The many facets of directed flow in heavy-ion collisions

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Kent, December 1, 2023

BERKELEY LAB

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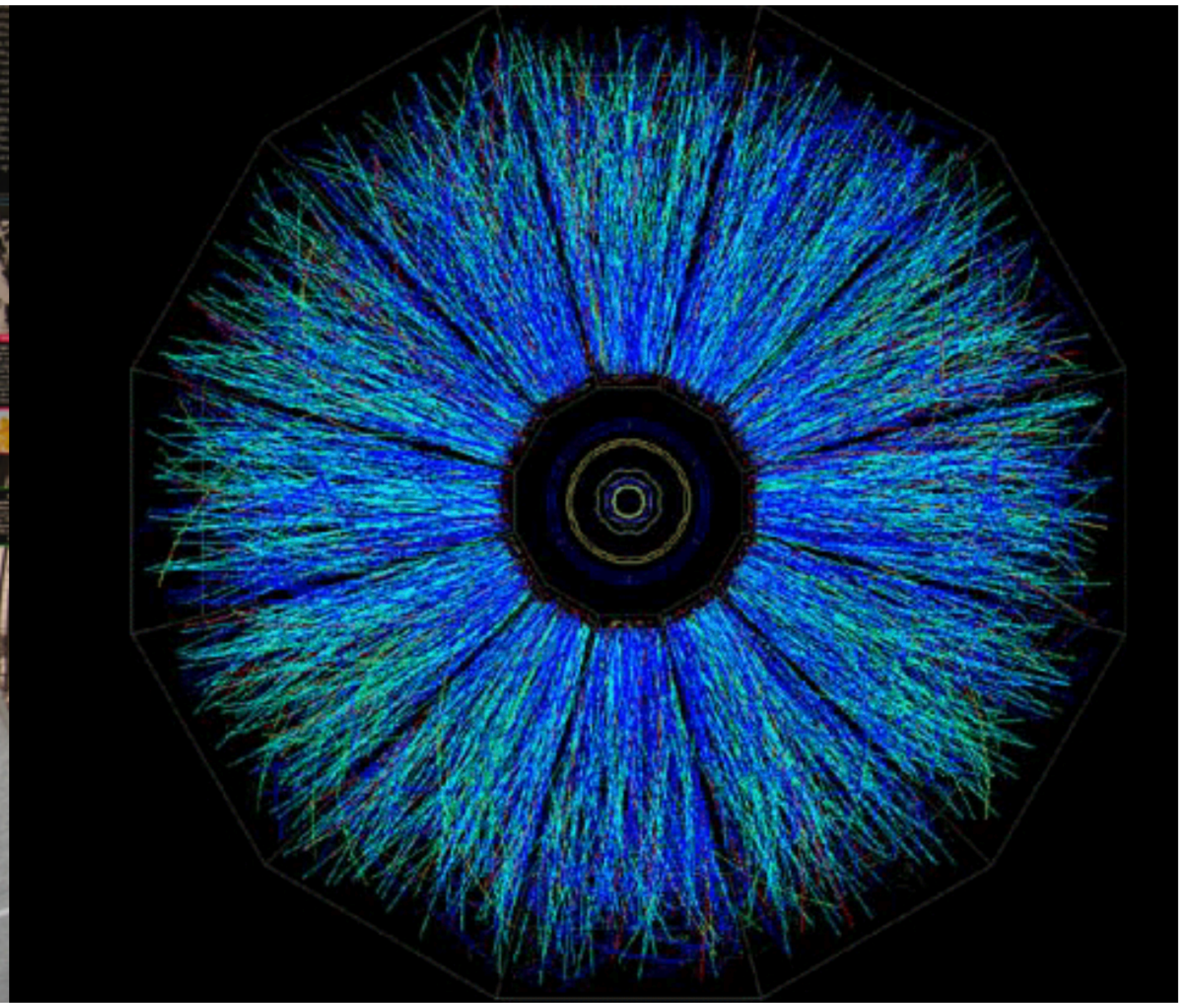
STAR and Declan directing the flow!



- Directed flow in Au+Au collisions at sqrt(sNN)=62 GeV — ***PRC (2006)***
- Directed flow at the Relativistic Heavy-Ion Collider: incident-energy and system-size dependence — ***PRL (2008)***
- Directed and Elliptic Flow of Charged Particles in Cu+Cu Collisions at $\sqrt{s_{NN}}$ = 22.4 GeV — ***PRC (2012)***
- Directed flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27 and 39 GeV — ***PRL (2014)***
- Beam-Energy Dependence of Directed Flow of lambda's, K's, Kshort, and phi in Au+Au Collisions — ***PRL (2018)***
- Observation of D0 directed flow in 200 GeV Au+Au collisions at RHIC — ***PRL (2020)***
- Flow and interferometry results from Au+Au collisions at sqrt(sNN) = 4.5 GeV — ***PRC (2021)***
- Electric charge and strangeness dependent directed flow of produced quarks in Au+Au collisions at RHIC — ***Submitted (2023)***

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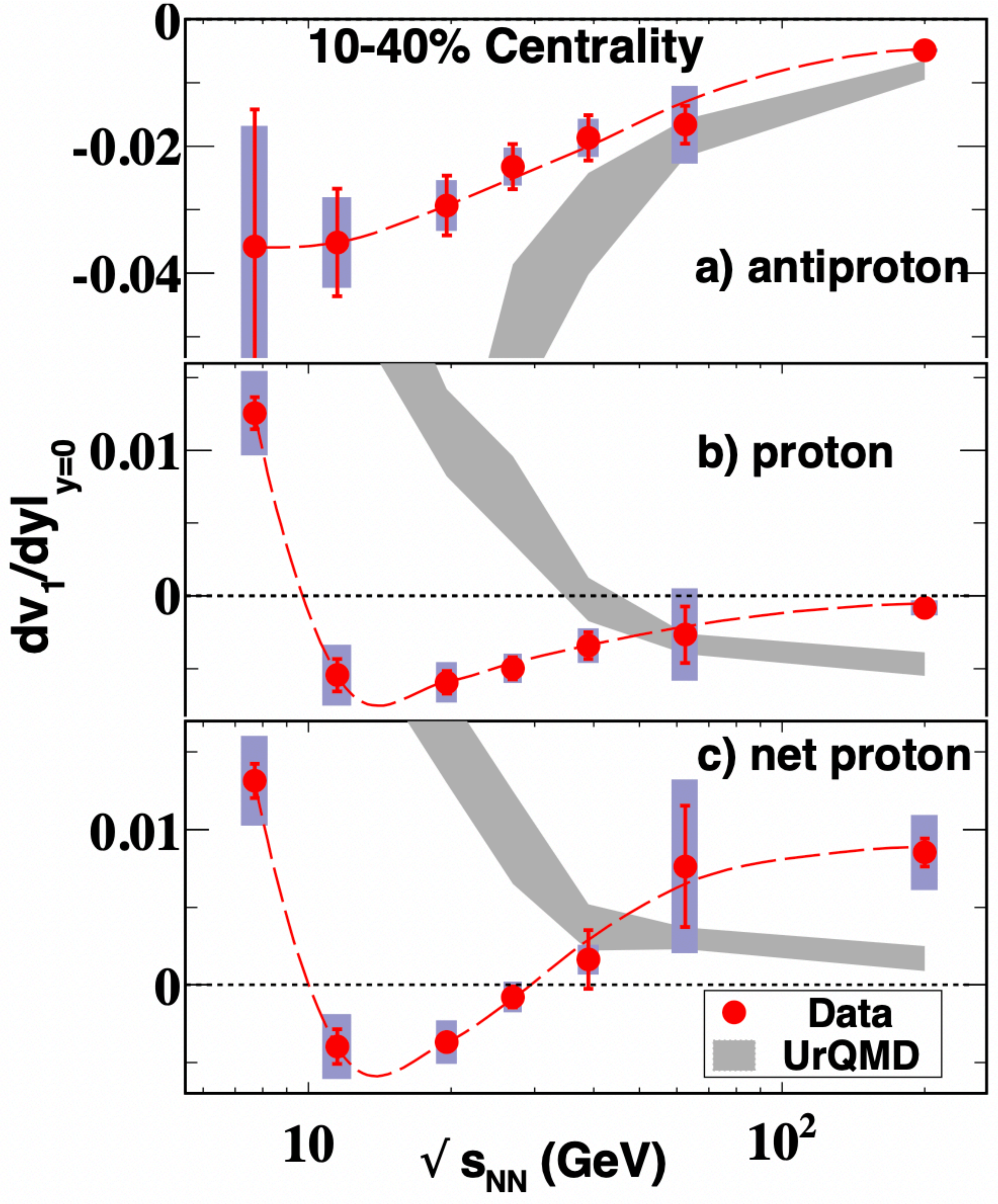
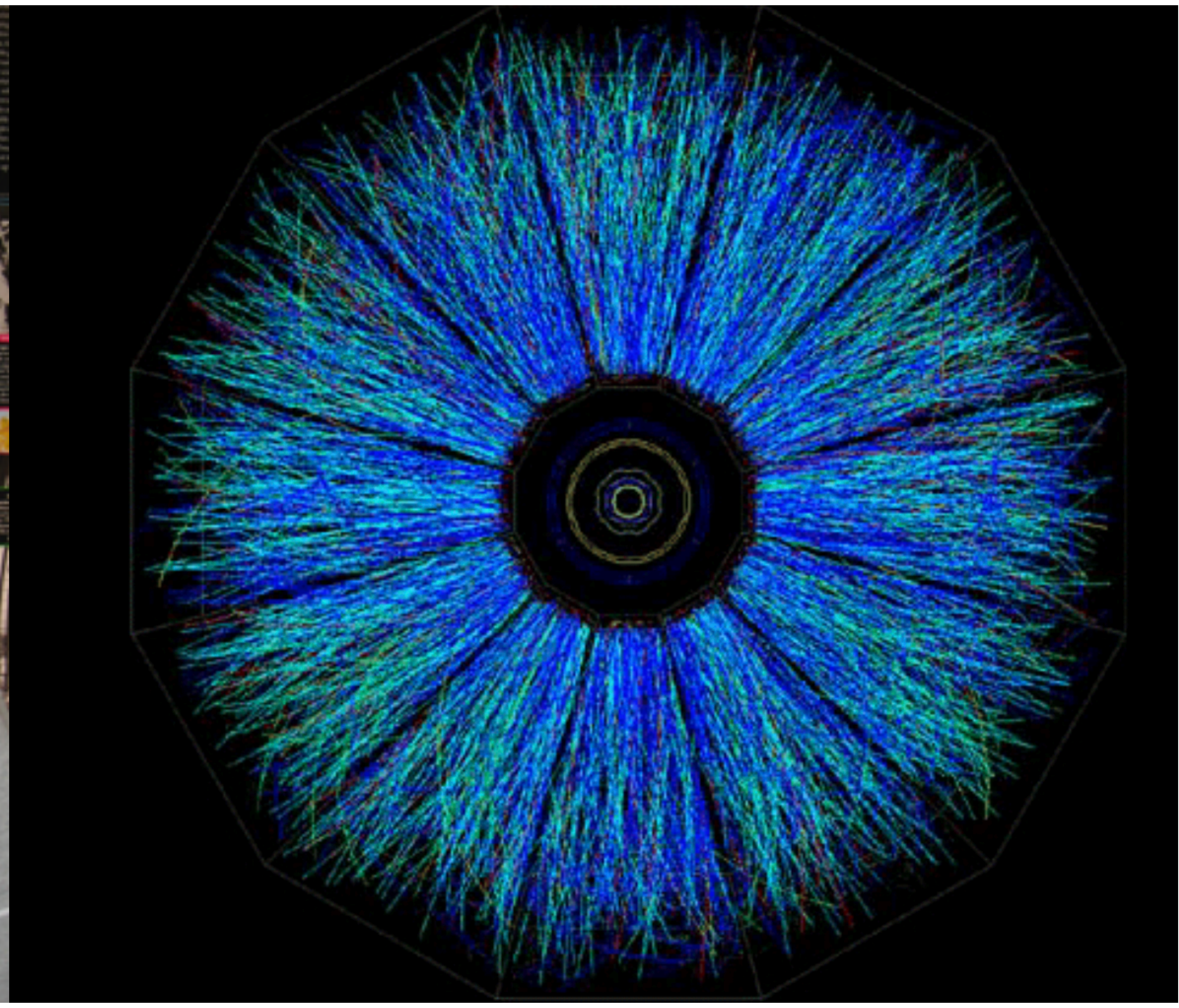
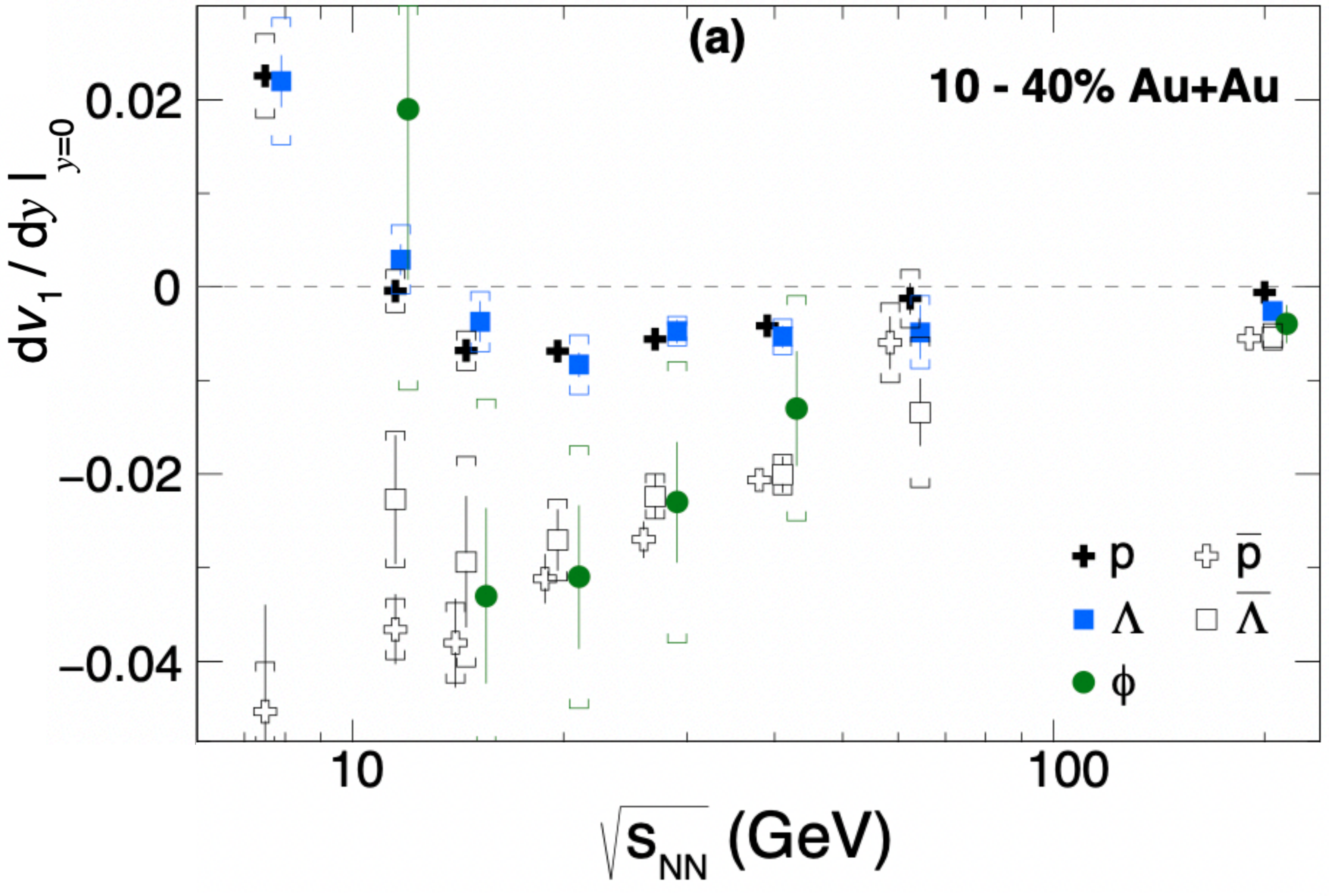
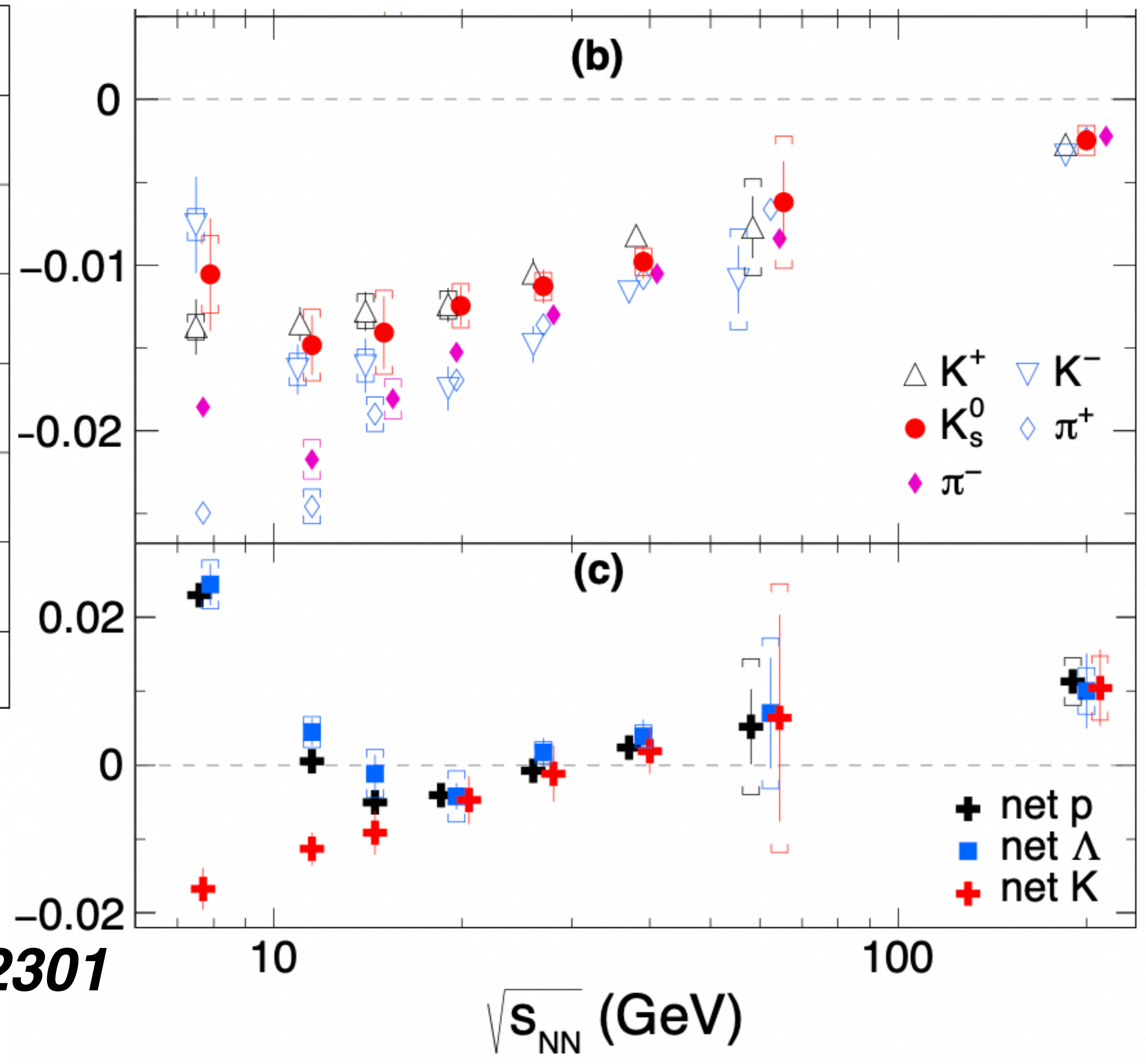


STAR, Phys. Rev. Lett. 112 (2014) 162301







STAR: Phys. Rev. Lett. 120 (2018) 62301

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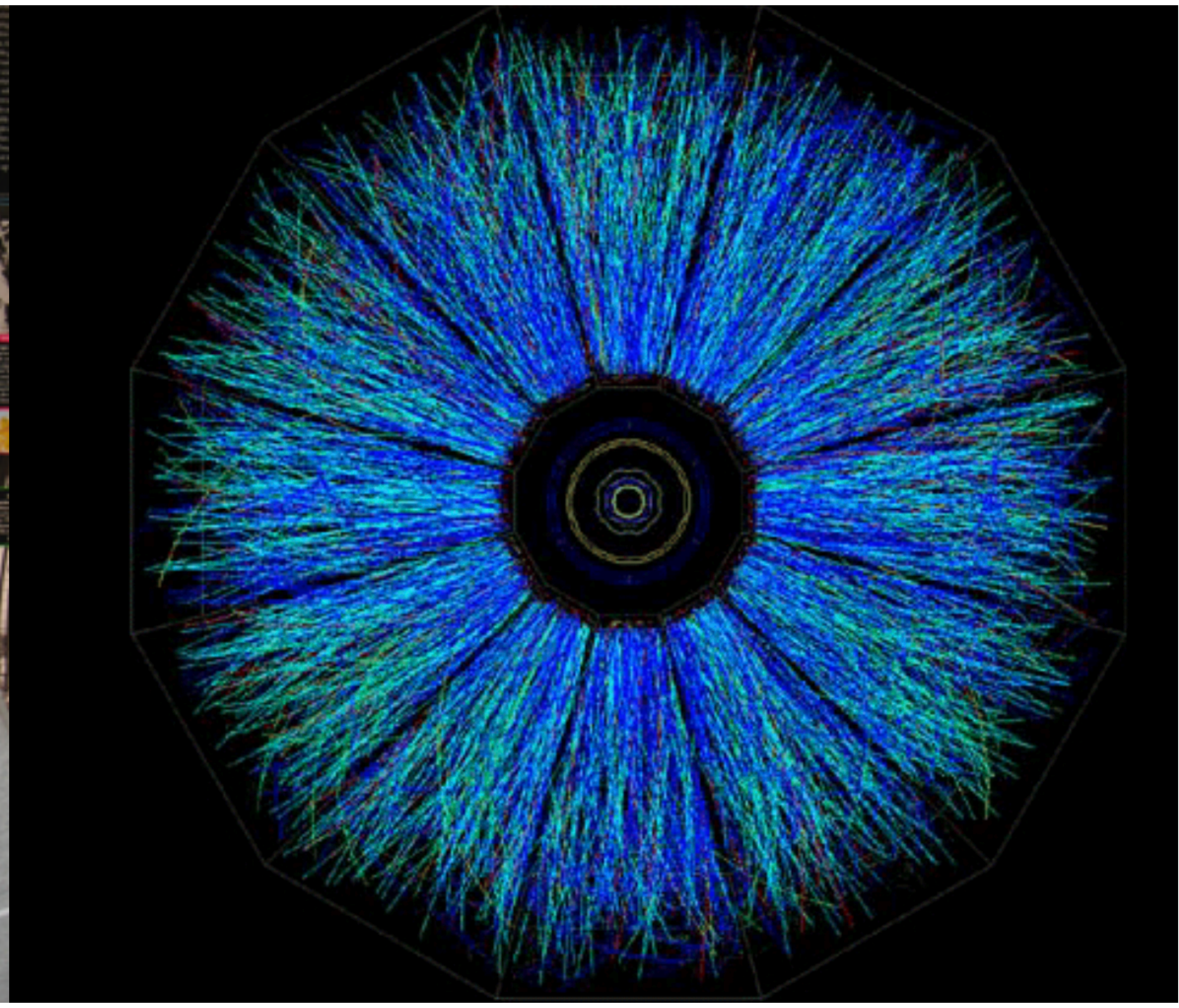
STAR and Declan directing the flow!



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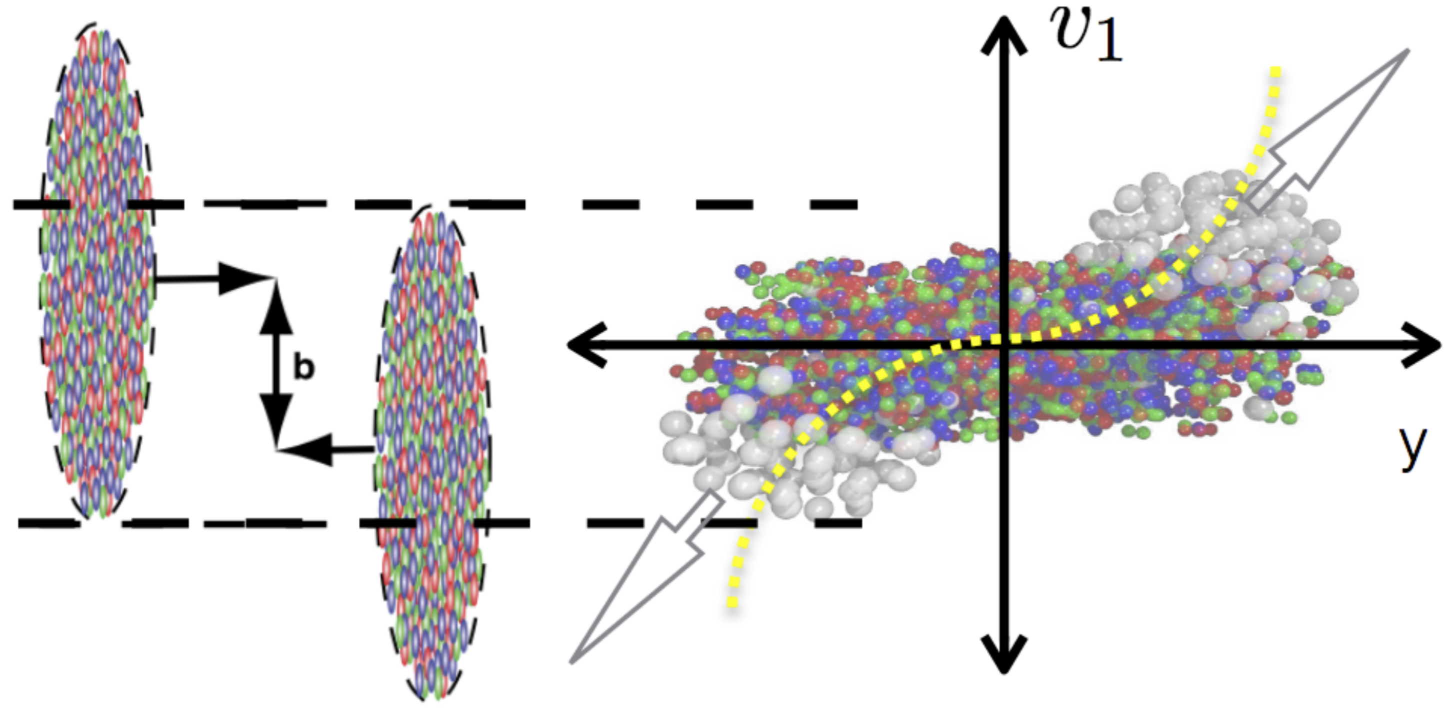
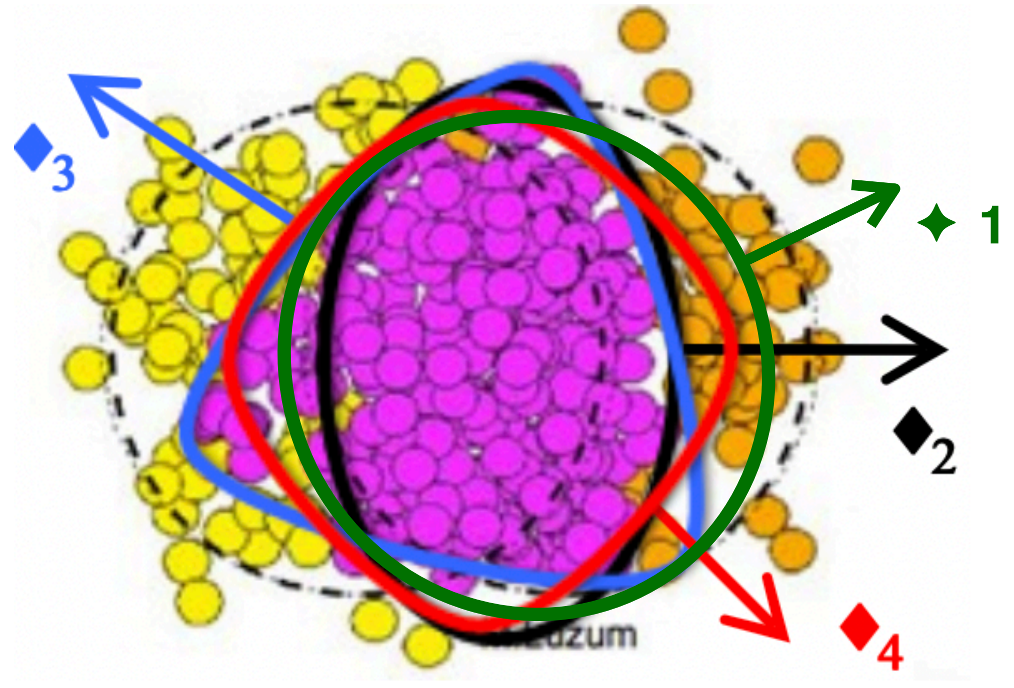
- Proton directed flow in BES-II (Ongoing)

Directed flow (v_1) - a versatile observable!

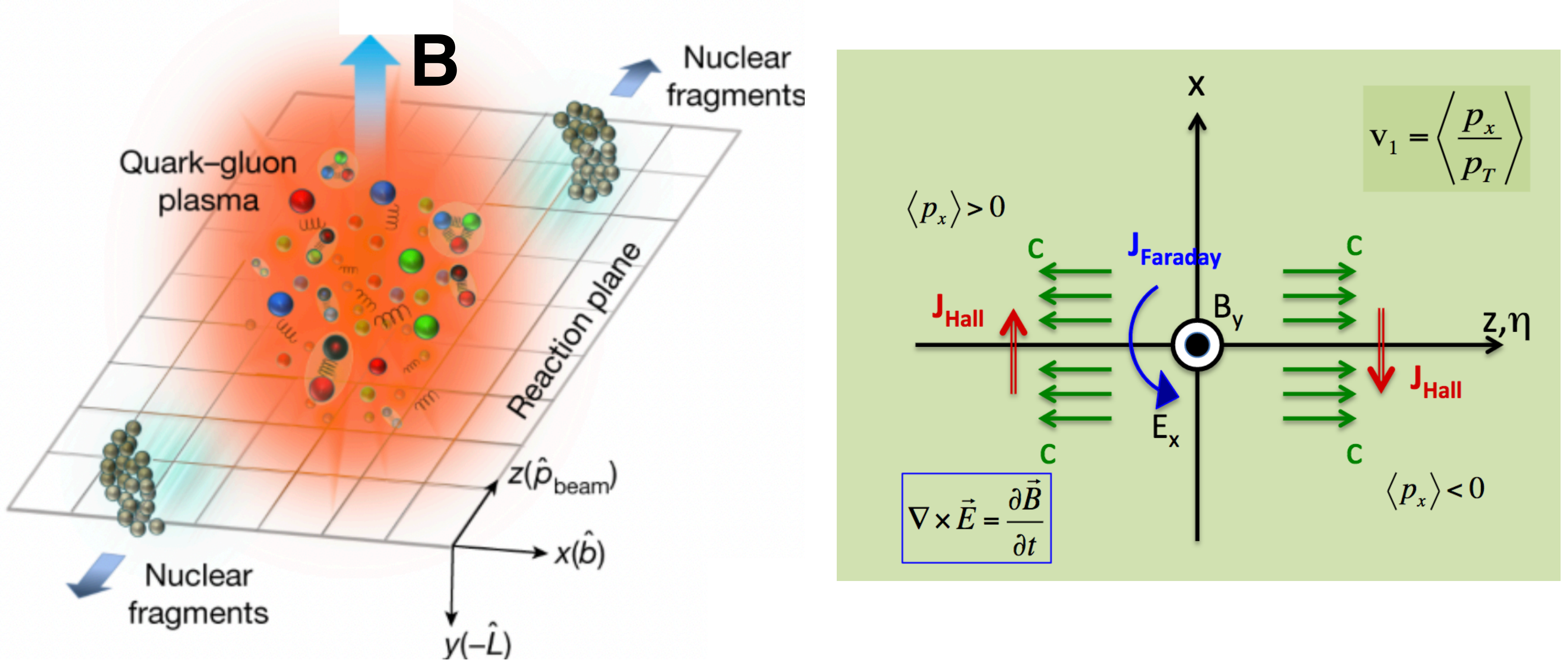
One of the first measured quantities in heavy-ion experiments

Rapidity odd v_1 — linked to EoS of matter and its softening

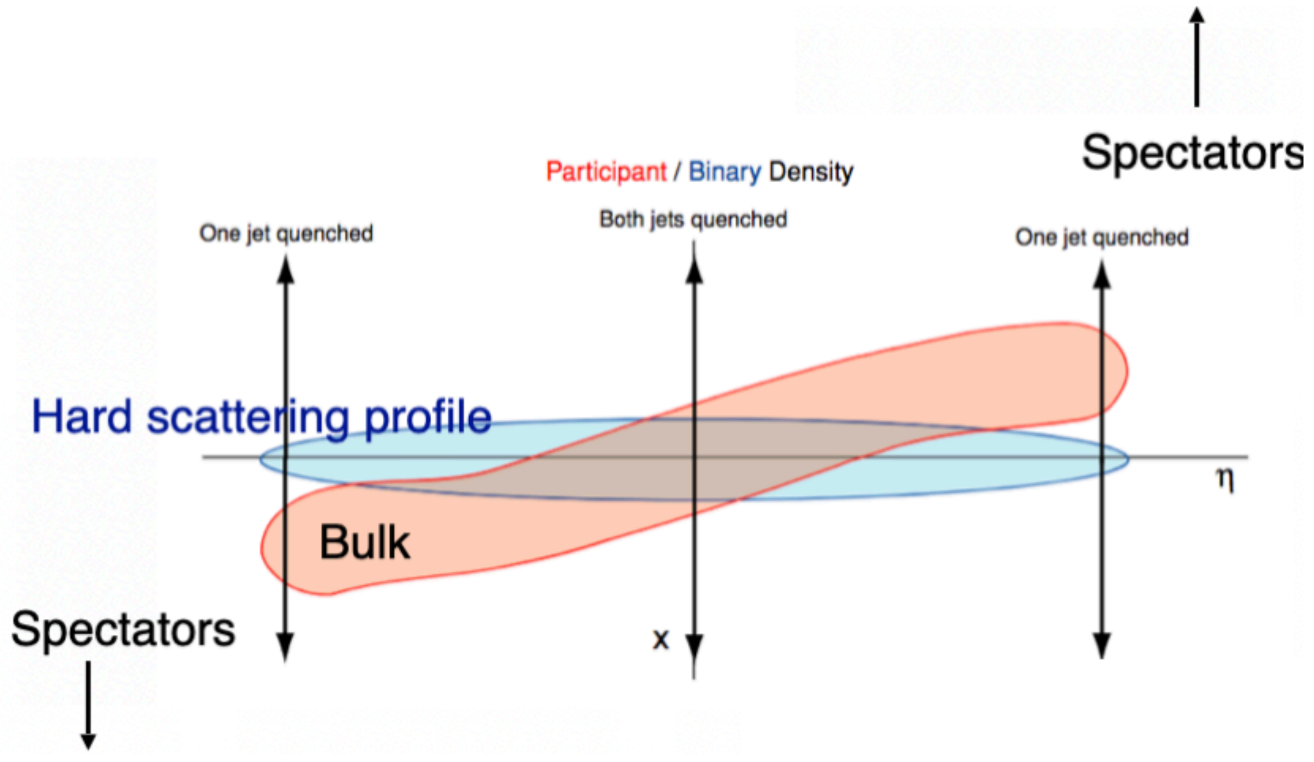




From density fluctuations — rapidity even v_1



Charge dependent splitting — initial B field



Hard-soft asymmetry in initial density distribution — energy loss

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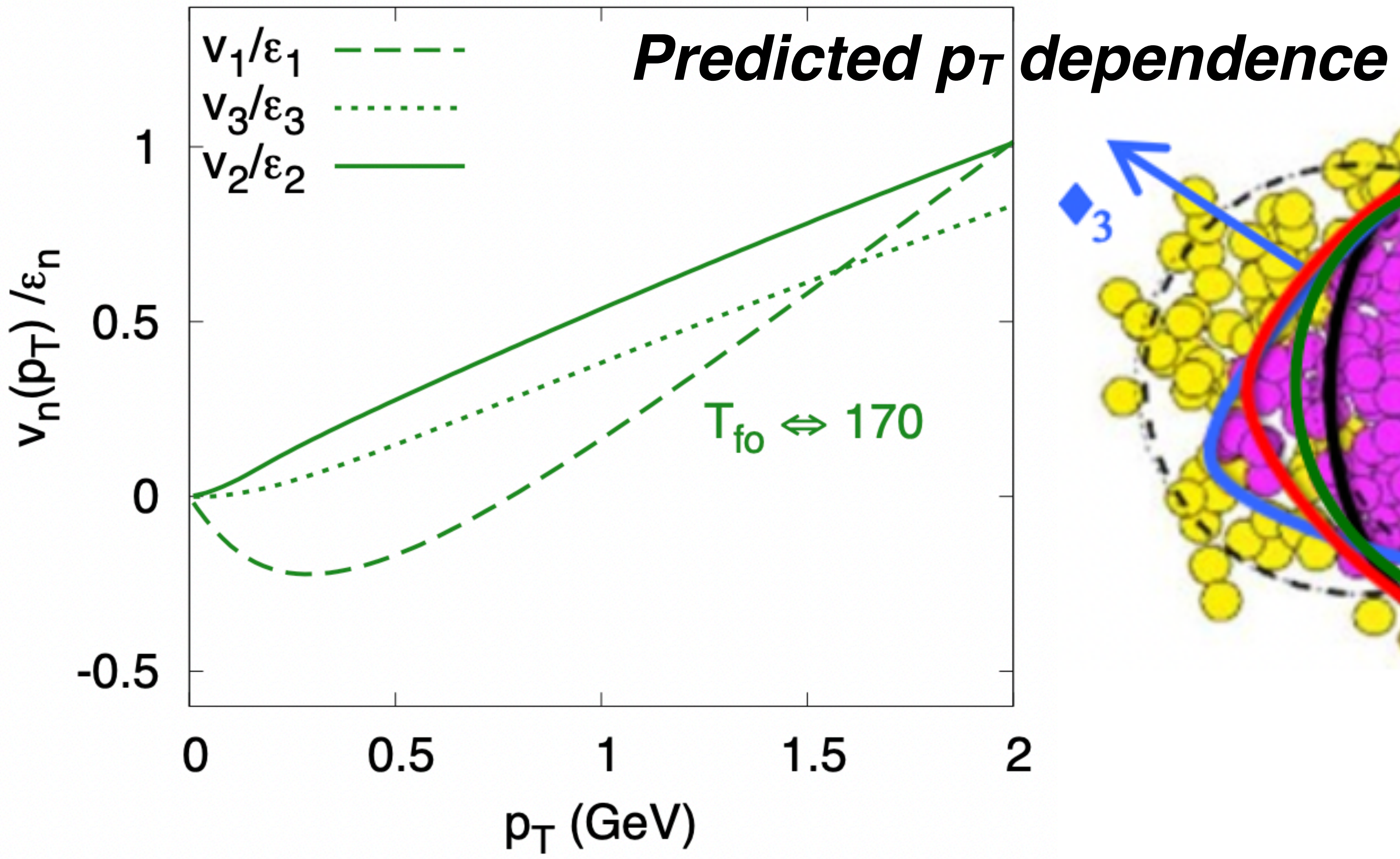
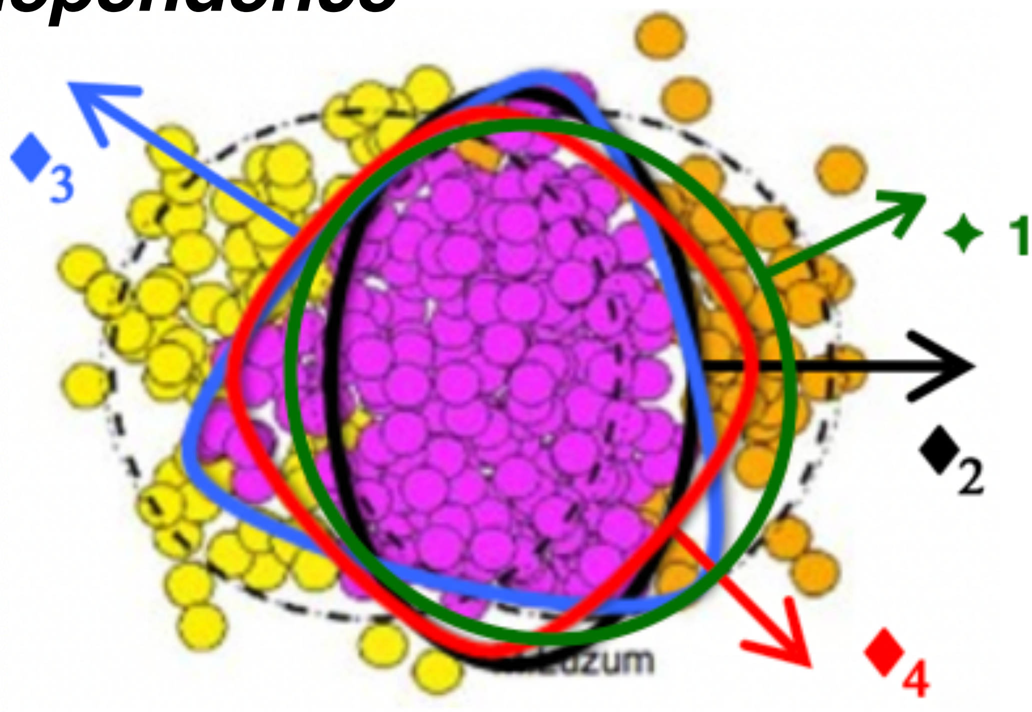
Directed flow from density fluctuation

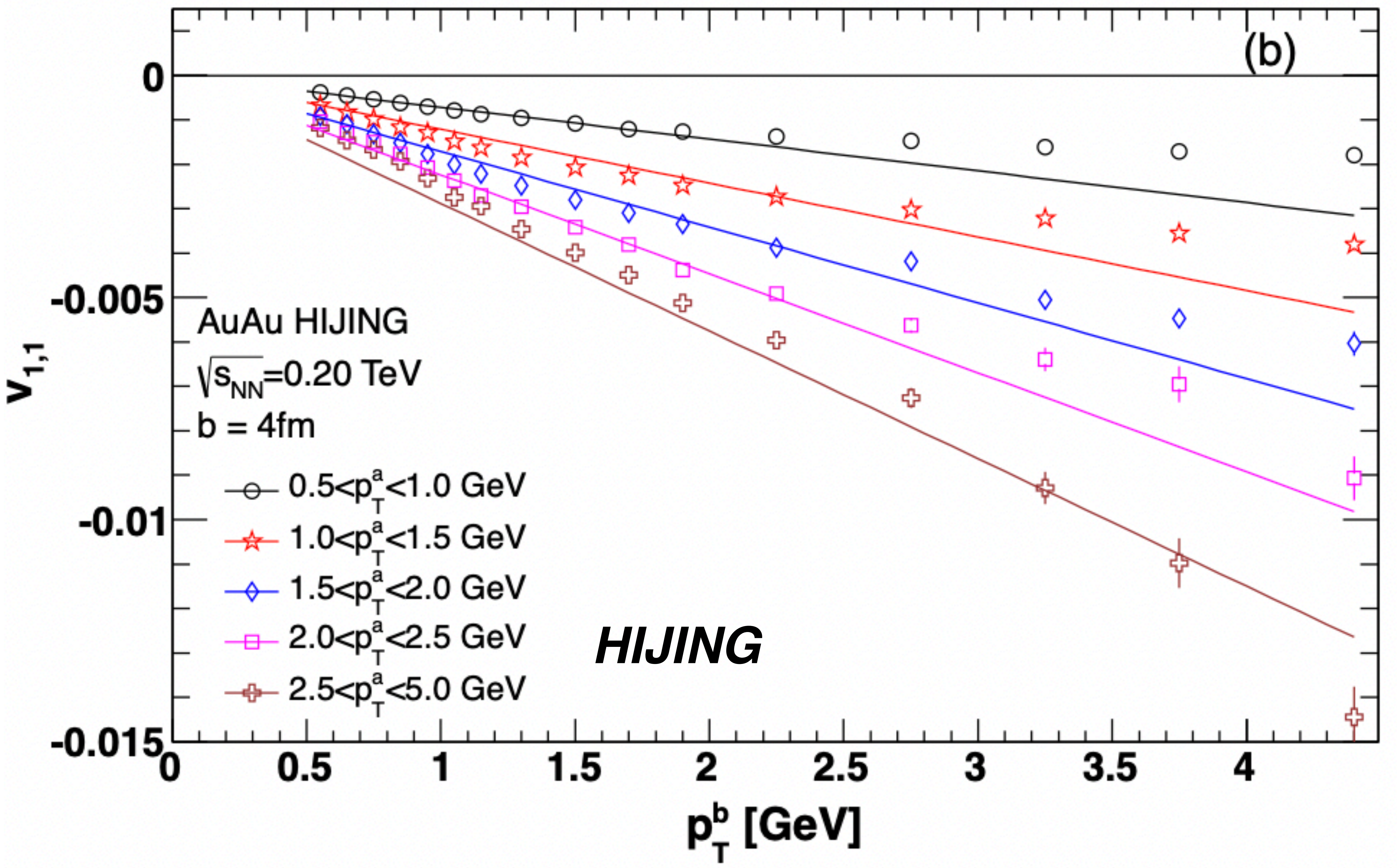
- Shows up in the first harmonic coefficient of azimuthal pair correlations
- HIJING has only momentum conservation
- AMPT also has flow from density fluctuations

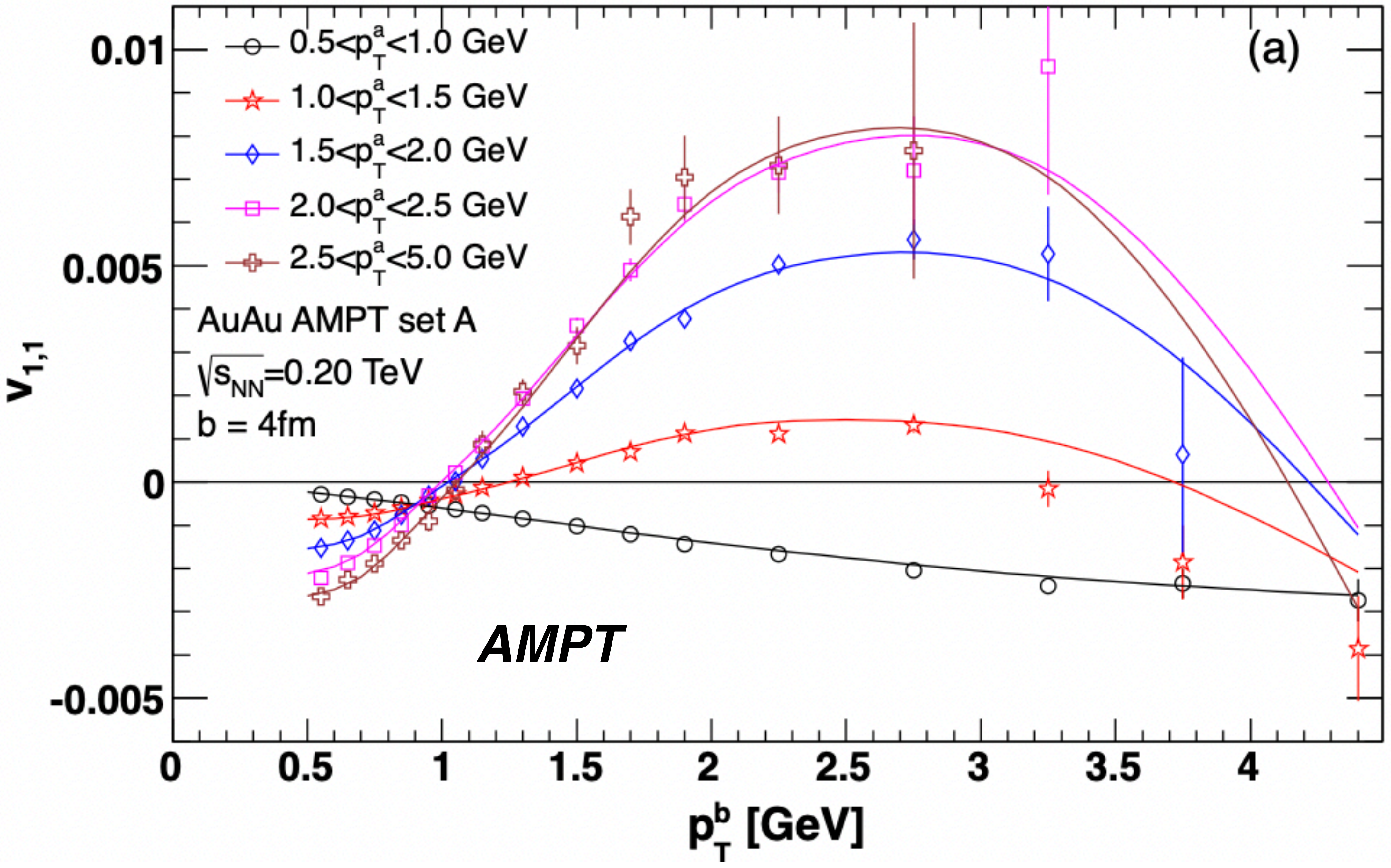
$$v_{1,1}(p_T^a, p_T^b) = v_1(p_T^a)v_1(p_T^b) - c p_T^a p_T^b$$



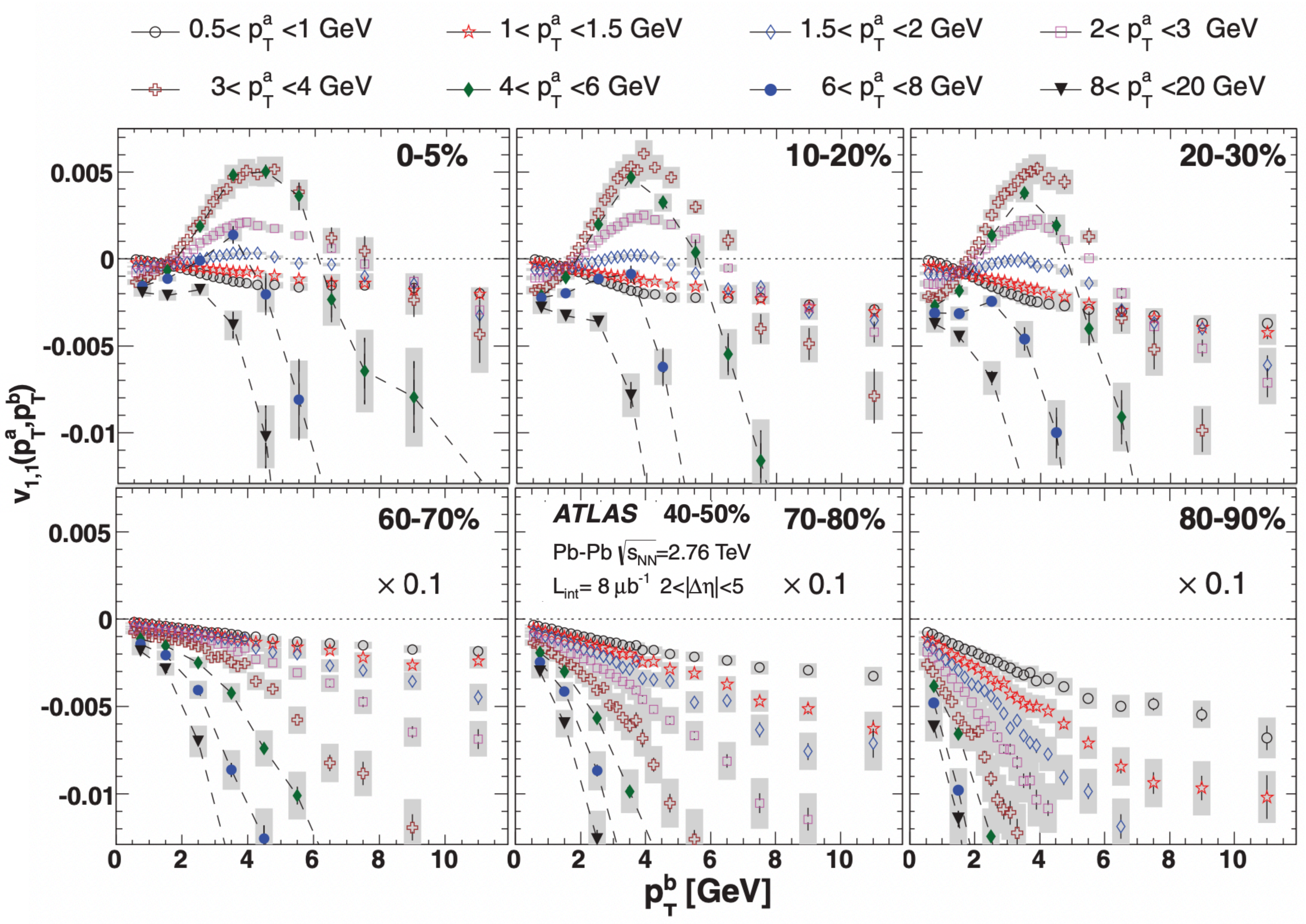


SR et al. arXiv:1203.3410

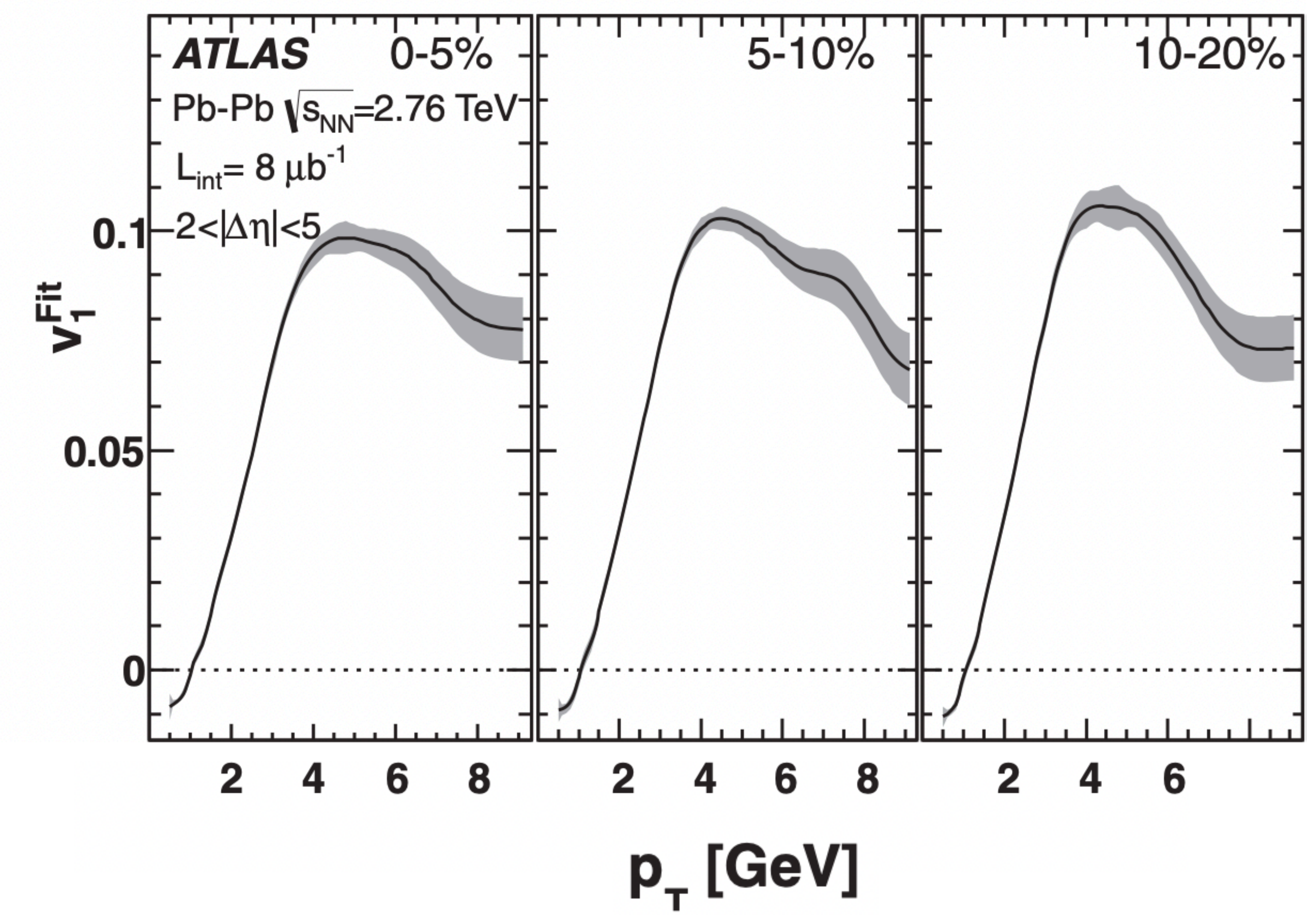




Directed flow from density fluctuations in A+A



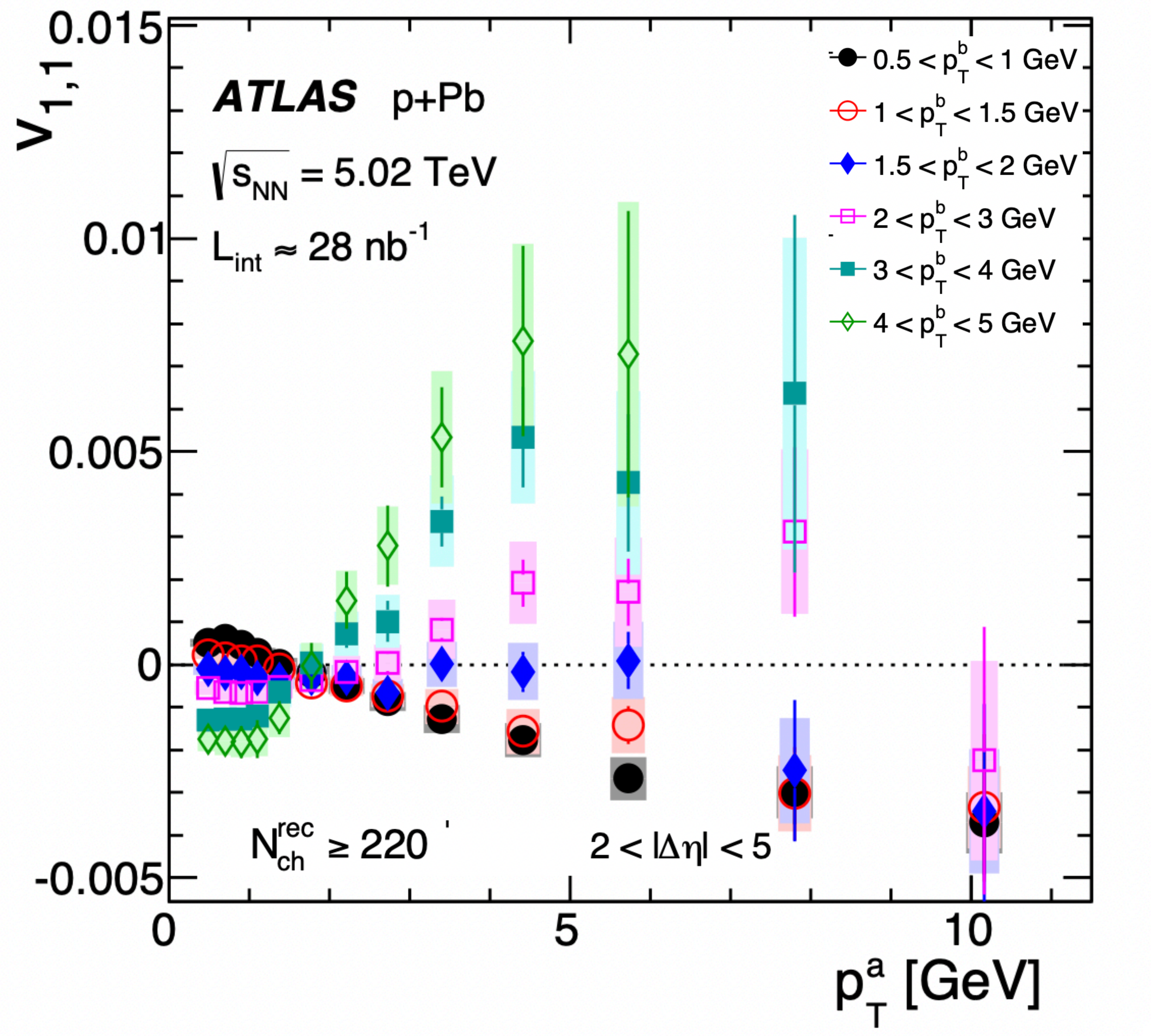
$$v_{1,1}(p_T^a, p_T^b) = v_1(p_T^a)v_1(p_T^b) - cp_T^a p_T^b$$

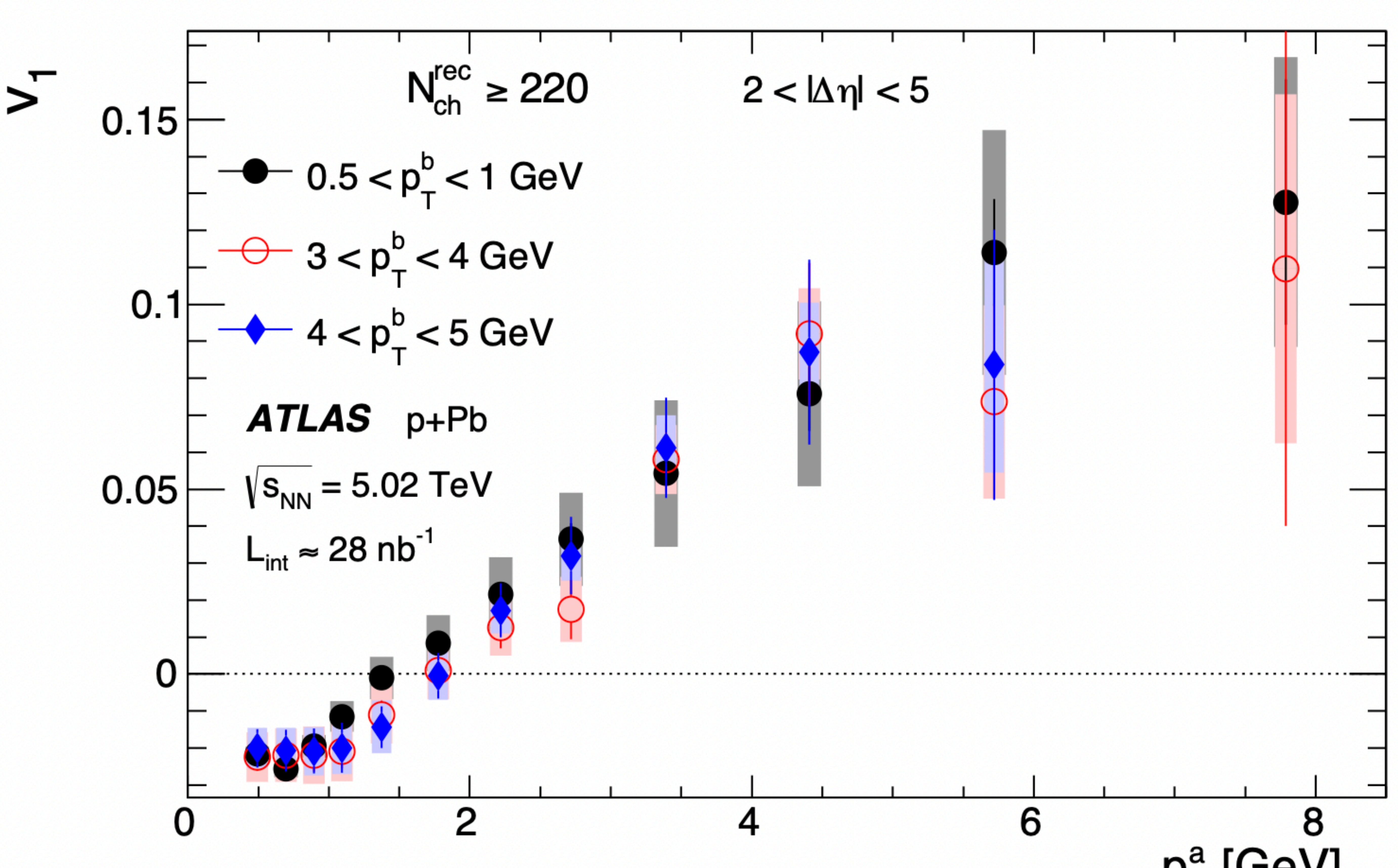


ATLAS, Phys. Rev. C 86, 014907

- Central A+A collisions show clear signature of v_1 from density fluctuations
- Peripheral collisions don't
- A two component fit can be used to extract the v_1 as function of p_T

Directed flow from density fluctuations in p+A!



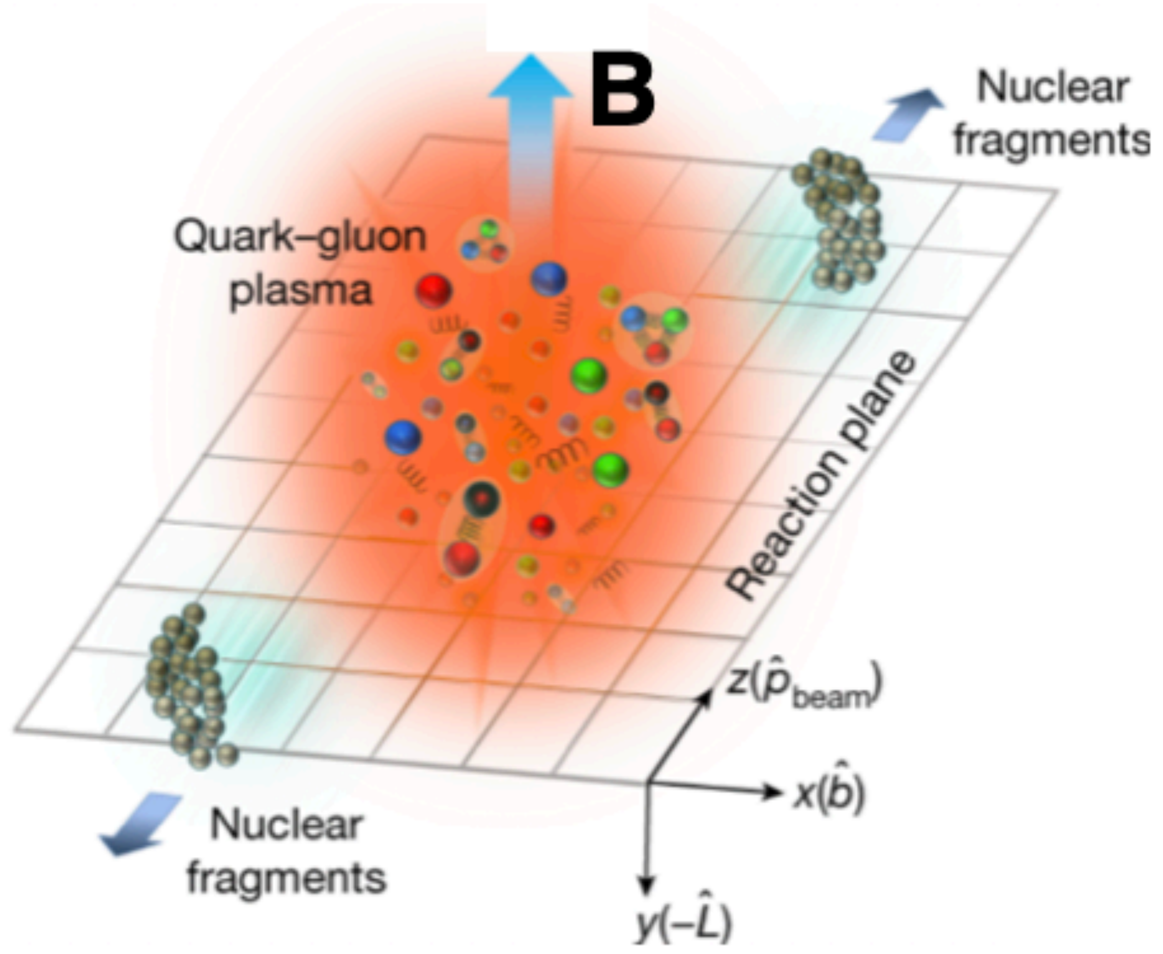


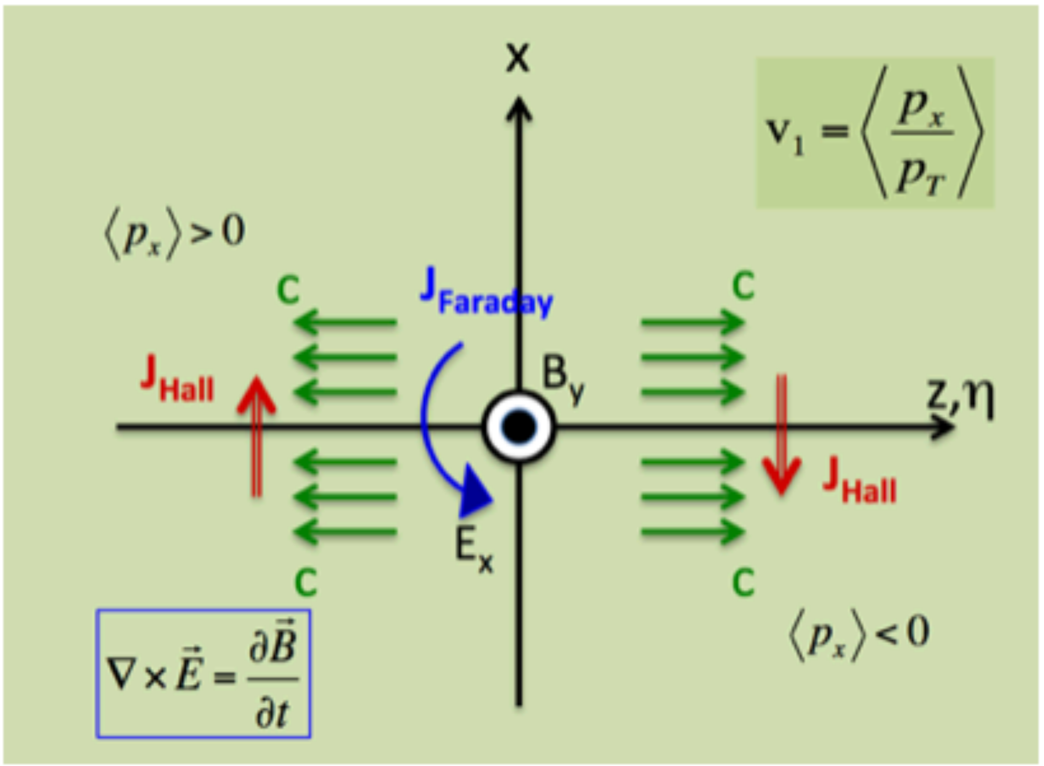
ATLAS, Phys. Rev. C 90, 044906

- A non-zero v_1 from density fluctuations can be extracted in high multiplicity p+A collisions also!
- Strongly supports the density anisotropy driven origin of long range correlations in p+Pb

Directed flow of charm hadrons

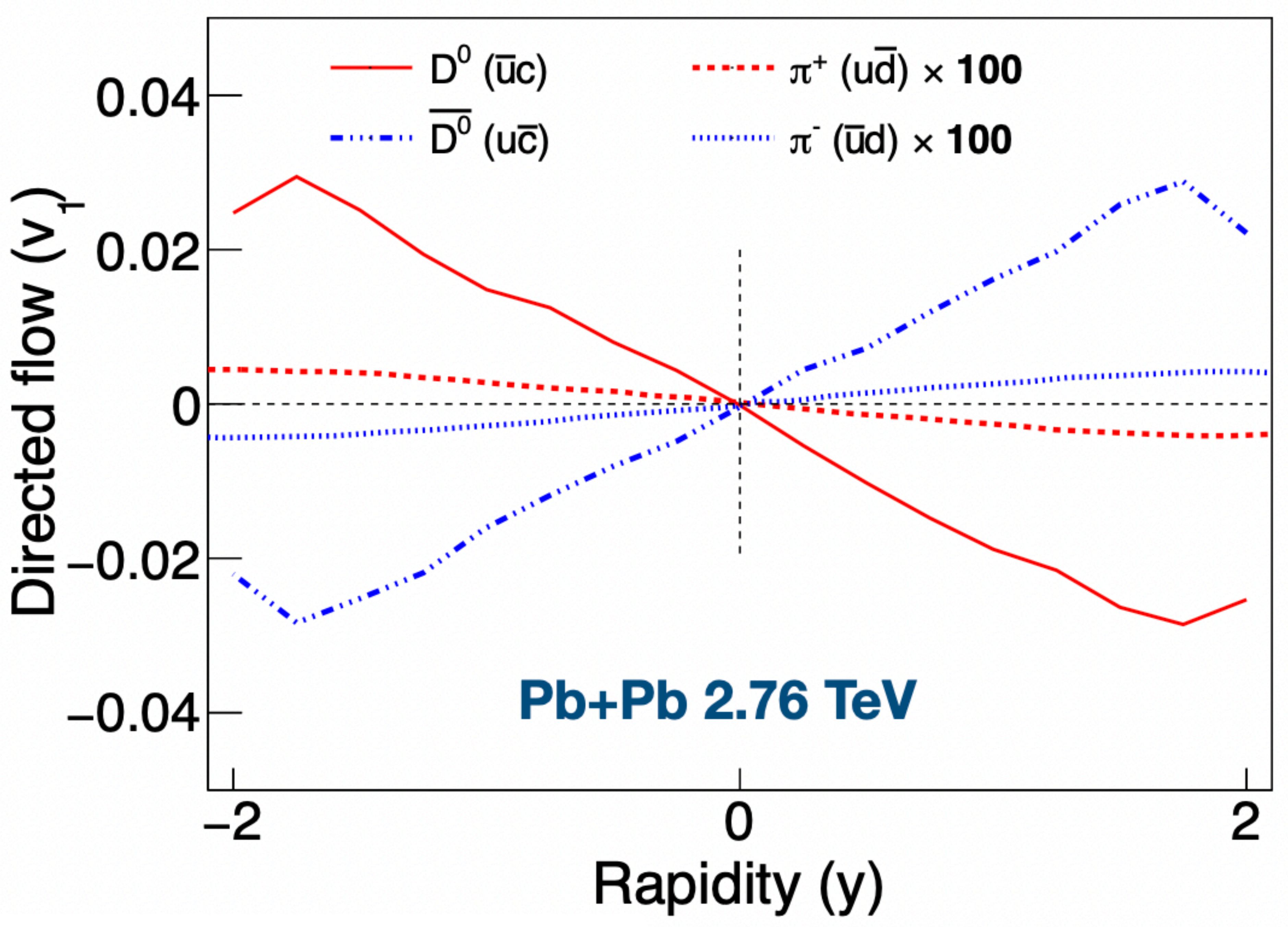
- Original motivation was to look for impact of strong B field in heavy ion collisions





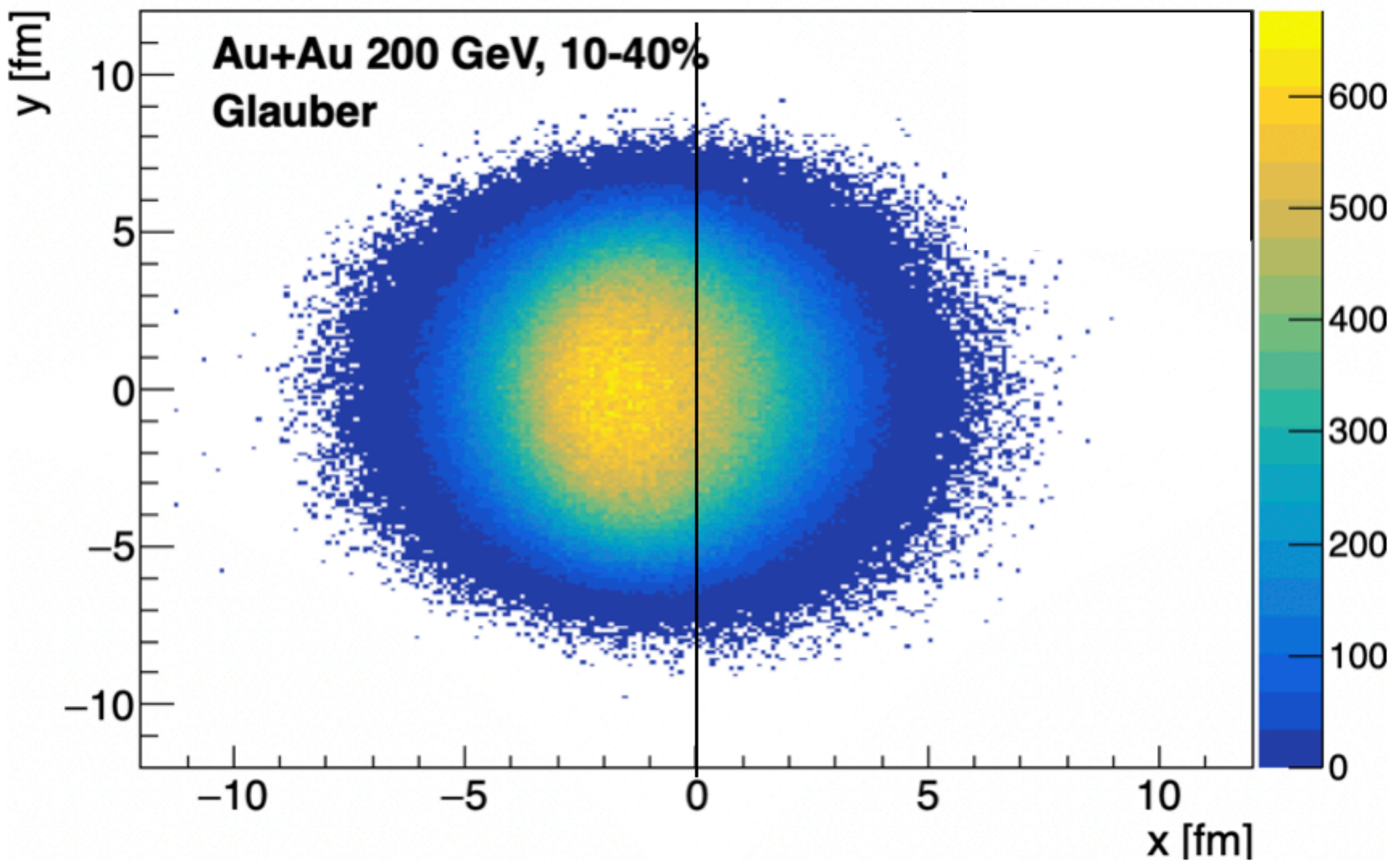
- Charm quarks produced early in the collisions, can be sensitive to the early time strong B fields
- Will produce opposite deflections for D^0 and D^0bar

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

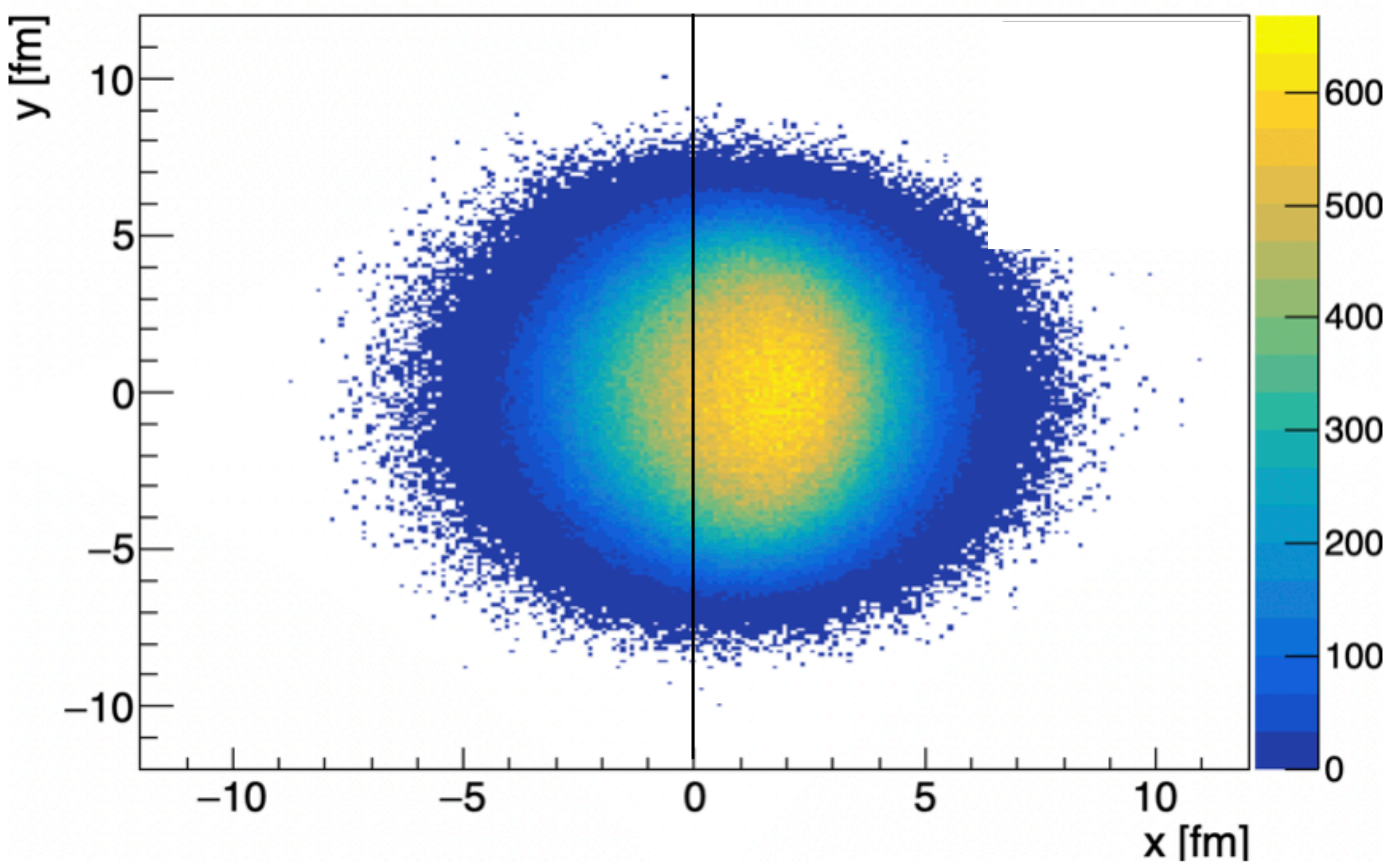


- Predicted splitting for charm hadrons order of magnitude larger than that for light flavor hadrons
- With STAR HFT we had a chance to look for this effect

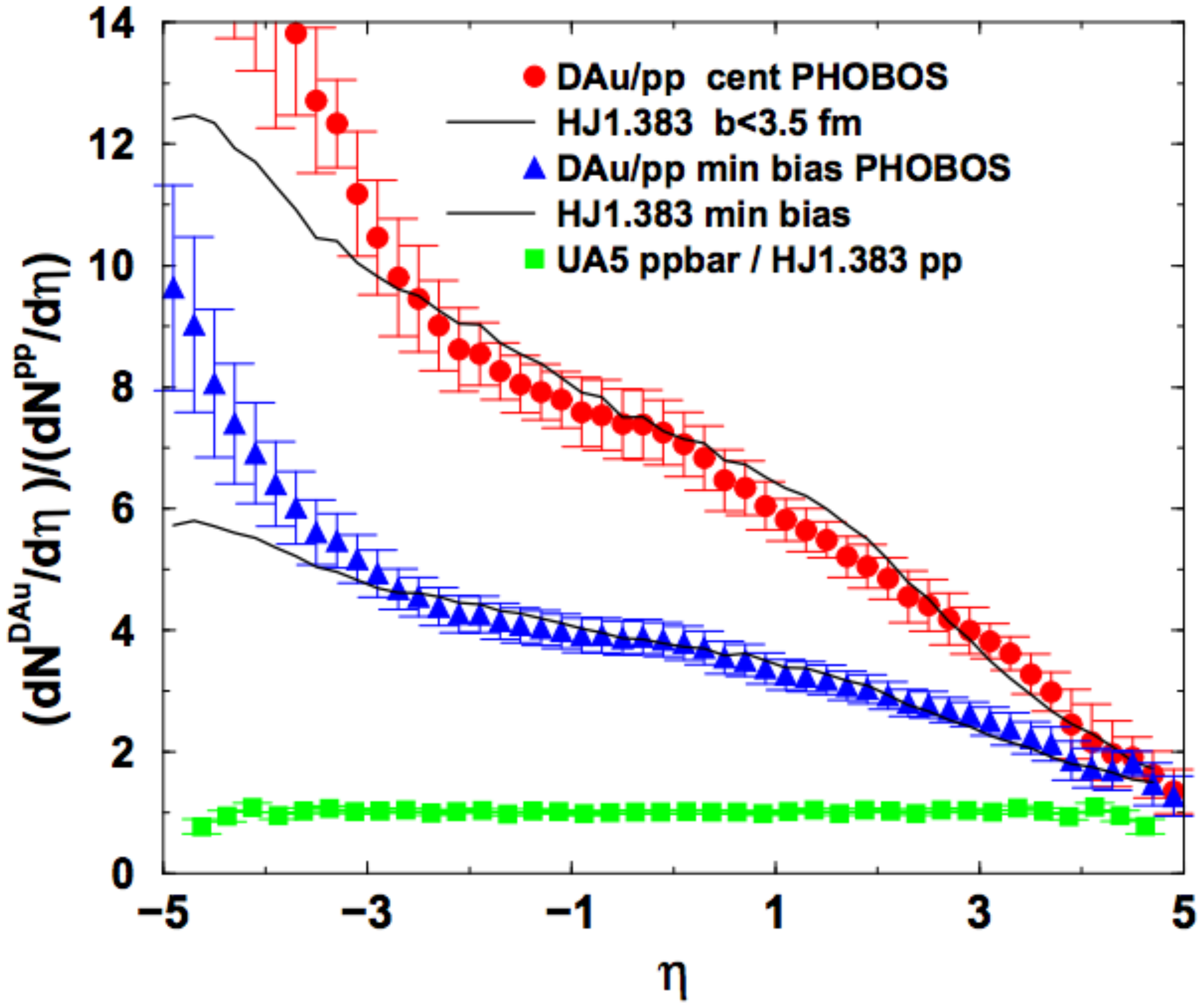
Also a geometric origin



Backward going participants

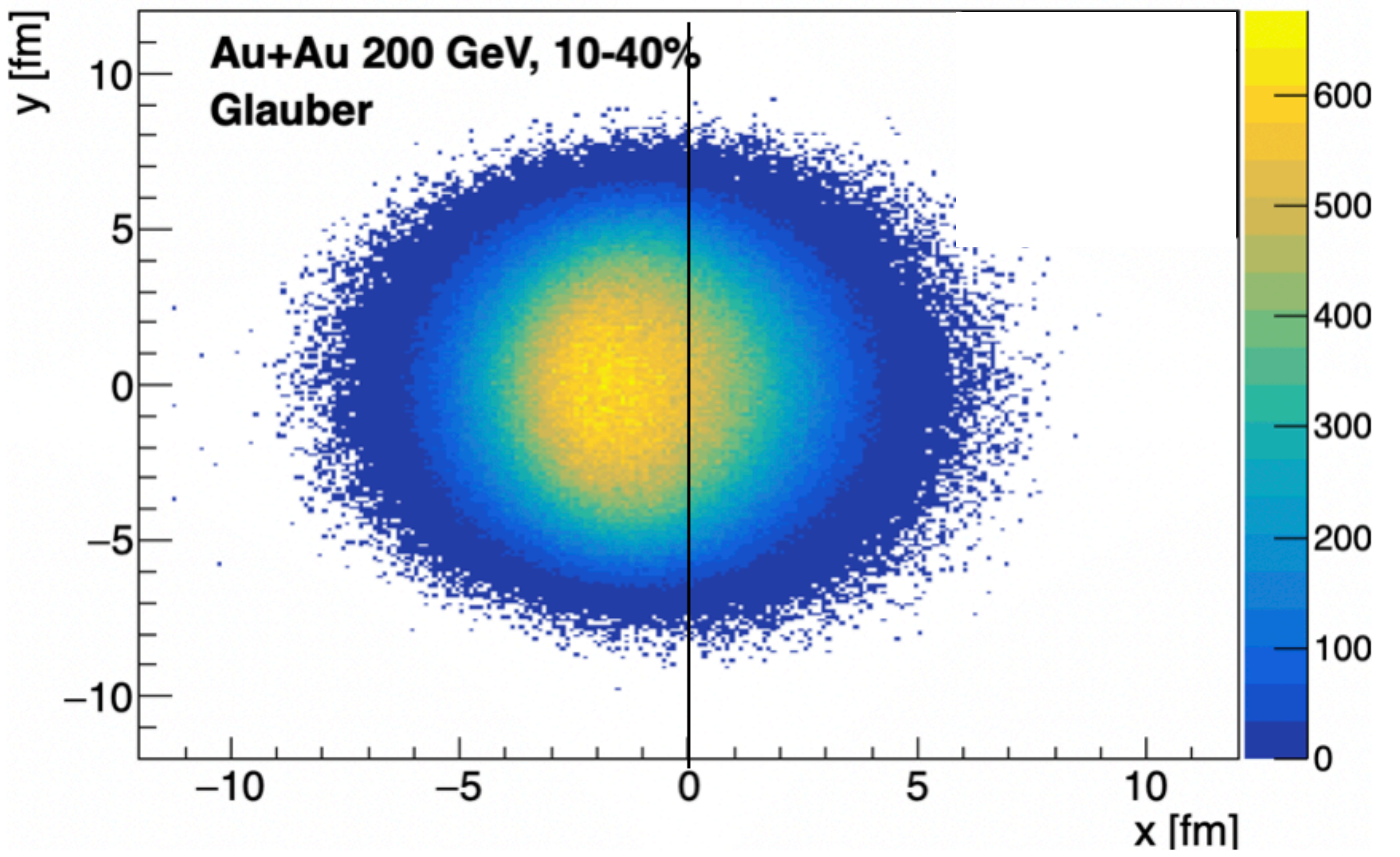


Forward going participants

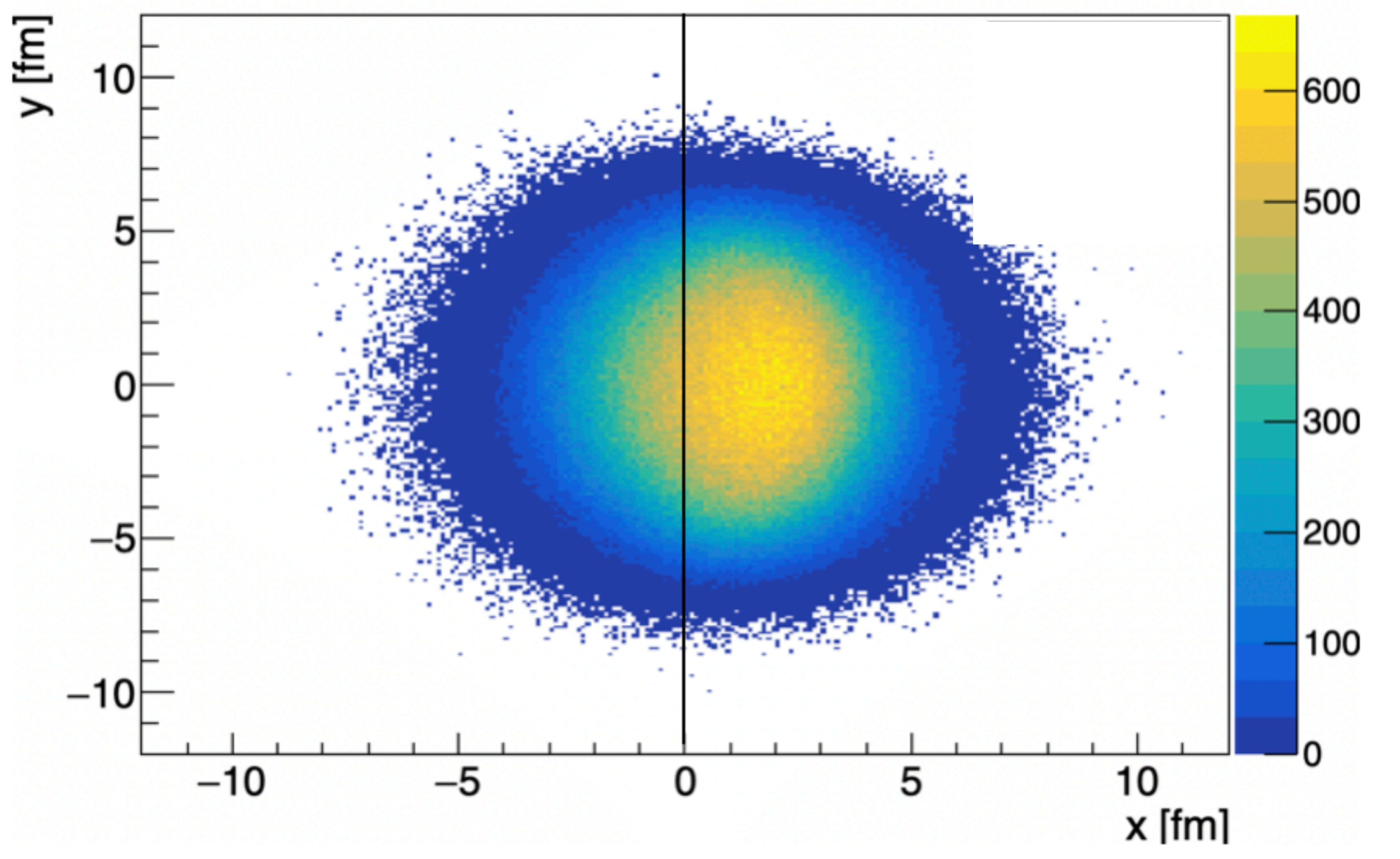


M. Gyulassy et al. Phys. Rev. C 72, 034907

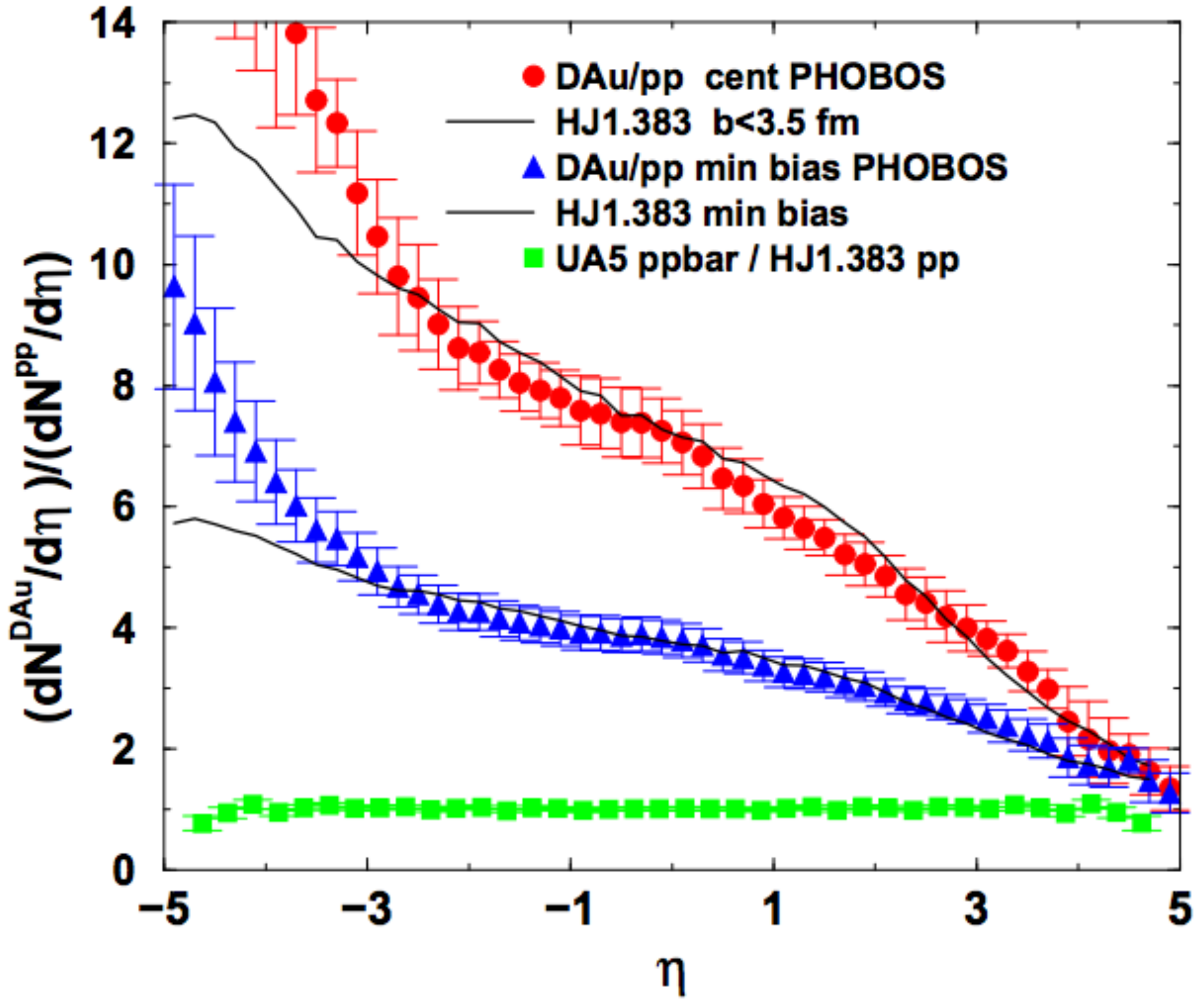
Also a geometric origin

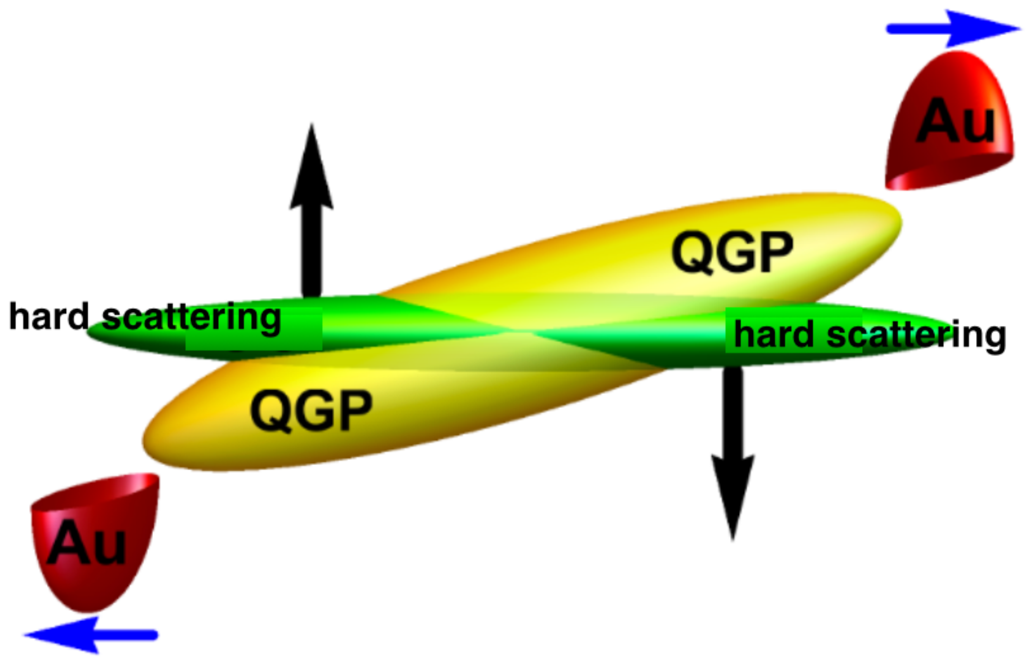


Backward going participants



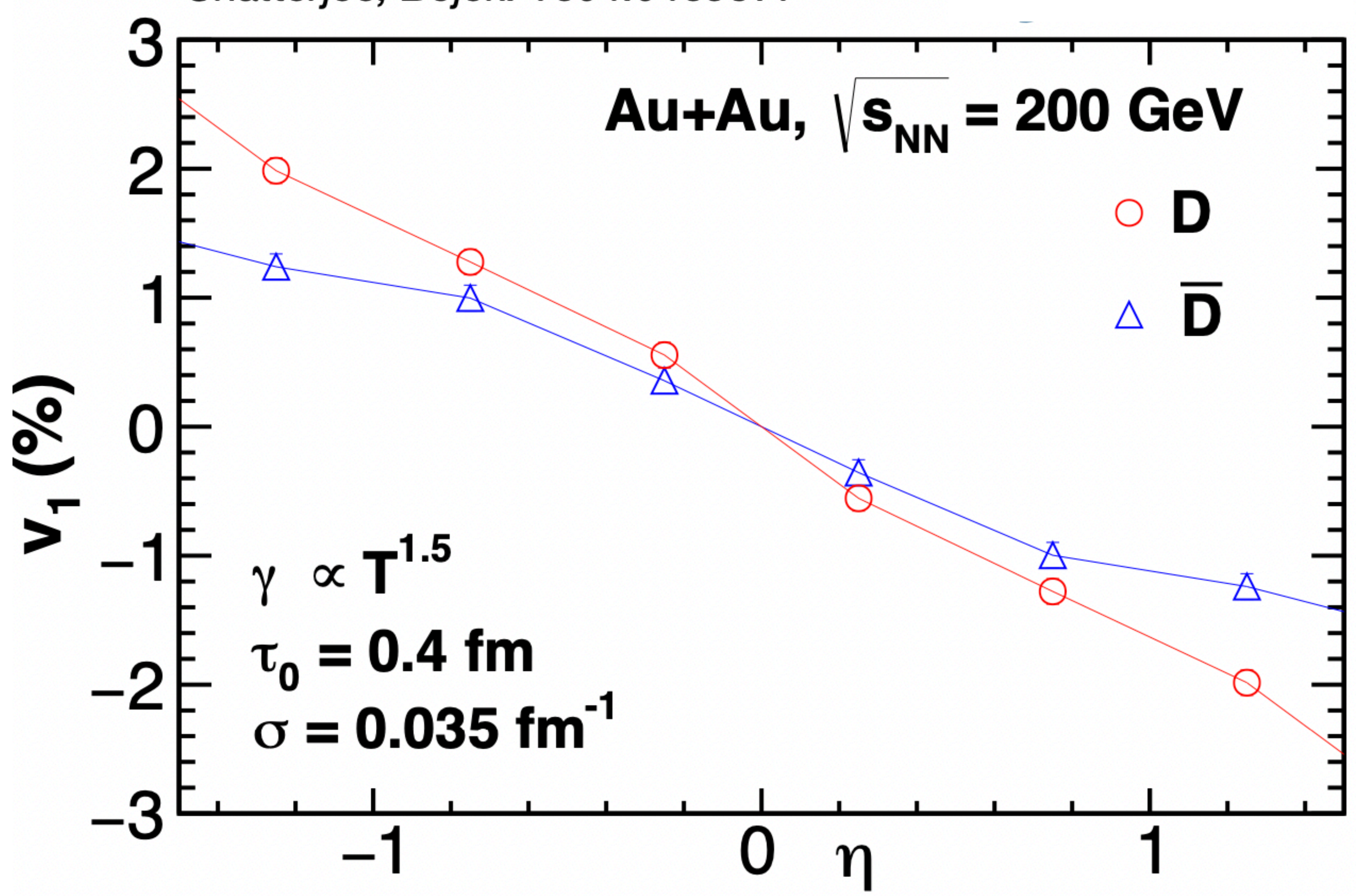
Forward going participants





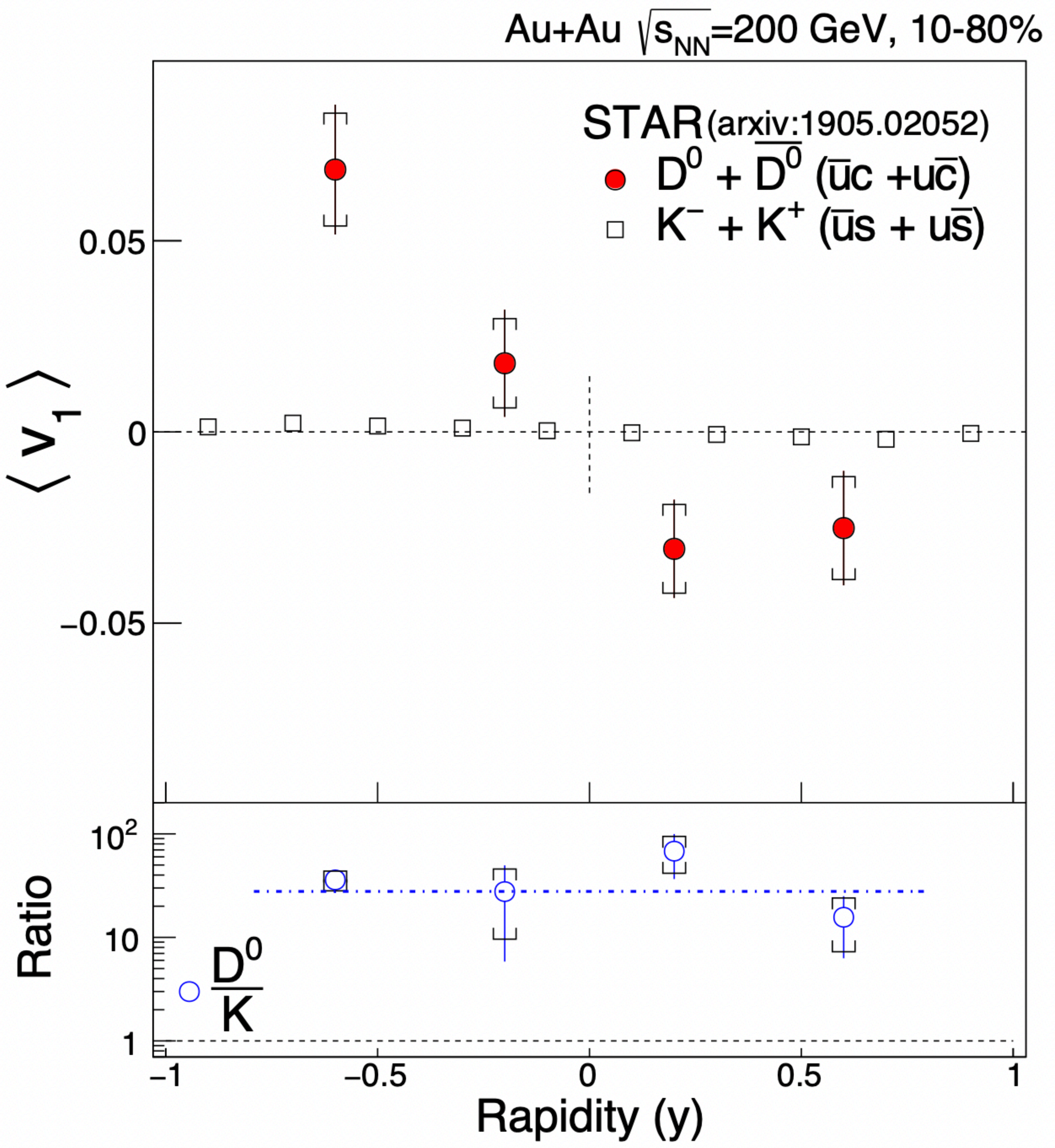
- Asymmetry in forward and backward going participants
- Causes tilt along impact parameter direction of the QGP bulk
- Hard-scattering profile not titled

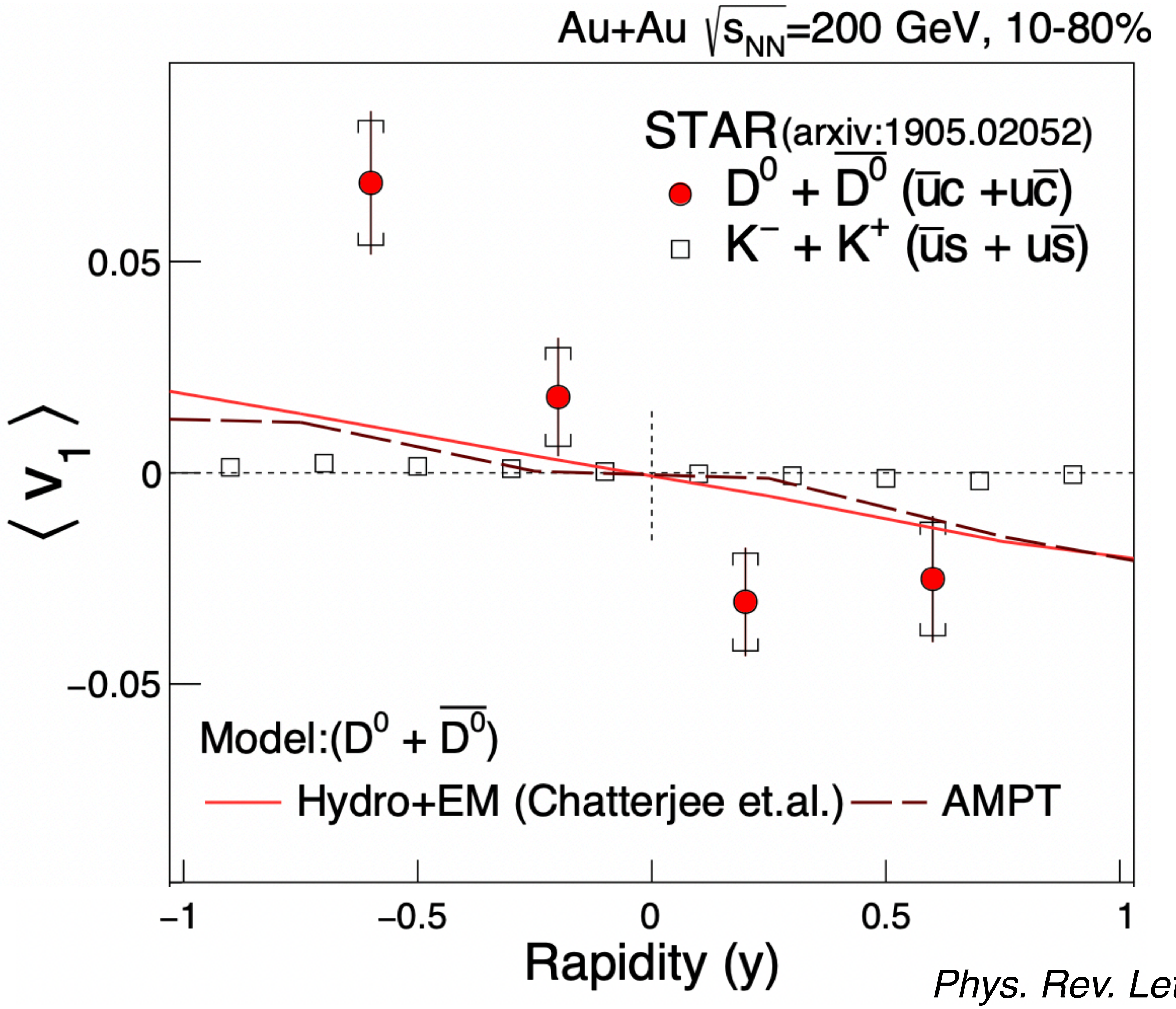
Chatterjee, Bojek: 1804.04893v1



- Induces large v_1 for heavy flavor hadrons

D⁰ directed flow in Au+Au collisions

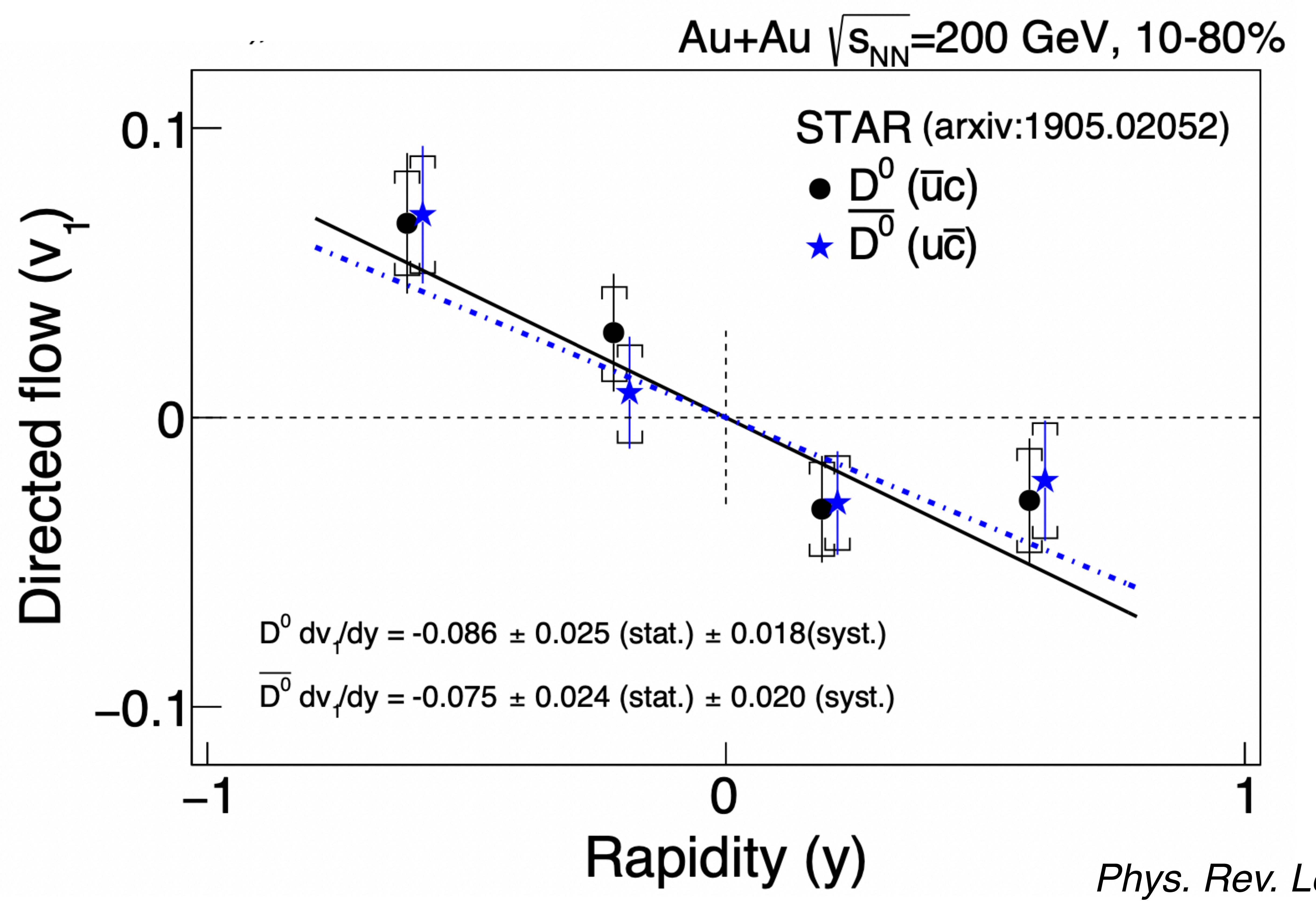


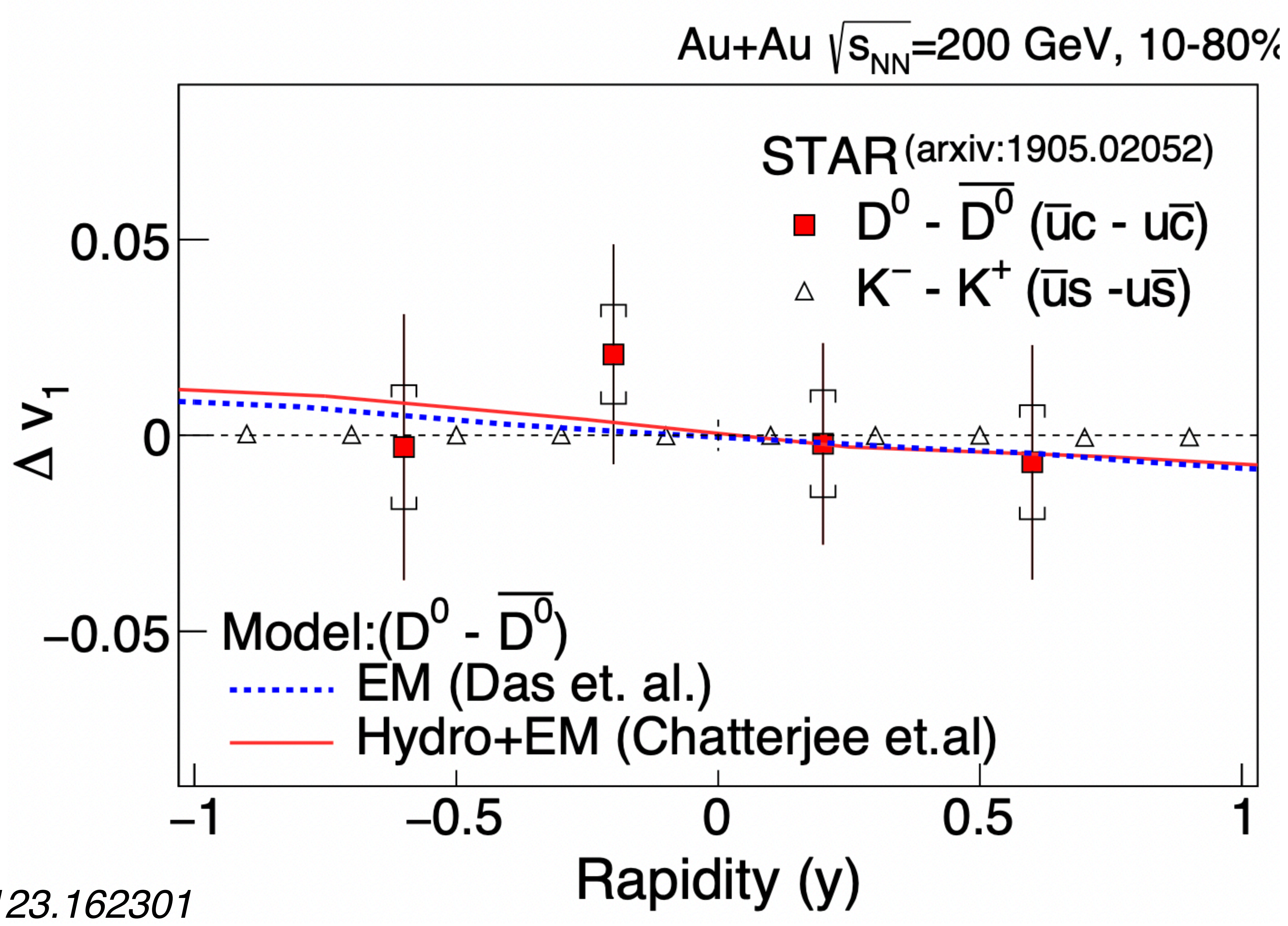


Phys. Rev. Lett.123.162301

- Order of magnitude larger v_1 observed for D mesons compared to that for kaons
- Large magnitudes predicted by hydro models taking into account initial offset in density distributions

Charge dependent splitting?

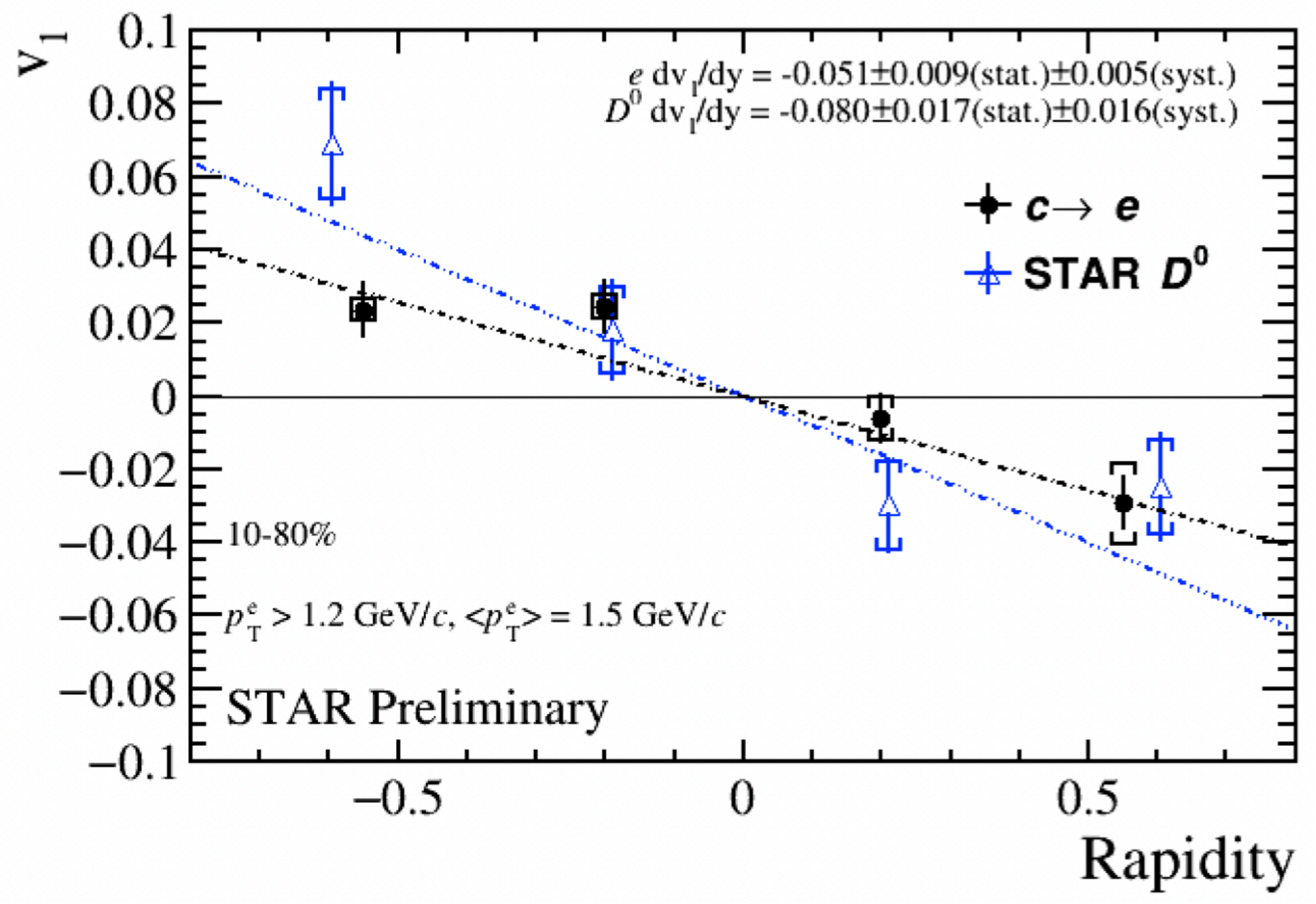




Phys. Rev. Lett.123.162301

- No splitting observed within uncertainties
- Current uncertainties are large, future measurements (sPHENIX, ALICE …) could give a definitive answer

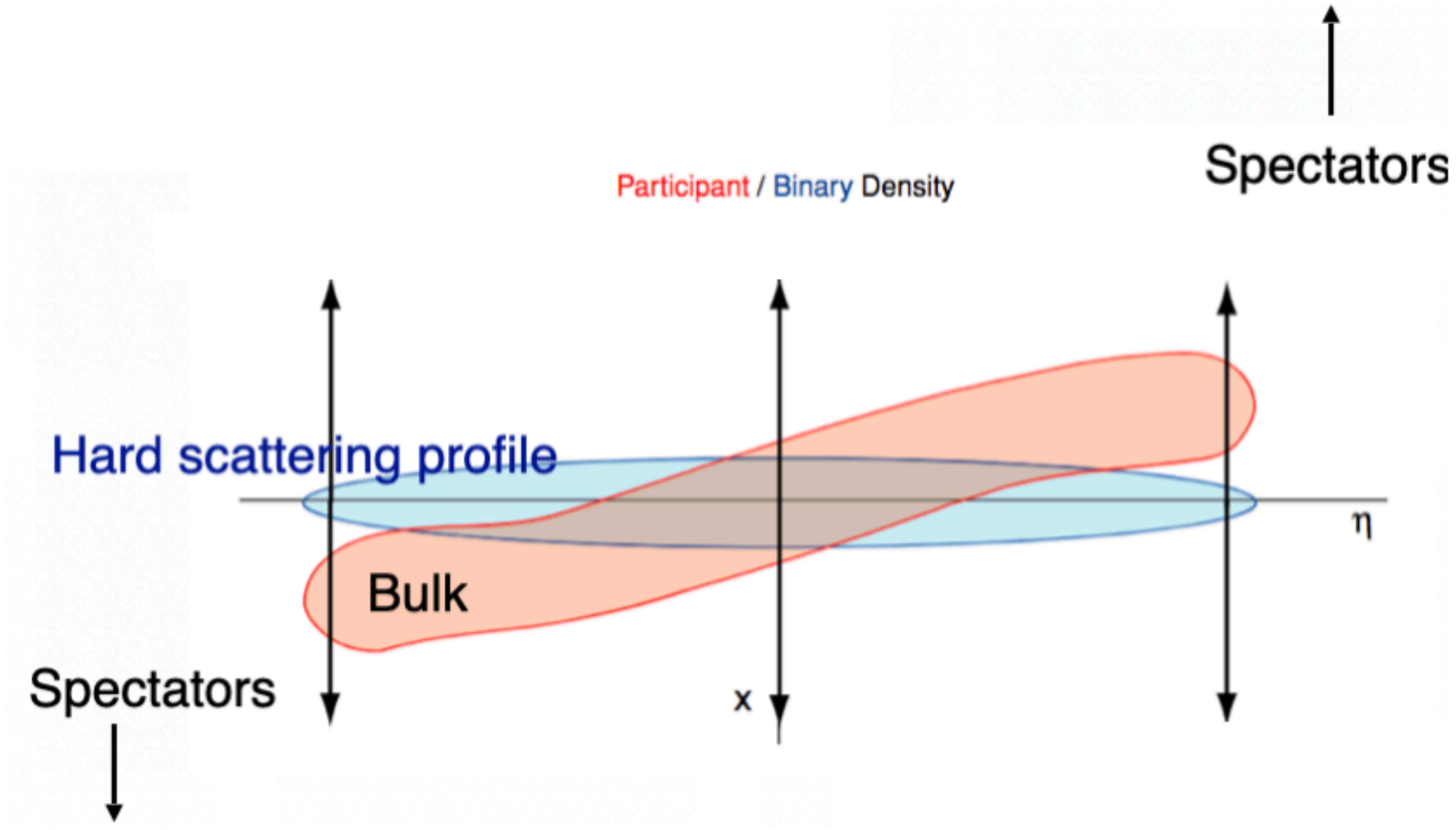
Directed flow of other hard probes



- Also measured for charm decayed electrons
- Mean p_T of parent charm and D^0 in the analyzed kinematics close to each other

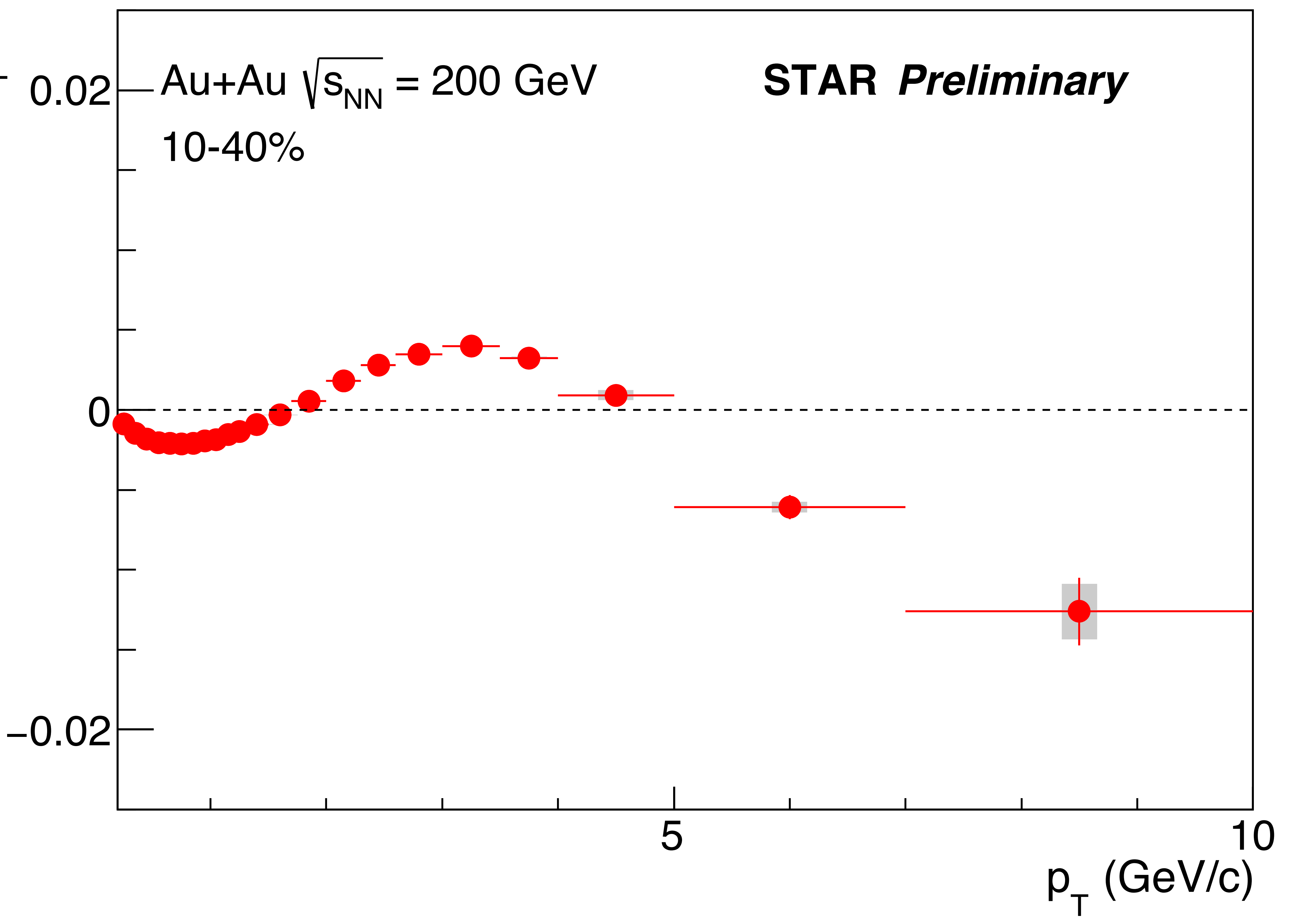
- Comparable magnitude to D^0 v_1, but much more significant
- Confirms the picture of v_1 origin from hard-soft asymmetry

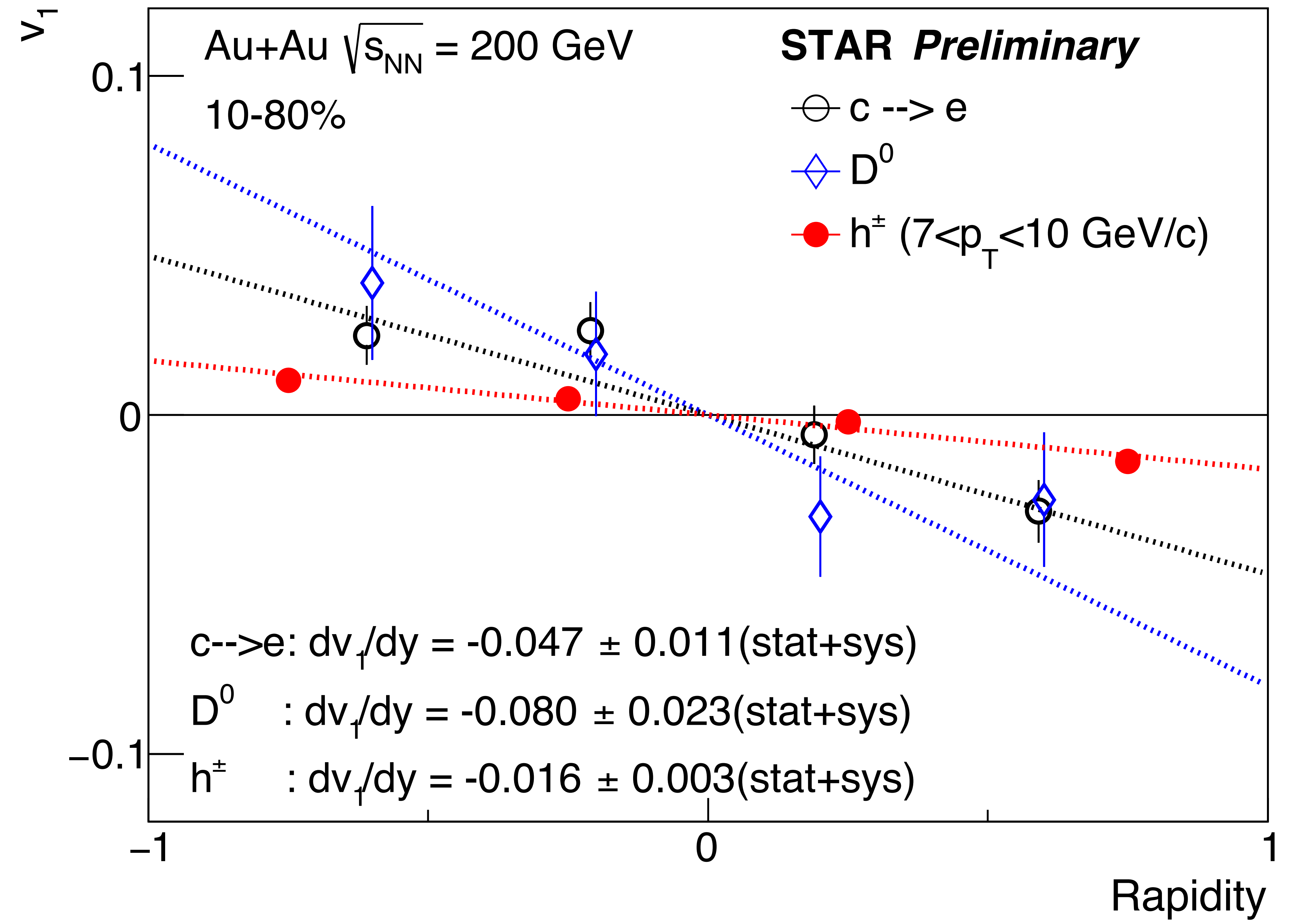
Directed flow of jets/high p_T hadrons

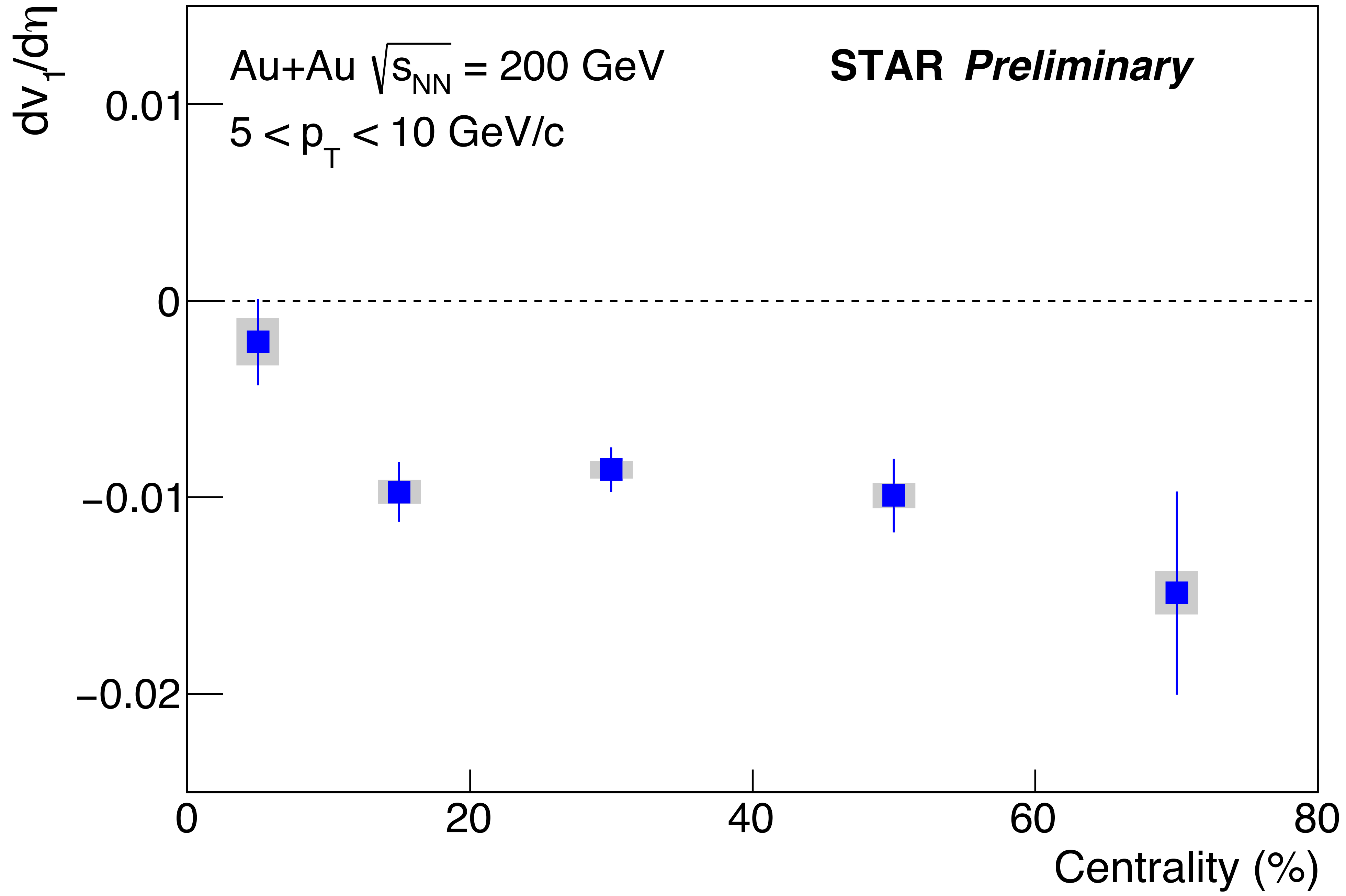


- Different path lengths through medium for patrons going along +x and -x as function of rapidity
- Can produce v_1 for jets from path length dependent energy loss

Directed flow of jets/high p_T hadrons

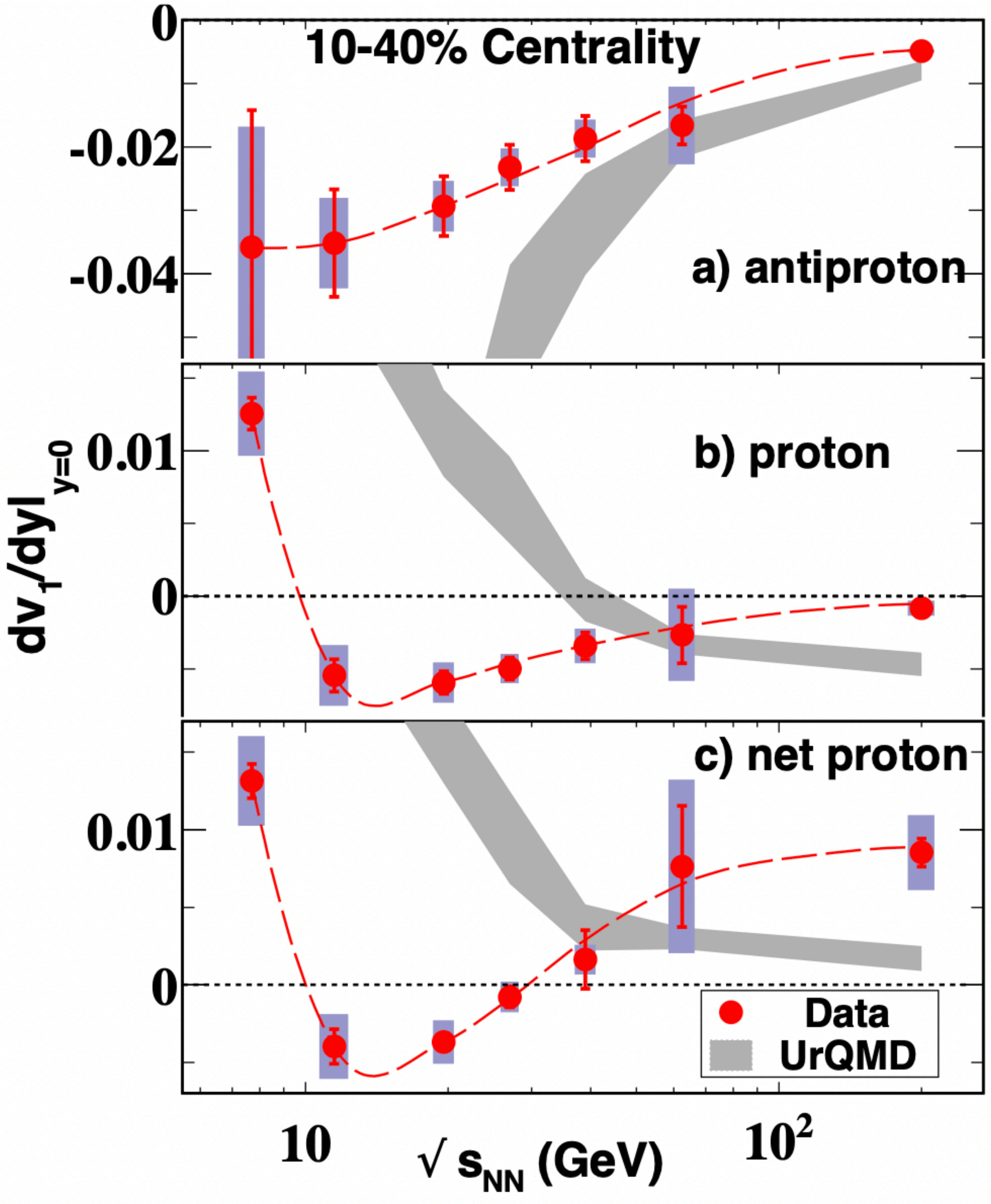






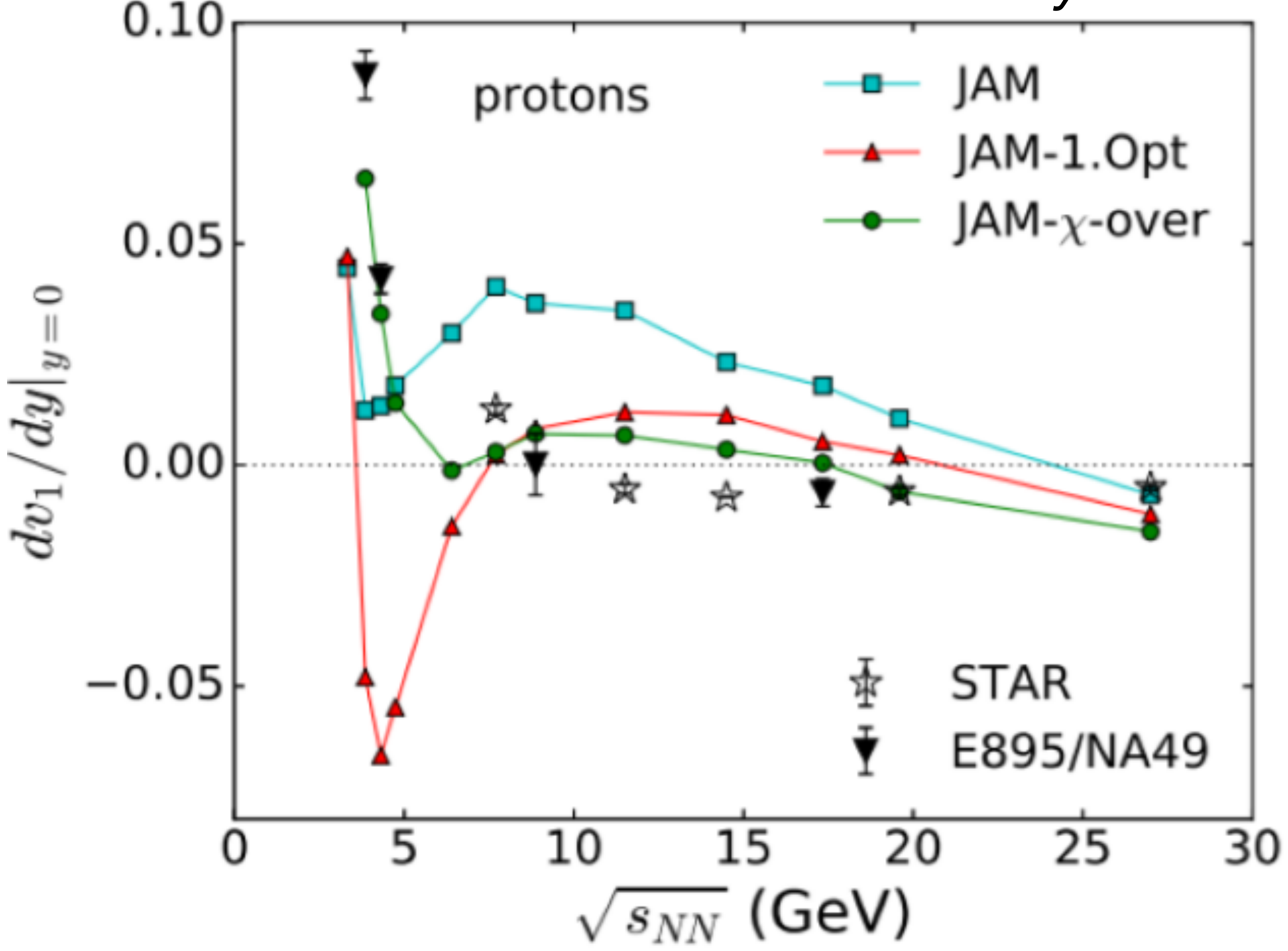
- High p_T hadrons also show the large negative v_1 from hard - soft asymmetry
- Driven by path length dependent energy loss
- Can be valuable probe to study jet energy loss

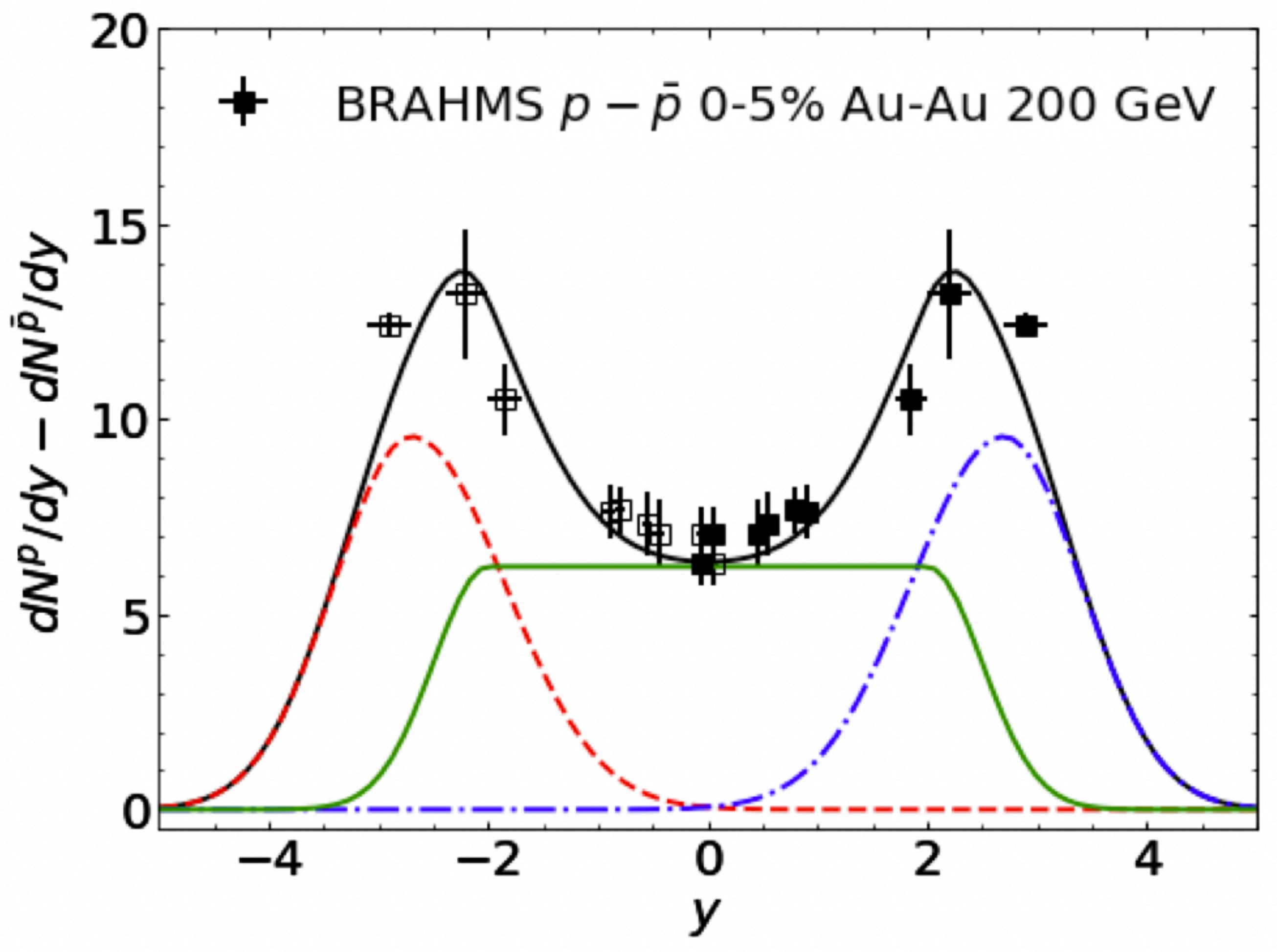
Proton directed flow and STAR BES-II



STAR, Phys. Rev. Lett. 112 (2014) 162301

Y. Nara et al. Phys. Lett. B 769 (2017) 543





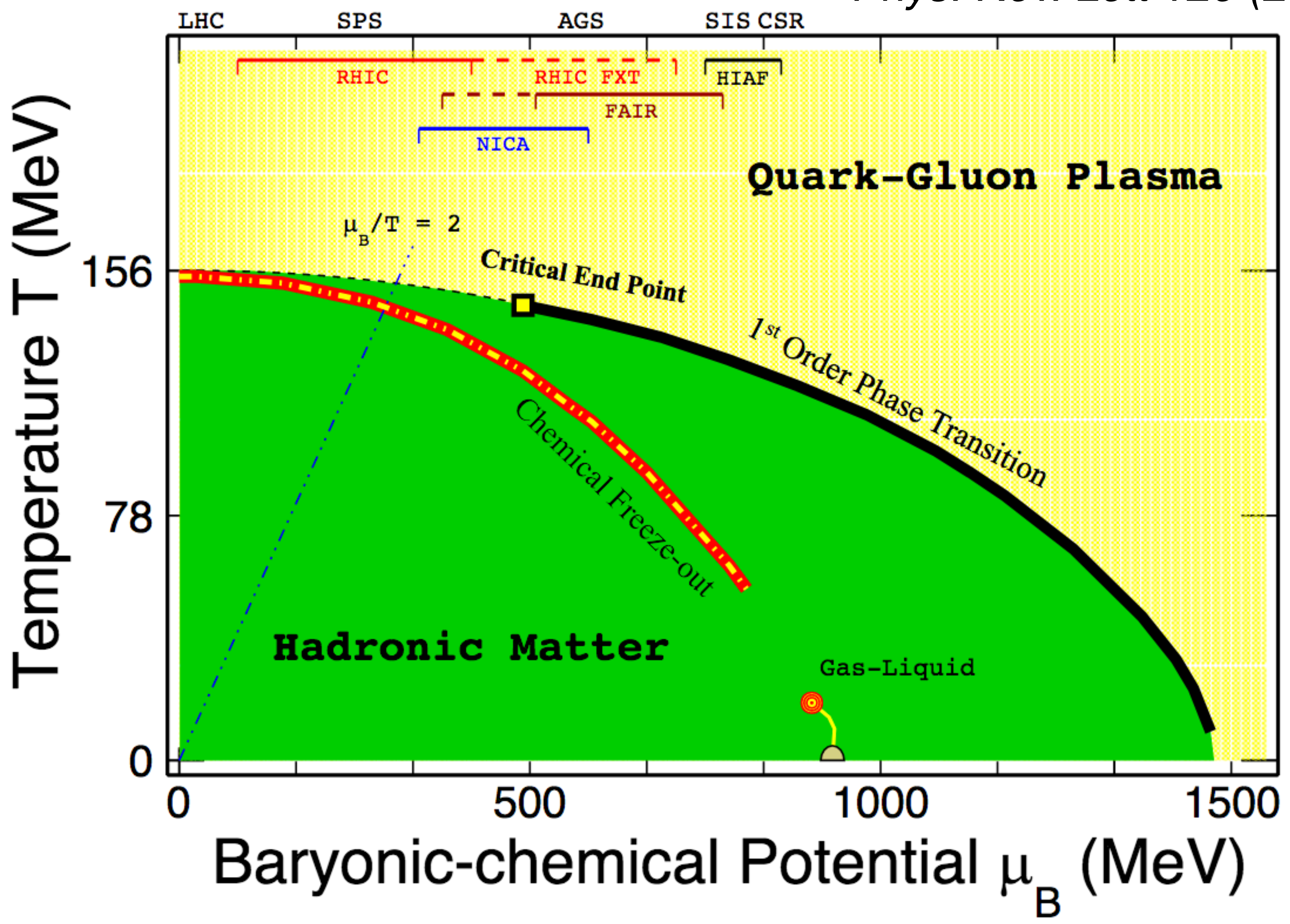
L. Du, QM 23

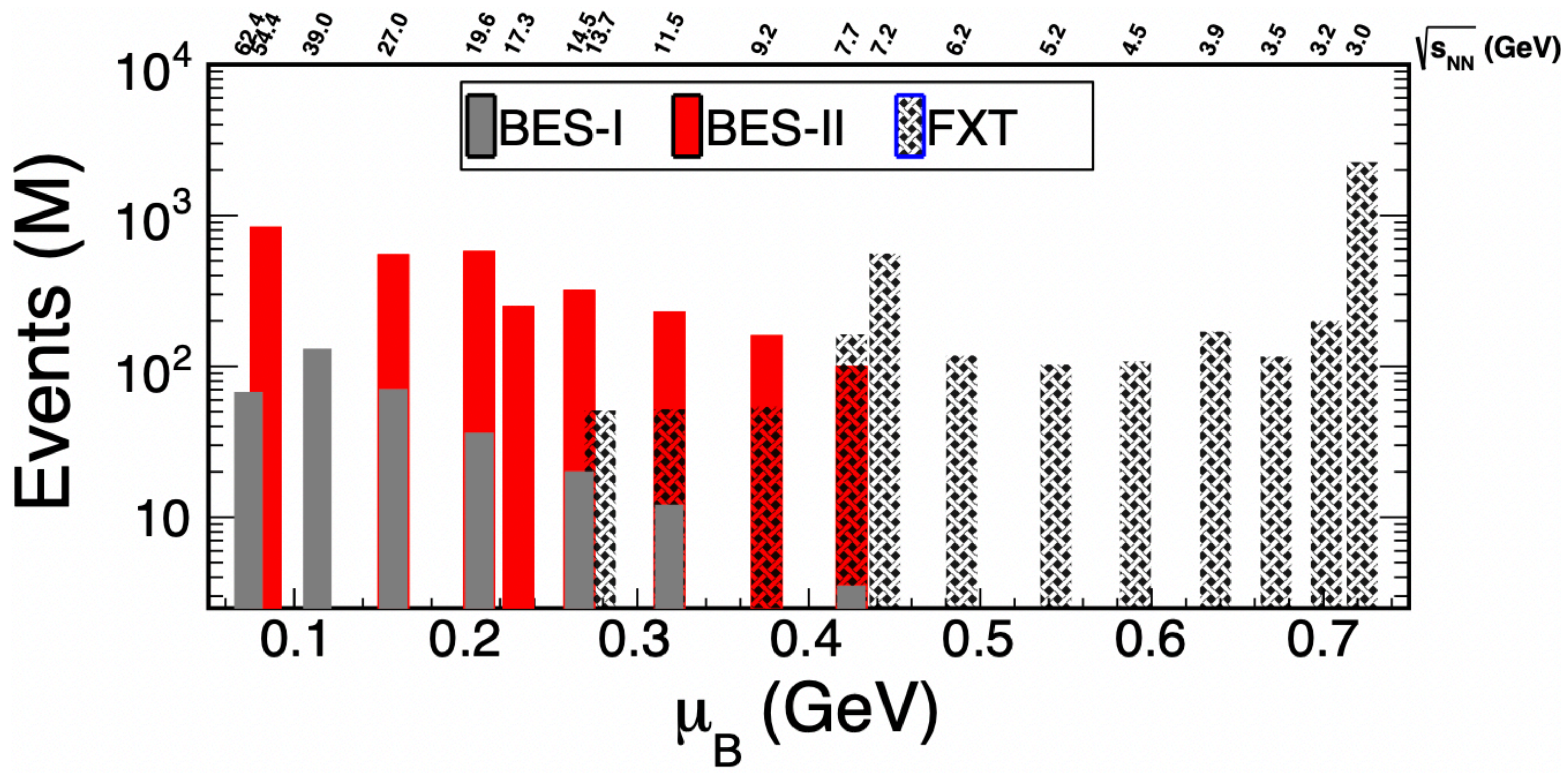
- Observed minimum at higher energy than predicted by models
- So far models unable to describe the energy dependence
- Also, interplay of transported and produced protons need to be better understood
- Interest also for understanding baryon transport

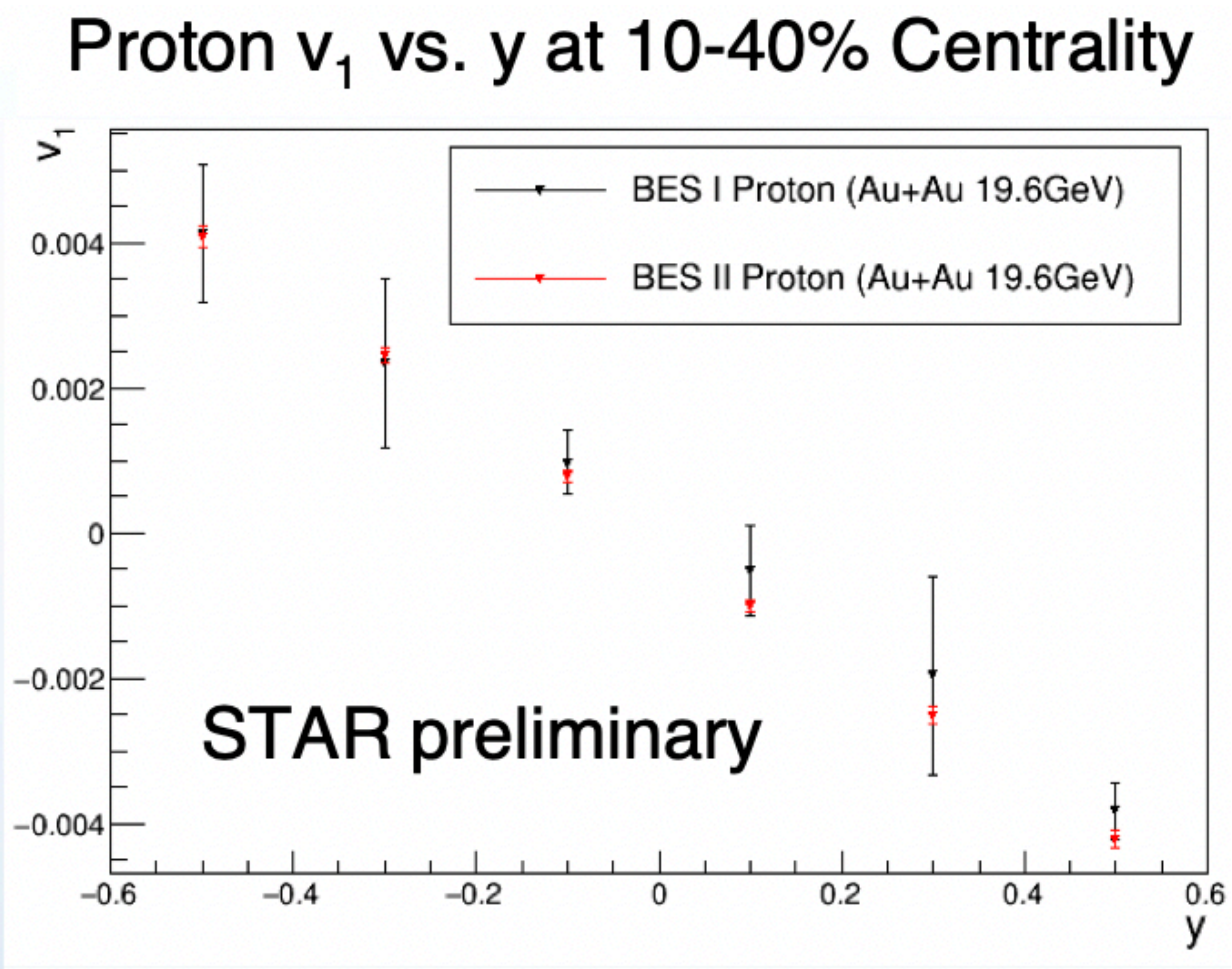
- Higher statistics data from BES-II to explore further

STAR BES-II

Phys. Rev. Lett 126 (2021) 92301

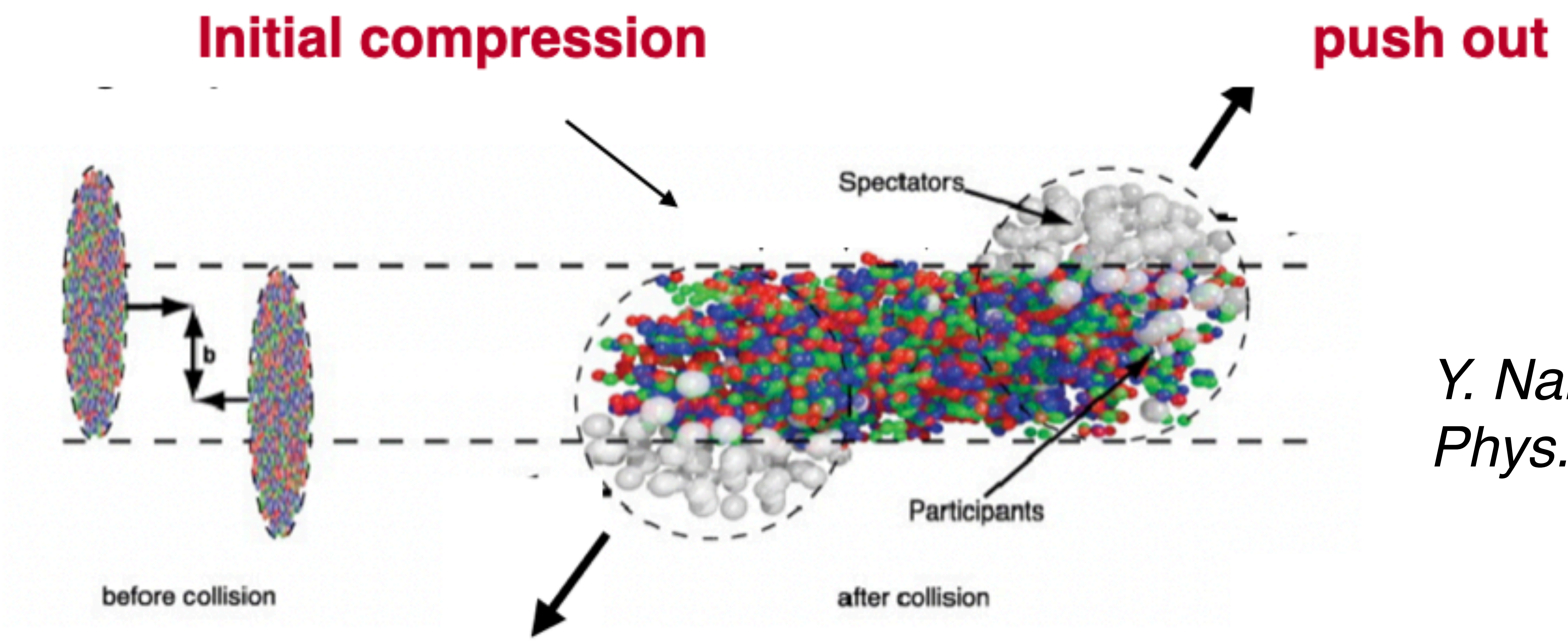




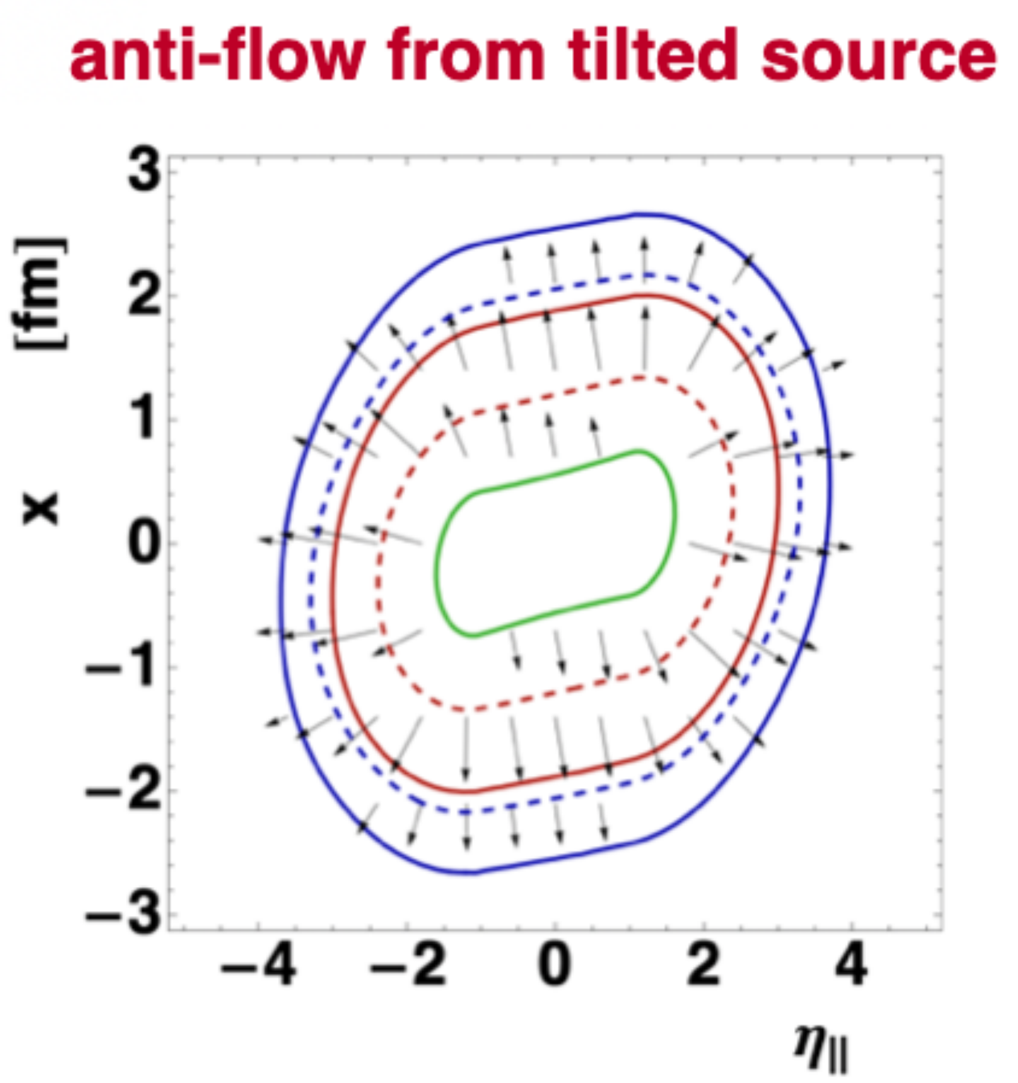


- Higher statistics, Extend reach to lower collision energies with FXT
- Detector upgrades at STAR (iTPC, EPD, ETOF) enhancing acceptance
- Significantly improved precision with BES-II

Can we understand proton directed flow better?



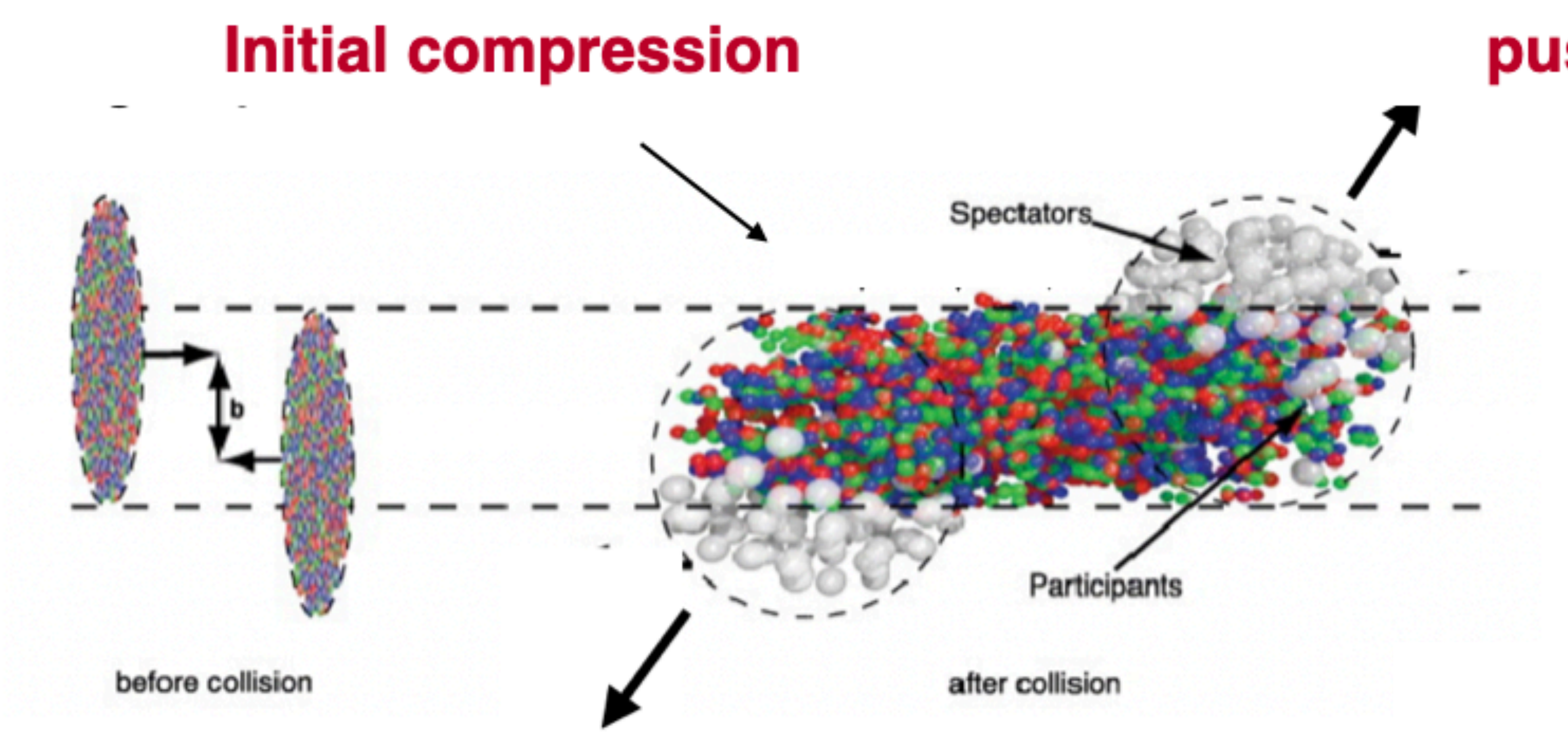
Y. Nara et al,
Phys. Rev. C.105.014911 (2021)

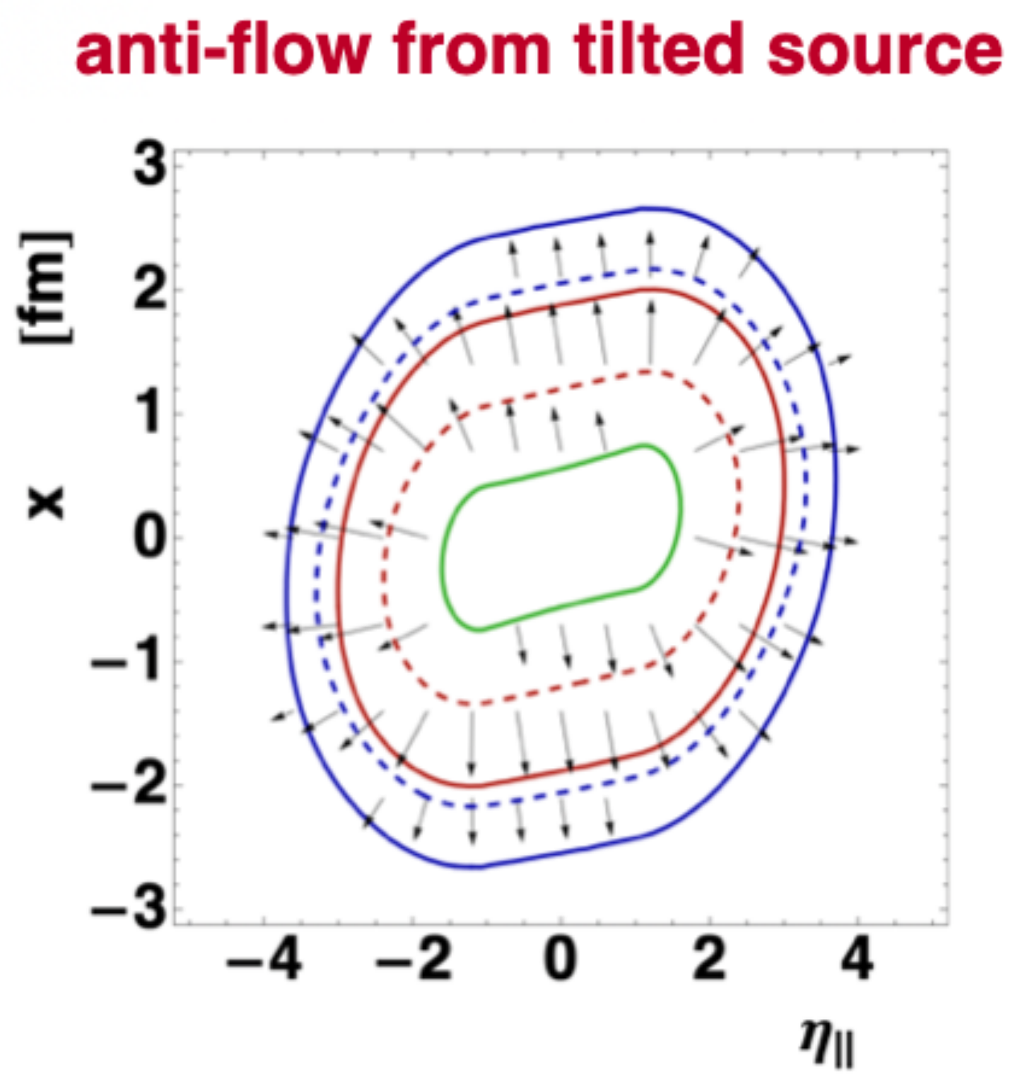


- Two contributions for proton directed flow:
  - positive contribution during initial compression stage, anti-flow (negative contribution) from tilted source during expansion stage

- Can we separate these two components?

Can we understand proton directed flow better?





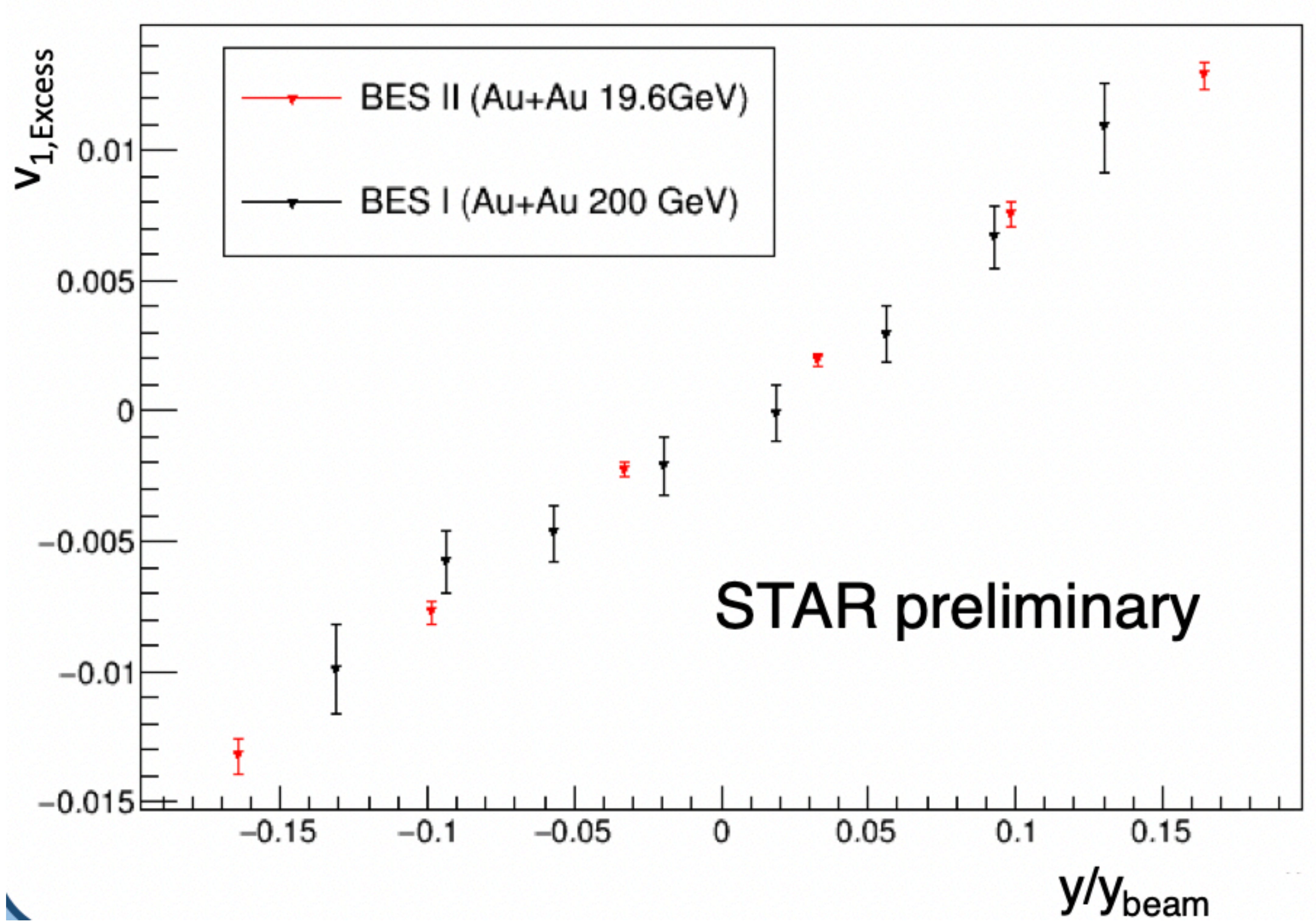
- Two contributions for proton directed flow:
  - positive contribution during initial compression stage, anti-flow (negative contribution) from tilted source during expansion stage

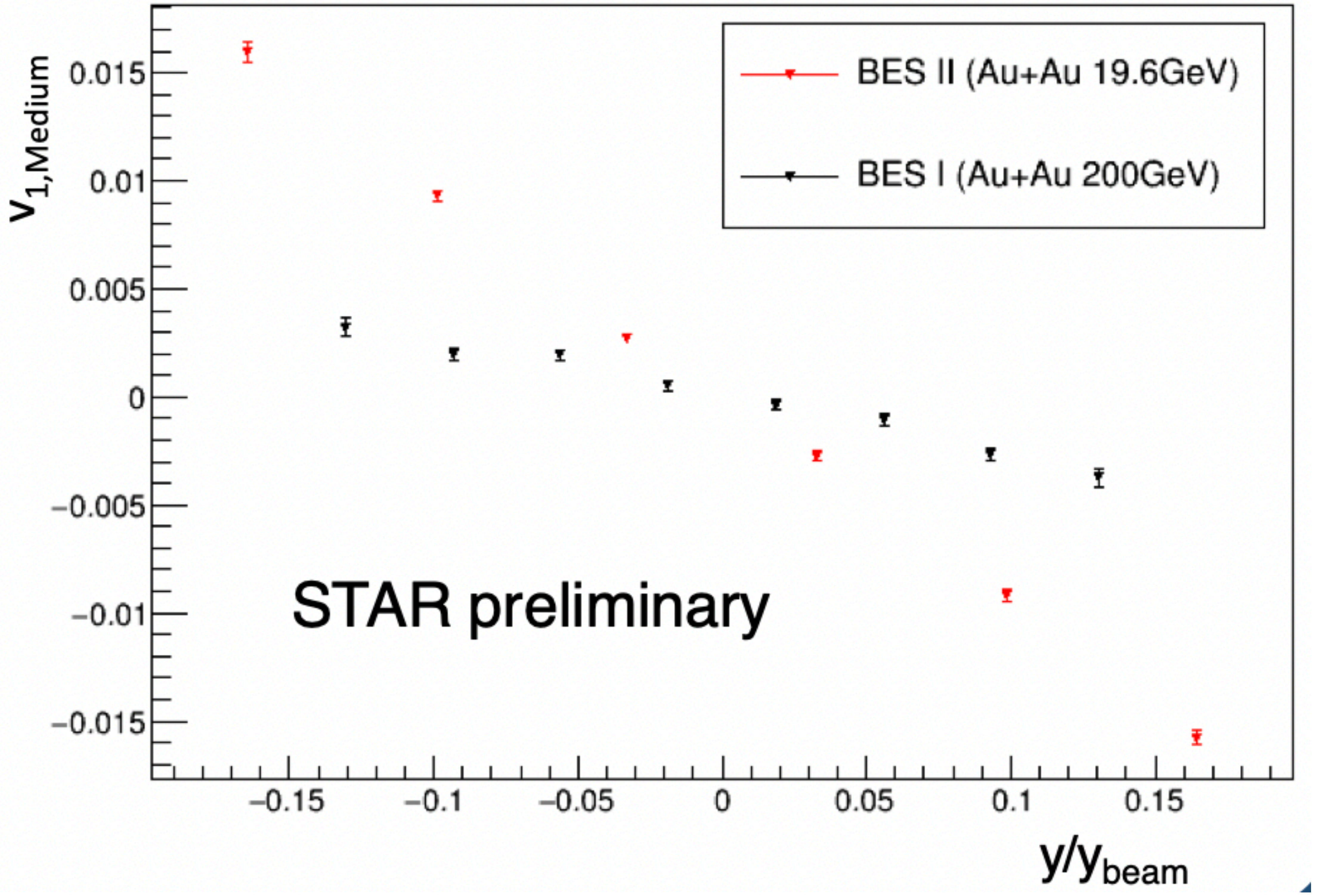
- Can we separate these two components?
  - Initial flow contributes to transported protons
  - Later medium component contributes to both protons and anti-protons

$$N_p v_1(p) = N_p v_1(\bar{p}) + (N_p - N_{\bar{p}}) v_1^{excess}(p) \qquad v_1^{excess}(p) = \left(v_1(p) - v_1(\bar{p})\right) / (1 - N_{\bar{p}}/N_p)$$

Two components of proton directed flow

$$N_p v_1(p) = N_p v_1(\bar{p}) + (N_p - N_{\bar{p}}) v_1^{excess}(p)$$

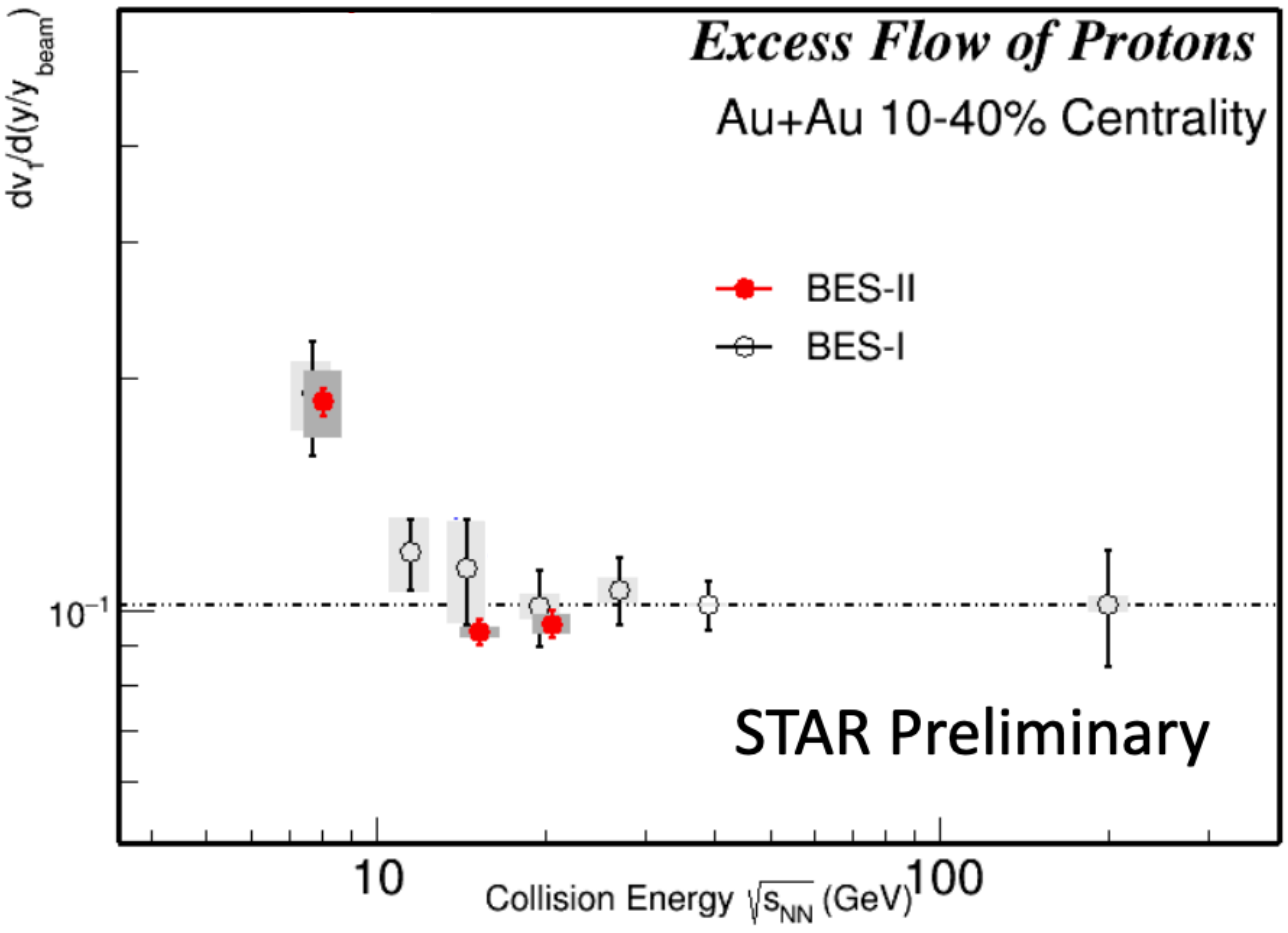




- Different beam energy dependence for the two components
- Scaling observed for $v_{1,excess}$ between 200 and 19.6 GeV. No scaling for medium component

Scaling of the initial component vs beam energy

$$N_p v_1(p) = N_p v_1(\bar{p}) + (N_p - N_{\bar{p}}) v_1^{excess}(p)$$

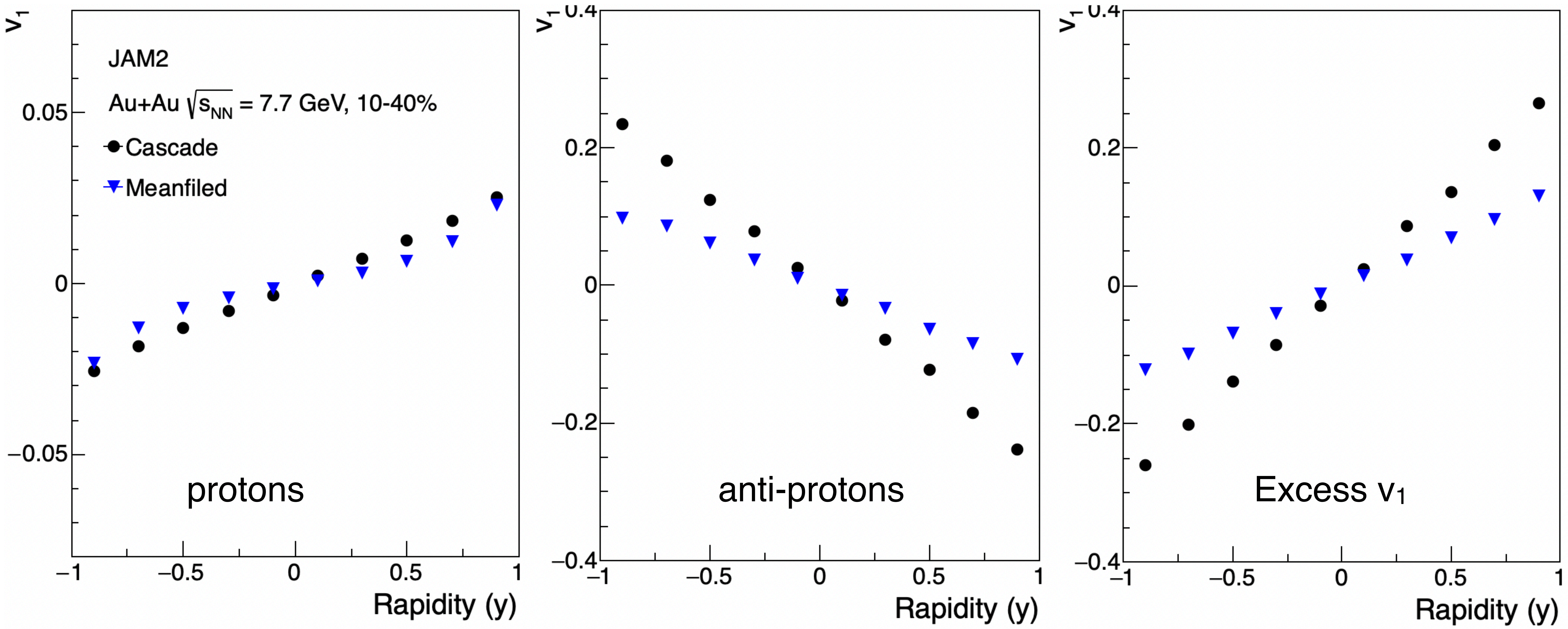


- Scaling for $v_{1,excess}$ found to hold till collision energy ~10 GeV
- Breaking of scaling at 7.7 GeV

- Change in medium/collision dynamics at 7.7 GeV

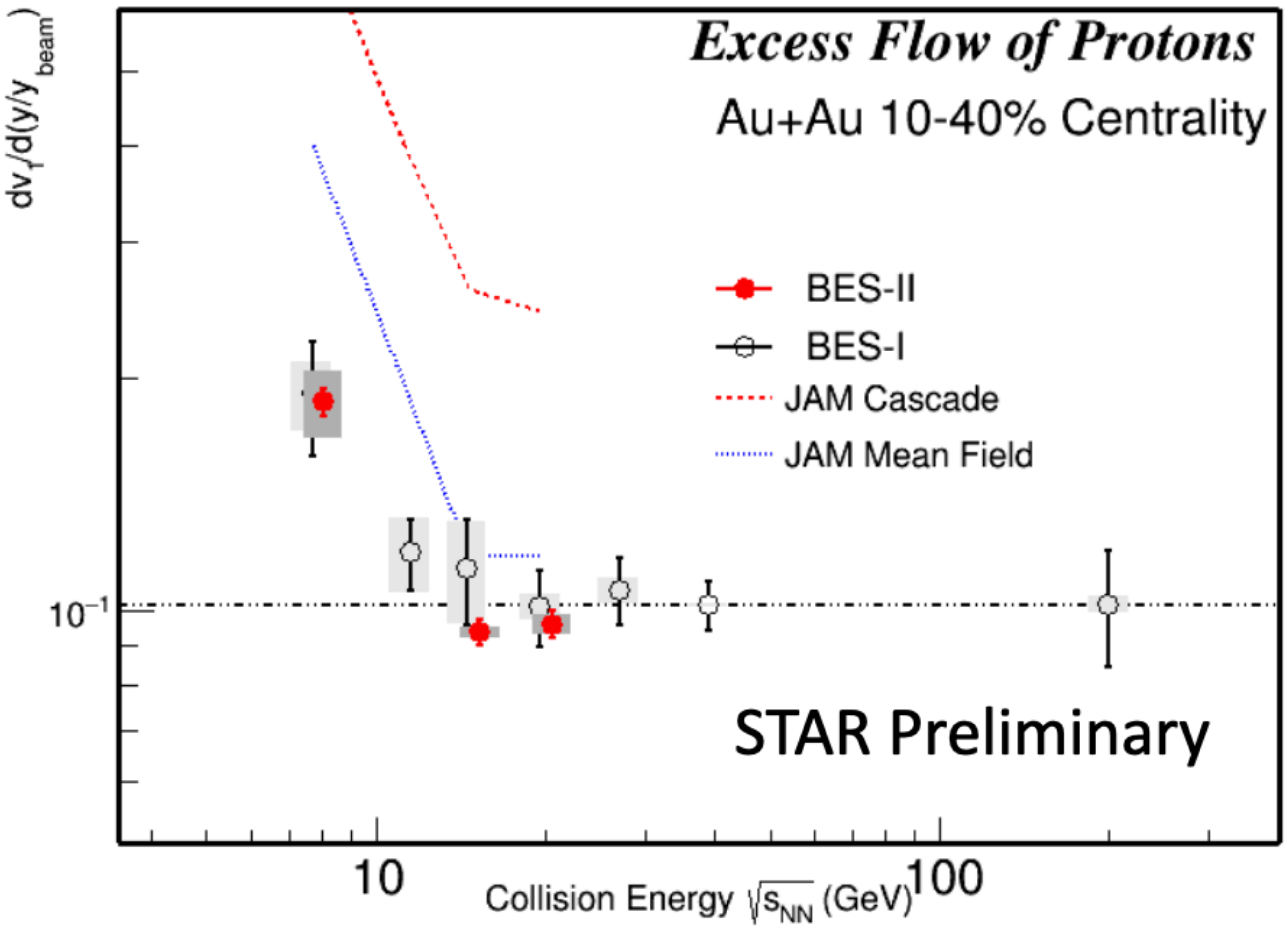
Hadronic transport model studies

$$N_p v_1(p) = N_p v_1(\bar{p}) + (N_p - N_{\bar{p}}) v_1^{excess}(p)$$



- Vastly different values for the two components between different modes, but proton v_1 similar
- More sensitivity to change in medium dynamics/EoS than just looking at proton v_1

Comparison to data



- JAM mean field (incompressibility = 380 MeV) calculations closer to data for 14.6 and 19.6 GeV

- Cannot simultaneously describe low energy and high energy results with the same equation of state

- More measurements to come from BES-II
- Will help constrain EoS at high μ_B
- Also important for studies of baryon transport

Summary

- Directed flow one of oldest measured quantities in heavy-ion collisions, still continues to provide crucial insights into heavy-ion collisions

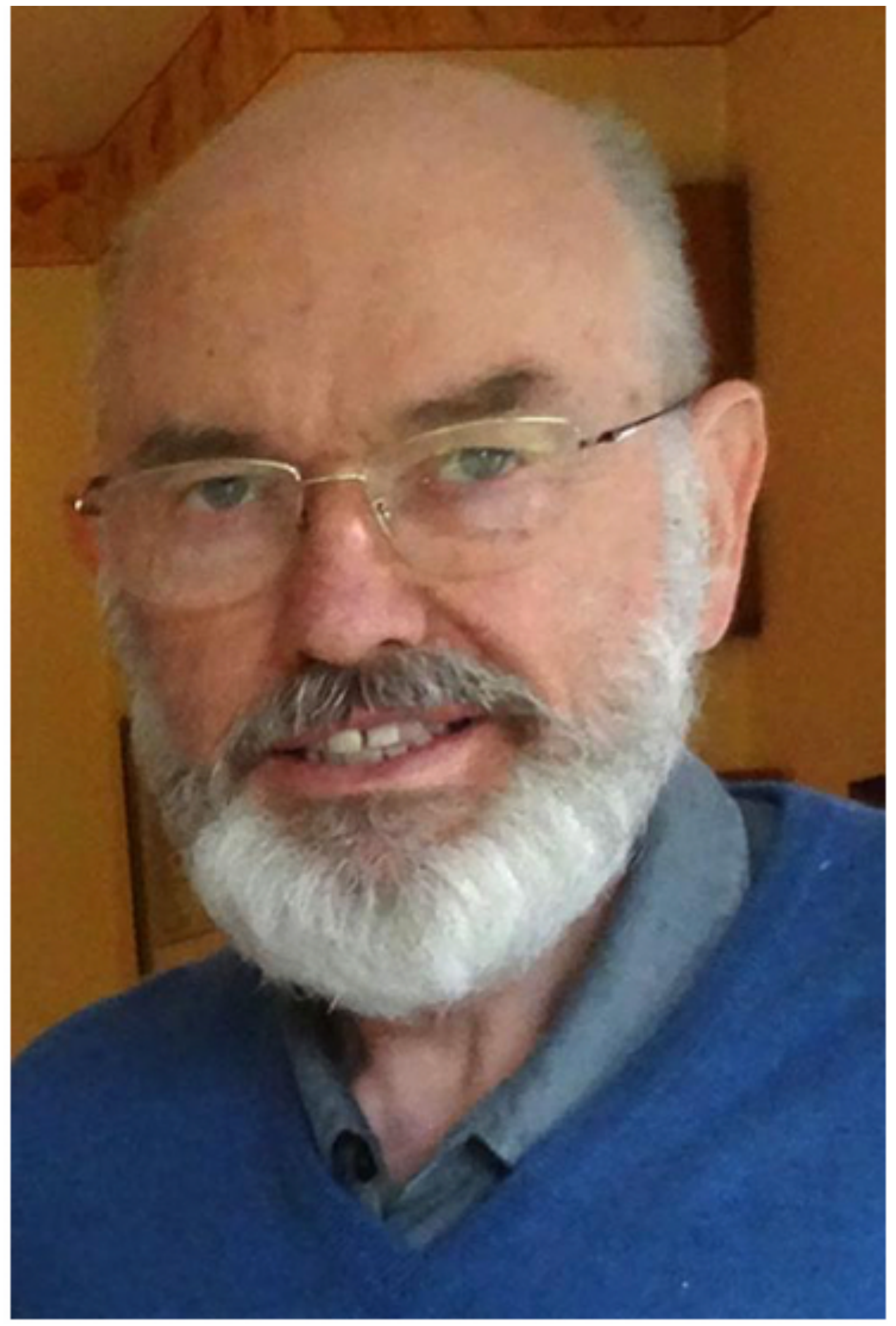
- Rapidity even v_1 in small systems — anisotropies driven by initial density fluctuations
- Heavy flavor directed flow order of magnitude larger than light flavor
- Promising tool to search for presence of strong B field in heavy-ion collisions
- Non-zero hight p_T charged hadron v_1 — arising from path length dependent energy loss

- Proton directed flow can be decomposed into an initial component contributing primarily to transported protons and medium component contributing to all
  - Initial component is positive and constant from 200 — 10 GeV
  - Deviates from constant value at 7.7 GeV — change in medium/collision dynamics
  - More sensitive to medium EoS. Mean field calculations cannot simultaneously describe data at 7.7 GeV and above

A Thank You to Declan

- Founding member of STAR Collaboration
- Declan has been chair of 14 GPCs and member/PA of another 51 GPCs for STAR!!
- Also many other roles for the collaboration

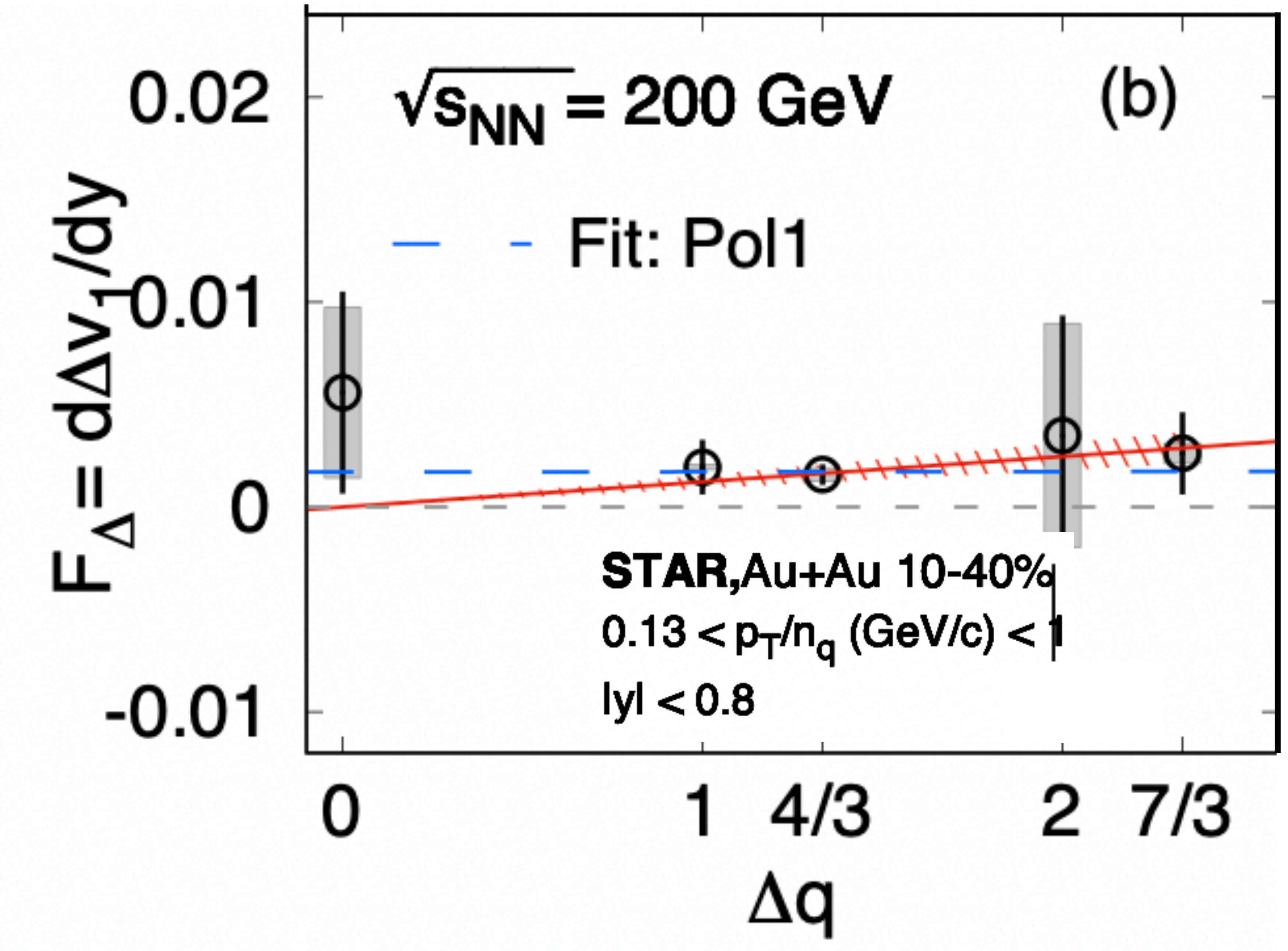
- Over the last few years, been my great pleasure to have collaborated and worked with you
- Wish you good health and more exciting research ahead!!



Back Up

Exploring charge dependent splitting with coalescence model

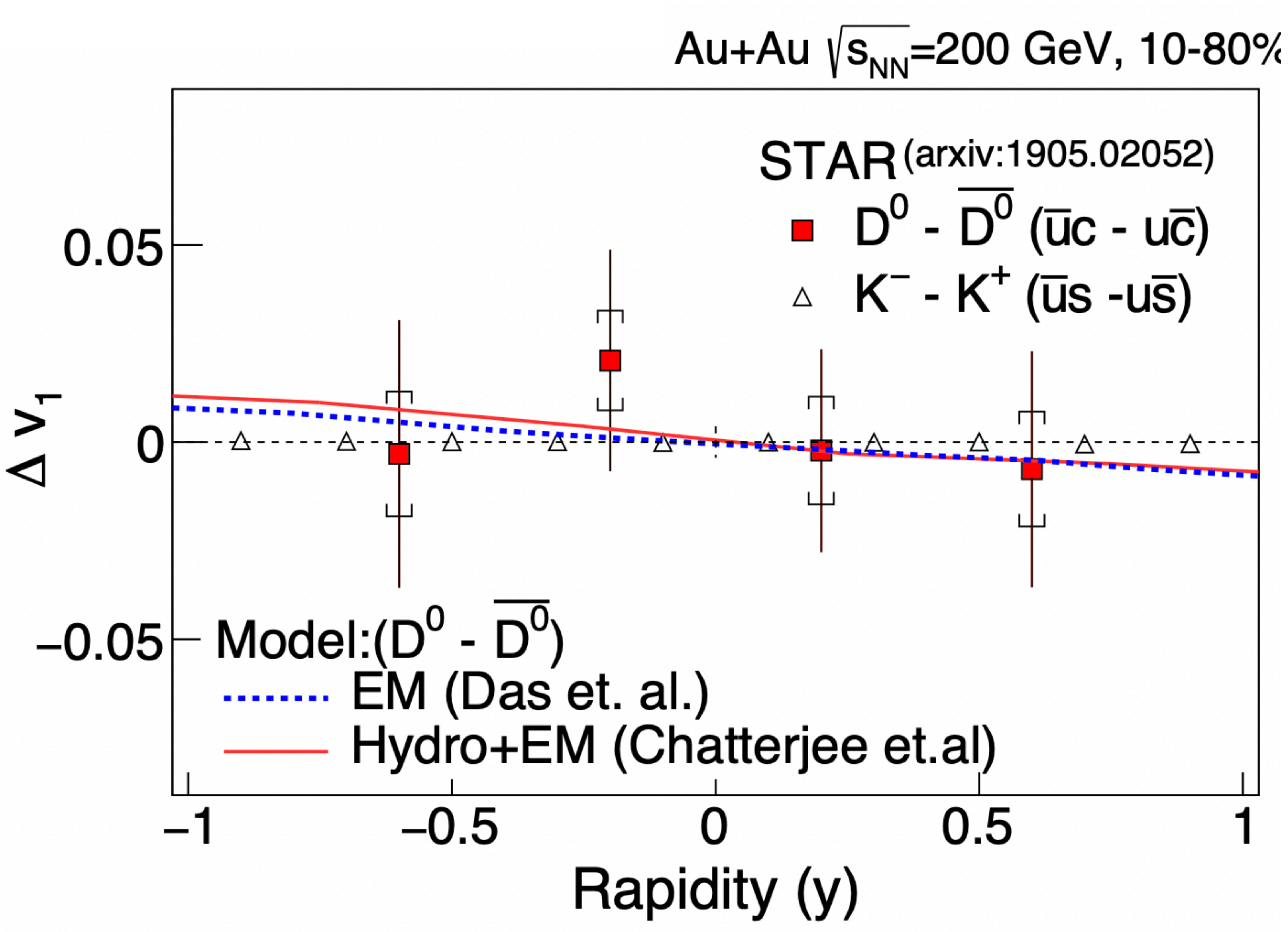
Index	Quark mass	Δq	ΔS	Δv_1 combination	$F_\Delta \times 10^4$ (27 GeV)	$F_\Delta \times 10^4$ (200 GeV)
1	$\Delta m = 0$	0	0	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$	$03 \pm 43 \pm 13$	$56 \pm 49 \pm 41$
2	$\Delta m \approx 0$	1	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$	$41 \pm 25 \pm 16$	$19 \pm 13 \pm 01$
3	$\Delta m \approx 0$	$\frac{4}{3}$	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$	$39 \pm 07 \pm 03$	$16 \pm 05 \pm 03$
4	$\Delta m = 0$	2	6	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$	$83 \pm 130 \pm 25$	$35 \pm 58 \pm 54$
5	$\Delta m \approx 0$	$\frac{7}{3}$	4	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$	$64 \pm 36 \pm 19$	$26 \pm 20 \pm 04$

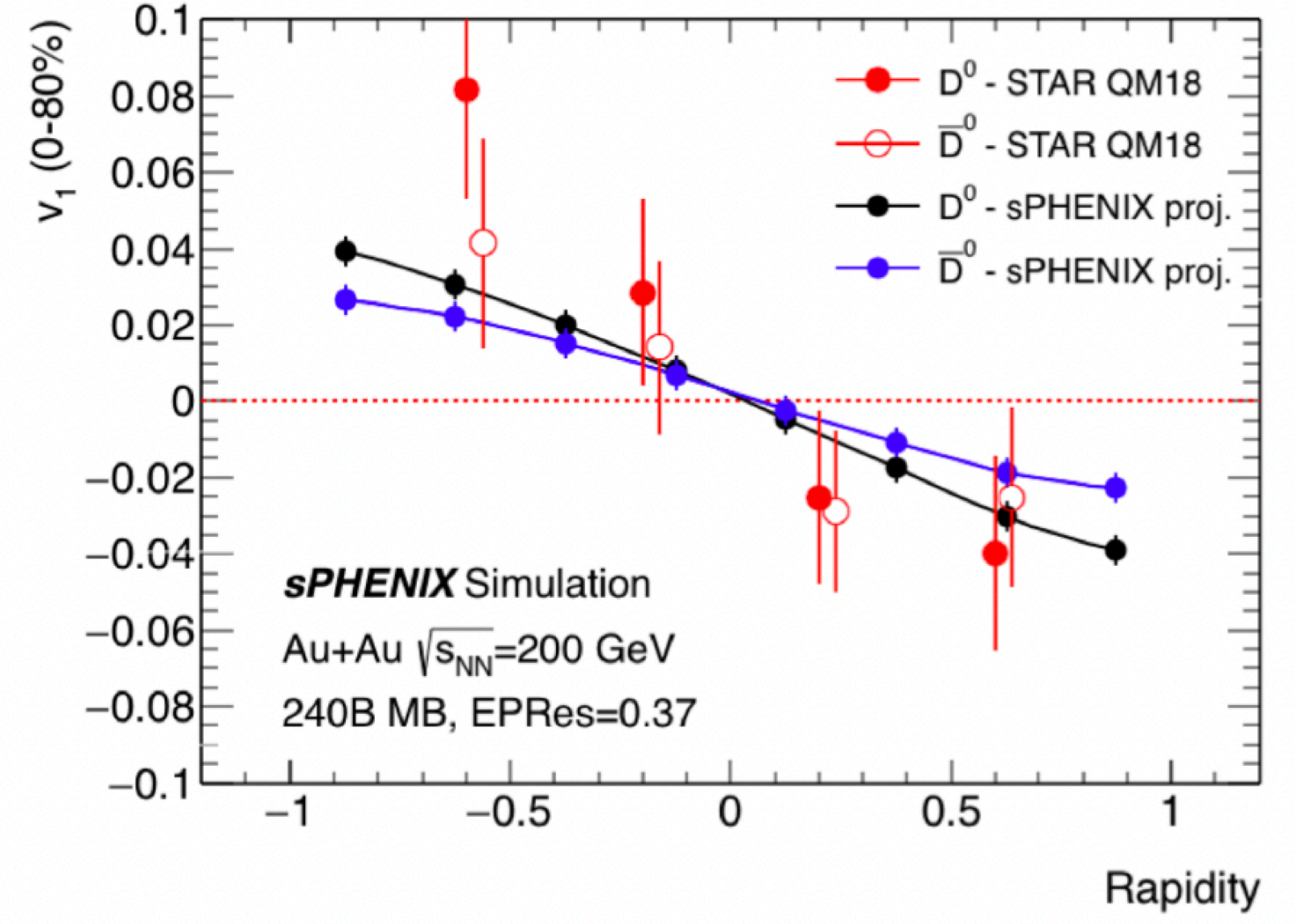


- Assuming coalescence sum rules hold for v_1 of produced particles, can make combination of hadrons to study v_1 splitting vs charge

- Observes non-zero slope
- Could be reflecting the splitting induced by B field

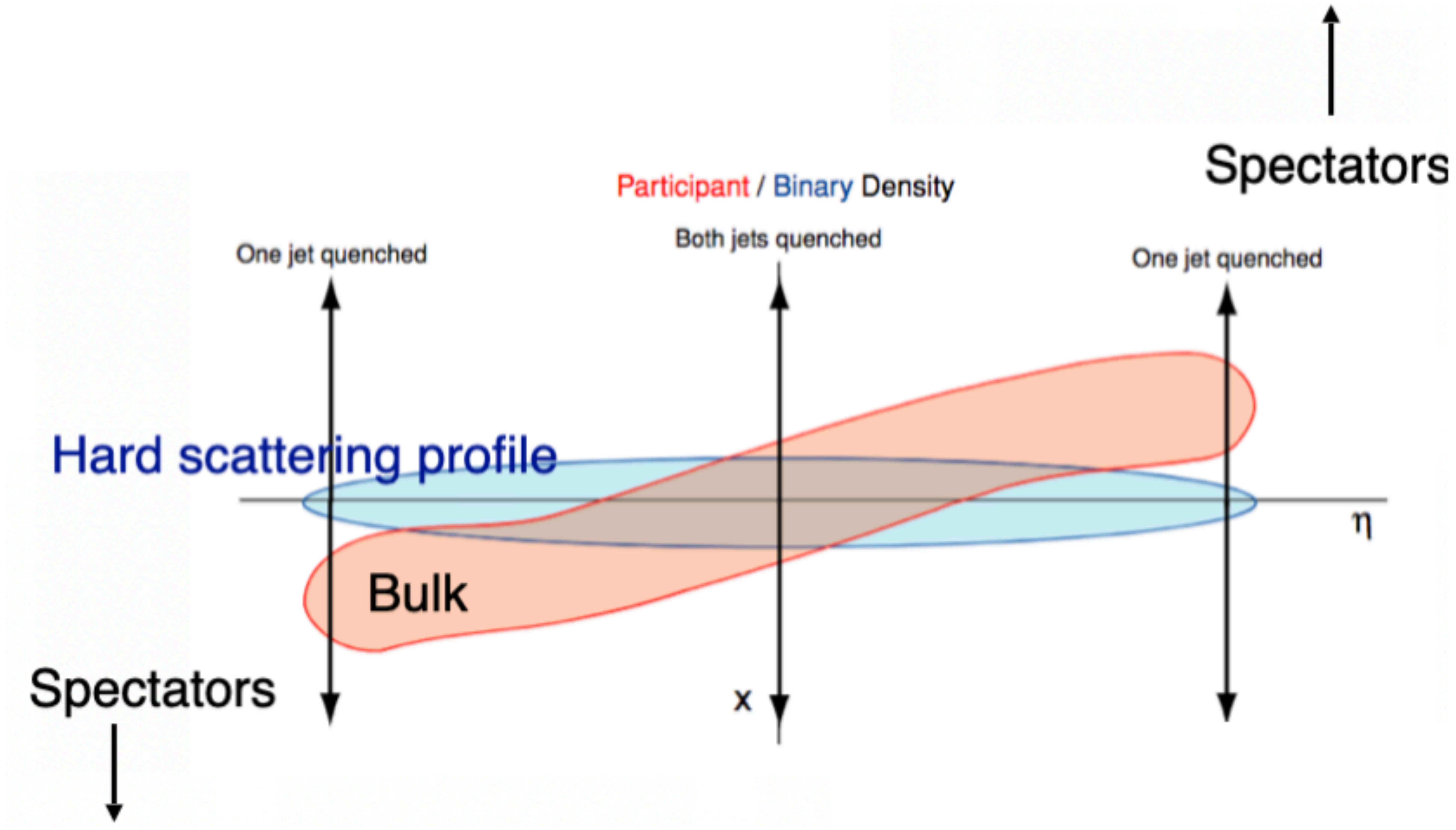
Charge dependent splitting?





- No splitting observed within uncertainties
- Current uncertainties are large, future measurements (sPHENIX, ALICE …) could give a definitive answer

Directed flow of jets/high p_T hadrons



- Different path lengths through medium for patrons going along +x and -x as function of rapidity
- Can produce v_1 for jets from path length dependent energy loss