Beam Energy Scan: Flow Measurements from the STAR Experiment

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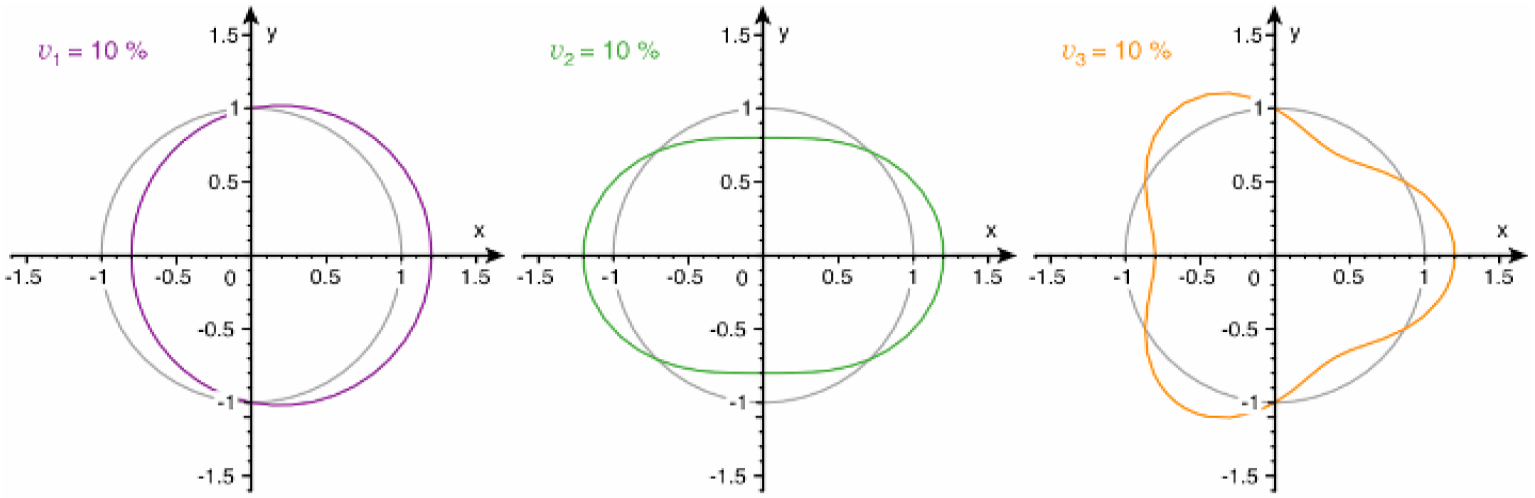
Anisotropic Flow in Heavy Ion Collisions

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

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



v_1: directed flow v_2: elliptic flow v_3: triangular flow

Provide accesses to

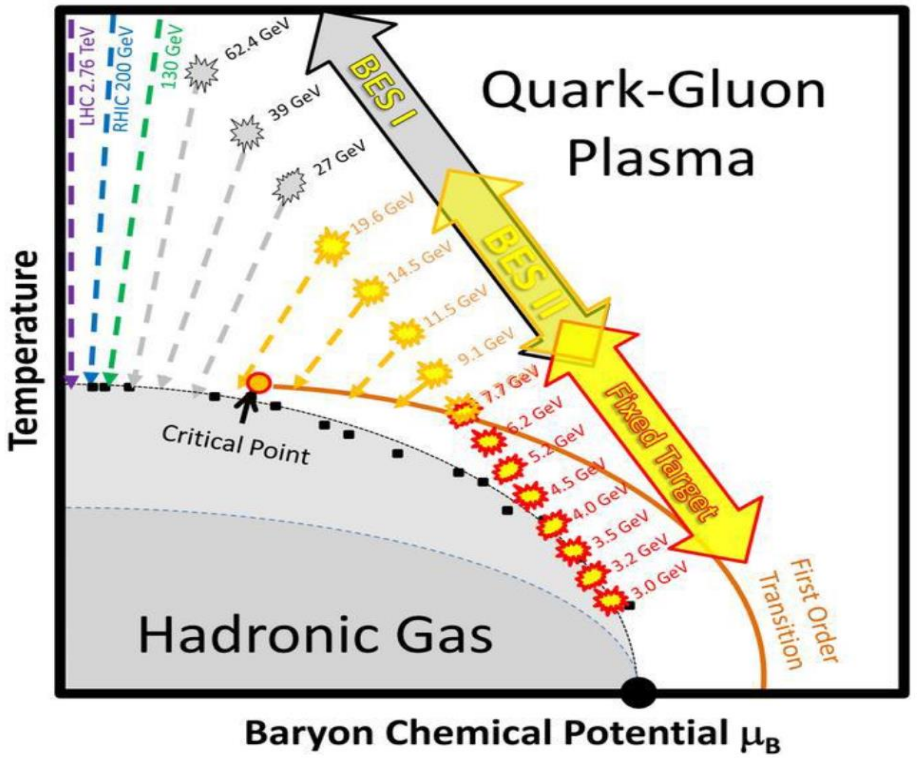
→ Equation of State (EoS)
Established at the early stage, sensitive to the initial pressure

→ Phase transition
Dependence on collision energy

→ Particle production
Number of constituent quark(nucleon) scaling

Beam Energy Scan (BES)

$\sqrt{s_{NN}}$ = 3 – 62.4 GeV Au+Au collisions



- Critical point
- 1st order QCD phase transition

Results from

- *BES-I*

$\sqrt{s_{NN}}$(GeV)	7.7	11.5	14.5	19.6	27	39
Events	4 M	12 M	11 M	36 M	70 M	130 M

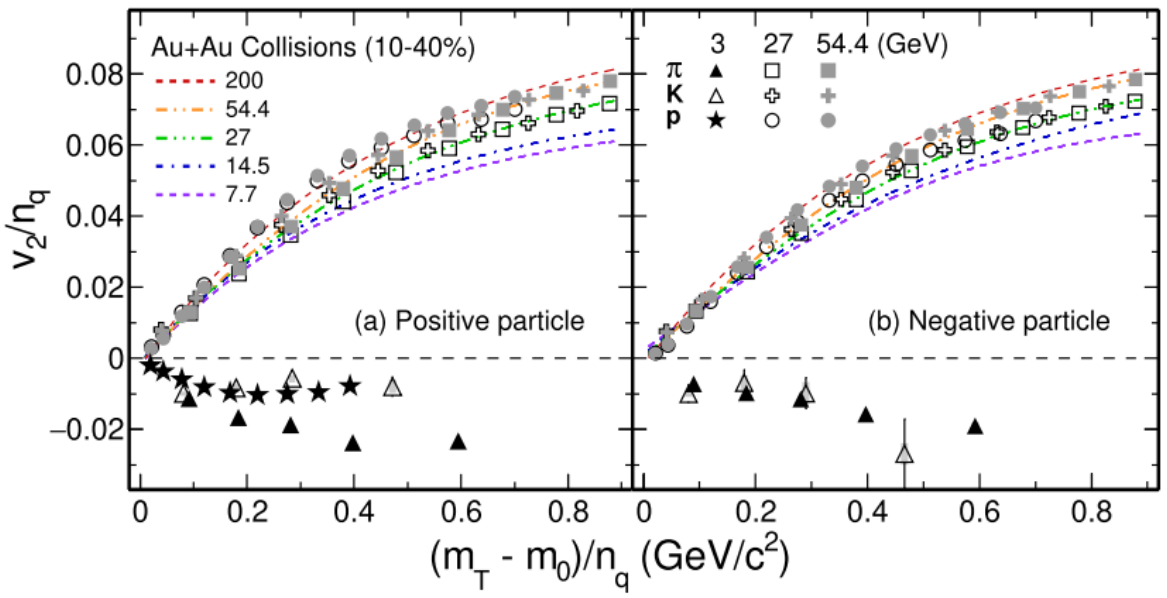
- *BES-II and FXT*

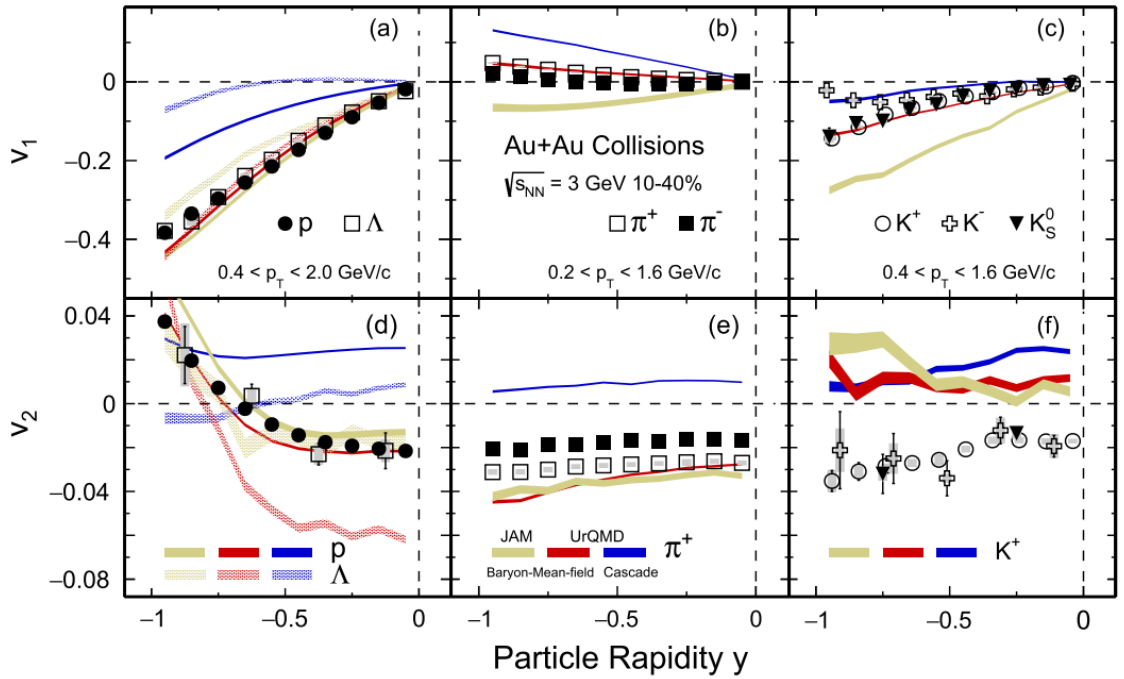
$\sqrt{s_{NN}}$(GeV)	3	7.2	14.6	19.6
Events	260 M	155 M	180 M	478 M

- ❑ Light and strange hadrons flow
- ❑ Light nuclei v_1 and v_2
- ❑ Hyper-nuclei v_1

v_1 and v_2 for Hadrons at $\sqrt{s_{NN}} = 3$ GeV

Physics Letters B 827, 137003 (2022)





- Values of v_2 for studied particles are negative
- NCQ scaling is absent

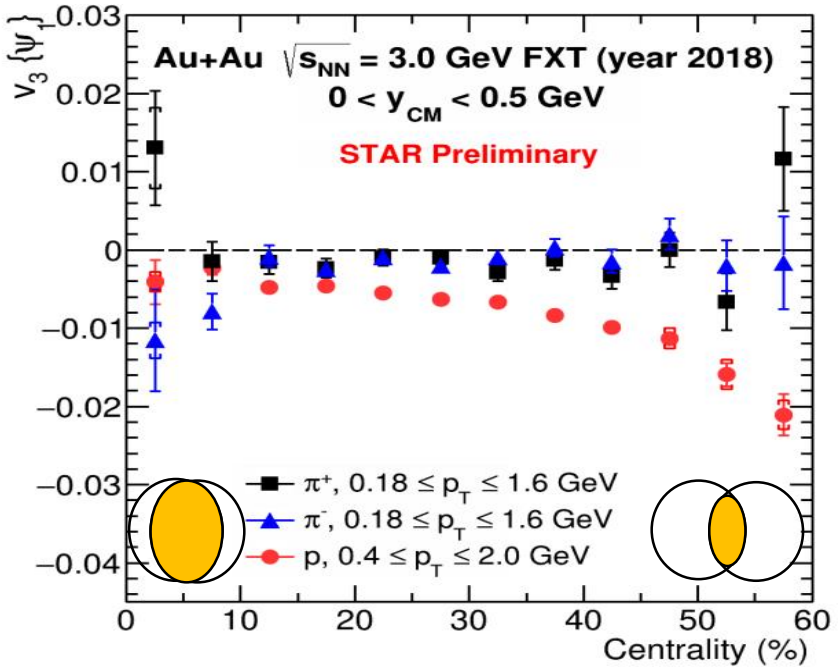
The data can be qualitatively reproduced with baryonic mean-field (incompressibility κ=380MeV) transport models.

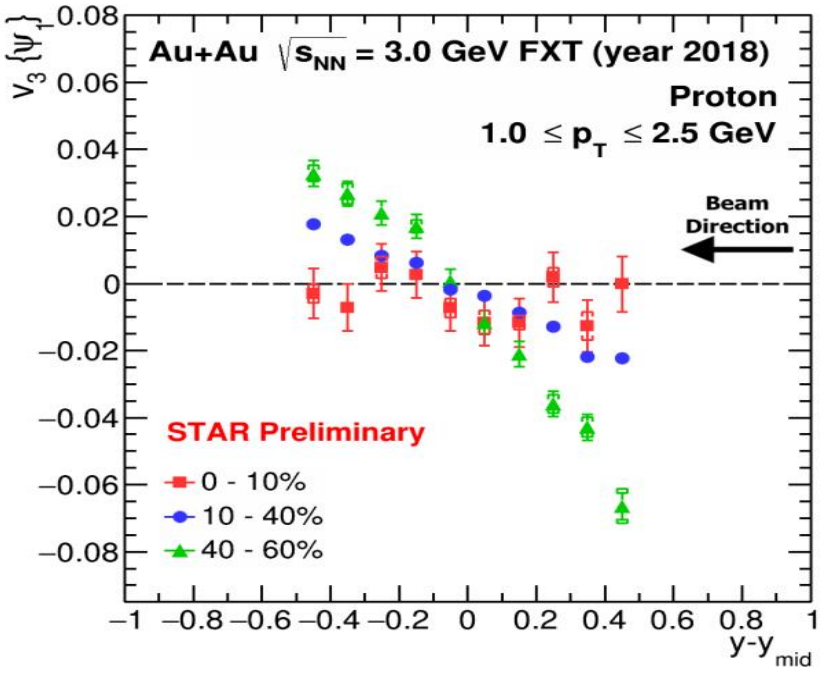
3 GeV: disappearance of partonic collectivity and likely dominated by baryonic interactions

v_3 for Hadrons at $\sqrt{s_{NN}} = 3$ GeV

Measured with respect to the first order event plane.

Quark Matter 2022





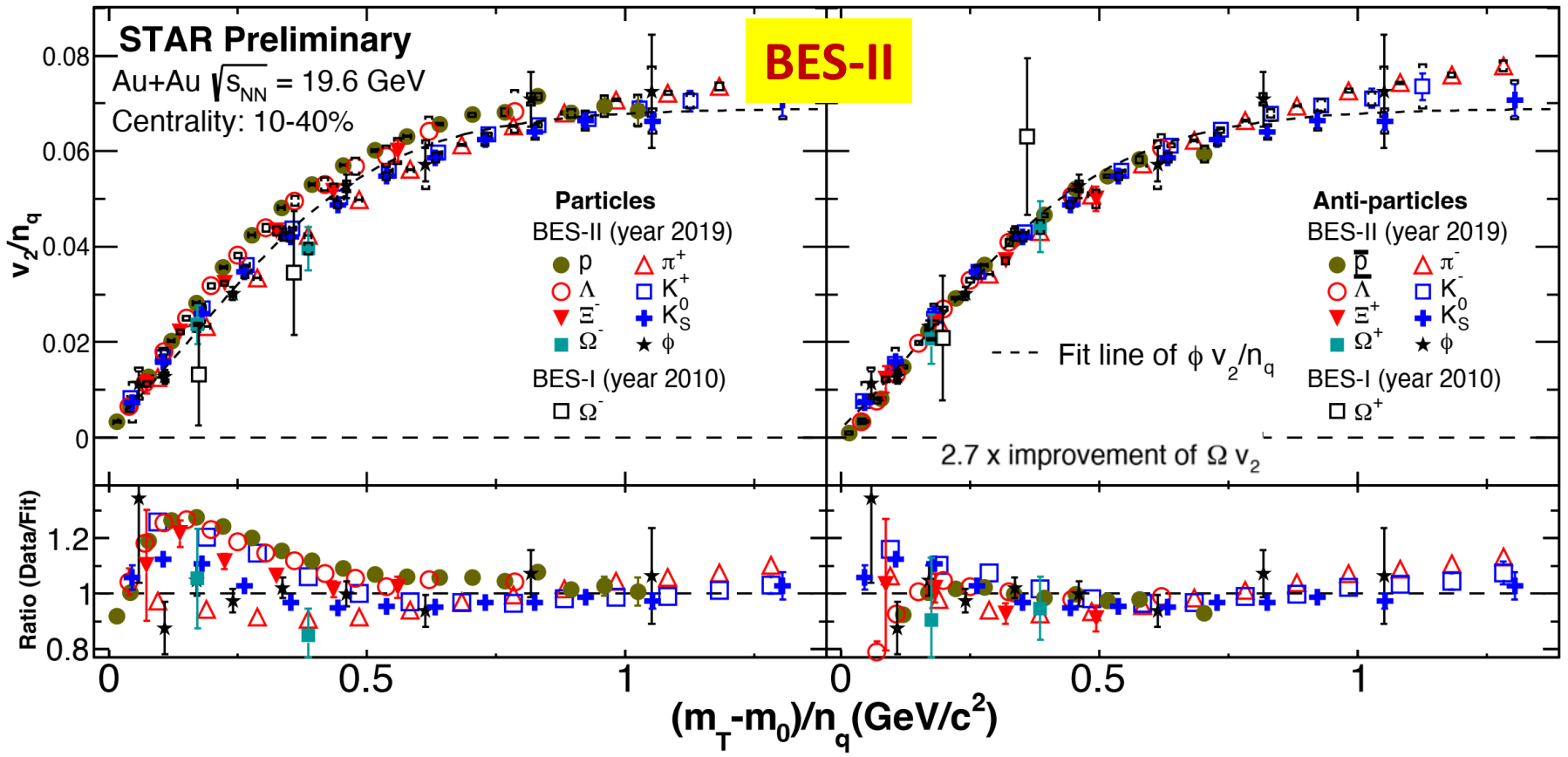
- Non-zero proton v_3, decreases monotonically with the collision centrality
- Negative slope of v_3 vs. rapidity (dv_3/dy=-0.025±0.005 for 10-40% centrality)

3 GeV: v_3 is found to be correlated with the first order event plane. *It is sensitive to EoS**.

**P. Hillmann et al J. Phys. G: Nucl. Part. Phys. 45, 085101(2018)*

v_2 for Hadrons at $\sqrt{s_{NN}} = 19.6$ GeV

Quark Matter 2022

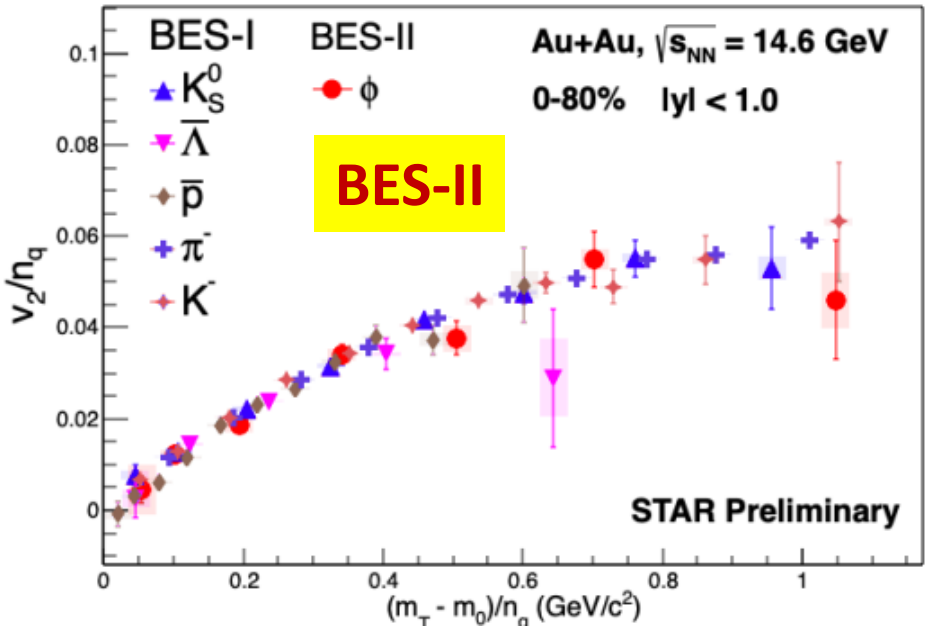


- v_2 for all light and strange hadrons follow the NCQ scaling
  → Partonic degree of freedom
- Scaling holds better for anti-particles than for particles

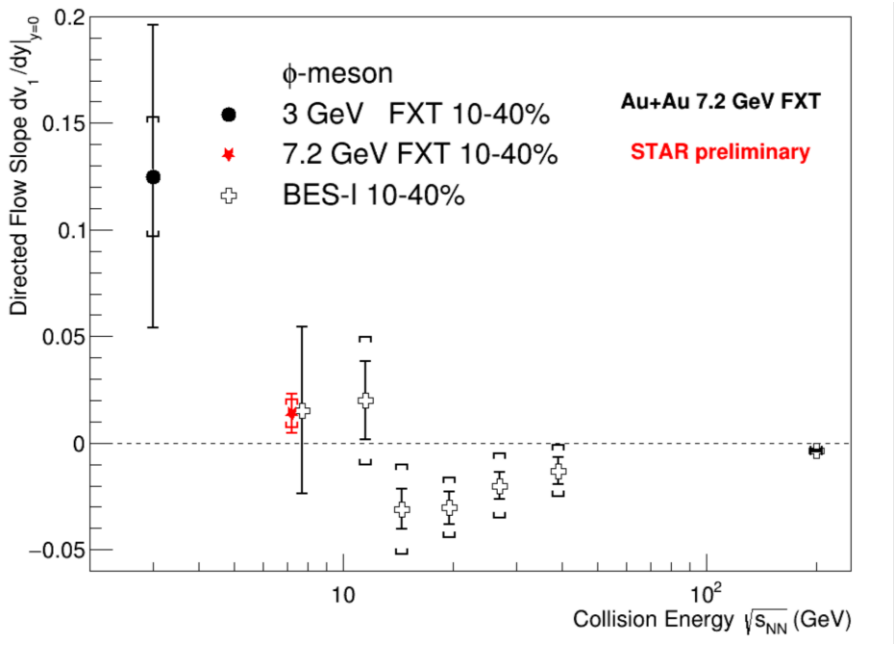
v_1 and v_2 for φ Meson

The φ meson flow is expected to be sensitive to the early stage of collision system.

Quark Matter 2022



Quark Matter 2022



- The φ meson v_2 follows the NCQ scaling at $\sqrt{s_{NN}} > 14.6$ GeV
- The φ meson v_1 slope shows the sign change at $\sqrt{s_{NN}} \sim 10$ GeV, similar to baryons, but not for anti-baryons and light mesons
- Need theoretical explanations

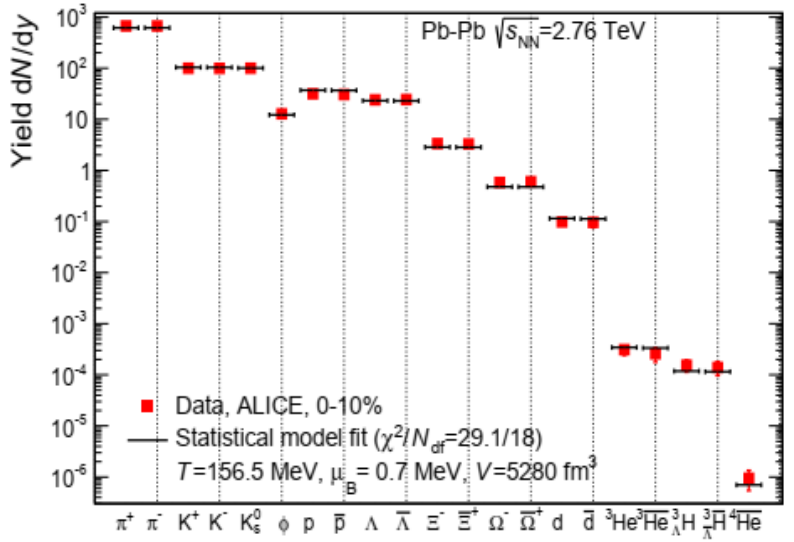
Light Nucleus Flow in Heavy Ion Collisions

Light nuclei: nucleon-nucleon correlation

- ❑ Same chemical freeze-out temperature with hadrons
- ❑ Small binding energies (2.2 MeV for deuteron)

The production mechanisms: thermal? coalescence of nucleons?

Andronic et al, J. Phys.: Conf. Ser. 779 012012(2017)

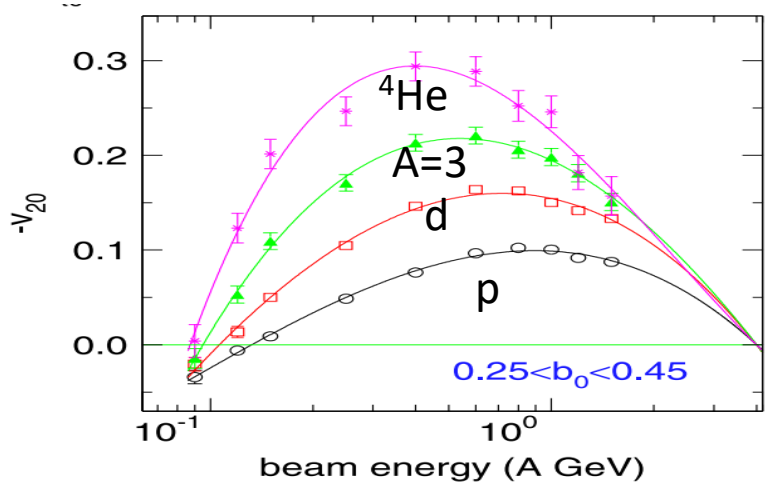


One of experimental probes: flow

The coalescence picture: **atomic mass number A scaling**

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

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

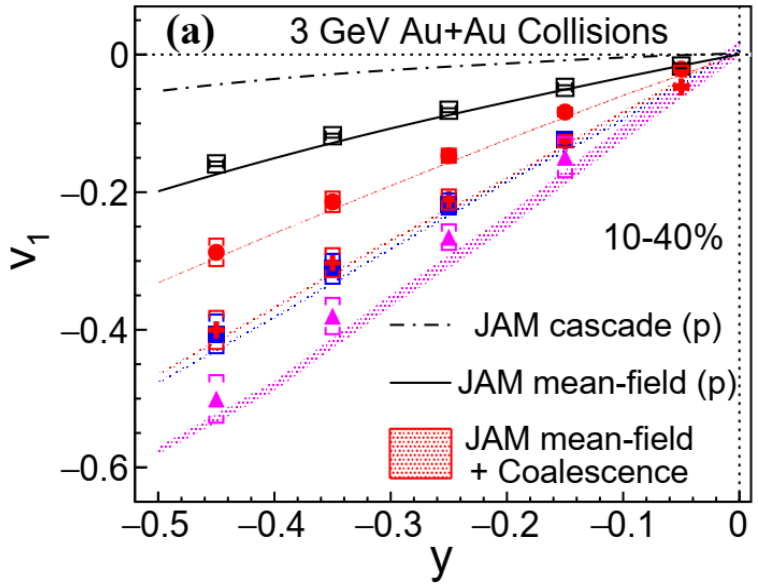


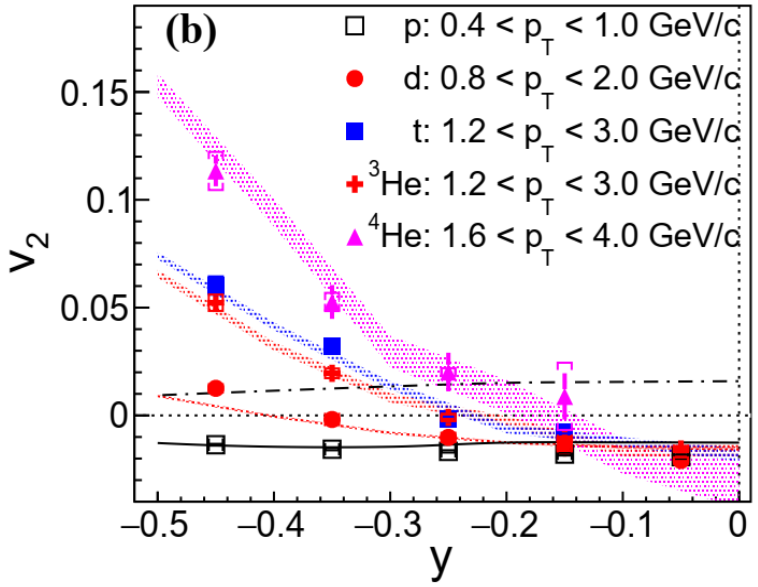
High baryon density

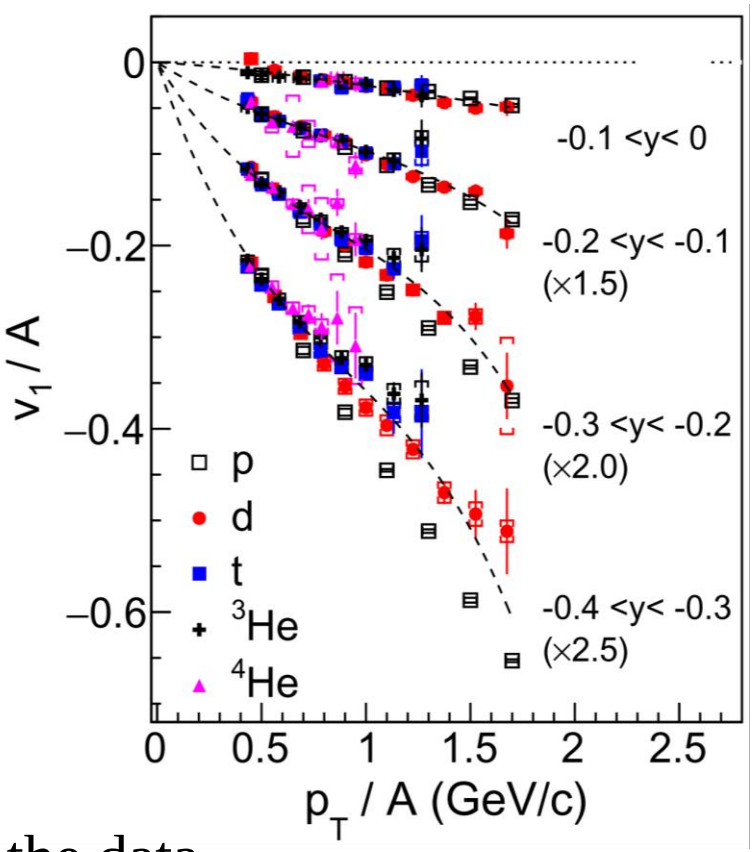
- ❑ Light nuclei flow has stronger energy dependence
- ❑ More sensitive to the EoS

v_1 and v_2 for Light Nuclei at $\sqrt{s_{NN}} = 3$ GeV

Physics Letters B 827, 136941 (2022)





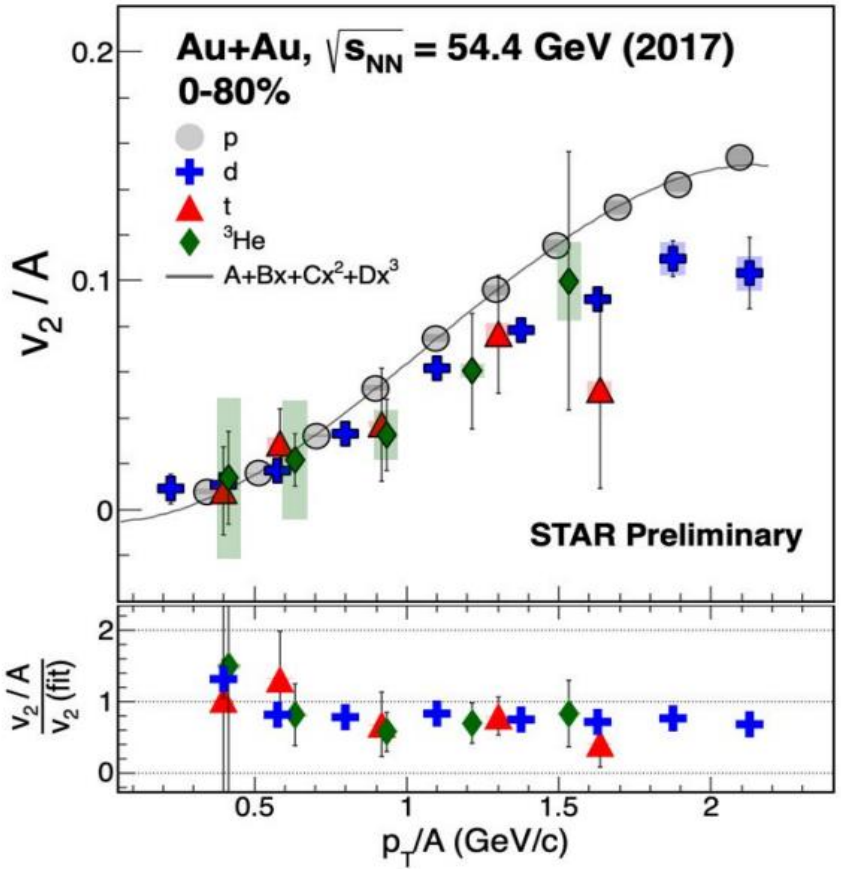


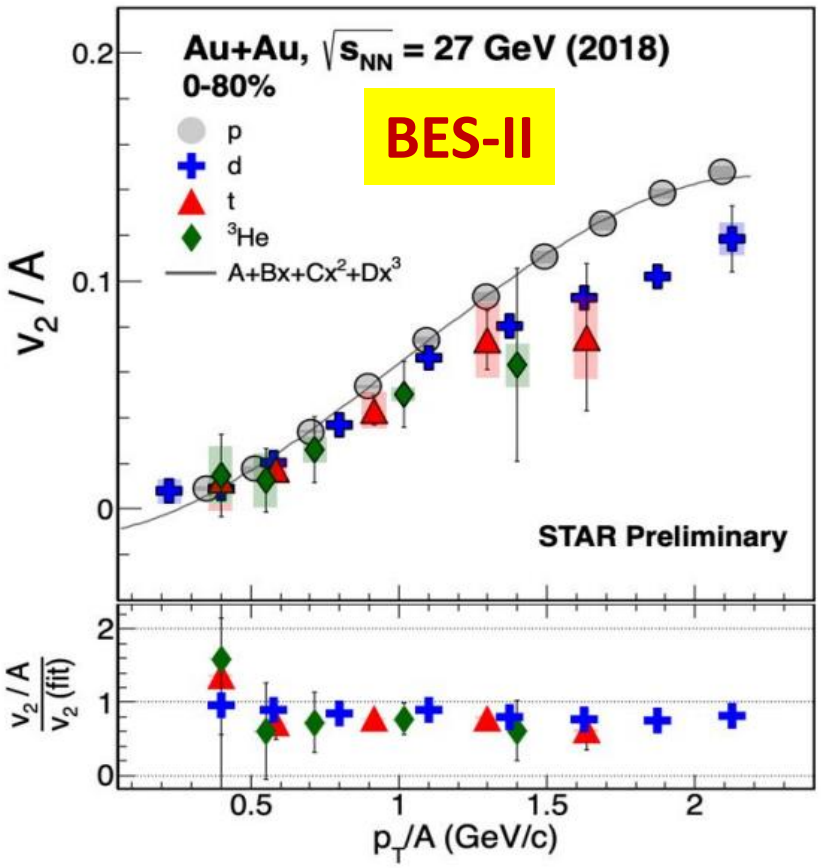
- Light nucleus $v_1(y)$ slope and $v_1(p_T)$ follow the A scaling
- v_2 values at midrapidity are negative and not scaled with A
- Simple nucleon coalescence picture qualitatively describes the data

Light nuclei production is consistent with the coalescence picture at 3 GeV.

Light Nuclei v_2 at 27 GeV and 54.4 GeV

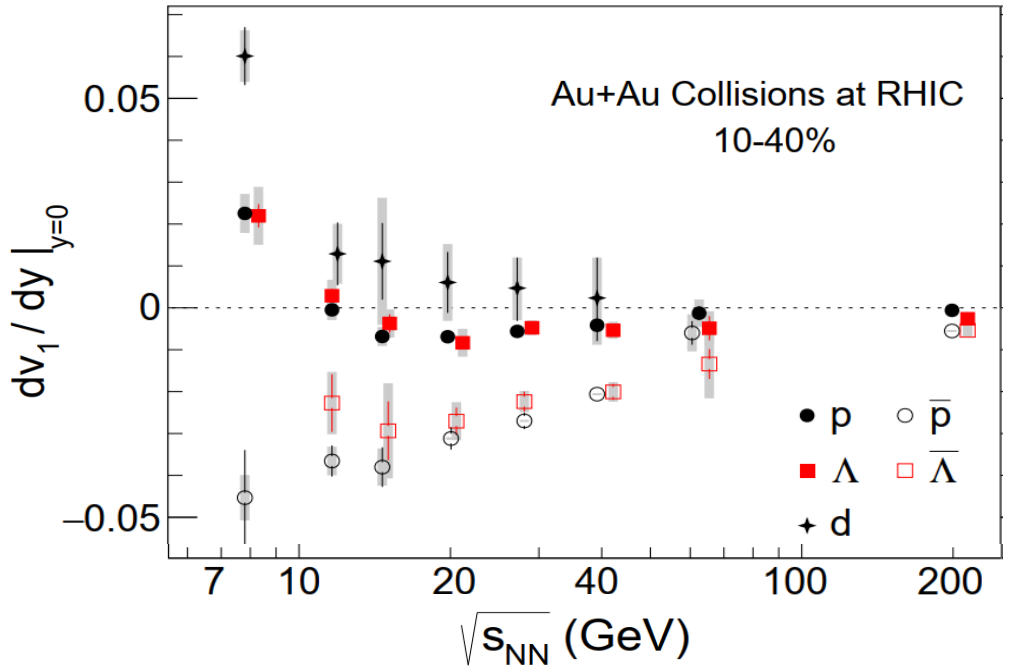
Quark Matter 2022



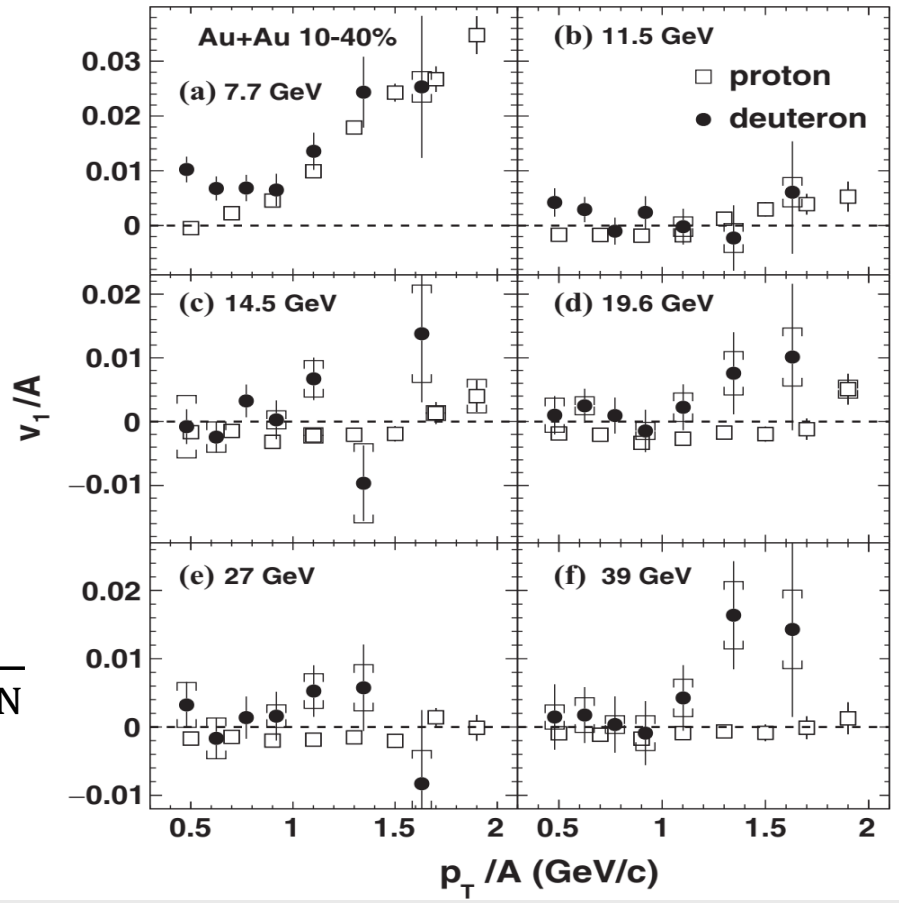


- **10-20% deviation from mass number scaling, coalescence production?**

Light Nuclei v_1 from BES-I



Physics Review C 102, 044906 (2020)



- The v_1 slopes for deuteron are positive in studied $\sqrt{s_{NN}}$
- At 7.7 GeV, deuteron v_1 shows enhancement towards very low p_T

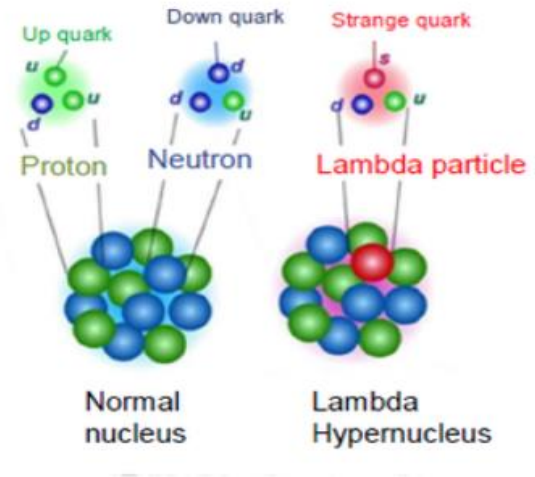
For $\sqrt{s_{NN}}$>7.7 GeV, there is a hint that the v_1 slopes for deuteron are in contrast to negative v_1 slopes for protons.

➢ *High precision measurement at BES-II is underway*

Hyper-Nuclei Flow in Heavy Ion Collisions

Hyper-nuclei: bound states of nuclei and hyperon

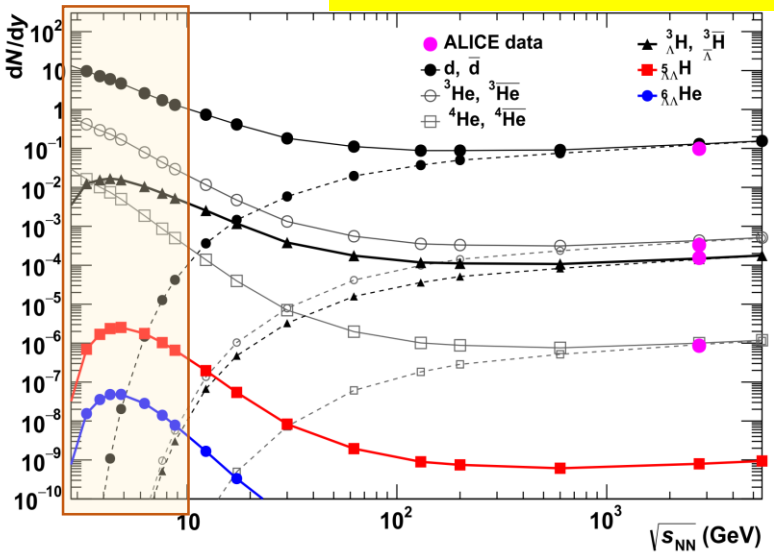
- Probe to the hyperon-nucleon (Y-N) interaction
- Properties of neutron star (EoS, radius)



Λ hyper-nuclei

- ❑ Small binding energies
- ❑ Comparable lifetime with Λ hyperon
- ❑ Maximum yield at several GeV (BES-II)
- ❑ **Unsettled production mechanisms in heavy-ion collision**

Thermal model prediction

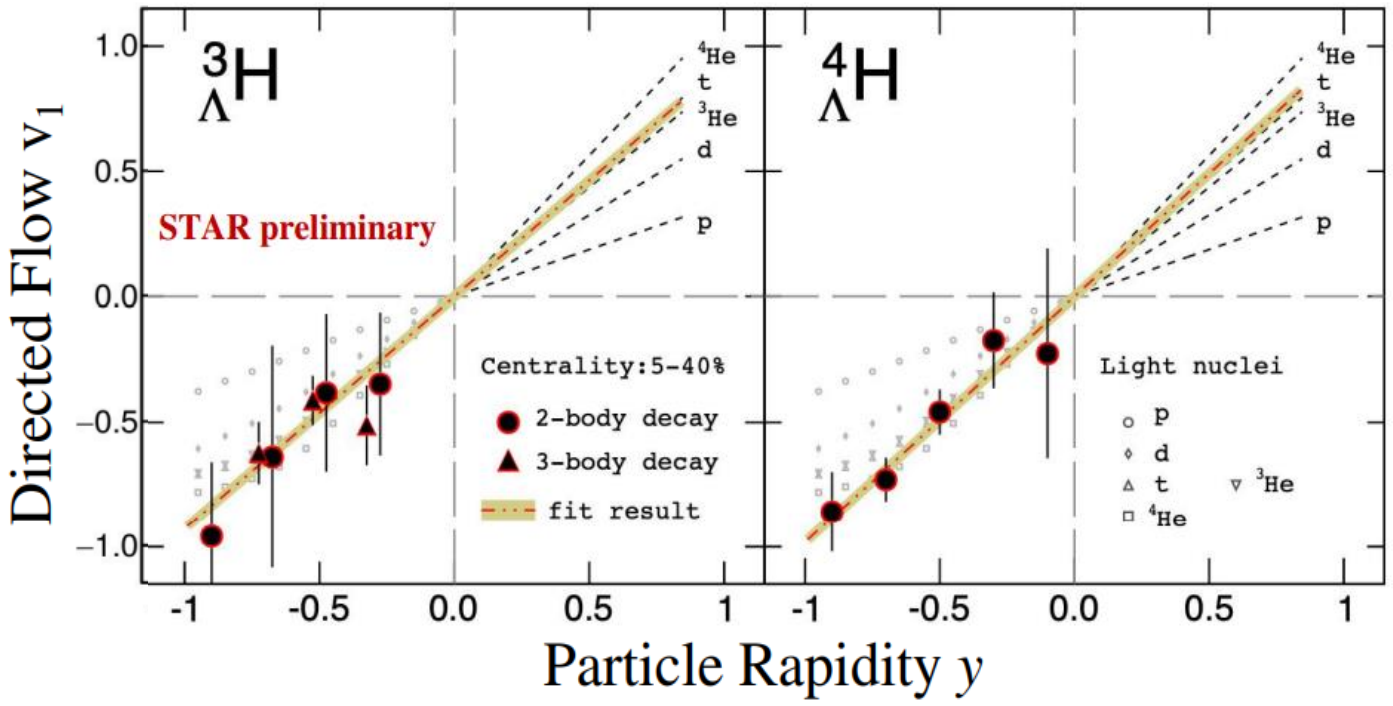


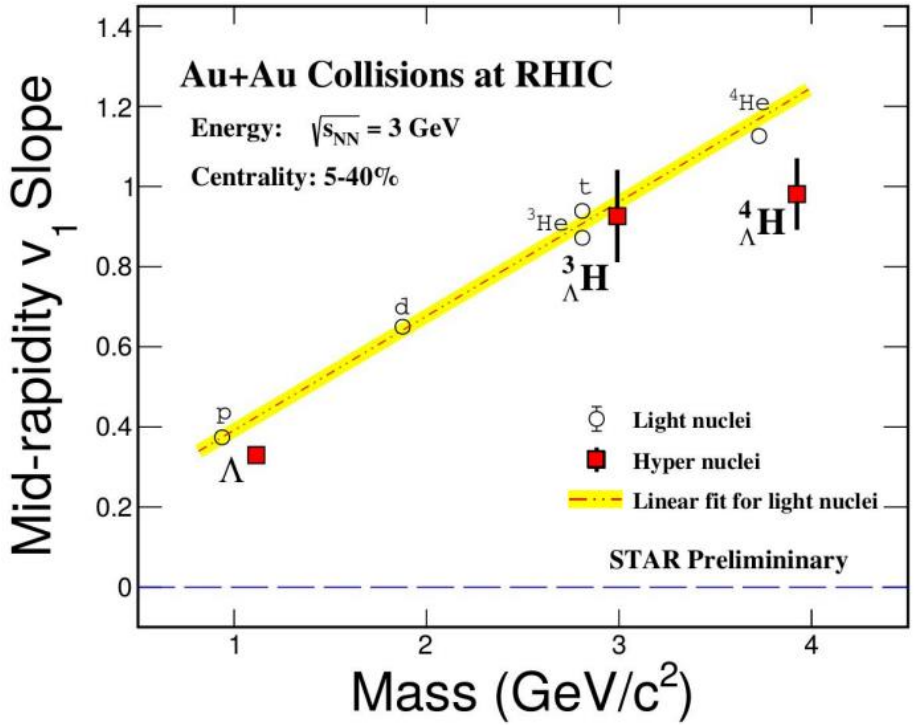
Nuclear Physics A 987, 144 (2019)

Hyper-nuclei v_1 at 3 GeV

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

19th Stangeness in Quark Matter, 2021





- First observation of hyper-nuclei collectivity in heavy-ion collisions
- $v_1(y)$ and slopes are close to those of light nuclei with a same A

Hyper-nuclei formation in the heavy-ion collisions: coalescence of hyperon and nuclei

Outlook

BES-II: high statistics + high event plane resolution → high precision measurements

$\sqrt{s_{NN}}$(GeV)	μ_B(MeV)	Events	Date collected
19.6	206	478 M	2019
14.6	262	324 M	2019
11.5	316	235 M	2020
9.2	373	162 M	2020
7.7	422	101M+163 M	2021
6.2	487	118 M	2020
5.2	541	103 M	2020
4.5	589	108 M	2020
3.9	632	170 M	2020
3.5	666	116 M	2020
3.2	697	201 M	2019
3.0	721	2361 M	2021

- **Light nuclei v_1**
  A hint of opposite sign of dv_1/dy with those of hadrons, important for understanding the production mechanism
- **Hyper-nuclei**
  Energy dependence of flow
- **v_3 for hadrons**
  Sensitive probe to the EoS
- Multi-strange hadrons' v_1

Summary

For the flow measurements at STAR, different behaviors have been observed at lower and higher collision energies.

Hadrons

❑ ***Lower collision energies (high baryon densities)***

- Baryons and φ-meson have positive v_1 slopes
- At 3 GeV, NCQ scaling is absent for v_2; **baryonic interaction** may dominate the evolution
- Non-zero proton $v_3(\psi_1)$ at 3 GeV, not likely to originate from initial state fluctuations

❑ ***Higher collision energies***

- NCQ scaling indicates partonic degree of freedom

Light nuclei and hyper-nuclei

❑ ***Lower collision energies***

- First measurement of hyper-nuclei collectivity
- Light nuclei and hype-nuclei flow are consistent with a production picture of nucleon coalescence

❑ ***Higher collision energies***

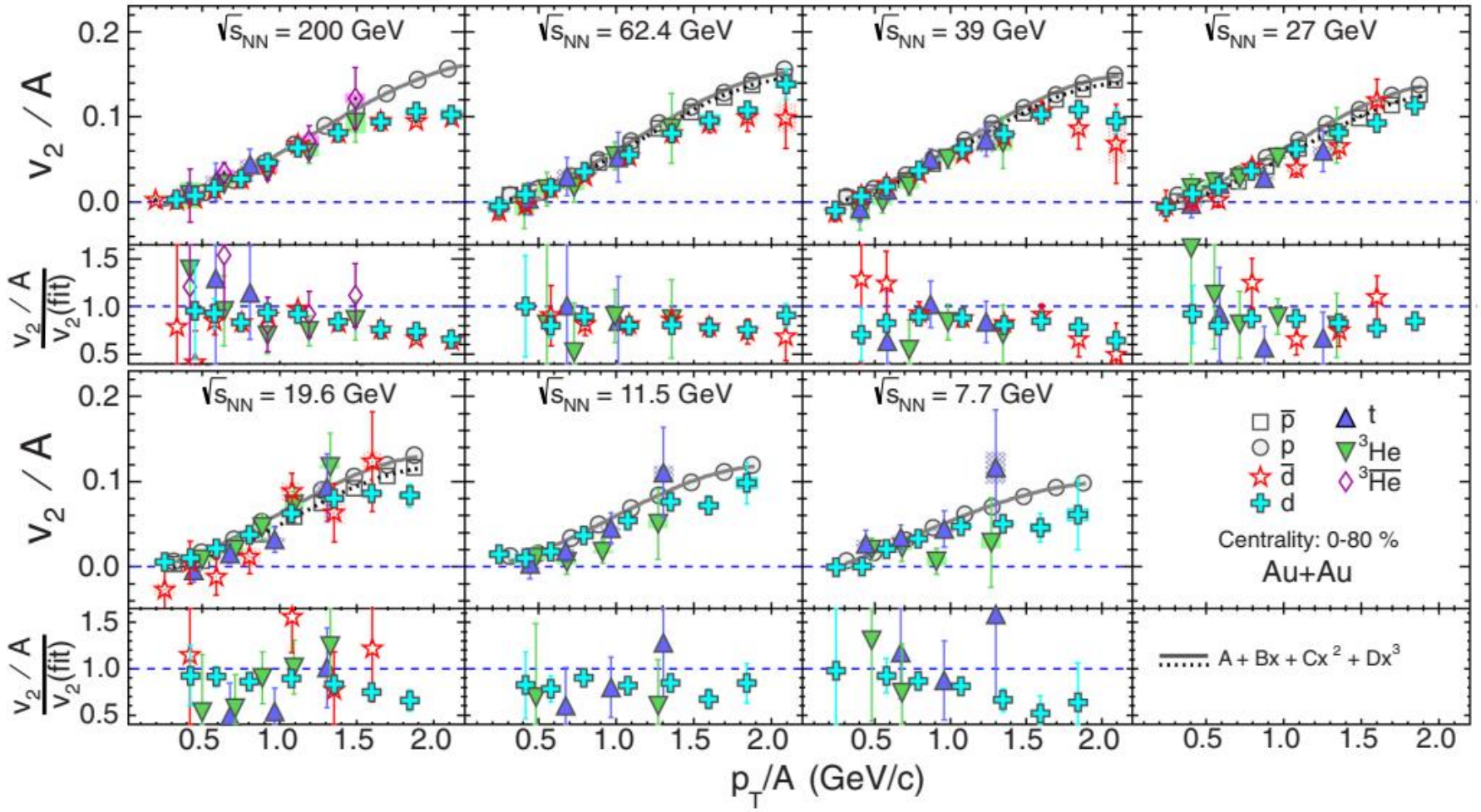
- Light nuclei v_2 shows tension in the atomic-mass number scaling
- Hint of positive deuteron v_1 slopes

High precision measurements from BES-II are ongoing!

Back Up

Light Nuclei v_2 from BES-I

Physics Review C 94, 034908 (2016)



For $\sqrt{s_{NN}}$>7.7 GeV, the light nucleus v_2 follow A scaling of at low p_T.
→ coalescence production