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

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## Abstract

The production mechanism of deuterons, which have a binding energy of 2.2 MeV, is a topic of current interest in high-energy heavy-ion collisions, where the system undergoes kinetic freeze-out at temperatures around 100 MeV. Two possible scenarios include (a) statistical thermal process and (b) coalescence of nucleons. Cumulants of deuteron number distributions and proton-deuteron correlations are sensitive to these physics scenarios. In addition, they are also sensitive to the choice of canonical versus grand canonical ensemble in statistical thermal models.

We report the first systematic measurements of collision energy and centrality dependence of cumulants (up to fourth order) of deuteron number distributions in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4, and 200 GeV. We will also discuss new measurements on proton-deuteron correlations. The measurements are performed in the STAR experiment at mid-rapidity ($|y| < 0.5$) and within transverse momentum range $0.8 < p_T$ (GeV/c) $< 4.0$, using Time Projection Chamber and Time-of-Flight detectors. The experimental results are compared to the statistical thermal model calculations with a grand canonical, canonical ensemble, and the UrQMD model that incorporates the coalescence of nucleons close by in space and momentum to form deuterons. These theoretical comparisons with the experimental measurements provide key insights into the mechanism of deuteron production in high-energy heavy-ion collisions.


## Outline:

- ➢ Physics motivation
- ➢ Analysis details
- ➢ Results

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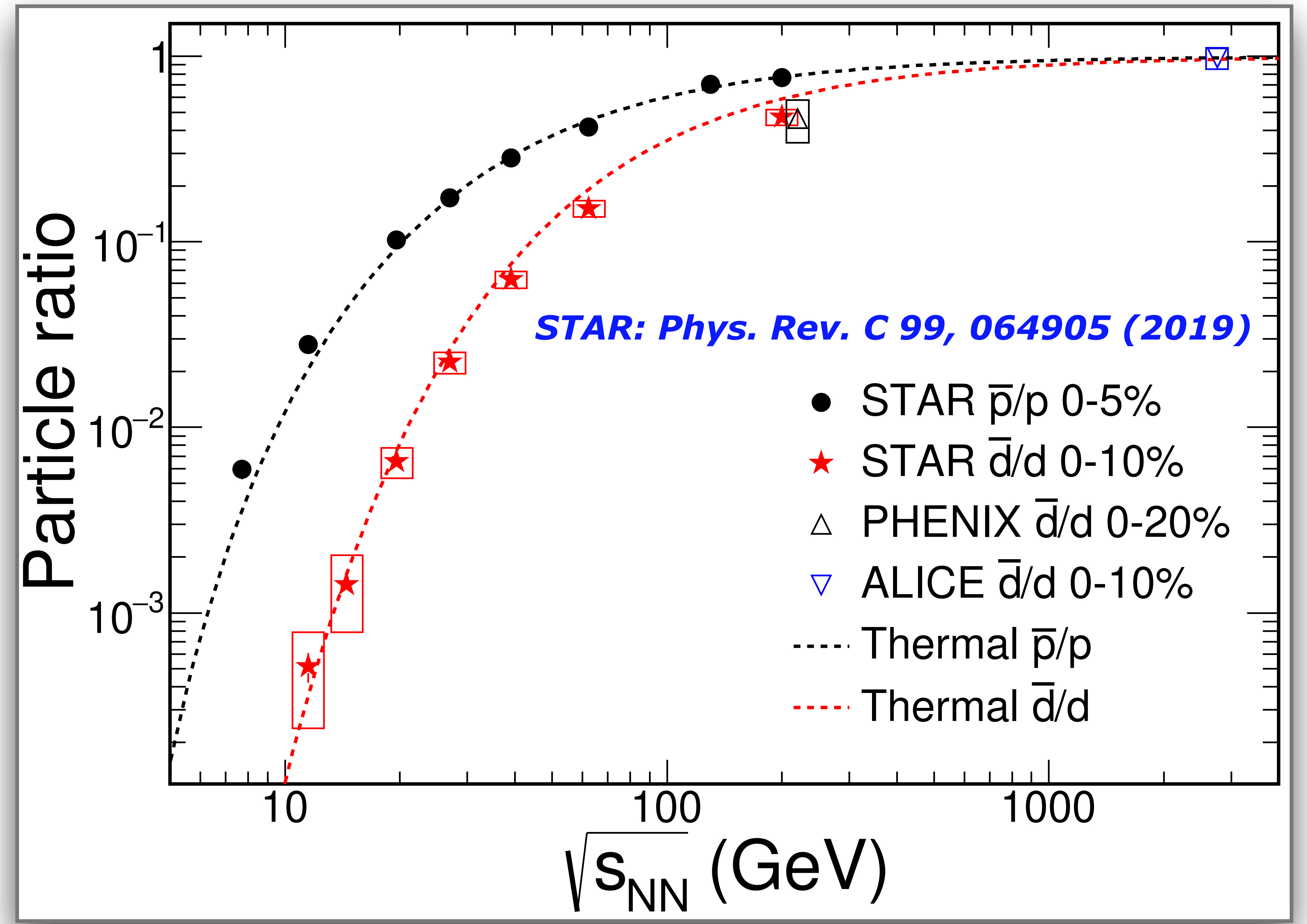
# Physics Motivation

## 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, $\mu_d$: 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 thermal model for a wide range of $\sqrt{s_{NN}}$.

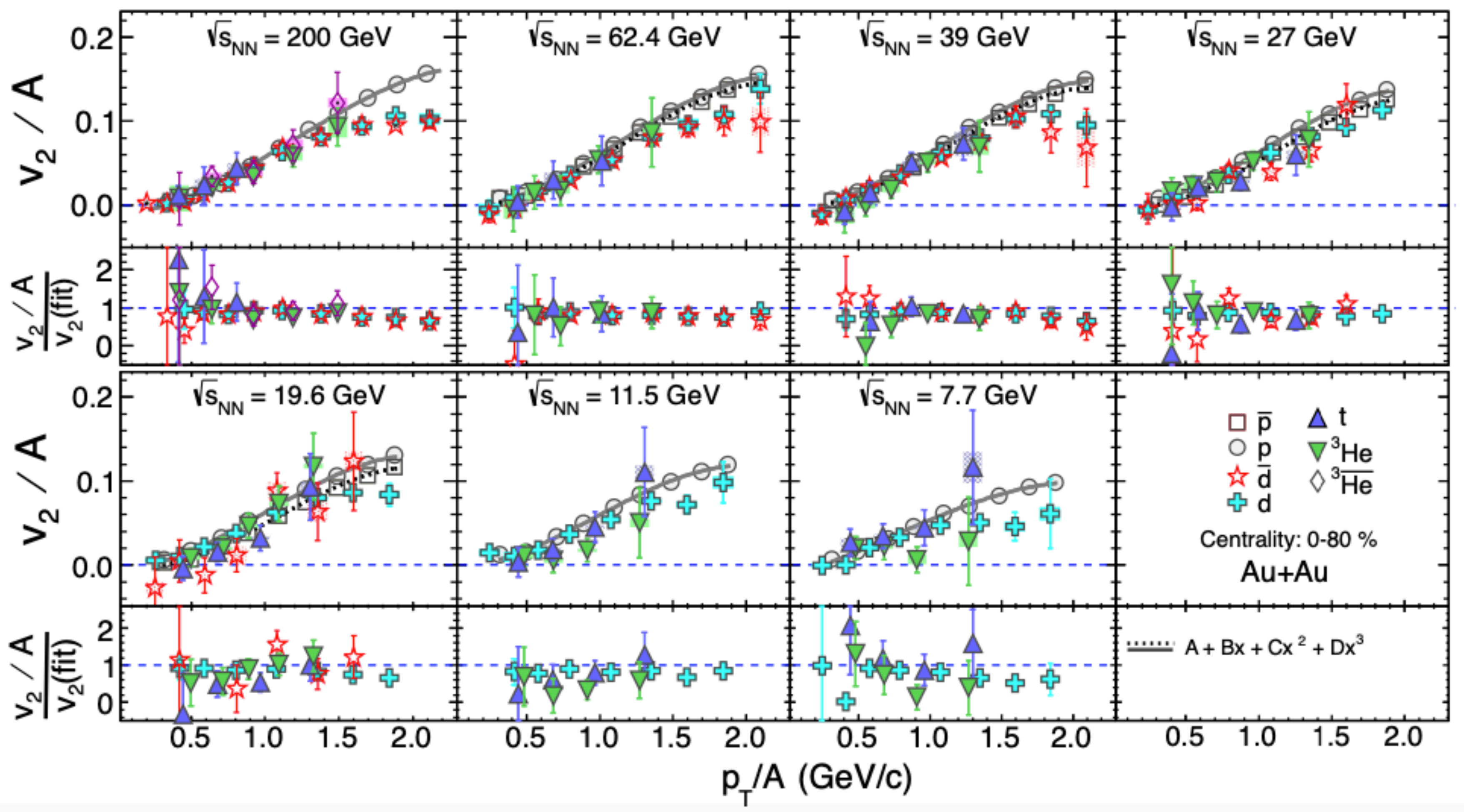
## Coalescence Model

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

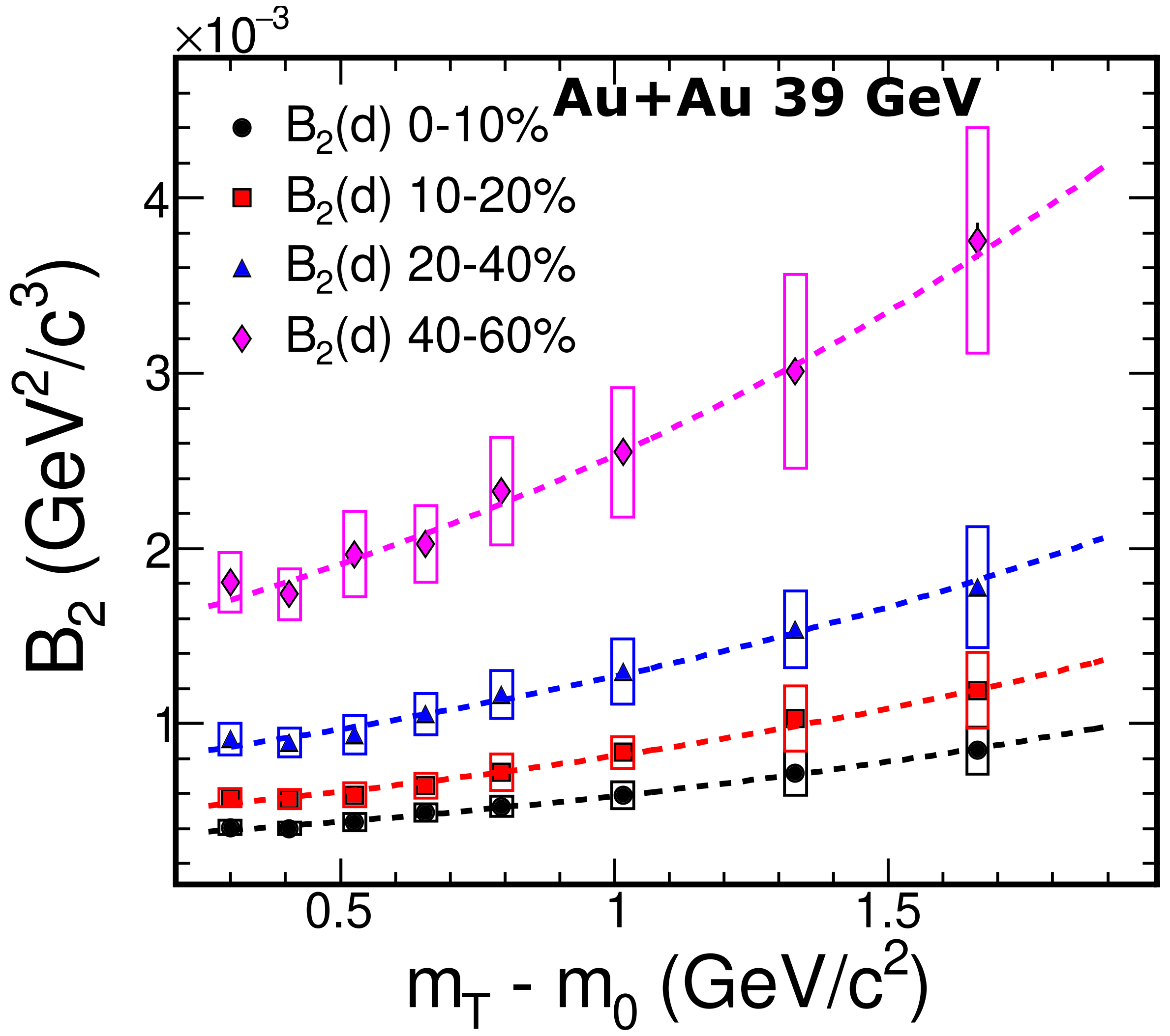
**Elliptic flow:** $v_2^d(p_T) \approx 2v_2^p(\frac{p_T}{2})$

- ☑ 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)

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

$p_0$: Radius in momentum space.

# Analysis Methods

**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

**1)** Correction for finite detection efficiency - Using binomial model

**2)** Centrality bin-width (CBW) correction:

❖ Suppresses volume fluctuation effects.

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

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

**3)** Uncertianties:

Statistical: Bootstrap method.

Systematic: Varying cuts for PID, background, track reconstruction, detection efficiency.

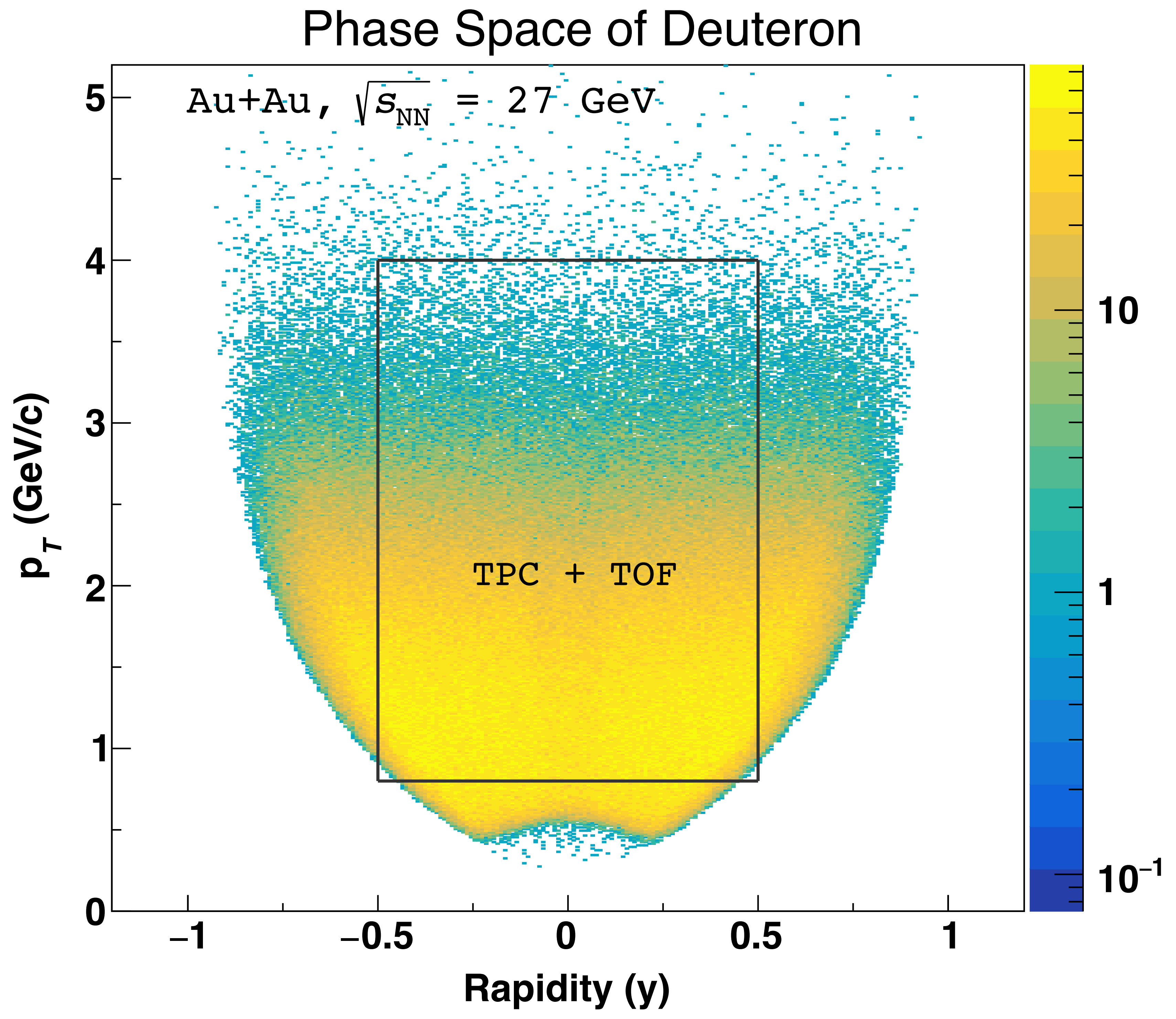
PID detector: TPC+TOF

Rapidity: |y| < 0.5

Transverse momentum ($p_T$): 0.8 to 4.0 GeV/c

Year : 2010 — 2017

Centrality: Using charged particles excluding deuteron.





*STAR: Phys. Rev. C 104, 024902 (2021)*
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*T. Nonaka et al, Phys. Rev. C 95, (2017) 064912*
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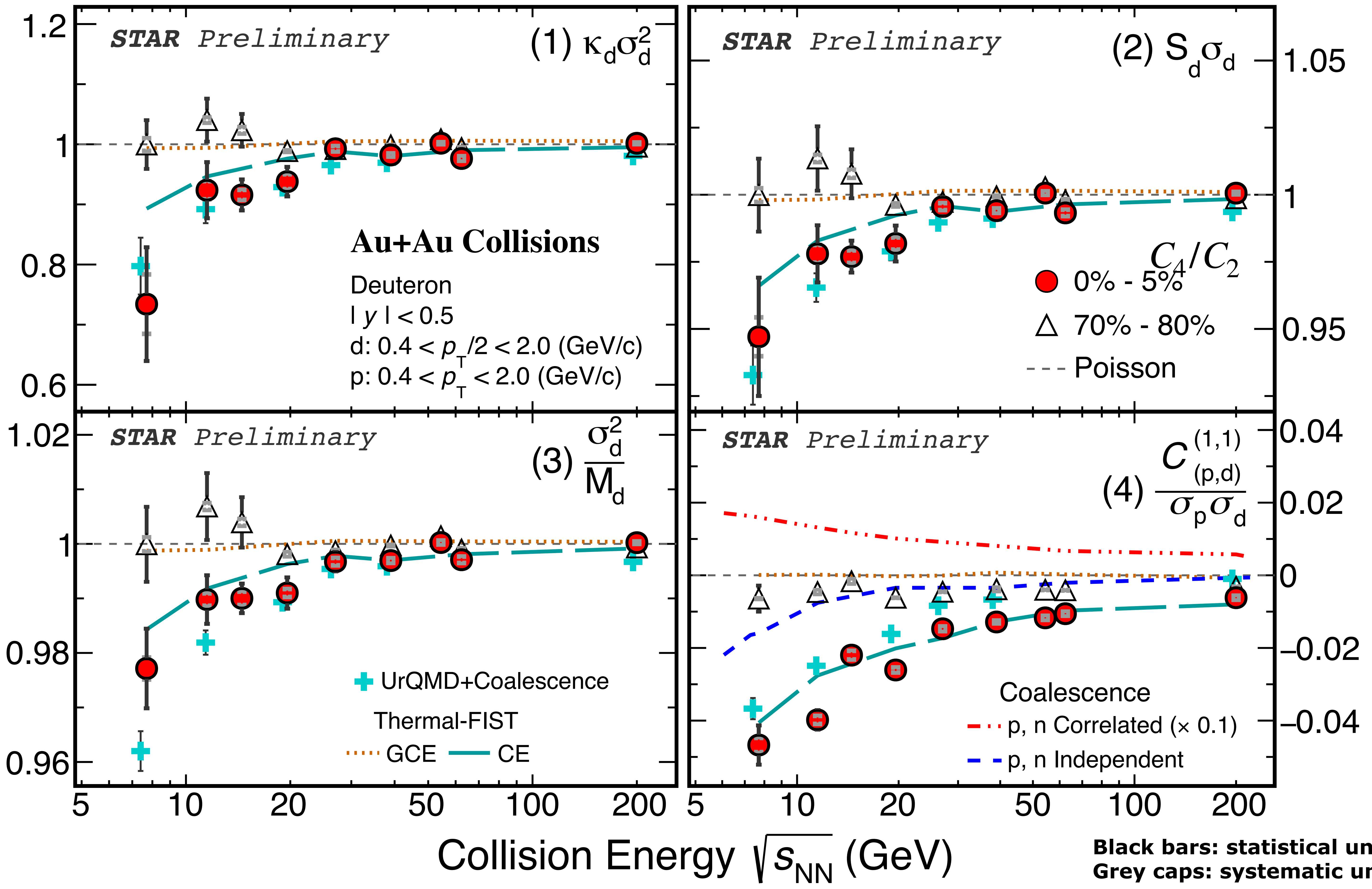
*A. Pandav et al, Nucl. Phys. A 991, (2019)121608*

# Cumulant Ratios and p-d Correlation

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

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

$C^{(1,1)}_{(p,d)}/(\sigma_p, \sigma_d) = \frac{\langle(\delta N_p\ \delta N_d)\rangle}{\sigma_p\ \sigma_d}$




**Black bars: statistical uncertainties**
**Grey caps: systematic uncertainties**

- 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 Pearson's coefficient suggests, proton and deuteron numbers are anti-correlated across all collision energy and centrality.
- With lowering the $\sqrt{s_{NN}}$, anti-correlation becomes stronger.
- GCE thermal model seems to fail to describe the cumulant ratios for lower $\sqrt{s_{NN}}$. CE thermal model qualitatively reproduces collision energy dependence.
- Neither correlated nor independent assumptions for proton and neutron in the toy model from ***Z. Fecková et. al,: PRC 93, 054906 (2016)*** reproduce the data.
- UrQMD+Coalescence also reproduces the trend and shows better agreement with the cumulant ratios.

# Summary

**Summary:**

- ☑ We reported the first measurements of cumulants of deuteron number distribution, their ratios, and proton-deuteron correlation in 0-5% and 70-80% centralities for Au+Au collisions for $\sqrt{s_{NN}}$ = 7.7 - 200 GeV.

- ☑ Anti-correlation between proton and deuteron numbers is observed across all collision energy and centrality studied. With lowering the $\sqrt{s_{NN}}$, anti-correlation becomes stronger for central collisions. The correlation in peripheral collisions does not show any $\sqrt{s_{NN}}$ dependence and is close to the statistical expectations.

- ☑ For central Au+Au collisions,
  (A) Thermal model:
  (i) Both GCE and CE thermal models reasonably describe the cumulant ratios and deuteron-proton correlation above $\sqrt{s_{NN}}$ = 20 GeV.
  (ii) CE model qualitatively agrees with the measurements for $\sqrt{s_{NN}}$ below 20 GeV, while GCE model fails.
  CE model explicitly conserves baryon number: Importance of the role of conservation in fluctuation studies at lower $\sqrt{s_{NN}}$.
  (B) Coalescence based model (UrQMD + phase-space coalescence) describes the cumulant ratios and deuteron-proton correlations across all the $\sqrt{s_{NN}}$.

- ☑ Kurtosis x Variance of deuteron number shows smooth dependence on $\sqrt{s_{NN}}$ in contrast to that of protons.
  Event-by-event low yield of deuterons might affect higher order cumulants.

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

***Outlook: Using BES-II data,***

— *Study contributions from p, d, t, $He^3$ etc. together to understand net-baryon fluctuation in lower $\sqrt{s_{NN}}$ region.*