Directed flow from RHIC Beam Energy Scan Au+Au collisions using the STAR experiment

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(On behalf of STAR Collaboration)

STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

KENT STATE UNIVERSITY

Outline

- ★ Directed flow in heavy-ion collisions
- ★ Beam energy scan (BES) program at RHIC
- ★ STAR detector at RHIC
- ★ Results:

  particles: $\pi^{\pm}$, $K^{\pm}$, K_s^0, p, anti-p, Λ, anti-Λ and ϕ

  $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV

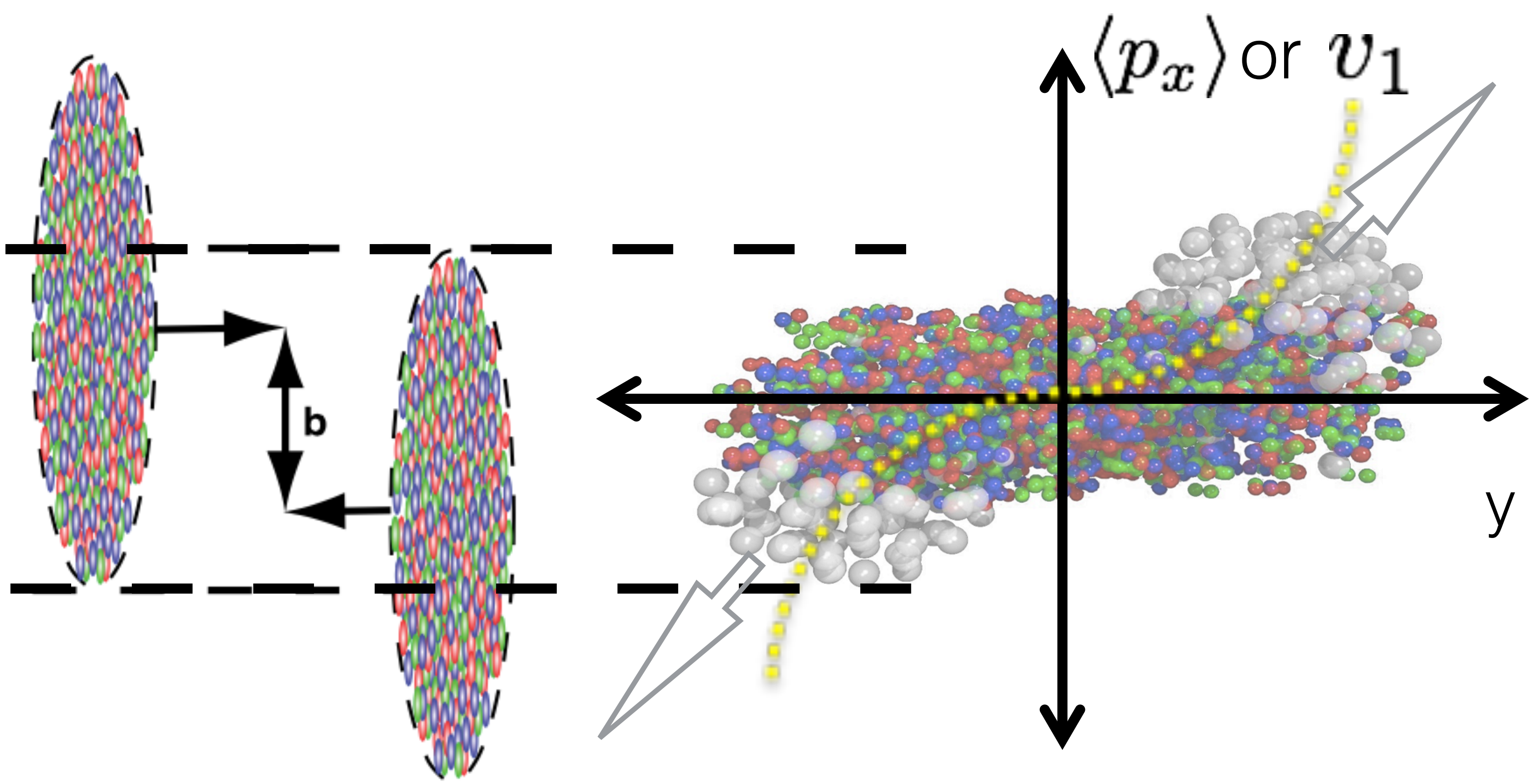
- ★ Summary and Outlook

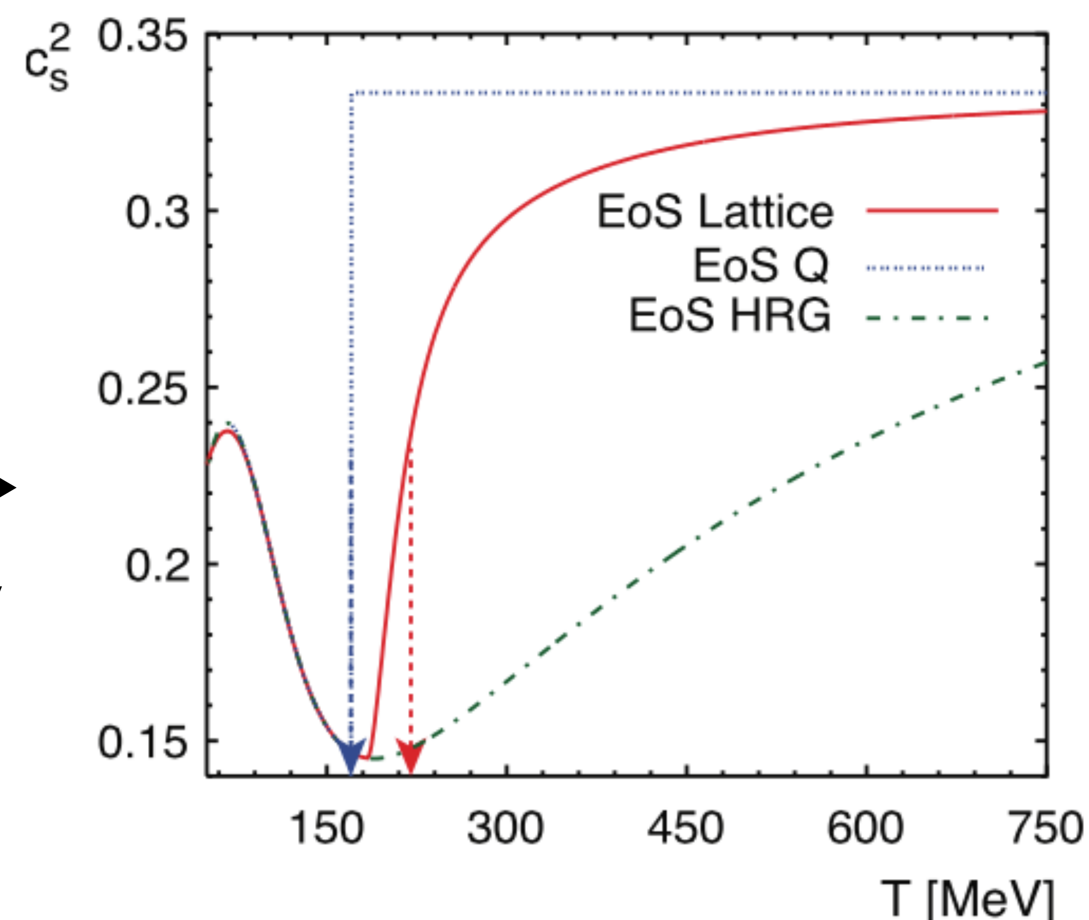
Flow in heavy-ion collisions

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

directed flow (v_1) — elliptic flow (v_2)

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

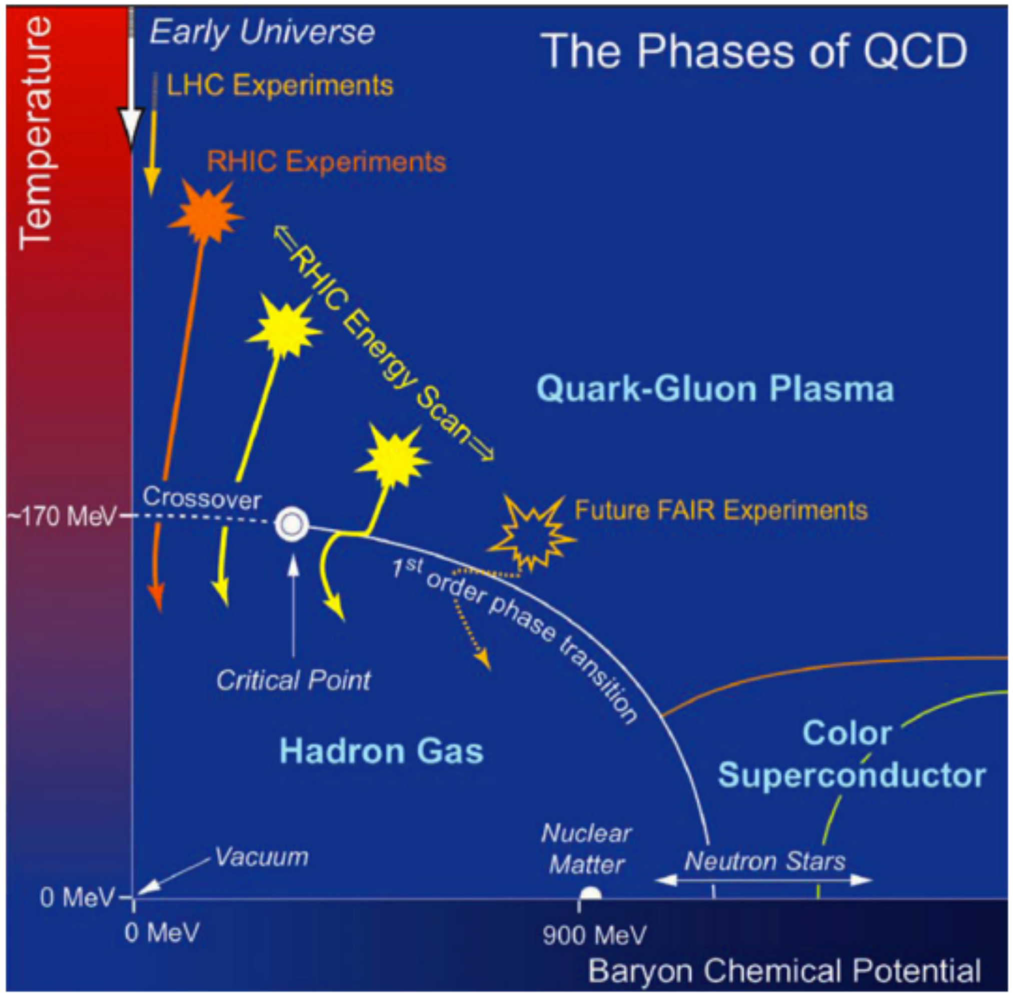




→ Nuclear passage time: 2R/γ ~ 0.1 fm/c
→ Probes early stages of collisions
→ Sensitive to EoS

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

BES-I at RHIC



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

J. Cleymans et al PRC 73, 034905 (2006)

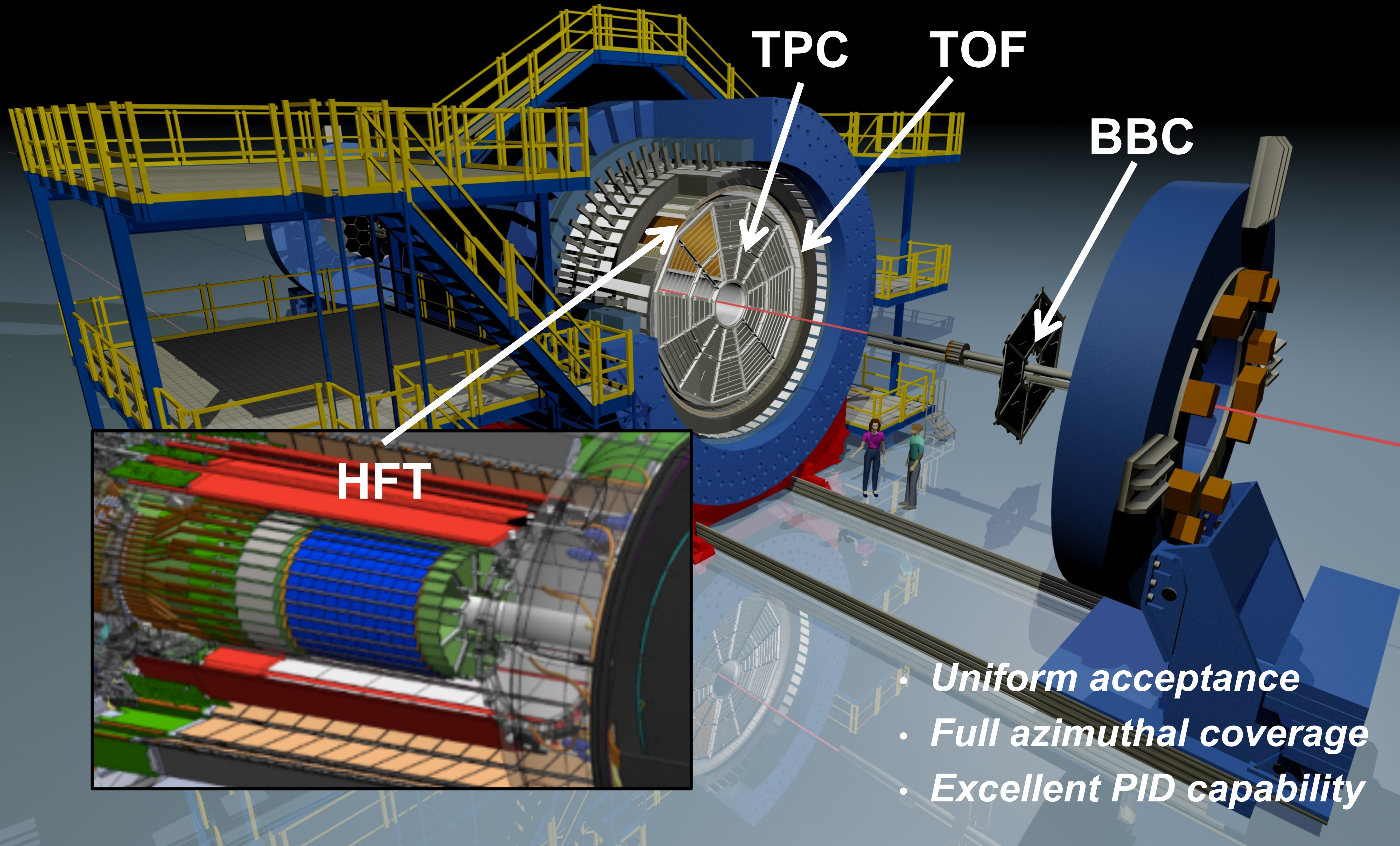
Energy(GeV)	Events (M)	T (MeV)	μ_B(MeV)
7.7	4	140	422
11.5	12	152	316
14.5	18	156	264
19.6	36	160	206
27	70	162	156
39	130	164	112
62.4	67	165	73
200	350	166	25

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*

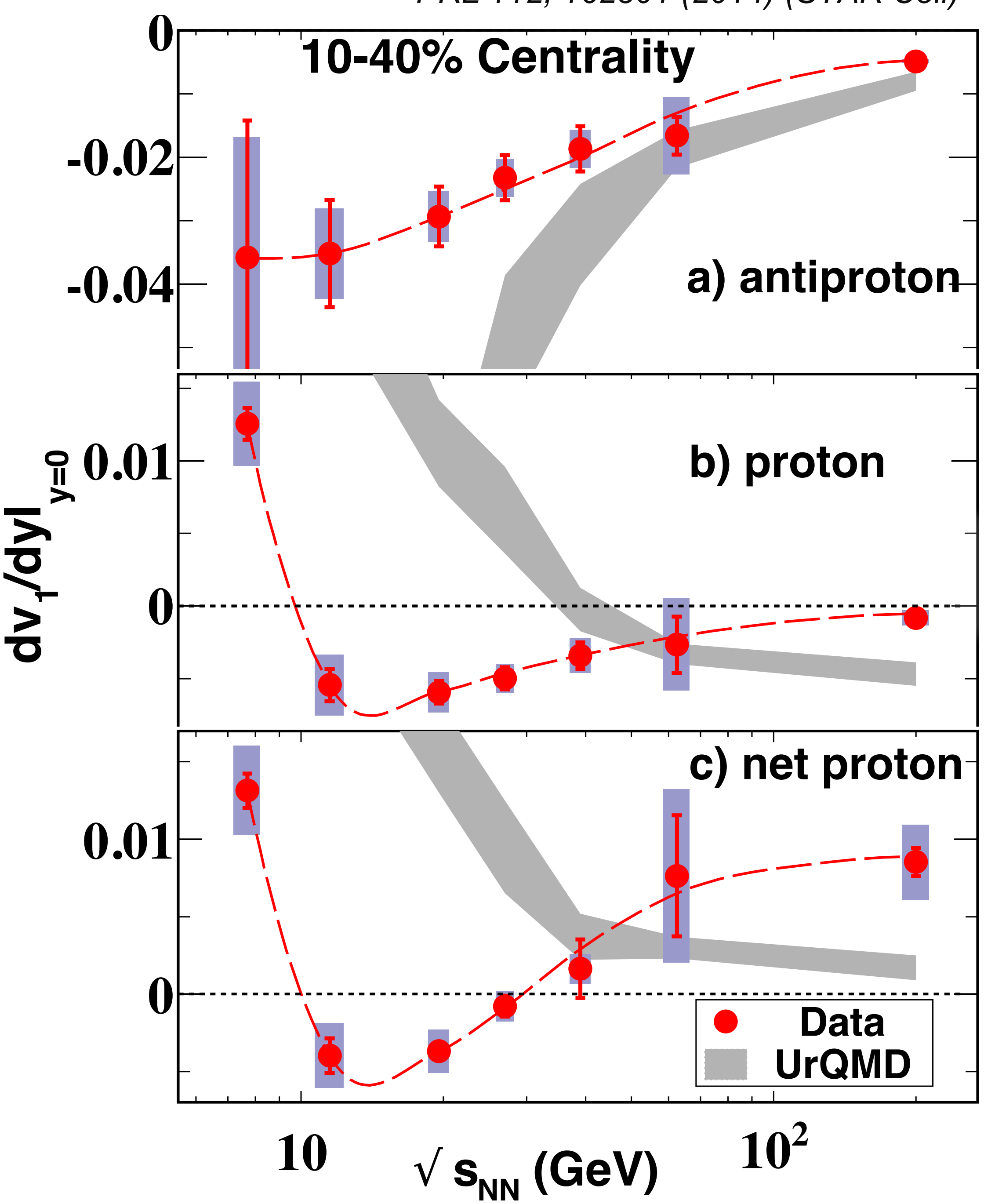
Directed flow (v_1) is a key observable to search for the signature of a 1st order phase transition

STAR Detector



- *Uniform acceptance*
- *Full azimuthal coverage*
- *Excellent PID capability*

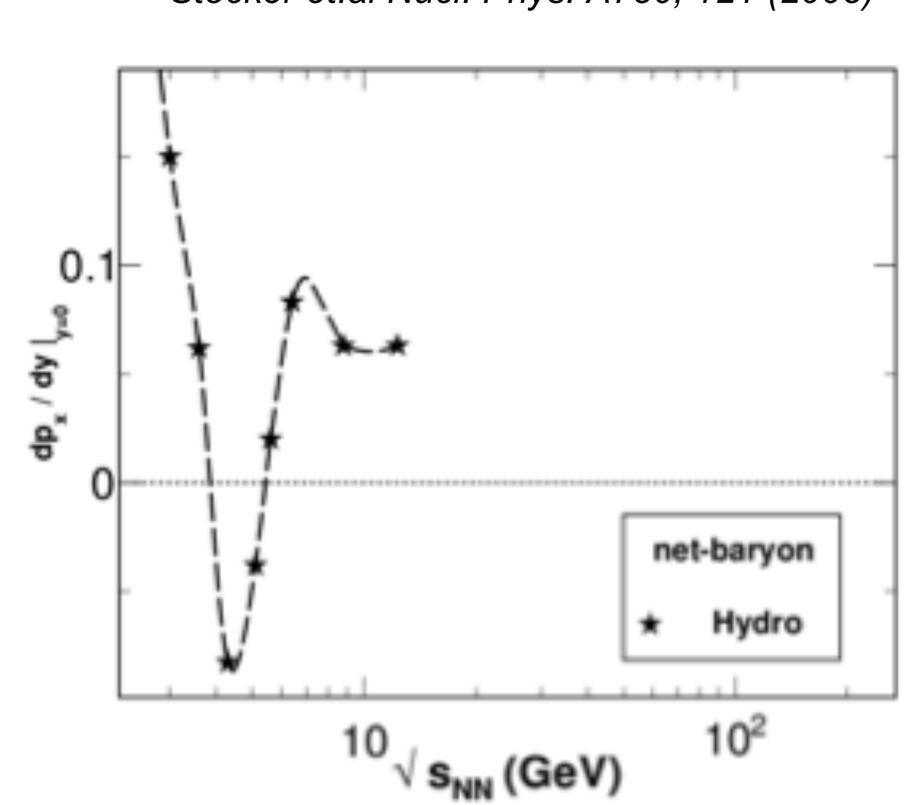
Energy dependence dv_1/dy



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

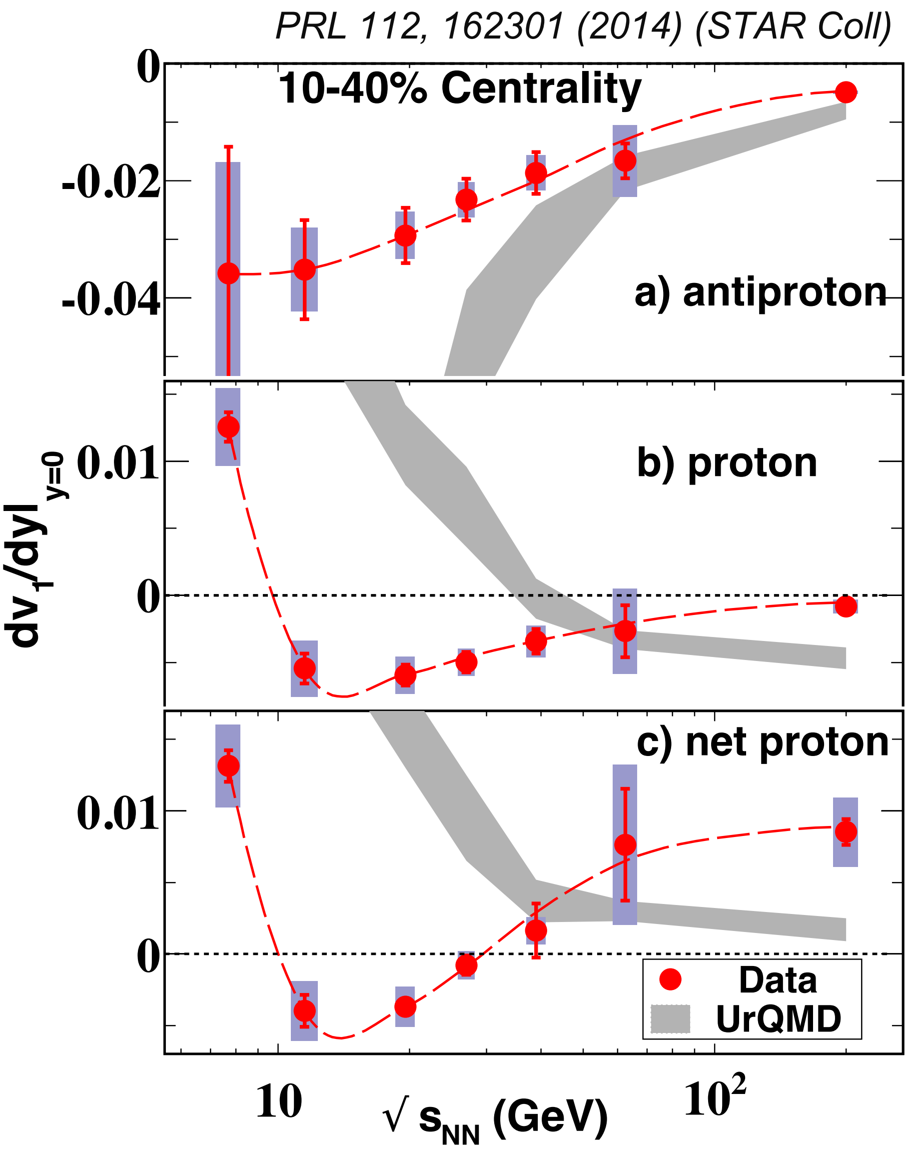
$F = dv_1/dy$, $r_1(y) = \text{anti-p}/p$

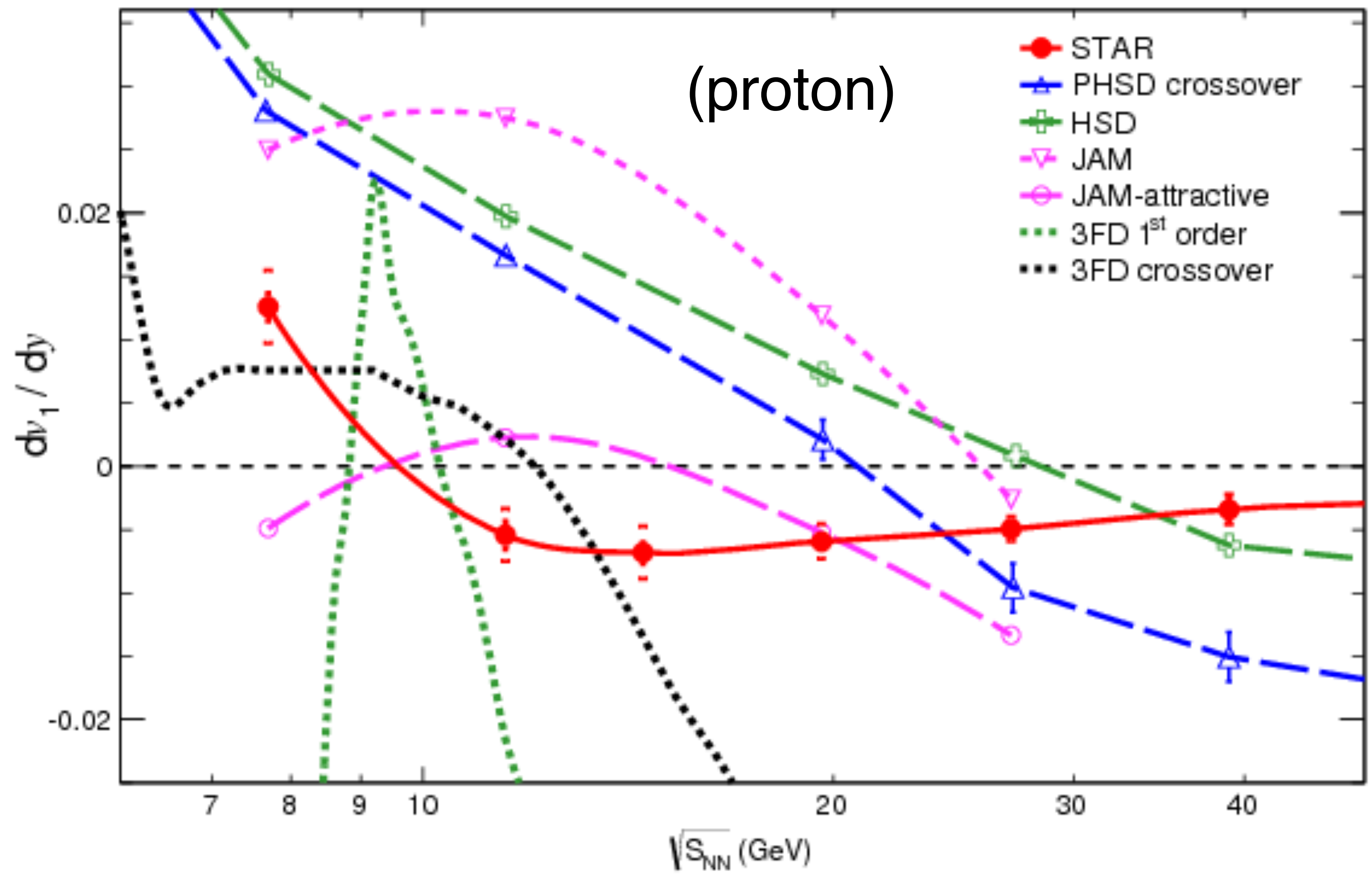
Qualitative resemblance to 3-fluid hydro calculations with 1st order Phase Transition



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

Energy dependence dv_1/dy with models



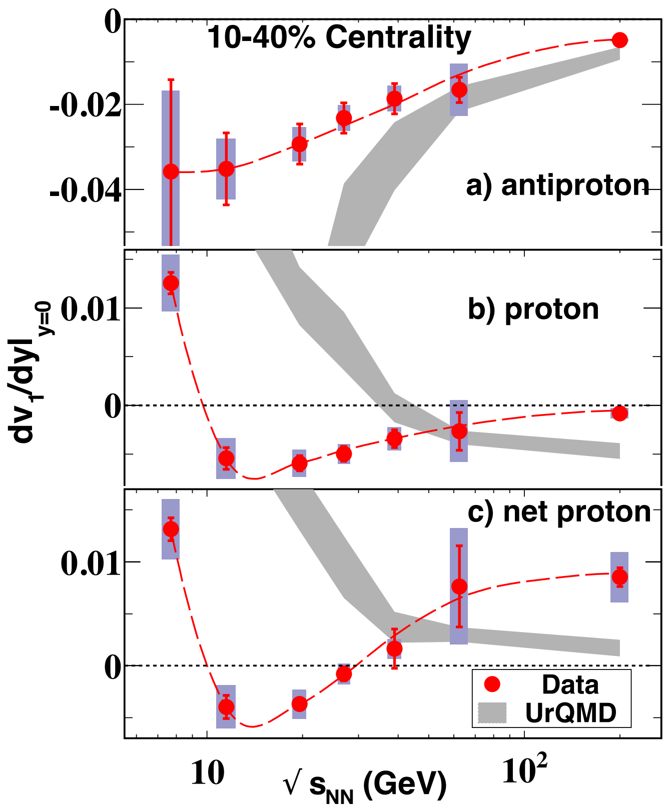


Singha et.al Adv. High Energy Physics 2836989 (2016)
Frankfurt hybrid: J. Steinheimer et al., PRC 89, 054913 (2014)
3 FD: Y. Ivanov et al., PRC 91, 024915 (2015)
PHSD: V. Konchakovski et al., PRC 90, 014903 (2014)
HSD: W. Cassing et al, arXiv: 1408.4313
UrQMD: S. Bass et al, Prog. Part. Nucl. Phys 41, 255, (1998)
JAM: Y. Nara et al., Phys Rev C 94, 034906 (2016)

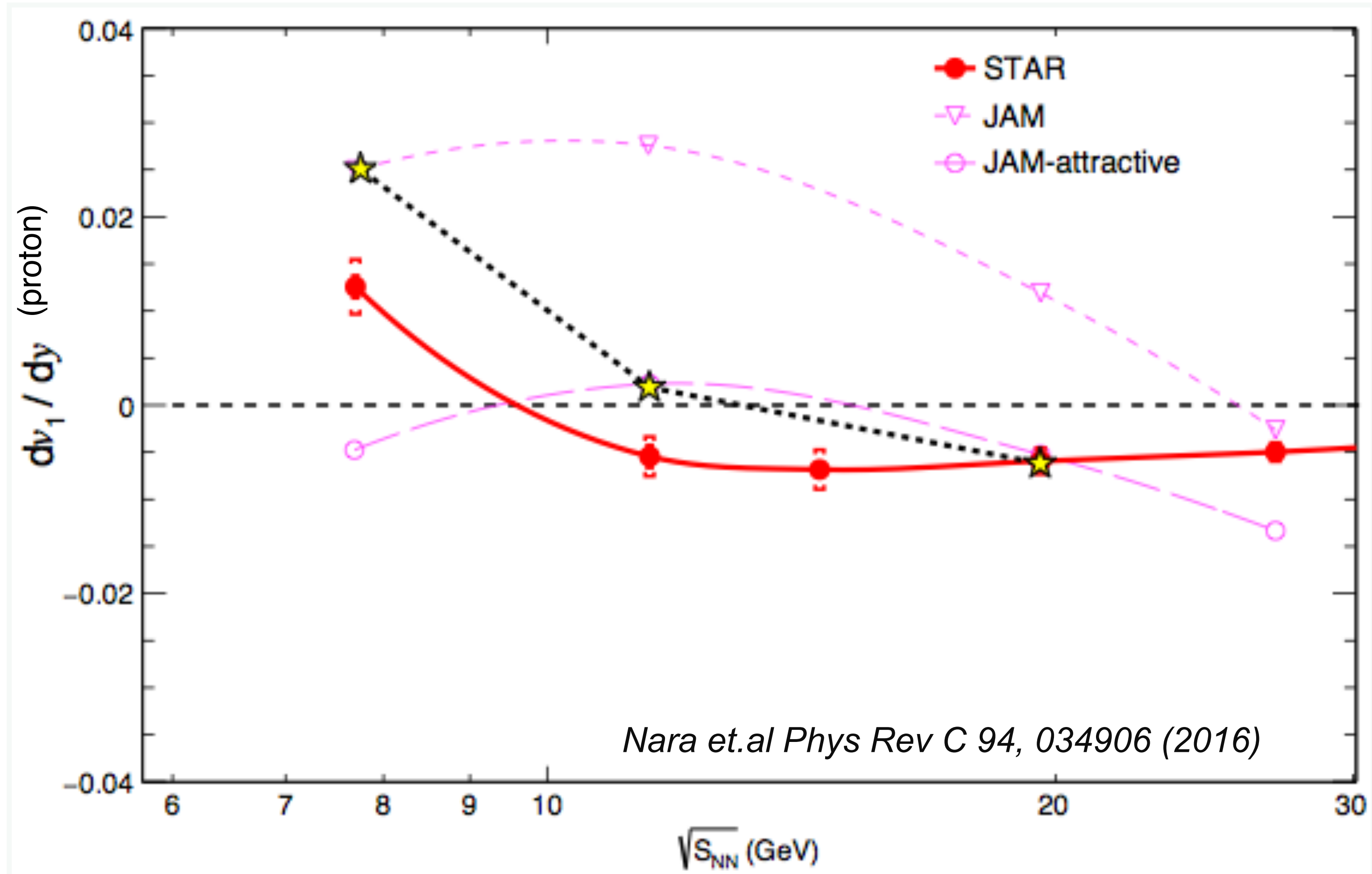
→ Present models can not reproduce the trend observed in data
→ More theoretical progress is needed in this direction

Energy dependence dv_1/dy with models

PRL 112, 162301 (2014) (STAR Coll)



Introduced attractive orbit interactions to simulate softening effect

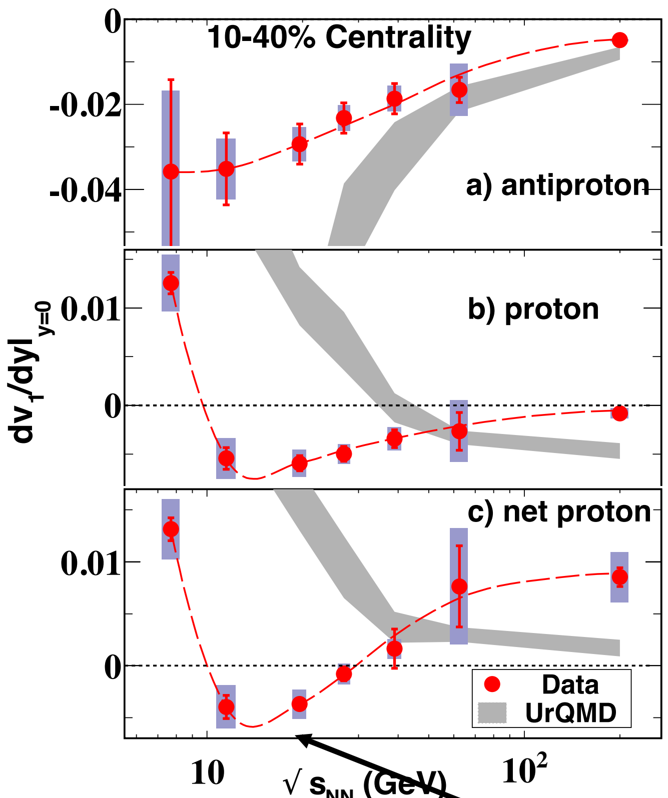


→ Standard JAM (hadronic description):
Close to data at 7.7 GeV
Overestimate data at 11.5 and 19.6 GeV

→ JAM-attractive (modeling of softening effect):
Close to data at 11.5 and 19.6 GeV

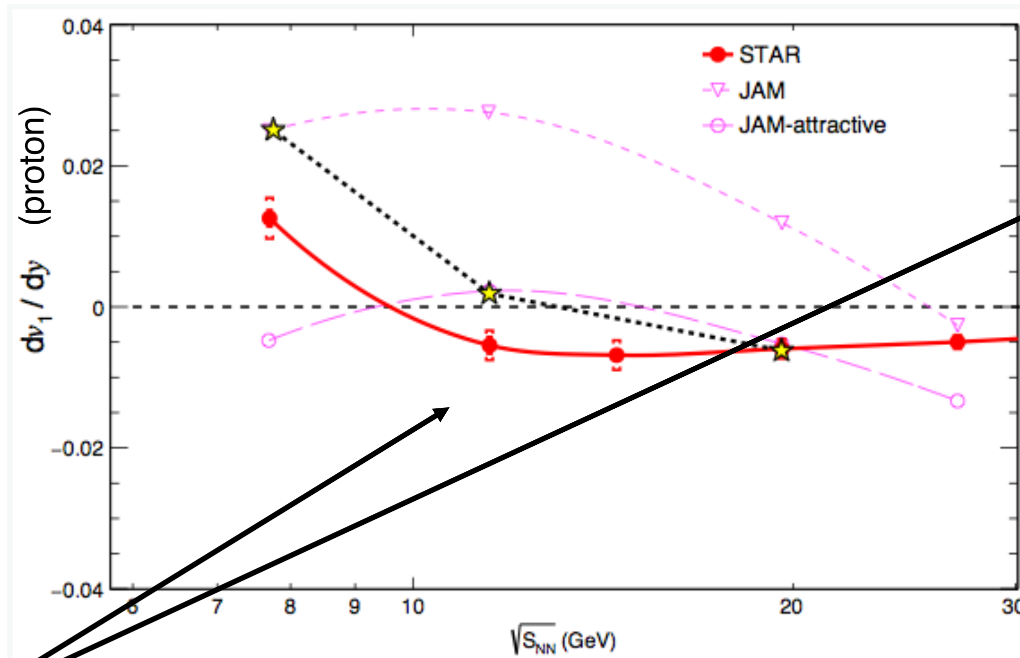
Interesting physics around 10 – 20 GeV

PRL 112, 162301 (2014) (STAR Coll)



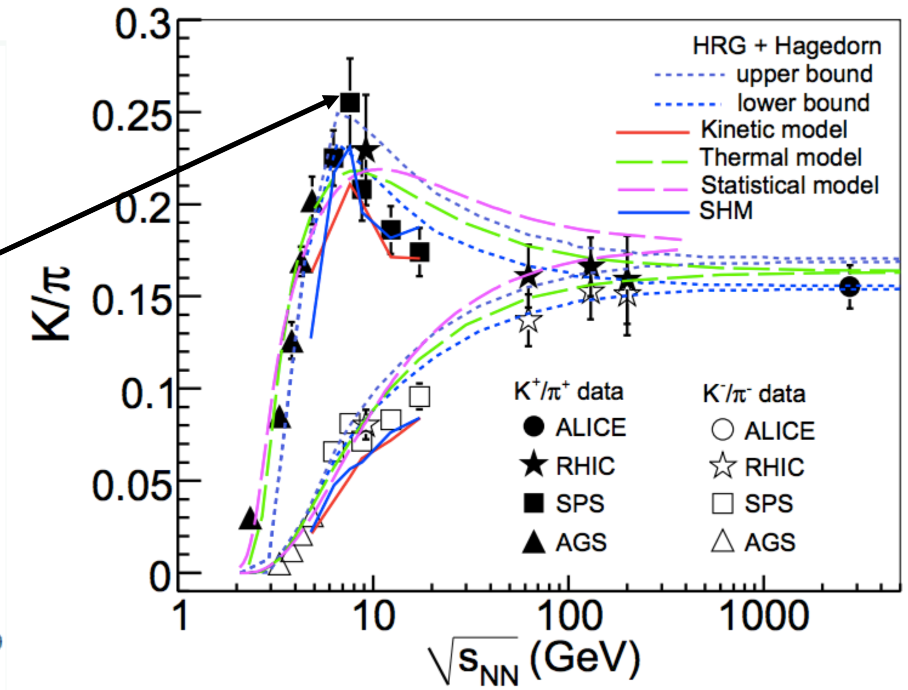
Nara et.al Phys Rev C 94, 034906 (2016)

Introduced attractive orbit interactions to simulate softening effect



Singh et.al arXiv: 1304.2969

Acta Phys Pol B 30, 2705 (1999)

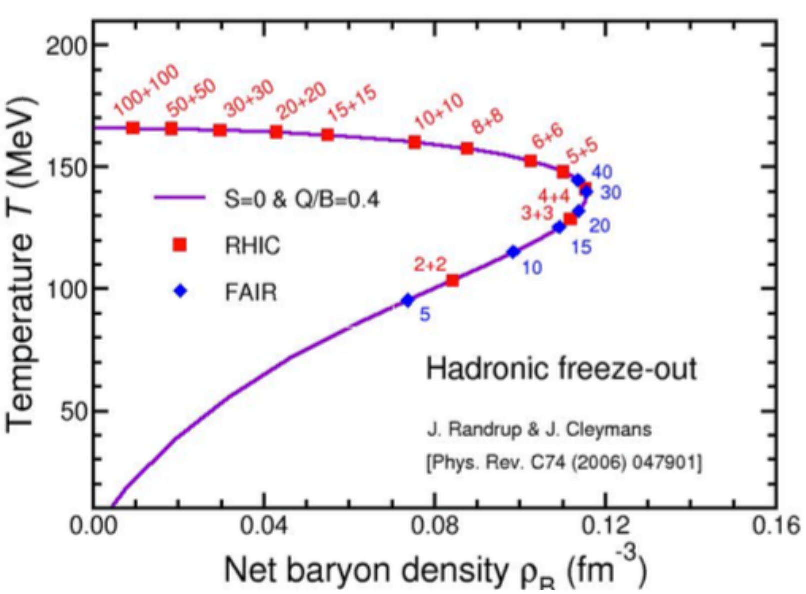


K^+/π^+ peak around 10 GeV

→ System reaches maximum baryonic density

Evidence for softening of EoS (?)

Randrup et.al Phys Rev C 74, 047901 (2006)



At high baryon (net-baryon) density, one might expect a repulsive force

We do see a sign change $\sqrt{s_{NN}}$ = 10 - 15 GeV

Light hadron v_1

<u>New measurements</u>

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

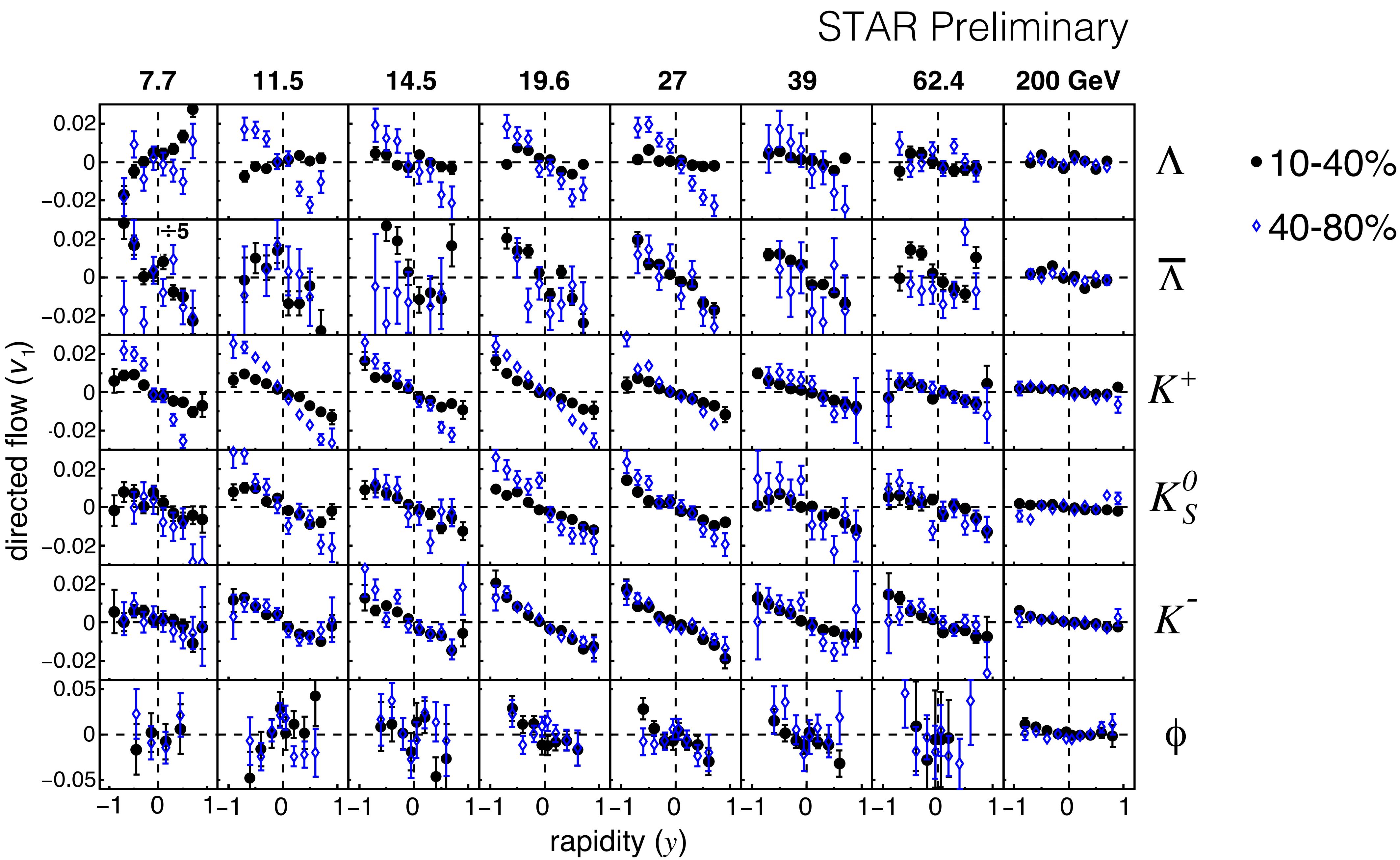
- Λ → Complimentary to p data
- K± → Probe kaon-nucleon potential
- φ → Mass close to p, but it is a vector meson
  Minimally affected by late-stage hadronic interactions

→ Study roles of produced and transported quarks

→ Test hypotheses about transport of initial-state quarks

→ Test constituent quark coalescence hypothesis

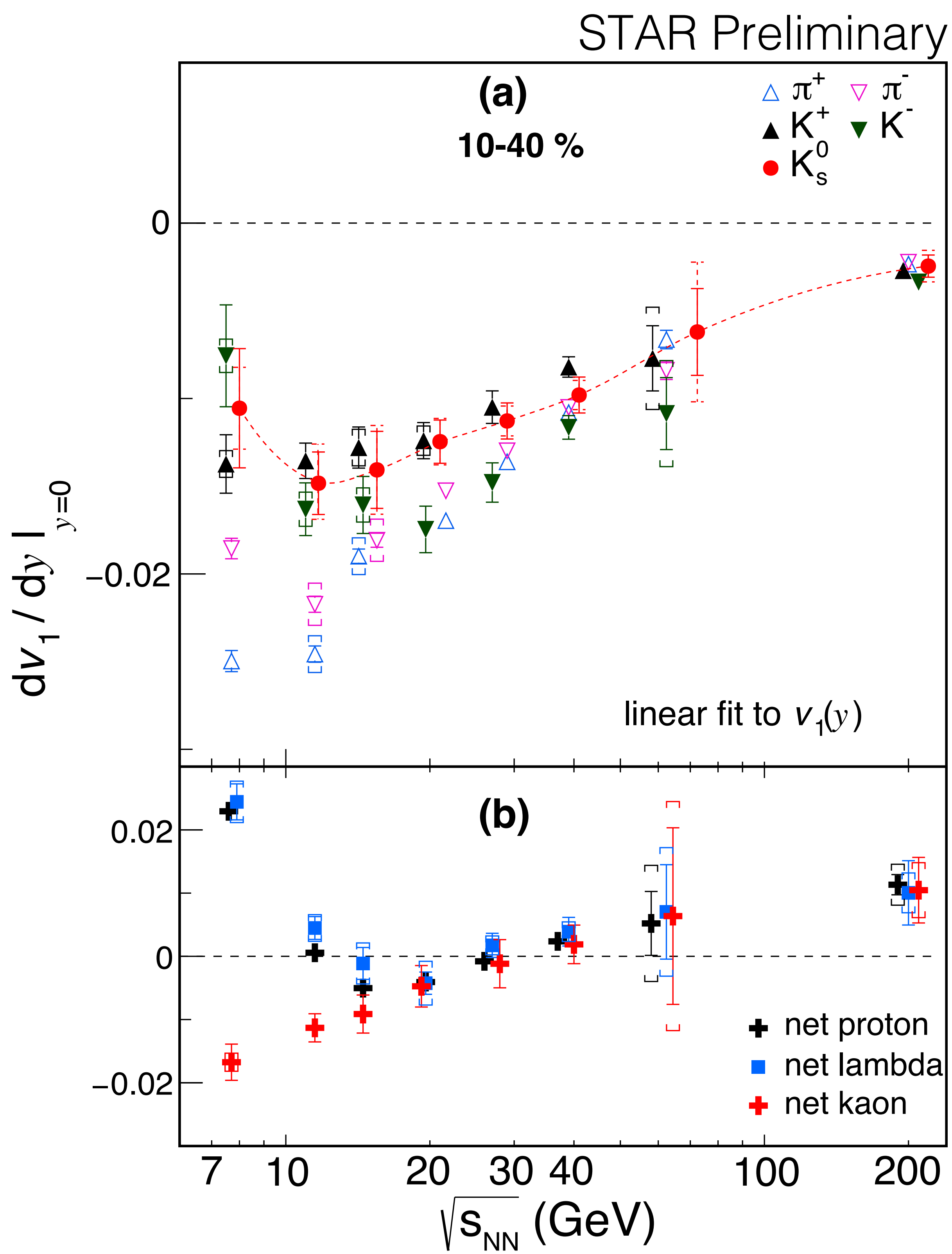
Rapidity dependence of v_1



→ v_1-slope extracted by linear fitting (|y| < 0.8)

→ Poor statistics for particles (e.g. for anti-Λ, ϕ) does not allow stable cubic fit

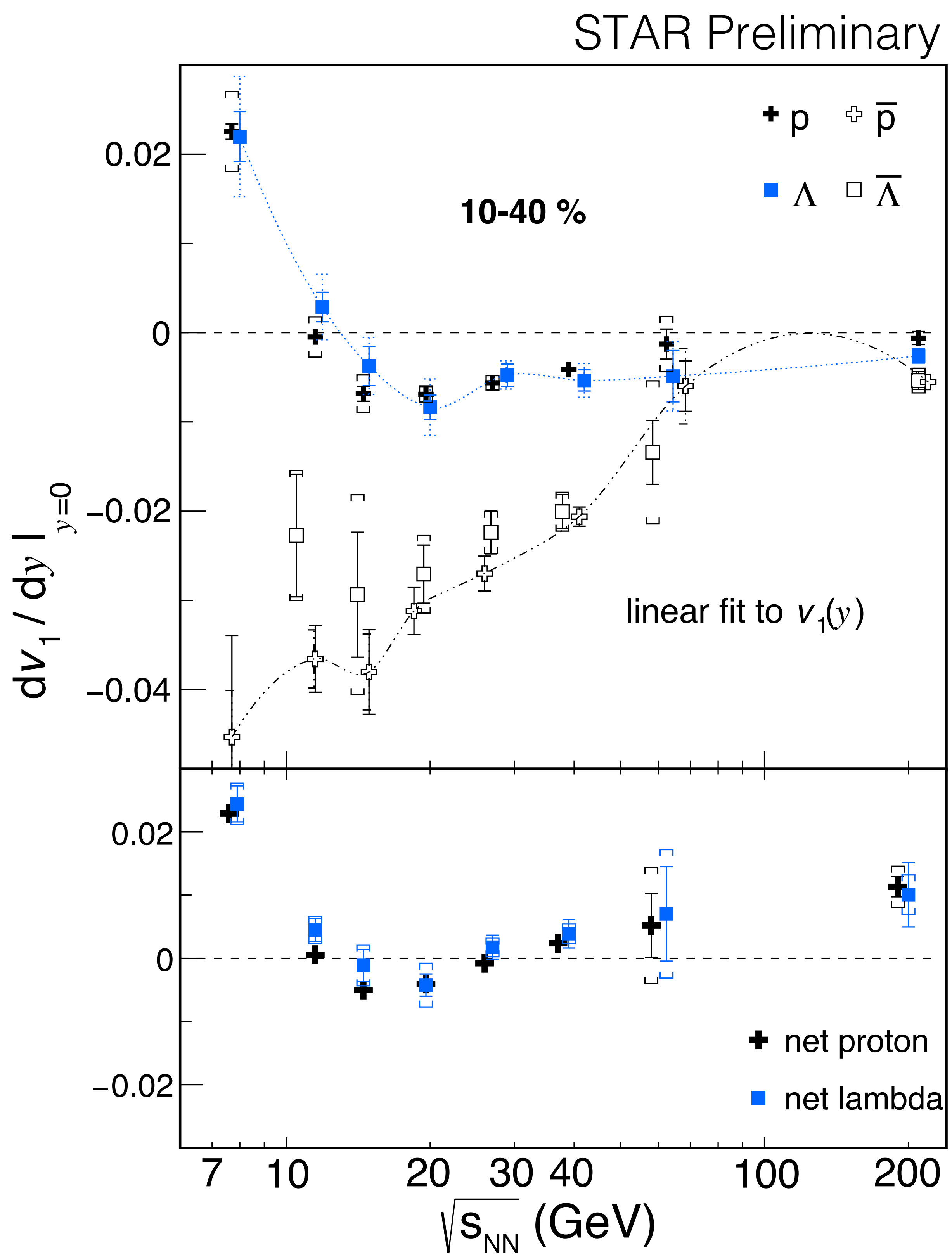
Energy dependence of dv_1/dy



→$(dv_1/dy)_{\pi, K, Ks^0}$ ~ Negative

→$(dv_1/dy)_{Ks^0}$ ~ lies in between $K^{\pm}$

Energy dependence of dv_1/dy



→ $(dv_1/dy)_p \sim (dv_1/dy)_\Lambda$

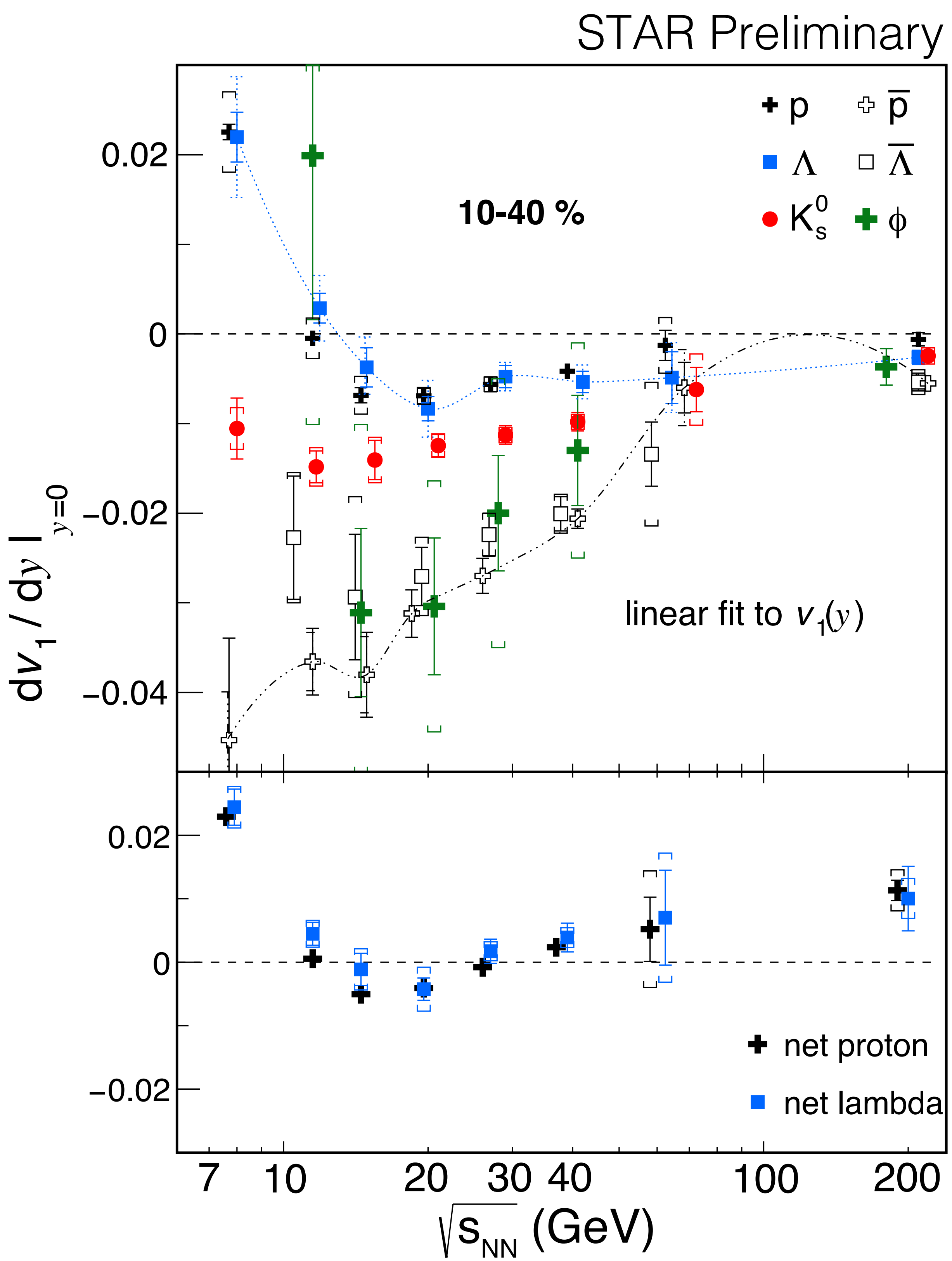
→ $(dv_1/dy)_{anti\text{-}p} \sim (dv_1/dy)_{anti\text{-}\Lambda}$

→ Both baryons show a sign change around $\sqrt{s_{NN}}$ = 10 - 15 GeV

→ Anti-baryons remain negative

→ Both net baryons indicate double sign change

Energy dependence of dv_1/dy

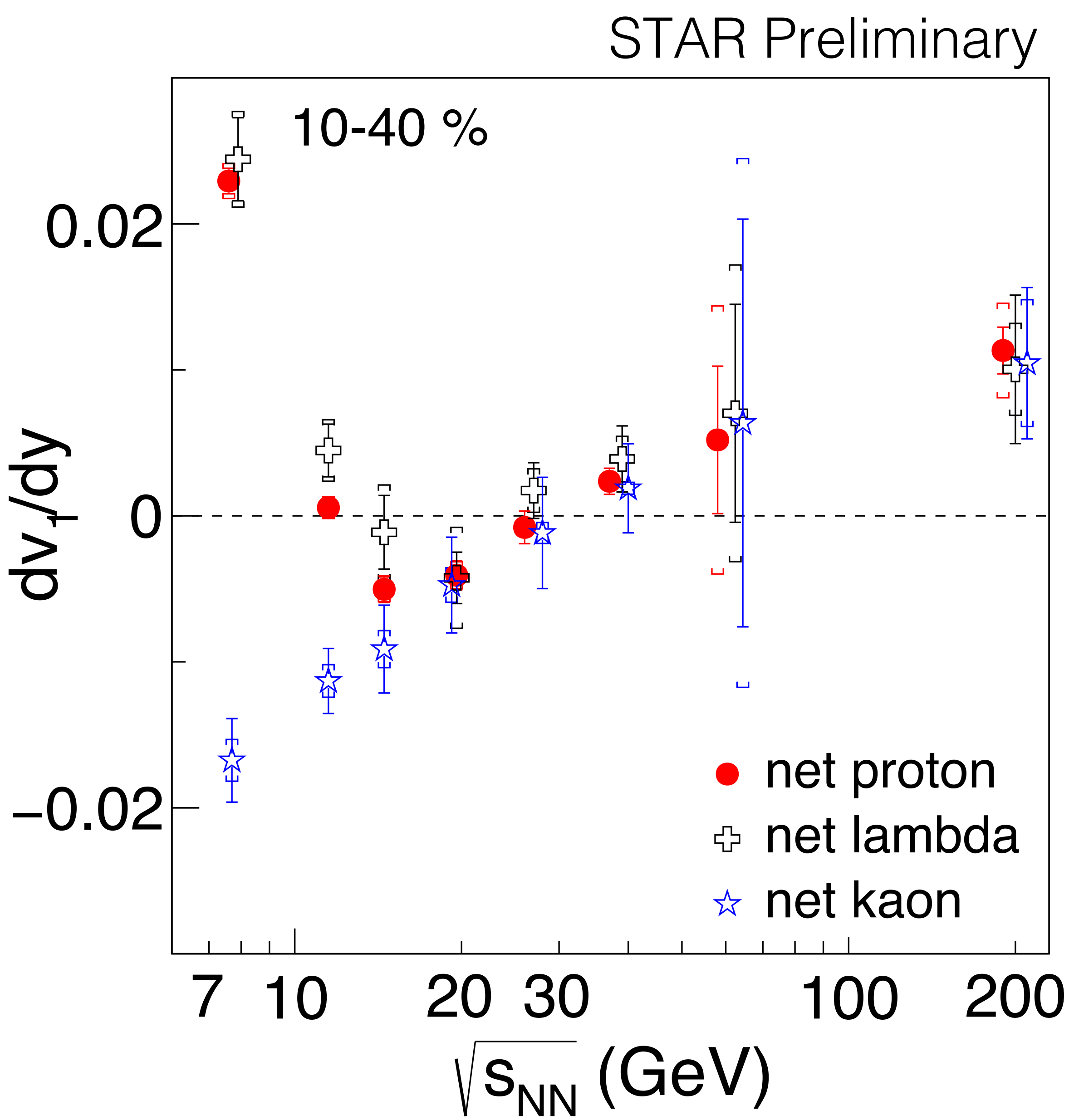


→ $(dv_1/dy)_{anti\text{-}p} \sim (dv_1/dy)_{anti\text{-}\Lambda} \sim (dv_1/dy)_{\phi}$

→ Particles (anti-p, anti-Λ, ϕ) with all the constituent quarks produced from collisions show similar behavior for $\sqrt{s_{NN}} > 14.5$ GeV

	quark content
anti-Λ	$\overline{uds}$
anti-p	$\overline{uud}$
ϕ	$s\bar{s}$

Energy dependence of dv_1/dy



Net particle v_1: enriches transported quarks

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

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

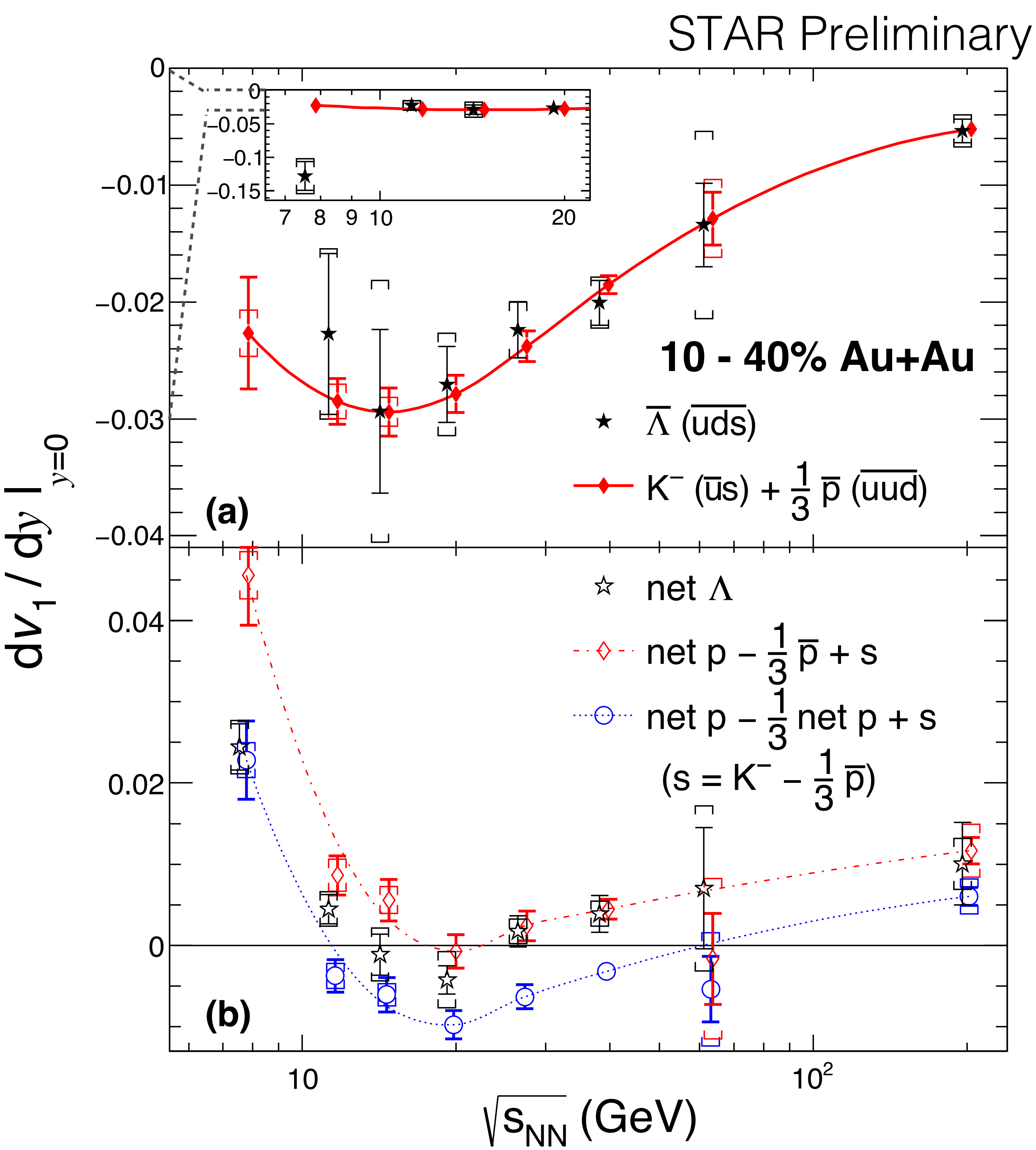
$F_\Lambda = r_3 F_{anti\text{-}\Lambda} + (1-r_3) F_{net\text{-}\Lambda}$

$F_p = dv_1/dy$, $r_1(y) = \text{anti-}p/p$
$F_K = dv_1/dy$, $r_2(y) = K^-/K^+$
$F_\Lambda = dv_1/dy$, $r_3(y) = \text{anti-}\Lambda/\Lambda$

→ $(dv_1/dy)_{net\text{-}p} \sim (dv_1/dy)_{net\text{-}\Lambda}$

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

Energy dependence of dv_1/dy



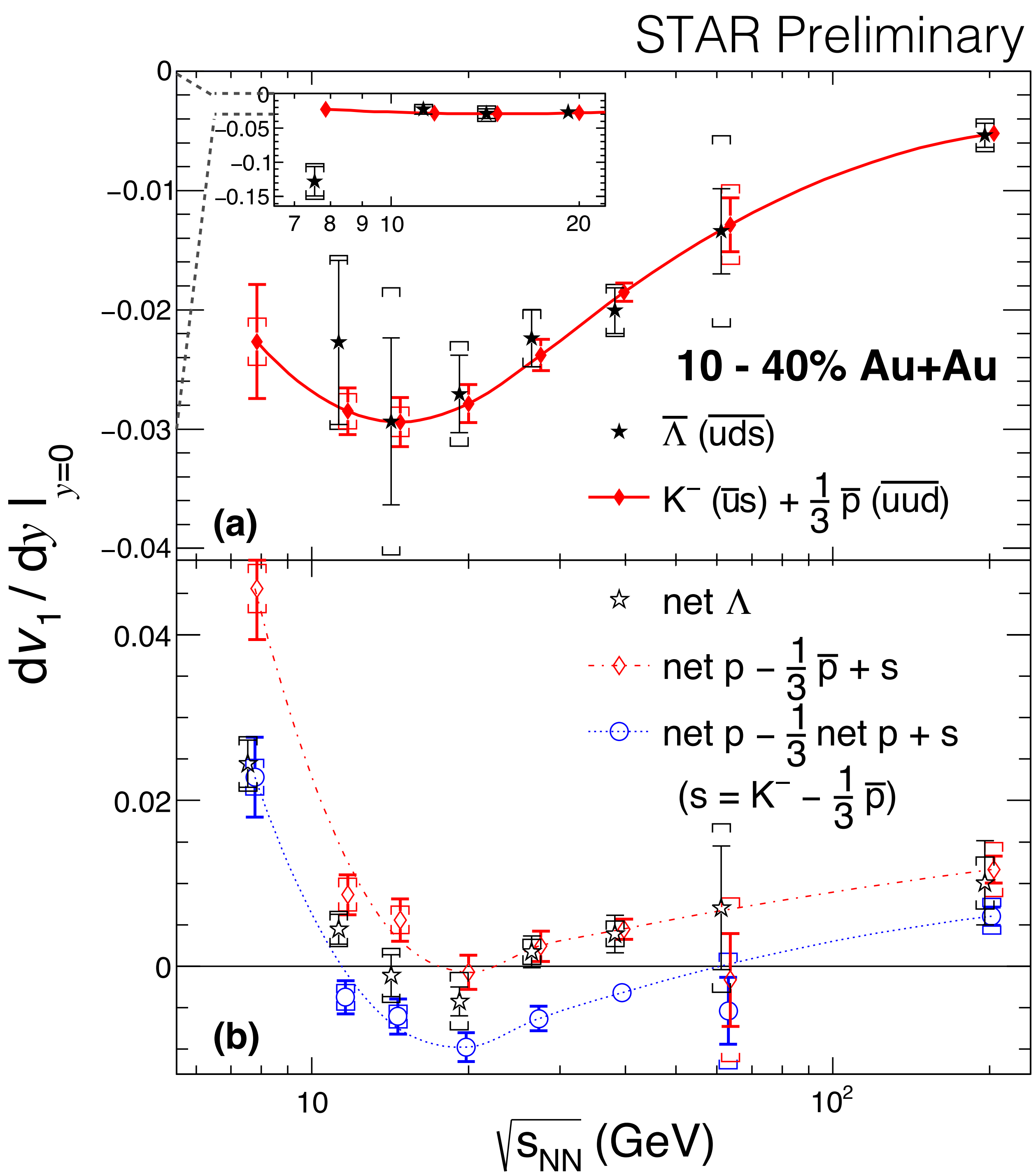
Test assumption that deconfined quarks acquire v_n, then form hadrons.
This assumption leads to v_n sum-rule:

$$(v_n)_{hadron} = \Sigma(v_n)_{\text{constituent quarks}}$$

<u>Using produced quarks:</u>

→ Sum rule holds for 11.5 – 200 GeV, while strong deviation from assumption at 7.7 GeV

Energy dependence of dv_1/dy



<u>Using produced quarks:</u>

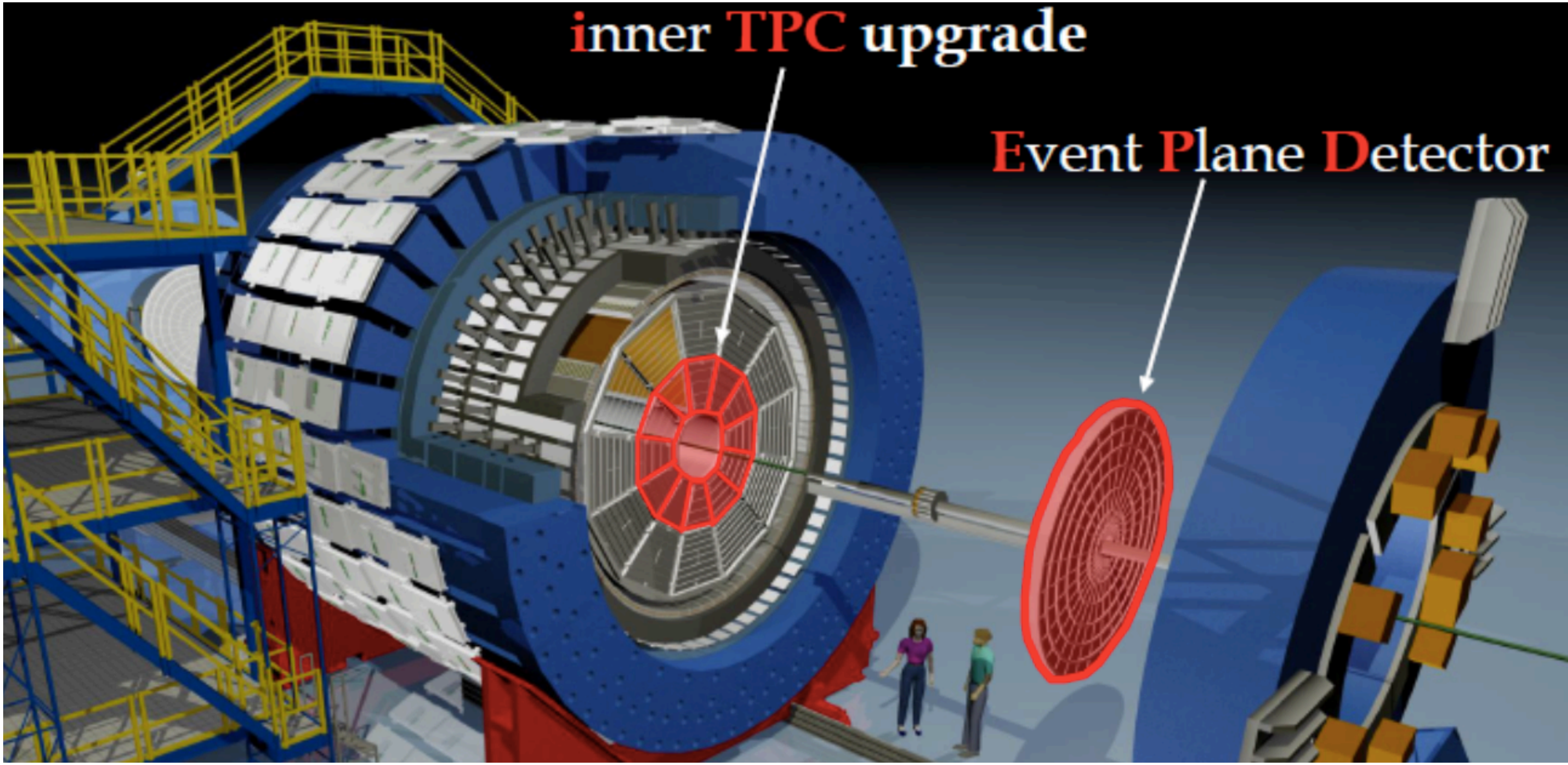
→ Sum rule holds for 11.5 – 200 GeV, while strong deviation from assumption at 7.7 GeV

<u>Using net-particle v_1 to enrich transported quark content:</u>

→ First test of sum rule
→ Second test of sum rule

→ Produced quarks consistent with the expected behavior at BES energies
→ Transported quarks difficult to separate, excepts in the limit of high and low beam energy

BES-II at RHIC



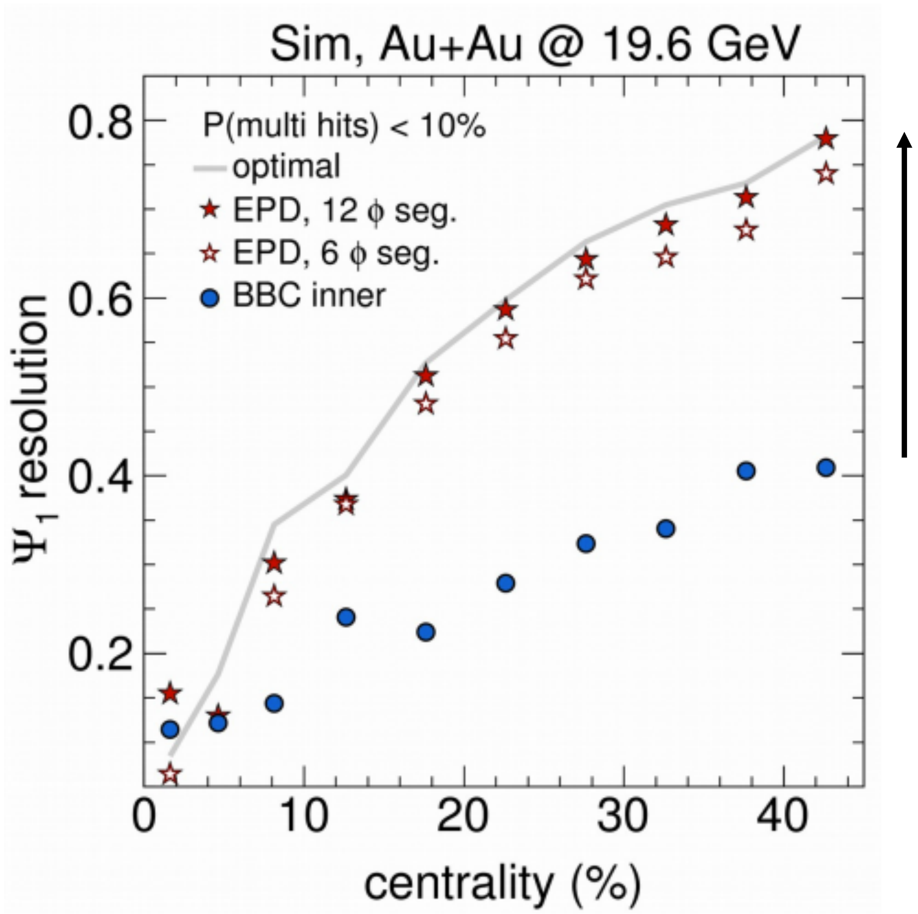
iTPC (-1.7 < |η| < 1.7)

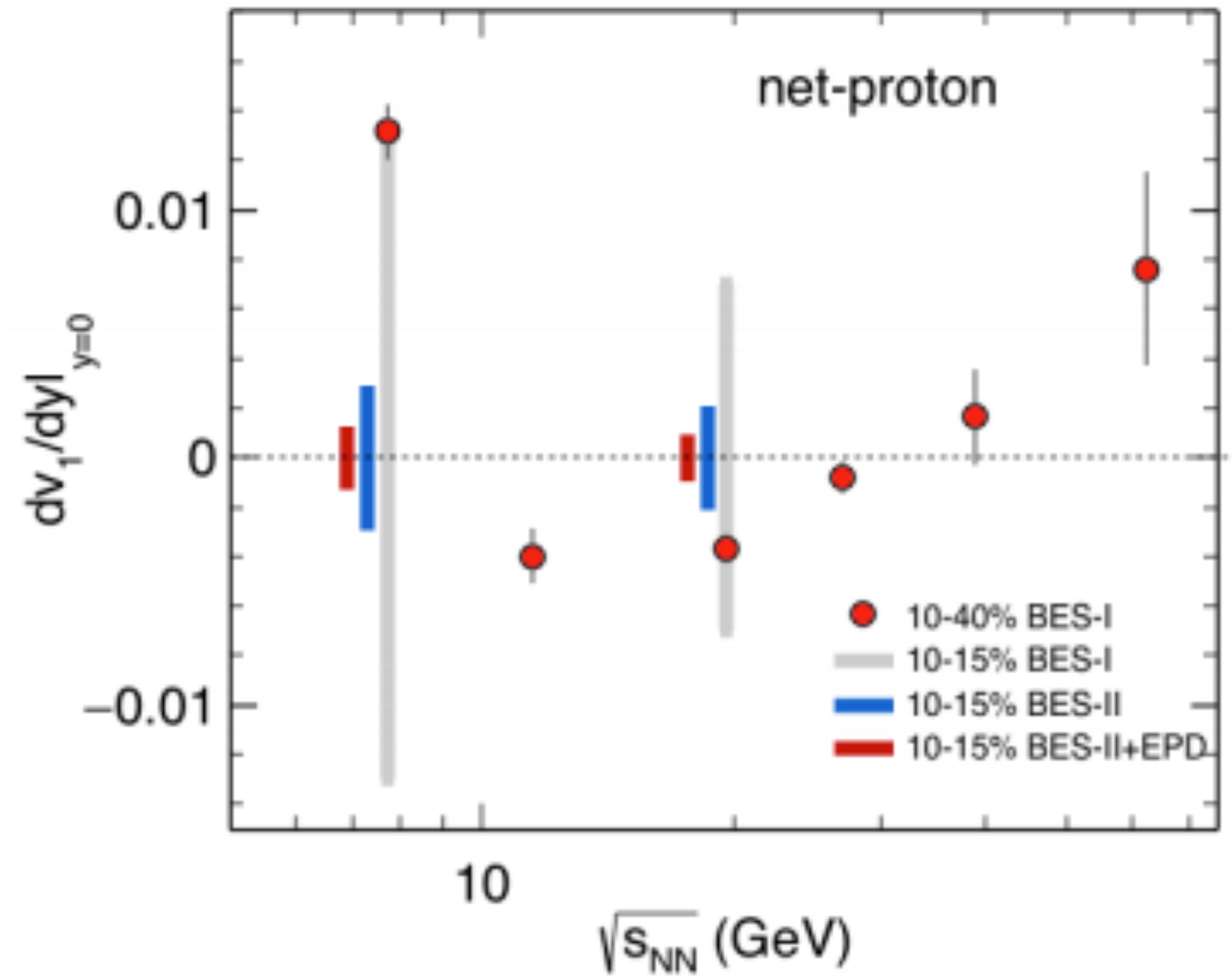
- Extended coverage
- Better dE/dx resolution

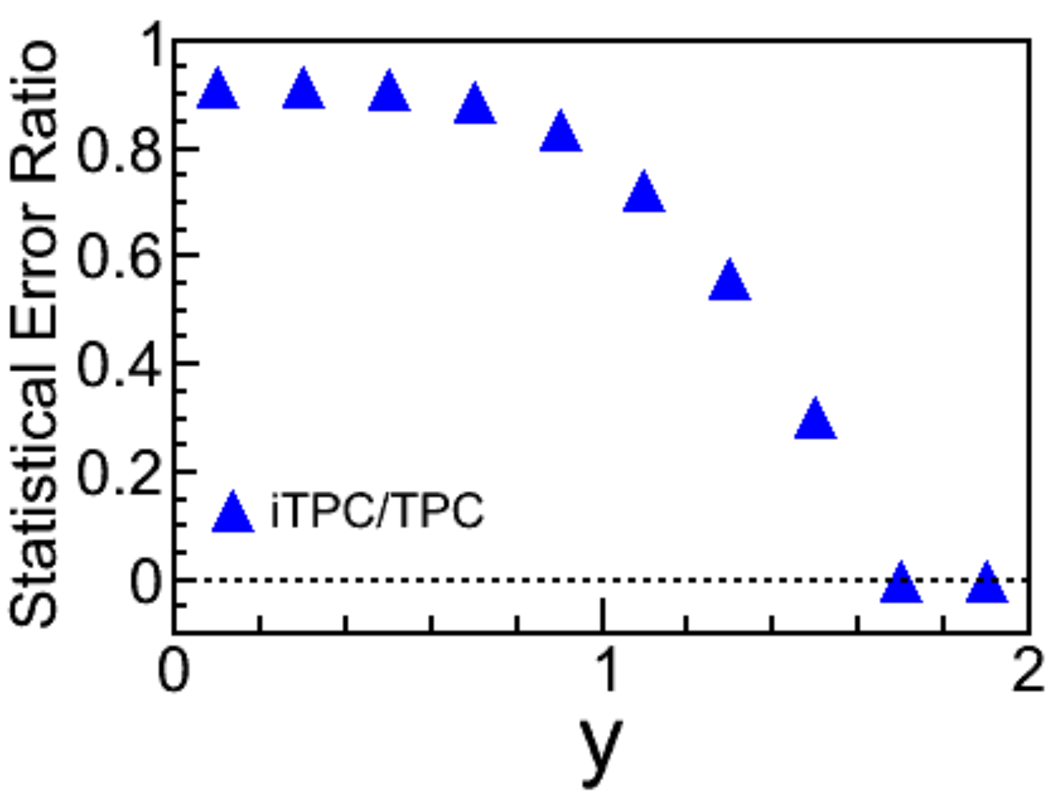
EPD (2.1< |η| < 5.1)

- Improved EP resolution
- Centrality determination independent of TPC

BES-II at RHIC



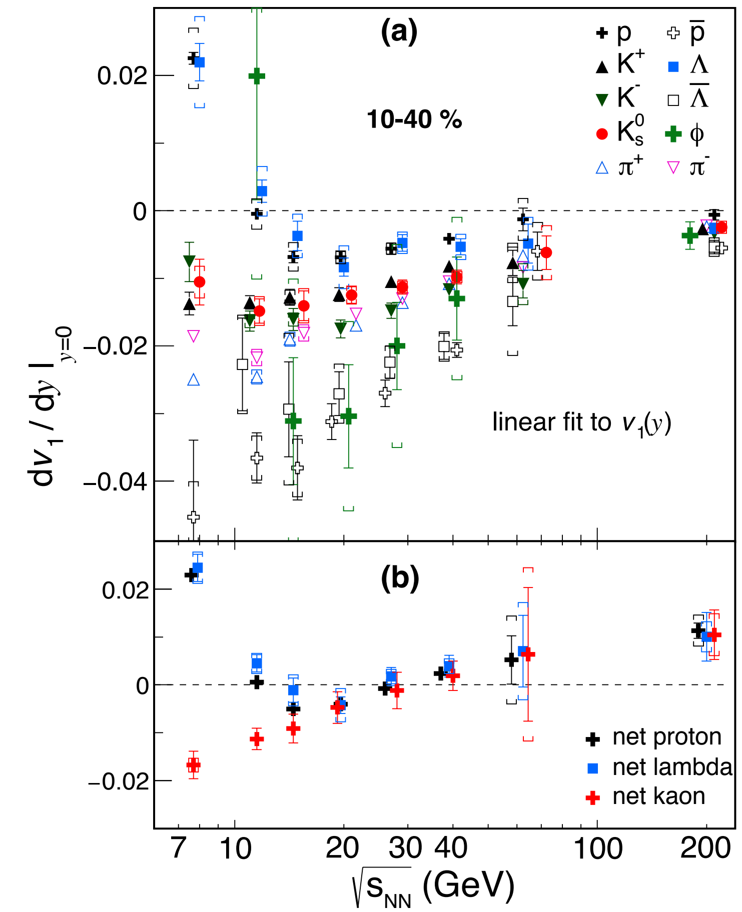




- improvement in EP resolution
- reduction in statistical uncertainty

Talk: Prashanth
09/08

Summary

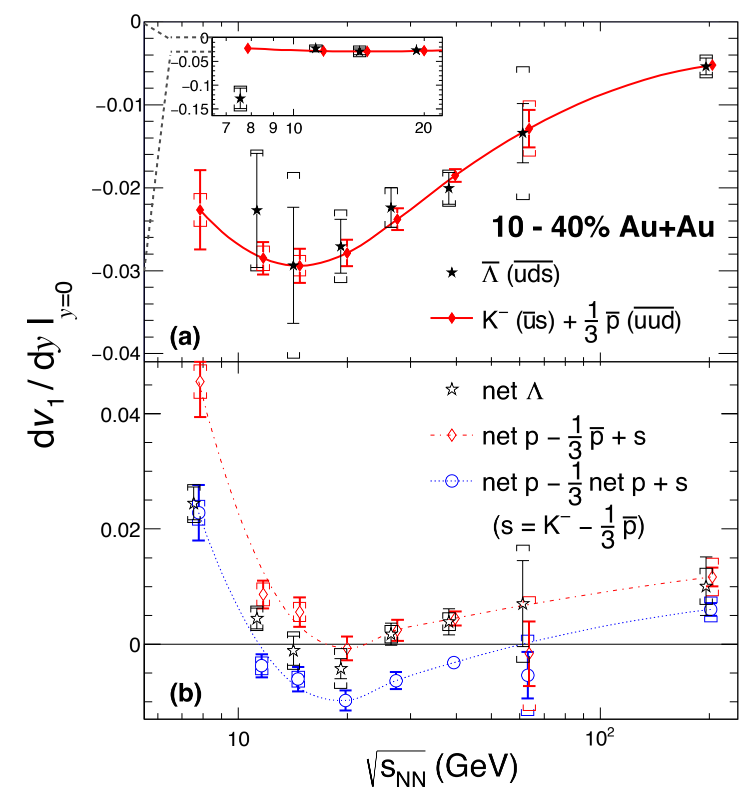


→ $(dv_1/dy)_p \sim (dv_1/dy)_\Lambda$

→ $(dv_1/dy)_{anti\text{-}p} \sim (dv_1/dy)_{anti\text{-}\Lambda} \sim (dv_1/dy)_\phi$

→ $(dv_1/dy)_{net\text{-}p} \sim (dv_1/dy)_{net\text{-}\Lambda}$
both changes sign at $\sqrt{s_{NN}} < 14.5$ GeV

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

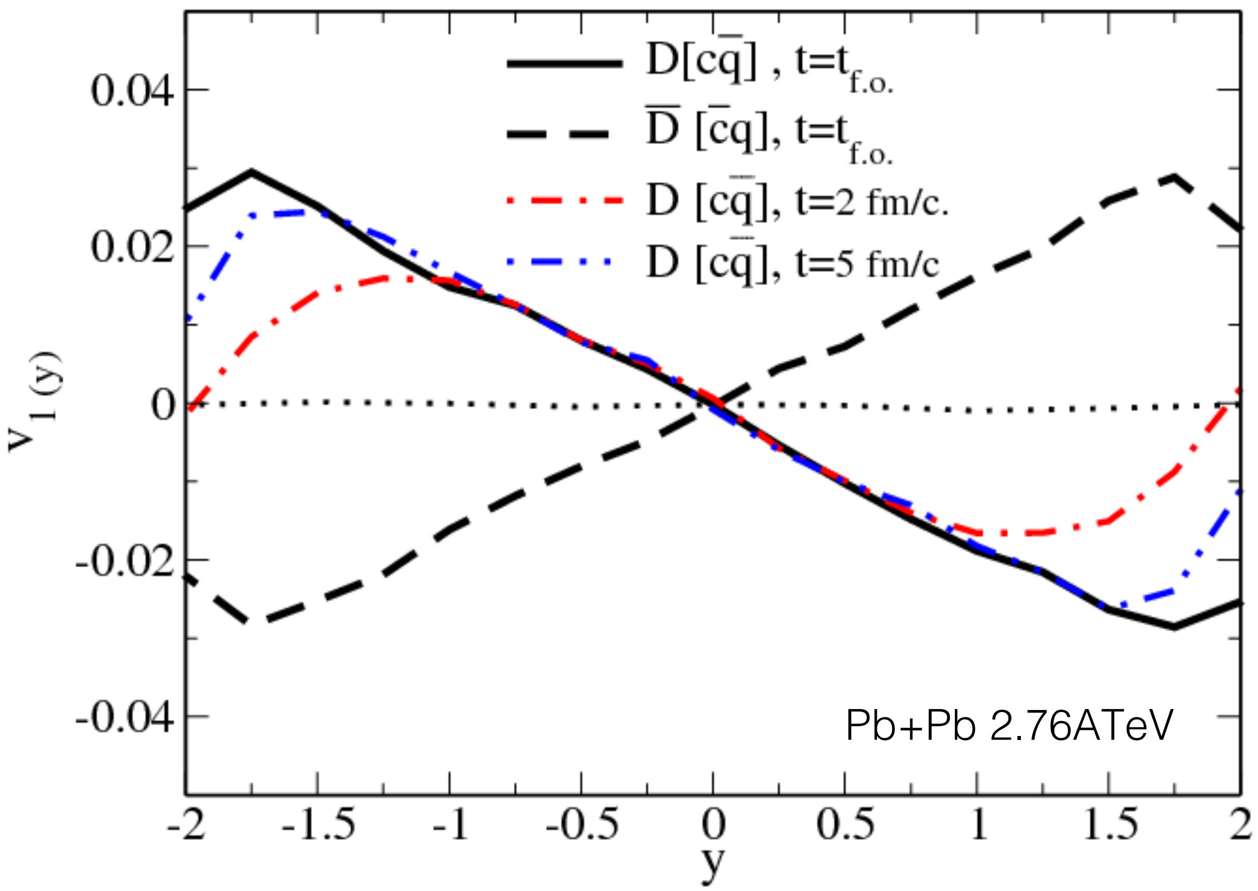


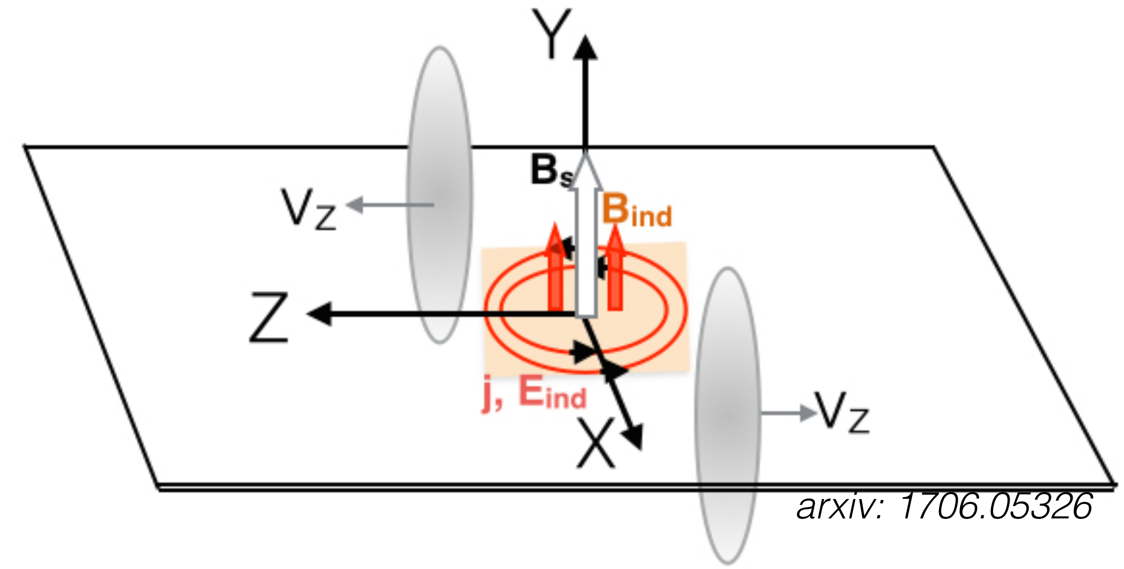
v_1 results are used to test quark coalescence:

→ Many measurements are consistent with the particles being formed via statistical coalescence of constituent quarks

Outlook: Charm quark v_1 as a probe for initial B field

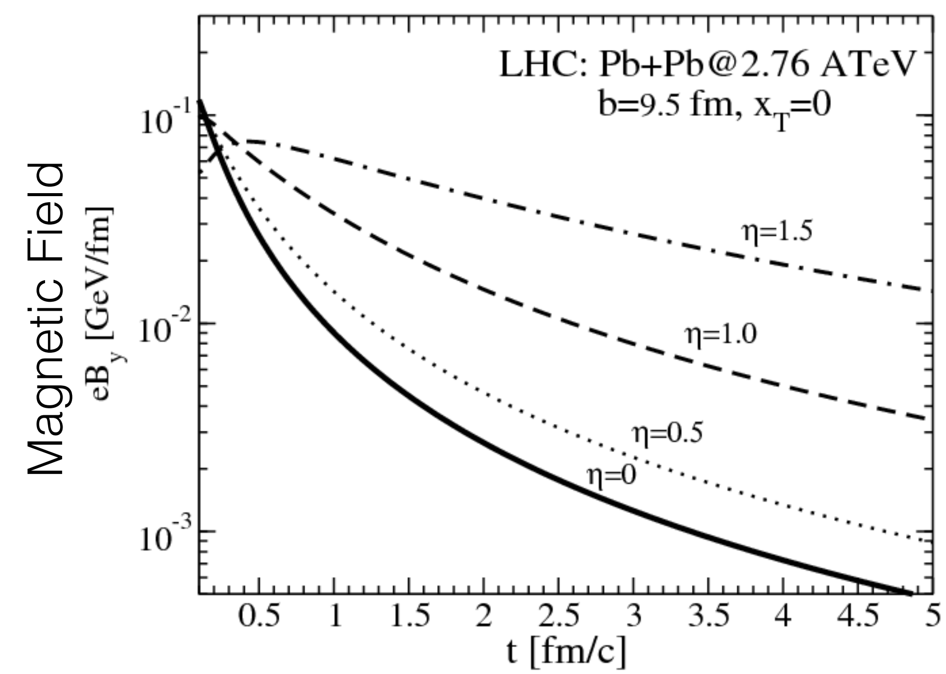
Das et. al. Phys Lett B 768, 260-264 (2017)





arxiv: 1706.05326

Das et. al. Phys LettB 768, 260-264 (2017)
Gursoy et.al. Phys. Rev. C 89, 054905 (2014)

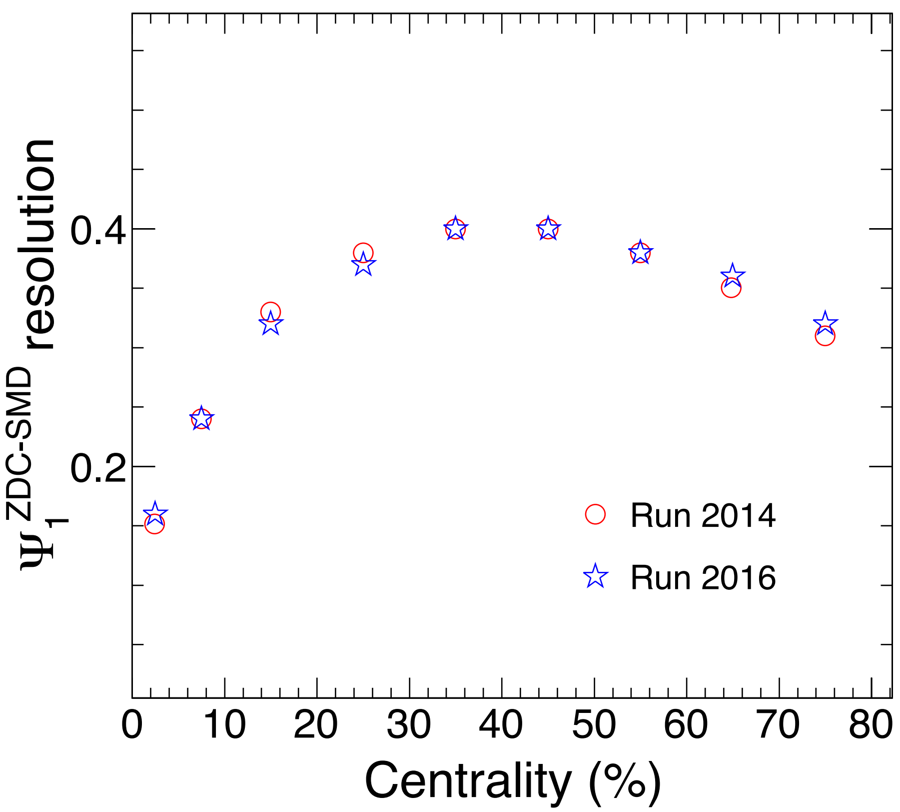


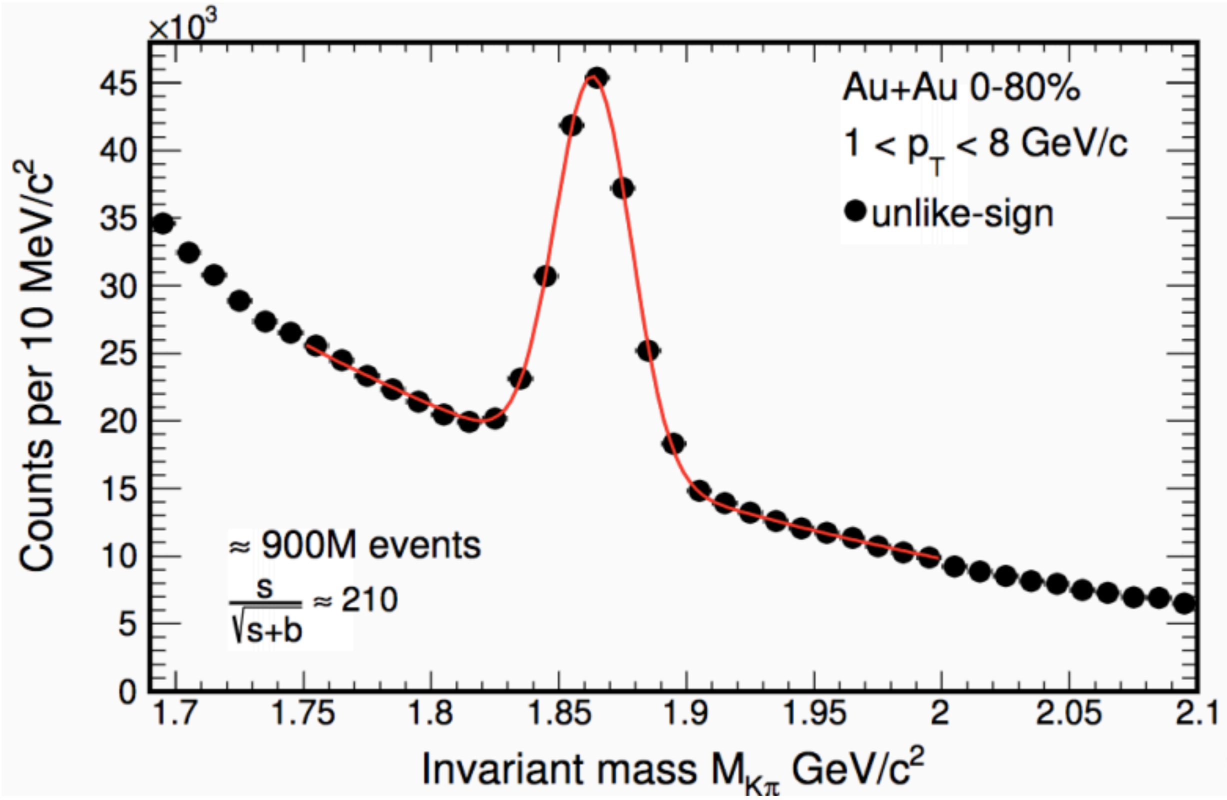
→ Model predicted sizable v_1 for charm quarks induced by initial electromagnetic field

Magnitude of v_1 depends on balance between E and B fields

→ Sign of dv_1/dy opposite for charm and anti-charm quarks

Measurement of D^0 (anti-D^0) v_1





→ First order event plane using ZDC-SMD

→ v_1 signal significant at forward η

→ Large η-gap reduces non-flow effects ($|\eta|_{ZDC-SMD} > 6.4$)

→ Analysis of D^0 (anti-D^0) v_1 utilizing HFT and ZDC is underway

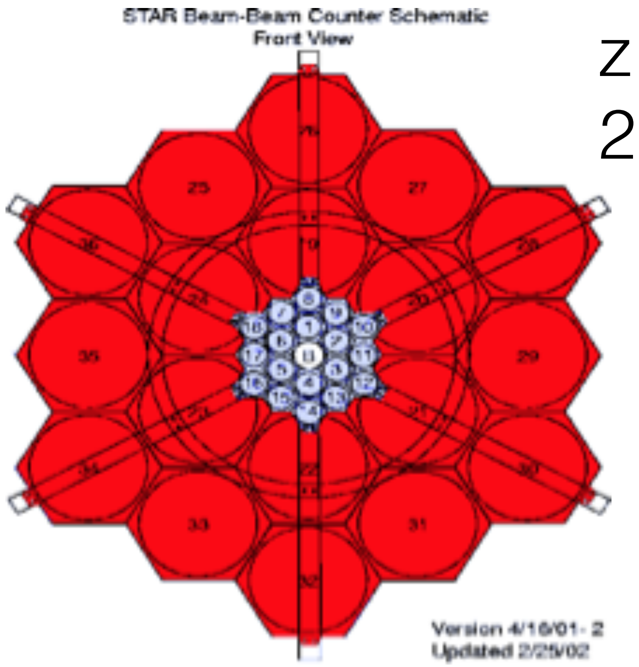
Stay tuned for more results

Thank you

Back up slides

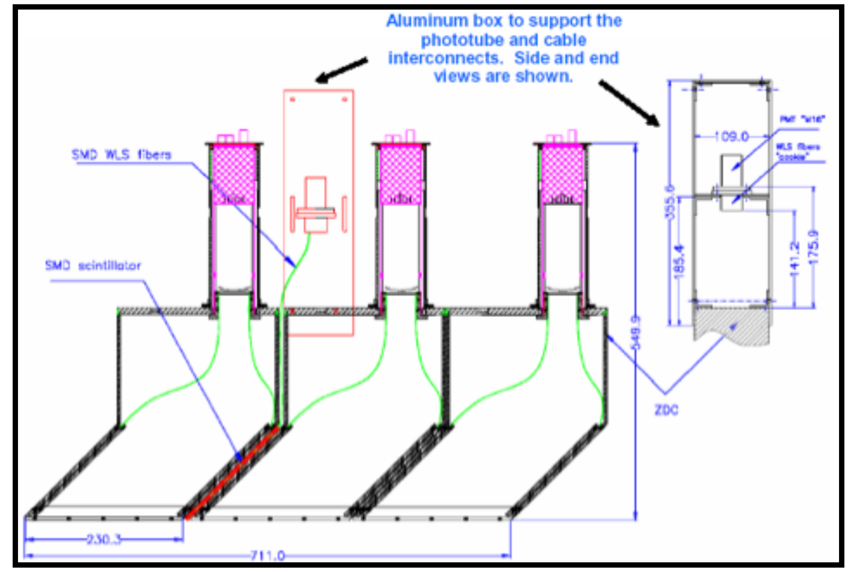
STAR Detector

BBC

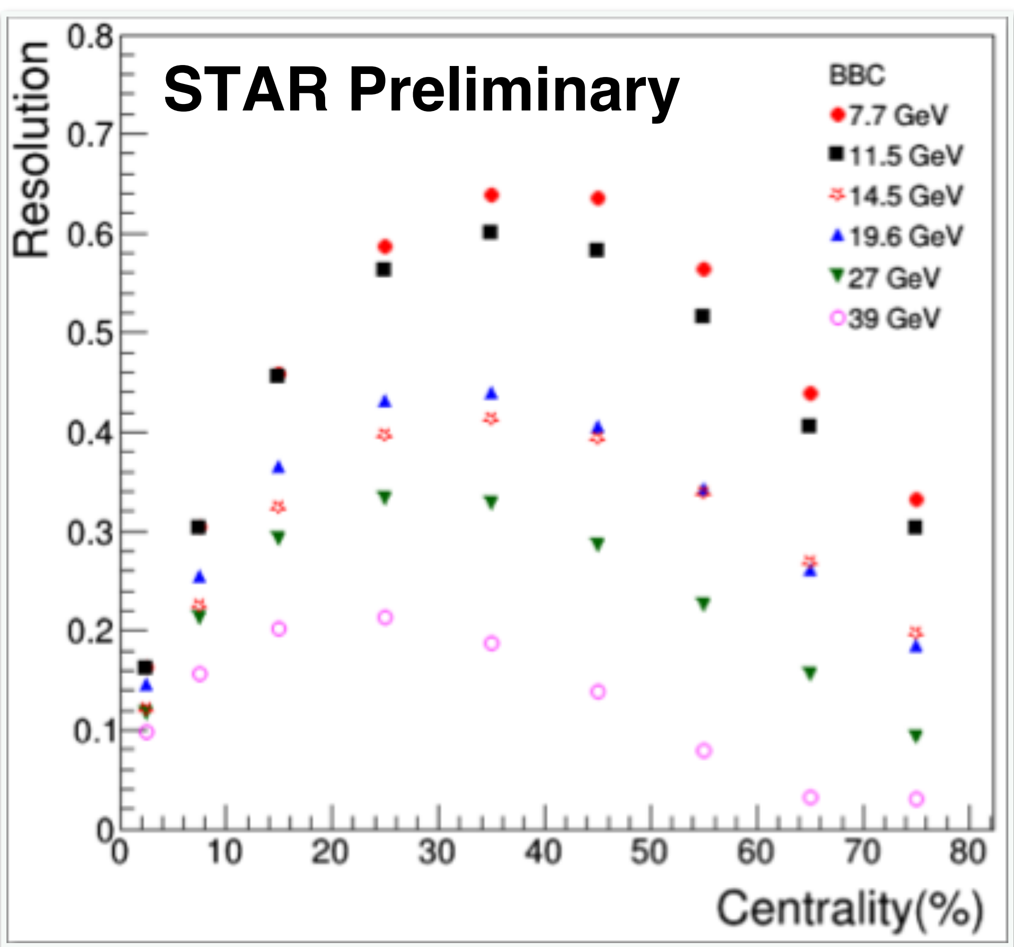


z =± 3.7 m
2.1 > | η| < 5

ZDC-SMD



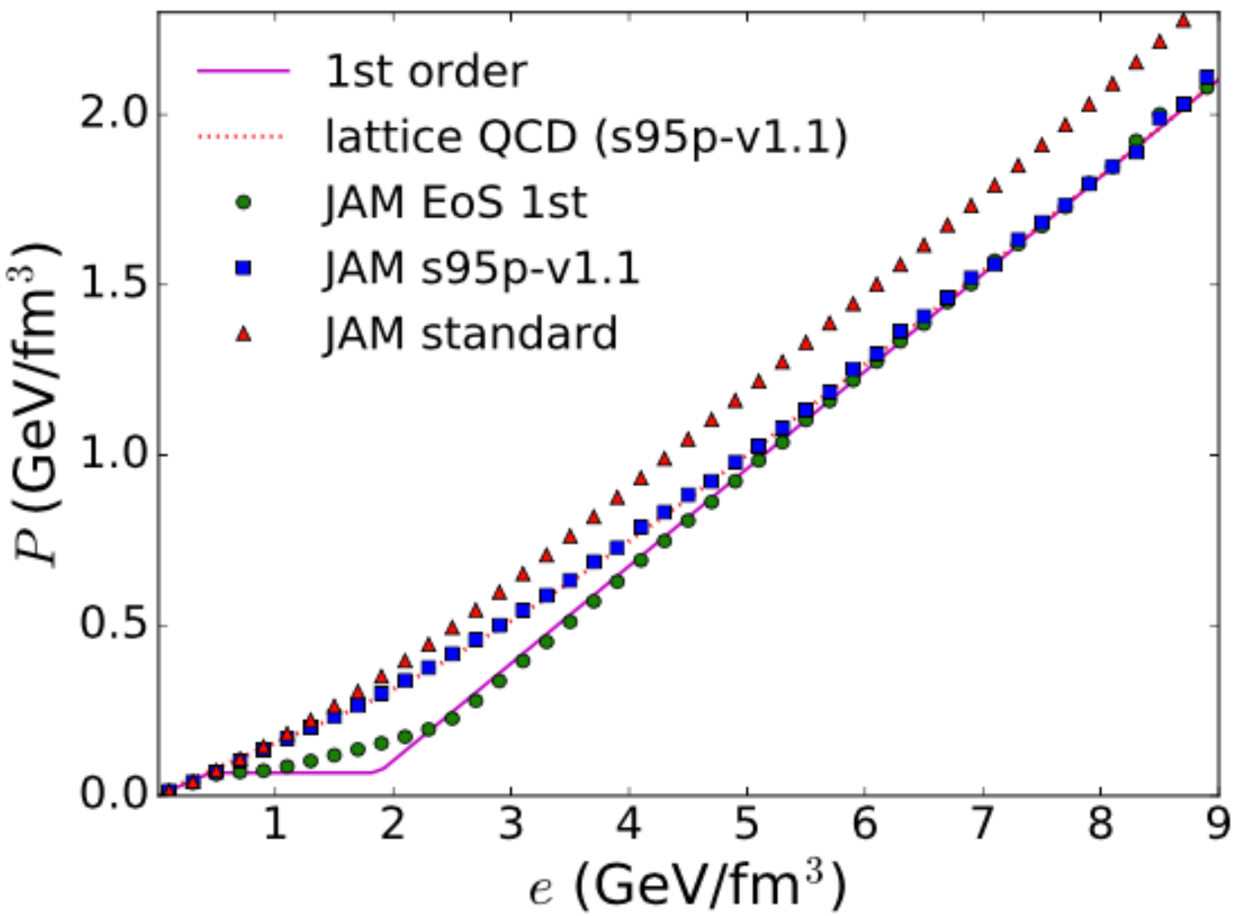
z =±18.25 m
θ < 2 mrad

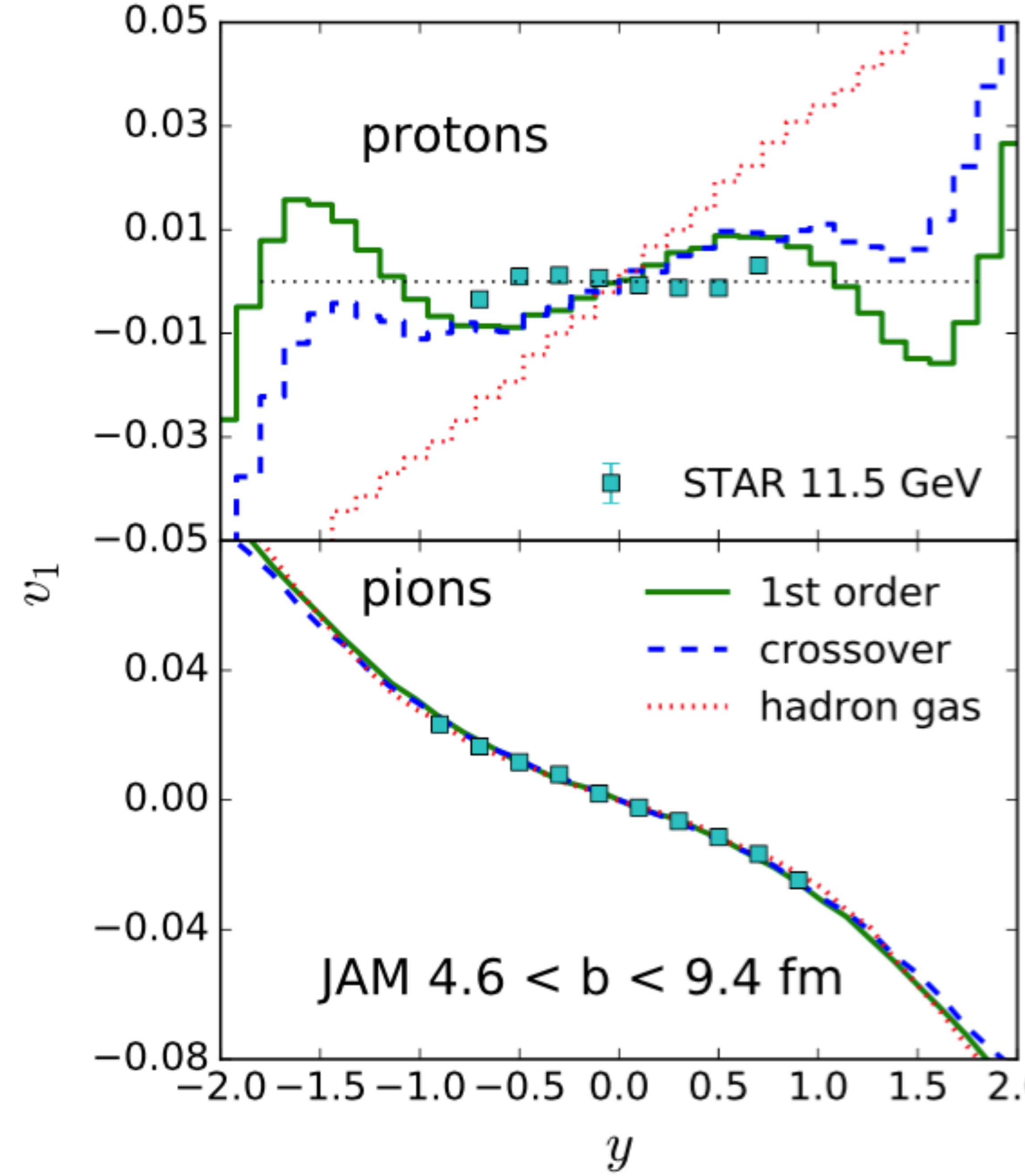


increasing energy

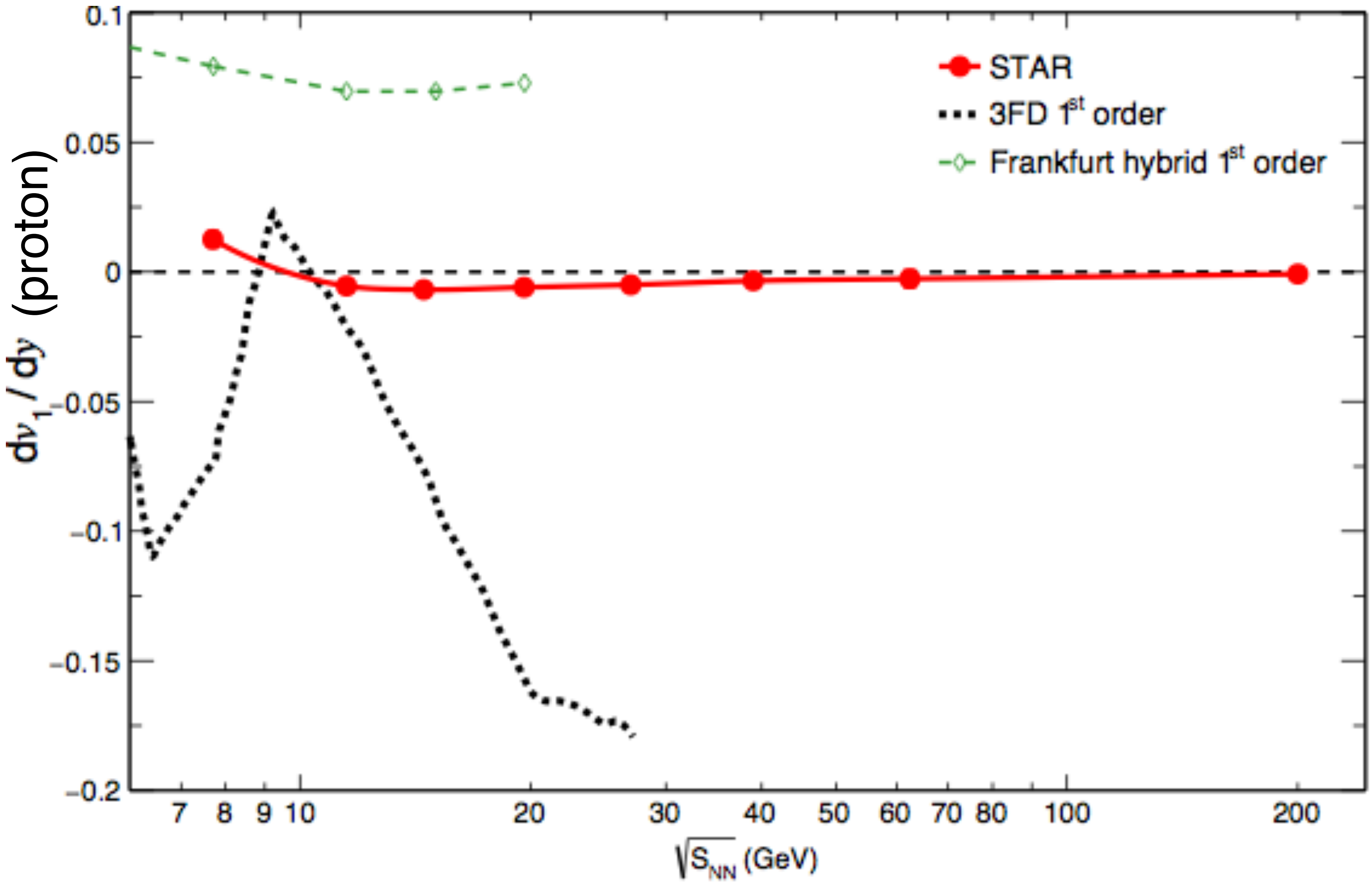
- 1st order event plane estimated using
  BBC (7.7 - 39 GeV)
  ZDC (62.4, 200 GeV)
- v_1 signal significant at forward rapidity
- Large η gap with TPC reduces non-flow effects

JAM Calculation





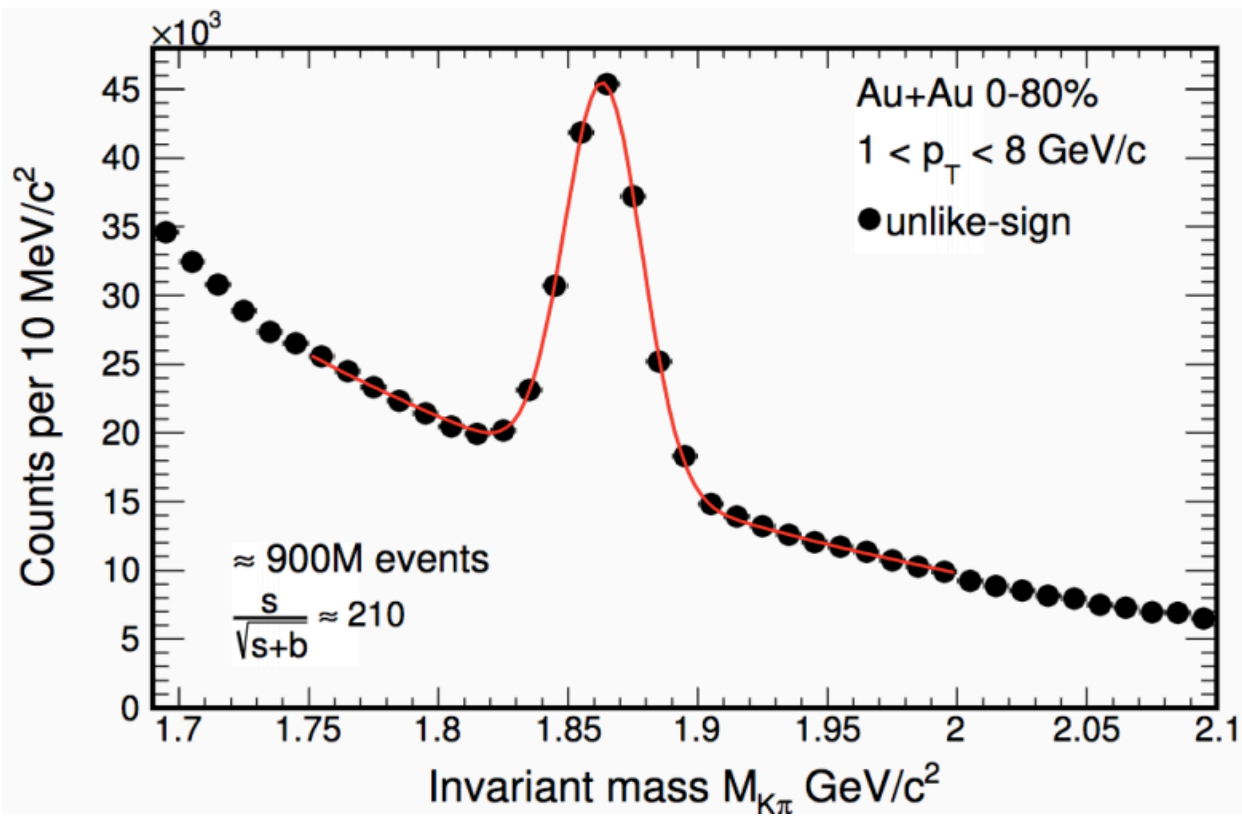
Energy dependence dv_1/dy with models



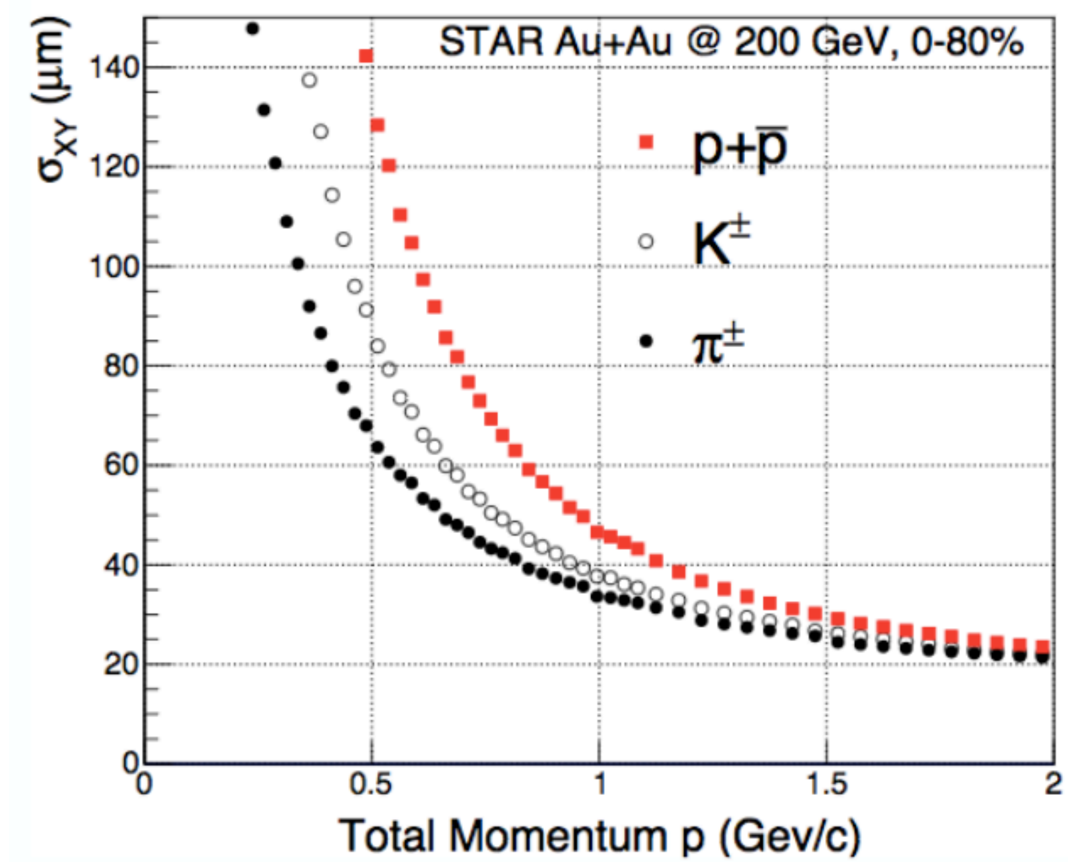
- None of the models explains the data
- Systematics associated with the models is quite large (~ 2 orders of magnitude bigger than experimental errors!)

HFT performance in D^0 reconstruction

$D^0 \rightarrow K\pi$ (BR:3.9%)
$c\tau \sim 120\ \mu m$



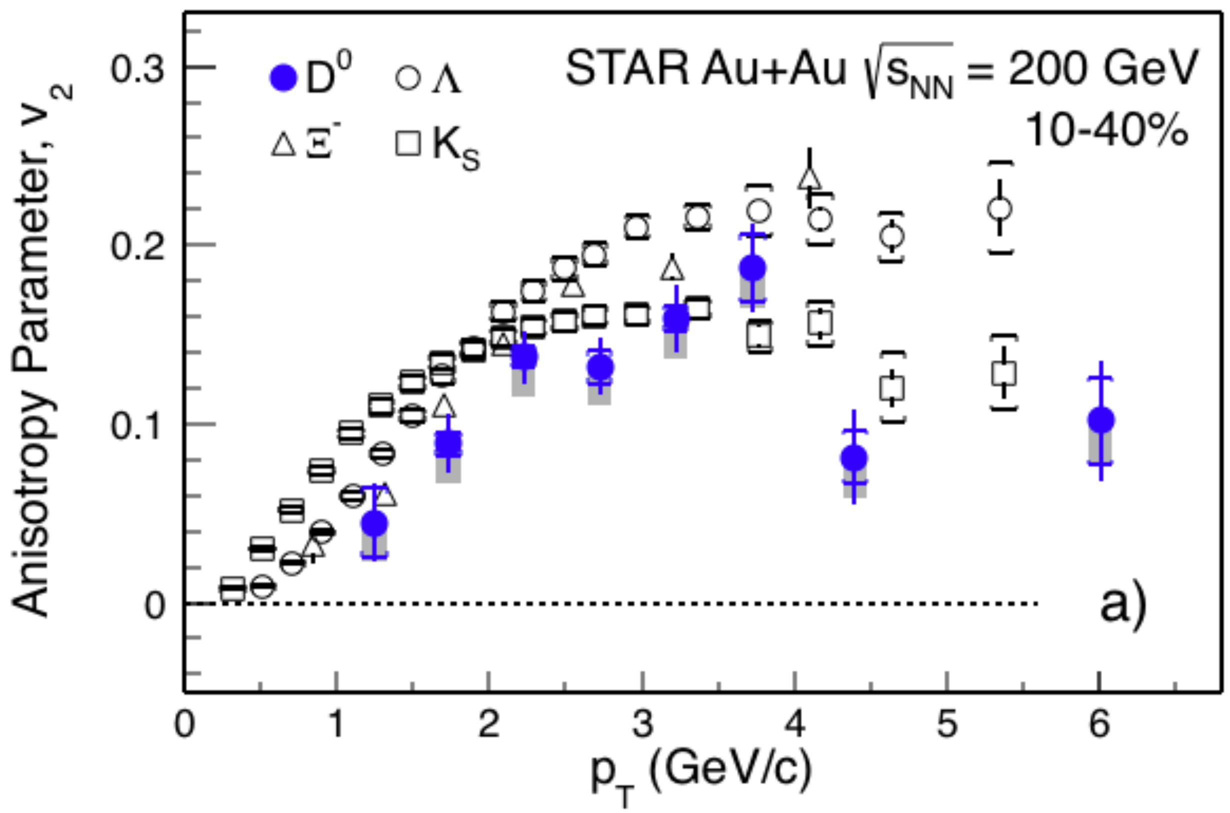
STAR Coll. Phys Rev. Lett 118, 212301 (2017)



Heavy Flavor Tracker:
→ Excellent pointing resolution
→ Allows topological reconstruction for heavy flavor particles

D^0 v_2 and π v_1 using HFT

STAR Coll. Phys Rev. Lett 118, 212301 (2017)



STAR 2011 Published: Phys. Rev. Lett. 108, 202301 (2012)