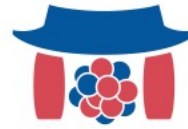




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Directed Flow of Light and Hyper-Nuclei at 3 GeV Au+Au collisions in STAR

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for the STAR Collaboration

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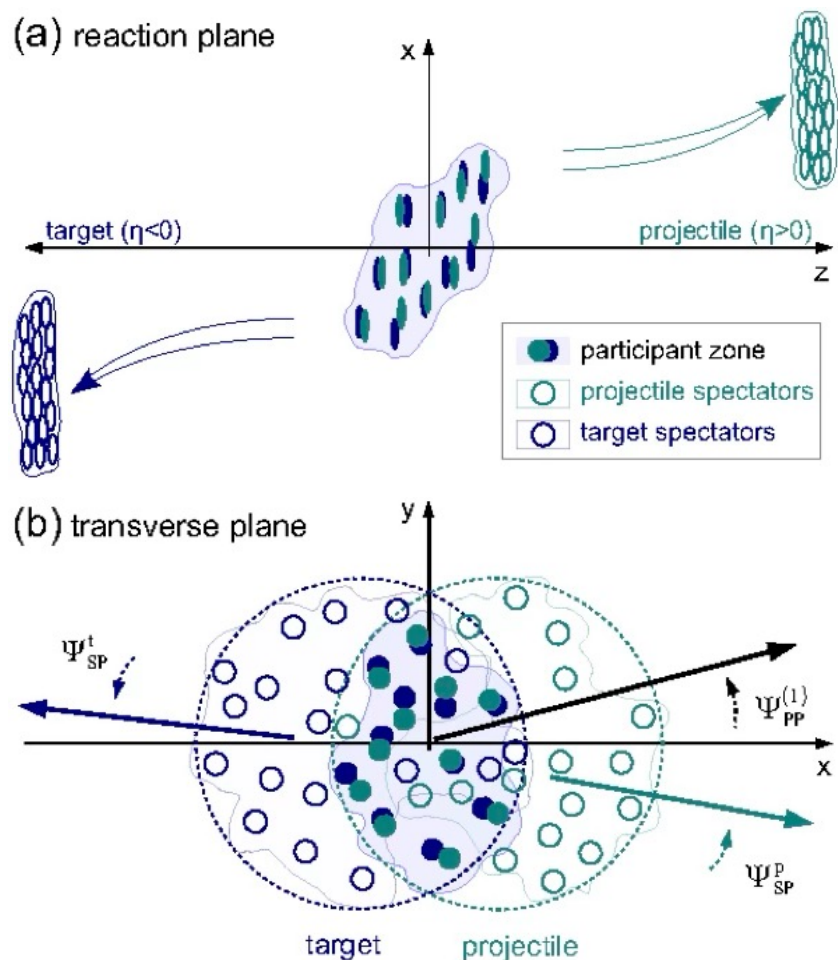
¹Central China Normal University

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Outline

1. Introduction
2. Datasets and Particle Reconstruction
3. Directed Flow of light nuclei and hyper-nuclei
4. Summary and Outlook

Directed Flow



- Directed flow is the collective sideways motion of particles produced in heavy-ion collisions.
- It reflects the first harmonic azimuthal anisotropy relative to the reaction plane.

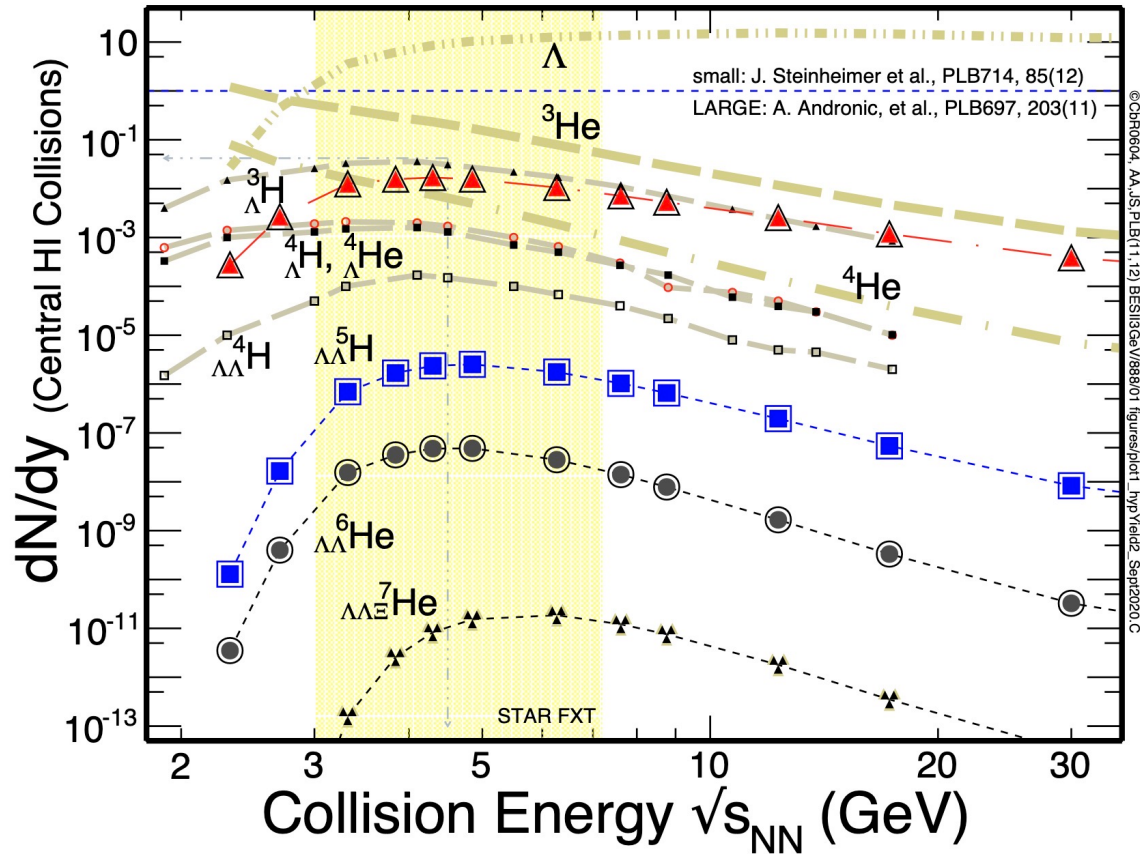
$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \psi_{RP}))$$

- Directed flow: $v_1 = \langle \cos(\phi - \psi_{RP}) \rangle$
- Probes the Equation of State (EOS) of nuclear matter under high baryon density region.
- Reveals the properties of dense baryonic matter created in heavy-ion collisions.

B.Abelev et al. Phys. Rev. Lett. **111**, 232302(2013)

Production of Light Nuclei and Hyper-Nuclei

Thermal model calculation results



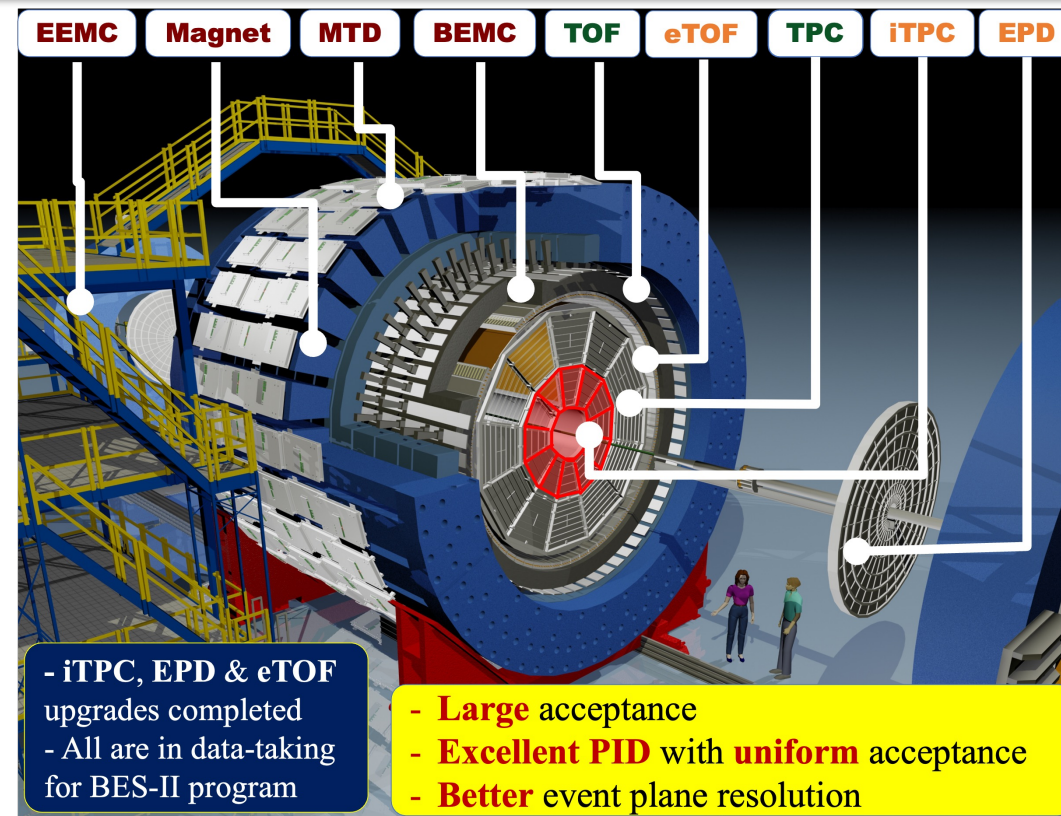
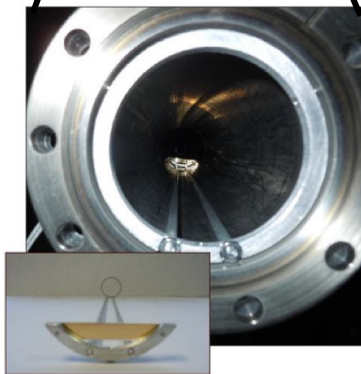
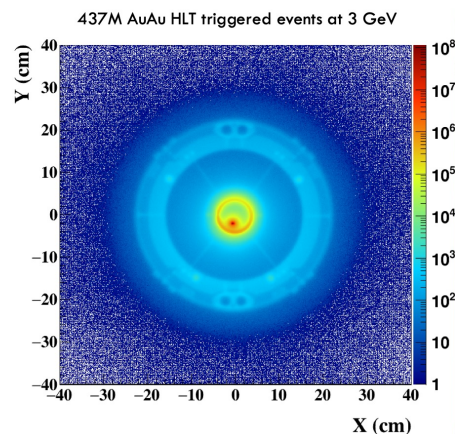
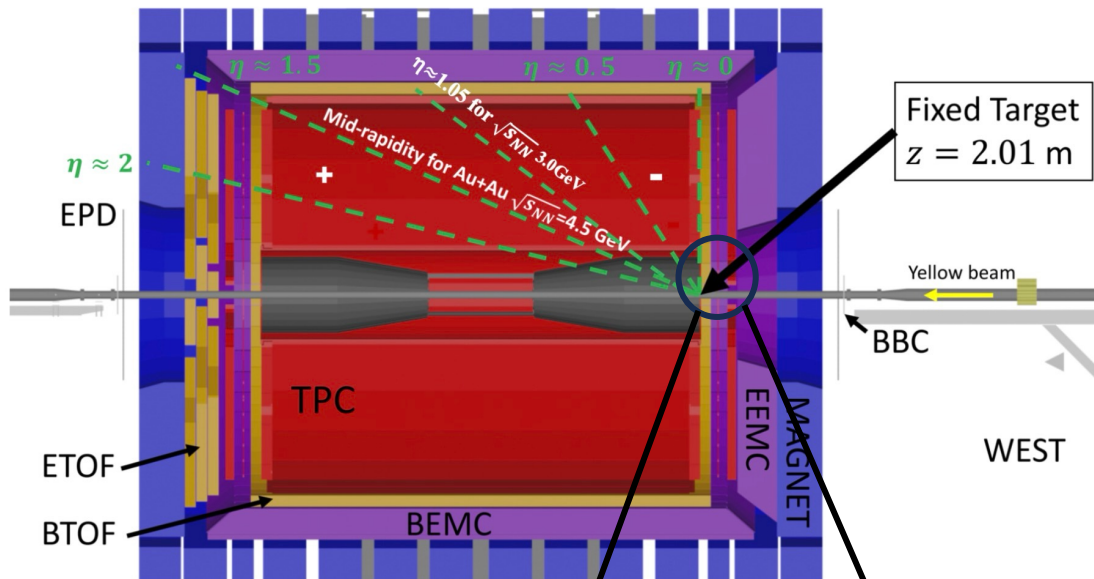
- 1) Light nuclei and hyper-nuclei production is enhanced in the high baryon density region.
- 2) Properties of light nuclei and hyper-nuclei provide important information about nucleon-nucleon (N-N) and hyperon-nucleon (Y-N) interactions.
- 3) Directed flow helps reveal the production mechanisms of both light nuclei and hyper-nuclei.

[1] A. Andronic et al, Phys. Lett. B **697**, 203(2011)

[2] J. Steinheimer et al. Phys. Lett. B **714**, 85(2012)

STAR BES-II

Fixed target mode ($\sqrt{s_{NN}} = 3.0 - 13.7$ GeV)



- STAR BES-II
 - ❑ 10× statistics compared to BES-I.
 - ❑ This analysis: $\sqrt{s_{NN}} = 3.0$ GeV (baryon chemical potential is 720 MeV).

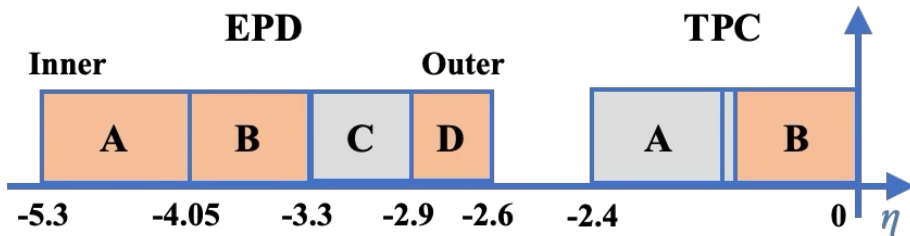
Dataset and Event Plane Reconstruction

DataSet	Analyzed Events	Target rapidity	Primary vertex cuts
$\sqrt{s_{NN}} = 3.0$ GeV (2021)	$\sim 1.97\text{B}$	-1.045	$(V_x + 0.47)^2 + (V_y + 2)^2 < 4 \text{ cm}^2$ $198 < V_z < 202 \text{ cm}$

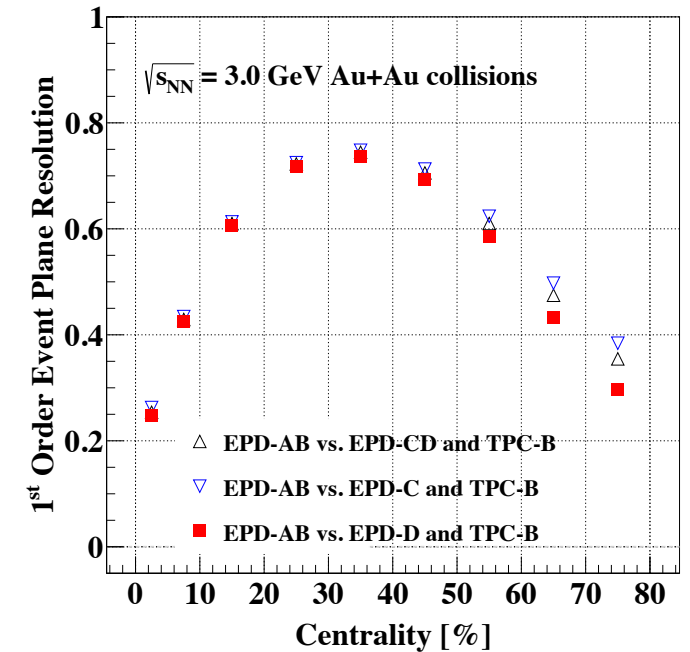
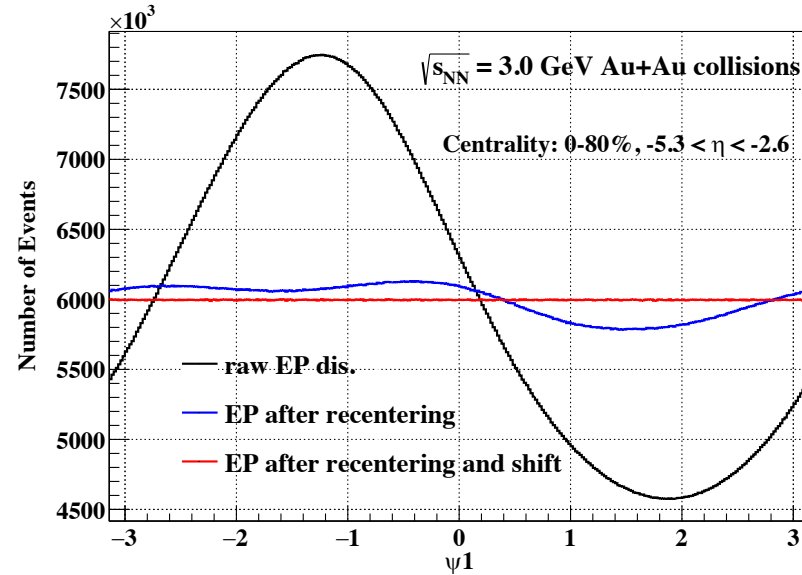
❖ Event Plane Reconstruction

- Reconstruction method: Q-vector method.
- Calibration: recentering and shift.
- EP resolution: three sub-events method

$$\langle \cos(\psi_1^a - \psi_r) \rangle = \sqrt{\frac{\langle \cos(\psi_1^a - \psi_1^b) \rangle \langle \cos(\psi_1^a - \psi_1^c) \rangle}{\langle \cos(\psi_1^b - \psi_1^c) \rangle}}$$

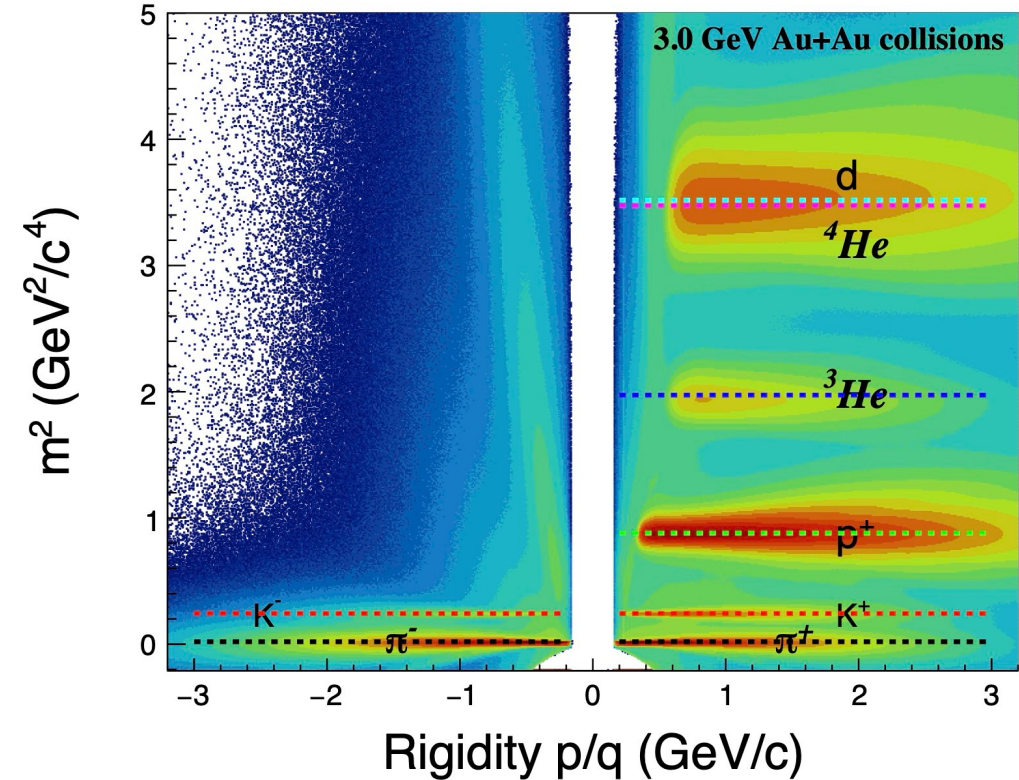
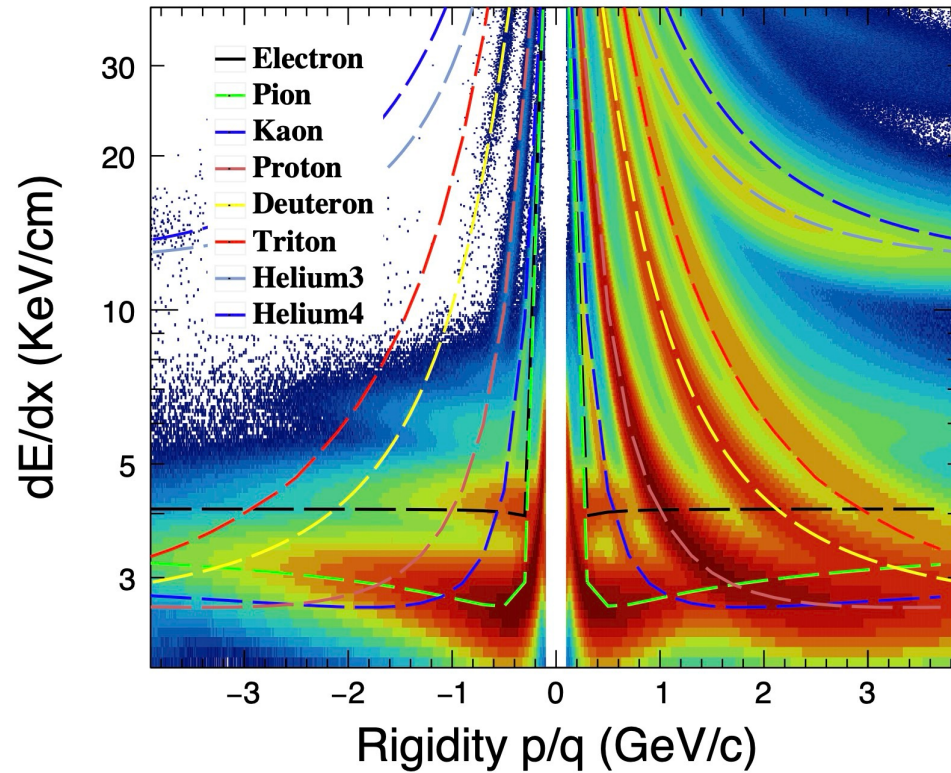


A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998)



- High event plane resolution achieved at $\sqrt{s_{NN}} = 3.0$ GeV.
- EPD-AB is selected for v_1 extraction

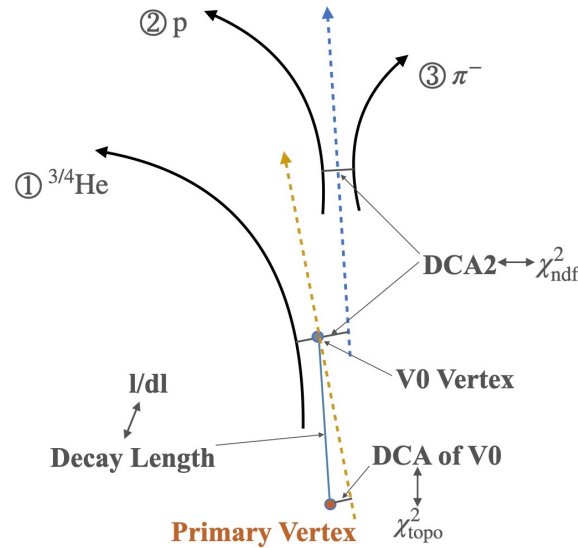
Particle Identification



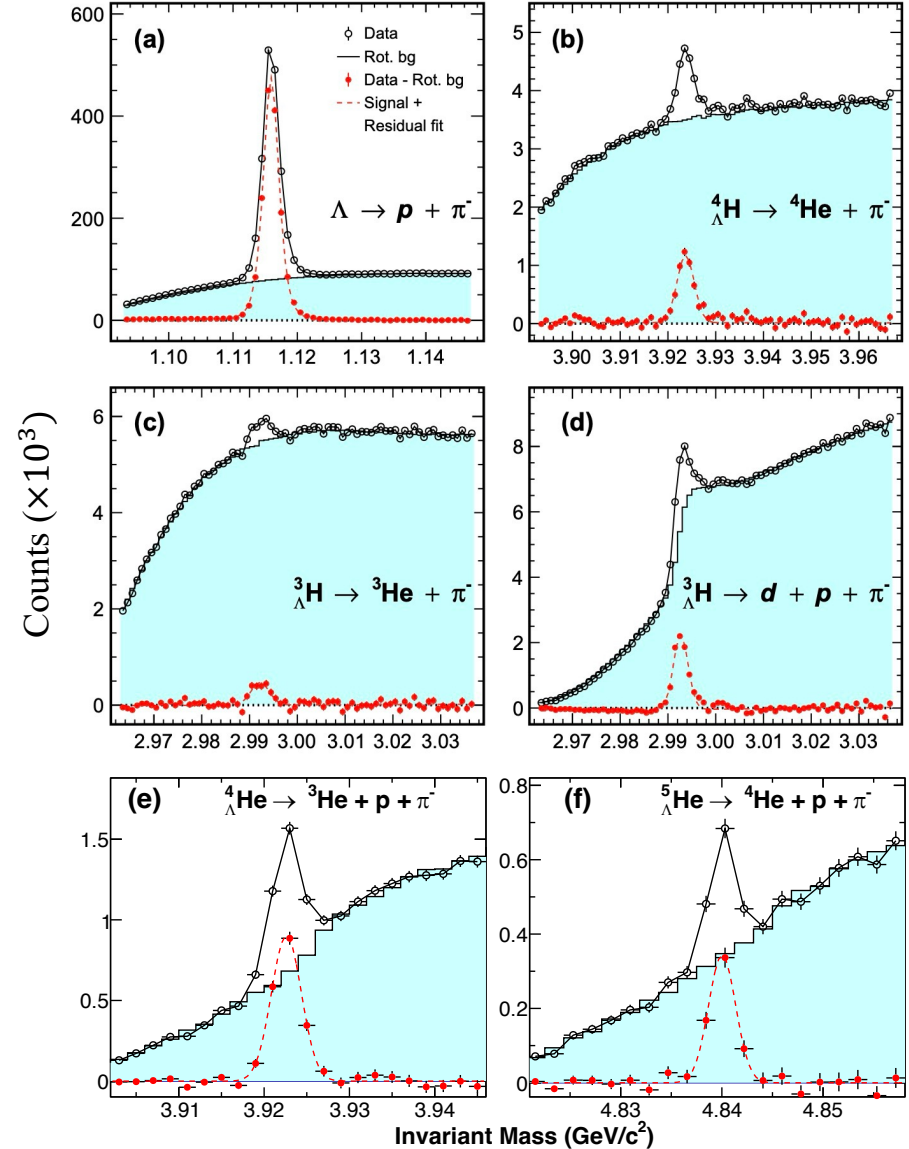
- The TPC enables excellent particle identification at low momentum through ionization energy loss (dE/dx) measurements.
- The TOF detector improves particle separation at higher momentum by providing squared mass (m^2) information.

Hyper-Nuclei Reconstruction

Decay Topology



- Hypernuclei are reconstructed using the KFParticle package, which applies a Kalman filter method to enhance signal significance.
- Clear signals are observed in the invariant mass spectra. The ${}^5_{\Lambda}\text{He}$ is observed for the first time with a significance of ~ 14 .



Run18

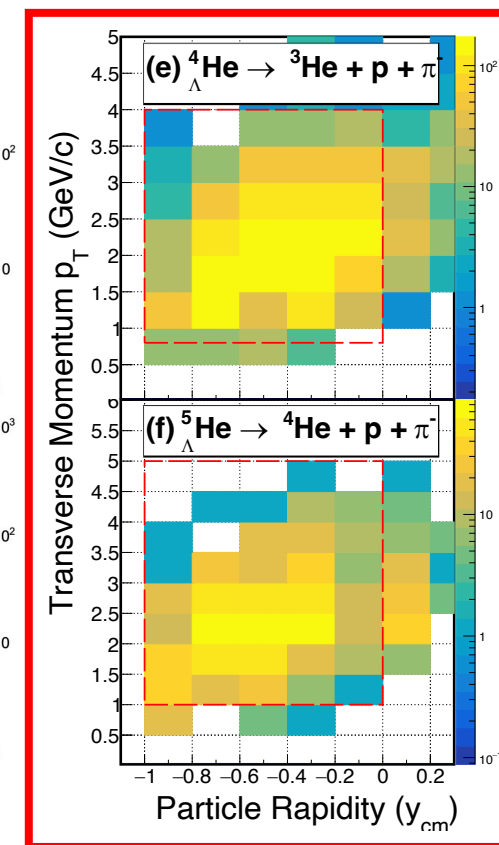
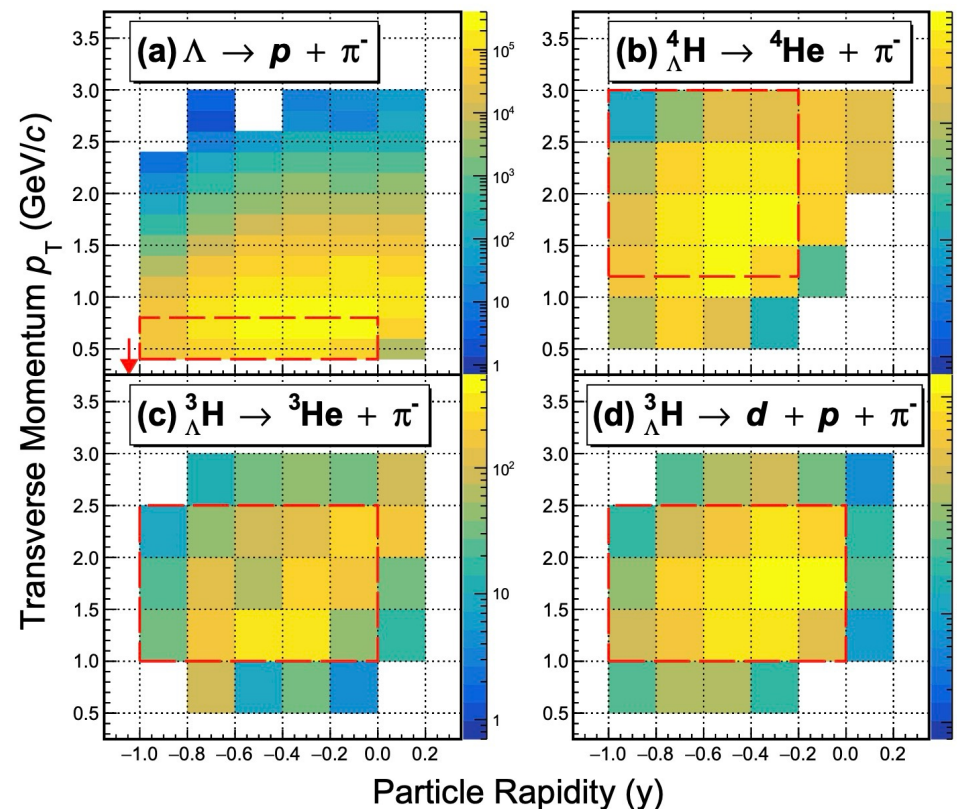
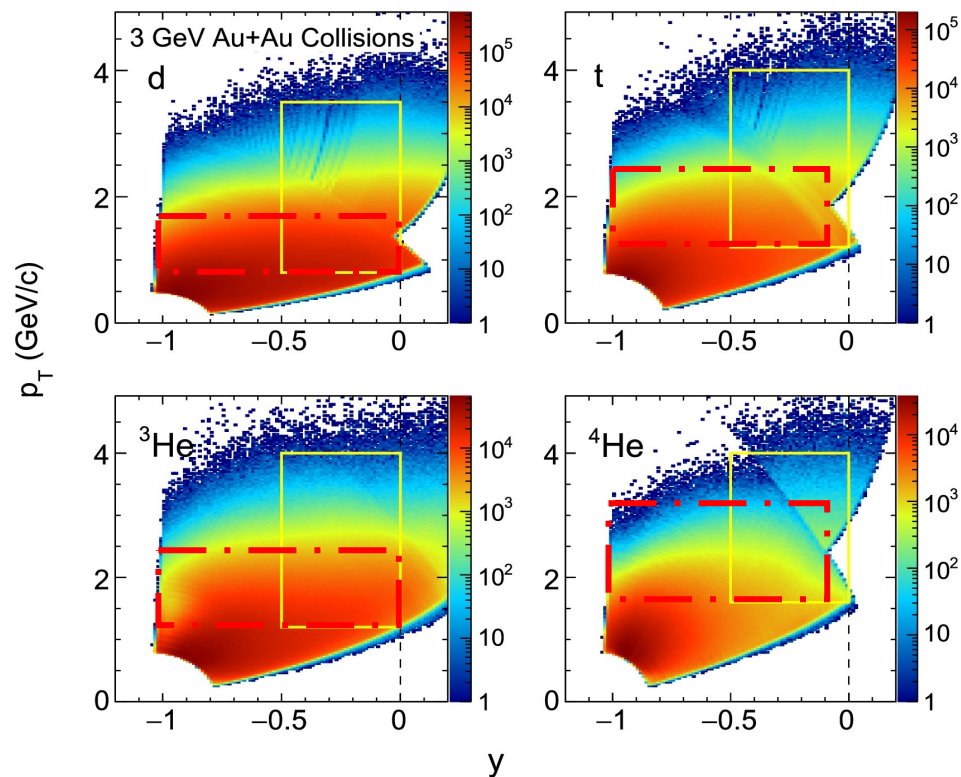
Run21

[1] Gorbunov and I. Kisel, Reconstruction of decayed particles based on the Kalman filter. CBM-SOFT-note-2007-003, 7 May 2007

[2] KF Particle Finder: M. Zyzak, Dissertation thesis, Goethe University of Frankfurt, 2016.

Light Nuclei and Hyper-Nuclei Acceptance

From Xionghong He's talk: 17:55 Mon.



❑ Signal yields are extracted using a bin counting method.

[1] Abdallah, M.S. *et al.*, Phys.Lett.B **827**, 136941, 2022.

[2] Aboona, Bassam *et al.*, Phys.Rev.Lett. **130**, 212301, 2023.

❑ The directed flow of light nuclei and hyper-nuclei is calculated within the p_T and y range, marked by red dashed boxes.

Directed Flow v_1 Extraction

Extract v_1 with **InvMass Method**:

- Calculate the mean azimuthal angle relative to the event plane, $\cos[n(\phi - \psi_m)]$, as a function of M_{inv}

$$v_n^{S+B}(M_{inv}) = \langle \cos[n(\phi - \psi_m)]_{inv} \rangle$$

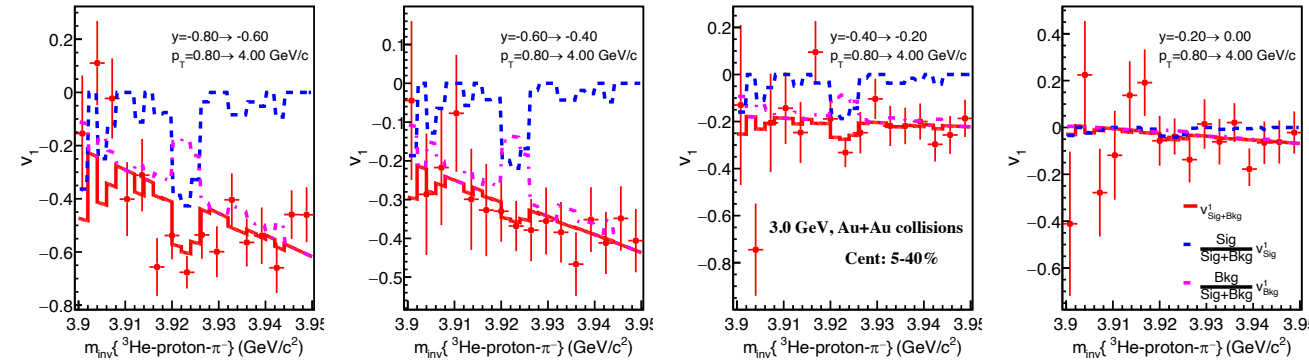
$$= v_n^S \frac{S}{S+B}(M_{inv}) + v_n^B(M_{inv}) \frac{B}{S+B}(M_{inv})$$

Here, S is the signal yield peaked at the M_{inv} of the particle, B is the background yield, v_n^S , v_n^B and v_n^{S+B} are the v_n for signal, background and the total particles, respectively.

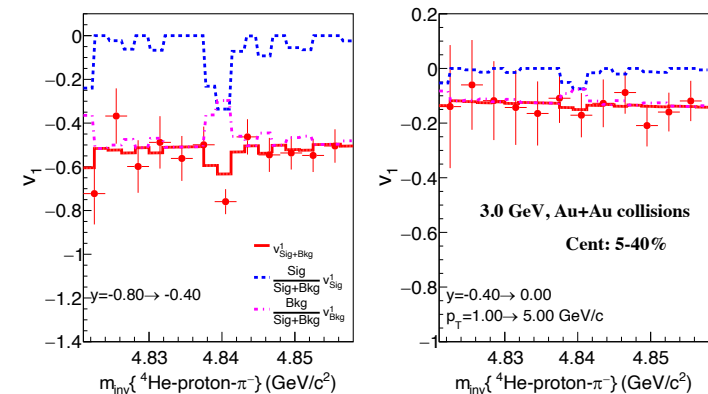
- v_n^B is parameterized as a first order polynomial $v_n^B = p_0 + p_1 M_{inv}$. v_n^S can be obtained as a free parameter of the fit.
- Add $1/R_n$ as a weight when filling the histograms of $\cos[n(\phi - \psi_m)]$ as a function of M_{inv} .

H. Masui et al., Nucl. Instrum. Methods Phys. Res. A **833**, 181 (2016)

${}^4_\Lambda\text{He}$

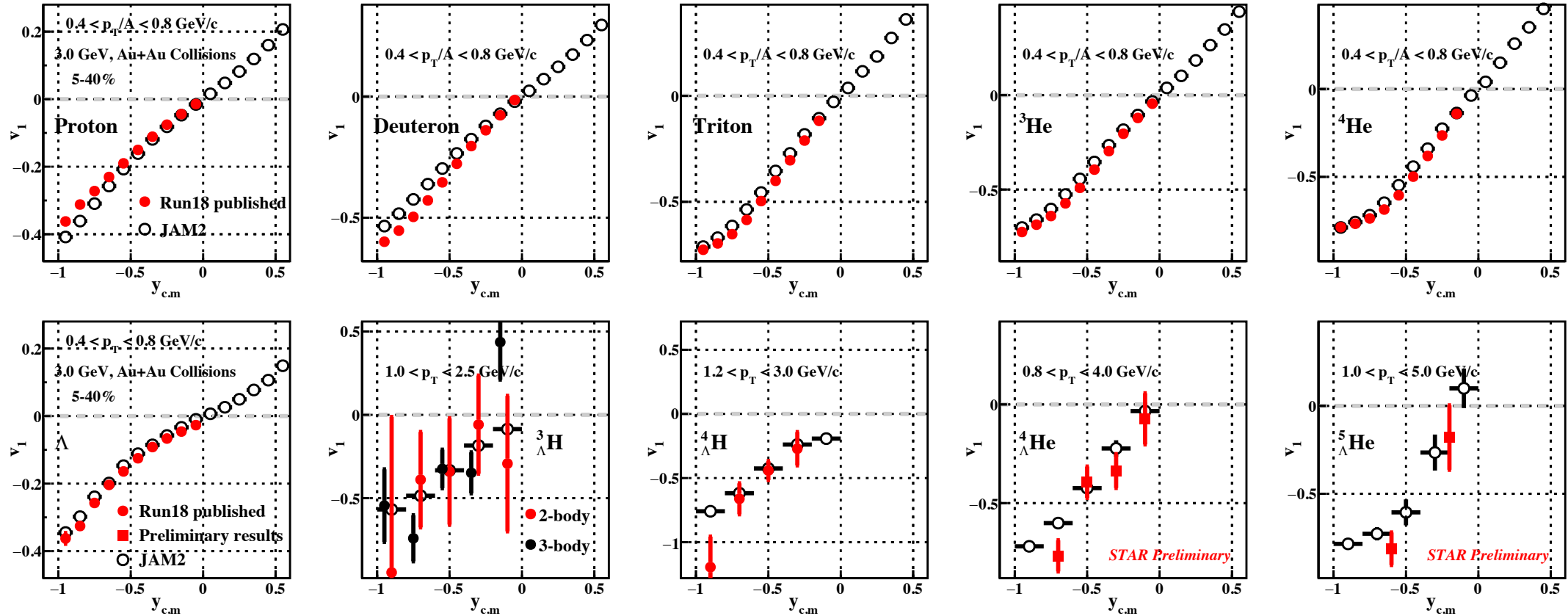


${}^5_\Lambda\text{He}$



Fitting function: $v_1 = p_0 * \frac{S}{S+B} + (p_1 + p_2 * M_{inv}) * \frac{B}{S+B}$

Light Nuclei and Hyper-Nuclei Directed Flow v_1



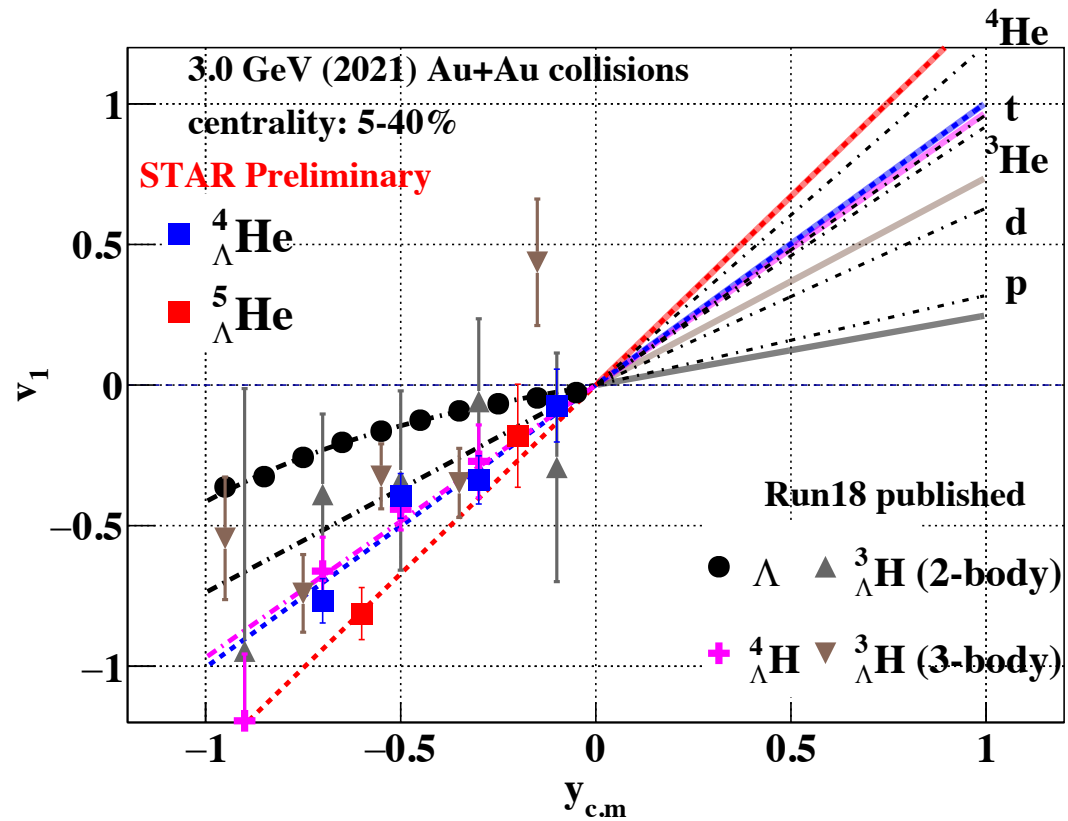
- Hadronic transport model (JAM2 mean field ($\kappa = 380$ MeV) + Coalescence) calculations describes the observed v_1 as a function of rapidity well for both light nuclei and hyper-nuclei.

[1] Abdallah, M.S. *et al.*, Phys.Lett.B **827**, 136941, 2022.

[2] Aboona, Bassam *et al.*, Phys.Rev.Lett. **130**, 212301, 2023.

[3] Y.Nara *et al.*, Phys.Rev.C **106**, 044902, 2022.

Particle Mass Dependence



- The v_1 slope is extracted by fitting the $v_1(y)$ distribution with a polynomial function, where p_0 corresponds to the v_1 slope at mid-rapidity ($dv_1/dy|_{y=0}$)

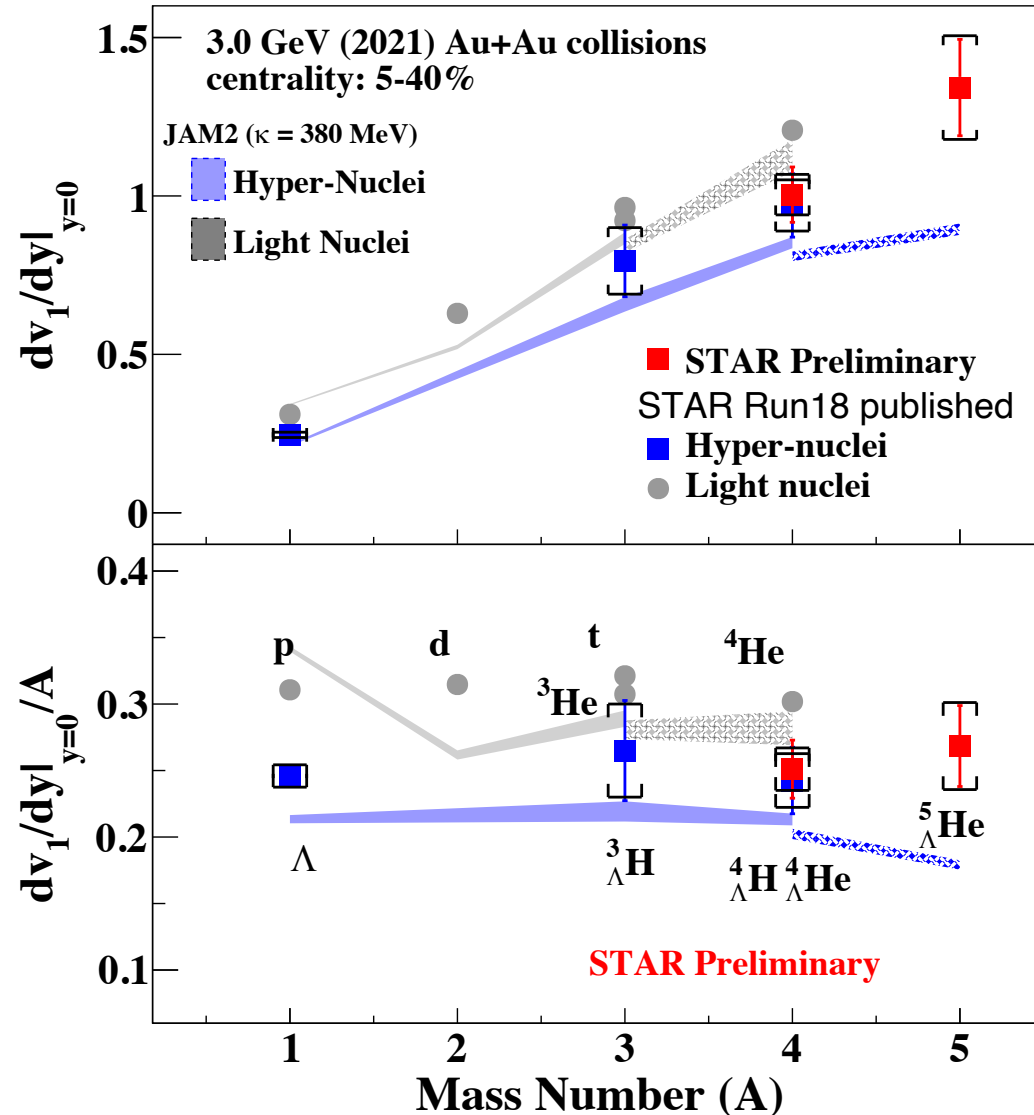
Hyper-Nuclei	Fitting Function
Λ	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$
${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{He}$, ${}^5_{\Lambda}\text{He}$	$v_1(y) = p_0 \cdot y$
Light-Nuclei	Fitting Function
p , d , t , ${}^3\text{He}$, ${}^4\text{He}$	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$

- In mid-central collisions, the directed flow (v_1) of both light nuclei and hyper-nuclei increases with rapidity, and its slope at mid-rapidity becomes larger with increasing mass number (A).
- This mass ordering reflects the collective motion of the constituent nucleons or hyperons, which is consistent with a coalescence picture.

[1] Abdallah, M.S. *et al.*, Phys.Lett.B **827**, 136941, 2022.

[2] Aboona, Bassam *et al.*, Phys.Rev.Lett. **130**, 212301, 2023.

Particle Mass Dependence



- The directed flow v_1 of light nuclei exhibits nucleon mass scaling, whereas that of hyper-nuclei is consistent with Λ hyperon mass scaling .
- The JAM2+coalescence model generally describes the experimental data.
- The JAM2 + coalescence model slightly underestimates the data.

- [1] Abdallah, M.S. *et al.*, Phys.Lett.B **827**, 136941, 2022.
 [2] Aboona, Bassam *et al.*, Phys.Rev.Lett. **130**, 212301, 2023.
 [3] Y.Nara *et al.*, Phys.Rev.C **106**, 044902, 2022.

Summary

- 1) Presented the directed flow (v_1) of light nuclei and hyper-nuclei in 3.0 GeV Au+Au collisions.
- 2) The v_1 of light and hyper-nuclei increases with mass number (A), indicating a clear mass ordering.
- 3) The JAM2 + coalescence model generally describes the experimental data, although it slightly underestimates the measurements.

Outlook:

- 1) Analyze v_1 of other hyper-nuclei (Λ , ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$) using the 2-billion-event dataset (Run21) in 3.0 GeV Au+Au collisions to achieve larger acceptance and improved precision.
- 2) Extract v_2 of hyper-nuclei from the 2-billion-event dataset in 3.0 GeV Au+Au collisions.

Thank you for your attention!