OVERVIEW OF FLOW FROM THE RHIC BEAM ENERGY SCAN PROGRAM

Cameron Racz
(for STAR Collaboration)

UC Riverside
(cracz001@ucr.edu)

RHIC-AGS Annual User's Meeting

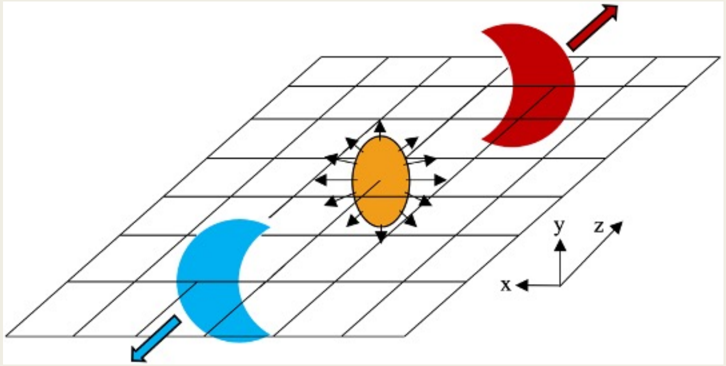
August 2, 2023

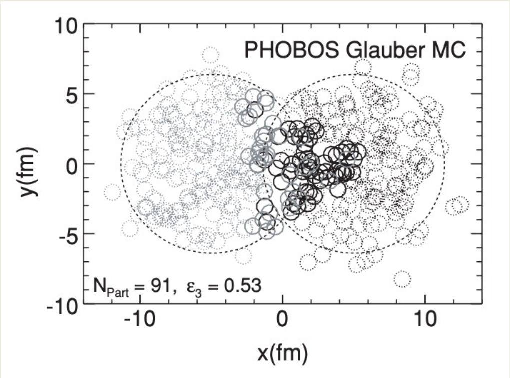
Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

Importance of Flow Measurements

- Anisotropic flow coefficients (v_1, v_2, v_3, etc.) describe the response of the medium created after collisions.
- Useful probe to study various characteristics including the initial state, viscosity, equation of state, fluctuations, and particle production.
- Directed Flow (v_1)
  - *Deflection of produced particles in the reaction plane.*
  - *Minimum of dv_1/dy linked to softening of EoS.*
- Elliptic Flow (v_2)
  - *Result of pressure gradients caused by the initial shape.*
  - *Sensitive to hydrodynamics and viscosity.*
- Triangular Flow (v_3)
  - *Produced by event-by-event fluctuations in the initial shape.**
  - *Sensitive to initial state fluctuations.**

* at high energies

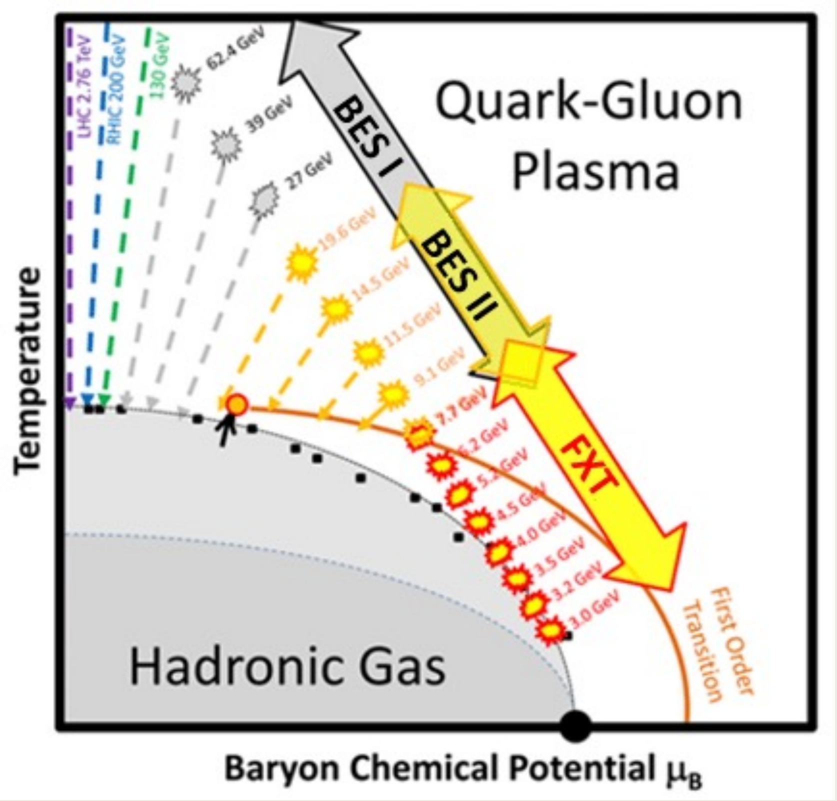




B. Alver and G. Roland, Phys. Rev. C, 81:054905 (2010)

STAR Beam Energy Scan (BES)

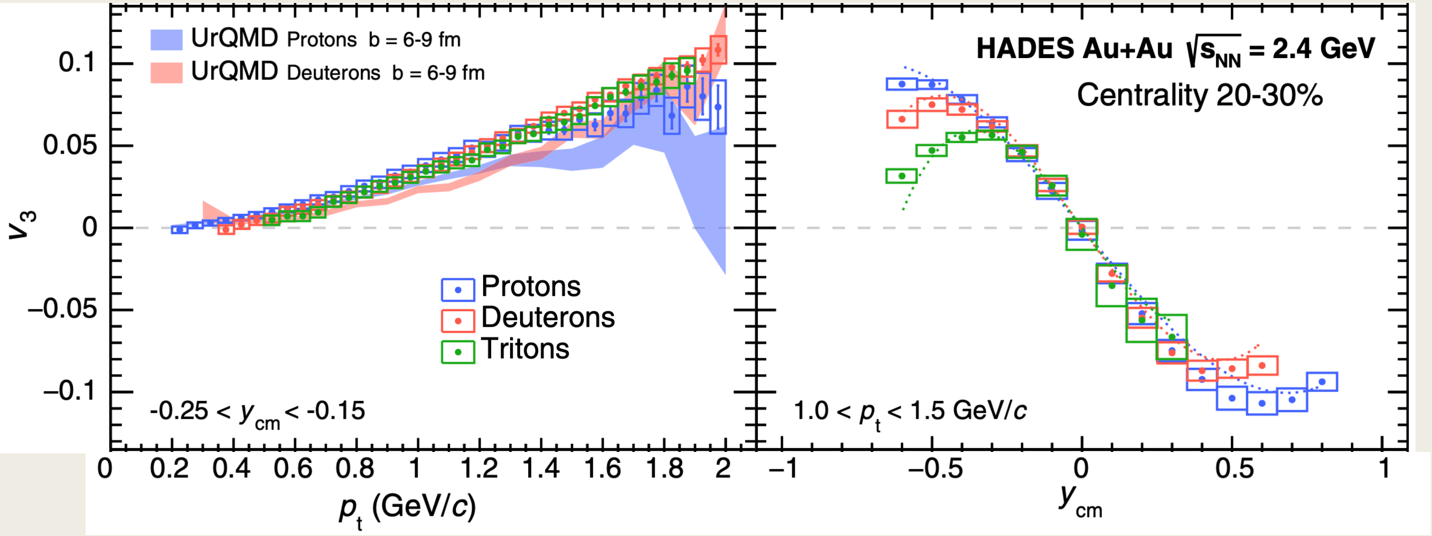
- BES-I
  - *Collider* $\sqrt{s_{NN}} = 7.7 - 62.4\ GeV$
- BES-II
  - *Collider* $\sqrt{s_{NN}} = 7.7 - 19.6\ GeV$
  - *Fixed Target* $\sqrt{s_{NN}} = 3.0 - 7.7\ GeV$
- Opportunity to probe the QCD phase diagram through flow observables.
  - *Wide range of baryon chemical potentials.*
  - *Constrain the equation of state below and above the transition.*
  - *Chance to locate and study the critical point.*



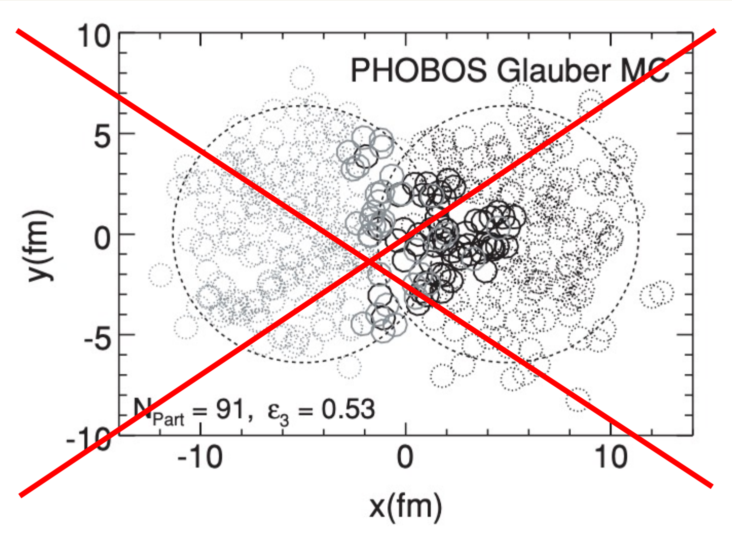
K. Meehan, Nuclear Phys. A, 967:808811 (2017)

v_3 at $\sqrt{s_{NN}} = 3.0$ GeV

- Recent studies by HADES at an energy where hadronic interactions dominate (2.4 GeV) have shown a clear v_3 signal calculated using the first-order event plane (Ψ_1) [1].
  - *Can't be created by fluctuations!*
- **What is the source of this v_3?**
- **What is the driving force?**

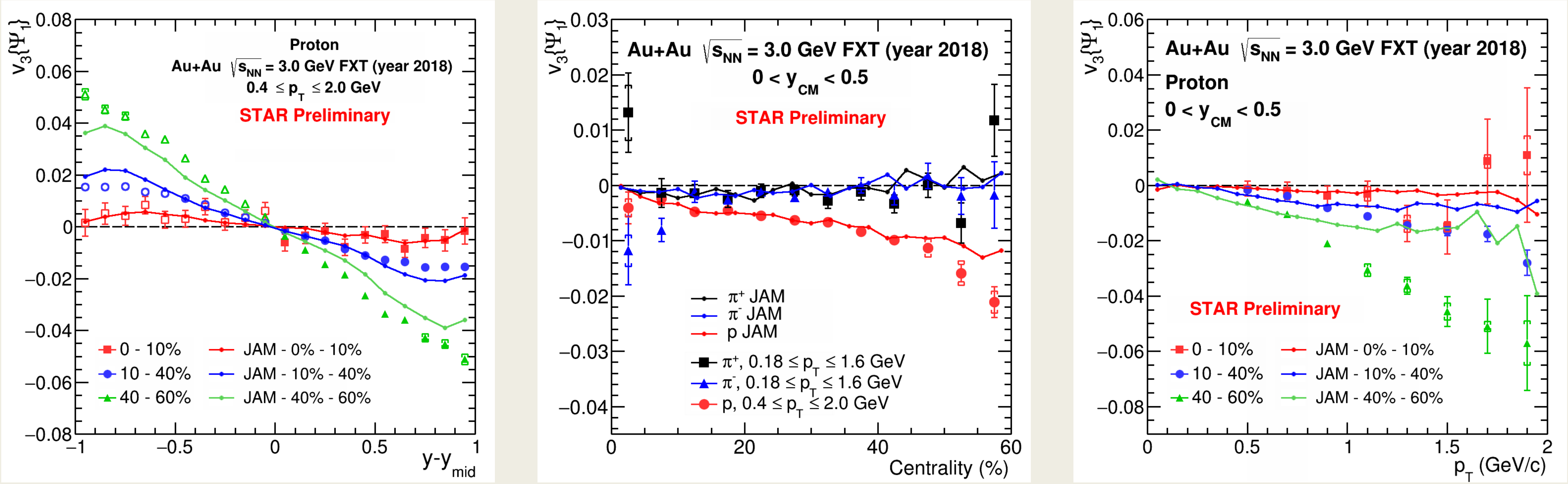


[1] HADES, Phys. Rev. Lett., 125:262301 (2020)



B. Alver and G. Roland, Phys. Rev. C, 81:054905 (2010)

v_3 at $\sqrt{s_{NN}} = 3.0$ GeV

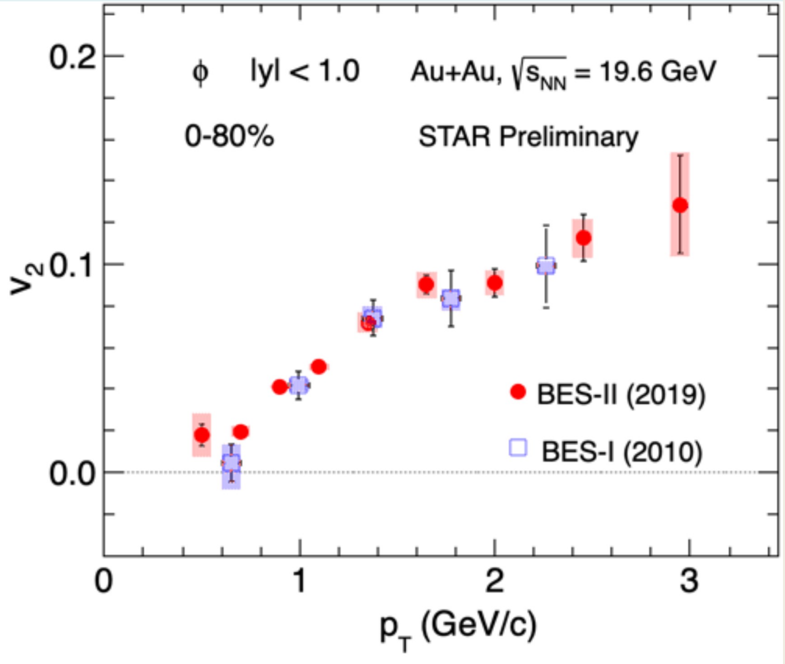


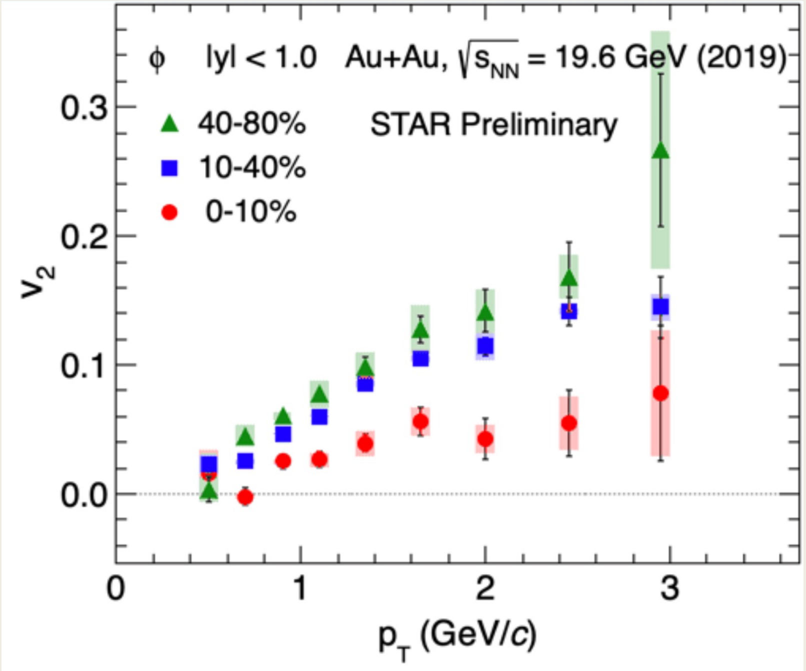
- $v_3\{\Psi_1\}$ was measured at 3 GeV with STAR; much weaker signal than 2.4 GeV.
- Signal could only be reproduced with the inclusion of a potential.
- $v_3\{\Psi_1\}$ could be a useful observable to determine the proper EoS below the phase transition.

v_2 and v_3 of ϕ meson $\sqrt{s_{NN}} = 19.6$ GeV

- The ϕ meson has a low hadronic cross-section; useful tool for studying the initial stages of collisions.

- BES-II reduced v_2 uncertainties by a factor of ~ 3.

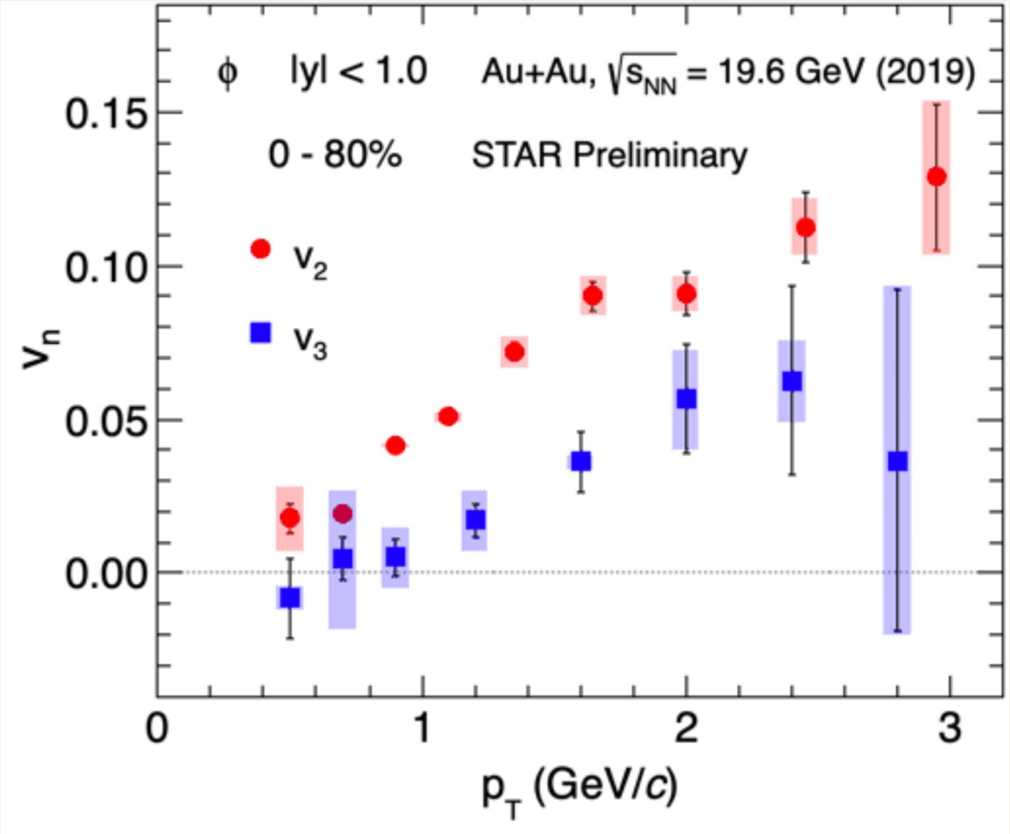




v_2 and v_3 of ϕ meson $\sqrt{s_{NN}} = 19.6$ GeV

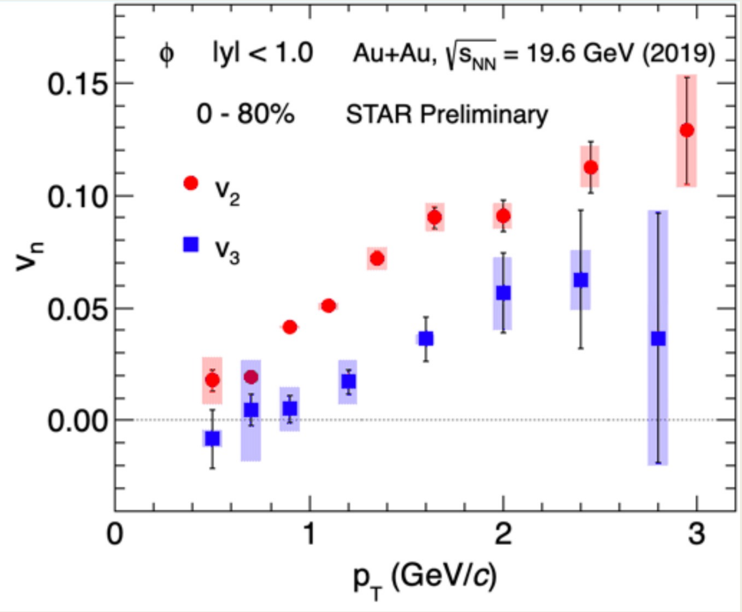
- The ϕ meson has a low hadronic cross-section; useful tool for studying the initial stages of collisions.

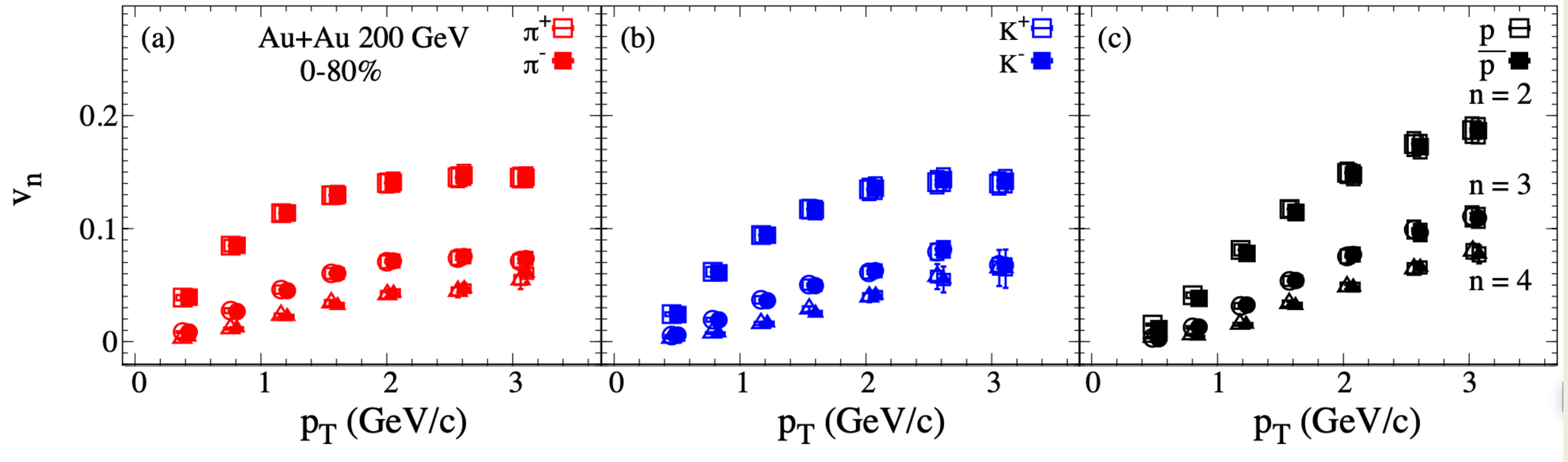
- BES-II reduced v_2 uncertainties by a factor of ~ 2.
- Higher statistics also facilitated new measurements of v_3 for the ϕ.
  - *Event-by-event fluctuations in the arrangement of the participants.*



v_2 and v_3 of ϕ meson $\sqrt{s_{NN}} = 19.6$ GeV

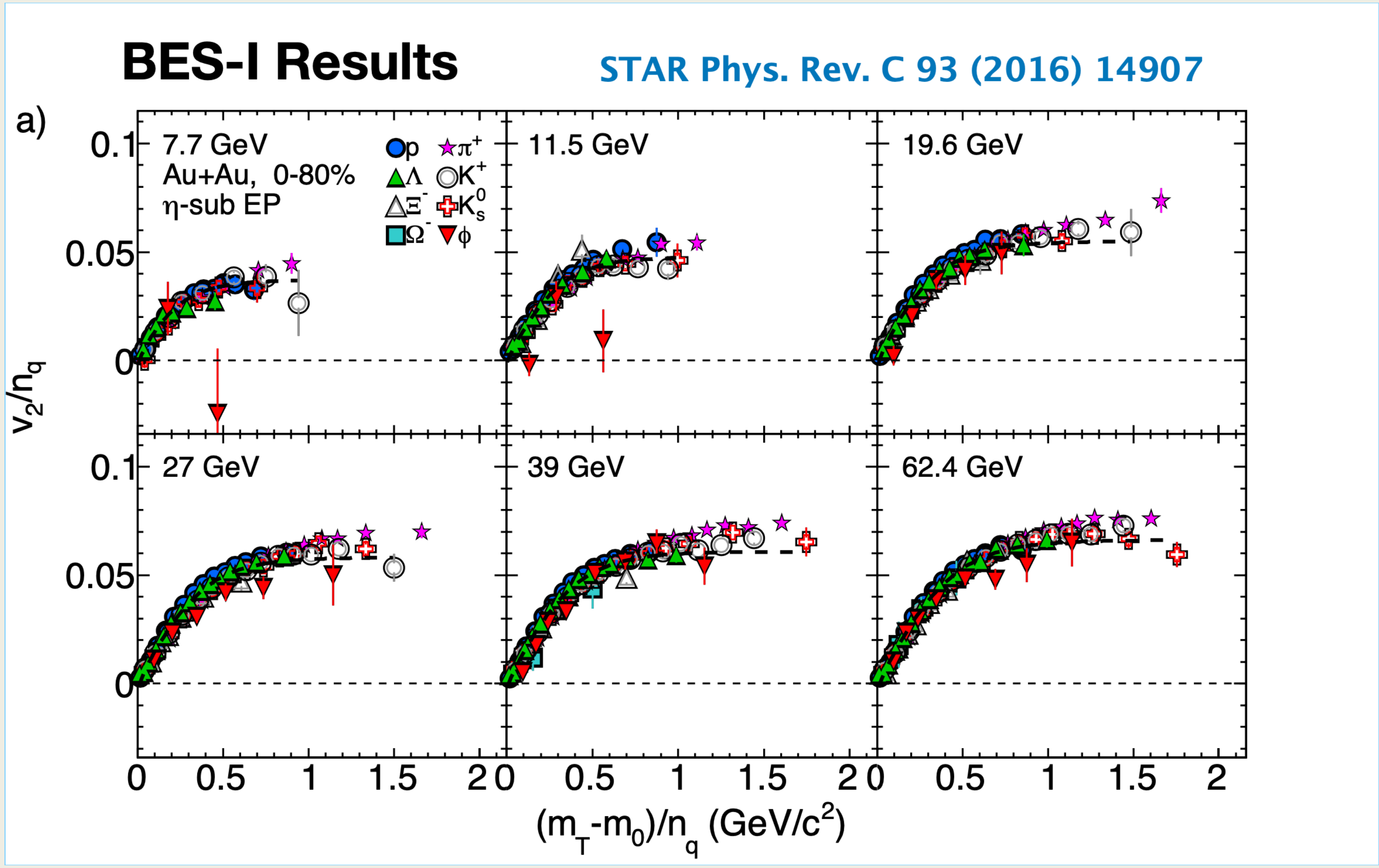
- Comparisons can be made to another recently published STAR paper at $\sqrt{s_{NN}} = 200$ GeV (lower plots).
    - *Phys. Rev. C 105, 064911 (2022)*
- ϕ meson qualitatively follows the same trends as $\pi, K,$ and p.
    - $v_2 > v_3$





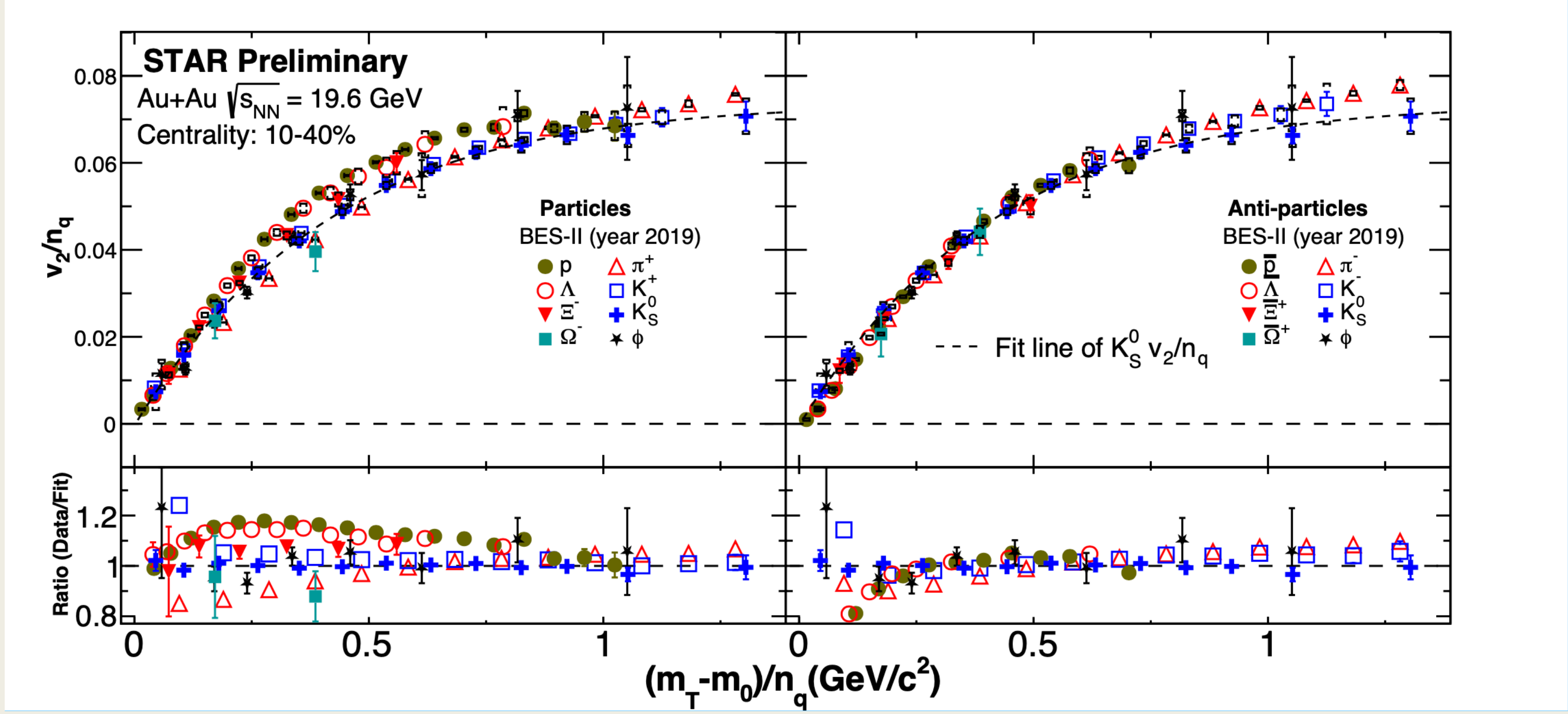
v_2 and v_3 at $\sqrt{s_{NN}} = 14.6, 19.6$ GeV

- Flow measurements can give us insight into the production mechanism when we scale it by the number of constituent quarks (NCQ or n_q).
- NCQ scaling supports the coalescence model of hadron production.
- Previous BES-I results show this scaling behavior.
- ϕ mesons measured during BES-I show hints of scaling breaking below $\sqrt{s_{NN}} < 19.6$ GeV with available statistics.



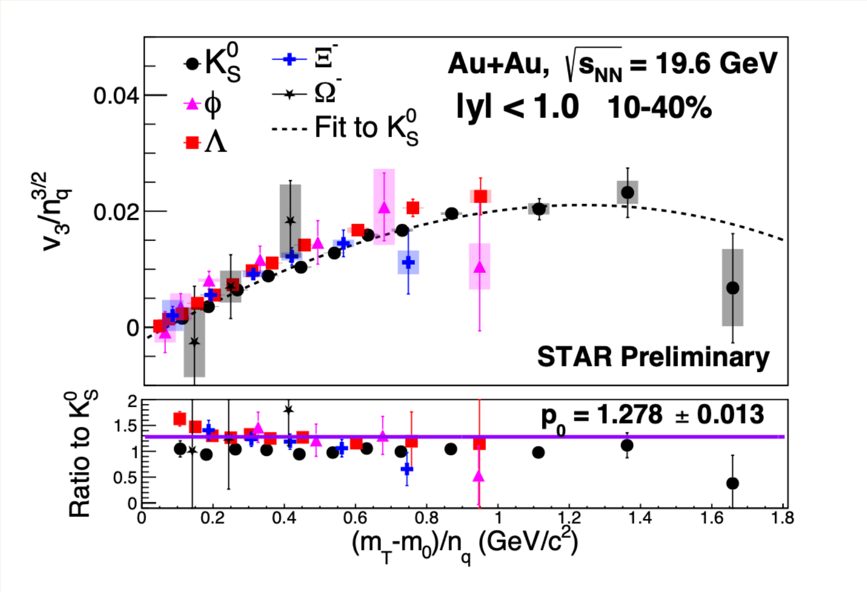
v_2 and v_3 at $\sqrt{s_{NN}} = 14.6, 19.6$ GeV

- BES-II has improved statistical significance for these measurements by a factor of 3.
- At 19.6 GeV, NCQ scaling for v_2 holds within 20% for particles and within 10% for anti-particles.

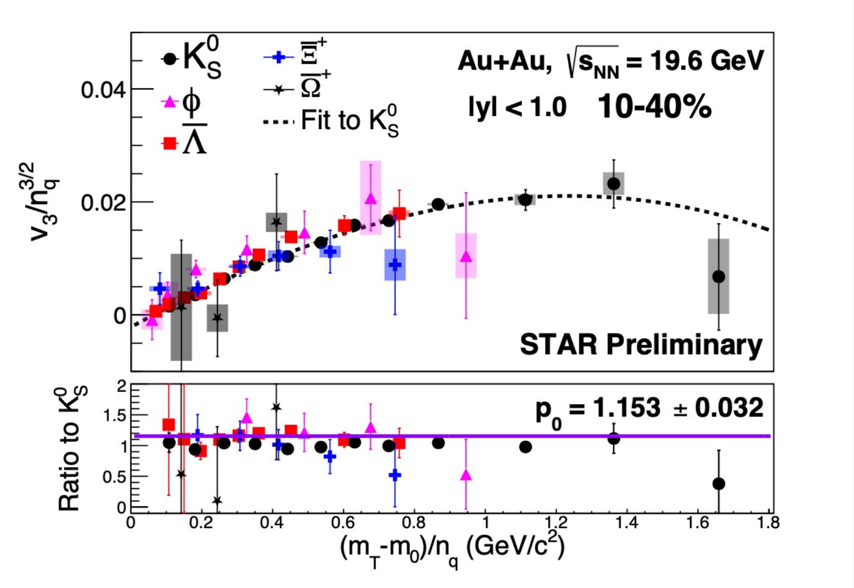


v_2 and v_3 at $\sqrt{s_{NN}} = 14.6, \underline{19.6}$ GeV

- BES-II has improved statistical significance for these measurements by a factor of 3.
- At 19.6 GeV, NCQ scaling for v_2 holds within 20% for particles and within 10% for anti-particles.
- At 19.6 GeV, NCQ scaling for v_3 holds within 30% for particles and within 15% for anti-particles.



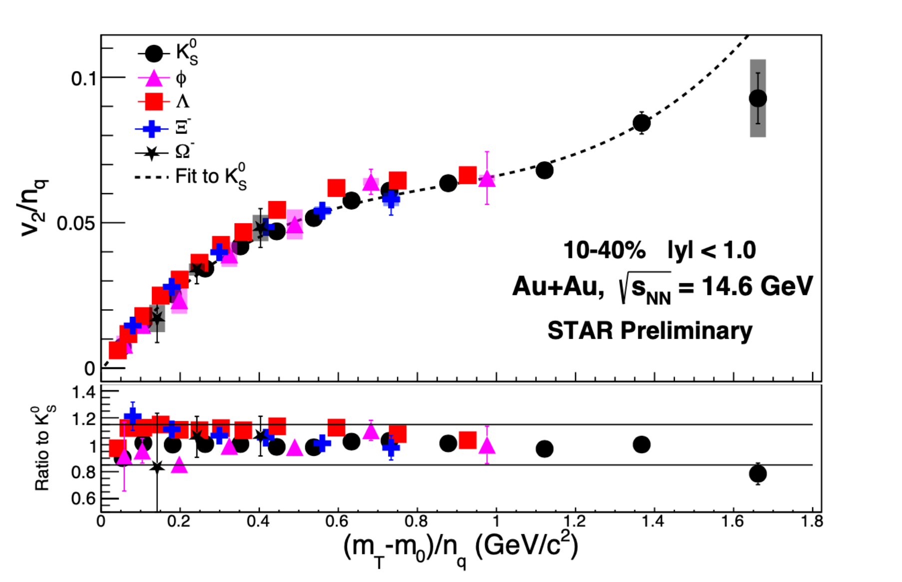
Particles



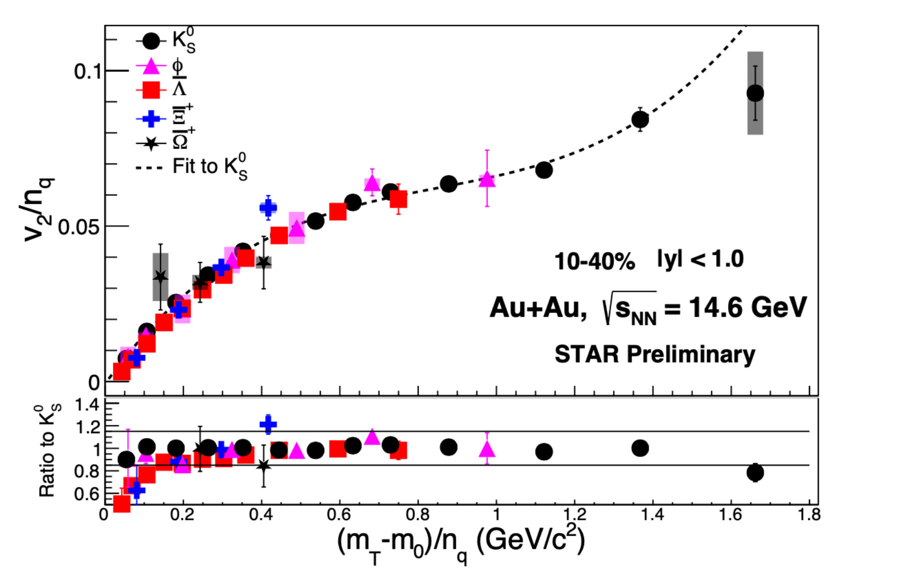
Anti-particles

v_2 and v_3 at $\sqrt{s_{NN}} = 14.6, 19.6$ GeV

- At 14.6 GeV, scaling for v_2 holds within 15% for (multi-)strange hadrons.
- We now have a more precise picture of NCQ scaling, particularly for the ϕ.
  - *ϕ mesons follow NCQ scaling down to 14.6 GeV as opposed to 19.6 as seen before.*
  - *Similar trends of flow as other hadrons.*



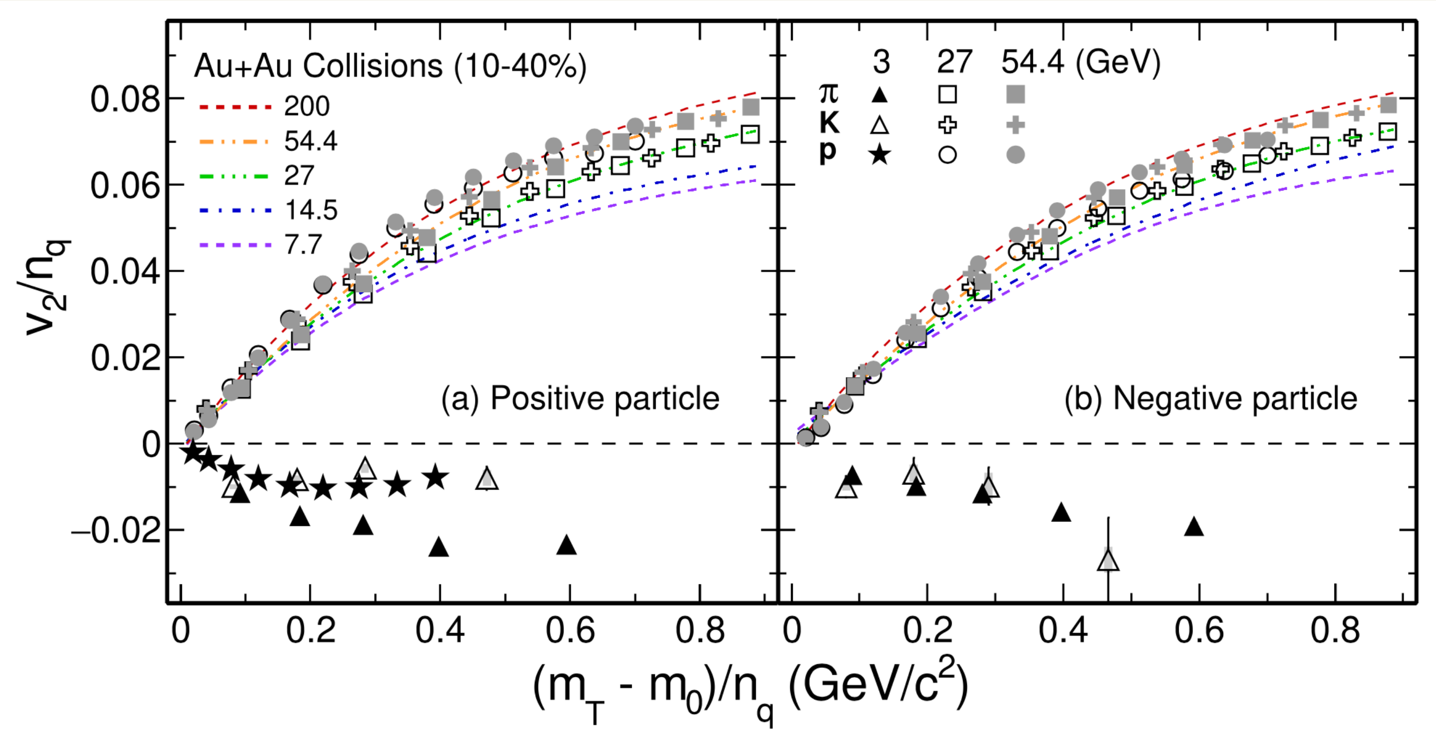
Particles



Anti-particles

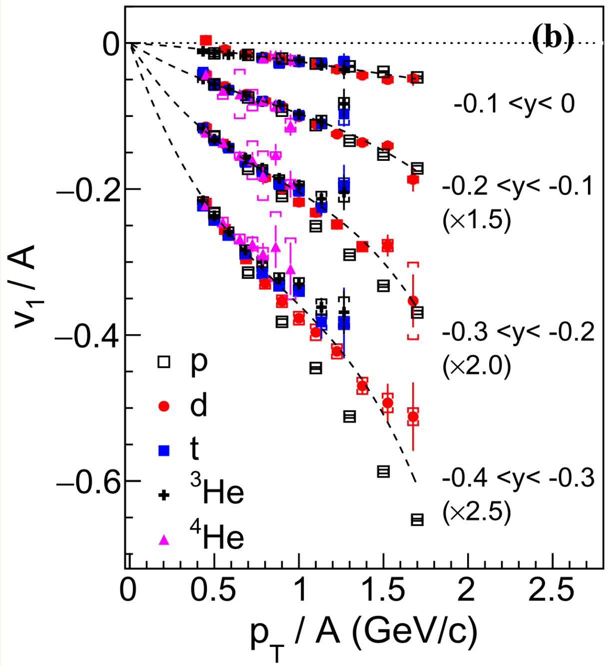
v_2 of π, K, p at $\sqrt{s_{NN}} = 3.0$ GeV

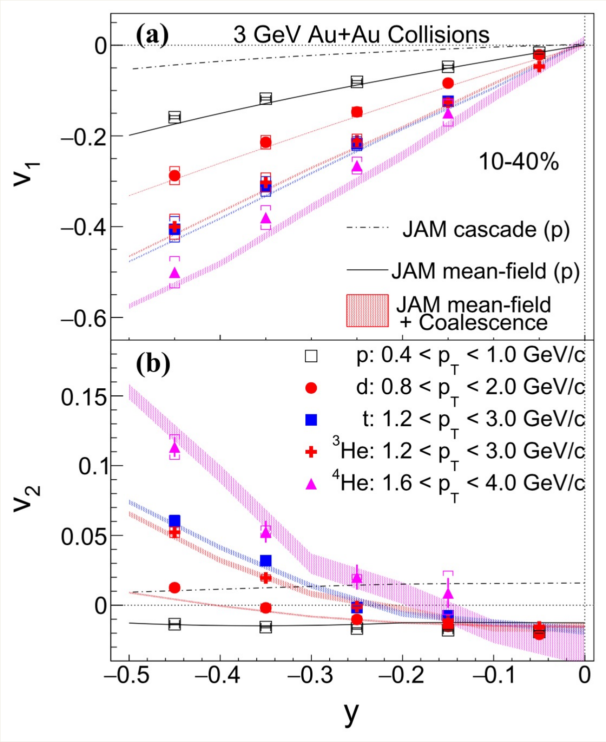
- Contrast: Recently published results from STAR show that NCQ scaling disappears at $\sqrt{s_{NN}} = 3.0$ GeV.
  - *Phys. Lett. B 827, 137003 (2022)*
- This indicates different EOS's between 3 and 14.6 GeV.

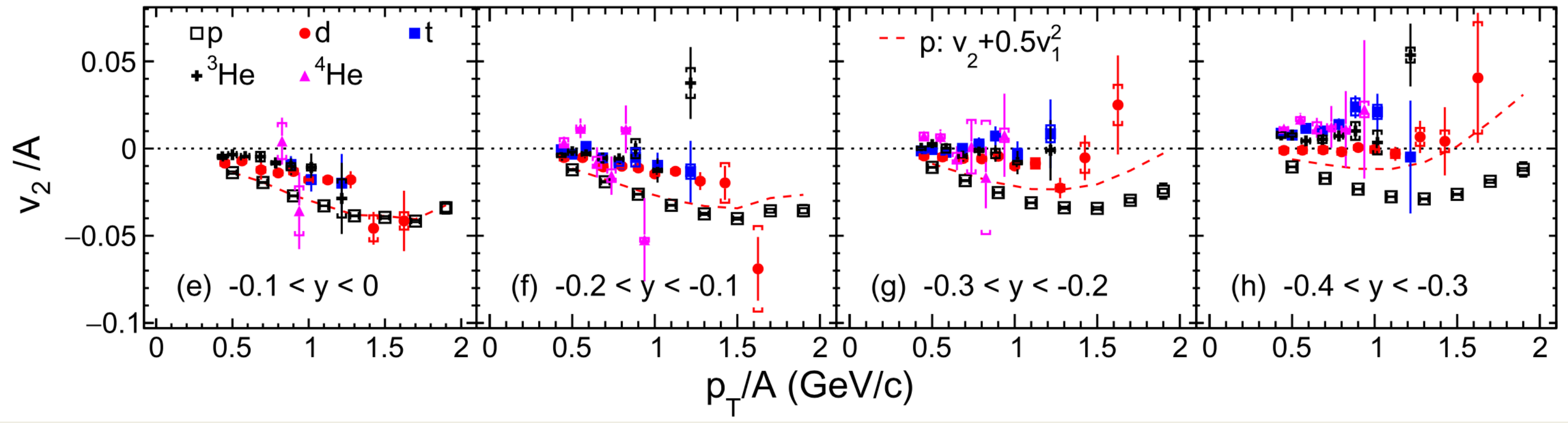


v_1 and v_2 of light nuclei at $\sqrt{s_{NN}} = 3.0$ GeV

- Furthermore, another STAR publication at 3 GeV showed approximate A-scaling for v_1 of light nuclei, but no scaling for v_2.
  - *Phys. Lett. B 827, 136941 (2022)*
- However, both v_1 and v_2 results are qualitatively reproduced with JAM + coalescence model.

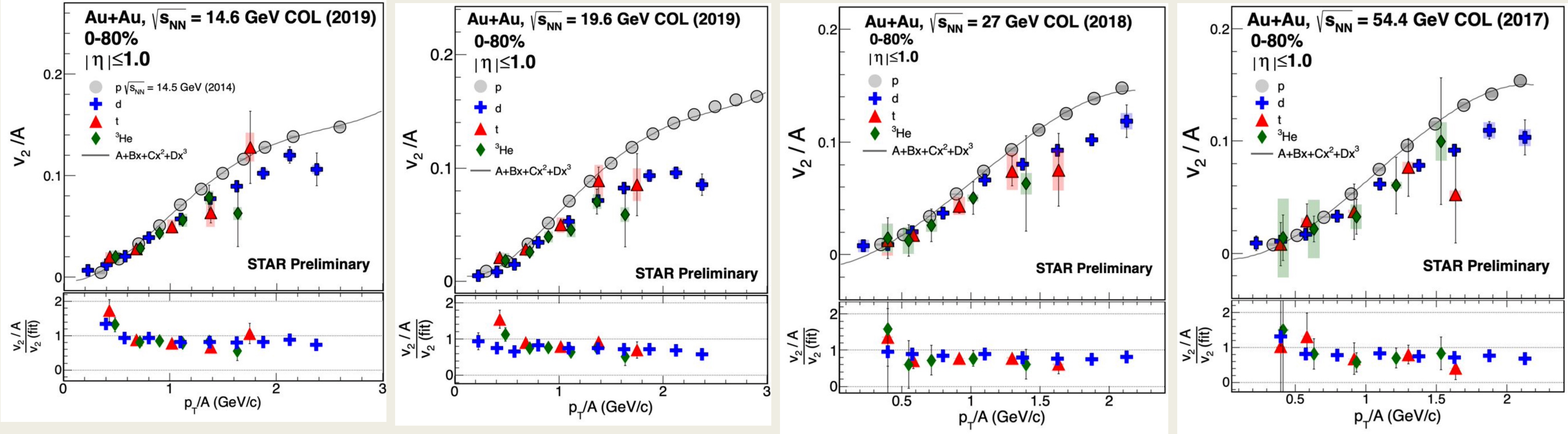






Lines show expectation for deuteron v_2 assuming coalescence.

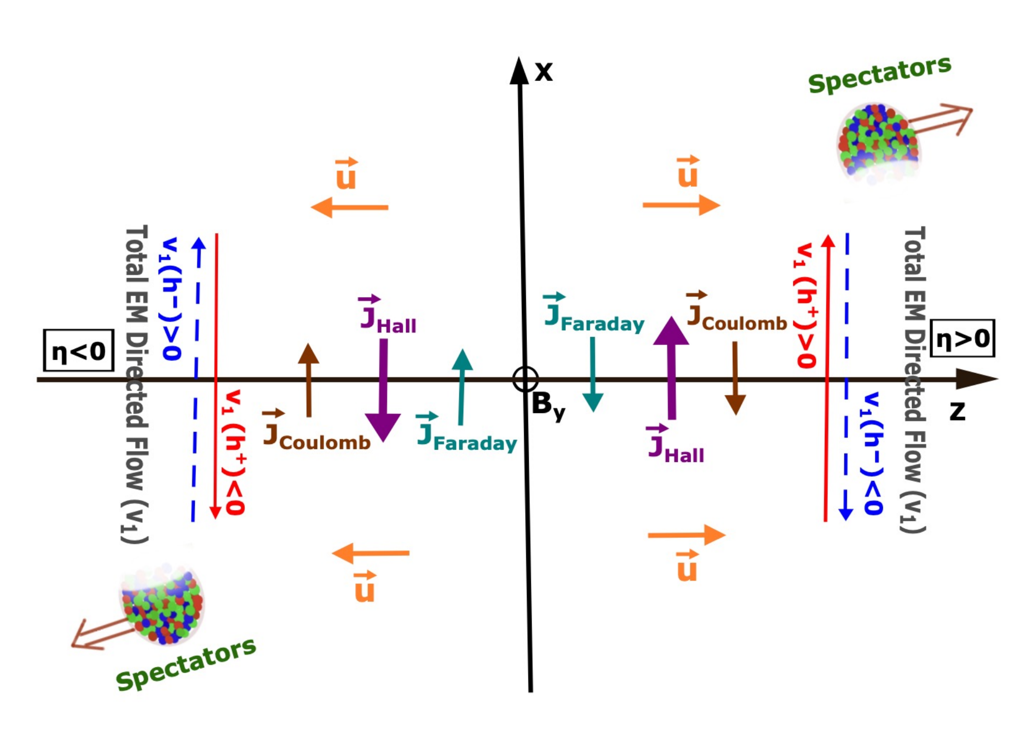
v_2 of light nuclei $\sqrt{s_{NN}} = 14.6 - 54.4$ GeV

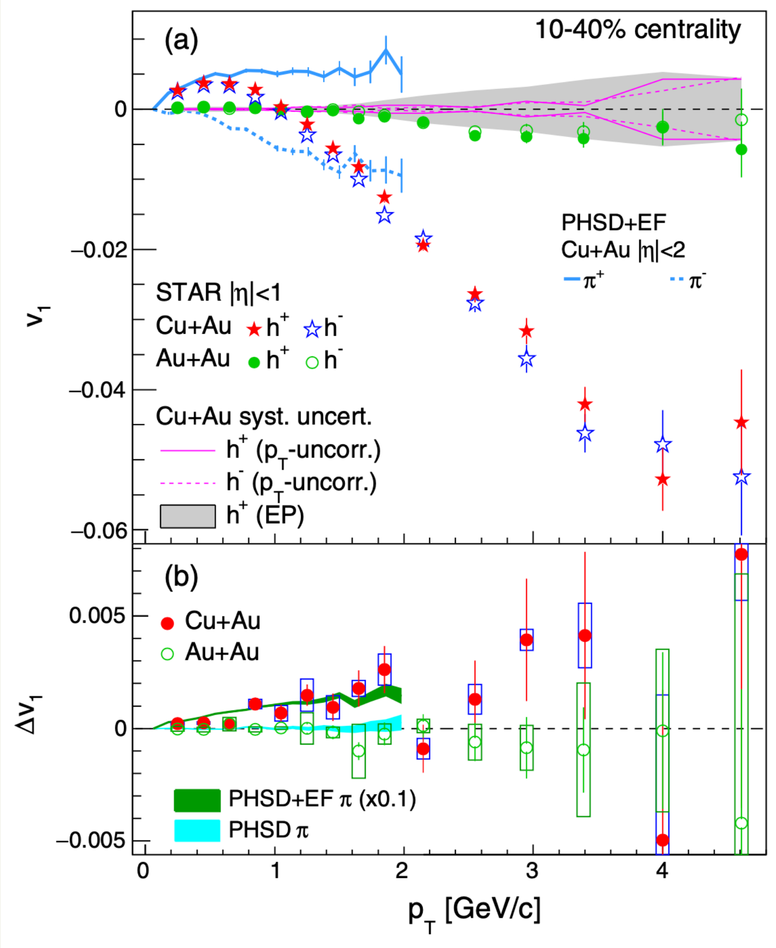


- For deuterons, tritons, and ^{3}He, we have measurements of v_2 at higher energies.
- We see that, with a wide centrality acceptance, these light nuclei only obey nuclear mass number scaling within 20 - 30%.
- Perhaps the centrality/rapidity selections in previous slides is important for scaling behaviors?

v_1 Splitting of Produced Quarks

- Strong EM field from spectator protons.
  - *$\vec{B}$ from passing protons.*
  - *Faraday induction from decreasing $\vec{B}$.*
  - *Coulomb force from proton charge.*
  - *Lorentz force ⊥ to $\vec{v}_{initial}$ and $\vec{B}$ (Hall).*
  - *Relative magnitudes influence the net effect.*



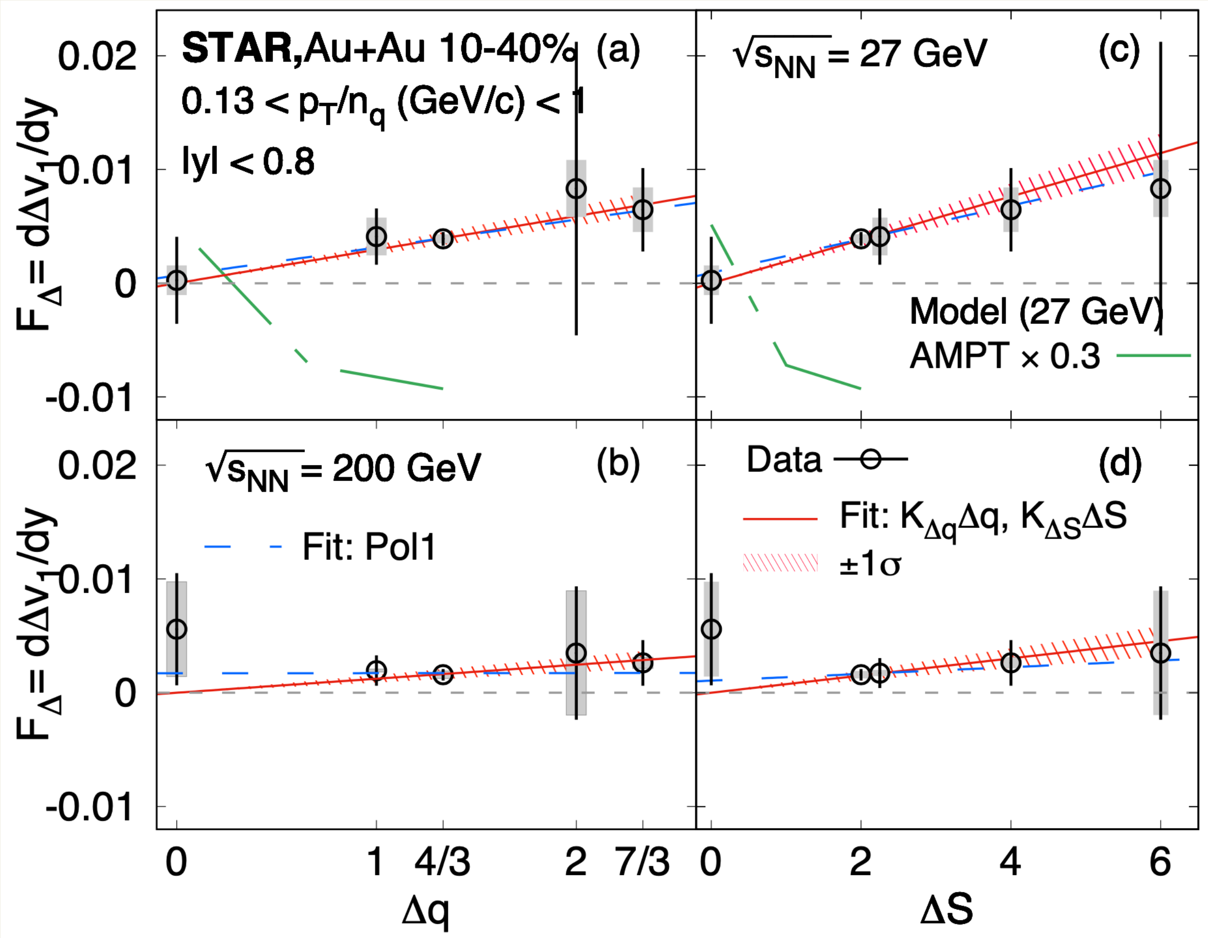


- STAR previously published observations of Δv_1 between h^+ and h^- in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (right image).
  - *Phys. Rev. Lett. 118, 012301 (2017)*
- v_1 splitting was also reported by ALICE in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
  - *Phys. Rev. Lett. 125, 022301 (2020)*

v_1 Splitting of Produced Quarks

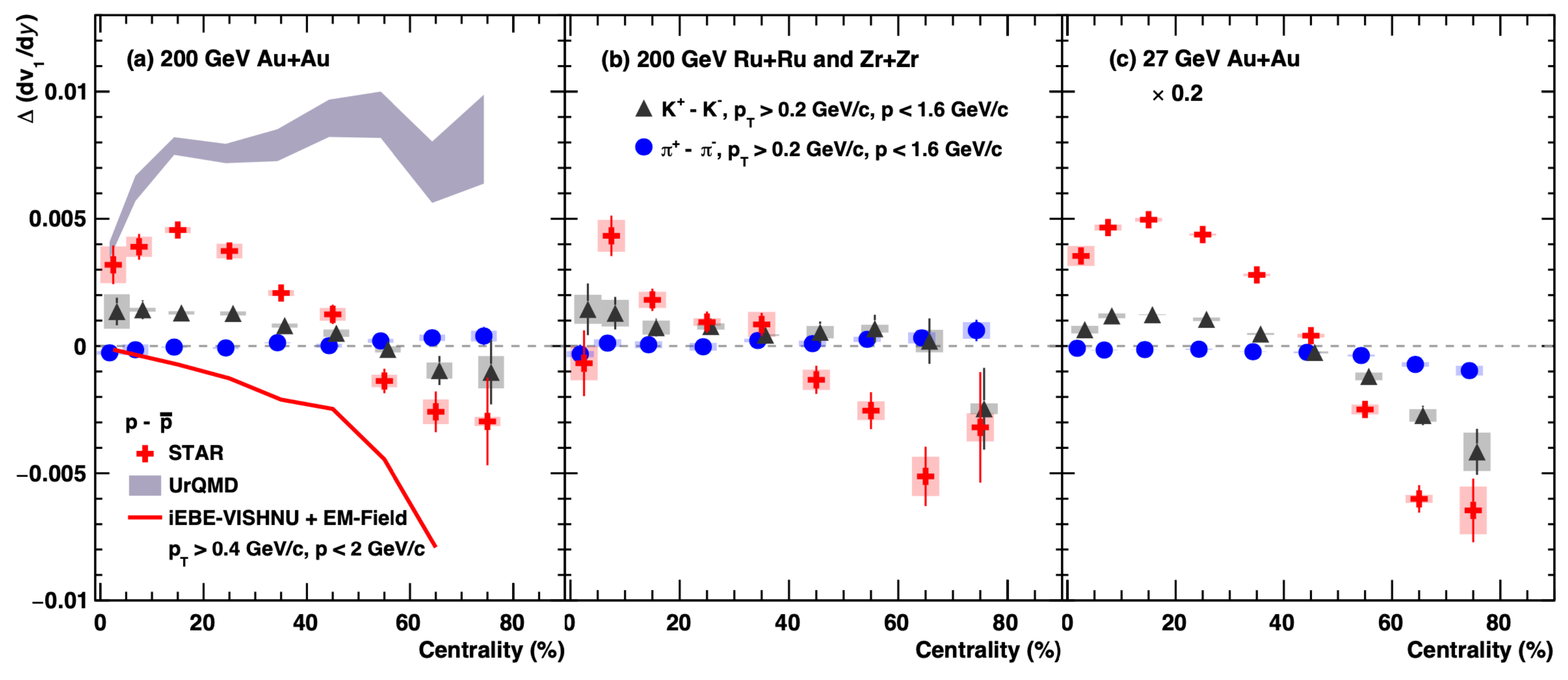
Index	Quark Mass	Charge	Strangeness	Expression
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^{-}(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^{-}(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\bar{\Omega}^{+}(\bar{s}\bar{s}\bar{s})] - [\Omega^{-}(sss)]$
5	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\bar{\Xi}^{+}(\bar{d}\bar{s}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\Omega^{-}(sss)]$

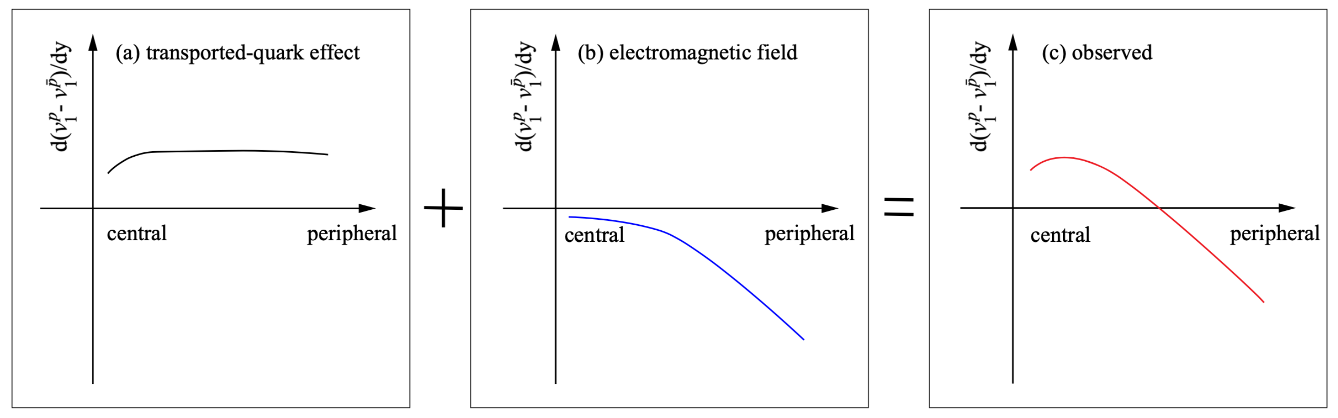
- STAR now has new measurements of v_1 splitting for produced quarks in Au+Au collisions at 27 GeV and 200 GeV.
- Assuming coalescence, combinations of hadrons from produced quarks (table above) were used to investigate the charge and strangeness dependence.
- Current results (right) have shown a dependence on charge and strangeness for splitting.
- Splitting is stronger at 27 GeV, and an AMPT model with no EM field fails to describe the measurements.
- The full study has since been submitted to PRL (arXiv:2304.02831).



v_1 Splitting of Light Hadrons

- In addition, there is a companion paper that reports EM effect measurements for $\pi, K,$ and proton.
  - *arXiv:2304.03430*
- Proton results in peripheral collisions are consistent with observation of the EM field effect.
- Kaons show a similar result to protons.
  - *Only $K^+(u\bar{s})$ affected by transported u quark.*
  - *Asymmetry of s and $\bar{s}$ production must be considered.*
- Pions show a much smaller effect due to transport effects for both π^+ and π^-.
  - *Low $\langle p_T \rangle$ and late formation = less transported v_1 and less EM effect.*
  - *27 GeV 50 – 80% centrality statistically significant.*

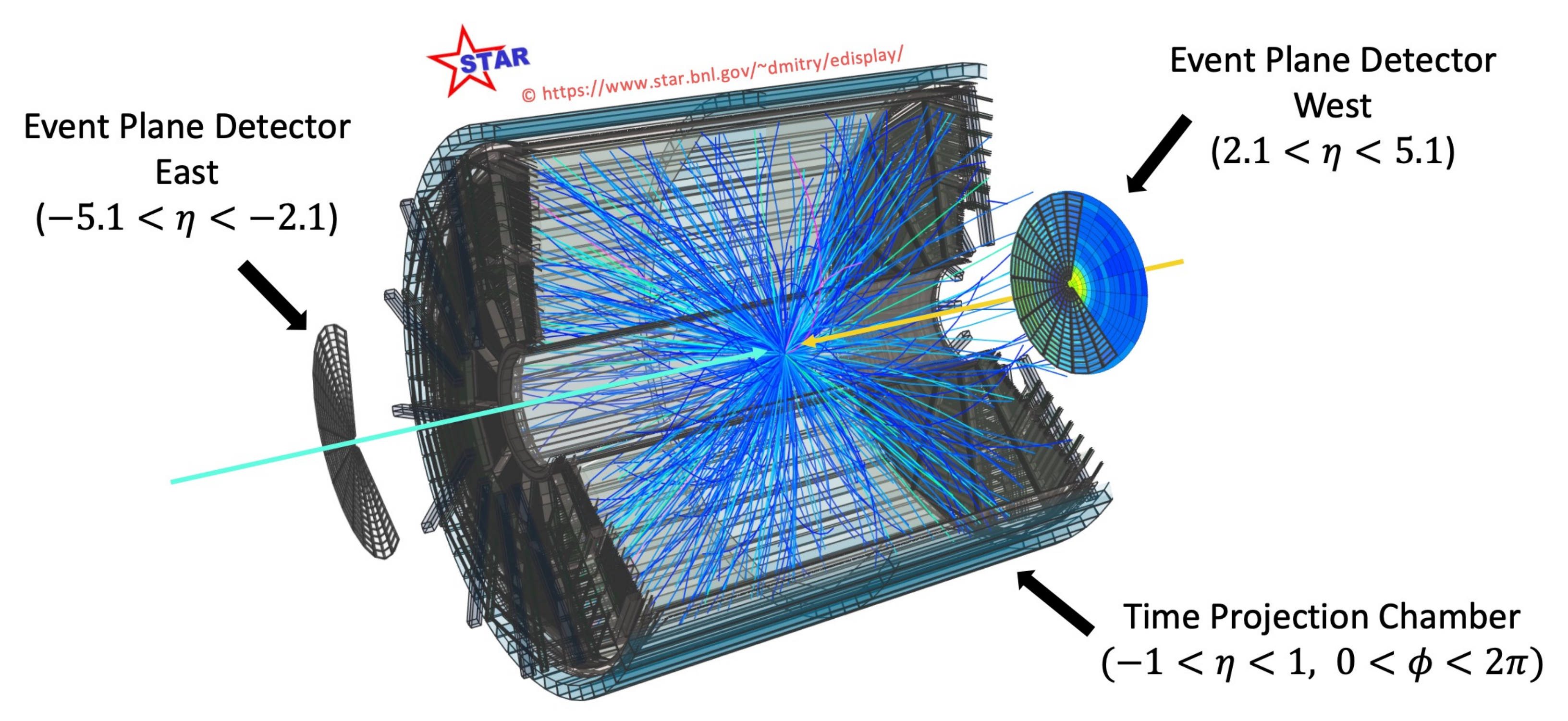




Bottom image: Illustration of contributions to $d(v_1^p - v_1^{\bar{p}})/dy$.

v_1 at Forward and Backward Pseudorapidity

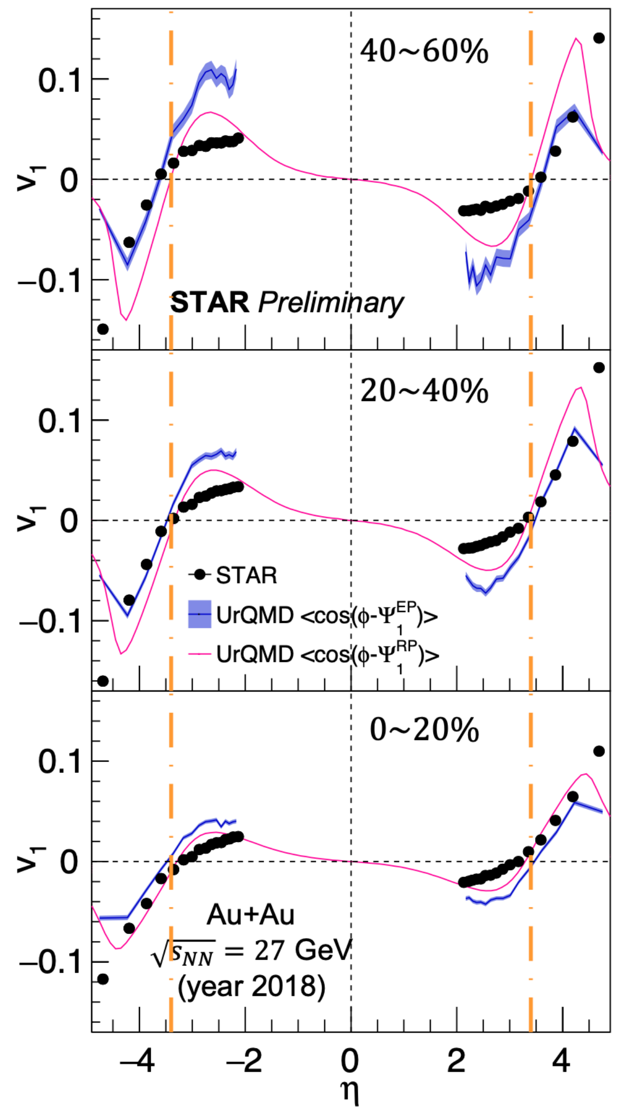
- $v_1(\eta)$ can constrain the shear viscosity of the QCD matter $\left(\frac{\eta}{s}(T, \mu_B)\right)$ [2].
- $v_1(\eta)$ measurements may also give us insight into the baryon stopping mechanism [3].
- BES-II and the Event Plane Detectors give us the opportunity to study $v_1(\eta)$ out to high η.



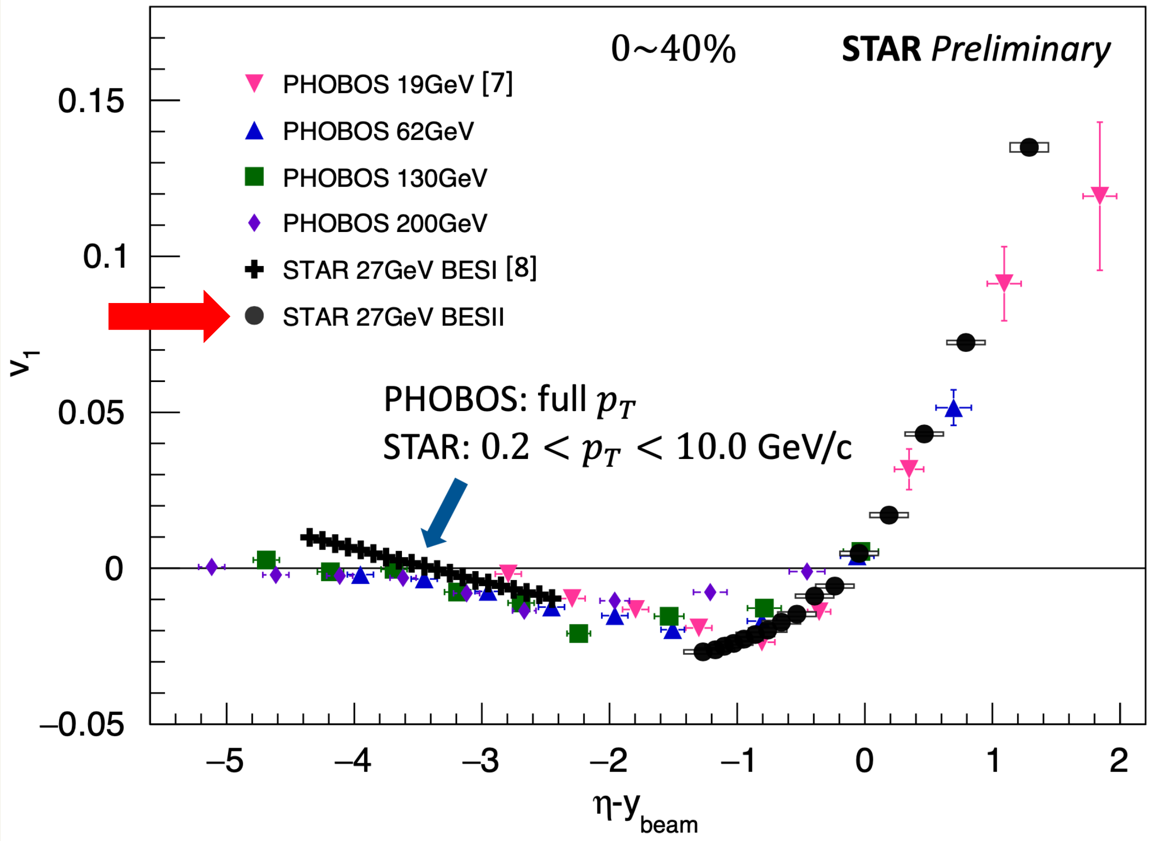
[2] Becattini, F., et al. Eur. Phys. J. C 75 (2015)
[3] Du, Lipei, et al. arXiv preprint arXiv:2211.16408 (2022)

- At $\sqrt{s_{NN}} = 27$ GeV, $v_1(\eta)$ was calculated from EPD hits with a reference event plane from the TPC to suppress non-flow effects.
- An iterative process is used to account for the STAR materials encountered between the vertex and the EPD wheels.
  - $\sim 50\%$ *of particles detected by the EPDs are secondary particles.*

v_1 at Forward and Backward Pseudorapidity



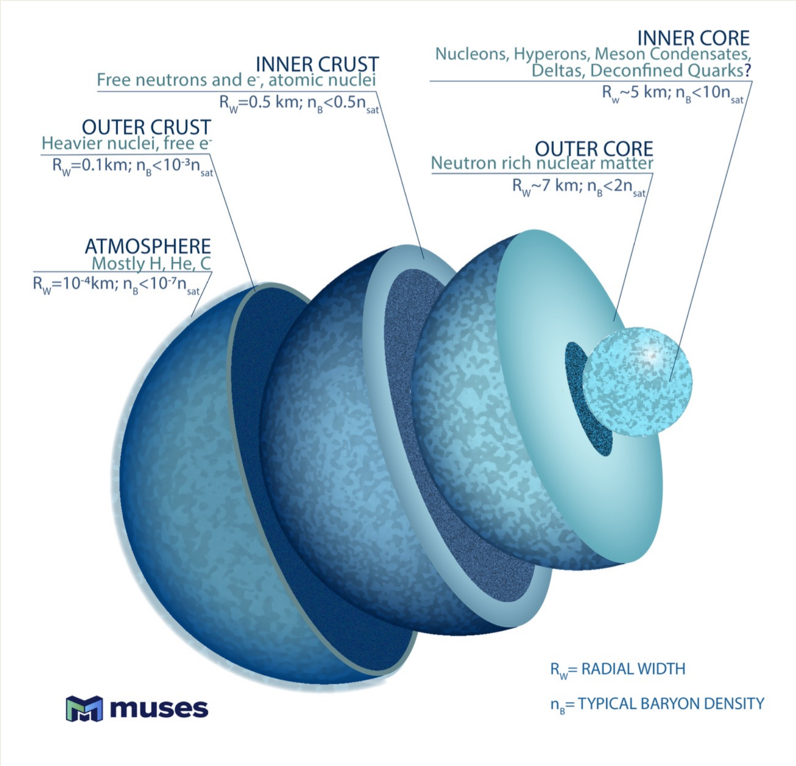
- Orange dashed lines show beam rapidity.
- $v_1(\eta)$ changes sign near beam rapidity at all centralities.
- UrQMD (with the event plane or reaction plane) fails to describe the measurements.
- Future comparison with hydro models will help constrain $\frac{\eta}{s}(T, \mu_B)$ of the medium.

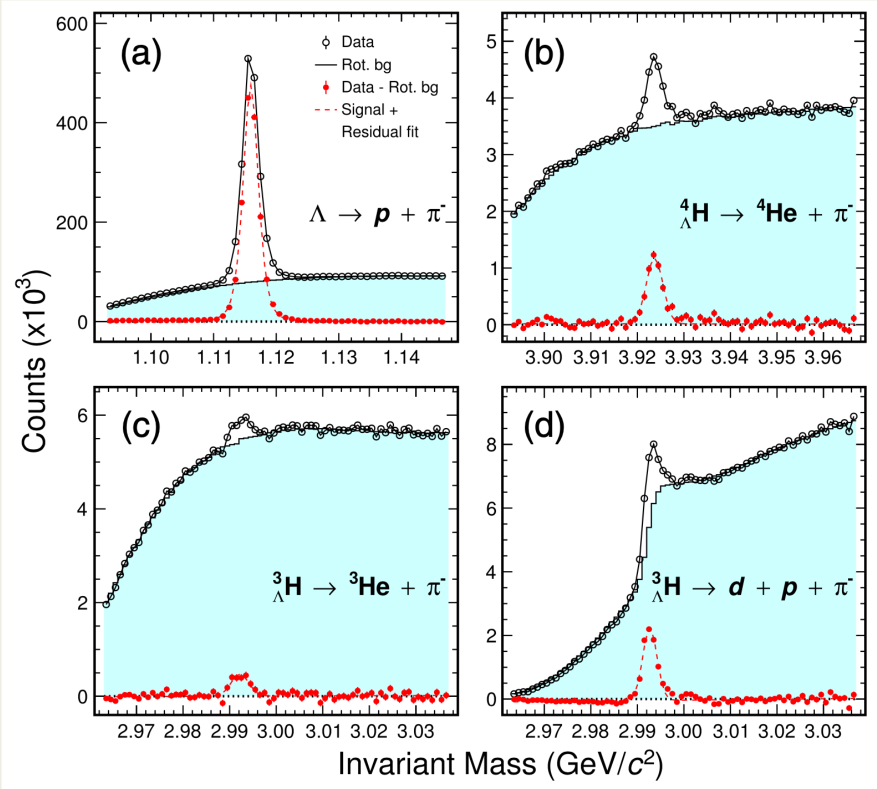


- This study can also test limiting fragmentation, where all energies overlap in a region of $\eta - y_{beam}$.

Hypernuclei v_1 at $\sqrt{s_{NN}} = 3.0$ GeV

- Hyperon-nucleon (Y-N) interactions at high baryon density are important for understanding the EoS for hot dense matter within neutron stars.





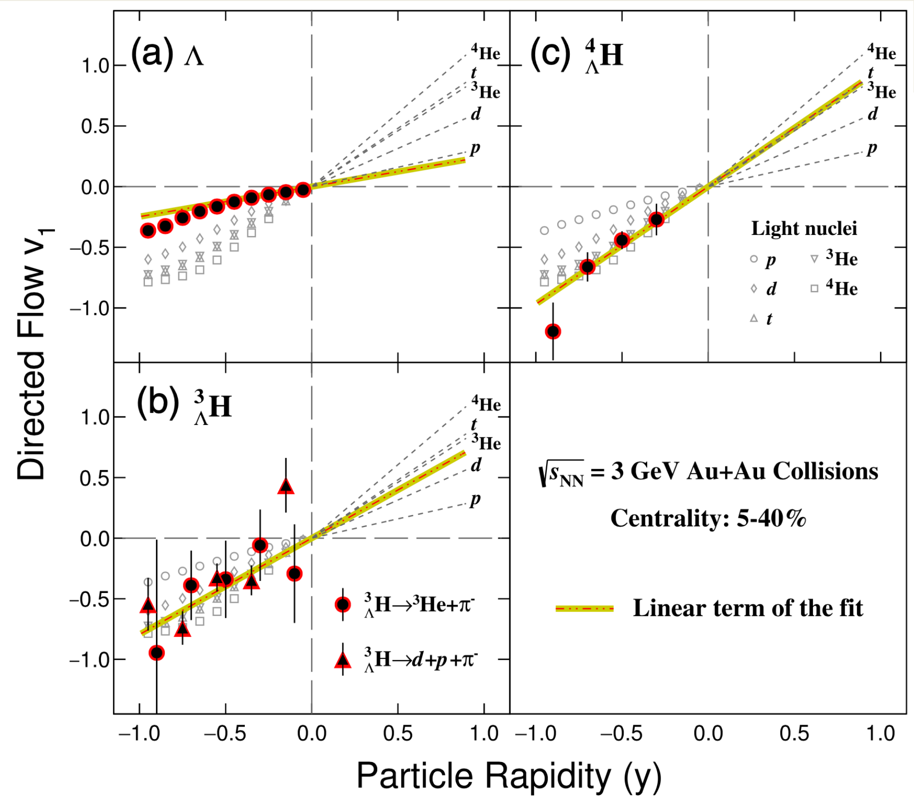
Left Image: arXiv:2303.17021

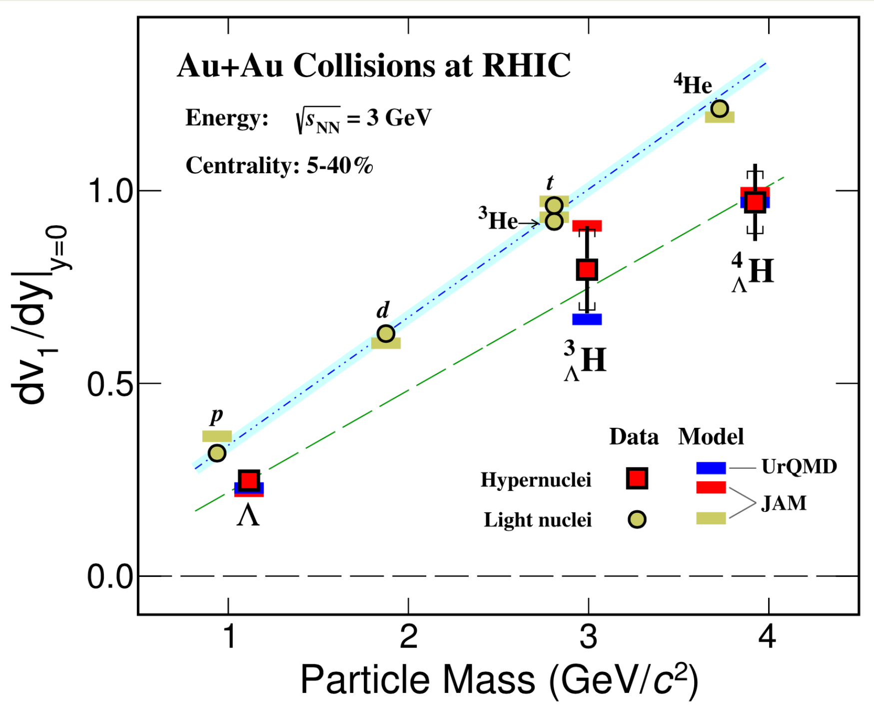
- $\mu_B = 760$ MeV at $\sqrt{s_{NN}} = 3.0$ GeV.
- STAR has now measured v_1 for Λ, ${}^3_\Lambda\mathrm{H}$ (2-body and 3-body decays) and ${}^4_\Lambda\mathrm{H}$.
- 8400 ${}^3_\Lambda\mathrm{H}$ and 5200 ${}^4_\Lambda\mathrm{H}$ identified in $5-40\%$ centrality.
- PRL 130, 212301 (2023)

Particle	p_T (GeV/c)	y
Λ, p	(0.4, 0.8)	(−1.0, 0.0)
d	(0.8, 1.6)	(−1.0, 0.0)
${}^3_\Lambda\mathrm{H}$	(1.0, 2.5)	(−1.0, 0.0)
t, ${}^3\mathrm{He}$	(1.2, 2.4)	(−1.0, −0.1)
${}^4_\Lambda\mathrm{H}$	(1.2, 3.0)	(−1.0, −0.2)
${}^4\mathrm{He}$	(1.6, 3.2)	

Hypernuclei v_1 at $\sqrt{s_{NN}} = 3.0$ GeV

- Hypernuclei v_1 follows similar trends as the light nuclei with the same mass number.
- The v_1 slopes from hypernuclei are lower than light nuclei, but the slope of the mass dependence is similar (fits on the right)
  - *Light nuclei:* 0.3323 ± 0.0003
  - *Hypernuclei:* 0.27 ± 0.04





- This analysis contributes unique and important results for Y-N interactions that can be considered alongside other recent publications:
  - *$\Lambda - p$ elastic scattering* *Phys. Rev. Lett. 127, 272303 (2021)*
  - *$\Sigma^- - p$ elastic scattering* *Phys. Rev. C 104, 045204 (2021)*
  - *$\Sigma^- p \to \Lambda n$ reaction* *Phys. Rev. Lett. 128, 072501 (2022)*

Summary

- Recent analyses from the BES program have given us many important results of v_1, v_2, and v_3.
- v_3 is present at 3.0 GeV, but no longer produced by initial state fluctuations.
  - *Correlated to Ψ_1 and requires a potential in the EoS.*
- Higher statistics BES-II measurements of v_2 and v_3 for the ϕ meson presented.
  - *Flow follows similar trends to that of other particles.*
- NCQ scaling has been tested at 14.6 and 19.6 GeV.
  - *Observed to be valid down to 14.6 GeV with BES-II.*
  - *Scaling with v_3 has been presented at 19.6 GeV.*
  - *The point where the ϕ stops scaling is now constrained to $\sqrt{s_{NN}} < 14.6$ GeV.*
  - *Clear difference in the EoS between 3 GeV and 14.6 GeV.*

Summary

- With BES-I and BES-II, we have compiled measurements of $p, d, t,$ and ^{3}He v_2/A.
  - *A-scaling rule doesn't seem as clear as other NCQ scaling results shown.*
  - *Results overall consistent with light nuclei coalescence.*
- v_1 splitting has been investigated at 27 GeV Au+Au and 200 GeV Au+Au, Ru+Ru, and Zr+Zr.
  - *Results suggest a strong EM field that drives h^+ and h^- in opposite directions.*
- The EPDs have been used to study v_1 at high η.
  - *Useful for shear viscosity, baryon stopping, and limiting fragmentation.*
- Hypernuclei v_1 for $^3_\Lambda$H and $^4_\Lambda$H has been measured and published for the first time.
  - *Valuable information contributed to the study of the hot dense nuclear matter EoS.*

Considerations for the Future

- Where does the Ψ_1 correlated v_3 end and the fluctuation driven v_3 begin?
- Can we get more information out of the ϕ where it deviates from NCQ scaling?
- Where (in y, p_T, centrality) does coalescence dominate the production process for light nuclei?
- What does fragmentation look like in various flow measurements?
- How do hypernuclei behave with respect to v_2 or v_3? Is it always the same as light nuclei?
- Since we have a large scan of energies at our disposal, and more currently undergoing production, how do any of these observables look at other energies?

- Thank you, and we will see you at Quark Matter 2023!