The centrality and energy dependence of the elliptic flow of light nuclei and hadrons in STAR

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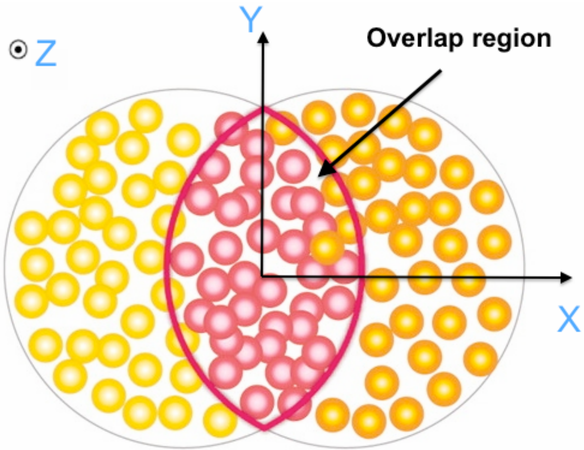
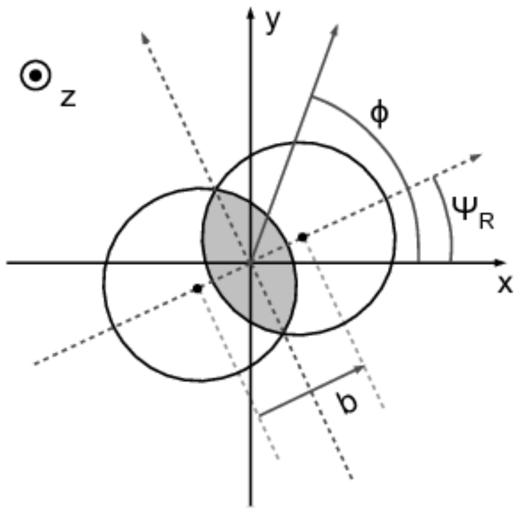
Outline
- **Introduction & motivation**
- **STAR experiment at RHIC**
- **Results**
- **Summary**

Quark Matter
Darmstadt
May 19-24, 2014

Azimuthal anisotropy



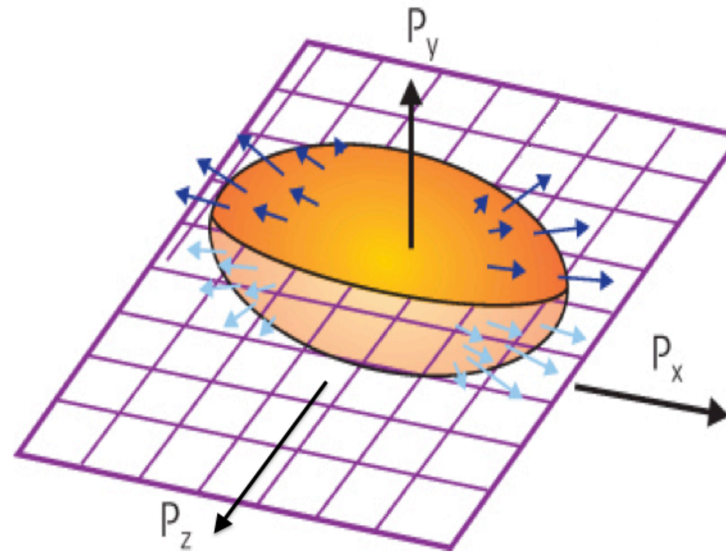


Interactions

↓

Pressure (P)

$$y > x \longrightarrow \frac{\partial P}{\partial x} > \frac{\partial P}{\partial y}$$



Azimuthal distribution of produced particles can be described as a Fourier series. The second order coefficient,

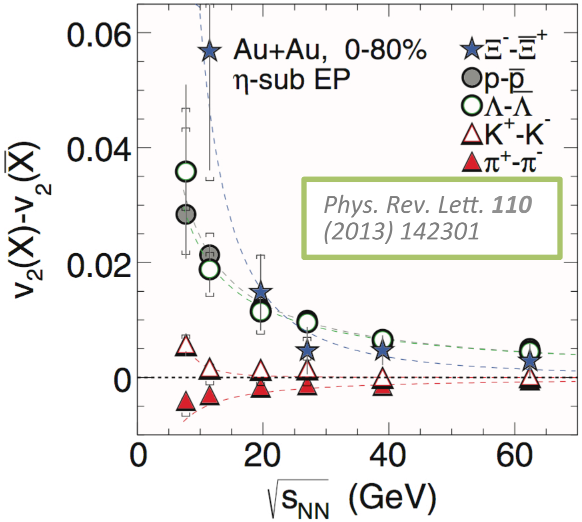
$$v_2 = \langle \cos(2(\phi - \psi_R)) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

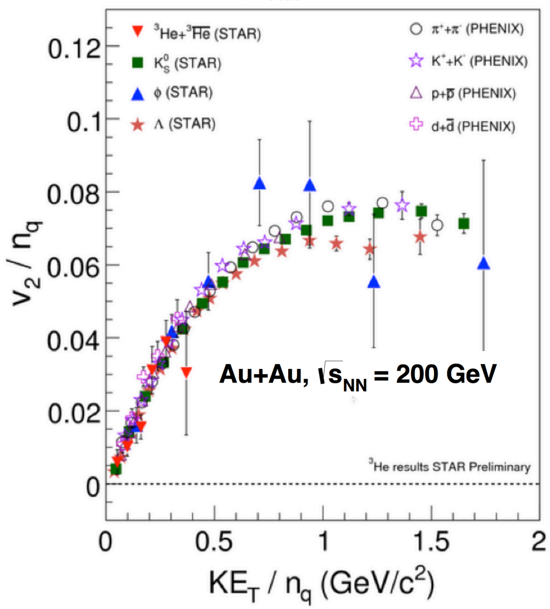
– Sensitive to early times in the evolution of the system

An estimate of ψ_R, namely Event Plane (ψ_2) is calculated using produced particles in mid-rapidity.

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

Motivation





- ✓ Particle anti-particle v_2 shows difference.

→ *How does the difference depend on centrality and energy?*

- ✓ hadron v_2 show constituent quark (NCQ) scaling.
- ➢ Nuclei are expected to form at a later stage due to their low binding energy

→ *Can we expect mass number scaling of nuclei v_2 ?*

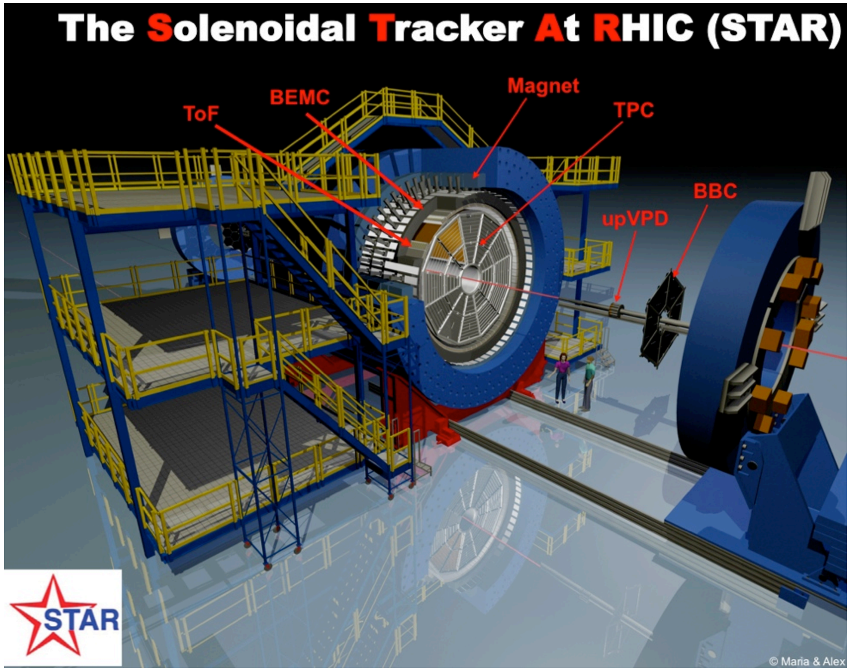
→ *How does nuclei and anti-nuclei v_2 compare?*

→ *Is there any centrality dependence of nuclei v_2 ?*

J. I. Kapusta, Phys. Rev. C 21, 1301 (1980)
R. Scheibl, U. Heinz, Phys. Rev. C 59, 1585 (1999)
D. Molnár, S. A. Voloshin, Phys. Rev. Lett. 91, 92301 (2003)

Figure ref: *Phys. Rev. C 75, 054906* (2007), *Phys. Rev. Lett. 99, 112301* (2007), *Phys. Rev. Lett. 98, 162301* (2007)

The STAR experiment



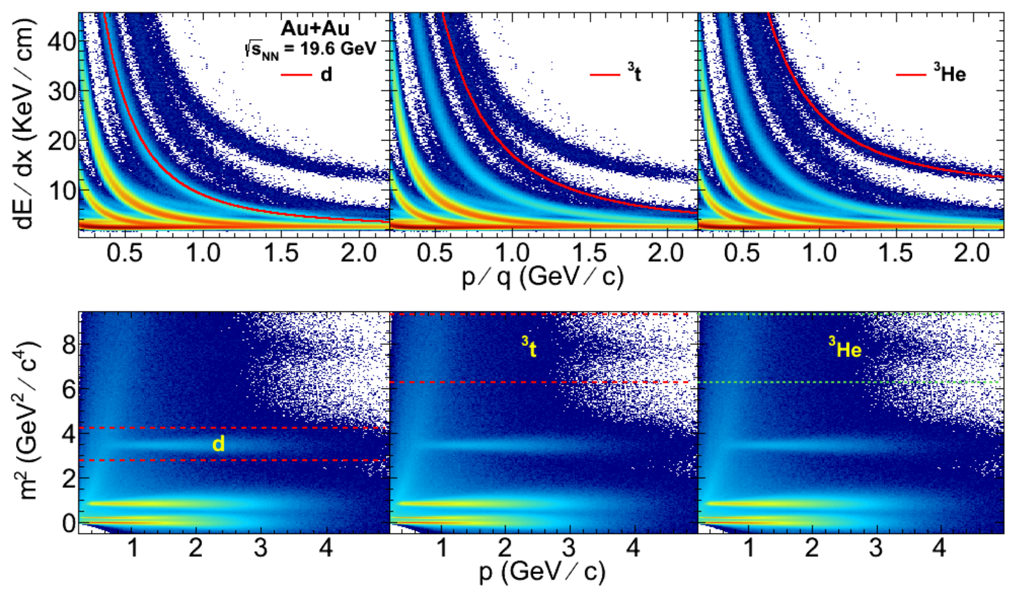
1. **Time Projection Chamber (TPC)**
   pseudo-rapidity window: $-1.0 < \eta < 1.0$
   full azimuthal coverage.

2. **Time of Flight (ToF)**
   pseudo-rapidity window: $-0.9 < \eta < 0.9$
   full azimuthal coverage

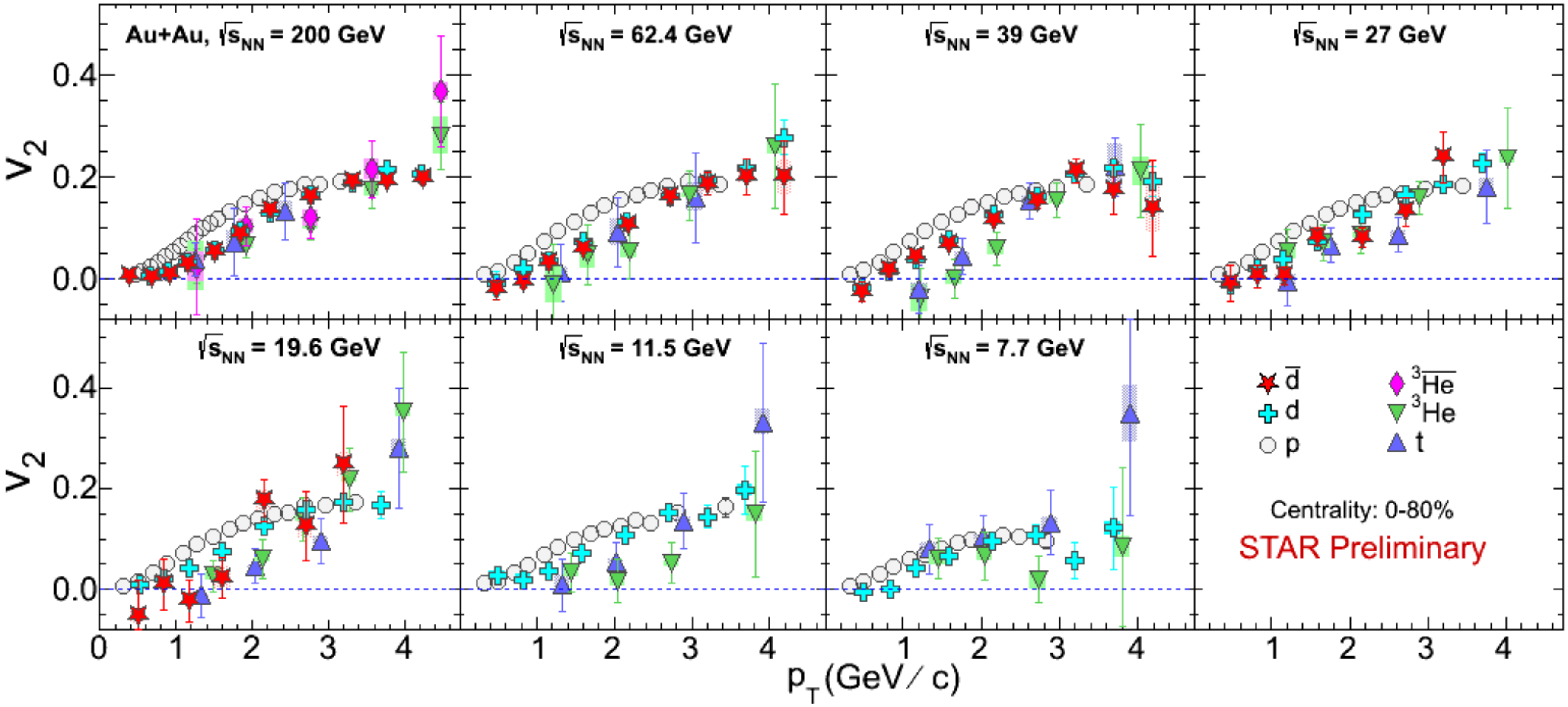
Using TPC and ToF *π, K, p* can be identified up to p_T ~3.0 GeV/c,

Light nuclei identification using TPC →
d, dbar, triton: p_T ~1.0 GeV/c, and ^{3}He up to 4.5 GeV/c

Light nuclei identification using ToF →
d, dbar, triton: p_T ~4.0 GeV/c,



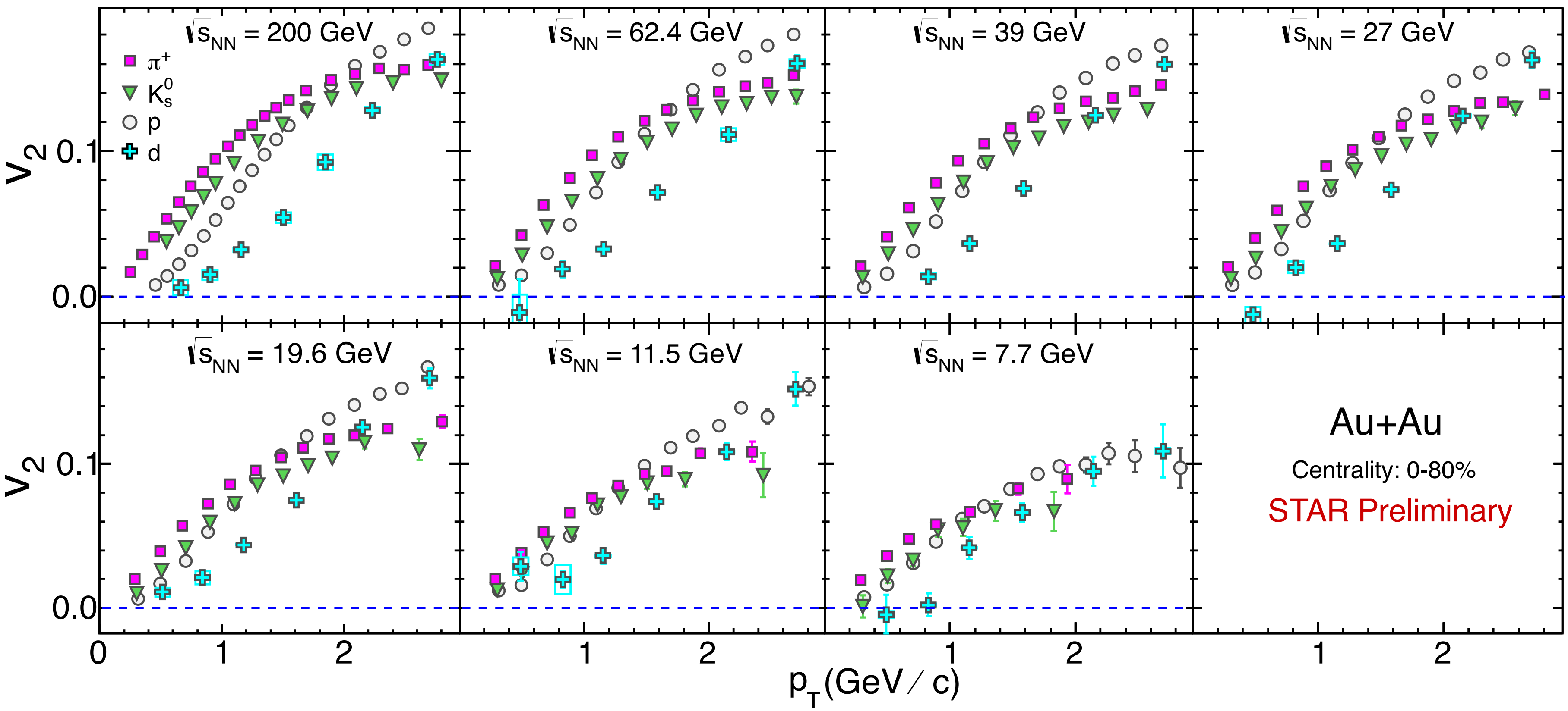
Measurement of nuclei v_2



- ✓ Elliptic flow of *d*, *$\bar{d}$*, *t*, *^{3}He*, *$^3\overline{He}$* measured at mid-rapidity.
- ✓ η sub-eventplane method was used with η-gap = 0.1

proton v_2 from Phys. Rev. C 88, 014902 (2013)

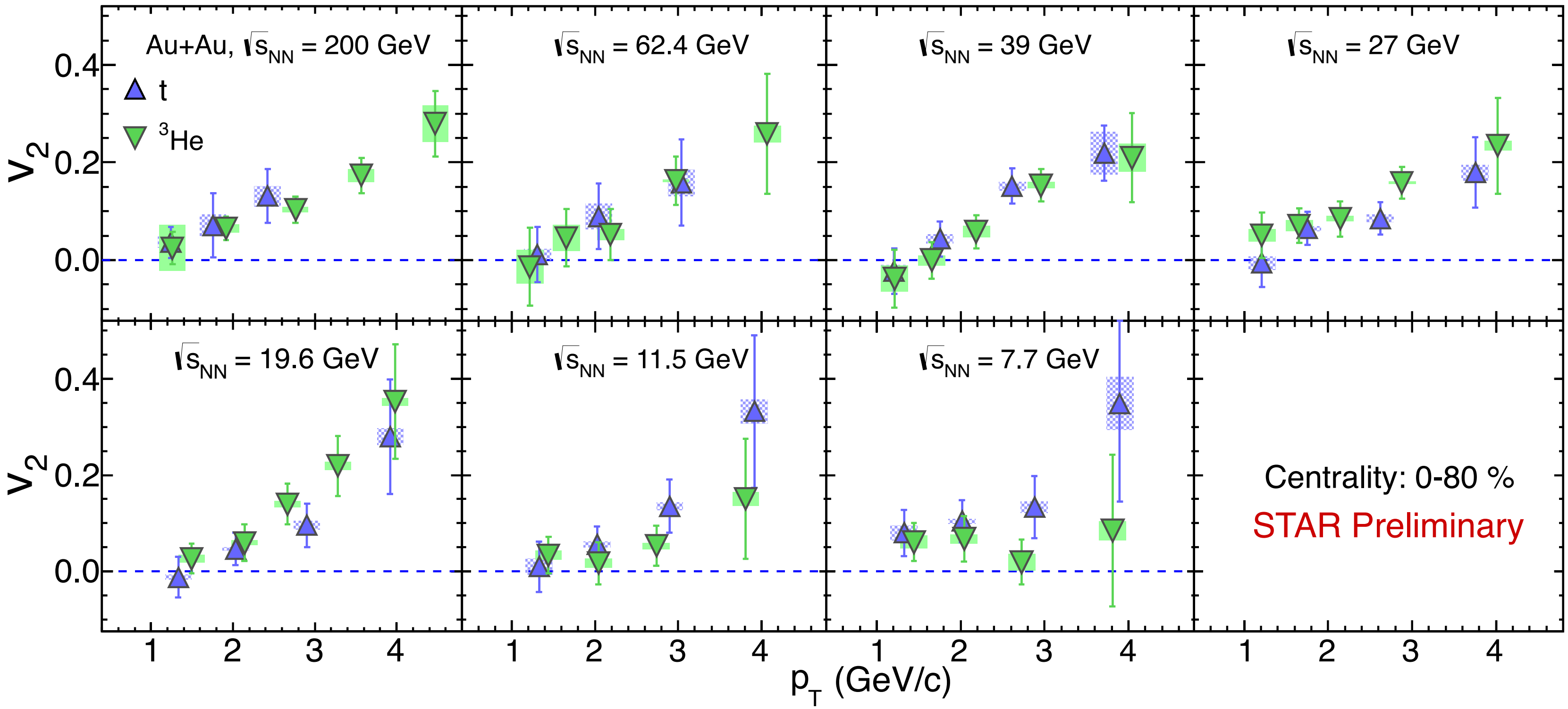
Mass ordering of v_2



→ *Nuclei v_2 shows mass ordering at low p_T similar to hadrons*

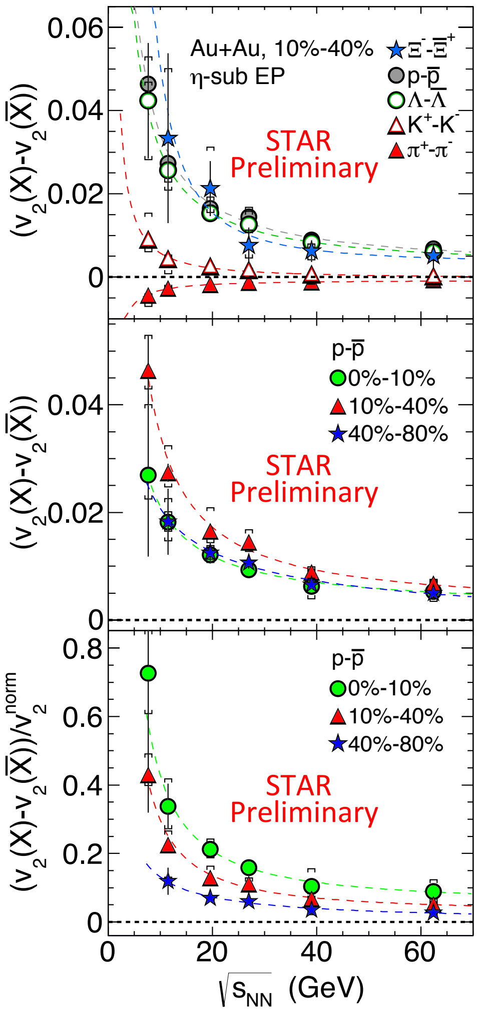
hadron v_2 from Phys. Rev. C 88, 014902 (2013)

v_2 of triton (*t*) and ^{3}*He*

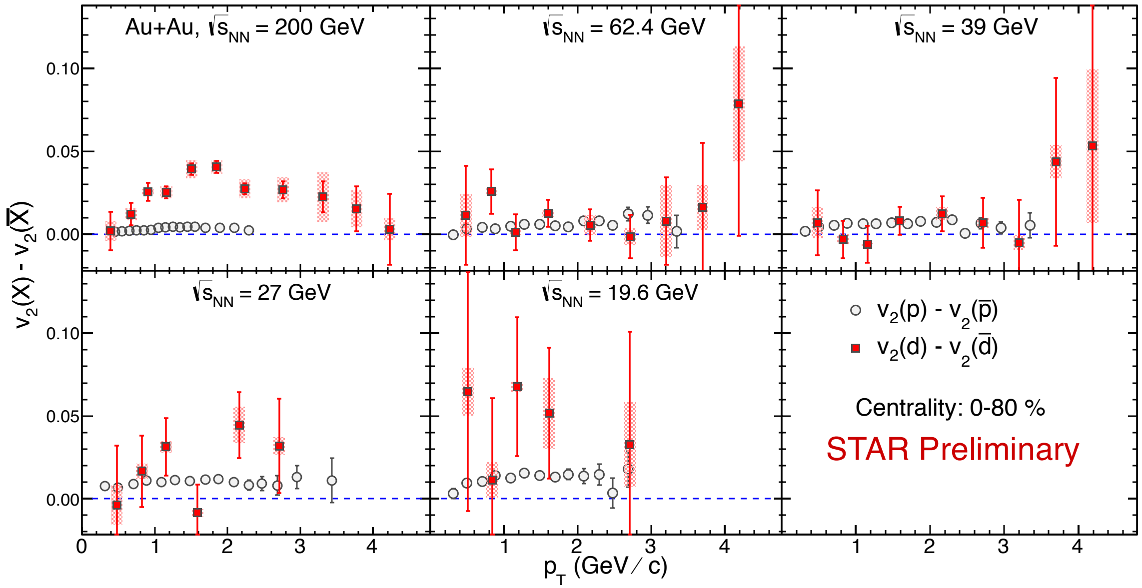


→ v_2 of t and ^{3}He are of similar magnitude (within statistical uncertainty)

v_2 of particles and anti-particles



$v_2^{norm} = v_2$ of proton



→ *Nuclei and anti-nuclei v_2 shows a difference at 200 GeV*

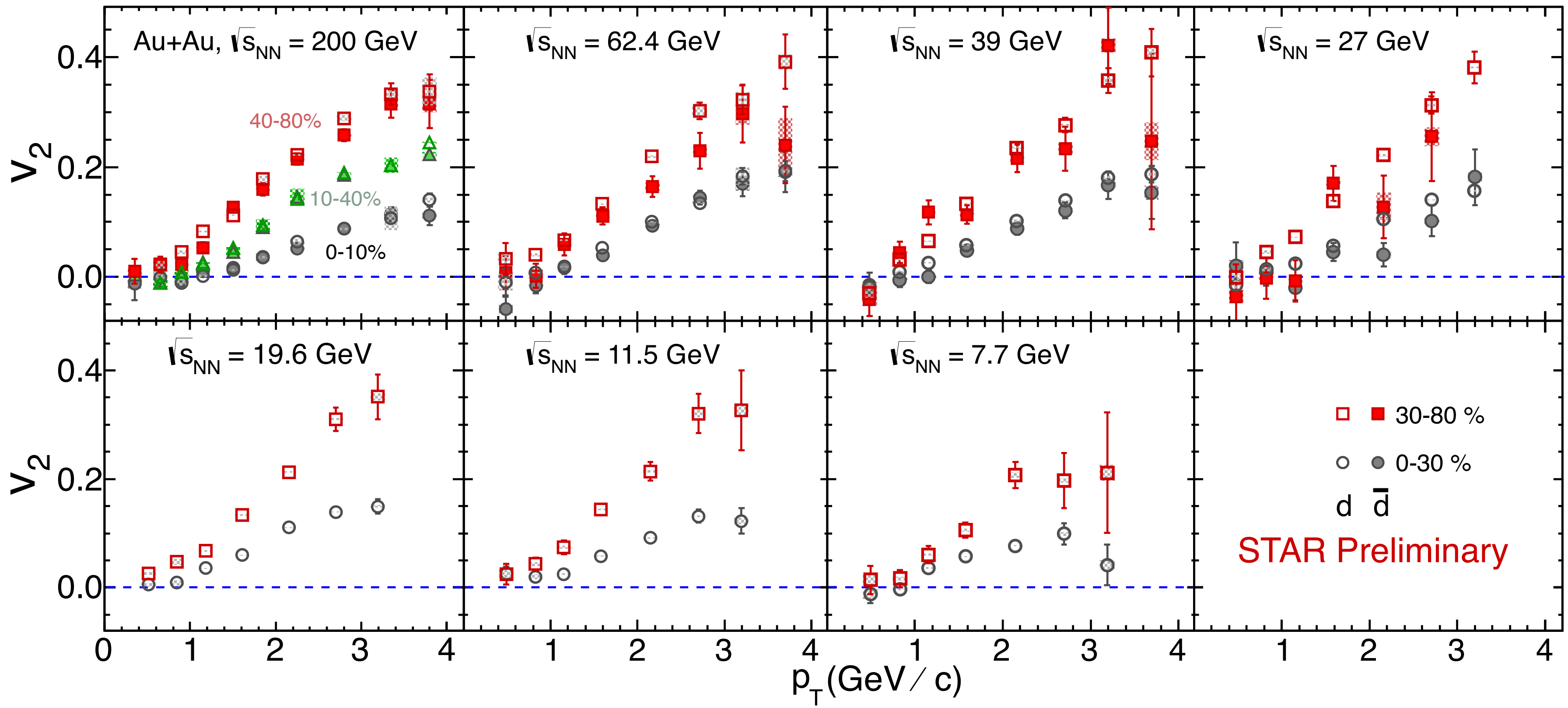
→ *Statistical uncertainties large at lower beam energies to make definite conclusions.*

→ *Δv_2 for 10-40% centrality is similar to minimum bias result*

→ *Centrality dependence not observed in Δv_2*

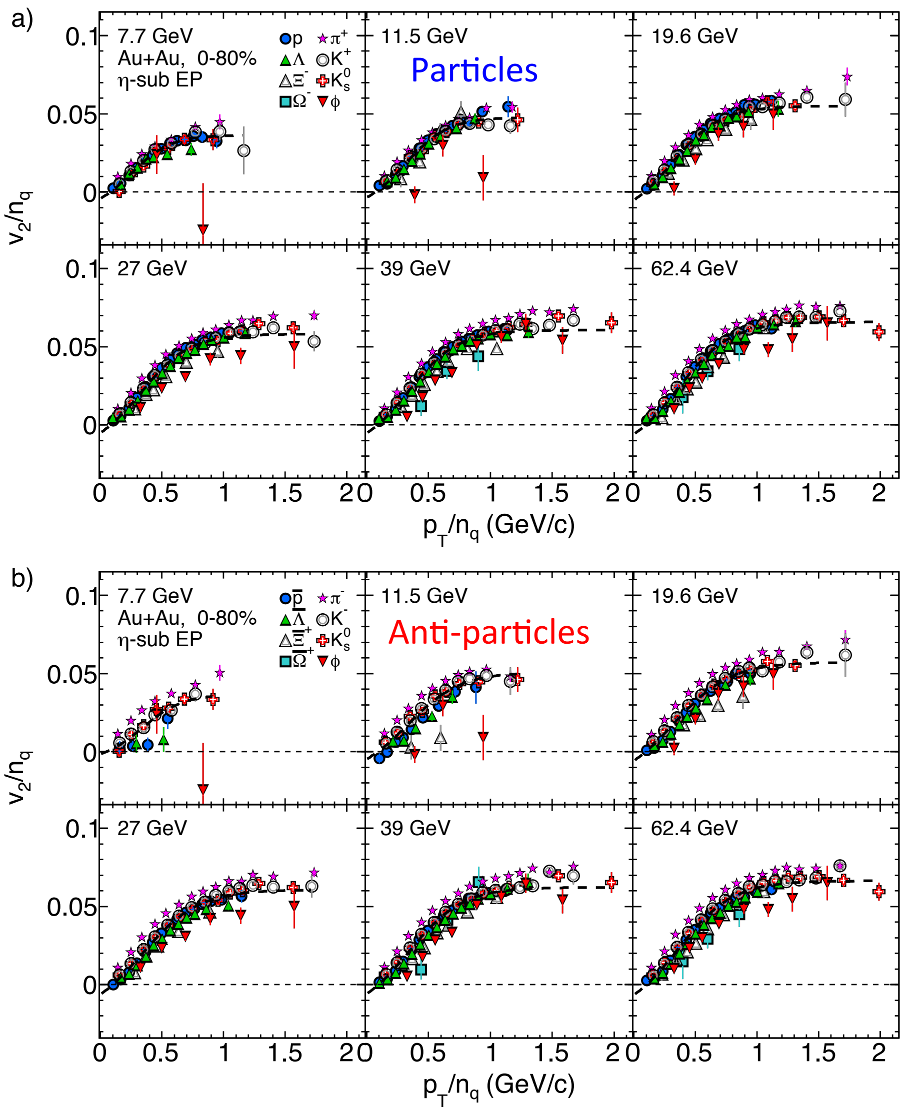
→ *Δv_2 relative to proton v_2 shows a centrality dependence*

Centrality dependence of nuclei v_2



→ *Nuclei v_2 shows centrality dependence for all energies*

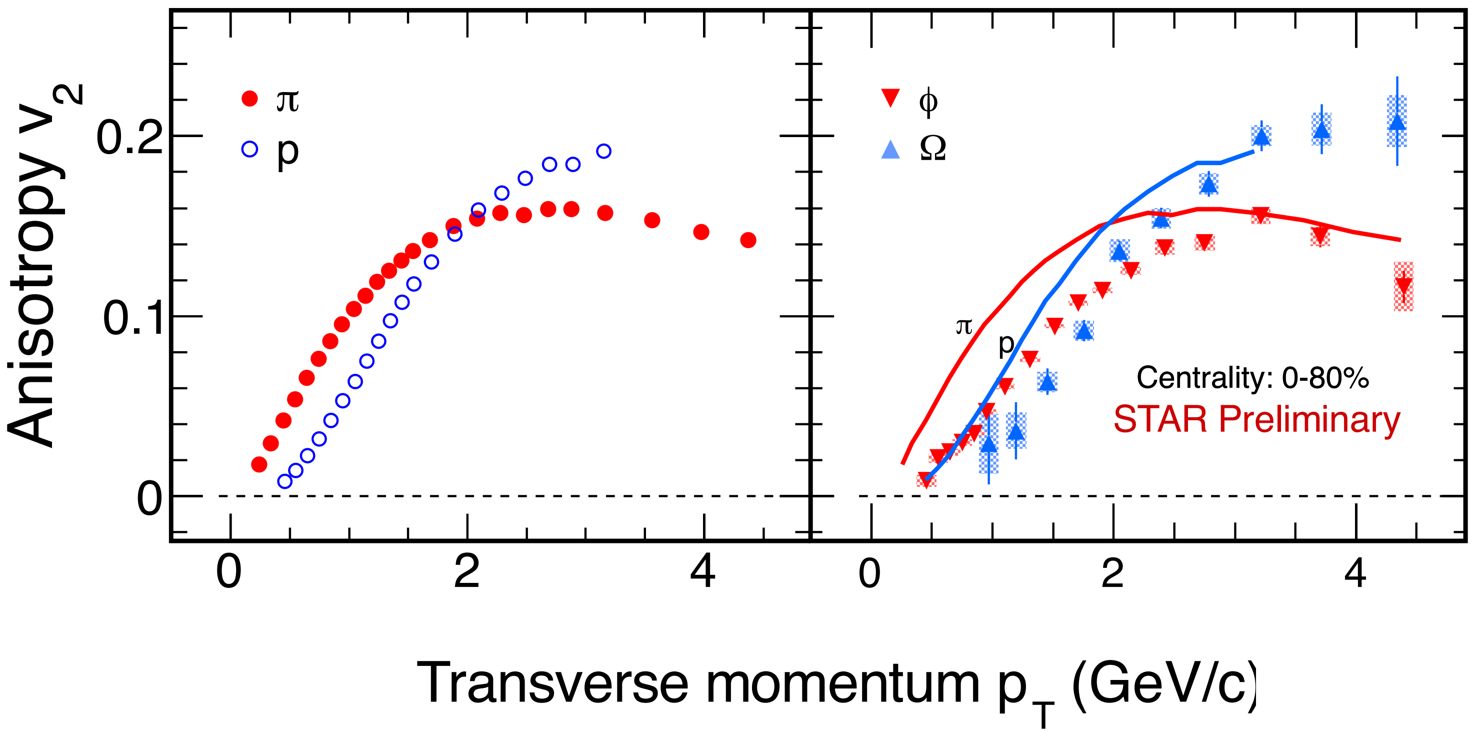
NCQ scaling of hadron v_2



- ✓ NCQ scaling observed for particle and anti-particle groups separately for beam energy ≥ 19.6 GeV
- ✓ Scaling holds for $1.5 < p_T < 5.0$ GeV/c
- ✓ More statistics is needed for 7.7 and 11.5 GeV/c

Figures: Phys. Rev. C 88, 014902 (2013)

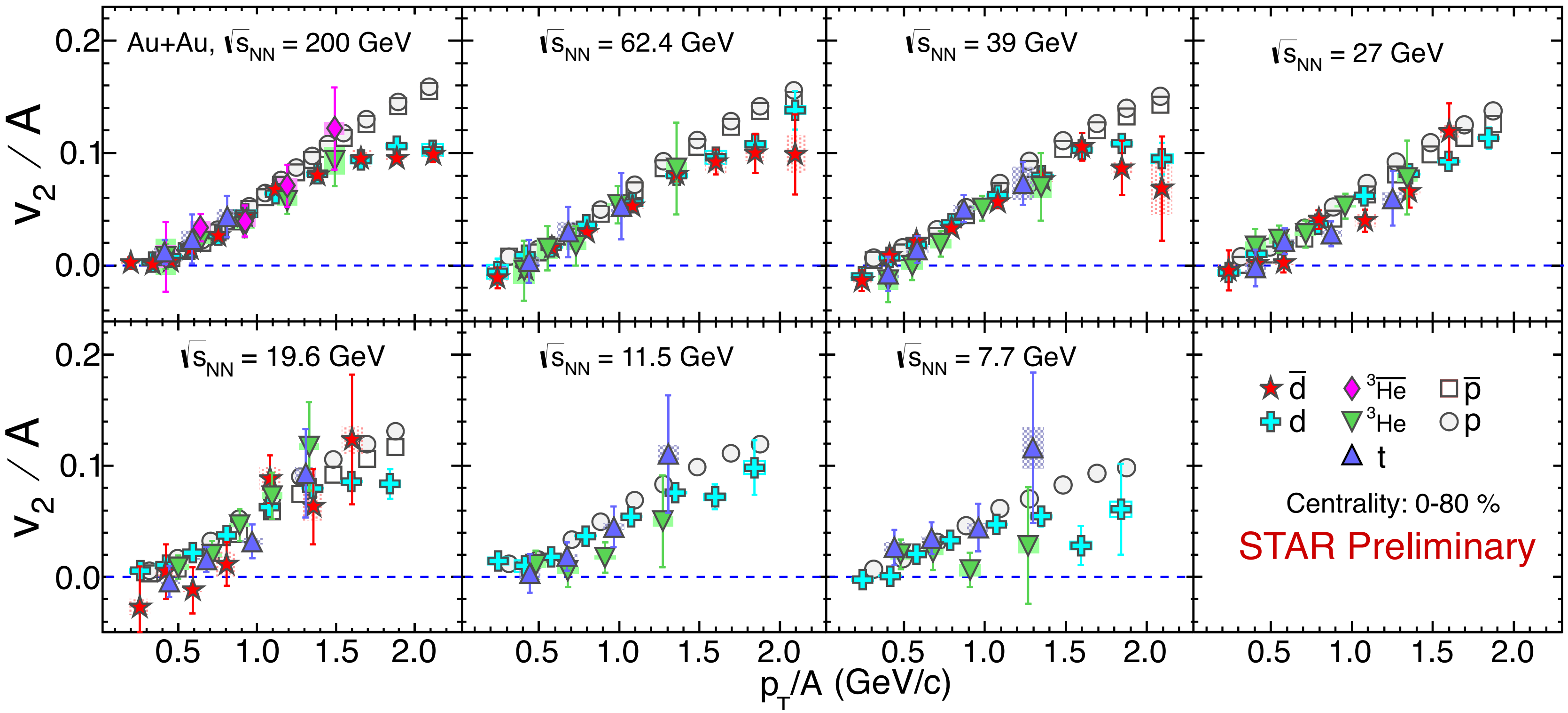
Precision measurement of v_2 of ϕ *and* Ω



- ✓ Mass ordering observed for $p_T < 2.0$ GeV/c
- ✓ Baryon – meson splitting for $2.0 < p_T < 5.0$ GeV/c

→ *High precision measurement of ϕ and Ω v_2 agree with the previous physics conclusion of partonic collectivity at 200 GeV*

Mass number scaling of v_2

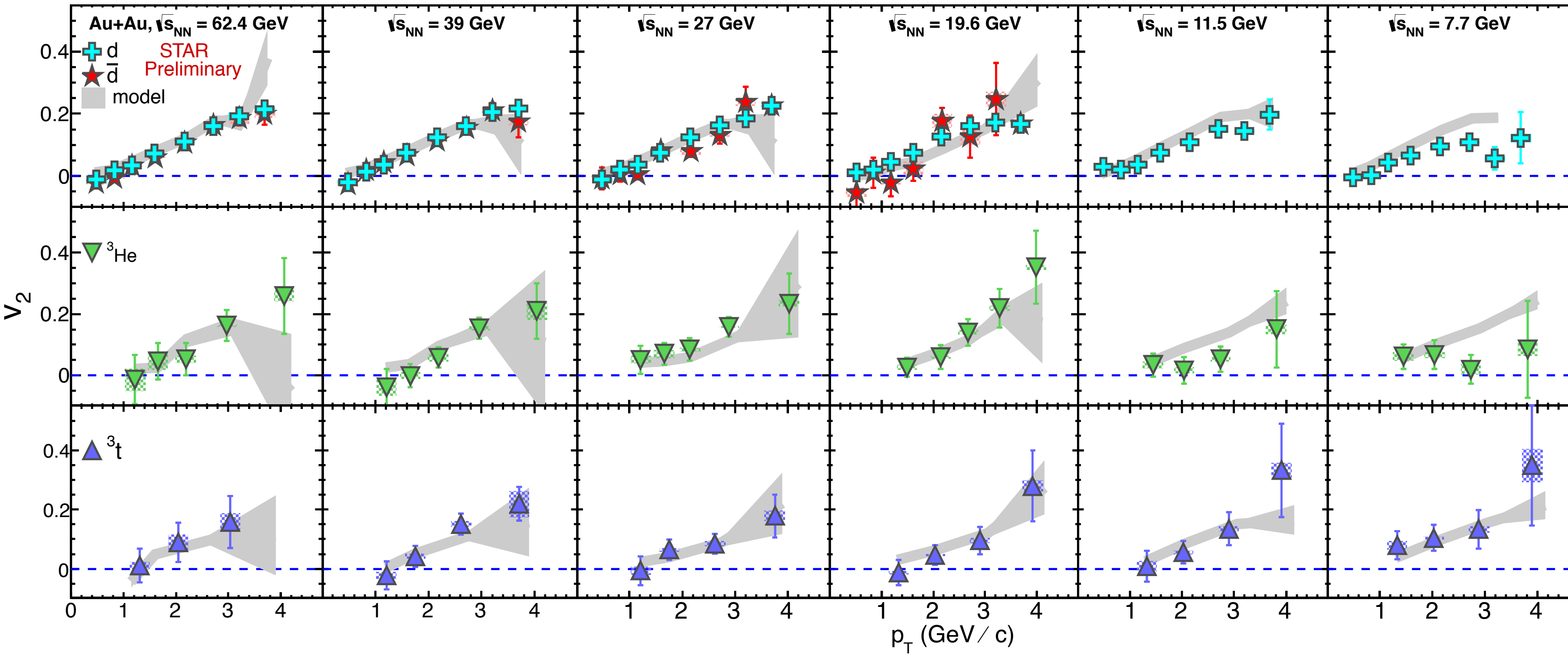


Nuclei v_2 show mass number scaling for p_T /A ~1.5 GeV/c for all beam energies

→ *Support the general idea that nuclei are formed by coalescence of nucleons*

(anti-) proton v_2 from Phys. Rev. C 88, 014902 (2013)

Coalescence model results



Coalescence model agrees with data

→ Another indication of coalescence of nucleons to form nuclei

- ✓ Probability for producing a nucleus is given by the overlap of nucleon phase-space distribution with the Wigner phase-space function of nucleons inside the nuclei.
- ✓ Nucleon phase space information used from a transport (AMPT) model.

R. Mattiello et al. Phys. Rev. Lett. 74, 2180 (1995), L. W. Chen et al. Phys. Rev. C 68, 017601 (2003)
AMPT model: Zi-Wei Lin et al. Phys. Rev. C 72, 064901 (2005)

Summary

(A) New Measurement presented:

✓ Energy ($\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV) and centrality dependence of nuclei v_2 presented.

✓ Centrality dependence of difference in v_2 of proton and anti-proton at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 62.4 presented.

(B) Observation and Physics conclusion:

1. Nuclei v_2 versus p_T shows a clear centrality dependence and mass ordering when compared to identified hadrons at all beam energies studied

→ *Mass ordering of v_2 occurs naturally in a hydrodynamic model.*

2. Nuclei v_2 versus p_T shows mass number scaling upto p_T/A = 1.5 GeV/c and the magnitude of nuclei v_2 versus p_T are reproduced by a Coalescence model.

→ *Both these support the physics picture of coalescence of nucleons as the dominant mechanism of nuclei production.*

3. The difference in v_2 of proton and anti-proton is observed to be similar at all collision centralities studied for the BES energies. A centrality dependence appears when this difference is normalized to proton v_2 at the respective beam energies

→ *The results implies hadronic interactions play an important role at lower beam energies.*

Other interesting results on flow from STAR (Posters):

Triangular Flow of Identified Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 39 and 200 GeV

- *Xu Sun* *(Poster Id: H-37)*

Measurement of higher harmonic flow of ϕ meson in STAR at RHIC

- *Mukesh Sharma* *(Poster Id: H-03)*

Thanks..

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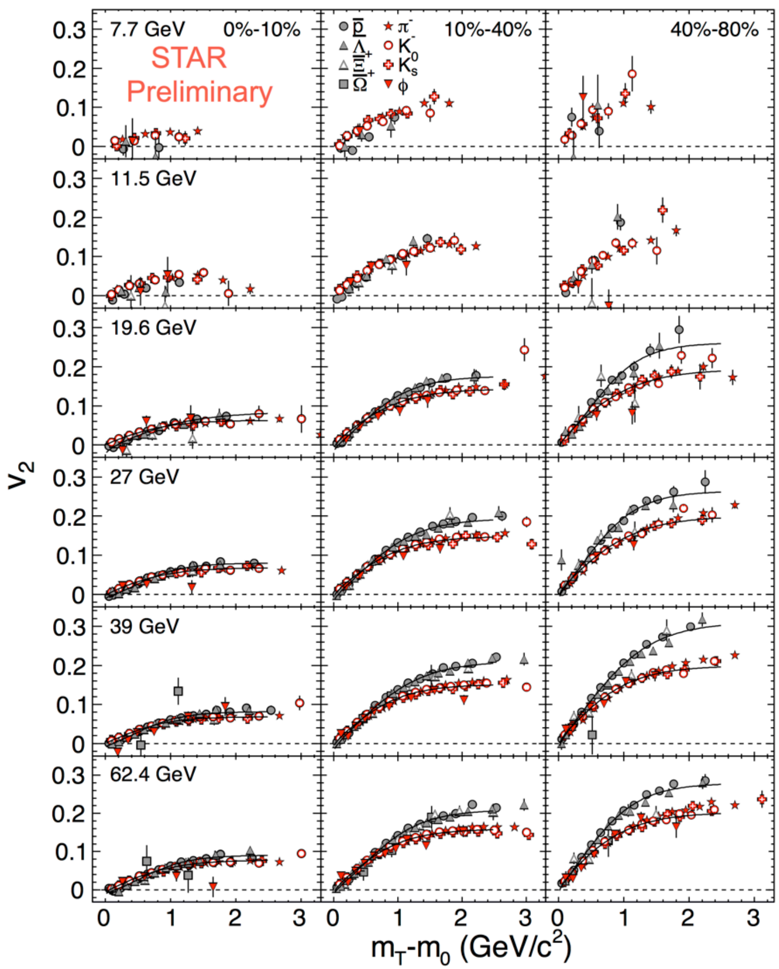
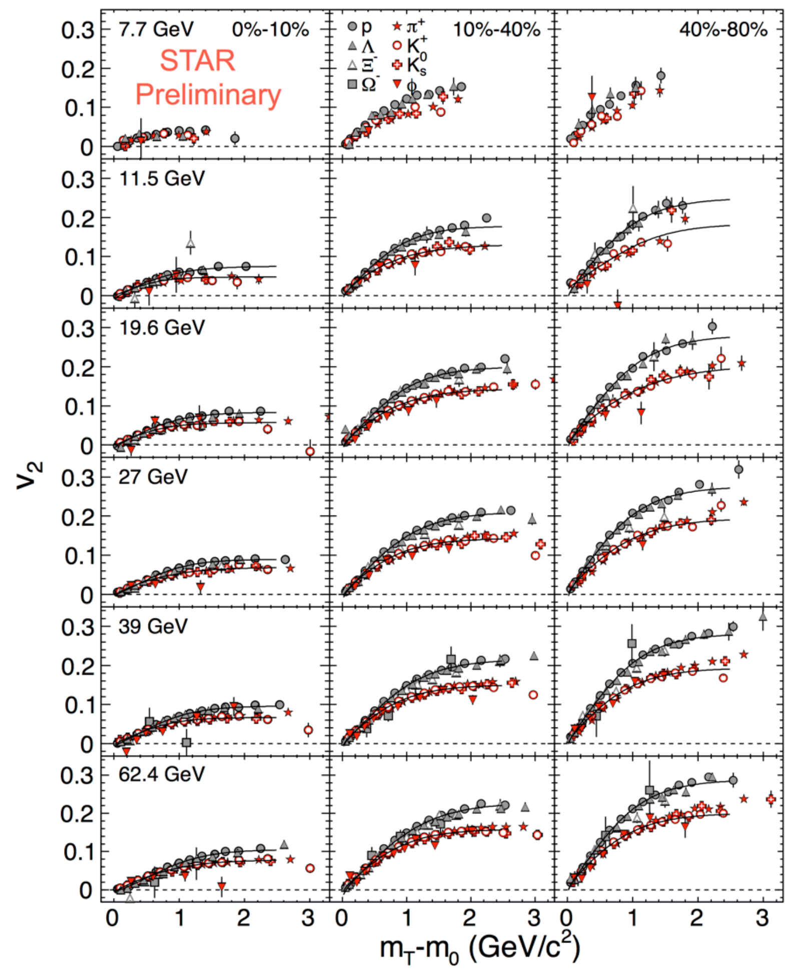
Back up is here…

Centrality dependence of hadron v_2

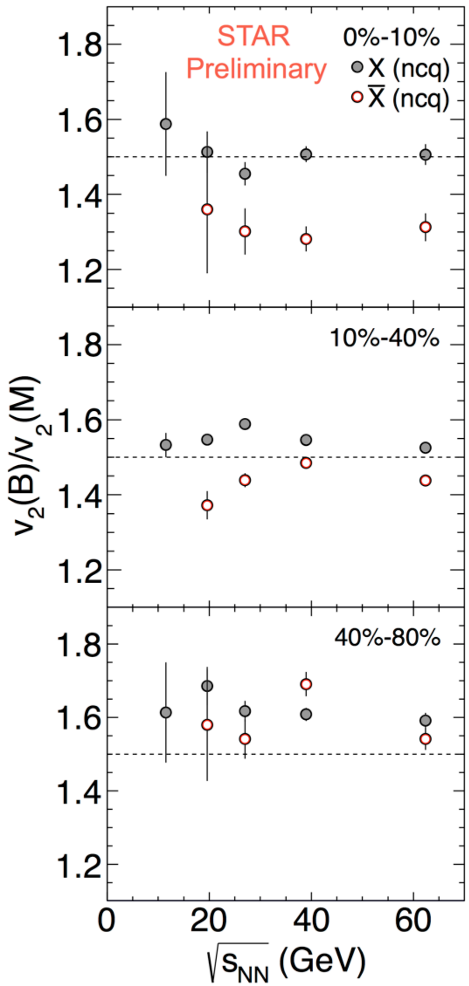
Anti-particles:



particles:



Baryon meson ratio



v_2 vs. m_T-m_0 data fitted

v_2 baryon to v_2 meson ratio taken at m_T-m_0 = 2.0 GeV/c for baryons and (2/3) of that value for mesons

- *Splitting larger for particles than for anti-particles*
- *Centrality dependence only for anti-particles*
- *No energy dependence*