# Reaction plane correlated triangular flow in BES-II and its connection to the EoS

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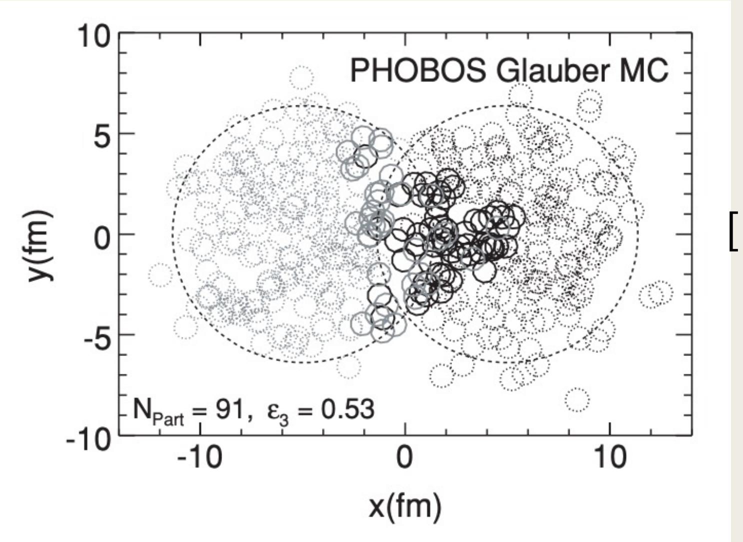
# Contents

- Motivation: Why triangular flow?
- Analysis Methods
- Results of $v_3$
- Model Comparisons and the EOS

# Triangular Flow ($v_3$) – Short Overview

- Often mentioned in heavy-ion collisions above the QCD phase transition when a QGP is present.
- Develops solely due to event-by-event fluctuations in the participant region geometry [1].
  - *Sensitive to the viscosity of the medium [2].*
  - *No correlation to the reaction plane [1].*

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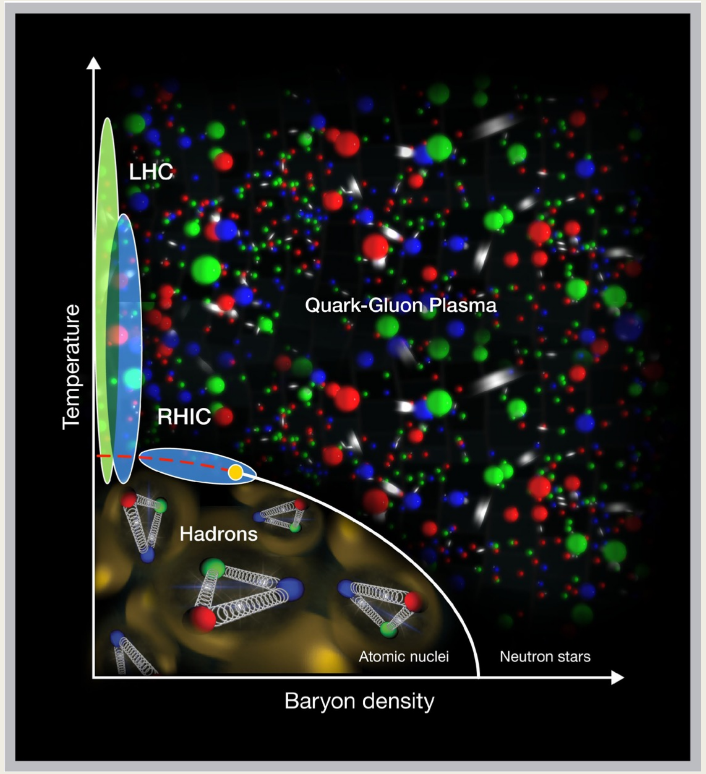
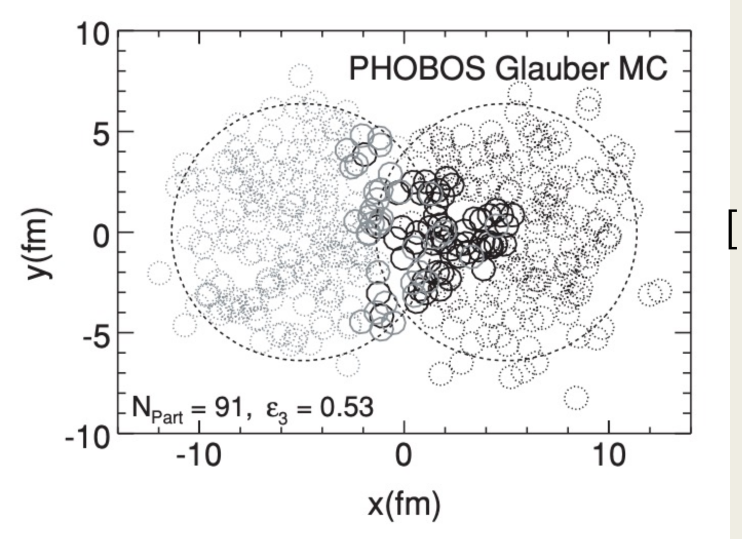



bnl.gov


[1] B. Alver and G. Roland, Phys. Rev. C, 81:054905 (2010)
[2] B. Alver *et al.*, Phys. Rev. C, 82:034913 (2010)

# Triangular Flow ($v_3$) – Developments

- A hybrid transport + hydrodynamics model suggested that $v_3 \to 0$ at low collision energies (~ 5 GeV) while $v_2$ does not due to transport dynamics [3].
  - *Can't get rid of the elliptic shape of the overlap region.*
  - *The more monotonic $v_3$ gives a clearer signal of QGP formation.*
  - *Maybe we should check this out with STAR!*

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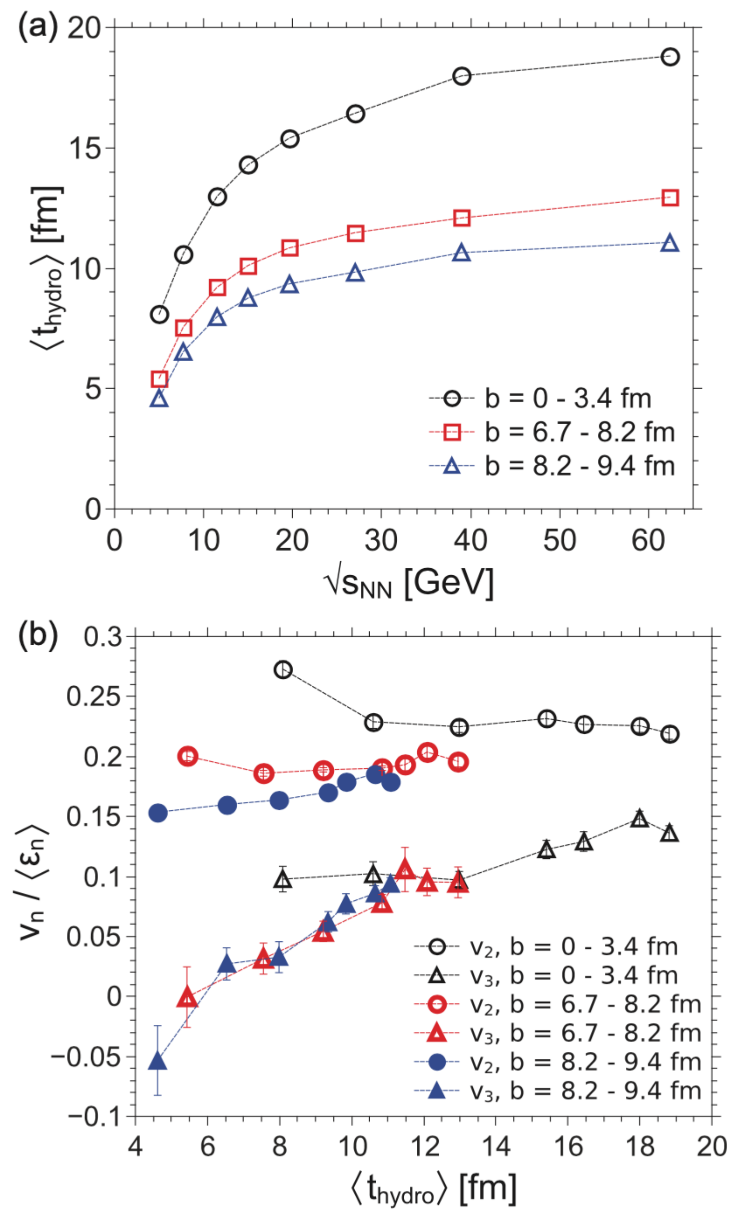
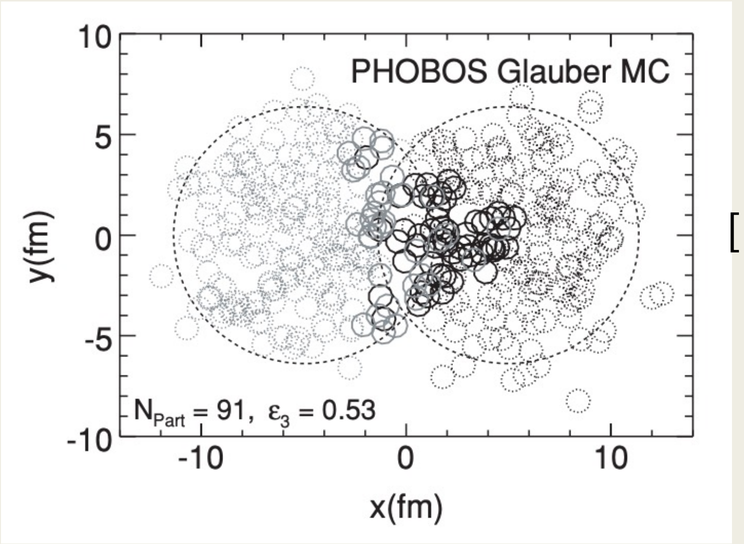



[3] J. Auvinen and H. Petersen, Phys. Rev. C, 88:064908 (2013)

# Triangular Flow ($v_3$) – Developments

- Recent studies by HADES at an energy well below the phase transition (2.4 GeV) have shown a clear $v_3$ signal calculated using the first-order event plane ($\Psi_1$) [4].

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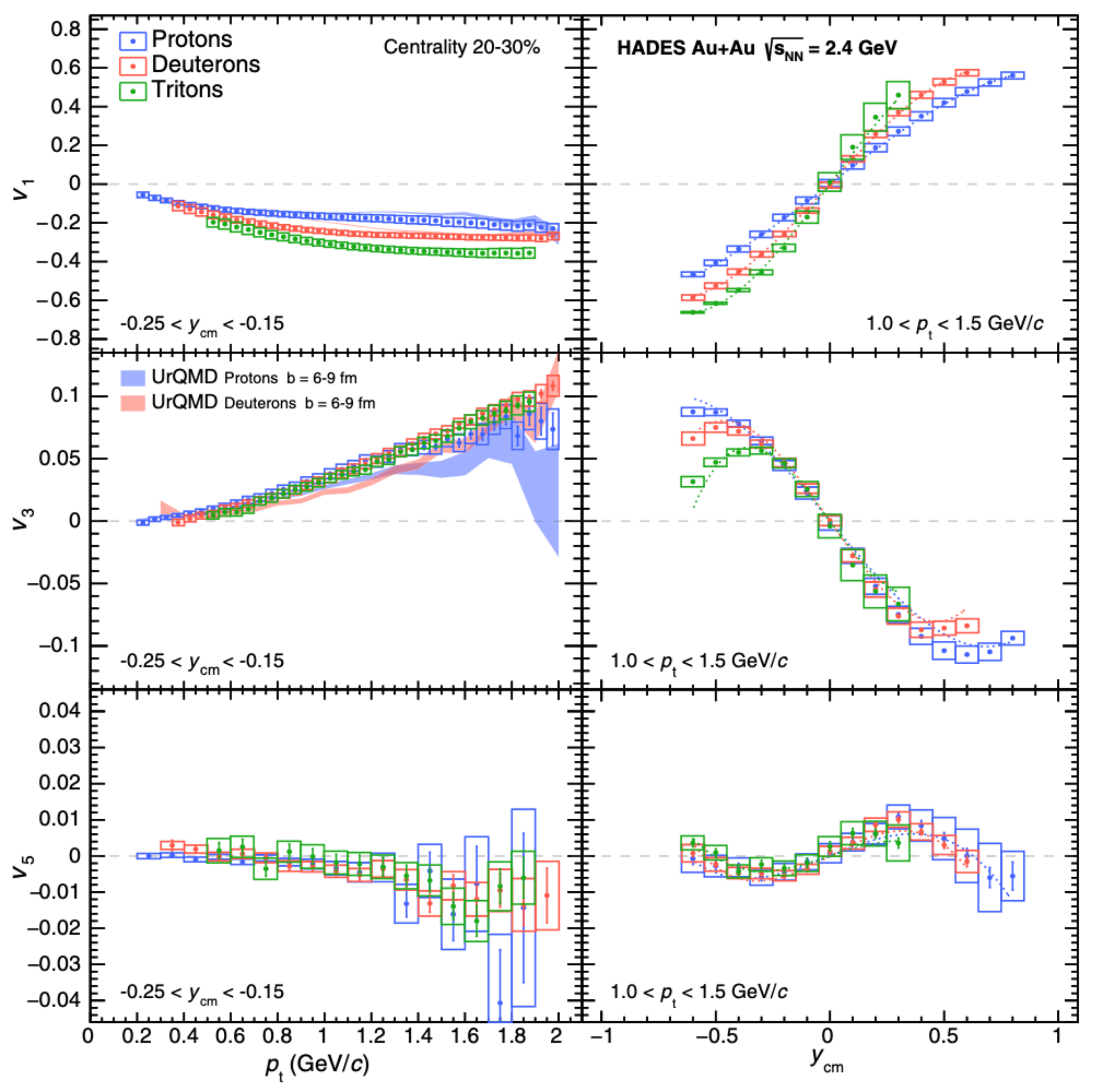


[4] HADES, Phys. Rev. Lett., 125:262301 (2020)

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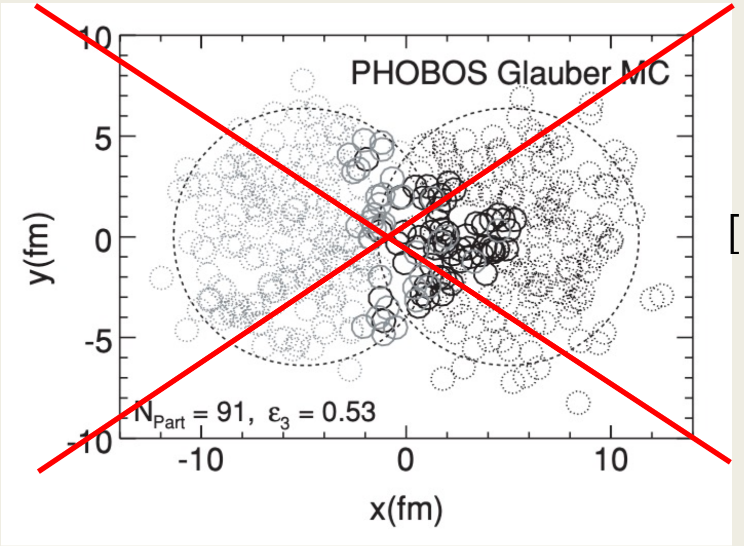
  - *Can't be created by fluctuations!*

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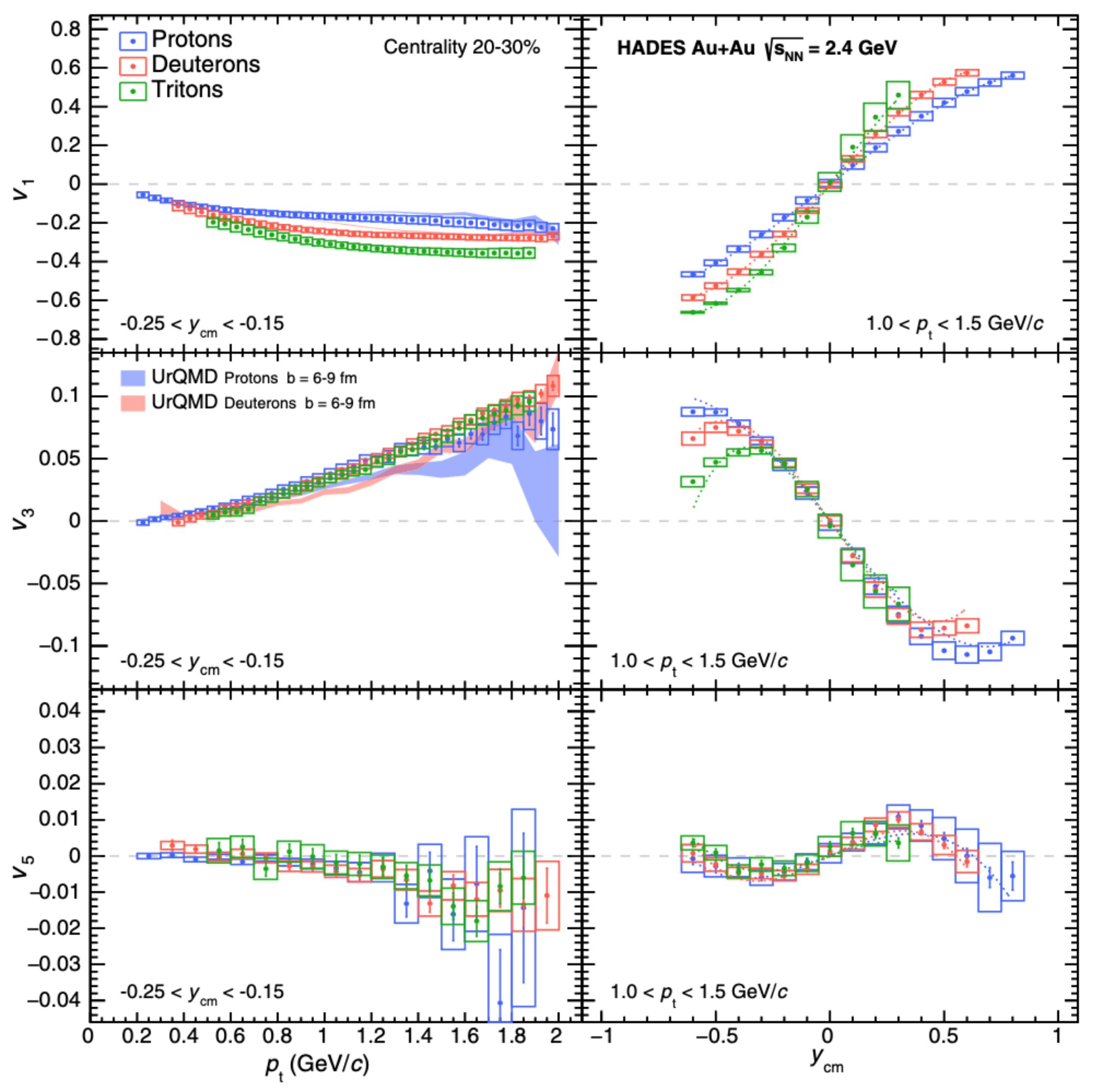


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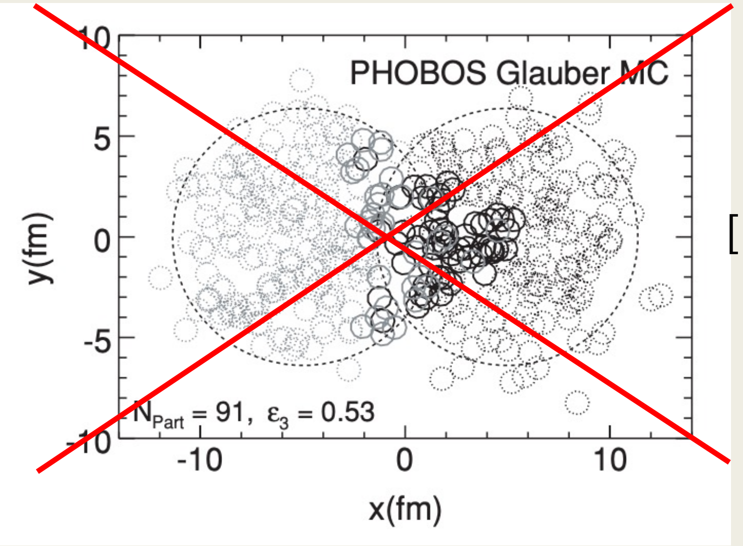
  - *Can't be created by fluctuations!*
- **What is the source of this $v_3$?**
- **What is the driving force?**

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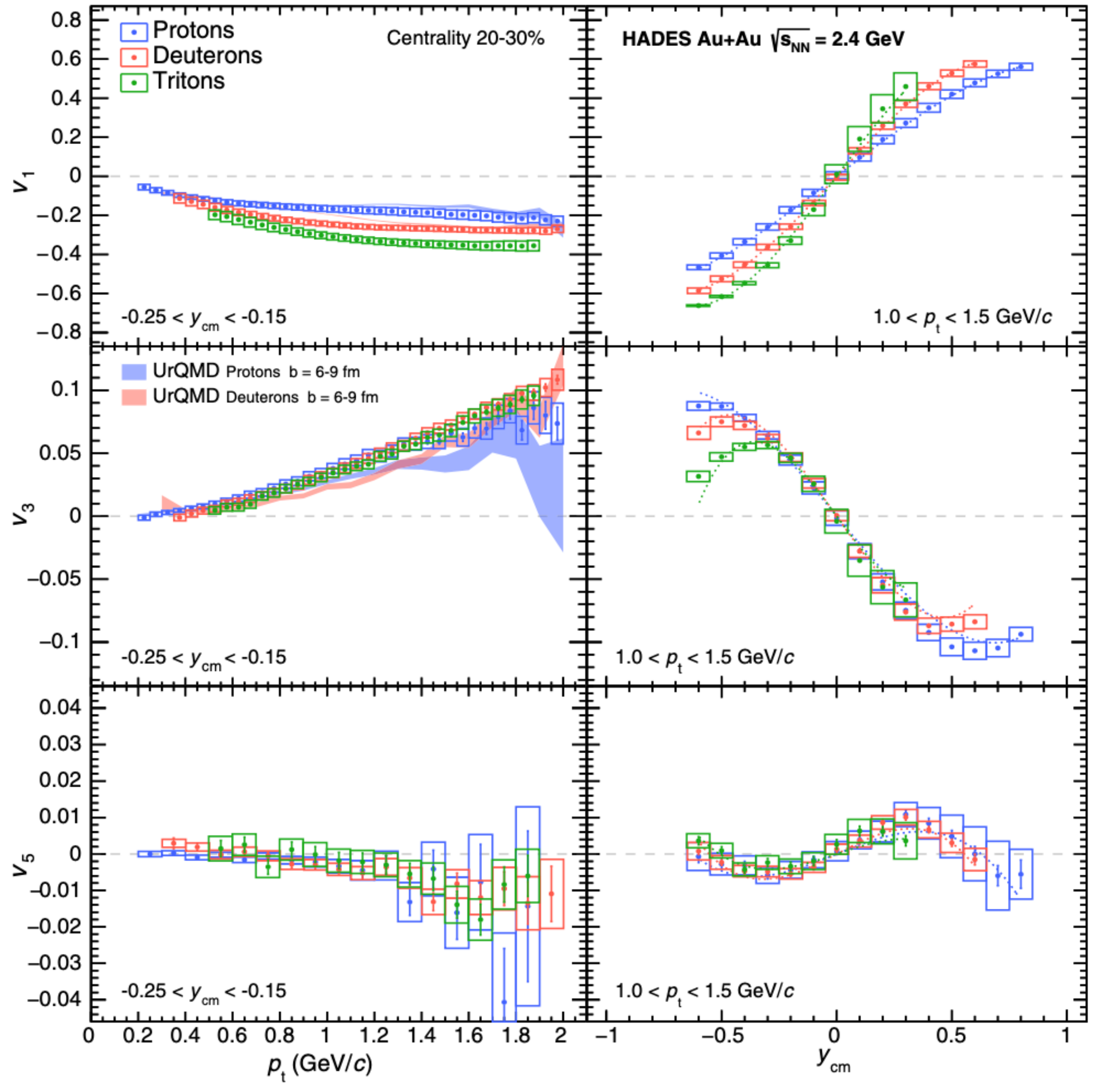


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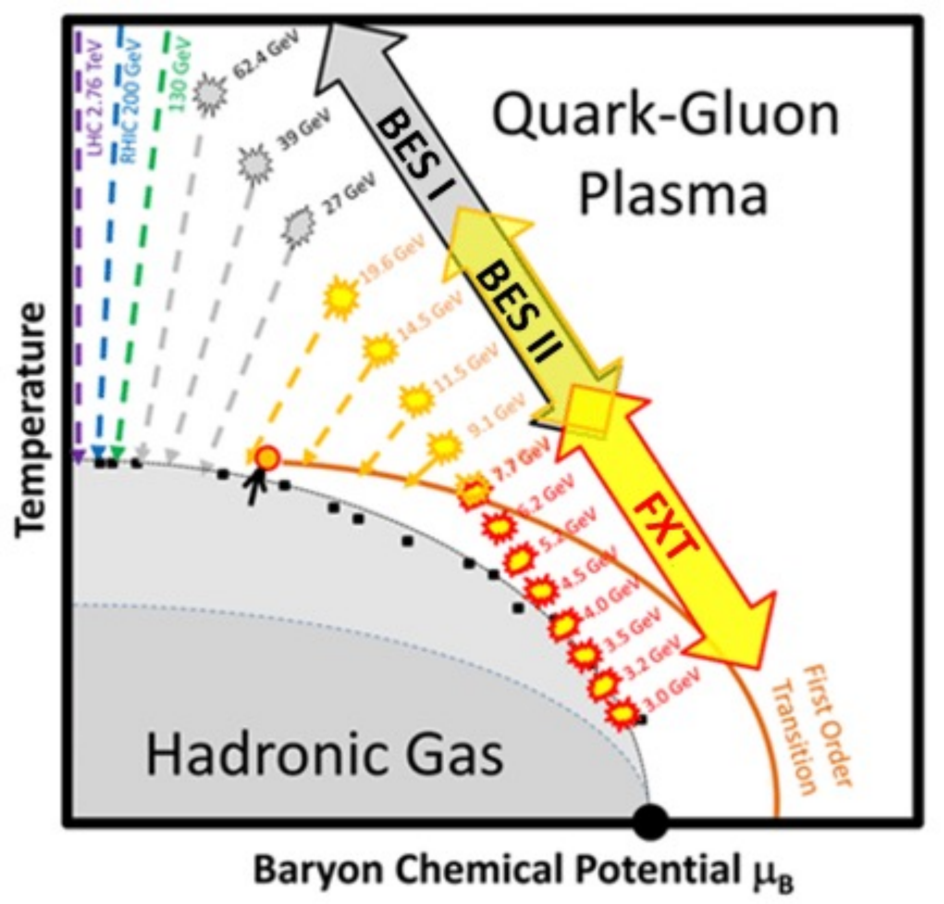
- STAR fixed target (FXT) mode in BES-II provides an opportunity to scan all the way down to $\sqrt{s_{NN}} = 3.0$ GeV.

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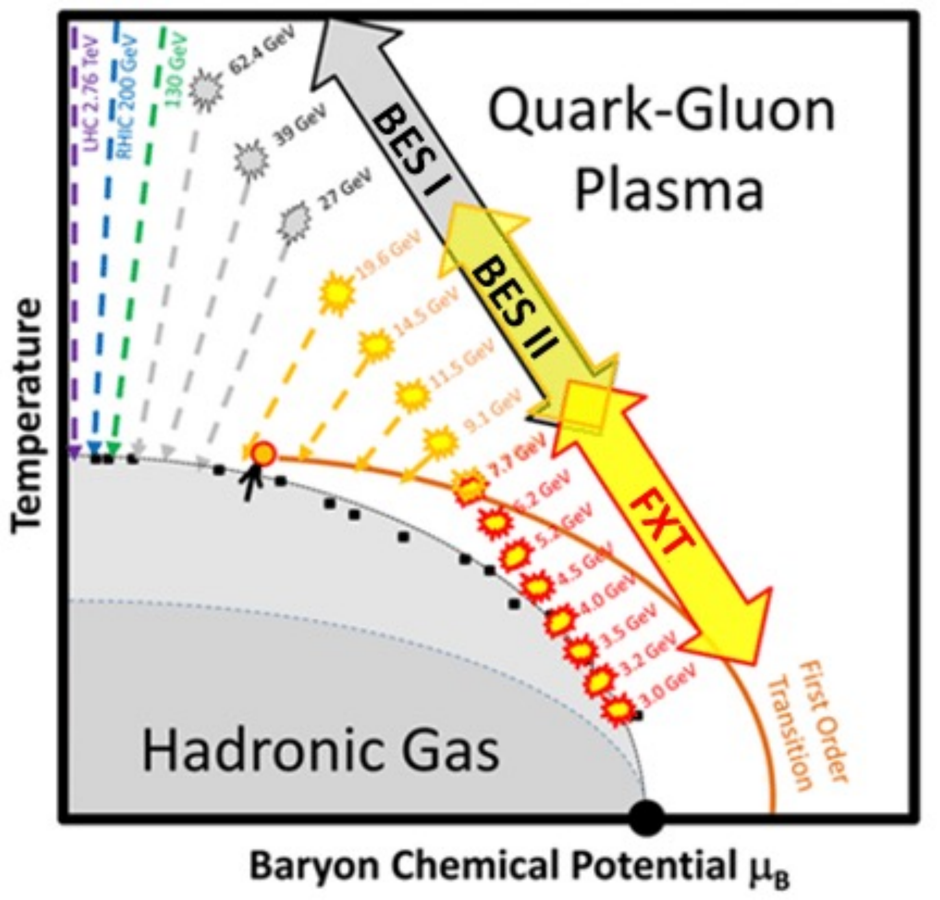
  - *Can't be created by fluctuations!*
- **What is the source of this $v_3$?**
- **What is the driving force?**
- STAR fixed target (FXT) mode in BES-II provides an opportunity to scan all the way down to $\sqrt{s_{NN}} =$ 3.0 GeV.
- Our analysis pivoted from fluctuation-driven $v_3$ to looking for this new $v_3$ and answering the questions above utilizing the lowest energy of 3.0 GeV.
- ($v_3$ from $\Psi_3$ should also be explored but is much more difficult.)





[4] HADES, Phys. Rev. Lett., 125:262301 (2020)
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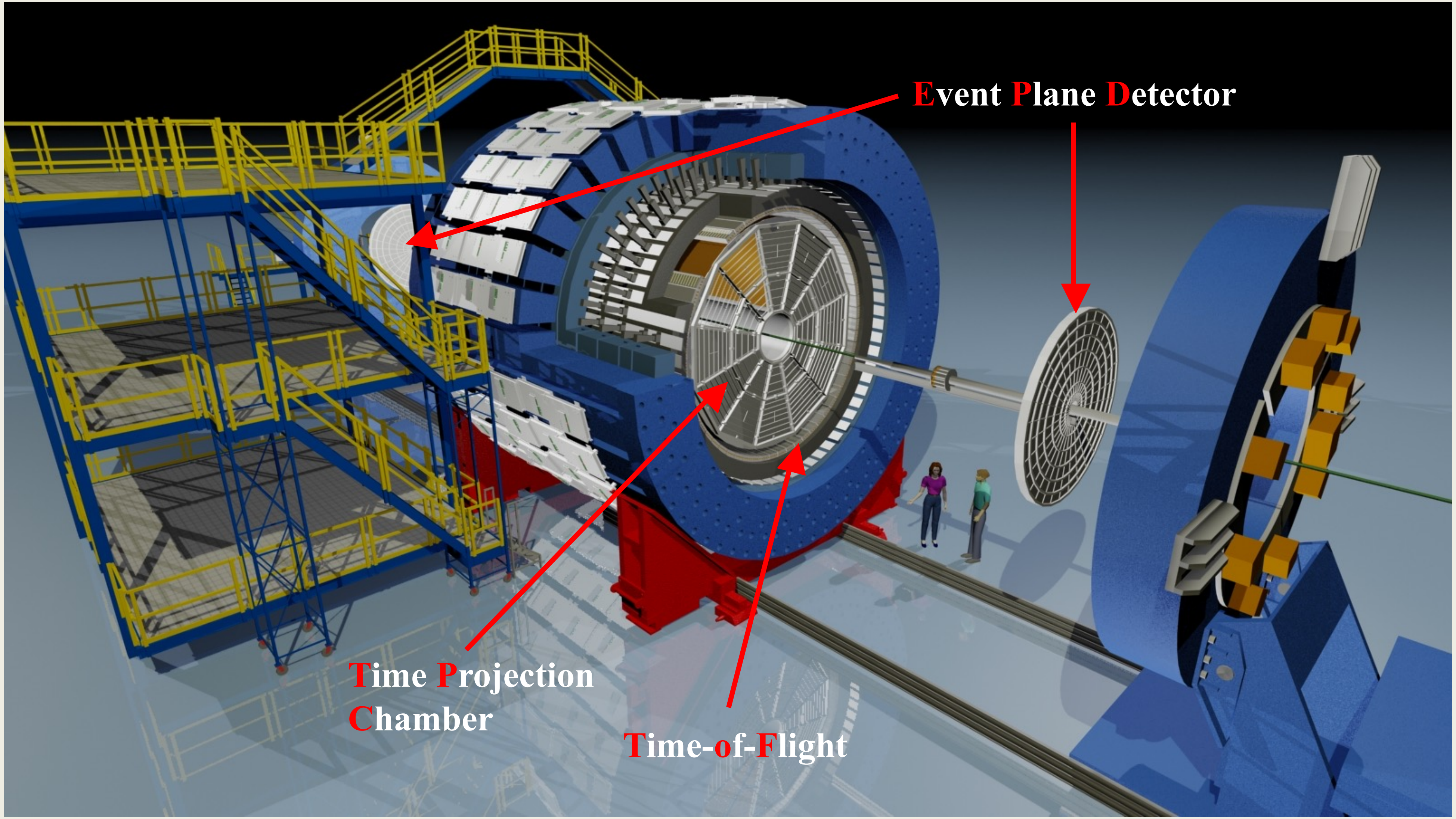
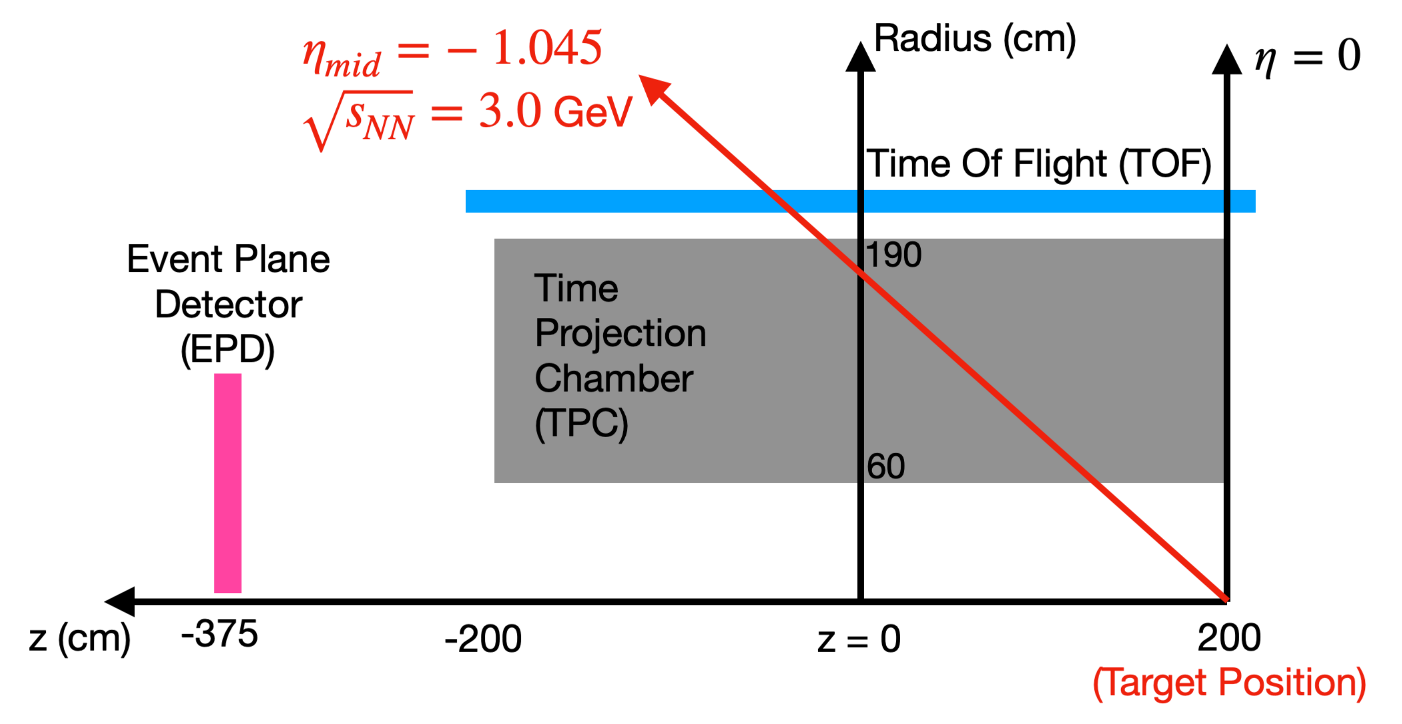
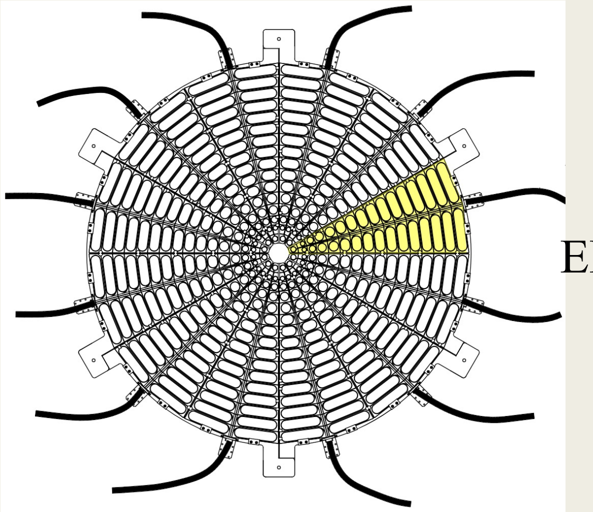
# Analysis Methods



# STAR Fixed Target Experimental Setup

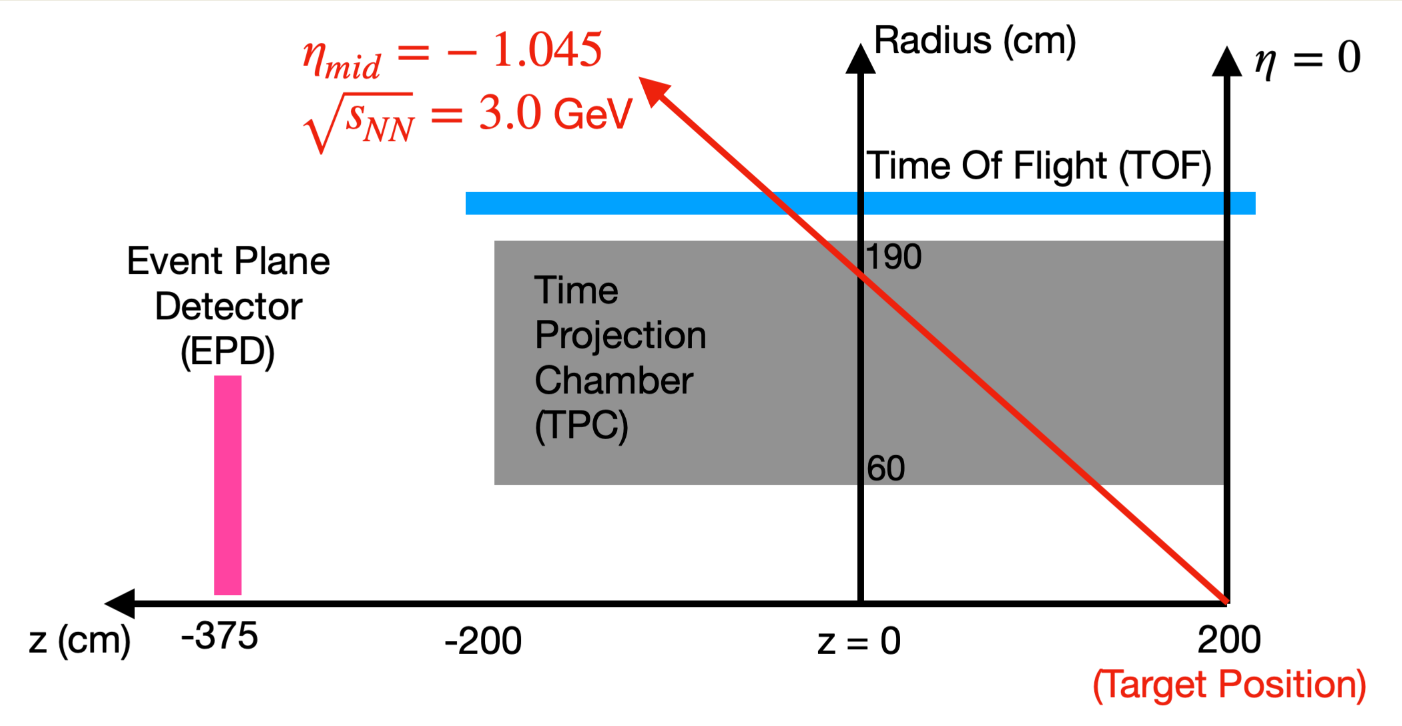
- FXT mode utilizes a 1 mm thick gold foil fixed at one end of the TPC.
- One gold beam is circulated to strike the foil in the direction of the TPC.
  - $E_{beam} = 3.85\ GeV$
  - $y_{mid} = -1.045$
- This beam direction is normally defined as the negative rapidity direction; in this analysis $y < 0$ is forward.



EPD

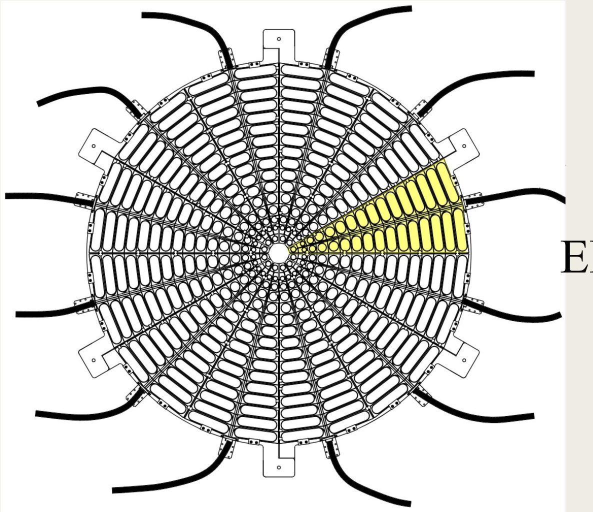
# STAR Fixed Target Experimental Setup




- The TPC and TOF are used for particle identification from dE/dx and $\beta$ measurements, respectively.

- The EPD is a circular detector at far forward $y$ made of many scintillating tiles to measure hits of charged particles.

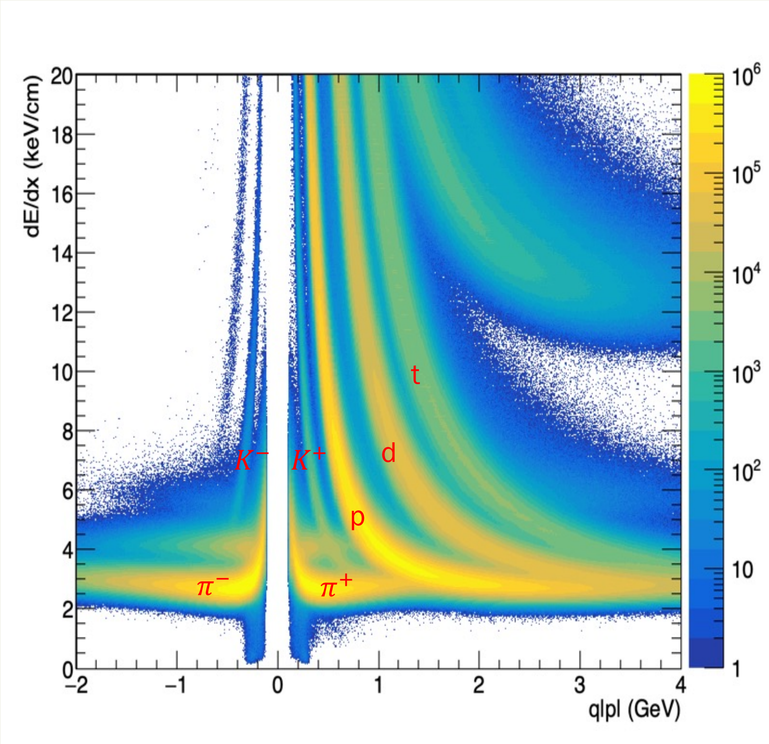
- We can extract the nMIP value and azimuthal angle $\phi$ from each hit to reconstruct event plane angles $\Psi$.

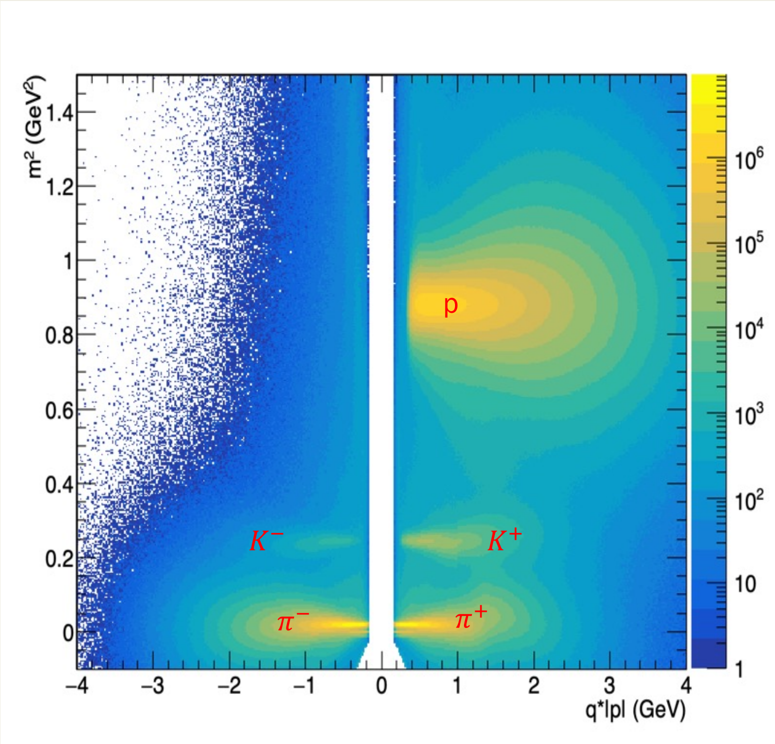


EPD

# Particle Identification

- $\pi^{\pm}$ and $K^{\pm}$ are identified with dE/dx from the TPC and $m^2$ info from the TOF.
- Protons are identified with dE/dx.

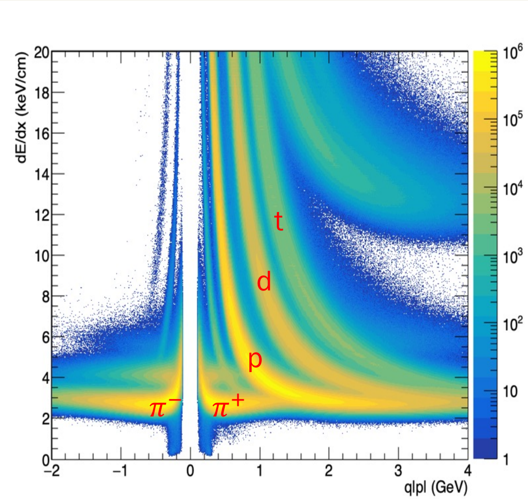


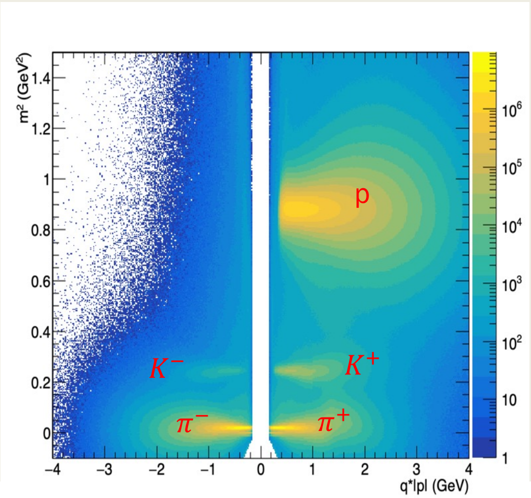



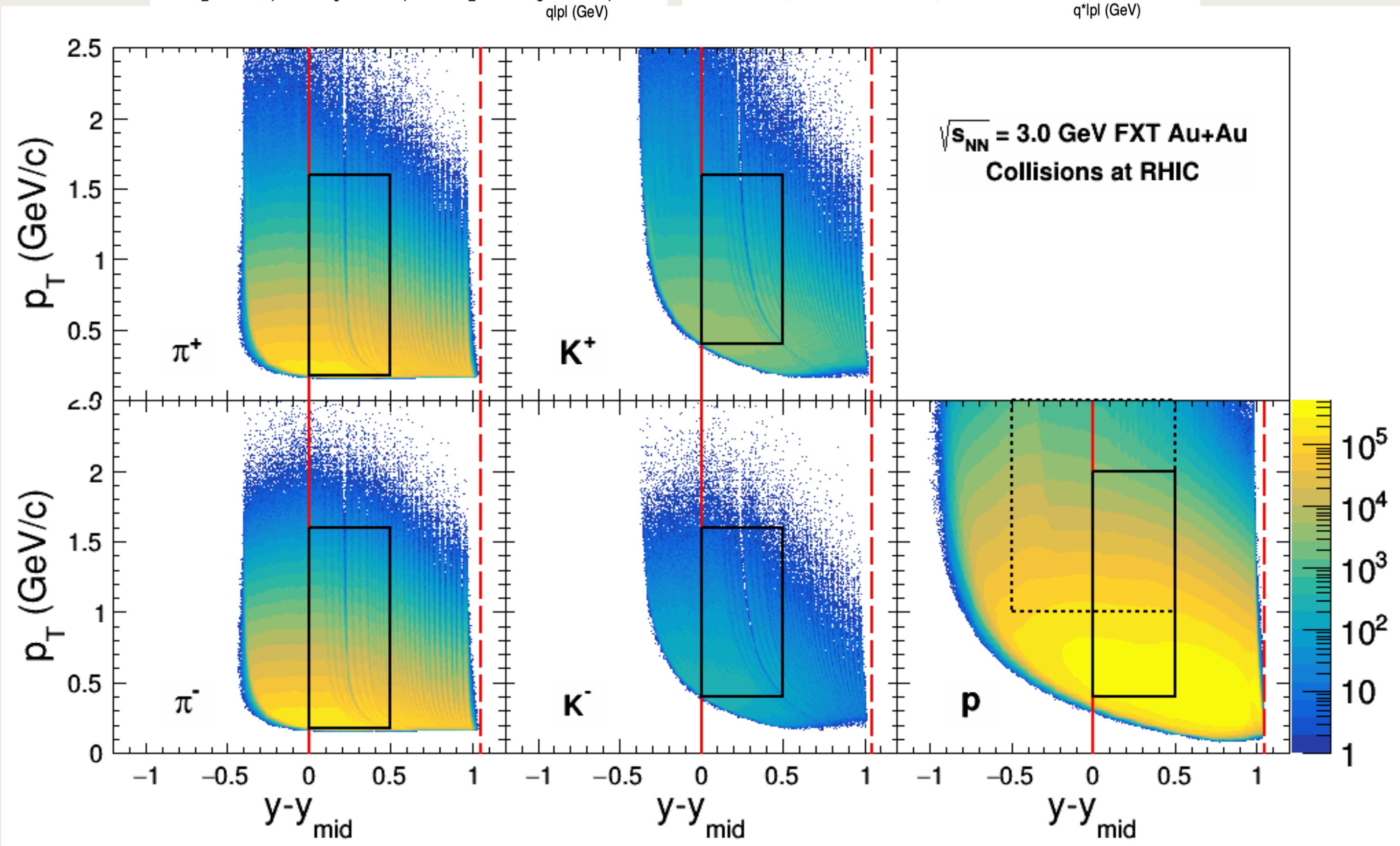

$$m^2 = |p|^2\left(\frac{1}{\beta^2} - 1\right)$$

# Particle Identification

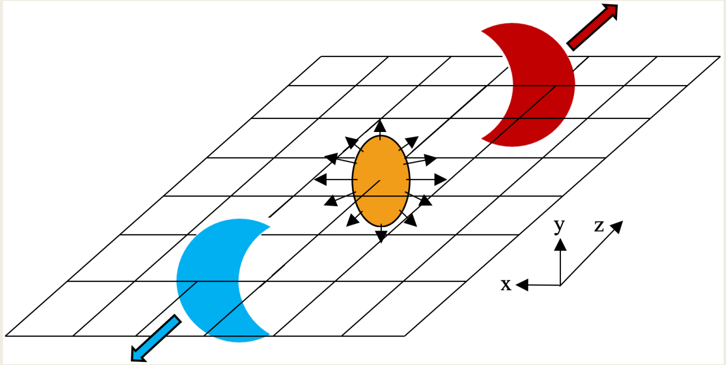
- $\pi^{\pm}$ and $K^{\pm}$ are identified with dE/dx from the TPC and $m^2$ info from the TOF.
- Protons are identified with dE/dx.
- Black solid boxes = acceptance for $v_3$ vs centrality.
- Black dashed box = acceptance for $v_3$ vs rapidity.
- Red solid (dashed) lines = mid (target) rapidity.



# Event Plane Reconstruction




- Flow vectors $\overrightarrow{Q_m}$ are used to reconstruct event planes $\Psi_m$ [3].
  - $m = 1$ *(event plane harmonic)*
  - $n = 3$ *(flow harmonic)*

- $\sum_i$ are over all tracks/hits in a particular region to get $\Psi_m$ from that region.

- TPC tracks: $w_i = p_{T,i}$

- EPD hits: $w_i = (\text{Truncated nMIP})_i$
  - $\text{nMIP} < 0.3 \rightarrow \text{nMIP} = 0$
  - $\text{nMIP} > 2.0 \rightarrow \text{nMIP} = 2.0$

$$\overrightarrow{Q_m} = \left( \sum_i w_i \cos(m\phi_i), \sum_i w_i \sin(m\phi_i) \right)$$

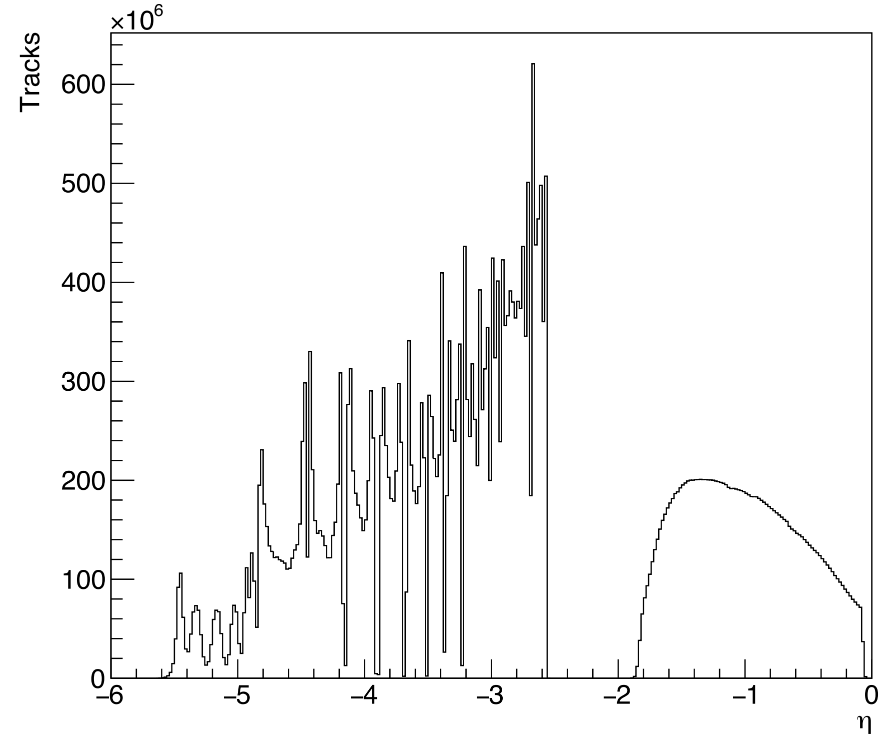
$$\Psi_m = \frac{1}{m} \arctan\left( \frac{Q_{m,y}}{Q_{m,x}} \right)$$


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

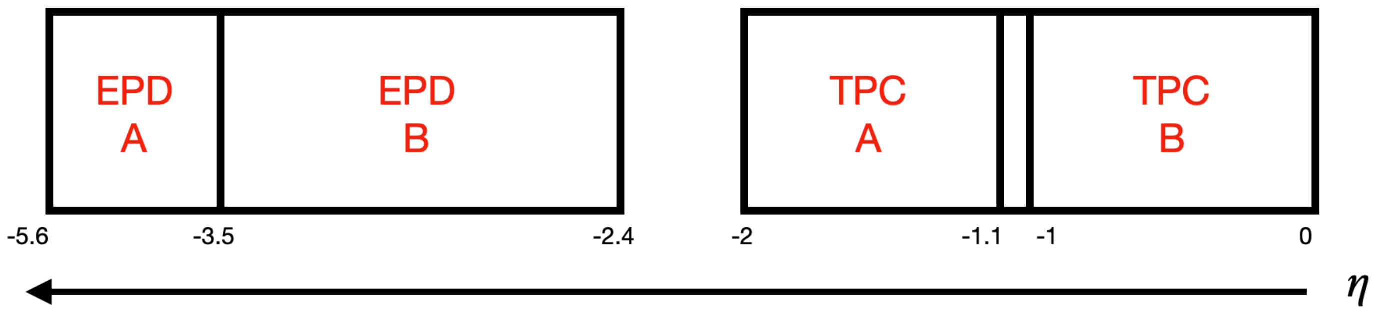
# Event Plane Reconstruction

- To calculate flow, we need the event plane resolution correction terms $R_{nm}$.

- In FXT, there are no two regions in $\eta$ with equal multiplicity.
  - *Can't use the 2-subevent method.*
  - *Must use 3-subevent method; one main region, 2 reference regions.*



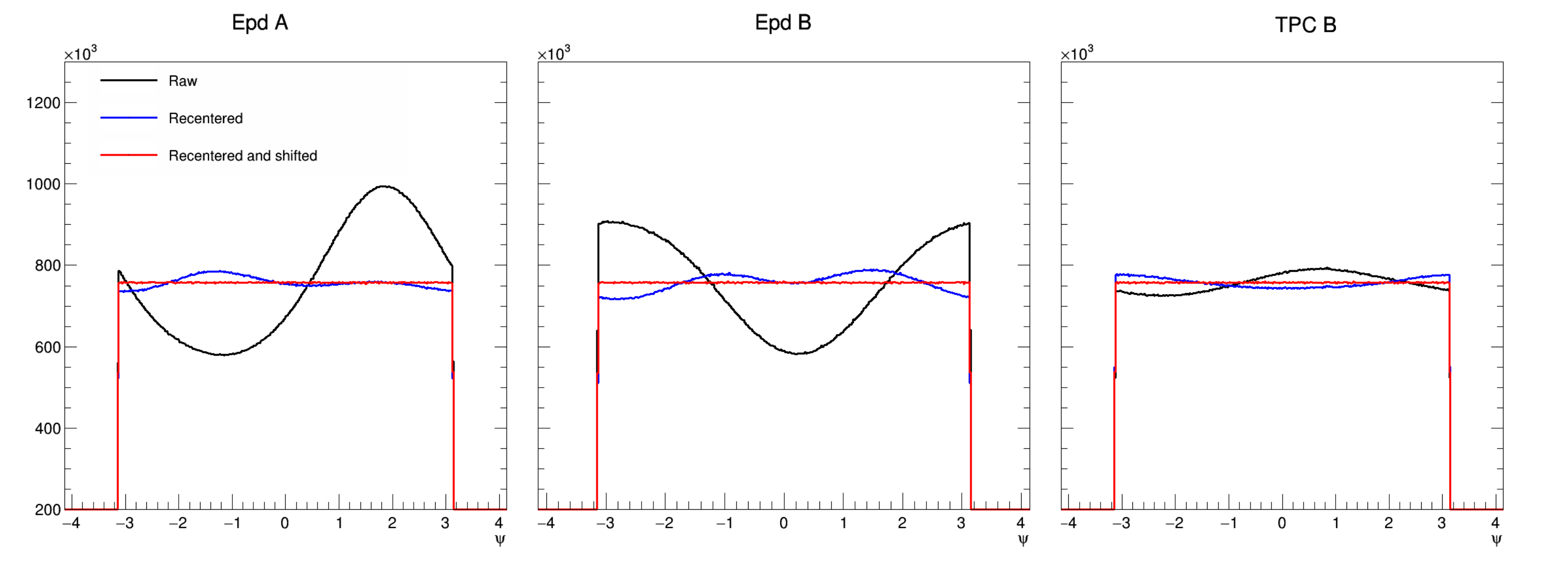

- EPD A: inner 8 rings (> 5 hits).
- EPD B: outer 8 rings (> 9 hits).
- TPC B: $-1 < \eta < 0$ (> 5 tracks).



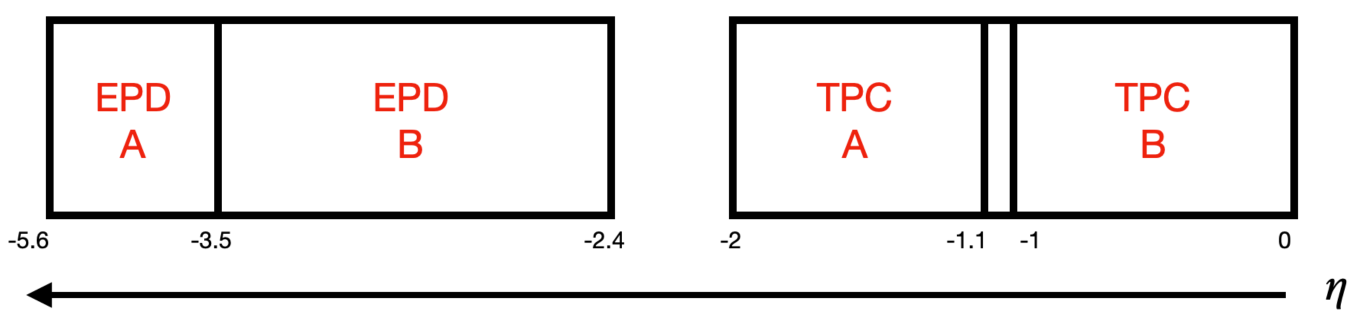
# Event Plane Reconstruction

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

- Non-uniform detector effects are corrected with two processes [3]:
- Recentering
  - $\overrightarrow{Q_{m,RC}} = \overrightarrow{Q_m} - \langle\overrightarrow{Q_m}\rangle$
  - *Produces* $\Psi_{m,RC}$
- Fourier shifting
  - $\Delta\Psi_m = \sum_{j=1}^{\infty} \frac{2}{jm}[\langle -\sin(jm\Psi_m)\rangle \cos(jm\Psi_m) + \langle\cos(jm\Psi_m)\rangle \sin(jm\Psi_m)]$
  - $\Psi_{shifted} = \Psi_m + \Delta\Psi_m$



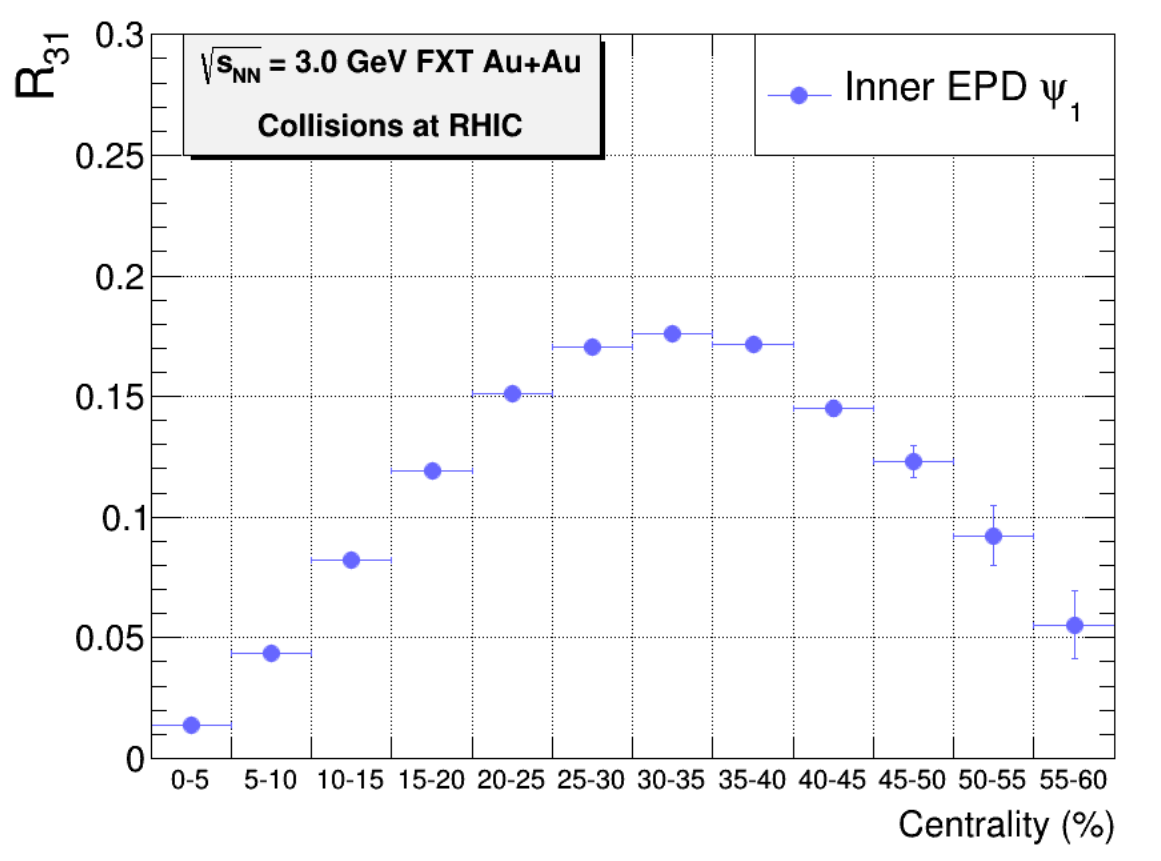
# Event Plane Resolution



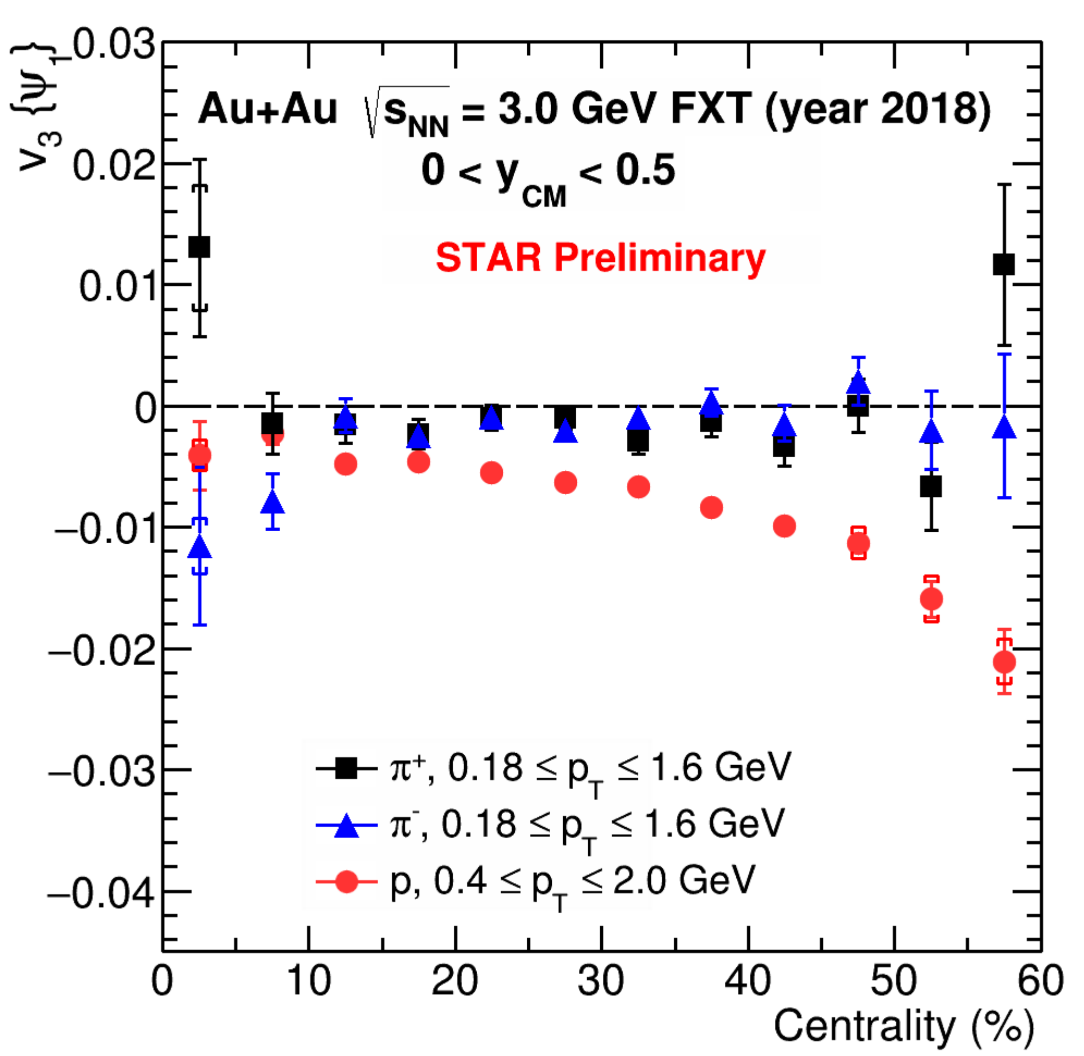

- Final event plane angles are used to calculate the resolution correction factors and the flow is corrected.

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

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



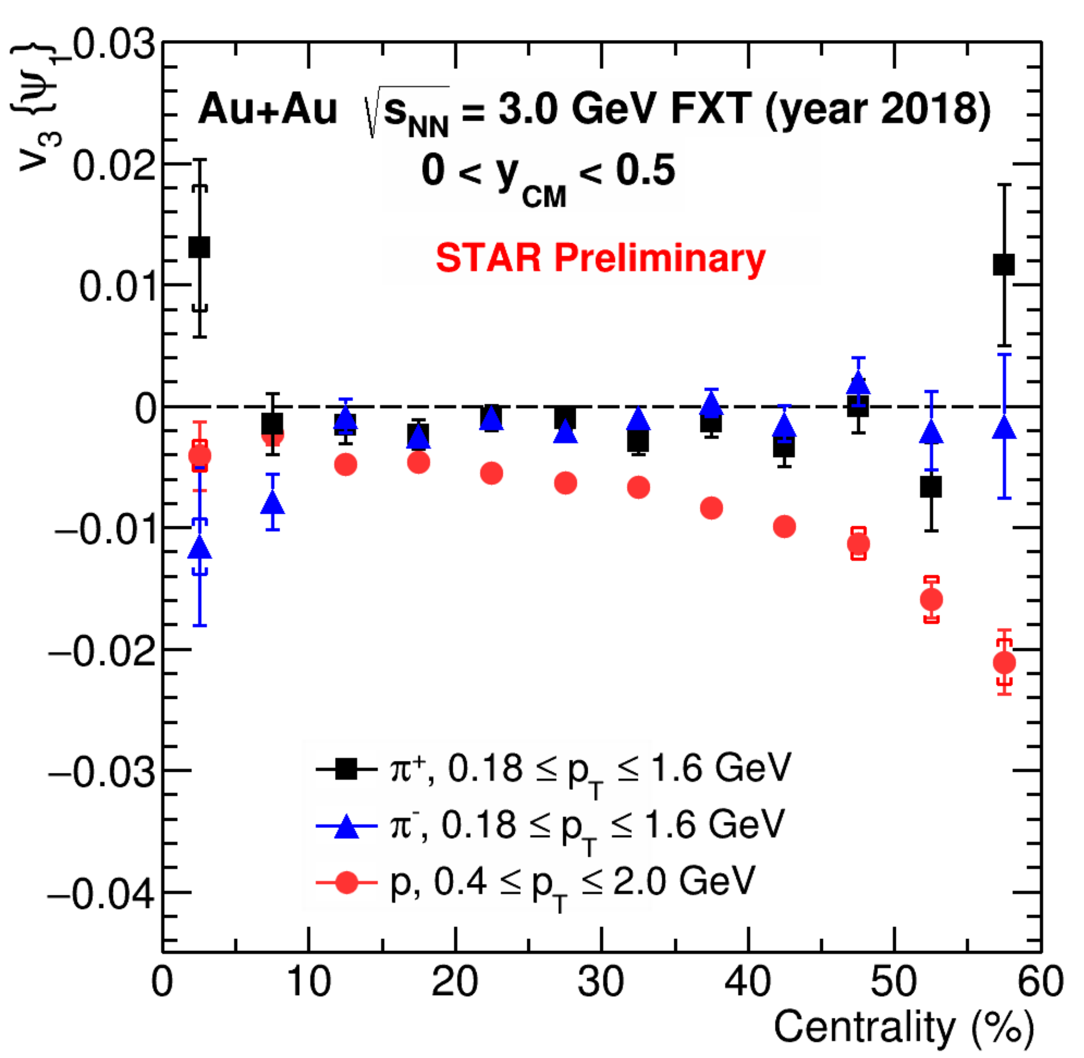
# Results: $v_3\{\Psi_1\}$ vs Centrality



# Results: $v_3\{\Psi_1\}$ vs Centrality

## Pions

- No significant $v_3\{\Psi_1\}$ signal.



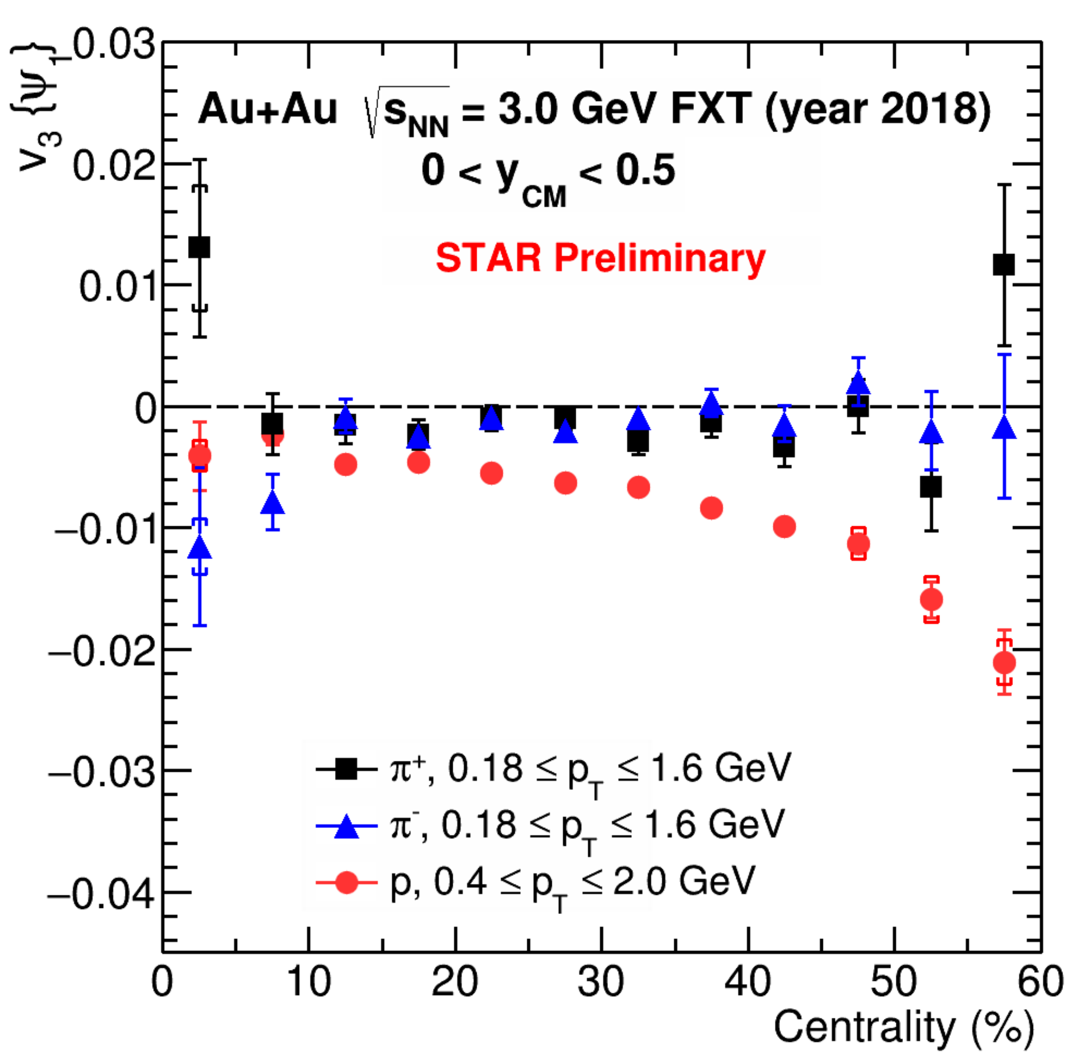
# Results: $v_3\{\Psi_1\}$ vs Centrality

**Pions**

- No significant $v_3\{\Psi_1\}$ signal.

**Protons**

- Clear $v_3\{\Psi_1\}$ signal at $\sqrt{s_{NN}} = 3.0$ GeV!
- $v_3\{\Psi_1\} < 0$ in the backward rapidity region.



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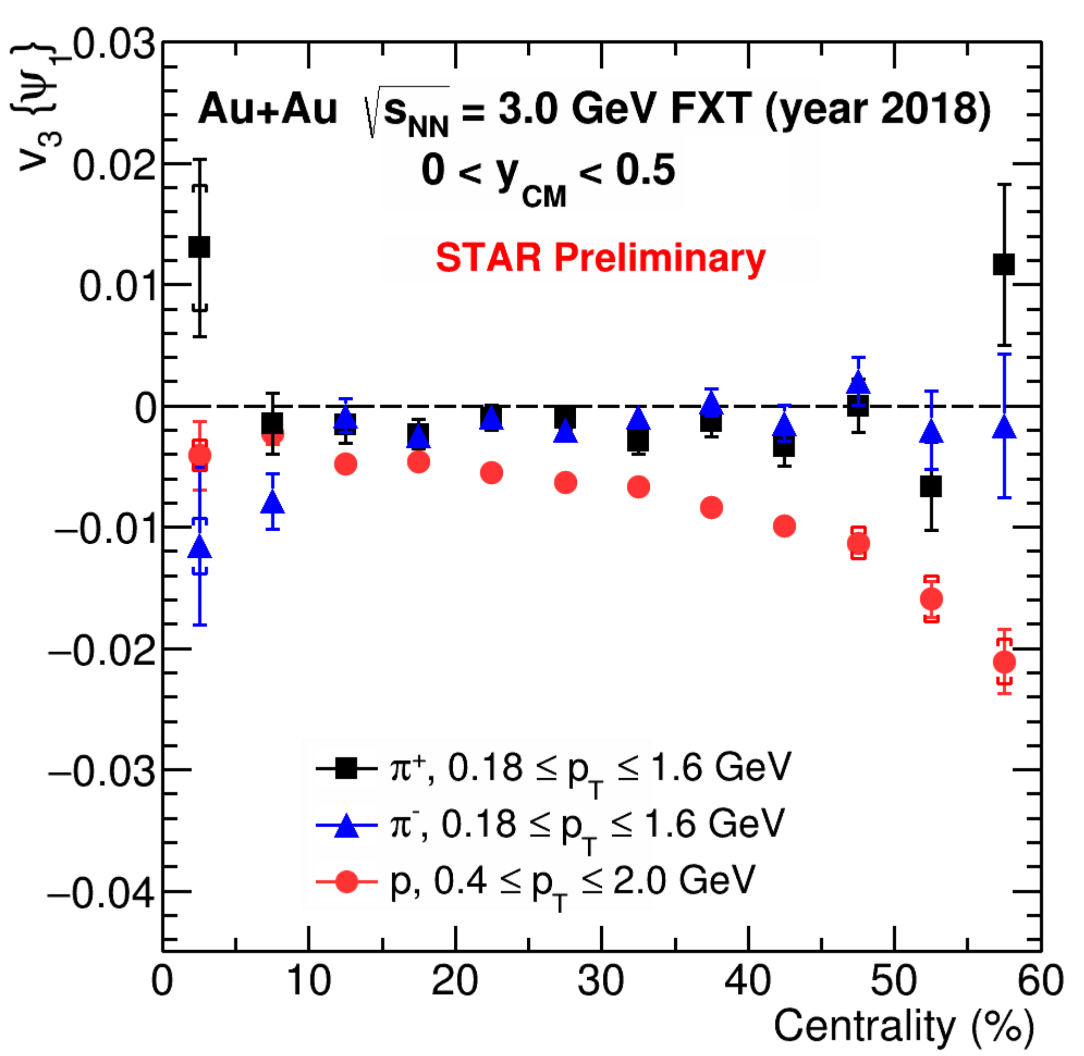


Kaons

- (Not shown) No conclusion due to very low statistics.

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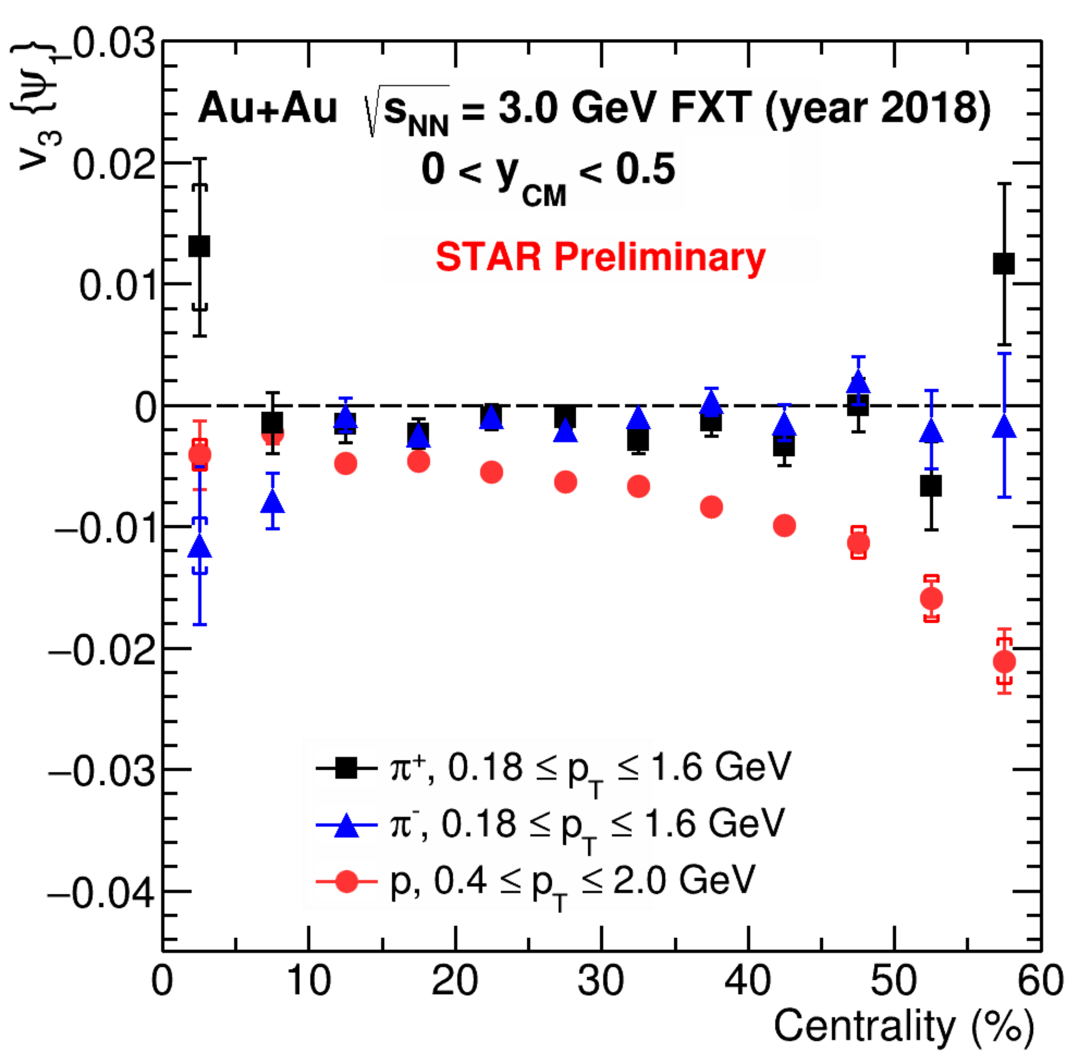


Kaons

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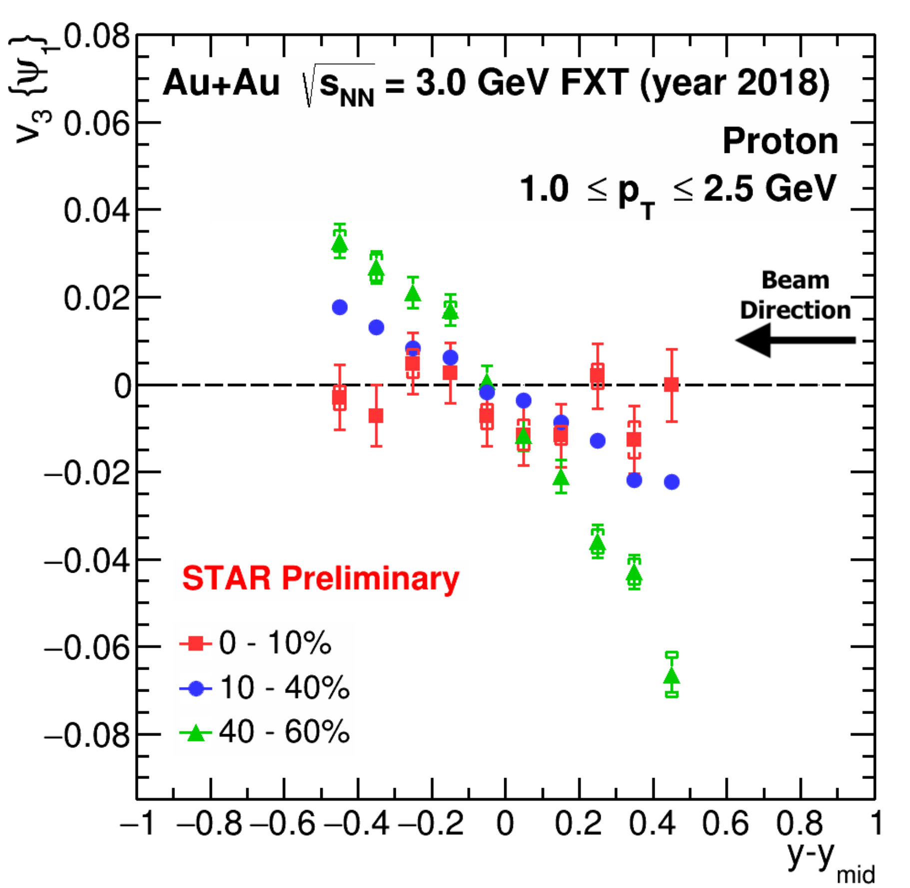
All systematics at this point include contributions from

- Event/track QA
- $R_{31}$ estimation
- Pion and proton identification

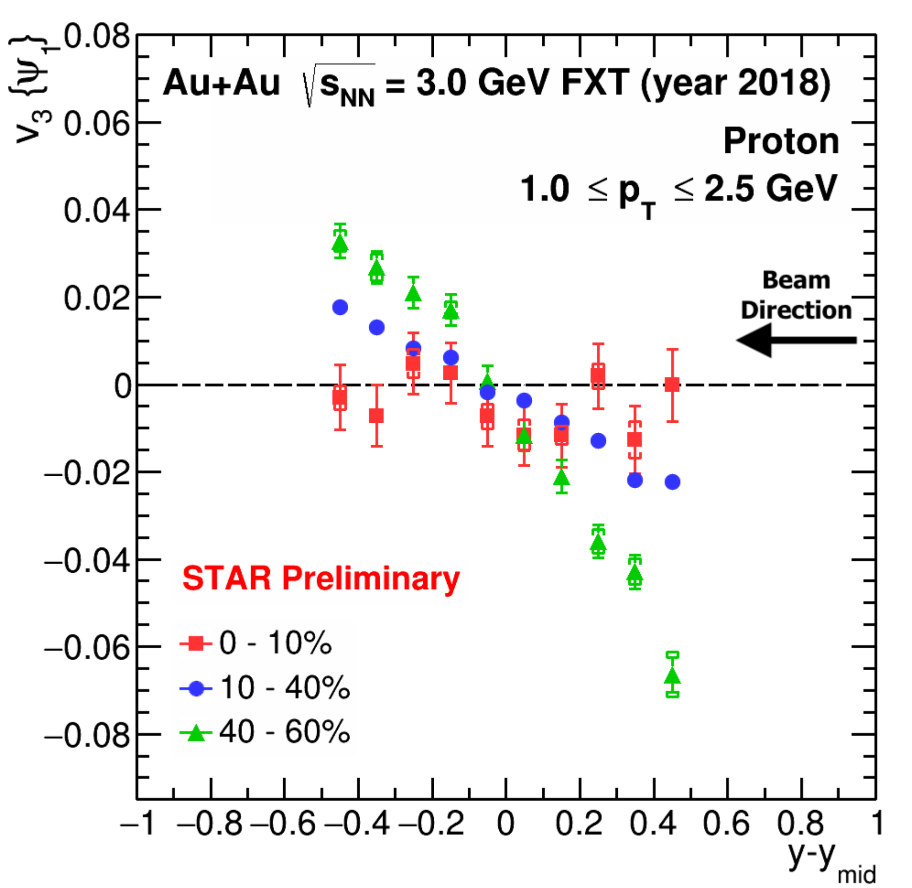
# Results: $v_3\{\Psi_1\}$ vs Rapidity



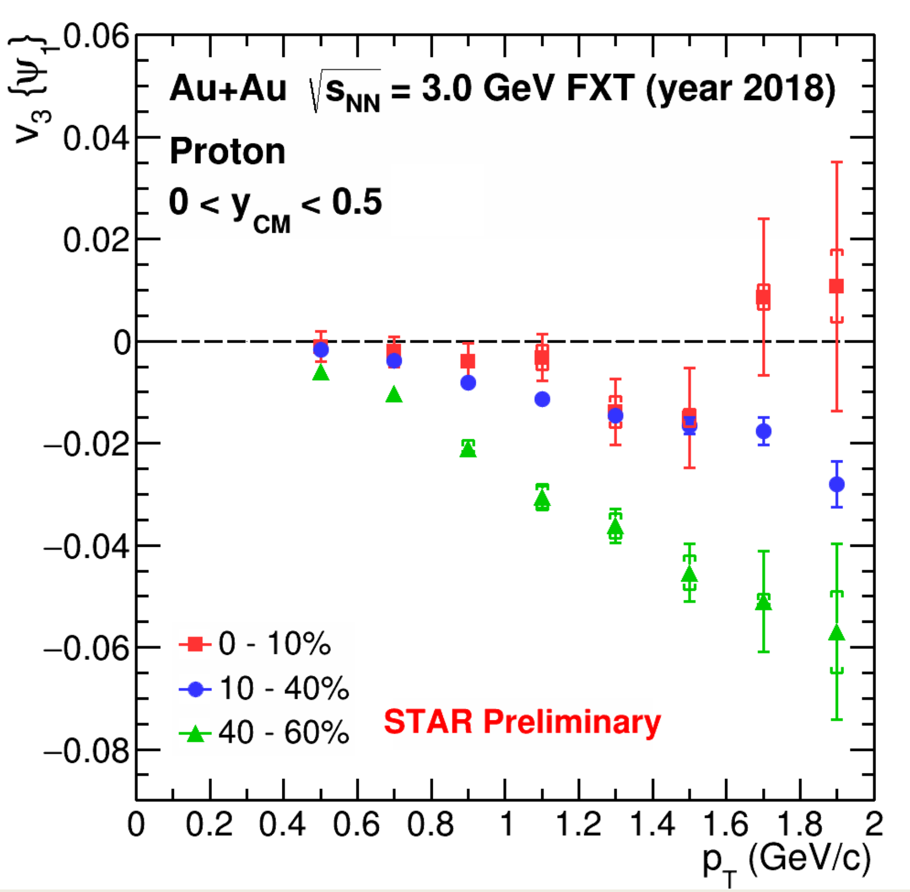

- Proton $v_3\{\Psi_1\}$ is rapidity odd.
- Negative slope; opposite sign to $v_1$ at 3 GeV [6,7].


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

# Results: $v_3\{\Psi_1\}$ vs Rapidity and $p_T$




- Proton $v_3\{\Psi_1\}$ is rapidity odd.
- Negative slope; opposite sign to $v_1$ at 3 GeV [6,7].
- Strength increases with $y$ and $p_T$.





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

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

- Due to the correlation to $\Psi_1$ this triangular flow is not from event-by-event fluctuations, so:
  - *Question 1: Where does the triangular geometry (that also preserves the $\Psi_1$ correlation) come from?*
  - *Question 2: What drives the flow?*

- 3 GeV is likely 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.

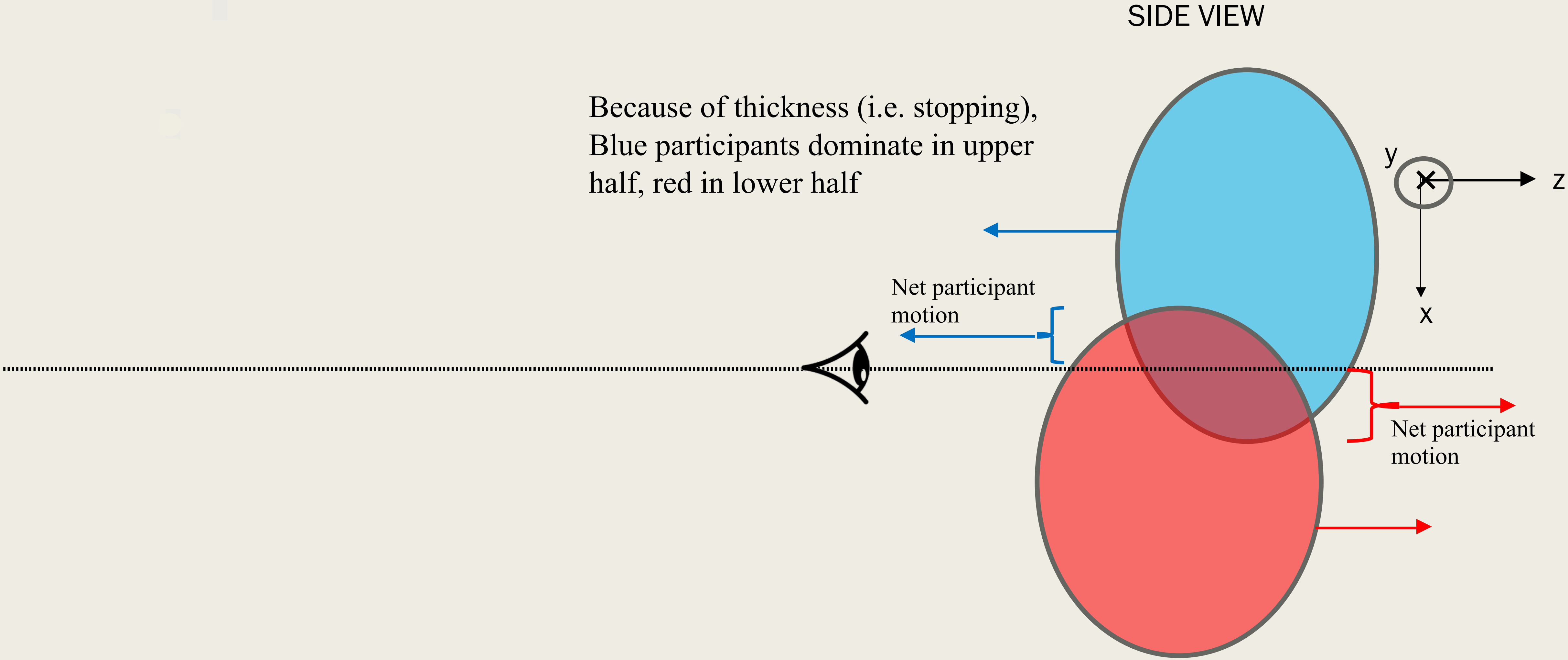
- Known at 3 GeV:
  - *Passing time is important (~10 fm/c). Particle formation, interactions, etc. < passing time.*
  - *Stopping is important.*

- For an initial check of our ideas, we found two models to use with options for potentials.
  - *SMASH [8] – Cascade, Skyrme potential that is non-relativistic and good at ~ 3 GeV. Vector density functional can be used at higher energies.*
  - *JAM1 [9] – Cascade, Relativistic mean field with sigma-omega potential. This does well in a recent 3 GeV STAR paper.*

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

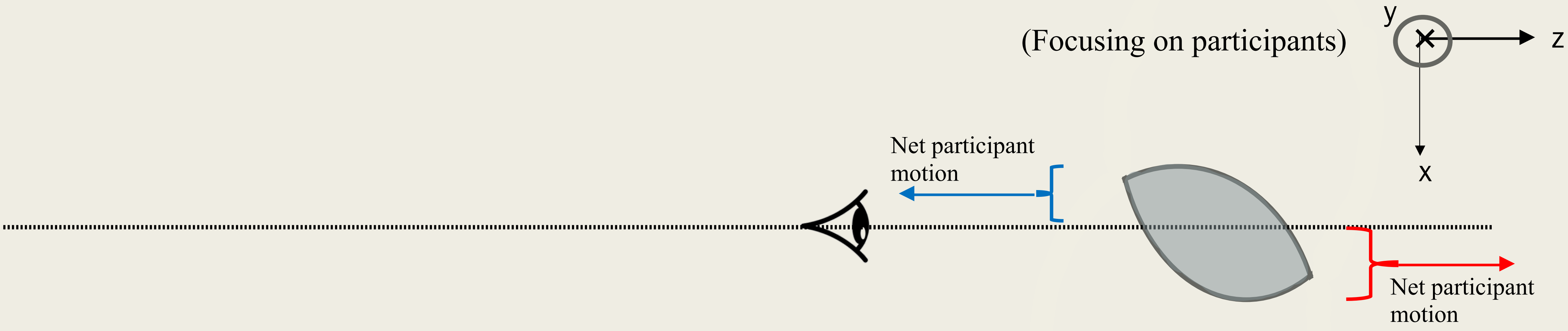
# Where does the triangular geometry come from?

Because of thickness (i.e. stopping), Blue participants dominate in upper half, red in lower half



# Where does the triangular geometry come from?

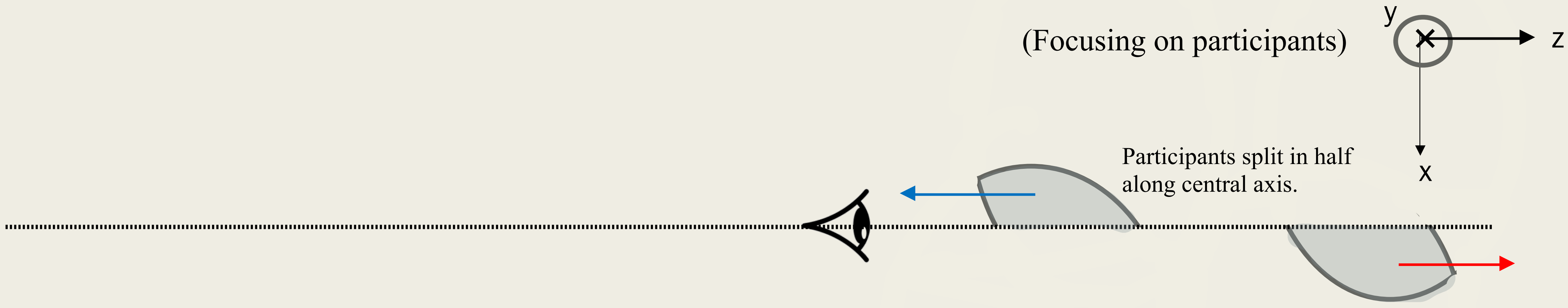
SIDE VIEW



# Where does the triangular geometry come from?

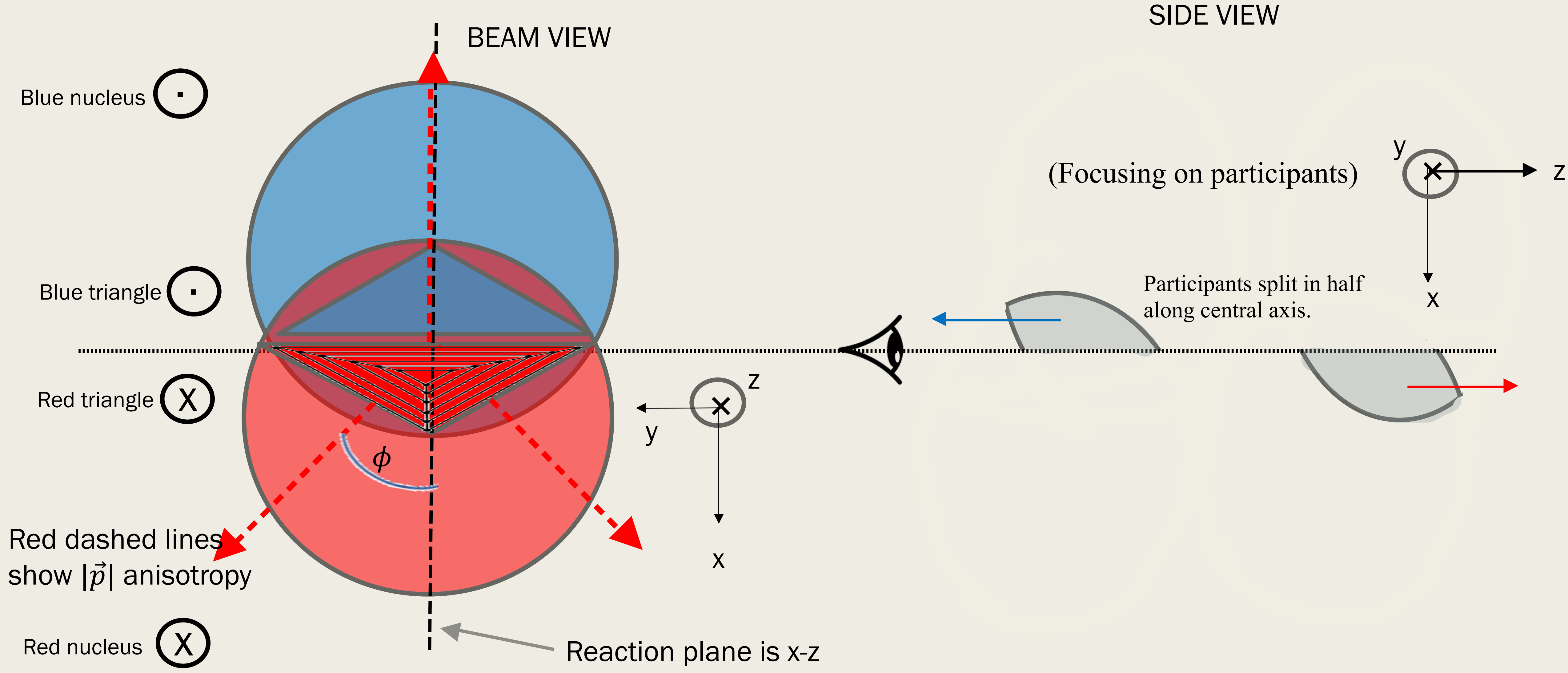
SIDE VIEW

(Focusing on participants)




Participants split in half along central axis.

# Where does the triangular geometry come from?



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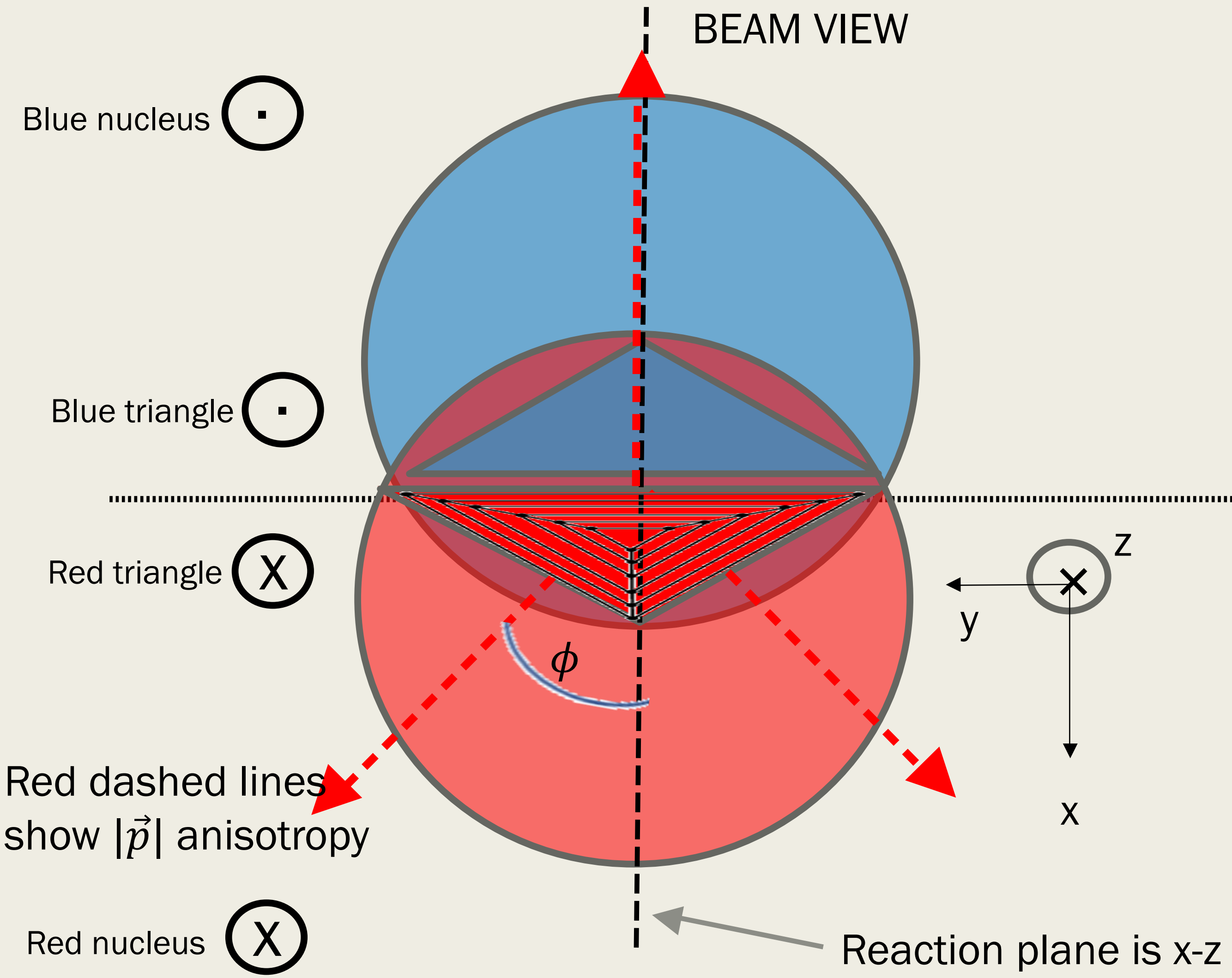
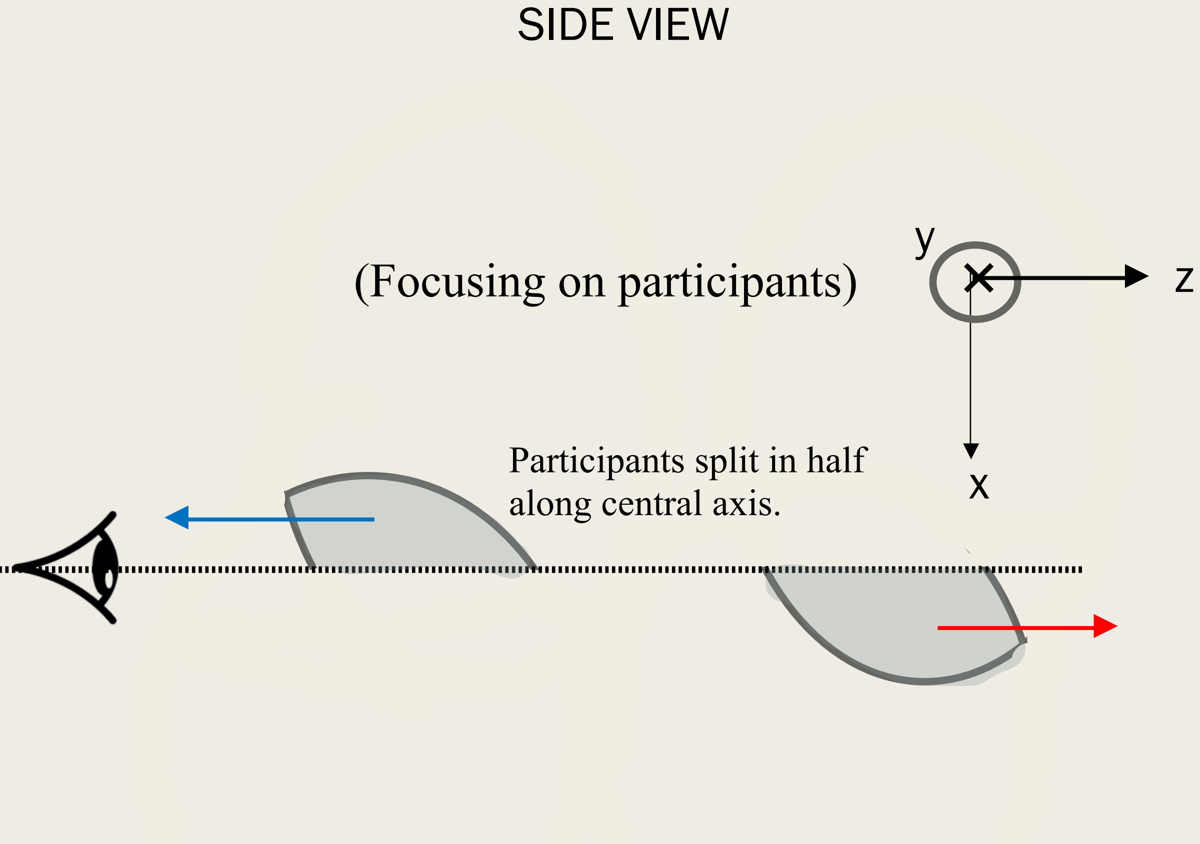
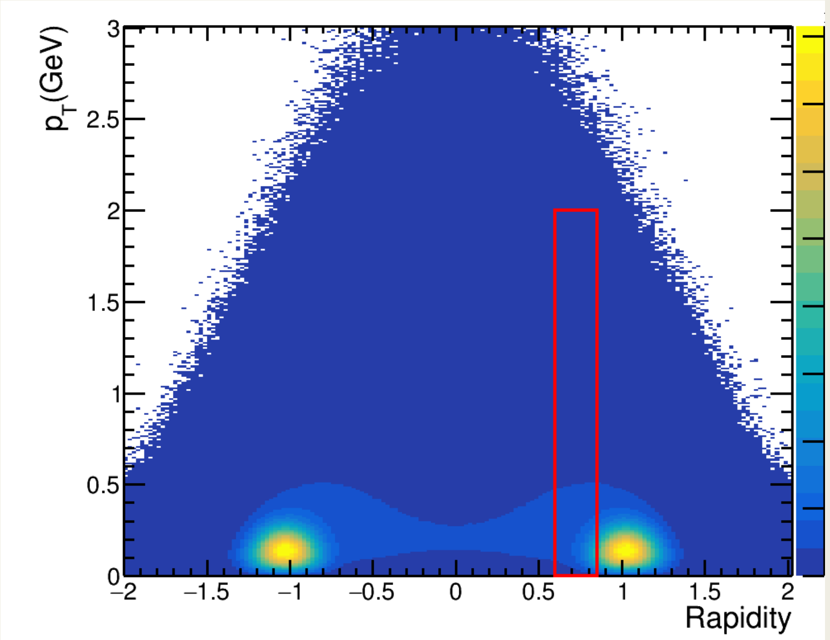



- Triangles are always aligned with $\Psi_r$.
- Momentum points opposite to $v_1$.

# Check Geometry idea

- Plot x vs y from JAM (+ potential) 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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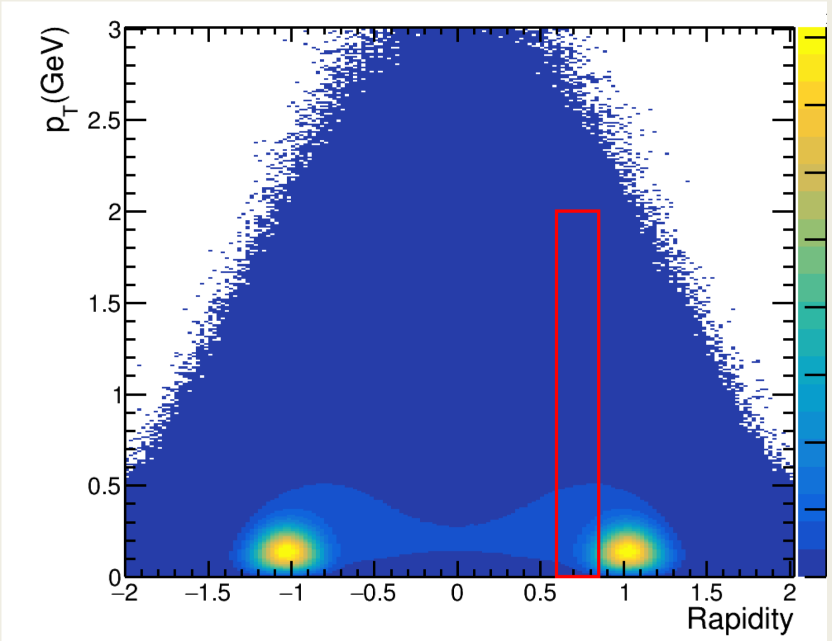
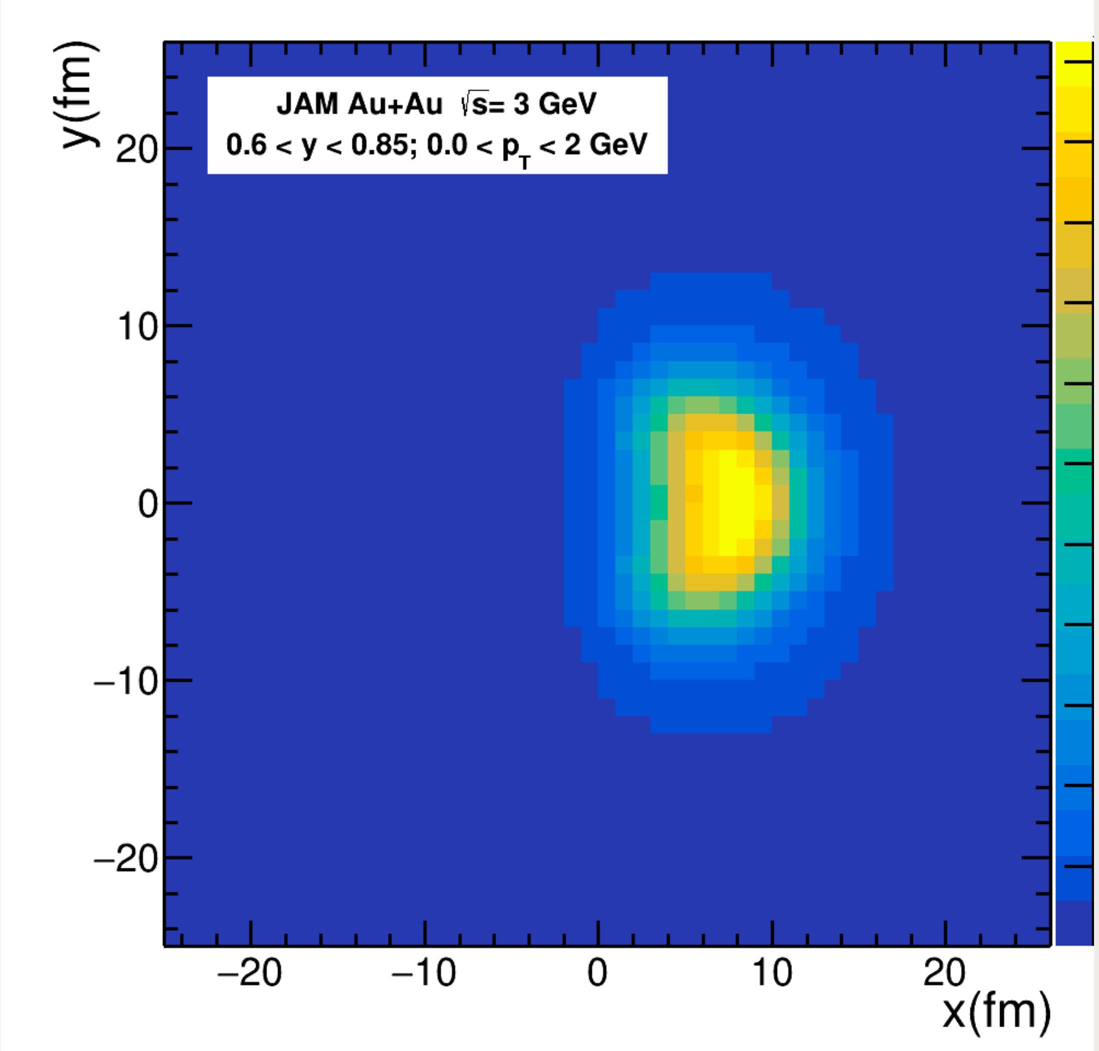
  - $t = 50\ fm/c$
  - $0.6 < y < 0.85$
  - $0 < p_T < 2\ GeV/c$



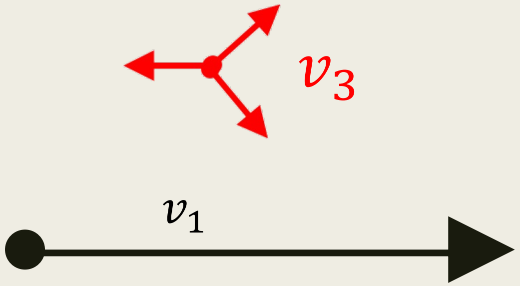




JAM: Triangle shape

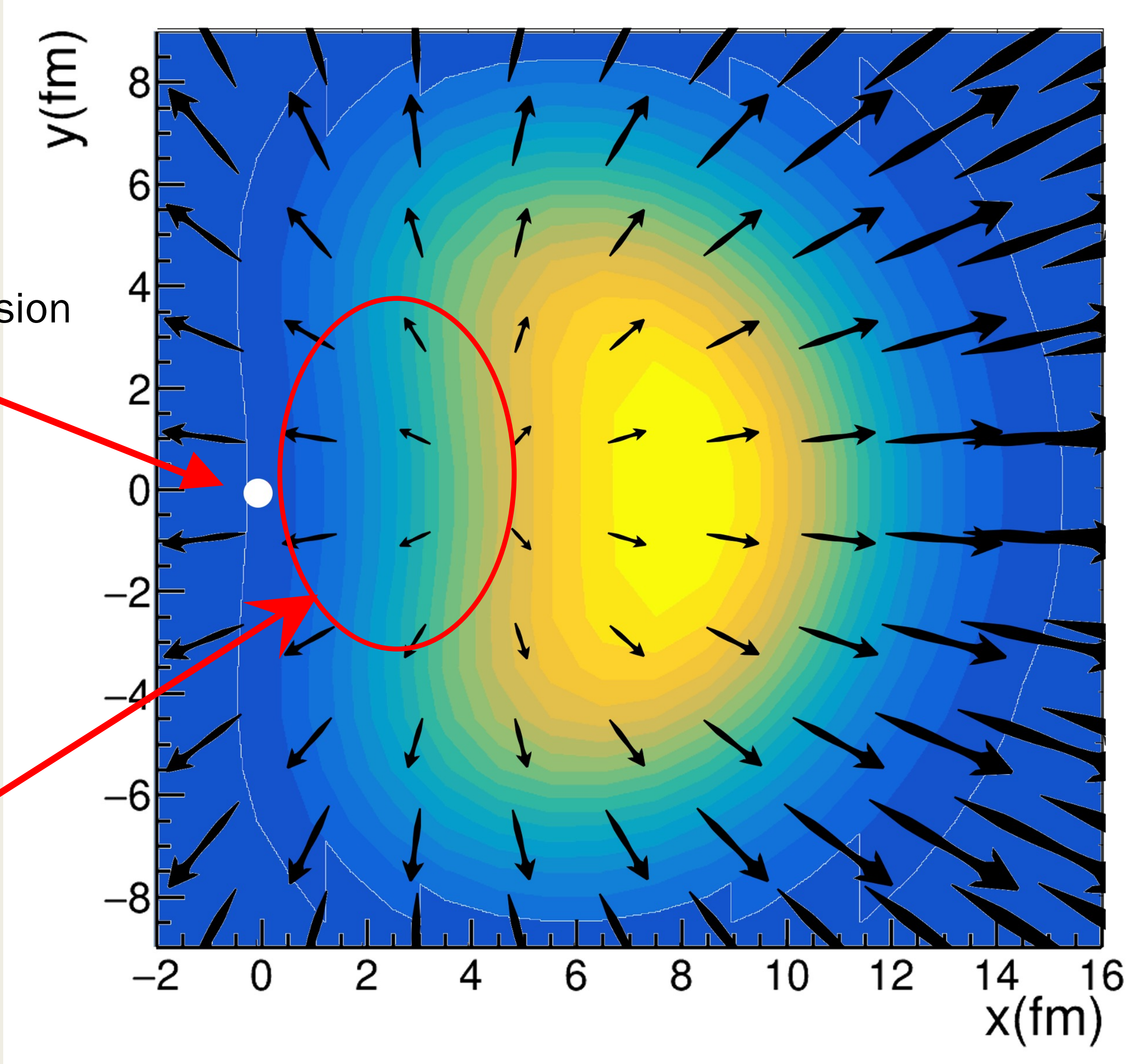
SMASH gives similar picture

Simillar also at $t = 20$ fm/$c$

# Looking at Momentum of “cells”




Center of collision (0,0)

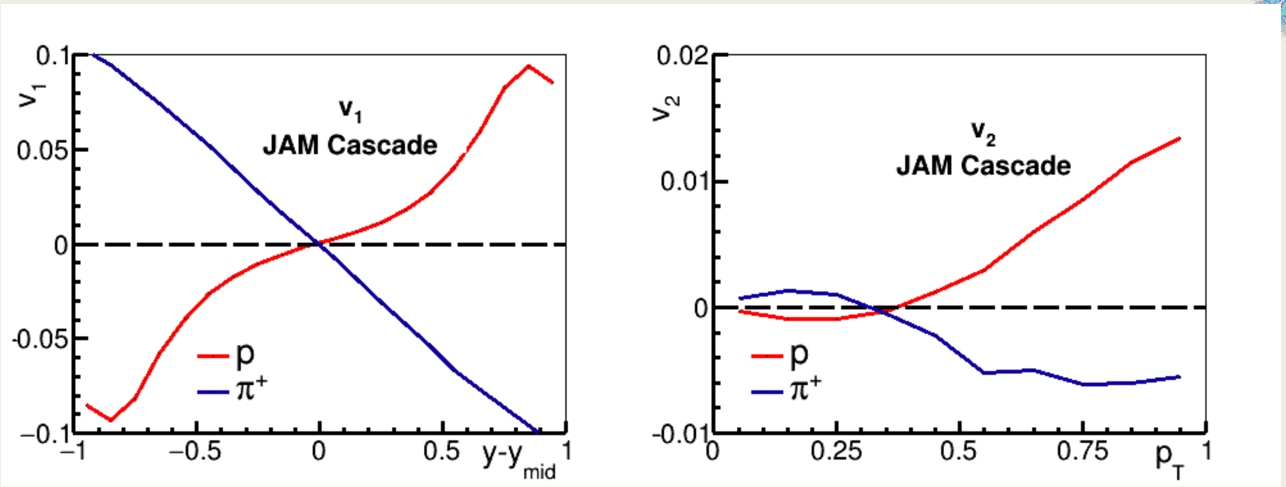



Despite being right of the center,
the flow is left due to $v_3$ overcoming $v_1$.

# 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)



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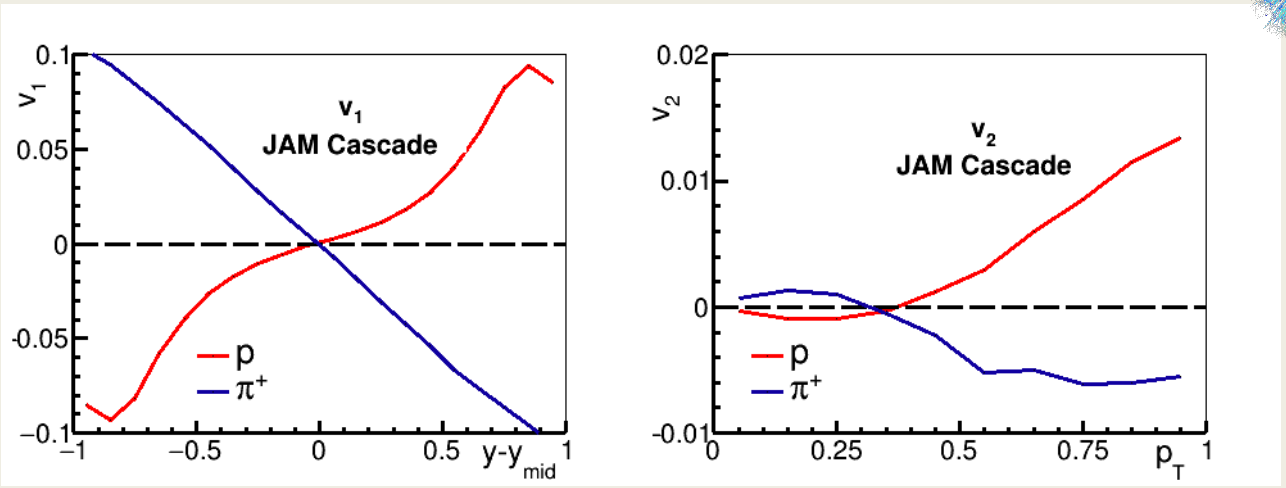
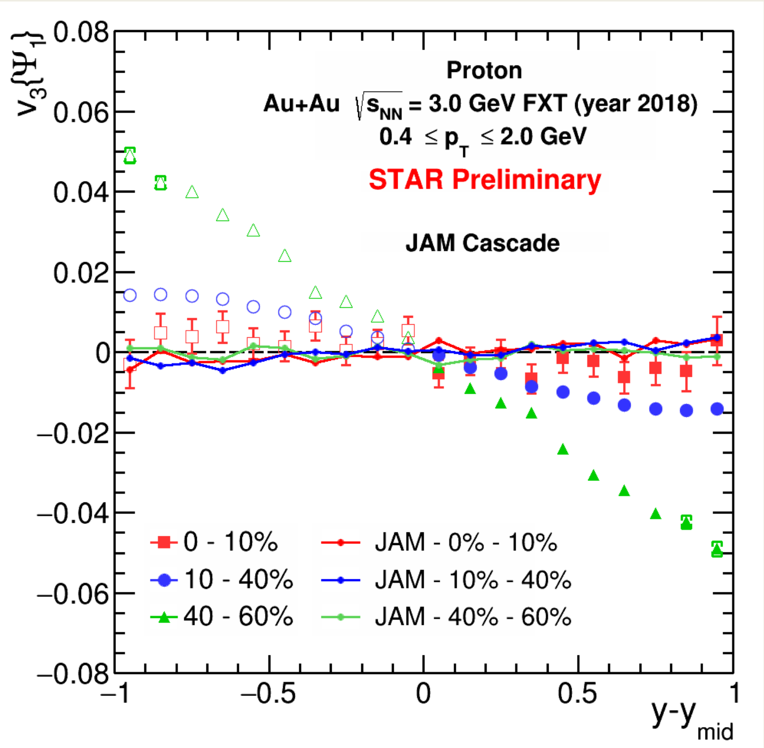
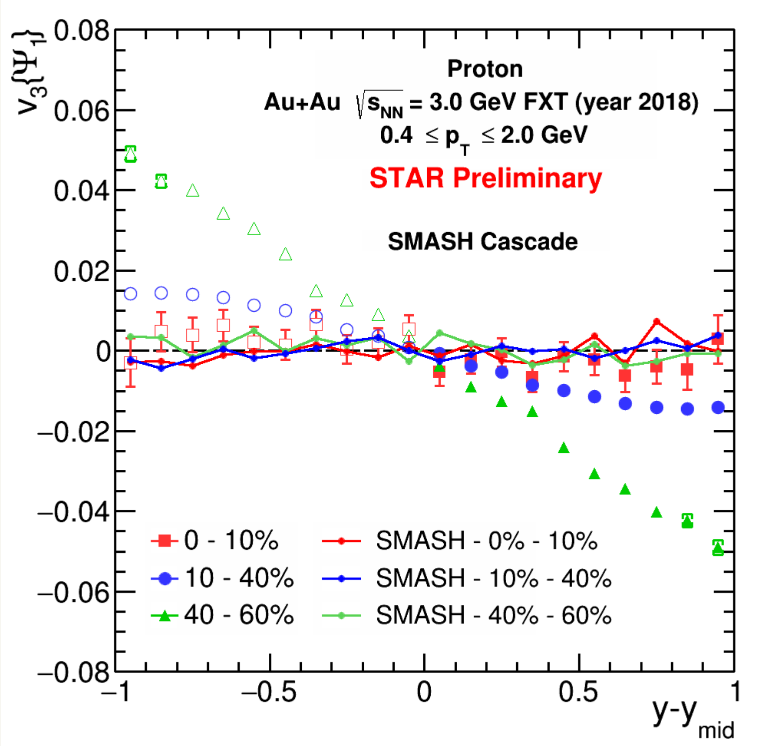



$v_3\{\Psi_1\}$ does NOT develop!

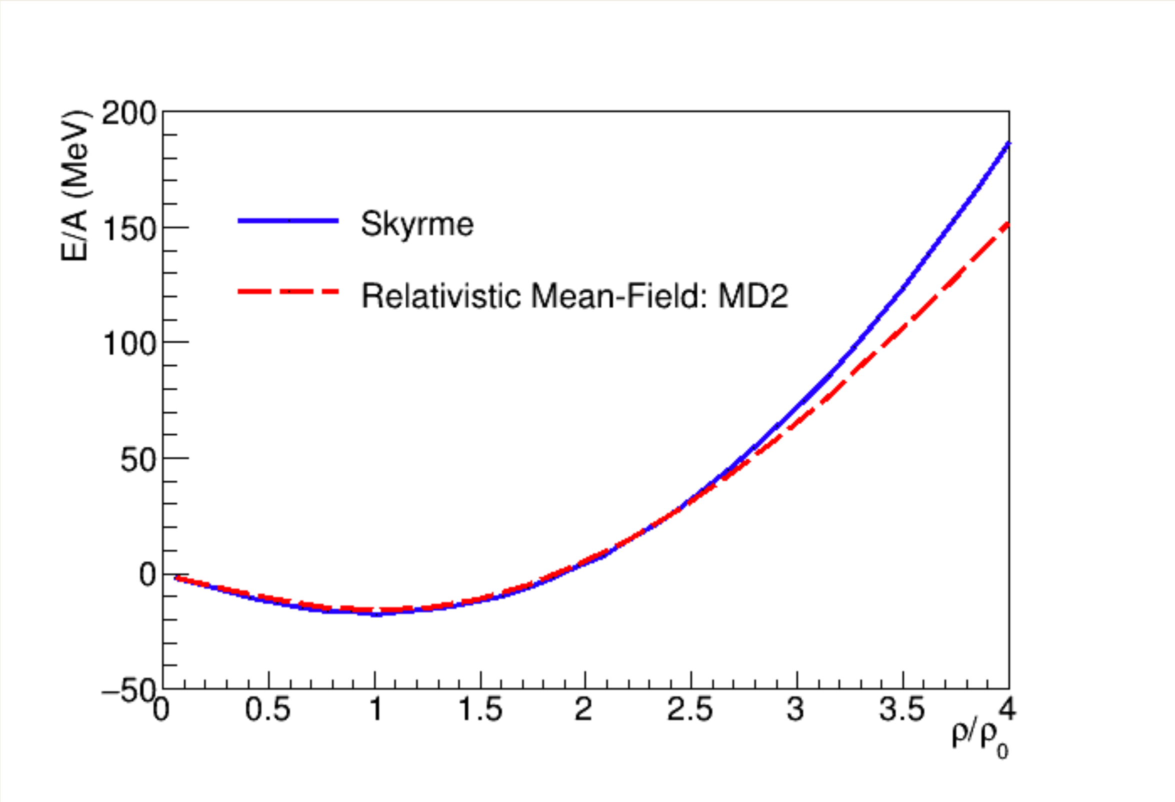
(JAM (left) & SMASH (right))



# 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 $v_1, v_2$ [10,11].*
- SMASH
  - *Non-relativistic Skyrme + Symmetry Potential with Fermi motion & Pauli blocking.*
  - $U = A\left(\frac{\rho}{\rho_0}\right) + B\left(\frac{\rho}{\rho_0}\right)^{\tau} \pm 2S_{pot}\left(\frac{\rho_{I_3}}{\rho_0}\right)$
  - $\rho_0 = 0.1681\ \mathrm{fm}^{-3}$
  - $A = -124$ MeV, $B = 71$ MeV, $\tau = 2$
  - $S_{pot} = 18\ MeV$
  - *Parameters used to fit HADES data [12].*

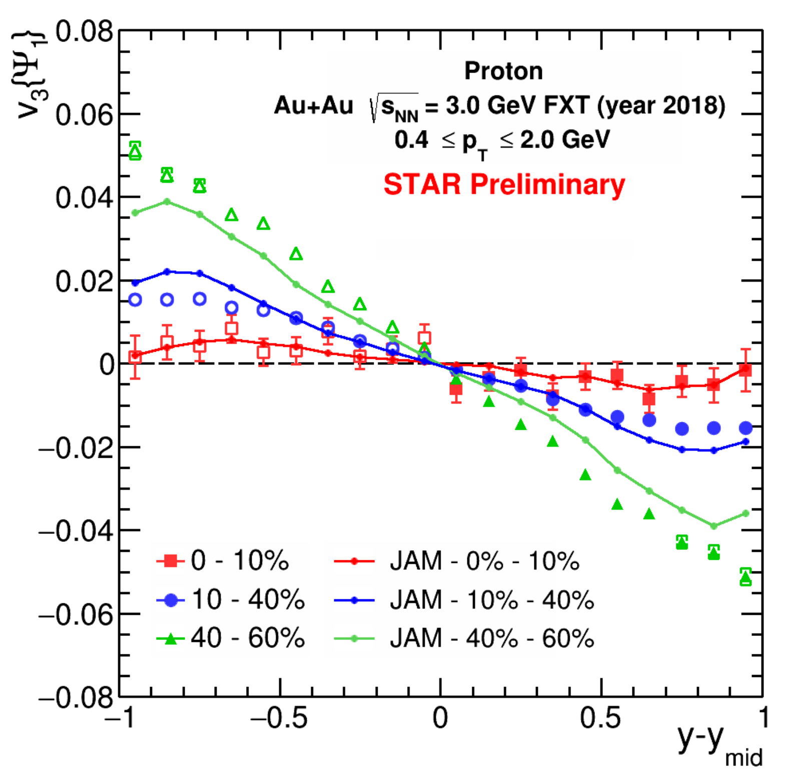


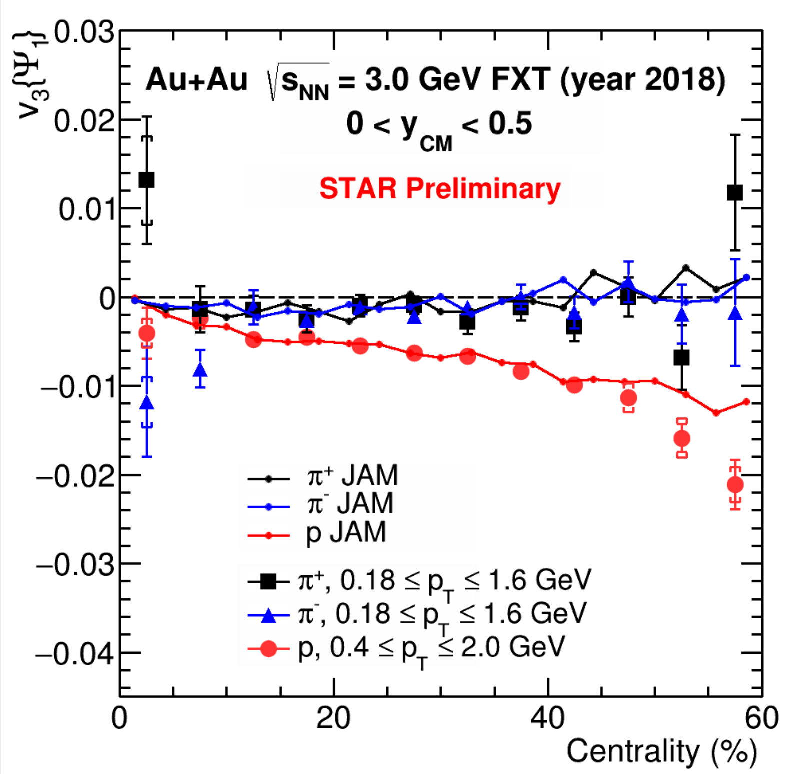

$\rho$ = Baryon Density

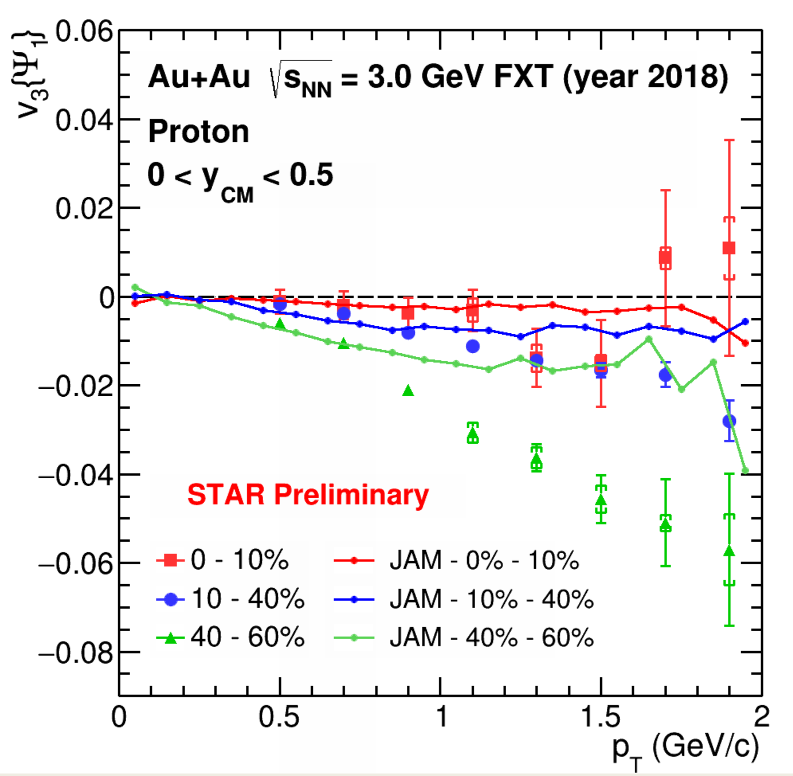
$\rho_{I_3}$ = Baryon isospin density of the relative isospin projection $I_3/I$.

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

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

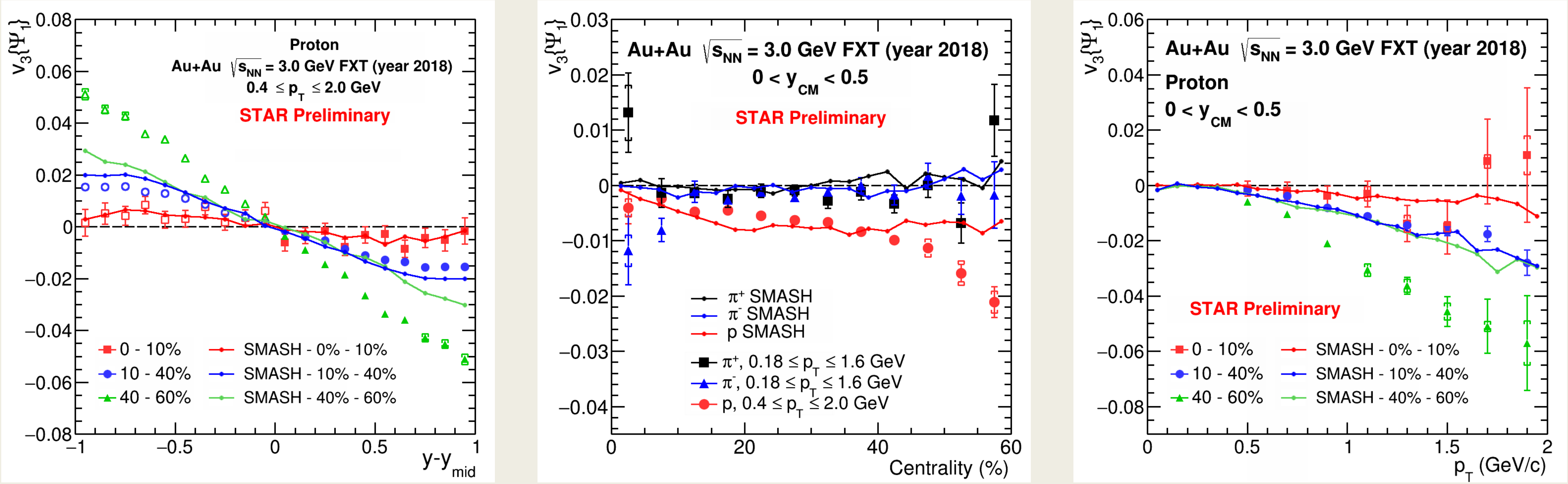


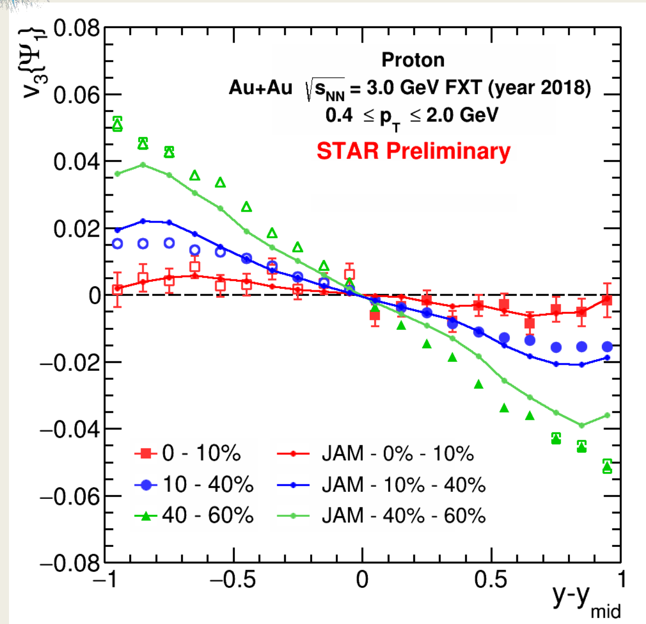

- Note: JAM centralities defined with impact parameter, not multiplicity.
- $v_3\{\Psi_1\}$ can indeed be reproduced with the inclusion of a potential!
- $v_3\{\Psi_1\}$ could be a useful observable to determine the proper EoS below the phase transition!
- More work for models is necessary, but it is apparent that a proper EoS should be capable of reproducing $v_3\{\Psi_1\}$ alongside other observables.

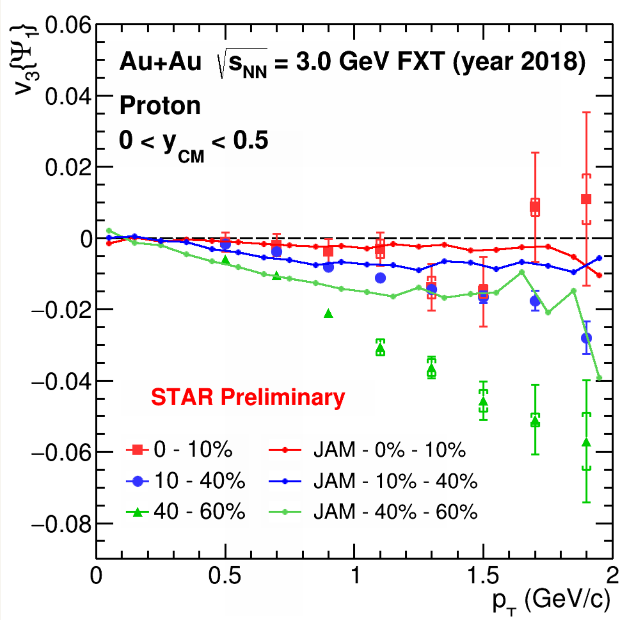
# What drives $v_3\{\Psi_1\}$? Results with SMASH

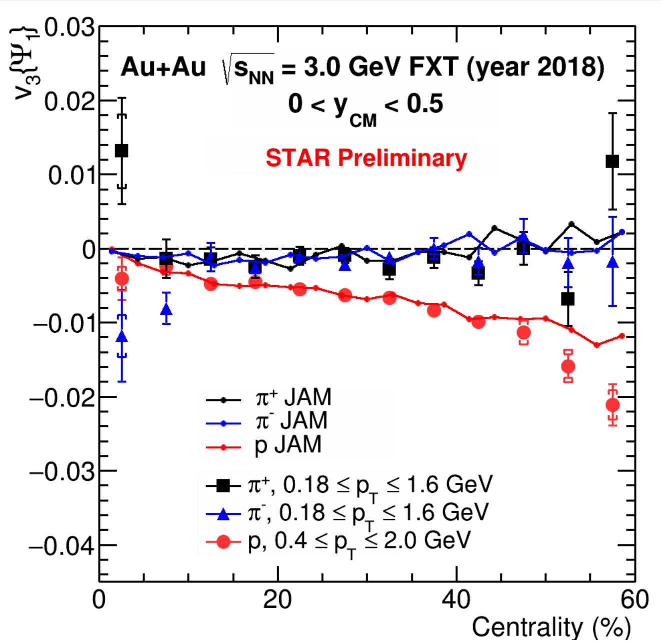


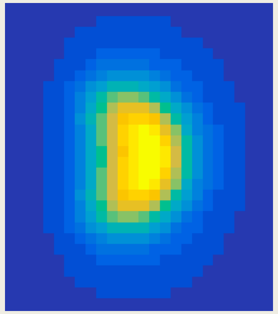

- SMASH also works fairly well here!
- SMASH does very well in mid-central $p_T$ dependence.
- Like JAM, SMASH has difficulty with peripheral collisions.

# Quantify the triangle geometry – Eccentricity

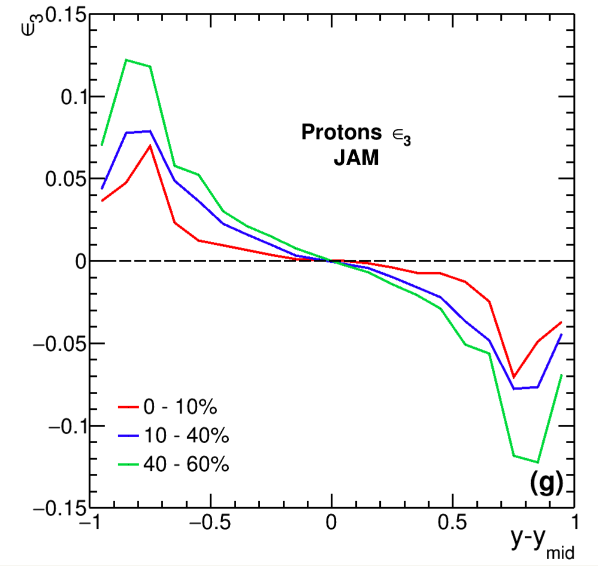


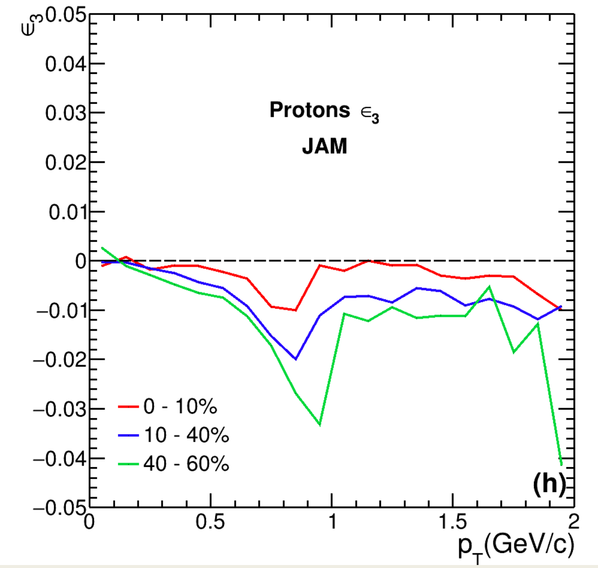



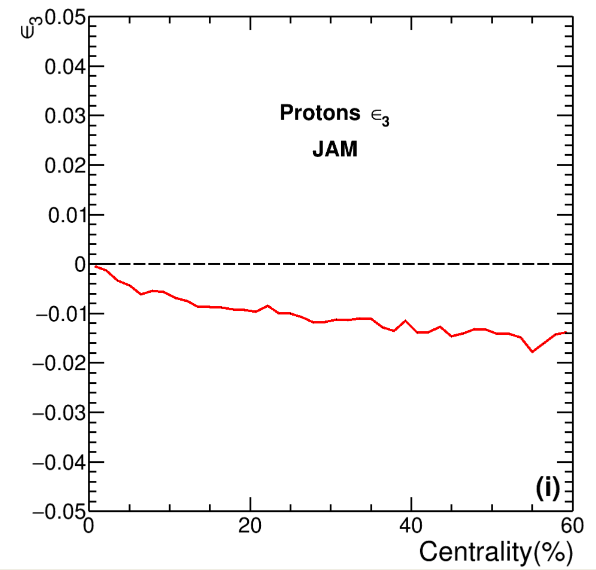



Eccentricity + potential drives $v_3\{\Psi_1\}$.



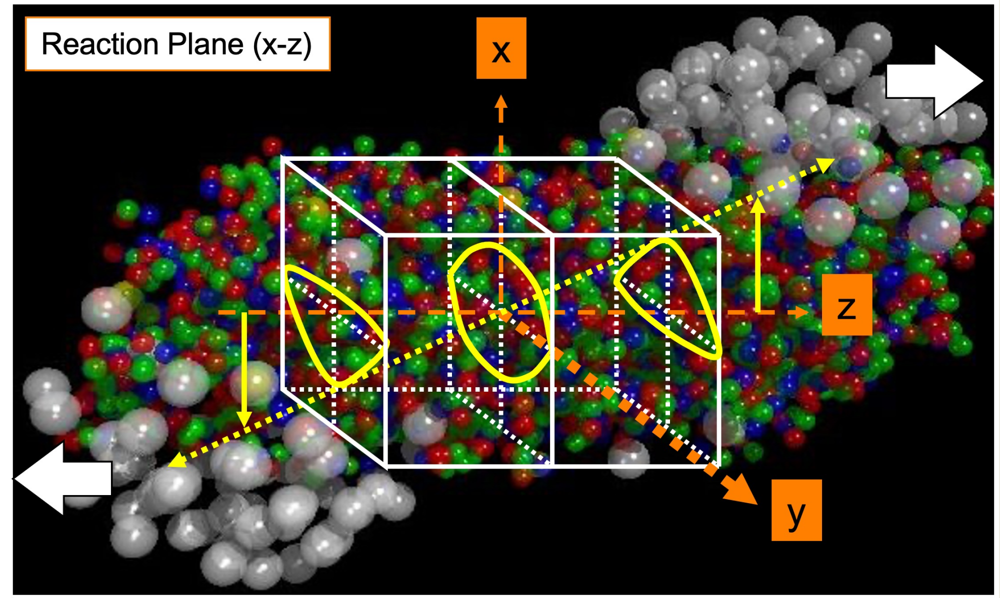




$$\epsilon_3 = \frac{\langle r^2 \cos(3\phi) \rangle}{\langle r^2 \rangle}$$

(Sin term ignored to get correct sign)

# 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 $p_T$.*
  - *Similar observations as HADES at 2.4 GeV.*
- 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 is available (necessary for π and K).*
  - *Investigations of A scaling for $v_3\{\Psi_1\}$ are underway – Ding Chen (UCR).*
  - *Scan higher energies to complete the picture of $v_3\{\Psi_1\}$ (3.2, 3.5, 3.9, 4.5 GeV).*

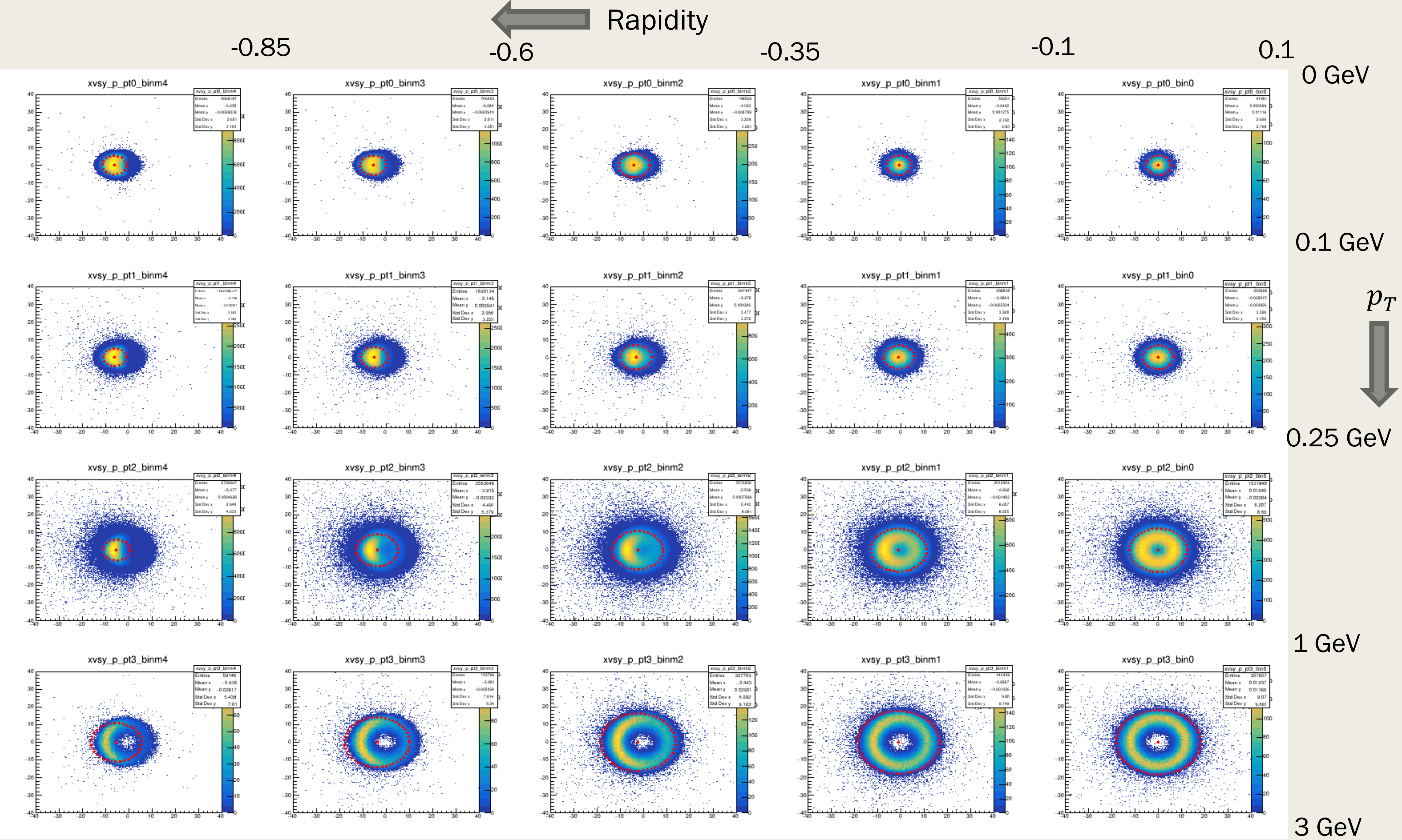
*Thank you!*

# Backup

JAM

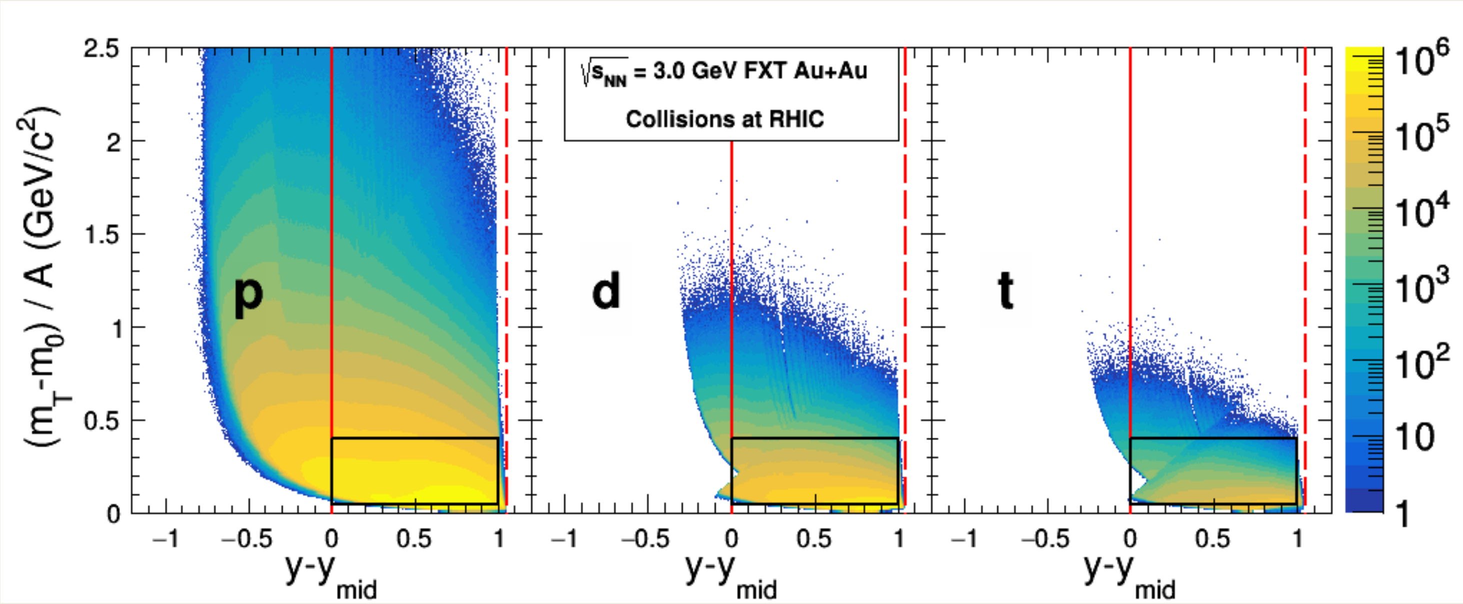
20fm

Scale:
x,y = -40 to 40



# Particle Identification

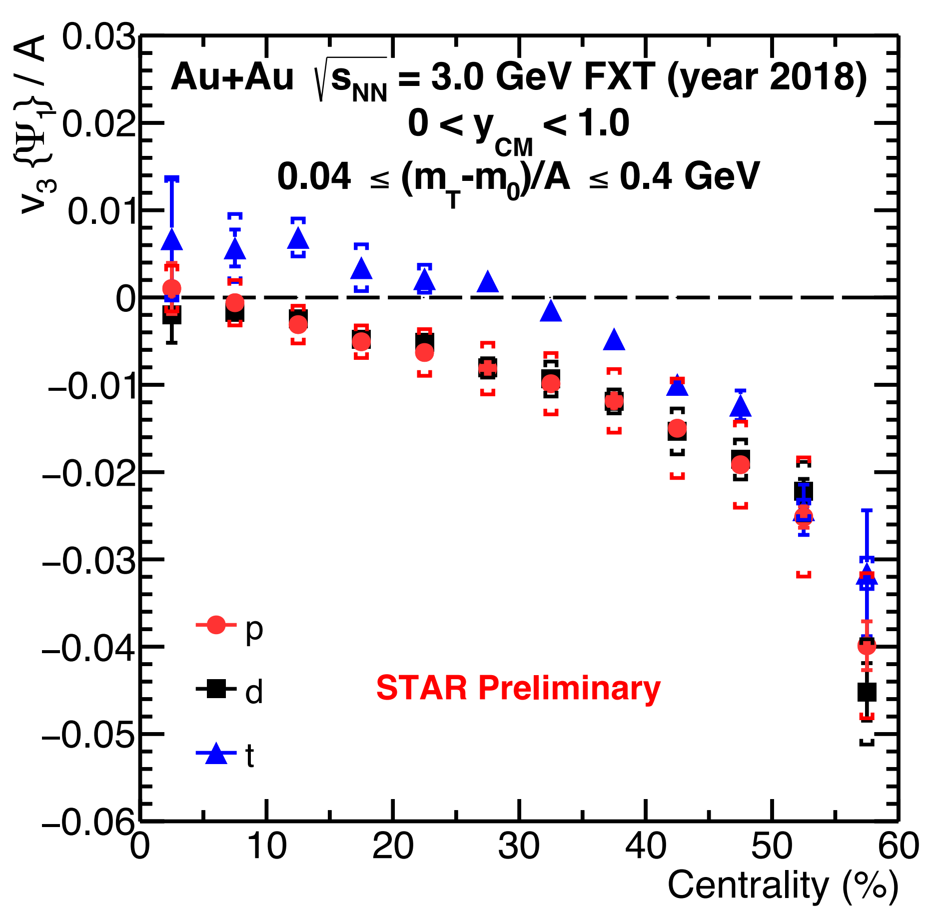
- Alternate acceptance made for proton, deuteron, and triton comparisons.
- Rather than $p_T$, we used $m_T - m_0$ scaled by mass number $A$.
- Black solid boxes = acceptance for $v_3$ vs centrality.
- Red solid (dashed) lines = mid (target) rapidity.




- $d$ 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.

# 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.