Light Nuclei Collectivity in Heavy-Ion Collisions at High Baryon Density

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CHINESE ACADEMY OF SCIENCES

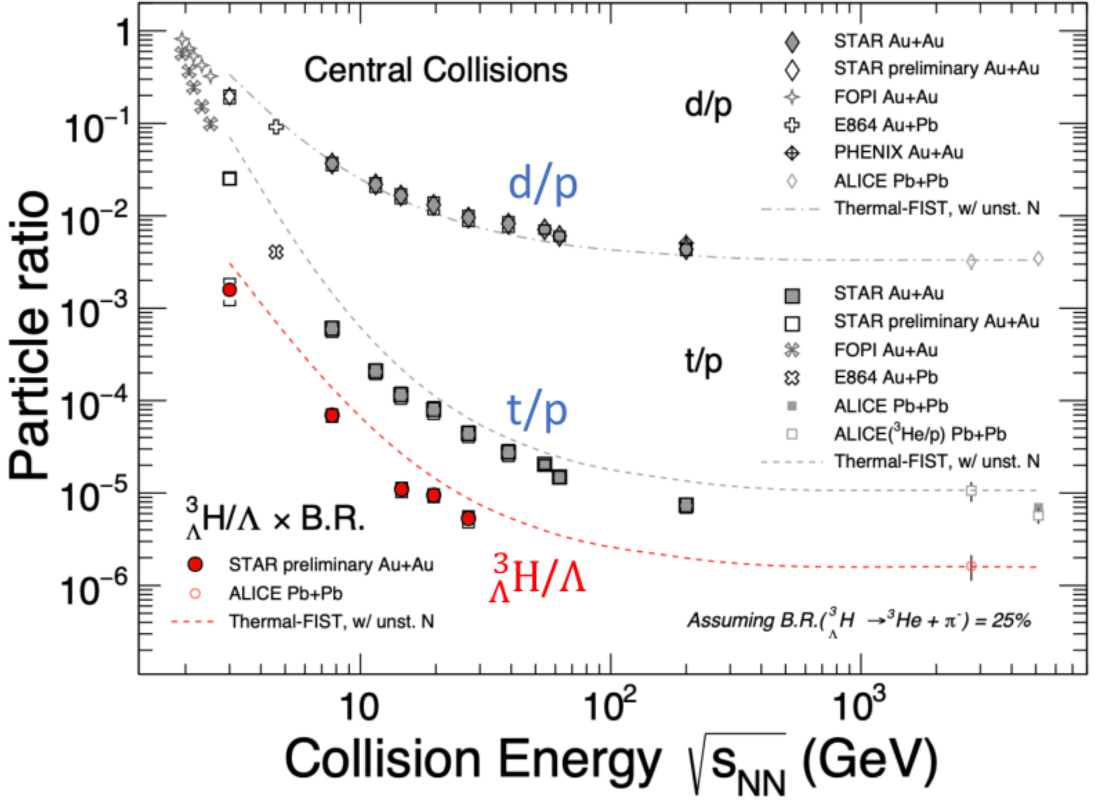
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Outline

- Introduction
- Collective flow measurements for light nuclei (v_1, v_2, v_3)
- Summary

Light nuclei production in heavy-ion collisions

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



STAR Collaboration, Quark Matter 2023

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- ❑ **Abundant at high baryon density, unclear production mechanisms**

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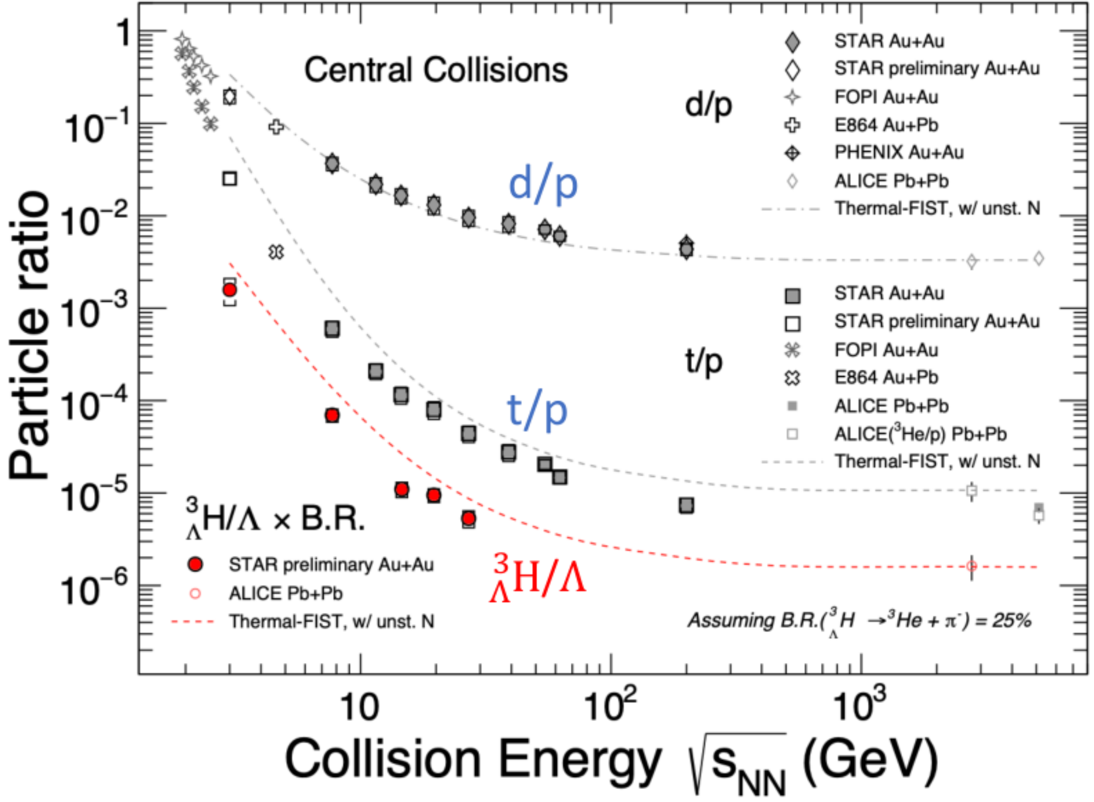
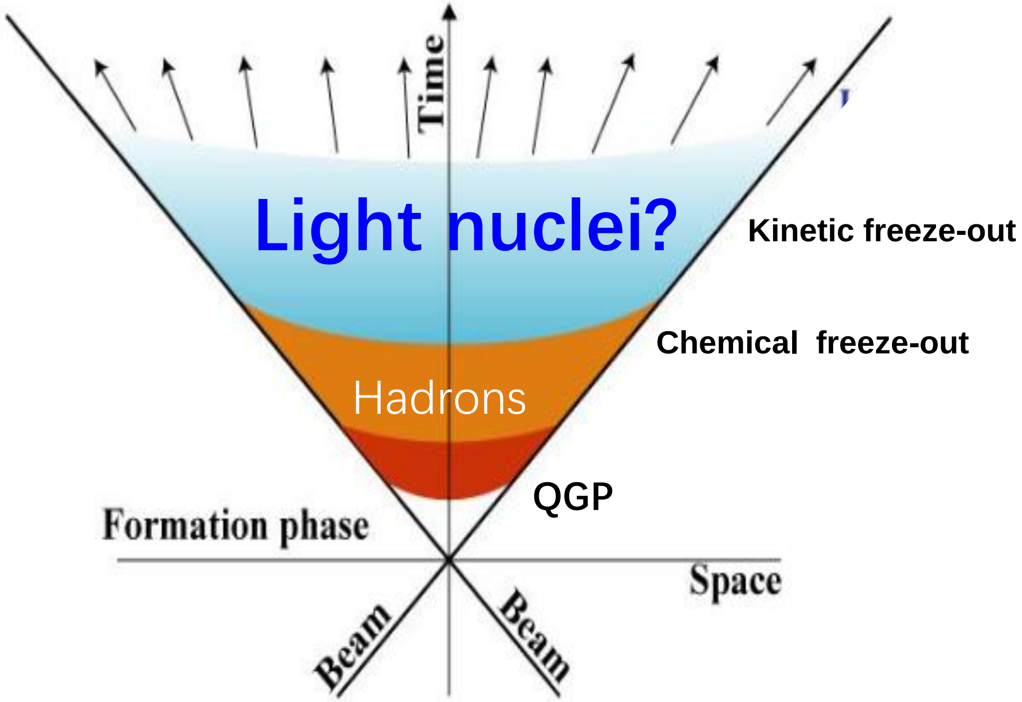


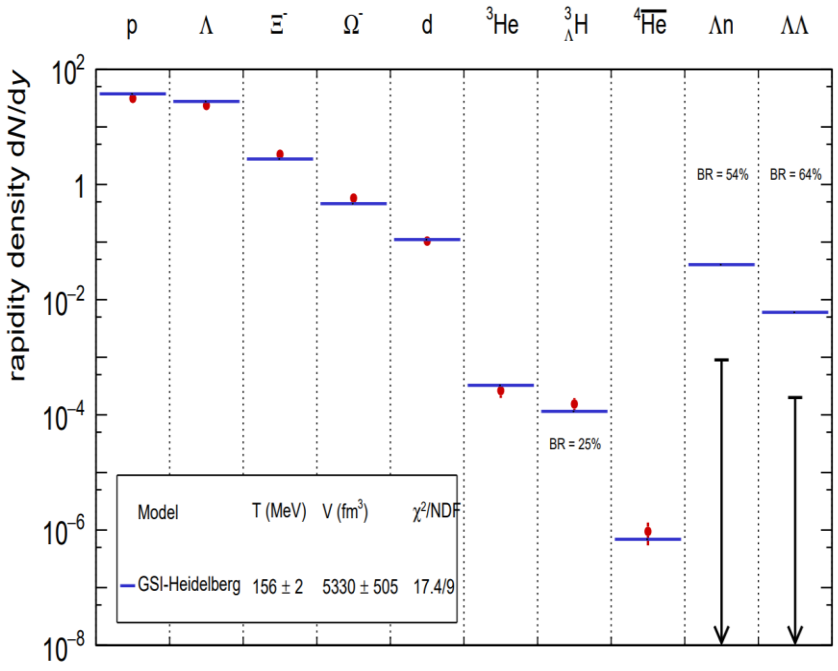


Light nuclei production mechanisms

Thermal model

assumption of thermal equilibrium

Nuclear Physics A 987, 144 (2019)



T_{cfo}=156 ±2 MeV

Binding energy: ~MeV

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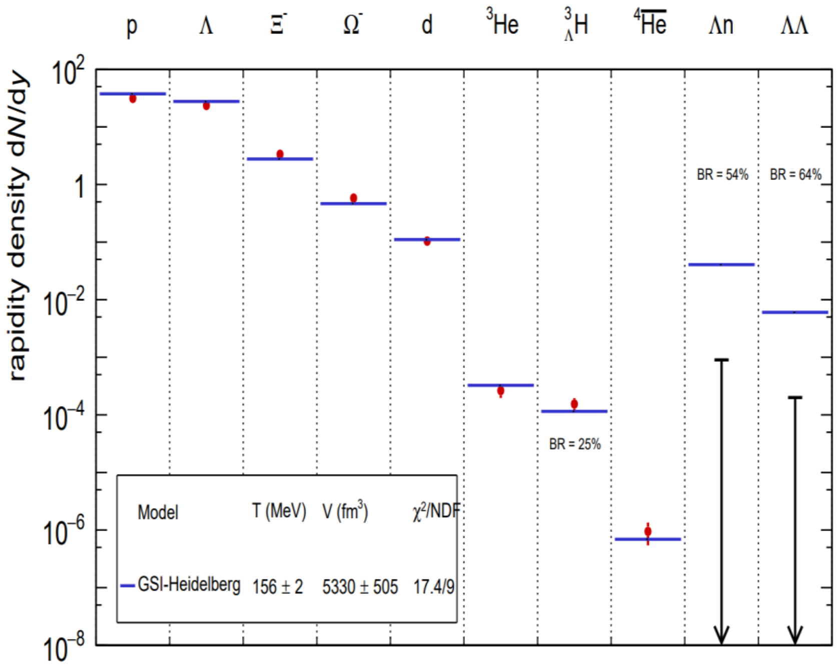

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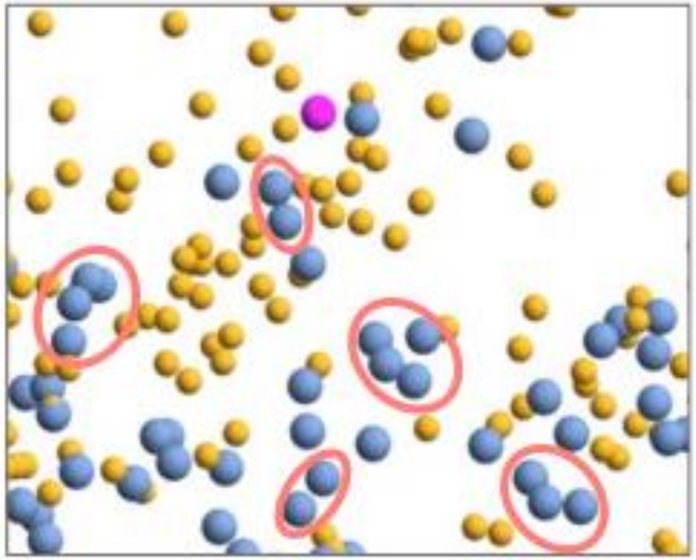
Coalescence of nucleons

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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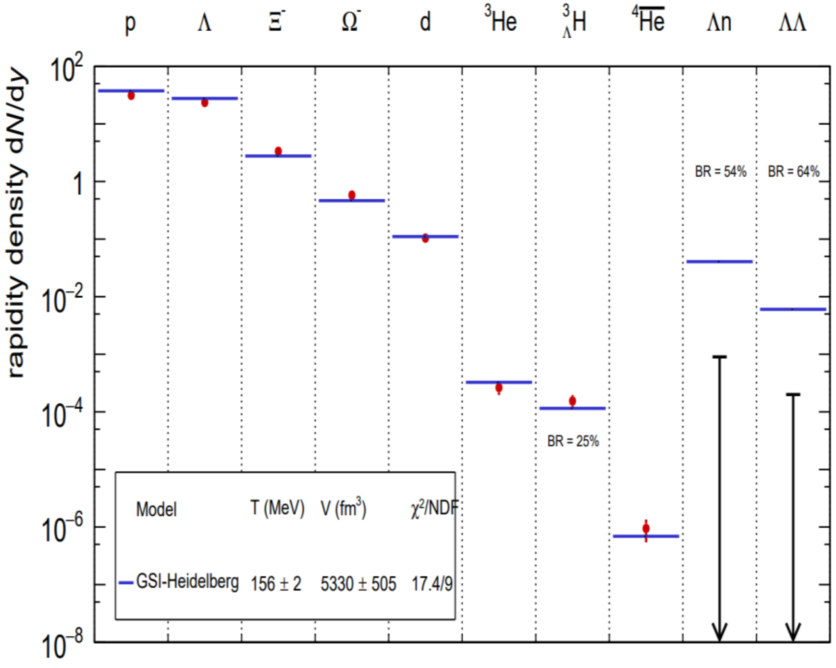

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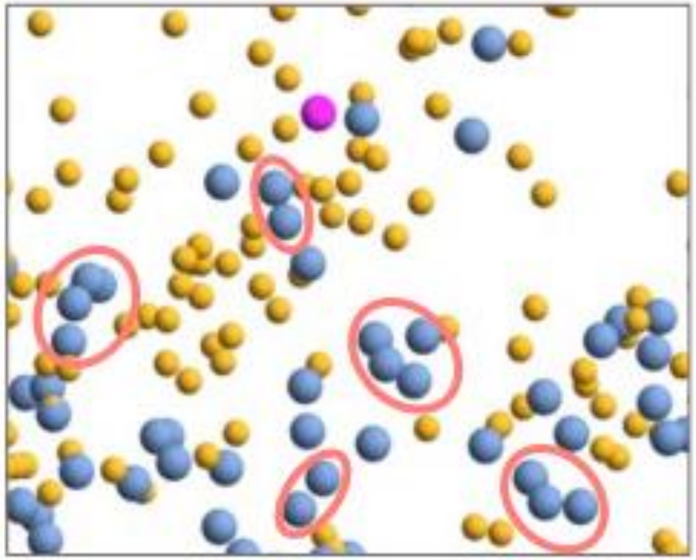

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$$\times f_A(\mathbf{x}'_1, \ldots, \mathbf{x}'_A; \mathbf{p}'_1, \ldots, \mathbf{p}'_A)\delta^{(3)}\left(\mathbf{P}_A - \sum_{i=1}^{A} \mathbf{p}_i\right)$$

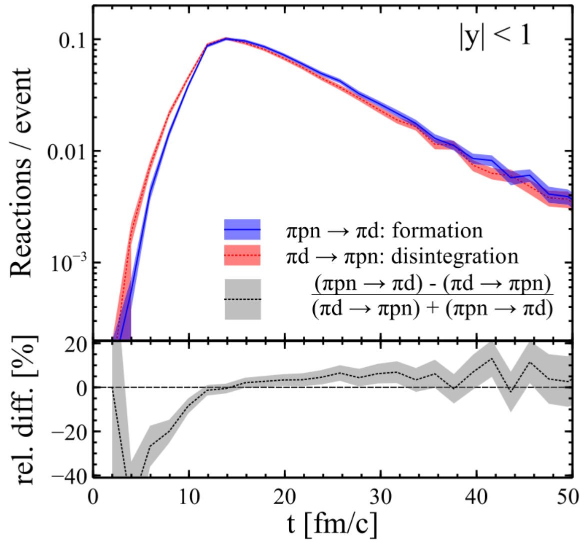
Kinetic transport

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)

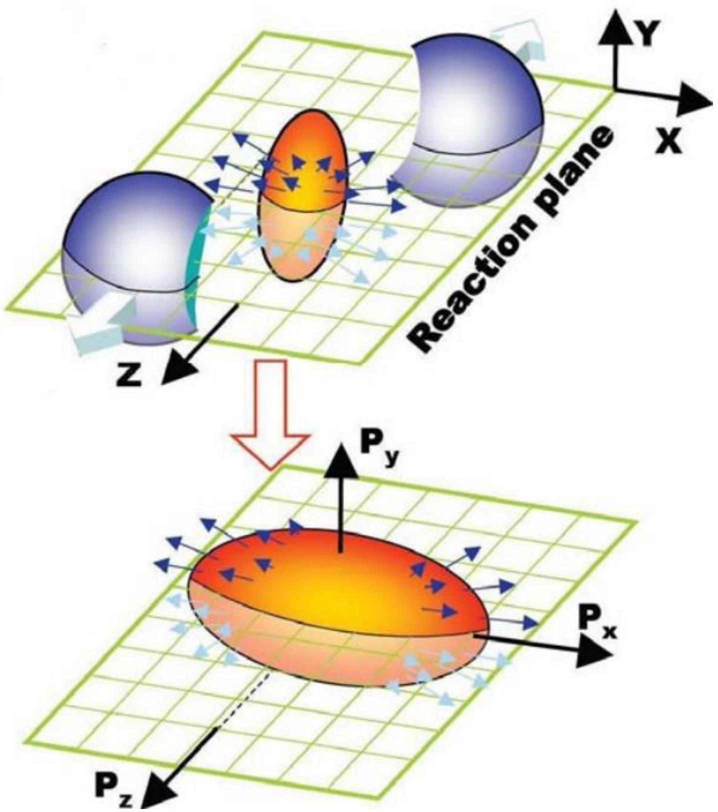
Initial spatial anisotropy

↓

Pressure gradient

↓

Final momentum asymmetry



Anisotropic flow: non-central collision or initial fluctuations

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

☐ $\mathbf{v_1}$: deflection happens during passing time

☐ $\mathbf{v_2}$: sensitive to initial eccentricity

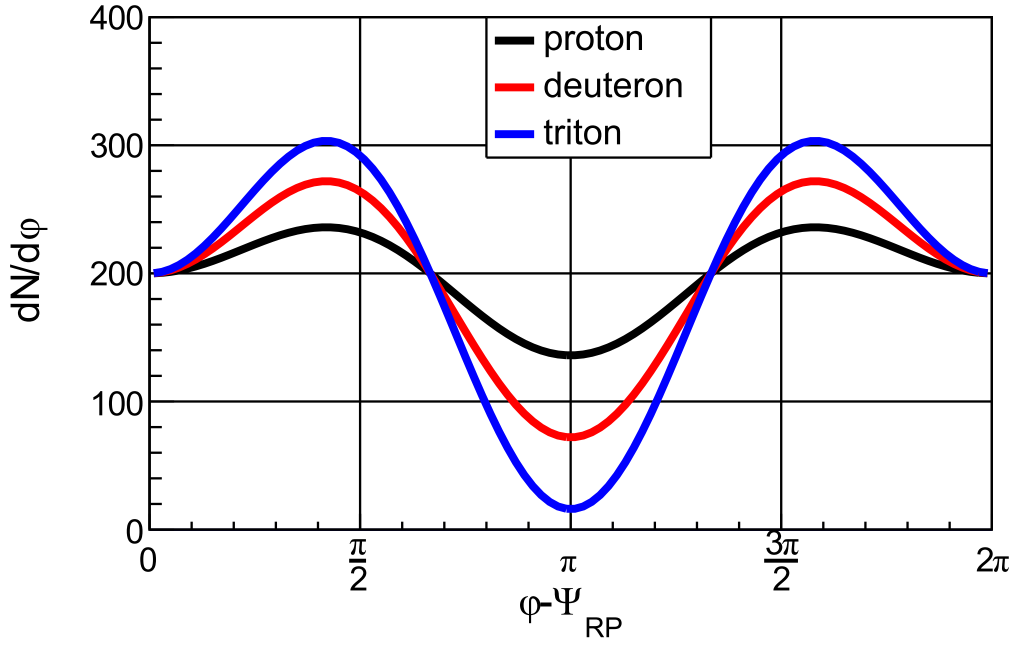
☐ $\mathbf{v_3}$: fluctuation of overlap zone

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)

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

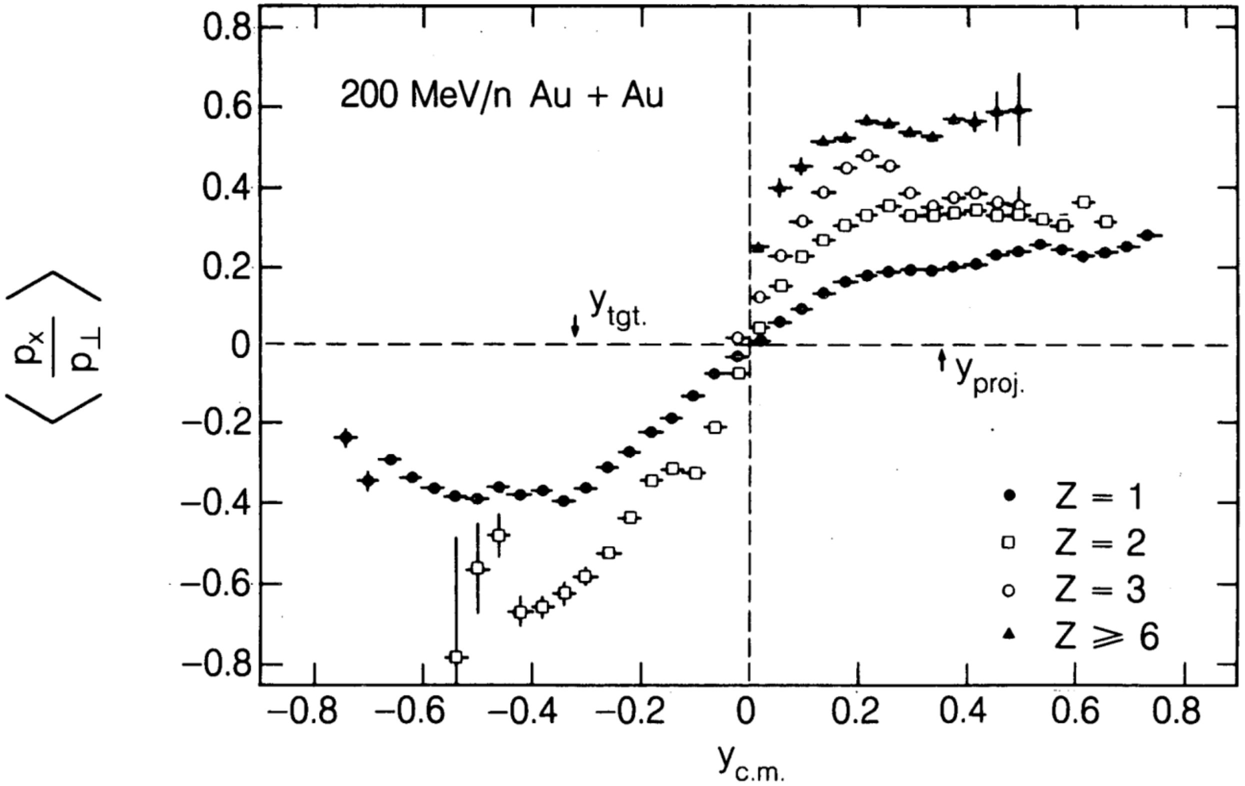


- **Provide valuable information on production mechanisms, incompressibility, in-medium NN interactions**
- **Both proton and light nuclei are measurable**

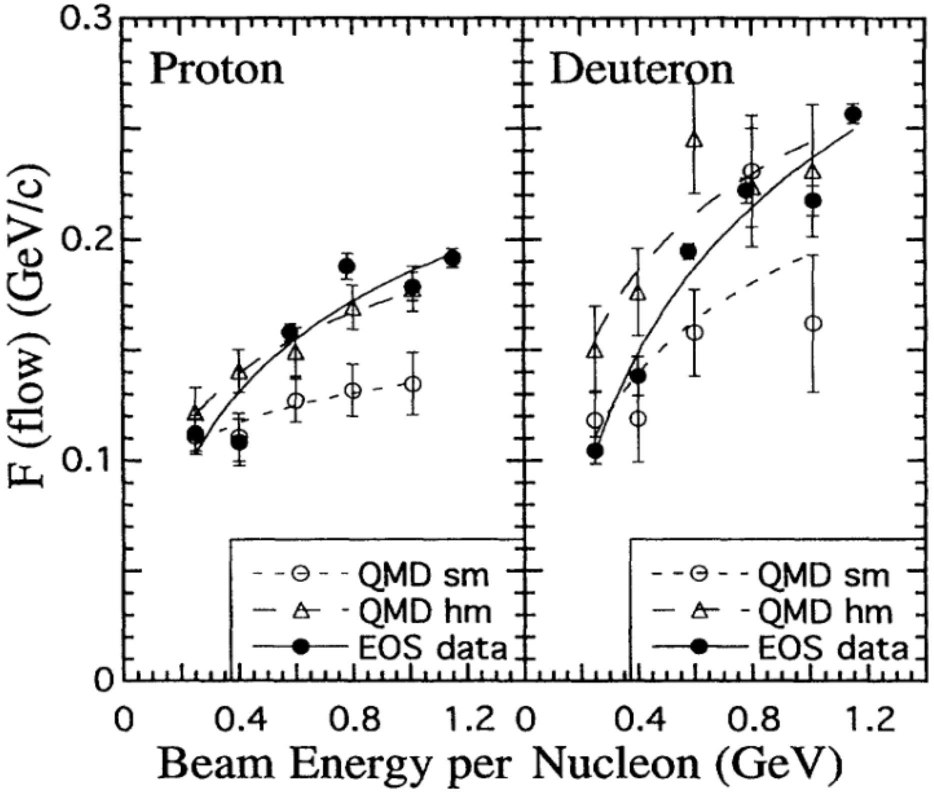
Light nuclei flow measurement

First measurement: Lawrence Berkeley Laboratory Plastic Ball/Wall detector system

Phys. Rev. Lett. 59, 2720(1987)

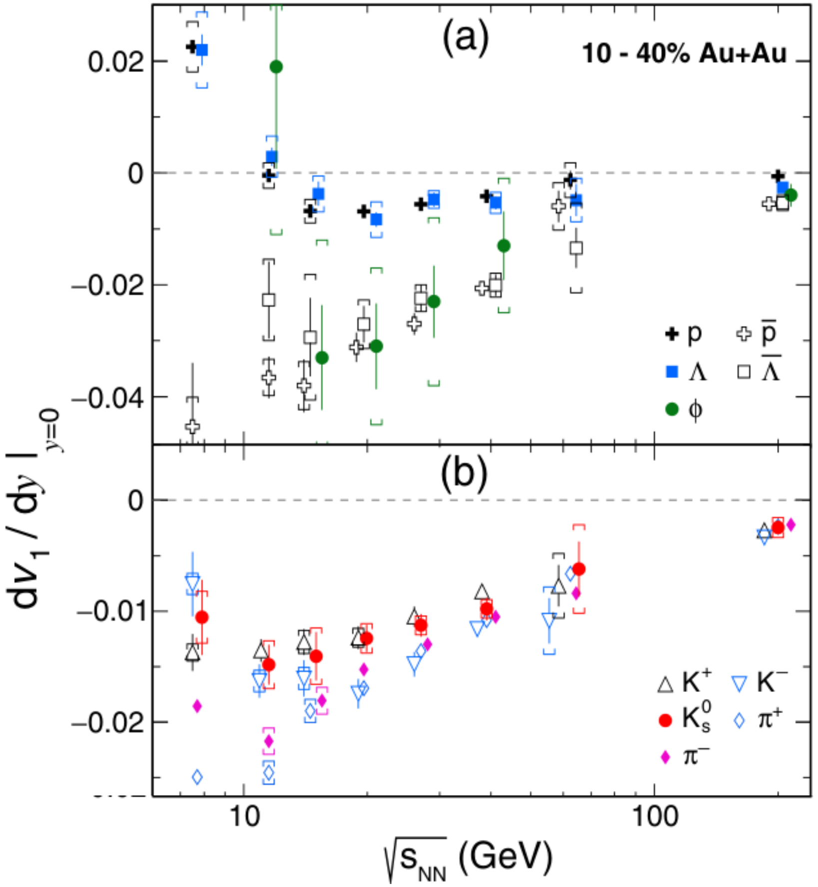


EOS Collaboration Phys. Rev. Lett. 75, 2100(1995)



Proton flow at high baryon densities

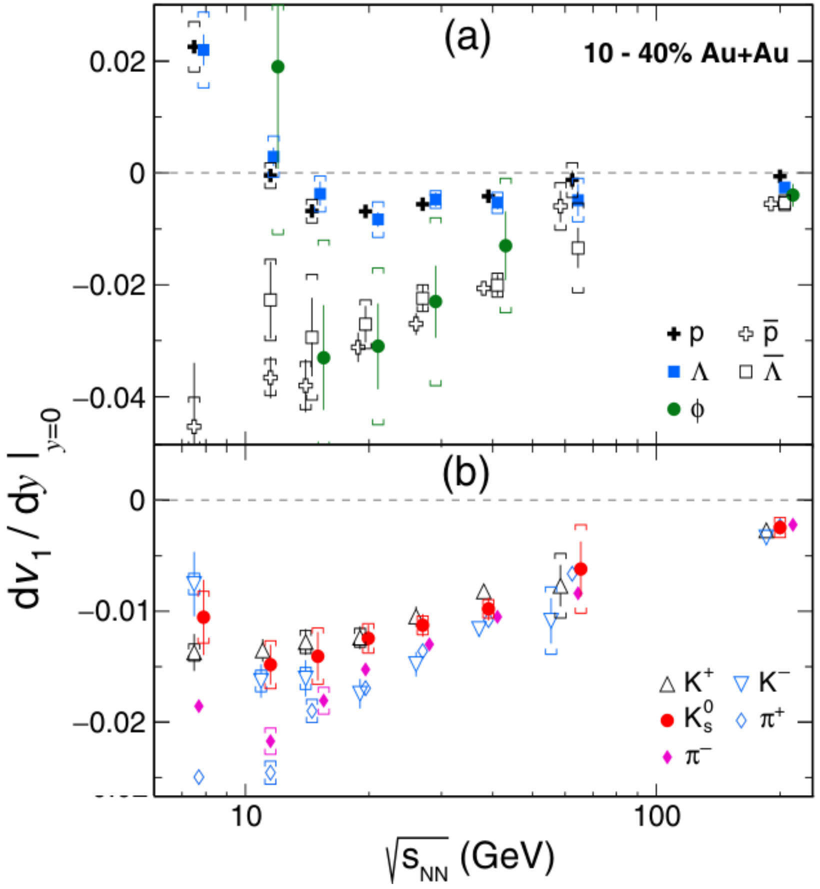
STAR Collaboration, Phys. Rev. Lett. 120, 062301 (2018)



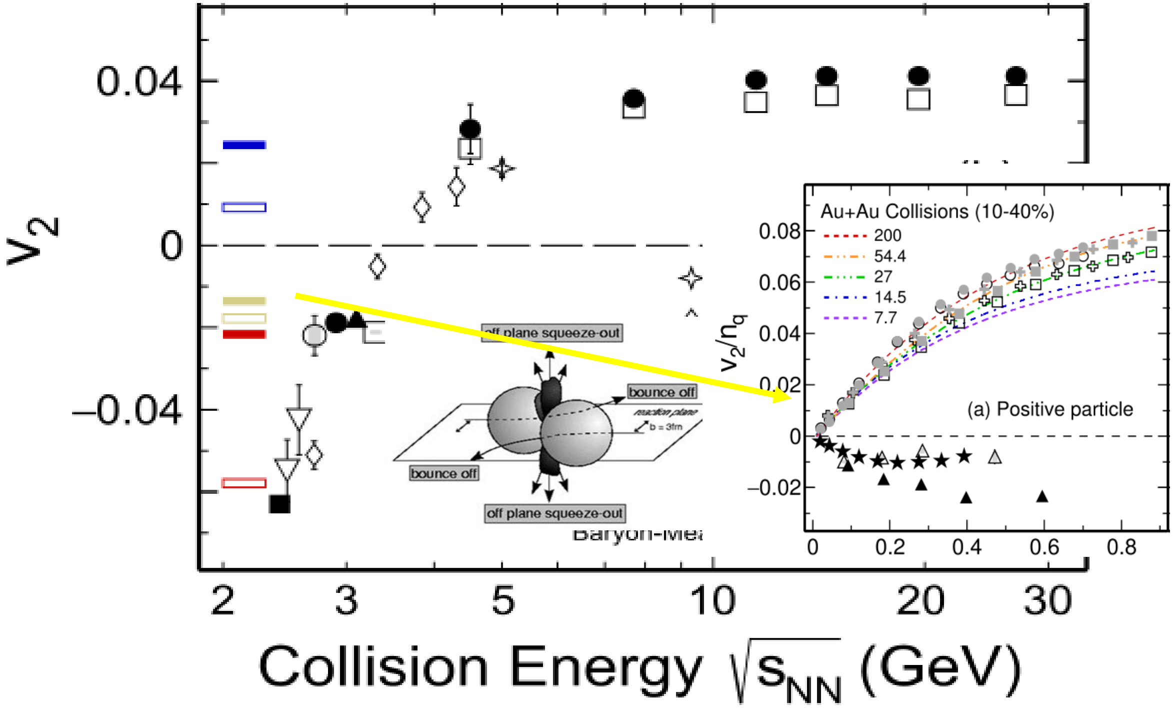
- ☐ dv_1/dy decreases with increasing energy and changes sign at higher collision energies

Proton flow at high baryon densities

STAR Collaboration, Phys. Rev. Lett. 120, 062301 (2018)



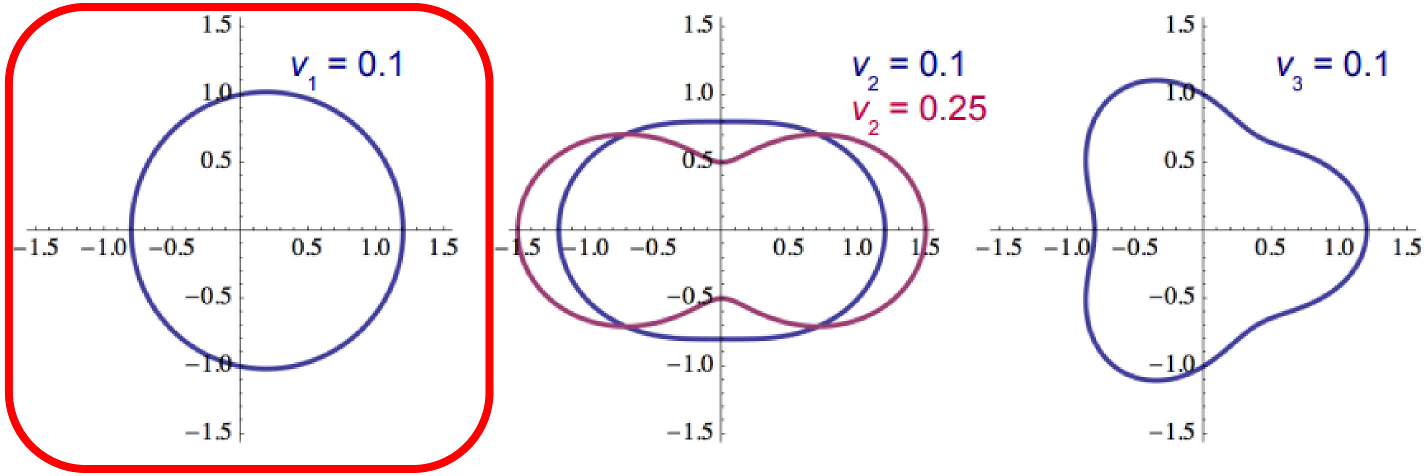
STAR Collaboration, Phys. Lett. B 827,137003 2022



- dv_1/dy decreases with increasing energy and changes sign at higher collision energies

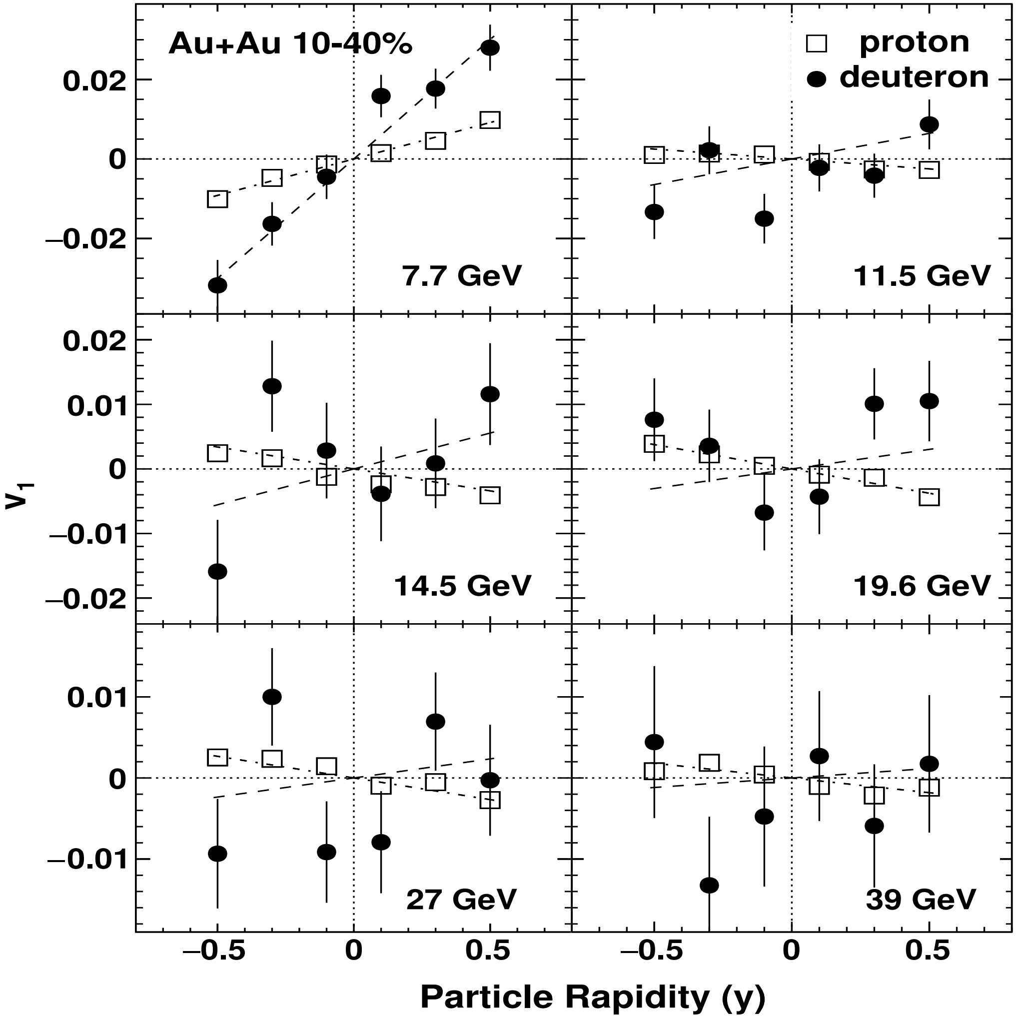
- **Negative v_2 (2-3.5 GeV): squeeze-out effect by the spectator;**
  Disappearance of partonic v_2 at 3 GeV

Directed Flow of Light Nuclei

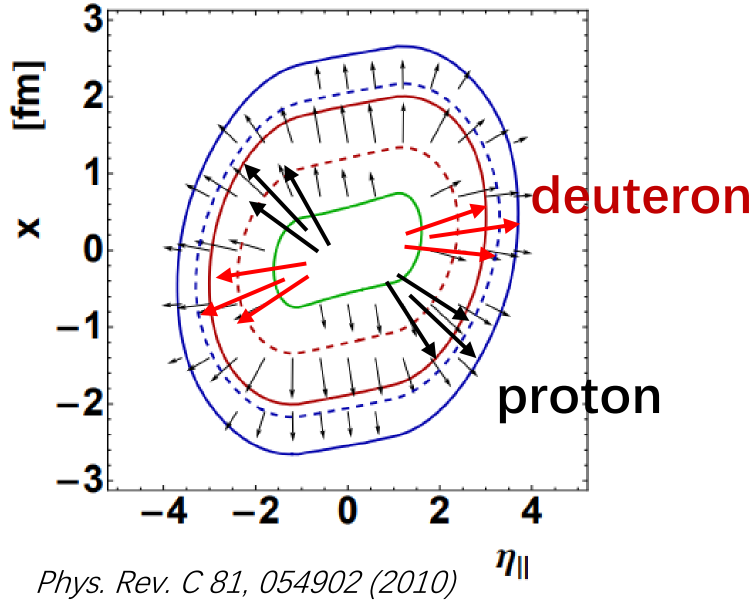


Deuteron v_1 for $\sqrt{s_{NN}} \geq 7.7$ GeV

STAR Collaboration, Phys. Rev. C 102, 044906 (2020)



- **Hint of positive of deuteron v_1 slopes within 7.7-39 GeV**

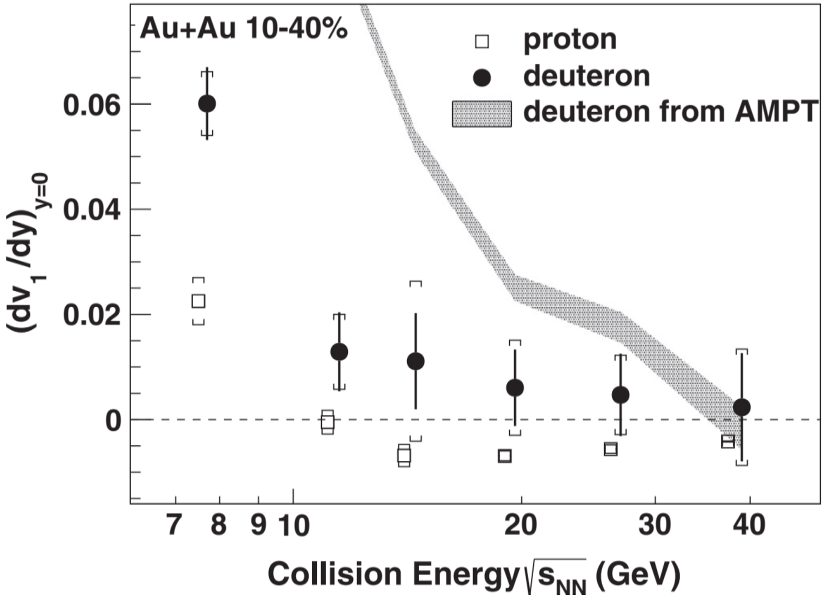


Phys. Rev. C 81, 054902 (2010)

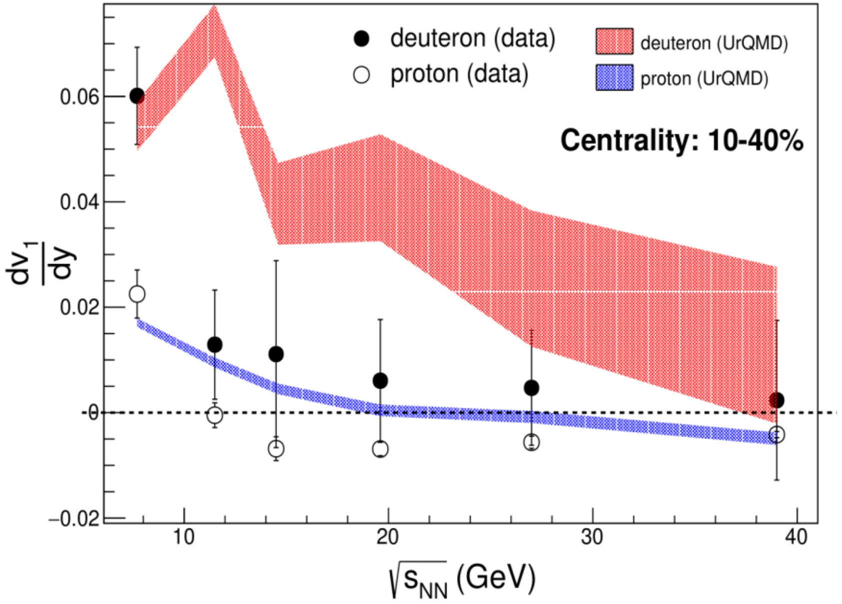
- **Both precise measurements and theoretical insight needed**

Model calculations for deuteron v_1

STAR Collaboration, Phys. Rev. C 102, 044906 (2020)



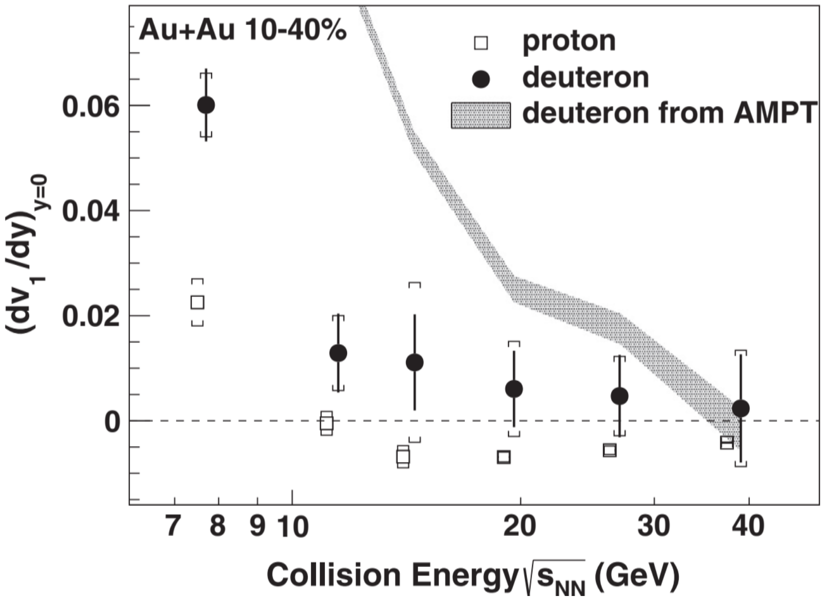
Modern Physics Letters A 39, 07 (2023)



- ❑ Model calculations failed to describe both the proton and deuteron v_1

Model calculations for deuteron v_1

STAR Collaboration, Phys. Rev. C 102, 044906 (2020)



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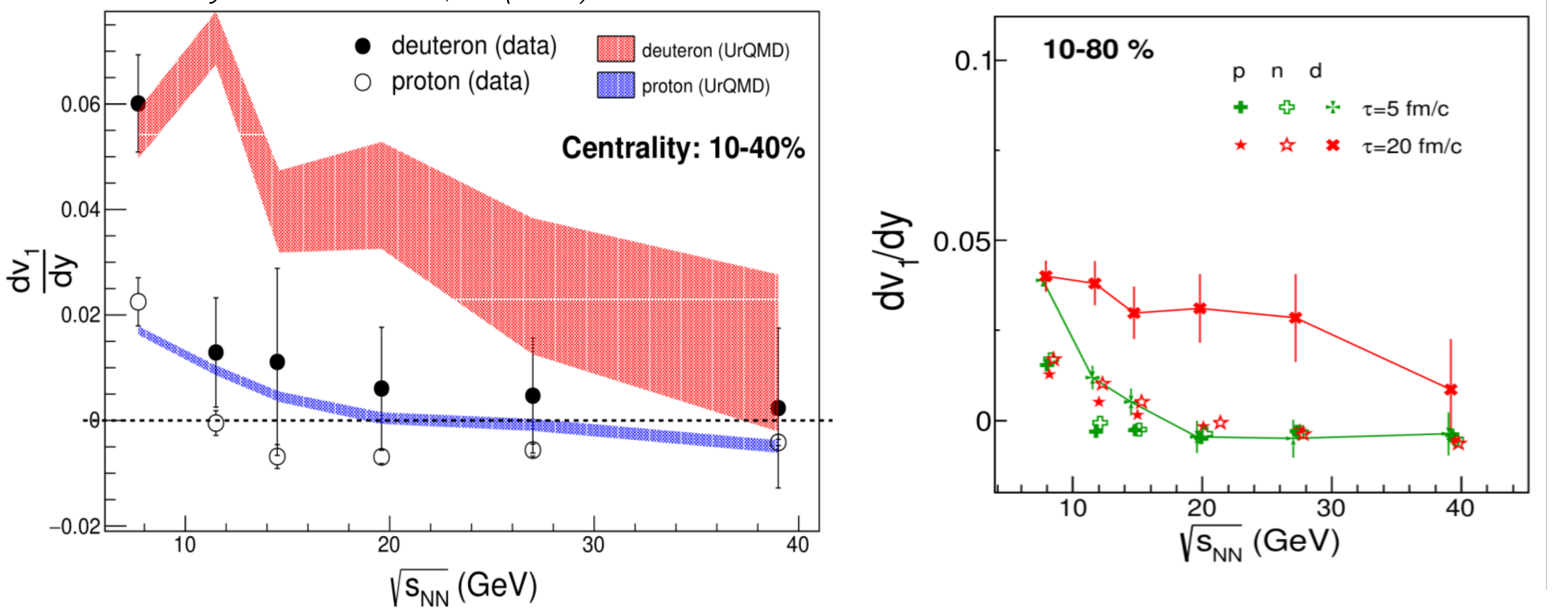
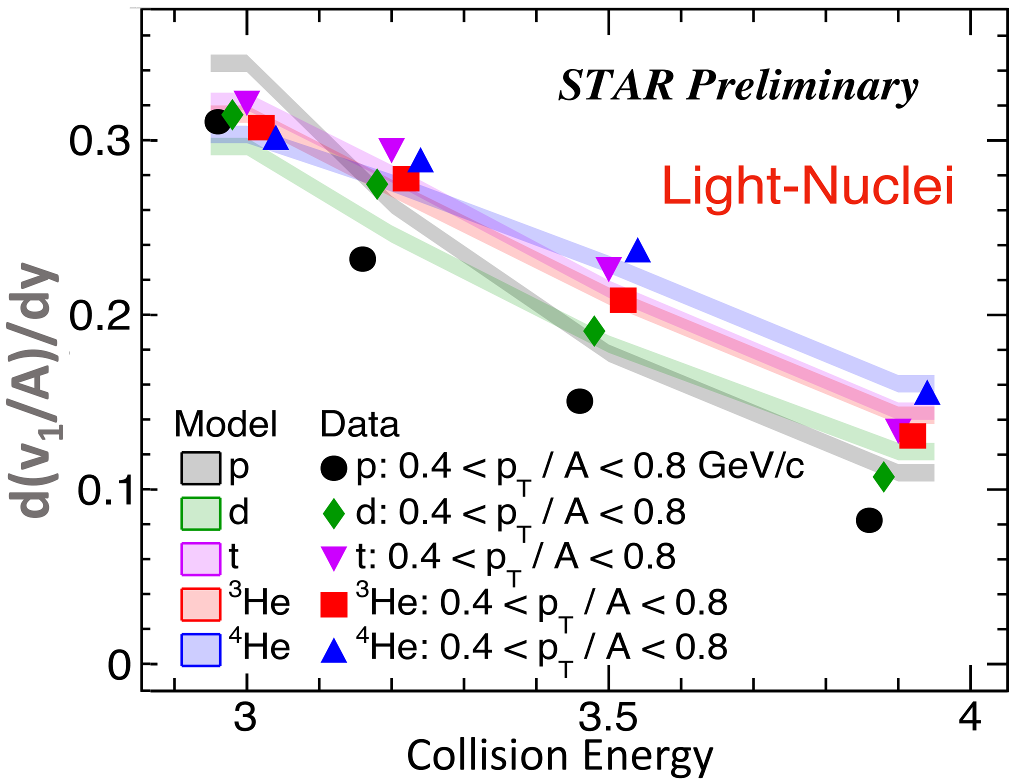


- ☐ Model calculations failed to describe both the proton and deuteron v_1
- ☐ Deuteron v_1 is much sensitive to evolution time(hadronic interactions)

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

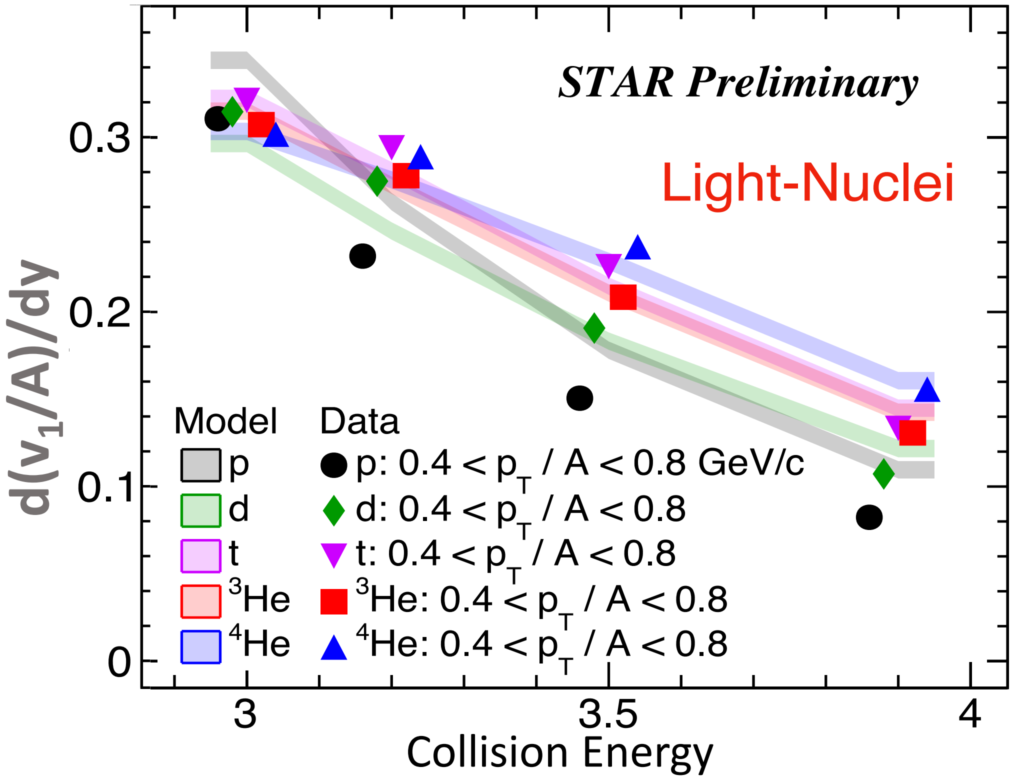


Collision Energy

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

1. *STAR Collaboration, Phys. Lett. B 827, 136941 (2022)*
2. *STAR Collaboration, Quark matter 2023*

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



Collision Energy

1. *STAR Collaboration, Phys. Lett. B 827, 136941 (2022)*
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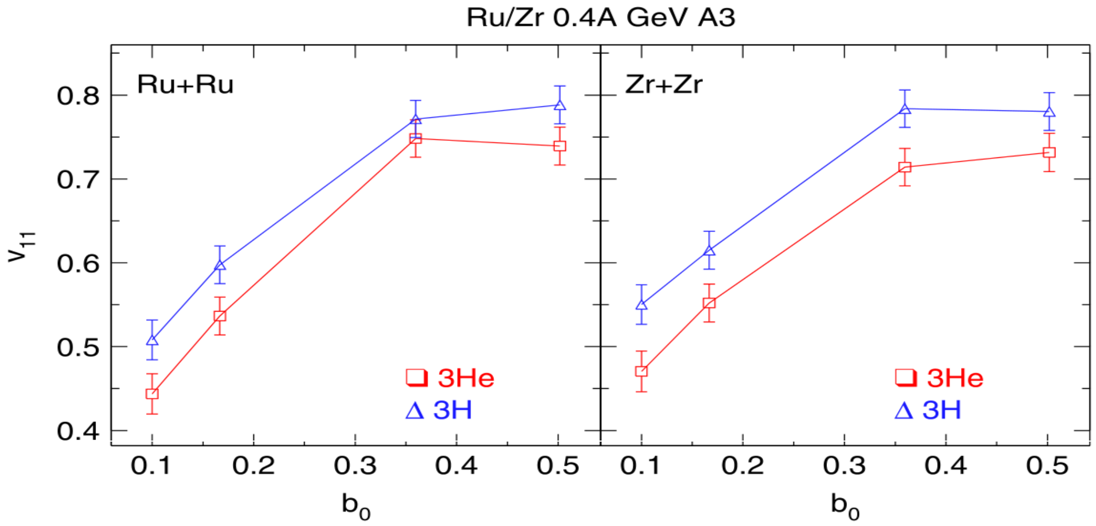
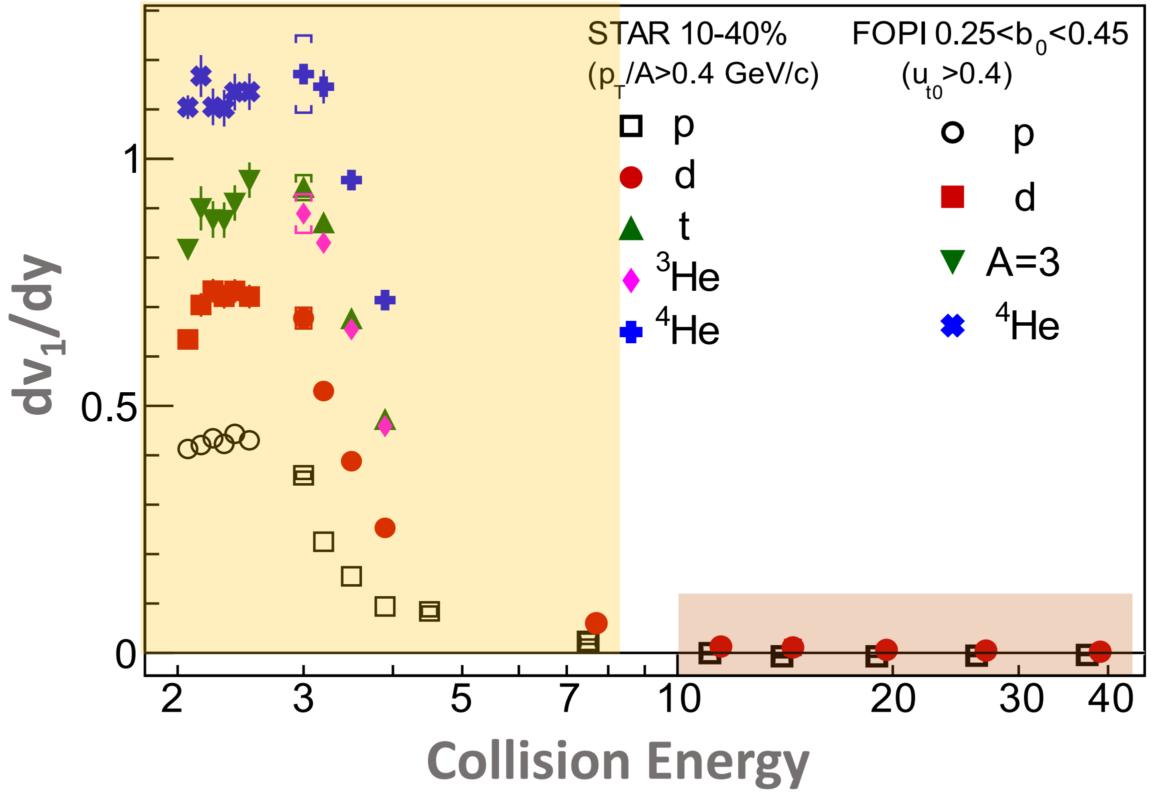
- Mass number scaling holds at 3 GeV, tends to be broken at higher energies
- **Triton v_1 is slightly stronger than that of ^{3}He, neutron see a more repulsive mean-field?**



FOPI Collaboration, Nuclear Physics A 876, 1 (2012)

Light nuclei v_1 slope at mid-rapidity



1. *STAR Collaboration, Phys. Rev. C 102, 044906 (2020)*
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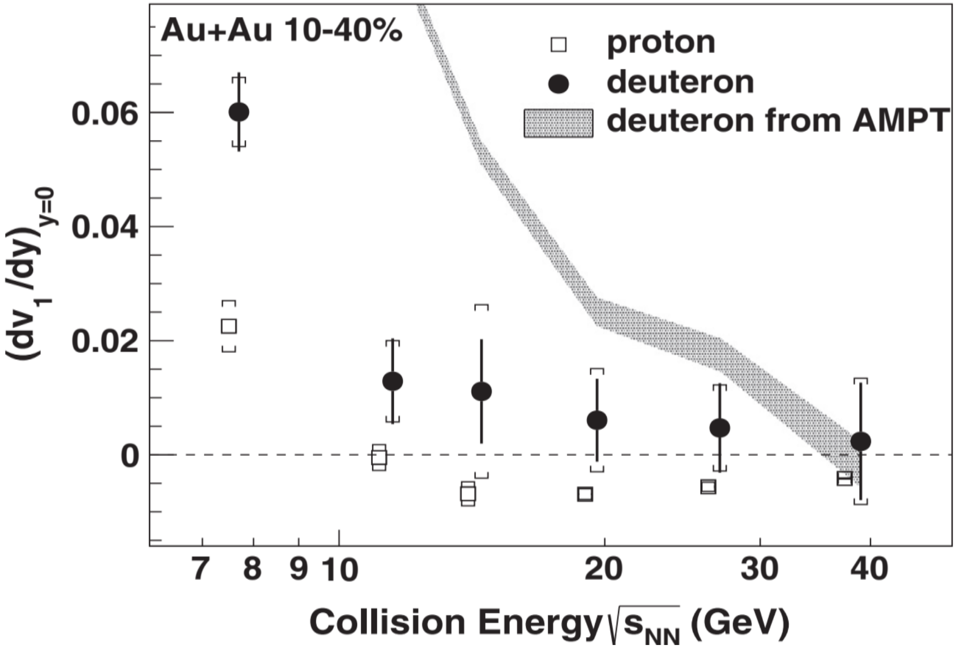
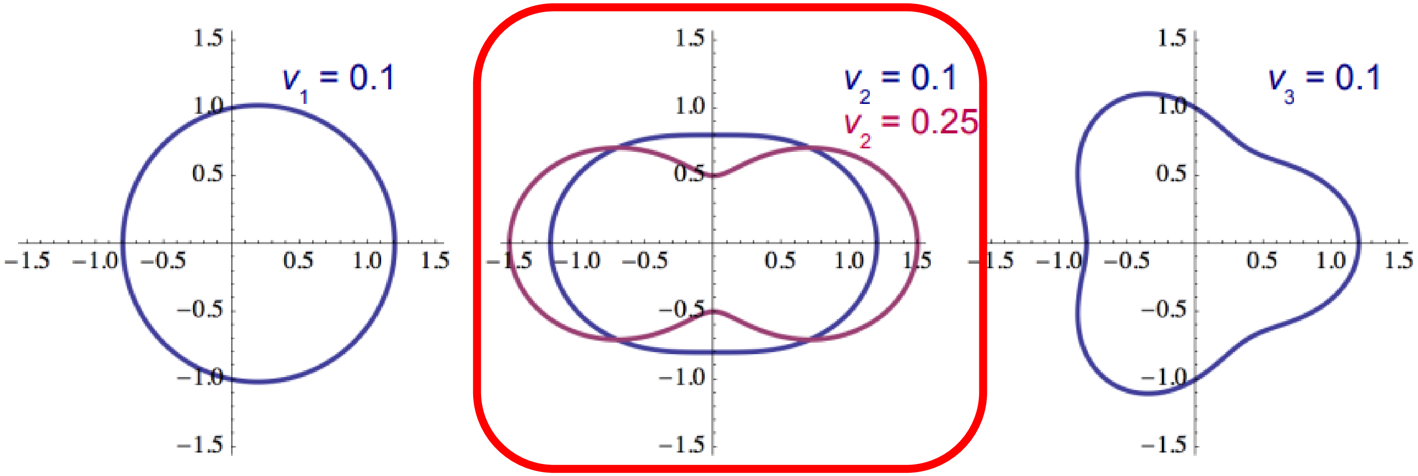
3. *FOPI Collaboration, Nuclear Physics A 876, 1 (2012)*



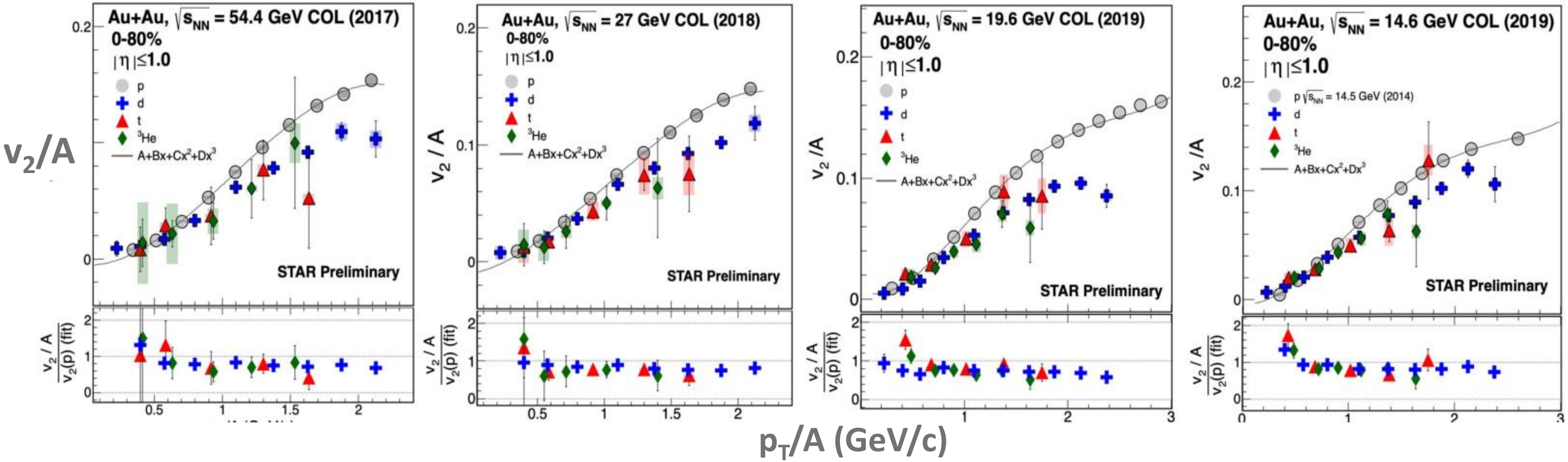
- ❑ Flat dv_1/dy within 2-3 GeV **(maximum)**, then decreases with the increasing collision energies
- ❑ Above 7.7 GeV, **hint of positive slopes for deuteron v_1**, the reason is unclear
- ❑ **Pronounced energy dependence for heavier nuclei at high baryon density**

Elliptic Flow of Light Nuclei



Light nuclei v_2 at $\sqrt{s_{NN}} \geq 14.6\text{GeV}$

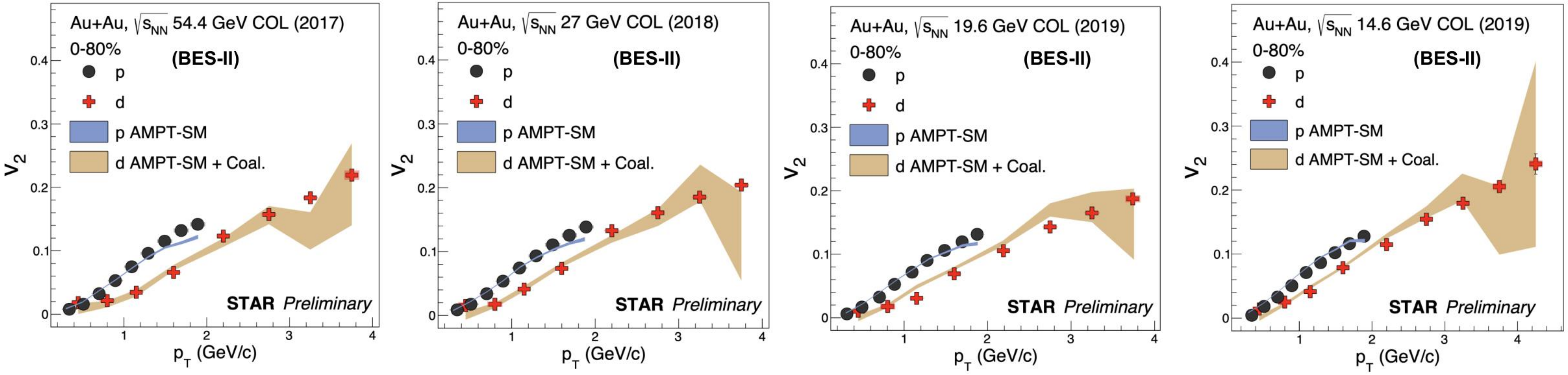
STAR Collaboration, Quark Matter 2023



Systematic deviation of around 20-30% from mass number scaling is observed for all light nuclei in measured energies.

Light nuclei v_2 at $\sqrt{s_{NN}} \geq 14.6\text{GeV}$

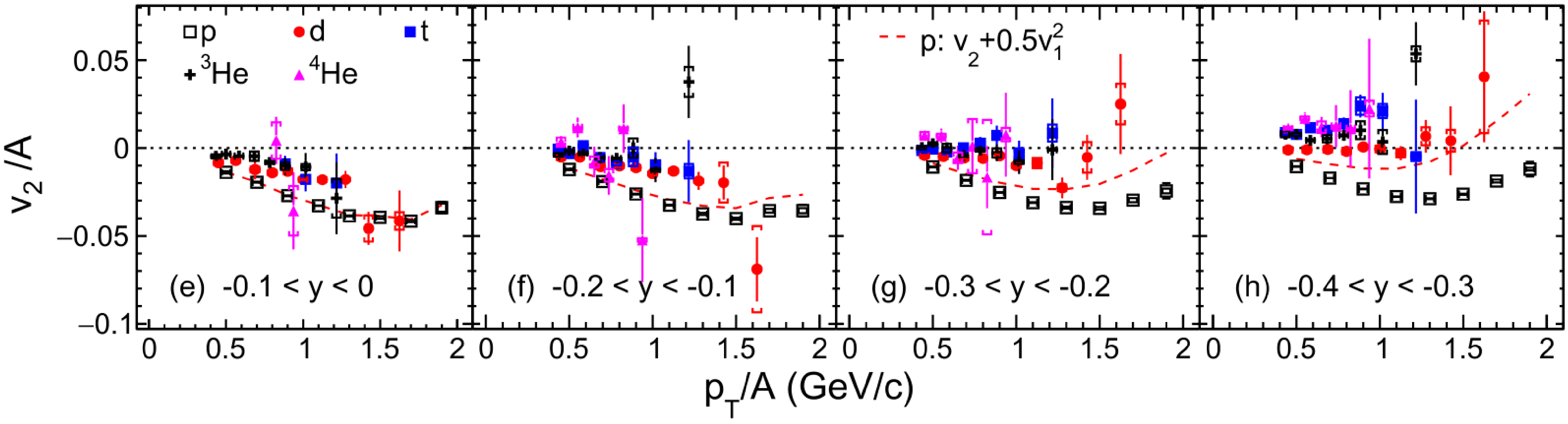
STAR Collaboration, Quark Matter 2023



Coalescence afterburner calculations are in good agreement with data → coalescence in both momentum and coordinate space are in important

Light nuclei v_2 at $\sqrt{s_{NN}} = 3.0$ GeV

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



No mass number scaling! But v_1 has the scaling. Why?

Light nuclei v_2 at $\sqrt{s_{NN}} = 3.0$ GeV

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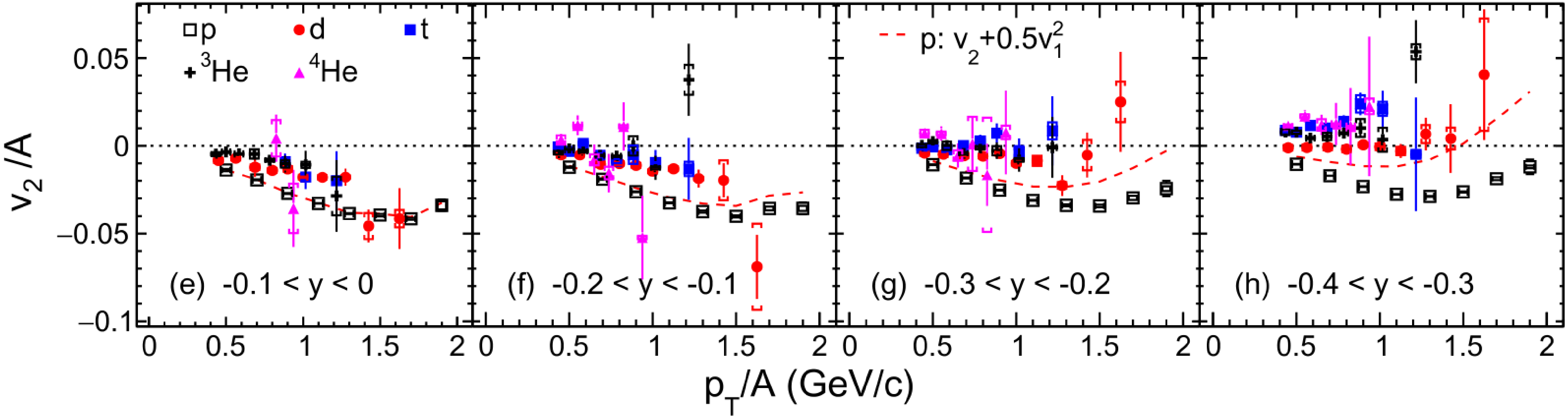
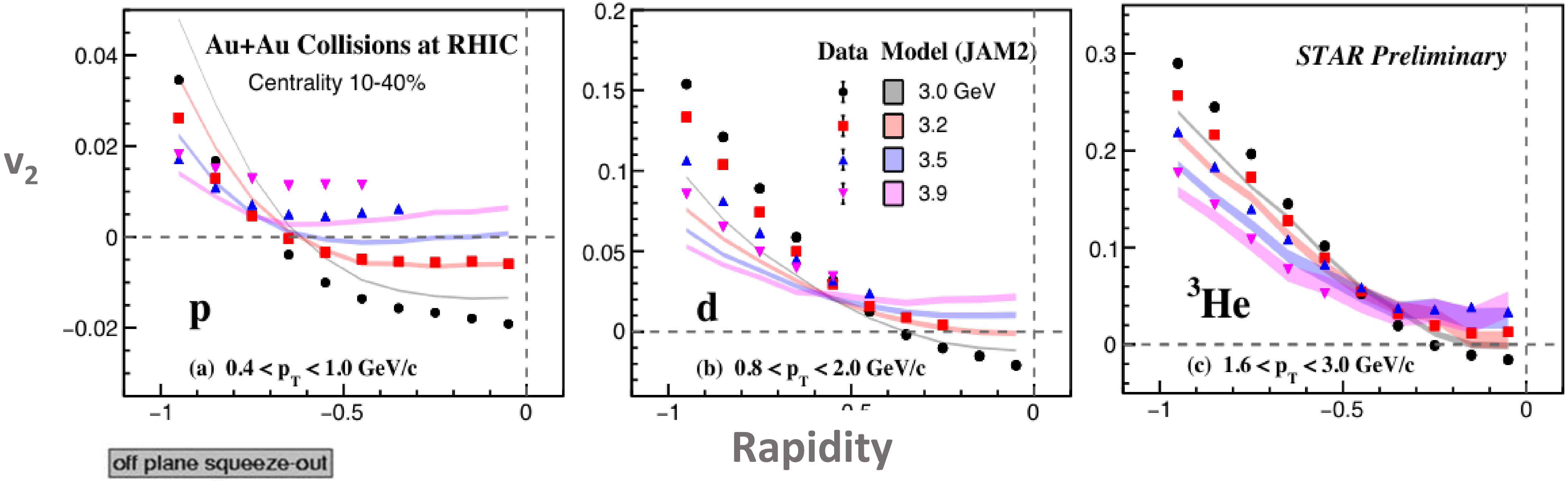


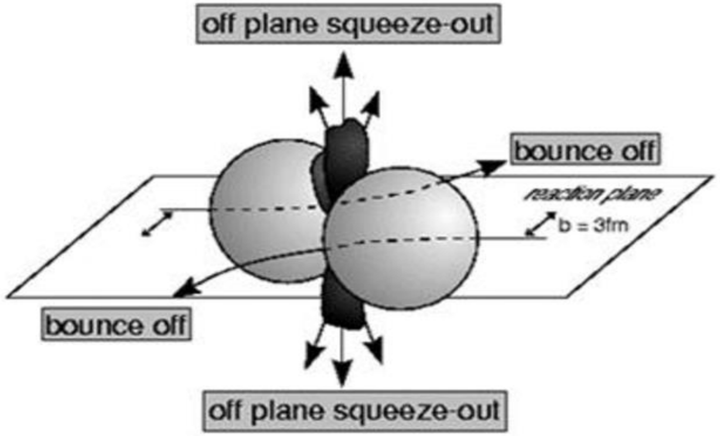
$$f(\varphi, p_T) \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos n\varphi, \qquad F(\varphi) \propto f(\varphi)^2 \propto 1 + 2\sum_{n=1}^{\infty} V_n \cos n\varphi$$

$$v_n^A(\mathrm{p_T}, \mathrm{y}) \approx A\, v_n^p(\mathrm{p_T}/A, \mathrm{y}) \;\; (v_n^p << 1) \;\; \rightarrow v_2^A(\mathrm{p_T}, \mathrm{y}) \approx A v_2^p(\mathrm{p_T}/A, \mathrm{y}) + \frac{A(A-1)}{2}\left(v_1^p(\mathrm{p_T}/A, \mathrm{y})\right)^2$$

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

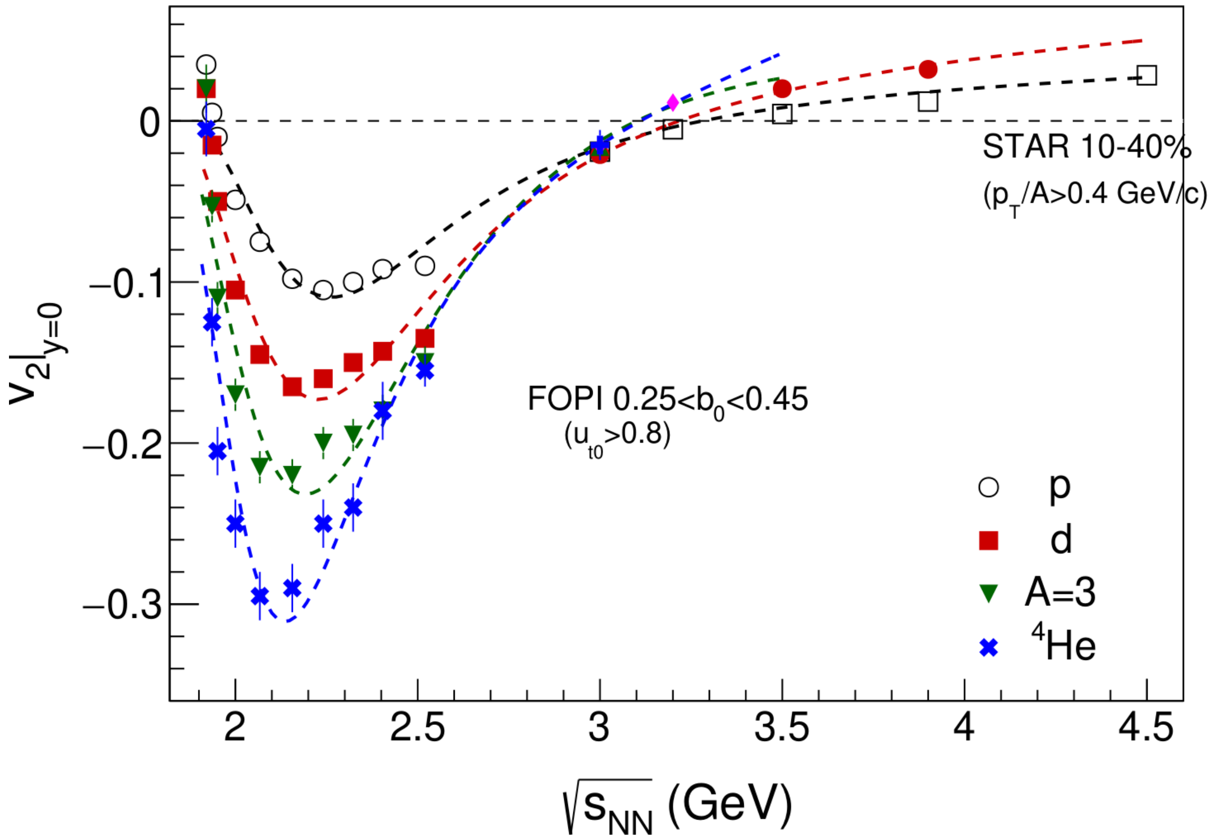
STAR Collaboration, Quark Matter 2023

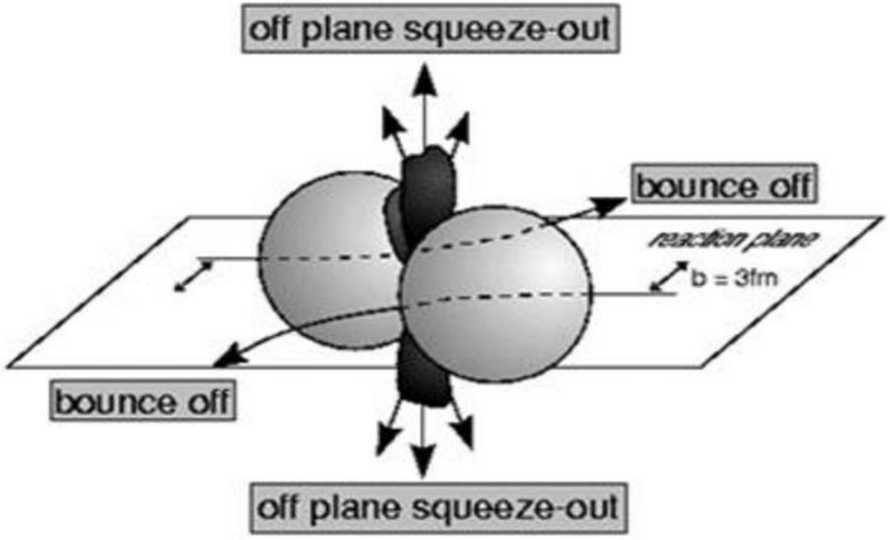




- **Heavier nuclei is less sensitive to the shadowing of the spectators**
- Mass hierarchy at mid-rapidity disappears at 3 GeV

Energy dependence of light nuclei v_2 at mid-rapidity

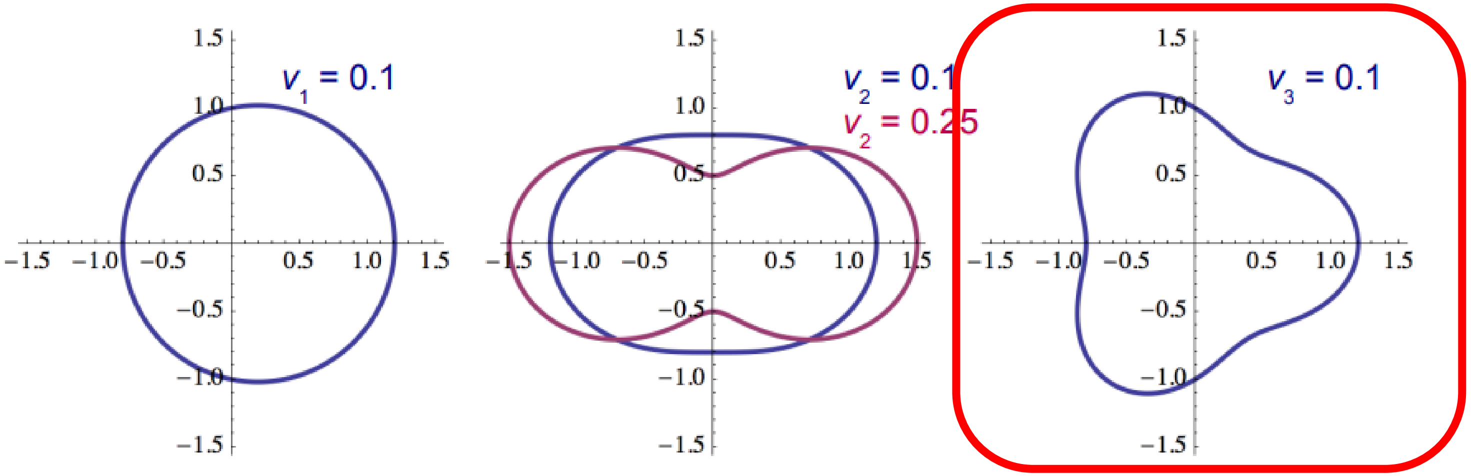




- ❑ **Pronounced energy dependence with the increasing mass**
- ❑ Location of the minimum value varies with the mass
- ❑ Zero crossing point is different for different light nucleus species

1. *STAR Collaboration, Phys. Lett. B 827, 136941 (2022)*
2. *STAR Collaboration, Quark Matter 2023*
3. *FOPI Collaboration, Nuclear Physics A 876, 1 (2012)*

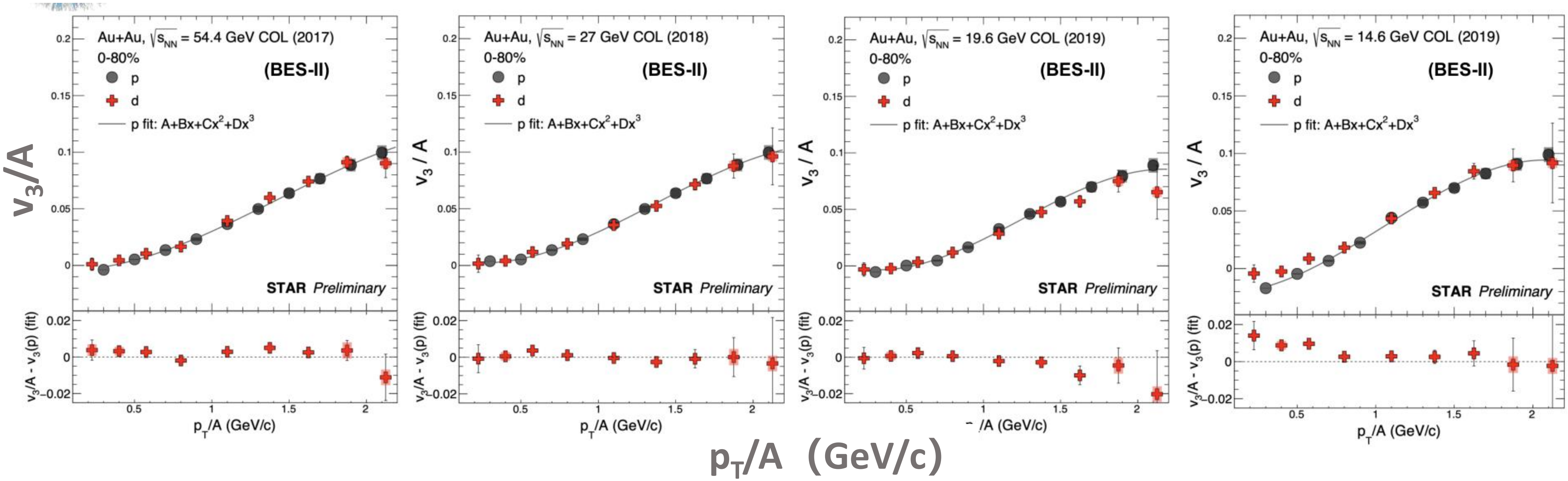
Triangular Flow of Light Nuclei



Light nuclei v_3

14.6 – 54.4 GeV

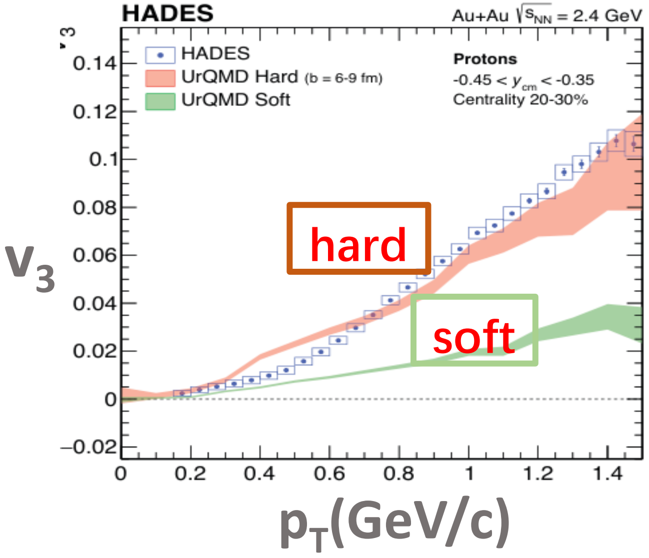
STAR Collaboration, Quark Matter 2023



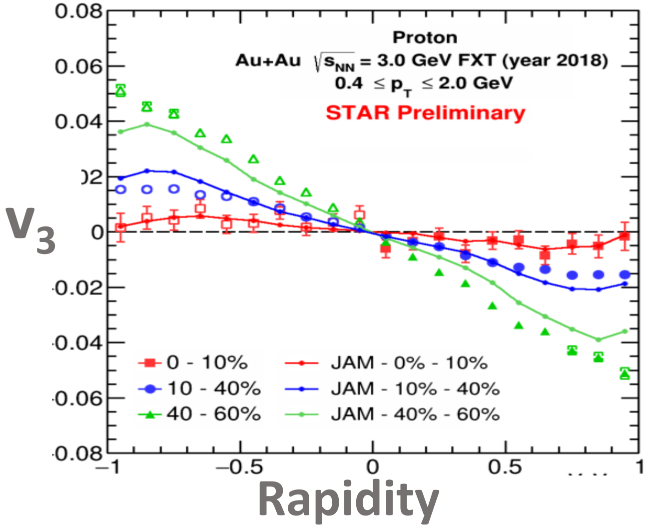
Perfect mass number scaling within 10%

Light nuclei v_3 at high baryon density

2.4 GeV

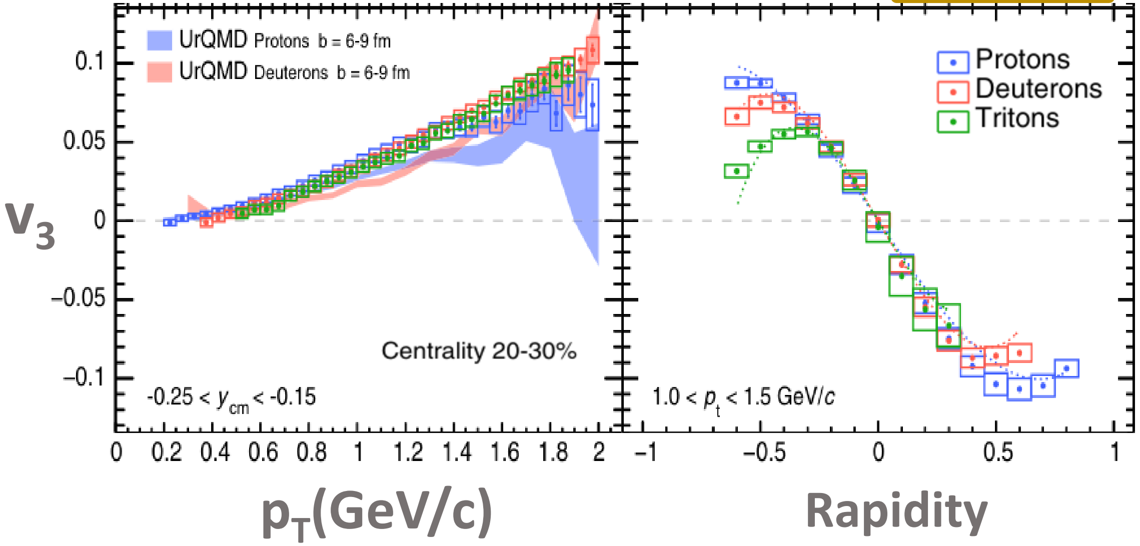


3 GeV



1. *HADES Collaboration, Quark Matter 2023*
2. *STAR Collaboration, Quark Matter 2023*
3. *BES-Tea Seminar, 2023 (Cameron Racz)*

2.4 GeV



- ❑ Highly sensitive probe to EoS, hard EoS is favored
- ❑ No significant mass dependence

Summary

❑ **Pronounced energy dependence of flow for heavier nuclei**

❑ **Production mechanisms:**

11.5-54 GeV (μ_B < 315 MeV)

- v_2 and v_3 consistent with coalescence model
- Hint of positive deuteron v_1 slopes, opposite to those of protons

→ **need more efforts**

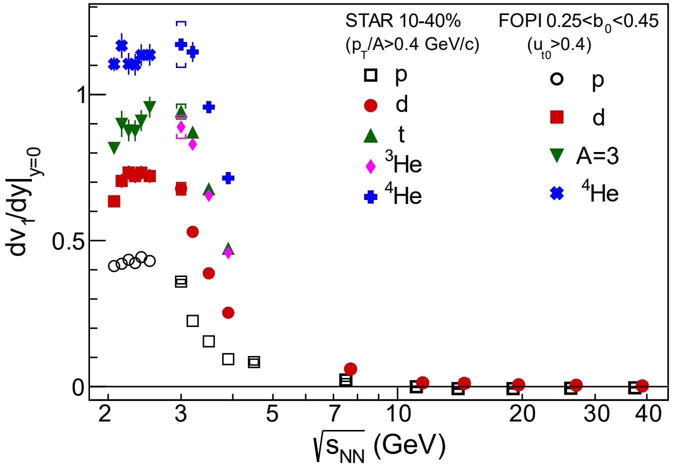
2-7.7 GeV (μ_B > 420 MeV)

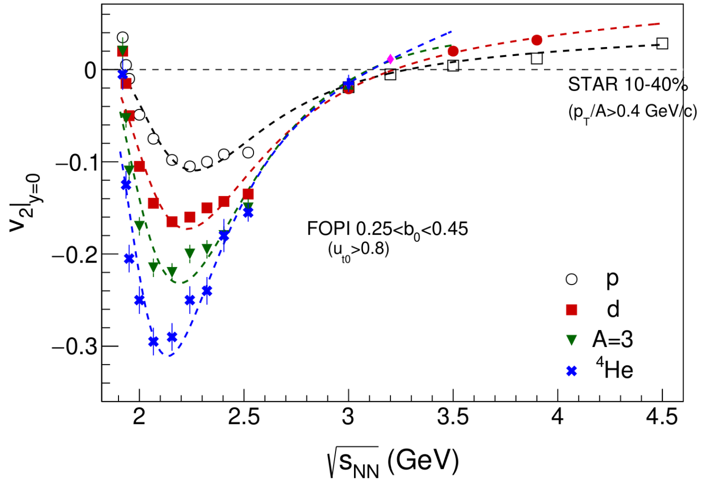
- Mass number scaling for v_1, not for v_2

→ **coalescence model**

Coalescence in both momentum and coordinate space

❑ **Hard EoS at high baryon density**





Thank you for your attention!