



Light- and Hyper-Nuclei Collectivity in Au+Au Collisions at RHIC-STAR

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(for the STAR Collaboration)

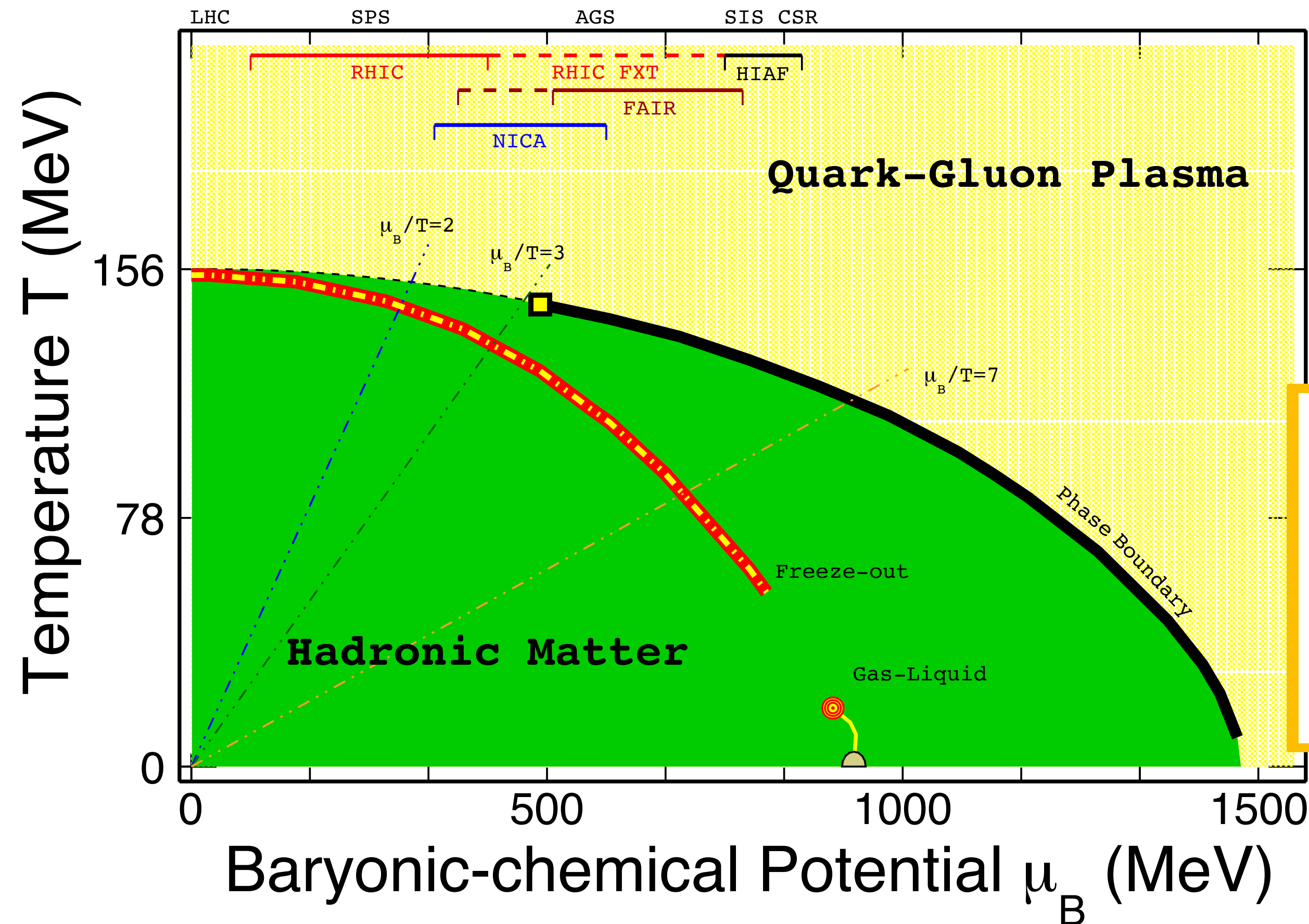
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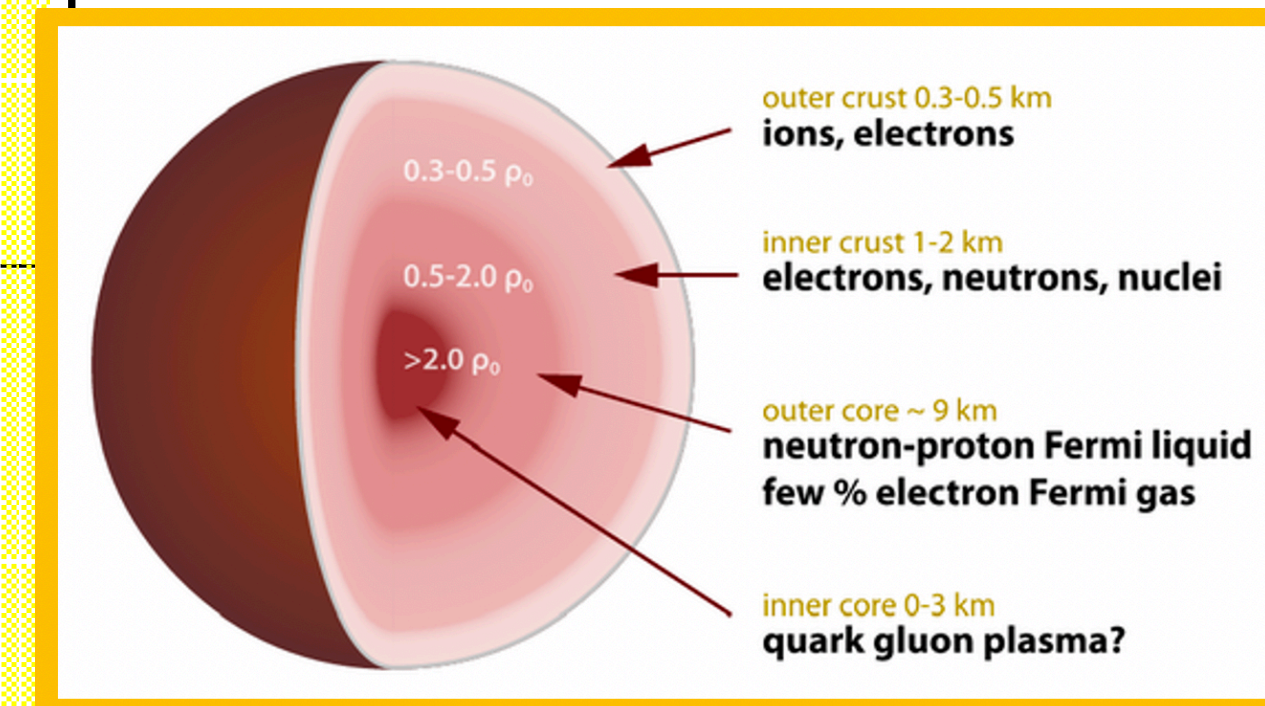
Outline

1. Introduction
2. Dataset and Particle Reconstruction
3. Light- and Hyper-Nuclei Collectivity
 - i. Light- and Hyper-Nuclei Directed Flow v_1
 - ii. Mass and Energy Dependence of v_1
 - iii. Light-Nuclei Elliptic Flow v_2
4. Summary and Outlook

High-Energy Nuclear Collisions and QCD Phase Diagram

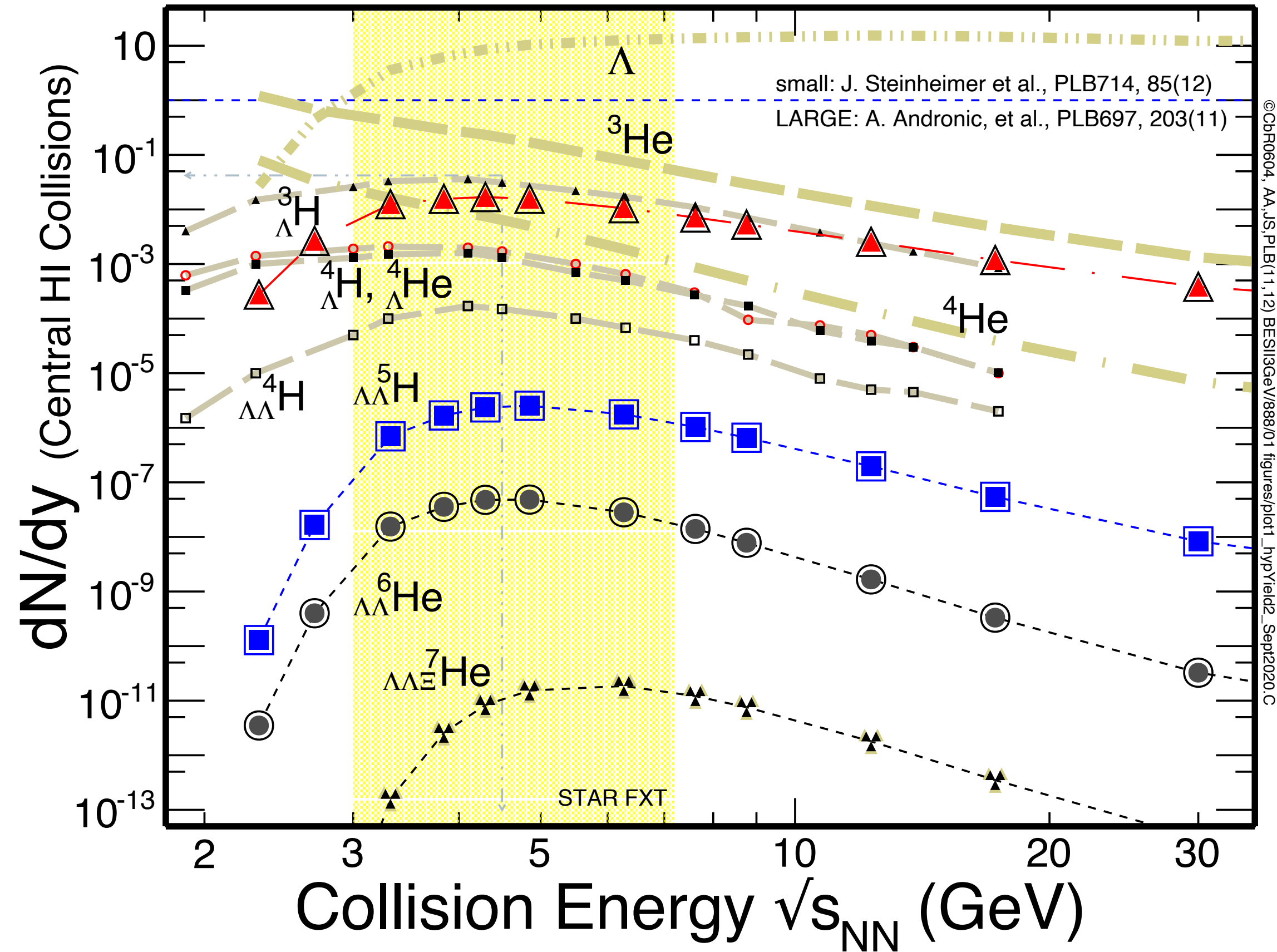


Hyperon Puzzle: difficulty to reconcile the measured masses of neutron stars with the presence of the hyperons in their interiors



- 1) RHIC beam energy scan \rightarrow search for 1st-order phase transition and QCD critical point
- 2) Baryon-baryon interaction (e.g. N-N, Y-N) \rightarrow inner structure of compact stars

Light- and Hyper-nuclei Productions



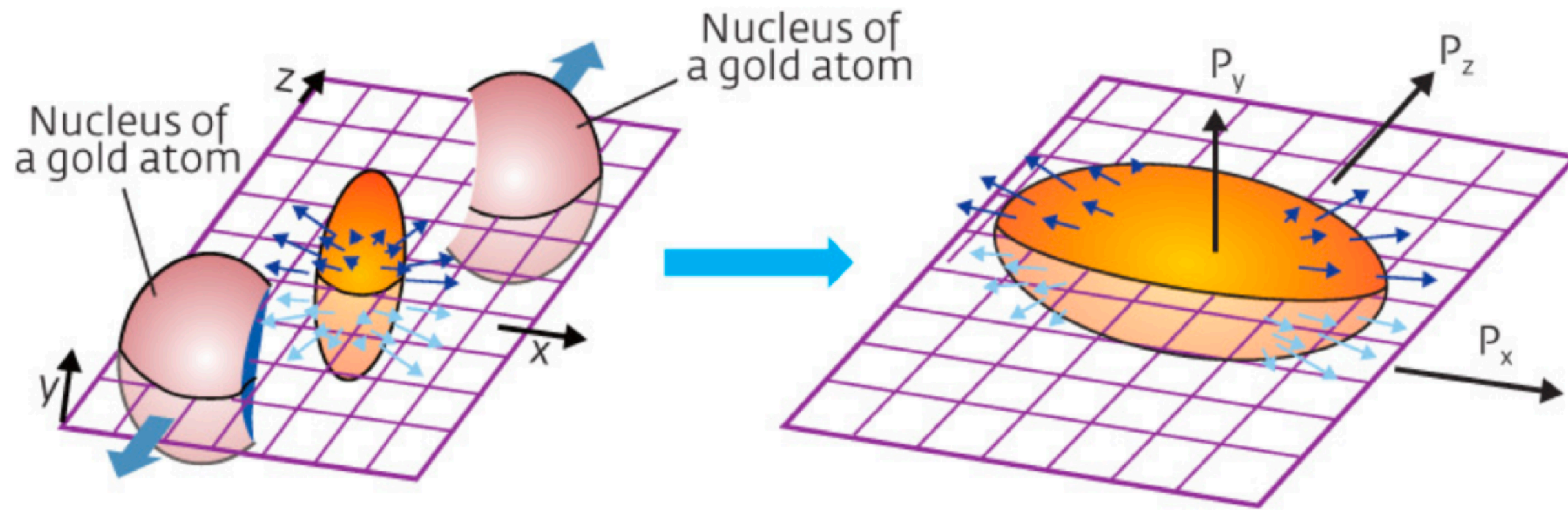
- 1) Light- and Hyper-Nuclei are abundantly produced at high baryon density region
- 2) Light-Nuclei carry information about local baryon density fluctuations at freeze-out; offers insights on the Final State Interaction (FSI): N-N
- 3) Hyper-Nuclei provide access to the hyperon-nucleon interaction: Y-N
- 4) Furthermore, collective flow is sensitive to the Equation-of-State of nuclear matter

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

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

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 initial pressure gradient of the collision system is directly related to the magnitude of v_n , which is a sensitive observable for studying EoS

■ Collective Flow analysis

► The n^{th} order coefficient of the fourier expansion of the azimuthal distribution in the momentum space

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi p_T dp_T dy} \left(1 + \sum_1^{\infty} 2v_n \cos [n (\phi - \psi_{RP})] \right)$$

— v_1 Directed flow

— v_2 Elliptic flow

■ Analysis steps with event plane method

1) Signal extraction for a given $\phi - \Psi_n$ bin:

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

2) Fit $dN/d(\phi - \Psi_n)$ distribution in rapidity bins to extract observed flow coefficients v_n^R

3) Correct v_n^R with signal number weighted EP resolution $\langle \frac{1}{R_n} \rangle$:

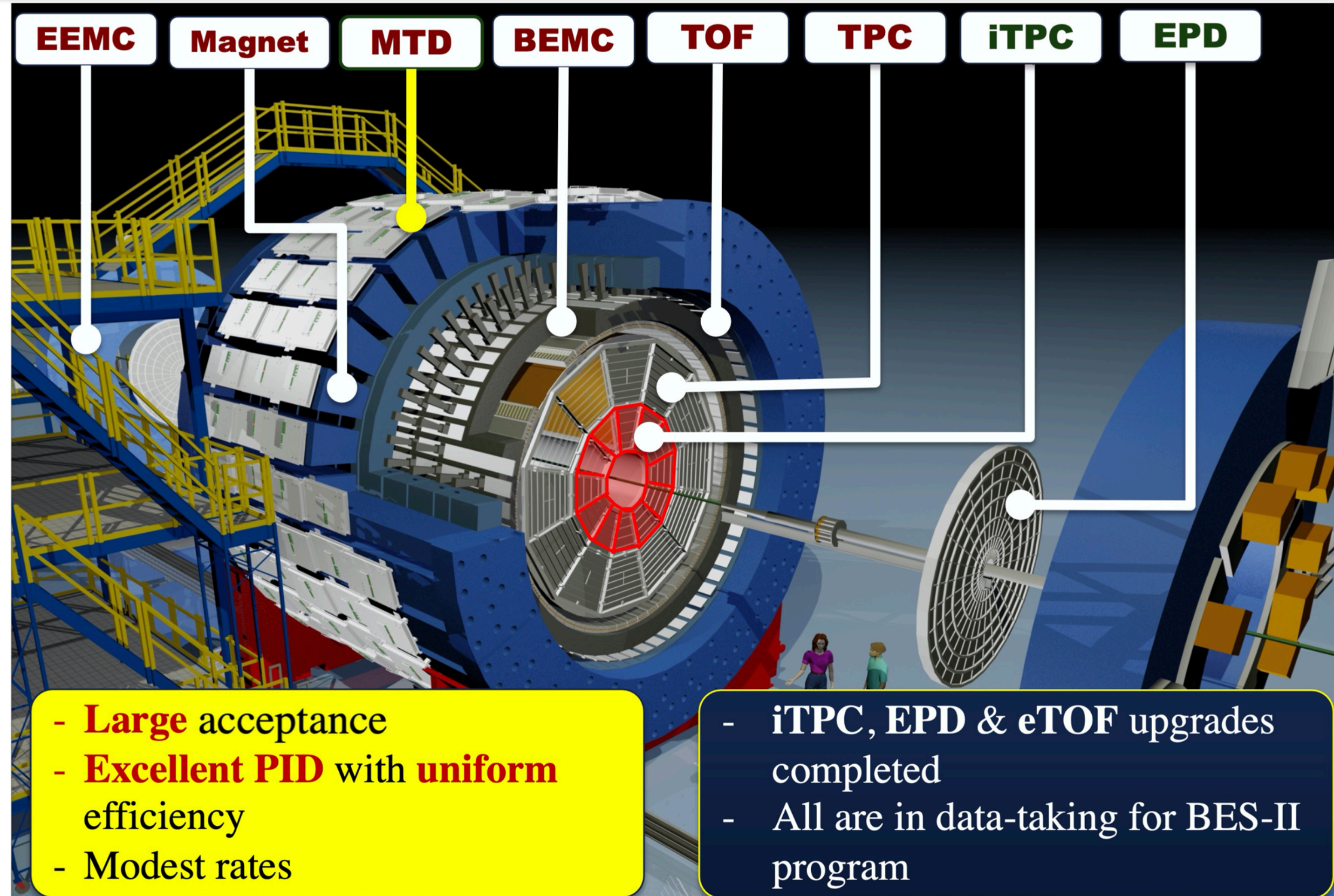
$$\langle v_n \rangle = \langle v_n^R \rangle \langle \frac{1}{R_n} \rangle$$

$$\langle \frac{1}{R_n} \rangle = \frac{\sum_i N_i^* \langle \frac{1}{R_n} \rangle}{\sum_i N_i}$$

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

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

STAR Detector System



- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

- 1) Enlarged rapidity acceptance
- 2) Improved particle identification
- 3) Enhanced event plane resolution

Major Upgrades in BES-II:

iTPC:

- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

eTOF:

- Forward rapidity coverage
- PID at $\eta = -1.1$ to -1.6
- Ready in 2019

EPD:

- Improves trigger
- Event plane measurements
- Ready in 2018

[1] iTPC: <https://drupal.star.bnl.gov/STAR/starnotes/.public/sn0619>.

[2] eTOF: STAR and CBM eTOF group, arXiv: 1609.05102.

[3] EPD: J. Adams, et al. NIM A**968**, 163970 (2020)

Dataset and Event Plane Reconstruction

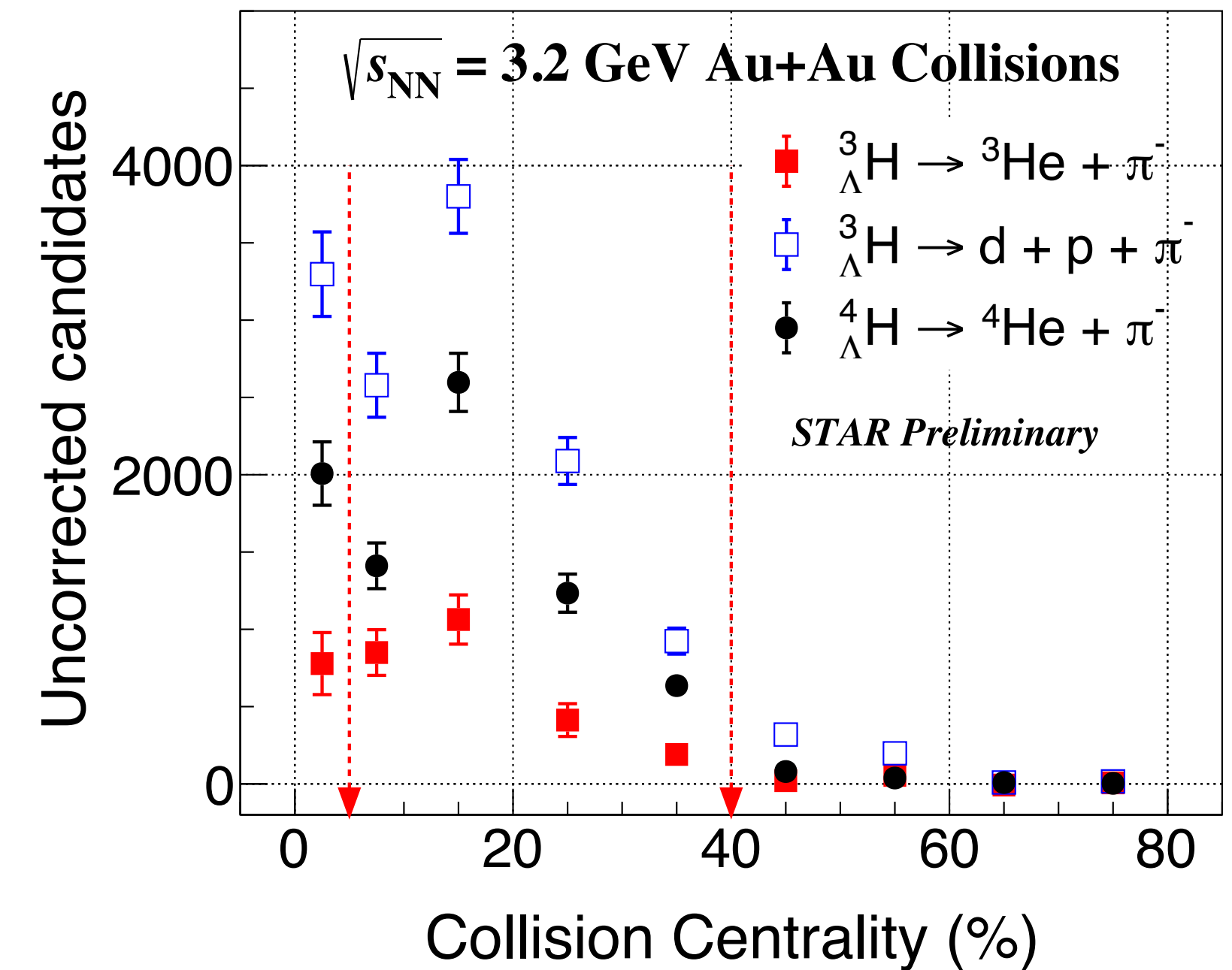
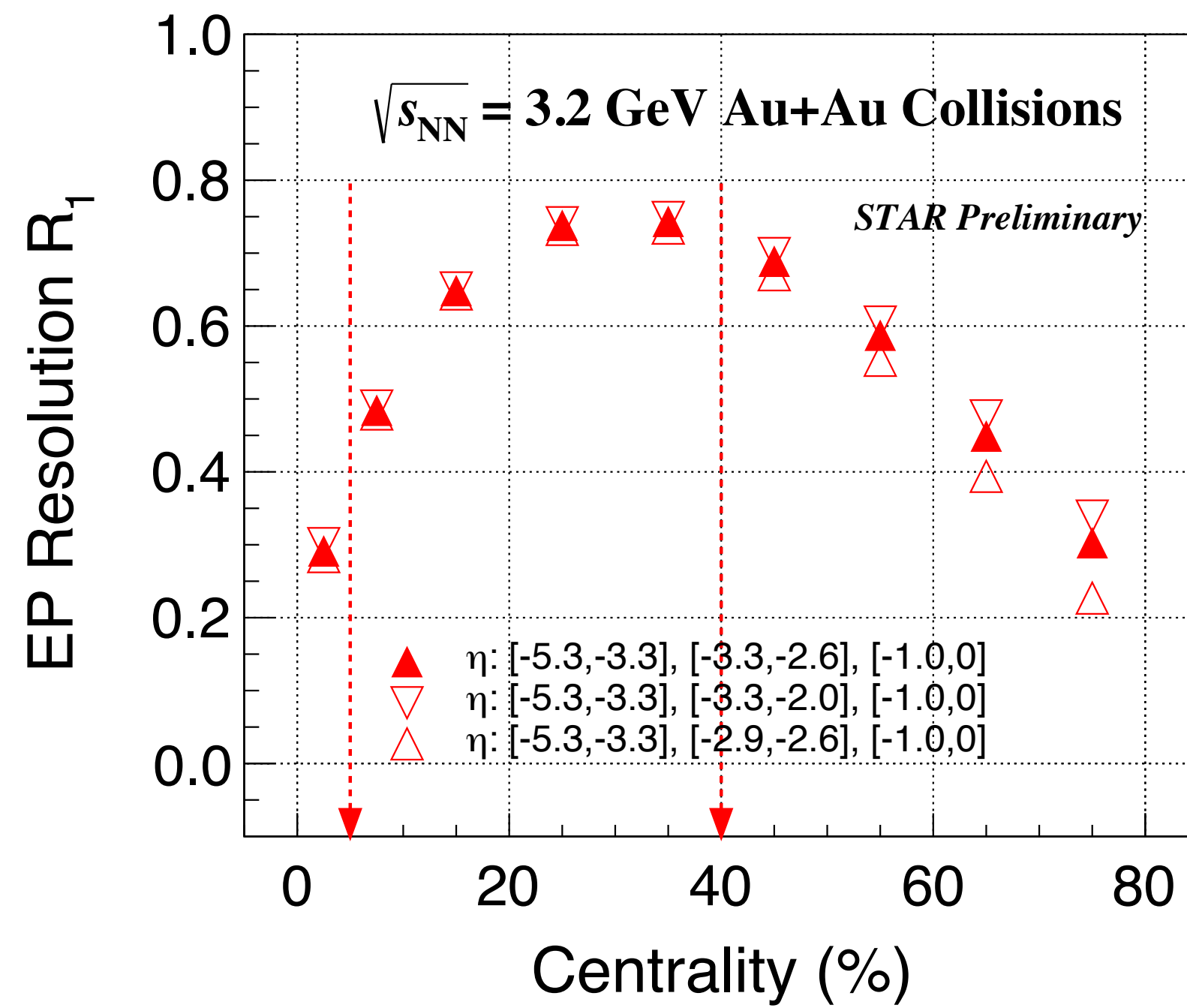
DataSet	$\sqrt{s_{NN}} = 3.0 \text{ GeV (2018)}$ ($y_{\text{target}} = -1.04$)	3.2 GeV (2019) ($y_{\text{target}} = -1.14$)	3.5 GeV (2020) ($y_{\text{target}} = -1.25$)	3.9 GeV (2020) ($y_{\text{target}} = -1.37$)
Events	~260 M	~200 M	~110 M	~120 M

Event plane reconstruction

- EP reconstruction: Q vector method
- Re-center and shift calibration
- EP resolution: three sub-events method

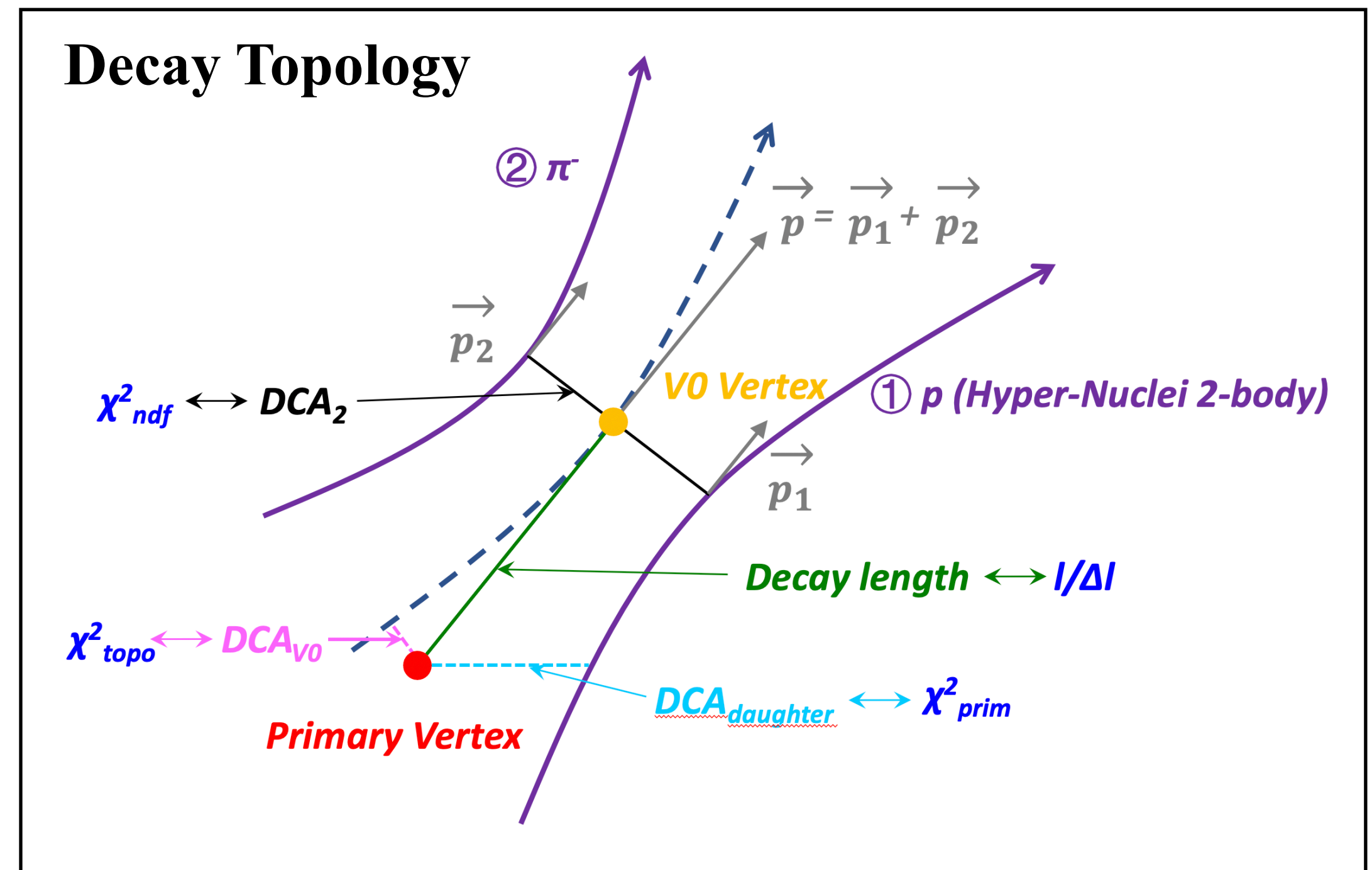
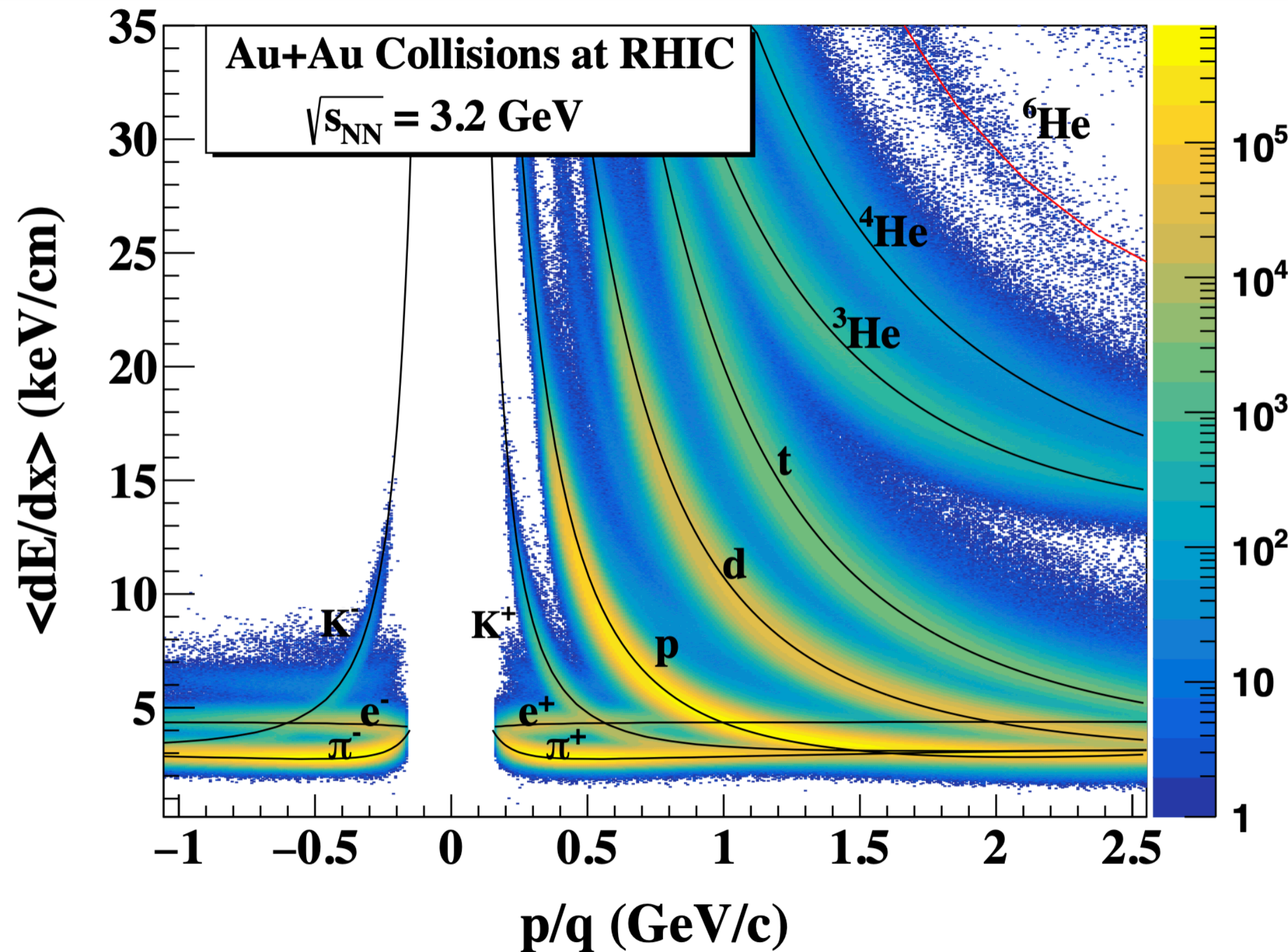
The EP resolution is determined as:

$$\langle \cos(\Psi_1^a - \Psi_r) \rangle = \sqrt{\frac{\langle \cos(\Psi_1^a - \Psi_1^b) \rangle \langle \cos(\Psi_1^a - \Psi_1^c) \rangle}{\langle \cos(\Psi_1^b - \Psi_1^c) \rangle}}$$



► 5-40% centrality bin used in this analysis

Particle Identification and Topological Selection

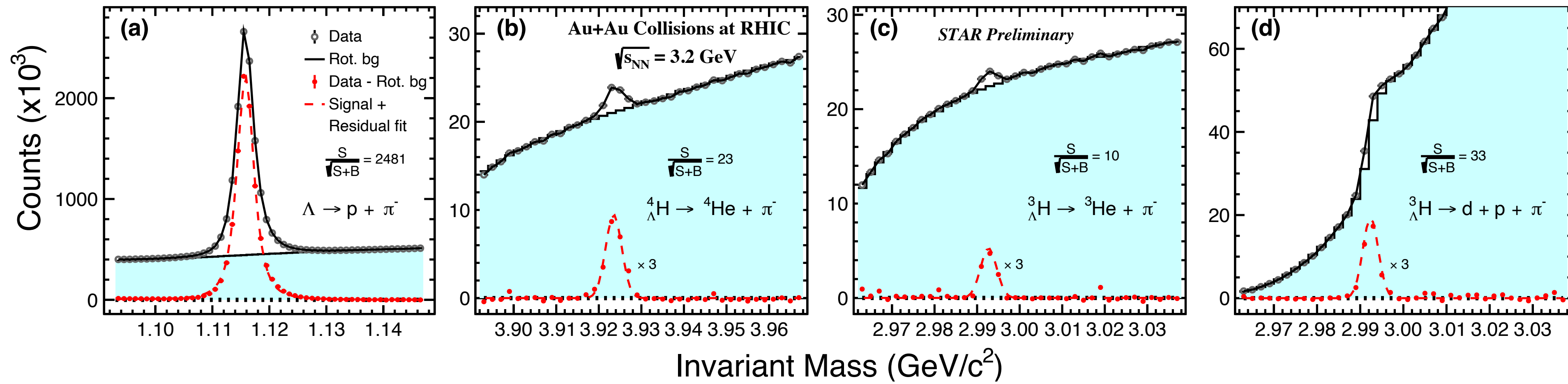


- 1) Good particle identification capability based on TPC and TOF
- 2) The hyper-nuclei reconstruction with KFParticle package based on the Kalman filter method providing a full set of the particle parameters together with their uncertainties
- 3) Decay topology tremendously helped on particle identification and background suppression

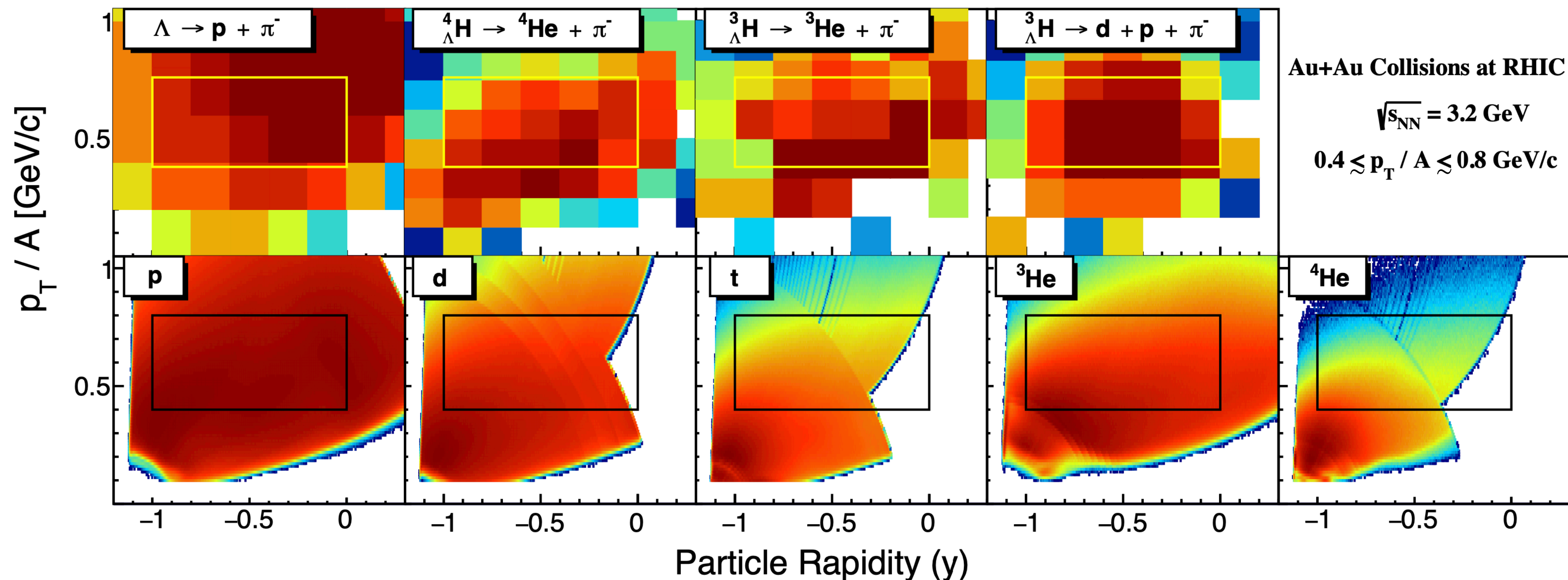
[1] Gorbunov and I. Kisel, Reconstruction of decayed particles based on the Kalman filter. CBM-SOFT-note-2007-003, 7 May 2007

[2] Ivan Kisel. Event Topology Reconstruction in the CBM Experiment. J. Phys. Conf. Ser. **1070(1)**, 012015 (2018)

Hyper-Nuclei ID, Light- and Hyper-Nuclei Acceptance

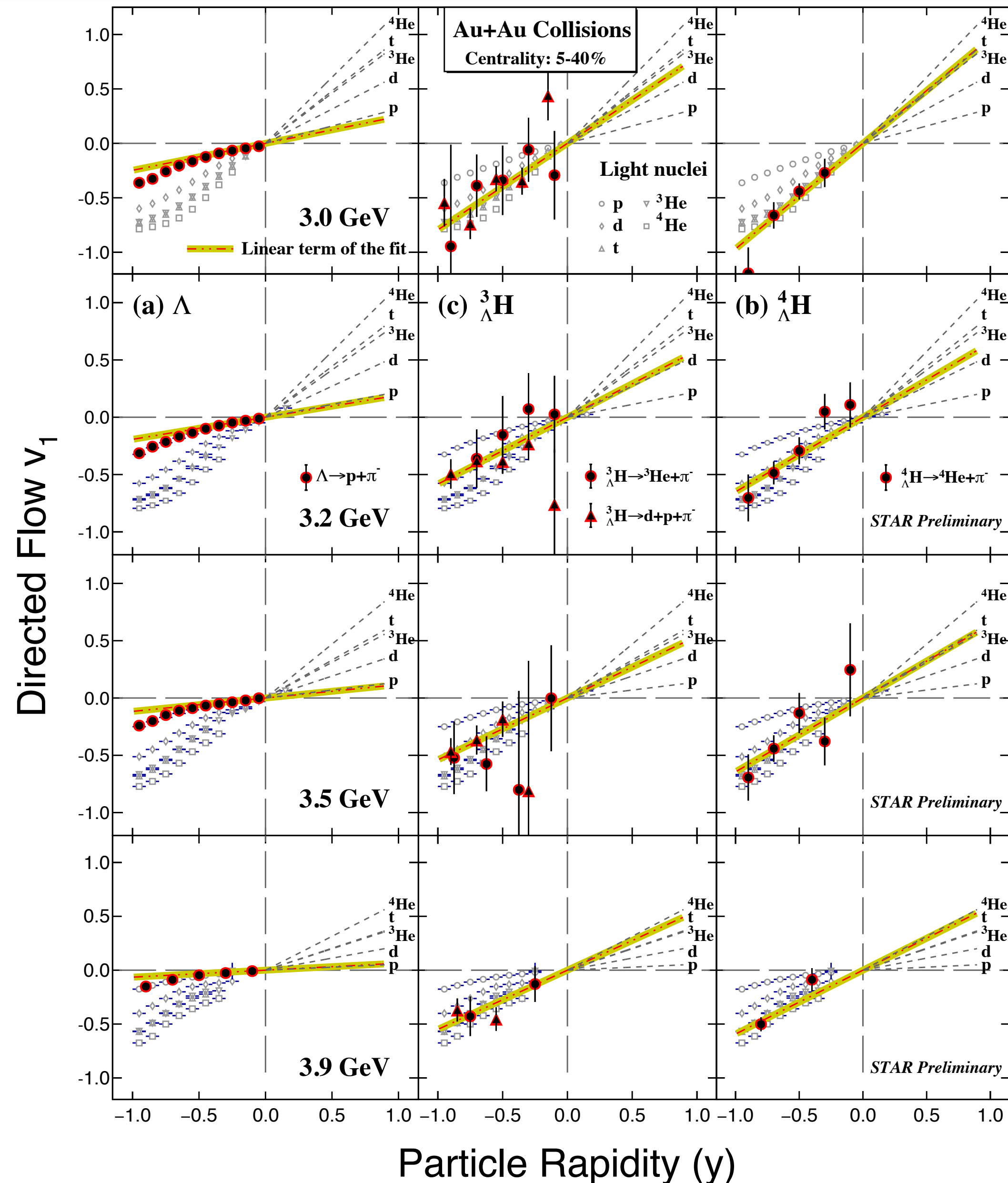


1) Obvious hyper-nuclei signals can be observed with the reconstructed invariant mass distributions



2) Collective flow of light- and hyper-nuclei are calculated within the selected p_T / A range as indicated by the boxes

Light- and Hyper-Nuclei 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 slope $(v_1)^s = dv_1/dy \Big|_{y=0}$

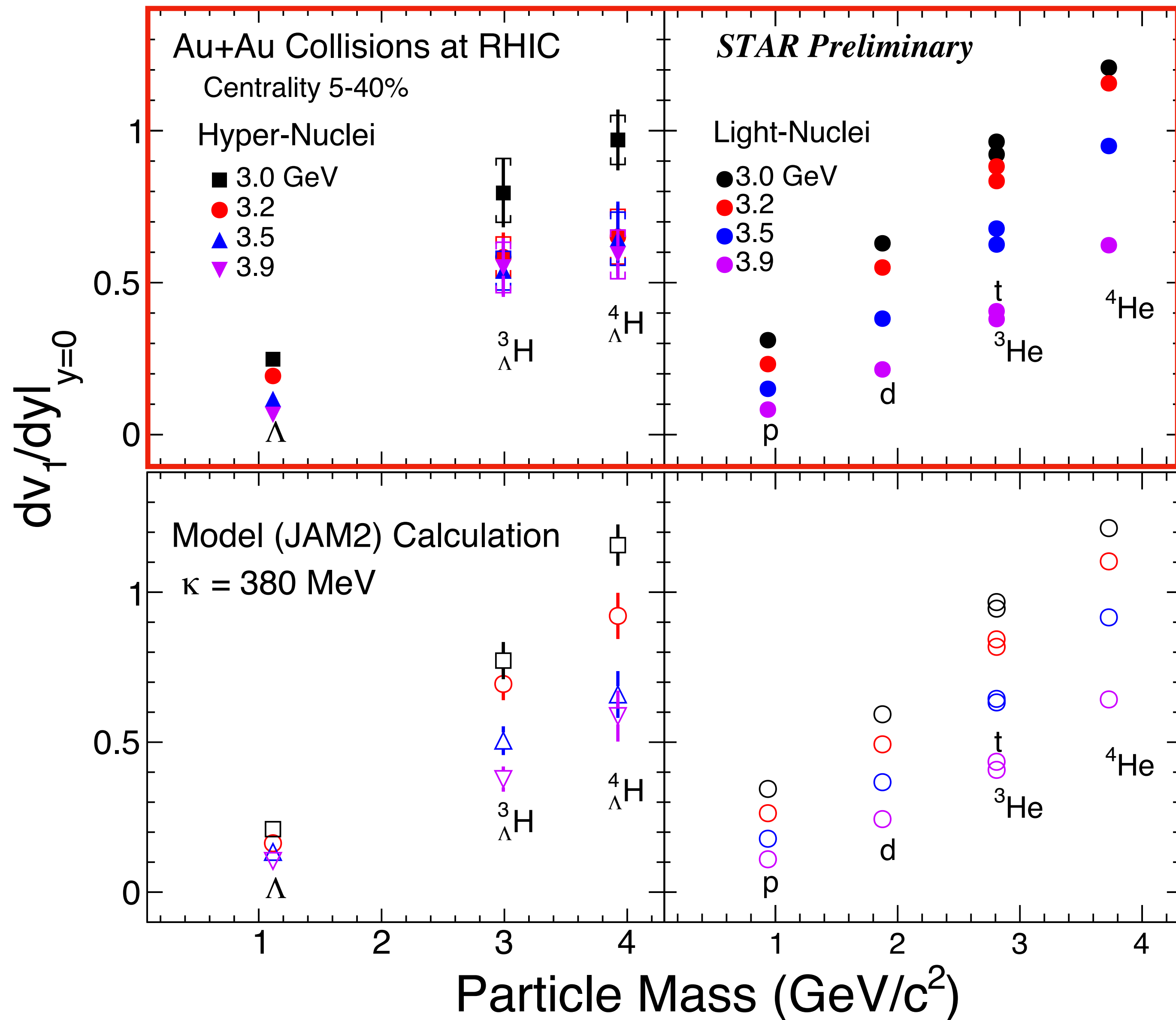
Hyper-Nuclei	Fitting Function	y	p_T / A
Λ	$v_1(y) = (v_1)^s \cdot y + p_1 \cdot y^3$	(-1.0, 0.0)	(0.4, 0.8)
${}^3_{\Lambda}H$	$v_1(y) = (v_1)^s \cdot y$	(-1.0, 0.0)	(0.33, 0.83)
${}^4_{\Lambda}H$	$v_1(y) = (v_1)^s \cdot y$	(-1.0, 0.0)	(0.30, 0.75)

Light-Nuclei	Fitting Function	y	p_T / A
p	$v_1(y) = (v_1)^s \cdot y + p_1 \cdot y^3$	(-1.0, 0.0)	(0.4, 0.8)
d	$v_1(y) = (v_1)^s \cdot y + p_1 \cdot y^3$	(-1.0, -0.2)	(0.4, 0.8)
t	$v_1(y) = (v_1)^s \cdot y + p_1 \cdot y^3$	(-1.0, -0.3)	(0.4, 0.8)
3He	$v_1(y) = (v_1)^s \cdot y + p_1 \cdot y^3$	(-1.0, 0.0)	(0.4, 0.8)
4He	$v_1(y) = (v_1)^s \cdot y + p_1 \cdot y^3$	(-1.0, -0.4)	(0.4, 0.8)

[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**, 211301(2023)

Particle Mass Dependence



► Systematic uncertainties for v_1 slope:

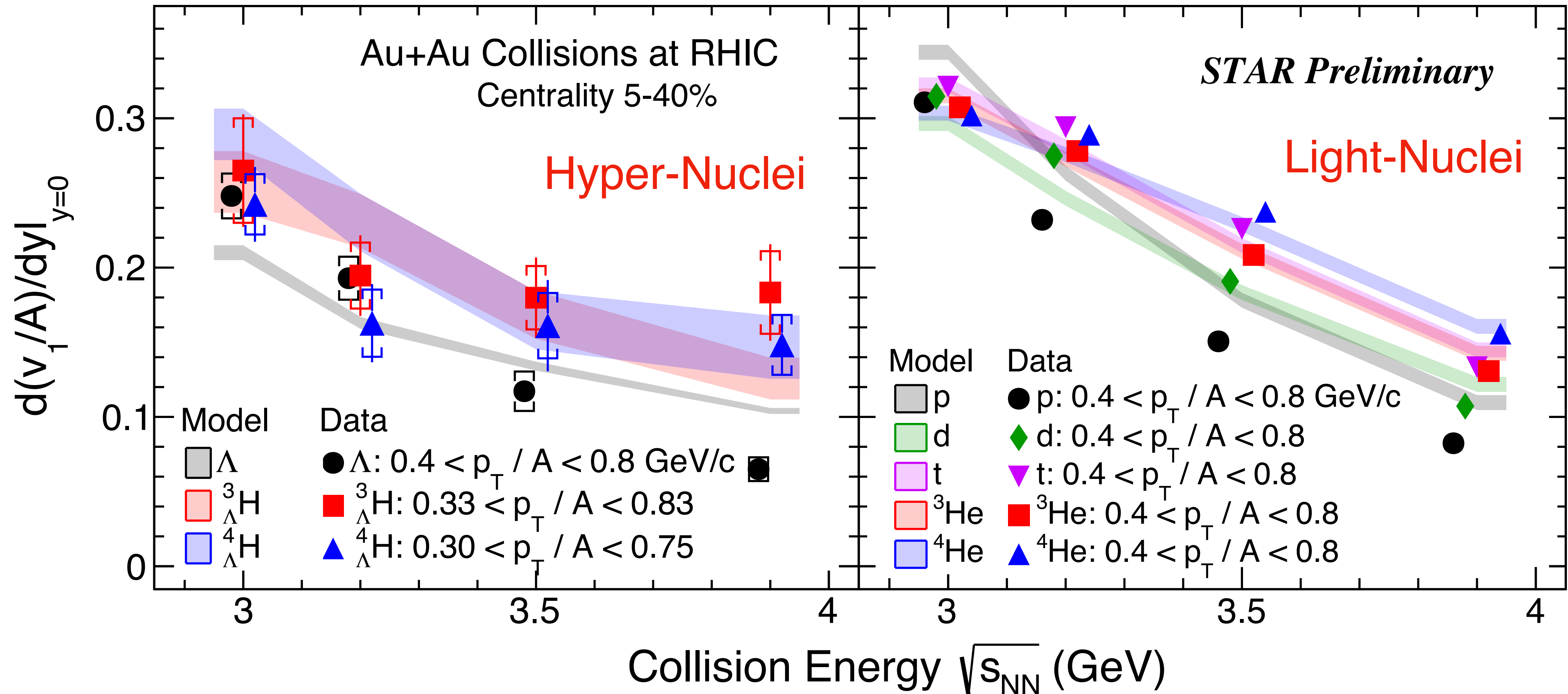
Major source	${}^3_\Lambda\text{H}$	${}^4_\Lambda\text{H}$	light-nuclei
EP resolution	4%	4%	4%
Efficiency	2%	2%	2%
Topological cuts / PID cuts	12%	11%	5%
Total	13%	12%	6%

► 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

[1] B. E. Aboona *et al.*, (STAR Collaboration), Phys. Rev. Lett. **130**, 211301(2023)

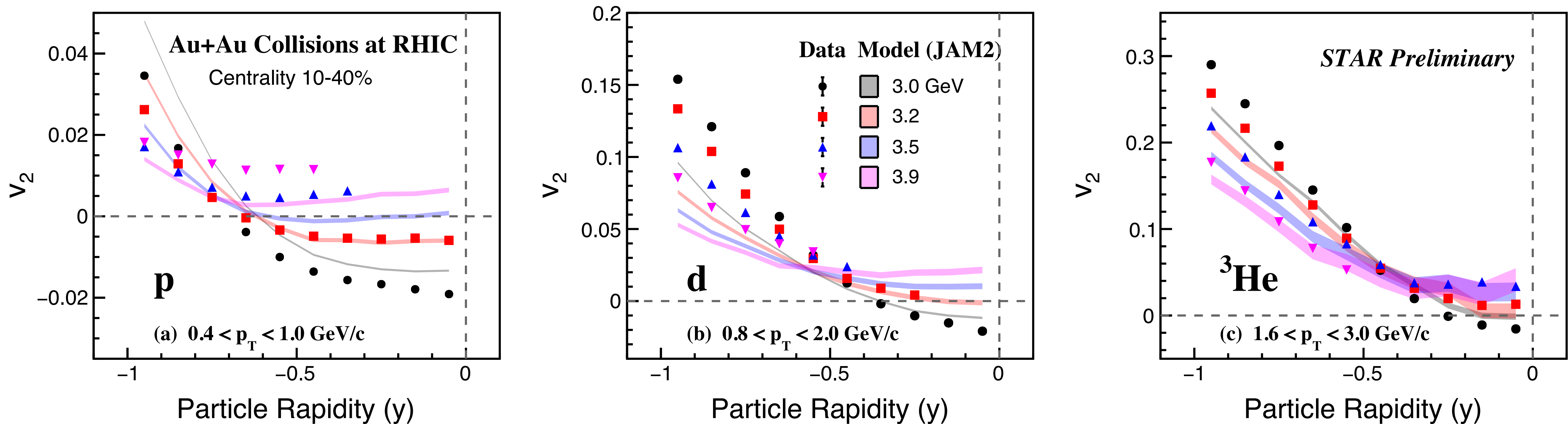
[2] Y. Nara *et al.*, Phys. Rev. C **106**, 044902 (2022)

Collision Energy Dependence



- 1) As the collision energy increases, the v_1 slope of light- and hyper-nuclei decreases
- 2) Hadronic transport model (JAM2 mean field + Coalescence) calculations are consistent with observed energy dependence

Light-Nuclei Elliptic Flow v_2

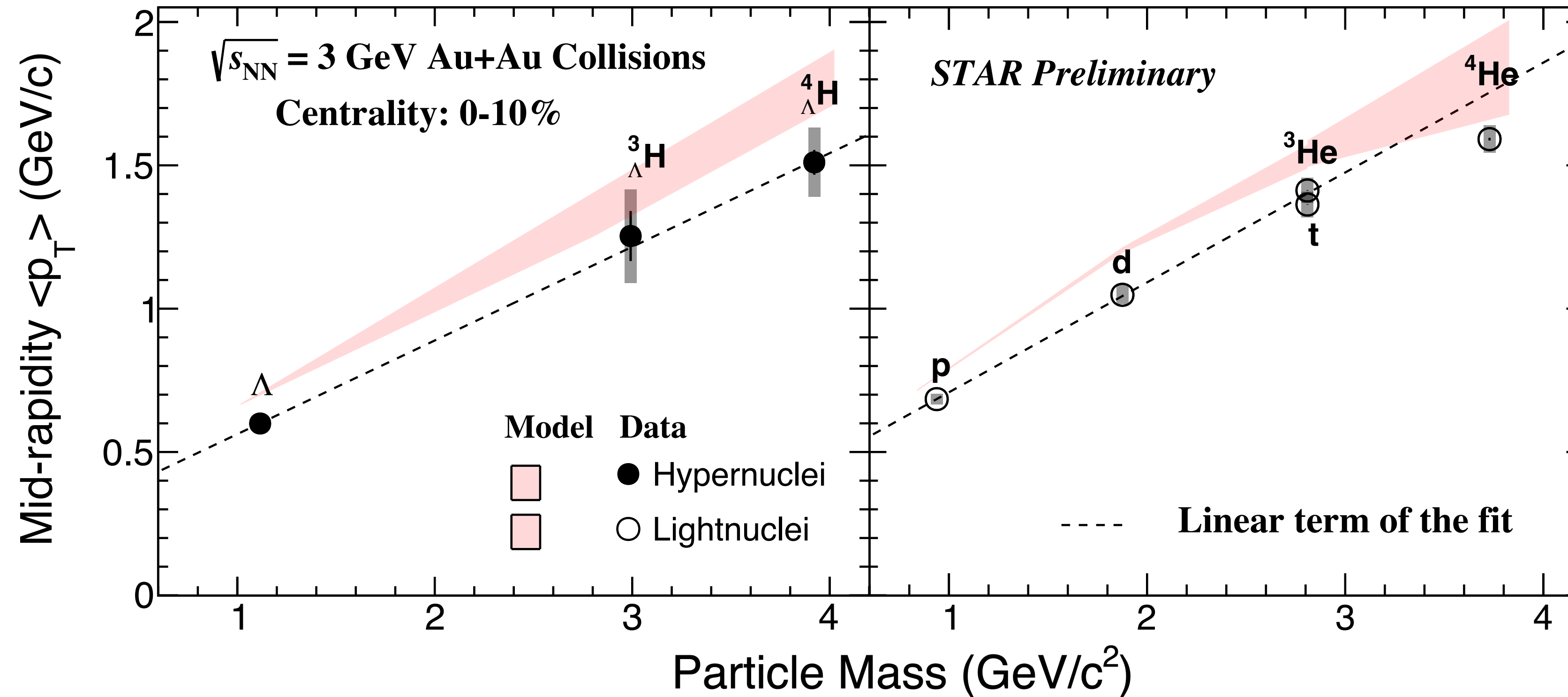


- 1) Light-Nuclei elliptic flow v_2 measurements in 10-40% mid-central Au+Au Collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$ GeV
- 2) Mid-rapidity elliptic flow results indicate an out-of-plane expansion ($v_2 < 0$) at the lowest collision energy, whereas in-plane expansions ($v_2 > 0$) are evident at higher collision energies

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

[2] Y. Nara *et al.*, Phys. Rev. C **106**, 044902 (2022)

Particle Mass Dependence of $\langle p_T \rangle$



$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T} \left\{ 1 + \sum_{n=1}^{\infty} 2v_n(p_T \cos[n(\varphi - \psi_R)]) \right\}$$

- v_0 Mean p_T $\langle p_T \rangle$
- v_1 Directed flow
- v_2 Elliptic flow

- 1) Averaged transverse momentum $\langle p_T \rangle$ evaluated over the full p_T range from the p_T spectra corresponds to the v_0 , radial flow
- 2) $\langle p_T \rangle$ of light and hyper-nuclei: both data and model (JAM2 mean field + Coalescence) show mass scaling

[1] Yue-Hang Leung, Quark Matter 2022 Report. [2] Yuanjing Ji, Quark Matter 2023 Poster.

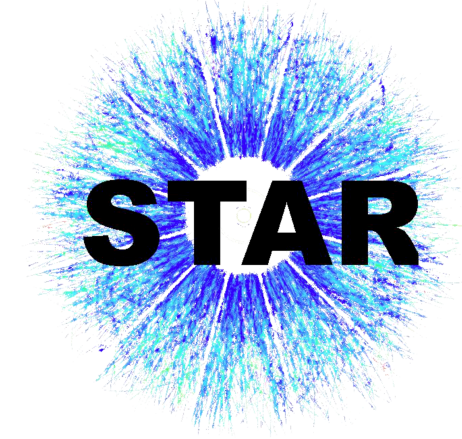
[3] M. S. Abdallah *et al.*, (STAR Collaboration), Phys. Rev. Lett. 128, 202301 (2022). [4] Y. Nara *et al.*, Phys. Rev. C **106**, 044902 (2022)

Summary and Outlook

- 1) Particle mass and collision energy dependence of directed flow v_1 for light- and hyper-nuclei implies coalescence mechanism dominates the production in 3.0 - 3.9 GeV collisions
- 2) Hadronic transport model (JAM2 mean field + Coalescence) calculations for v_1 are consistent with observed mass and energy dependence
- 3) Mid-rapidity elliptic flow v_2 of light-nuclei shows clear energy dependence. At higher collision energy, the effect of the spectator shadowing becomes weaker and expansion becomes in-plane ($v_2 > 0$)

Outlook:

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



Thank you for your attention!