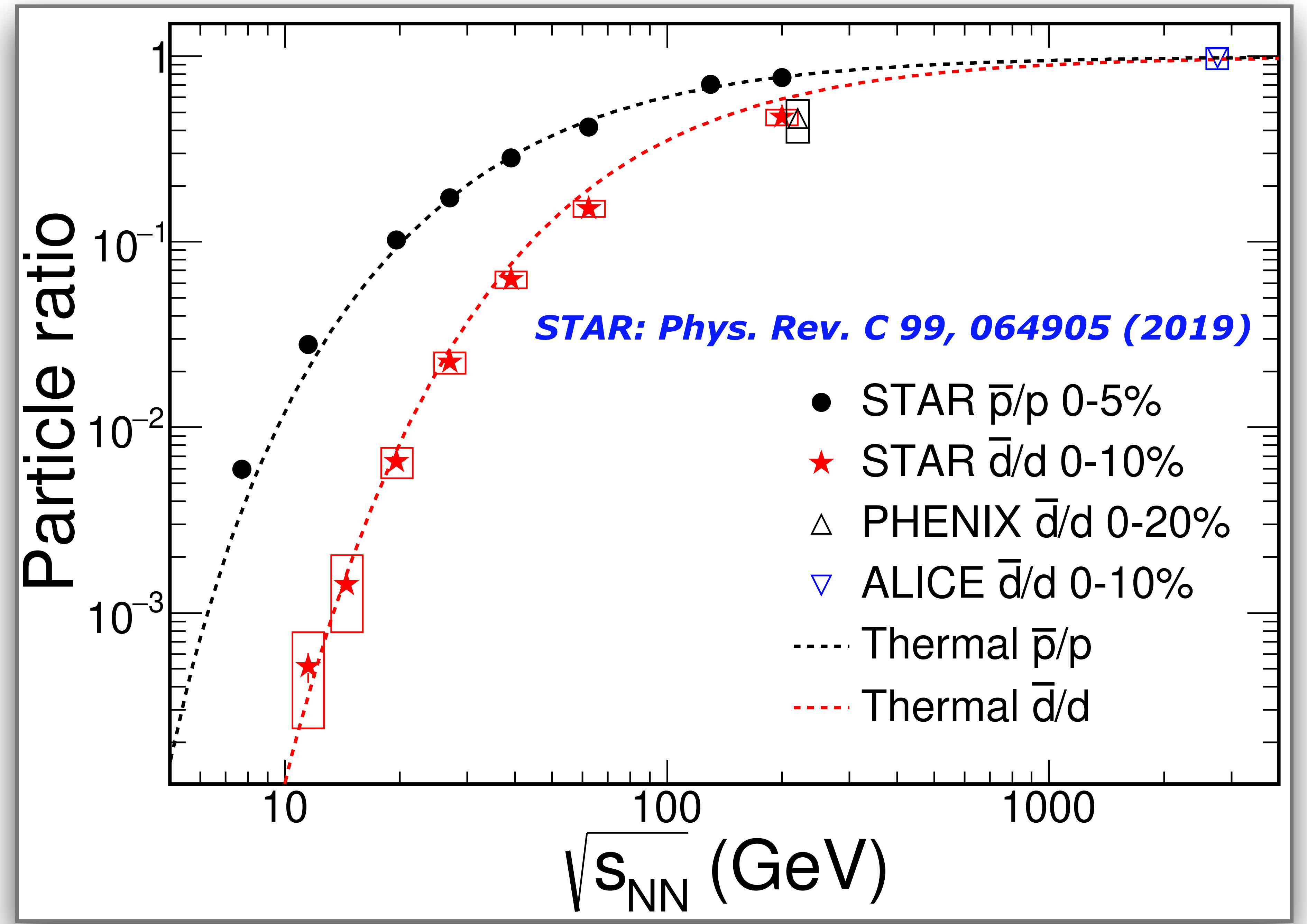
Light Nuclei Synthesis

GCE Thermal Model

Yield of deuteron: $N_d = \frac{g_d V}{\pi^2} m_d^2 T\, K_2(m_d/T)\ \exp(\mu_d/T)$

where, g_d: degeneracy, μ_d: chemical potential.

- ☑ Deuteron is treated as a free and point particle.
- ☑ Degeneracy, mass and baryon number are inputs.



☑ Anti-particle to particle ratio well explained by the thermal model for a range of $\sqrt{s_{NN}}$.

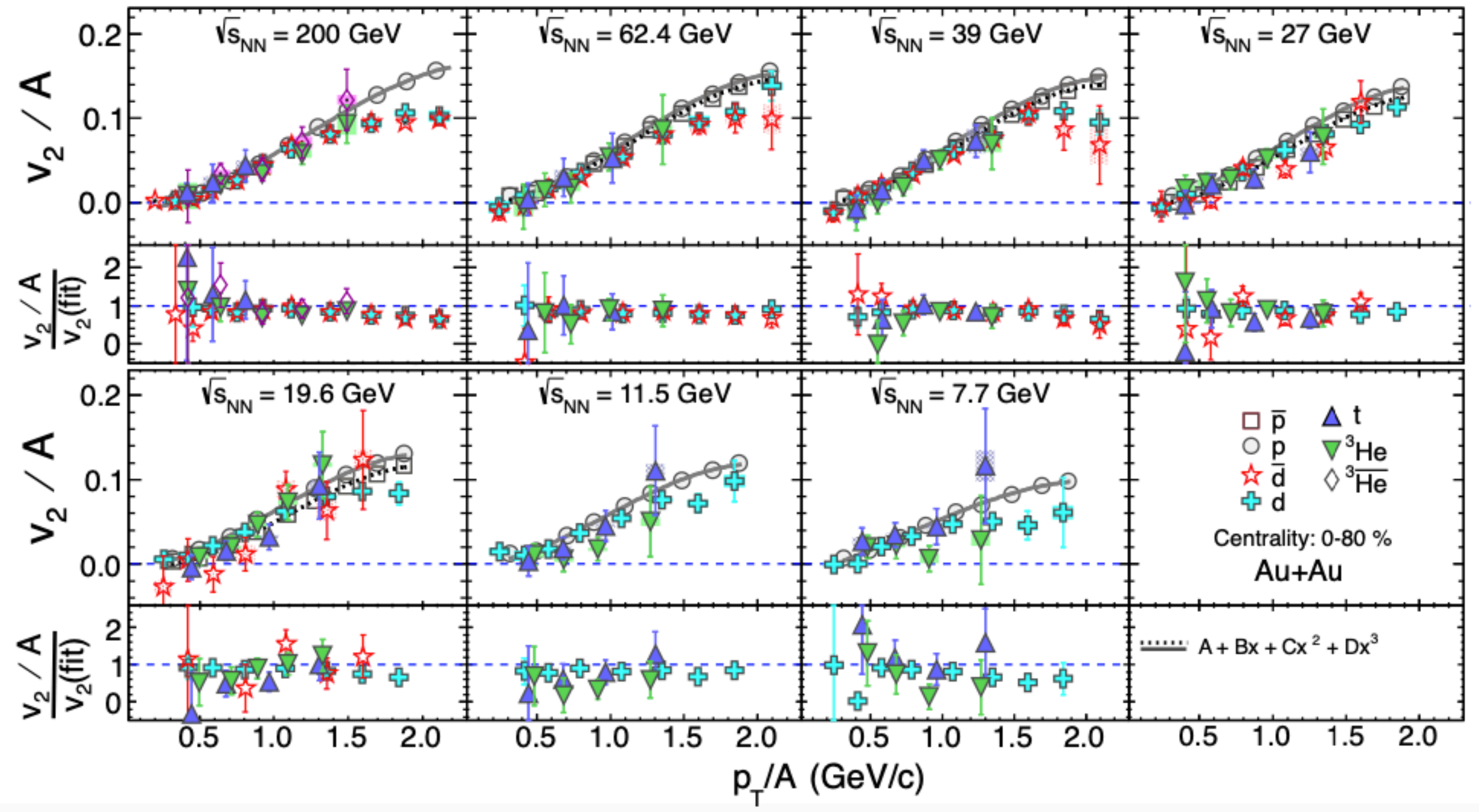
Coalescence Model

Invariant Yield: $E_d \frac{d^3N_d}{dp_d^3} = B_2 \left(E_p \frac{d^3N_p}{dp_p^3}\right) \left(E_n \frac{d^3N_n}{dp_n^3}\right)$

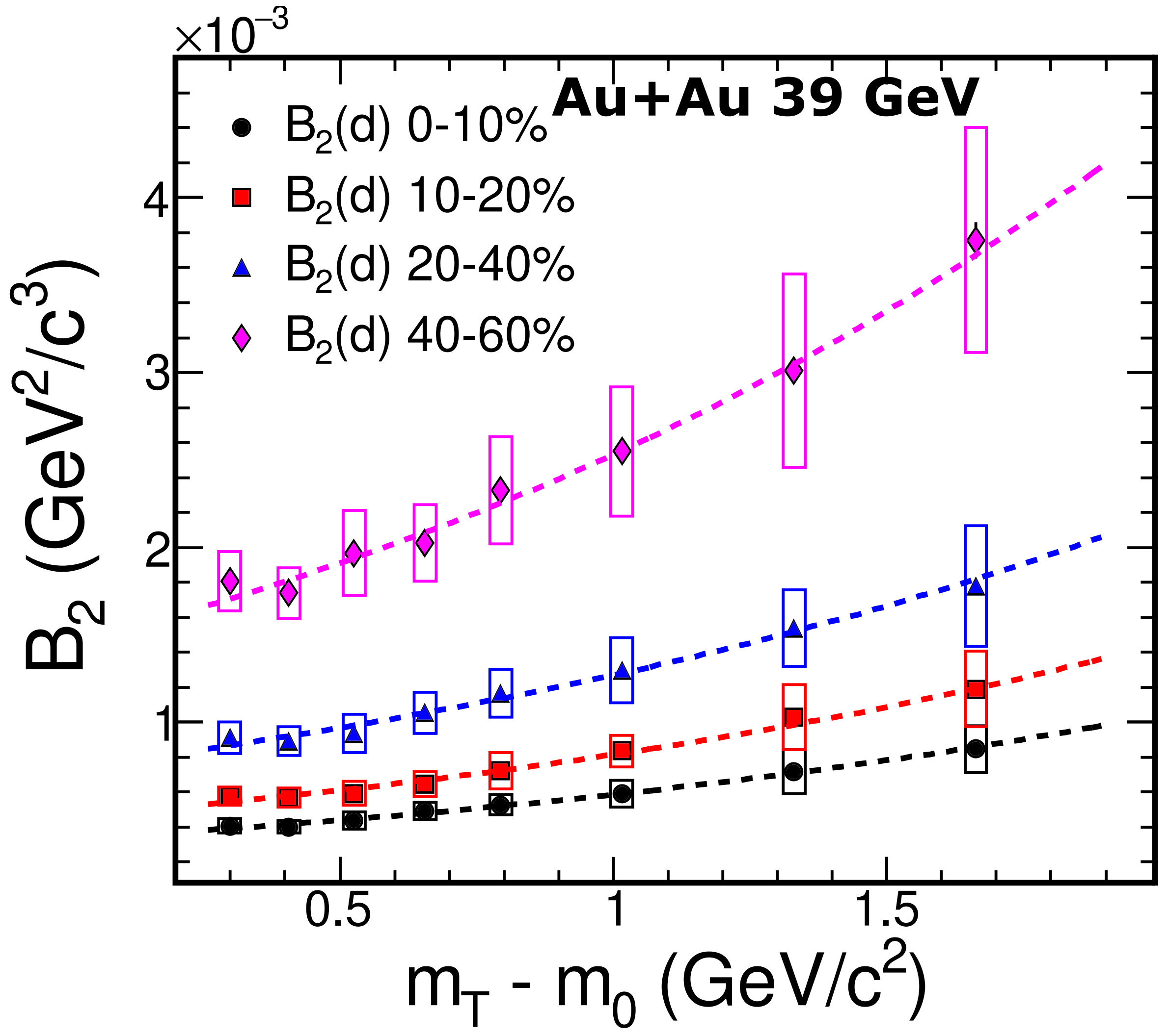
Elliptic Flow: $v_2^d(p_T) \approx 2 v_2^p\left(\frac{p_T}{2}\right)$

- ☑ Light nuclei created using protons and neutrons.
- ☑ B_2 extracted as a function of centrality, m_T , and $\sqrt{s_{NN}}$.

STAR: Phys. Rev. C 94 (2016) 3, 034908



☑ Nucleon coalescence picture works up to $p_T/A \leq 1.5$ GeV/c.



STAR: Phys. Rev. C 99, 064905 (2019)

- ☑ $B_2 \propto e^{(m_T - m)}$
- ☑ $B_2 \propto (4/3)\pi p_0^3$

p_0 is the radius in momentum space.

Light Nuclei Synthesis

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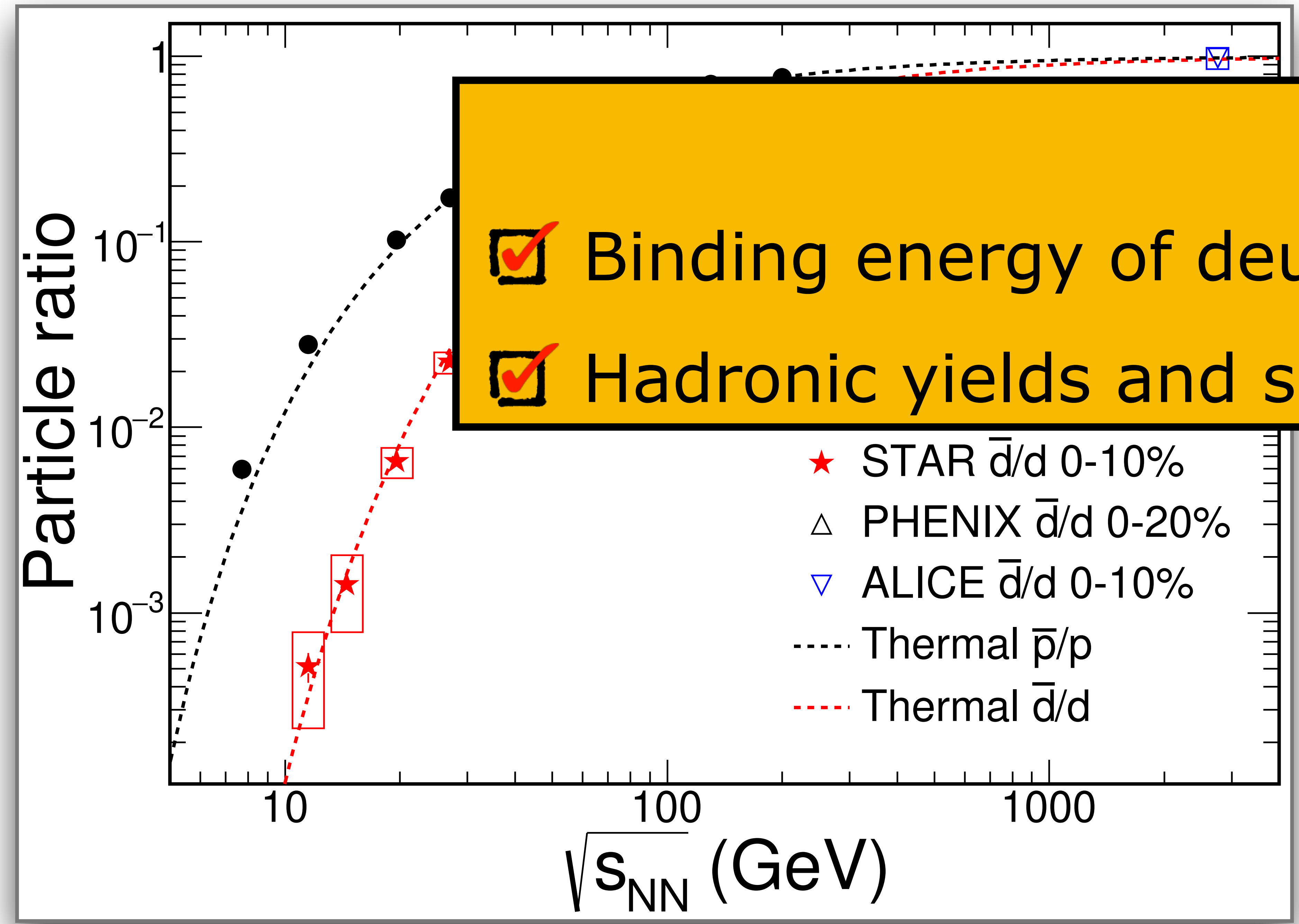
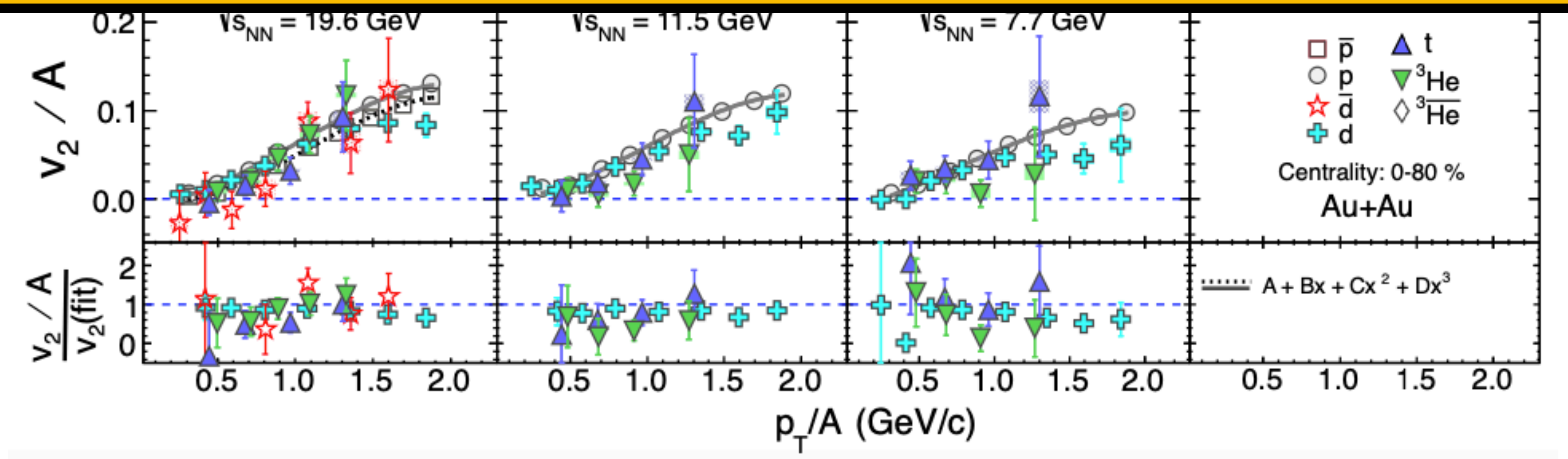
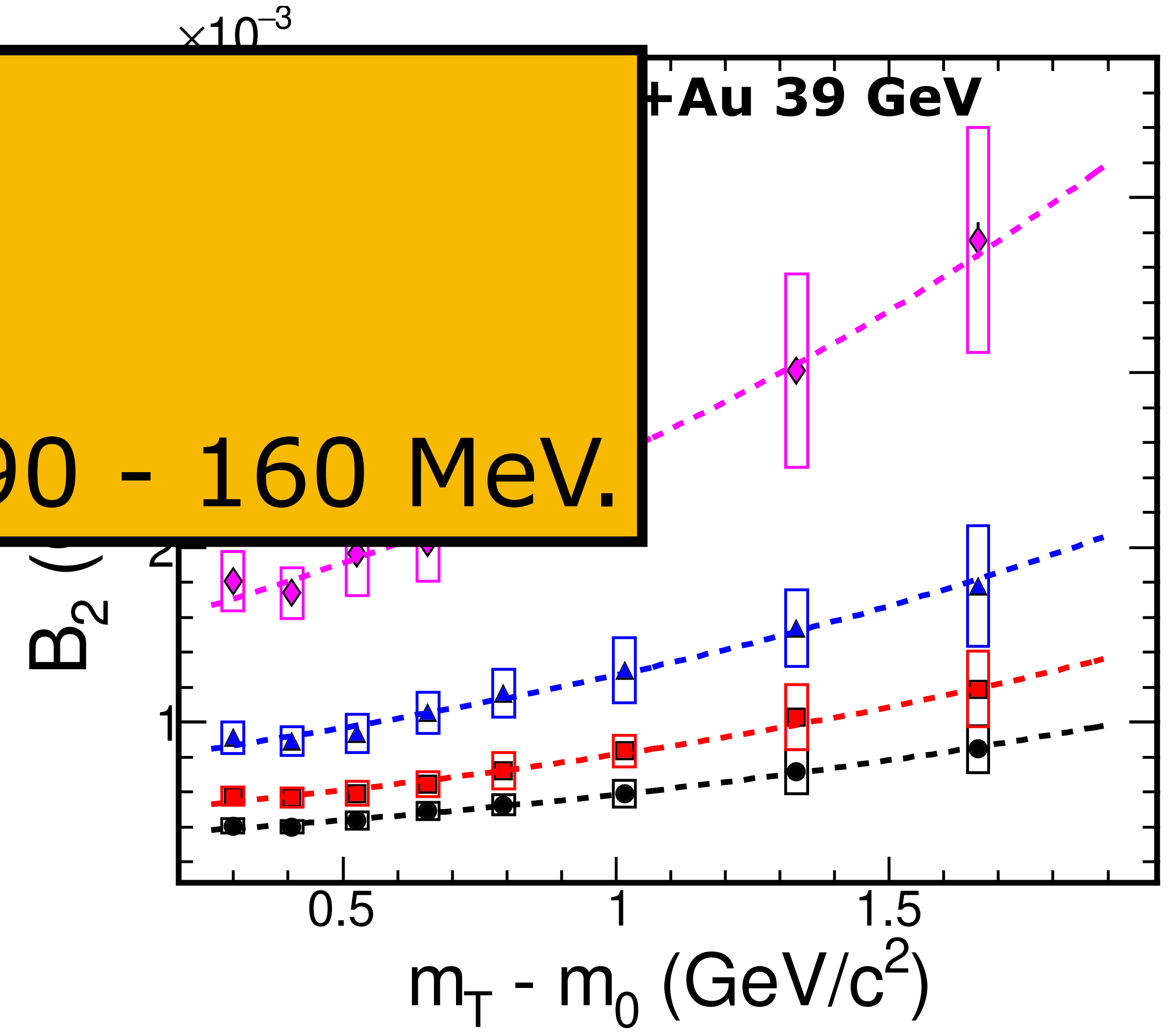


Typical Scales

- ☑ Binding energy of deuteron ~ 2.2 MeV.
- ☑ Hadronic yields and spectra are fixed around temperature ~ 90 - 160 MeV.





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p_0 is the radius in momentum space.

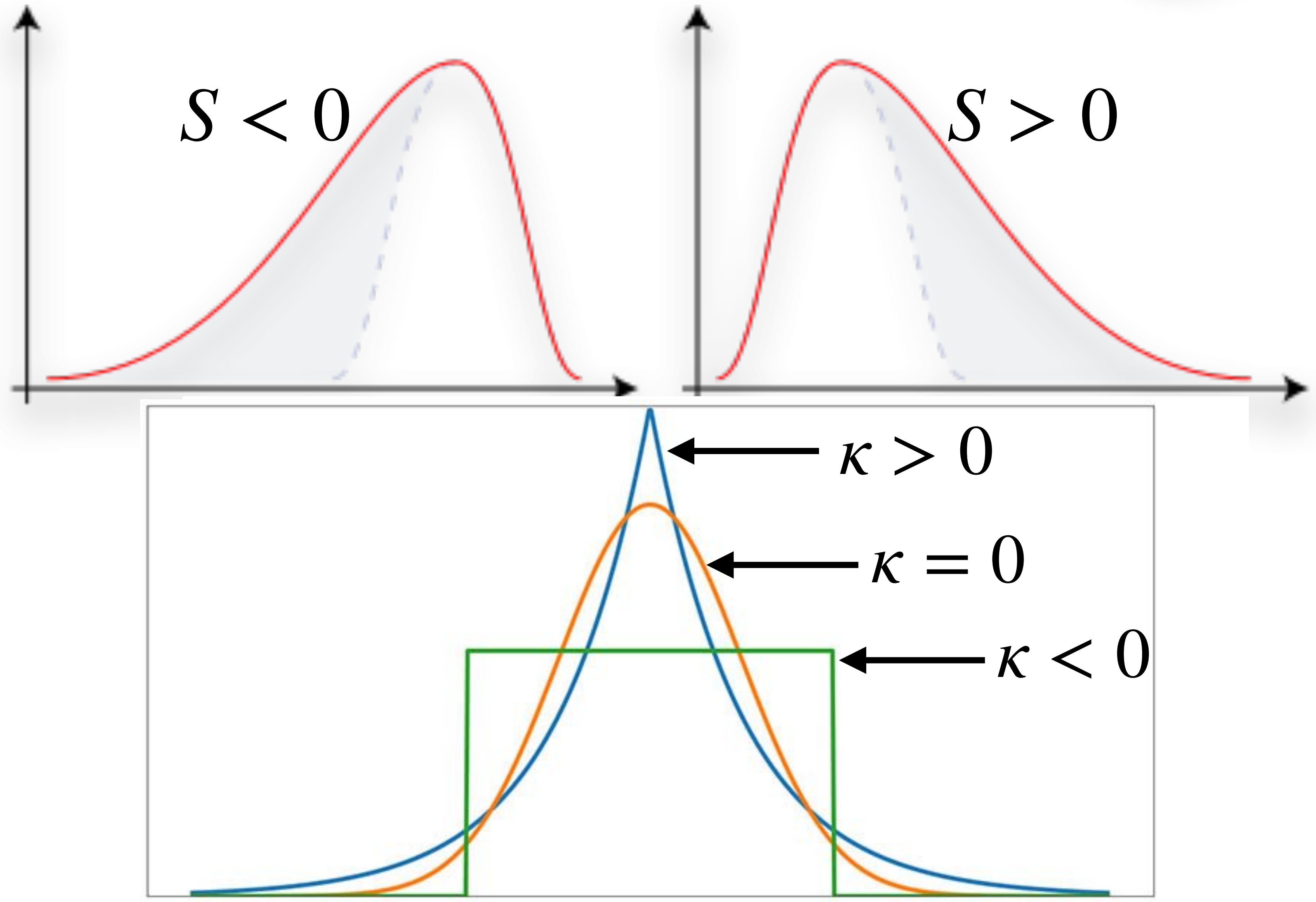
Observables

- Higher-order cumulants characterise the subtle features of a distribution.

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

$$\frac{C_2}{C_1} = \frac{\sigma^2}{M} \qquad \frac{C_3}{C_2} = S\sigma \qquad \frac{C_4}{C_2} = \kappa\sigma^2$$

M = Mean
σ^2= Variance
S = Skewness
κ = Kurtosis



- Higher order cumulants of conserved number distributions are, in general, sensitive observables.
  — Related to the correlation length and susceptibilities.
  — Deuteron cumulants add more information on baryon number fluctuation.

$C_2 \sim \xi^2$ $\quad C_4 \sim \xi^7$ $\quad$ *Quantitative numbers - Model dependent

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

S. Ejiri, F. Karsch, K. Redlich, Phys. Lett. B633 (2006) 275-282
M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
R.V. Gavai, S. Gupta, Phys. Lett. B696:459-463,2011
A. Bazavov et. al, Phys. Rev. Lett. 109, 192302 (2012)
A. Bzdak et. al, Physics Reports 853 (2020) pp. 1-87
S. Borsanyi et. al, Phys. Rev. Lett. 111, 062005 (2013)

Pearson correlation coefficient

$$\rho(N_x, N_y) = \frac{\langle(\delta N_x\ \delta N_y)\rangle}{\sigma_x\ \sigma_y}$$

ρ measures linear correlation between two variables.
ρ>0: Positive correlation
ρ<0: Anti-correlation

Fluctuation as Probe of Synthesis Mechanism

Coalescence Toy Model

Z. Fecková, J. Steinheimer, B. Tomášik and M. Bleicher: Phys. Rev. C 93, 054906 (2016)

Probability of deuteron formation, $\lambda_d = B_2\, n_p\, n_n$

Assume, proton (n_p) and neutron (n_n) follow Poisson distributions,

- ☐ At low $\sqrt{s_{NN}}$, B_2 increases. *STAR: Phys. Rev. C 99, 064905 (2019)*
- ☐ Larger value of n_p and n_n at low $\sqrt{s_{NN}}$.
- ☑ Results in rise of scaled moments of deuteron number.

Scaled Moments: $\sigma^2/M = C_2/C_1$, $S\sigma = C_3/C_2$, $\kappa\sigma^2 = C_4/C_2$

Two assumptions in the model:

Model A: Correlated p and n (n_p=n_n).

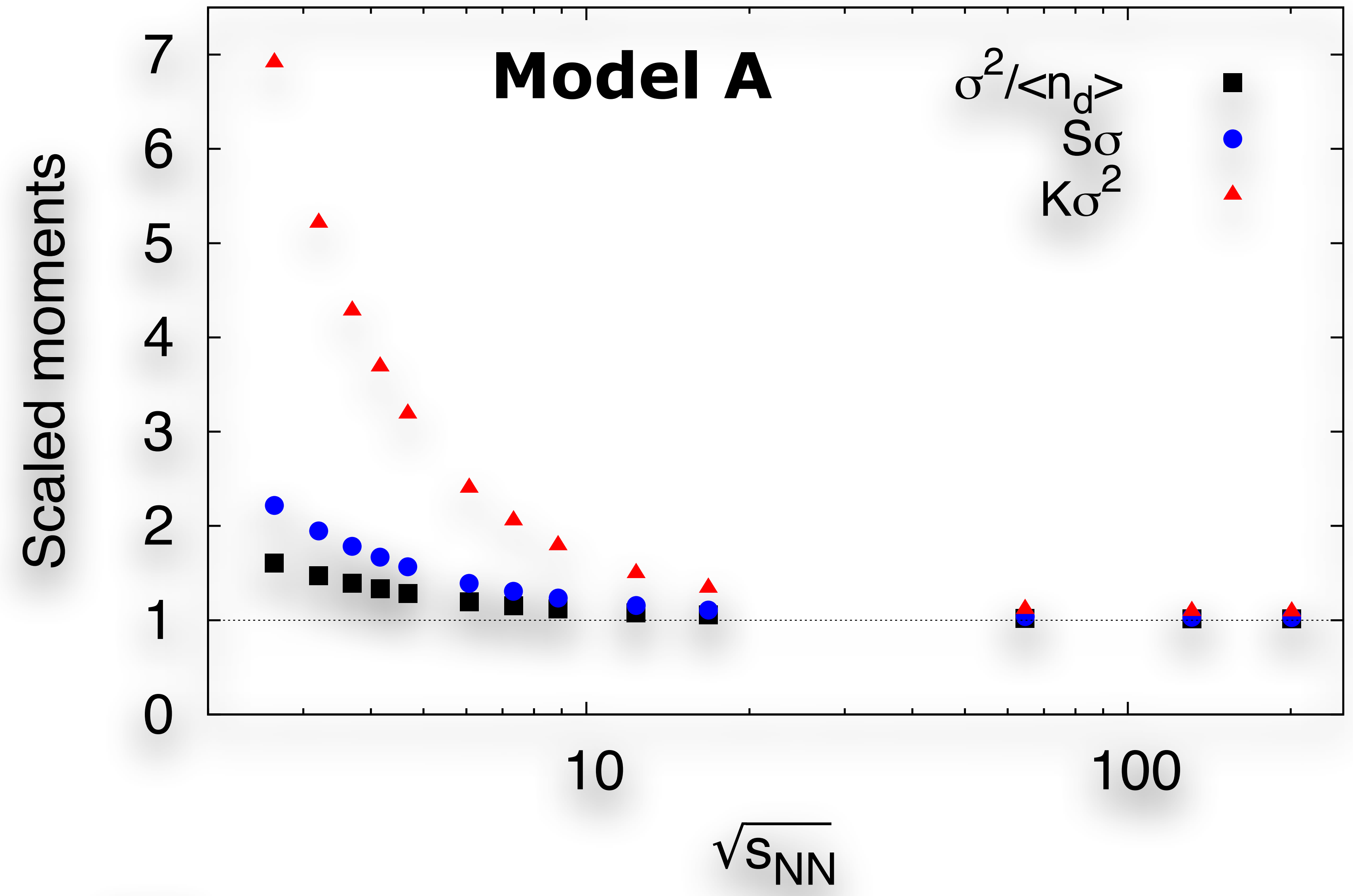
$$\lambda_d = B_2\, n_p^2$$

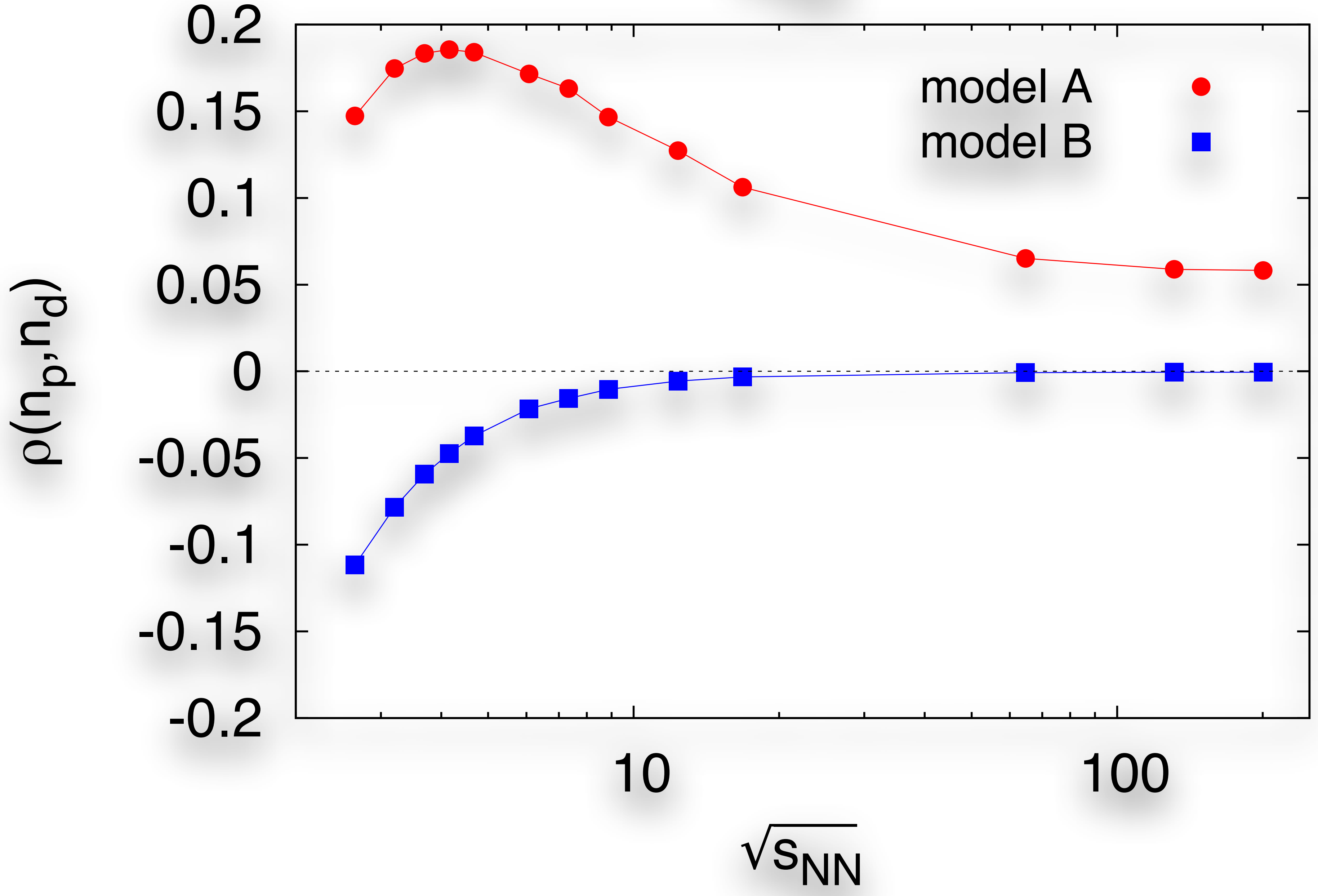
Model B: Independent p and n.

$$\lambda_d = B_2\, n_p\, n_n$$

$$\rho(n_p, n_d) = \frac{\langle (n_p - \langle n_p \rangle)(n_d - \langle n_d \rangle) \rangle}{\sigma_p \sigma_d}$$

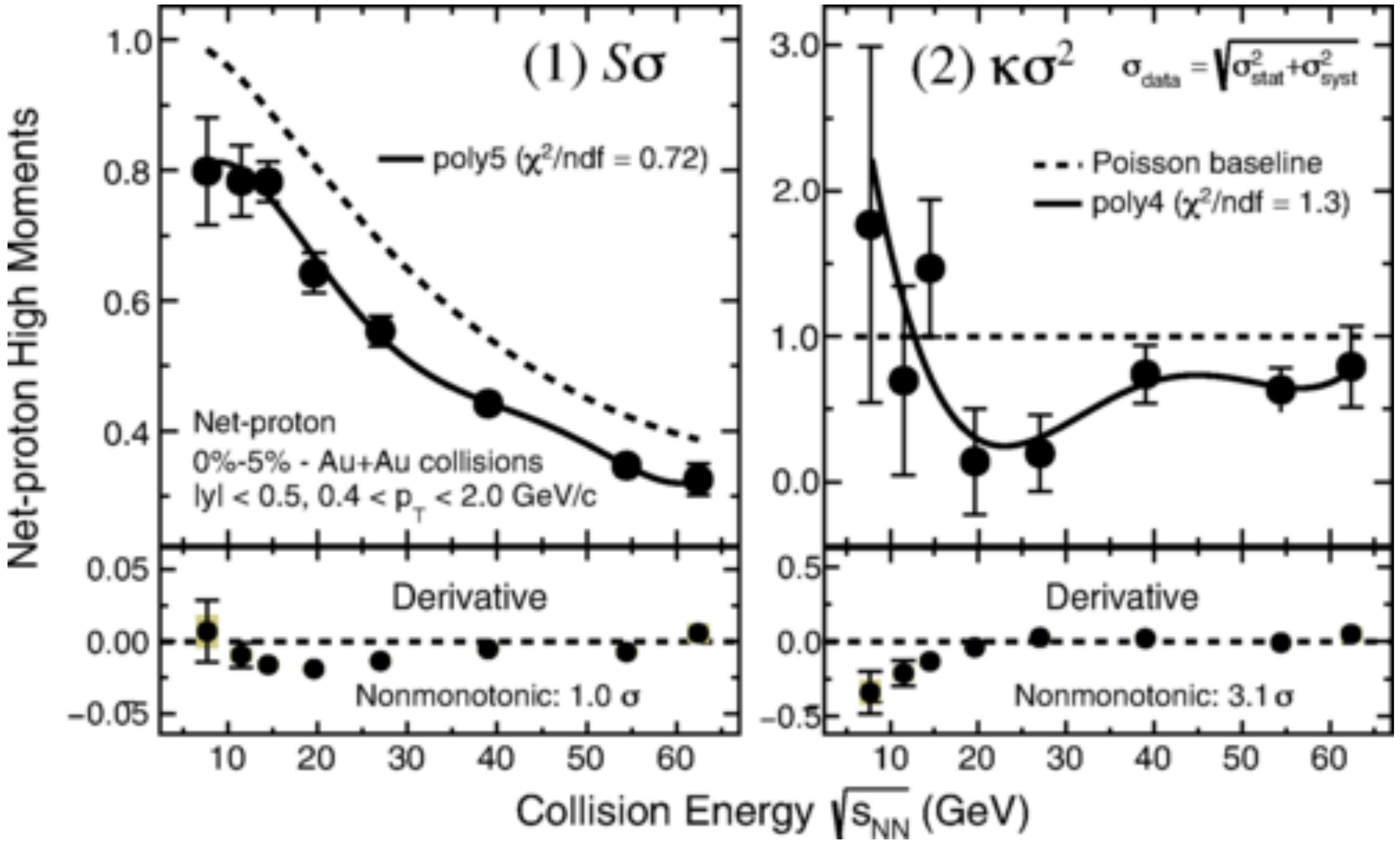
☑ Model A: $\rho > 0$ Model B: $\rho < 0$

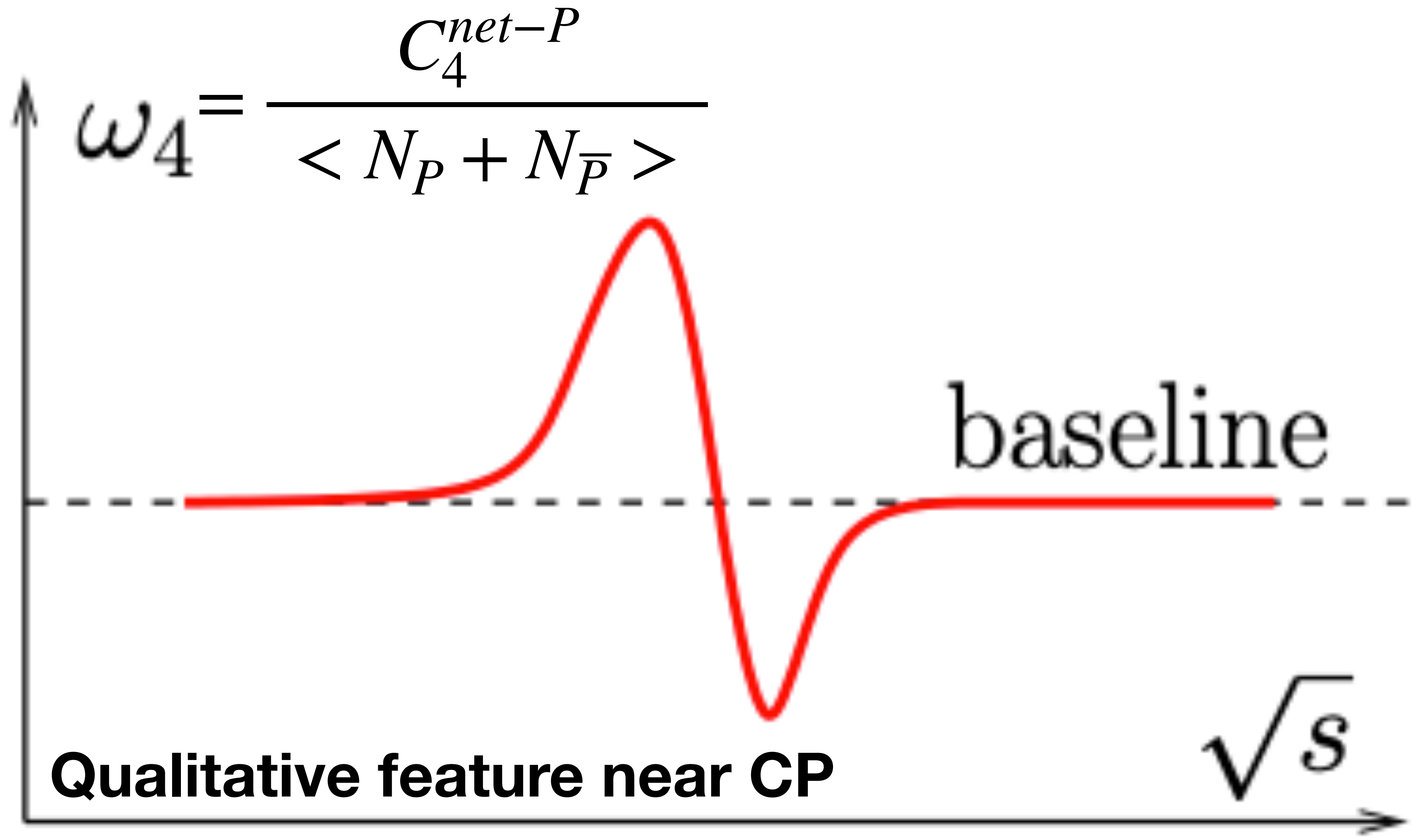




Baryon Number Fluctuation

STAR: Phys. Rev. Lett. 126 (2021) 092301





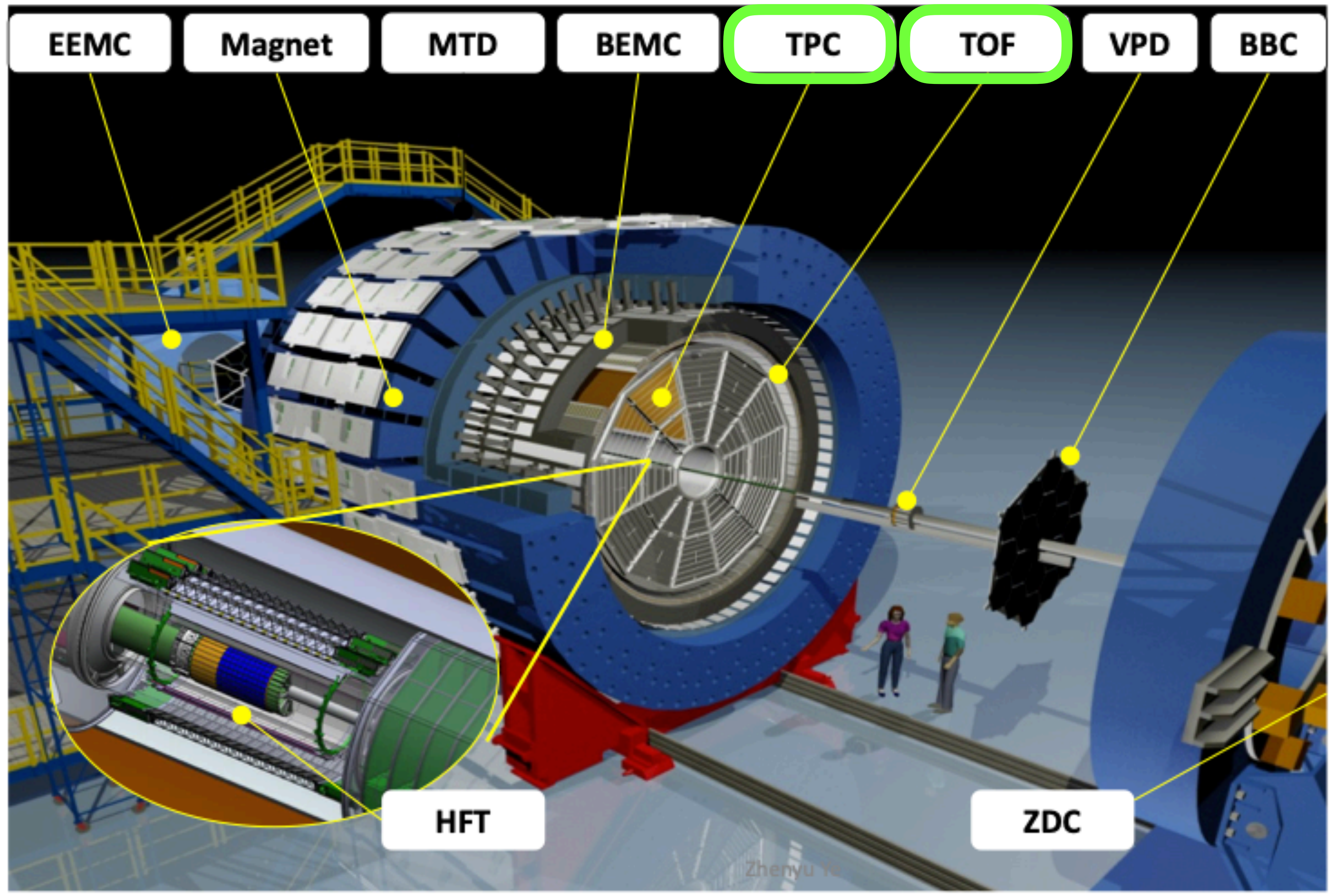
M. A. Stephanov Phys. Rev. Lett. 107, 052301 (2011)
M. A. Stephanov 2011 J. Phys. G: Nucl. Part. Phys. 38 124147

- Cumulants of deuteron number distribution and proton-deuteron correlation are sensitive to production mechanism.
- Until now studies have been done only with baryons of |B|=1.
- QCD critical point leads to large density fluctuation within certain correlation length.

  Deuteron production might be affected by local density fluctuations.

Ed. Shuryak et. al, Phys. Rev. C 101 (2020) 3, 034914
K.J. Sun et. al, Phys. Lett. B 774 (2017) 103-107

STAR Detector



STAR: Nucl.Instrum.Meth.A 499 (2003) 624-632

PID and Centrality: Using both Time Projection Chamber (TPC) and Time-of-Flight (ToF) detectors.

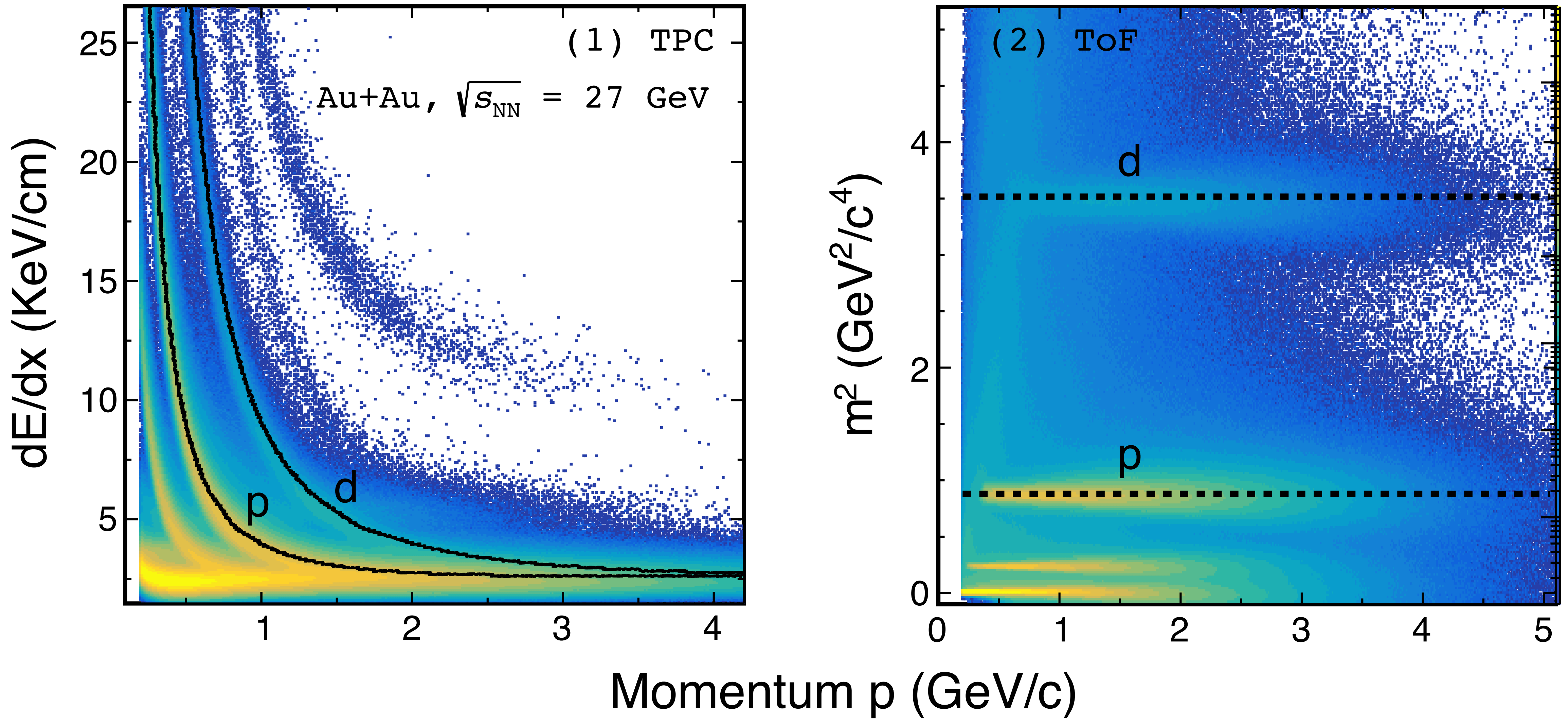
Uniform coverage for full azimuth and |η|<1. Excellent PID capability.

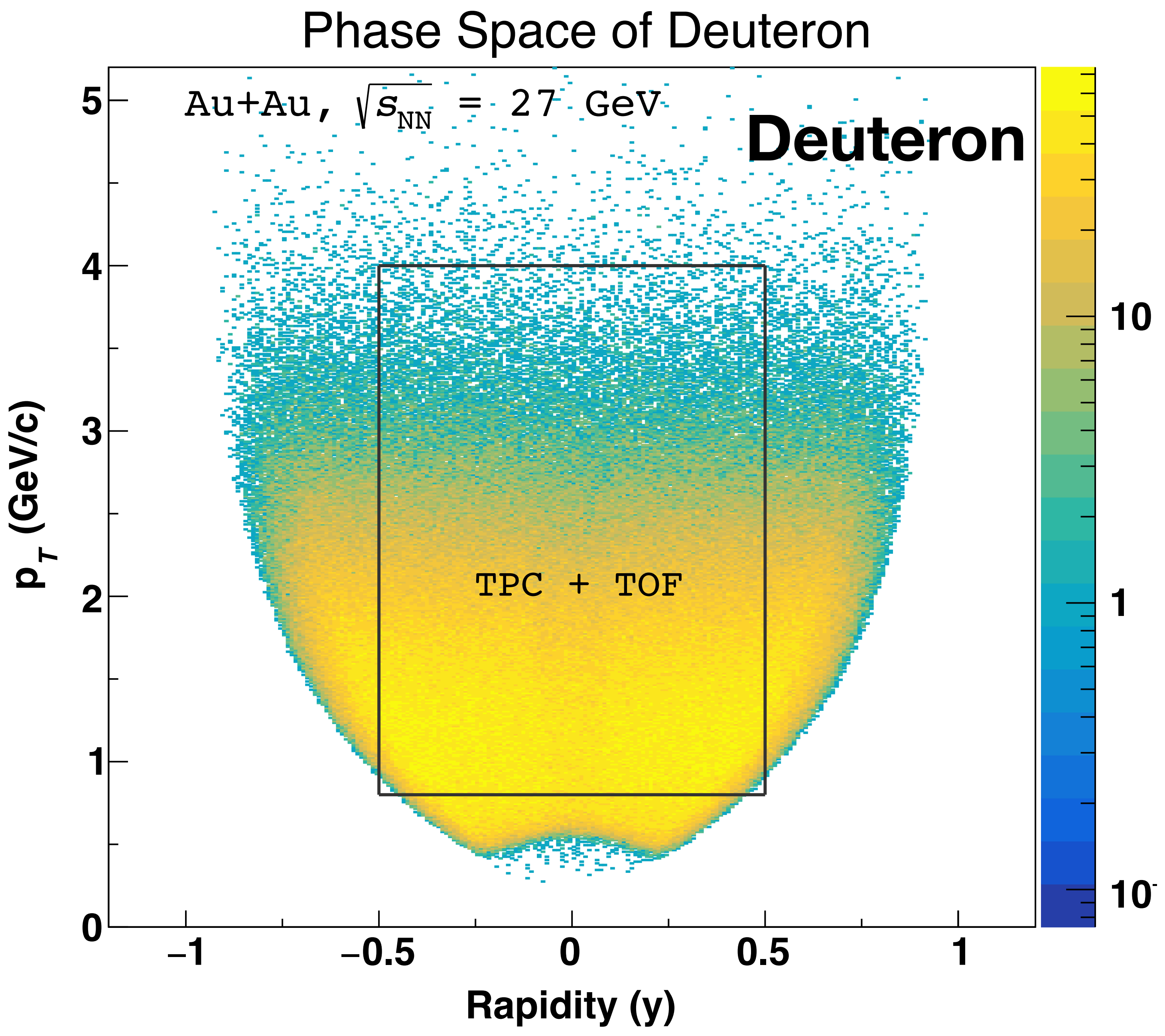
Dataset: BES-I

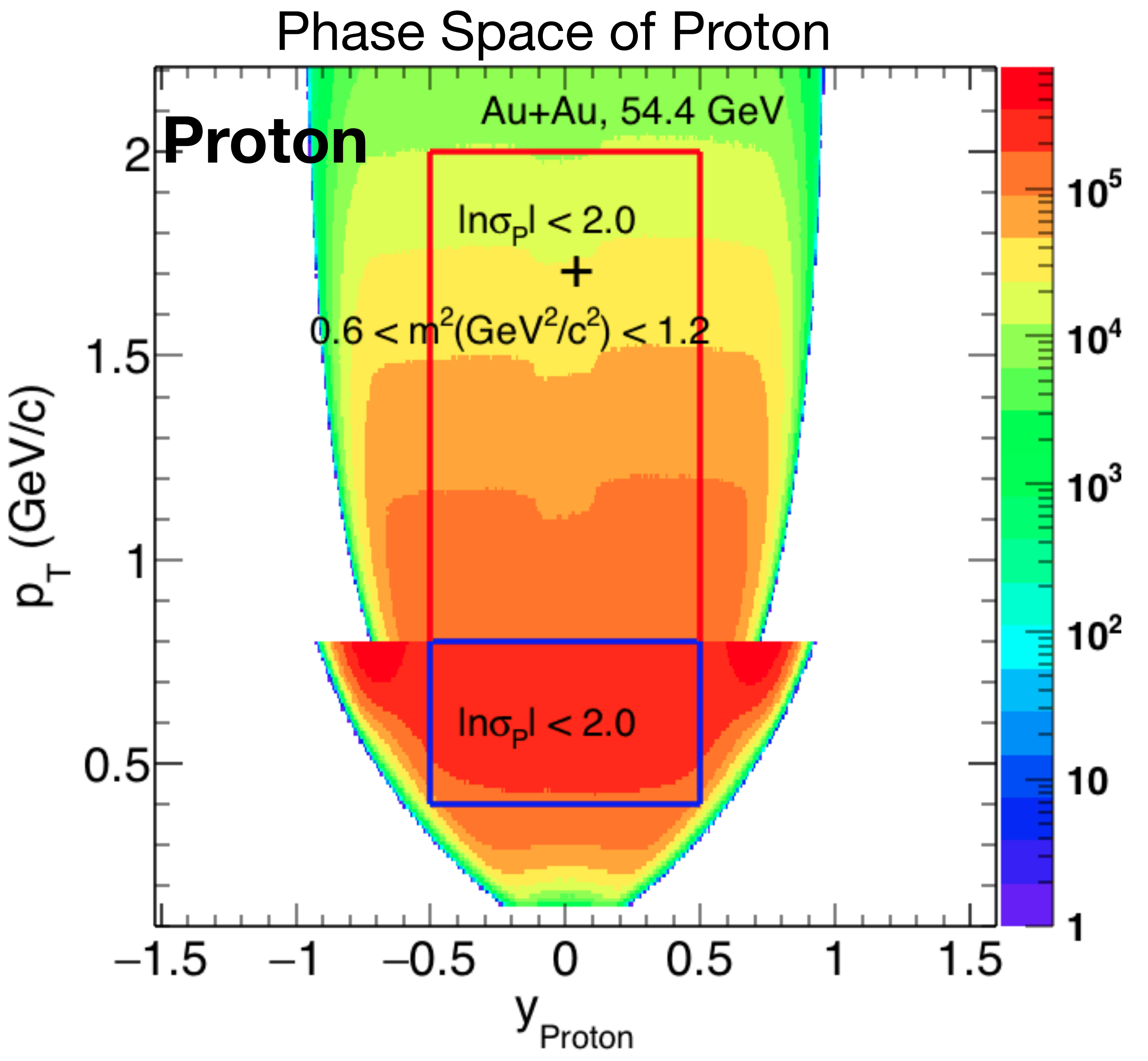
Collision system: Au+Au collision (centrality: 0-5% , 70-80%)

CoM energy: 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4, 200 GeV

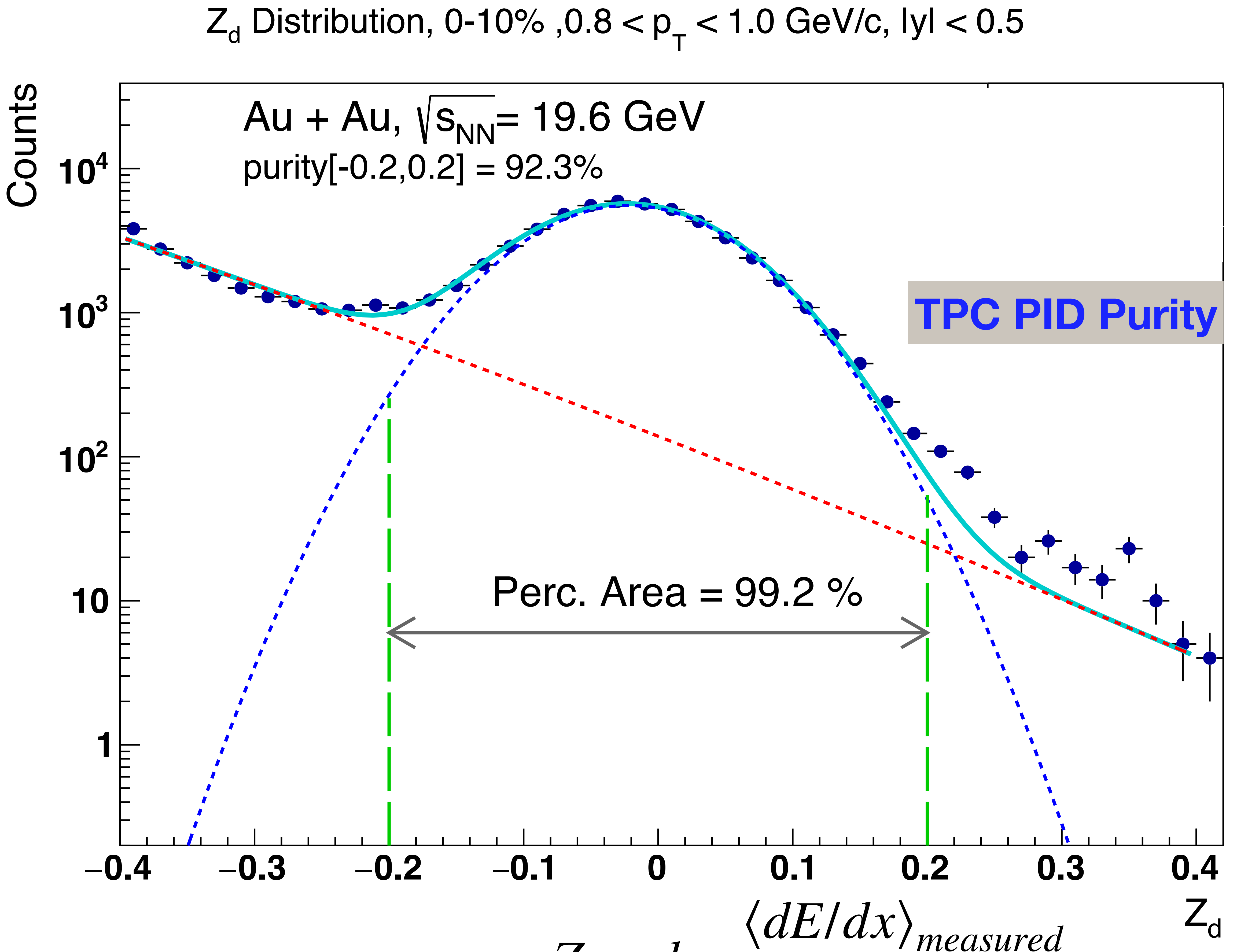
Year : 2010 — 2017



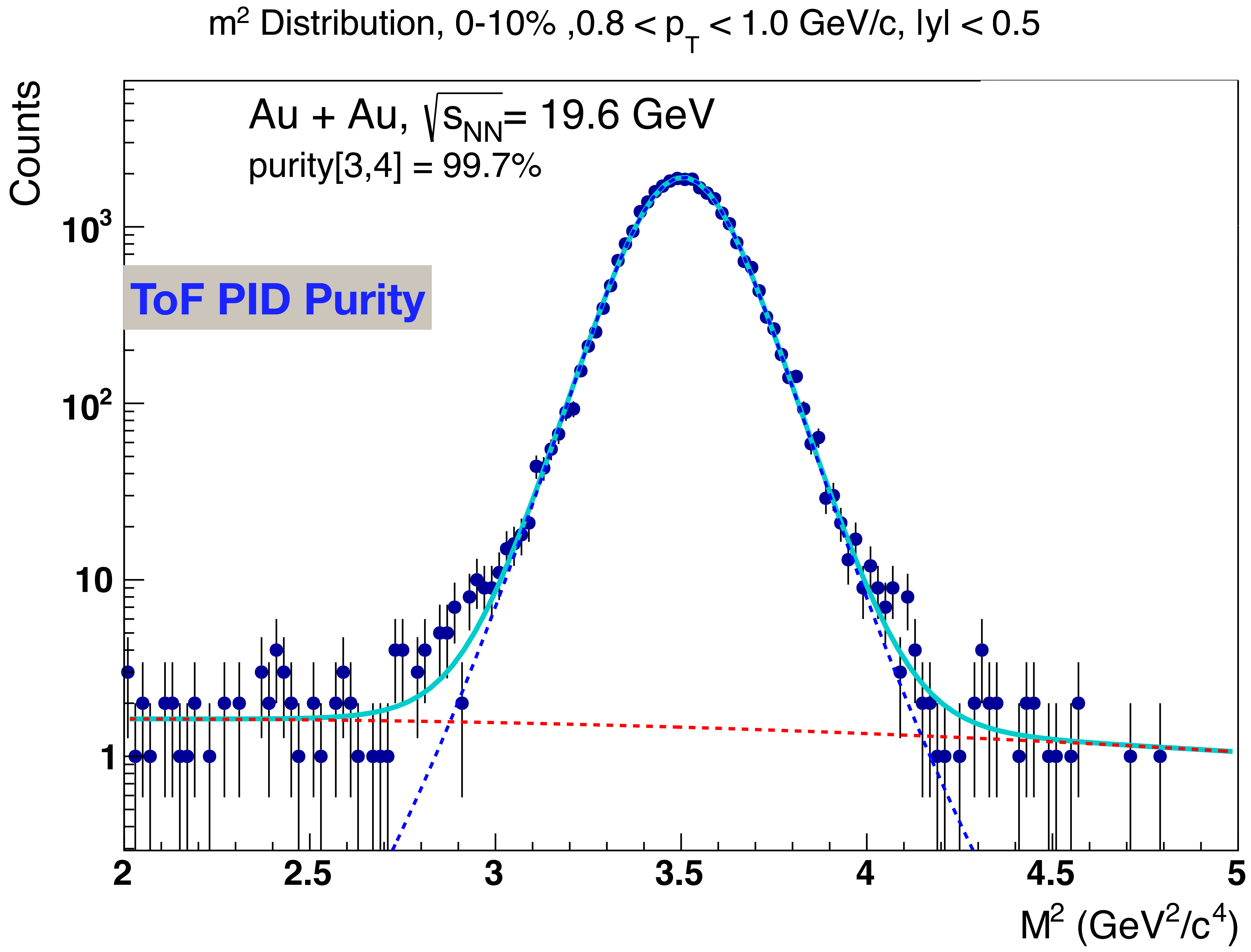




Purity



$$Z_d = log\frac{\langle dE/dx\rangle_{measured}}{\langle dE/dx\rangle_{Bichsel}}$$

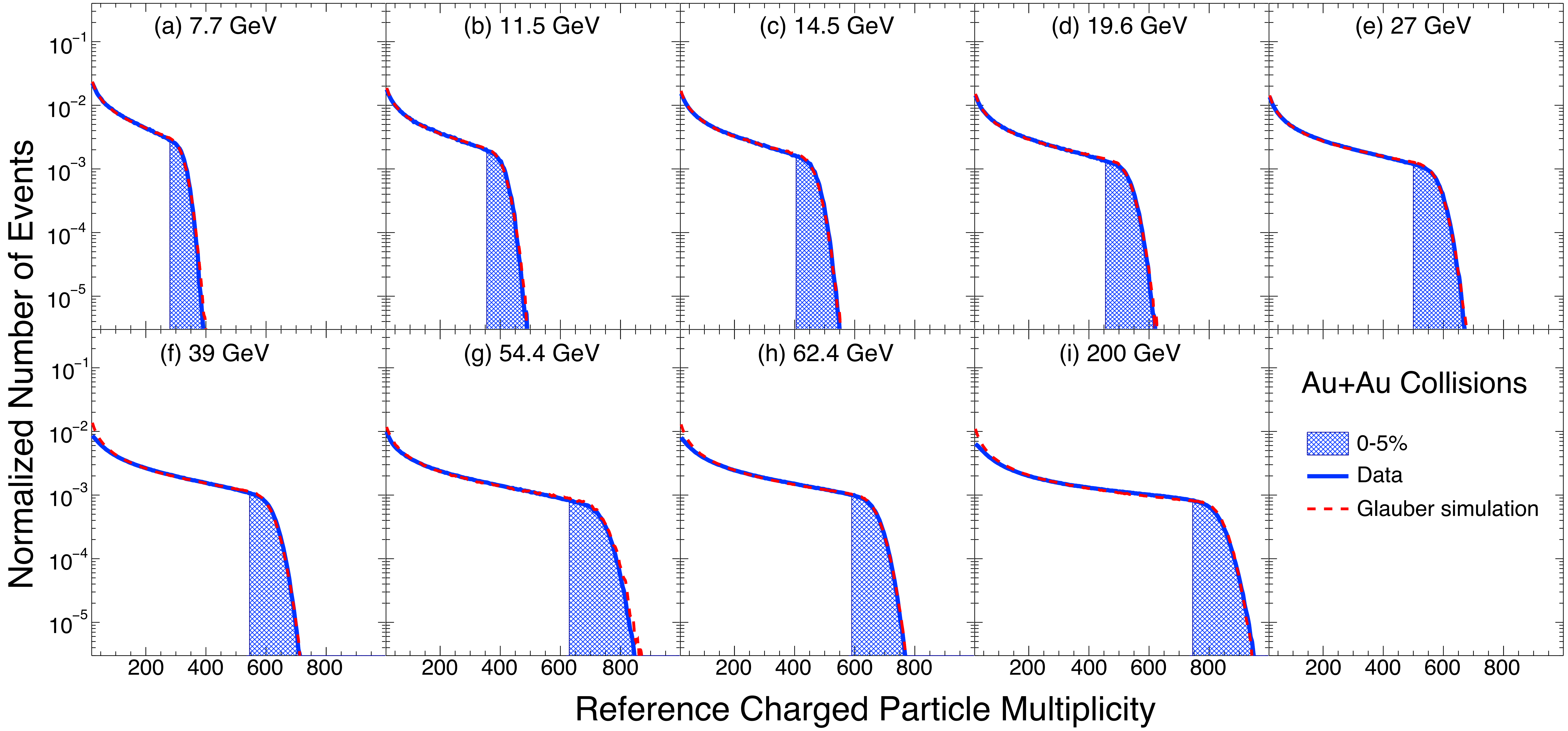


To achieve better PID purity, deuterons are identified using always both TPC and ToF detector.

Distance of Closest Approach (DCA) is kept as DCA<1cm to reduce the background contribution.

Centrality Definition

Centrality using charged particles within $|\eta| < 1.0$, **excluding protons and deuterons**



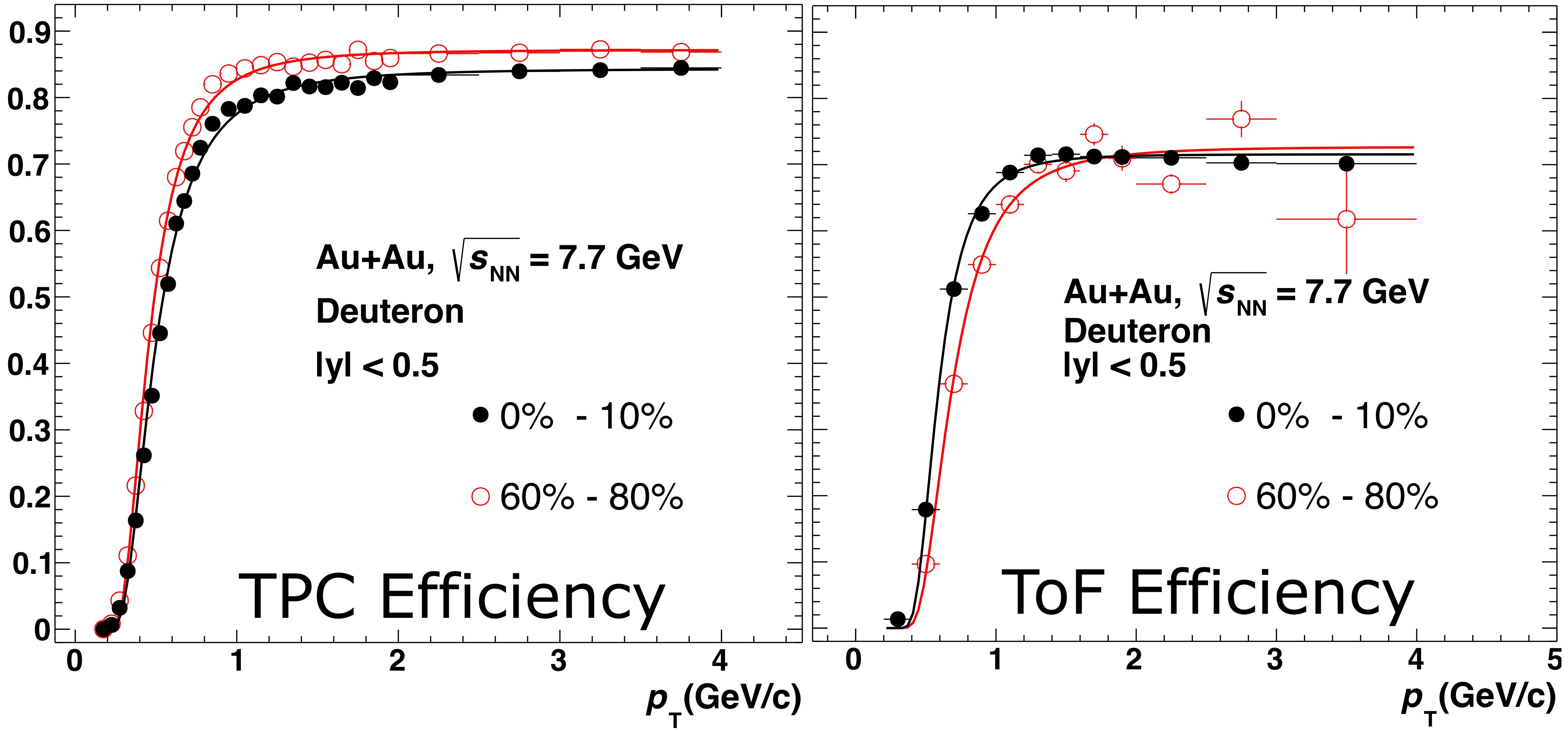
Charged particle multiplicity is corrected for
(a) Collision vertex and
(b) Beam luminosity dependencies

STAR: Phys. Rev. C 104, 024902 (2021)

This definition excludes self/auto -correlations between centrality and particle of interest.

Analysis Methods

1) Detection efficiency correction - binomial model



2) Centrality bin-width (CBW) correction:

❖ Effect arises from the dependence of $\mathbf{C}_n$ on multiplicity.

$$C_n = \sum_r \omega_r C_{n,r} \,, \quad \omega_r = \frac{n_r}{\sum_r n_r}.$$

n_r is number of events in r-*th* multiplicity bin.

3) Statistical uncertainty:
Using re-sampling technique called Bootstrap method.

For a statistic X, $\mathrm{Var}(X) = \frac{1}{S-1}\sum_{s=1}^{S}(X_s^* - \overline{X})^2$.

S is the number of samples.
X_s^* is "X" measured from s-*th* sample.

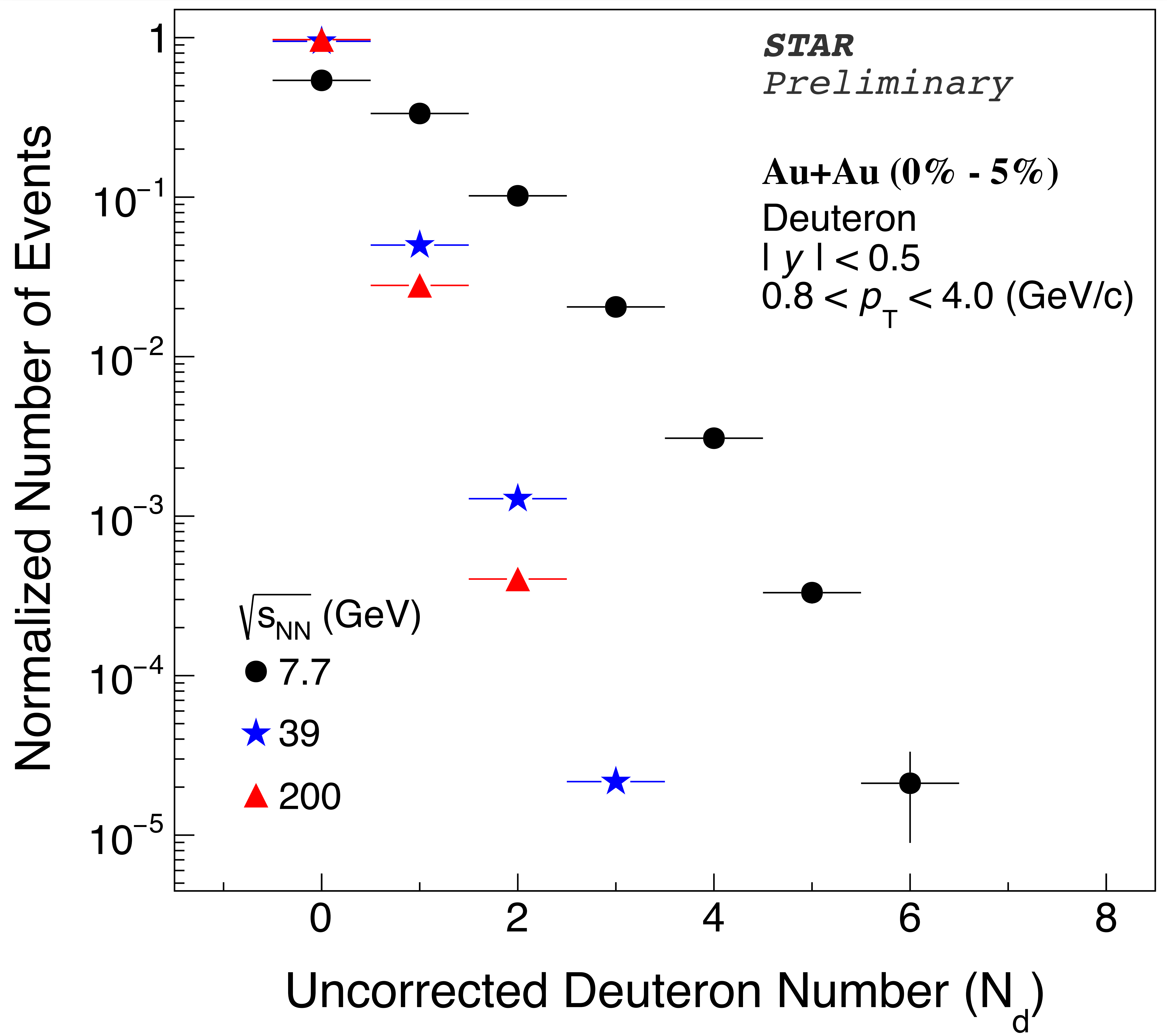
4) Systematic uncertainty:

Sources:

— Particle identification from TPC and ToF
— Background/decay estimates (DCA)
— Quality cuts for track reconstruction
— Uncertainty in detection efficiency estimation

STAR: Phys. Rev. C 104, 024902 (2021)
X. Luo , Phys. Rev. C 91, (2015) 034907
T. Nonaka et al, Phys. Rev. C 95, (2017) 064912
X. Luo et al, J.Phys. G 40, 105104 (2013)
X. Luo, J. Phys. G 39, 025008 (2012)
X.Luo et al, Phys.Rev. C99 (2019) no.4, 044917
A.Pandav et al, Nucl. Phys. A 991, (2019)121608

Raw Deuteron Number Distribution

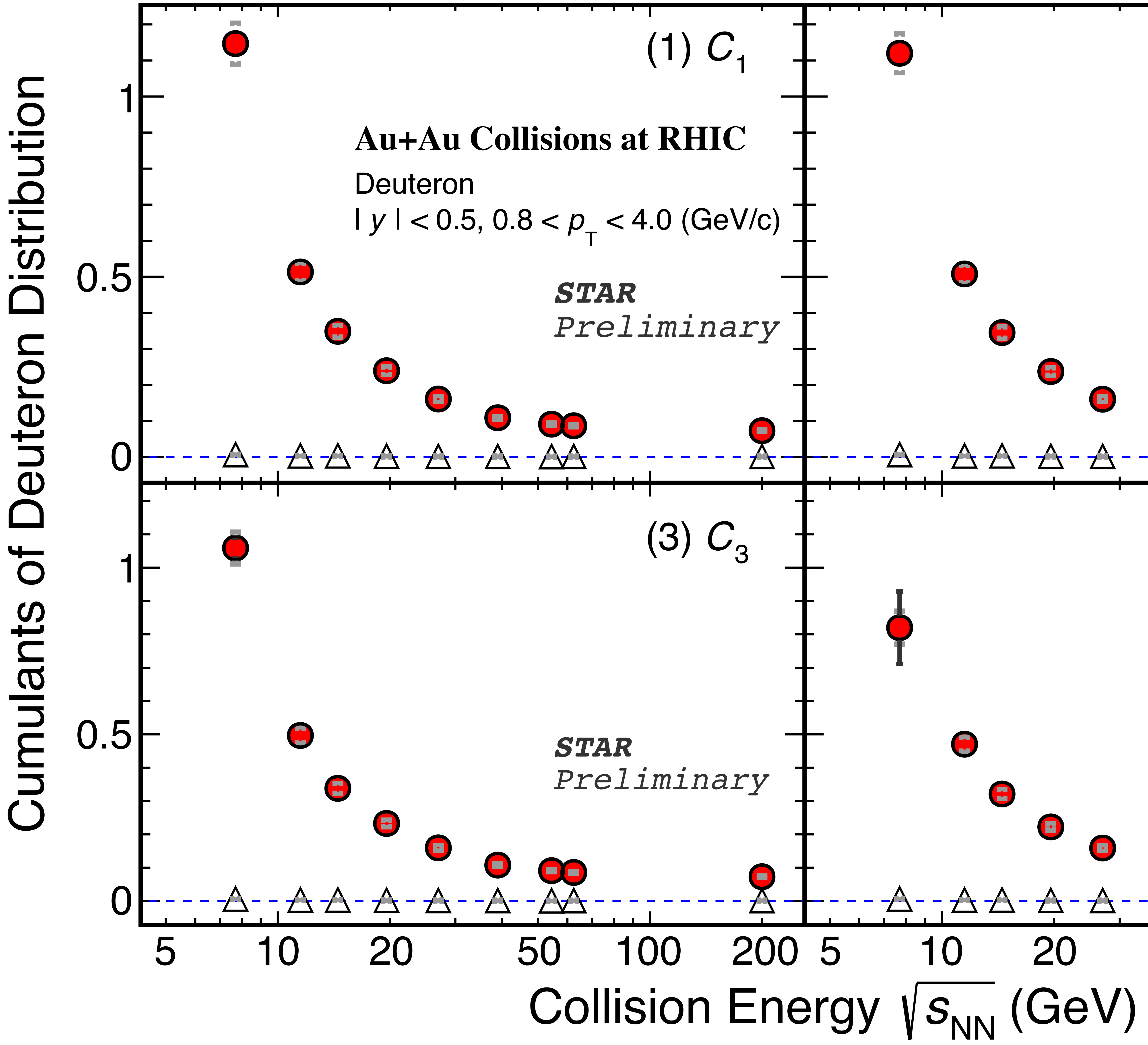


Uncorrected for efficiency and CBW effect.

Deuteron production increases towards low $\sqrt{s_{NN}}$.

Events with zero N_d value are most probable.

Cumulants of Deuteron Distribution

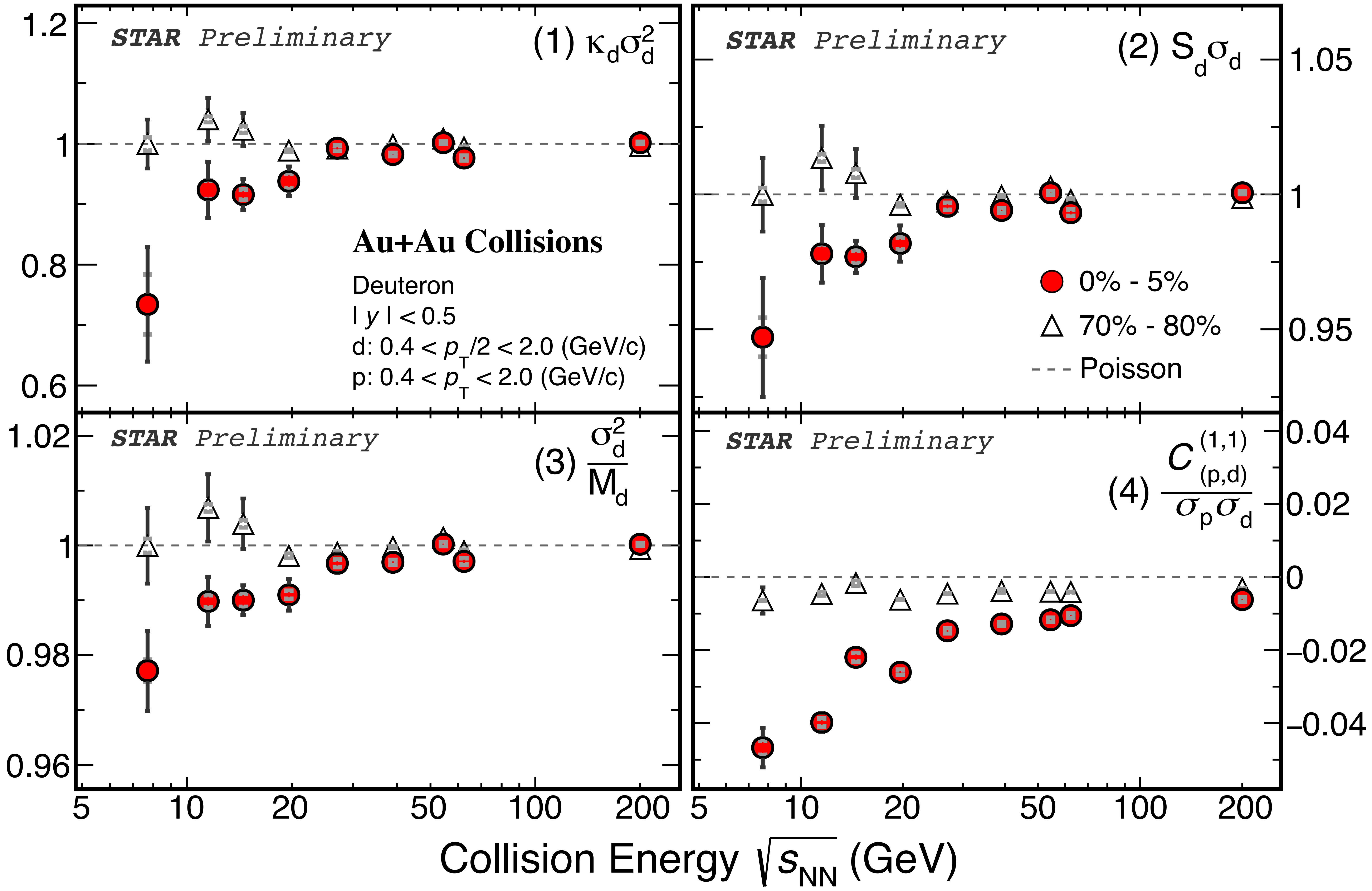


Black bars: statistical uncertainties
Grey caps: systematic uncertainties

Cumulants (C_n) of the deuteron distributions.

- For peripheral (70%-80%) Au+Au collisions, cumulants are close to zero.
- In most central (0-5%) collisions, cumulants increase as the collision $\sqrt{s_{NN}}$ decreases.

Cumulant Ratios and p-d Correlation



- ☑ Cumulant ratios in 0-5% centrality, show monotonic dependence on $\sqrt{s_{NN}}$.
- ☑ Ratios in 70-80% centrality show weak $\sqrt{s_{NN}}$ dependence and are close to 1.
- ☑ In panel(4), negative value of correlation suggests, proton and deuteron number are anti-correlated across all collision energy and centrality.
- ☑ With lowering the $\sqrt{s_{NN}}$, anti-correlation becomes stronger.

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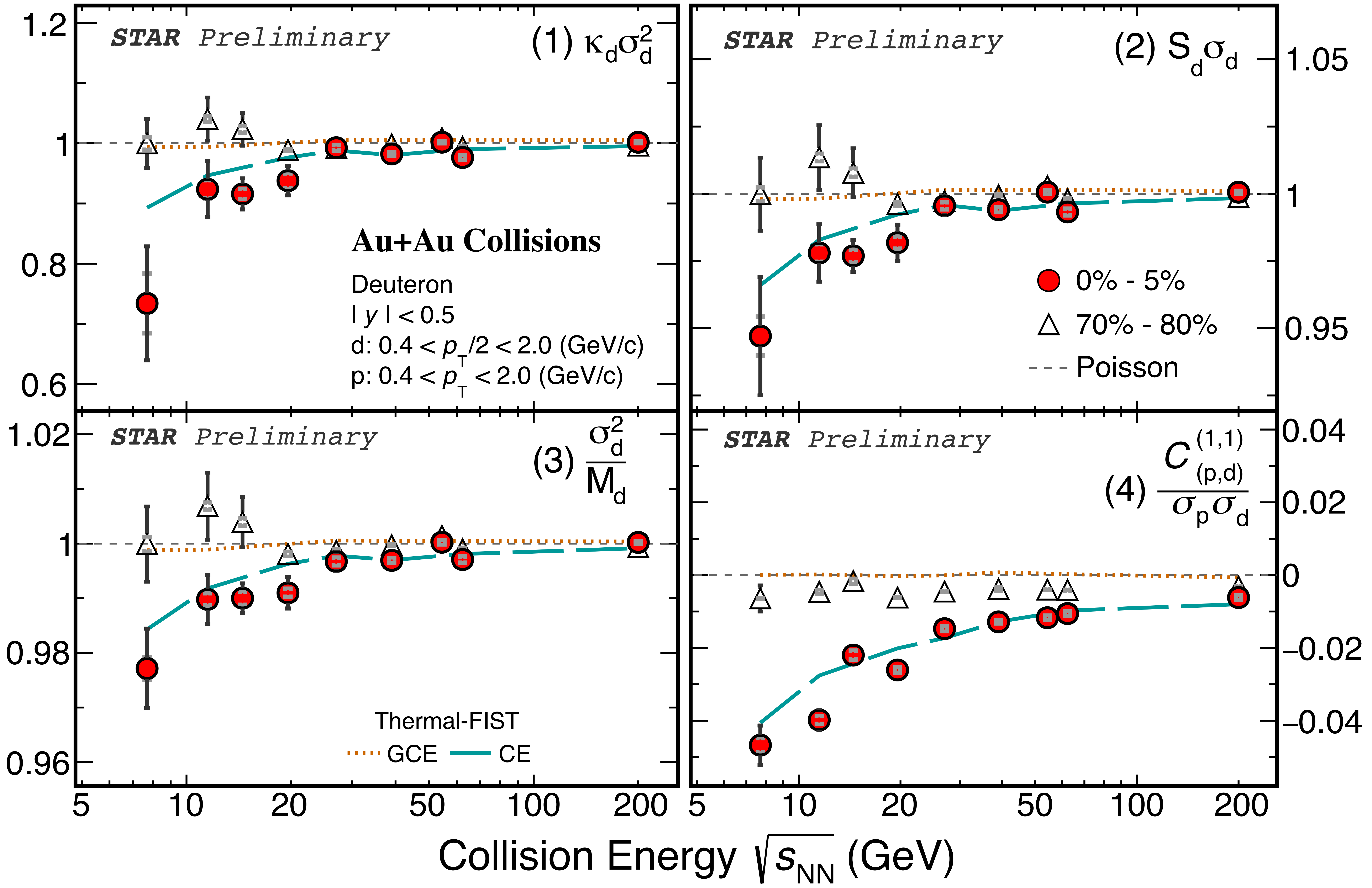
* **Model-A: Correlated Proton and Neutron numbers ($n_p = n_n$)**
Model-B: Independent Proton and Neutron numbers.

Cumulant Ratios and p-d Correlation



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- GCE thermal model seems to fail to describe the cumulant ratios for lower $\sqrt{s_{NN}}$.

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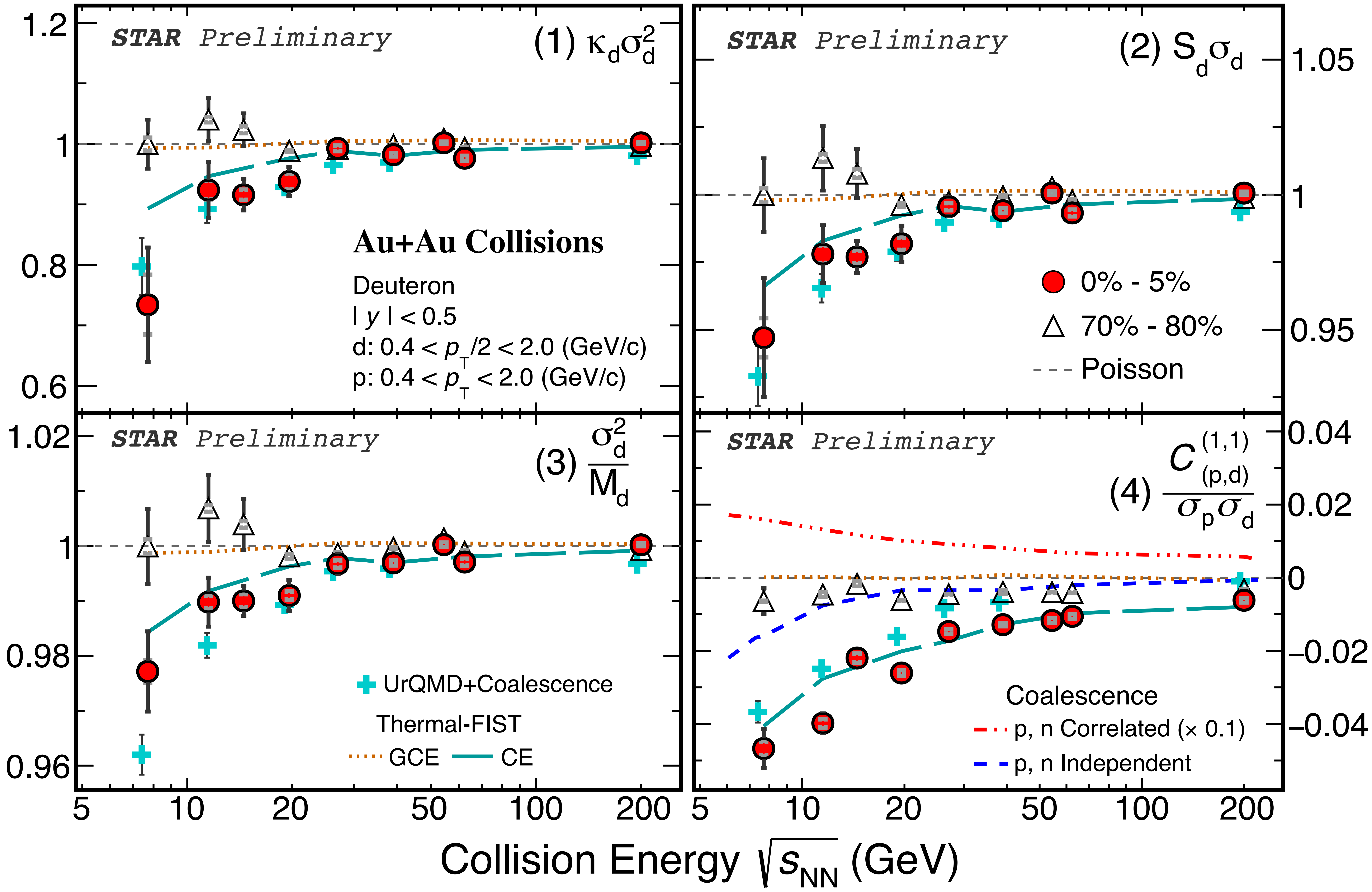

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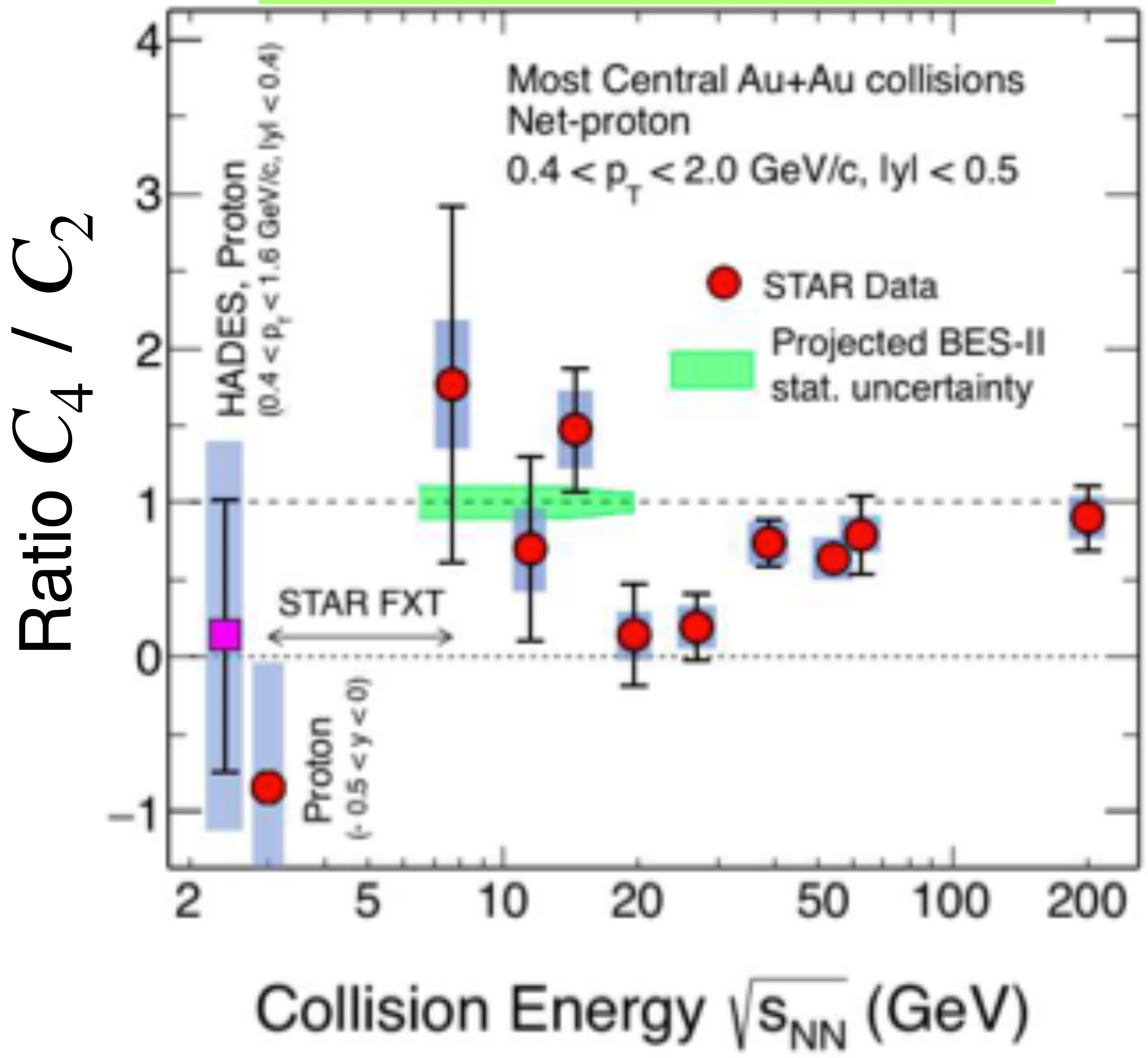
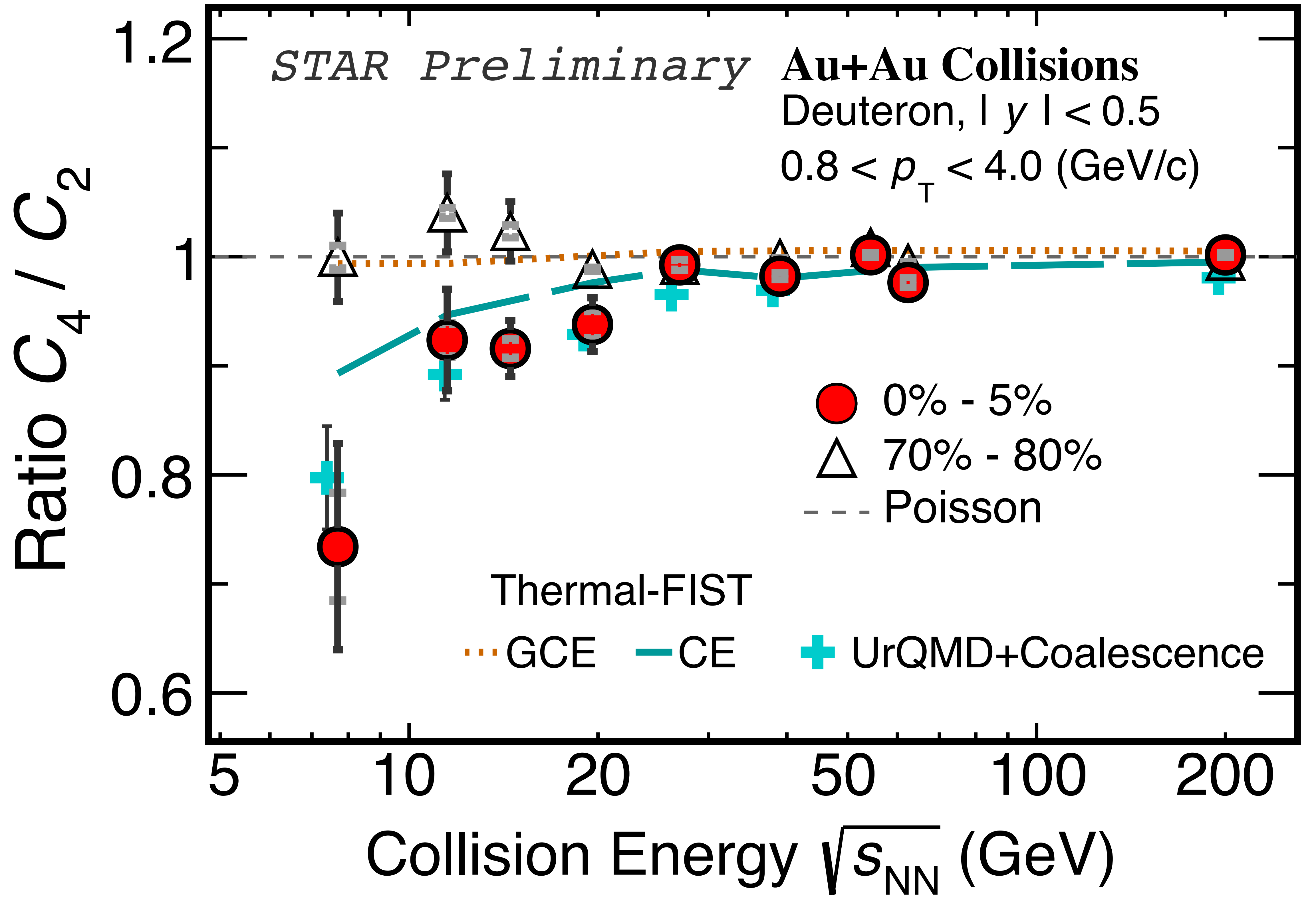
- ☑ With lowering the $\sqrt{s_{NN}}$, anti-correlation becomes stronger.
- ☑ GCE thermal model seems to fail to describe the cumulant ratios for lower $\sqrt{s_{NN}}$.
- ☑ UrQMD+Coalescence model qualitatively reproduces collision energy dependence.
- ☑ Neither correlated nor independent assumption for proton and neutron in the toy model from *Z. Fecková et. al,: Phys. Rev. C 93, 054906 (2016)* reproduce the data.

Comparison with Net-proton

Non-Monotonic at a level 3.1σ



Monotonic



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☑ Deuteron number $\kappa\sigma^2$ in 0-5% centrality show monotonic energy dependence in contrast to protons.

Possibilities:

— ***Low yield*** *of deuteron affecting sensitivity to critical point physics ?*

— *Probing* ***different freeze-out*** *surfaces ? More Investigation ongoing. Theoretical inputs are also needed.*

Summary

Summary:

- ☑ We reported the first measurements of cumulants of deuteron distribution, their ratios and proton-deuteron correlation in 0-5% and 70-80% central Au+Au collisions for $\sqrt{s_{NN}}$ = 7.7 - 200 GeV.
- ☑ UrQMD + phase-space coalescence model fairly describes the cumulant ratios and correlation for 0-5% centrality.
- ☑ For all $\sqrt{s_{NN}}$, proton and deuteron numbers are anti-correlated. With lowering $\sqrt{s_{NN}}$, anti-correlation in 0-5% centrality becomes stronger.
- ☑ HRG GCE thermal model fails to describe cumulant ratios at collision energies $\sqrt{s_{NN}} \leq$ 19.6 GeV. HRG CE and UrQMD show suppression below unity for lower $\sqrt{s_{NN}}$, as seen in the data, could arise from the effect of global baryon number conservation. Sensitive to the choice of ensembles.
- ☑ $Kurtosis \times Variance$ of deuteron number in 0-5% centrality shows monotonic energy dependence in contrast to proton fluctuations. ***STAR: Phys. Rev.Lett. 126 (2021) 092301***

Outlook:
Using BES-II data,
— *Study contribution of p, d, t, He^3 etc. together to understand net-baryon fluctuation in low $\sqrt{s_{NN}}$.*
— *Understand the production mechanism and freeze-out properties of light nuclei.*