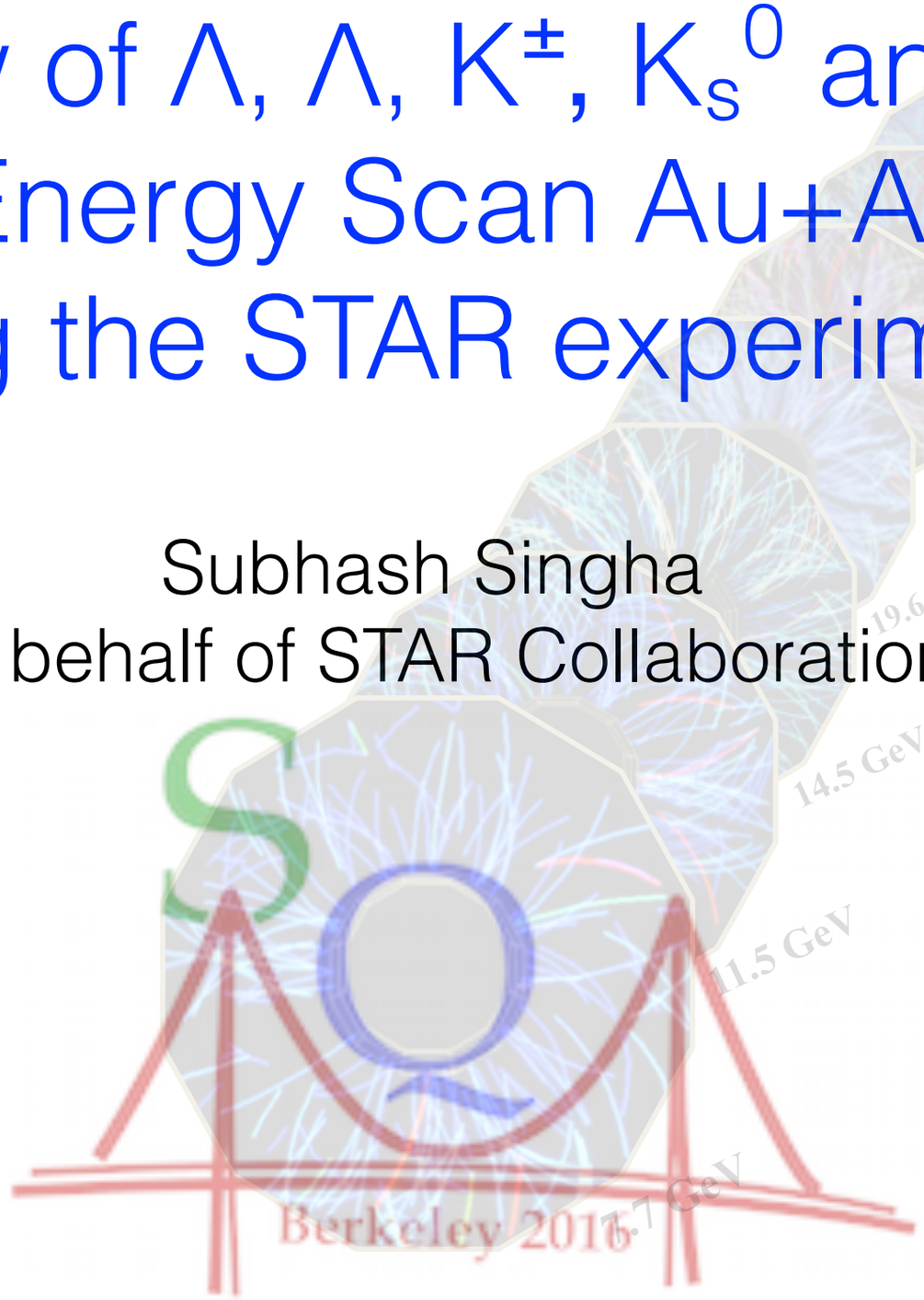
Directed Flow of Λ, $\bar{\Lambda}$, $K^{\pm}$, K_s^0 and ϕ mesons from Beam Energy Scan Au+Au Collisions using the STAR experiment

Subhash Singha
(on behalf of STAR Collaboration)



Outline

- Motivation
- Beam energy scan (BES) program at RHIC
- STAR detector
- Event plane reconstruction
- Signal reconstruction
- Results
- Summary

Beam energy: 7.7, 11.5, 14.5, 19.6, 27 & 39 GeV

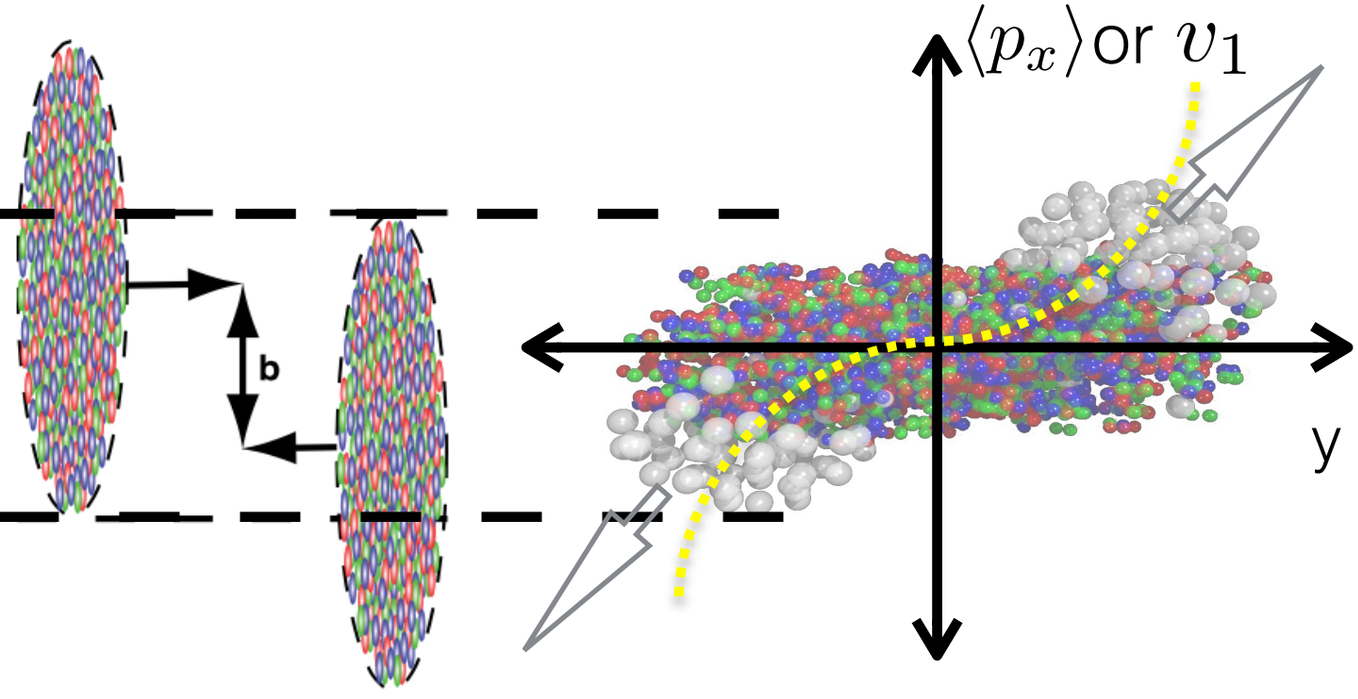
Particle species: p, anti-p, $\pi^{\pm}$, Λ, anti-Λ, $K^{\pm}$, K_S^0 and ϕ

Directed flow in heavy-ion collisions

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}[1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos 2(\phi - \Psi_R) + ...]$$

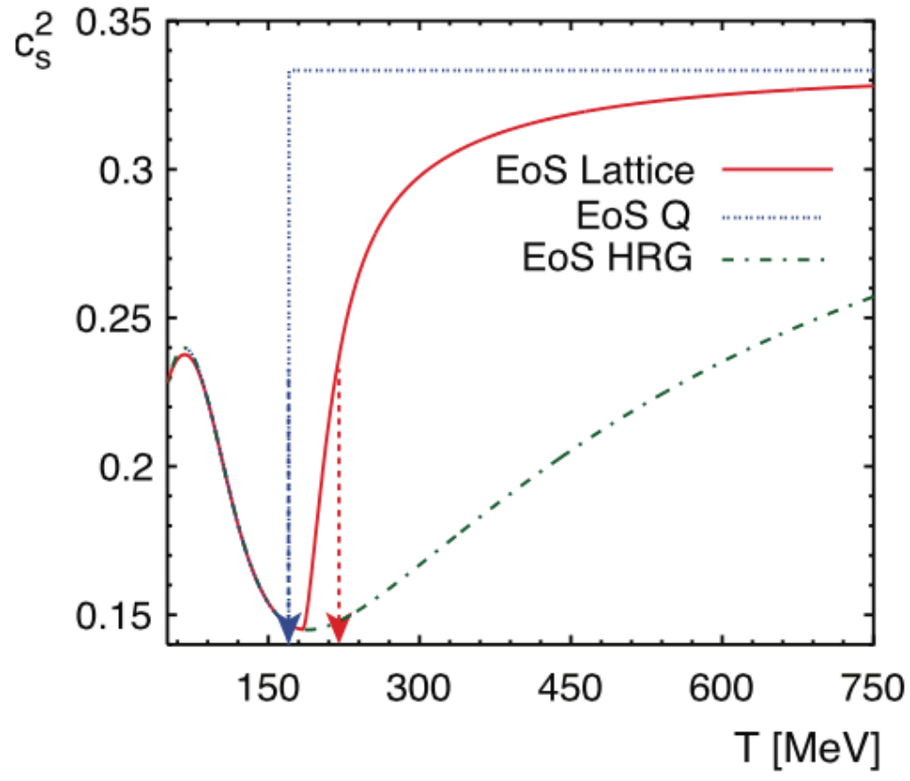
directed flow

$$v_1 \sim \langle\cos(\phi - \Psi_R)\rangle$$



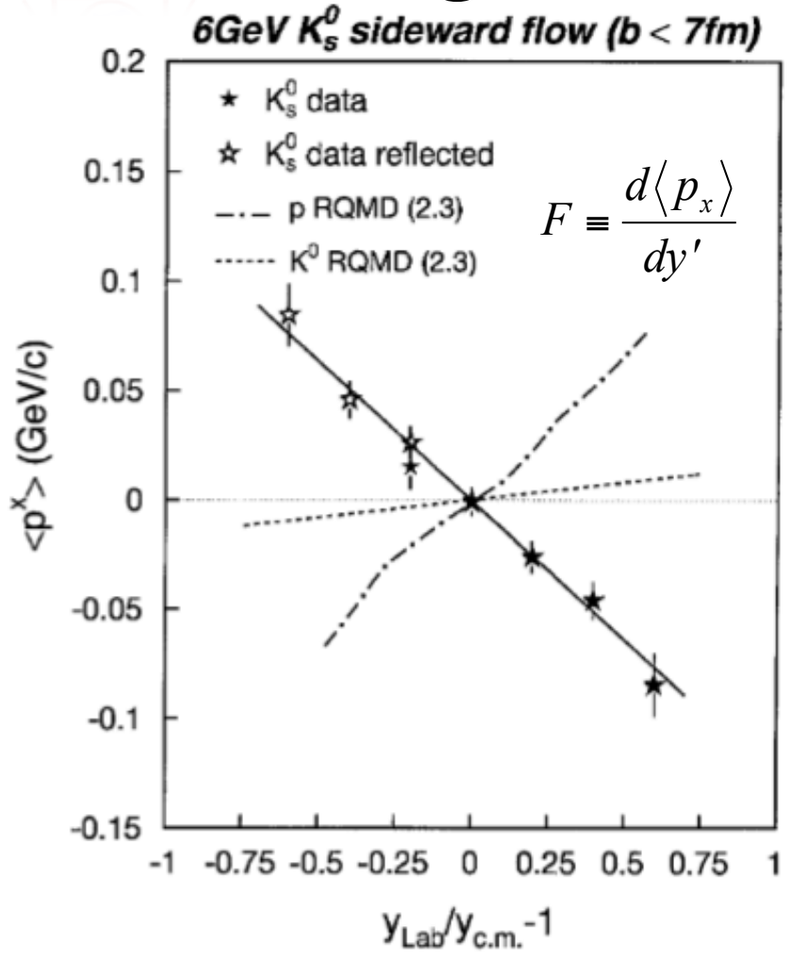
Nuclear passage time: 2R/γ

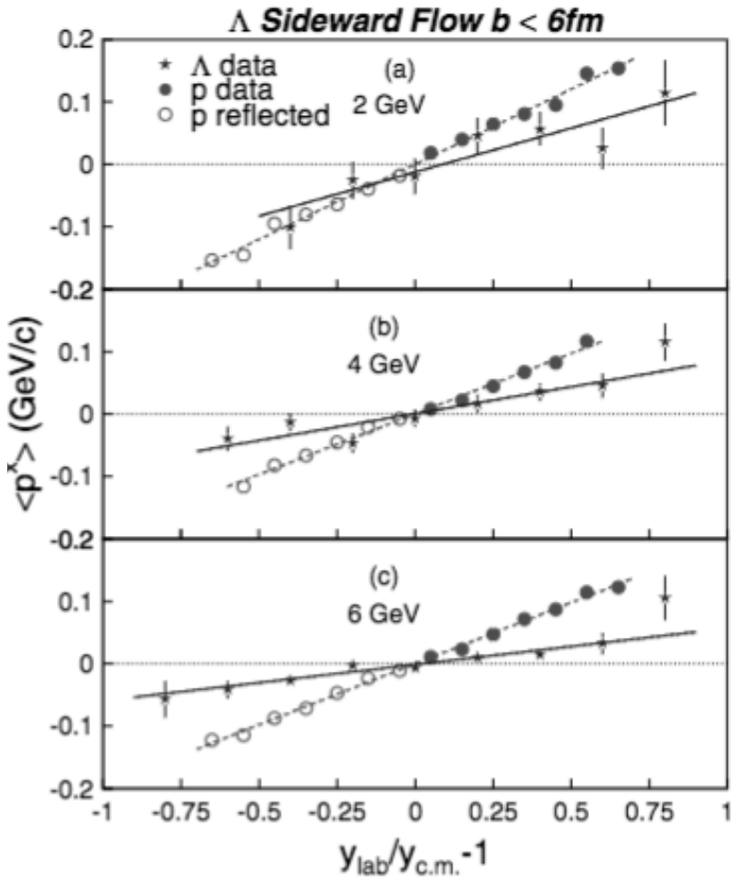
*R. Snellings, New J of Phys **13**, 055008 (2011)*
*P. Huovinen et al, Nucl Phys **A837**, 26 (2010)*

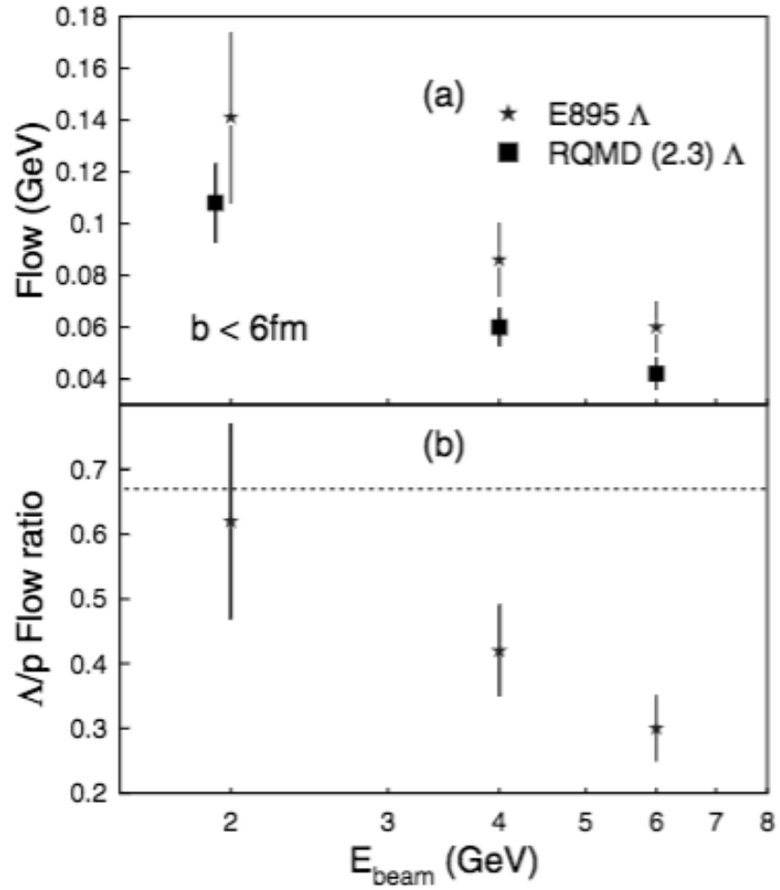


- *Early time phenomenon*
- *Sensitive to the pressure*
- *Sensitive to EoS*

Strange hadrons (Λ,K_s^0) from AGS energies



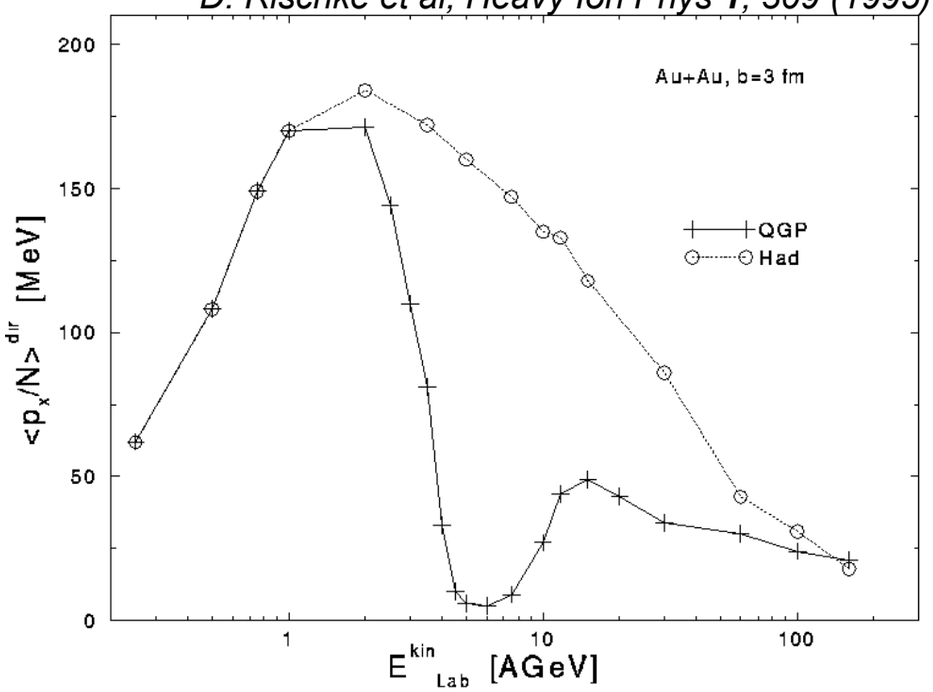




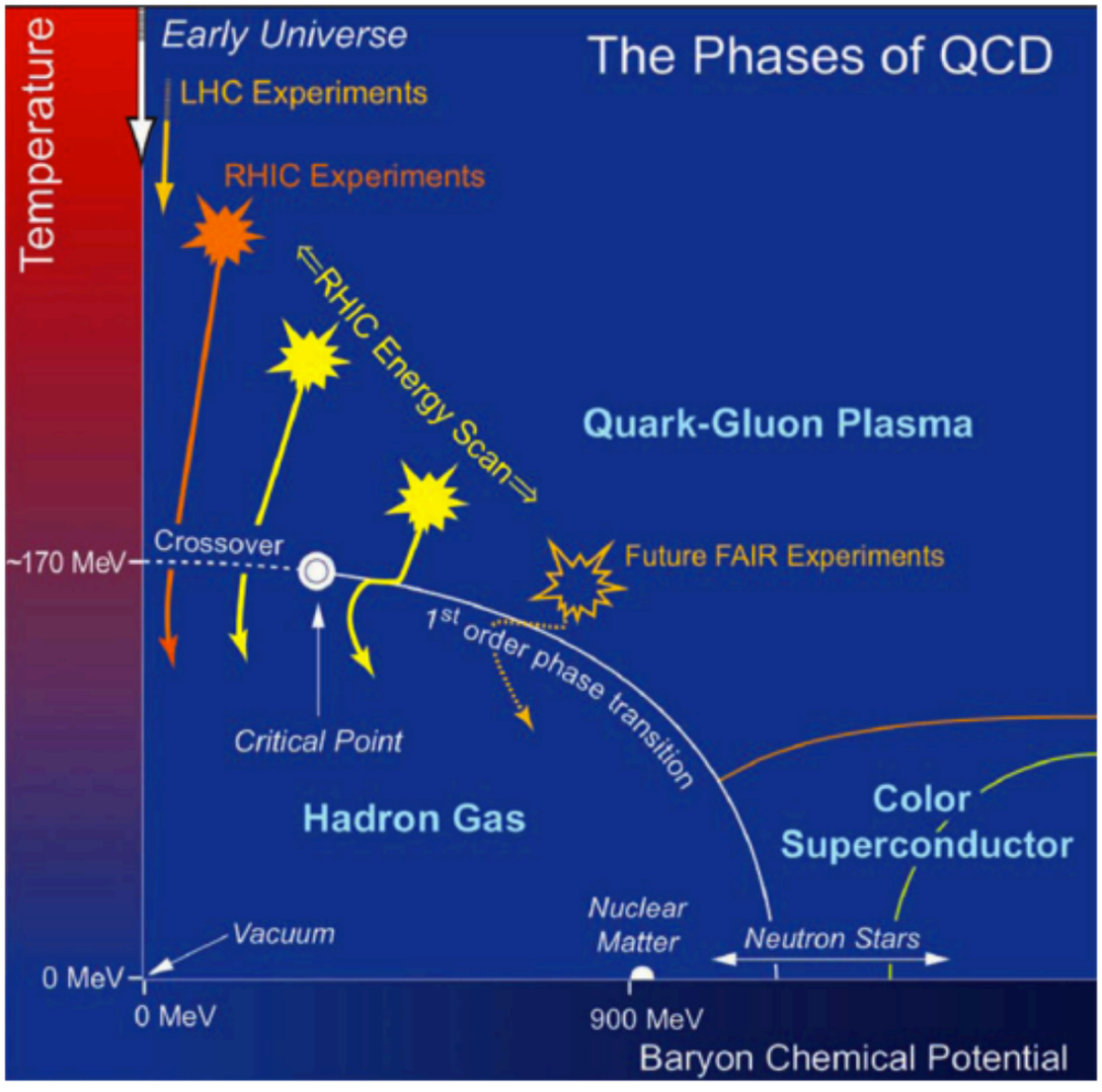
*PRL **84**, 162301 (2014) (E895 Coll)*
*PRL **85**, 162301 (2014) (E895 Coll)*
*PRL **86**, 162301 (2014) (E895 Coll)*

- Antiflow for K_s^0-mesons
- no dip observed at AGS around $\sqrt{s_{NN}}$ ~ 3.5 GeV

*D. Rischke et al, Heavy Ion Phys **1**, 309 (1995)*



BES-I at RHIC



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

Energy	Events (M)
7.7	4
11.5	12
14.5	18
19.6	36
27	70
39	130
62.4	67

BES program: To explore QCD phase diagram by varying beam energy

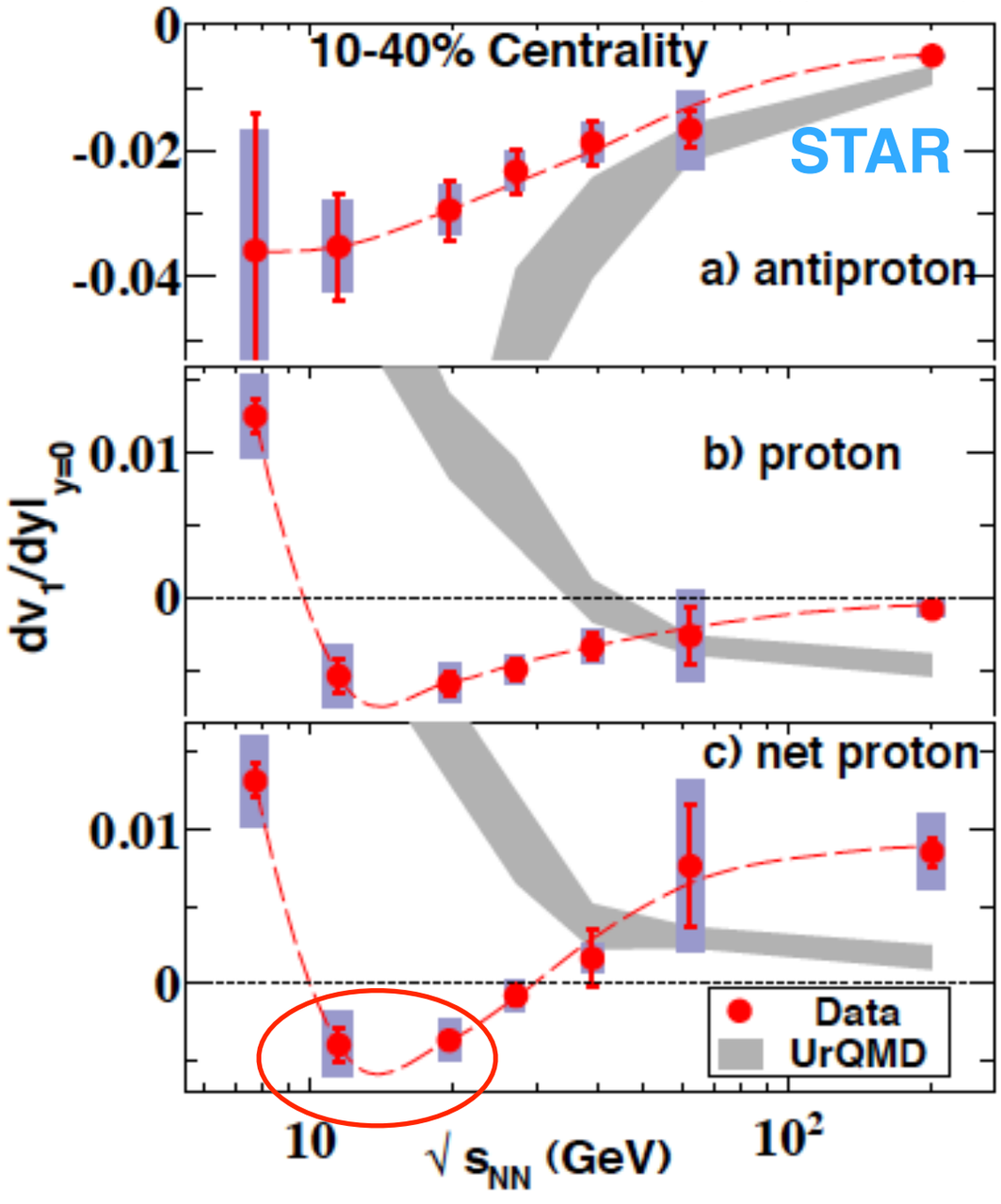
- ✦ Map turn-off of QGP signatures
- ✦ Search for Critical Point
- ✦ Search for First-Order Phase Transition

Large softening signature → First-Order Phase Transition

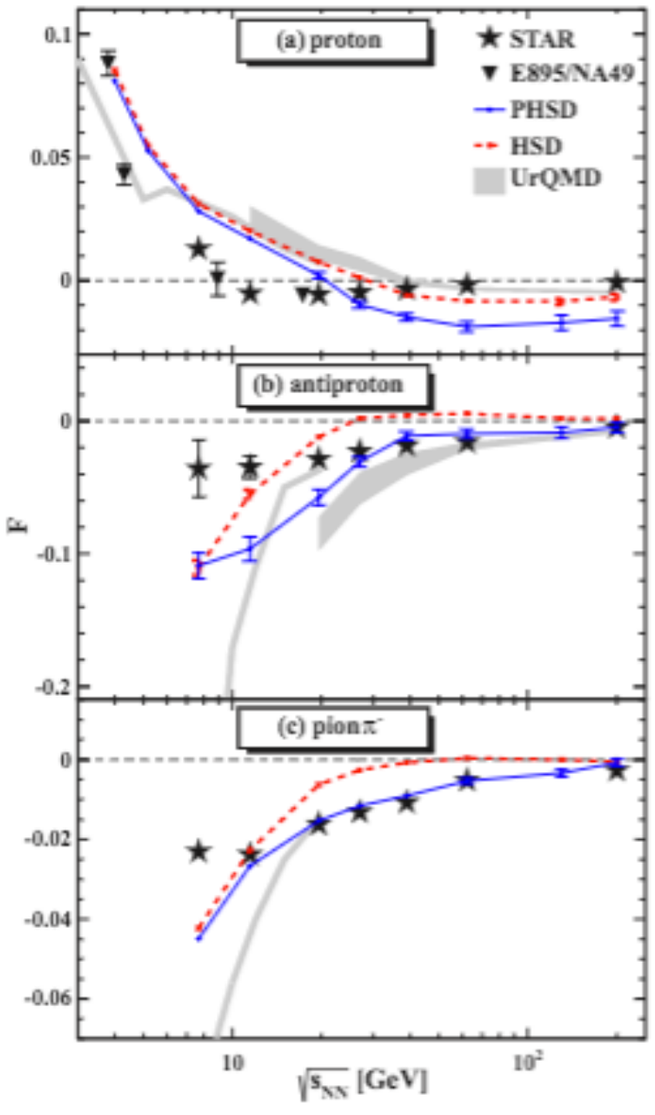
Smaller softening signature → Could have other explanations (e.g., crossover)

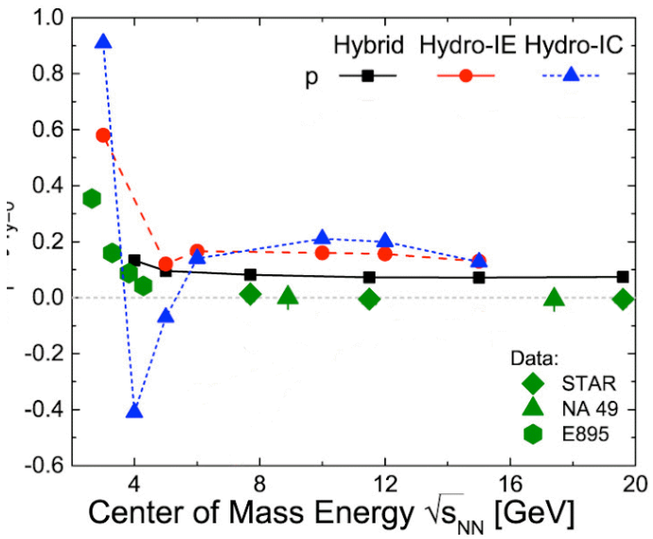
Directed flow from BES-I at RHIC

*PRL **112**, 162301 (2014) (STAR Coll)*



*Frankfurt hybrid: J. Steinheimer et al., PRC **89,** 054913 (2014)*
*PHSD: V. Konchakovski et al., PRC **90,** 014903 (2014)*
HSD: W. Cassing et al, arXiv: 1408.4313
*UrQMD: S. Bass et al, Prog. Part. Nucl. Phys **41**, 255, (1998)*





UrQMD, HSD, PHSD, Frankfurt-hybrid

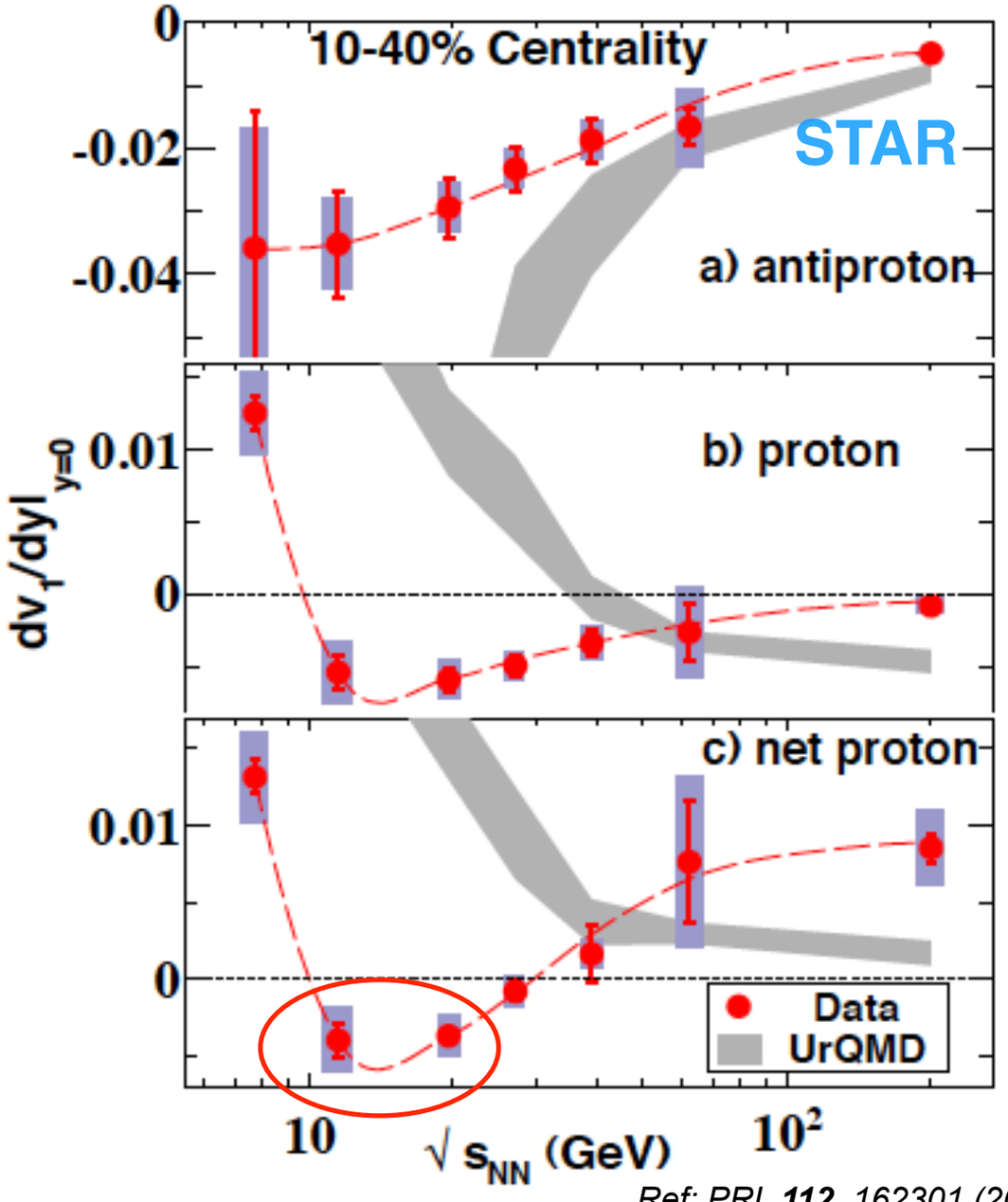
Can't explain the data

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

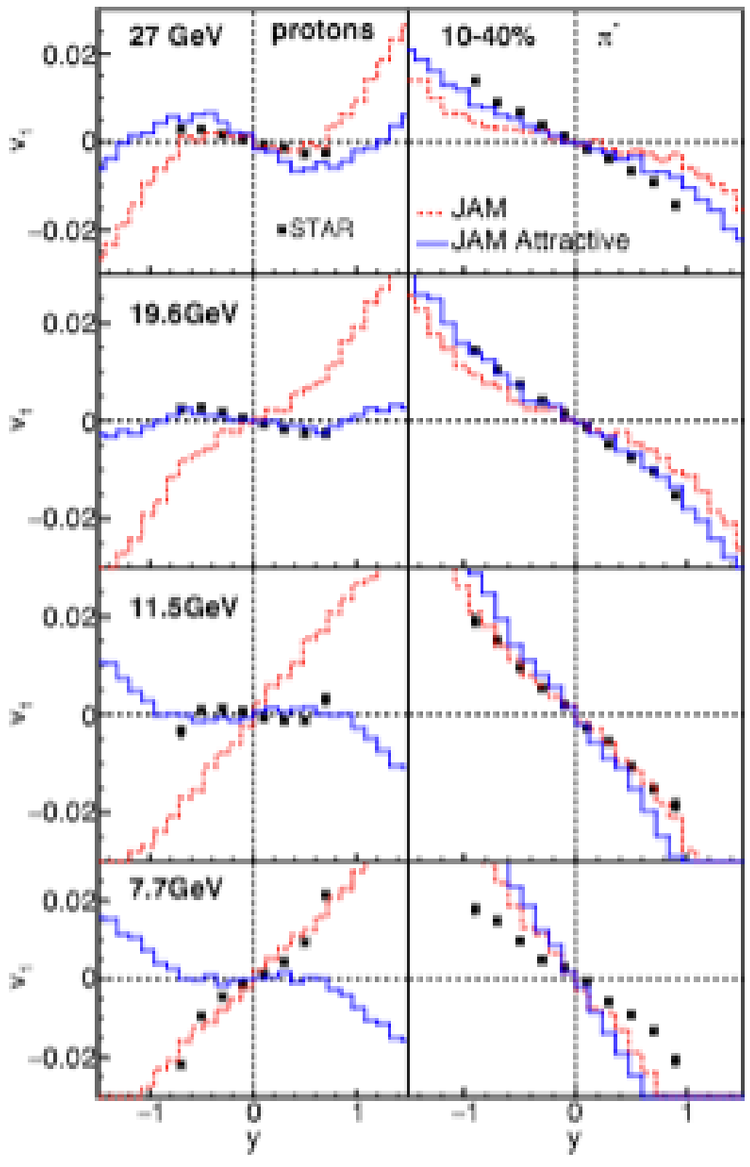
Softening of EoS (?)

Directed flow from BES-I at RHIC

*PRL **112**, 162301 (2014) (STAR Coll)*



JAM: Y. Nara et al., arxiv: 1601.07692



Softening effect modeled by attractive orbit scatterings

Authors argued for collapse of v_1 around $9<\sqrt{s_{NN}}<20$ GeV

*Ref: PRL **112**, 162301 (2014) (STAR Coll)*

Minimum in net-proton dv_1/dy with double sign change → Softening of EoS (?)

v_1 for strange hadrons

	quark content
Λ	uds
$K^{\pm}$	$u\bar{s}$
K_s^0	$(d\bar{s} - s\bar{d})/\sqrt{2}$
ϕ	$s\bar{s}$

→ Complimentary to p data

→ Probe kaon-nucleon potential

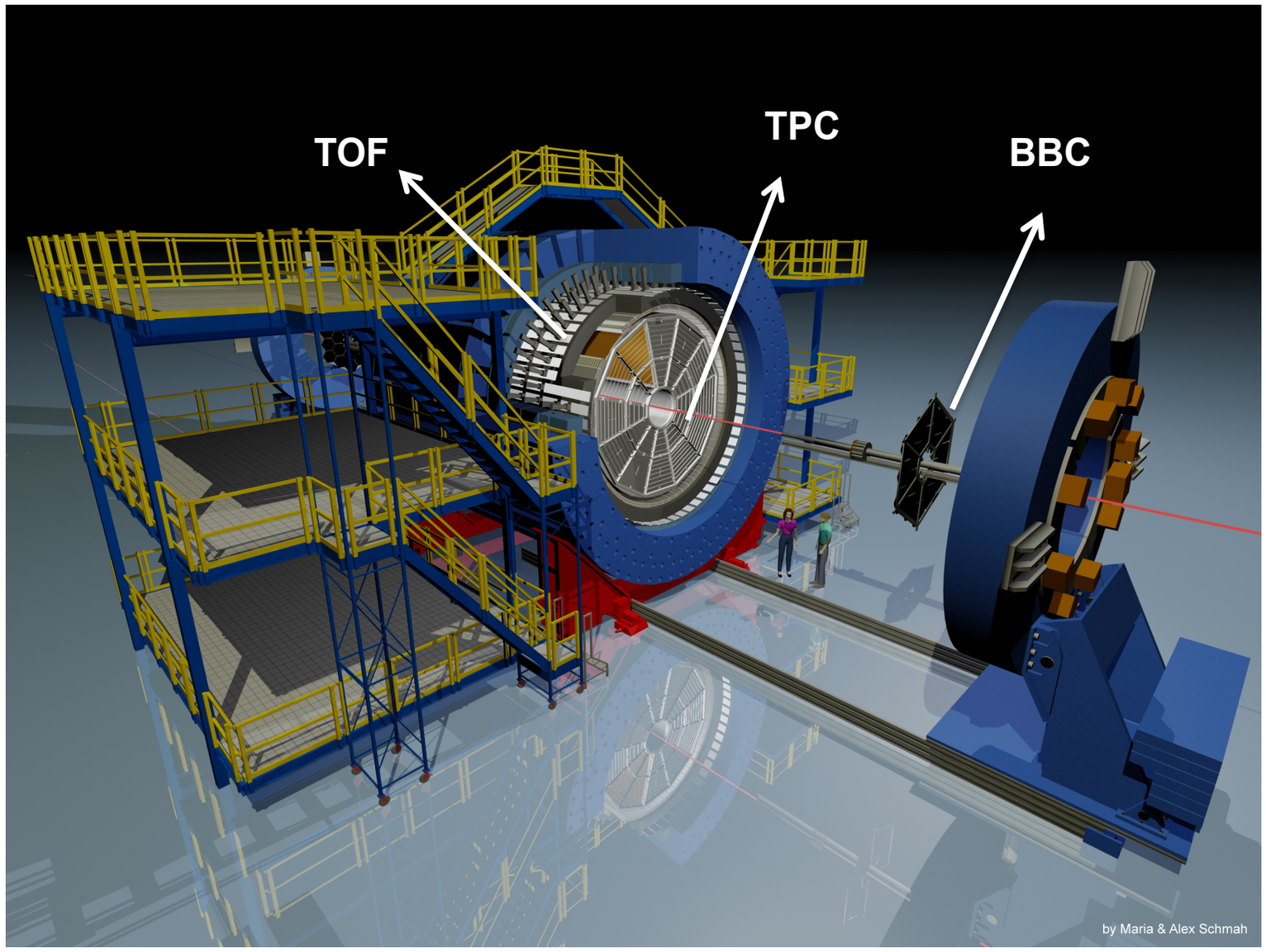
→ Mass close to p, but it is a vector meson

Minimally affected by late-stage hadronic interactions

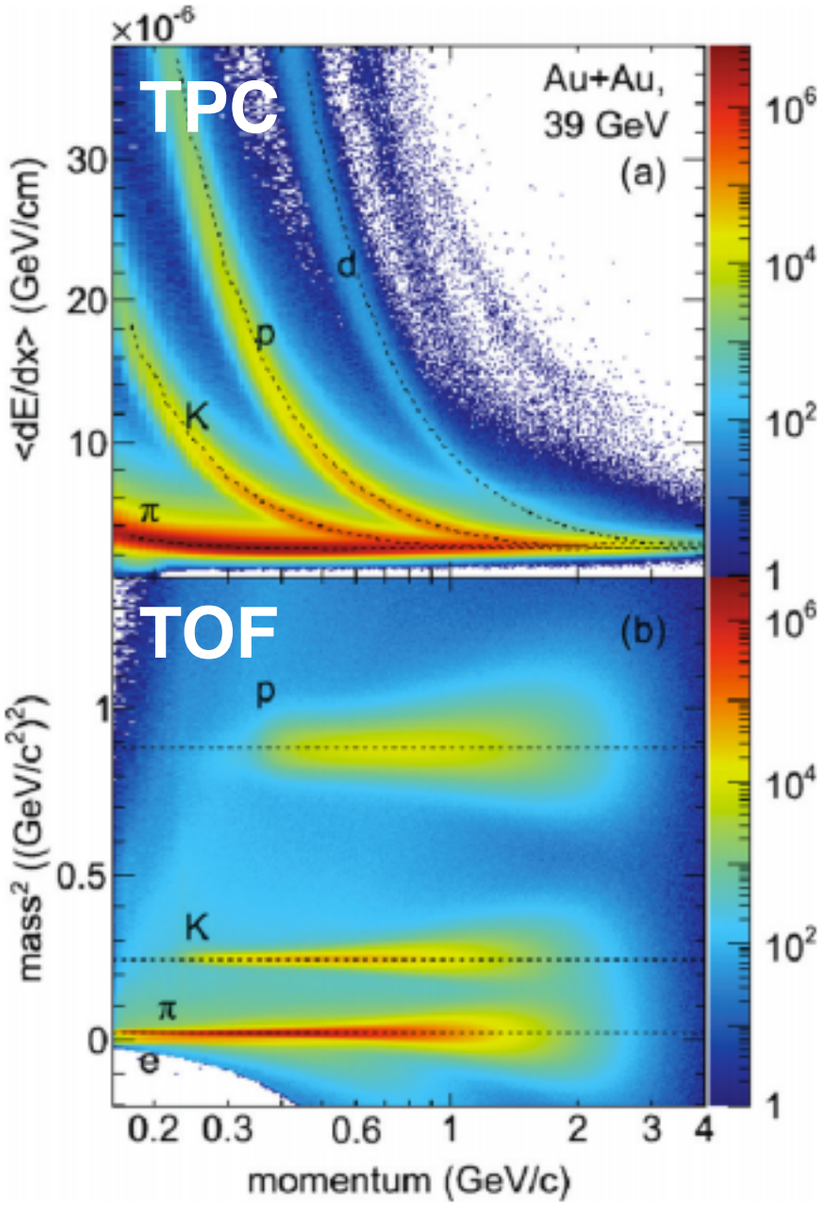
We can address

- Role of produced quarks in HIC
- Test hypothesis about transport of initial-state quarks

STAR Detector



Particle Identification:



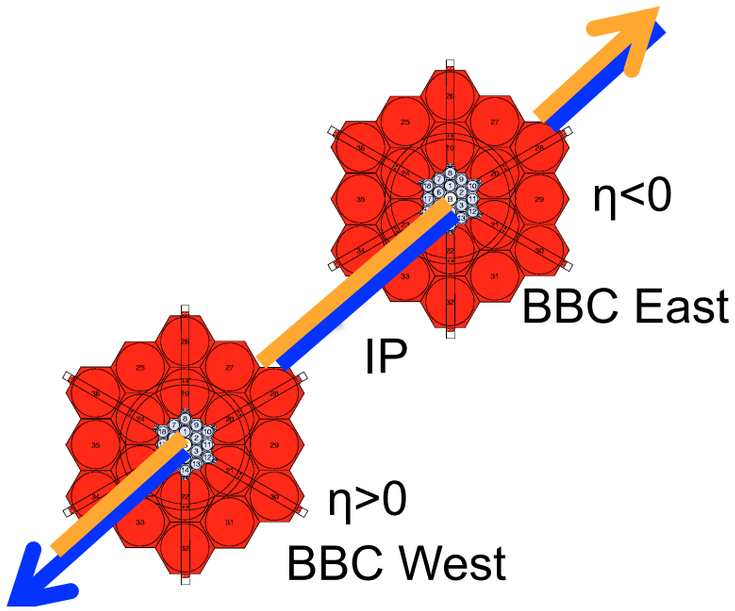
- Uniform acceptance
- Full azimuthal coverage
- $|\eta| < 1$
- Excellent PID capability

BBC event plane reconstruction

First order event plane is estimated using the hits in BBC

BBC event plane is based on the 1st harmonic, since the v_1 signal is significant in the forward rapidity

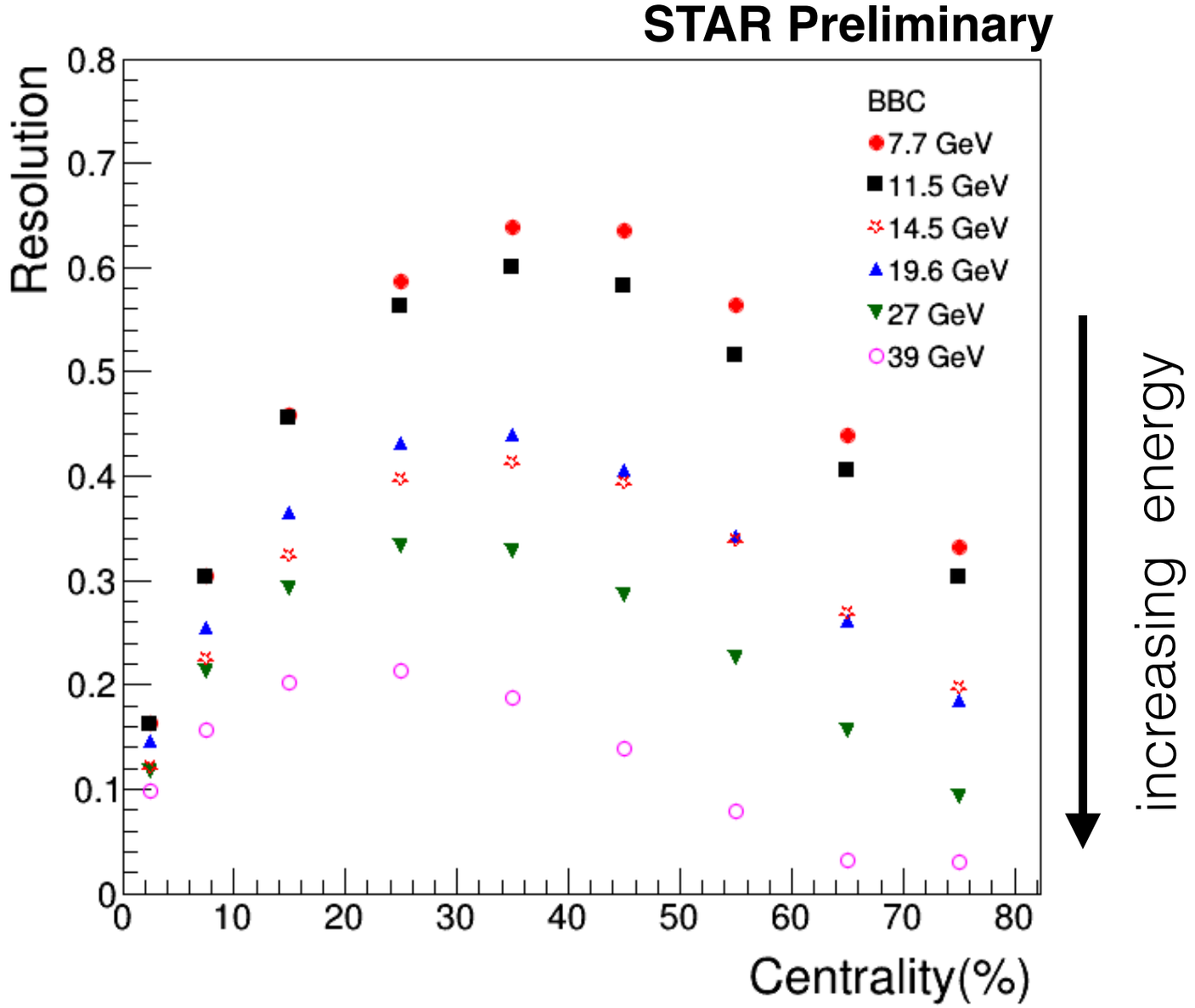
Large η gap with TPC reduces non-flow effects



$$Q_n \cos n\Psi_n = Q_{nx} = \sum_i w_i \cos n\phi_i,$$

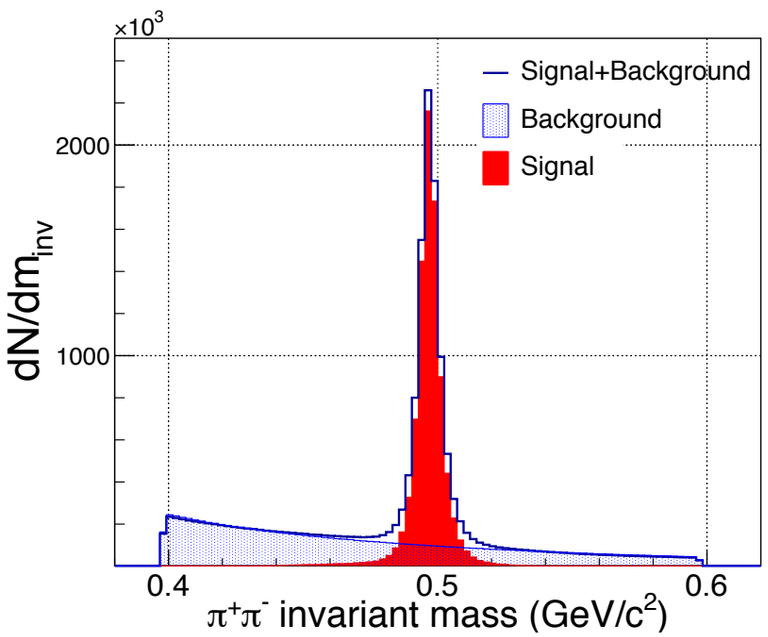
$$Q_n \sin n\Psi_n = Q_{ny} = \sum_i w_i \sin n\phi_i,$$

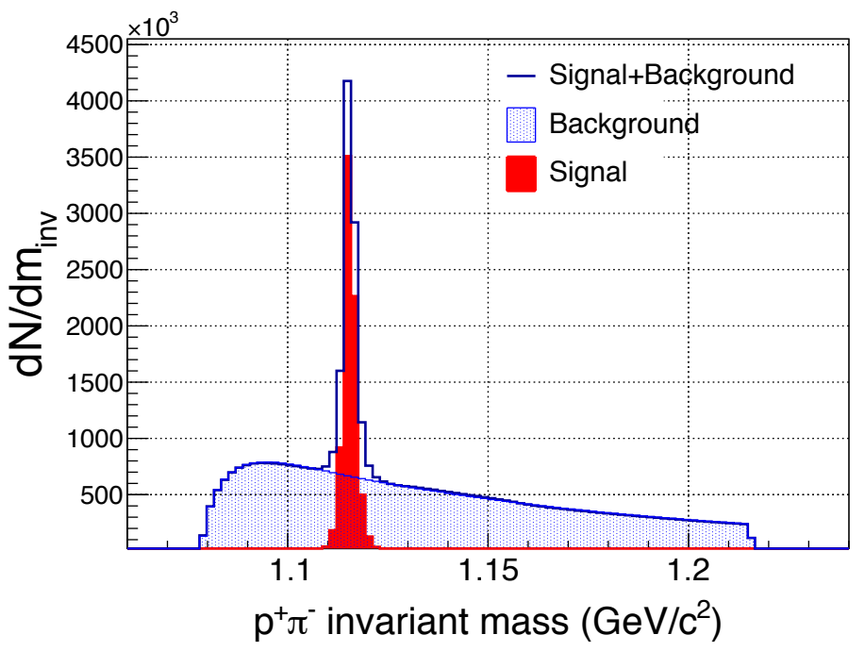
$$\Psi_n = \left(\tan^{-1} \frac{Q_{ny}}{Q_{nx}}\right)/n,$$

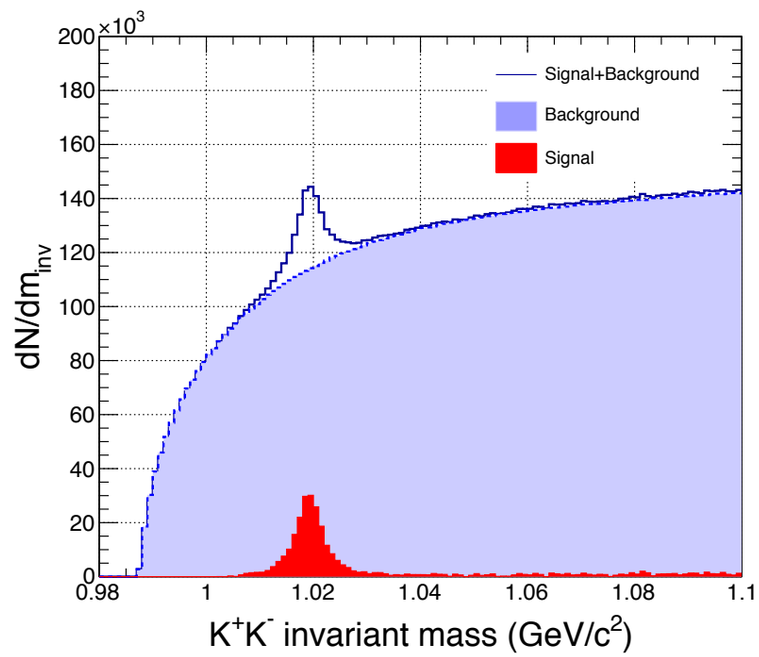


Signal reconstruction

$\sqrt{s_{NN}}$ =11.5 GeV, 10-40%, |y|< 1.0







Decay channels (BR):

$K_s^0 \rightarrow \pi\pi$ (69%)

$\Lambda \rightarrow p\pi$ (64%)

$\phi \rightarrow KK$ (48%)

Signal from invariant mass

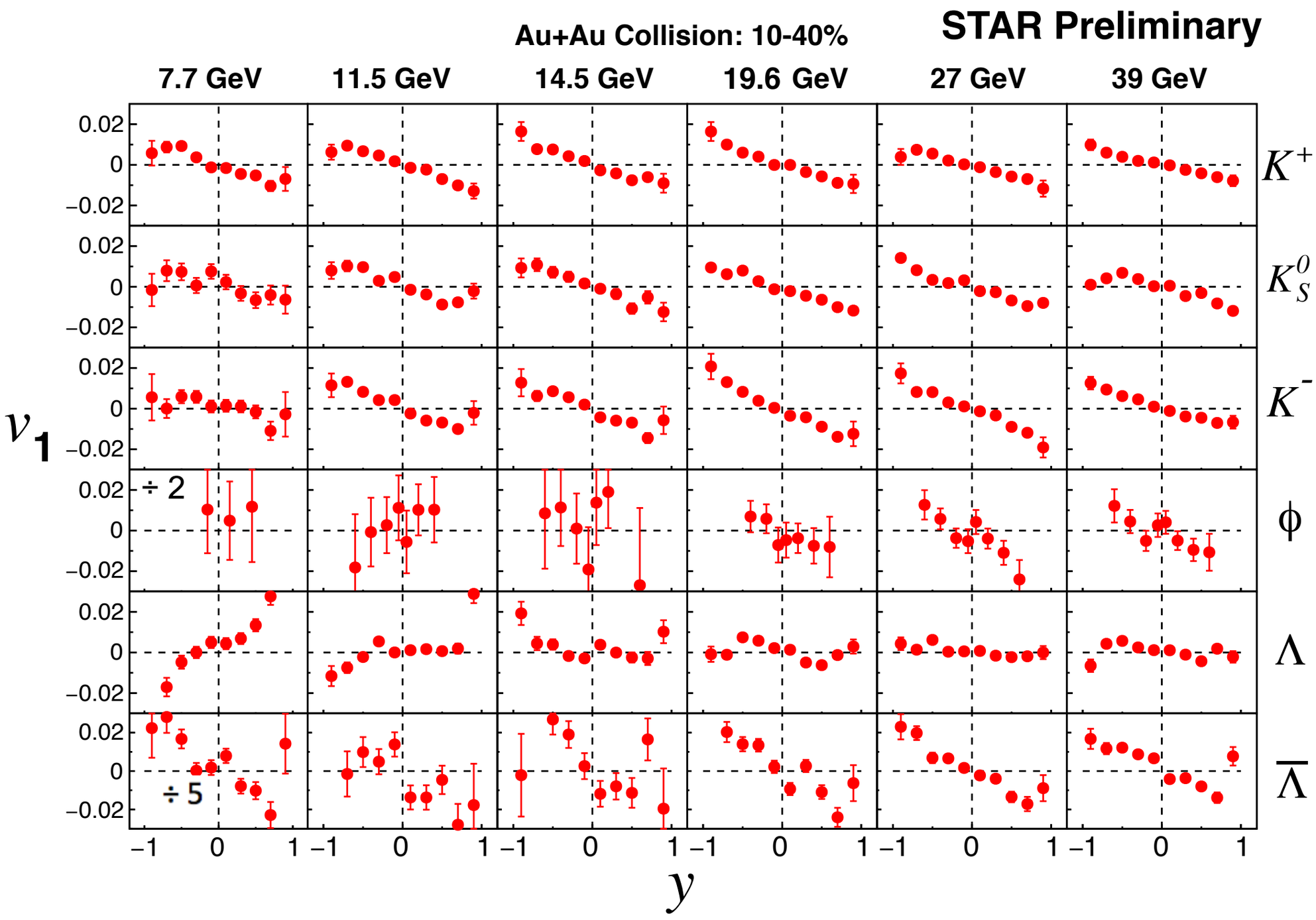
Background from mixed event

V0 topological cuts for Λ,K_s^0

v_1 extracted from invariant mass method

*N. Borghini et al, PRC **70**, 064905 (2004)*

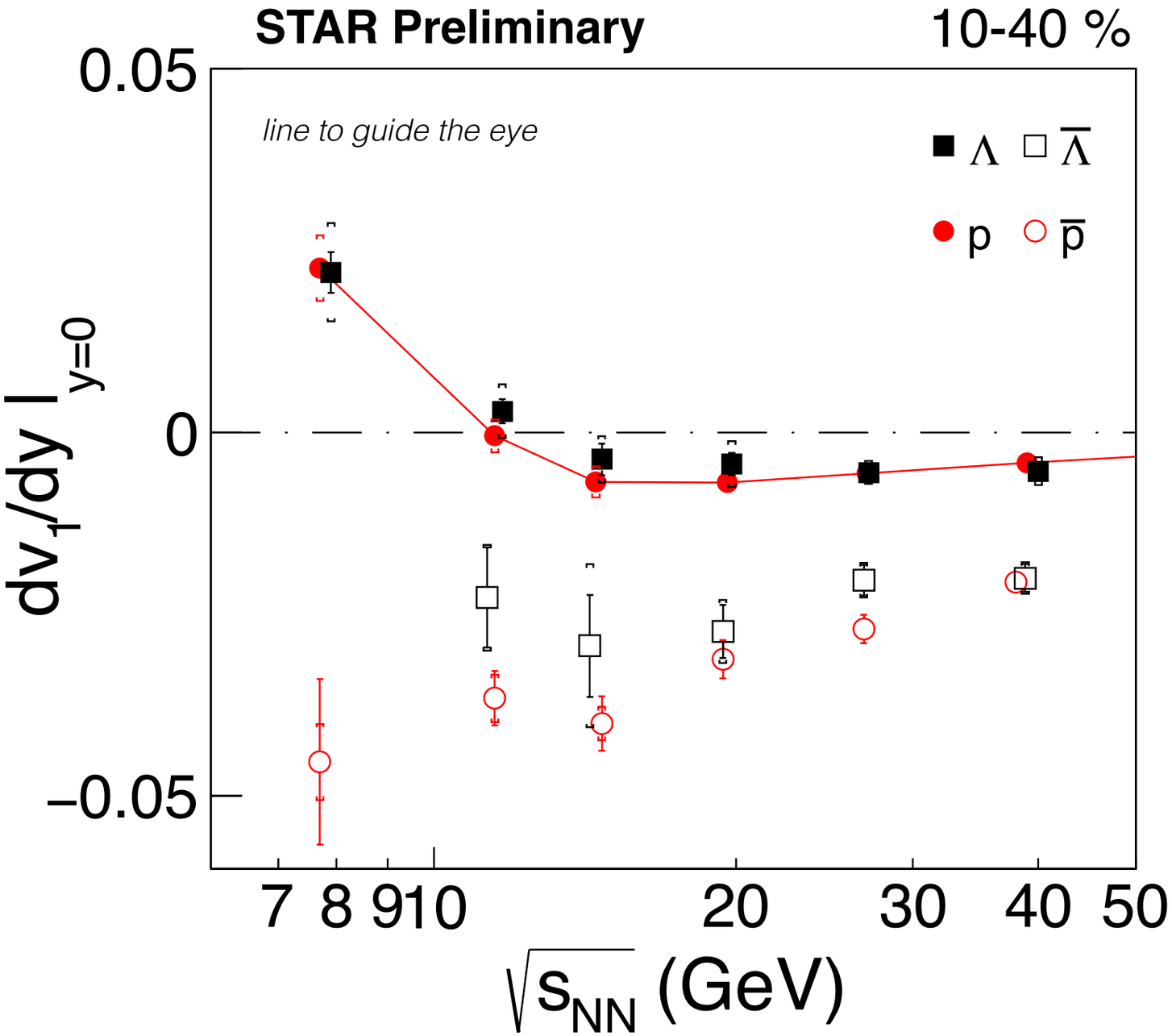
Rapidity dependence of v_1



- the slope of v_1 extracted by linear fitting ($|y| < 0.8$)

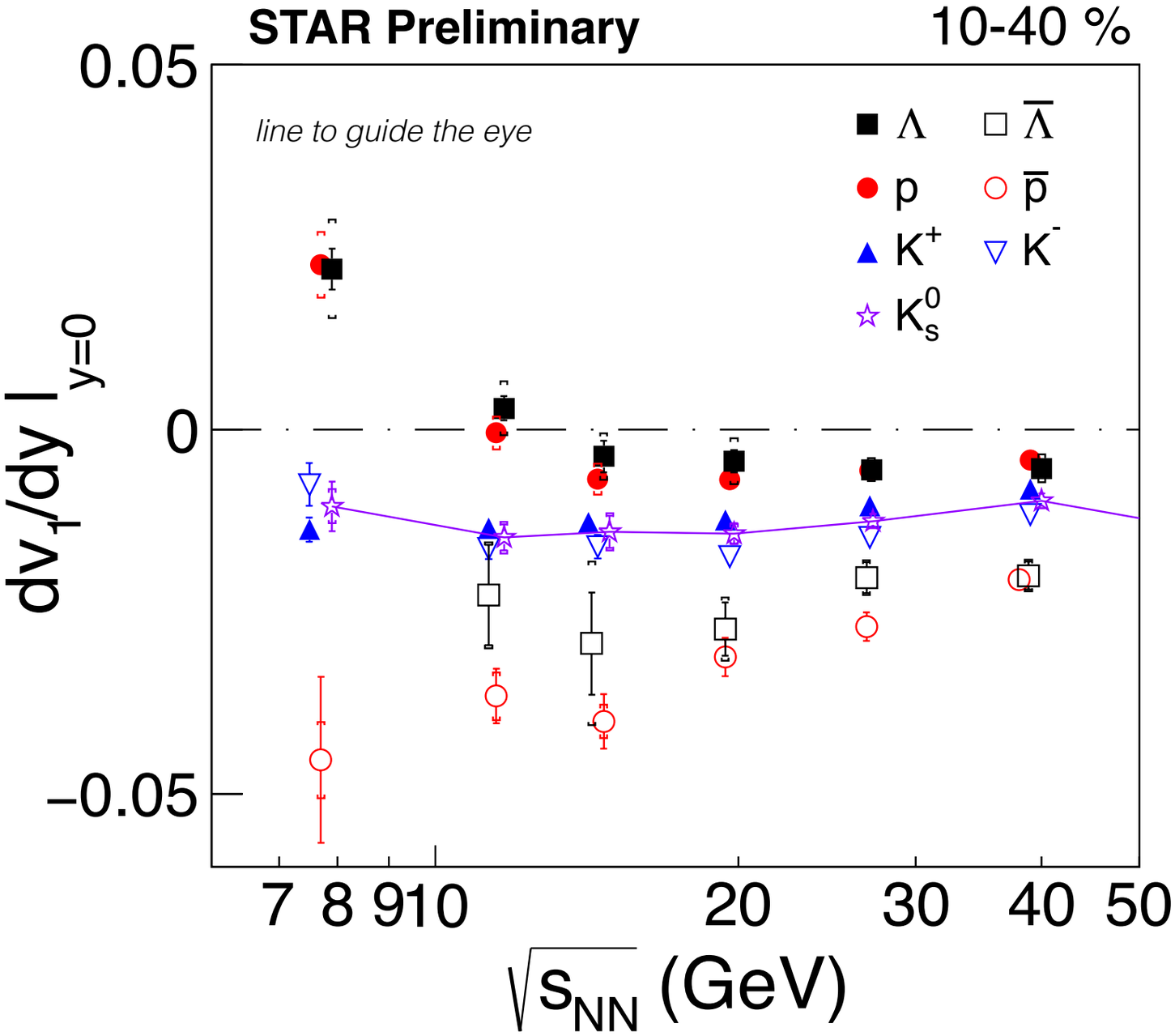
Ref: QM 2015: .P Shanmuganathan (for STAR Collaboration), arXiv:1512.09009

Energy dependence of dv_1/dy



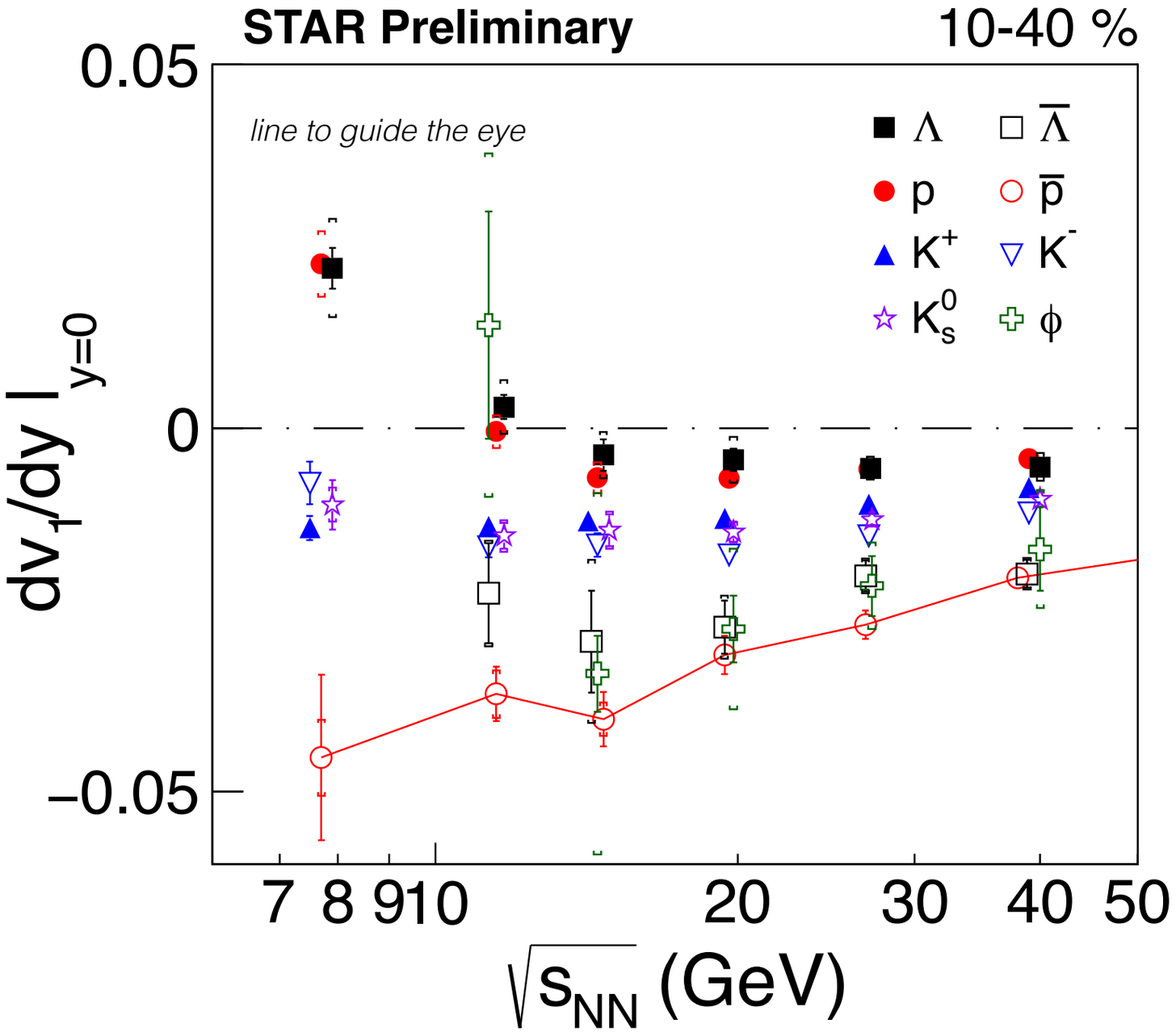
- $(dv_1/dy)_p \sim (dv_1/dy)_\Lambda$
- $(dv_1/dy)_{\bar{p}, \bar{\Lambda}} \sim$ negative
- $(dv_1/dy)_{\bar{p}} \sim (dv_1/dy)_{\bar{\Lambda}}$

Energy dependence of dv_1/dy



- $(dv_1/dy)_{K^{\pm}}$ ~ negative
- $(dv_1/dy)_{K_s^0}$ lies in between K±

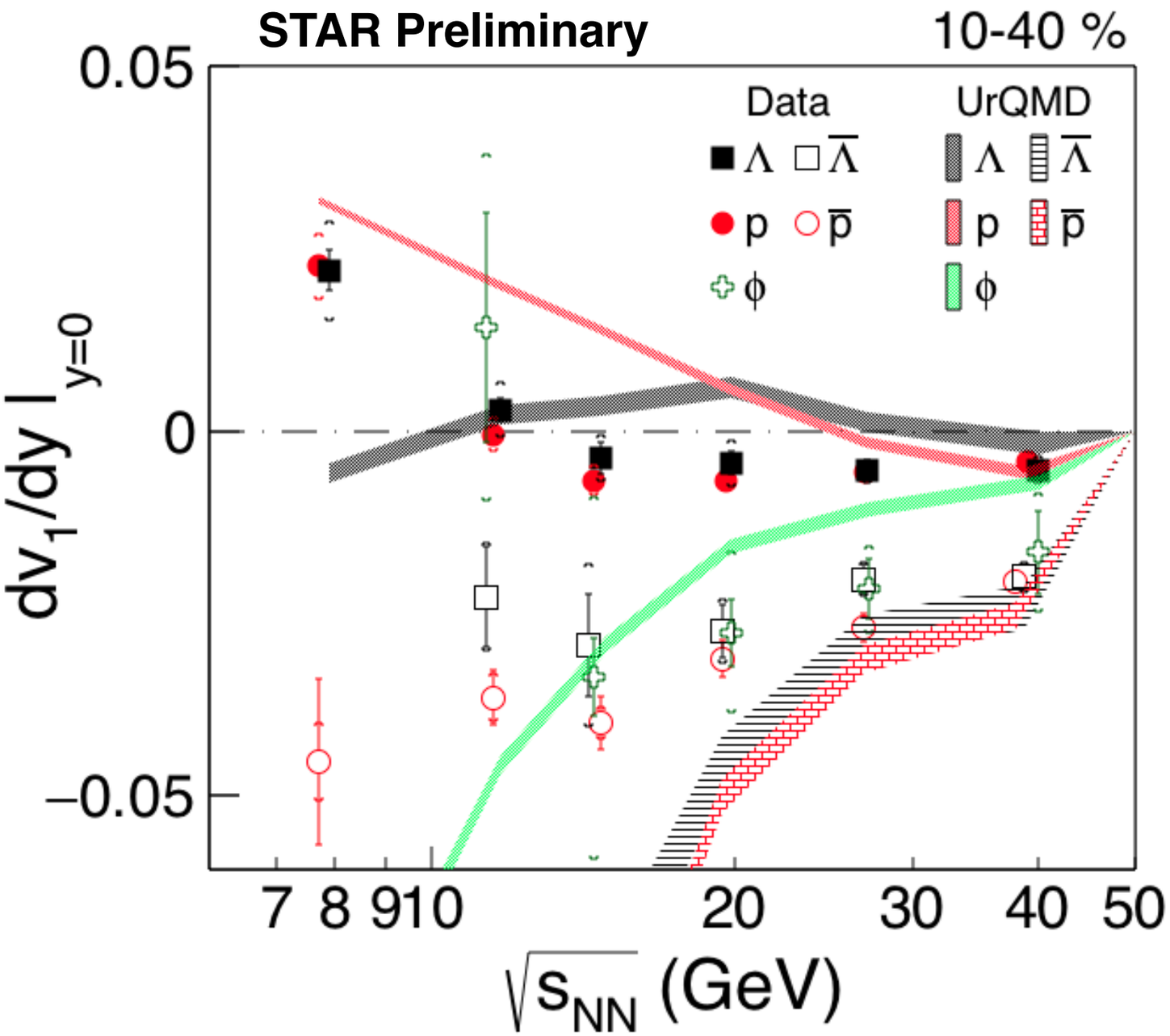
Energy dependence of dv_1/dy



- $(dv_1/dy)_{\bar{\Lambda},\bar{p}} \sim (dv_1/dy)_{\phi}$ for energies above 14.5 GeV
- $(dv_1/dy)_{\phi} \sim 0$ at 11.5 GeV with large stat. uncertainty

Energy dependence of dv_1/dy

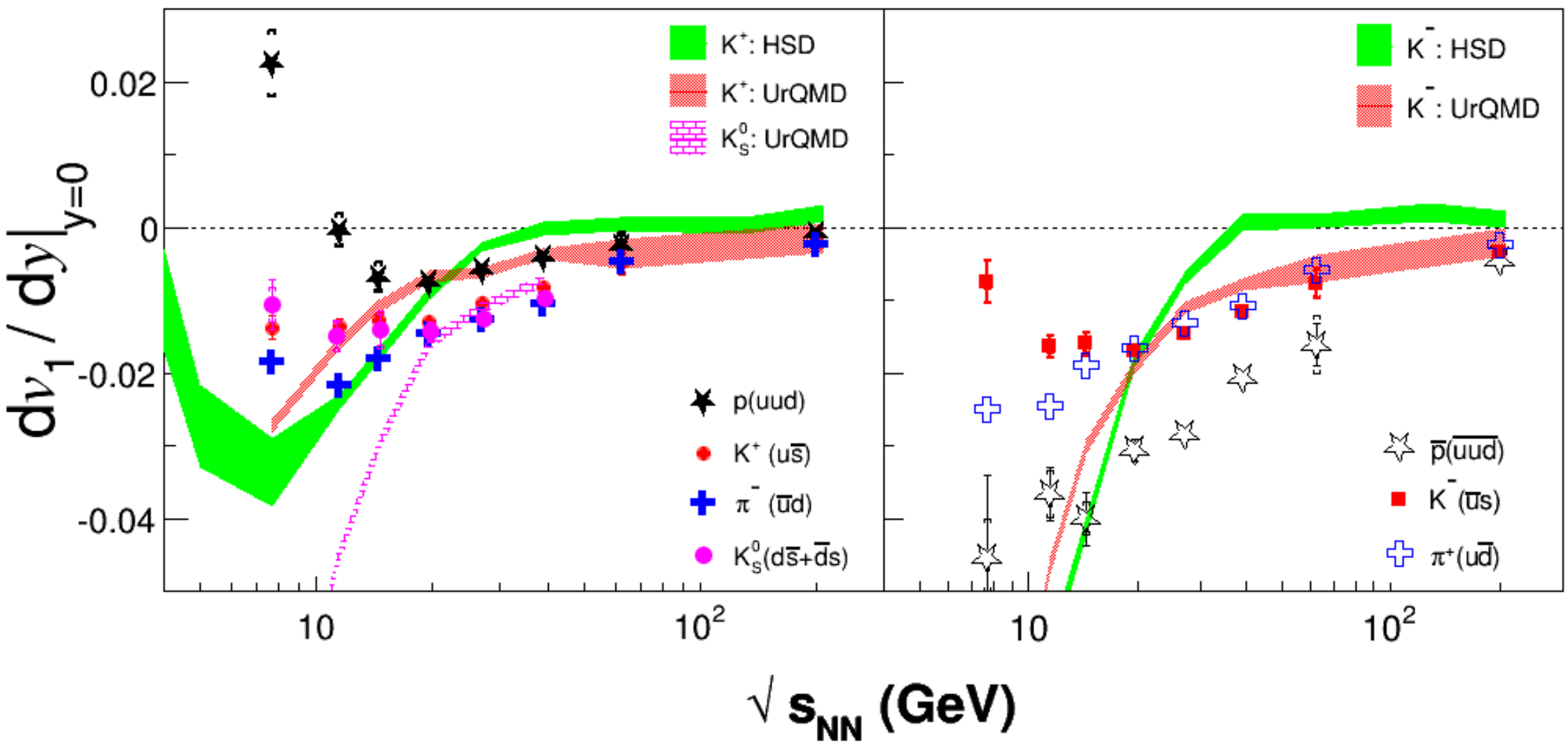
*UrQMD: S. Bass et al, Prog. Part. Nucl. Phys **41**, 255, (1998)*



- $(dv_1/dy)_{UrQMD\text{-}\Lambda,\phi}$: deviate from data below19.6 GeV
- $(dv_1/dy)_{UrQMD\text{-}\bar{\Lambda},\phi}$: qualitatively similar trend to data for higher energies

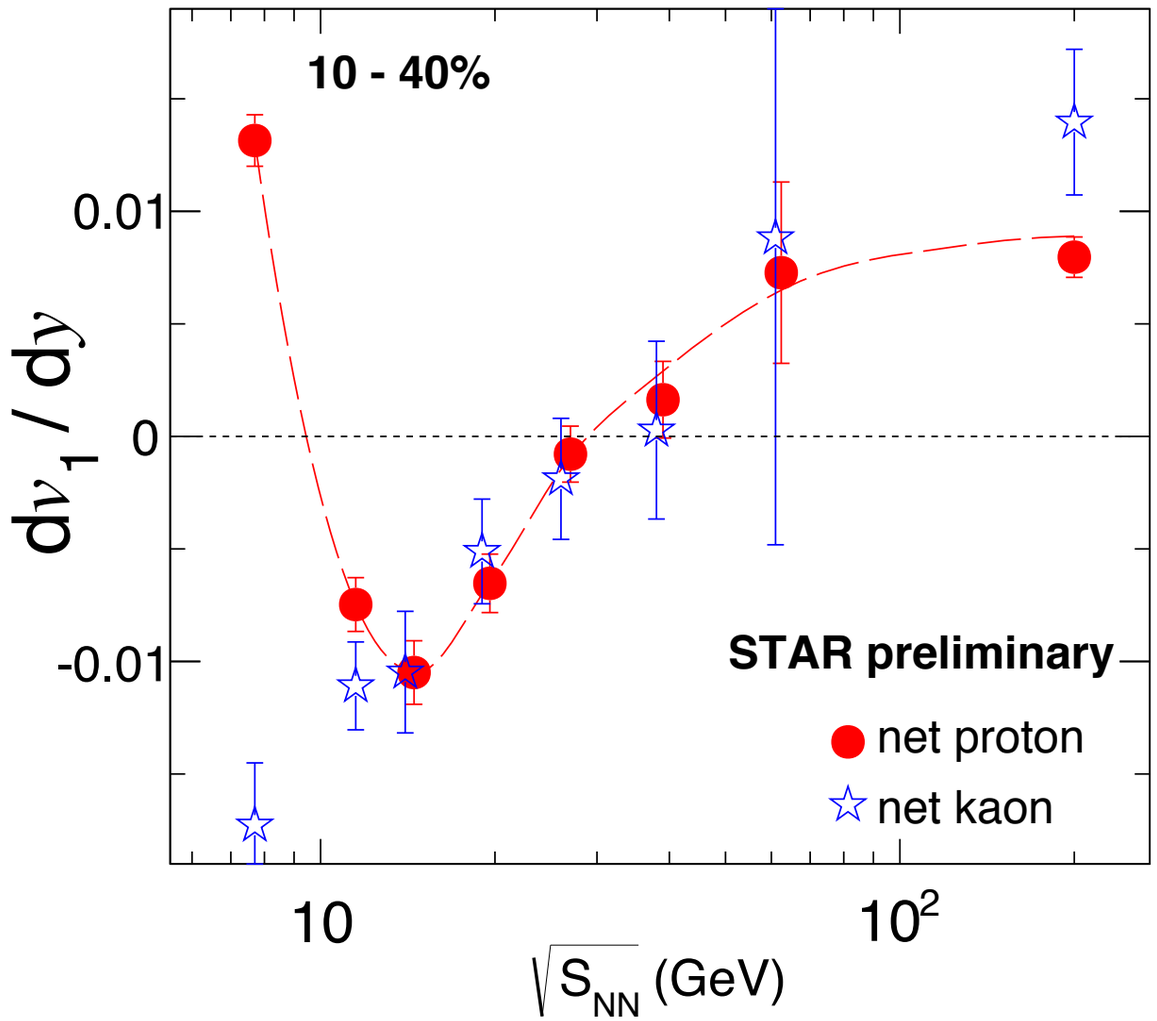
Energy dependence of dv_1/dy

HSD: W. Cassing et al, arXiv: 1408.4313
*UrQMD: S. Bass et al, Prog. Part. Nucl. Phys **41**, 255, (1998)*



- $dv_1/dy(K^{\pm}, K_s^0)$ from UrQMD/HSD model can't explain data

Energy dependence of net-particle v_1



To disentangle contributions from produced quarks & transported quarks

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

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

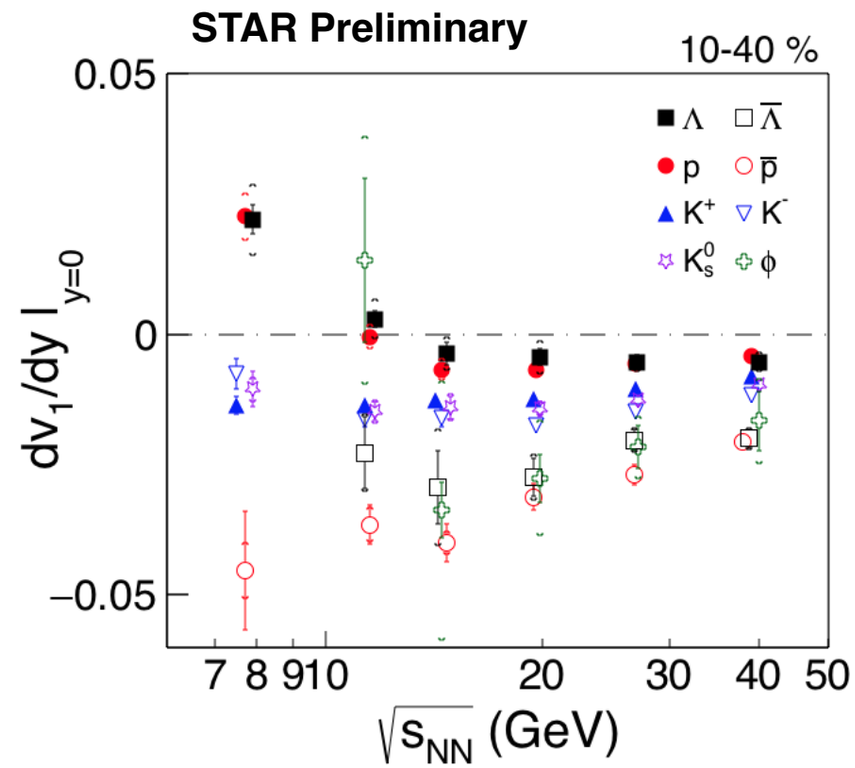
$F=dv_1/dy$, $r_1(y)=$anti-p/p
$r_2(y)=K^-/K^+$

- $(dv_1/dy)_{net\text{-}K} \sim (dv_1/dy)_{net\text{-}p}$ at and above 14.5 GeV but they deviate at lower energies

Summary

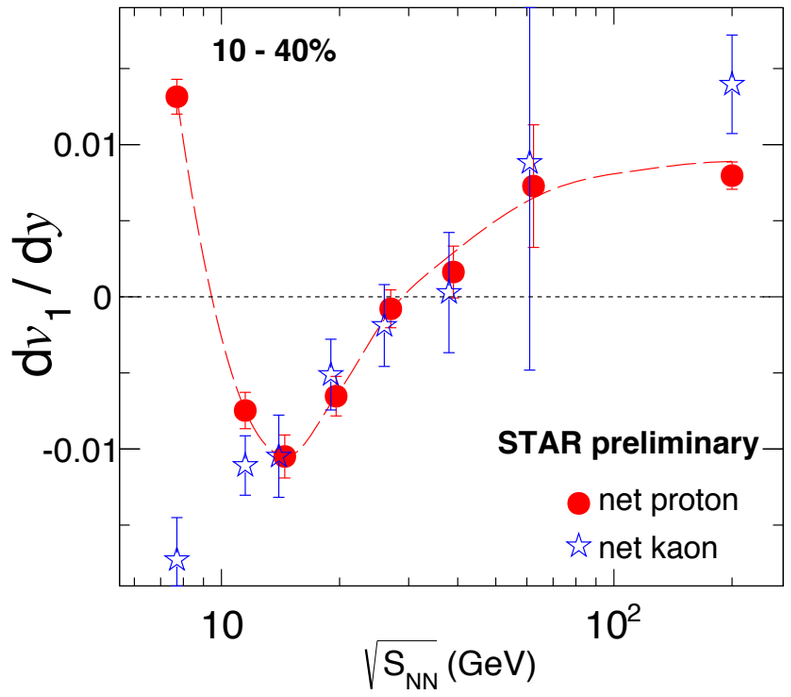
- $dv_1/dy(p) \sim dv_1/dy(\Lambda)$ and both show sign-change $\sqrt{s_{NN}} < 14.5$ GeV

- $dv_1/dy(\text{anti-}\Lambda,\text{anti-p}) \sim dv_1/dy(\phi)$ for $\sqrt{s_{NN}} > 11.5$ GeV



- $dv_1/dy(\text{net-p}) \sim dv_1/dy(\text{net-K})$ for $\sqrt{s_{NN}} > 14.5$ GeV: quark transport

  while $dv_1/dy(\text{net-K})$ stays negative for $\sqrt{s_{NN}} < 14.5$ GeV



Present models do not describe the data.
More theoretical progress needed for an interpretation.

Thank you