Light Nuclei and Hyper Nuclei Collectivity Measurements at High Baryon Density Region

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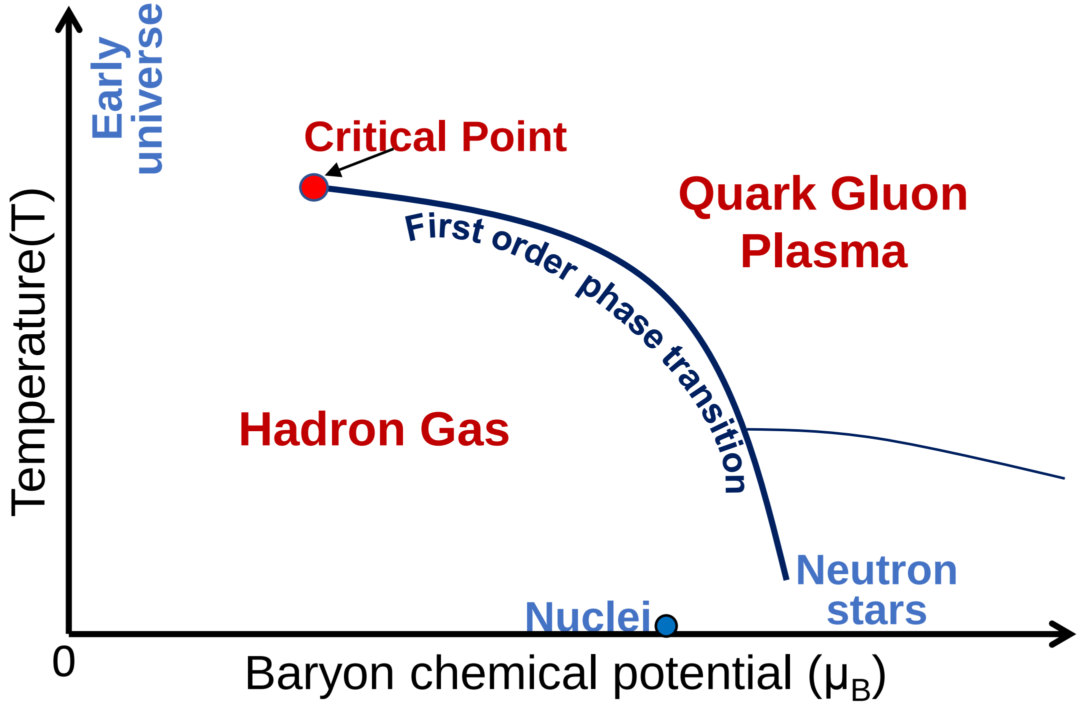
Outline

- Introduction
- Light nuclei flow measurements from high/finite baryon density region
- Hyper nuclei flow measurement
- Summary

QCD Phase Diagram at Finite Baryon Density



Finite baryon density

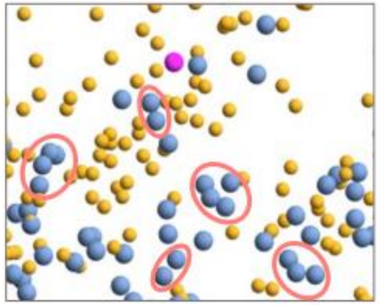
- → **First order phase transition**
- → **Critical point**
- → **Equation of state (EoS)**

Correlations are essential feature of interacting many body system.

Light Nuclei Production in Heavy Ion Collisions

Light nuclei: bound state of nucleons

- ❑ Affect the chemical composition, thermodynamical properties
- ❑ **Unclear production mechanisms in HIC**



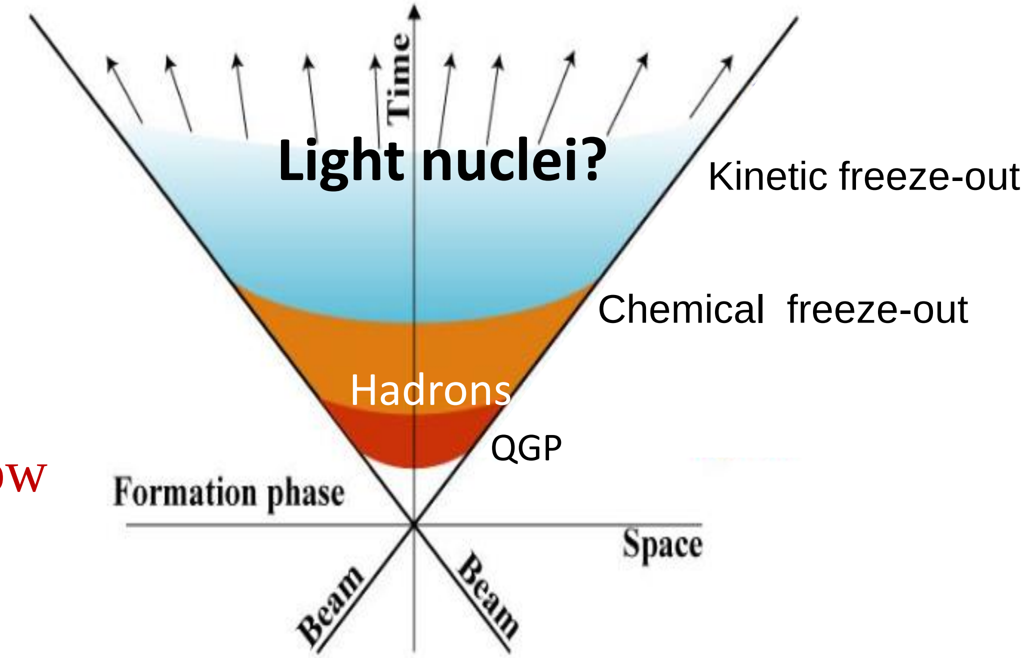
Picture from Susanne's talk at QM2022

- ➢ **Thermal model**

  Formed before chemical freeze-out

- ➢ **Coalescence of nucleons**
  - Formed near kinetic freeze-out
  - Atomic mass number (A) scaling of collective flow

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



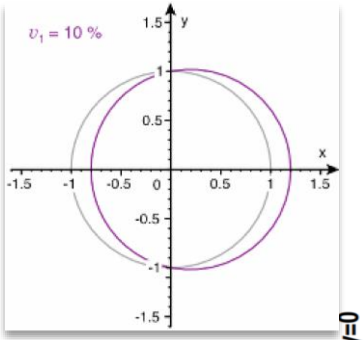
Both proton and light nuclei are measurable

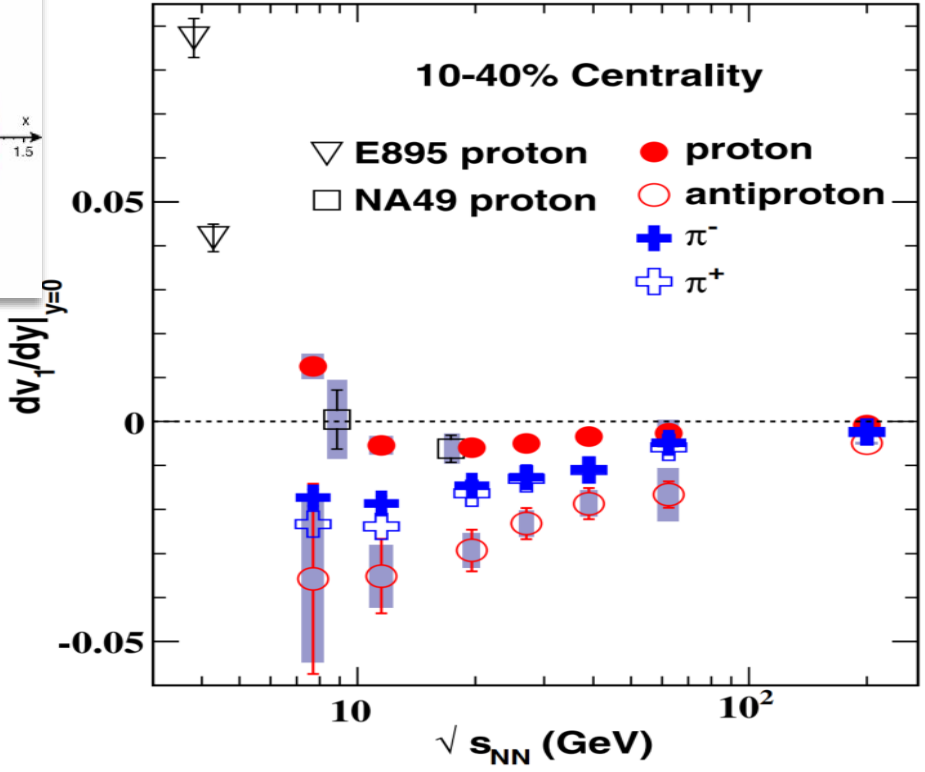
Proton Flow in Heavy Ion Collisions

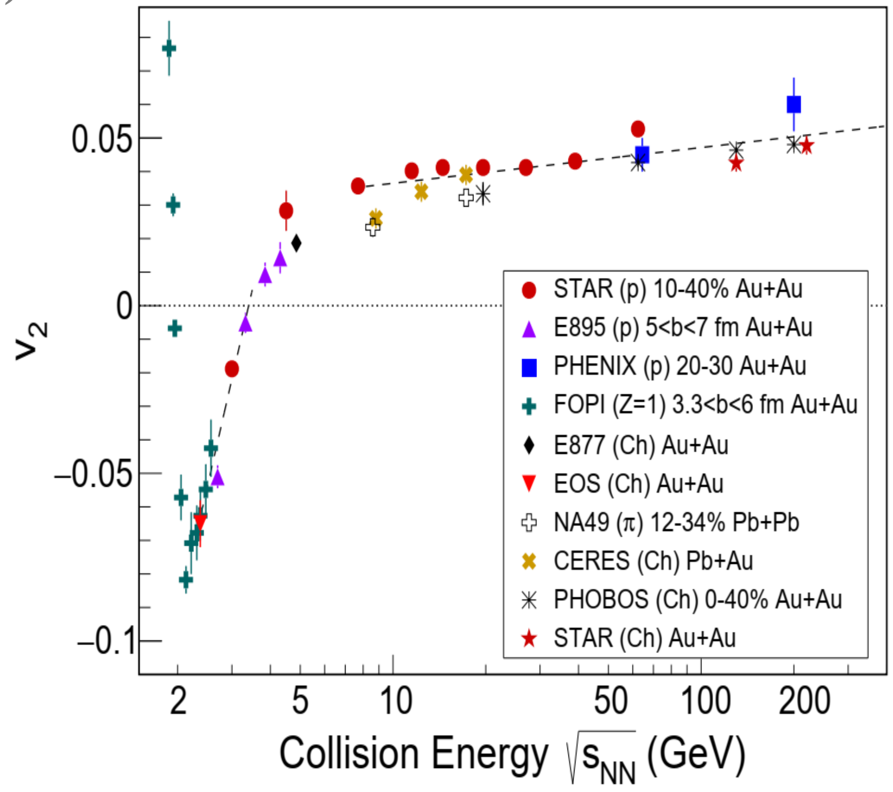
v_1: directed flow

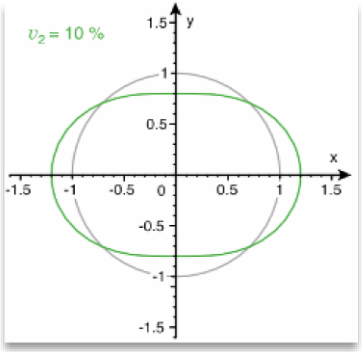
STAR Collaboration, PRL112, 162301 (2014)

v_2: elliptic flow









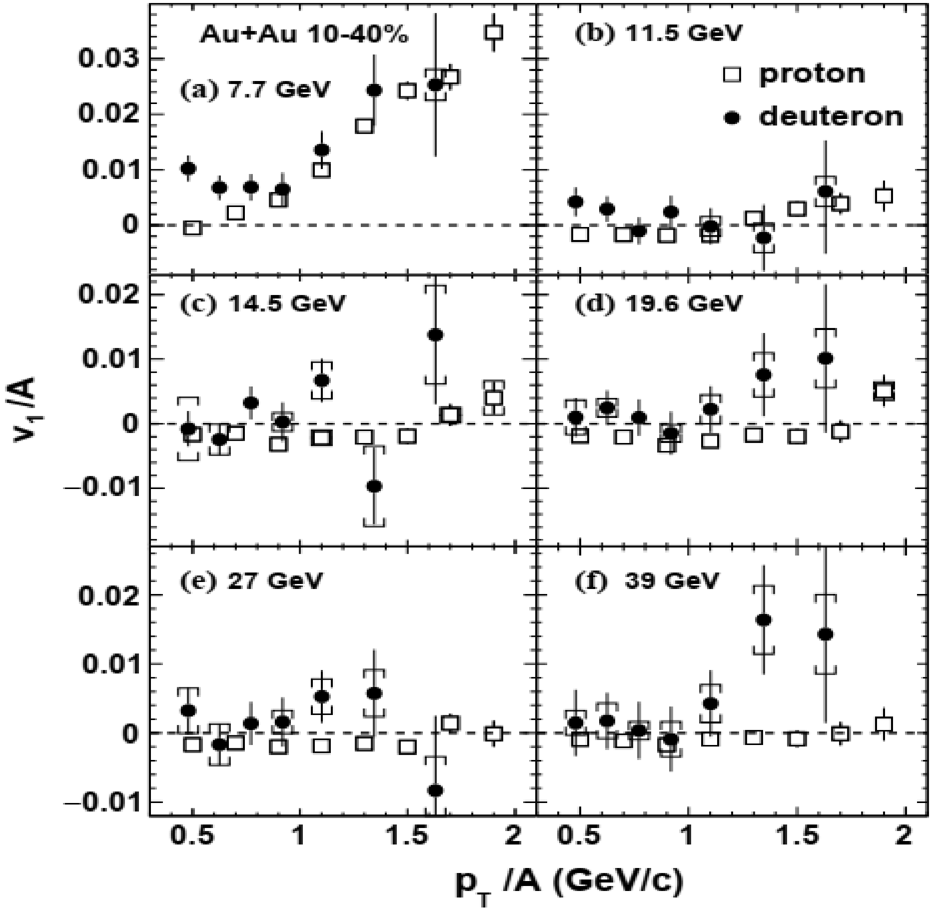
Proton's dv_1/dy are positive below 7.7 GeV and change sign at higher collision energies

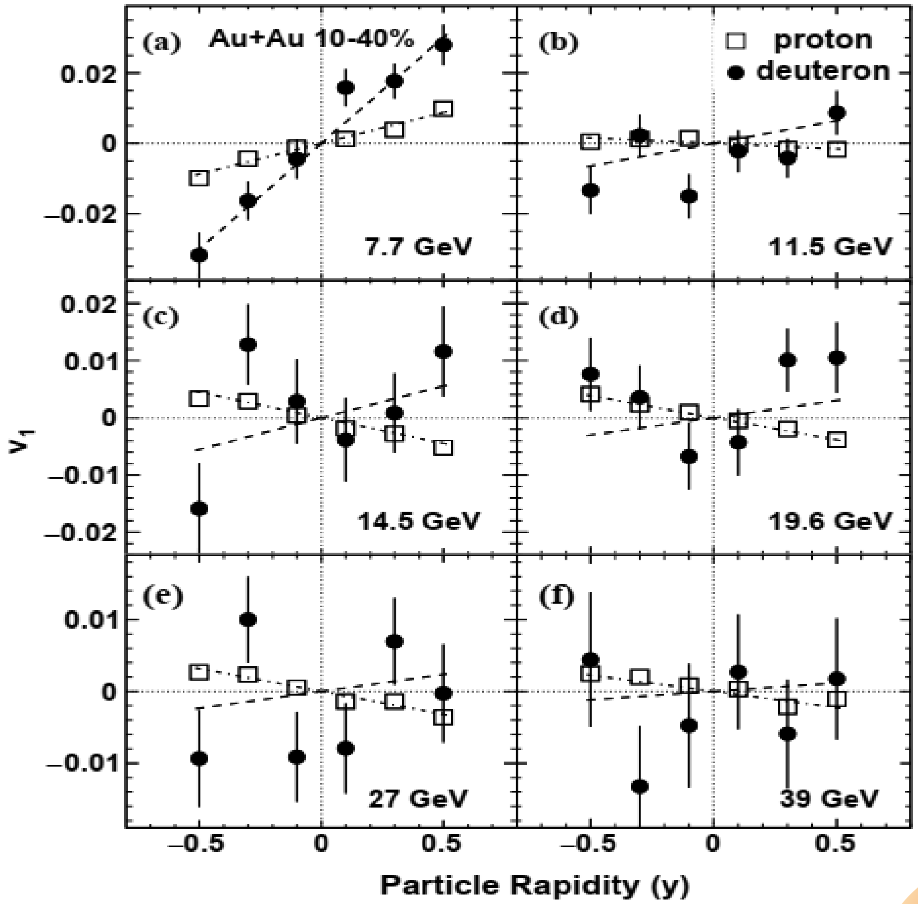
Negative proton v_2 (2-3.5 GeV)

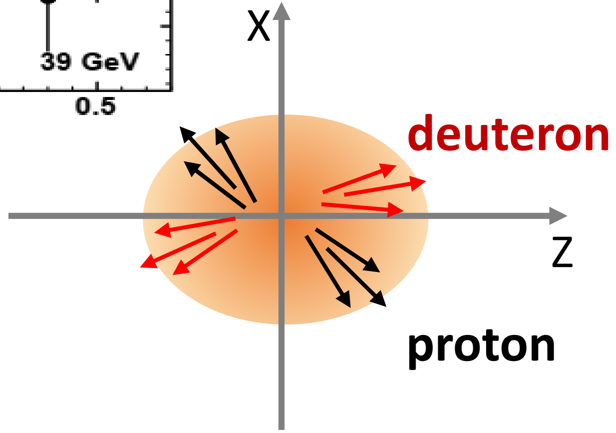
Light nuclei flow: strong energy dependence, constrain the EoS at high baryon density

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

STAR Collaboration, PRC102, 044906 (2020)



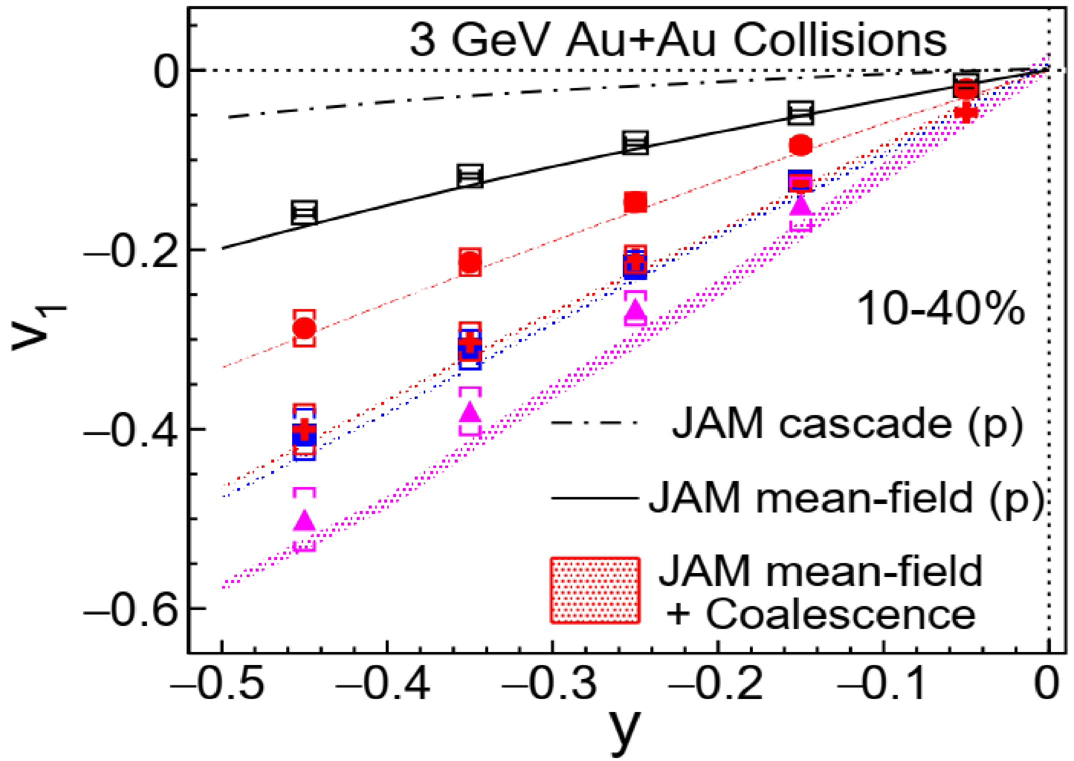


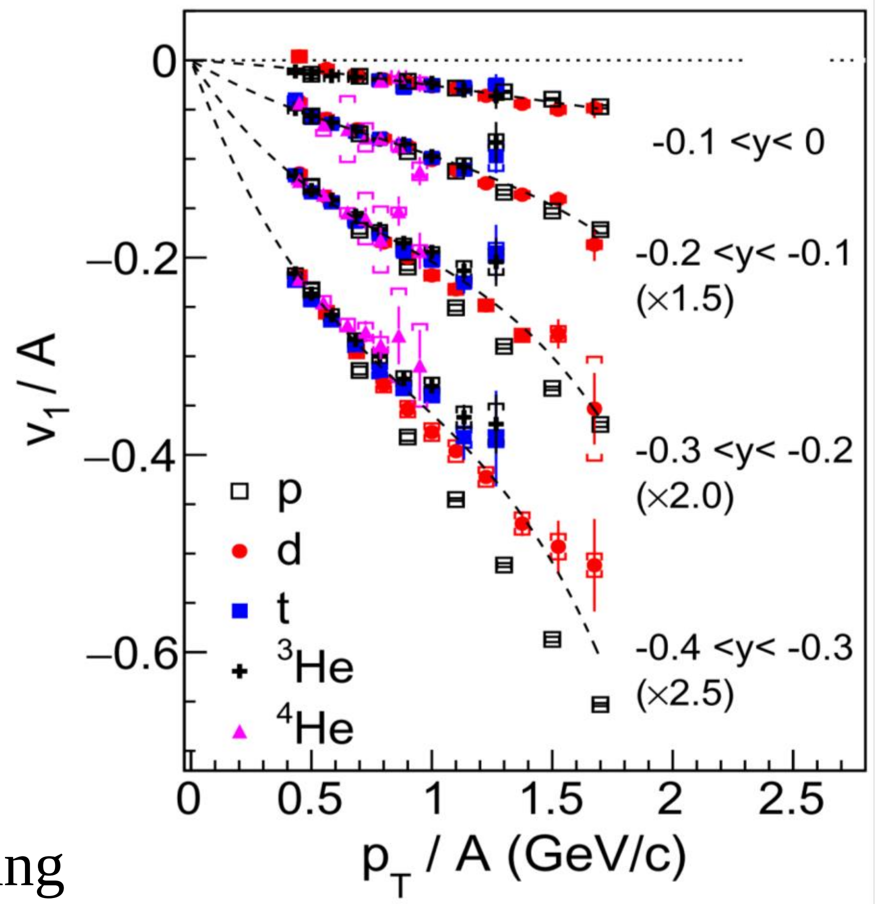


- Hint of positive of deuteron v_1 slopes within 7.7-39 GeV
- At 7.7 GeV, deuteron v_1 shows enhancement towards very low p_T

Light Nuclei v_1 at $\sqrt{s_{NN}} = 3$ GeV

STAR Collaboration, PLB 827, 136941 (2022)



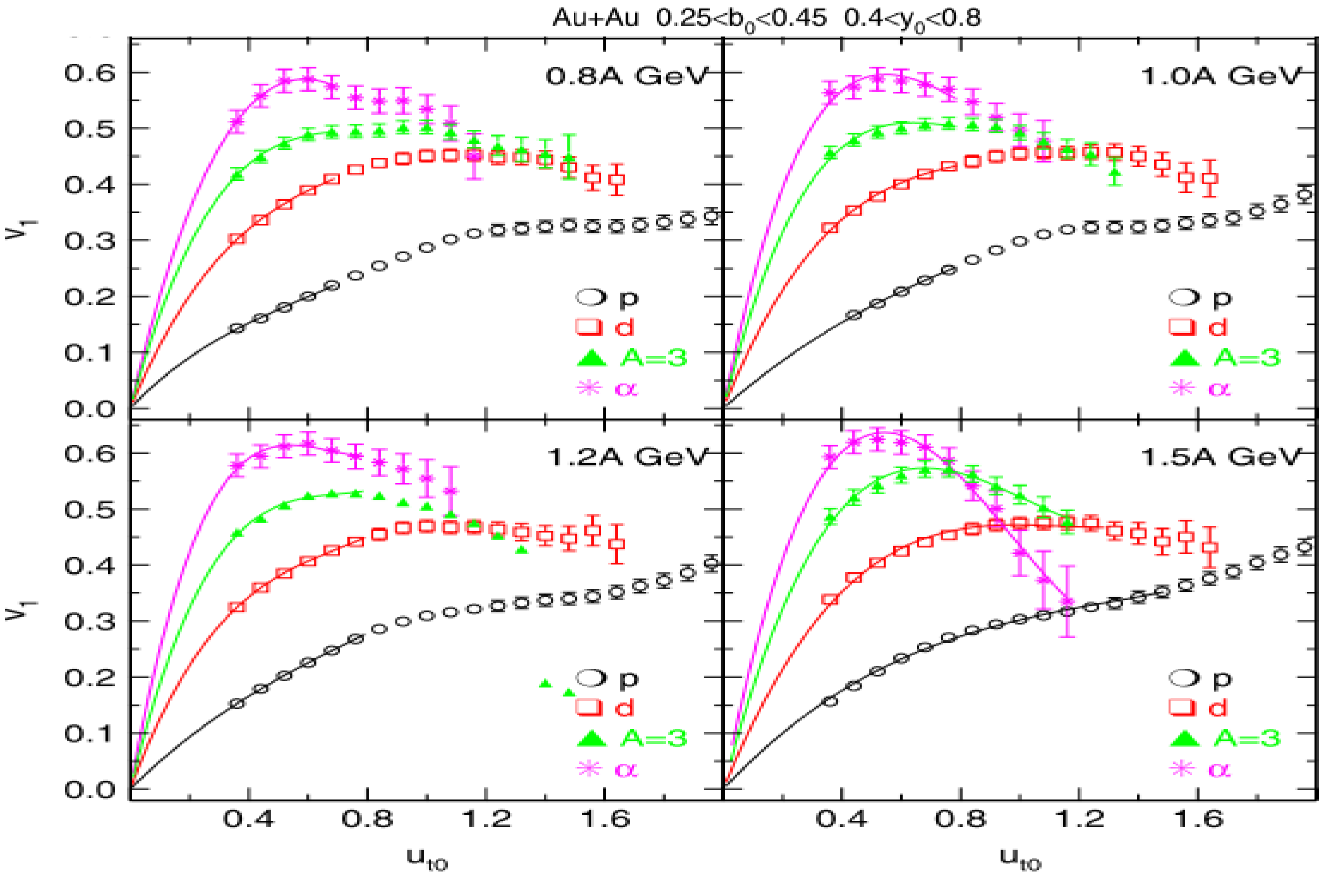


- Light nuclei $v_1(y)$ slope and $v_1(p_T)$ follow an A scaling
- Transport + nucleon coalescence qualitatively describes the data

3 GeV: likely light nuclei formed via nucleon coalescence

Light Nuclei v_1 at $\sqrt{s_{NN}} = 2 - 2.5$ GeV

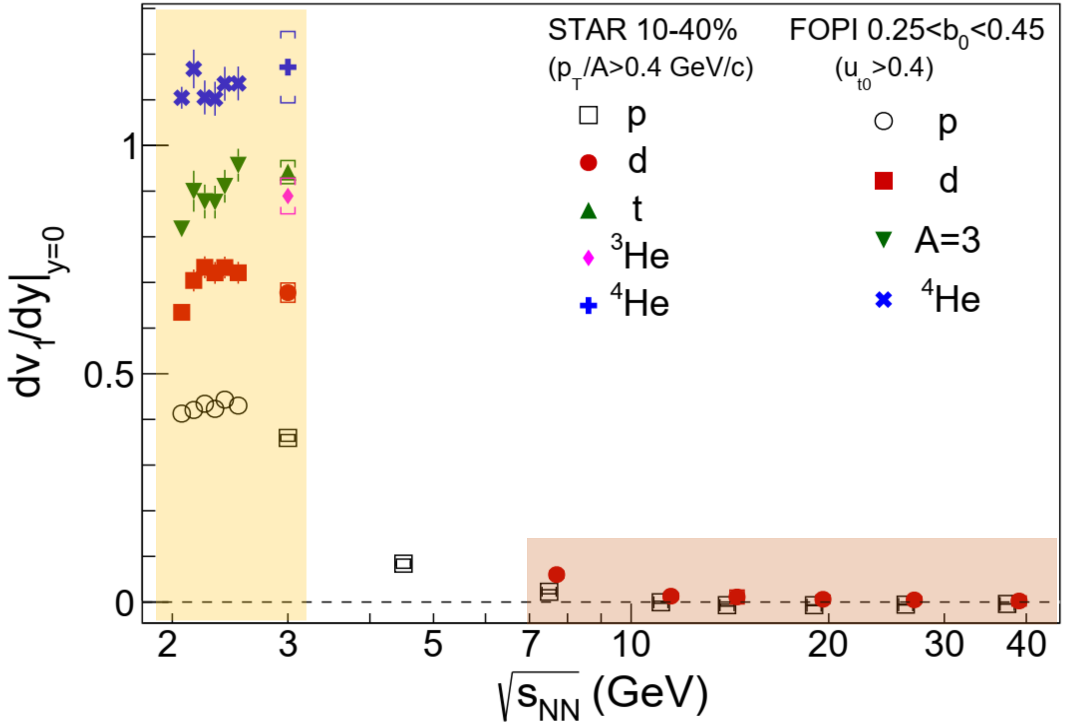
FOPI Collaboration, Nuclear Physics A 876, 1 (2012)



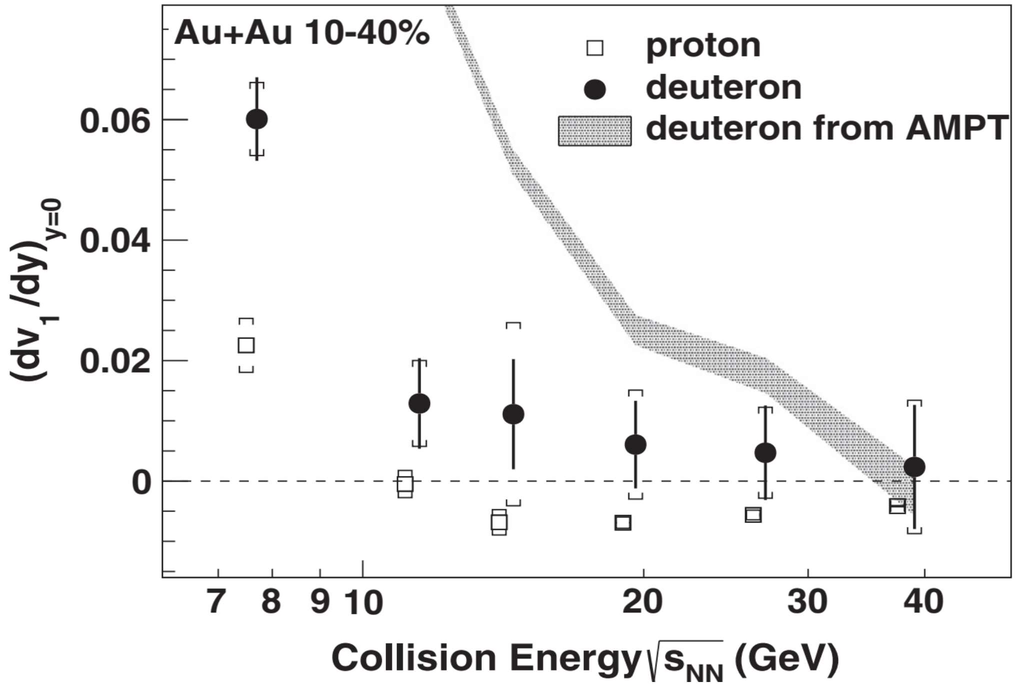
- Away from mid-rapidity, non-monotonic p_T dependence for A>1
- Don’t show a perfect mass number scaling

* $\mu_t = \beta_t \gamma, \mu_{t0} = \mu_t / \mu_{pro}$

Light Nuclei v_1 Slope



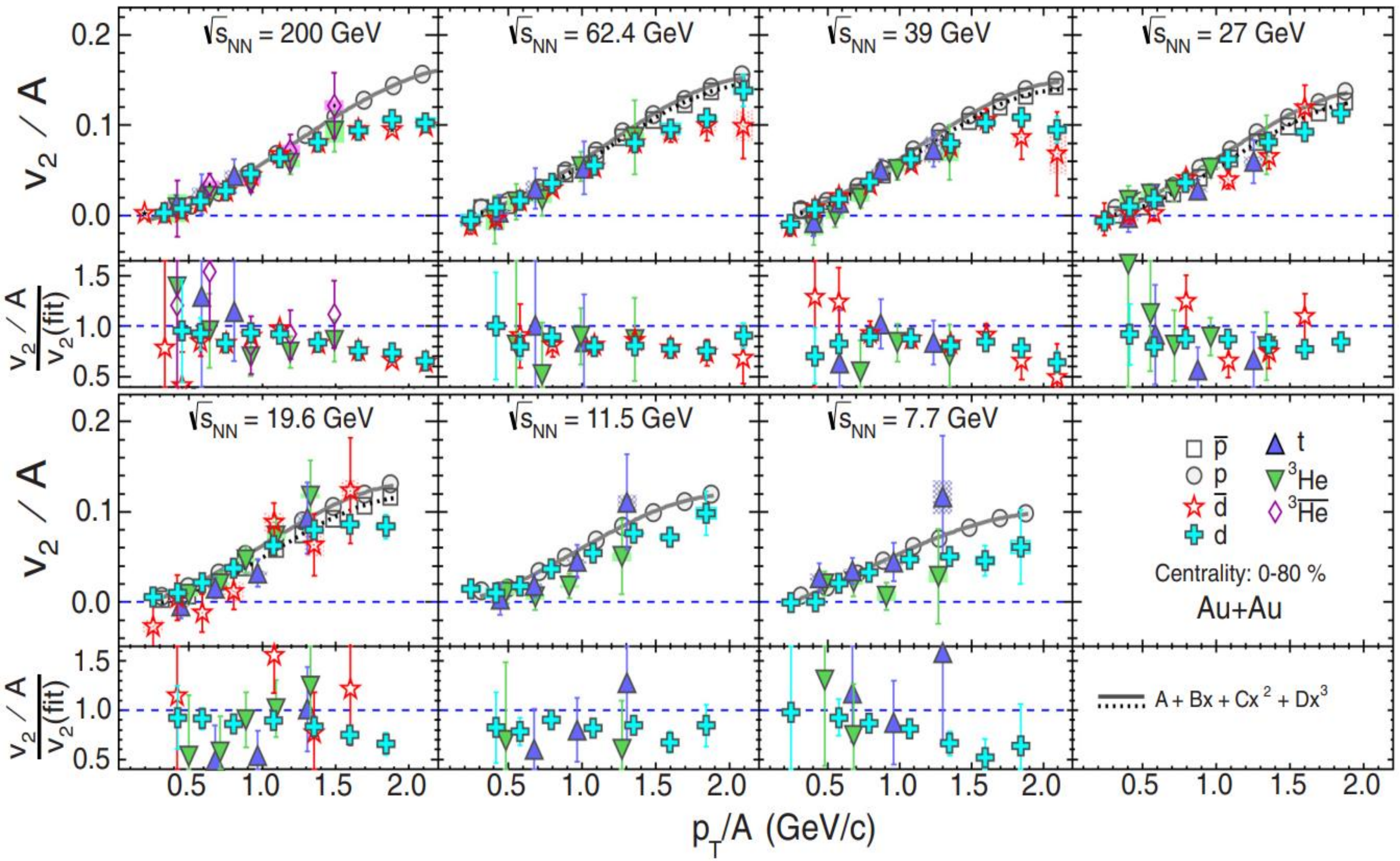
STAR Collaboration, PRC 102, 044906 (2020)



- 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**

Light Nuclei v_2 for $\sqrt{s_{NN}}$≥7.7 GeV

STAR Collaboration, PRC 94, 034908 (2016)

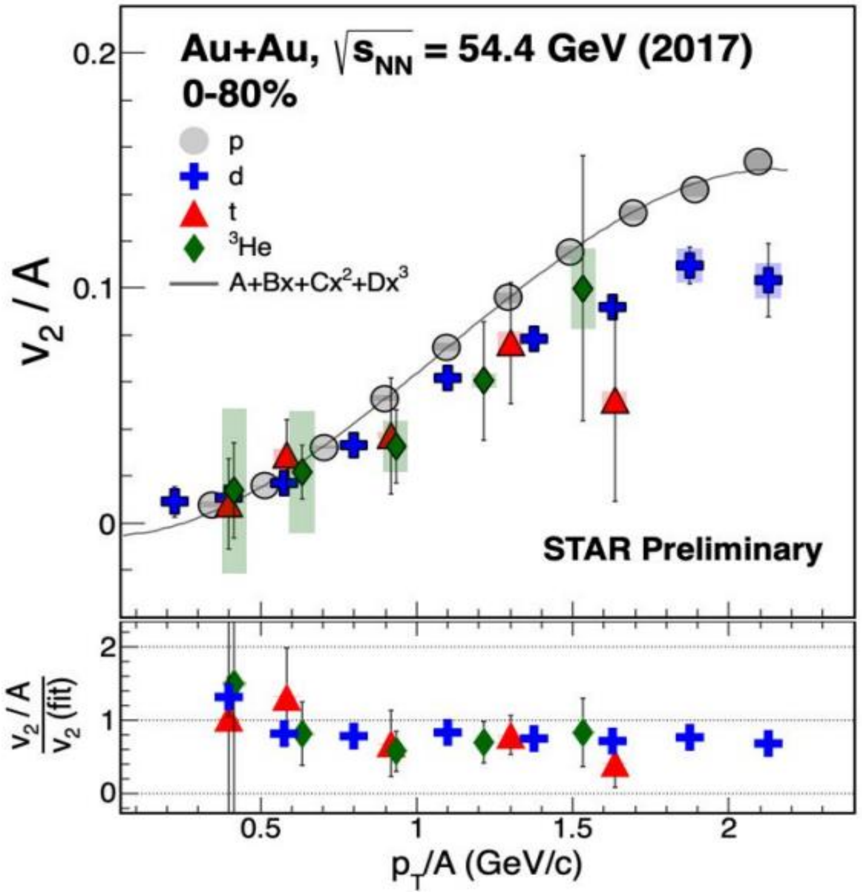


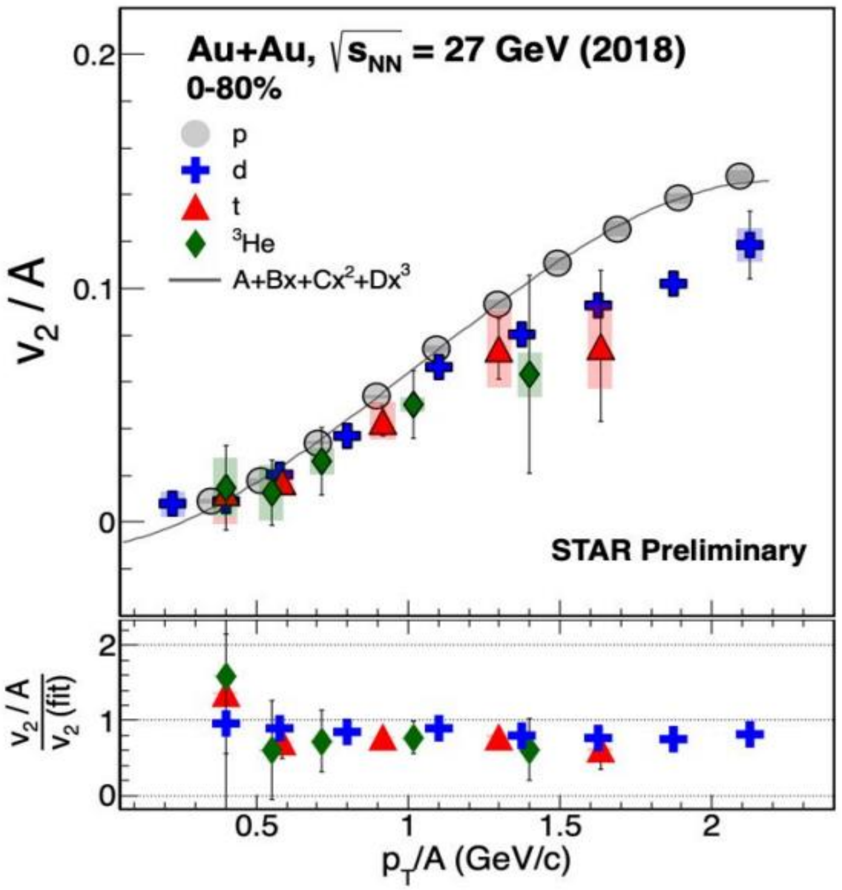
- Light nuclei v_2 follow A scaling at p_T/A<1.5 GeV/c
- Deviation of the A scaling at higher p_T for all measured energies

Light Nuclei v_2 for $\sqrt{s_{NN}} \geq 7.7$ GeV

STAR Collaboration, Quark Matter 2022

talk by Rishabh Sharma

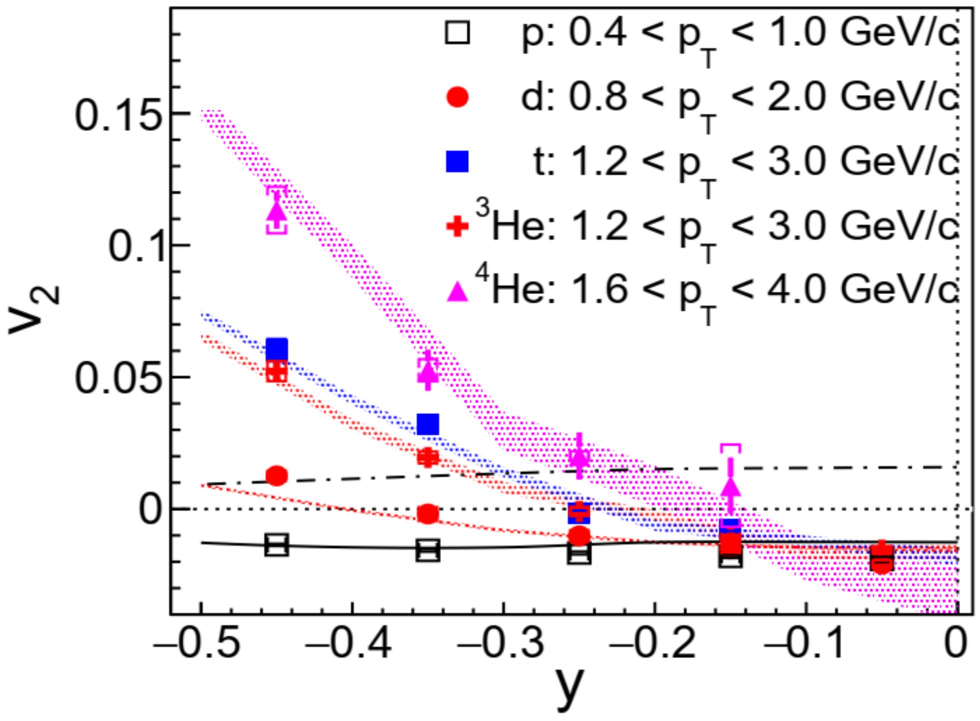


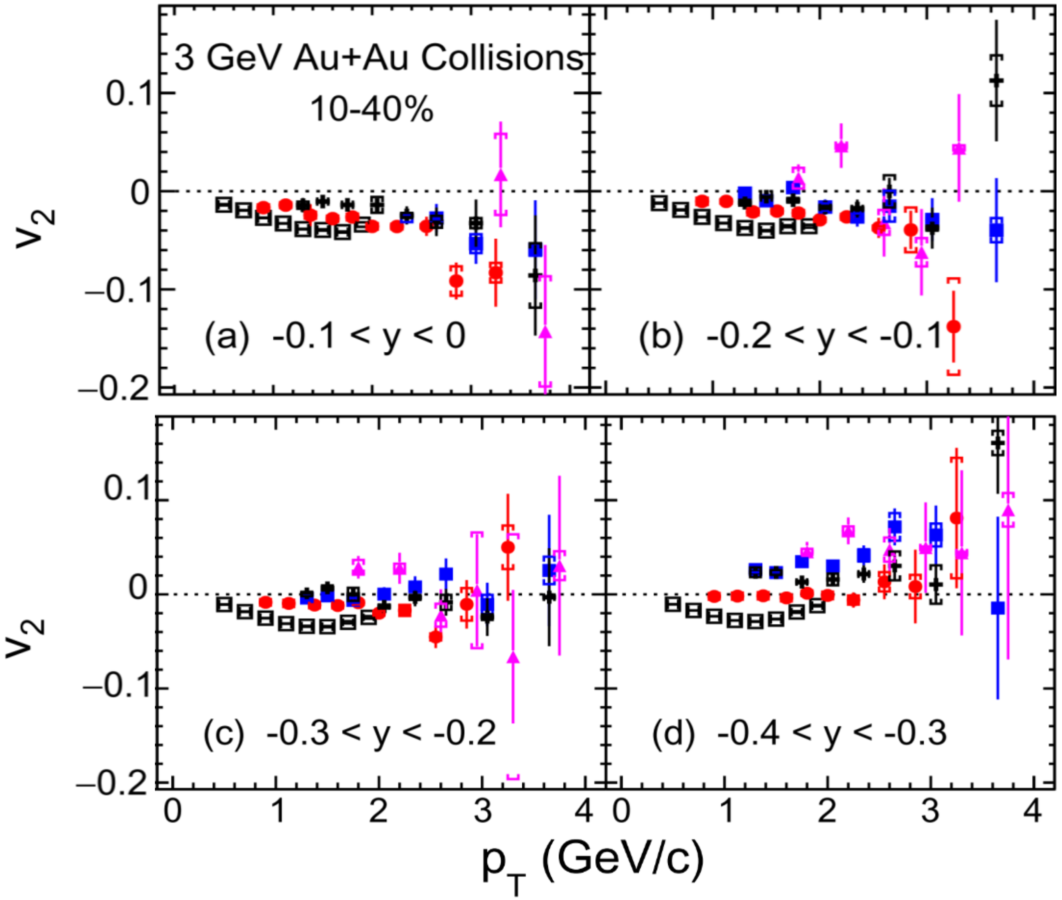


20-30% overall deviations from A scaling

Light Nuclei v_2 at $\sqrt{s_{NN}} = 3$ GeV

STAR Collaboration, PLB 827, 136941 (2022)



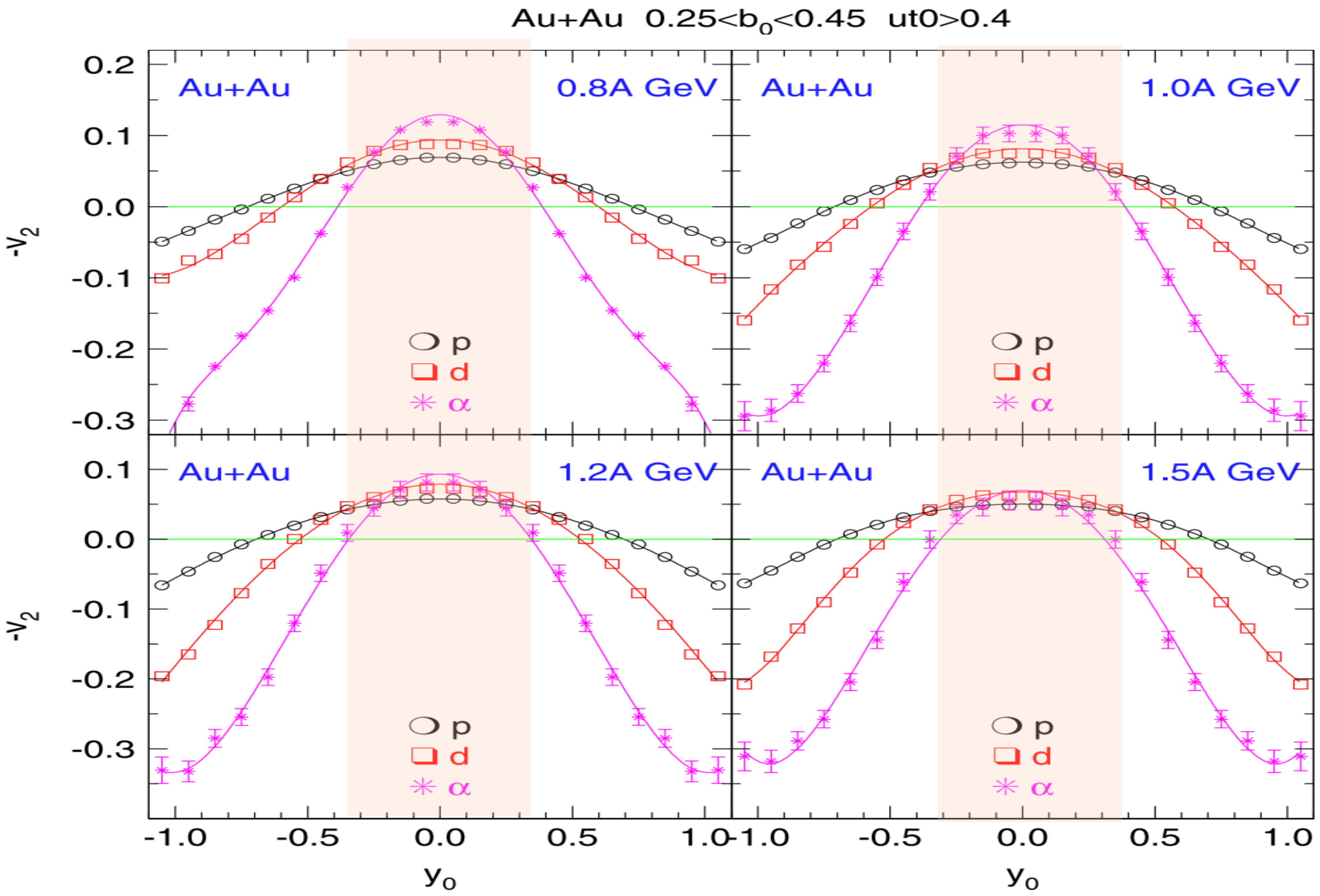


- v_2 value at mid-rapidity are identical for all nuclei species
- More compact shape with increasing mass

Coalescence qualitatively describes the rapidity dependence

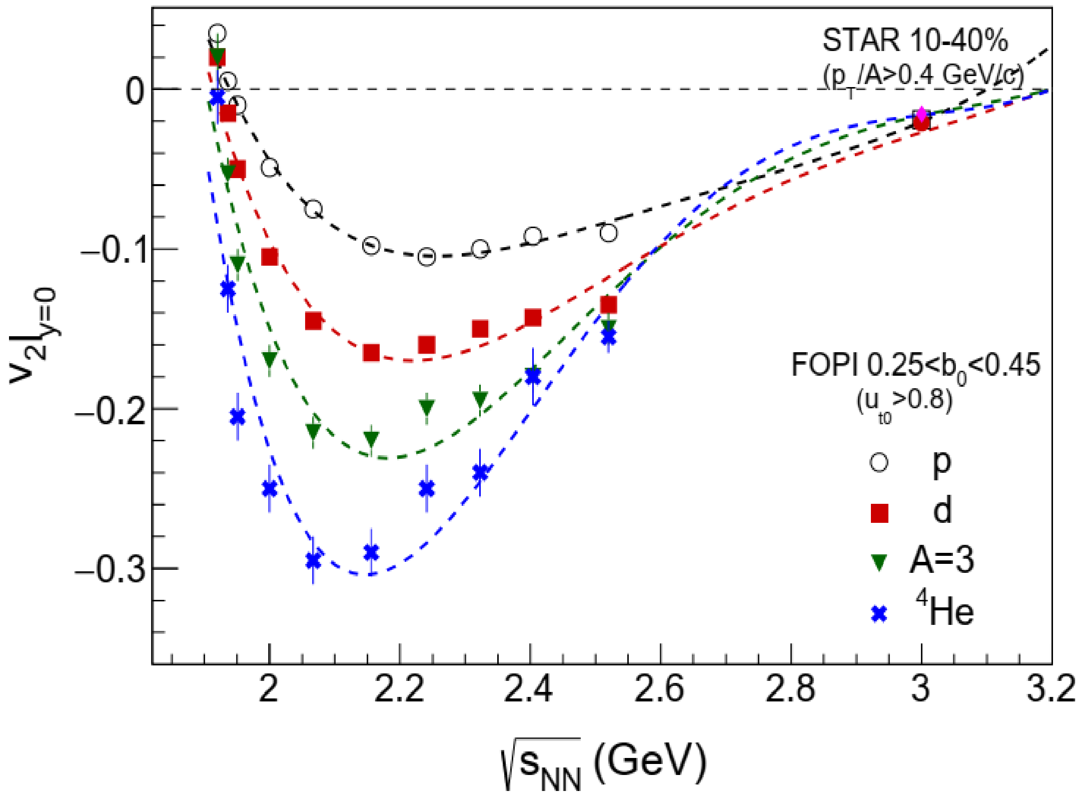
Light Nuclei v_2 at $\sqrt{s_{NN}} = 2 - 2.5$ GeV

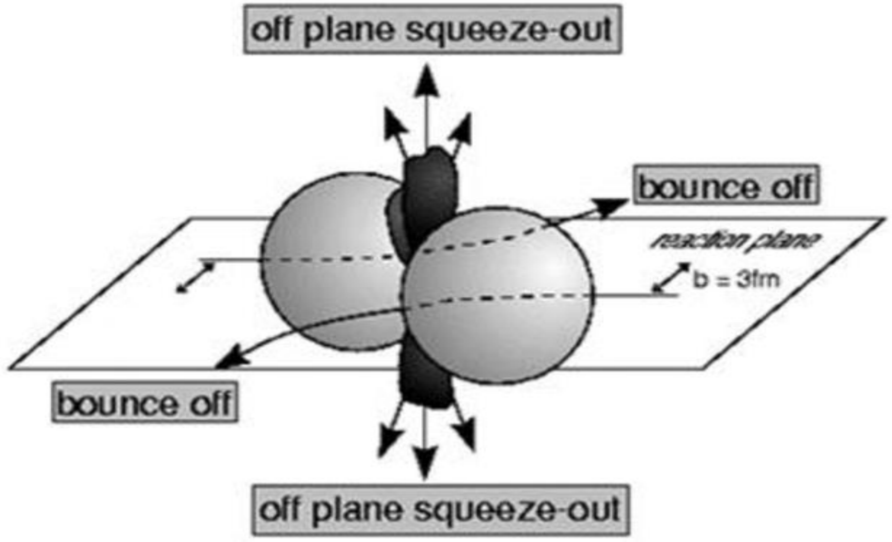
FOPI Collaboration, Nuclear Physics A 876, 1 (2012)



- Disappearance of mass hierarchy in mid-rapidity with the increasing collision energy

Light Nuclei v_2 at Mid-rapidity (y=0)



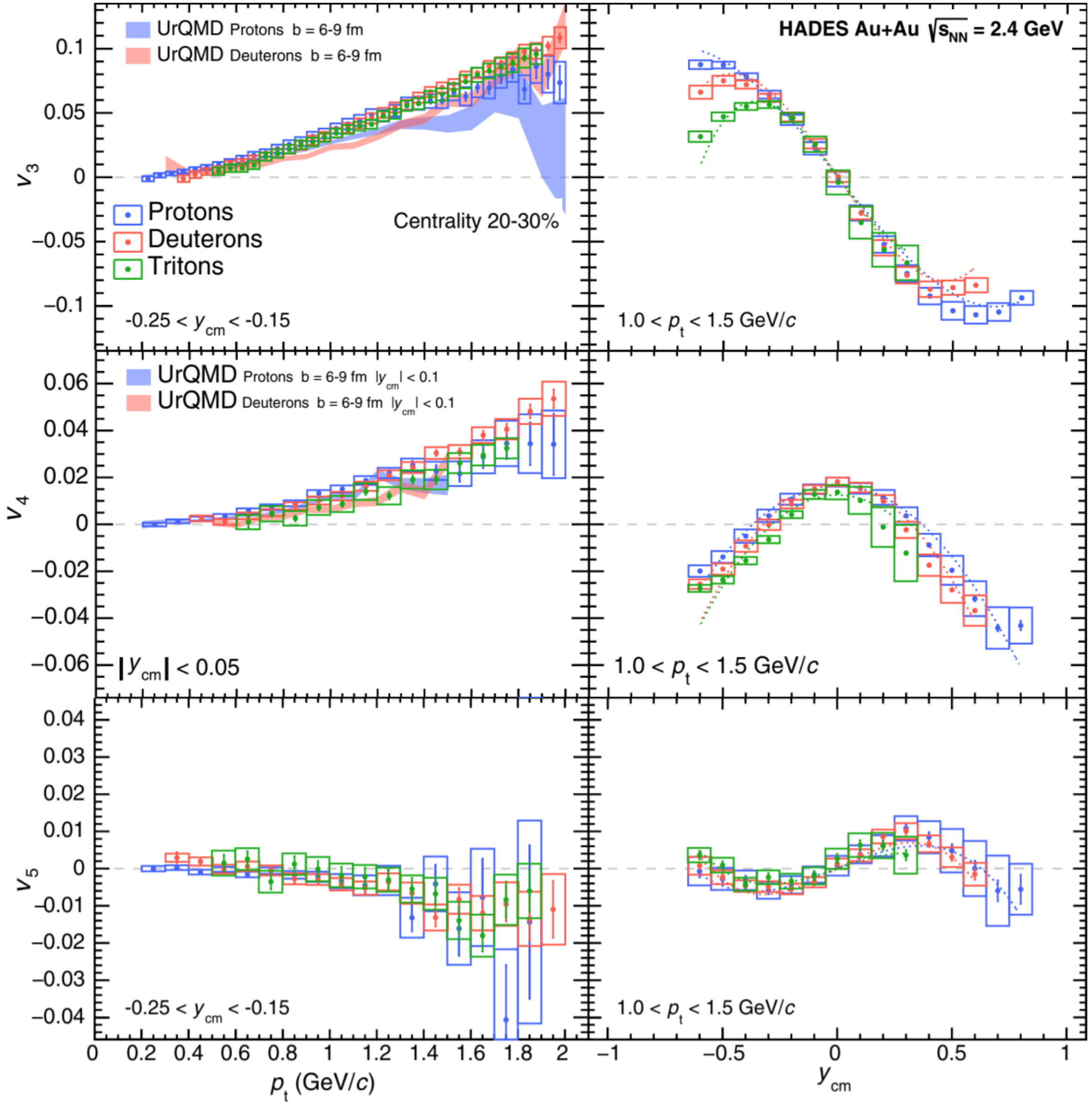


v_2 (y=0) for all light nuclei are negative (squeeze-out/shielding)

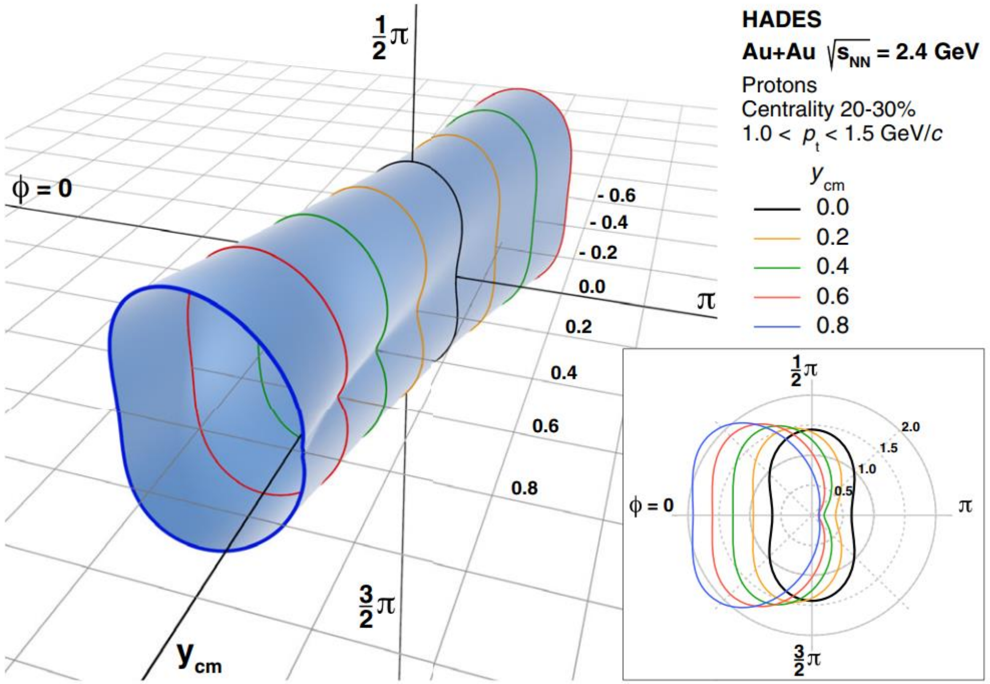
- Stronger energy dependence with the increasing mass
- Location of the minimum value varies with the mass
- Is the zero crossing the same for all light nuclei? (3.2<$\sqrt{s_{NN}}$<3.8 GeV for proton)

Higher Order Flow for Light Nuclei

HADES Collaboration, PRL 125, 262301 (2020)



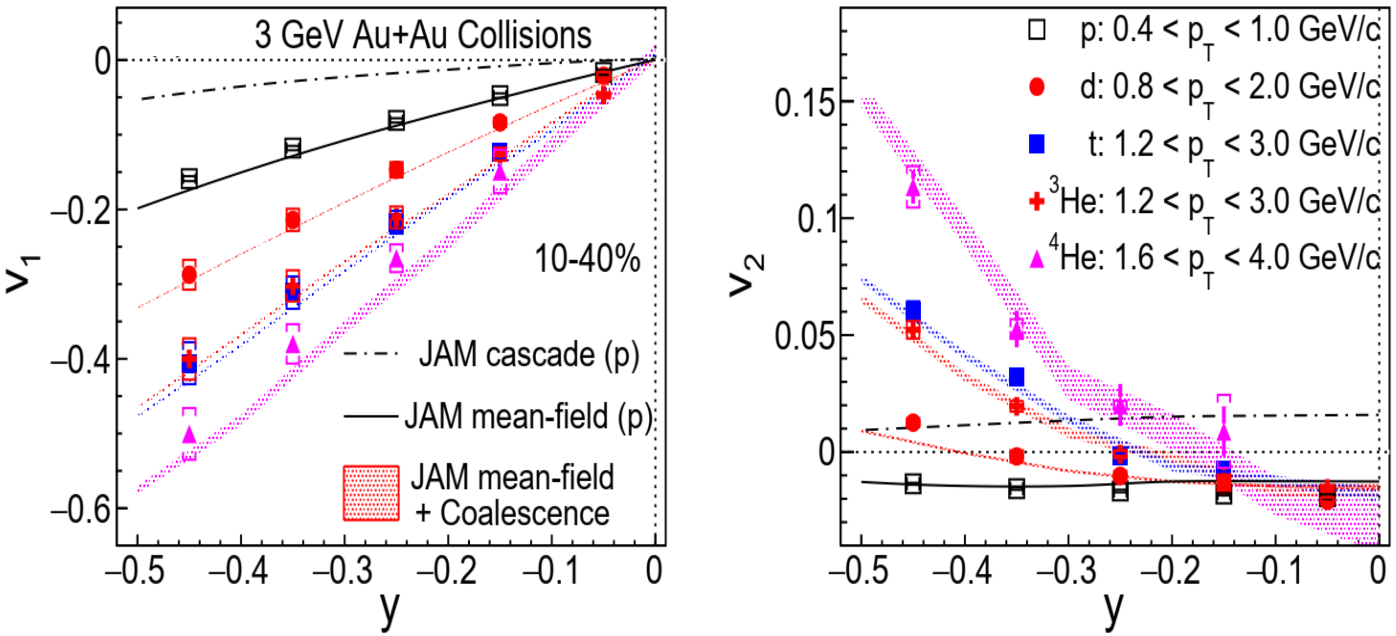
Measured relative to the 1st event plane



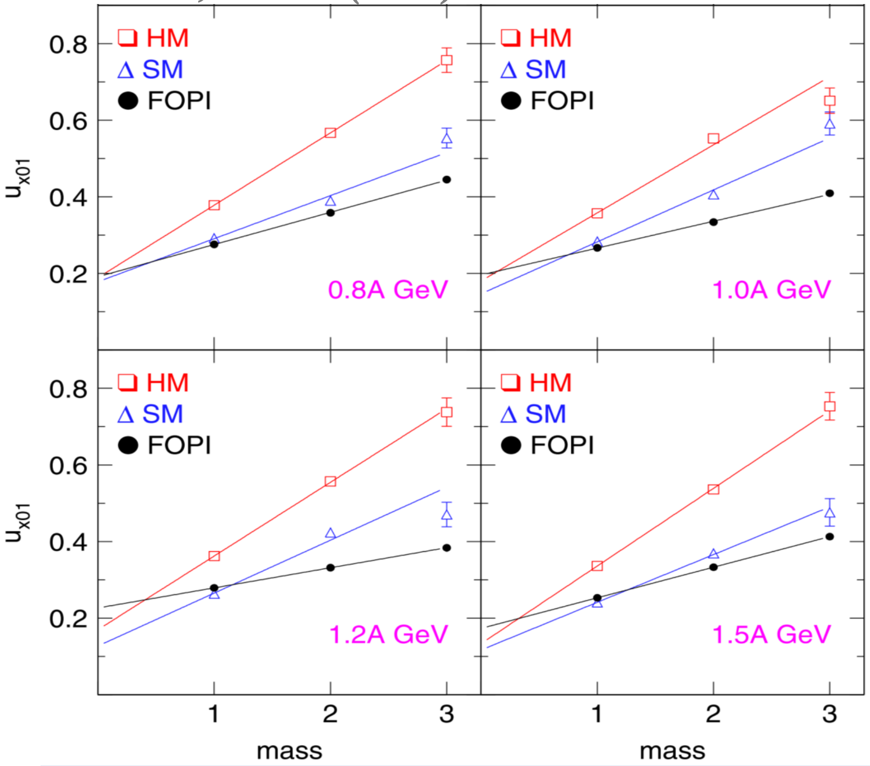
- v_3 -v_5 are not zero, not an initial state fluctuation at high baryon density
- No mass hierarchy for v_3-v_5 at mid-rapidity

Stiffness of EoS at High Baryon Density

STAR Collaboration, PLB 827, 136941 (2022)



FOPI Collaboration, Nuclear Physics A 876, 1 (2012)
PRC 98, 034901 (2018)

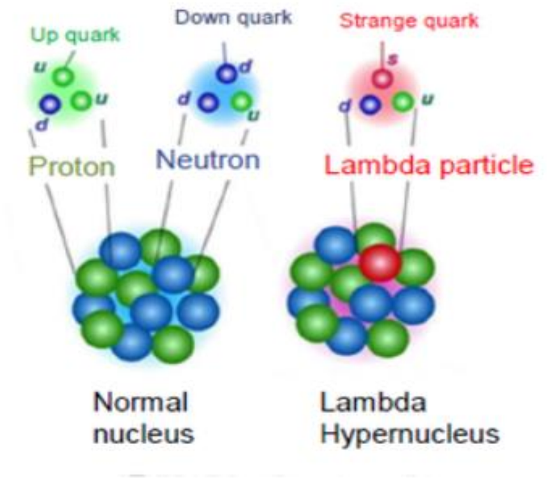


3 GeV: JAM with a **hard EoS** (K=380 MeV)

2-2.5 GeV: IQMD with **soft EoS** (K=200 MeV)

Tension in different models

Hyper Nuclei Flow in Heavy Ion Collisions



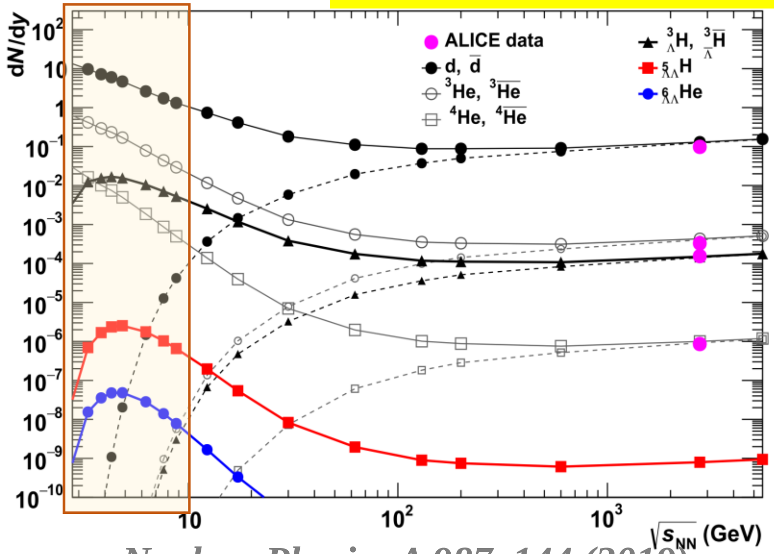
Hyper-nuclei: bound states of nuclei and hyperon

- Probe to the hyperon-nucleon (Y-N) interaction
- Properties of neutron star (EoS)

Λ hyper-nuclei

- ❑ Small binding energies
- ❑ Comparable lifetime with Λ hyperon
- ❑ **Unclear production mechanisms in heavy-ion collision**
- ❑ Maximum yield at several GeV

Thermal model prediction

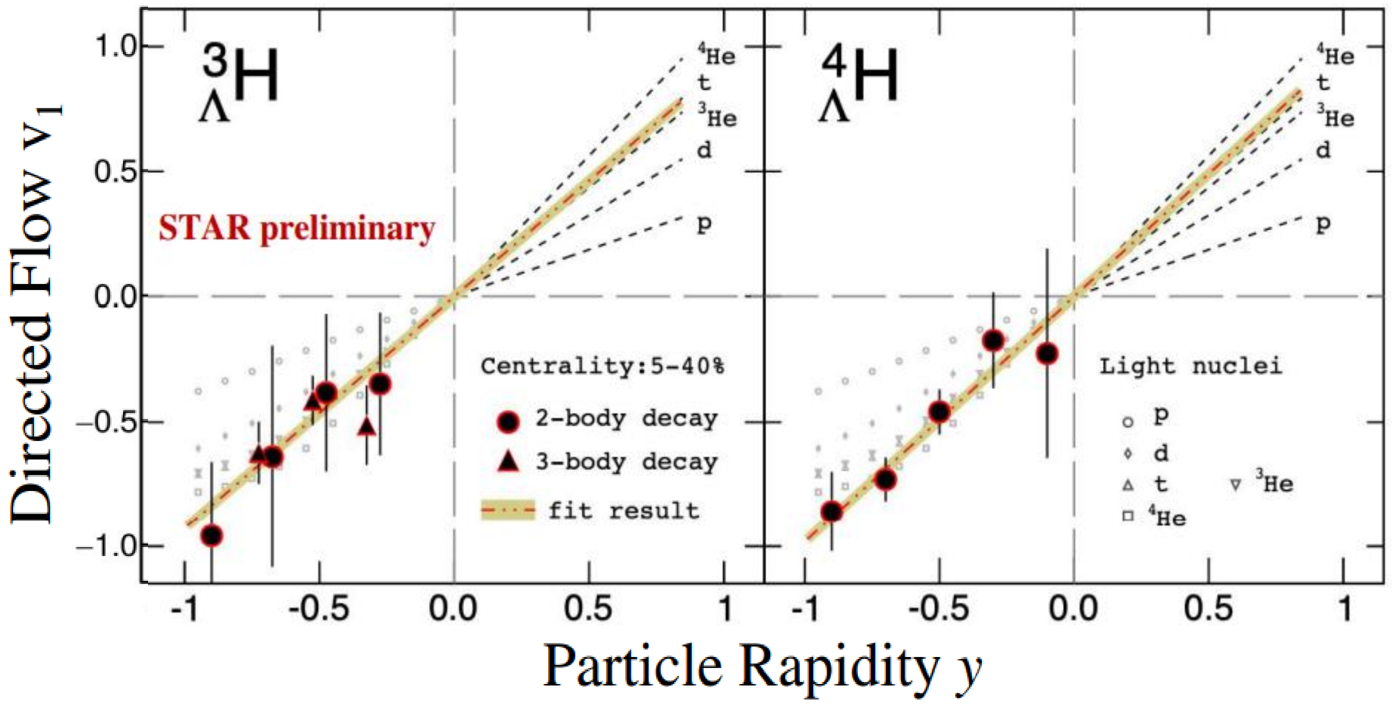


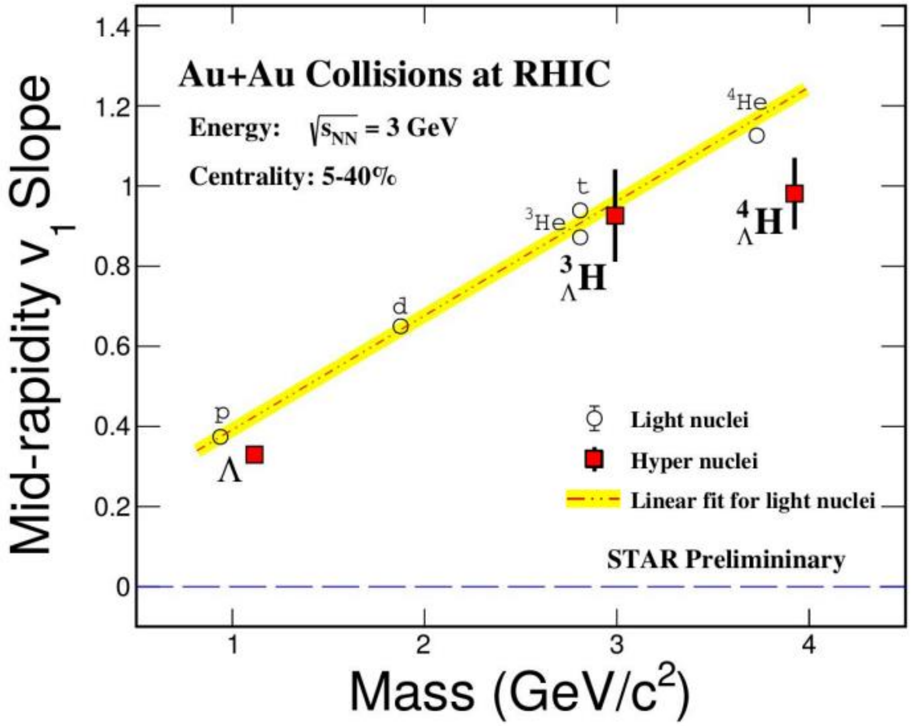
Nuclear Physics A 987, 144 (2019)

Hyper-nuclei v_1 at 3 GeV

Chenlu Hu for STAR, 19th Strangeness in Quark Matter, 2021

Talk by Rishabh Sharma





- First observation of hyper-nuclei collectivity in heavy-ion collisions
- v_1 distribution and slope are close to those of light nuclei with a same A

Hyper-nuclei formation: likely by coalescence of hyperon and nuclei

Summary

Light nuclei flow at 7.7-200 GeV (μ_B < 420 MeV)

- Hint of positive deuteron v_1 slopes, opposite to those of protons
- A scaling for v_2 is broken (20-30%)

→ **Light nuclei production: tensions with coalescence model**

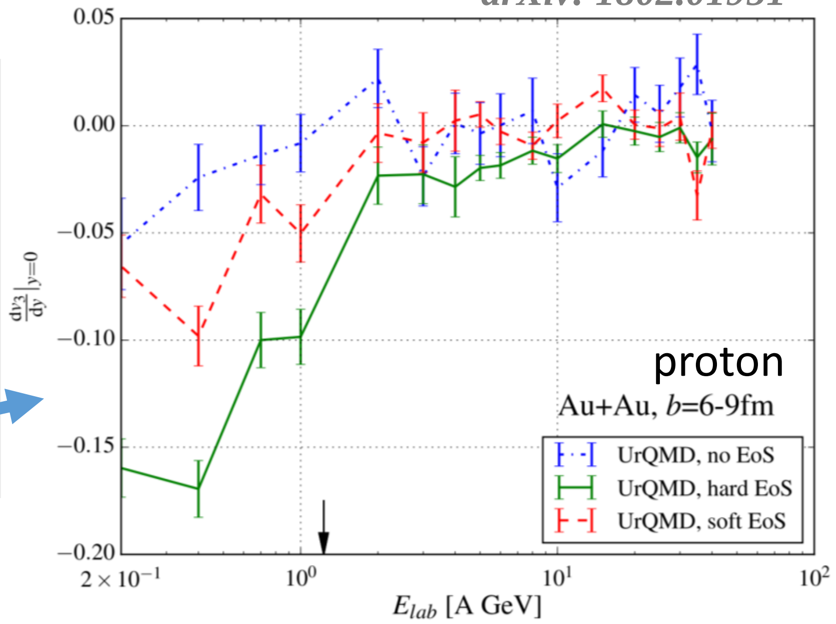
Light nuclei flow at 2-3 GeV (μ_B > 750 MeV)

- v_1 slope saturate (maximum); negative v_2(y=0) (minimum), mass hierarchy of v_2 disappears at 3 GeV; non-zero v_3-v_5

→ **Light nuclei production: coalescence model**

→ **Stiffness of EoS: no definitive conclusion, v_3?**

arXiv: 1802.01951



First flow measurement of hyper-nuclei: hyperon nucleon coalescence

Thank you for your attention!

SQM2022

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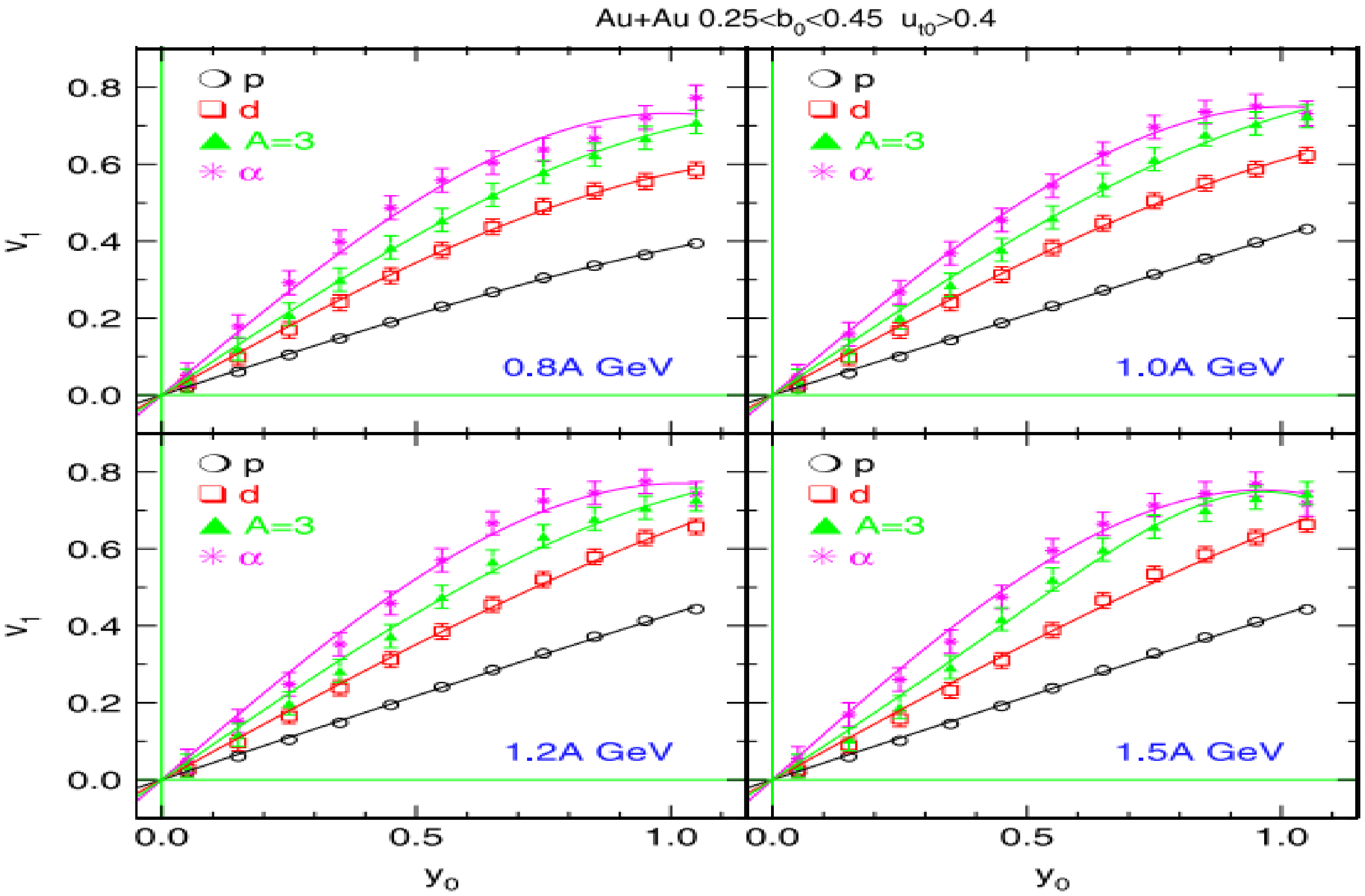
13-17 June 2022 Busan, Republic of Korea

Back Up

Light Nuclei v_1 at $\sqrt{s_{NN}} = 2 - 2.5$ GeV

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

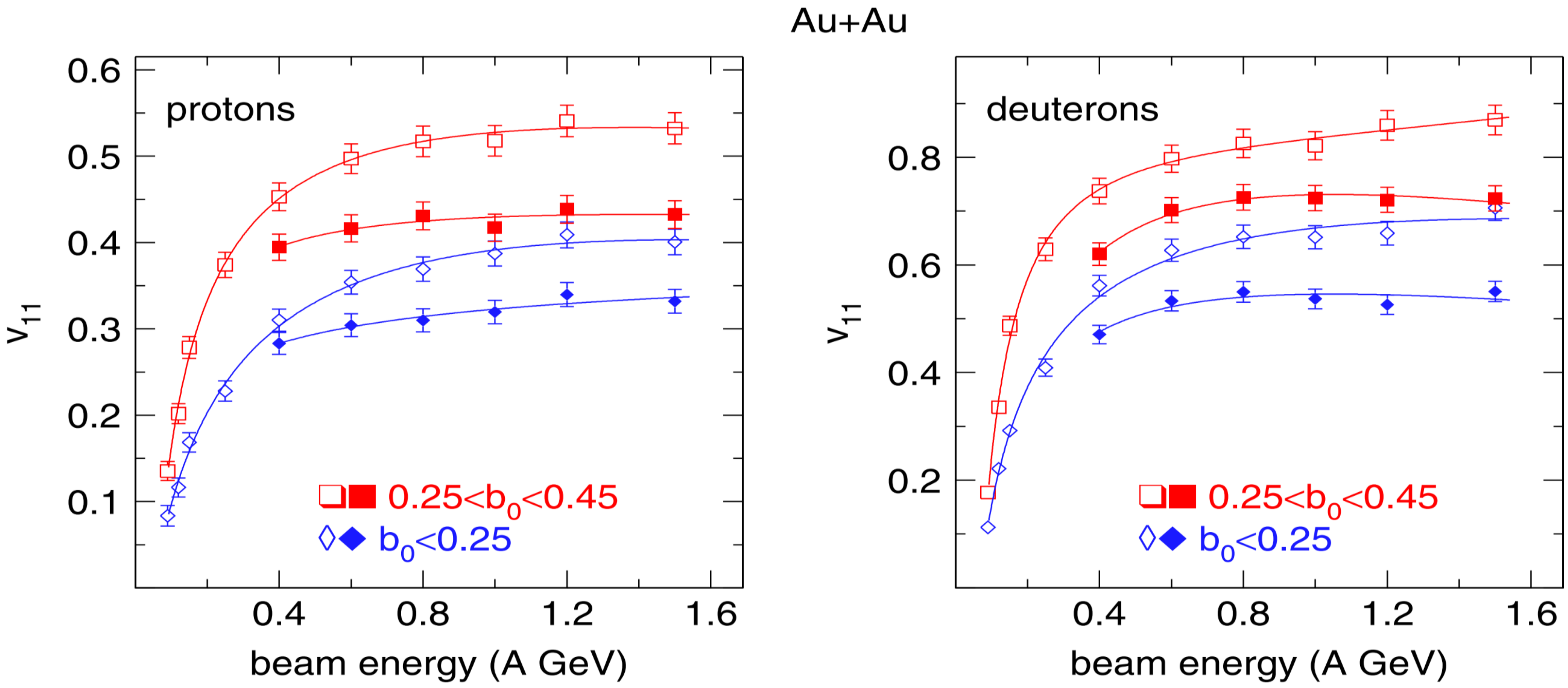


- Similar rapidity dependence for all the 2-2.5 GeV

* $y_0 = y/y_{pro}$

Light Nuclei v_1 Slope for $\sqrt{s_{NN}}$<2 GeV

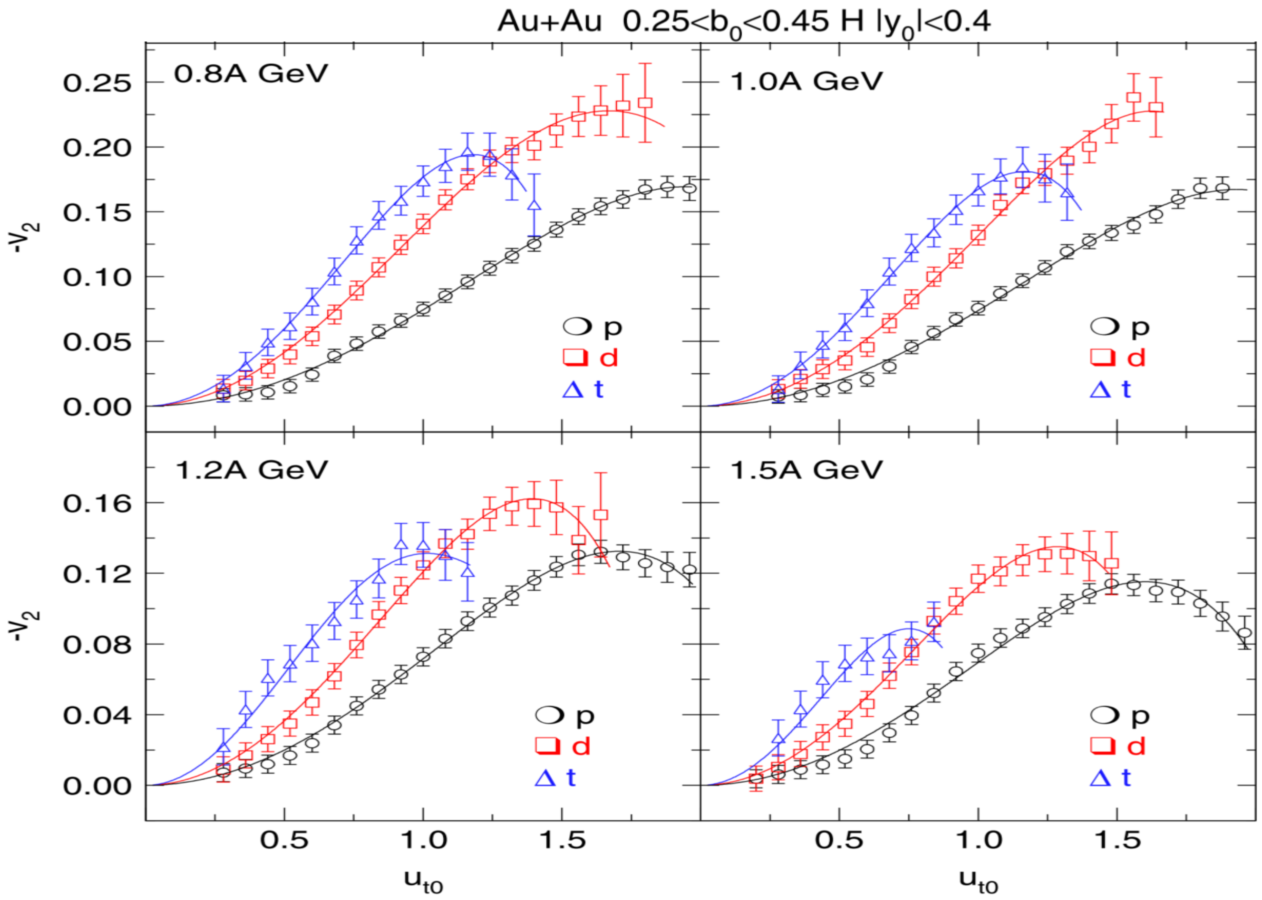
Nuclear Physics A 876, 1 (2012)



Steep rise up to 2 GeV, flat dv_1/dy within 2-2.5 GeV

Light Nuclei v_2 at $\sqrt{s_{NN}} = 2 - 2.5$ GeV

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

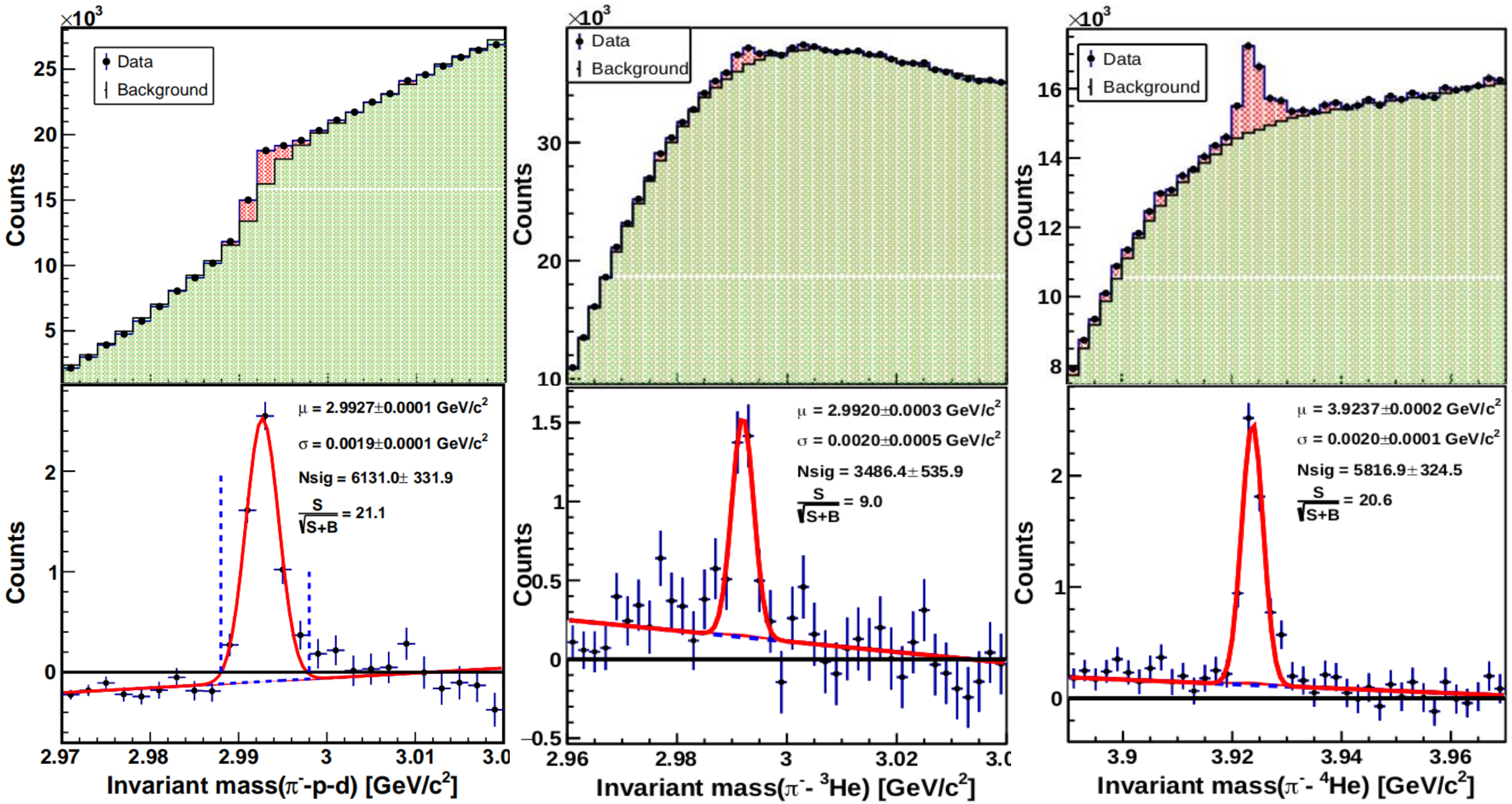


- Different from higher energies, non-monotonic p_T dependence

Hyper-nuclei Reconstruction at 3 GeV

$^{3}_{\Lambda}H \rightarrow p + d + \pi^{-};\ ^{3}_{\Lambda}H \rightarrow\ ^{3}He + \pi^{-};\ ^{4}_{\Lambda}H \rightarrow\ ^{4}He + \pi^{-}$

Chenlu Hu for STAR, 19th Strangeness in Quark Matter, 2021



- Background estimated by rotating one of the daughter track
- Precise measurement of lifetime with this data

STAR Collaboration, PRL 128, 202301 (2022)