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Directed Flow of Hyper-Nuclei at High Baryon Density in STAR

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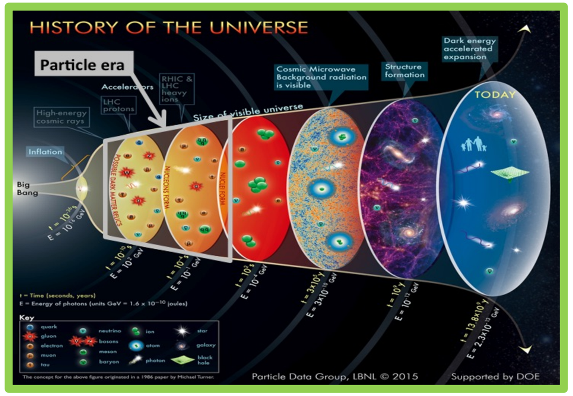
Outline

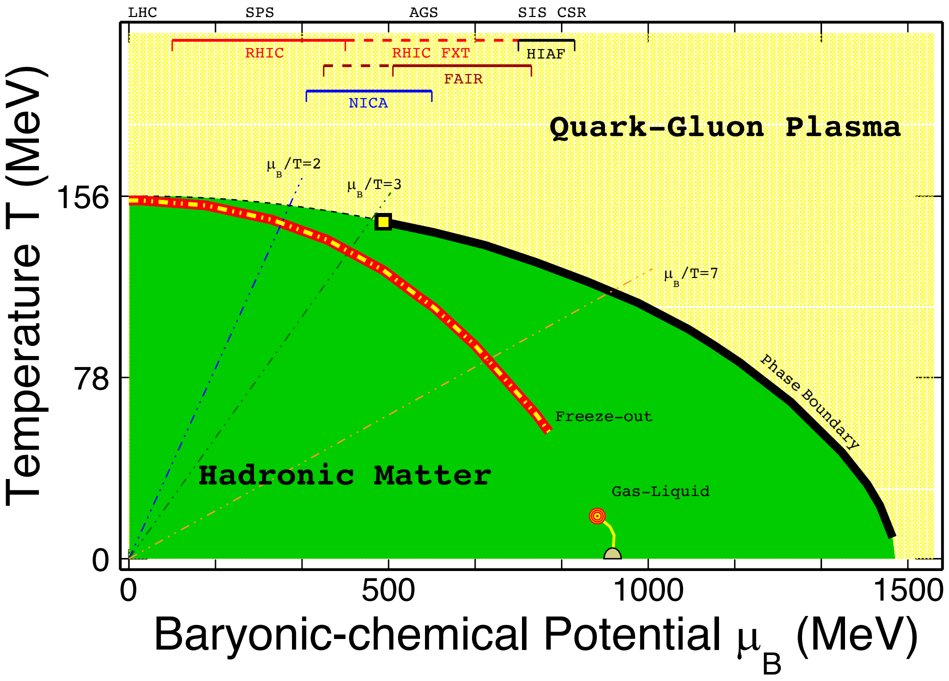
1. Motivation
2. Datasets and Particle Reconstruction
3. Hyper-Nuclei analysis in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2-4.5 GeV
   I. Directed Flow v_1
   II. Mass and Energy Dependence of v_1
4. Summary and Outlook

Heavy-Ion Collisions and QCD Phase Diagram



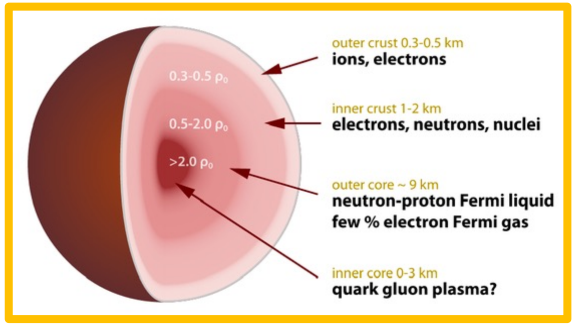
High temperature:
Early Universe evolution

LHC | RHIC BES | FAIR, NICA, …



Ref.: N. Xu @sQM2022

High baryon density:
Inner structure of
compact stars

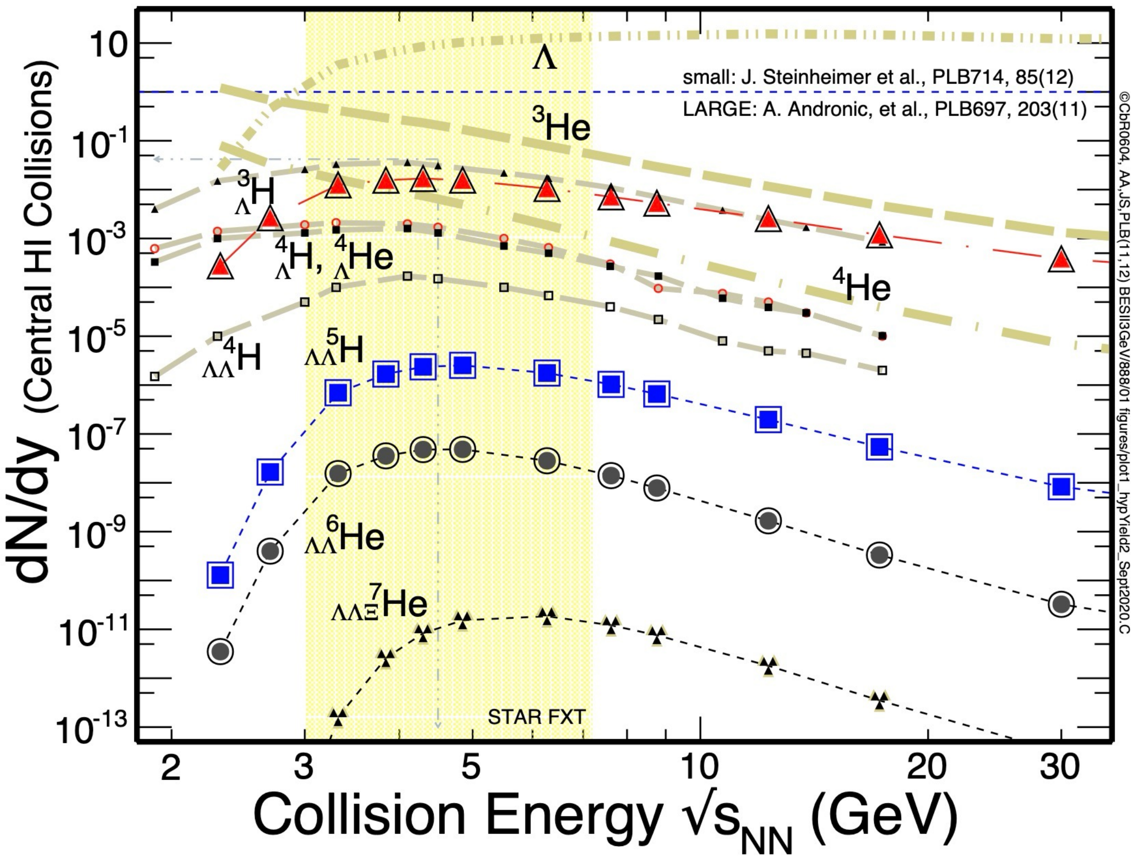


- At $\mu_B = 0$, smooth crossover (LGT + data)
- At large μ_B, may have 1st order phase transition → **QCD critical point**

- Hyperon Puzzle: difficult to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors
- Understanding hyperon-nucleon(Y-N) interaction in high density region is essential for solving the hyperon puzzle

Production of Light- and Hyper-Nuclei

Thermal model calculation results



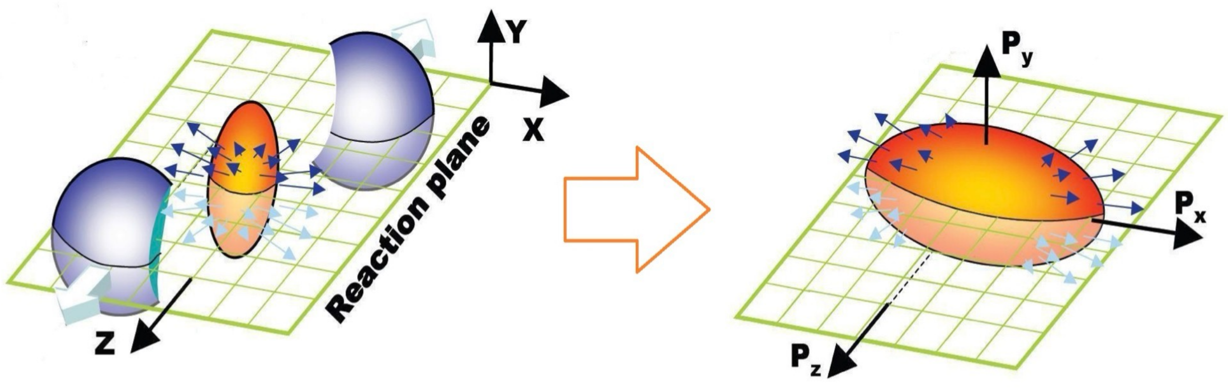
[1] A. Andronic et al, Phys. Lett. B697, 203(2011)

[2] J. Steinheimer et al. Phys. Lett. B714, 85(2012)

1) Light- and Hyper-Nuclei production are enhanced at high baryon density region
2) Light-Nuclei carry information about local baryon density fluctuations at freeze-out; offers insights on the Final State Interaction(FSI): N-N interation
3) Study Hyper-Nuclei properties provide important information about Y-N interation
4) Collective flow is sensitive to the equation of state of nuclear matter -> help explore Hyper-Nuclei production mechanism and hyperon interactions in the medium

Collective Flow

Heavy ion collisions: Initial spatial anisotropy
➡ Pressure gradient ➡ Anisotropic flow



$v_1 = \langle p_x / p_T \rangle$

$v_2 = \langle (p_x^2 - p_y^2)/p_T^2 \rangle$

- The particle azimuthal distribution measured with respect to the reaction plane can be expanded in Fourier series:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \psi_{RP}))\right)$$

Directed flow: $v_1 = < \cos(\phi - \psi) >$

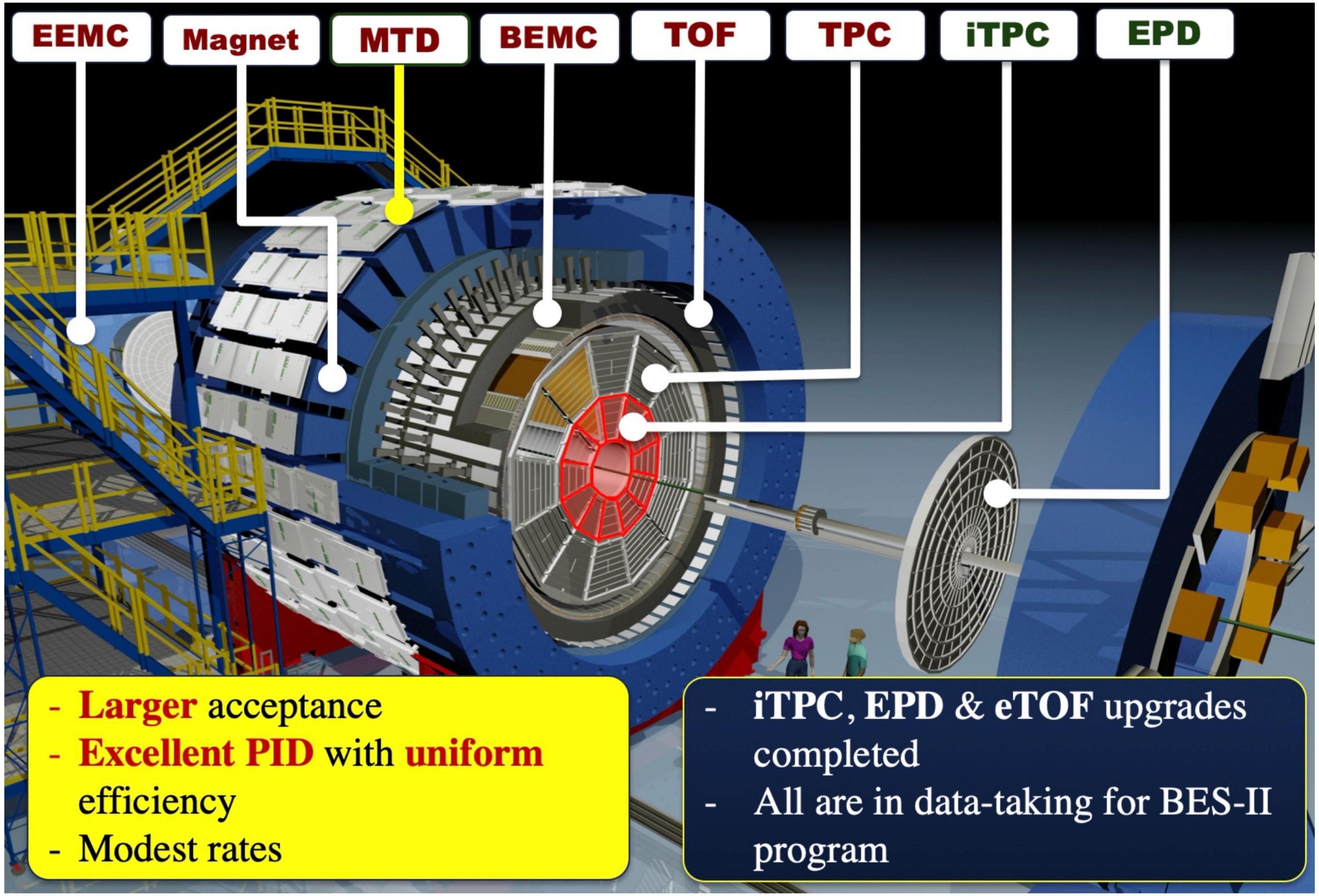
Elliptic flow: $v_2 = < \cos(2(\phi - \psi)) >$

……

- In heavy ion collisions, particles show collective motion due to pressure gradients within the dense nuclear matter
- Directed flow considered as a sensitive probe of the equation of state of the dense matter

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

STAR Detector



Time Projection Chamber (TPC)

- ❑ Momentum reconstruction
- ❑ Particle tracking and Identification
- ❑ Pseudorapidity coverage $-2.0 < \eta < 0$ (for fixed target)

barrel Time-of-Flight (bTOF)

- ❑ Particle Identification
- ❑ Pseudorapidity coverage $-1.5 < \eta < 0$ (for fixed target)

end-cap Time-of-Flight (eTOF)

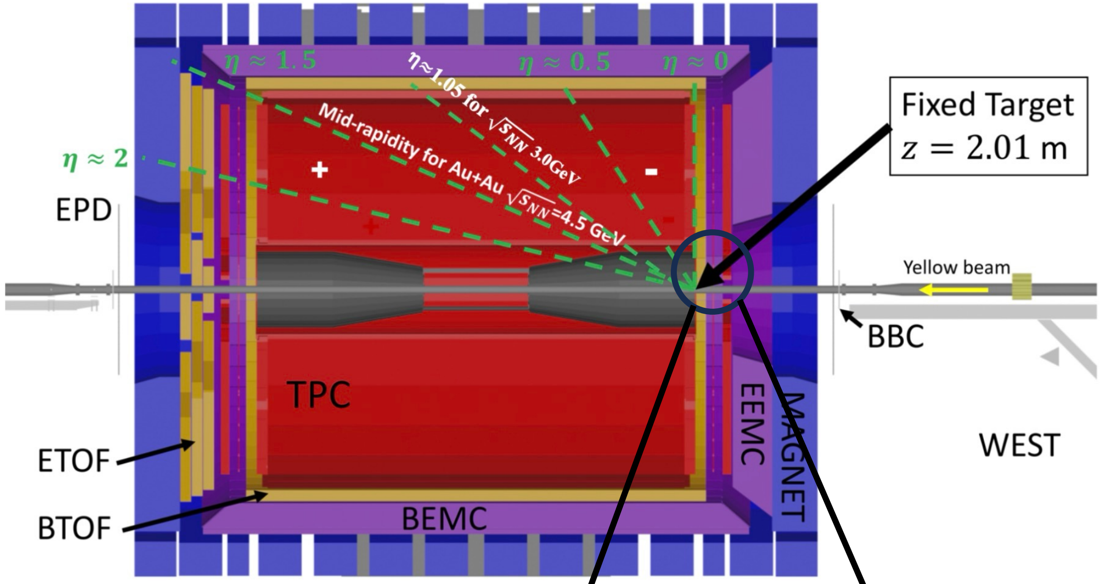
- ❑ Particle Identification
- ❑ Pseudorapidity coverage $-2.2 < \eta < -1.5$ (for fixed target)

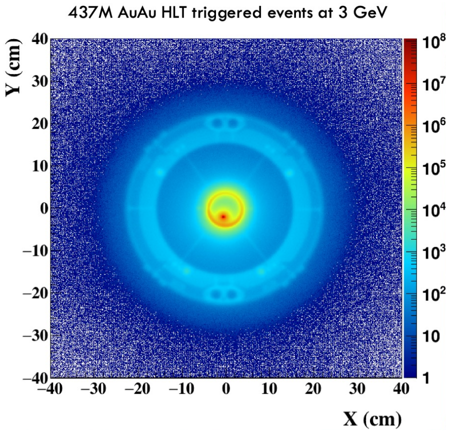
Event Plane Detector (EPD)

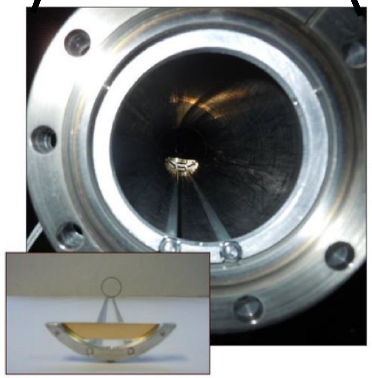
- ❑ Event plan reconstruction
- ❑ Pseudorapidity coverage $-5.3 < \eta < -2.6$ (for fixed target)

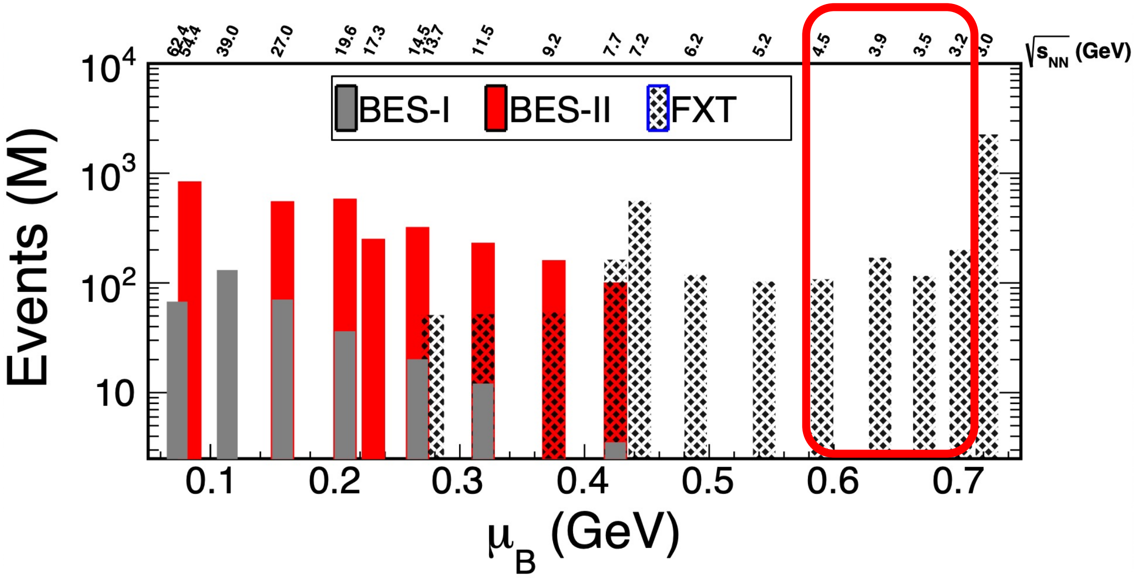
STAR BES-II

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









- STAR BES-II
  - ❑ 10× statistics compared to BES-I
  - ❑ FXT energy extends down to 3 GeV
  - ❑ This analysis: $\sqrt{s_{NN}}$ = 3.2 → 4.5 GeV (eTOF is not used in this analysis)

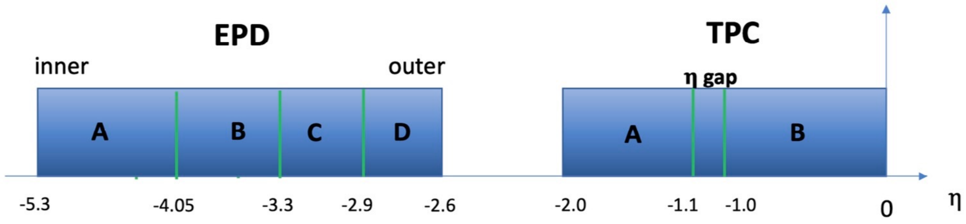
Dataset and Event Plane Reconstruction

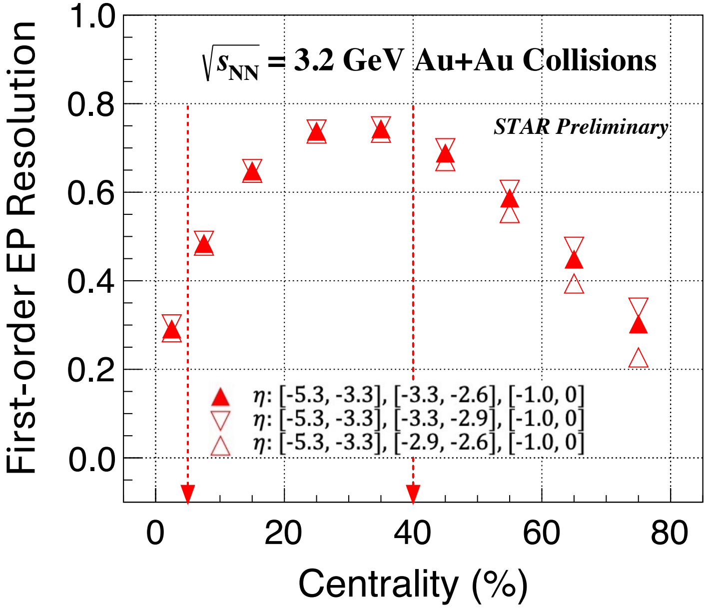
DataSet	$\sqrt{s_{NN}}$ = 3.2 GeV (2019) (y_{target} = -1.14)	3.5 GeV (2020) (y_{target} = -1.25)	3.9 GeV (2020) (y_{target} = -1.37)	4.5 GeV (2020) (y_{target} = -1.52)
Analyzed Events	~200M	~110M	~120M	~120M

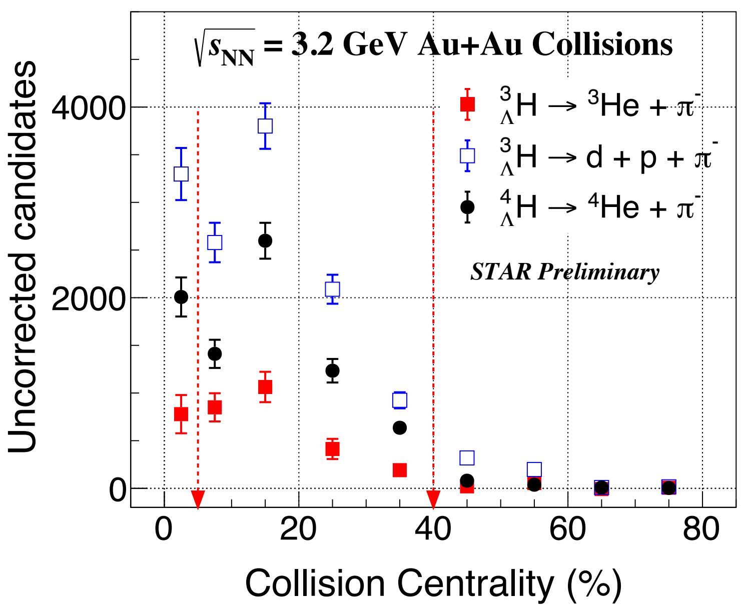
❖ Event Plane reconstruction

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

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



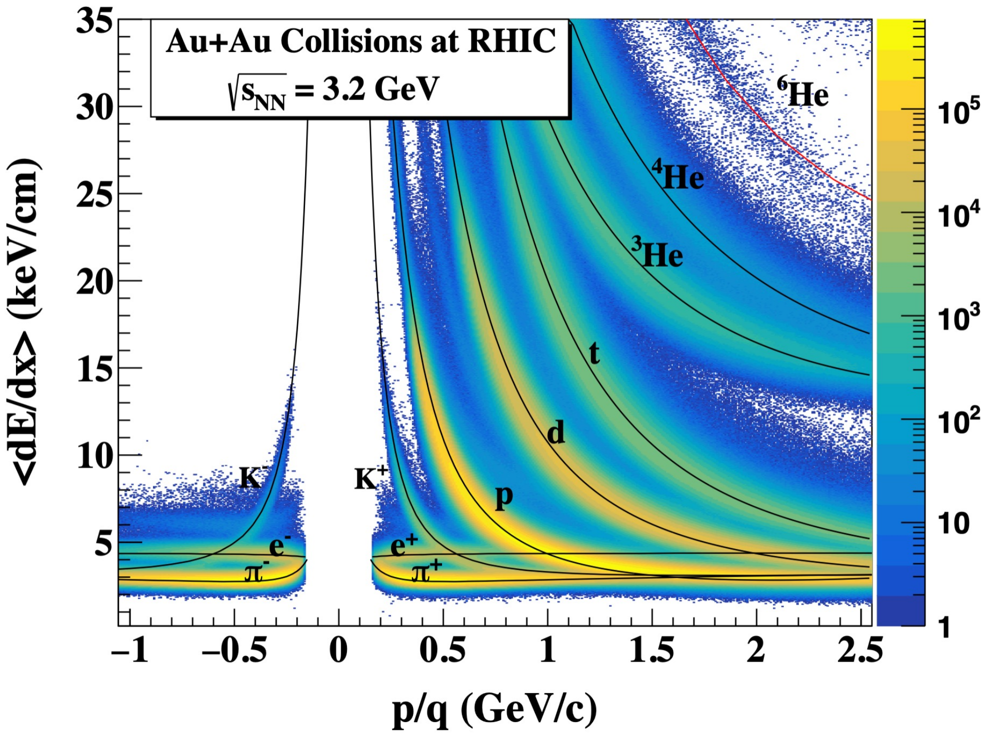


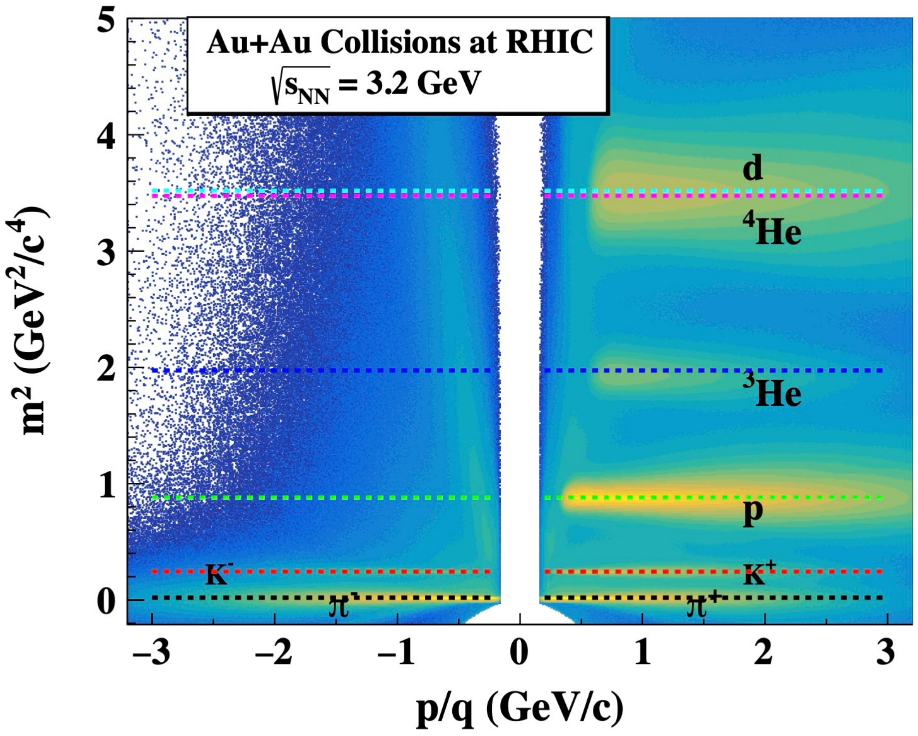


➢ 5-40% centrality bin used in this analysis

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

Particle Identification



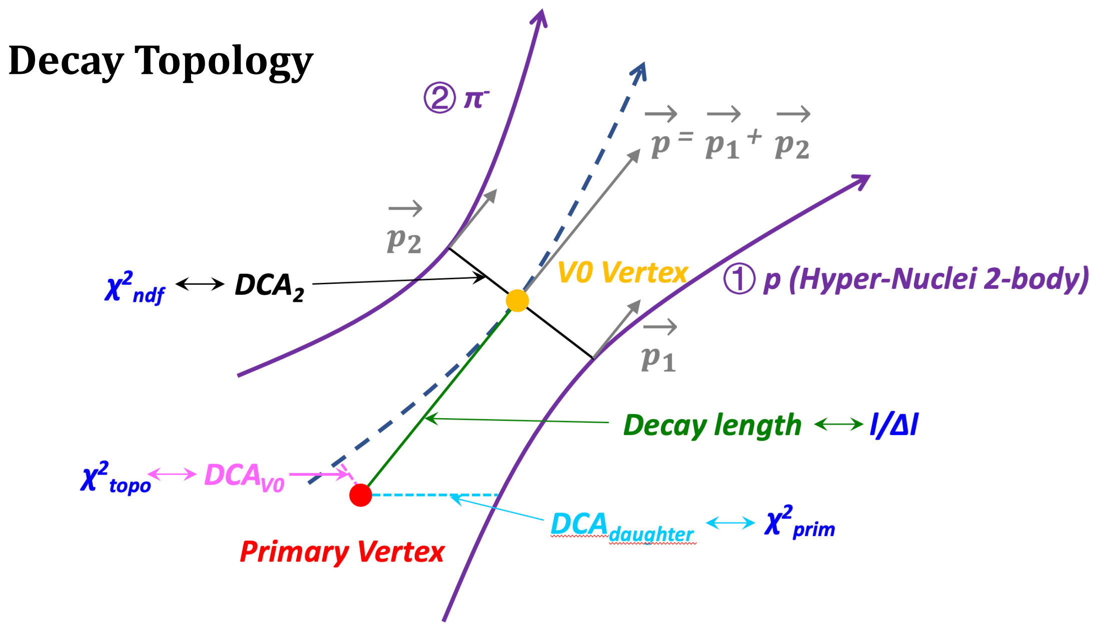


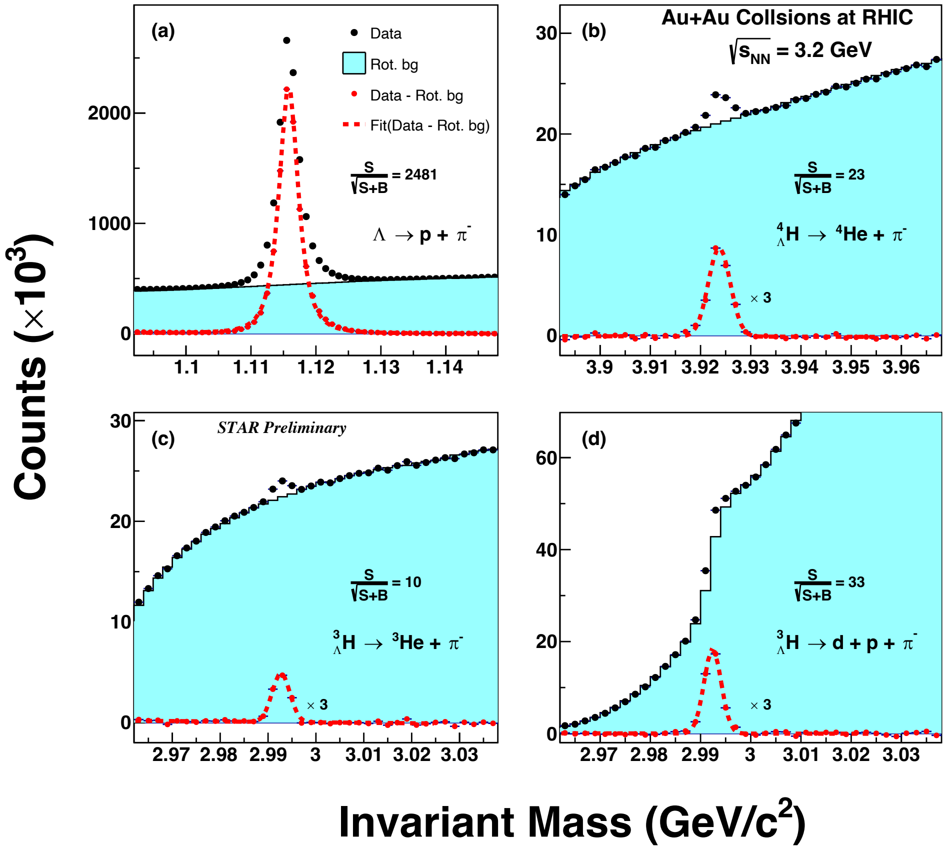
➢ Good particle identification capability based on TPC and TOF

1) π^{-}, ^{3}He and ^{4}He PID: only TPC

2) proton and deuteron PID: TPC (+bTOF for high momentum daughter track of ${}^{3}_{\Lambda}$H when $\sqrt{s_{NN}}$ = 3.9 GeV and above)

Hyper-Nuclei Reconstruction



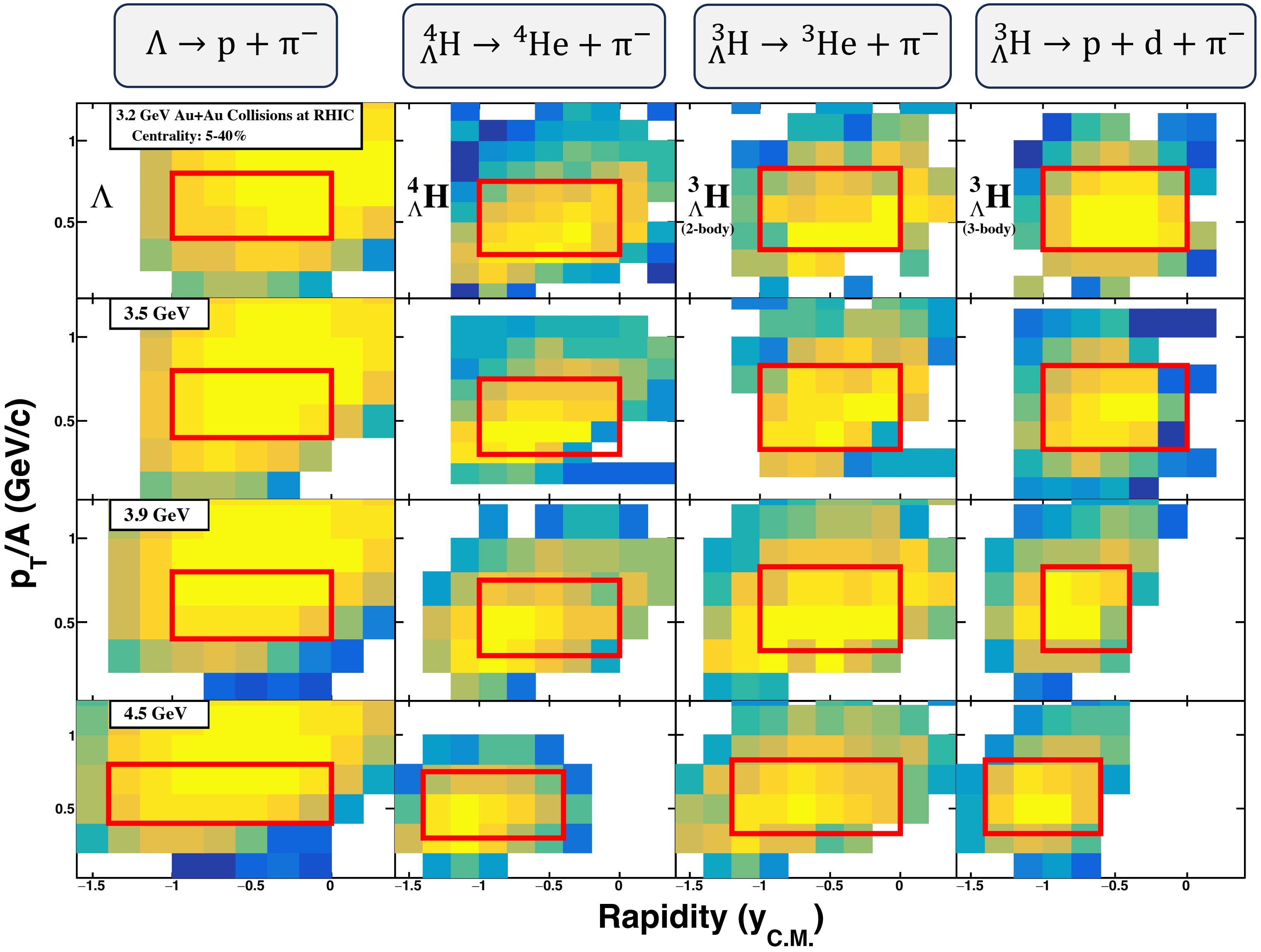


[1] Gorbunov and I. Kisel, Reconstruction of decayed particles based on the Kalman filter. CBM-SOFT-note-2007-003, 7 May 2007

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

- Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ are reconstructed with KFParticle package based on Kalman filter method to improve signal significance
- Obvious hyper-nuclei signals can be observed with the reconstructed invariant mass distributions

Hyper-Nuclei Acceptance



$0.4 \lesssim p_T/A \lesssim 0.8$ GeV/c

- Bin counting method used to extract signal counts
- Collective flow of hyper-nuclei are calculated within the selected p_T/A range as indicated by the boxes

Directed Flow v_1 Extraction

Extract v_1 with Event Plane Method:

- Extract signal N^R(weighted by the inverse of EP resolution of each centrality bin) in a given $(\phi - \psi_1)$ bin

$$N^R(\phi - \psi_1) = \int dM \frac{1}{R_n} \frac{dN}{d(\phi - \psi_1)}$$

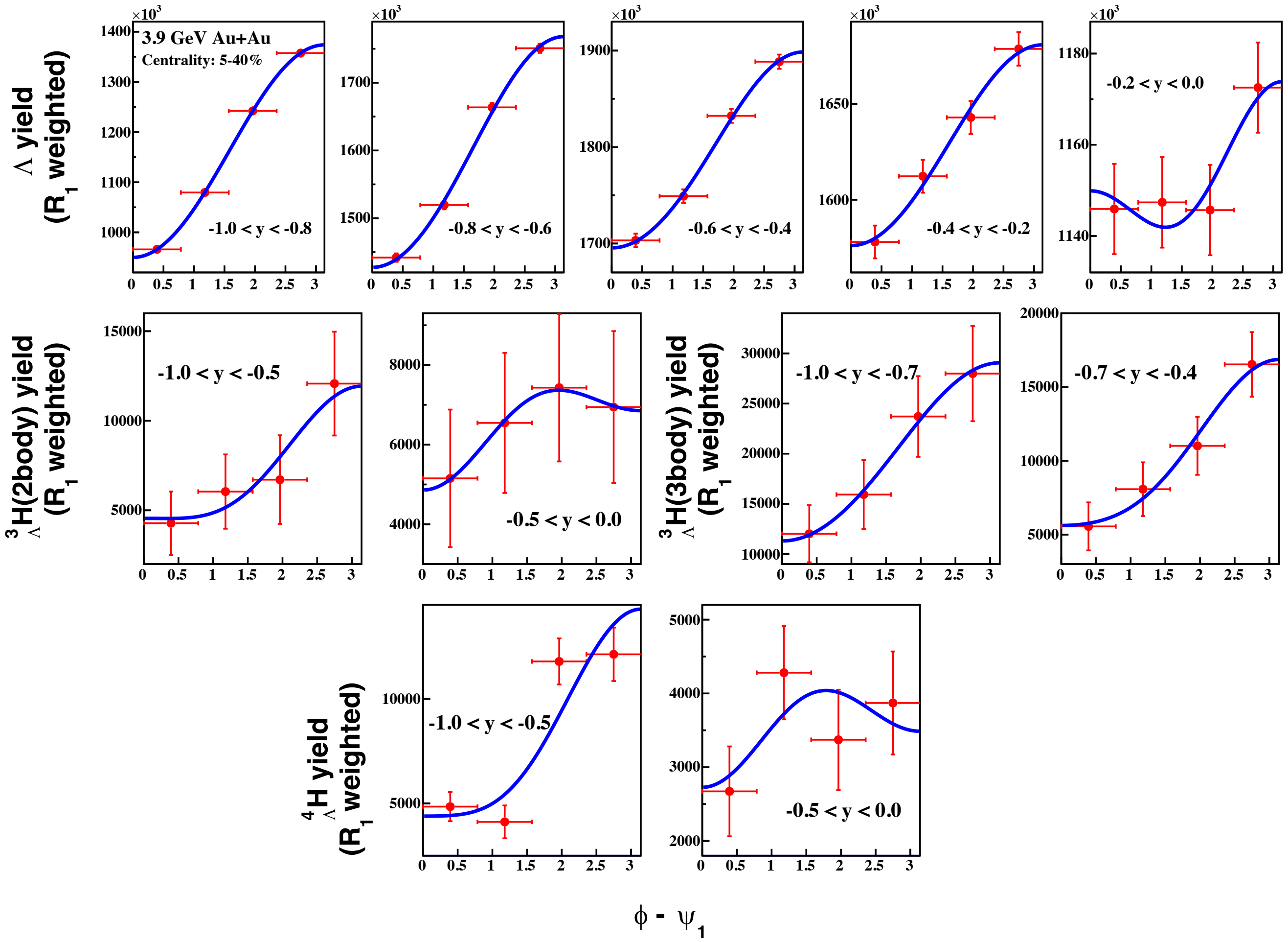
- Fit the N^R in different rapidity to extract $< v_1^{obs} >$, then $< v_1 >$ is corrected by the average EP resolution.

$$< v_1 > = < v_1^{obs,R} > < \frac{1}{R_1} >$$

- The average of resolution in wide centrality bin is determined from equation below, it is weighted by particle multiplicity.

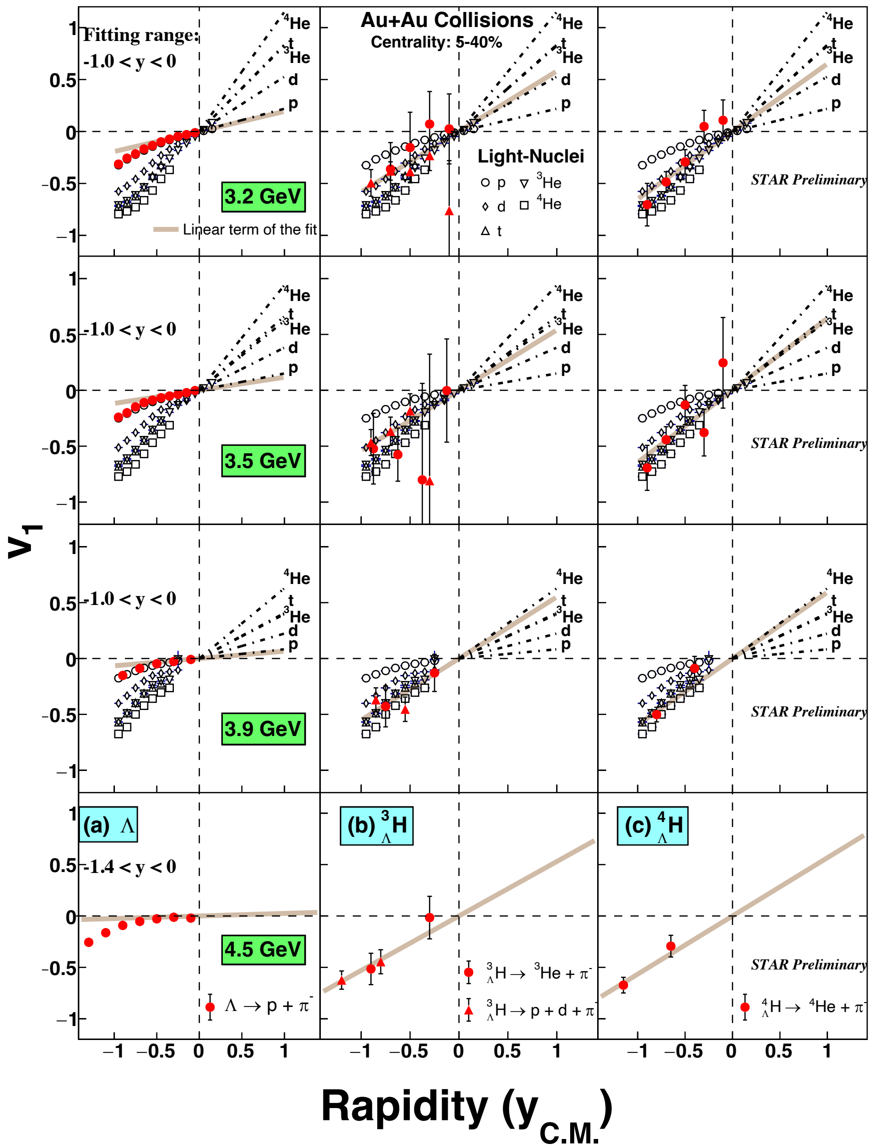
$$< \frac{1}{R_1} > = \frac{\Sigma_i^R \frac{1}{R_1(i)} \times N_0(i)}{\Sigma_i^R N_0(i)}$$

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



Fitting function: $y = p_0\left(1 + 2p_1\cos(\phi - \psi_1) + 2p_2\cos\left(2(\phi - \psi_1)\right)\right)$

Directed Flow v_1

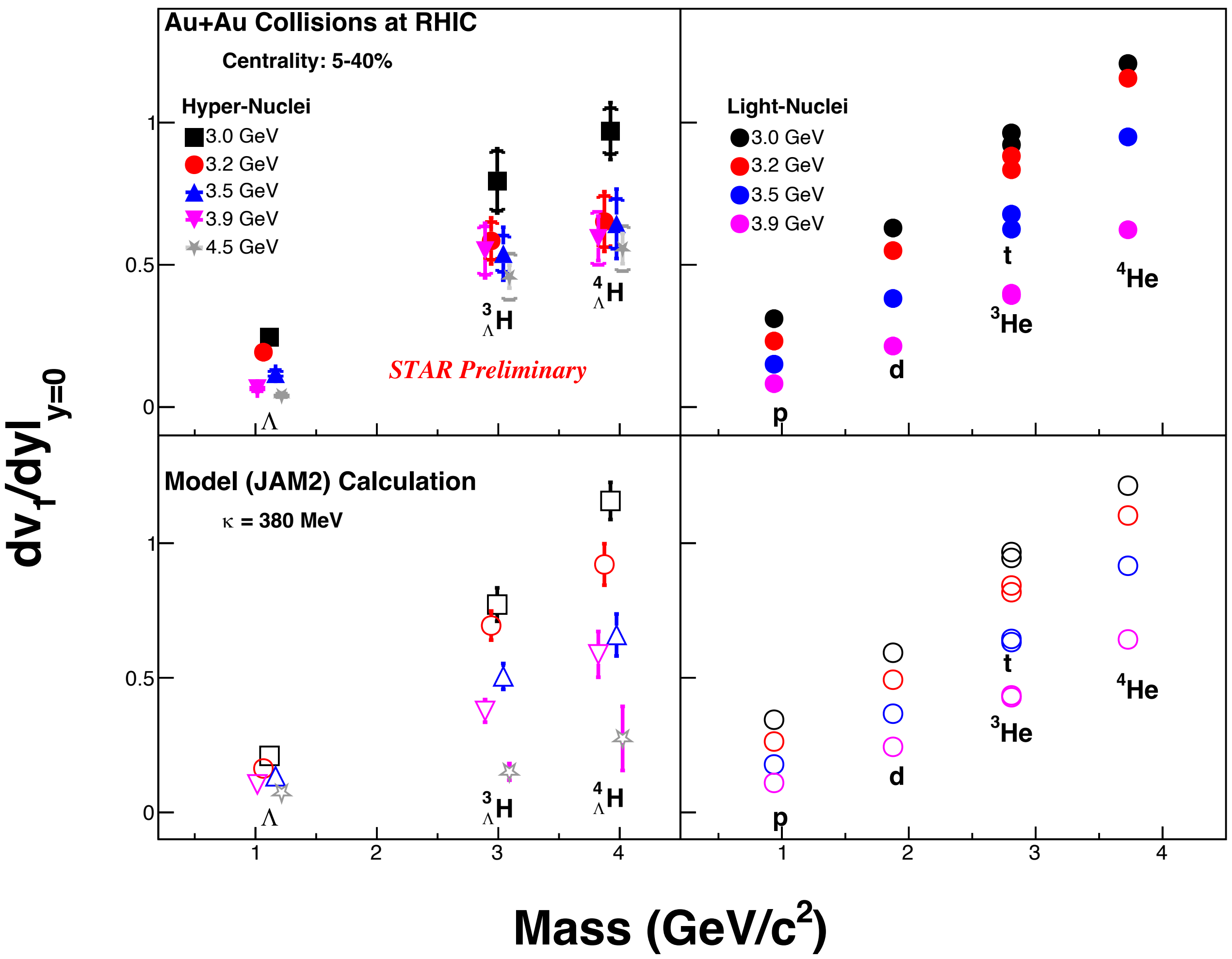


- The v_1 slope is obtained by fitting the $v_1(y)$ distribution with a polynomial function, where p_0 is the mid-rapidity v_1 slope ($dv_1/dy|_{y=0}$)

Hyper-Nuclei	Fitting Function	p_T / A
Λ	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$	(0.4, 0.8)
$^3_\Lambda H$	$v_1(y) = p_0 \cdot y$	(0.33, 0.83)
$^4_\Lambda H$	$v_1(y) = p_0 \cdot y$	(0.30, 0.75)

Light-Nuclei	Fitting Function	p_T / A
p	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$	(0.4, 0.8)
d	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$	(0.4, 0.8)
t	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$	(0.4, 0.8)
^{3}He	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$	(0.4, 0.8)
^{4}He	$v_1(y) = p_0 \cdot y + p_1 \cdot y^3$	(0.4, 0.8)

Particle Mass Dependence



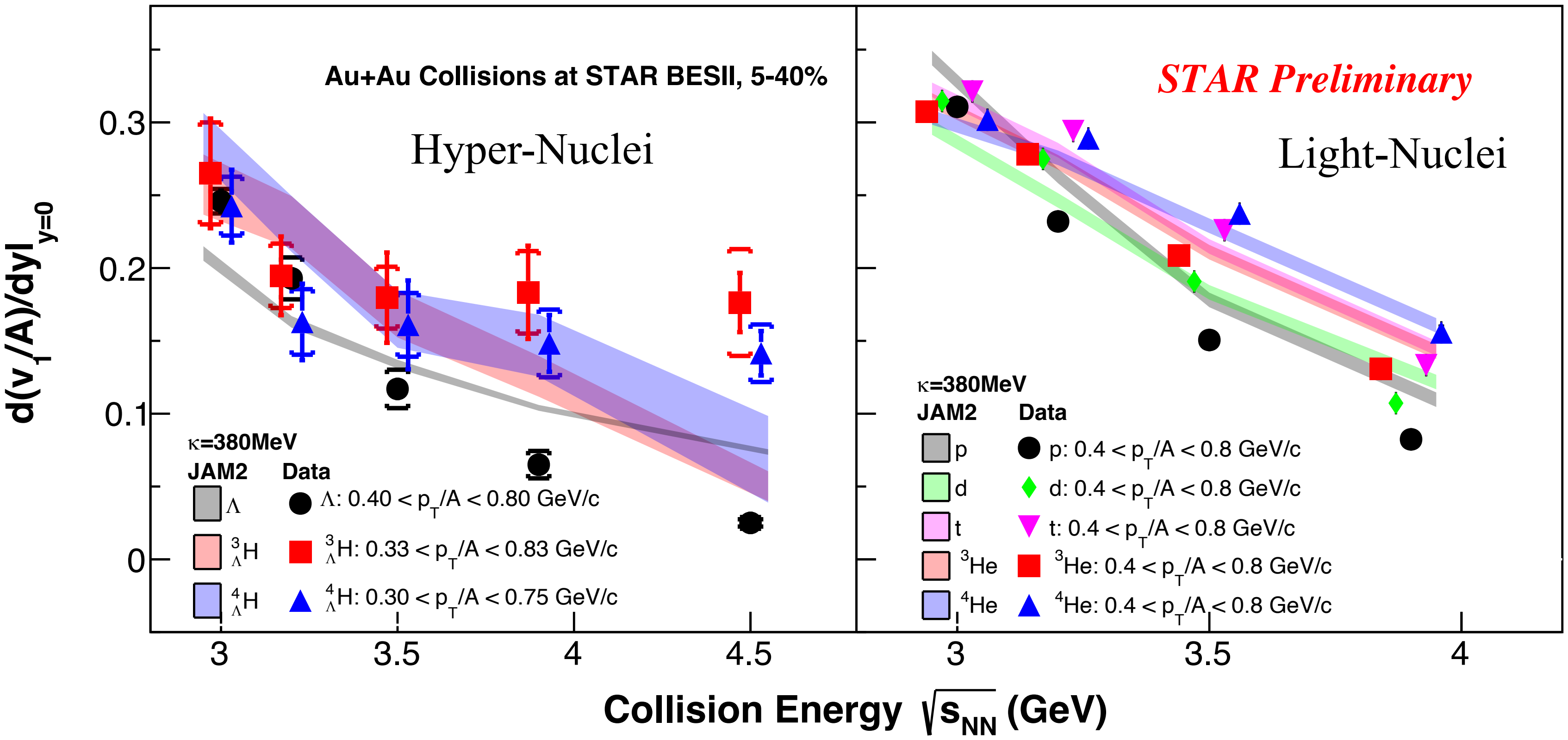
[1] M.S. Abdallah et al., (STAR Collaboration), Phys. Lett. B 827, 136941 (2022)
[2] B. E. Aboona et al., (STAR Collaboration), Phys. Rev. Lett. 130, 212301(2023)
[3] Y. Nara et al., Phys. Rev. C 106, 044902 (2022)

- Systematic uncertainties for v_1 slope:

Major source	${}^{3}_{\Lambda}H$	${}^{4}_{\Lambda}H$	light-nuclei
EP resolution	4 %	4 %	4 %
Efficiency	2 %	2 %	2 %
Topological cuts / PID cuts	12 %	11 %	5 %
Total	13 %	12 %	6 %

- At given energy, for both light- and hyper-nuclei, it seems that the slopes of mid-rapidity v_1 are scaled with atomic mass number A or/and particle mass
- Hadronic transport model (JAM2 mean field κ = 380 MeV, potential with momentum dependence) plus coalescence calculations show similar mass dependence

Collision Energy Dependence



1) As the collision energy increases, the v_1 slope of light- and hyper-nuclei decreases, but trend of hyper-nuclei is rather independent from 3.5 to 4.5 GeV
2) Hadronic transport model (JAM2 mean field + Coalescence) calculations are consistent with observed energy dependence

Summary

1) Hyper-nuclei directed flow v_1 are compared to light-nuclei for $\sqrt{s_{NN}}$ = 3.2 - 4.5 GeV in STAR (at high baryon density)

2) Hadronic transport model (JAM2 mean field + Coalescence) calculations for v_1 are consistent with observed mass and energy dependence

3) Particle mass and collision energy dependence of v_1 slope for light- and hyper-nuclei indicates coalescence mechanism dominates the production

Outlook:

1) STAR has collected 2 billion events for 3 GeV Au+Au collisions which will help us to constrain coalescence parameters for both light- and hyper-nuclei

2) eTOF data will help us to extend the acceptance for v_1 analysis

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Thank you for your attention!