Measurements of the Jet Internal Structure

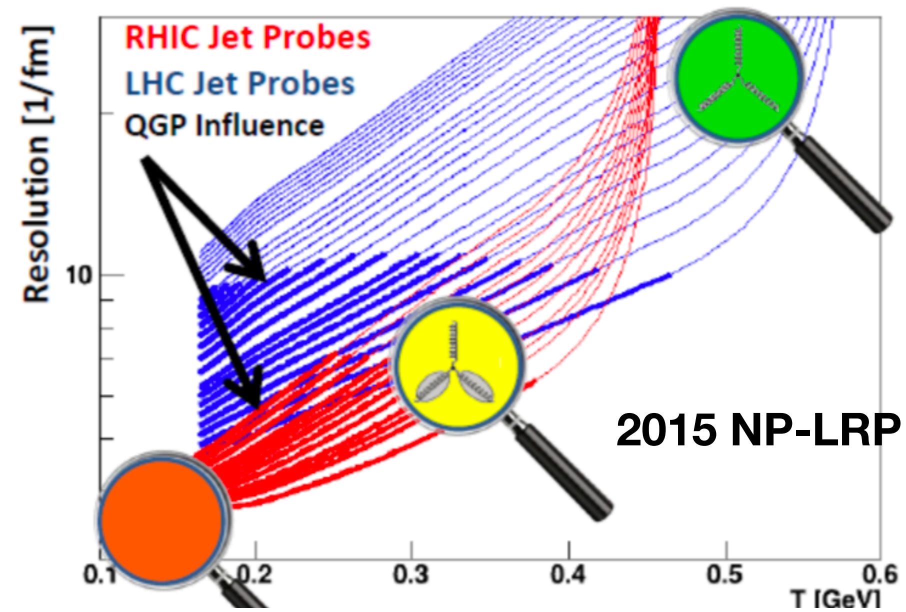
Relevance to parton evolution in p+p and Au+Au collisions at STAR

Raghav Kunnawalkam Elayavalli
Wayne State University
On behalf of the STAR Collaboration

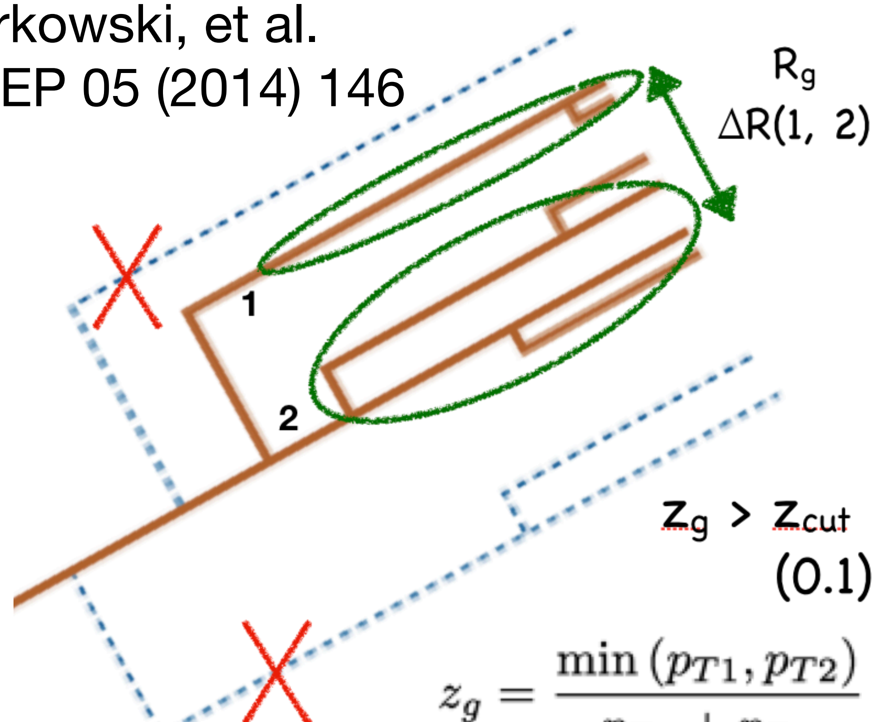
Hard Probes @ Aix-Les-Baines
October 2nd 2018

What do we want to measure?

- Parton shower (jet evolution) in vacuum is inherently a multi-scale processes
  - momentum and angular/virtuality scale
- In heavy ion collisions - we can relate the angular/virtuality scale to a resolution scale at which the jet probes the medium



Larkowski, et al.
JHEP 05 (2014) 146



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

Dasgupta et al.
JHEP 09 (2013) 029

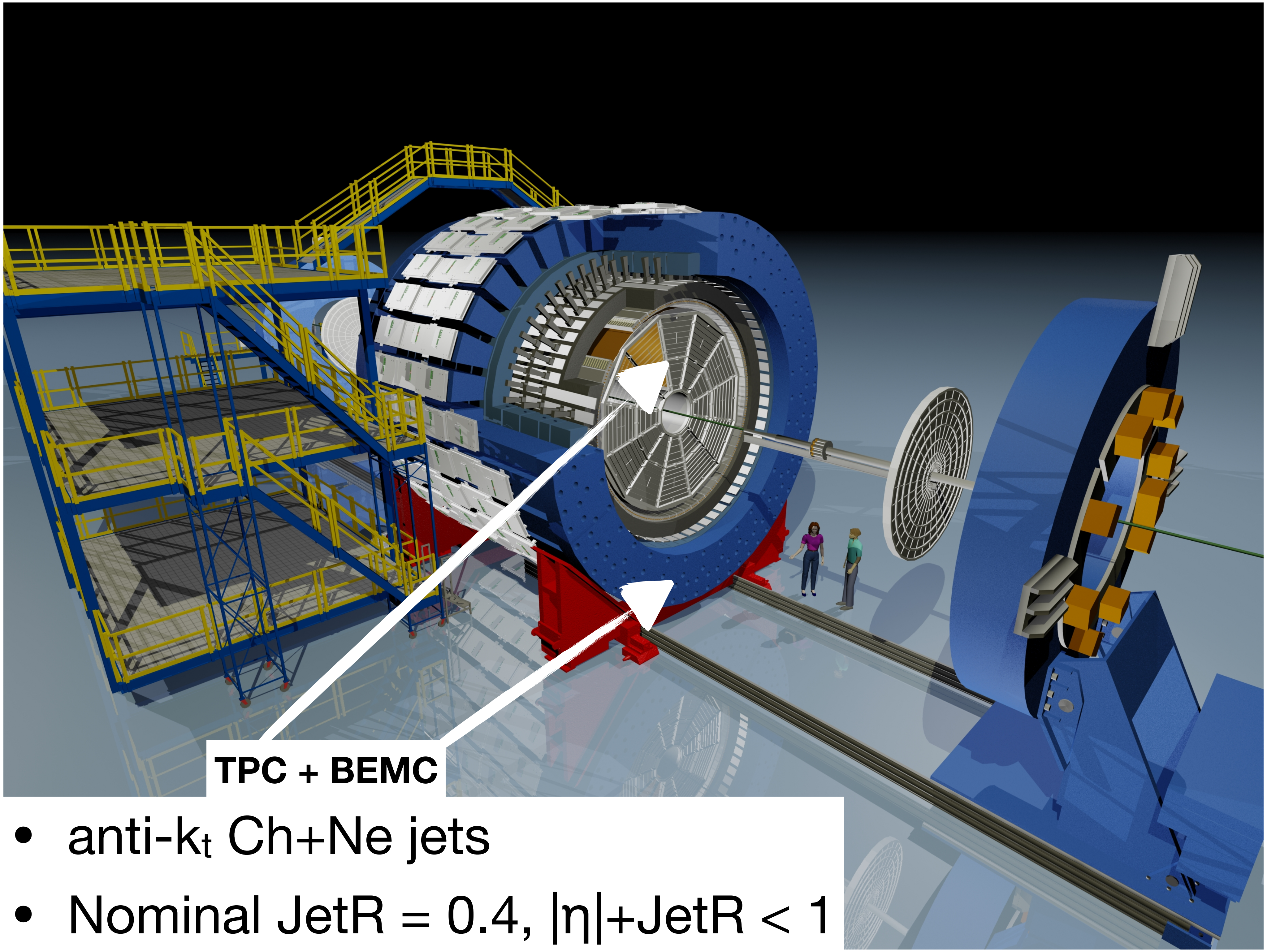
- Utilize SoftDrop algorithm
  - momentum scale - z_g
  - virtuality/angular scale - R_g

multi-scale jet evolution in vacuum

Lets begin with this measurement in p+p

STAR

Jet reconstruction at STAR



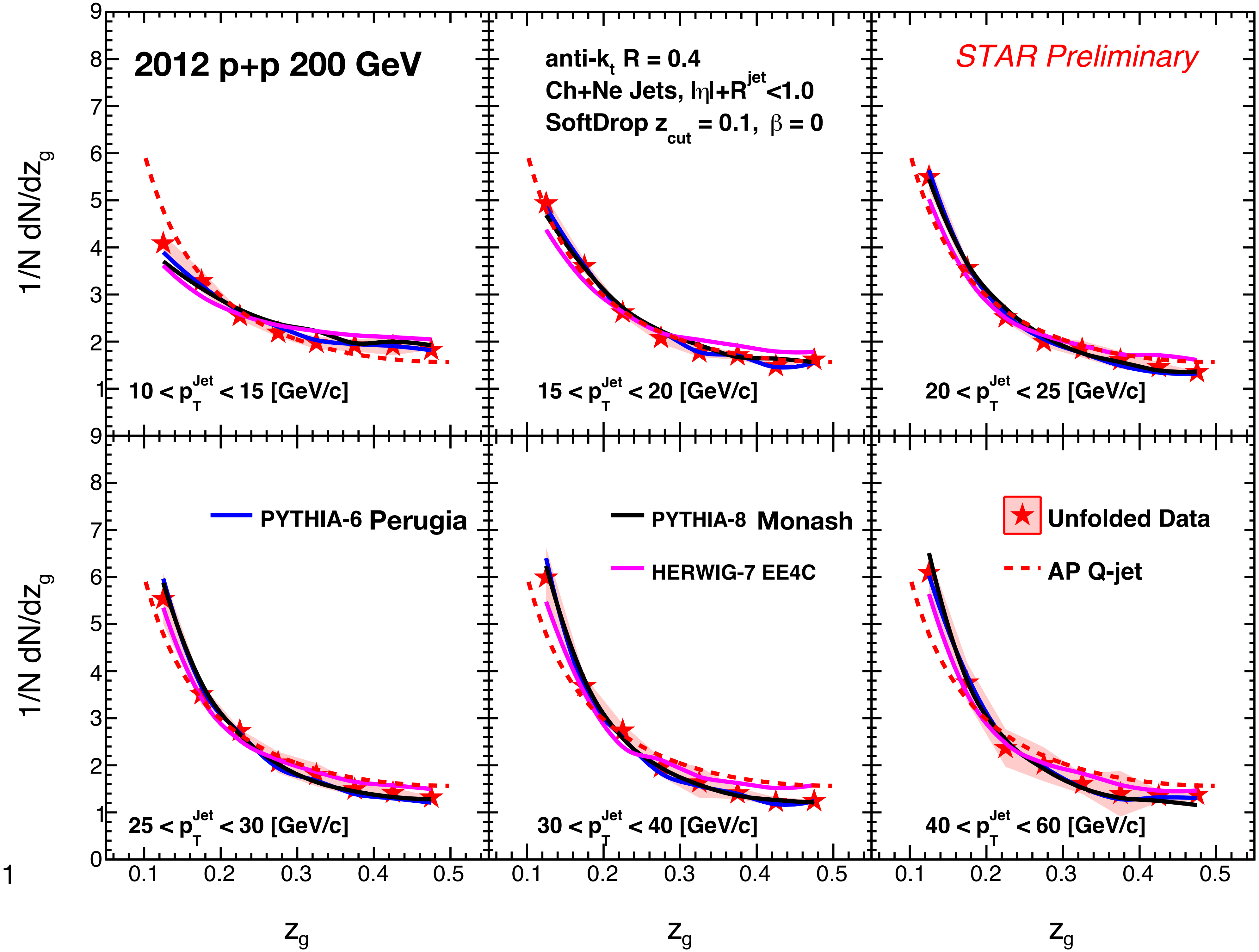
- anti-k_t Ch+Ne jets
- Nominal JetR = 0.4, $|\eta|$+JetR < 1

SubJet momentum fractions (z_g)

p+p collisions @ 200 GeV

- z_g in vacuum **described by leading order MC generators**
- Recover the universal ***1/z behavior*** starting from $p_T \sim 20$ GeV/c

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



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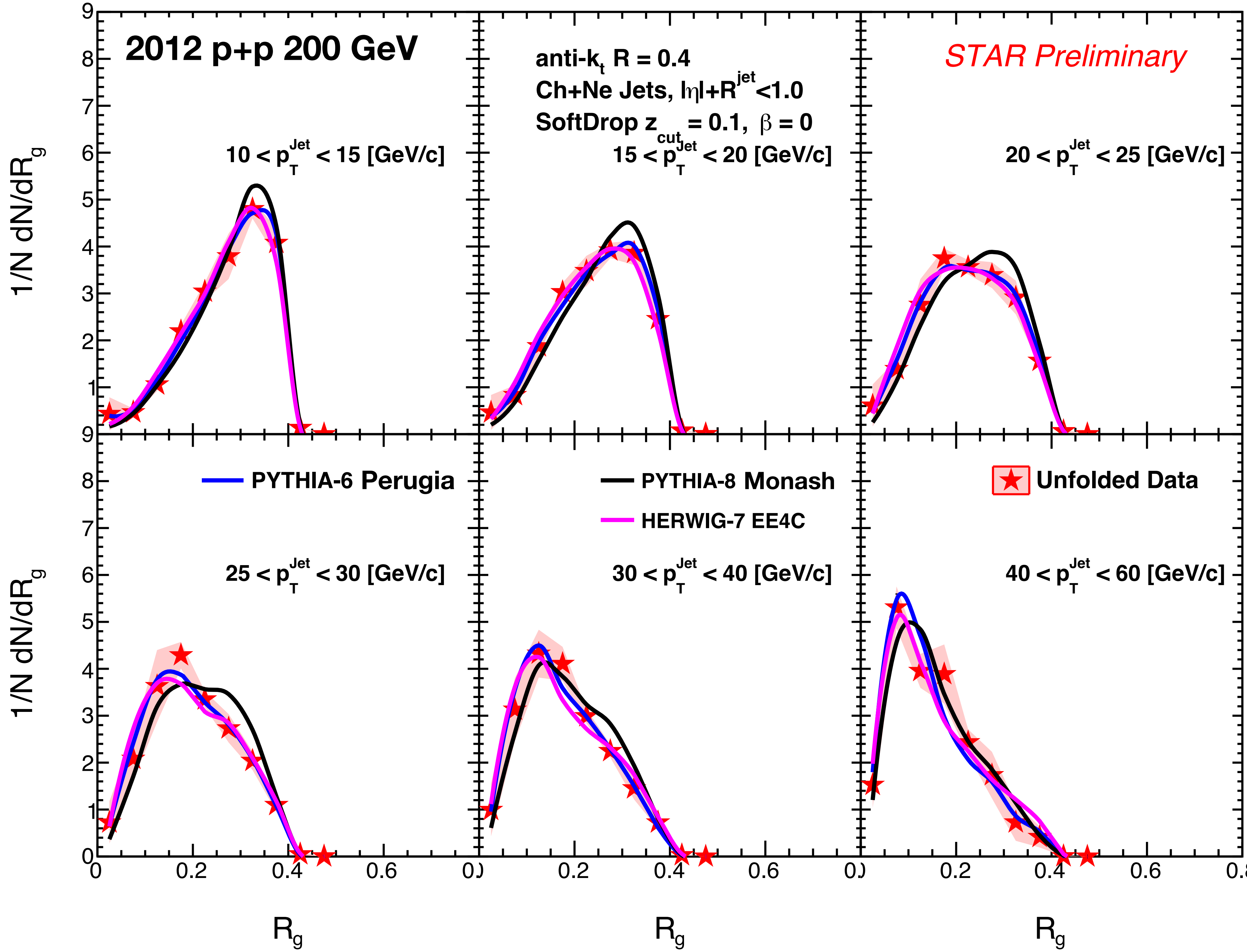
Groomed jet radius (R_g)

p+p collisions @ 200 GeV

- SoftDrop R_g reflects **momentum dependent narrowing** of jet structure (higher p_T - narrower R_g)
- **Overall shape in R_g described by leading order models** (opportunity to further tune MC at RHIC kinematics)



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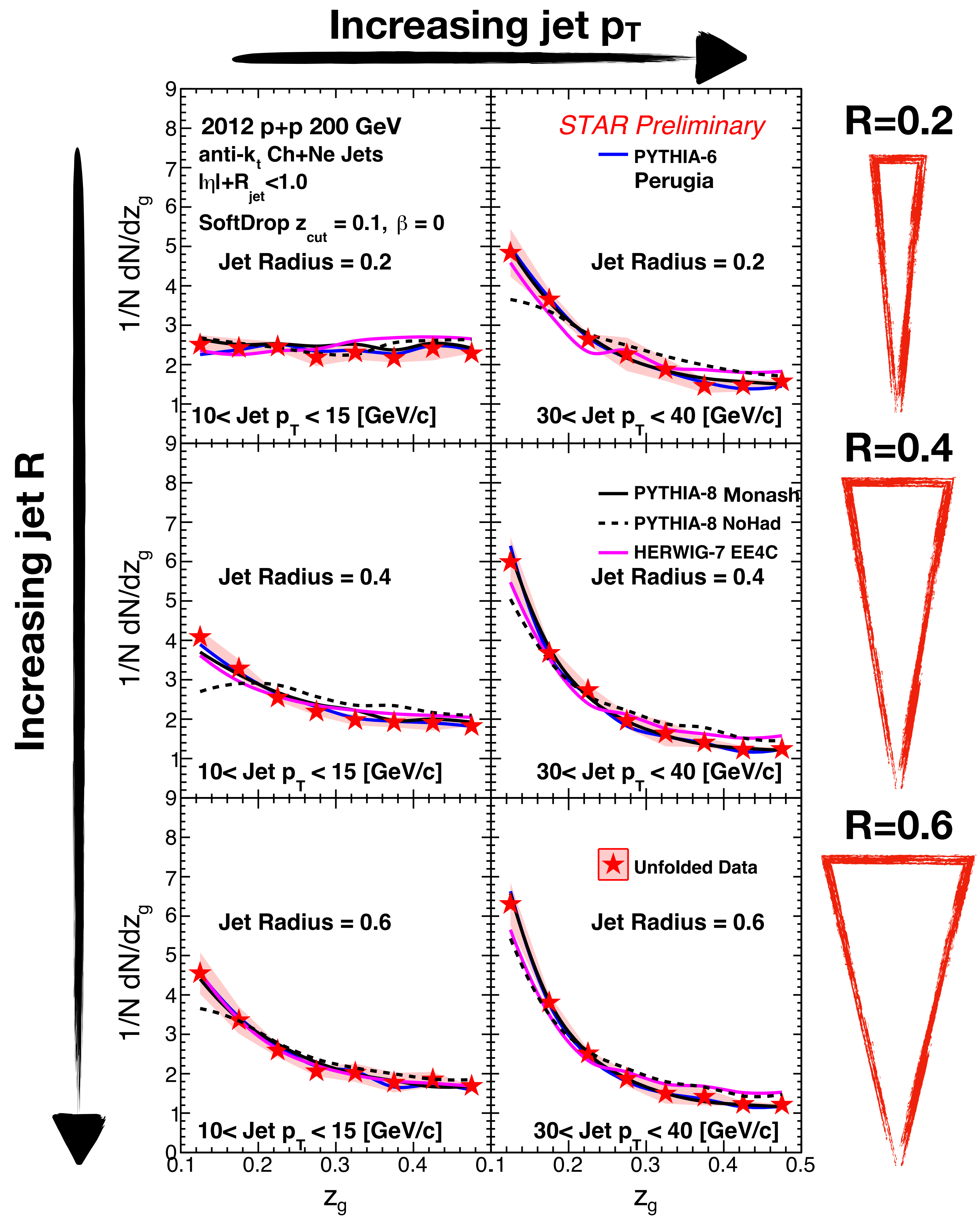
Dependence on the jet R

- z_g **flattens at low p_T for small R jets**
- Deviation from universal *1/z behavior* for **small R and low p_T due to reduced phase space/ angular scale**
- Moderate effect due to hadronization in PYTHIA-8



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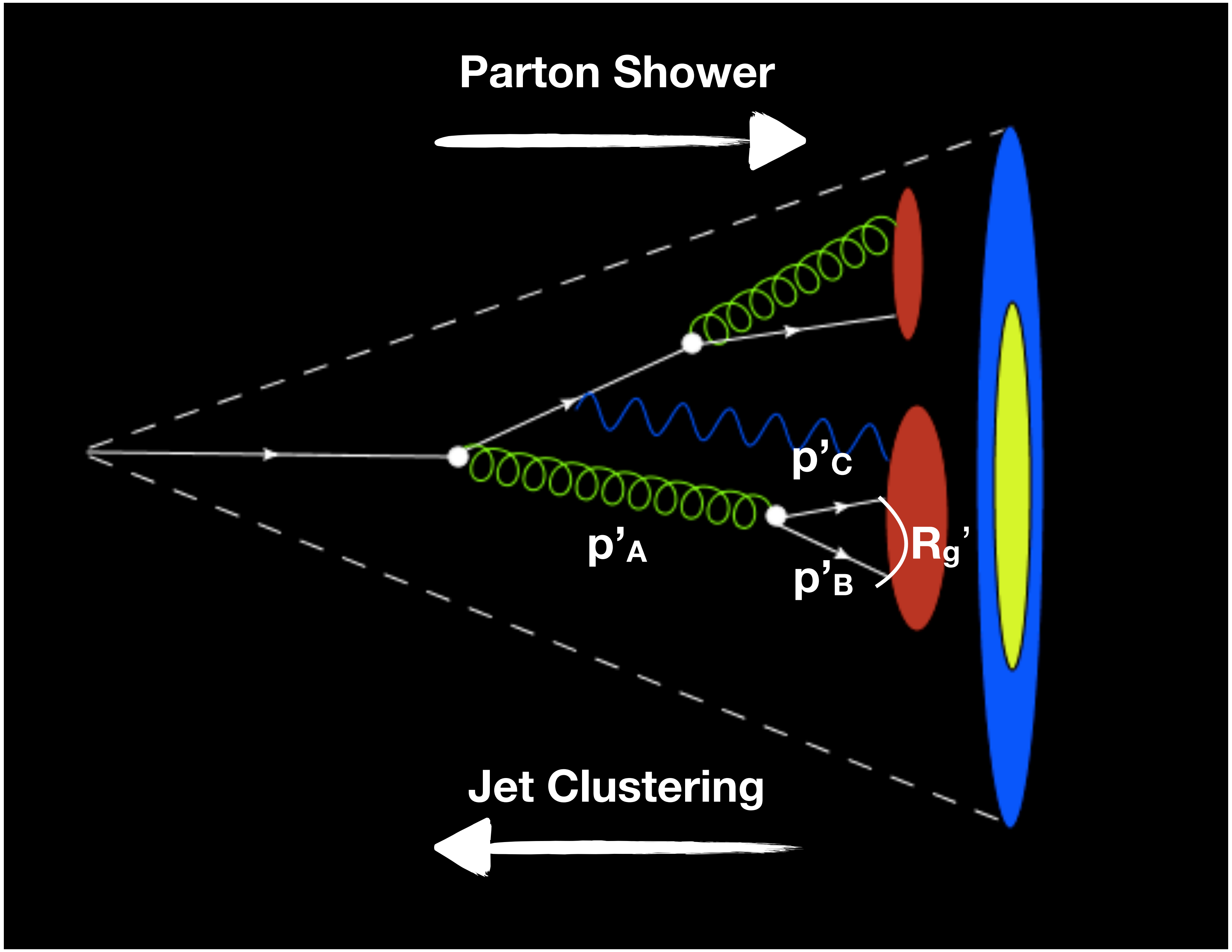
Recursive SoftDrop

Dreyer et al.
JHEP 06 (2018) 093

- Follow the leading split

$$z'_g = \frac{p_T^{C'}}{p_T^{C'} + p_T^{B'}}$$

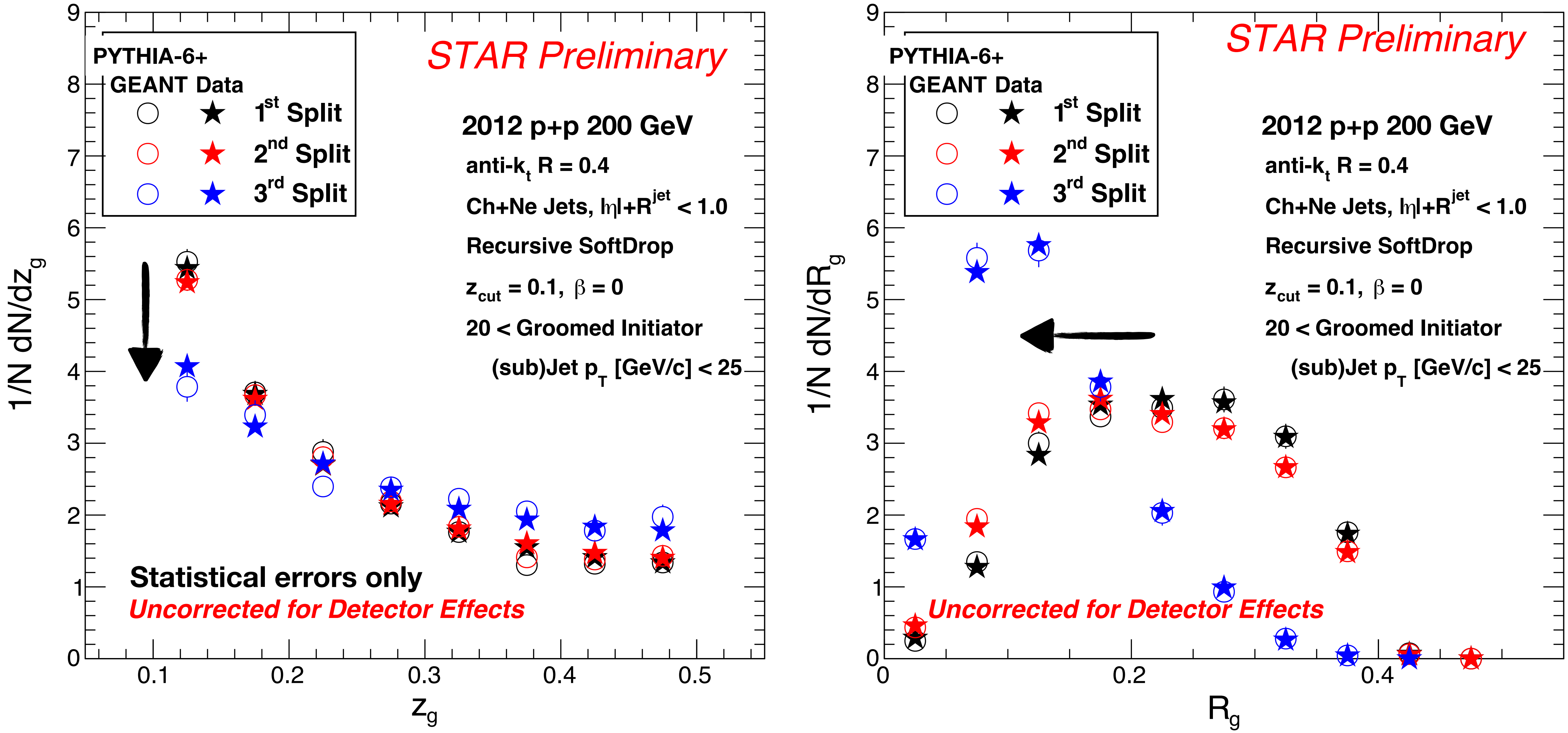
$$R'_g = \Delta R(C', B')$$



In vacuum : opportunity to experimentally reconstruct the parton shower history

—> Test **self similarity** of the AP splitting in p+p collisions

First measurement of the jet internal structure via recursive SoftDrop at STAR



- **1st and 2nd splits are similar** in both z_g and R_g
- **3rd split is significantly constrained** in phase space/ angular scale - Deviation from universal *1/z behavior*

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What do we want to measure?

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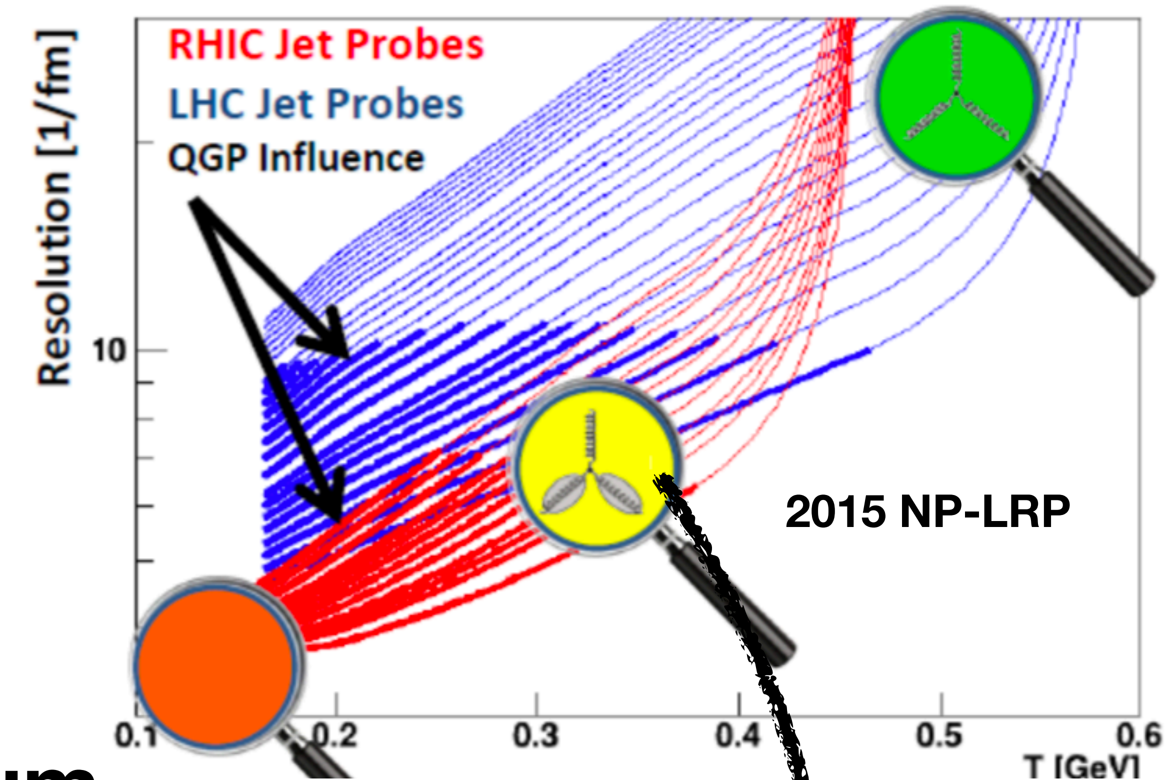
  - Momentum and Angular/Virtuality Scale
- In heavy ion collisions - we can relate the angular/virtuality scale to a resolution scale at which the jet probes the medium



multi-scale jet evolution in vacuum

Interaction of the jet w/ the medium could depend on the resolution scale

Majumder, A and Putschke, J
Phys. Rev. C 93 (2016) 054909

Mehtar Tani, Y and Tywoniuk, K
Phys. Rev. D 98 (2018) 051501(R)

Partonic energy loss as a function of the resolution scale -> jet's angular scale

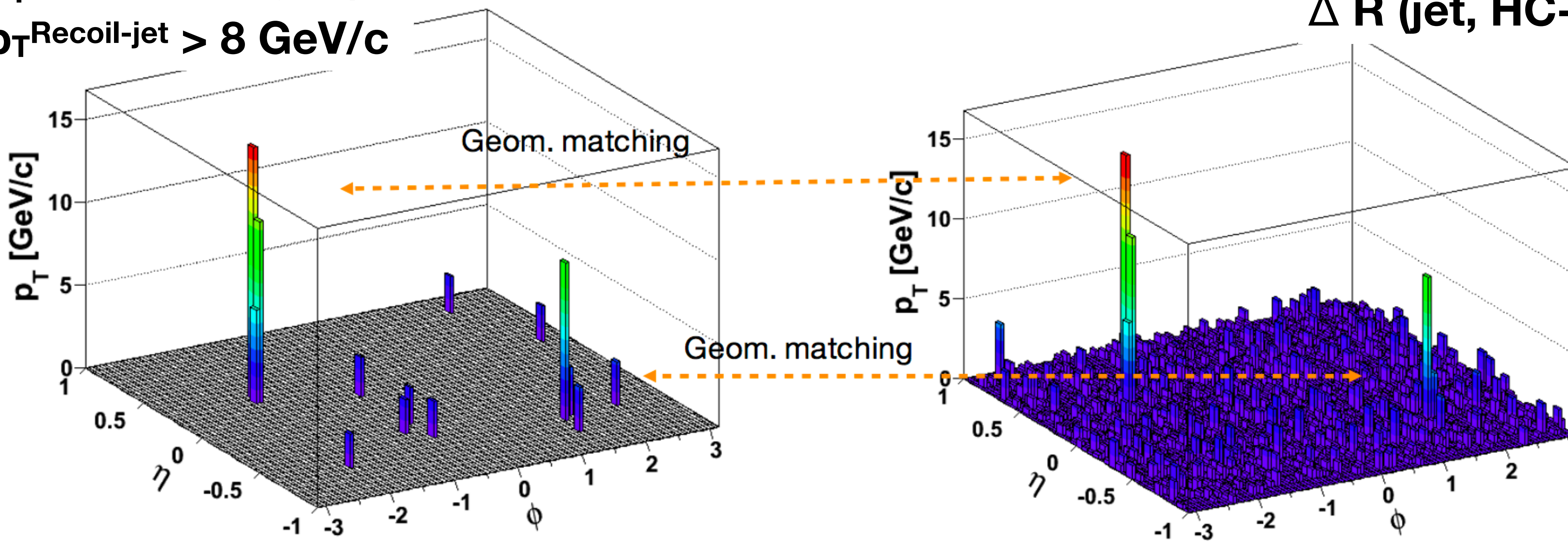
Jet selection in Au+Au events

Select events based on High Tower (HT) trigger
highest tower E_T > 5.4 GeV/c

Hard Core jets
p_T^{const} > 2 GeV/c
$p_T^{Lead\text{-}jet}$ > 16 GeV/c
$p_T^{Recoil\text{-}jet}$ > 8 GeV/c

Δ R (Lead-jet, HT) < 0.4
$\Delta\,\phi$ (Recoil-jet, HT) > $2\pi/3$

Matched jets
p_T^{const} > 0.2 GeV/c
Δ R (jet, HC-jet) < 0.4



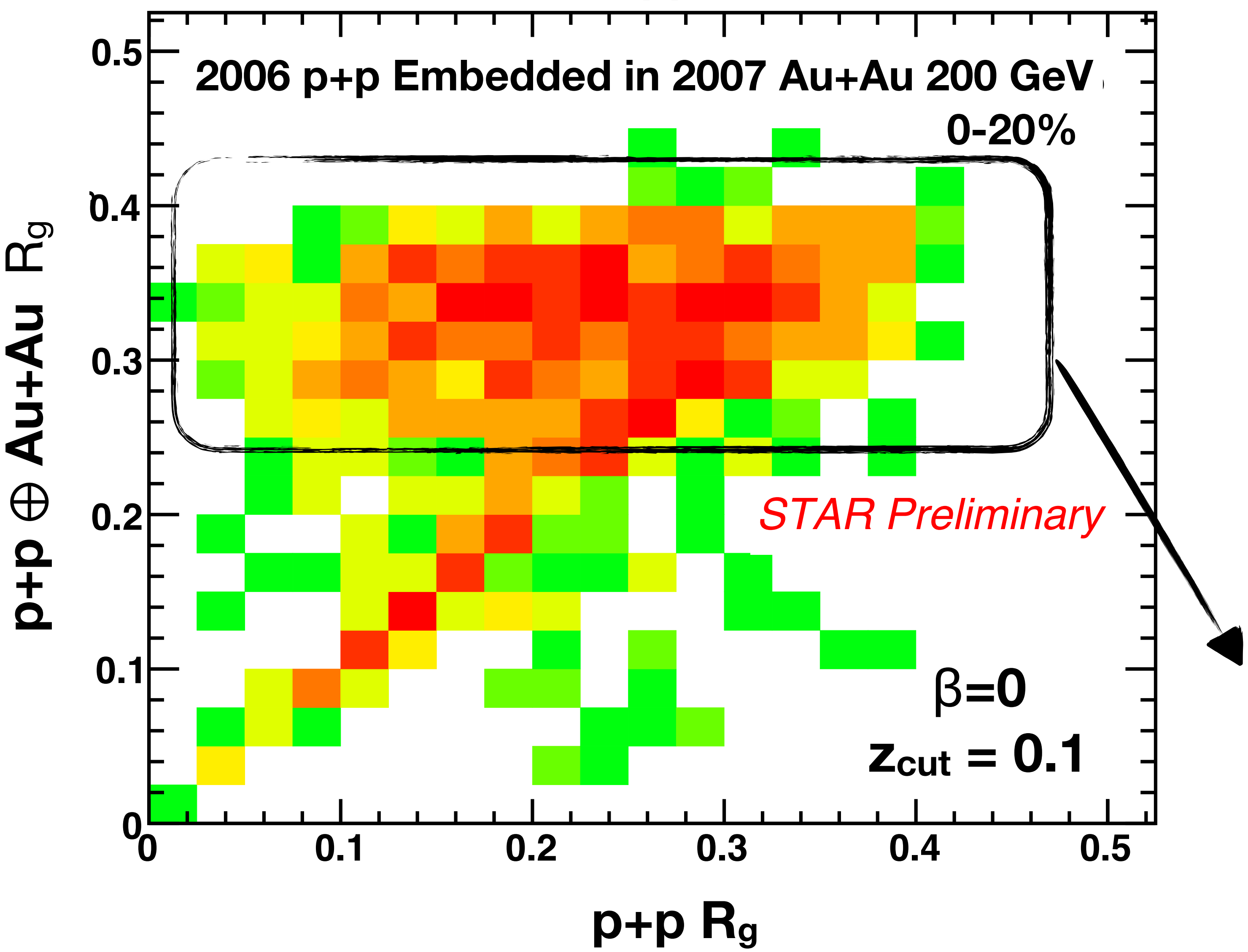
p_T^{const}>2 GeV/c cut → **removes almost all background**

p_T^{const} > 0.2 GeV/c
geometric matching → **no combinatoric jets, recover all constituents**

See Nick Elsey's Talk
on Tuesday 11:25 am Parallel-2

STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)

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

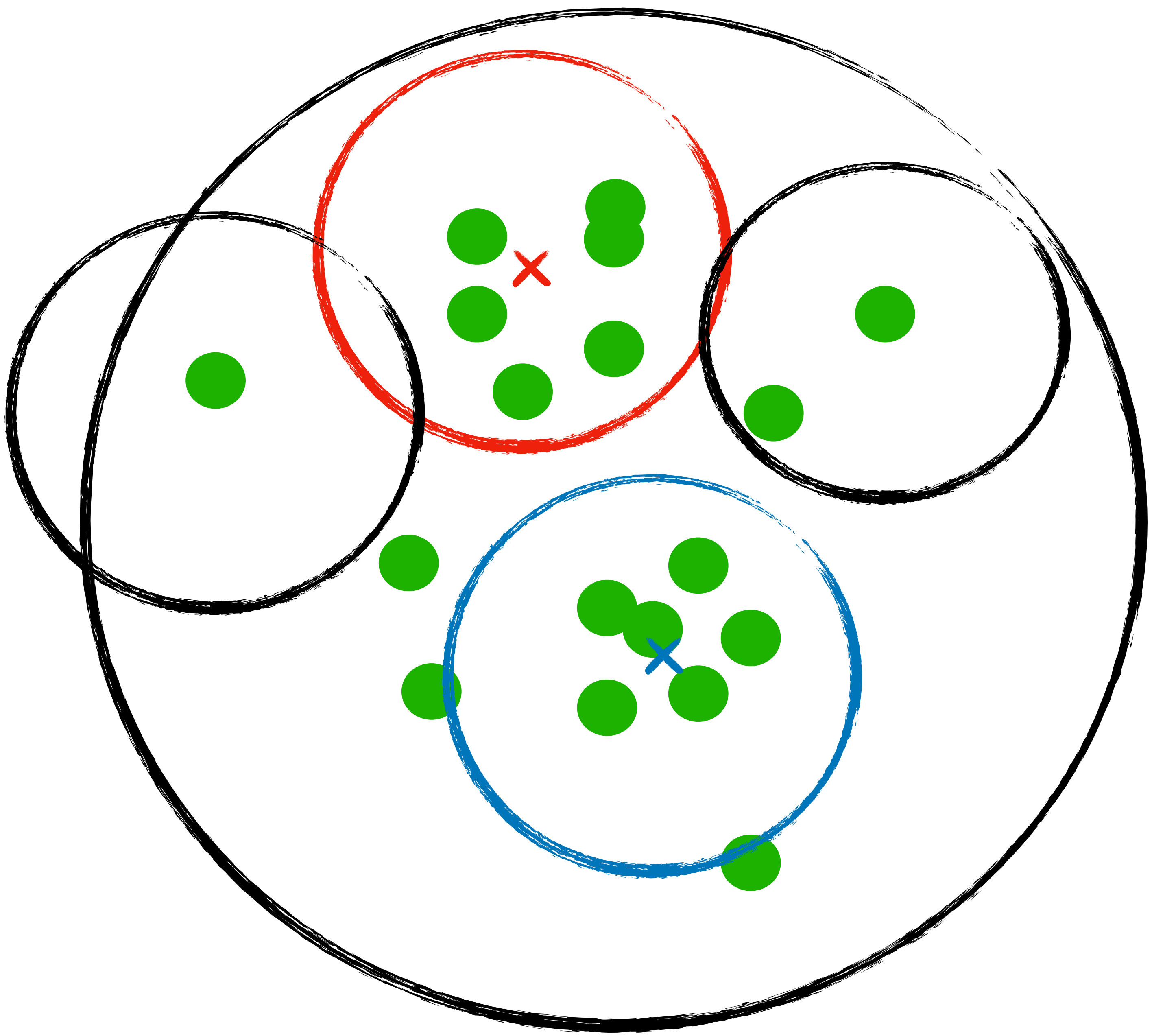
Constituent-subtracted jets

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

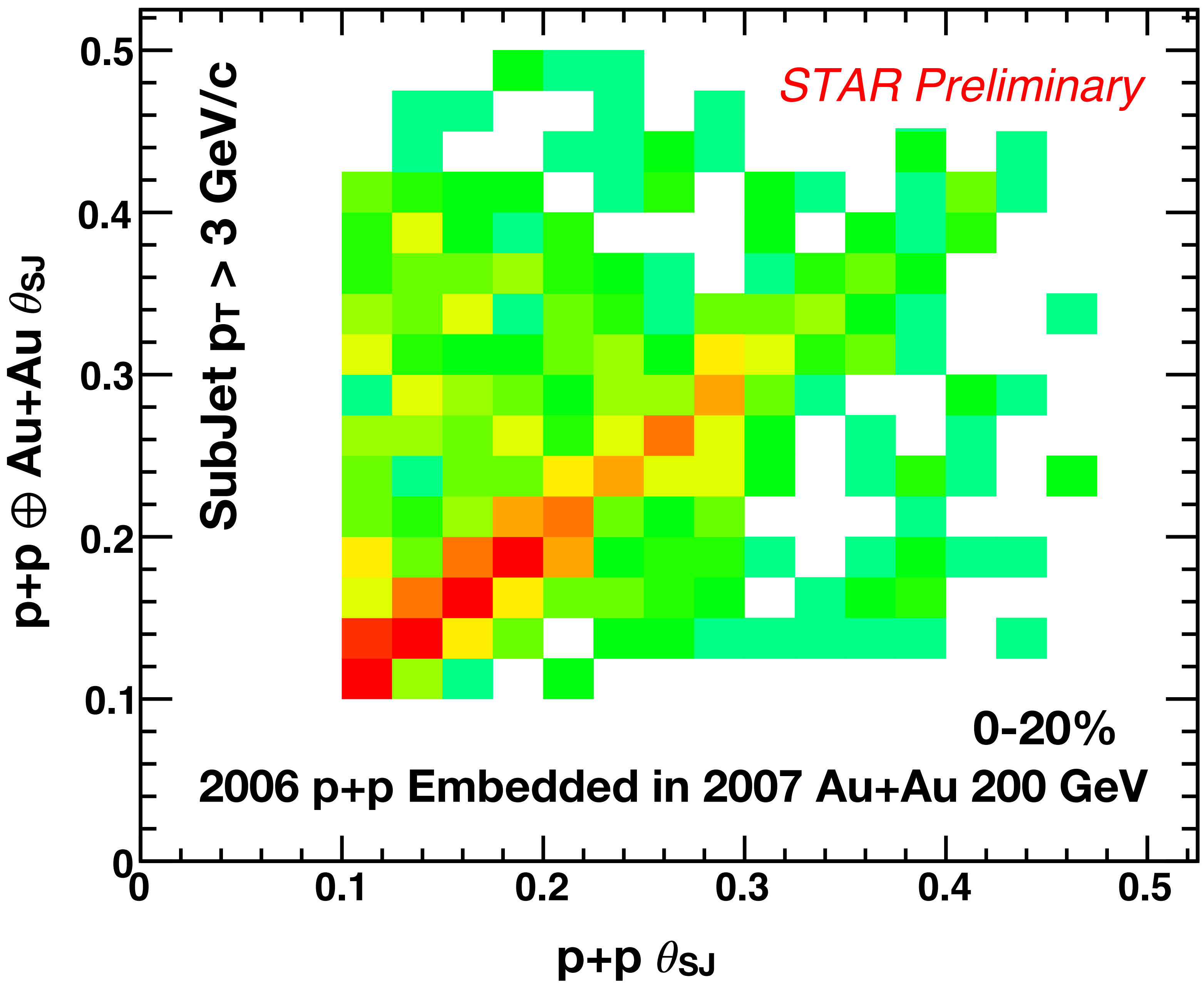
TwoSubJet z/θ



- Cluster all jet constituents into anti-k_t jets of smaller radii (0.1)
- Choose the **leading** and **subleading** SubJets
- z_{SJ} = **Blue p_T** / (**Blue p_T** + **Red p_T**)
- θ_{SJ} **= Δ R (Blue Axis, Red Axis)**

For recent literature on using subjet observables in heavy ion simulations please see
Apolinario, L et al. Eur. Phys. J. C (2018) 78:529

θ_{SJ} 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

- θ_{SJ} (w/ R=0.1 SubJets) **less sensitive to AuAu underlying event**

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

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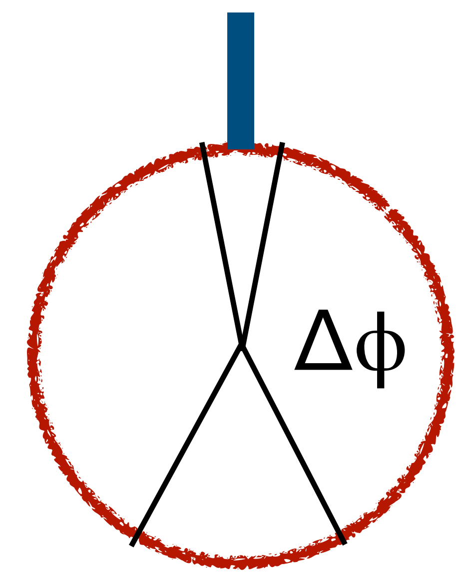
TwoSubJet (R=0.1) observables in Au+Au

- 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 purity > 98%
- Systematic uncertainty applied to the embedded p+p curves
  - relative tower energy scale (2%)
  - tracking efficiency (6%)
  - TwoSubJet tagging fake rate (2%)

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

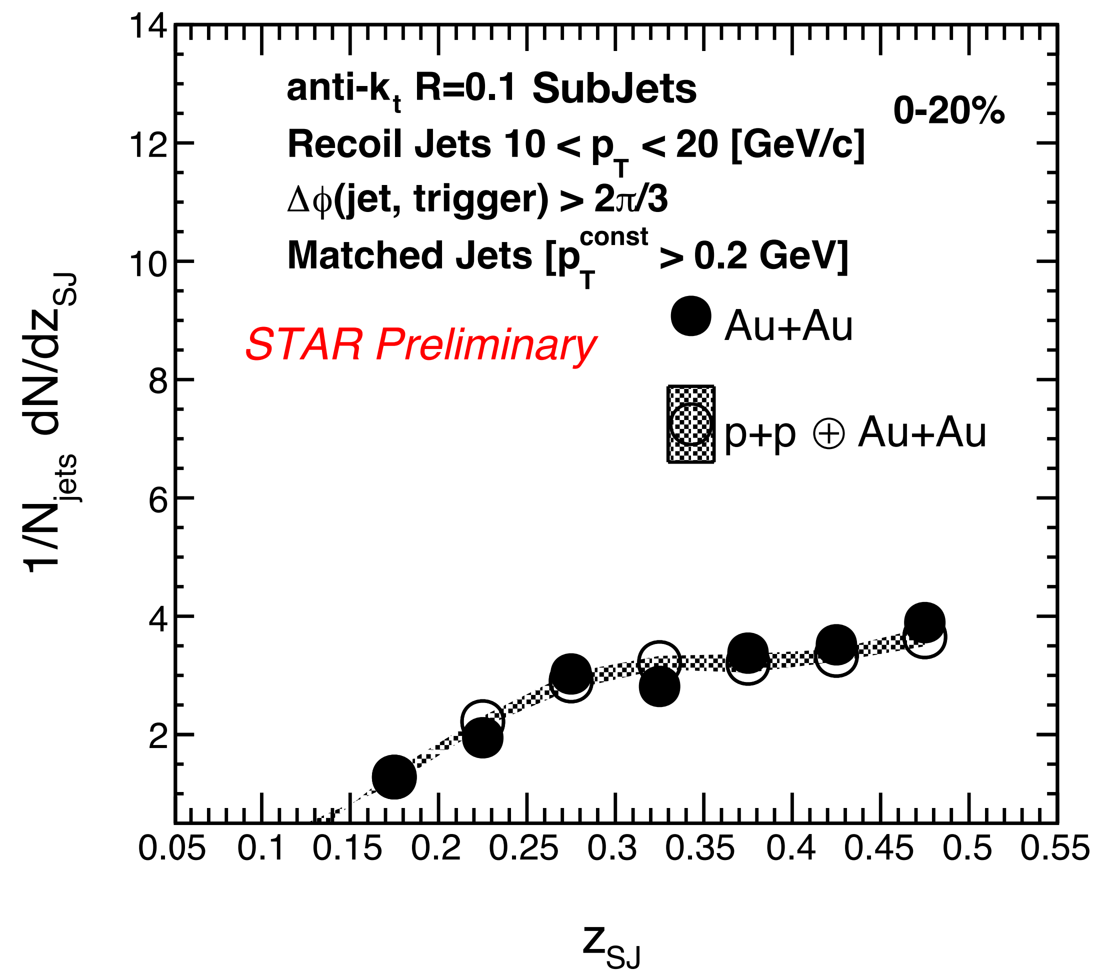


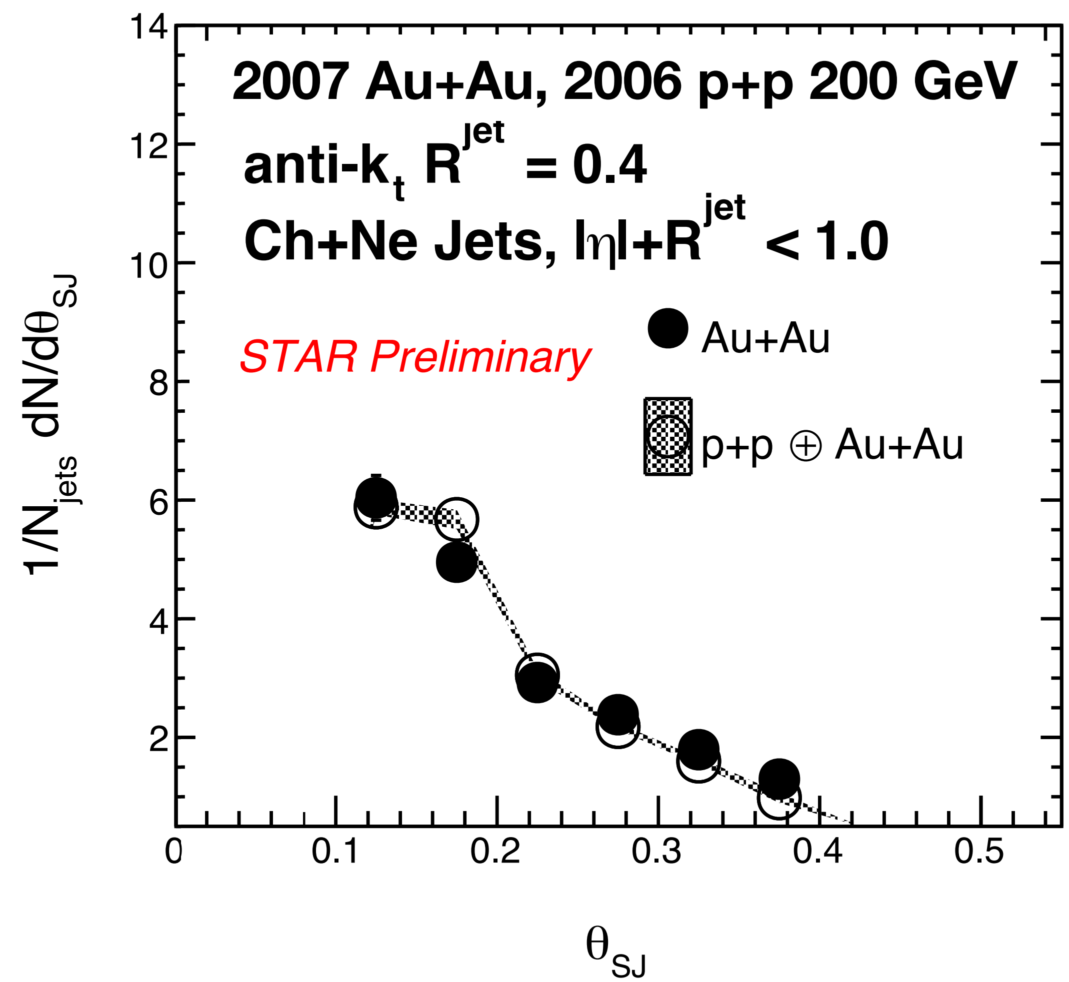
HardCore
Recoil Jet p_T > 8 GeV/c

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

TwoSubJet observables

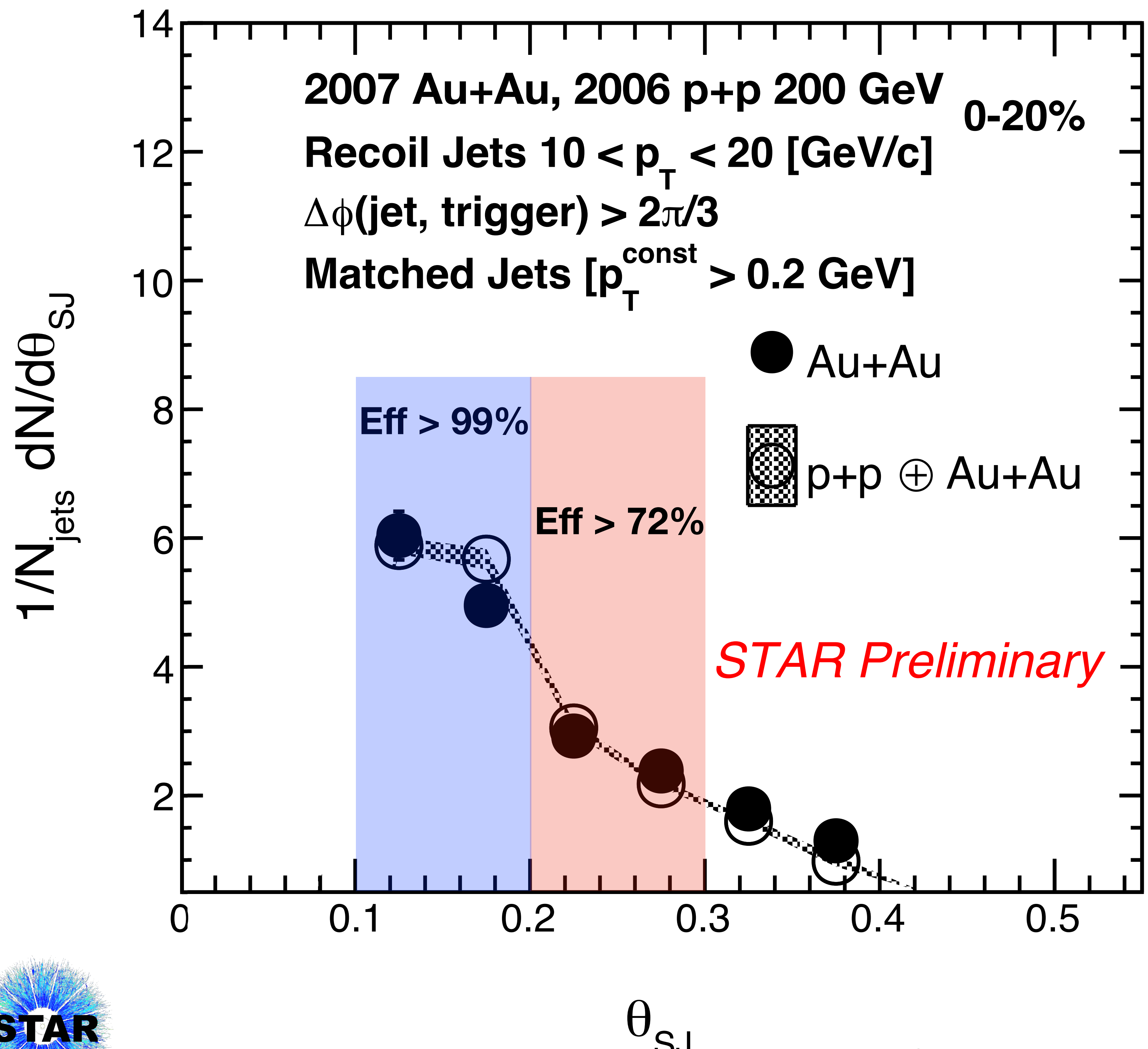
anti-k_t R=0.1 SubJets





- For both z_{SJ} and θ_{SJ}, we observe **no significant difference in shape** due to jet quenching
- The z_{SJ} distribution is biased towards harder splits (in vacuum ~ earlier formation time)

For the first time - we differentially utilize an angular scale



Select jets with a particular angular scale (θ_{SJ})

Tagging Efficiency: Probability that p+p ⊕ Au+Au and the p+p jet utilized in the embedding have a resolved θ_{SJ} in the same range.

Lets look at standard jet quenching observables - A_J and Recoil Jet Yield

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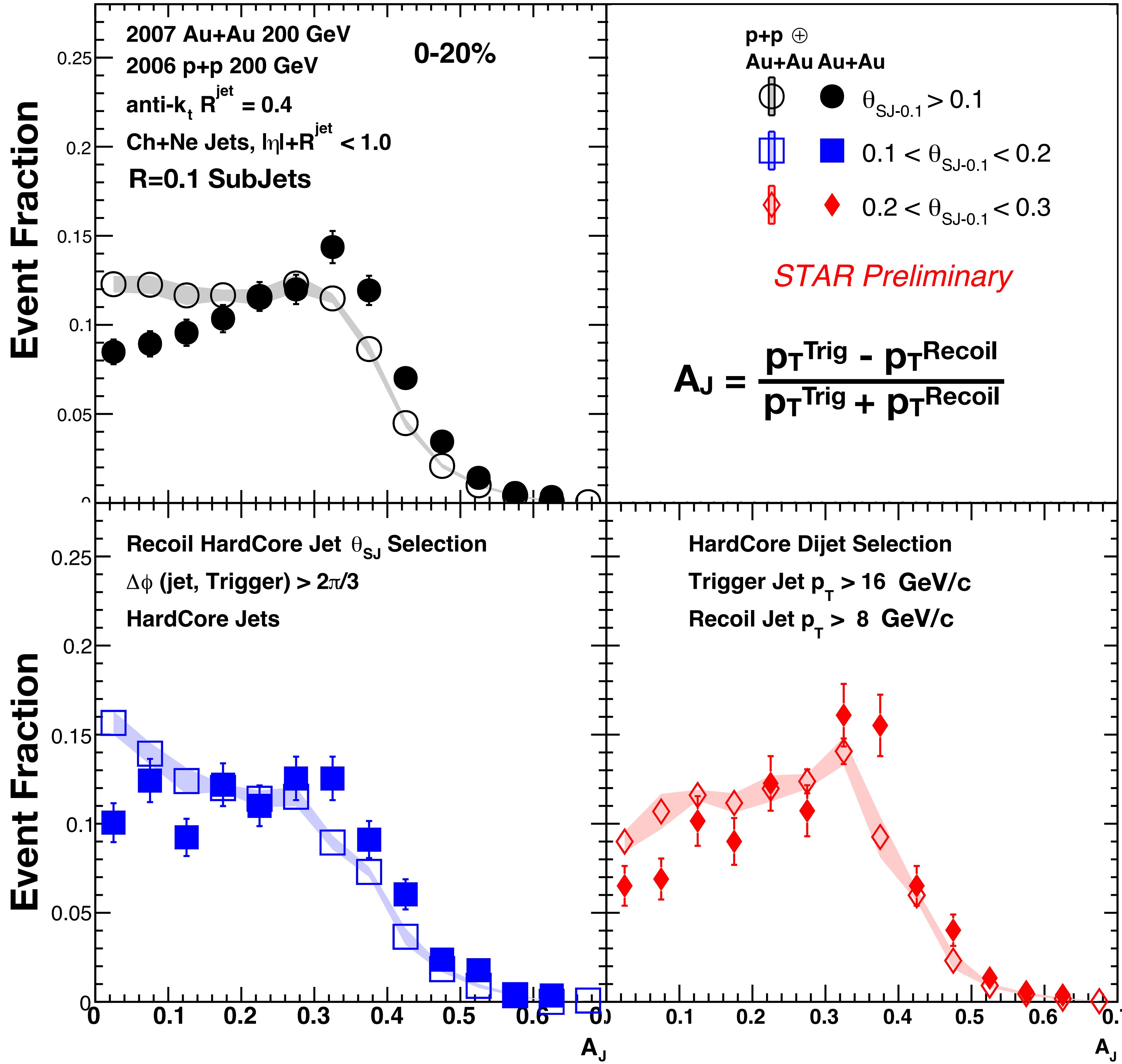
HardCore A_J

p_T^{const} > 2 GeV/c

Significant modifications in Au+Au for our θ_{SJ} selections in comparison to p+p ⊕ Au+Au



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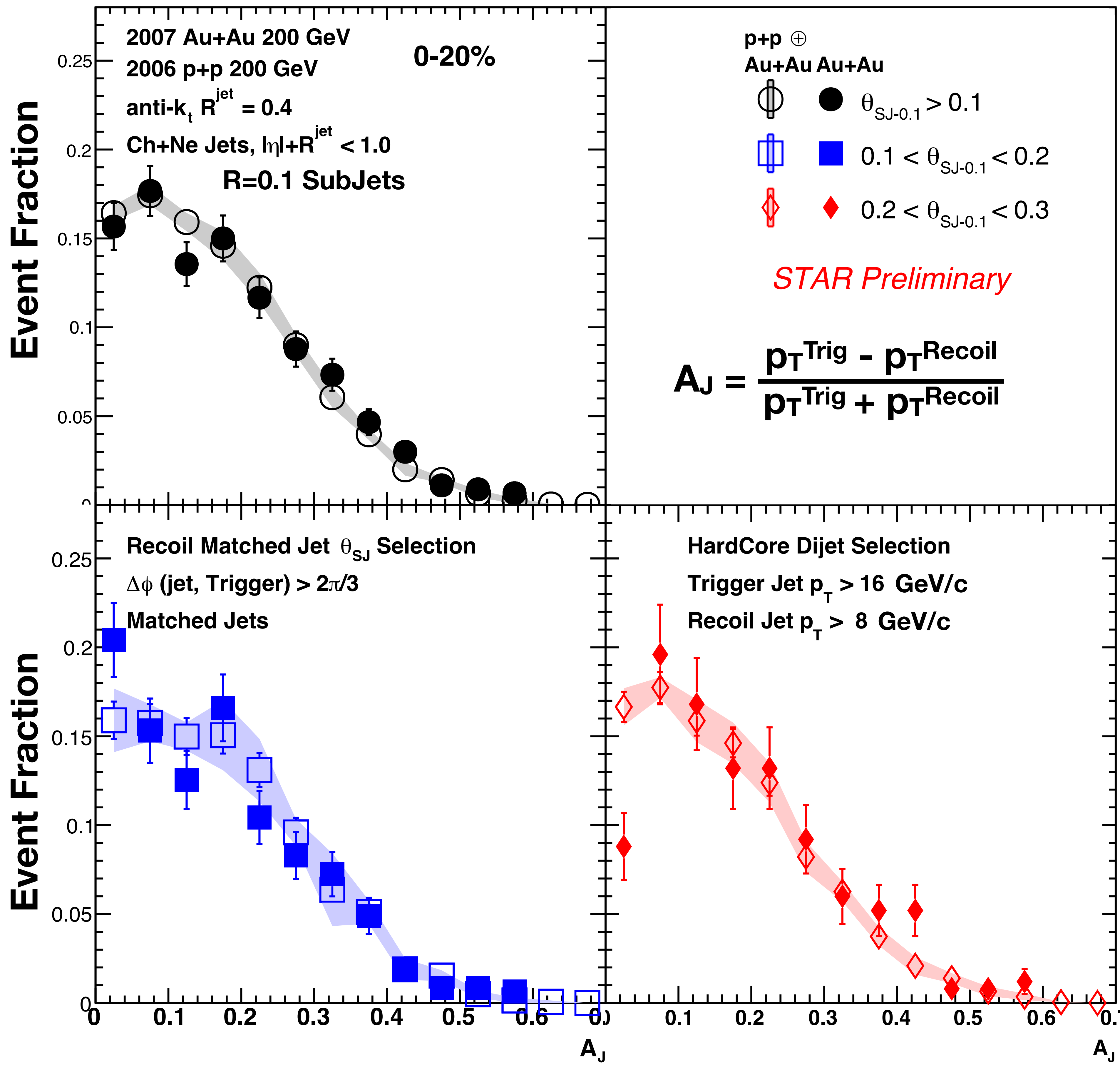
Matched A_J

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

Matched jets of different θ_{SJ} selections are balanced at RHIC



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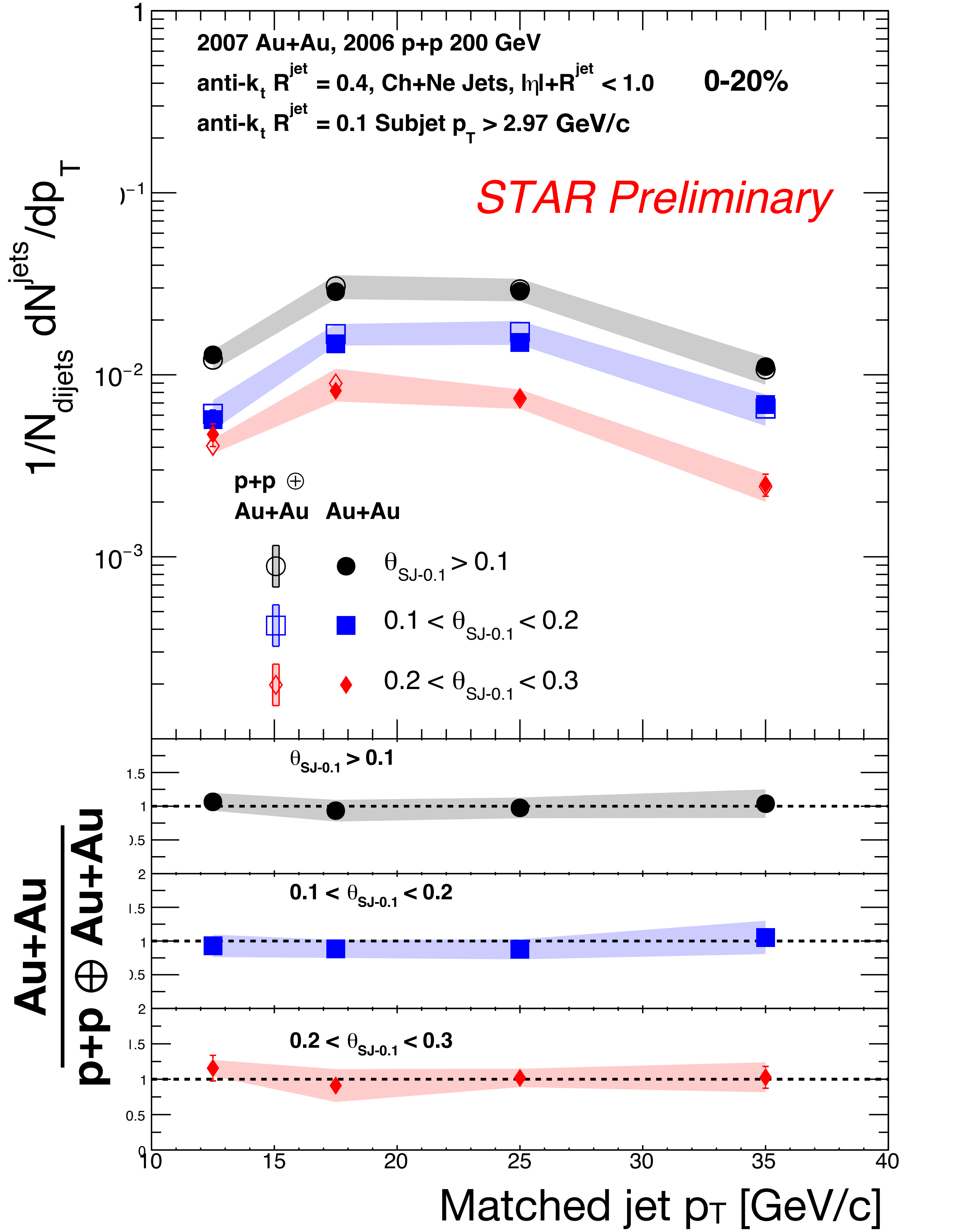
Recoil matched jet yield

p_T^{const} > 0.2 GeV/c

- Normalized per dijet yield
- Confirmation that **Matched jets recover** the energy lost by quenching within R = 0.4
- **Observe no significant differences between θ_{SJ} selections**



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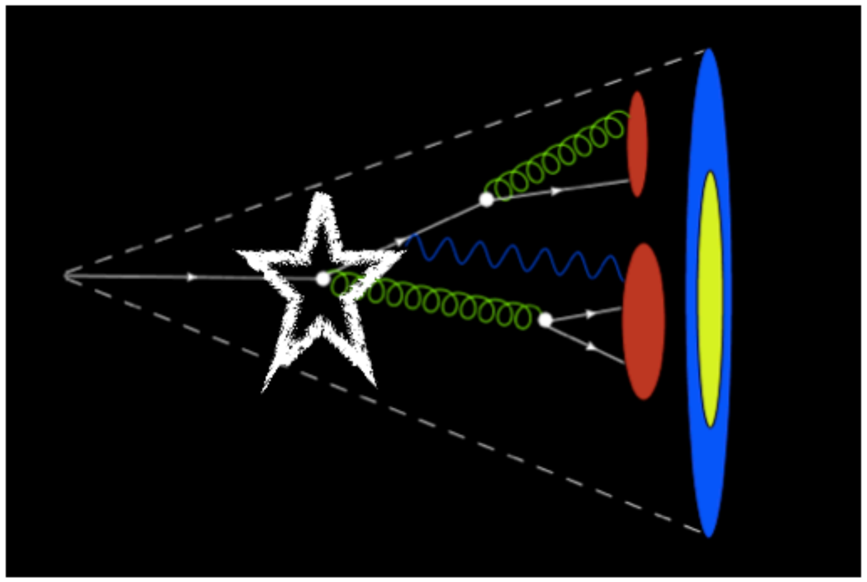
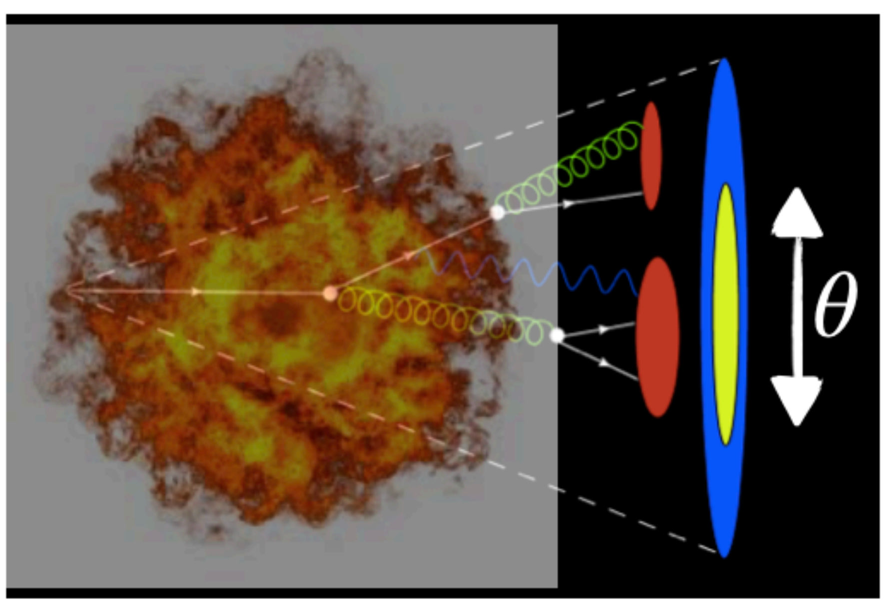
Conclusions



- First **fully unfolded z_g and R_g** in p+p collisions at RHIC kinematics
- Radial scans highlight **deviations** from universal ***1/z behavior*** due to phase space constraints
- Recursive SoftDrop offers **experimental access to the parton shower**

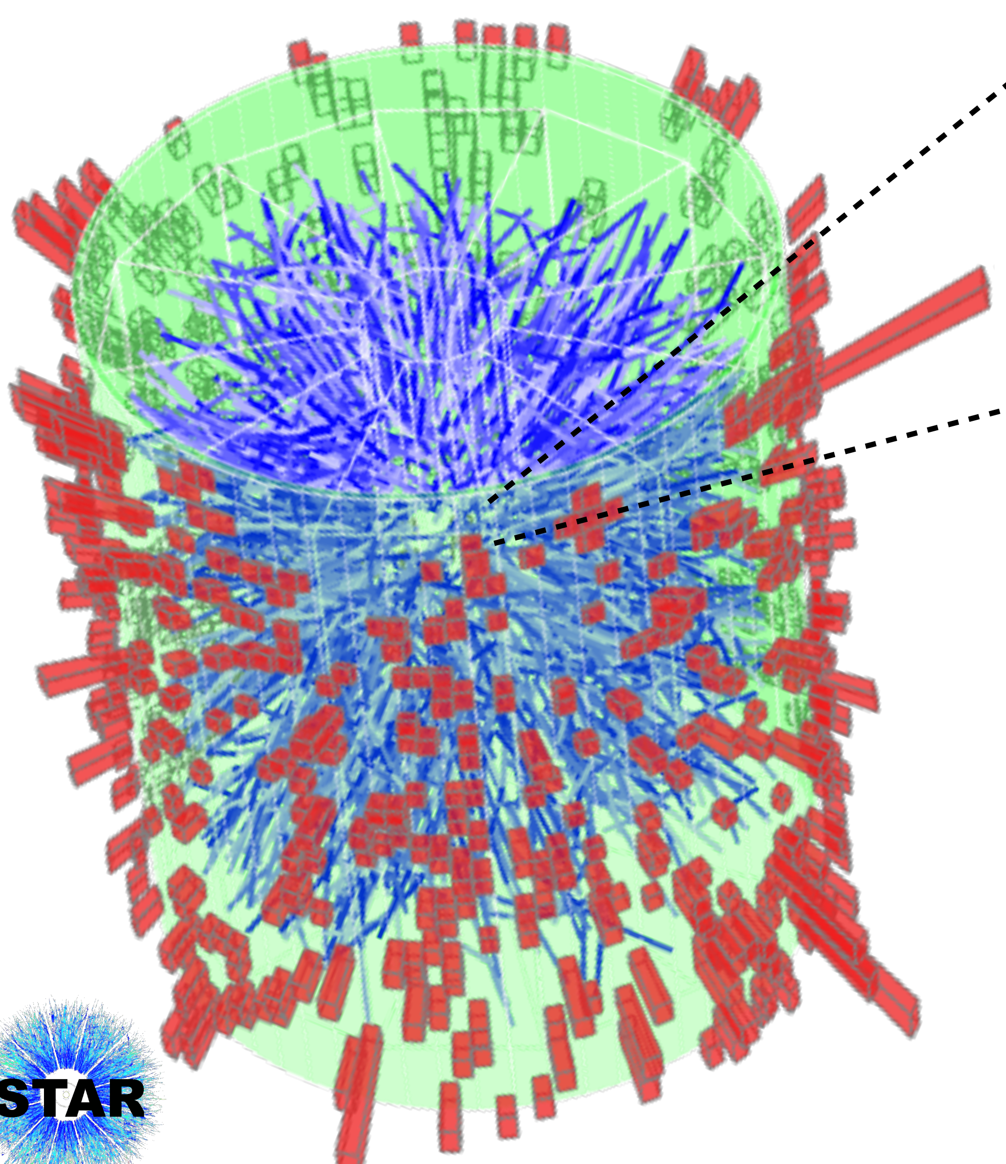


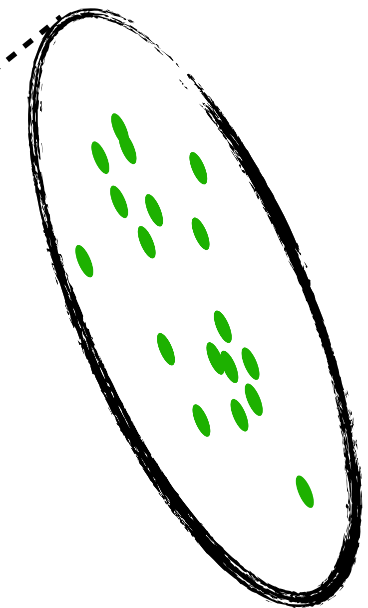
- **First differential measurement** of dijet A_J/Recoil Jet Coincidence at different angular/resolution scales
  - **Significant modification** observed in HardCore A_J
  - **Recover "lost energy" for Matched** jets within the jet radius of R=0.4
- Next steps - higher statistics, kinematic reach, and centrality evolution —> then move towards semi-inclusive recoil jets

Bonus Slides!

Going from Partons to Jets

Hard Scattered partons in high energy collisions fragment and hadronize jets





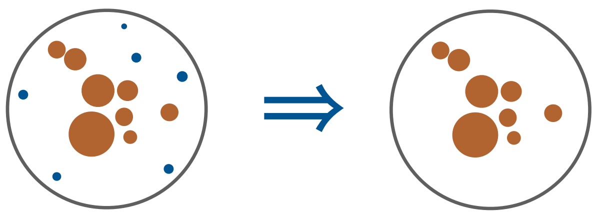
Reconstruct Jets from tracks/towers based on clustering algorithms
Most popular - anti-k_t

Requires a minimum p_T cut and an angular scale

- Parton evolution characterized by the momentum and angular scales of its emissions
- In vacuum, this is governed by the DGLAP evolution equations

SoftDrop

(tools of the trade)

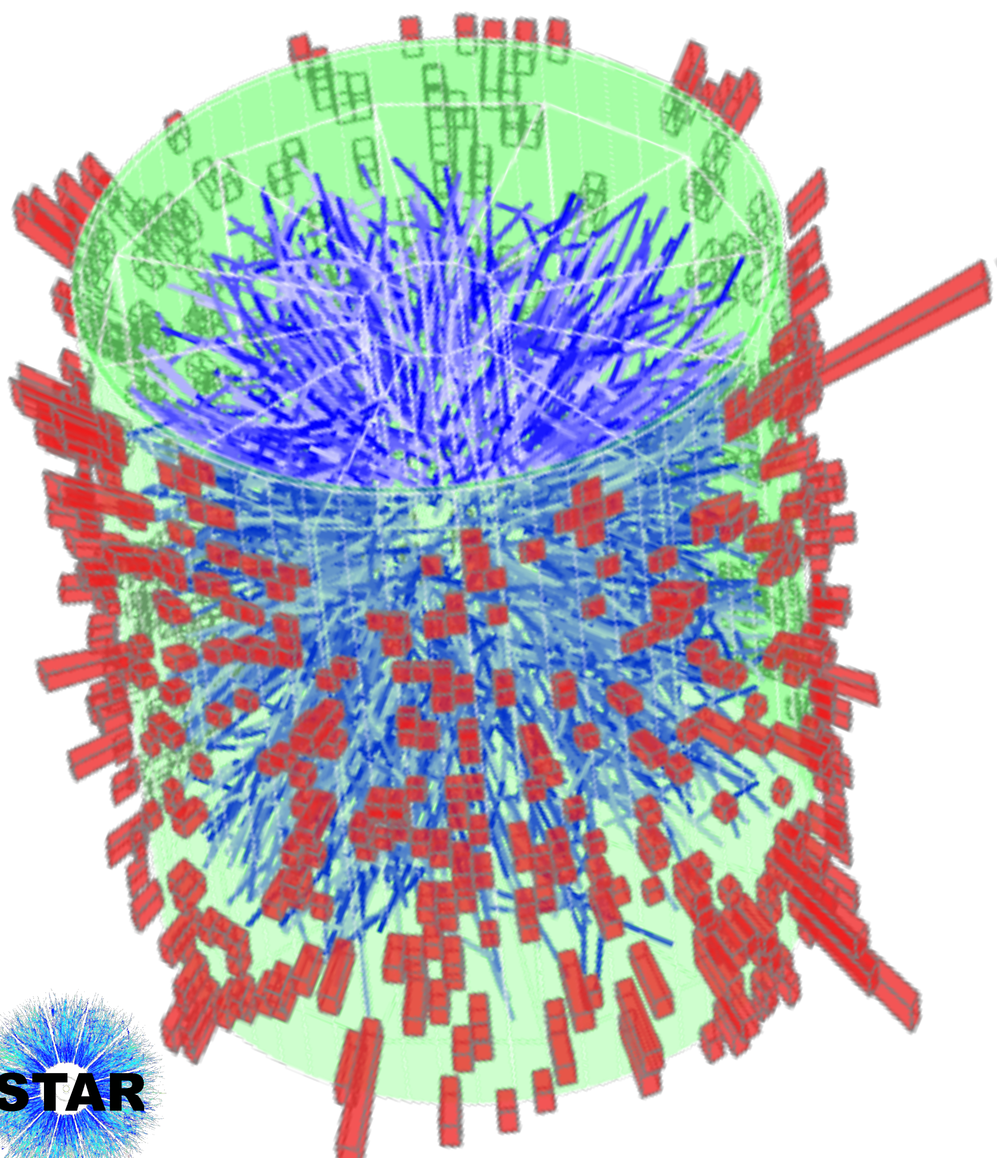


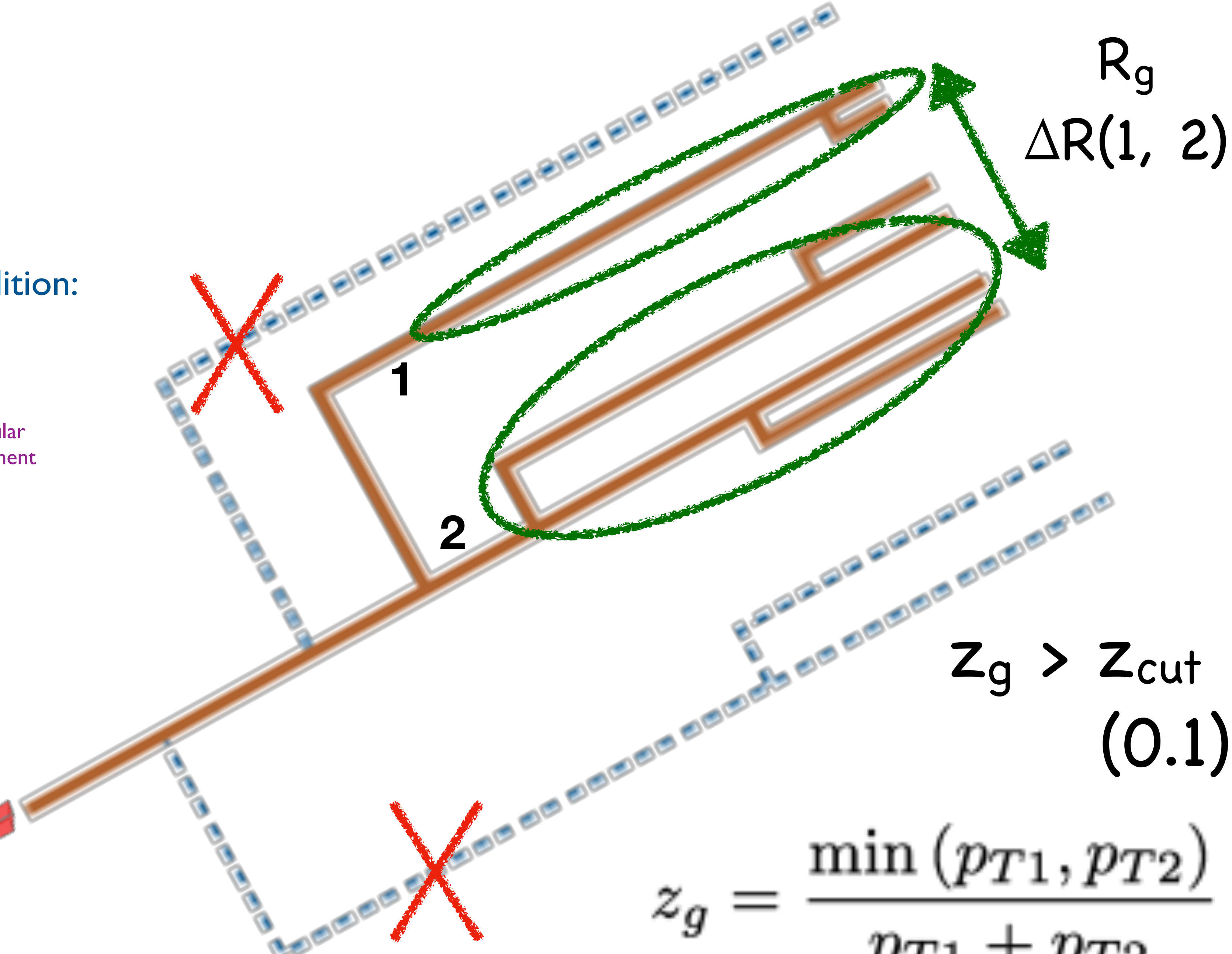
Soft Drop Condition:

$$z > z_{\mathrm{cut}}\, \theta^{\beta}$$

energy threshold — angular exponent

Larkoski et al.,
PRD 91, 111501 (2015)



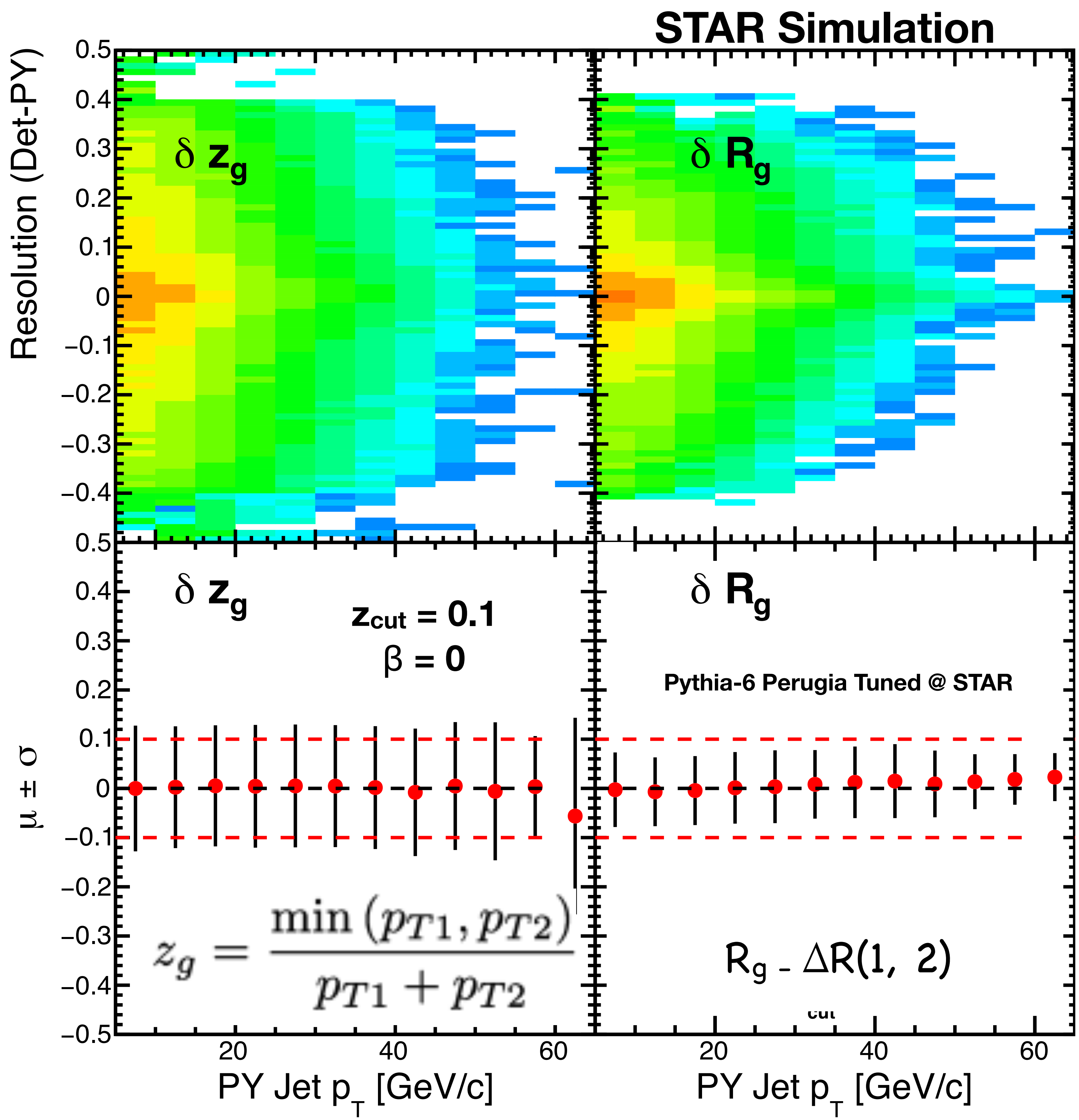


$$z_g = \frac{\min\left(p_{T1}, p_{T2}\right)}{p_{T1} + p_{T2}}$$

- Reclustering w/ C/A ensures an angular ordered behavior in the tree
- Baseline behavior in p+p collisions shown to asymptote to AP splitting functions at high p_T

Detector Effects on SoftDrop in p+p simulations

- z_g and R_g resolutions are independent of the generator jet p_T
- Bayesian 2D unfolding with jet p_T vs z_g, and p_T vs R_g



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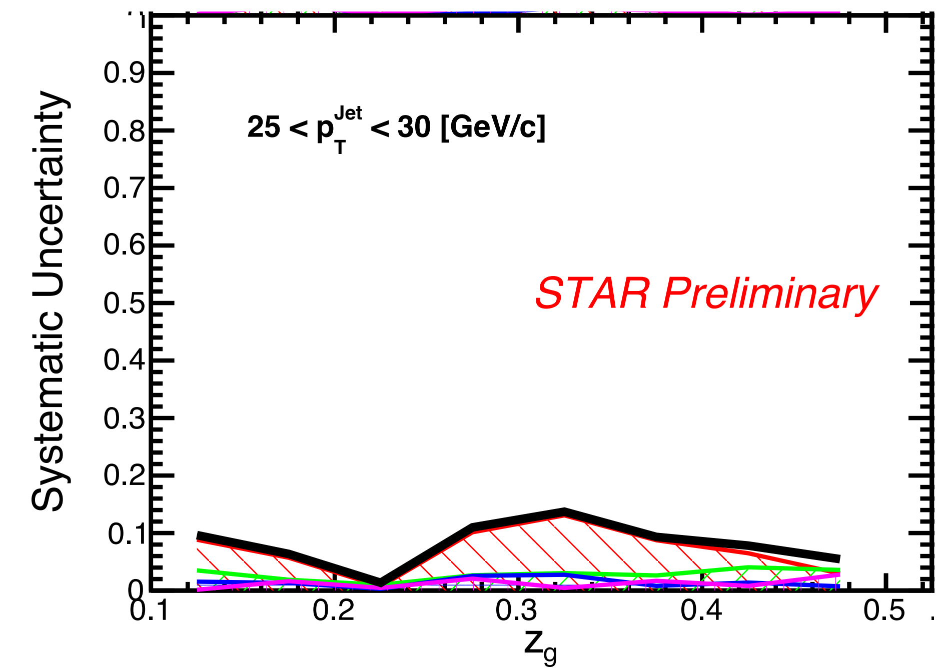
p+p z_g and R_g

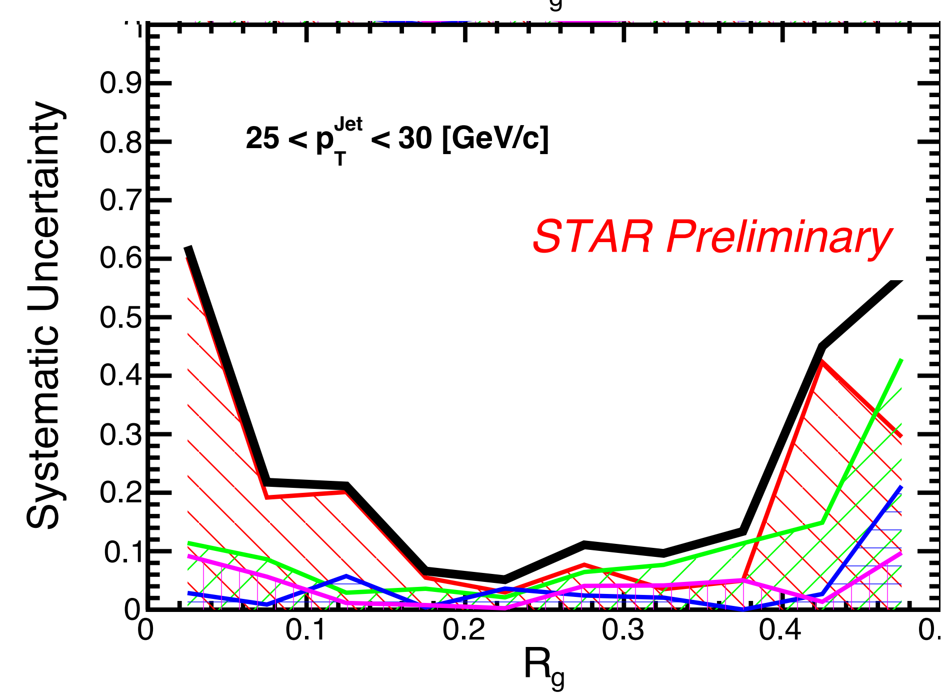
Systematic Uncertainties

- Hadronic Correction (HC)
  - Using MIPs (no HC) and 0.5 HC
- Tower Scale - 3.8% in the tower gain
- Tracking - 4% variation (flat in track p_T)
- Unfolding (@ the response level) -
  - Prior shape variations
  - Varying the iteration parameter from 2 - 6 (nominal=4)

Hadronic Correction
TowerScale var 3.8%
Tracking Efficiency 4%
Unfolding
Total Systematics

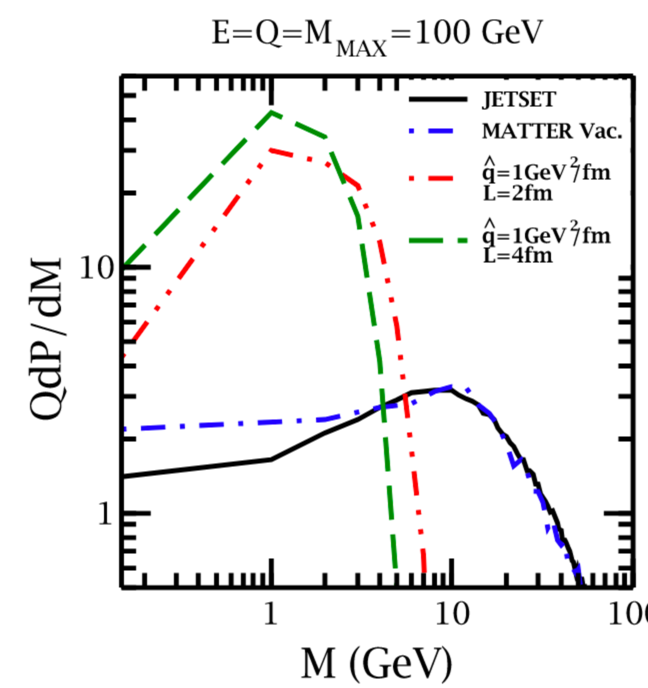
anti-k_t R = 0.4
SoftDrop z_{cut} = 0.1, β=0
Ch+Ne Jets, $|\eta + R| < 1$
Systematic Uncertainties





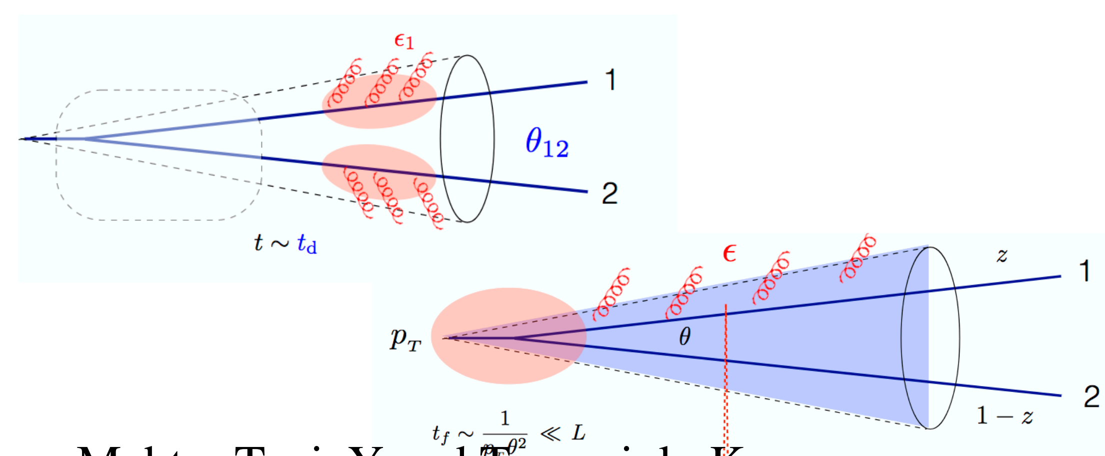
Need for differential measurements

- It is necessary to disentangle the correlations built within observables by selecting jets of a certain class
- Does the medium resolve the two prongs of a jet as a single object or two individual objects
- There are a variety of theoretical models and calculations that predict a larger absolute energy loss for jets of a large virtuality or wider resolution scales



Majumder, A and Putschke, J
Phys Rev C 93 054909

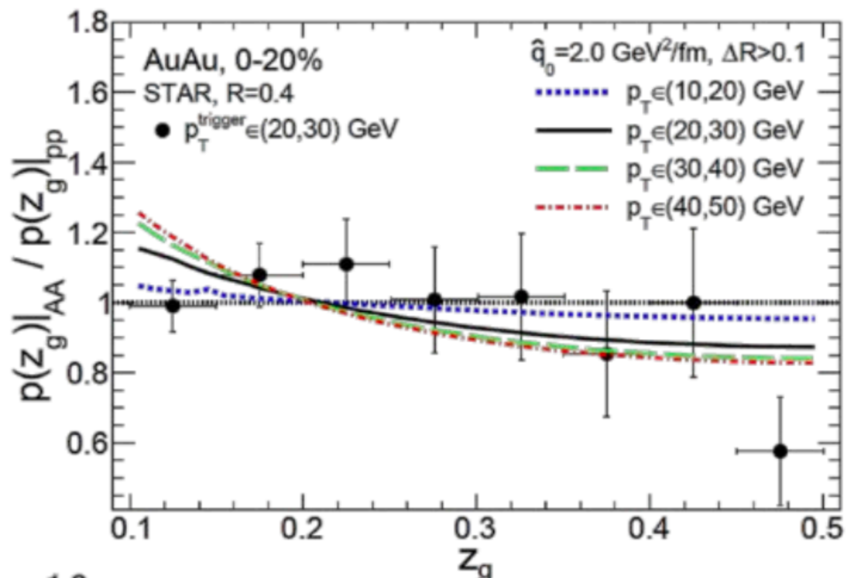
Virtuality reduction

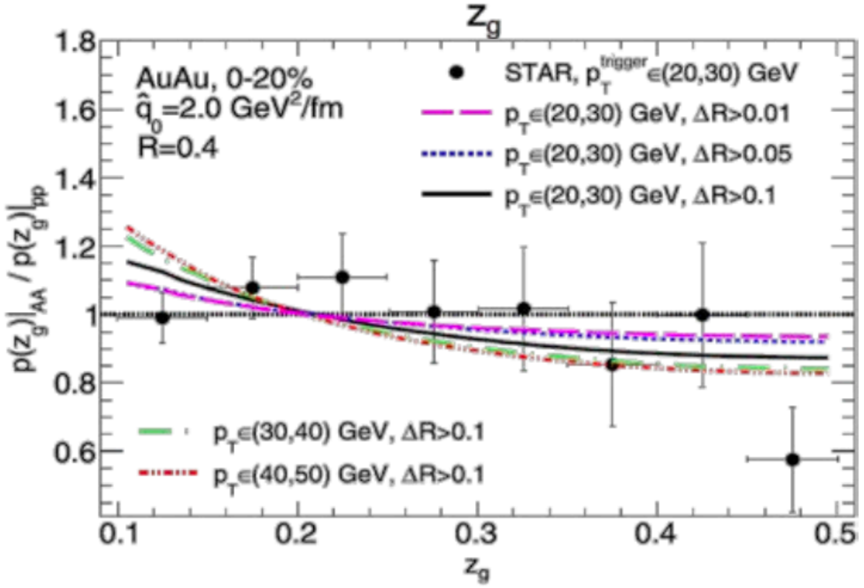


Mehtar Tani, Y and Tywoniuk, K
arXiv:1707.07361

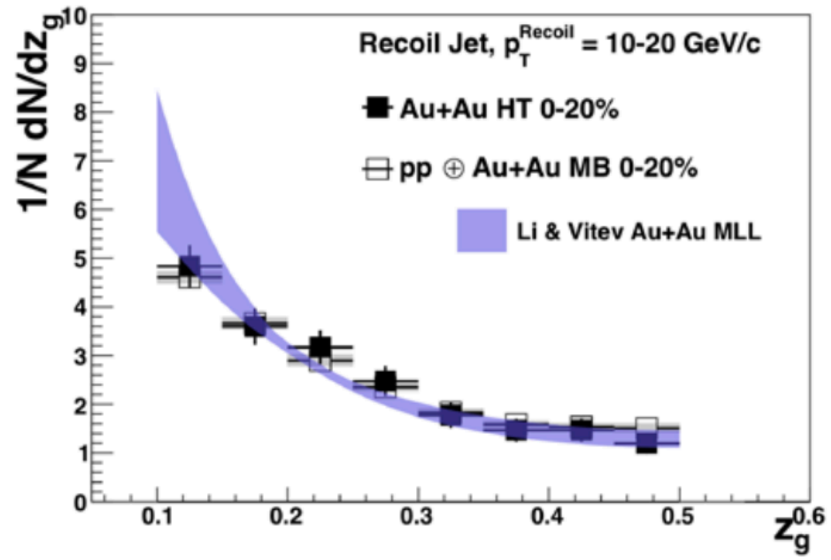
de-coherence vs Coherence

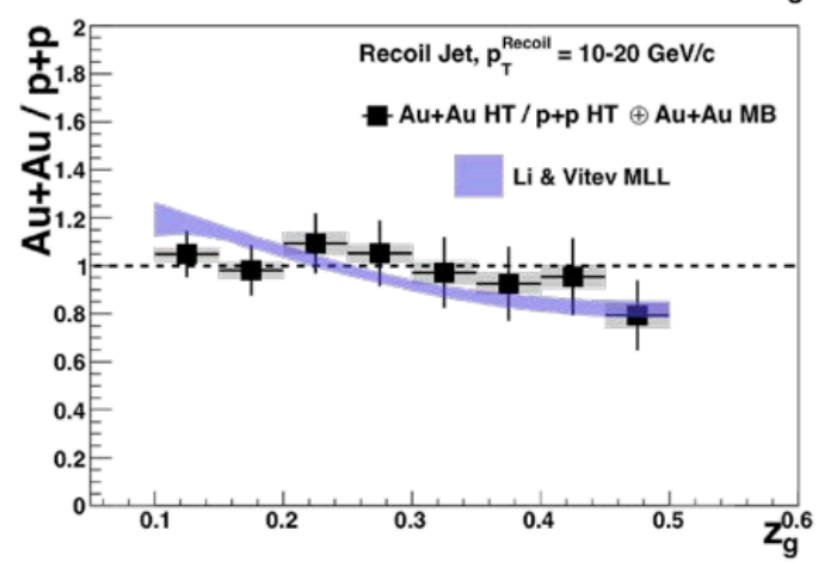
Jet SubStructure: z_g in Au+Au





Ning-Bo Chang
et al. QM18





Li & Vitev
arXiv: 1801.0008

KK, HP16, QM17

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

Modelers: Be mindful of cuts and detector effects

Slide from Kolja Kauder, RHIC AGS Users Meeting 2018

TwoSubJet (R=0.1) θ_{SJ}

Tagging Efficiency and Purity

- **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

- **Tagging Efficiency**: Probability that a p+p ⊕ Au+Auand 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.
  - $0.1 < \theta_{SJ} < 0.2$: Efficiency > 99%
  - $0.2 < \theta_{SJ} < 0.3$: Efficiency > 72%