Energy Dependence of Directed Flow for Light Nuclei

Study the QCD Phase Structure in High-Energy Nuclear Collisions

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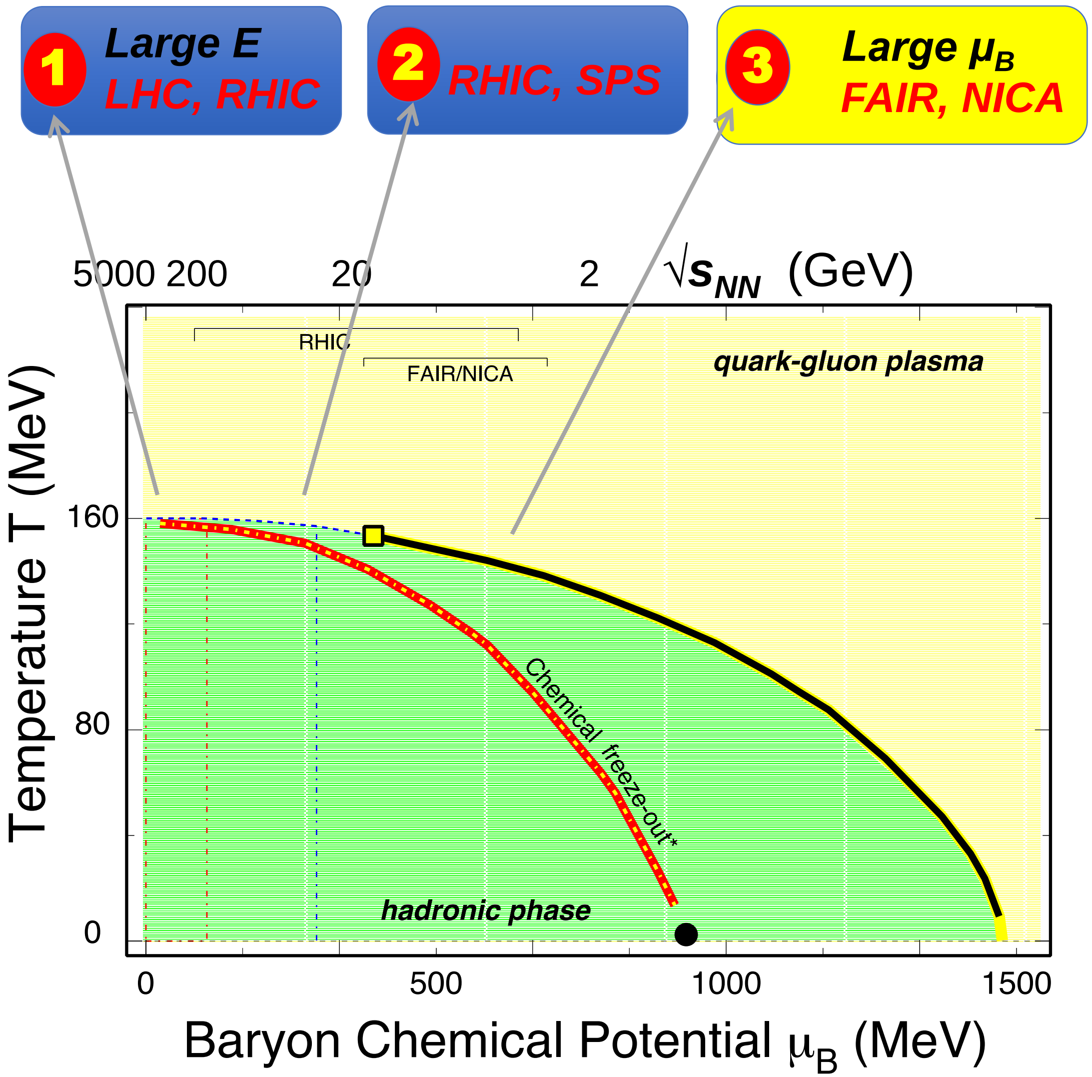
Outline

- *Motivation*
- *AMPT simulation*
- *STAR data sets from BES*
- *Summary and Outlook*

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



Observable:

1^{st} order phase transition

(1) Azimuthally HBT

(2) Directed flow v_1 ··· *d*

Degrees of freedom

(3) R_{AA}: N.M.F.

(4) Dynamical correlations

(5) v_2 - NCQ scaling ··· *d*

- Critical Point

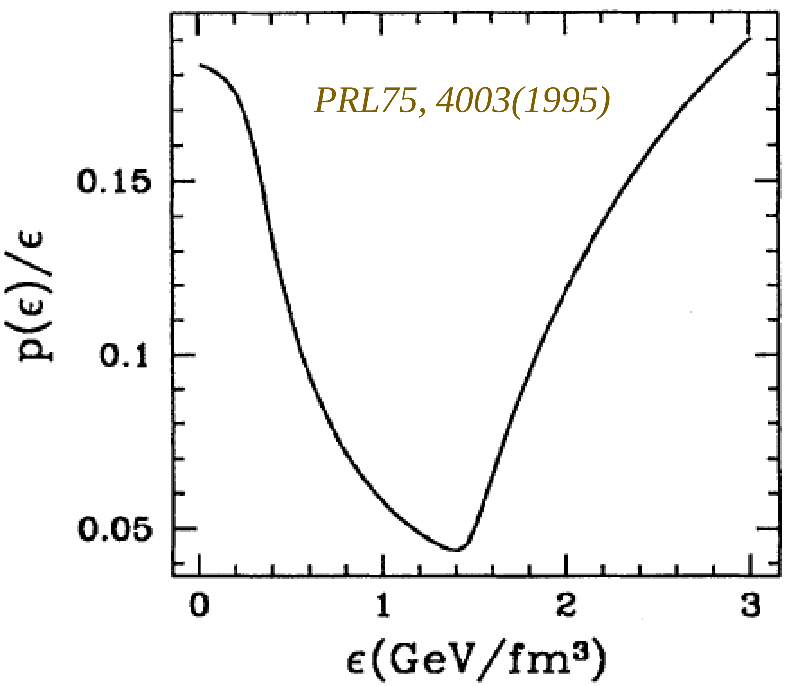
(6) Fluctuations ··· *d*

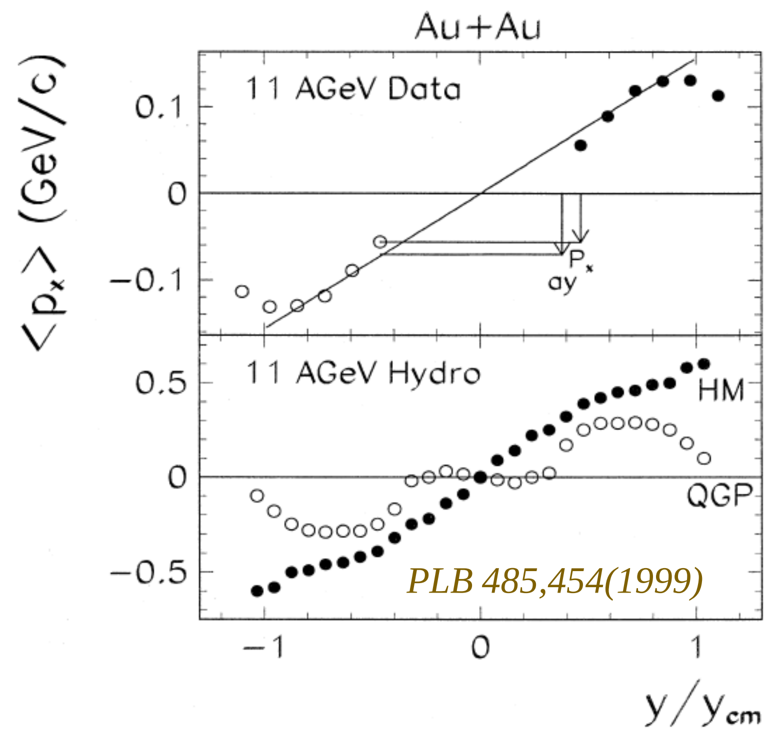
(7) Di-lepton production

Phase Transition and Directed Flow

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

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



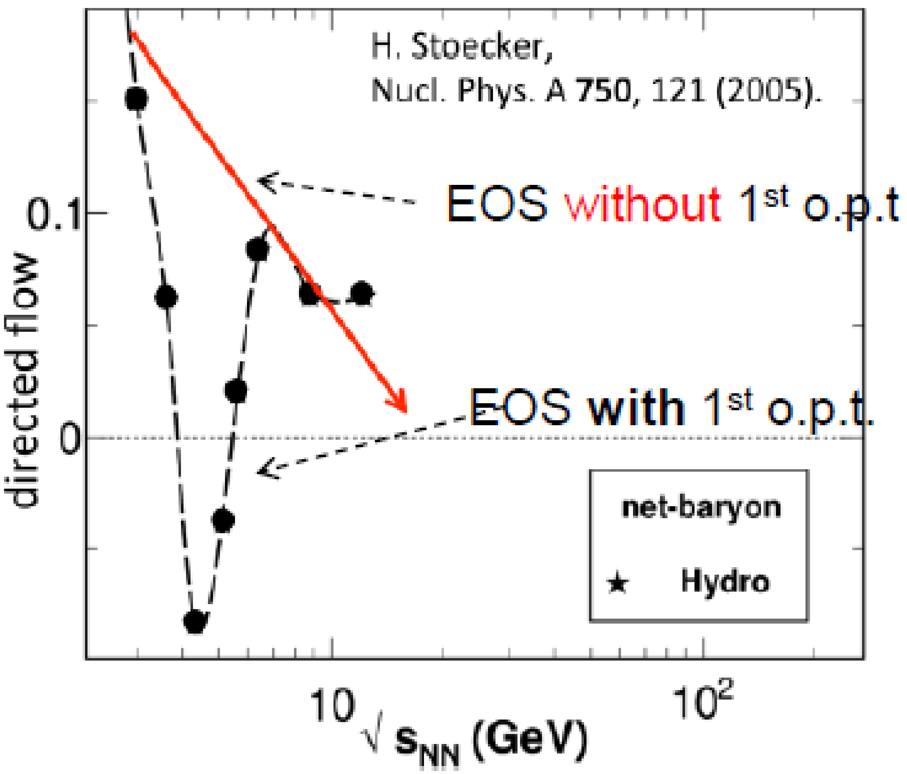


- The EOS is especially soft near the QCD phase transition
- Scan of collision energy can be used to search for phase transition

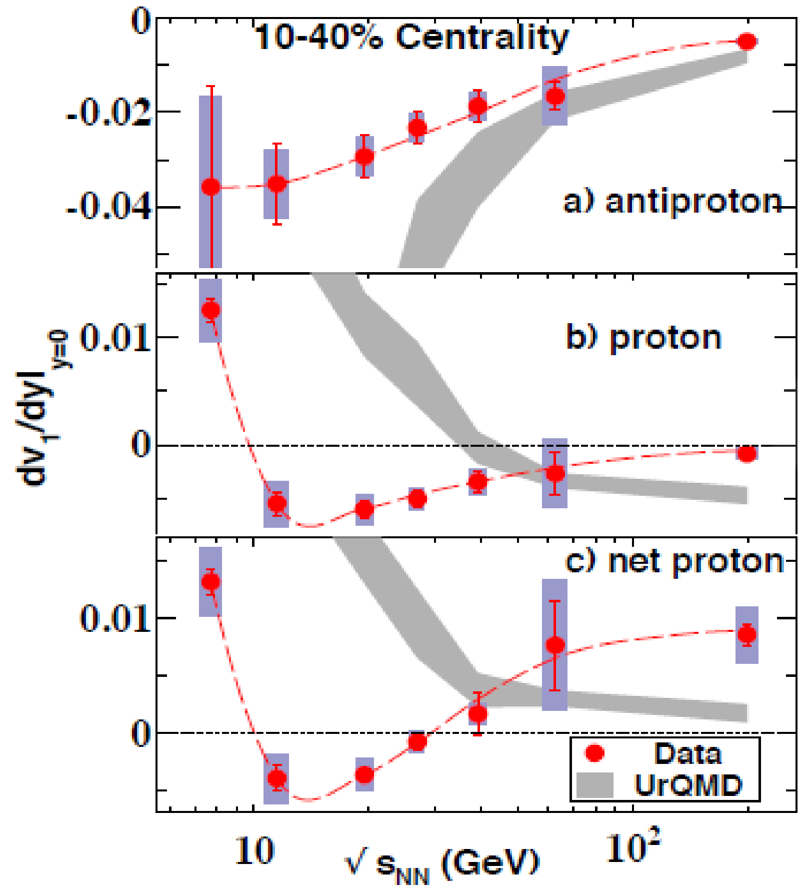
- The directed flow slope at mid-rapidity is sensitive to softening of EOS
- Fluid dynamic calculation indicates a flat v_1 at mid-rapidity due to first order phase transition

Directed Flow of Net-Baryon

arXiv:9505014



STAR Collaboration :PRL112, 162301(2014)

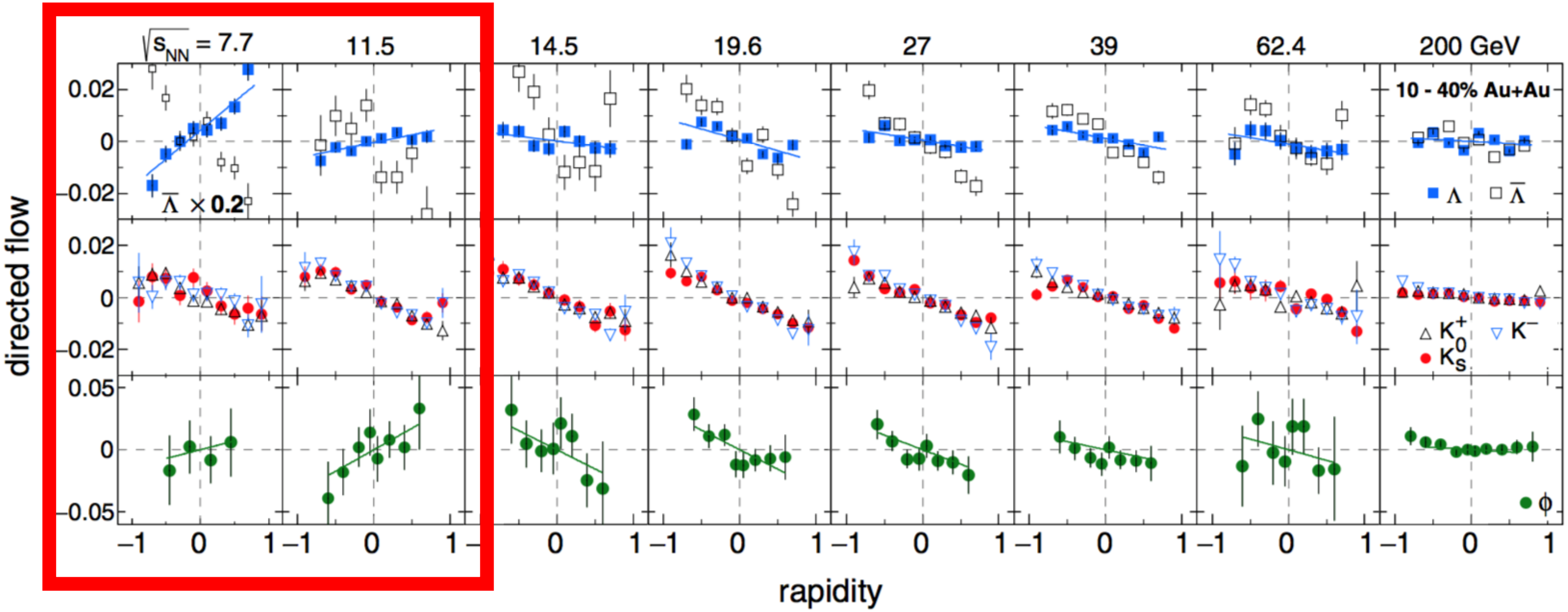


Three-fluid hydrodynamic calculation with a first-order phase transition predicts a minimum in directed flow of net baryon.

Minimum in net-proton dv_1/dy with double sign change.

Softening of EOS?

Directed Flow v_1 in RHIC BES-I



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

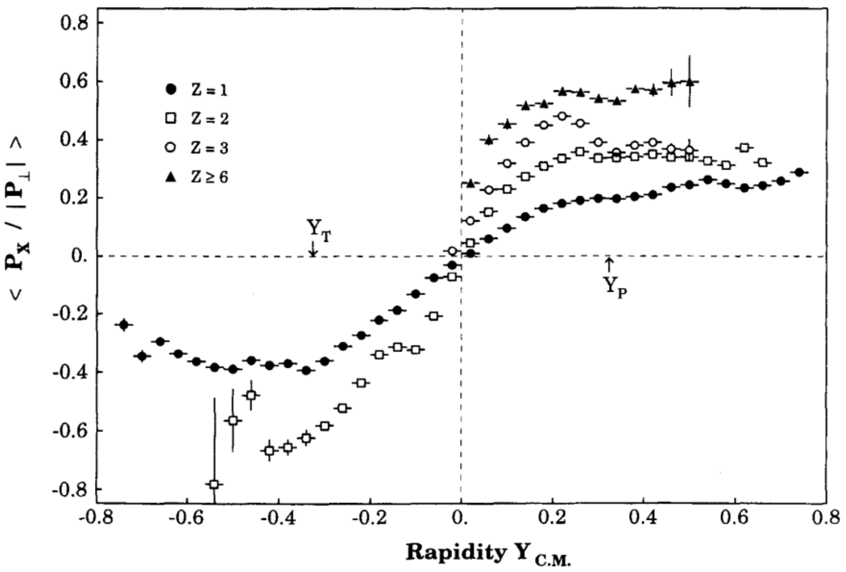
STAR: Phys. Rev. Lett. **120**, 062301(2018)

What about light nuclei???

Light Nuclei v_1 Measurements

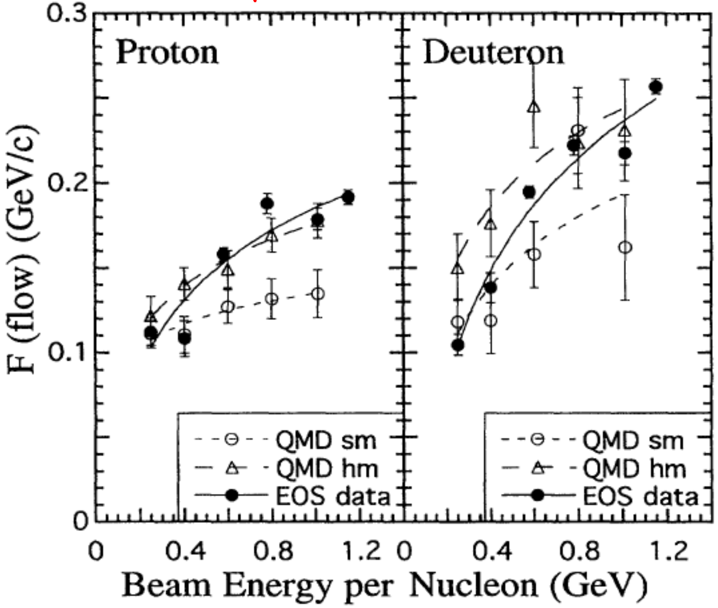
PRL 59, 2720(1987)

Au+Au $\sqrt{s_{NN}}$ =0.2 GeV



PRL 75, 2100(1995)

Au+Au $\sqrt{s_{NN}}$ =0.25-1.15 GeV

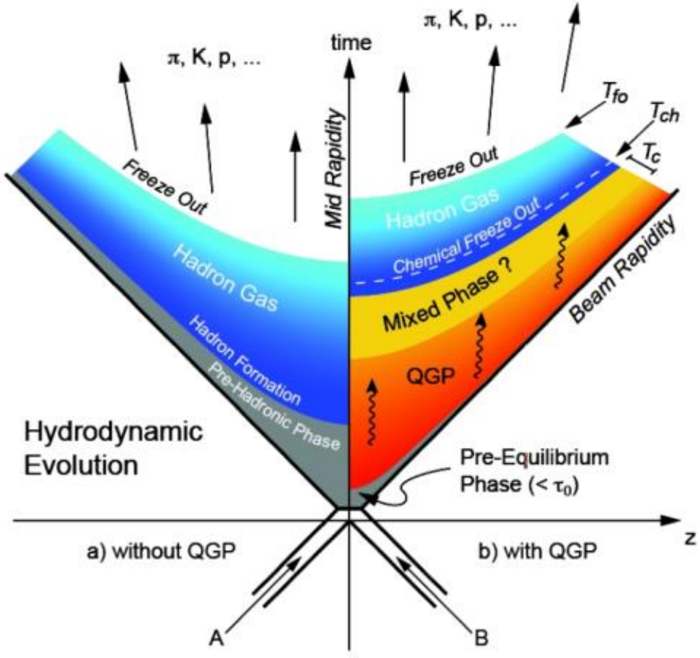


- Stronger collective flow observed for heavier nuclei
- The proton and deuteron directed flow increase monotonically with rising beam energy
- The differences in fragment flow become larger with rising beam energy
- How about light nuclei, d for example???

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.
- Their spectral distributions related to nucleons

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

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

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)

PRC 72, 064901(2005)
PRC 94, 054909 (2016)
PRC 96, 014910 (2017)

Two different deuteron production mechanisms in the simulation:

1. Produced and dissolved via nuclear reaction in the hadronic transport stage of AMPT (transport).

2. Produced via coalescence of nucleons.

Deuteron from Coalescence in AMPT Simulation

The production probability of nucleus of atomic number A is :

$$\frac{d^3N_A}{d\mathbf{P}_A^3} = g_A \int \prod_{i=1}^{z} \frac{d^6N_p}{dr_p^3 dp_p^3} \prod_{i=z+1}^{A} \frac{d^6N_n}{dr_n^3 dp_n^3}$$

$$\times \rho^W (\mathbf{r}_1, \mathbf{p}_1 \cdots \mathbf{r}_A, \mathbf{p}_A) \times \delta\left(\mathbf{P} - \sum_{i=1}^{A} \mathbf{p}_i \right)$$

where g_A is factor related to degeneracy, ρ^w is Wigner phase-space density.

For deuteron, the Wigner function is *PRC 80, 064902(2009)*

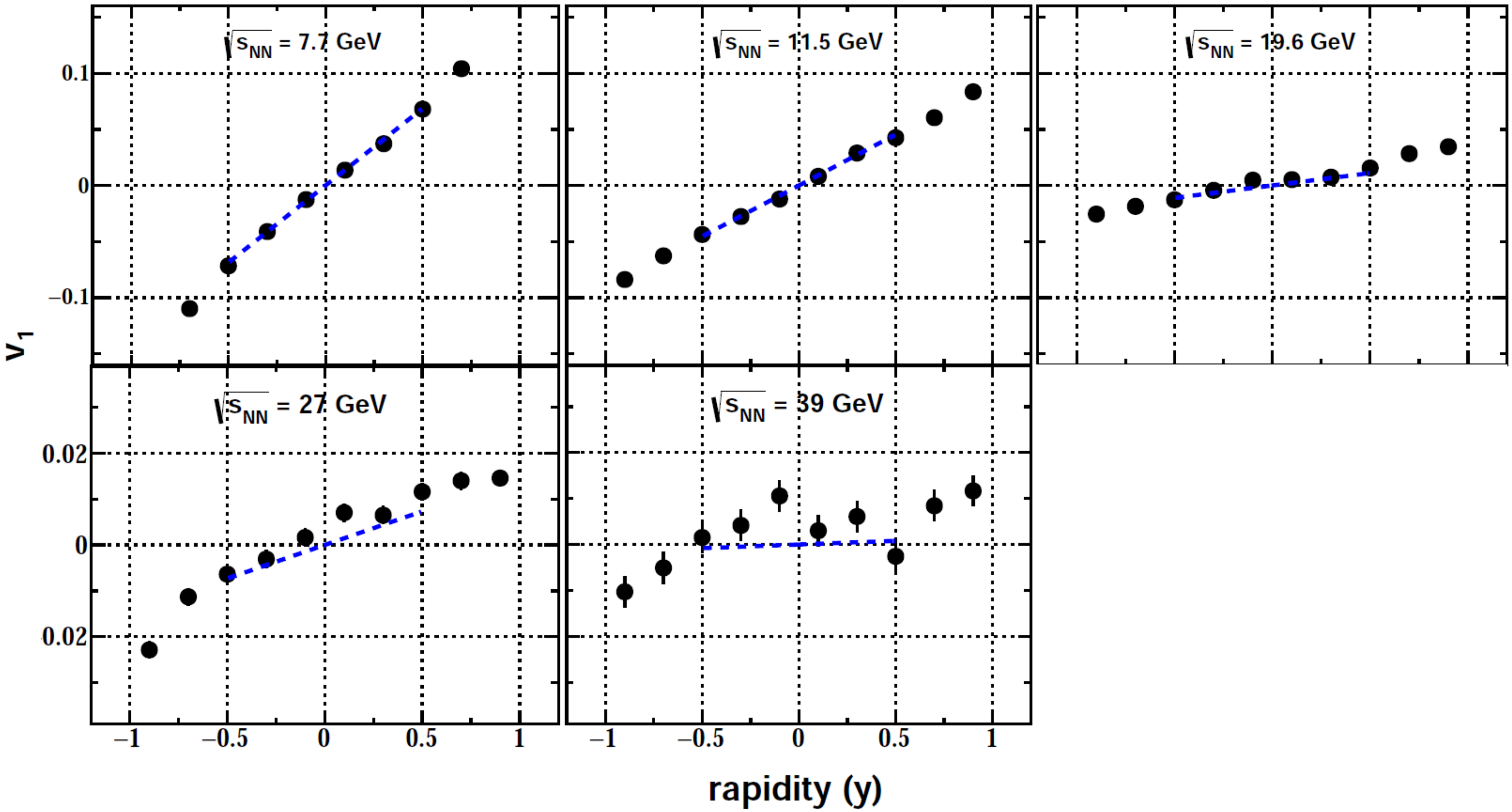
$$\rho^W(\mathbf{t}, \mathbf{q}) = 8\exp\left[-\frac{\mathbf{t}^2}{\sigma^2} - \frac{\mathbf{q}^2\sigma^2}{4}\right]$$

$$\mathbf{t} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2), \quad \mathbf{q} = \frac{1}{\sqrt{2}}(\mathbf{p}_1 - \mathbf{p}_2)$$

Deuteron v_1 from AMPT Transport

The energies are corresponding to beam energies at STAR (Beam Energy Scan experiment).

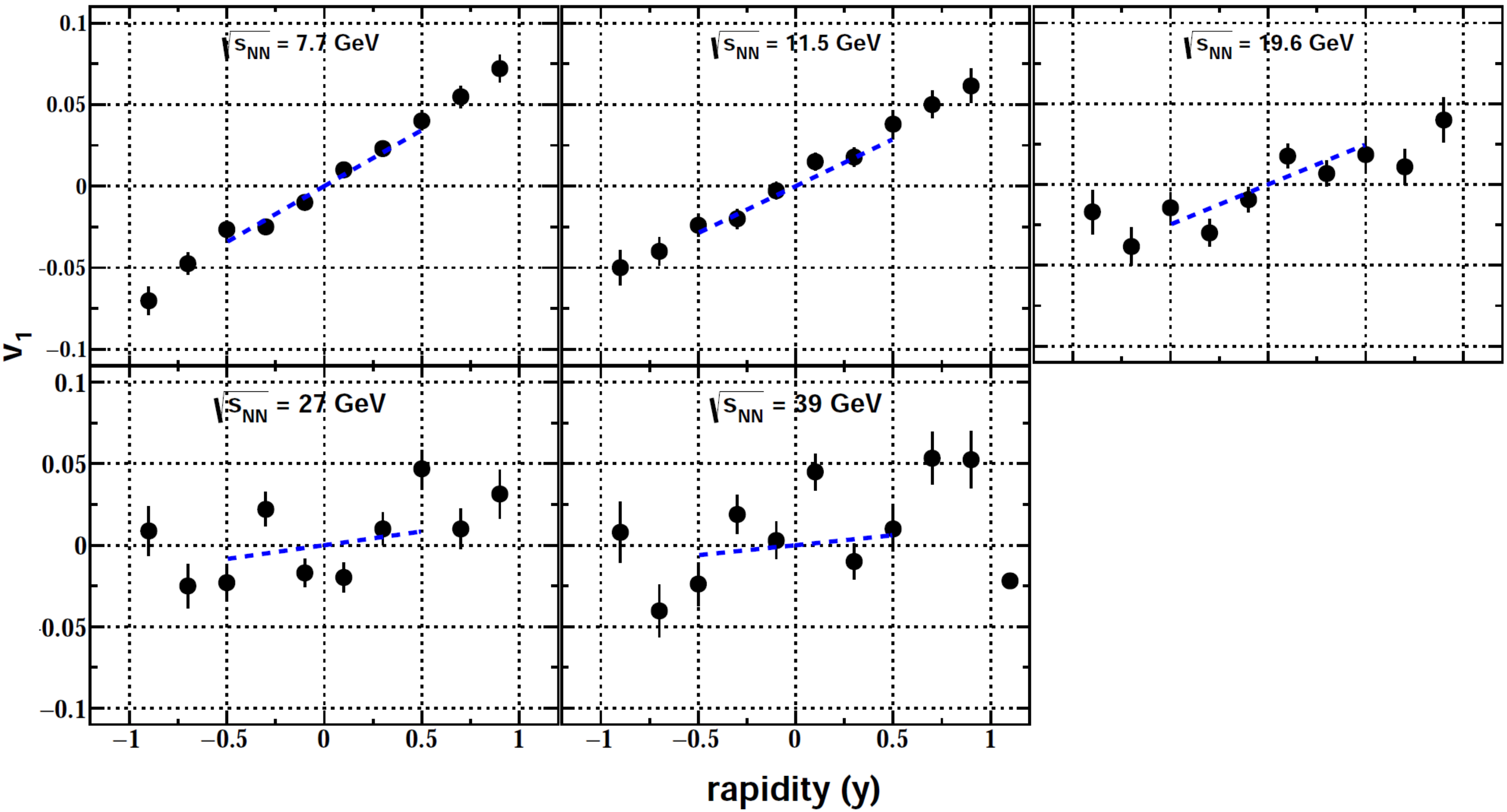
Au+Au, centrality 10-40%



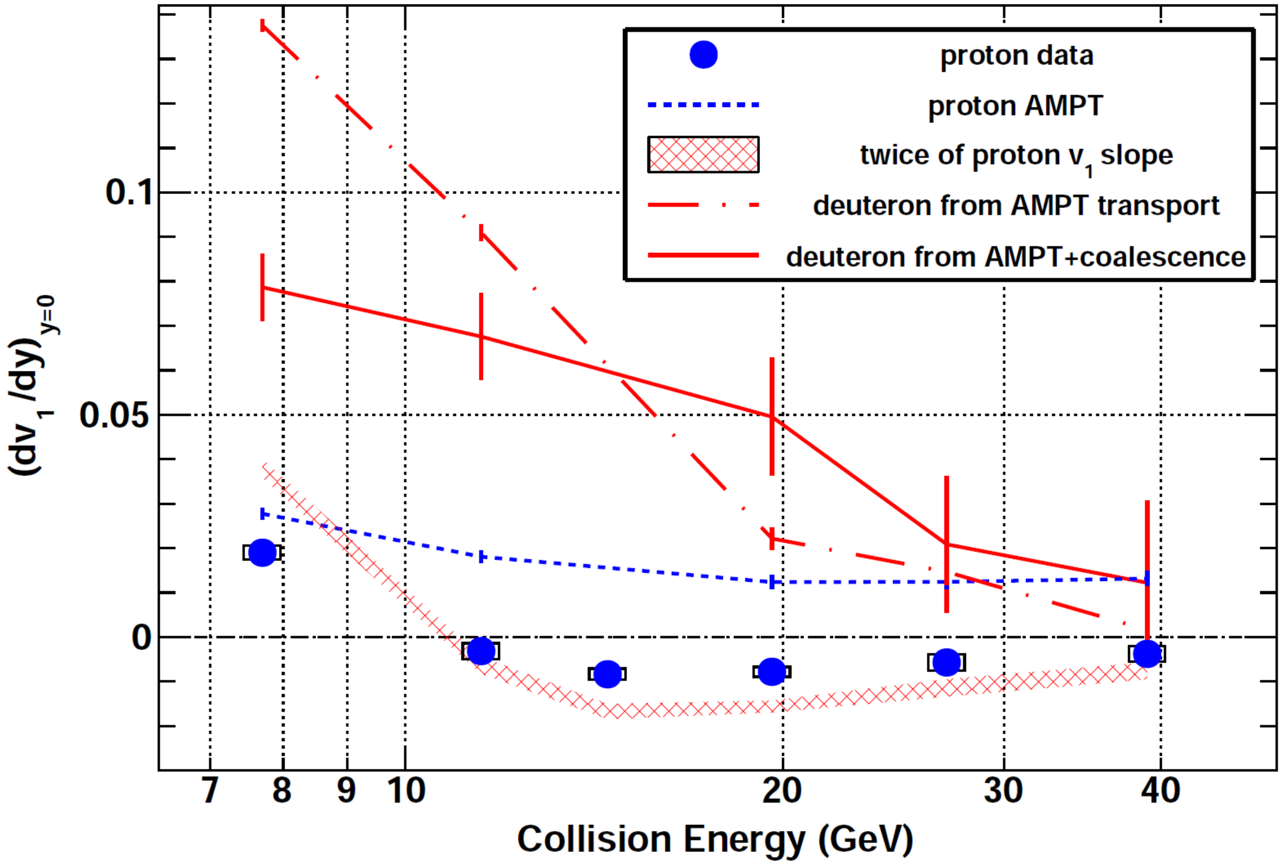
Deuteron v_1 from AMPT + Coalescence

AMPT + coalescence

Au+Au, centrality 10-40%



Slope of Deuteron v_1 at Mid-Rapidity



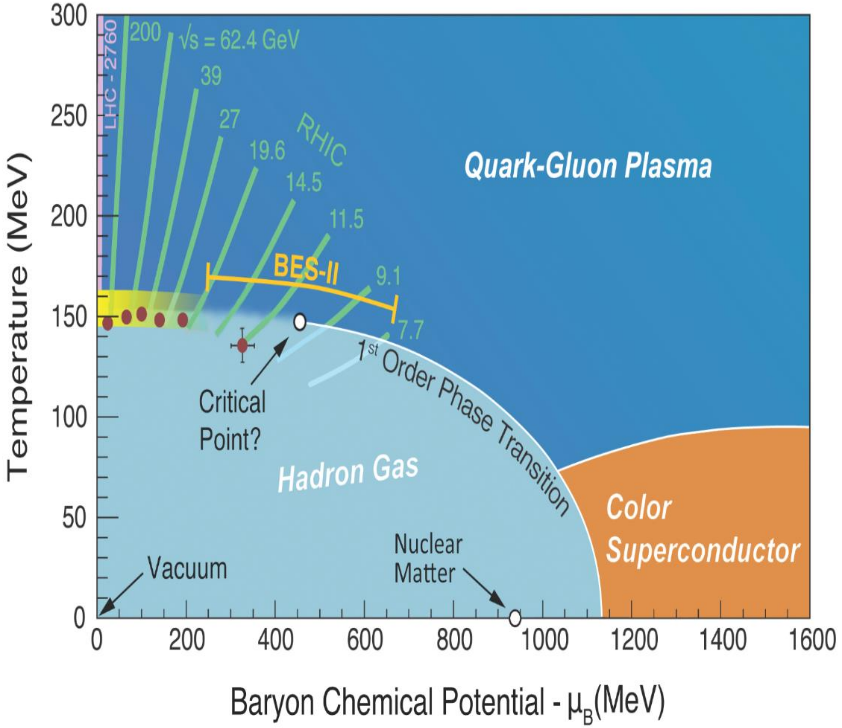
The dots are proton's v_1 slope at mid-rapidity from STAR collaboration.

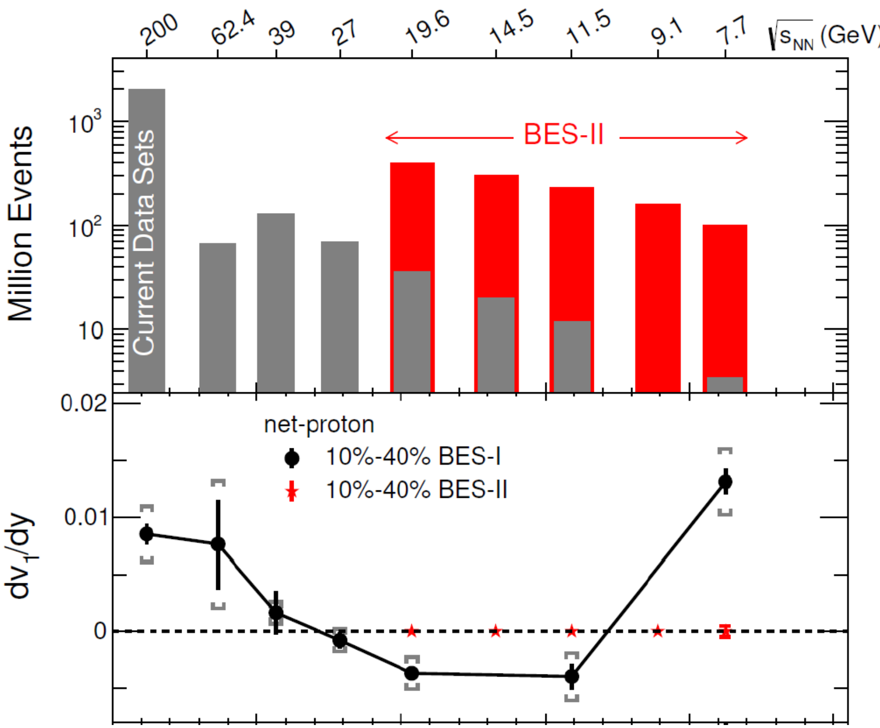
For AMPT simulation, the slopes at mid-rapidity for deuteron v_1 are positive for all energies.

2019-2021: BES II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	130	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019**/ 2011	**3**	206	160
14.5	**300** / 20	**2019**/ 2014	**2.5**	264	156
11.5	**230** / 12	**2019**/ 2010	**5**	315	152
9.2	**160** / 0.3	**2020** / 2008	**9.5**	355	140
7.7	**100** / 4	**2020** / 2010	**14**	420	140

Beam Energy Scan (BES) Program at STAR





Au + Au Minimum bias

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

Summary

- The energy dependence of deuteron v_1 slope at mid-rapidity may be more sensitive than proton's v_1
- From AMPT simulation, the slopes at mid-rapidity for deuteron v_1 are positive for $\sqrt{s_{NN}}$ =7.7 - 39 GeV
- Stay tuned: Data analysis is ongoing
- Will start to work with CBM at FAIR

Thank You for Your Attention!