Heavy flavor and high-p_T results from STAR

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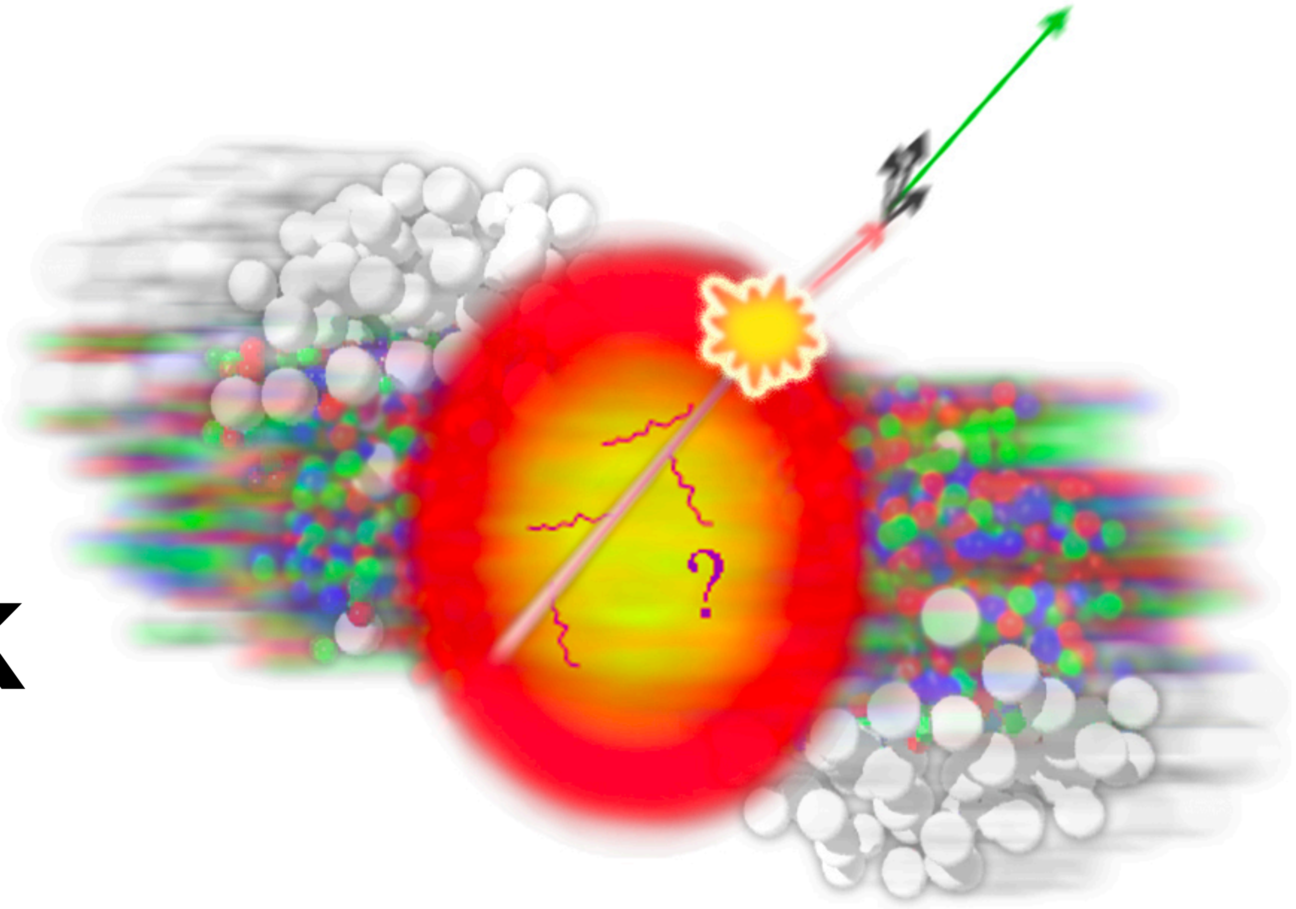
The STAR Collaboration
https://drupal.star.bnl.gov/STAR/presentations

WAYNE STATE UNIVERSITY

Probing the Quark-Gluon Plasma

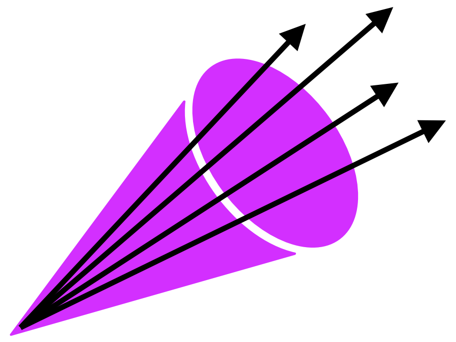
Lifetime ~10^{-23} s

Temperature ~$2 \cdot 10^{12}$ K

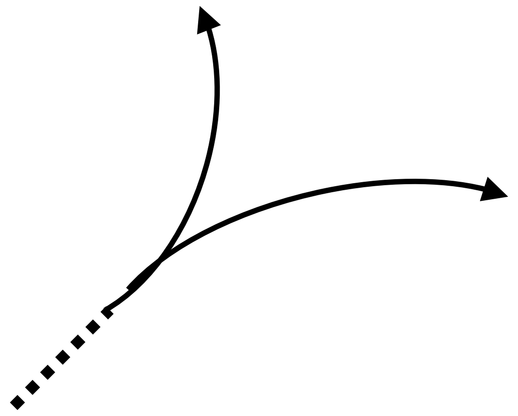


Colored objects experience energy loss in a colored medium

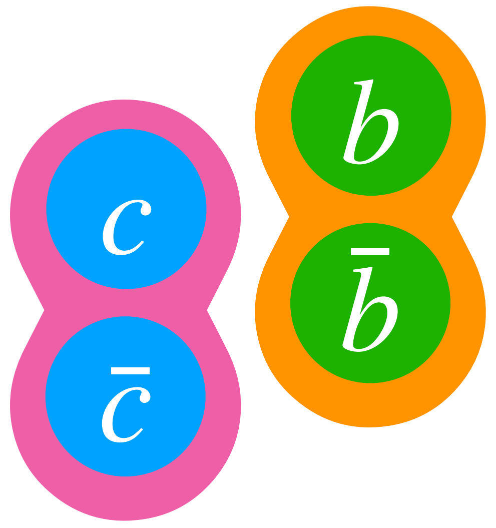
→ measure QGP properties and evolution using high-Q^2/large mass hard probes



- **Jets**: energy loss and broadening from interactions with the QGP (jet quenching)



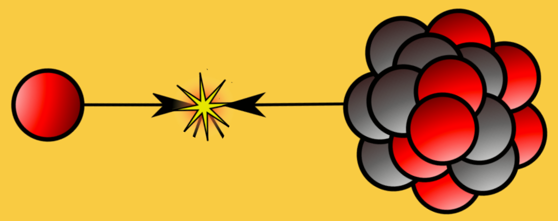
- **Open heavy flavor**: larger mass → less energy loss (dead cone effect)
- **Quarkonia**: colored dipole → sensitive to the temperature of QGP
  - Higher excited quarkonium states → lower binding energy → “thermometer”



Collision systems

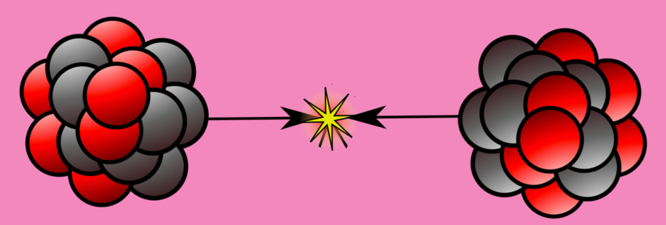
p+p

- Vacuum reference
- Jet and heavy flavor production in vacuum described by pQCD



***p*+A**

- *Null experiment*
    - Assume no hot nuclear mater
- CNM effects: all but hot nuclear effects



A+A

- Nuclear density large enough to create a hot, dense QGP
- Modification of hard probes as a tool to study microscopic structure

If we understand production in *p+p* and have assessed CNM effects, we can attribute modification of hard probes in heavy-ion collisions to hot nuclear effects

The STAR detector

Beam-beam counter (BBC)
- Triggering detector
- East inner BBC: $-5.2 < \eta < -3.3$

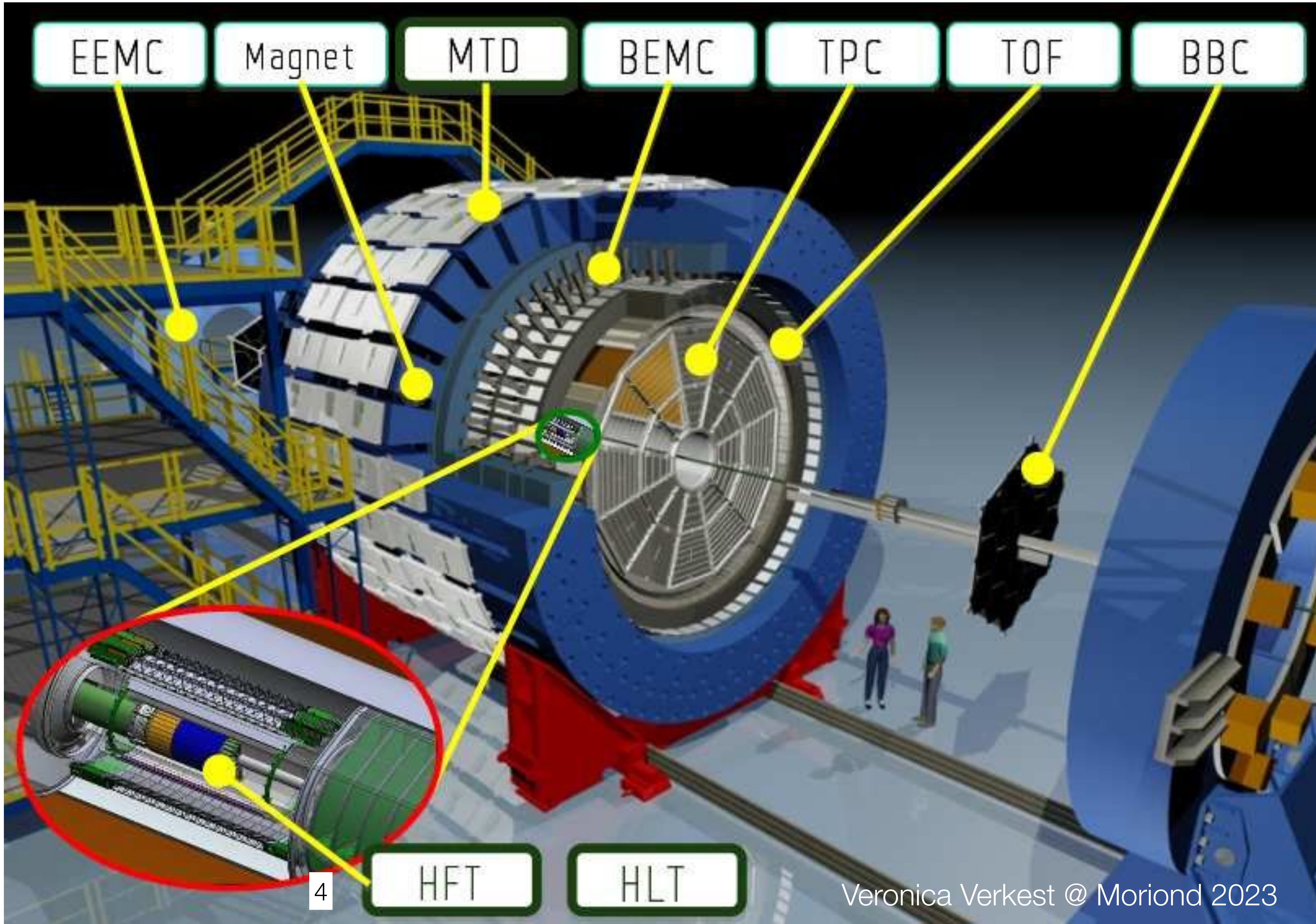
Barrel electromagnetic calorimeter (BEMC)
- γ, π^0, $e^\pm$, …
- $|\eta| < 1; \quad 0 < \phi < 2\pi$

Time projection chamber (TPC)
- Charged tracks
- Measures momentum & PID (*dE/dx*)
- $|\eta| < 1; \quad 0 < \phi < 2\pi$

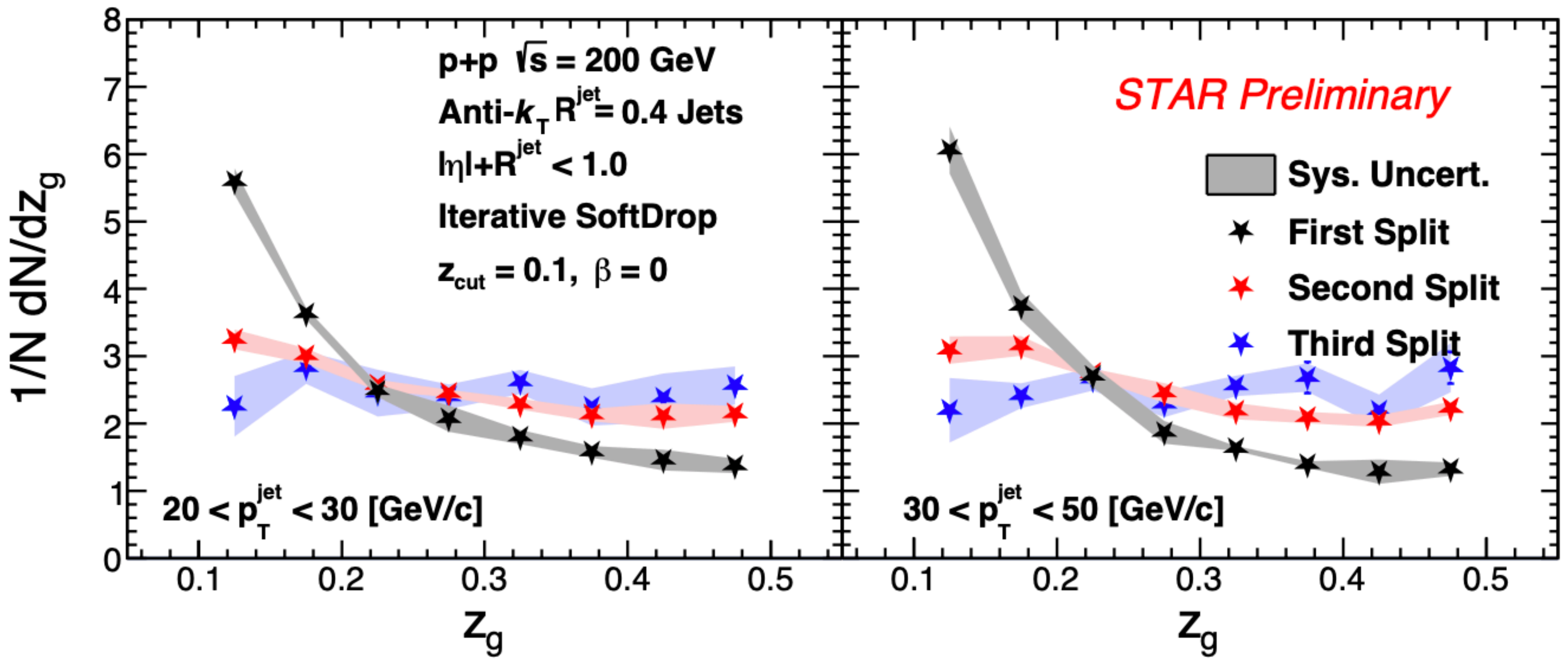
Time-of-flight (TOF)
- Time of flight measurement
- PID for π, K, p at intermediate p_{T}

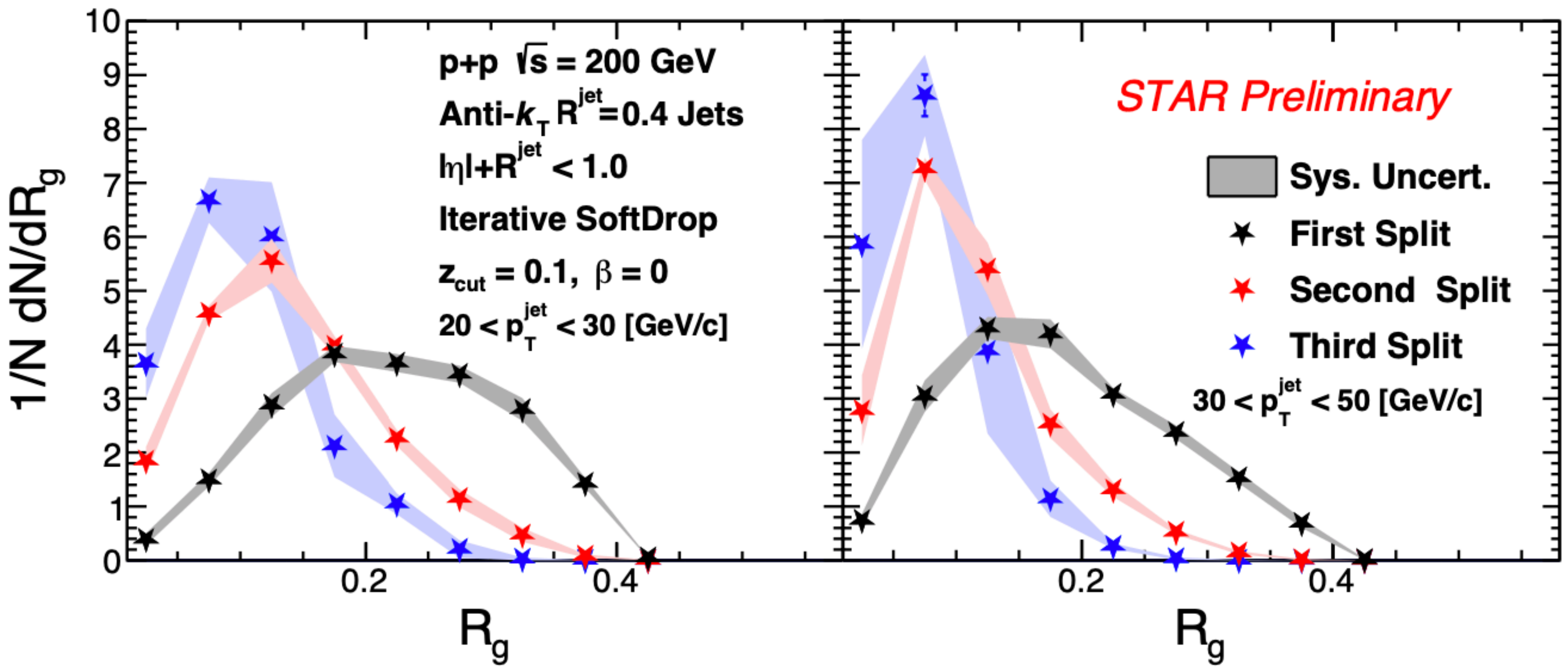
Heavy flavor tracker (HFT)
- Vertex reconstruction from HF decays

Muon telescope detector (MTD)
- Identifies muons; triggers on quarkonia



Jet sub-structure in vacuum

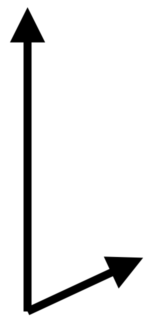
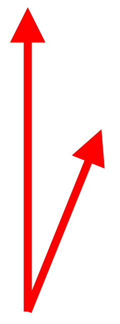
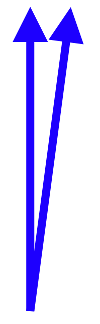




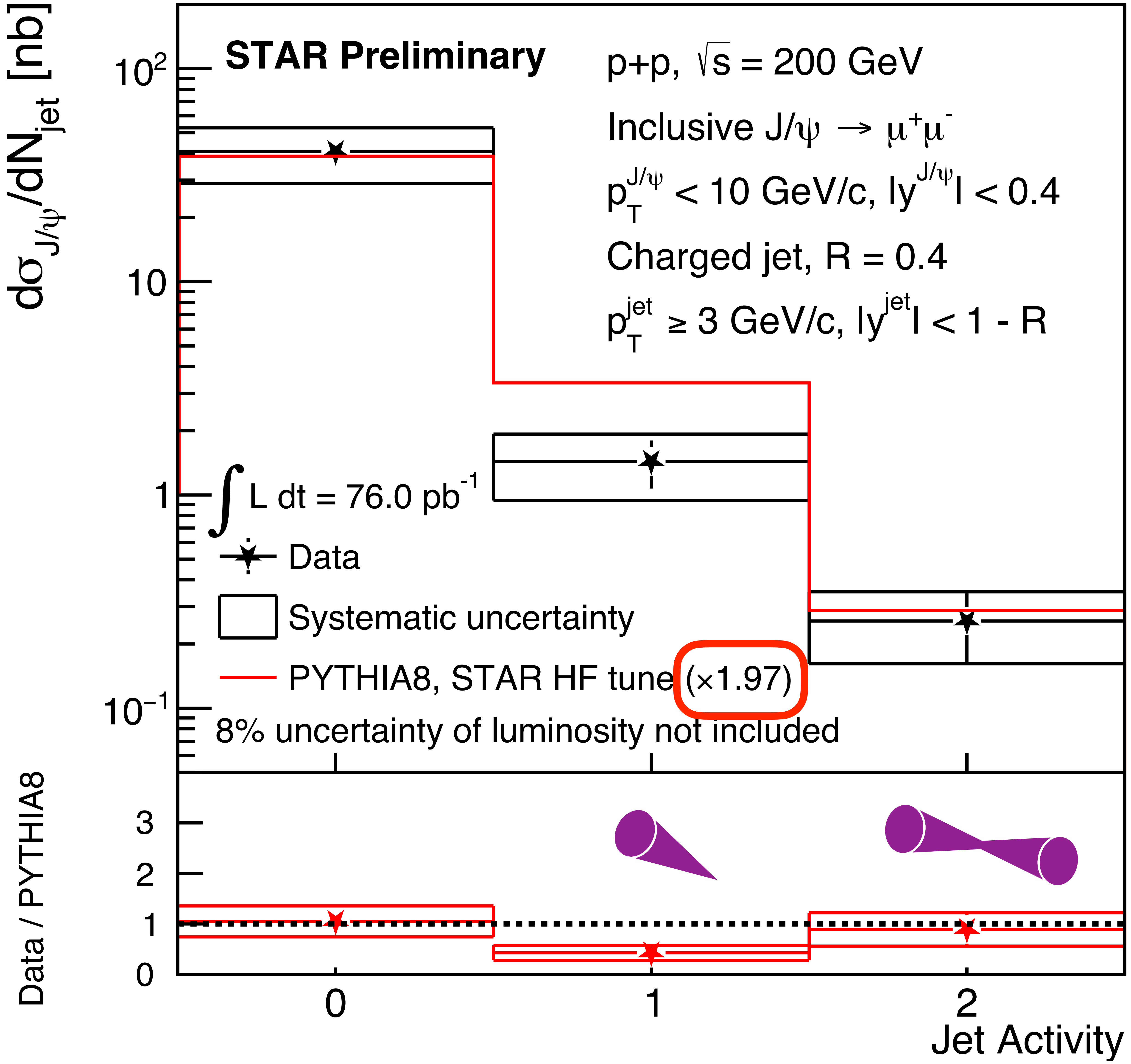
- Strong dependence of groomed jet momentum fraction (z_g) and radius (R_g) on split number
- z_g becomes flat at the third split
- R_g becomes narrower with successive splits

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \qquad R_g = \Delta R(1,2)$$

➡ **Change from soft, wide-angle to hard, collinear splitting over time**

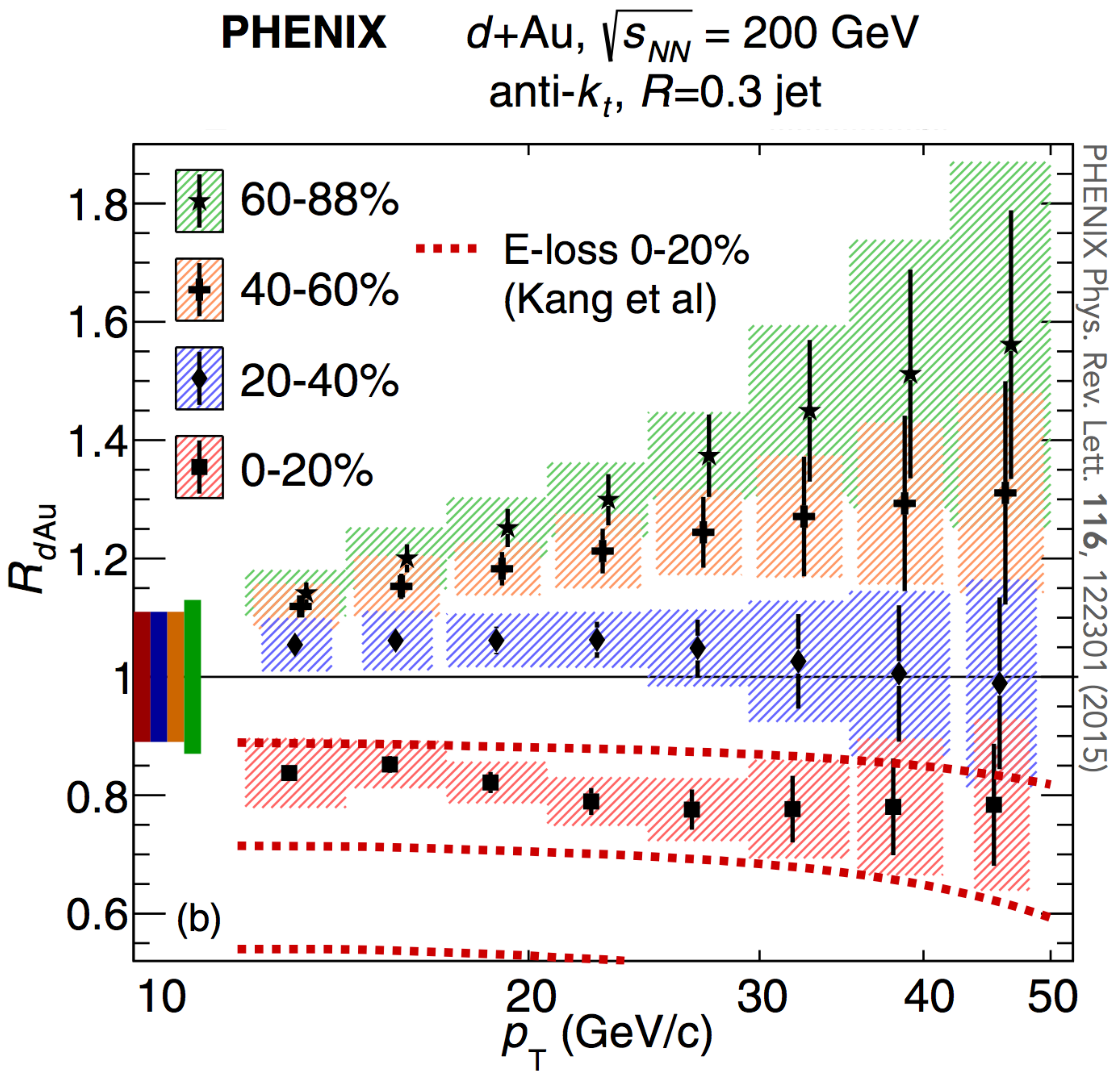
J/ψ production with jet activity



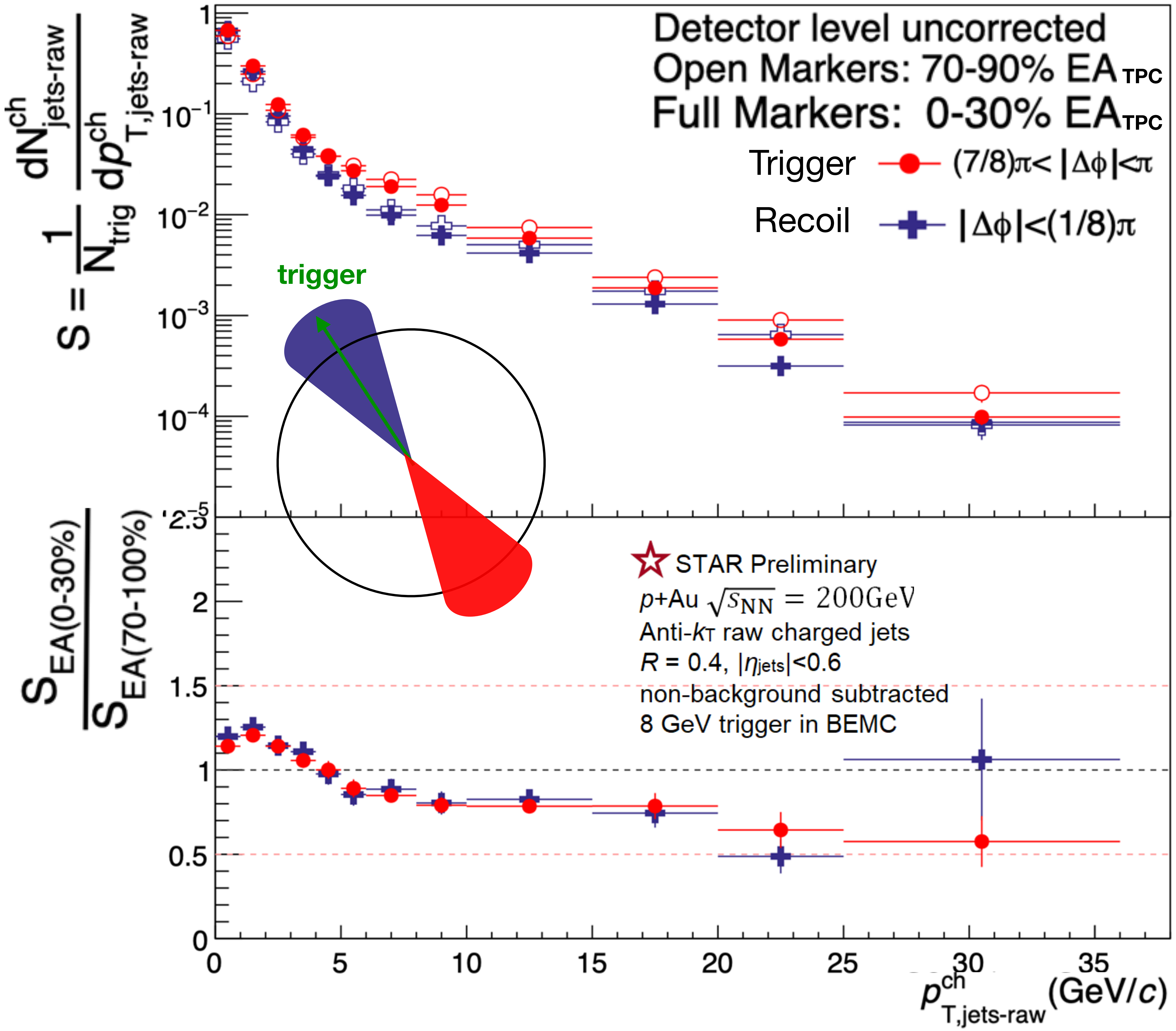
- Dependence of the J/ψ production cross section on the jet activity (jet multiplicity per event)
- Corrected for overall scale, PYTHIA8 over-predicts J/ψ production in events with jets
- Ongoing: can be used to discriminate between different production mechanisms (color-singlet vs. color-octet)

p+A: cold nuclear matter

- **Null experiment** to study cold nuclear matter effects
    - CNM effects: all effects of a larger collision system NOT due to hot nuclear matter effects
- *Is a p+A collision simply a superposition of p+p collisions?*
- Recent studies show unexpected modification of cross-sections as a function of centrality in *p*(*d*)+A collisions—typically characteristic of hot nuclear effects
    - are there hot or cold nuclear matter effects or something else?

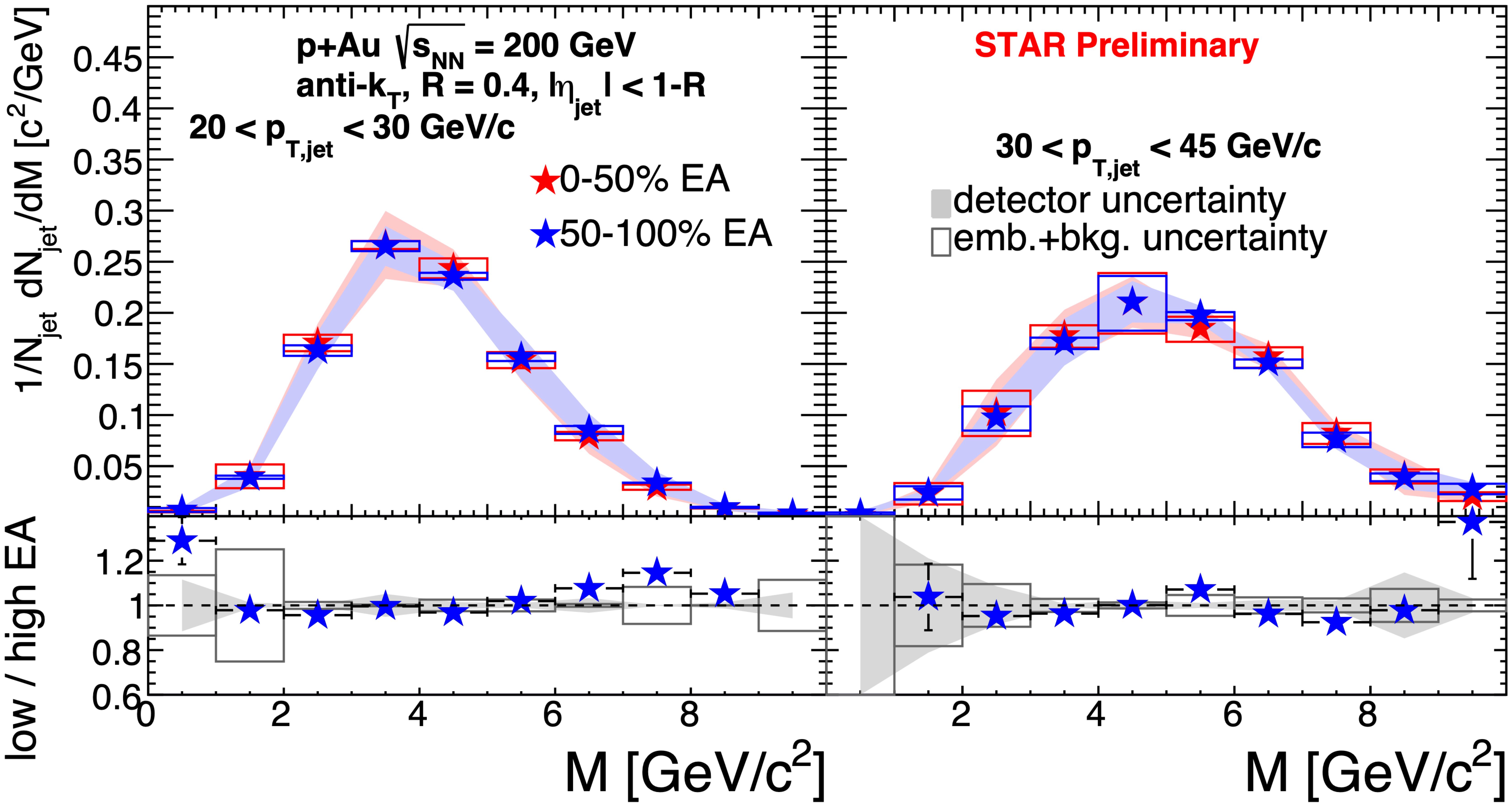


Are jets modified in *p*+Au?



- Yield of semi-inclusive jets per high-p_T charged hadron trigger is suppressed in high event activity (EA) events relative to low EA events, where **EA is the charged underlying event p_T density at mid-rapidity** ($|\eta| < 1$)
- The suppression is comparable for jets on the trigger and recoil side—inconsistent with energy loss in medium

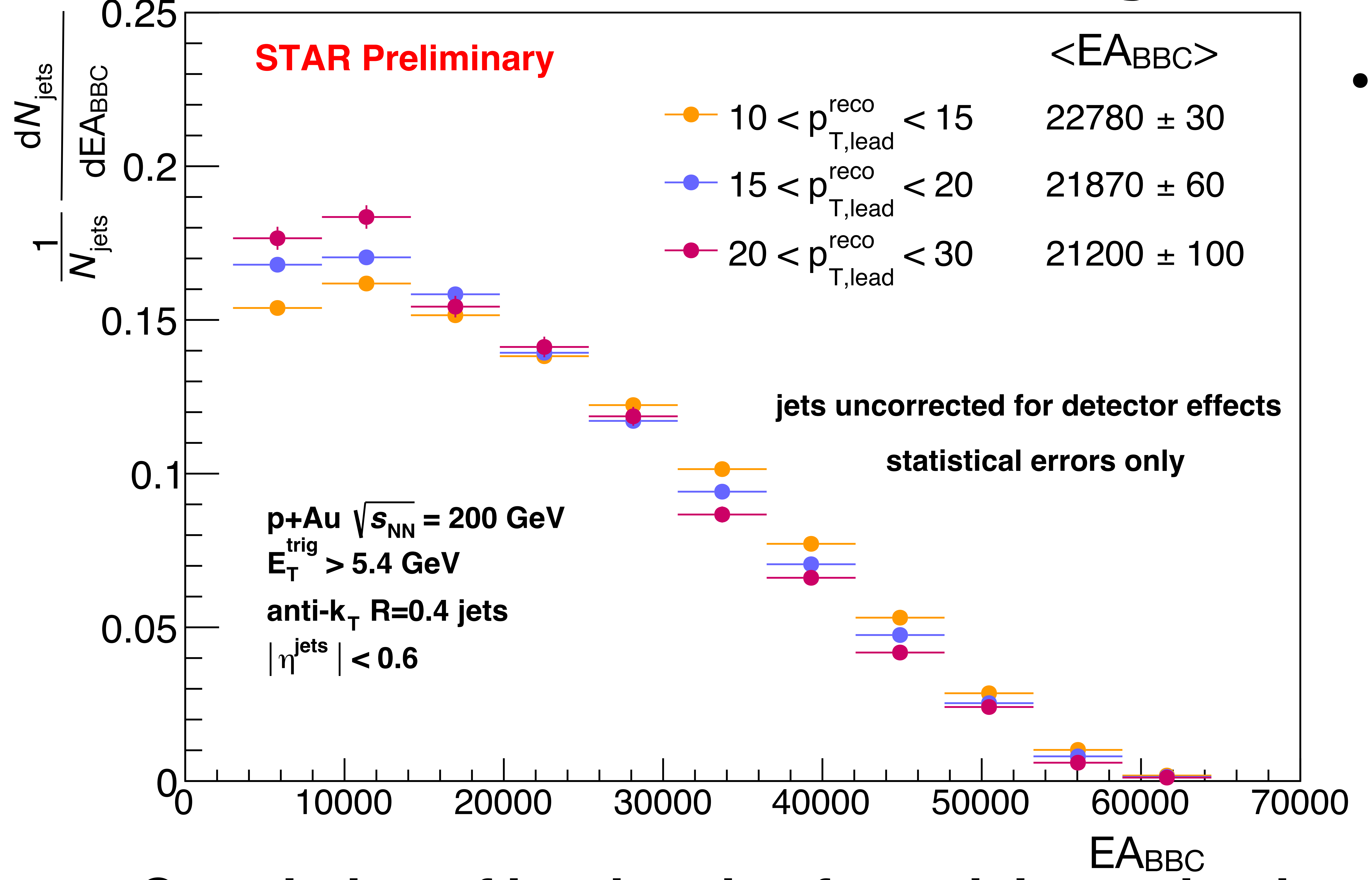
Are jets modified in p+Au?



$$M = \sqrt{E^2 - \mathbf{p}^2}$$

Jet mass is consistent between events with high and low EA, therefore **the jet itself is not modified within uncertainty**

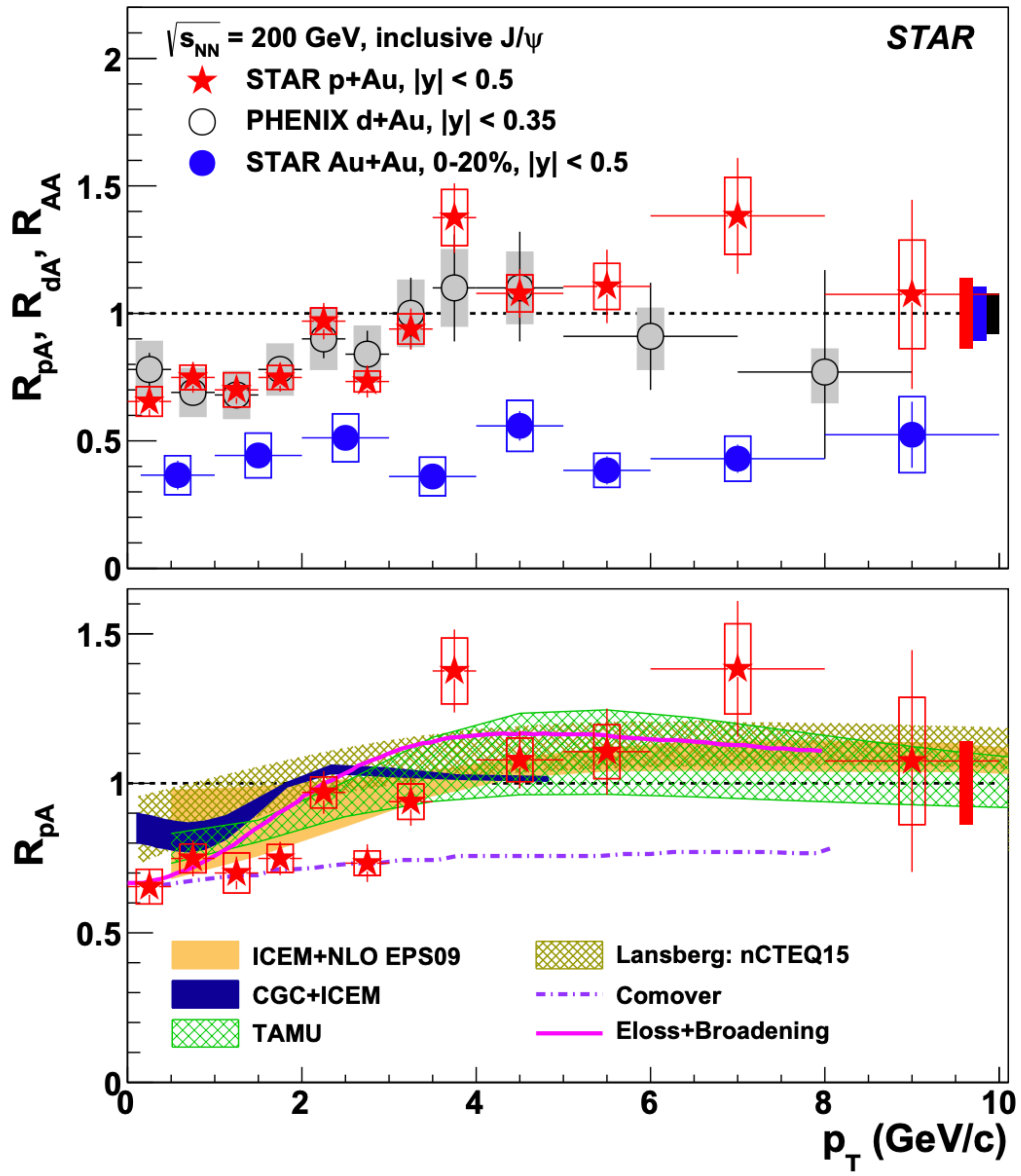
Event activity in p+Au



- Anti-correlation between EA_{BBC} at large backward rapidity and leading jet p_T at mid-rapidity
  - Events selected by higher (lower) jet p_T have a lower (higher) average EA_{BBC}, naively classified as more peripheral (central)

Correlation of hard and soft particle production due to early-time effects (over large rapidity)

J/ψ R_{pA} in p+Au via dimuon



$$R_{pA} = \frac{1}{N_{coll}} \frac{d^2N_{pA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

- J/ψ R_{p+Au} consistent with unity above 3 GeV/c; agreement with R_{d+Au} measured in PHENIX

  ➡**Therefore, little CNM observed for J/ψ above 3 GeV/*c* in small systems within uncertainty**

- Suppression in central Au+Au mostly due to hot medium effects

- R_{pA} described reasonably by models within uncertainty

STAR, Phys.Lett.B 825 (2022) 136865

Small systems summary

p+*p*

- Jet substructure measurements → study jets' evolution and resolving power
- Investigate J/ψ production mechanism

p+A

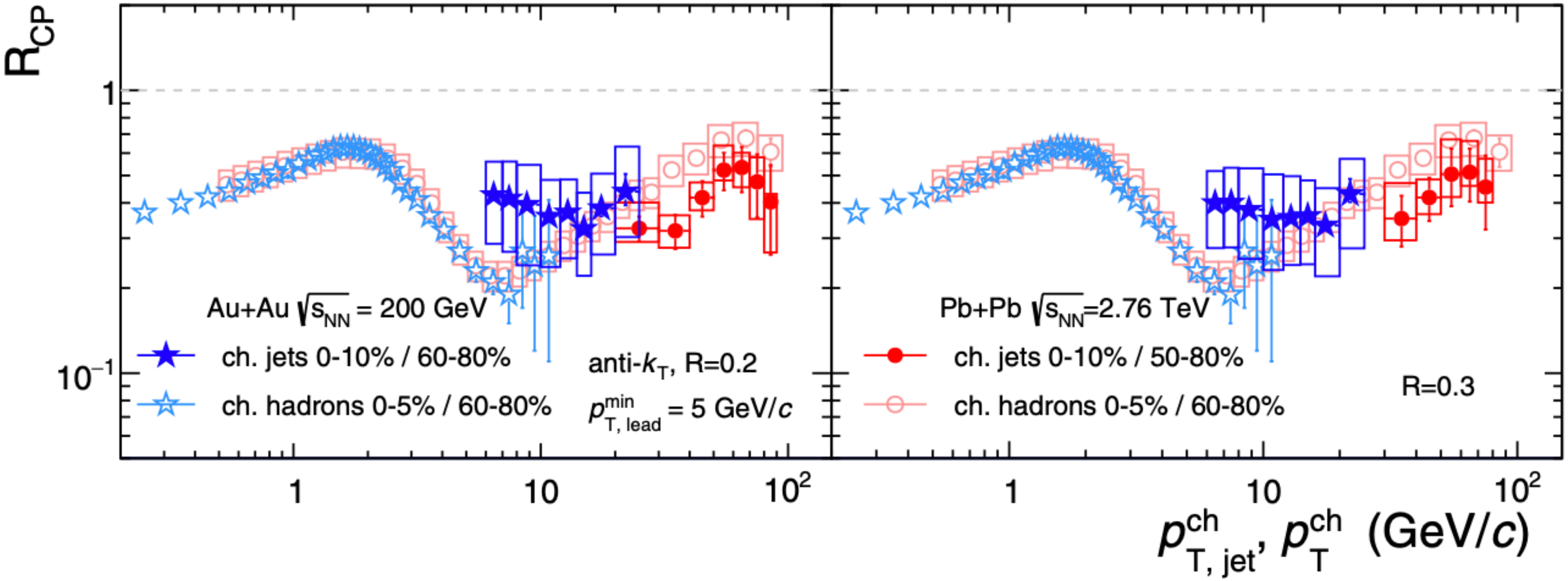
- Jet yield suppression suggests correlation between hard and soft production (no mass modification)
- No CNM effects observed for J/ψ at high-p_T within systematics

A+A

How are these hard probes modified by hot nuclear matter in heavy-ion collisions?

vacuum → **nuclear density**

R_{CP}: Au+Au and Pb+Pb



- Charged jets and hadrons strongly suppressed in central Au+Au collisions relative to peripheral
- R_{CP} in Au+Au at 200 GeV is similar to LHC measurements of Pb+Pb at 2.76 TeV within region of overlap
  - Energy loss at LHC is larger than at RHIC

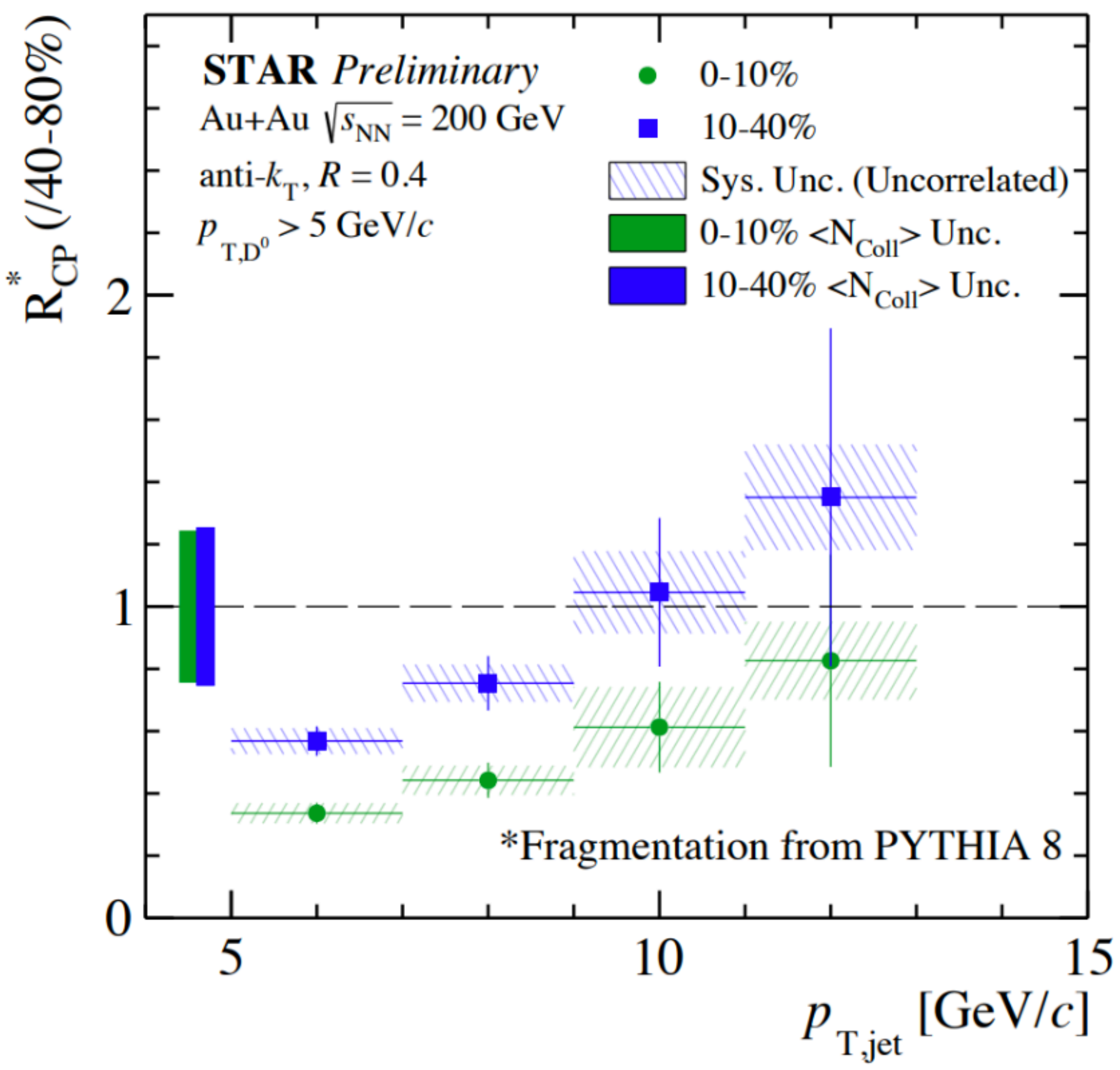
$$R_{CP} = \frac{\left(d^2N_{AA}/dp_T d\eta\right)^{cent.}/N_{coll}^{cent.}}{\left(d^2N_{AA}/dp_T d\eta\right)^{periph.}/N_{coll}^{periph.}}$$

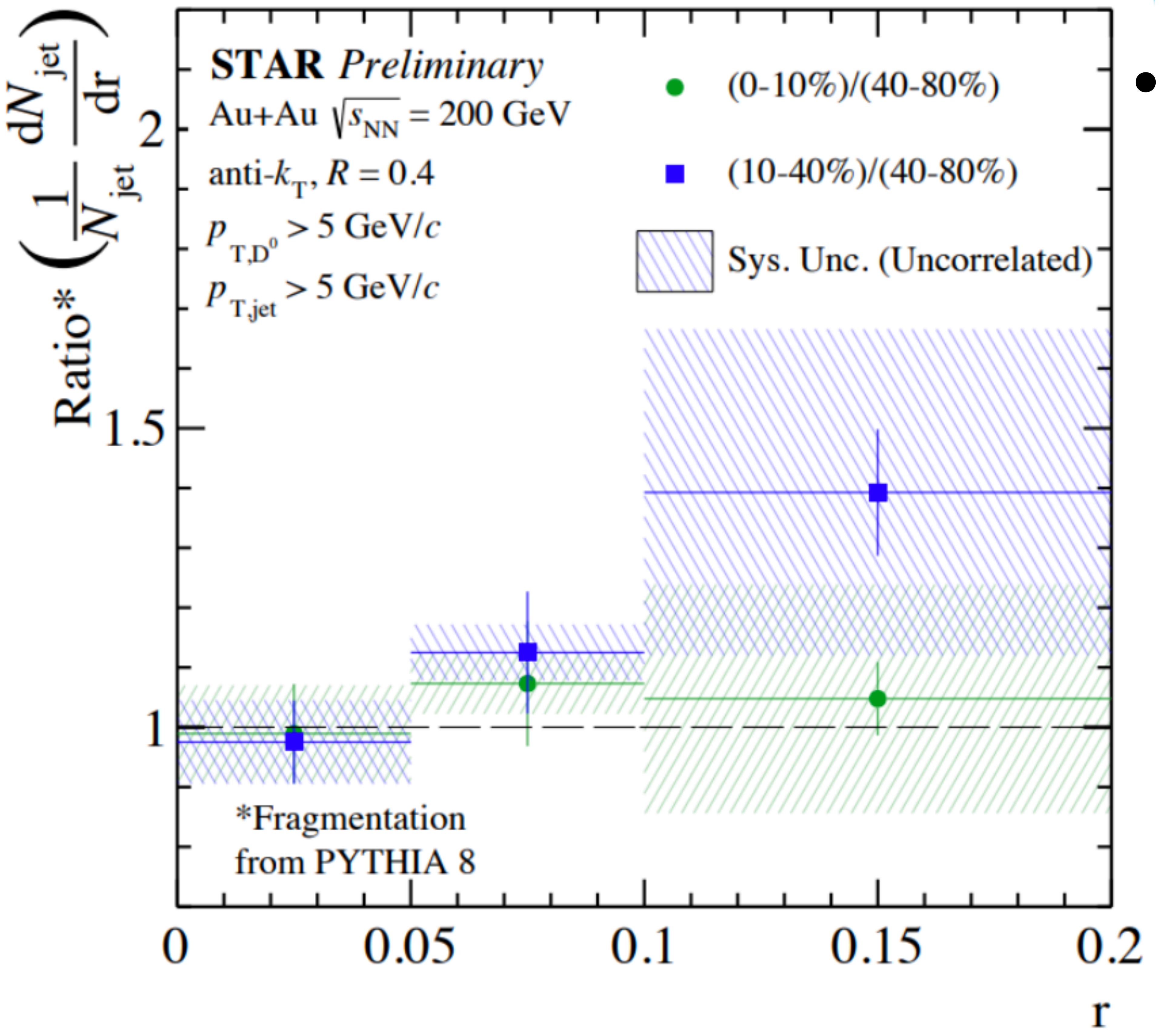
STAR, Phys.Rev.C 102 (2020) 054913

Suppression of D^0 jets

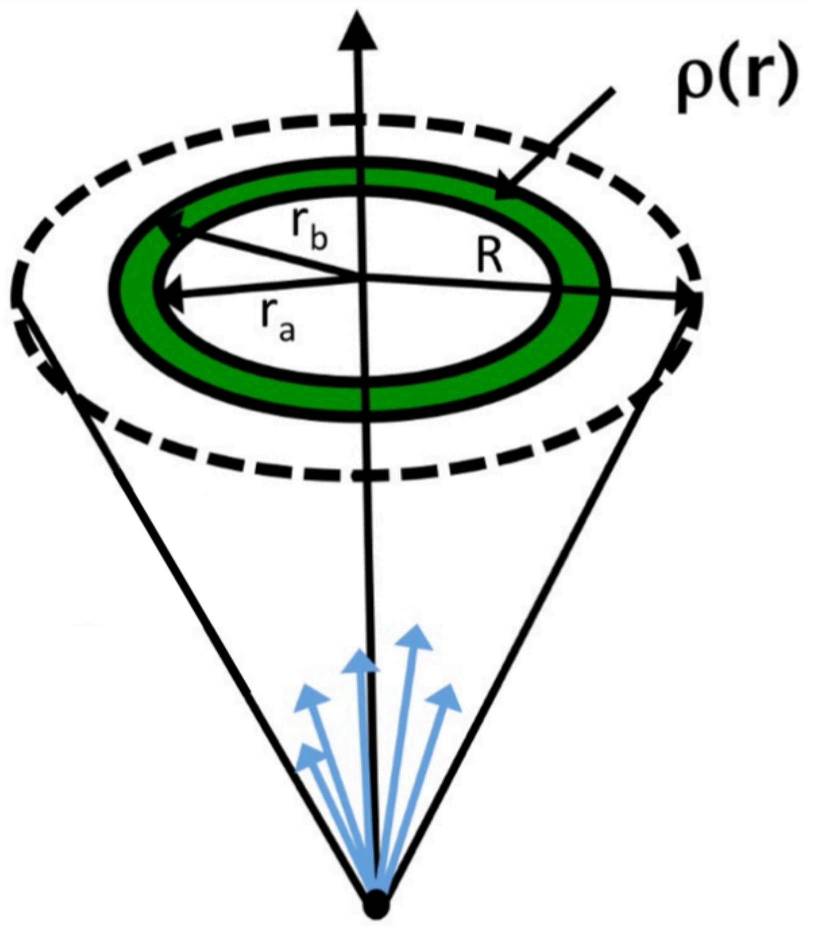
$$R_{CP} = \frac{\left(d^2N_{AA}/dp_T d\eta\right)^{cent.}/N_{coll}^{cent.}}{\left(d^2N_{AA}/dp_T d\eta\right)^{periph.}/N_{coll}^{periph.}}$$

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\sum_{jet}\frac{\sum_{jet\in(r_a,r_b)} p_{T,track}}{p_{T,jet}}$$



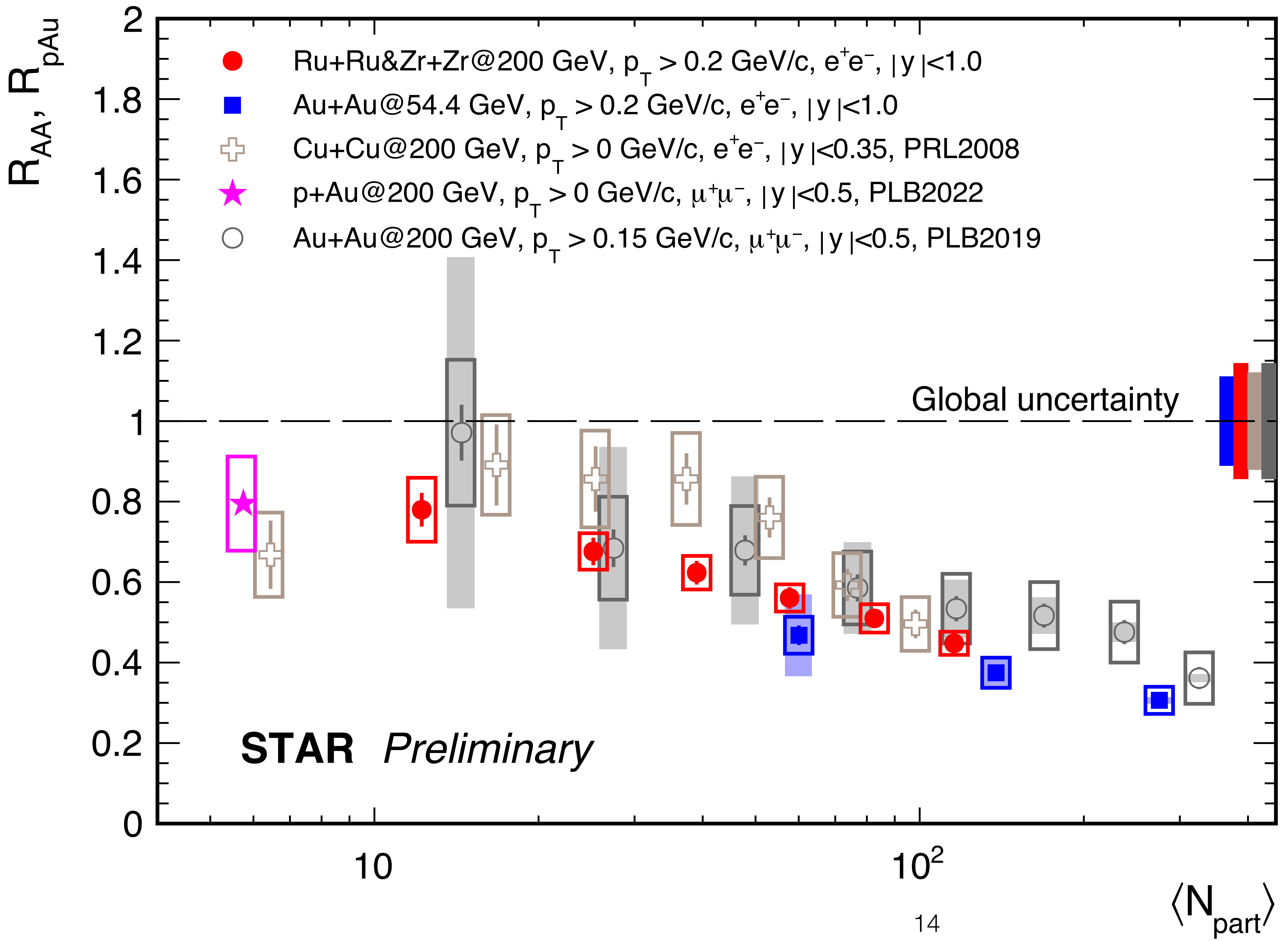


- Significant D^0 suppression at low jet p_T in central and mid-central events
- Jet radial profile ratios for D^0 p_T>5 GeV/*c* consistent with unity within uncertainties



Veronica Verkest @ Moriond 2023

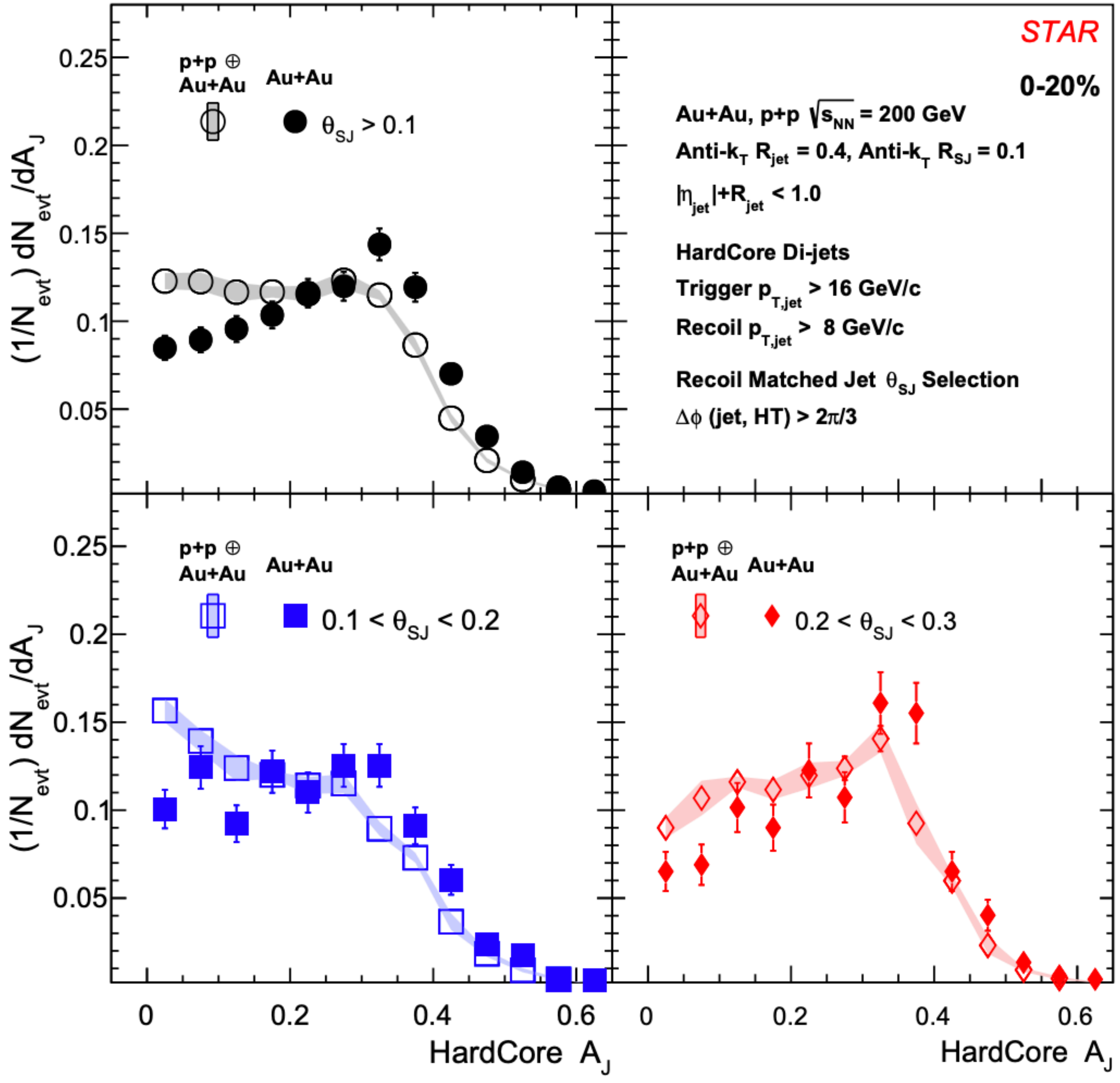
J/ψ R_{AA} in isobar

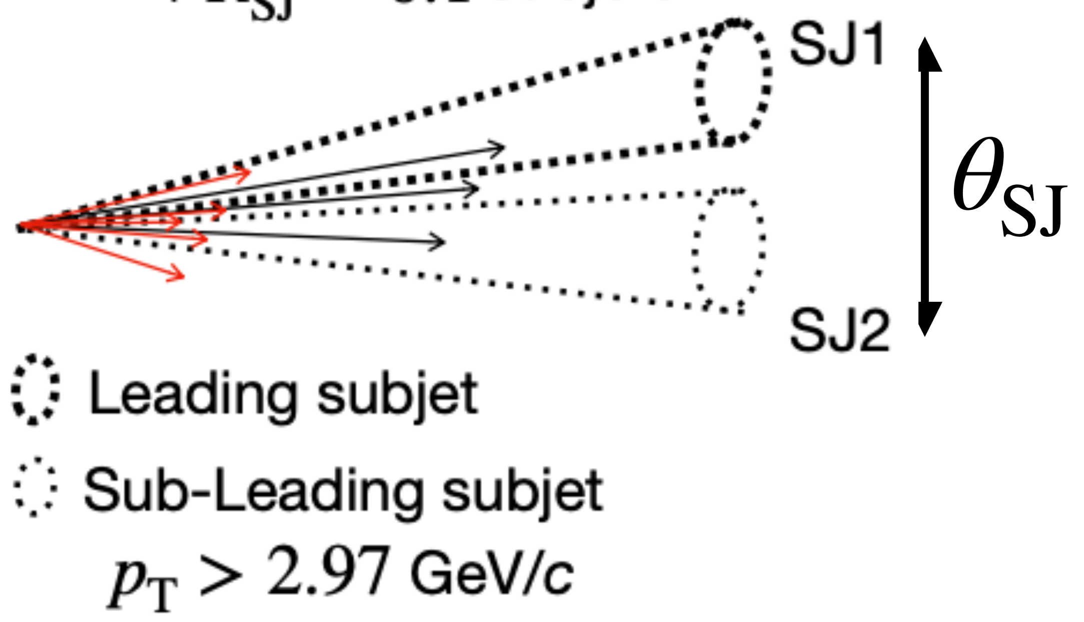


- Isobar collisions: medium-sized system
- J/ψ R_{AA} suppression in isobar is consistent with Au+Au collisions at comparable <N_{part}>
- **Suppression driven by system size <N_{part}>, not collision geometry**

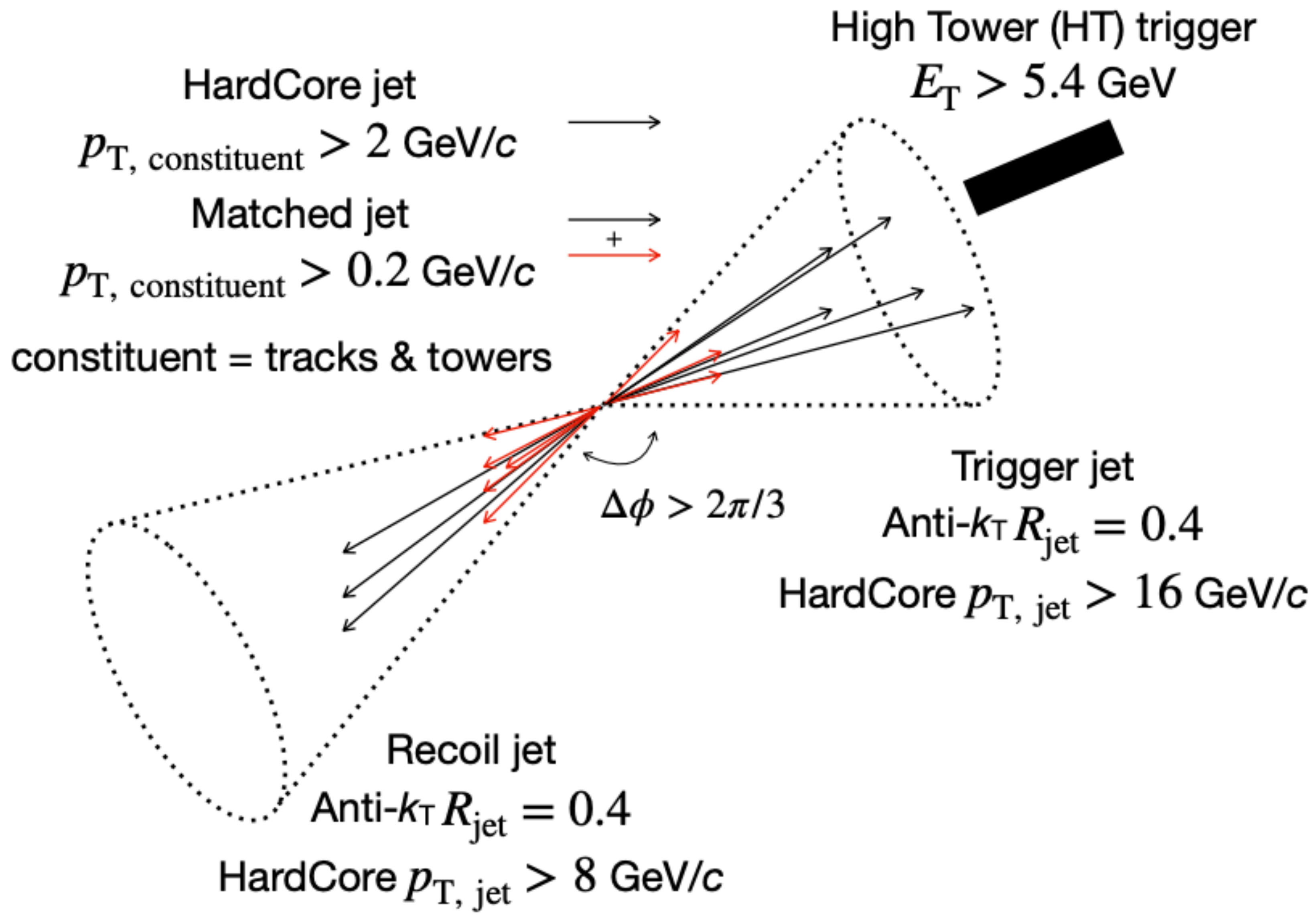
HARDCORE Dijet asymmetry

$$A_J = \frac{p_T^{lead} - p_T^{sub}}{p_T^{lead} + p_T^{sub}}$$

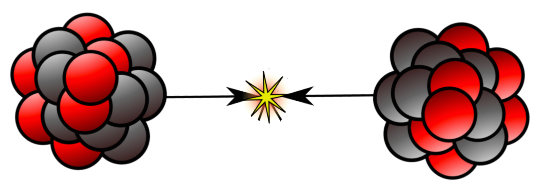




$$\theta_{SJ} = \Delta R_{SJ1,SJ2}$$

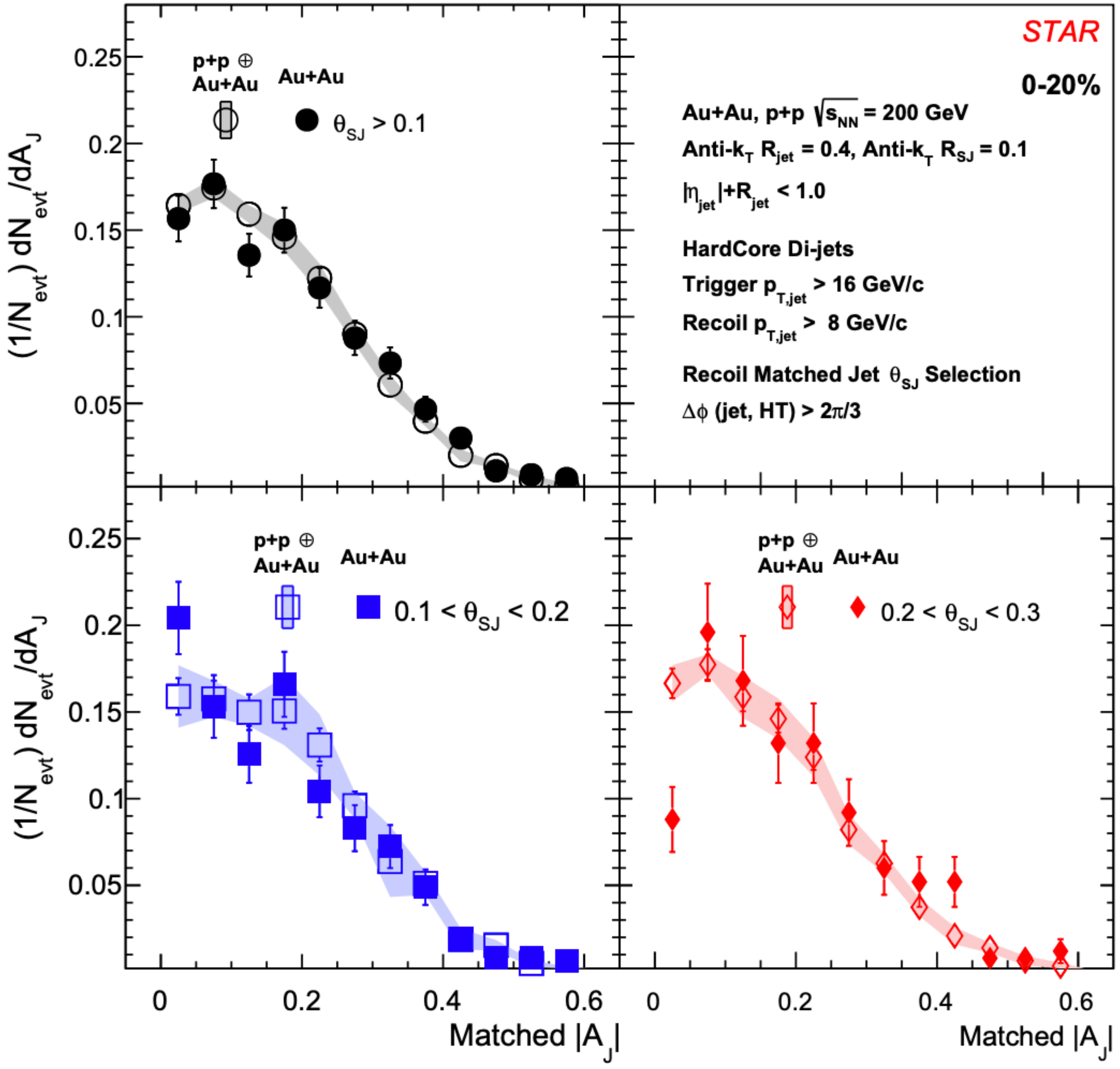


- A_J for HardCore dijets (constituent $p_T > 2$ GeV/*c*) measured for Au+Au as well as *p*+*p*⊕ Au+Au for different θ_{SJ}
- Disagreement between Au+Au and *p*+*p*⊕ Au+Au at all angles—jets are modified in Au+Au

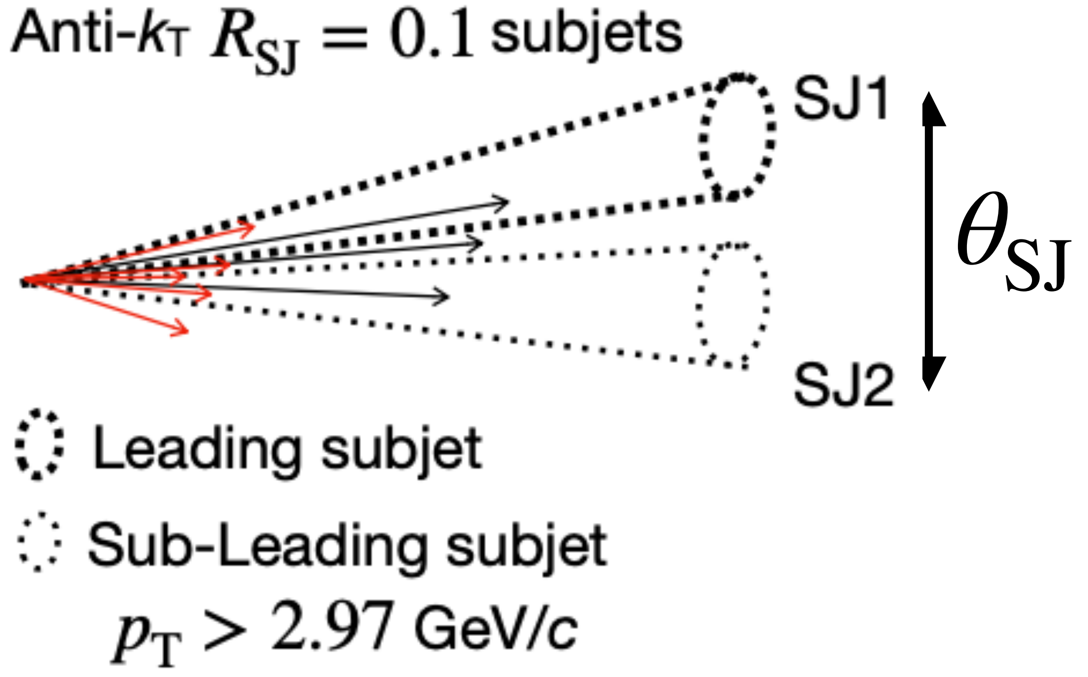


MATCHED Dijet asymmetry

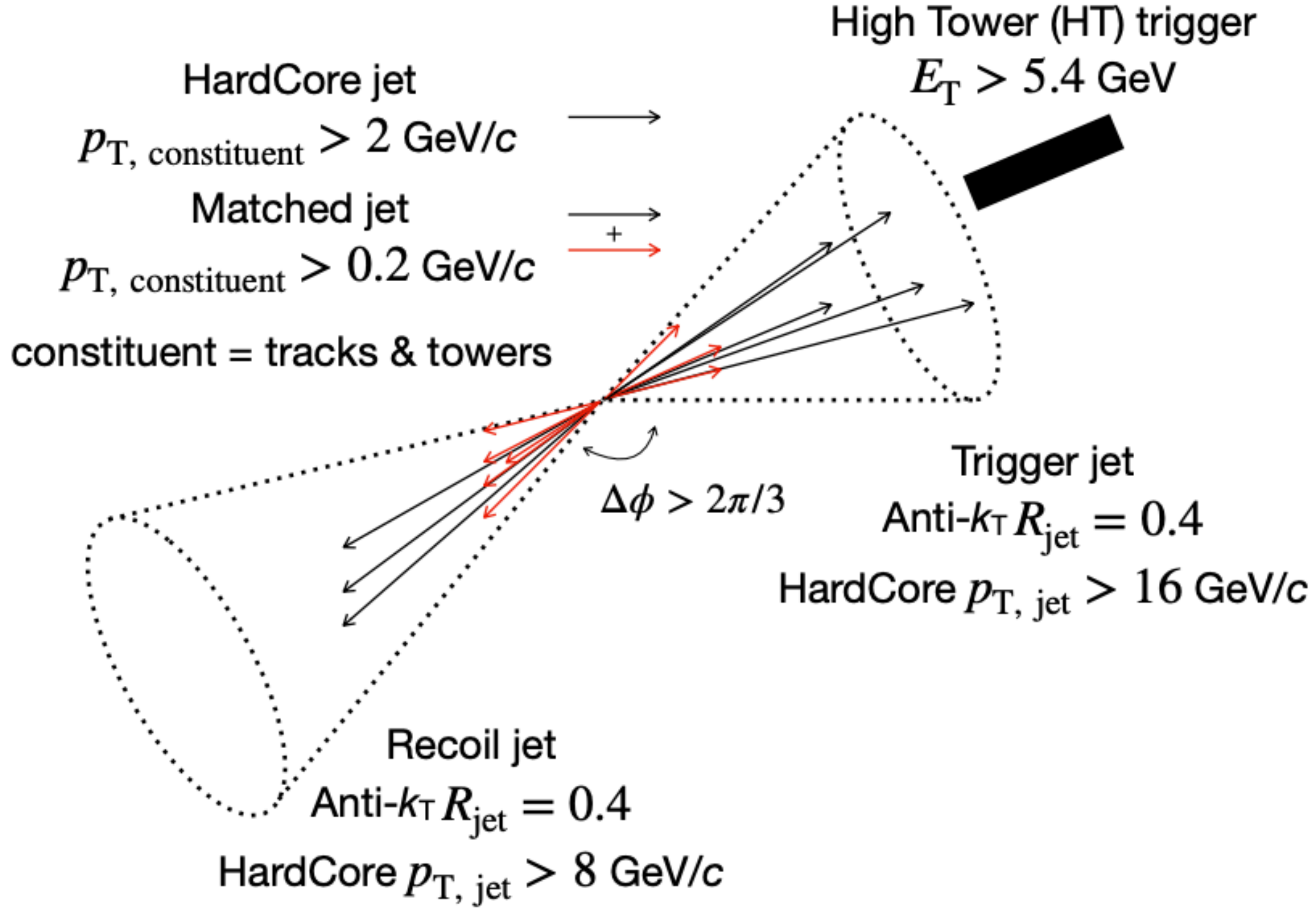
$$A_J = \frac{p_T^{lead} - p_T^{sub}}{p_T^{lead} + p_T^{sub}}$$



STAR, Phys.Rev.C 105 (2022) 044906

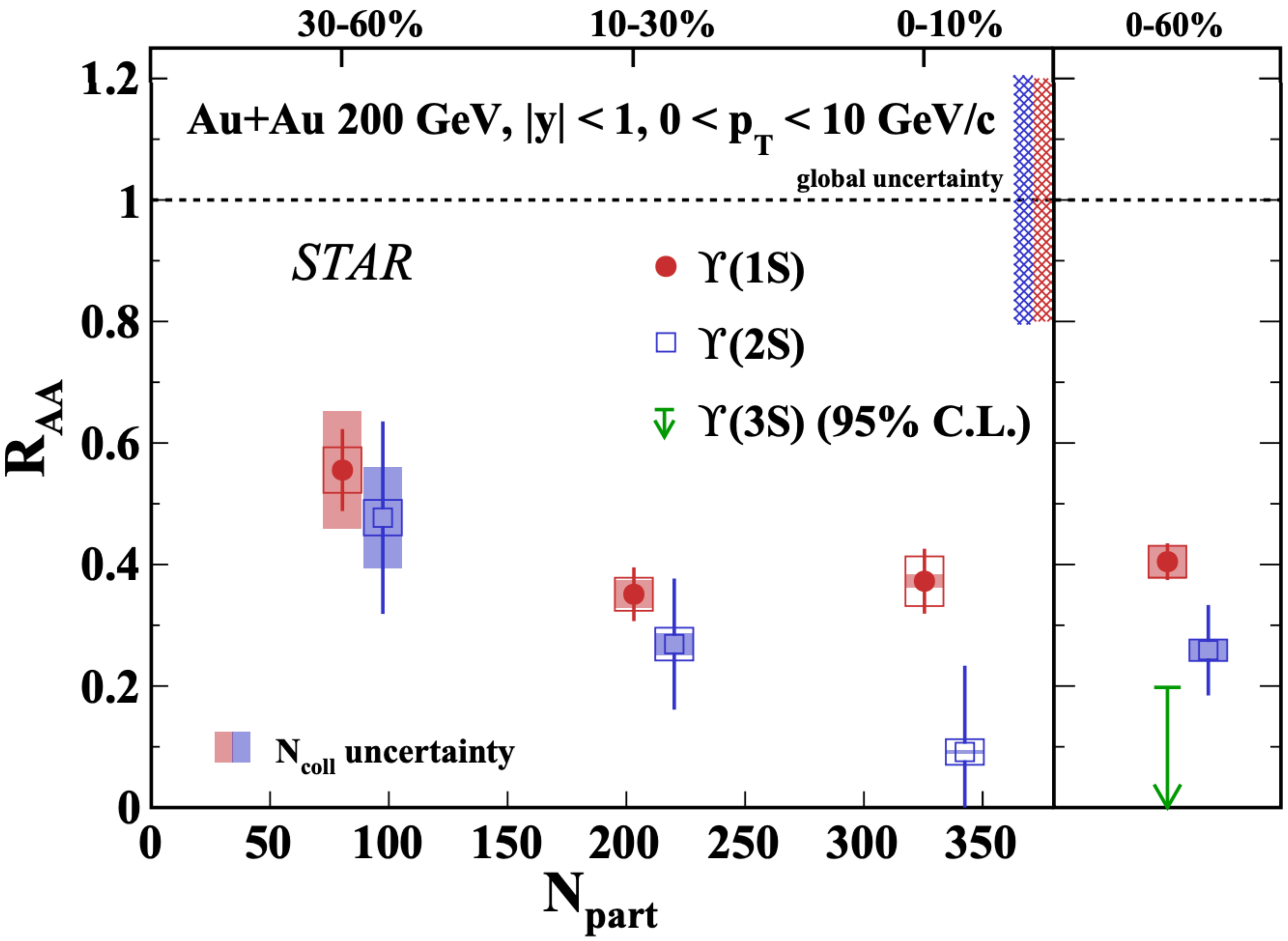


$$\theta_{SJ} = \Delta R_{SJ1,SJ2}$$



- Agreement between Au+Au and $p+p \oplus$ Au+Au A_J for dijets matched to the HardCore jets
- Matched jets are balanced—energy is recovered in low-p_T constituents
- No apparent angular dependence
- **Indicates recoil jet loses energy as single color charge radiating in medium!**

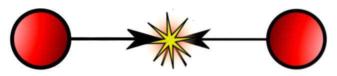
Upsilon R_{AA} in Au+Au



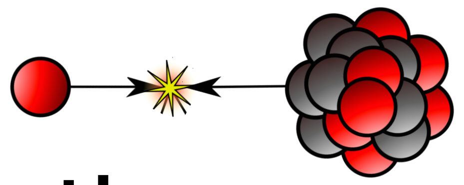
- Possibility for hot medium to "melt" bound states; use different ϒ states like a QGP "thermometer"
- Suppression of all ϒ in Au+Au; suppression is larger in more central collisions
- Higher excited states more suppressed due to their lower binding energies

STAR, Phys.Rev.Lett. 130 (2023) 112301

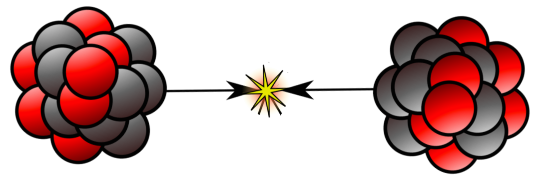
Summary

p*+*p 

- Used differential substructure to probe parton shower evolution
  - Change from soft, wide-angle to hard, collinear splits
- J/ψ is measured with associated jet activity to discriminate different models (color-singlet vs. color octet)

***p*+A** 

- Early-time correlations found between hard, mid-rapidity and soft, backward-rapidity particle production
  - Possible explanation for jet yield modification as a function of centrality
- No significant CNM effects at high p_T in J/ψ

A+A 

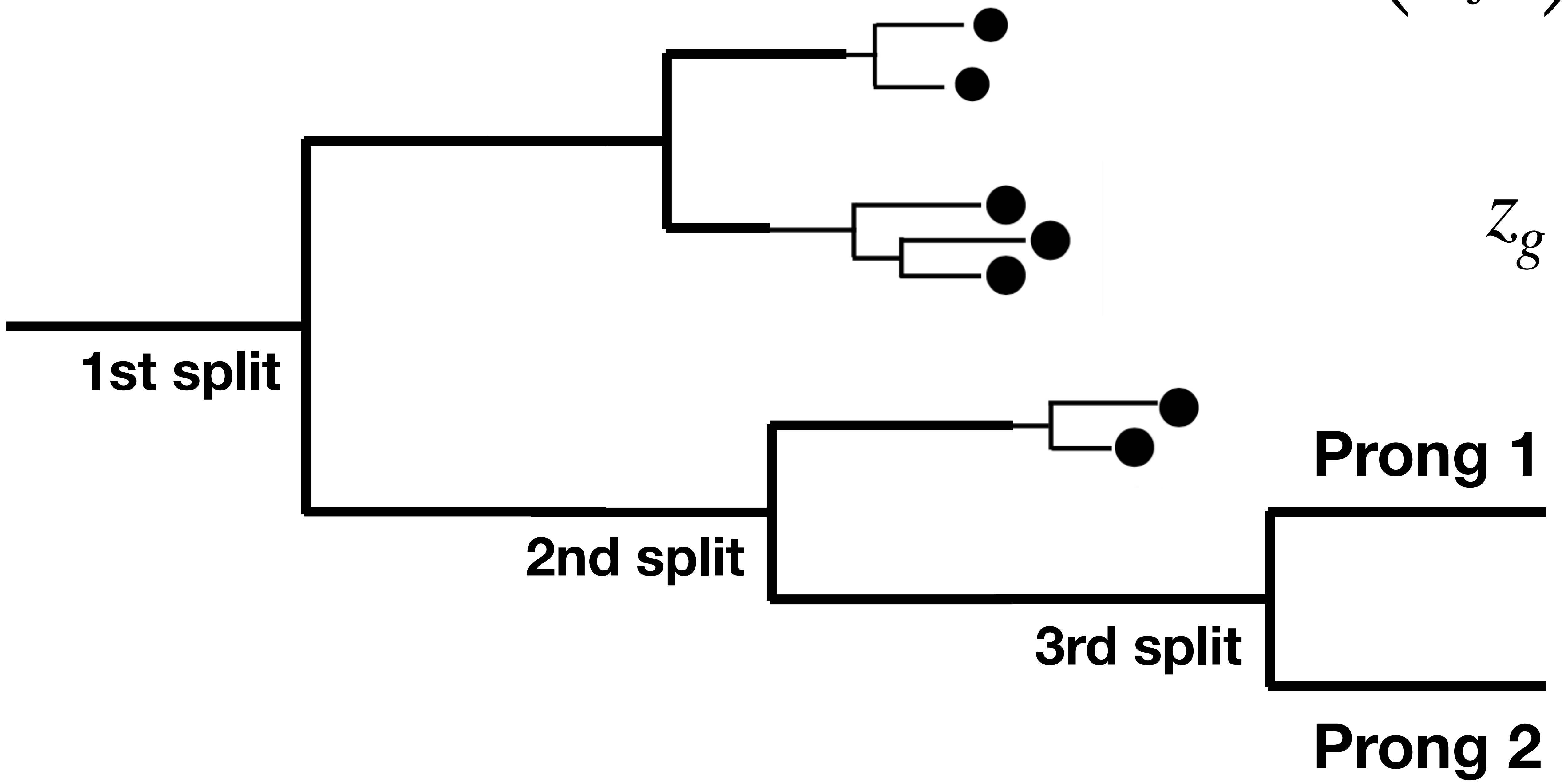
- J/ψ suppression in isobar consistent with suppression in Au+Au at similar $\langle N_{part} \rangle$
- Matched dijet asymmetry shows no angular dependence of jet energy loss
- Upsilon R_{AA} in Au+Au shows greater suppression of higher excited states

Backup

SoftDrop and jet substructure

SoftDrop grooming criteria:

$$z_g > z_{\rm cut}\left(\frac{R_g}{R_{\rm jet}}\right)^{\beta}, \quad z_{\rm cut} = 0.1, \quad \beta = 0 \quad \rightarrow \quad z_g > 0.1$$



$$z_g = \frac{\min(p_{\rm T,1}, p_{\rm T,2})}{p_{\rm T,1} + p_{\rm T,2}}$$

$$\hat{q} = \frac{{\rm d}\left\langle k_{\rm T}^2 \right\rangle}{\rm dL}$$

$$k_{\rm T} = z_g p_{\rm T} \sin \Delta R_{1,2}$$

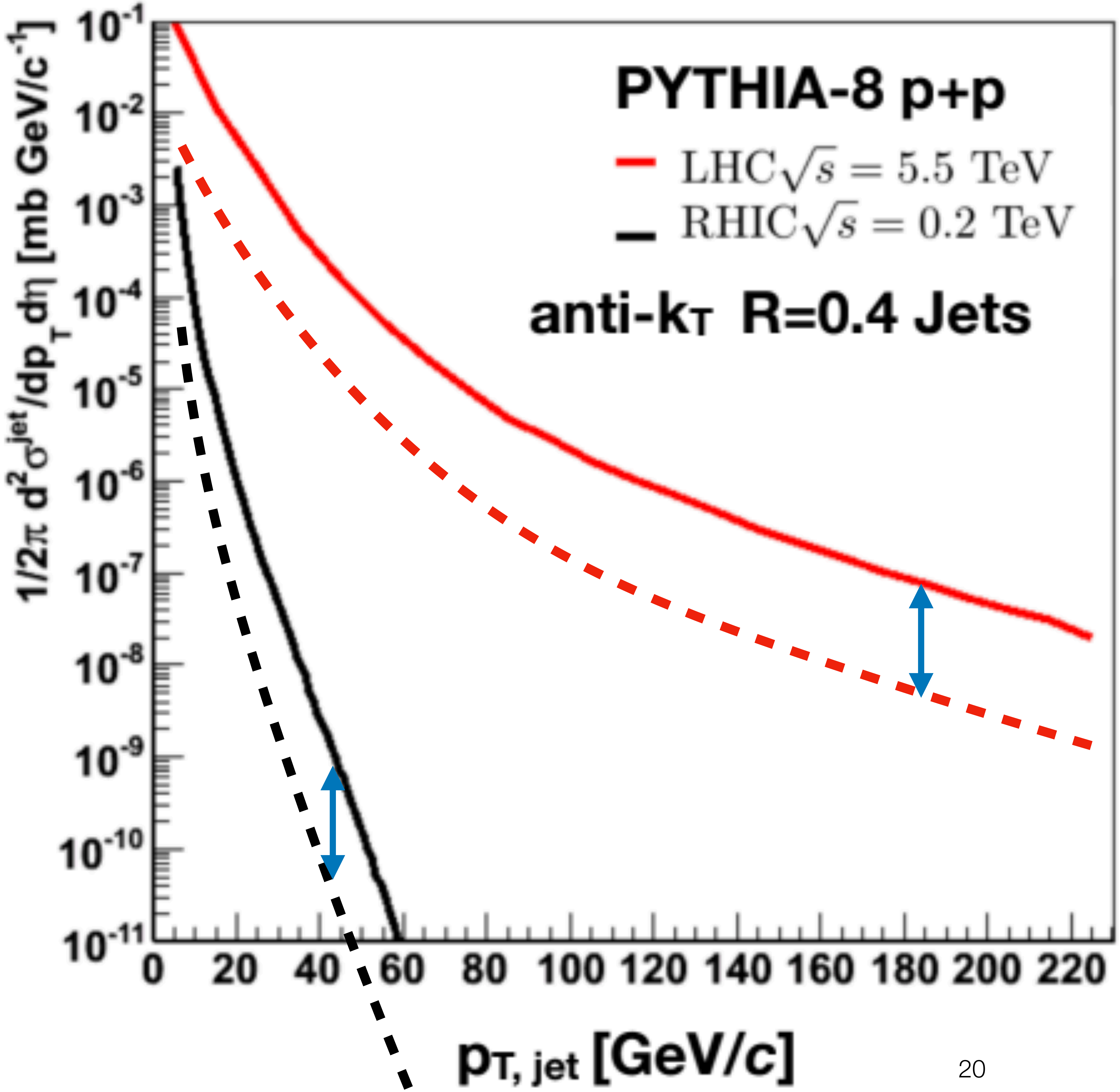
$p_{\rm T,1}$ ↕ $p_{\rm T,2}$

$$R_g = \Delta R(1,2)$$

$$\tau_{\rm form} \sim \frac{1}{Q^2}$$

$$\tau_{\rm f} = \frac{1}{z(1-z)\theta^2 E}$$

$$\text{splitting probability} : {\rm dP} \approx \frac{{\rm d}\theta}{\theta}\frac{{\rm d}\omega}{\omega}$$

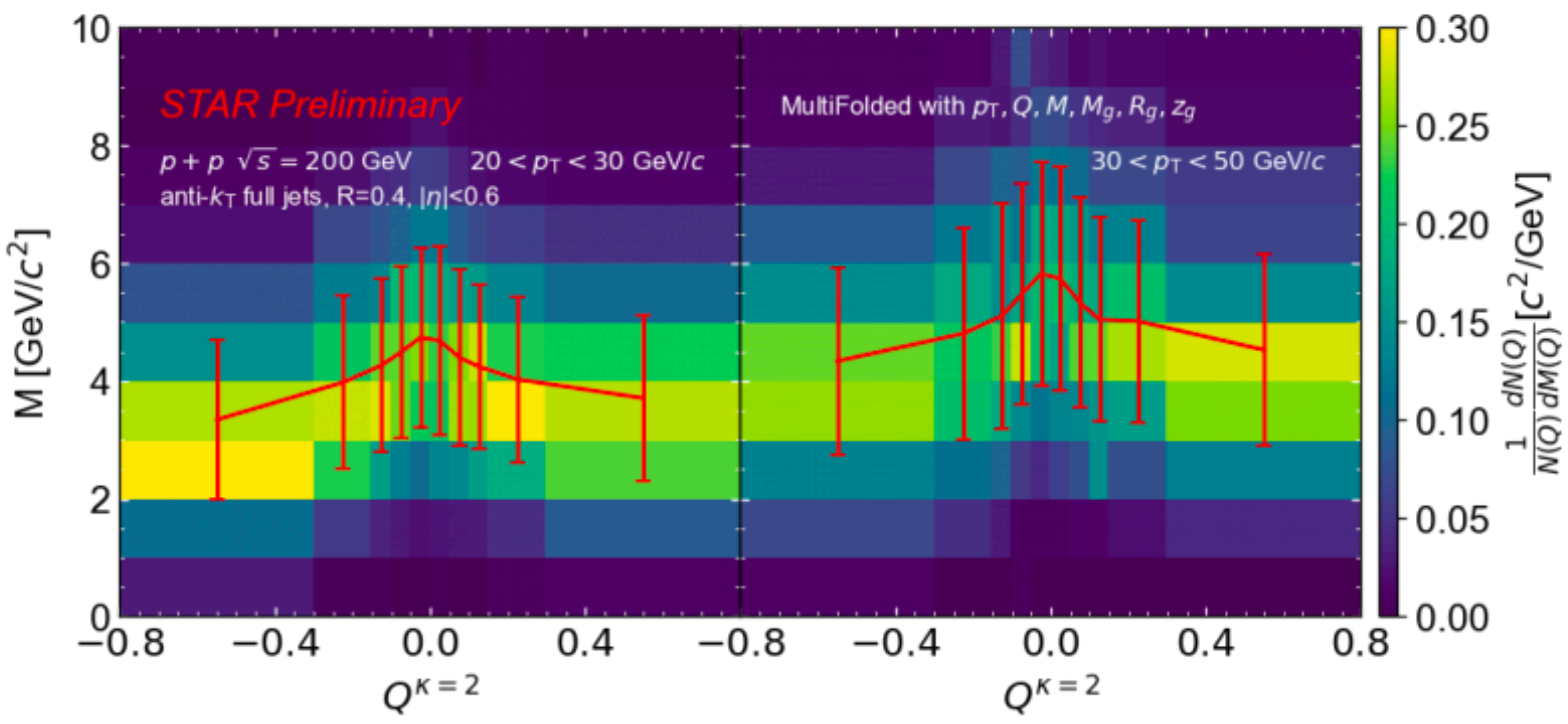


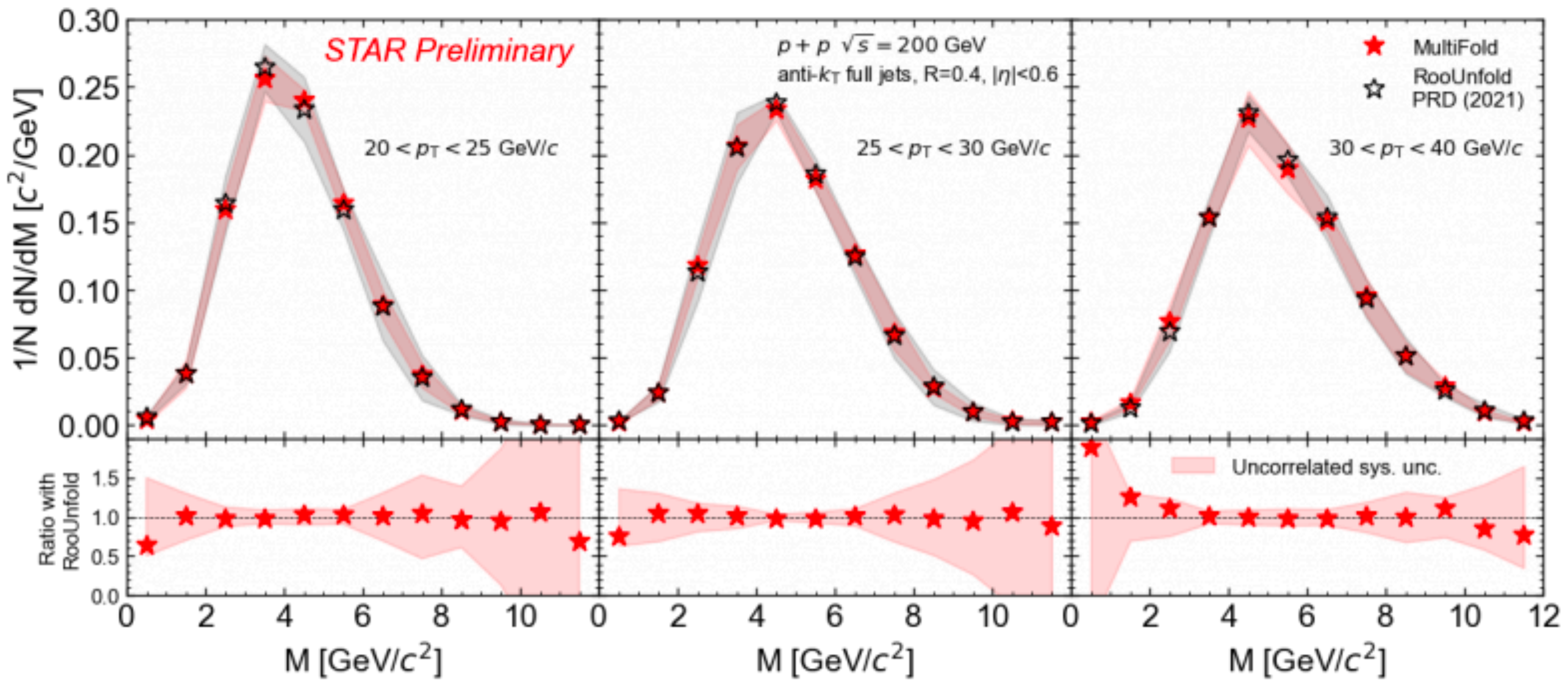
- $\frac{d^2\sigma}{dp_T d\eta}$ is *much* steeper at RHIC energies than LHC energies

- In order to have suppression comparable to that at RHIC, the jet p_T spectrum at the LHC would need to shift downward even further

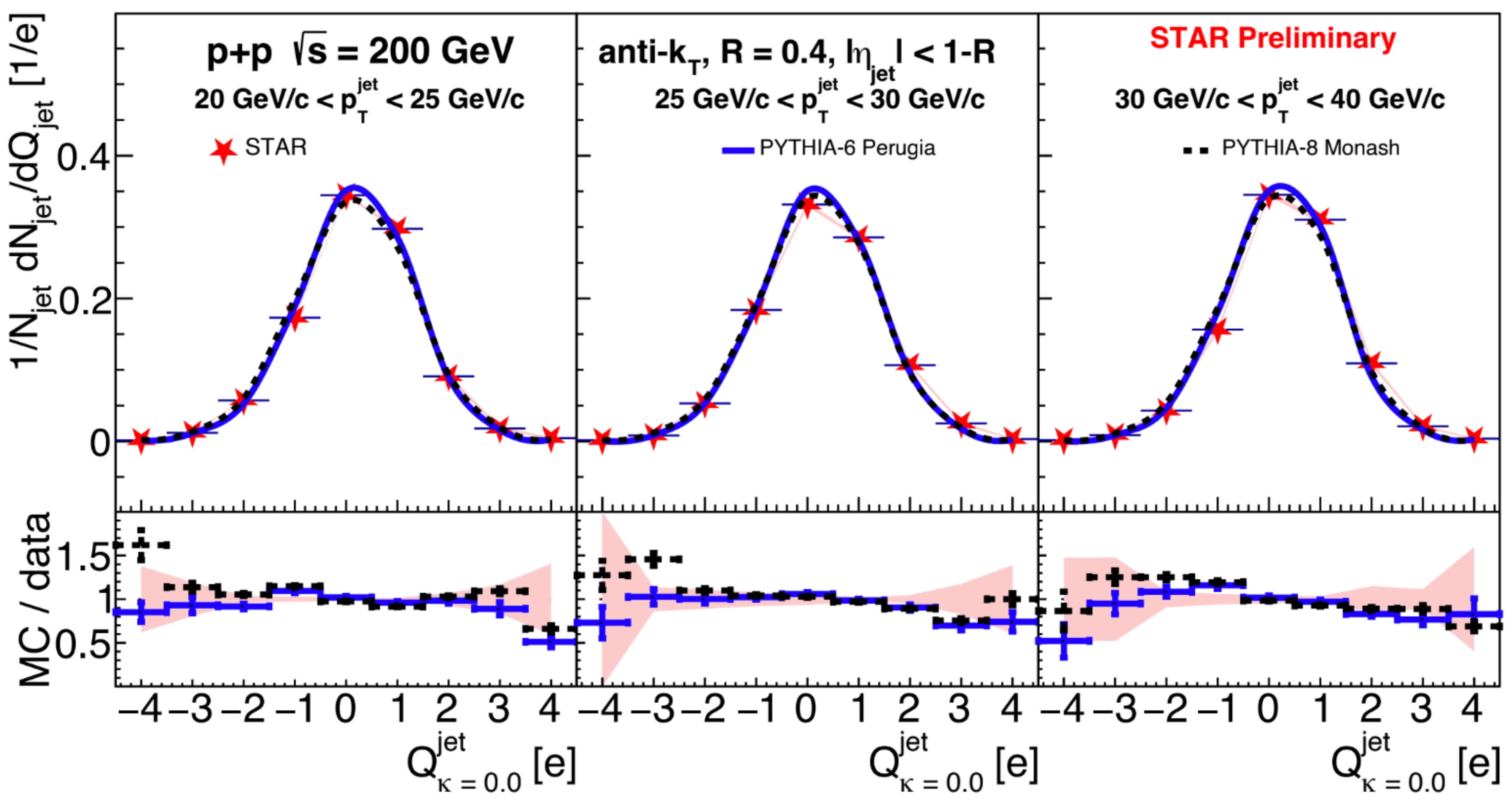
$$R_{CP} = \frac{\left(d^2N_{AA}/dp_T d\eta\right)^{cent.}/N_{coll}^{cent.}}{\left(d^2N_{AA}/dp_T d\eta\right)^{periph.}/N_{coll}^{periph.}}$$

Multidimensional substructure



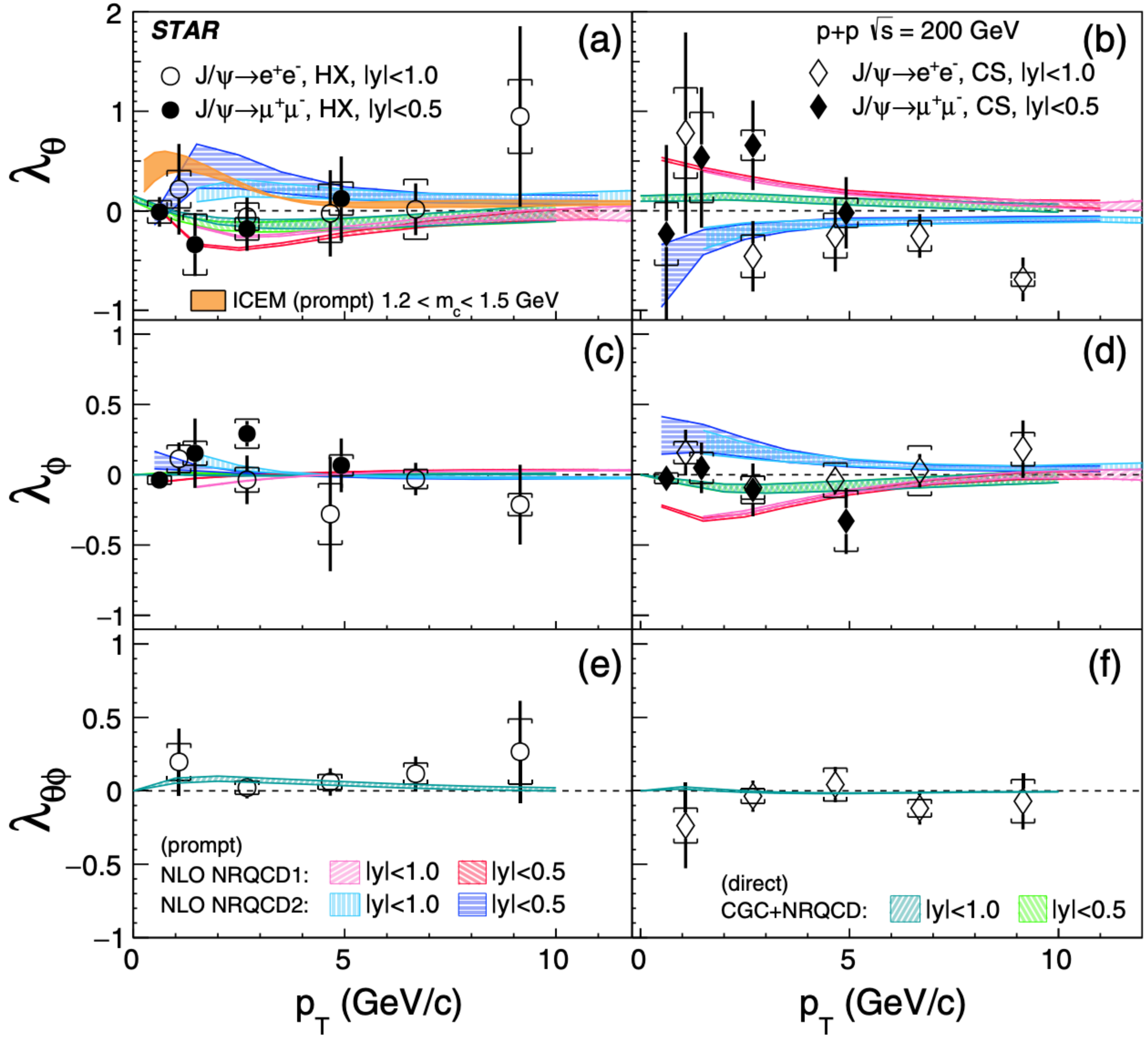


$$Q_k^i = \frac{1}{\left(p_T^{jet}\right)^\kappa} \sum_{j \in jet} Q_j \left(p_T^j\right)^\kappa \qquad M = \sqrt{E^2 - \mathbf{p}^2}$$



- MultiFold: simultaneous, unbinned unfolding, agreement with RooUnfold
- Study substructure observables (p_T, Q, M, M_g, R_g, z_g) **at the hardest split** to characterize jets
- Study mass and weighted jet charge → determine initiator (gluon or quark flavor)

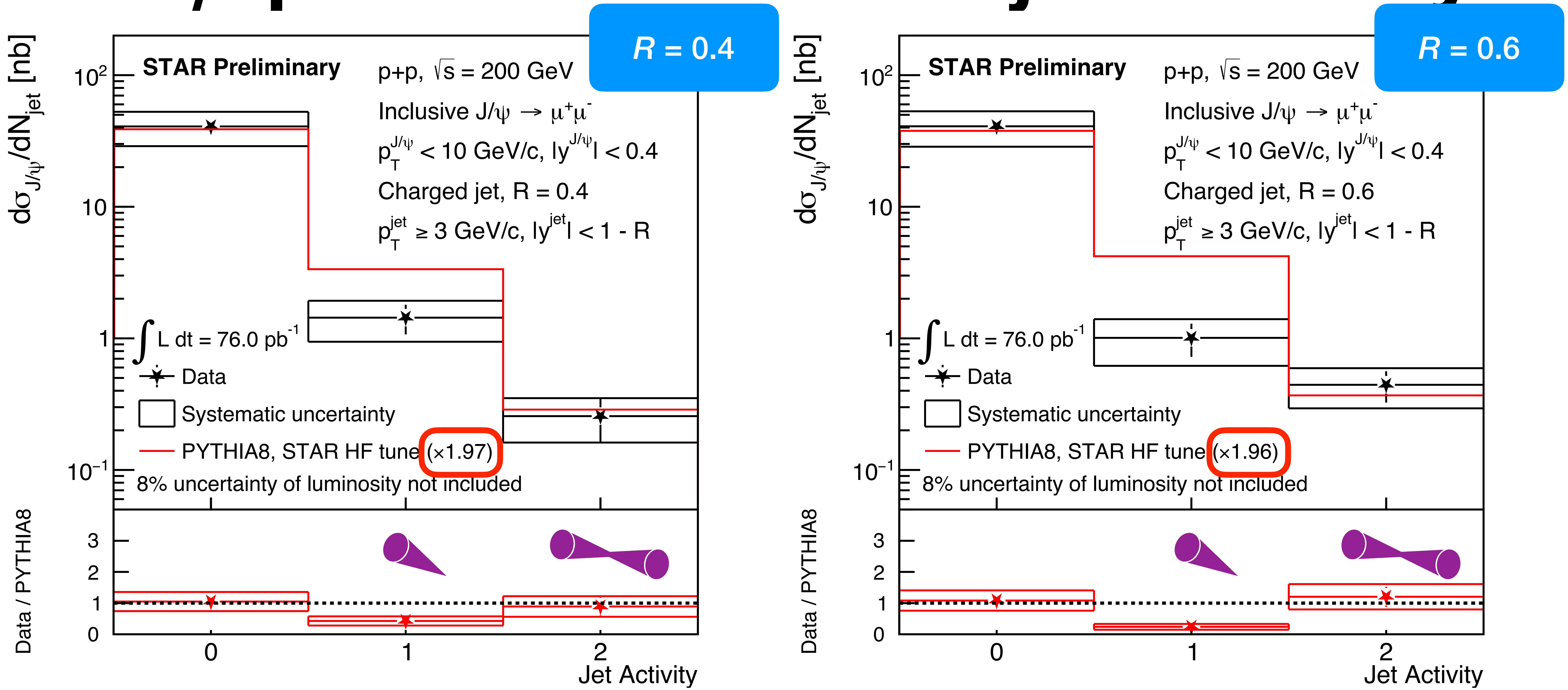
J/ψ polarization in p+p



- *J/ψ* polarization is dependent on production mechanism; polarization measurements can help inform and discern between mechanisms
- Measurements show polarization is consistent with zero within errors; this is in agreement with the models shown
- These values are also in agreement with measurements from PHENIX in 2020 PHENIX, Phys.Rev.D 102 (2020) 072008

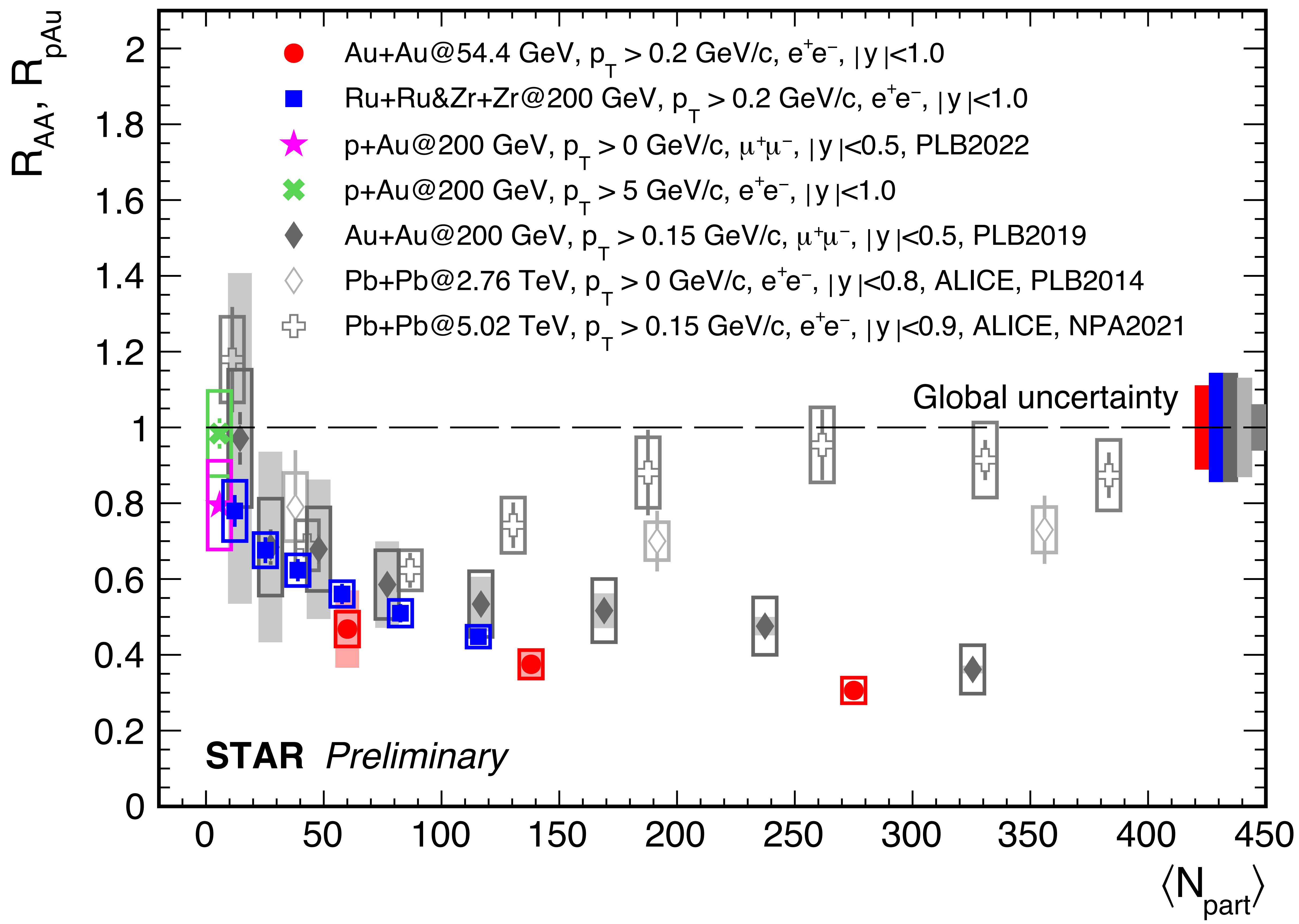
STAR, Phys.Rev.D 102 (2020) 092009

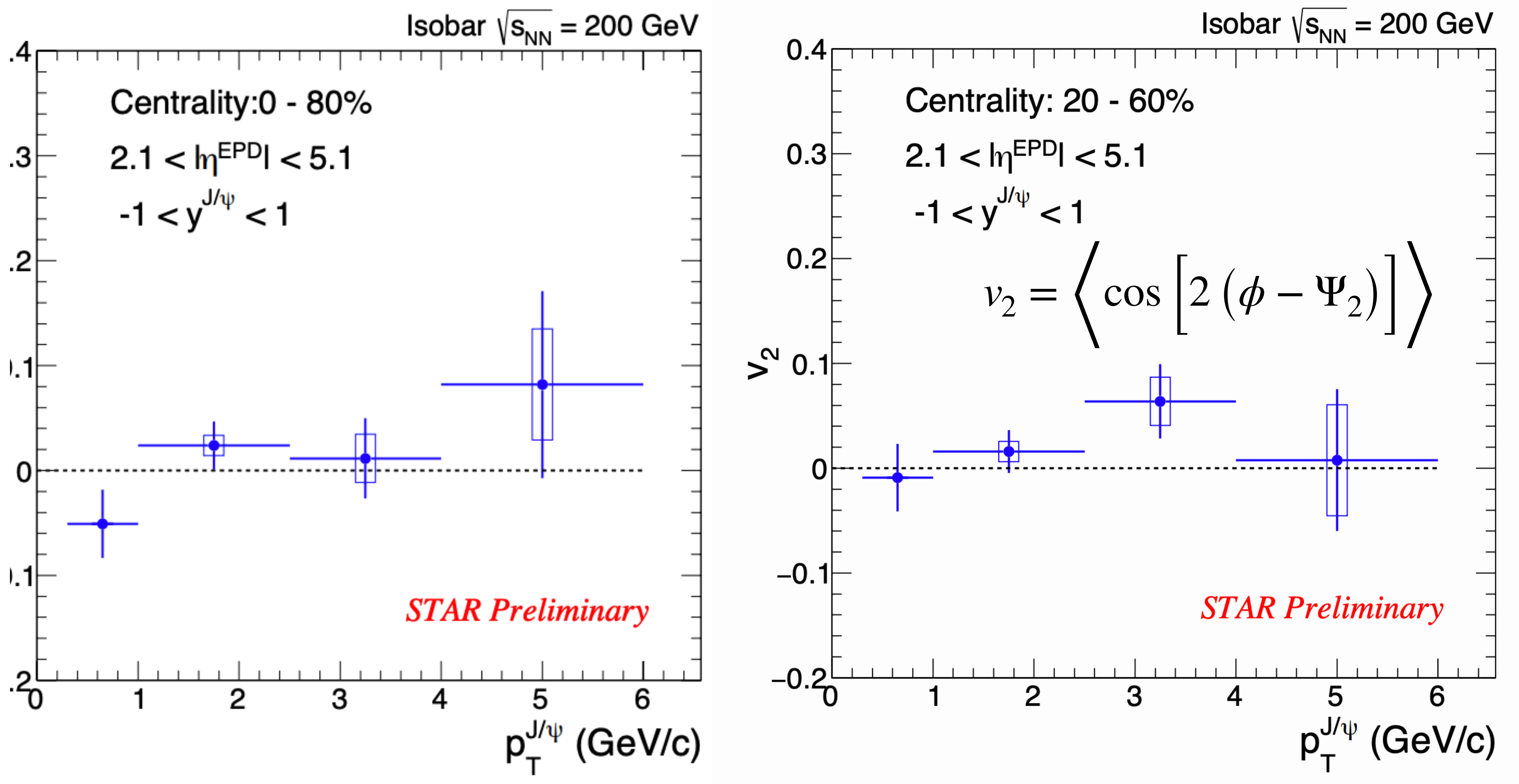
J/ψ production with jet activity



- Corrected for overall scale, PYTHIA8 over-predicts J/ψ production in events with jets
- Different J/ψ production mechanisms may be associated with different jet multiplicities
- Ongoing: compare different production mechanisms (color-singlet and color-octet models)

J/ψ R_{AA} and v_2 in isobar





- J/ψ R_{AA} shows suppression in isobar is consistent with Au+Au at comparable N_{part}
    - Similar densities → similar E-loss
- Elliptic flow measured in STAR Au+Au consistent with zero (https://arxiv.org/pdf/1212.3304.pdf)
- Isobar expected to have less non-flow (contamination) due to lower mass
- v_2 in isobar also consistent with zero

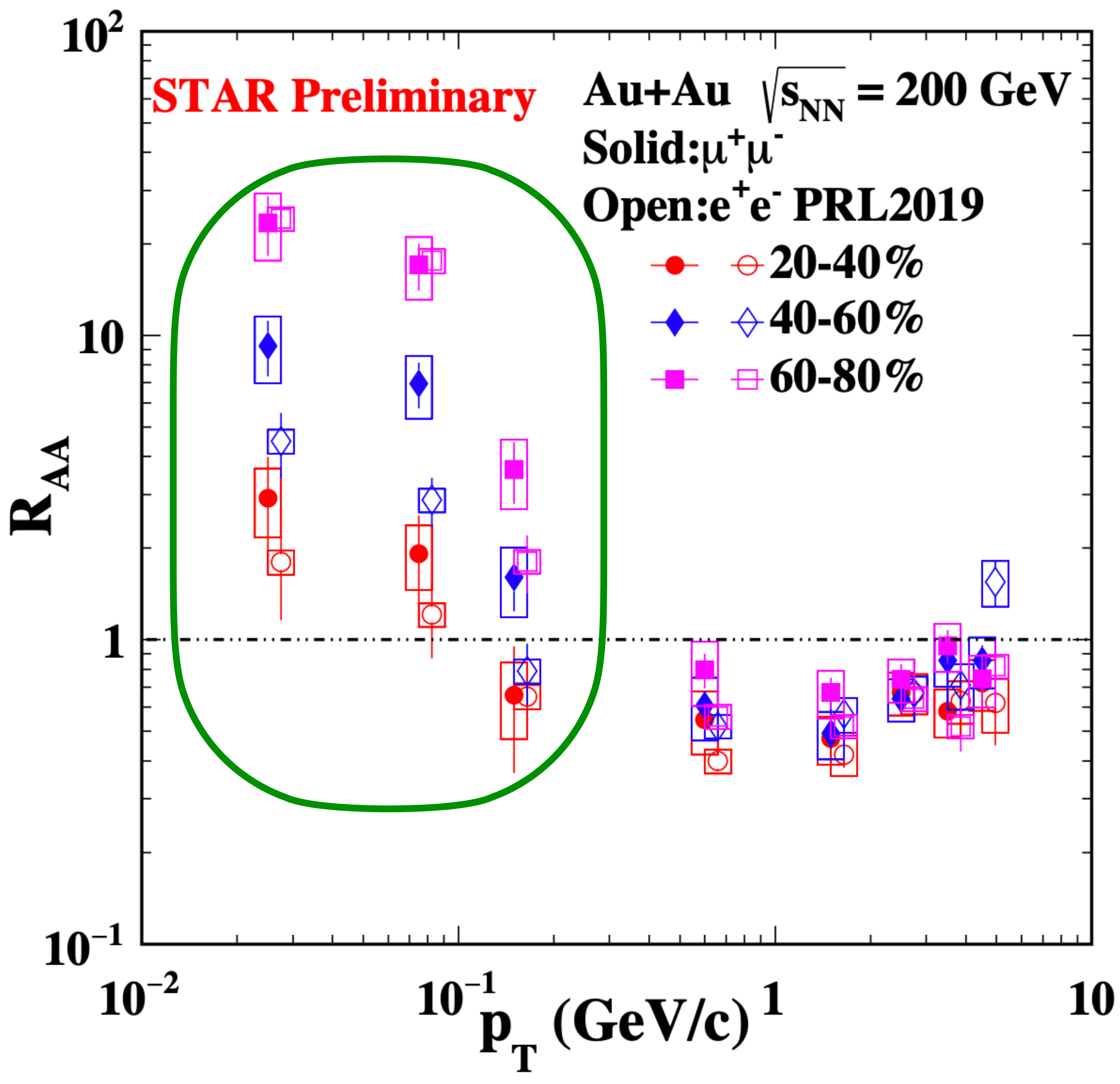
J/ψ dimuon & dielectron R_{AA}

- J/ψ via dielectron in STAR shows excess J/ψ production at low p_T in peripheral collisions

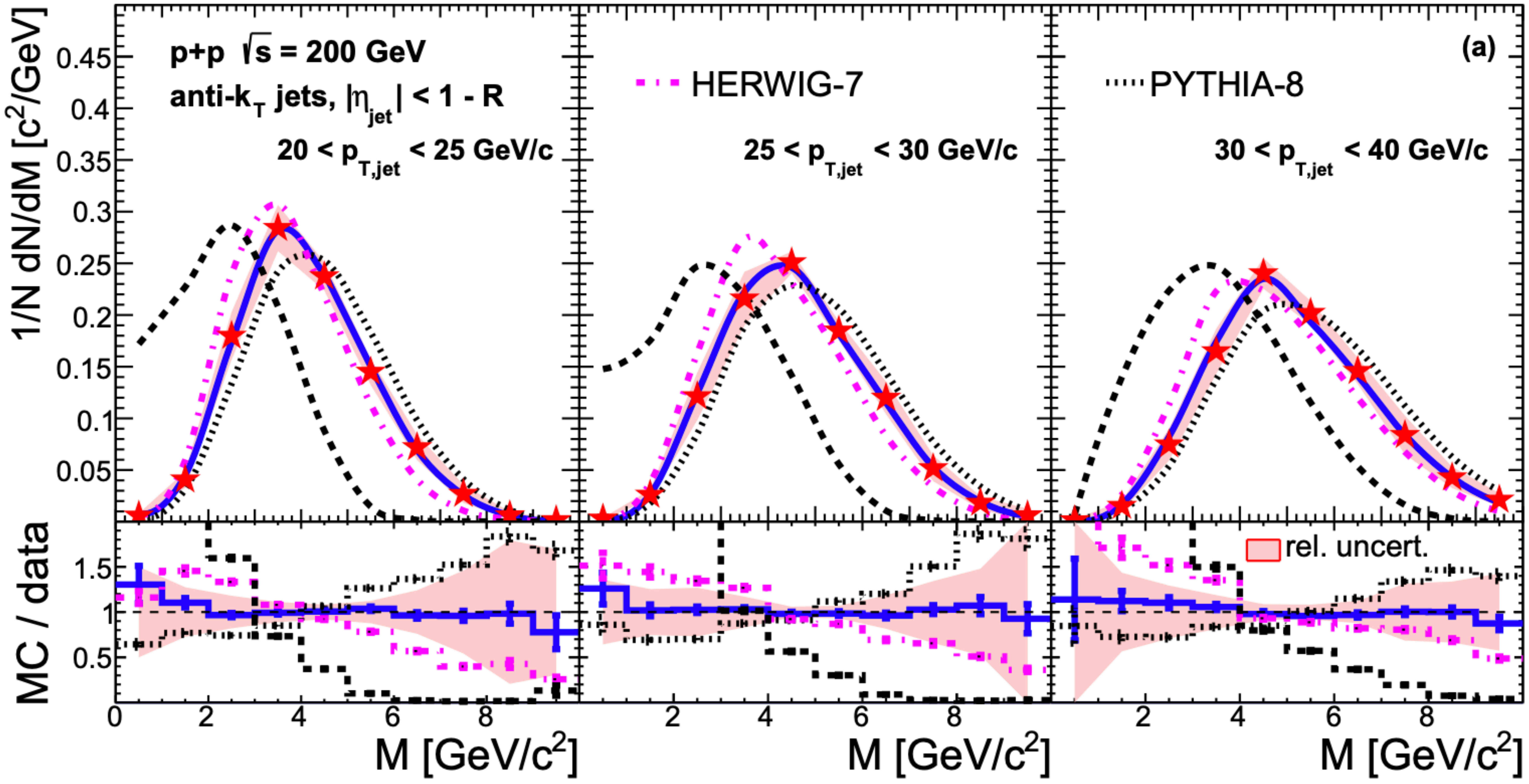
J. Adam et al. (STAR Collaboration), Phys. Rev. Lett. 123, 132302

- Comparison with preliminary dimuon measurements show similar trends—enhancement at low p_T is confirmed
- These observations are consistent with coherent photon-nucleon interactions

$$R_{AA} = \frac{1}{N_{coll}} \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$



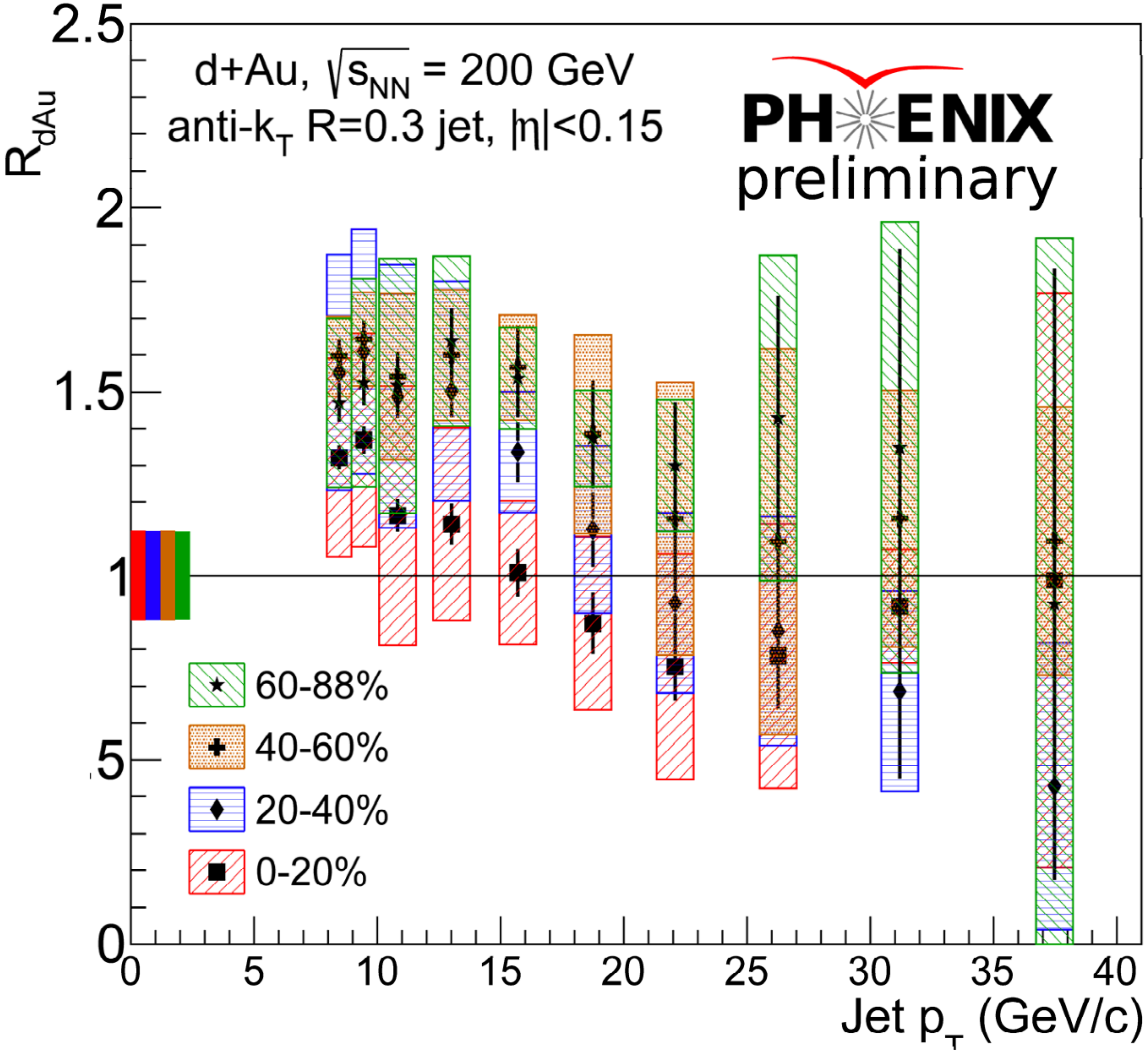
Are jets modified in p+Au?



$$M = \sqrt{E^2 - \mathbf{p}^2}$$

Jet mass in p+Au events are consistent with p+p jet mass

PHENIX R_{d+Au} erratum



- An erratum to the PHENIX R_{d+Au} is being prepared
- The analysis was re-done after removing noisy towers
- R_{d+Au} no longer shows jet suppression in central events, but still shows enhancement in peripheral events

Lajoie https://moriond.in2p3.fr/2021/QCD/

PARTICLE	SYMBOL	MASS (GEV)
PHOTON	γ	0
NEUTRINO	ν	0
ELECTRON	e	.0005
MUON	μ	.105
PI MESONS	π^0 $\pi^\pm$	.135 .140
K MESONS	$K^\pm$	.494
PROTON	p	.938
NEUTRON	n	.940
PHI	ϕ	1.020
LAMBDA	Λ	1.116
CHARMED MESONS	D^0 D^+	1.863 1.868
CHARMED LAMBDA	Λ_c	2.260
J OR PSI FAMILY	J/ψ ψ'	3.098 3.684
UPSILON FAMILY	Υ Υ' Υ''	9.4 10.0 10.4

http://physics.gmu.edu/~rubinp/courses/440-540/undergrad/LedermanUpsilon.pdf