Light nuclei collective flow in Au+Au Collisions from STAR BES-II experiment

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STAR

INPC 2025

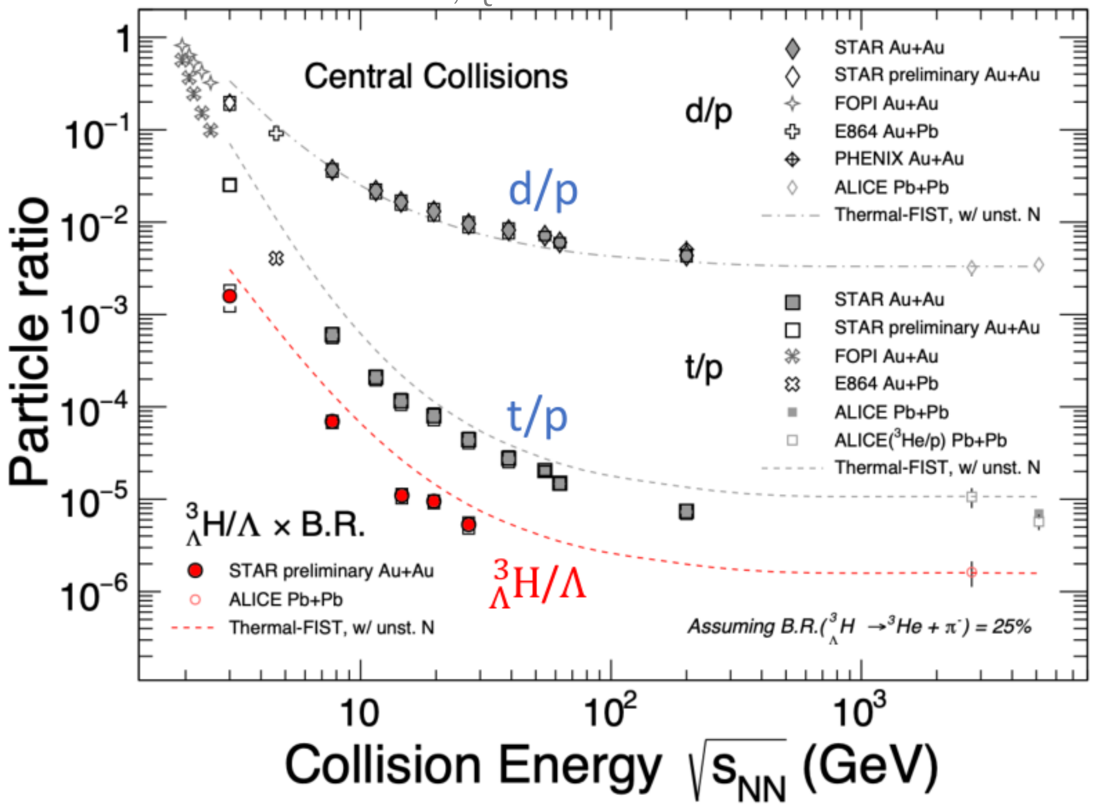
Outline

- Introduction
- STAR experiment
- Collective flow measurements for light nuclei
- Summary

Light nuclei production in heavy-ion collisions

- Affect the chemical composition, thermodynamical properties of the system
- **Abundant at high baryon density, unclear production mechanisms**

STAR Collaboration, Quark Matter 2023



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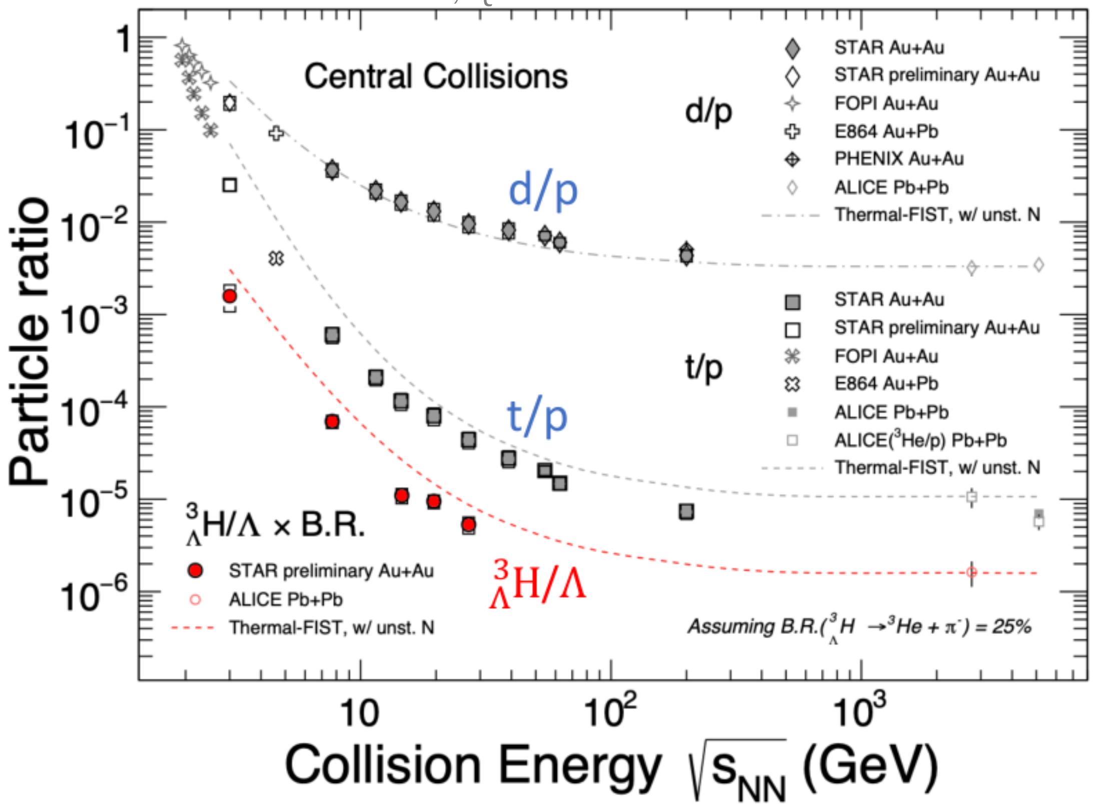
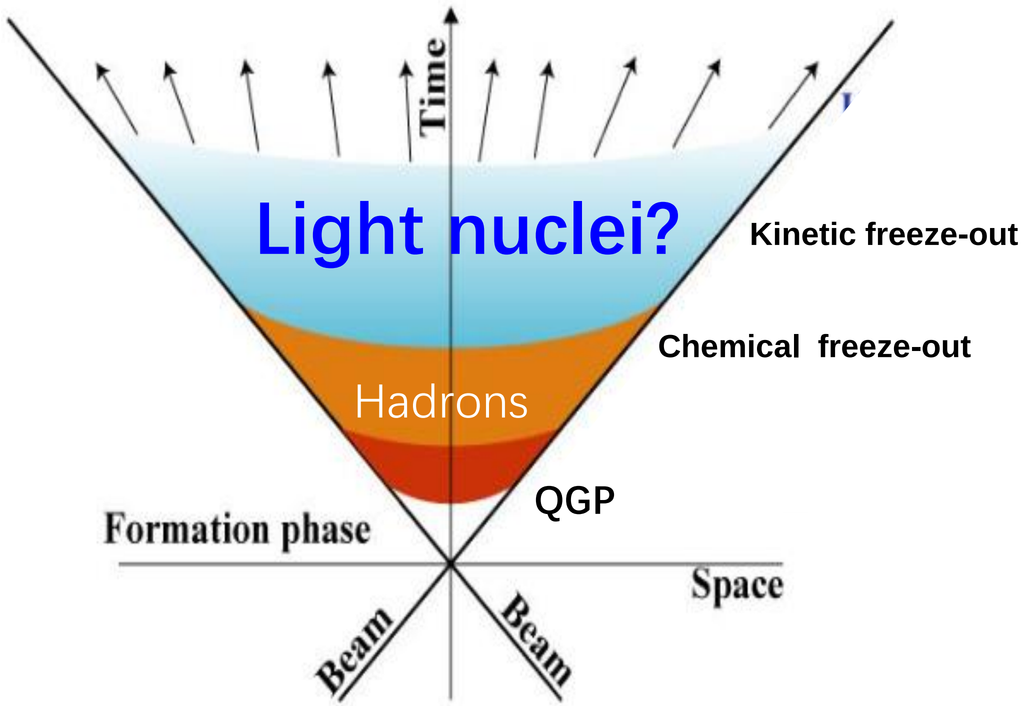


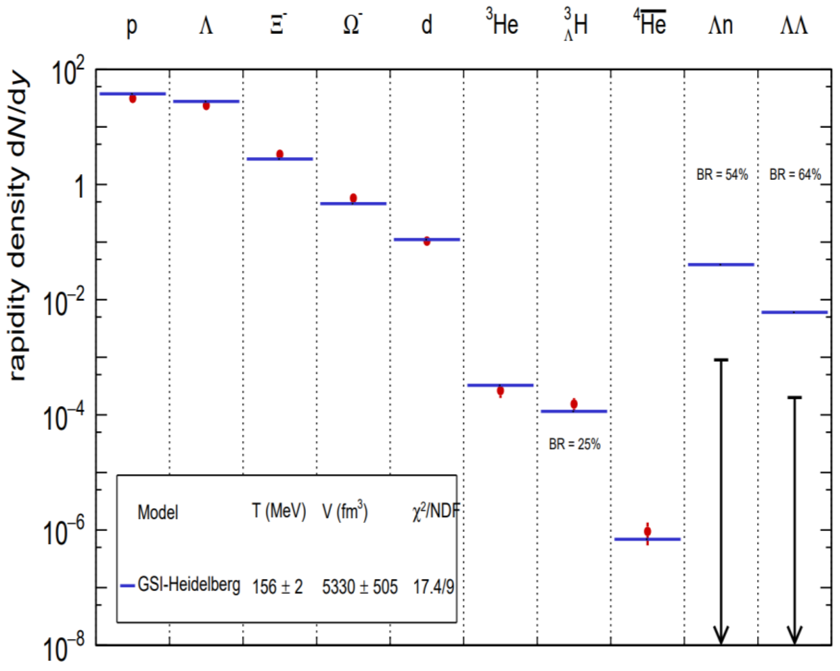


Light nuclei production mechanisms

Thermal model

assumption of thermal equilibrium

Nuclear Physics A 987, 144 (2019)



T_{cfo}=156 ±2 MeV
Binding energy: ~MeV

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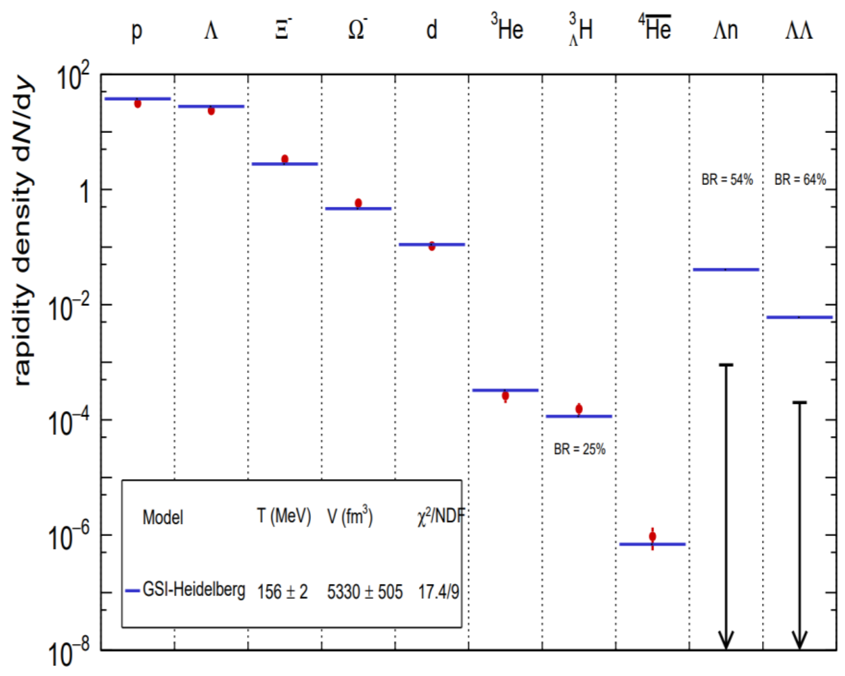

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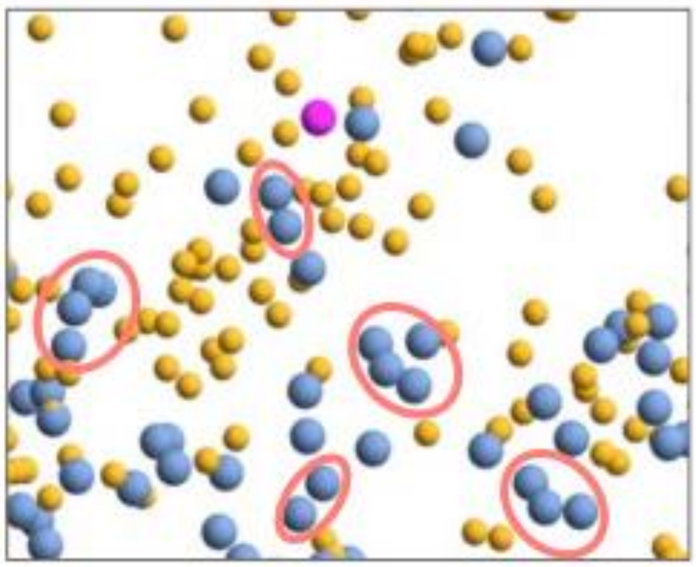
Coalescence of nucleons

formed near kinetic freeze-out



$$\frac{dN_A}{d^3\mathbf{P}_A} = g_A \int \Pi_{i=1}^{A} d^3\mathbf{x}_i d^3\mathbf{p}_i\, f_N(\mathbf{x}_i, \mathbf{p}_i)$$

$$\times\, f_A(\mathbf{x}'_1, \ldots, \mathbf{x}'_A; \mathbf{p}'_1, \ldots, \mathbf{p}'_A)\delta^{(3)}\left(\mathbf{P}_A - \sum_{i=1}^{A} \mathbf{p}_i\right)$$

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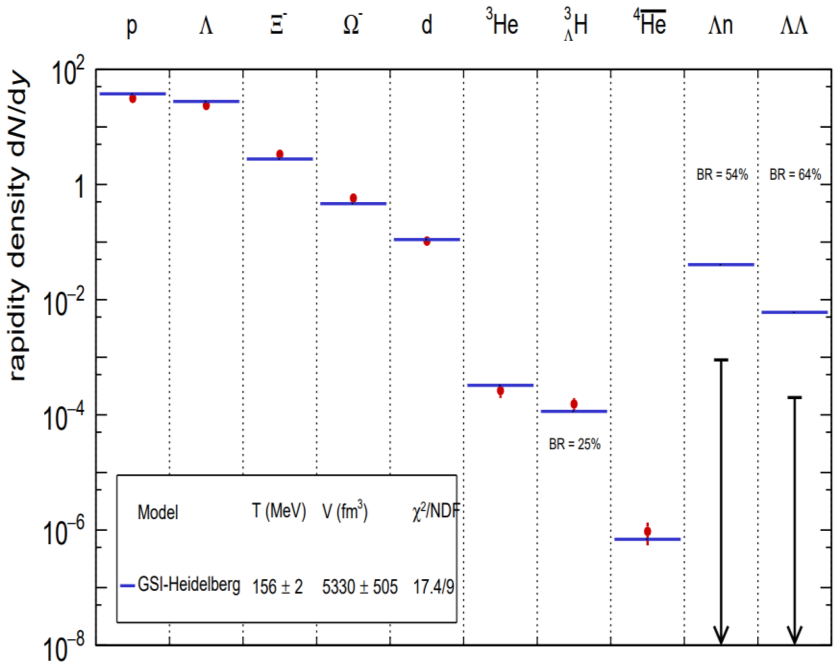

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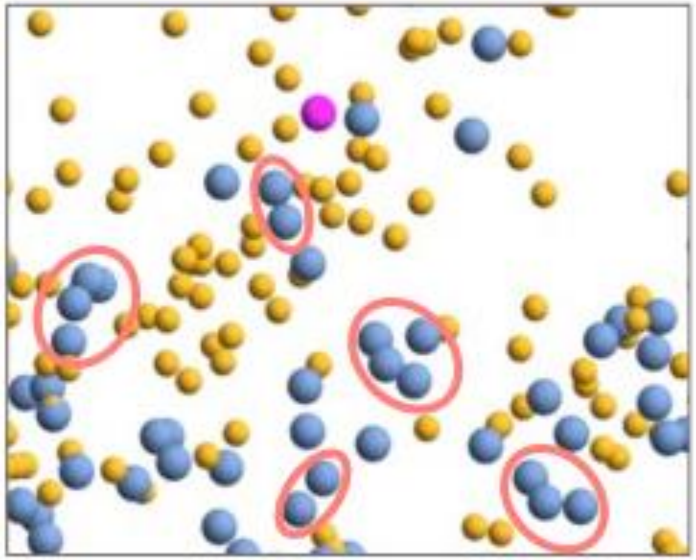

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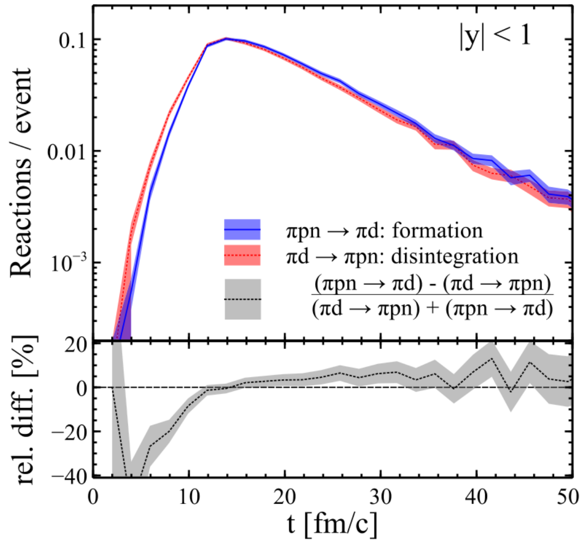
Kinetic transport
dynamical formation and dissociation

d+π ⇔ N+N
d+N ⇔ N+N+N
d+ π ⇔ N+N+ π



Phys. Rev. C 99, 044907(2019)

Collective flow in heavy-ion collisions

Collective motion of particle (due to high pressure arising from compression of nuclear matter)

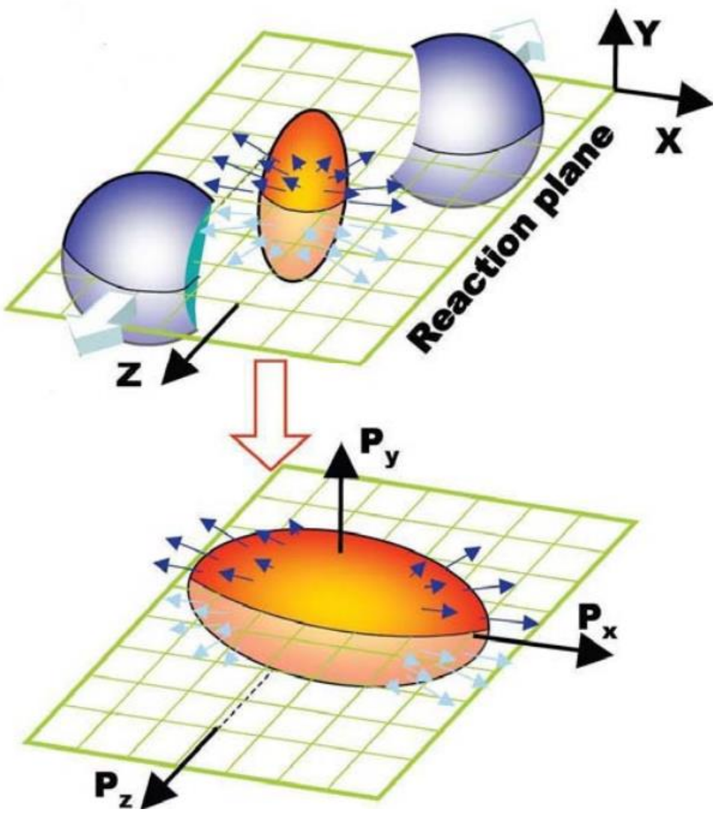
Initial spatial anisotropy

↓

Pressure gradient

↓

Final momentum asymmetry



Anisotropic flow: non-central collision or initial fluctuations

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

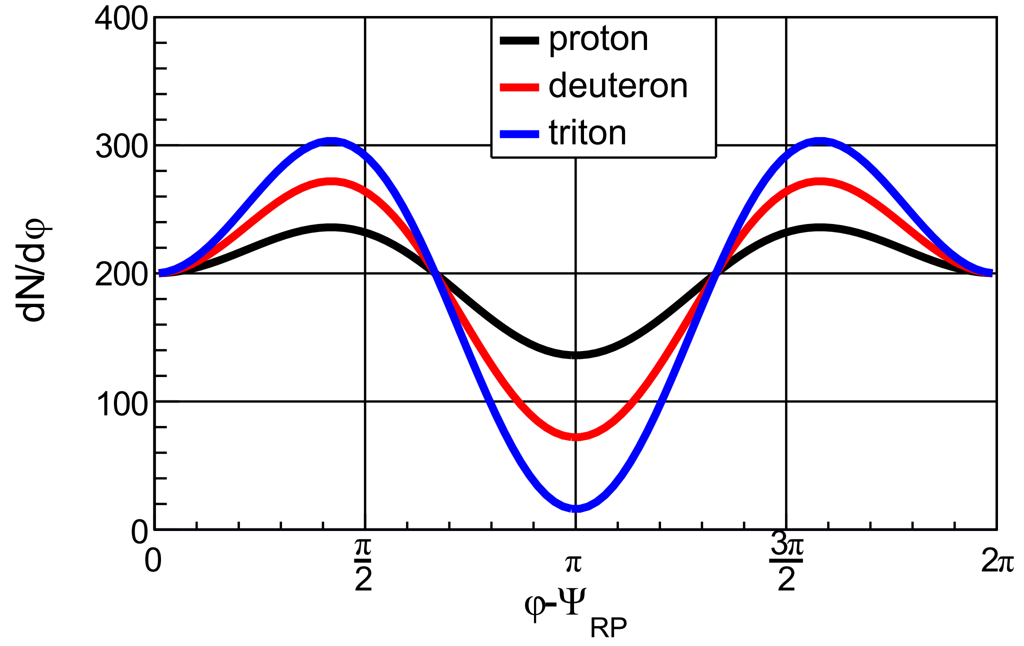
- **v_1**: deflection happens during passing time
- **v_2**: sensitive to initial eccentricity

Light nuclei flow

- Less affected by the thermal dispersion, carry more direct information on the EoS

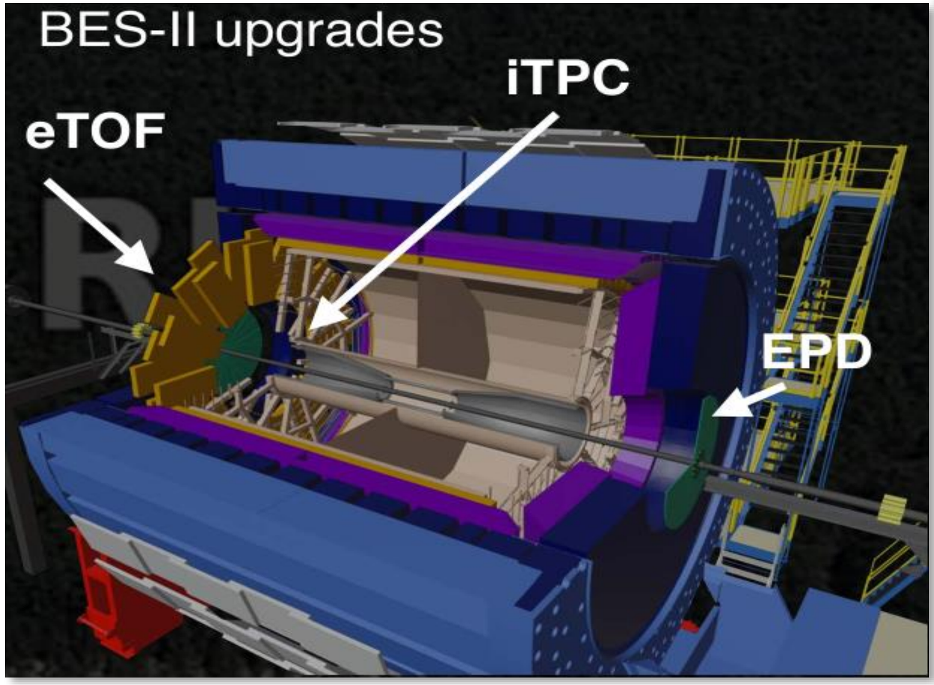
- Coalescence model:
  - atomic **mass number (A) scaling** of collective flow (pure momentum space)

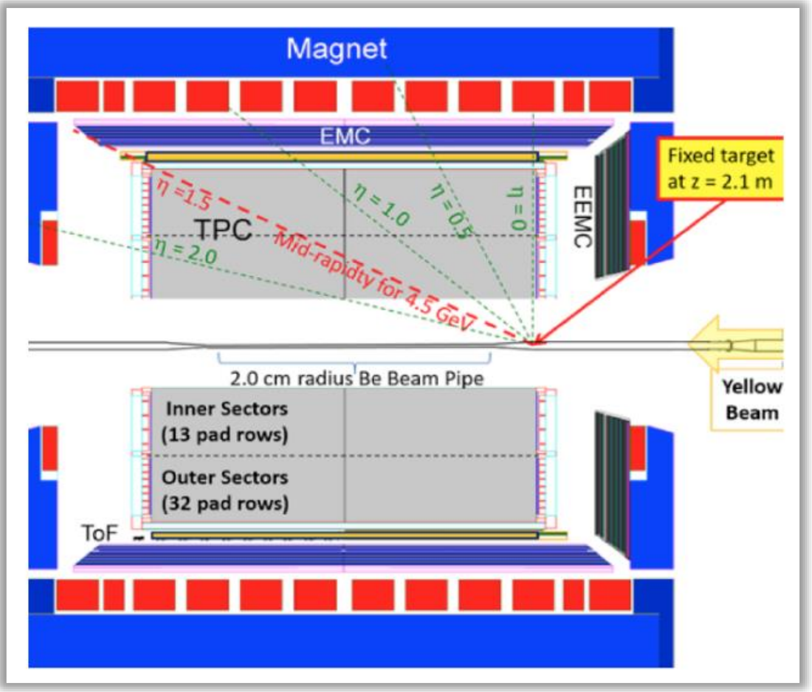
$$v_n^A(p_T, y) \approx A\, v_n^p(p_T/A, y) \quad (v_n^p << 1)$$

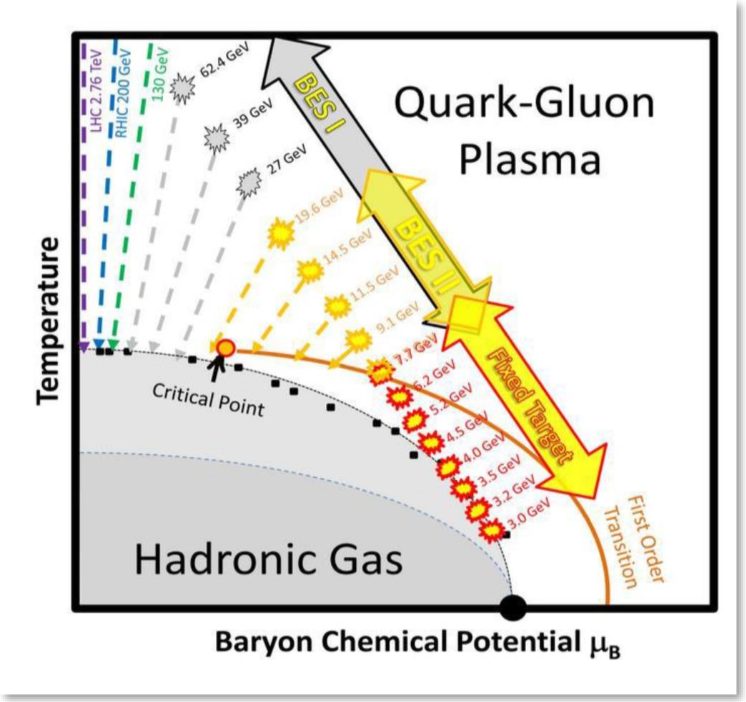


- **Provide valuable information on production mechanisms, incompressibility, in-medium NN interactions**
- **Both proton and light nuclei are measurable**

STAR BES-II experiment



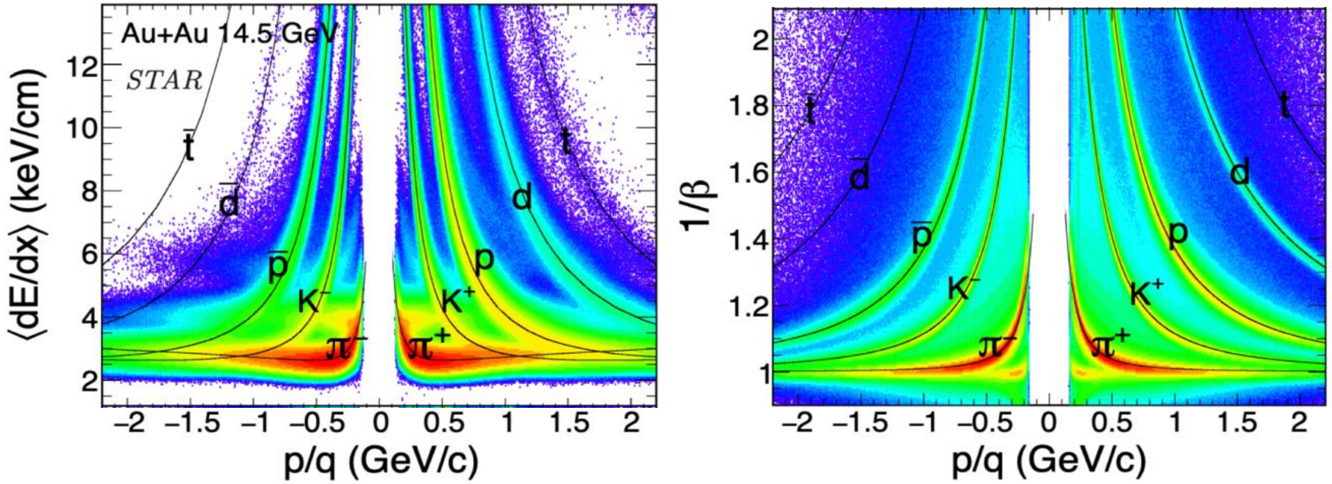




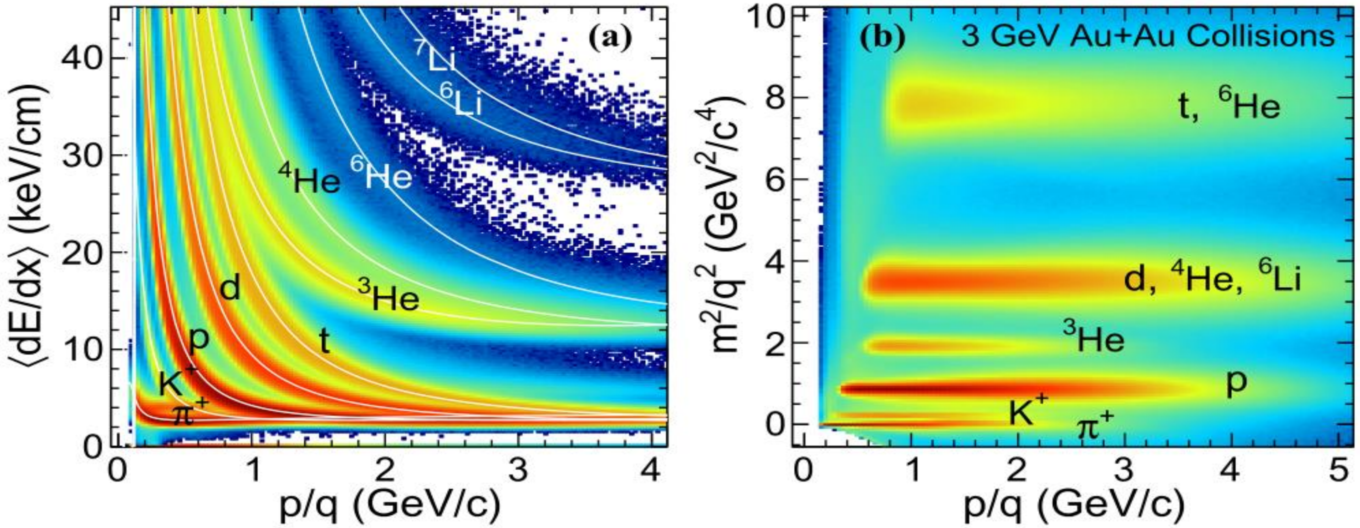
- ❑ **Major upgrades for BES-II: particle identification, acceptance, event-plane resolution**
- ❑ **3 GeV-27GeV: coverage of baryon chemical potential from 156 MeV to 720 MeV**

Particle identification

Collider



Fixed target

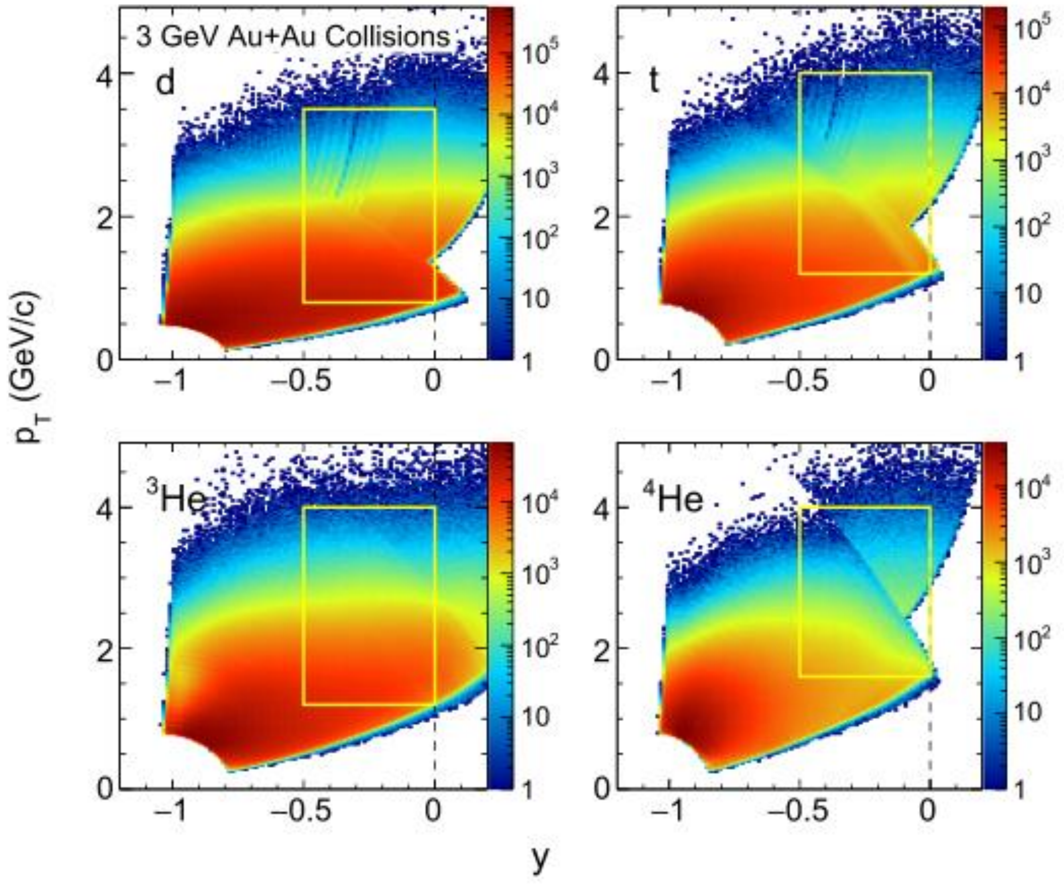


Light nuclei : d, t, ^{3}He, and ^{4}He

The TPC was used at low momentum, and the TPC+TOF was used at high momentum.

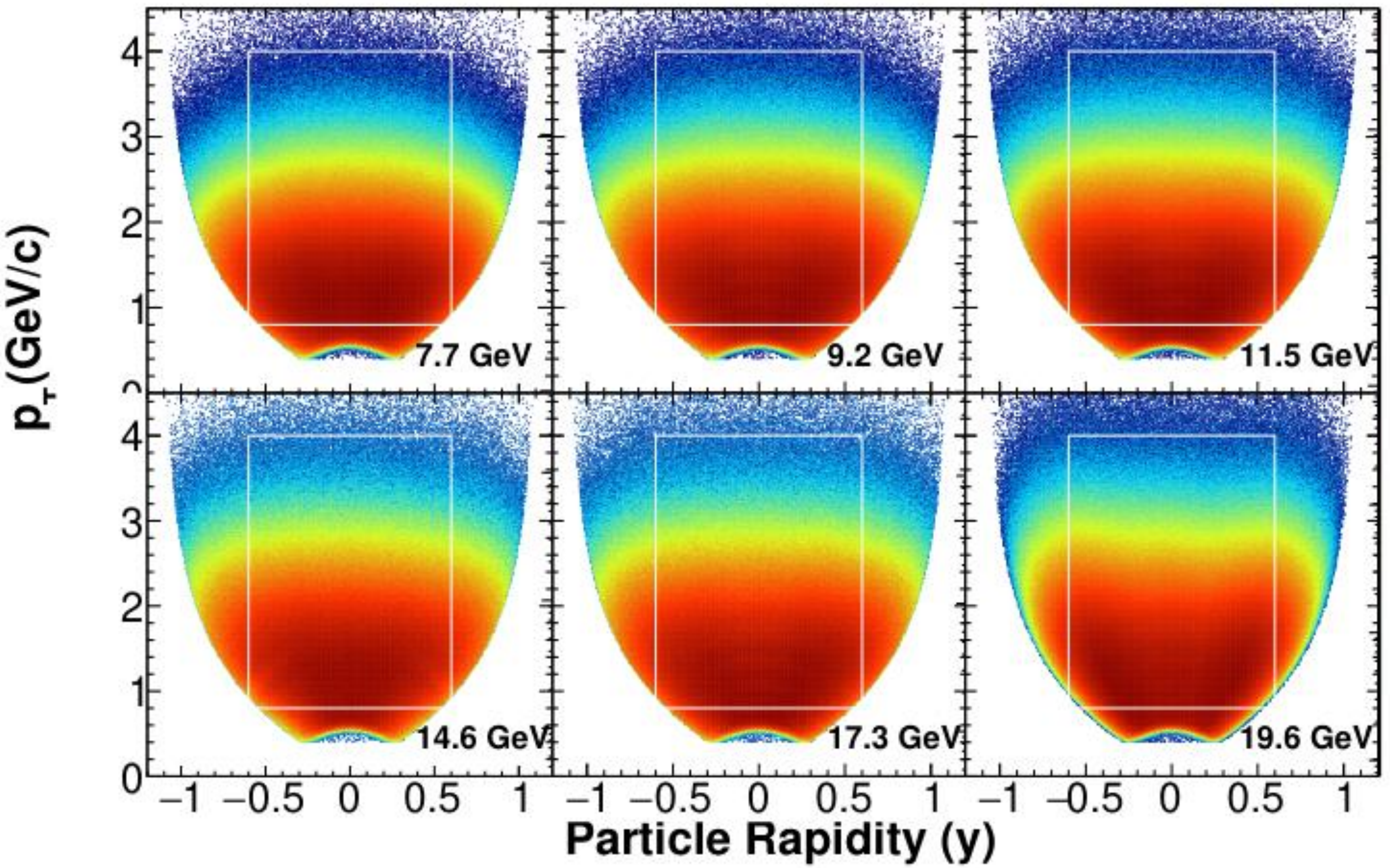
Light nuclei acceptance

Fixed-target



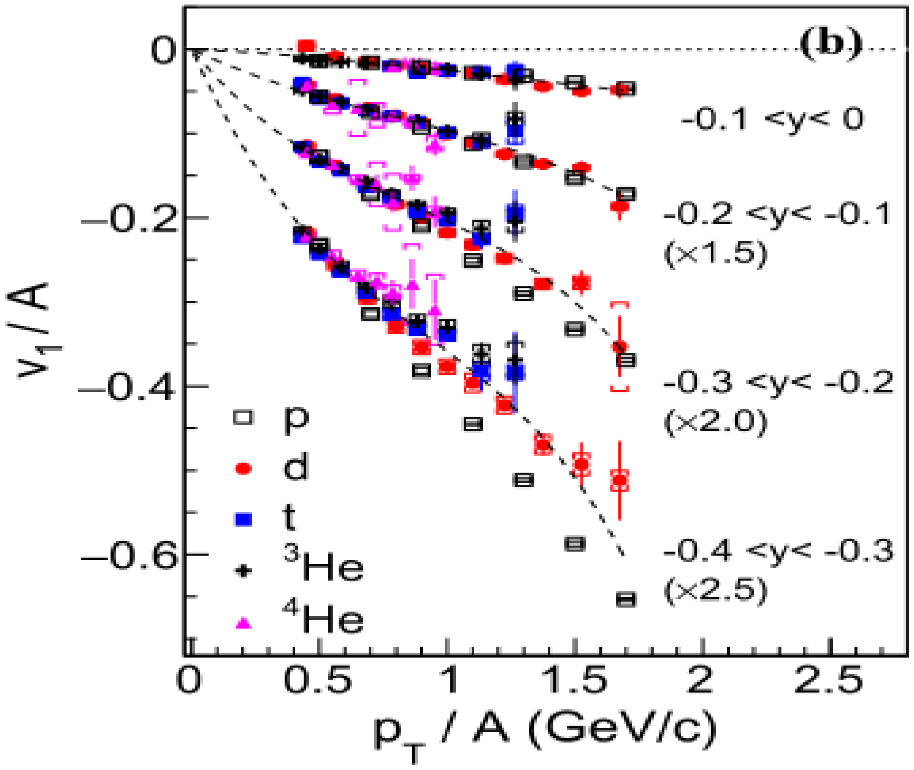
- $0.4 \times A < p_T < 4$ GeV/c
- $-0.5 < y < 0$

Collider ((anti-)deuteron)

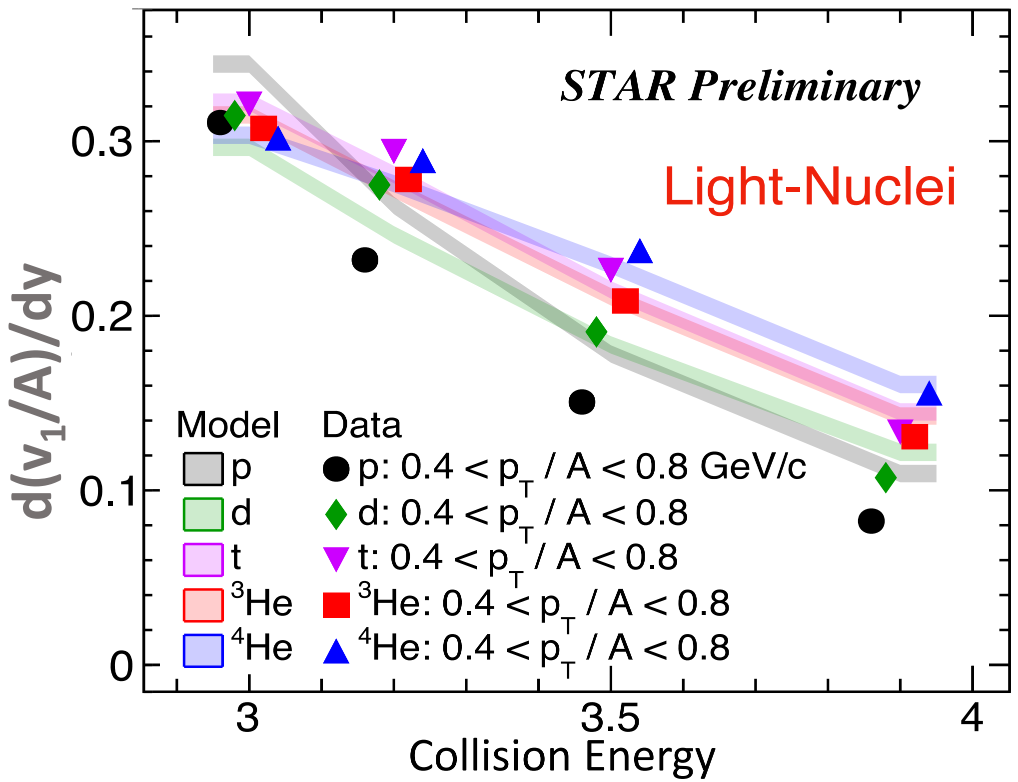


- $0.8 < p_T < 4$ GeV/c
- $-0.6 < y < 0.6$

Light nuclei v_1 at $\sqrt{s_{NN}} = 3 - 3.9$ GeV

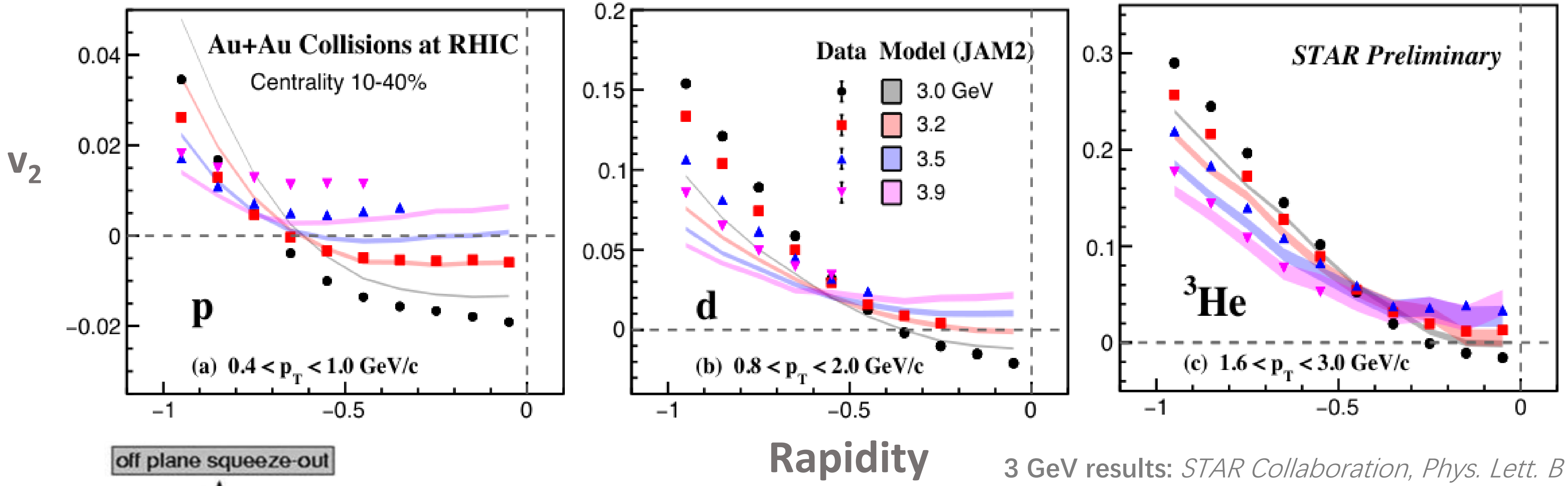


STAR Collaboration, Phys. Lett. B 827, 136941 (2022)

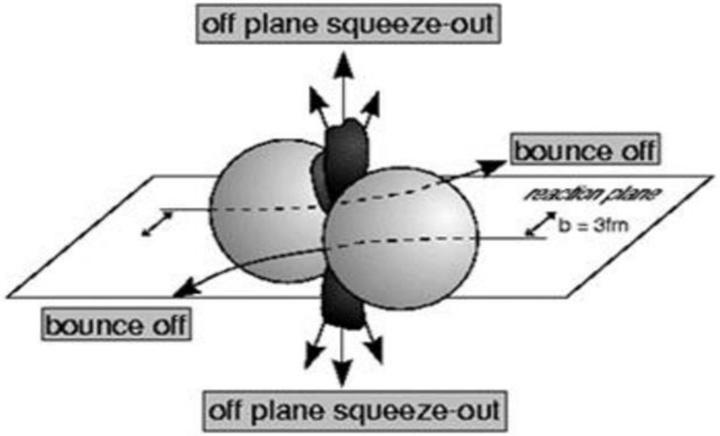


Mass number scaling holds at 3 GeV, tends to be broken at higher energies

Light nuclei v_2 at $\sqrt{s_{NN}} \leq 3.9$ GeV

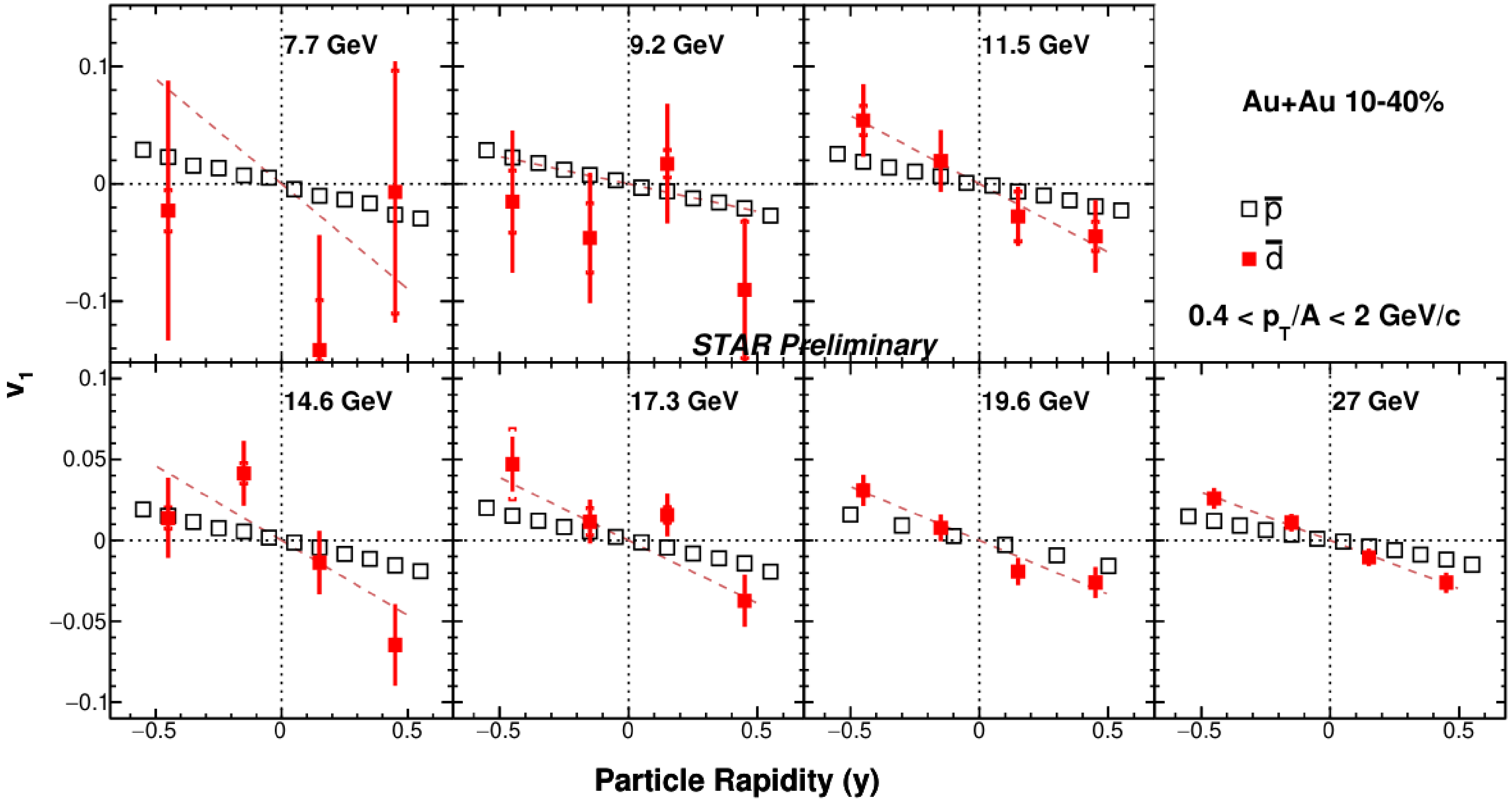


3 GeV results: *STAR Collaboration, Phys. Lett. B 827, 136941 (2022)*



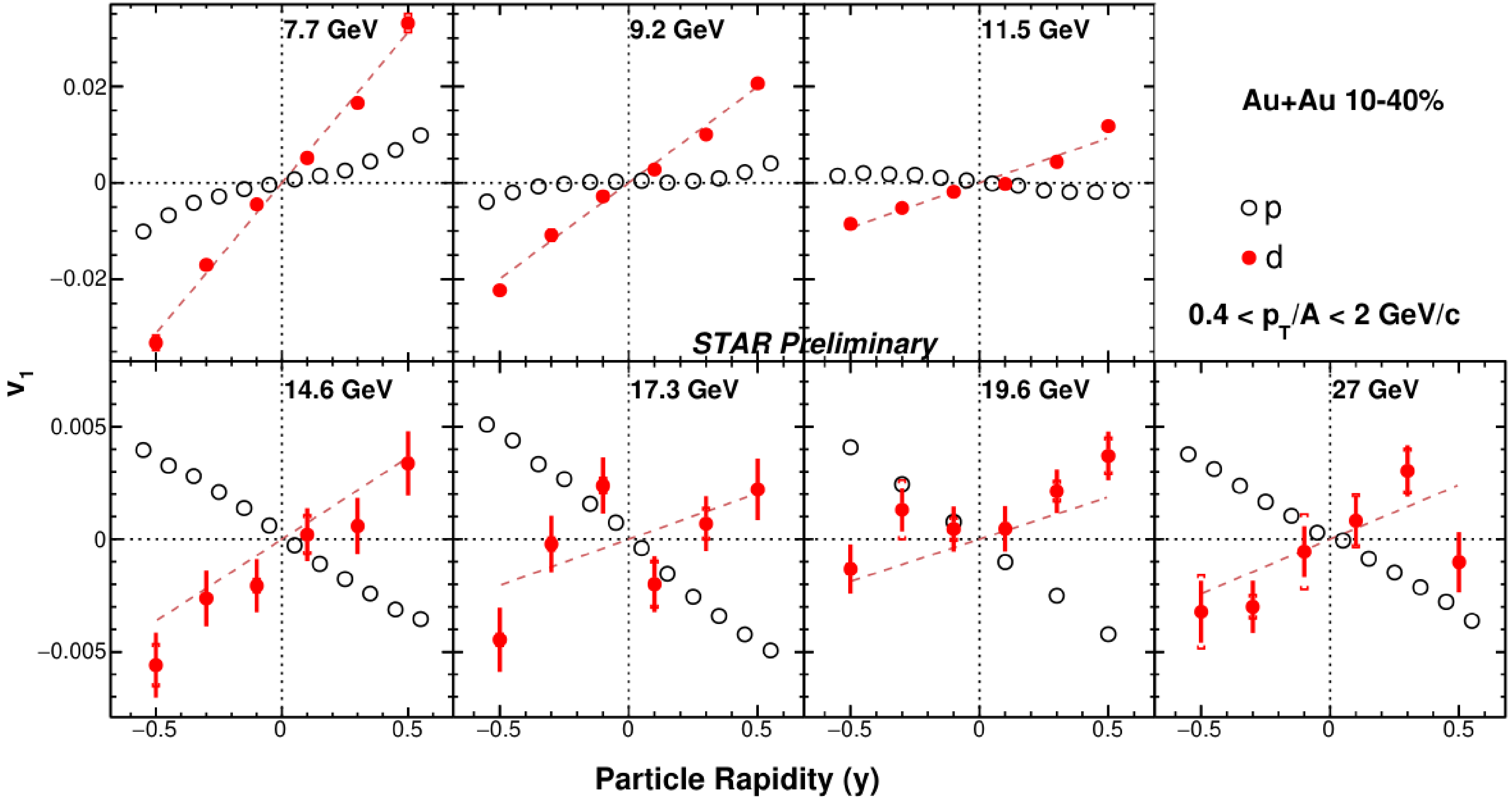
Heavier nuclei is less sensitive to the shadowing of the spectators

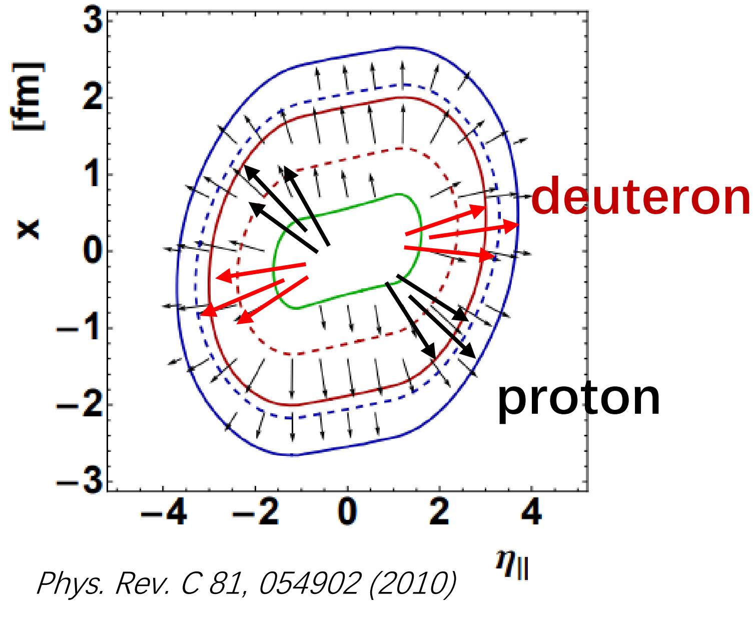
Anti-deuteron v_1 for $\sqrt{s_{NN}} \geq 7.7$ GeV



- **First measurement for anti-deuteron v_1**
- **v_1 sign is consistent with that of anti-proton**
- **Mass number scaling hold within uncertainties**

Deuteron v_1 for $\sqrt{s_{NN}} \geq 7.7$ GeV

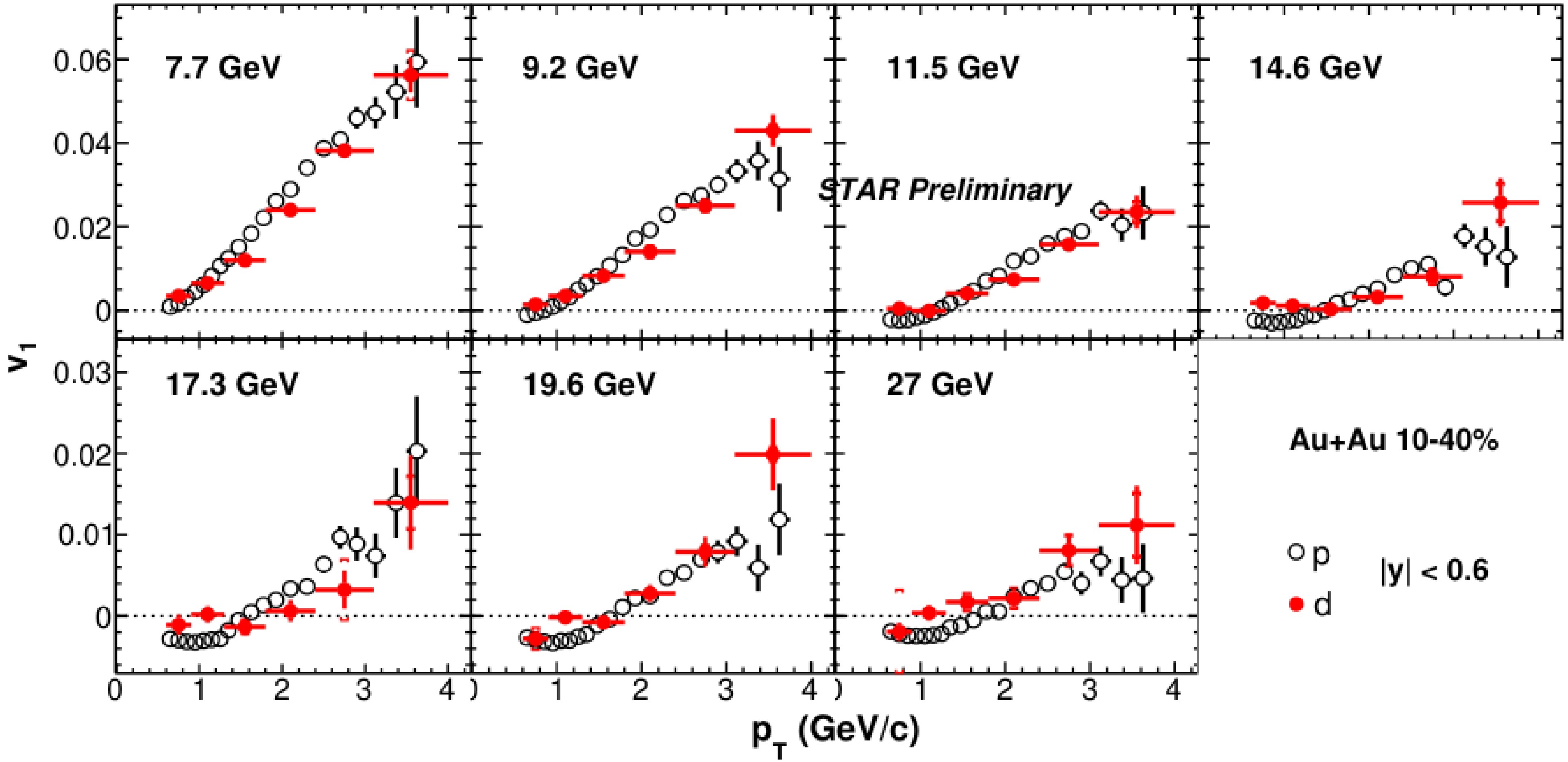




Phys. Rev. C 81, 054902 (2010)

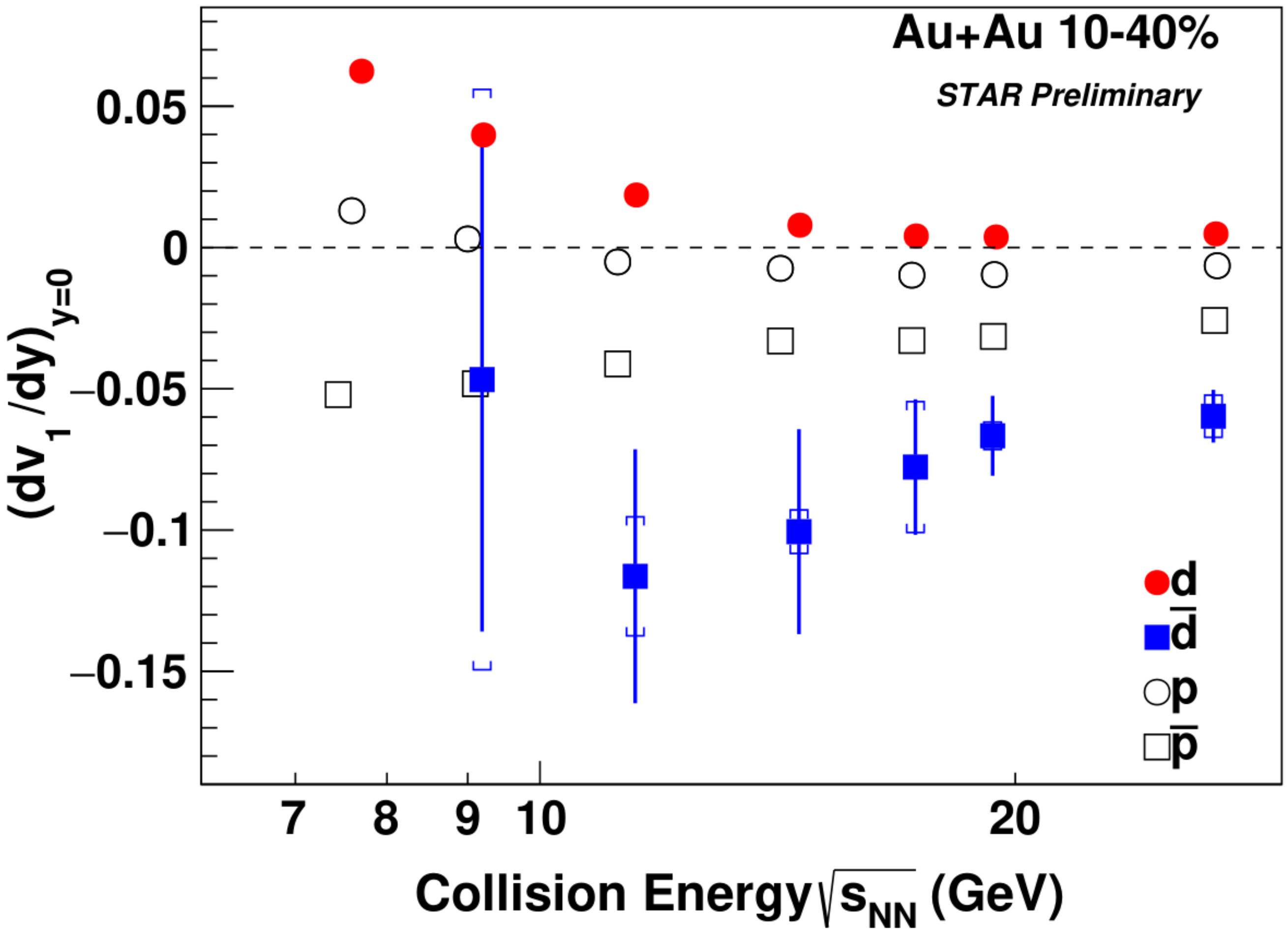
- **v_1 slopes of deuteron is positive, opposite to protons, at $\sqrt{s_{NN}}$ = 7.7-27 GeV is observed**
- **Disfavor coalescence mechanisms, theoretical insight needed**

p_T dependence of deuteron v_1



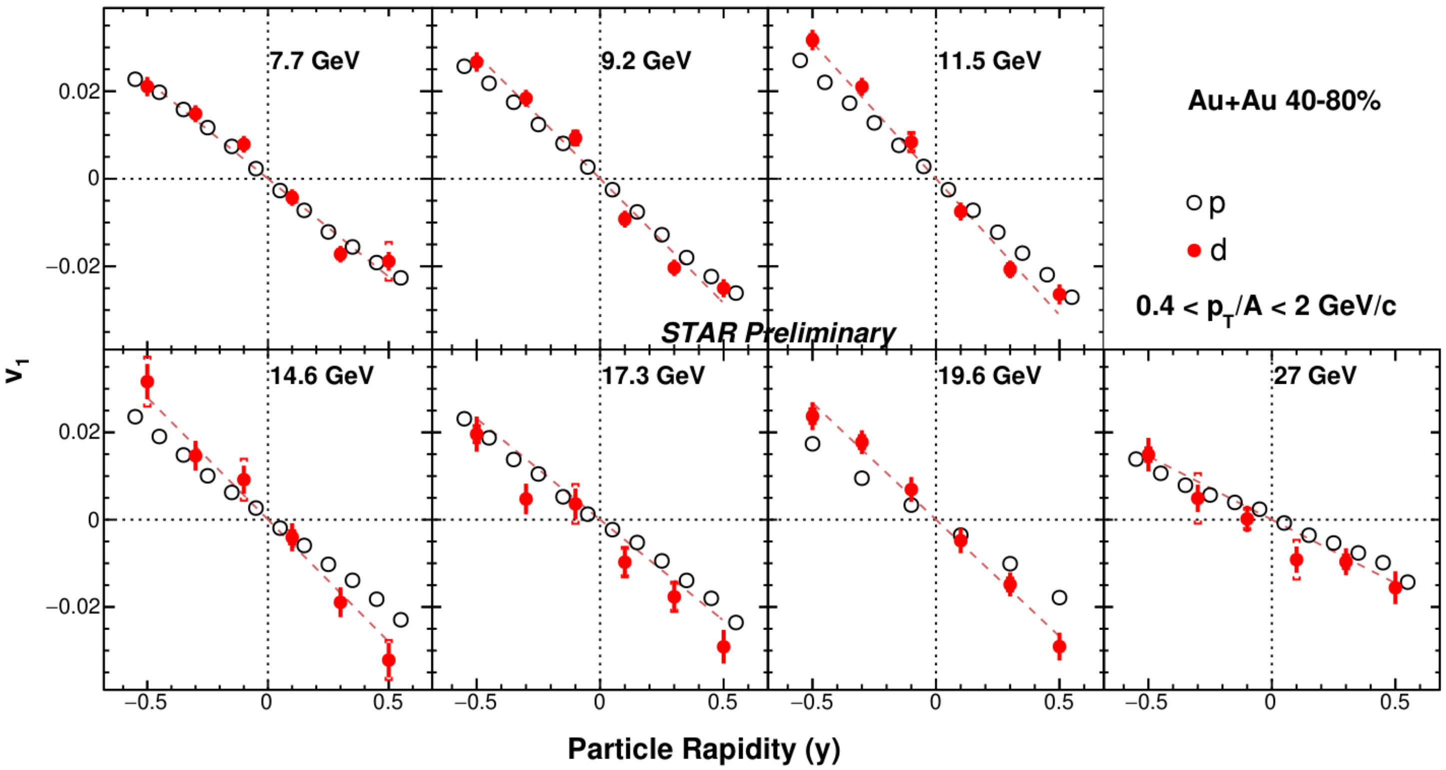
- **Proton: negative v_1 mainly attributed to low p_T particles**
- **Deuteron: linear dependence on p_T, tends to be negative at low p_T**

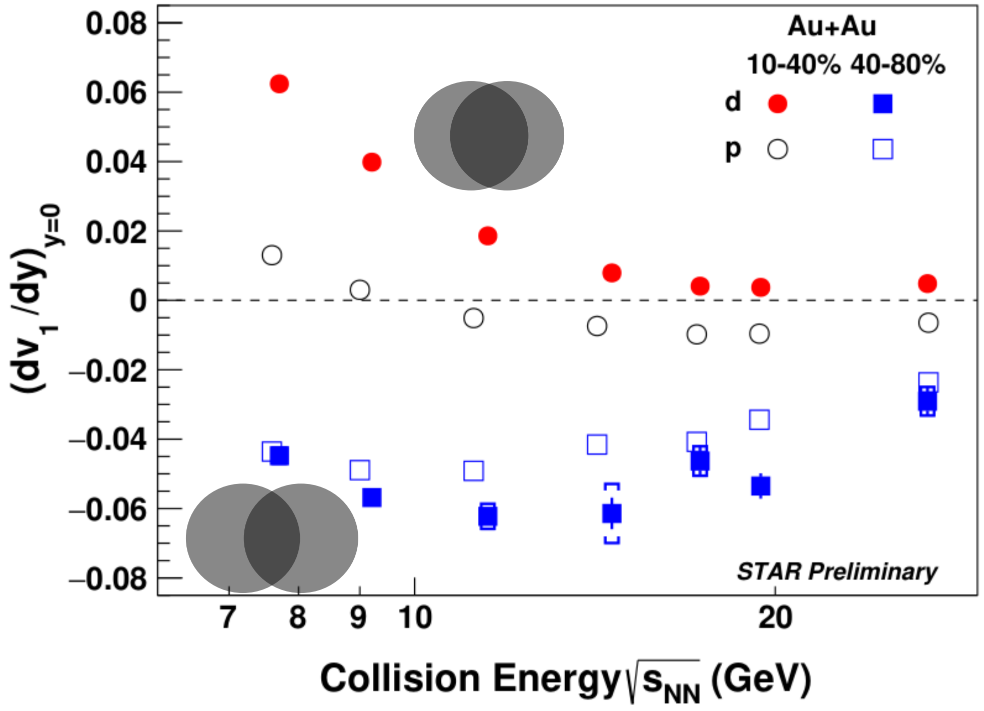
(Anti-) deuteron v_1 slope at mid-rapidity



- **For deuteron, energy dependence follows a monotonic trend, with opposite sign compared to proton at $\sqrt{s_{NN}}$ > 9.2 GeV**
- **Anti-deuteron v_1 follows A scaling**
- **Different contribution from produced and transported protons?** model calculations failed to describe the proton v_1

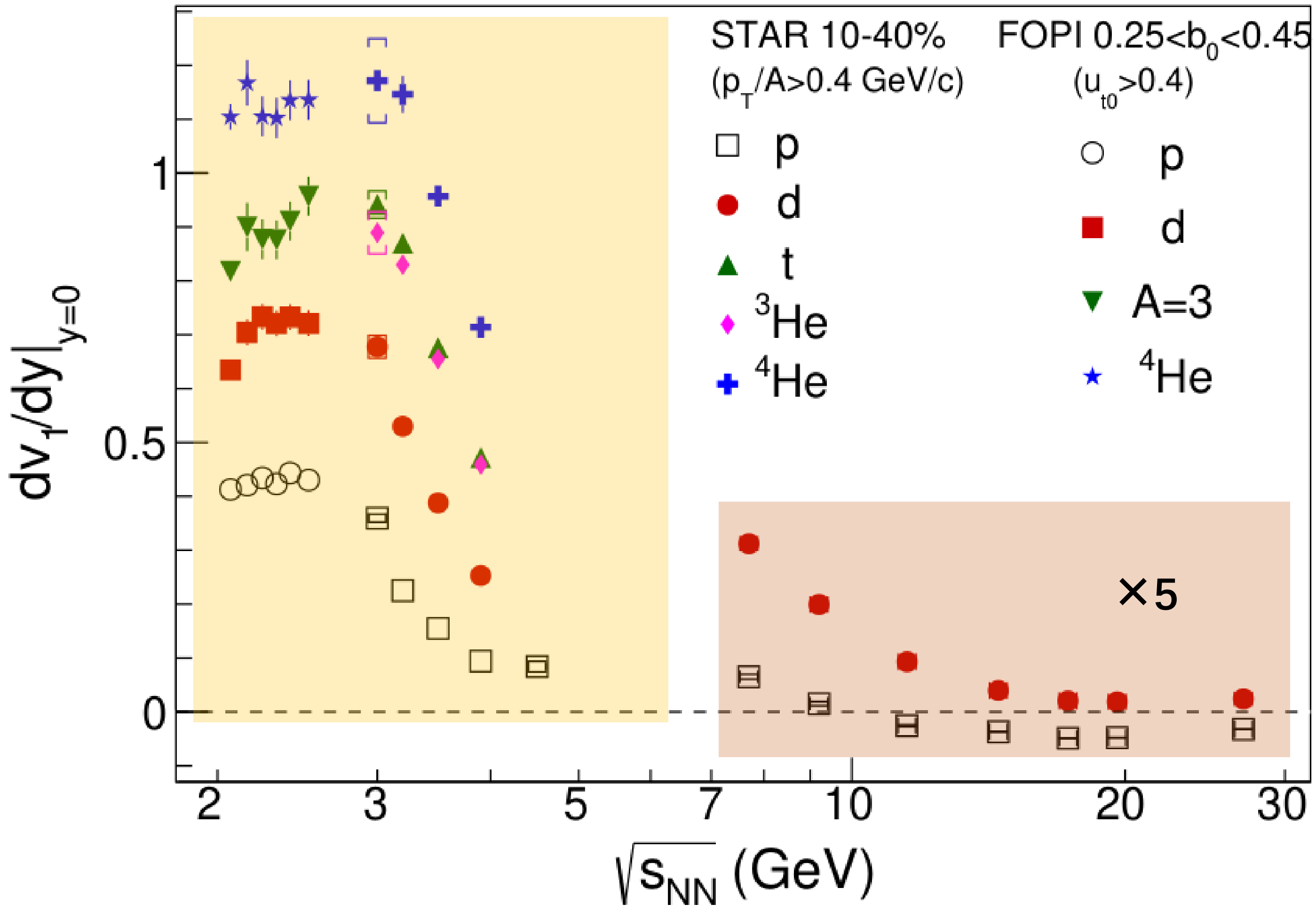
Deuteron v_1 at peripheral collisions





Same v_1 sign but no A scaling, dv_1/dy sign changes from mid-central to peripheral collisions

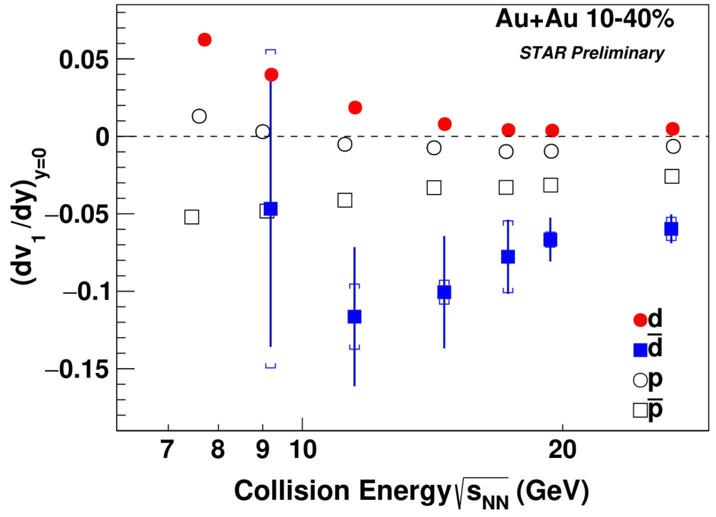
Energy dependence of light nuclei v_1 at mid-rapidity



- **Strong mass dependence at low energies $\sqrt{s_{NN}}$ < 7.7 GeV (high μ_B)**
- **Opposite sign compared to proton at $\sqrt{s_{NN}}$ > 9.2 GeV**

Summary

- **Pronounced energy dependence of flow for heavier nuclei**
- **Production mechanisms:**
  - 3-7.7 GeV (μ_B > 420 MeV): Approximate mass number scaling holds for v_1
    → **coalescence mechanism**
  - 11.5-27 GeV (μ_B < 315 MeV) **Positive deuteron v_1 slopes at 10-40% centrality, opposite to those of protons**; **mass number scaling for anti-deuteron**
    → **transport proton contribution? baryon stopping?**
    need more theoretical input



Thank you for your attention!