Beam-Energy and Centrality Dependence of Directed Flow of Identified Particles

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(for the STAR Collaboration)

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DATA TO BE PRESENTED

$v_1(y)$ and $dv_1/dy|_{y=0}$ presented for

- Au+Au $\sqrt{s_{NN}}$: 7.7, 11.5, 14.5, 19.6, 27 & 39 GeV
- 10-40 % collisions and 9 centrality bins
- Particle species: p, anti-p, $\pi^{\pm}$, Λ, anti-Λ, $K^{\pm}$, K^0_S

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STAR
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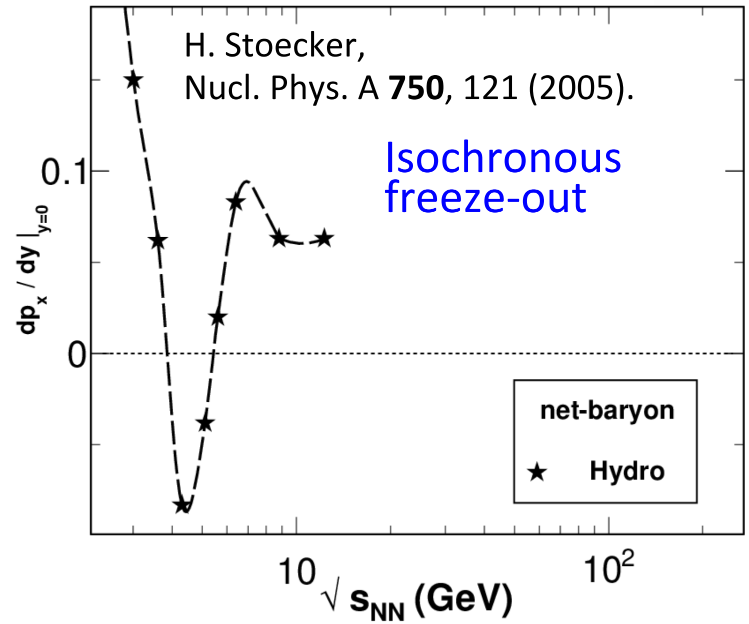
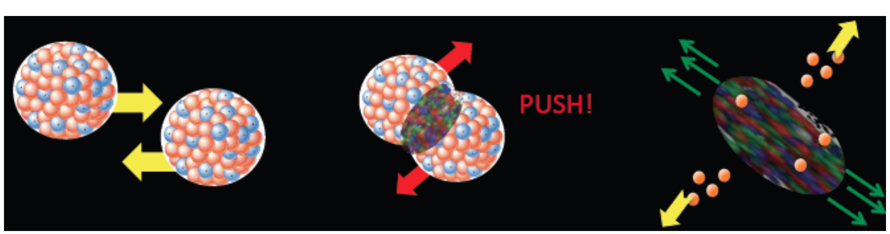
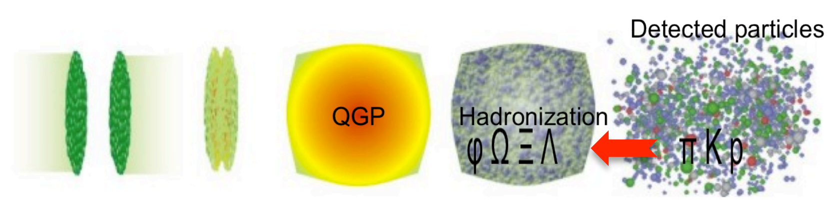
Directed flow (v_1)

- v_1, produced early, gives info about EOS
- Hydro with 1st-order phase transition shows dip in directed flow vs. beam energy due to sudden softening of EOS

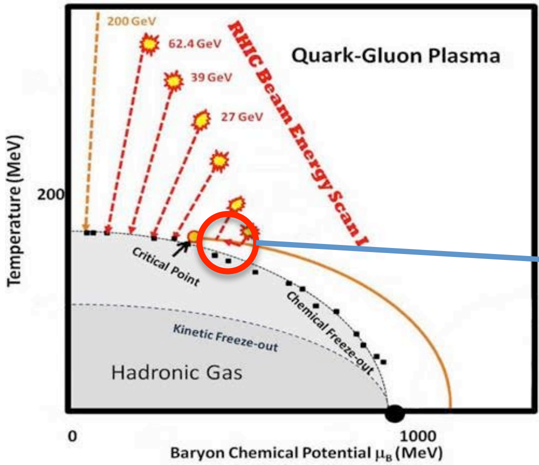


- Proton v_1 probes interplay of baryon transport and hydro behavior
- New Λ data offer more insight into transport of baryons





BES Program at STAR and Directed Flow



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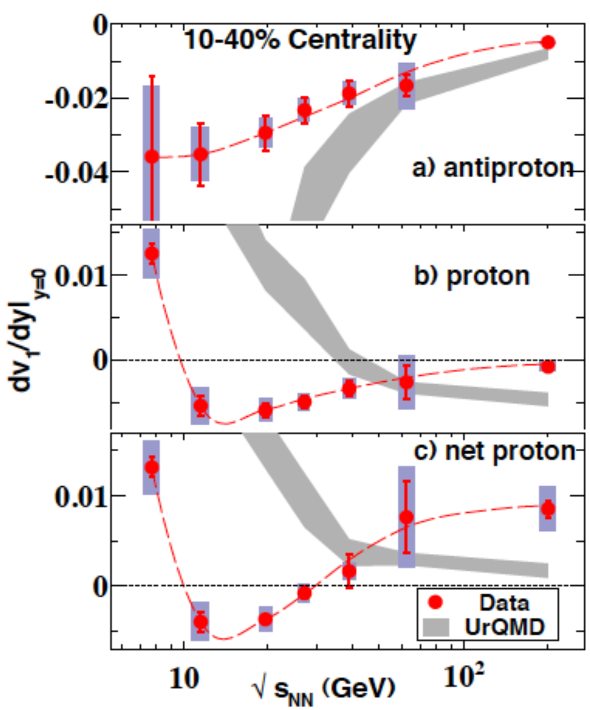


PRL **112**, 162301 (2014)

Goals of BES : Explore QCD phase diagram

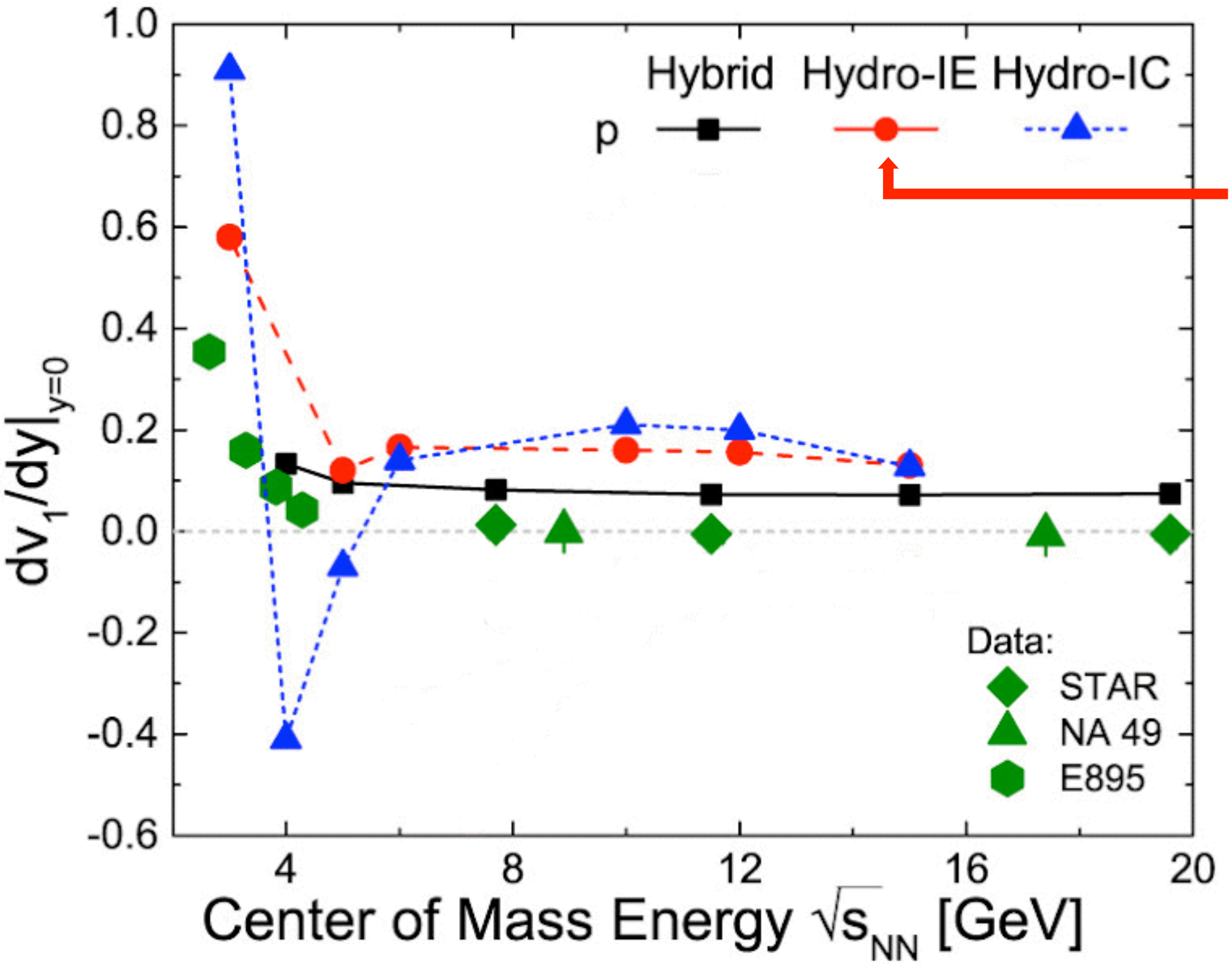
- Map turn-off of QGP signatures
- Search for Critical Point
- Search for First-Order Phase Transition

Data: Au+Au collisions

$\sqrt{s_{NN}}$(GeV)	7.7	11.5	14.5	19.6	27	39
Events (10^6) Minimum-bias	4	12	20	36	70	130

- Rapidity-odd v_1 at AGS energies positive and large for p, Λ - PRL **86**, 2533 (2001)
- For 10-40 % centrality, proton dv_1/dy vs. beam energy changes sign, with a minimum. Net protons change sign twice
- Pion and antiproton slope remain negative.
- EOS softening?

Frankfurt Hybrid Model



IC =Isochronous freeze-out (sim. to 2005 hydro).

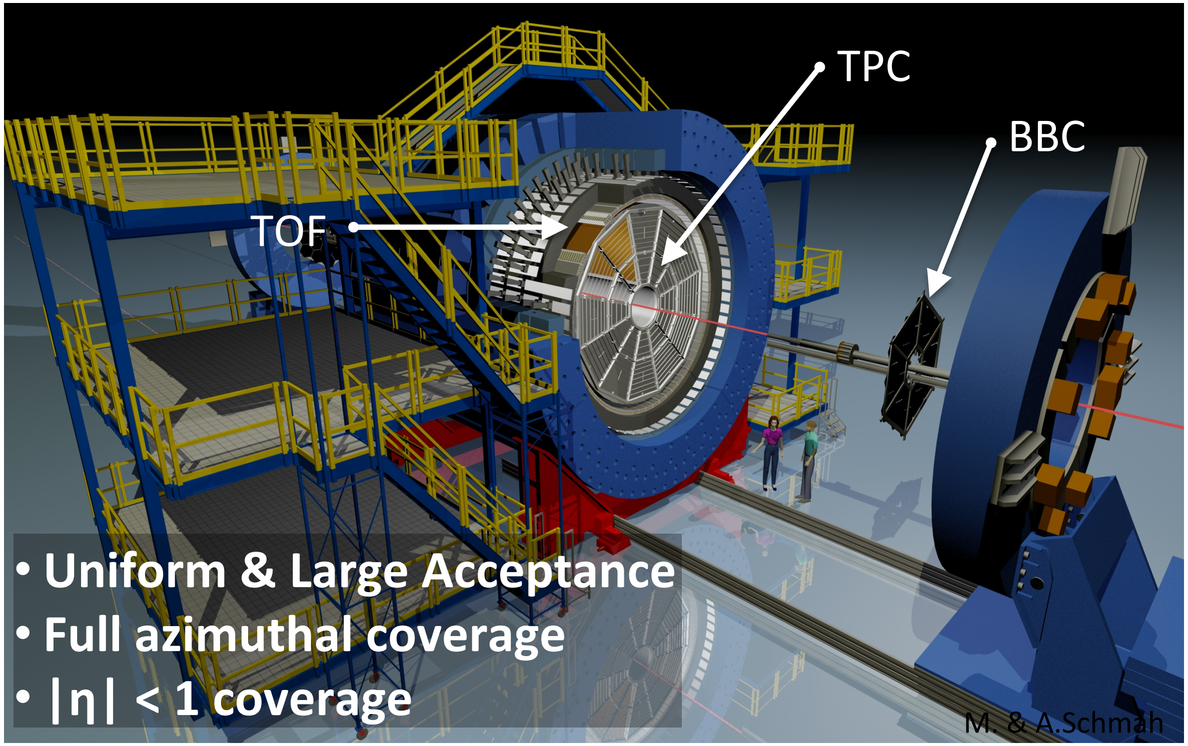
IE =Iso-ρ_E freeze-out (ρ_E is energy density)

All three model cases have 1st order PT

J. Steinheimer et al., PRC **89,** 054913 (2014).

- **Sign change, minimum and error bars for STAR protons are all invisible with this vertical scale**
- **All three model cases disagree strongly with experiment**

STAR & Particle Identification

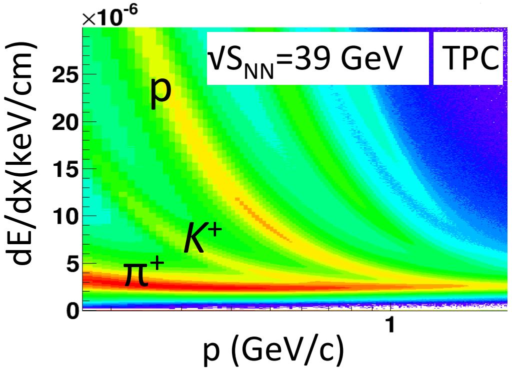


Long lived: *p*, *K*, π

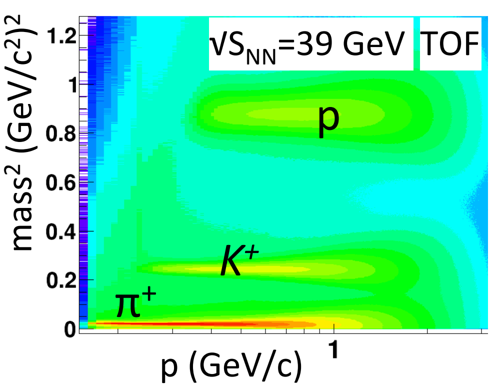
- Requires TPC & TOF hits
- *dE/dx* cut of $n\sigma \leq 2$
- p : $0.4 < p_T < 2.0$ GeV/c
- $K^{\pm}$ & $\pi^{\pm}$: $p_T > 0.2$ GeV/c
- $p < 1.6$ GeV/c

Short lived : Λ & K^0_S

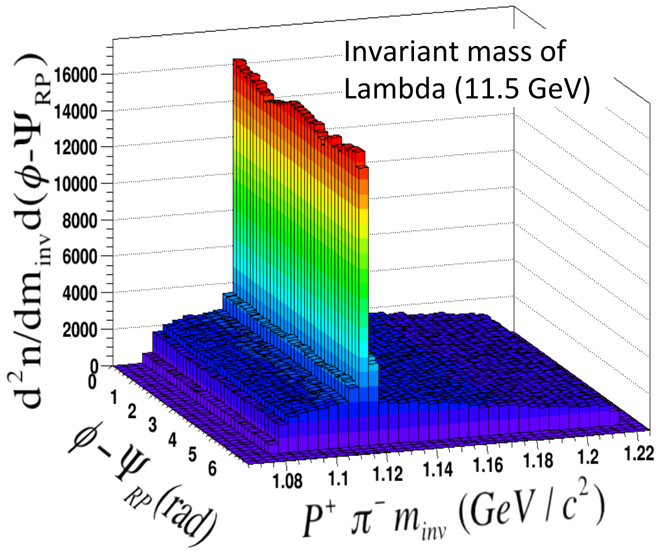
- Invariant mass technique
- Mixed-event background
- V0 topological cuts
- TPC and/or ToF hits for daughters
- $0.2 < p_T < 5.0$ GeV/c



• PID using energy loss in TPC d*E*/dx



• PID using time of flight and momentum from TPC



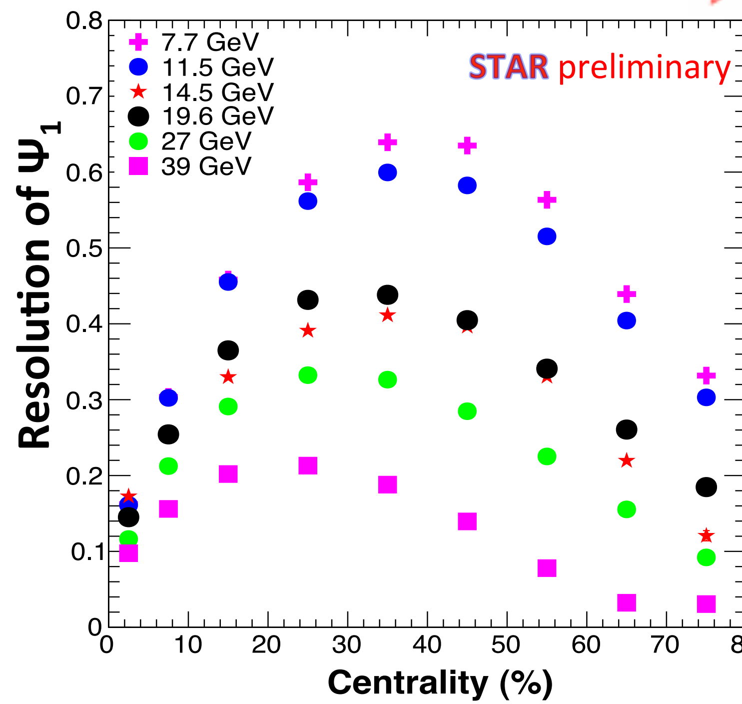
Event Plane Estimation

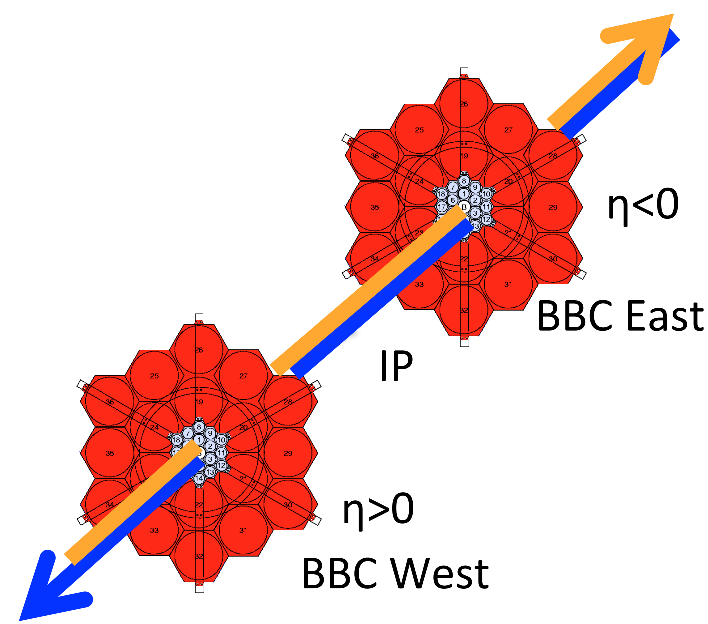
- 1^{st}-order reaction plane estimated using East & West BBC detectors
  - Coverage: $3.3 < |\eta| < 5.0$
  - η gap between TPC and BBC reduces non-flow

- BBC event plane resolution improves at lower energies due to strong v_1 signal near beam rapidities aligning with BBC acceptance

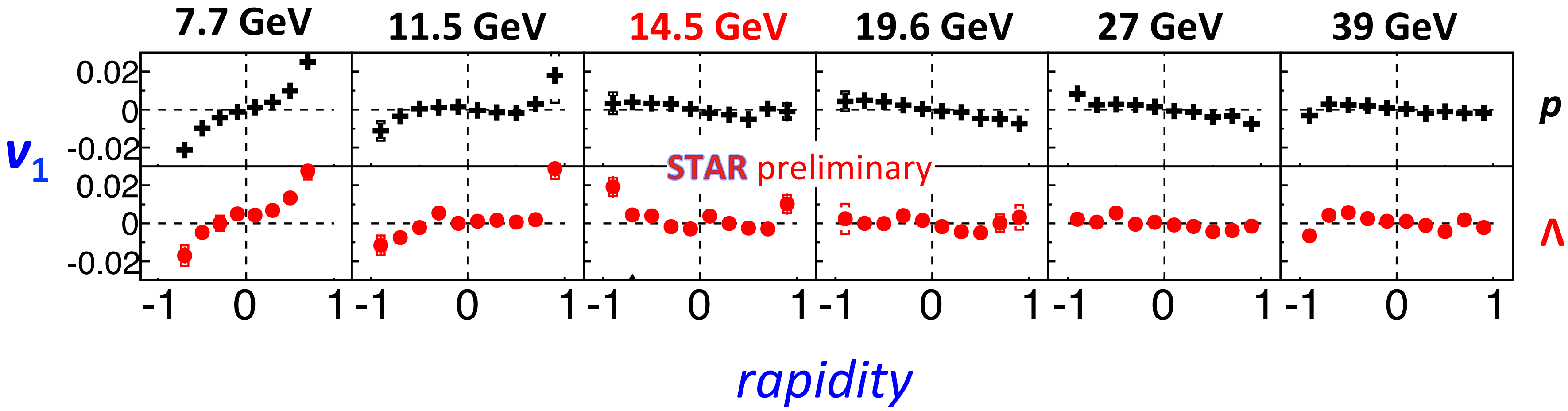
- Non-flat BBC Ψ_1 distribution corrected by shifting method

(Voloshin, Poskanzer, Snellings, arXiv: 0809.2949)





v_1 vs. rapidity for 10-40% centrality



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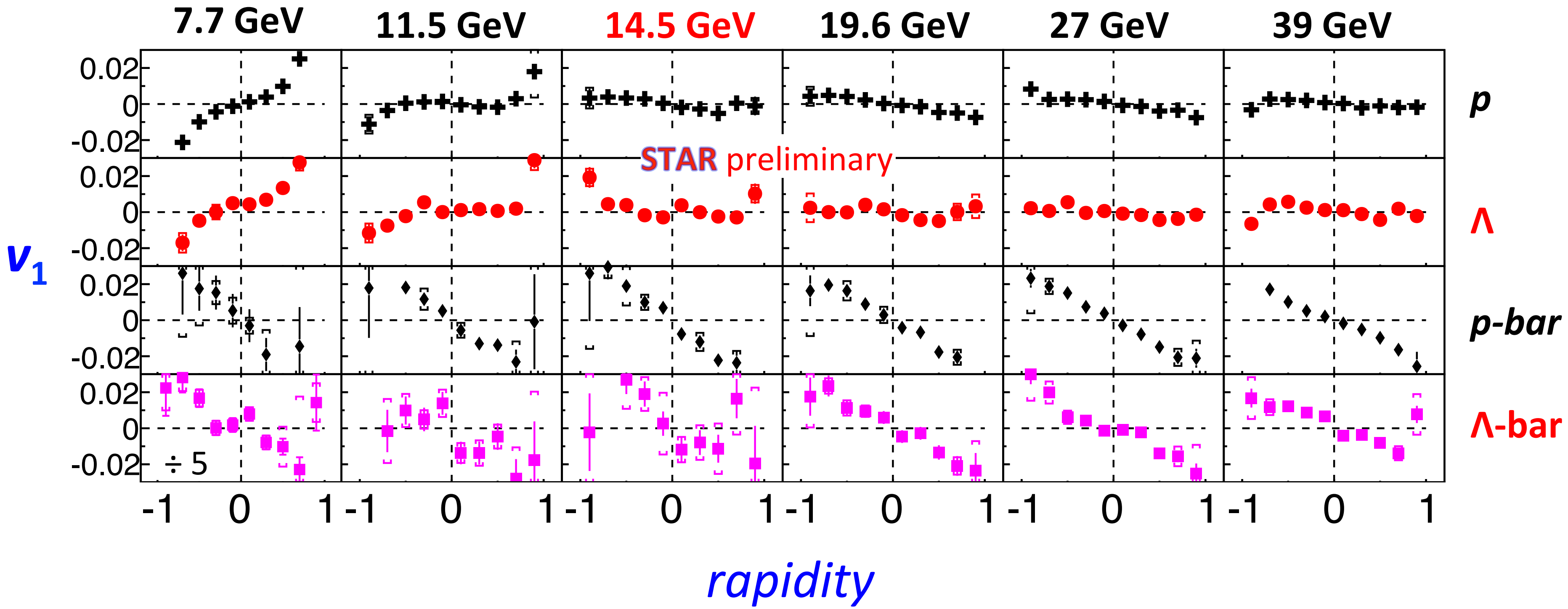

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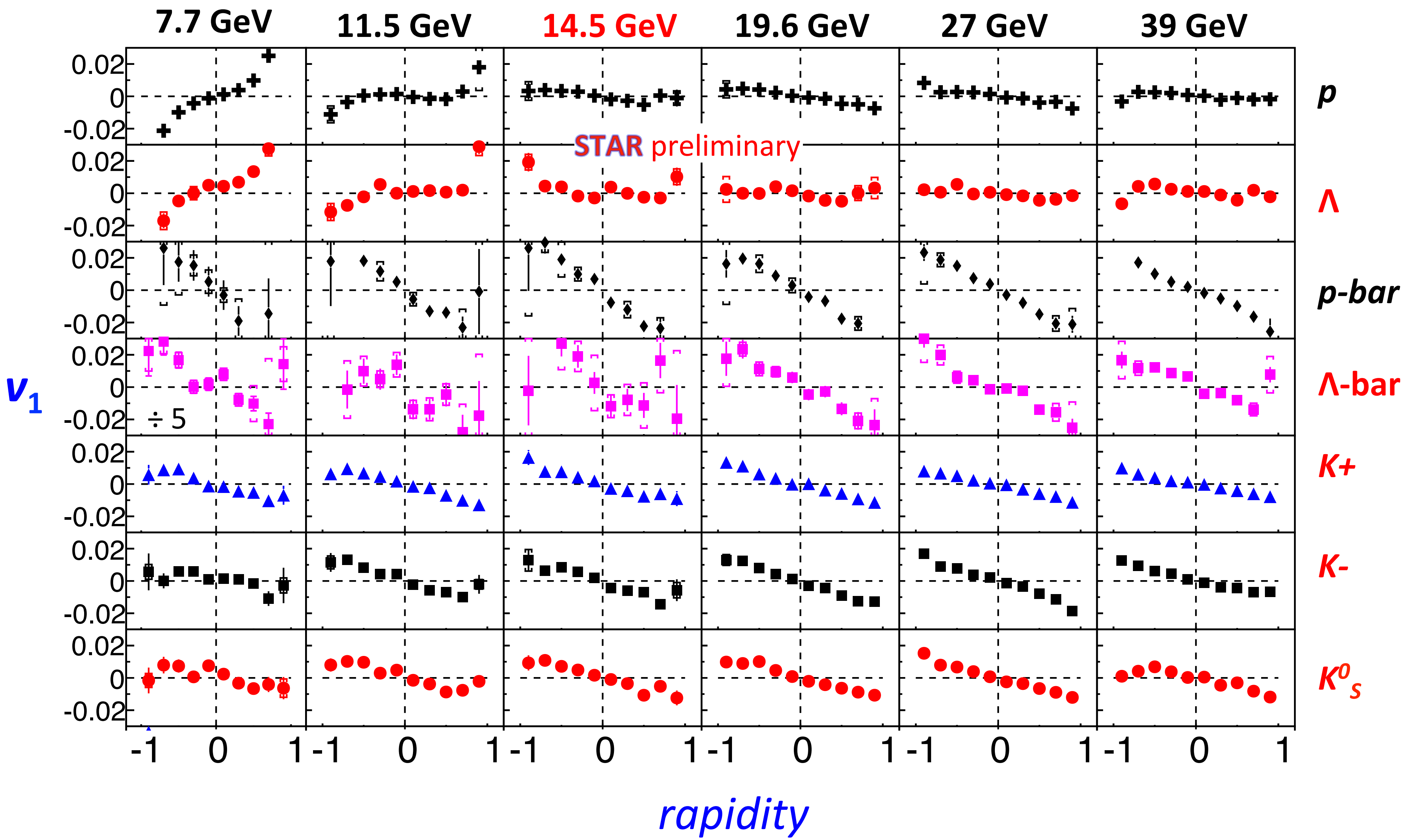

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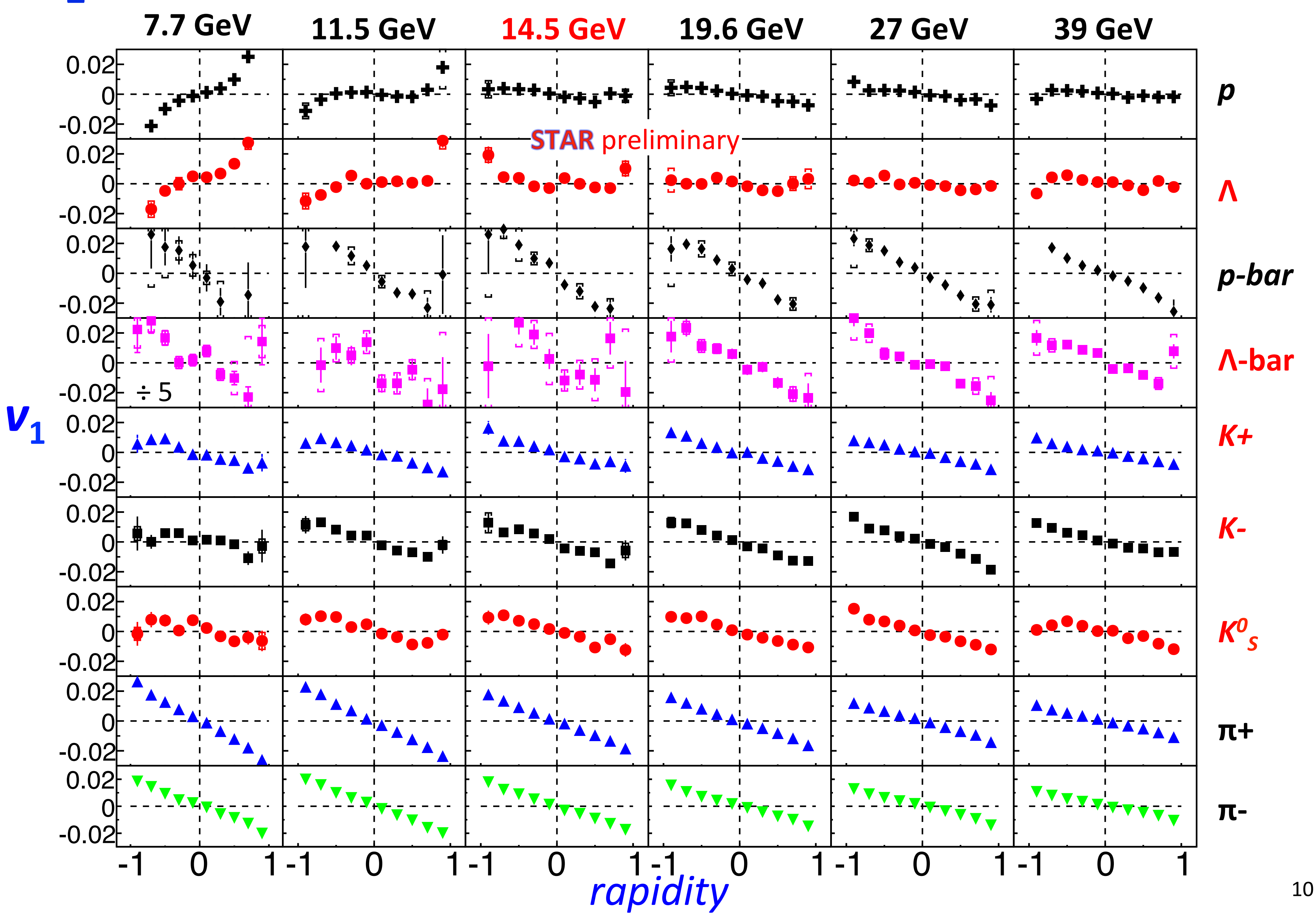
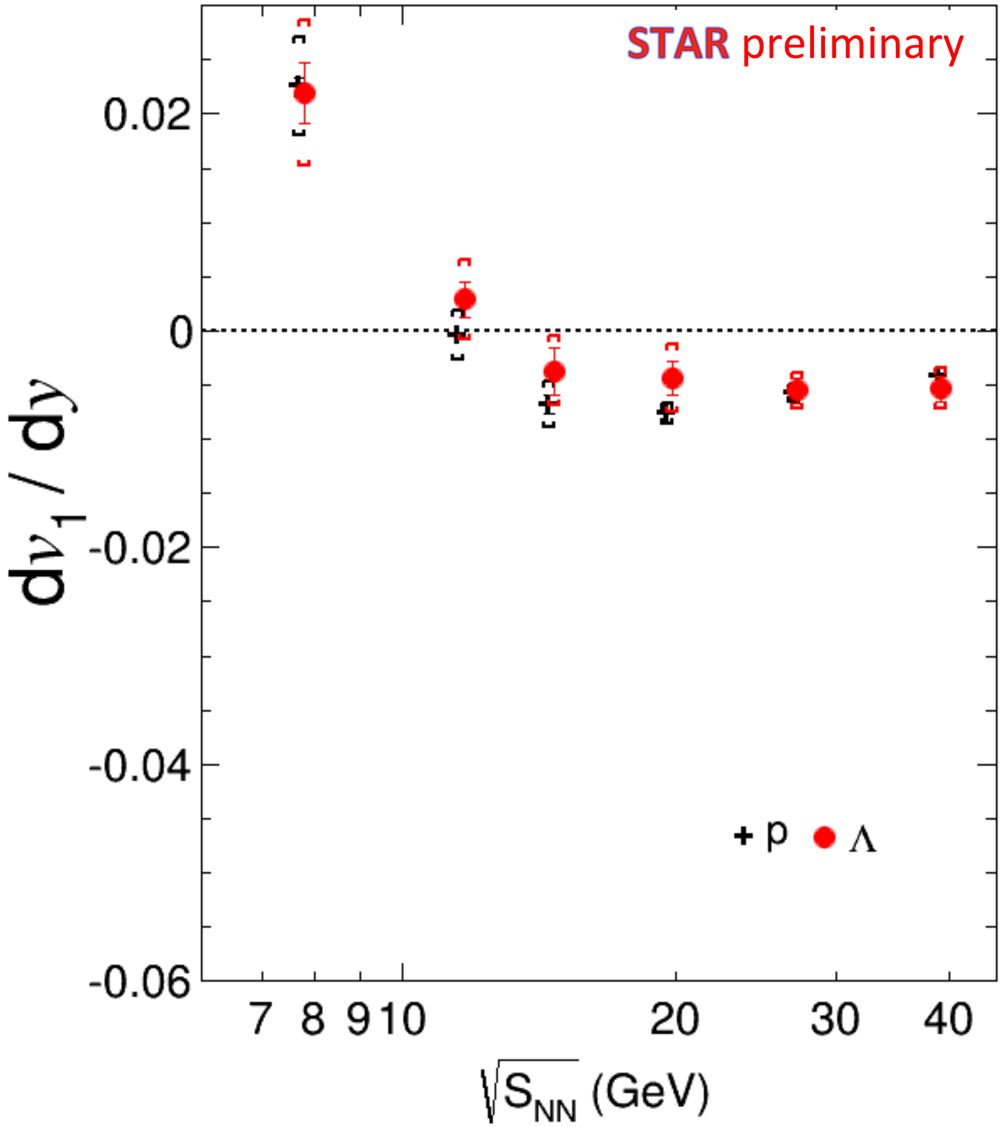


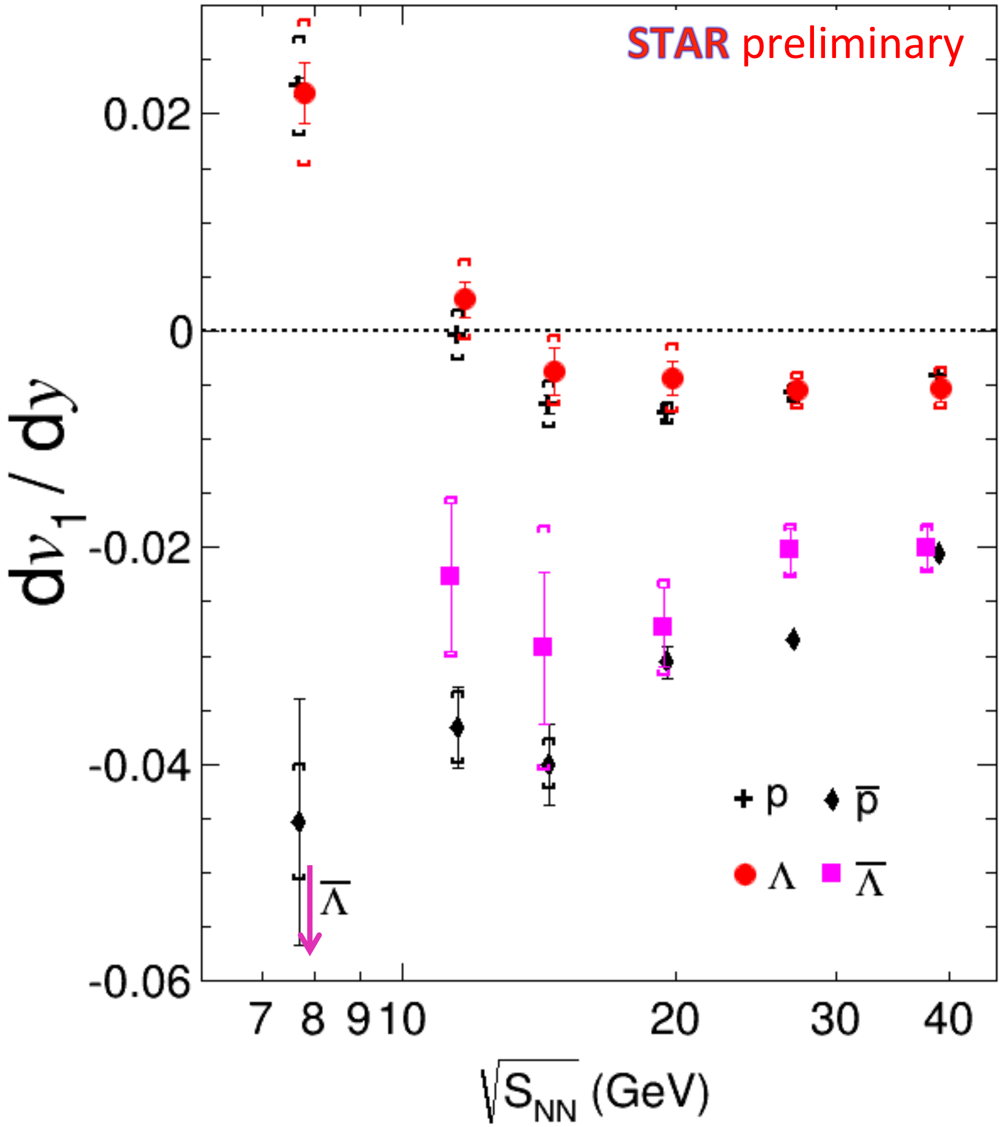
dv_1/dy vs. Beam Energy for 10-40% centrality



- A linear fit over |y| ≤ 0.8 used to find dv_1/dy for all species & energies
- Λ follows *p* within errors

Published STAR analysis uses linear term in cubic fit, but results are same within errors

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



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

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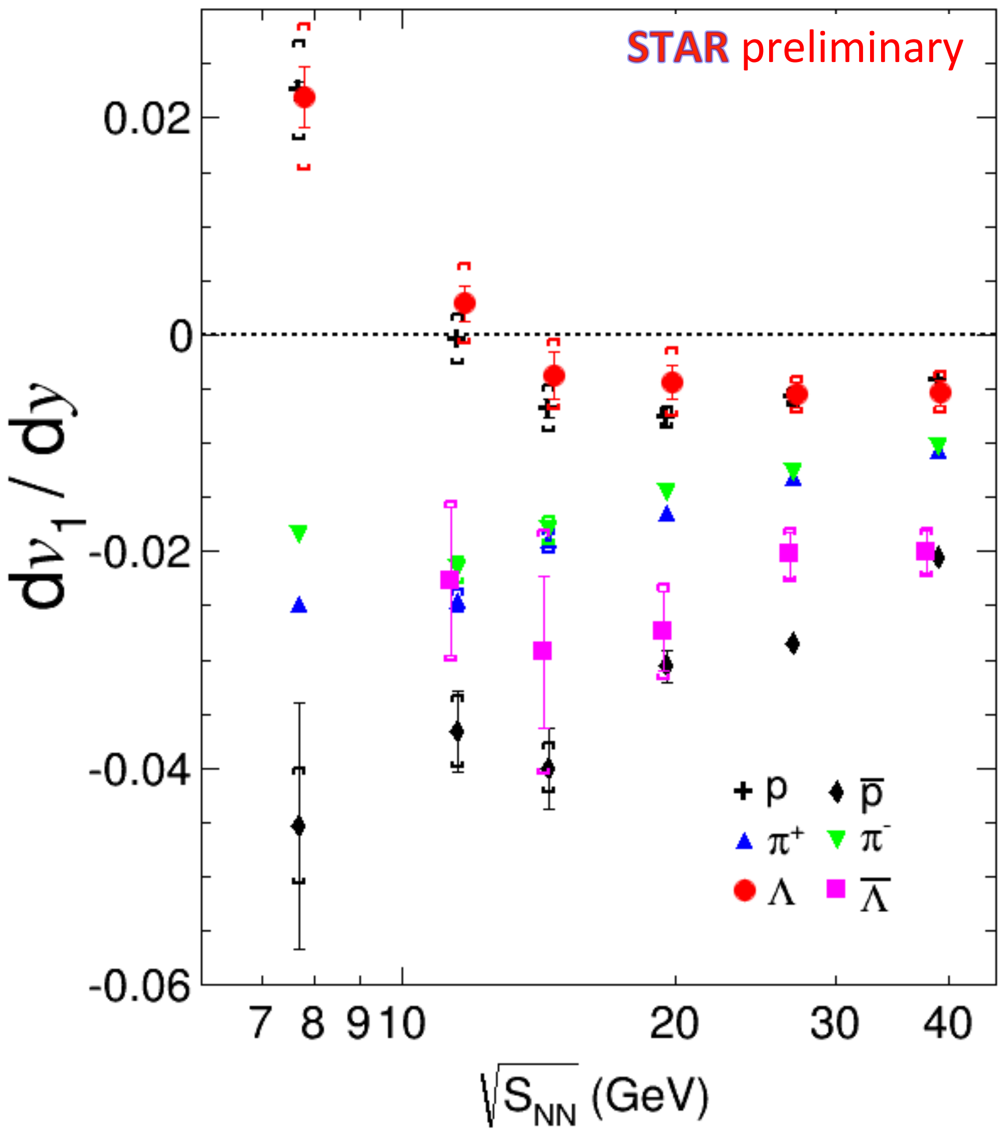

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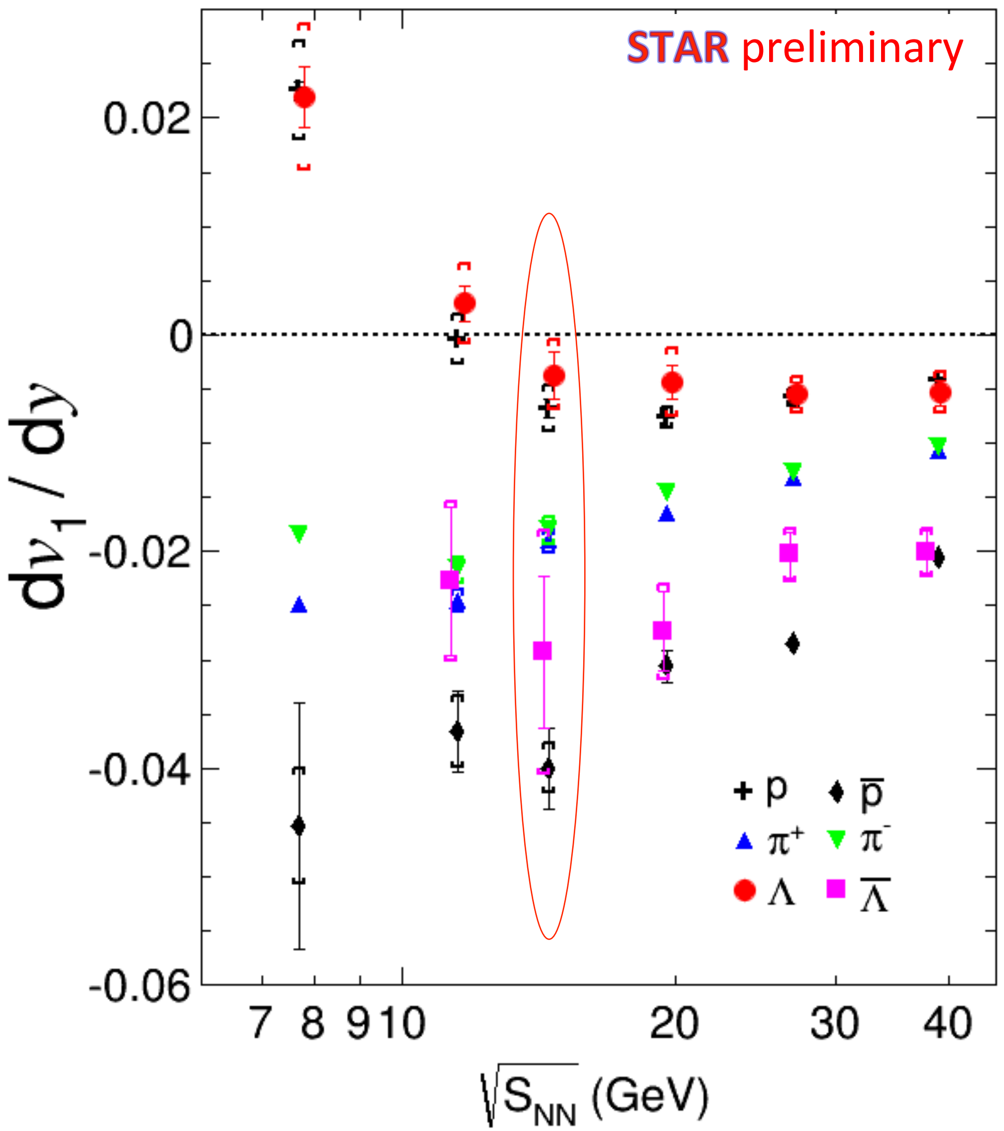

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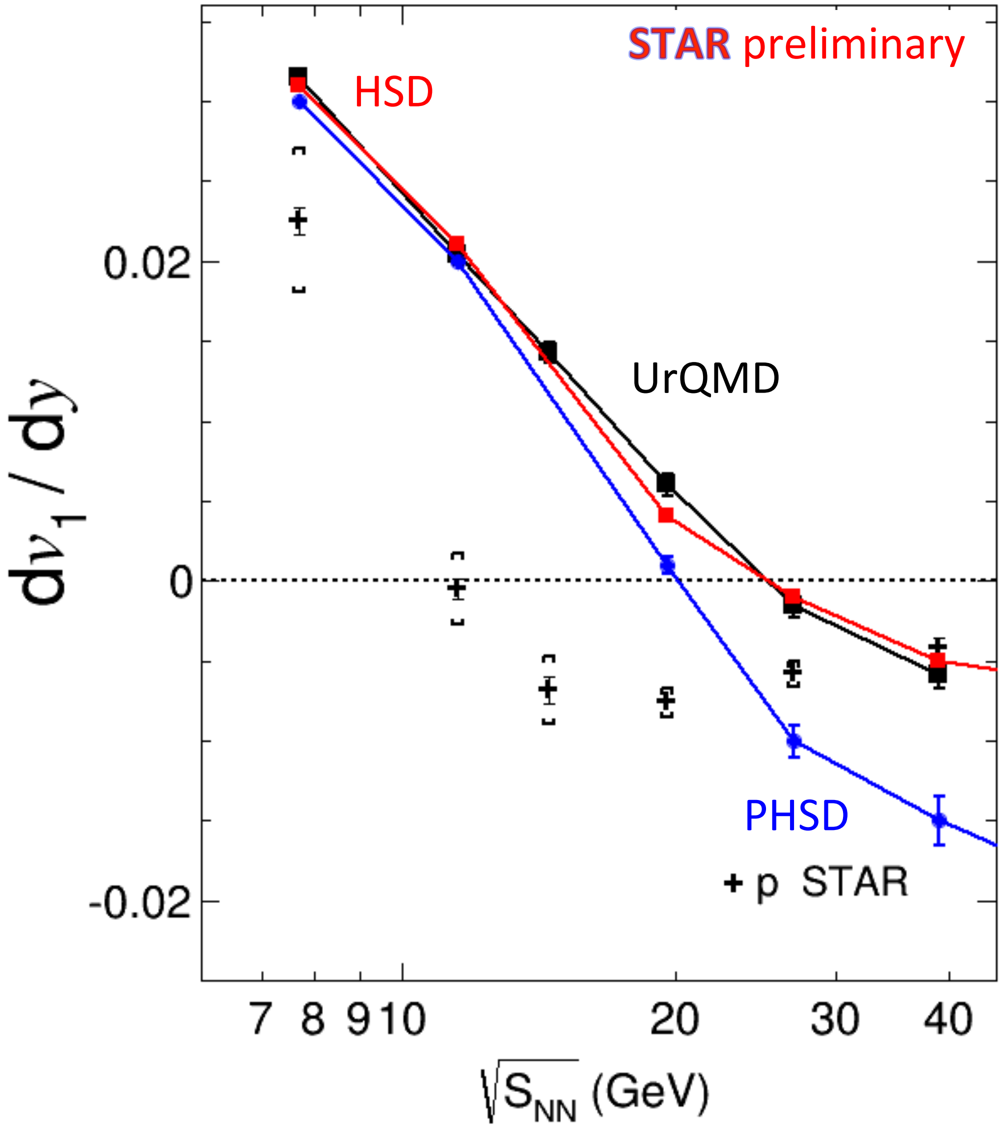
- Λ follows *p* within errors
- Anti-p and anti-Λ have negative slope for all BES energies
- Charged pions have negative slope for all BES energies
- Measurements at 14.5 GeV for all particles follow smooth trend of earlier BES data

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



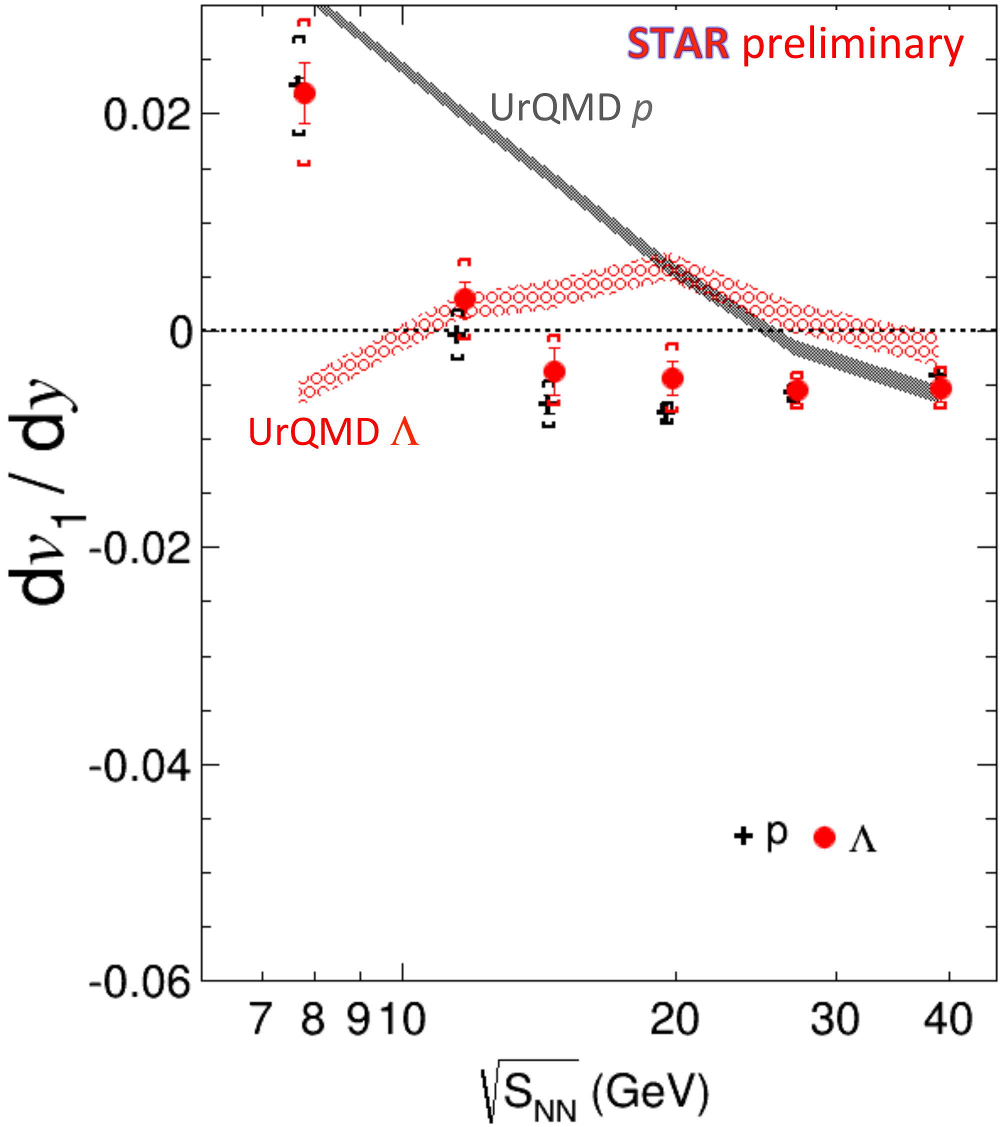
- Hybrid Model for *p* is off-scale at the top, at all energies
- PHSD (crossover PT) qualitatively similar to hadronic (HSD & UrQMD)
- **Model (with/without PT) shows**
  - **No proton minimum**
  - **Beam energy of sign change is too high**

  Thus, conclusion about PT needs further model development

PHSD/HSD: V. P. Konchakovski *et al.* Phys. Rev. C **90,** 014903 (2014).

UrQMD (ver 3.3p2) events are generated with default settings.
S. A. Bass *et al*., Prog. Part. Nucl. Phys. **41**, 255 (1998);
M. Bleicher *et al*., J. Phys. G **25**, 1859 (1999).

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



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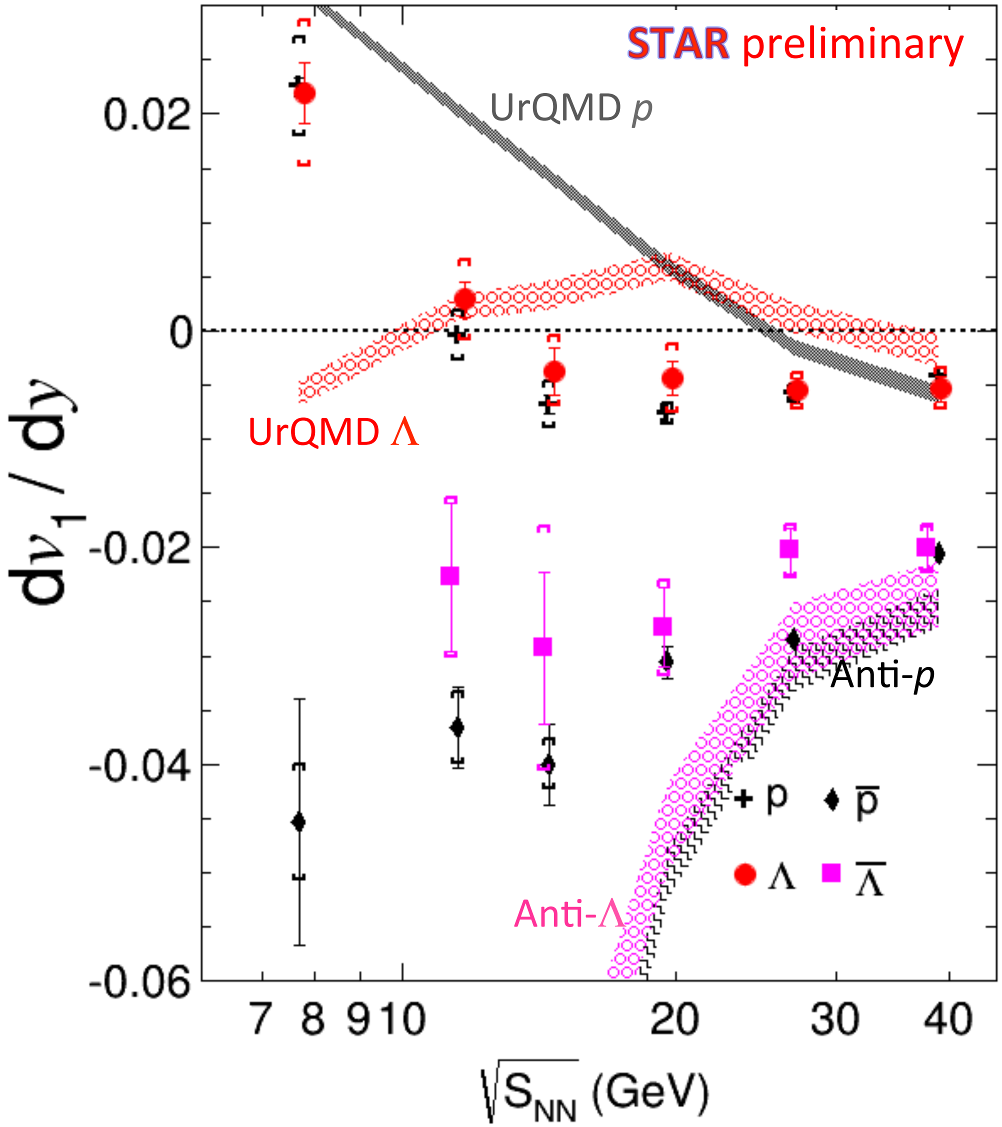

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  Thus, conclusion about PT needs further model development
- UrQMD *p* & Λ deviate strongly below 20 GeV, unlike data
- UrQMD anti-*p* & anti-Λ have qualitatively similar trend at higher BES energies

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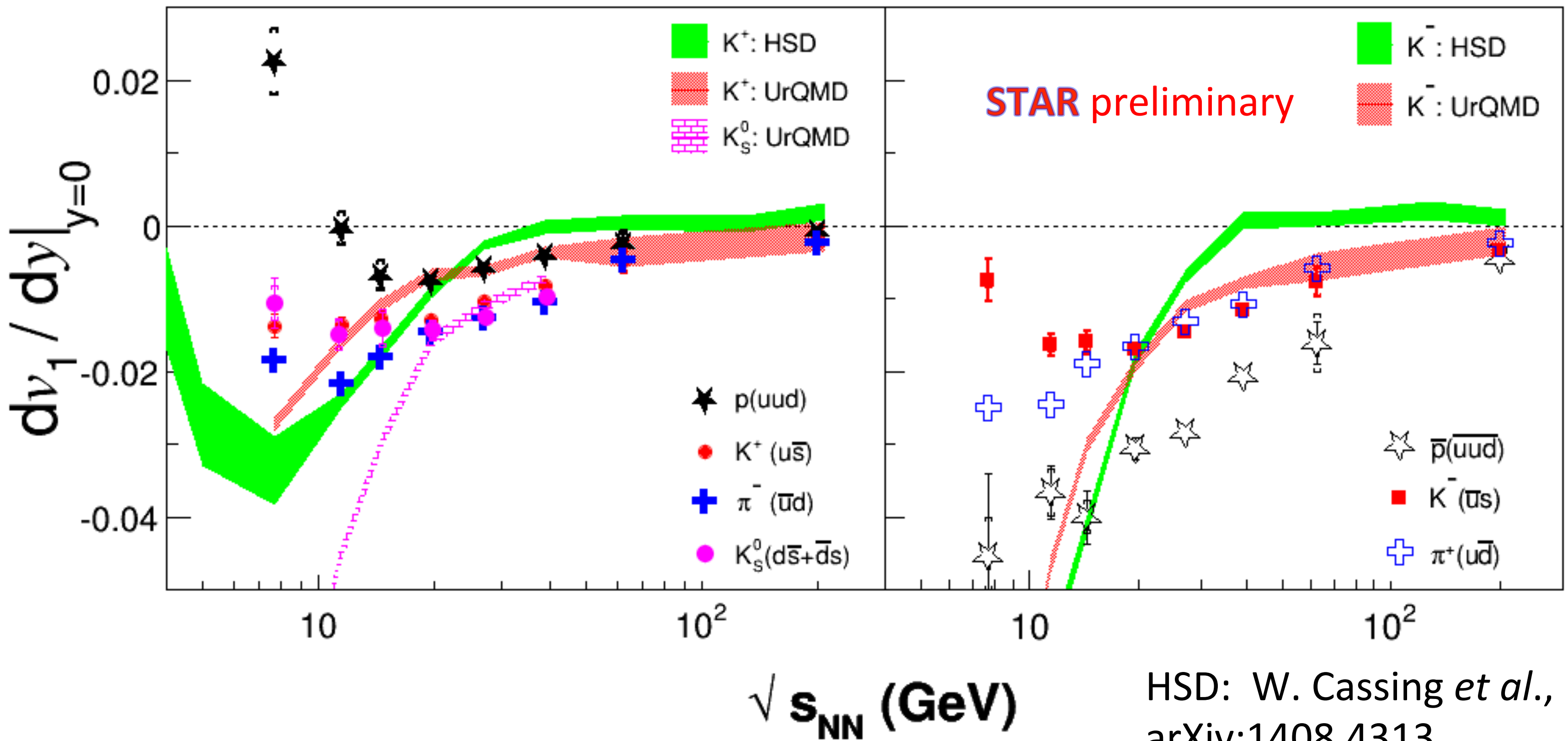
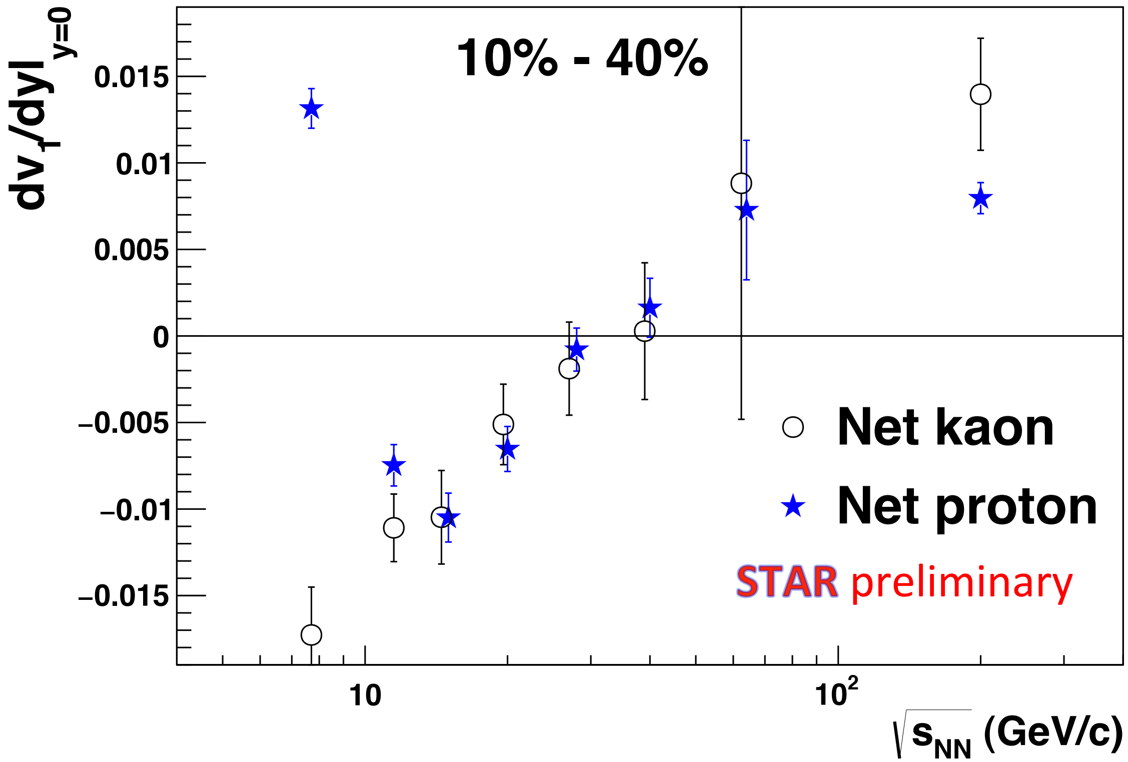
dv_1/dy vs. Beam Energy for 10-40% centrality



HSD: W. Cassing *et al.*, arXiv:1408.4313

- Particles in left panel (p, π^-, K^+) have more quarks from stopped initial nucleons than antiparticles in right panel
- K^0_S lies mid-way between K^+ and K^-

Net-kaon vs. net-proton



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*:

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

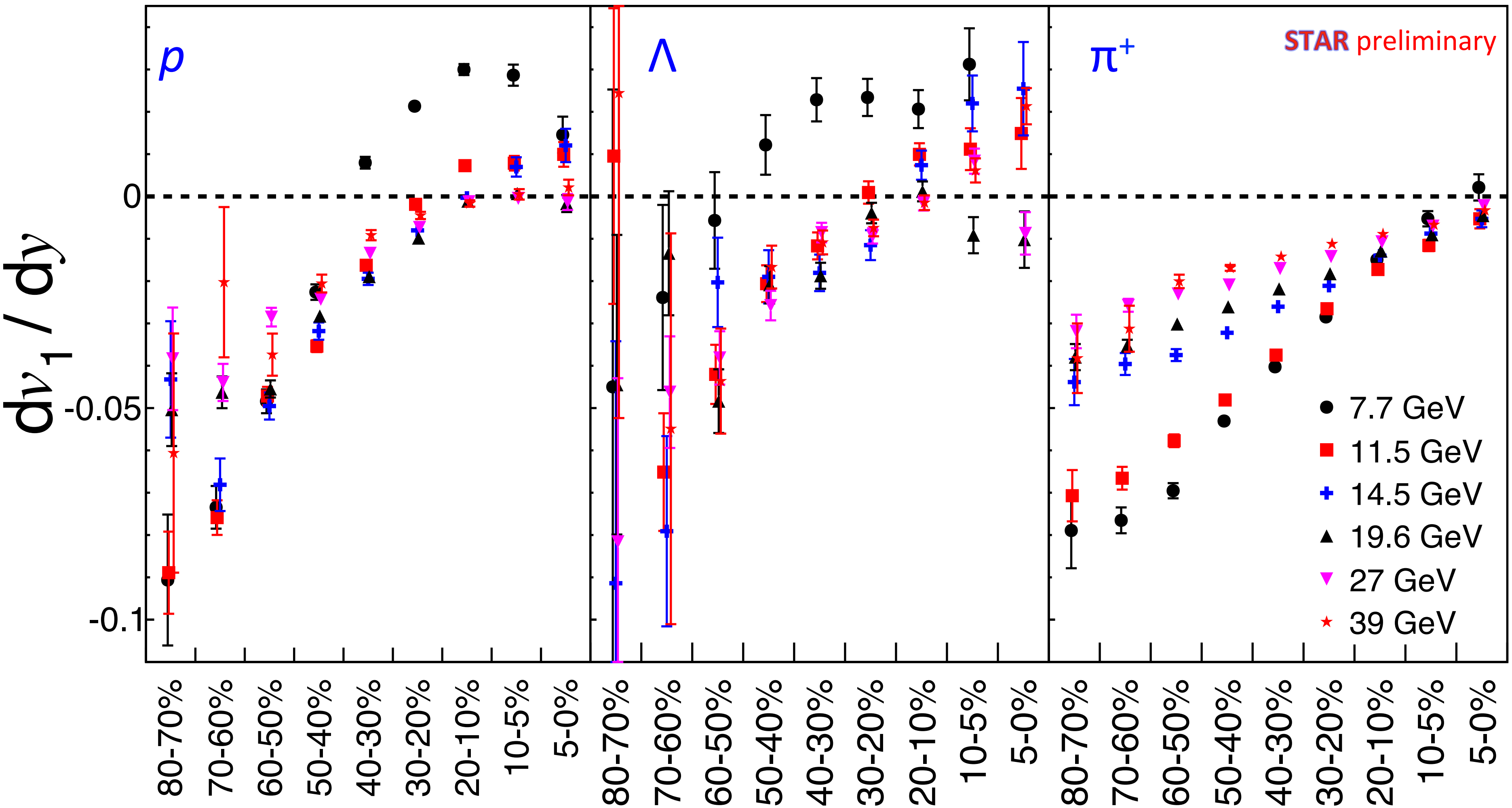
$$F_{K+} = r_2 F_{K-} + (1 - r_2) F_{net\text{-}K}$$

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

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

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

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



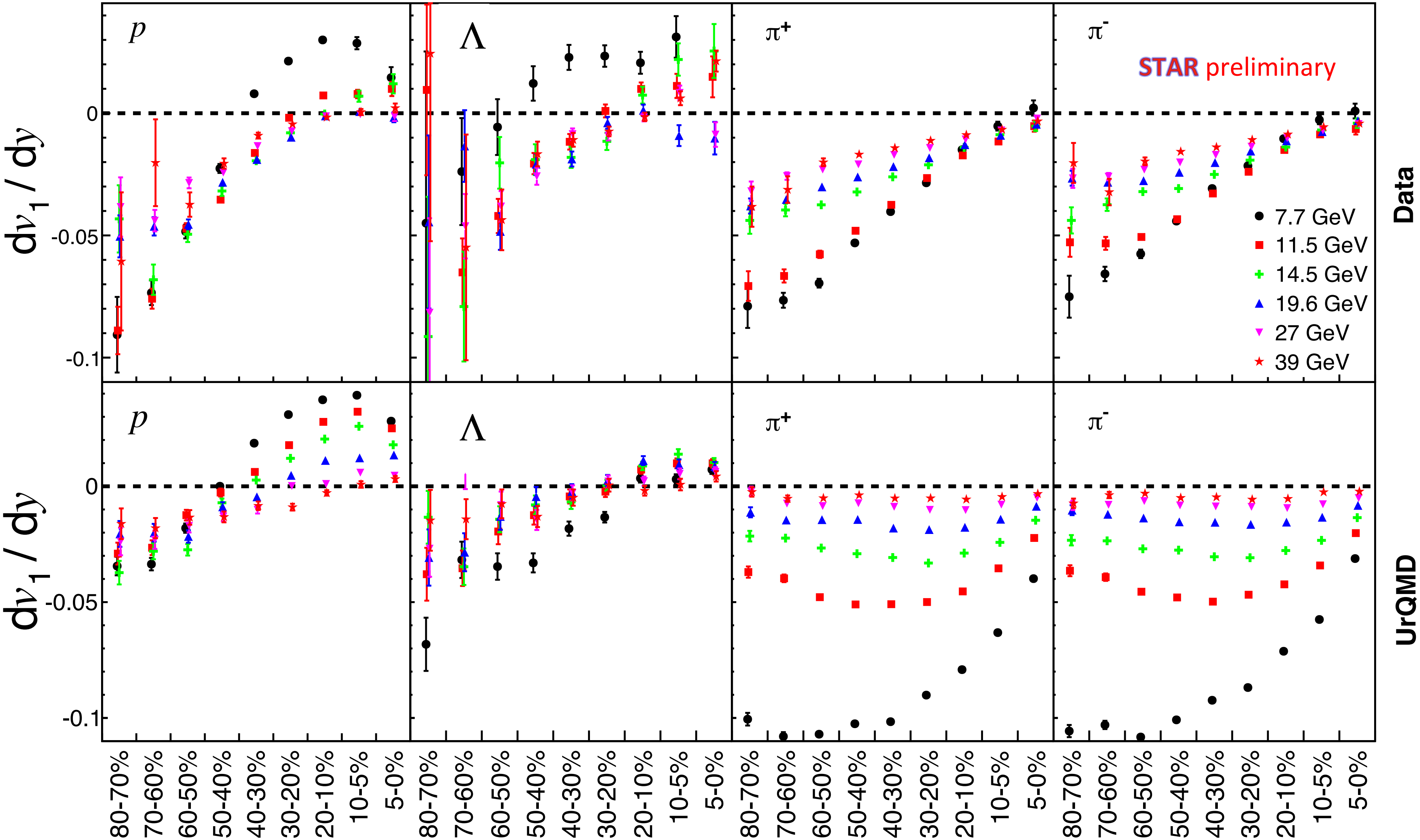
- dv_1/dy for p, Λ strongly depends on centrality
- Minimum in slope vs beam energy is statistically significant only for p at intermediate centrality
- Different centralities may probe different regions of phase diagram --> important for BES-II

Summary

- We present $v_1(y)$ and midrapidity dv_1/dy at 7.7, 11.5, 14.5, 19.6, 27 and 39 GeV in Au+Au collisions for *p*, anti-*p*, Λ, anti-Λ, $K^{\pm}$, K^0, $\pi^{\pm}$, at 9 centralities
- $dv_1/dy|_{y=0}$ for both *p*, Λ shows sign change and strongly depends on beam energy and collision centrality
- There are distinct qualitative features in 10-40% centrality dv1/dy for baryons (sign change & minimum), antibaryons (always negative), mesons (negative & smaller magnitude)
- Net-*p* & net-*K* is similar for $\sqrt{s_{NN}} \geq 14.5$ GeV (reflects quark transport?). Below ~14.5 GeV, net-*p* dv_1/dy changes sign to positive while net-*K* stays negative
- Models with and without phase transitions don't reproduce notable qualitative features of data (especially *p*, Λ)

Backup

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



- UrQMD tends to follow qualitative trends in centrality for p and Λ