Proton Directed Flow in Beam Energy Scan II

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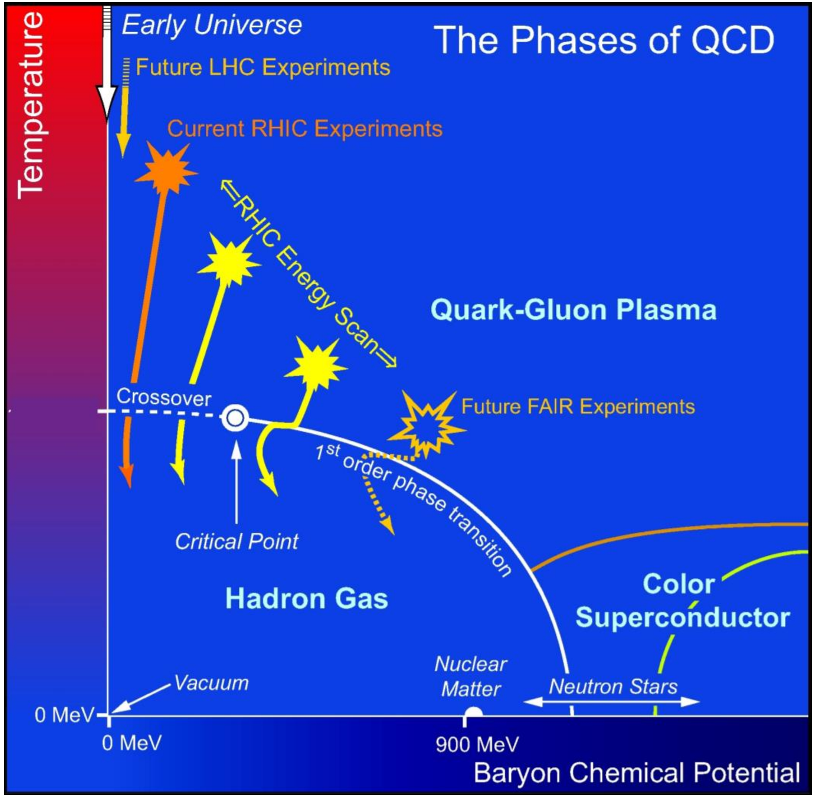
The STAR Collaboration
https://drupal.star.bnl.gov/STAR/presentations

Beam Energy Scan

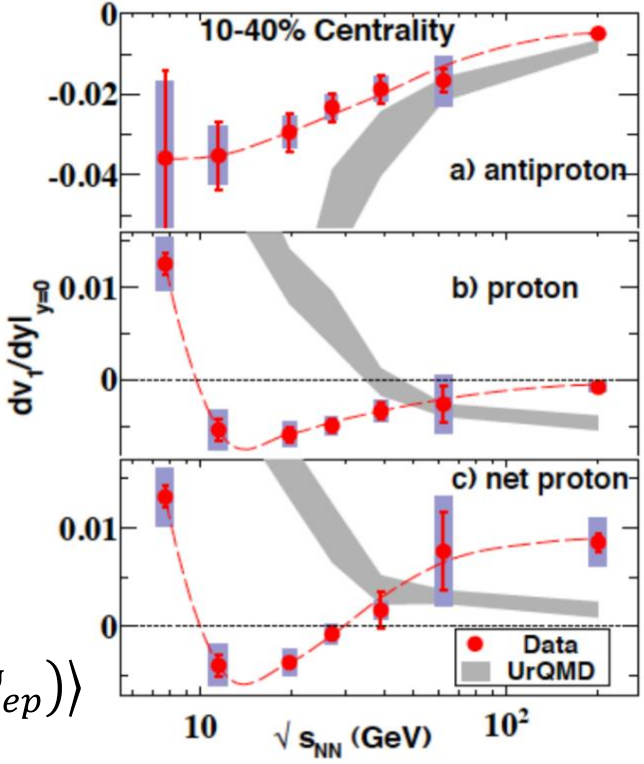


- STAR Beam Energy Scan gives us access to a wide sweep of phase space
  - Search for critical point
  - Understand the QCD phase structure
- Hydro and nuclear transport models suggest that directed flow is sensitive to the dynamics of the expanding medium
- Proton flow predicted to be sensitive to softening of the equation of state near first order phase transition

Motivation

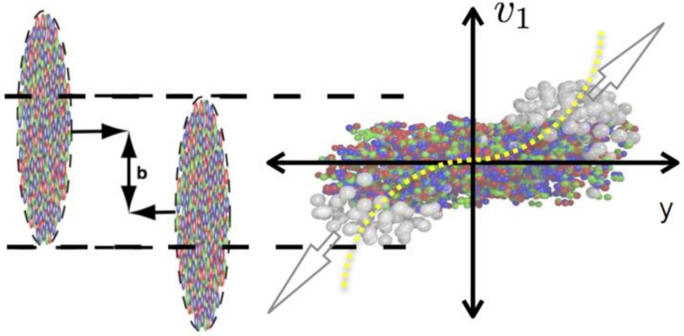
- In BES-I we saw a nonmonotonic trend in the proton v_1 slope vs collision energy
  - Occurring much higher than predicted

- Proton v_1 is driven by 2 different sources:
  - *Net protons*: the initial protons that are the source of baryon number
  - *Produced protons*: the protons produced during the collision
- How to separate these two components???



(PRL 112, 162301 (2014))

$$v_1 = \langle \cos(\phi - \Psi_{ep}) \rangle$$



Motivation

- To capture this behavior, we first broke it down as:

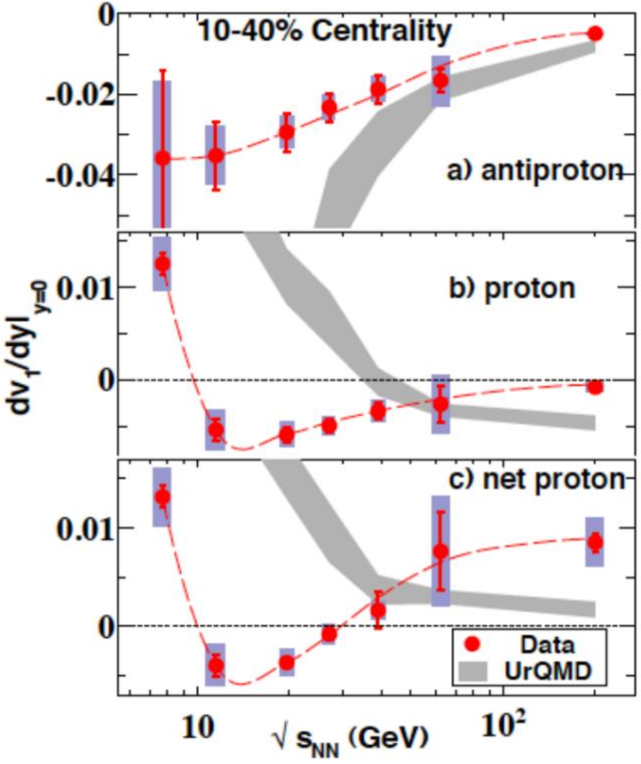
$$N_p v_{1,p} = N_{p,produced} v_{1,produced} + (N_p - N_{\bar{p}}) v_{1,net}$$

- We assume $N_{p,produced} v_{1,produced} = N_{\bar{p}} v_{1,\bar{p}}$ and solve:

$$v_{1,net} = \frac{(v_{1,p} - r v_{1,\bar{p}})}{1 - r}$$

(r is the yield ratio of anti-protons to protons)

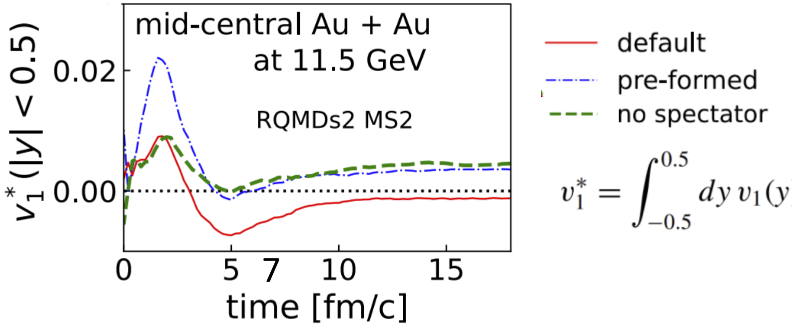
- Net proton v_1 slope at mid-rapidity also exhibits non-monotonic behavior in the same region



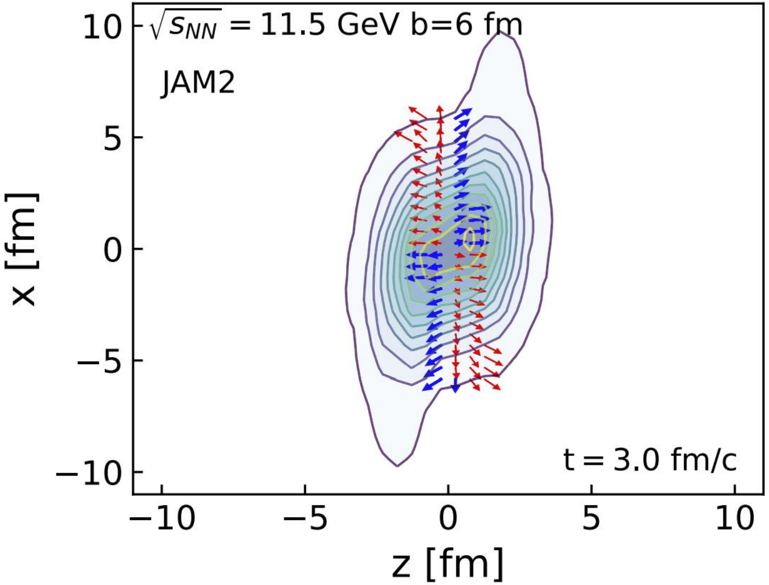
(PRL 112, 162301 (2014))

Motivation

- Driving phenomena behind Proton v_1:
  - Initial interaction between hadrons in the compression stages
    - Contributes to positive flow
    - Affects initial protons
    - Our “Excess” component
  - Tilted matter expansion
    - Produces negative flow
    - Affects all protons
    - Our “Medium” component



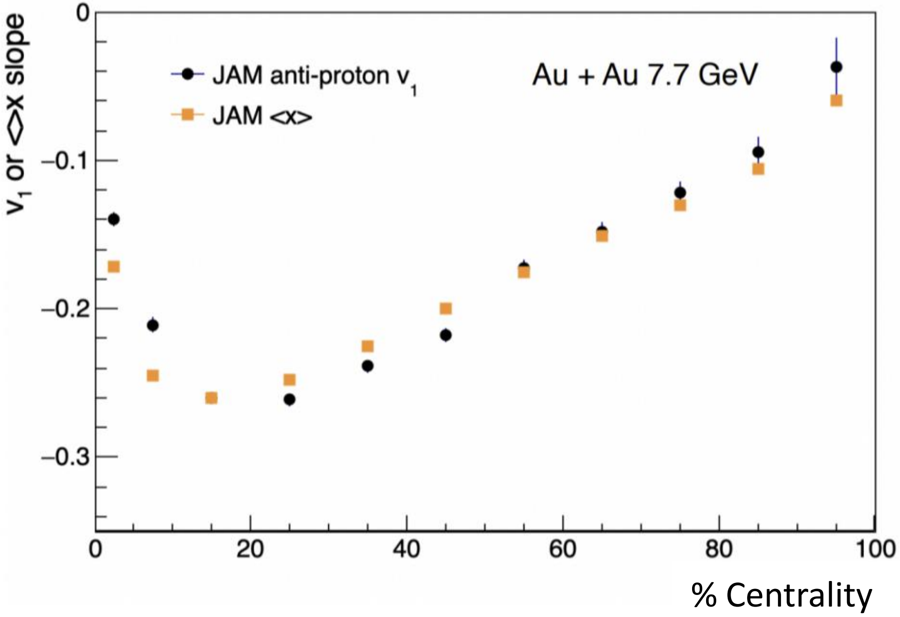
$$v_1^* = \int_{-0.5}^{0.5} dy\, v_1(y)\, \mathrm{sgn}(y).$$

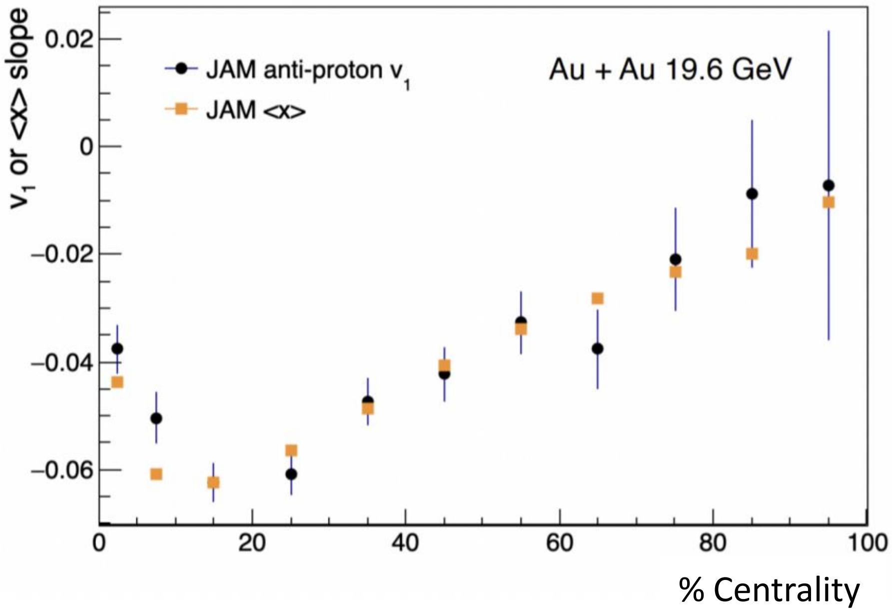


Baryon density distribution for Au+Au collisions using JAM RQMDs2 MS2 model, blue arrows indicate flow, red arrows antiflow. K = 210 MeV
Phys. Rev. C 105, 014911 (2022)

Anti Proton v_1 as a Proxy for Medium Flow

- Initial geometry values scaled to match the v_1 in 10-20% centrality





- Initial geometry largely captures the centrality dependence of anti-proton v_1
- Agrees very well in JAM
- Reflects origin from medium response to initial geometry

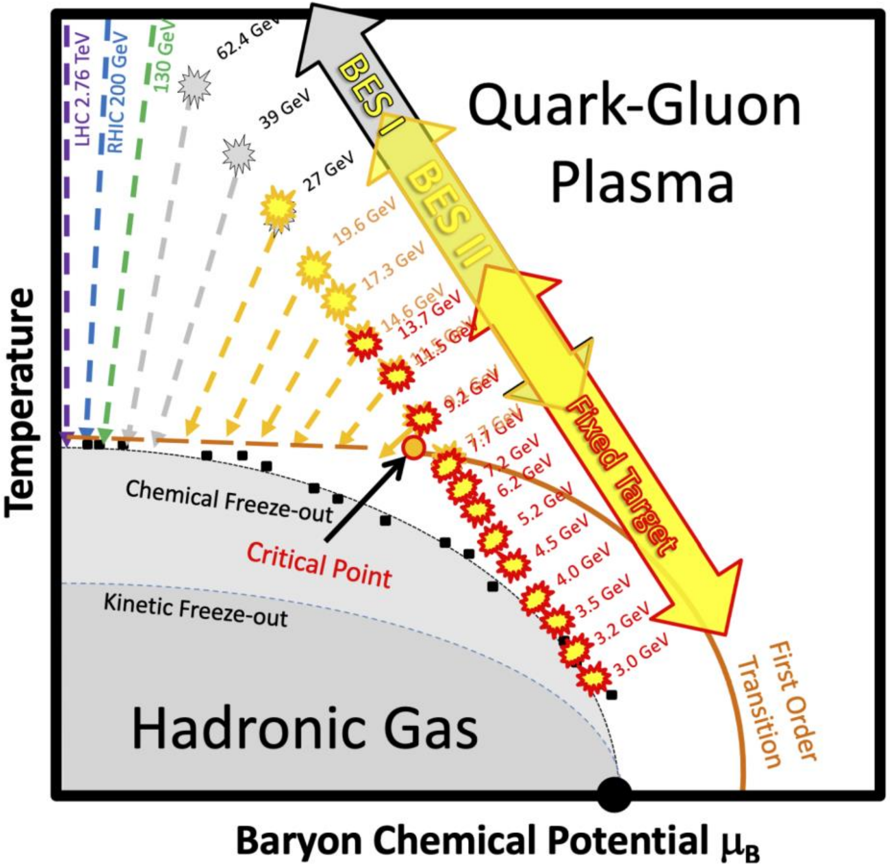
Motivation

- Thus, instead break it down to the initial interactions and the medium expansion:

$$N_p v_{1,p} = \enclose{circle}{N_p} v_{1,medium} + \left(N_p - N_{\bar{p}}\right) v_{1,excess}$$

- Assuming $v_{1,medium} = v_{1,\bar{p}}$ gives:

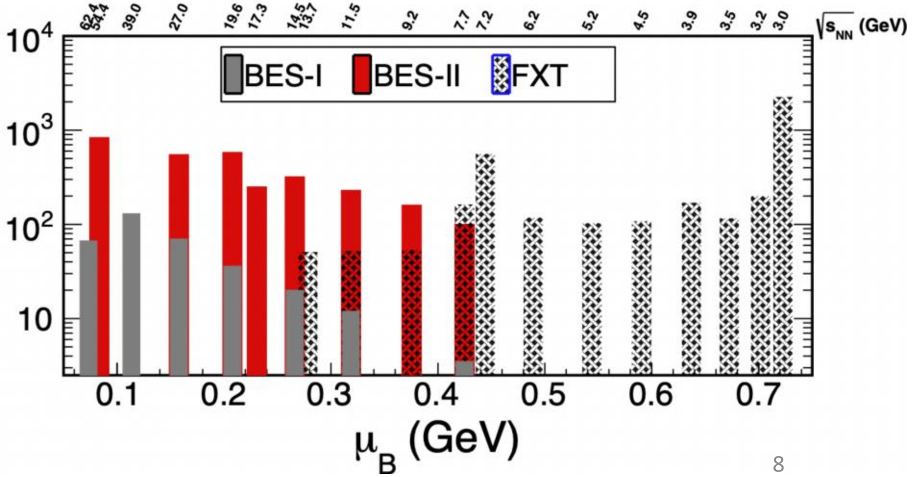
$$v_{1,excess} = \frac{\left(v_{1,p} - v_{1,\overline{p}}\right)}{1-r} \quad (\text{vs. } v_{1,net} = \frac{\left(v_{1,p} - r v_{1,\overline{p}}\right)}{1-r})$$



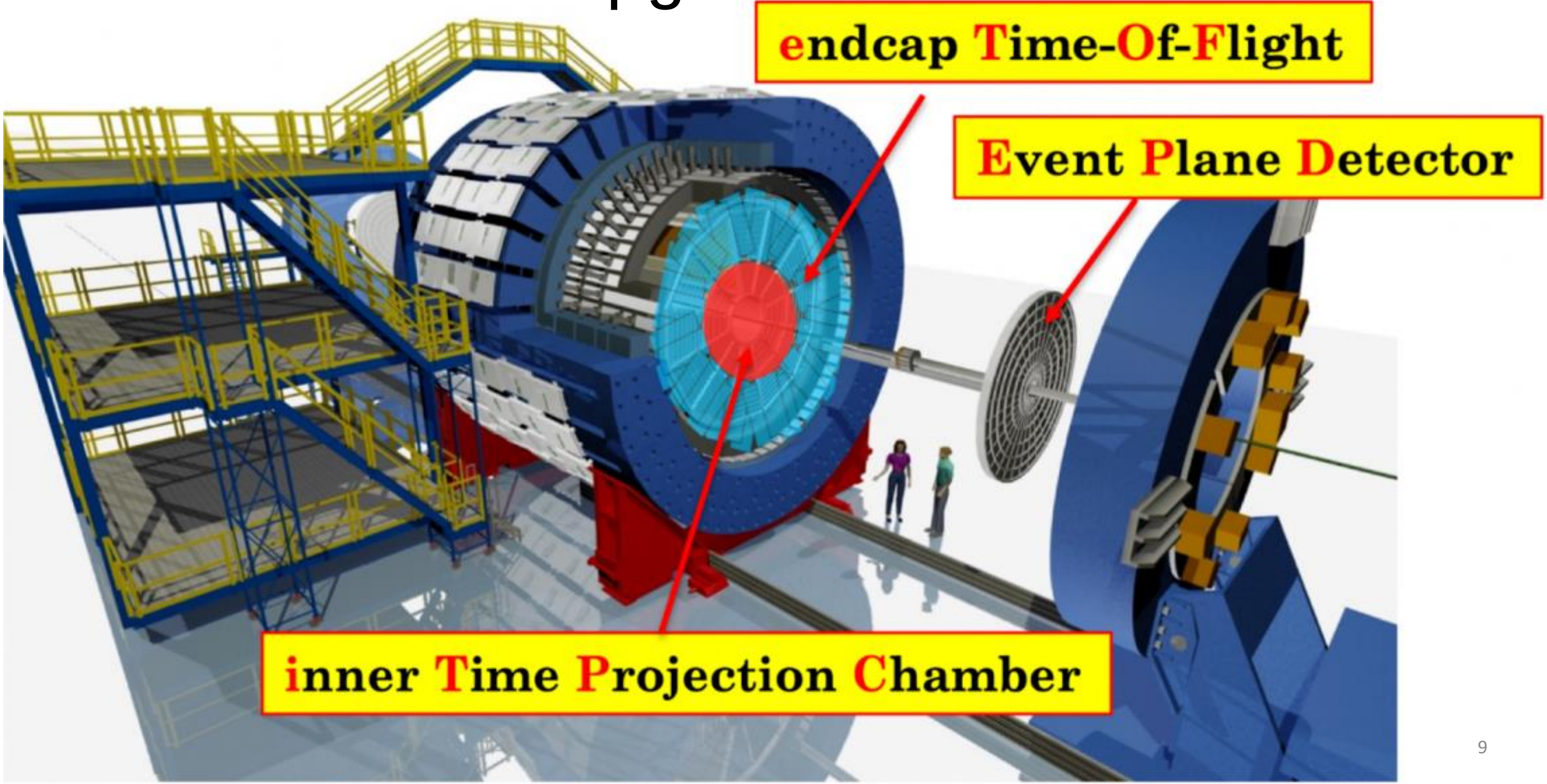
https://doi.org/10.1016/j.nuclphysa.2017.05.042

BES-II Dataset

- We are using the BES-II dataset:
  - 10x the statistics of BES-I
  - Upgraded detector to include the EPD, iTPC, and eTOF
- Ranges from $\sqrt{s_{NN}}$ =3.0 GeV (Fixed target) up to 27 GeV (collider mode)
- Extends the μ_B range to 200 – 420 MeV
  - Up to 720 MeV with FXT

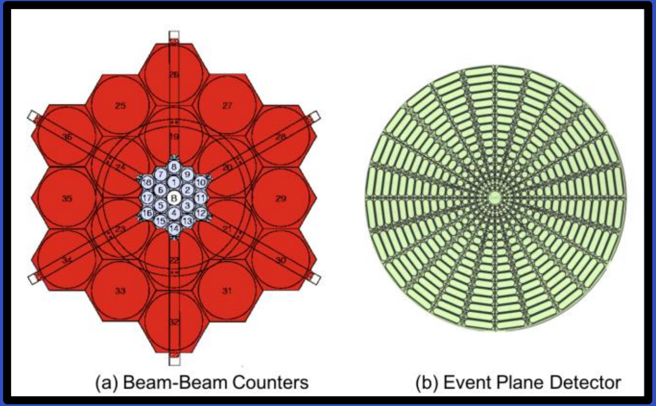


STAR Detector Upgrades

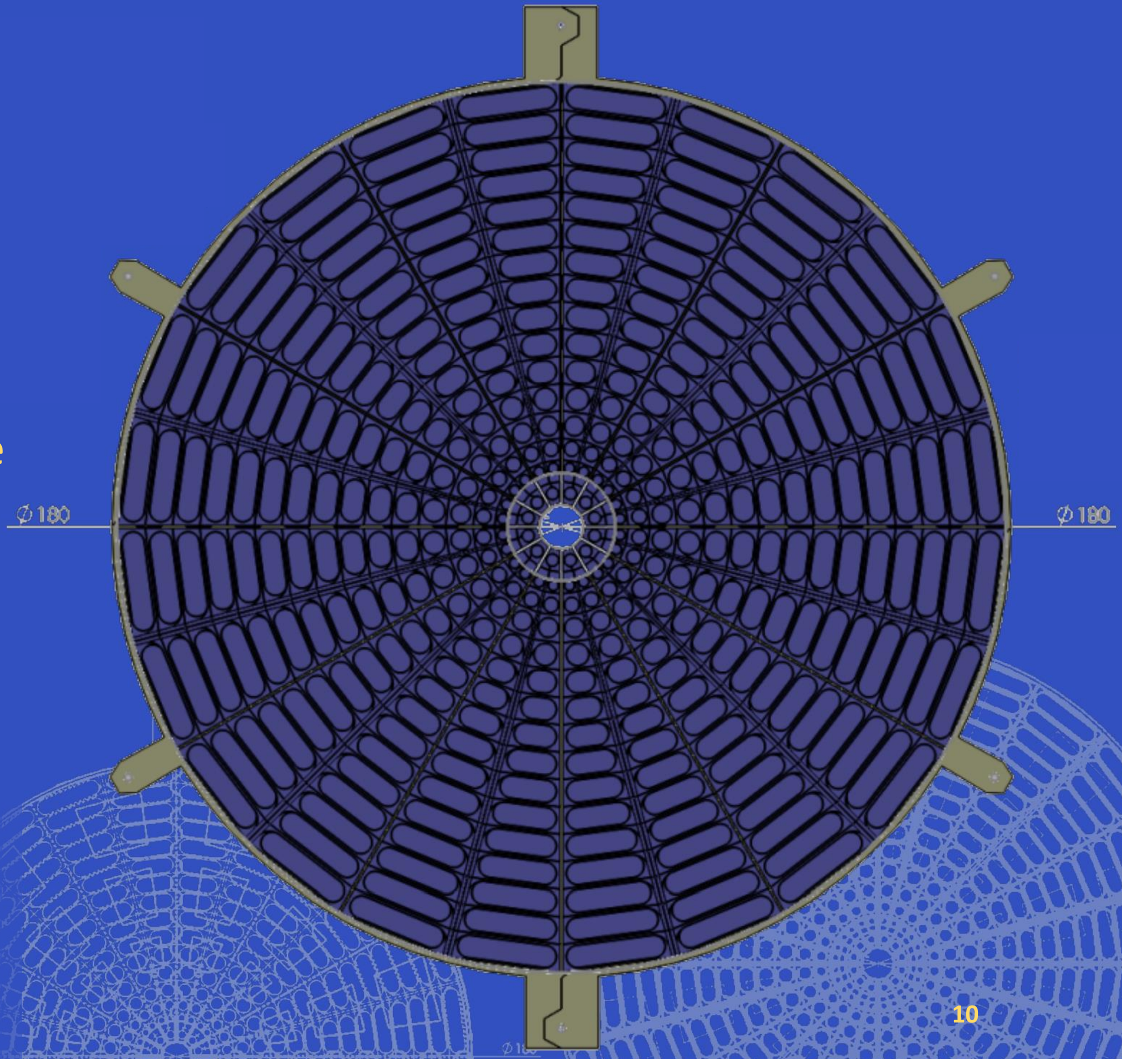


Event Plane Detector

- Pseudorapidity range: 2.1 to 5.1
- 372 tiles are Eljen scintillators
- Significantly increased Event plane accuracy as compared to Beam-Beam Counters (BBC)

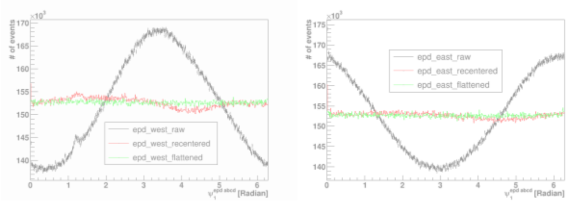

(a) Beam-Beam Counters

(b) Event Plane Detector

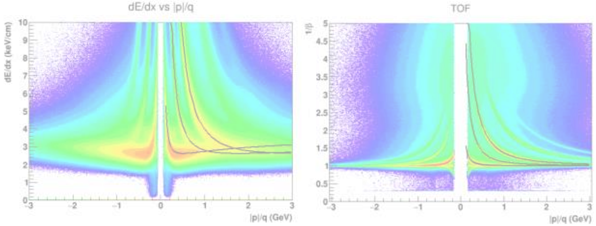


Procedure

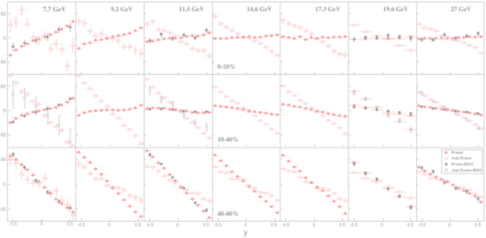
- Measure the event plane angle for each event



- Identify the (anti-)protons from the collision



- Measure the v_1 of (anti)protons and calculate excess v_1



Event Plane Determination

- The event plane is measured by the EPD based on number of Minimally Ionizing Particles (nMIP)

$$\vec{Q} = \sum_{i \in tile} w_{x,i} \cos\phi_i \,\hat{x} + w_{y,i} \sin\phi_i \,\hat{y}$$

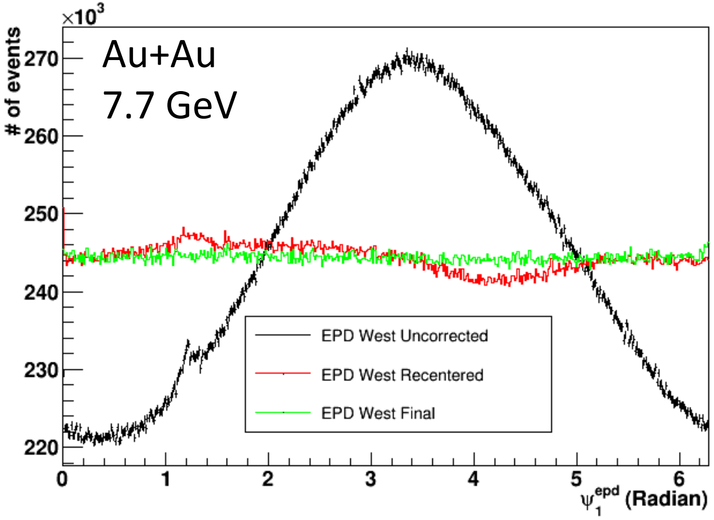
- We then recenter the event plane

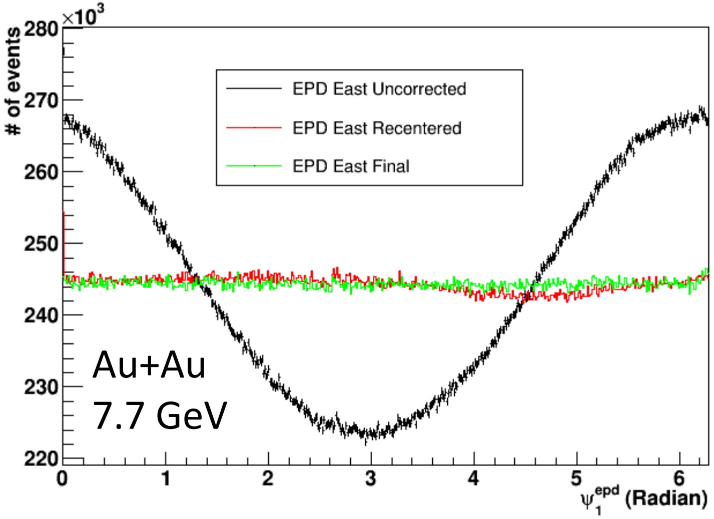
$$\vec{Q}_{recentered} = -\left\langle \vec{Q} \right\rangle_{run} + \sum_{i \in tile} w_{x,i} \cos\phi_i \,\hat{x} + w_{y,i} \sin\phi_i \,\hat{y}$$

- Then flatten the event plane distribution

$$\phi_{EP} = \sum_{n=1}^{20} \frac{-2}{n} \langle \sin n\phi_Q \rangle_{run} \cos n\phi_Q + \frac{2}{n} \langle \cos n\phi_Q \rangle_{run} \sin n\phi_Q$$

Ref: Phys.Rev.C 58 (1998) 1671-1678

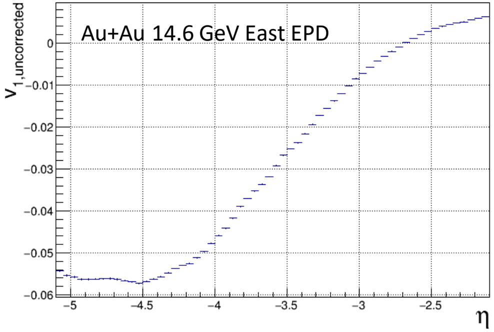


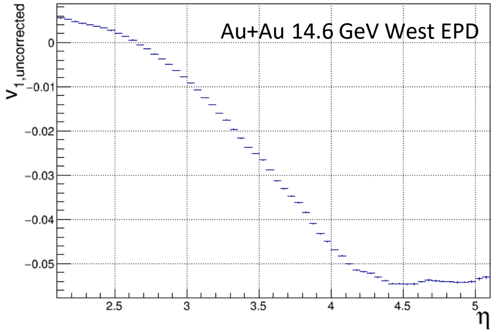


Resolution

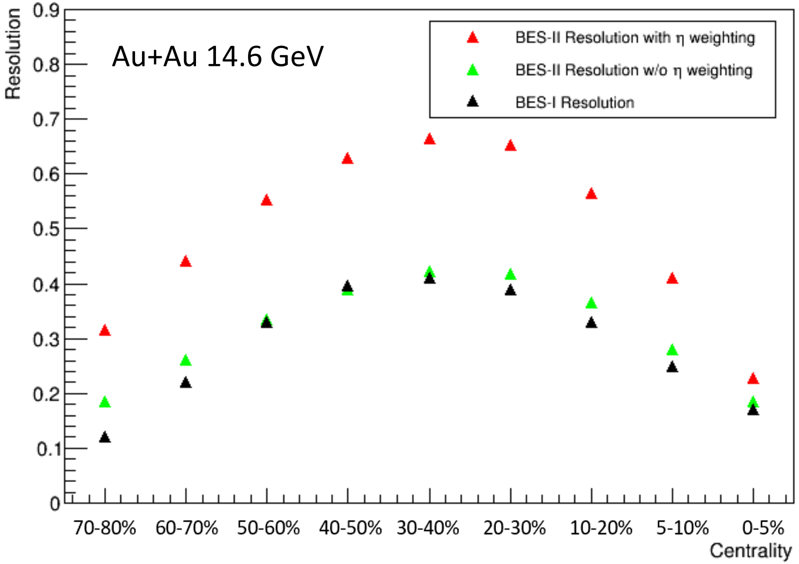
$$\vec{Q} = \hat{x} \sum_{i \in tile} w_i \cos \phi_i + \hat{y} \sum_{i \in tile} w_i \sin \phi_i$$

$$w_i = w(nMIP) * v_{1,raw}(\eta)$$

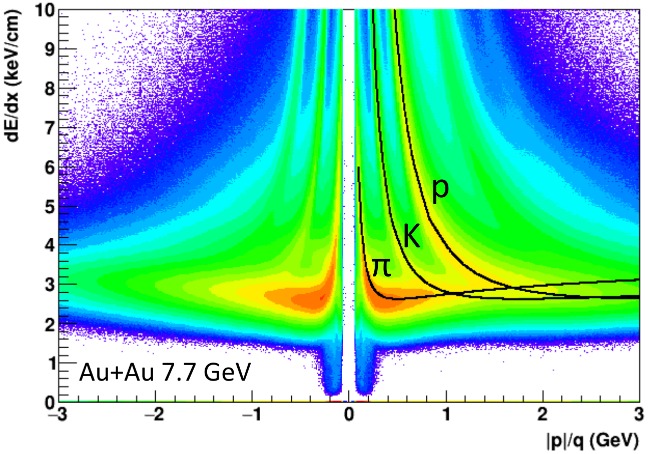


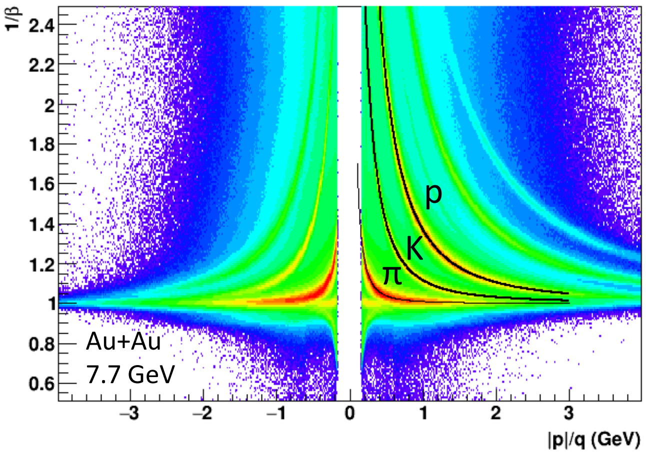


- For 9.2 to 27 GeV, there is a sign change of v_1 in the region of the EPD, lowering resolution
- To Correct for this, we can add an additional weighting factor based on the raw v_1 vs. η
- This η weighting is highly effective at increasing event plane resolution
- Gives significantly higher resolution than BES-I



Particle Identification

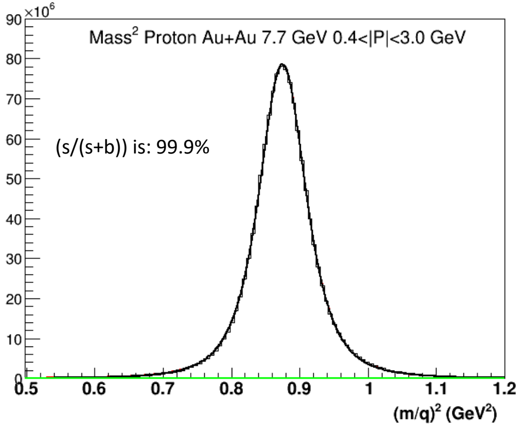


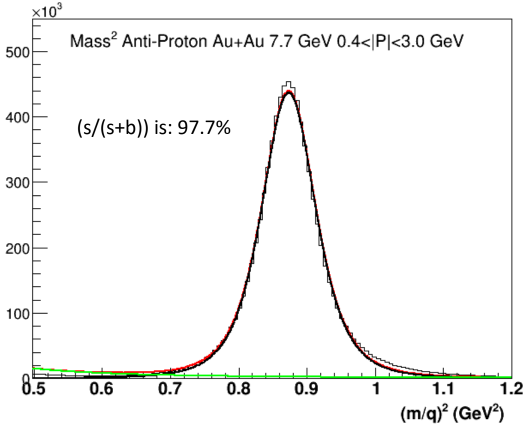


PID is:

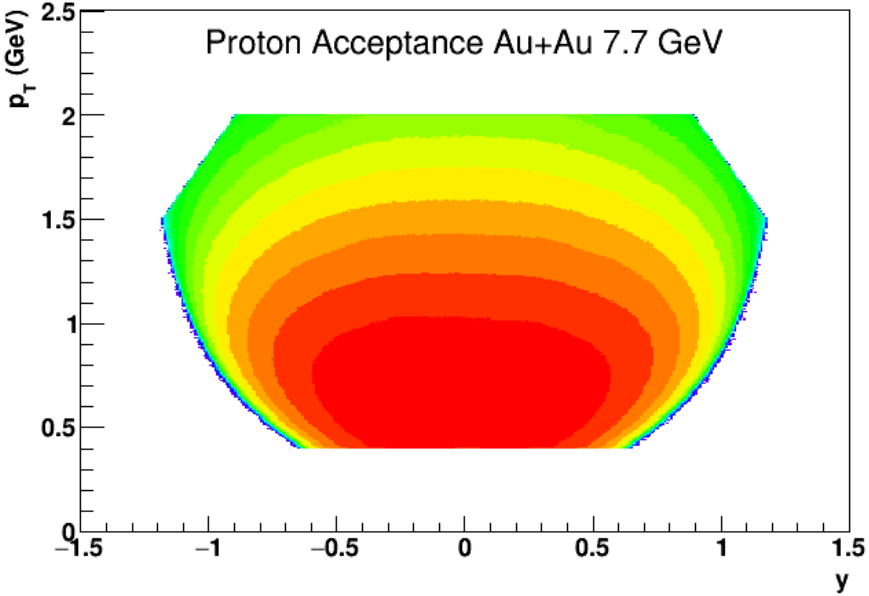
- Require TOF: $0.8 < \text{mass}^2 < 1.0\ \text{GeV}^2$
- $|N\sigma_{dE/dx}| < 3.0$ Relative to expected dE/dx value

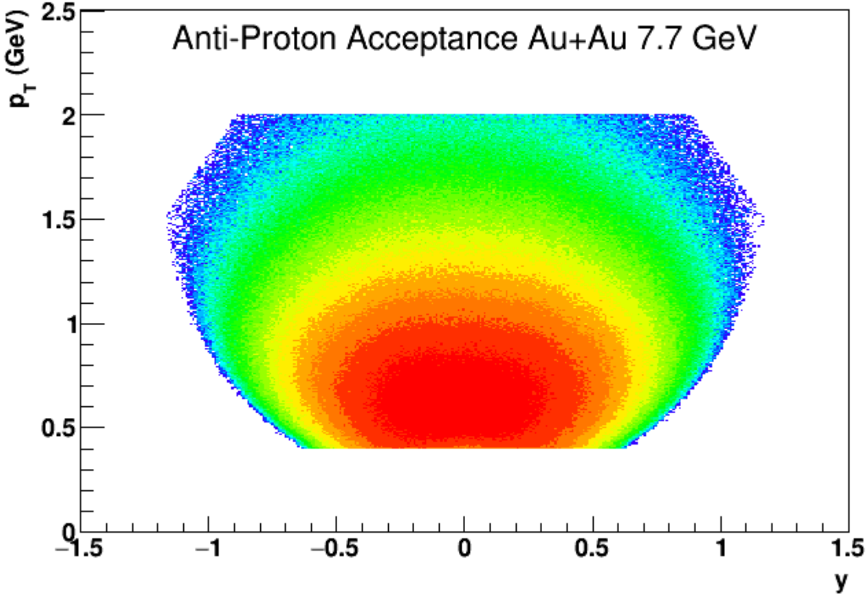
- Both Proton and antiproton have high purity signals





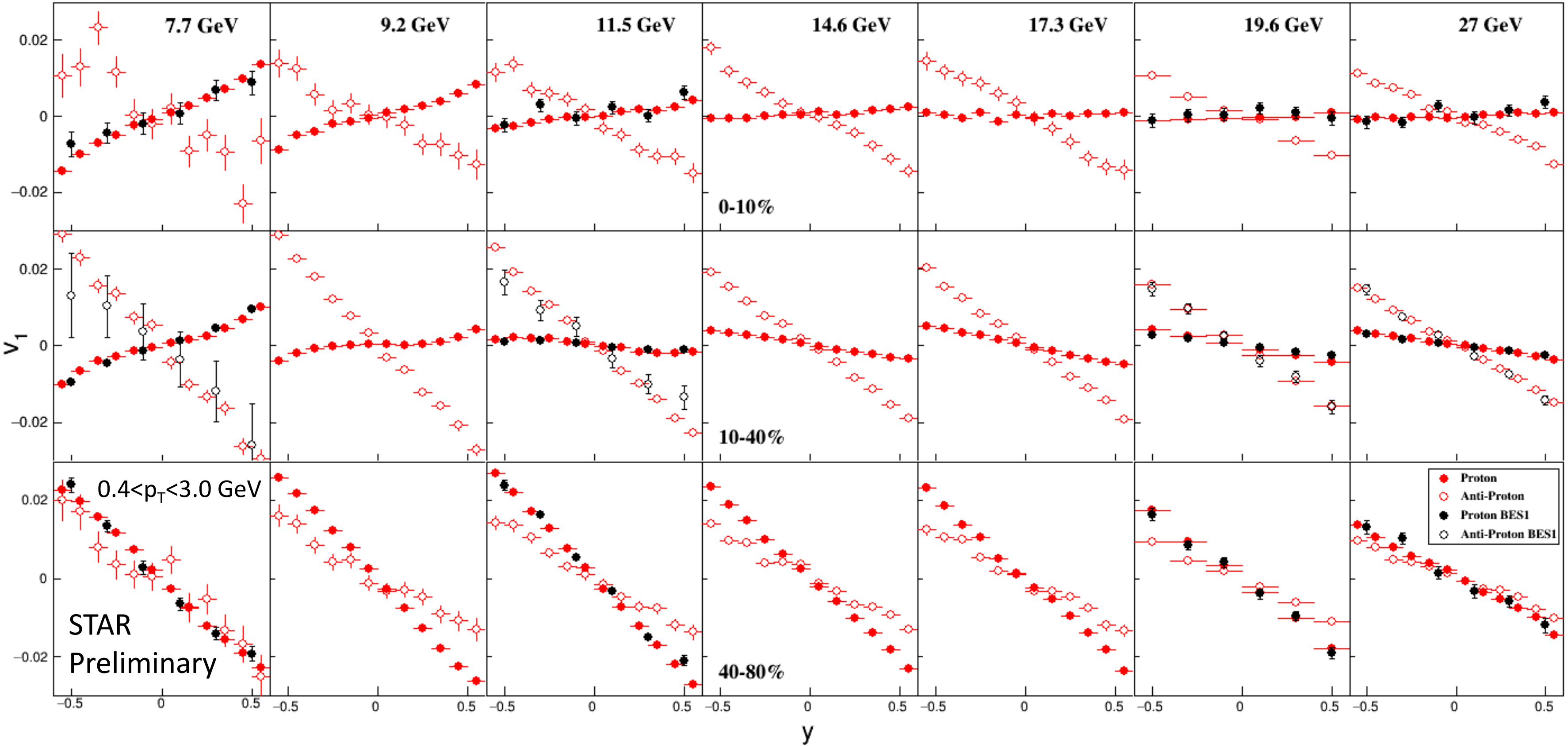
Acceptance





We see that we have good acceptance over the measured p_T range in the mid rapidity window (-0.5<y<0.5)

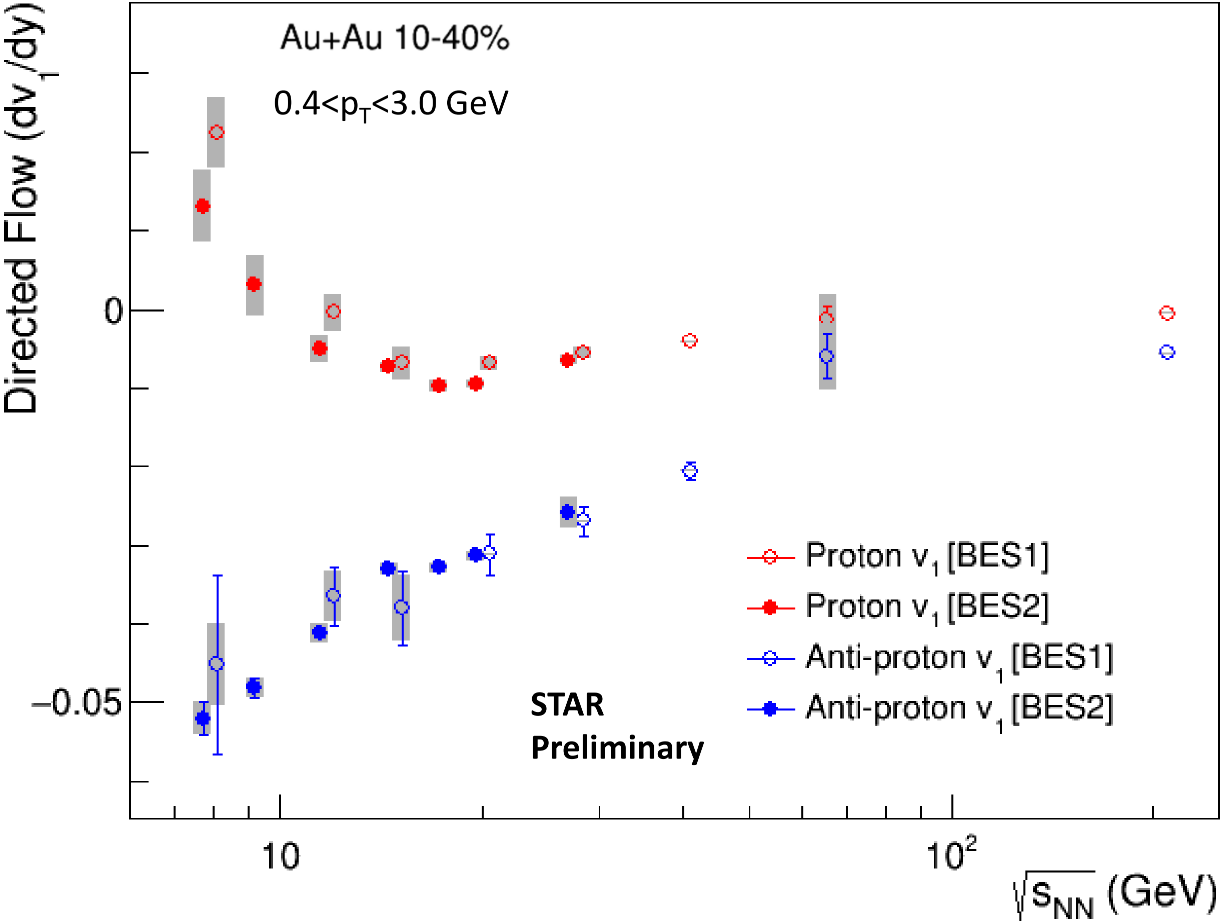
BES II Proton and Anti-Proton Directed Flow



- Consistent results with BES-I
- Slope is extracted by using a linear fit over $-0.5<y<0.5$

BES-I to BES-II Comparison

- BES-II Fit is linear over range -0.5<y<0.5
  - -0.8<y<0.8 for BES-I
- Significantly more accurate anti-proton results with the BES-II data
- Proton systematic error for BES-II dominated by cubic fit at low energies

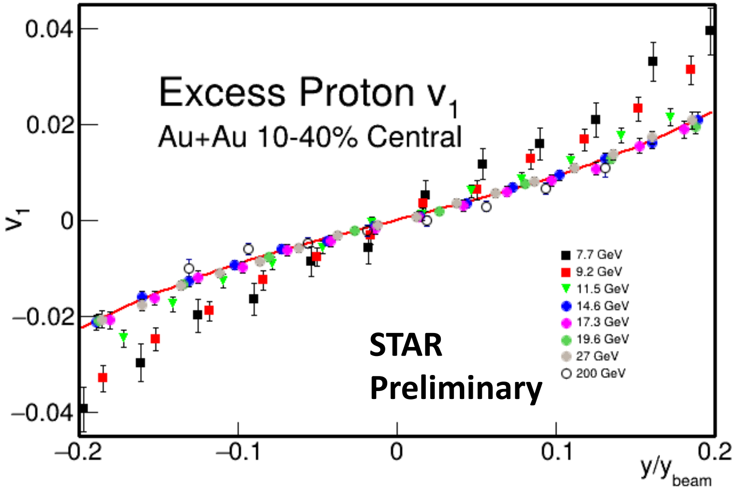


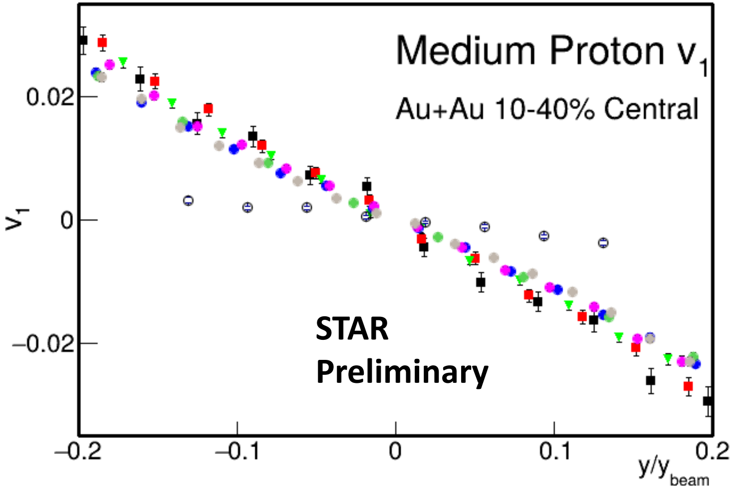
Collision Energy Dependence Of The Two Components

$$N_p v_{1,p} = N_p v_{1,medium} + \left(N_p - N_{\bar{p}}\right) v_{1,excess}$$

$$y_{beam}\left(\sqrt{s_{NN}}\right) = \cosh^{-1}\left(\sqrt{s_{NN}}/m_p\right)$$

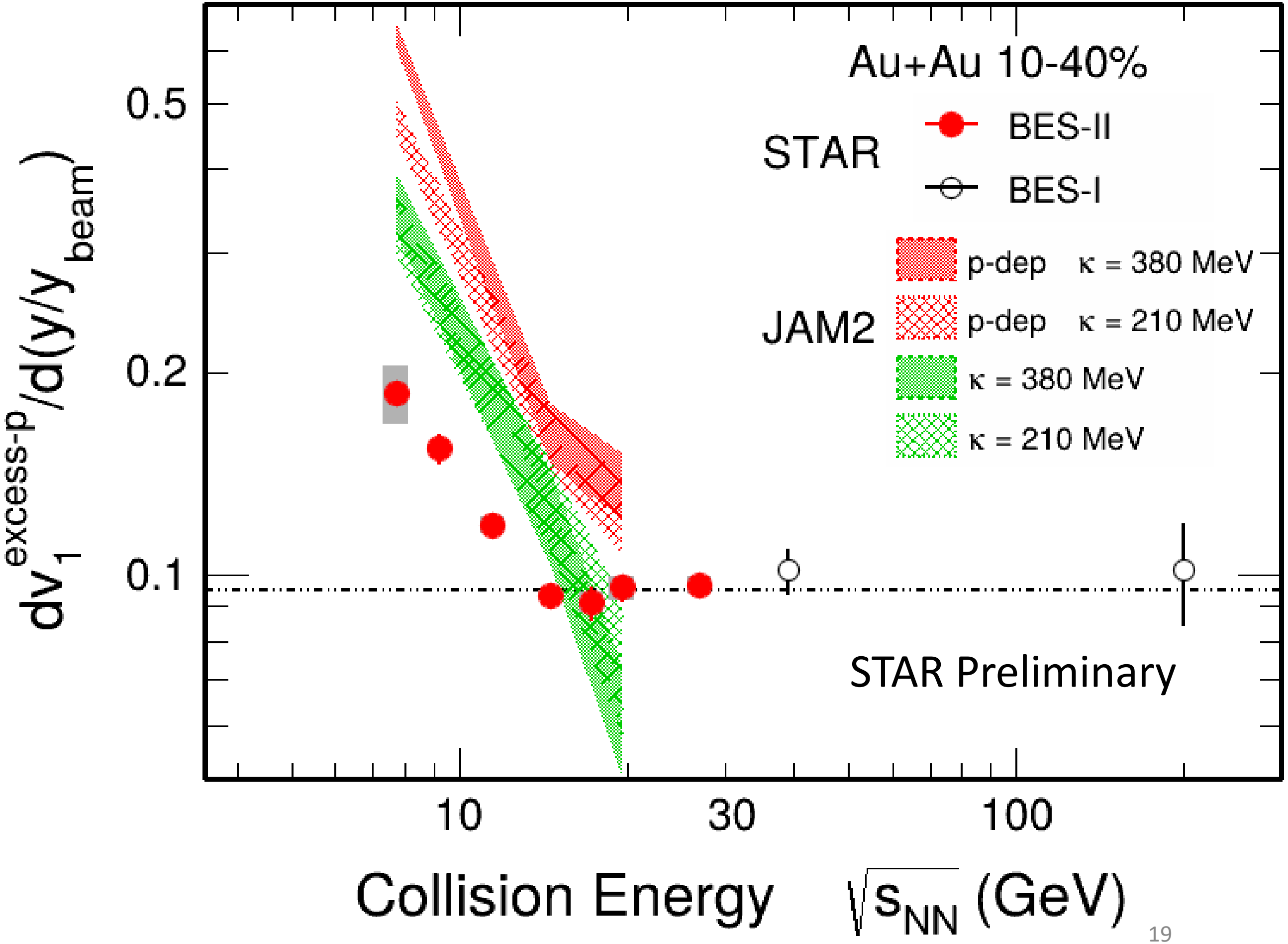
- Clear scaling of excess Proton flow with collision energy
    - Excess flow per transported consistent across collision energy from 200 -14.6 GeV
- Scaling starts to break at 11.5 GeV (light green)
- Medium v_1 shows no scaling





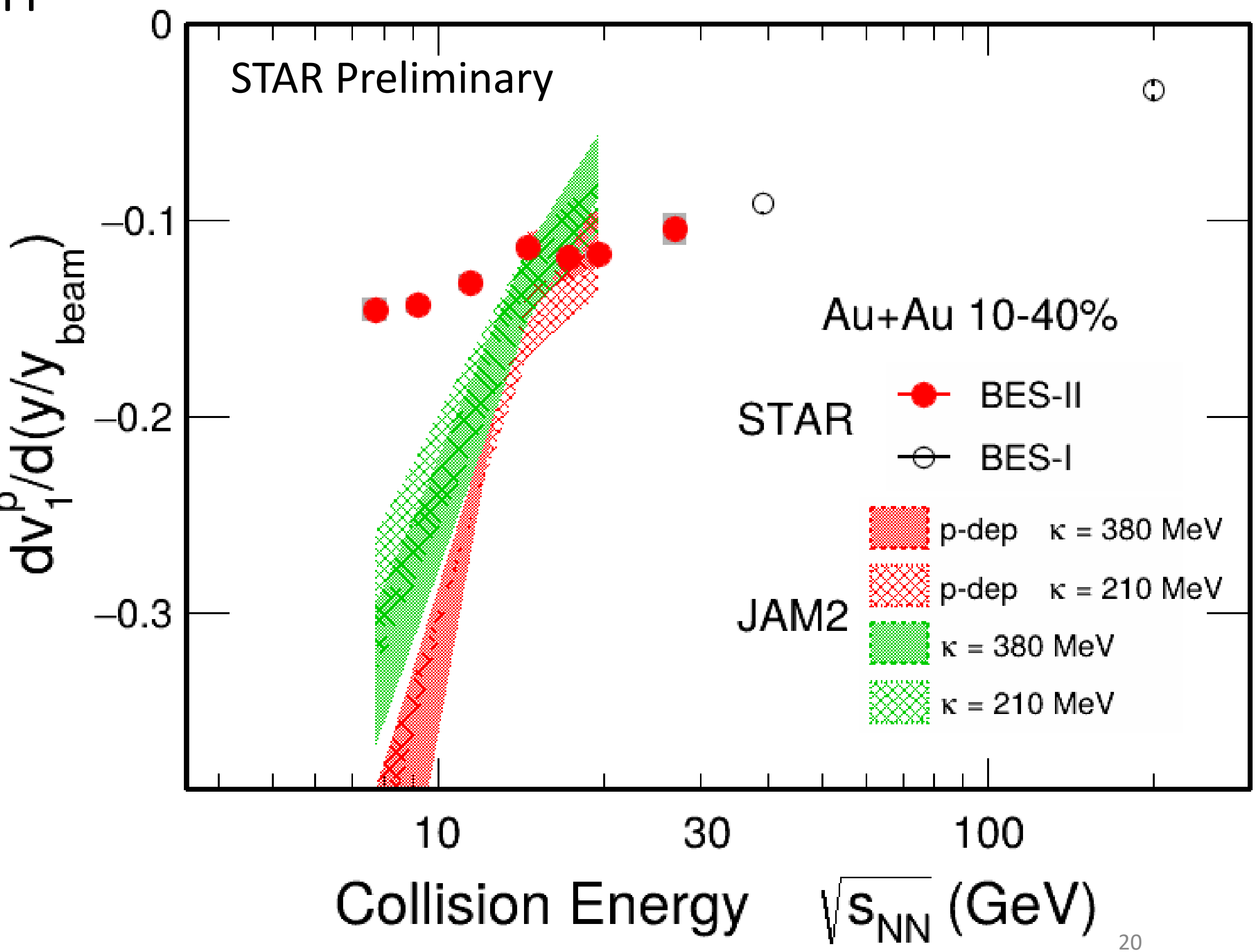
Model Comparison

- Models fail to show the scaling behavior above 14.6 GeV
- Below 14.6 GeV models overpredict the magnitude of the data
- Adding momentum dependence to the potential increases this overprediction



Model Comparison

- Momentum dependent models agree well above 14.6 GeV
- Below 14.6 GeV, JAM model calculations using different EOS all overpredict the magnitude of the data

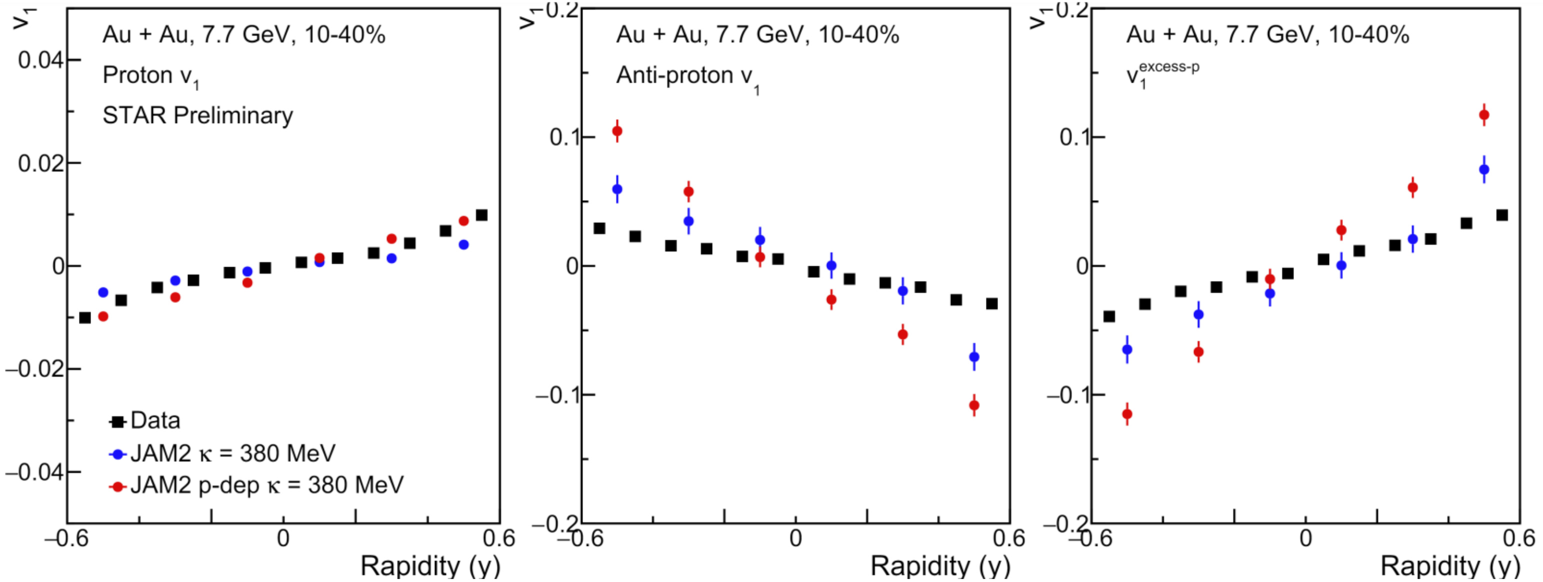


Summary

- Precision measurement of proton and antiproton v_1 from 7.7 to 27 GeV
- Excess v_1 of transported protons vs y/y_{beam} is constant from 200 — 14.6 GeV
- Deviates from scaling at 11.5 GeV and below — change in initial collision dynamics?
- Mean field calculations overpredict magnitude the data, even for the softest EoS tried
  - New data expected to offer better constraints on EOS parameters

Backup

Comparisons with JAM model: Cascade and Meanfield

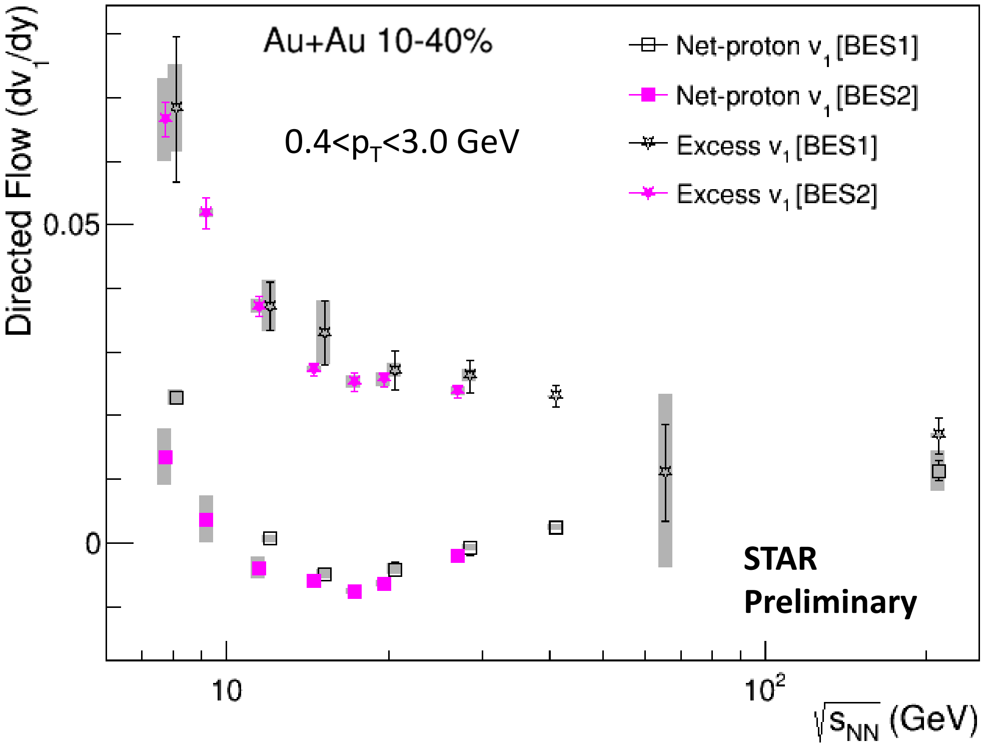


- Vastly different values for the two components between different modes, but proton v_1 similar

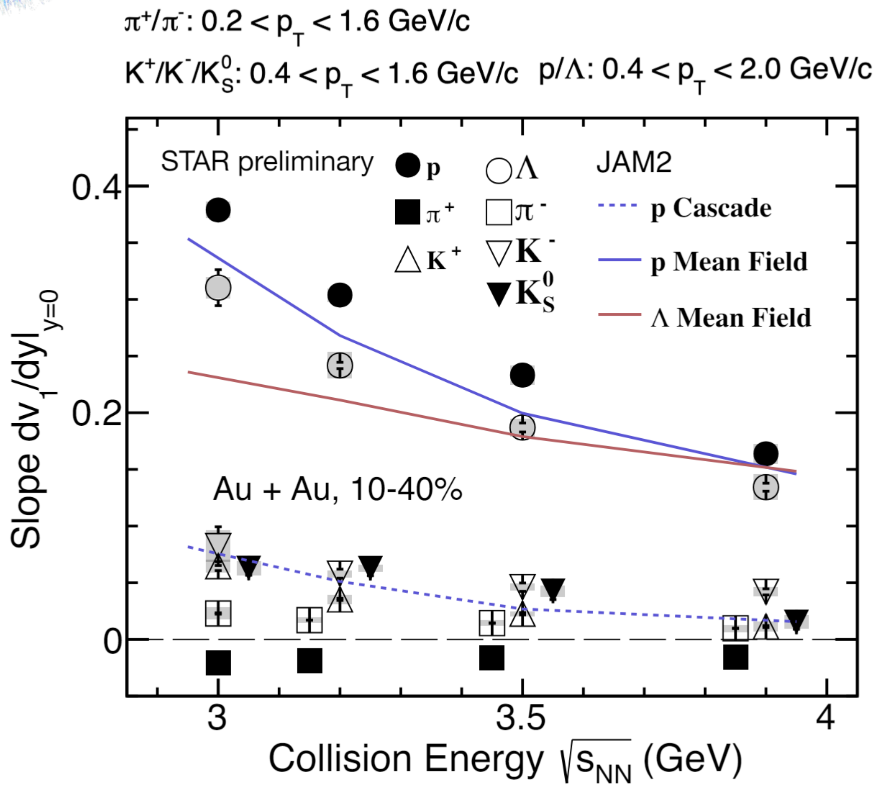
- More sensitivity to change in medium dynamics/EoS than just looking at proton v_1

Excess Proton Flow and Net Proton Flow

- BES-II Fit is linear over range $-0.5<y<0.5$
  - $-0.8<y<0.8$ for BES-I
- We see monotonic behavior in excess proton flow
- This behavior scales with beam rapidity from 14.6 GeV to 200 GeV
- Net-Proton systematic error for BES-II dominated by cubic fit at low energies
  - This check was not included for BES-I



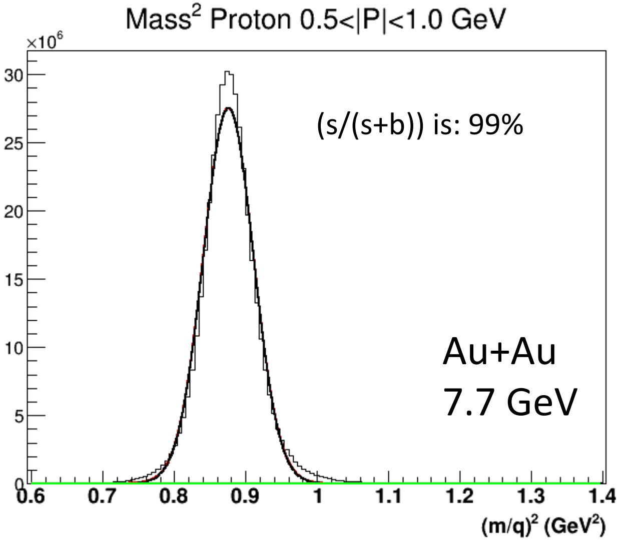
Energy dependence of v_1 slope

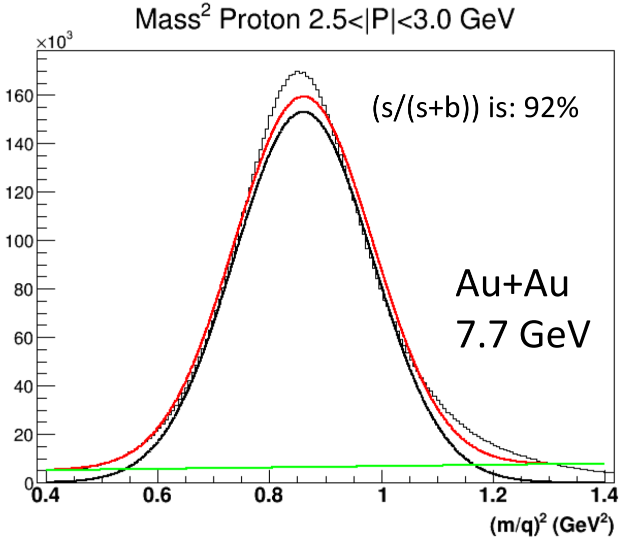


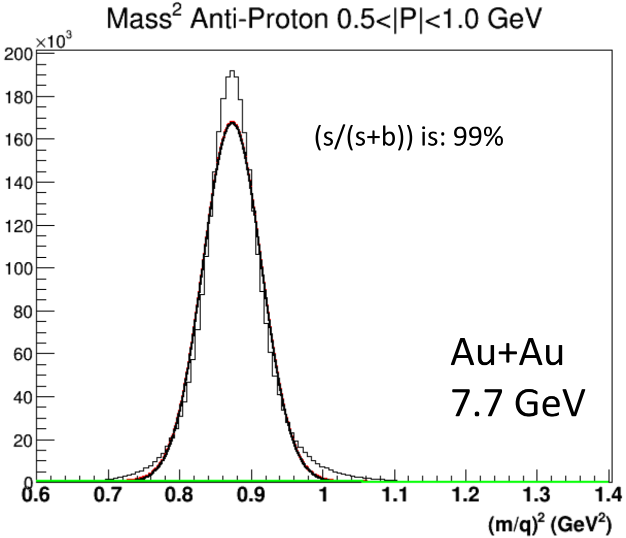
1) v_1 slope of baryons drops as collision energy increases
2) JAM with baryonic Mean Field better describe data
   - Mean field potential play important role

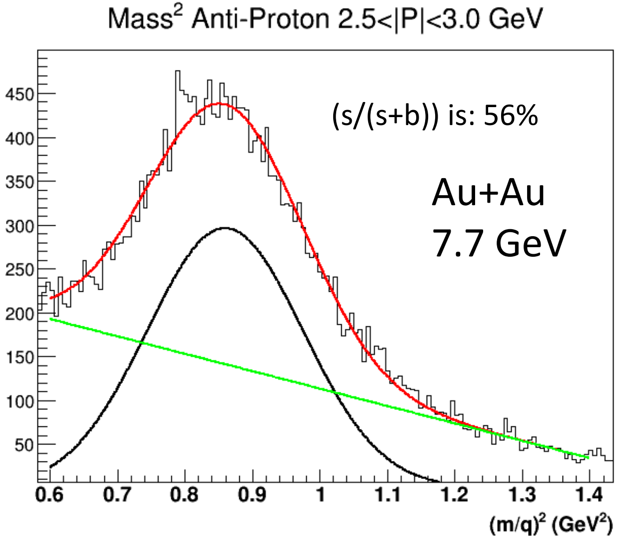
PID Purity

- Signal purity decreases at higher momentum so its important to check
- At 7.7 GeV up to 11.5 GeV the anti-proton signal is not pure enough to just to sum up identified tracks.


Mass^2 Proton 0.5<|P|<1.0 GeV

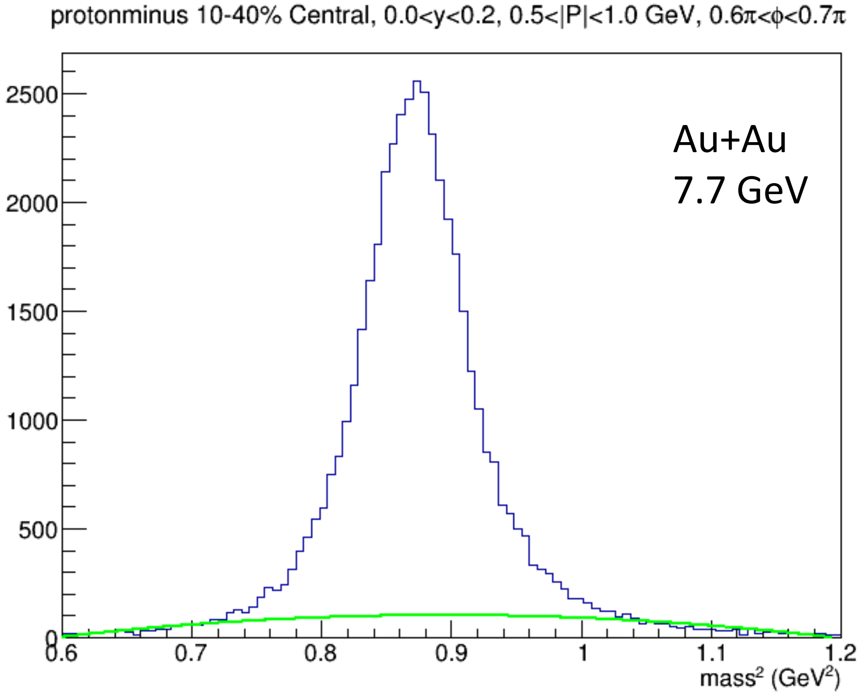

Mass^2 Proton 2.5<|P|<3.0 GeV


Mass^2 Anti-Proton 0.5<|P|<1.0 GeV


Mass^2 Anti-Proton 2.5<|P|<3.0 GeV

Background subtraction of Anti-Proton signal

- The mass^2 of tracks satisfying the <dE/dx> PID were divided into bins based on centrality, y, ϕ-ψ_r, and |P|.
- The signal and background of mass^2 was then measured for each.
- Then the signals were combined over |P| to get the signal vs ϕ-ψ_r in 10 different rapidity windows.



RQMD Modeling

- Idea is to use classical Hamiltonian formalism
- We start with 8N phase space variables and reduce them with 2N constraints:
    - On-mass-shell constraint (gives N constraints)
    - Time fixation (gives N-1 constraints)
    - Define evolution temporal parameter t (gives 1 constraint)
- Each one of these constraints can be written as an equation $\phi_i = 0$, and so the Hamiltonian consists of the constraint conditions with their lagrange multipliers.

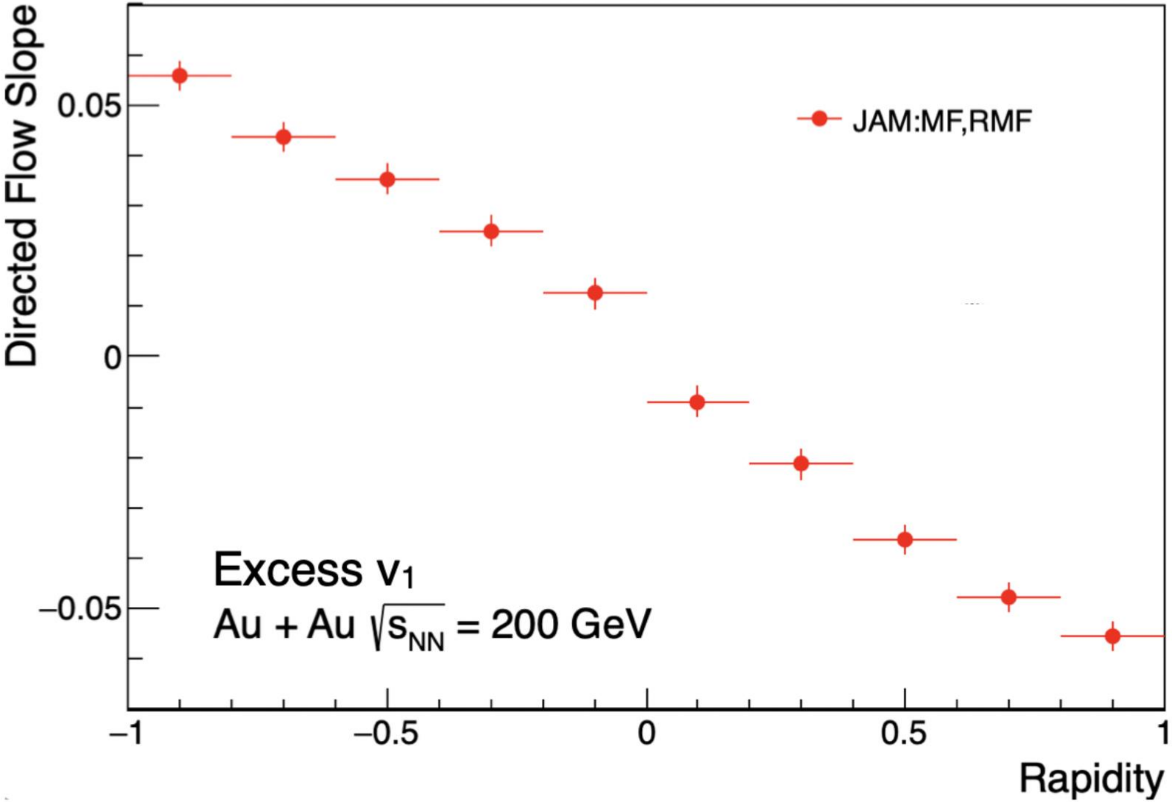
$$H = \sum_{i=1}^{2N-1} u_i \phi_i$$

For RQMD/S the on-mass-shell constraint is: $\phi_i = p_i^2 - m_i^2 - 2m_i V_i$

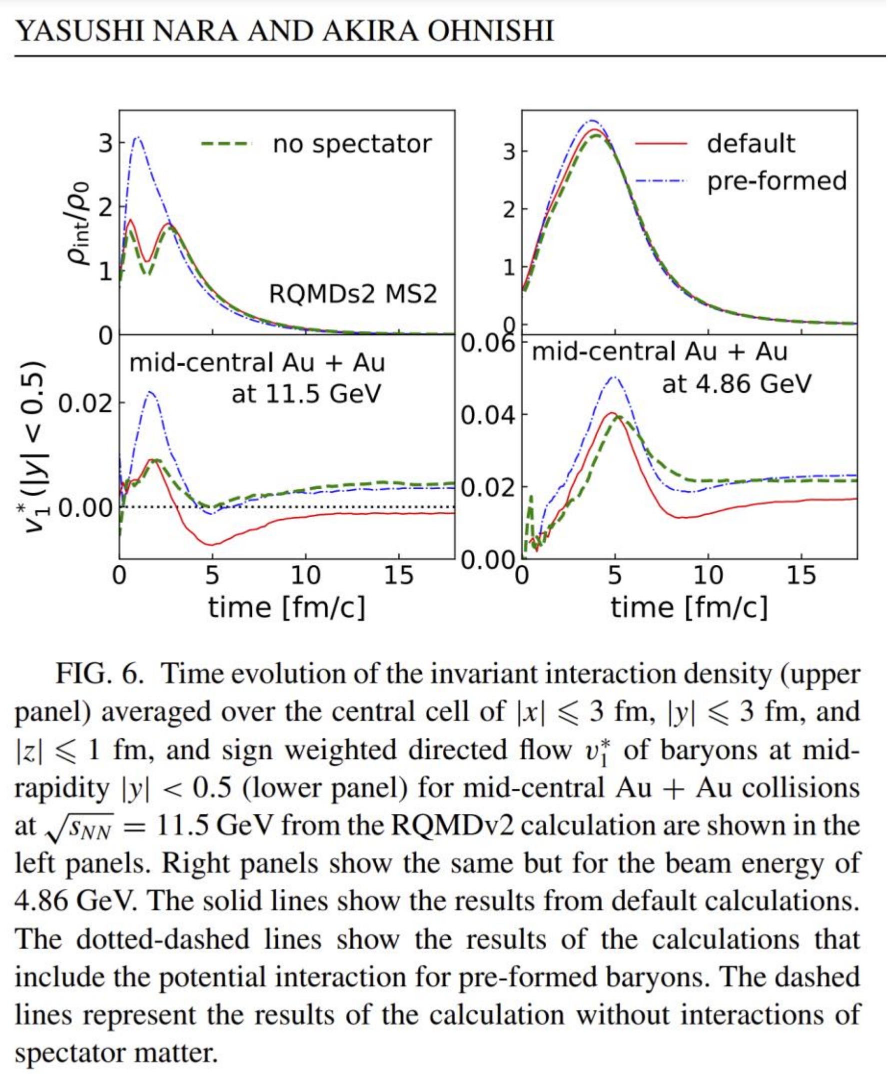
For RQMDs and RQMDv: $\phi_i = (p_i - V_i)^2 - (m_i - S_i)^2$

200 GeV

- JAM Model calculation of flow at 200 GeV turns negative



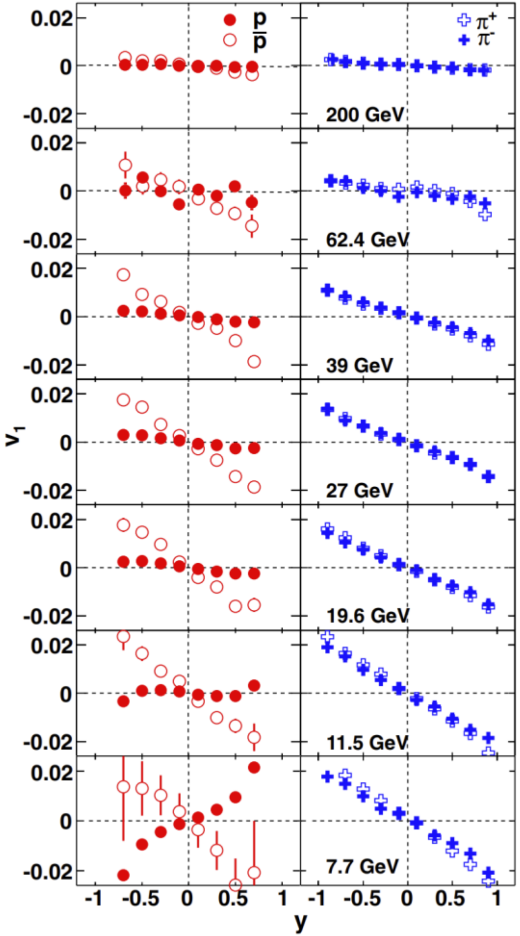
Time Dependent Flow



YASUSHI NARA AND AKIRA OHNISHI

FIG. 6. Time evolution of the invariant interaction density (upper panel) averaged over the central cell of $|x| \leqslant 3$ fm, $|y| \leqslant 3$ fm, and $|z| \leqslant 1$ fm, and sign weighted directed flow v_1^* of baryons at mid-rapidity $|y| < 0.5$ (lower panel) for mid-central Au + Au collisions at $\sqrt{s_{NN}} = 11.5$ GeV from the RQMDv2 calculation are shown in the left panels. Right panels show the same but for the beam energy of 4.86 GeV. The solid lines show the results from default calculations. The dotted-dashed lines show the results of the calculations that include the potential interaction for pre-formed baryons. The dashed lines represent the results of the calculation without interactions of spectator matter.

Directed Flow (v_1)



Directed flow of protons and pions from BES-I (PRL 112, 162301 (2014))

- Hydro and nuclear transport models suggest that v_1 offers sensitivity to the dynamics of the expanding medium
- Proton flow is believed to be sensitive to the softening of the equation of state near a first order phase transition
- The behavior at mid-rapidity is highly linear, thus an important characteristic is the slope v_1 w.r.t rapidity

$$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$$