Jet Substructure through Splitting Functions in pp and PbPb collisions at 5.02 TeV with CMS

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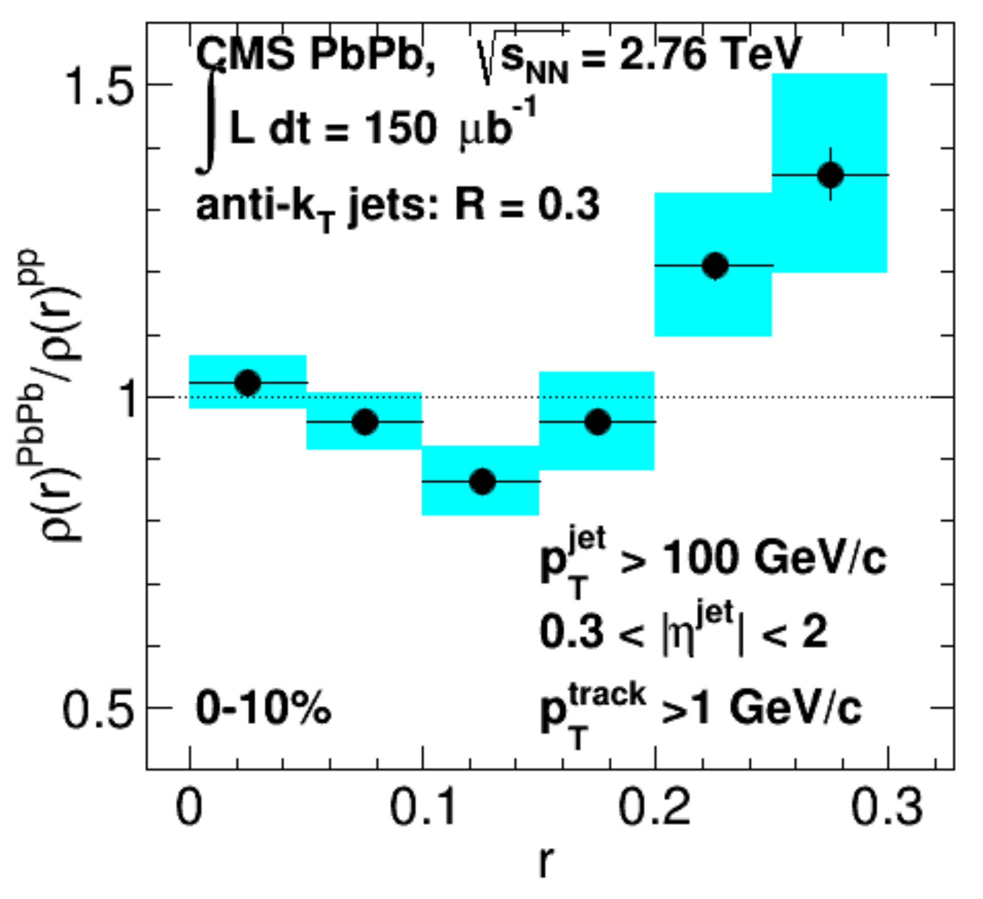
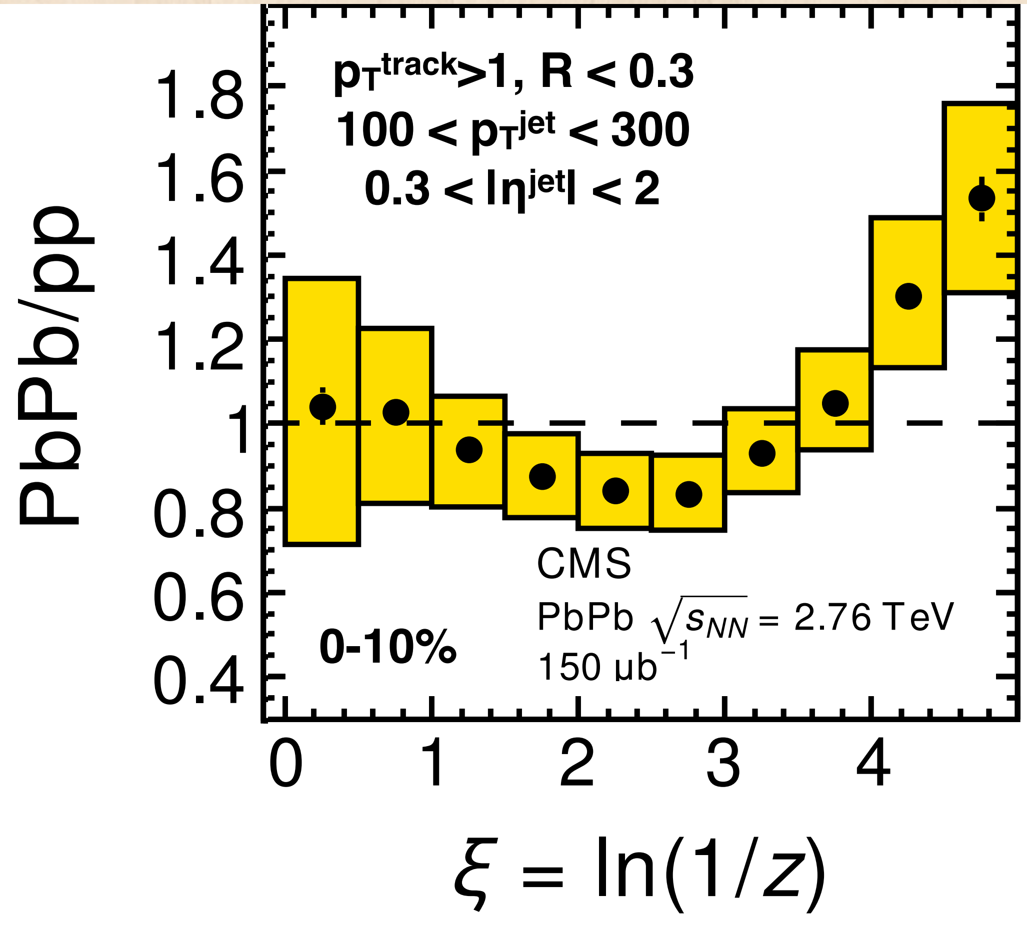
QM2017, Feb 7, 2017

Jet Structure in Run I

Measurement of the jet shape

Measurement of the jet fragmentation function (multiplicity as a function of p_T fraction to jet)

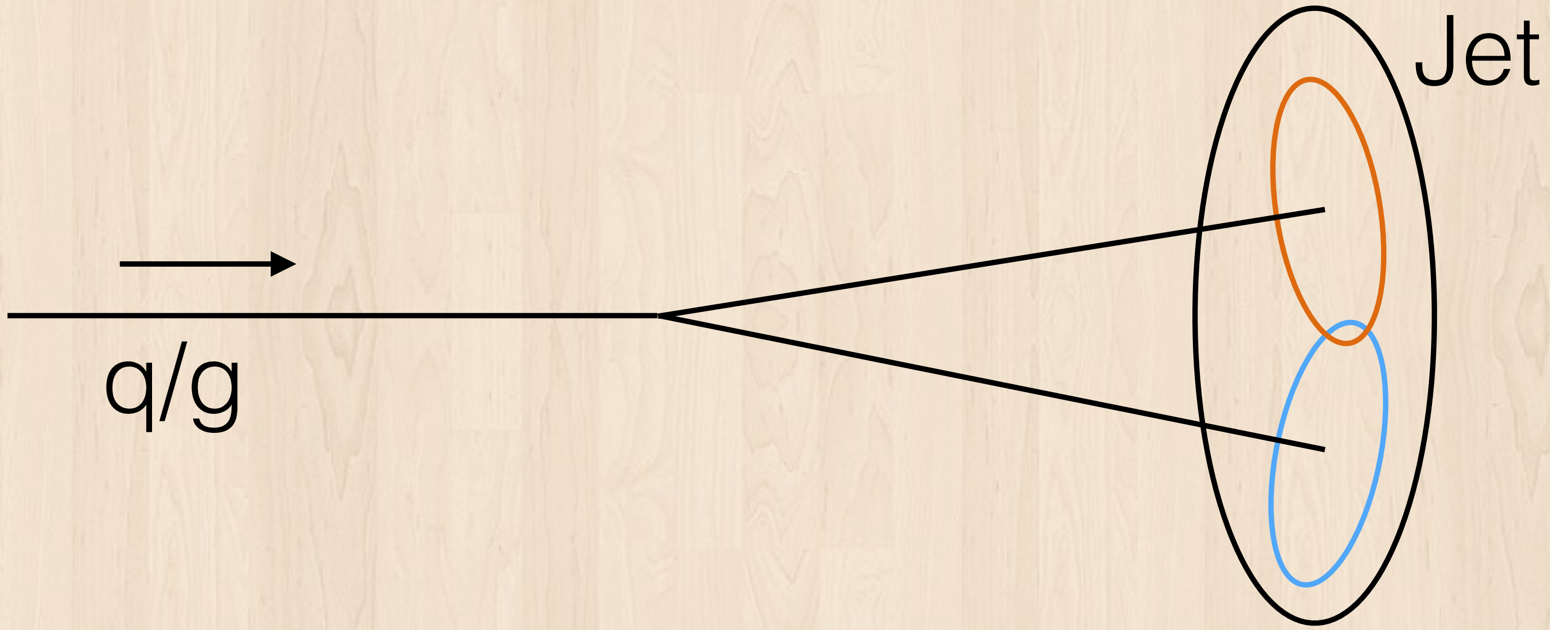




CMS HIN 12-002, CMS HIN 12-013

Hard splitting

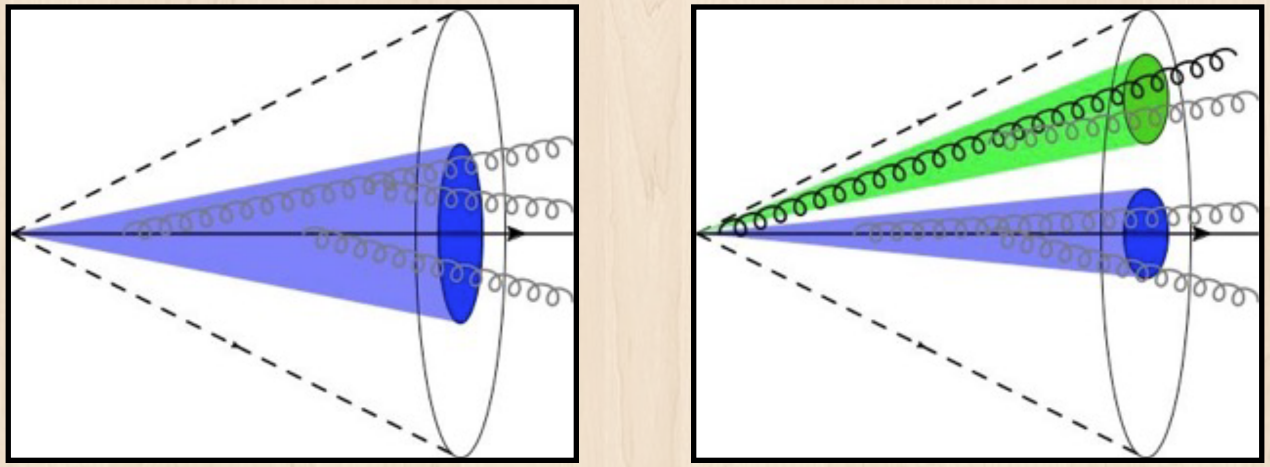
At the first hard splitting level, what can we measure?



1. Overall energy loss — e.g. di-jet imbalance
2. Relative energy loss — shared momentum fraction
3. Opening angle — correlated with jet mass

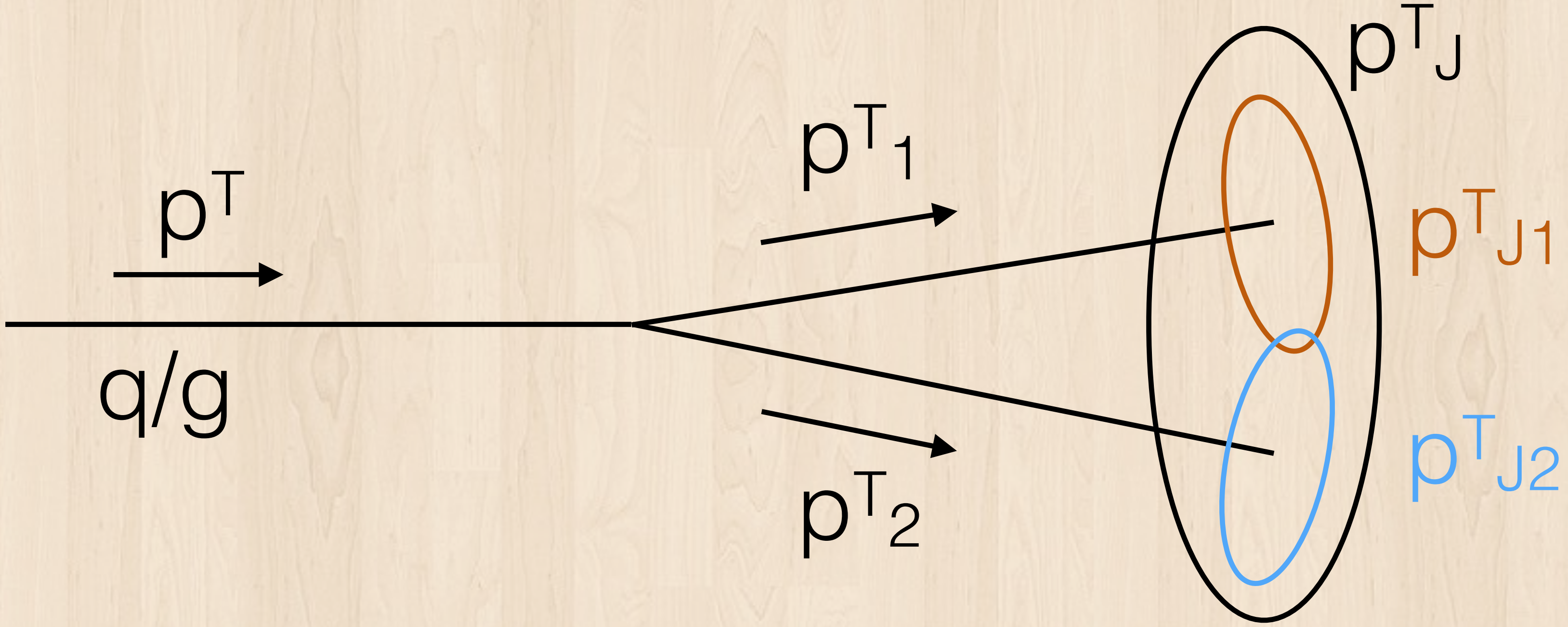
Why relative energy loss?

- Probes important properties of the medium
- How would the jet structures be modified when the two partons interact with the medium?
- For example, can the medium resolve the two partons? → color coherence / decoherence



Relative energy loss

How to measure relative energy loss?



1. Define momentum sharing $z_g^{\text{true}} = \frac{\min(p_1^T, p_2^T)}{p_1^T + p_2^T}$
2. We want to compare z_g^{true} with observed z_g from reconstructed sub-jets: $z_g = \frac{\min(p_{J1}^T, p_{J2}^T)}{p_{J1}^T + p_{J2}^T}$

Relative energy loss

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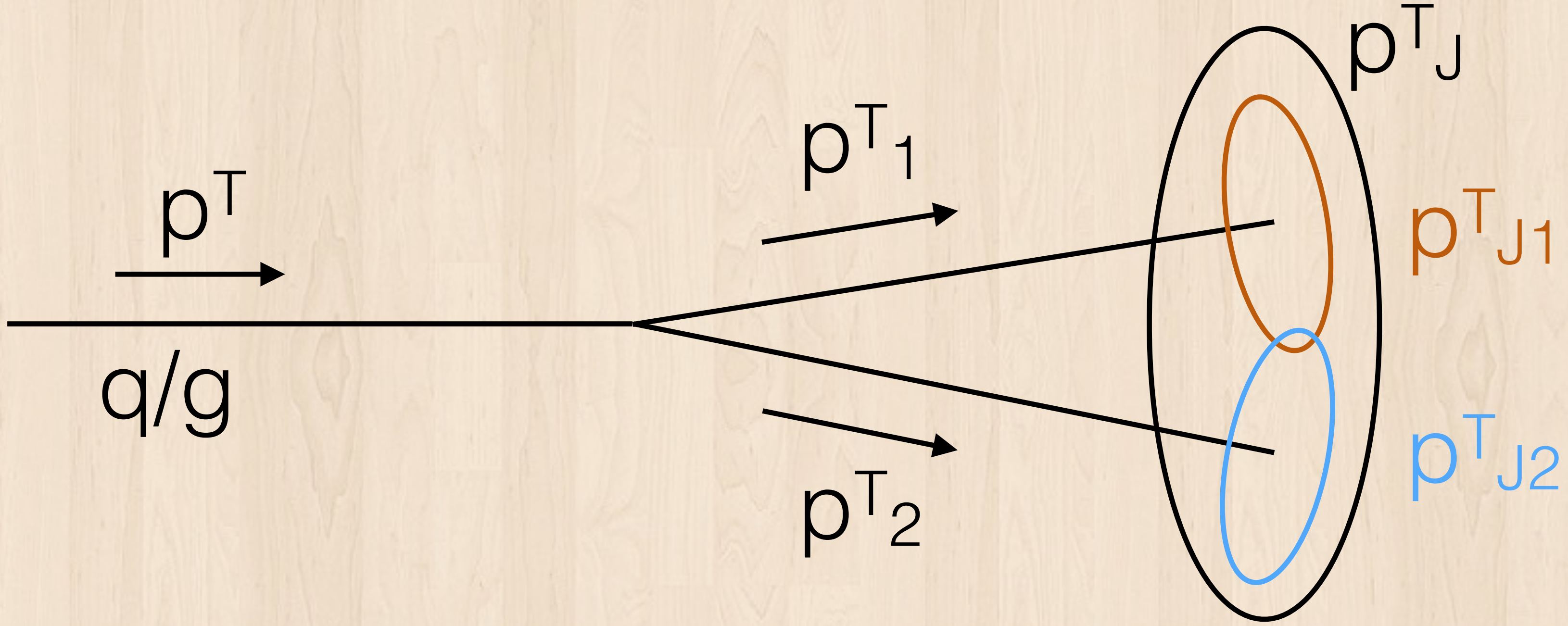

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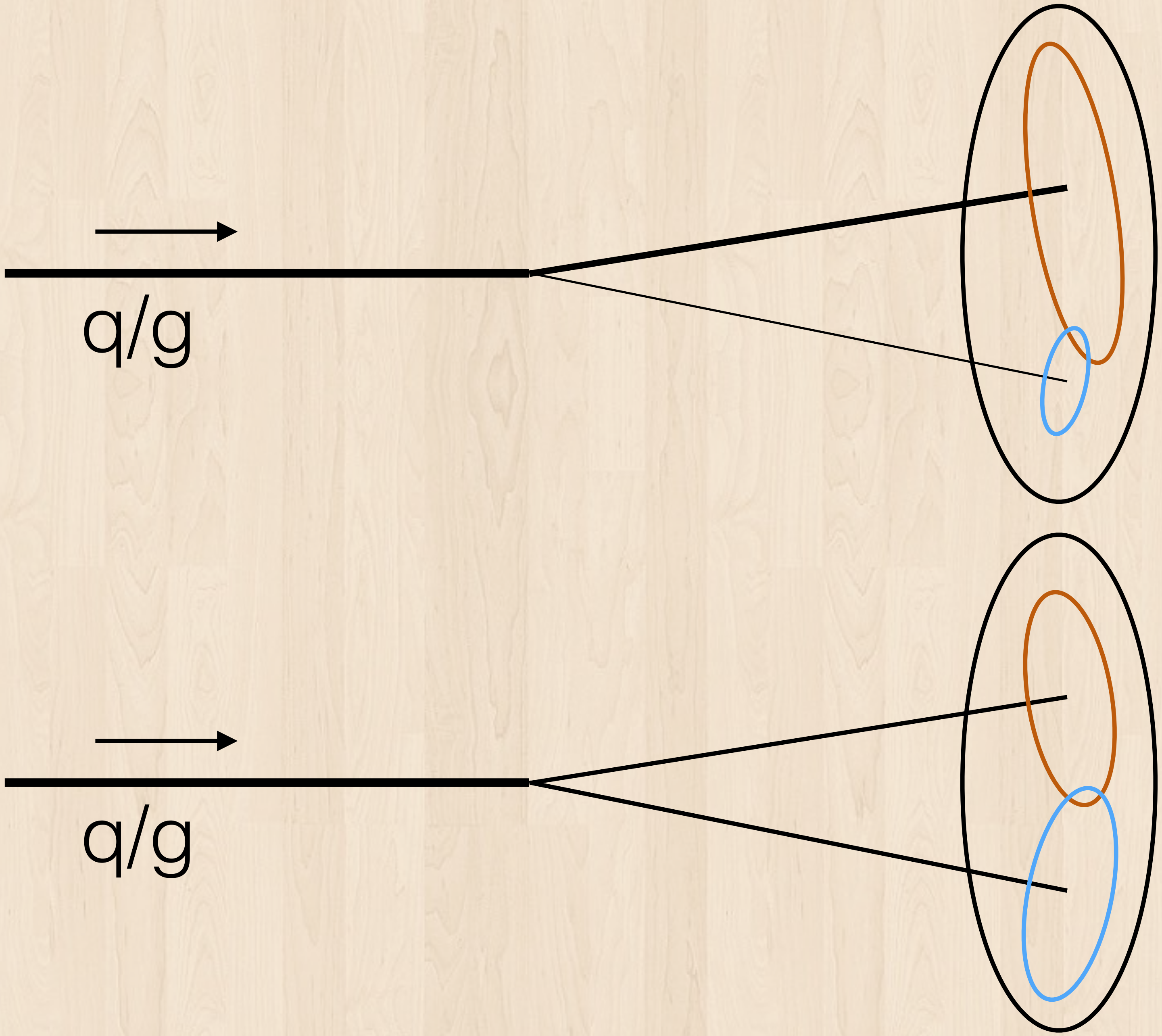
Related to the Altarelli-Parisi splitting function

Momentum sharing



Uneven momentum sharing: z_g small

Even momentum sharing: z_g large ~ 0.5

Analysis Overview

Goal of the analysis: is there modification in PbPb?

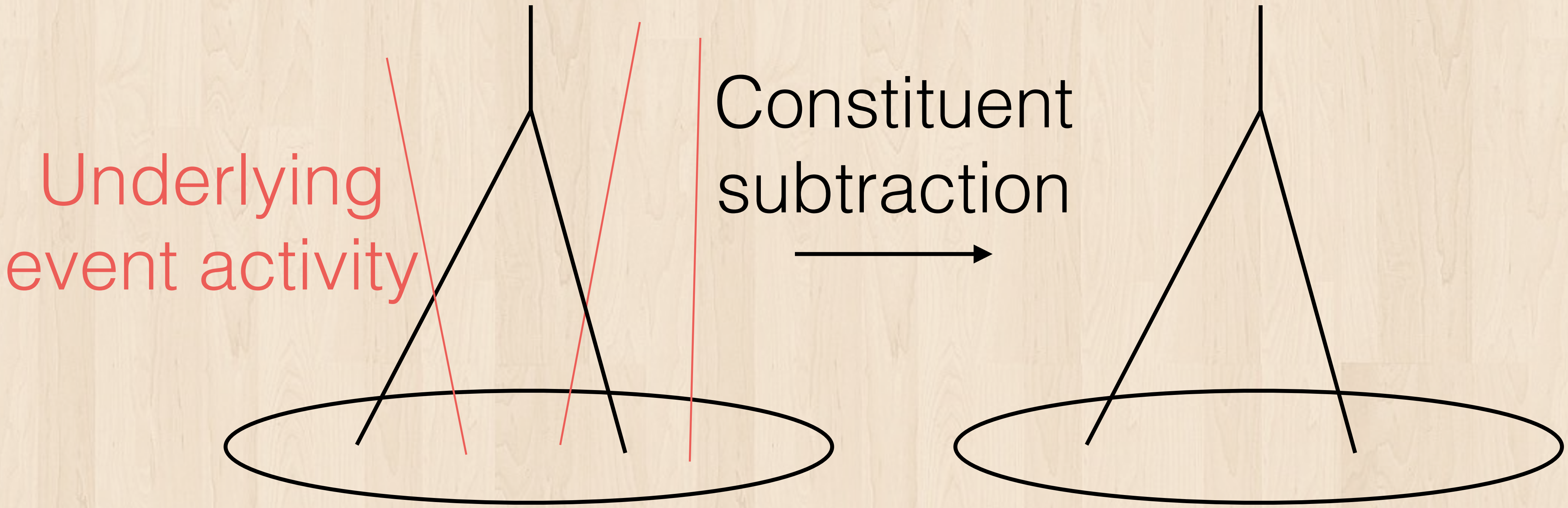
pp data $\longrightarrow$ z_g^{pp} = true z_g + detector

PbPb data $\longrightarrow$ z_g^{PbPb} = true z_g + medium + detector

Measure observed distribution in PbPb and compare with pp

Jet finding

- We use particle flow jets clustered with the anti-k_T algorithm and radius $R_{jet} = 0.4$, jet $|\eta| < 1.3$
- Perform a particle-level constituent subtraction to remove contribution from underlying event activity



Arxiv: 1403.3108, Berta et al.

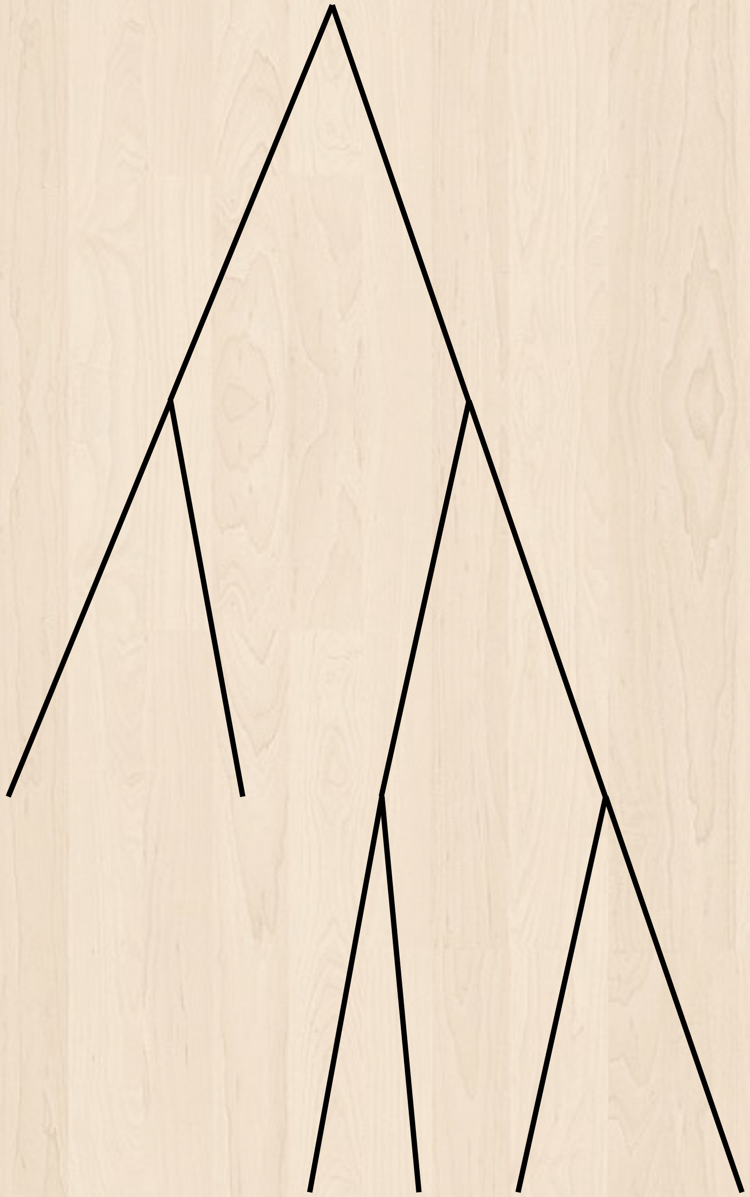
Jet grooming

- In addition to removing residual effect from underlying event and soft radiations, we perform jet grooming to further clean up the jet

- We use the soft drop algorithm
    - Allows us to focus on the hard structure of the jet by removing soft parts of the jet

JHEP 1405 (2014) 146, Larkoski et al

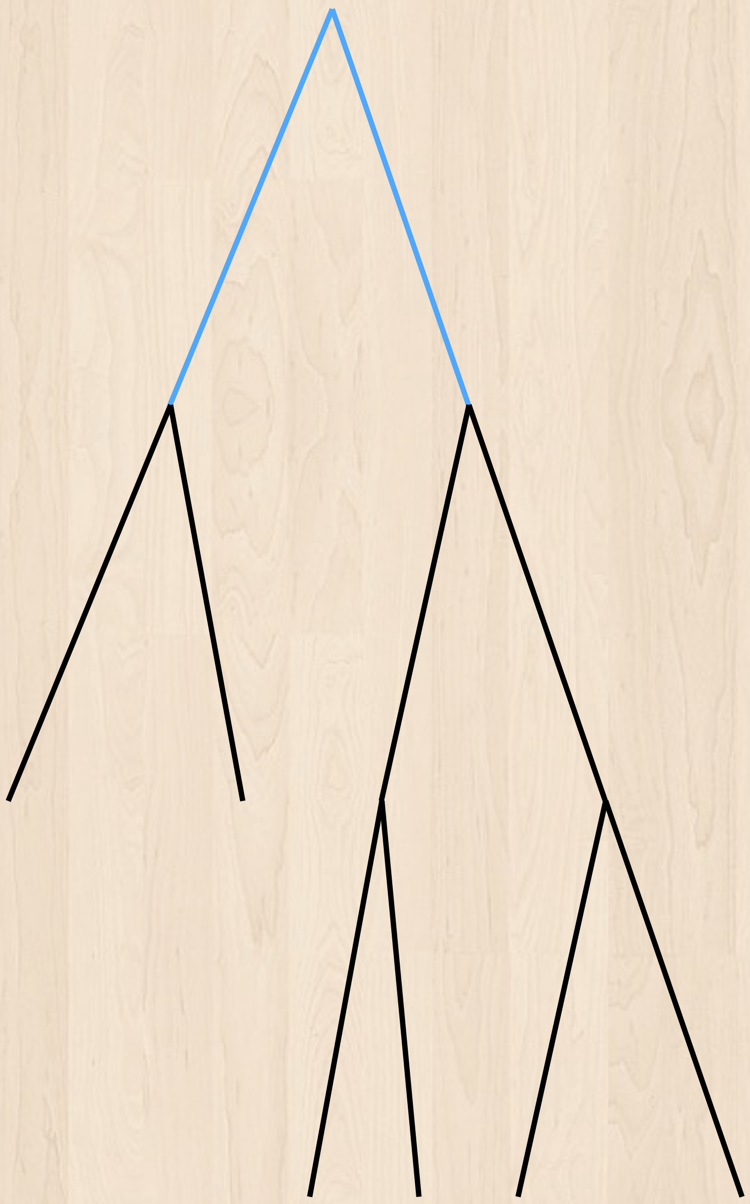
Soft drop algorithm



1. Build angular-ordered binary tree from jet constituents

JHEP 1405 (2014) 146, Larkoski et al

Soft drop algorithm



1. Build angular-ordered binary tree from jet constituents
2. From the root node, examine if the two children satisfy the soft drop condition

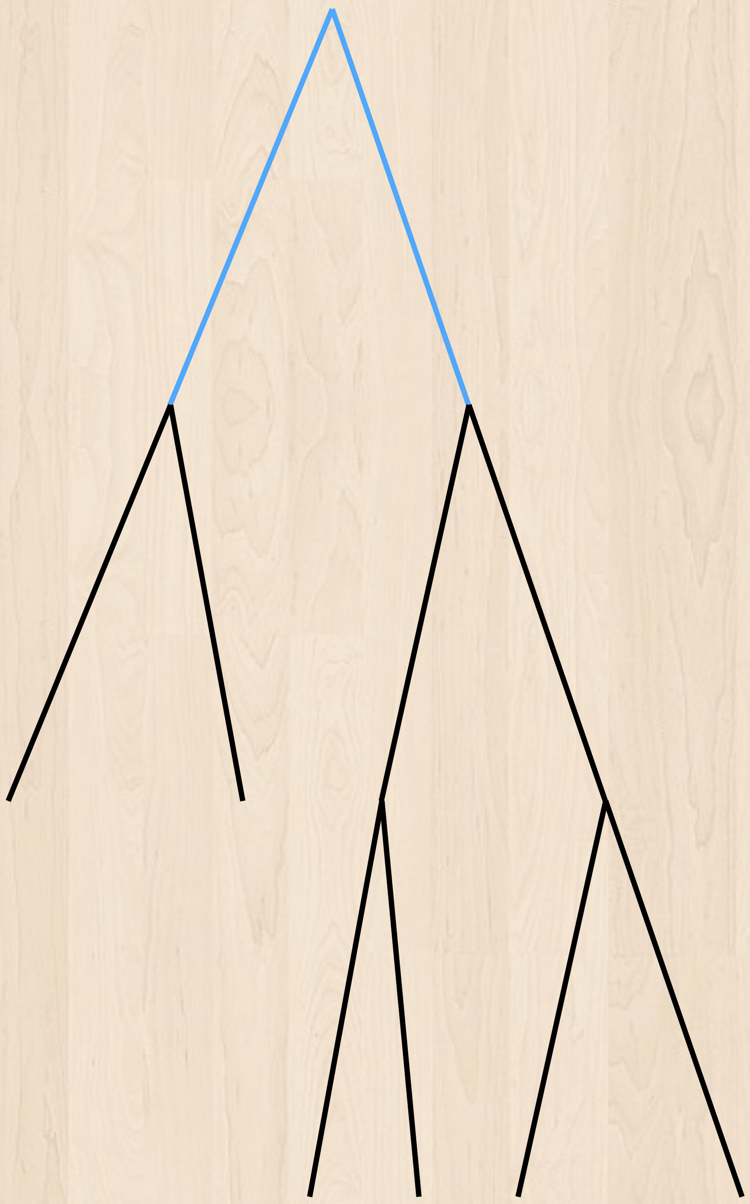
$$z_g \geq z_{\text{cut}} \left(\frac{\Delta R}{R_{\text{jet}}} \right)^{\beta}$$

Threshold on z_g

Angular dependence

JHEP 1405 (2014) 146, Larkoski et al

Soft drop algorithm



1. Build angular-ordered binary tree from jet constituents
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Free parameters

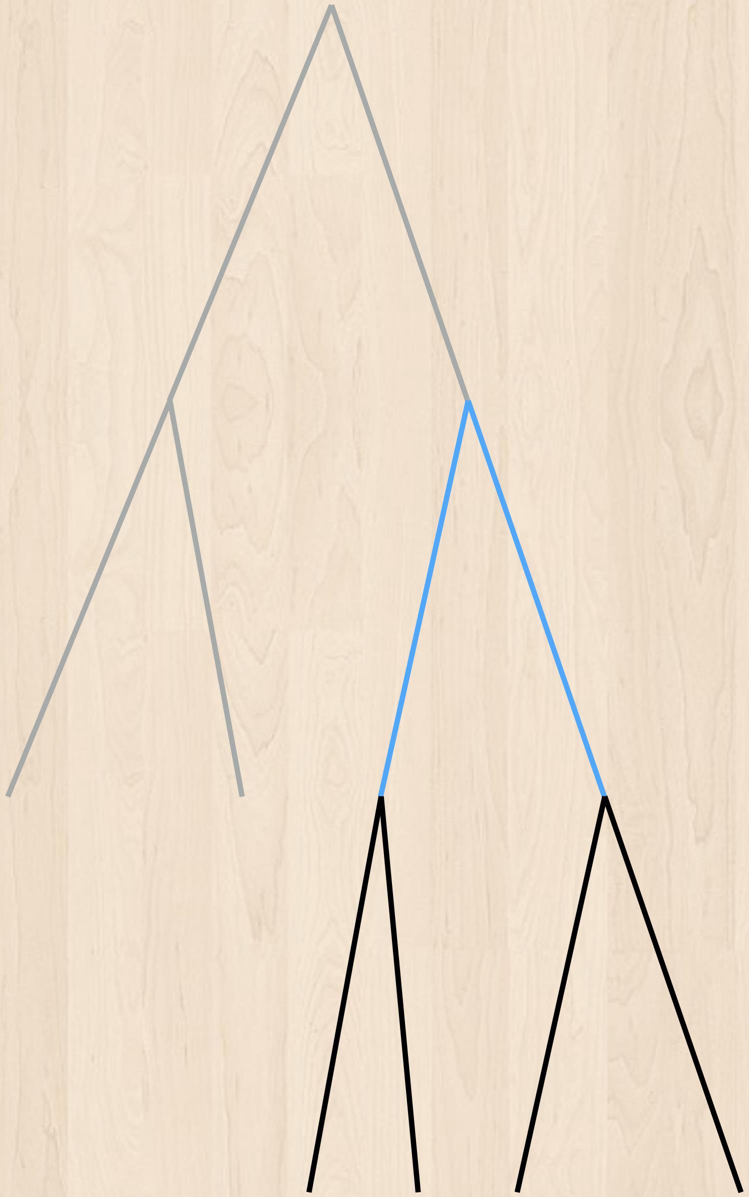
$$z_g \geq z_{\text{cut}} \left(\frac{\Delta R}{R_{\text{jet}}} \right)^{\beta}$$

Threshold on z_g

Angular dependence

JHEP 1405 (2014) 146, Larkoski et al

Soft drop algorithm

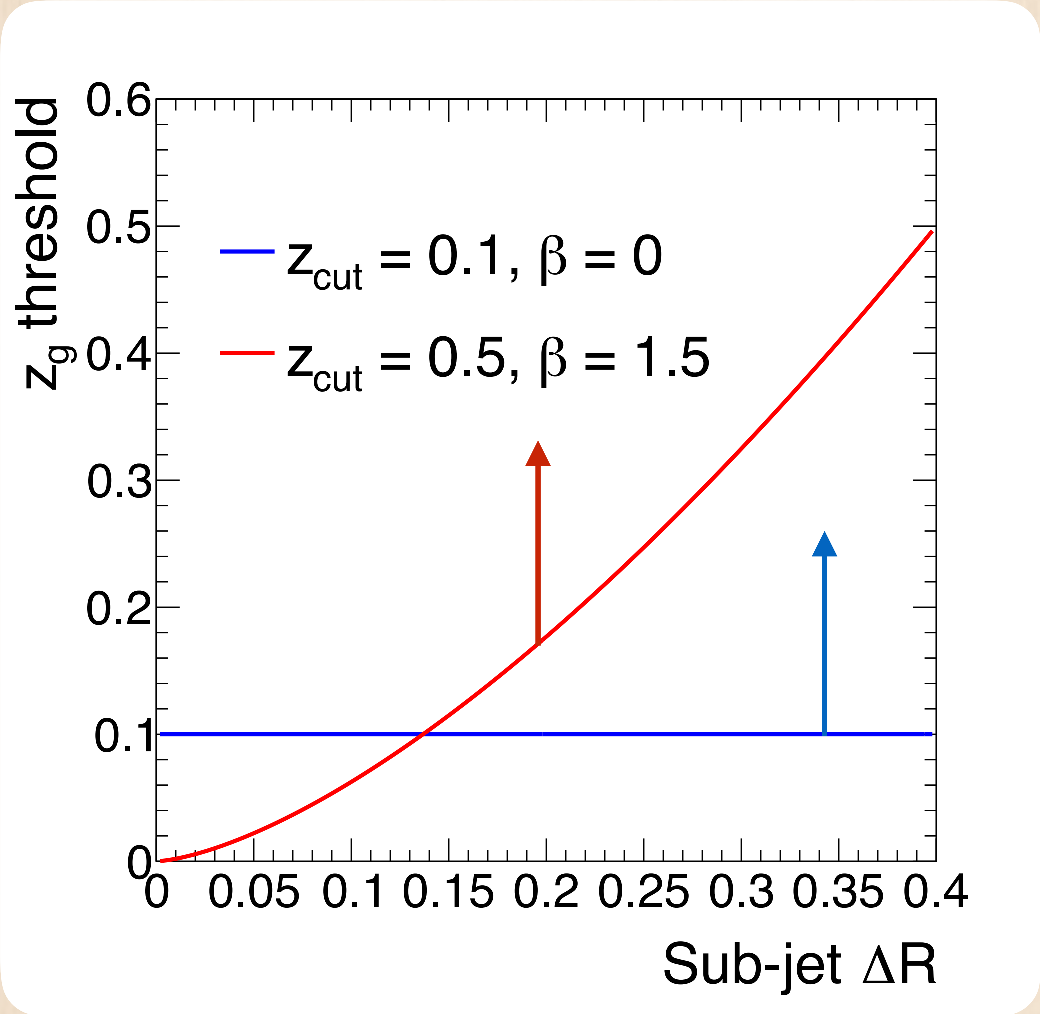


1. Build angular-ordered binary tree from jet constituents
2. From the root node, examine if the two children satisfy the soft drop condition
   - Not satisfied → discard smaller branch and repeat with larger branch
   - Satisfied → terminate algorithm

JHEP 1405 (2014) 146, Larkoski et al

Phase space

Different choices of z_{cut} and β probes different phase space of the jet

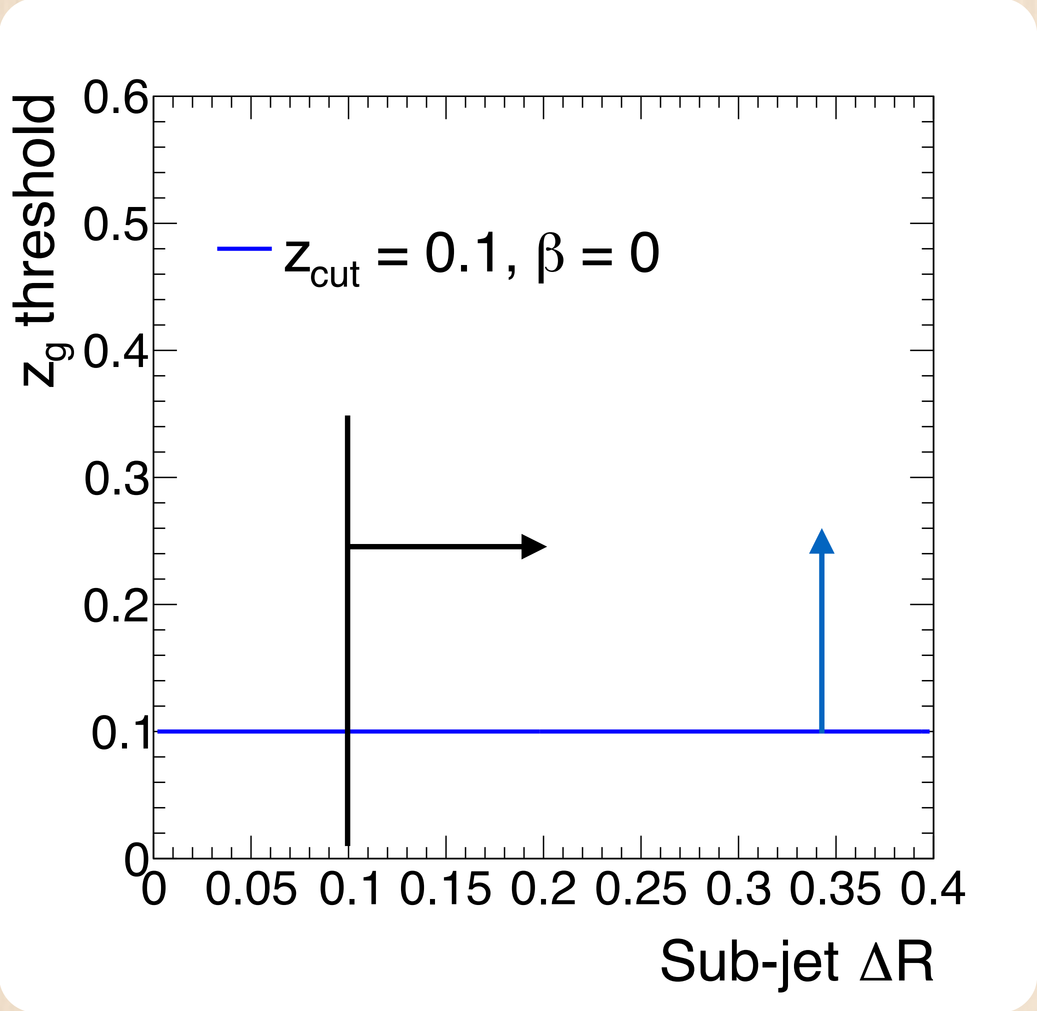


- z_{cut} = 0.1, β = 0.0
  Universal z_{cut} with no dependence on angle — used in this analysis

- z_{cut} = 0.5, β = 1.5
  Focus more on the small angle structure of the jet

Phase space

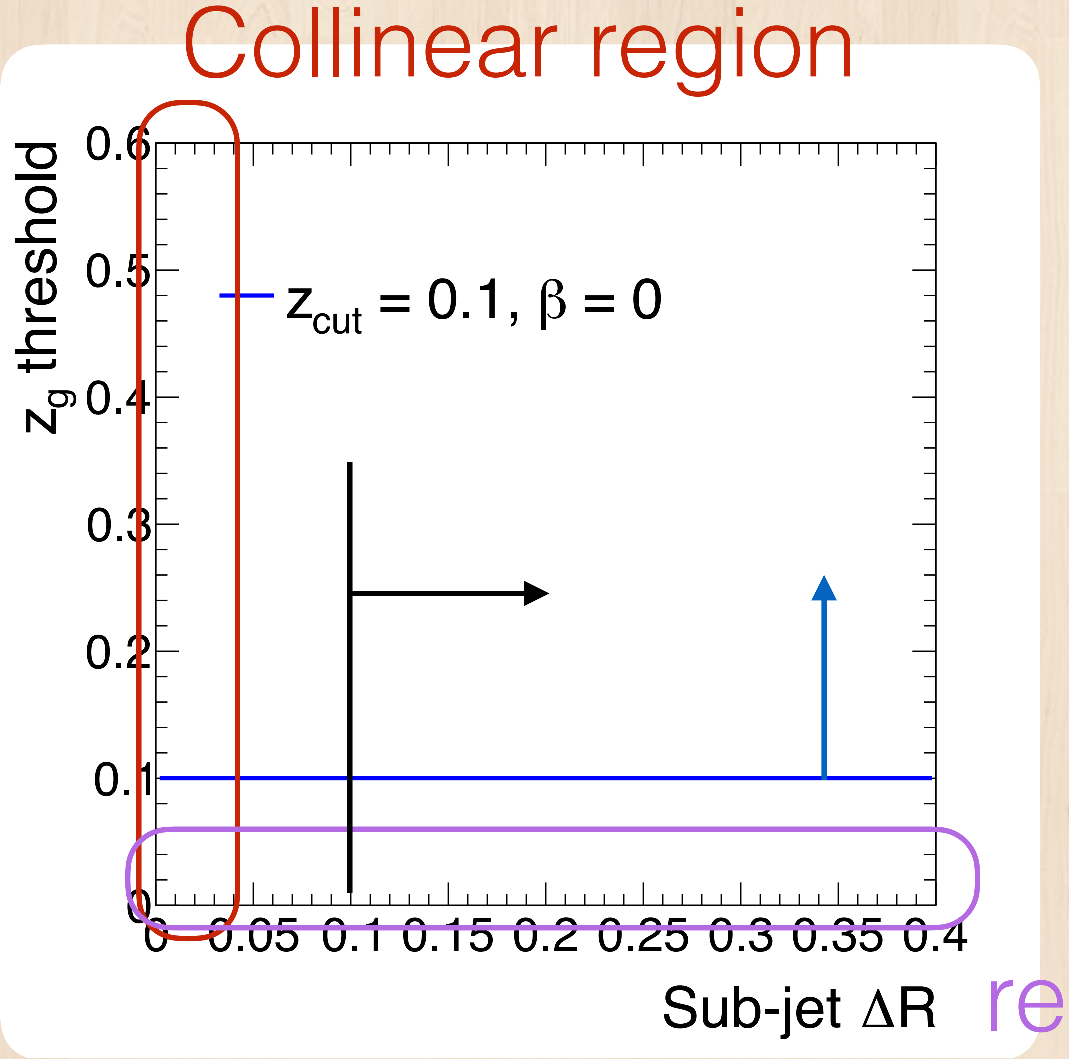
Different choices of z_{cut} and β probes different phase space of the jet



A cut of ΔR > 0.1 is also used in the analysis

Phase space

Different choices of z_{cut} and β probes different phase space of the jet



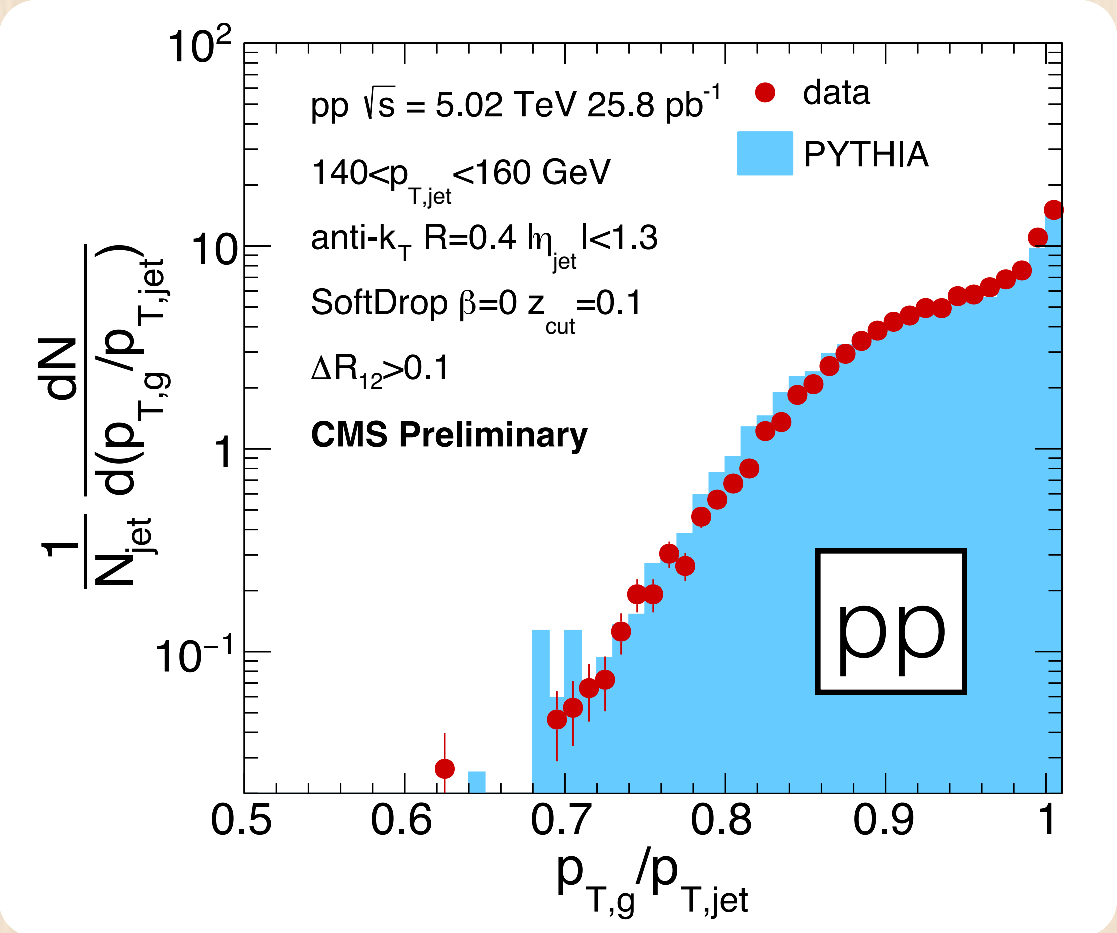
A cut of $\Delta R > 0.1$ is also used in the analysis — mainly due to detector granularity, and also avoiding the collinear region

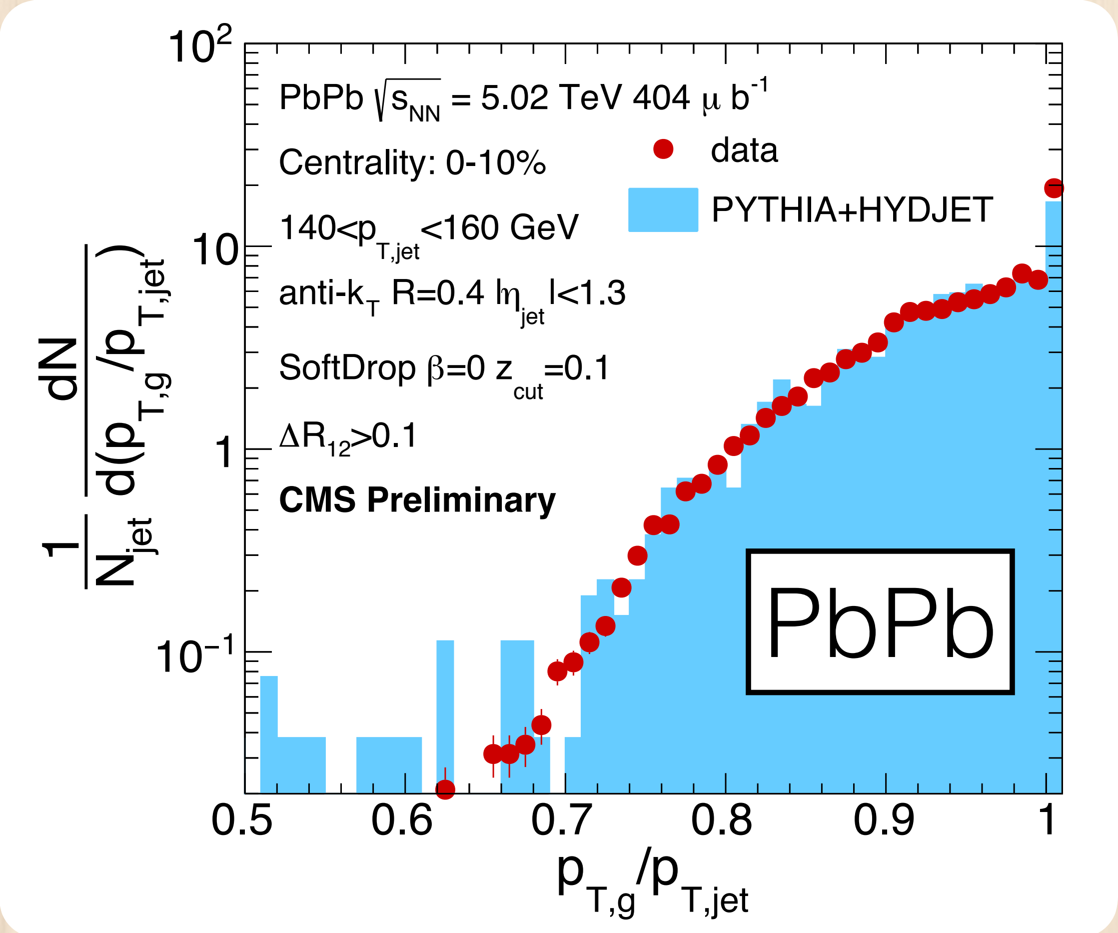
Soft region / residual background

Groomed energy fraction

Groomed jet p_T / non-groomed jet p_T

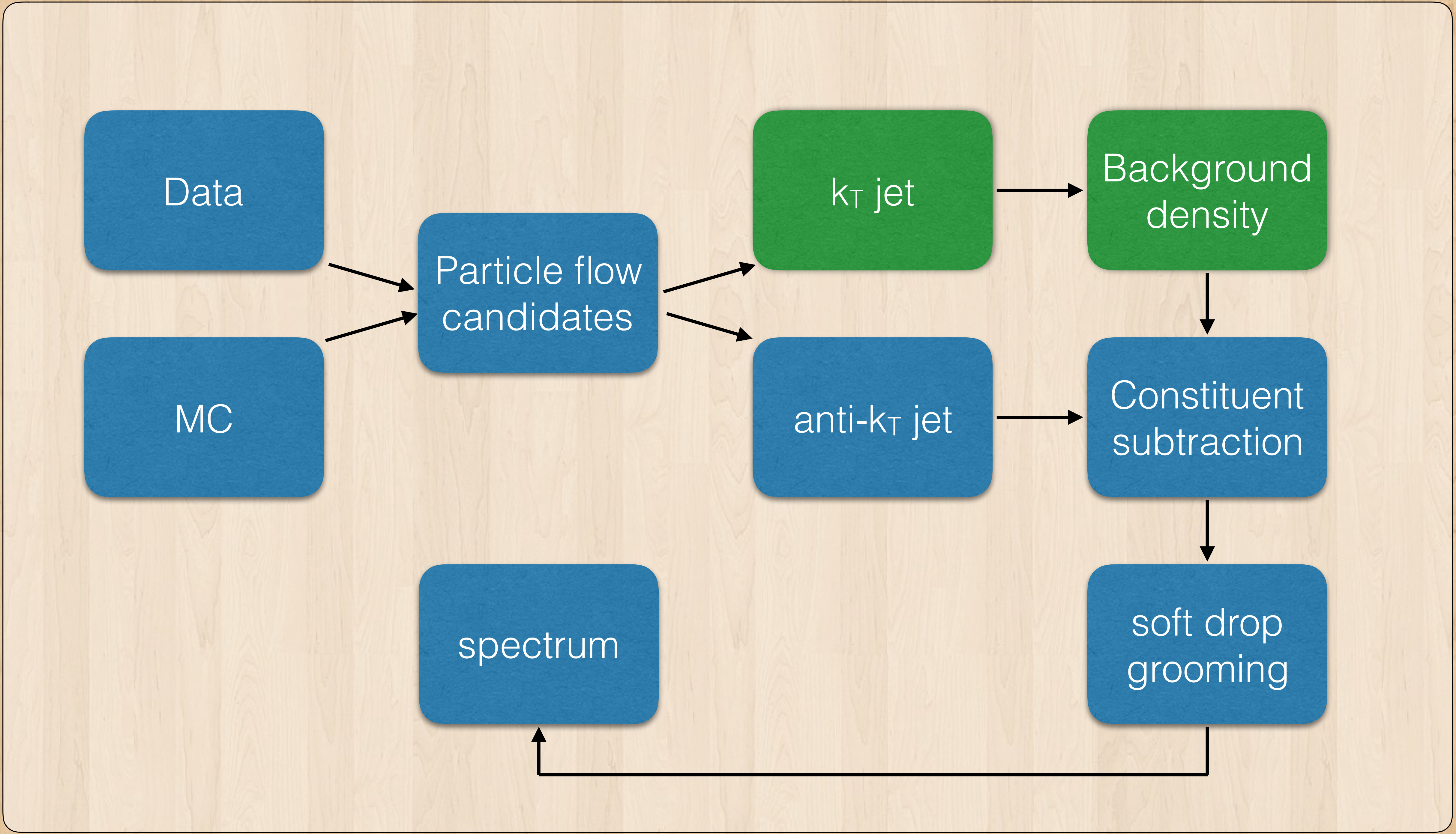
Data is well reproduced by MC





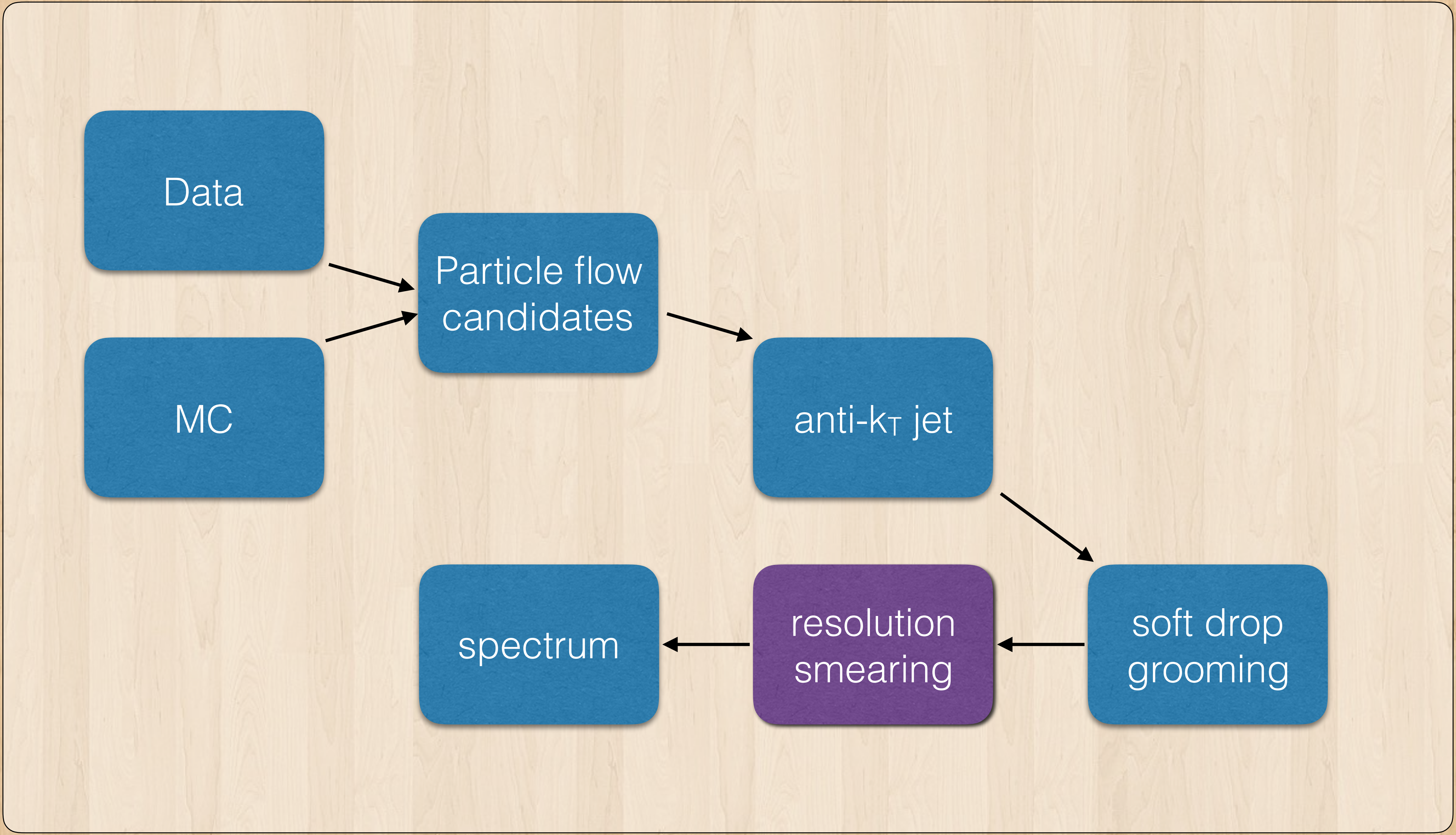
CMS PAS HIN 16-006

Analysis flow (PbPb)



Phys. Rev. Lett. 110, 162001, Soyez et al; CMS HIN 16-006

Analysis flow (pp)



Data

MC

Particle flow candidates

anti-k_T jet

soft drop grooming

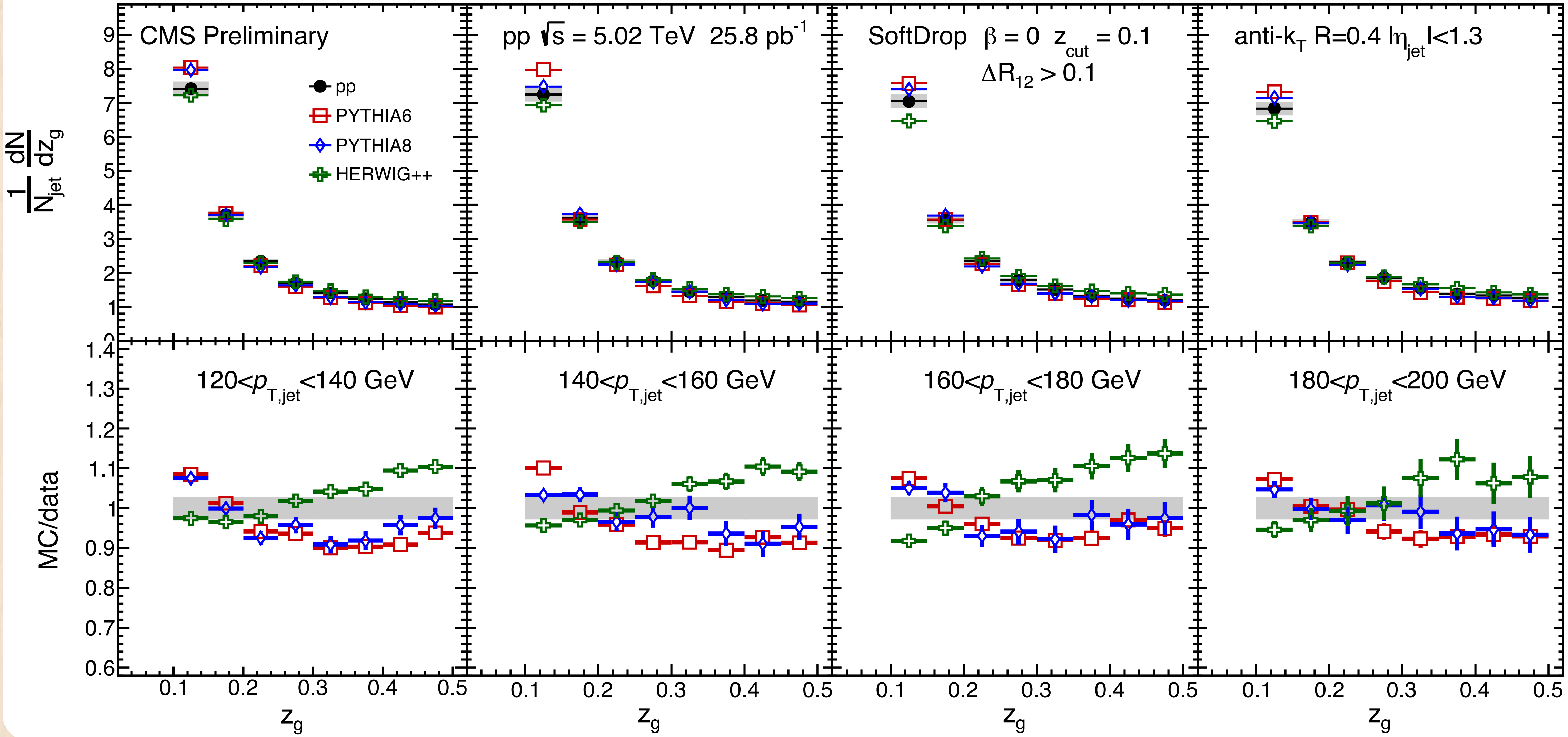
resolution smearing

spectrum

Splitting function in pp

Data agrees within 15% by PYTHIA and HERWIG

$p_{T,jet}$: 120-140 | 140-160 | 160-180 | 180-200



Splitting function in pp

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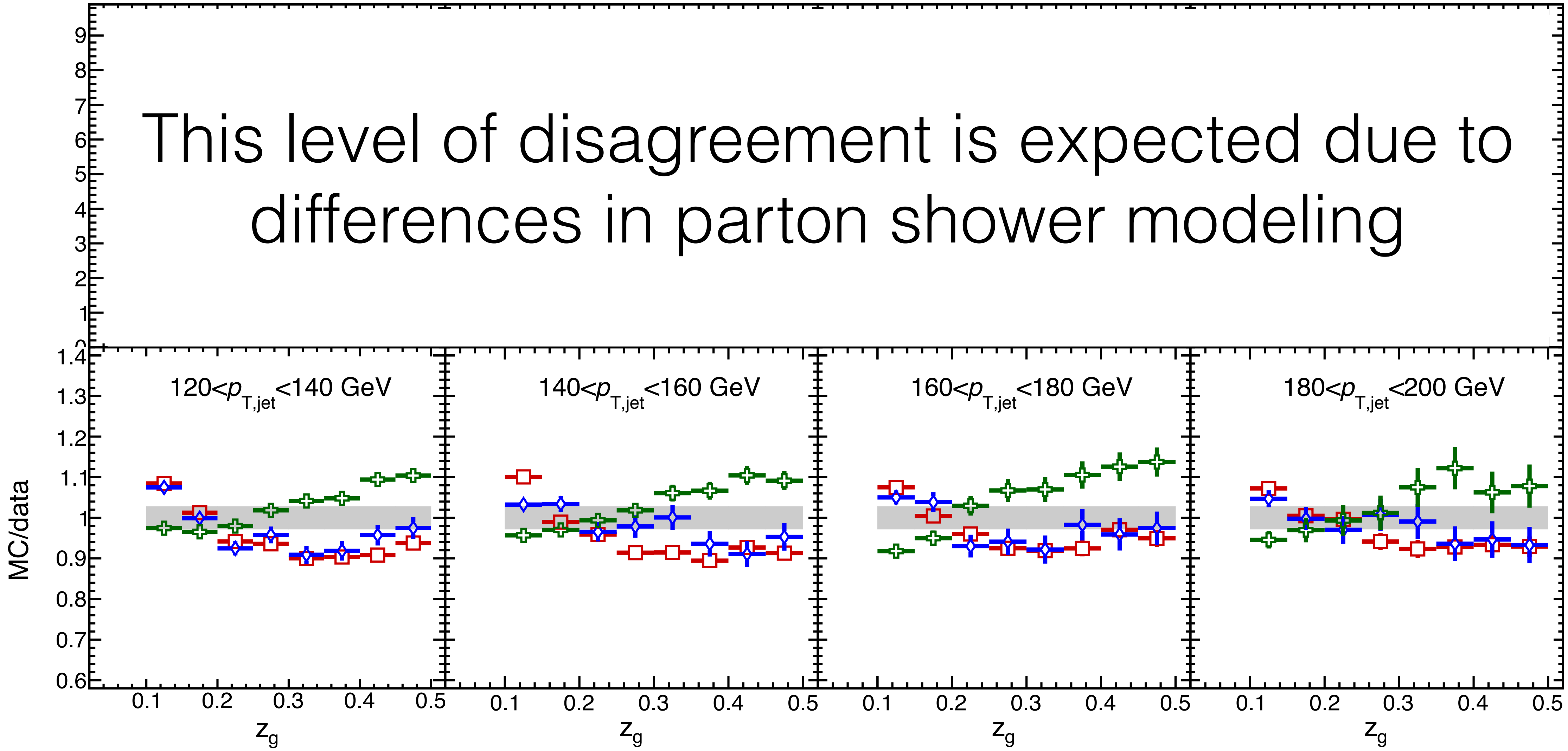
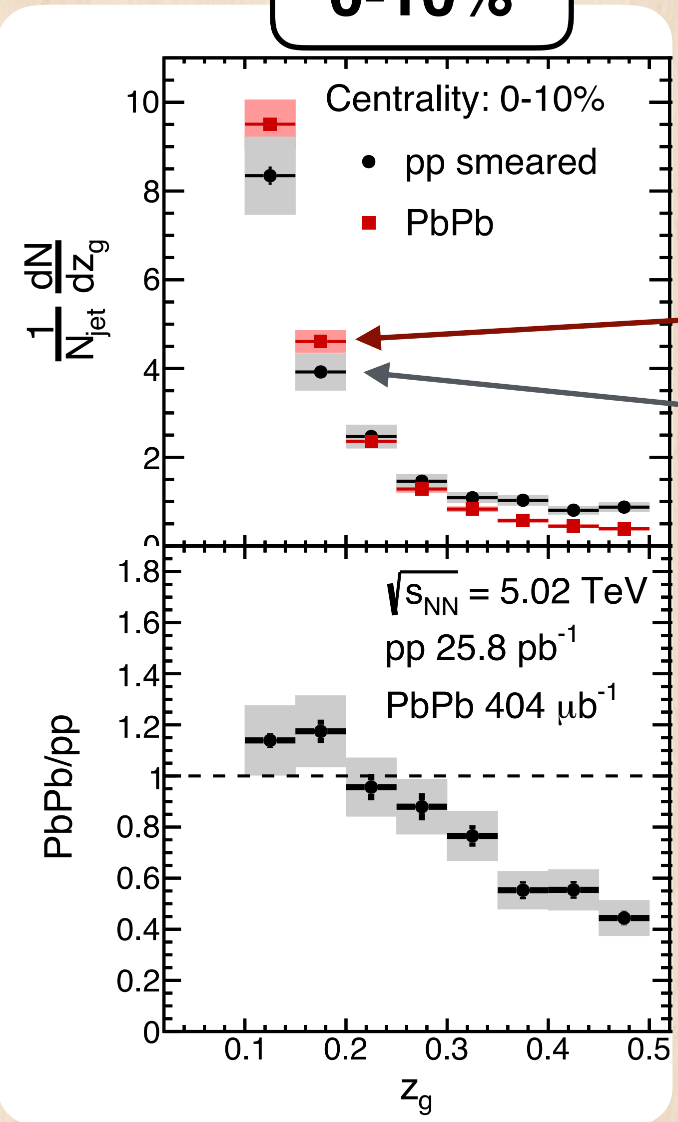


This level of disagreement is expected due to differences in parton shower modeling

PbPb vs pp

$p_{T,jet}$ = 140-160

0-10%



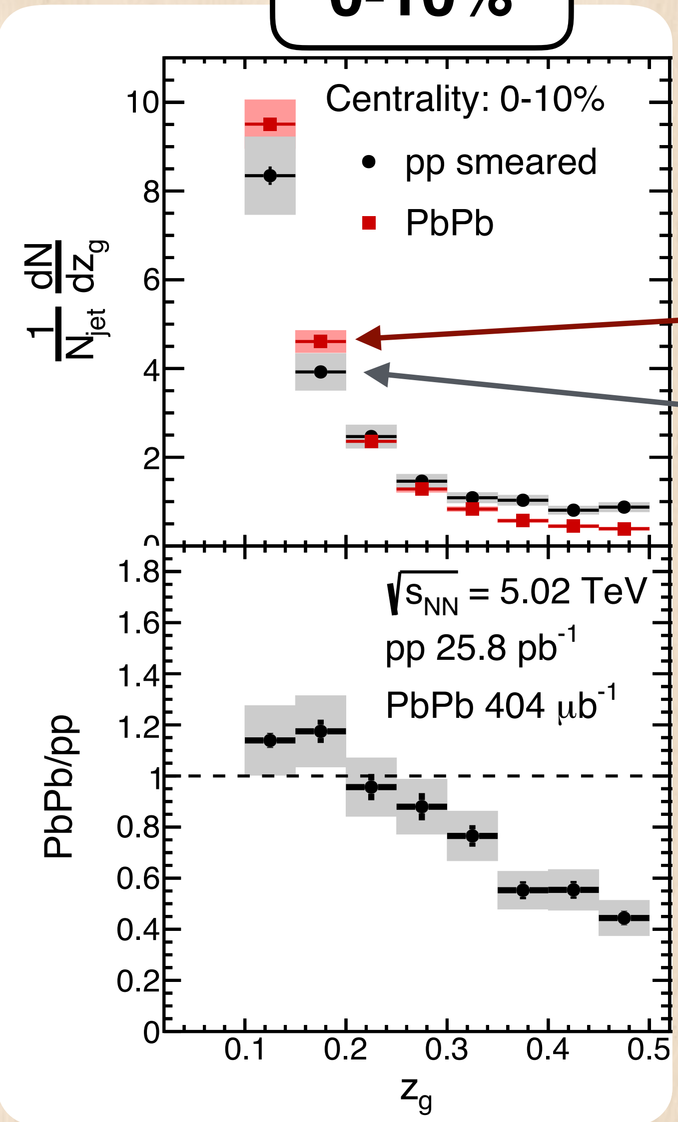
Spectrum of PbPb and pp

Ratio PbPb / pp

PbPb vs pp

$p_{T,jet}$ = 140-160

0-10%



Spectrum of PbPb and pp

Ratio PbPb / pp

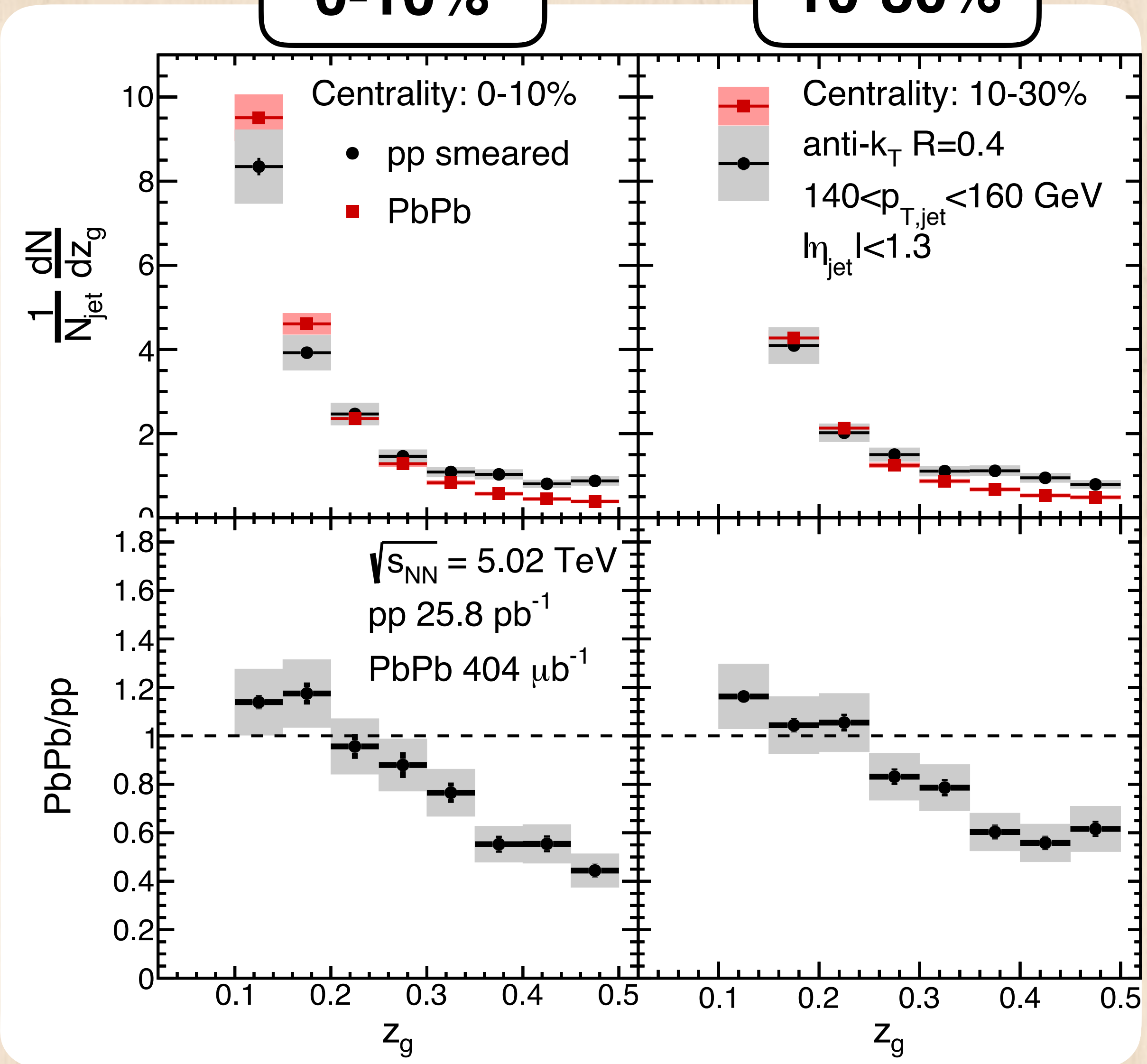
We observe significant deviation for central events

PbPb vs pp

Modification diminishes in peripheral events

0-10%

10-30%



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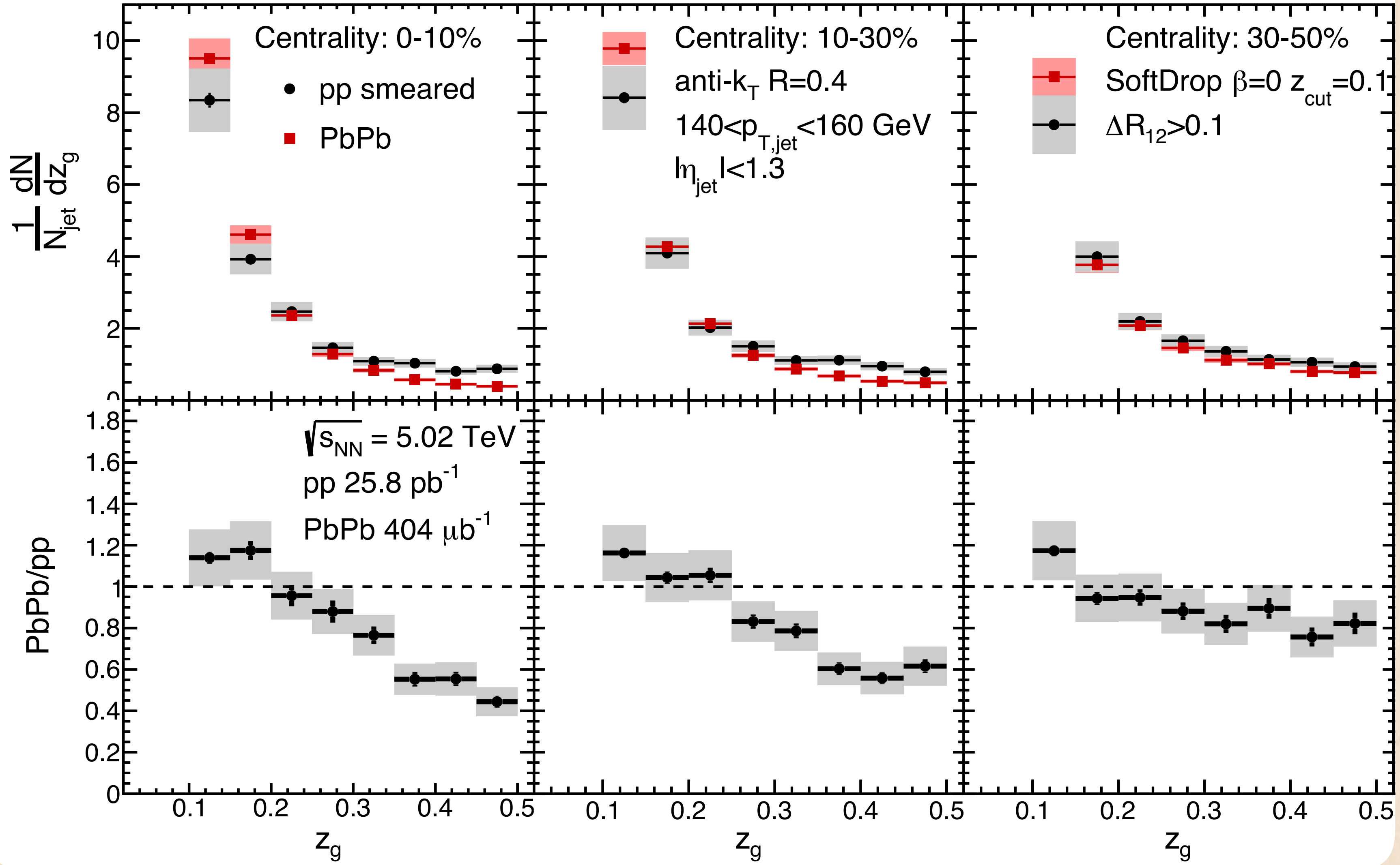
PbPb vs pp

Modification diminishes in peripheral events

0-10% **10-30%** **30-50%**



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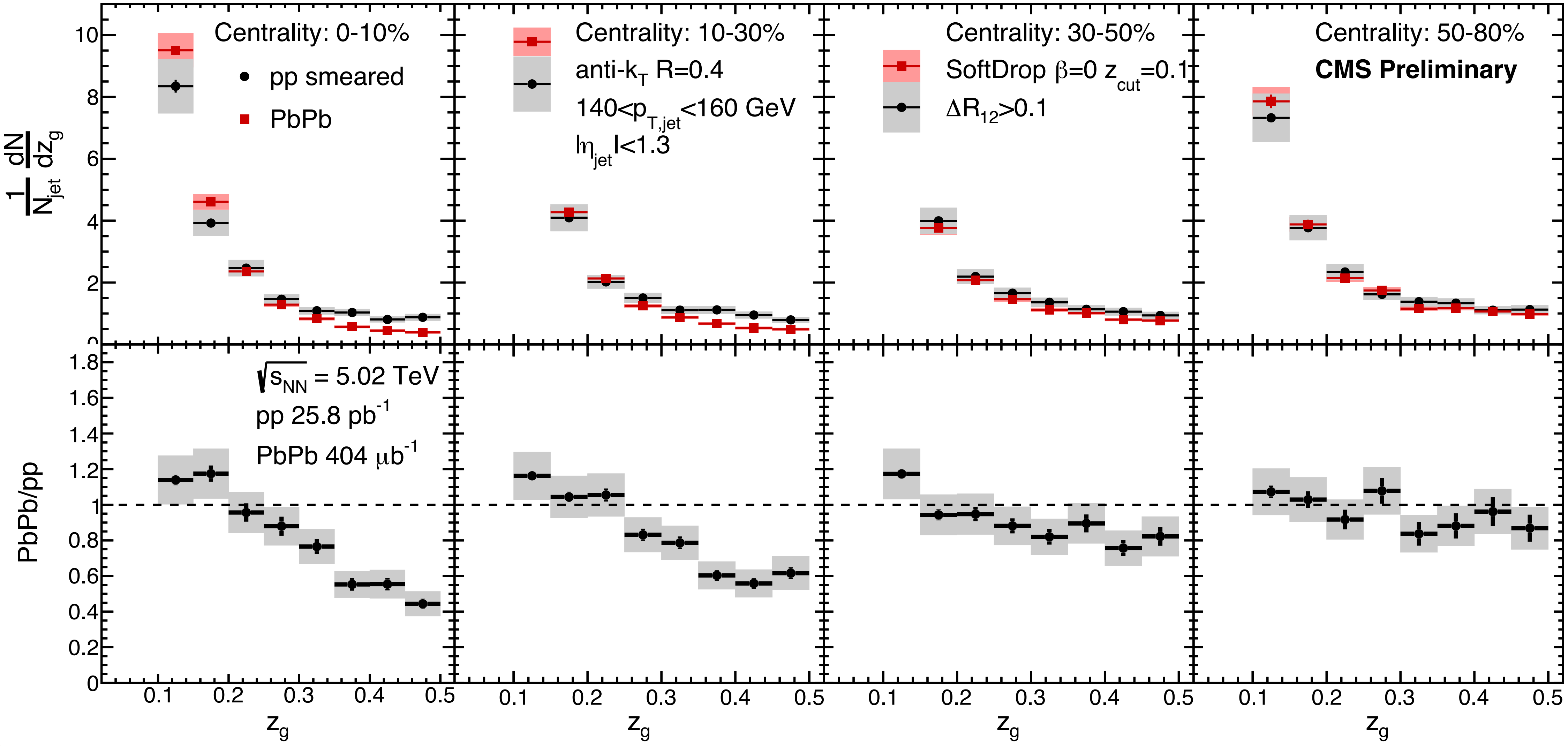
PbPb vs pp

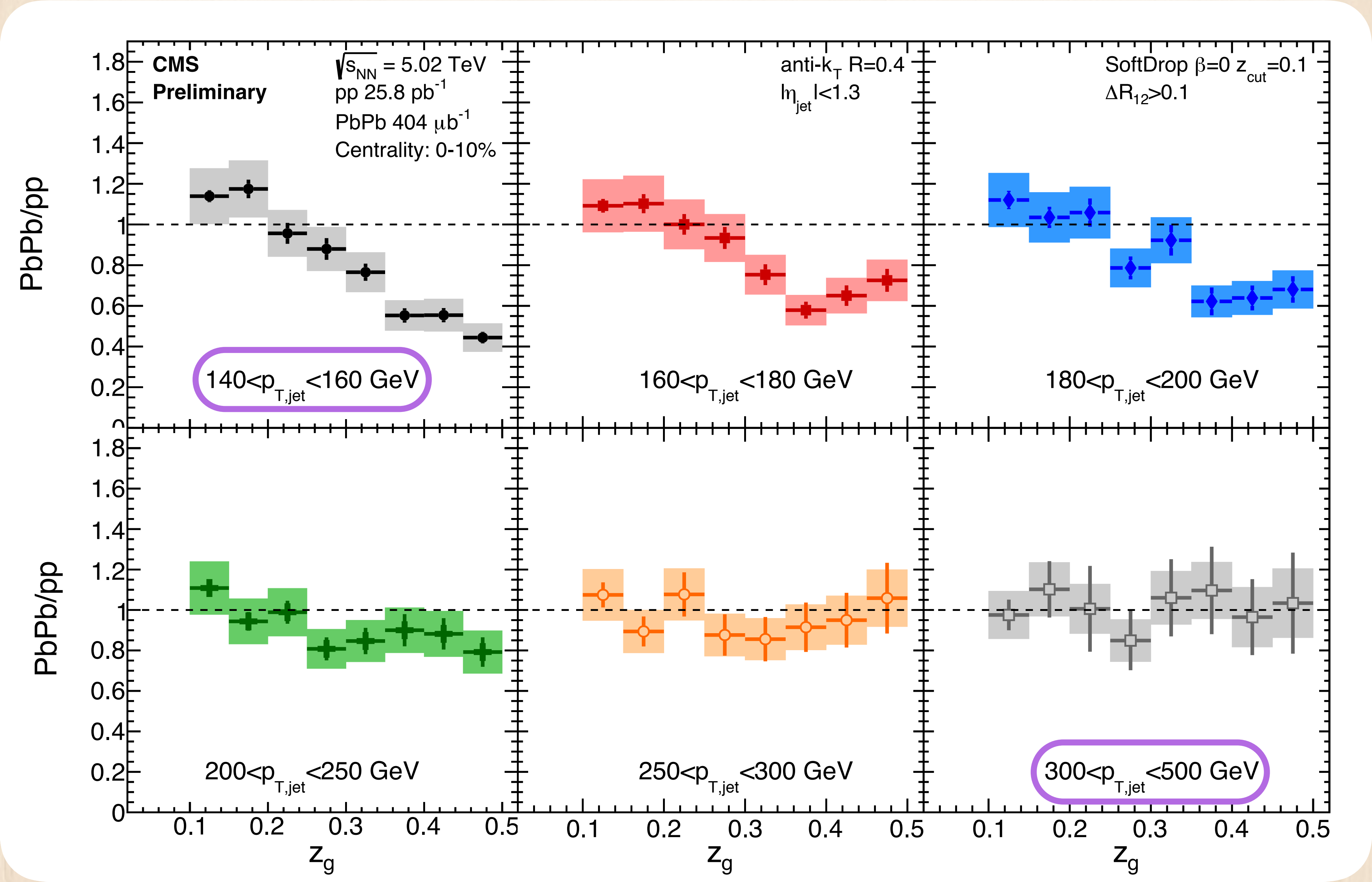
Modification diminishes in peripheral events

0-10% **10-30%** **30-50%** **50-80%**



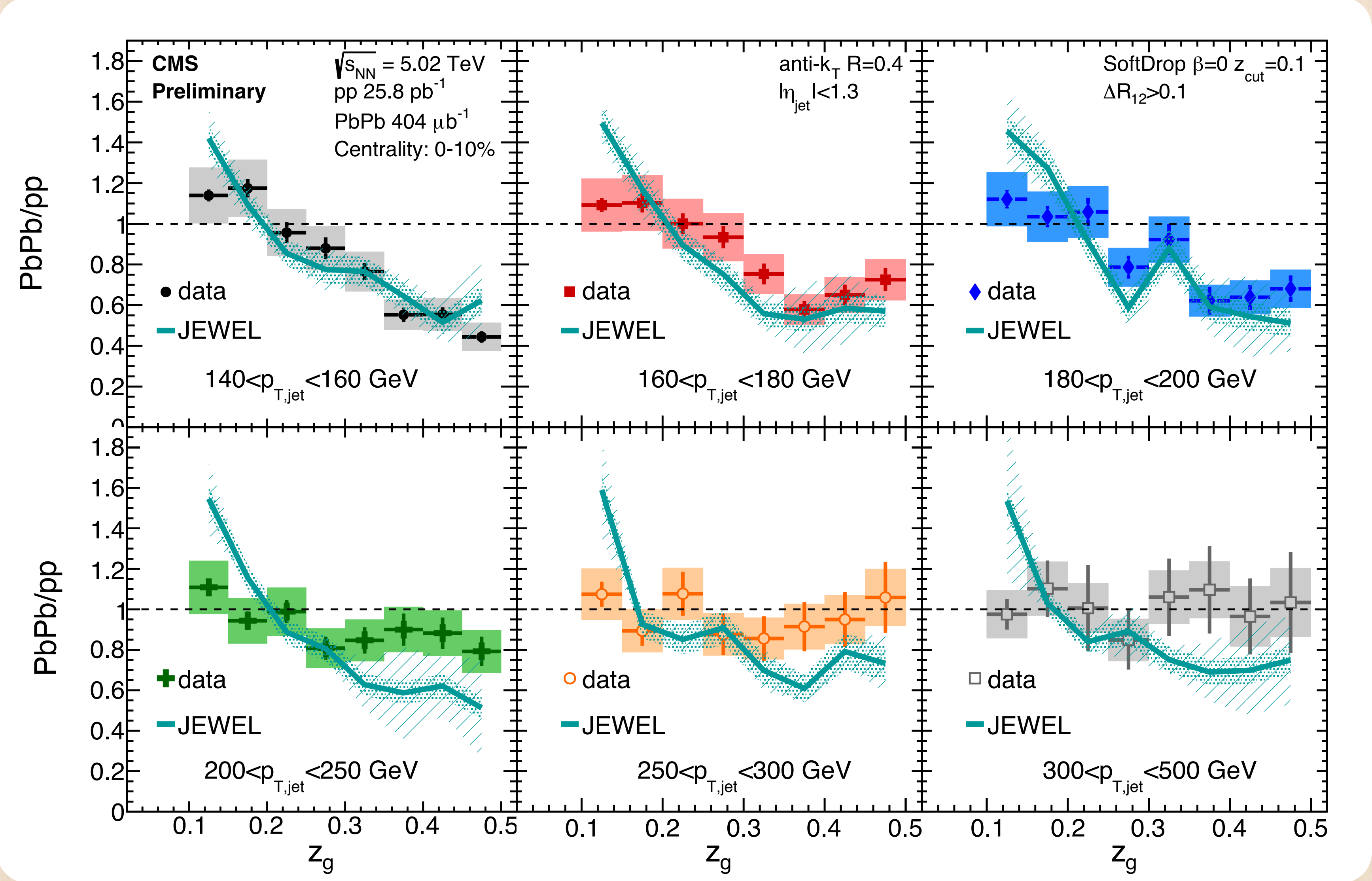
Dependence on Jet p_T

With larger jet p_T, modification appears weaker



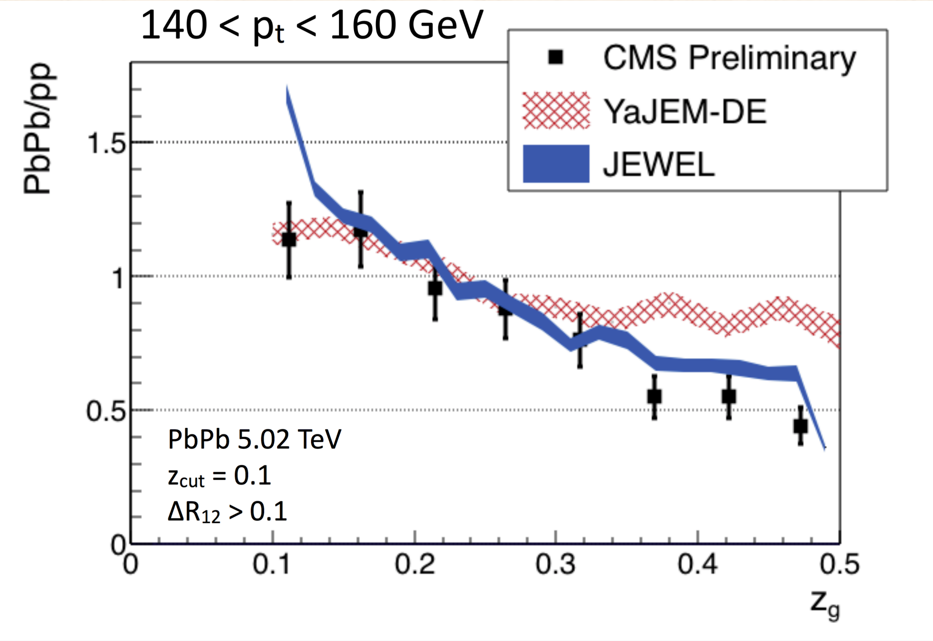
Comparison with JEWEL

General trend described by JEWEL, MC with quenching effect



JHEP03 (2013) 080, Zapp et al

Example of Comparisons



K. Lapidus

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1608.07283

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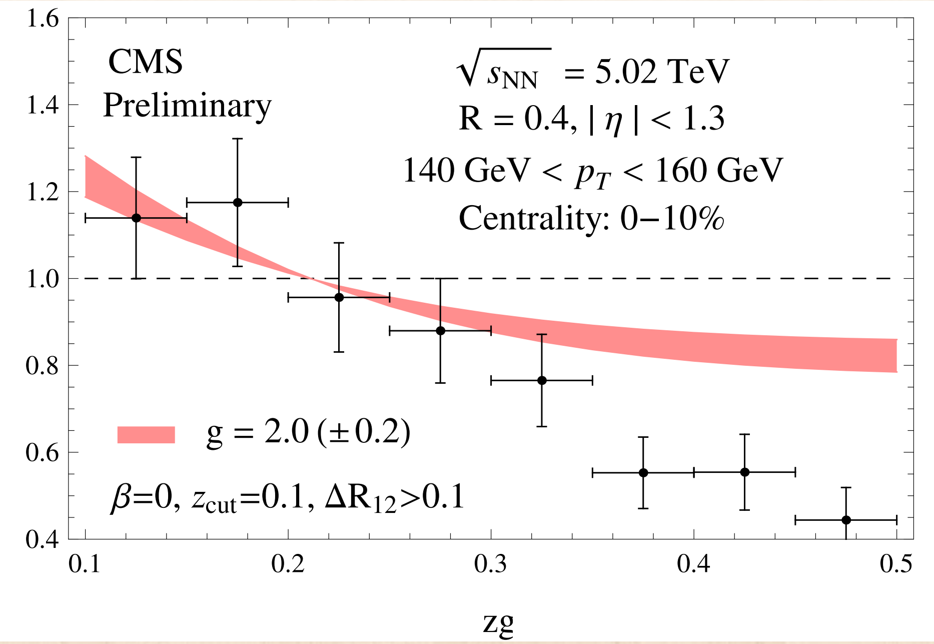

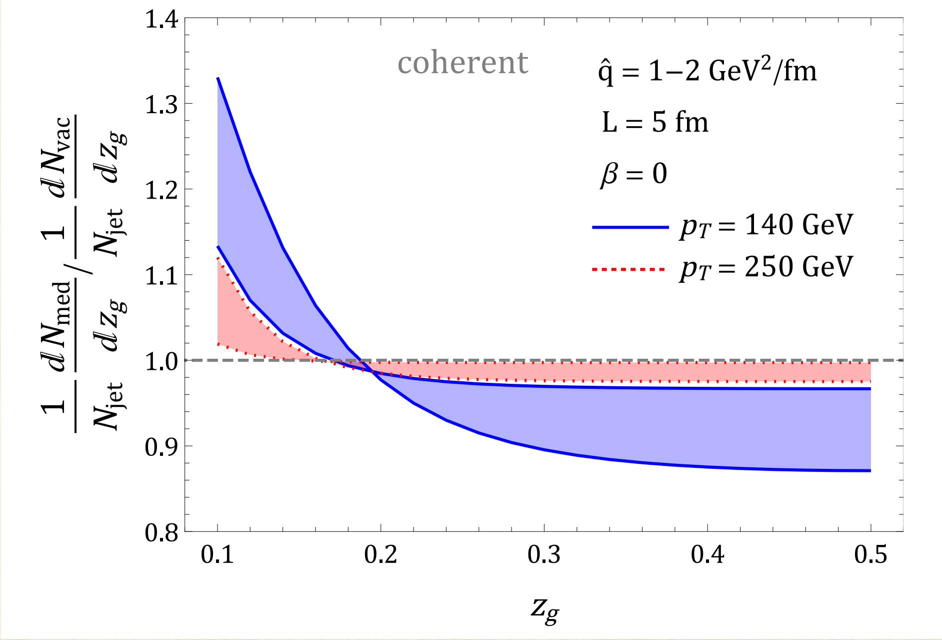

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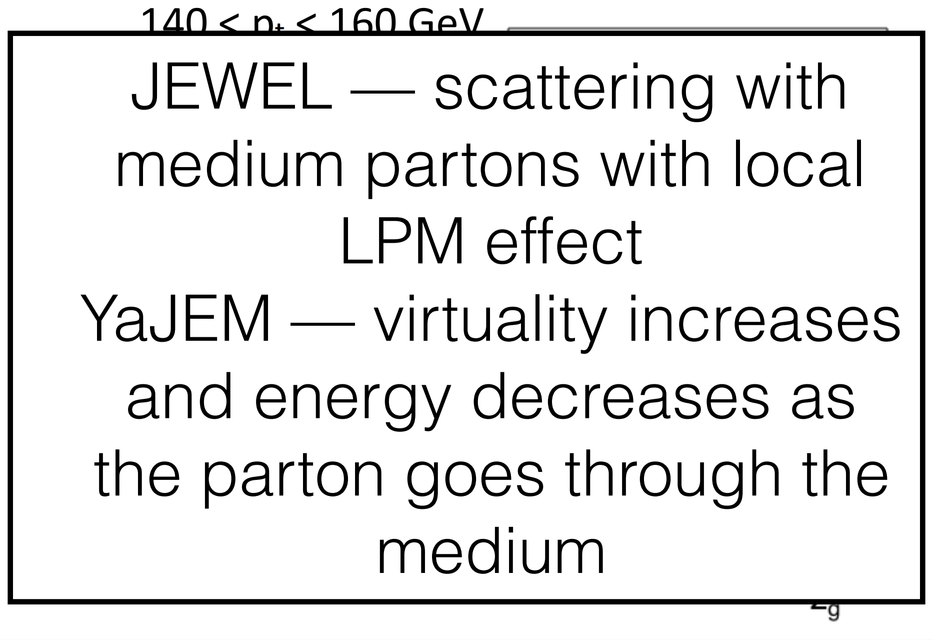

JEWEL — scattering with medium partons with local LPM effect
YaJEM — virtuality increases and energy decreases as the parton goes through the medium

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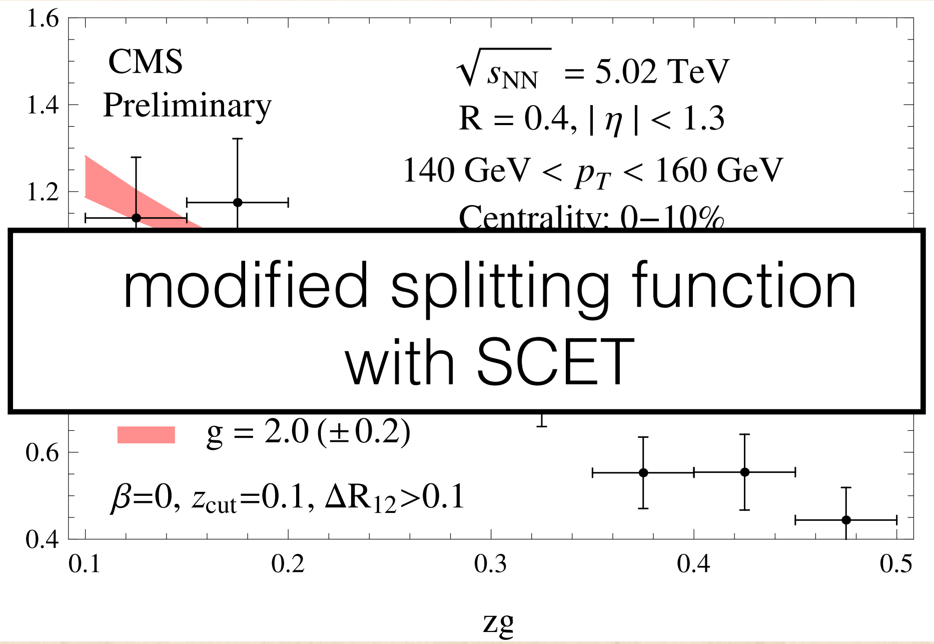
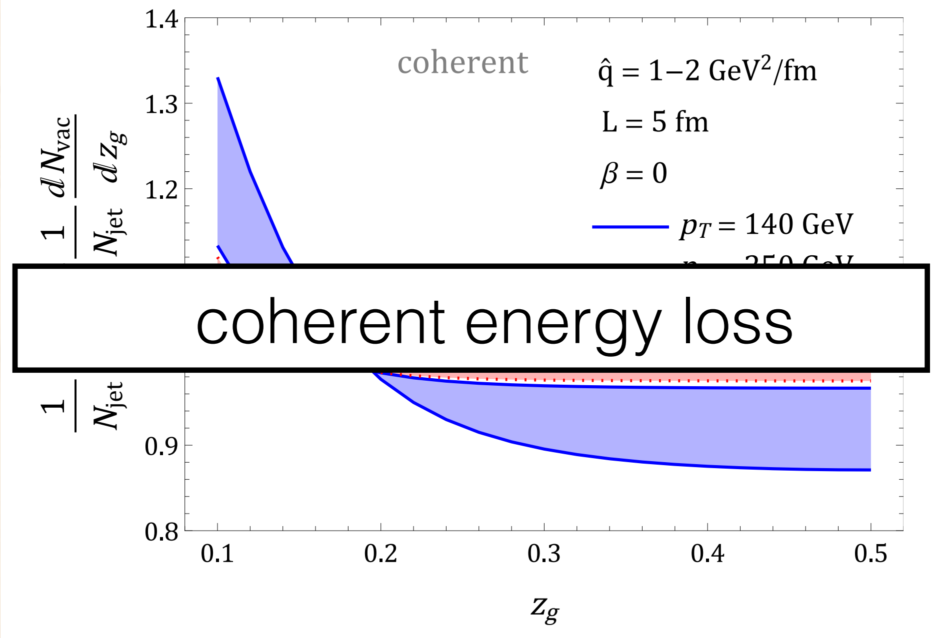
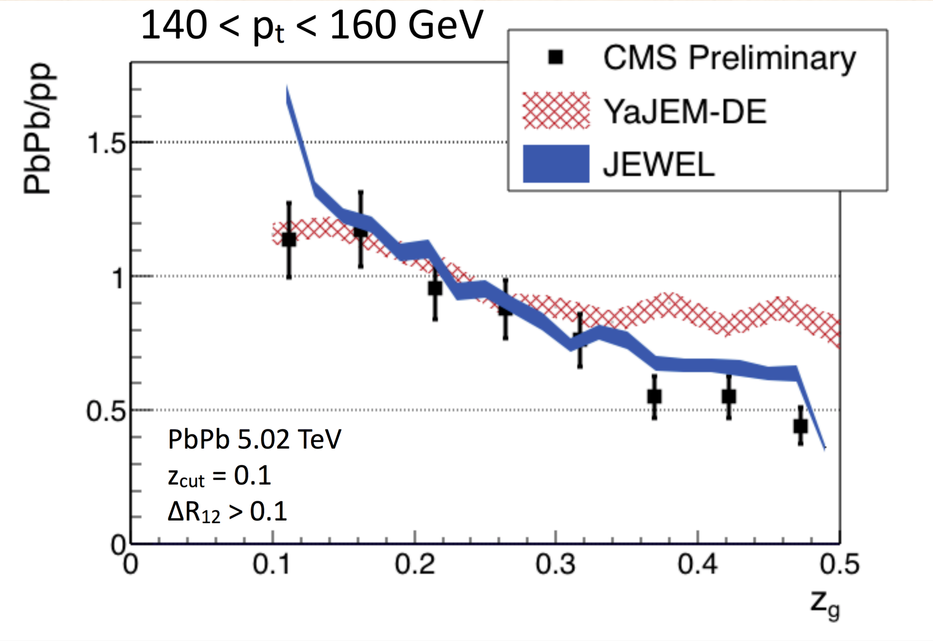


modified splitting function with SCET



coherent energy loss

Example of Comparisons



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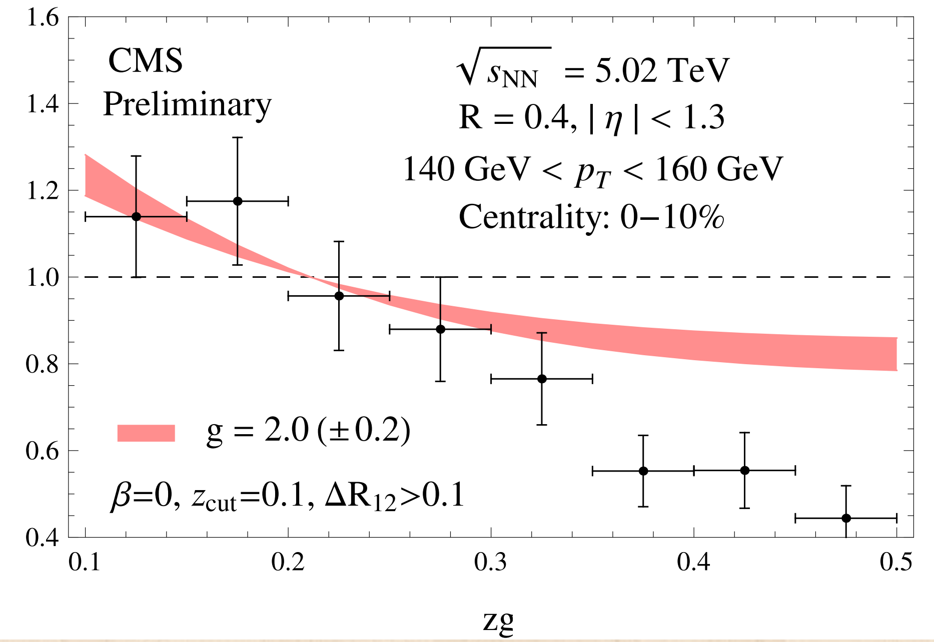

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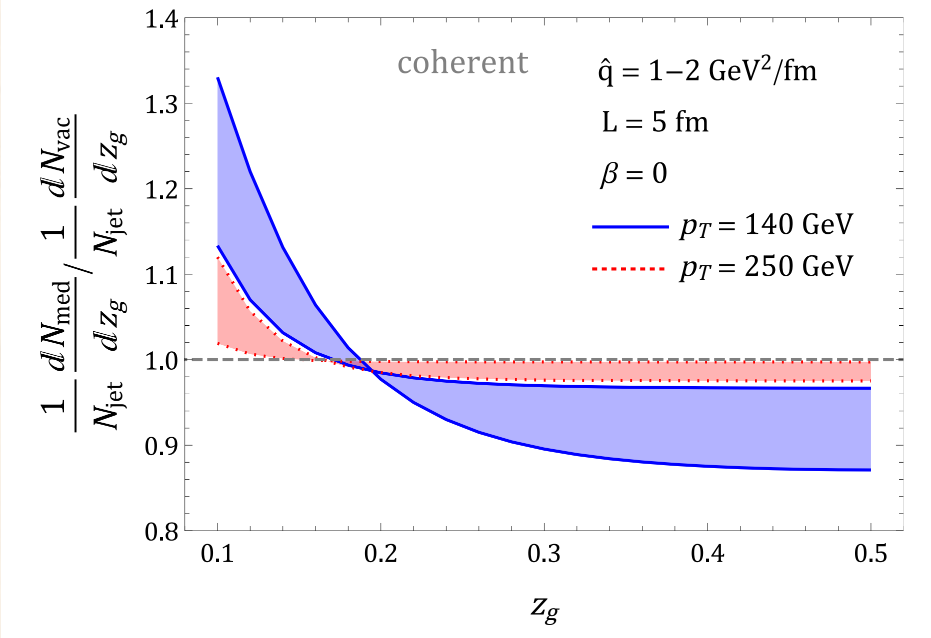


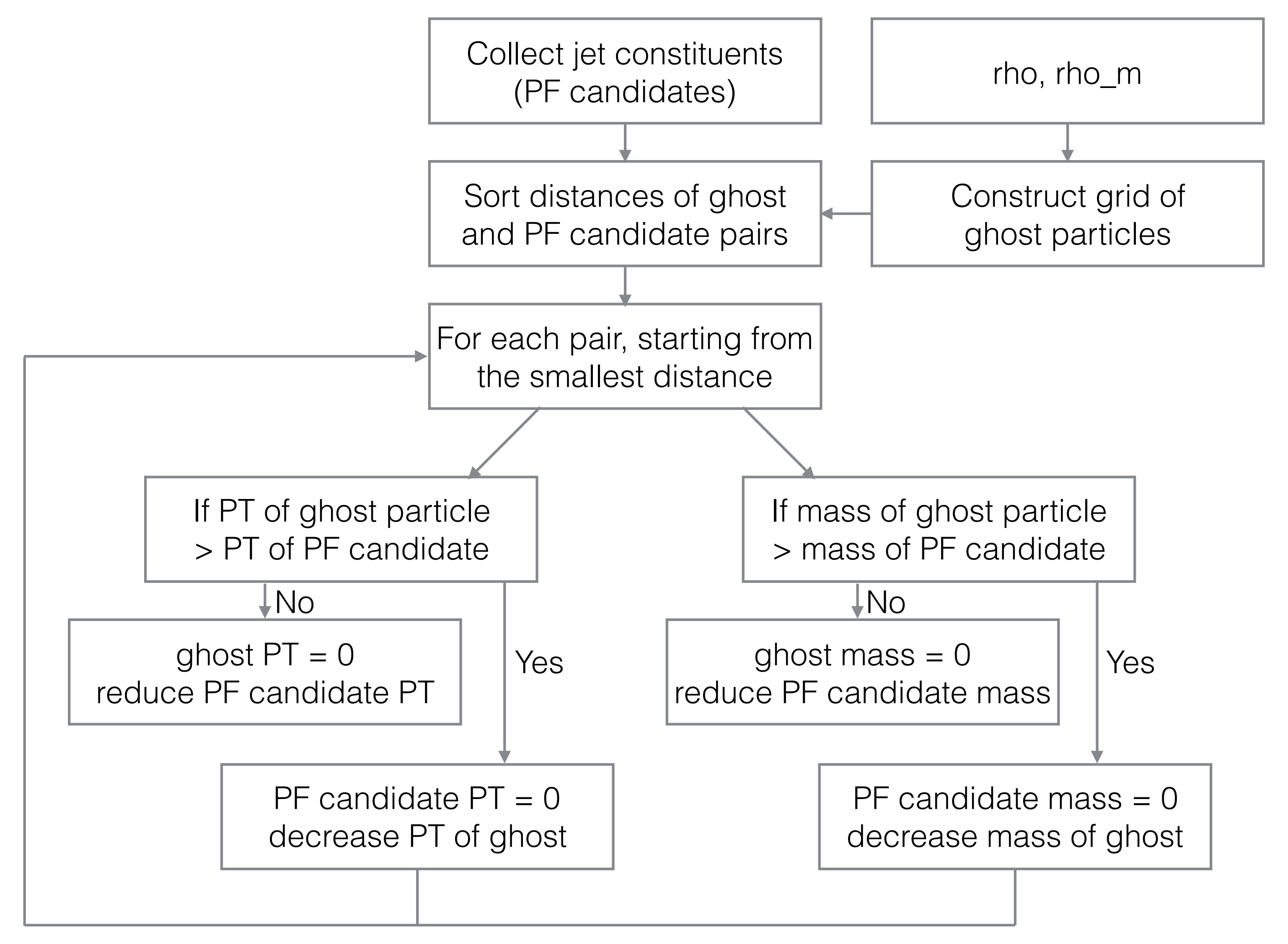
z_g measurement helps constrain models

Summary and Outlook

- Presented measurement of jet splitting function in pp and PbPb collisions at 5.02 TeV in CMS
- We observe a stronger modification in central collisions and in jets with small p_T
- Useful in discriminating between different models
- The next step of the program is to measure groomed jet mass / opening angle for different soft drop settings

Backup Slides Ahead

Constituent subtraction



Collect jet constituents (PF candidates)

rho, rho_m

Sort distances of ghost and PF candidate pairs

Construct grid of ghost particles

For each pair, starting from the smallest distance

If PT of ghost particle > PT of PF candidate

If mass of ghost particle > mass of PF candidate

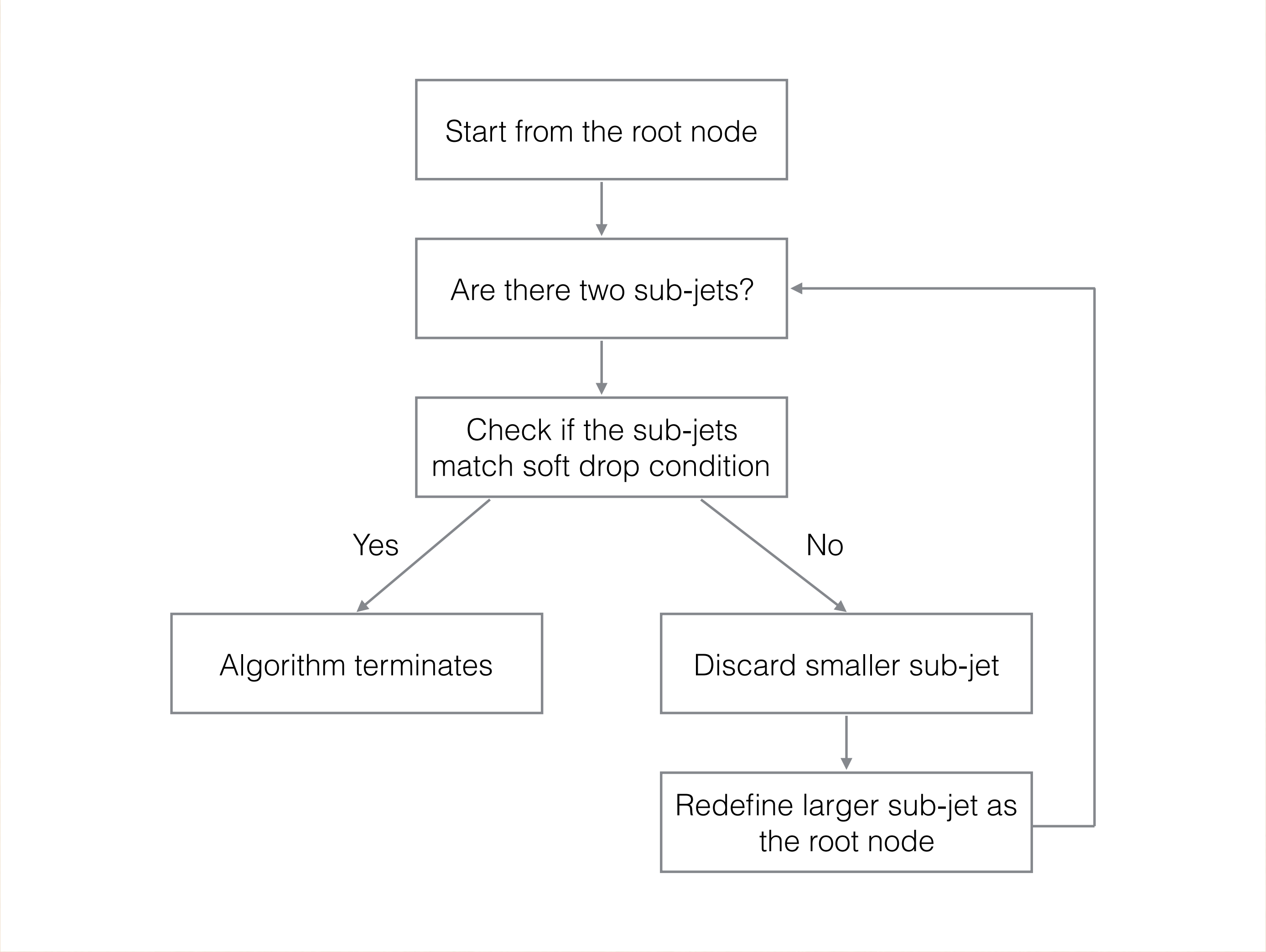
ghost PT = 0
reduce PF candidate PT

ghost mass = 0
reduce PF candidate mass

PF candidate PT = 0
decrease PT of ghost

PF candidate mass = 0
decrease mass of ghost

Soft drop flow chart



Start from the root node

Are there two sub-jets?

Check if the sub-jets match soft drop condition

Yes

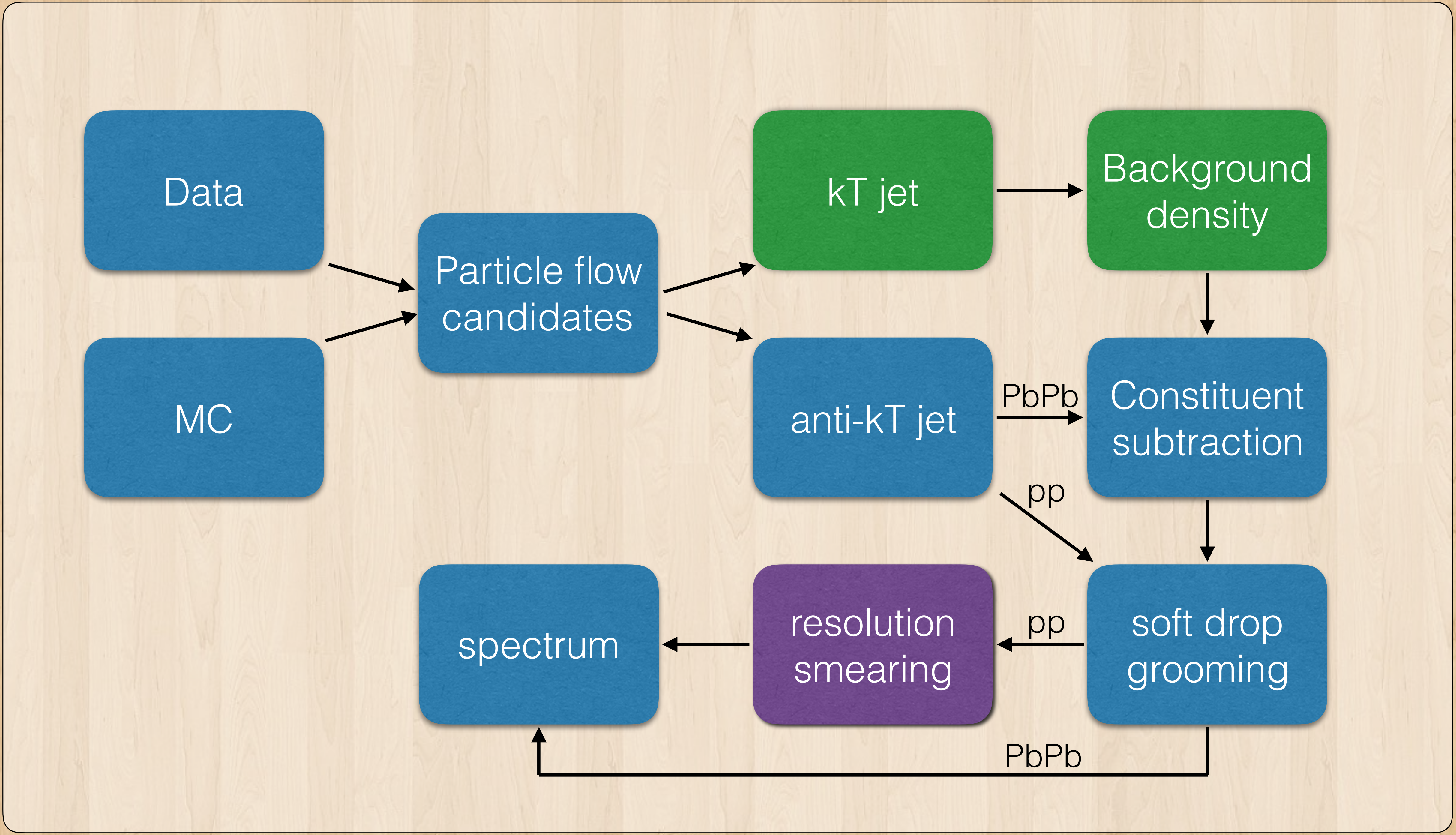
Algorithm terminates

No

Discard smaller sub-jet

Redefine larger sub-jet as the root node

Analysis flow



Data

MC

Particle flow candidates

kT jet

Background density

anti-kT jet

PbPb

Constituent subtraction

pp

soft drop grooming

pp

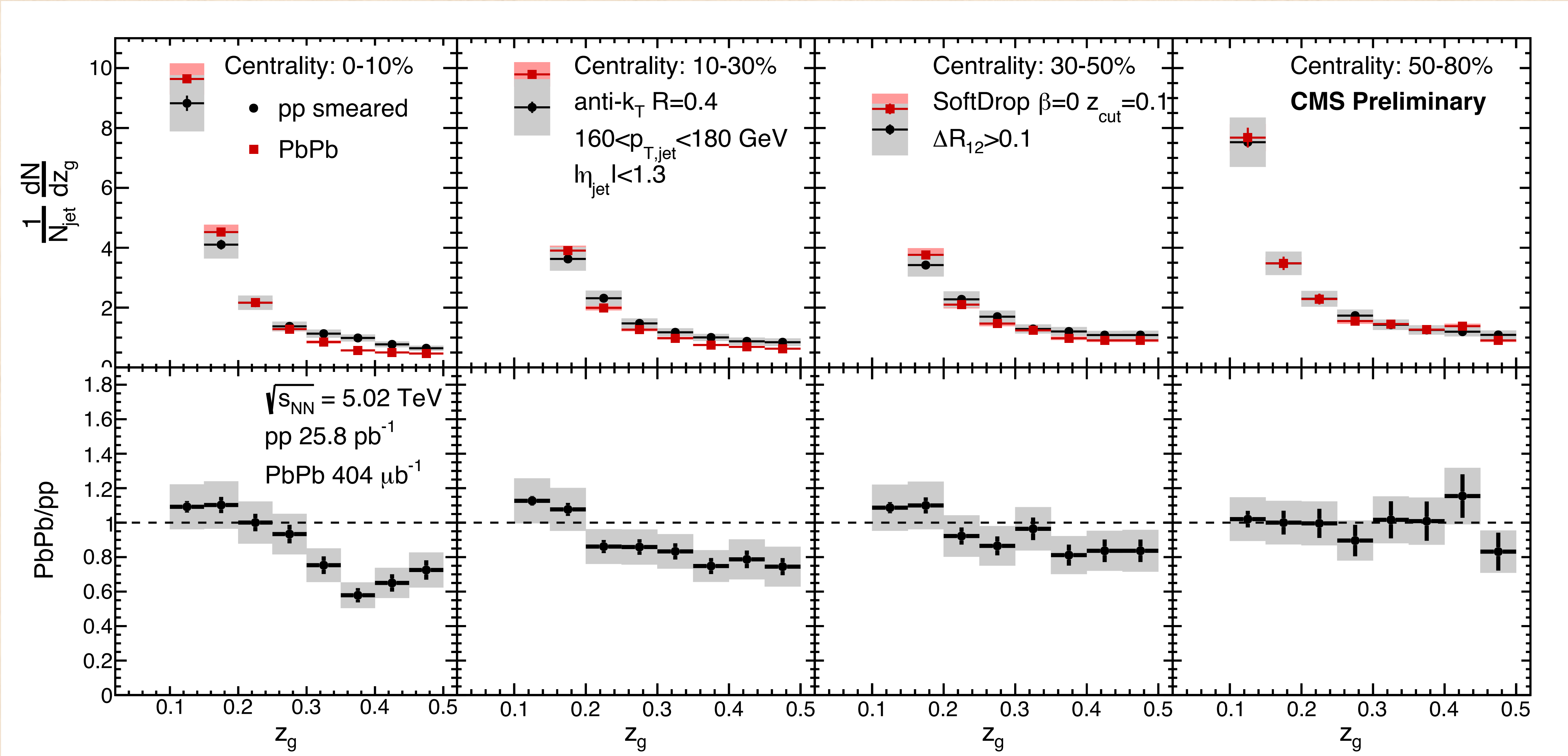
resolution smearing

spectrum

PbPb

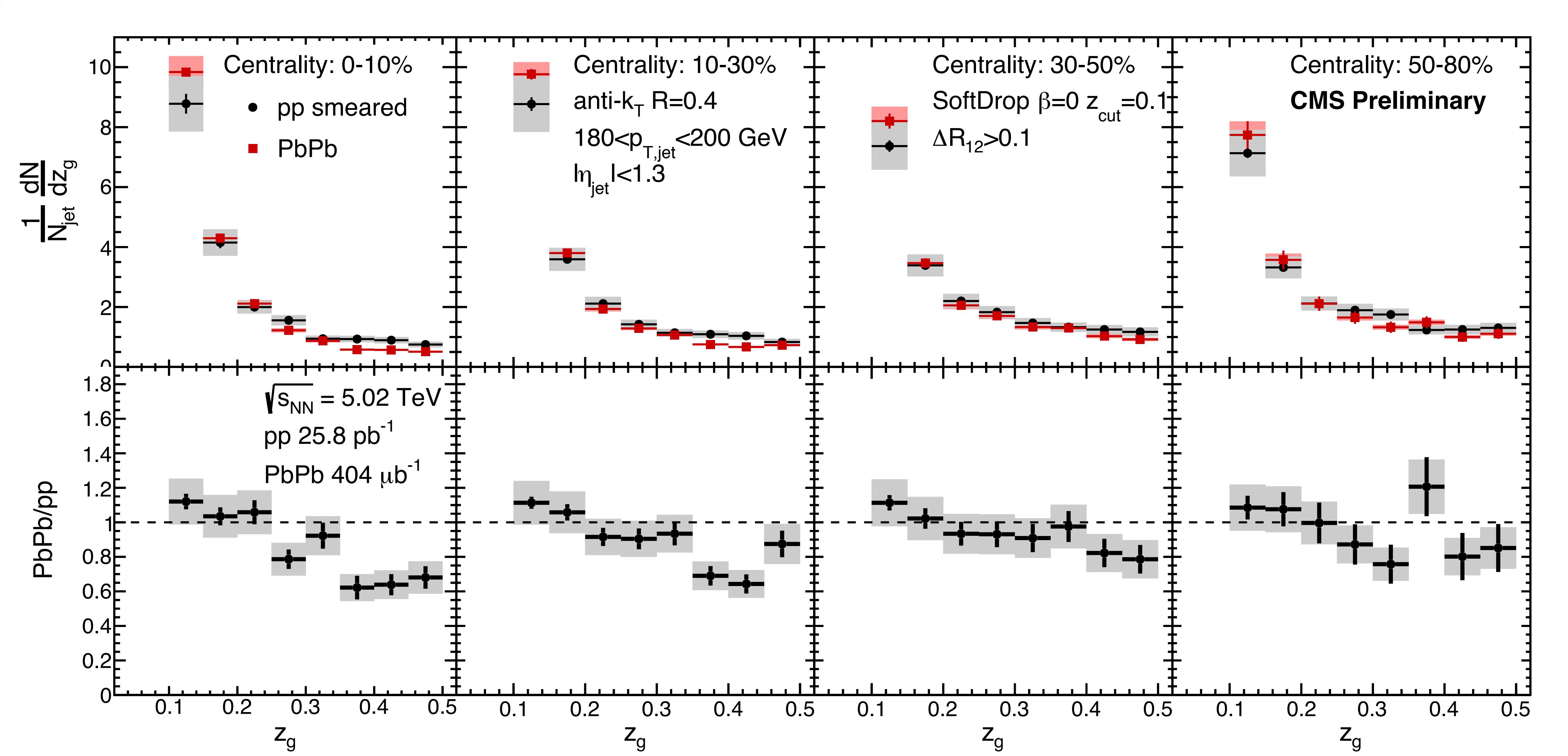
Result for other p_T bins

Jet p_T = 160-180



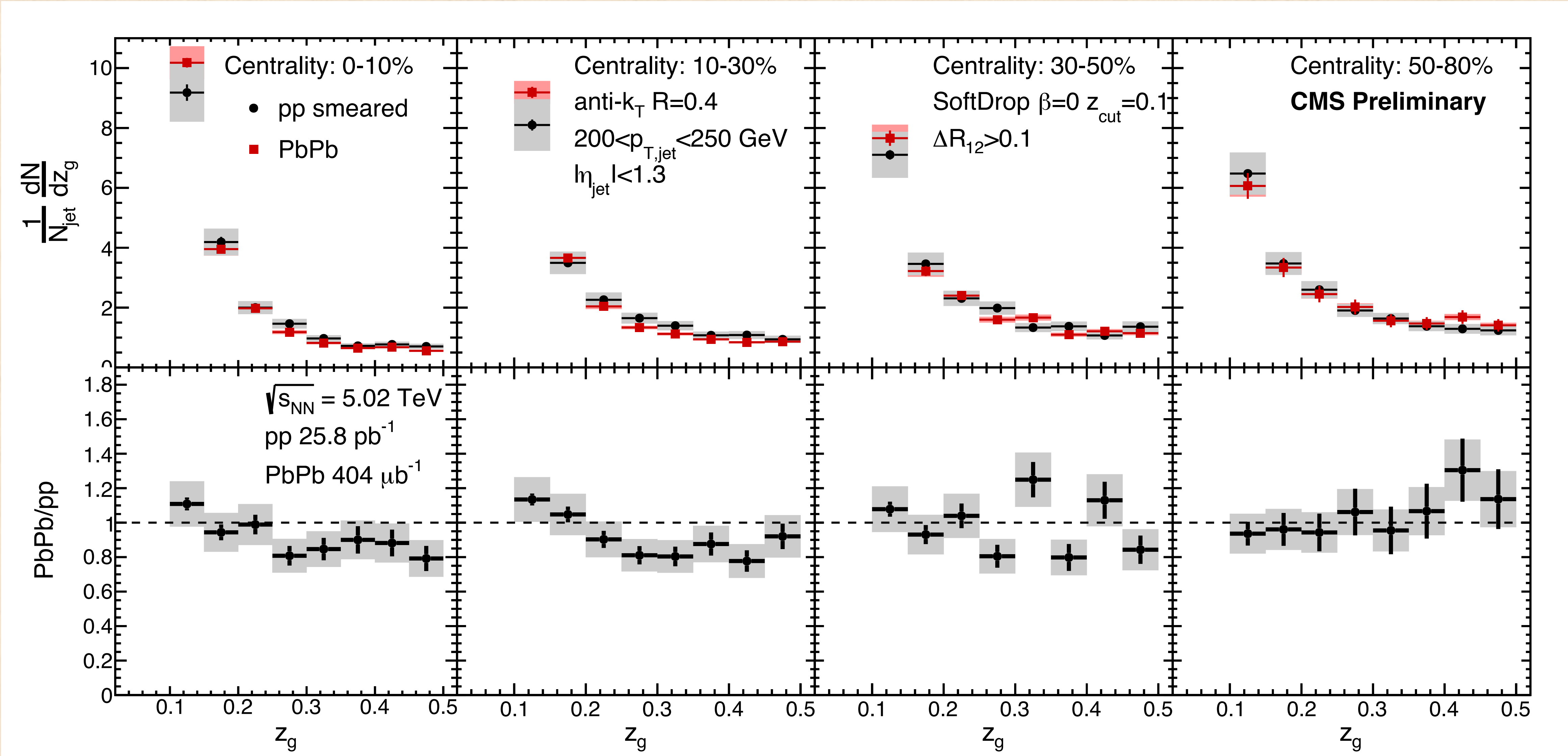
Result for other p_T bins

Jet p_T = 180-200



Result for other p_T bins

Jet p_T = 200-250

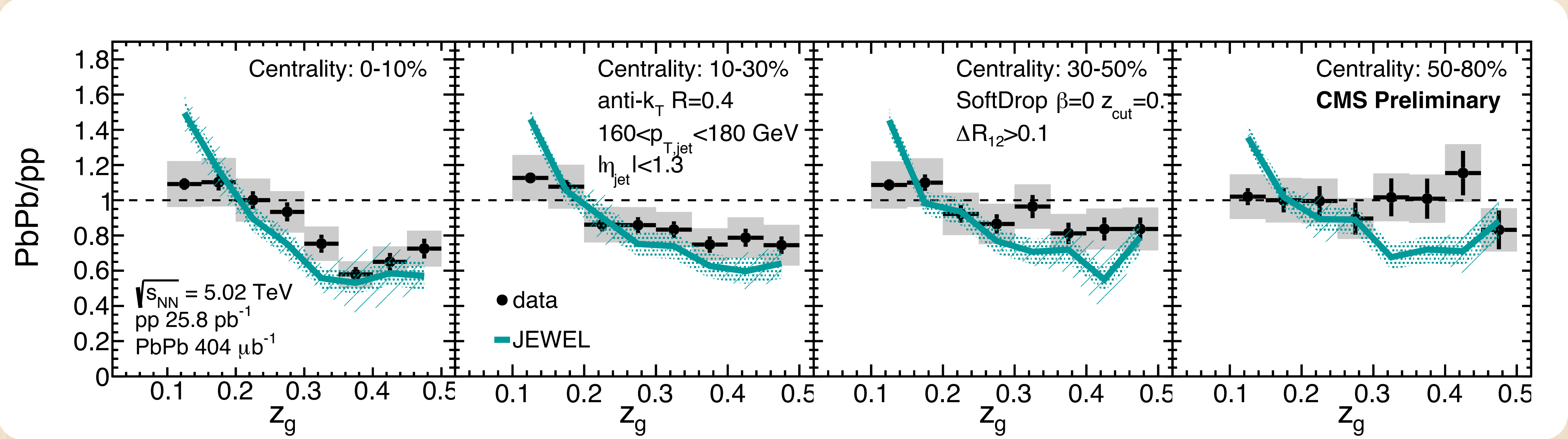


Groomed jet mass

- Mass of the jet is sensitive to the opening angle of the hard splitting, as well as any modulation in the jet evolution in the medium
- Much more sensitive to underlying event modeling and residual effect even with constituent subtraction and grooming
- Different soft drop parameter settings can help probe different aspects of jet modulation

Comparison with JEWEL

General trend described by JEWEL



JHEP03 (2013) 080, Zapp et al

Partial list of MC generators and calculations

- MC Generators
  - JEWEL — scattering with medium partons with local LPM effect
  - YaJEM — virtuality increases and energy decreases as the parton goes through the medium
- Calculations
  - Chien, Vitev — modified splitting function with SCET$_G$
  - Mehtar-Tani, Tywoniuk — coherent energy loss

JHEP03 (2013) 080, Zapp et al; Int J Mod Phys E, 20, 1954 (2011), Renk
1608.07283, Chien, Vitev; 1610.08930, Methar-Tani, Tywoniuk