Jet sub-structure and parton shower evolution in p+p and Au+Au collisions at STAR

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On behalf of the STAR collaboration

13th International Workshop on High-pT physics in the **RHIC**/LHC era
Knoxville, TN
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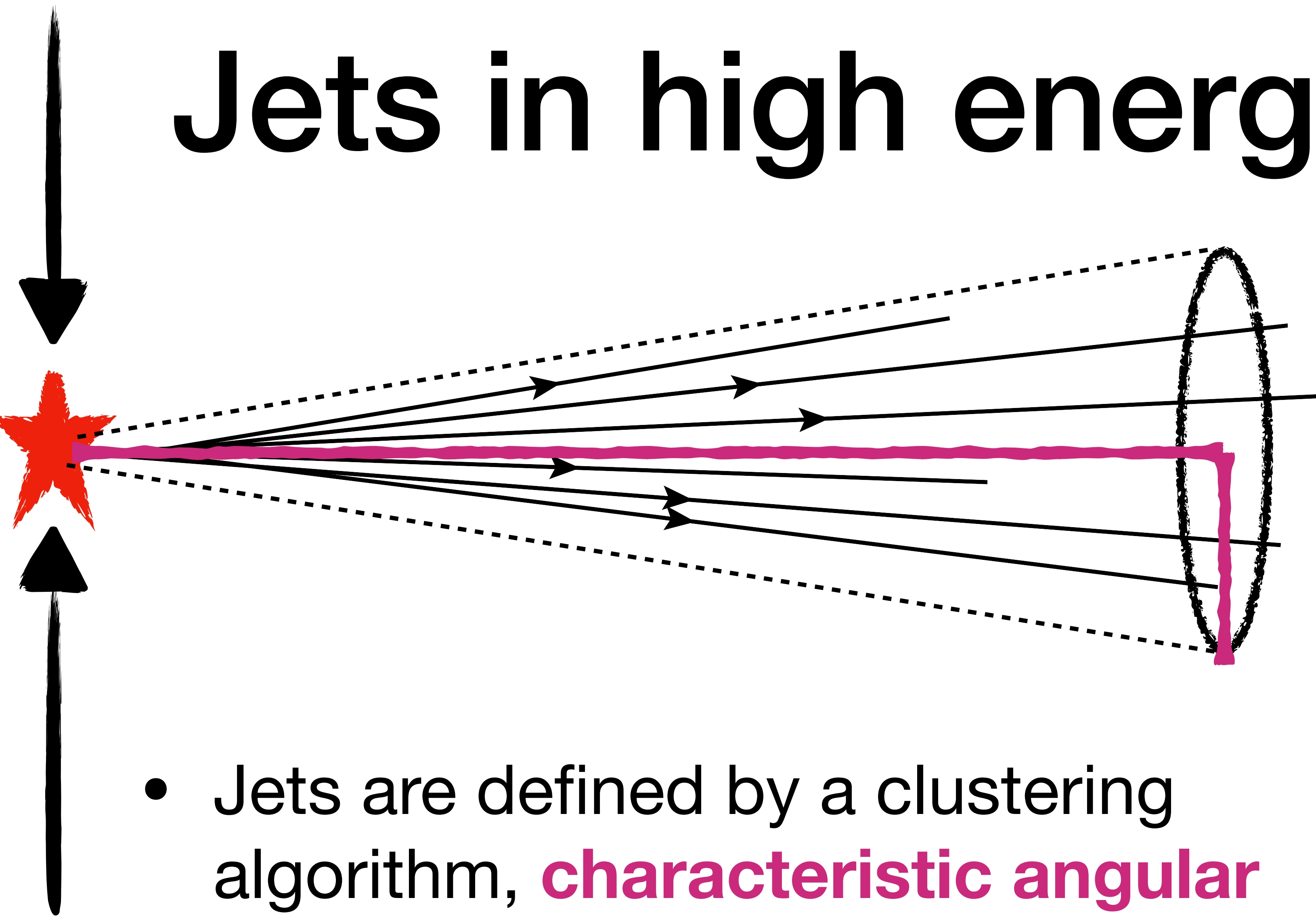
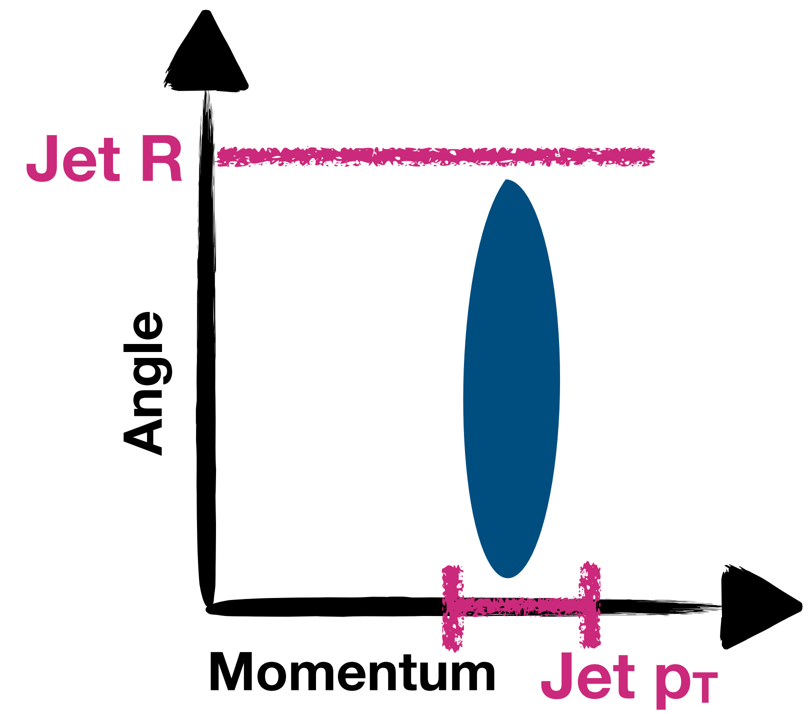
Talk outline

- Parton showers and jets - a lightning introduction
- Measurement of SoftDrop z_g, R_g and jet mass in p+p collisions at 200 GeV
- Studying jet energy loss differentially in two relevant scales (angle and momentum) in heavy ion collisions
- Introducing TwoSubJet z_{SJ}, θ_{SJ}
- Standard jet quenching measurements for ‘wide’ vs ‘narrow’ jets at STAR in Au+Au collisions at 200 GeV

Jets in high energy collisions



- Jets are defined by a clustering algorithm, **characteristic angular scale** (Jet R) and their **momentum** (p_T)
- Jets can also have an **inherent angular scale** and a **momentum fraction** due to angular ordering in the vacuum splitting



Jets in high energy collisions

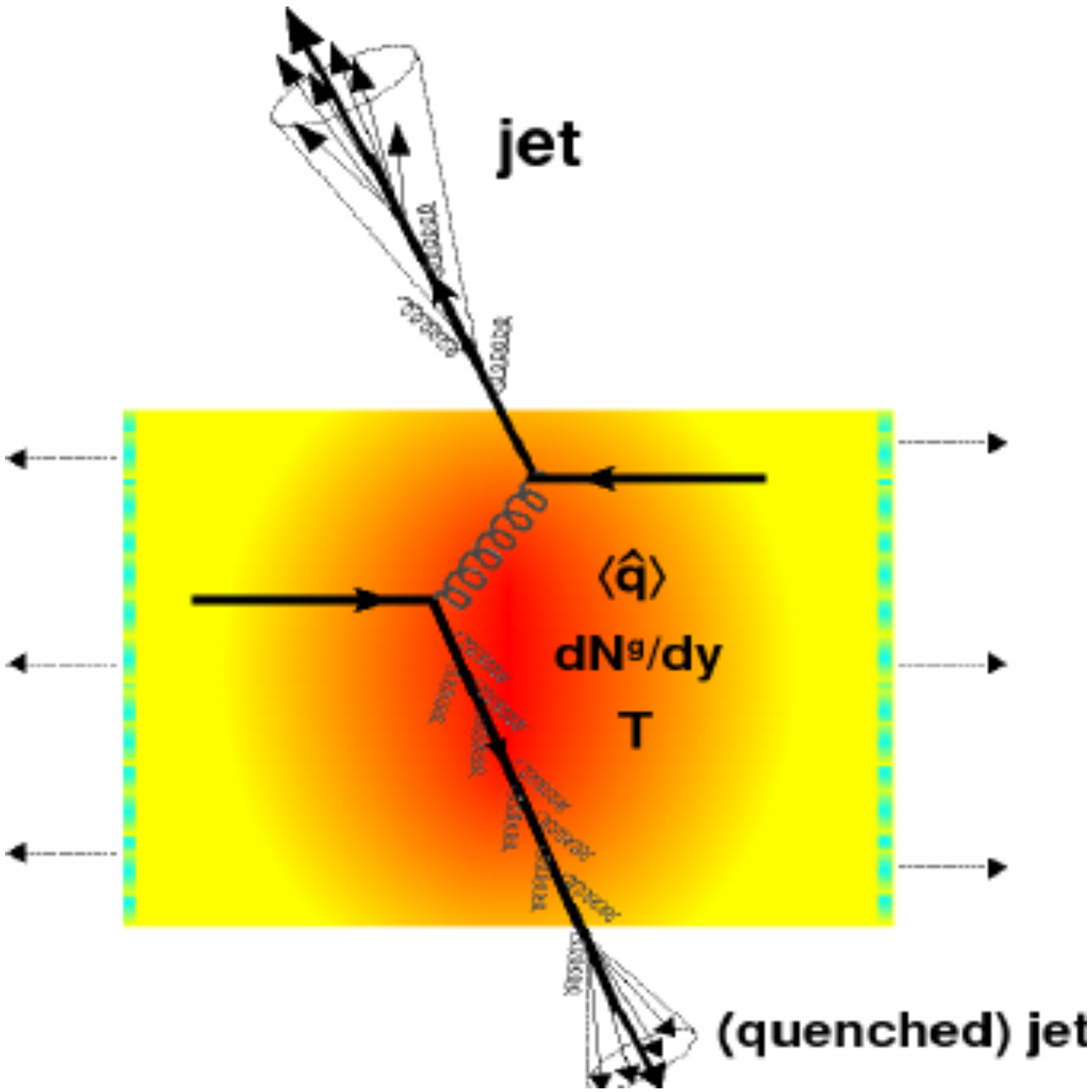
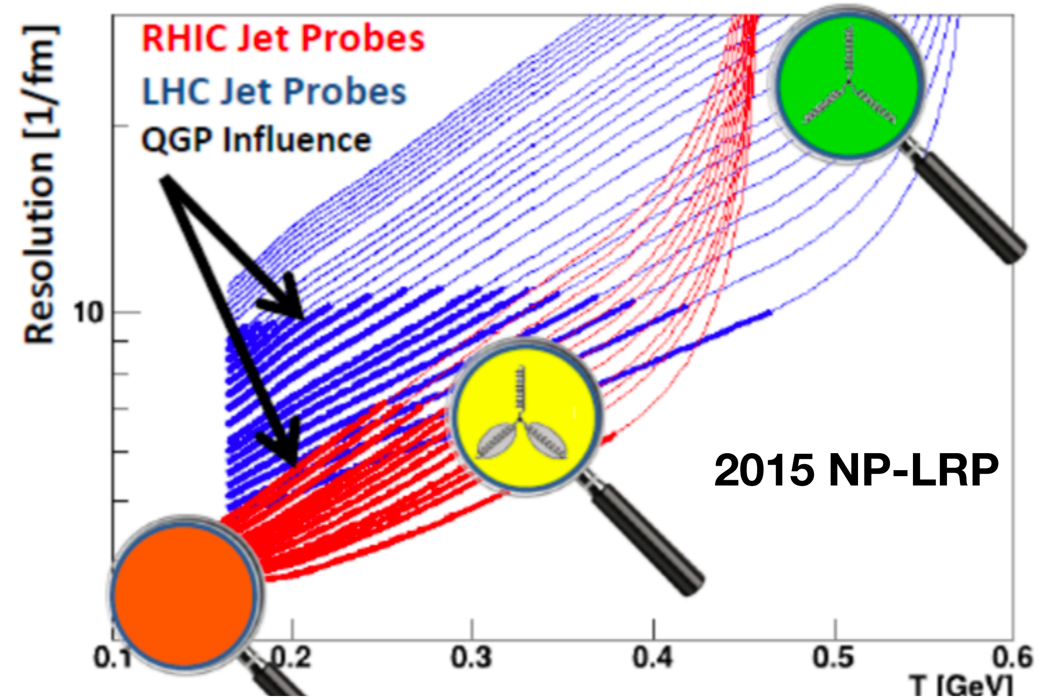


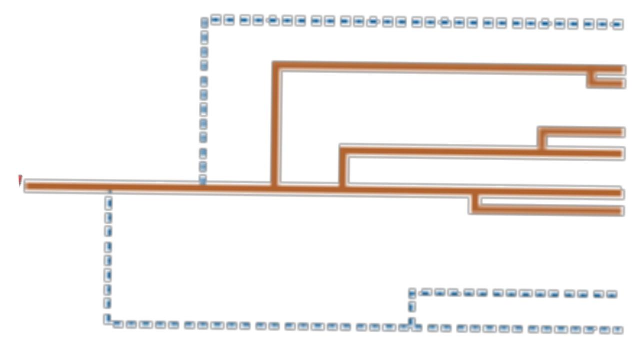
Image credit - Barbara Betz
https://link.springer.com/book/10.1007%2F978-3-642-02286-9



- Parton shower in vacuum is a multi-scale process
  - momentum and angular(virtuality) scale
- In heavy ion collisions - we can relate the angular scale to a resolution scale at which the jet probes the medium
- **Study differential jet energy loss in the inherent scales - momentum and angle**

Measured observables

- Correlate physical quantities in jet evolution to experimental observables

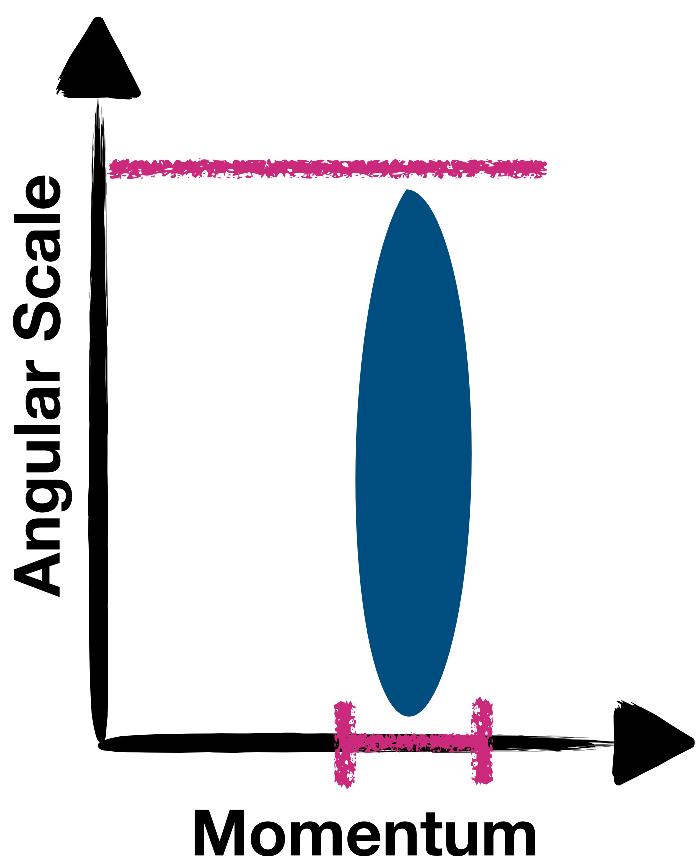


$z_g = \min(p_{T1}, p_{T2})/(p_{T1} + p_{T2})$

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

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

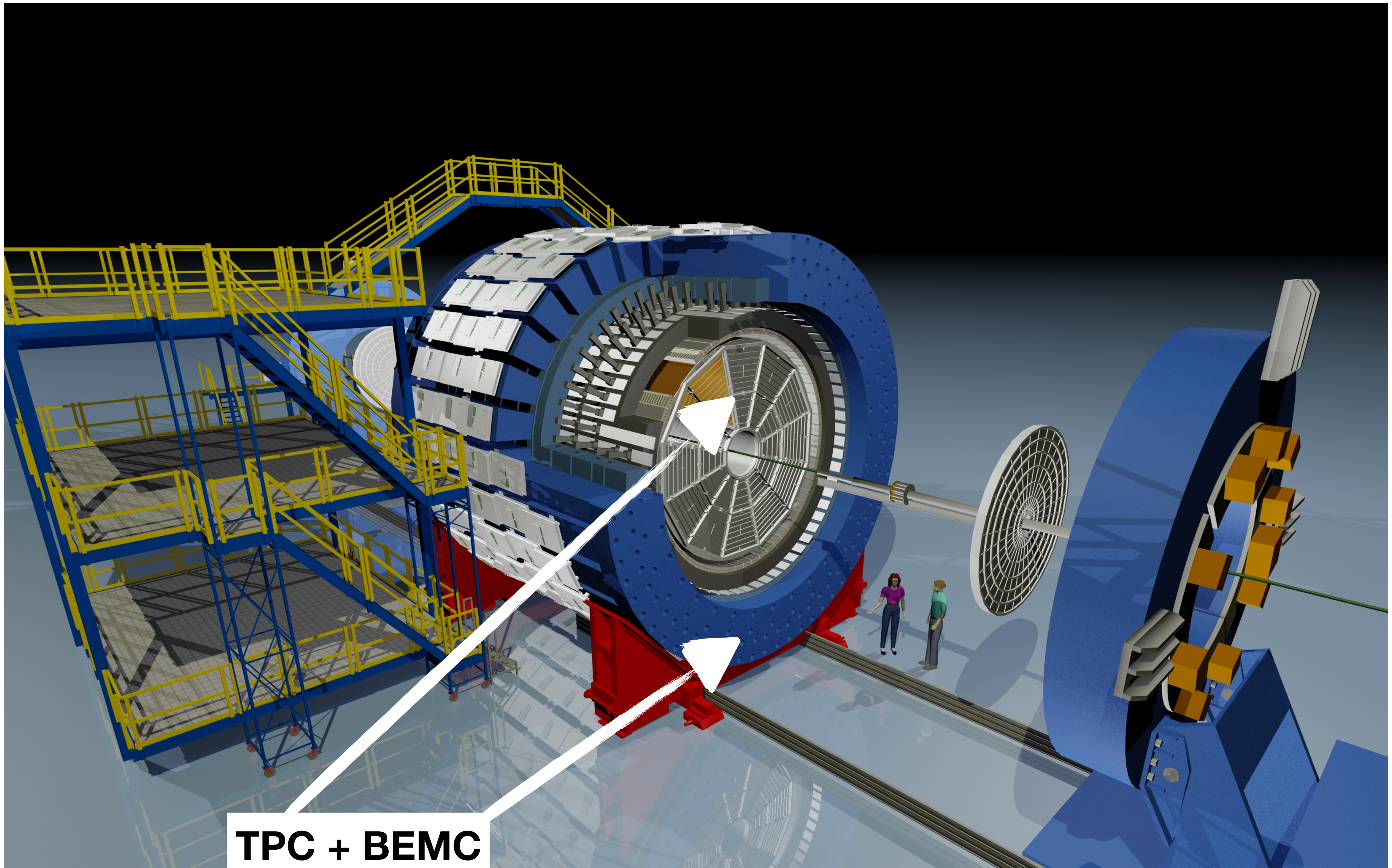
Larkowski et al.
Phys. Rev. D 91, 111501 (2015)



- Utilize SoftDrop algorithm
  - momentum scale - z_g
  - angular scale - R_g
- Invariant jet mass ($M \sim z\theta^2$) NEW

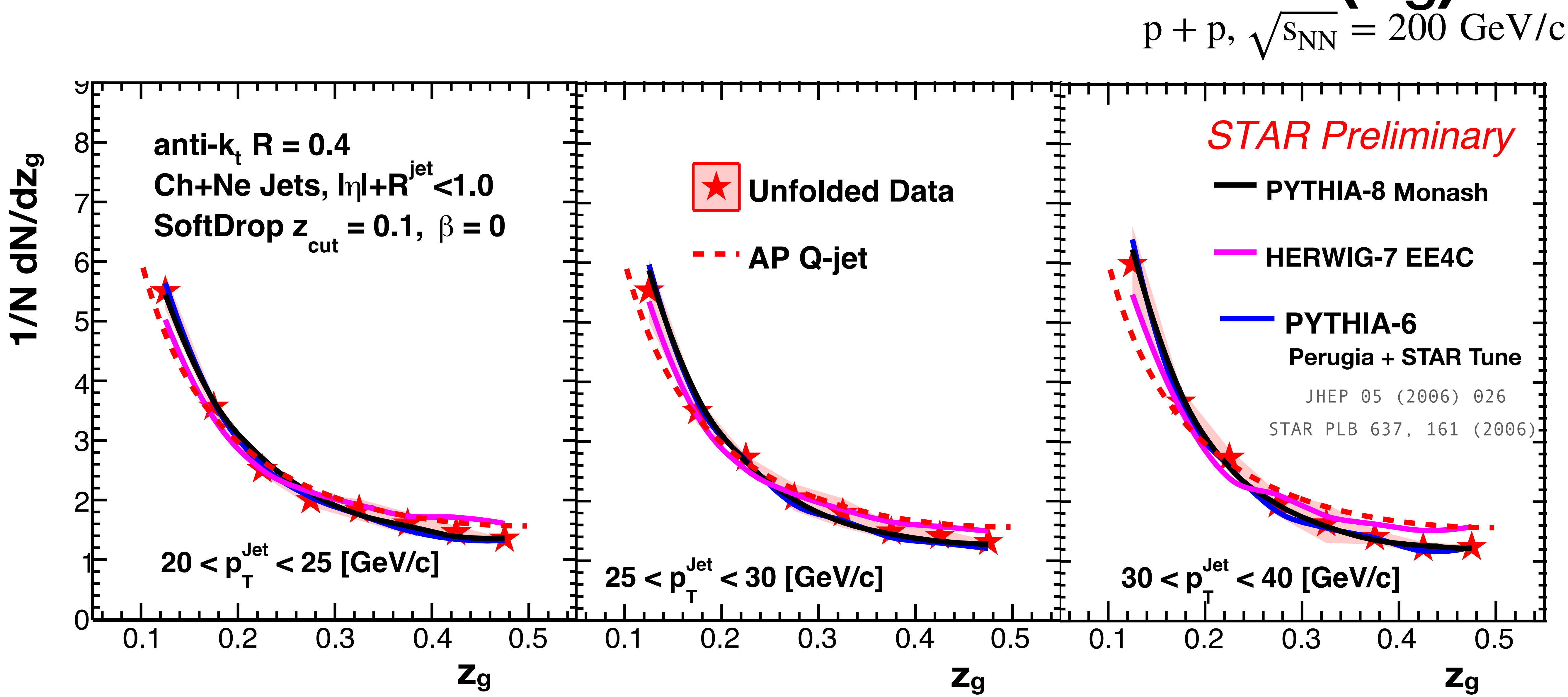
Establish a vacuum baseline -
Understand observables in p+p collisions

Jet reconstruction at STAR



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

SubJet momentum fractions (z_g)

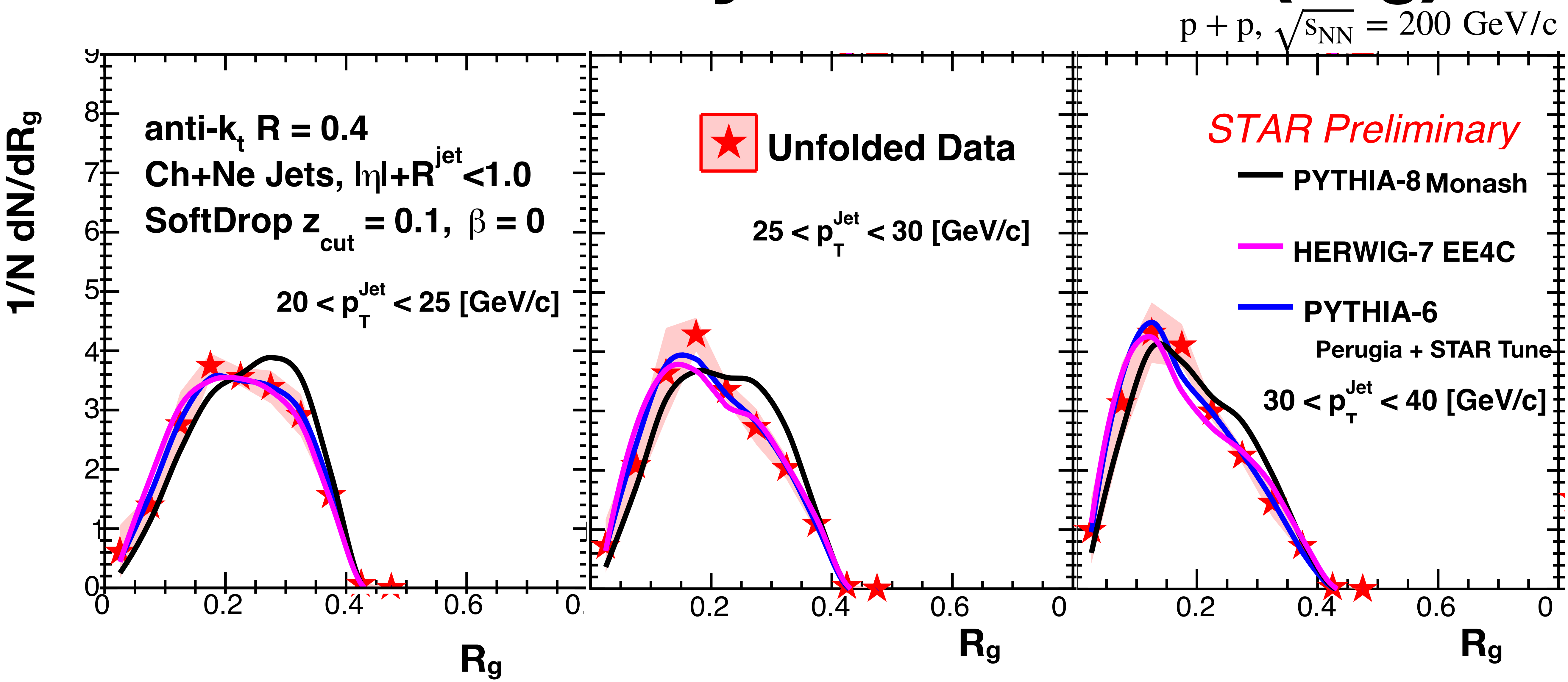


- Recover the p_T independent ***1/z behavior*** starting from p_T ~ 20 GeV/*c*
- z_g in vacuum **described by leading order MC generators**
- HERWIG slightly favors more symmetric splits

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

See backup for more p_T bins

Groomed jet radius (R_g)

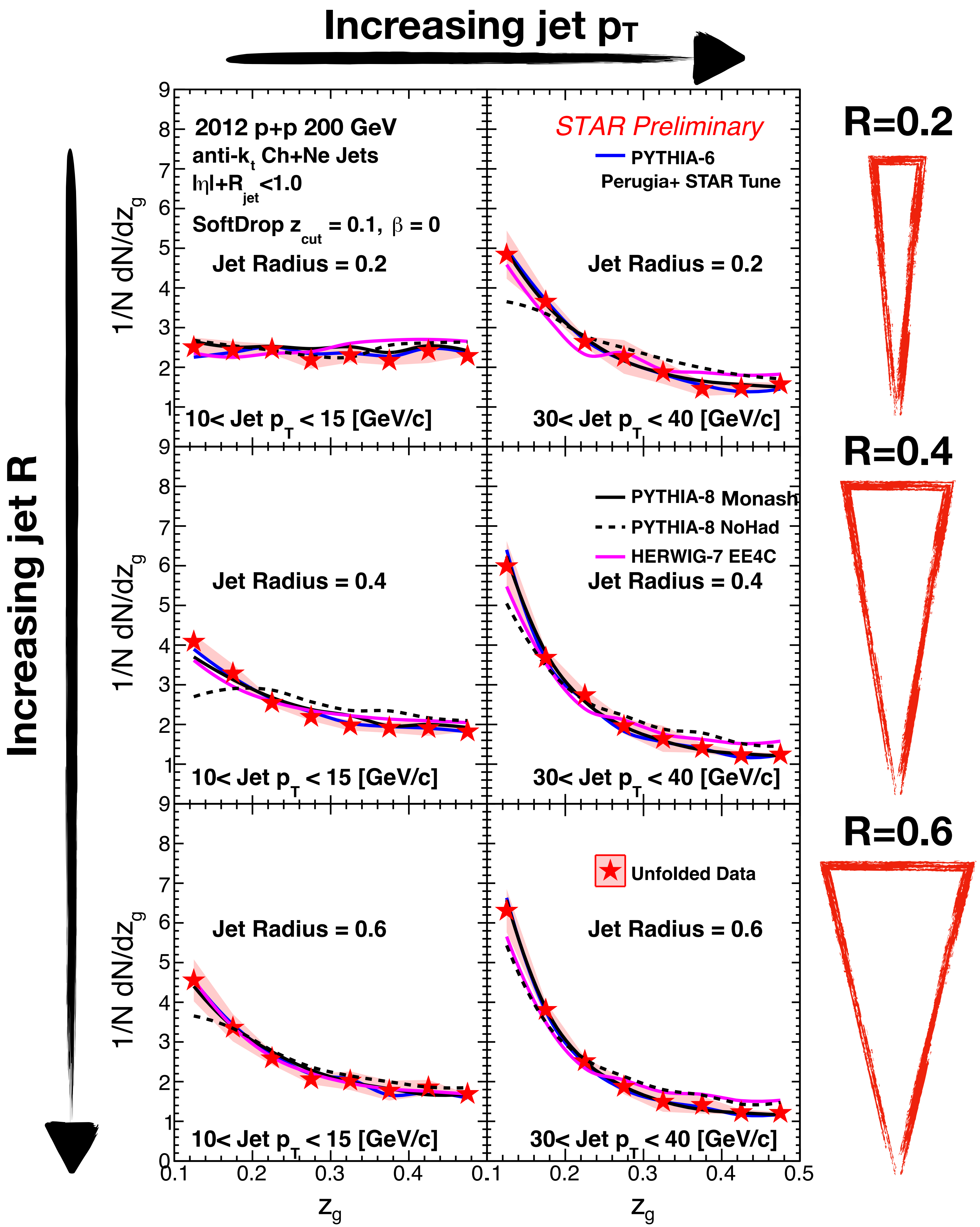


- R_g reflects **momentum dependent narrowing** of jet structure
- PYTHIA-8 predicts jets with larger R_g
- Opportunity to further tune MC at RHIC kinematics

See backup for more p_T bins

Dependence on the jet R

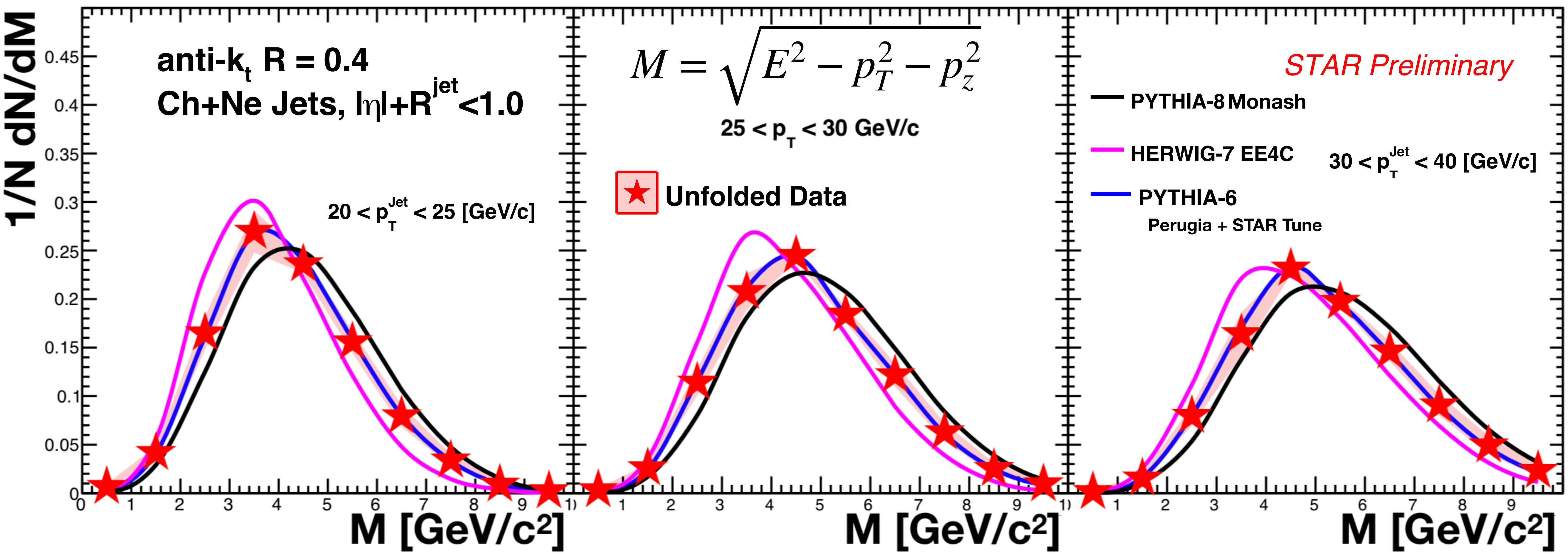
- **Uniform** z_g distribution **at low p_T for small R jets - symmetric splits enhanced**
- Deviation from universal *1/z behavior* for **small R and low p_T**
- Moderate effect due to hadronization in PYTHIA-8



Invariant jet mass

NEW

First fully corrected jet mass measurement at RHIC $\mathrm{p+p}, \sqrt{s_{NN}} = 200\ \mathrm{GeV/c}$



- Jet mass increases with increasing jet p_T
- PYTHIA-8 generally over-predicts jet mass and HERWIG-7 under-predicts jet mass

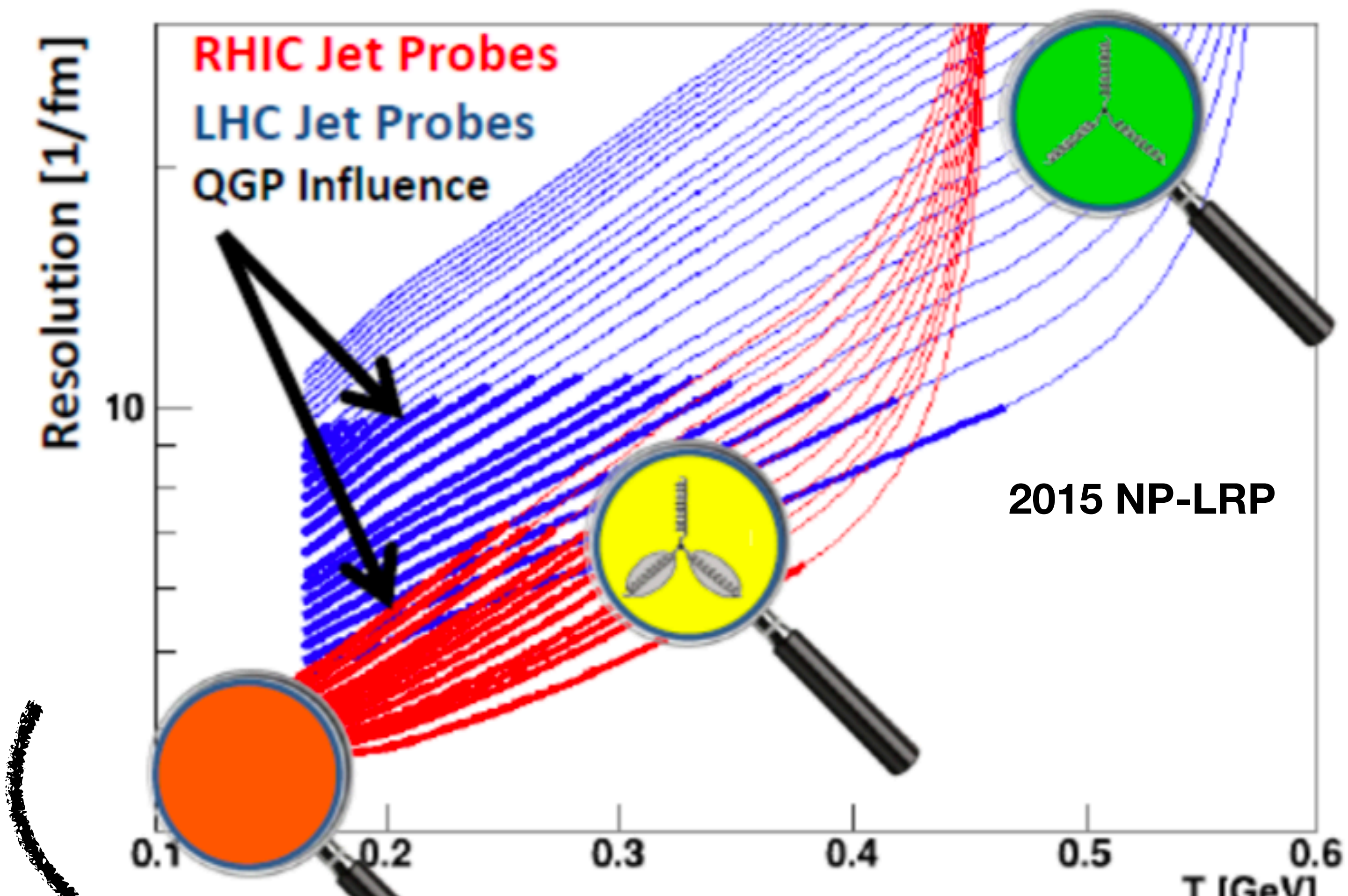
Conclusions - I

- Overall shapes of $\mathbf{z_g}$, $\mathbf{R_g}$ in p+p collisions at RHIC are reproduced by LO-MC event generators
- Jet Mass sensitive to description of shower and MC parameters

- Observations at RHIC -
  - **PYTHIA-6** Tuned to STAR data - excellent prediction of jet sub-structure
  - **PYTHIA-8** creates jets with wider angle splits and larger mass (tuned at LHC)
  - **HERWIG-7** Smaller mass jets and more symmetric splits (also tuned at LHC)

- Complementary to LHC kinematics - w.r.t tuning and $\sqrt{s}$ scaling

What do we want to measure?



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

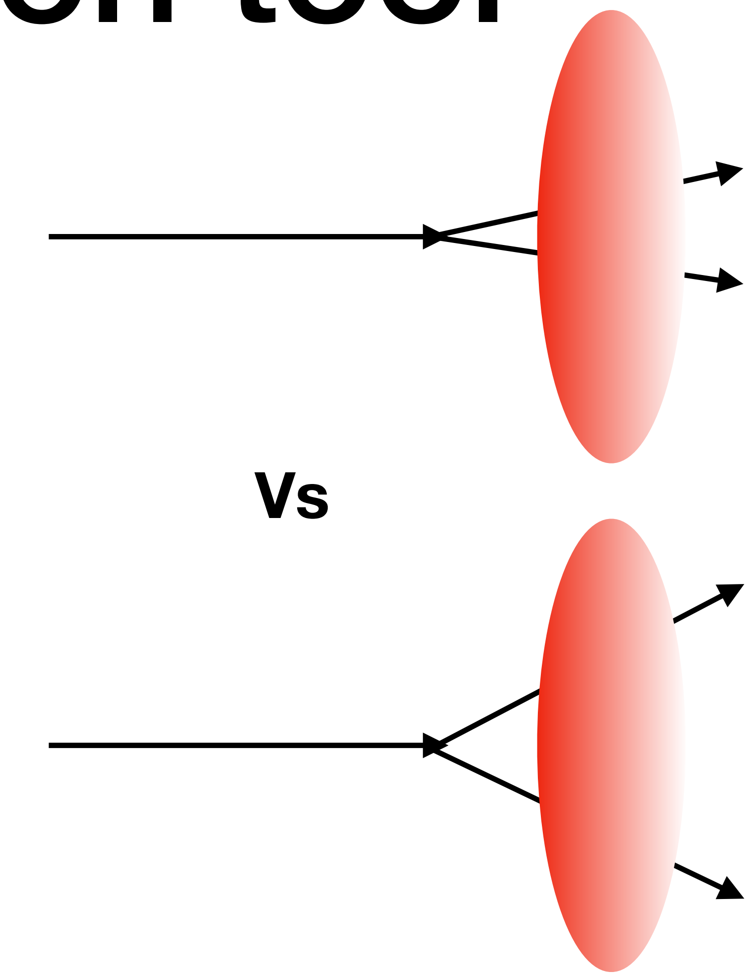
Mehtar Tani, Y and Tywoniuk, K
Phys. Rev. D 98 (2018) 051501(R)

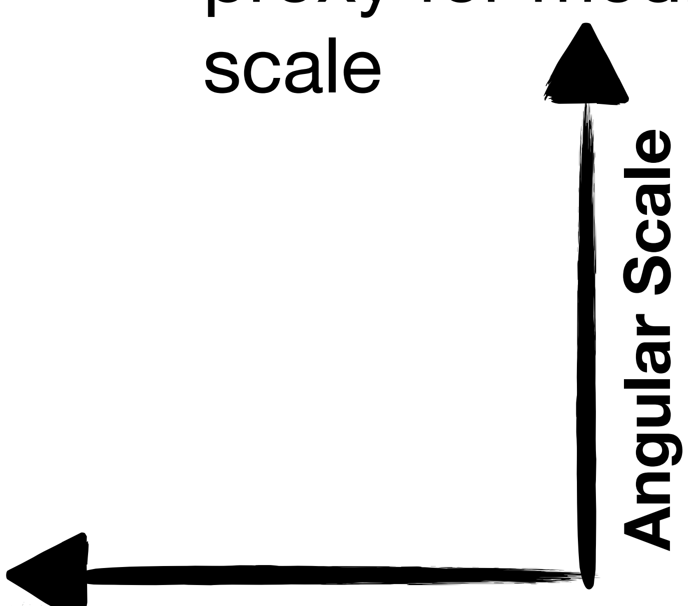
Majumder, A and Putschke, J
Phys. Rev. C 93 (2016) 054909

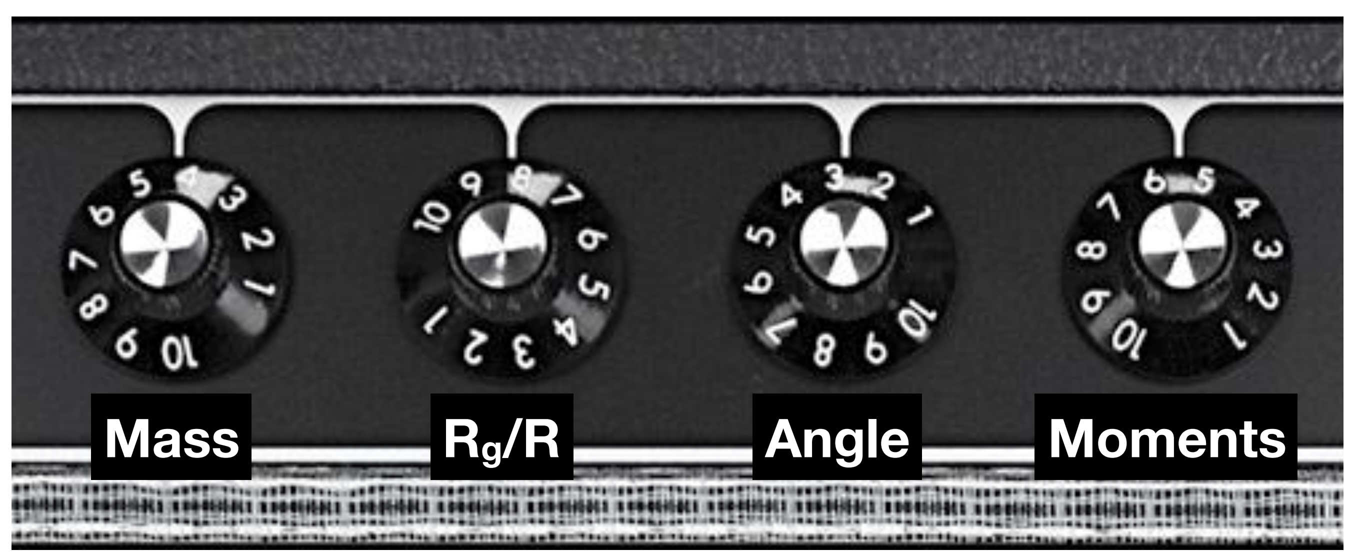
Partonic energy loss as a function of the resolution scale ⟶ jet's angular scale

Key idea - Use jet-substructure as a selection tool

- Identify an observable sensitive to 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







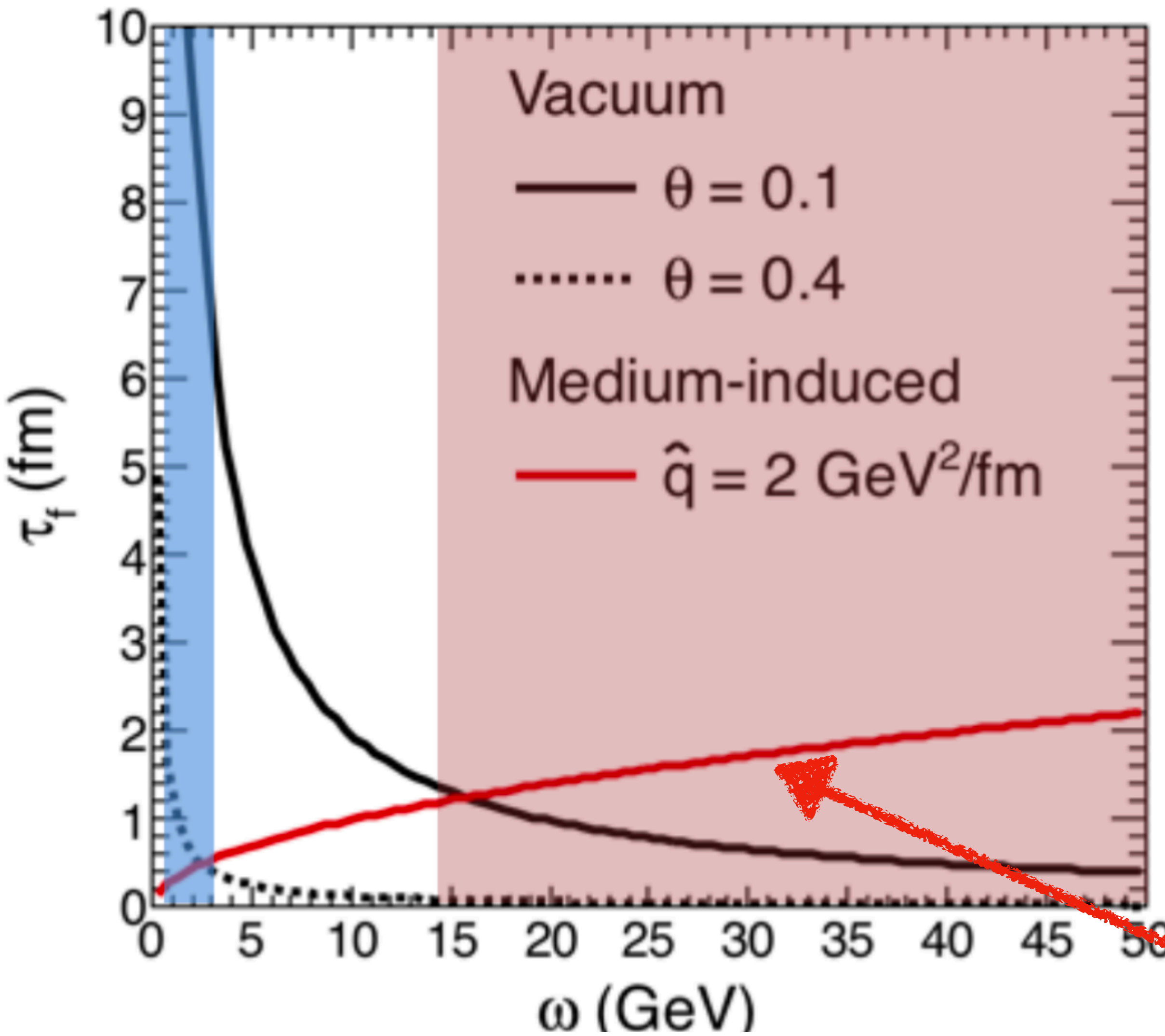
...

Why look at splits?

Marta Verweij, QM2017

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

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

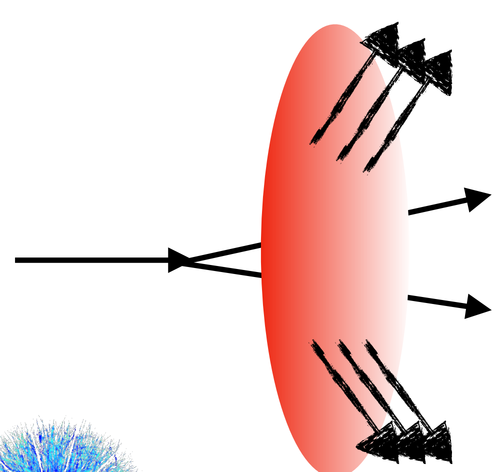


Phase space covered for z_g=0.1

STAR

CMS

Hard medium-induced radiation happens late



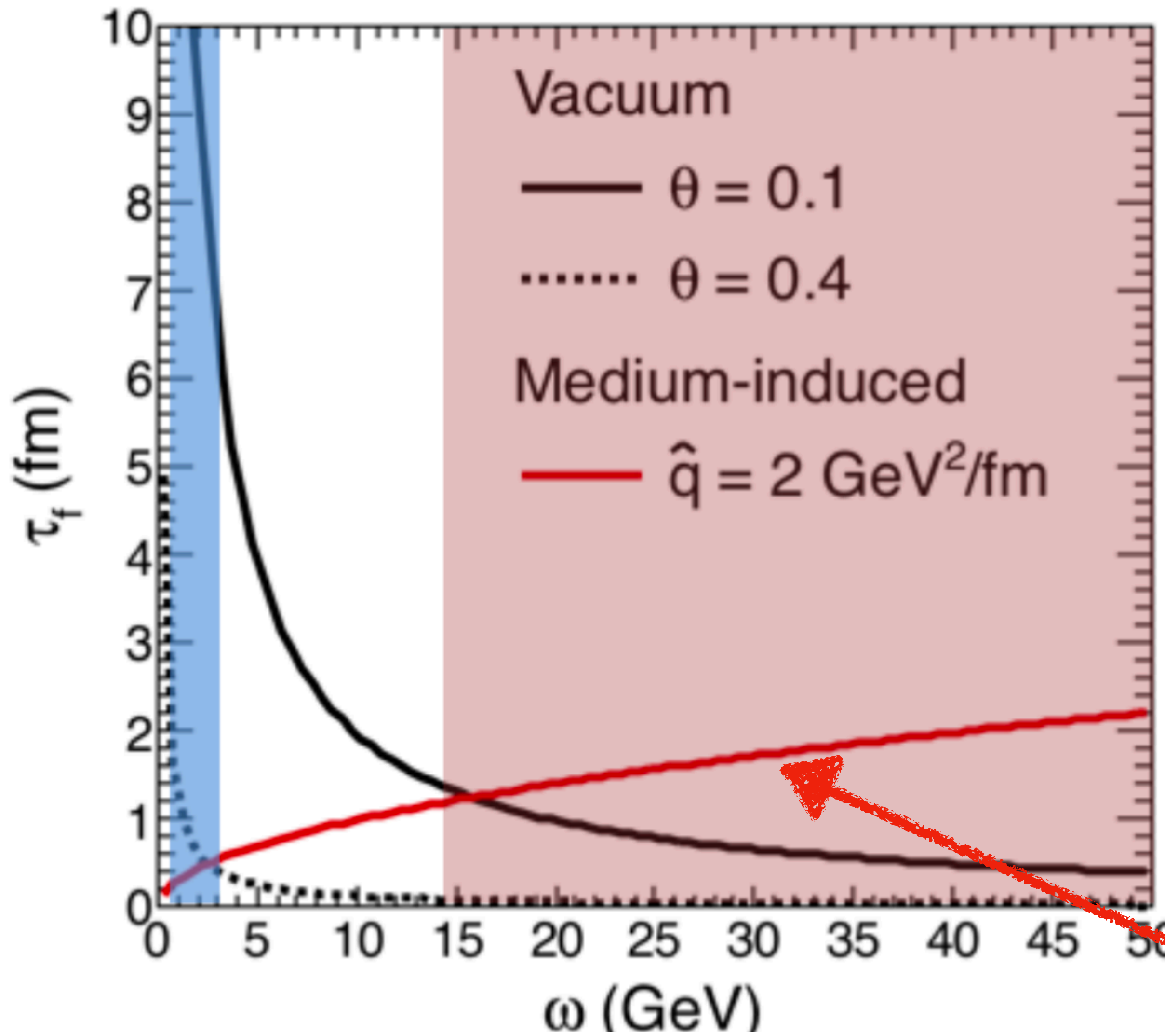
Early splits probe the coherence length and antenna splits

Why look at splits?

Marta Verweij, QM2017

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

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



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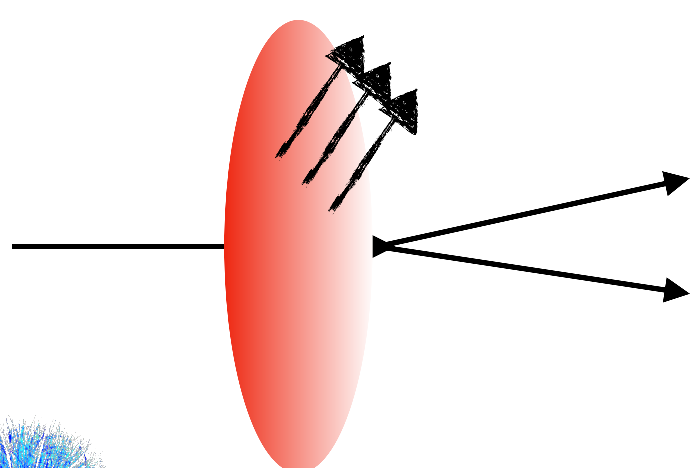


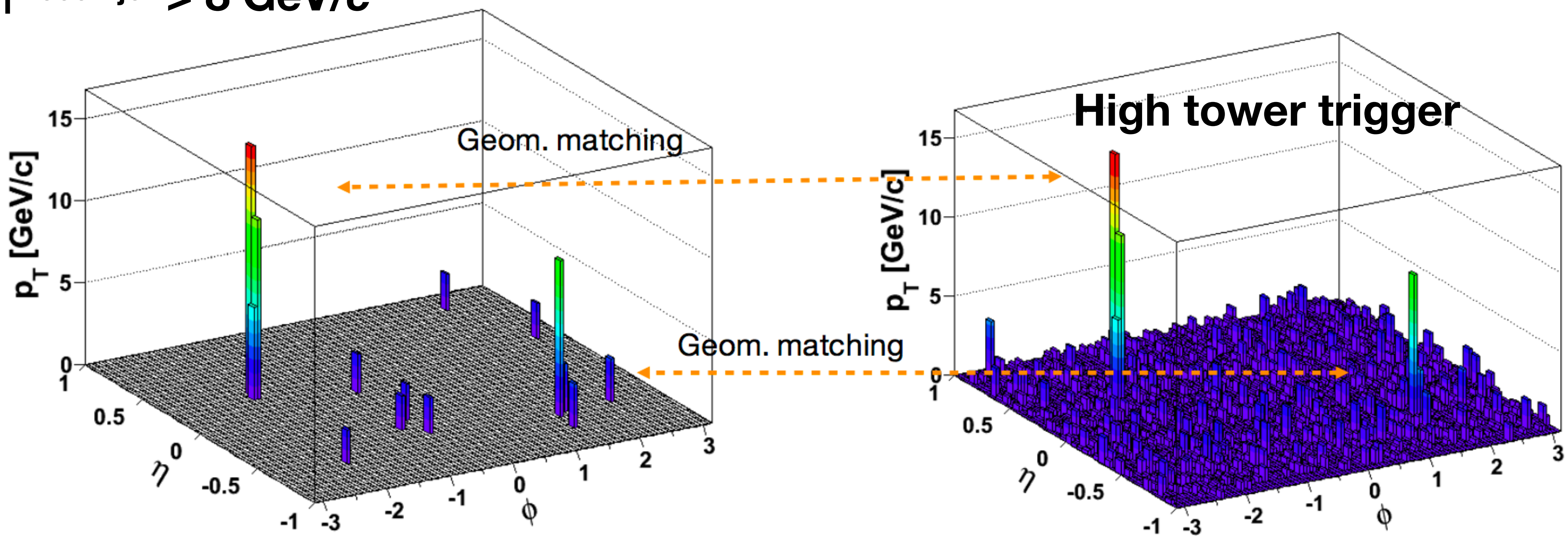
Later splits with jet modification probe gluon radiation off a single color charge

Selecting dijets at STAR

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

See Talk by Nick Elsey on Thursday 11:30am

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



HardCore selection → removes almost all background

geometric matching → no combinatoric jets, recover all constituents

STAR, PRL 119 062301 (2017)

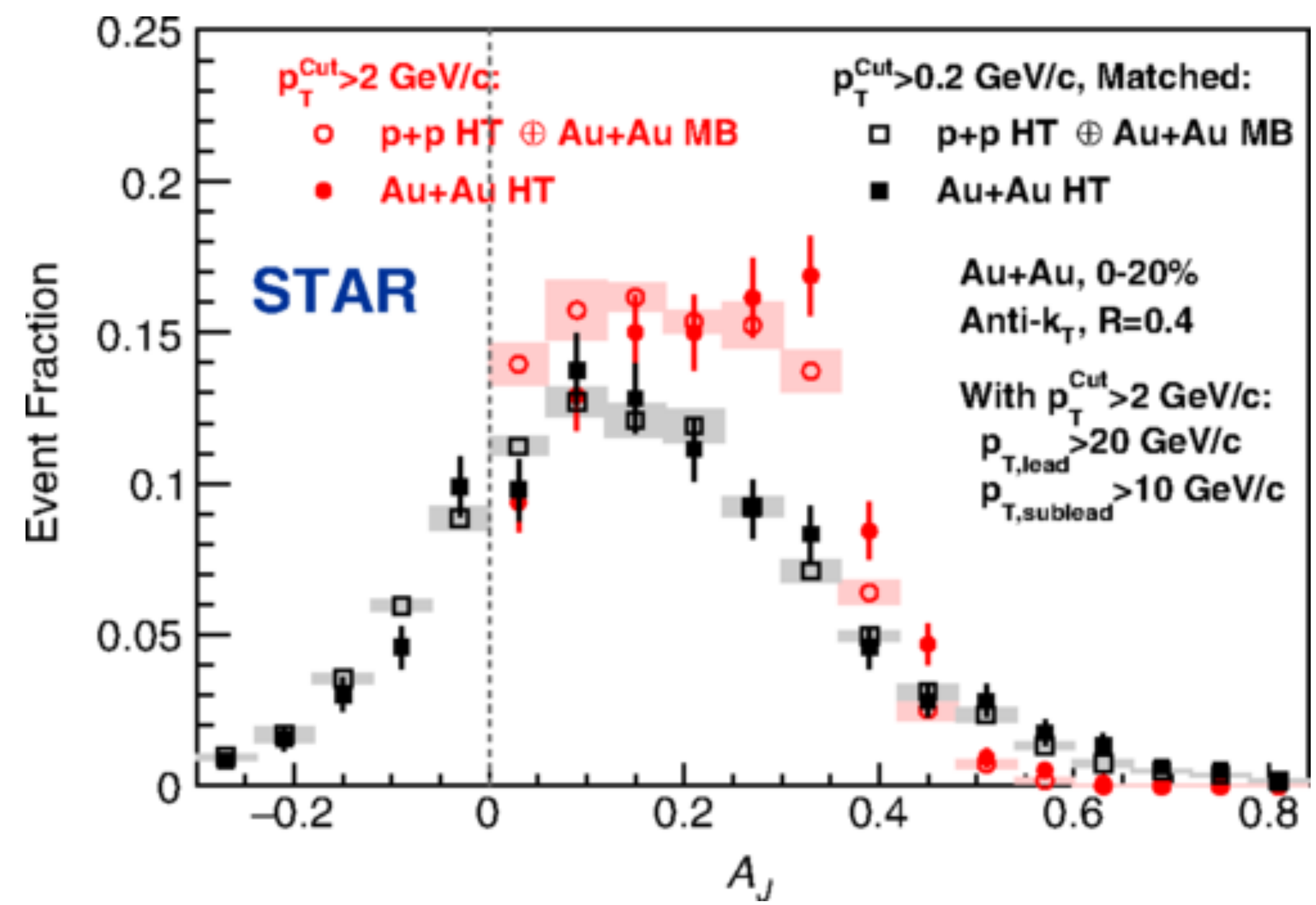
Dijet balancing at STAR

- HardCore Au+Au jets are imbalanced compared to p+p⊕Au+Au

- Matched jets are balanced!

- Quenched energy is recovered within R=0.4 radius

STAR, PRL 119 062301 (2017)



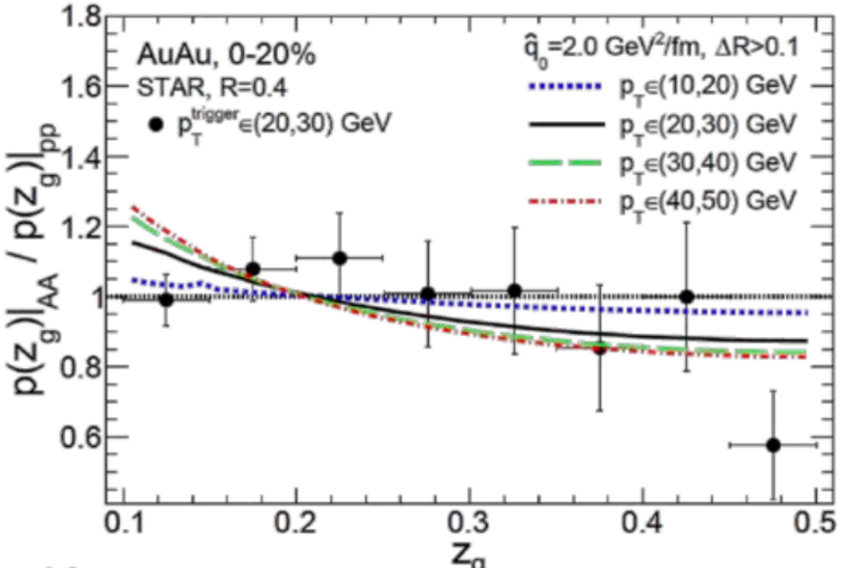
These are ideal to study differentially! We can tag collections of these jets in both momentum and angular scales

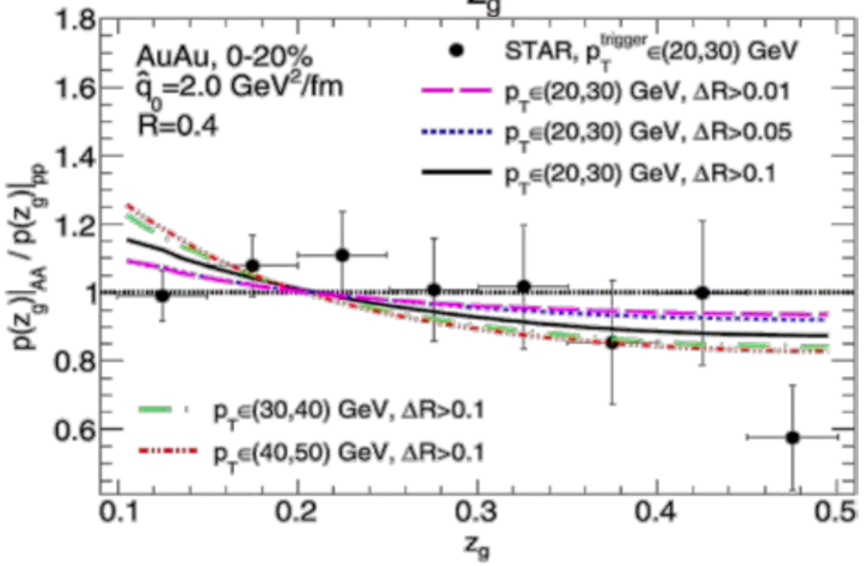
See Talk by Nick Elsey on Thursday 11:30am

z_g in Au+Au 200 GeV

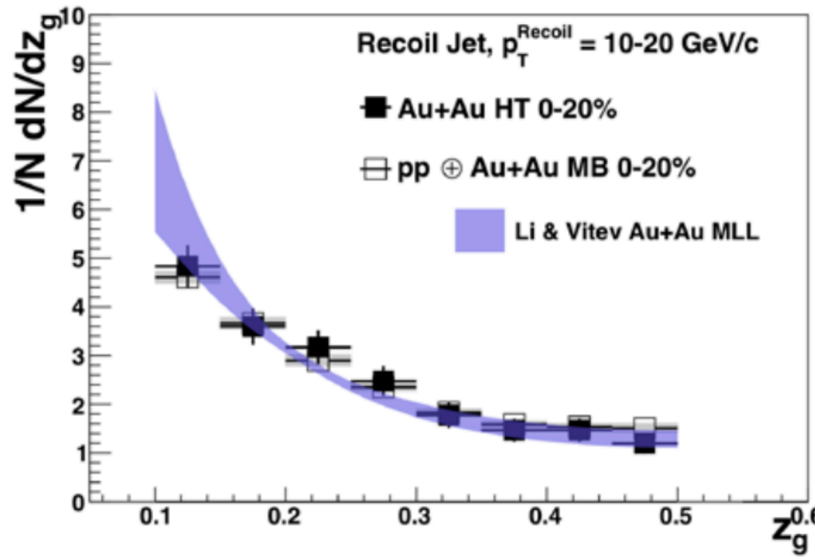
Slide shown by Kolja Kauder, RHIC AGS Users Meeting 2018

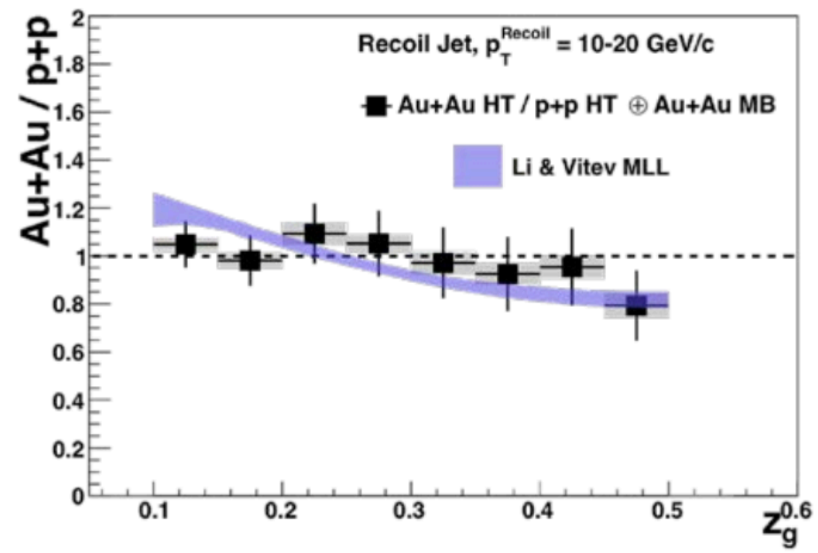
KK, HP16, QM17





Ning-Bo Chang et.al. QM18





Li & Vitev, arXiv:1801.0008

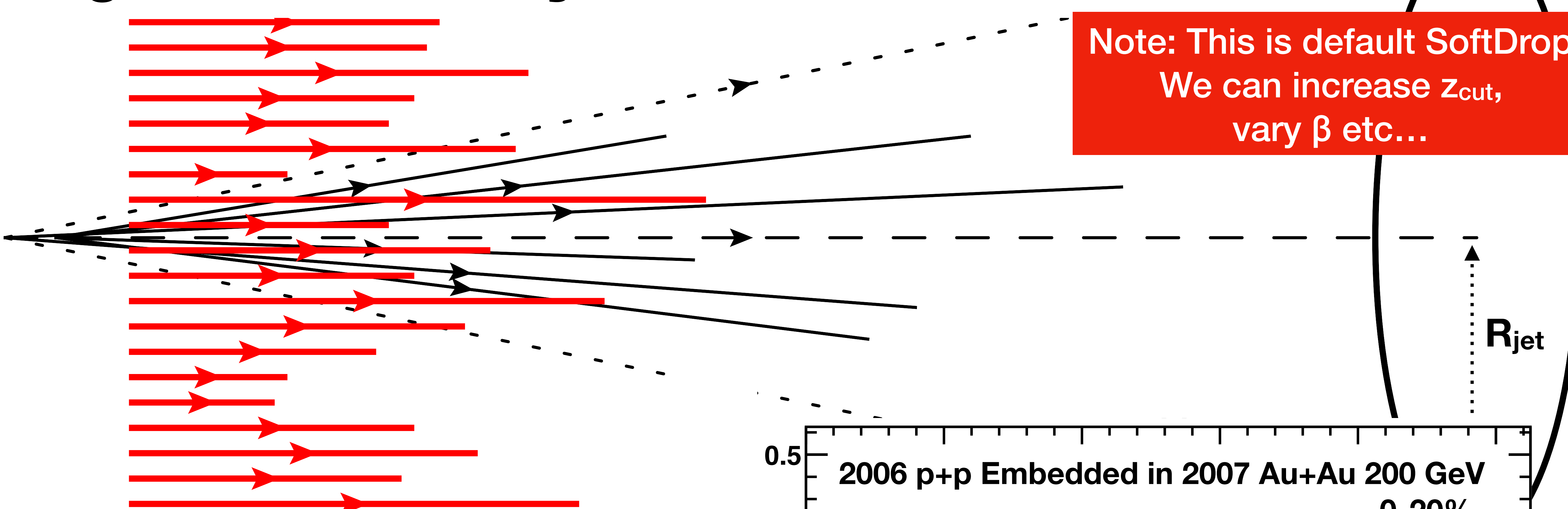
- No significant modification on trigger and recoil side of hard-core dijets
- Theoretical models capture this well
- More statistics: Test downward slope

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

Splitting unmodified for these matched jets

What about the angular scale?

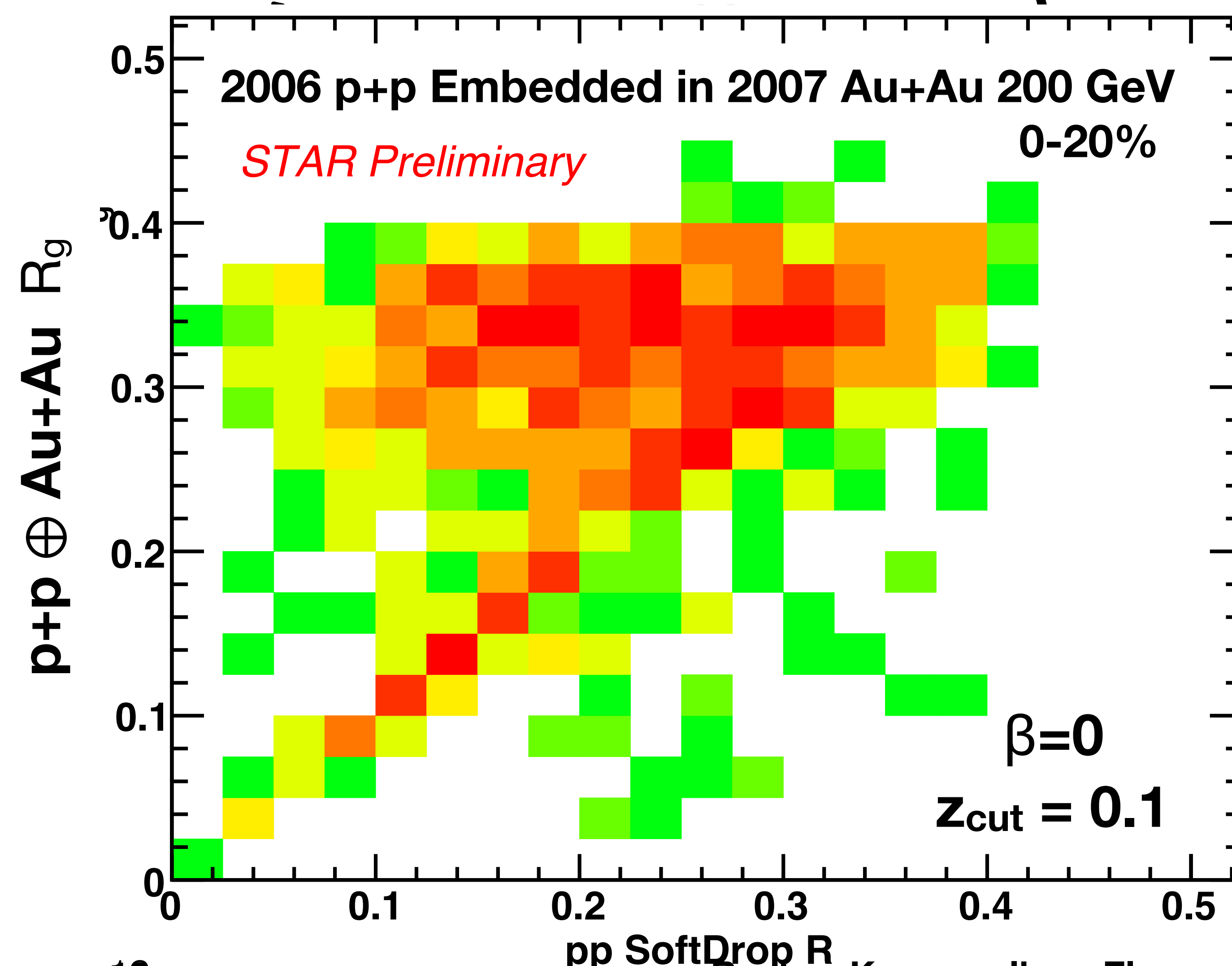
R_g in a heavy ion environment



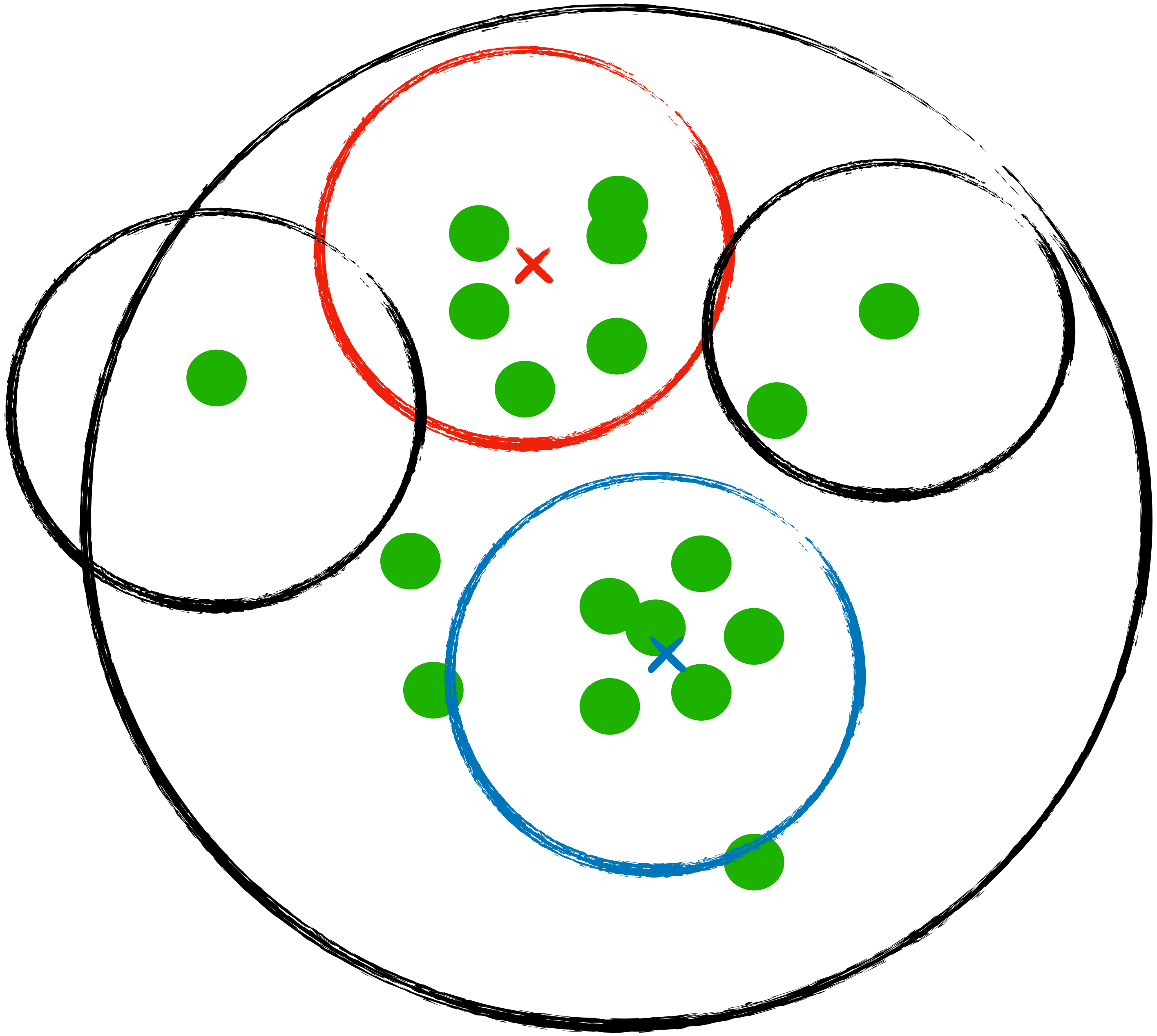
Note: This is default SoftDrop
We can increase z_{cut},
vary β etc…

SoftDrop R_g sensitive to background fluctuations

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

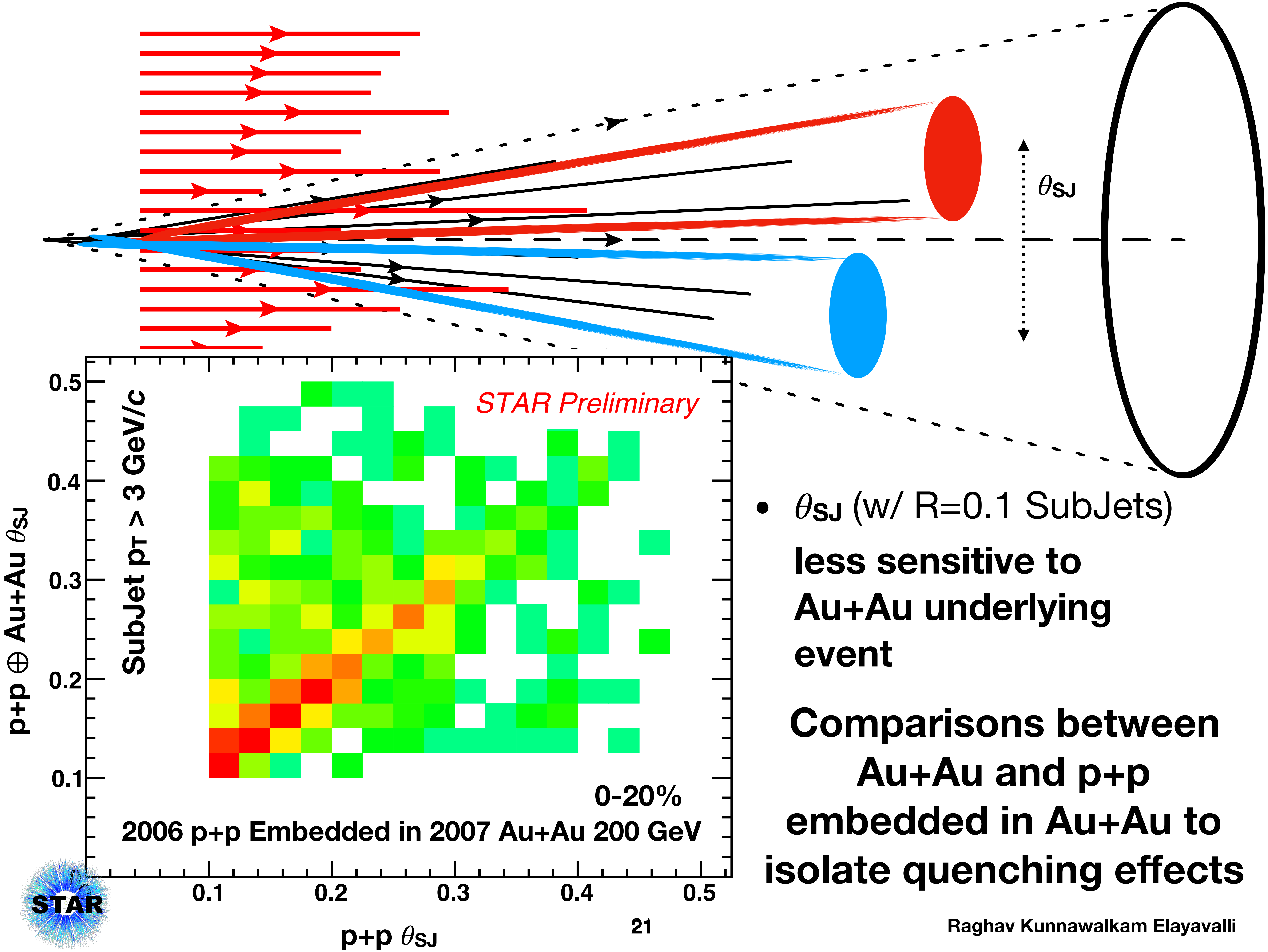


TwoSubJet z/θ



- Cluster all jet constituents into anti-k_t jets of smaller radius (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



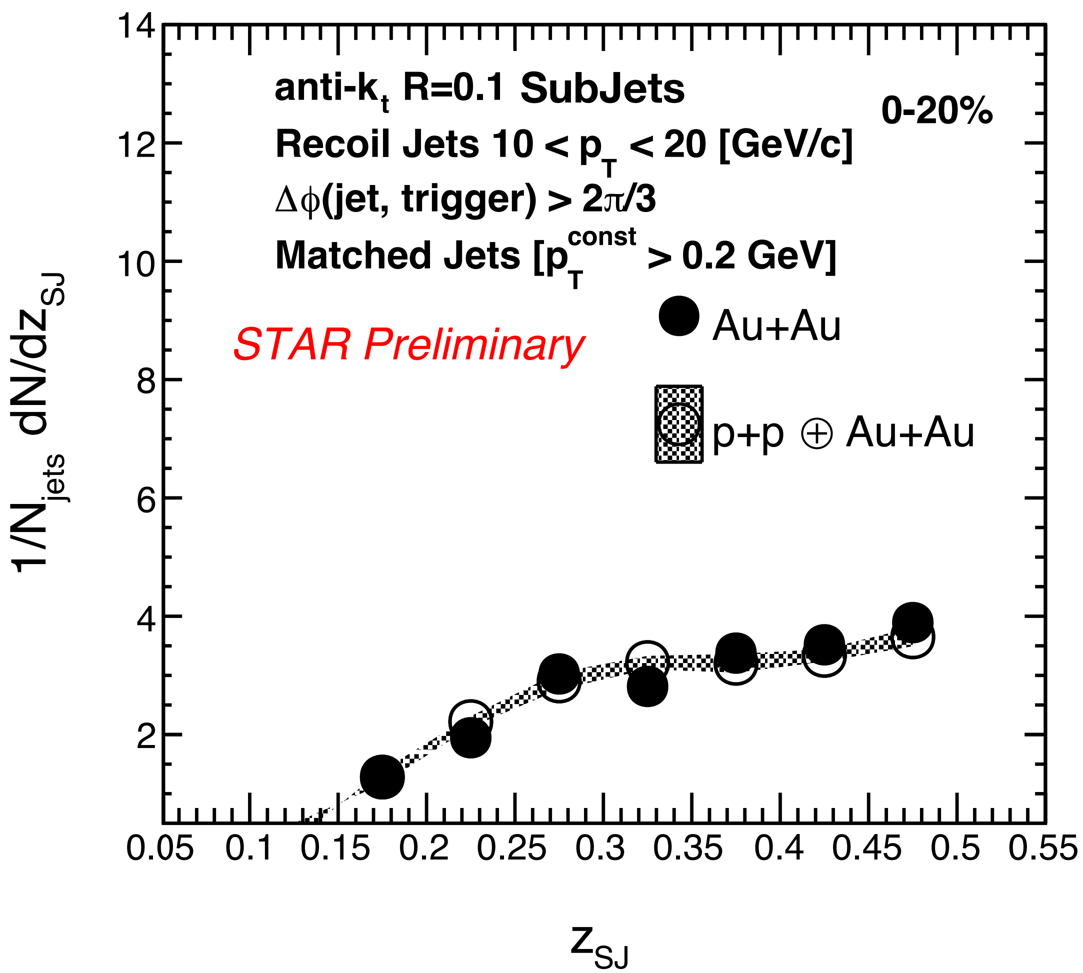
- θ_{SJ} (w/ R=0.1 SubJets) **less sensitive to Au+Au underlying event**

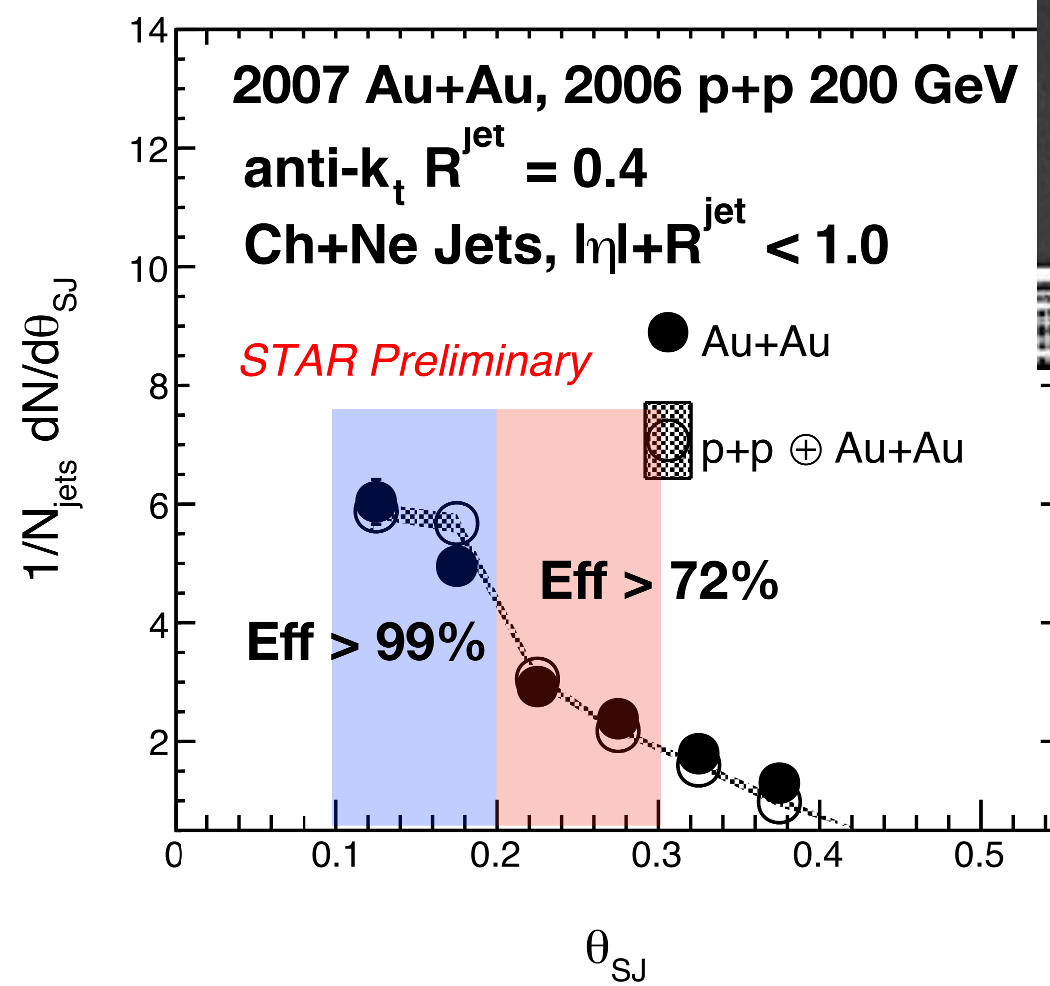
Comparisons between Au+Au and p+p embedded in Au+Au to isolate quenching effects

Raghav Kunnawalkam Elayavalli

TwoSubJet observables

anti-k_t R=0.1 SubJets





- 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

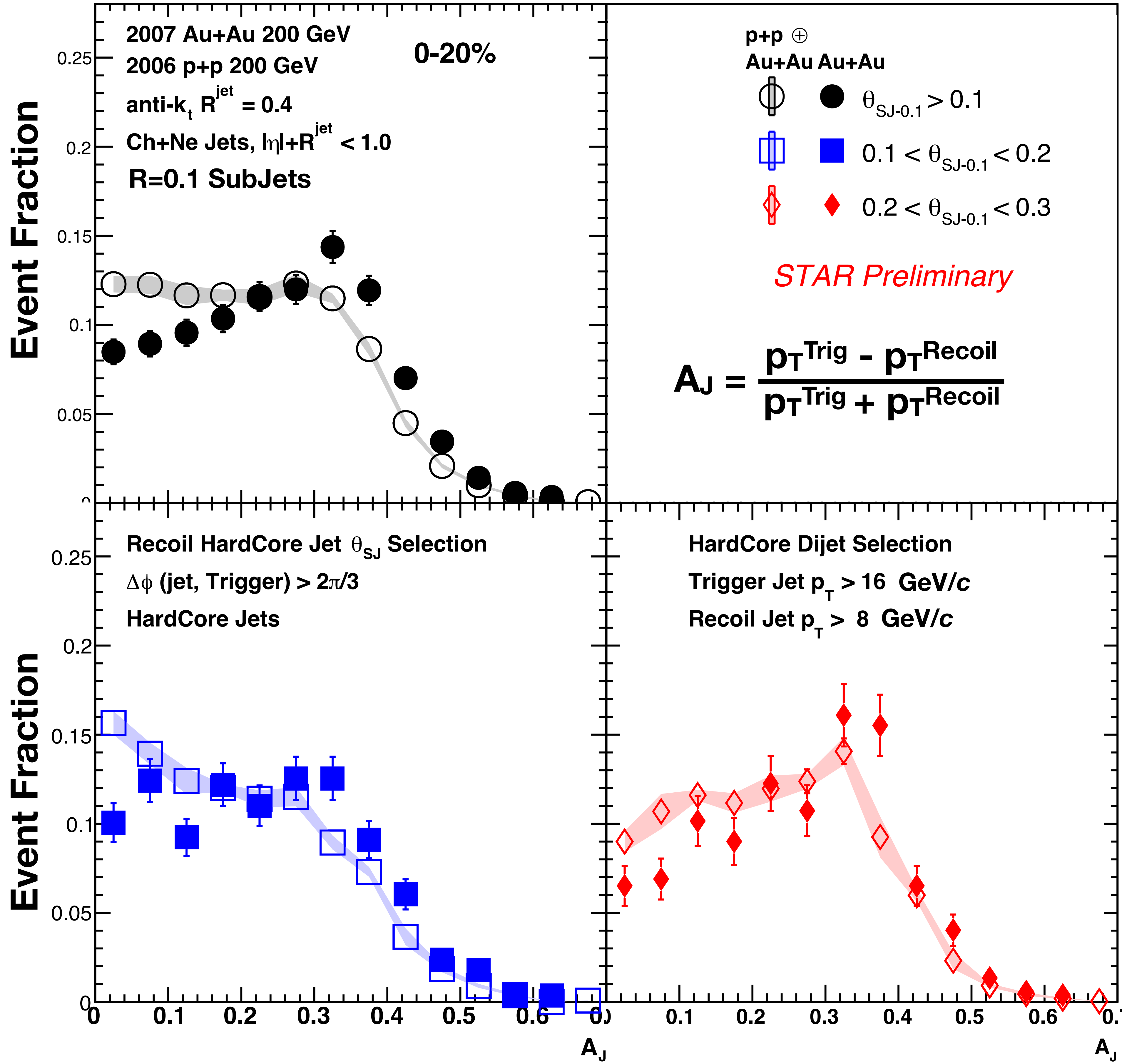
Select jets with a particular angular scale (θ_{SJ})

Let's look at standard jet quenching observables - A_J and Recoil jet yield

HardCore A_J

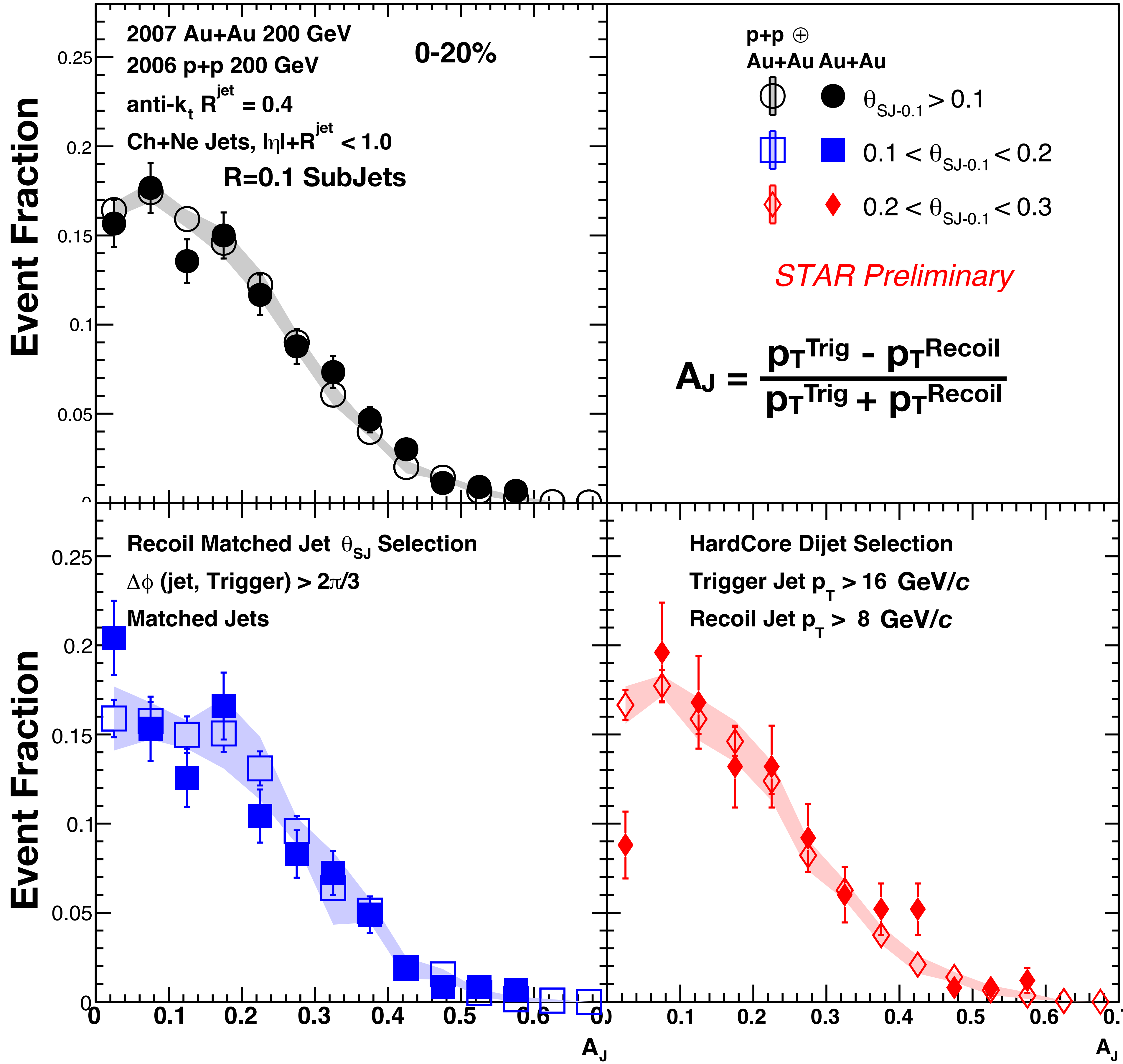
$p_T^{const} > 2$ GeV/c

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



Matched A_J

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

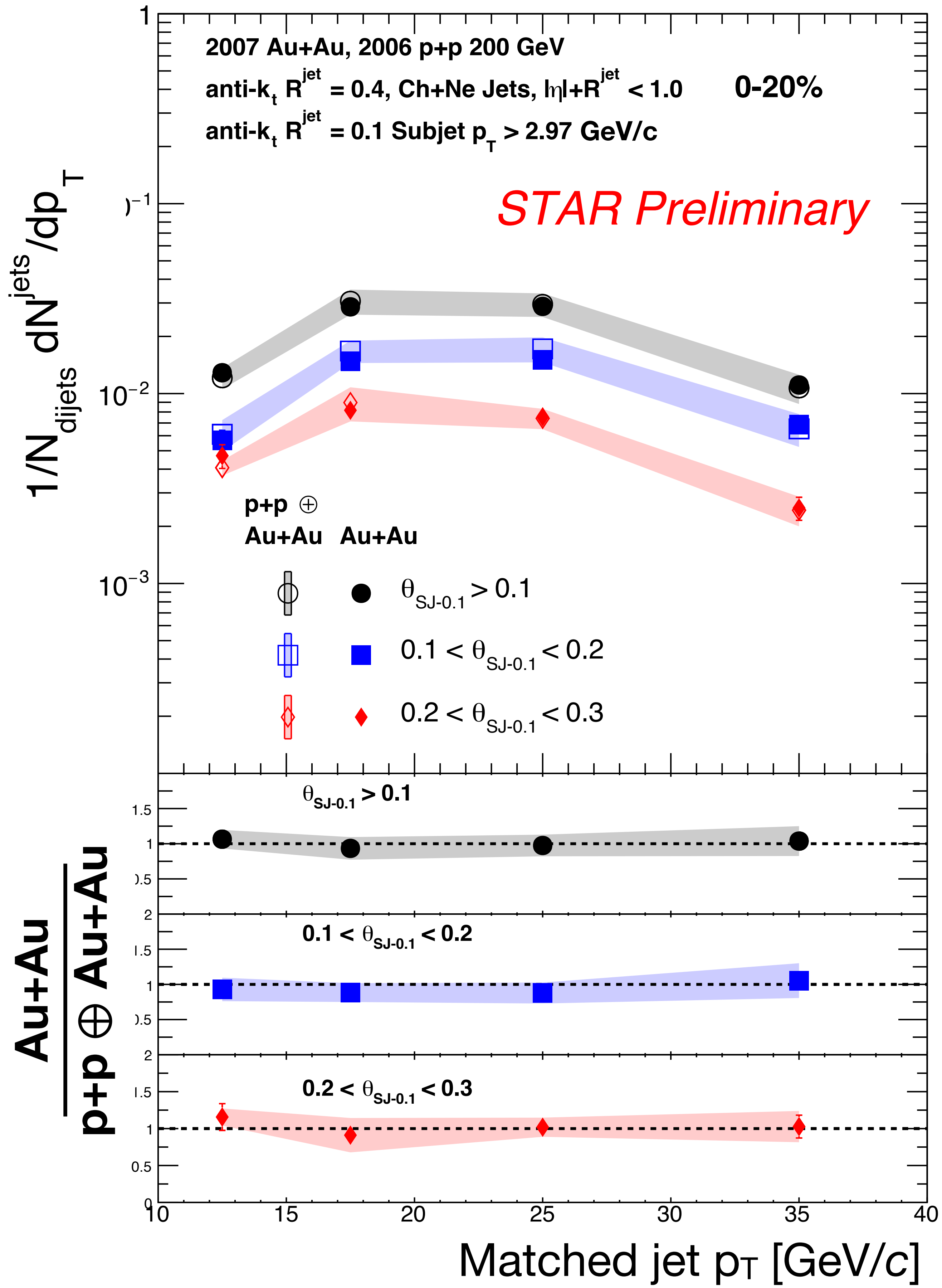


Matched jets of different θ_{SJ} selections are balanced at RHIC

Recoil matched jet yield

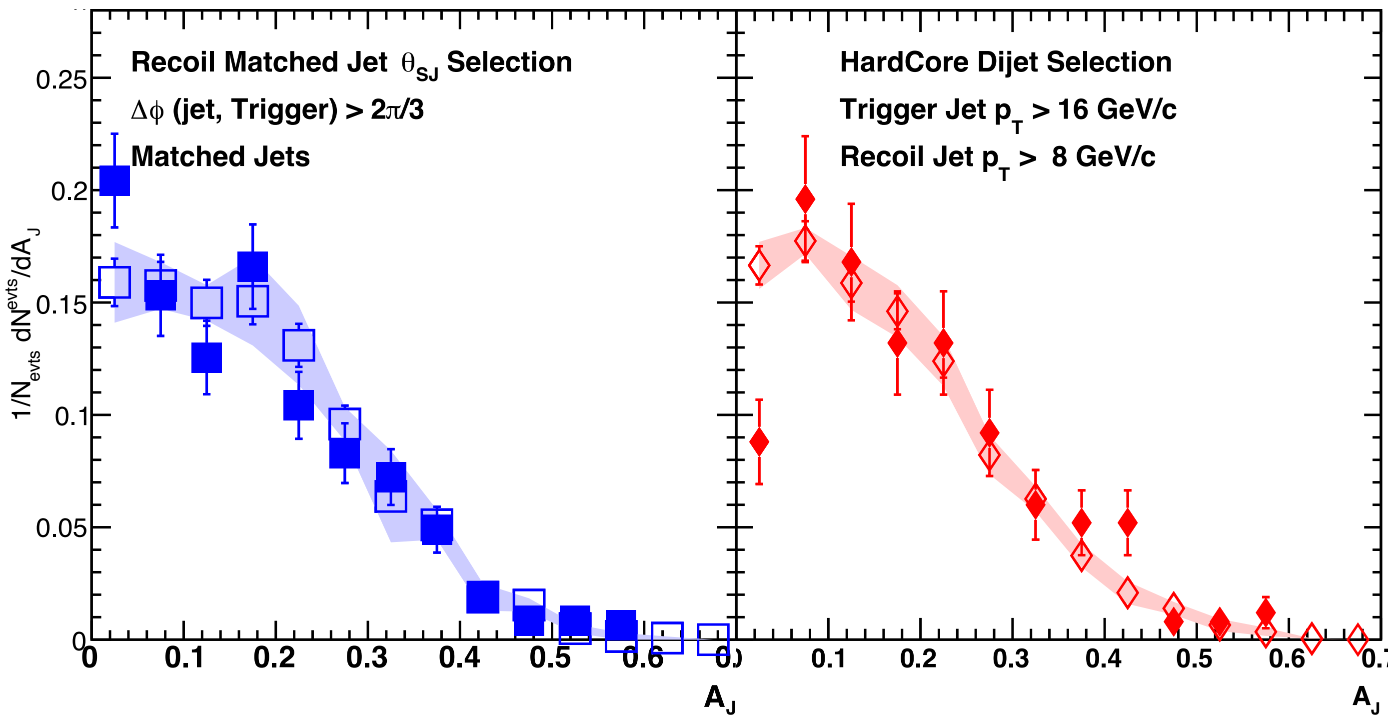
p_T^{const} > 0.2 GeV/*c*

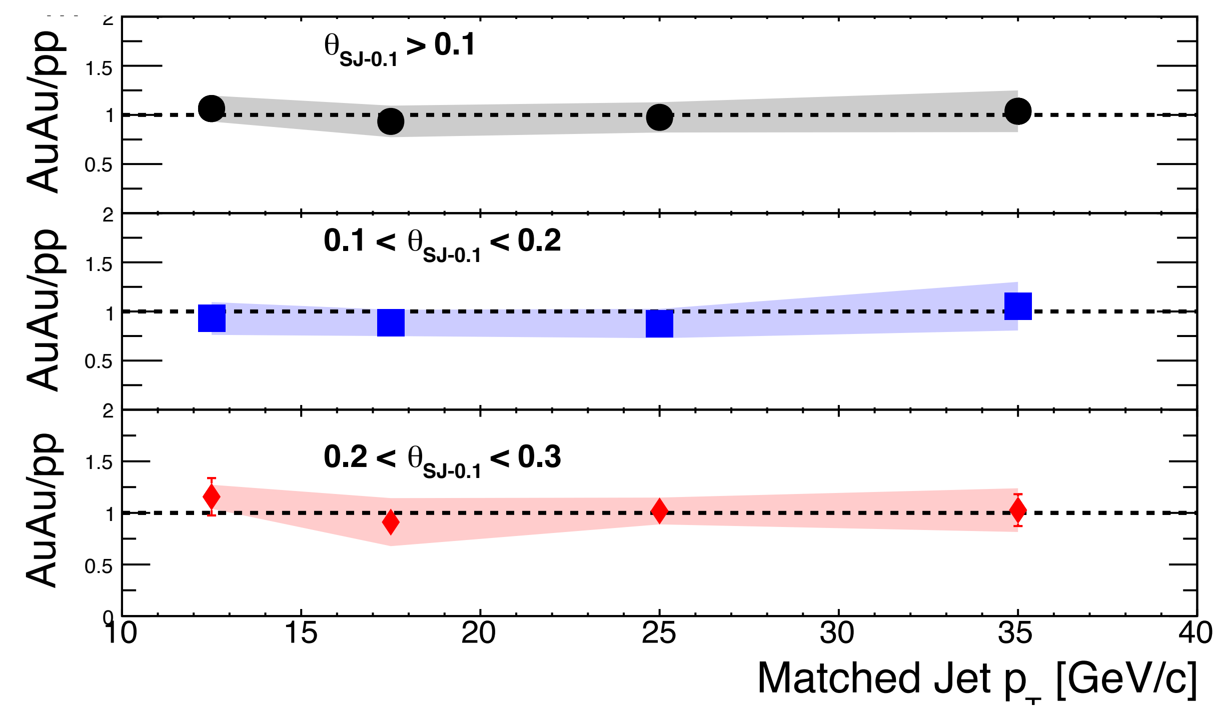
- Yield normalized per di-jet
- Confirmation that **matched jets recover** the energy lost by quenching within R = 0.4
- **Observe no significant differences among θ_{SJ} selections**



Conclusions - II

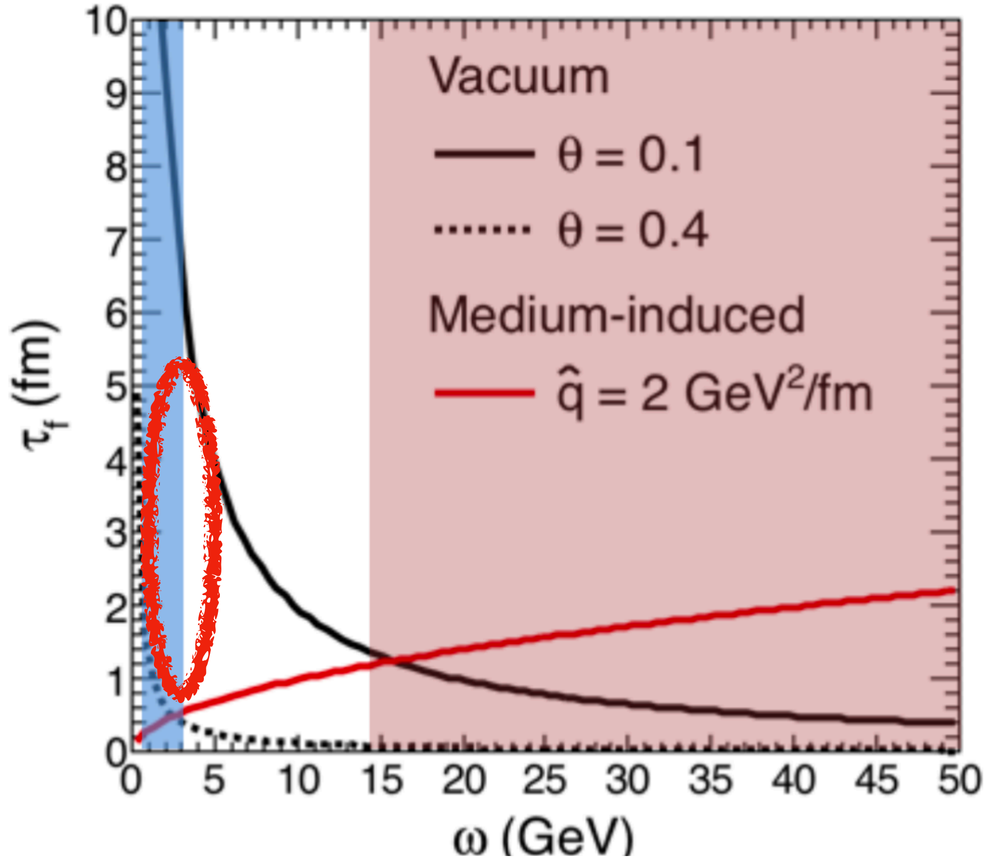
STAR Preliminary

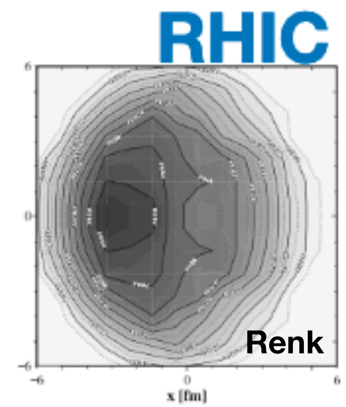




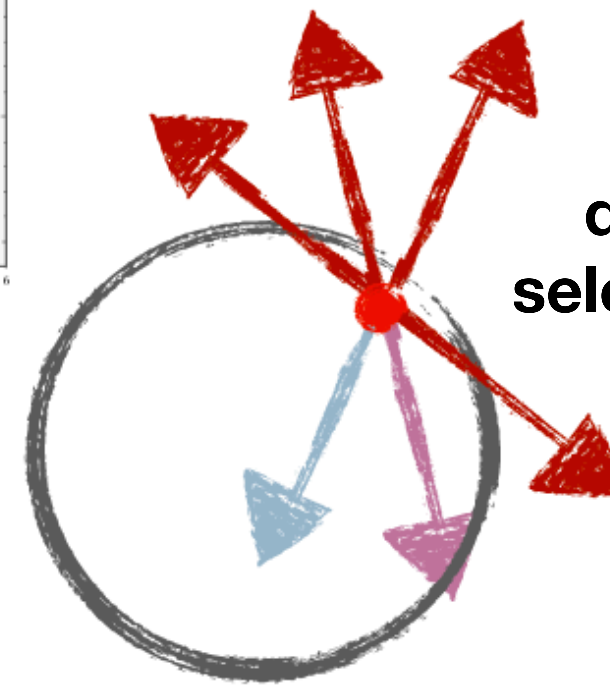
- TwoSubJet observables more robust to UE
- z_{SJ} and θ_{SJ} are similar in Au+Au compared with p+p⊕Au+Au
- **Observe no significant differences between wide/narrow jets in matched jet A_J and recoil jet spectra**

Conclusions - II





Surface bias



dijet selection

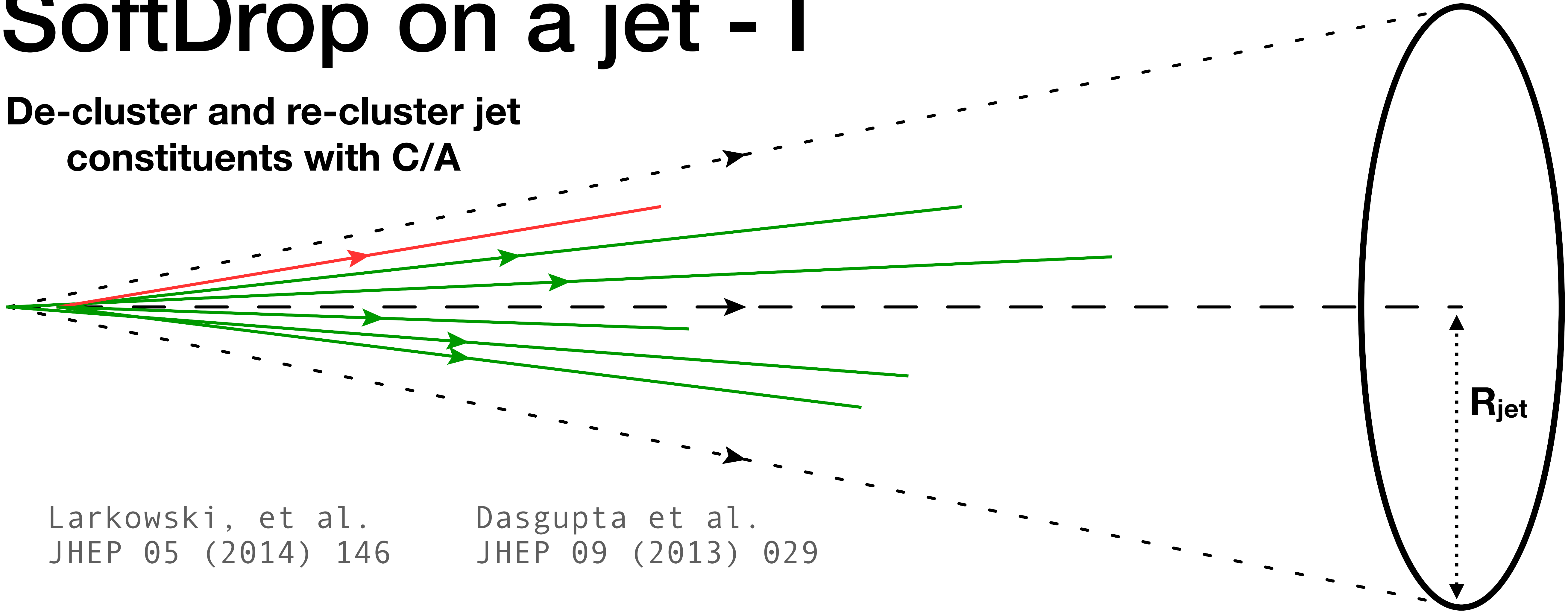
Nick Elsey (this workshop), Thursday

- Trigger and HardCore Dijet requirements indicate potential surface bias
  - Jet angular scale (θ_{SJ}) not resolved by the medium ⟶ earlier splits
  - (likely) Favor shorter path length ⟶ given 'Jet Geometry Engineering' and surface bias ⟶ split most likely outside the medium ⟶ modification due to radiation from a single color charge
- Differential E-Loss measurements in jet momentum and angle ⟶ further constrain models and probe medium at varying length scales

Backup

SoftDrop on a jet - I

De-cluster and re-cluster jet constituents with C/A



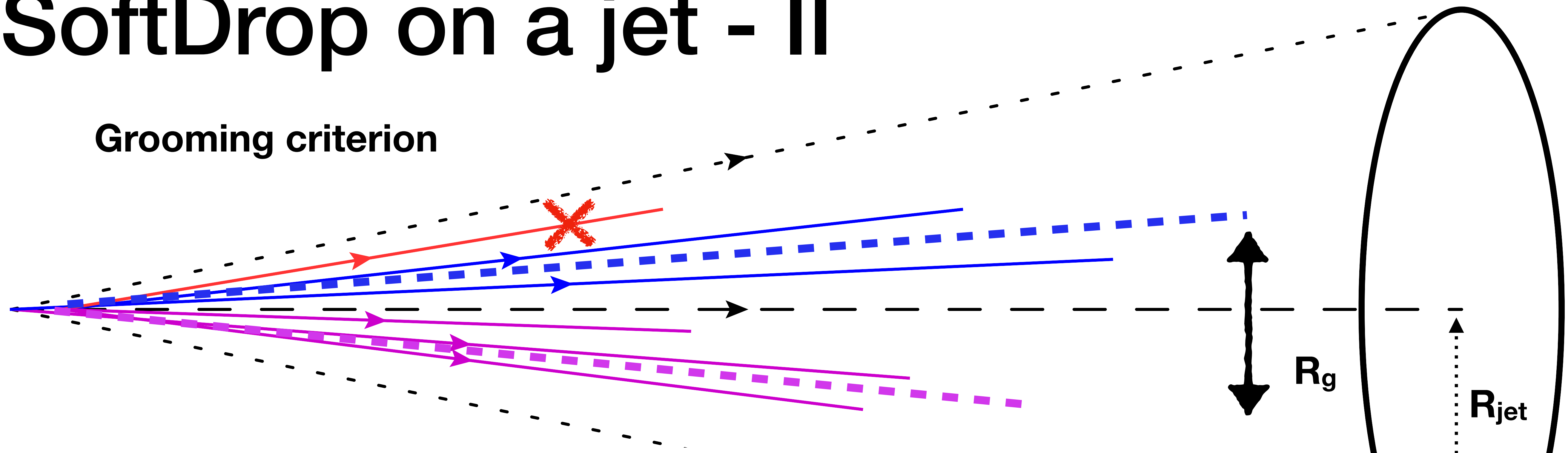
Larkowski, et al. JHEP 05 (2014) 146

Dasgupta et al. JHEP 09 (2013) 029

- Walking backwards in an angular ordered de-clustering tree
- Follows "First In Last Out" criterion
- Sensitive to soft radiation, MPI, UE, non-global and non-perturbative corrections

SoftDrop on a jet - II

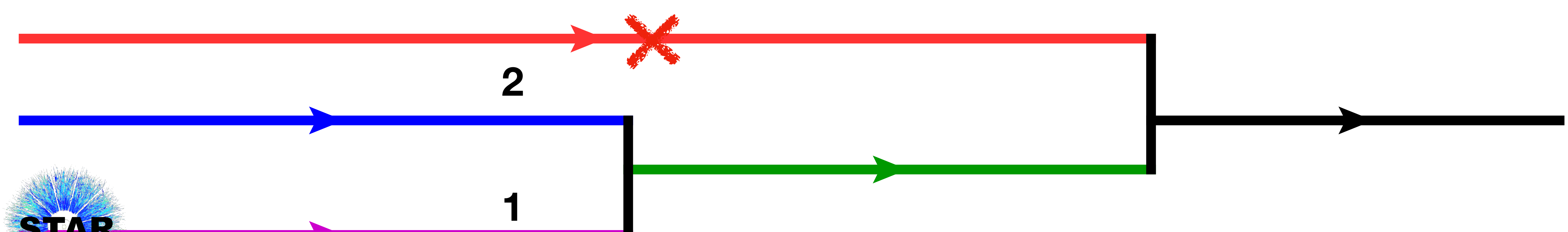
Grooming criterion



- Require subjet momentum fraction to pass the following criterion

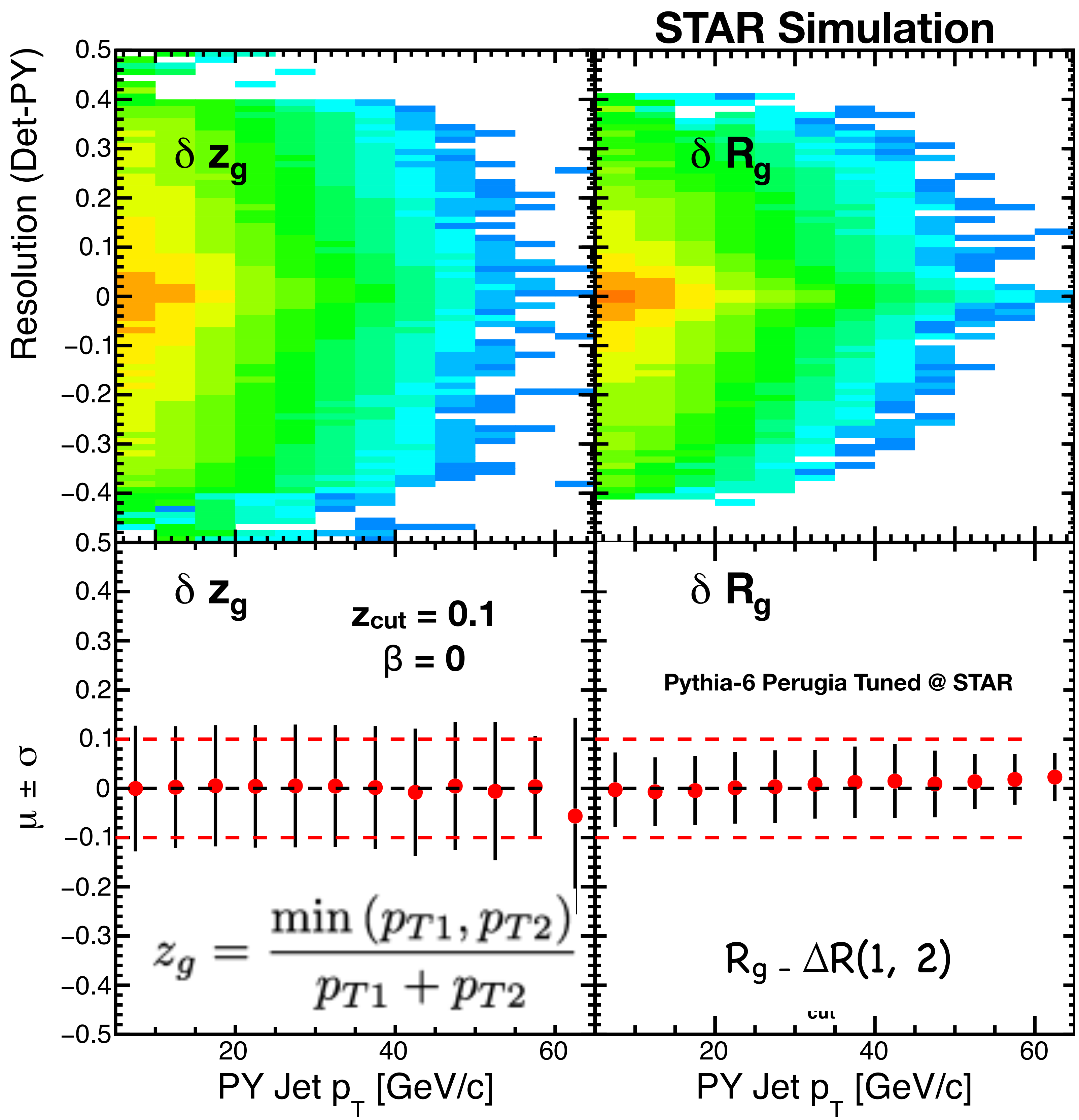
$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta} \qquad \begin{aligned} z_{cut} &= 0.1 \\ \beta &= 0 \end{aligned}$$

- With the two surviving branches - we have two observables that characterize a jet's substructure



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

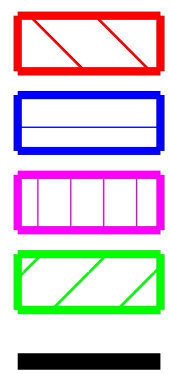


$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

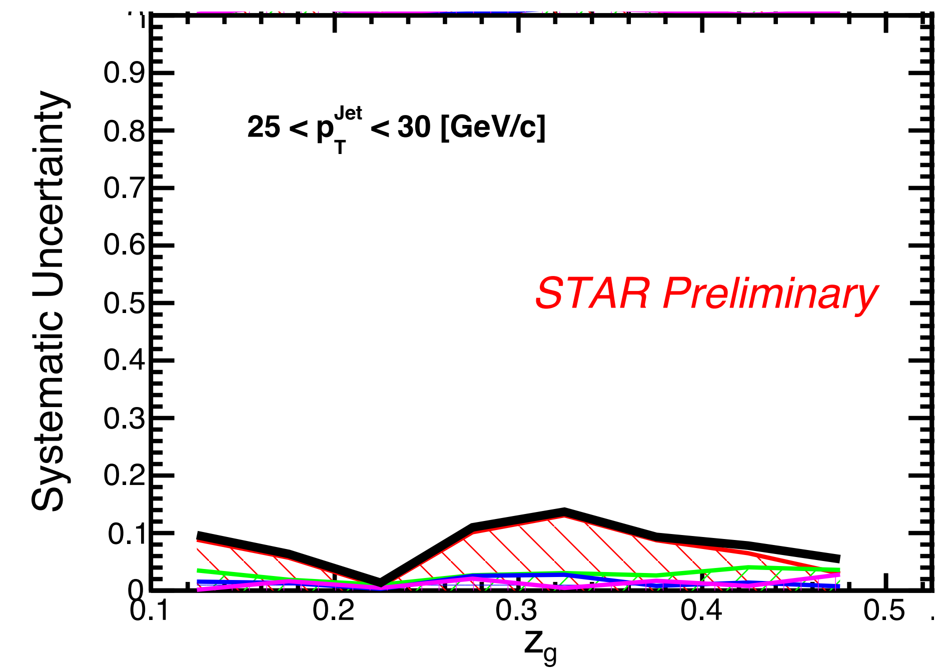
p+p z_g and R_g

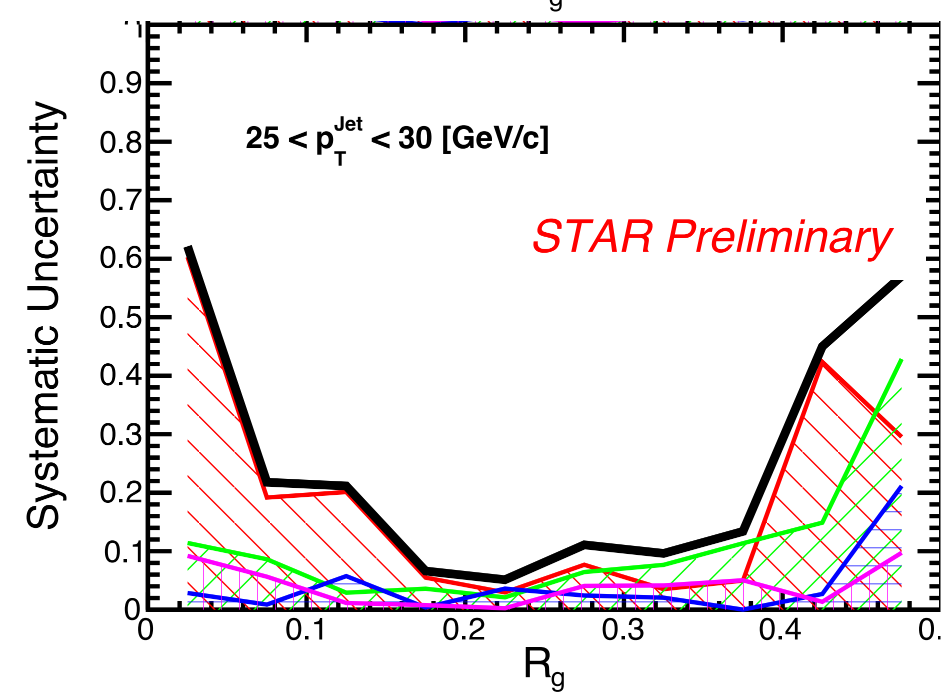
Systematic Uncertainties

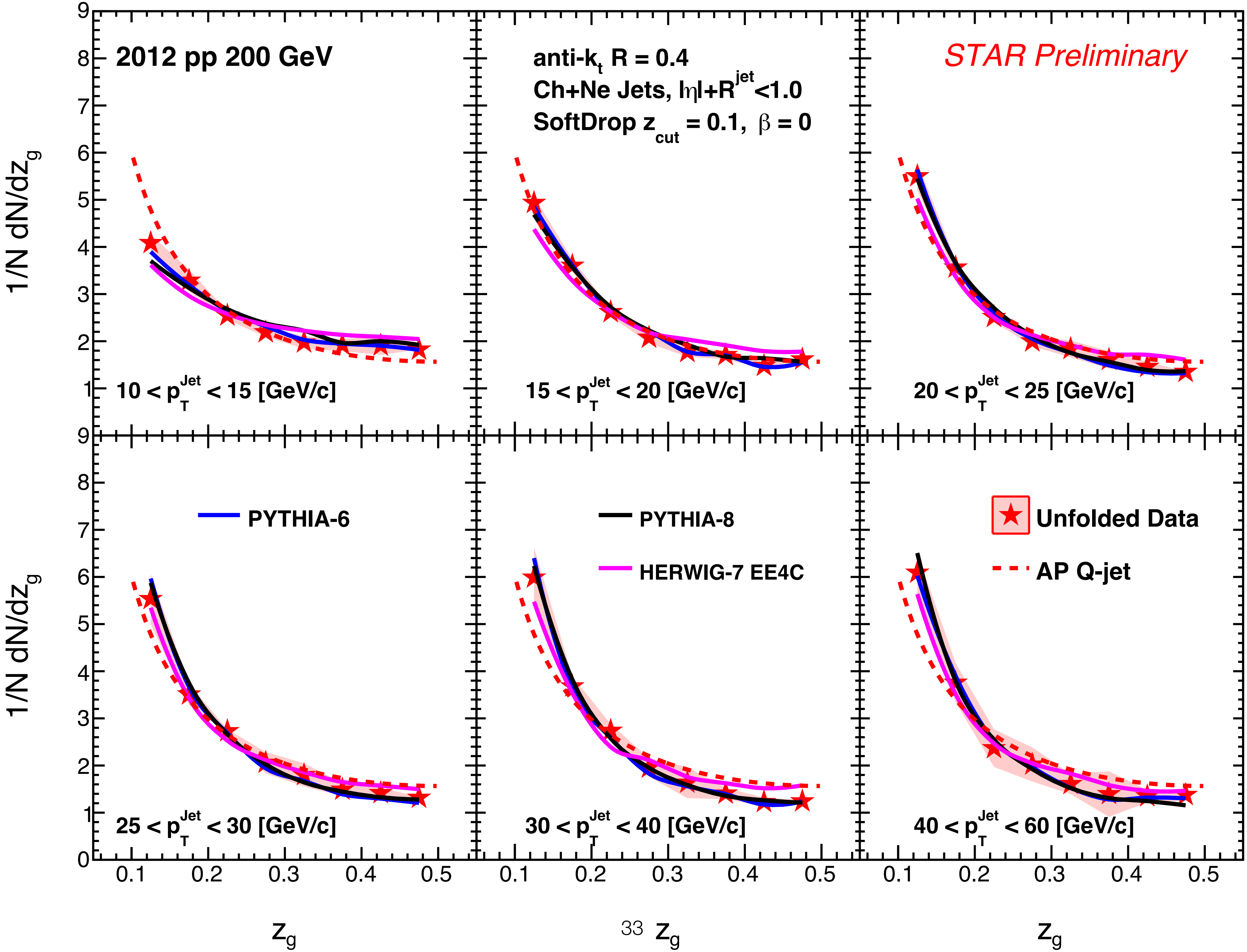
- Hadronic Correction (HC)
  - Using MIPs (no HC) and 0.5 HC
- Tower Scale - 3.8% in the tower gain
- Tracking - 4% variation (flat in track p_T)
- Unfolding (@ the response level) -
  - Prior shape variations
  - Varying the iteration parameter from 2 - 6 (nominal=4)



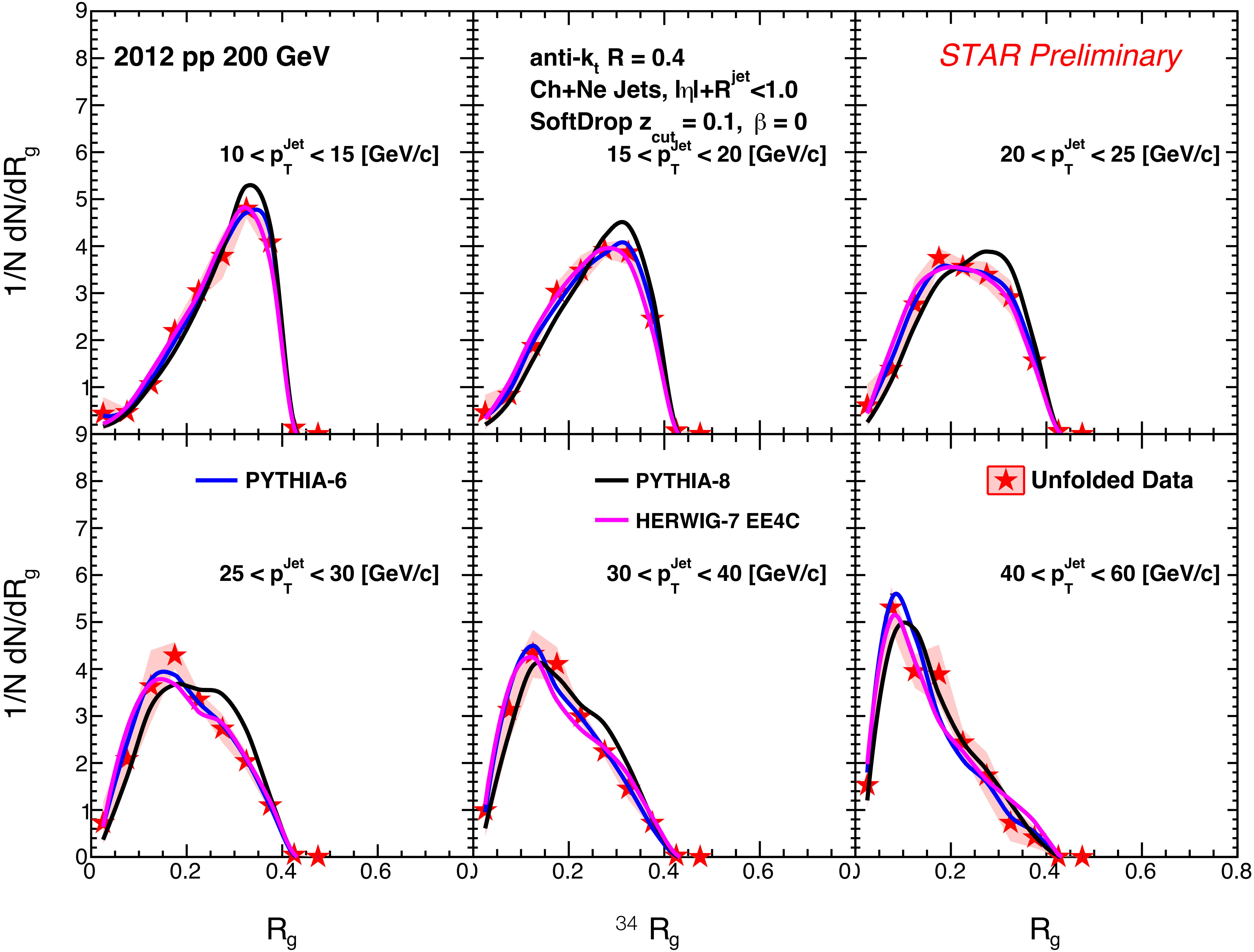
anti-k_t R = 0.4
SoftDrop z_{cut} = 0.1, β=0
Ch+Ne Jets, |η + R| < 1
Systematic Uncertainties





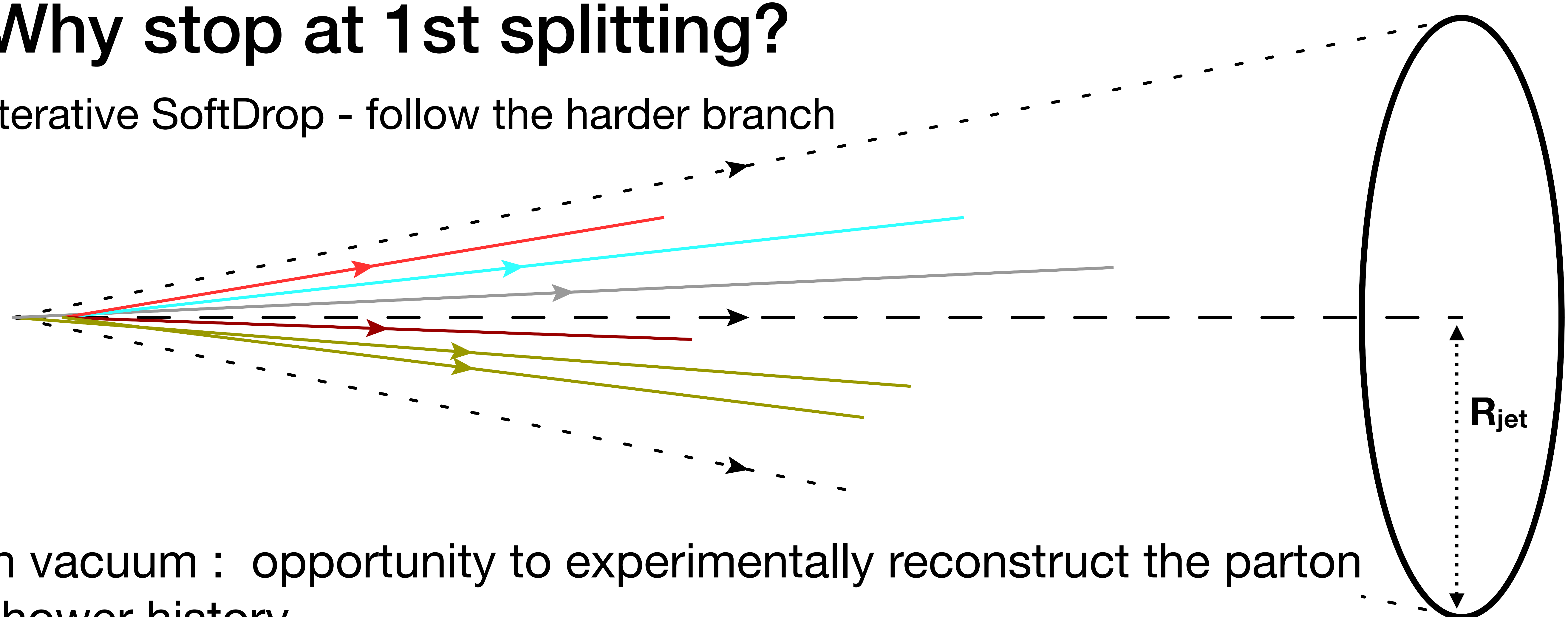


2012 pp 200 GeV
anti-k_t R = 0.4
Ch+Ne Jets, $|\eta|+R^{jet}<1.0$
SoftDrop z_{cut} = 0.1, β = 0
STAR Preliminary
$10 < p_T^{Jet} < 15$ [GeV/c]
$15 < p_T^{Jet} < 20$ [GeV/c]
$20 < p_T^{Jet} < 25$ [GeV/c]
$25 < p_T^{Jet} < 30$ [GeV/c]
$30 < p_T^{Jet} < 40$ [GeV/c]
$40 < p_T^{Jet} < 60$ [GeV/c]
PYTHIA-6
PYTHIA-8
HERWIG-7 EE4C
Unfolded Data
AP Q-jet
$1/N\ dN/dz_g$
z_g


2012 pp 200 GeV
anti-k$_t$ R = 0.4
Ch+Ne Jets, |η|+R^{jet}<1.0
SoftDrop z$_{cut}$ = 0.1, β = 0
STAR Preliminary
10 < p$_T^{Jet}$ < 15 [GeV/c]
15 < p$_T^{Jet}$ < 20 [GeV/c]
20 < p$_T^{Jet}$ < 25 [GeV/c]
25 < p$_T^{Jet}$ < 30 [GeV/c]
30 < p$_T^{Jet}$ < 40 [GeV/c]
40 < p$_T^{Jet}$ < 60 [GeV/c]
PYTHIA-6
PYTHIA-8
HERWIG-7 EE4C
Unfolded Data
1/N dN/dR$_g$
R$_g$

Why stop at 1st splitting?

Iterative SoftDrop - follow the harder branch

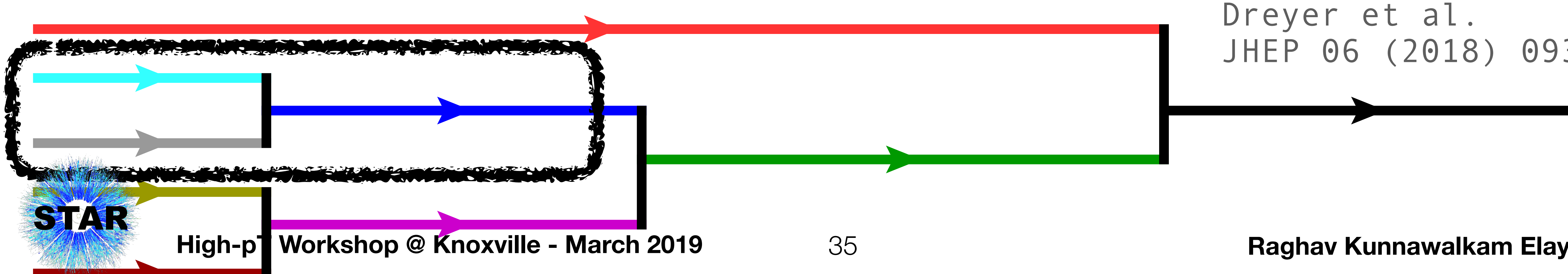


In vacuum : opportunity to experimentally reconstruct the parton shower history

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

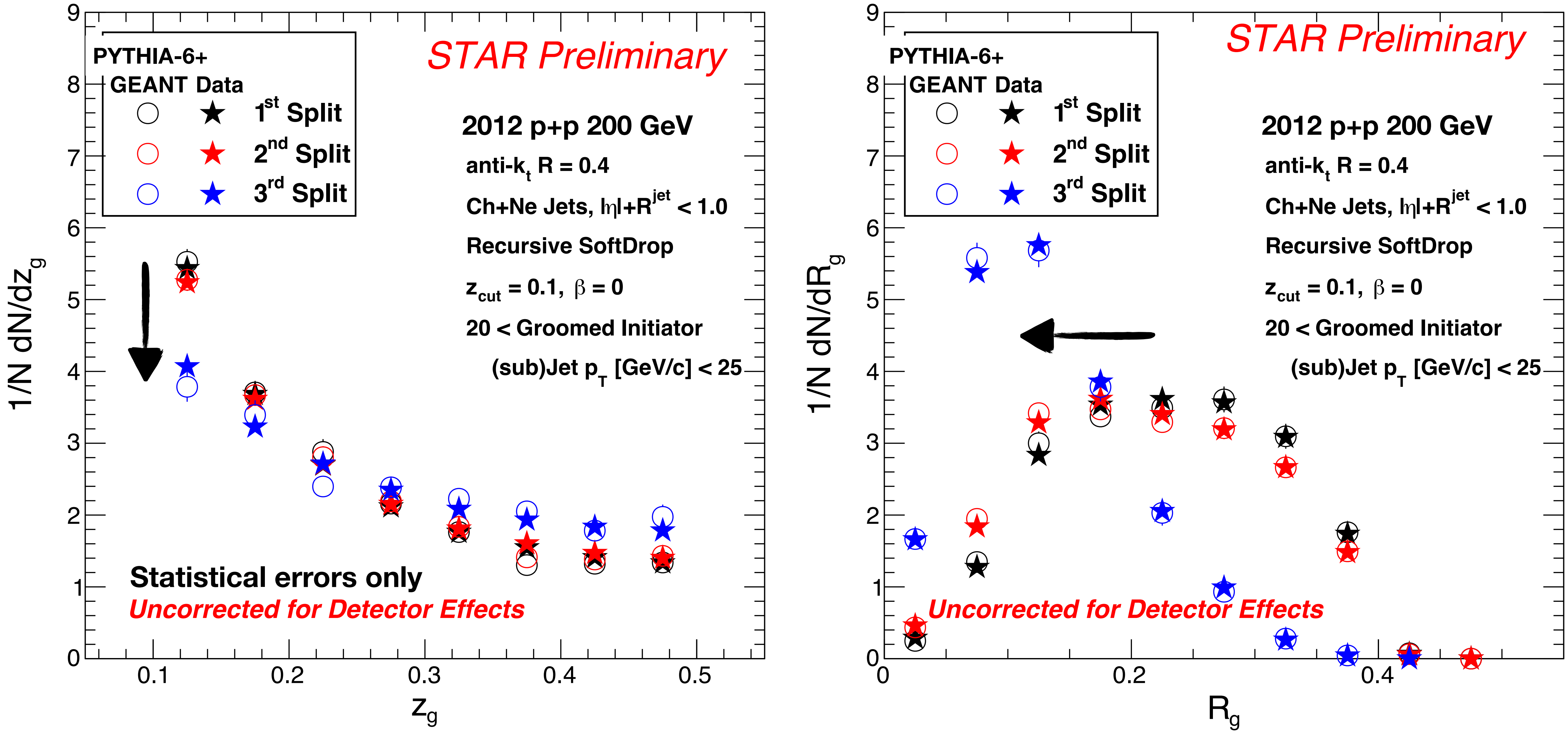
In medium : differential energy loss in formation time of a split hierarchy

→ Test **medium properties** as it evolves!



Dreyer et al. JHEP 06 (2018) 093

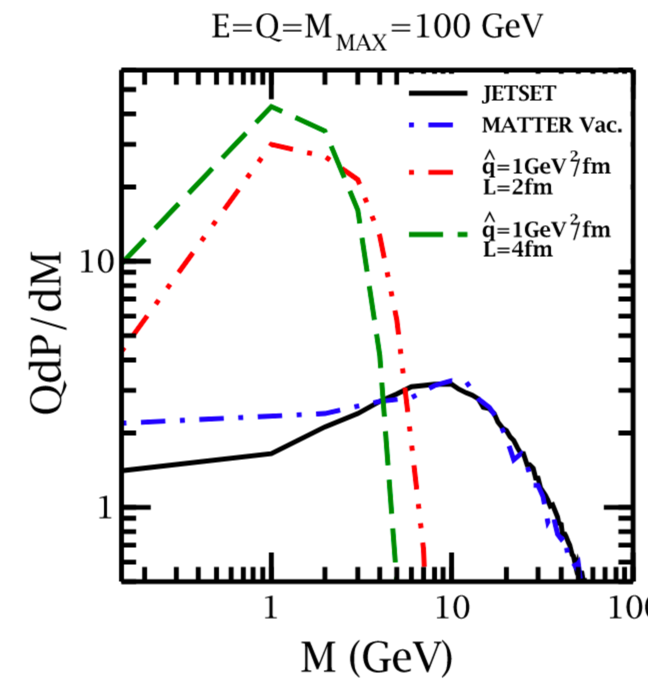
First measurement of the jet internal structure via recursive SoftDrop at STAR



- **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*

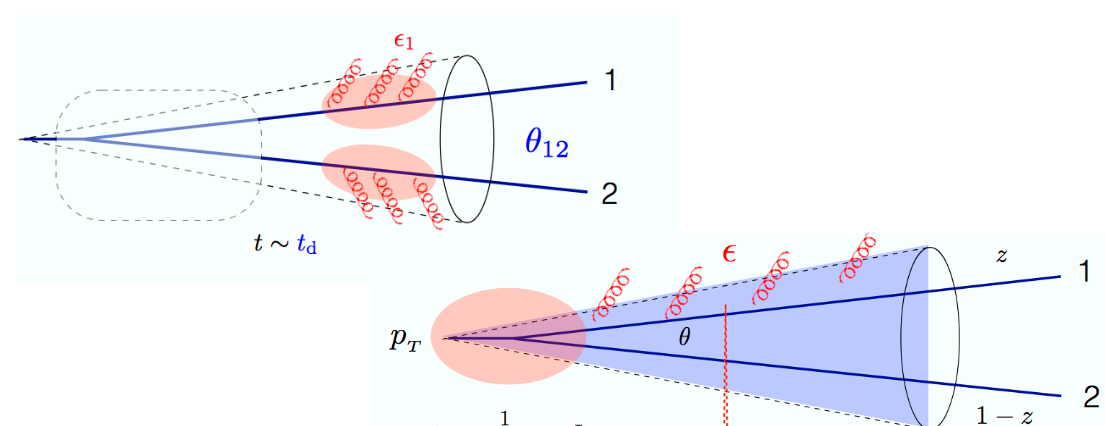
Need for differential measurements

- 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



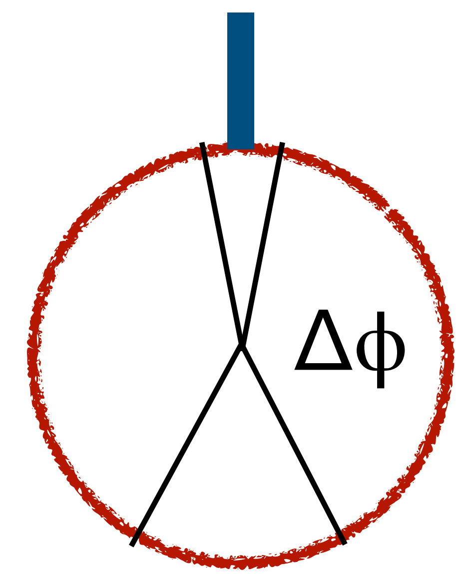
Mehtar Tani, Y and Tywoniuk, K
arXiv:1707.07361

de-coherence vs Coherence

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*

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

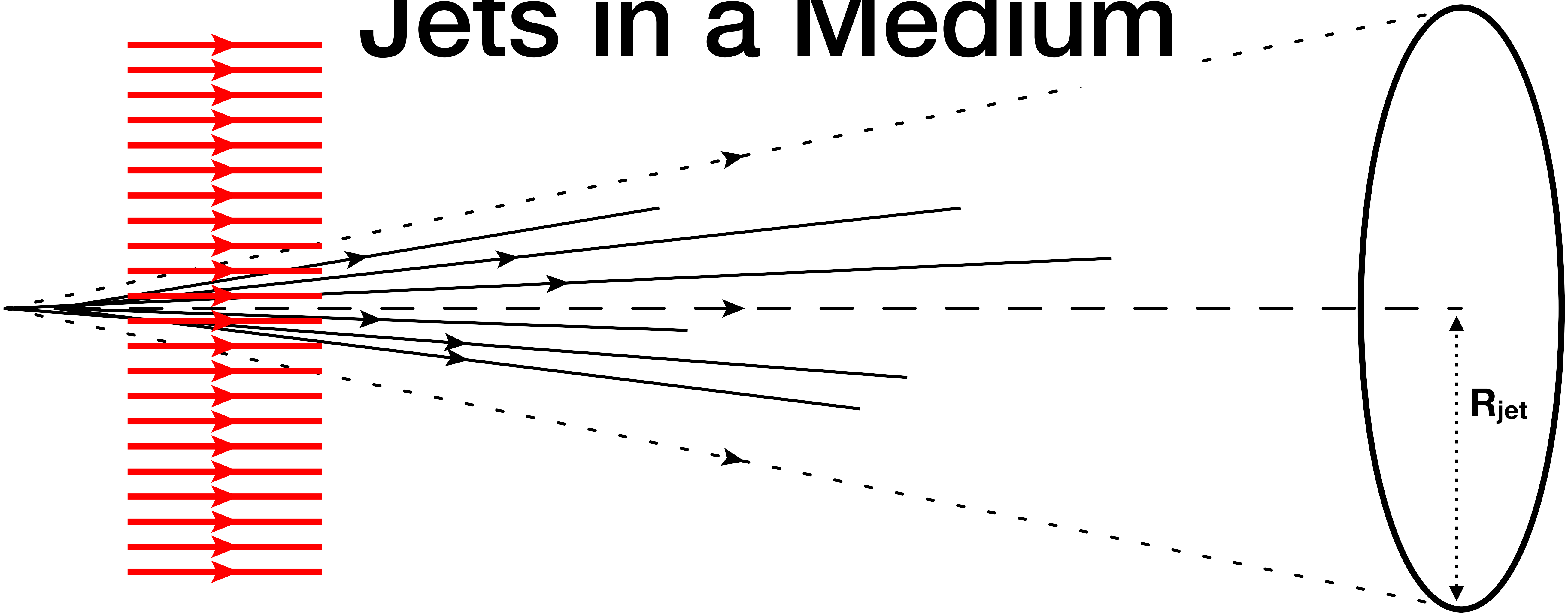
TwoSubJet (R=0.1) θ_{SJ}

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

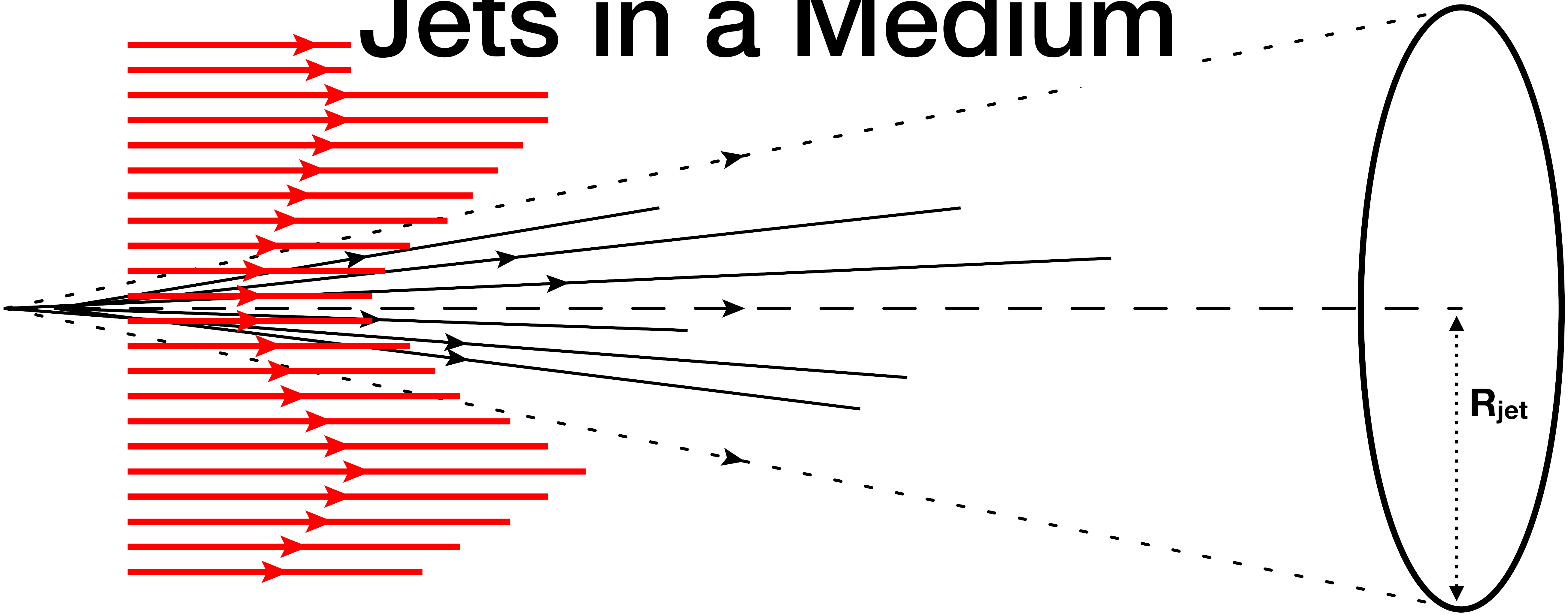
- **Tagging Efficiency**: Probability that a p+p ⊕ Au+Au and the p+p jet utilized in the embedding has a resolved θ_{SJ} in the same range. These are the cases where both jets have two resolved SubJets.
  - $0.1 < \theta_{SJ} < 0.2$: Efficiency > 99%
  - $0.2 < \theta_{SJ} < 0.3$: Efficiency > 72%

Jets in a Medium



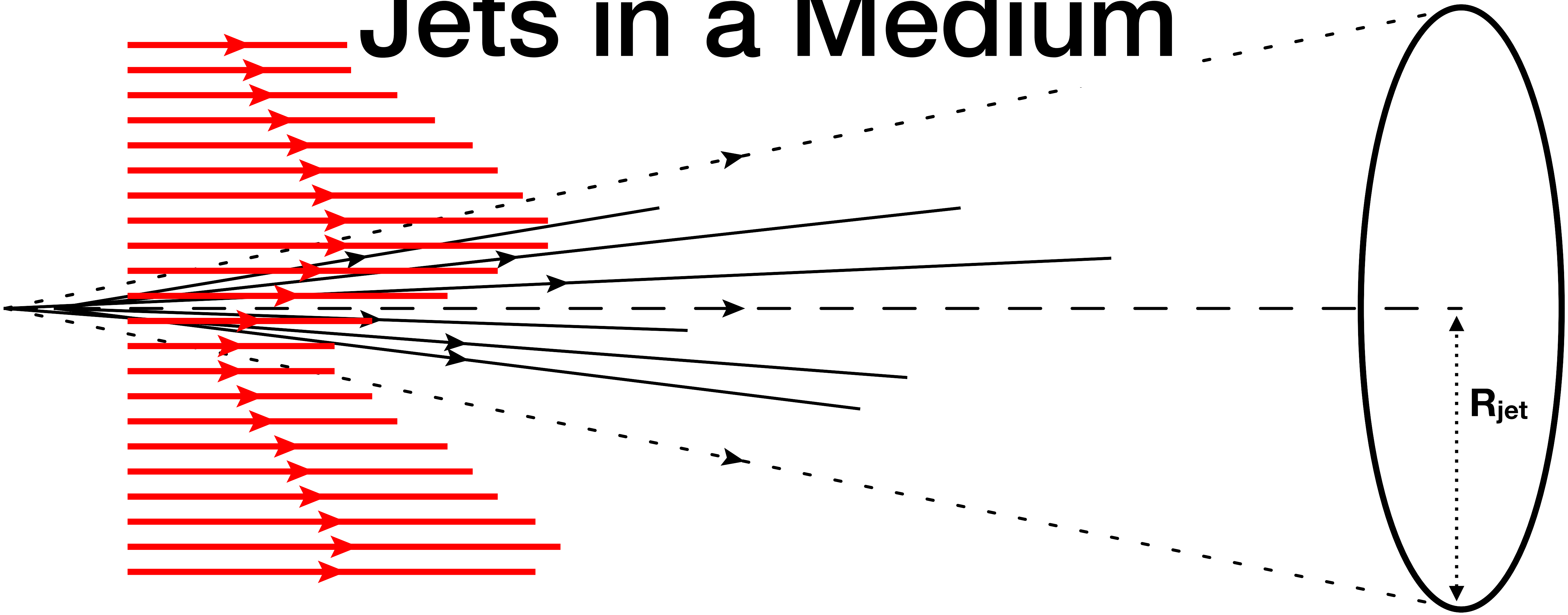
- Flat background - ideal medium can be easily subtracted

Jets in a Medium



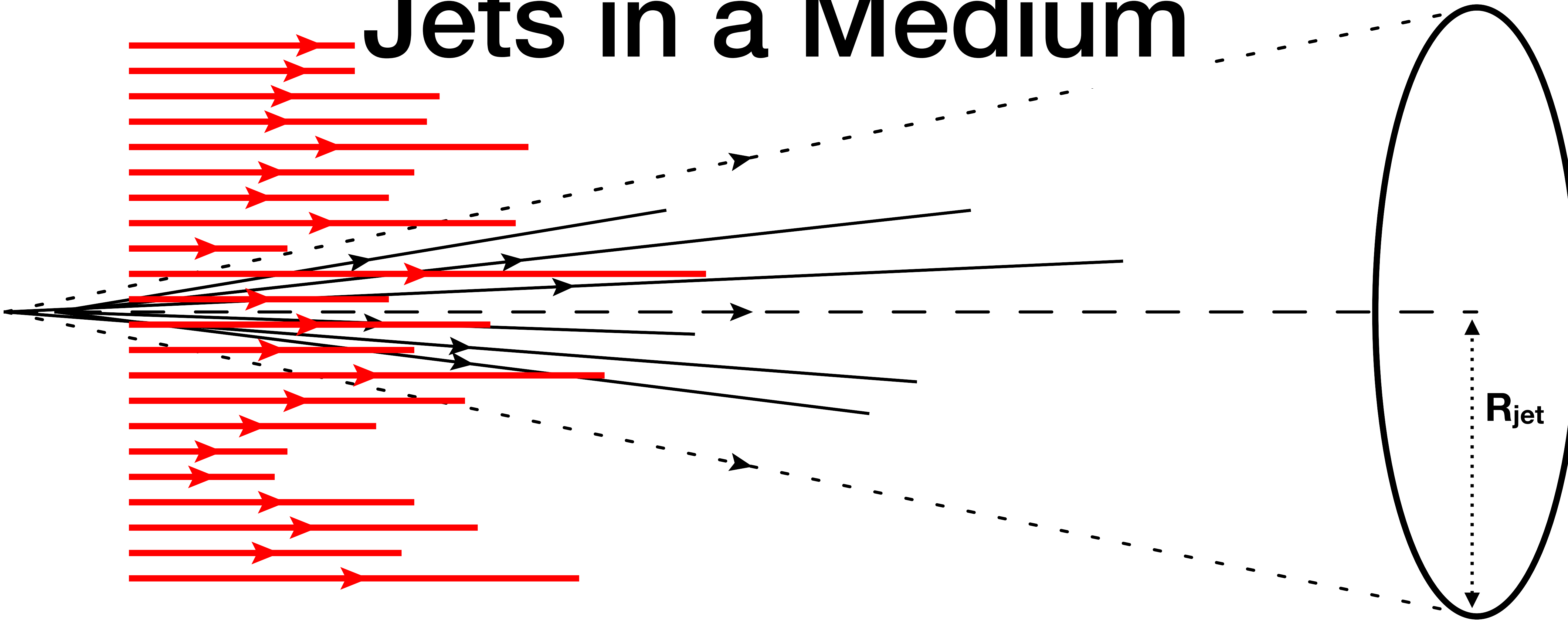
- Flat background - ideal medium can be easily subtracted
- Fluctuating background - can be modeled but effects persists within substructure

Jets in a Medium



- Flat background - ideal medium can be easily subtracted
- Fluctuating background - can be modeled but effects persists within substructure
- Off-center fluctuation within the jet - greatly modifies jet substructure - introduces large smearing effects

Jets in a Medium



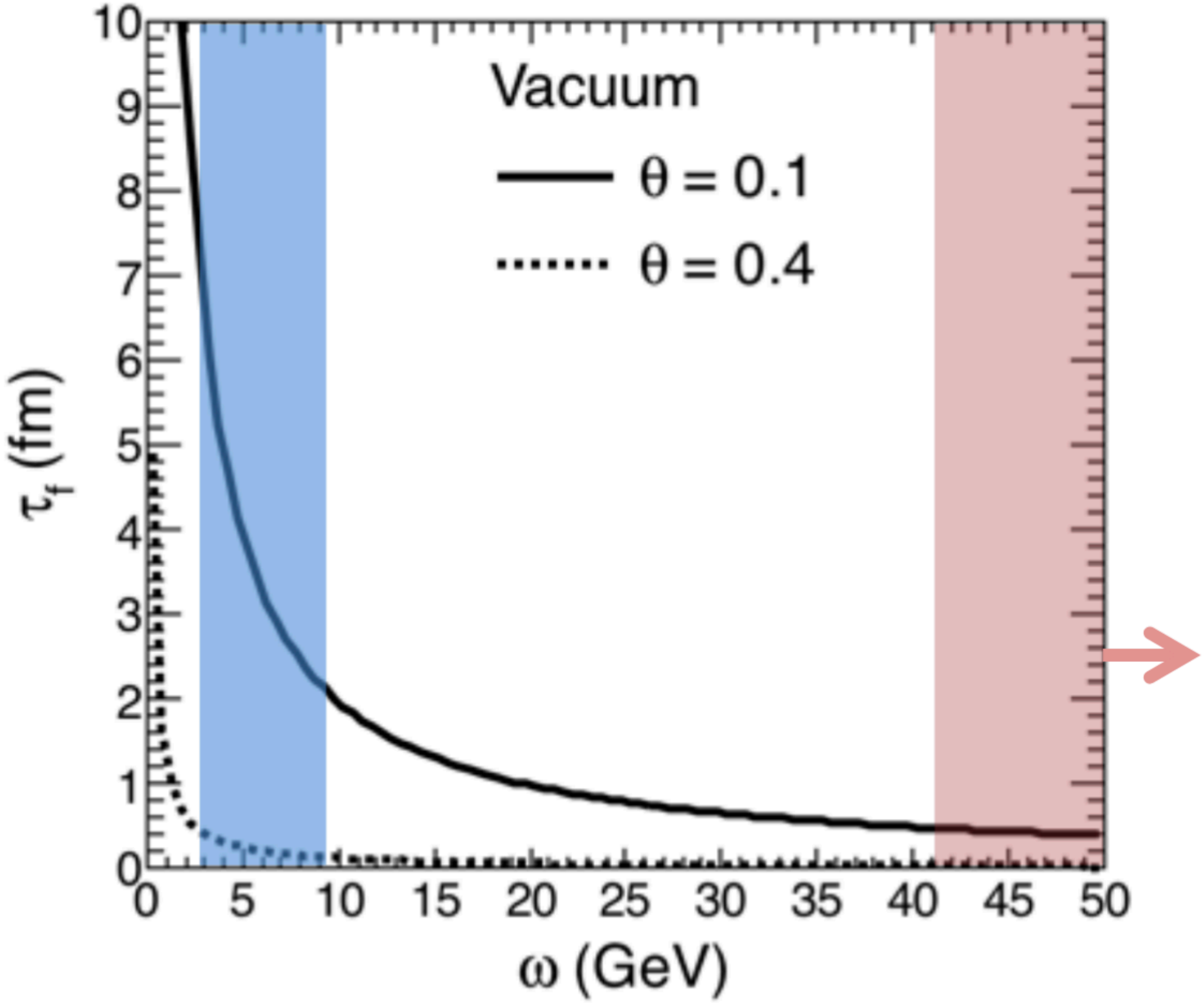
- Flat background - ideal medium can be easily subtracted
- Fluctuating background - can be modeled but effects persists within substructure
- Off-center fluctuation within the jet - greatly modifies jet substructure - introduces large smearing effects

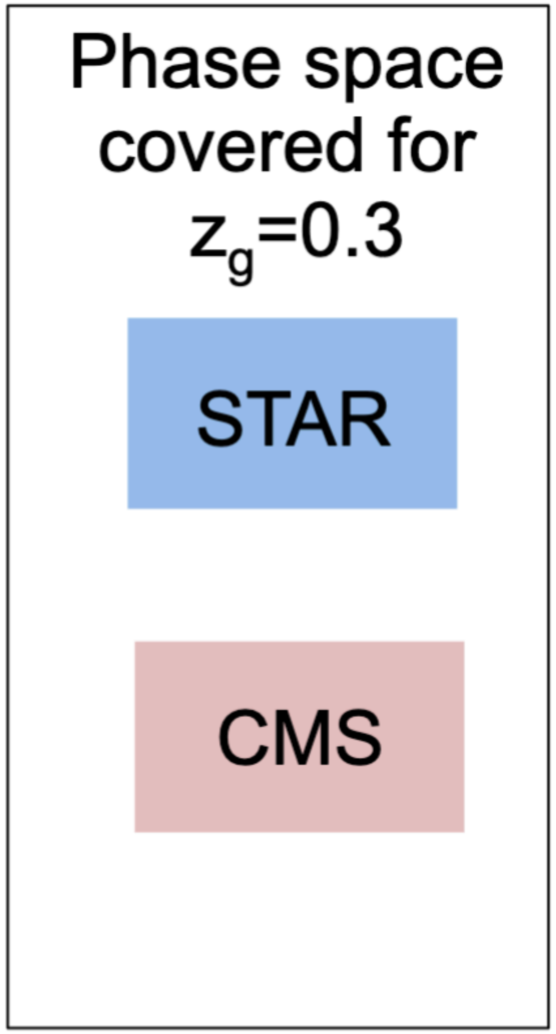
Realistic - Fluctuations rule the game

z_g – RHIC vs LHC

Vacuum formation time of gluons with certain energy

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

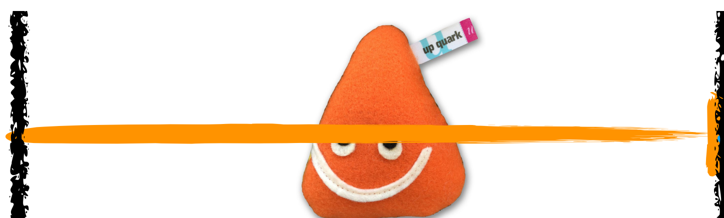


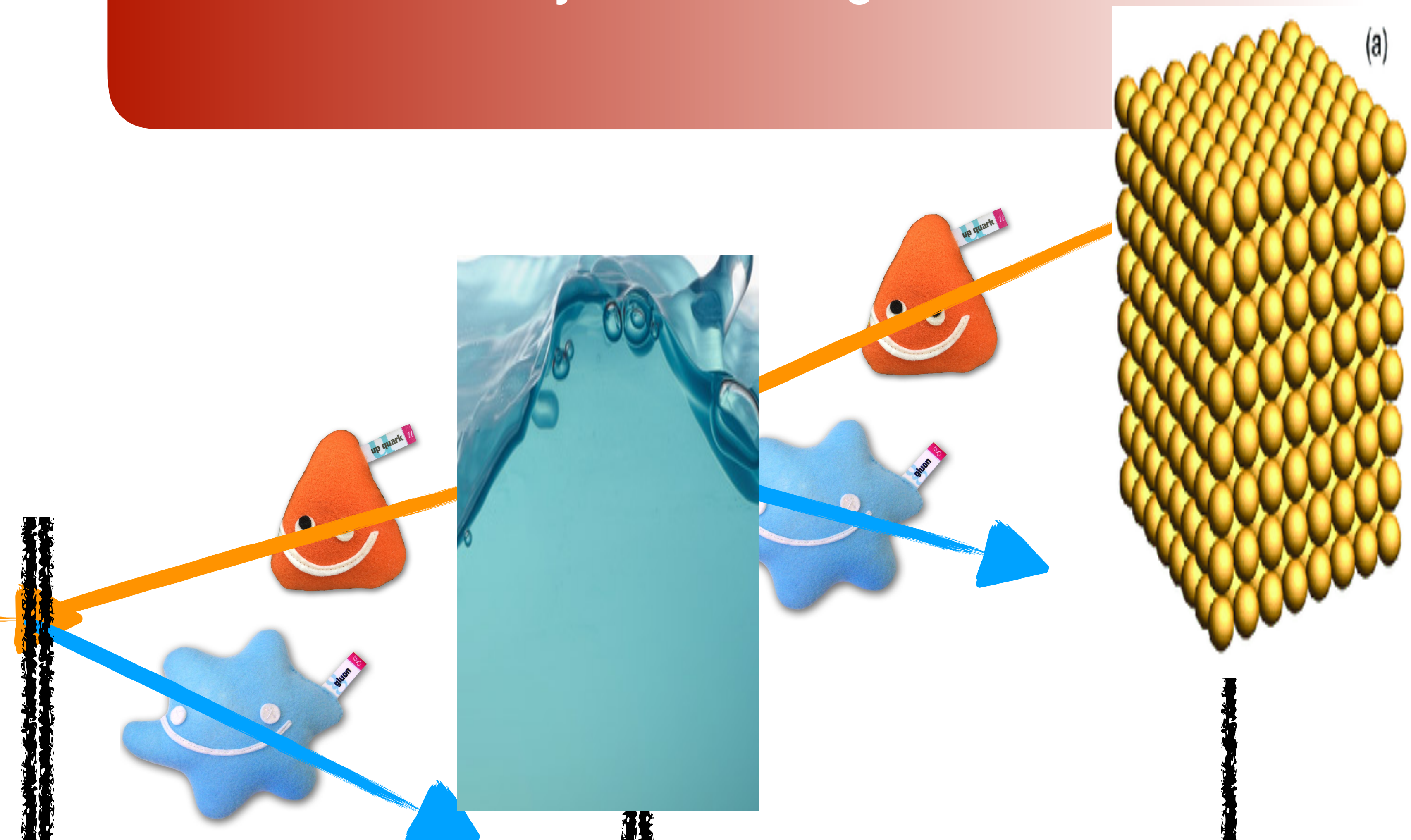


Verweij, QM 17

STAR and CMS are probing very different formation times. No overlap density of scattering centers

evolution of splits





Very early formation times - Does not see any medium activity

Depending on the split - first interaction with the medium

Medium expansion occurring concurrently with jet evolution