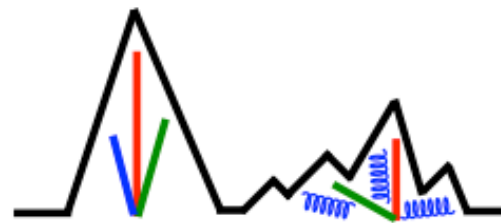


What can we learn from jet sub-structure?

Raghav Kunnawalkam Elayavalli (WSU)



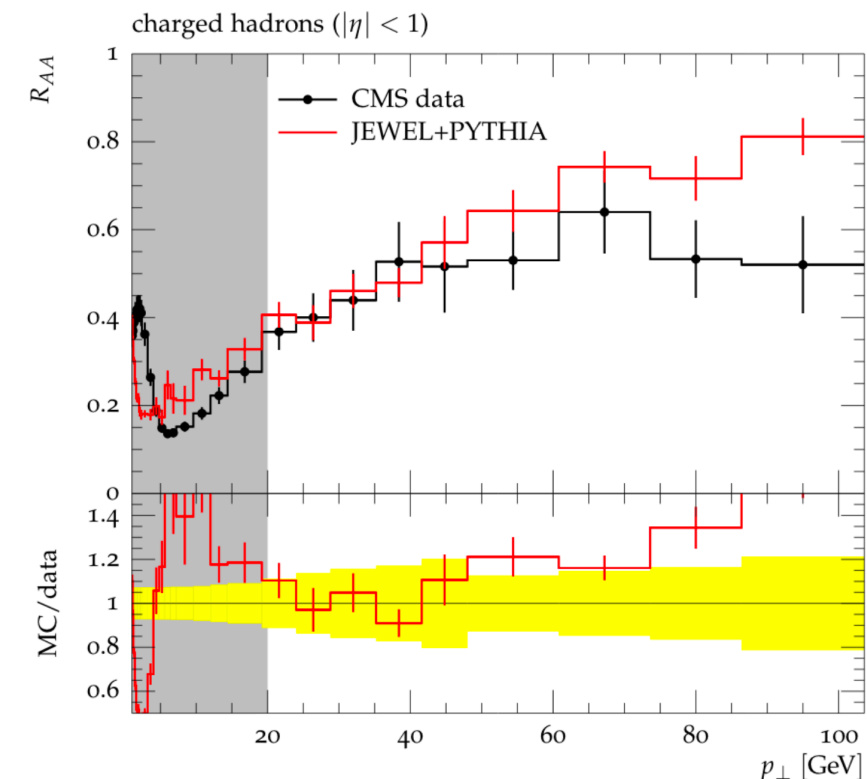
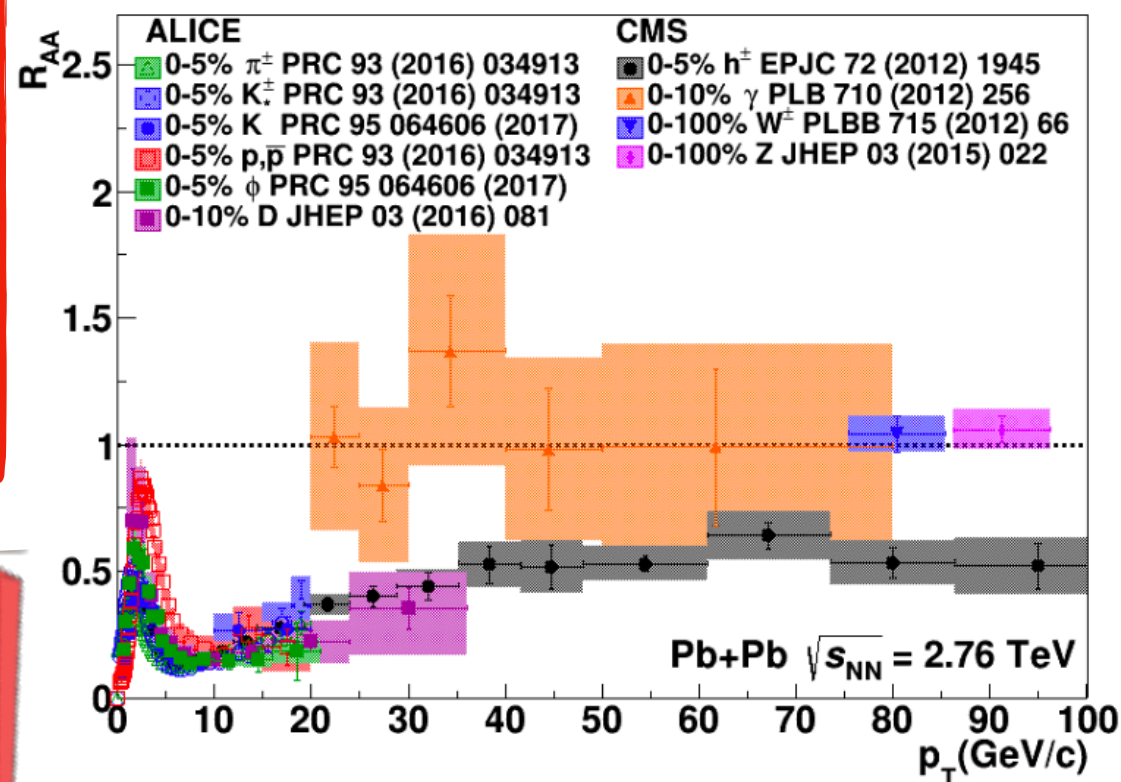
2nd **JETSCAPE** Workshop 2019

Jan 11-13, 2019

Texas A&M University

Evolution of (single) jet measurements

- High p_T hadrons
jet proxy



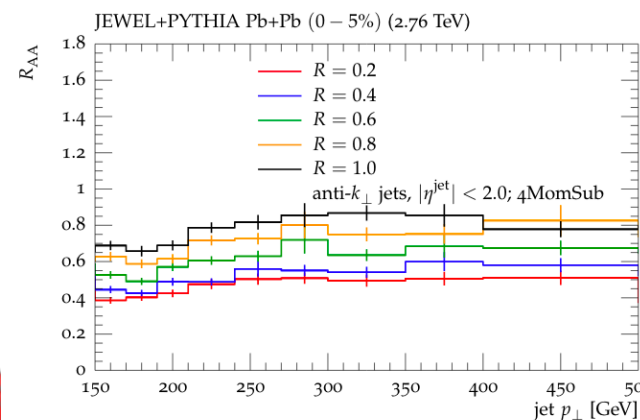
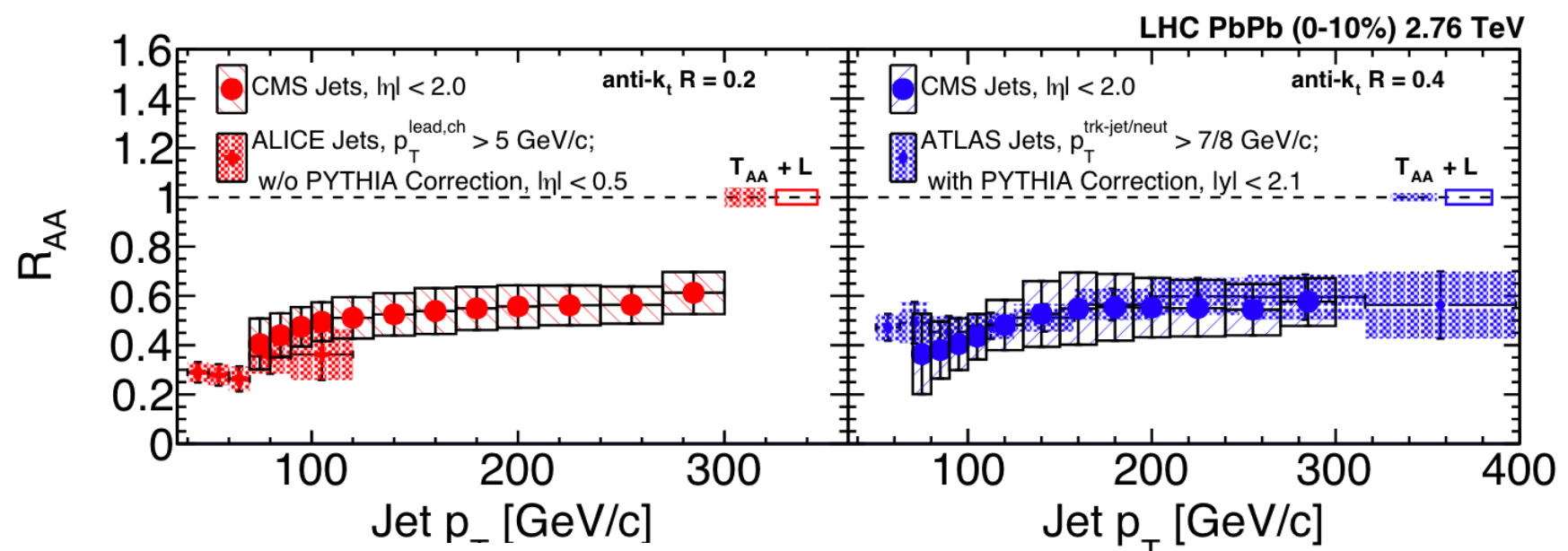
Reed, Connors, Nattrass, Salur,
Rev. Mod. Phys. 90, 025005 (2018)

Korinna Zapp,
EPJ C, Volume 74, Issue 2, 2014

Evolution of (single) jet measurements

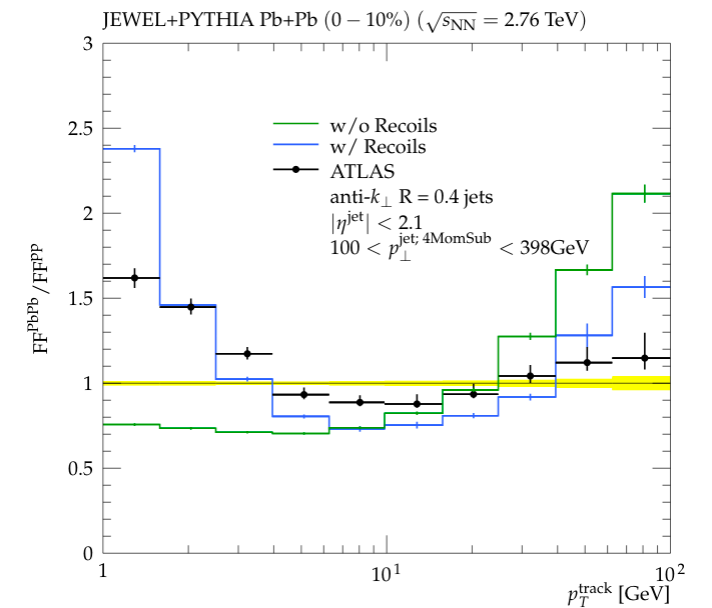
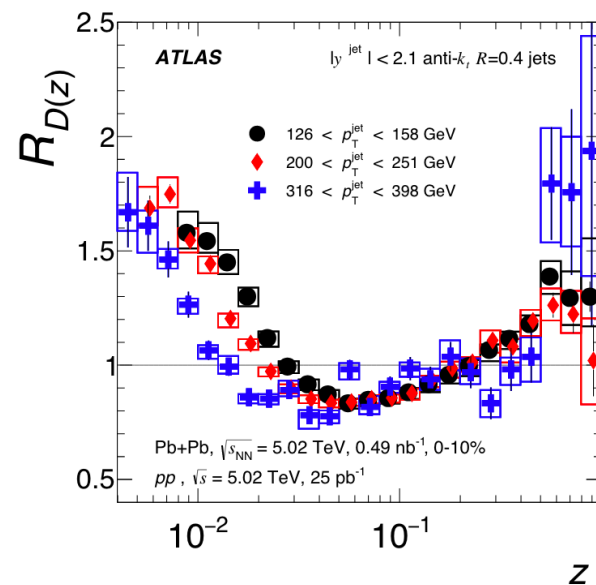
**Jet clustering algorithm
returns jet p_T , η , ϕ , M**

- Reconstructed jets



RKE, KCZ,
JHEP 1707 (2017) 141

Evolution of (single) jet measurements



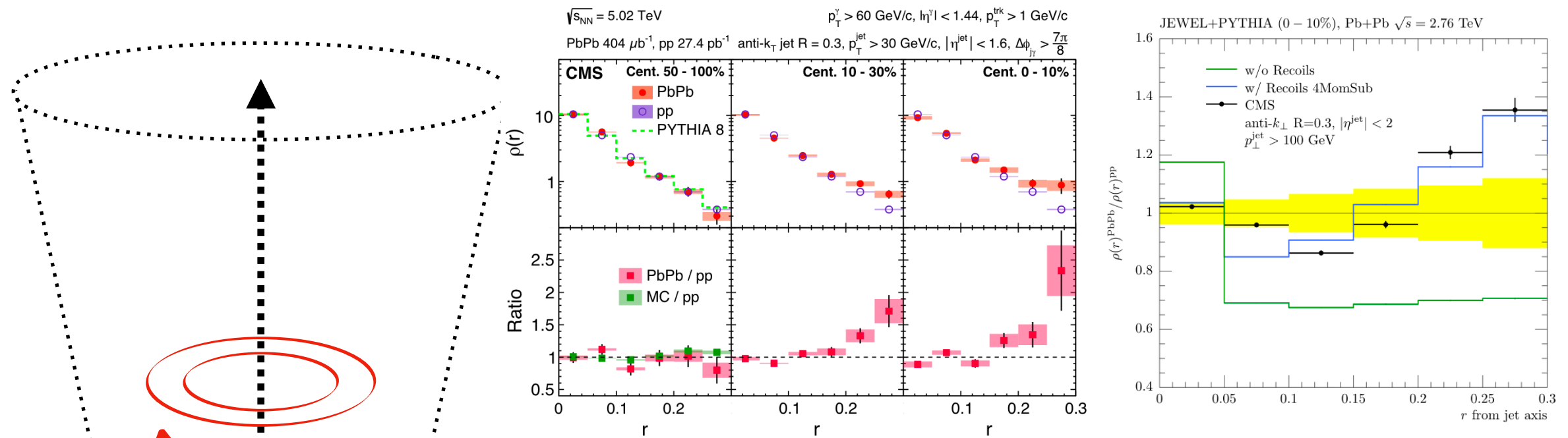
- Fragmentation functions $D(z)$, $D(\xi)$

Momentum (fraction) carried by hadrons near the jet

ATLAS Collaboration,
Phys. Rev. C 98, 024908 (2018)

RKE, KCZ,
JHEP 1707 (2017) 141

Evolution of (single) jet measurements



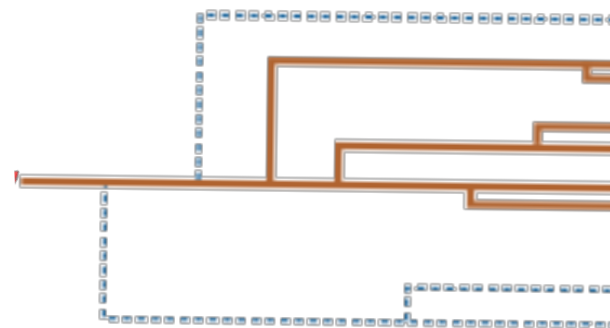
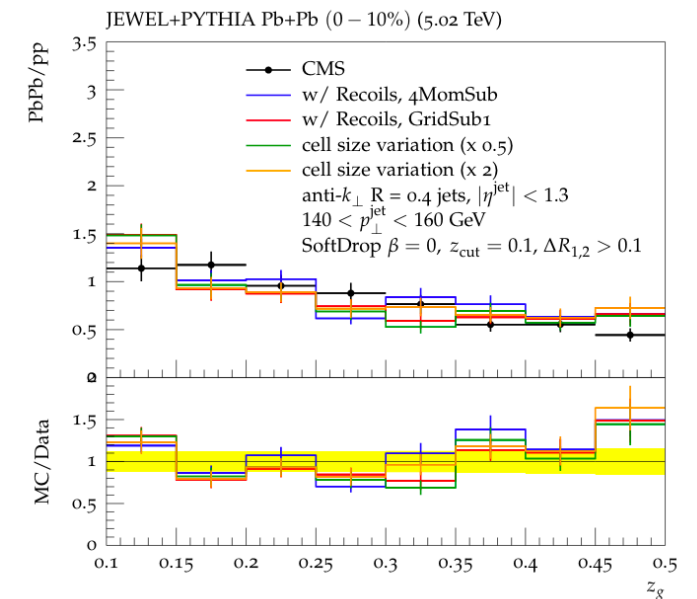
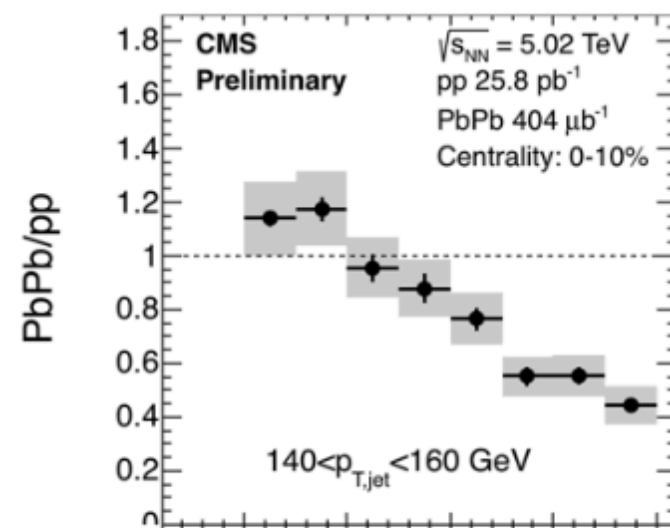
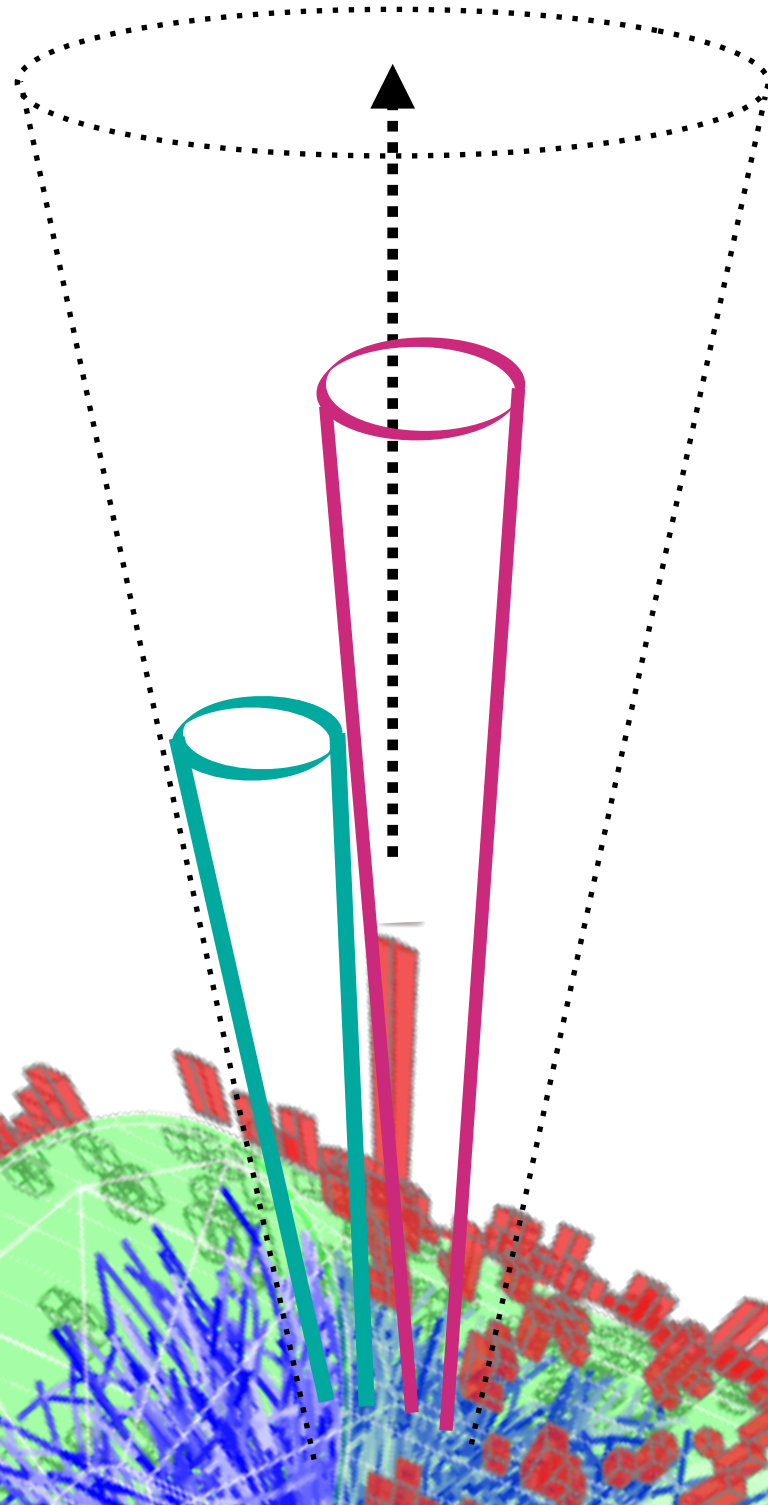
Angular (spacial) distributions of hadrons near the jet

- Jet Shapes $\rho(\Delta r)$

CMS Collaboration, [arXiv:1809.08602](https://arxiv.org/abs/1809.08602)

RKE, KCZ,
JHEP 1707 (2017) 141

Evolution of (single) jet measurements



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

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

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

SoftDrop

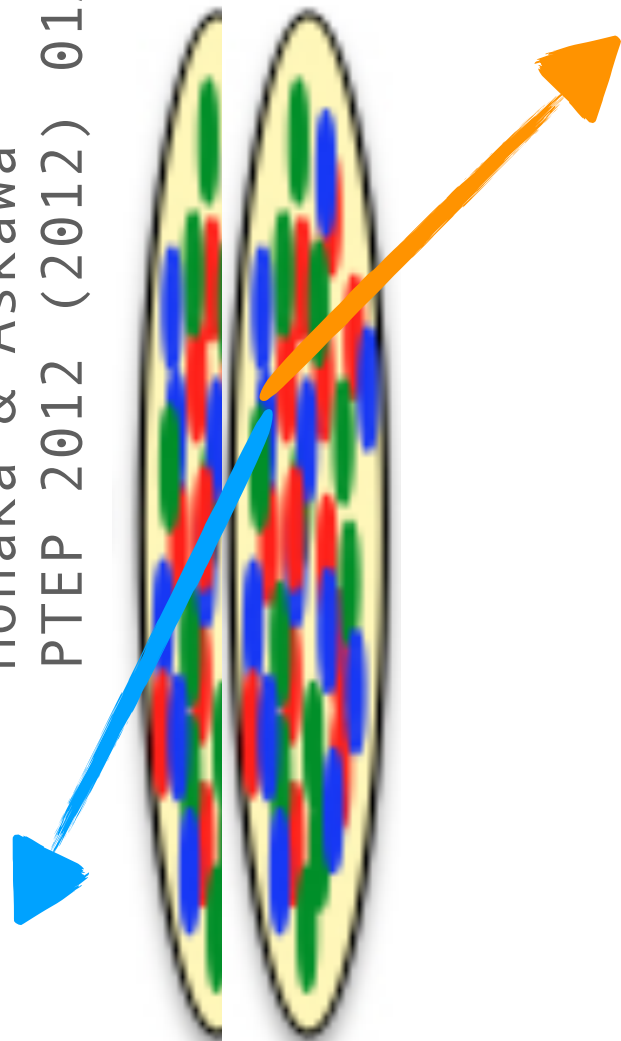
- Groomed substructure (z_g , R_g) and M_g

CMS Collaboration,
 Phys. Rev. Lett. 120, 142302 (2018)

Lets imagine we are a parton



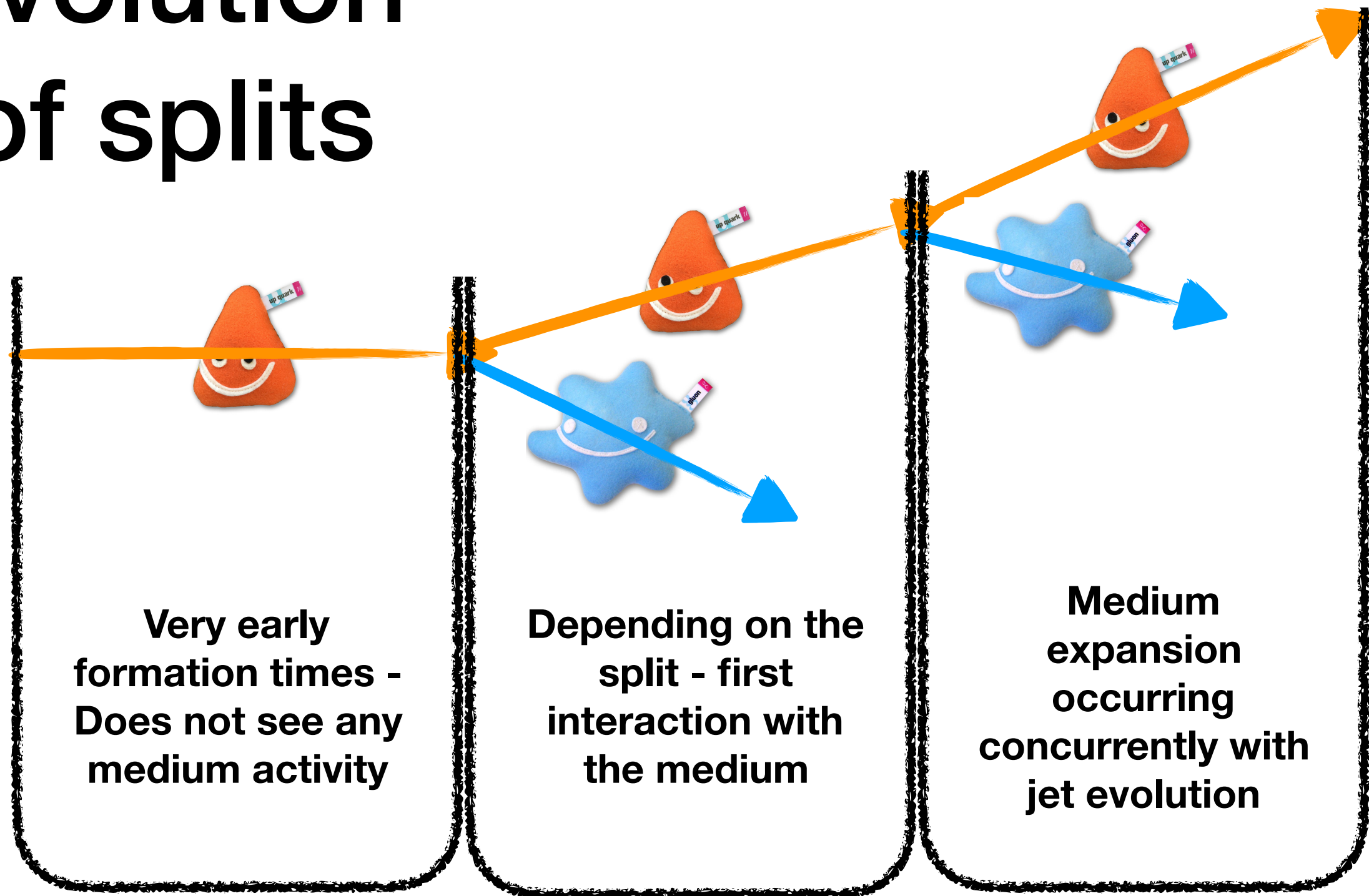
Monaka & Askawa
PTEP 2012 (2012) 01A208



What do we see, what happens to us along our path to the detector?

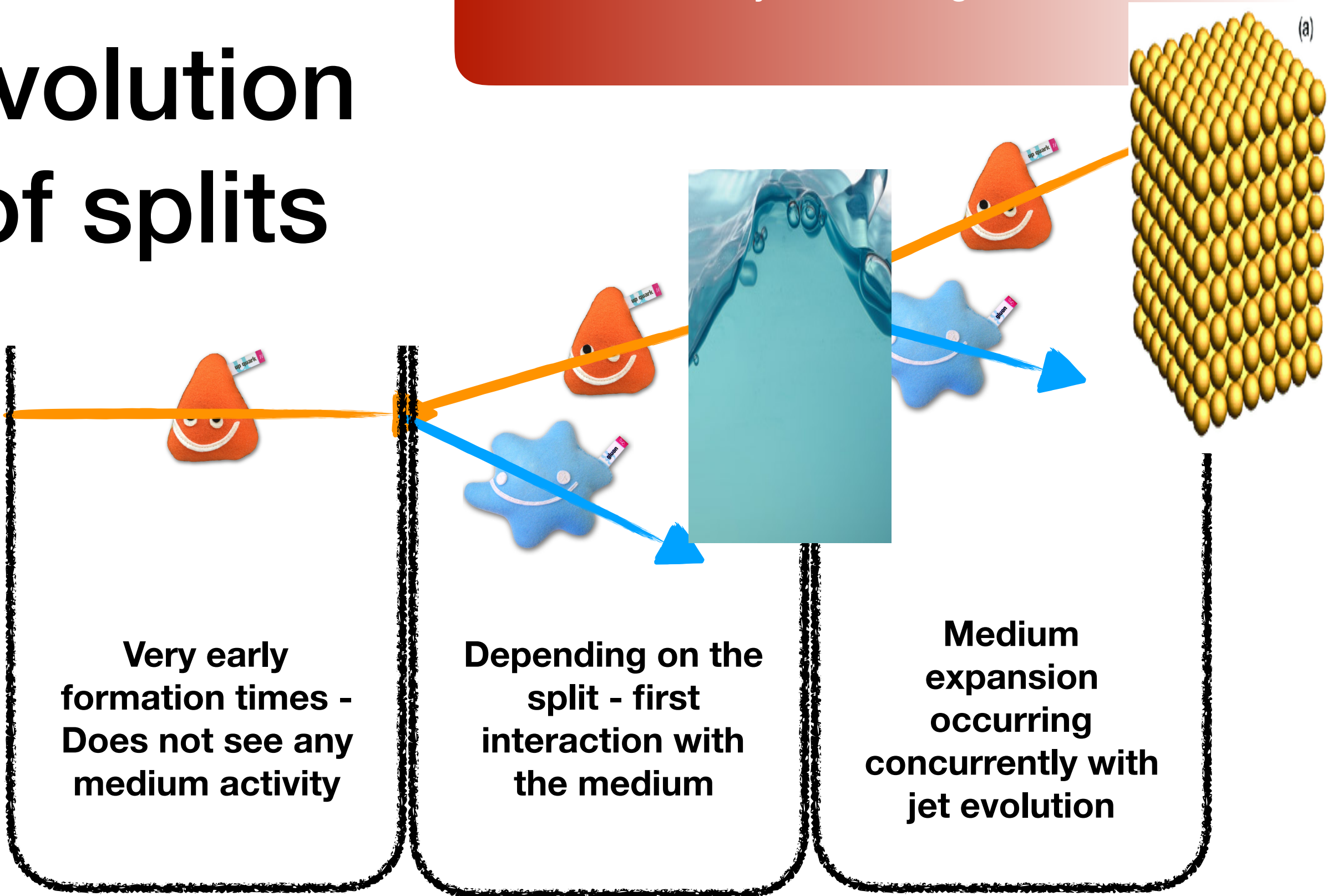
density of scattering centers

evolution of splits

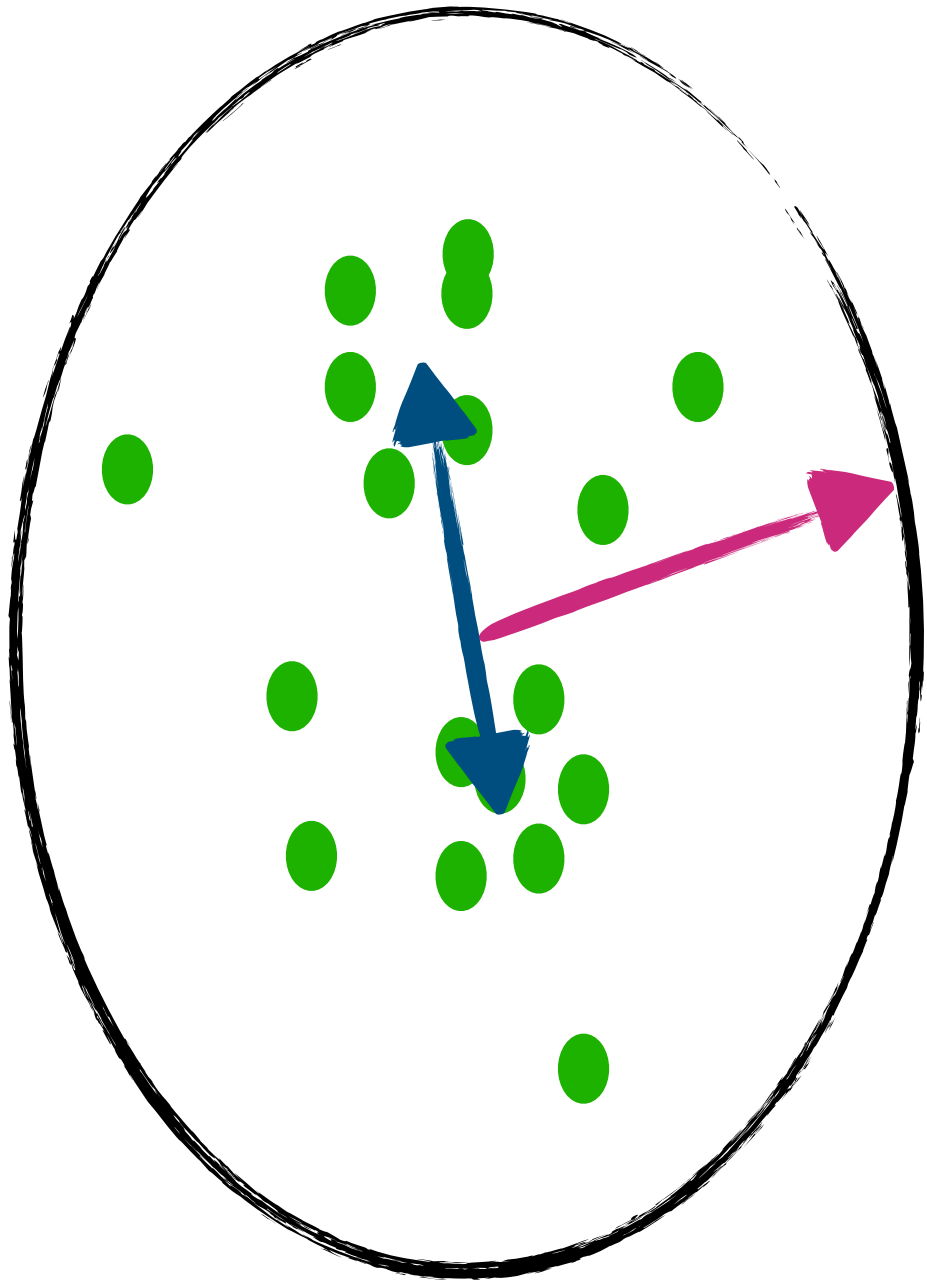


evolution of splits

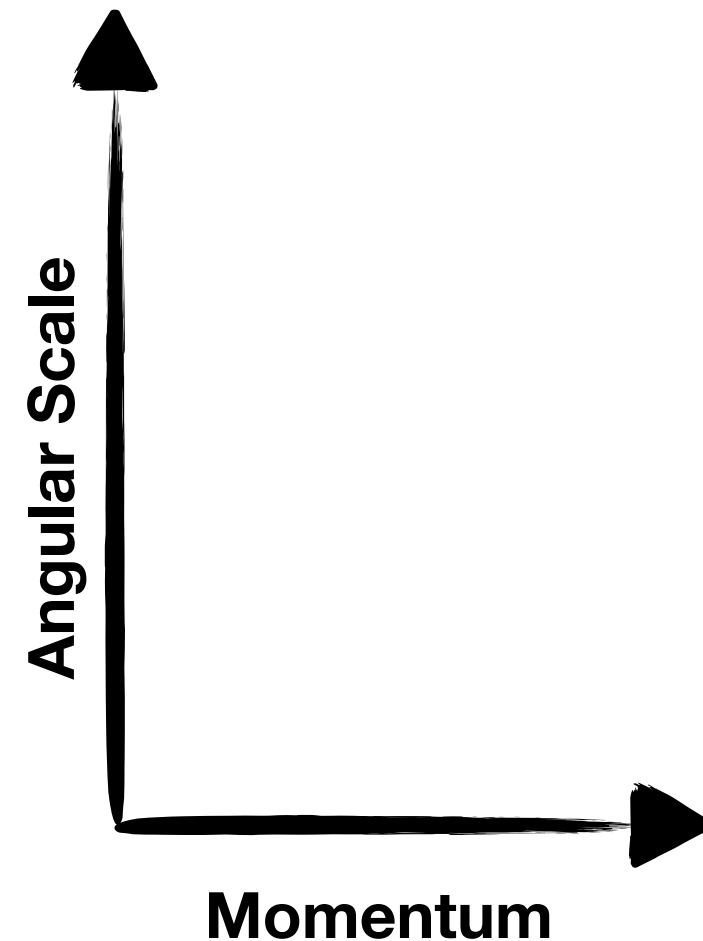
density of scattering centers



What do we want to measure?

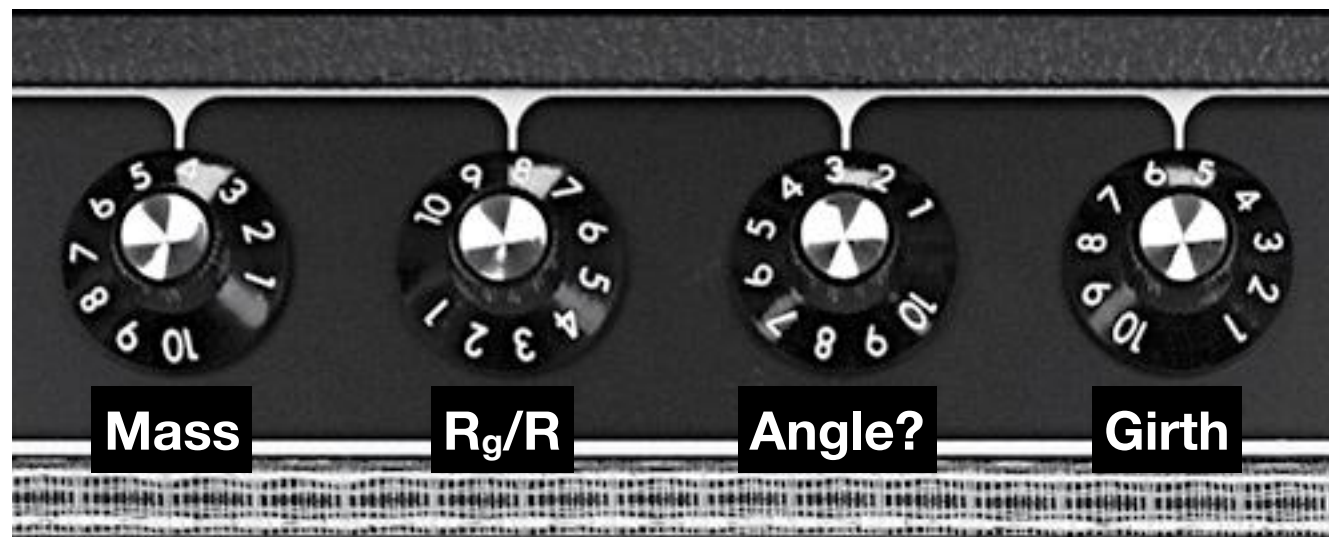
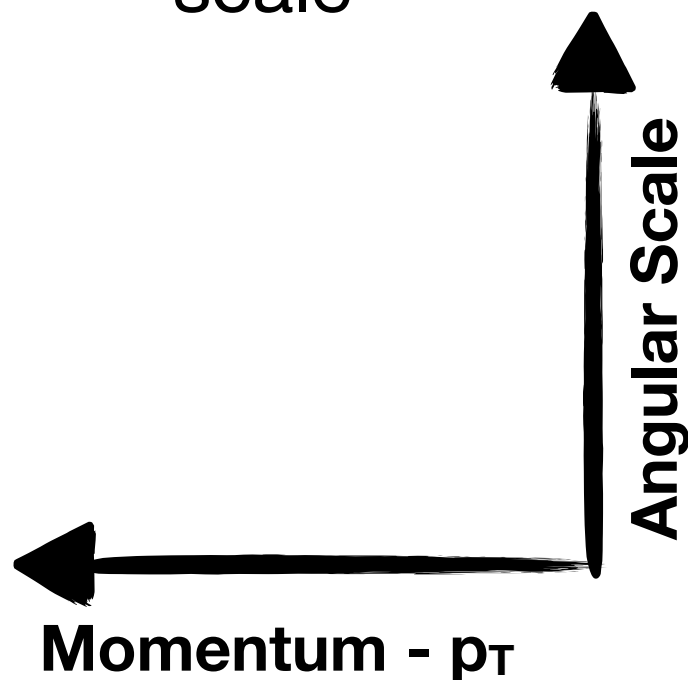
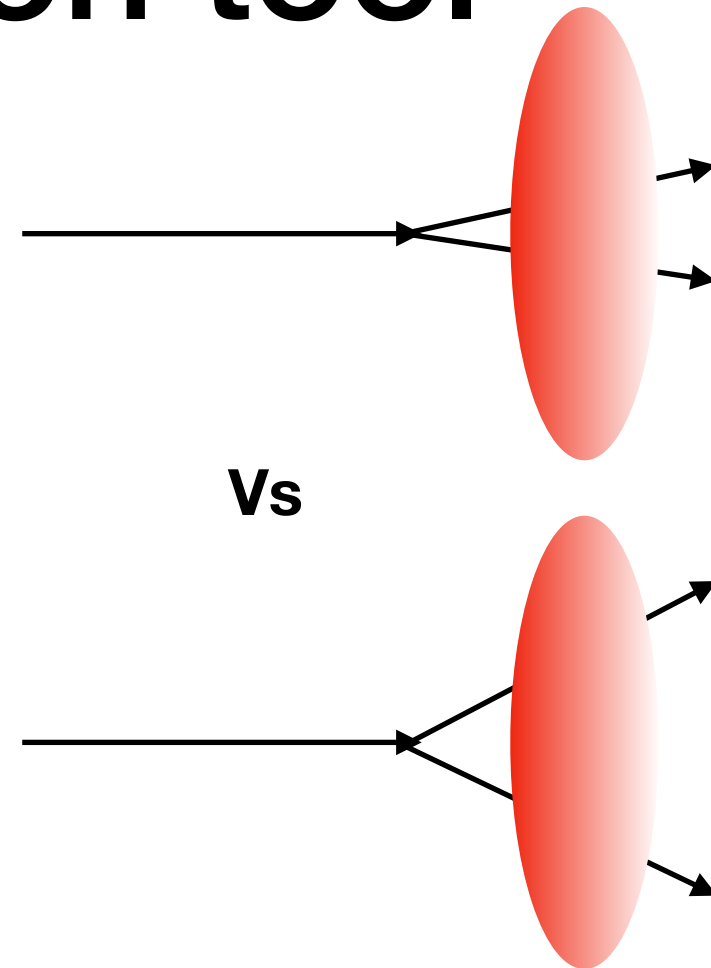


- Jets are defined by a **characteristic** angular scale
- Jets also have an **inherent** angular scale as a result of partonic shower/evolution
- Can we tag jets based on its angular scale
- **How does medium interaction vary differentially?**



Key Idea - Use jet-substructure as a selection tool

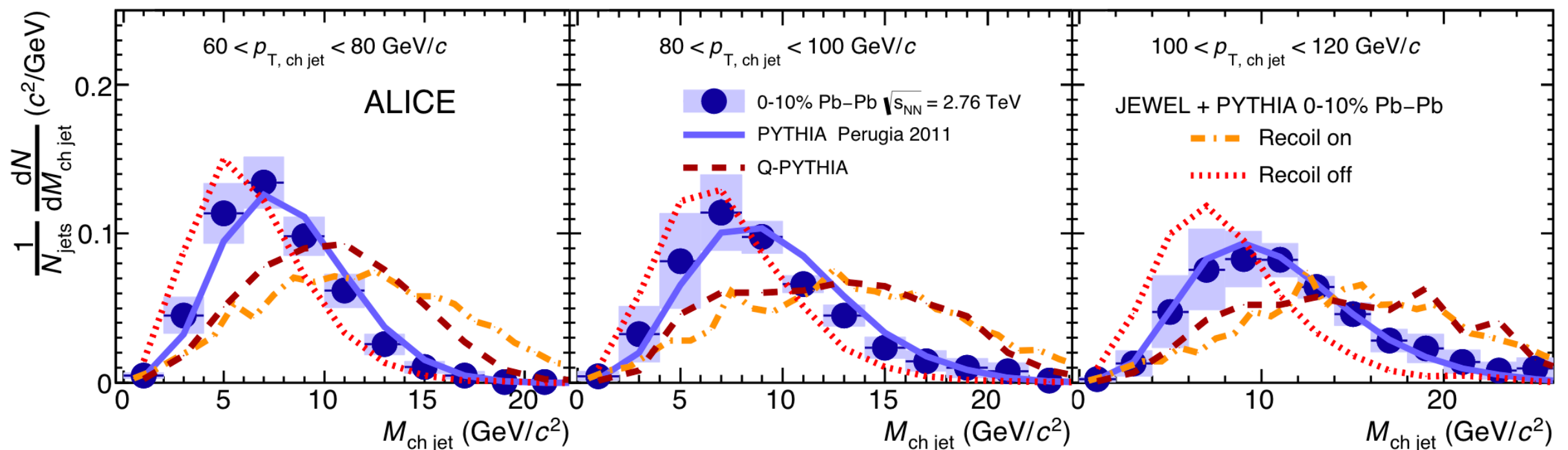
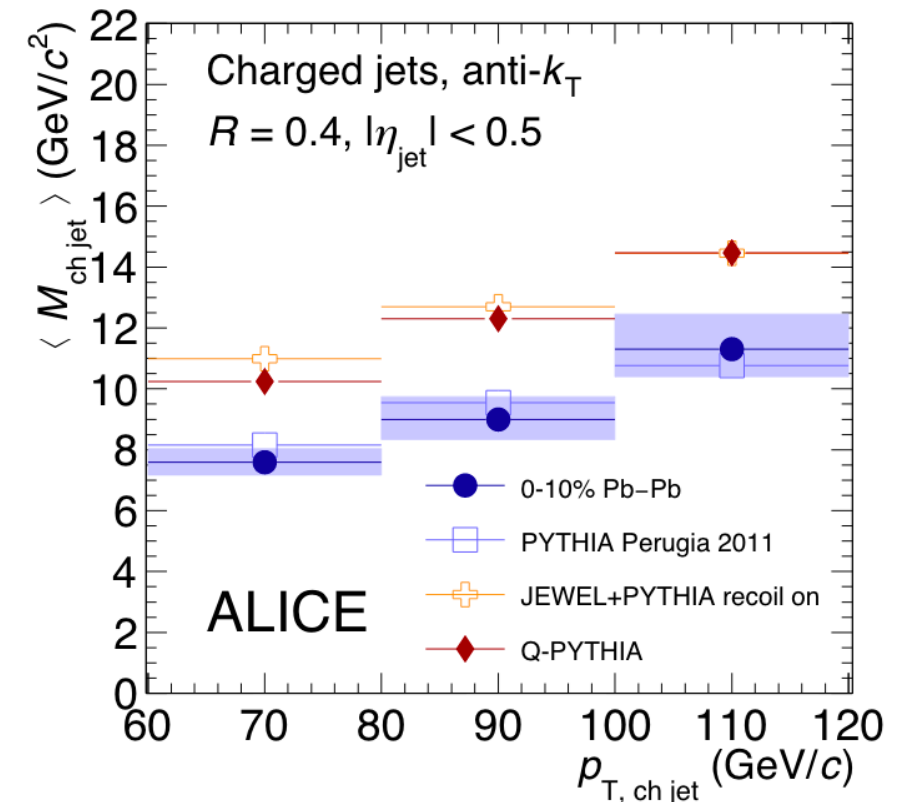
- Identify an observable sensitive to the jet's inherent angular scale
- Measure jet energy loss differentially in the angular scale
- Relate jet angular scale as a proxy for medium resolution scale



ALICE Jet Mass ($M \sim z\theta^2$)

- 2D-Unfolded mass measurement
- Mass increases nearly linearly with p_T and is relatively independent on the subtraction method
- Jet Mass remains quite similar to PYTHIA and less than JEWEL

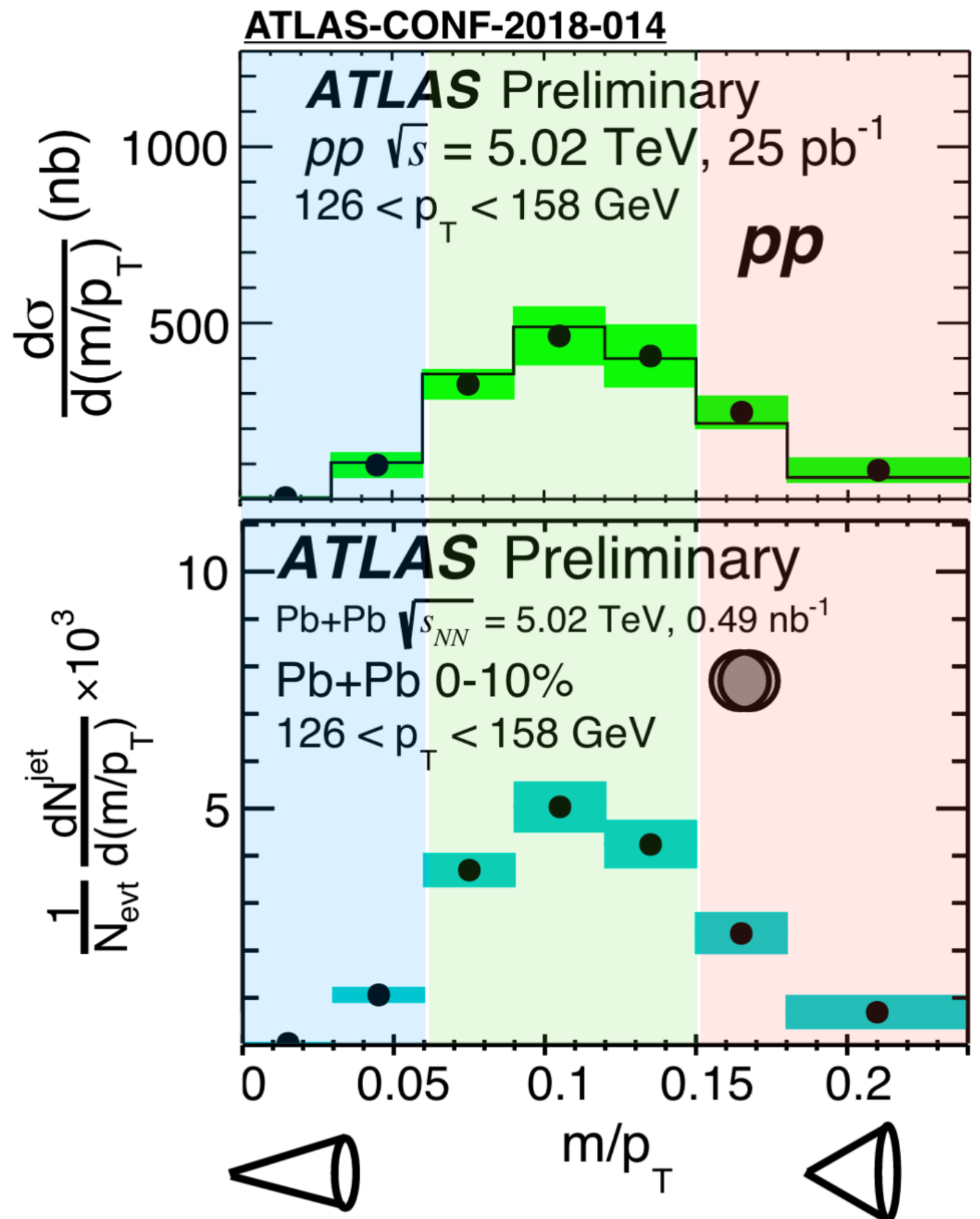
ALICE PLB 776(2018)249



ATLAS

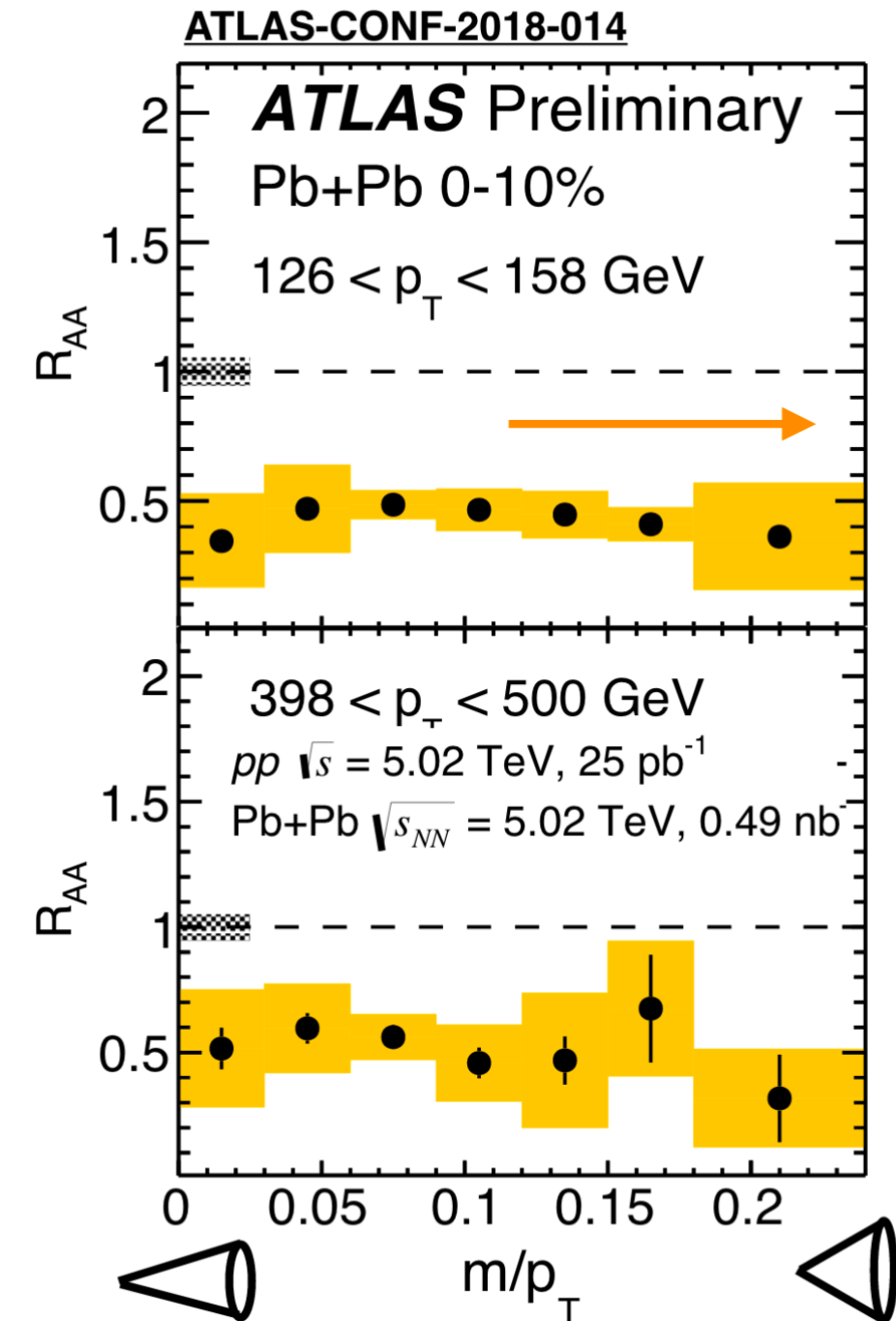
Jet m/p_T

- m/p_T is essentially related to the overall size of the momentum weighted jet constituents
- Easier to unfold - reduced dependence on jet p_T
- Requires model comparisons and a bit of thought to directly translate it to a resolution scale



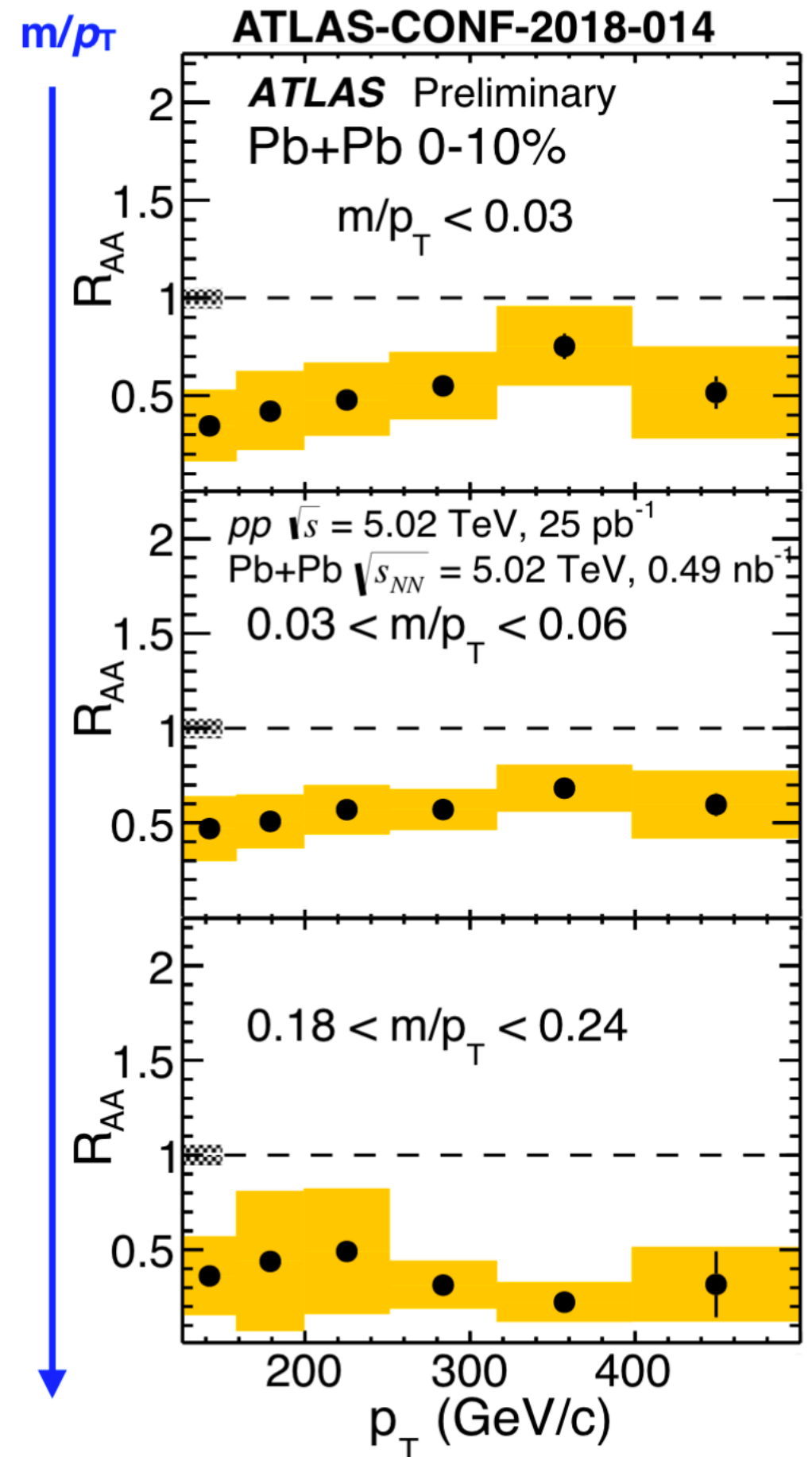
Figures taken from Laura Haver's talk at WWND 2019

RAA for various mass selections



Figures taken from Laura Haver's talk at WWND 2019

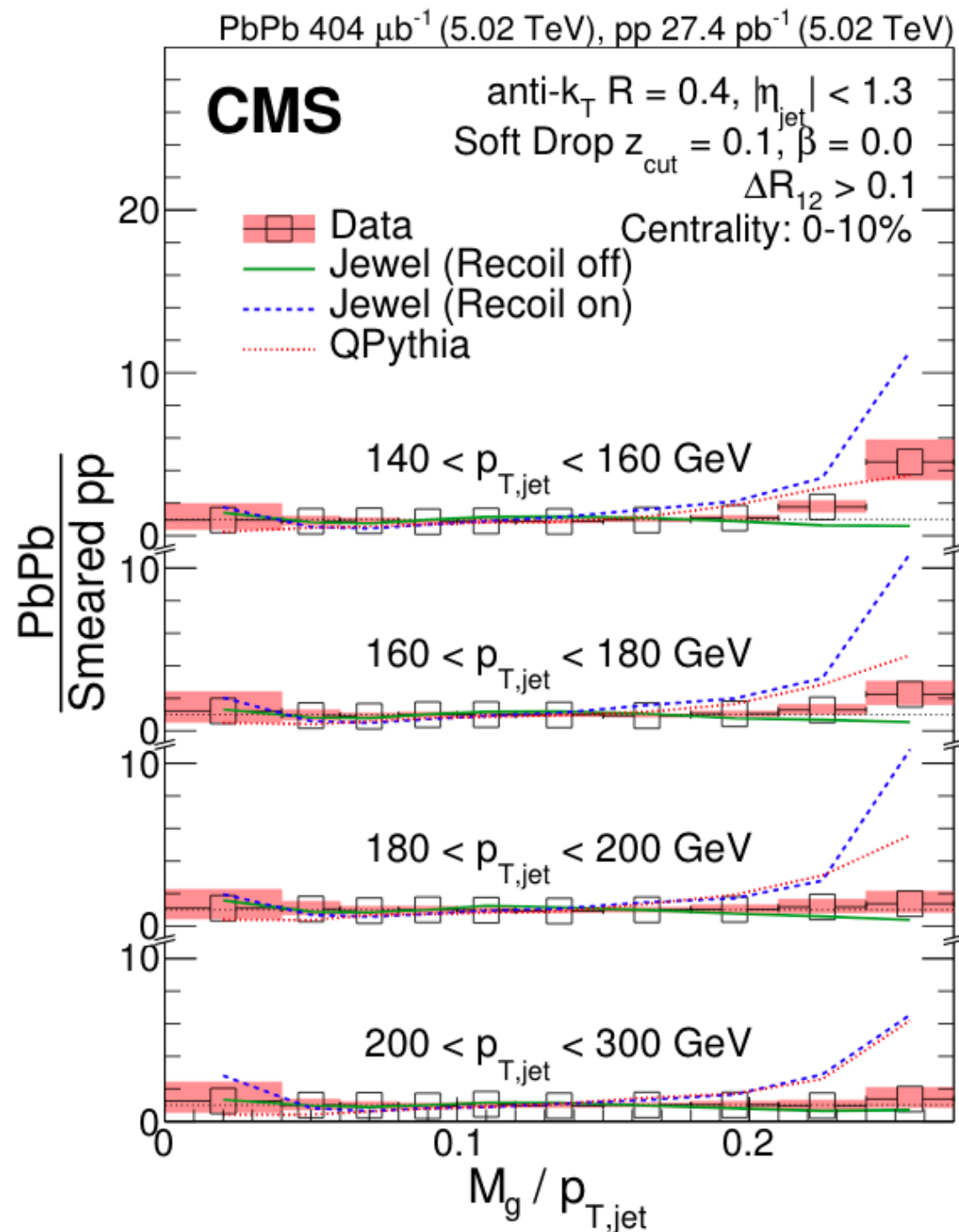
- Observe no significant effect of varying m/p_T
- Jet p_T possibly too high?
- m/p_T bins include jets of varying mass/resolution scales



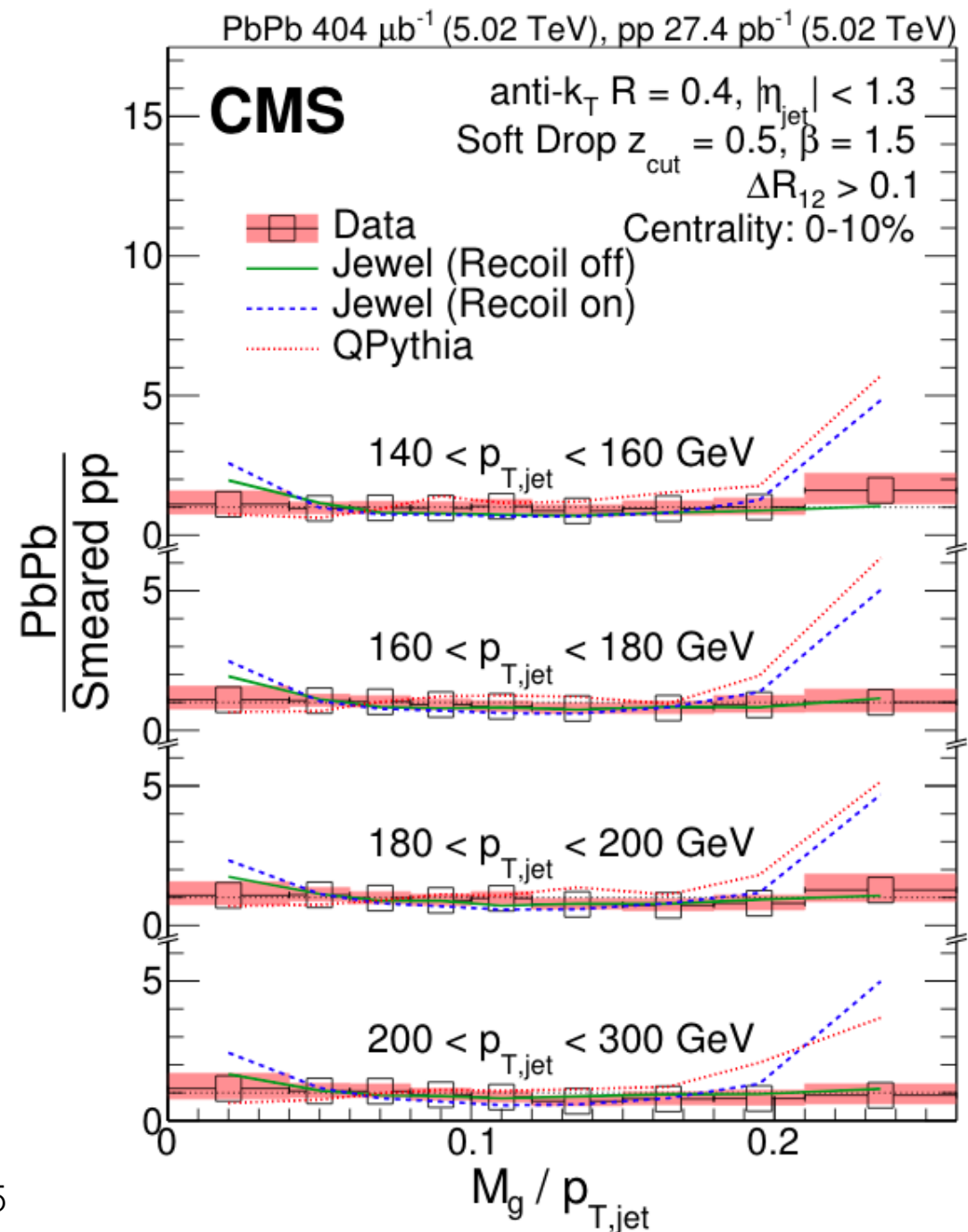
CMS Groomed M_g/p_T

Hints of modification at large M_g/p_T but not as large as MC models.
No modifications in the core!

- Soft exterior grooming

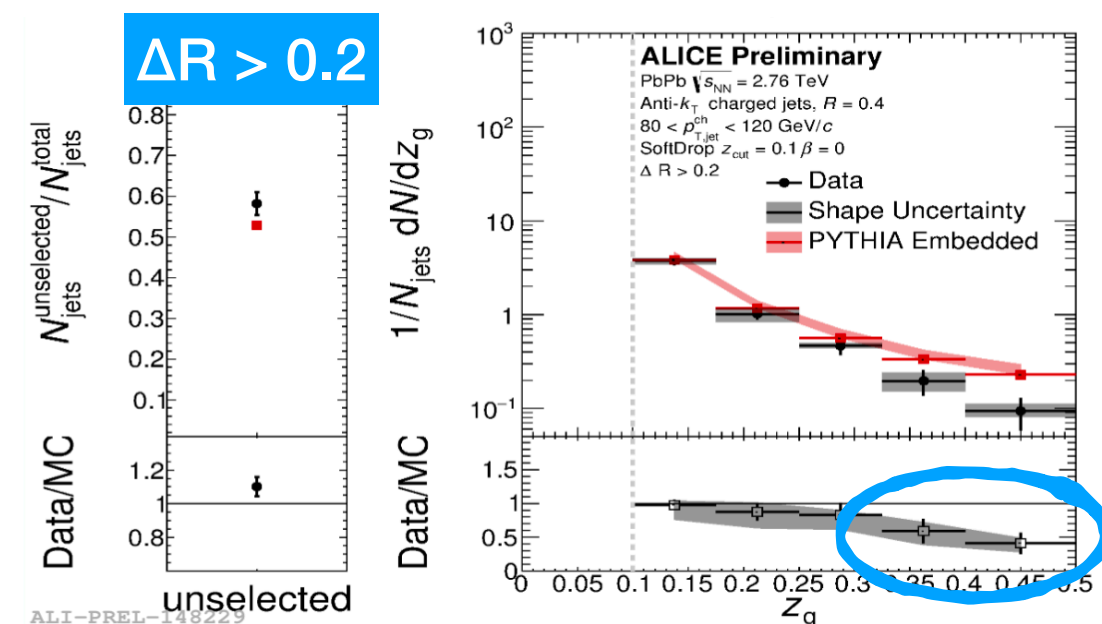
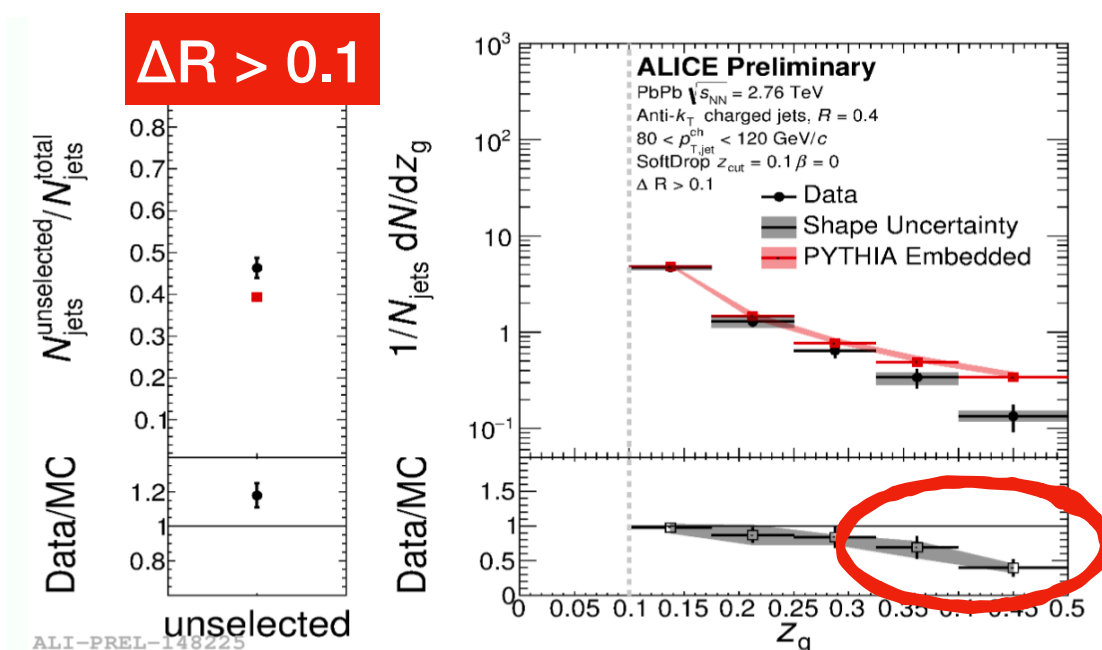
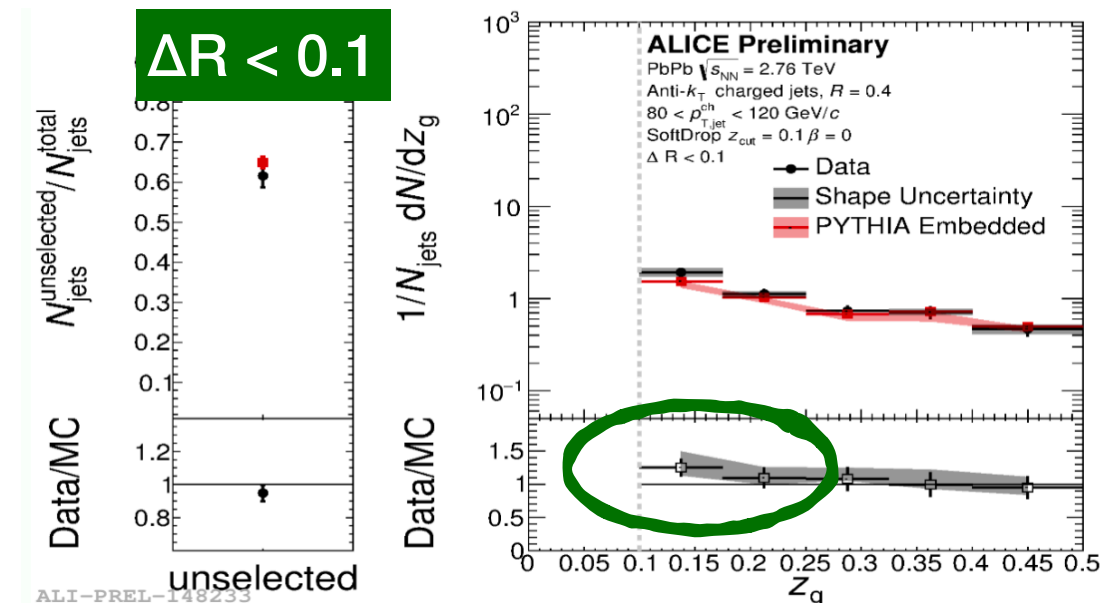


- Core grooming



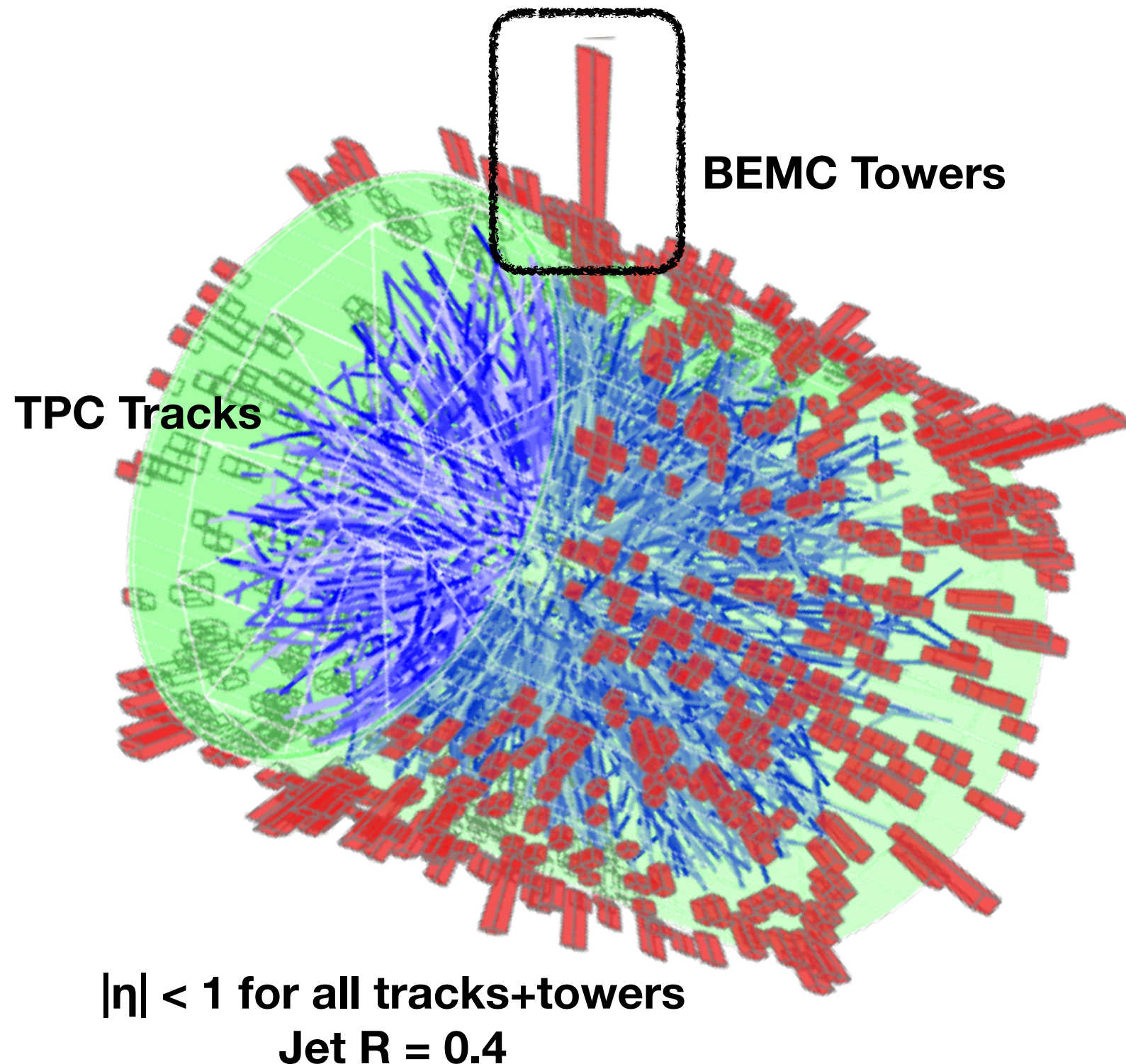
ALICE z_g for ΔR selections

Figures taken from Nima Zardoshti's talk at HP 2018



- About half of the jets are removed at jet $p_T > 80$ GeV/c with $\Delta R > 0.1$ cut
- Significant suppression in high z splits at large ΔR

Jets at RHIC and STAR



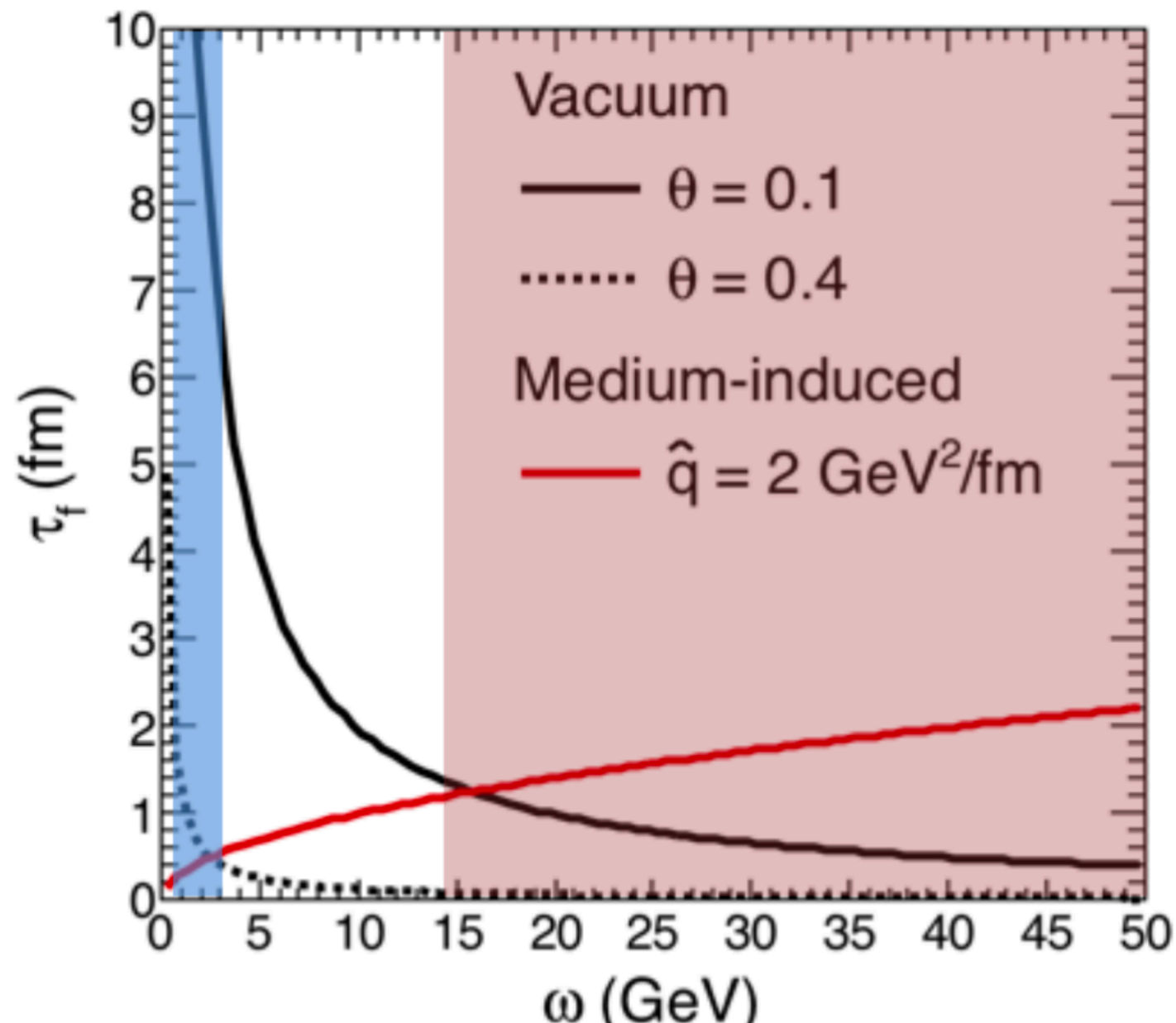
- 200 GeV AuAu - steeply falling jet spectra
- High Tower trigger - BEMC $E_T > 5.4$ GeV ensure high scattered event
- Trigger Jet $p_T > 20$ GeV/c
- Recoil jets in the range 10 - 40 GeV/c

Split formation @ RHIC

Marta Verweij,
QM2017

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$



Phase space
covered for
 $z_g=0.1$

STAR

CMS

- Large angle or large mass jets could see medium interactions earlier in time and thus split along with it

STAR Jet Selection

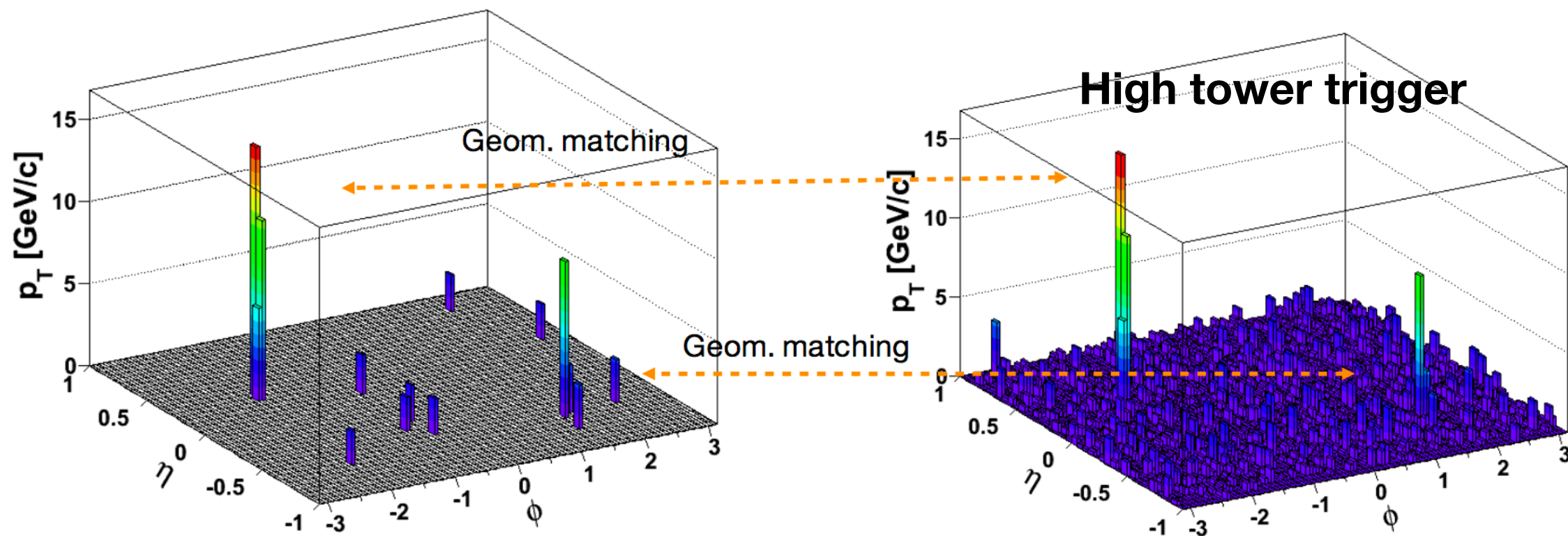
Select events based on High Tower (HT) trigger
highest tower $E_T > 5.4$ GeV/c

ΔR (Lead-jet, HT) < 0.4

$\Delta \phi$ (Recoil-jet, HT) $> 2\pi/3$

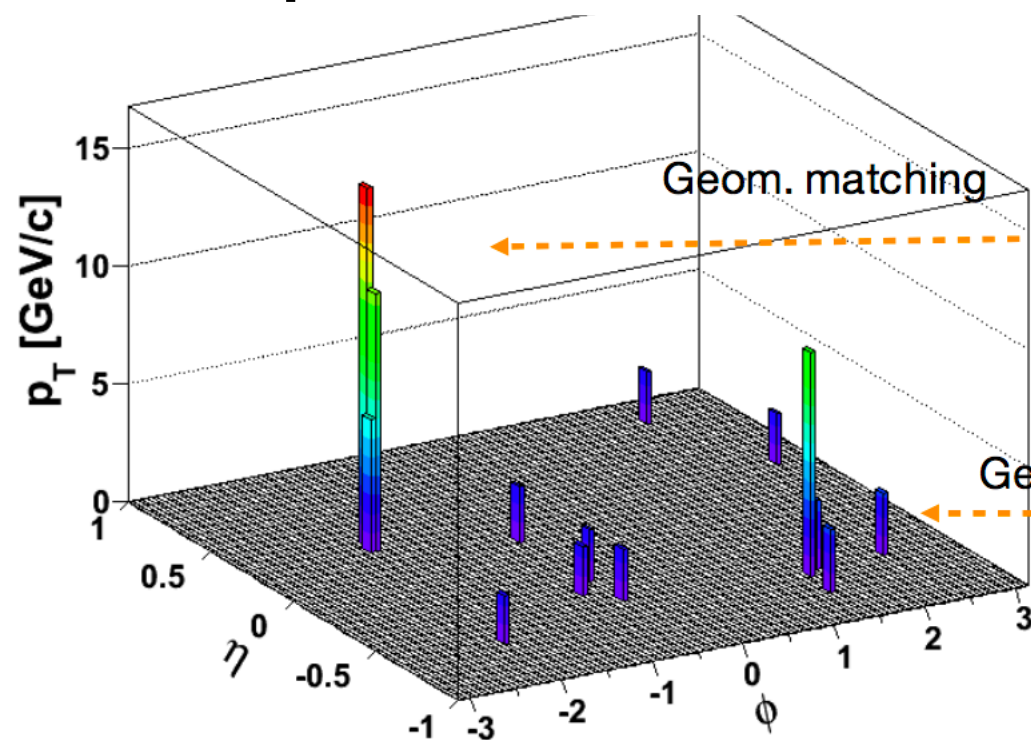
$p_T^{\text{const}} > 2$ GeV/c

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

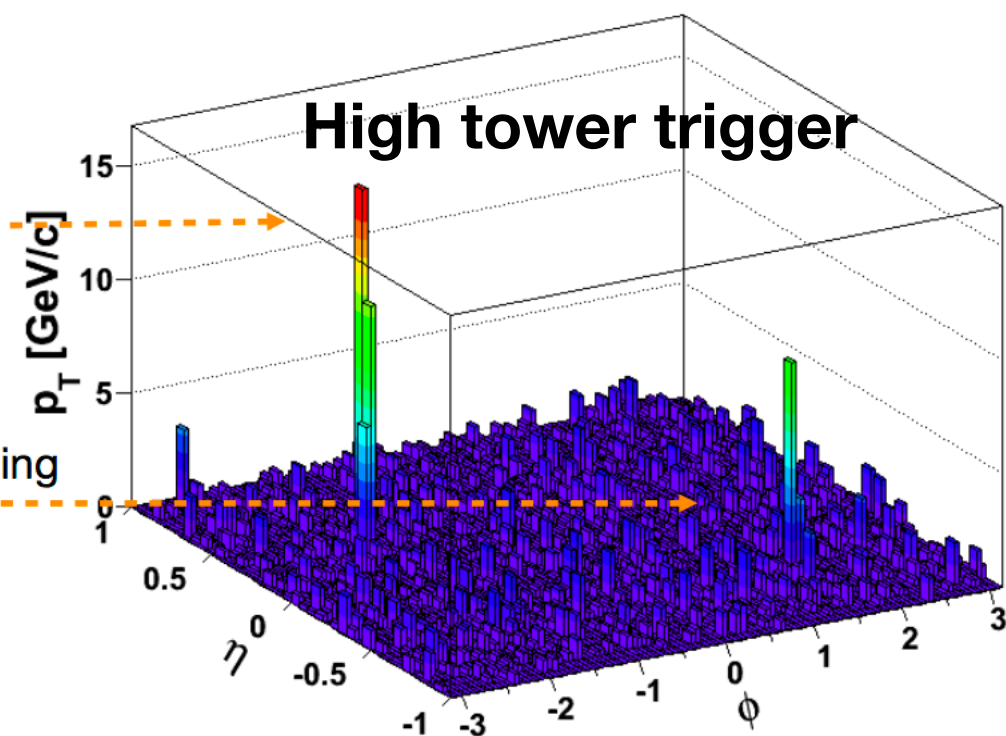


STAR Jet Selection

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



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



Hard Core selection $\longrightarrow$ **removes almost all background**

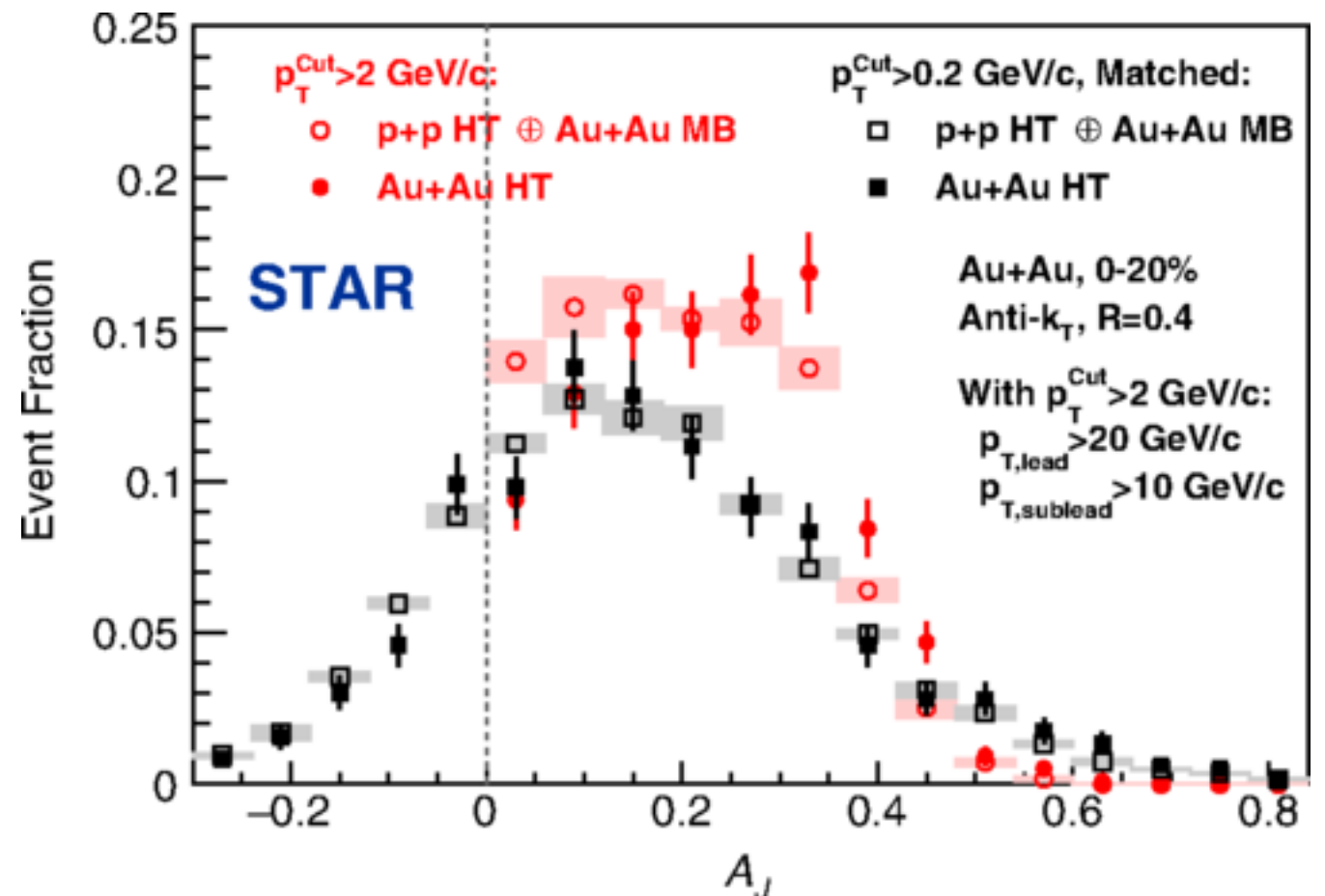
geometric matching $\longrightarrow$ **no combinatoric jets, recover all constituents**

STAR, PRL 119 062301 (2017)

Special Jets!

- Hard Core AuAu Jets are imbalanced compared to pp+AuAu
- Matched Jets are balanced!
- Quenched energy is recovered within $R=0.4$ radius

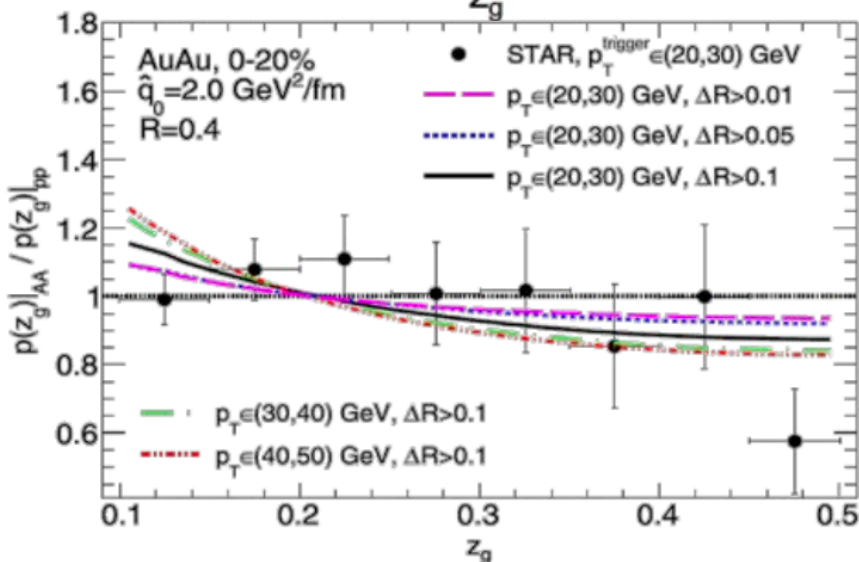
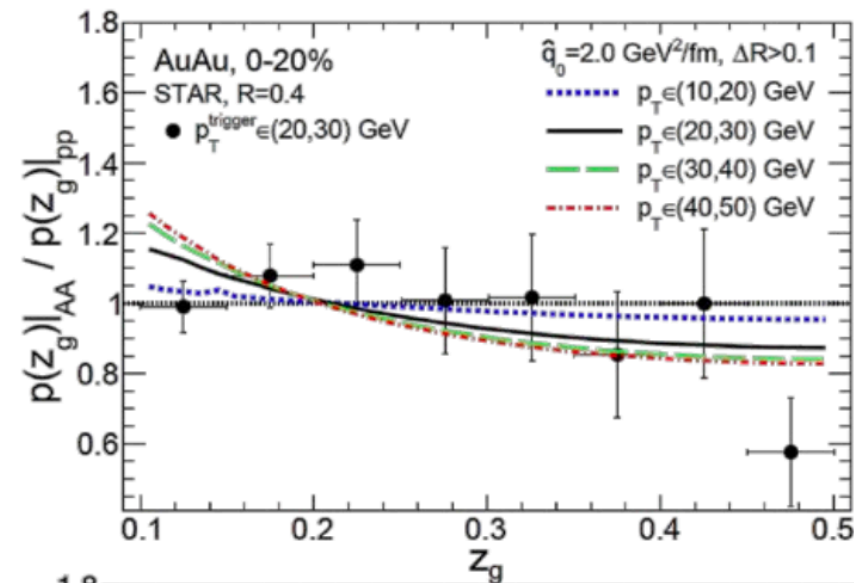
STAR, PRL 119 062301 (2017)



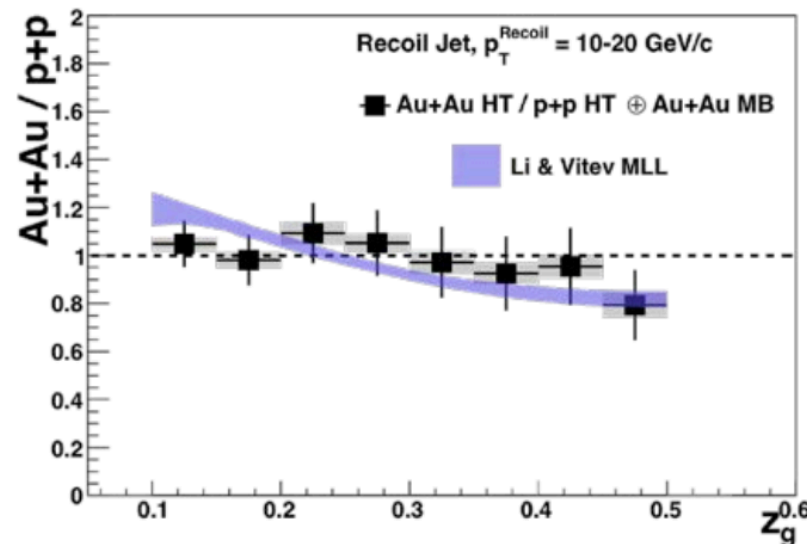
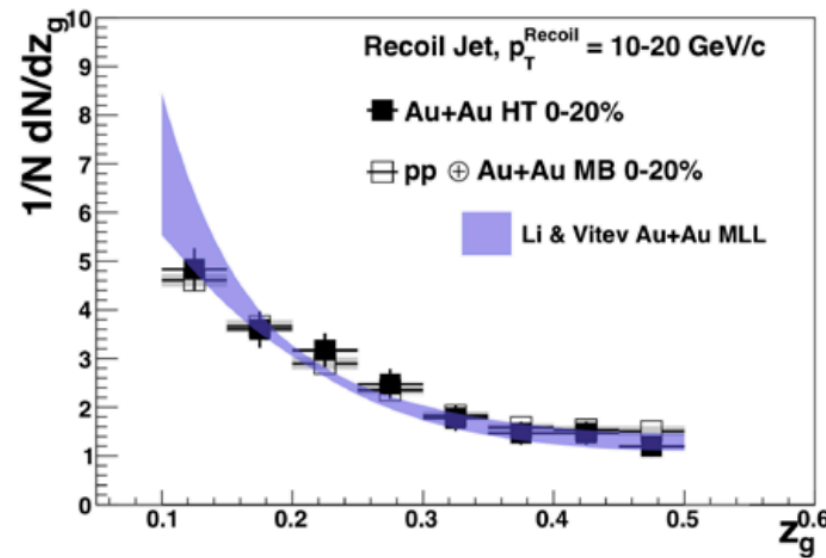
These are ideal to study differentially! We can tag collections of these jets in both momentum and angular scales

z_g in Au+Au 200 GeV

KK, HP16, QM17



Ning-Bo Chang
et al. QM18



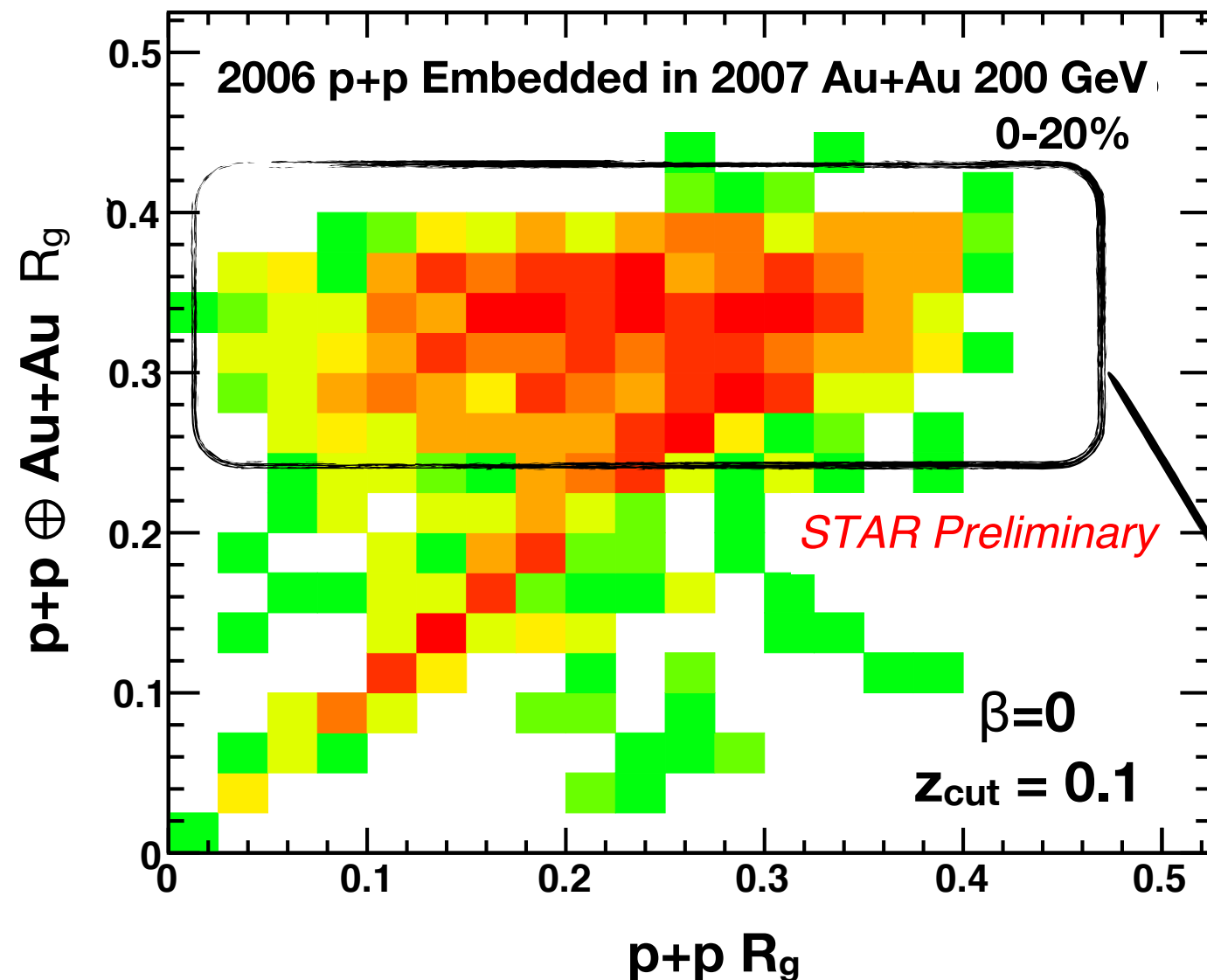
Li & Vitev
arXiv: 1801.0008

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

Modelers: Be mindful of cuts and detector effects

Slide shown by Kolja Kauder, RHIC AGS Users Meeting 2018

SoftDrop R_g in the presence of a Heavy Ion event



anti- k_t $R^{\text{jet}} = 0.4$

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

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

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

Constituent-subtracted jets

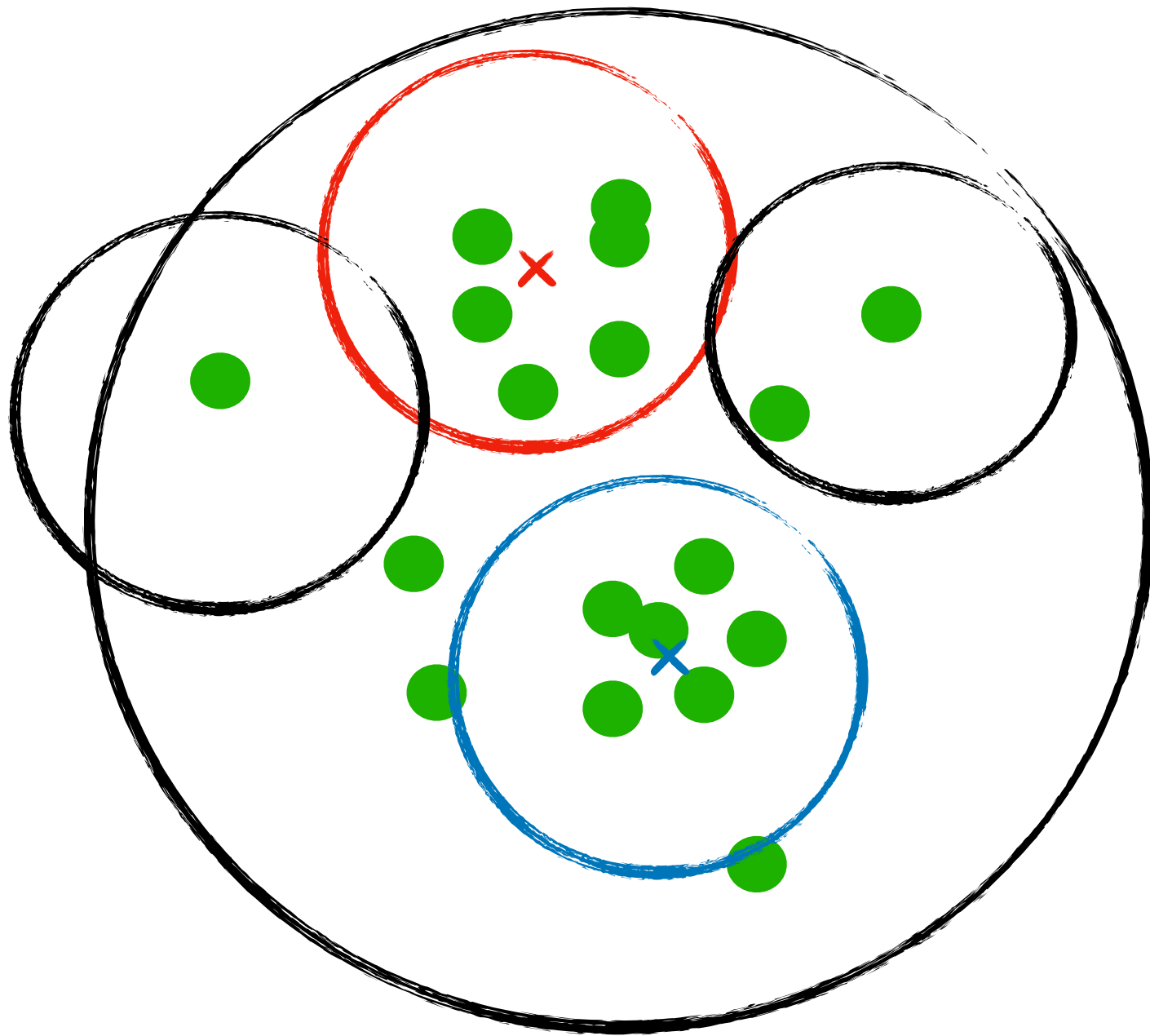
Berta, P et al. JHEP 06 (2014) 092

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

Slide shown by RKE, HP 2018

TwoSubJet z/θ

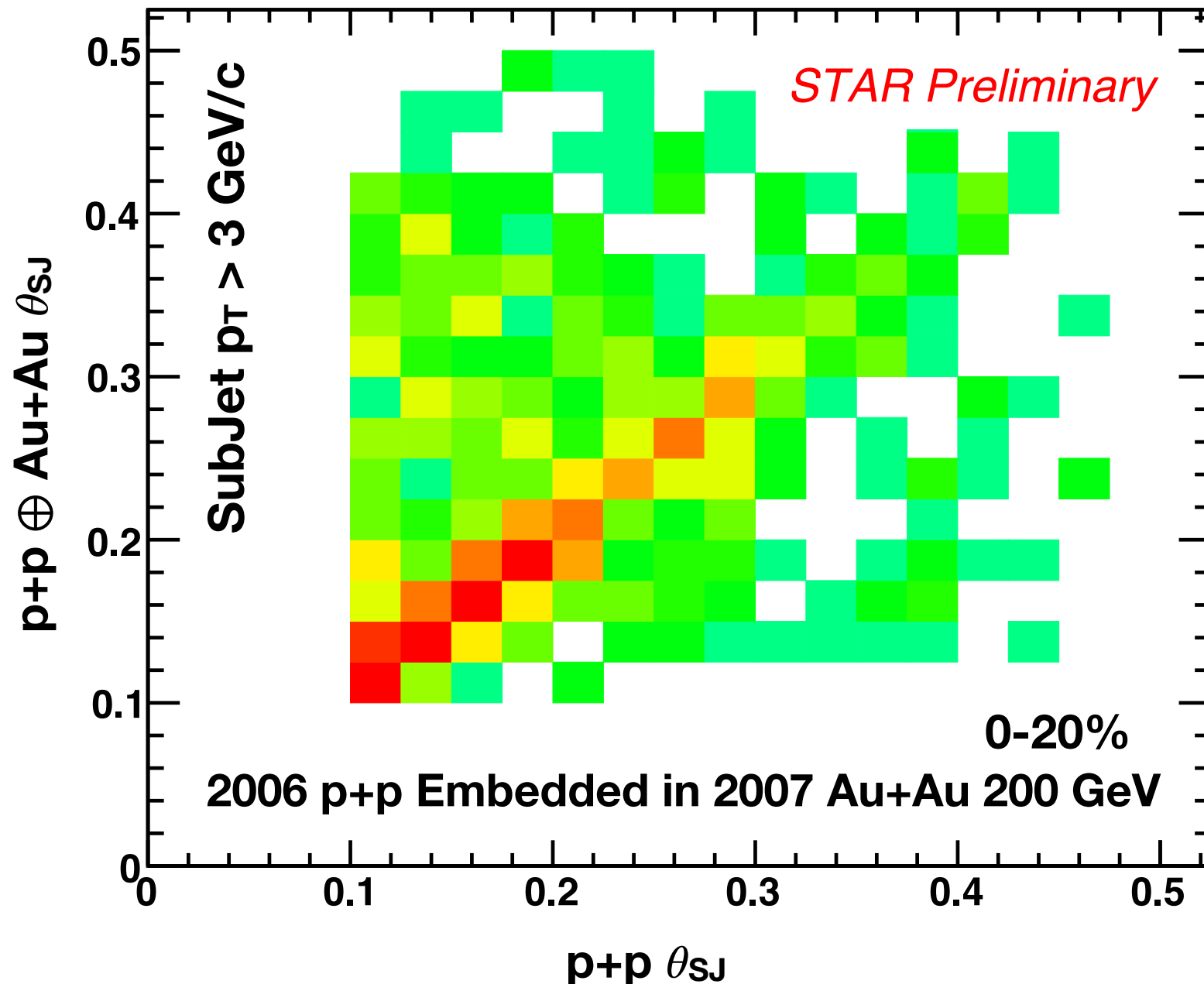


- Cluster all jet constituents into anti- k_t jets of smaller radii (0.1)
- Choose the **leading** and **subleading** SubJets
- $z_{SJ} = \frac{\text{Blue } p_T}{(\text{Blue } p_T + \text{Red } p_T)}$
- $\theta_{SJ} = \Delta R (\text{Blue Axis}, \text{Red Axis})$

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

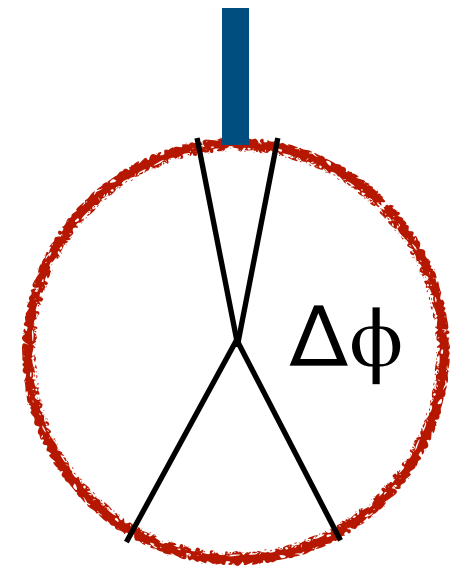
- θ_{SJ} (w/ $R=0.1$ SubJets)
**less sensitive to AuAu
 underlying event**

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

TwoSubJet (R=0.1) observables in Au+Au

- Fix trigger jet selection:
Study recoil HardCore/Matched Jets
($p_{T}^{\text{const}} > 0.2 \text{ GeV}/c$)
- Matched jet's SubJet $p_T > 3 \text{ GeV}/c$:
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 $p_T > 16 \text{ GeV}/c$
w/ High Tower Trigger Object

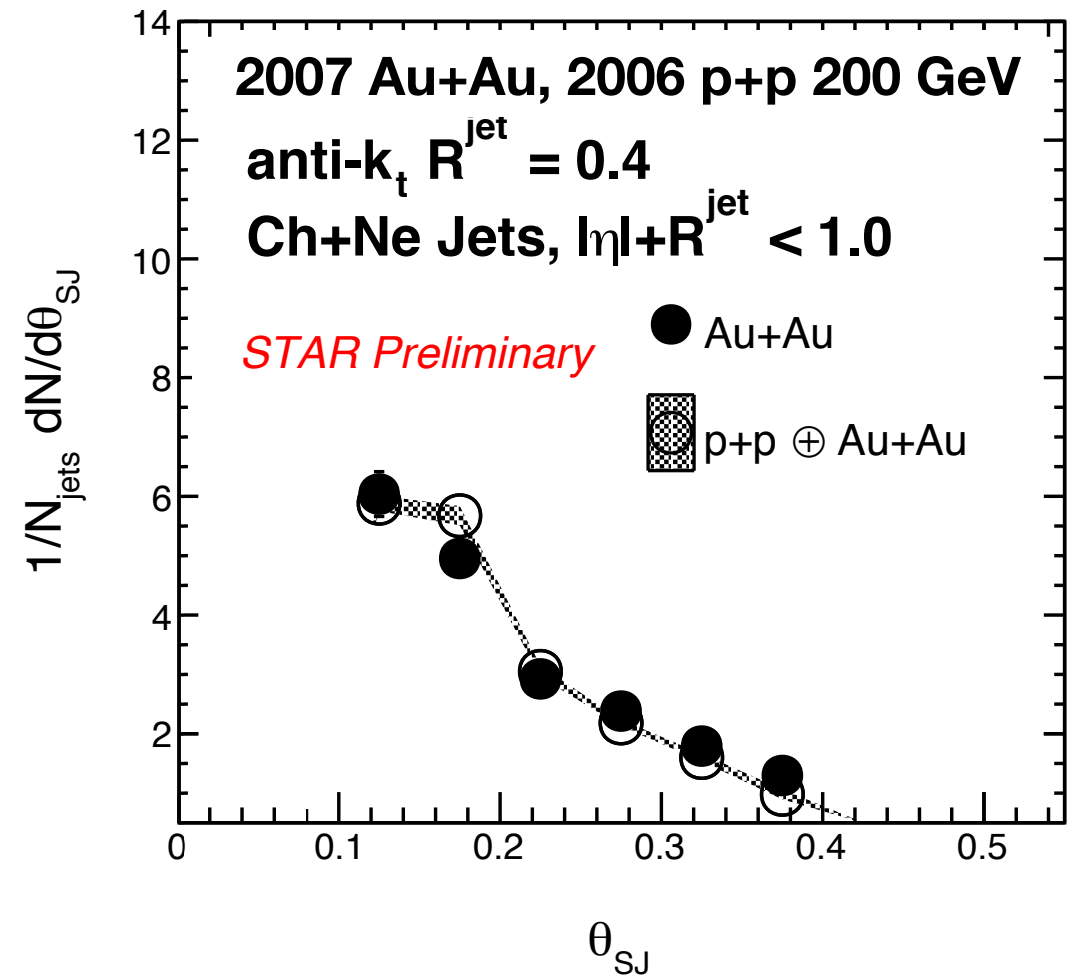
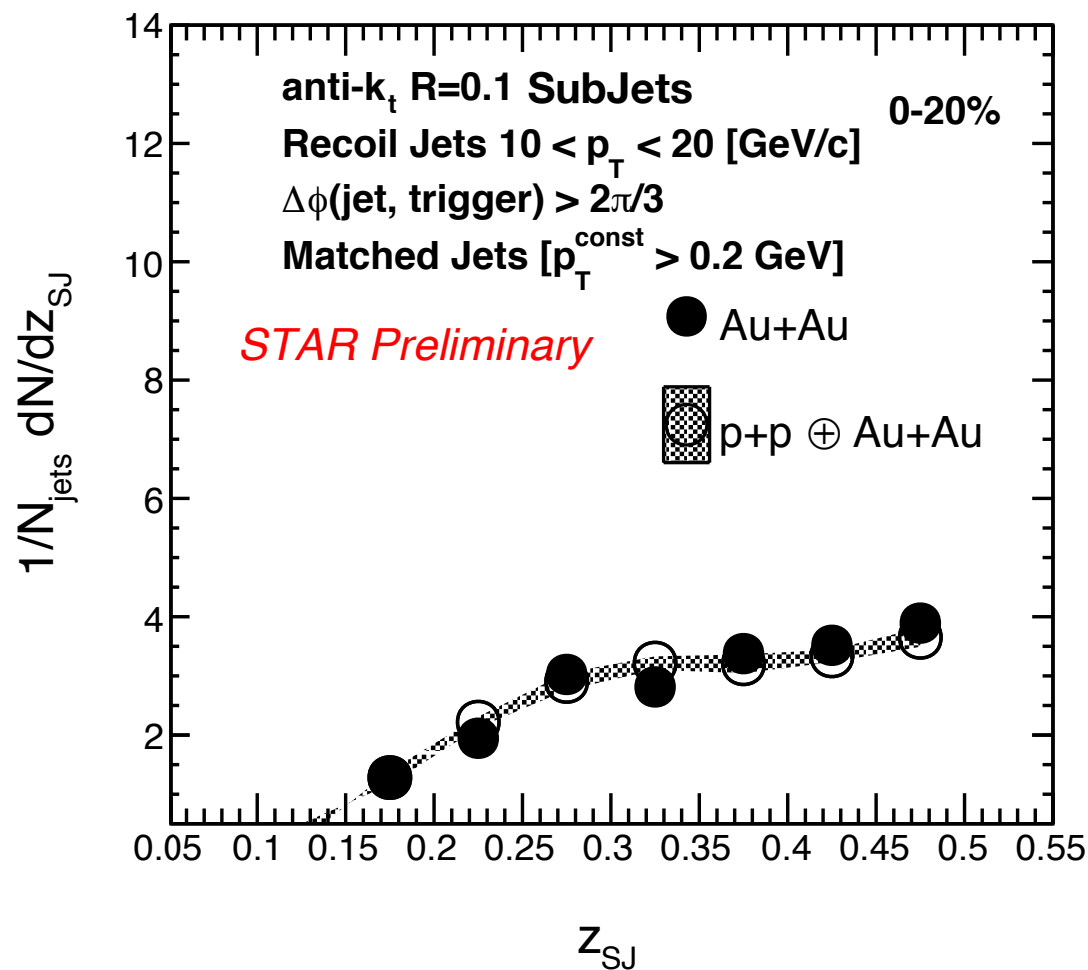


HardCore
Recoil Jet $p_T > 8 \text{ GeV}/c$

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

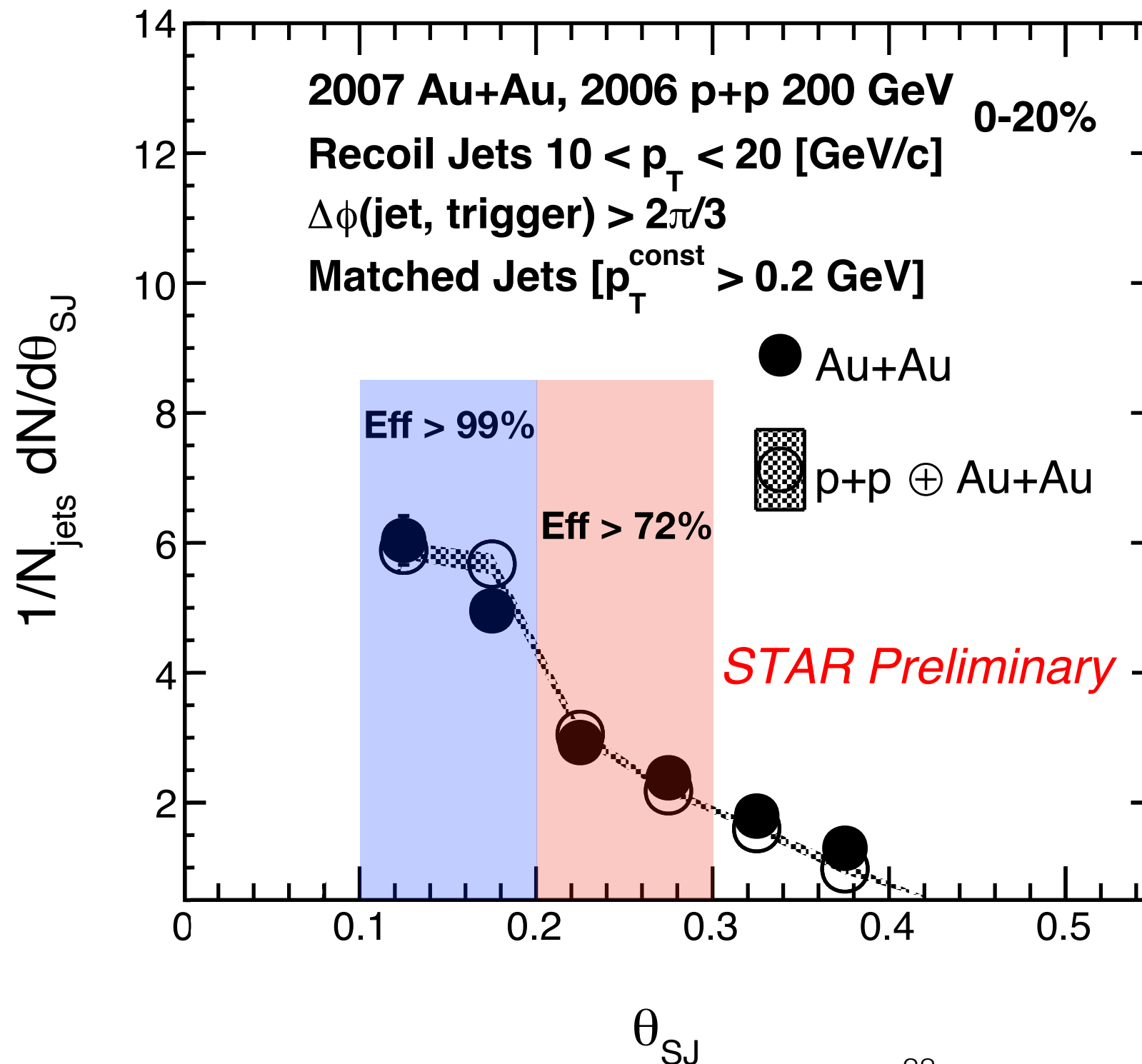
TwoSubJet observables

anti- k_t $R=0.1$ SubJets



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

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



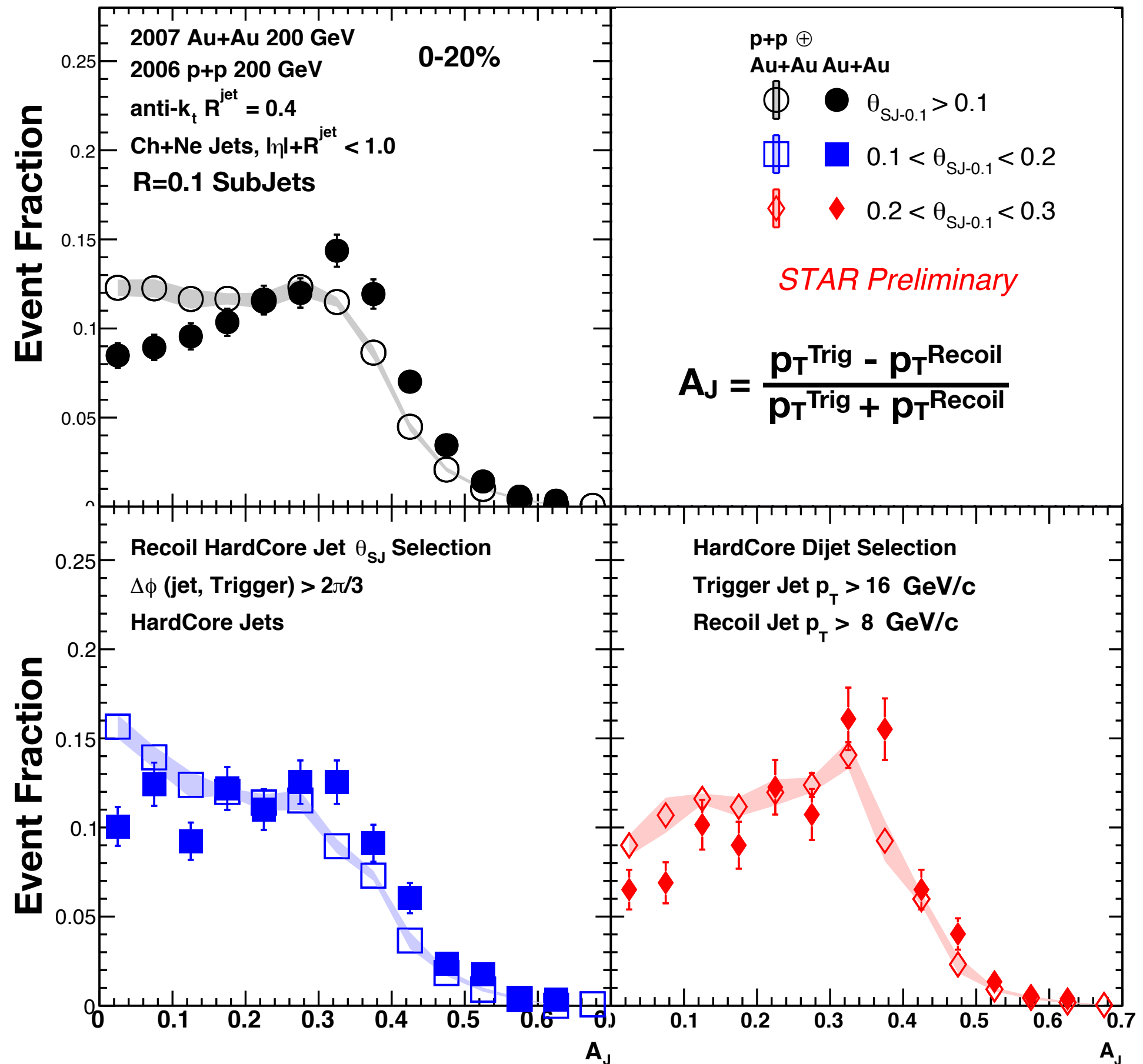
Tagging Efficiency: Probability that p+p ⊕ Au+Au and the p+p jet utilized in the embedding have a resolved θ_{SJ} in the same range.

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

HardCore A_J

$p_{T}^{\text{const}} > 2 \text{ GeV}/c$

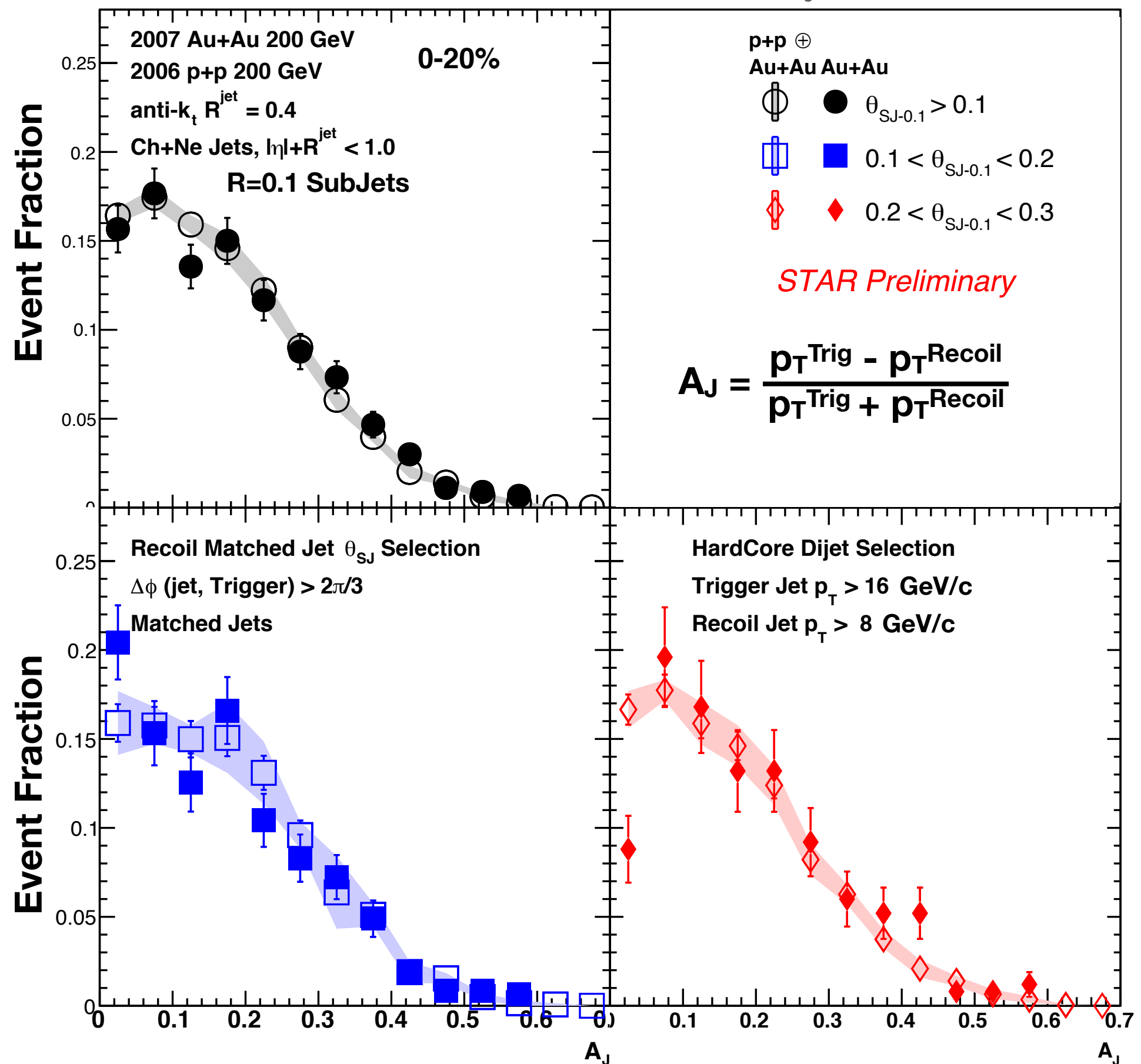
**Significant
modifications in
Au+Au for the
different θ_{SJ}
selections in
comparison to
 $p+p \oplus \text{Au+Au}$**



Matched A_J

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

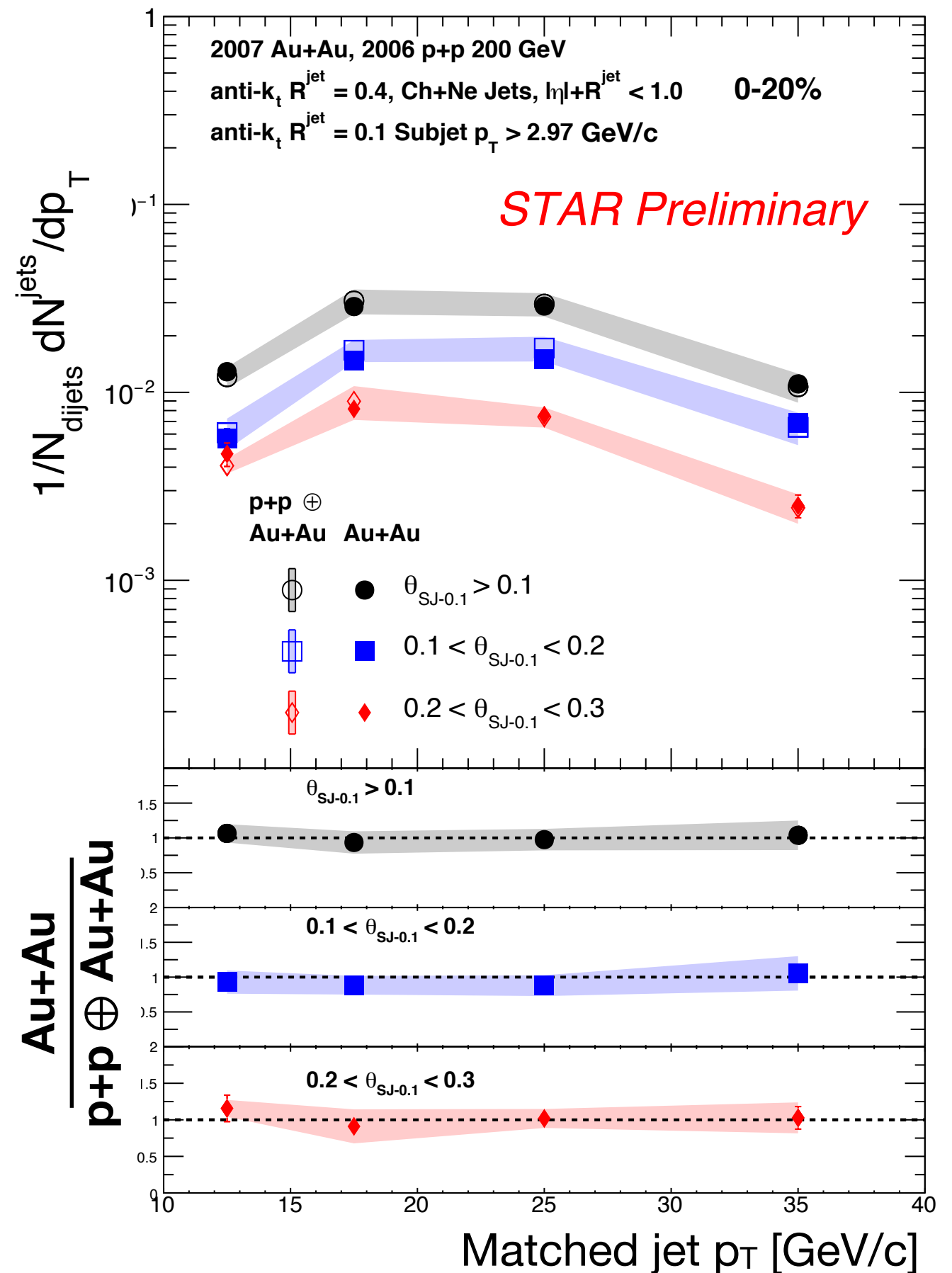
Matched jets of
different θ_{SJ}
selections are
balanced at
RHIC



Recoil matched jet yield

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

- 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



Conclusions

- Jet substructure measurements are an evolution of studying differential parton evolution and energy loss
- Two scales to consider - momentum and angle/resolution - we need observables (absolute quantities as opposed to ratios) robust to UE and BKG-SUB to tag jets
- State of the art measurements - double differential in momentum and angle - models should be able to predict correlations and combinations
- Thus far - at both LHC and RHIC (special Matched $R=0.4$ jets) - no significant differences in jet quenching signatures for narrow or wide jets

New Year Wish list - 2019

- We have access to quite high statistics at both LHC (Run2) and RHIC (Run14) - time to slice and dice jet measurements in both phase spaces
- JETSCAPE as a tool, in addition to varying jet substructure observables, we can vary models (additional dimensionality in data comparisons)

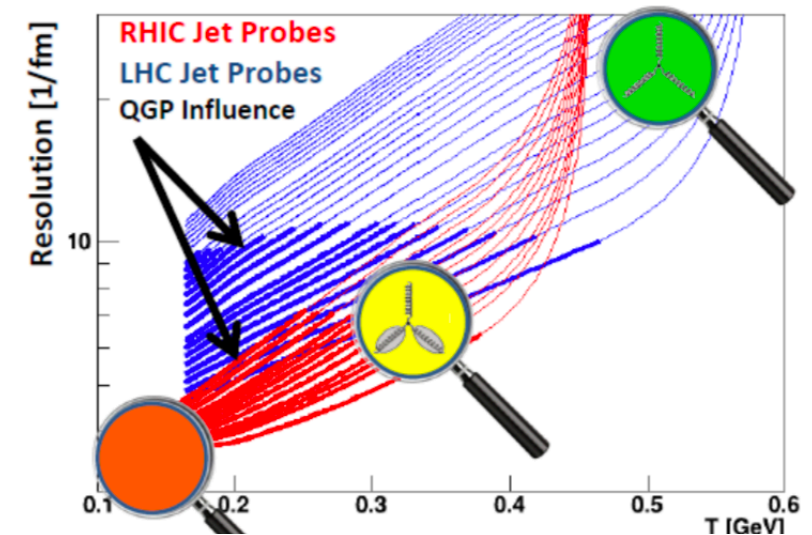
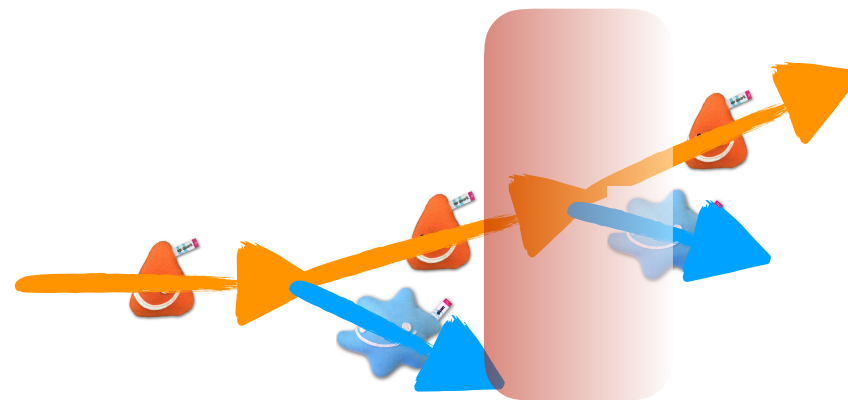
New Year Wish list - 2019

- We have access to quite high statistics at both LHC (Run2) and RHIC (Run14) - time to slice and dice jet measurements in both phase spaces
- JETSCAPE as a tool, in addition to varying jet substructure observables, we can vary models (additional dimensionality in data comparisons)
- India to win the world cup!

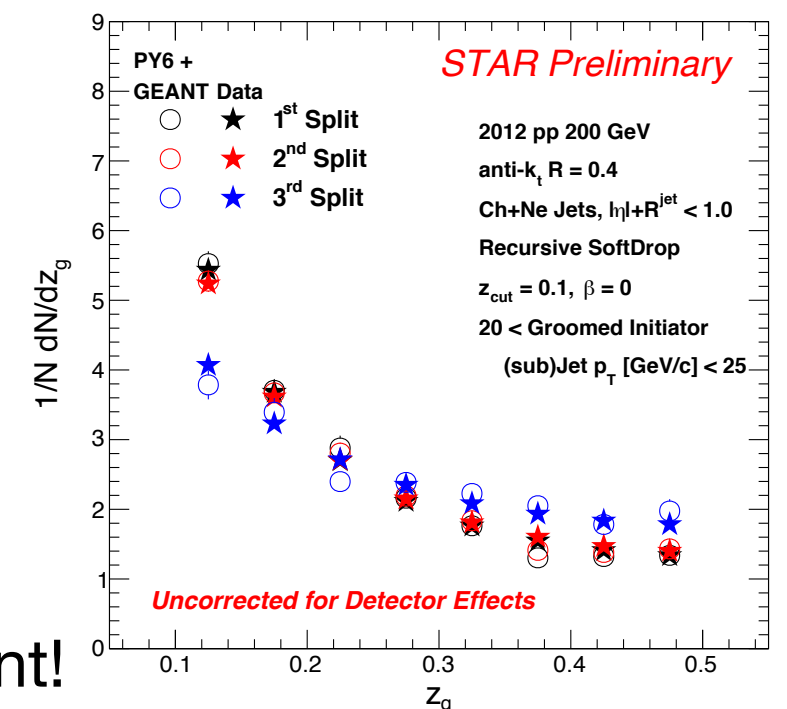


New Year Wish list - 2019

- Measuring jet quenching at varying angular scales are a direct probe of medium properties -
Topographical study of the QGP

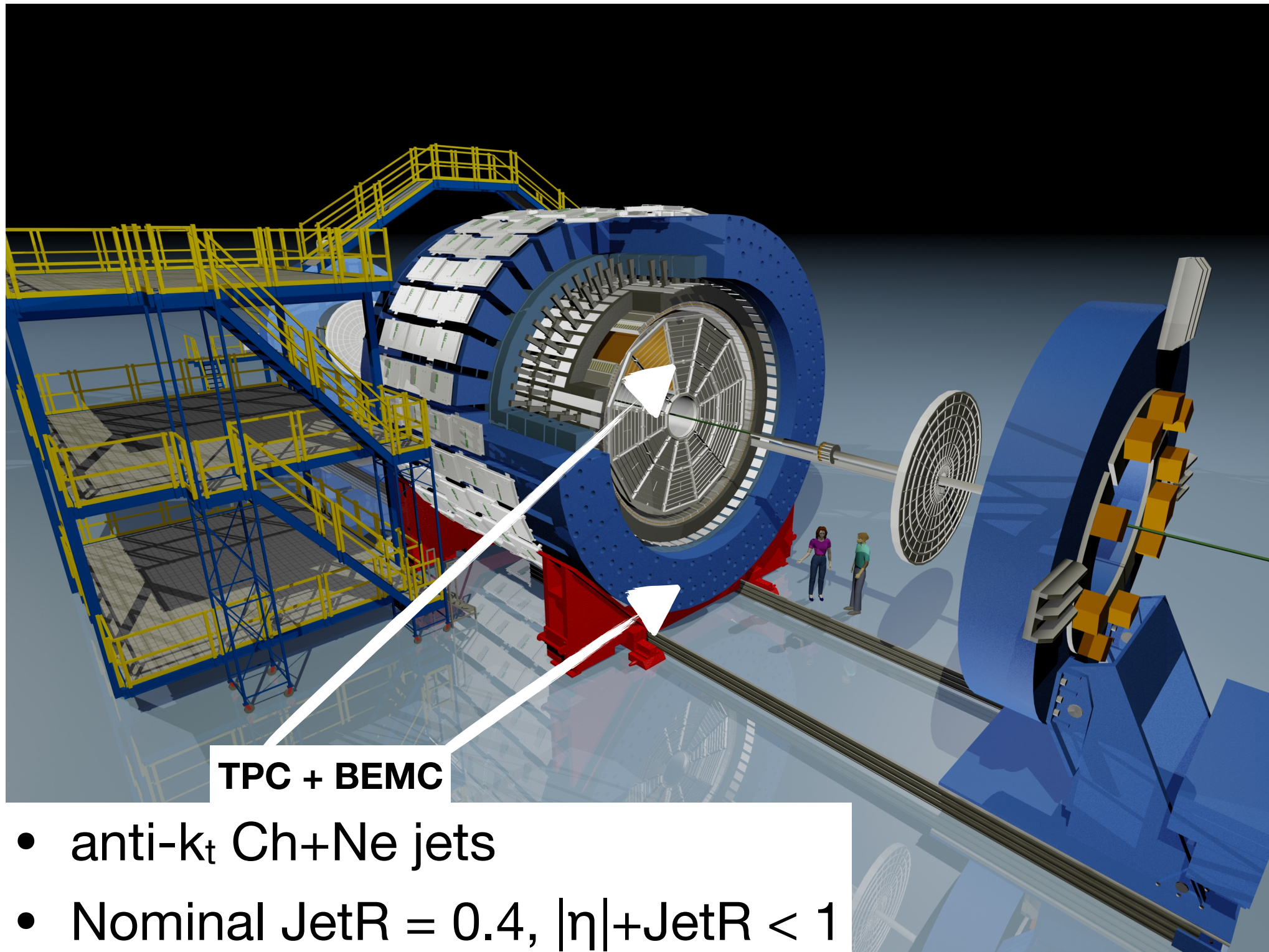


- Can we access the jet evolution tree via algorithms?
 - At particle level? - compare to MC via multi-D matched split unfolding
 - At parton level??? - medium at each split is different!



Bonus Slides

Jet reconstruction at STAR



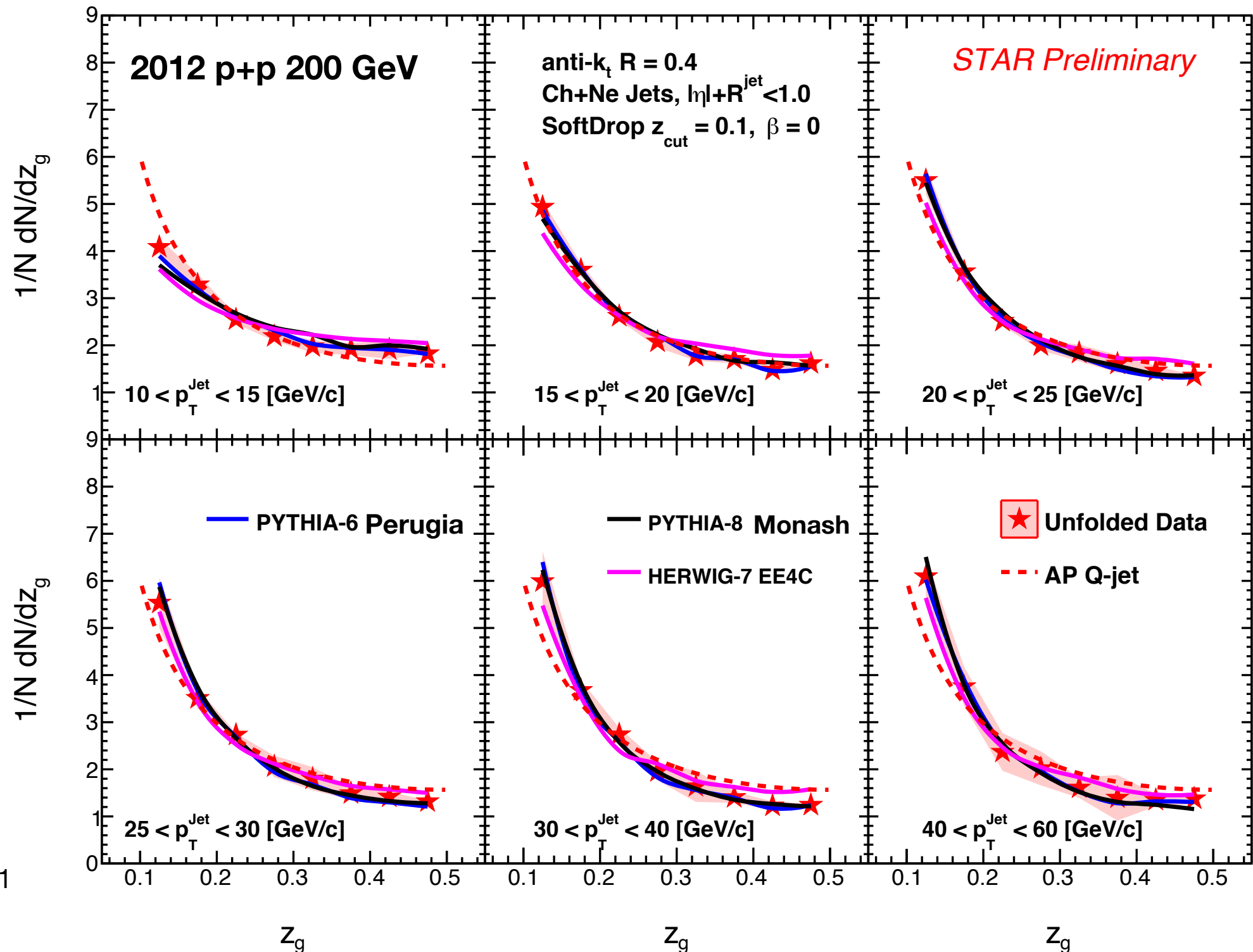
SubJet momentum fractions (z_g)

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

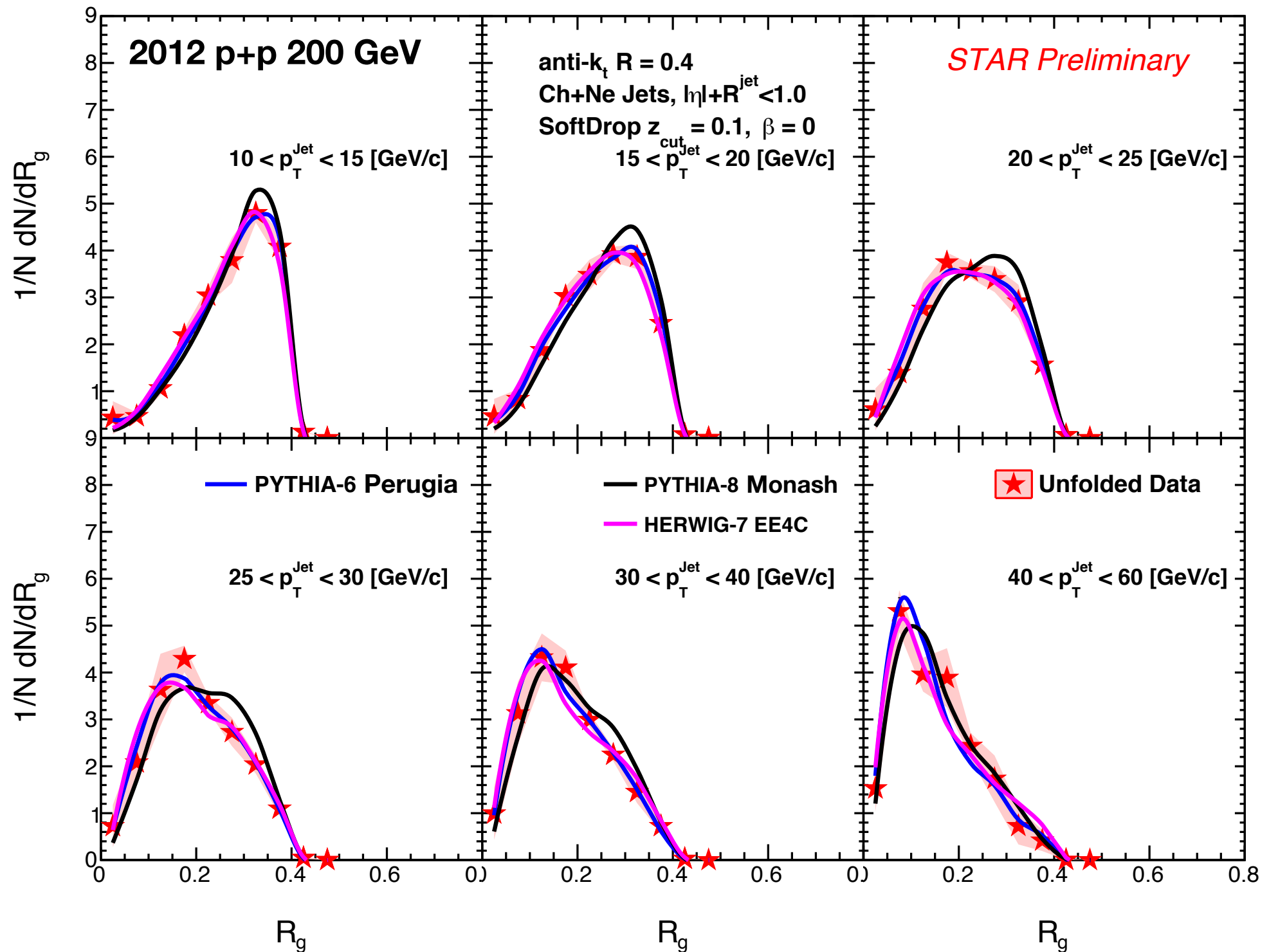
Larkoski et al.,
Phys. Rev. D 91 (2015) 111501



Groomed jet radius (R_g)

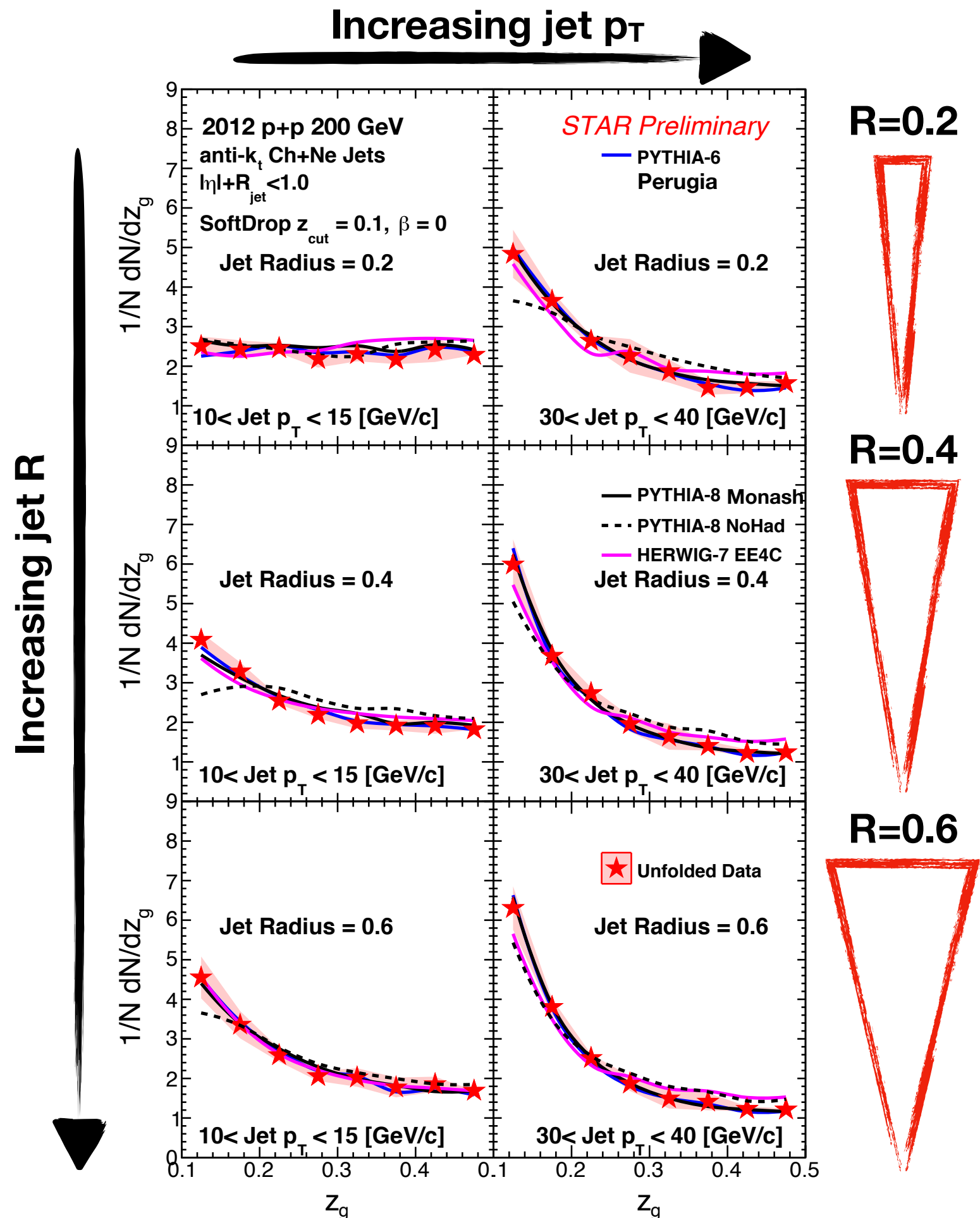
p+p collisions @ 200 GeV

- 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)



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



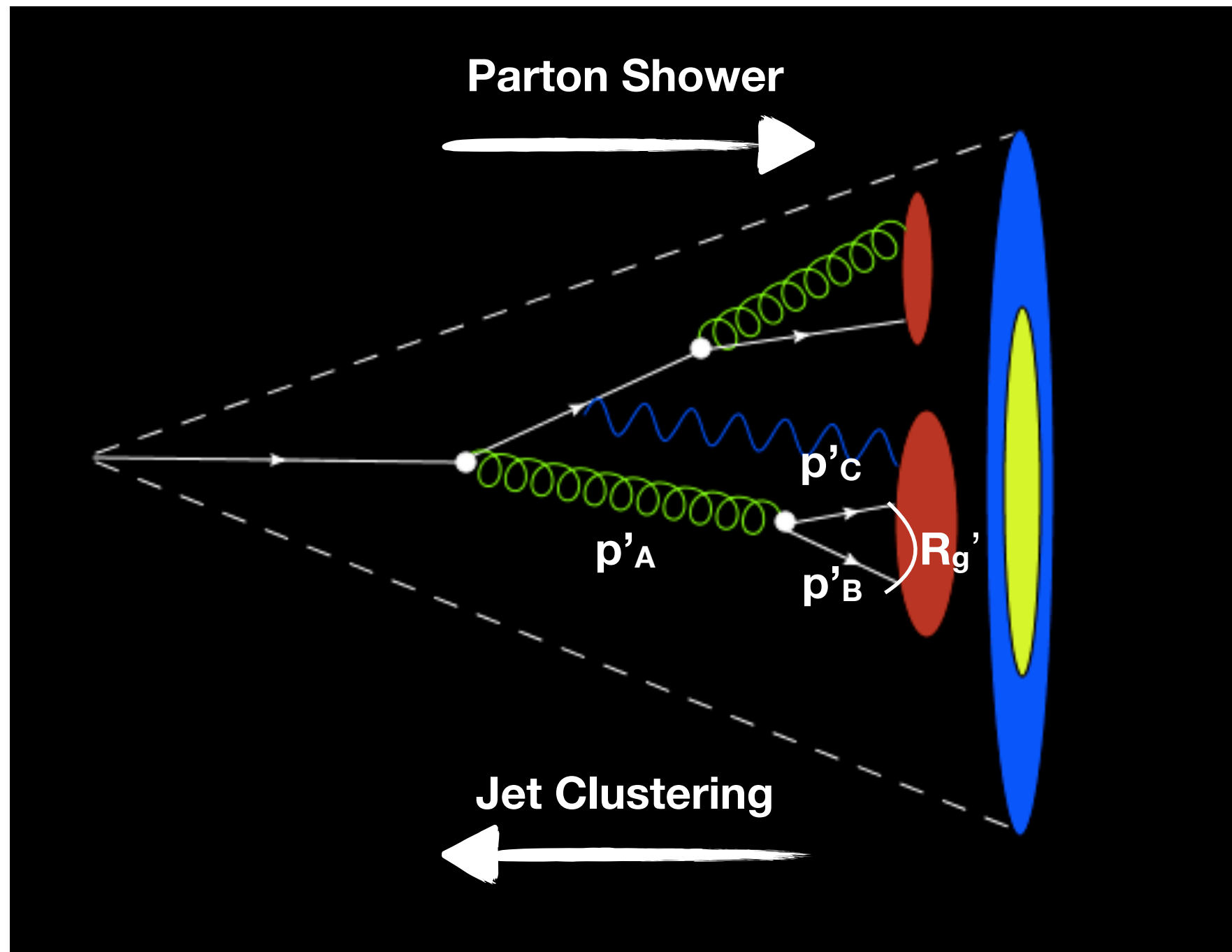
Recursive SoftDrop

Dreyer et al.
JHEP 06 (2018) 093

- Follow the leading split

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

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

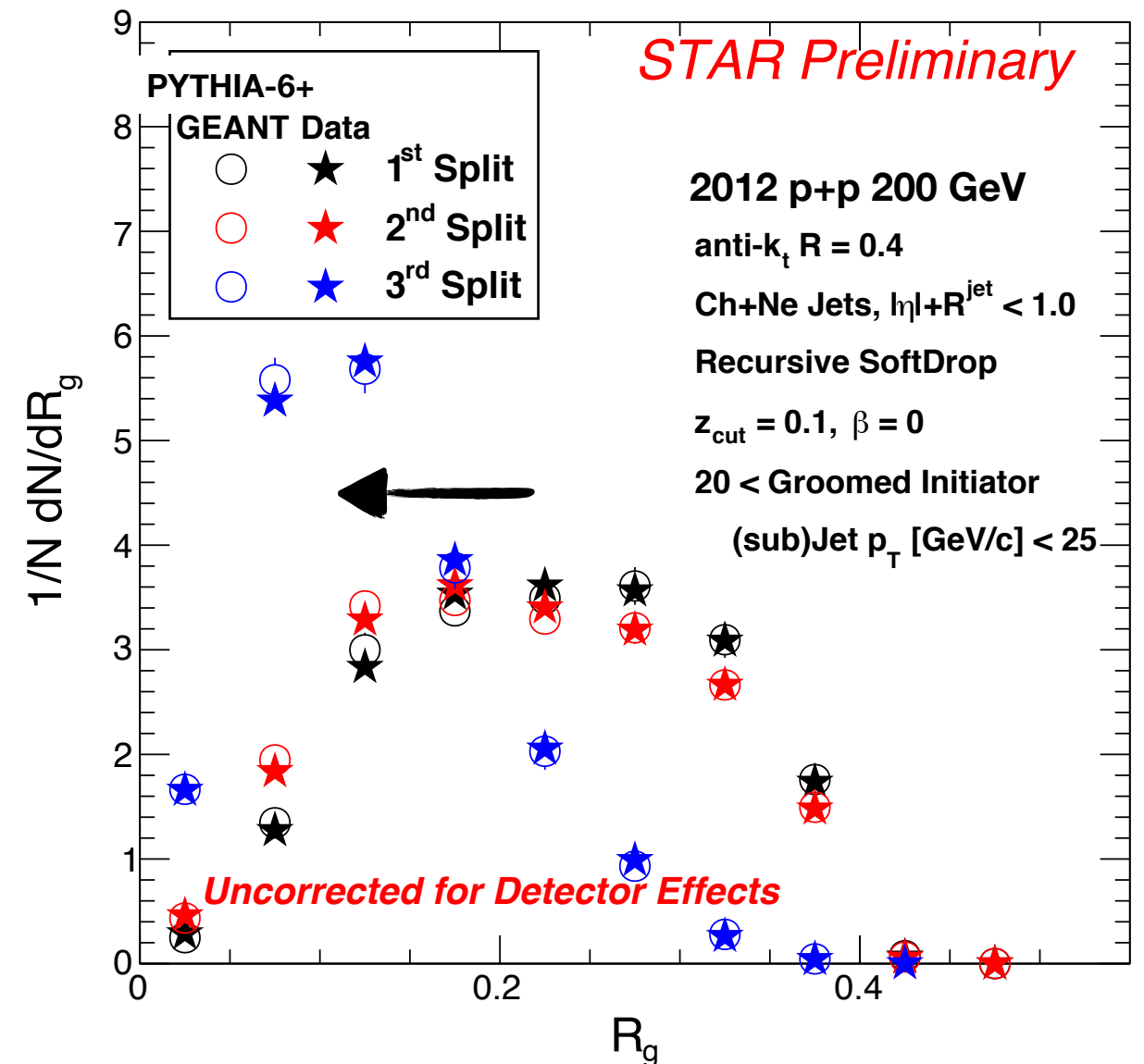
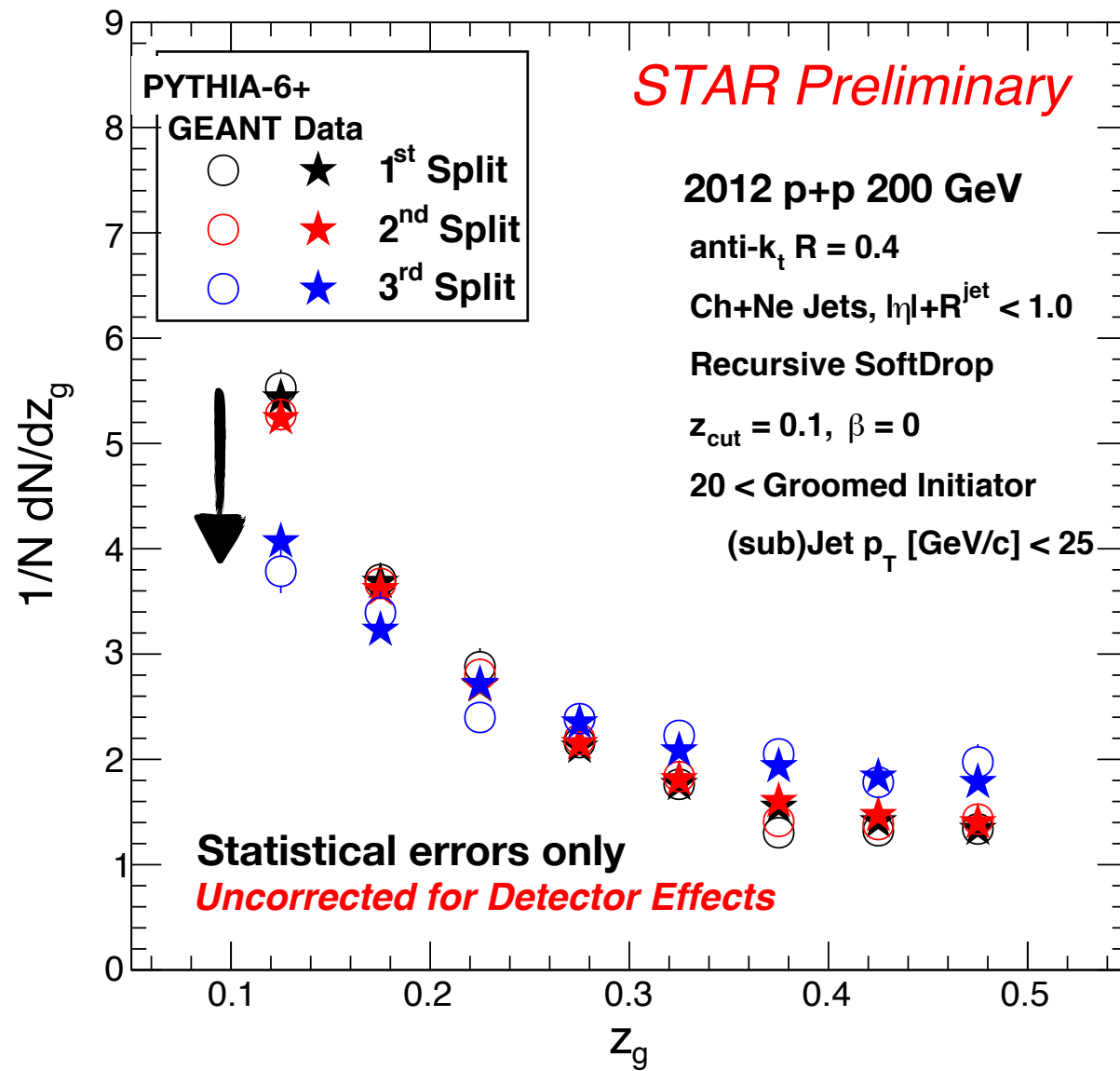


In vacuum : opportunity to experimentally reconstruct the parton shower history

—> 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

