Flow in Beam Energy Scan II

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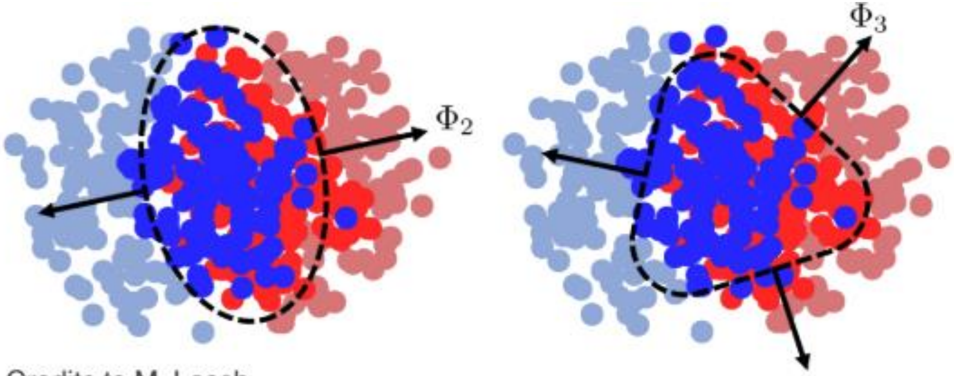
Flow Coefficients

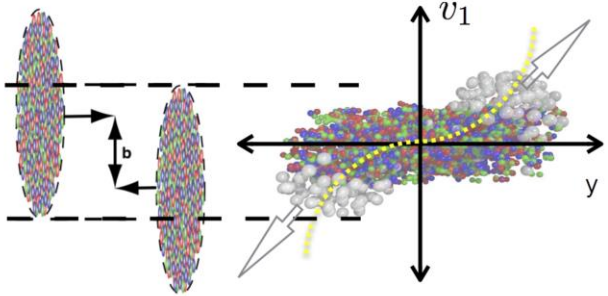
- Flow Coefficients are all sensitive to the early stages of the collision

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_t}\frac{d^2N}{dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_n)\right)\right)$$

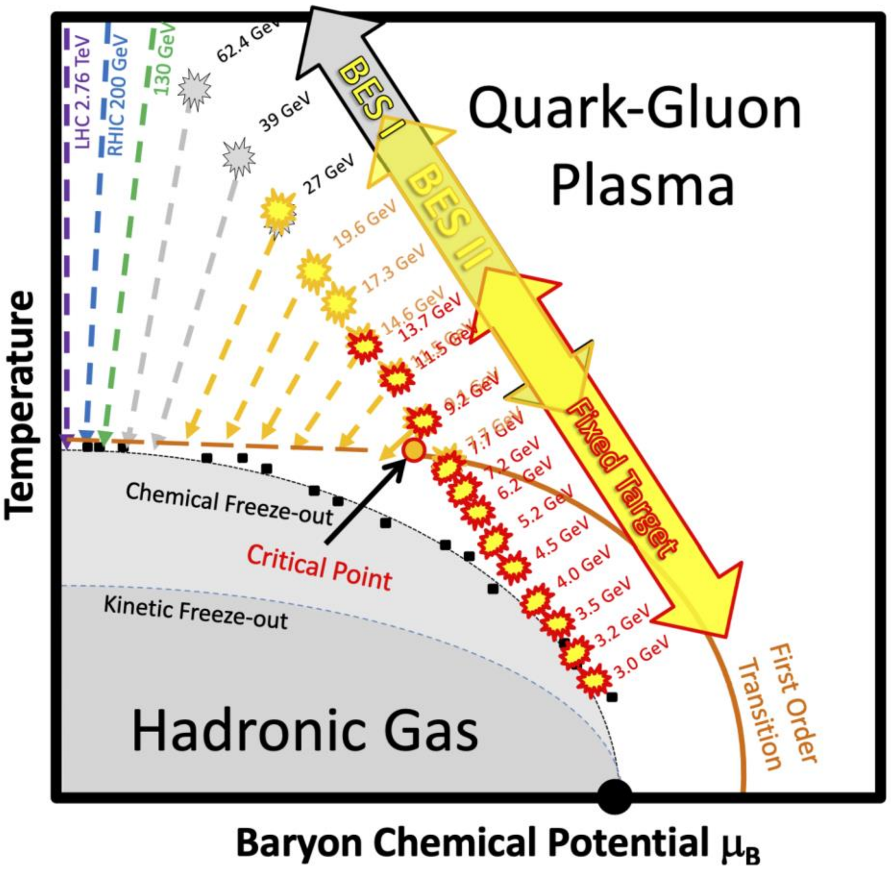
$$v_n = \left\langle \cos\left(n(\phi - \Psi_n)\right)\right\rangle$$



Credits to M. Lesch



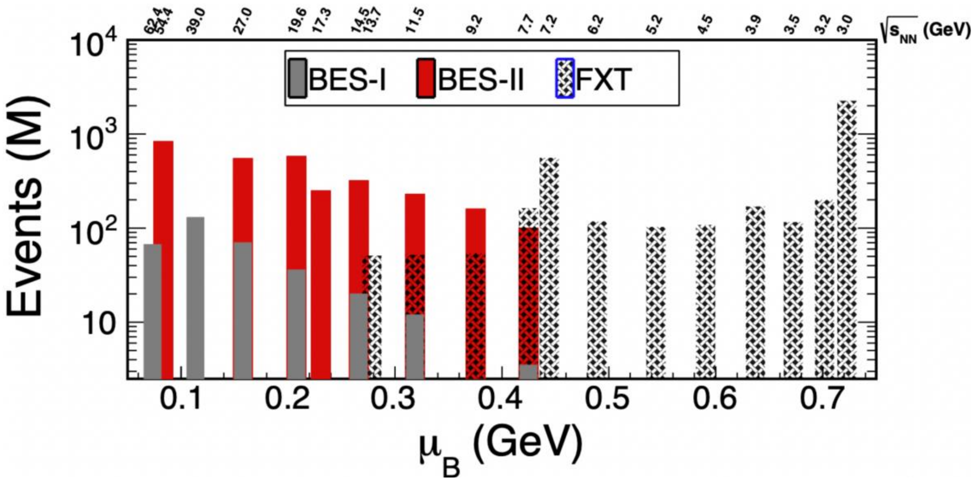
- Give us insight into:
  - Initial energy density
  - Initial particle distribution
  - Equation of State



https://doi.org/10.1016/j.nuclphysa.2017.05.042

BES-II Dataset

- The BES-II dataset:
  - 10x the statistics of BES-I
  - Upgraded detector to include the EPD, iTPC, and eTOF
- Ranges from 3.0 GeV (Fixed target) up to 27 GeV (collider mode)
- Extends the μ_B range to 20 - 720 MeV



Charge Dependence in Flow

Charge Dependence in Flow

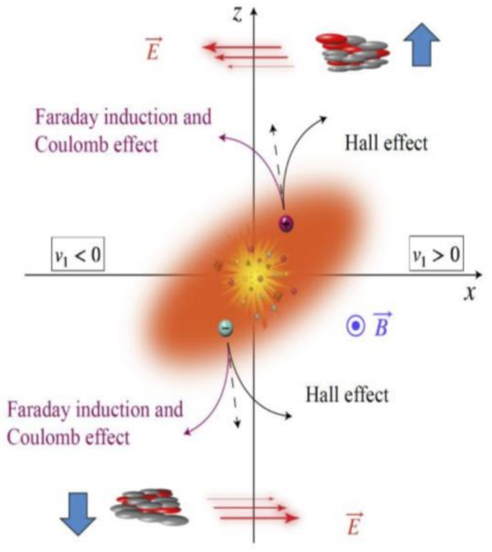
- **Important to understand QGP evolution in the presence of initial electromagnetic fields [1]**

Quarks experience several different electromagnetic effects:

- **Hall Effect:** F = q (v x B) by Lorentz Force
- **Coulomb Effect:** **E** generated by spectator nucleons
- **Faraday Induction:** decreasing **B** as spectators fly away

These electromagnetic forces provide opposite contribution of v_1 to particles with opposite charges

$$I_{(total)} = I_{(Hall)} + I_{(Faraday)}$$

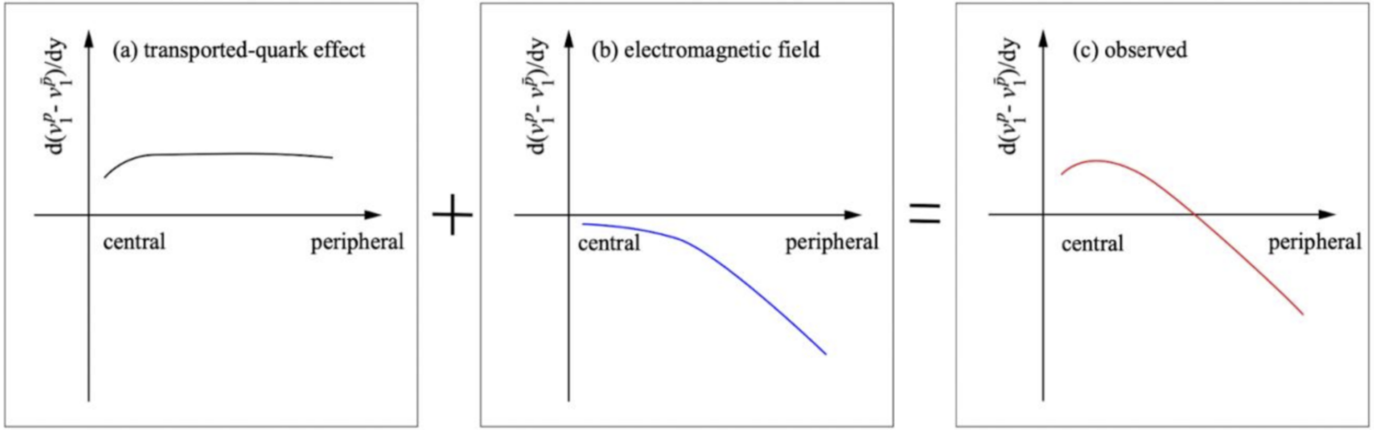


PRX 14, 011028 [STAR]

Charge Dependence in Flow

- **The splitting of v_1 between particle and antiparticle is measured as:**

$$\Delta v_1 = dv_1^{+}/dy \ - \ dv_1^{-}/dy$$

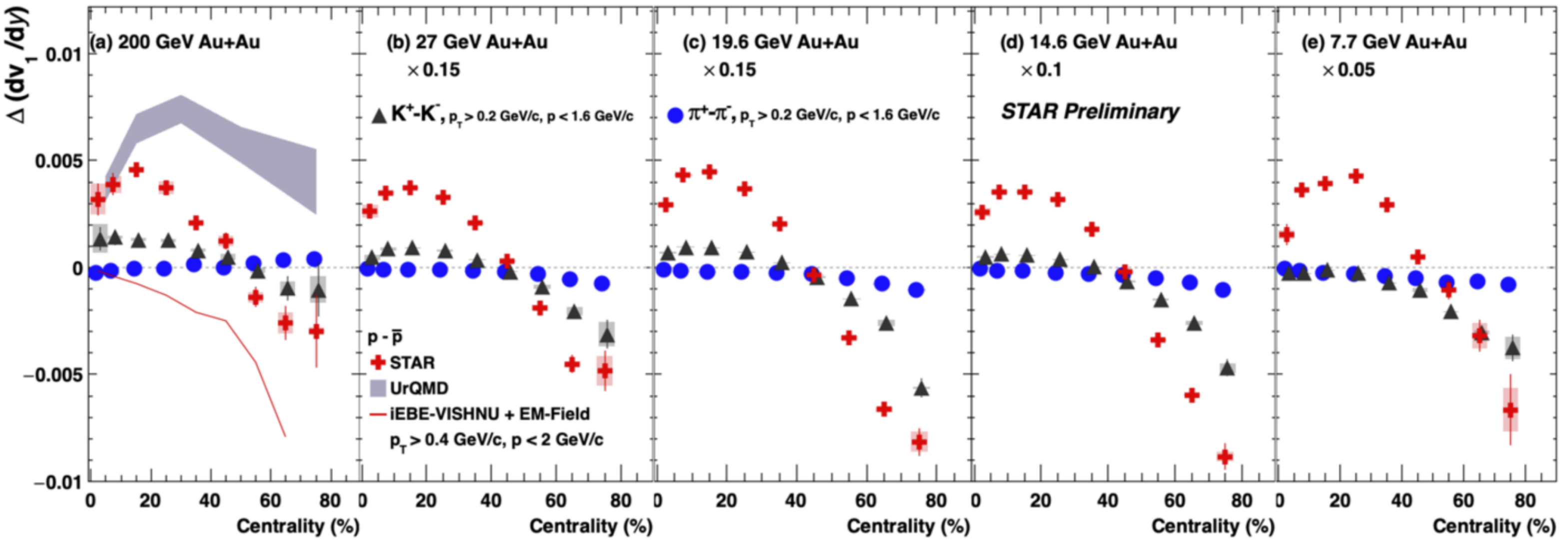


Transported Quark → **Positive Δv_1**

EM Field → **Negative Δv_1**

Combination
(Transported Quarks + EM)

Charge Dependence in Flow



- Negative $\Delta(dv_1/dy)$ in peripheral collisions meet naive expectation from transport + EM effects
- Δv_1 increases with decrease in beam energy
- Consistent with the dominance of (Faraday + Coulomb) effect in peripheral collisions (other mechanisms such as baryon inhomogeneities are under investigation)

[T. Parida et al. arXiv:2305.8806]

Excess Proton Flow

Excess Proton Flow

- If we treat transported and produced proton as having two distinct v_1 sources:

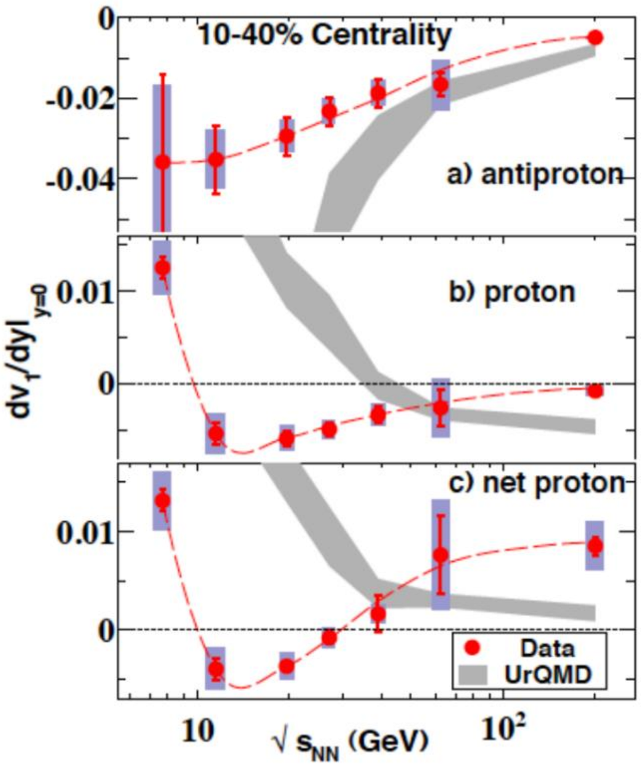
$$v_{1,net} = \frac{(v_{1,p} - r v_{1,\bar{p}})}{1-r} \qquad v_{1,produced} = v_{1,\bar{p}}$$

(r is the yield ratio of anti-protons to protons)

- Net proton v_1 slope at mid-rapidity exhibits non-monotonic behavior as a function of collision energy
  - Occurring much higher than expected

- Alternatively, we can separate it into:
  - a component from the medium dynamics affecting all
  - an excess component affecting only transported protons

$$v_{1,excess} = \frac{(v_{1,p} - v_{1,\bar{p}})}{1-r} \qquad v_{1,medium} = v_{1,\bar{p}}$$



(PRL 112, 162301 (2014))

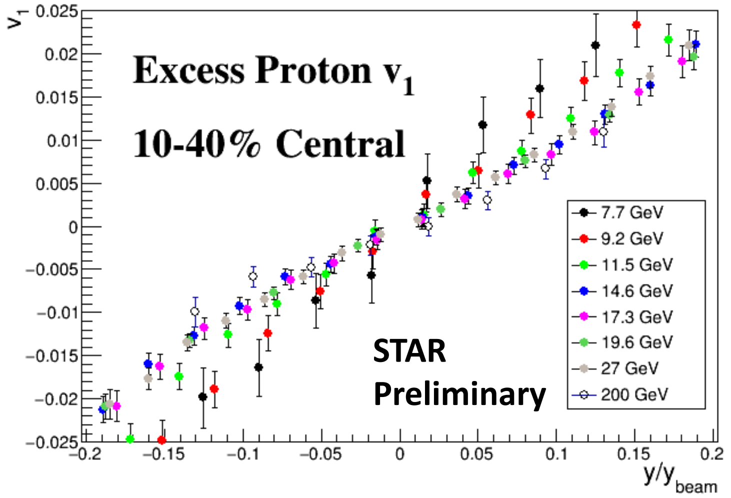
Collision Energy Dependence

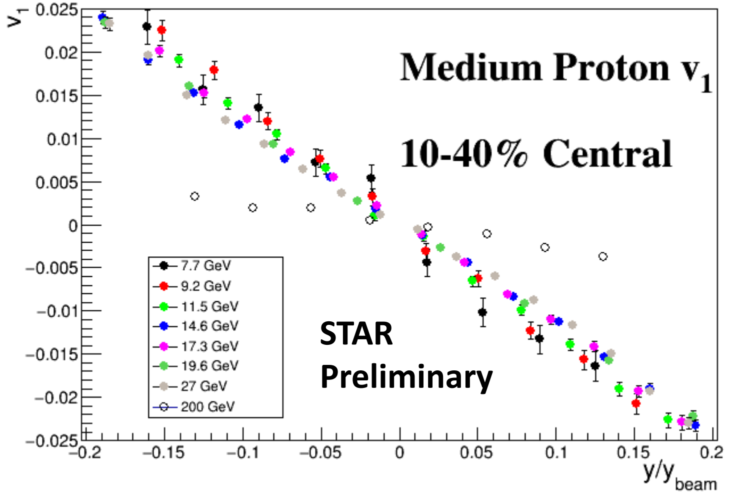
$$N_p v_{1,p} = N_p v_{1,medium} + (N_p - N_{\bar{p}}) v_{1,excess}$$

$$y_{beam}(\sqrt{s_{NN}}) = \cosh^{-1}(\sqrt{s_{NN}}/m_p)$$

- Clear scaling of excess Proton flow with collision energy

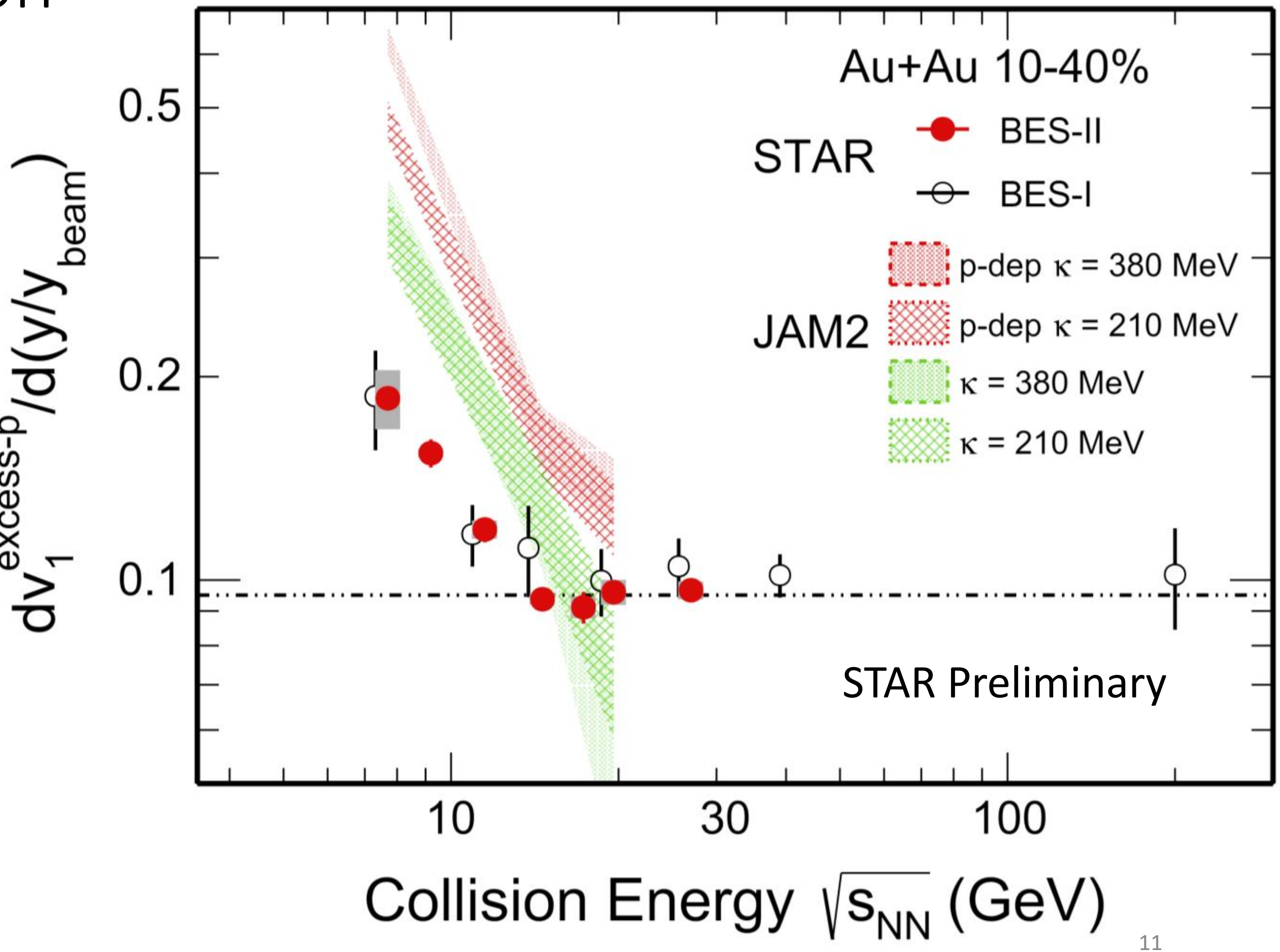
- Scaling starts to break at 11.5 GeV





Model Comparison

- Models fail to show the scaling behavior above 14.6 GeV
- Below 14.6 GeV models overpredict the magnitude of the data
- Adding momentum dependence to the potential increases this overprediction



Linear and Mode-Coupled Flow Harmonics

Linear and Mode-Coupled Flow Harmonics

- Flow measurements allow us to estimate shear viscosity (η/s) by reflecting the initial-state energy density

$$\mathcal{E}_n \equiv \varepsilon_n e^{in\Phi_n} \equiv -\frac{\int dx\,dy\,r^n\,e^{in\phi}\,\rho_e(r,\phi)}{\int dx\,dy\,r^n\,\rho_e(r,\phi)},\ (n\ >\ 1),$$

$\rho_e(r,\phi)$ is the initial energy density profile

- For low orders the relationship is linear only

$$v_n = \kappa_n \varepsilon_n, \quad n = 2,3$$

- For higher orders have an additional mode-coupled response

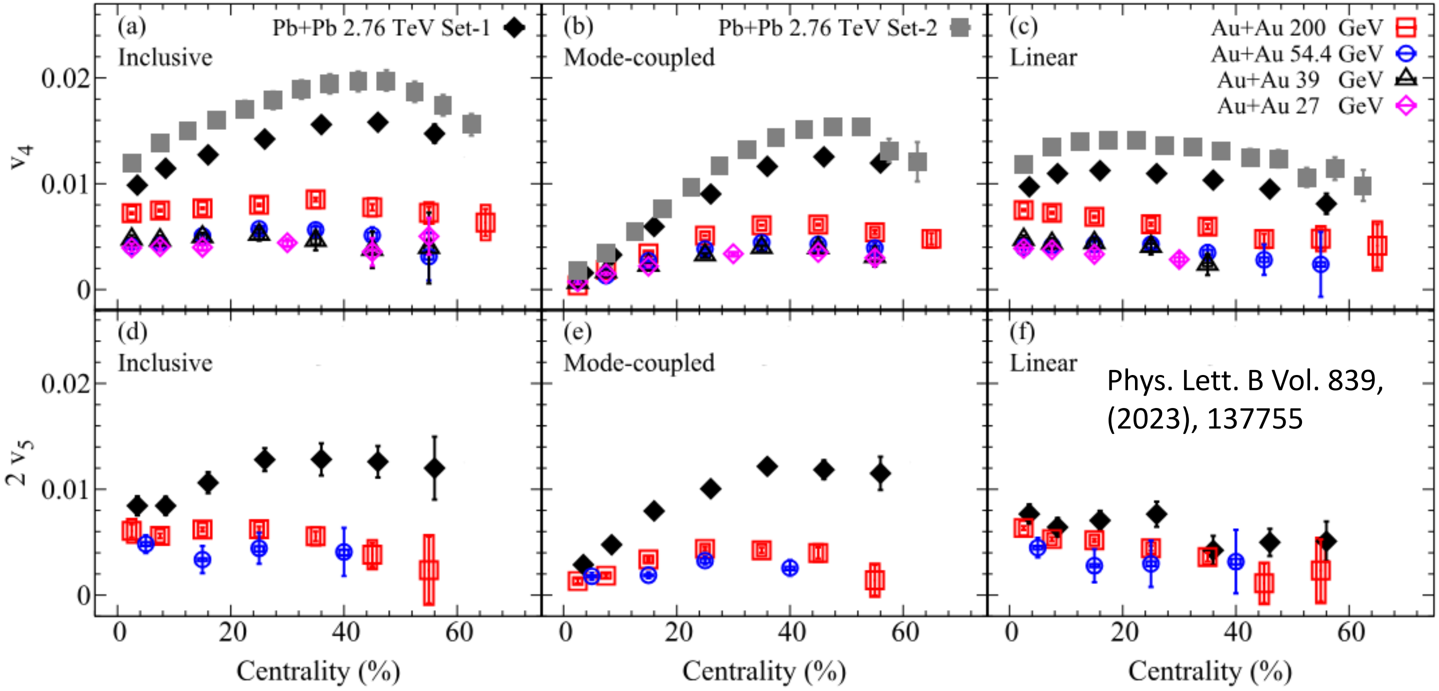
$$V_4 = v_4 e^{i4\psi_4} = \kappa_4 \varepsilon_4 e^{4i\Phi_4} + \kappa_4' \varepsilon_2^2 e^{4i\Phi_2} = V_4^{\text{Linear}} + \chi_{4,22} V_4^{\text{MC}},$$

$$V_5 = v_5 e^{i5\psi_5} = \kappa_5 \varepsilon_5 e^{5i\Phi_5} + \kappa_5' \varepsilon_2 e^{2i\Phi_2} \varepsilon_3 e^{3i\Phi_3} = V_5^{\text{Linear}} + \chi_{5,23} V_5^{\text{MC}},$$

Phys. Lett. B Vol. 839,(2023), 137755

Linear and Mode-Coupled Flow Harmonics

- Mode-Coupled has higher centrality dependence than linear
  - Suggests larger viscous attenuation for linear component



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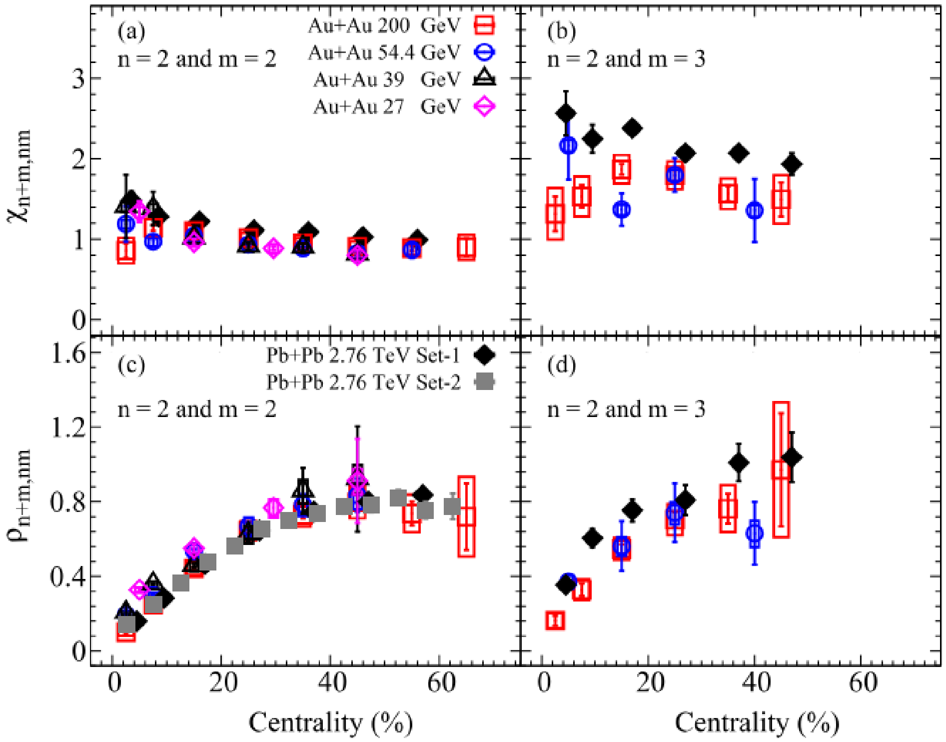
Linear and Mode-Coupled Flow Harmonics

- Mode Coupling coefficients, $\chi_{m+n,nm}$, also see little centrality dependence
  - Further indicating weak (η/s) dependence
  - More sensitive to initial-state effects

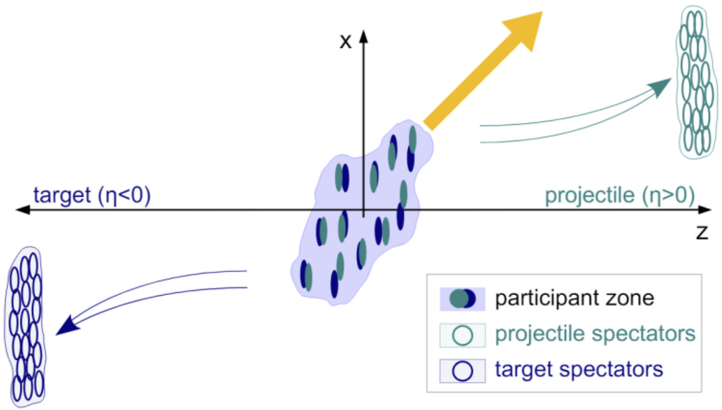


Phys. Lett. B Vol. 839, (2023), 137755

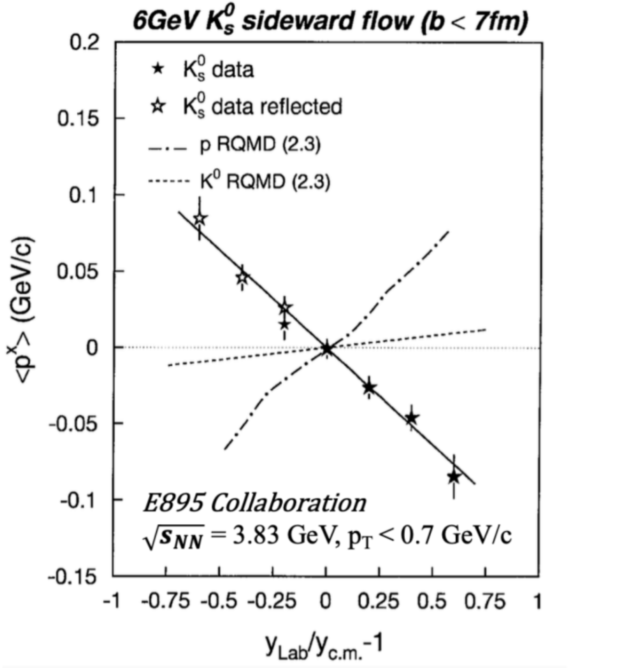
Kaon Potential

Kaon Potential

Figure taken from: Phys. Rev. Lett. 111, 232302 (2013)



E895 Collaboration, Phys. Rev. Lett. 85, 940 (2000)

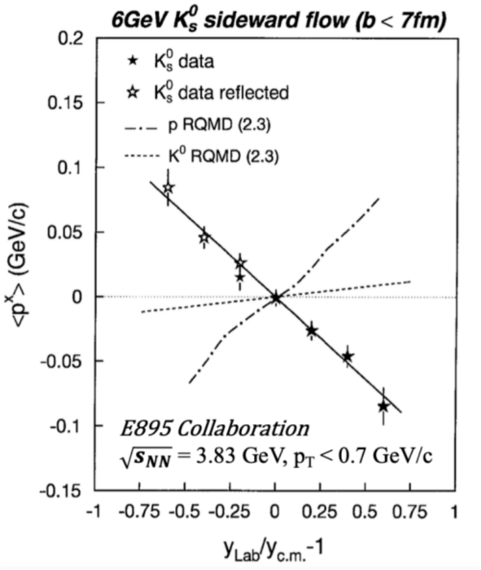


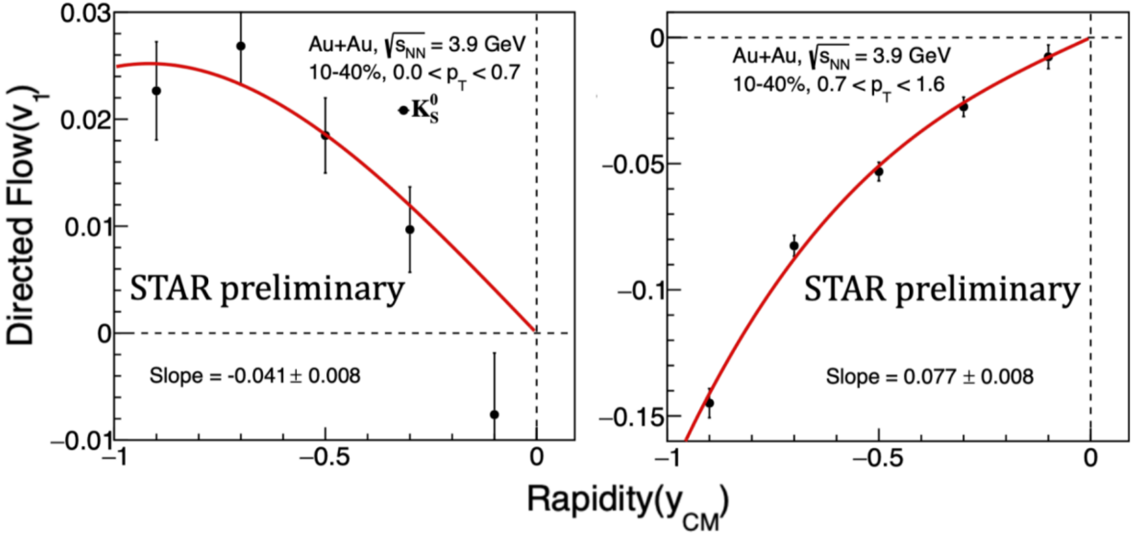
1) Bounce-off: Positive flow in positive rapidity

2) Au+Au 3.83 GeV: anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential ?

Kaon Potential

E895 Collaboration, Phys. Rev. Lett. 85, 940 (2000)



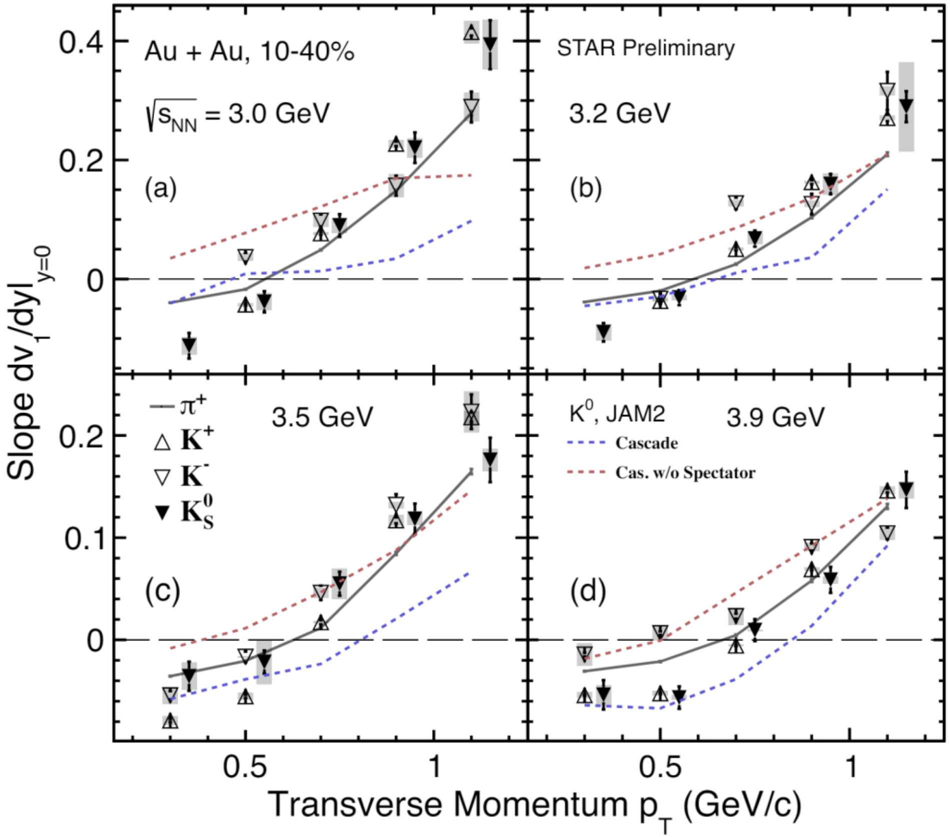


1) 3.9 GeV: anti-flow observed for K_S^0 at $p_T < 0.7$ GeV/c

2) Positive directed flow slope of K_S^0 at $p_T > 0.7$ GeV/c

Strong p_T dependence of K_S^0 v_1 slope

Kaon Potential

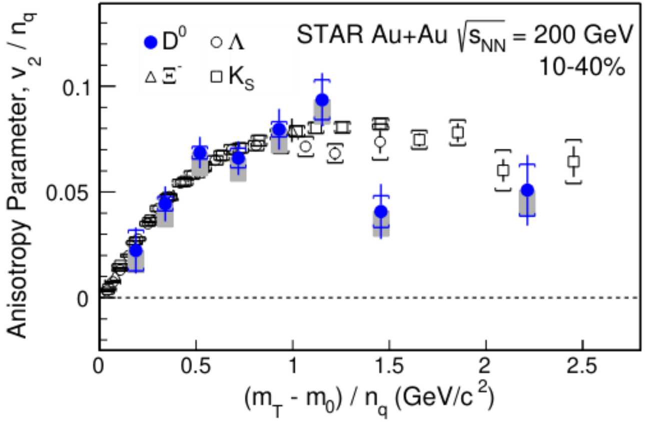


1) Anti-flow of π^+ and $K_S^0, K^\pm$ at low p_T
2) Anti-flow could be explained by shadowing effect from spectator, kaon potential is not necessary

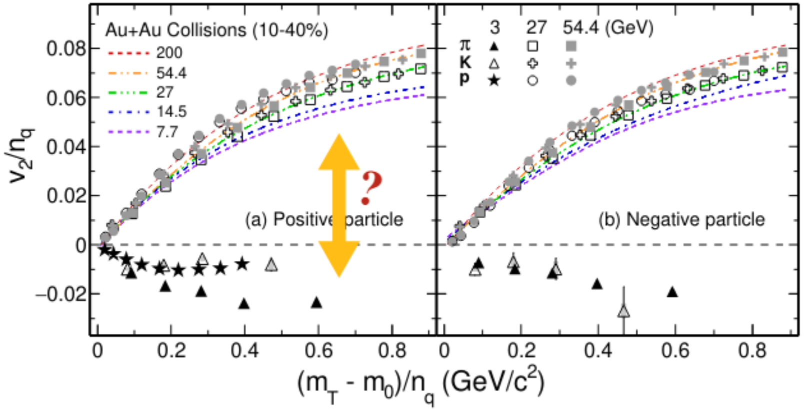
Partonic Collectivity

Partonic Collectivity

STAR Collaboration, Phys. Rev. Lett. 118, 212301 (2017)



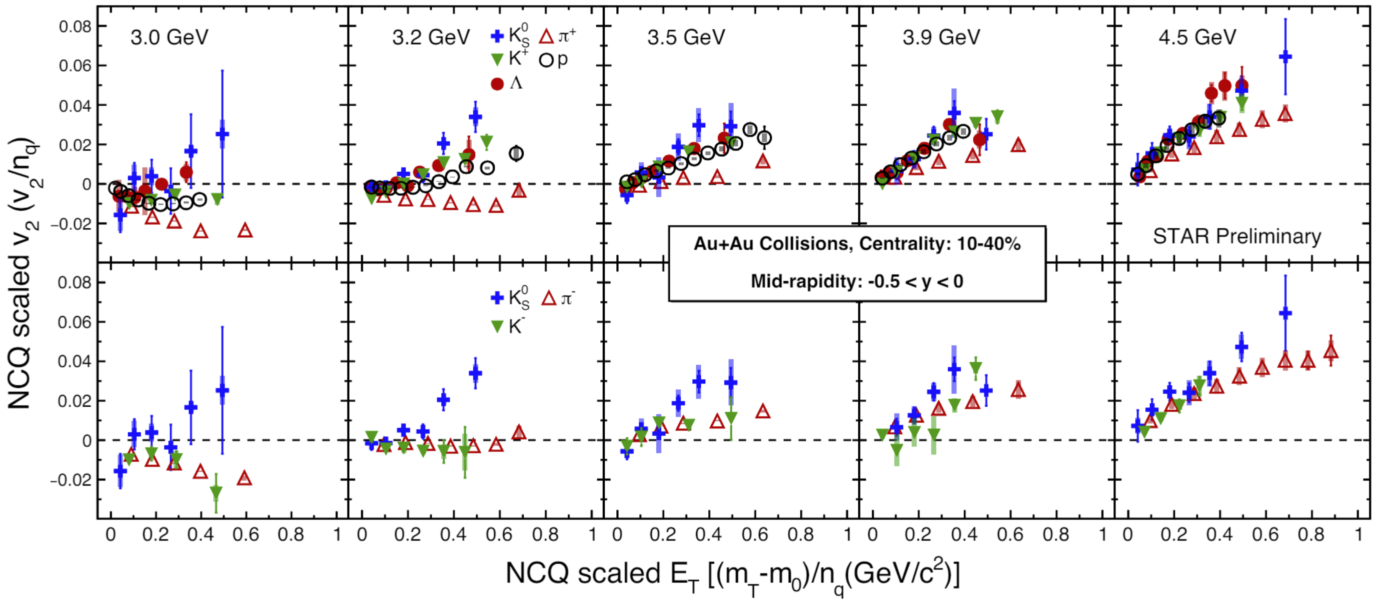
STAR Collaboration, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)



- Partonic collectivity key signature of QGP
- See partonic collectivity in NCQ scaling from BES I
- No scaling at 3 GeV, where is the onset?
- Other collective behavior?

Partonic Collectivity

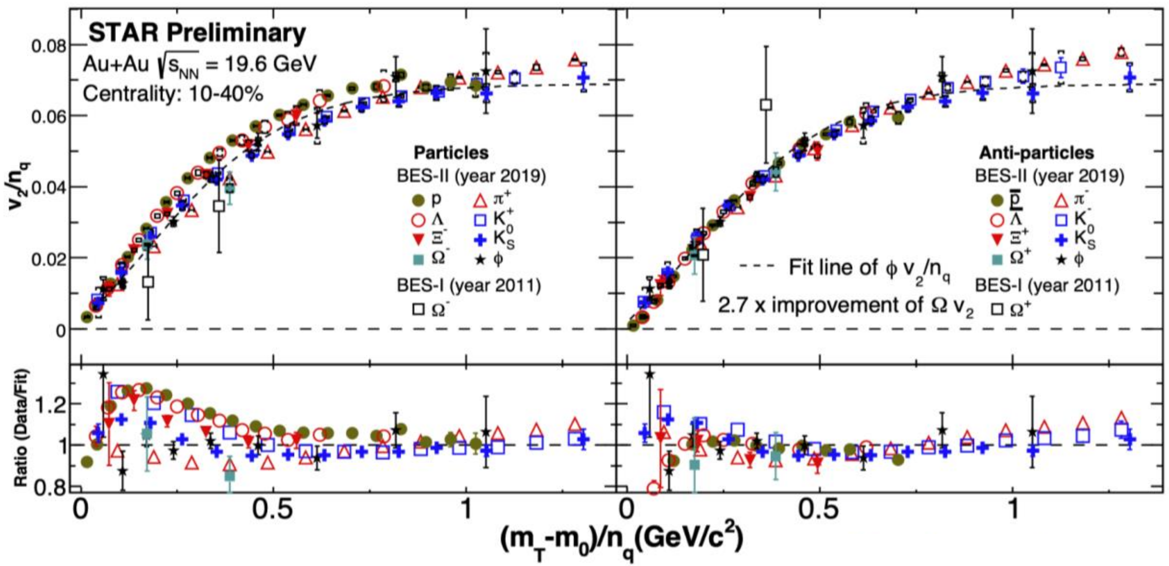
Hadronic interaction

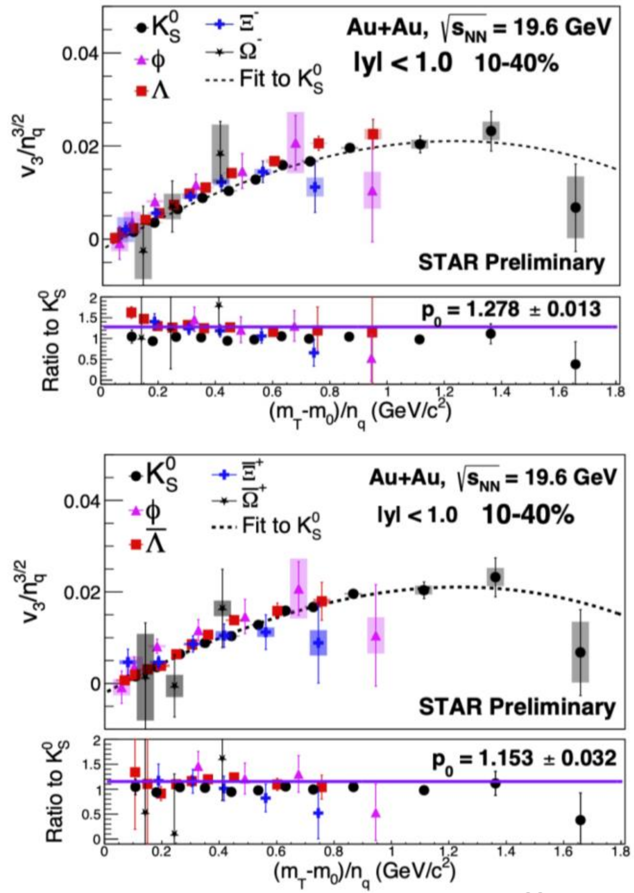


Partonic collectivity

1) NCQ scaling completely breaks below 3.2 GeV
2) NCQ scaling becomes better gradually from 3.2 to 4.5 GeV

Partonic Collectivity





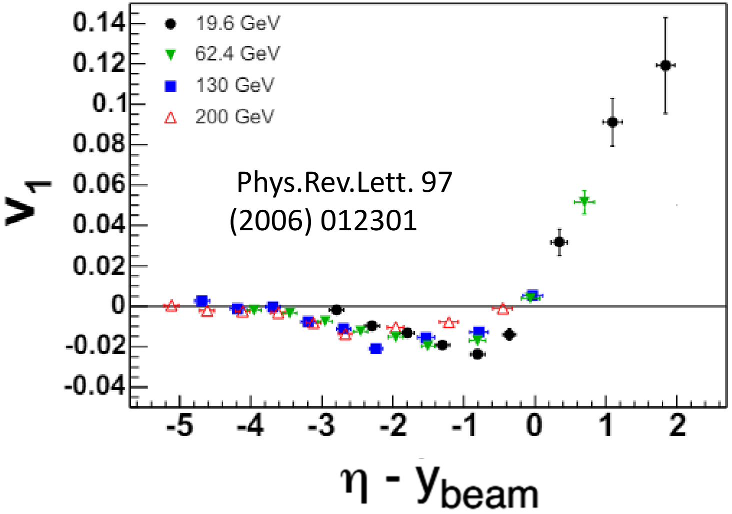
- Enhanced statistics from BES-II enable the test of NCQ scaling.
- NCQ scaling of v_2 (v_3) holds within 10(15)% for anti-particles, 20(30)% for particles.
  → Partonic interaction plays important role at 19.6 GeV.

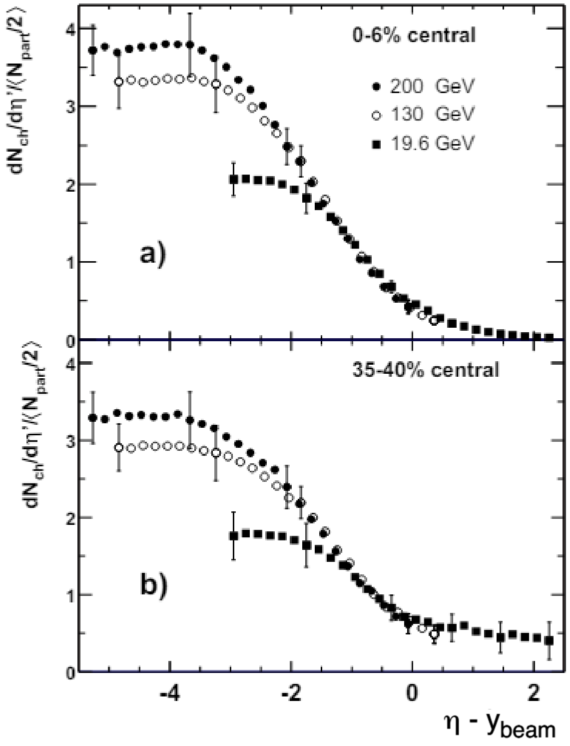
Limiting Fragmentation

Limiting fragmentation

- Limiting fragmentation :
  two colliding nuclei go through each other and break into fragments instead of completely stopping

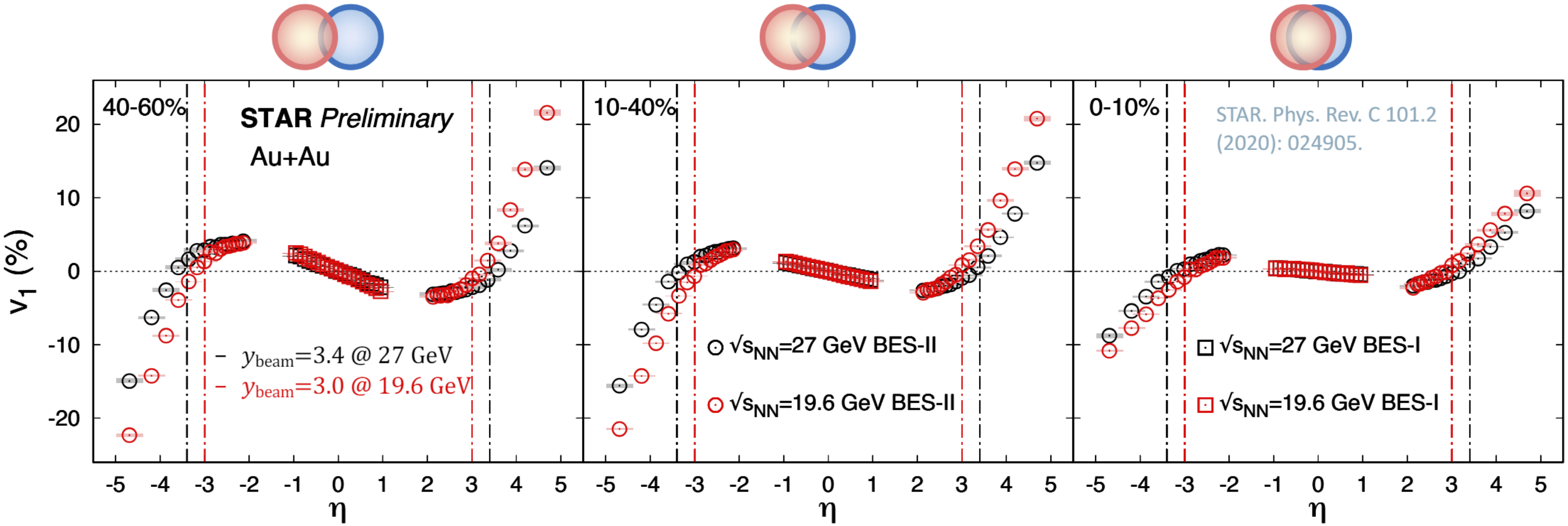
- Predicts that near beam rapidity, particle yields and ratios reach a limiting value



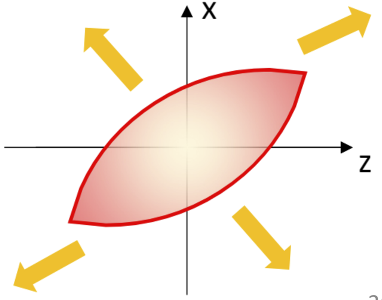


Phys. Rev. Lett. 91, 052303

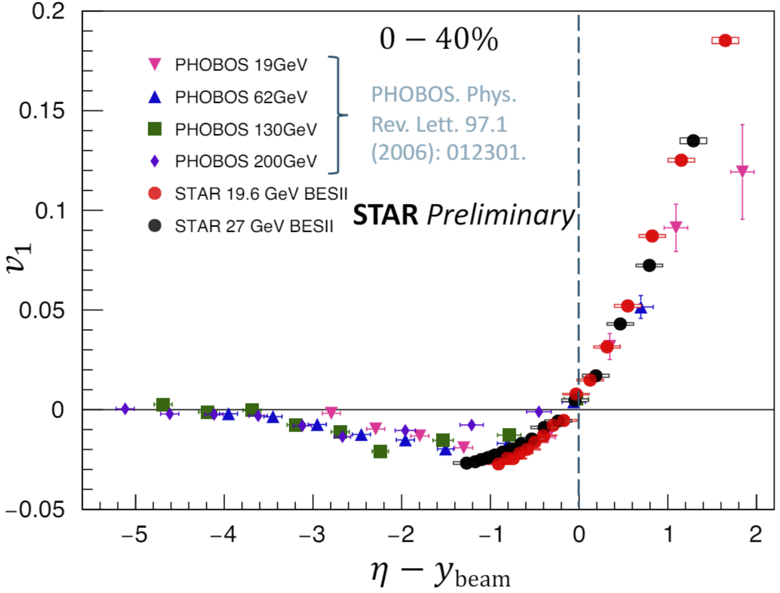
Limiting Fragmentation

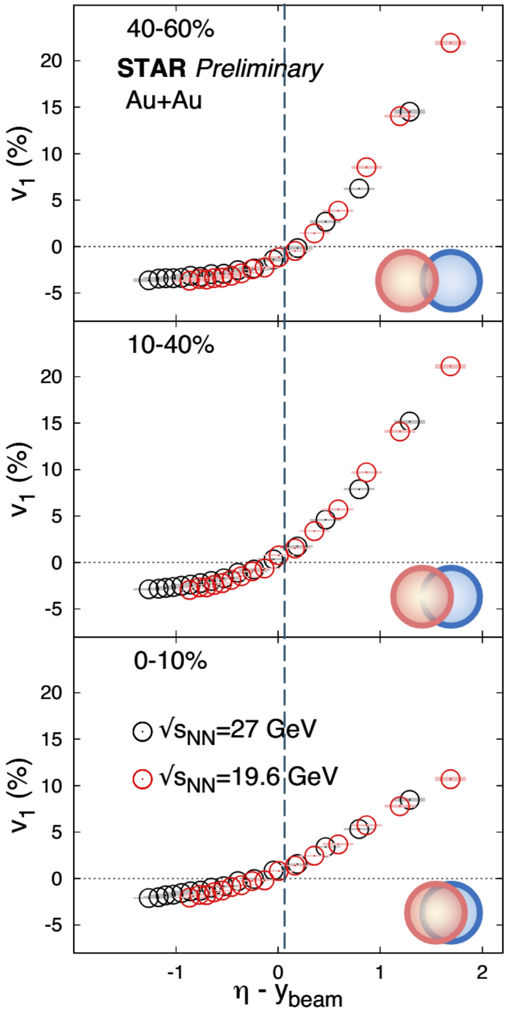


- v_1 at large $|\eta|$ was measured with particles in the full p_T space; v_1 around the mid-rapidity was measured in $0.2 < p_T < 10.0$ GeV/c.



Limiting Fragmentation Of v_1

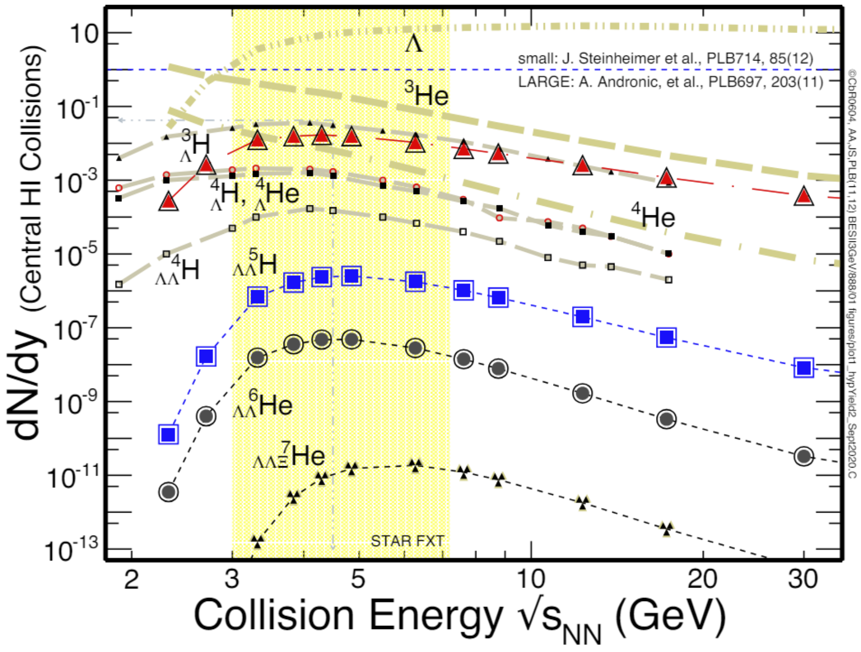




- "Limiting fragmentation" of v_1 observed for all the centralities.
- The phenomenon extends beyond yields to dynamics.

Light and Hyper Nuclei Flow

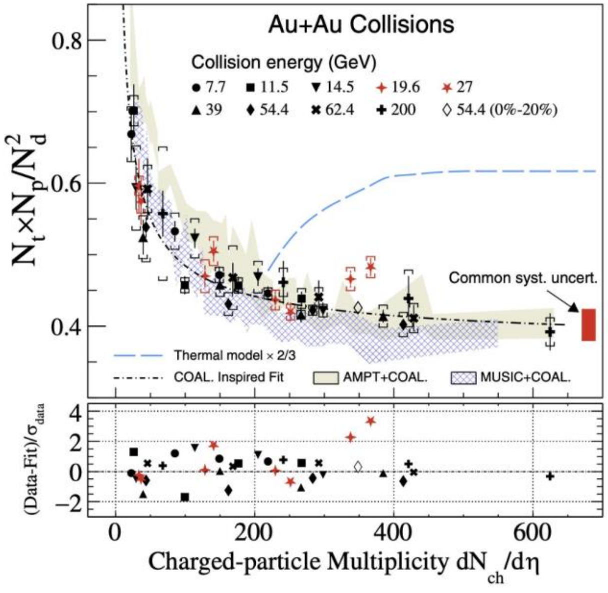
Light and Hyper Nuclei Flow



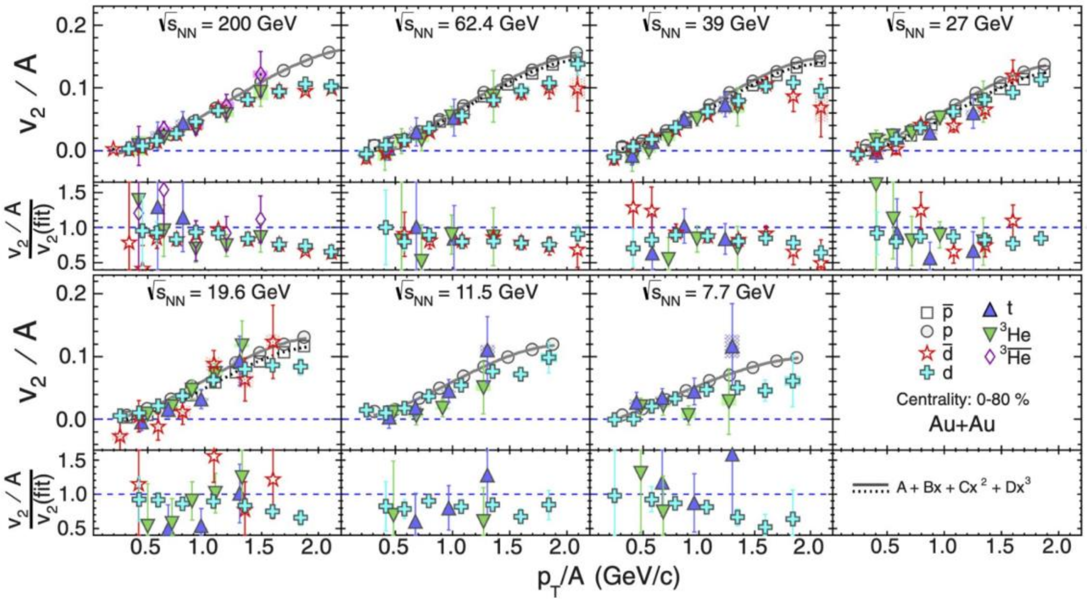
- Light and Hyper Nuclei are produced at high baryon density region
- Hyper Nuclei provide access to the hyperon-nucleon interaction: Y-N
- Collective flow is sensitive to the Equation of State of nuclear matter

[1] A. Andronic *et al*. Phys.Lett.B 697, 203 (2011)
[2] J. Steinheimer *et al*. Phys.Lett.B 714, 85 (2012)

Nuclei Formation



STAR, PRL 130, 202301 (2023)

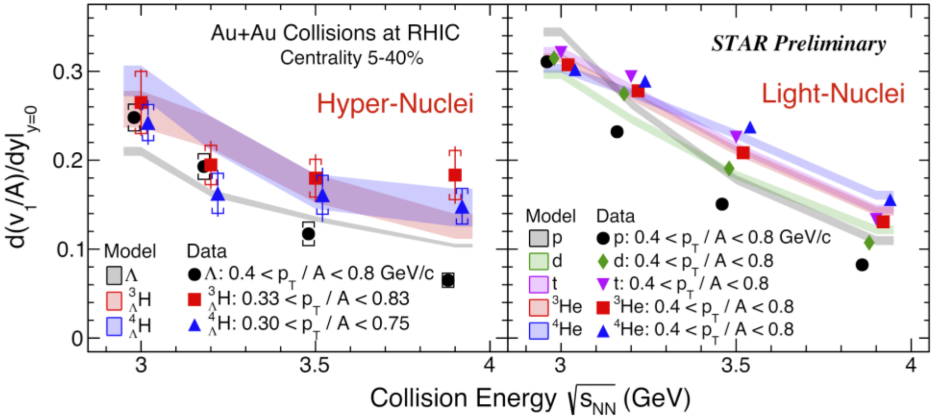


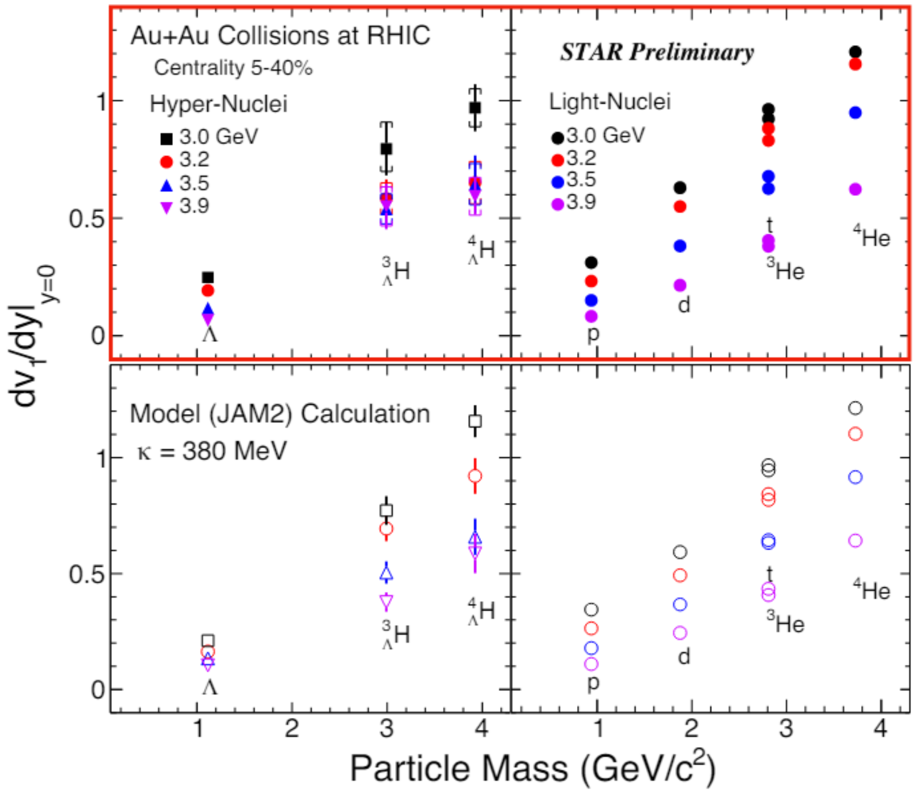
STAR, PRC 94, 034908 (2016)

- **Coalescence model**: Light nuclei are formed in the later stages of heavy-ion collision by the coalescence of protons and neutrons
- Recent measurements indicate **coalescence model** can reproduce light nuclei yields/ratios
- v_2/A of light nuclei was observed to be close to v_2 of protons for $p_T/A < 1.5$ GeV/c in BES-I data → Supporting **coalescence model**
- Higher statistics dataset in BES-II program will allow us to revisit and better understand the production mechanism of light nuclei

Light Nuclei Flow

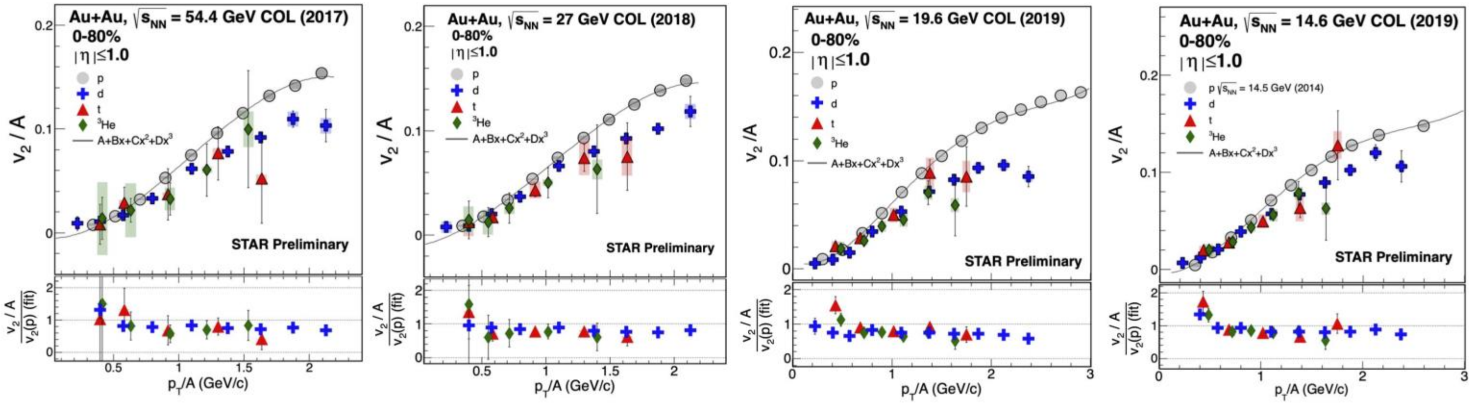
- Slopes at mid rapidity scale with mass number
- Implies coalescence mechanism dominates at FXT energies



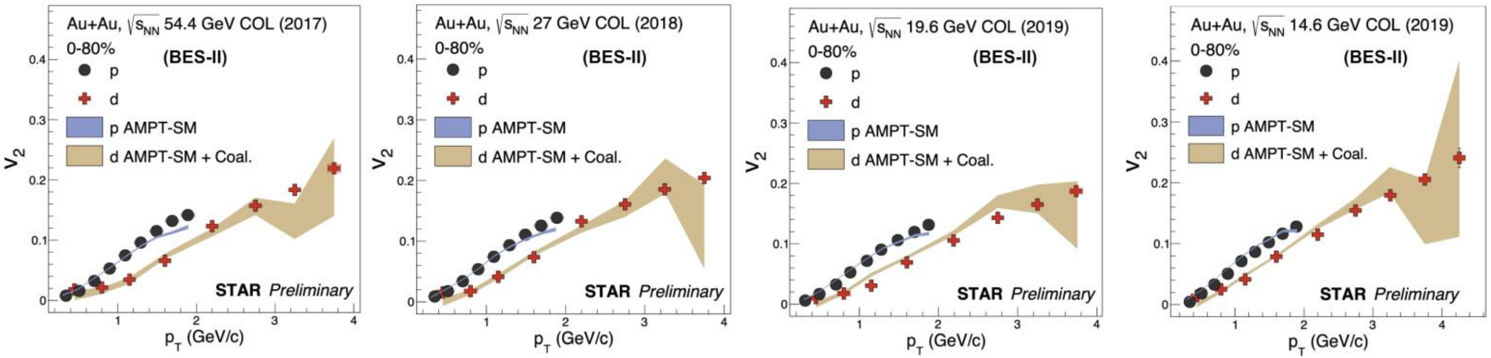


[1] B. E. Aboona *et al*., (STAR Collaboration), Phys. Rev. Lett. **130**, 211301(2023). [2] M.S. Abdallah *et al*., (STAR Collaboration), Phys. Lett. **827** (2022) 136941.
[3] Y. Nara *et al*., Phys. Rev. C **106**, 044902 (2022)

Nuclei Formation



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



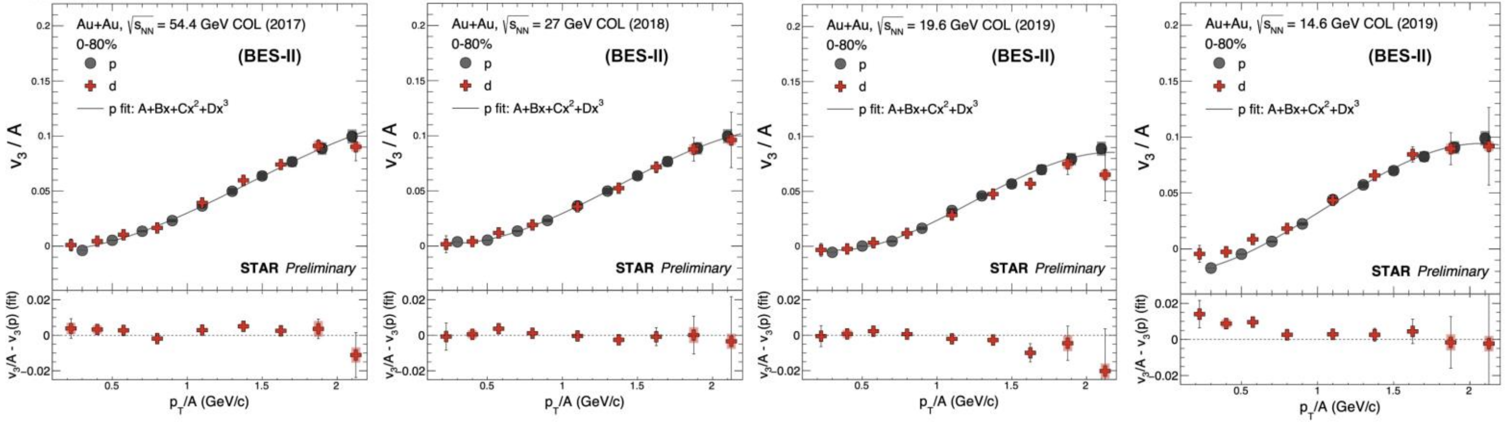
➢ AMPT-SM model with a coalescence afterburner is in good agreement with $v_2(p_T)$ of *d*

PRC 72, 064901 (2005)

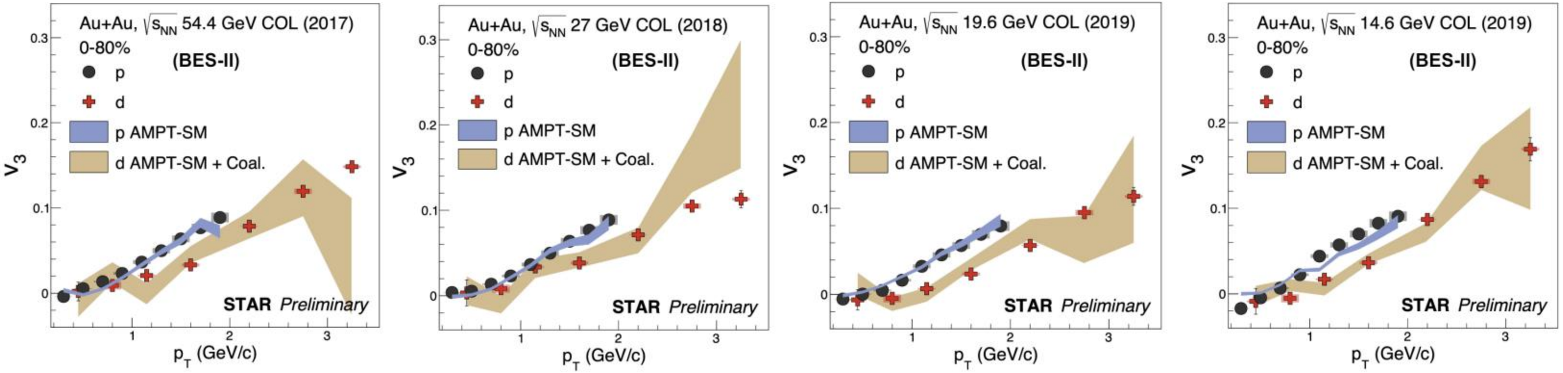
Nucl. Phys. A 729 (2003) 809–834

Proton v_2: Phys. Rev. C 93, 014907 (2016); Phys. Rev. C 88, 014902 (2013); Phys. Lett. B 827, 137003 (2022)

Nuclei Formation



➢ $v_3(p_T)$ of *d* shows a good agreement with mass number scaling within ~10%



PRC 72, 064901 (2005)
Nucl. Phys. A 729 (2003) 809–834

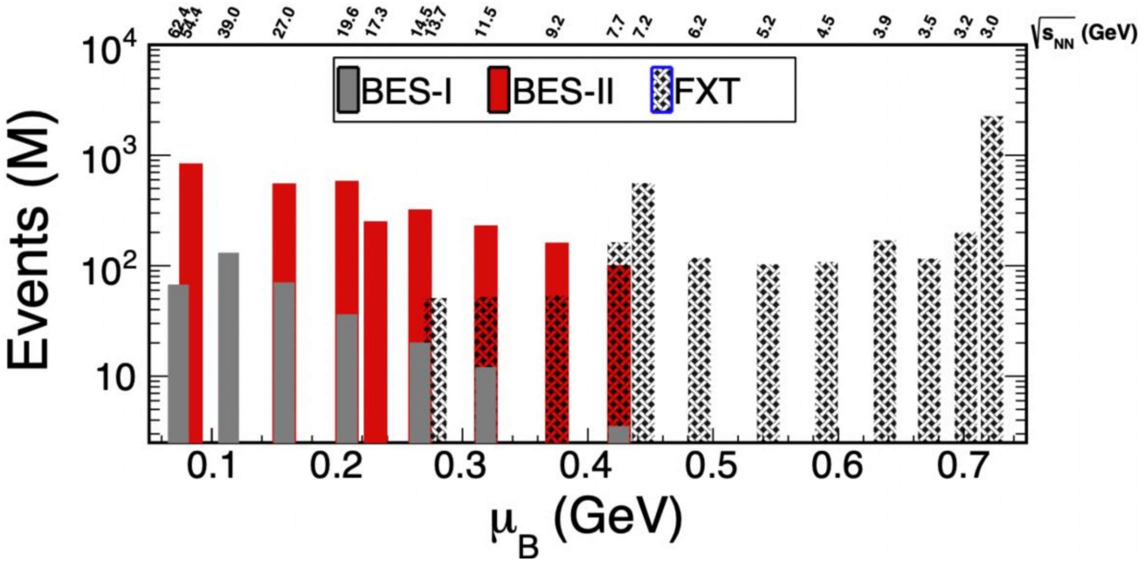
➢ AMPT-SM model with a coalescence afterburner is in good agreement with $v_3(p_T)$ of *d*

Summary

- Lots of measurements!
  - Equation of State:
    - Splitting in Δv_1 of identified particles increases with decreasing beam energies, indicating possible sensitivity to electromagnetic effects
    - Scaling behavior of excess proton v_1 with normalized rapidity shown from 200 to 14.6 GeV, breaking at lower energies
    - Linear and mode-coupled flow components help further constrain influence of shear viscosity
    - Spectator shadowing can reproduce kaon anti-flow
    - Partonic collectivity is gradually restored through FXT energies
      - also holds for triangular as well as elliptic flow at higher energies
  - Particle Production:
    - v_1 at forward rapidity shows evidence of limiting fragmentation
    - Coalescence model dominates the formation of light nuclei at FXT and collider energies

Outlook

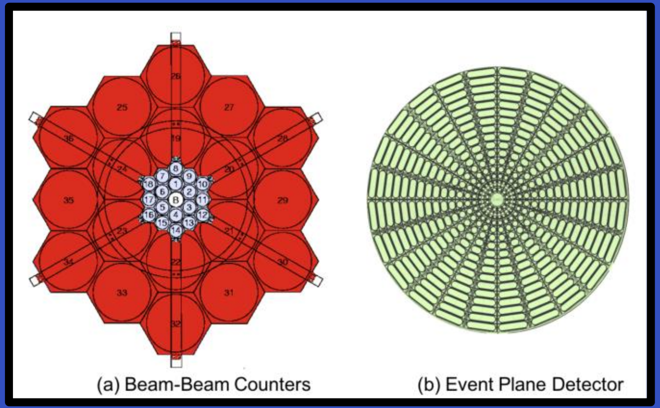
- Beam Energy Scan has brought a lot of new avenues of physics!
- 3 GeV high statistics still to be analyzed
- Many more exciting analysis from BES II datasets ongoing!



Backup

Event Plane Detector

- Pseudorapidity range: 2.1 to 5.1
- 372 tiles are Eljen scintillators
- Significantly increased Event plane accuracy as compared to Beam-Beam Counters (BBC)


(a) Beam-Beam Counters (b) Event Plane Detector