Directed flow of identified particles from Beam Energy Scan Au+Au collisions

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(on behalf of STAR Collaboration)

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Outline

★ Directed flow in heavy-ion collisions

★ Beam energy scan (BES) program at RHIC

★ STAR detector at RHIC

★ Measurements at lower energies (AGS/SPS)

★ Results from STAR

★ Comparison of data with available models

★ Summary and outlook

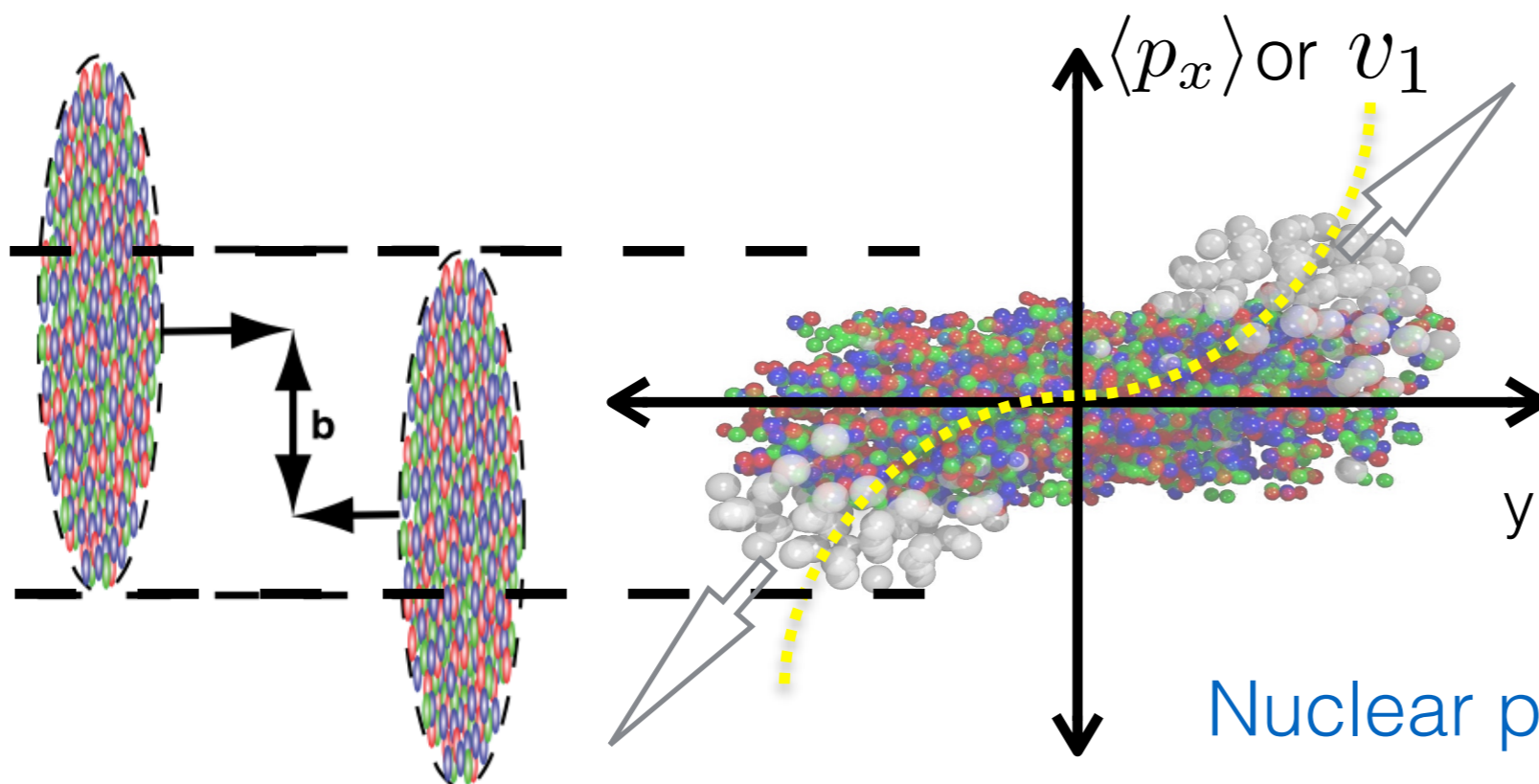# Directed flow in heavy-ion collisions

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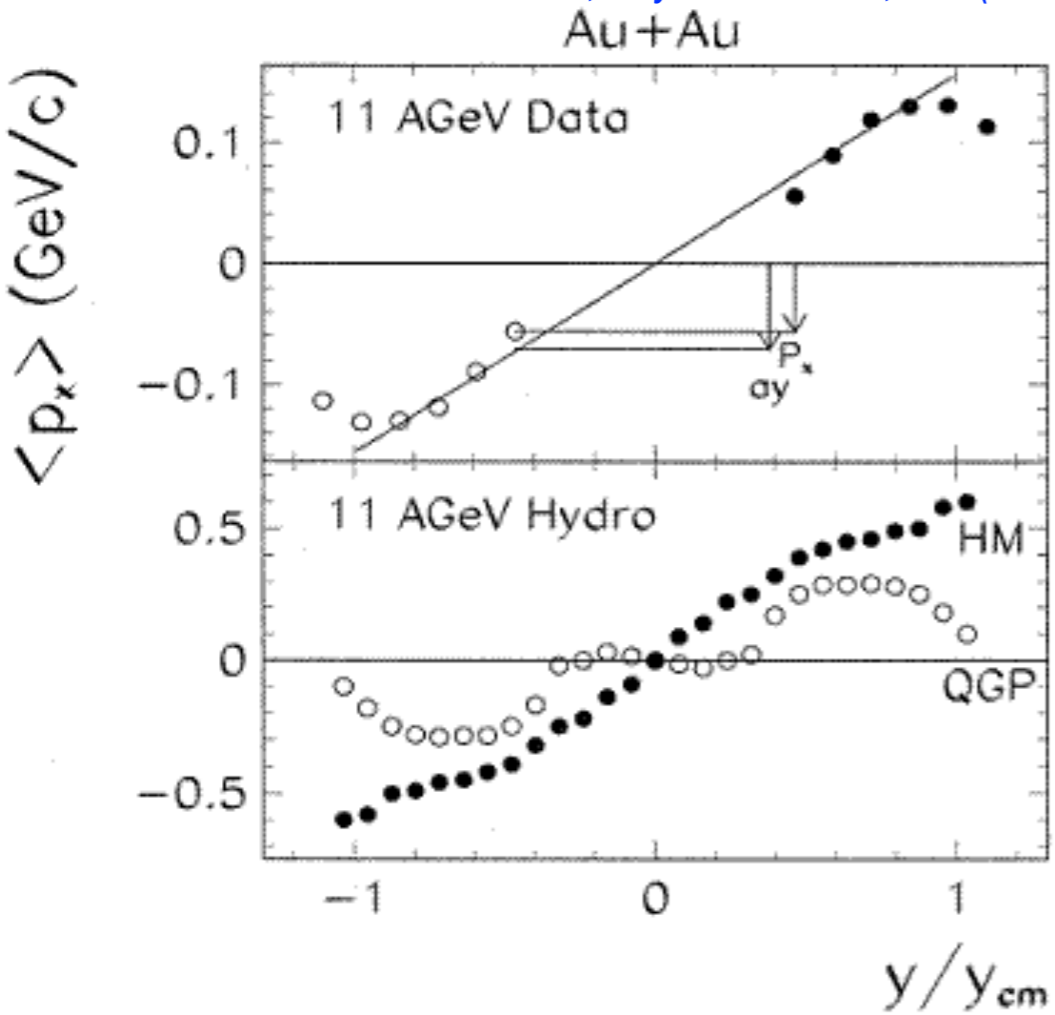
directed flow   elliptic flow

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

Nuclear passage time: 2R/γ ~ 0.1 fm/c

Probes early stages of collisions

*H. Sorge, Phys Rev. Lett **78**, 2309 (1997)*
*N. Herrmann et al, Annu. Rev. Nucl Part Sci **49**, 581 (1999)*

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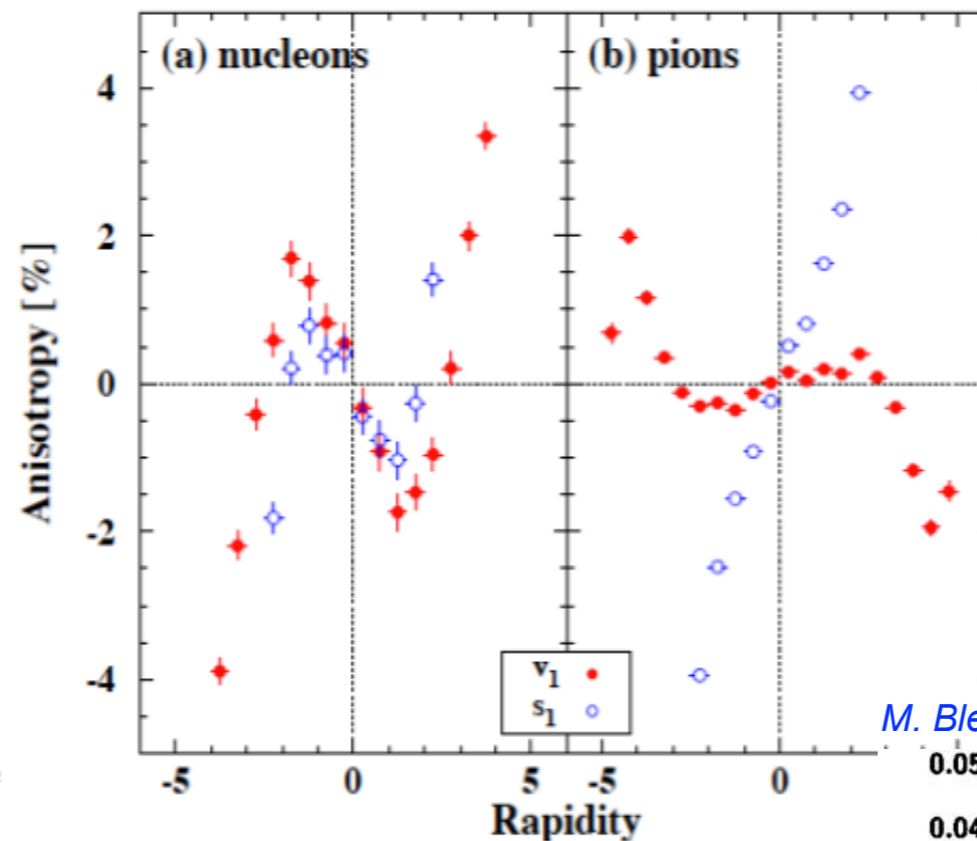# Rapidity dependence of directed flow

Au+Au

Models with QGP predicted a "wiggle"/ flat v_1 at mid-rapidity due to a 1st order phase transition
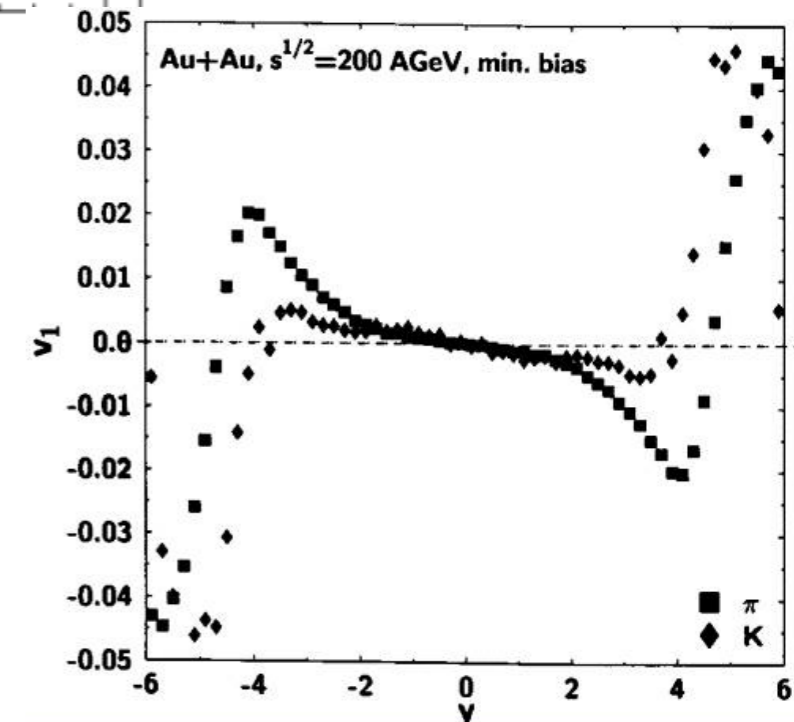
4

Rapidity dependence of directed flow

*L. P. Csernai et al., Phys. Lett. **B458**, 454 (1999)*
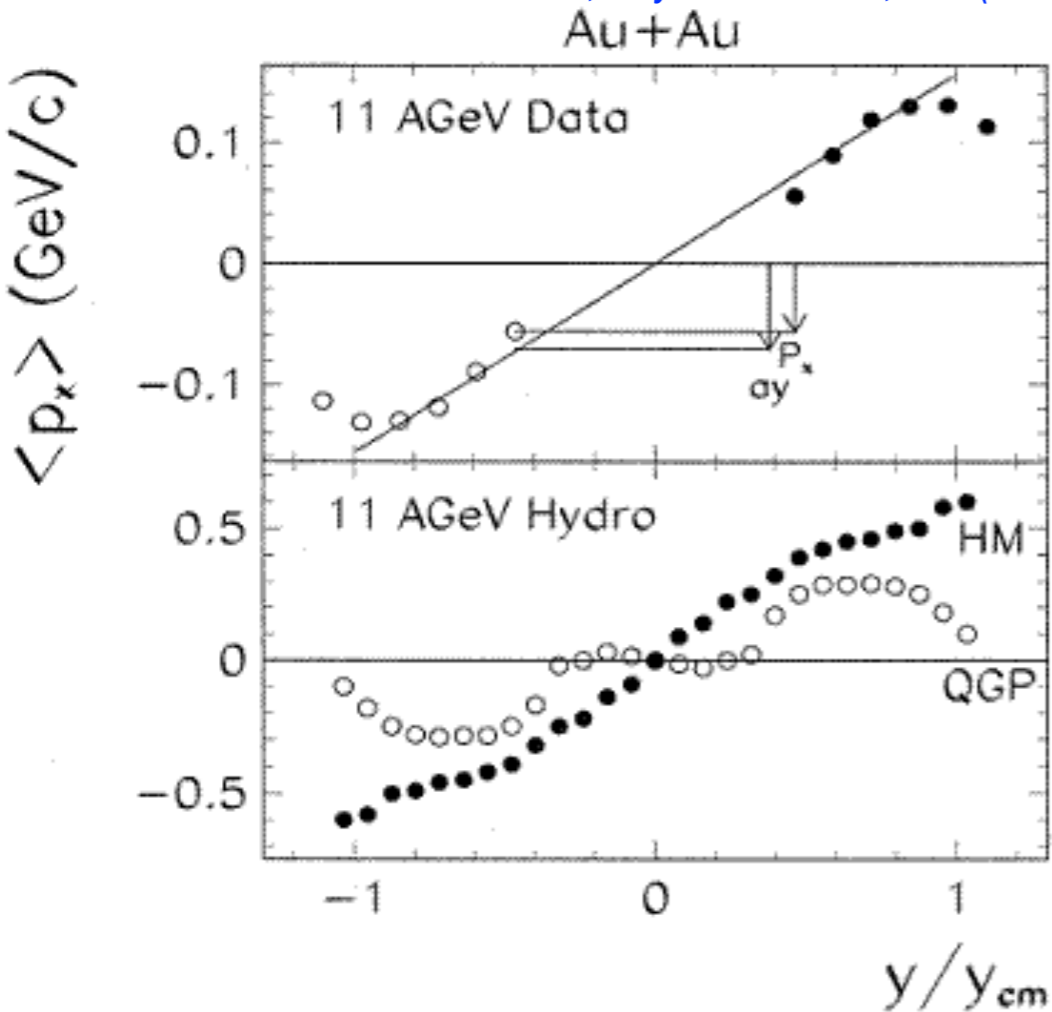
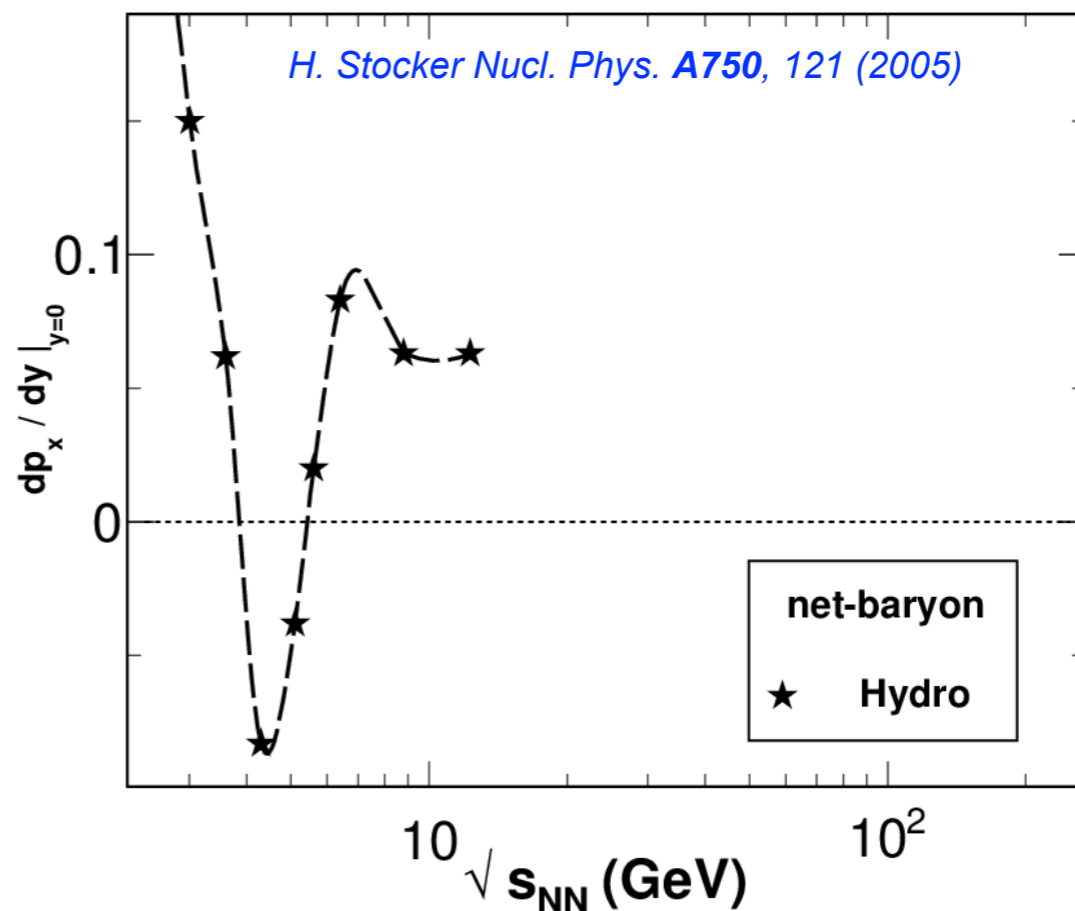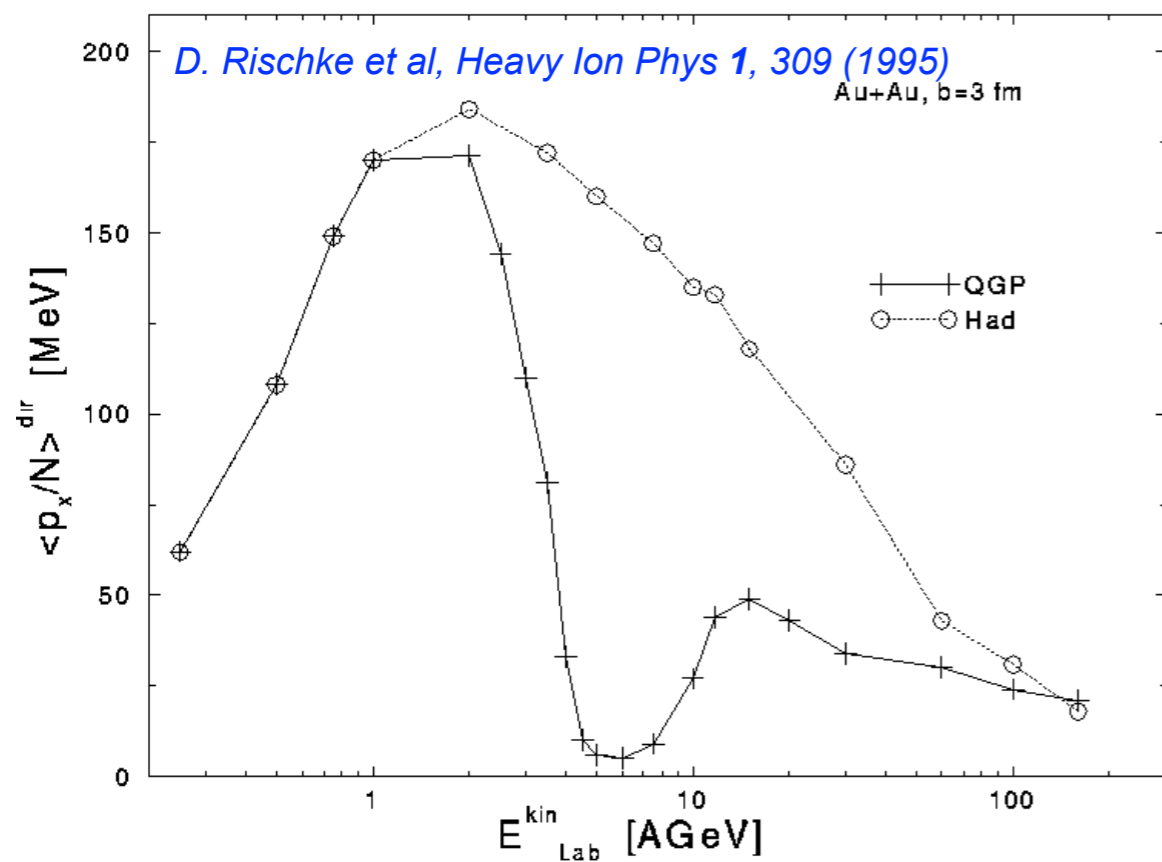*R. Snellings et al., Phys. Rev. Lett. **84**, 2803 (2000)*

*M. Bleicher et al., Phys. Lett .**B526**, 309 (2002)*

Models with QGP predicted a "wiggle"/ flat v_1 at mid-rapidity due to a 1st order phase transition

Models without QGP may also give a "wiggle" structure e.g., Baryon stopping + positive space-momentum correlation

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Directed flow and phase transition

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

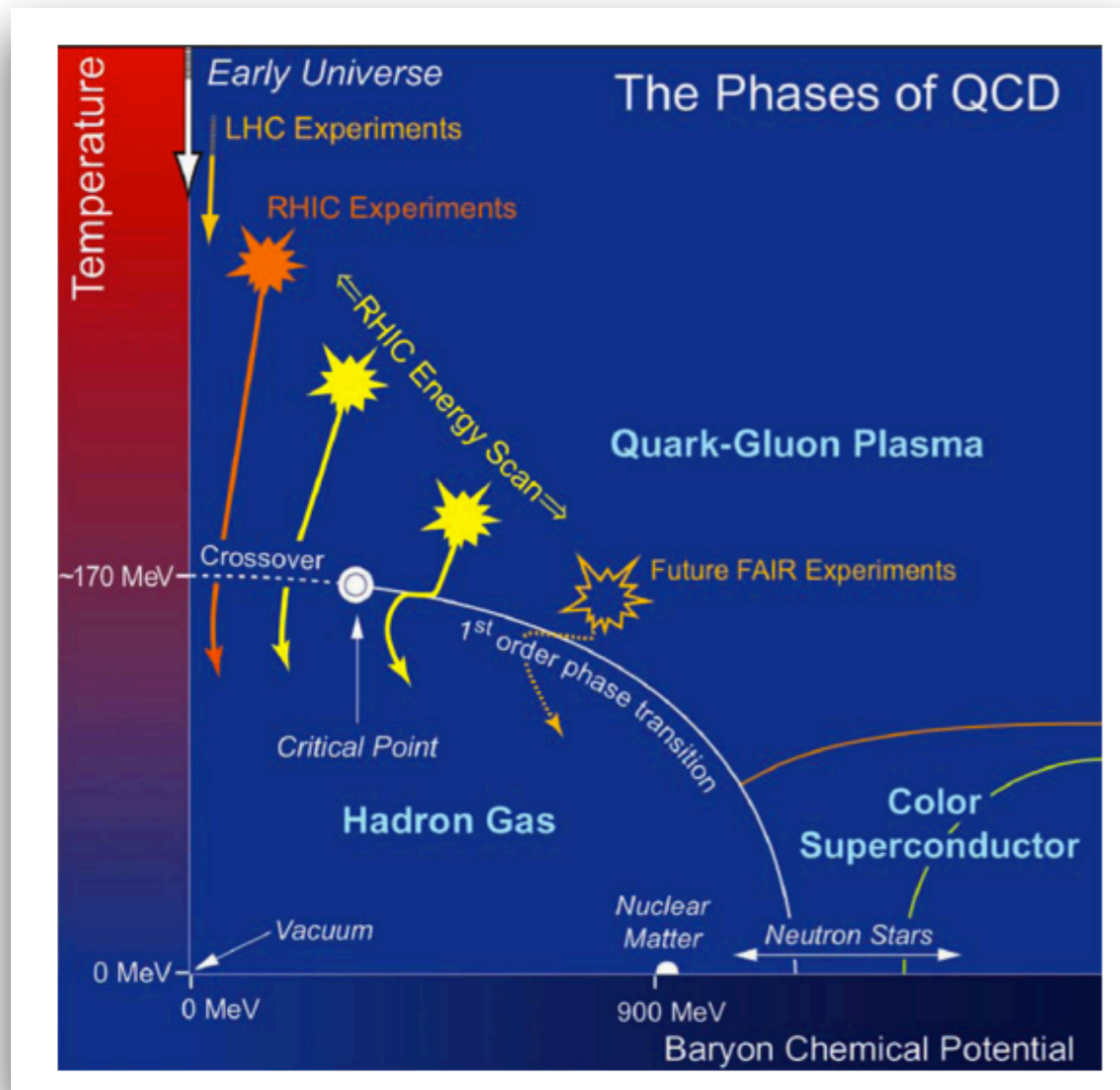*H. Stocker Nucl. Phys. **A750**, 121 (2005)*

Model calculations indicated that v_1-slope (specially for baryons) at mid-rapidity is sensitive to the EoS of the system

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

6

BES-I at RHIC

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
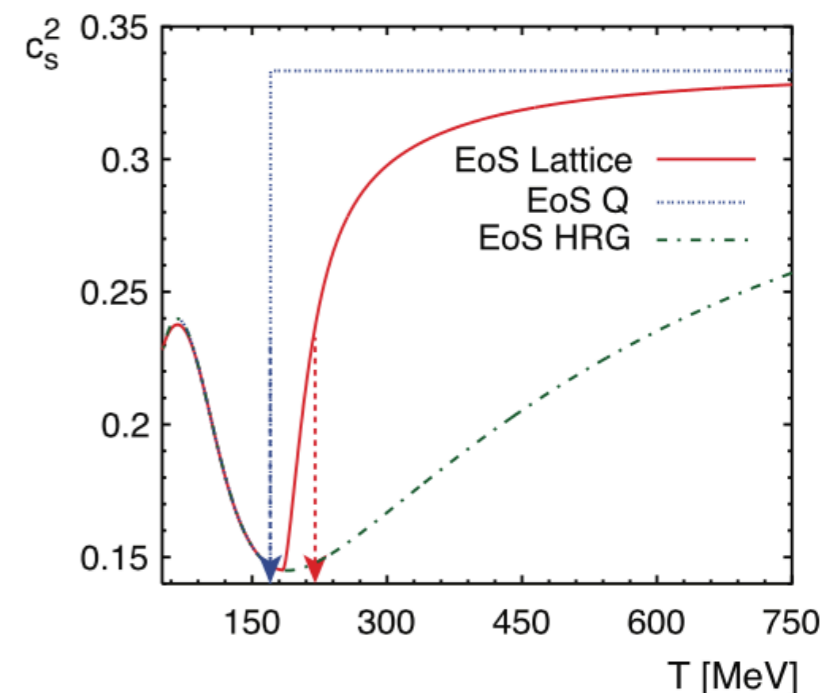
| Energy(GeV)	Events (M)	T (MeV)	mu_B(MeV)
7.7	4	140	422
11.5	12	152	316
14.5	18	156	264
19.6	36	160	206
27	70	162	156
39	130	164	112
62.4	67	165	73
200	350	166	25

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

✦ *Map turn-off of QGP signatures*

✦ *Search for Critical Point*

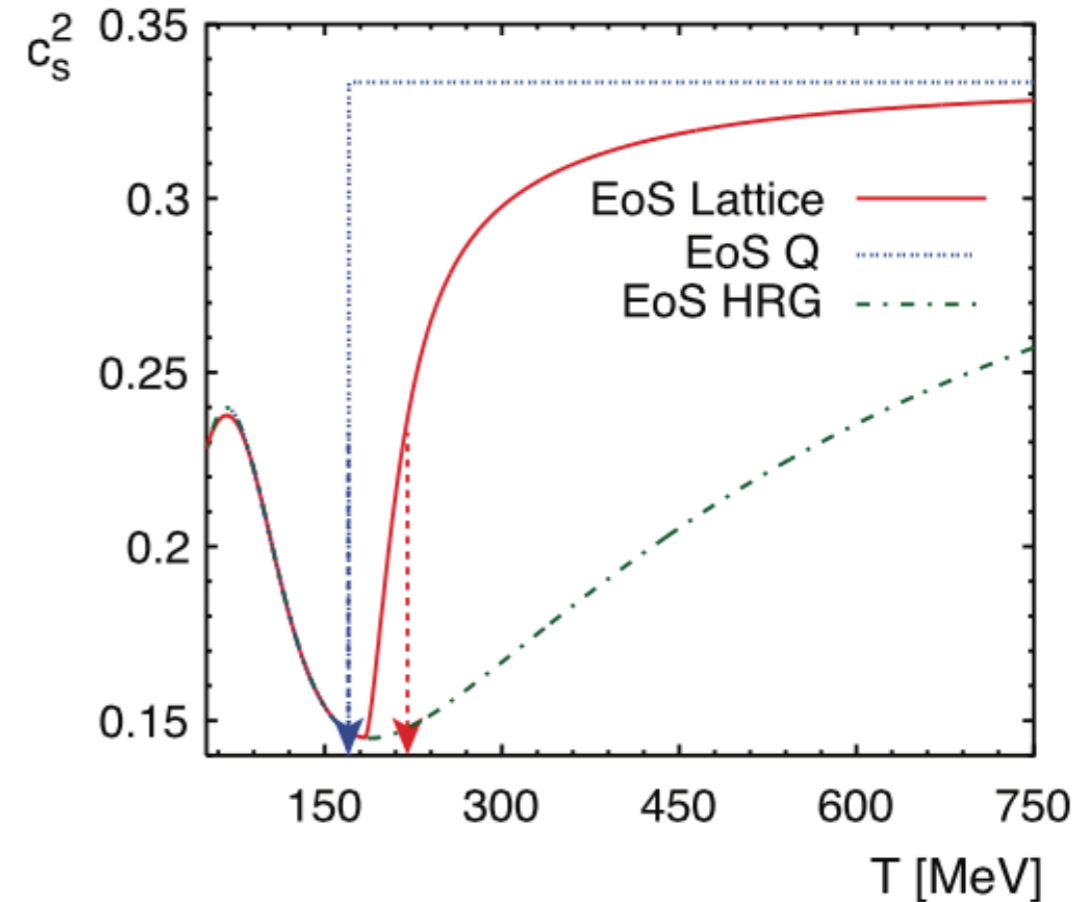✦ *Search for First-Order Phase Transition*

Directed flow (v_1) is a key observable to search for the signature of a 1st order phase transition

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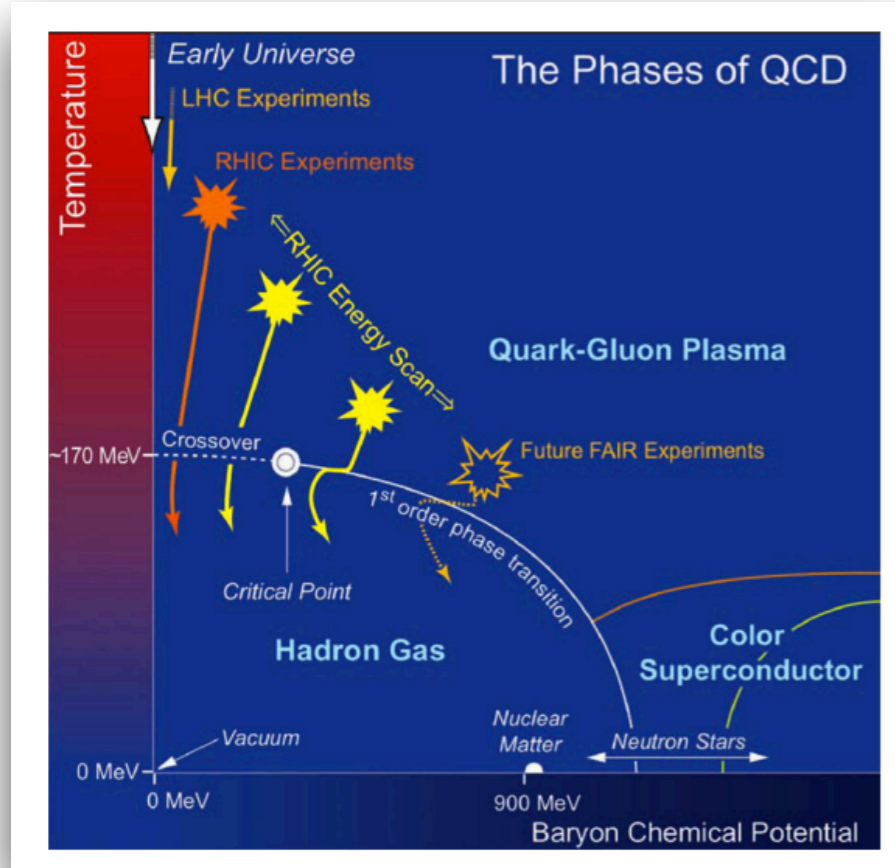
*R. Snellings, New J of Phys **13**, 055008 (2011)*
*P. Huovinen et al, Nucl Phys **A837**, 26 (2010)*

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
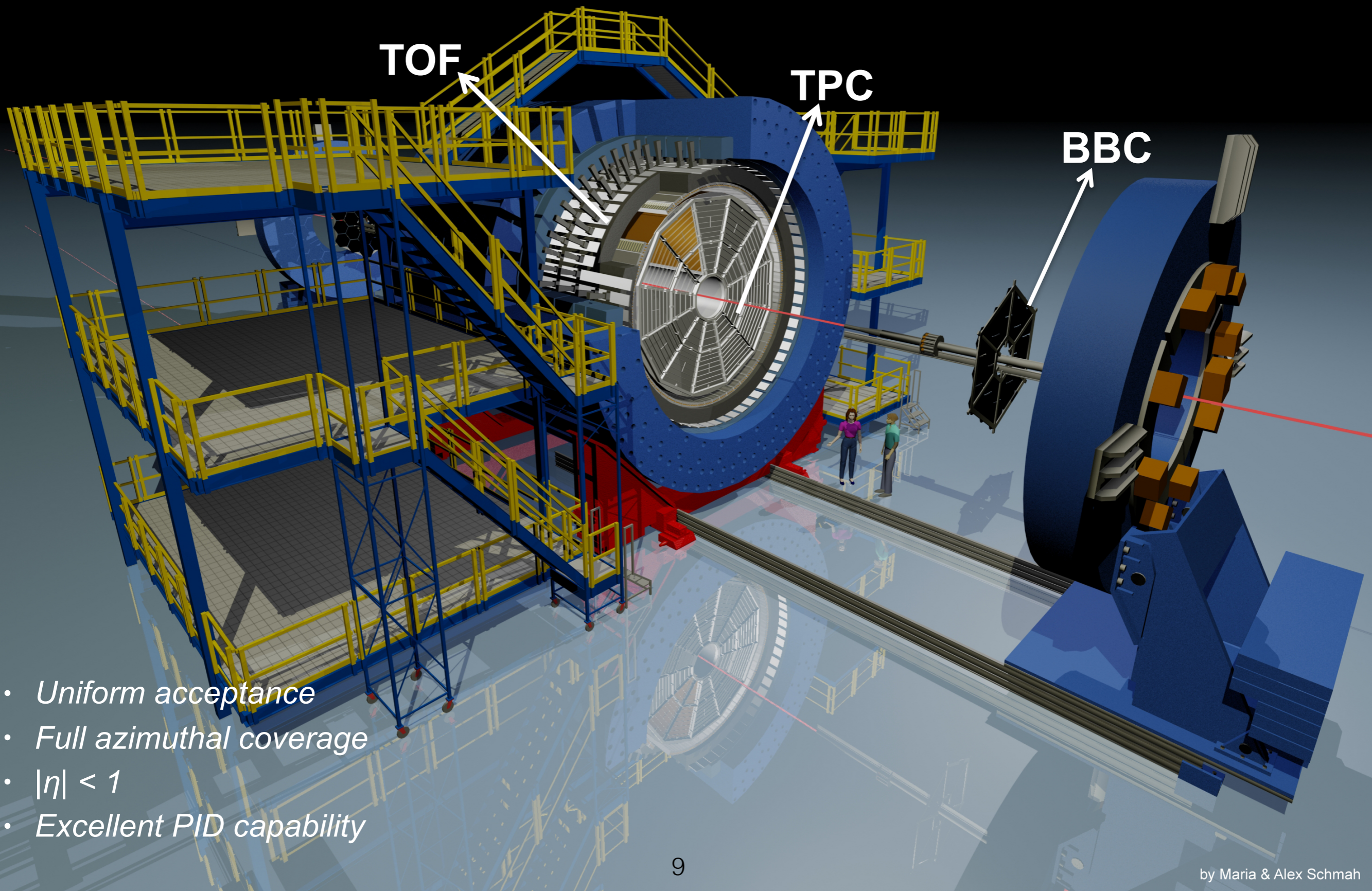
Large softening signature ➡ First-Order Phase Transition

Smaller softening signature ➡ Could have other explanations (e.g., crossover)
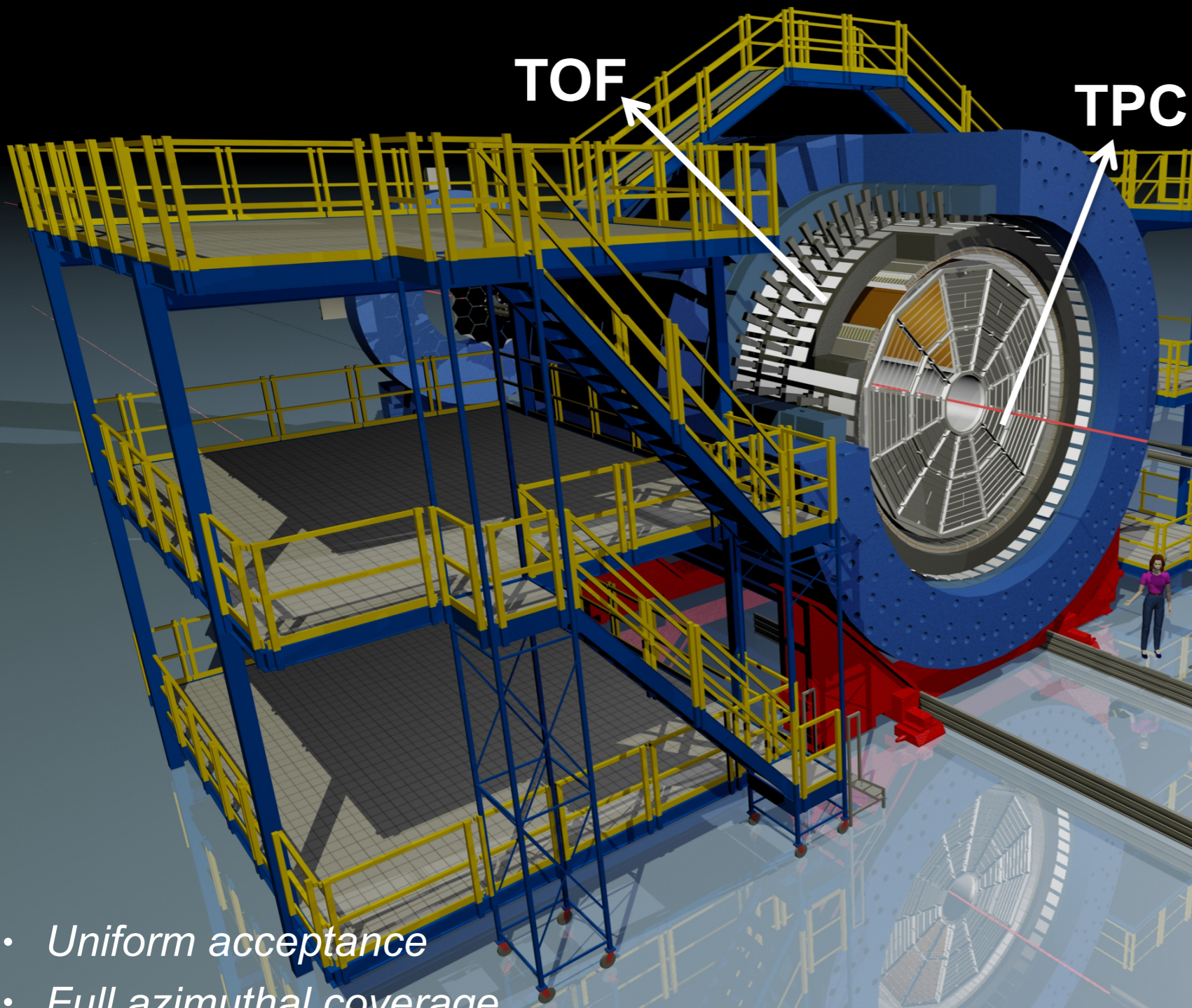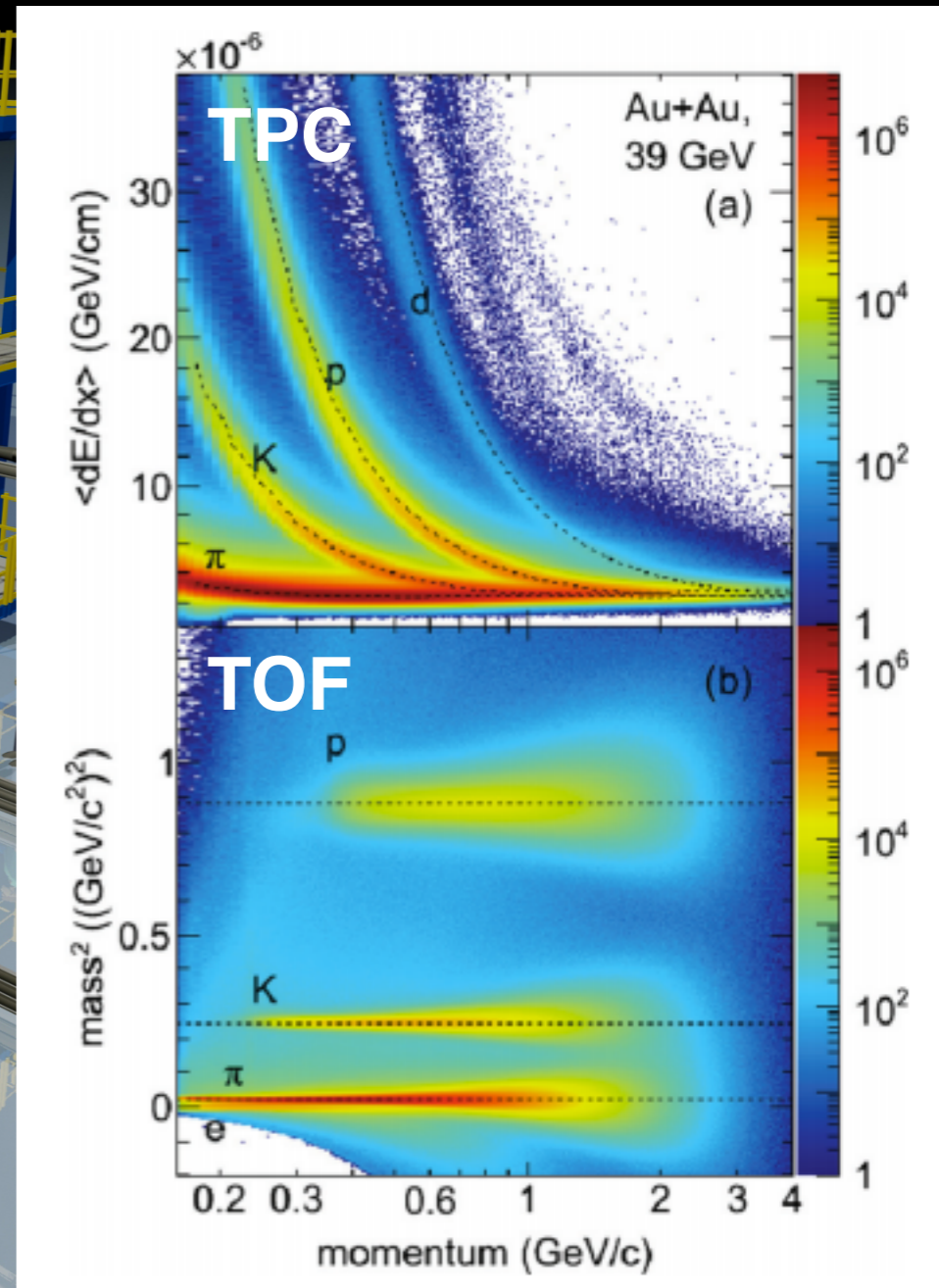
STAR Detector

TOF

TPC

BBC

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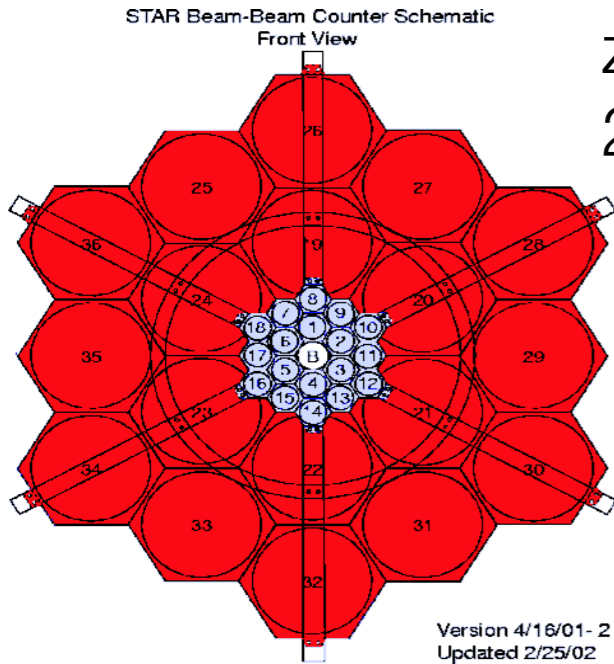- *$|\eta| < 1$*
- *Excellent PID capability*

STAR Detector

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

by Maria & Alex Schmah

STAR Detector

BBC

STAR Beam-Beam Counter Schematic
Front View

Version 4/16/01- 2
Updated 2/25/02

$z = \pm 3.7$ m
$2.1 > |\eta| < 5$

ZDC-SMD

Aluminum box to support the phototube and cable interconnects. Side and end views are shown.

SMD WLS fibers

SMD scintillator

$z = \pm 18.25$ m
$\theta < 2$ mrad

STAR Preliminary

BBC
- 7.7 GeV
- 11.5 GeV
- 14.5 GeV
- 19.6 GeV
- 27 GeV
- 39 GeV
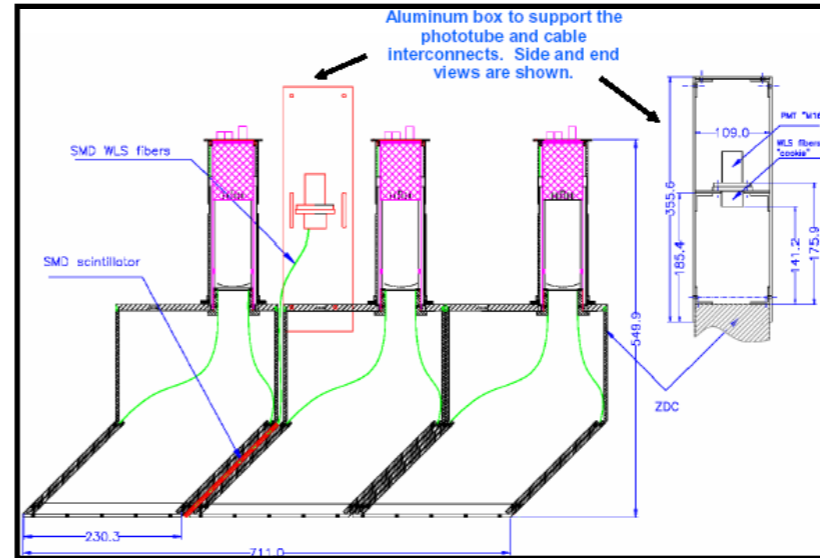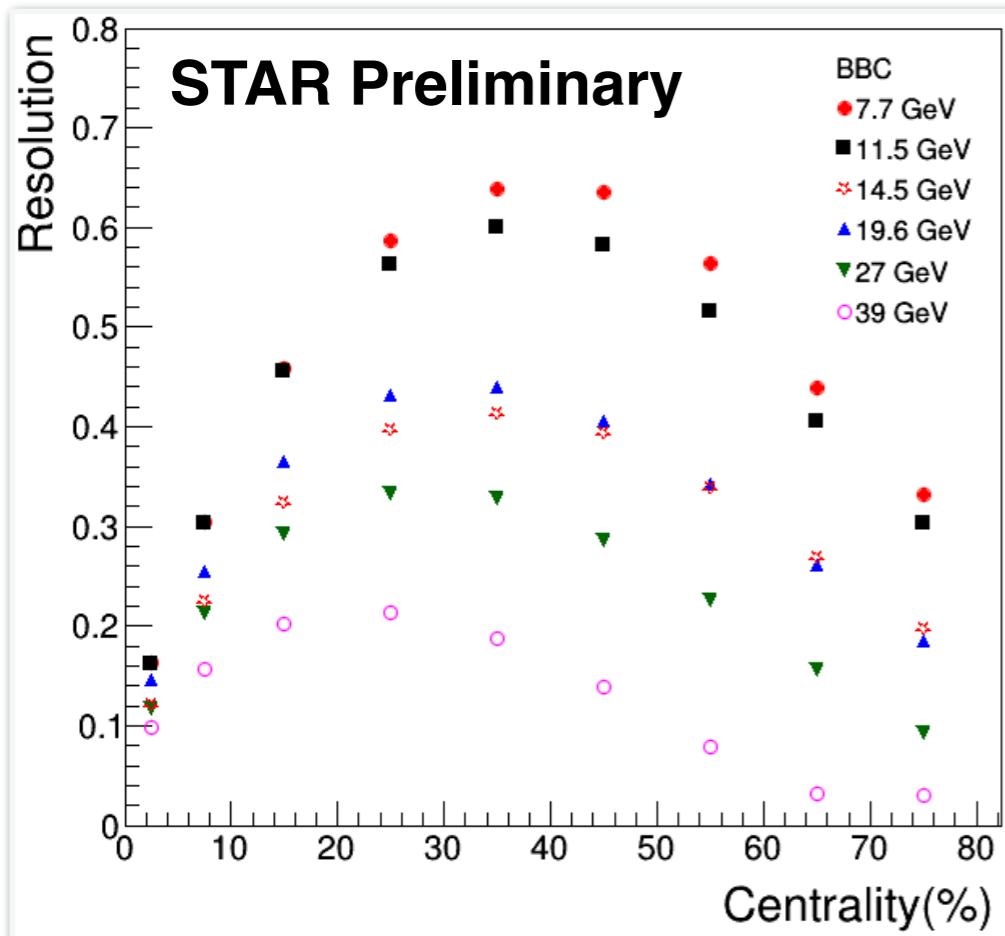
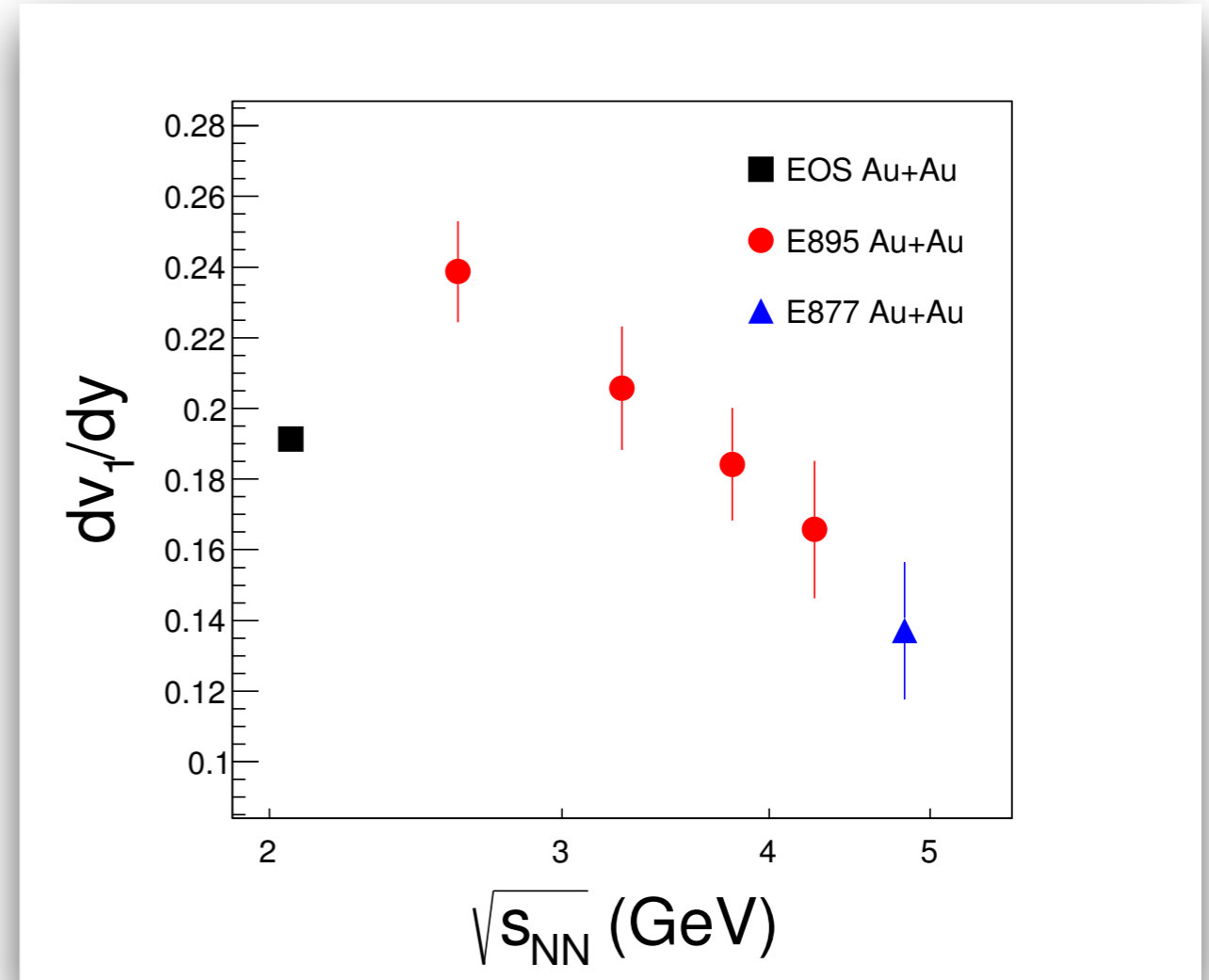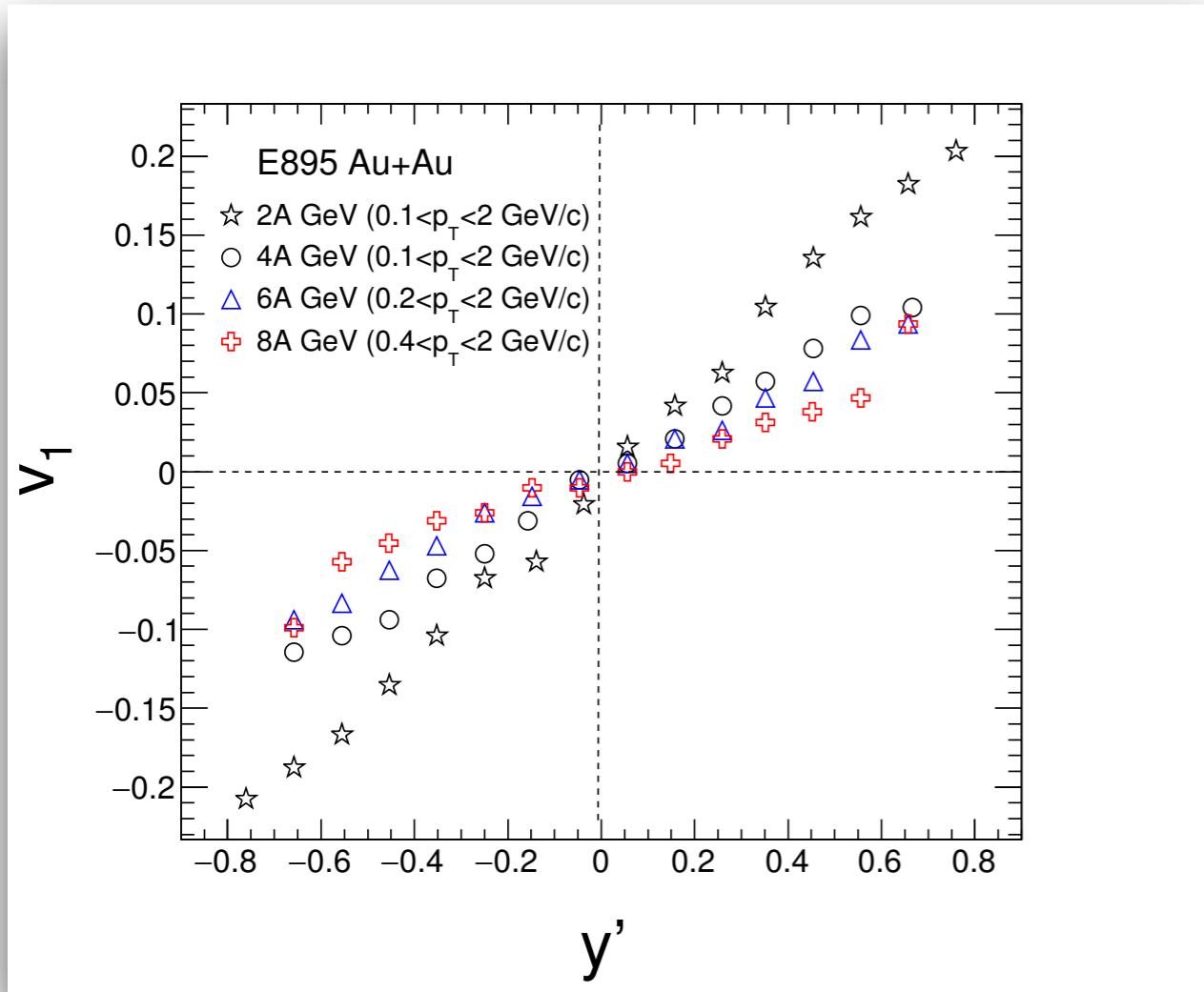increasing energy

- 1st order event plane estimated using BBC (7.7 - 39 GeV) ZDC (62.4, 200 GeV)

- v_1 signal significant at forward rapidity

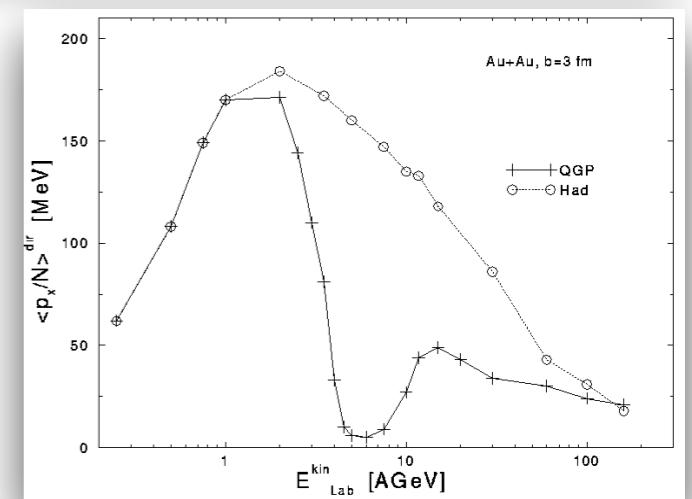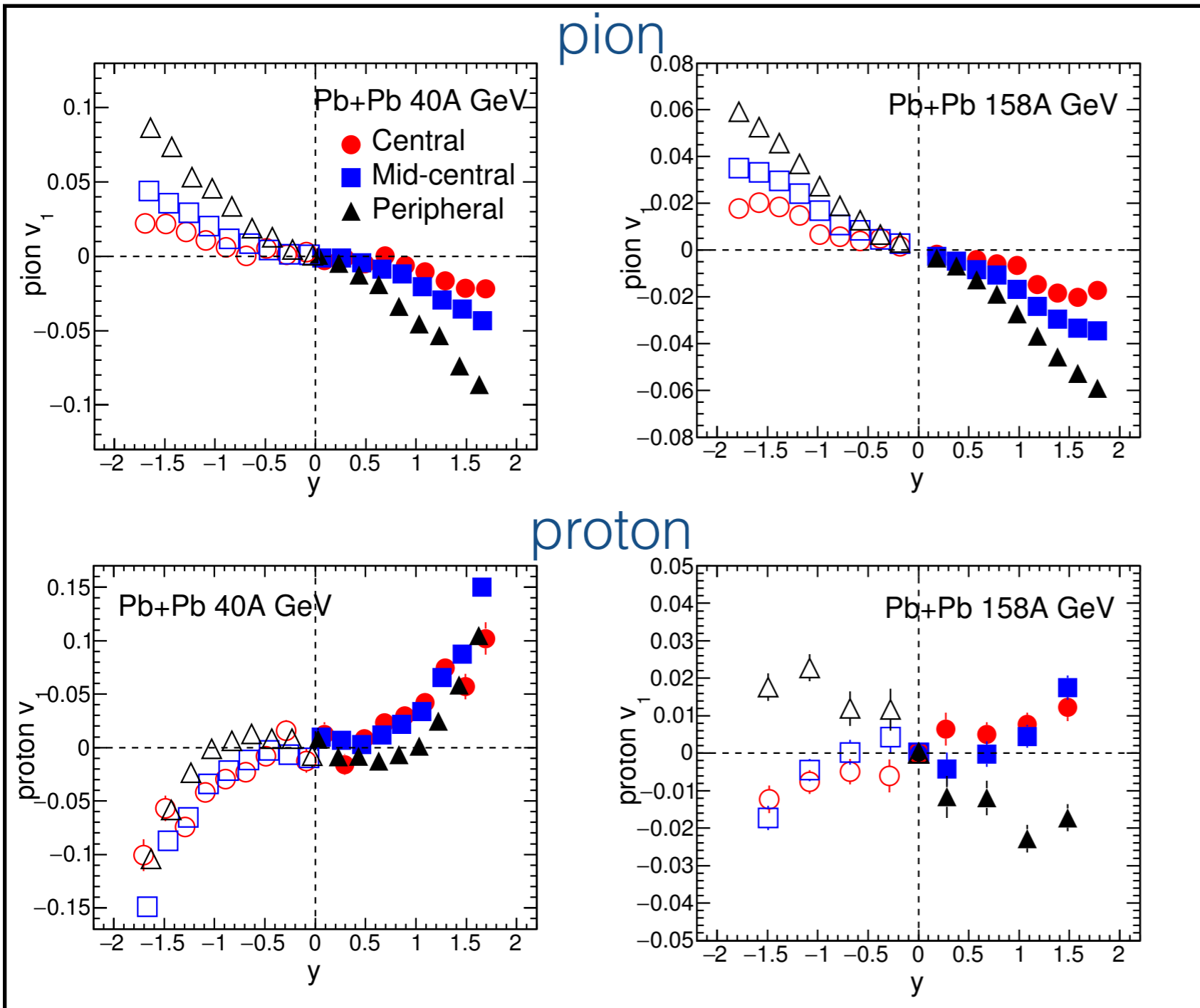- Large η gap with TPC reduces non-flow effects

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Results from AGS

- positive dv_1/dy of protons for all energies
- no dip observed at AGS around $\sqrt{s_{NN}} \sim 3.5$ GeV

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Results from SPS

pion

proton

- $(dv_1/dy)_{pion}$ ~negative for 40A, 158A GeV

- $(dv_1/dy)_{proton}$ ~positive 40A GeV, all centrality

  158A GeV, central/mid central

- $(dv_1/dy)_{proton}$ ~negative 158A GeV, peripheral

Shadowing effect from spectators in peripheral collisions
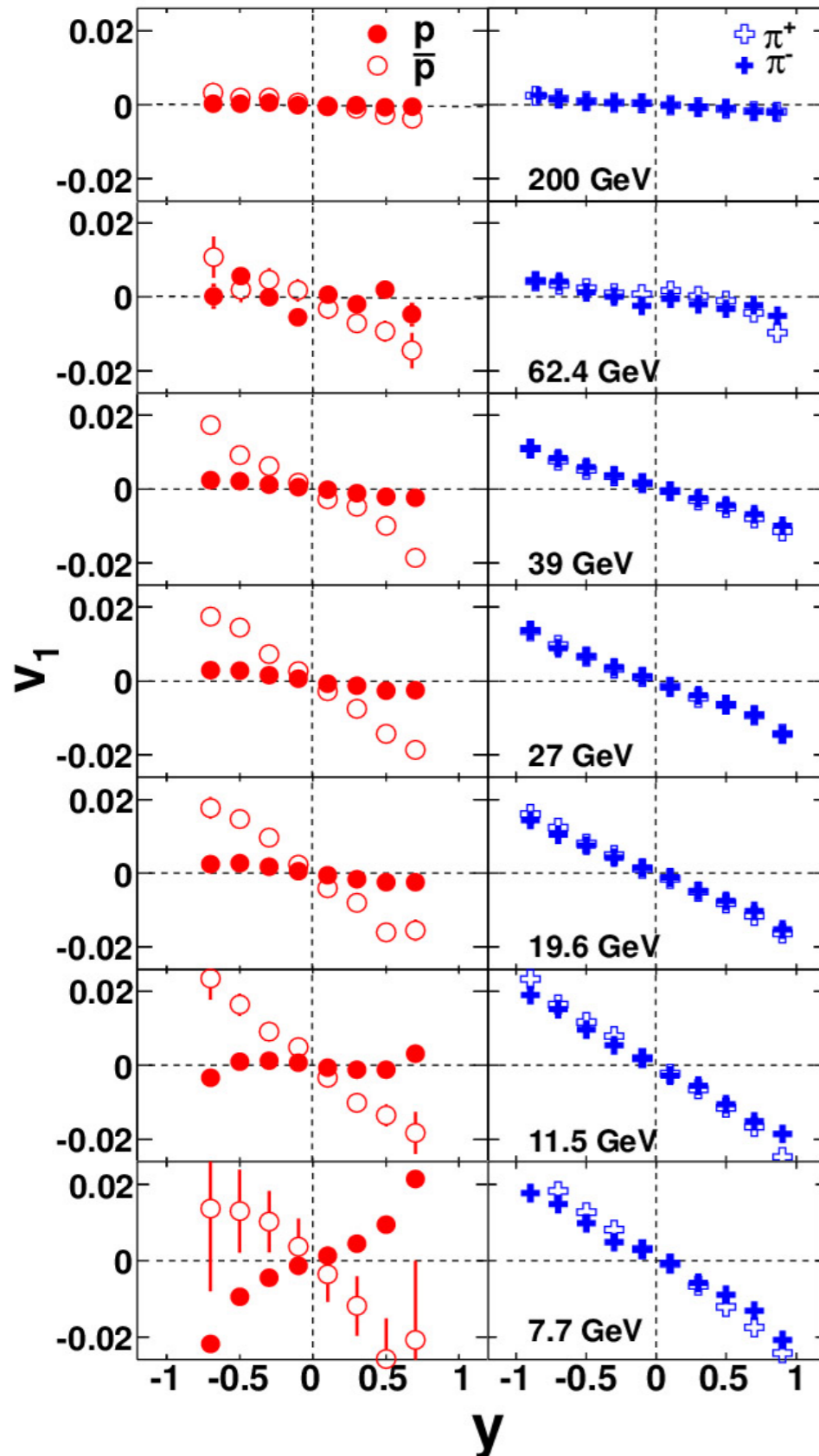
13

Results from RHIC

Charged hadron v_1
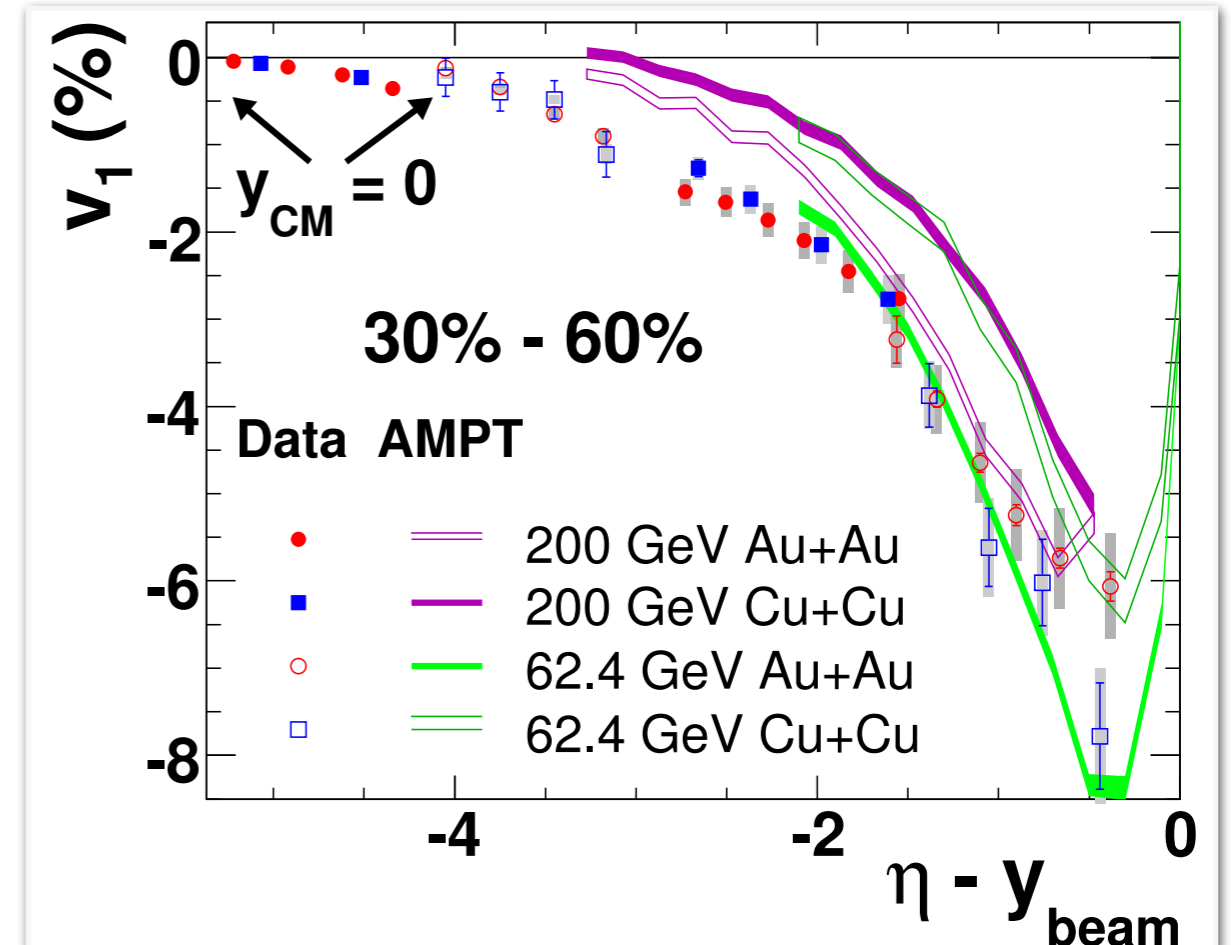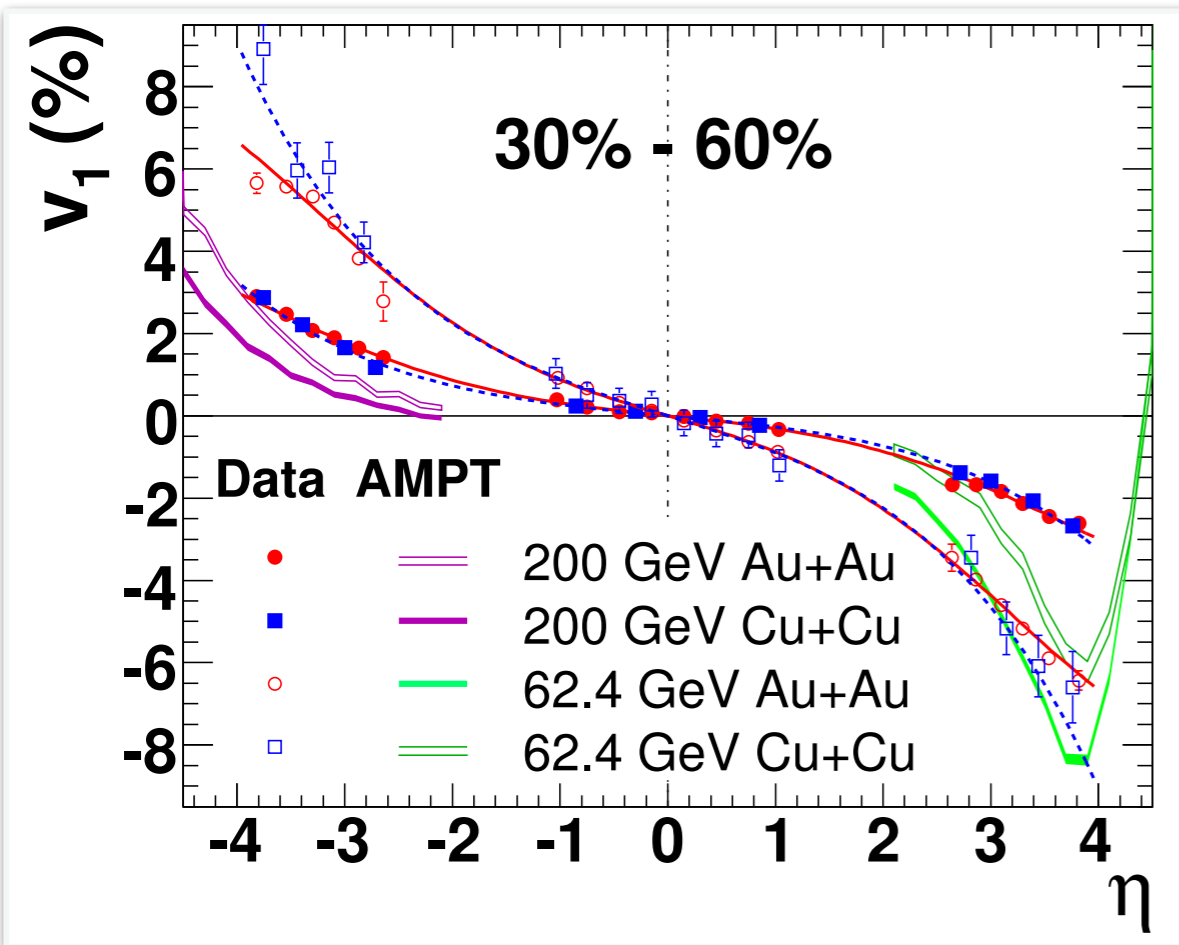
- v_1 is independent of system size (Au+Au ~ Cu+Cu)
- v_1 shows limiting fragmentation behavior

System size behavior can be explained by Hydro+tilted source

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Energy dependence of proton and pion v_1

- $(dv_1/dy)_{pion}$ ~negative for $\sqrt{s_{NN}} = 7.7\text{-}200$ GeV

- $(dv_1/dy)_{proton}$ ~negative $\sqrt{s_{NN}} >= 11.5$ GeV changes sign at $\sqrt{s_{NN}} = 7.7$ GeV

- $(dv_1/dy)_{antiproton}$ ~negative for $\sqrt{s_{NN}} = 7.7\text{-}200$ GeV

v_1-slope extracted by fitting a cubic function

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Energy dependence of proton and pion v_1
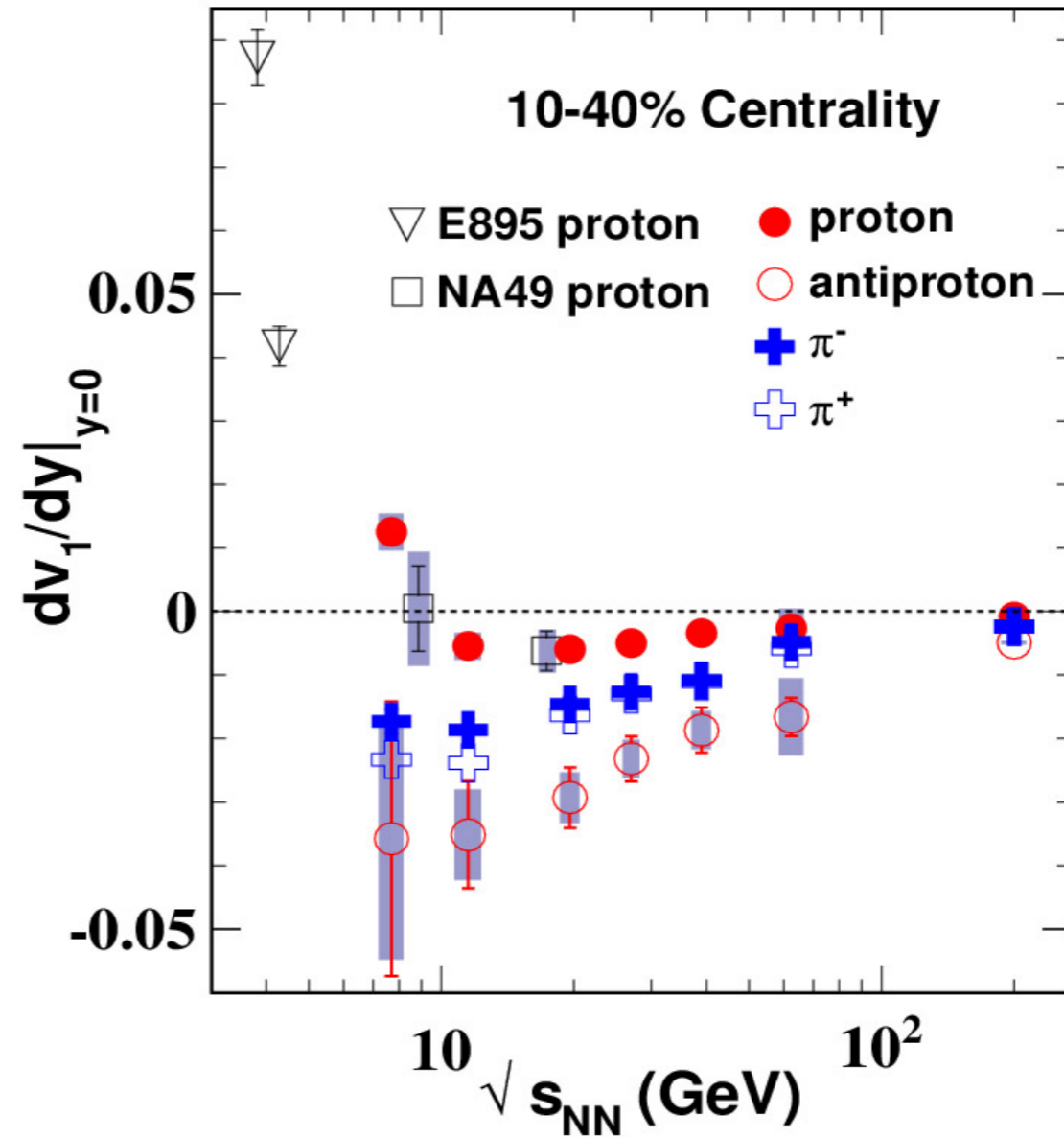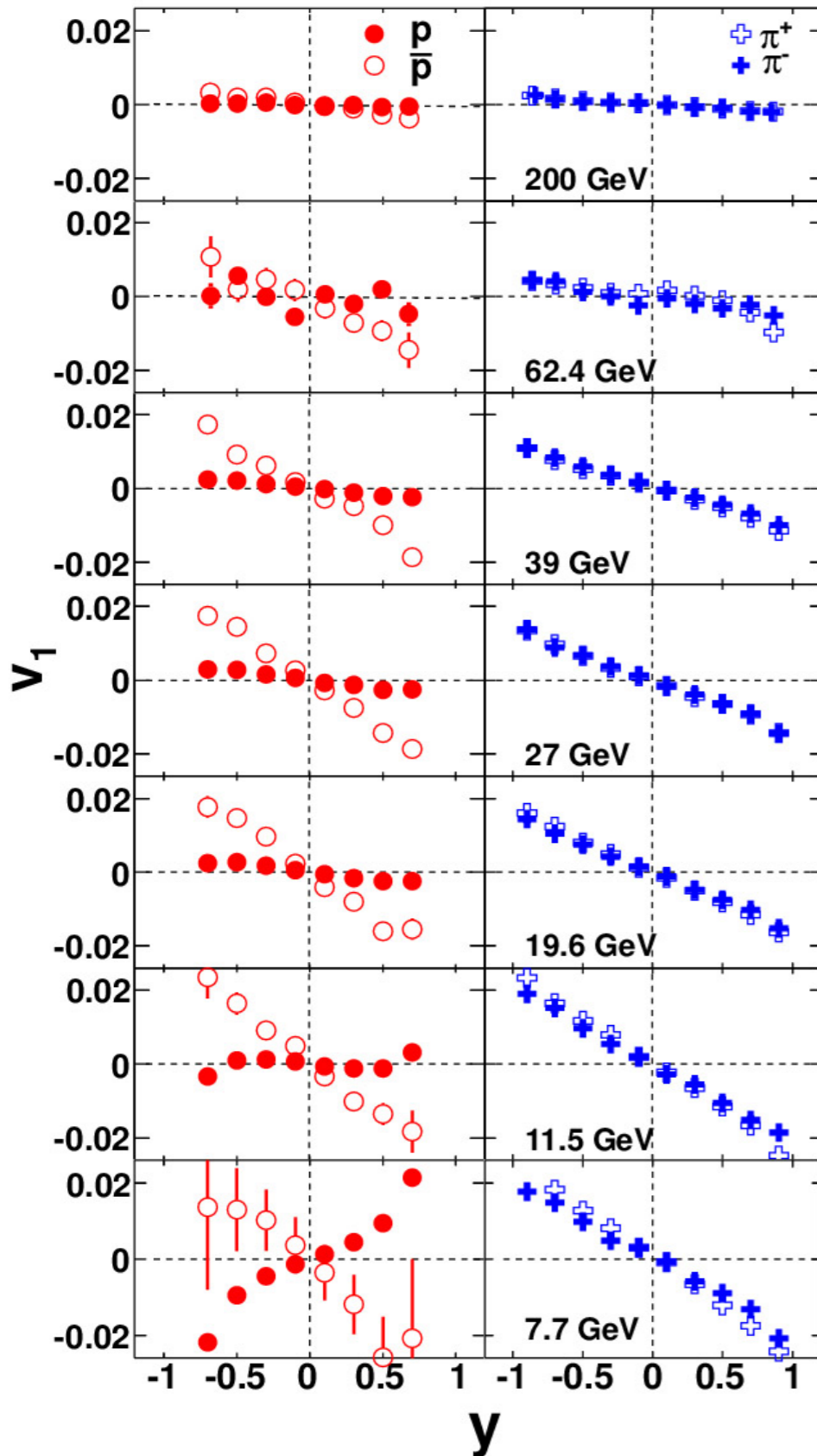
- Trend observed by STAR inline with NA49 and E895 data

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Energy dependence of proton and pion $v_1(y)$

AMPT
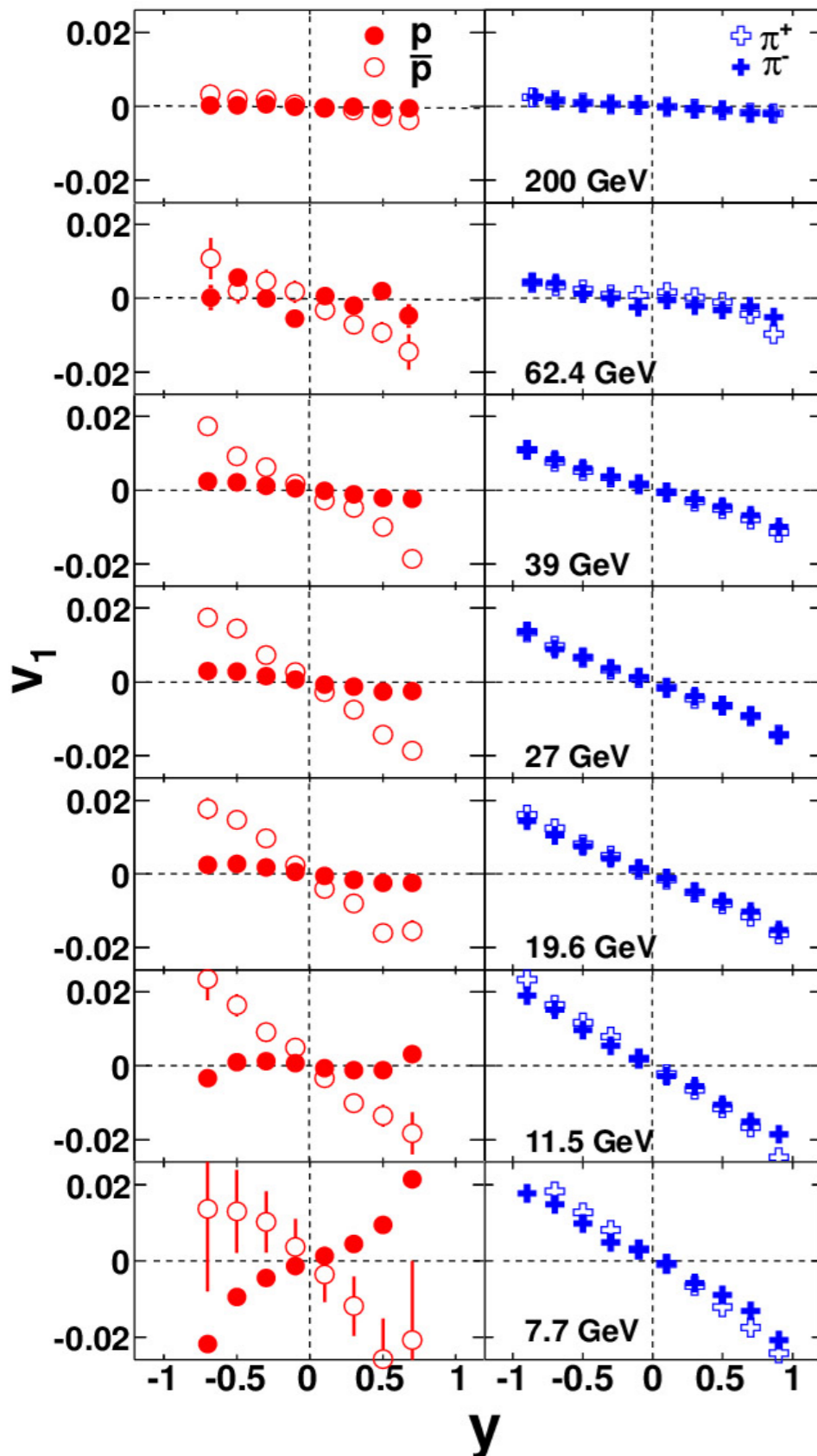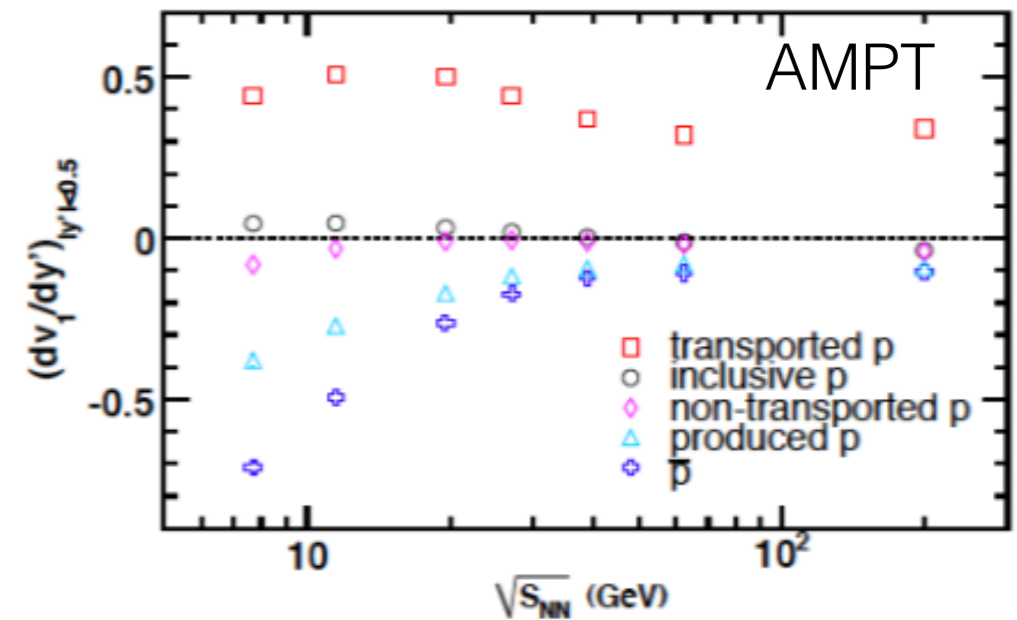
- Observed proton v_1 has contributions from produced and transported quarks

To disentangle these contributions, we define

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

$F = dv_1/dy, \quad r_1(y) = anti\text{-}p/p$

proxy for transported protons

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Energy dependence dv$_1$/dy
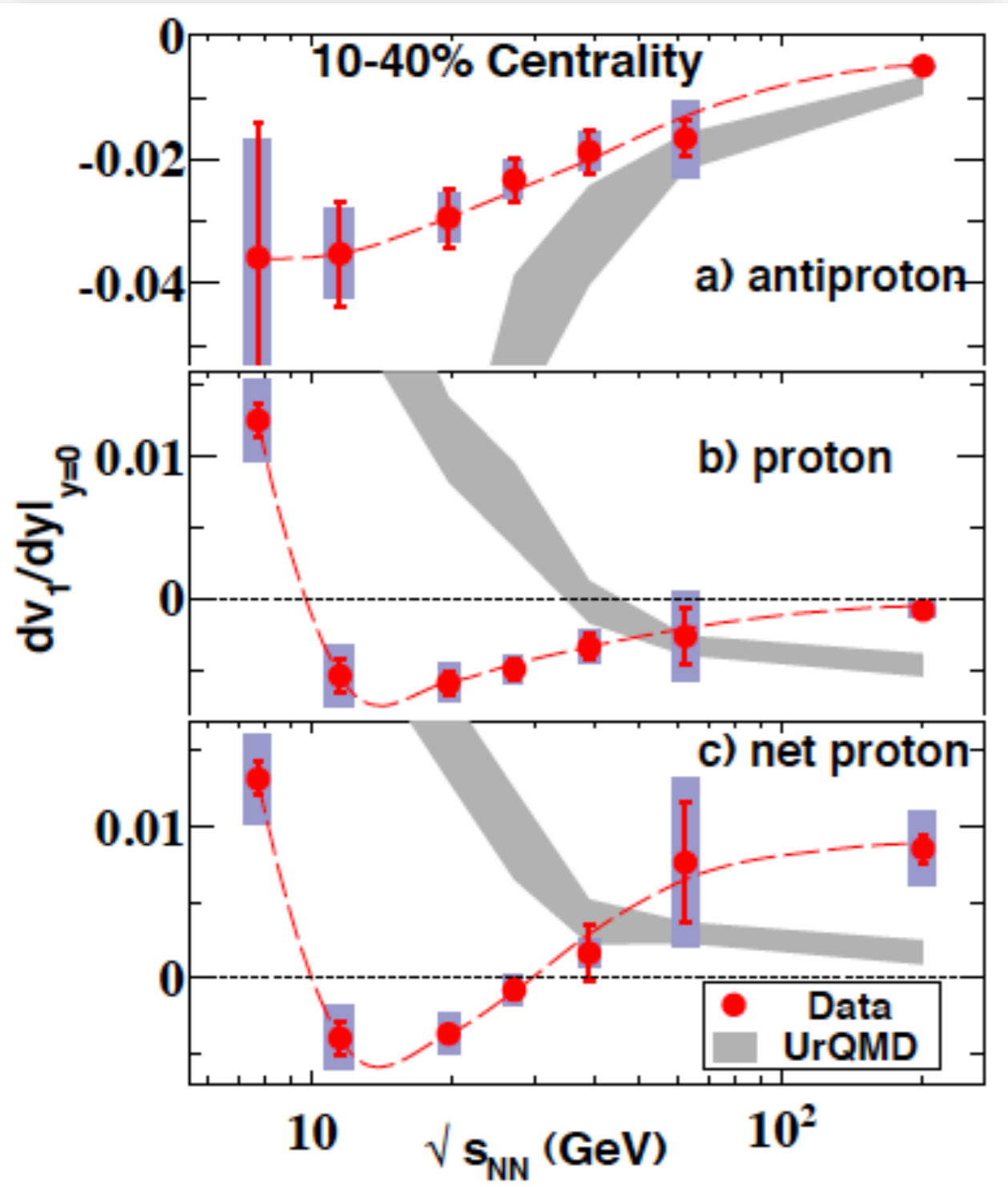
$$F_p = r_1 F_{anti-p} + (1-r_1) F_{net-p}$$

$F = dv_1/dy$, $r_1(y) = anti-p/p$

Energy dependence dv_1/dy
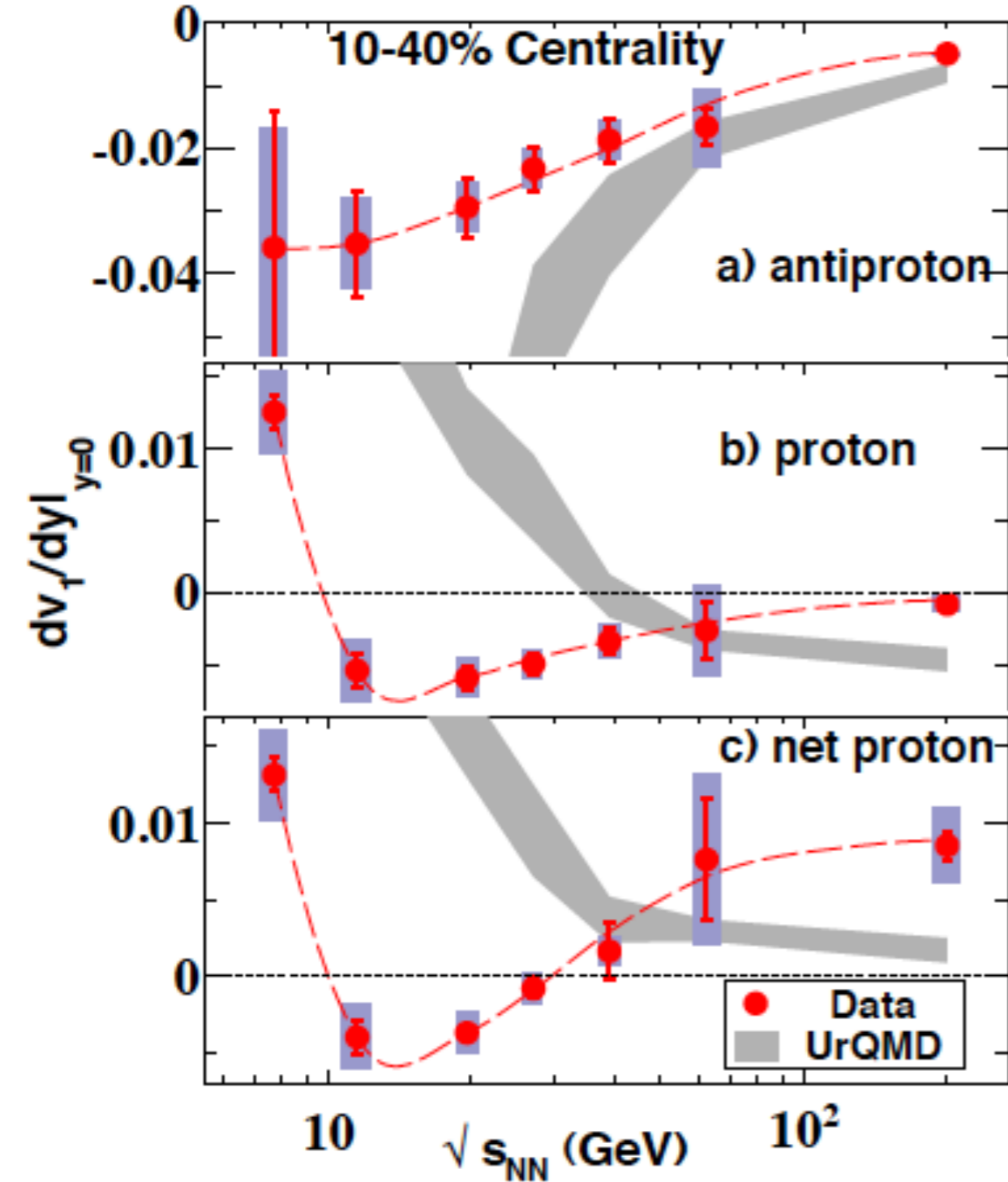
Qualitative resemblance to 3-fluid hydro calculations with 1st order PT
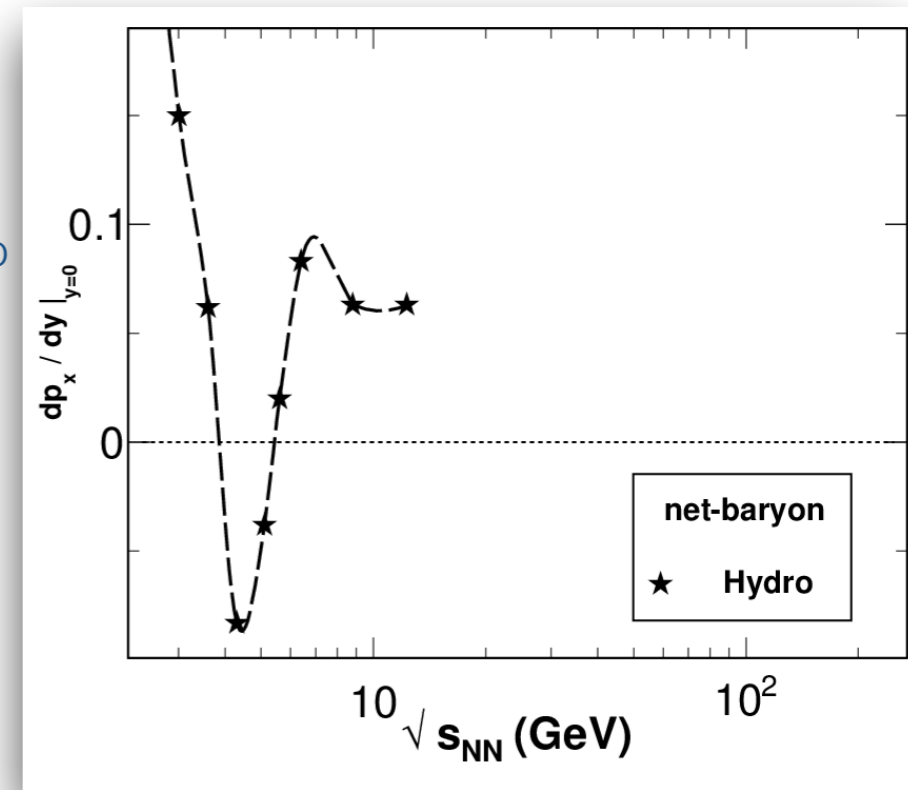
Minimum in net-proton dv_1/dy with double sign change → Softening of EoS (?)

Energy dependence dv_1/dy with models
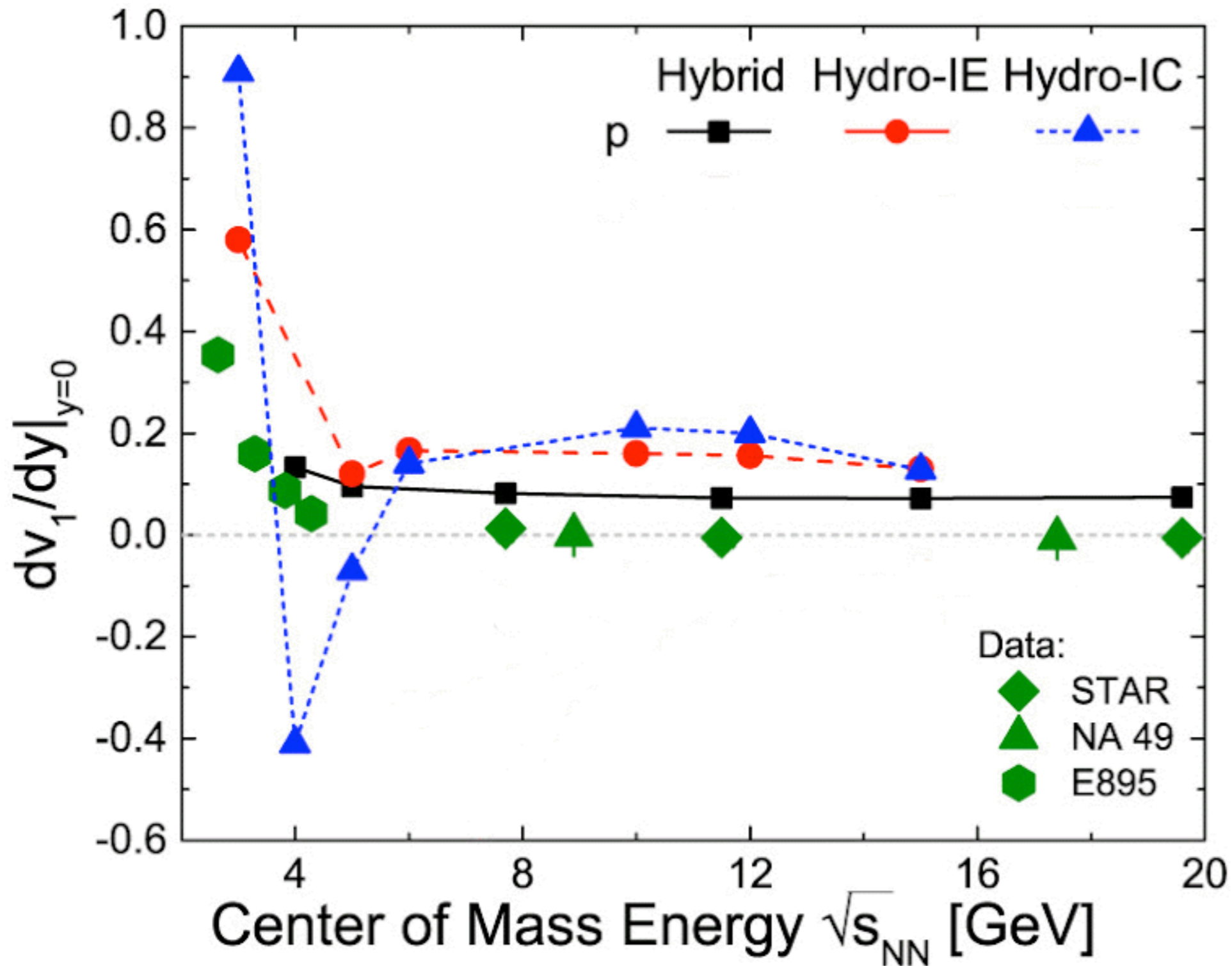
Energy dependence dv_1/dy with models
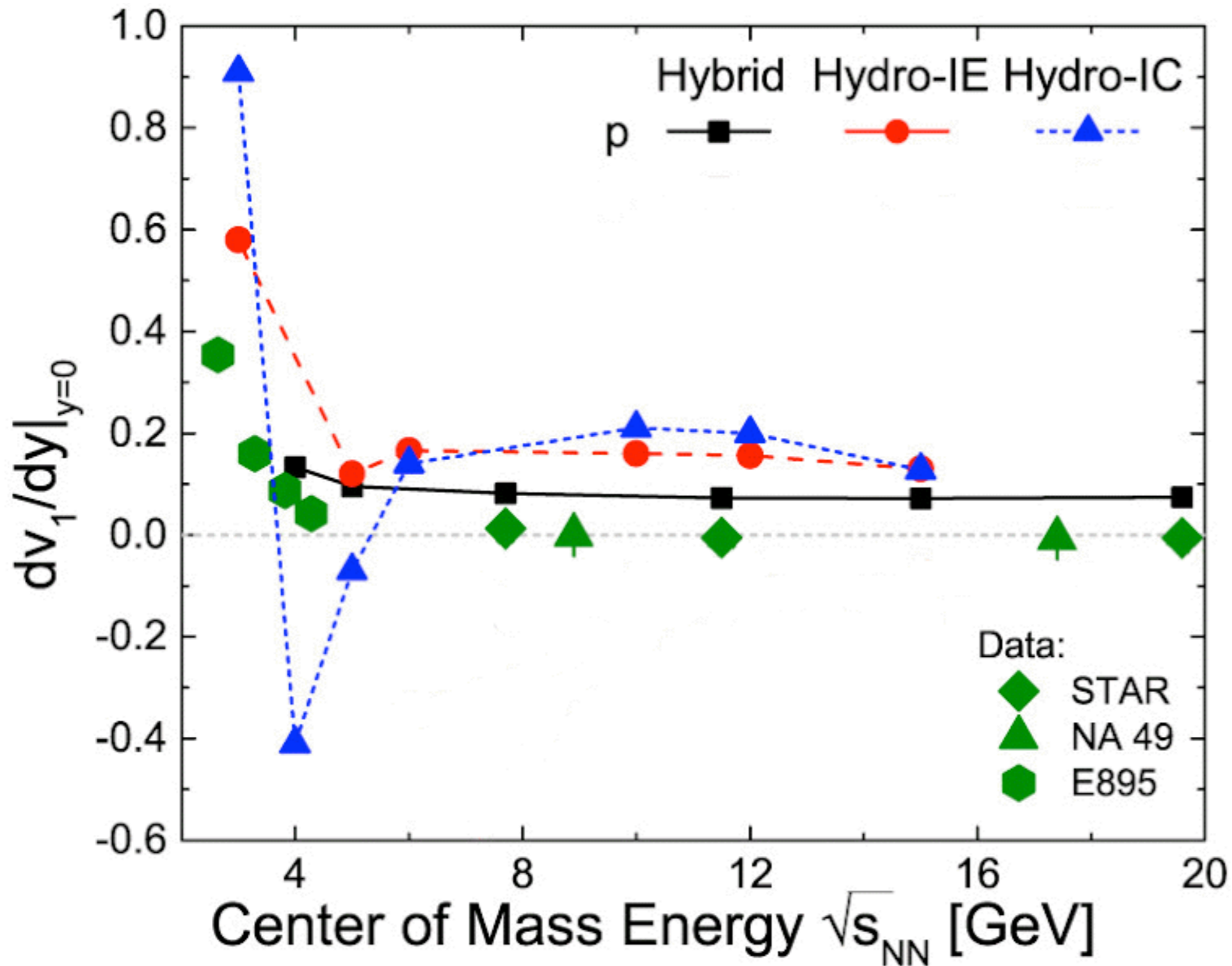
"All models severely underestimate the data"

Energy dependence dv₁/dy with models

3 FD: Y. Ivanov et al., PRC **91,** 024915 (2015)
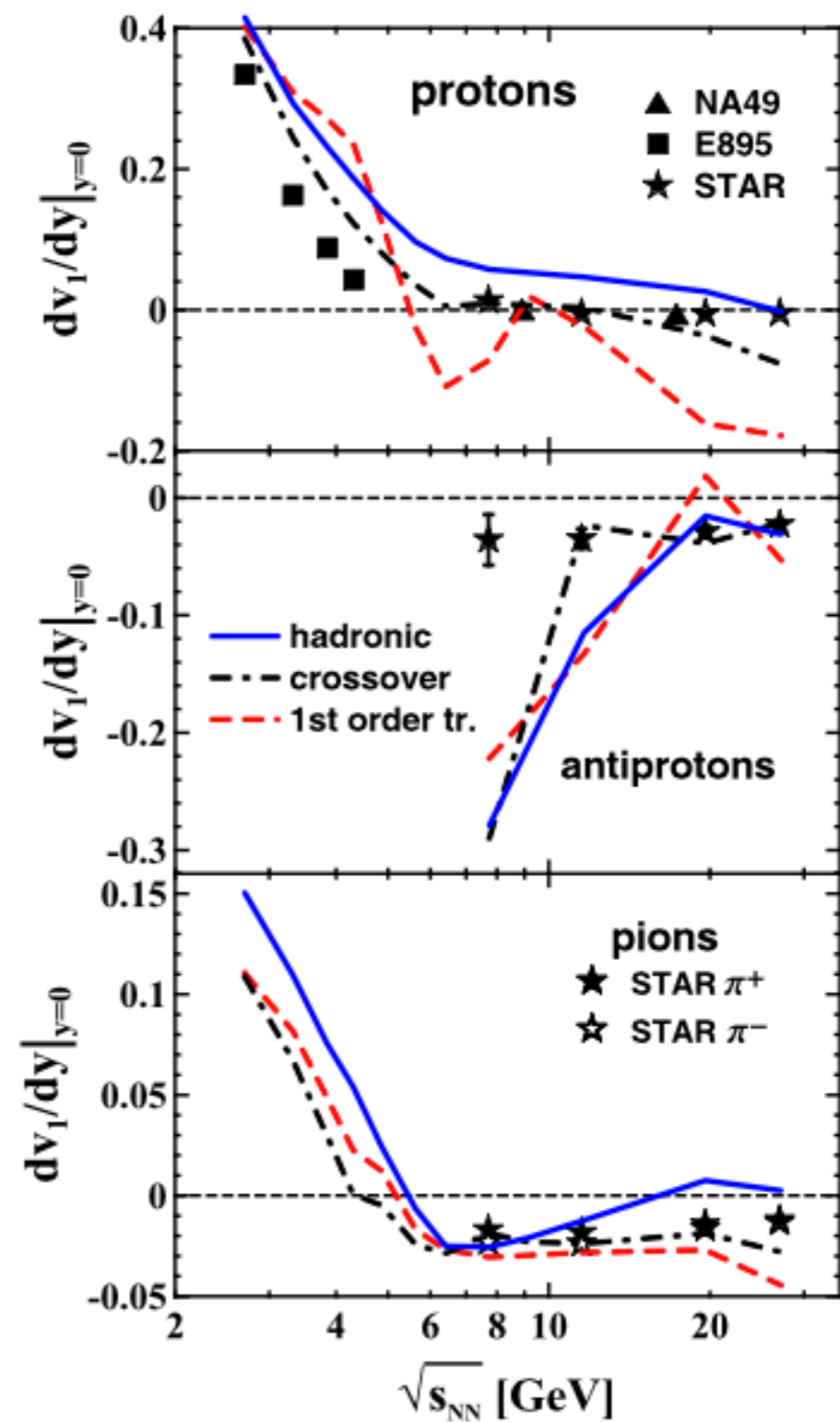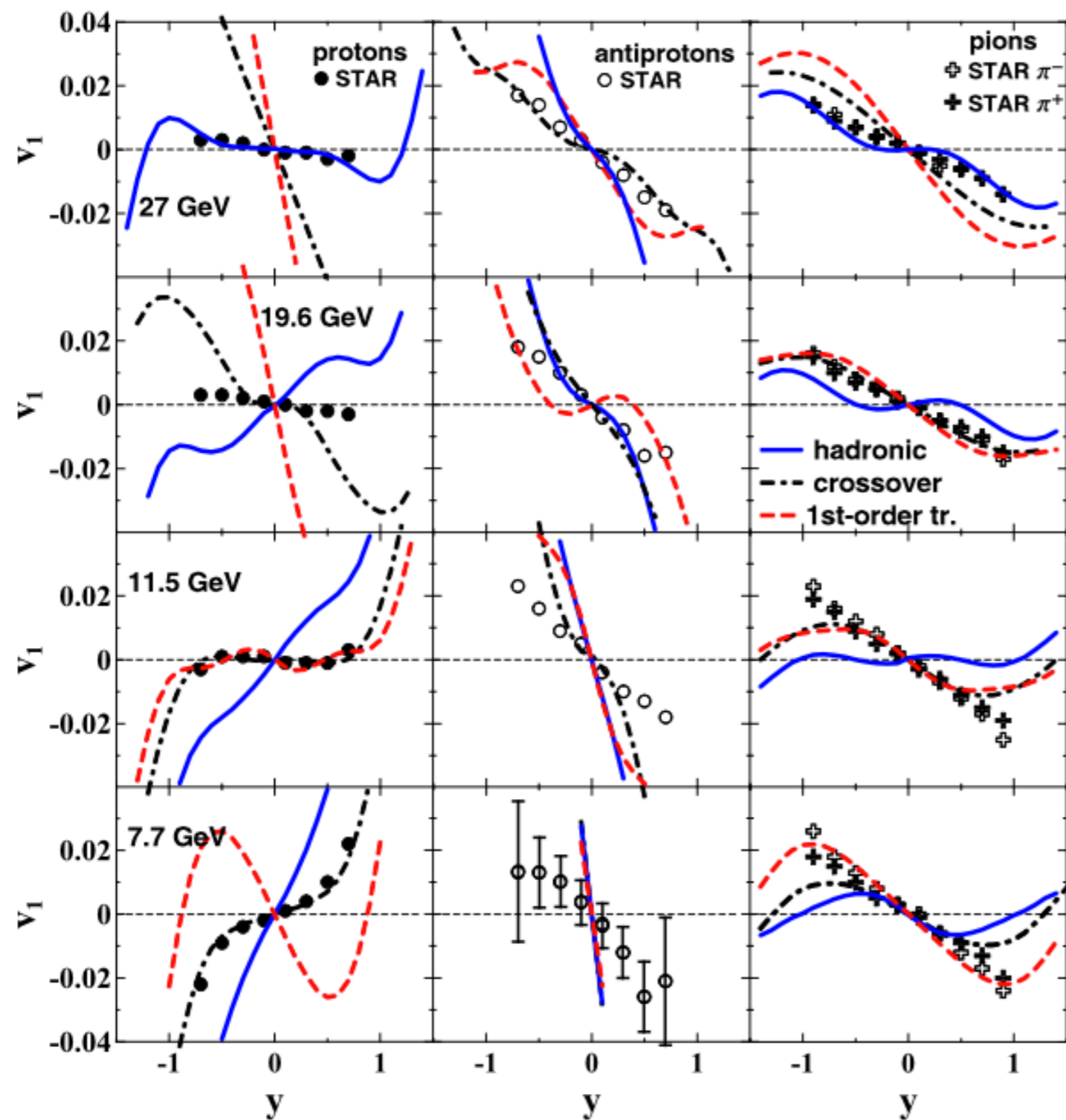
Energy dependence dv₁/dy with models
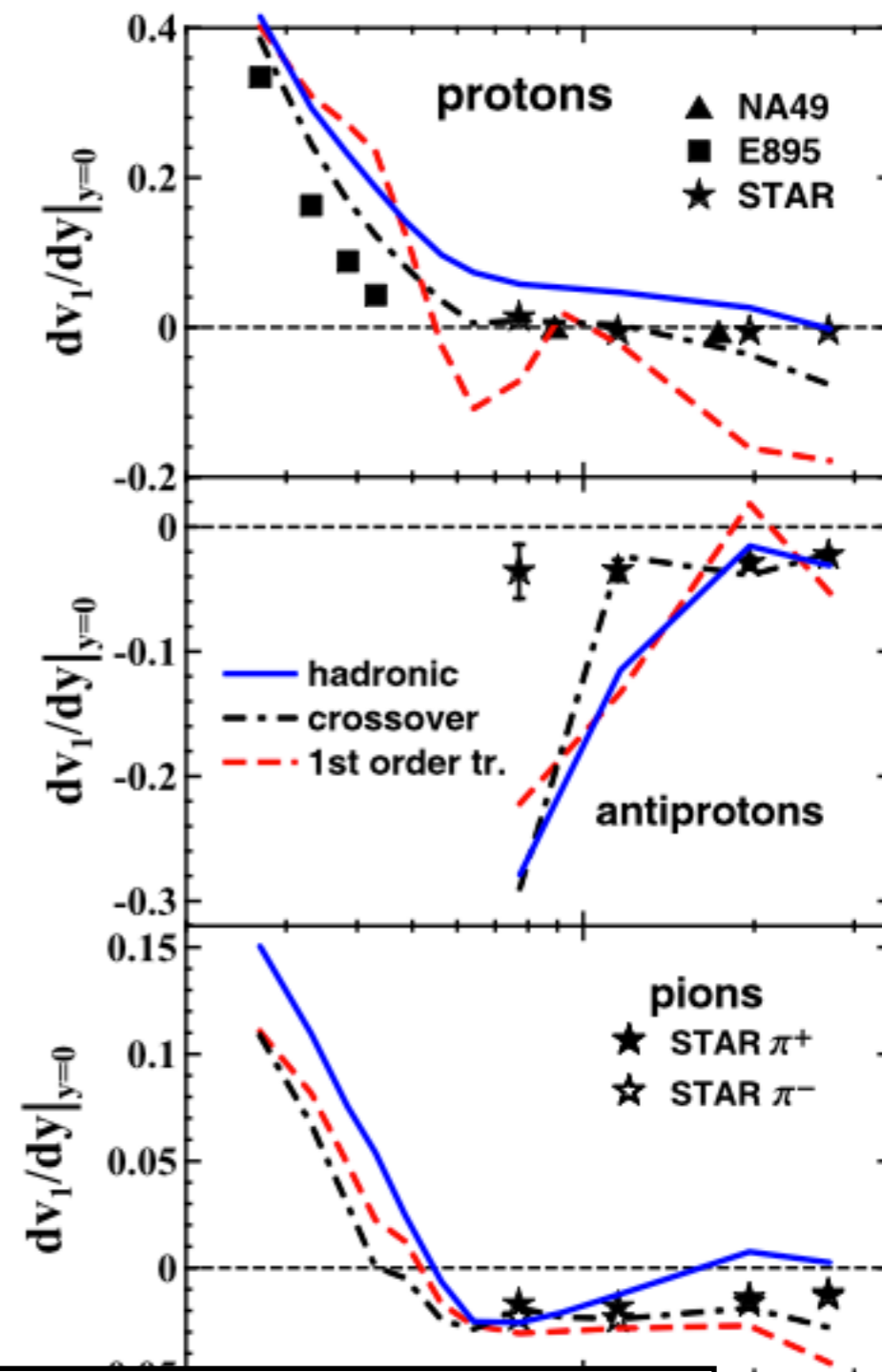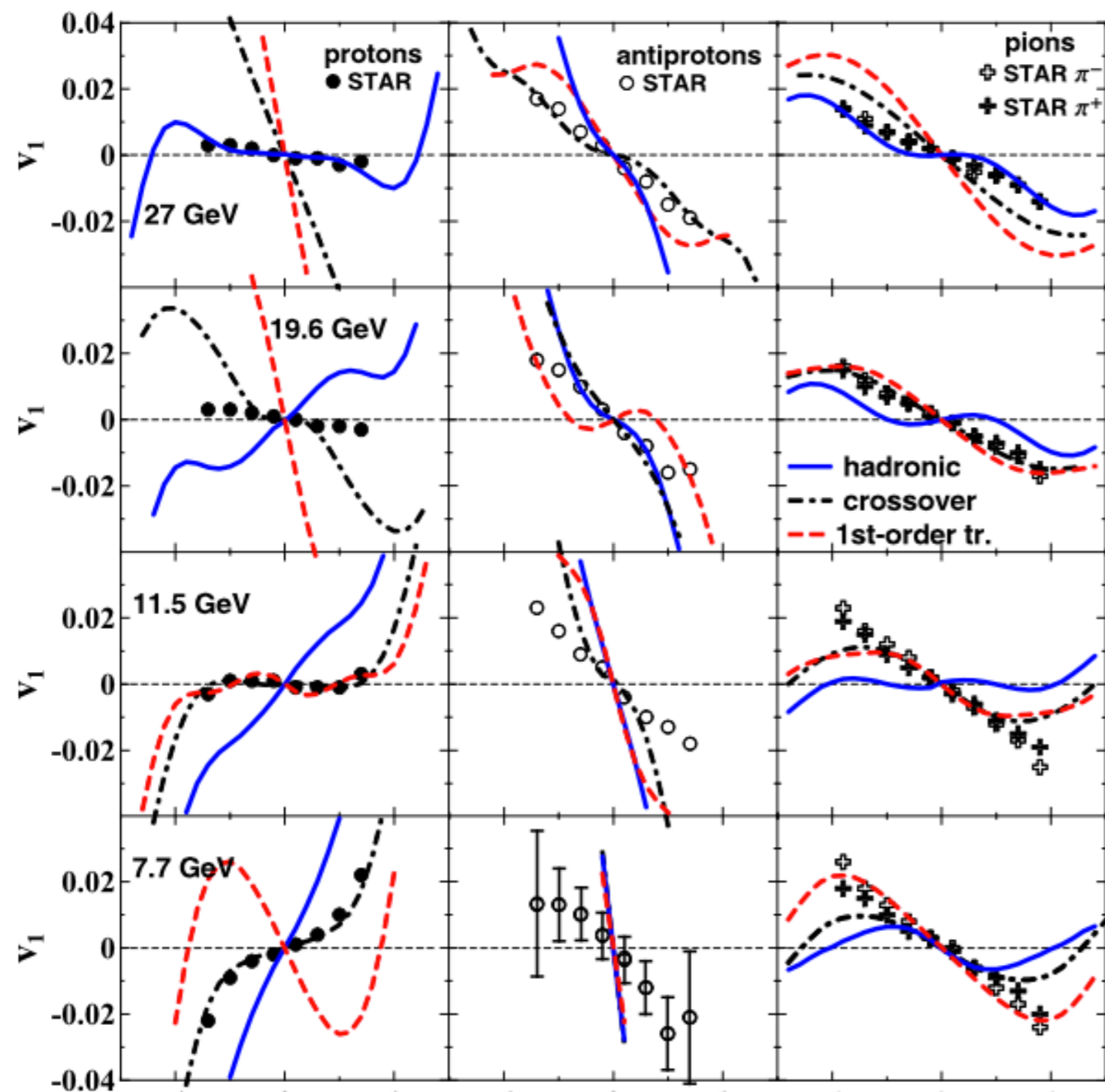
3 FD: Y. Ivanov et al., PRC **91,** 024915 (2015)

"However, predictions of the crossover and first-order-transition scenarios looked very similar so far. Only a slight preference could be given to the crossover EoS … best overall reproduction of the STAR data is achieved with the crossover EoS."

Energy dependence dv₁/dy with models

Energy dependence dv$_1$/dy with models

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)

JAM: Y. Nara et al., arxiv: 1601.07692
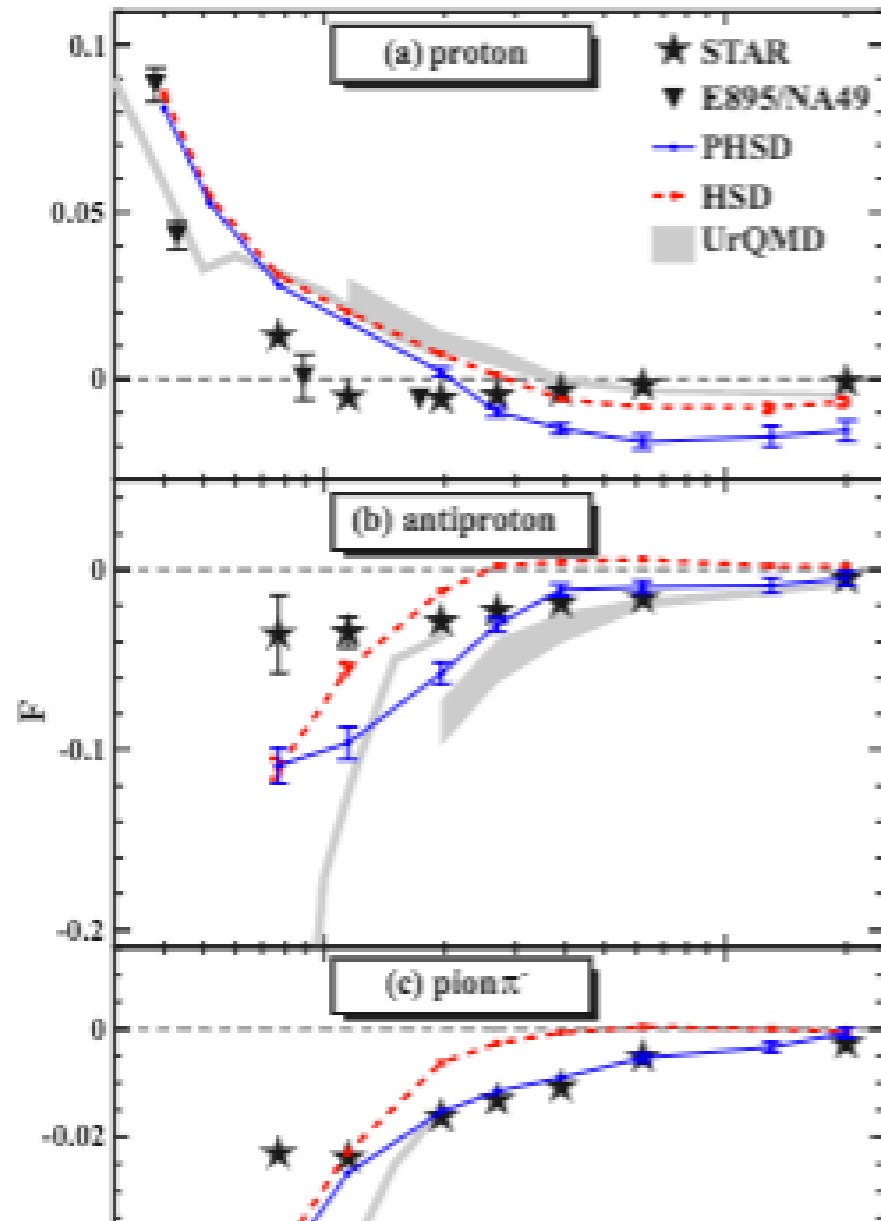
"*Still sizable discrepancies with experimental measurements in the directed flow …. Our flow analysis shows no indication of a first-order transition.*"

"*More detailed systematic studies are needed by using a fully baryon density dependent EoS, in order to draw a conclusion that minimum of dv$_1$/dy is a result of the softening of the EoS which may be caused by a first-order phase transition.*"

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Energy dependence dv₁/dy with models

- None of the models explains the data
- Systematics associated with the models is quite large

27
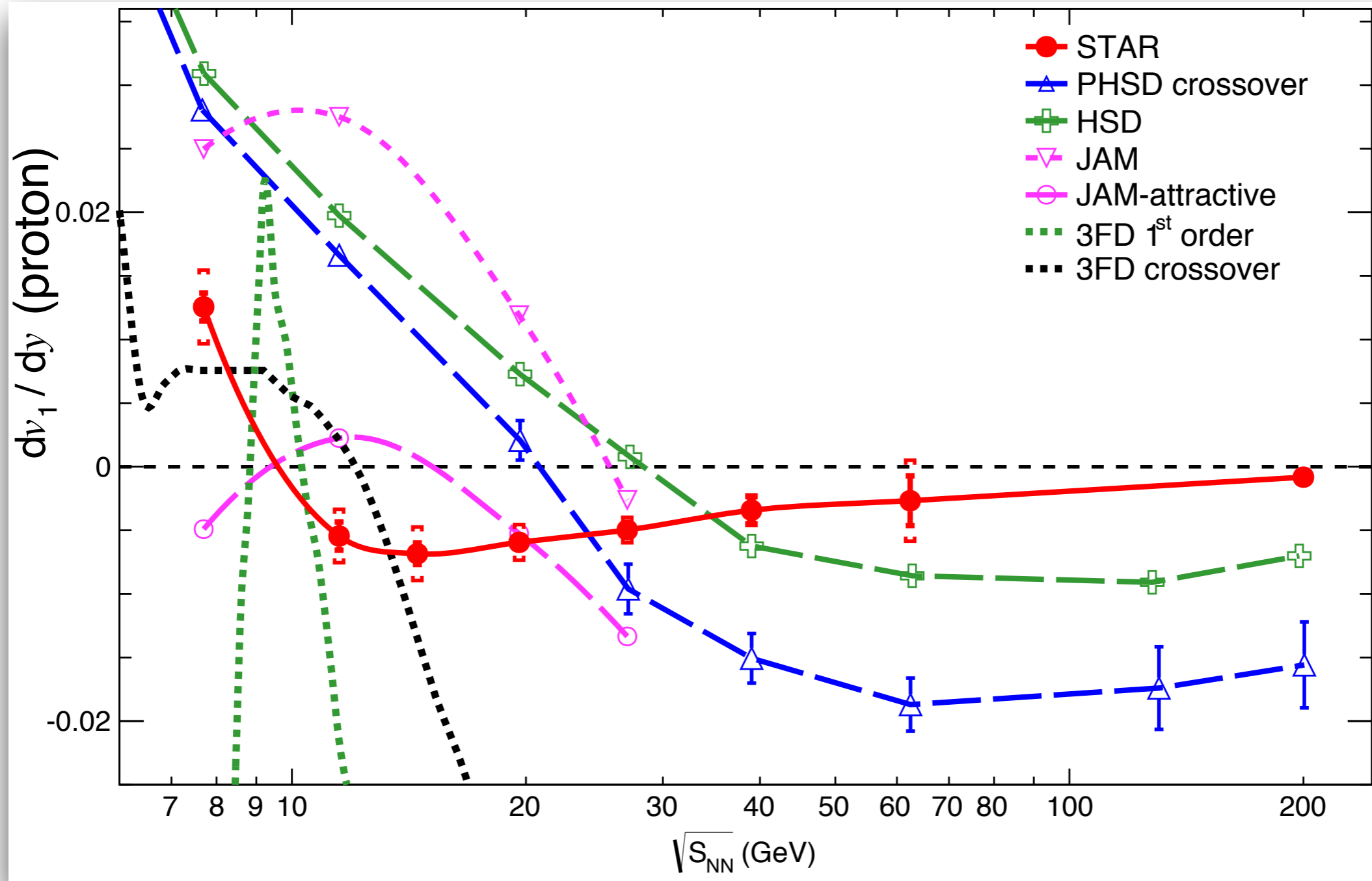
Energy dependence dv₁/dy with models

- None of the models explains the data
- Systematics associated with the models is quite large
  (~ 2 orders of magnitude bigger than experimental errors!)

Energy dependence dv₁/dy with models
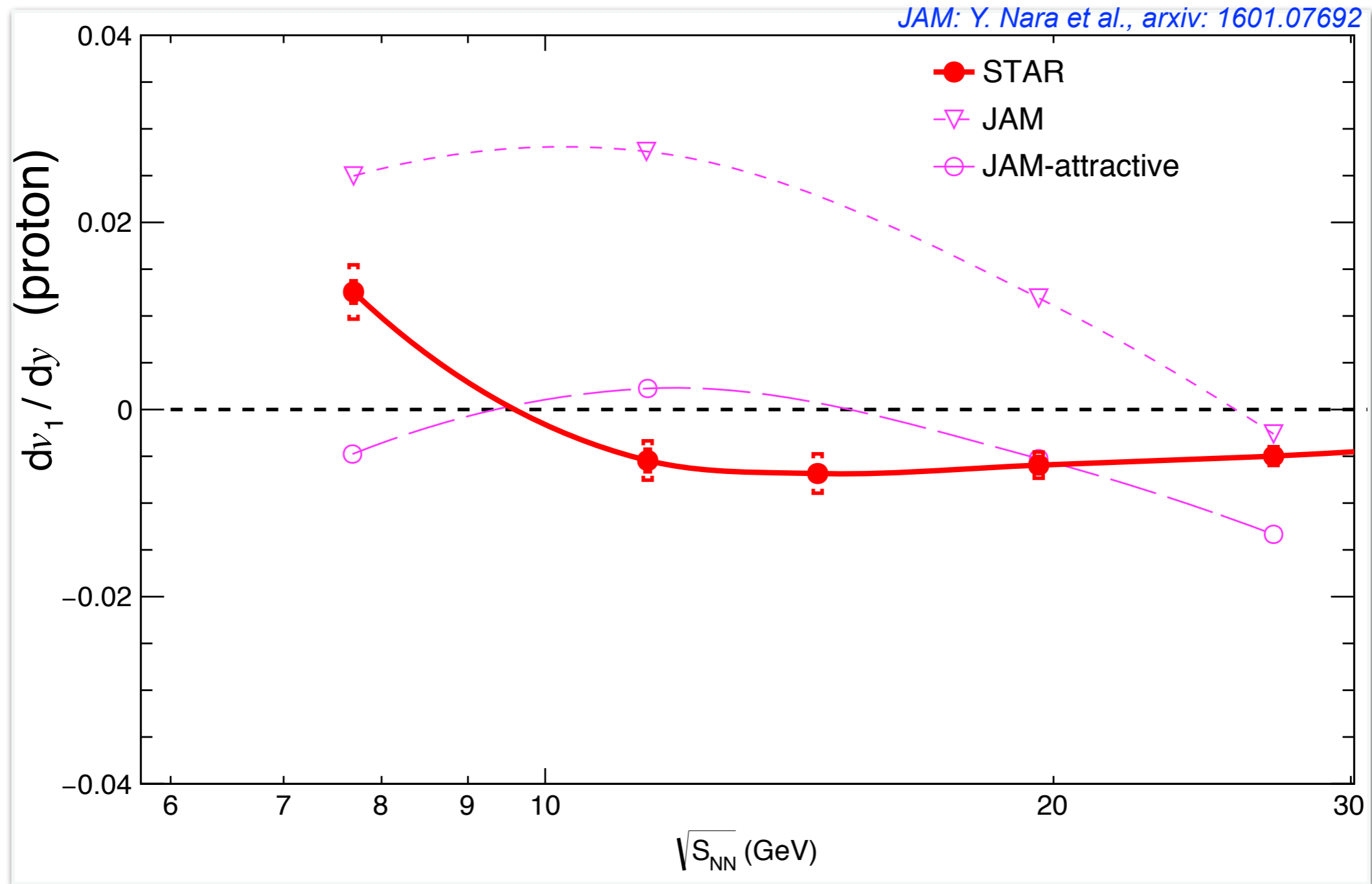
JAM: Y. Nara et al., arxiv: 1601.07692

- Standard JAM: Close to data at 7.7 GeV (hadronic description) Overestimate data at 11.5 and 19.6 GeV

- JAM attractive: Close to data at 11.5 and 19.6 GeV

Energy dependence dv₁/dy with models

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

- STAR
- JAM
- JAM-attractive

dv_1 / dy (proton)

$\sqrt{S_{NN}}$ (GeV)

Evidence for softening of EoS (?)

- Standard JAM: Close to data at 7.7 GeV (hadronic description) Overestimate data at 11.5 and 19.6 GeV

- JAM attractive: Close to data at 11.5 and 19.6 GeV

Energy dependence dv_1/dy with models

a) antiproton
b) proton
c) net proton

10-40% Centrality

Data
UrQMD

$dv_1/dy|_{y=0}$

$\sqrt{s_{NN}}$ (GeV)

STAR
JAM
JAM-attractive

dv_1/dy (proton)

$\sqrt{s_{NN}}$ (GeV)
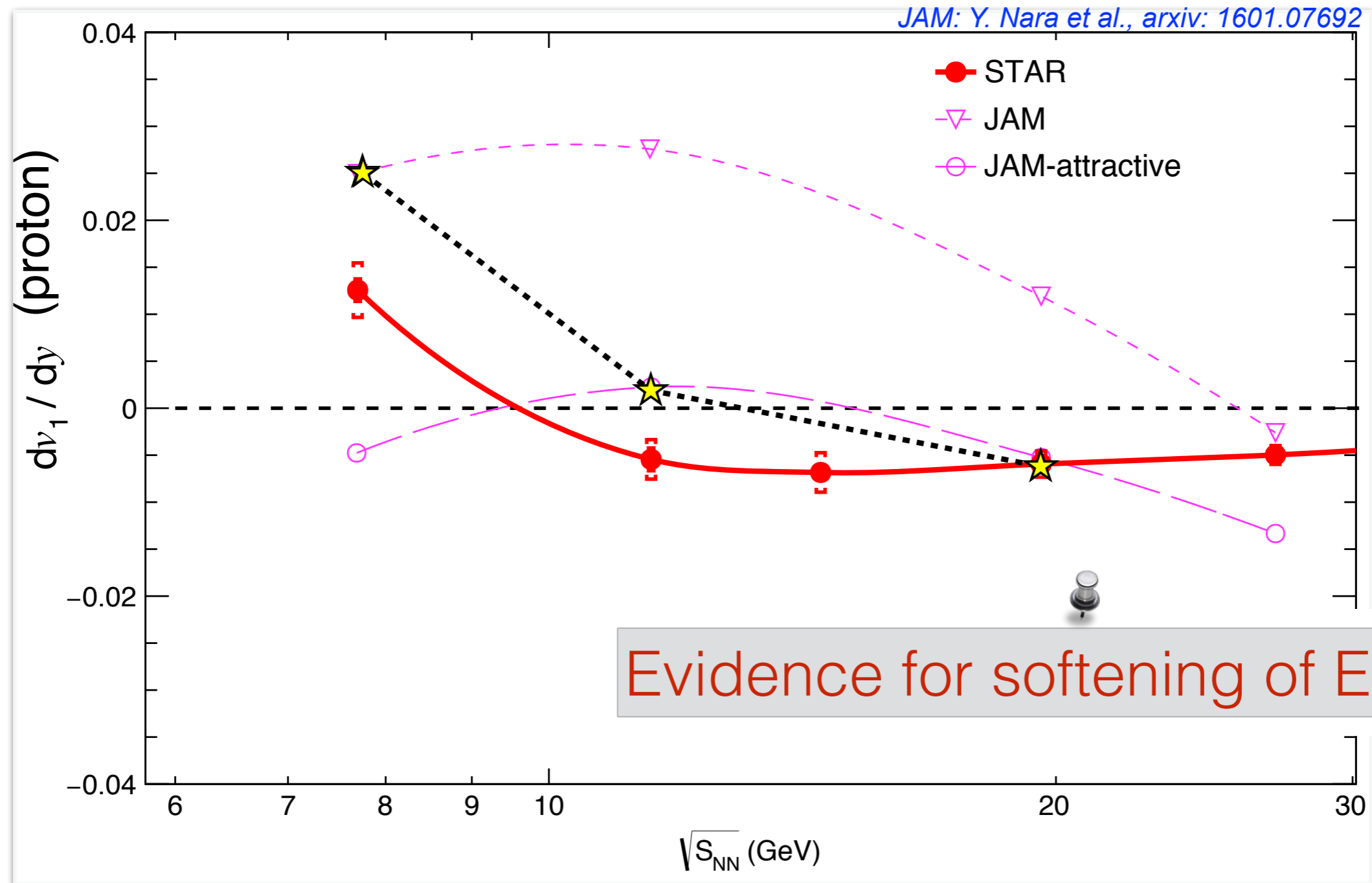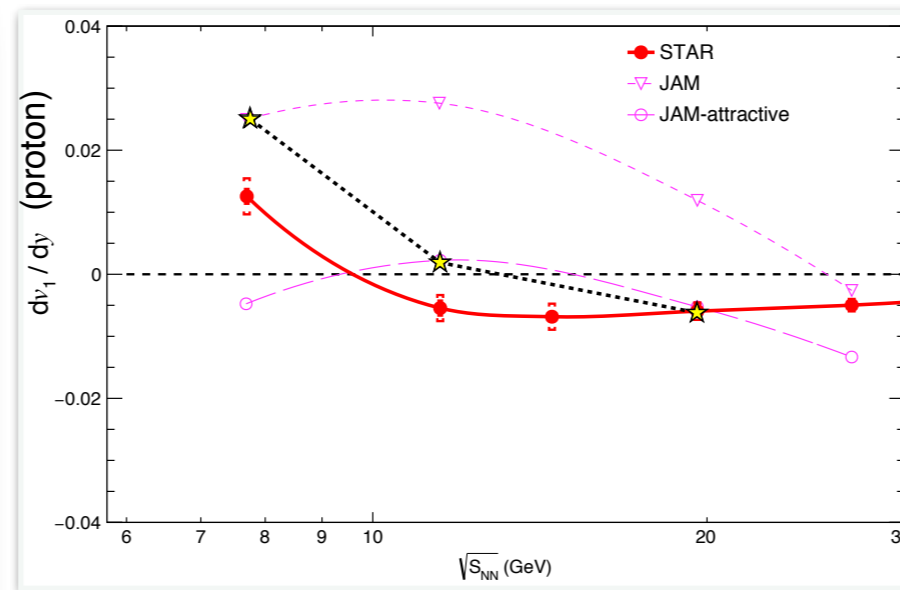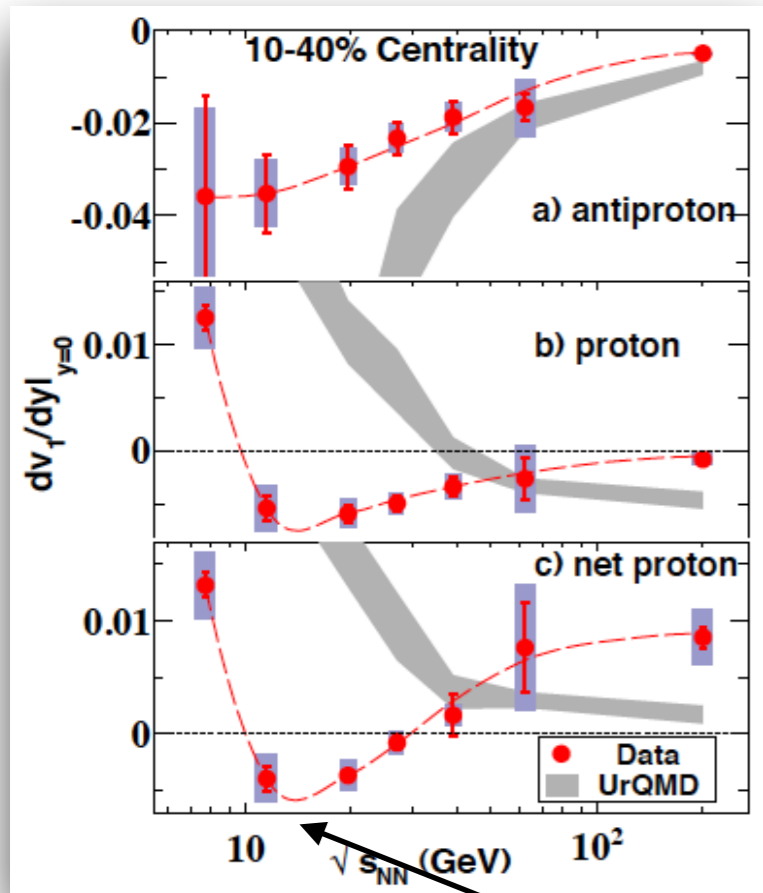
*R Singh et. al, arXiv:1304.2969
Acta Phys Pol B, 30, 2705, (1999)*

HRG + Hagedorn
upper bound
lower bound
Kinetic model
Thermal model
Statistical model
SHM

K^+/π^+ data
ALICE
RHIC
SPS
AGS

K^-/π^- data
ALICE
RHIC
SPS
AGS

K/π

$\sqrt{s_{NN}}$ (GeV)

Evidence for softening of EoS (?)
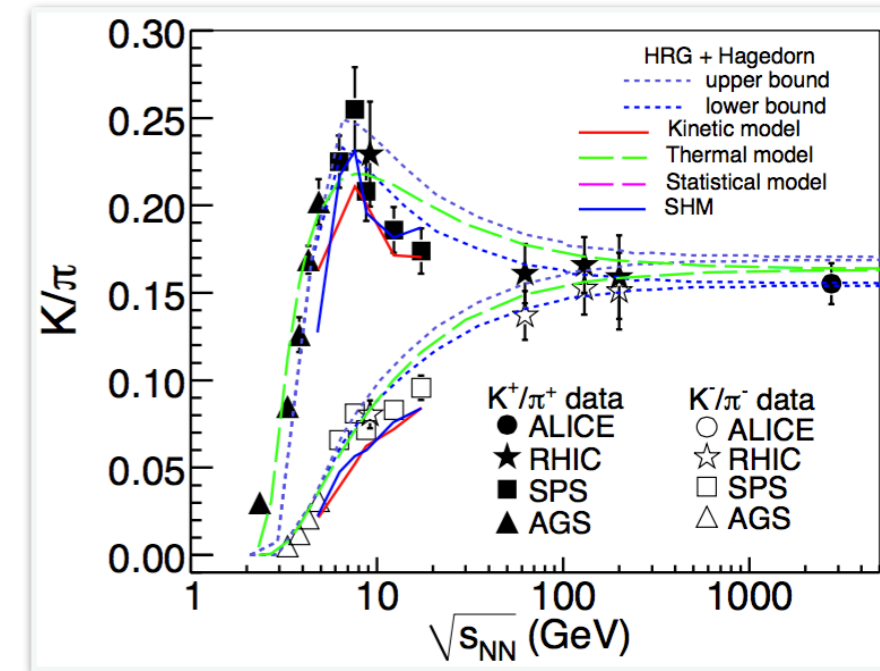
The peak indicates that the system reaches maximum baryonic density at around 10 GeV

Pair production dominant at higher energies.

J Randrup et. al, PRC 74, 047901 (2006)

Temperature T (MeV)

100+100 50+50 30+30 20+20 15+15 10+10 8+8 6+6 5+5
4+4
3+3
2+2

40
30
20
15
10
5

S=0 & Q/B=0.4
RHIC
FAIR

Hadronic freeze-out

J. Randrup & J. Cleymans
[Phys. Rev. C74 (2006) 047901]

Net baryon density ρ_R (fm^{-3})
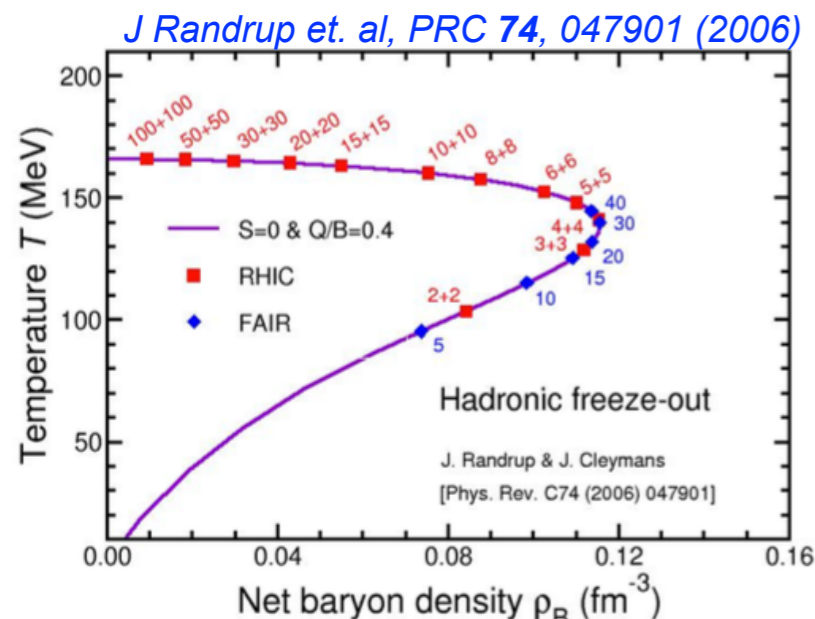
At high baryon (net-baryon) density, one might expect a repulsive force

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Strange hadron v_1 at RHIC

	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

Rapidity dependence of v_1

Au+Au Collision: 10-40% **STAR Preliminary**
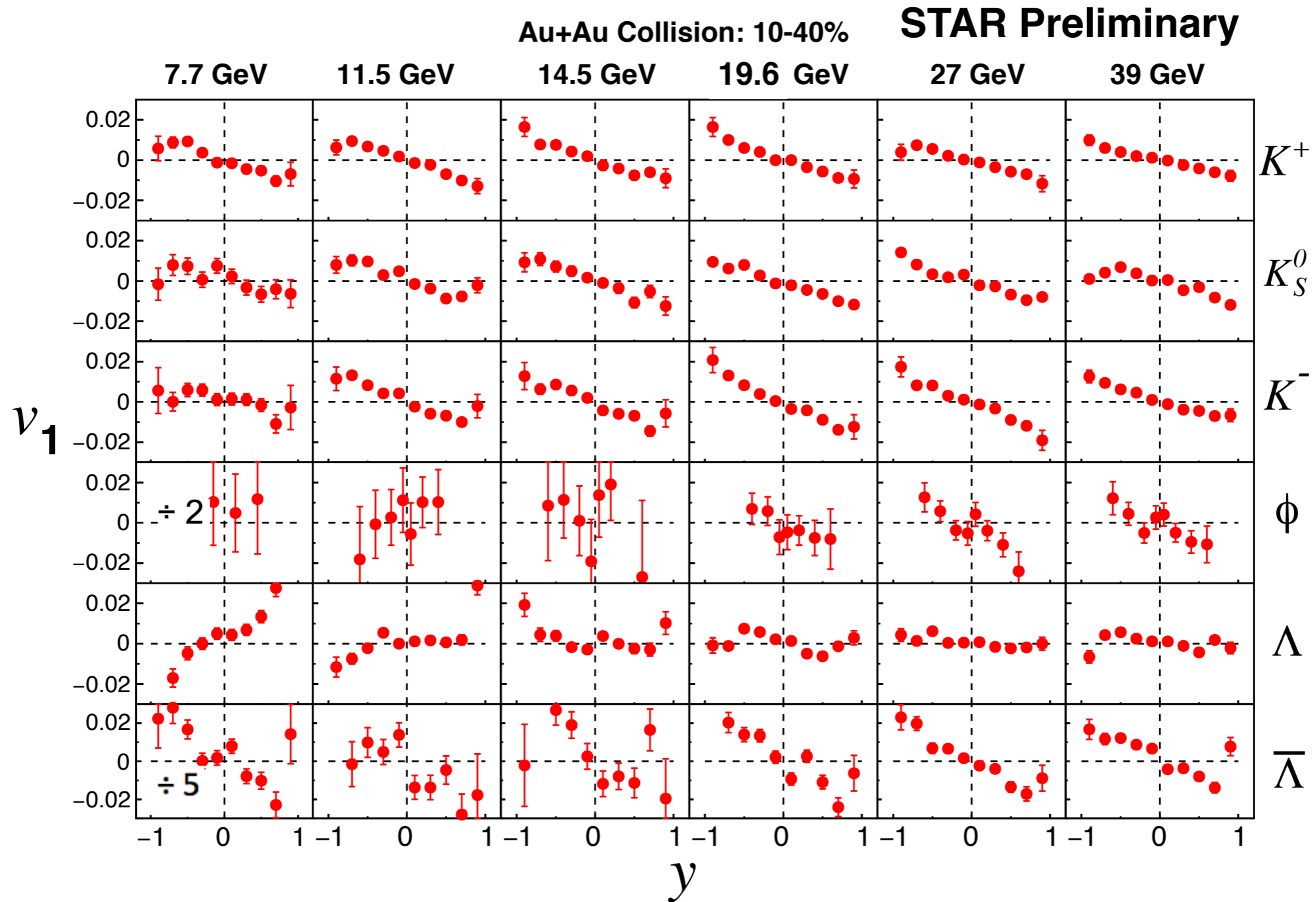
- v_1-slope extracted by linear fitting ($|y| < 0.8$)
- poor statistics for particles (e.g. $\overline{\Lambda}, \phi$) does not allow stable cubic fit

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

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Energy dependence of dv_1/dy

STAR Preliminary   10-40 %

line to guide the eye

■ Λ □ $\overline{\Lambda}$

● p ○ $\overline{p}$
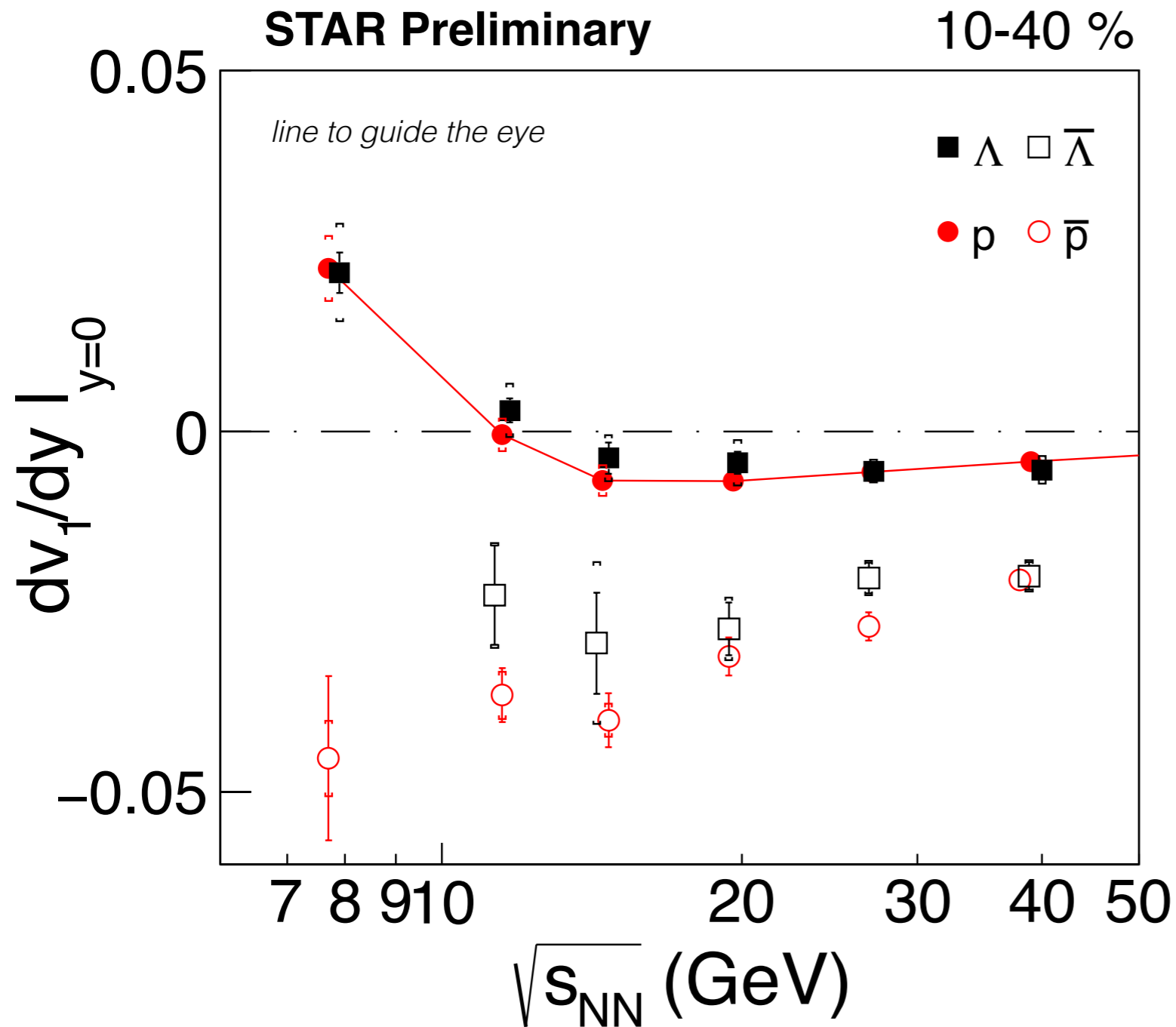
- $(dv_1/dy)_p \sim (dv_1/dy)_\Lambda$

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

- $(dv_1/dy)_{\overline{p}} \sim (dv_1/dy)_{\overline{\Lambda}}$

Energy dependence of dv_1/dy

STAR Preliminary   10-40 %

line to guide the eye

Legend: Λ $\bar{\Lambda}$ p $\bar{p}$ K^+ K^- K_s^0

y-axis: $dv_1/dy \, |_{y=0}$ (0.05, 0, −0.05)

x-axis: $\sqrt{s_{NN}}$ (GeV) (7 8 9 10 20 30 40 50)
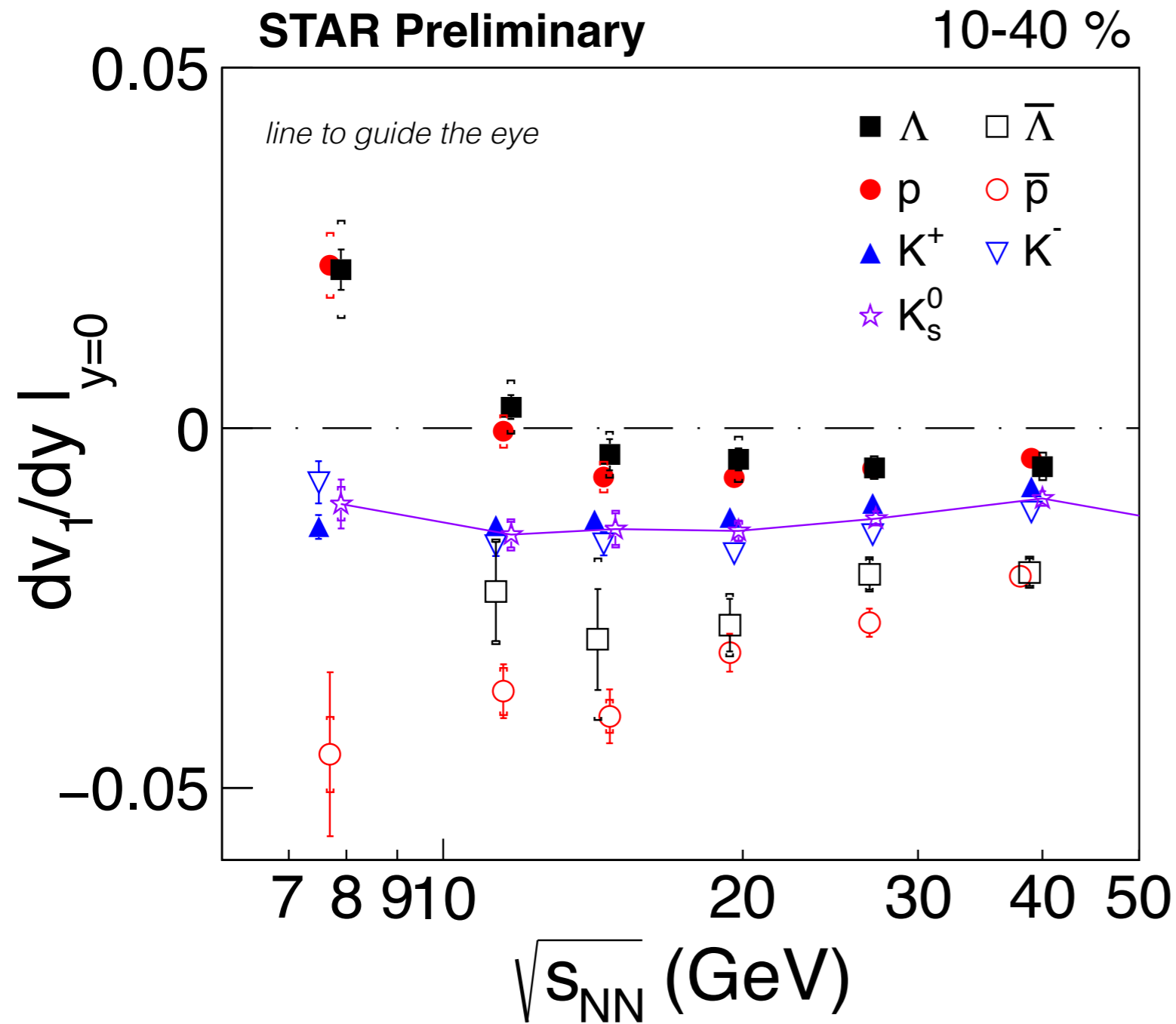
- $(dv_1/dy)_{K^\pm}$ ~ negative

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

Energy dependence of dv_1/dy

STAR Preliminary   10-40 %

line to guide the eye

Legend:
- ■ Λ □ $\overline{\Lambda}$
- ● p   ○ $\overline{p}$
- ▲ K^+ ▽ K^-
- ☆ K_s^0 ✛ ϕ

y-axis: $dv_1/dy \,|_{y=0}$ (0.05, 0, −0.05)

x-axis: $\sqrt{s_{NN}}$ (GeV) (7 8 9 10 20 30 40 50)
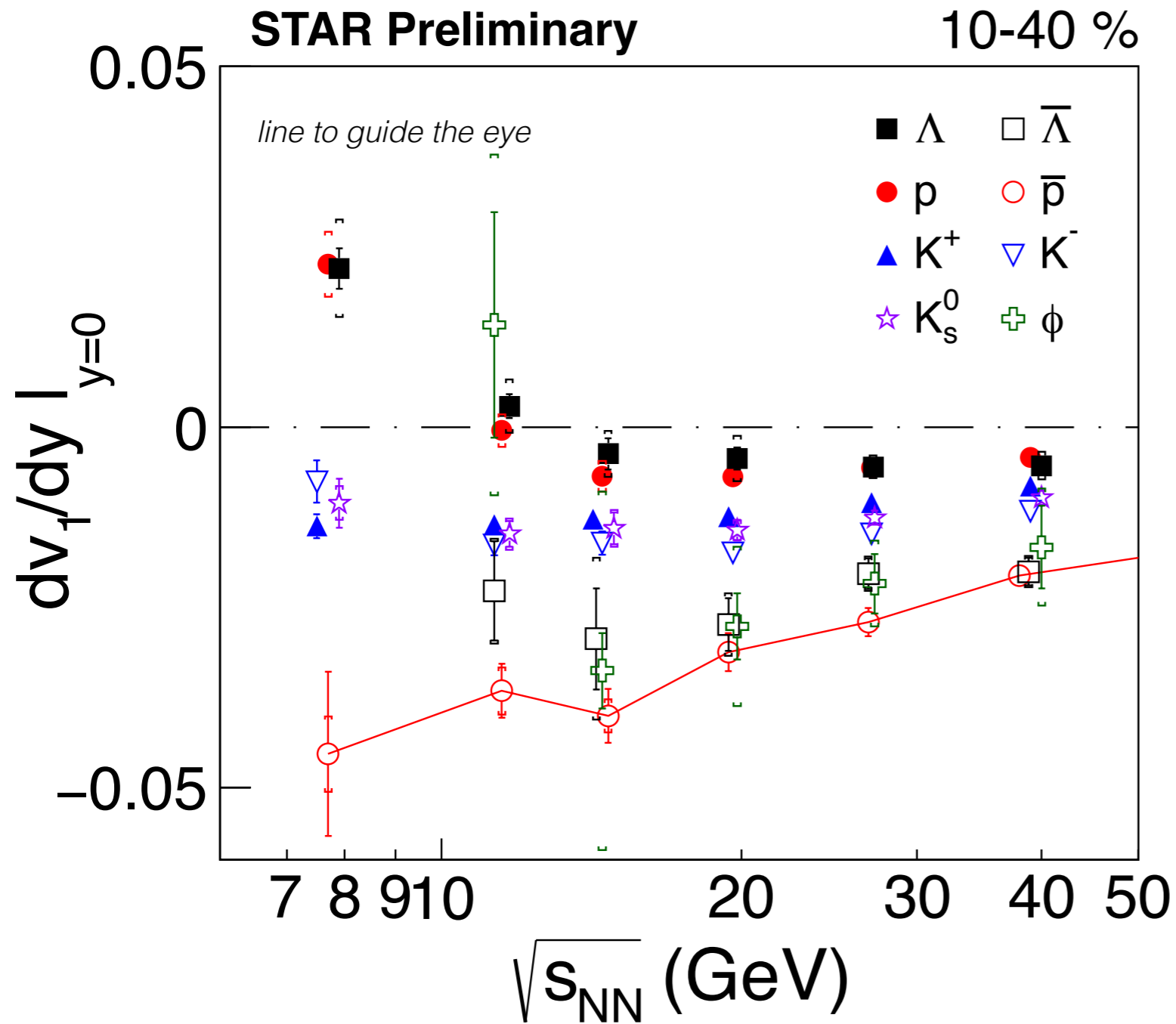
- $(dv_1/dy)_{\overline{\Lambda},\overline{p}} \sim (dv_1/dy)_\phi$ for energies above 14.5 GeV

- $(dv_1/dy)_\phi \sim 0$ at 11.5 GeV with large stat. uncertainty
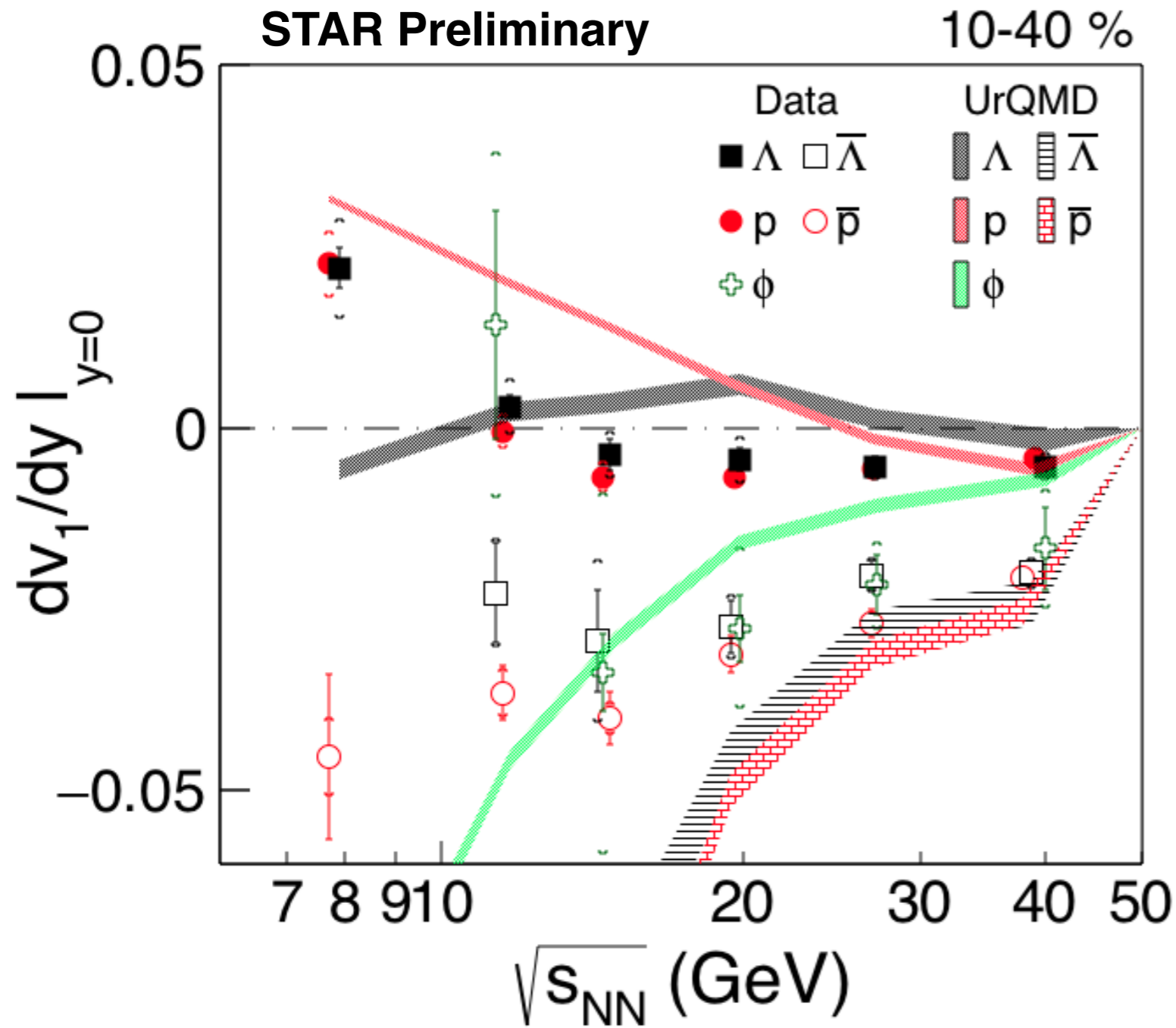
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Energy dependence of dv_1/dy
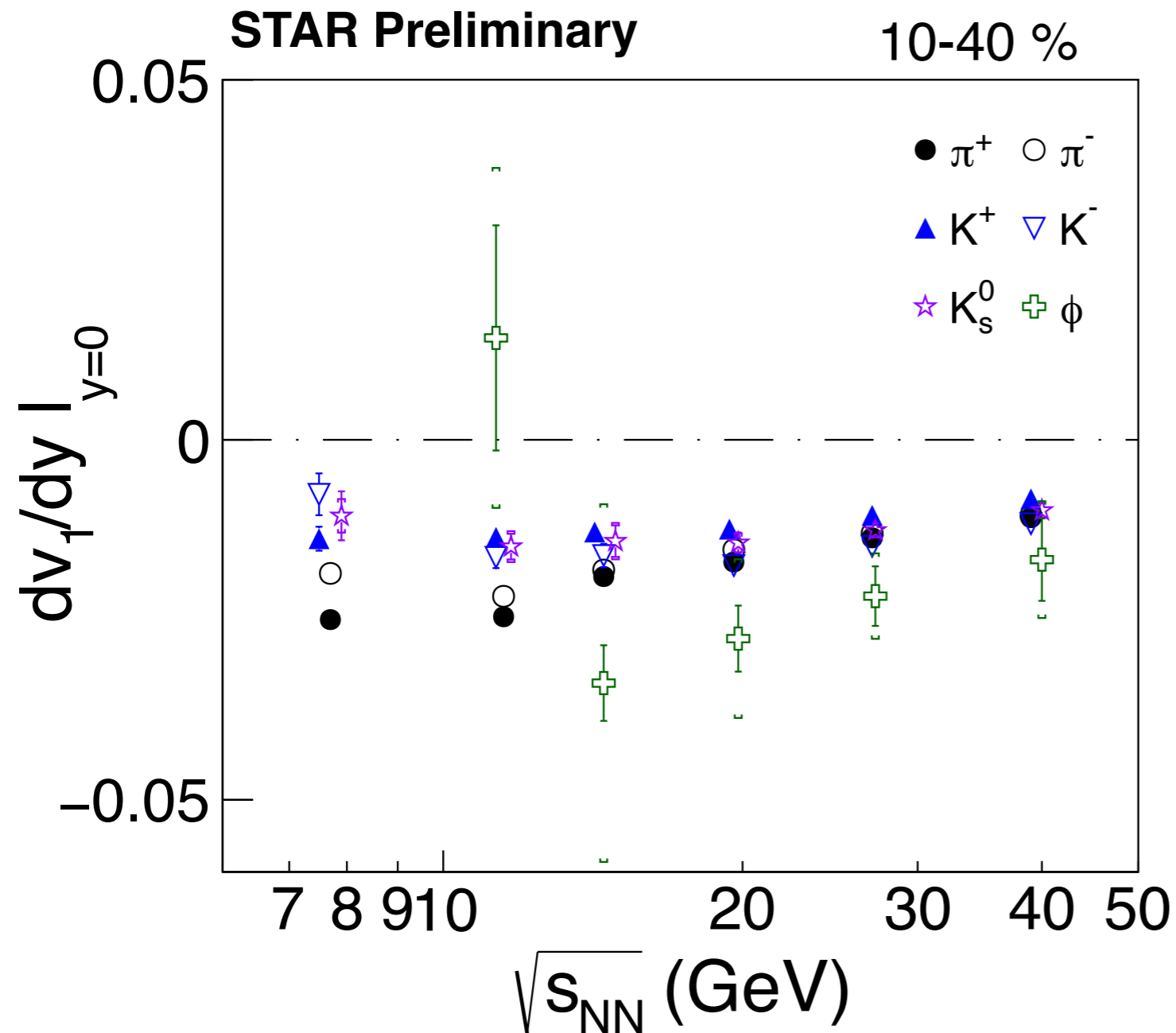
- $(dv_1/dy)_K < (dv_1/dy)_\phi$ for energies above 14.5 GeV

- $(dv_1/dy)_\phi \sim 0$ at 11.5 GeV with large stat. uncertainty

Among the mesons, the particle (e.g. ϕ) with more produced quarks have larger magnitude of v_1-slope.

Energy dependence of dv_1/dy

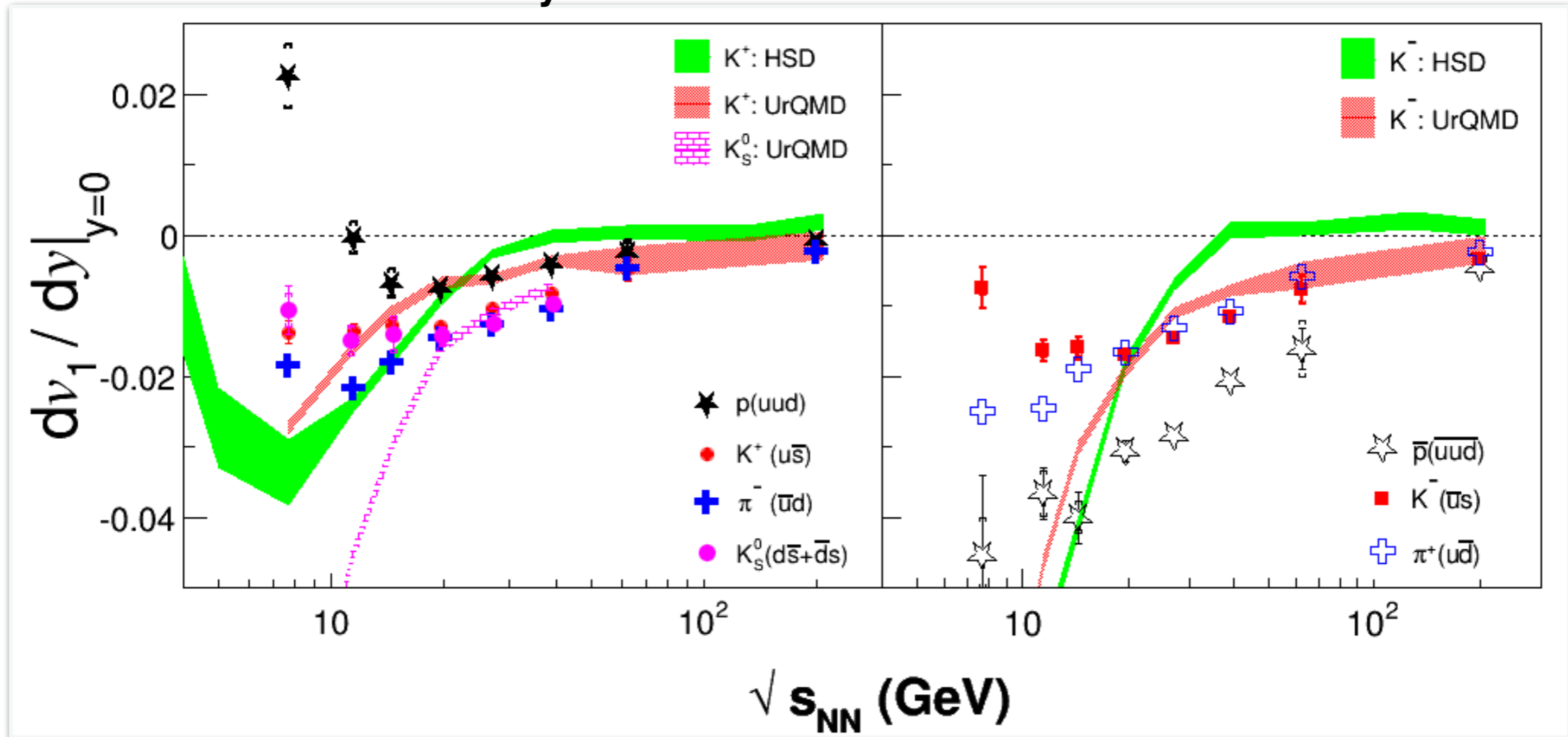*UrQMD: S. Bass et al, Prog. Part. Nucl. Phys **41**, 255, (1998)*

- $(dv_1/dy)_{UrQMD-\Lambda,\phi}$: deviate from data below 19.6 GeV

- $(dv_1/dy)_{UrQMD-\overline{\Lambda},\phi}$: qualitatively similar trend to data for higher energies

Energy dependence of dv_1/dy
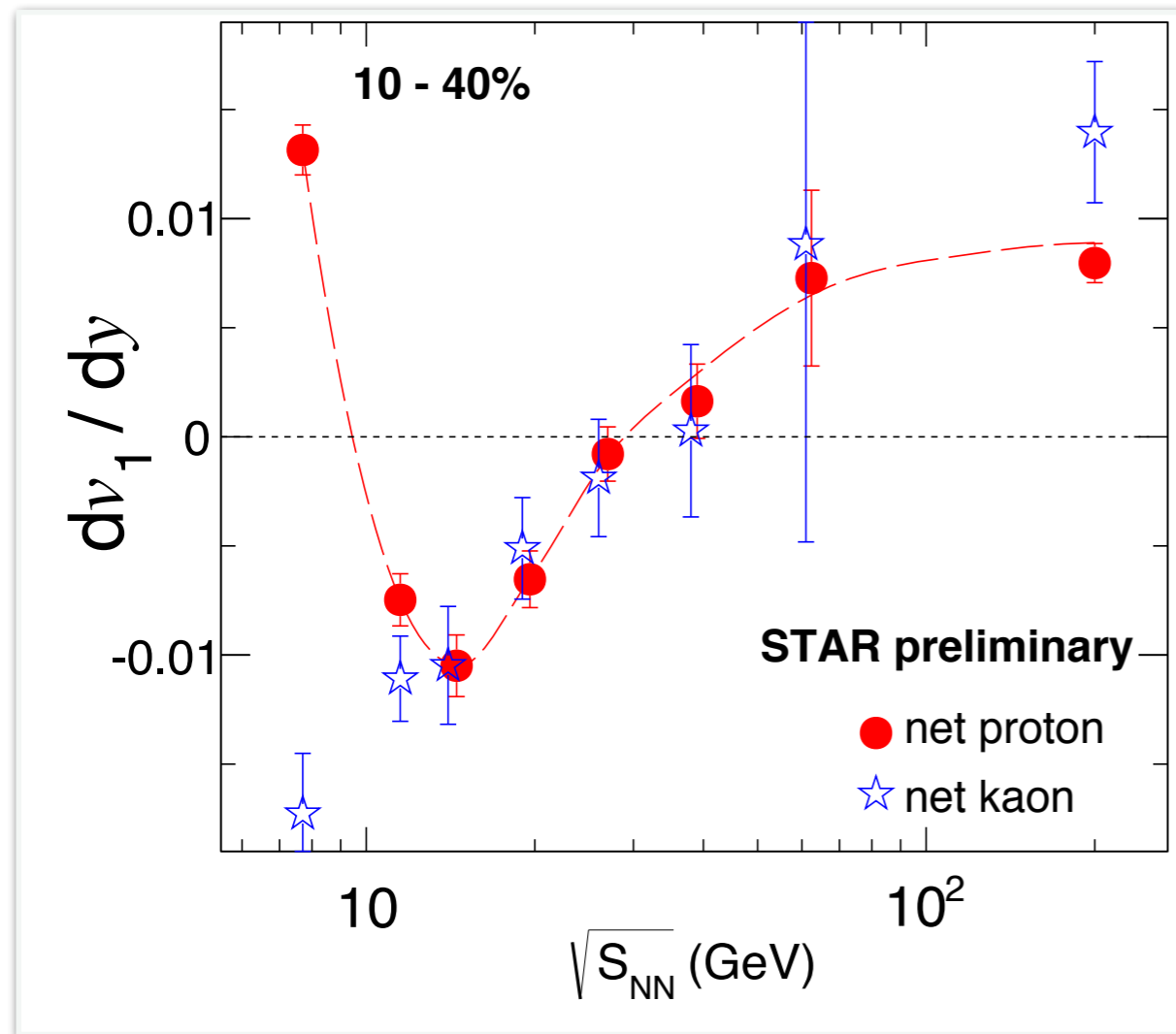

HSD: W. Cassing et al, arXiv: 1408.4313
UrQMD: S. Bass et al, Prog. Part. Nucl. Phys **41**, 255, (1998)

STAR Preliminary

- Particles in left panel expected have more stopped initial-state nucleons than the anti-particles in right panel
- dv_1/dy(K±, K_s^0) from UrQMD/HSD model can not explain data

Energy dependence of net-particle v_1

To disentangle contributions from produced quarks & transported quarks

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

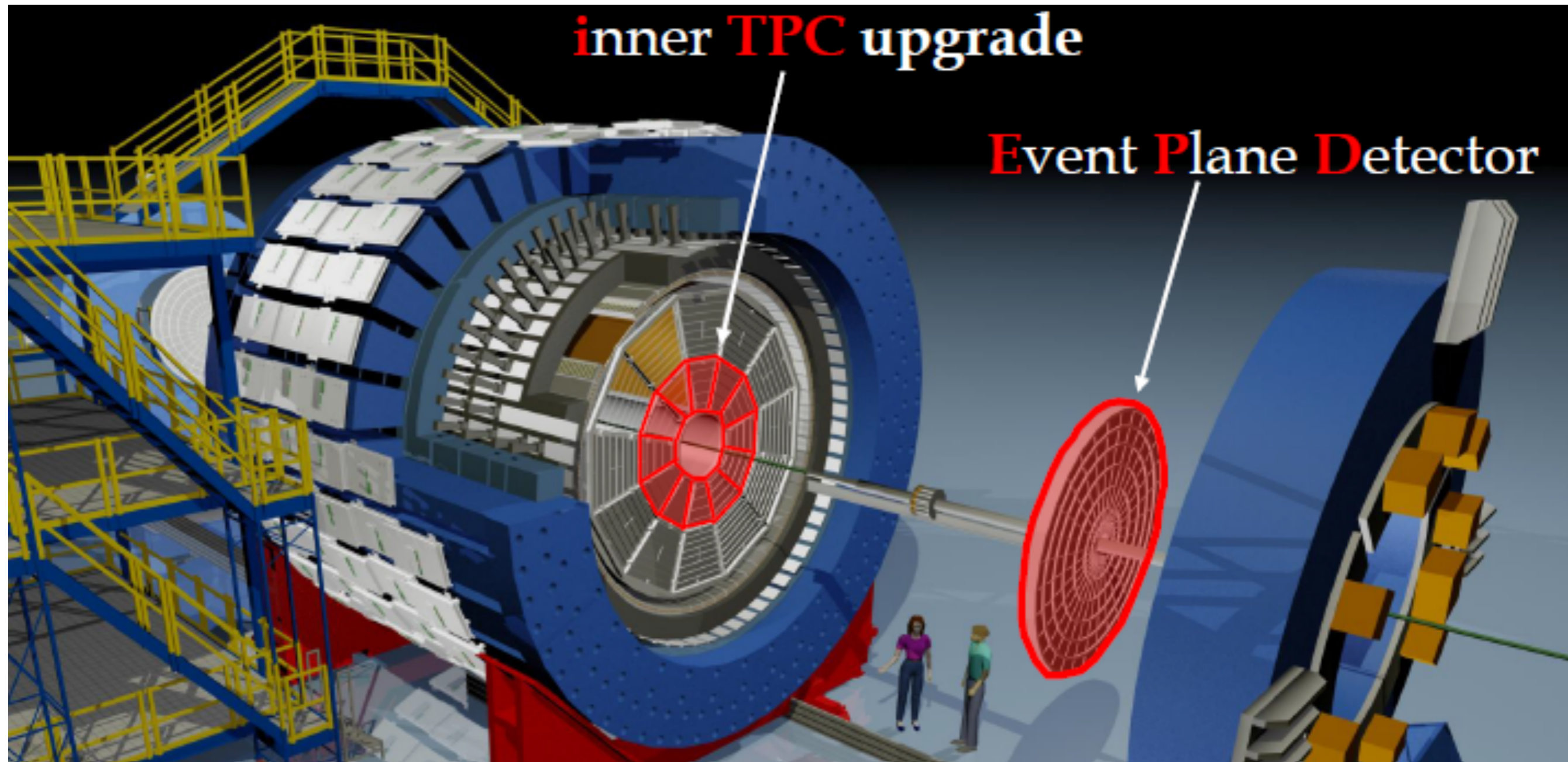$$F_{K^+} = r_2 F_{K^-} + (1-r_2) F_{net-K}$$

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

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

BES-II at RHIC

inner **TPC** upgrade

Event **P**lane **D**etector
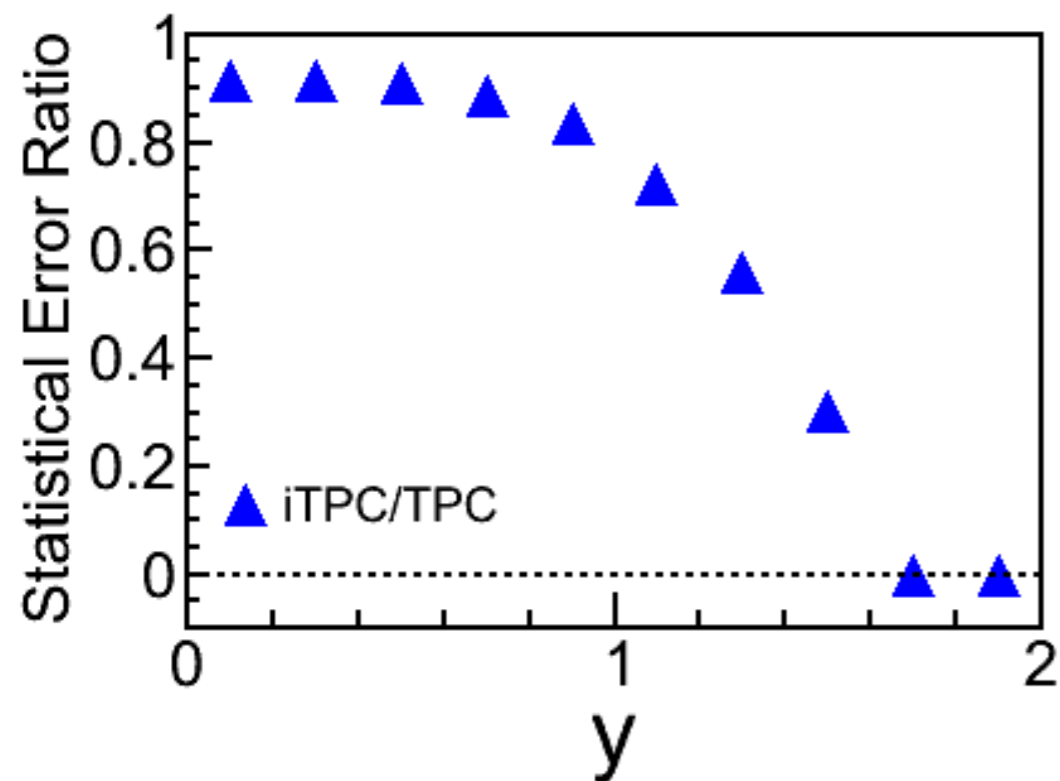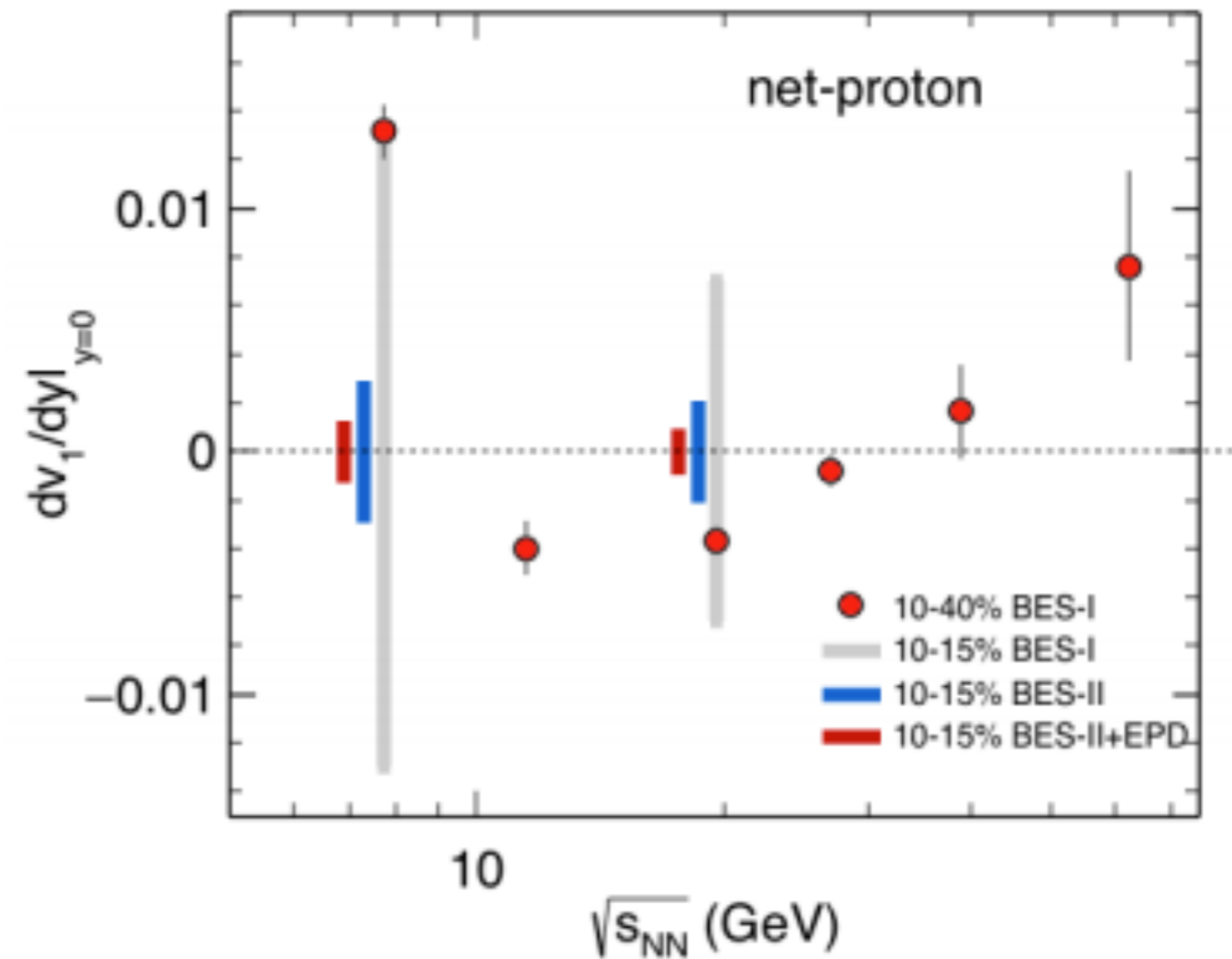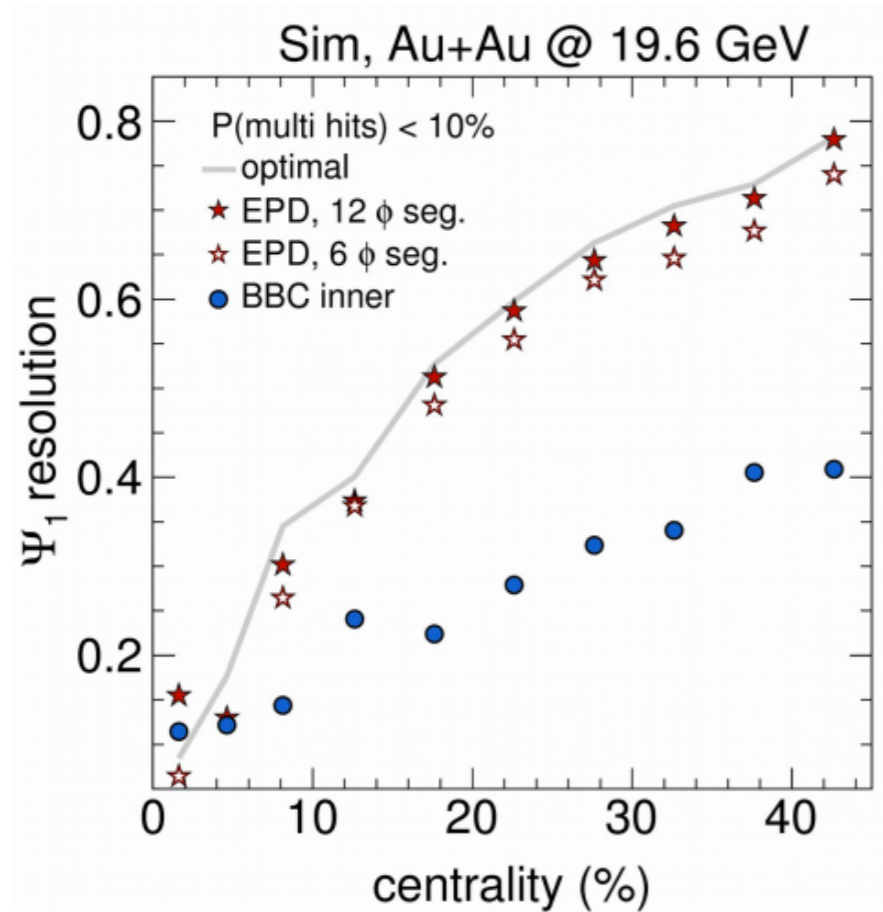
iTPC (-1.7 < |η| < 1.7)
- extended coverage
- better dE/dx

EPD (2.1< |η| < 5.1)
- improved EP resolution
- TPC independent centrality estimation

BES-II at RHIC

Sim, Au+Au @ 19.6 GeV

net-proton

- improvement in EP resolution
- reduction in statistical uncertainty

42

Summary and outlook

STAR published results show a minimum in dv_1/dy for proton and net-protons and a double sign-change in net-proton dv_1/dy
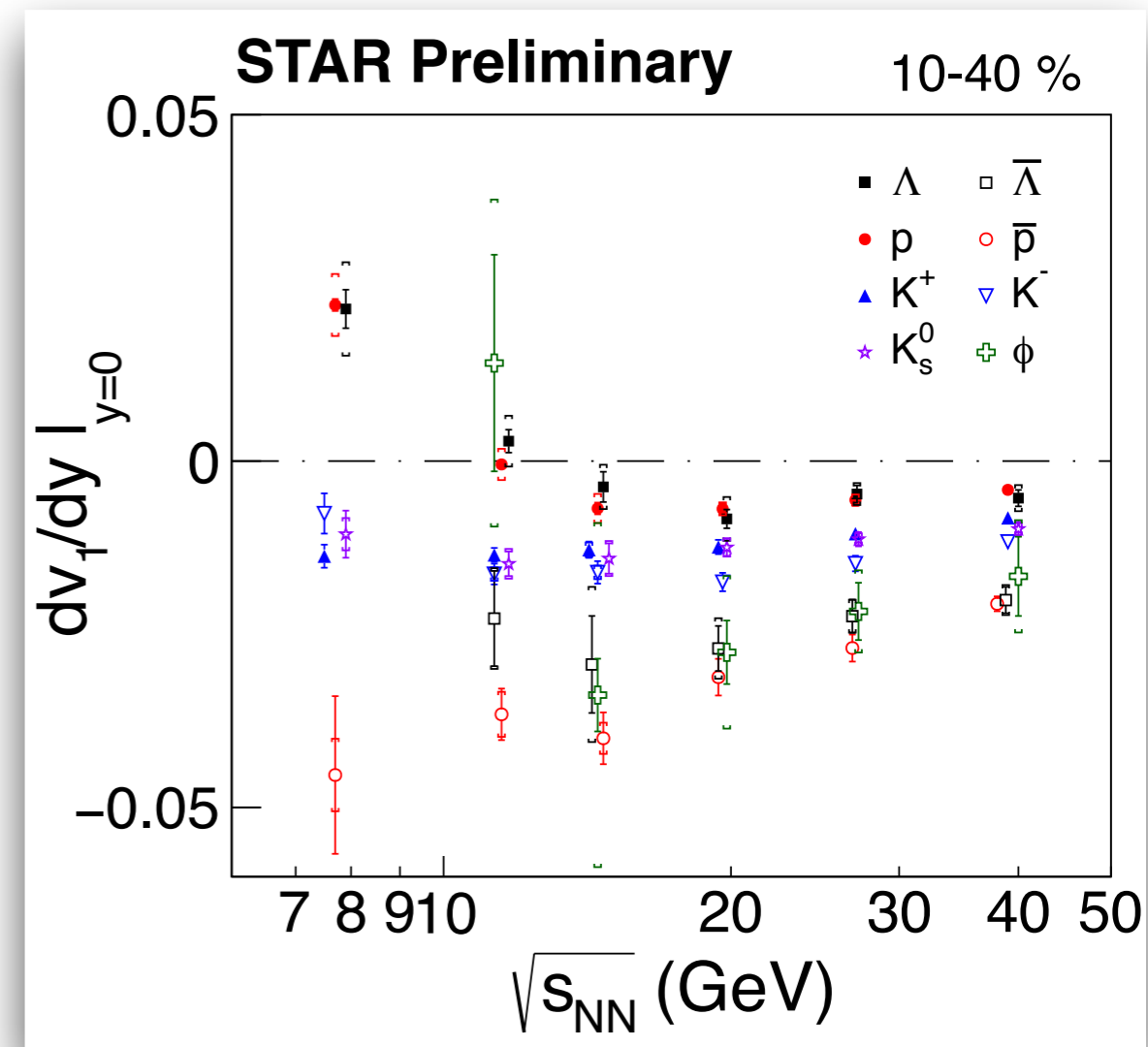
New preliminary results:

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

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

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

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

Summary and outlook

➡ *Present models can not explain main features of data*

➡ *New set of results from STAR will put stringent constraint on theoretical models*

➡ *More theoretical progress needed for a clear interpretation of data*

➡ *Data from BES-II with more statistics and upgraded detectors will provide results with more precision*

200 GeV

62.4 GeV

39.0 GeV

27.0 GeV

19.6 GeV

14.5 GeV

11.5 GeV

7.7 GeV
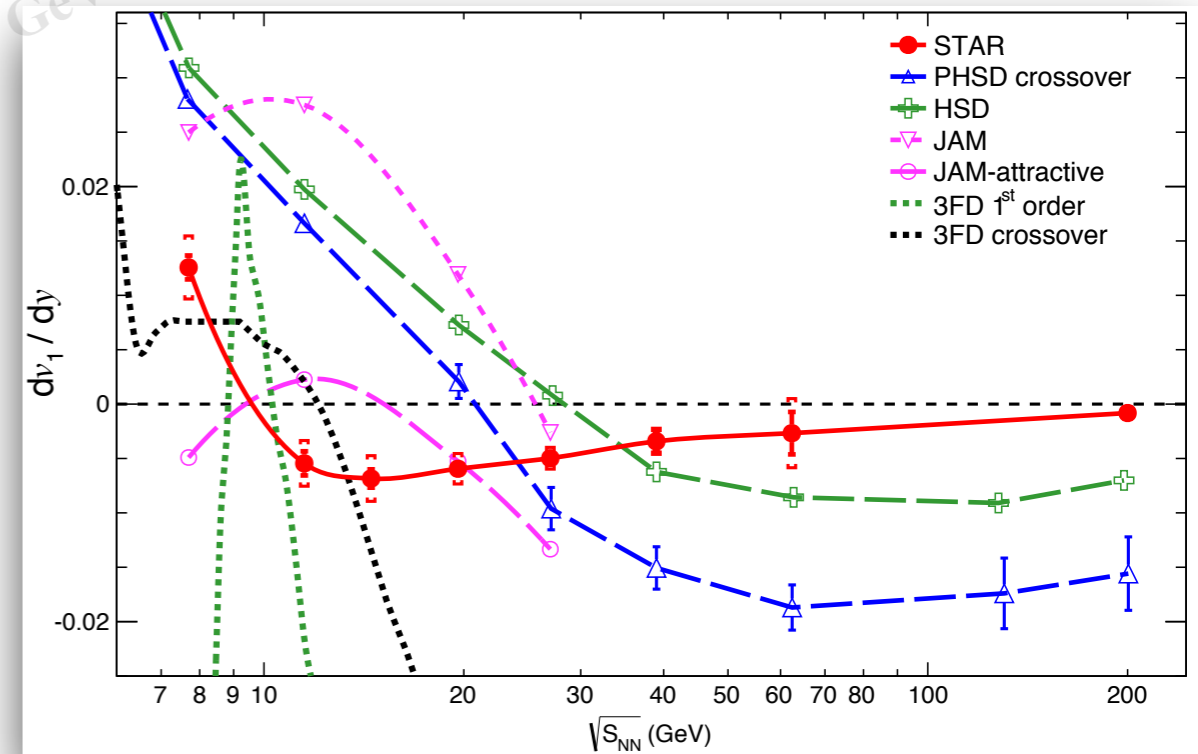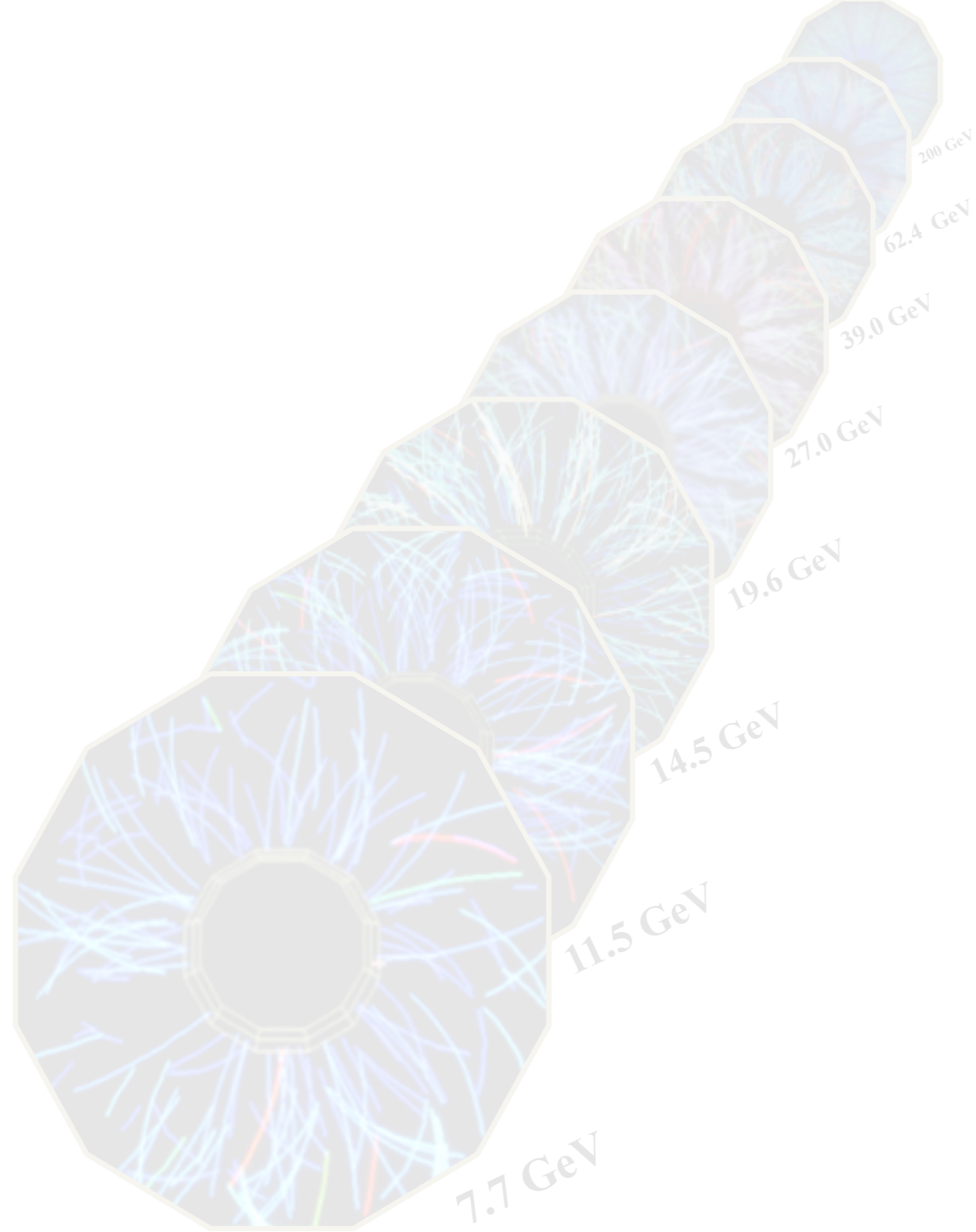
Thank you

Interpretation of STAR dv_1/dy data by different models

Frankfurt hybrid

"…we find that essentially all models, including the standard hadronic transport UrQMD, cannot even describe the qualitative behavior, observed by experiment, of the proton directed flow. All models severely overestimate the data, even though other observables, like the radial or elliptic flow, are usually well described within these models."

3FD

"… with available data indicated a definite advantage of the deconfinement (crossover and first-order) scenarios over the purely hadronic one, especially at high (RHIC) collision energies. However, predictions of the crossover and first-order-transition scenarios looked very similar so far. Only a slight preference could be given to the crossover EoS. In the case of the directed flow we can definitely conclude that the best overall reproduction of the STAR data is achieved with the crossover EoS. The first-order-transition scenario gives results which strongly differ from those in the crossover scenario, especially for the proton v1."

PHSD/HSD

"… Still sizable discrepancies with experimental measurements in the directed flow characteristics are found .... Our flow analysis shows no indication of a first-order transition. However, we have found further strong evidence that the dynamics of heavy-ion reactions at lower SPS and AGS energies is far from being understood especially on the hadronic level."

JAM:

""More detailed systematic studies are needed by using a fully baryon density dependent EoS, in order to draw a conclusion that minimum of dv_1/dy is a result of the softening of the EoS which may be caused by a first-order phase transition. … It seems obvious to infer a softening of the EoS from the experimentally observed collapse of net-proton flow when the c.m. energy is increased from 7 to 11 GeV. However, the statement of a discovery of the "softening" of the EoS from the net-proton v1 data shows even more convincing evidence for the "phase transition" as we observe the re-bound at higher energies, namely STAR observed second change of sign of the v1 values of the net-protons at $\sqrt{s_{NN}} \approx 40$ GeV back to positive v1 at higher energies [1]. This shows that the soft region is overcome, and the directed flow picks up steam again, due to the re-hardening of the EoS at considerably larger energy densities."
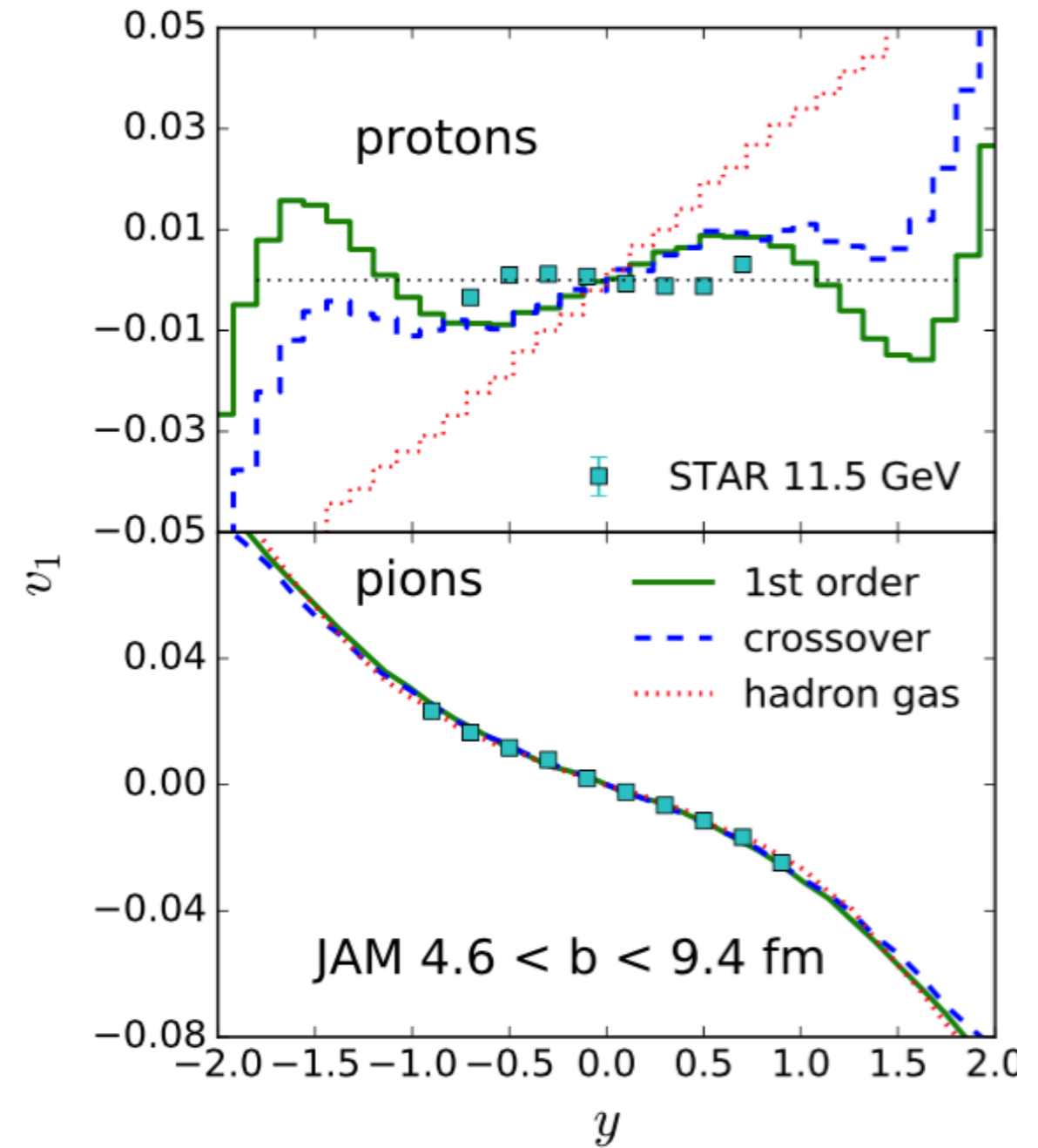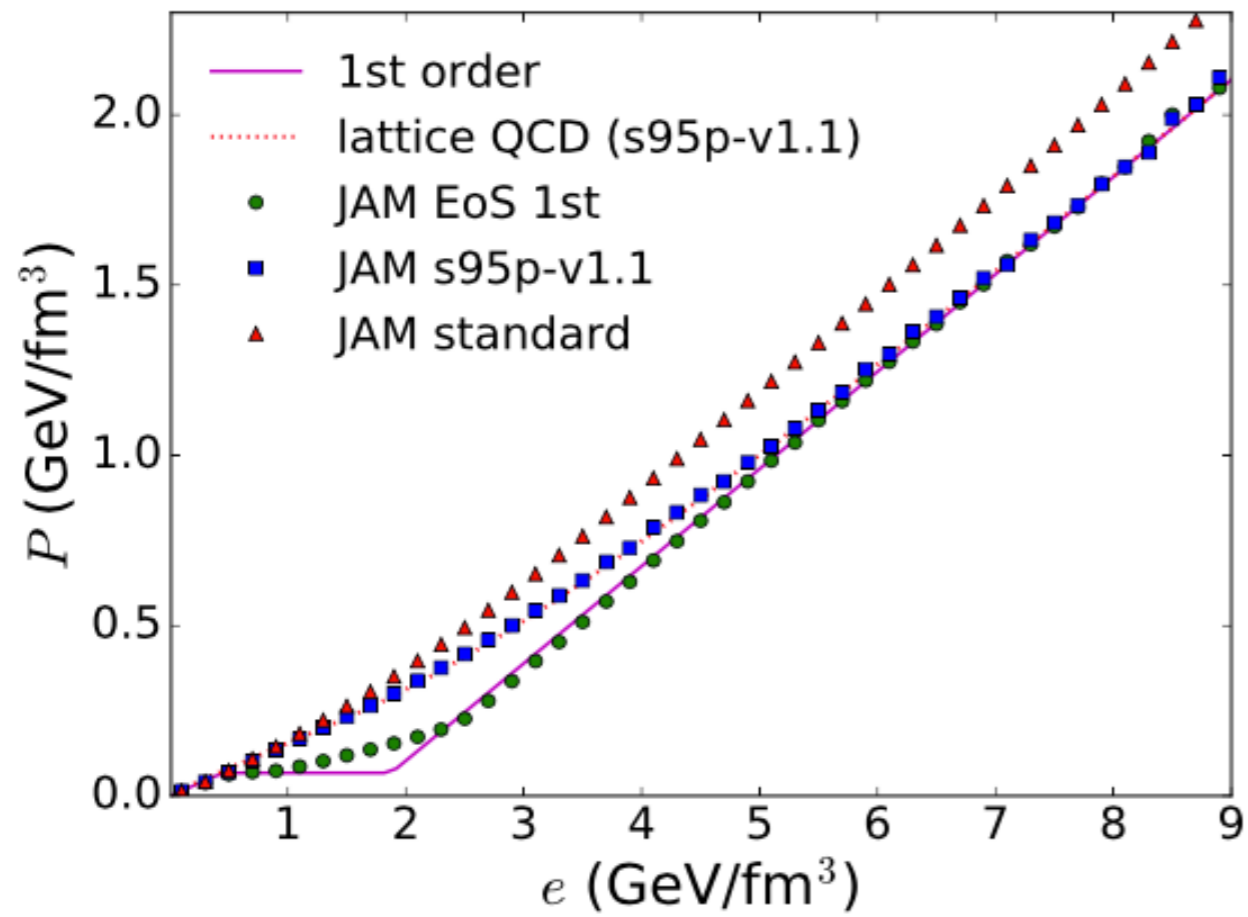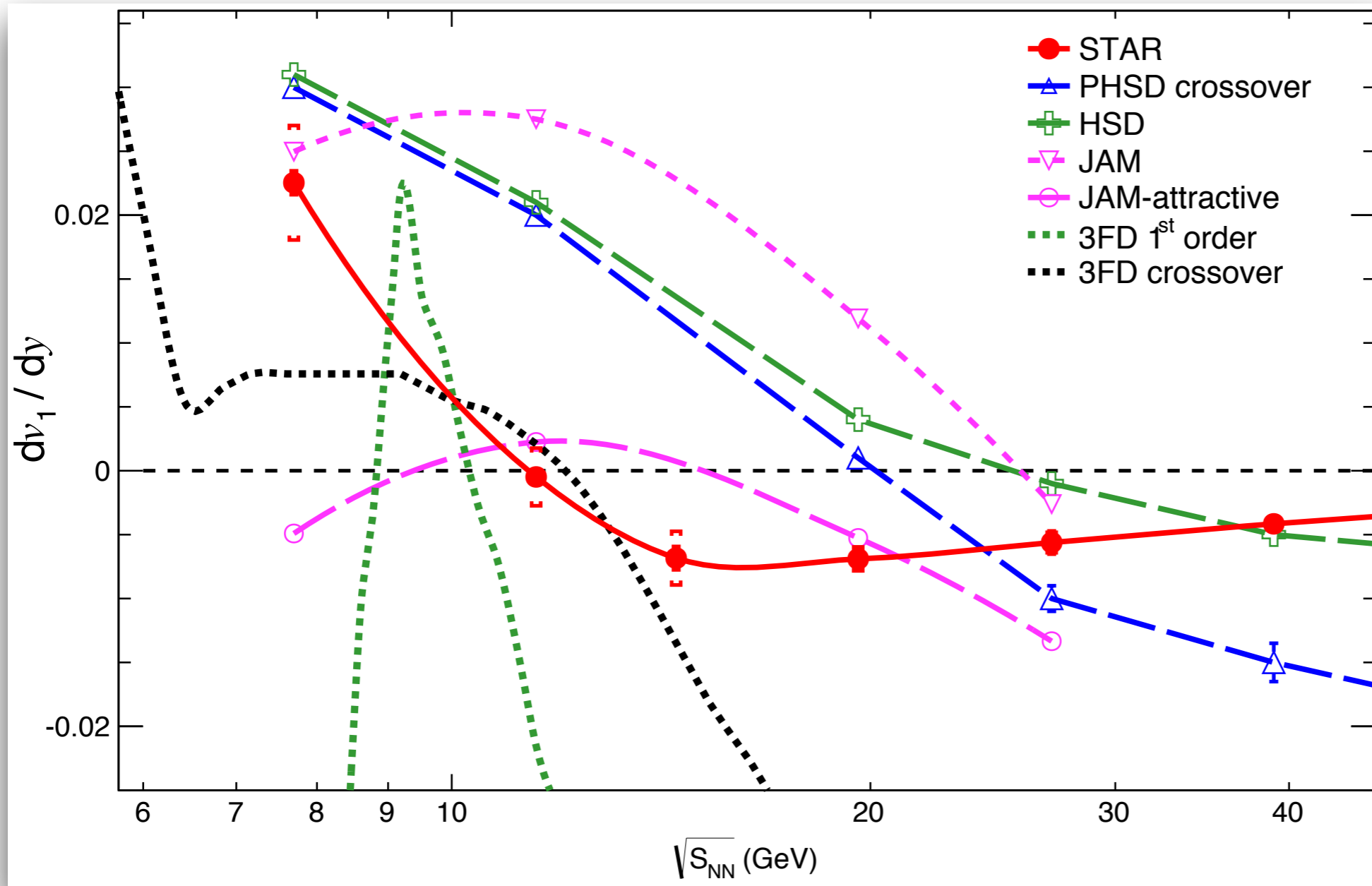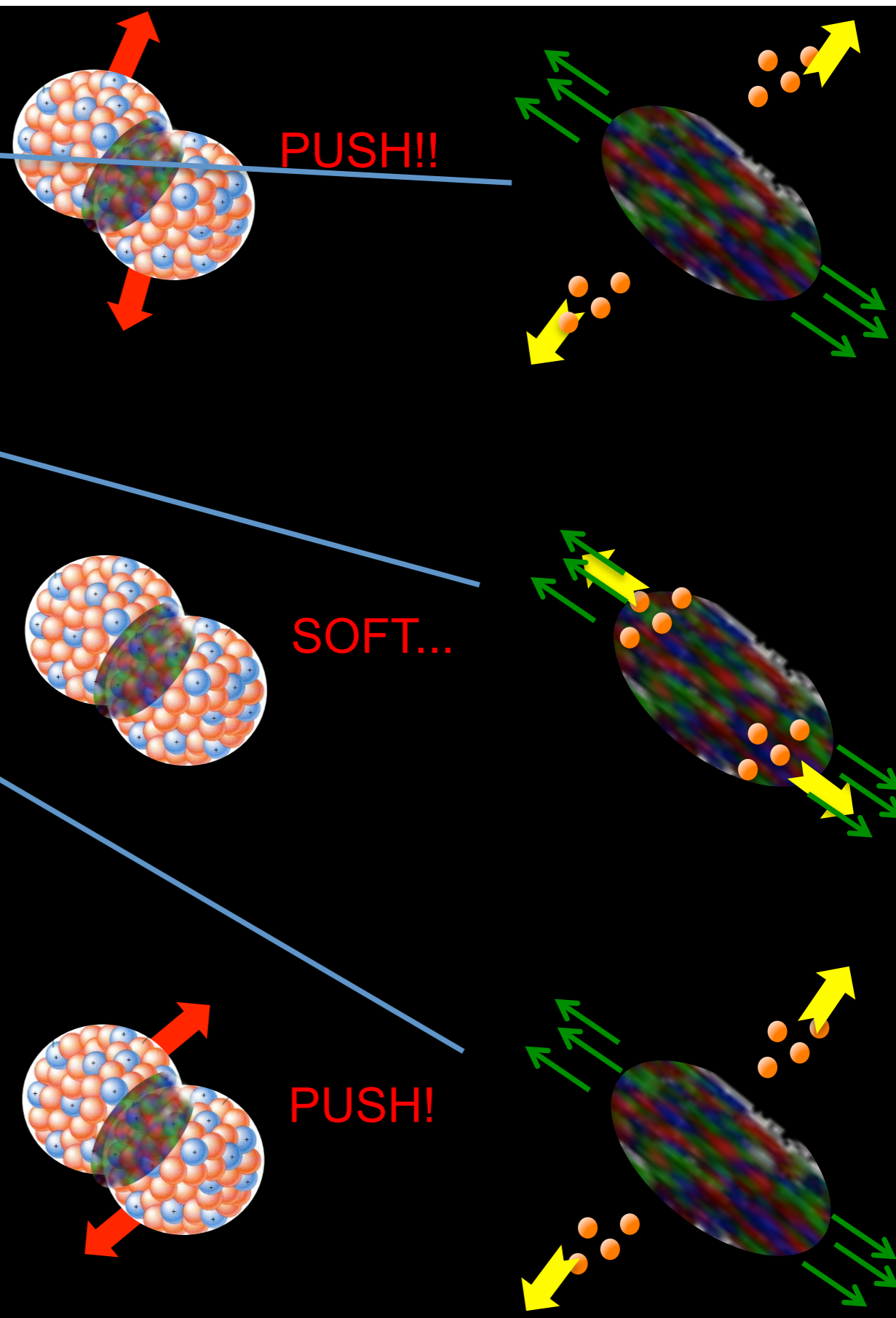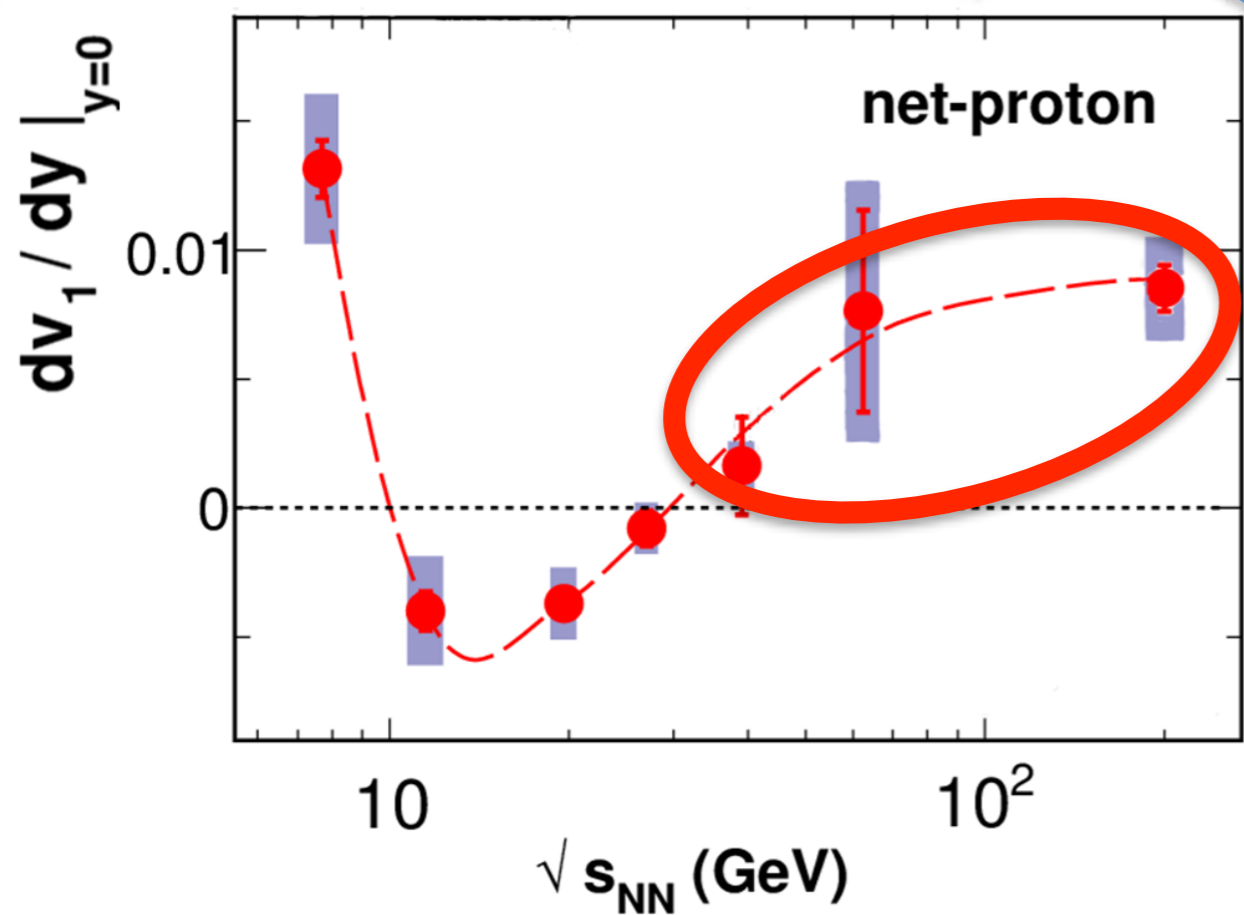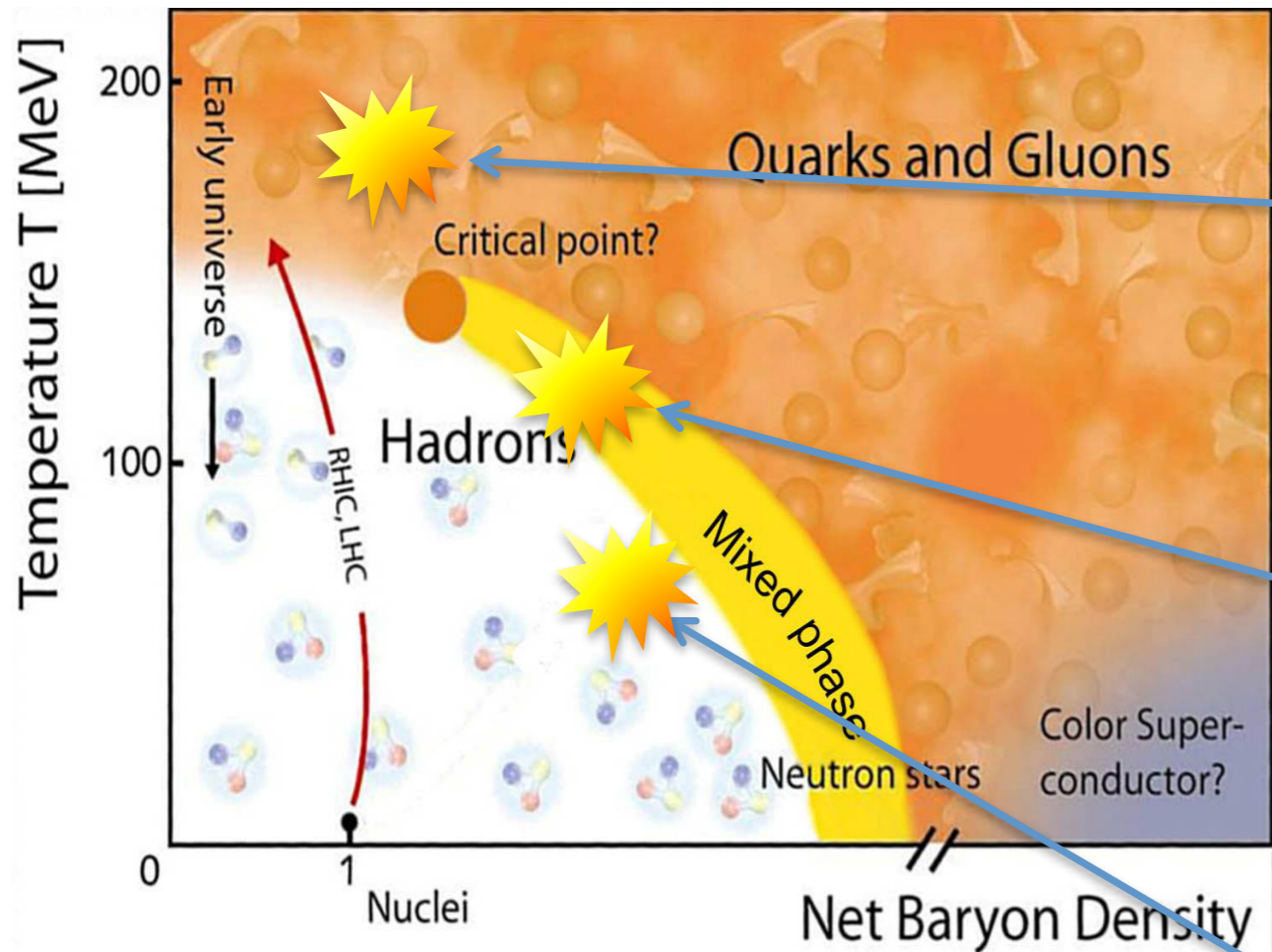
Results from RHIC and LHC
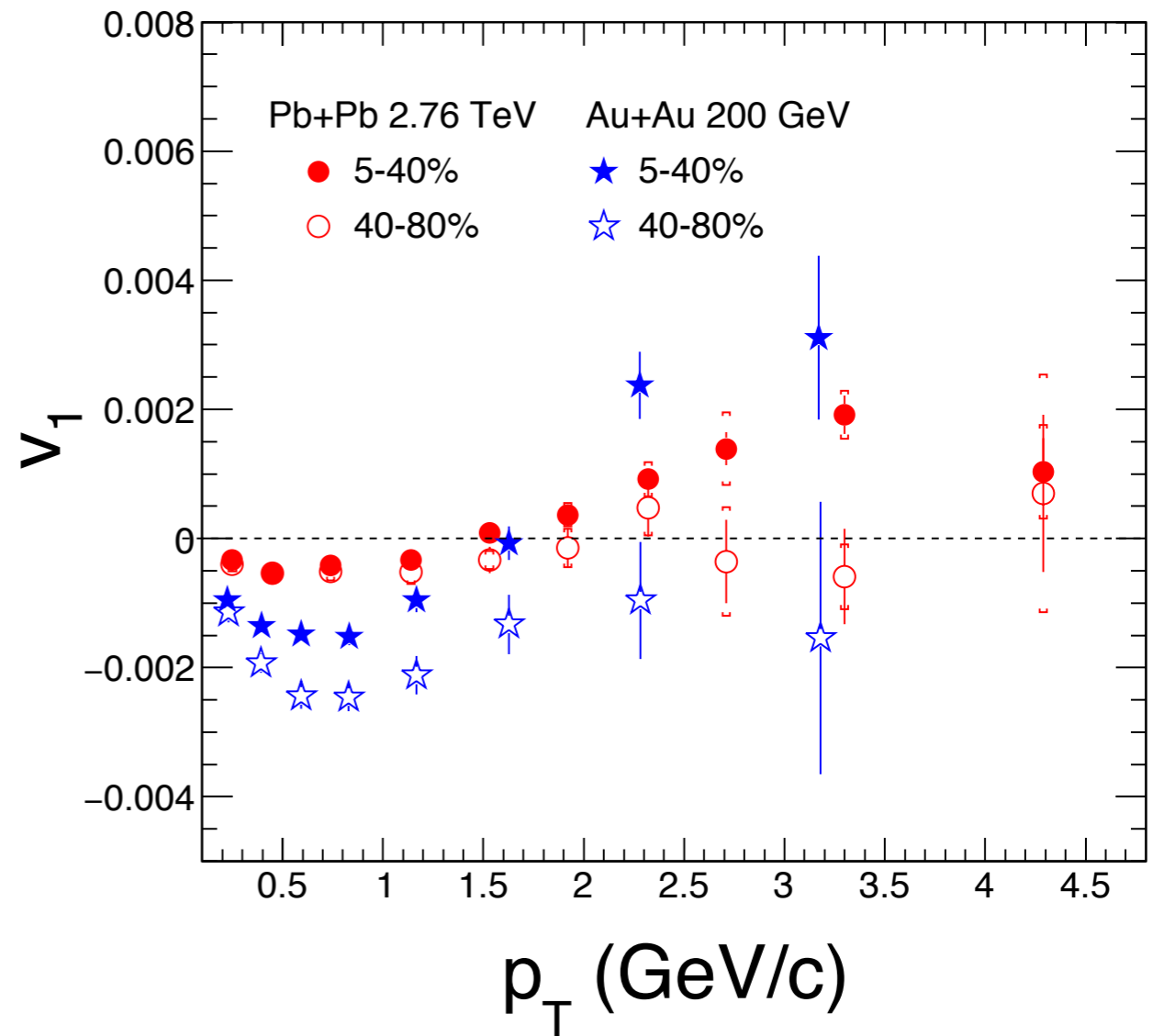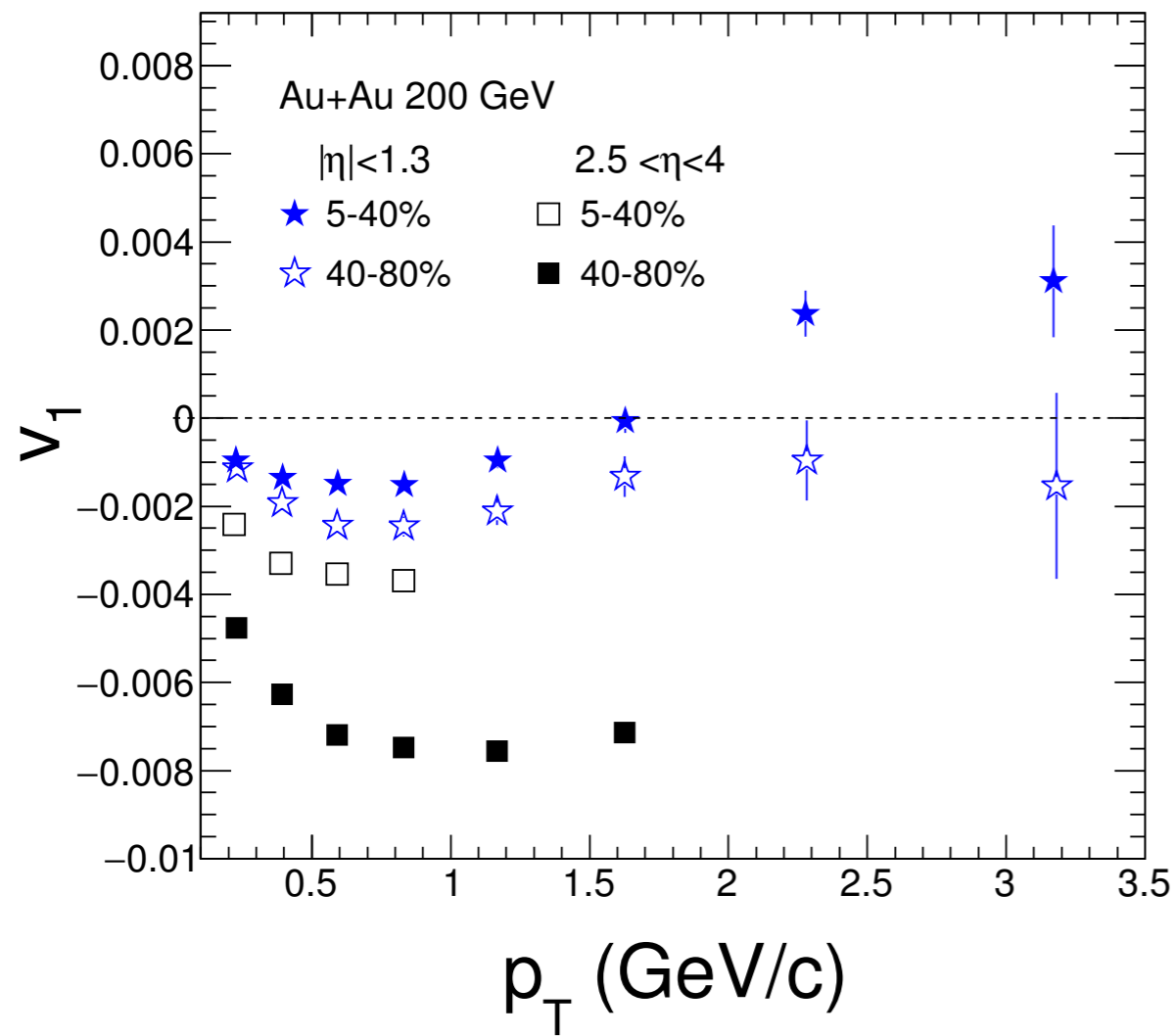
Baryon Density
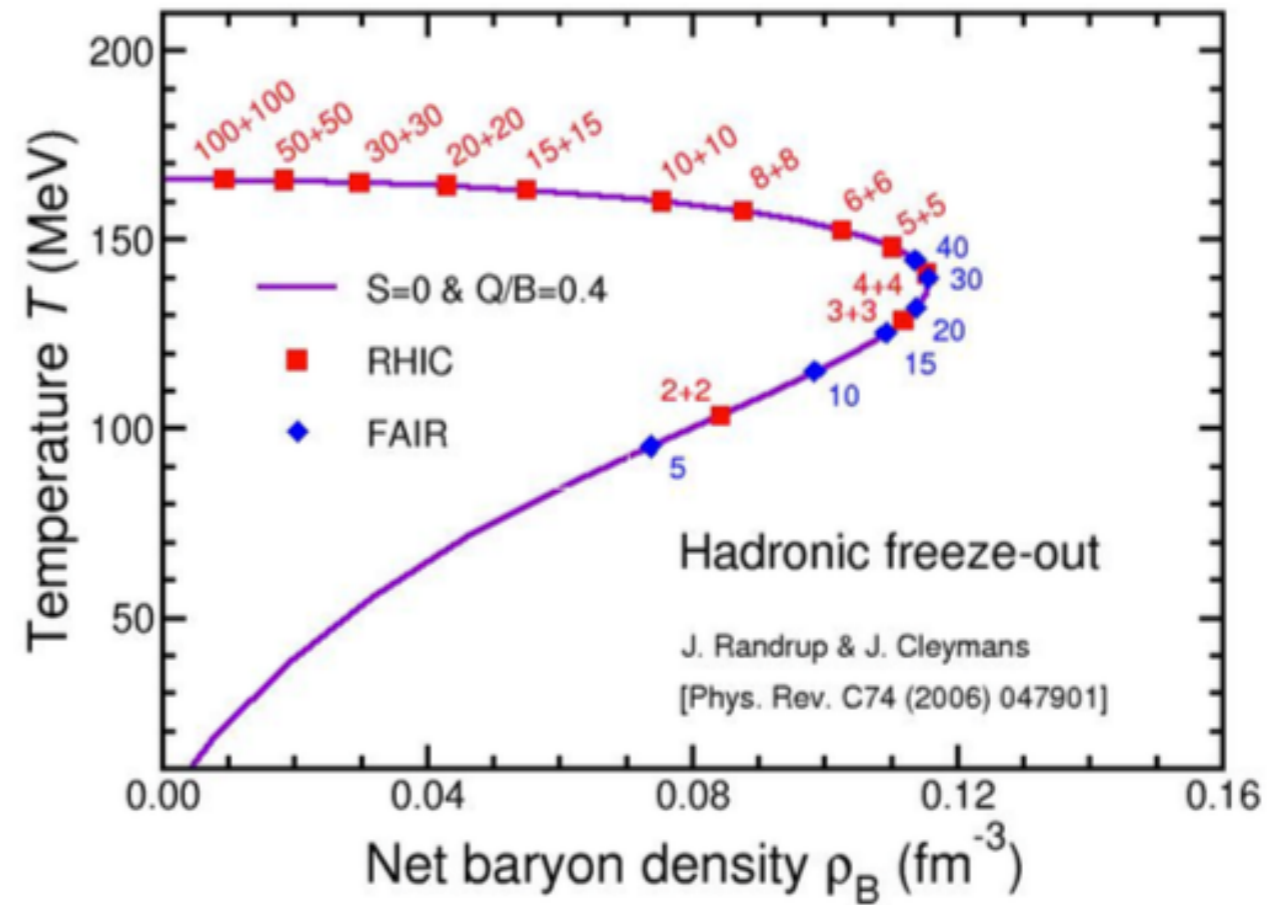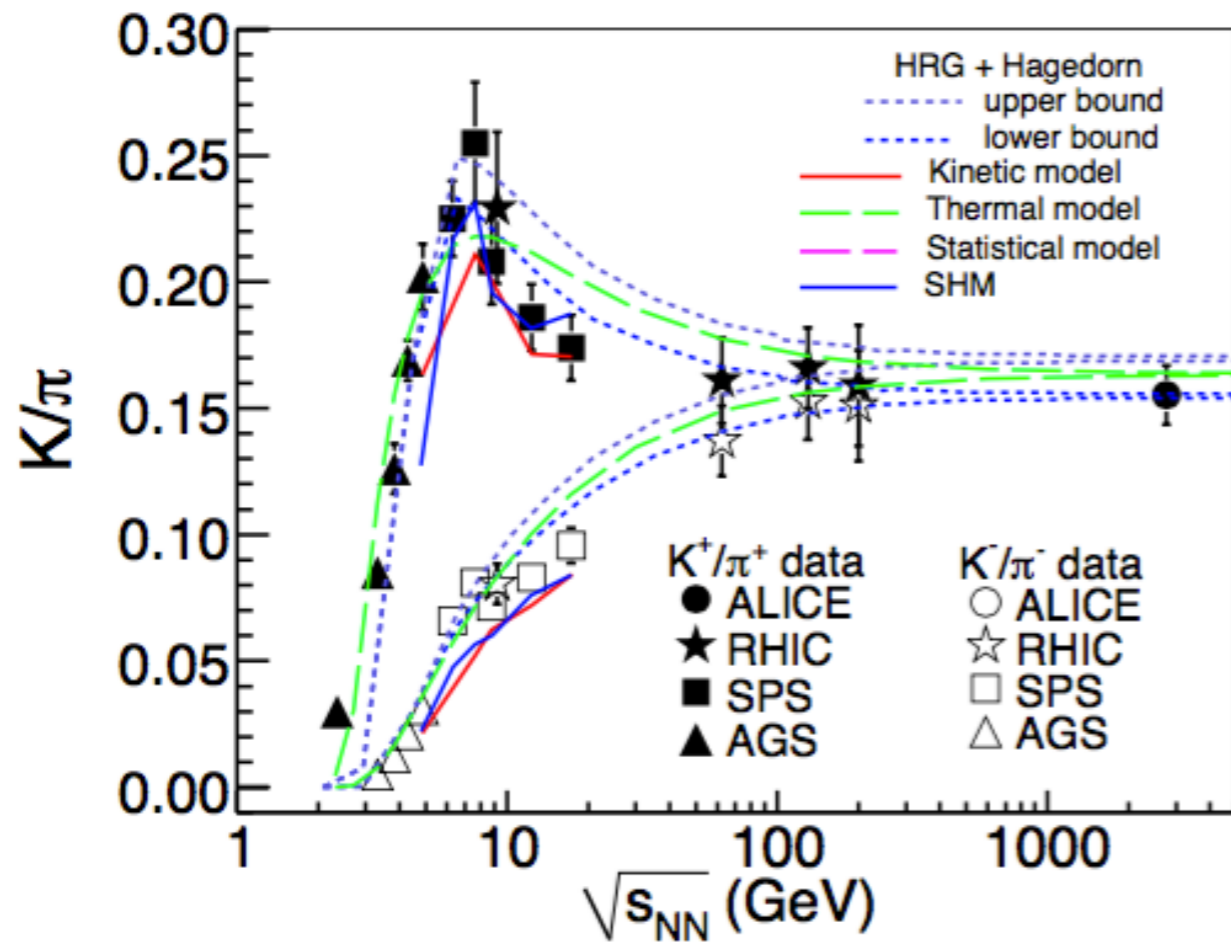
JAM Calculation

BES at RHIC

Cartoon made by Mike Lisa