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Energy Dependence Measurement of Deuteron Directed Flow at RHIC

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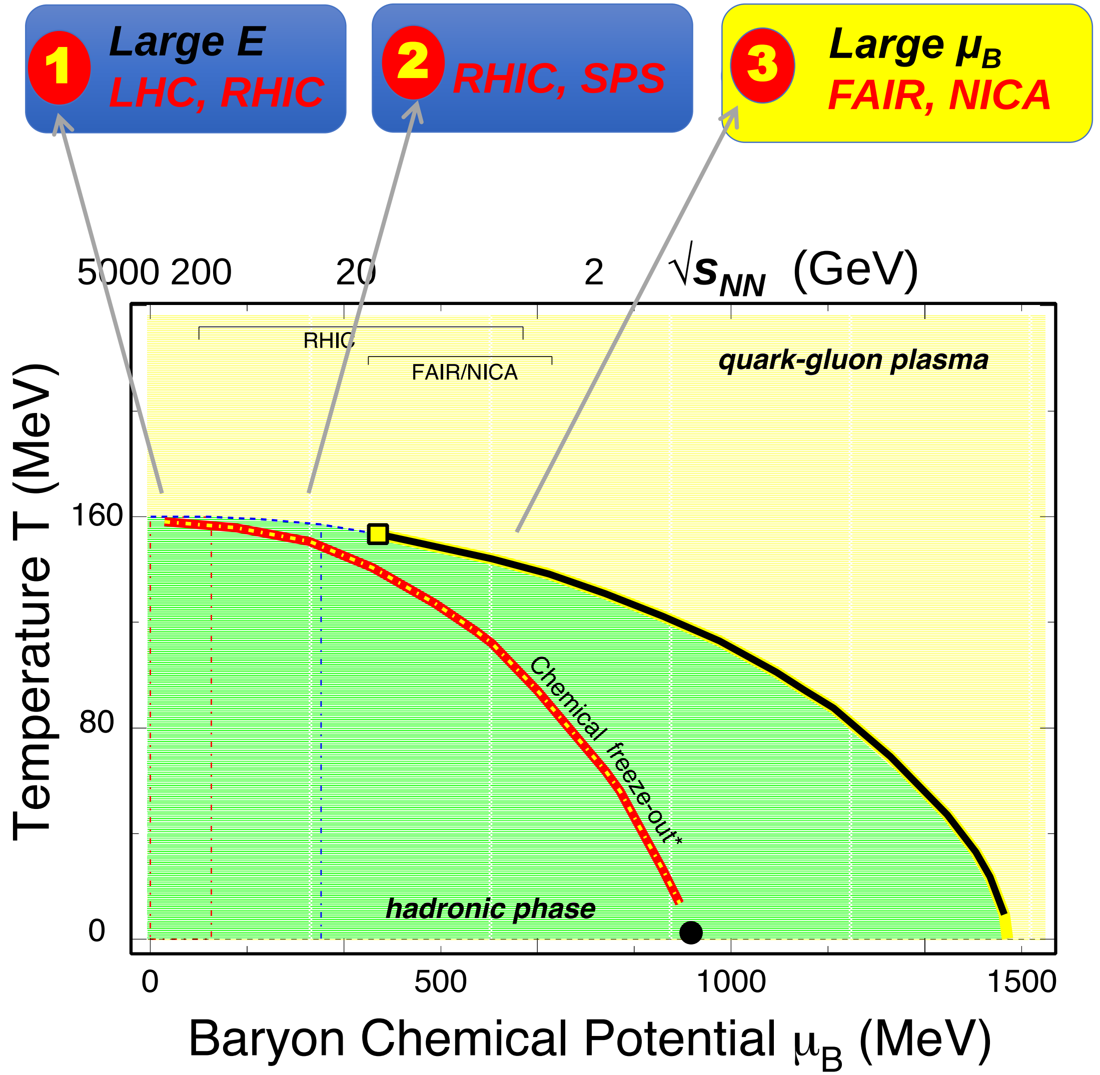
Outline

1. Motivation
2. Data analysis from STAR BES I
3. Results and discussion
4. Summary

Study the QCD Phase Structure via Light Nuclei Production in High-Energy Collisions



Observable:

1^{st} order phase transition

(1) Directed flow v_1 … *d*

Degrees of freedom

(2) v_2 - NCQ scaling … *d*

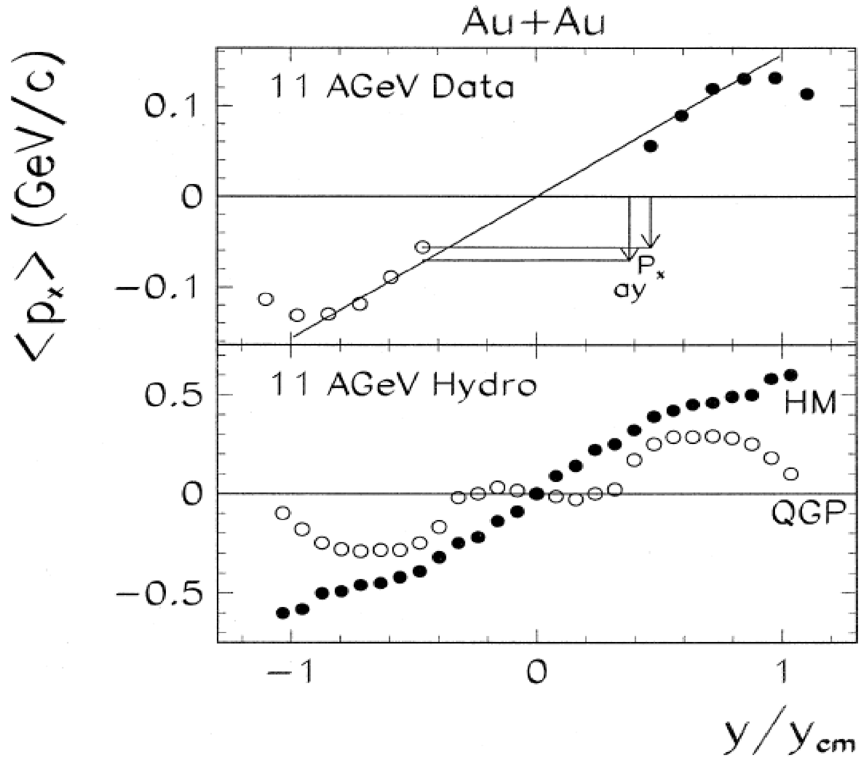
Critical Point

(3) Fluctuations … *d*

Phase Transition and Directed Flow

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

$$\frac{d^3N}{dp_T dy d\phi} = \frac{d^2N}{dp_T dy}\left(1 + 2\boldsymbol{v_1}\cos(\phi-\psi) + 2v_2\cos2(\phi-\psi) + \cdots\right)$$

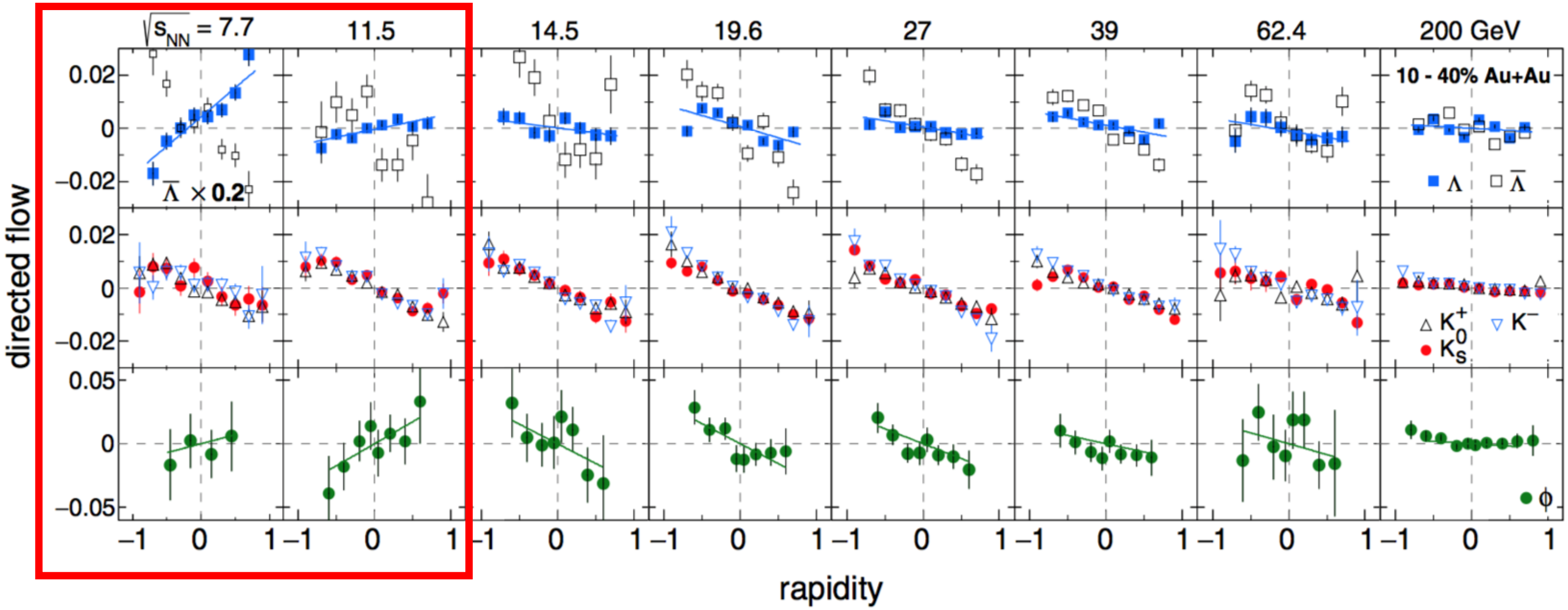


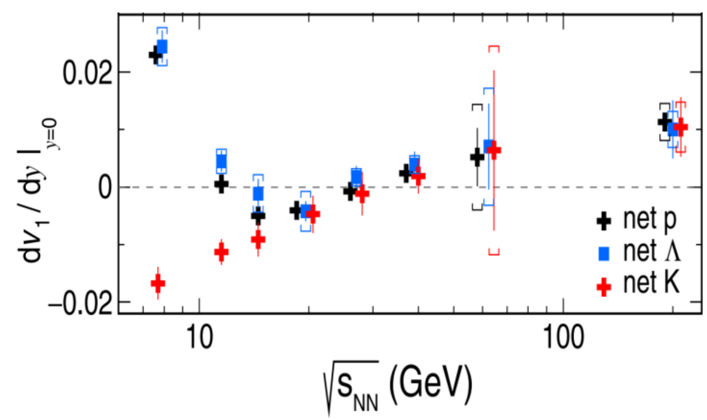
Phys. Lett. B **485,** 454(1999)

- The EOS is especially soft near the QCD phase transition
- Scan of collision energy can be used to search for phase transition
- 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)





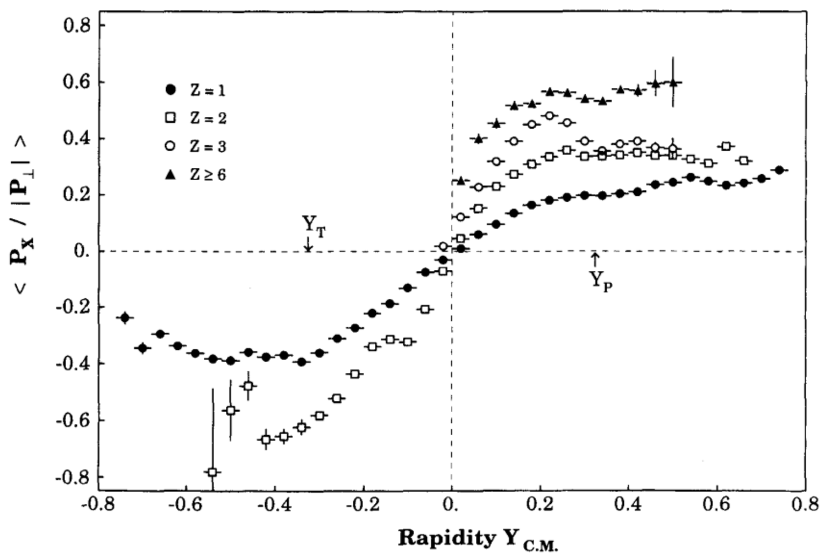
Mesons and all produced baryons show negative slope except **φ** mesons when collisions energy < 14.5 GeV.

What about light nuclei???

Light Nuclei v_1 Measurements

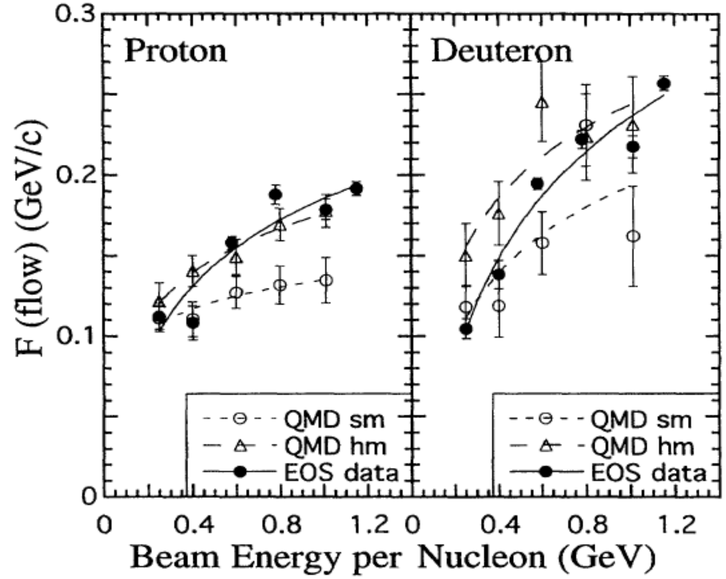
Phys. Rev. Lett. **59**, 2720(1987)

Au+Au 0.2GeV/nucleon



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

Au+Au 0.25A-1.15A GeV



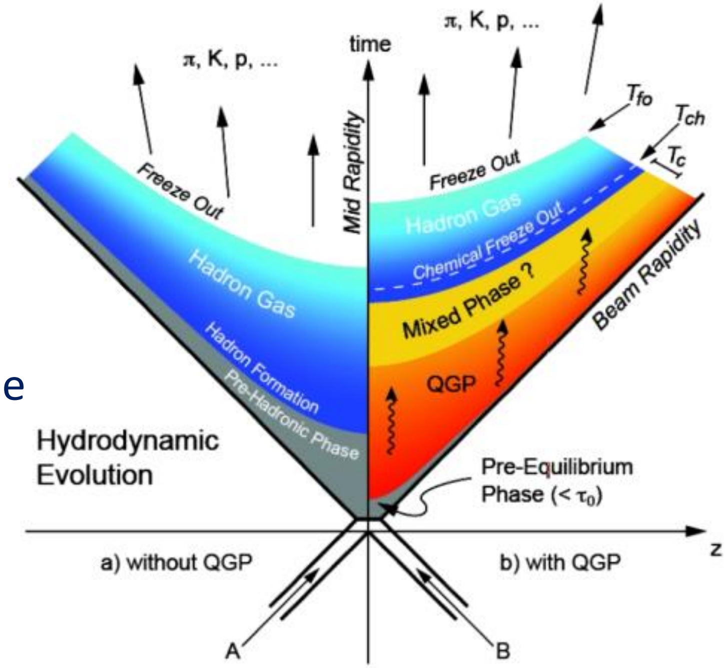
- Stronger collective flow observed for heavier nuclei
- The proton and deuteron directed flow increase monotonically with rising beam energy
- The differences in fragment flow become larger with rising beam energy

How about BES program energies???

Light Nuclei Production in Heavy Ion Collisions

Thermal model

- Assume chemical equilibrium
- Hadrons and nuclei are produced before chemical freeze-out(CFO)
- Their yields dN/dy and p_T distribution can be described with parameters related to CFO



Coalescence model

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

$$\frac{d^3N}{dp^3} \propto \left(\frac{d^3N_p}{dp_p^3}\right)^A$$

Deuteron v_1 from Nucleon Coalescence

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

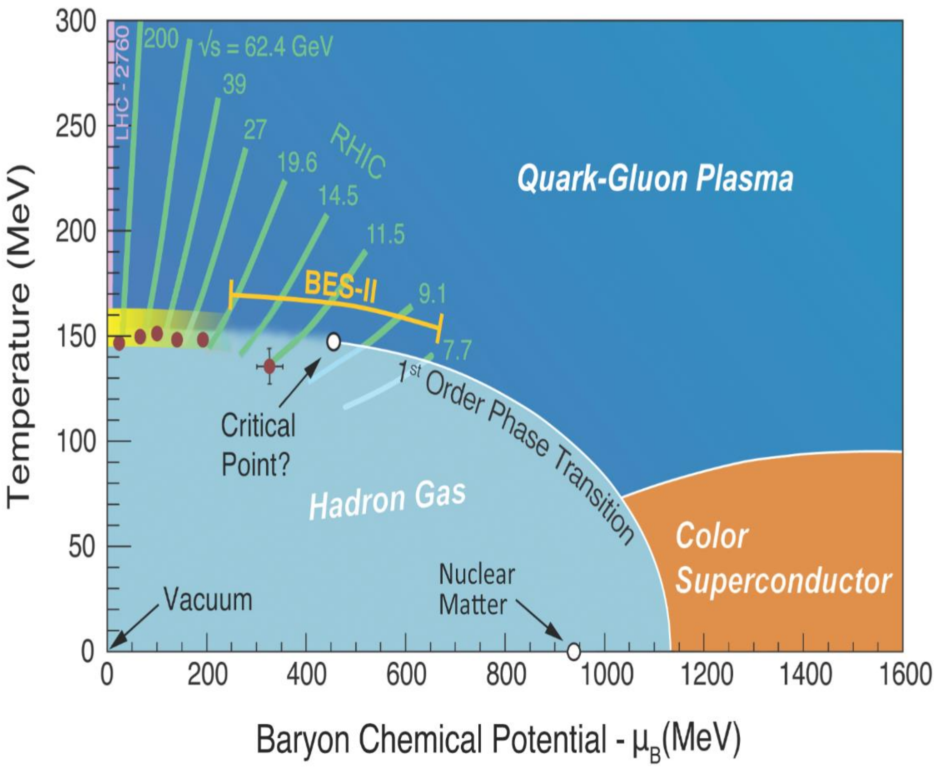
$$\vec{p}(p) \approx \vec{p}(n) \quad \rightarrow \quad \vec{p}(d) \approx 2\vec{p}(p) \quad \rightarrow \quad E(d) \approx 2E(p)$$

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

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

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

The Beam Energy Scan at RHIC/STAR



Map QCD phase diagram

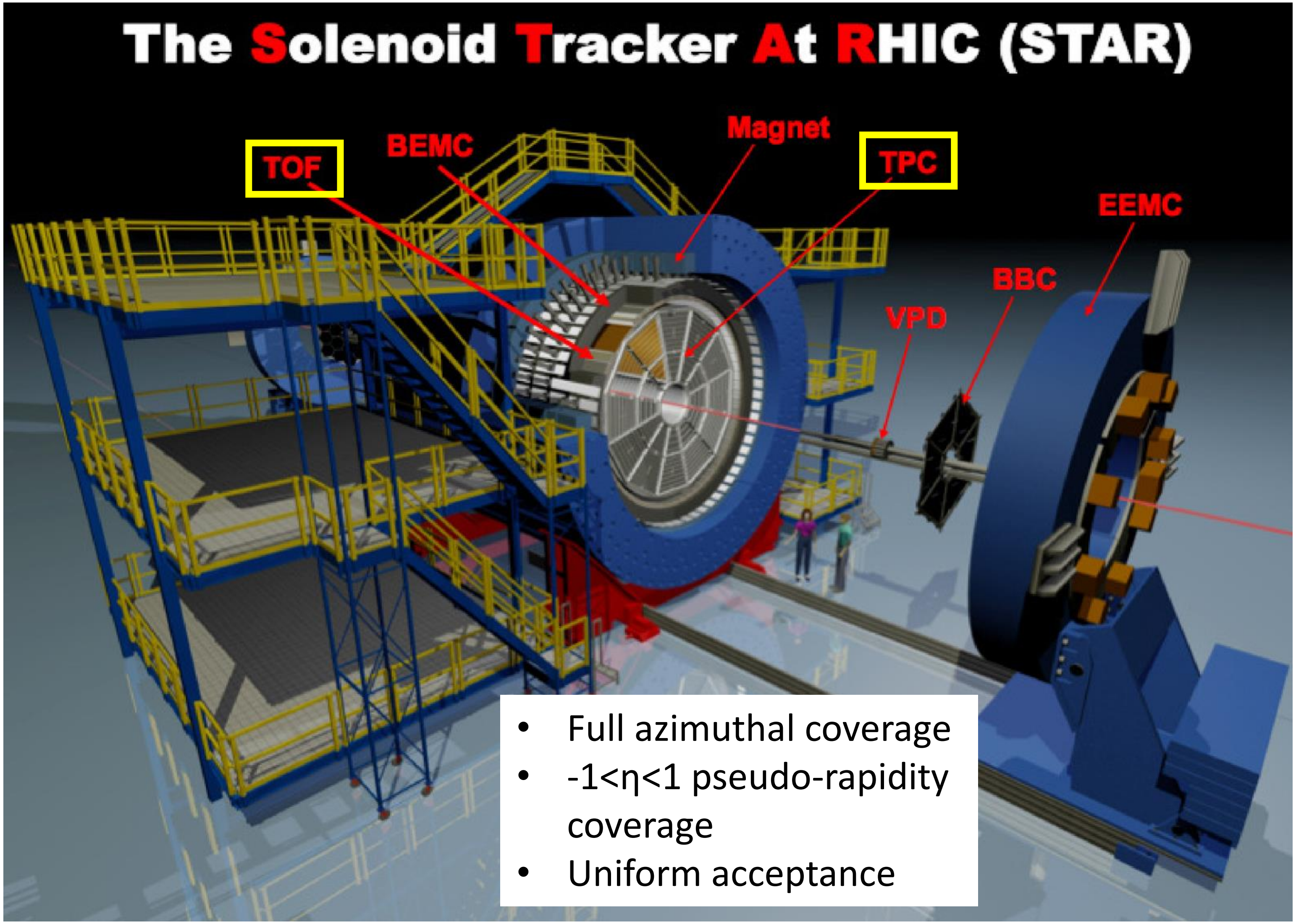
- Search for 1st order phase transition
- Search for critical point

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

Au+Au minimum bias events usable for analysis

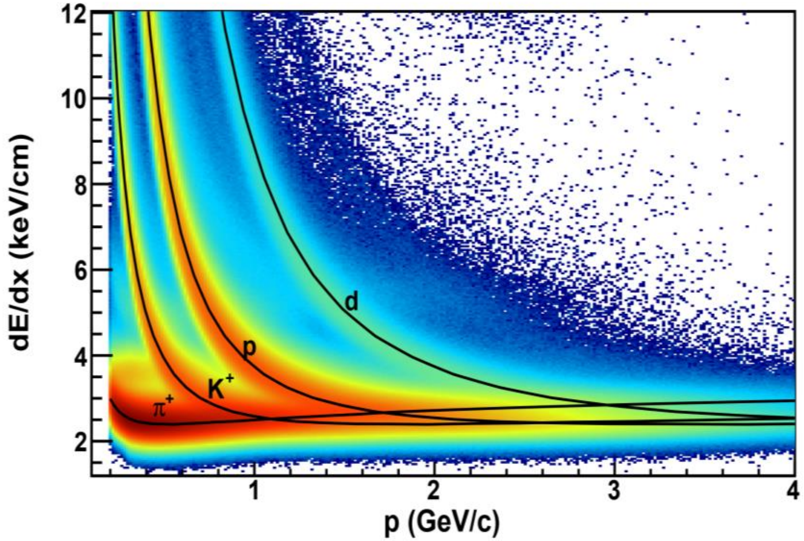
$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39
Events ($\times 10^6$)	4	12	10	36	70	130

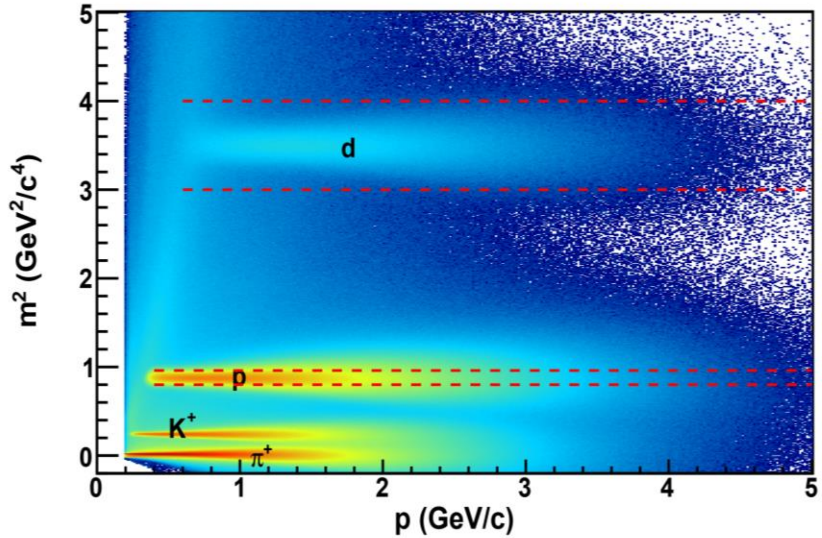
Diagram of the STAR Detector

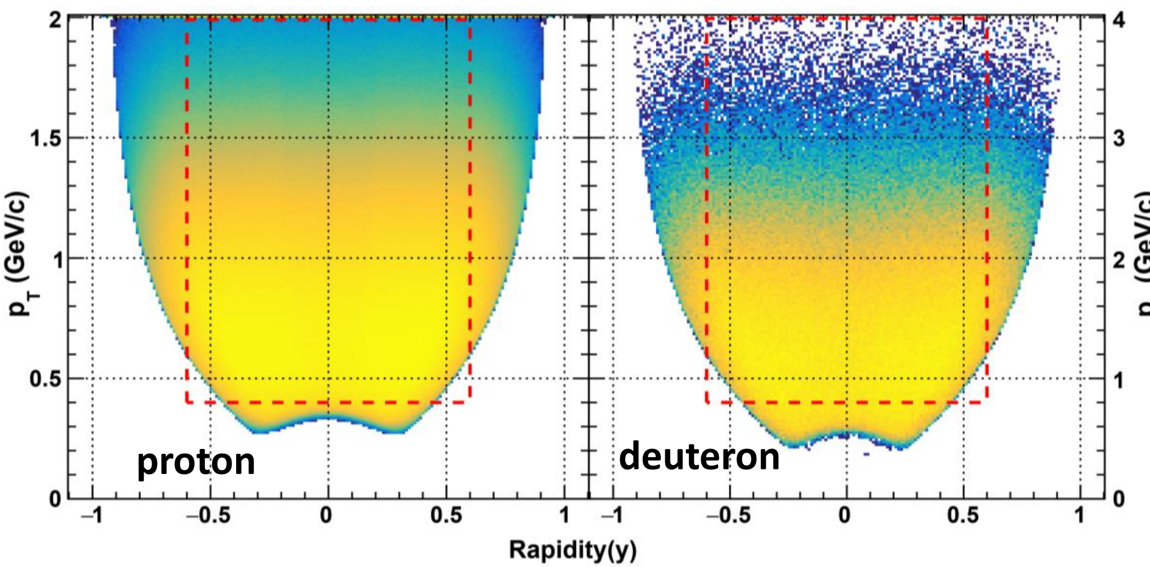


- Full azimuthal coverage
- -1<η<1 pseudo-rapidity coverage
- Uniform acceptance

Particle Identification







For v_1 calculation

- $-0.6 < y < 0.6$
- $0.4 < p_T < 2.0$ GeV/c for proton
- $0.8 < p_T < 4.0$ GeV/c for deuteron

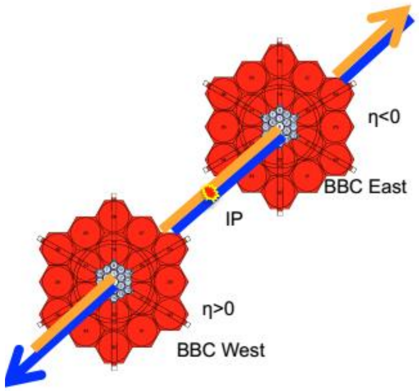
1st Order Event Plane Reconstruction

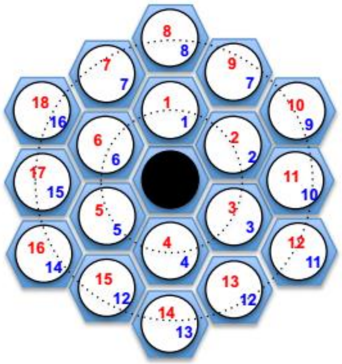
$$v_1 = \langle \cos(\phi - \psi_{RP}) \rangle$$

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

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

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





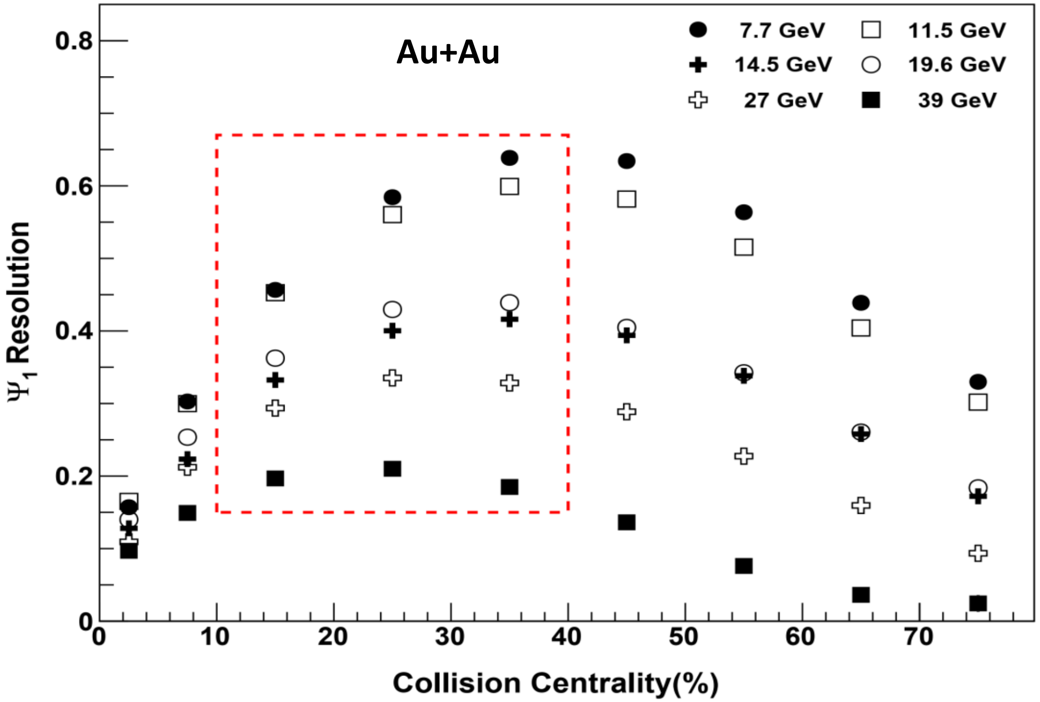
- 1st order event plane (ψ_1) estimated with east and west BBC detectors
  - →BBC coverage 3.3 <|η|<5.0
  - →large η gap between TPC and BBC reduces non-flow effects
- The raw ψ_1 distributions were flatten by shifting method

Event Plane Resolution

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

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

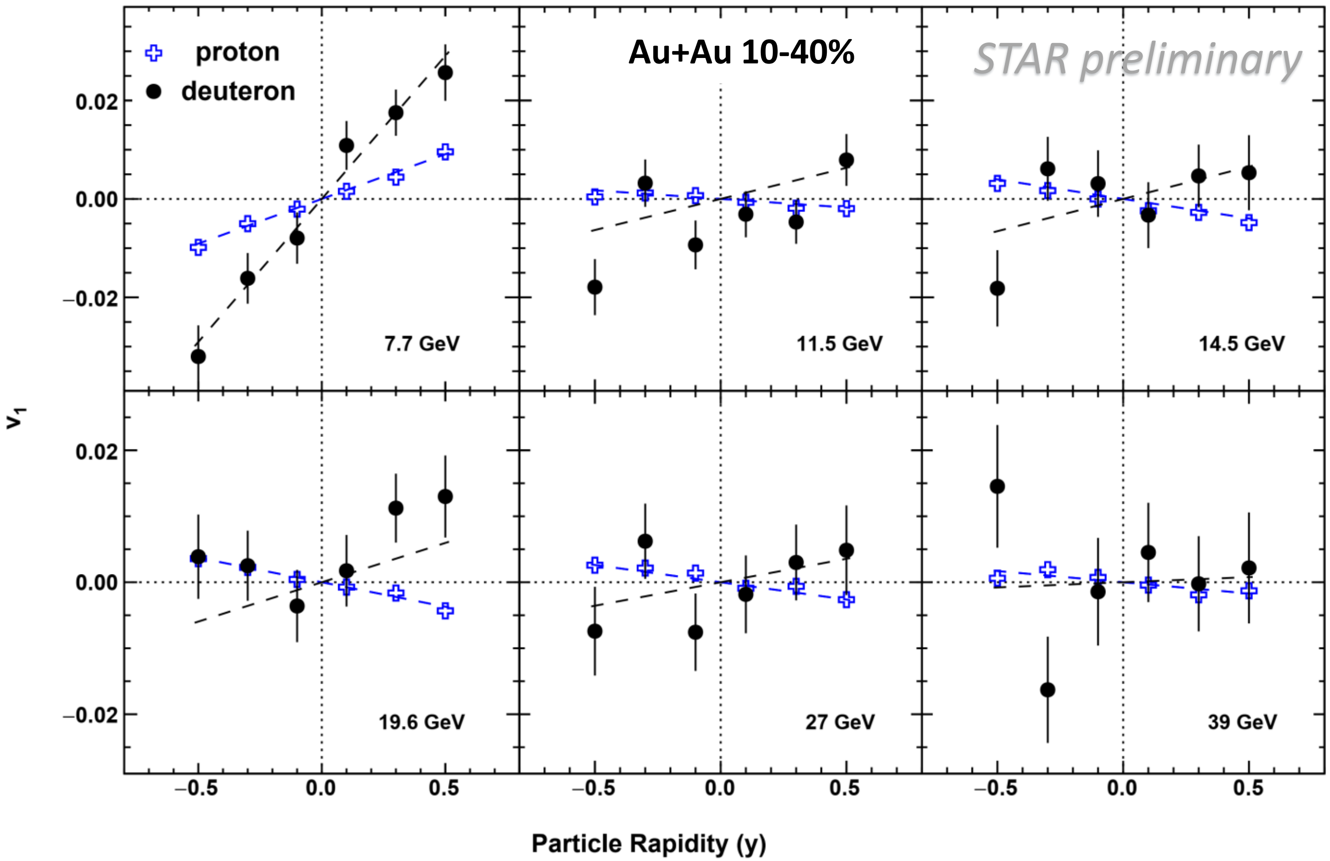
$$\langle \cos(\psi_{east} - \psi_{west}) \rangle = \langle \cos(\psi_{east} - \psi_{RP}) \rangle \langle \cos(\psi_{RP} - \psi_{west}) \rangle$$



ψ_1 resolution improves at low collision energies because the stronger v_1 near the BBC rapidity coverage.

Rapidity Dependence of v_1

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

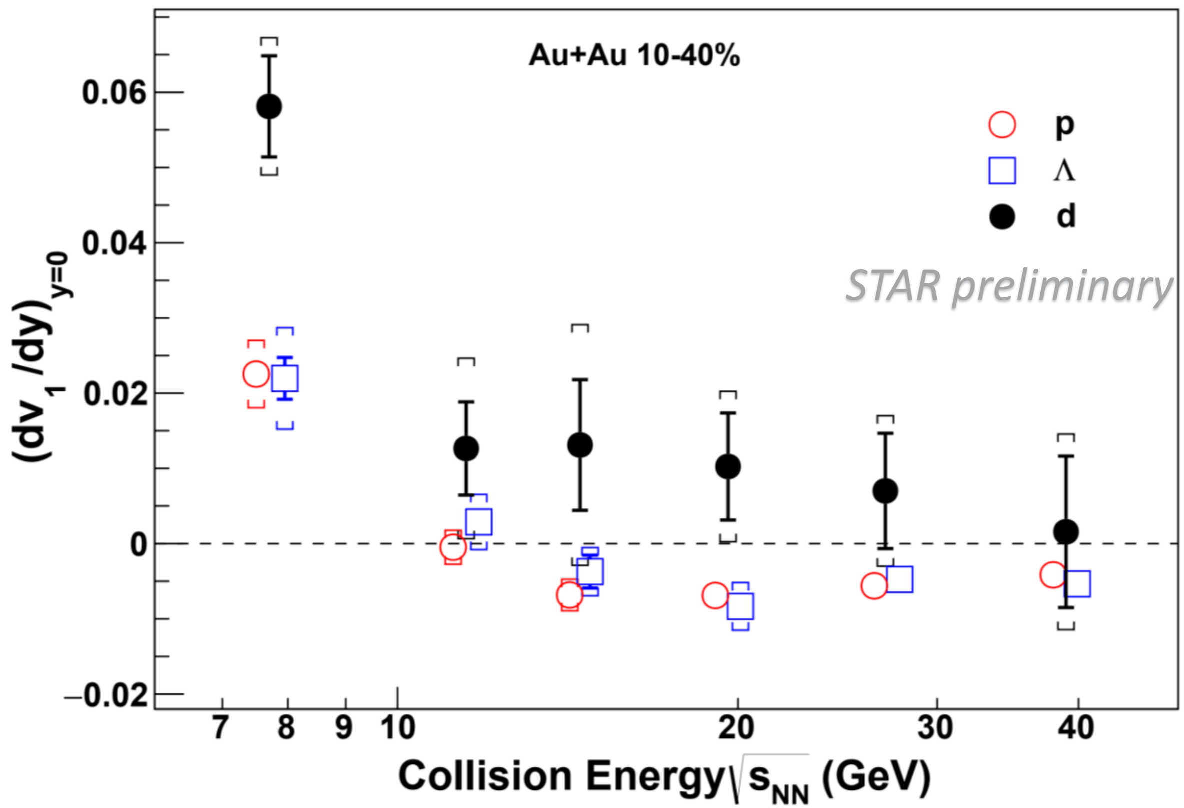


The slopes at the mid-rapidity (|y|<0.6) were extracted with linear functions for mid-central collisions.

Systematic Uncertainties

- non-flow effects (resonances, jets, final-states interactions) are reduced due to the large η gap between TPC and BBC
- Particle misidentification, background contamination and detector inefficiency was estimated by varying the track and particle selection cuts
- The difference of the slopes fitted with rapidity between $|y|<0.6$ and $|y|<0.5$ is considered as a systematic uncertainty related to the acceptance

Energy Dependence of v_1 Slope



- The v_1 slopes at mid-rapidity ($dv_1/dy|_{y=0}$) of deuteron are positive for all energies
- Strong enhancement of deuteron v_1 slope observed at $\sqrt{s_{NN}} < 7.7$ GeV, while close to zero for $\sqrt{s_{NN}}$ >10 GeV

AMPT Simulation

- A Multi-Phase Transport : a Monte Carlo transport model for heavy ion collisions at relativistic energies
- Hadronization : Lund string model for default AMPT
- Hadron cascade : A Relativistic Transport model (ART)

Phys. Rev. C 72, 064901(2005)

Phys. Rev. C 94, 054909 (2016)

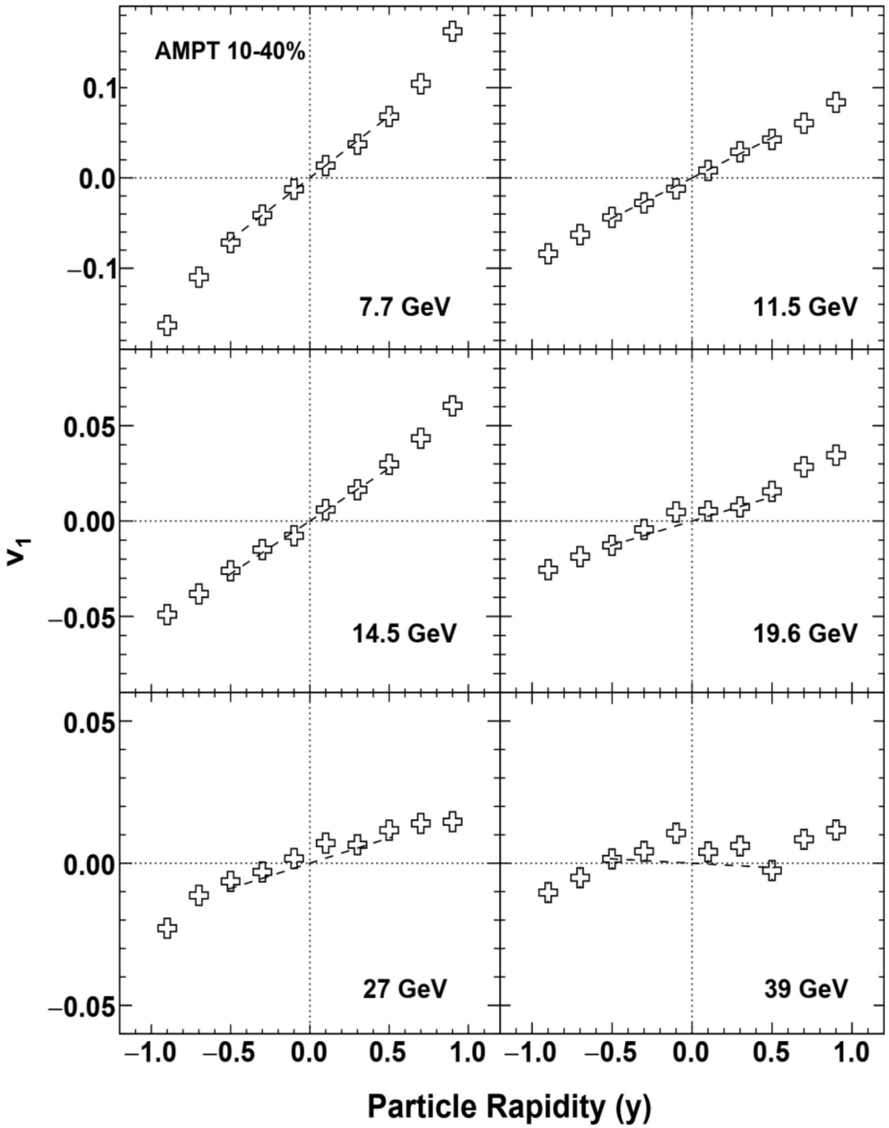
Phys. Rev. C 96, 014910 (2017)

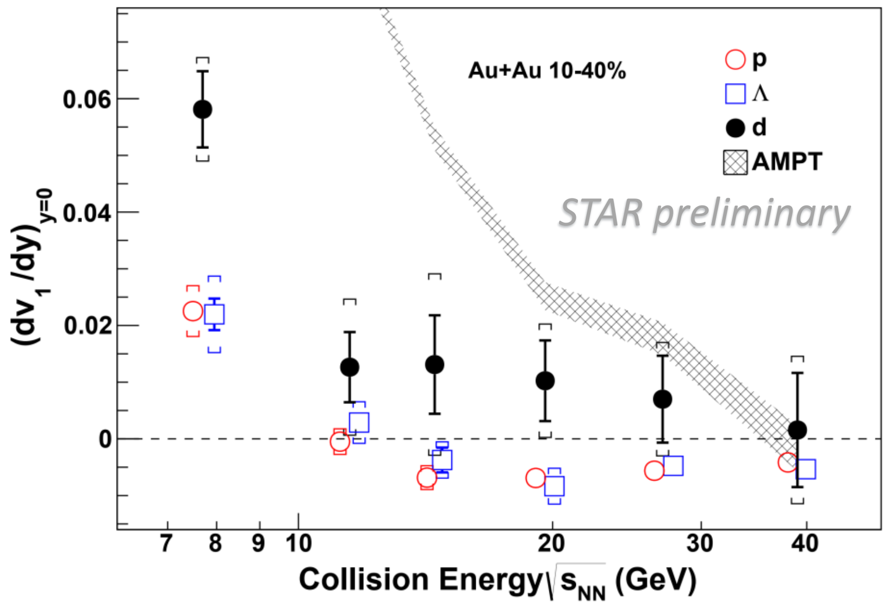
In AMPT, (anti-)deuterons are produced and dissolved via nuclear reaction in the hadronic transport stage of AMPT.

→0.2 million events were produced for each collision energy

→ event centrality was determined by the multiplicity

Deuteron v_1 from AMPT Simulation





For AMPT simulation, values of dv_1/dy are positive for all energies and larger than the data.

Summary

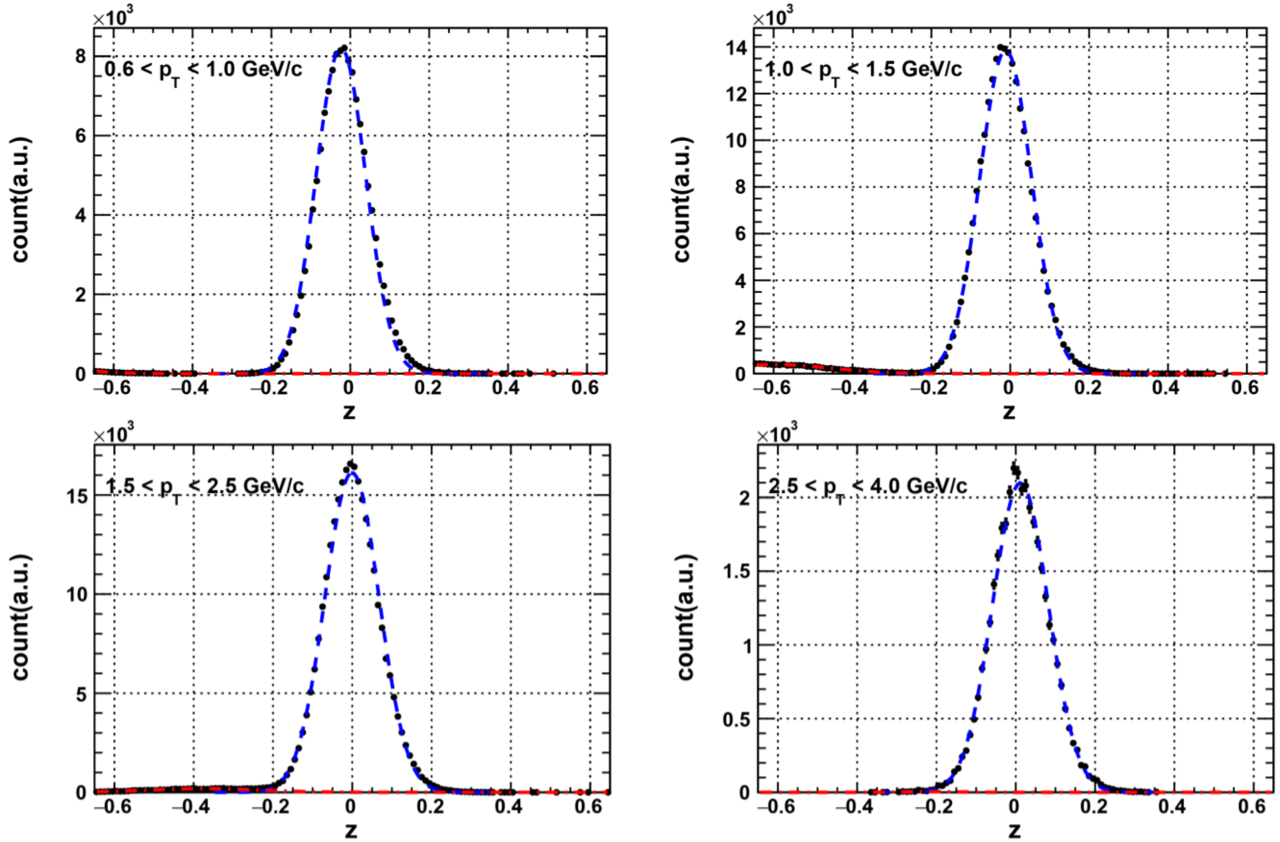
- The deuteron $v_1(y)$ was measured in Au+Au collisions at $\sqrt{s_{NN}}$=7.7 -39 GeV with STAR experiment data. The slopes at midrapidity (|y|<0.6) were extracted.

- 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.

- In AMPT simulation, deuterons are produced via the nuclear reaction in the hadronic transport stage. The dv_1/dy are also positive for all energies, while are much larger than the measurement.

Back Up

Deuteron Selection



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

- Energy loss from TPC
  → $-0.2 < z < 0.2$
- m^2 from TOF
  → $3.0 < m^2 < 4.0$ GeV/c^2