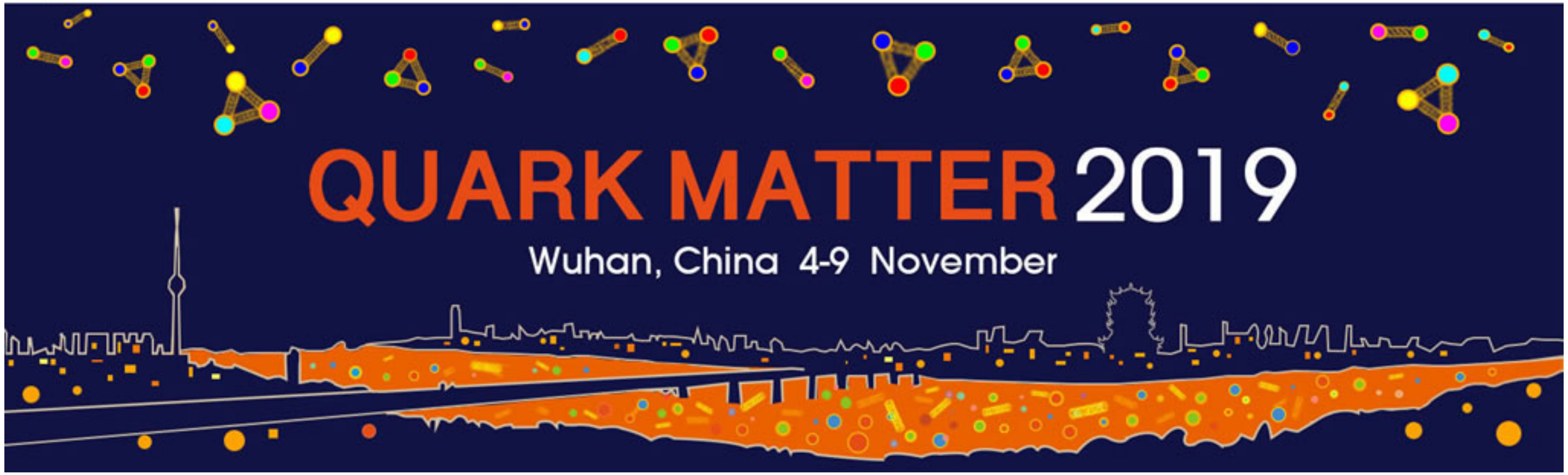
In part supported by U.S. DEPARTMENT OF ENERGY | Office of Science

STAR

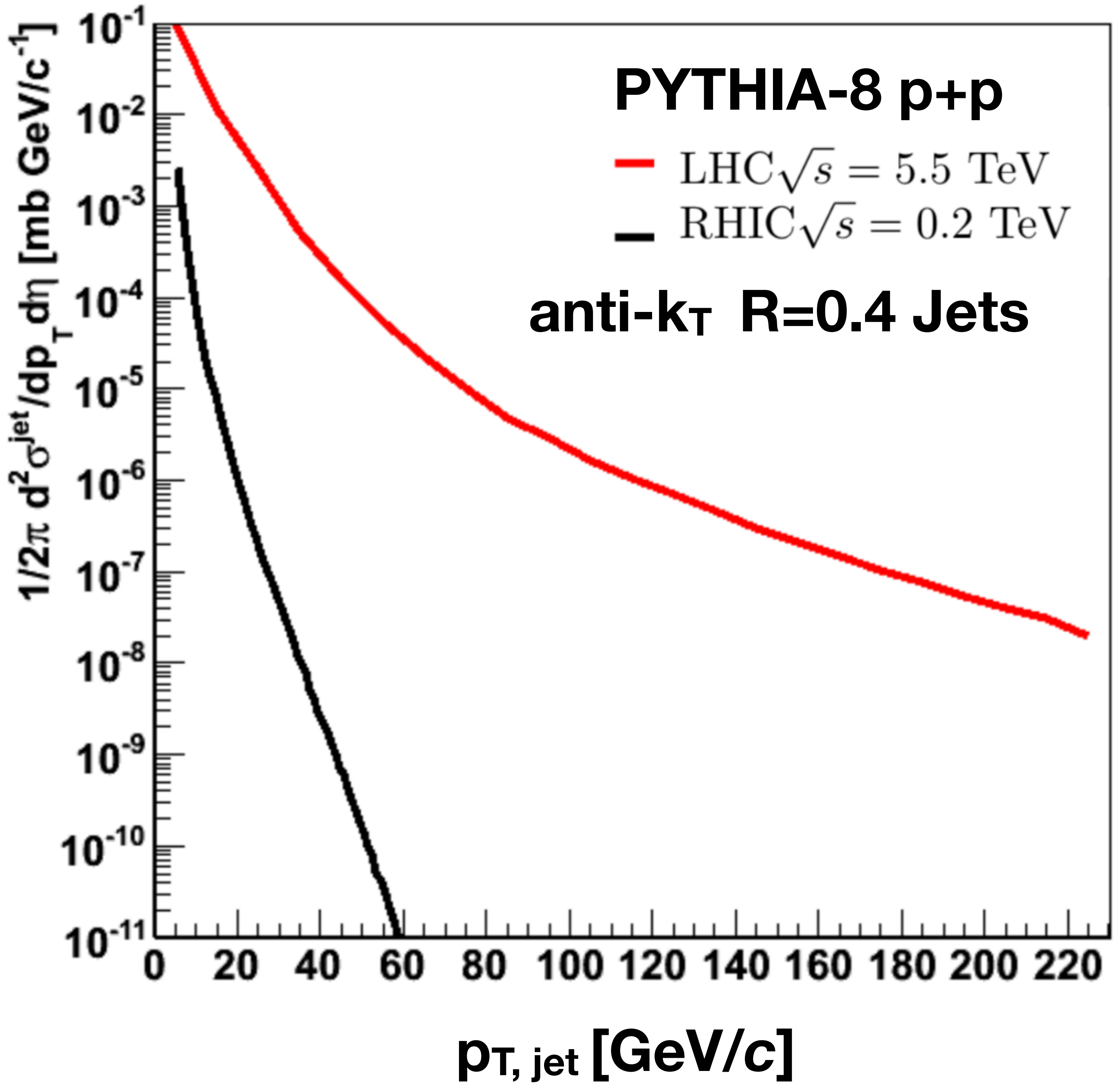
WAYNE STATE

Constraining parton energy loss via angular and momentum based differential jet measurements at STAR

Raghav Kunnawalkam Elayavalli (WSU)
for the STAR Collaboration



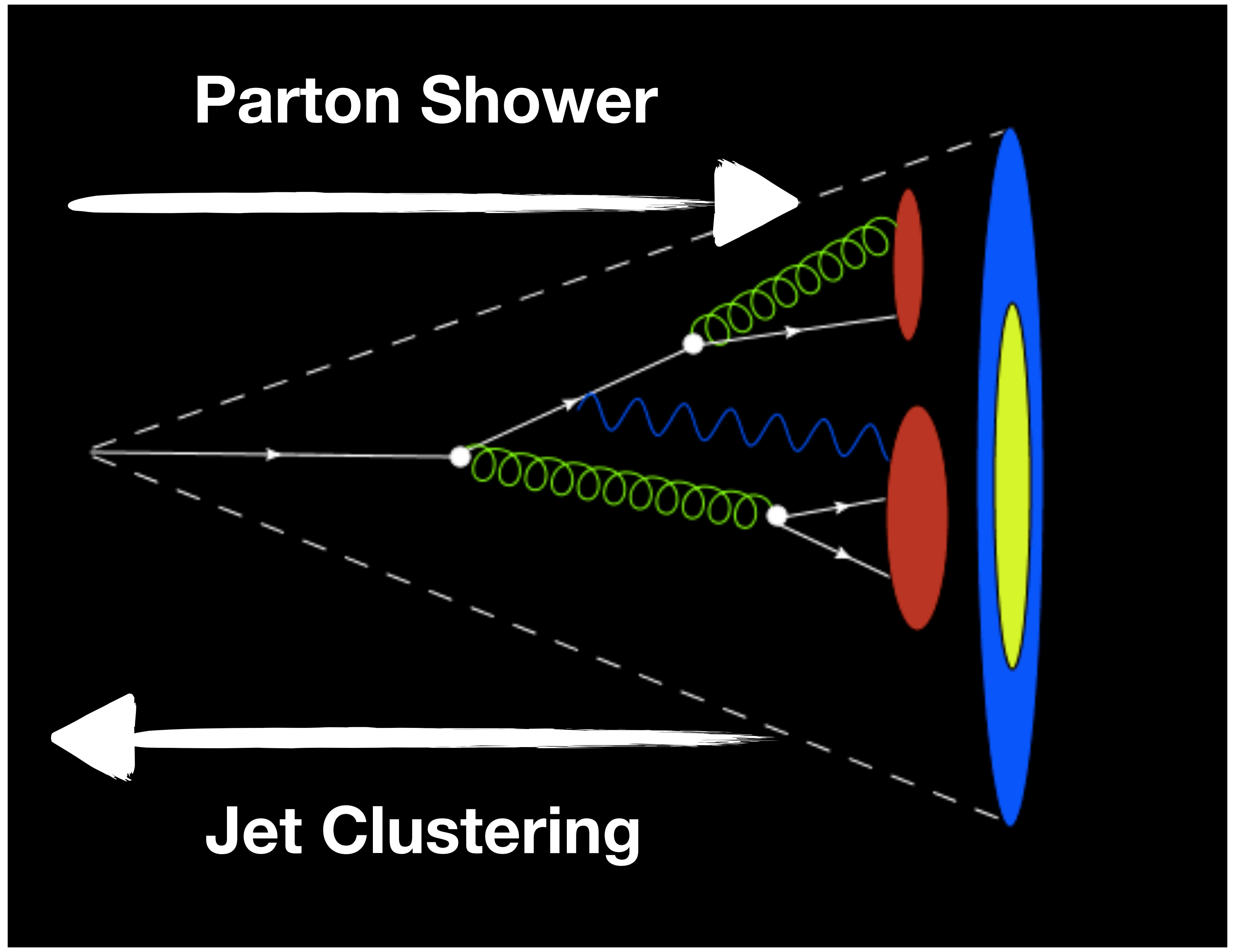
Jets at RHIC



- Significantly steeper jet spectra compared to LHC
- Access to 15 - 60 GeV/*c* jets - Kinematic range offers sensitivity to study both QCD and HI physics (complementarity with LHC)

Jet evolution/parton shower in vacuum is described by two fundamental scales

- virtuality/opening angle
- momentum



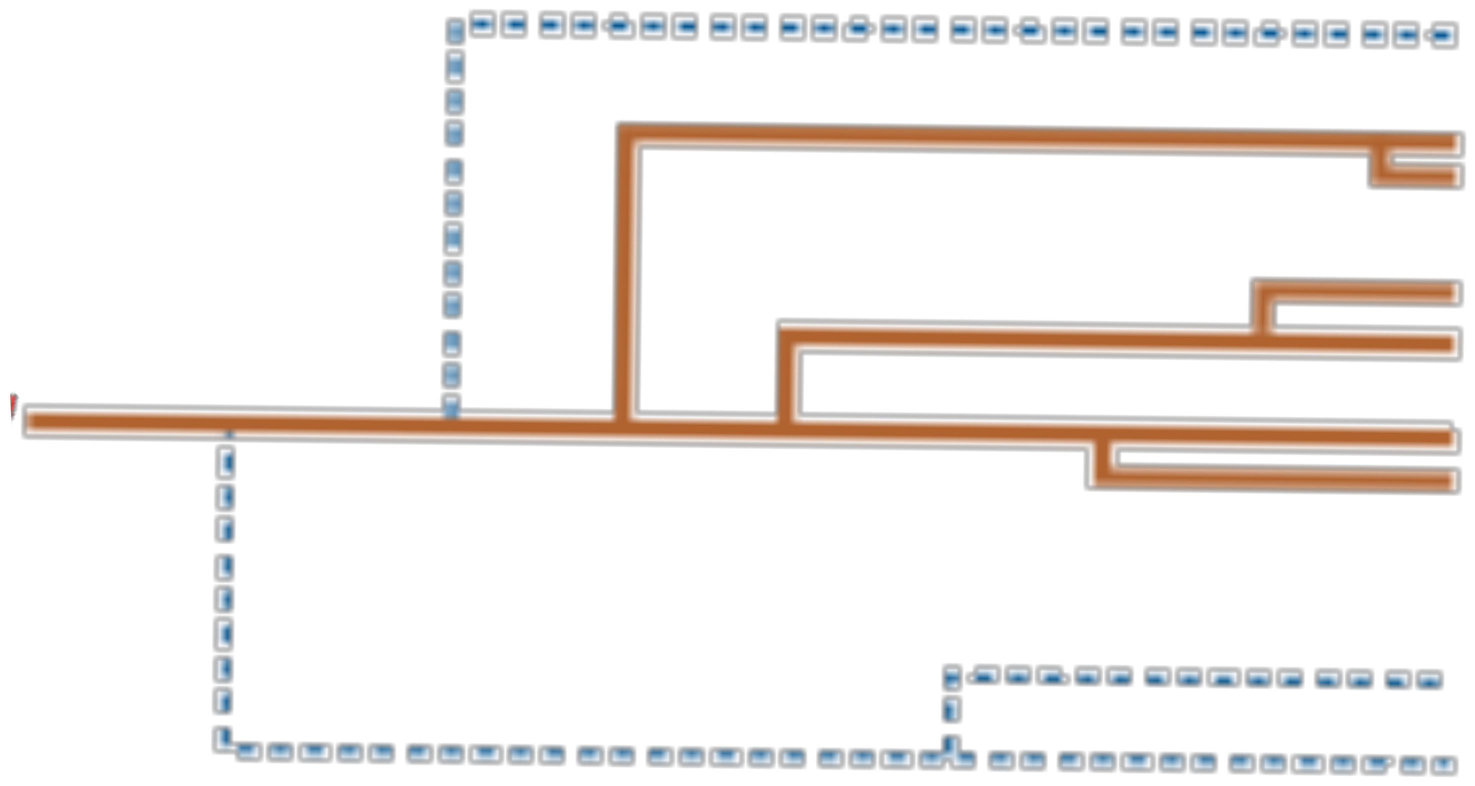
Jet reconstruction at STAR

TPC + BEMC

- anti-k_T Charged + Neutral jets
- Nominal $R_{Jet} = 0.4$, $|\eta_{Jet}|+R_{Jet} < 1$

Jet substructure measurements

- Correlate physical quantities in jet evolution to experimental observables
- SoftDrop Grooming reduces sensitivity to non-perturbative effects

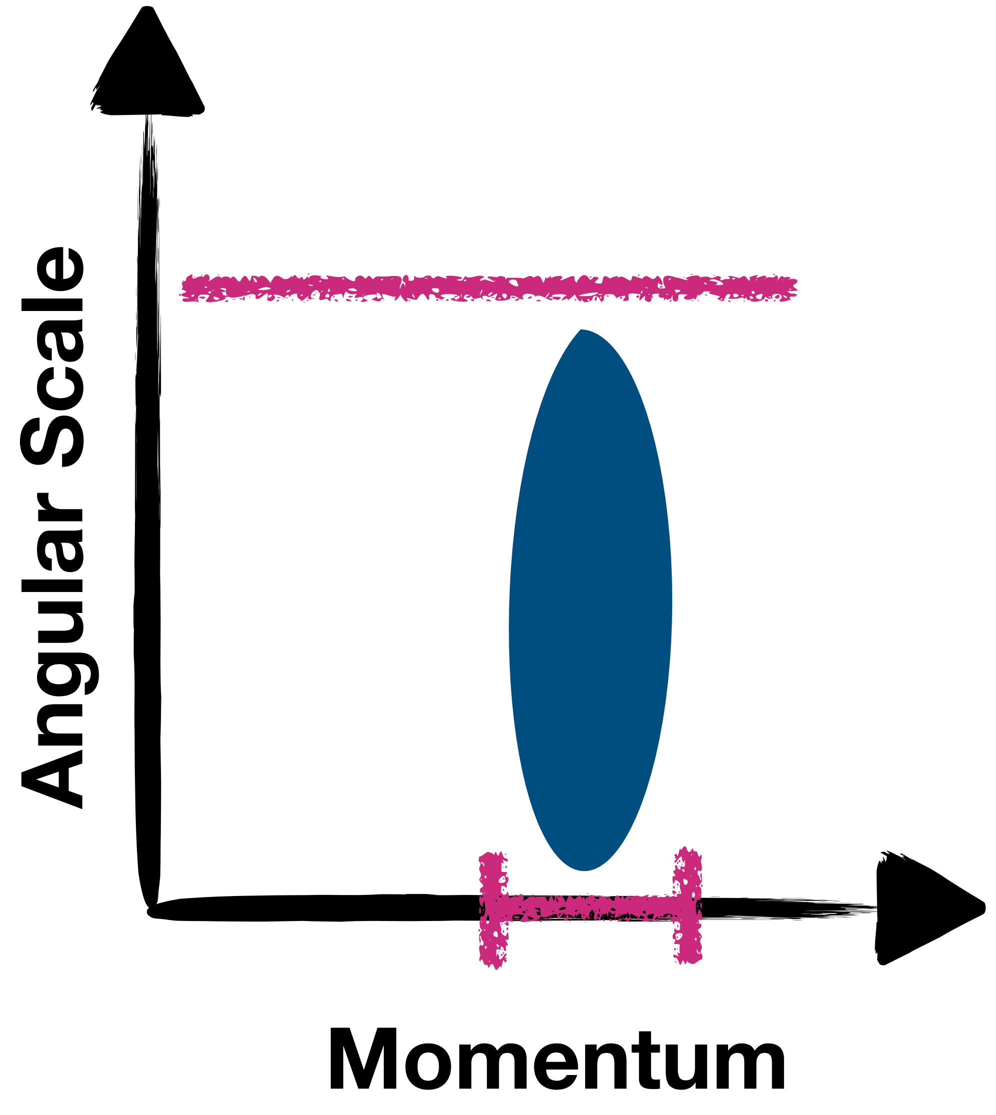


$z_g = \min(p_{T1}, p_{T2}) / (p_{T1} + p_{T2})$

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

$z_g > z_{cut}\ (0.1),\ \beta = 0$

Larkowski et al.
Phys. Rev. D 91, 111501 (2015)

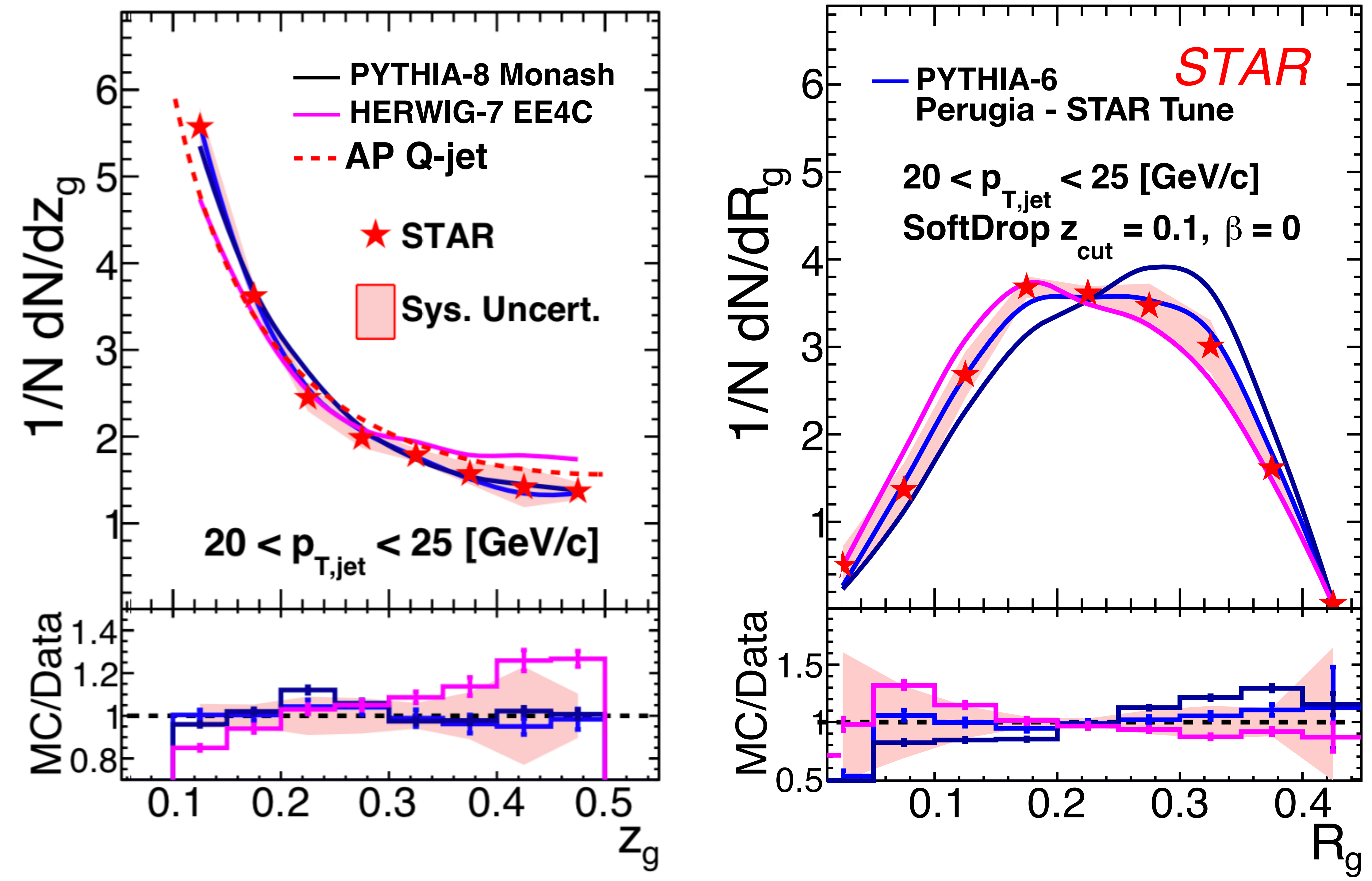


- Splitting Functions
  - momentum scale - z_g
  - angular scale - R_g
- Invariant and Groomed Jet Mass ($z\theta^2$)

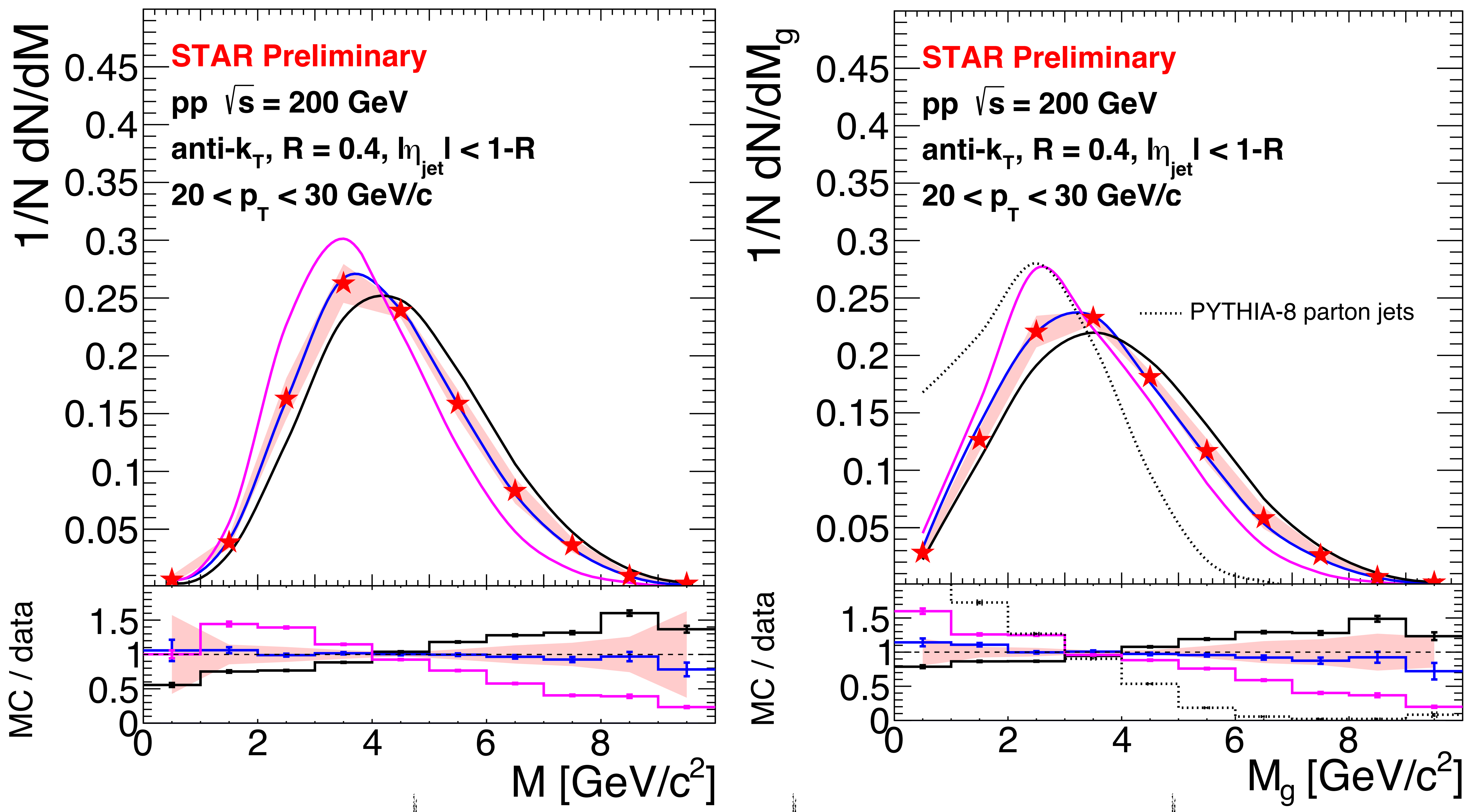
Study QCD in pp collisions at RHIC
Establish a vacuum baseline for HI measurements

pp jet substructure in STAR

STAR Soon to be submitted



Preliminary Measurement



- Jet substructure observables generally described by leading order tuned MC
- PYTHIA-8 and HERWIG-7 LHC tunes show deviations leading to an exciting opportunity to tune at RHIC kinematics!

	z_g	R_g	M	M_g
PYTHIA-6 Tuned to STAR Data 1906.02740	excellent	excellent	excellent	good
PYTHIA-8 LHC Tune	good	larger R_g	larger Mass	larger Mass
HERWIG-7 LHC Tune	flatter z_g	smaller R_g	smaller Mass	smaller Mass

Jet quenching in a nutshell

Image credit - Barbara Betz

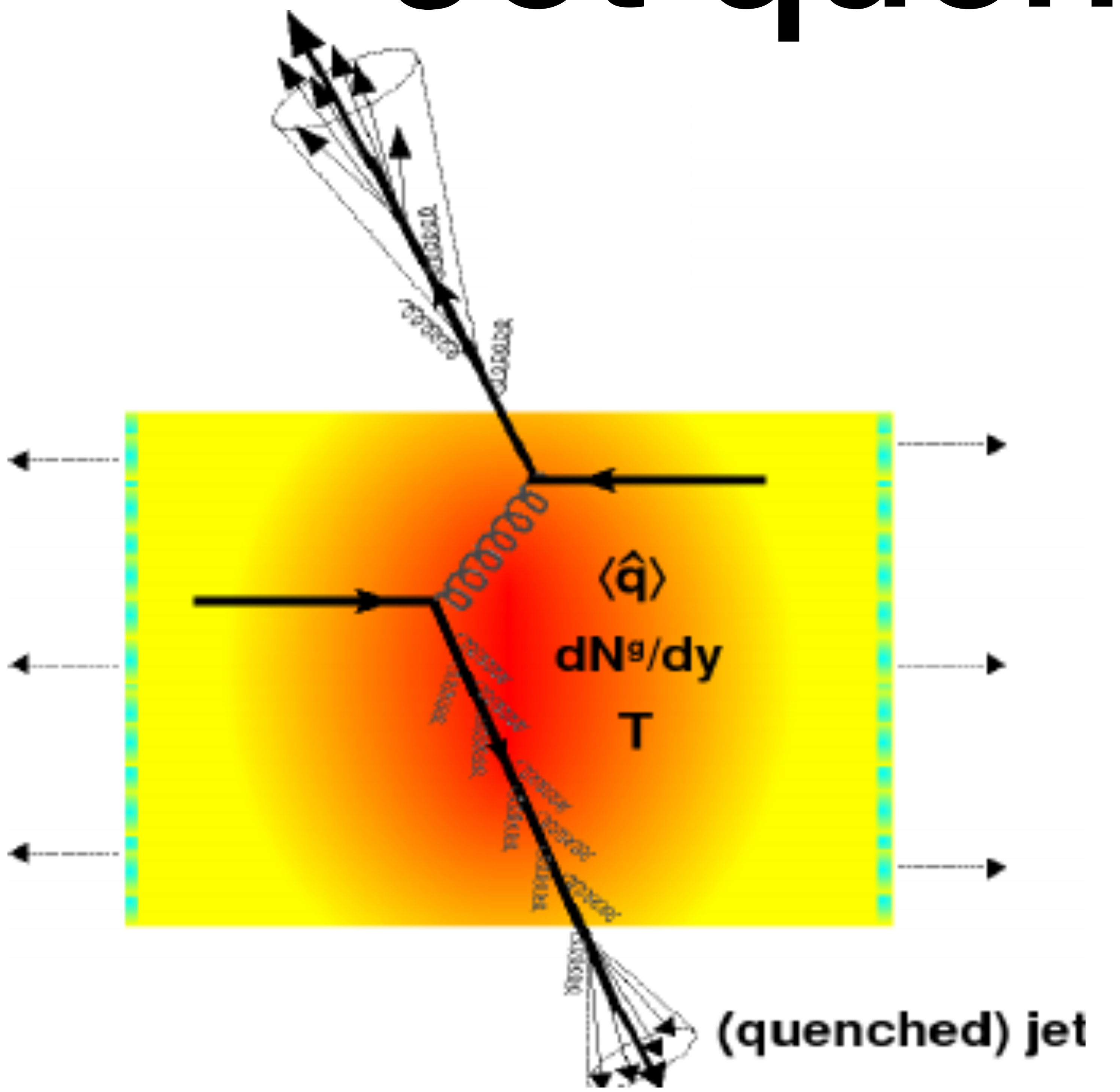
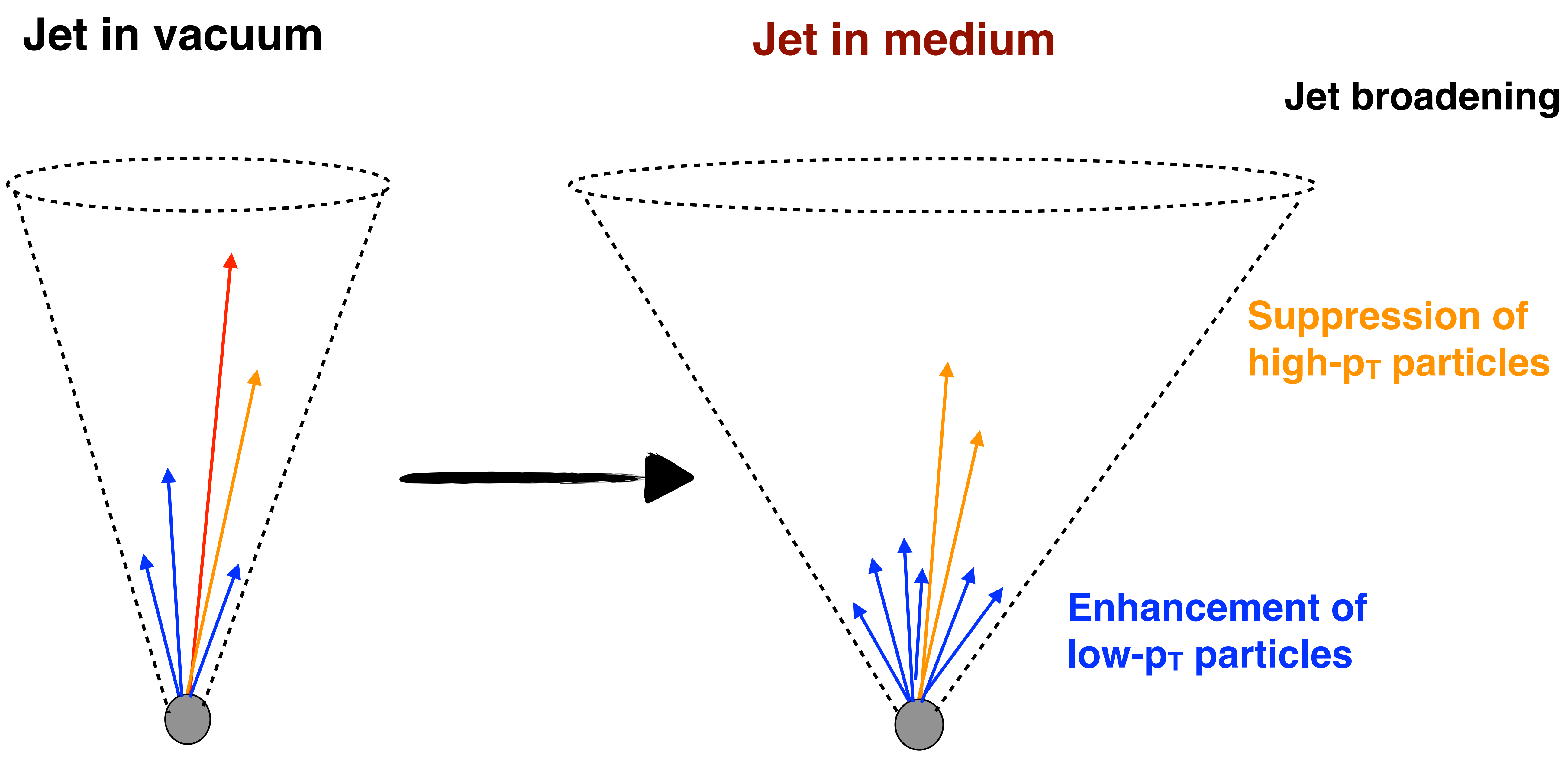


Image credit - Joern Putschke



Hard scattered parton emanating with early formation time probes evolution of QGP

Modifications of jet properties interpreted as medium interaction

Several MC implementations of jet energy loss

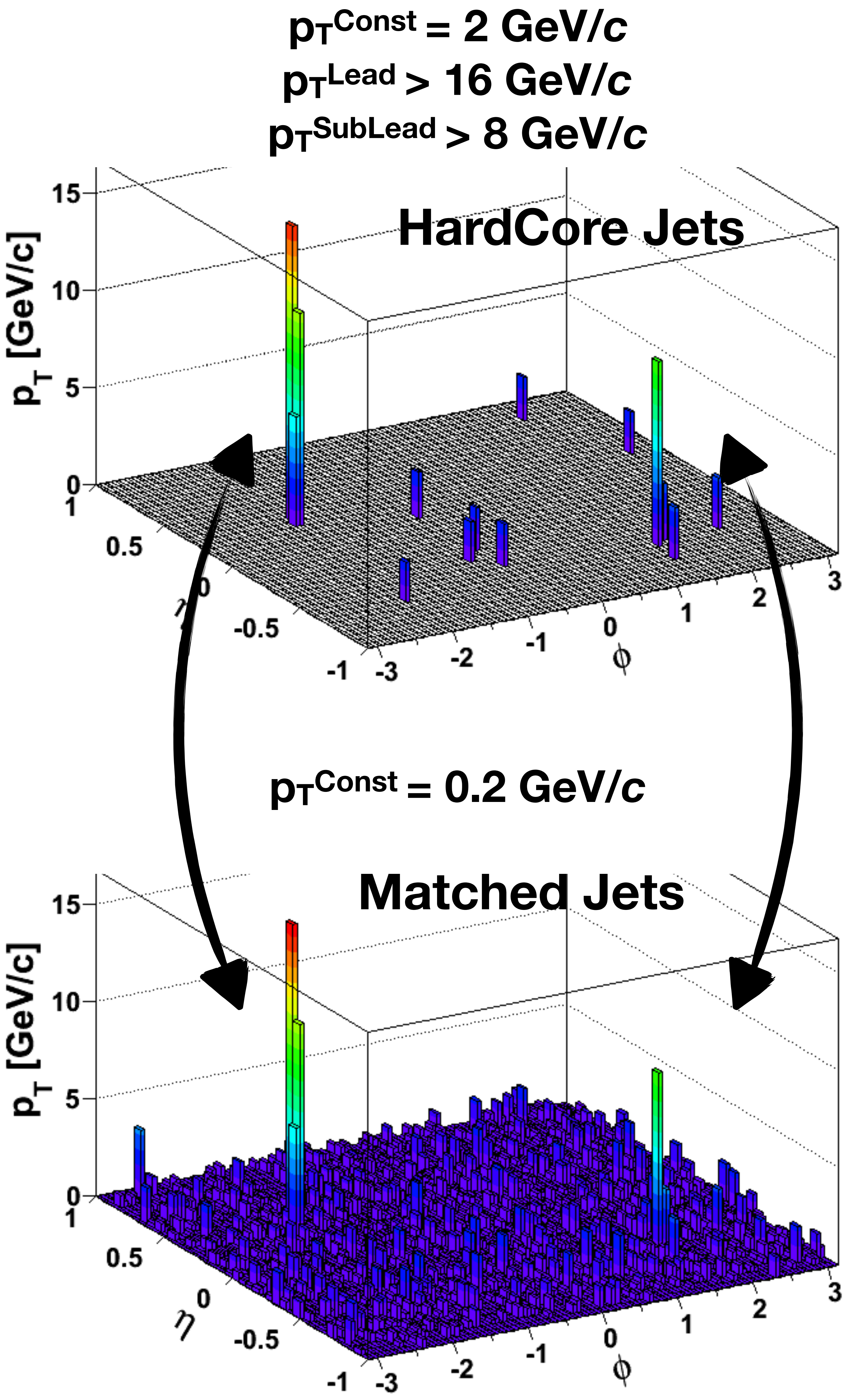
Weidemann 0908.2306   Solano et al 1405.3864   Qin, Wang, 1511.00790   Mehtar-Tani 1602.01047   Zapp et al. 1212.1599

Need for differential measurements that are able to distinguish between models!

Differential measurements of jet quenching at STAR

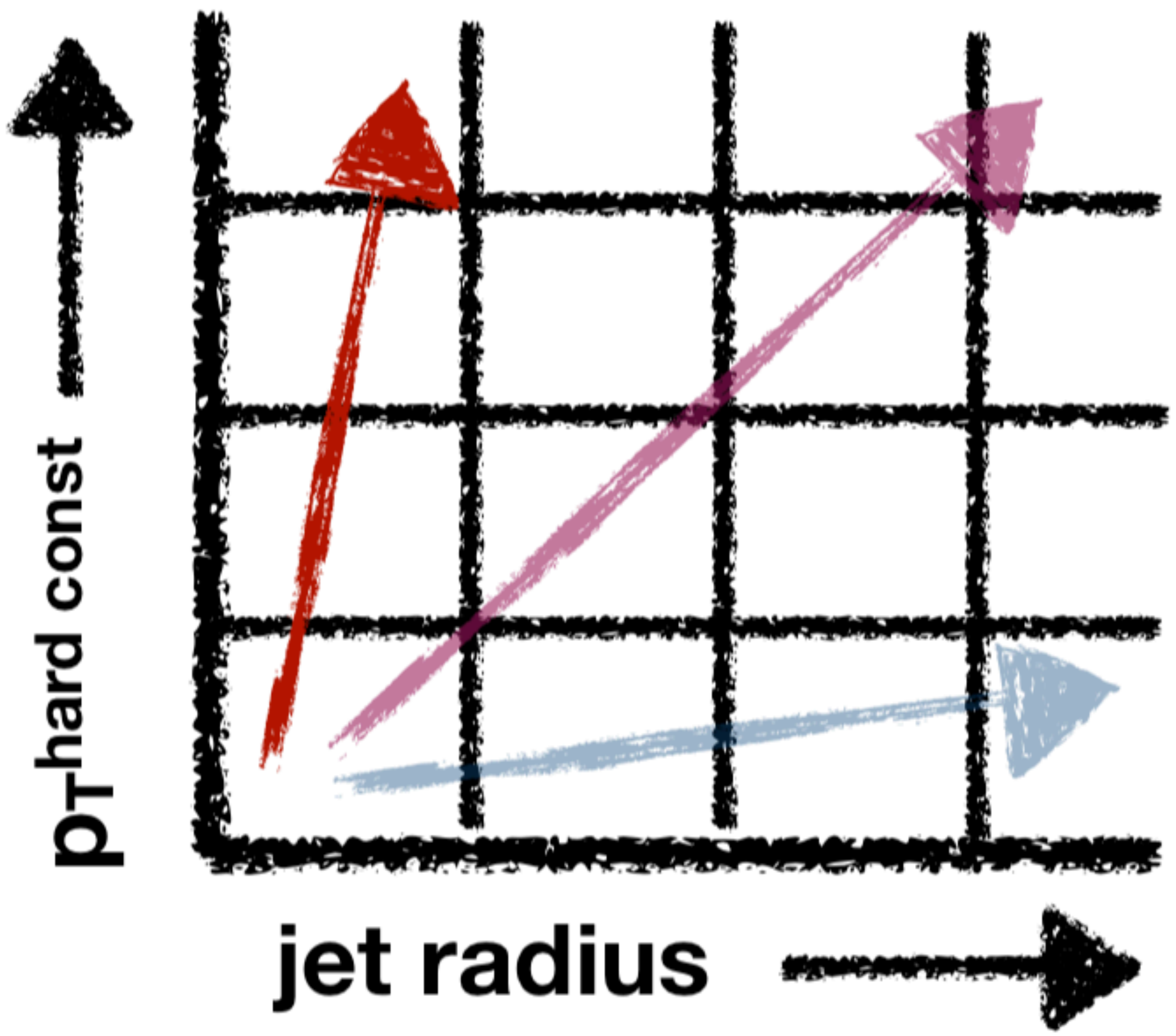
- We have two handles -
  - Jet Geometry Engineering (JGE) : Vary hardcore constituent threshold and jet finding radius for dijets
  - Given a dijet definition, measure jet modification as a function of opening angle

Identifying dijets



- Dijet selection with both leading and subleading momentum threshold
  STAR, PRL 119 062301 (2017)
- HardCore selection removes combinatorial jets
- Matching recovers the jet fragments/ particles down to 0.2 GeV/*c*
- Dijet finding introduces a bias - Let's utilize the bias in a systematic fashion

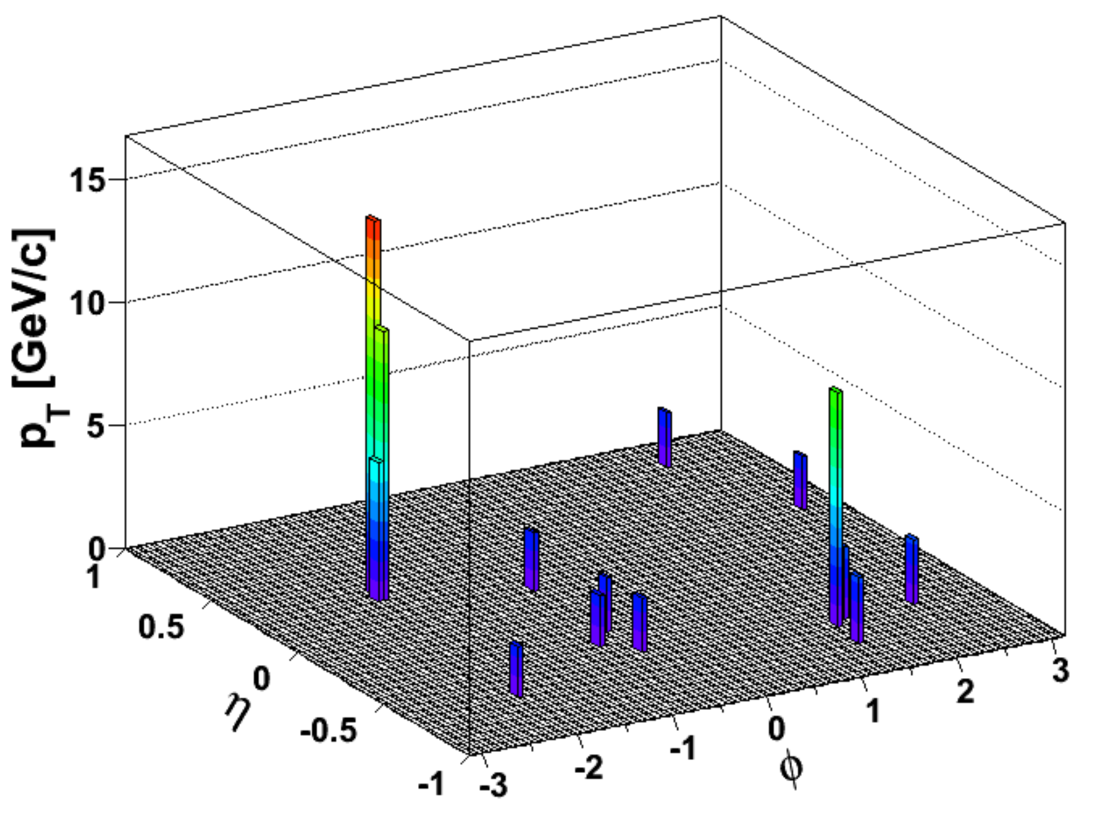
Quantifying selection bias with Jet Geometry Engineering (JGE)



$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$

Systematically measure dijet A_J in Au+Au across various jet definitions and compare with p+p ⊕ Au+Au

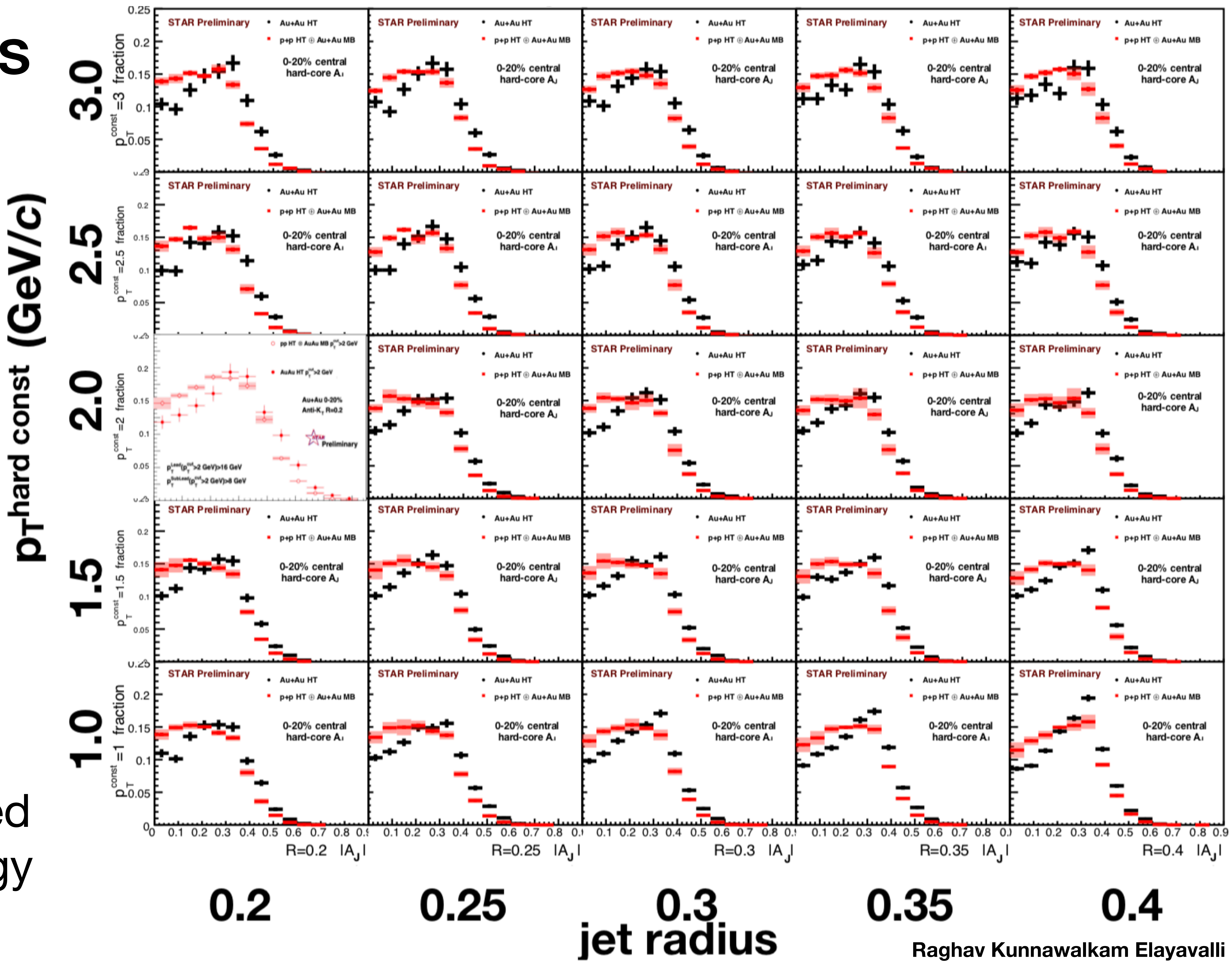
HardCore dijets



Au+Au

p+p ⊕ Au+Au

All selections of HardCore dijets are imbalanced - Modified due to partonic energy loss



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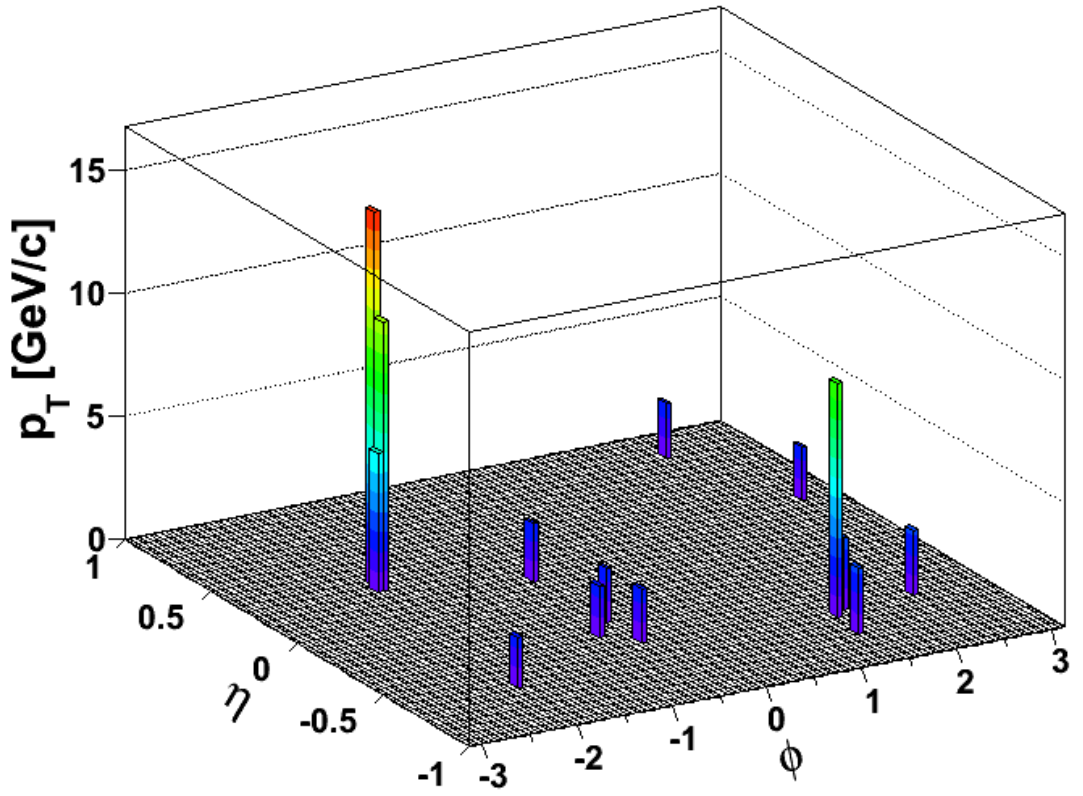
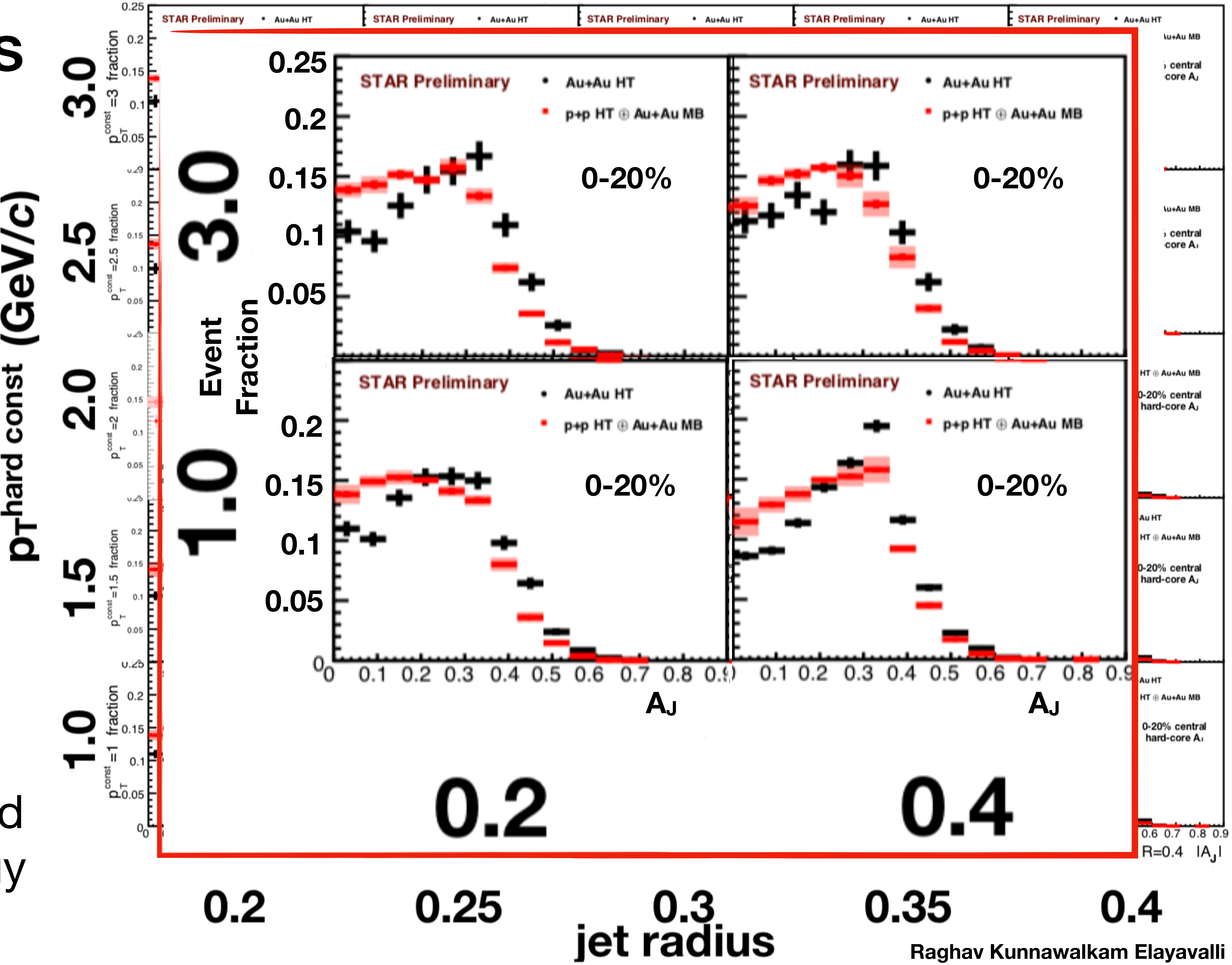
HardCore dijets



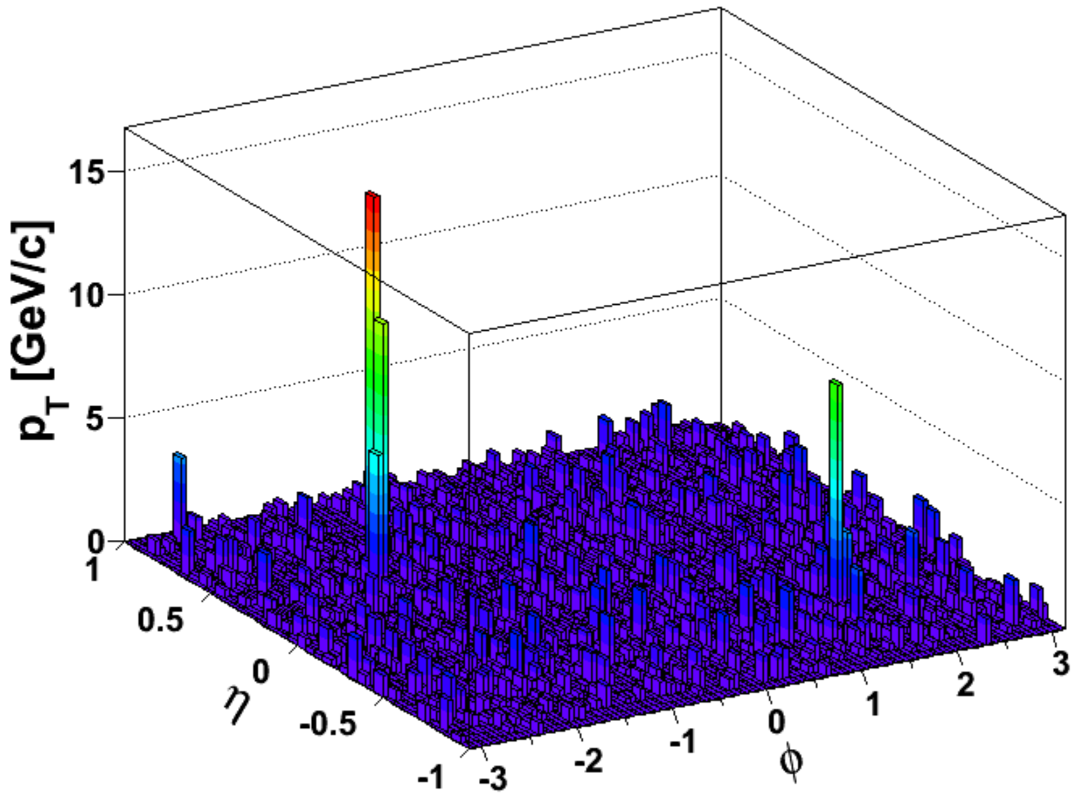
Au+Au

p+p ⊕ Au+Au



All selections of HardCore dijets are imbalanced - Modified due to partonic energy loss

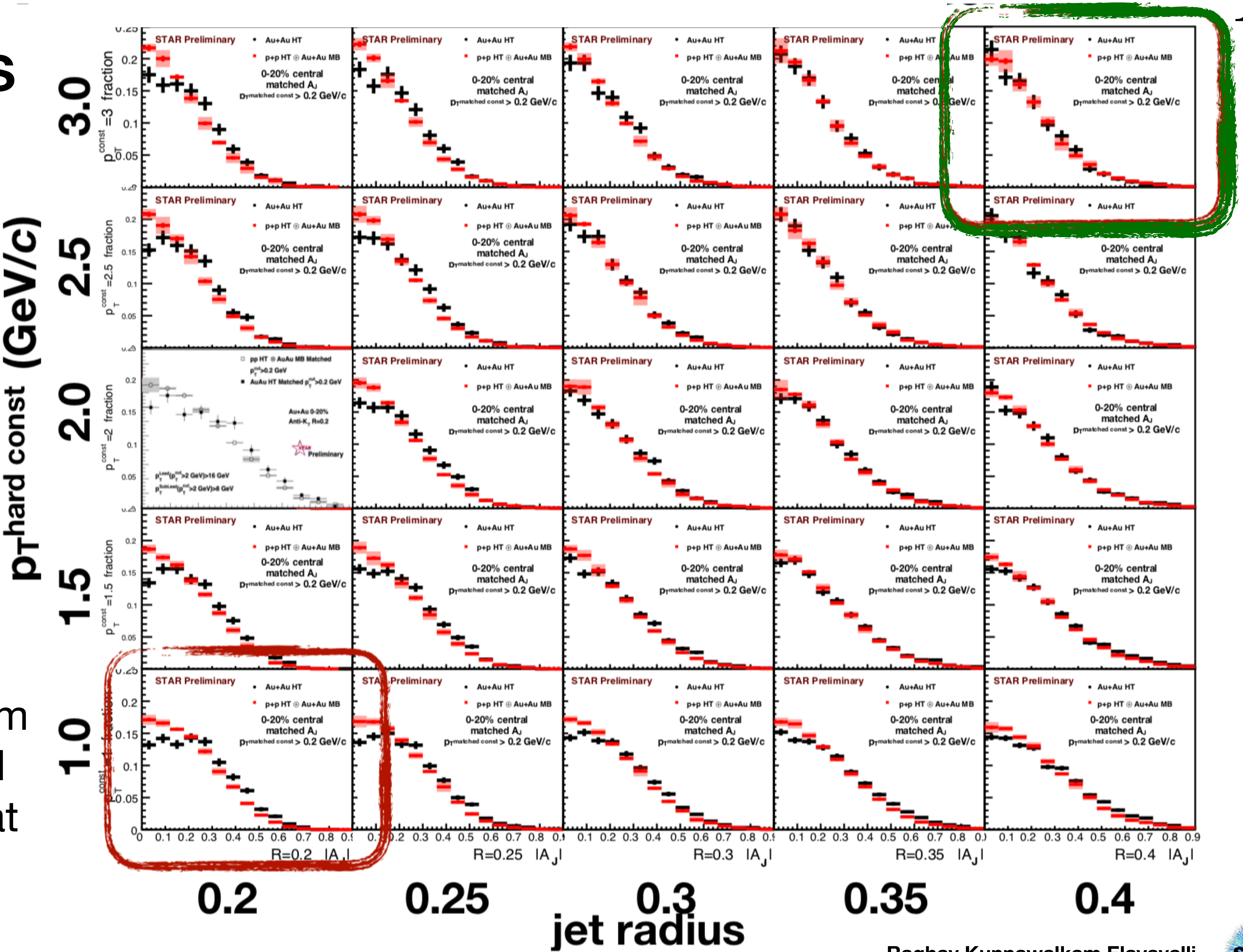
Matched dijets



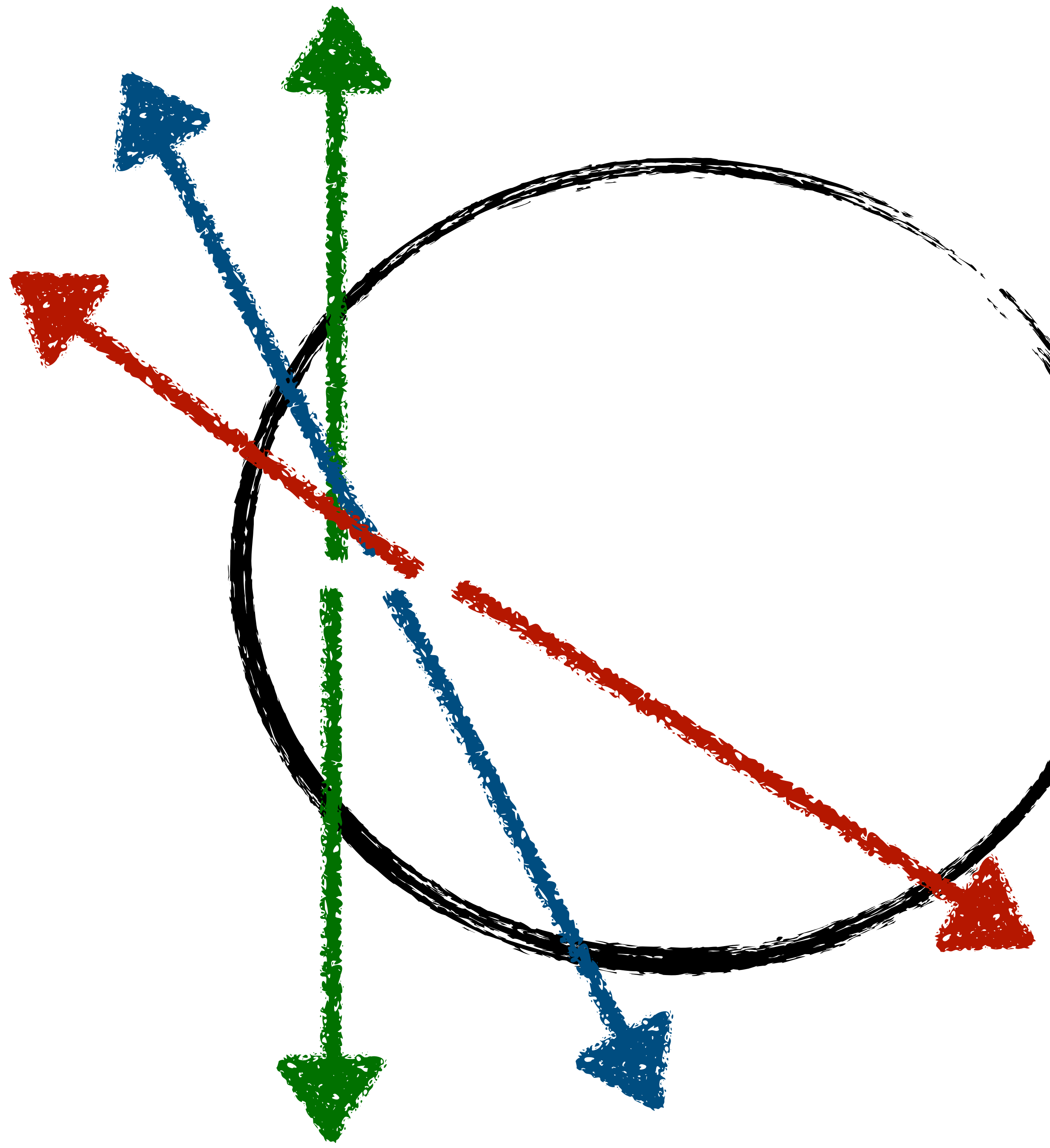
Au+Au

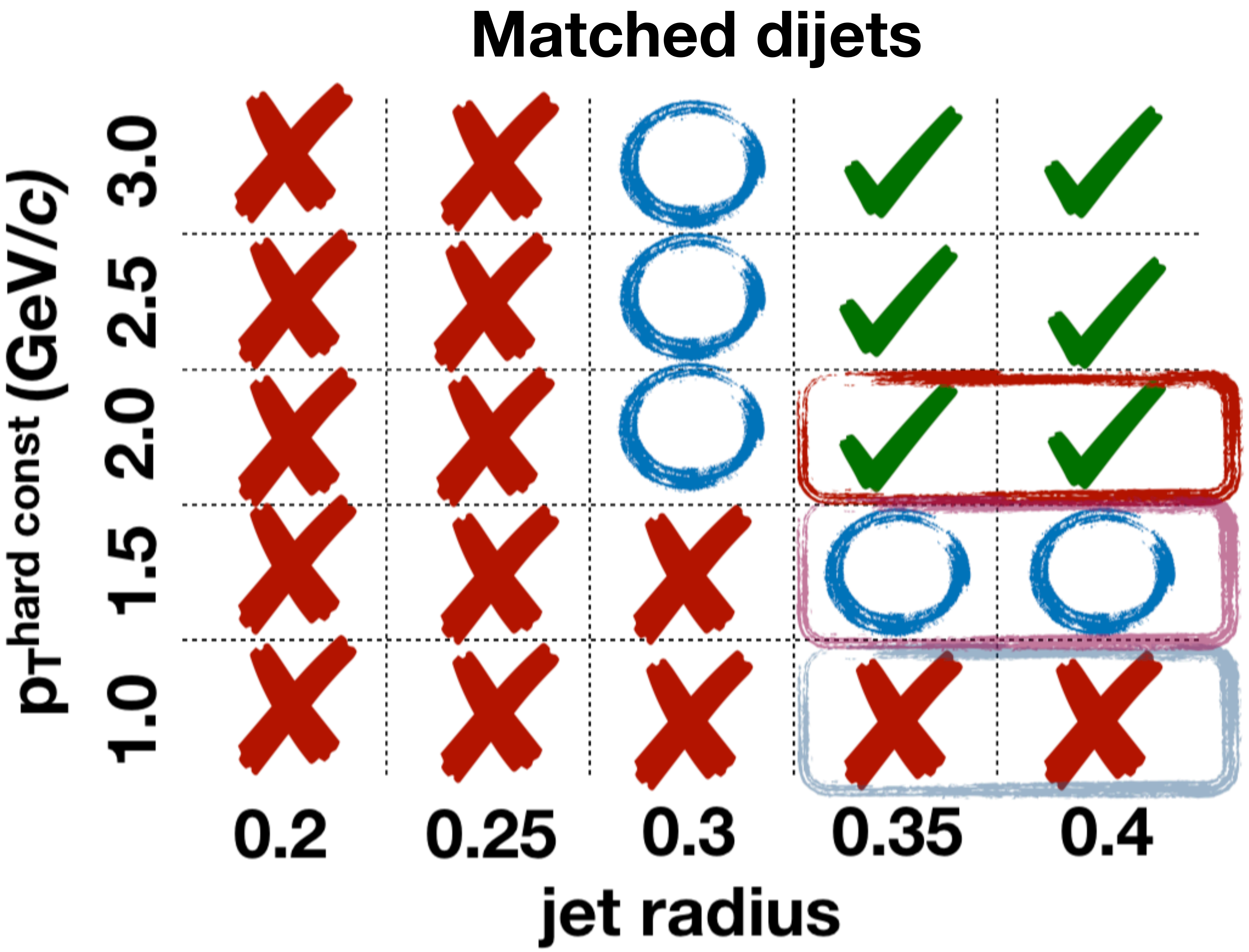
p+p ⊕ Au+Au

Matched dijets vary from **imbalanced** (quenched energy not recovered) at small radii to **balanced** at large radii!



JGE @ RHIC





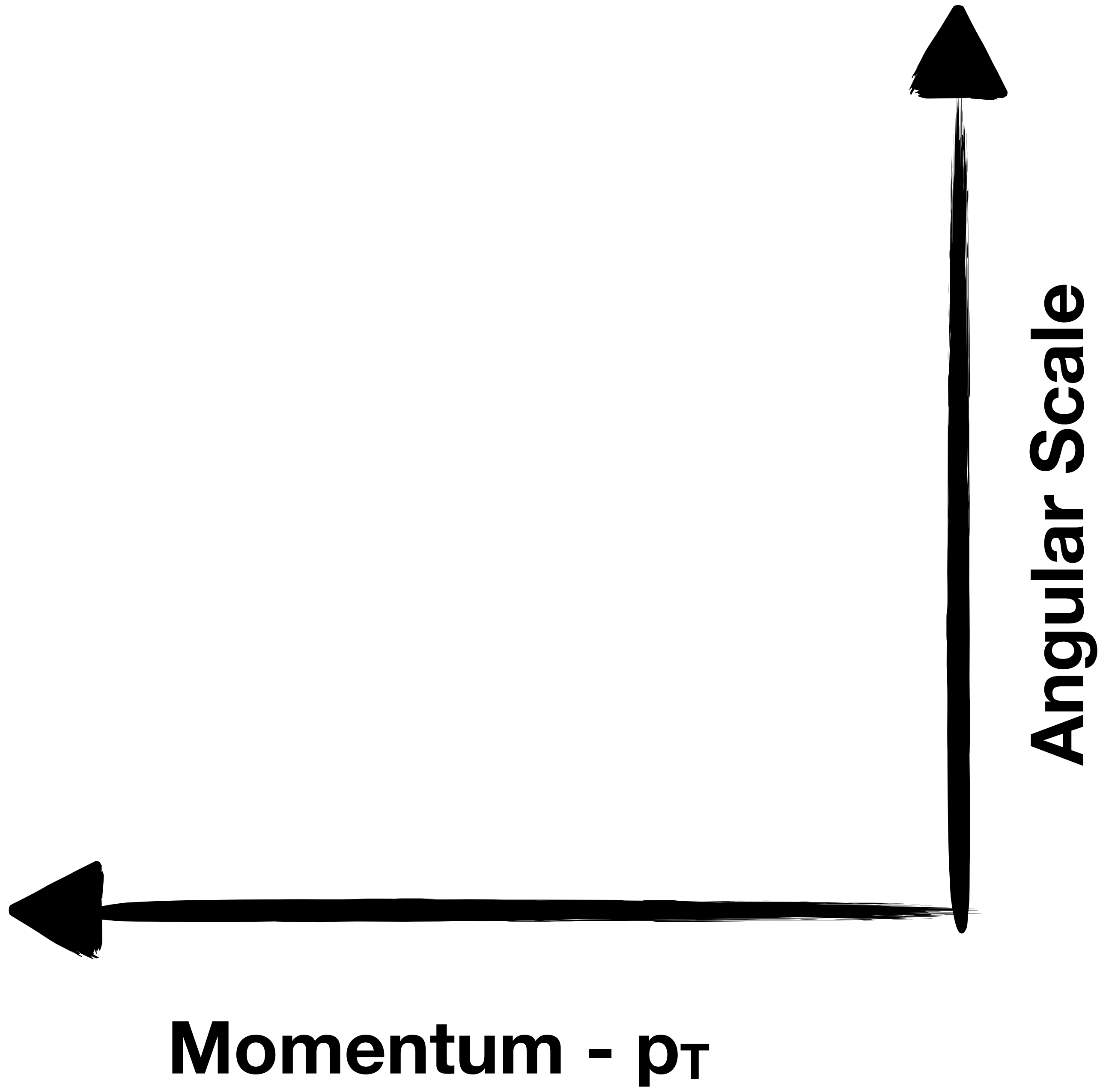
- "Dialing in/out" the energy loss by varying HardCore constituent threshold and jet radius
- Under the assumption of sensitivity to path length dependence of recoil jets - with a steeply falling spectra we evidently see JGE
- Theoretical input and comparisons at RHIC energies are essential!

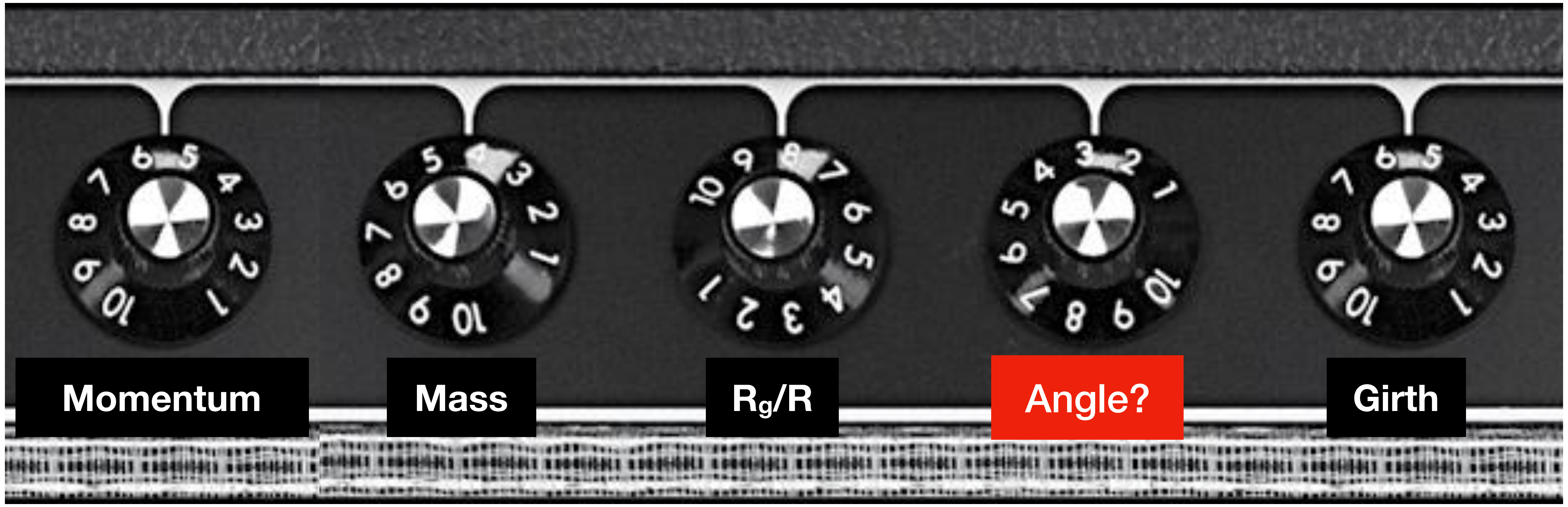
Differential measurements of jet quenching at STAR

- We have two handles -
  - Jet Geometry Engineering (JGE) : Vary hardcore constituent threshold and jet finding radius for dijets
  - Given a dijet definition, measure jet modification as a function of opening angle

Key idea
Use jet-substructure as a selection tool

Identify jet observable(s) sensitive to the parton shower kinematics





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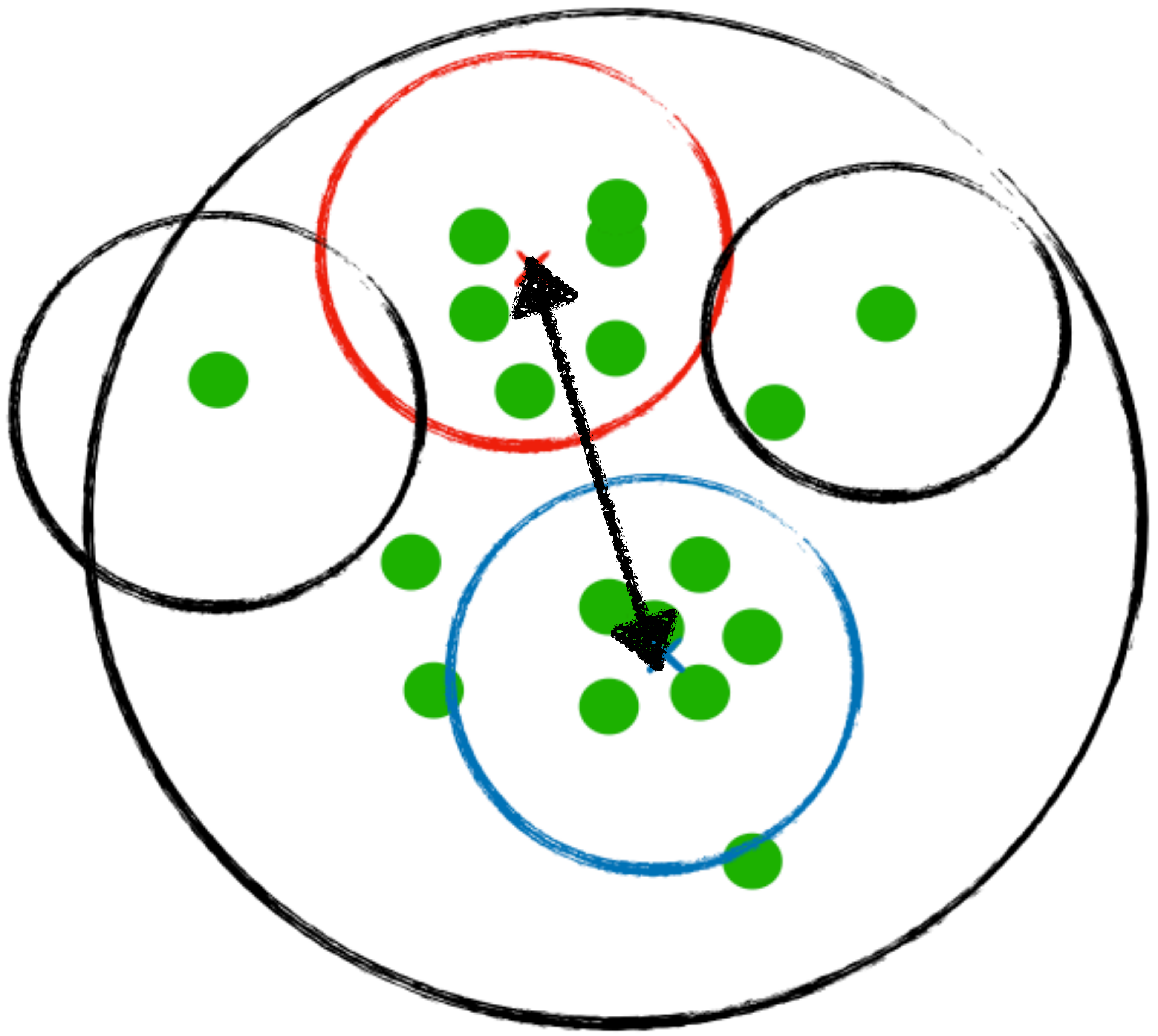
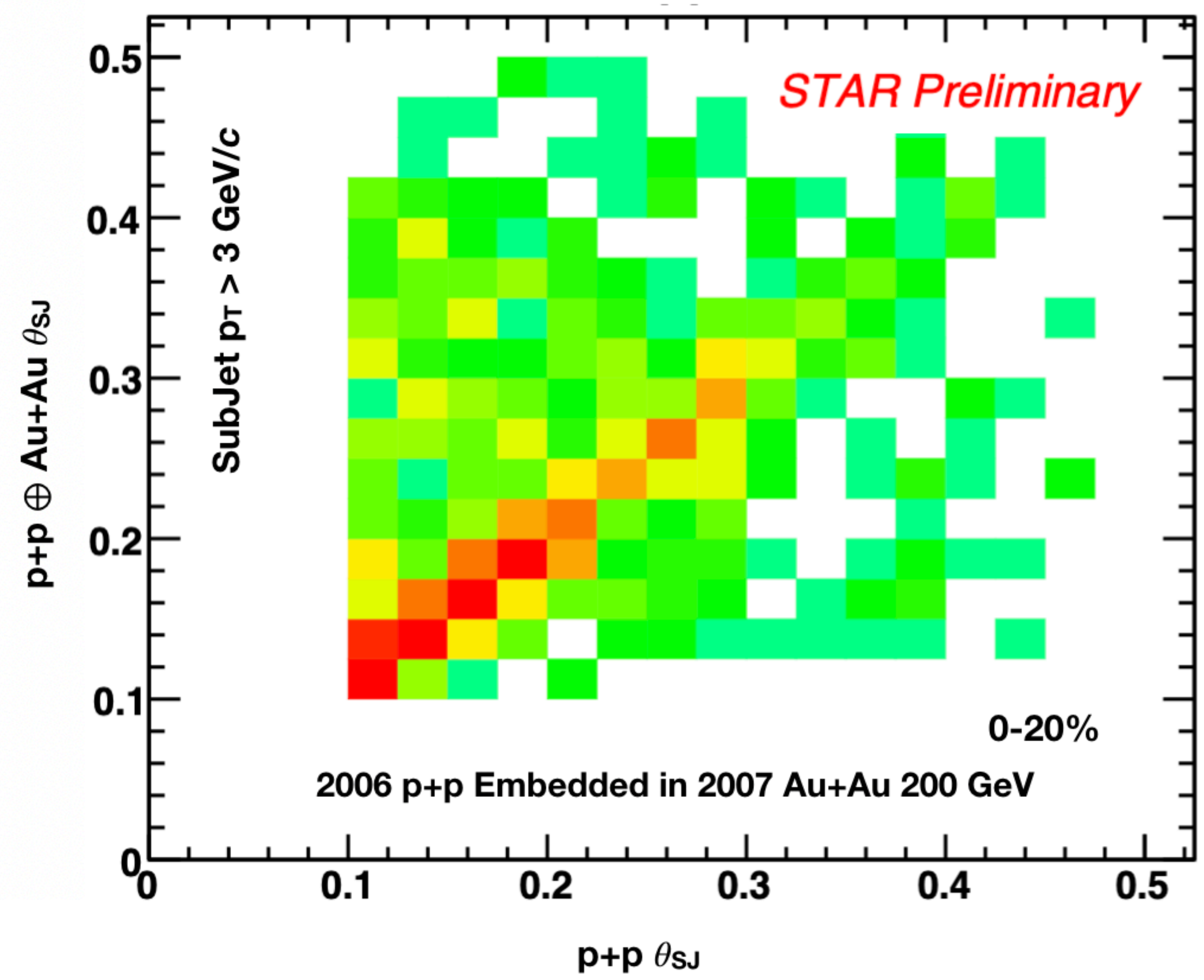
Partonic energy loss via a differential study in momentum scale and angular scale

Utilizing subjets of smaller R

Need techniques and observables that are robust to underlying event background especially at RHIC





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

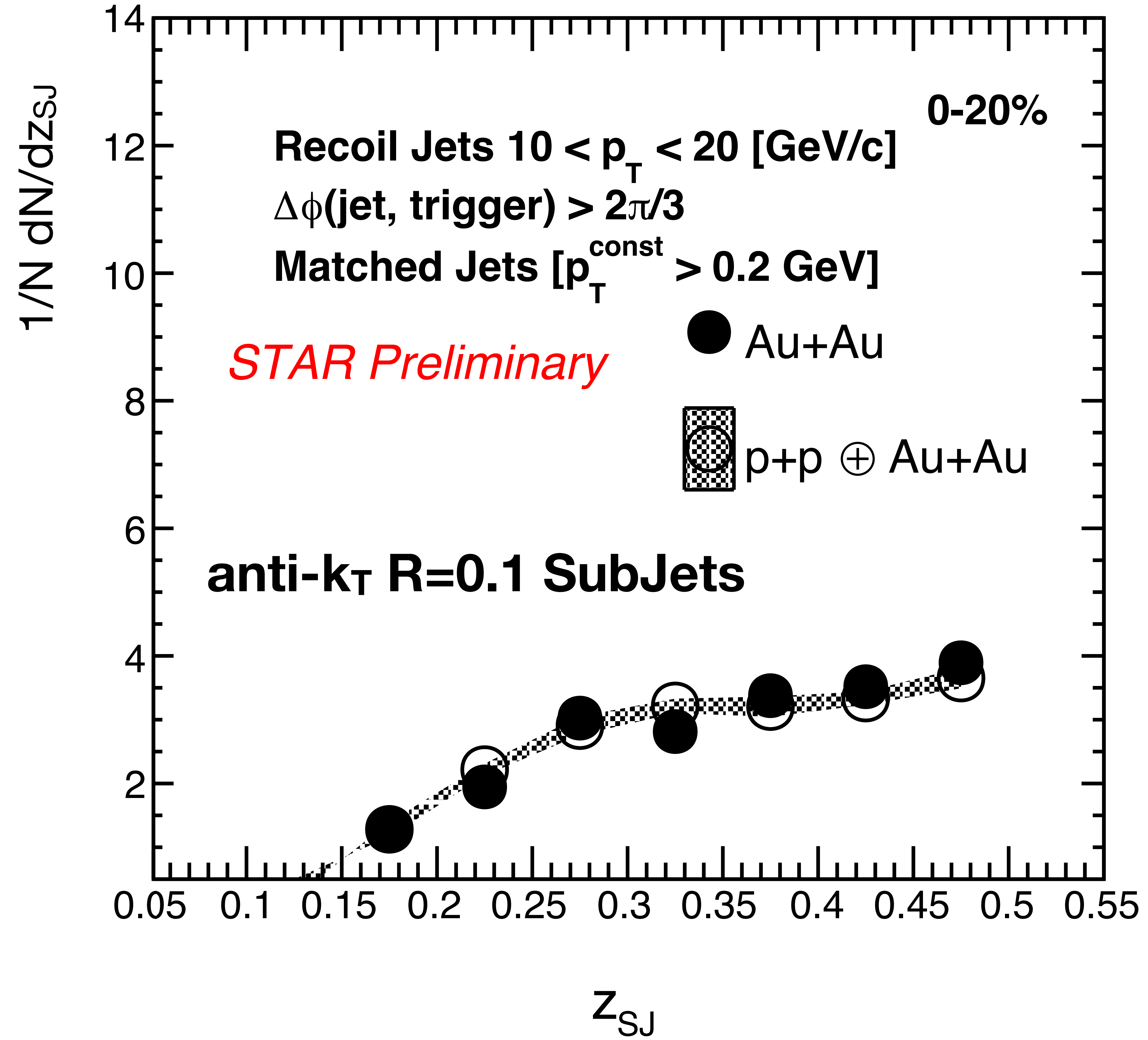
Berta, P et al. JHEP 06 (2014) 092

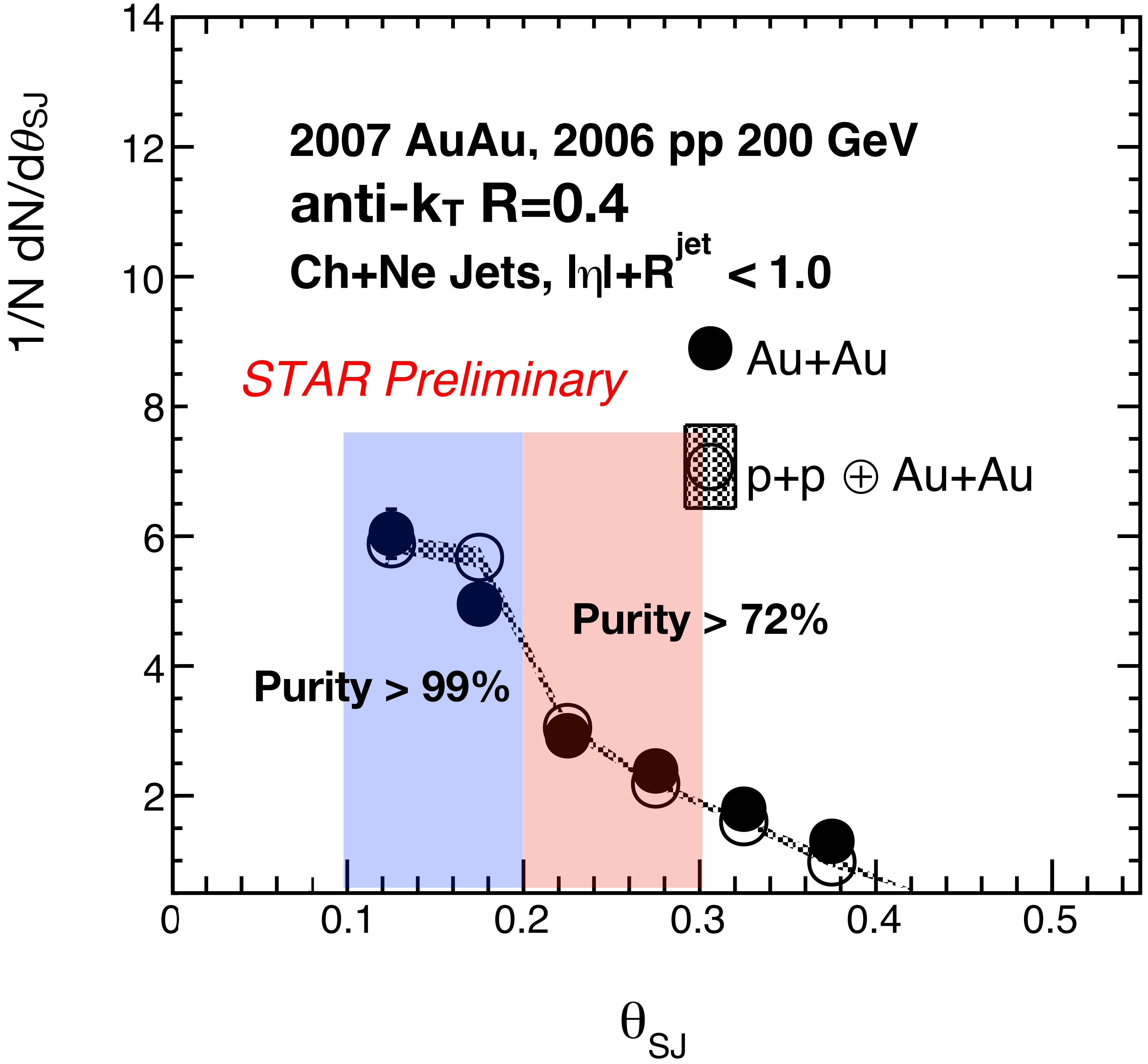
θ_{SJ} (w/ R=0.1 subjets) less sensitive Au+Au underlying event

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

- **Reclusters jet constituents with a smaller radius** - identify regions of jet-like features within the mother jet
- Choose the **leading** and **subleading** Subjets
- z_{SJ} = **subleading p_T** / (**subleading p_T** + **leading p_T**); θ_{SJ} = ΔR (**subleading**, **leading**)

TwoSubJet observables

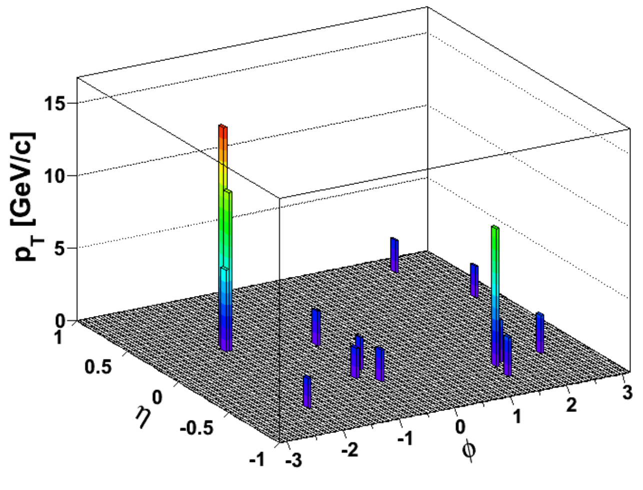


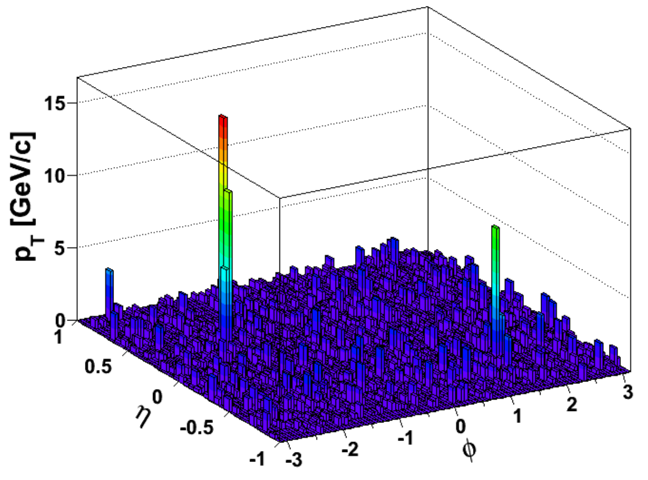


- The z_{SJ} distribution is biased towards harder splits
- For both z_{SJ} and θ_{SJ}, **no significant difference in shape** due to jet quenching

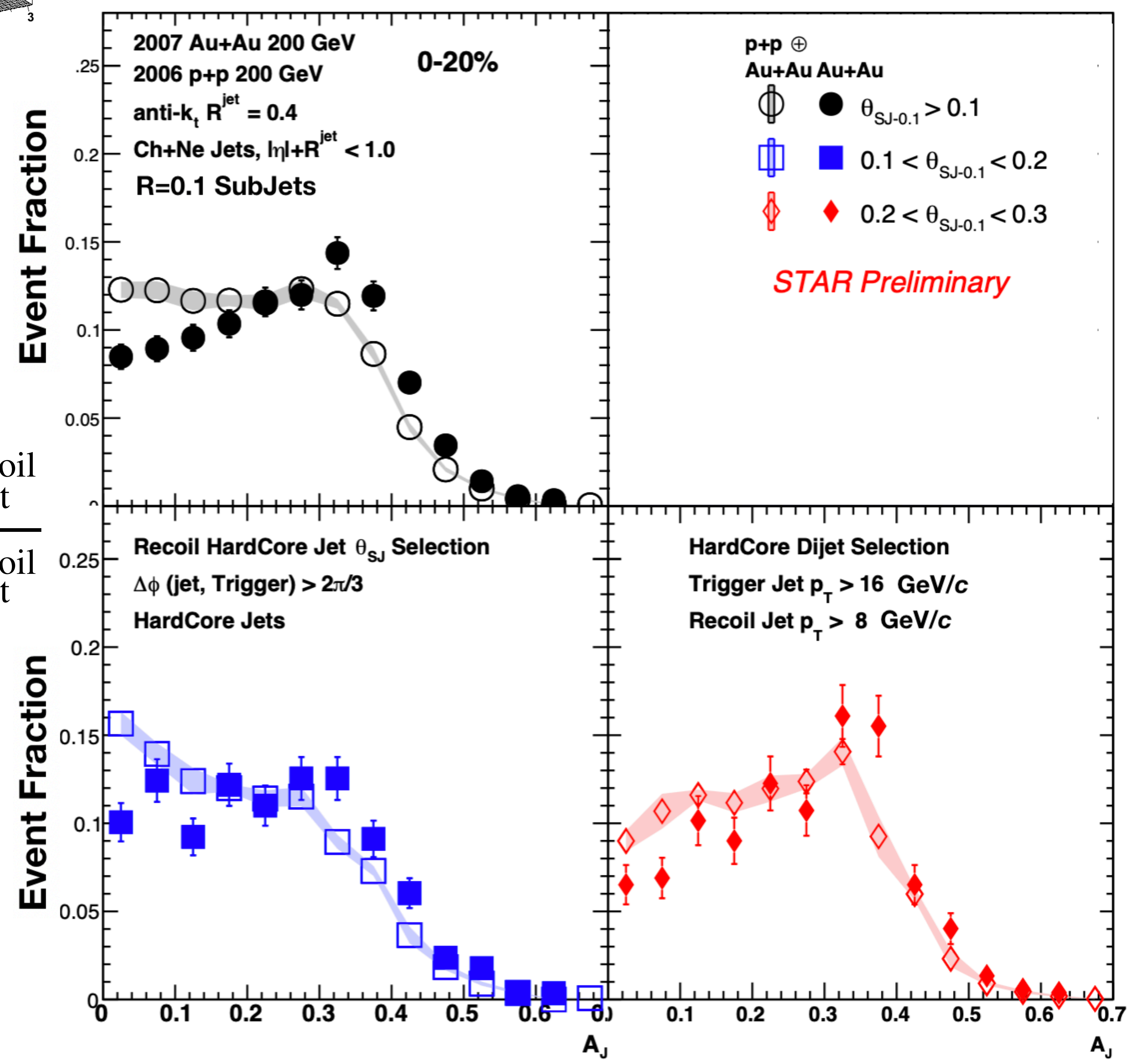
Let's measure the A_J for wide vs. narrow recoil jets!

Dijet A_J

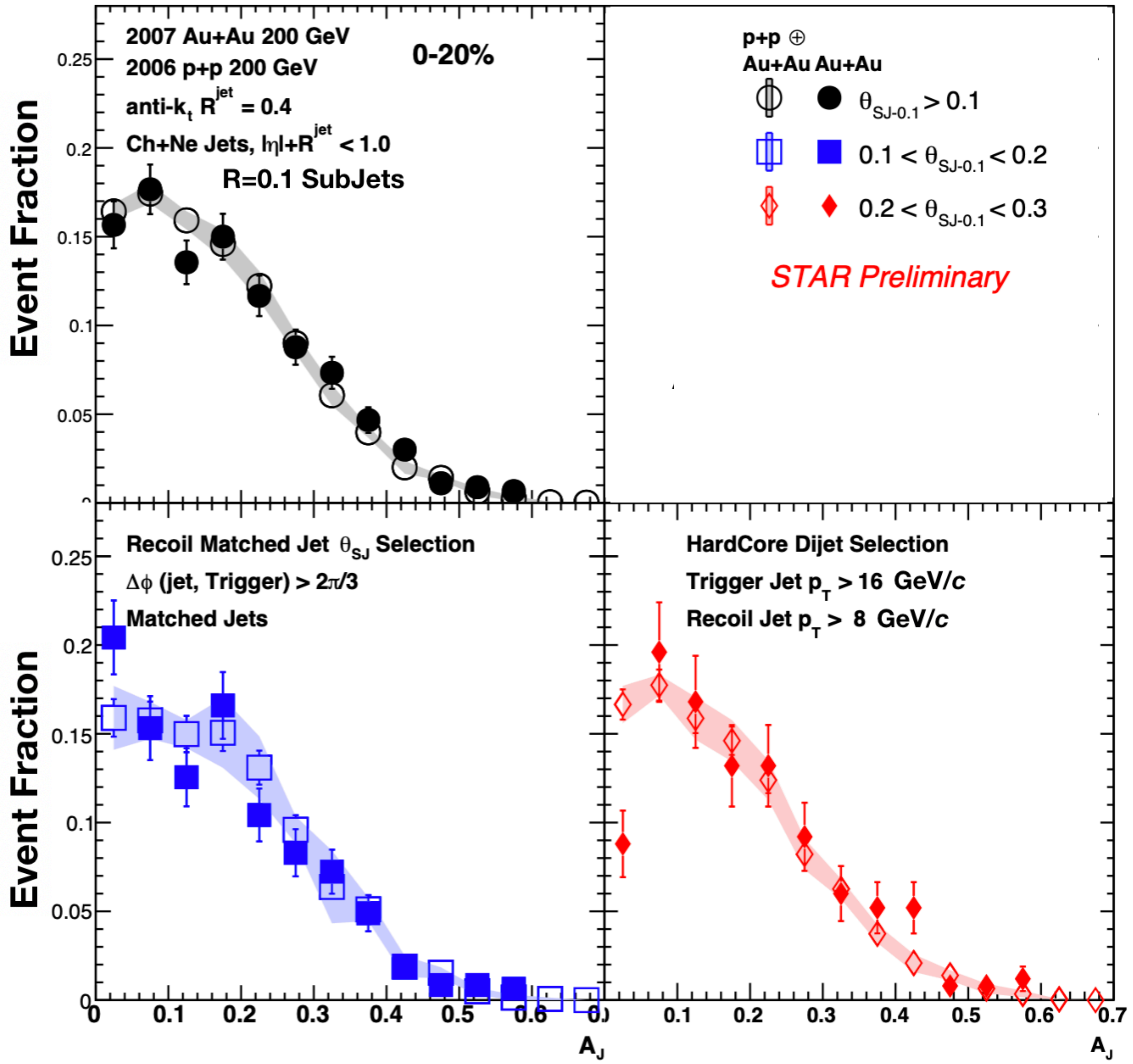




HardCore Jets



Matched Jets



$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$

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

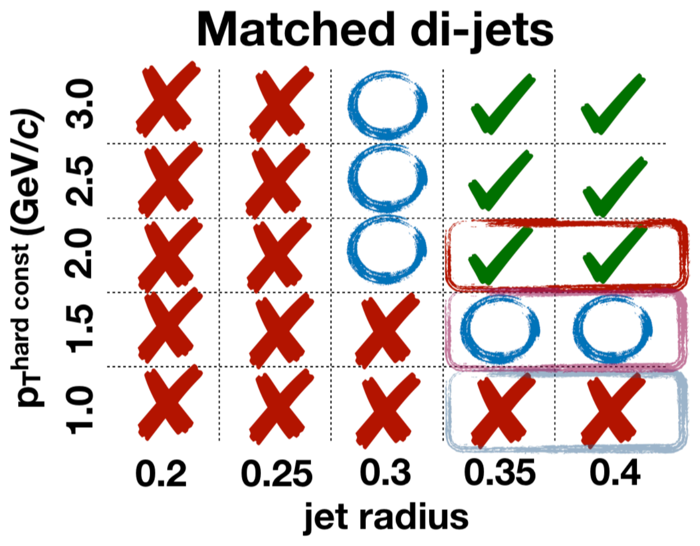
Matched A_J **similar** for wide vs. narrow jets
Balance indicating **recovery for all θ_{SJ}**

Conclusions

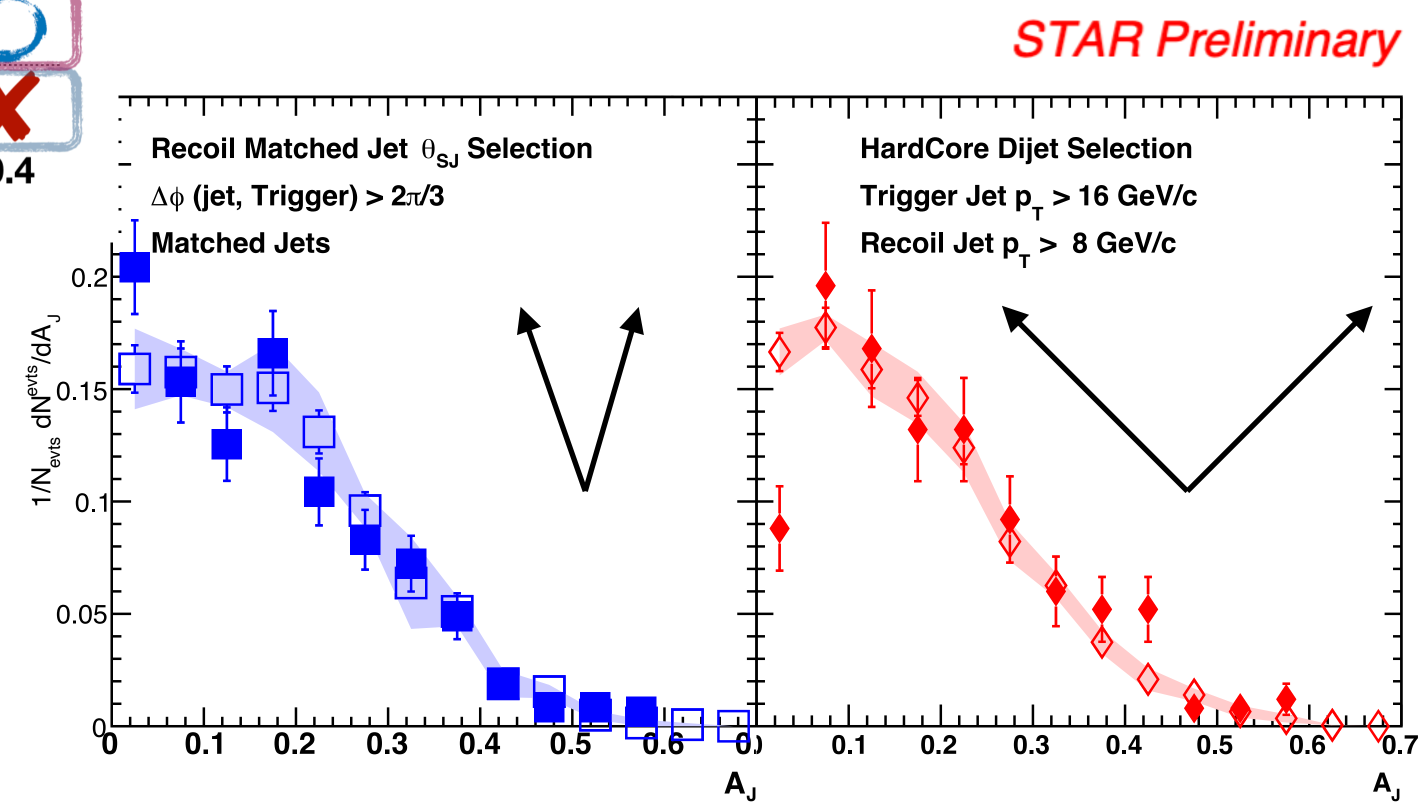
- RHIC tuned MC describe p+p jet substructure measurements very well
  - Opportunity to understand/tune the jet shower/non-perturbative/ $\sqrt{s}$ dependence of MC models

	z_g	R_g	M	M_g
PYTHIA-6 (Tuned to STAR Data)	excellent	excellent	excellent	good
PYTHIA-8 (LHC Tune)	good	larger R_g	larger Mass	larger Mass
HERWIG-7 (LHC Tune)	flatter z_g	smaller R_g	smaller Mass	smaller Mass

- Jet Geometry Engineering - varying dijet constituent threshold and jet radius leads to dialing in/out energy loss!



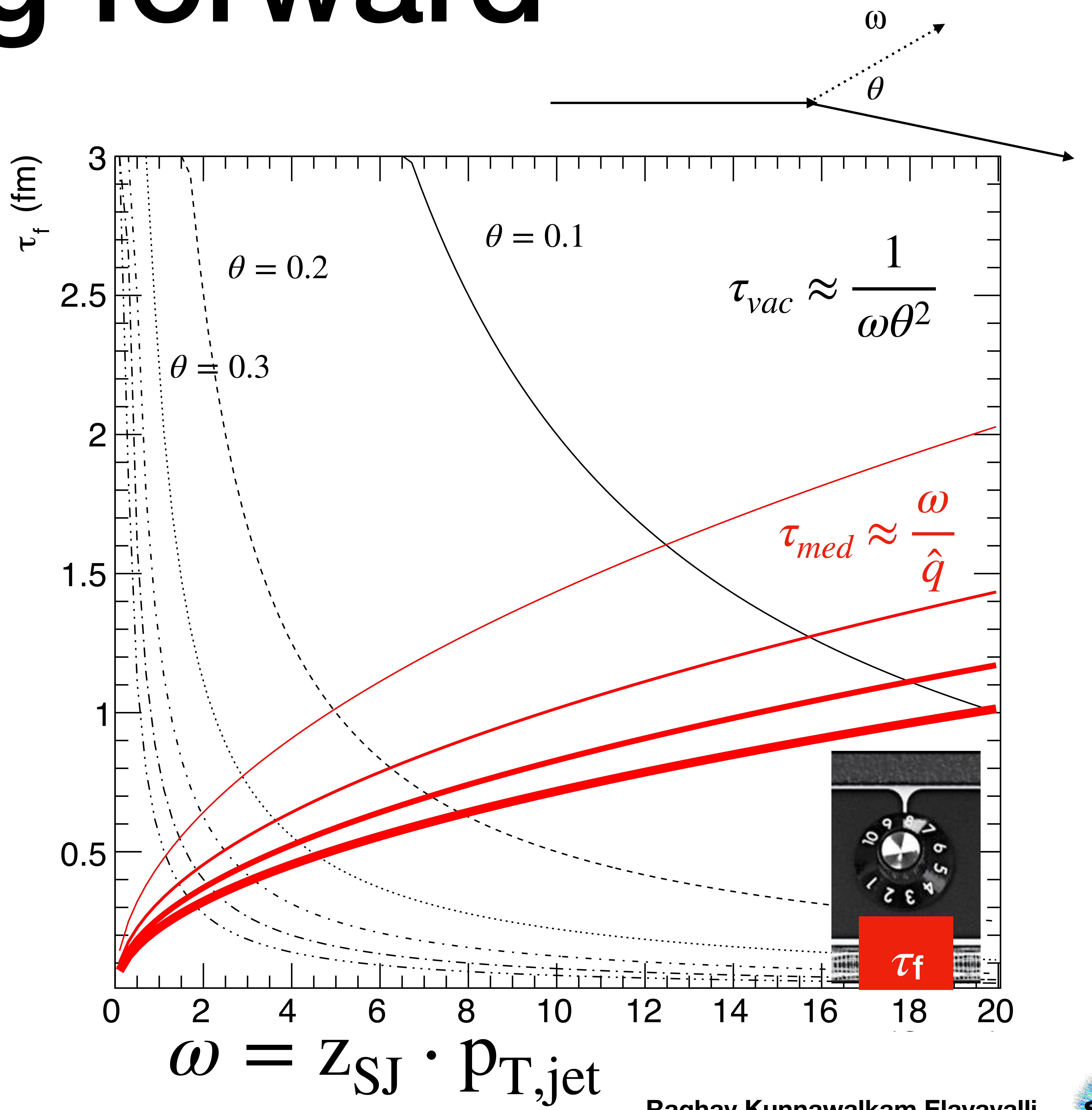
- Narrow and wide recoil jets reveal similar behavior of modified/quenched HardCore and balanced Matched
  - Quenched energy recovered within R=0.35



Consistent picture of energy loss at RHIC
given 'Jet Geometry Engineering' results in shorter path lengths and surface biases → splits most likely outside medium ⇒ modification due to **radiation from a single color charge**

Moving forward

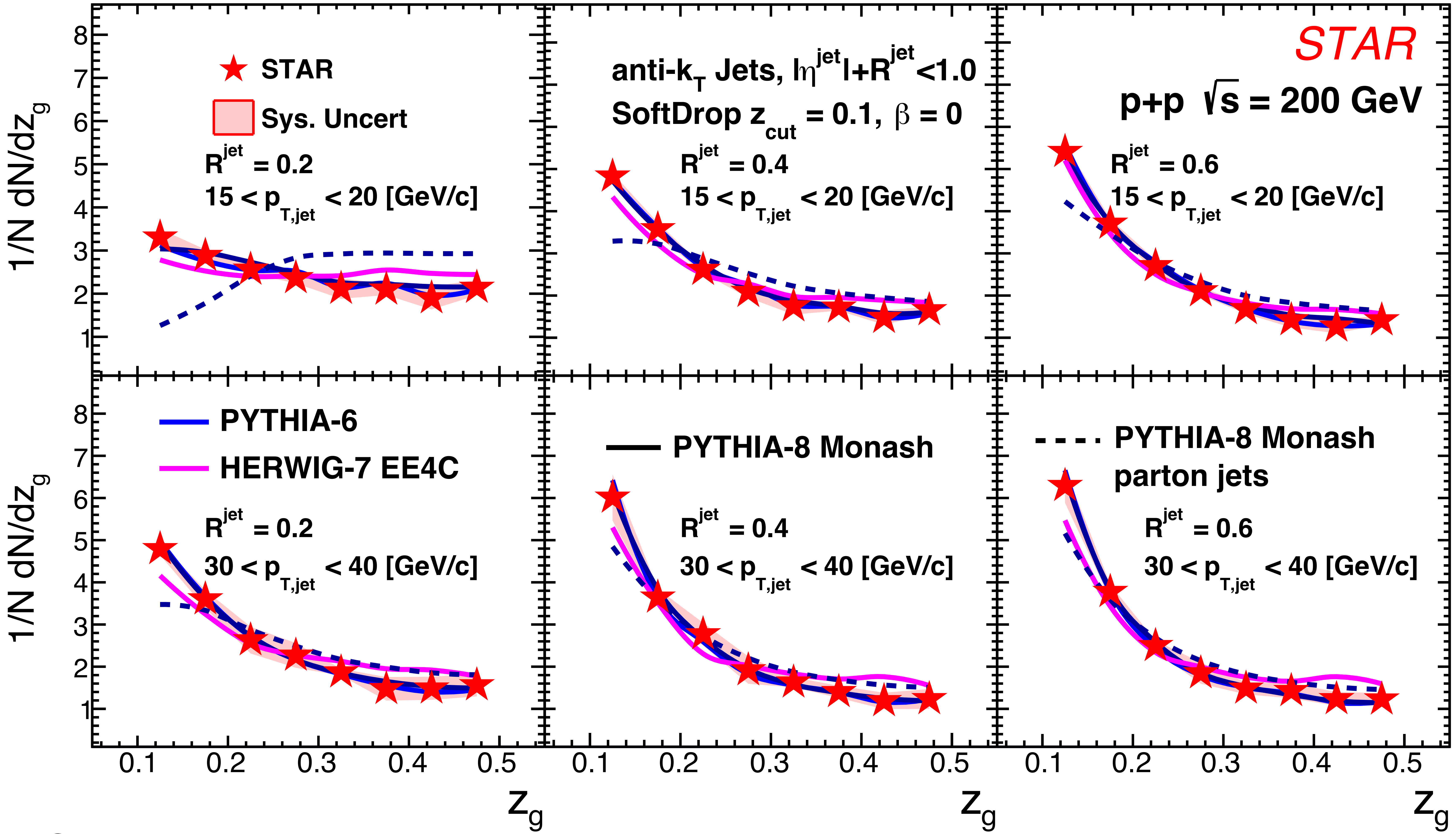
- Differential studies in both momentum and angular scales
- Utilize Jet Geometry Engineering biases to have a direct handle on energy loss in dijets
- Increase kinematic range of the dijet selection and centrality dependence
- Systematic mapping of the splitting phase space within jets - via formation time arguments



Backup slides

Radial Dependence on jet substructure in pp

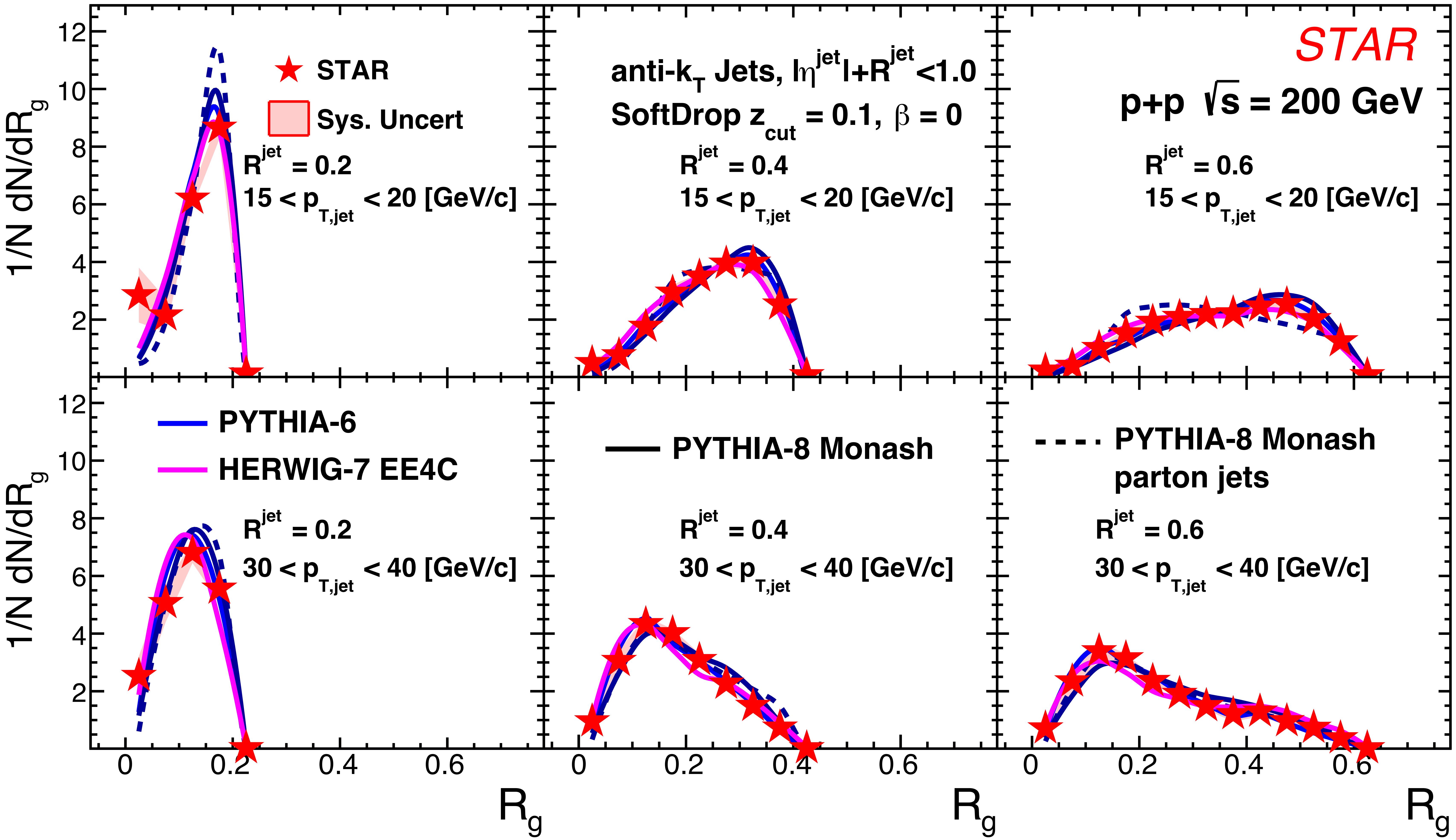
SoftDrop Splitting z_g



SoftDrop z_g is significantly dependent on the jet p_T - higher p_T leads to smaller z_g

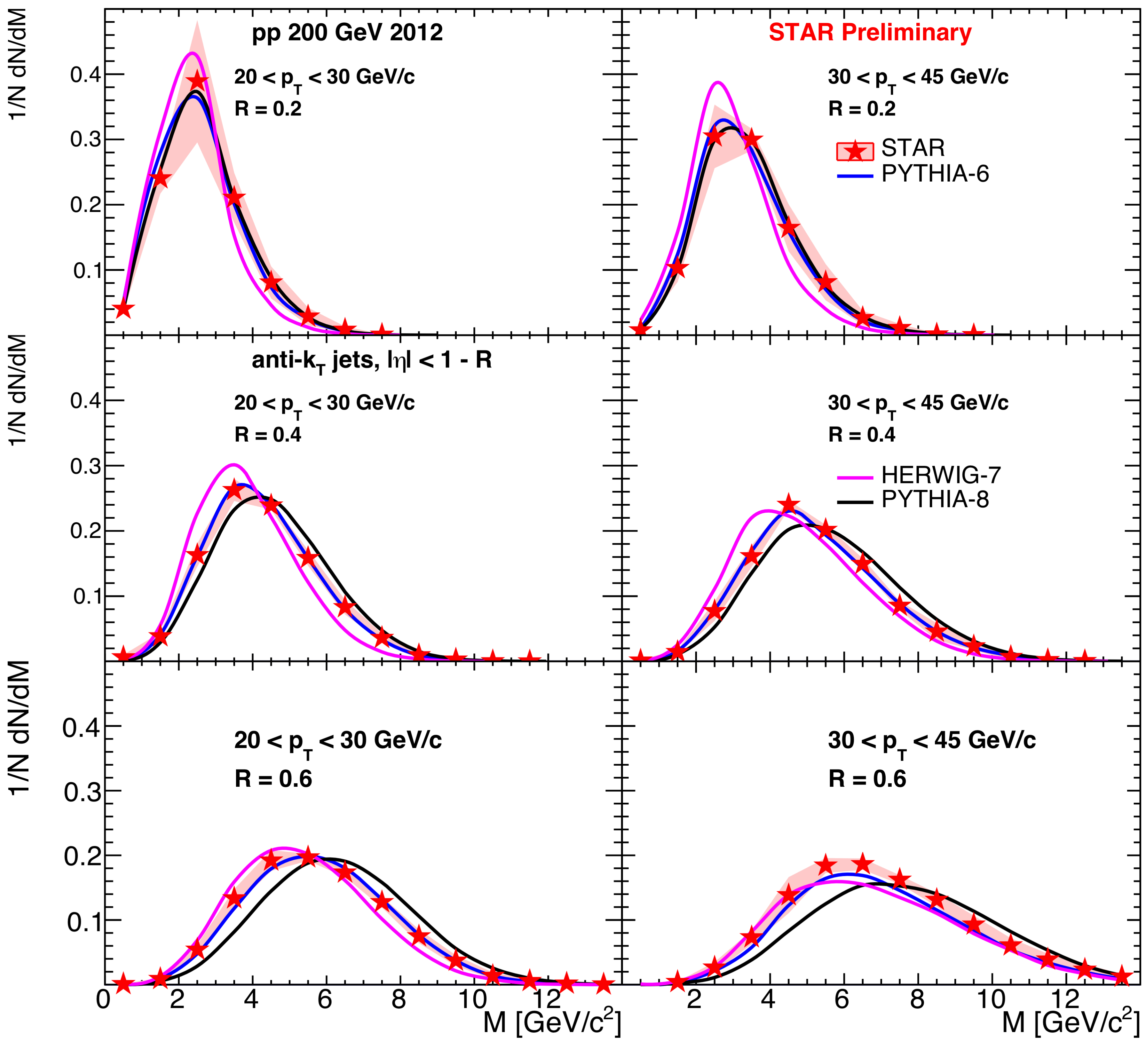
Larger radius jets include more softer radiation results in a more steeper z_g

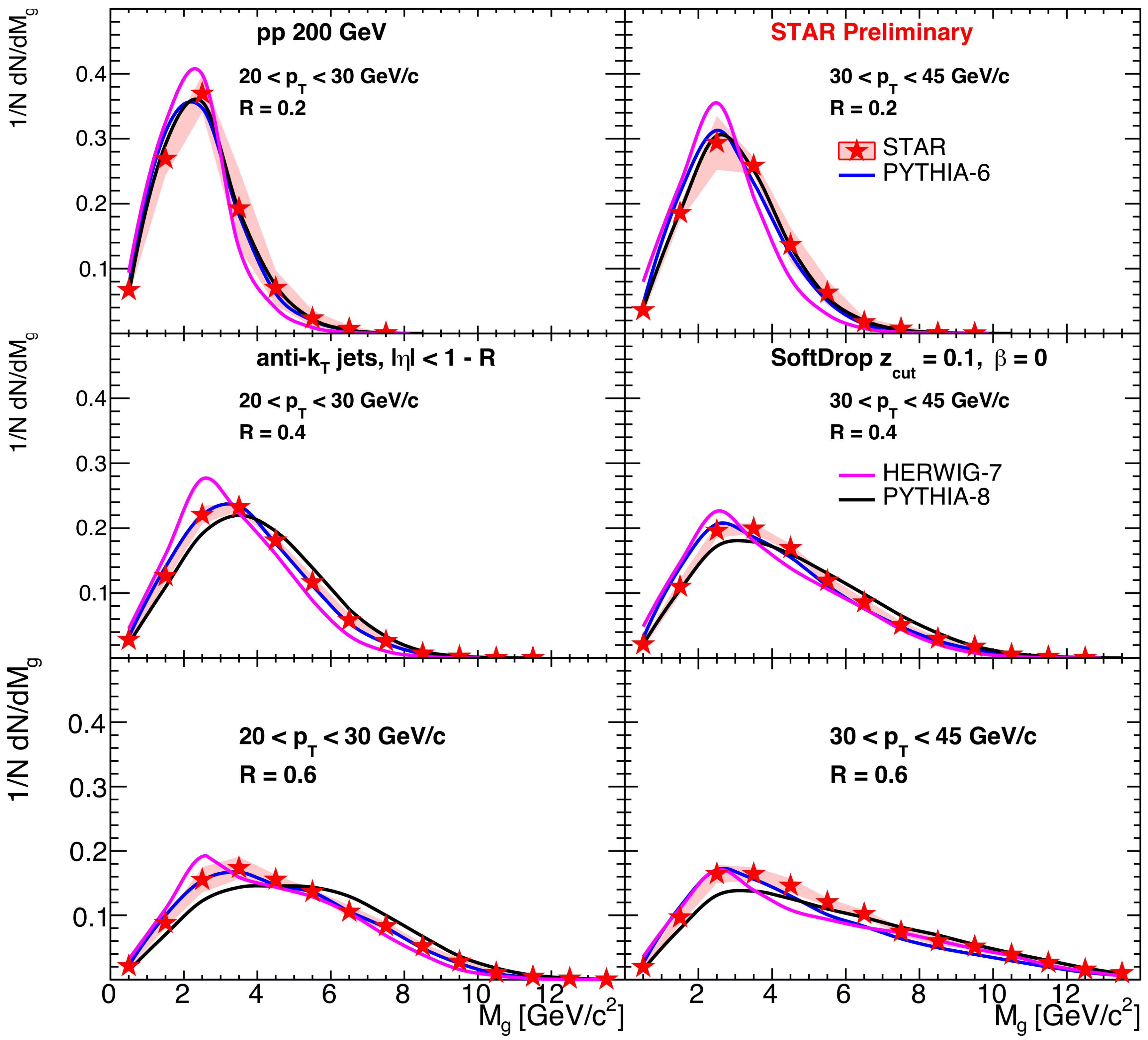
Radial Dependence on jet substructure in pp
Groomed Jet Radius R_g



Clear evidence of jet p_T dependent narrowing of jet substructure! high p_T - small R_g

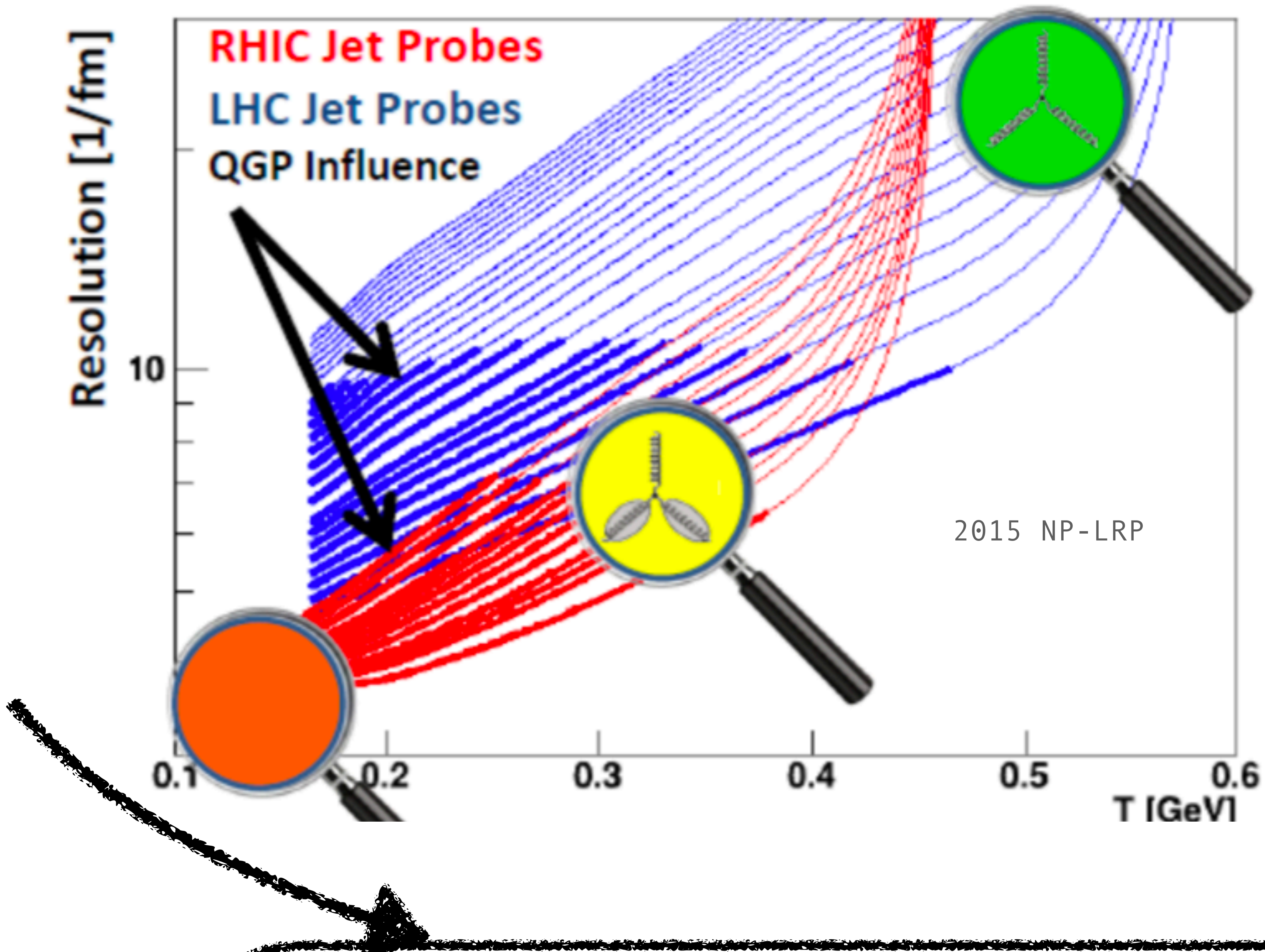
Radial Dependence on jet substructure in pp
Jet Mass and Groomed Jet Mass





- Jet mass increases with increased phase space (jet p_T) and inclusion of more wide-angle soft radiation (jet R), consistent with pQCD expectation
- SoftDrop groomed mass is observed to be closer to ungroomed parton level mass

What do we want to measure?



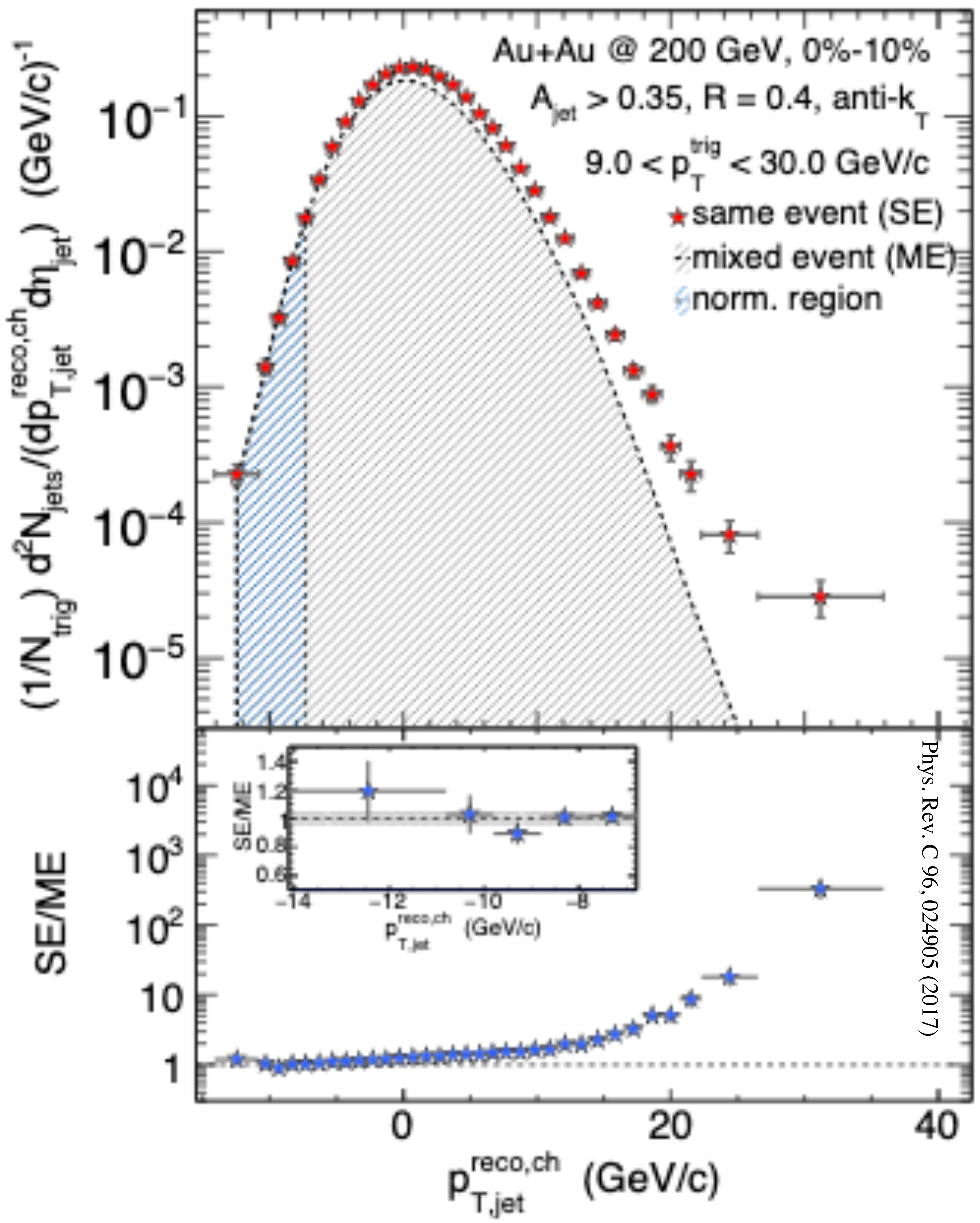
Microscopic properties of the QGP Medium - structure at varying scales

Interaction of the jet with the medium could depend on the resolution scale

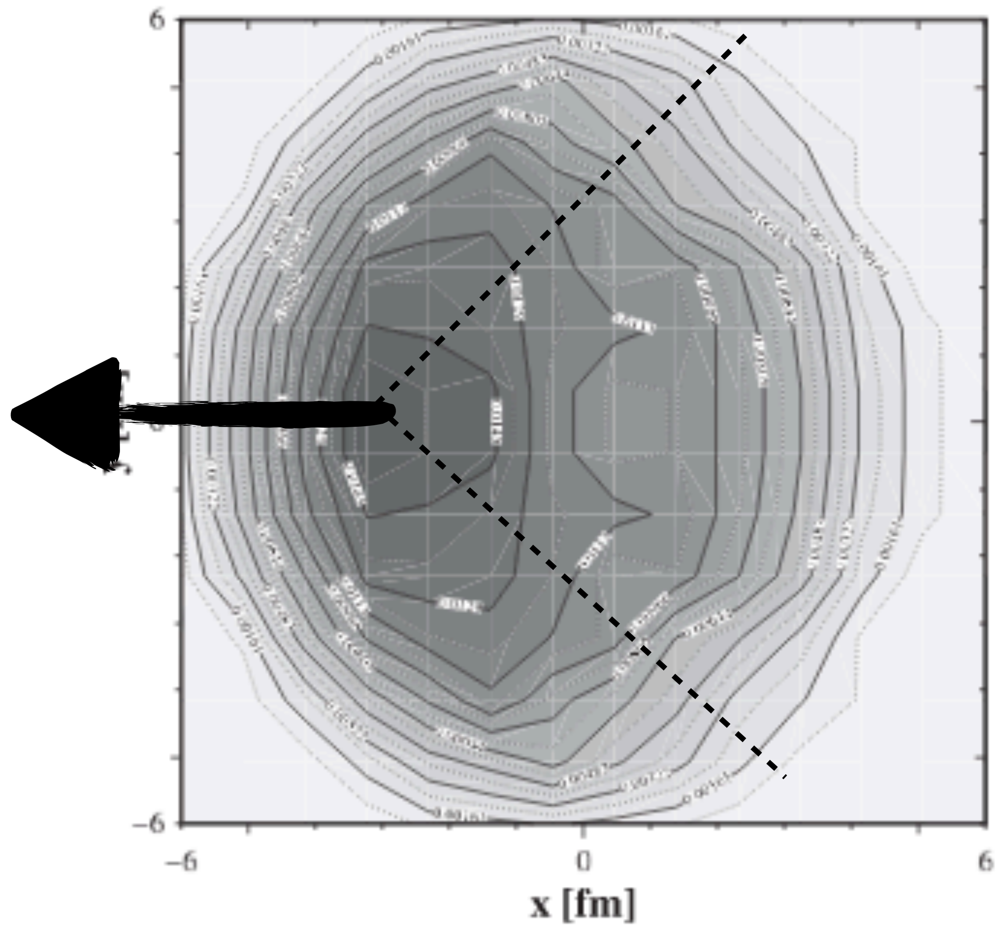
Jets at RHIC kinematics are ideal to study these effects

Partonic energy loss via a differential study in momentum scale and angular scale

Semi-Inclusive recoils



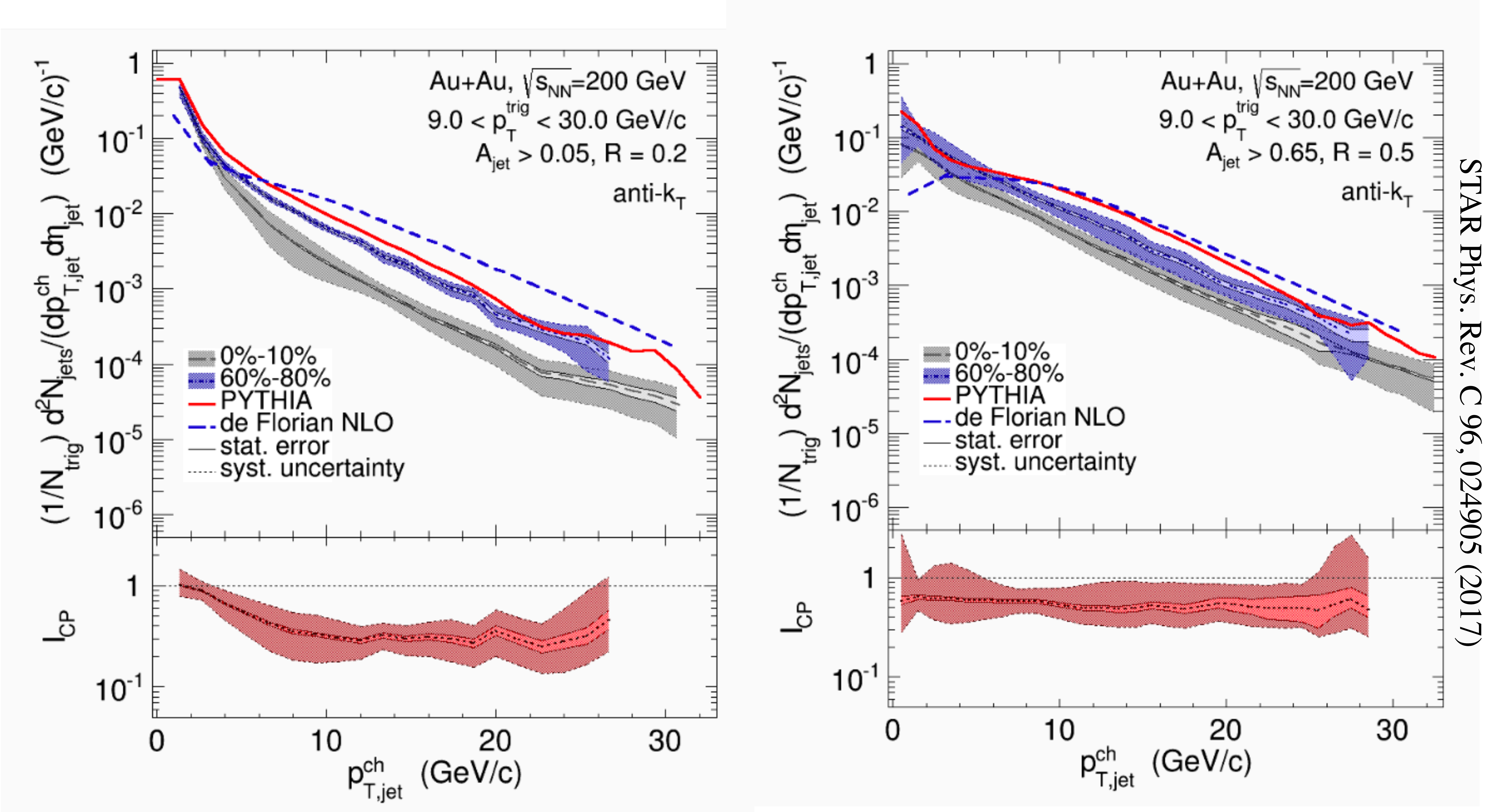
STAR Phys. Rev. C 96, 024905 (2017)



Renk, Phys.Rev. C 87, 024905 (2013)

- No selection on recoil jet momenta
- Statistical correction of the combinatorial jet yields via mixed events

I_{CP} for jets of varying radii



STAR Phys. Rev. C 96, 024905 (2017)

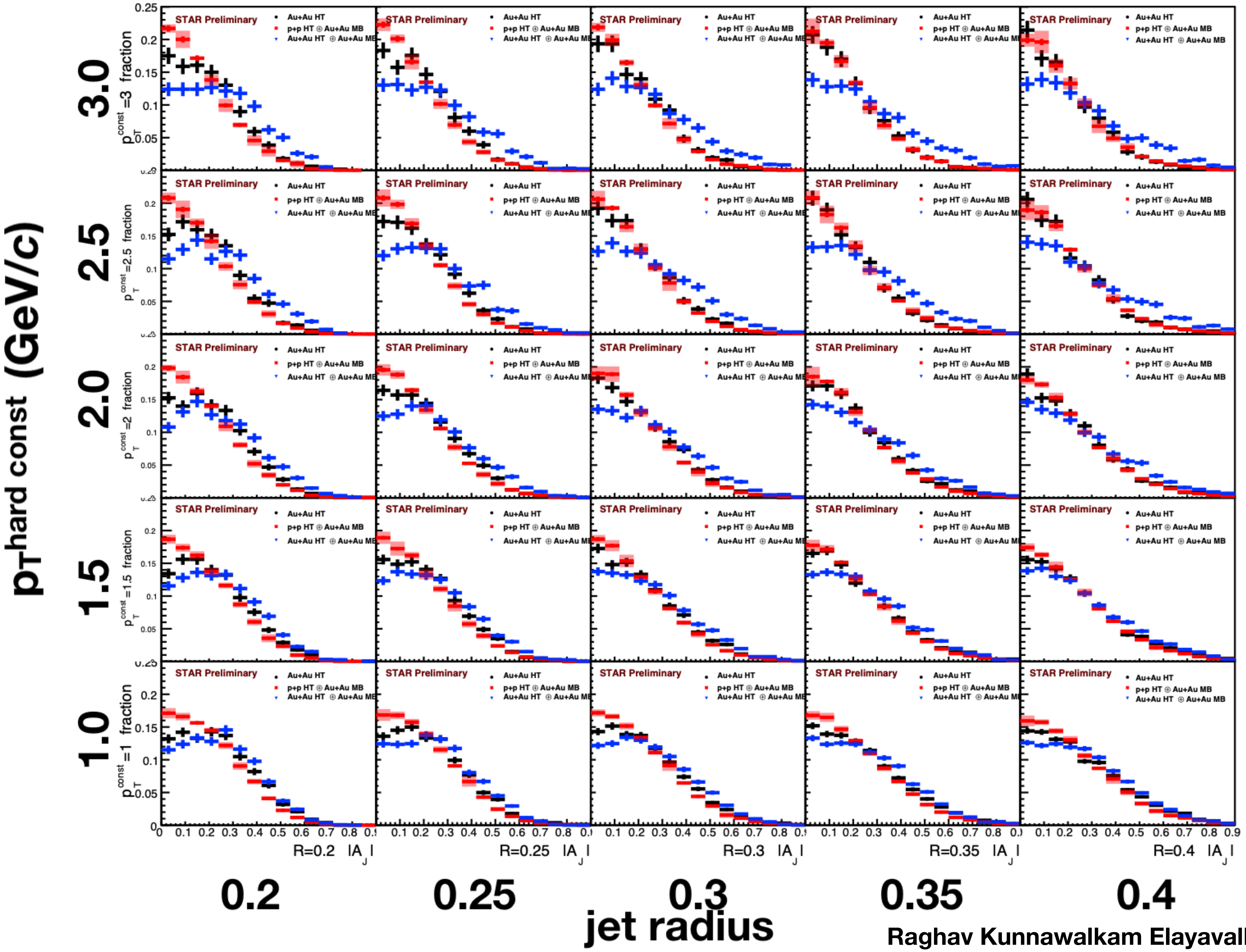
The recoil coincidence yield for R=0.2 (left) jets are suppressed compared to R=0.5 (right)

[p_T shifts for R=0.2 : -4.4 +/- 0.2 +/- 1.2 and R=0.5 : -2.8 +/- 0.2 +/- 1.5]

Sensitivity of Matched dijet imbalance

- ● Au+Au HT
- ■ p+p HT ⊕ Au+Au MB
- ▼ Au+Au HT ⊕ Au+Au MB

- Embedding a HardCore Au+Au dijet in a different Au+Au minimum bias event to check sensitivity to distinguish energy loss
- The blue markers are significantly different than both black and red markers implying we are sensitive to physics of energy loss



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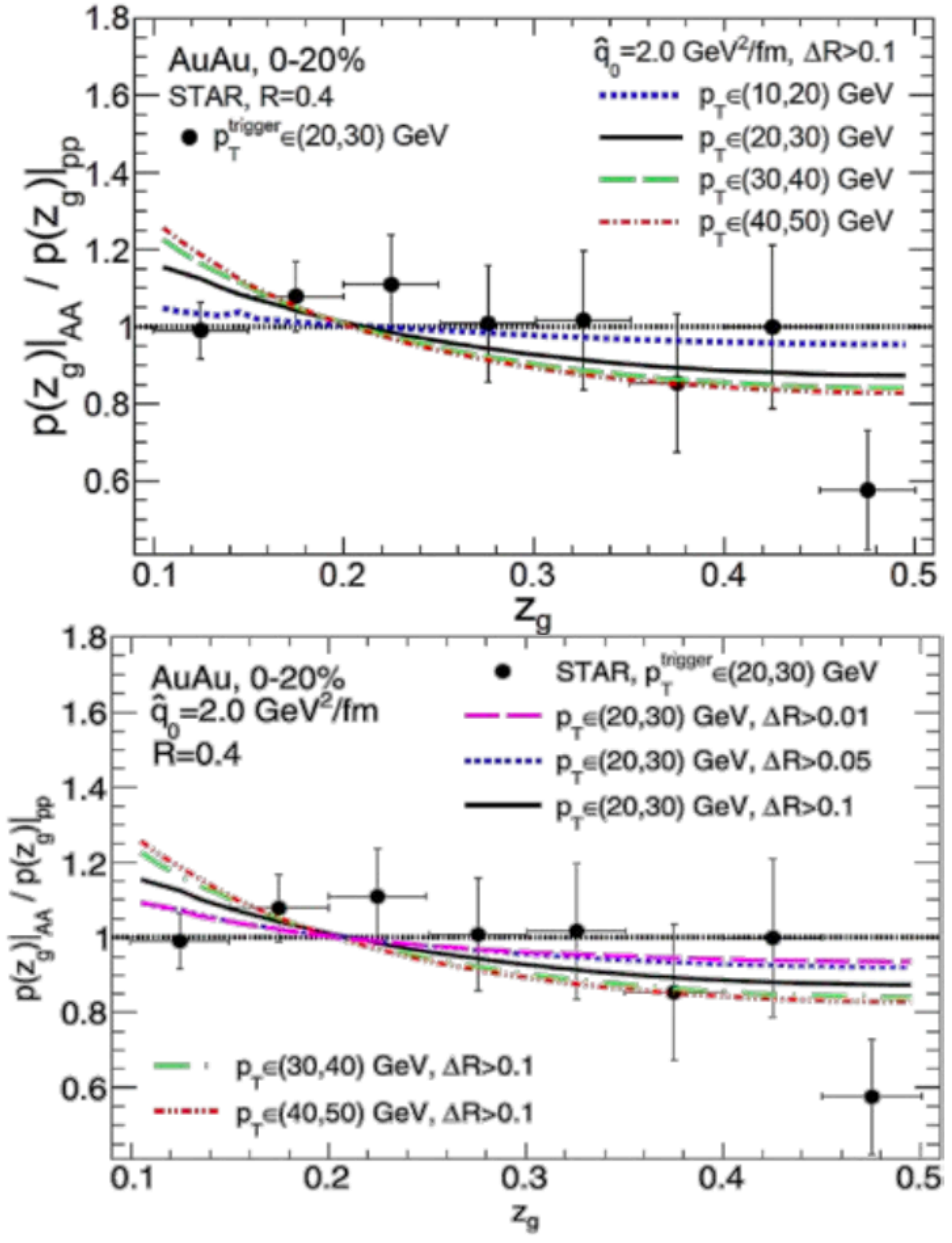
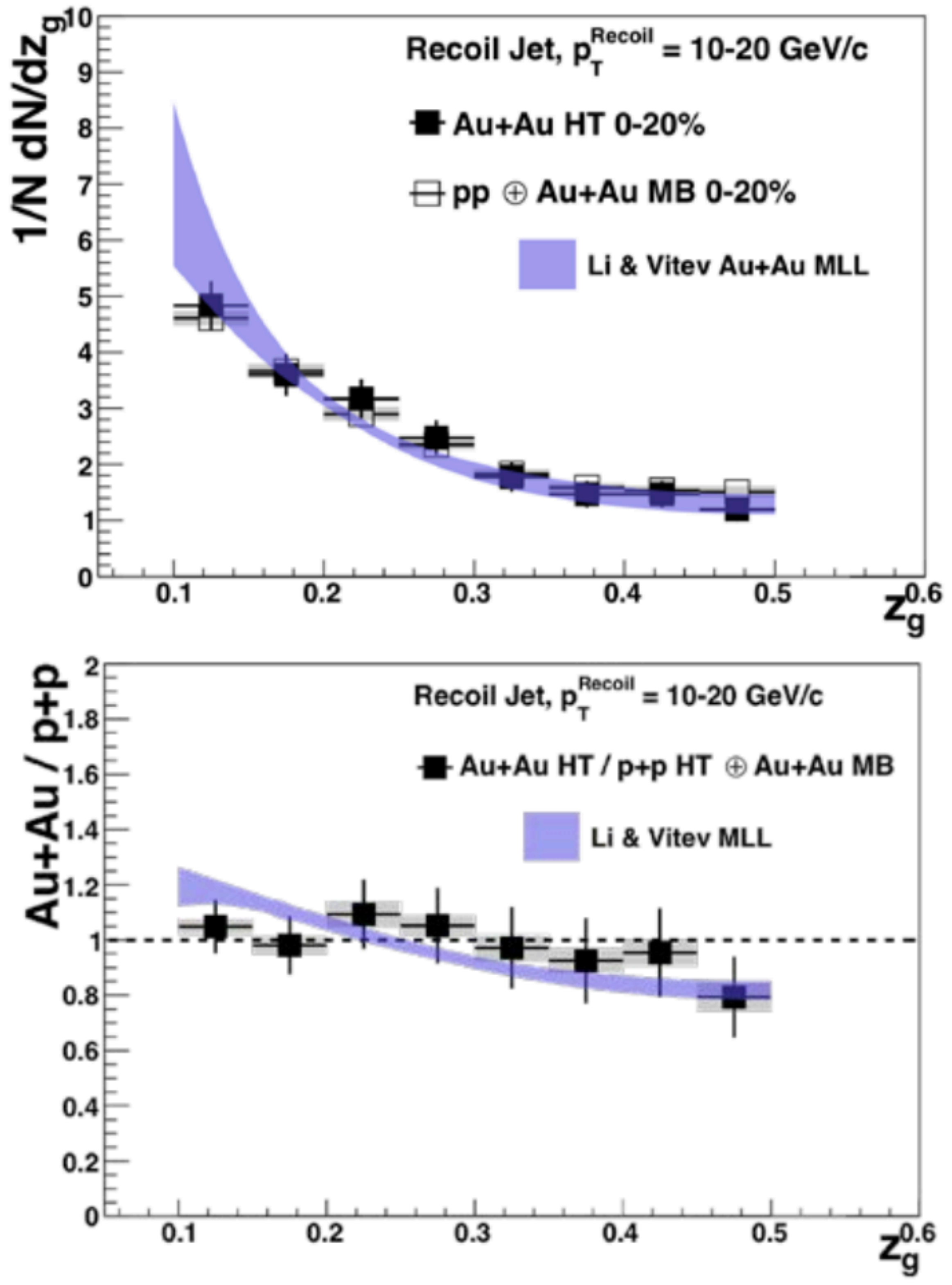
z_g in Au+Au 200 GeV



Ning-Bo Chang et.al. QM18



Li & Vitev, arXiv:1801.0008

- No significant modification on trigger and recoil side of hard-core dijets
- Theoretical models capture this well
- More statistics: Test downward slope

Note -These are detector level observables. Au+Au compared with p+p ⊕ Au+Au

Splitting unmodified for these matched jets

TwoSubJet (R=0.1) observables in Au+Au

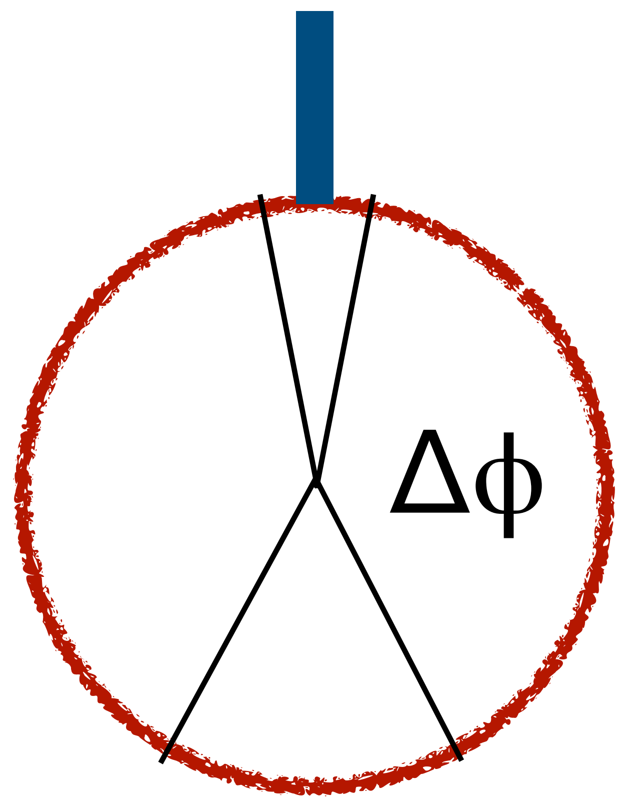
- Fix trigger jet selection:
  Study recoil HardCore/Matched Jets
  (p_T^{const} > 0.2 GeV/*c*)

- Matched jet's Subjet p_T > 3 GeV/*c*:
  reduce sensitivity to UE fluctuations

- TwoSubJet tagging fake rate ~ 2%

- Systematic uncertainty applied to the embedded p+p curves
  - relative tower energy scale (2%)
  - tracking efficiency (6%)
  - Subjet threshold cut varied by +/- 1 sigma of background fluctuations

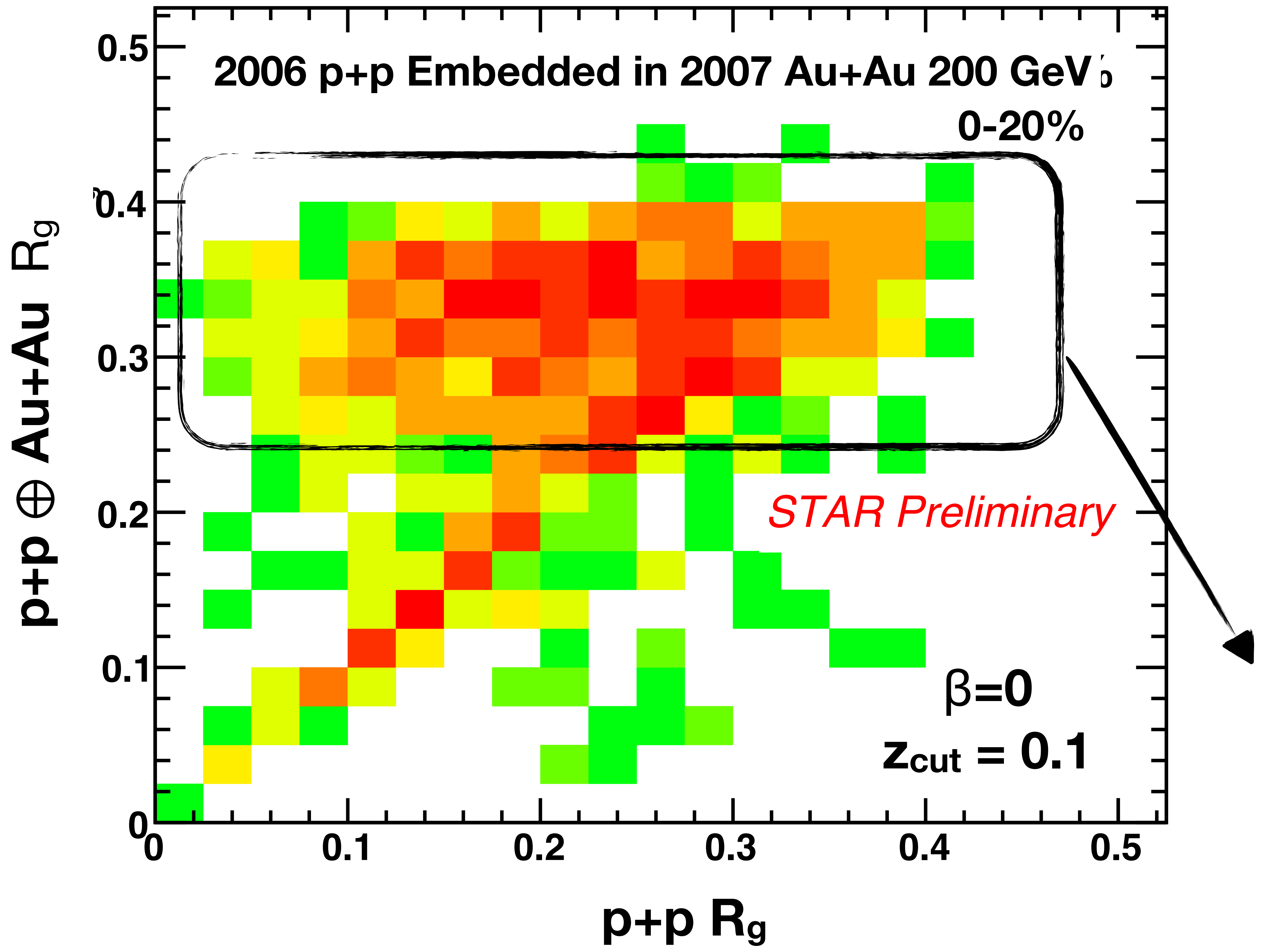
HardCore
Trigger Jet p_T > 16 GeV/*c*
w/ High Tower Trigger Object



HardCore
Recoil Jet p_T > 8 GeV/*c*

$p_T^{Trig} > p_T^{Recoil}$

SoftDrop R_g in the presence of Au+Au event



anti-k_t R^{jet} = 0.4

Ch+Ne Jets, $|\eta|+R^{jet} < 1.0$

$20.0 < p_T < 30.0$ [GeV/c]

Recoil jets $\Delta\phi_{jet, HT} > 2\pi/3$

Constituent-subtracted jets

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

SoftDrop R_g sensitive to background fluctuations

We need an observable that is more **robust** to the AuAu fluctuating underlying event but still **sensitive** to jet kinematics

TwoSubJet (R=0.1) θ_{SJ}

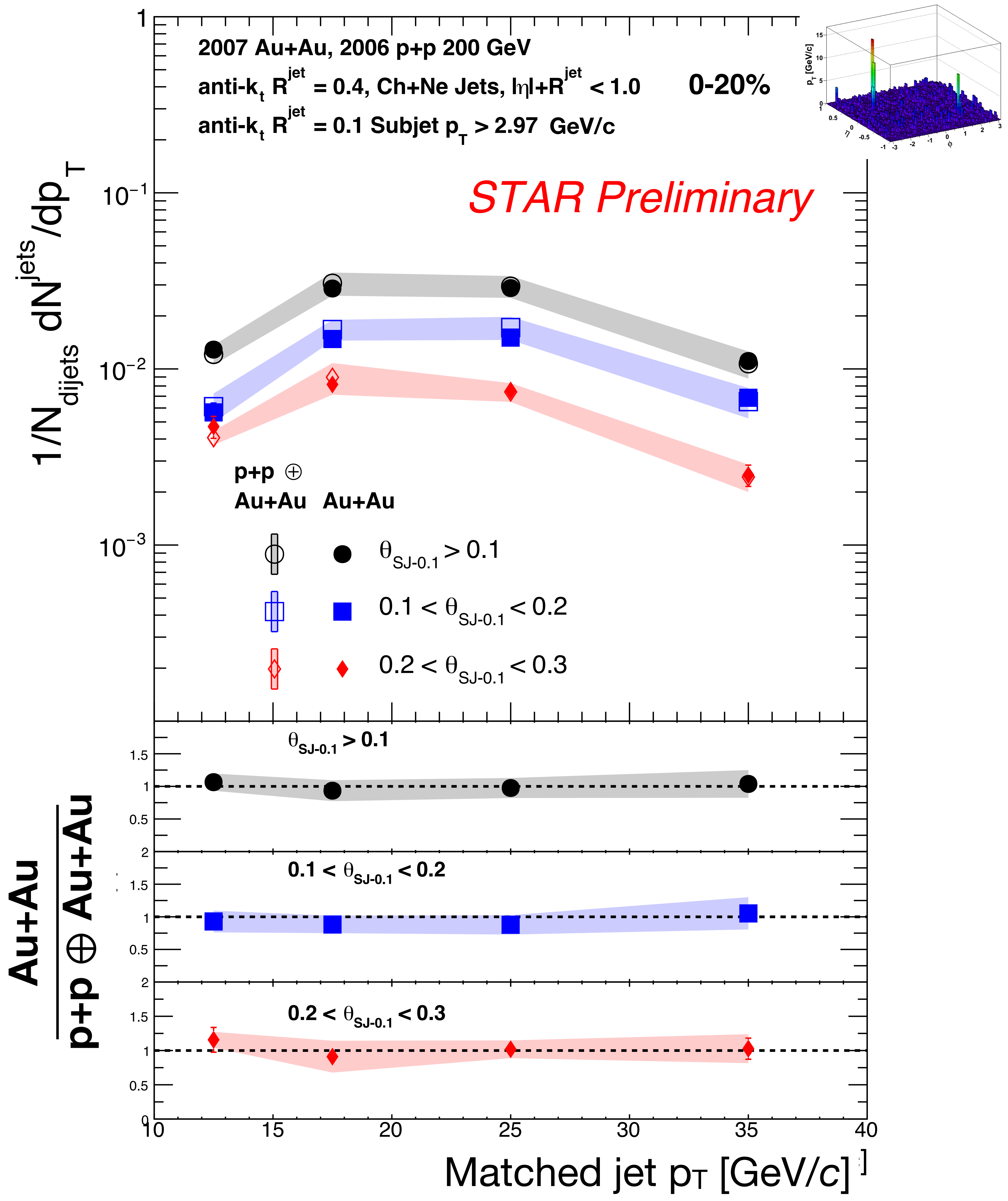
Tagging Purity

- Given a p+p ⊕ Au+Au jet with two resolved Subjets, how often does the input p+p jet utilized in the embedding also have two resolved Subjets.
  - For Matched jet $p_T > 10$ GeV, purity > 98%
  - Systematic uncertainty estimated by varying the SubJet p_T threshold by 1 sigma variation in the background fluctuations
- Probability that a p+p ⊕ Au+Au and the p+p jet utilized in the embedding has a resolved θ_{SJ} in the same range. These are the cases where both jets have two resolved SubJets.
  - $0.1 < \theta_{SJ} < 0.2$: purity > 99%
  - $0.2 < \theta_{SJ} < 0.3$: purity > 72%

Recoil matched jet yield

$p_T^{const} > 0.2$ GeV/c

- Confirmation that **matched jets recover** the energy lost by quenching within R = 0.4
- **Observe no significant differences among θ_{SJ} selections**



Two subjet distributions in PYTHIA-8