# Beam energy dependence of directed flow of deuteron in Au+Au collisions at RHIC

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Workshop on the QCD Phase Structure at High Baryon Density Region

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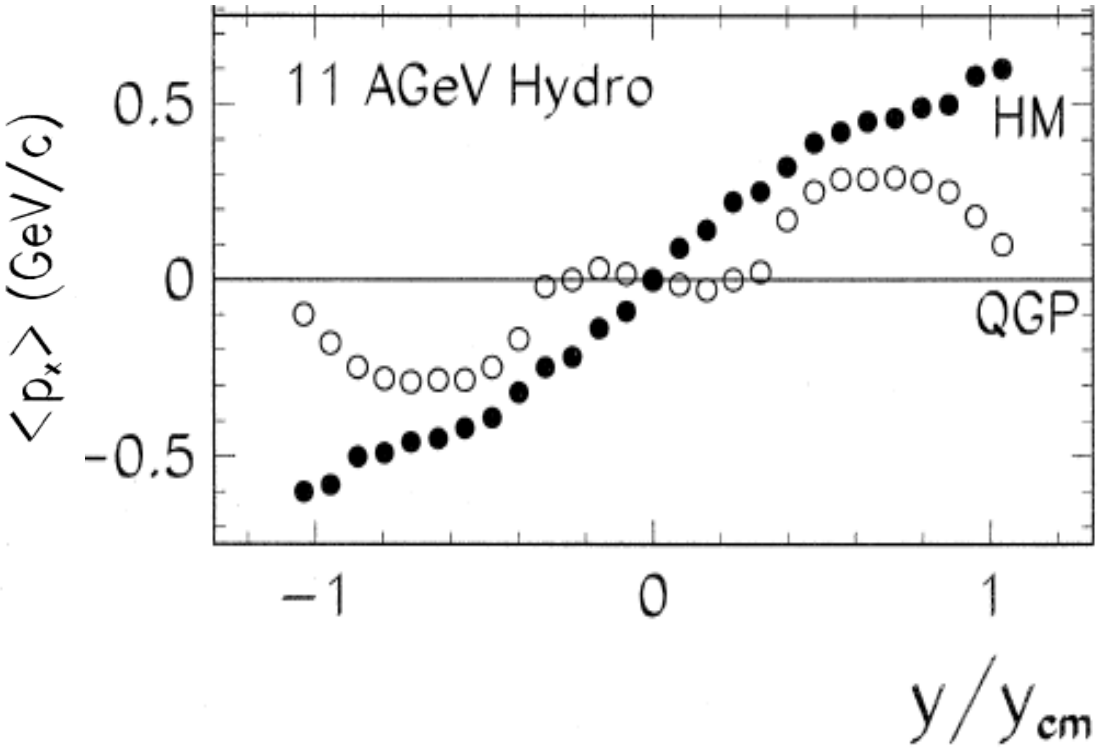
# Outline

1. Introduction
2. Data analysis : STAR BES I
3. Results and discussion
4. Summary

# Directed Flow

Directed Flow ($v_1$) : 1st harmonic in the Fourier expansion of particle azimuthal spectrum.

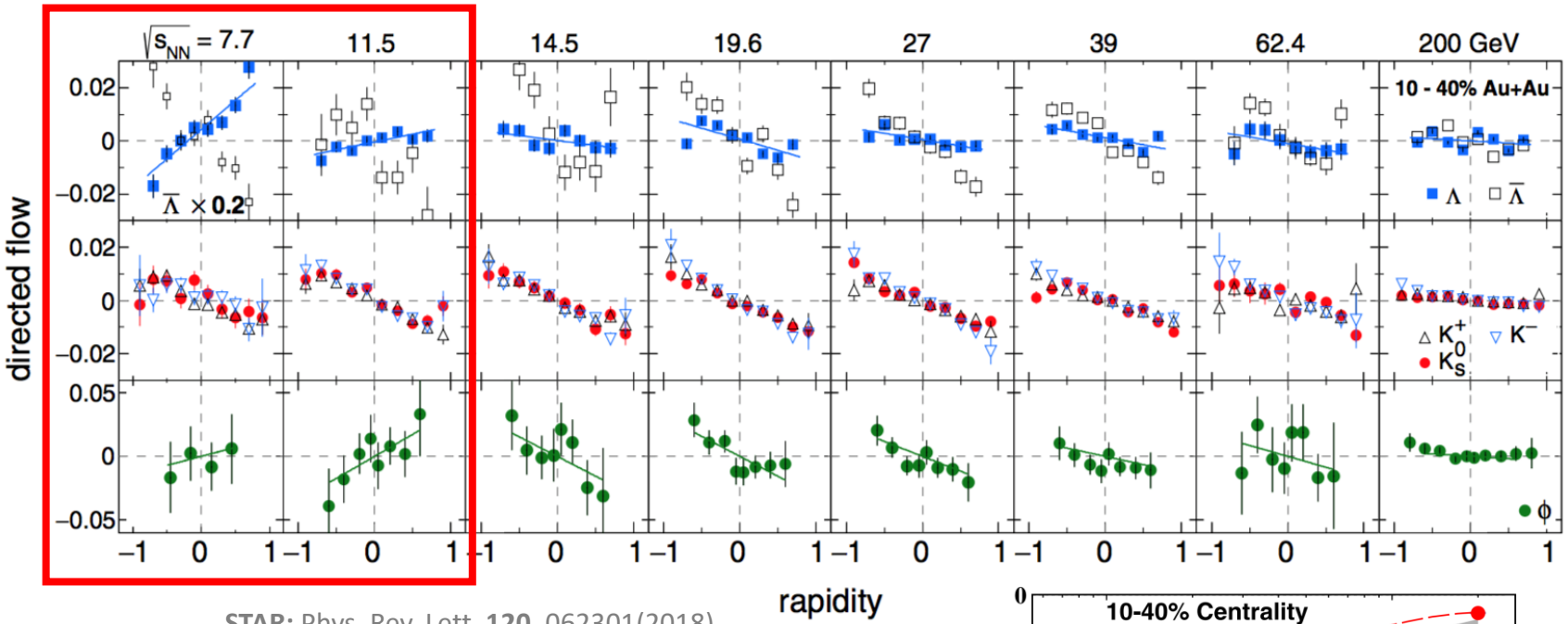
$$\frac{d^3N}{dp_T dy d\phi} = \frac{d^2N}{dp_T dy}(1 + 2\boldsymbol{v_1}\cos(\phi - \psi) + 2v_2\cos 2(\phi - \psi) + \cdots)$$



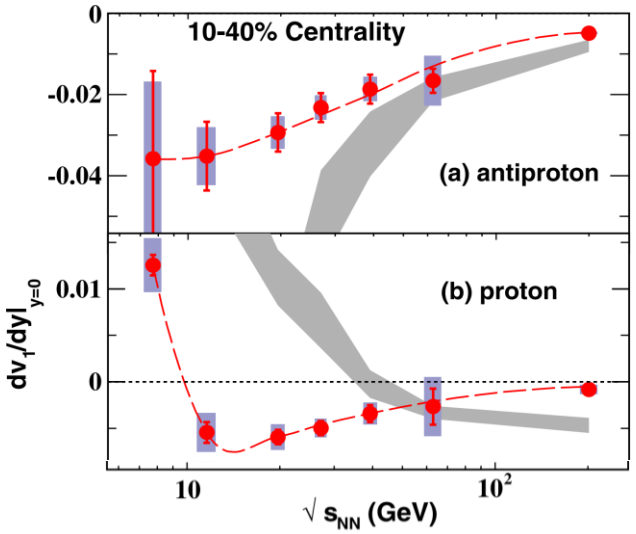

Phys. Lett. B **485,** 454(1999)

The directed flow slope at mid-rapidity is sensitive to softening of EOS?

# Directed Flow $v_1$ in RHIC BES-I




STAR: Phys. Rev. Lett. **120**, 062301(2018)




Mesons and all produced baryons show negative slope except **φ** mesons when collisions energy < 14.5 GeV.

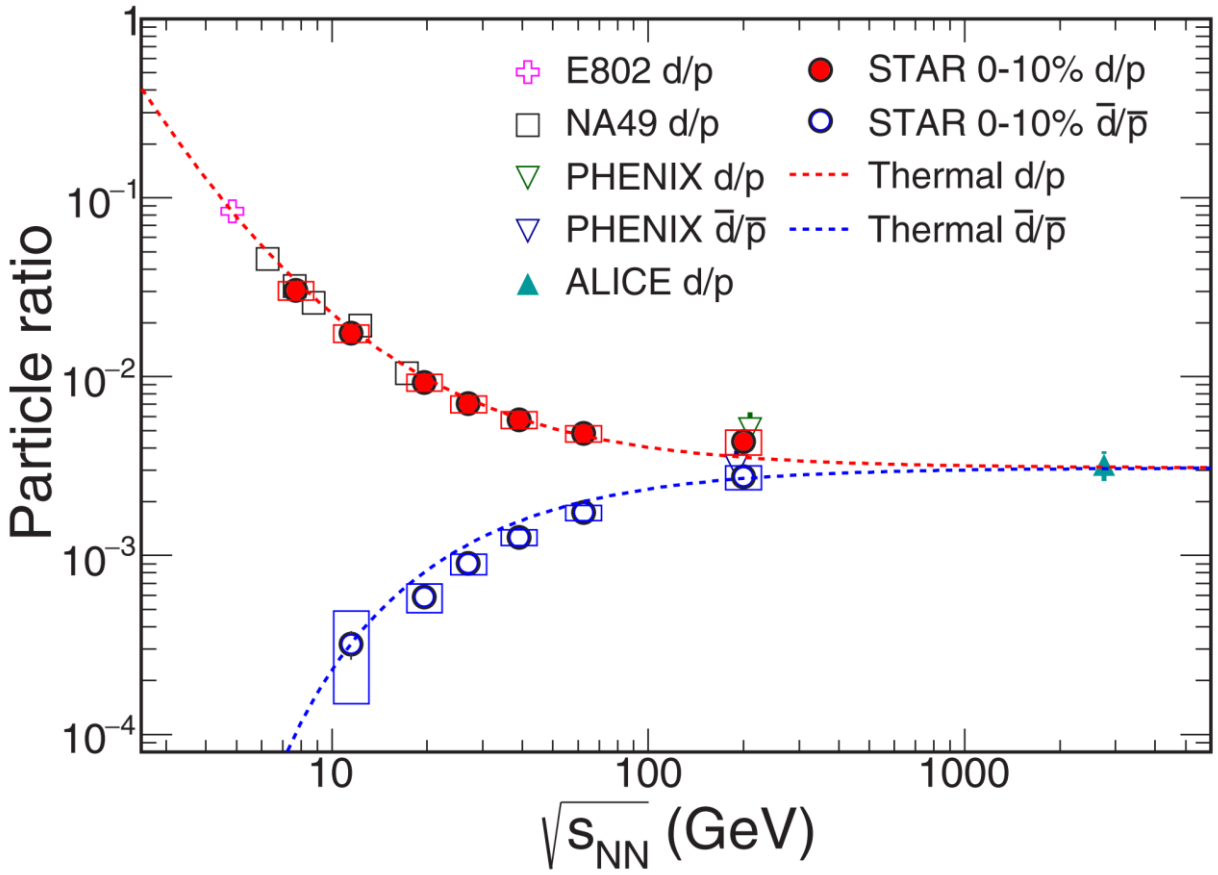
***What about light nuclei??***

# Deuteron Production

**Thermal model**

- Nuclei formed early | at hadronic freeze-out
- Deuteron yield can be described

**STAR:** Phys. Rev. C **99**, 064905(2019)



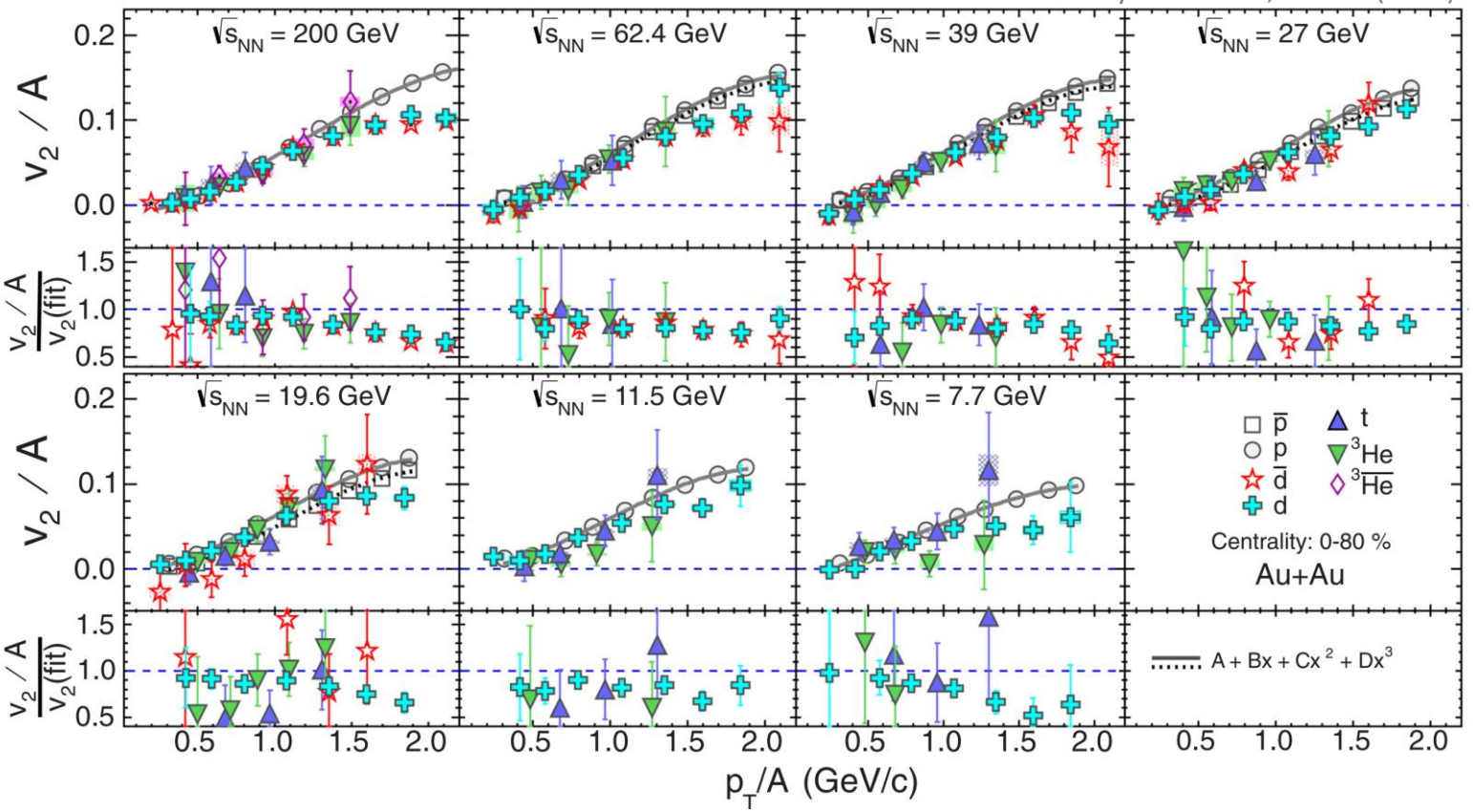

**Deuteron binding energy is 2.2 MeV, how to keep bound in the fireball?**

# Light nuclei $v_2$

**Coalescence Model**

- Light nuclei formed at later stage of fireball evolution
- Through combination of protons and neutrons with close position and momentum

**STAR:** Phys. Rev. C **94**, 034908(2016)

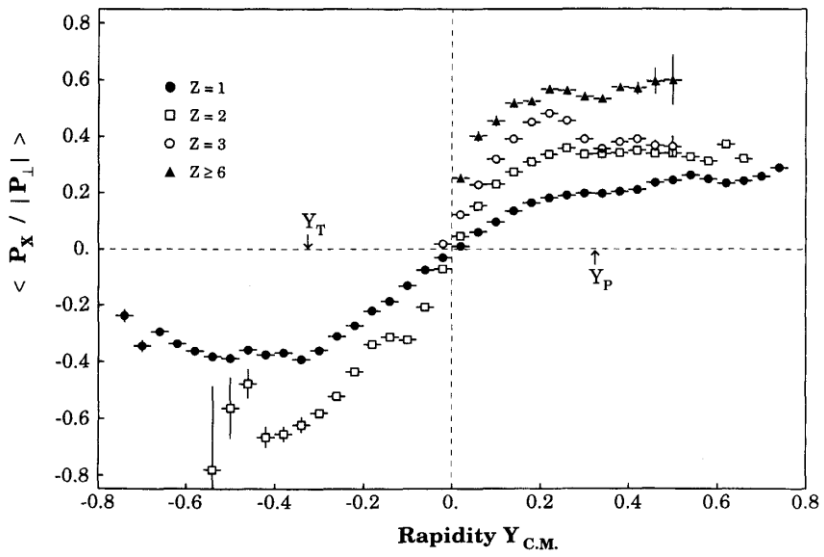



Mass scaling behavior of deuteron $v_2$ within $p_T$<3.0 GeV/c nearly for all energies

# Light Nuclei $v_1$ Measurements

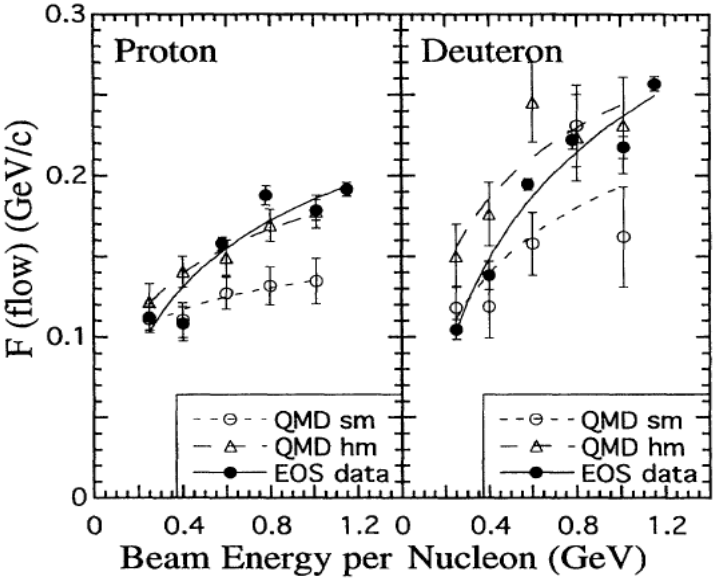
Phys. Rev. Lett. **59**, 2720(1987)

Au+Au 0.2GeV/nucleon




Phys. Rev. Lett. **75,** 2100(1995)

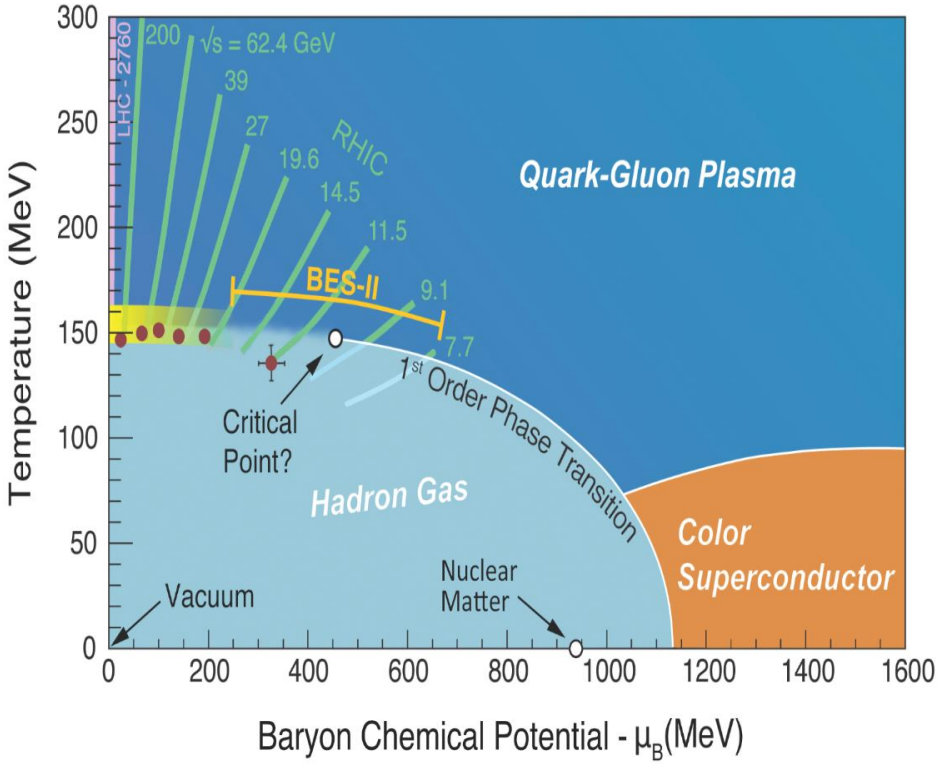
Au+Au 0.25A-1.15A GeV




- Stronger collective flow observed for heavier nuclei
- The proton and deuteron directed flow increase monotonically with rising beam energy
- The differences in fragment flow become larger with rising beam energy

How about BES program energies???

# The Beam Energy Scan at RHIC/STAR




**Map QCD phase diagram**

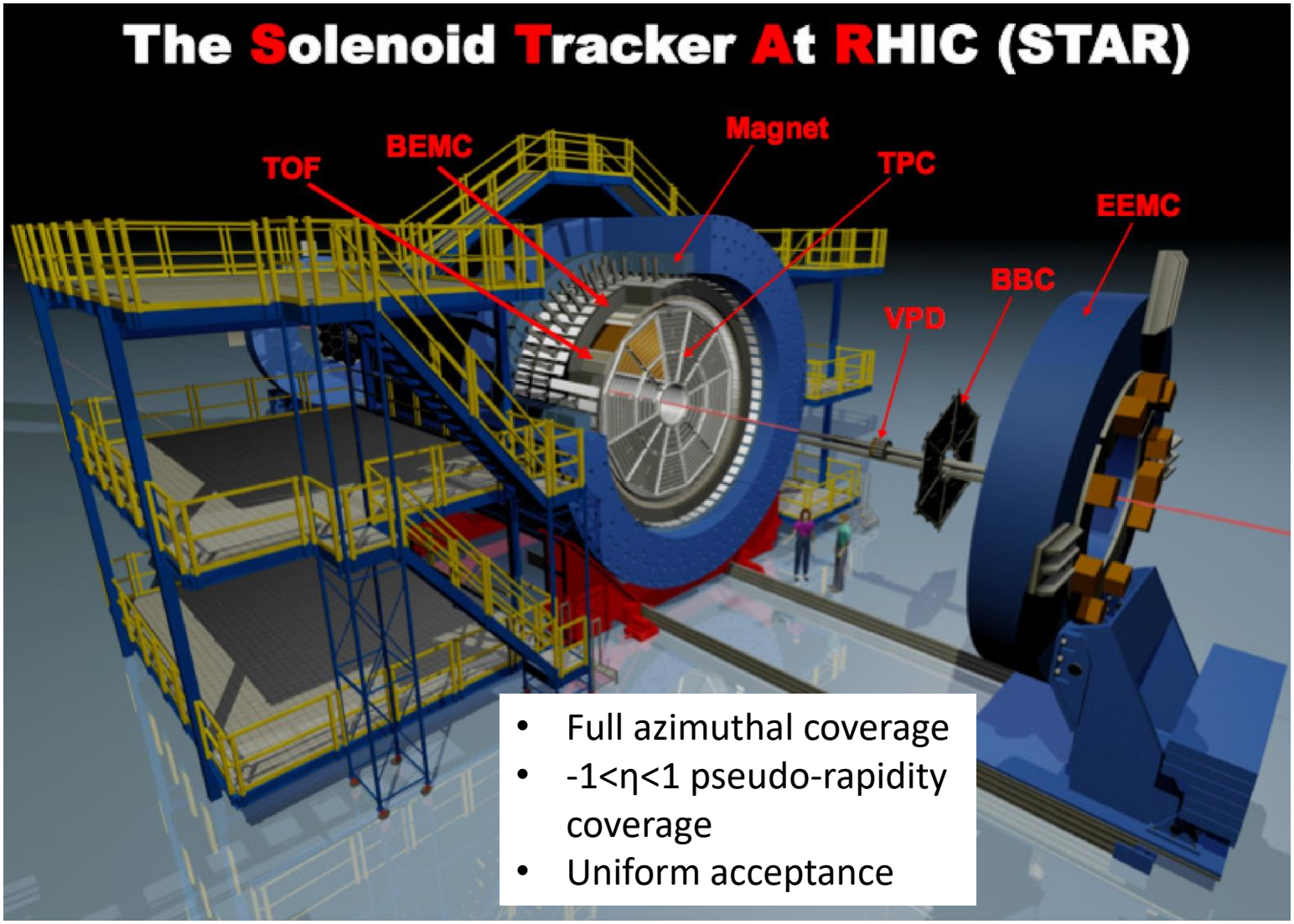
- Search for 1st order phase transition
- Search for critical point

Directed flow ($v_1$) is a key observable to search for the signature of 1st order phase transition.

Au+Au events usable for analysis

| $\sqrt{s_{NN}}$ (GeV) | 7.7 | 11.5 | 14.5 | 19.6 | 27 | 39 |
|---|---|---|---|---|---|---|
| Events ($\times 10^6$) | 4 | 12 | 10 | 36 | 70 | 130 |

# Diagram of the STAR Detector



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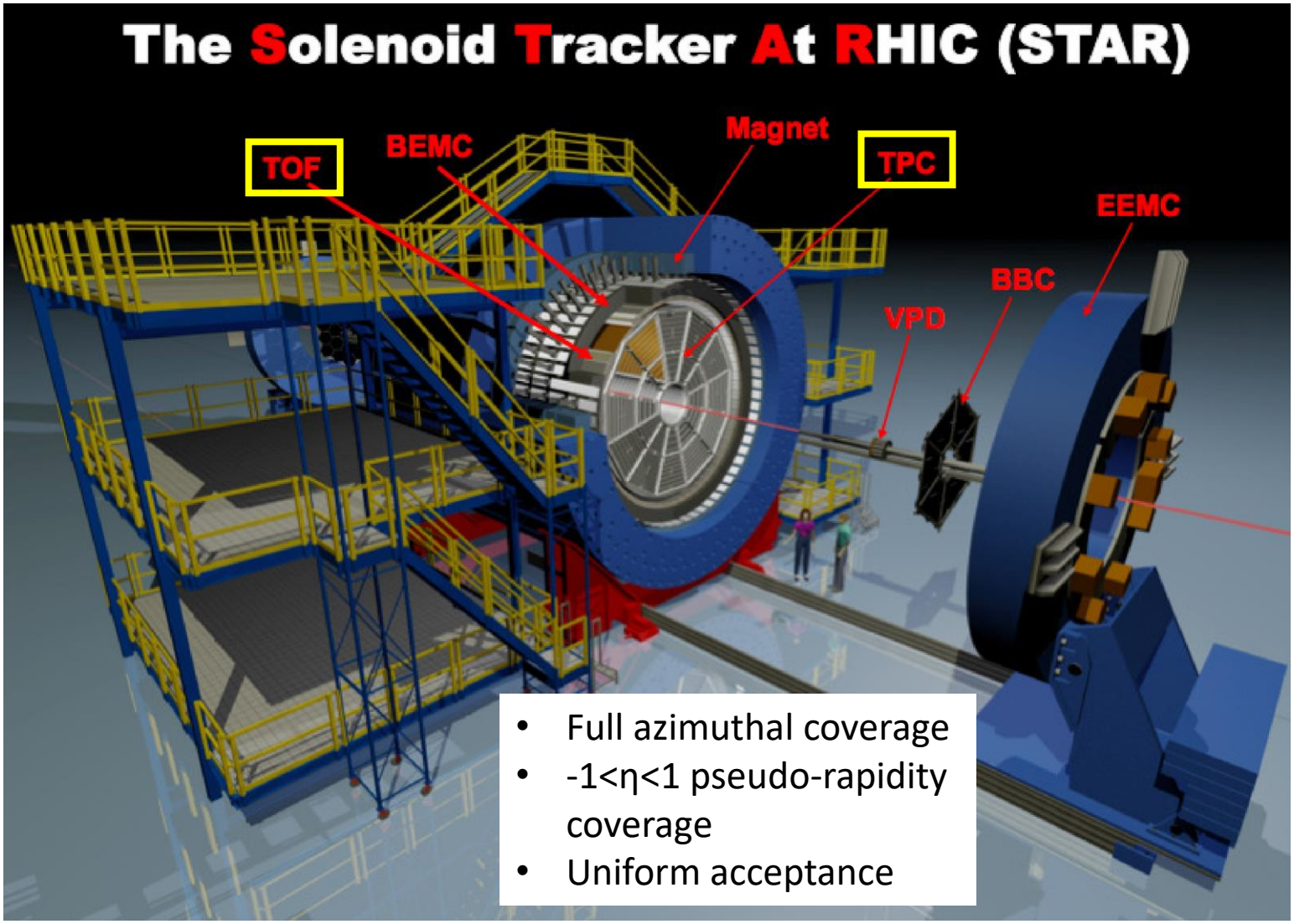

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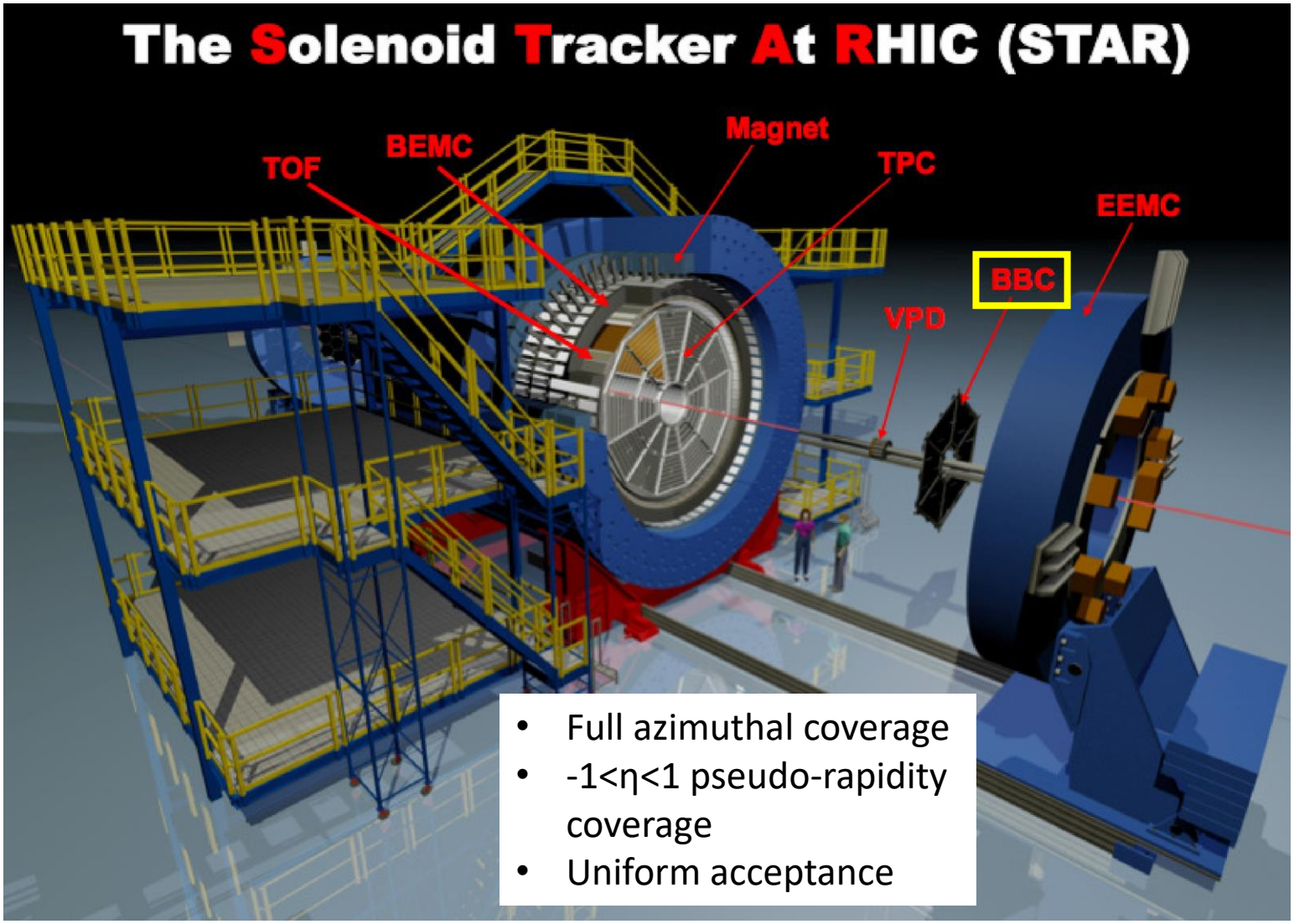
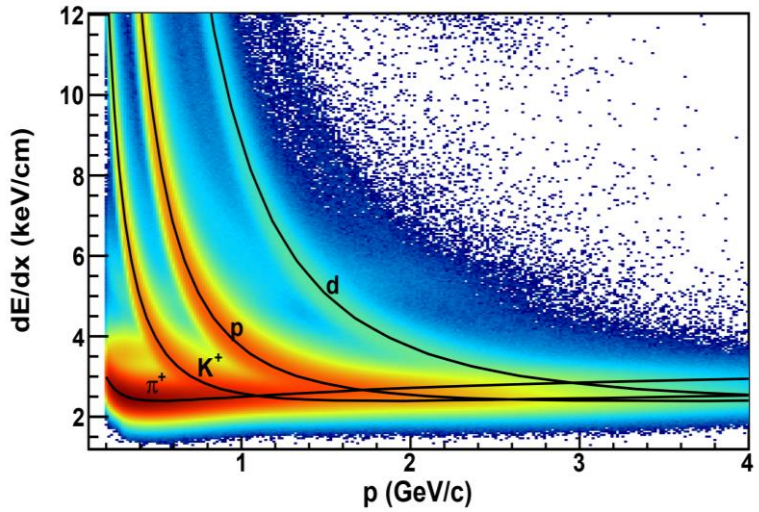
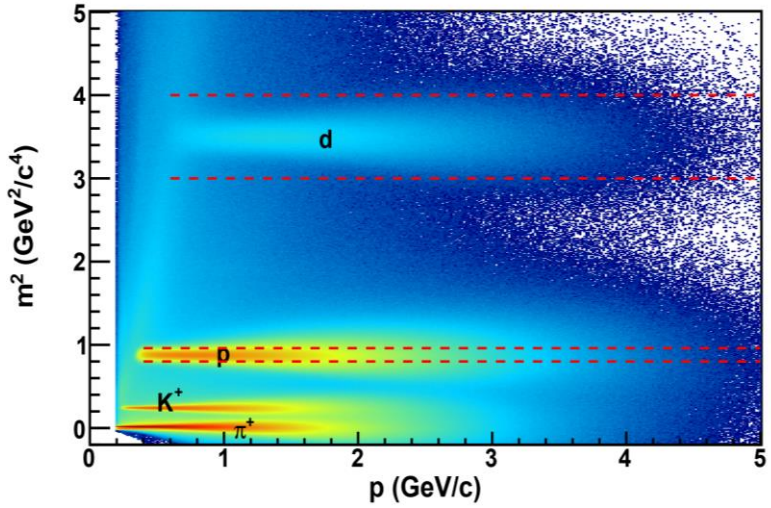
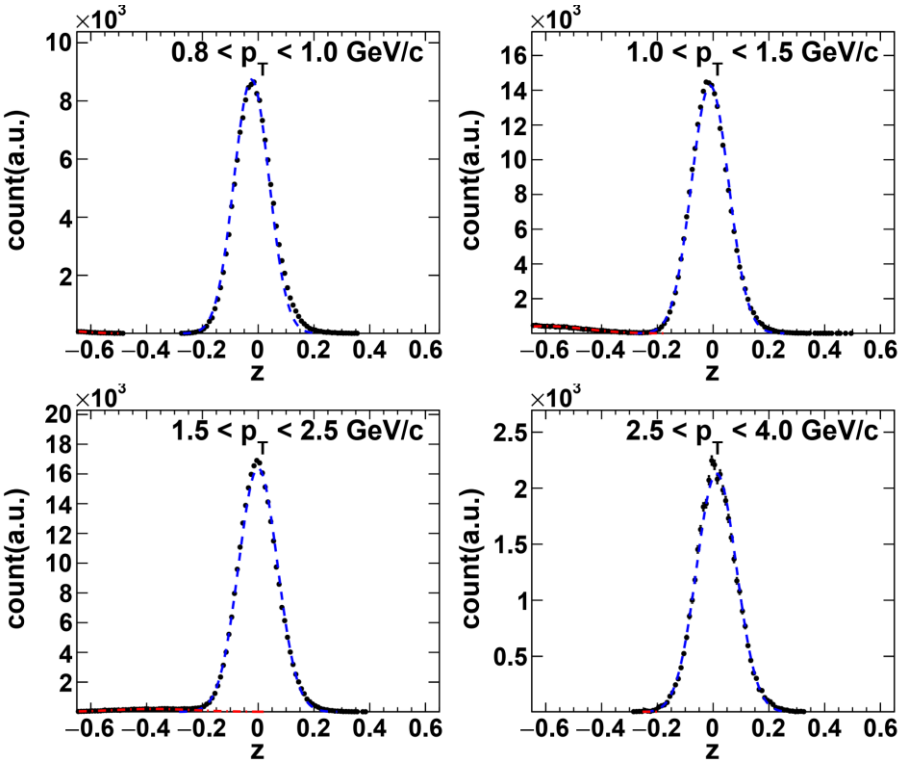


# Particle Identification



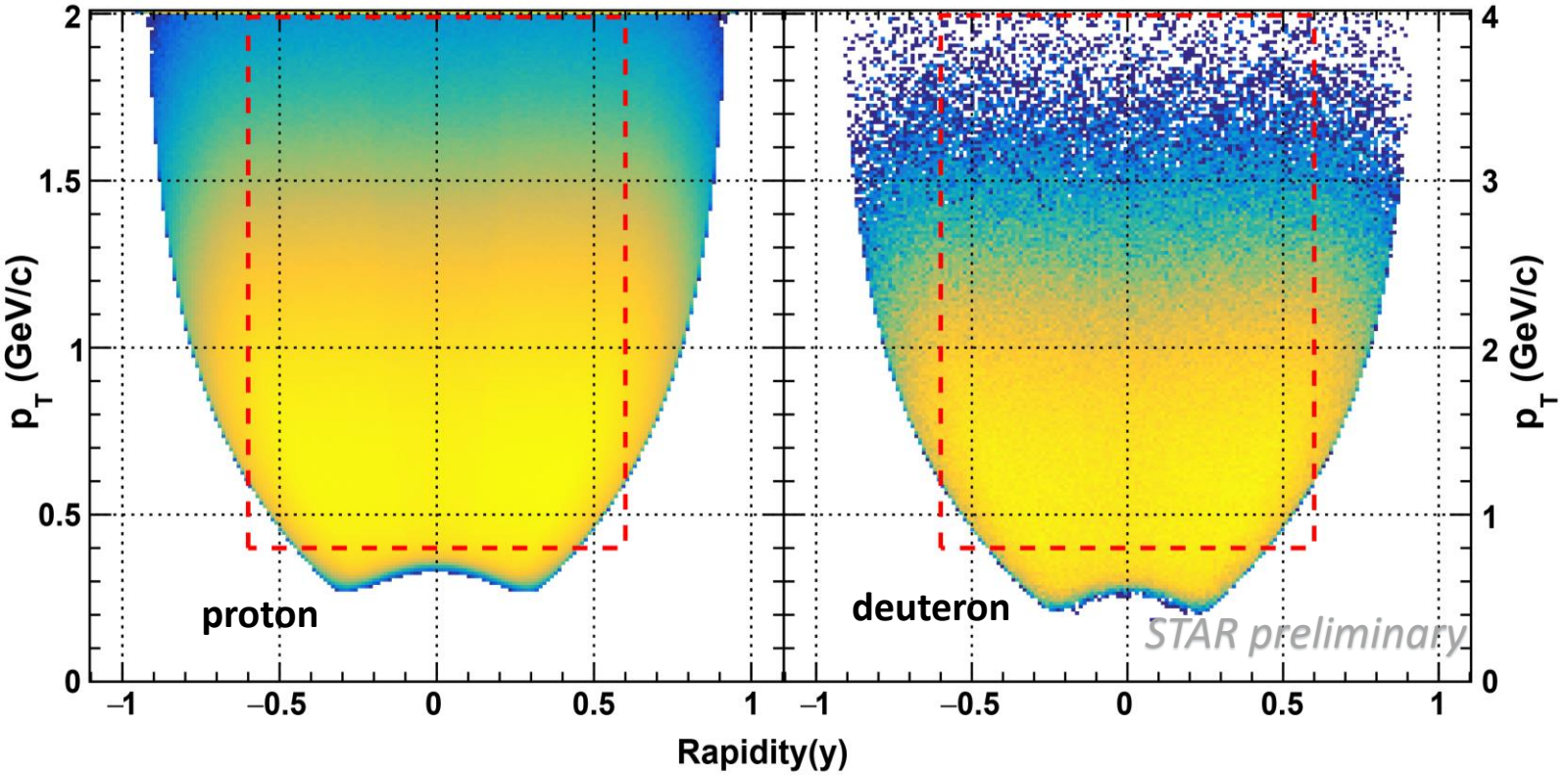




$$z = \ln\left(\frac{(dE/dx)_{measured}}{(dE/dx)_{Bichsel}}\right)$$




- Energy loss: -0.2 < z < 0.2
- $m^2$ : 3.0< $m^2$ < 4.0 $(GeV/c^2)^2$

# Phase Space Distribution




For $v_1$ calculation

- Rapidity : -0.6 < y < 0.6
- Transverse momentum : 0.4 < $p_T$ < 2.0 GeV/c for proton;
  0.8 < $p_T$ < 4.0 GeV/c for deuteron

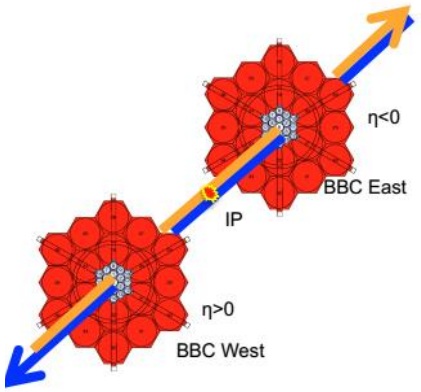
# 1st Order Event Plane Reconstruction

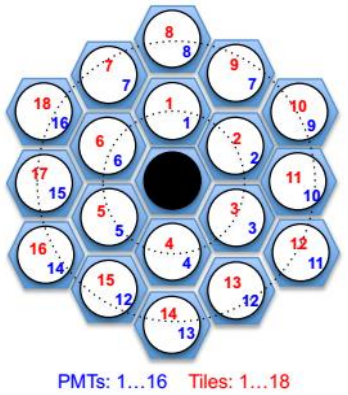
$$v_1 = \langle \cos(\phi - \psi_{RP}) \rangle$$

$$Q_n \cos(n\Psi_n) = X_n = \sum_i w_i \cos(n\phi_i),$$

$$Q_n \sin(n\Psi_n) = Y_n = \sum_i w_i \sin(n\phi_i),$$

$$\Psi_n = \left( \tan^{-1} \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) \Big/ n.$$



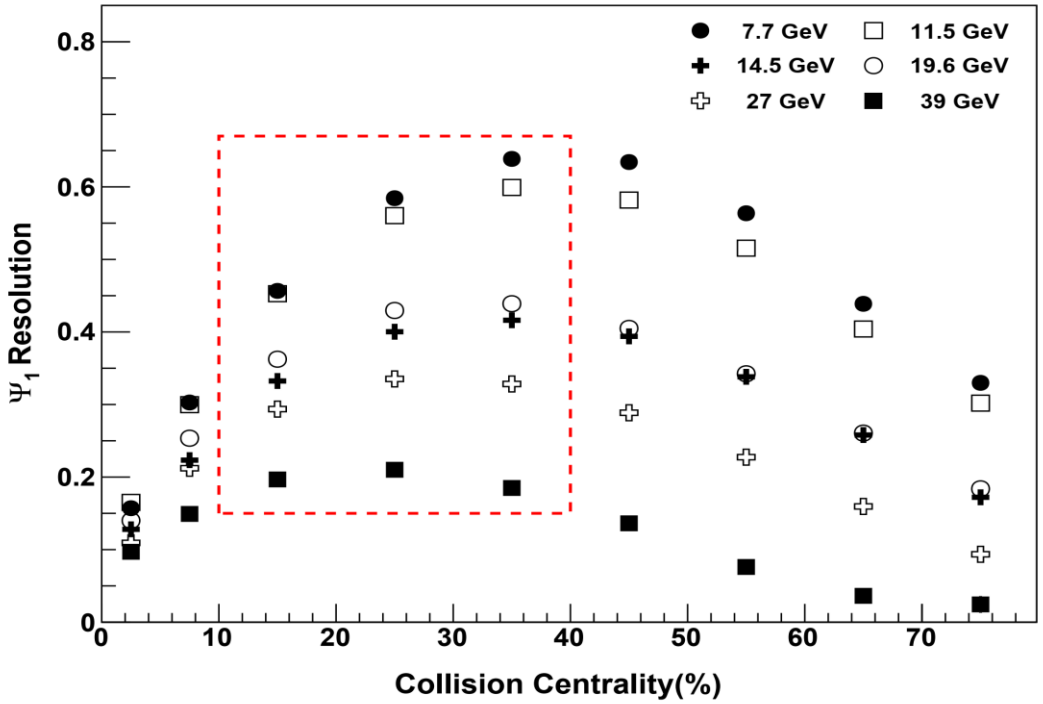

- 1st order event plane ($\psi_1$) estimated with east and west BBC detectors
  - →BBC coverage 3.3 <|η|<5.0
  - →large η gap between TPC and BBC reduces non-flow effects
- The raw $\psi_1$ distributions were flatten by shifting method

# Event Plane Resolution

The estimated event plane with respect to the real reaction plane is calculated by the event plane resolution.

$$R_1 = \langle \cos(\psi_1 - \psi_{RP}) \rangle$$

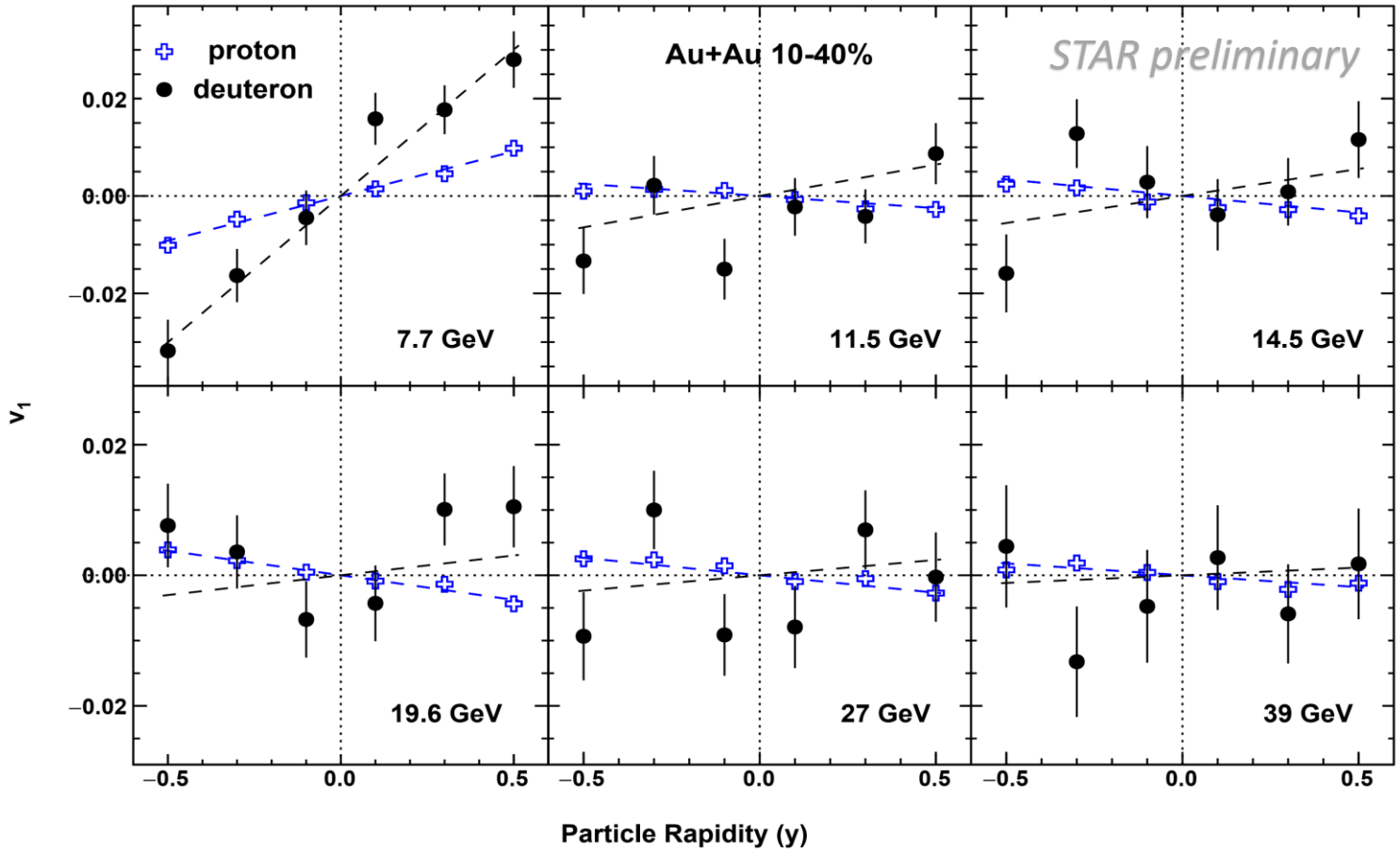
$$\langle \cos(\psi_{east} - \psi_{west}) \rangle = \langle \cos(\psi_{east} - \psi_{RP}) \rangle \langle \cos(\psi_{RP} - \psi_{west}) \rangle$$




$\psi_1$ resolution improves at low collision energies because the stronger $v_1$ near the BBC rapidity coverage.

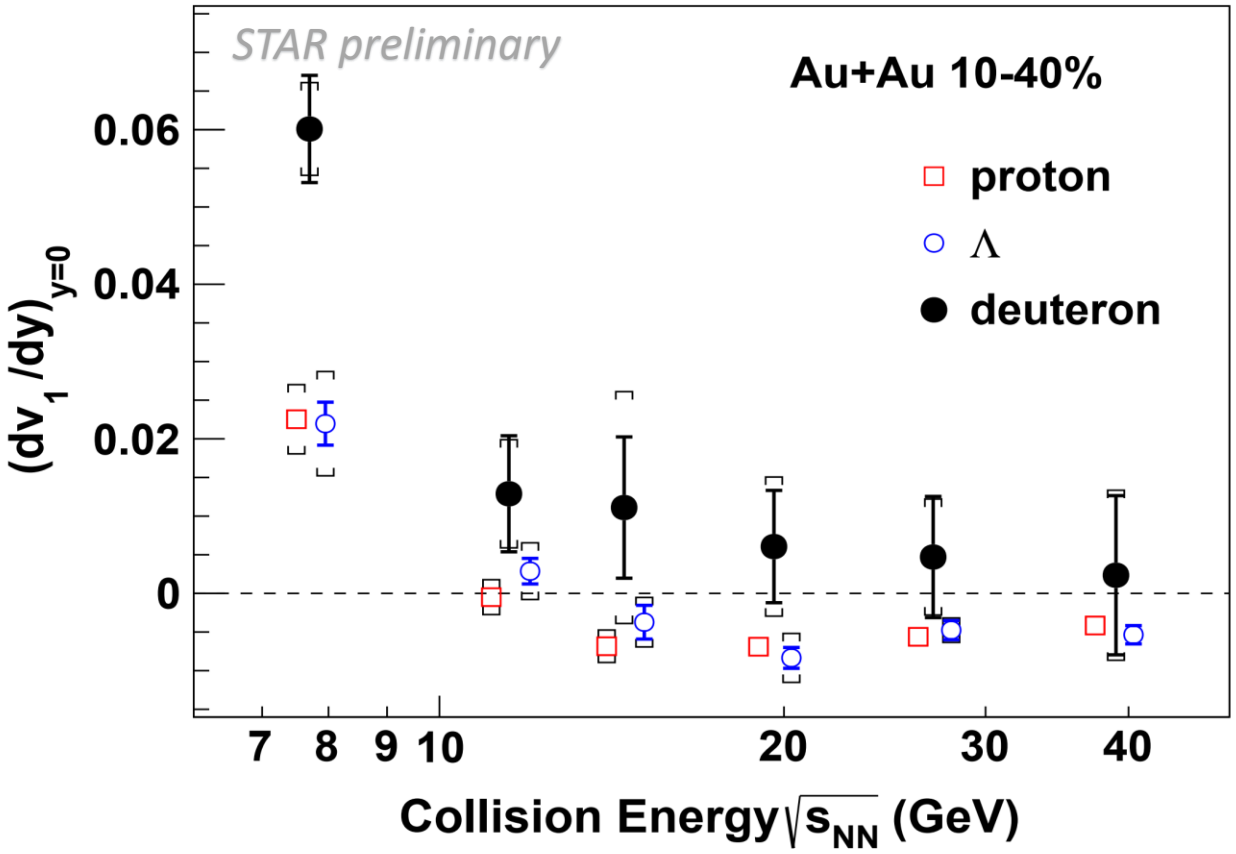
# Rapidity Dependence of $v_1$

$$v_1 = \frac{v_1^{obs}}{R_1} = \frac{\langle \cos(\phi - \psi_1) \rangle}{R_1}$$




The slopes at the mid-rapidity (|y|<0.6) were extracted with linear functions for mid-central collisions.

# Energy Dependence of $v_1$ Slope




- The $v_1$ slopes at mid-rapidity of deuteron are positive for all energies
- Strong enhancement of deuteron $v_1$ slope observed at 7.7 GeV, while close to zero for 10 GeV

# Coalescence Model

## Deuteron $v_1$

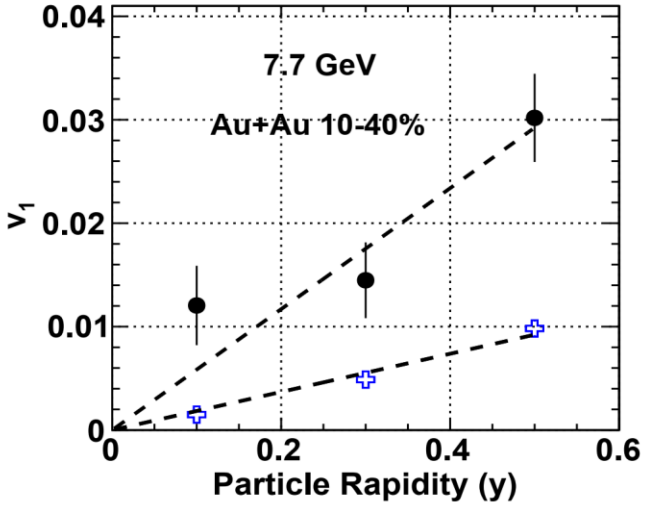
constituent nucleons are close in space and have similar velocities.
At mid-rapidity:

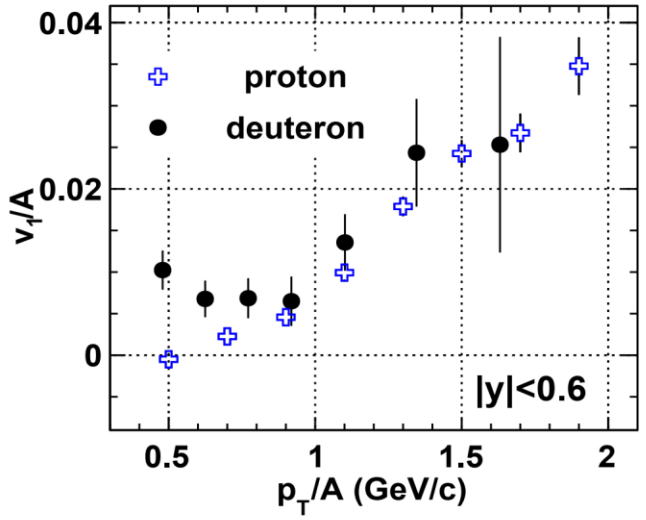
$$\vec{p}_T(d) \approx 2\vec{p}_T(p), \quad y(d) \approx y(p)$$

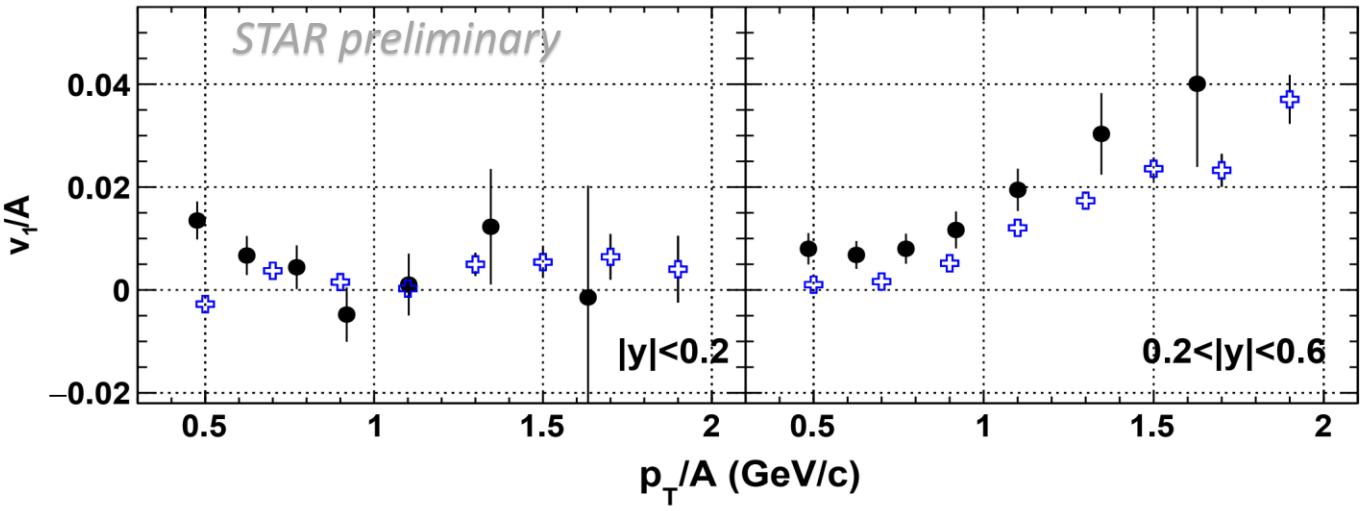
$$v^d{}_1(p_T, y) = \frac{2v^p{}_1(\frac{p_T}{2}, y)}{1+\left(2v^p{}_1(\frac{p_T}{2}, y)\right)^2}$$

if $v_1 << 1$ $\quad v^d{}_1(p_T, y) \approx 2v^p{}_1(\frac{p_T}{2}, y)$

# $p_T$ Dependence of Deuteron $v_1$ at 7.7GeV

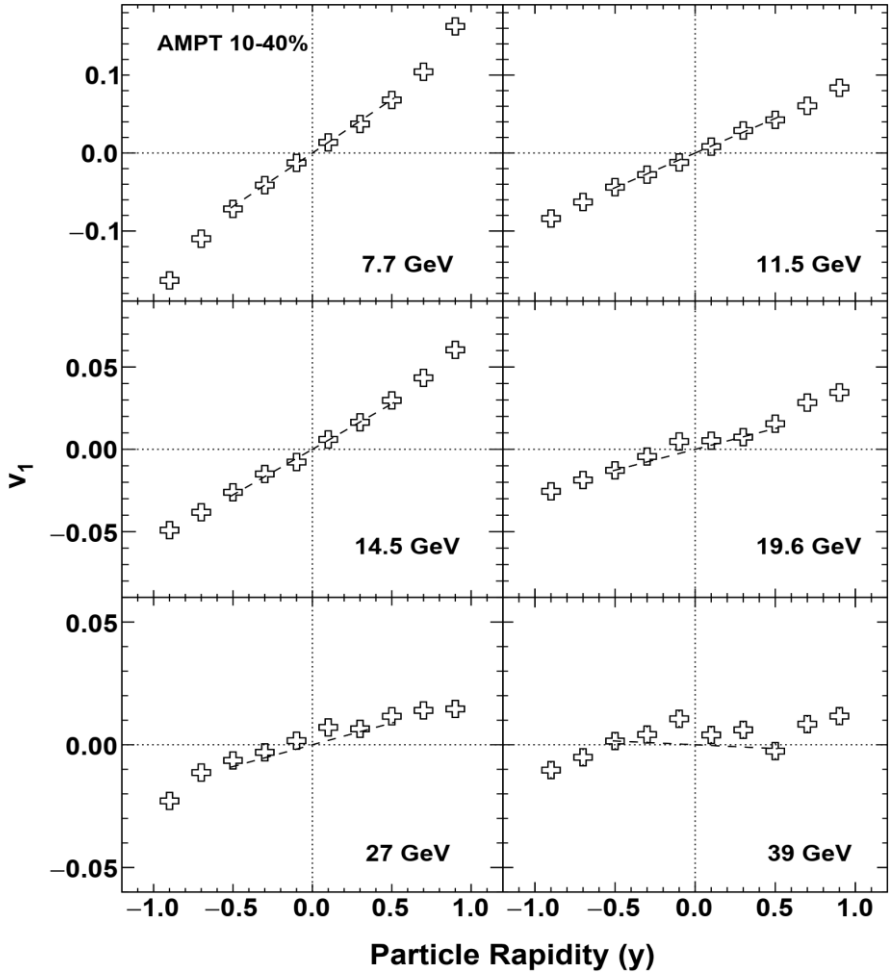


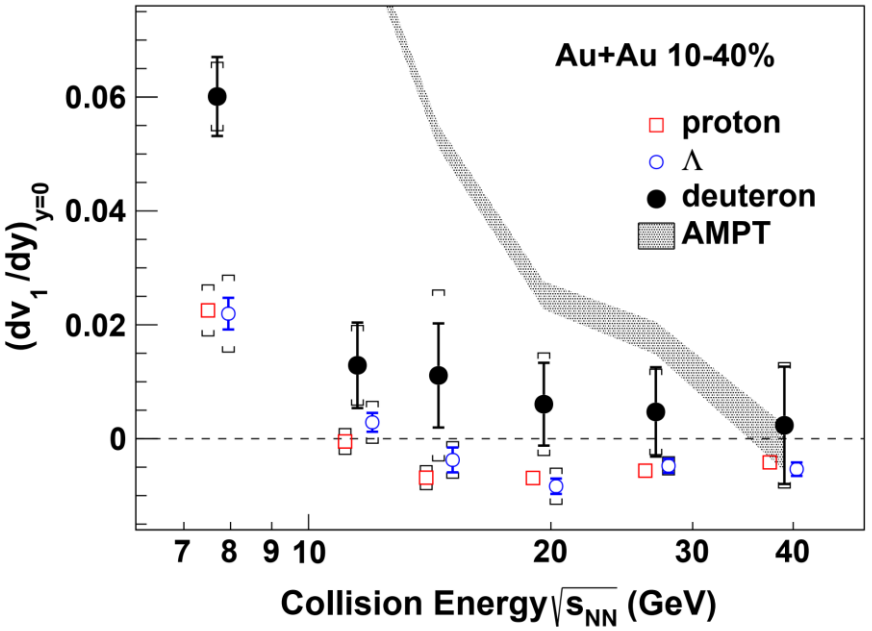



# Deuteron $v_1$ from AMPT Simulation

In AMPT, (anti-)deuterons are produced and dissolved via nuclear reaction in the hadronic transport stage of AMPT.




For AMPT simulation, values of $dv_1/dy$ are also positive for all energies.

# Summary

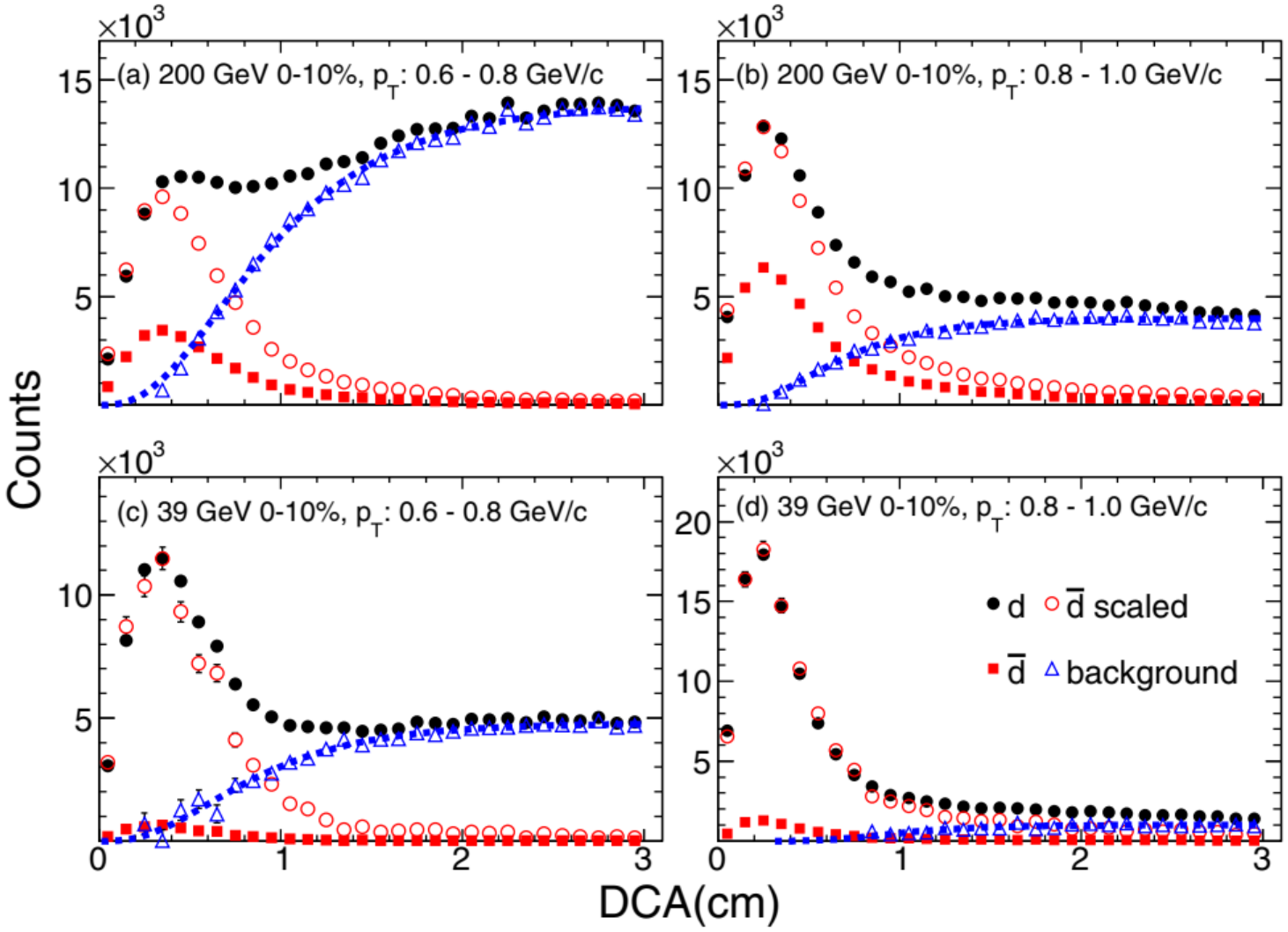
- The deuteron $v_1$ was measured in Au+Au collisions at $\sqrt{s_{NN}}$=7.7 -39 GeV. The slopes at midrapidity (|y|<0.6) were extracted
- The $dv_1/dy$ of deuteron are positive for all energies. Strong enhancement observed at $\sqrt{s_{NN}}$ =7.7 GeV, while close to zero for $\sqrt{s_{NN}}$ >10 GeV
- AMPT simulation : the $dv_1/dy$ are larger than the measurement for most energies
- **Outlook** : precise measurement of $v_1$ for light nuclei with BES II

**Thank you for Your Attention!**

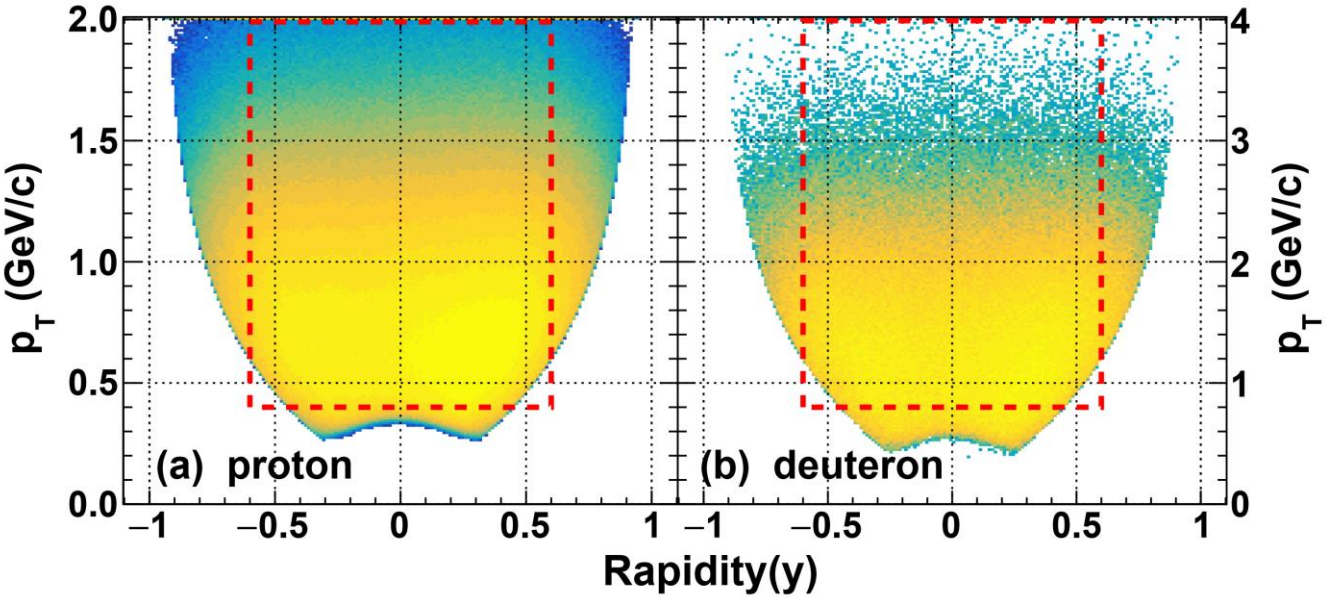
# Back Up

# DCA distribution

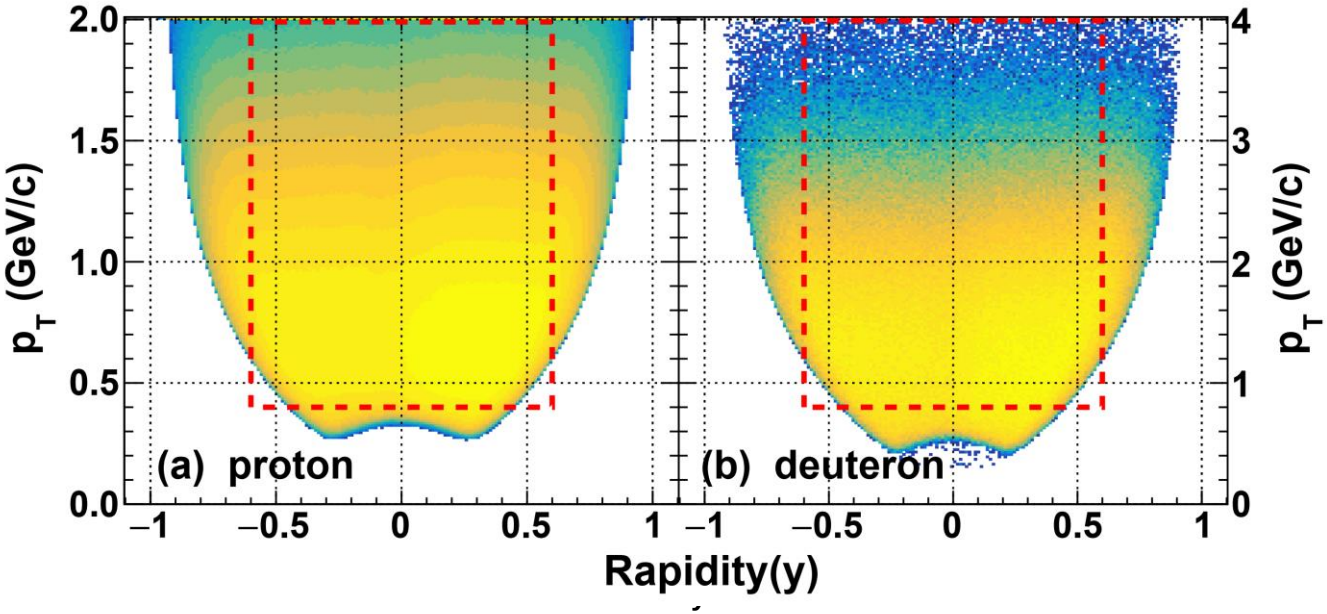
**STAR:** Phys. Rev. C **99**, 064905(2019)



# Phase space distribution




7.7 GeV




39 GeV