Reaction Plane Correlated Triangular Flow in Au+Au Collisions at $\sqrt{s_{NN}} = 3.0$ GeV from STAR

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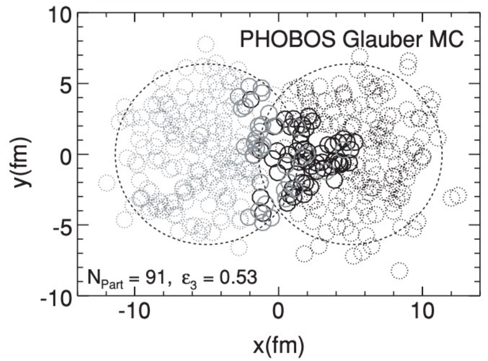
Motivation



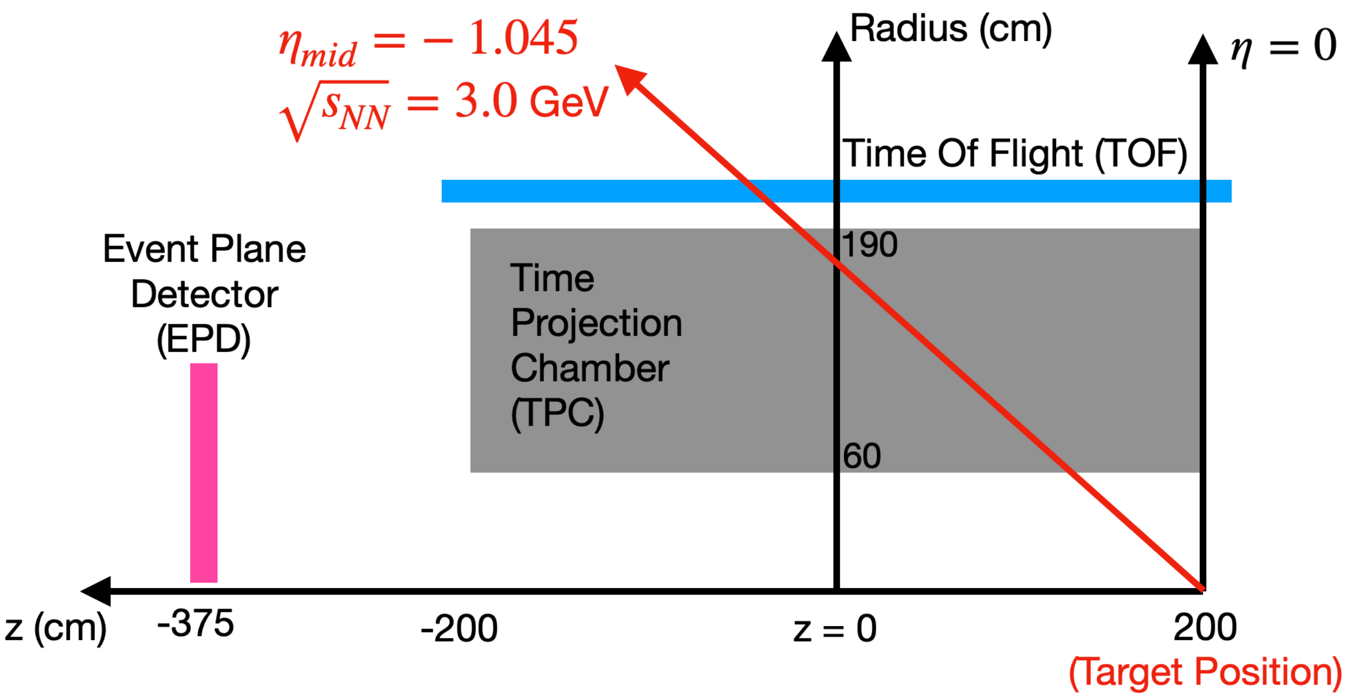
B. Alver & G. Roland, Phys. Rev. C 81, 054905

- Most STAR analyses of triangular flow (v_3) have been using collider mode data ($\sqrt{s_{NN}} = 7.7 - 200$ GeV) with a focus on rapidity-even v_3 studies.
  - v_3 arises from event-by-event collision geometry fluctuations.
  - v_3 has no direct correlation to the first-order event plane (Ψ_1), only to Ψ_3.
- Some models show that v_3 should fall to zero at much lower energies (~5 GeV) [1].
- Recent HADES results show there is a v_3 at $\sqrt{s_{NN}} = 2.4$ GeV, but now correlated to Ψ_1 [2].
- STAR fixed target (FXT) mode provides a unique opportunity to reach energies down to $\sqrt{s_{NN}} = 3.0$ GeV.
- What kind of v_3 will we see at 3.0 GeV? If there is a correlation to Ψ_1, can we understand the source?

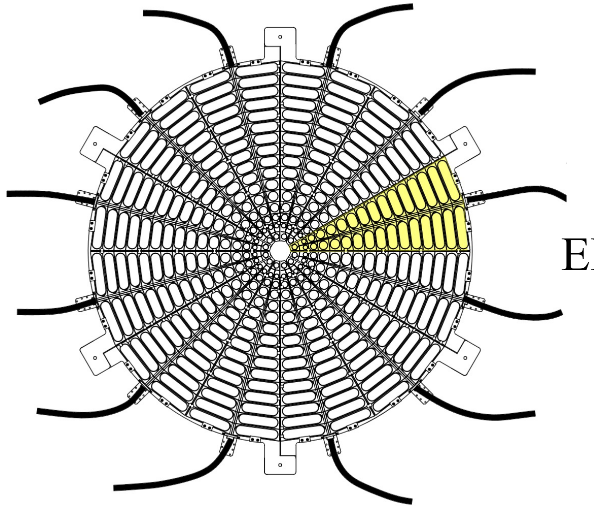
[1] J. Auvinen and H. Petersen, Phys. Rev. C 88, 064908
[2] J. Adamczewski-Musch *et al.,* Phys. Rev. Lett. 125, 262301

STAR Fixed Target Experimental Setup

- Au foil target + Au beam
  - $E_{beam} = 3.85$ GeV
  - $y_{mid} = -1.045$
  - Beam used is the one pointing in the negative direction during normal collider operation; <u>Forward direction is defined to be negative.</u>

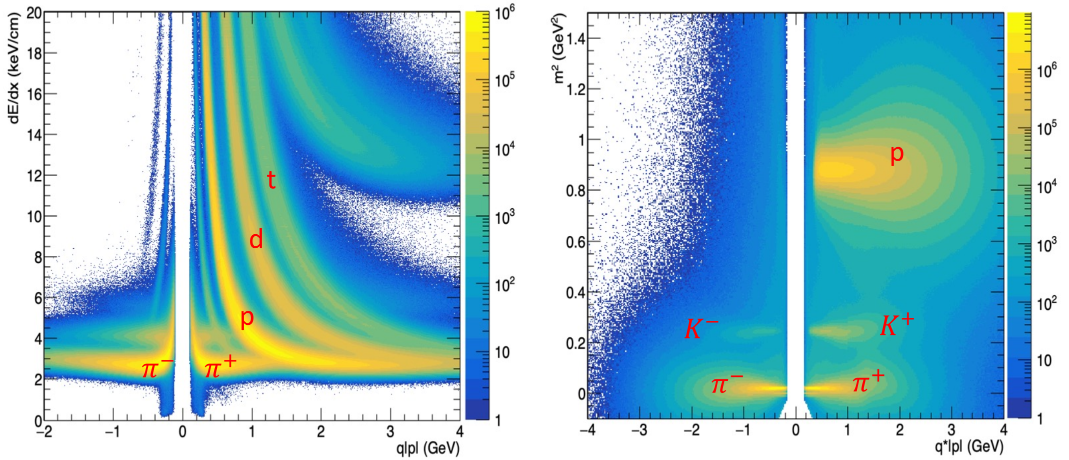


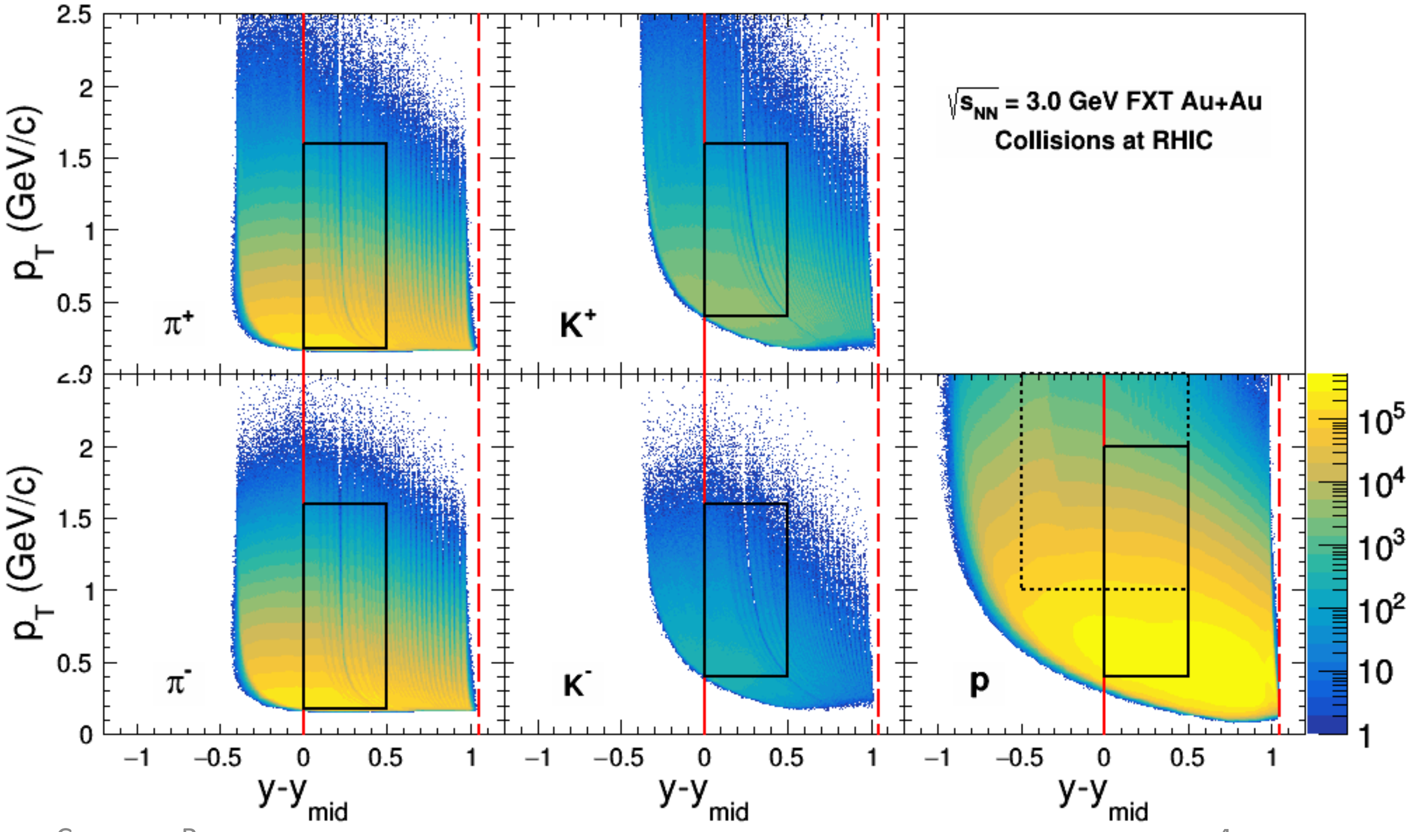
- Time Projection Chamber (TPC) and Time-of-Flight (TOF) used for particle identification.
- Event Plane Detector (EPD) used for event plane reconstruction.



Particle Identification

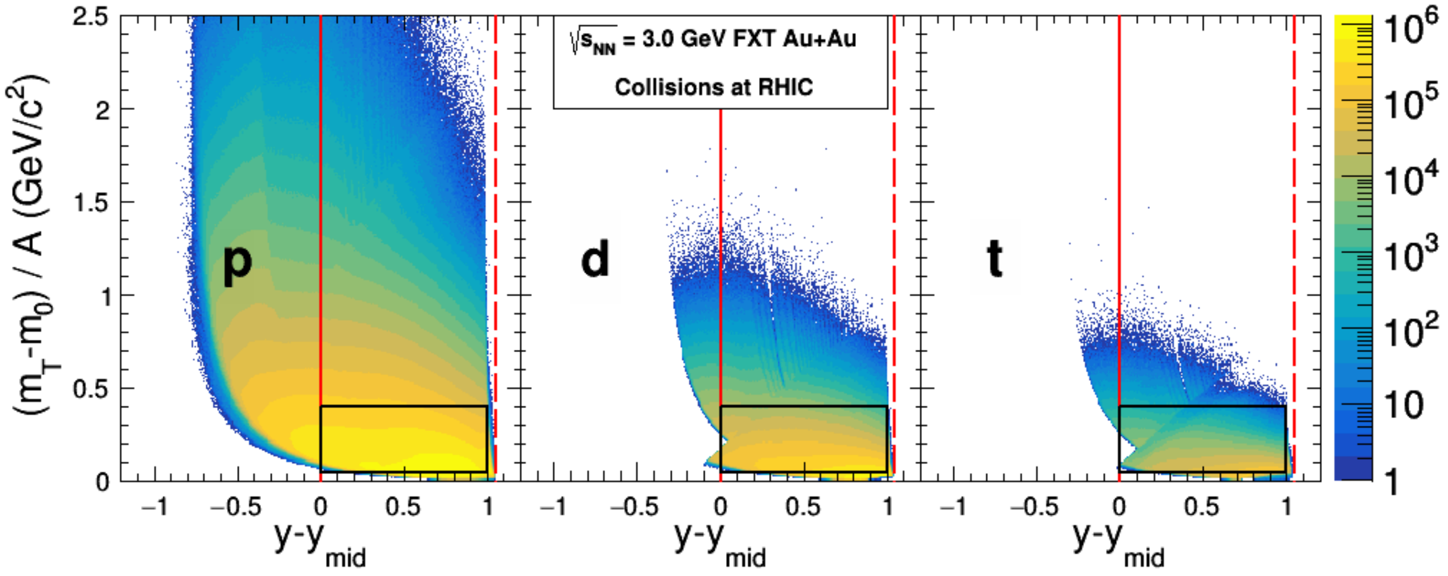
- $\pi^{\pm}$ and $K^{\pm}$ are identified with dE/dx and m^2 info; protons identified with dE/dx.
- Black solid boxes = acceptance for v_3 vs centrality.
- Black dashed box = acceptance for v_3 vs rapidity.
- Red solid (dashed) lines = mid (target) rapidity.





Particle Identification

- Alternate acceptance made for proton, deuteron, and triton comparisons.
- Rather than p_T, we used $m_T - m_0$ scaled by mass number A.
- Black solid boxes = acceptance for v_3 vs centrality.
- Red solid (dashed) lines = mid (target) rapidity.



- d and t identification:
  - dE/dx cuts vary for $|\vec{p}|$ bins of 0.1 GeV/c when
    - $|\vec{p}| \in [0.4, 3.0)$ for deuterons.
    - $|\vec{p}| \in [1.0, 4.0)$ for tritons.
  - For other $|\vec{p}|$, constant dE/dx and m^2 cuts are both used.

Analysis Methods

$$\vec{Q}_m = (Q_{m,x}, Q_{m,y}) = \left(\sum_i w_i \cos(m\phi_i), \sum_i w_i \sin(m\phi_i)\right)$$

$$\Psi_m = \frac{1}{m}\tan^{-1}\left(\frac{Q_{y,m}}{Q_{x,m}}\right)$$

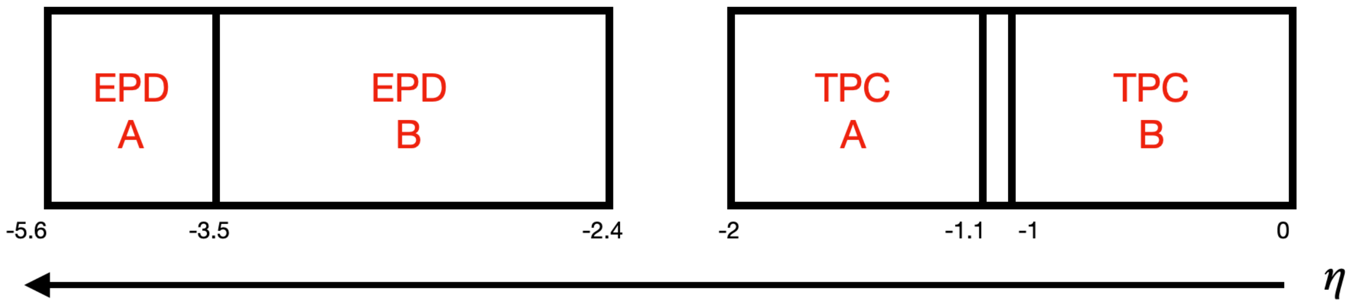
- Flow vectors $\overrightarrow{Q_m}$ are used to reconstruct event planes [3].
  - m = order of event plane harmonic; Ψ_m
- Weights w_i are p_T for TPC tracks and truncated nMIP (TnMIP) values for EPD hits.
- 0.3 < TnMIP < 2.0
  - Hits with TnMIP < 0.3 are rejected.
  - Hits with TnMIP > 2.0 are replaced with 2.0.
- Recentering and Fourier shifting (10 terms) used to correct non-uniform detector effects.

$$\vec{Q}_{m,recentered} = \vec{Q}_m - \langle \vec{Q}_m \rangle$$

$$\Delta\Psi_m = \sum_{j=1}^{\infty} \frac{2}{jm}[\langle -\sin(jm\Psi_m)\rangle \cos(jm\Psi_m) + \langle \cos(jm\Psi_m)\rangle \sin(jm\Psi_m)]$$

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

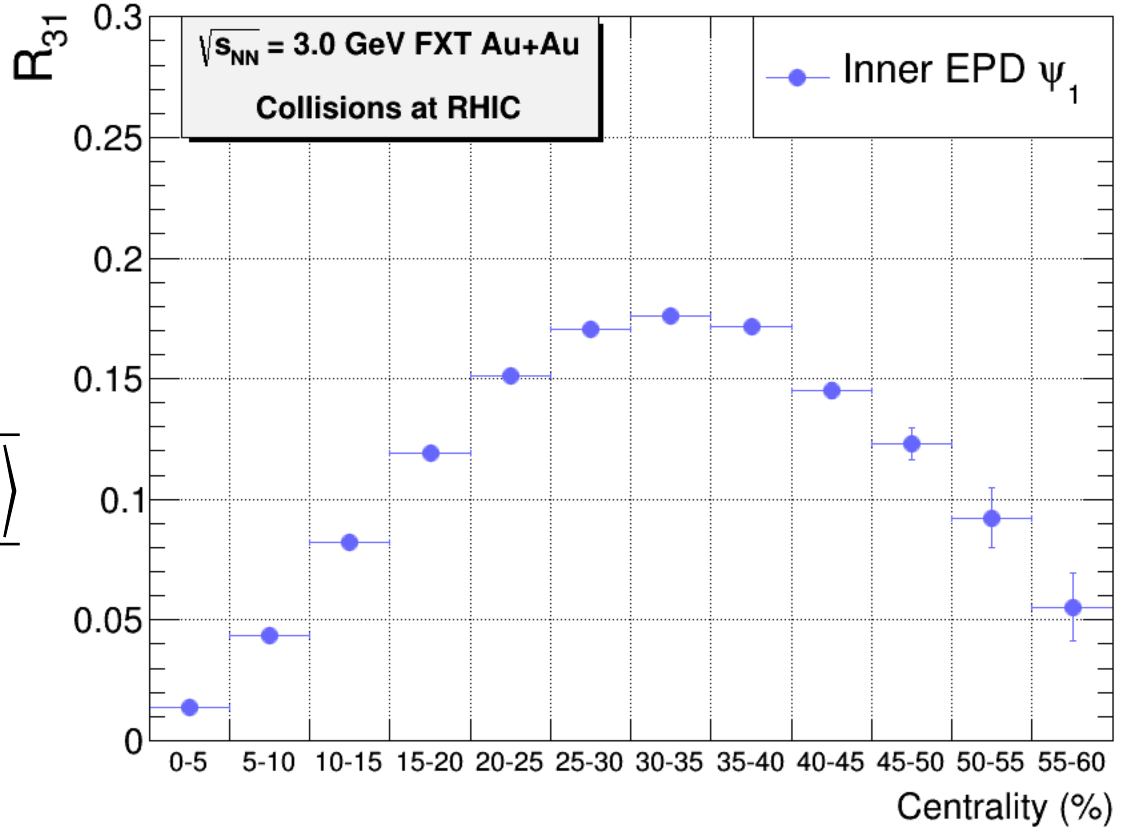
Analysis Methods



- 3 subevents used to calculate event plane resolution R_{nm}.
  - n = order of flow harmonic; v_n
  - EPD A: inner 8 rings (> 5 hits).
  - EPD B: outer 8 rings (> 9 hits).
  - TPC B: $-1 < \eta < 0$ (> 5 tracks).

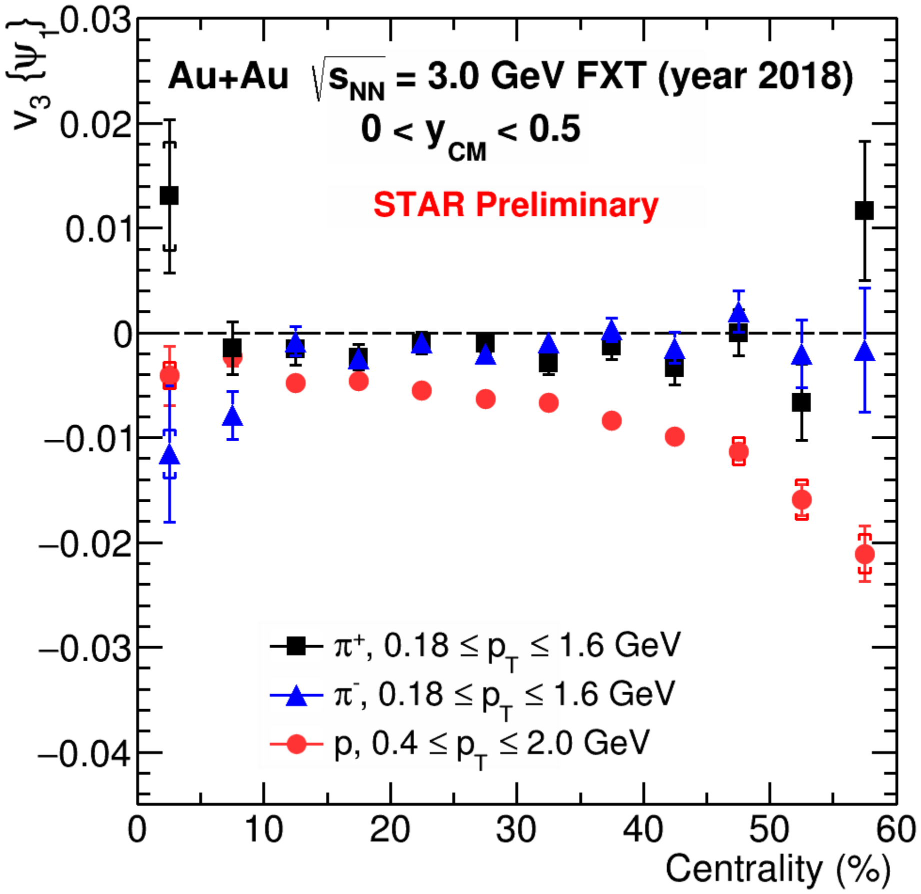
$$R_{nm} = \sqrt{\frac{\left\langle \cos\left(n(\Psi_m^{EPD,A} - \Psi_m^{EPD,B})\right)\right\rangle \left\langle \cos\left(n(\Psi_m^{EPD,A} - \Psi_m^{TPC,B})\right)\right\rangle}{\left\langle \cos\left(n(\Psi_m^{EPD,B} - \Psi_m^{TPC,B})\right)\right\rangle}}$$

$$v_3\{\Psi_1\} = \frac{\left\langle \cos\left(3(\phi - \Psi_1)\right)\right\rangle}{R_{31}}$$



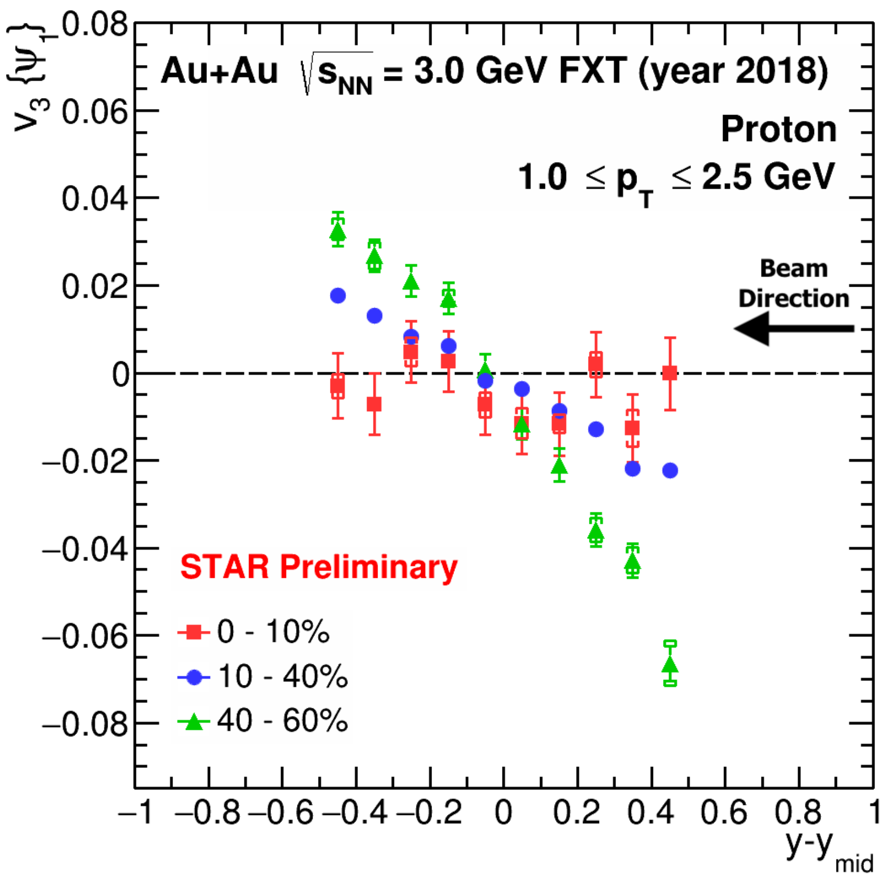
Centrality Dependence

- Backward region ($0 < y_{CM} < 0.5$) shows significant non-zero v_3 for protons.
- v_3 is correlated to Ψ_1 at $\sqrt{s_{NN}} = 3$ GeV.
- Effect has a strong dependence on centrality.

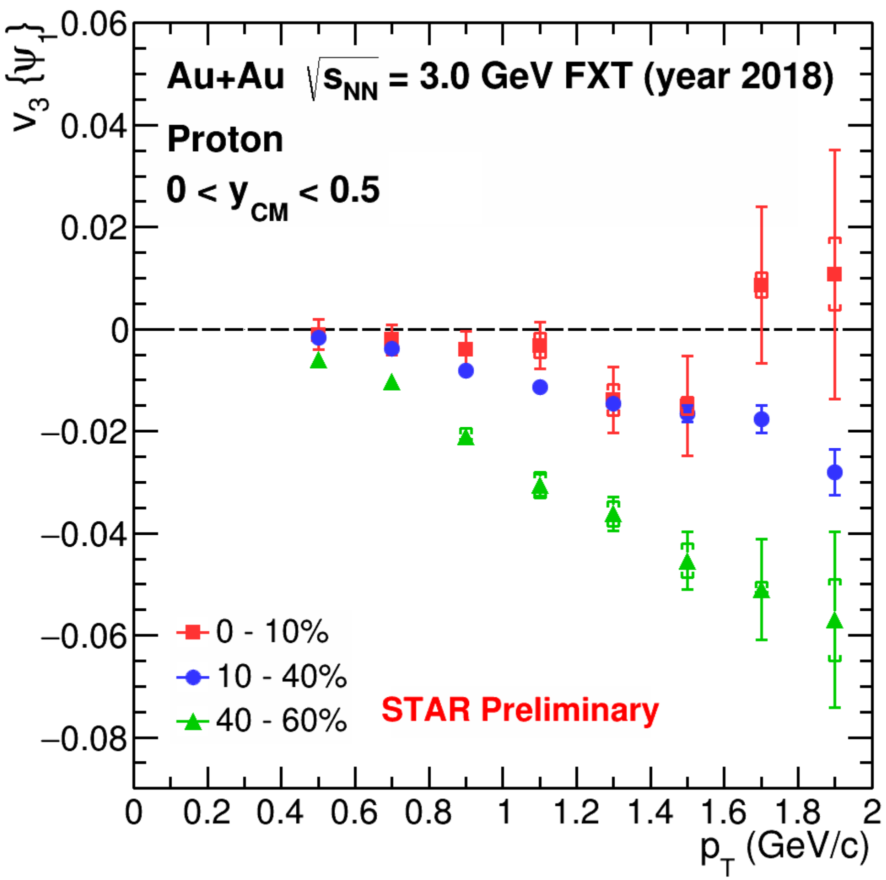


- All systematic uncertainties in the following include contributions from
  - Event/track QA cuts
  - Event plane resolution
  - Pion and proton identification cuts.
- Pions show no significant signal of v_3.
- No conclusion can be made about kaons (not shown) due to low statistics.

Rapidity and p_T – Protons



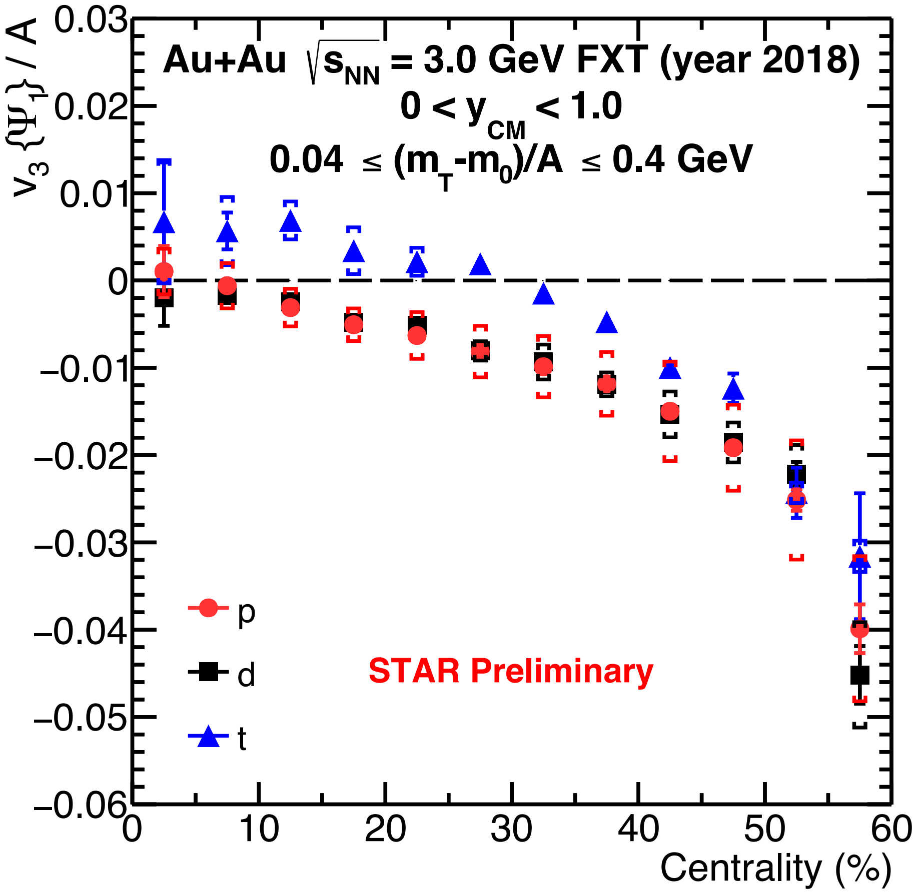
- Proton $v_3\{\Psi_1\}$ is rapidity odd.
- Negative slope; opposite sign to v_1 at 3 GeV [4,5].
- Strength increases with y and p_T.



[4] M. A. *et al.* (STAR Collaboration), Phys. Lett. B 827, 136941 (2022).
[5] M. A. *et al.* (STAR Collaboration), Phys. Lett. B 827, 137003 (2022).

Nuclear Mass Number Scaling (A)

- A-scaling supports that nuclei are formed via coalescence.
- Significant non-zero $v_3\{\Psi_1\}$ observed for deuterons and tritons.
- In this acceptance region, deuterons scale with mass number, tritons do not.
- Triton results are currently under investigation for the following effects:
  - Fragmentation effects
  - Other unexpected effects



- All three species include TPC reconstruction efficiency corrections.
- $A = N_{proton} + N_{neutron}$
  - 2 for deuterons.
  - 3 for tritons.

Where does $v_3\{\Psi_1\}$ come from?

- Due to the correlation to Ψ_1 this triangular flow is not from event-by-event fluctuations, so:
  - Question 1: Where does the triangular geometry (that also preserves the Ψ_1 correlation) come from?
  - Question 2: What drives the flow?

- 3 GeV is probably below the phase transition, but $v_3\{\Psi_1\}$ could give us another way to understand how QCD manifests itself and what degrees of freedom are important.

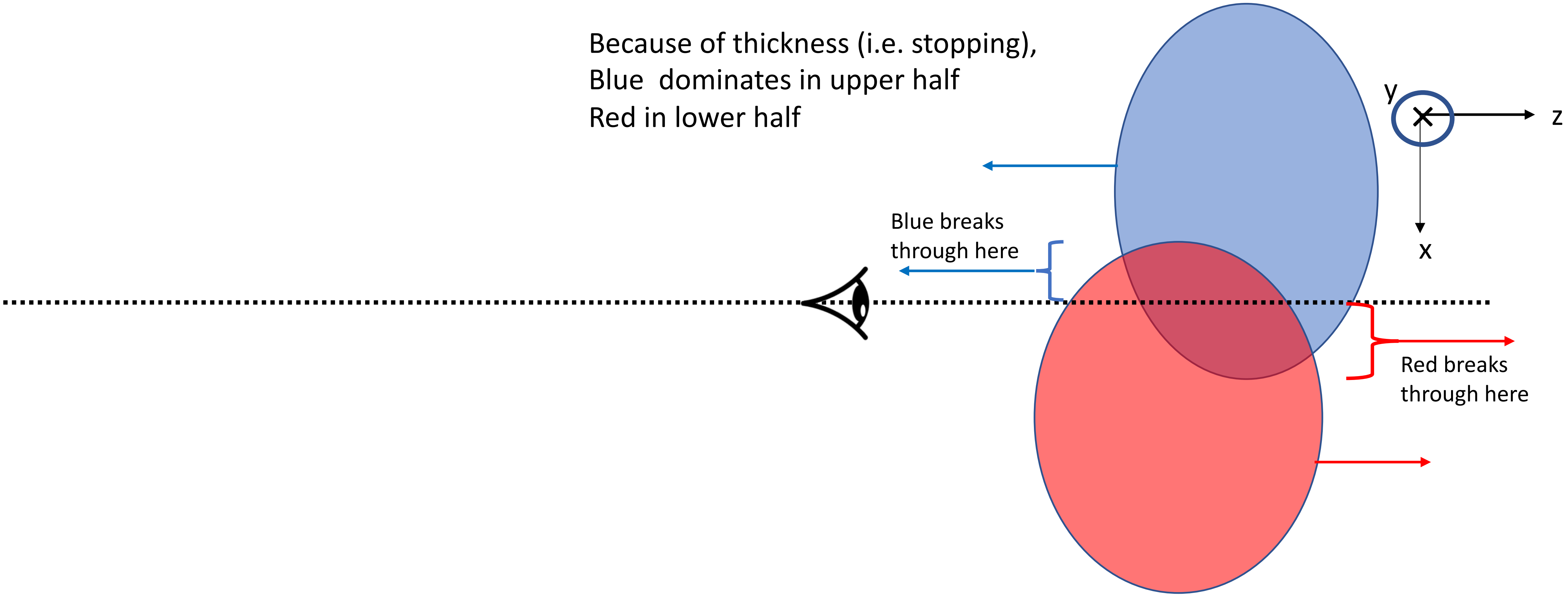
- Known at 3 GeV:
  - Passing time is important (~10 fm/c). Particle formation, interactions, etc. < passing time.
  - Stopping is important.

- For an initial check of our ideas, we found two models to use with options for potentials.
  - SMASH [6] – Cascade, Skyrme potential that is non-relativistic and good at ~ 3 GeV. Vector density functional can be used at higher energies.
  - JAM1 [7] – Cascade, Relativistic mean field with sigma-omega potential. This does well in a recent 3 GeV STAR paper.

[6] J. Weil *et al.*, Phys. Rev. C 94, 054905 (2016)
[7] Y. Nara and H. Stoecker, Phys. Rev. C 100, 054902 (2019)

Where does the triangular geometry come from?

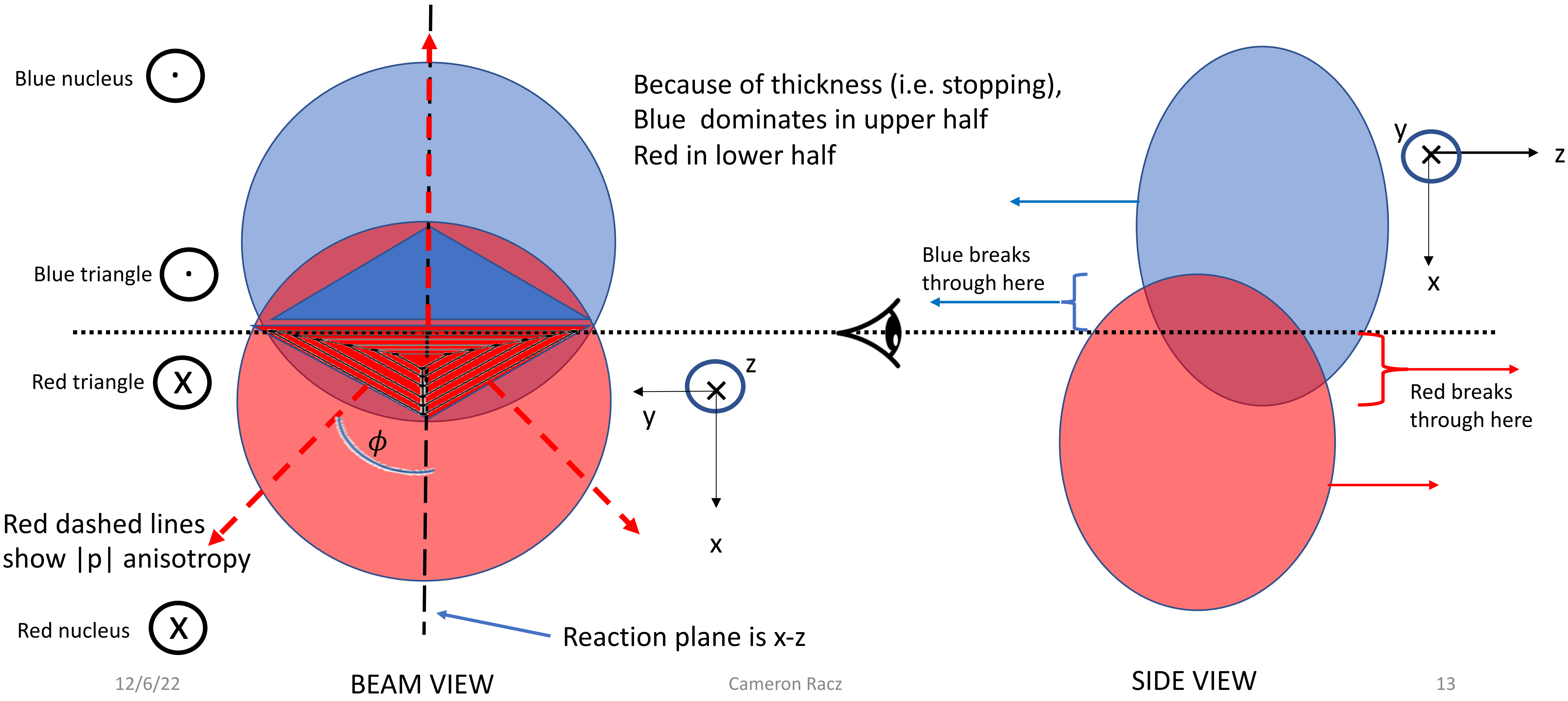
Because of thickness (i.e. stopping),
Blue dominates in upper half
Red in lower half



SIDE VIEW

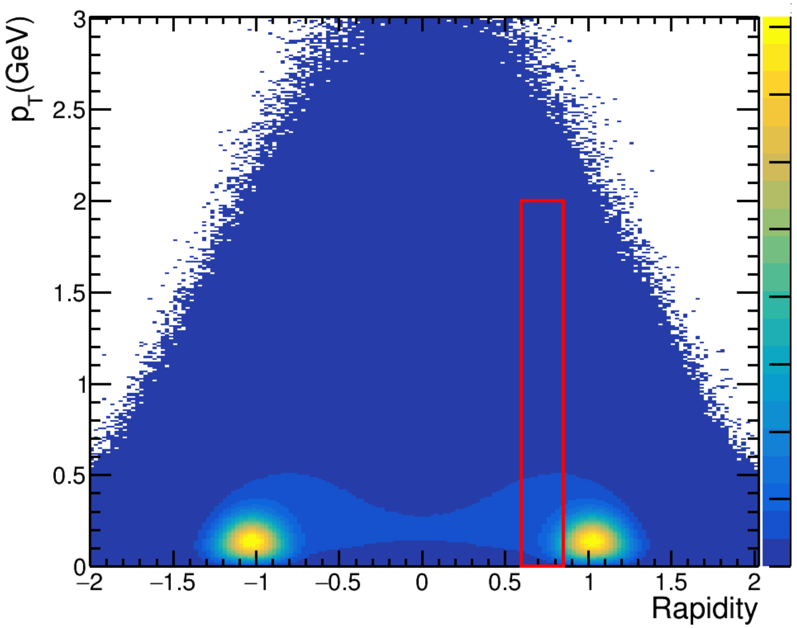
Where does the triangular geometry come from?

Because of thickness (i.e. stopping),
Blue dominates in upper half
Red in lower half



Check Geometry idea

- Plot x vs y from JAM avoiding spectators ($y_{beam,CM} = 1.05$):
  - $t = 50$ fm/c
  - $0.6 < y < 0.85$
  - $0 < p_T < 2$ GeV/c



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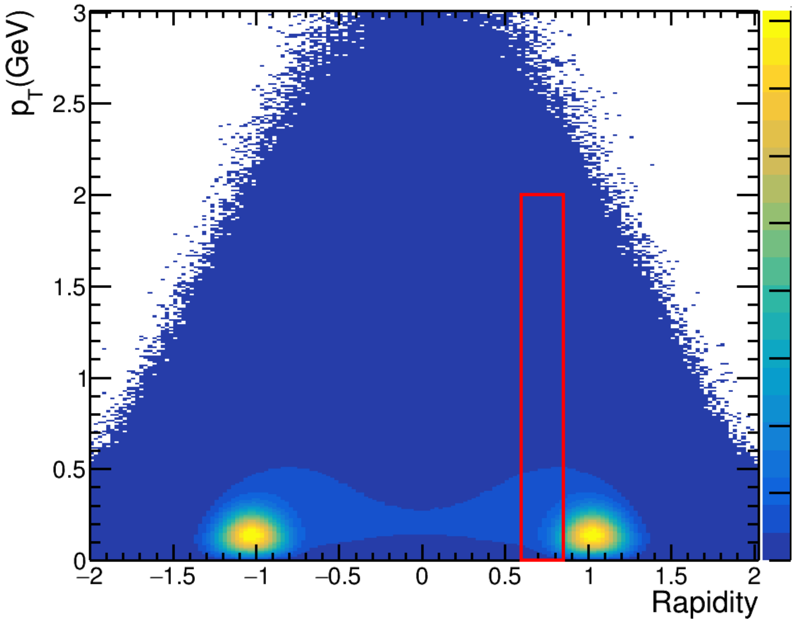
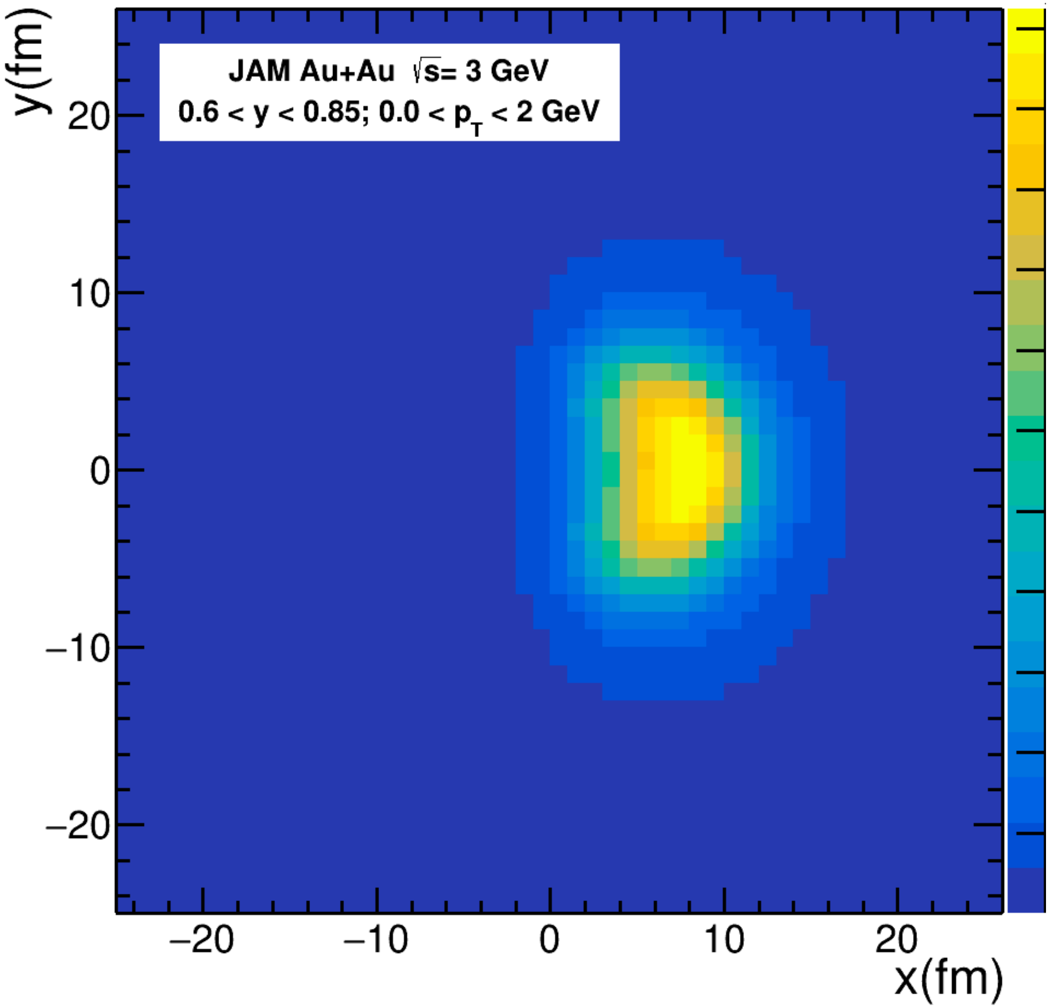
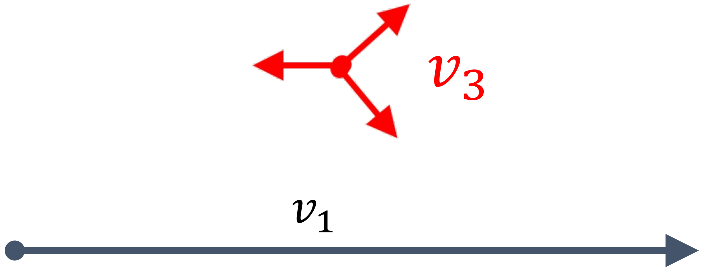


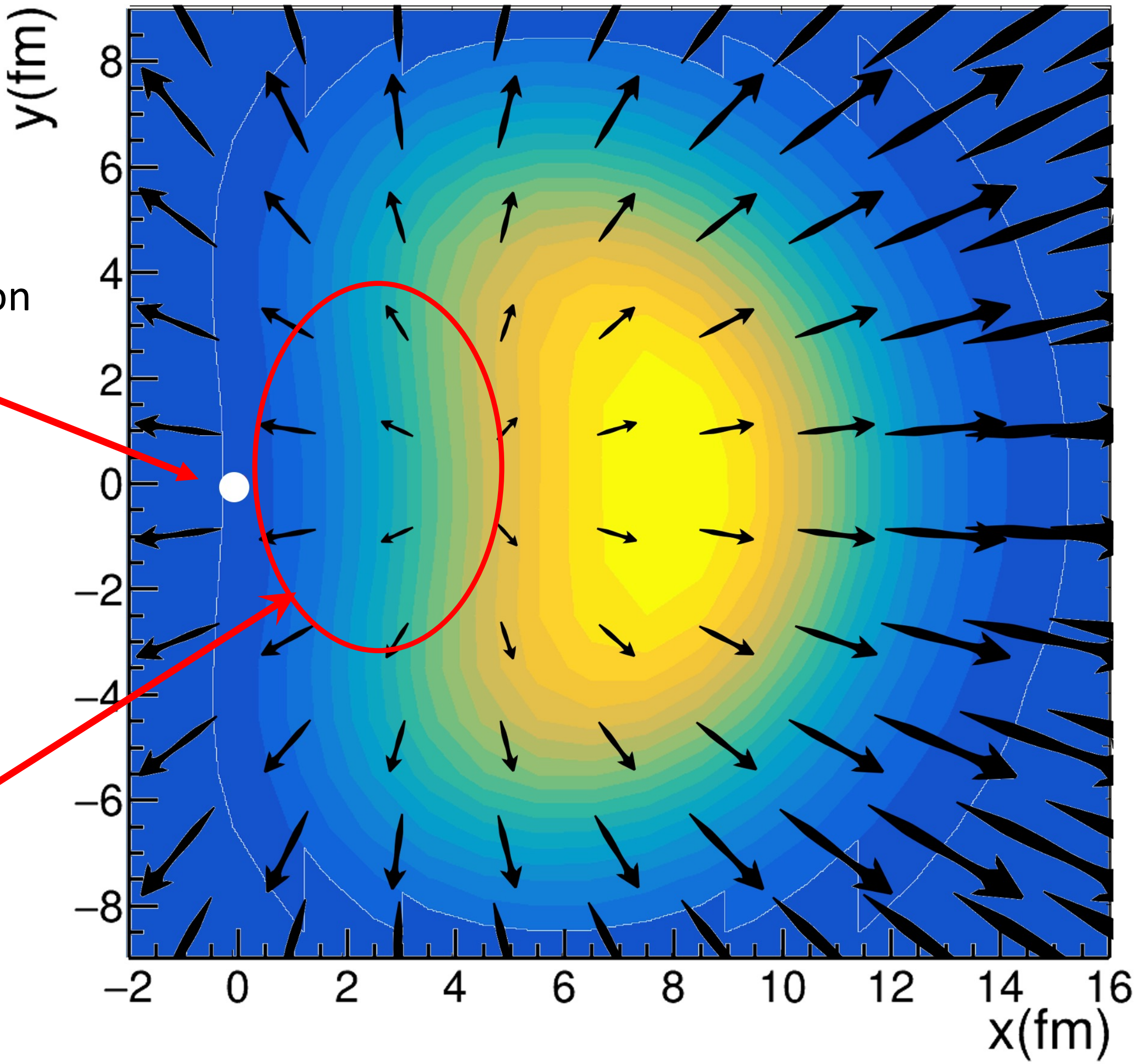


JAM: Triangle shape
SMASH gives similar picture
Simillar also at $t = 20$ fm/c

Looking at Momentum of "cells"

Center of collision
(0,0)





Despite being right of the center,
the flow is left due to v_3 overcoming v_1.

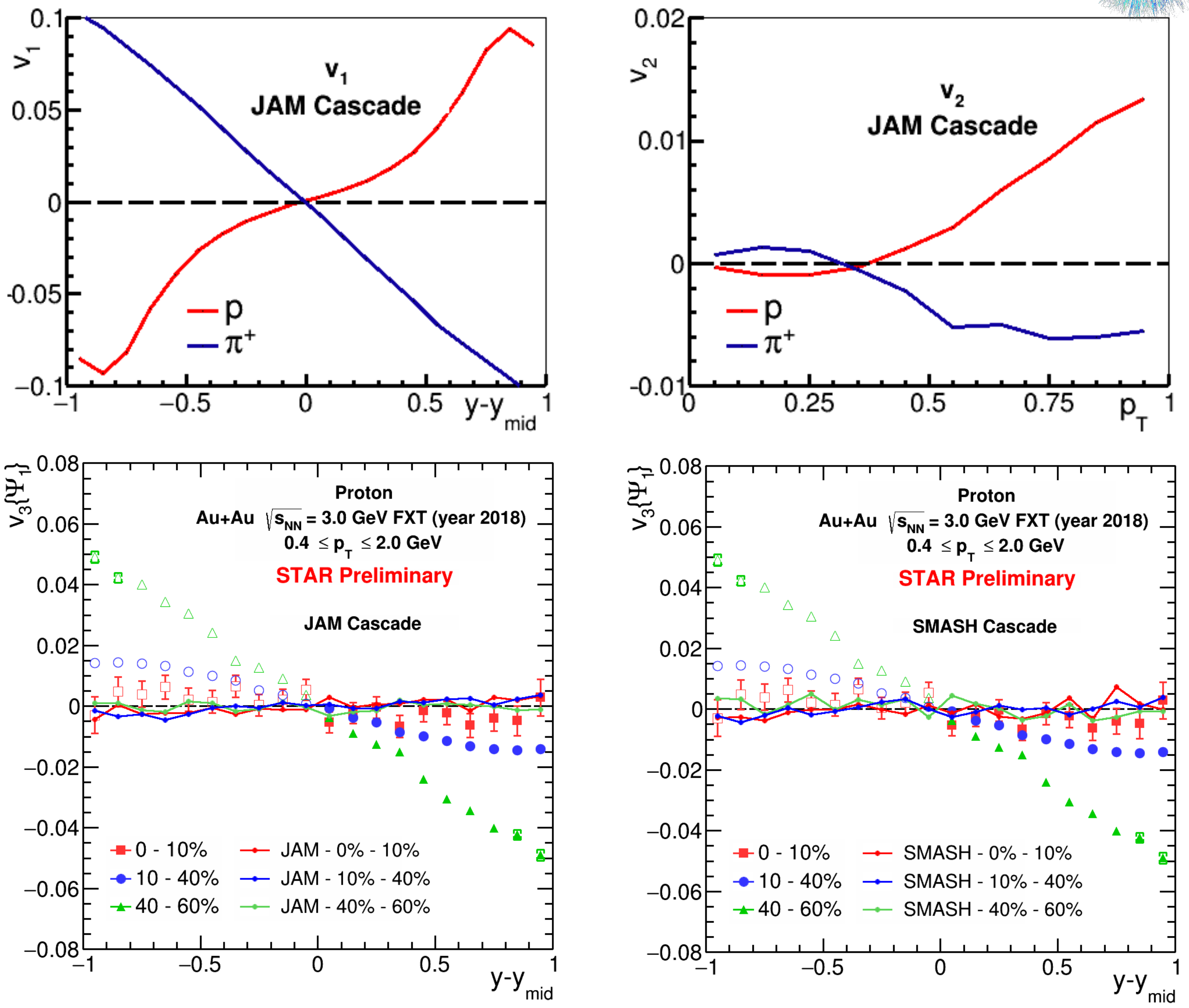
What drives $v_3\{\Psi_1\}$? Checking cascade

In JAM, both v_1 and v_2 develop

($\sqrt{s_{NN}}$ = 3 GeV Minimum bias Au+Au)

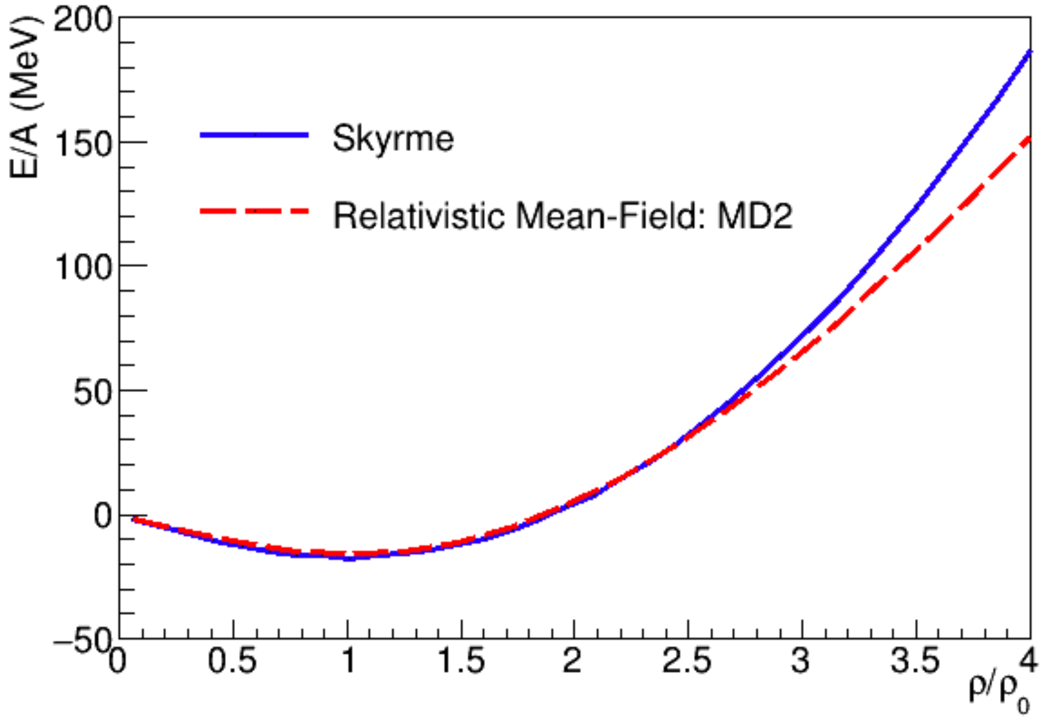
$v_3\{\Psi_1\}$ does NOT develop

(JAM (left) & SMASH (right))



What drives $v_3\{\Psi_1\}$? Checking Potentials

- JAM1
  - Relativistic Mean Field (RQMD.RMF).
  - σ- and ω-meson-baryon interactions.
  - Momentum-dependent potentials.
  - Parameter set MD2; consistent with $\sqrt{s_{NN}} = 3$ GeV proton v_1, v_2 [8,9].
- SMASH
  - Non-relativistic Skyrme+Symmetry Potential with Fermi motion & Pauli blocking.
  - $U = A\left(\frac{\rho}{\rho_0}\right) + B\left(\frac{\rho}{\rho_0}\right)^{\tau} \pm 2S_{pot}\left(\frac{\rho_{I_3}}{\rho_0}\right)$
  - $\rho_0 = 0.1681\ \mathrm{fm}^{-3}$
  - $A = -124\ \mathrm{MeV}, B = 71\ \mathrm{MeV}, \tau = 2$
  - $S_{pot} = 18\ \mathrm{MeV}$
  - Parameters used to fit HADES data [10].

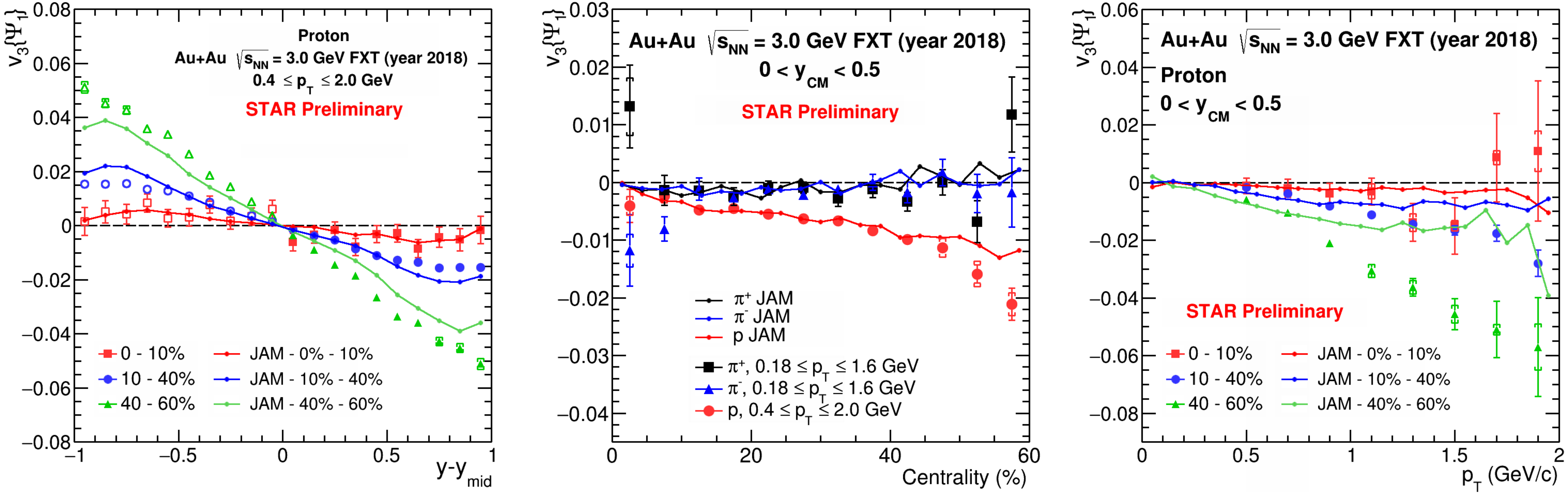


ρ = Baryon Density

ρ_{I_3} = Baryon isospin density of the relative isospin projection I_3/I.

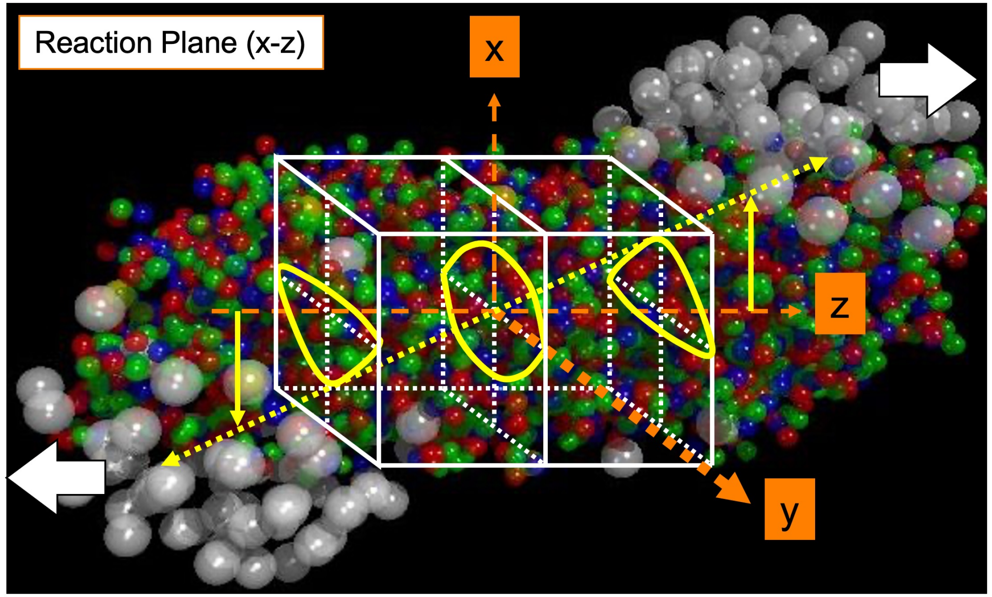
[8] M. A. *et al.* (STAR Collaboration), Phys. Lett. B 827, 137003 (2022).
[9] J. Weil *et al.*, Phys. Rev. C 94, 054905 (2016).
[10] P. Hillmann *et al.*, J. Phys. G 45, 085101 (2018).

What drives $v_3\{\Psi_1\}$? Results with JAM



- $v_3\{\Psi_1\}$ can indeed be reproduced with the inclusion of a potential!
- Note: JAM centralities defined with impact parameter, not multiplicity.
- $v_3\{\Psi_1\}$ could be a useful observable to determine the proper EoS below the phase transition.

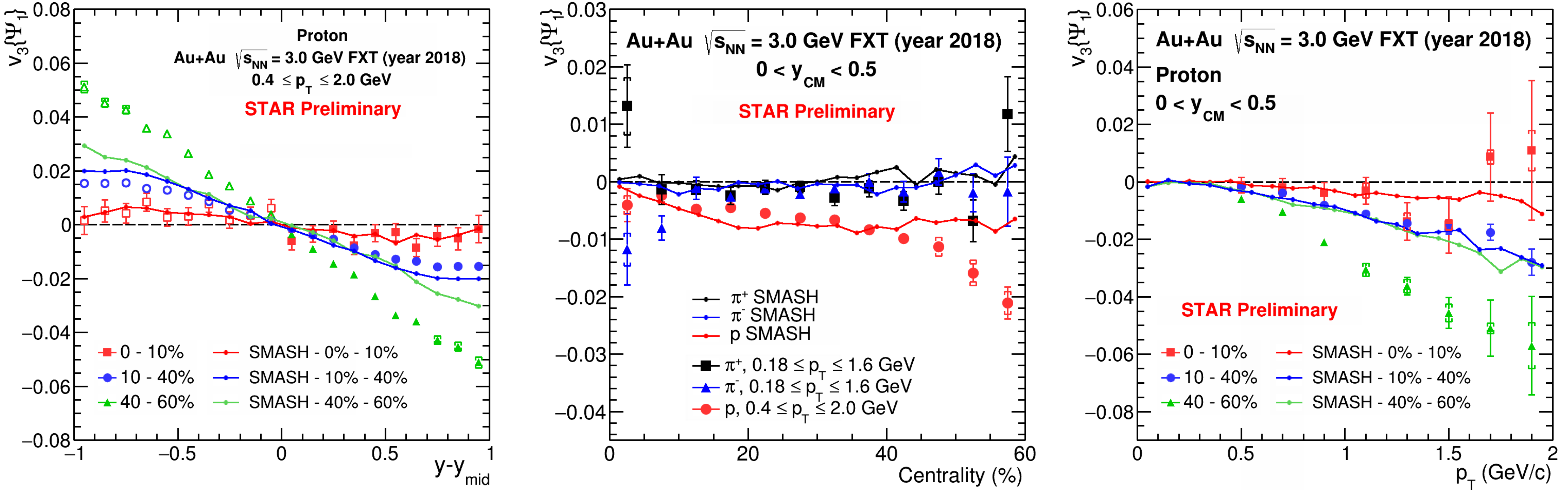
Conclusions and Plans



- Measurements of $v_3\{\Psi_1\}$ at $\sqrt{s_{NN}} = 3.0$ GeV have been presented.
- Protons show a strong $v_3\{\Psi_1\}$ signal.
  - Rapidity odd.
  - Opposite slope to v_1 at 3 GeV.
  - Increases with centrality, rapidity, and p_T.
- The nuclear mass number scaling ($v_3\{\Psi_1\}/A$) for p, d, and t was studied.
  - In our first look, deuterons scale with A while tritons do not.
- Idea for geometric origins of $v_3\{\Psi_1\}$ presented and supported by JAM simulations.
- Requirement of a driving force tested with models using cascade mode vs potentials.
  - Potential in the EoS is required to develop $v_3\{\Psi_1\}$.
  - Baryon density dependent potentials perform fairly well at reproducing the data.
- Future Plans:
  - Incorporate larger STAR 3 GeV dataset when it becomes available (may reveal more about π and K).
  - Investigate A scaling of $v_3\{\Psi_1\}$ in more depth.

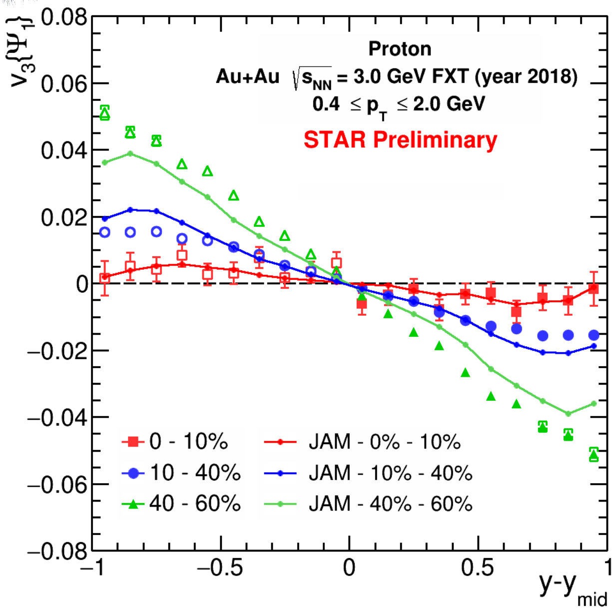
Backup

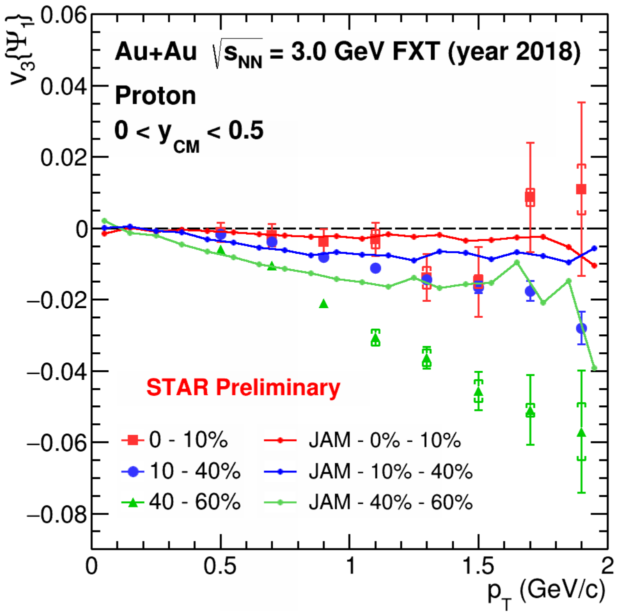
What drives $v_3\{\Psi_1\}$? Results with SMASH

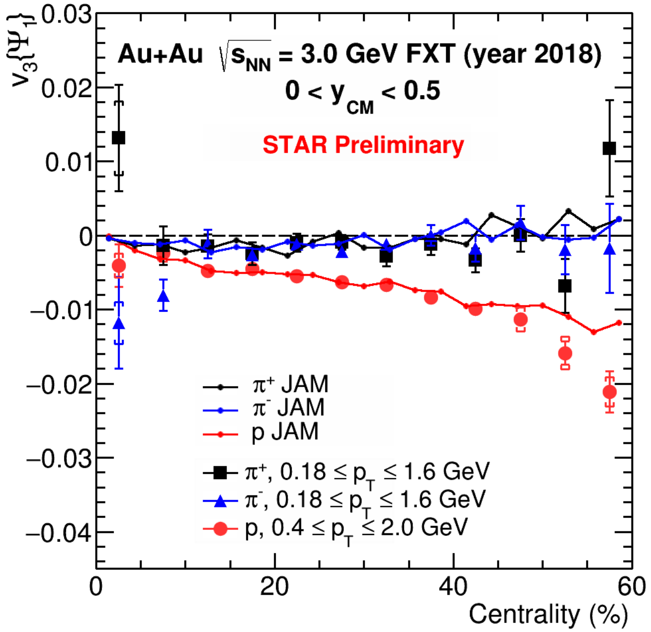


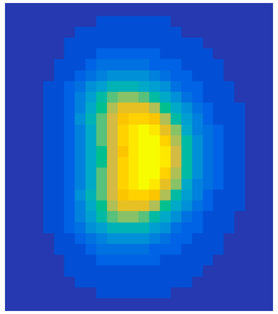
- SMASH also works fairly well here.
- It has difficulty with peripheral collisions like JAM.
- SMASH does well in mid-central p_T dependence.

Quantify the triangle geometry – Eccentricity

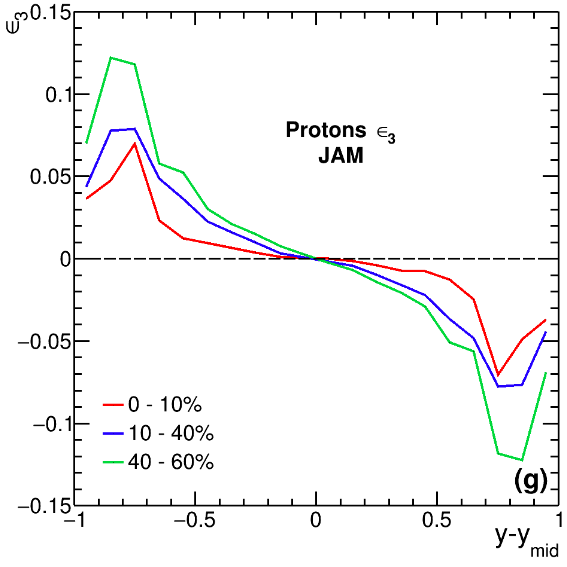


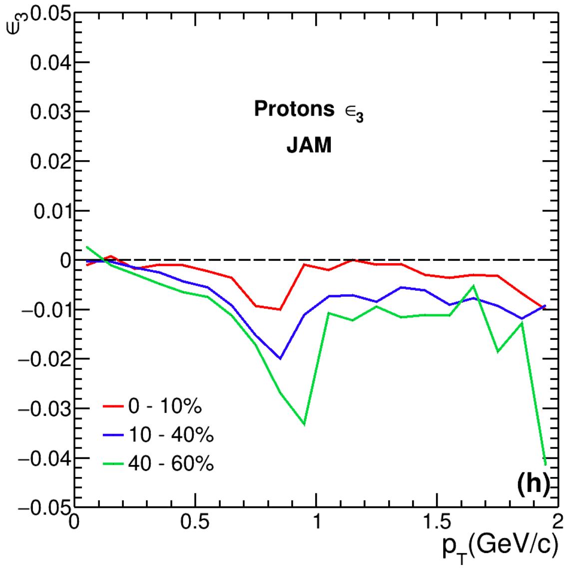


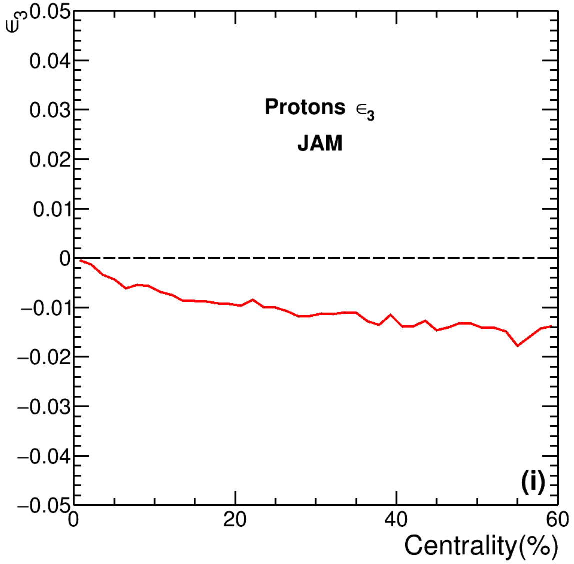




Eccentricity + potential drives $v_3\{\Psi_1\}$.







$$\epsilon_3 = \frac{\langle r^2 \cos(3\phi) \rangle}{\langle r^2 \rangle}$$

(Sin term ignored to get correct sign)