Effects of Initial Nucleon-Nucleon Correlations on Light Nuclei Production in Au+Au Collisions at $\sqrt{S_{\mathrm{NN}}} = 3$ GeV

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arXiv: 2503.01128

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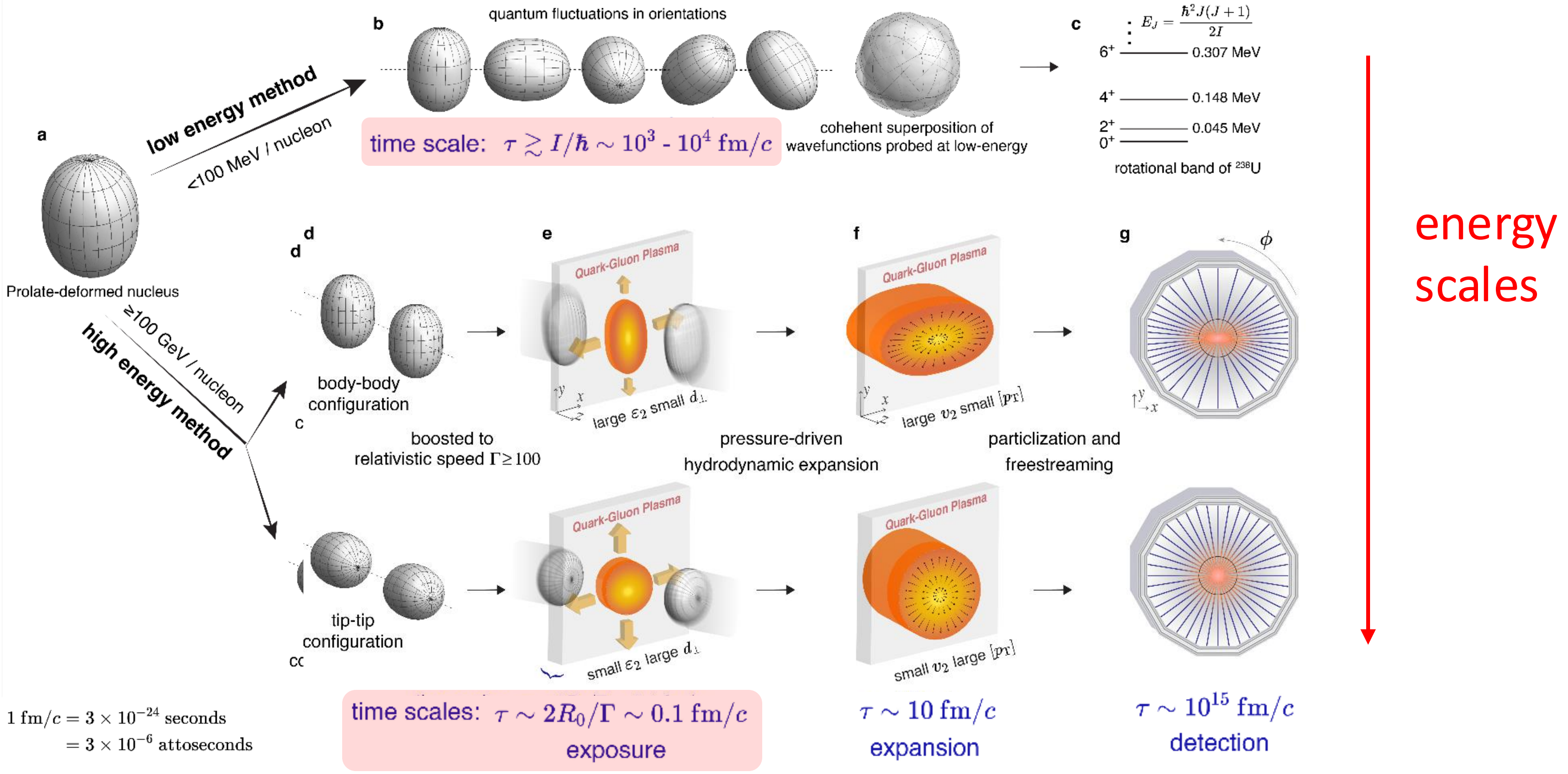
From HIC to initial nuclear structure

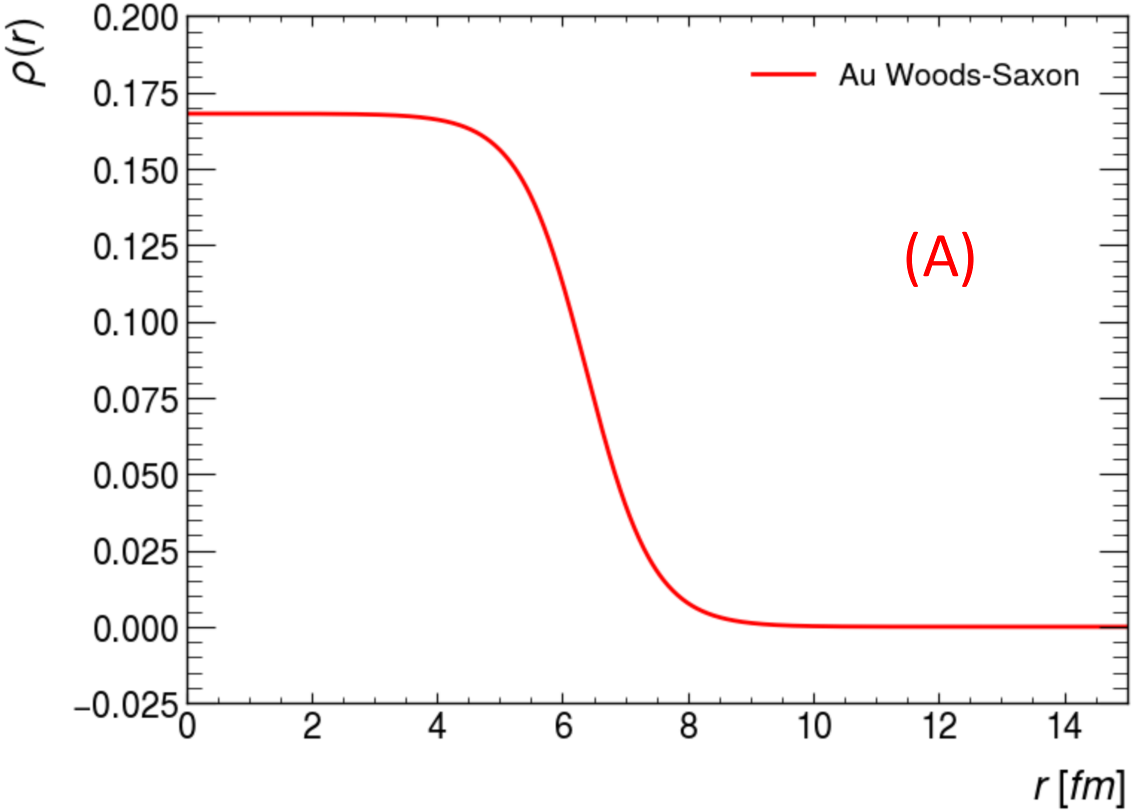


STAR Collaboration, Nature 635 (2024) 8037

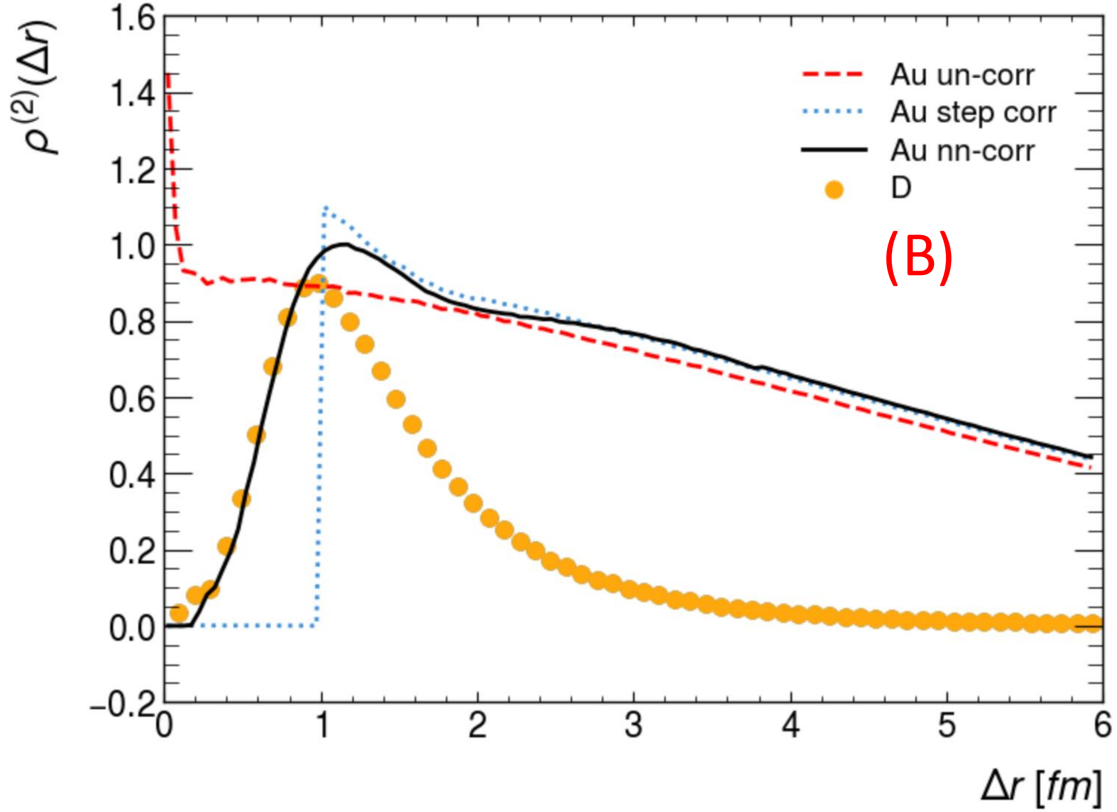
- The intrinsic frame shape is not directly visible in the low-energy-lab frame at the time scale $10^3 \sim 10^4$ fm/c.

Single-nucleon distribution and Nucleon-Nucleon Correlation

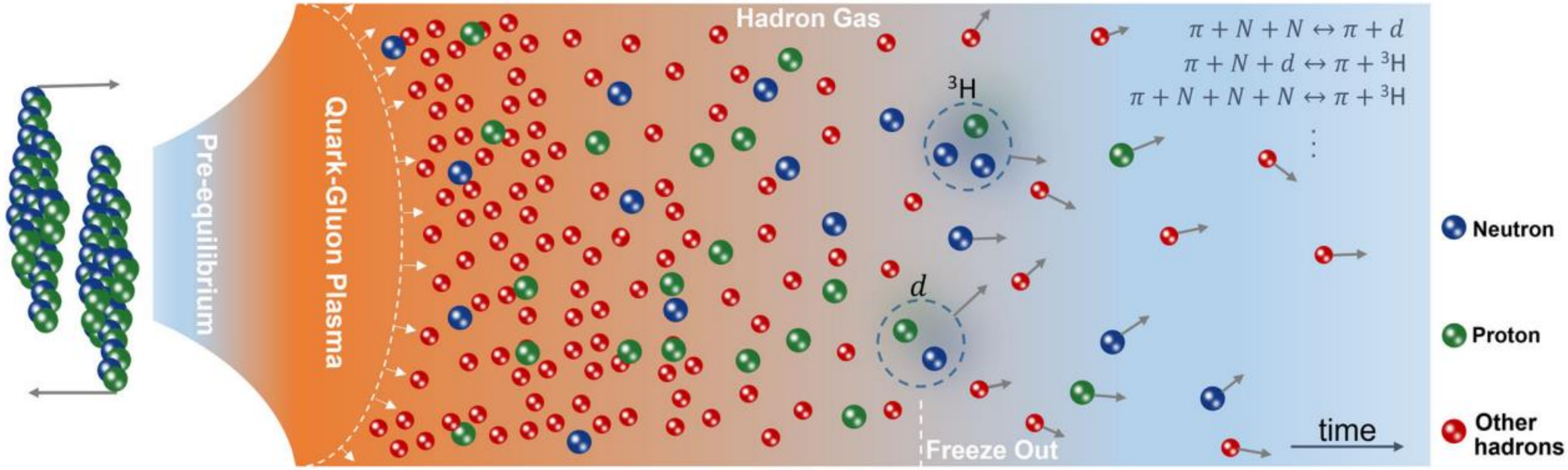
Woods-Saxon distribution



two-nucleon relative distance probability density distribution



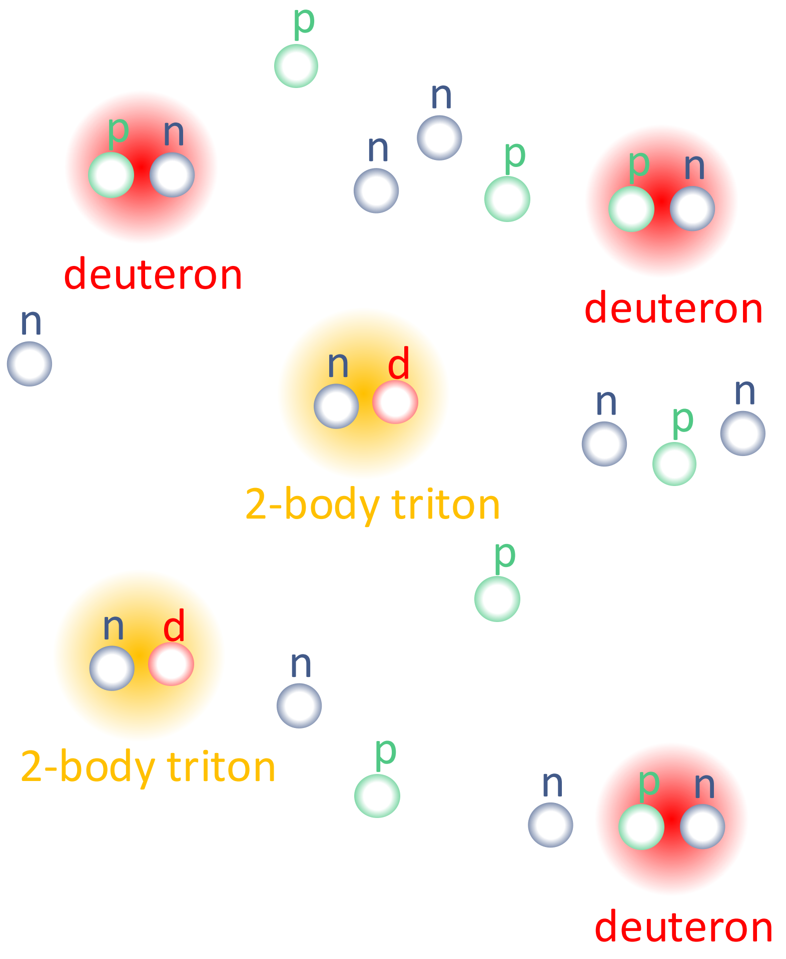
Light nuclei production in HIC



Sun, Kai-Jia and Wang, Rui and Ko, Che Ming and Ma, Yu-Gang and Shen, Chun, Nature Commun. 15 (2024) 1, 1074

- Light nuclei carry information about local baryon density fluctuations.
- Light nuclei provide an effective probe for studying the boundary of the first-order phase transition and the QCD critical point.

Coalescence model and NN correlation



$$\frac{\mathrm{dN_A}}{\mathrm{d^3}\mathbf{P}_\mathrm{A}} = \frac{g_A}{Z!N!}\int \Pi_{i=1}^{Z} p_i^{\mu}\mathrm{d}^3\sigma_{\mathrm{i}\mu}\frac{\mathrm{d}^3\mathbf{p}_\mathrm{i}}{\mathrm{E_i}} f_{\mathrm{p}/\bar{\mathrm{p}}}(\mathbf{x}_\mathrm{i},\mathbf{p}_\mathrm{i},\mathrm{t_i})$$
$$\times \int \Pi_{j=1}^{N} p_j^{\mu}\mathrm{d}^3\sigma_{\mathrm{j}\mu}\frac{\mathrm{d}^3\mathbf{p}_\mathrm{j}}{\mathrm{E_j}} f_{\mathrm{n}/\bar{\mathrm{n}}}(\mathbf{x}_\mathrm{j},\mathbf{p}_\mathrm{j},\mathrm{t_j})$$
$$\times f_A(\boldsymbol{\rho},\lambda,\cdots,\mathbf{p}_\rho,\mathbf{p}_\lambda,\cdots)$$
$$\times \delta^{(3)}(\mathbf{P}_A - \sum_{i=1}^{Z}\mathbf{p}_i - \sum_{j=1}^{N}\mathbf{p}_j),$$

Wigner function f_A:

$$f_{A=2}(\boldsymbol{\rho},\mathbf{p}_\rho) = 8\exp[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \mathbf{p}_\rho^2\sigma_\rho^2]$$

$$\boxed{\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}_1' - \mathbf{x}_2'),} \boldsymbol{p}_\rho = \sqrt{2}\frac{m_2\boldsymbol{p}_1' - m_1\boldsymbol{p}_2'}{m_1 + m_2};$$

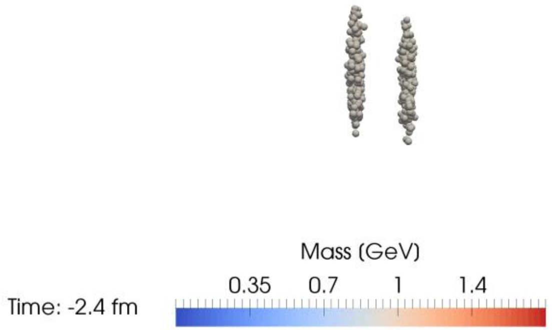
In our codes, we define a weight of coalescence as follows:

$W = \frac{g_A}{Z!N!} f_{A=2}$,

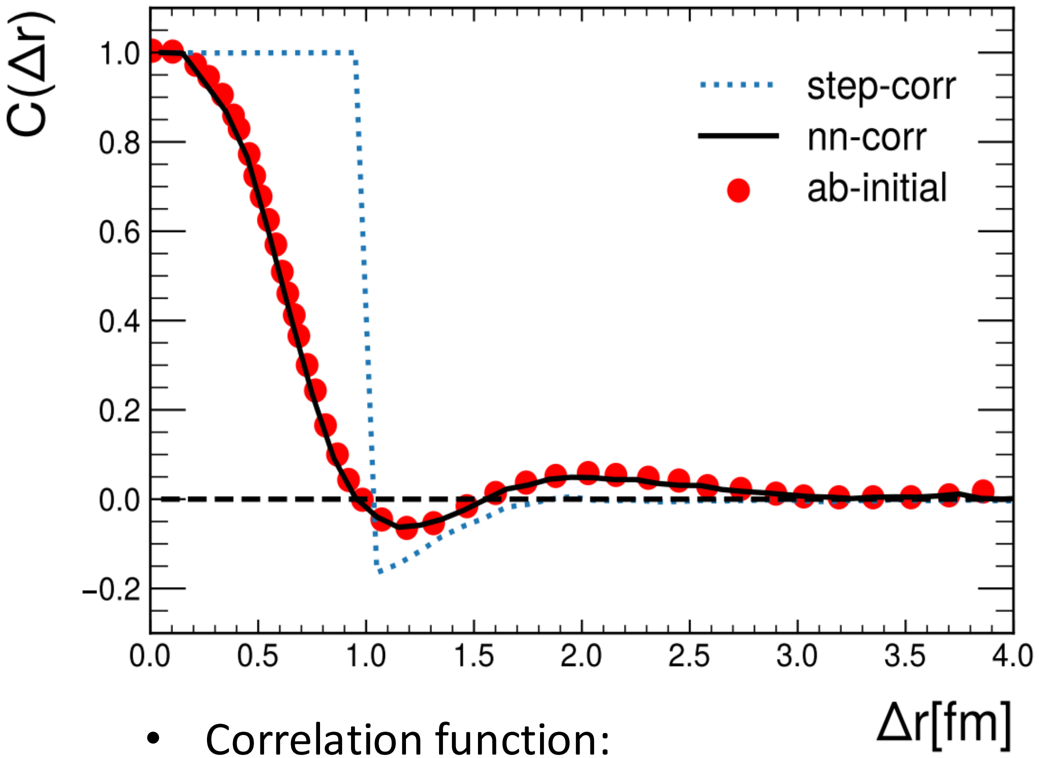
when $W \geq 1$, we set it to 1 to avoid complete overlap of two particles.

Model and set up

Alvioli, M. and Drescher, H. -J. and Strikman, M., Phys.Lett.B 680 (2009) 225-230



- Model:
  - SMASH + no correlation
  - SMASH + correlation
- Mode:
  - mean field
- Collision system: Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV
- Events: 200,000 events per mode



- Correlation function:

$$C(\Delta r) = 1 - \rho_C^{(2)}(\Delta r)/\rho_U^{(2)}(\Delta r)$$

where $\Delta r = |r_1 - r_2|$

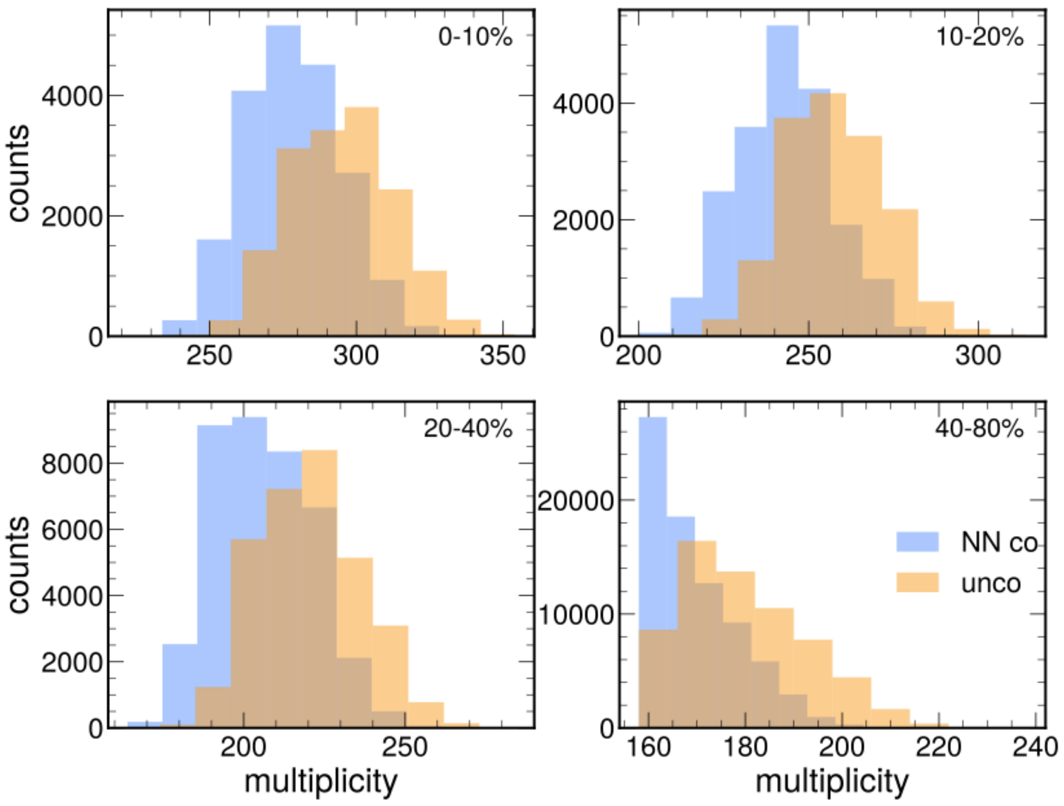
- The probability of accepting a newly sampled nucleon is:

$$\prod_i P(\Delta r_i) = \prod_i [\rho_c^{(2)}(\Delta r_i)/\rho_u^{(2)}(\Delta r_i)]$$

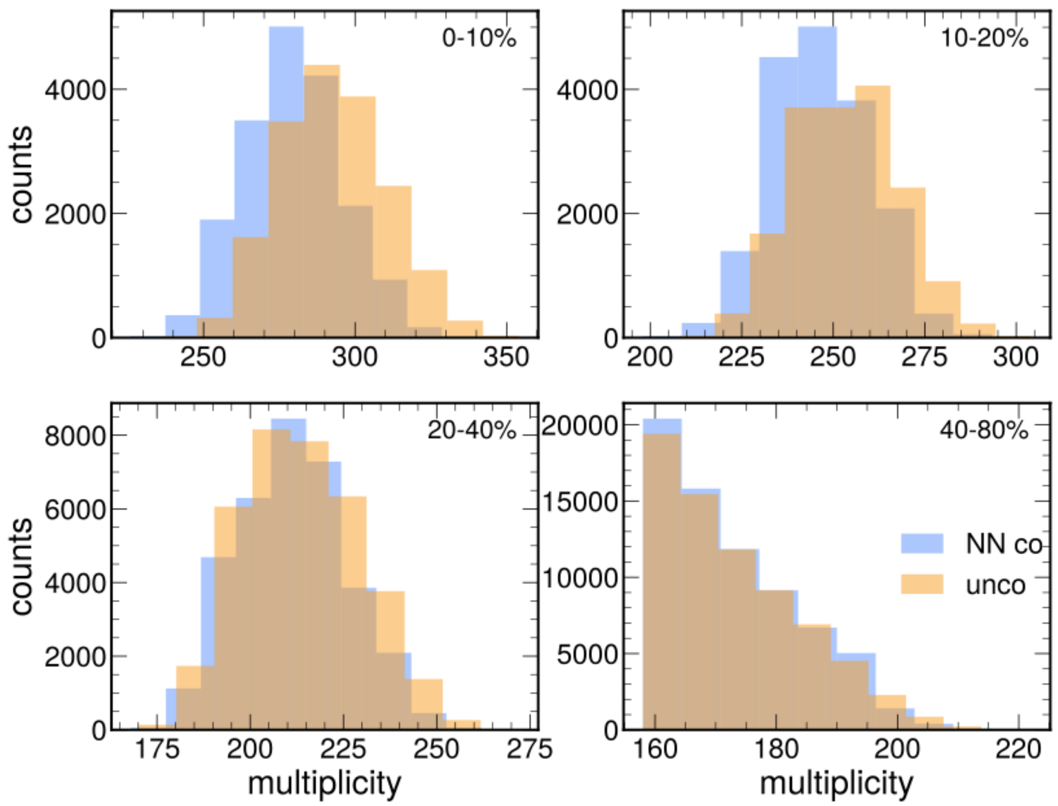
Method

Results: Centrality determination

Correct: determined by the charged-particle multiplicity

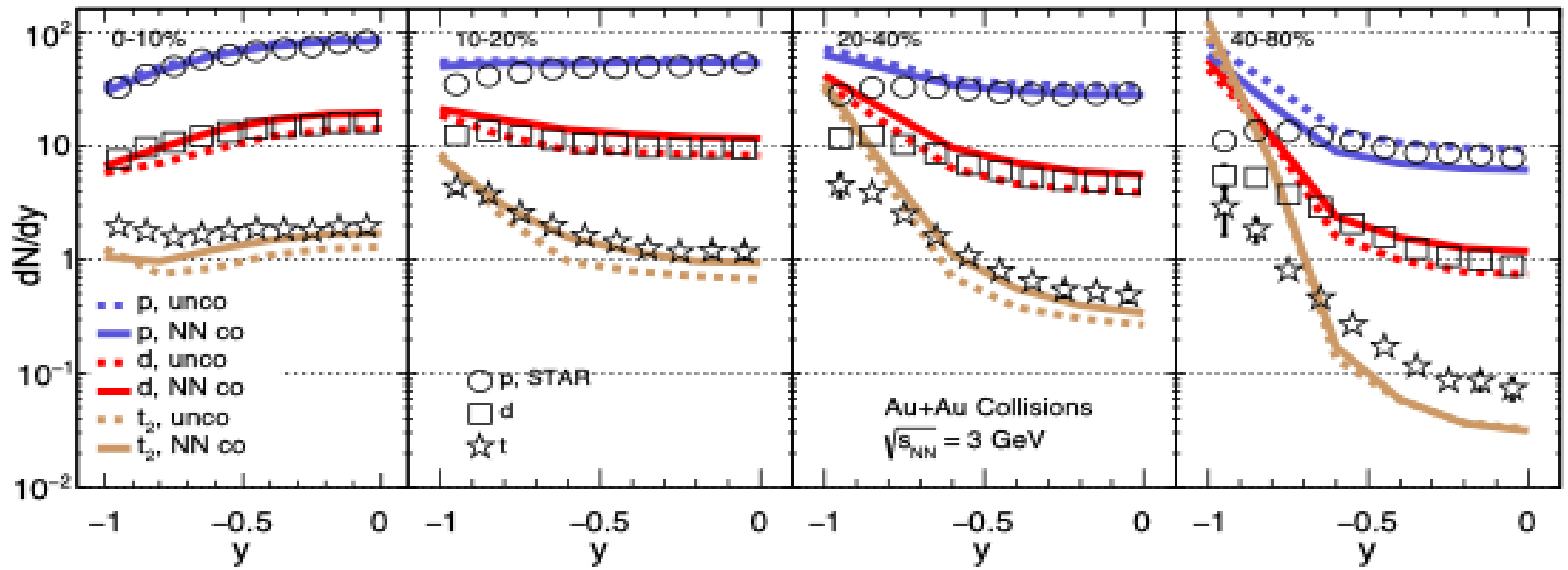


Incorrect: determined by the impact parameter



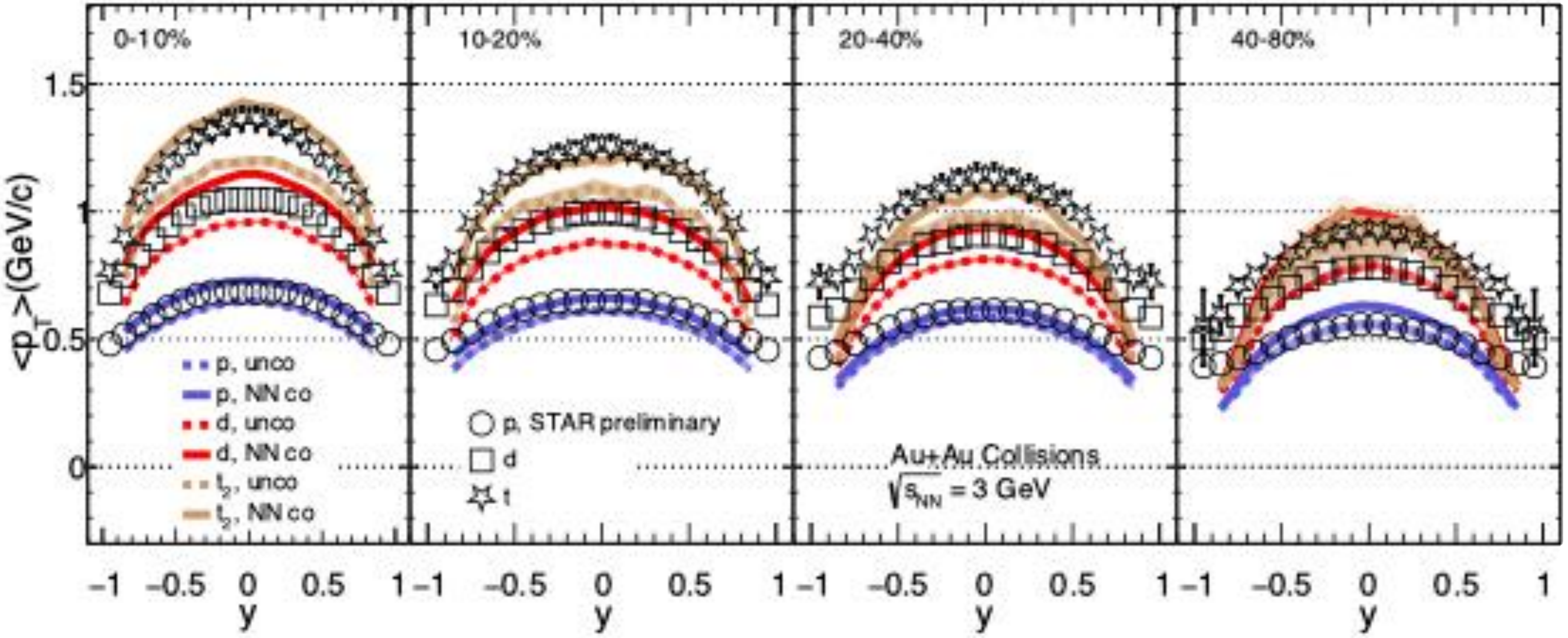
- Collision centralities were determined by dividing the charged-particle multiplicity (FXTMult), measured within the pseudo-rapidity range $0 < \eta < 2$, by the $p_T > 0.4$ GeV.

Rapidity distribution of light nuclei production



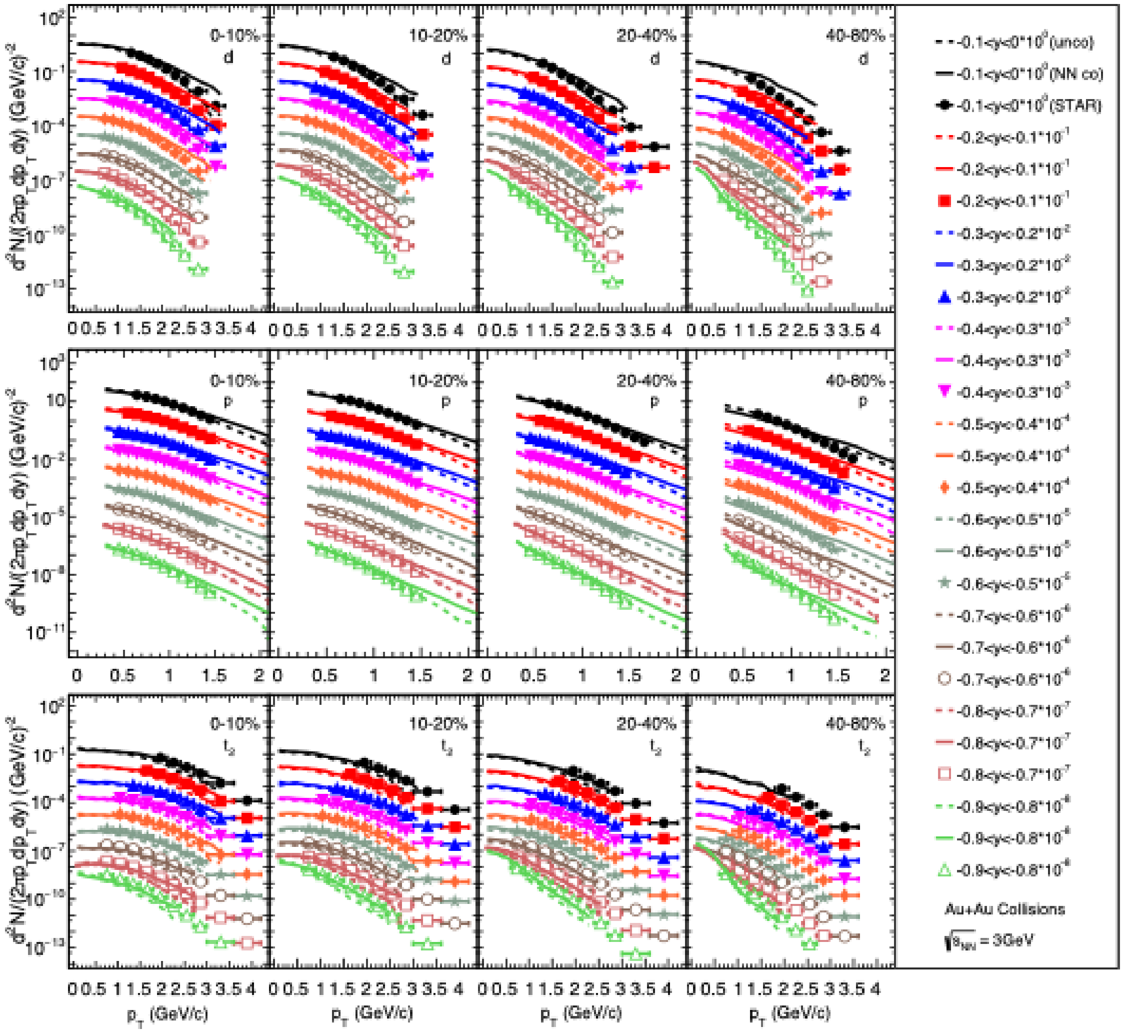
➢ Incorporating NN correlation into the SMASH simulation will lead to a visible enhancement in deuteron and triton yields and a suppression in proton yield.

Mean p_T distribution



➢After considering the correlation, the mean p_T of tritons, deuterons, and protons has **increased, aligning better with experimental data.**

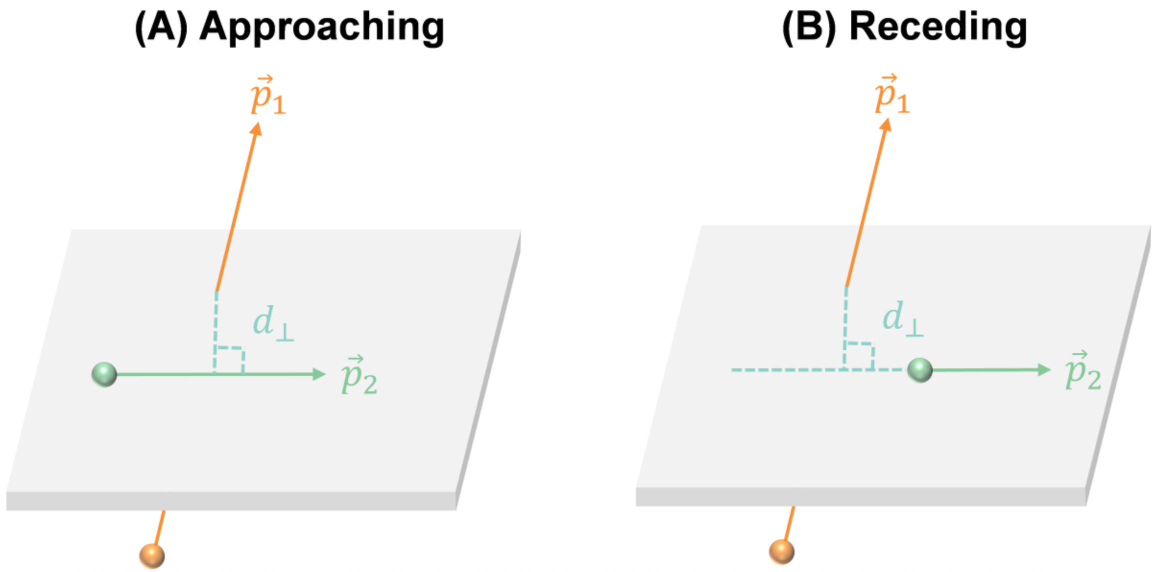
p_T spectra



- After incorporating NN correlation, the slopes of the p_T spectra are enhanced, and the p_T distribution of tritons aligns more closely with experimental data at low p_T.
- It can be observed that NN correlation significantly influences the momentum distribution of light nuclei.

Results

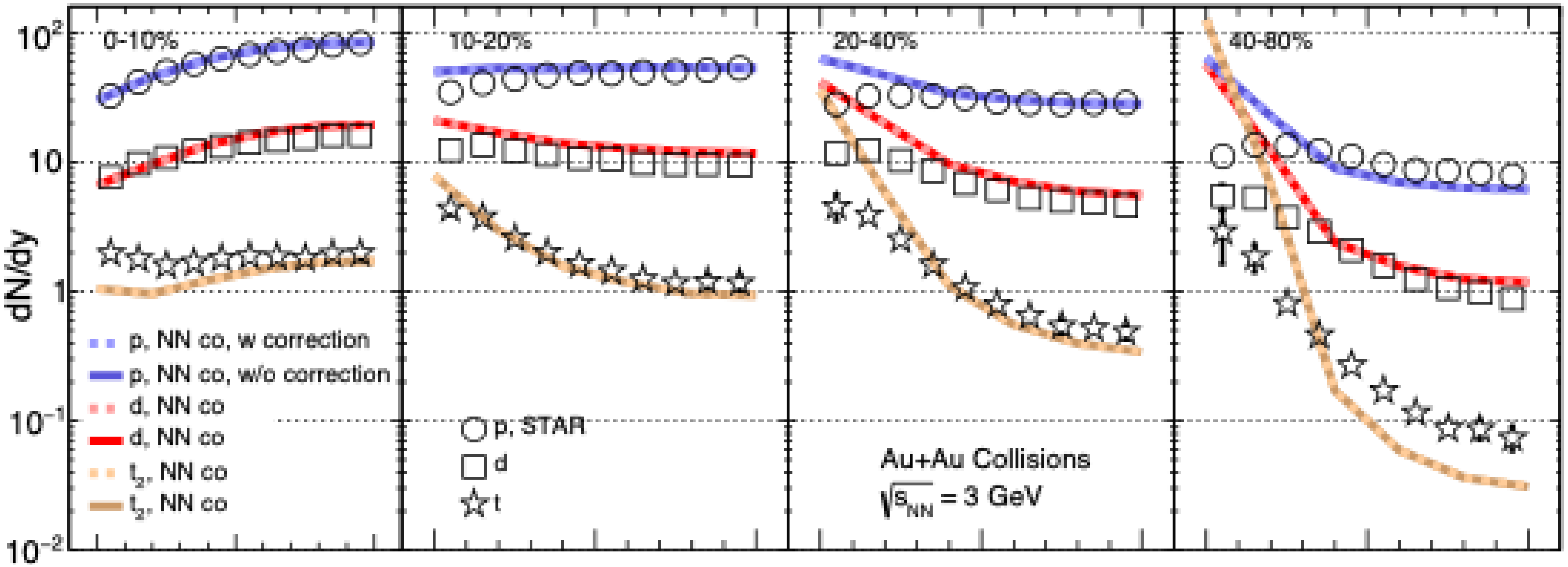
Coalescence Correction



$$d_\perp = \sqrt{(\vec{r_1} - \vec{r_2})^2 - \frac{[(\vec{r_1} - \vec{r_2}) \cdot (\vec{p_1} - \vec{p_2})]^2}{(\vec{p_1} - \vec{p_2})^2}}$$

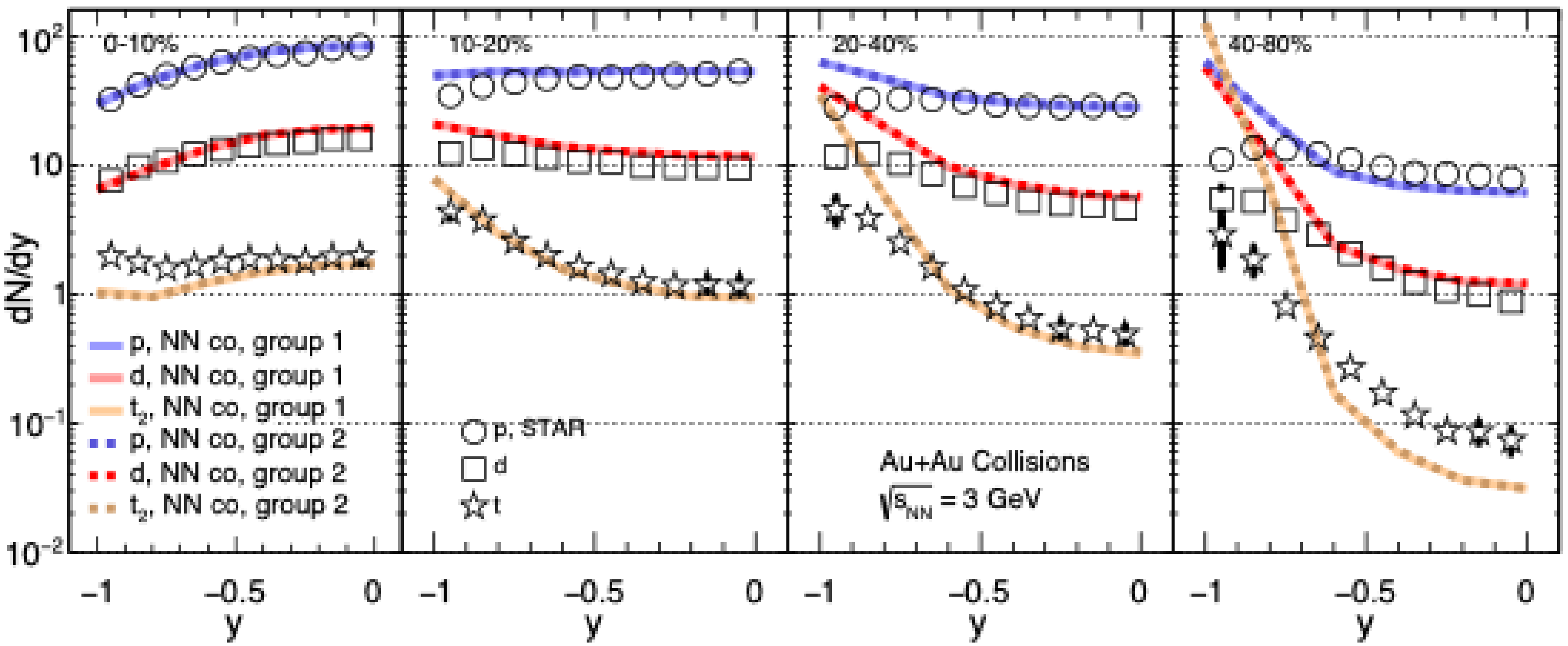
- The conventional coalescence method neglects relative momentum.
- Converging momenta reduce $d_\perp$, enhancing coalescence probability.
- Our method accounts for both approaching and receding scenarios.

Coalescence Correction



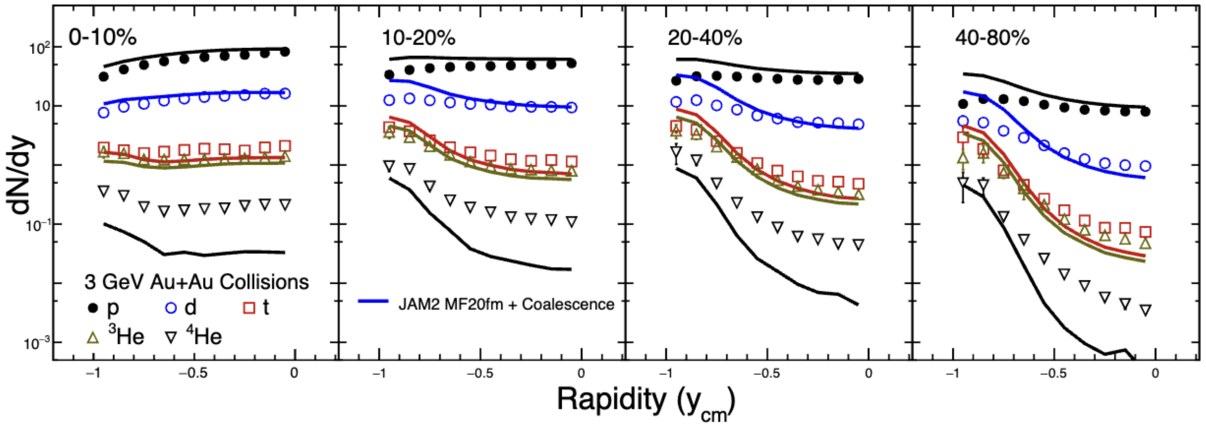
- After considering NN correlation, we found that whether to apply coalescence correction has little effect on the results.

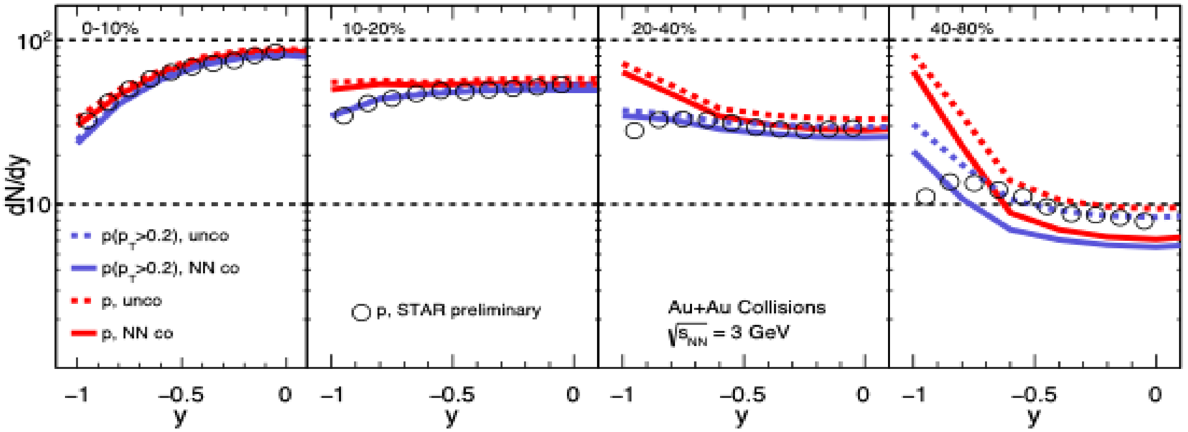
Model Uncertainty



- ➢ To check the effect of model uncertainty, we compared the results of two sets of 200,000 events after incorporating NN correlation and found almost no noticeable difference.

Spectator effect

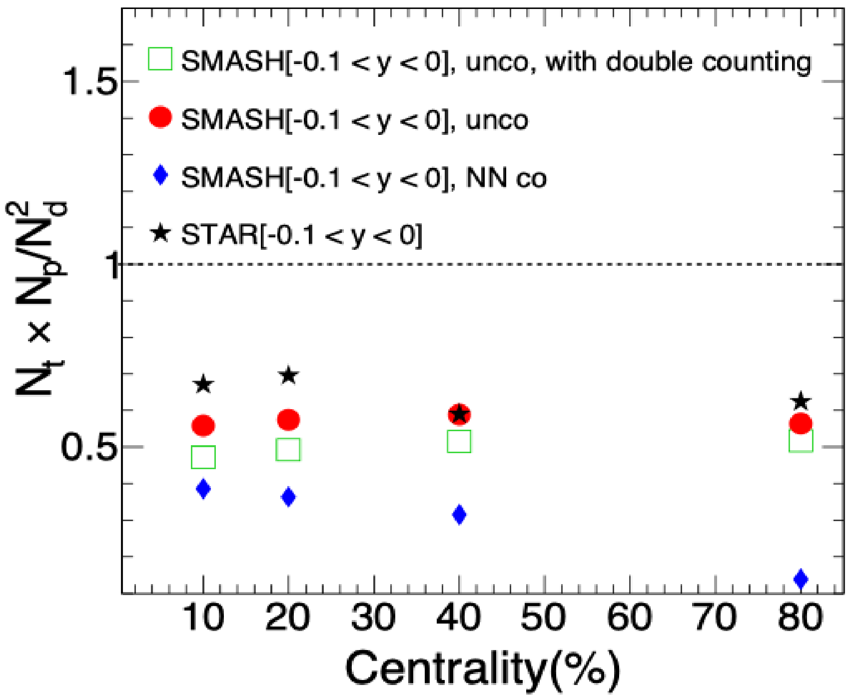


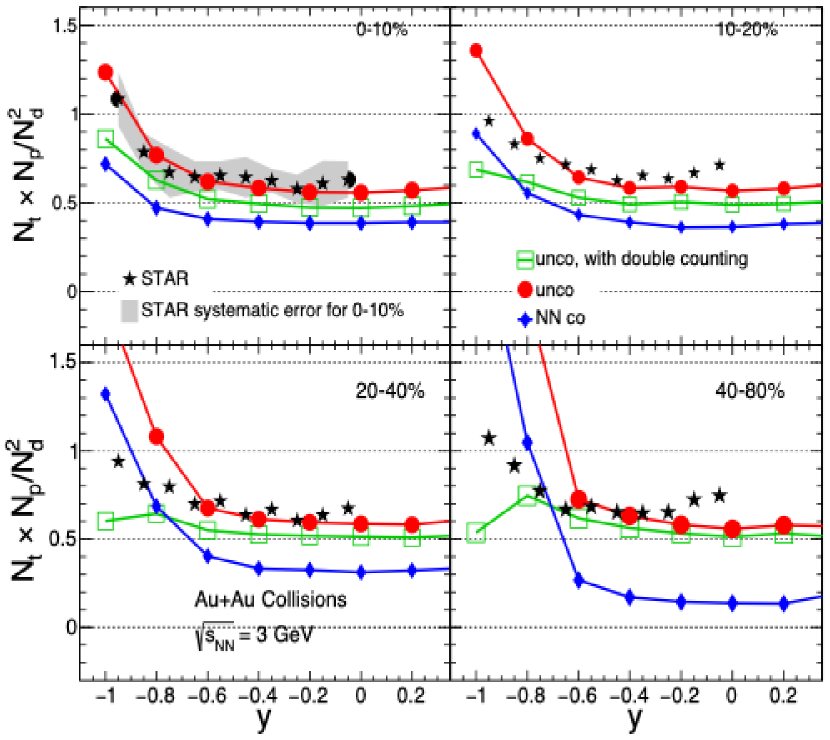


Liu, L. K. and Hu, C. L. and He, X. H. and Shi, S. S. and Xie, G. N., Physics Letters B, 138853

- The spectators lead to an overestimation of particle yields in the large rapidity region.

$$\frac{N_t\, N_p}{N_d^2}$$

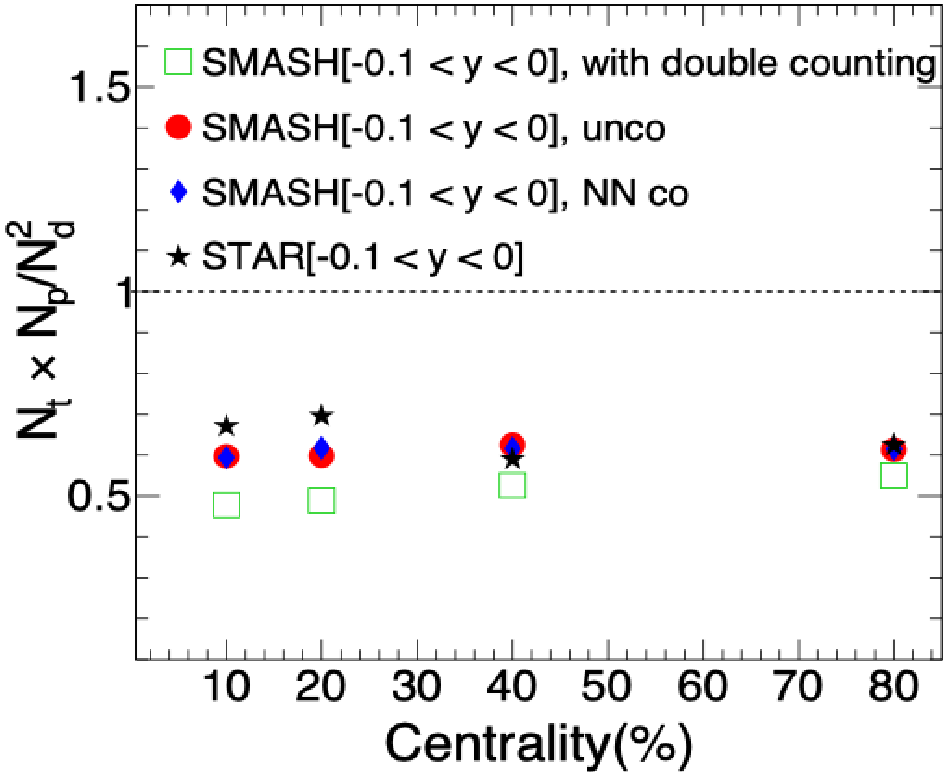




- ➢Without NN correlation, the yield ratio better matches experimental data (due to deuteron suppression and proton increase), while the mean p_T with NN correlation aligns more closely with experimental data.

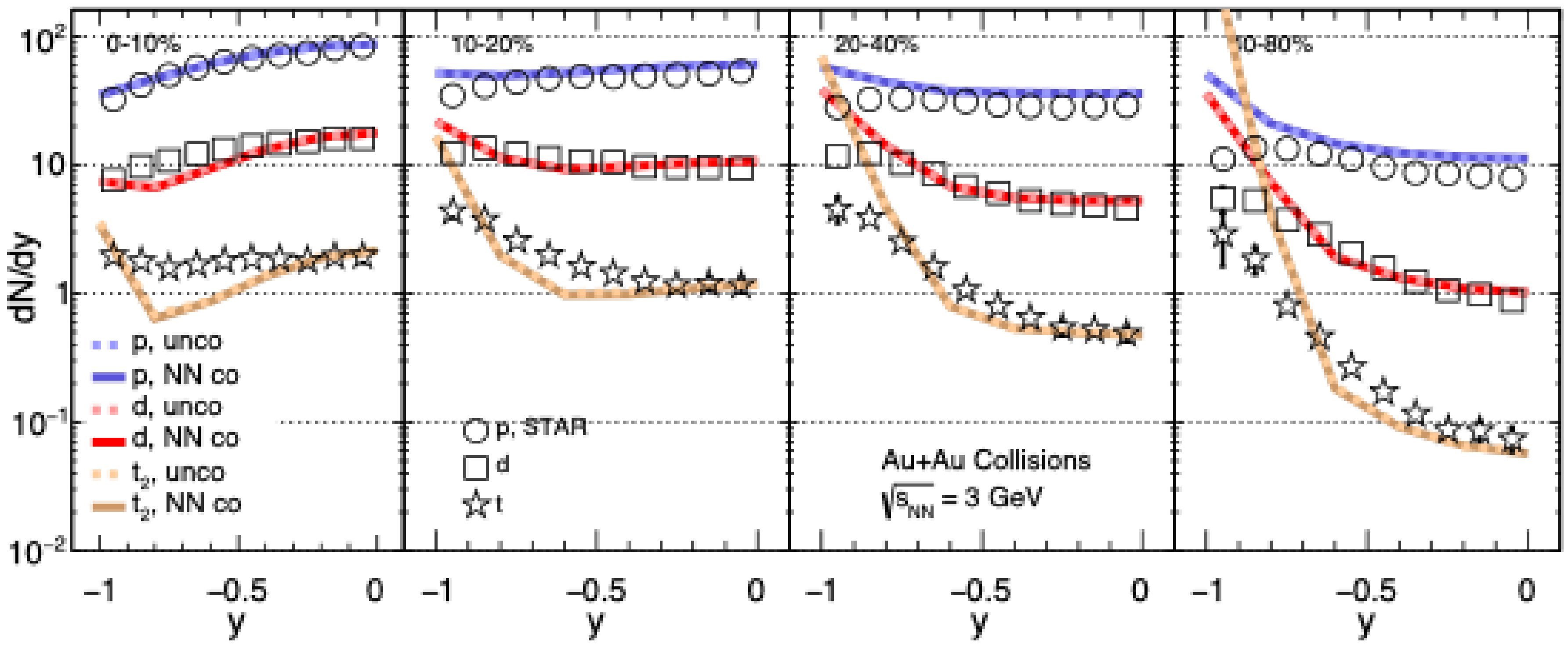
Results

Without Mean Field Potential



- Neglecting the mean field effect improves the yield ratio results, but at 3 GeV, the mean field potential plays a significant role.

Without Mean Field Potential



➢When the mean field is not considered, it can be observed that the effect of incorporating correlations on the yield of light nuclei is negligible.

Summary

1. Nucleon Spatial Correlations Enhance Light Nuclei Production

- Initial nucleon spatial correlations in SMASH simulations significantly increased deuteron/triton yields.
- Improved agreement with STAR data in rapidity distributions of mean pt.

2. Baryon Conservation Adjustment Optimizes Yield Ratios

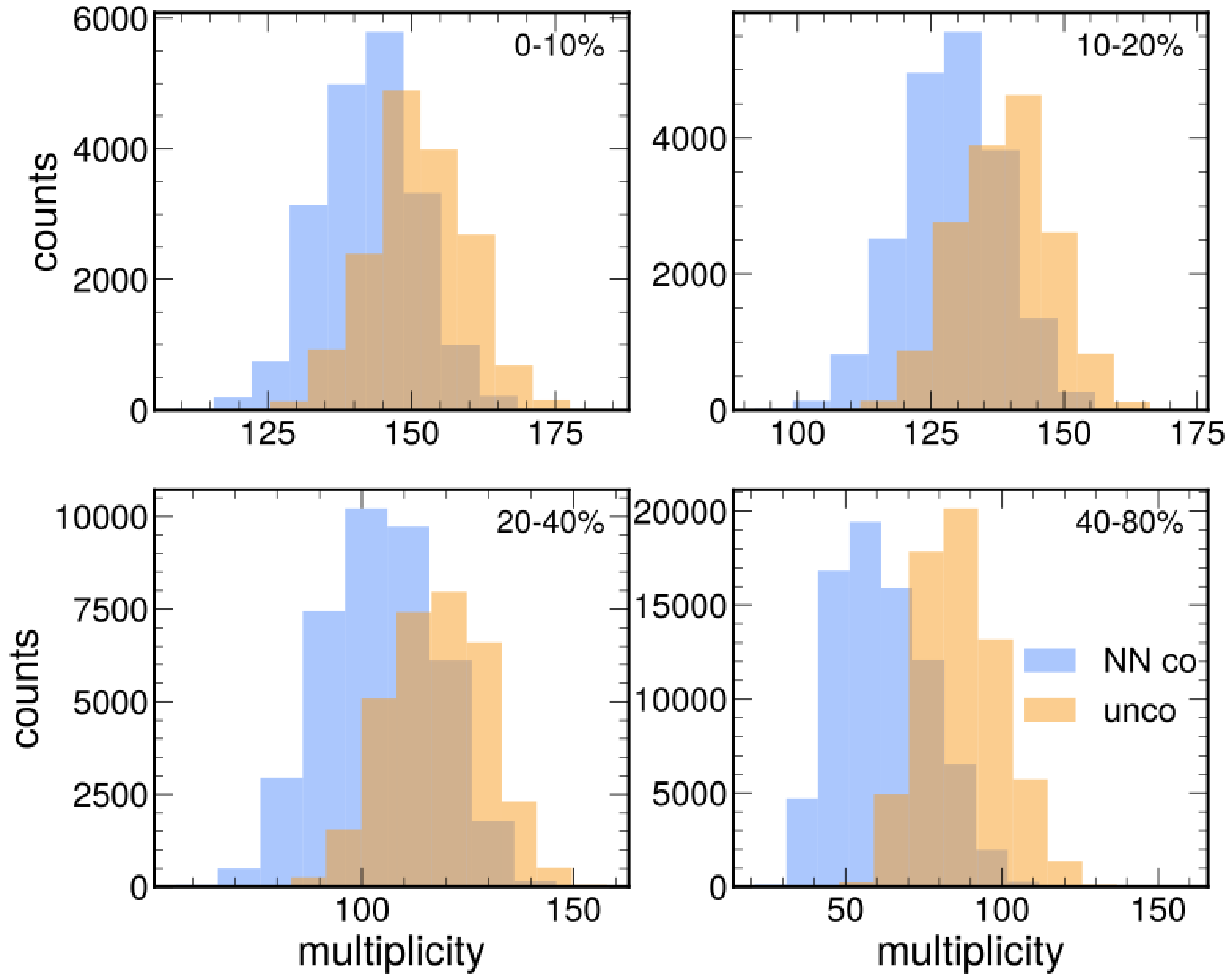
- Subtracting deuterons consumed in triton coalescence refined deuteron yield predictions.
- Critical for better modeling of $\frac{N_t N_p}{N_d^2}$ ratio in uncorrelated models.

3. Unresolved Discrepancies Highlight Key Mechanisms

- Baryon conservation, spectator exclusion, and centrality determination via multiplicity affect results.
- Double-yield ratio deviations suggest unmodeled physics (e.g., critical fluctuations, coalescence parameter errors), emphasizing initial nucleon correlations as a critical bridge between nuclear structure and collision dynamics.

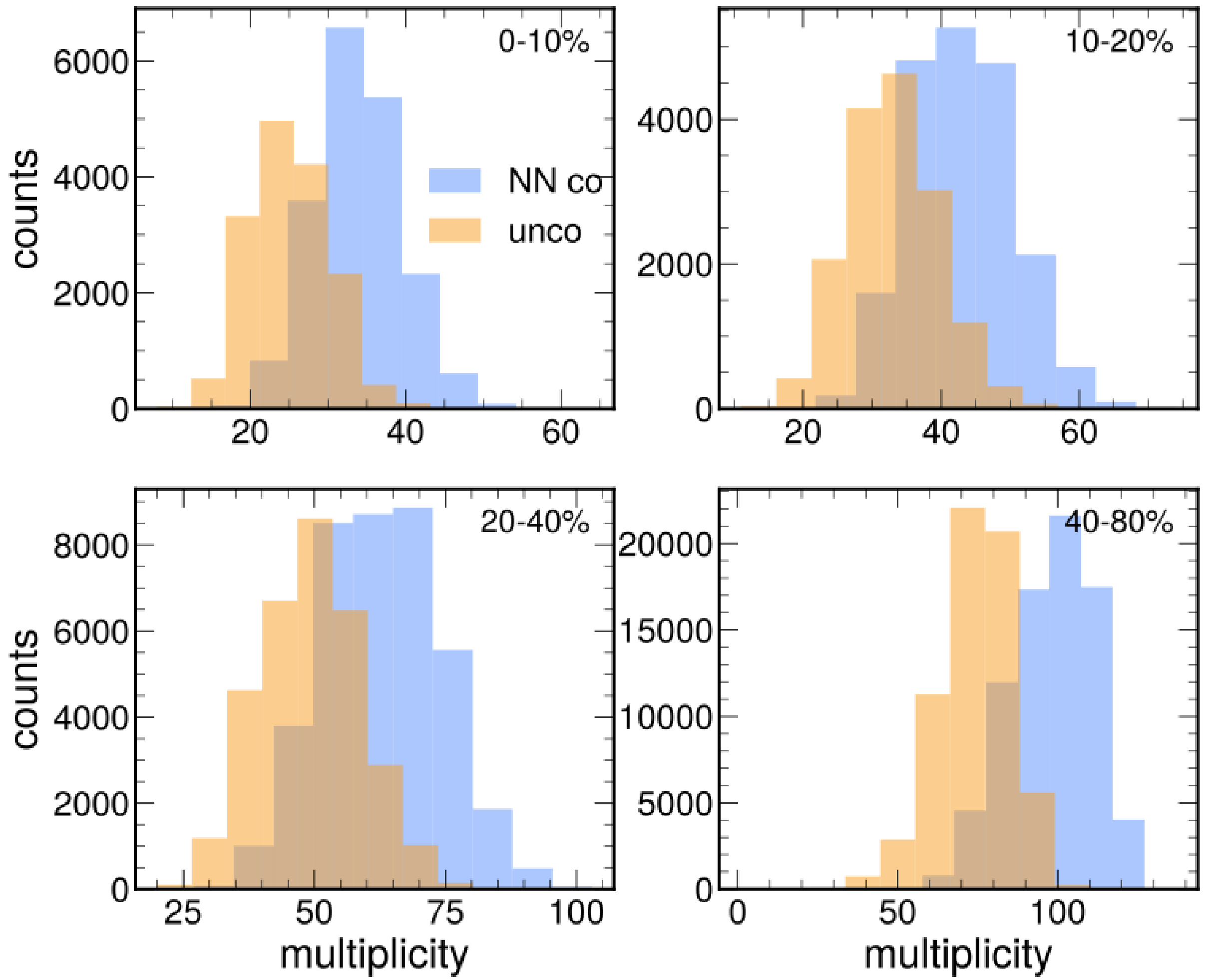
Thank you for your attention

Distribution of proton at four centralities



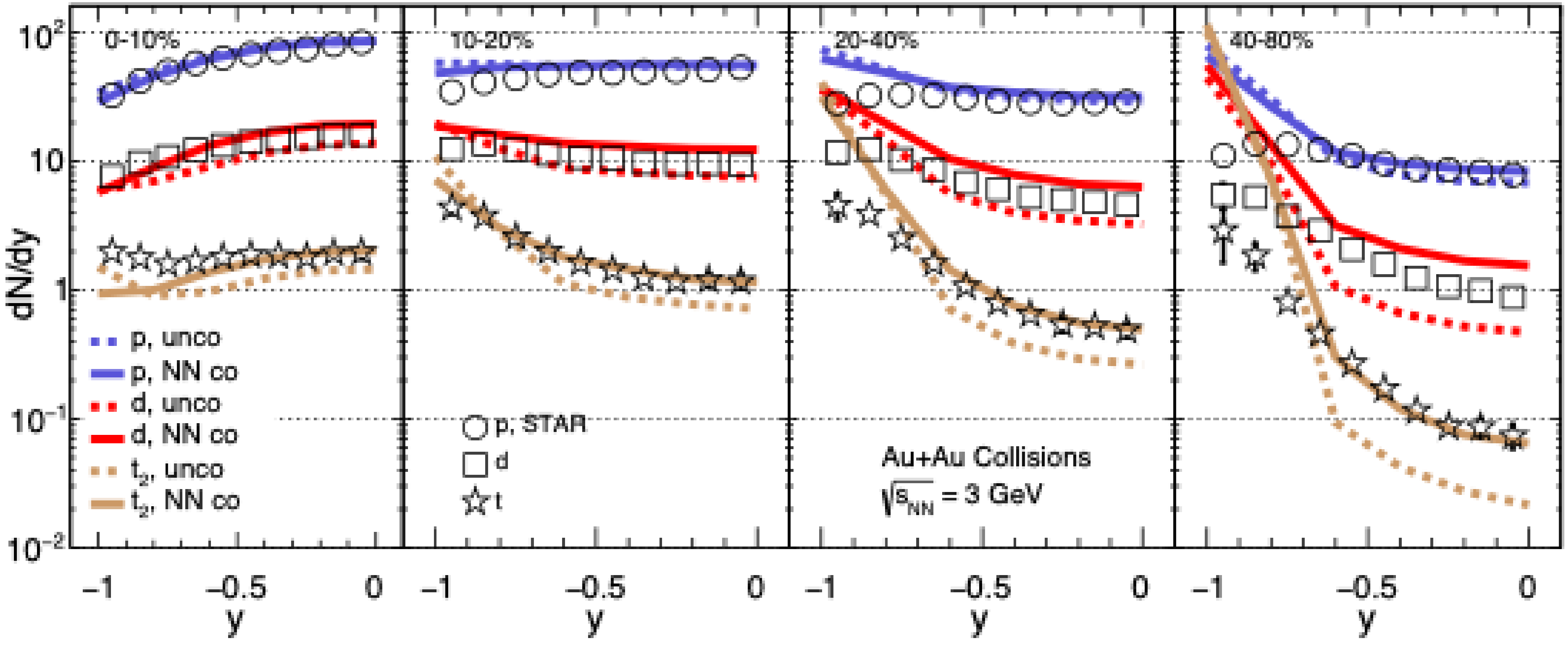
Appendix

Distribution of deuteron at four centralities



Appendix

Centrality is determined by impact parameter



Appendix