Recent Jet Measurements at STAR

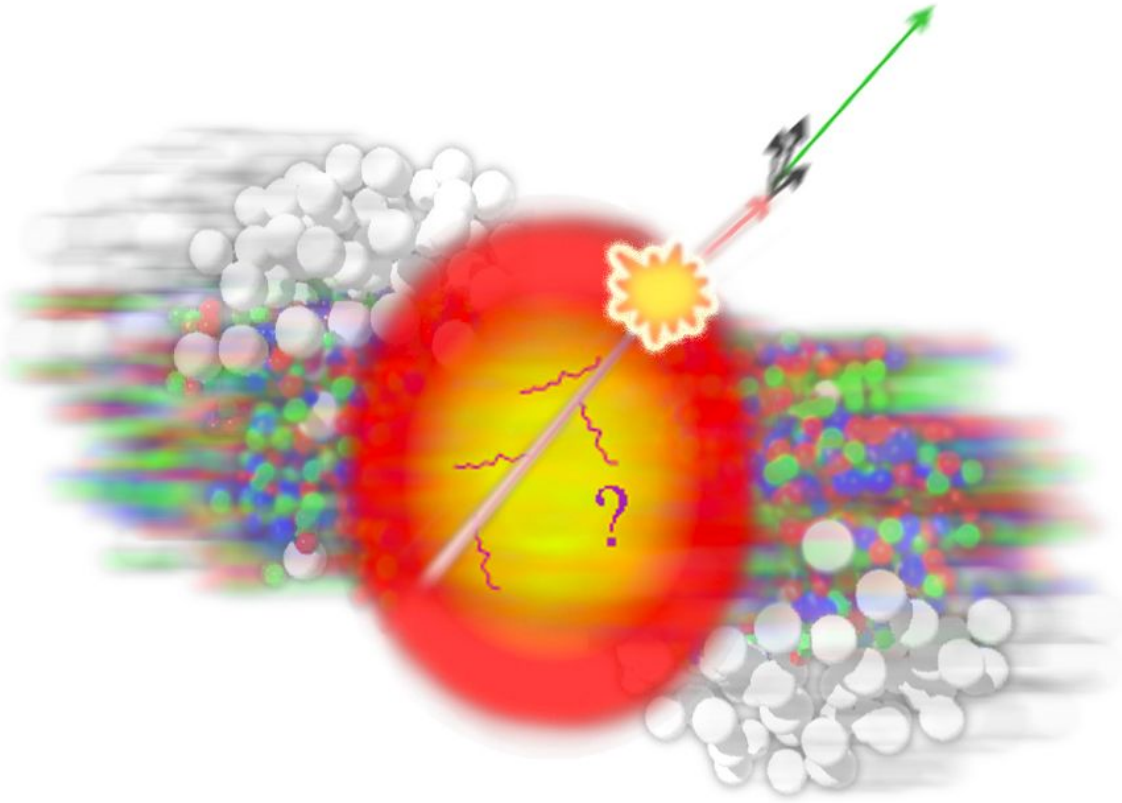
3/4/20

Annika Ewigleben for the STAR Collaboration

Supported in part by funding from the

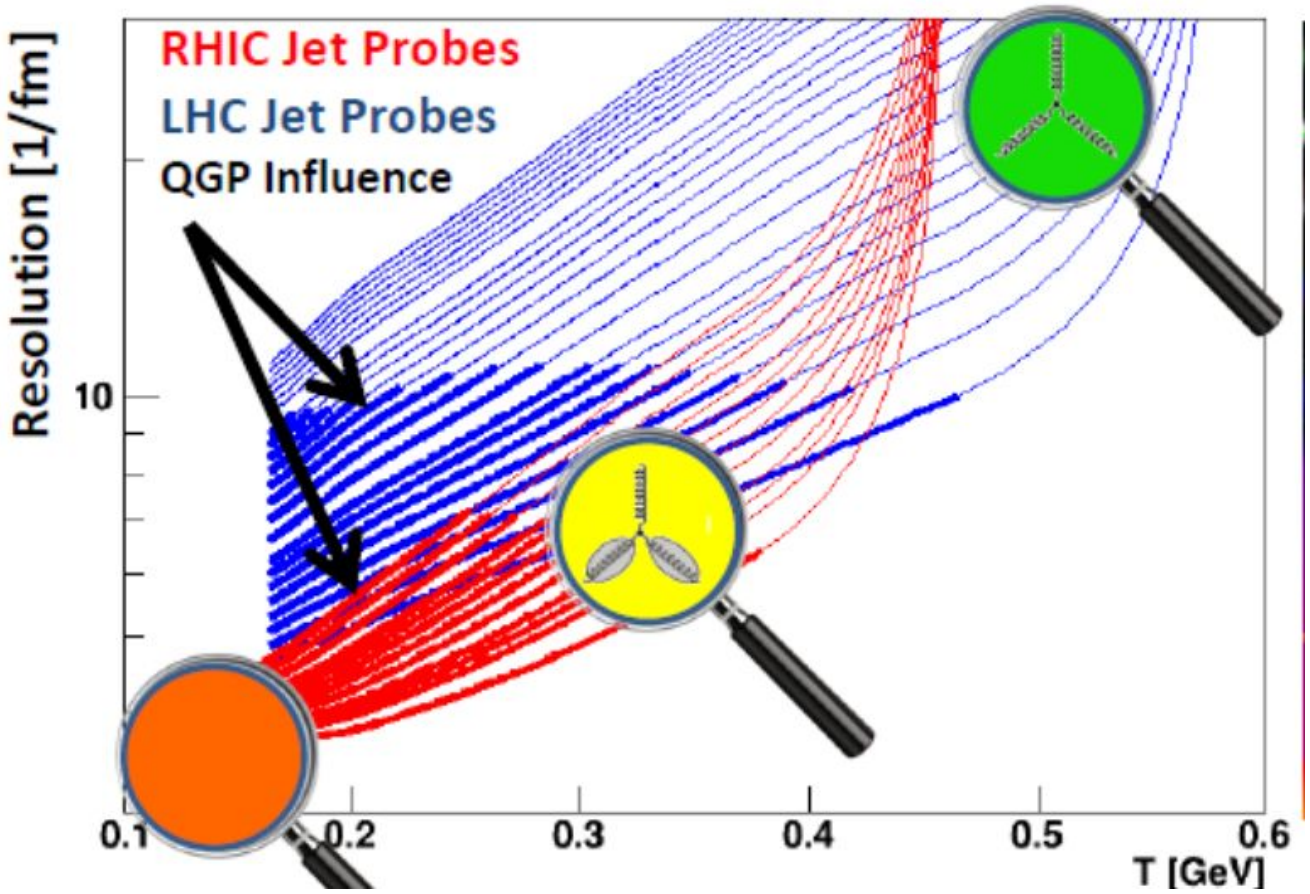
Why Measure Jets?

- Formed early in collision by hard partonic scatterings
  - ➢ Cross section calculable in pQCD
- Early formation time → can probe entire evolution of system
  - ➢ Concurrent evolution of jet shower and QGP
- Modification of jet observables resulting from interactions with the QGP medium can offer insight into medium properties

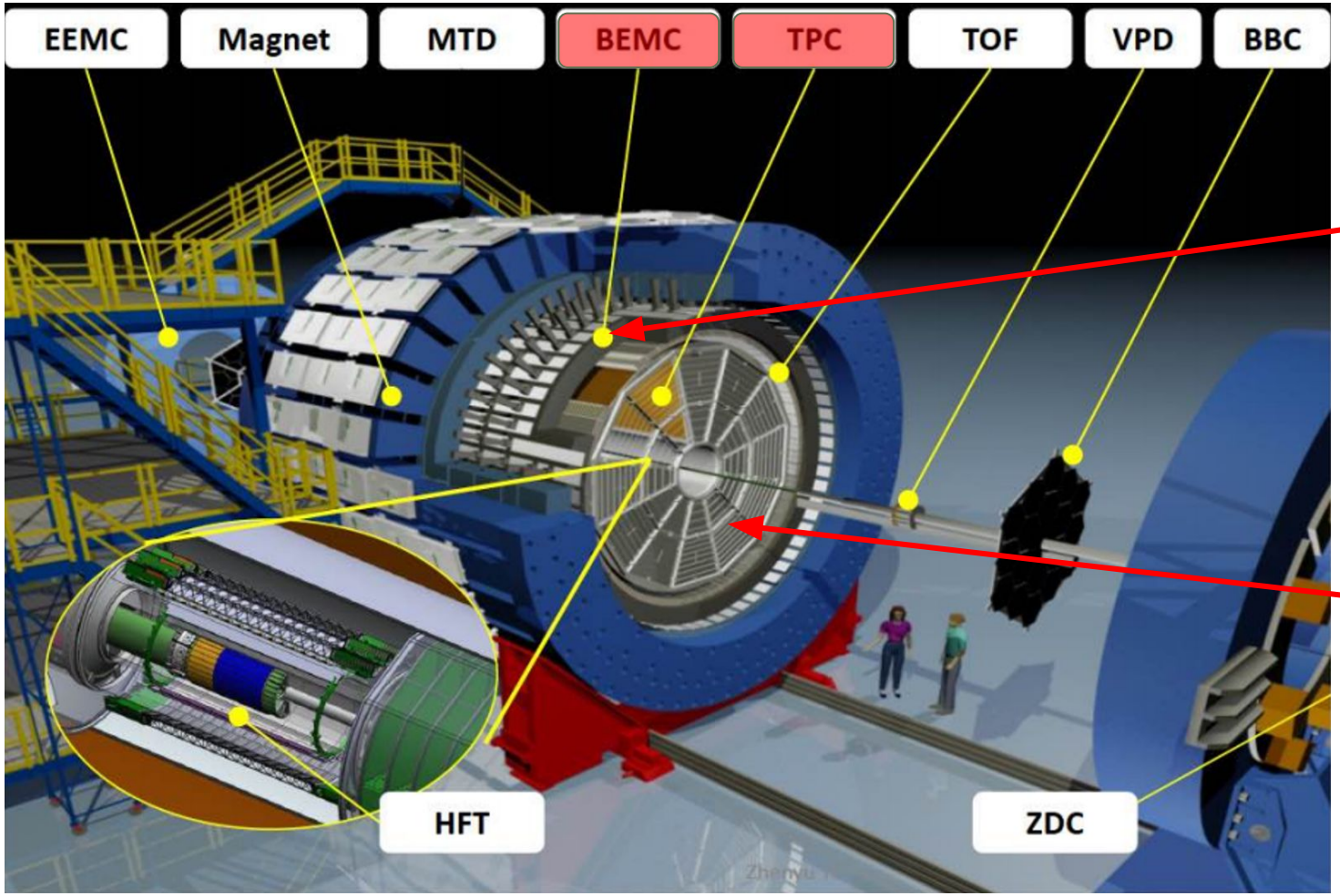


Why Measure Jets at RHIC?

- Lower energy jet probes at RHIC are expected to interact more strongly with the medium
- And...



The STAR Detector



Jet Finding Detectors

Barrel ElectroMagnetic Calorimeter (BEMC)

- $|\eta| < 1.0$
- Full 2π coverage in φ
- $0.2\text{GeV} < E < 30\text{GeV}$
- Electromagnetic Neutral particles

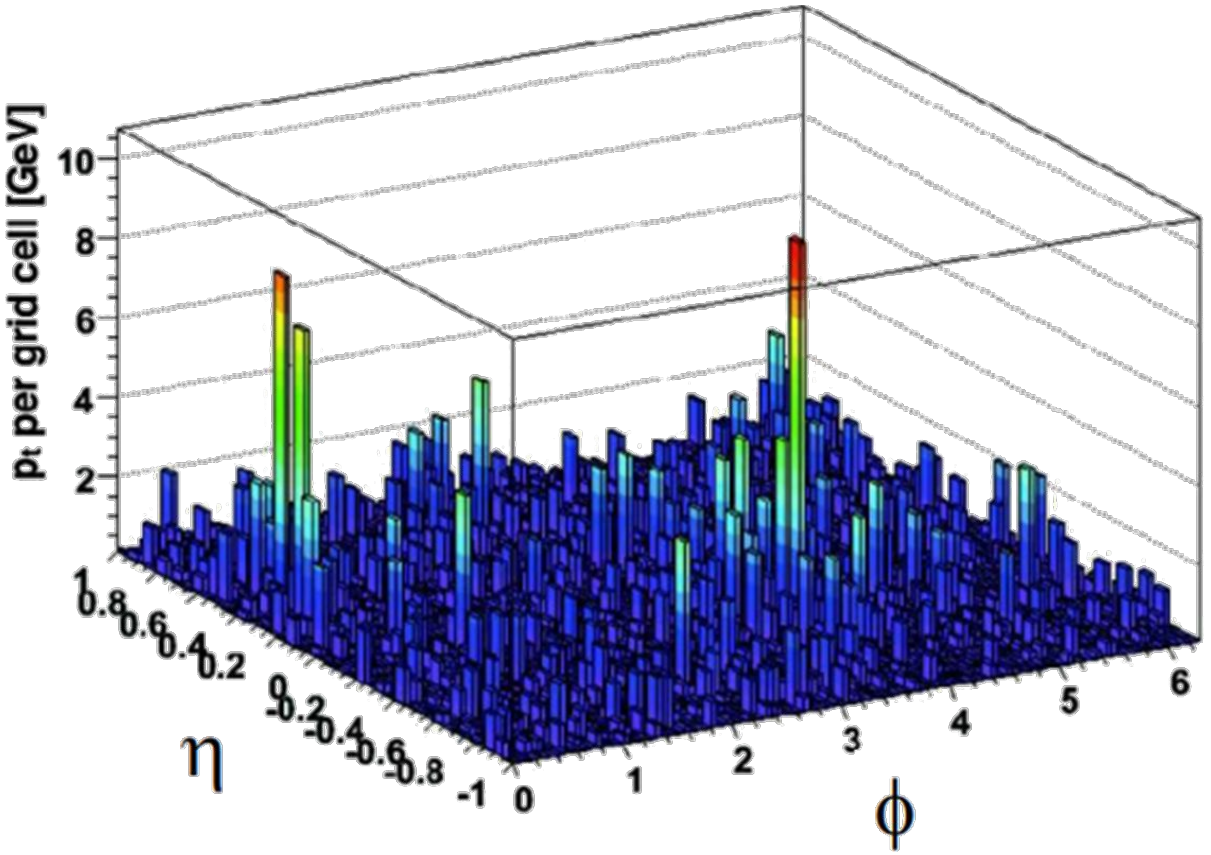
Time Projection Chamber (TPC)

- Primary tracking detector
- $|\eta| < 1.0$
- Full 2π coverage in φ
- $0.15\text{GeV}/c < p_T < 30\text{GeV}/c$
- Charged particles

Jets in HIC

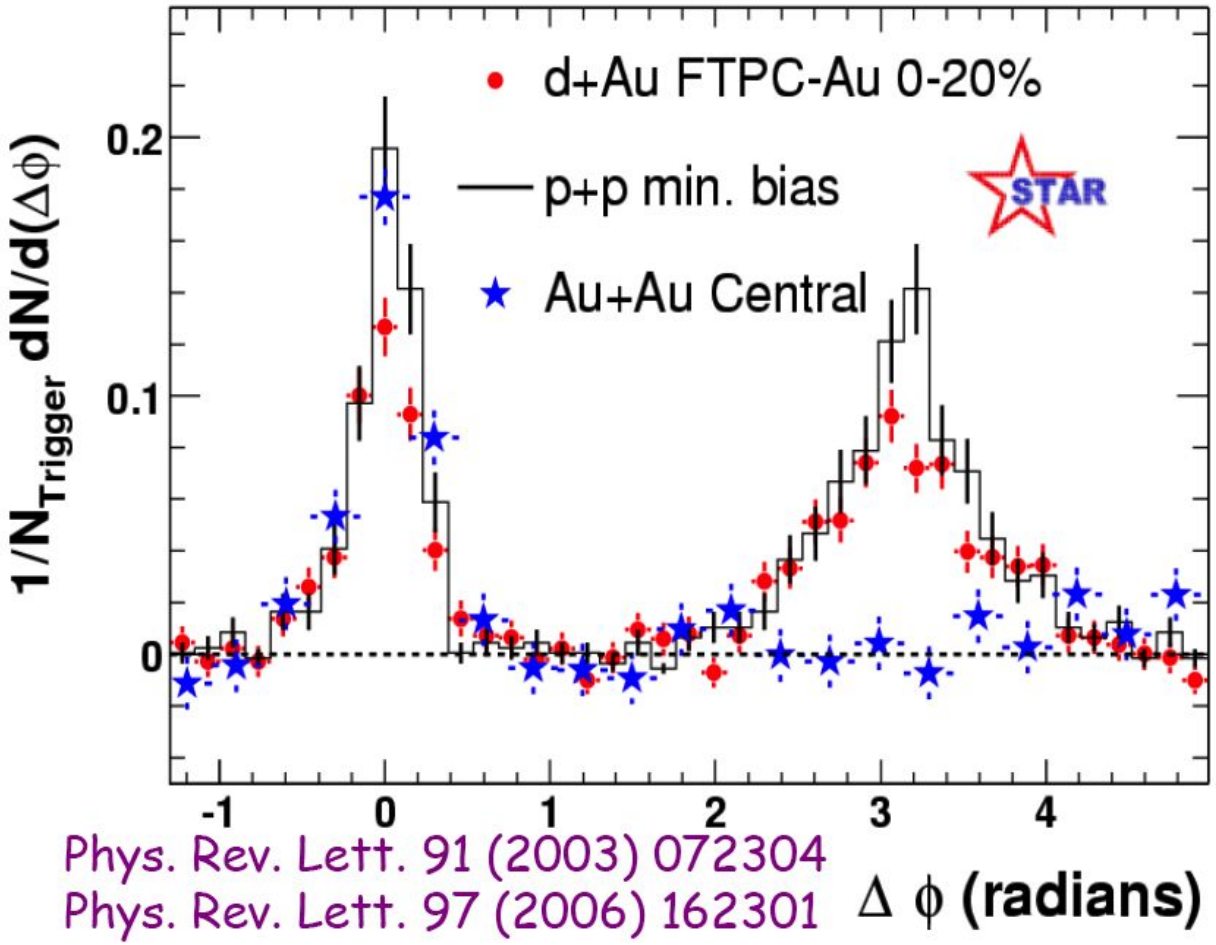
- Jet finding techniques developed in particle physics not directly applicable in HIC due to the high background environment
  - Jetfinding is computationally intensive
  - How to subtract background contributions to jet energy?
  - How to deal with combinatorial jets?

- First jet measurements at STAR used di-hadron correlations
- All jet definitions are inherently biased in some way
  - Not necessarily bad, can be another knob to tune



What Have Jets Ever Done For Us?

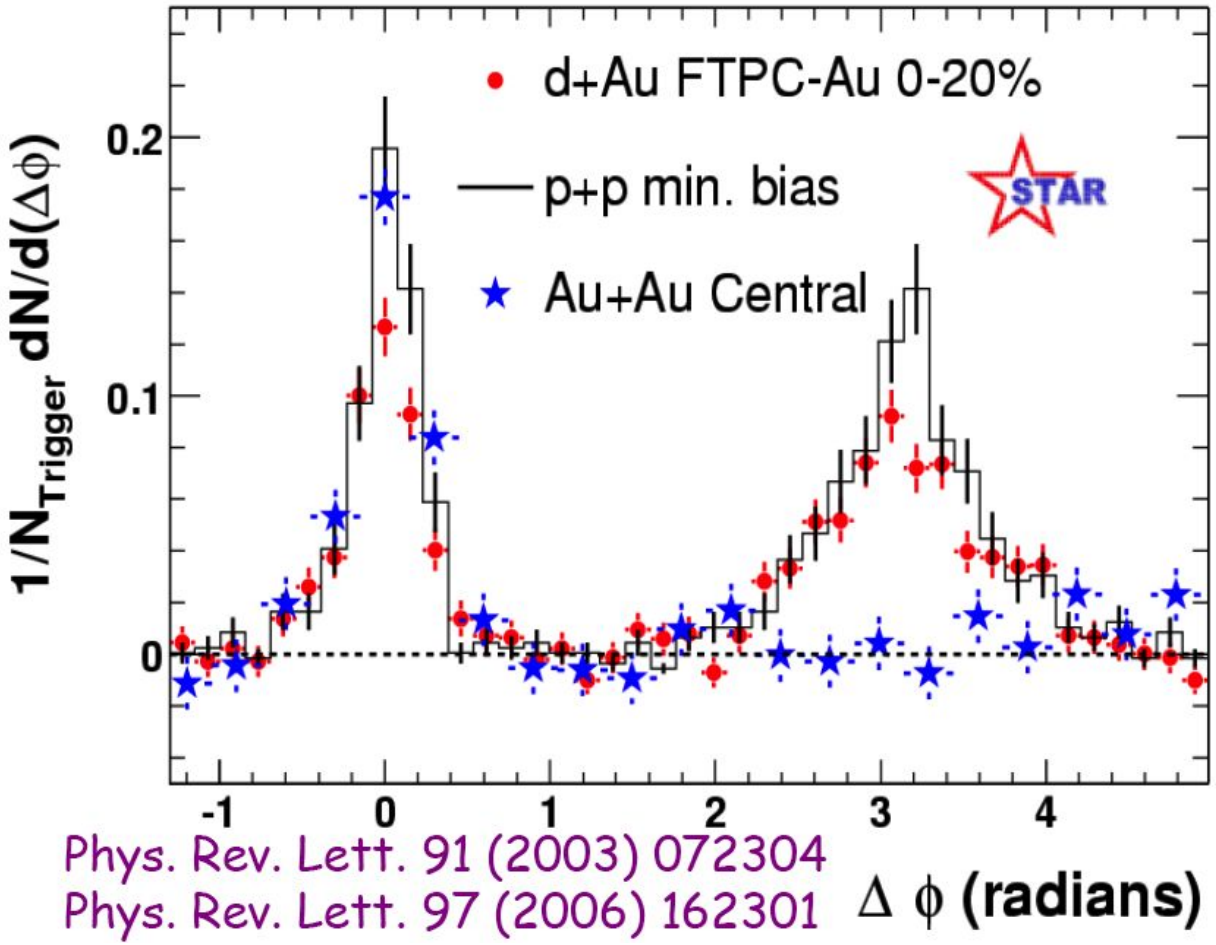
- Early di-hadron correlation (not fully reconstructed jet) from STAR
- Important measurement of jet quenching in HIC, supporting the creation of QGP
- Early result, have learned a lot since then, about both the medium and jetfinding



What Else Can We Learn From Jets?

- What is the form of partonic energy loss in the medium?
- Where does the lost energy in the jet go?
- How is the jet fragmentation modified when traversing the medium?
- Is there a flavor dependence of the energy loss?

➔ Understanding how jets interact with, and are modified by, the medium will help us to understand the medium



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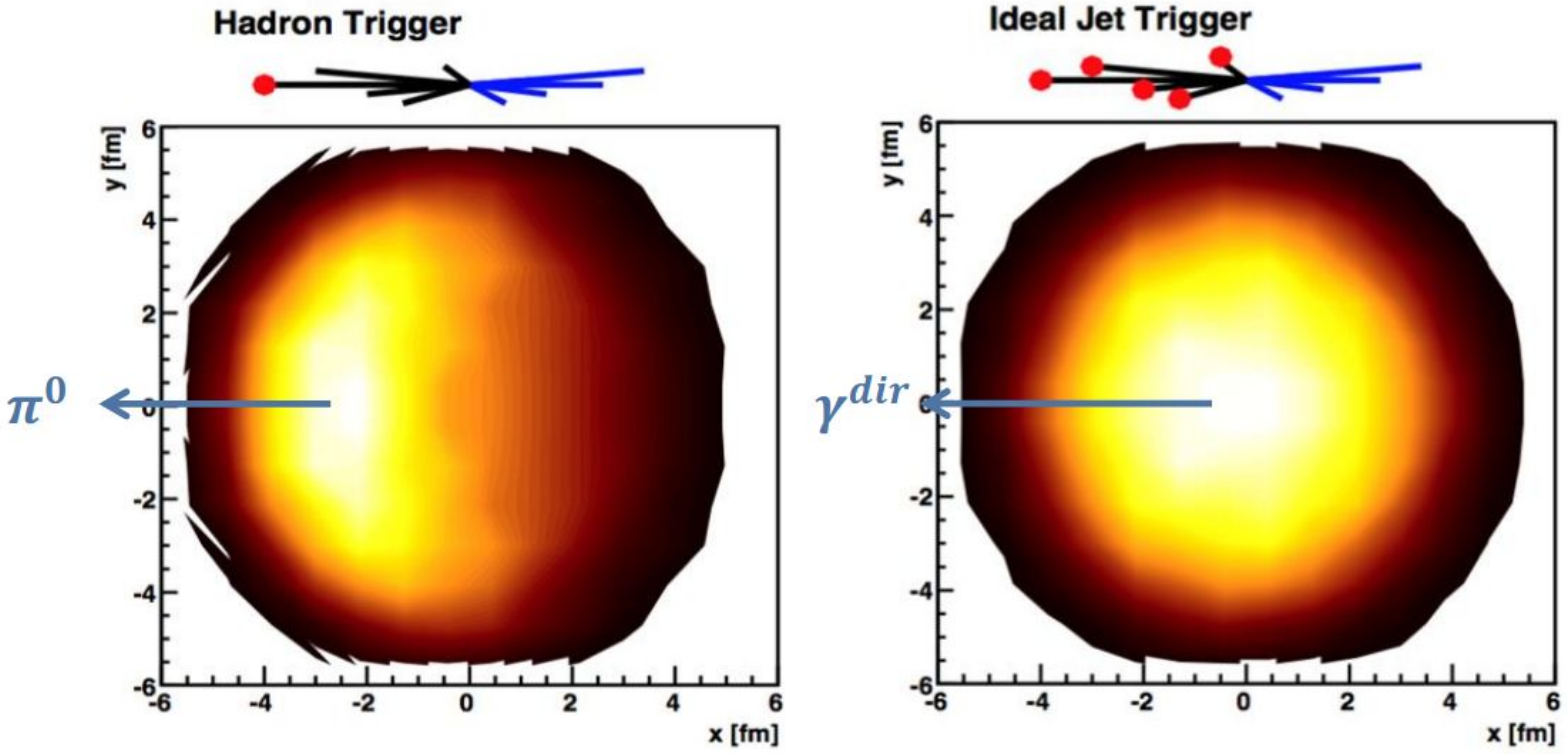
More Recent Jet Results

γ_{dir}+Jet and π^0+Jet

- γ+jet measurements have long been discussed as a prime candidate for probing the QGP created in HIC
  - Clean initial state (γ is p_T proxy for outgoing parton p_T, as it doesn't interact strongly with the medium)
  - Flavor bias (dominant process is q+g→ γ+q)

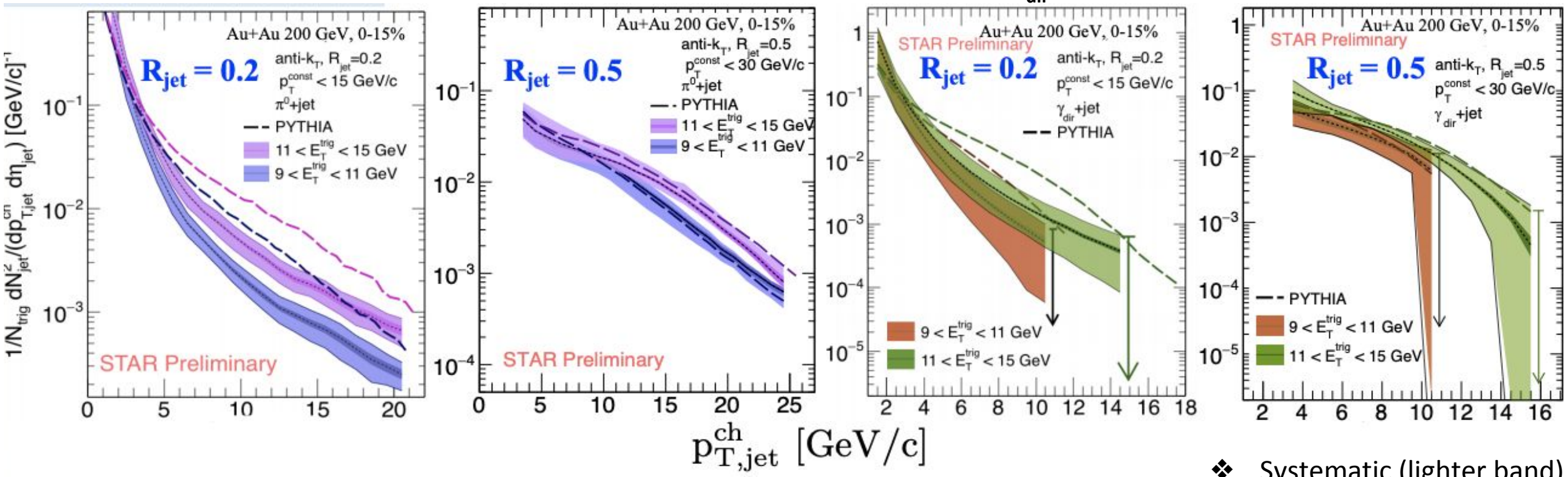
- Compare γ_{dir}+jet and π^0+jet
  - Path length
  - Color factor (toward *q*-jet)
  - Parton energy



T. Renk; arXiv:1212.0646

Jet Spectra from γ_{dir}+Jet and π^0+Jet

π^0-Triggered Recoil Jets | **γ_{dir}-Triggered Recoil Jets**



- A clear difference between recoil-jet spectra for different trigger E_T: 9-11 GeV and 11-15 GeV
- Dominant systematic uncertainties are from unfolding and from γ_{dir} background subtraction
- Systematic (lighter band) and statistical (darker band) uncertainties

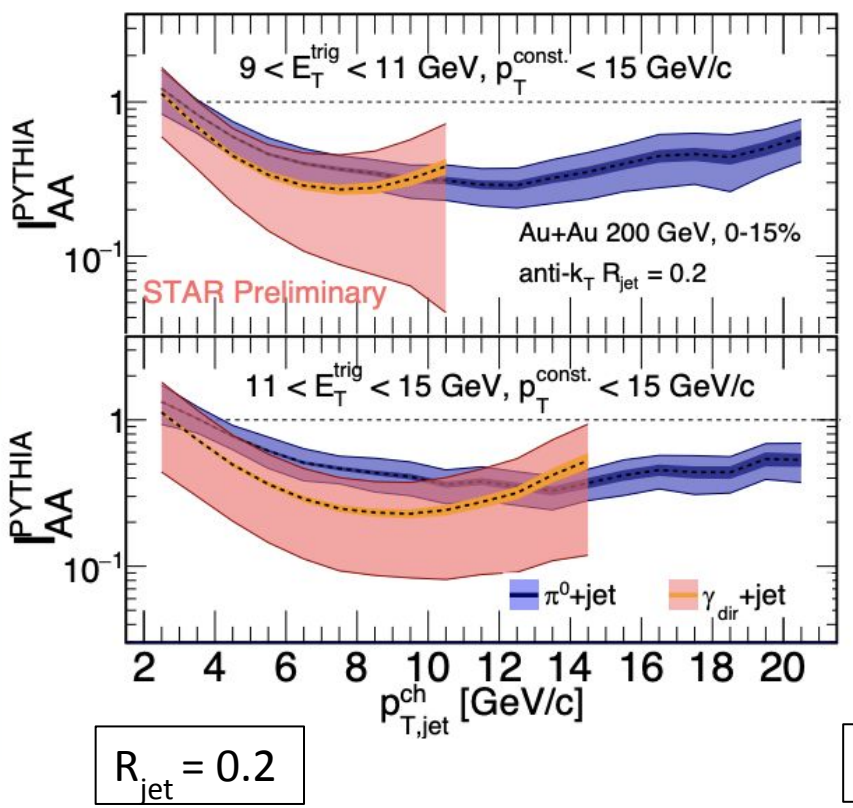
I_{AA} from π^0+Jet and γ_{dir}+Jet at STAR

$$I_{AA}(p_{T,jet}^{ch}) = \frac{Y(p_{T,jet}^{ch})^{Au+Au}}{Y(p_{T,jet}^{ch})^{p+p}}$$

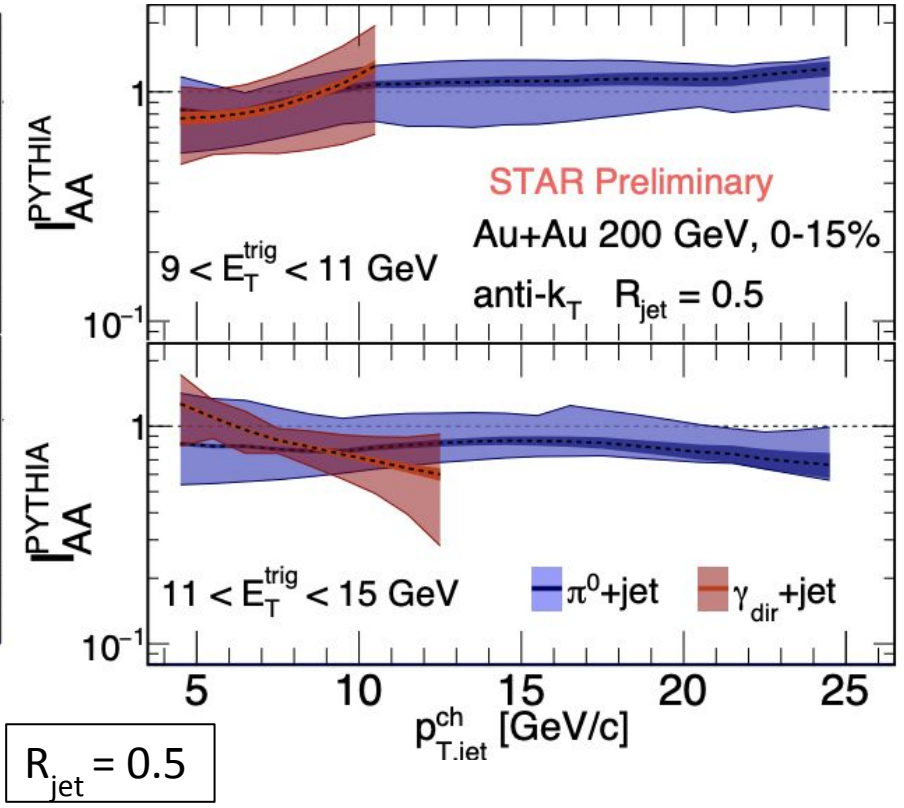
$Y(p_{T,jet}^{ch})$ are the jet per-trigger yields in Au+Au and p+p (with PYTHIA8 used for p+p).

- Clear suppression for **R=0.2**
- Negligible suppression for **R=0.5** (within uncertainties)
- Same level of suppression for π^0+Jet and γ_{dir}+Jet across different E_T bins and jet resolution parameters (R_{jet})

γ_{dir}+jet vs. π^0+jet: Recoil jet suppression for two jet radii



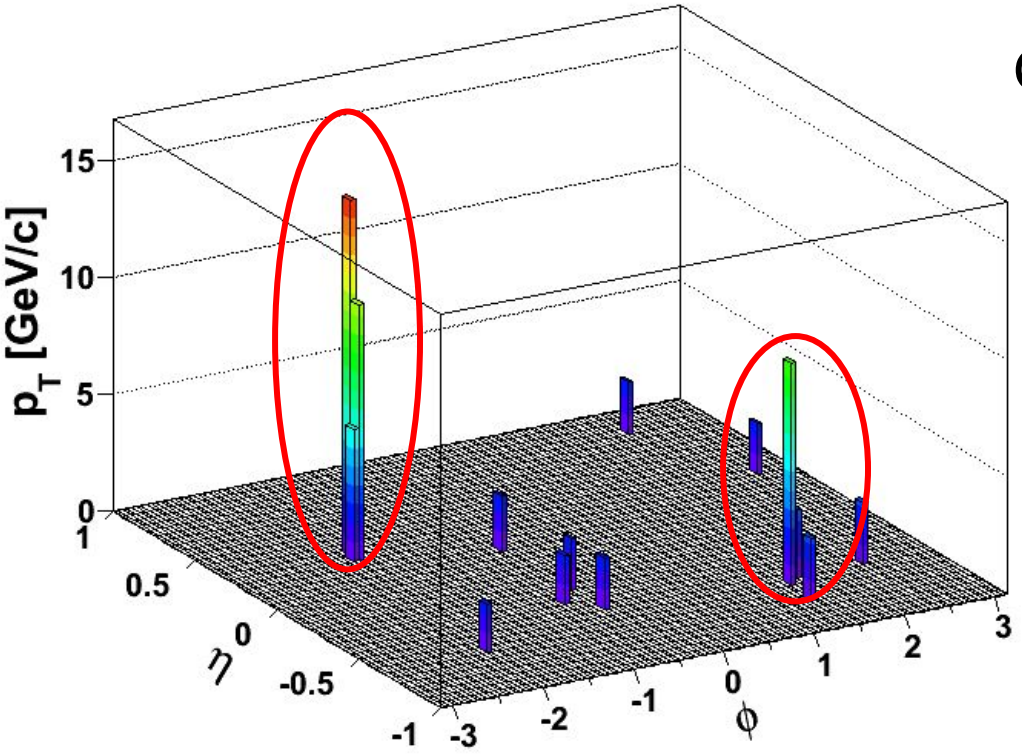
$R_{jet} = 0.2$



$R_{jet} = 0.5$

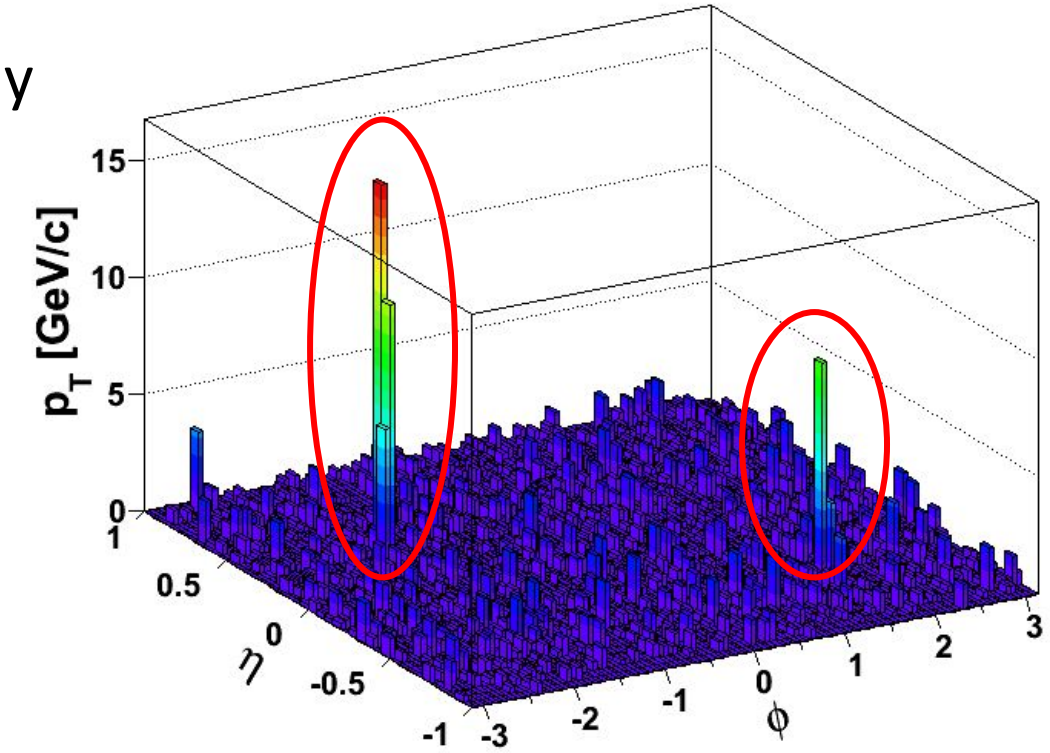
Hard-Core Jet Selection

- Hard-core kinematic cut ($p_T^{Const} > 2$ GeV/c)
- Combinatorial Jets and BG reduced



Geometrically match

- Now, $p_T^{Const} > 0.2$ GeV/c
- Biased jet population (not bad!)



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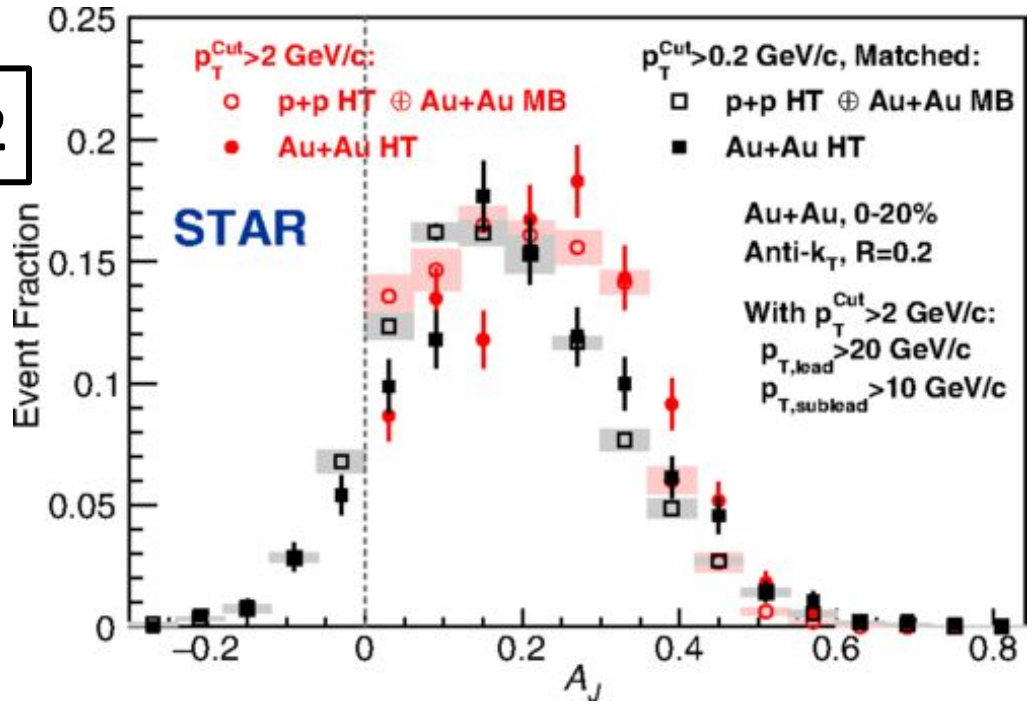
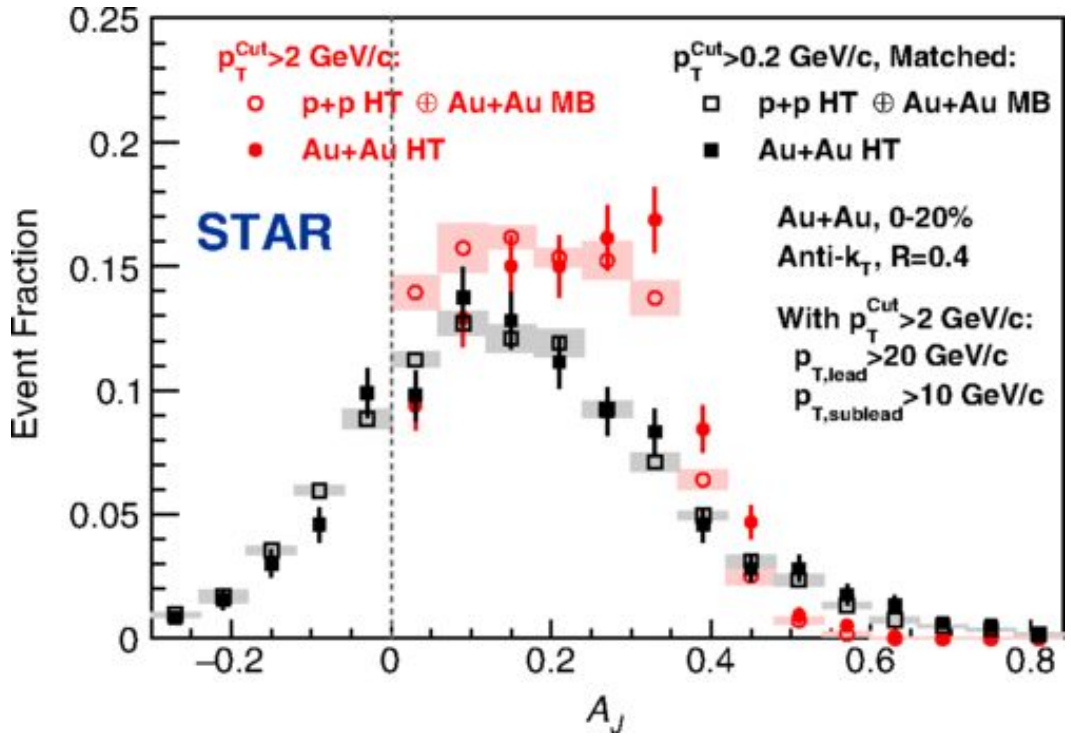
Hard Core Jet Selection ⟶ Di-Jet Imbalance

- $A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$
- **Hard-core jet** vs. **Matched jet**

R=0.2



R=0.4



- For **R=0.2**, balance not recovered in matched-jet
- For **R=0.4**, more di-jet momentum imbalance compared to p+p for hard-core jet
  - ➢ Balance recovered when soft constituents included (matched-jet)

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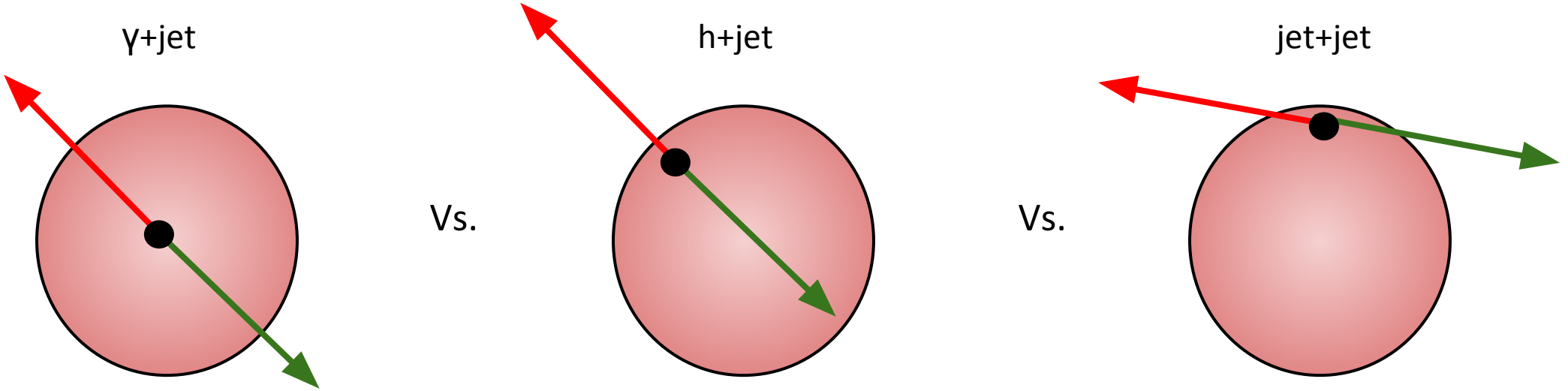
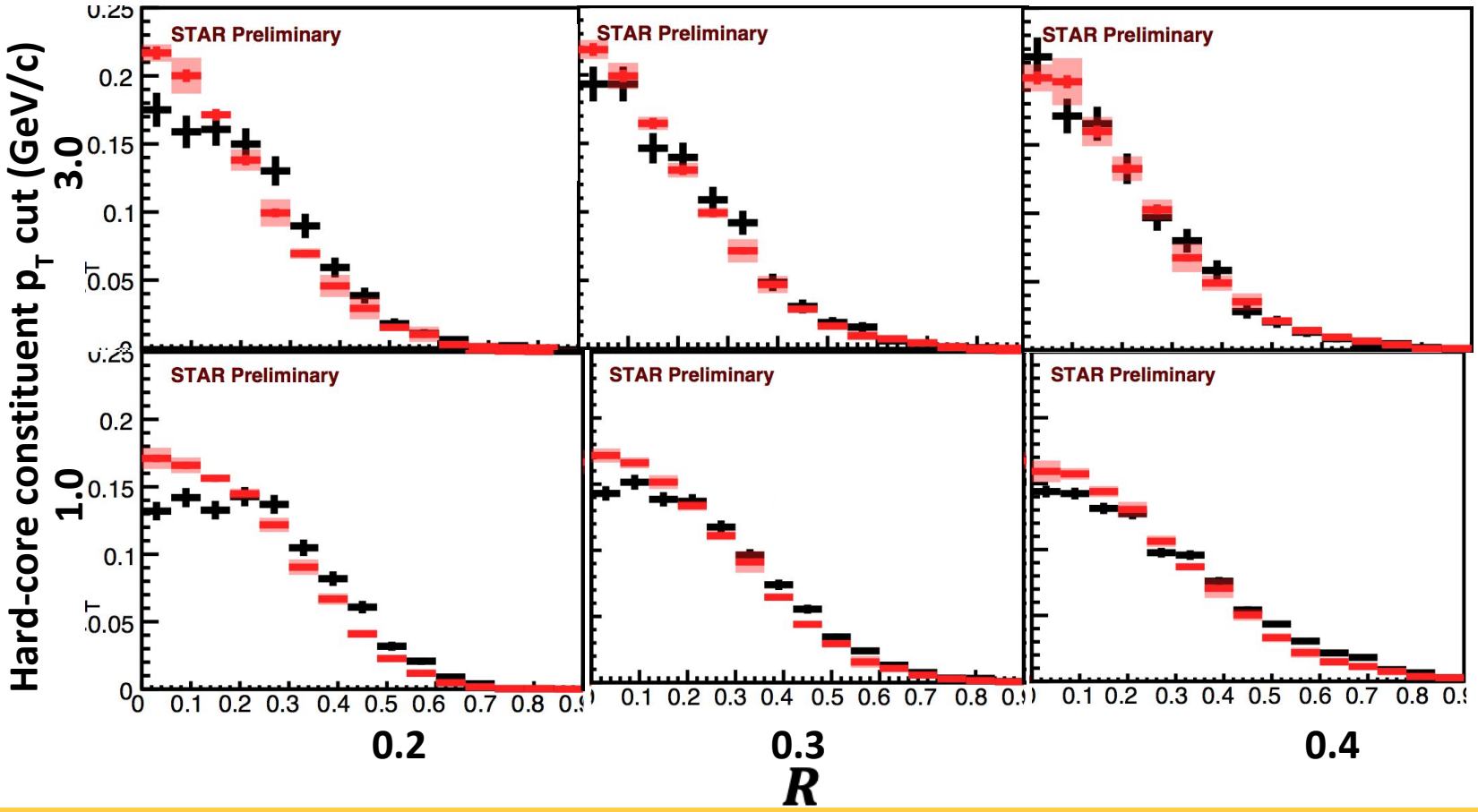
Jet Geometry Engineering



- Can we make precise jet selections to select jet events with different geometries (different path lengths through the medium)?
- Would allow better understanding of the path length dependence of jet quenching
- Requires high statistics and a method to select for different geometries

Hard Core Jet Selection → Jet Geometry Engineering

- Same analysis as before, but this time more differentially
  - ➢ Varying R, constituent p_T cut controls path length and jet vertex in medium
- At low R, softer core, balance not restored
  - ➢ Increasing R and "hardness" of core brings balance back



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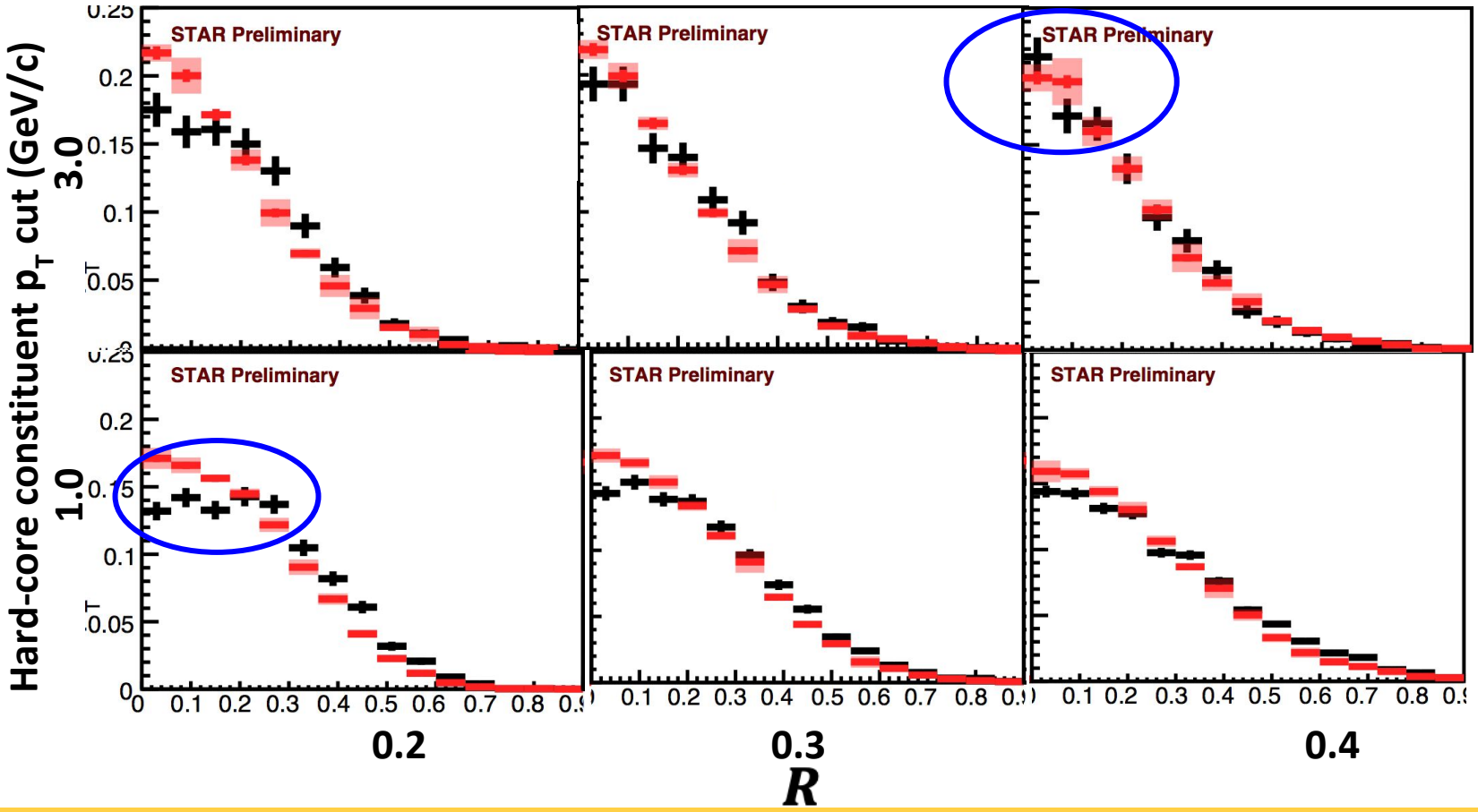
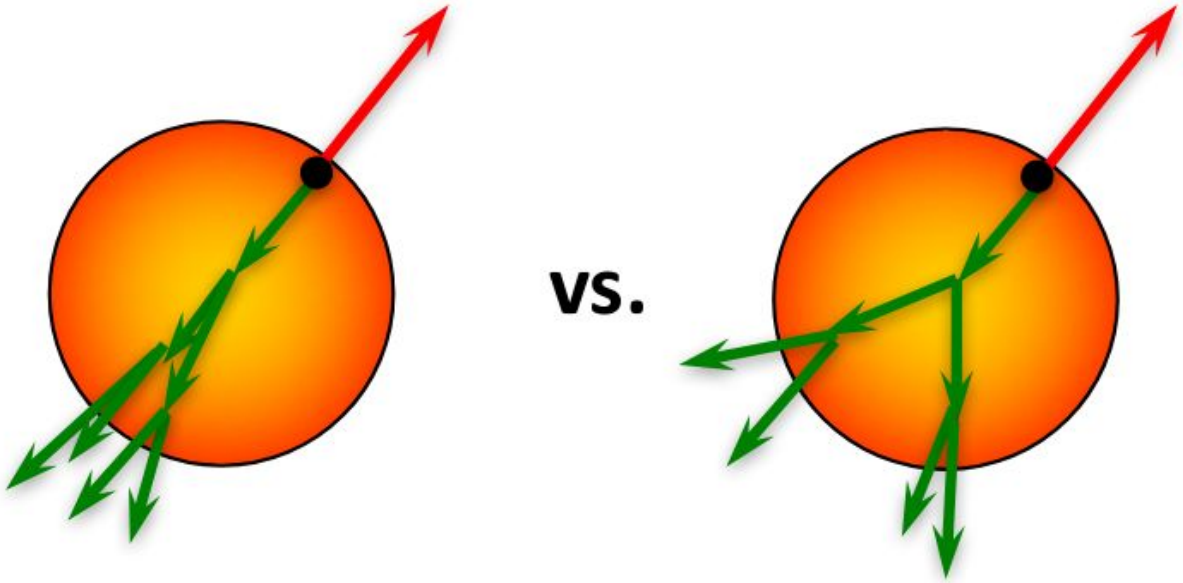


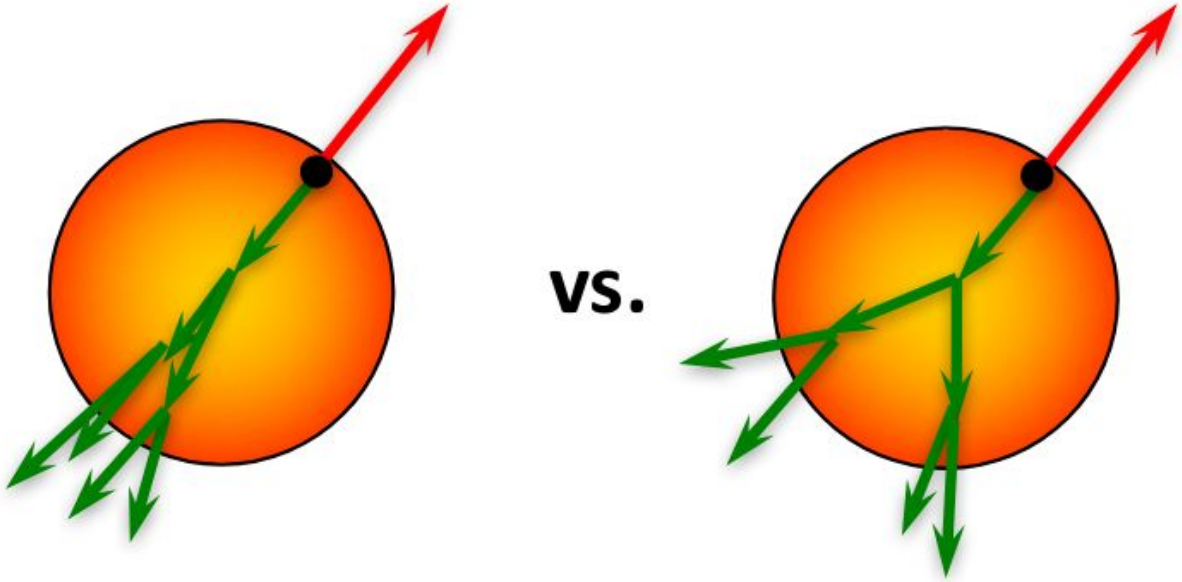
Jet Structure Observables

Sub-Jet Observables

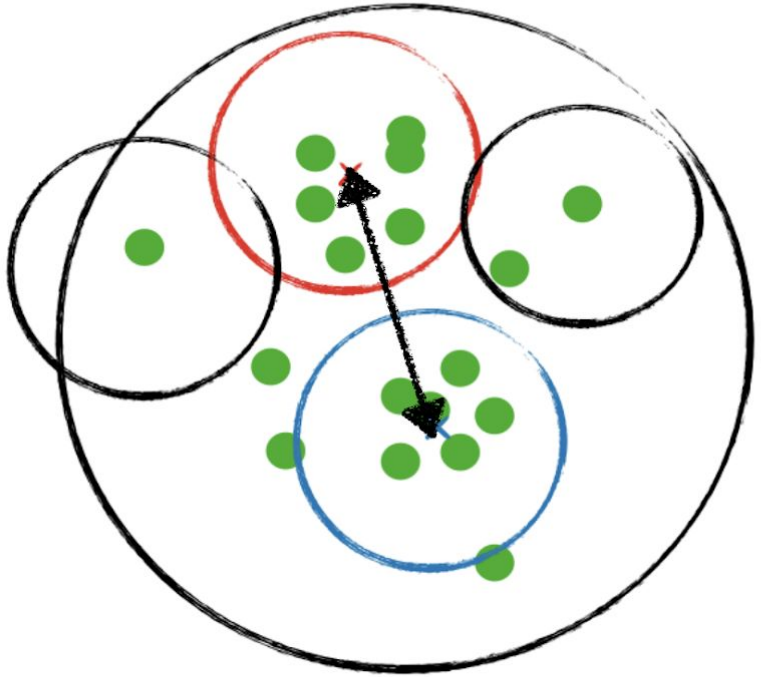


- Can we probe the coherence length of the medium?

Sub-Jet Observables



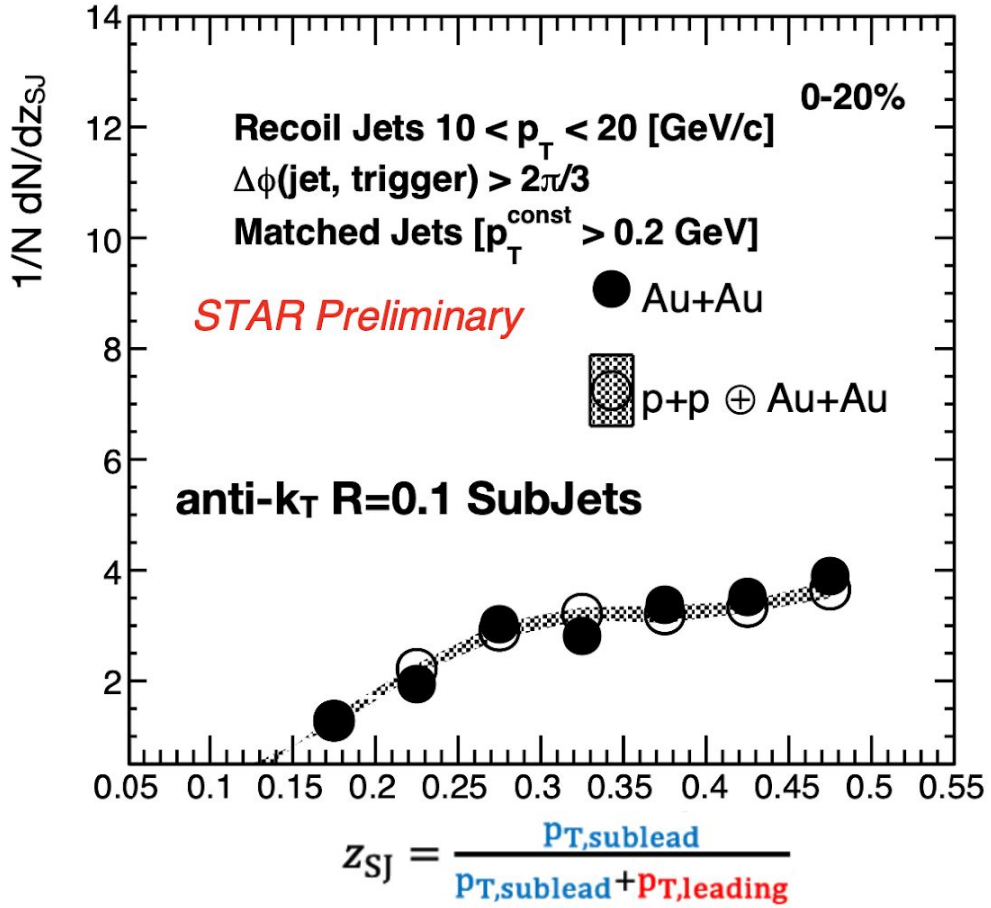
In practice with real jets

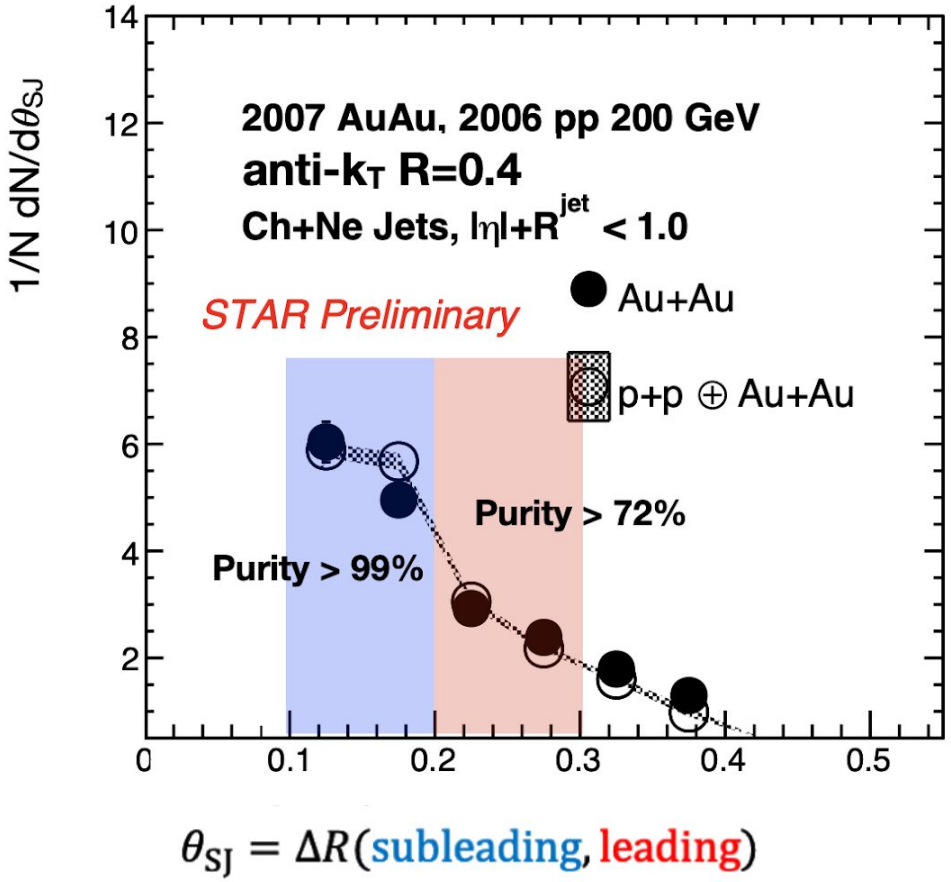


- Can we probe the coherence length of the medium?
  - **Recluster jet constituents with a smaller radius** – identify regions of jet-like features within the mother jet
  - Choose the **leading** and **subleading** subjets
  - $z_{SJ} = \frac{p_{T,sublead}}{p_{T,sublead}+p_{T,leading}}$; $\theta_{SJ} = \Delta R(\text{subleading}, \text{leading})$

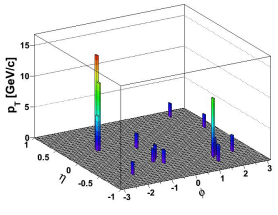
Sub-Jet Observables

- The z_{SJ} distribution favors harder splits
- For both z_{SJ} and θ_{SJ}, no significant difference in shape due to jet quenching

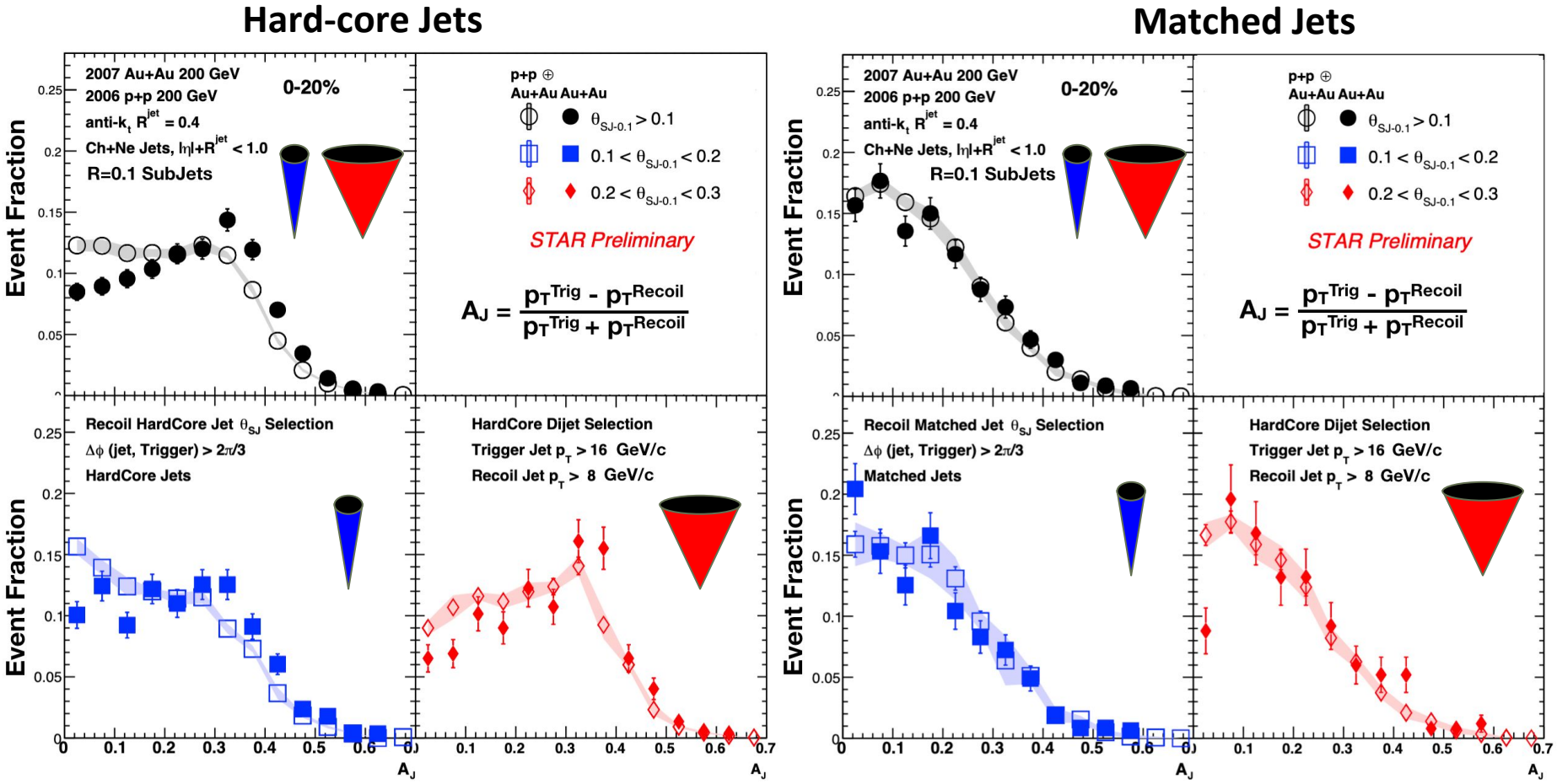


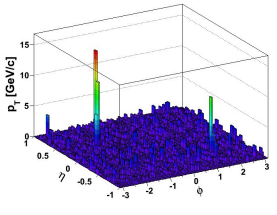


Di-Jet Imbalance as a Function of θ_{SJ}



- A_J shape different for wide vs. narrow jets
- Significant imbalance for all θ_{SJ}

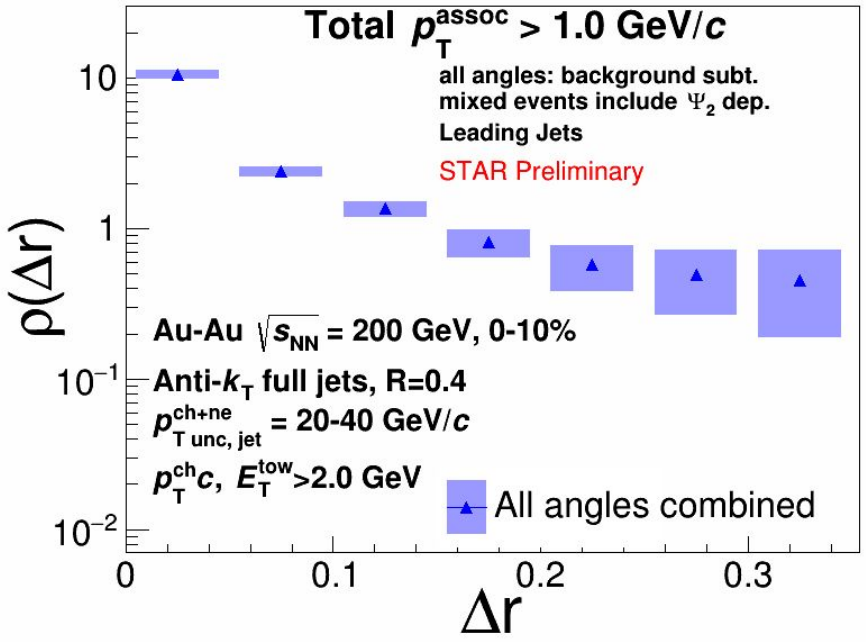




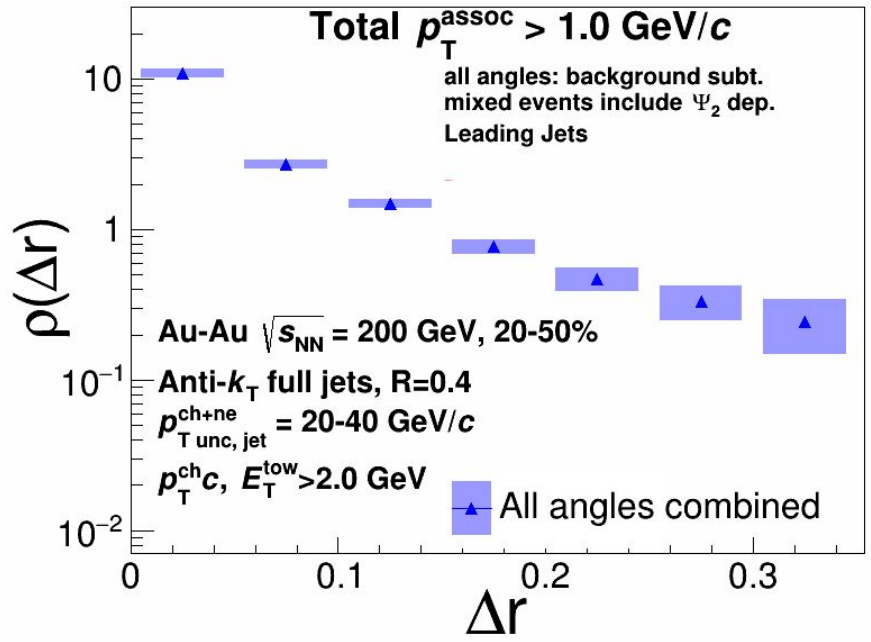
- Matched A_J similar for wide vs. narrow jets
- Balance indicating recovery for all θ_{SJ}

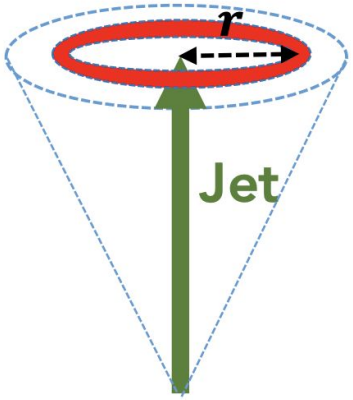
Jet Shape

0-10% Centrality



20-50% Centrality





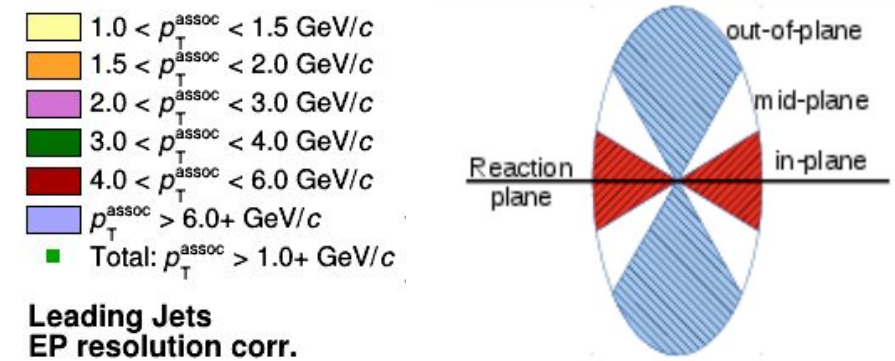
$$\Delta r = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$

- R=0.4 full jets, 20-40 GeV/c, "HardCore jet selection"
- Jet shapes less steep than LHC measurement
  - Due to different energies or kinematic and jet selections?

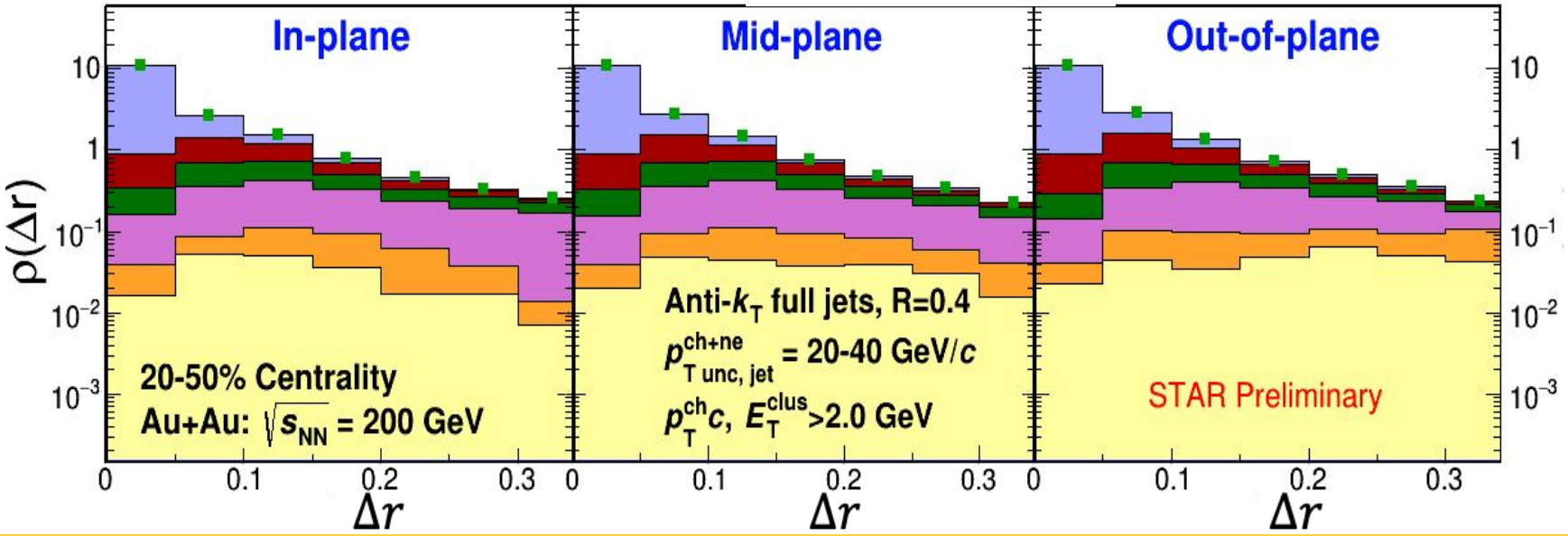
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jet}\frac{\sum_{track\in(r-\delta r/2,\, r+\delta r/2)} p_{T,track}}{p_{T,jet}}$$

Jet Shape Vs. Event Plane

- Can control the path-length of jet quenching by measuring as a function of centrality and jet azimuthal angle relative to the event plane
  - ➢ **Average path length out-of-plane > average path length in-plane**



- Below 2 GeV/c, hints of EP ordering:
  out > mid > in-plane
  - ➢ Indication that out-of-plane jets have more low-p_T hadrons than in-plane jets
- Above 2 GeV/c, no indication of dependence on the EP



Summary

- Jet energy lost in narrow core (R=0.2), and recovered in the periphery (R=>0.4); for hard core jets, γ_{dir} triggered jets and for jets of various subjet angles → all consistent with a softening and broadening of jet

- Moving towards more quantitative understanding of jet quenching
  - ➢ Energy not just lost, but recovered and measured using various different methods

- With its detector subsystems, high statistics datasets and collisional energies and systems, STAR is in a prime place for jet measurements

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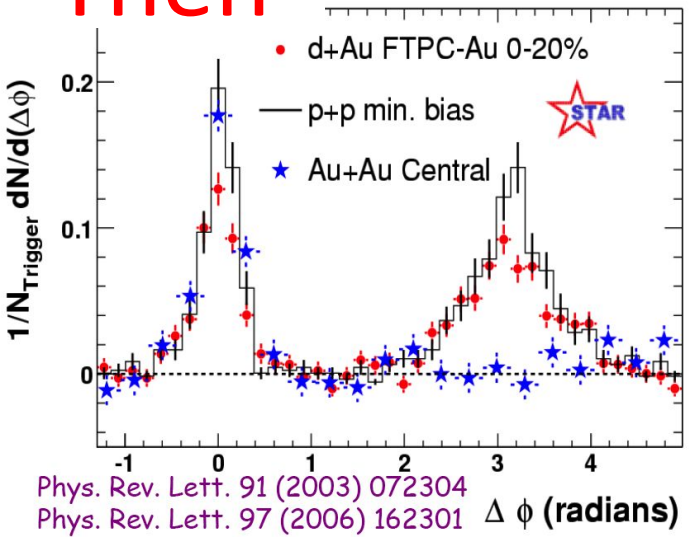

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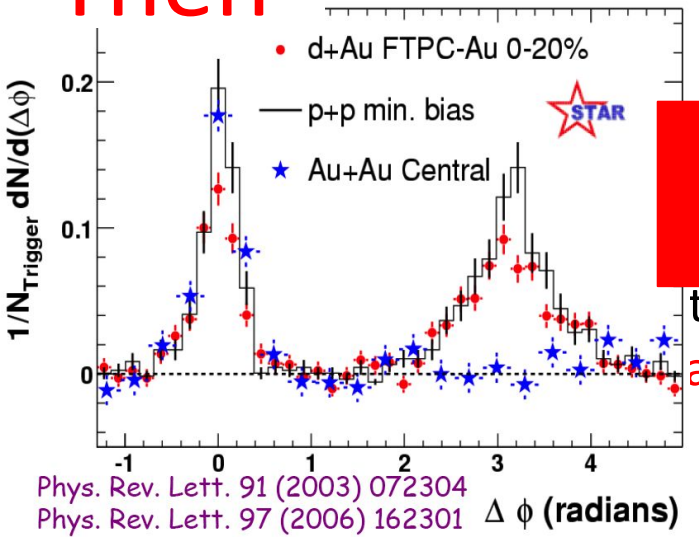

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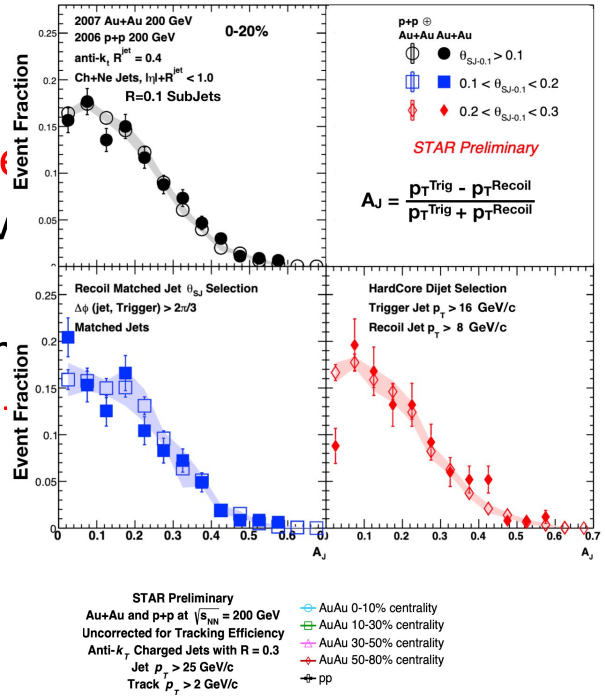

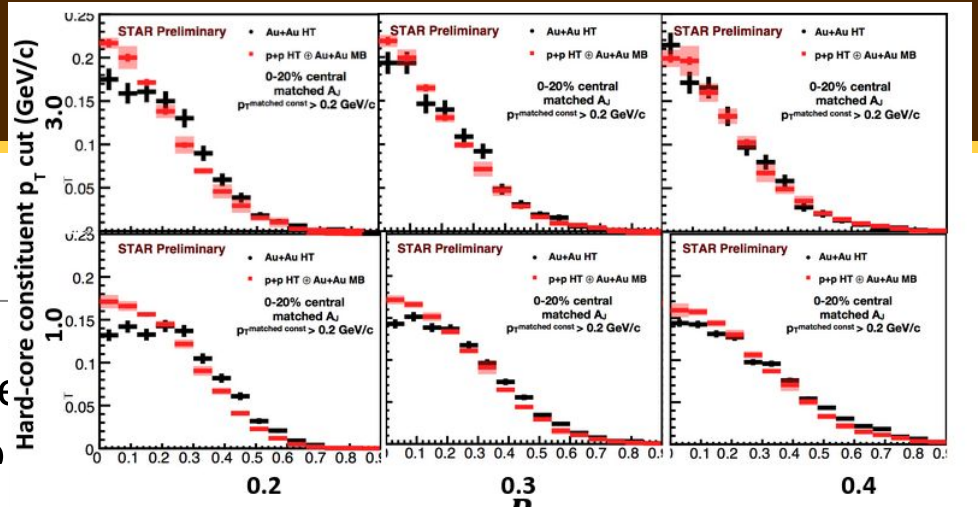

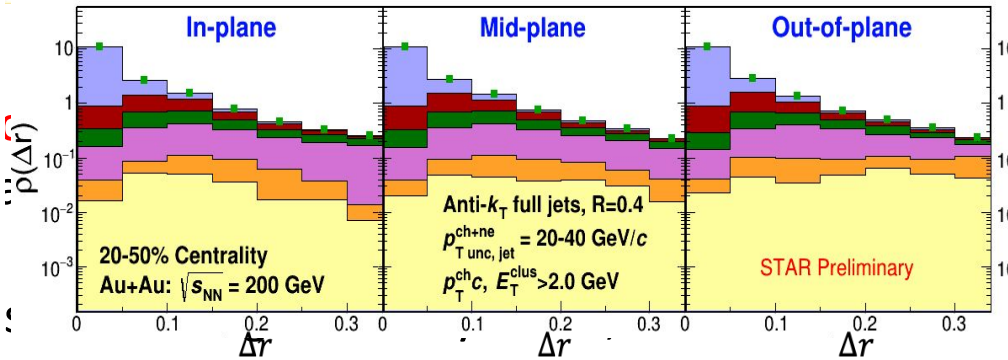

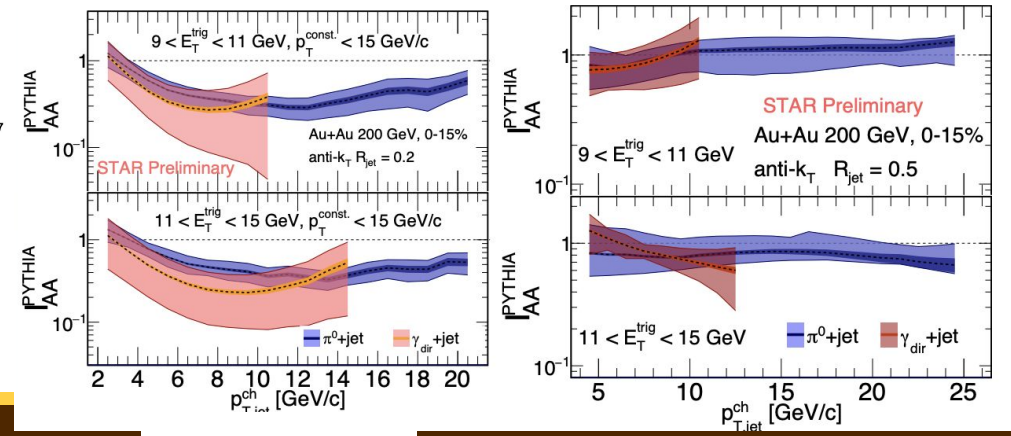

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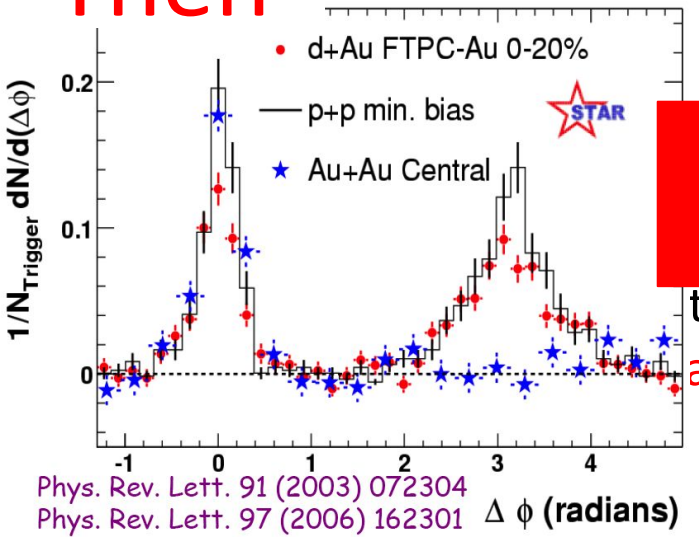
ping of jet



Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

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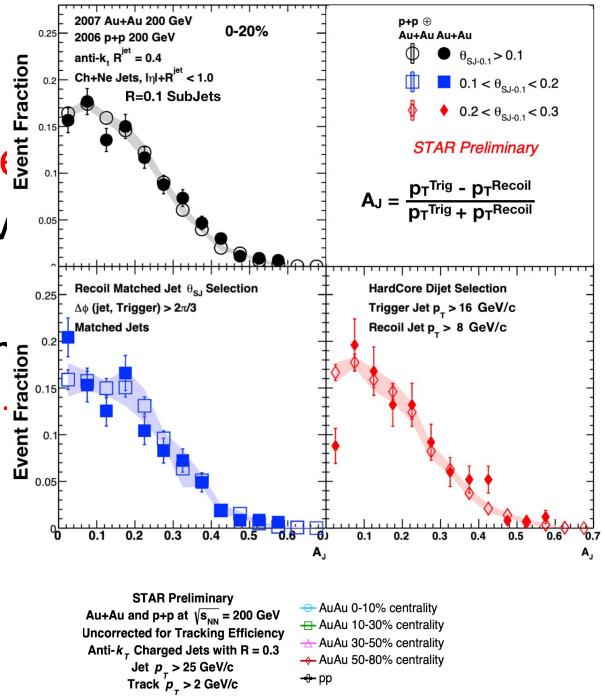
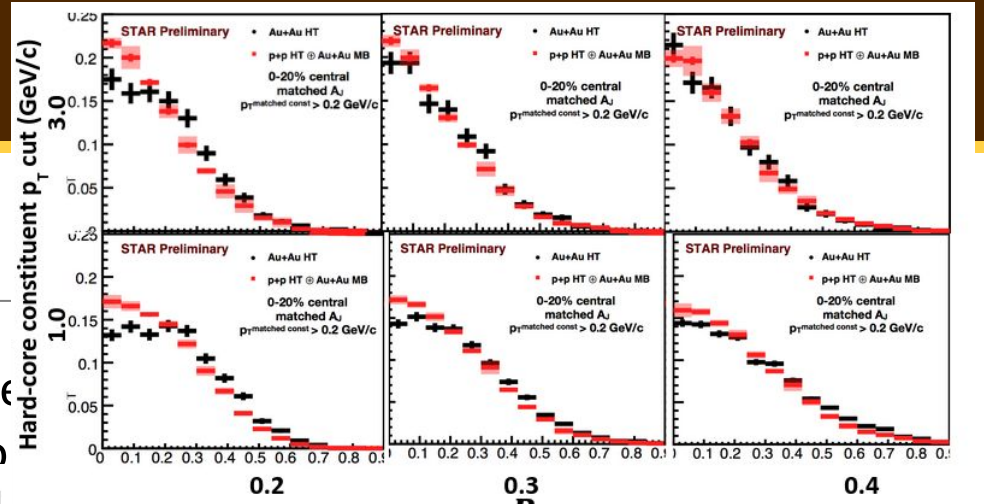
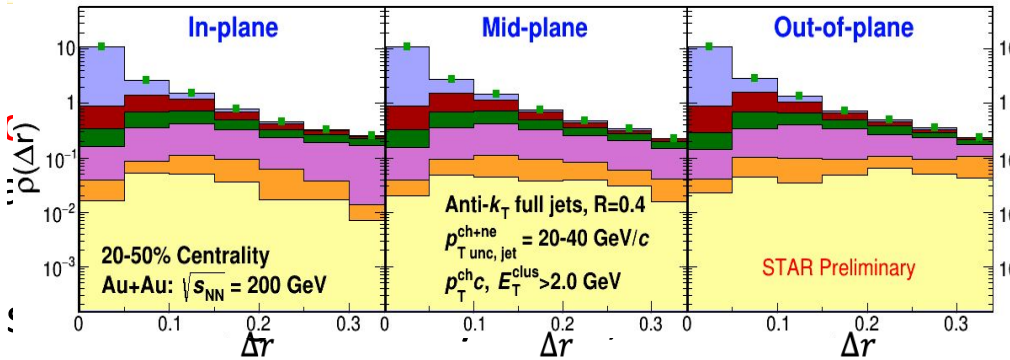
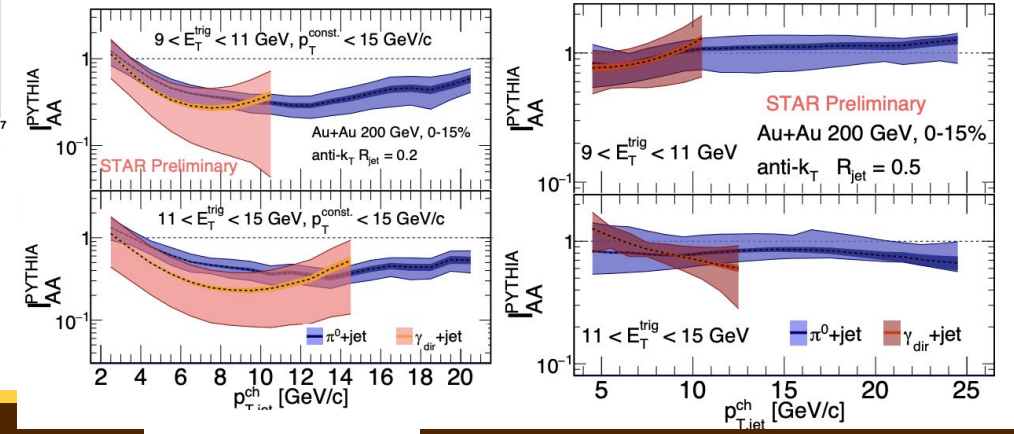


Stay tuned for more STAR jet results!



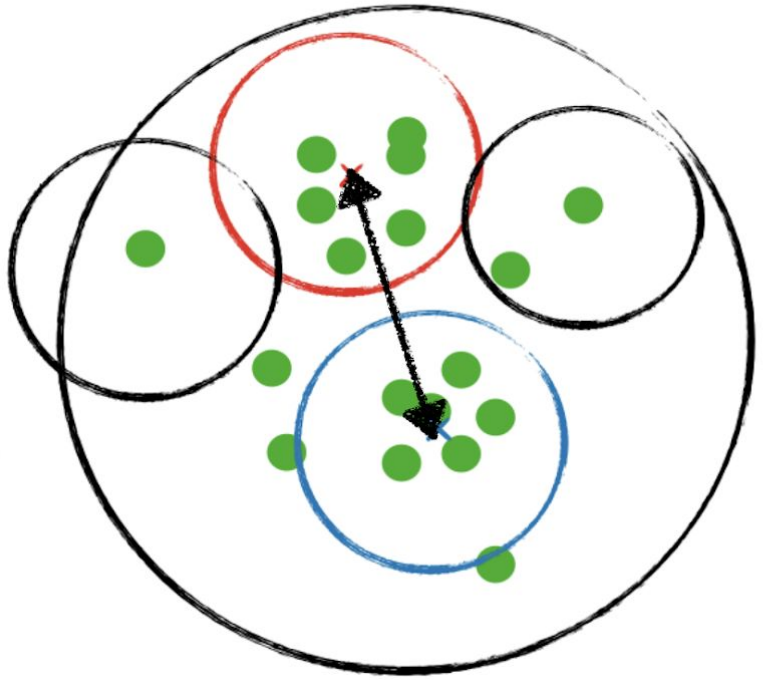


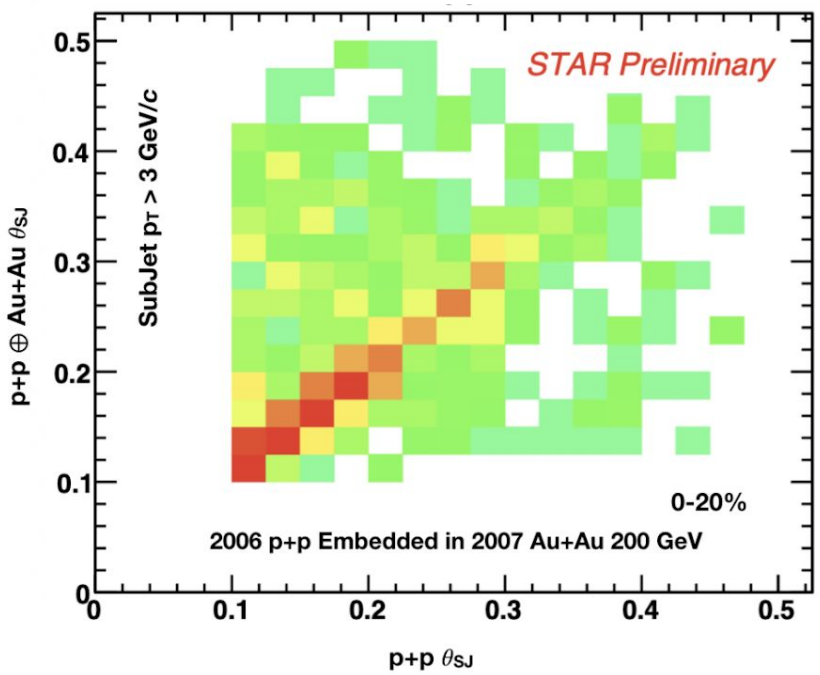


Now

Backup

Need observables that are robust to underlying event background.





anti-k_T R=0.4, 20 < p_T < 30 GeV/*c*
Constituent-Subtracted Jets

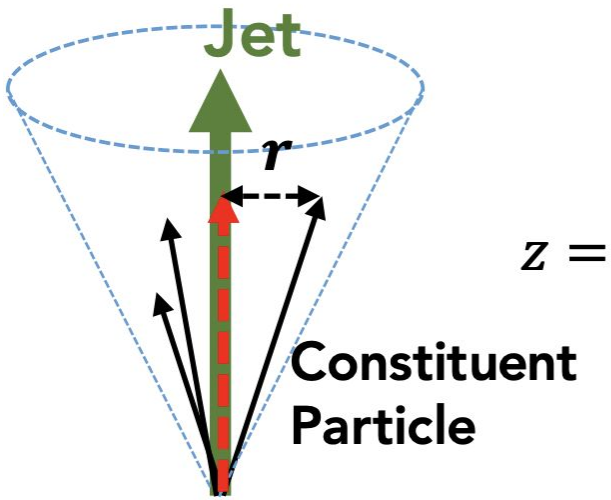
Berta, P et al. JHEP 06 (2014) 092

θ_{SJ} (w/ R=0.1 subjets) less sensitive Au+Au underlying event

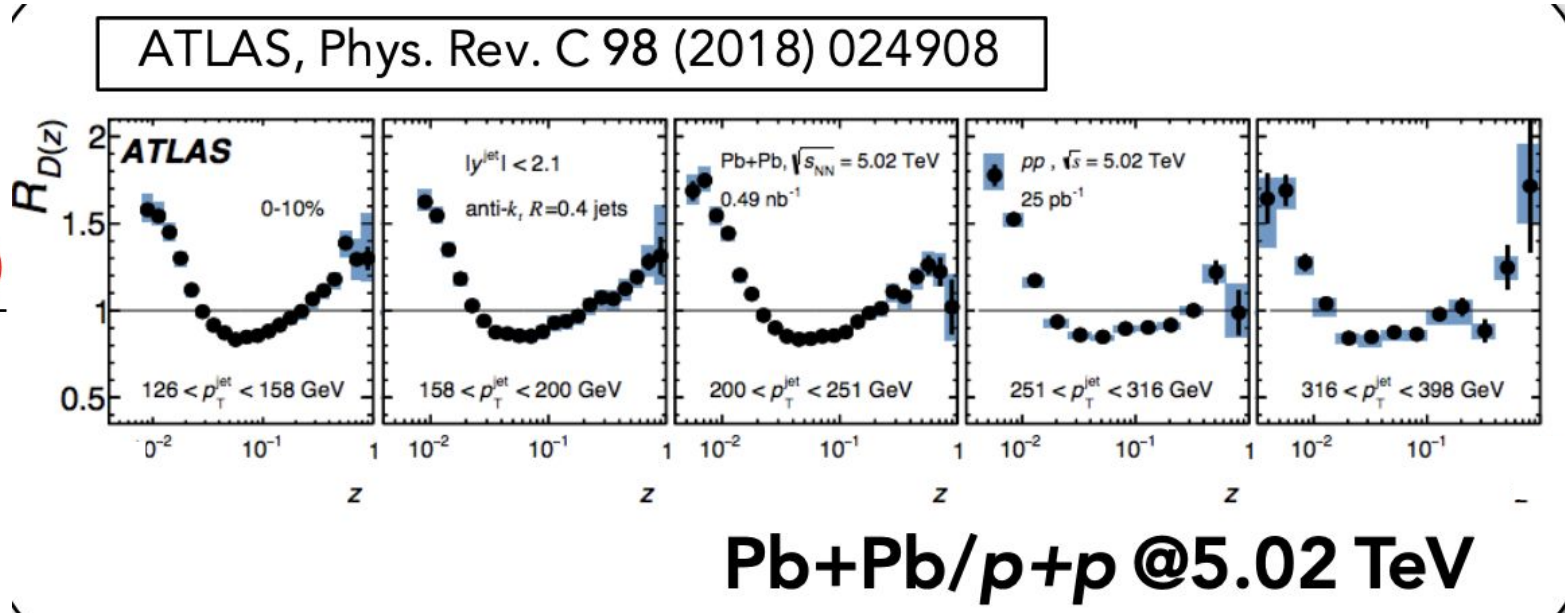
Comparisons between Au+Au and p+p embedded in Au+Au to isolate quenching effects

- **Recluster jet constituents with a smaller radius** – identify regions of jet-like features within the mother jet
- Choose the **leading** and **subleading** subjets
- $z_{SJ} = \frac{p_{T,\text{sublead}}}{p_{T,\text{sublead}} + p_{T,\text{leading}}}$; $\theta_{SJ} = \Delta R(\text{subleading}, \text{leading})$

Jet Fragmentation Functions



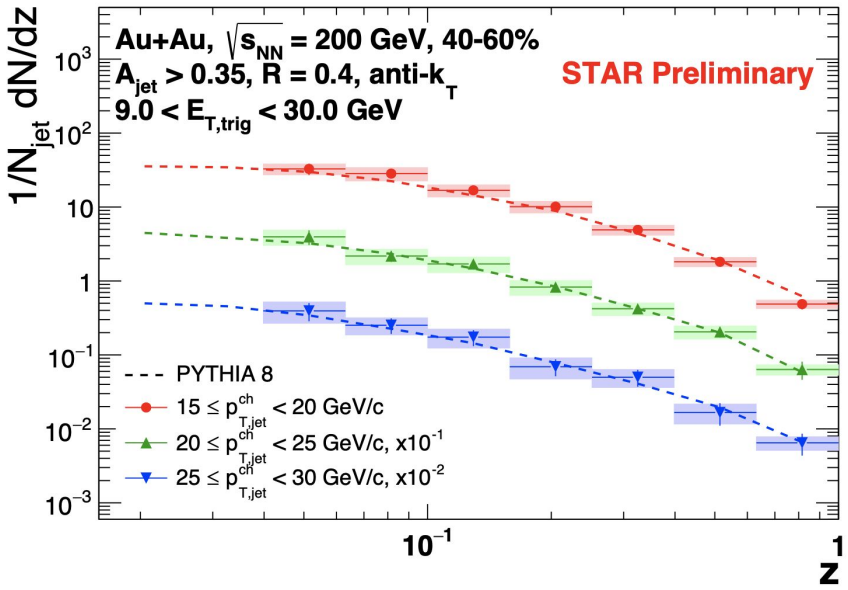
$$z = \frac{p_{\mathrm{T,track}} \cos(r)}{p_{\mathrm{T,jet}}}$$

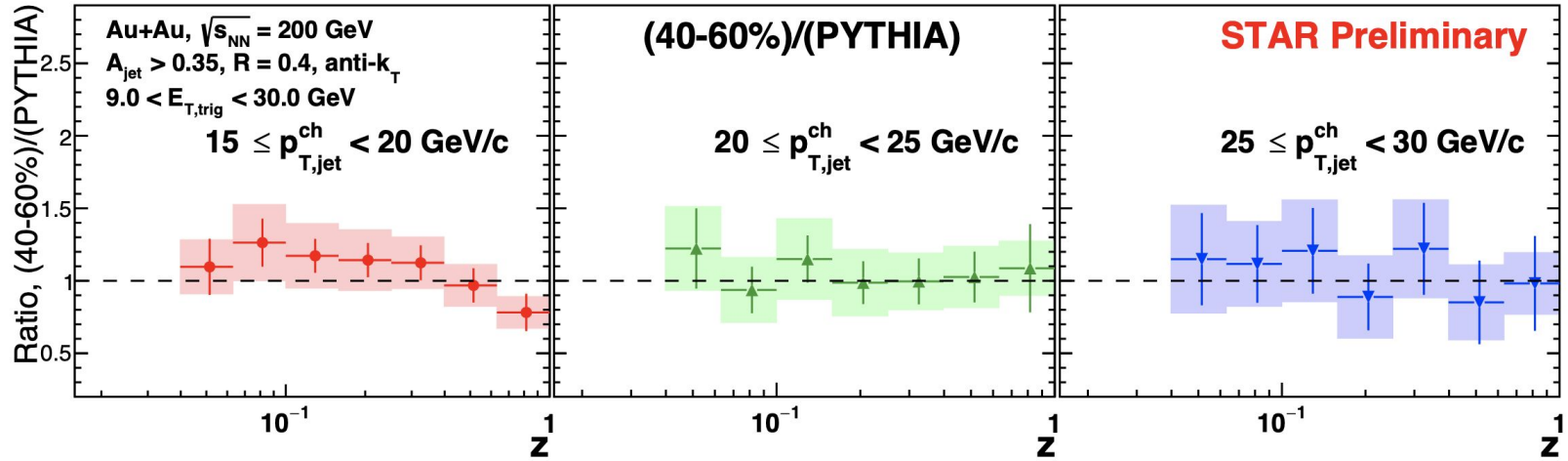


- Fragmentation function: $\frac{1}{\mathrm{N_{jet}}} \frac{\mathrm{dN}}{\mathrm{d}z}$
- Distribution of longitudinal momentum fraction of particles with respect to the jet.

Not previously measured at RHIC energy!

Jet Fragmentation Functions





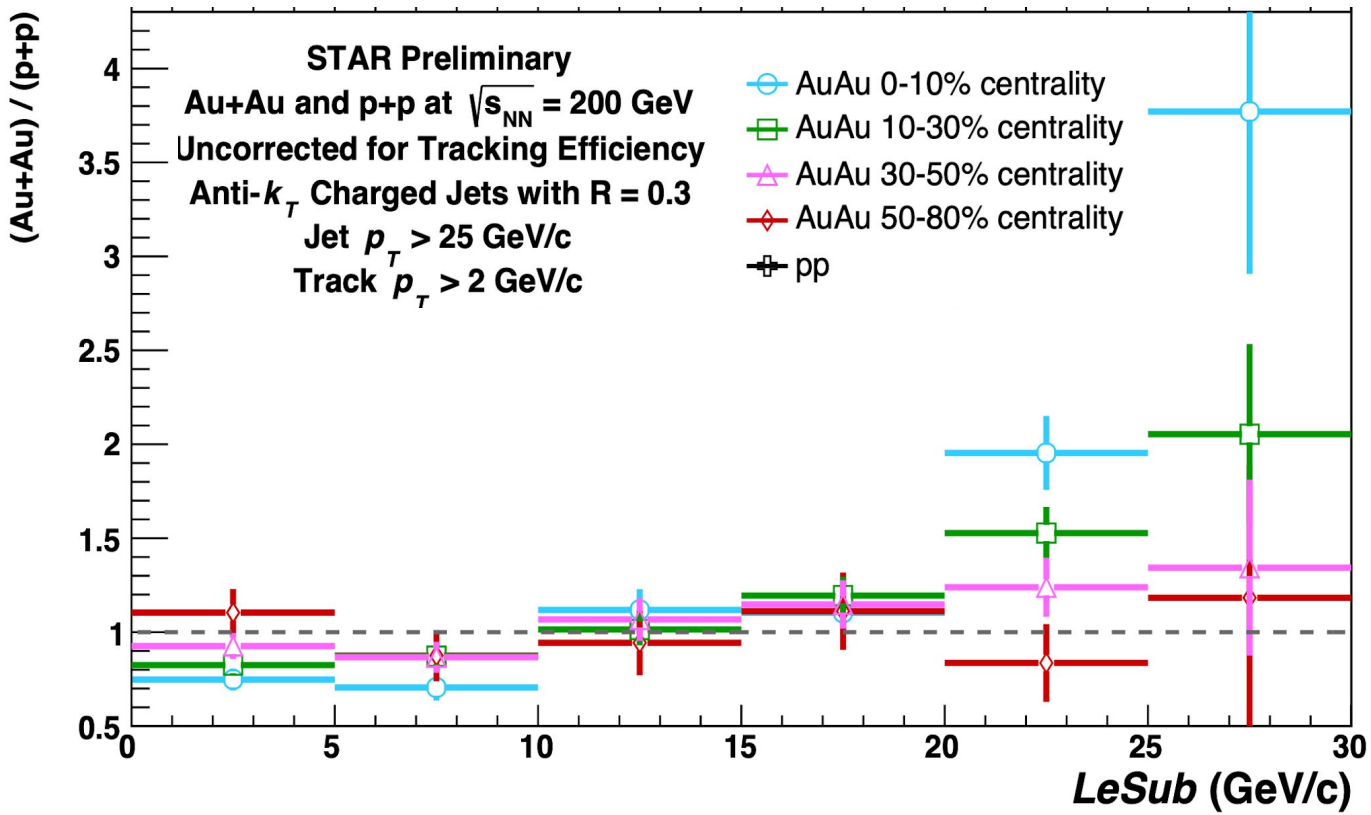
Au+Au 40-60%/PYTHIA8

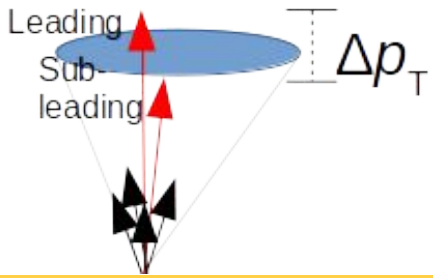
- Jet fragmentation functions for the 40-60% centrality class for three $p_{T,jet}$ ranges.
- Ratios consistent with 1 for all p_T ranges.
  - ➢ 40-60% too peripheral?
- Results for p+p and more-central events + higher statistics in progress!

LeSub

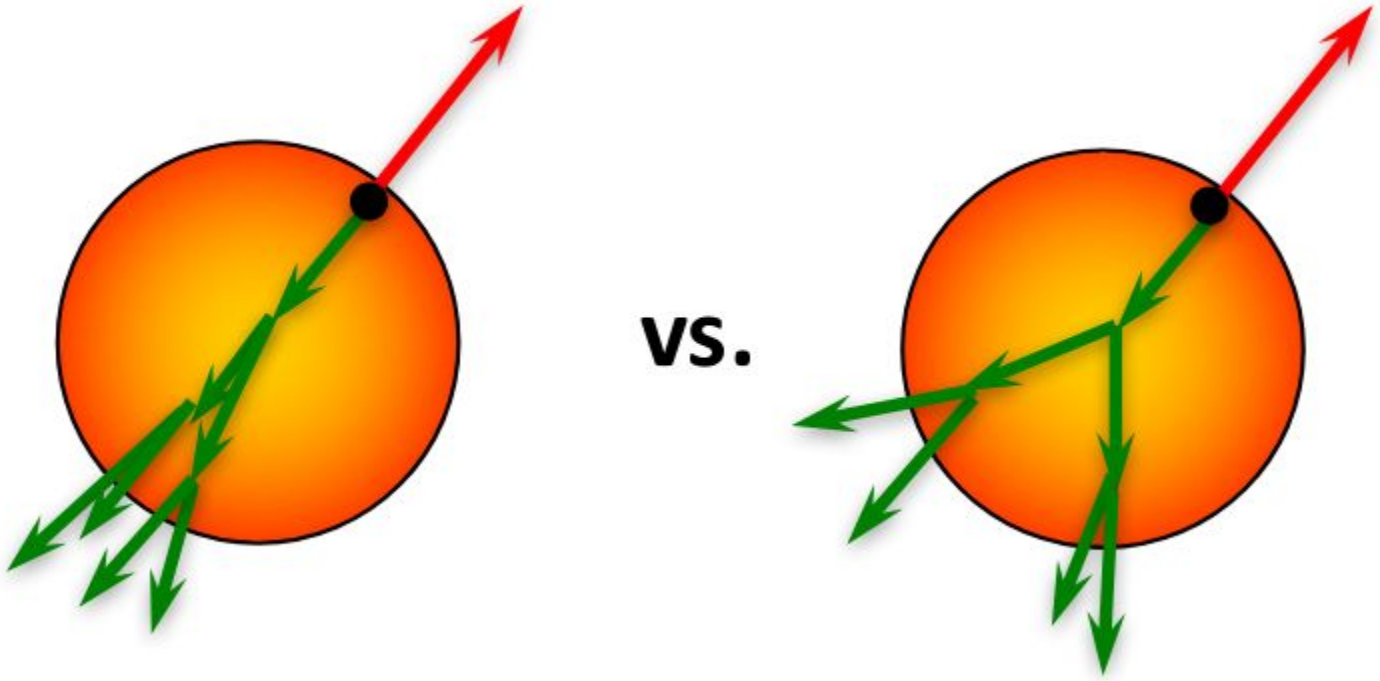
- The difference in momentum of the two highest constituents in a jet
- Robust against contributions of soft background particles
- Jets which produce more fragments with a soft momentum spectrum will have a low LeSub

$$LeSub = p_{T,track}^{lead} - p_{T,track}^{sublead}$$





Sub-Jet Observables



- Can also compare jets with different opening angles
- Understand the coherence length of the medium, at what angle is the jet resolved as one prong vs two prongs?