HP2024
NAGASAKI

Measurement of jet v_1 to study path length dependent energy loss in heavy-ion collisions at 200 GeV

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BERKELEY LAB

KENT STATE UNIVERSITY

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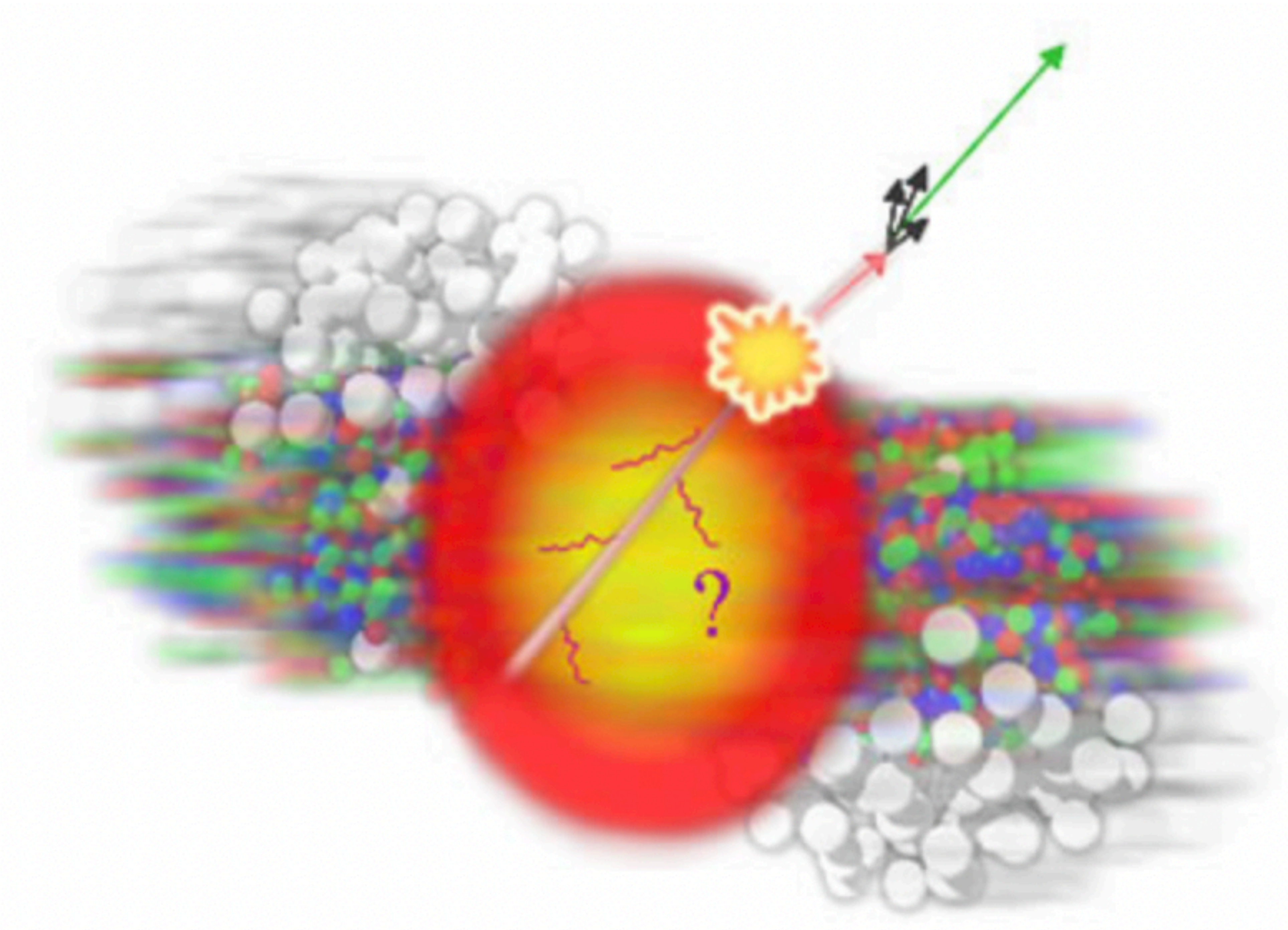
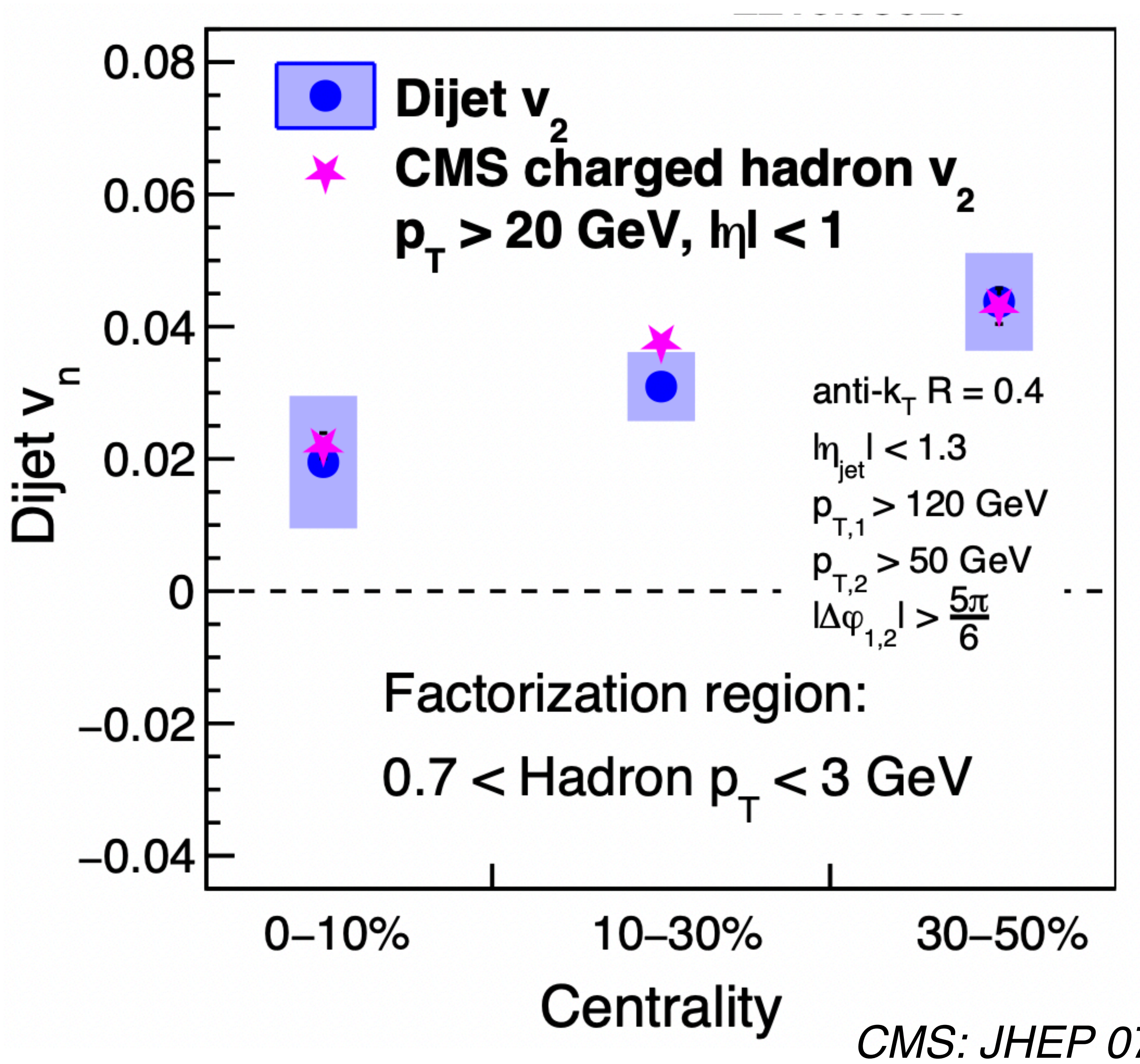
STAR

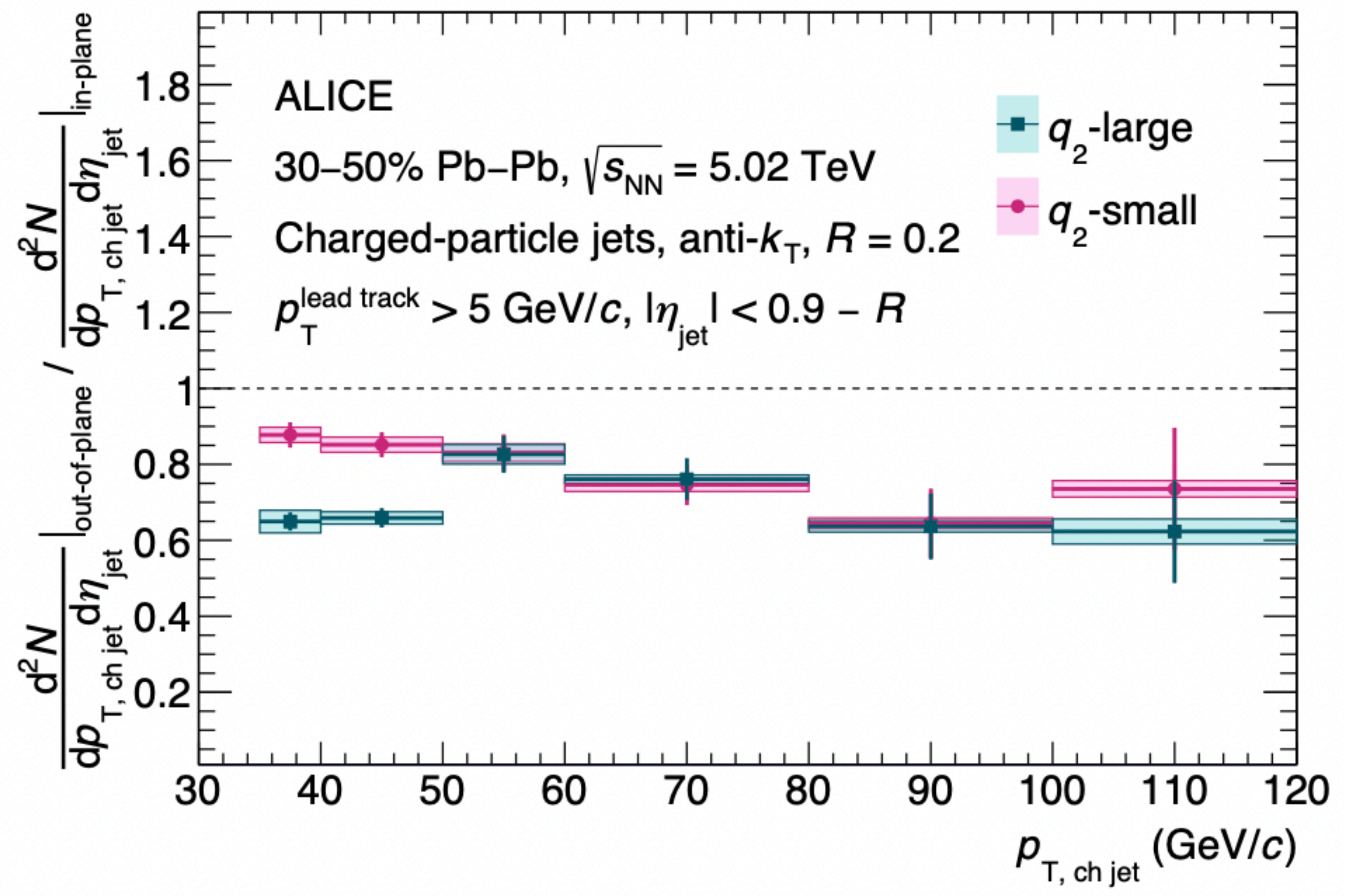
Path length dependence of energy loss

- How does parton energy loss depend on path length?
- Important for understanding parton energy loss mechanism in QGP, different mechanism have different dependence (eg. Collisional ~ L, radiative ~ L^2)





CMS: JHEP 07 (2023) 139



ALICE: Phys. Lett. B 851 (2024) 138584

- Impact of path length asymmetry probed
- Measurements w.r.t to second order EP, v_2 …

Path length dependence of energy loss

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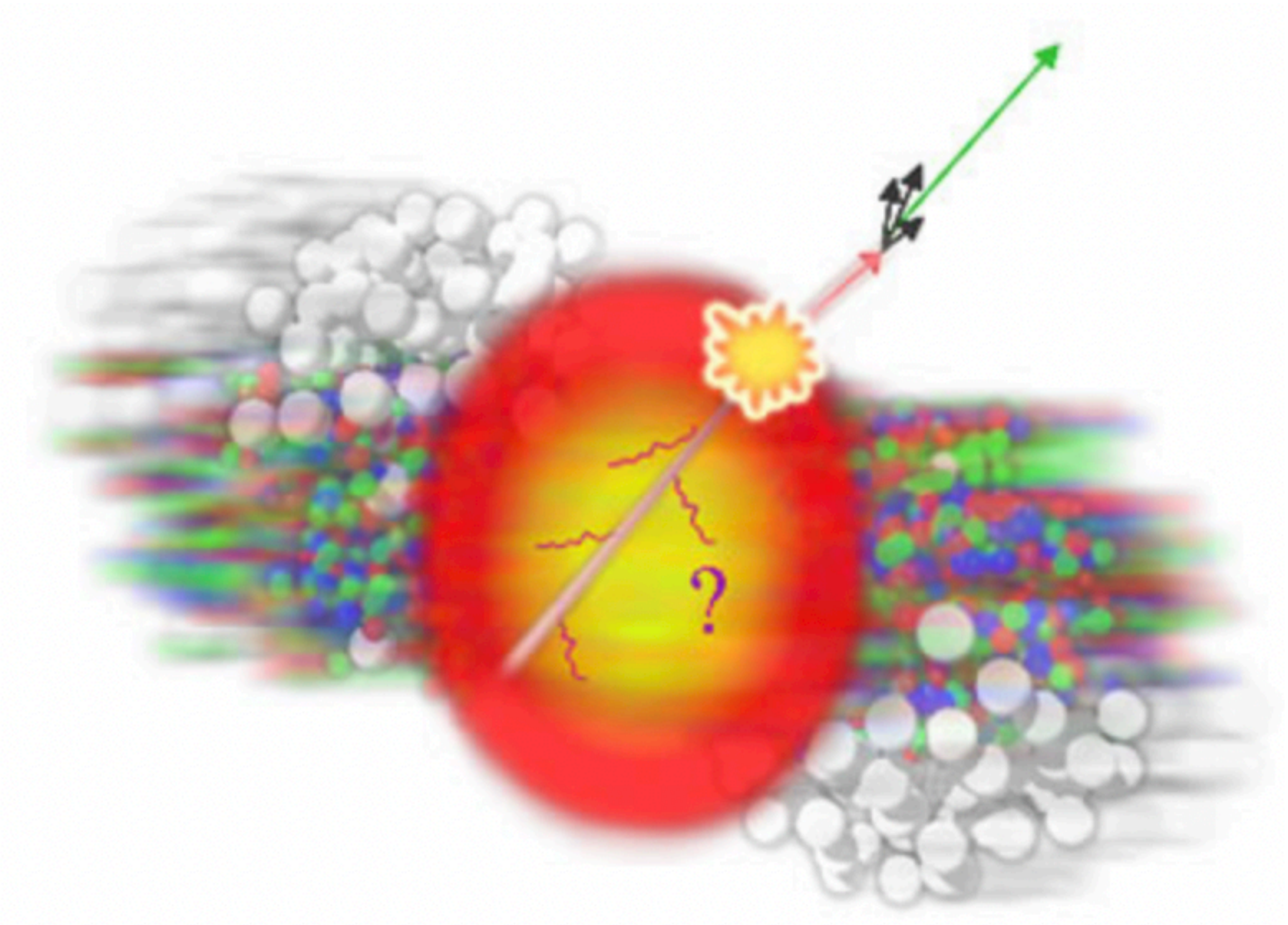

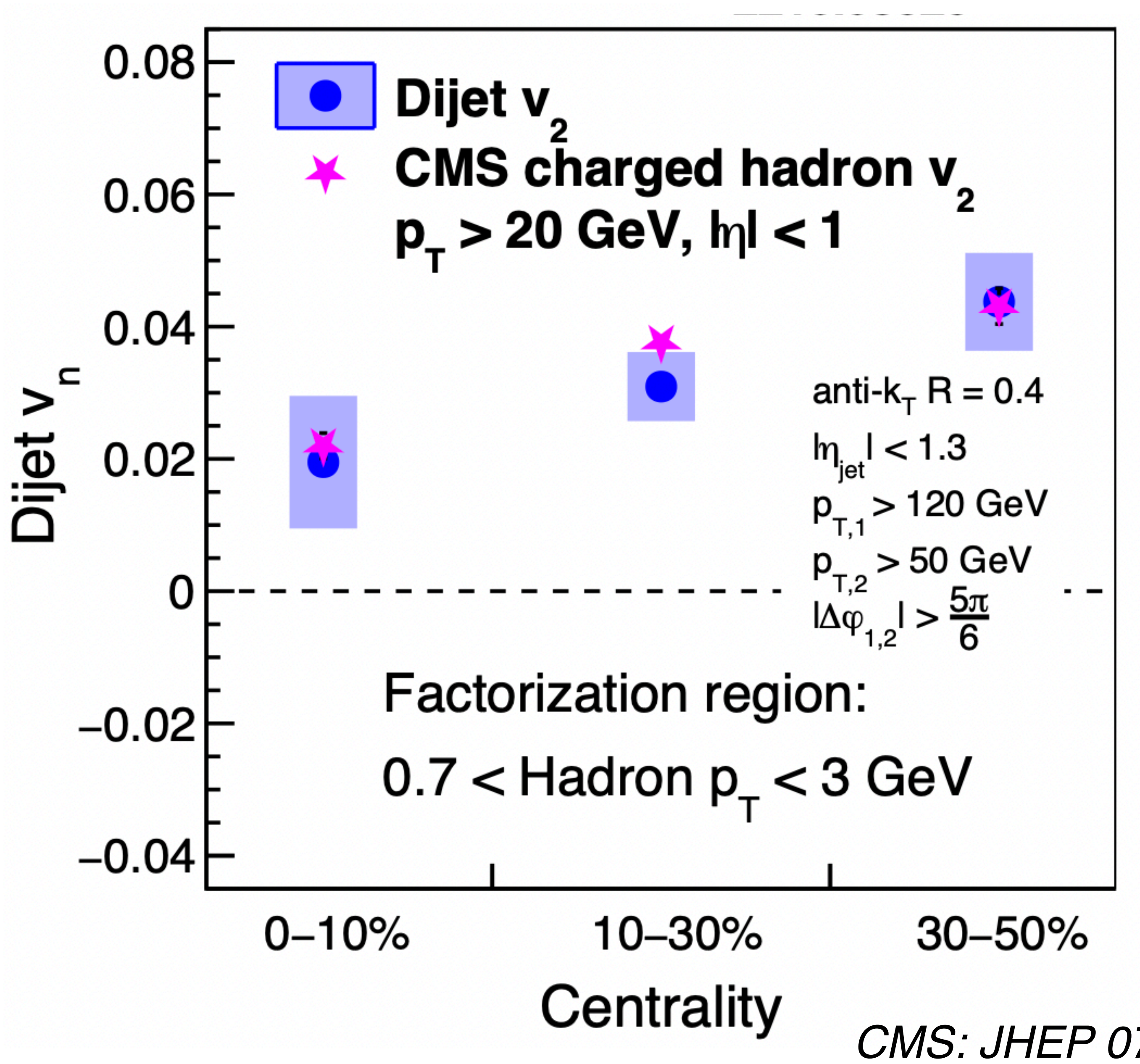

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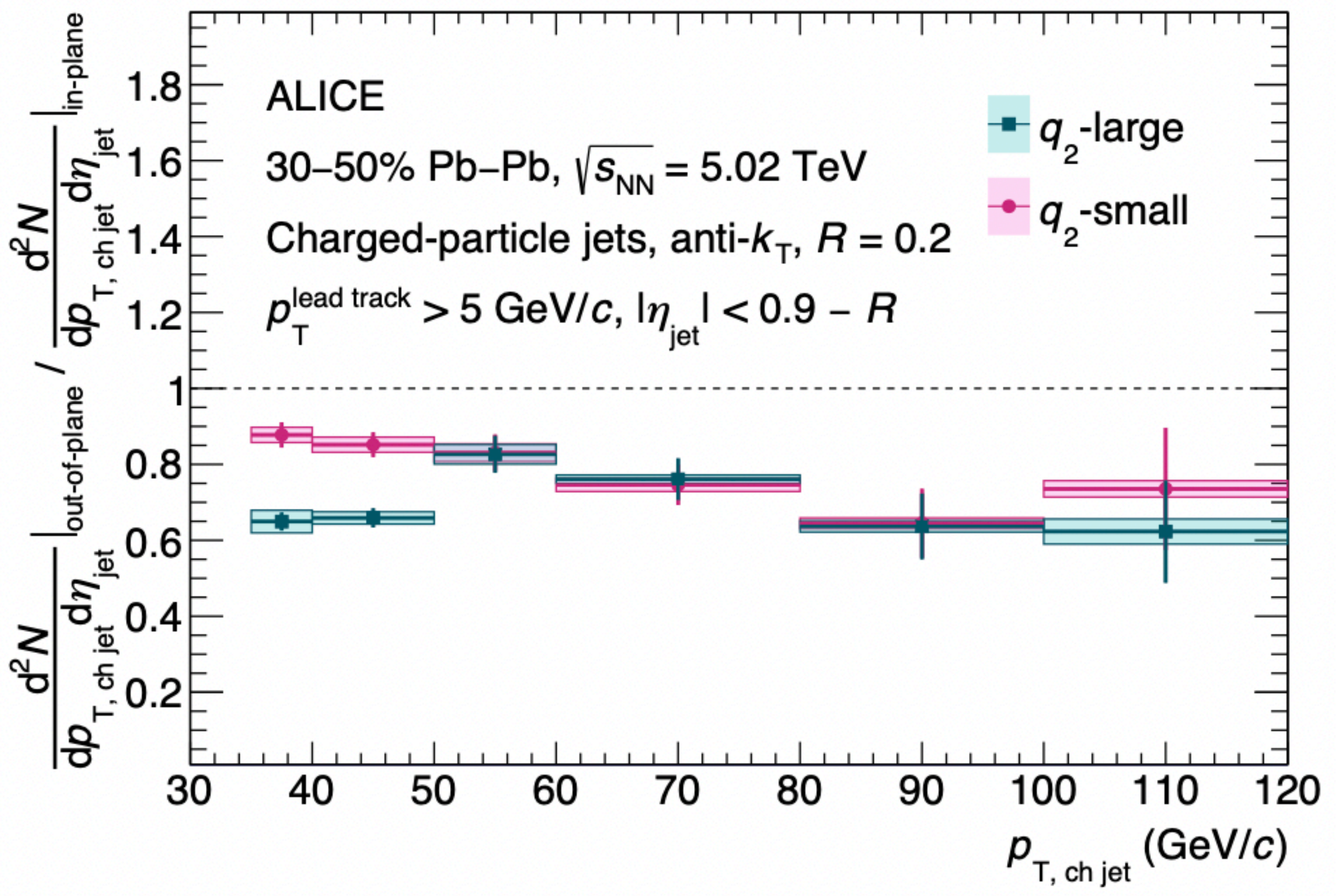


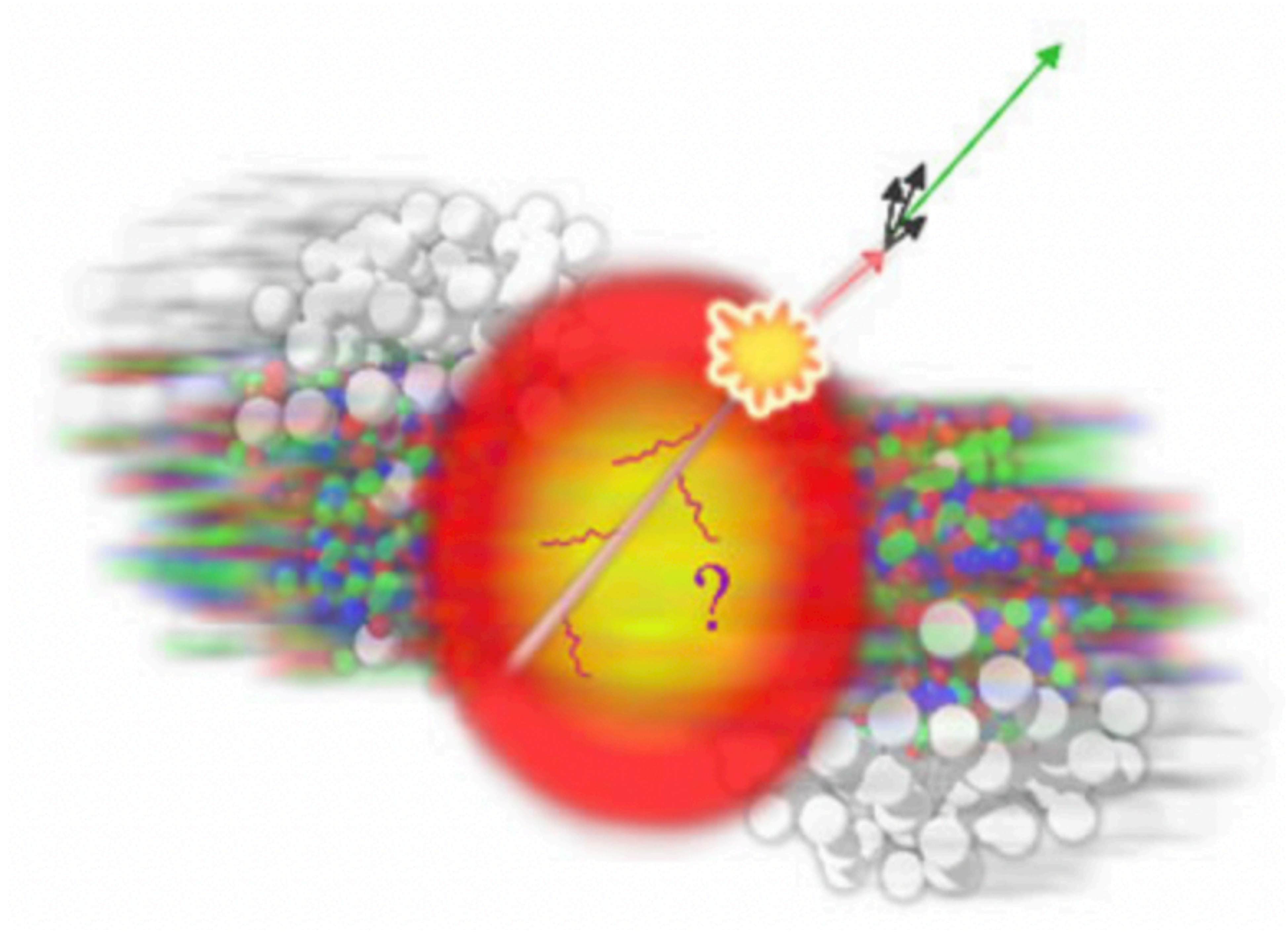
ALICE: Phys. Lett. B 851 (2024) 138584

- Impact of path length asymmetry probed
- Measurements w.r.t to second order EP, v_2 …

See poster by I. Mooney for ESE with v_2 at STAR

Jet v_1: a new observable

- How does parton energy loss depend on path length?



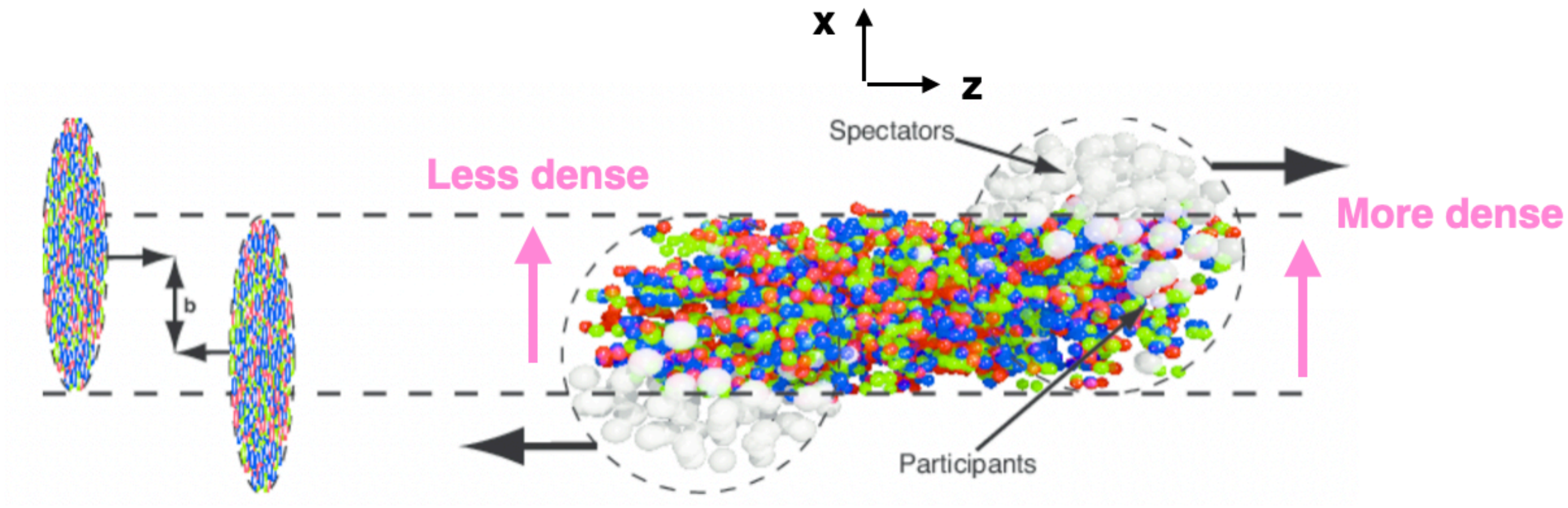
$$v_1 = \langle \frac{p_x}{p_T} \rangle \qquad v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

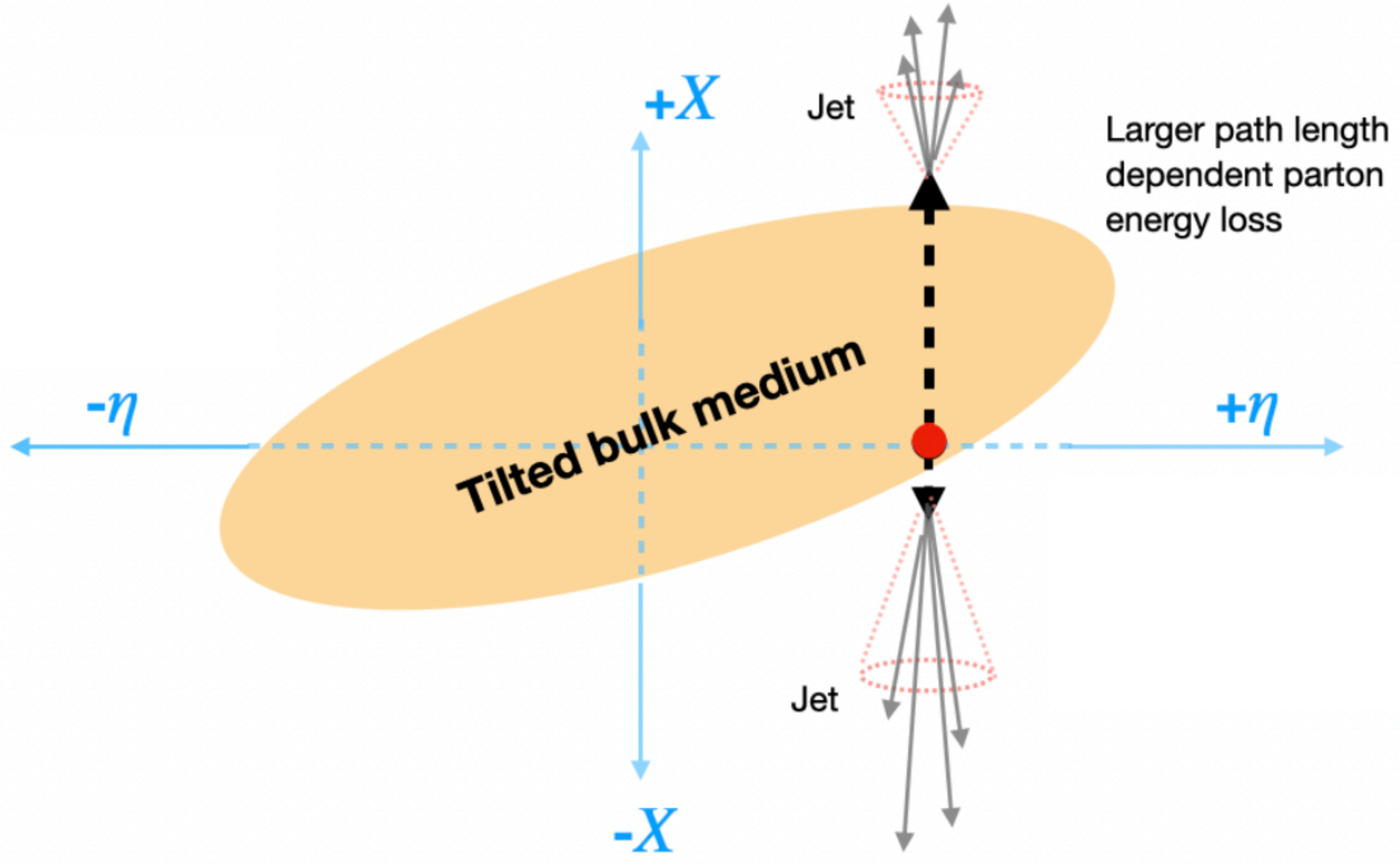
Why study jet v_1?

- Alternate observable - access to energy loss without need for p+p
- Can be related to path length difference
- Less affected by e-by-e fluctuations compared to v_2 that includes the variance
- Have constraints to evaluate initial path length difference
- Bulk v_1 is very small, less evolution of asymmetry

Origin of jet v_1

- Natural offset in hard-scattering profile (from binary collisions) and bulk particle production (from participants)



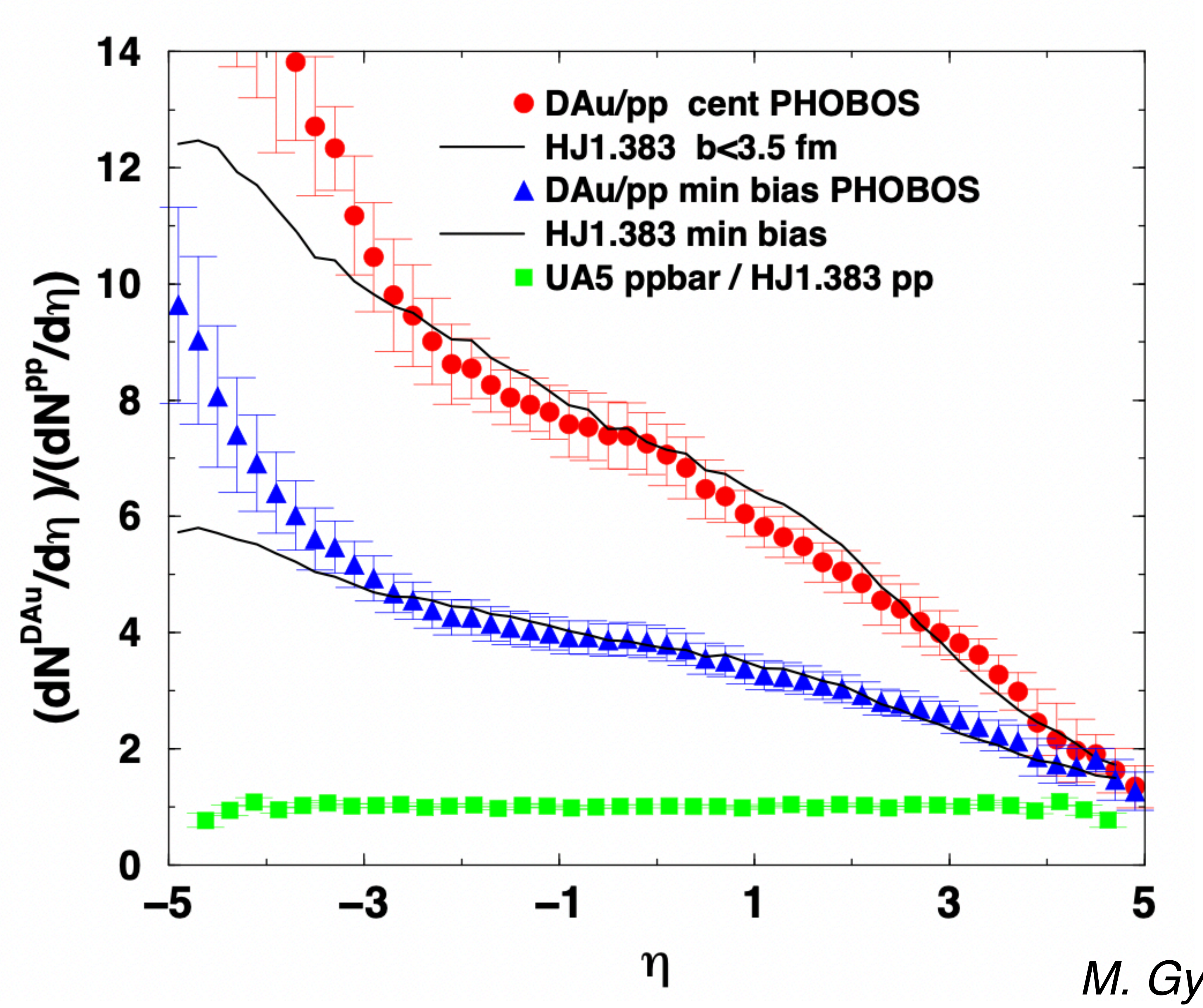


- Nucleon distribution inside nuclei have radial dependence
- Creates asymmetry for bulk particle production at finite rapidity

- Hard production from binary n - n scattering, does not have the asymmetry

M. Gyulassy et al. Phys. Rev. C 72, 034907, (2005)
S. Chatterjee et al. Phys. Rev. Lett. 120, 192301 (2017)

Evaluating the path length asymmetry



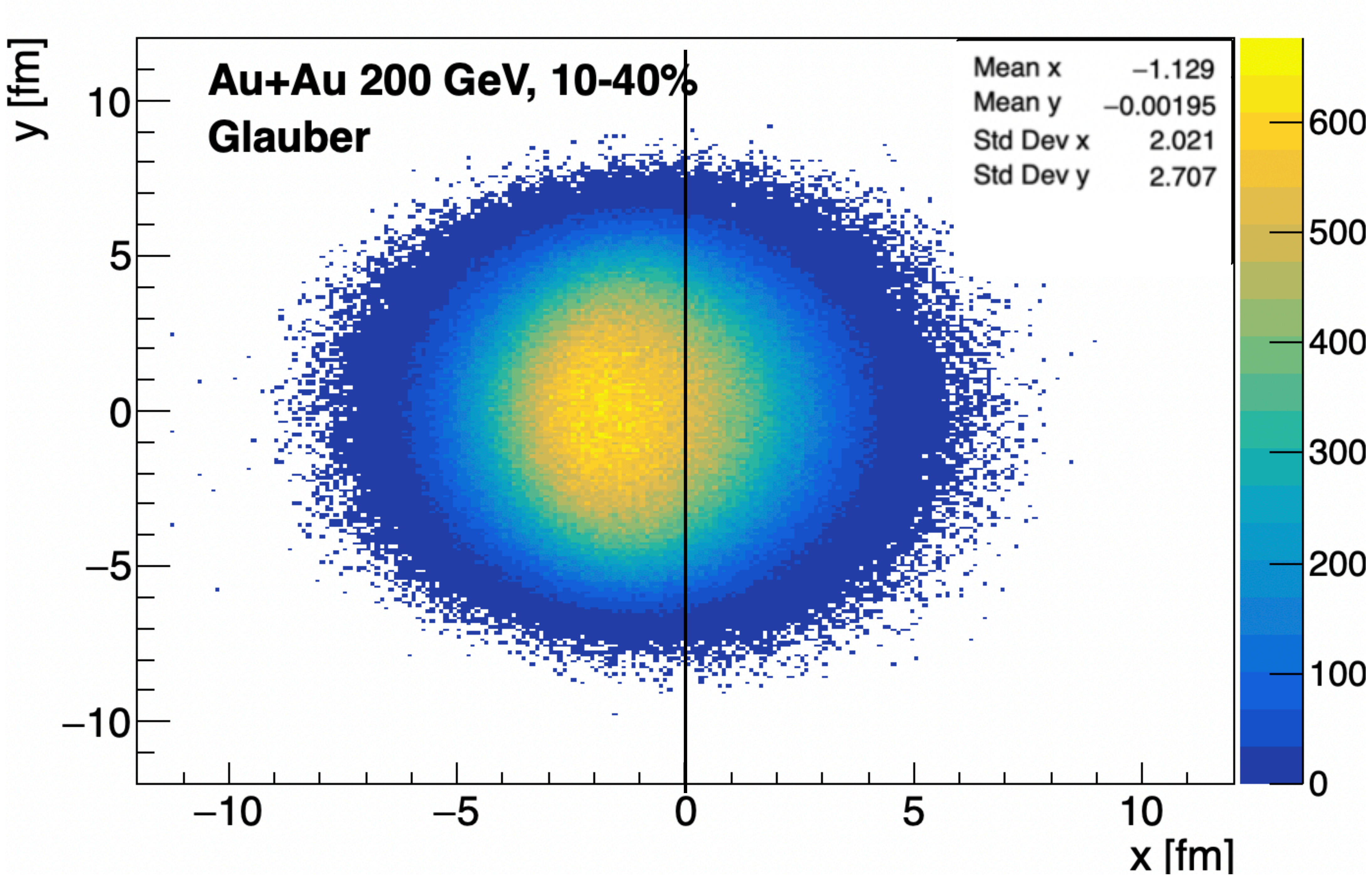
- Bulk particle production asymmetry controlled by participant asymmetry
- Particle production asymmetry roughly linear in η, can be reproduced by

$$\frac{dN_g}{dxdyd\eta} = \frac{C}{2Y}\ \exp[\frac{-\eta^2}{\sigma_\eta^2}]\ \theta(Y - |\eta|)$$
$$\left\{\frac{dN^A_{\text{Part}}}{dxdy}(Y-\eta) + \frac{dN^B_{\text{Part}}}{dxdy}(Y+\eta)\right\}$$

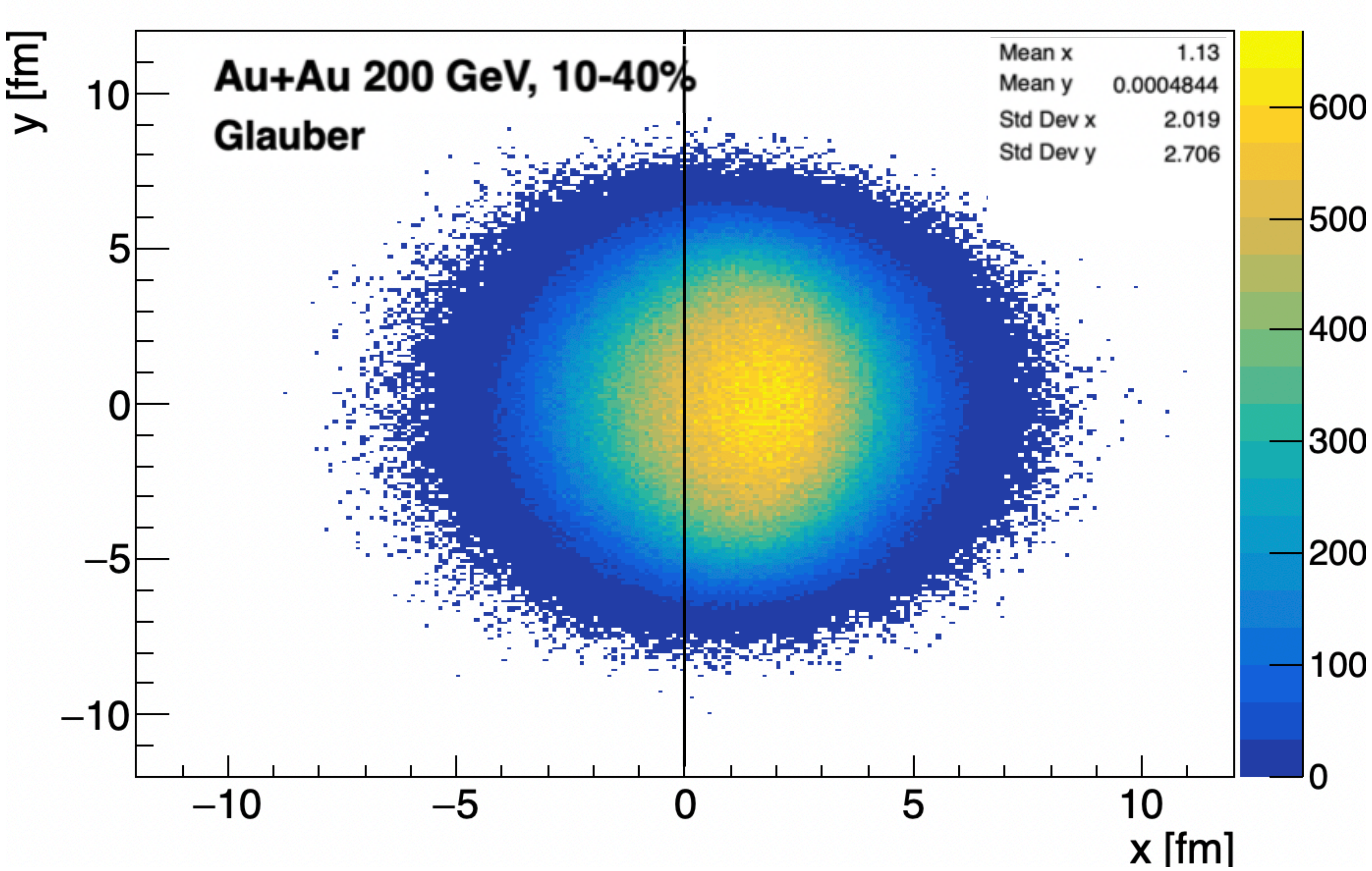
M. Gyulassy et al. Phys. Rev. C 72, 034907, 2005

- Participant asymmetry along x will translate to initial density asymmetry along x

Participant asymmetry along impact parameter direction (x)



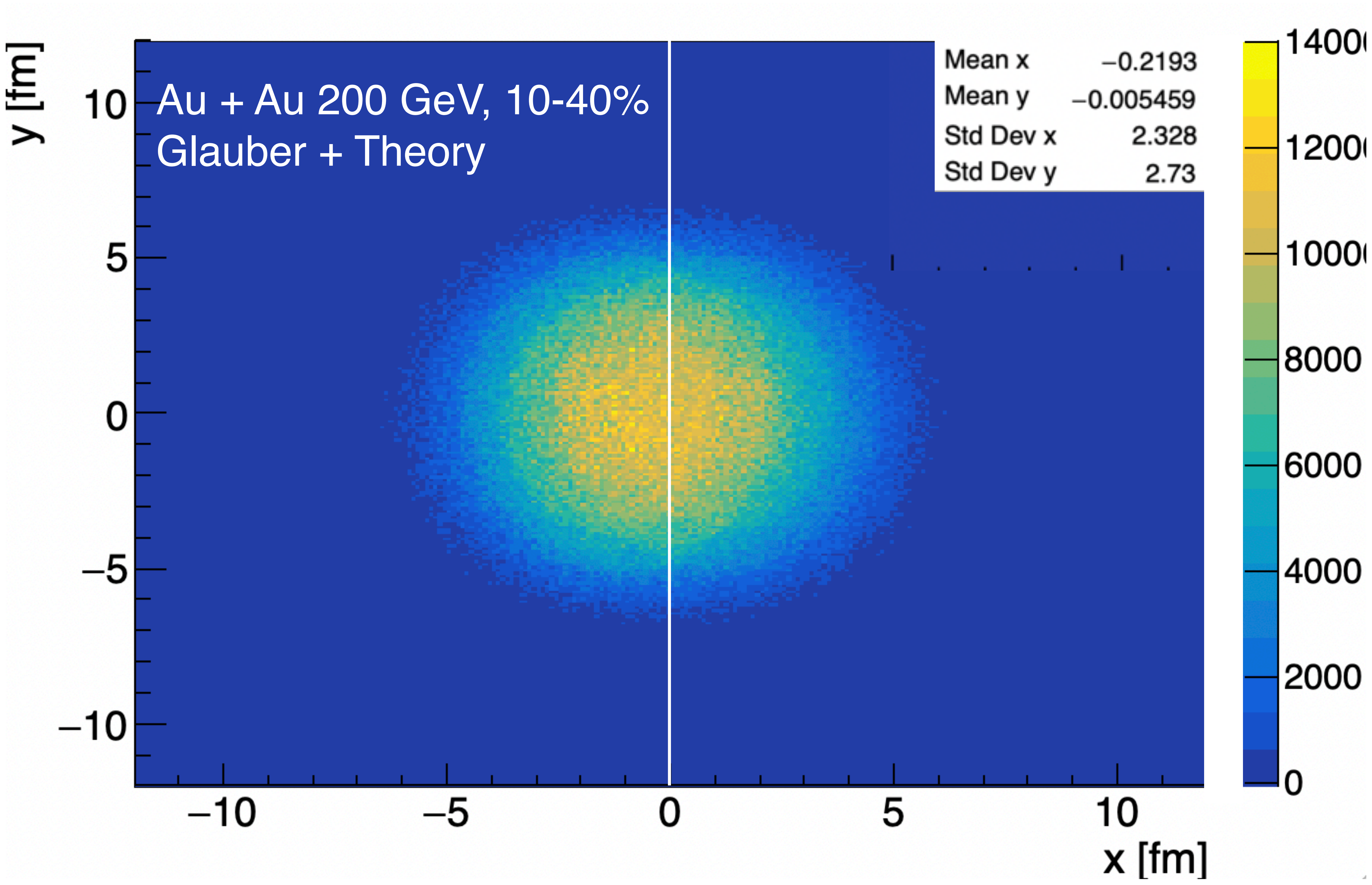
Backward going participants



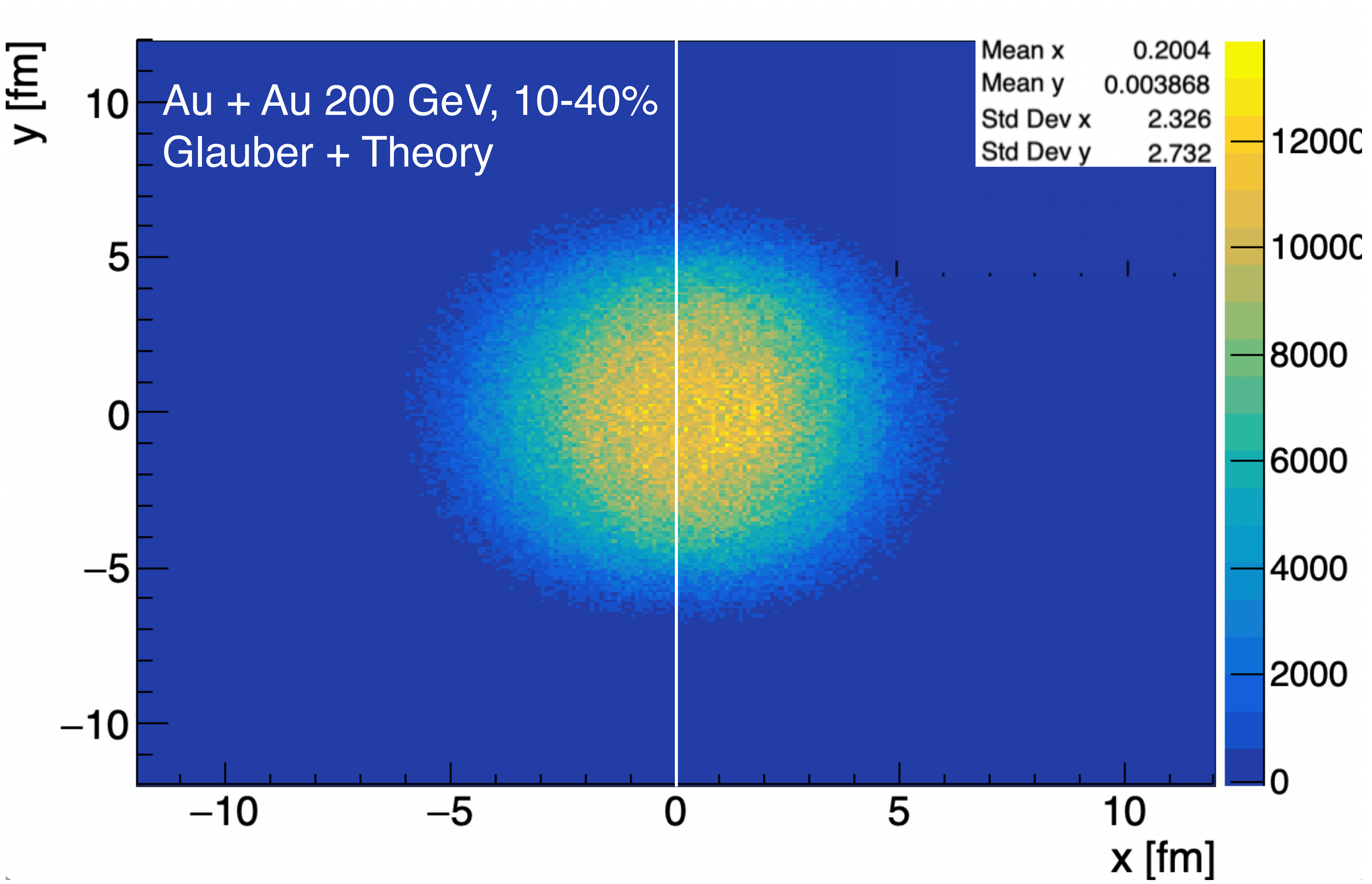
Forward going participants

- Clear asymmetry along impact parameter direction for forward and backward going participants

Asymmetry in initial bulk density distributions



-1.0 < η < -0.8

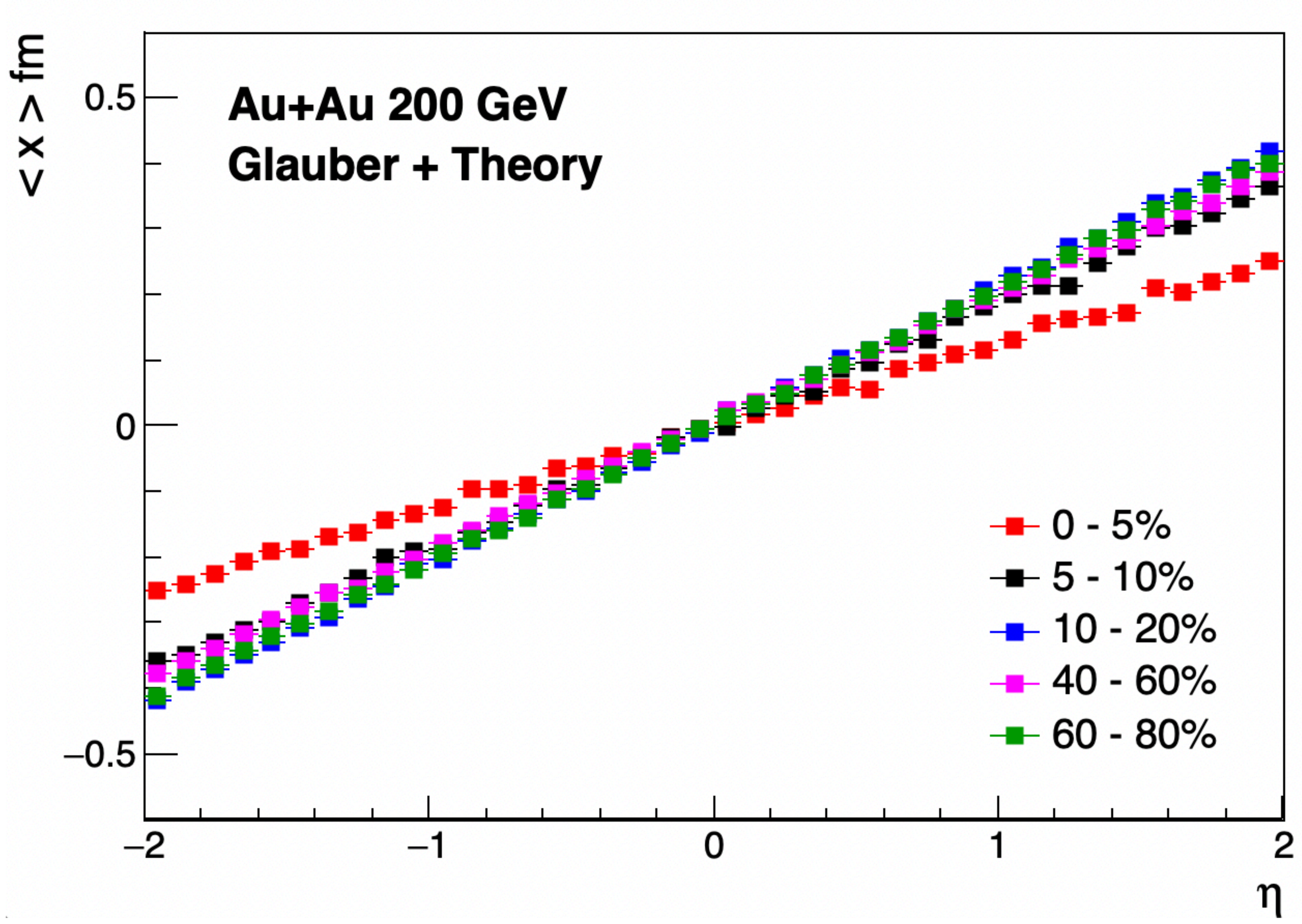


0.8 < η < 1.0

- Convoluting participant distribution with model for particle production in η
- Asymmetry along impact parameter direction at finite rapidity

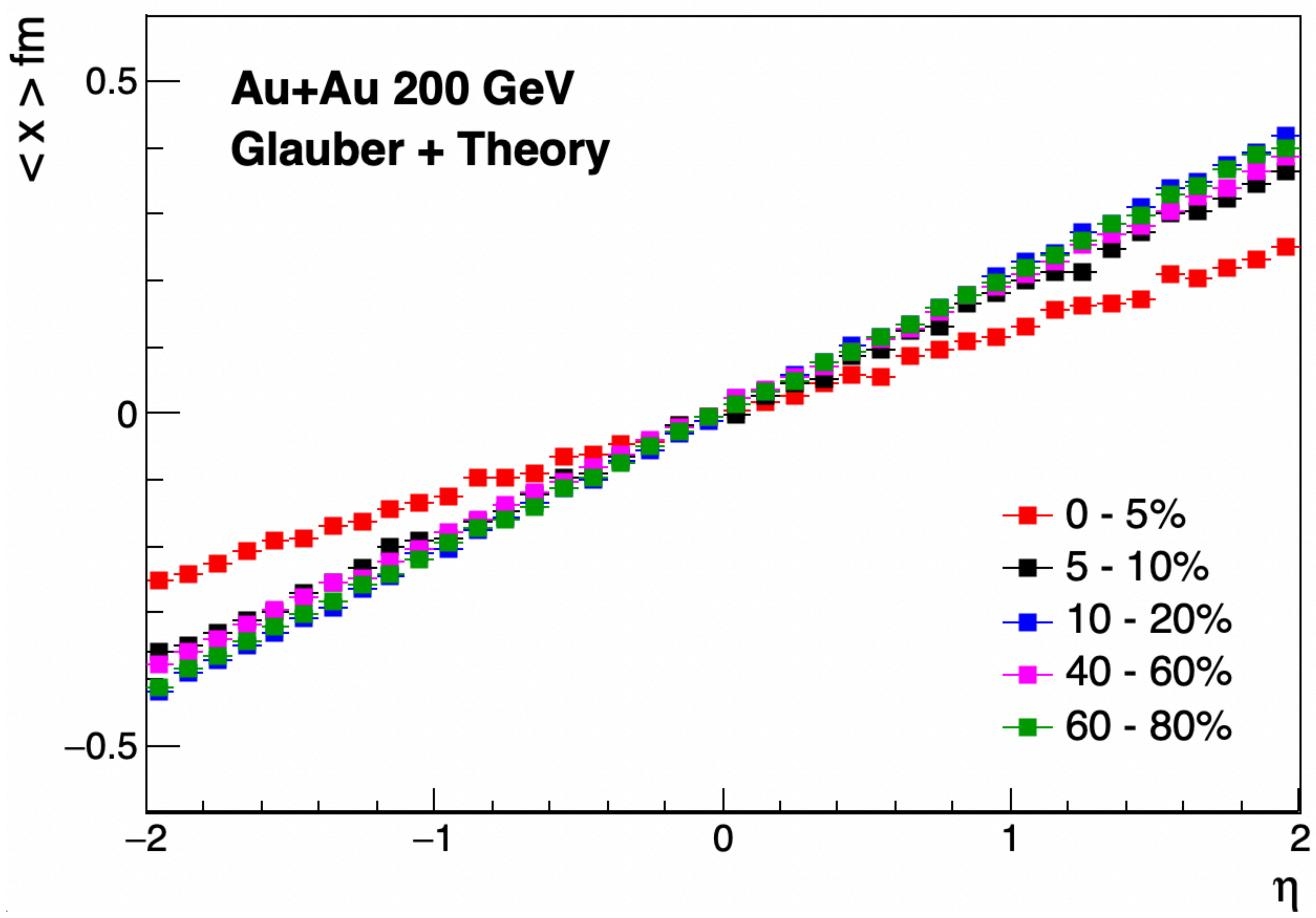
$$\frac{dN_g}{dxdyd\eta} = \frac{C}{2Y} \exp[\frac{-\eta^2}{\sigma_\eta^2}]\,\theta(Y-|\eta|)$$
$$\left\{\frac{dN^A_{\text{Part}}}{dxdy}(Y-\eta) + \frac{dN^B_{\text{Part}}}{dxdy}(Y+\eta)\right\}$$

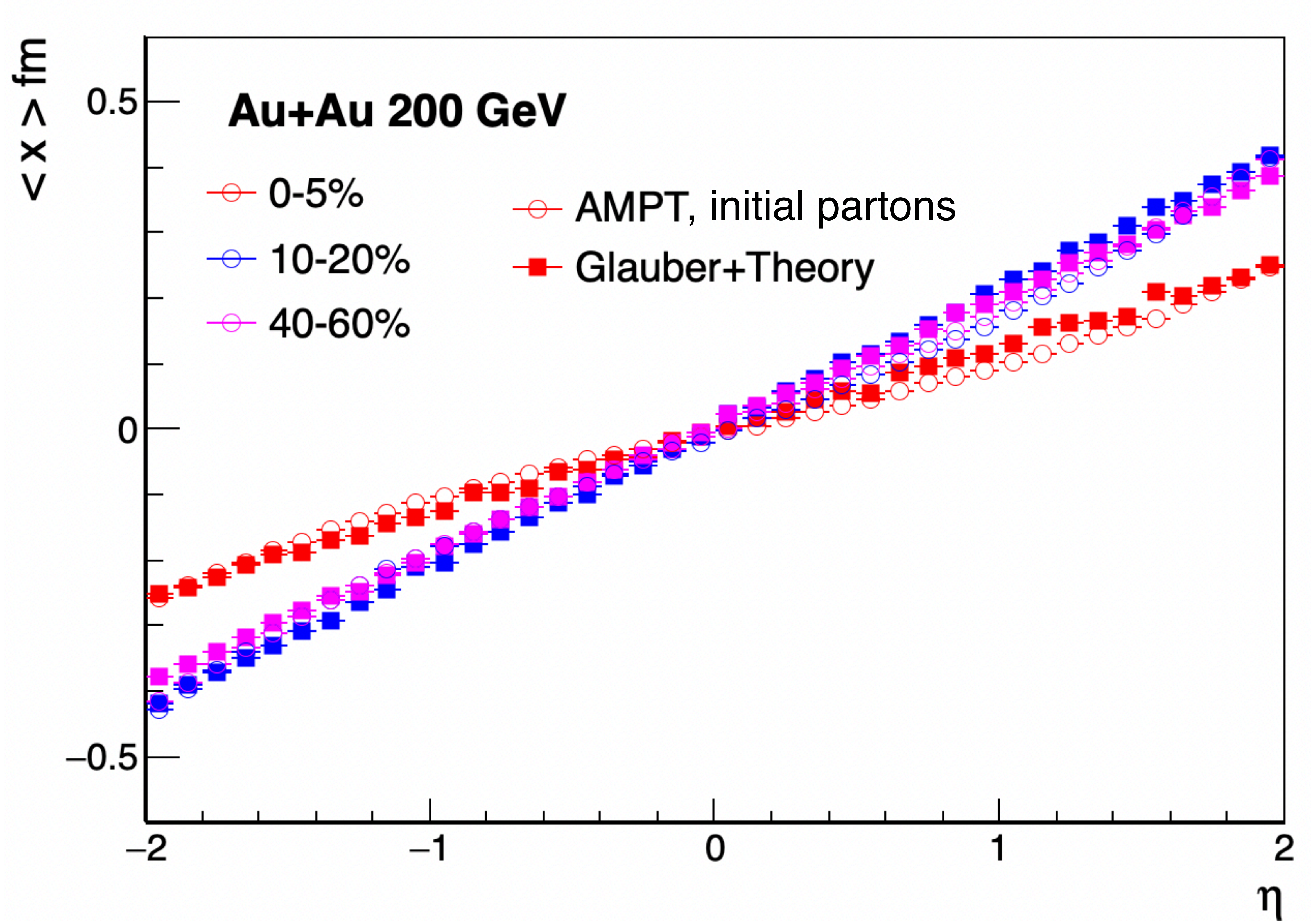
Asymmetry along x vs pseudorapidity



- Bulk distribution tilted along impact parameter direction at finite rapidity
- Centrality dependence primarily in most central collisions, expected as participant asymmetry decreases

Comparison to AMPT





- Can also look at a direct model calculation and the initial bulk distributions in the model
- Looking at initial partons (before cascade) from AMPT

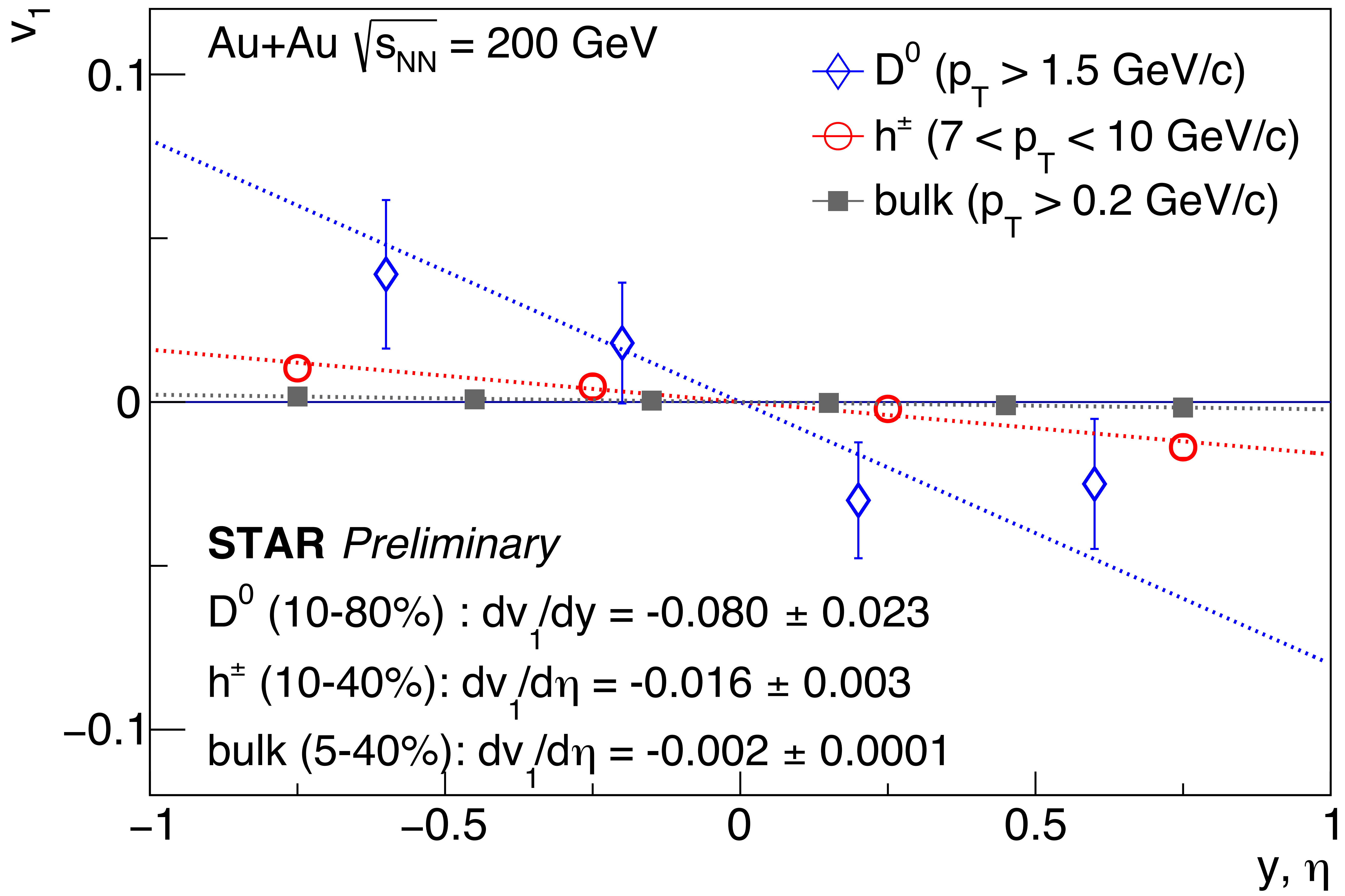
- Quite well reproduces the asymmetry from the theory calculation

Large v_1 observed for several hard probes

- Large v_1, order of magnitude larger than bulk v_1, observed for D^0
- Also for high p_T charged hadrons

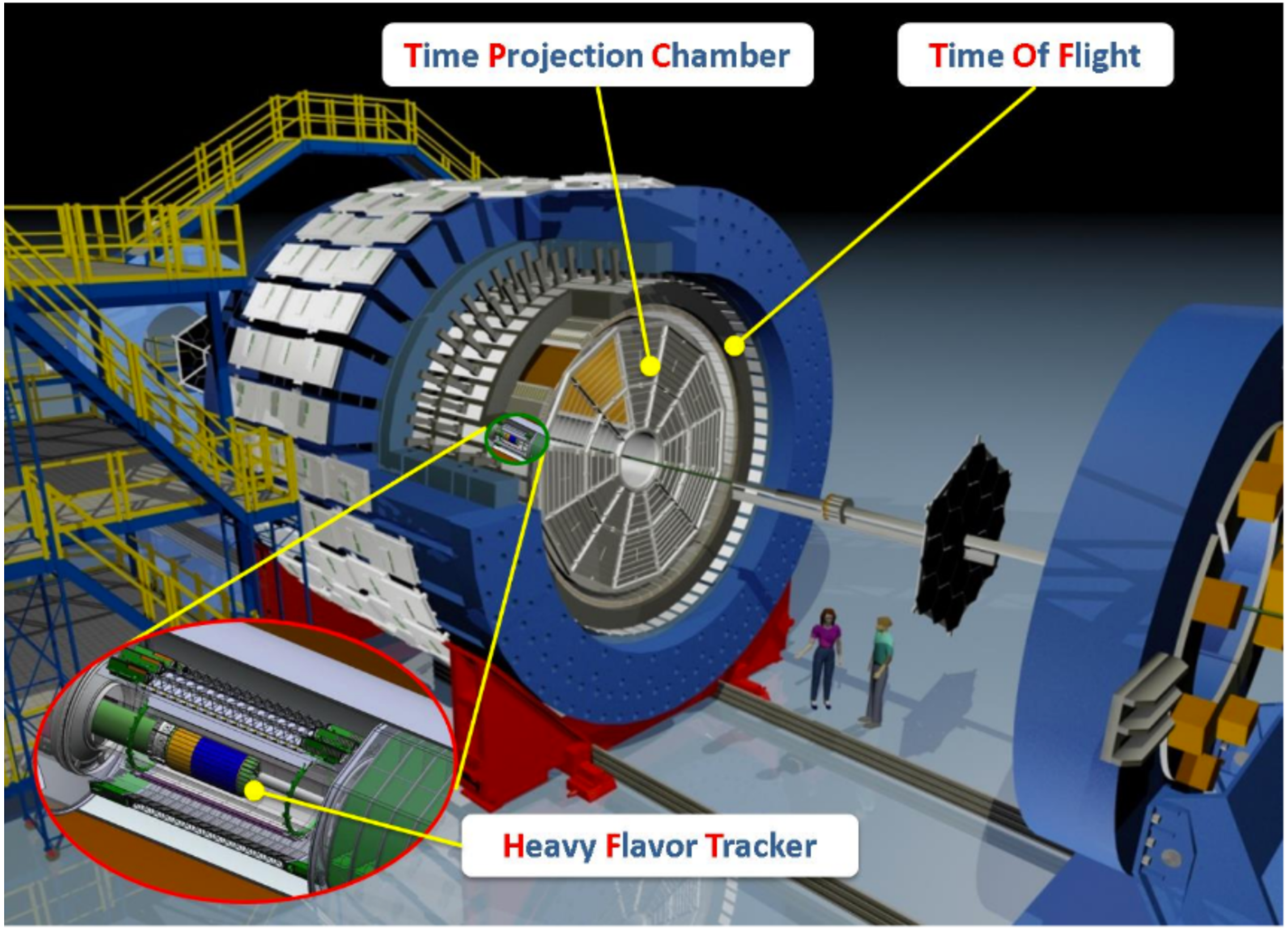
- Do we see large v_1 from the initial hard - soft asymmetry and path length dependent energy loss for jets also?

- With jet v_1 —> can access parton energy loss

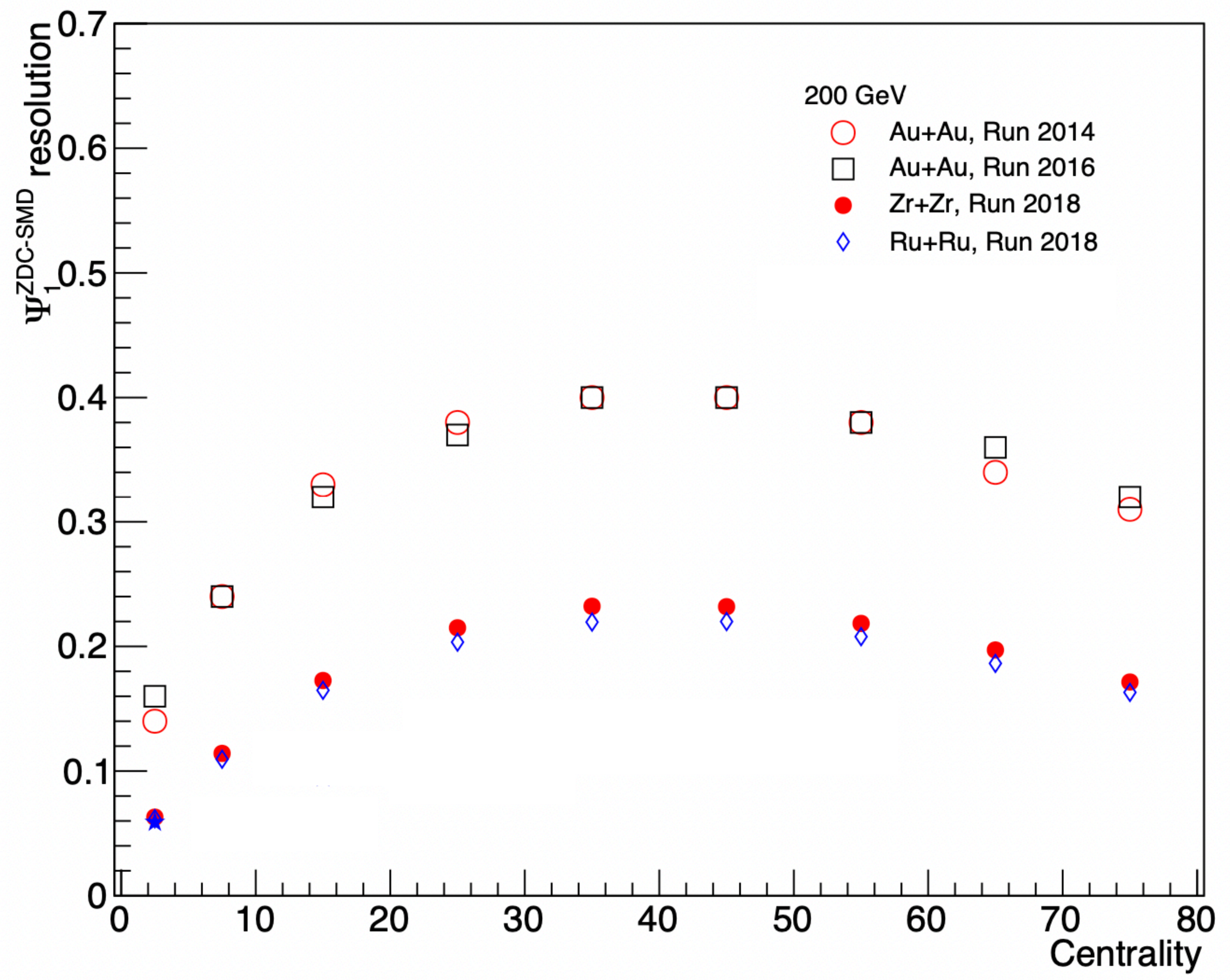


STAR D^0: Phys. Rev. Lett. 123, 162301 (2019)
STAR bulk: Phys. Rev. Lett. 101, 252301 (2008)

STAR detector and dataset

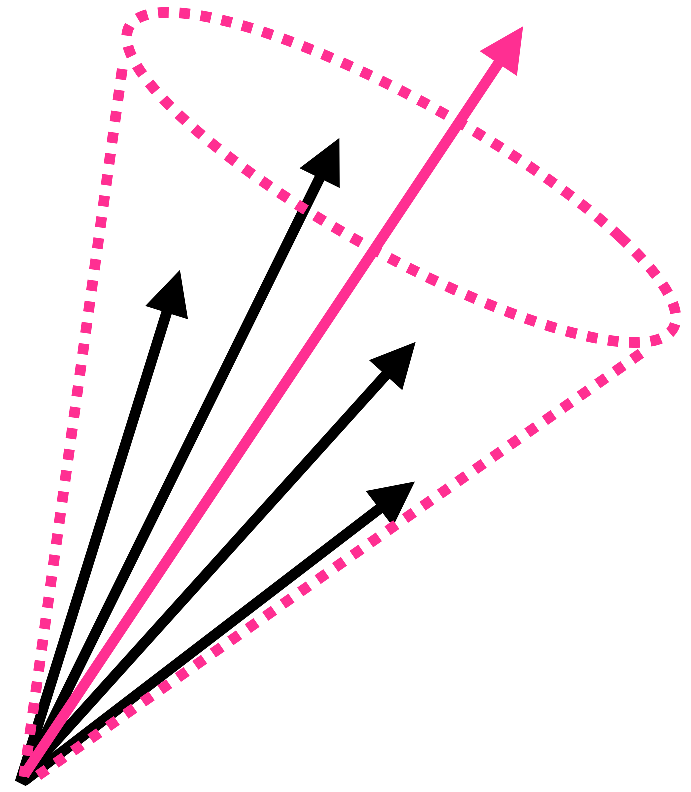


- Au + Au 200 GeV from 2014 and 2016: ~2 Billion MB events
- Ru+Ru, Zr+Zr collisions at 200 GeV from 2018: 3.6 Billion MB events



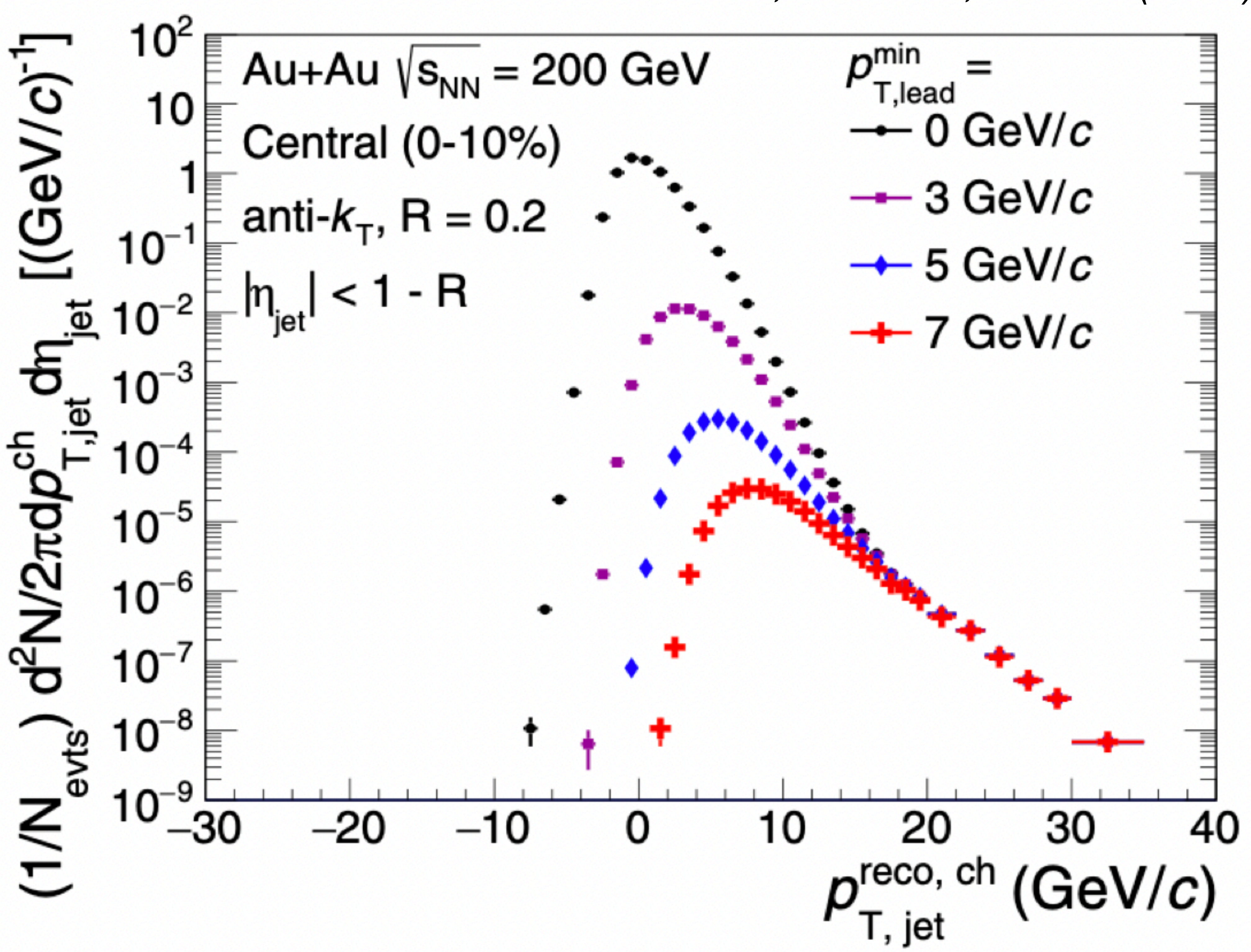
- First order EP from ZDC

Jet Reconstruction



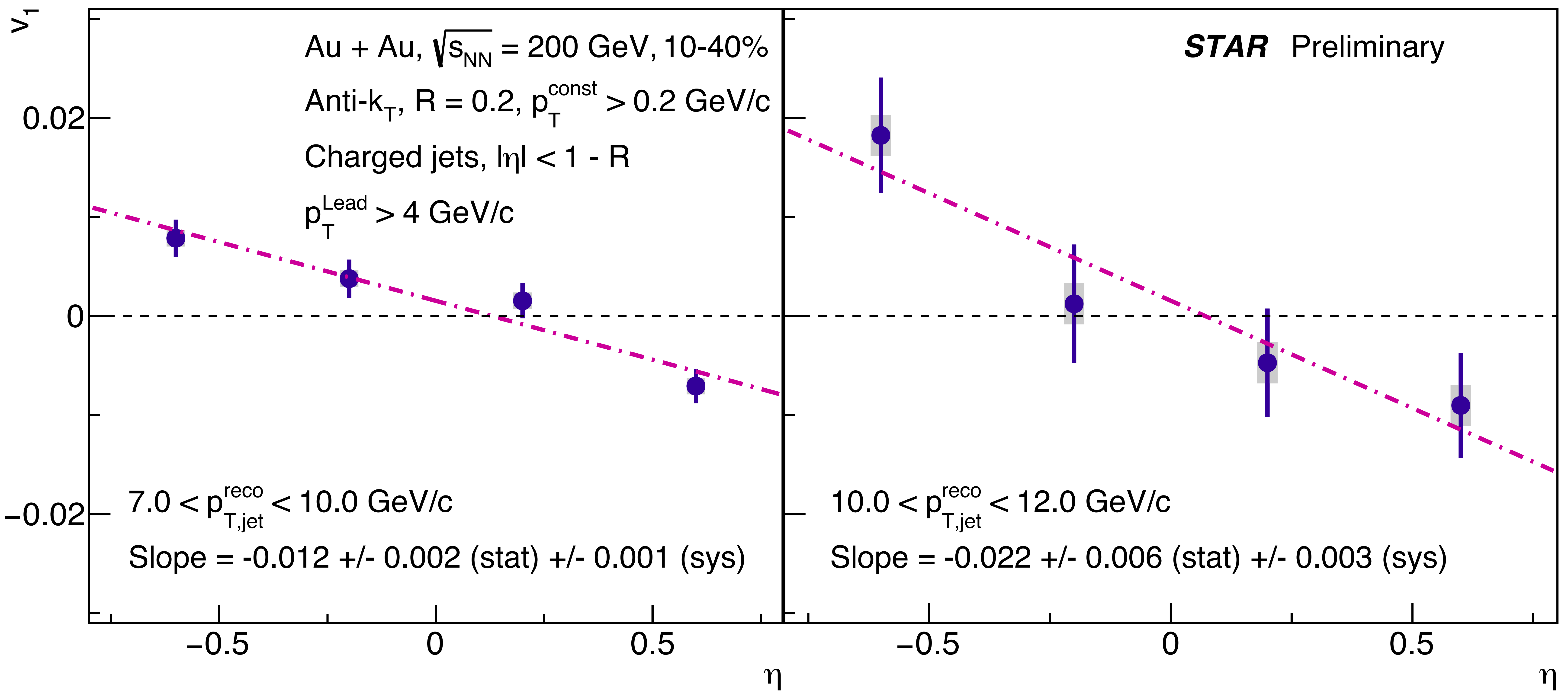
- Looking at charged particle jets with a high p_T leading hadron ($p_T^{Lead} > 4$ GeV/c)
- Anti-k_T R = 0.2 and 0.3 jets
- k_T algorithm for background energy density (ρ) calculation
- $p_{T,jet}^{reco} = p_{T,jet}^{raw} - \rho A$
- Results are also checked with changing leading hadron p_T requirement to > 5 GeV/c. Results are consistent within systematic uncertainties

STAR, PRC 102, 054913 (2020)



Results: Jet v_1 vs η

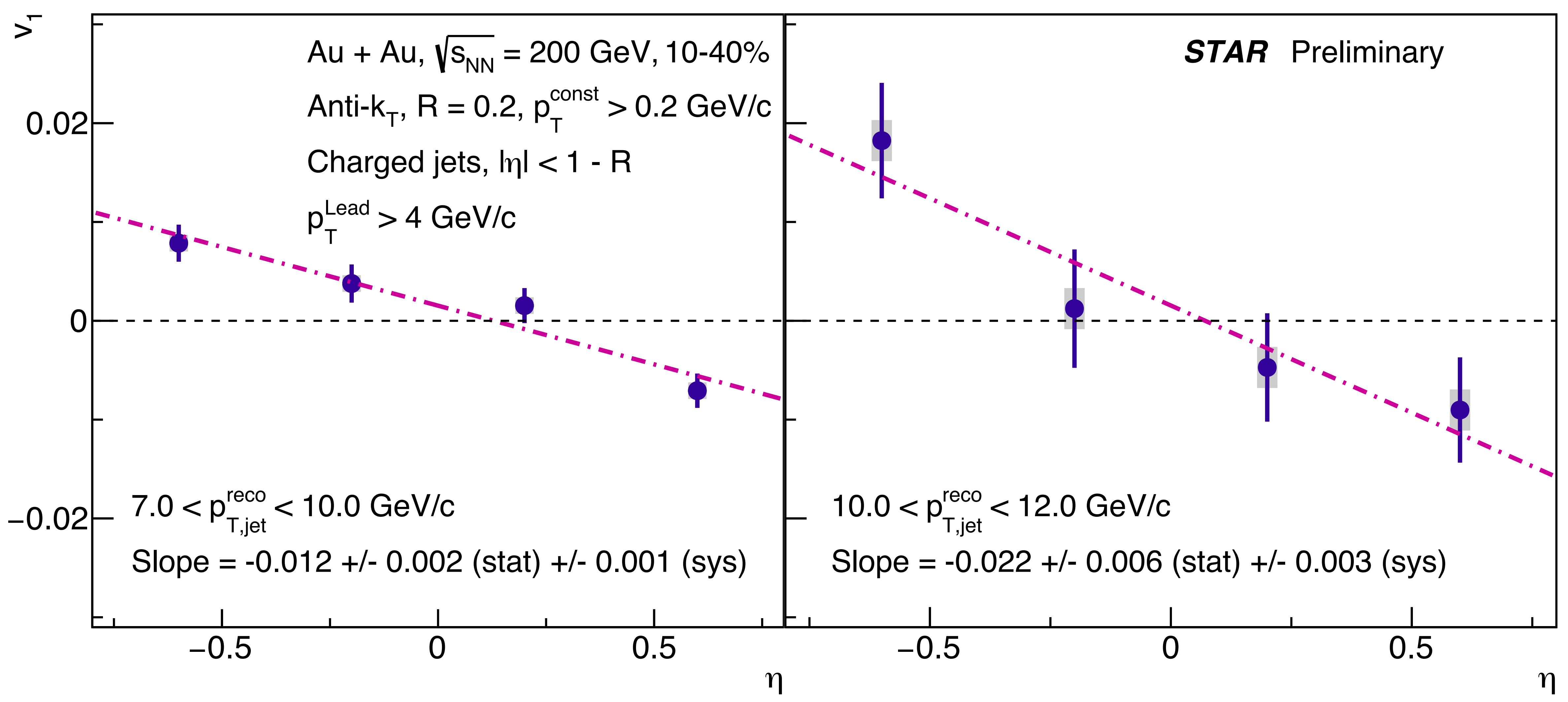
$$p_{T,jet}^{reco} = p_{T,jet}^{raw} - \rho A$$

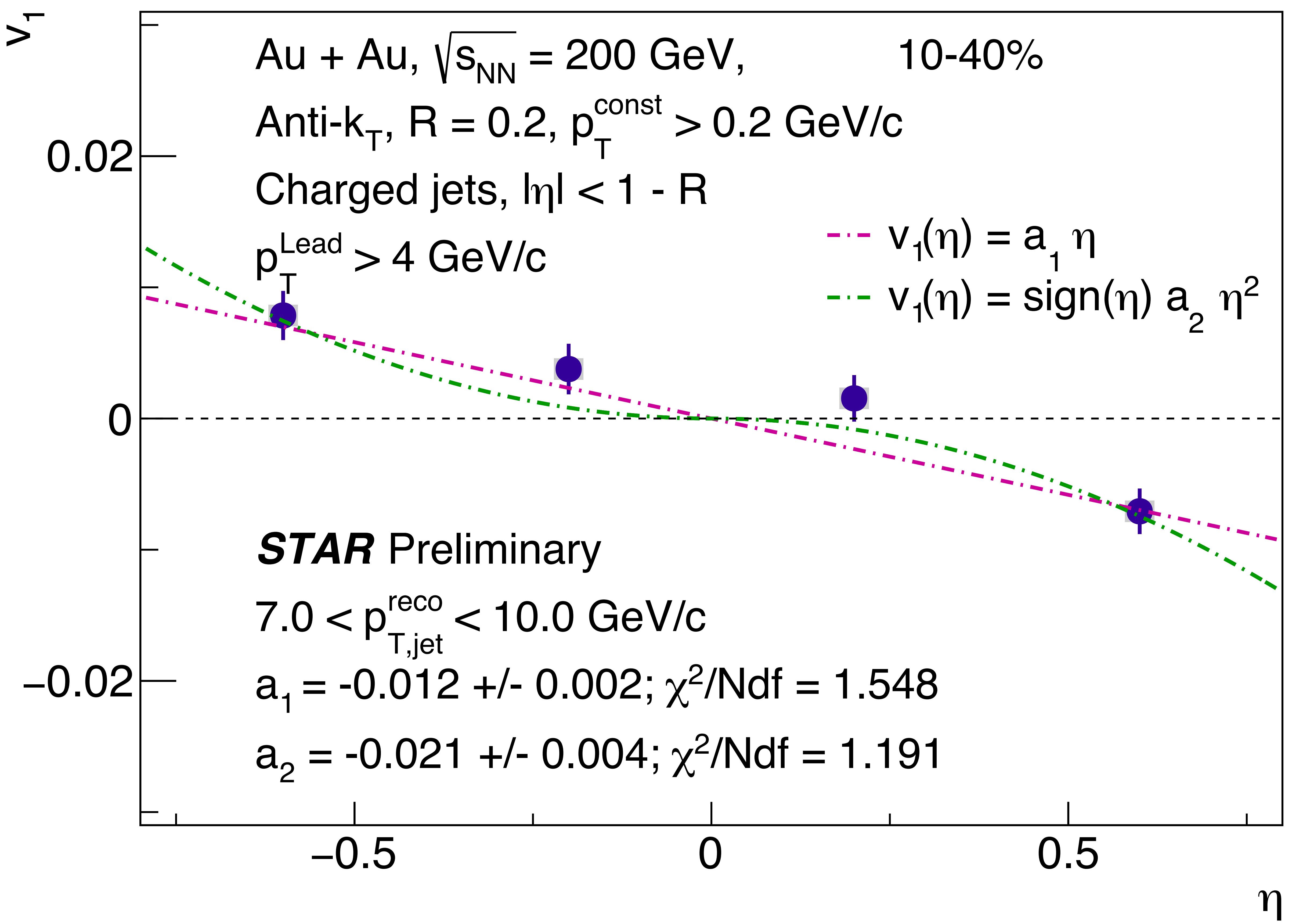


- Non-zero jet v_1 measured in mid-central heavy-ion collisions
- Significant values for the slope in 7 - 10 GeV/c (> 5σ) and 10 - 12 GeV/c (~3.5σ) bins

Results: Jet v_1 vs η

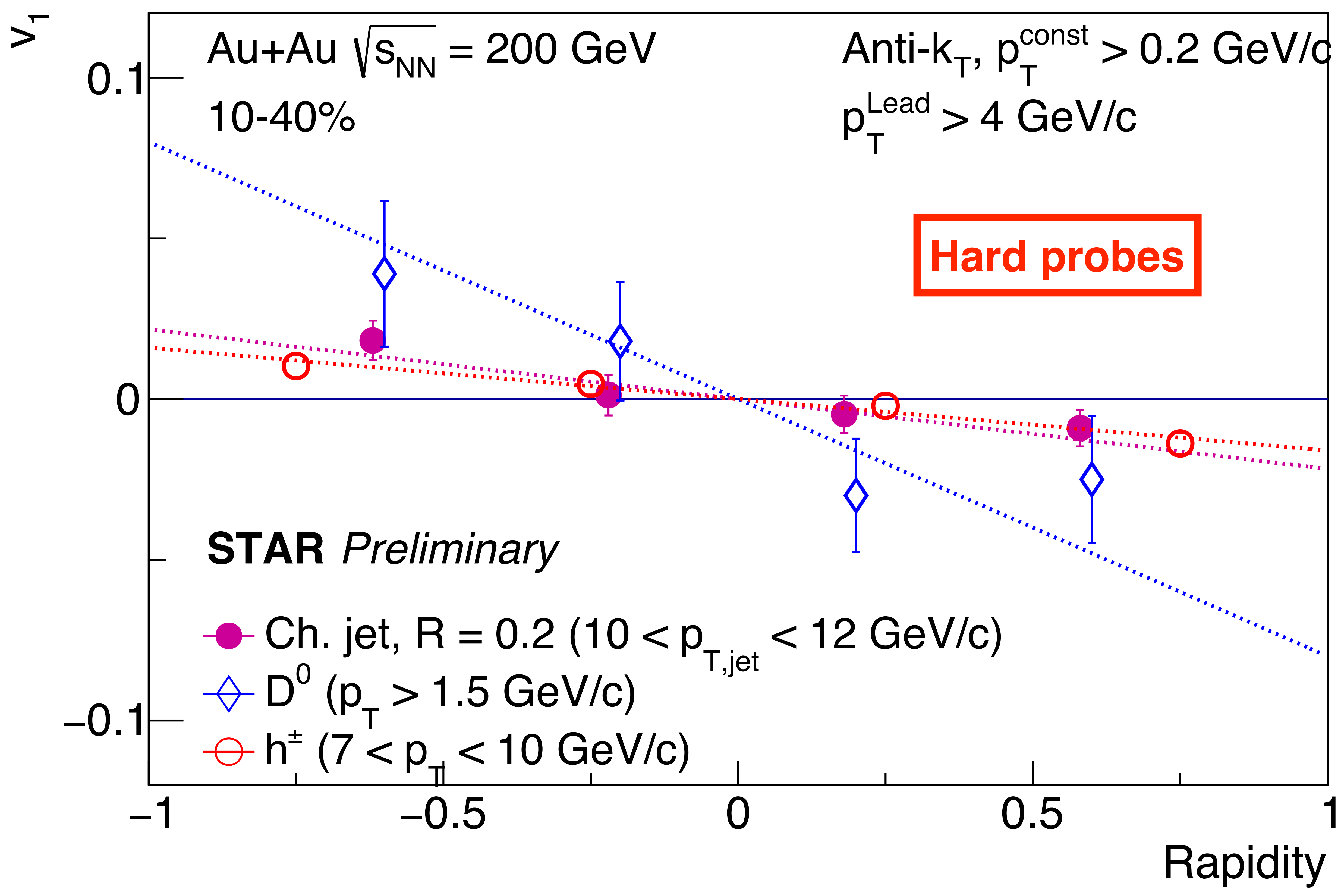
$$p^{reco}_{T,jet} = p^{raw}_{T,jet} - \rho A$$

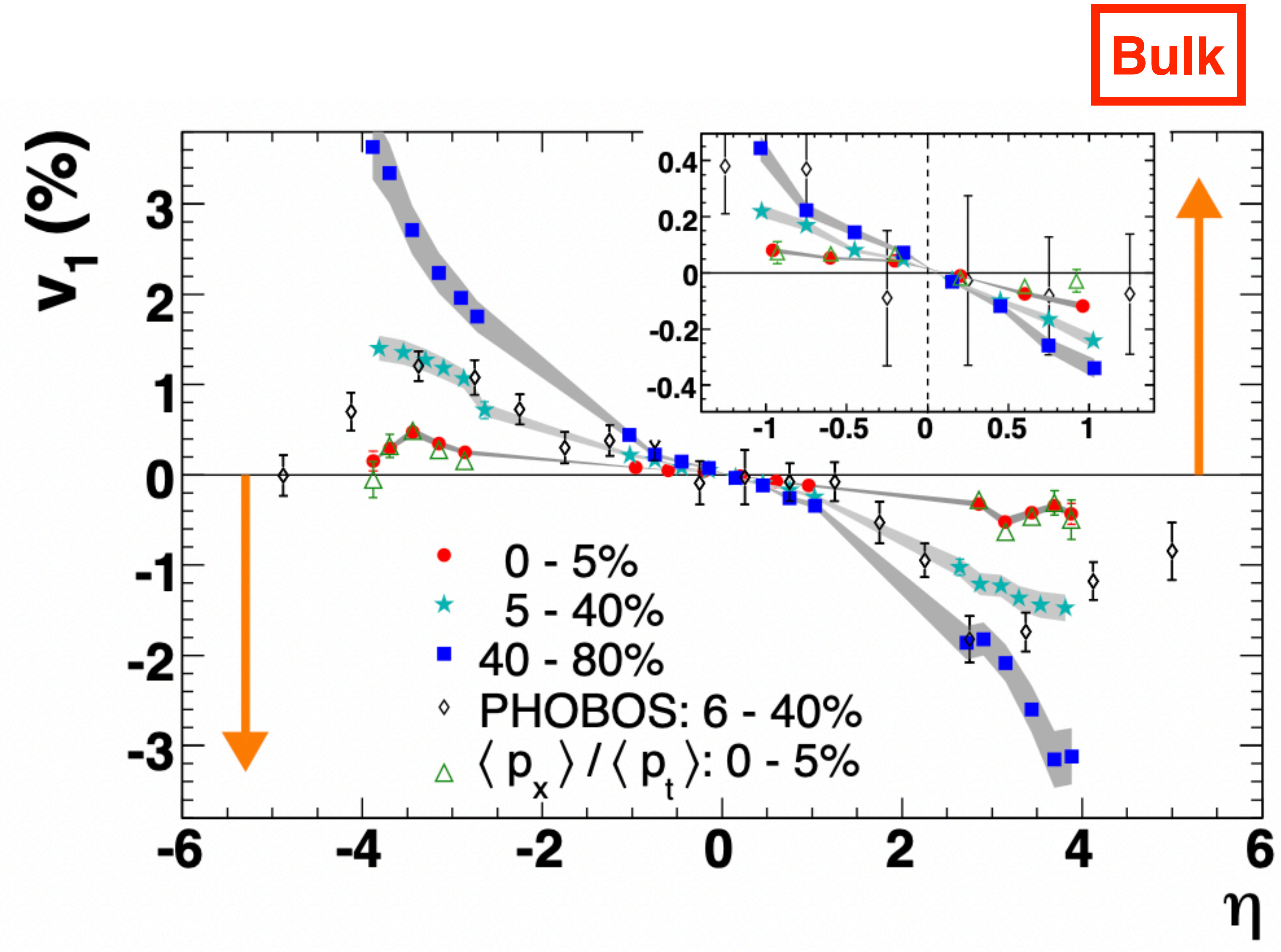




- Cannot distinguish linear or quadratic dependence on η at current precision

v_1 of hard probes

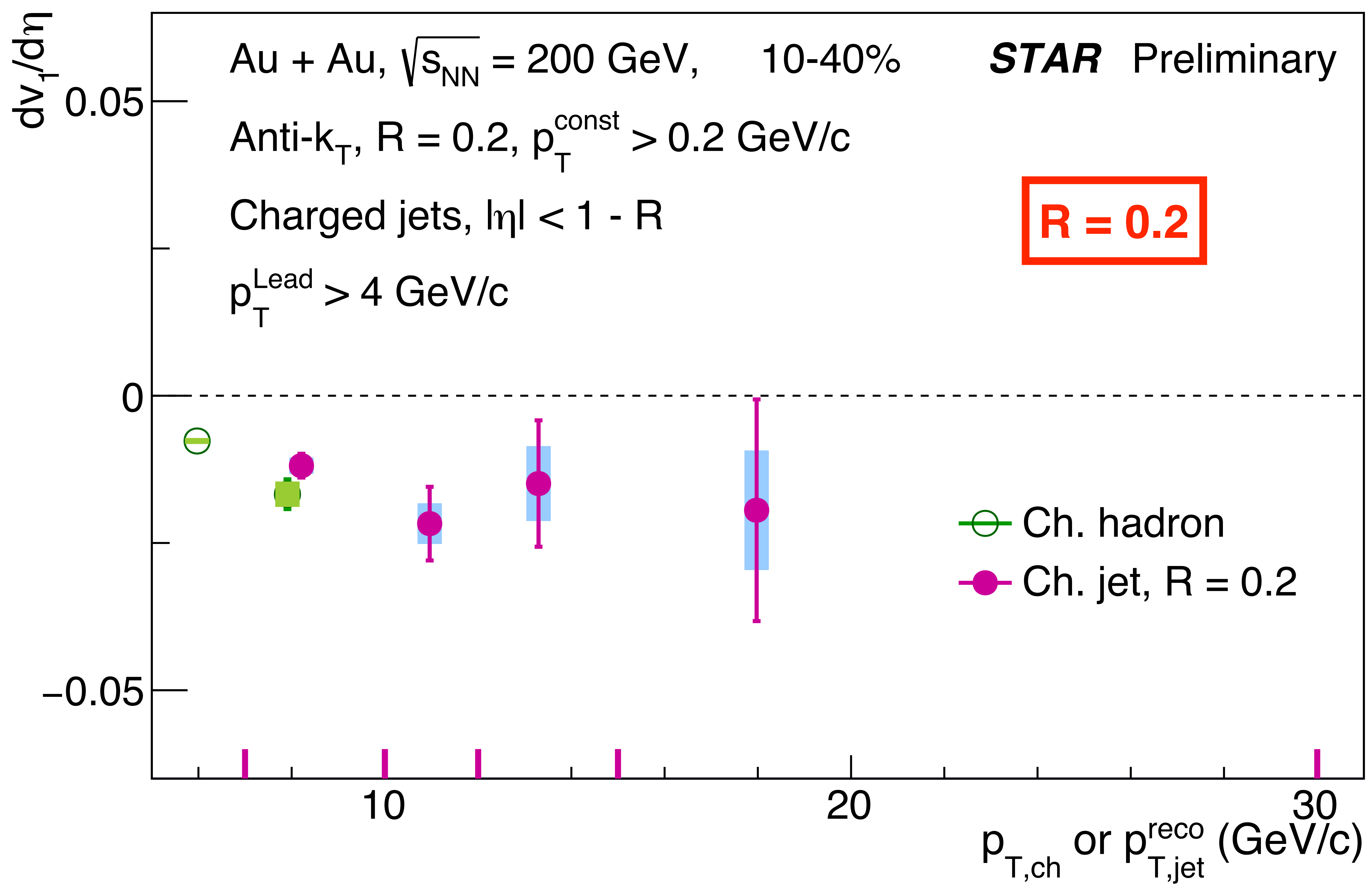


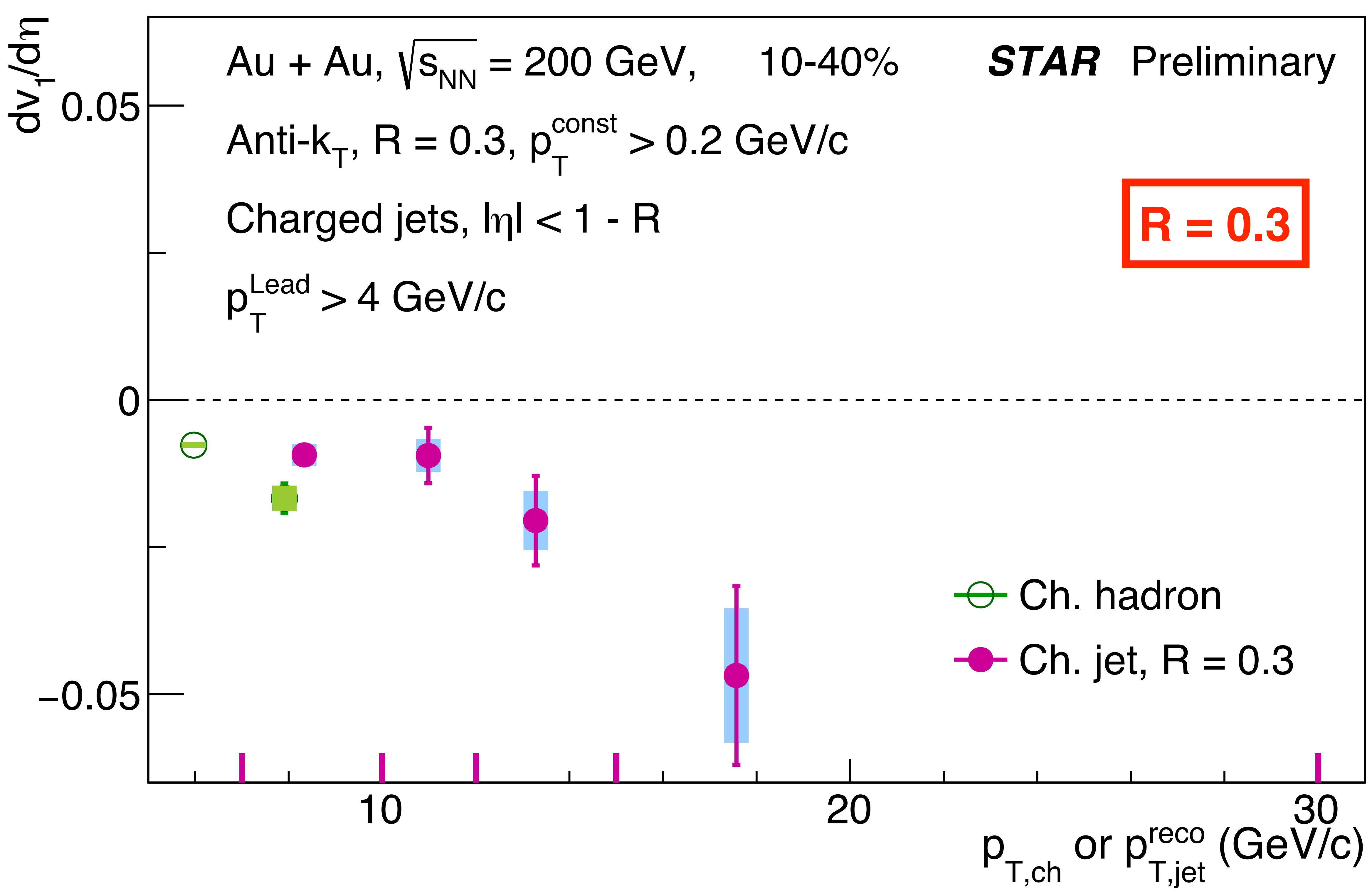


STAR D^0: Phys. Rev. Lett. 123, 162301 (2019)
STAR bulk: Phys. Rev. Lett. 101, 252301 (2008)

- Jet v_1 compared to v_1 of other hard probes for Au+Au collisions at 200 GeV
- Large negative v_1 for all hard probes, order of magnitude larger than compared to bulk v_1. Reflects response to initial hard-soft asymmetry

Jet v_1, p_T and jet radius dependence

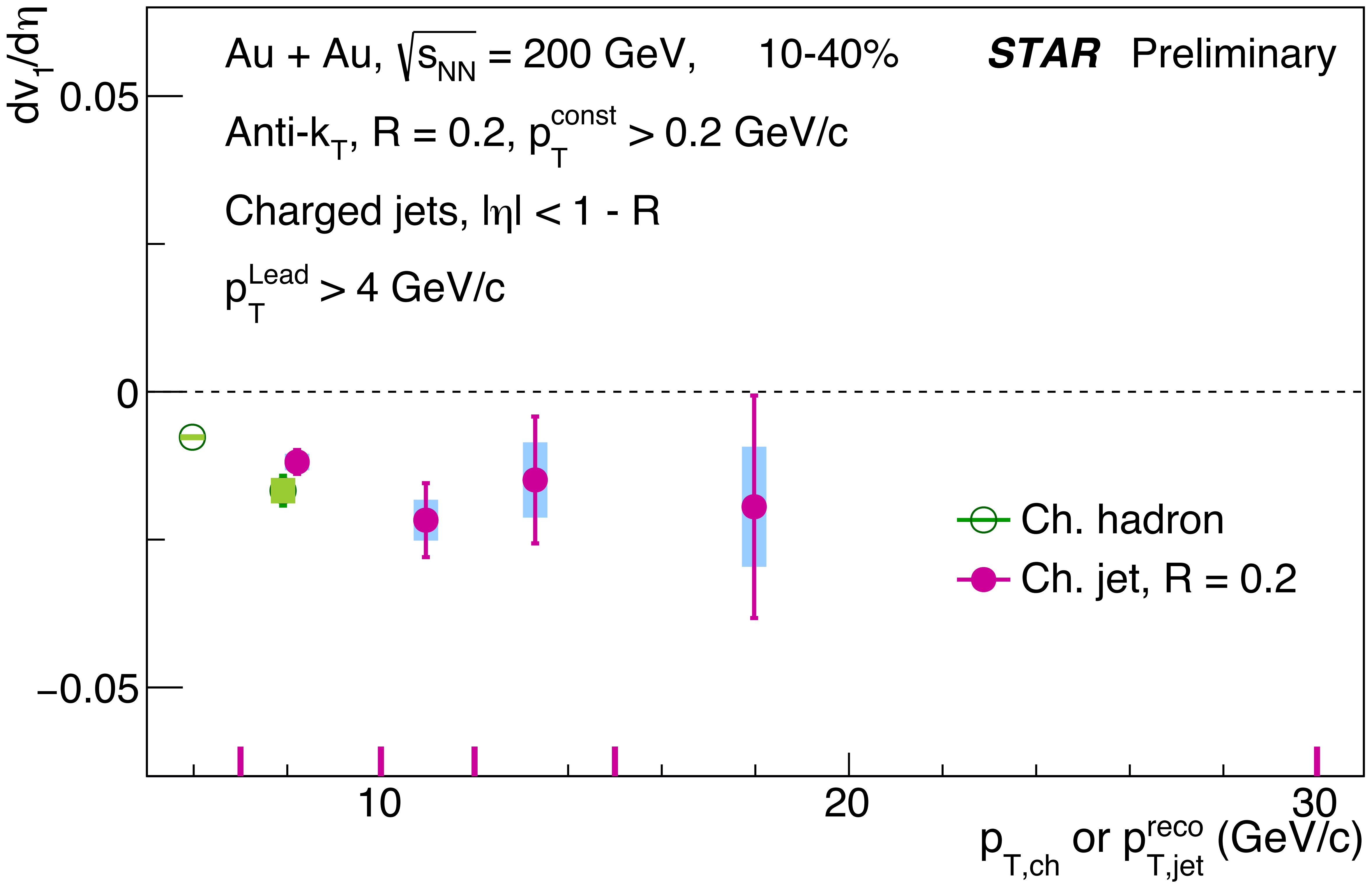


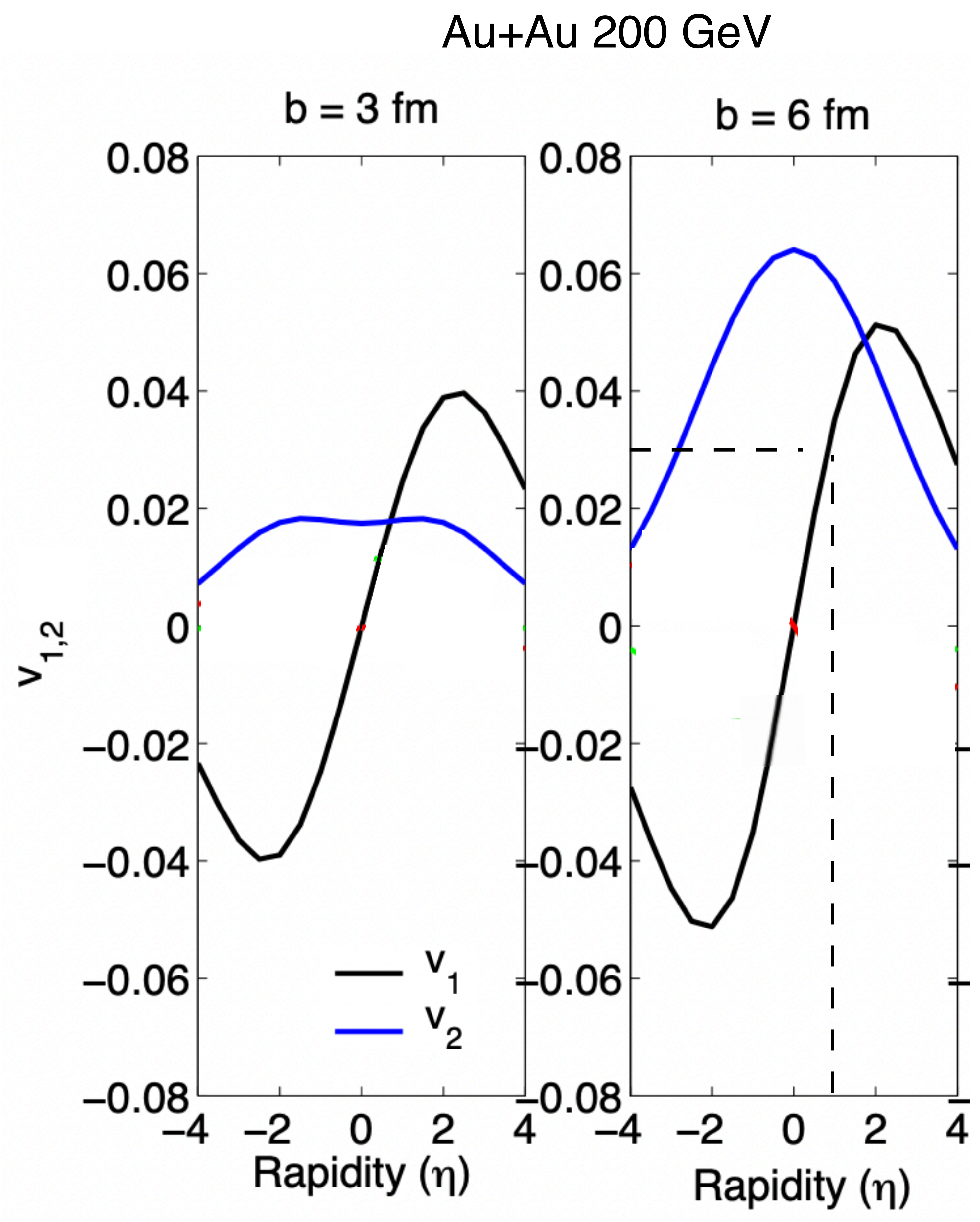


purple lines on x-axis show bin ranges

- Measured as function of p_T for jets with different radii
- No strong jet R dependence, indication of jet p_T dependence at low p_T for R = 0.2

Jet v_1, p_T and jet radius dependence



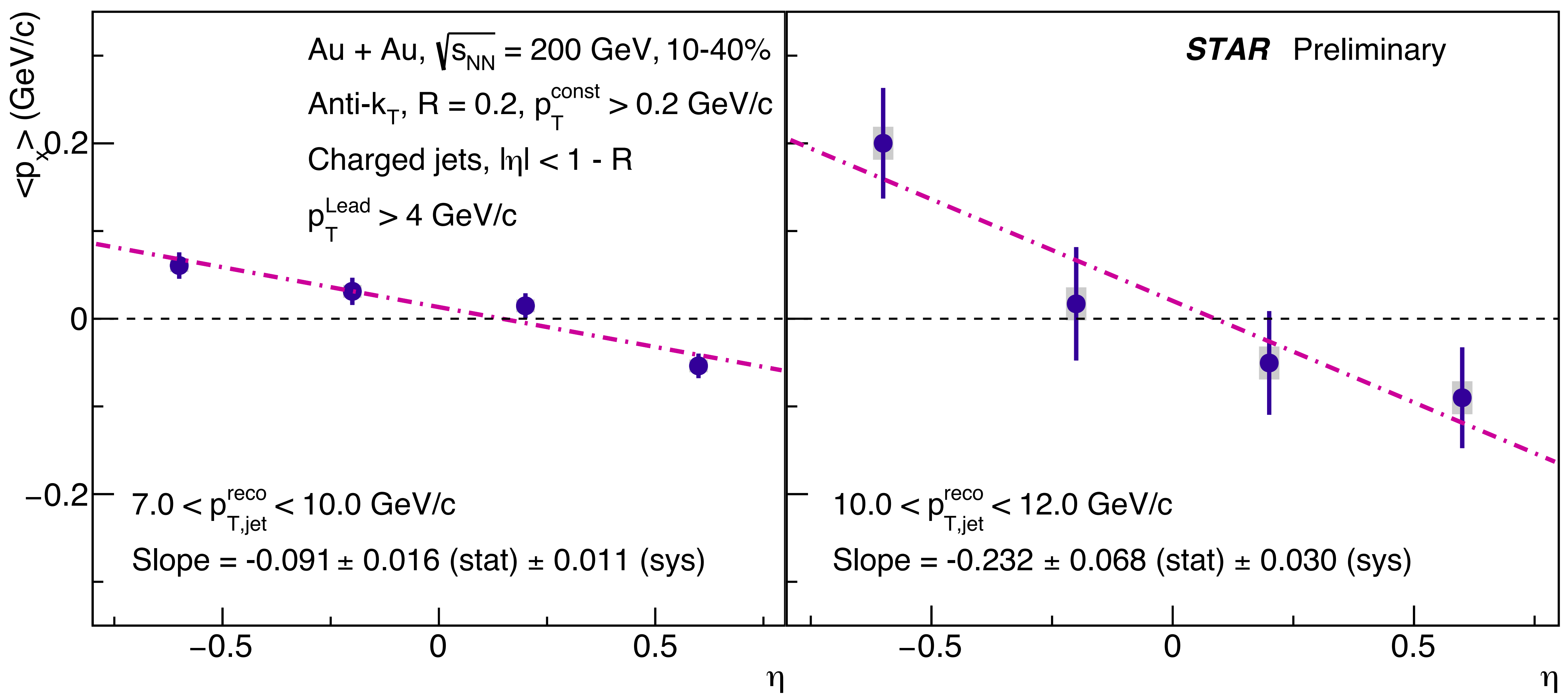


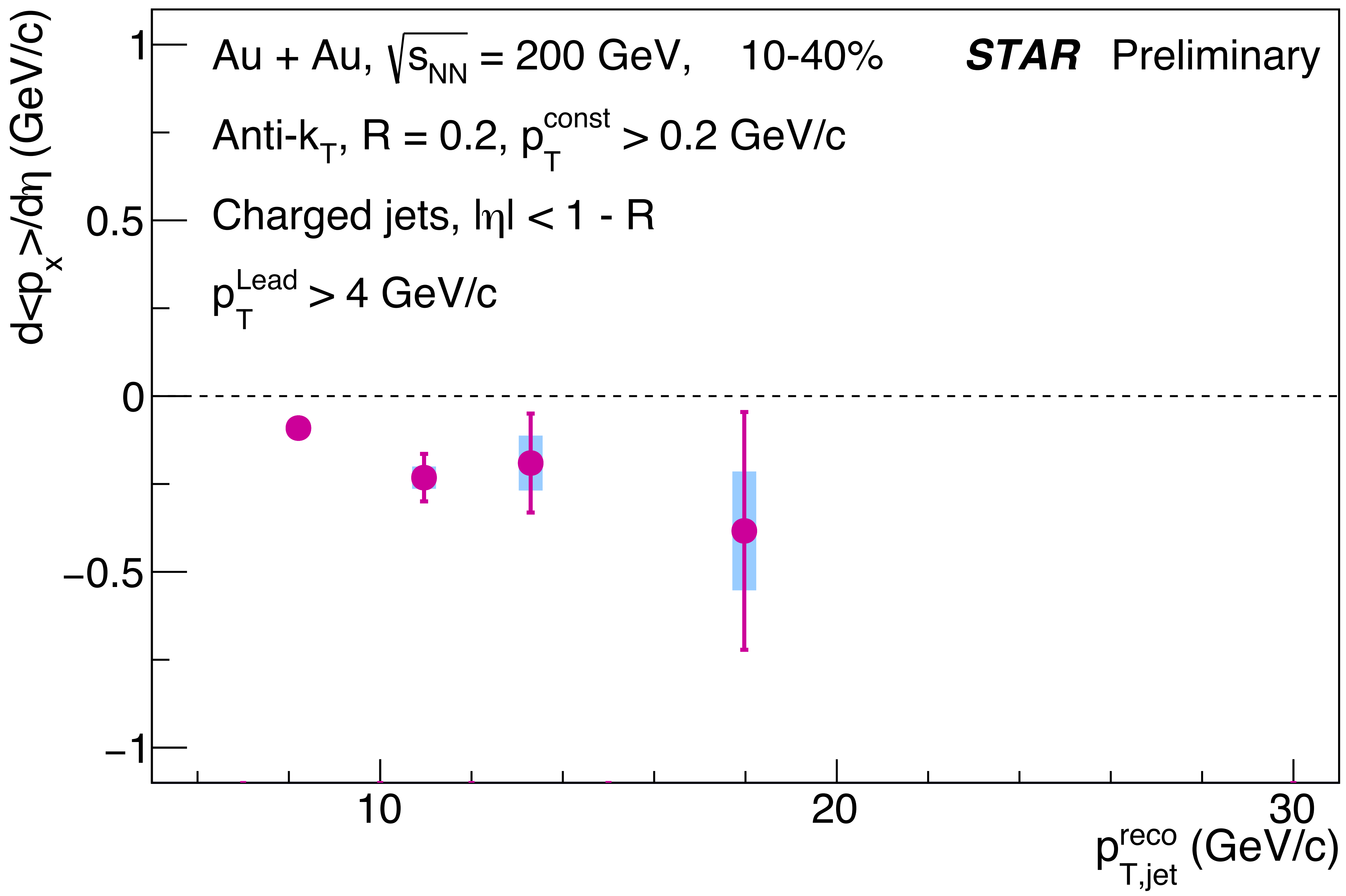
- Measured values comparable to previous estimates for jet v_1

Jet v_1 calculated with R_{AA} = 0.2 in central A+A collisions (sign convention is opposite)

M. Gyulassy et al: Phys. Rev. C 72, 034907, 2005

Jet <p_x> vs η

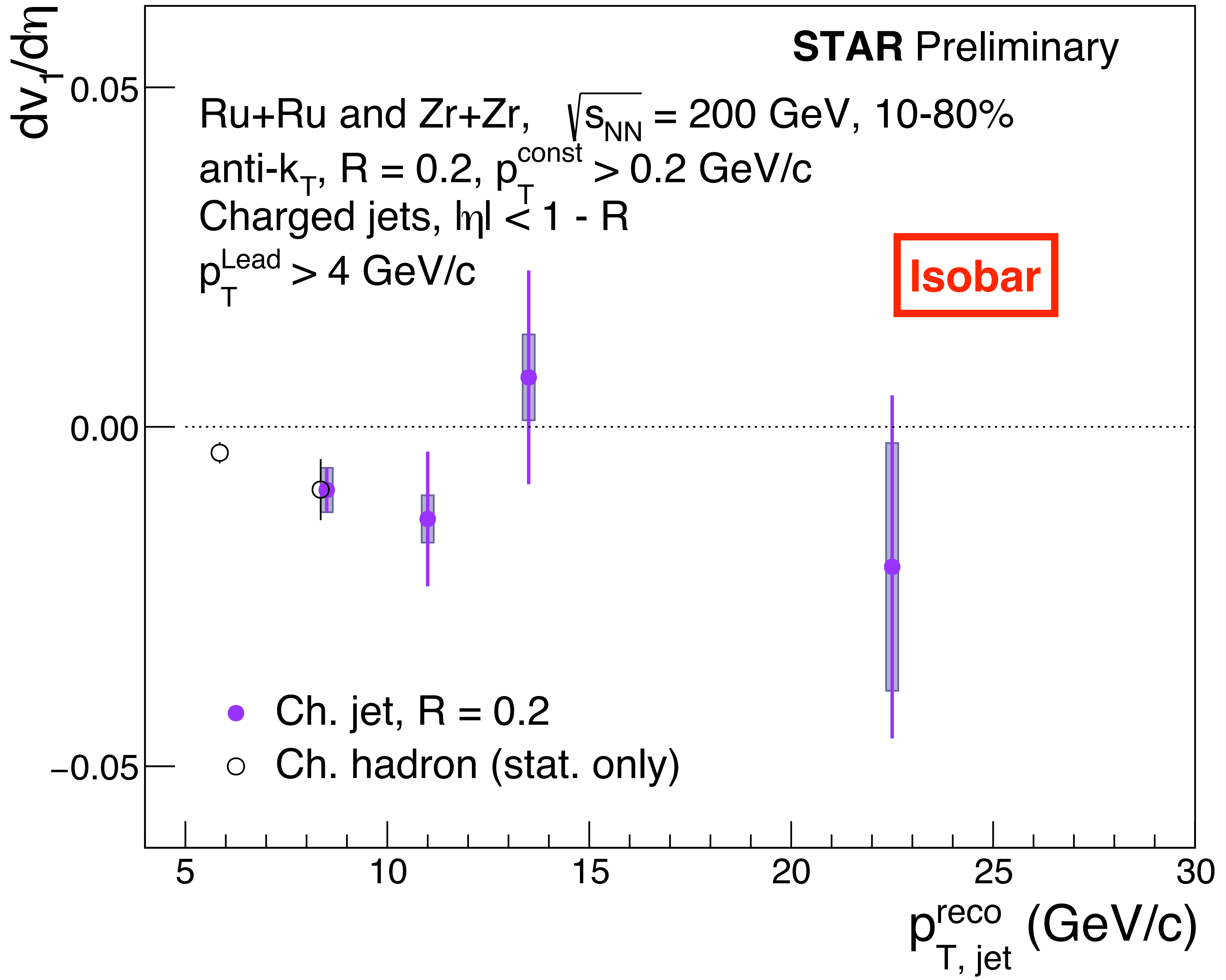


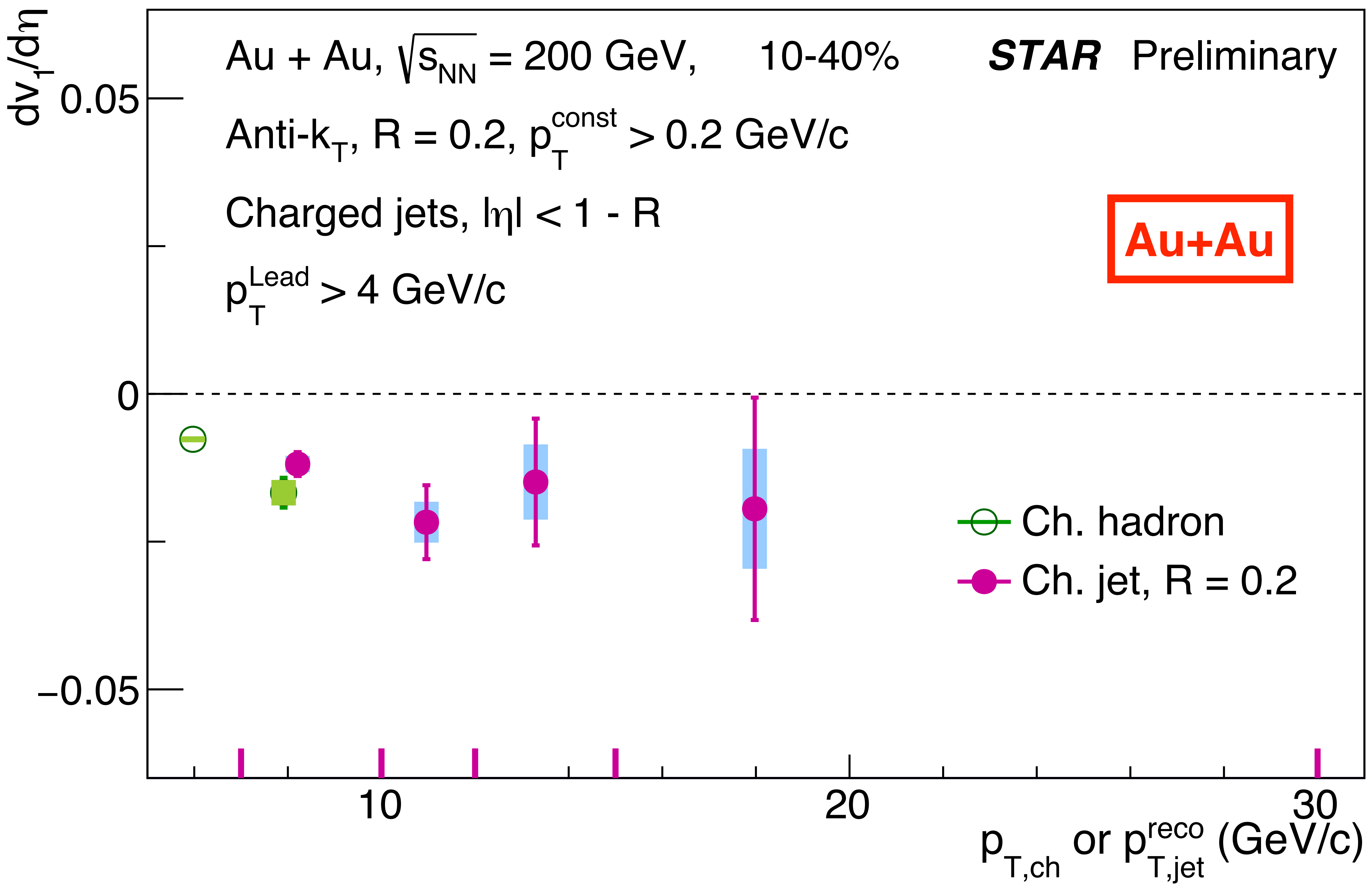


$$v_1 = \langle \frac{p_x}{p_T} \rangle$$

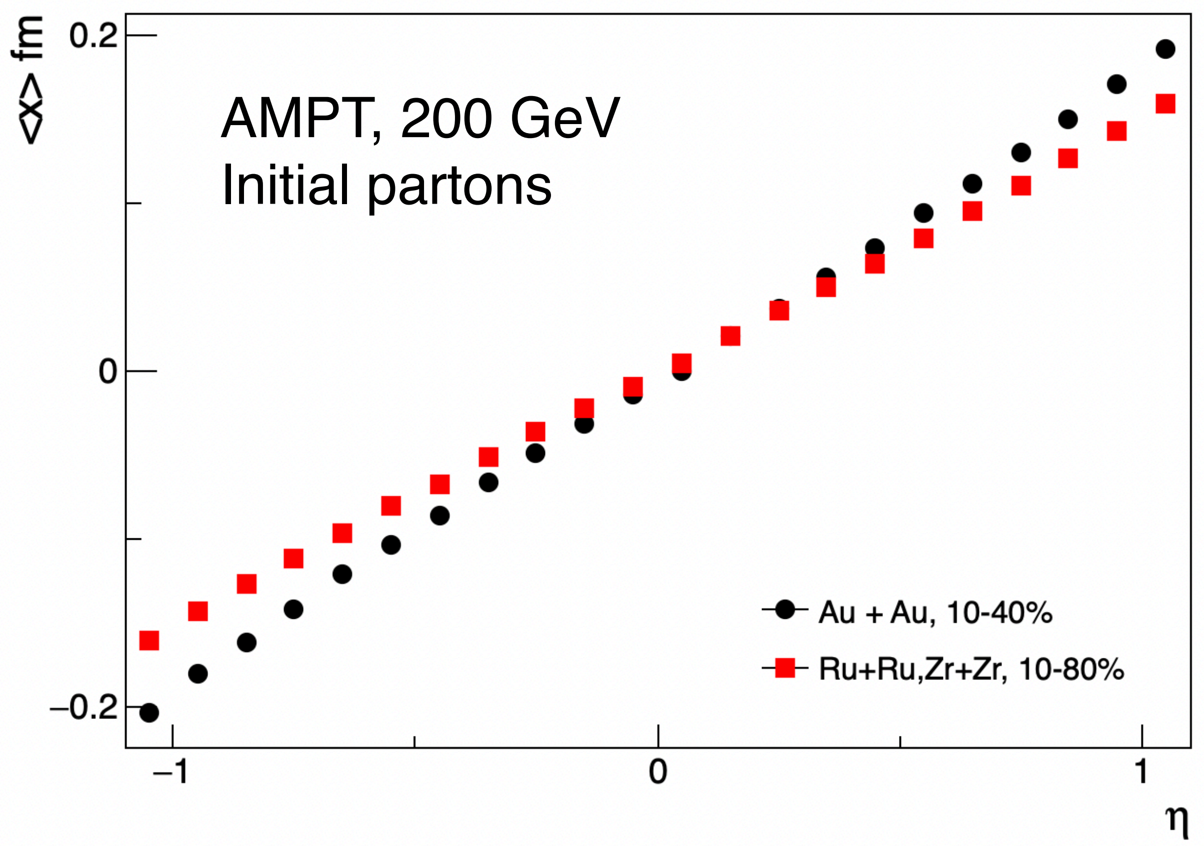
- Measured <p_x> indicates p_T dependence at low p_T
- Mean momentum asymmetry = 0.232 +/- 0.068 (stat) +/- 0.03 (sys) GeV/c for R = 0.2 jets with 10 < $p_{T,jet}^{reco}$ < 12 GeV/c in 10-40% central Au+Au collisions
- Related to jet energy loss in medium

Measurement in Ru+Ru and Zr+Zr collisions





- Measurements in isobar collisions consistent with Au+Au within uncertainties
- Expected, as initial asymmetry in the two systems are similar

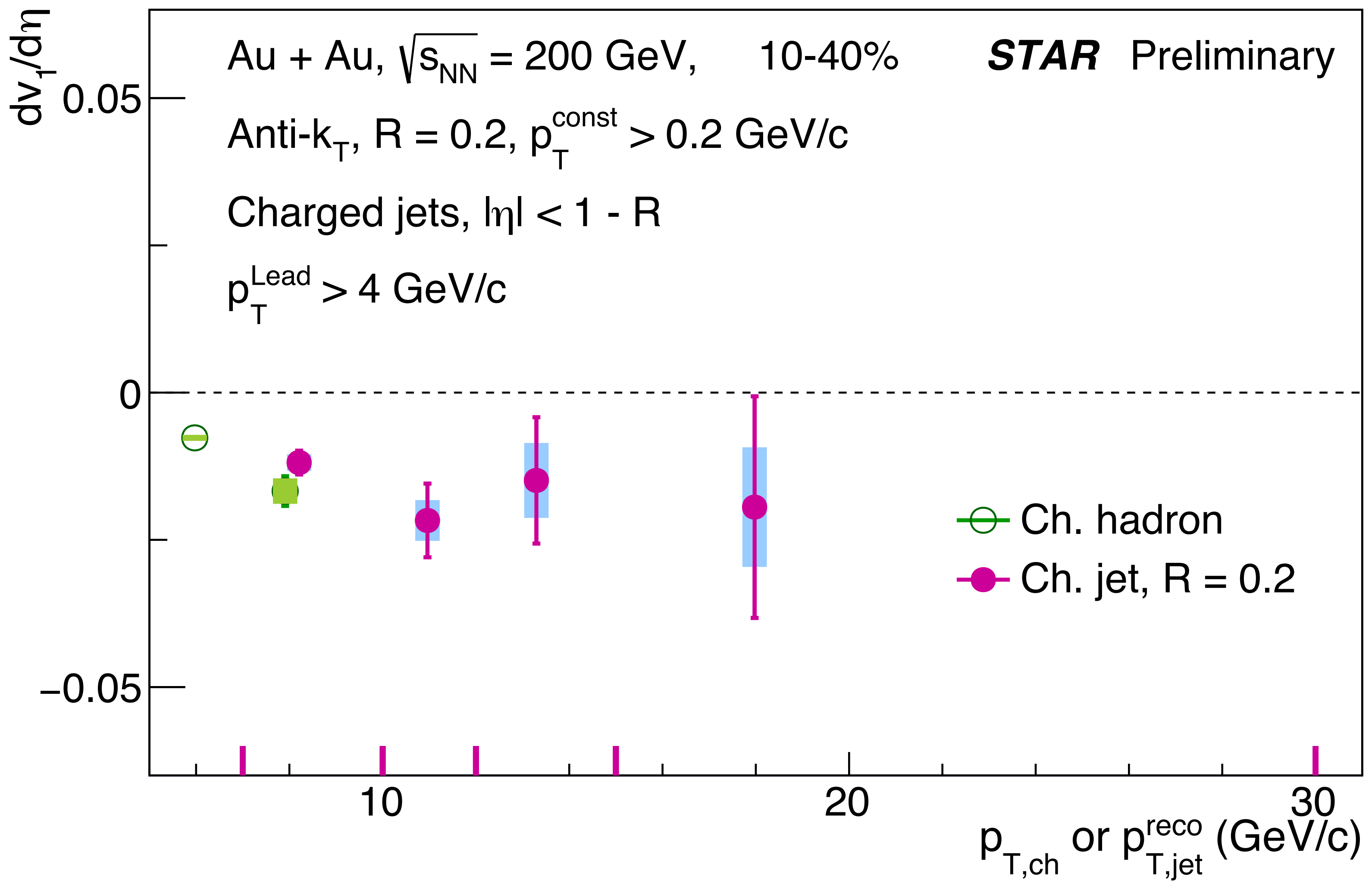


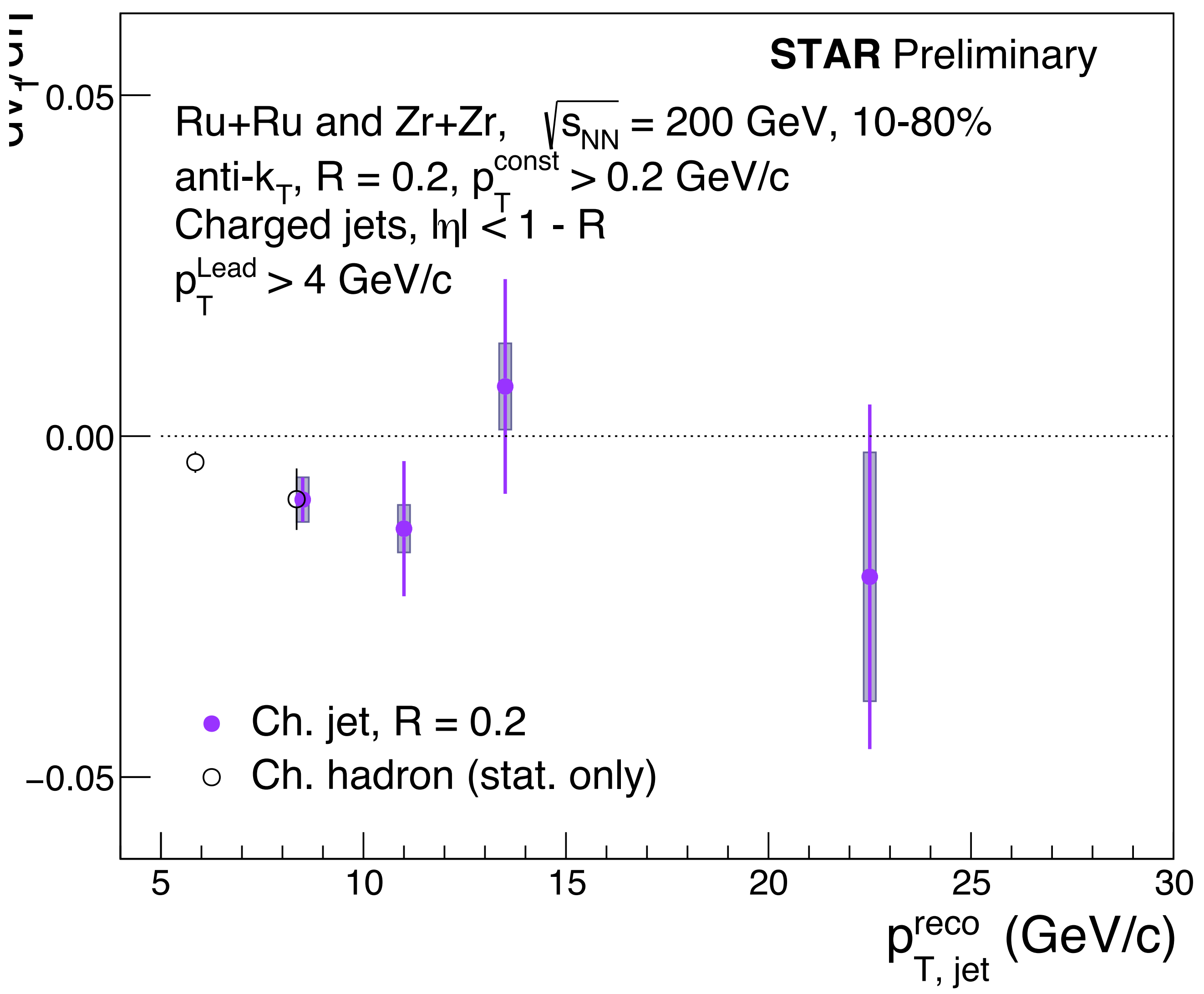
Summary and Outlook

- Jet v_1 an effective tool to study path length dependent energy loss in QGP

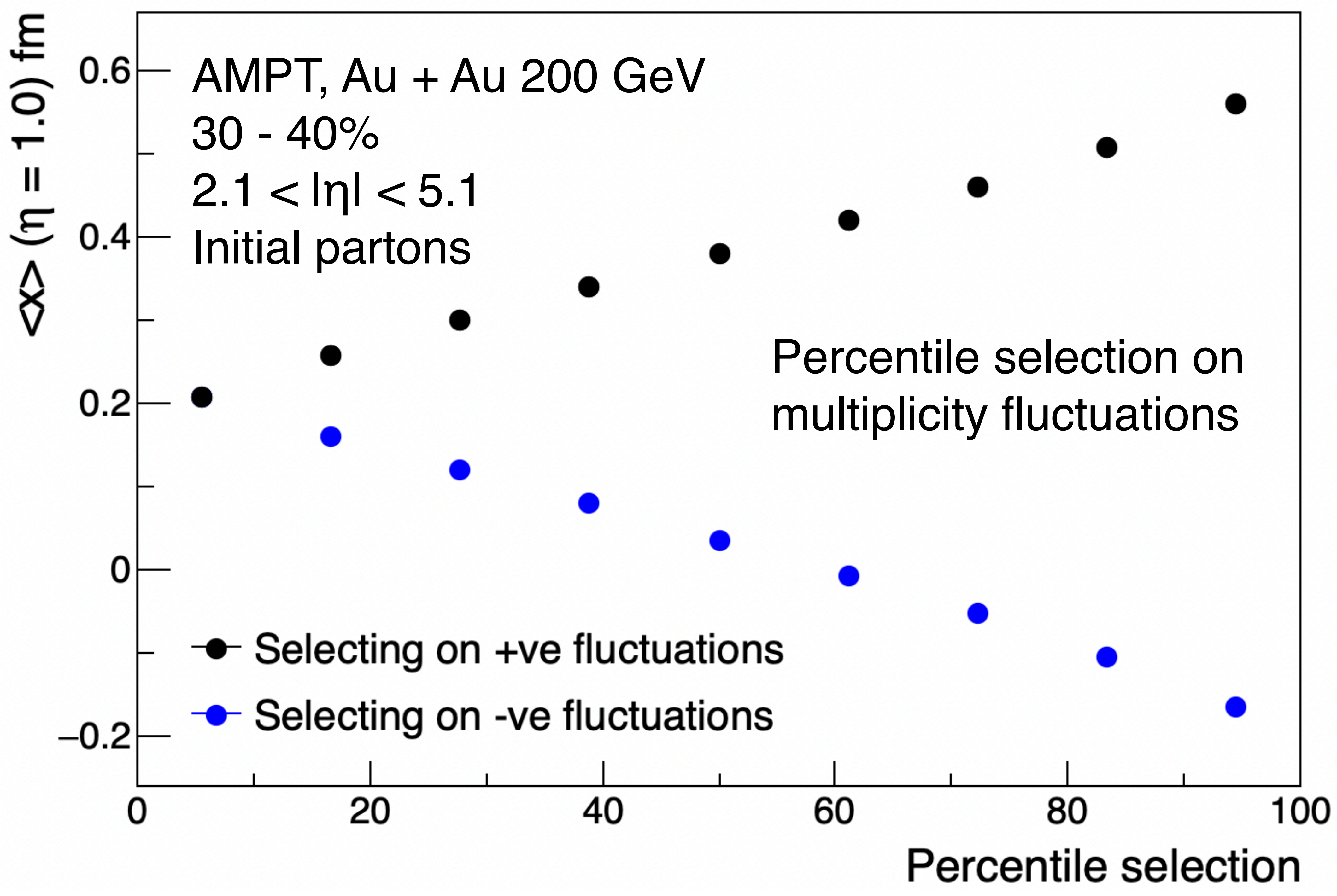
- First measurement of non-zero jet v_1 in heavy-ion collisions
- Order of magnitude larger than bulk v_1, comparable to v_1 of other hard probes
- Measurements in isobar collisions consistent with that in Au+Au

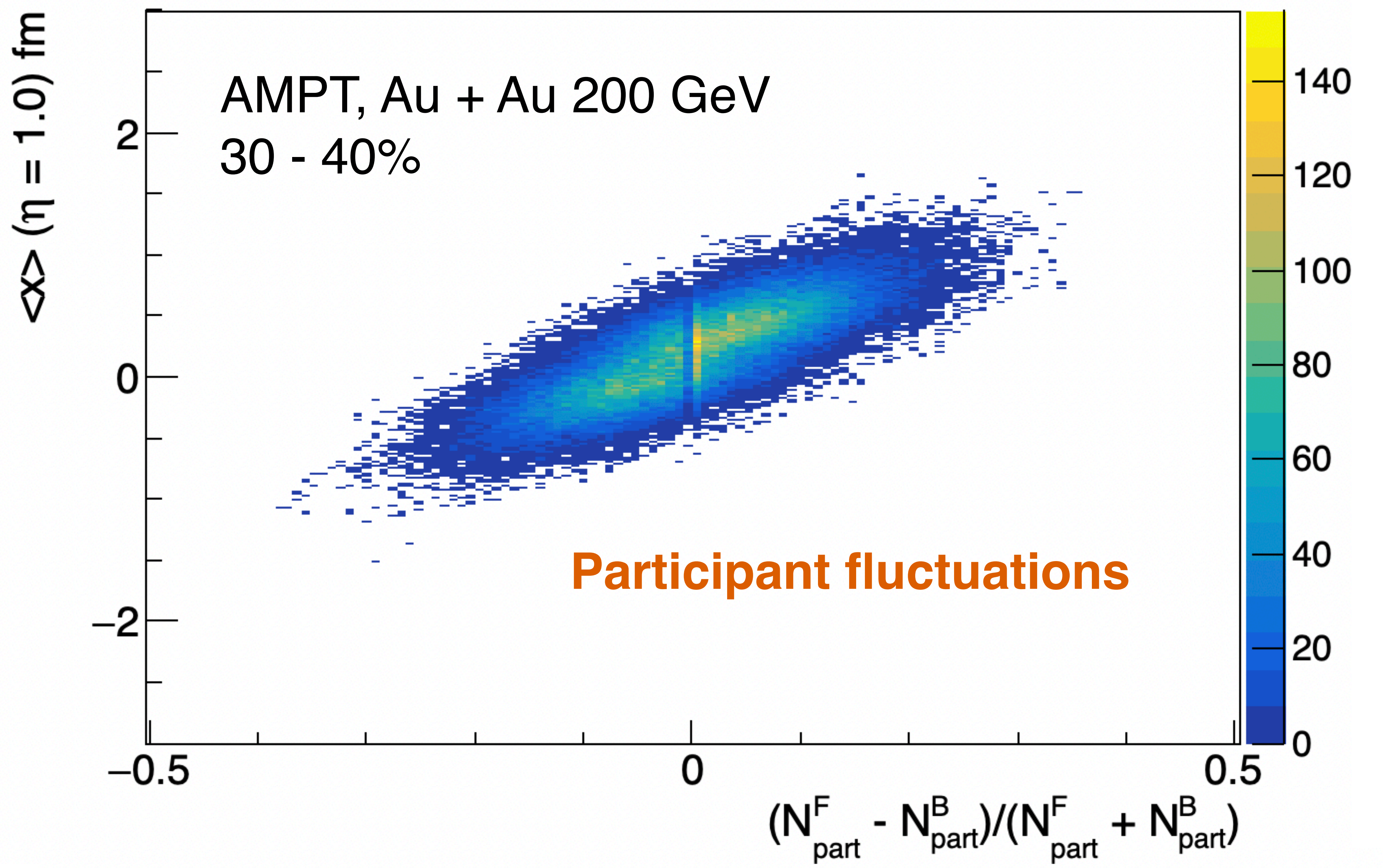
- With high statistics data at RHIC and LHC in the coming years can study path length dependent energy loss of jets of different flavor, sub-structure using jet v_1

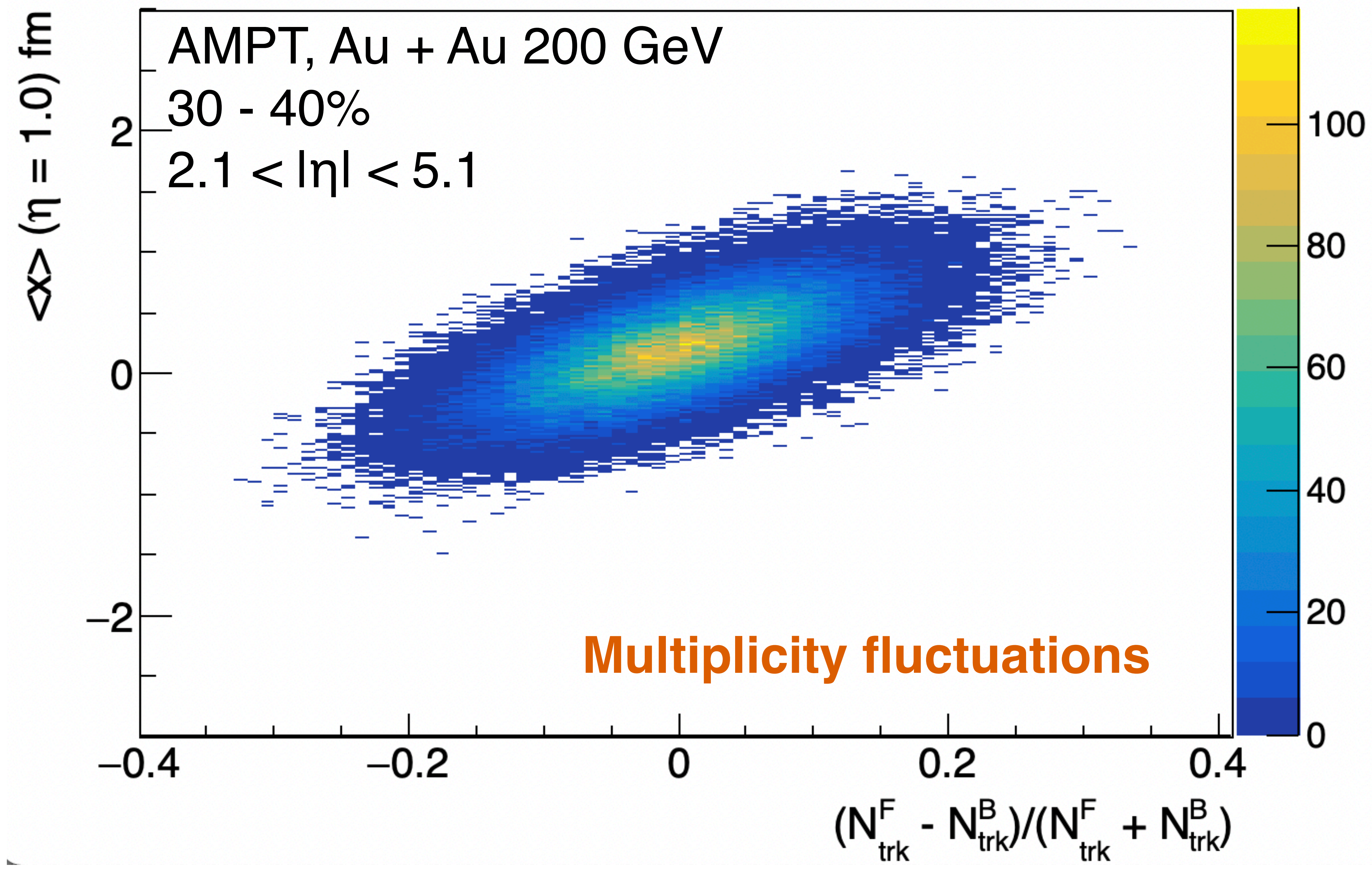




Outlook: Event shape engineering for v_1



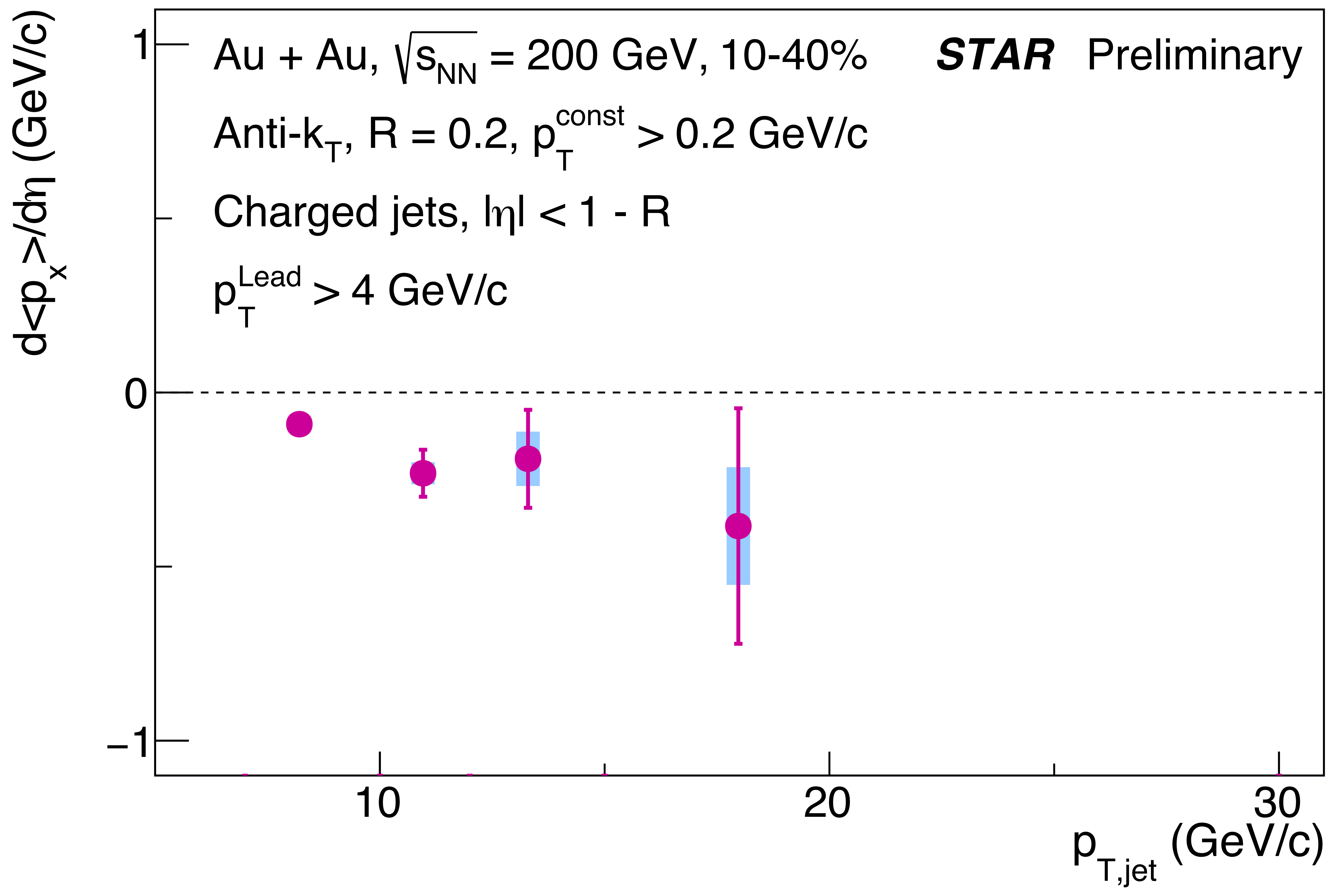


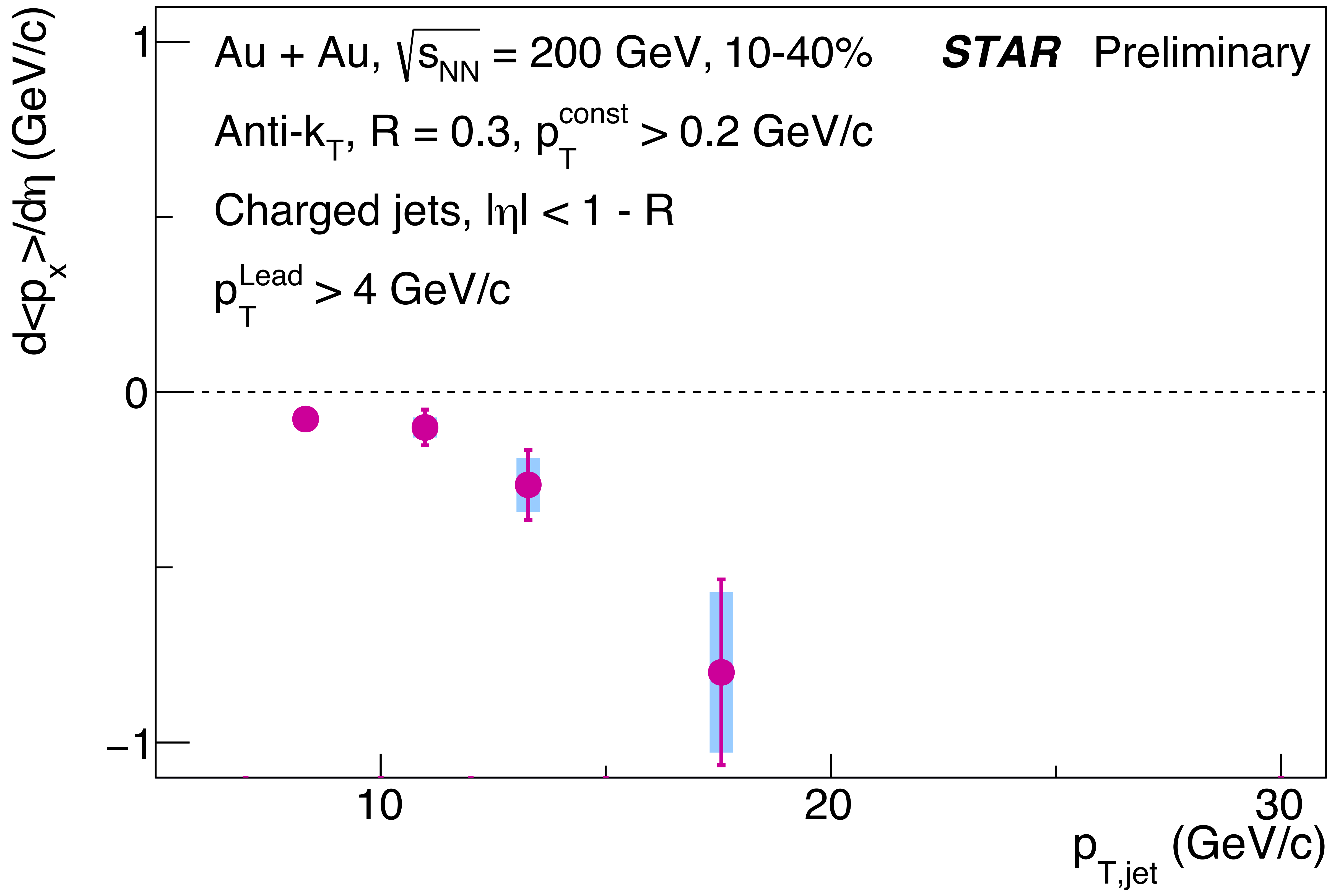


- Forward - backward participant fluctuations —> F - B multiplicity fluctuations —> correlated with asymmetry along impact parameter
- Can change the tilt of the bulk by selecting on forward - backward multiplicity fluctuations

Back Up

$\langle p_x \rangle$: p_T and R dependence





Model calculations

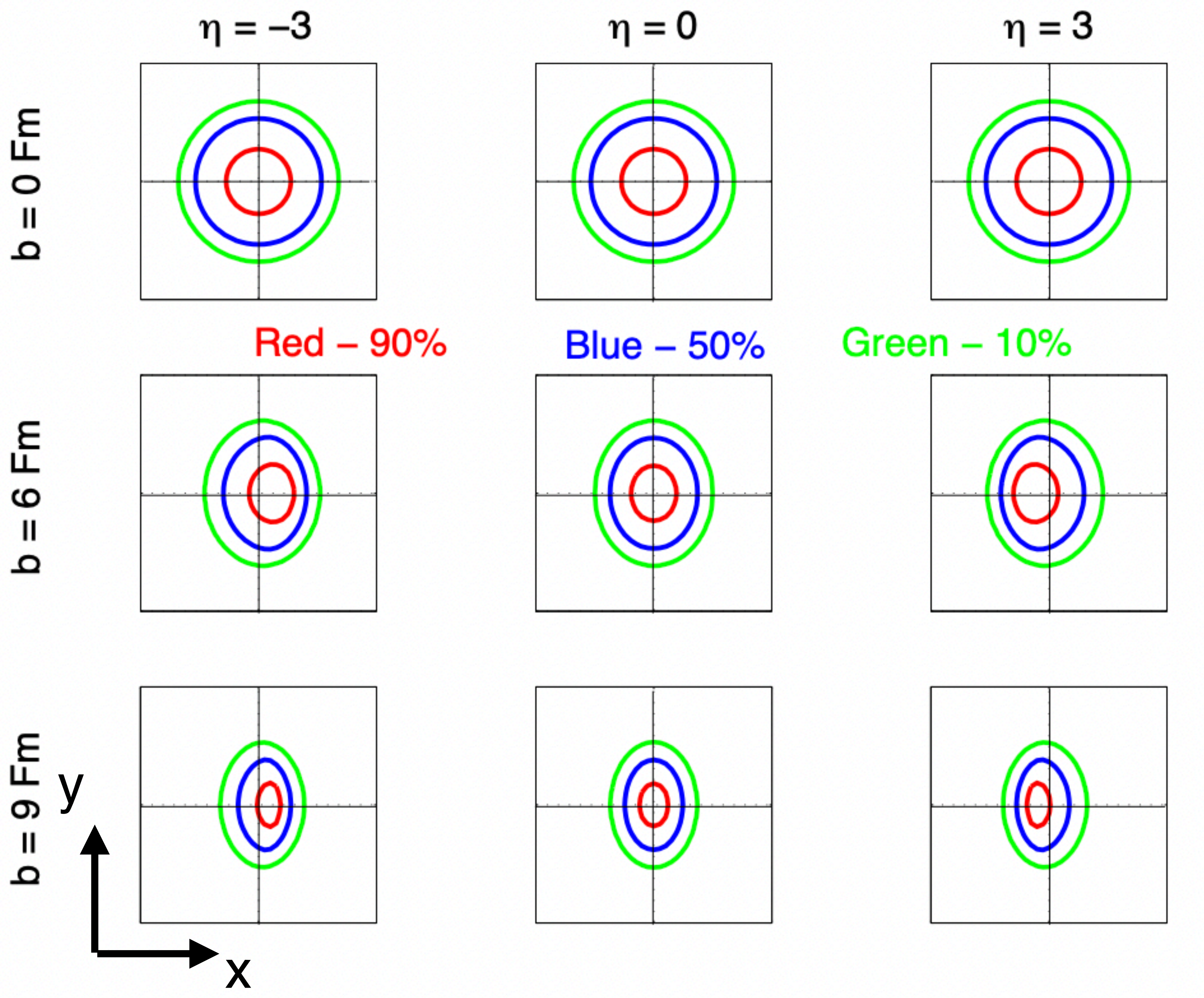
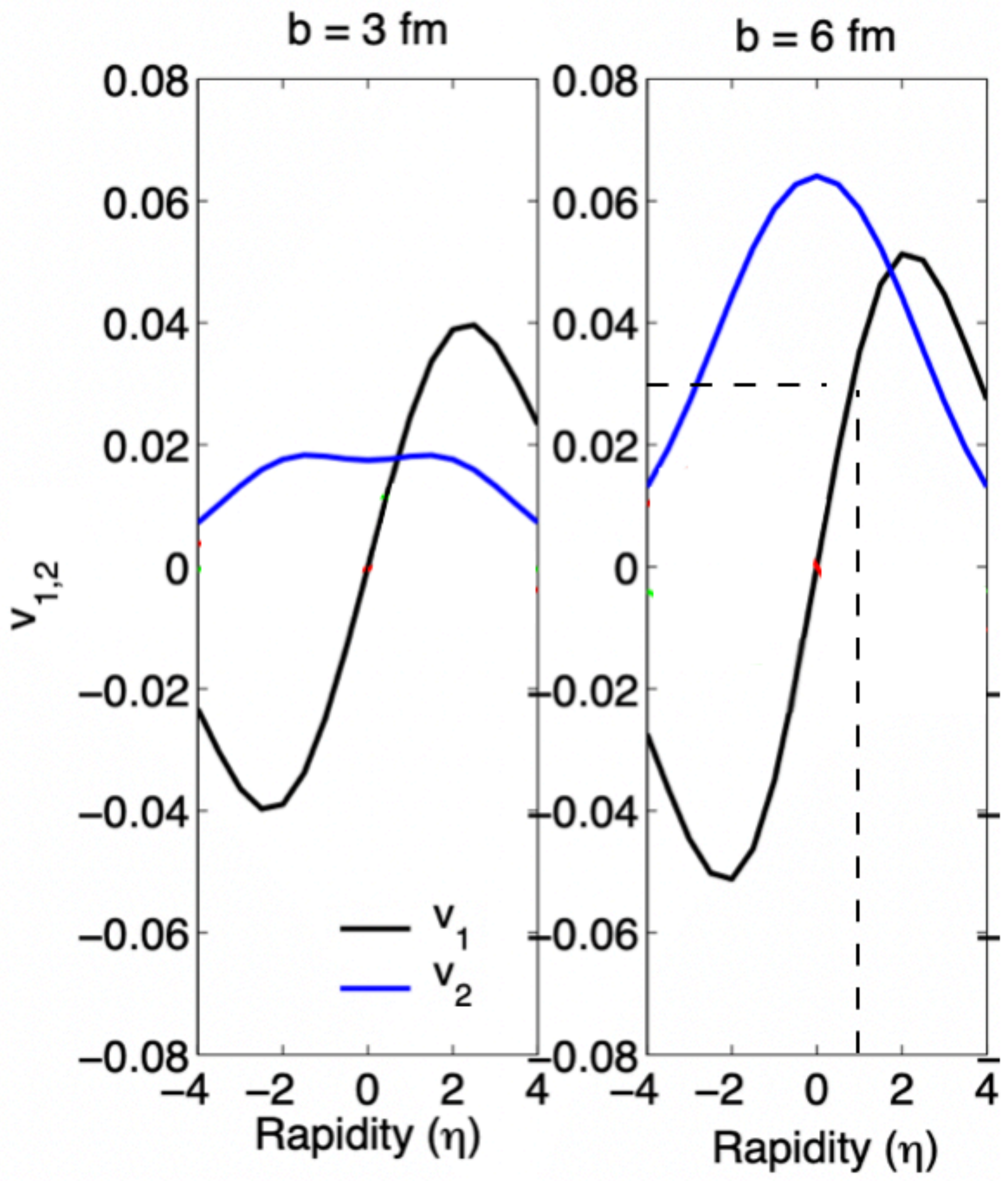
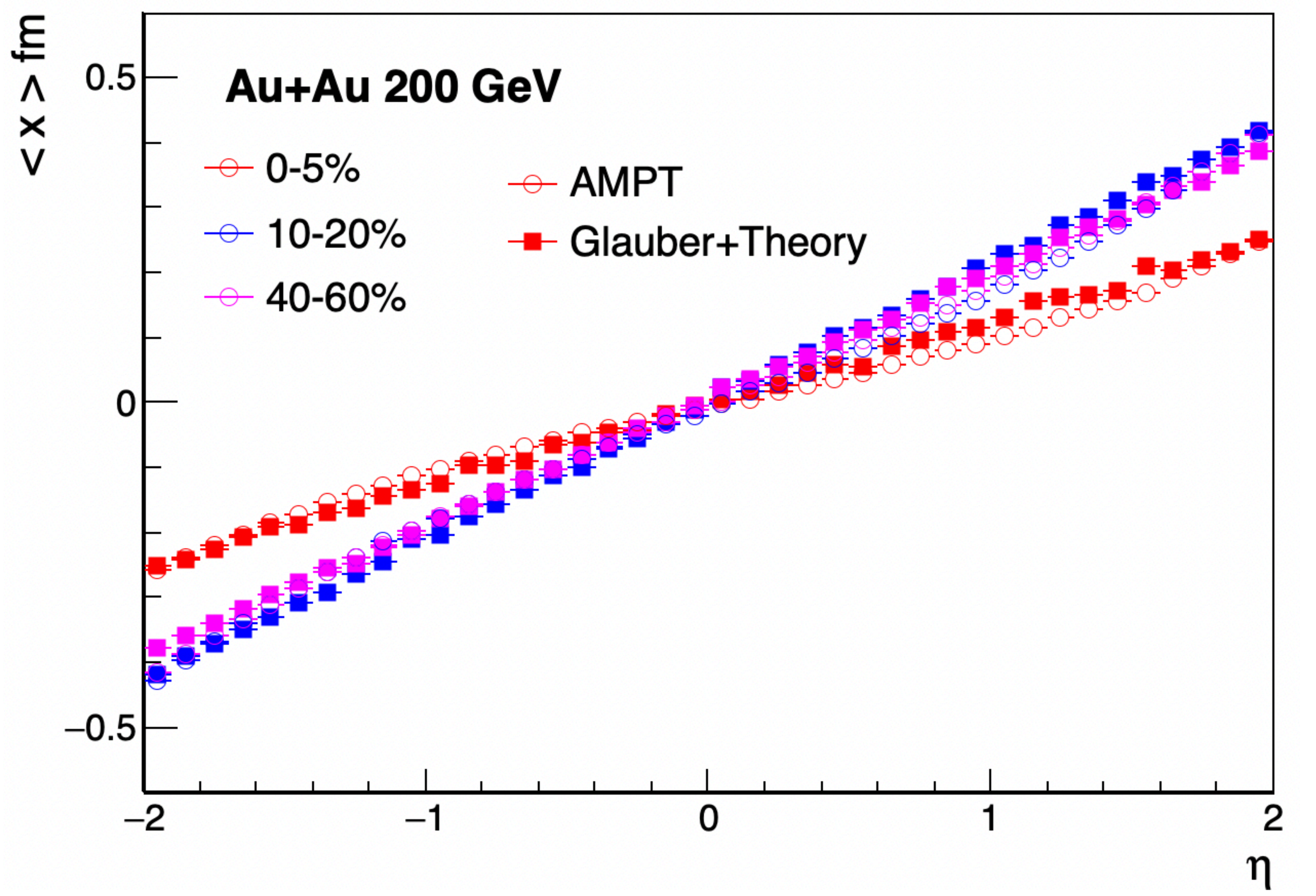
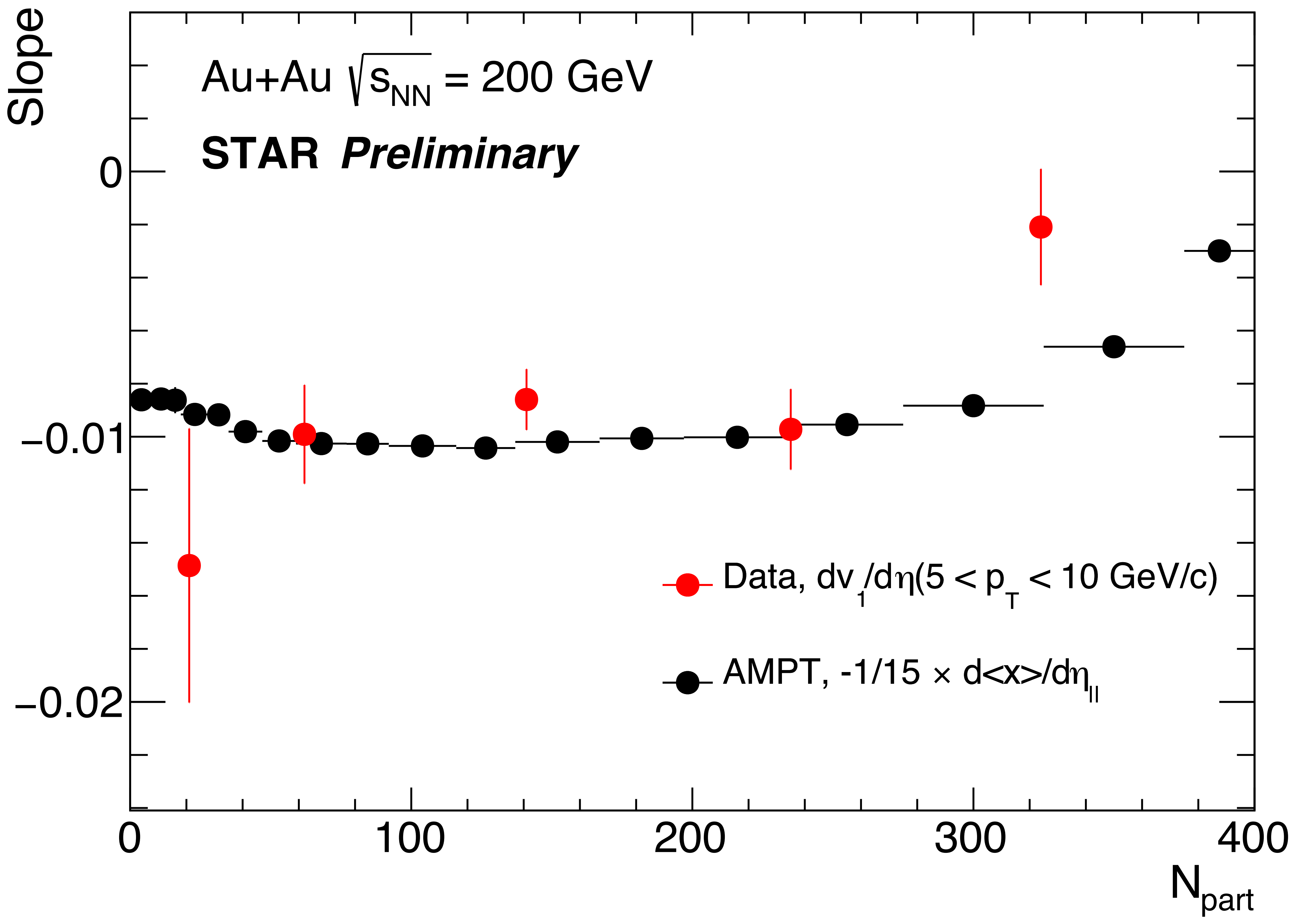


FIG. 6: Contours of the twisted sQGP initial density in the transverse plane (x, y) in different rapidity $\eta = -3, 0, 3$ and impact parameter $b = 0, 6, 9$ fm slices. Note the opposite transverse shifts at η and $-\eta$. (In color online)





Centrality dependence, charged hadron v_1



- Centrality dependence of high p_T v_1 follows the centrality dependence of bulk asymmetry

Initial hard - soft asymmetry

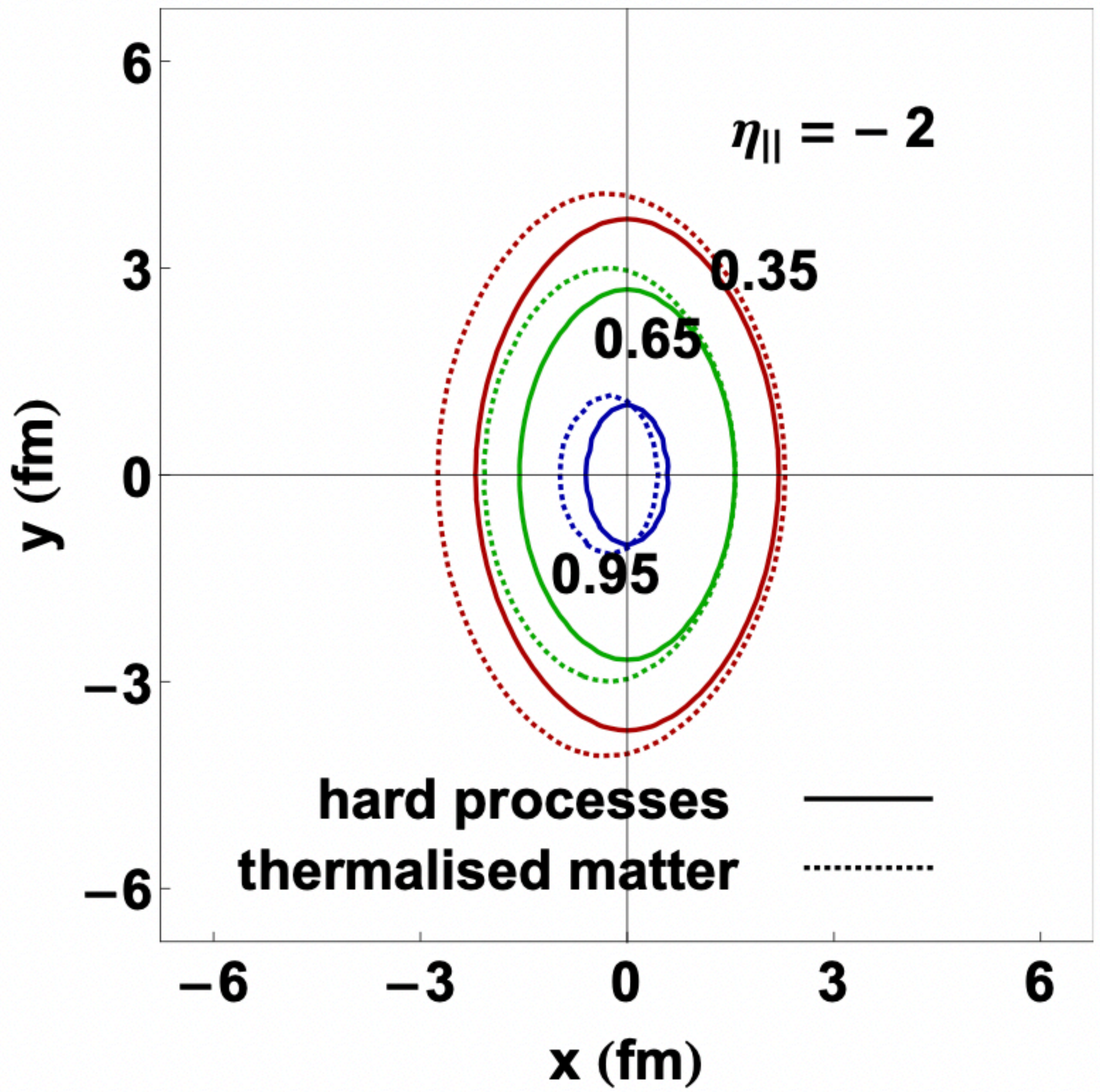
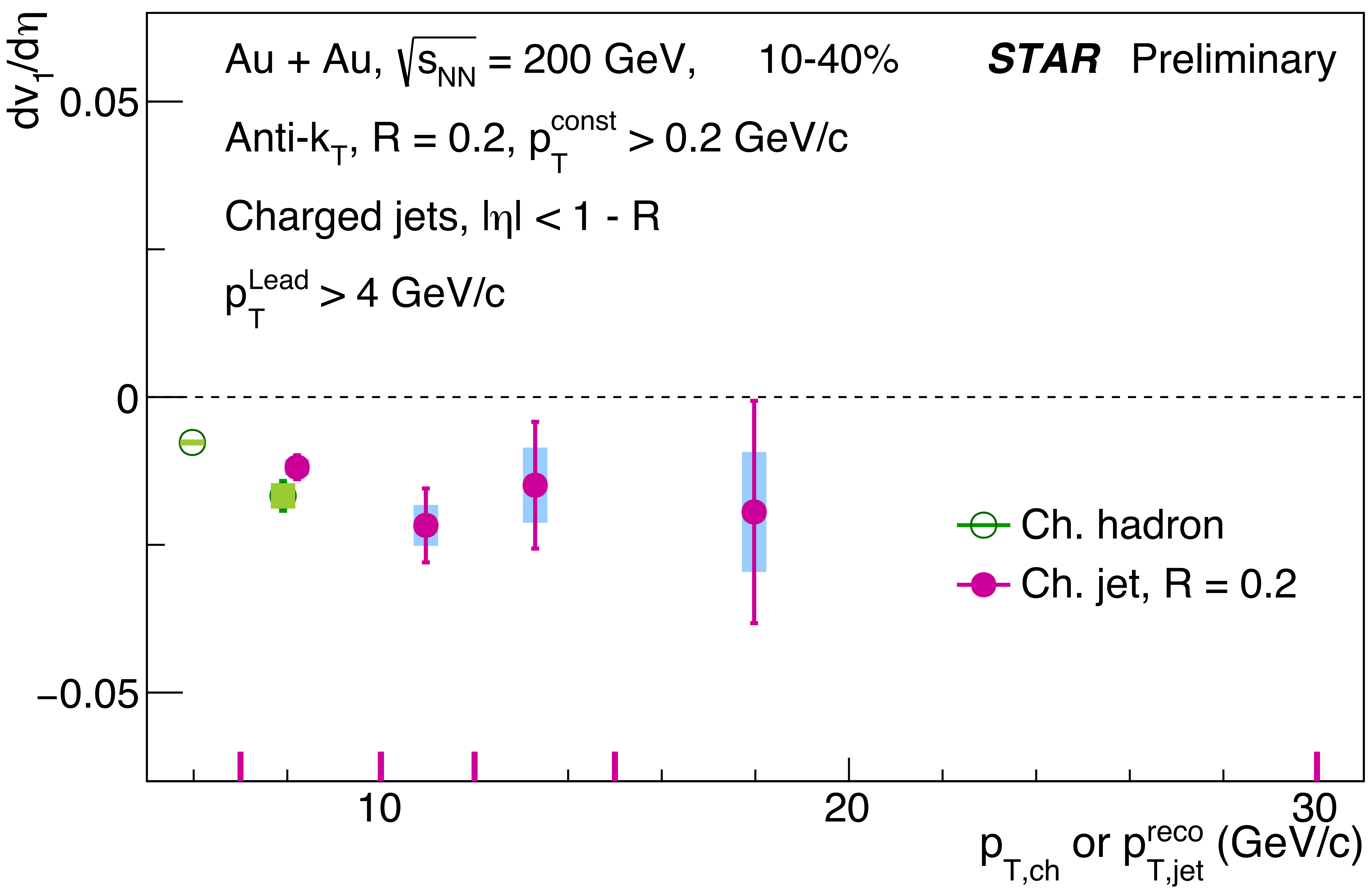


FIG. 1. The transverse density profile of the fireball tilted relative to the beam axis and the binary collision profile at $\eta_{||} = -2$.

- Bulk is offset along x at finite rapidity, hard scattering profile is not

S. Chatterjee et al. Phys. Rev. Lett. 120, 192301 (2017)

Systematic Uncertainties

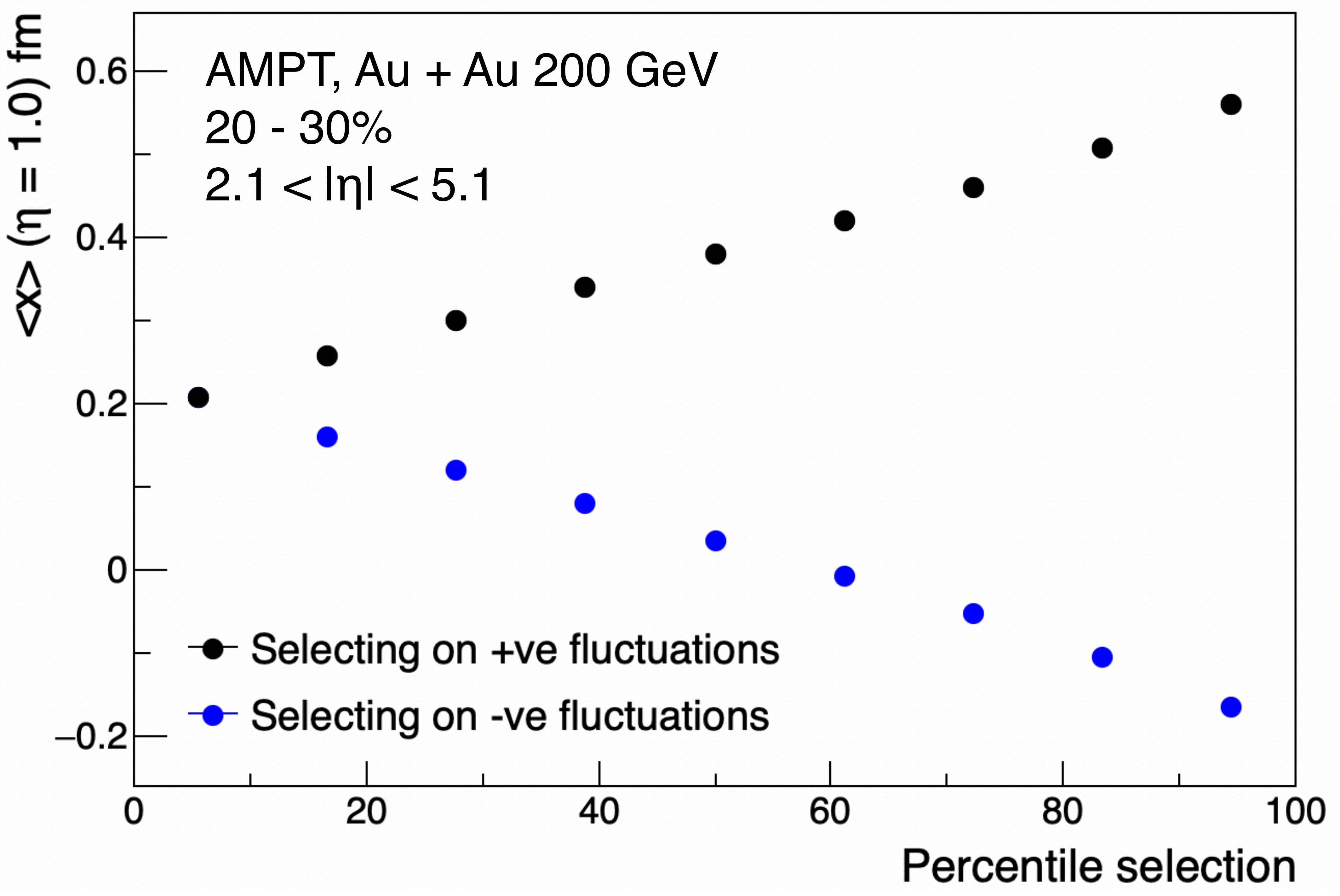


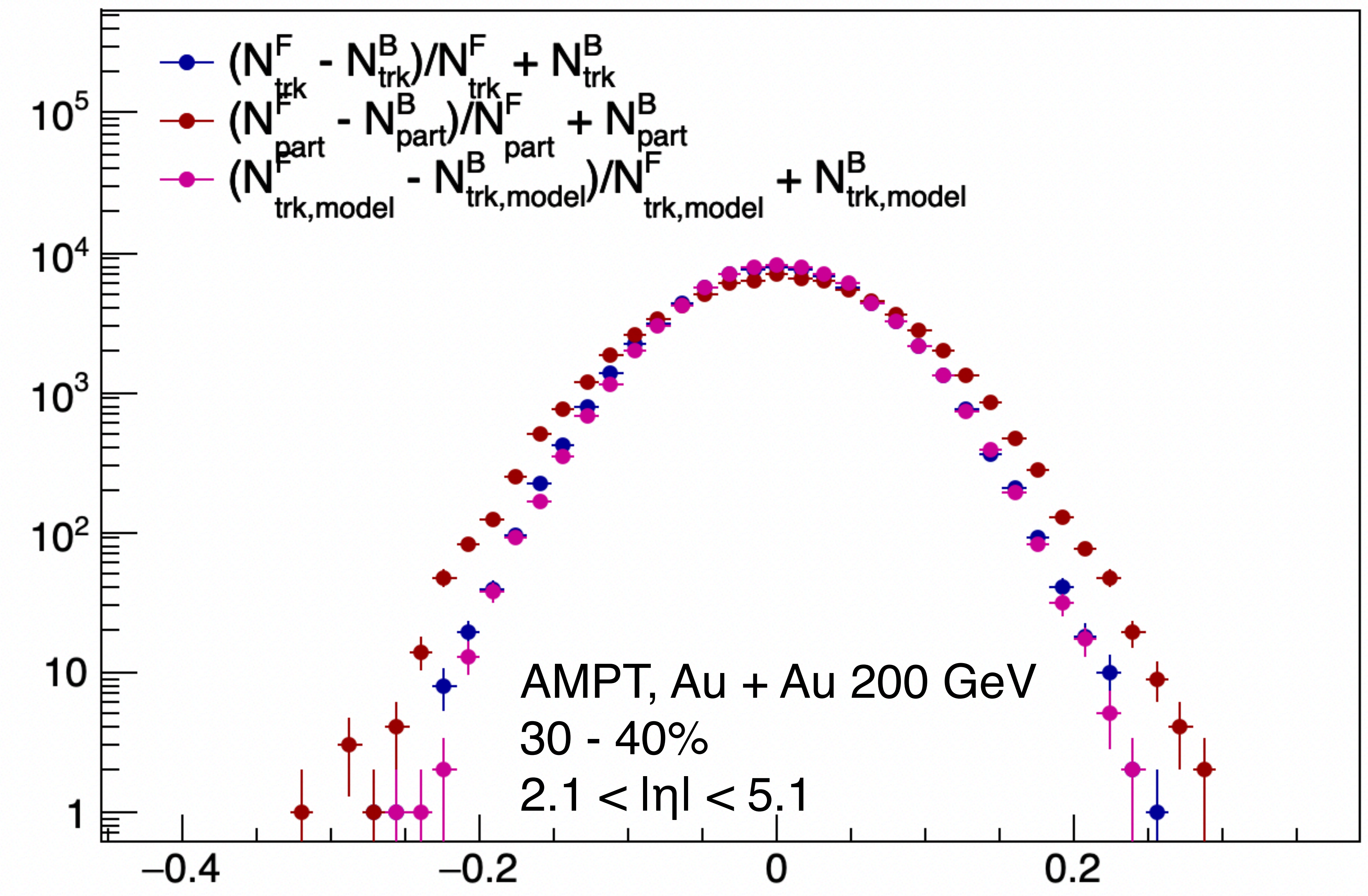
Systematic uncertainty sources:

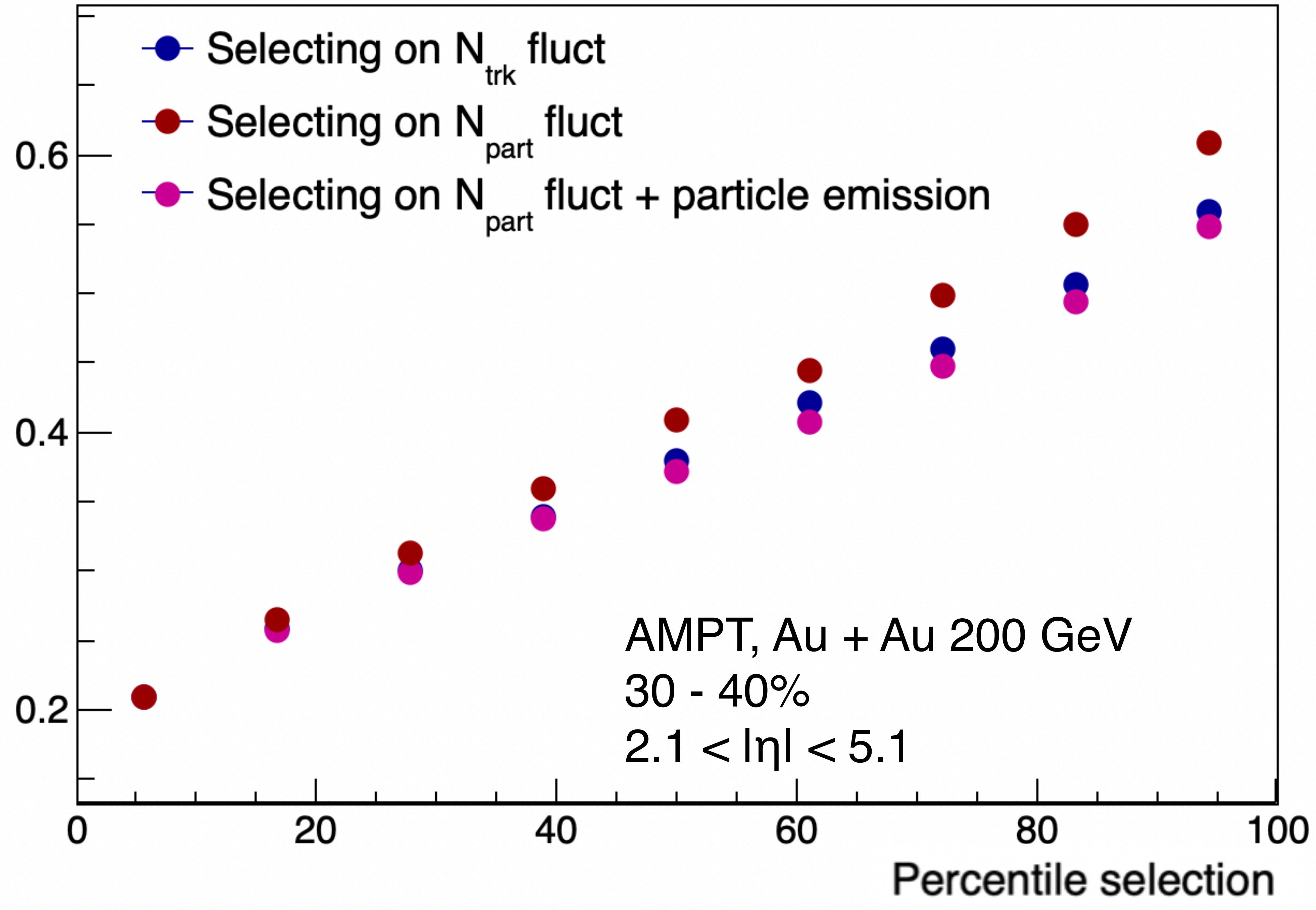
- Jet area selection
- Jet p_T resolution
- Contribution from bulk v_1

Results are also checked with changing leading hadron p_T cut to > 5 GeV/c. Results are consistent within systematic uncertainties

Event shape engineering for v_1







- Can vary Initial path length asymmetry selecting on forward - backward multiplicity fluctuations
- Selection on multiplicity fluctuation closely matches selection on N_{part} fluctuations