RHIC & AGS
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Beam Energy Scan Directed Flow and Study of Possible EOS Softening

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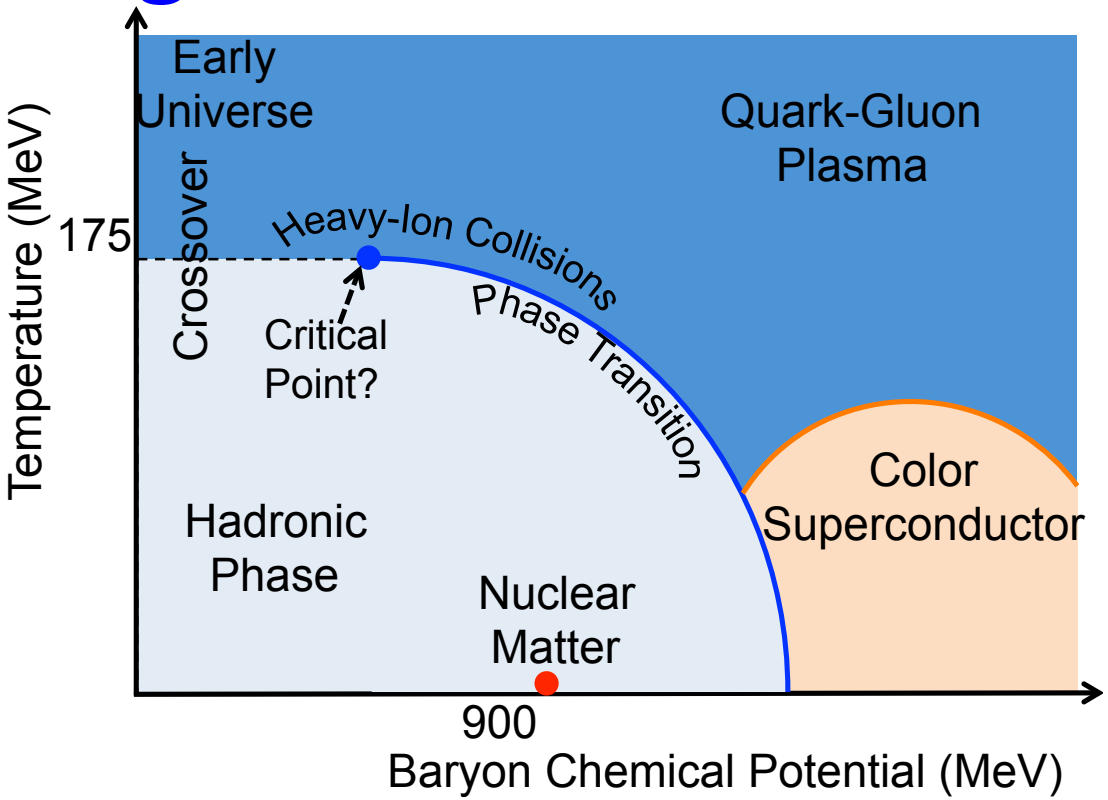
Office of Science
U.S. DEPARTMENT OF ENERGY

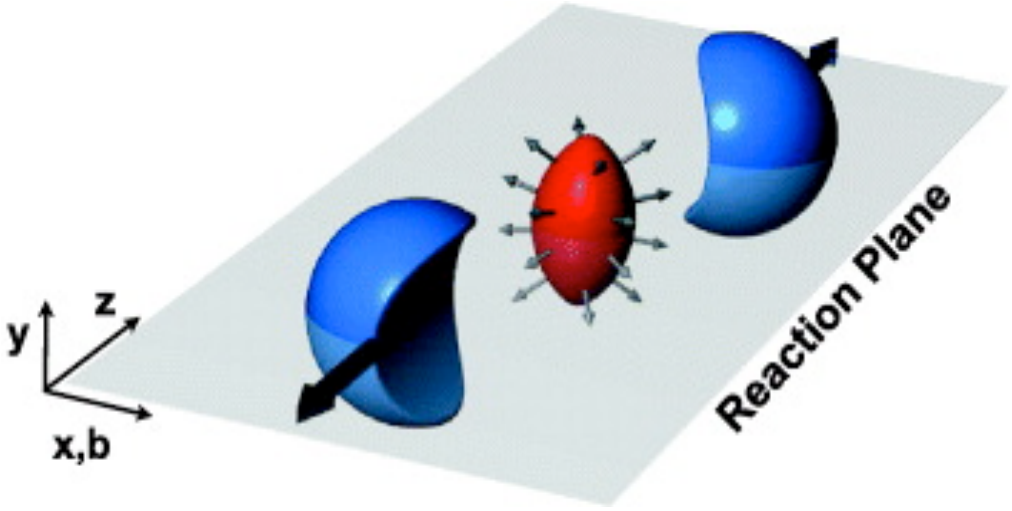
STAR

Phase Diagram of Quarks and Gluons



- Early universe smooth crossover between QGP⇔HG
- Lattice QCD predicts crossover ceases and becomes discontinuous
  - **Where is critical end point?**
  - **What is the nature of the phase transition?**
  - **Map turn-off of QGP signatures**

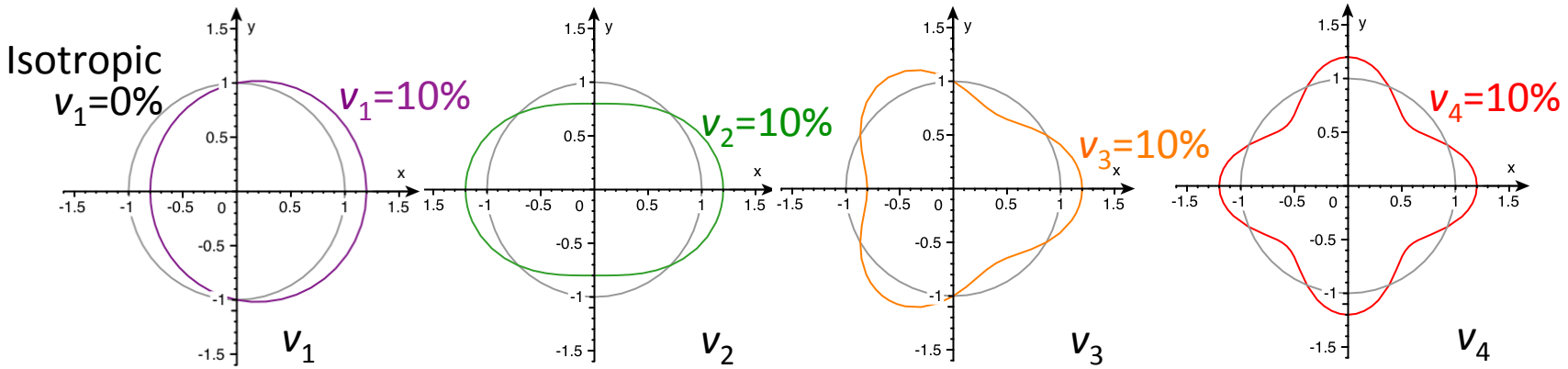
Anisotropic Flow



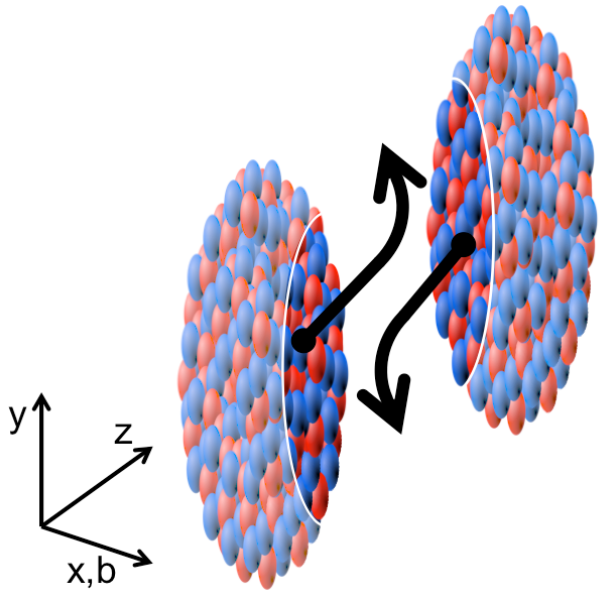
- **Anisotropy of the azimuthal distribution of particles with respect to reaction plane** $\left(\Psi_{RP}\right)$

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n \cos\, n\left(\phi - \Psi_{RP}\right)\right) \quad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- **v_1-Directed flow, v_2-Eliptic flow, v_3-Triangular flow**



Directed Flow (v_1)

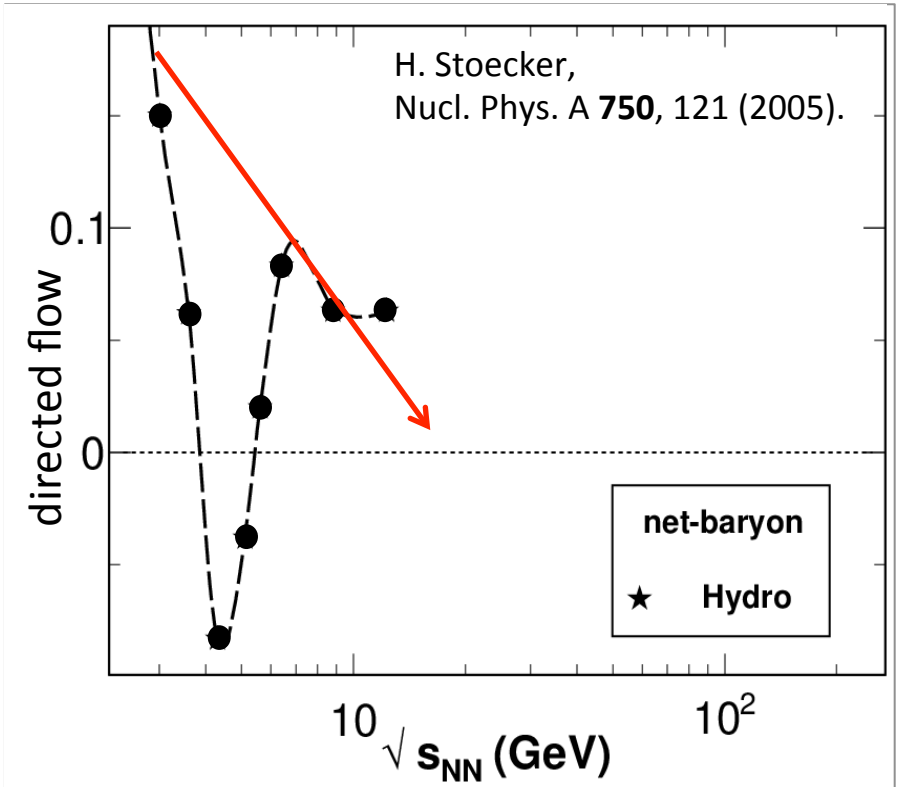


$$v_1 = \left\langle \cos\left(\phi - \Psi_{RP}\right) \right\rangle$$

- Directed flow describes the sideward motion of the particles within the reaction plane
- Generated during the nuclear passage time ($2R/\gamma \approx 0.1$ fm/c)
- Therefore probes the very earliest stage of the collision dynamics

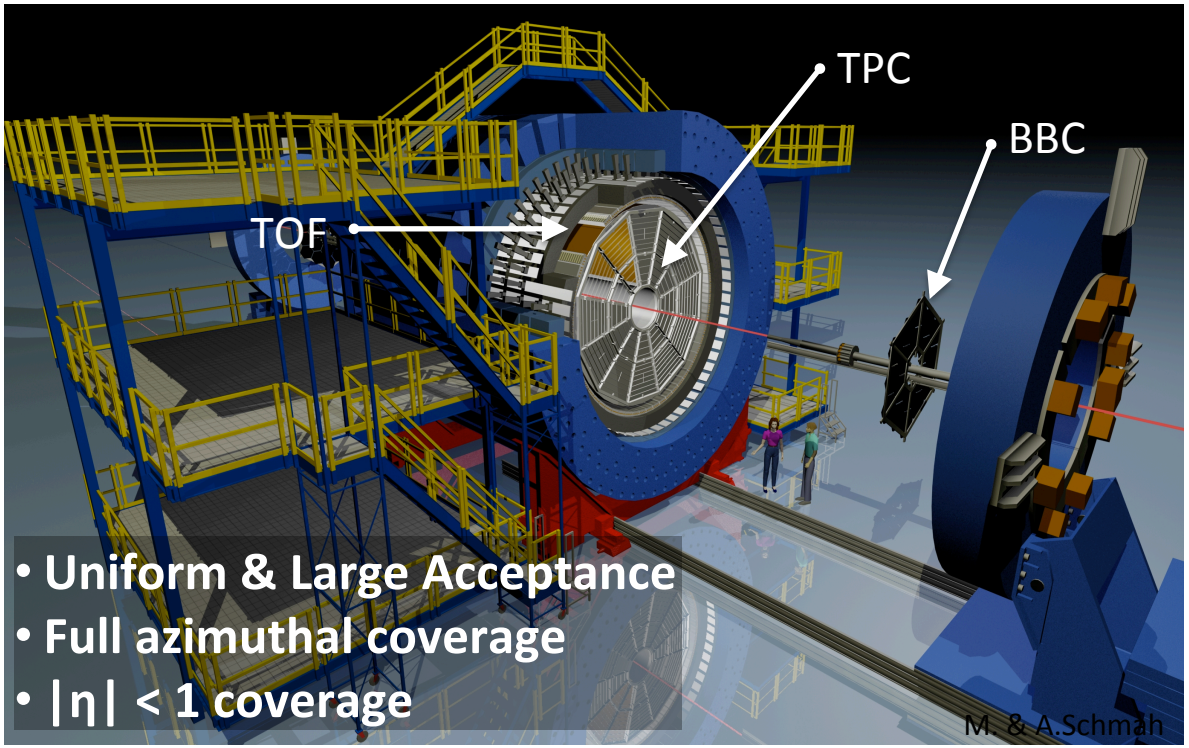
v_1 and search for 1st order phase transition

- Minimum in slope of directed flow (dv_1/dy) as a function of beam energy for baryons and double sign-change for net baryons suggest softening of EOS
- Softening of EOS suggests 1st order phase transition
- Proton v_1 probes interplay of baryon transport and hydro behavior
- New Λ data offer more insight into transport of baryons



- Dashed line: EOS with the assumption of 1st order phase transition
- Red line: EOS without a phase transition

STAR & Particle Identification

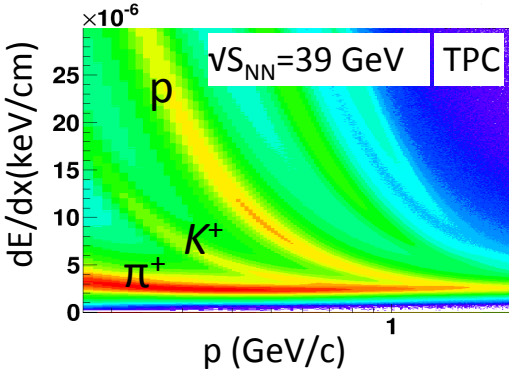


Long lived: *p*, *K*, π

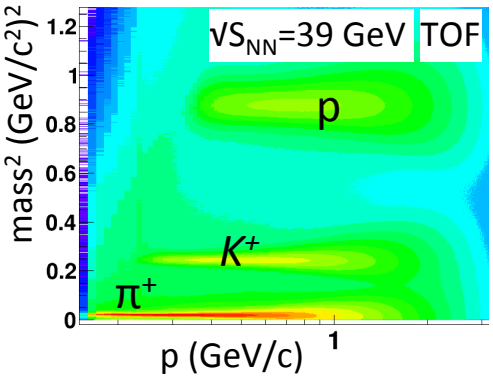
- Requires TPC & TOF hits
- *dE/dx* cut of $|n\sigma| \leq 2$
- *p* : $0.4 < p_T < 2.0$ GeV/c
- $K^{\pm}$ & $\pi^{\pm}$: $p_T > 0.2$ GeV/c
- $p < 1.6$ GeV/c

Short lived : Λ & K^0_S

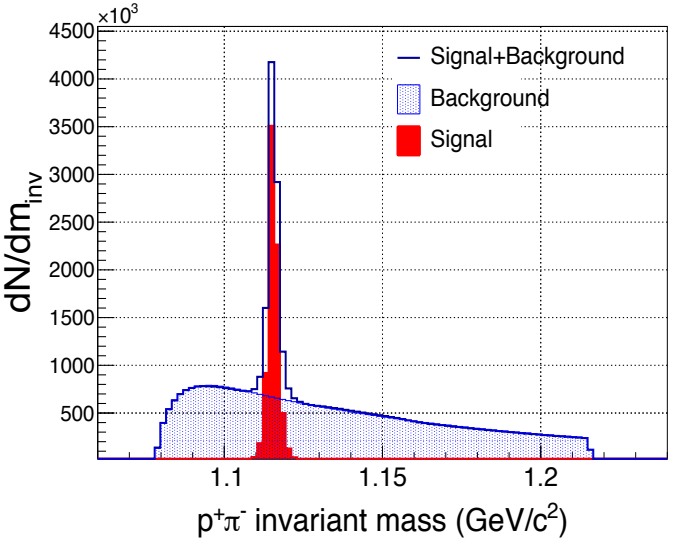
- Invariant mass technique
- Mixed-event background
- V0 topological cuts
- TPC and/or ToF hits for daughters
- $0.2 < p_T < 5.0$ GeV/c



- PID using energy loss in TPC d*E*/d*x*

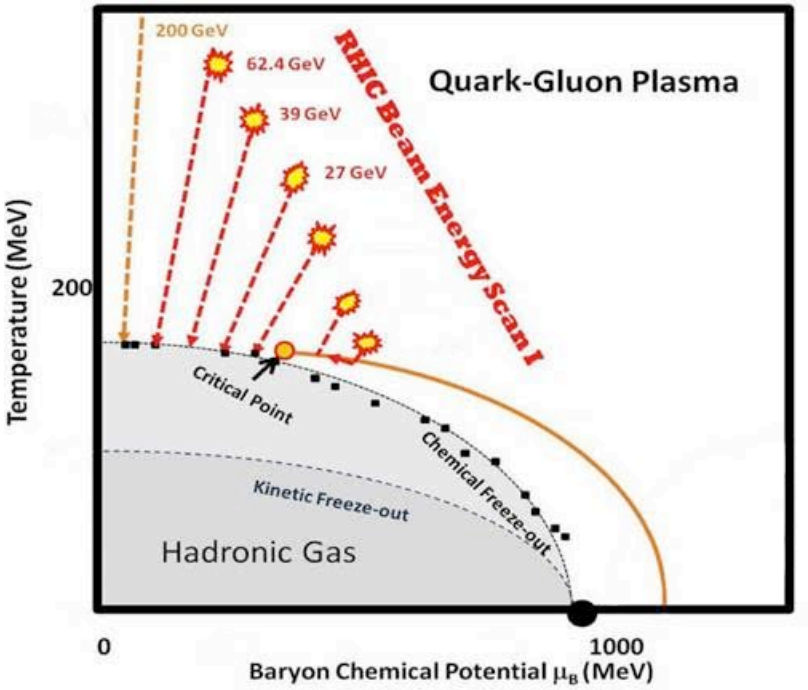


- PID using time of flight and momentum from TPC



Data Set

- RHIC-BES data
- Collected in 2010, 2011, 2014
- Gold + Gold collisions



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

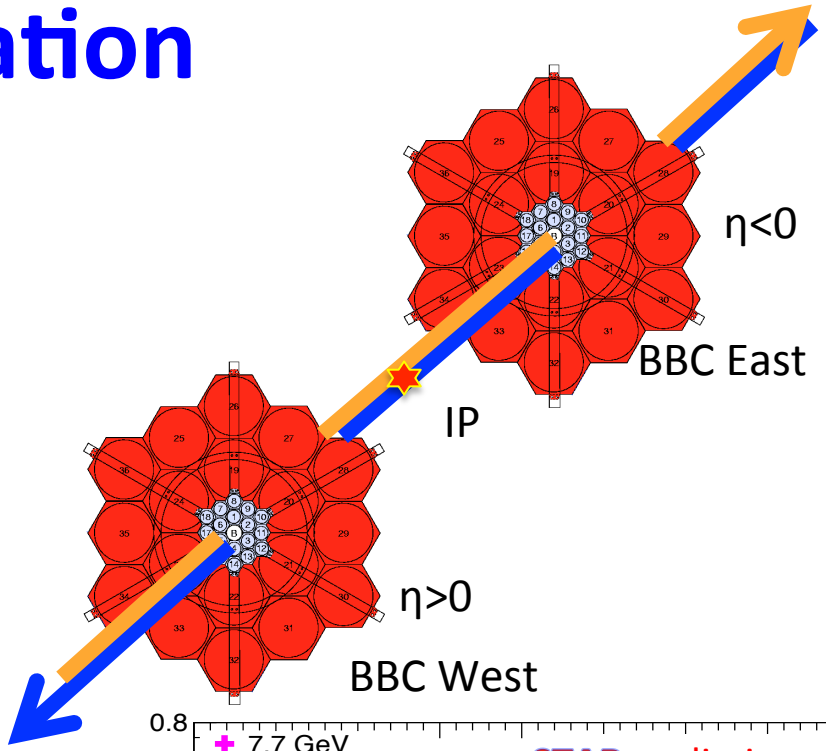
$\sqrt{s_{NN}}$ (GeV)	Baryon Chemical potential (μ_B)	Temperature (MeV)	Events (10^6) Minimum-bias
7.7	422	139.6	4
11.5	316	151.6	12
14.5	262	156.2	20
19.6	206	160	36
27	156	162.6	70
39	112	164.2	130

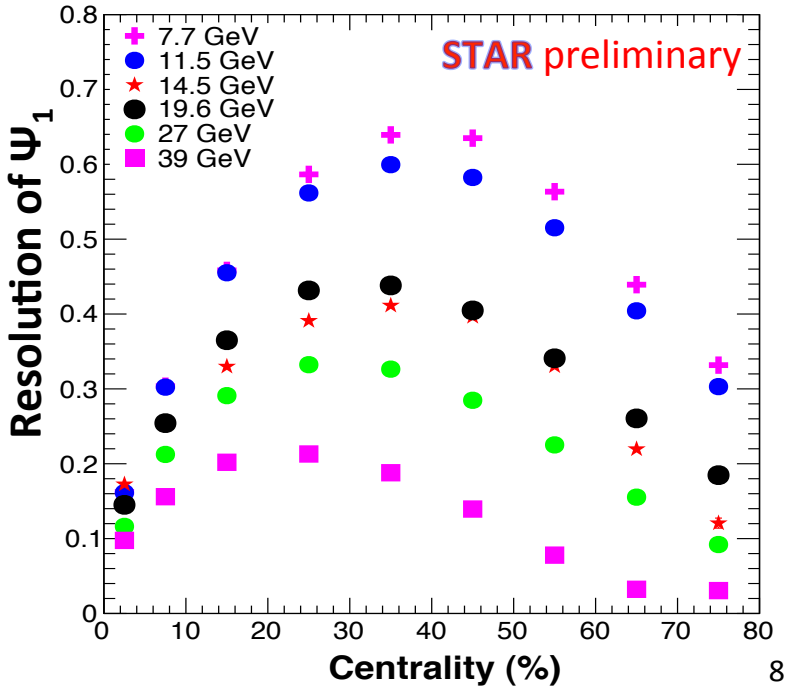
Beam energies where CP/ 1st order PT is predicted

Event Plane (Ψ) Estimation

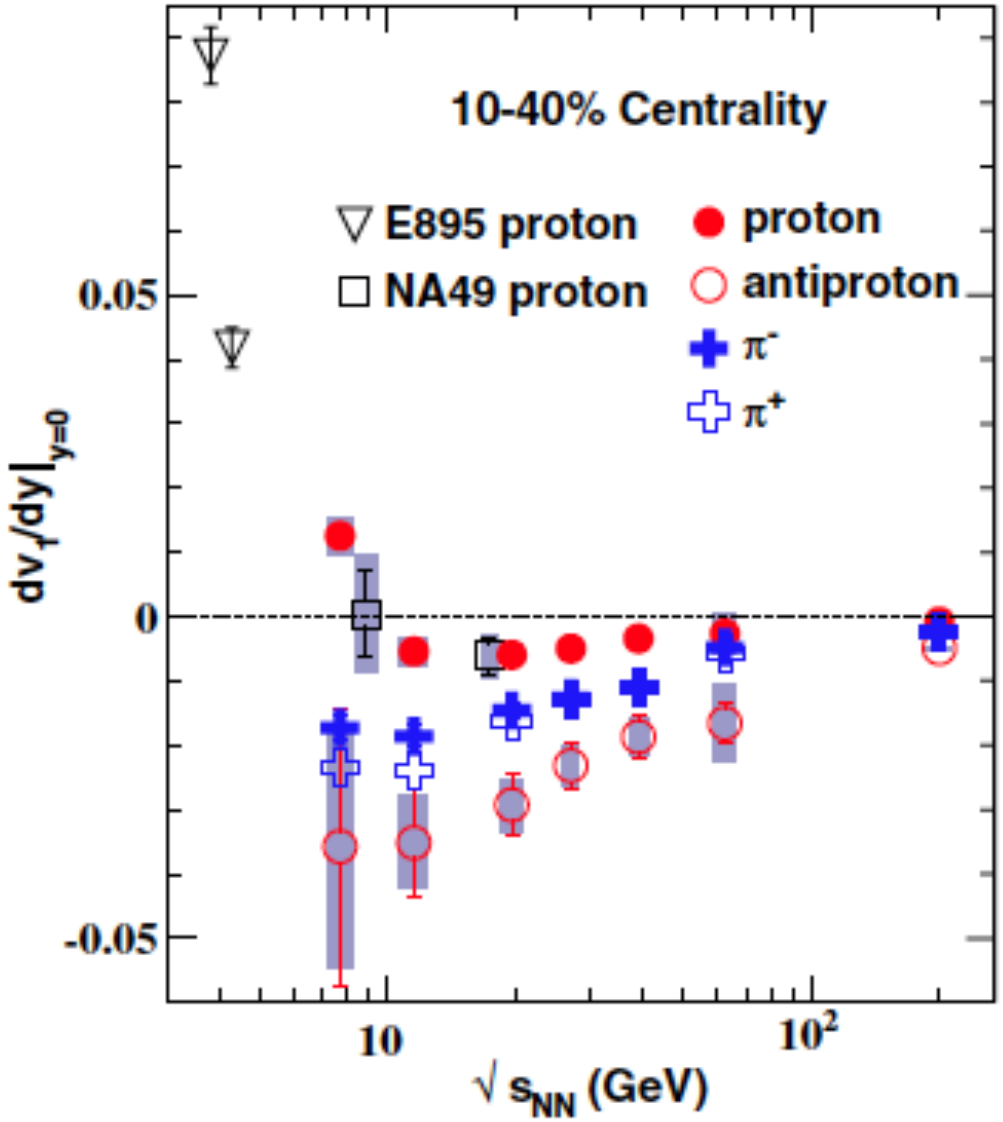
- 1st-order reaction plane estimated using East & West BBC detectors
  - Coverage: $3.3 < |\eta| < 5.0$
- Geometry of the detector limits the accepted particle multiplicity in an event
  - Any measurement relative to **Ψ** must be corrected for **Ψ** resolution
- BBC Ψ_1 resolution improves at lower energies due to strong v_1 signal near beam rapidities aligning with BBC acceptance

(Voloshin, Poskanzer, Snellings, arXiv:0809.2949)





Selected Literature - Experiment



STAR collaboration, PRL 112, 162301 (2014)

- Proton slope show a minimum between 11.5 to 19.6 GeV
- Extrapolations show good agreement with previous measurements
- Charged pions show negative slope in all energies

Models With Relevance to Directed Flow

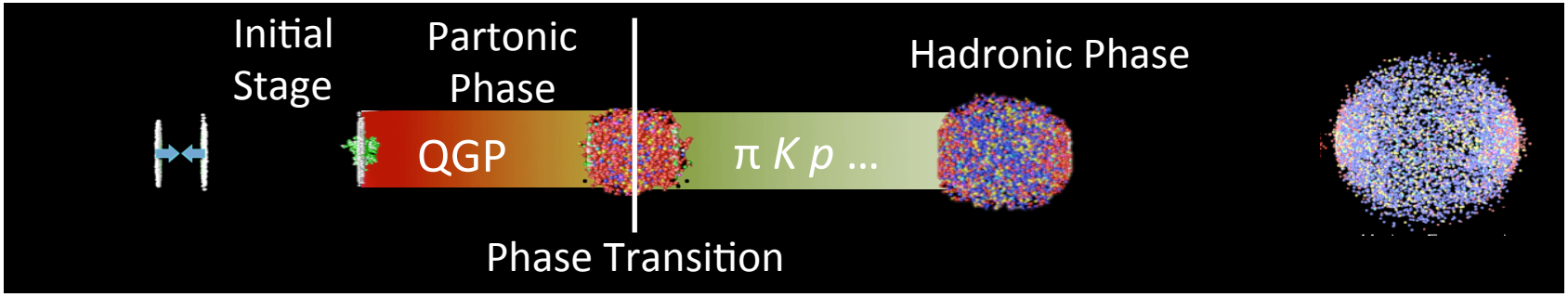
UltraRelativistic Quantum Molecular Dynamics (UrQMD)
- Hadronic Boltzmann transport
- No phase transition or QGP
- Very widely used and tested; code is available to everyone

Frankfurt Hybrid Model
- Early and late stages similar to UrQMD (Boltzmann transport)
- Hydro used for intermediate stage of high energy density
- Hydro has QGP phase, with crossover & 1st-order phase transition

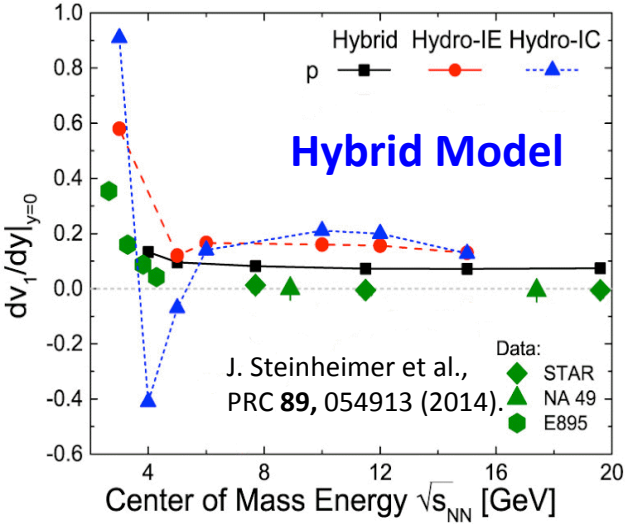
Parton-Hadron String Dynamics (PHSD)
- Partonic and hadronic degrees of freedom
- QGP phase is assumed
- Crossover phase transition between QGP and hadron gas

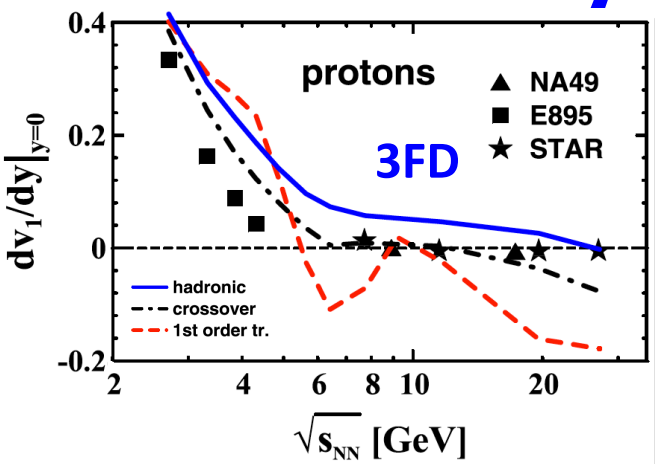
Jet AA Microscopic (JAM) Model
- Hadronic degrees of freedom
- No QGP
- 1st-order phase transition is mimicked by attractive scattering, generating a 'softening' near phase boundary

Three Fluid hydro model (3FD)
- Partonic and hadronic degrees of freedom
- Crossover & 1st-order phase transition



Selected Literature - Theory

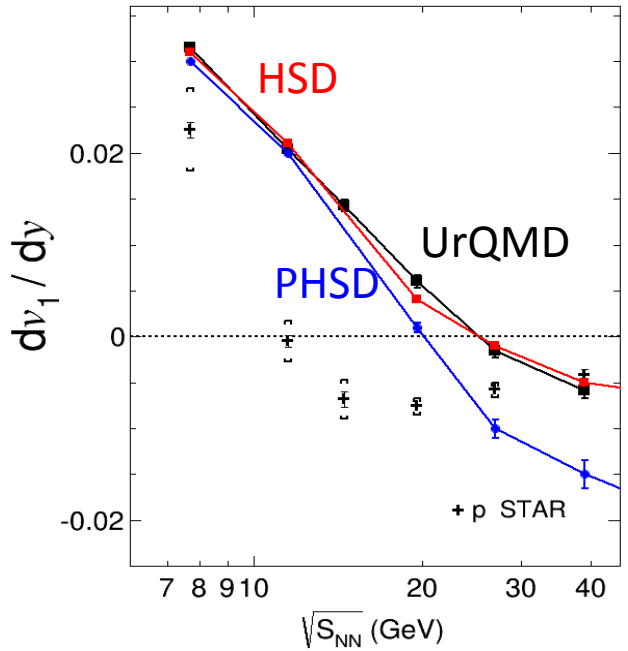




Ivanov & Soldatov PRC 91, 024915 (2015)

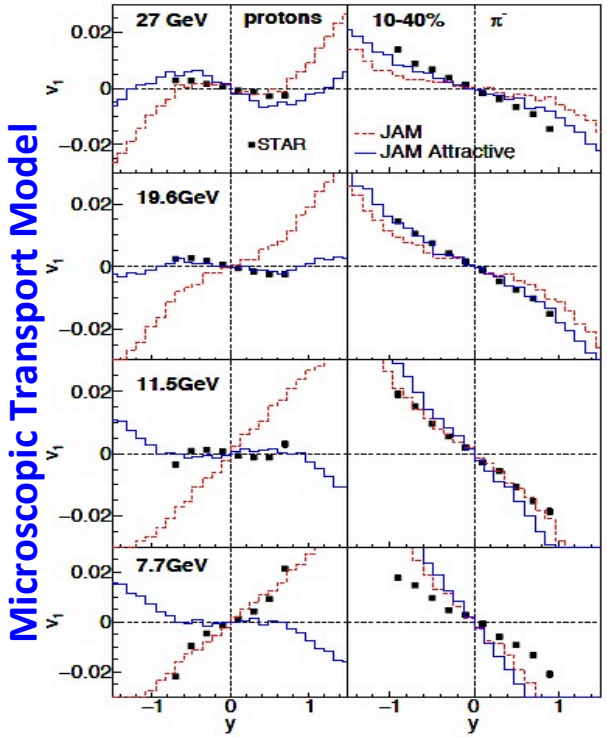
- Hadronic transport, Hydrodynamic, Hybrid, microscopic off-shell transport approach, 3FD – all show poor agreement with key feature of data.

Parton-Hadron-String Dynamics



V. P. Konchakovski *et al.* PRC **90,** 014903 (2014)

Microscopic Transport Model

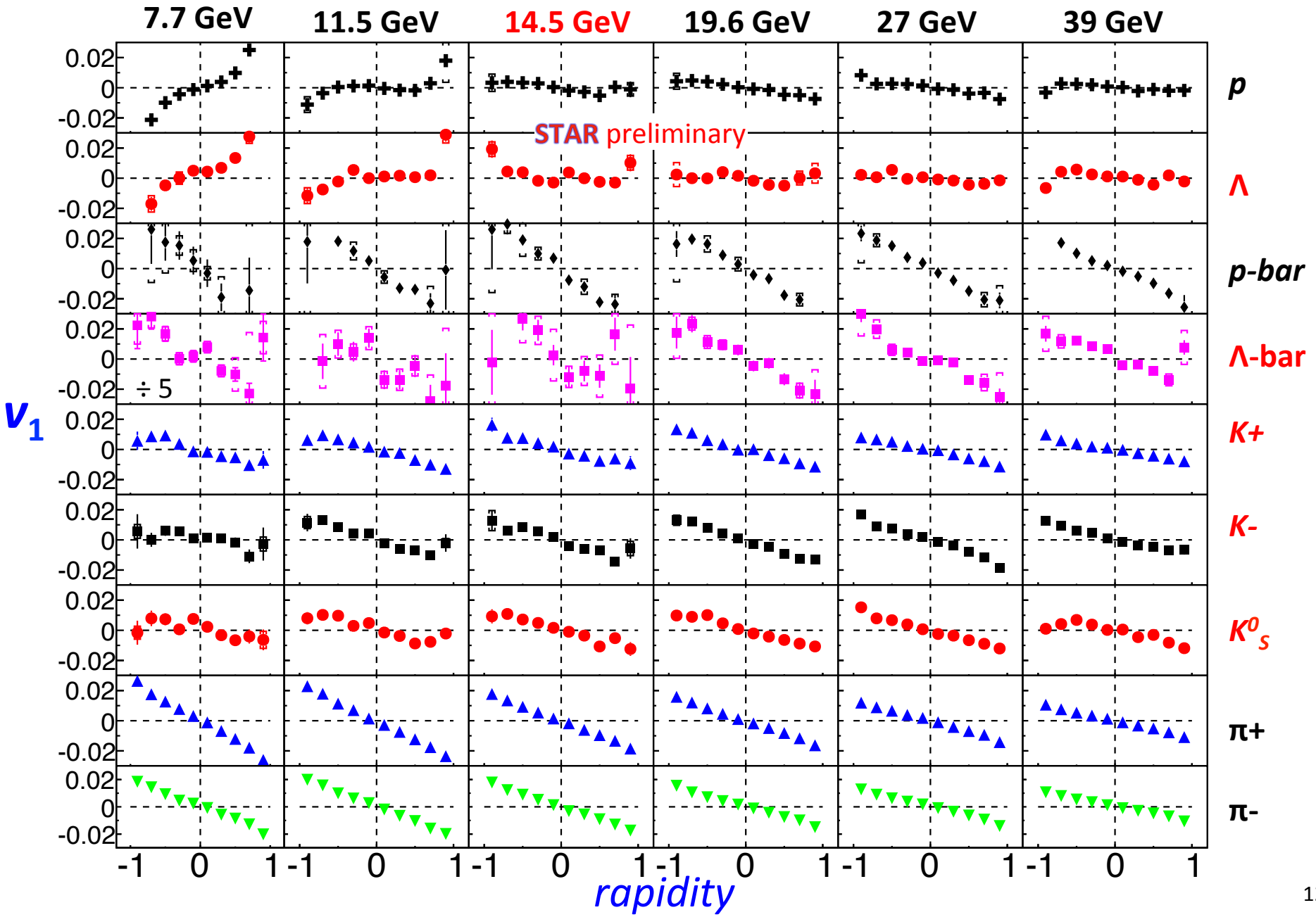


Nara, Ohnishi & Stoecker, (2016) arXiv:1601.07692

- JAM model with attractive potential shows reasonable qualitative agreement above 10 GeV; authors argue it favors 1st-order PT

Raw Measurements

PRL 112, 162301 (2014)
Prashanth S – QM15



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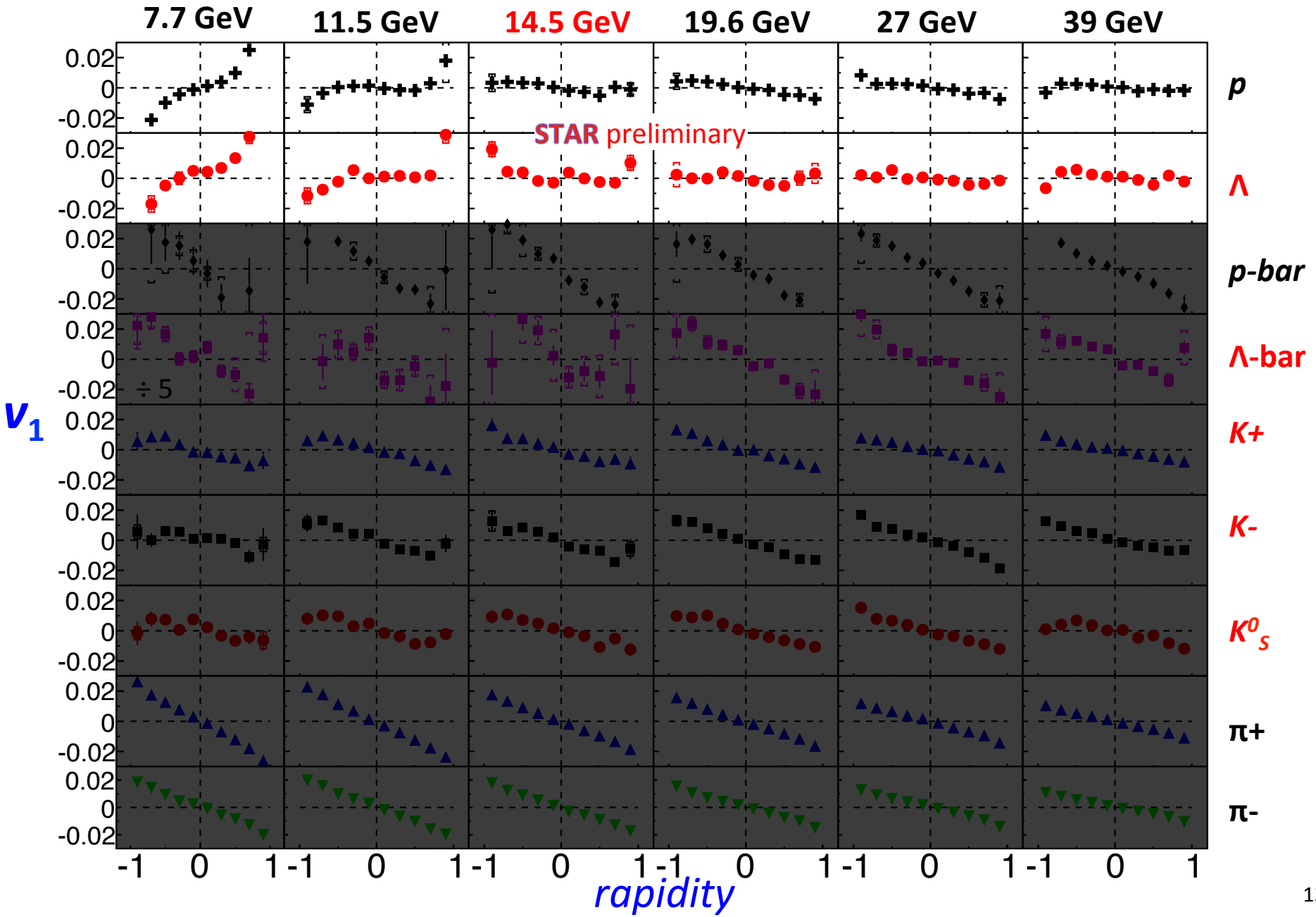

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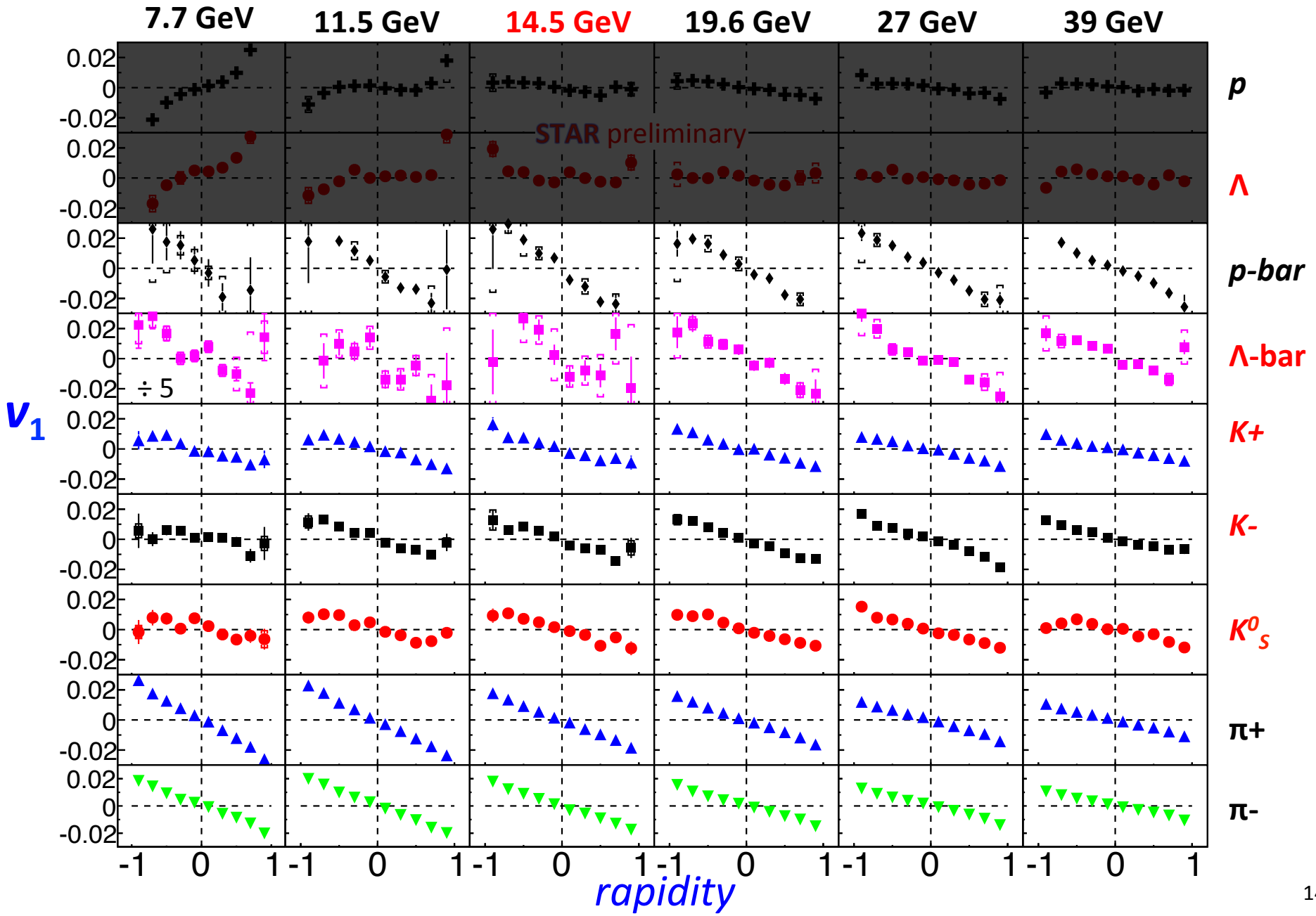
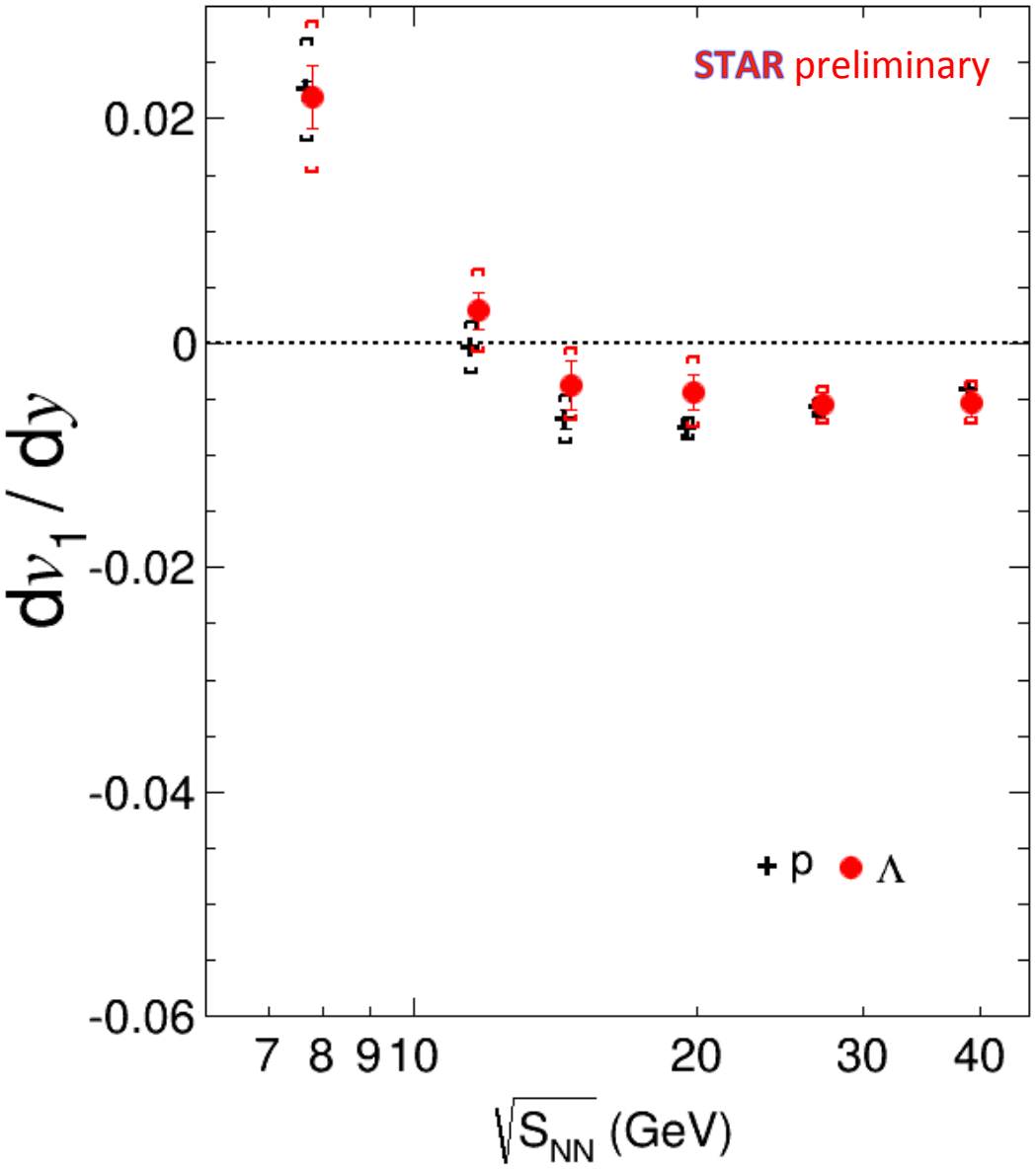


dv_1/dy vs. Beam Energy for 10-40% centrality

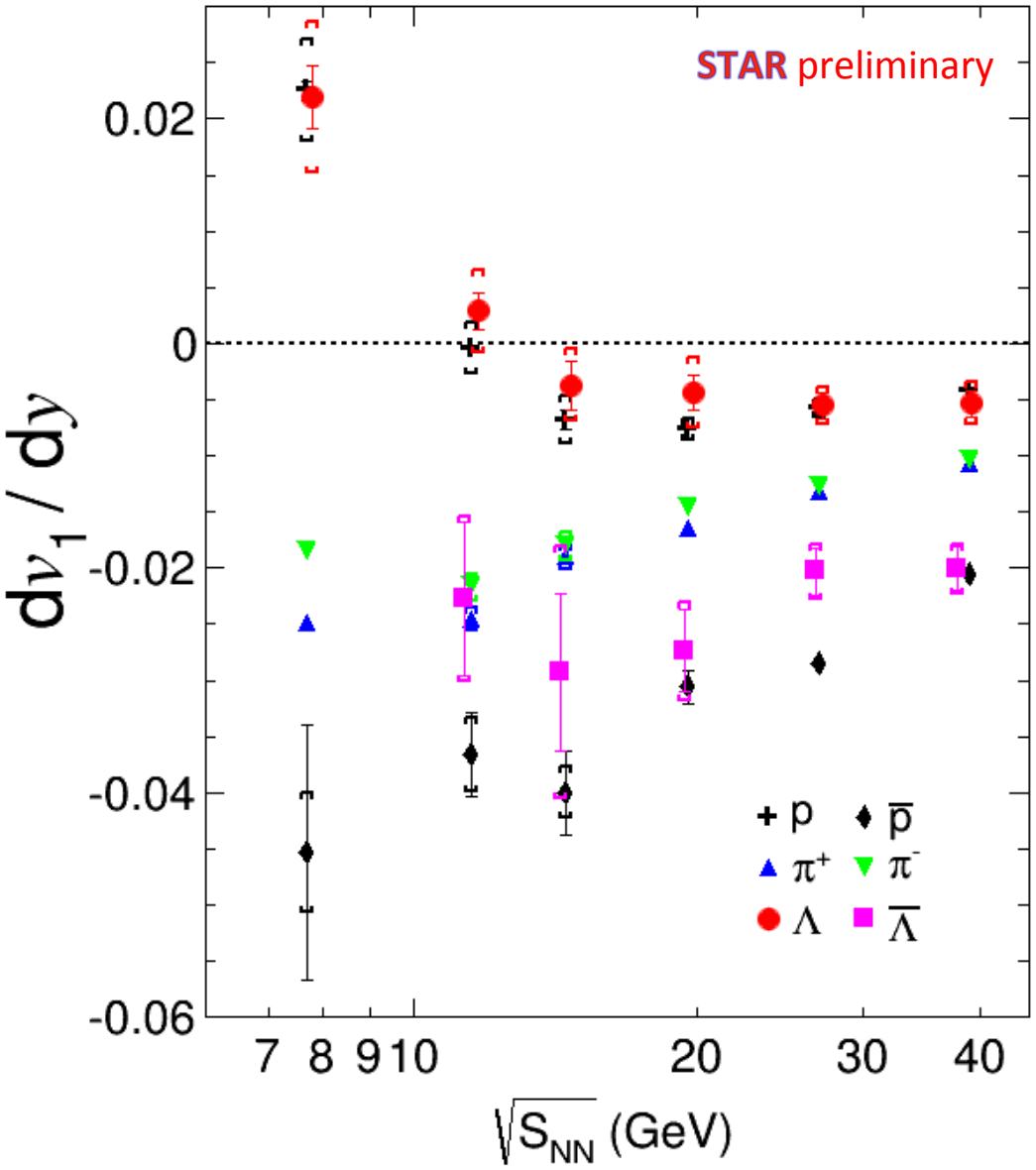


- A linear fit over $|y| \leq 0.8$ used to find dv_1/dy for all species & energies

- Protons with new fit & new beam energy point strengthen earlier observation of minimum in v_1 slope

- New Λ measurement follows *p* within errors

dv_1/dy vs. Beam Energy for 10-40% centrality



- A linear fit over $|y| \leq 0.8$ used to find dv_1/dy for all species & energies

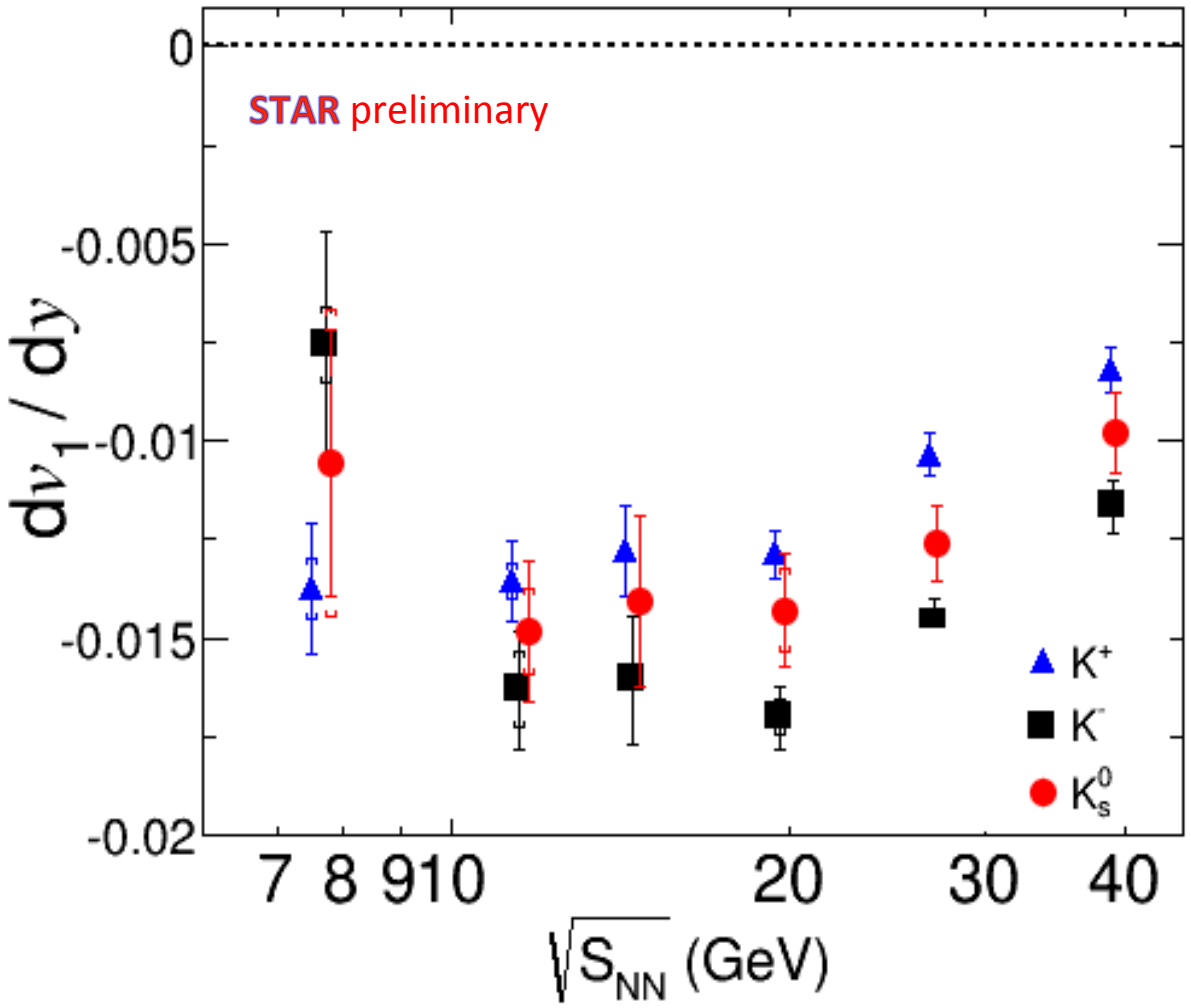
- Protons with new fit & new beam energy point strengthen earlier observation of minimum in v_1 slope

- New Λ measurement follows *p* within errors

- Anti-p and anti-Λ have negative slope for all BES energies

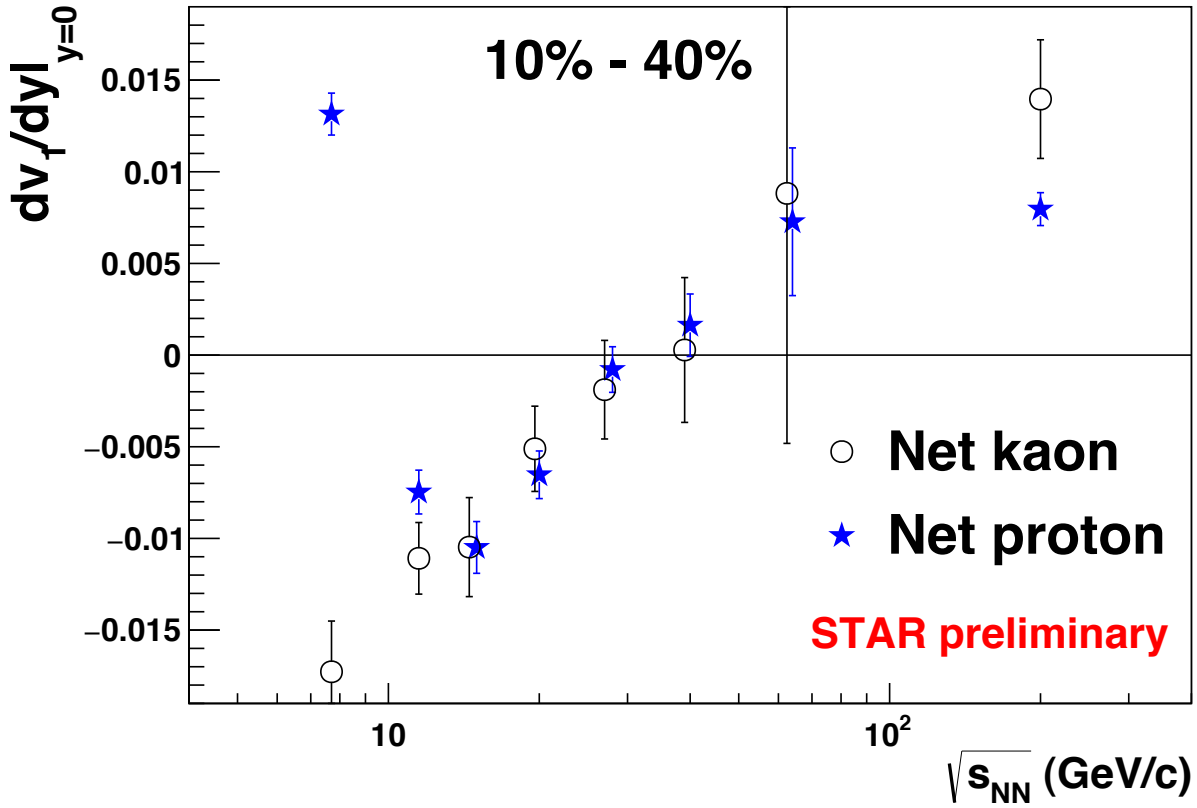
- Charged pions have negative slope for all BES energies

dv_1/dy vs. Beam Energy for 10-40% centrality



- dv_1/dy for K^+, K^-, and K^0_S are negative and similar to $\pi^{\pm}$
- dv_1/dy for K^0_S lies mid-way between K^+ and K^- within errors

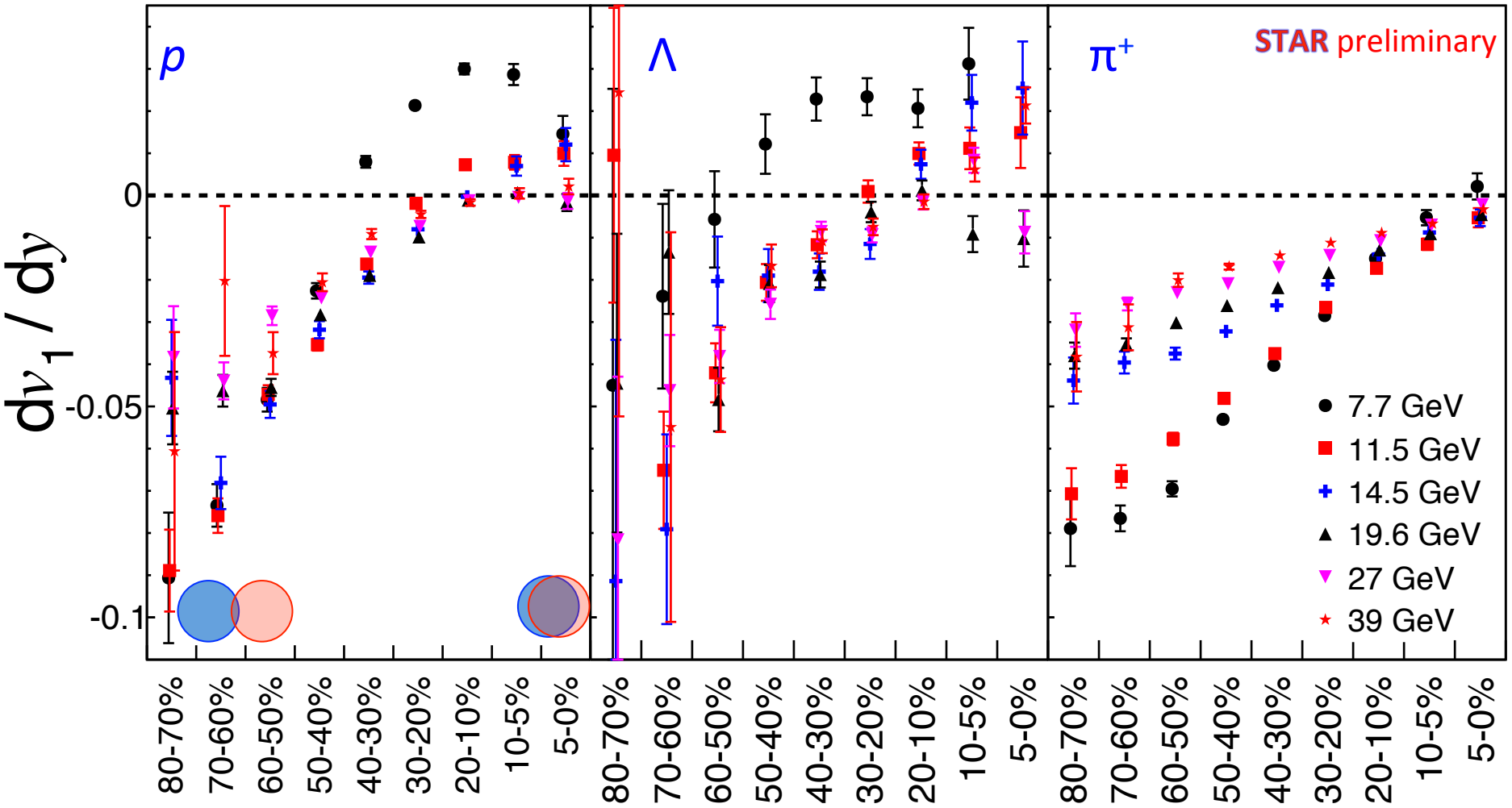
Net-particles dv_1/dy vs. Beam Energy for 10-40% centrality



- Since π^+ & π^-, K^+ & K^- have similar v_1, it is proposed that v_1 for anti-p can be proxy for v_1 of produced p. If this idea is valid, we can thus subtract produced baryons and isolate transported initial-state baryons.

- Net-particles = particles minus antiparticles, with appropriate weighting. Net baryons are a measure of initial-state baryons transported to midrapidity by the stopping process of the collision.

dv_1/dy vs. centrality for $\pi^{\pm}$, p, Λ



- dv_1/dy for p, Λ strongly depends on centrality

Summary

- Models suggest, with increasing μ_B, a minimum in dv_1/dy for baryons could be signature of 1st-order phase transition
- Earlier STAR measurements for protons show a minimum in dv_1/dy at BES energies
- Recent JAM model calculations imply softening and 1st-order phase transition is favored by STAR measurements

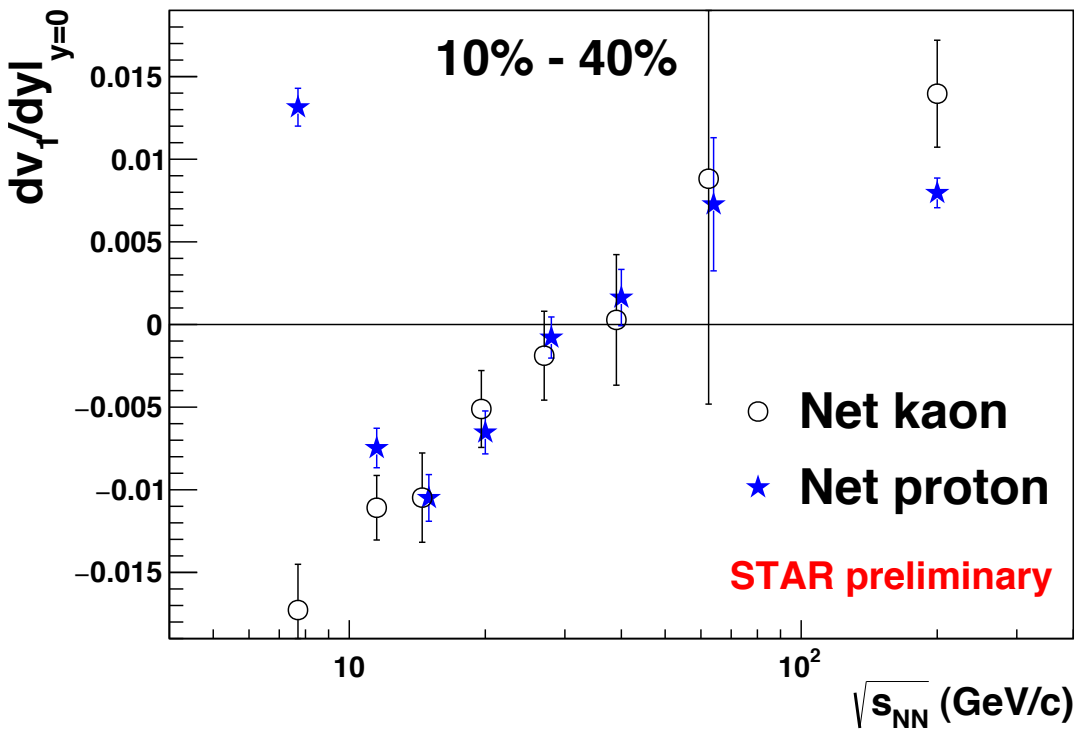
Summary

- Models suggest, with increasing μ_B, a minimum in dv_1/dy for baryons could be signature of 1st-order phase transition
- Earlier STAR measurements for protons show a minimum in dv_1/dy at BES energies
- Recent JAM model calculations imply softening and 1st-order phase transition is favored by STAR measurements

- **New proton measurement at 14.5 GeV is in good agreement with previous results, and strengthens the significance of dv_1/dy minimum for baryons**
- **New Λ measurements show similar results to protons; thus favor the softening interpretation where transported initial-state quarks cause the minimum**
- **dv_1/dy measurement for new particle types and centrality study together will strongly constrain models in the next round of comparisons**

Backup

Net-particles dv_1/dy vs. Beam Energy for 10-40% centrality



Assume final-state particles have two quark components, one from produced q-qbar pairs, another from stopped baryons

We try to disentangle the two contributions to the slope of directed flow, *F*, via net-*p* and net-*K*:

$$F_p = r_1 F_{\text{anti-}p} + (1 - r_1) F_{\text{net-}p}$$

$$F_{K+} = r_2 F_{K-} + (1 - r_2) F_{\text{net-}K}$$

where $r_1(y)$ =observed anti-*p* over *p*

and $r_2(y)$ =observed K^- over K^+

- $dv_1/dy|_{y=0}$ for net-*p* and net-*K* are consistent with each other down to ~14.5 GeV, and deviate at lower energies
- Cause of split of net-*K* dv_1/dy at low $\sqrt{s_{NN}}$ is unclear