# Probing Properties of the QCD Medium using Jet Substructure Techniques in pp and PbPb collisions at 5.02 TeV with CMS

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**for the CMS Collaboration**

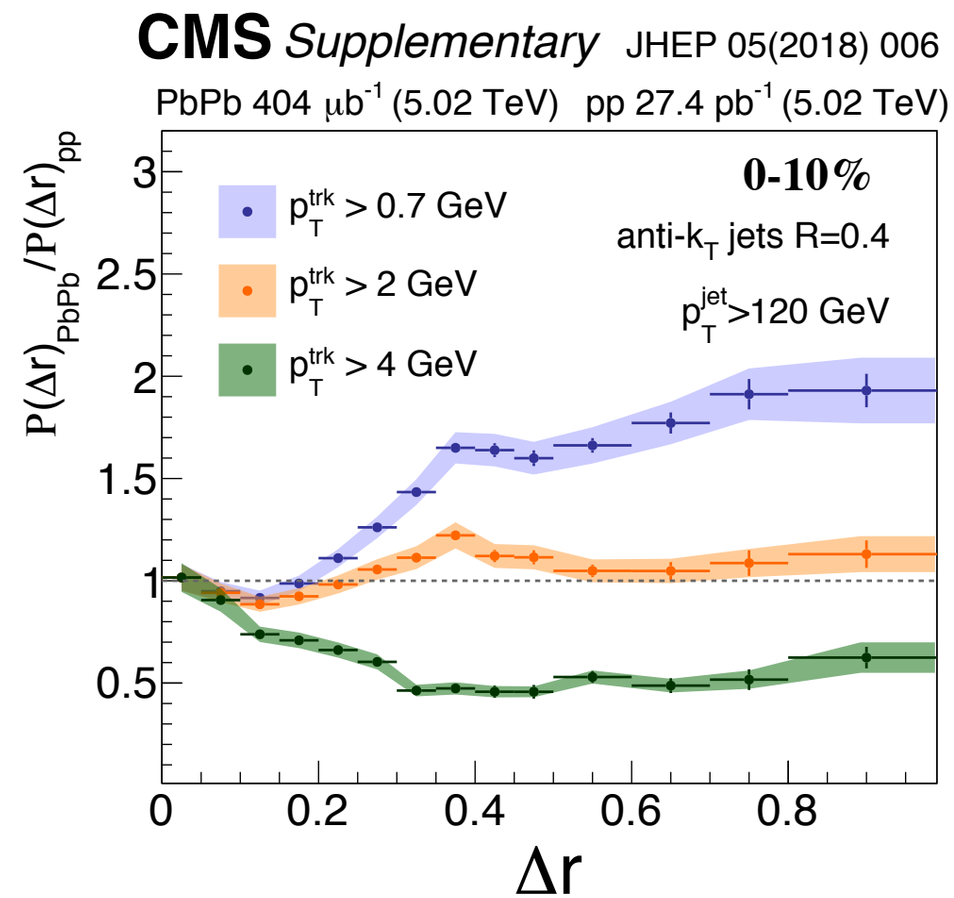
Hard Probes 2018
Aix-Les-Bains, France

# Why Jet Substructure?

- Jets are **quenched** and show significant **reshuffling of energy in and out of cone** in PbPb events compared to pp

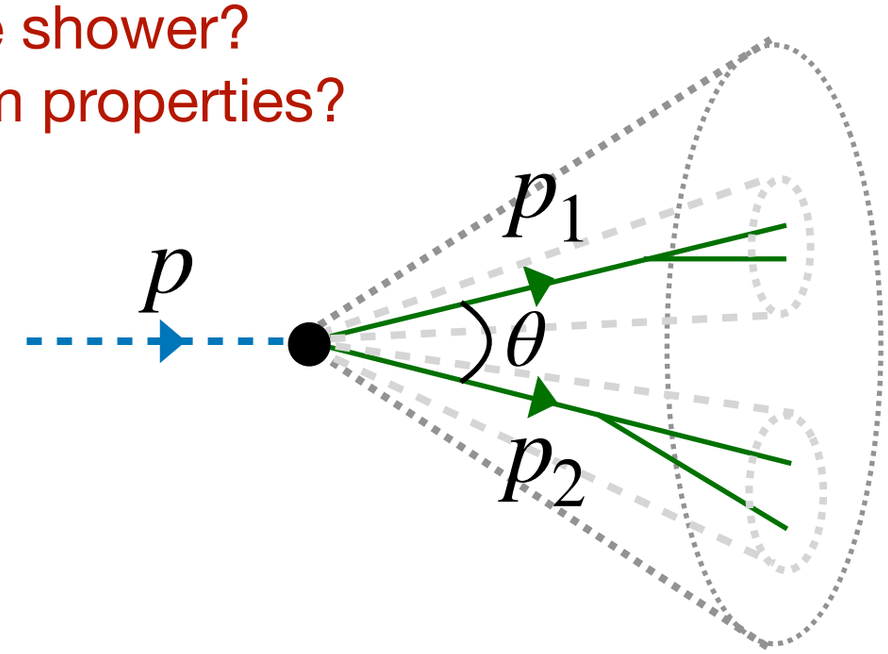
Talk by Xiao Wang (Thursday 10:20)

$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\left\{\sum_{\text{tracks}\in(r_a,r_b)} p_T^{\text{trk}}\right\}$$




- How is parton shower modified?
- What is the exact mechanism of modifying the shower?
- Can we relate shower modifications to medium properties?

**Tool : First splitting in parton shower ; only using hard jet components**



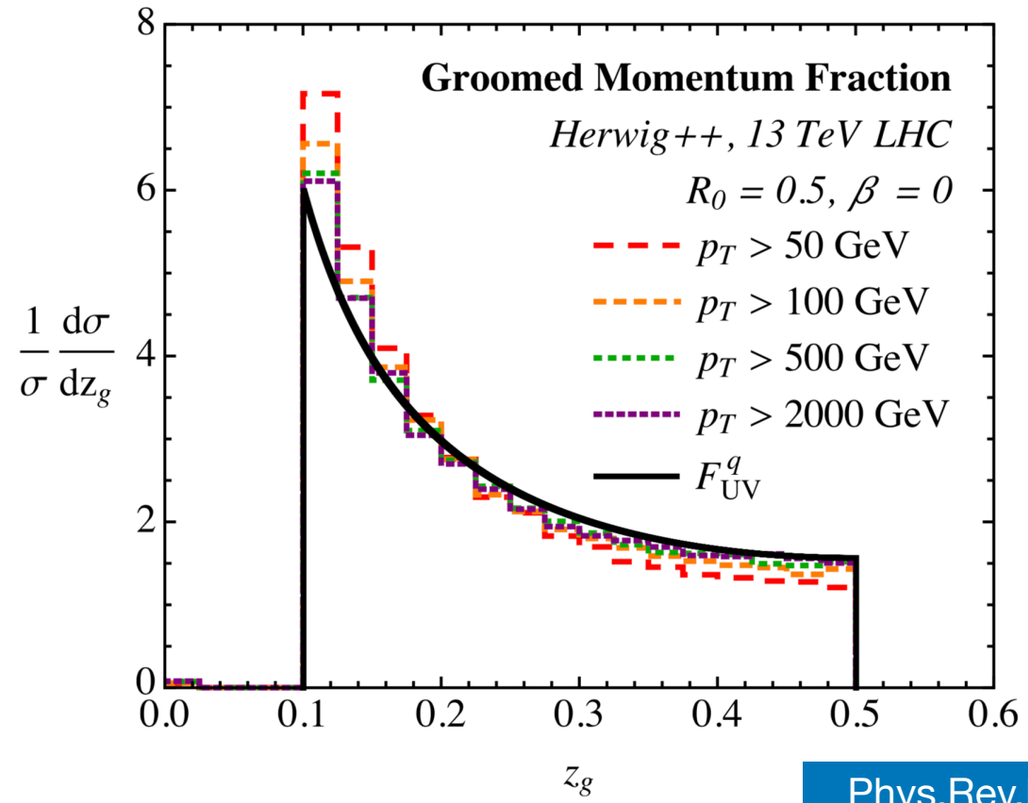
# Shared Momentum Fraction ($z_g$)

**In vacuum : $z_g$ relates directly to the Altarelli-Parisi QCD splitting function**

**Momentum fraction carried by the subleading branch of the first splitting**

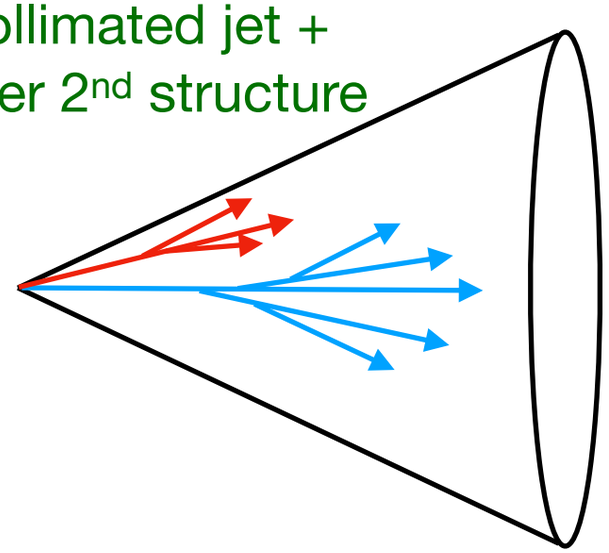
$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}}$$

- Independent of $\alpha_s$
- Weak dependence on jet $p_T$
- Same for quarks/gluons



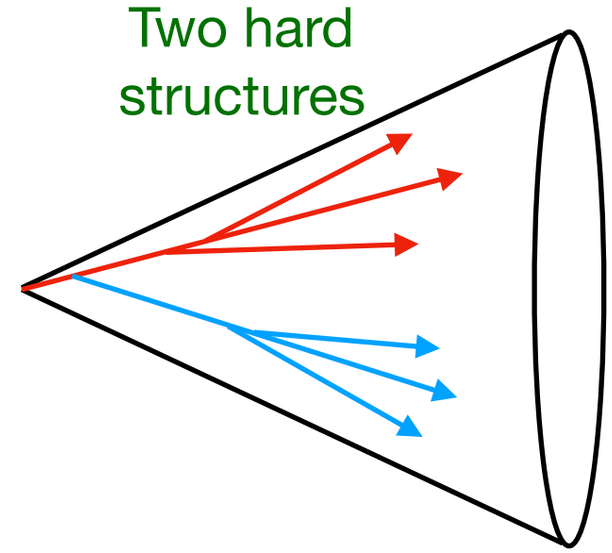

Phys.Rev.D91 111501(2015)

Collimated jet + softer 2nd structure



**Small $z_g$**

Two hard structures



**Large $z_g$ ~ 0.5**

Larkoski, Marzani, and Thaler Phys.Rev.D91,111501(2015)
Larkoski et. al. PhysRevLett.119.132003(2017)

# Color Coherence

- Relative energy loss, measured via **shared momentum fraction ($z_g$)**, helps probe important properties of medium including the **role of color coherence**

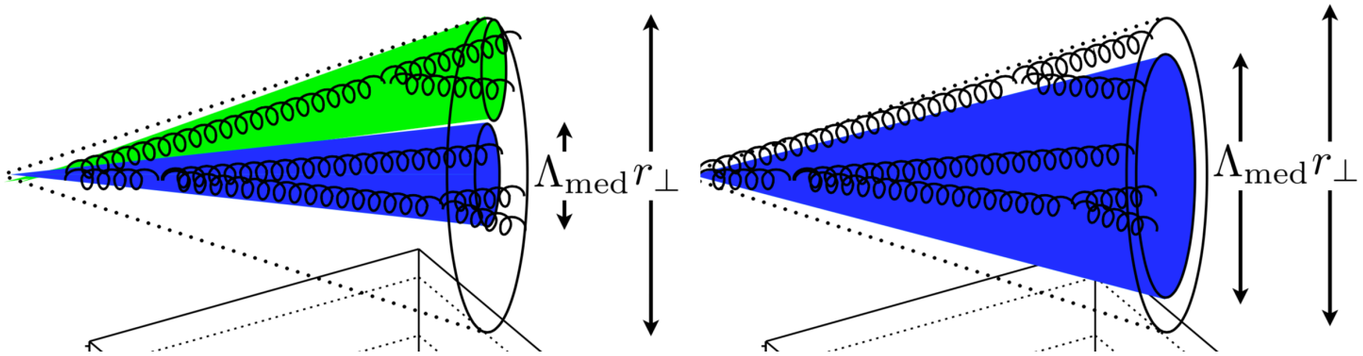
$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}}$$

- Can the medium resolve the two partons —> Can the medium break the color coherence among them?

$$\Lambda_{\rm med} = 1/\sqrt{\hat{q}L}$$

$$\hat{q} \propto T^3$$

2 coherent emitters: color disconnected subjets




1 coherent emitter: color connected subjets

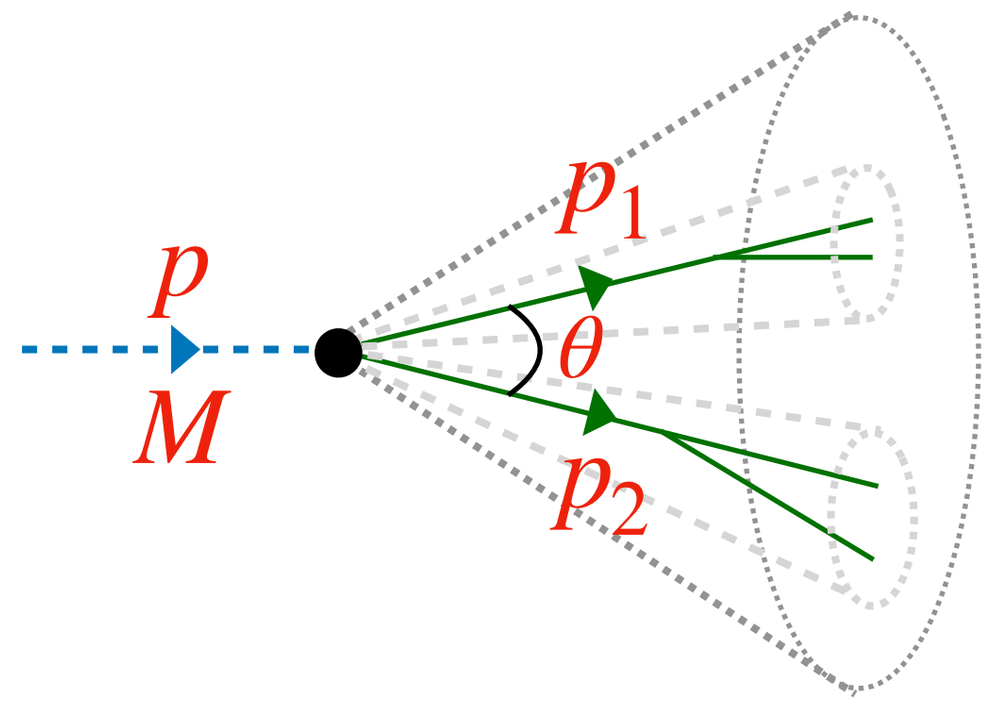
Fig. taken from :
*Phys.Lett.B* **725** (2013) 357-360

# Jet Mass

- The ability of the medium resolve the partons depends on how the opening angle (θ) compares to the critical angle
- Opening angle of the parton splitting is correlated with the **jet mass (M)**

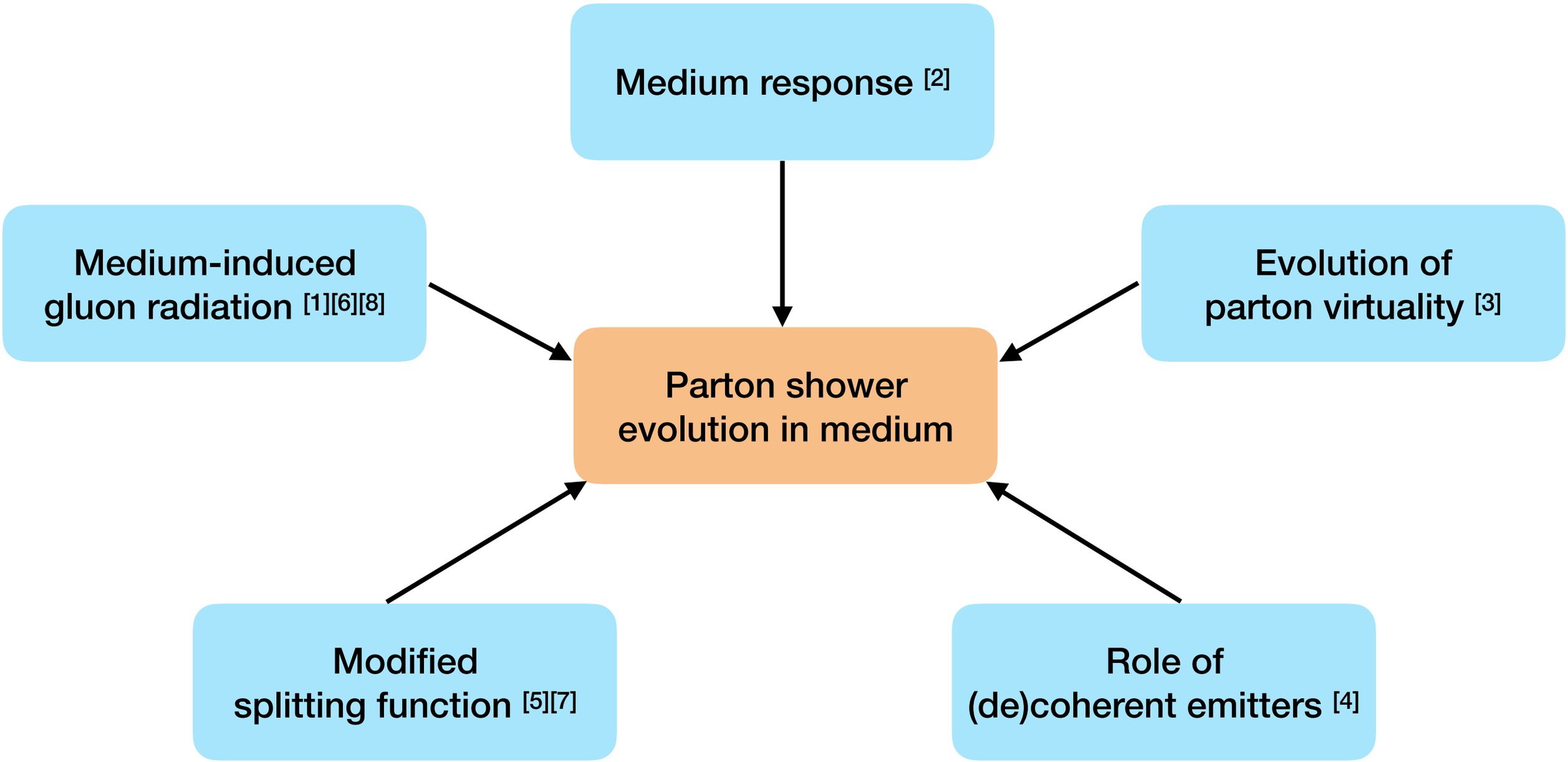
$$M \sim z\theta^2$$

- **Small mass**: collimated jet, small number of constituents. Low virtuality
- **Large mass**: broad jet, large number of constituents. High virtuality




- We measure $\frac{M}{p_{T,jet}}$ as mass scales with jet $p_T$ in vacuum and it also leads to better cancellation in systematics

# Physics Phenomena





[1] : Y Mehtar-Tani et al. JHEP 04 (2017) 125

[2] : G Milhano et al. Phys. Lett. B 779 (2018) 409

[3] : A Majumder et al. Phys. Rev. C 93, 054909

[4] : Y Mehtar-Tani et al. Phys. Lett. B 744 (2015) 284

[5] : Y-T. Chien et al. Phys. Rev. Lett. 119 (2017) 112301

[6] : C. A. Salgado et al. Phys. Rev. D 68, 014008

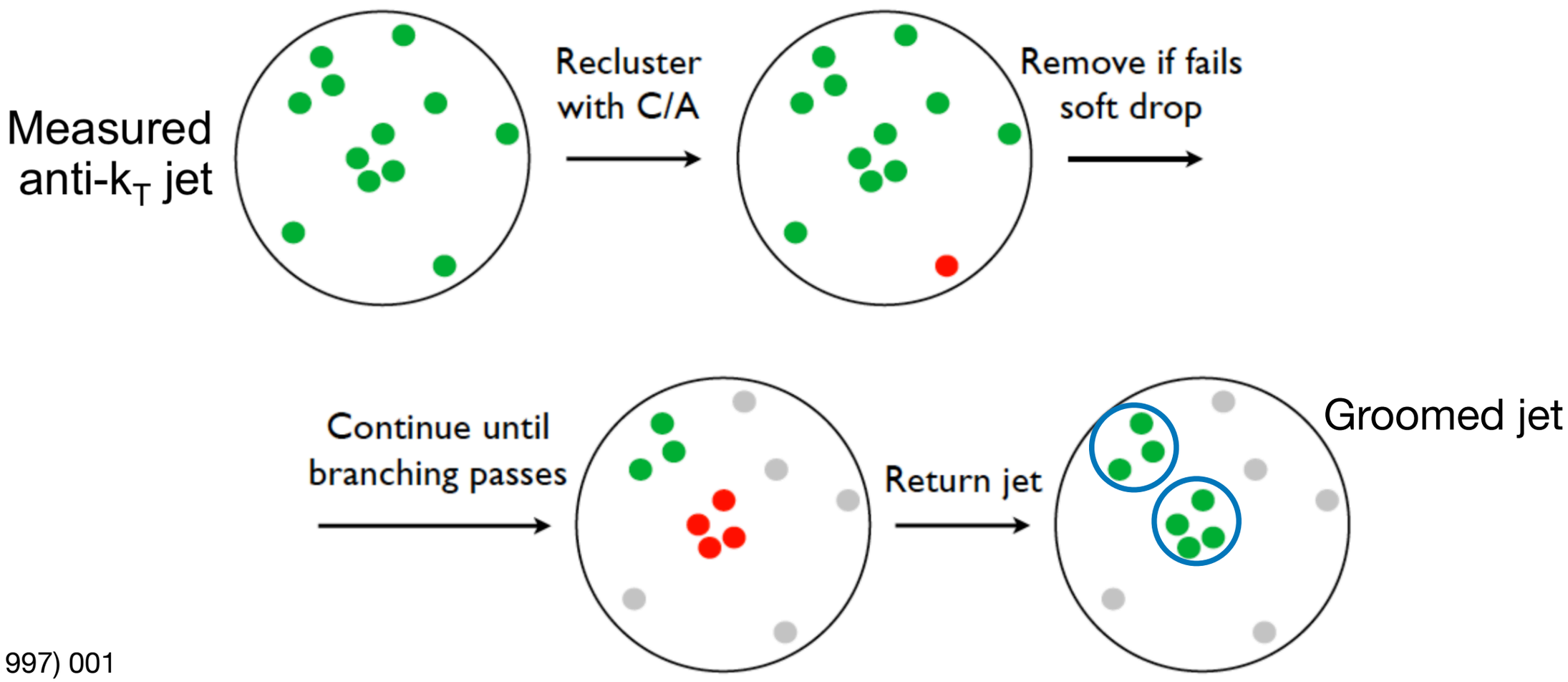
[7] : T. Renk Int.J.Mod.Phys. E20 (2011) 1594-1599

[8] : G-Y Qin et al. Phys. Rev. C 86, 064904

# Jet Grooming : Isolating hard structures

- Jets are reclustered to impose **angular ordering** using the C/A algorithm[1]
- Iteratively de-clustered into two subjets until the "**Soft Drop**"[2] condition is met

**Soft Drop condition :** $$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut}\left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$





[1] : JHEP 9708 (1997) 001

[2] : JHEP 1405 (2014) 146

# Grooming Settings

- Jet Grooming **removes soft divergences** and **uncorrelated background**

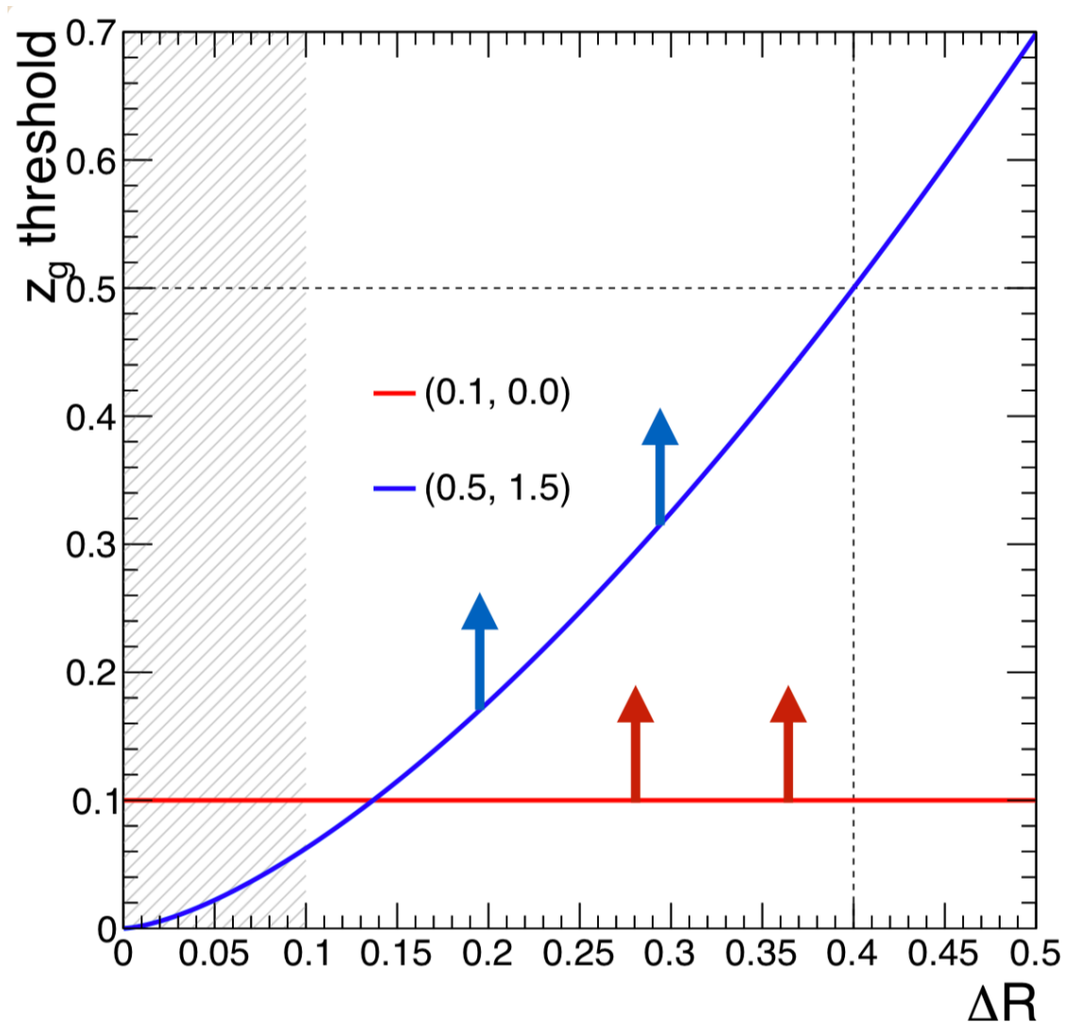
**Soft Drop condition :** $z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left( \frac{\Delta R_{ij}}{R_0} \right)^{\beta}$

**$z_{cut}$ = 0.1, $\beta$ = 0.0**

**"Flat grooming"**

Angle independent

Good theoretical properties




**$z_{cut}$ = 0.5, $\beta$ = 1.5**

**"Jet Core"**

Stronger grooming at large angle

More resilient to large angle soft radiation

- Additional cut of **$\Delta R_{ij}$ > 0.1** is applied to account for detector (in)efficiency and to avoid the collinear region

# Results

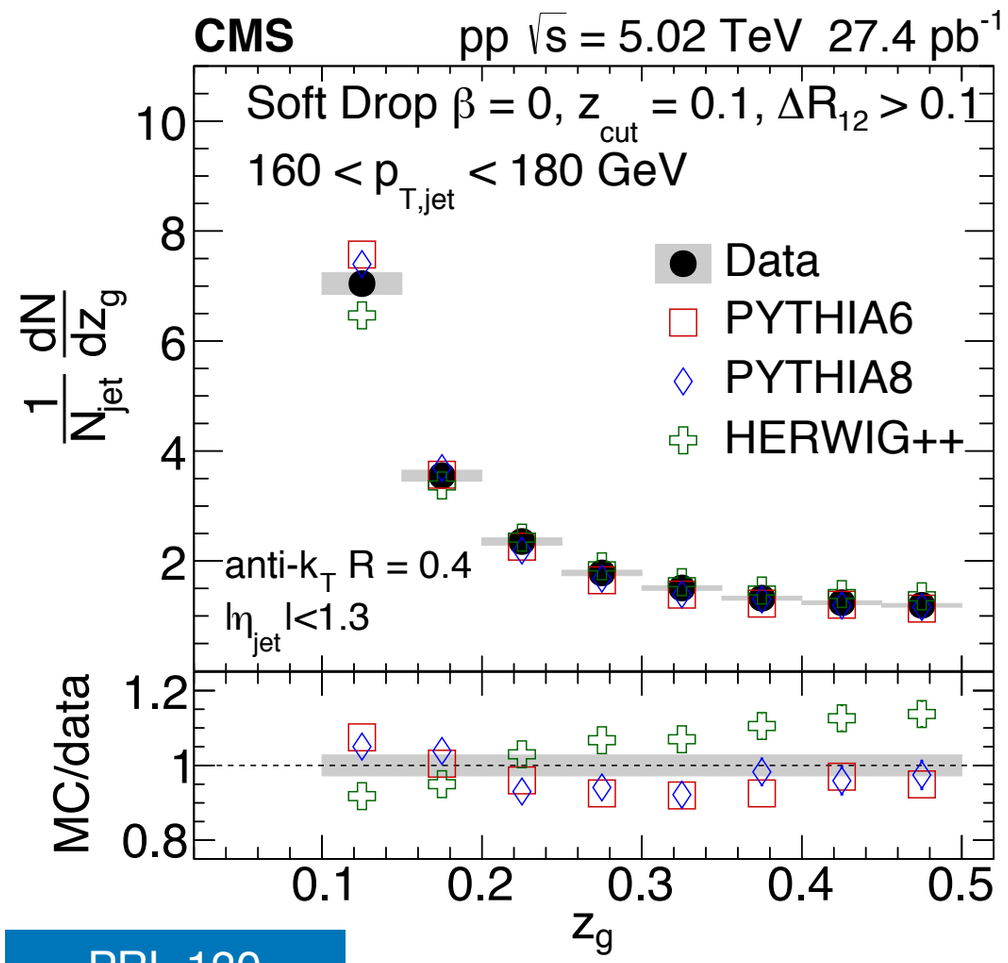
# Results in pp collisions

**$p_{T,\,jet}$ : 160 -180 GeV**

## Momentum sharing

**Flat grooming:**

**( $z_{cut}$ = 0.1, $\beta$ = 0.0 )**




PRL 120 (2018) 142302

- MC generally describes pp data well

# Results in pp collisions

## $p_{T,\,jet}$ : 160 -180 GeV

### Momentum sharing

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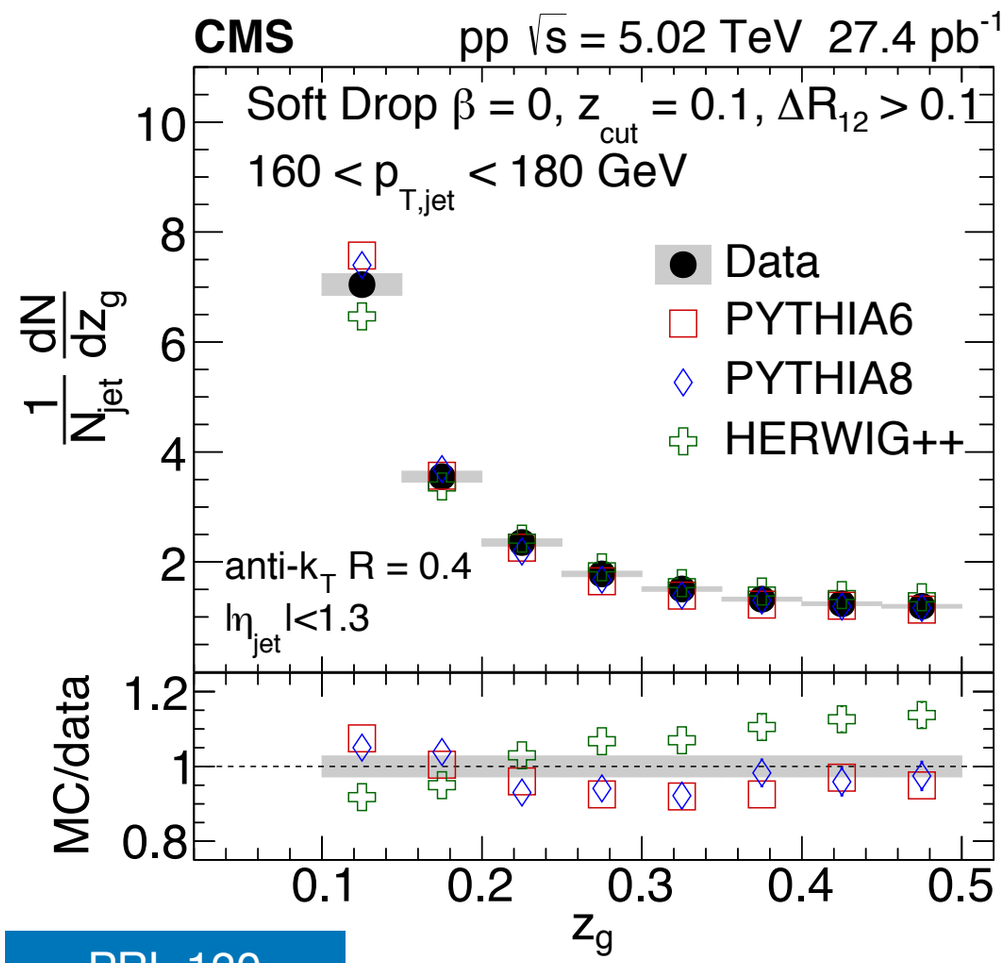
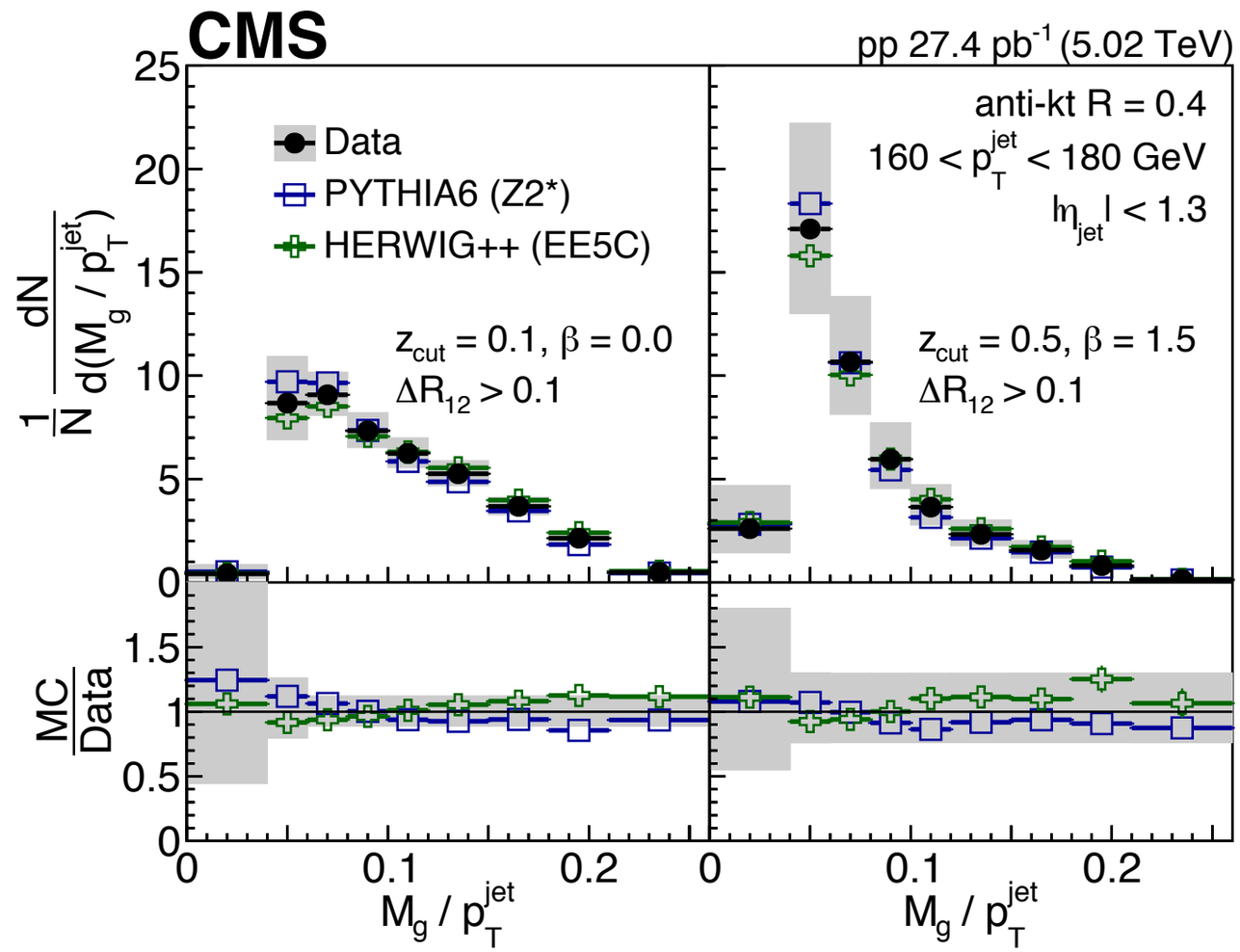



PRL 120 (2018) 142302

### Groomed jet mass

**Flat grooming:** **( $z_{cut}$ = 0.1, $\beta$ = 0.0 )**

**Jet core:** **( $z_{cut}$ = 0.5, $\beta$ = 1.5 )**




arXiv:1805.05145

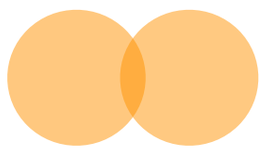
- MC generally describes pp data well
- Significant difference in the observed jet mass between the two grooming settings

# Shared Momentum Fraction (centrality bins)

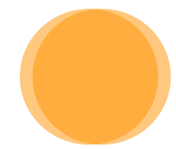
PRL 120 (2018) 142302

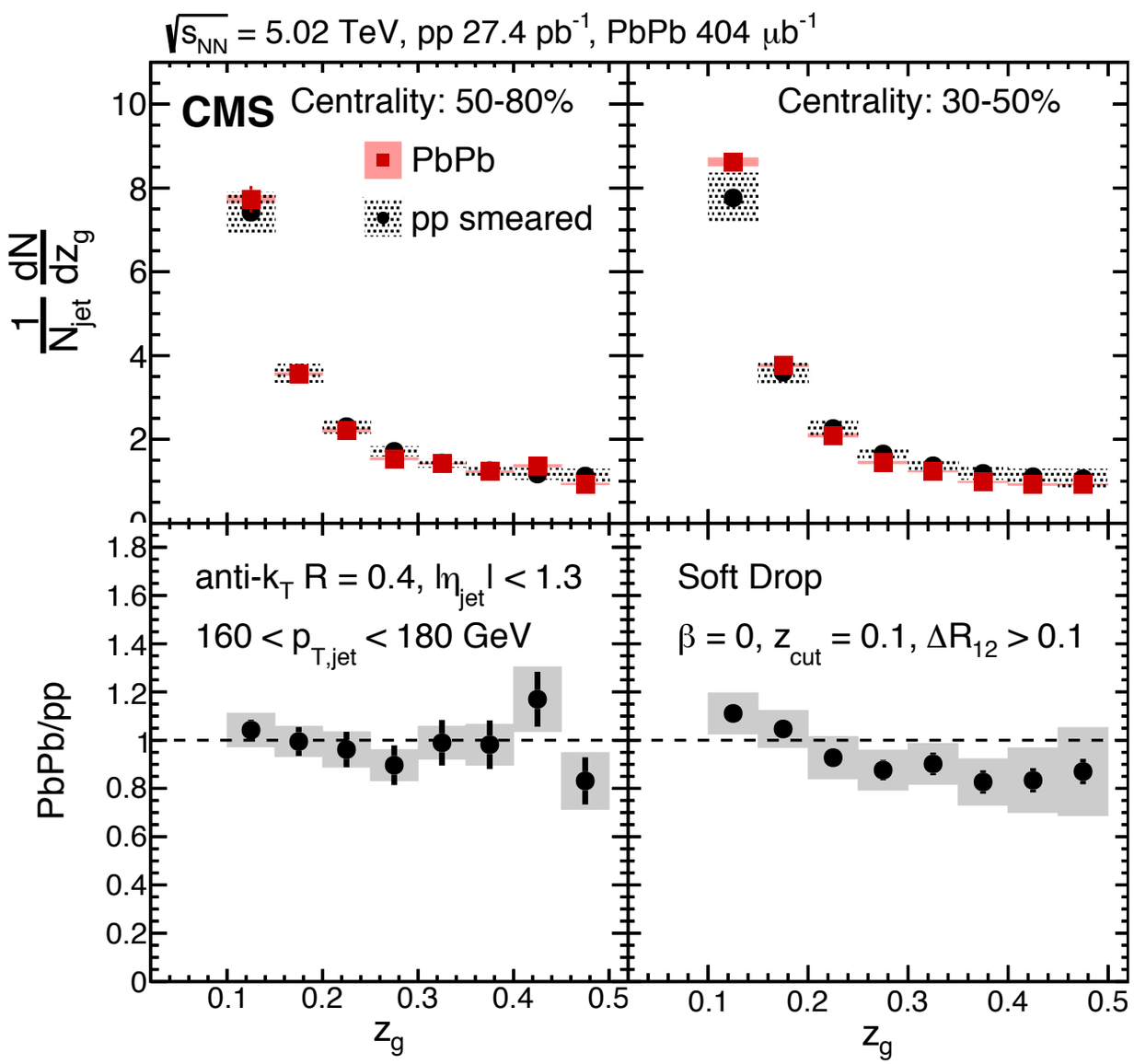
**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**

**$p_{T,\,jet}$ : 160 -180 GeV**



Peripheral Collisions → Central Collisions



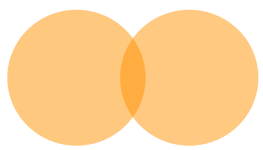


# Shared Momentum Fraction (centrality bins)

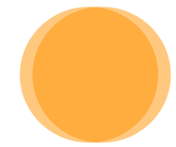
PRL 120 (2018) 142302

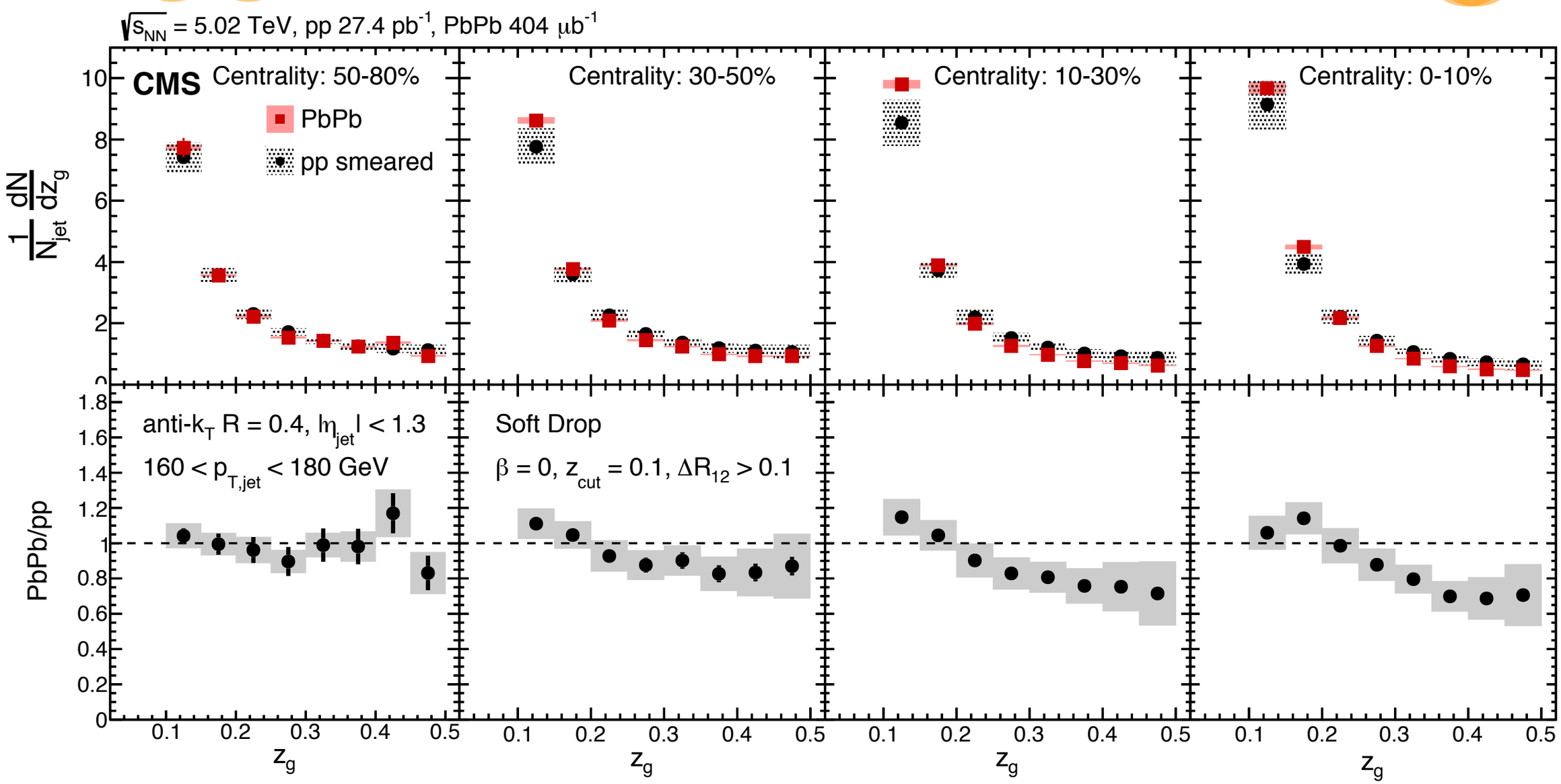
**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**

**$p_{T,\,jet}$ : 160 -180 GeV**



Peripheral Collisions → Central Collisions






- Modification of $z_g$ observed in central PbPb collisions relative to pp
- Branching more imbalanced in central PbPb

# Shared Momentum Fraction ($p_{T,jet}$ bins)

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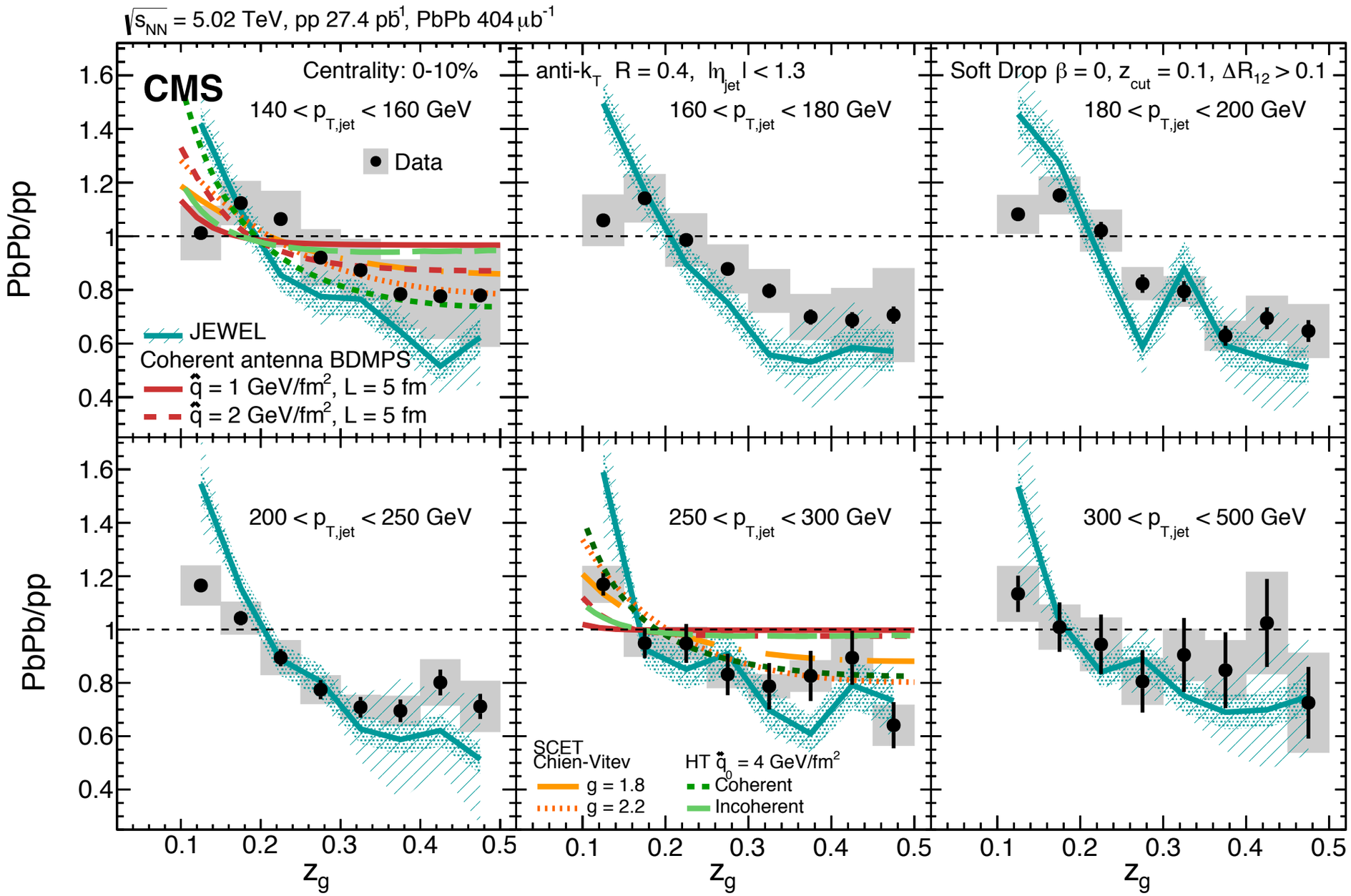
## ( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming

10% most central events




**Multiple medium-induced gluon bremsstrahlung (coherent):**
**Phys. Lett. B 345 (1995) 277**
**Nucl. Phys. B 483 (1997) 291**
**Nucl. Phys. B 484 (1997) 265**
**JHEP 04 (2017) 125**

**JEWEL:**
**JHEP 03 (2013) 080**
**arXiv:1707.04142**
**arXiv:1707.01539**

**Soft collinear effective theory: modified gluon splitting function: arXiv:1608.07283**

**Higher twist calculation: arXiv:1707.03767**

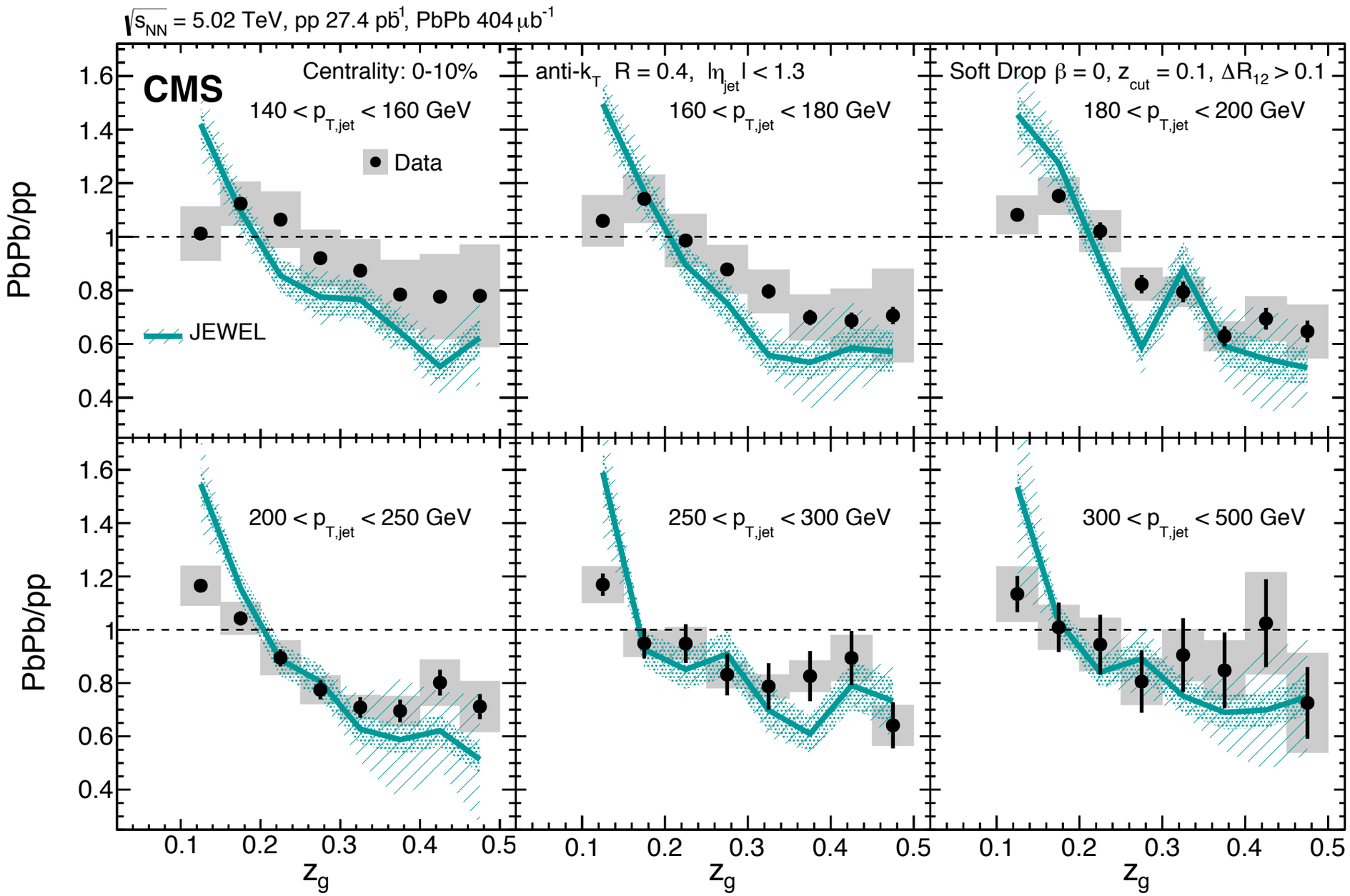
- No significant dependence of the modification on jet $p_T$ observed

# Shared Momentum Fraction (JEWEL)

**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**

PRL 120 (2018) 142302

10% most central events




Medium Response

Elastic Scattering

Medium-induced gluon radiation

**JEWEL generator:**
JHEP 03 (2013) 080
arXiv:1707.04142
arXiv:1707.01539

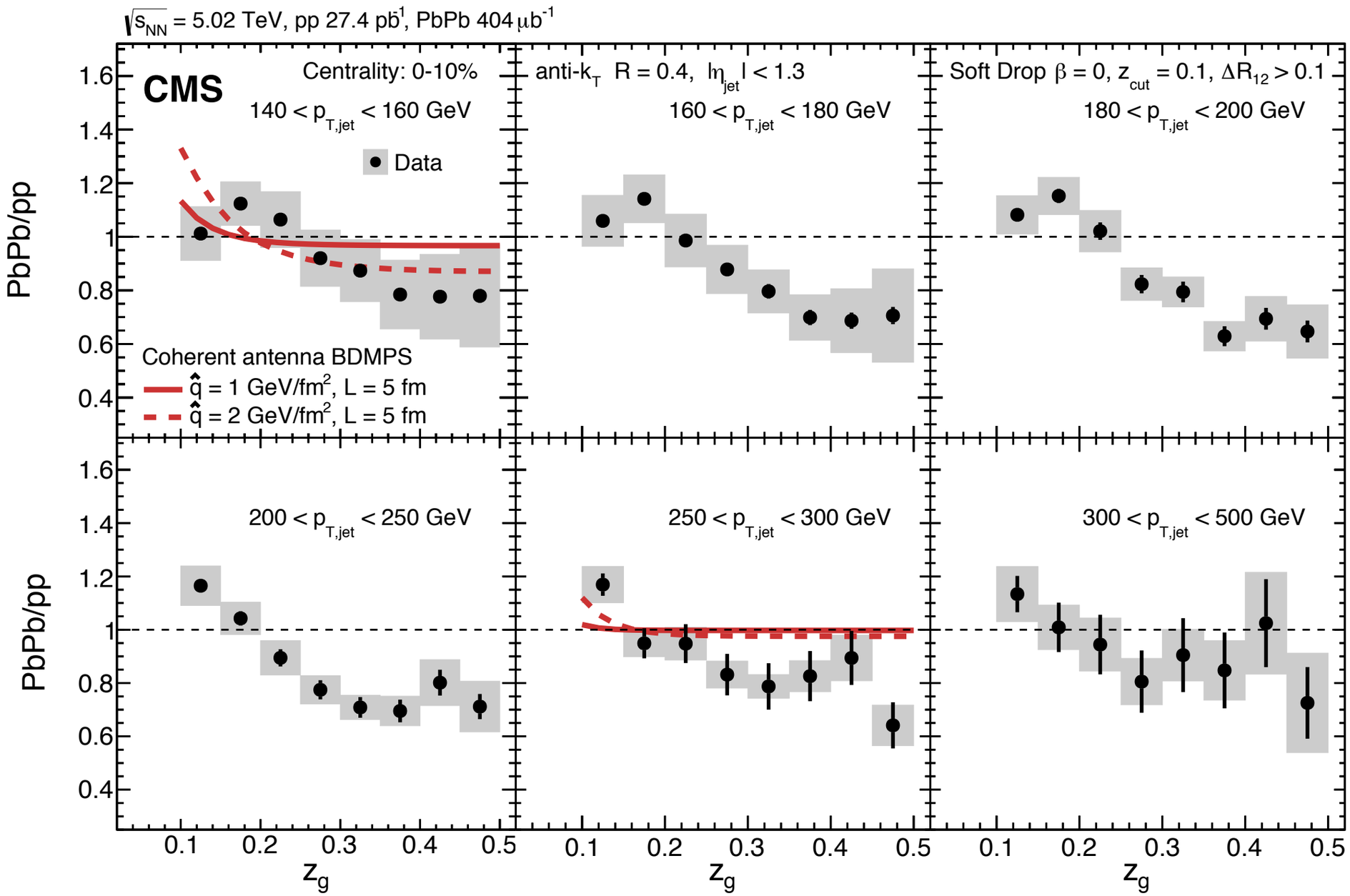
- Subleading subjet promotion by soft large-angle recoil contributions

# Shared Momentum Fraction (BDMPS)

PRL 120 (2018) 142302

## ( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming

10% most central events




Medium-induced gluon radiation

**Multiple medium-induced gluon bremsstrahlung (coherent):**
Phys. Lett. B 345 (1995) 277
Nucl. Phys. B 483 (1997) 291
Nucl. Phys. B 484 (1997) 265
JHEP 04 (2017) 125

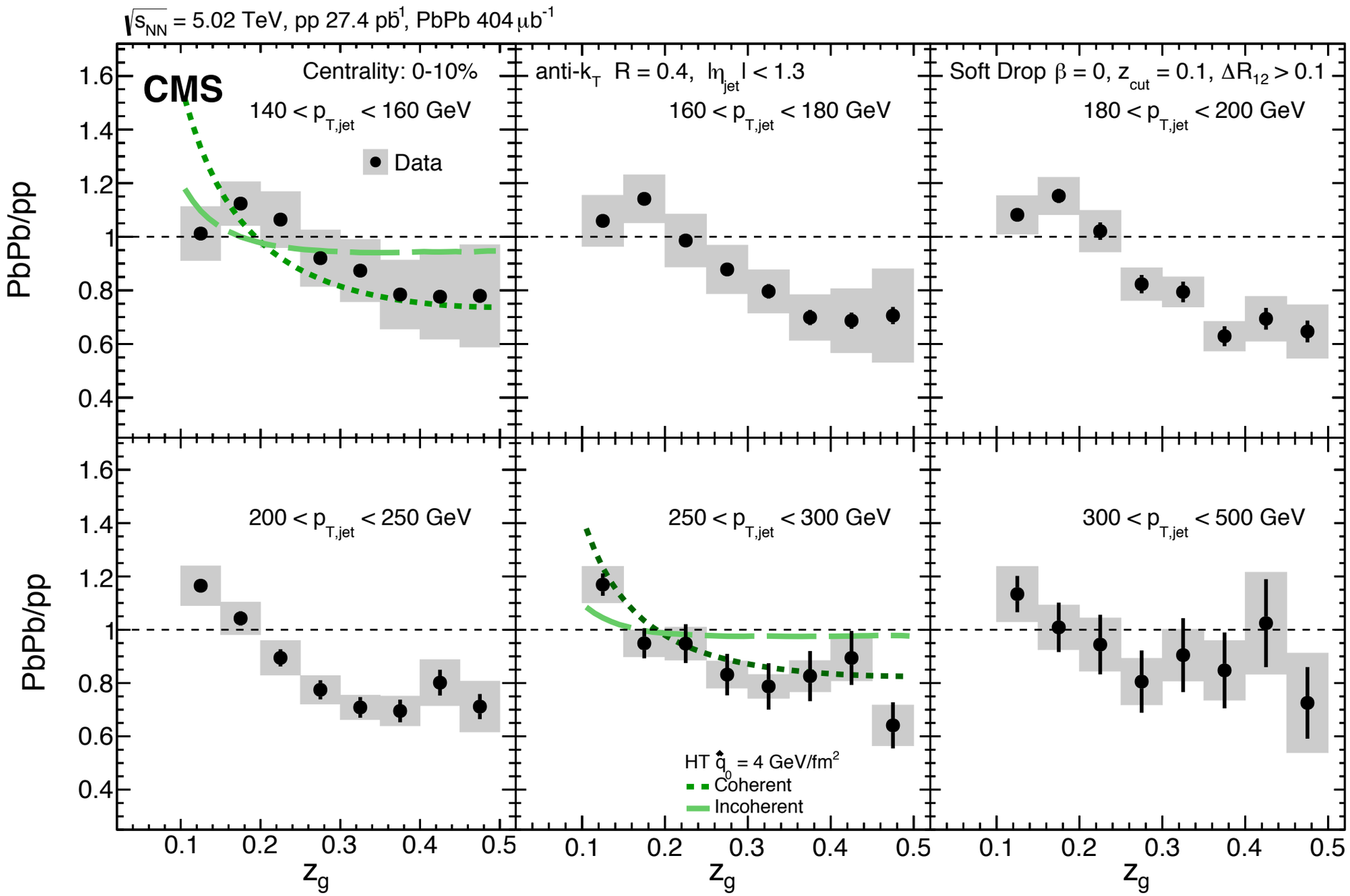
- Modification due to hard BDMPS emissions off coherent jets

# Shared Momentum Fraction (HT)

PRL 120 (2018) 142302

## ( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming

10% most central events




**Medium-induced gluon radiation**

Talk by Guang-You Qin (Wednesday 10:00)

**Higher twist calculation:**
arXiv:1707.03767

- Increased modification with coherent setting compared to incoherent setting

# Shared Momentum Fraction ($SCET_g$)

**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**

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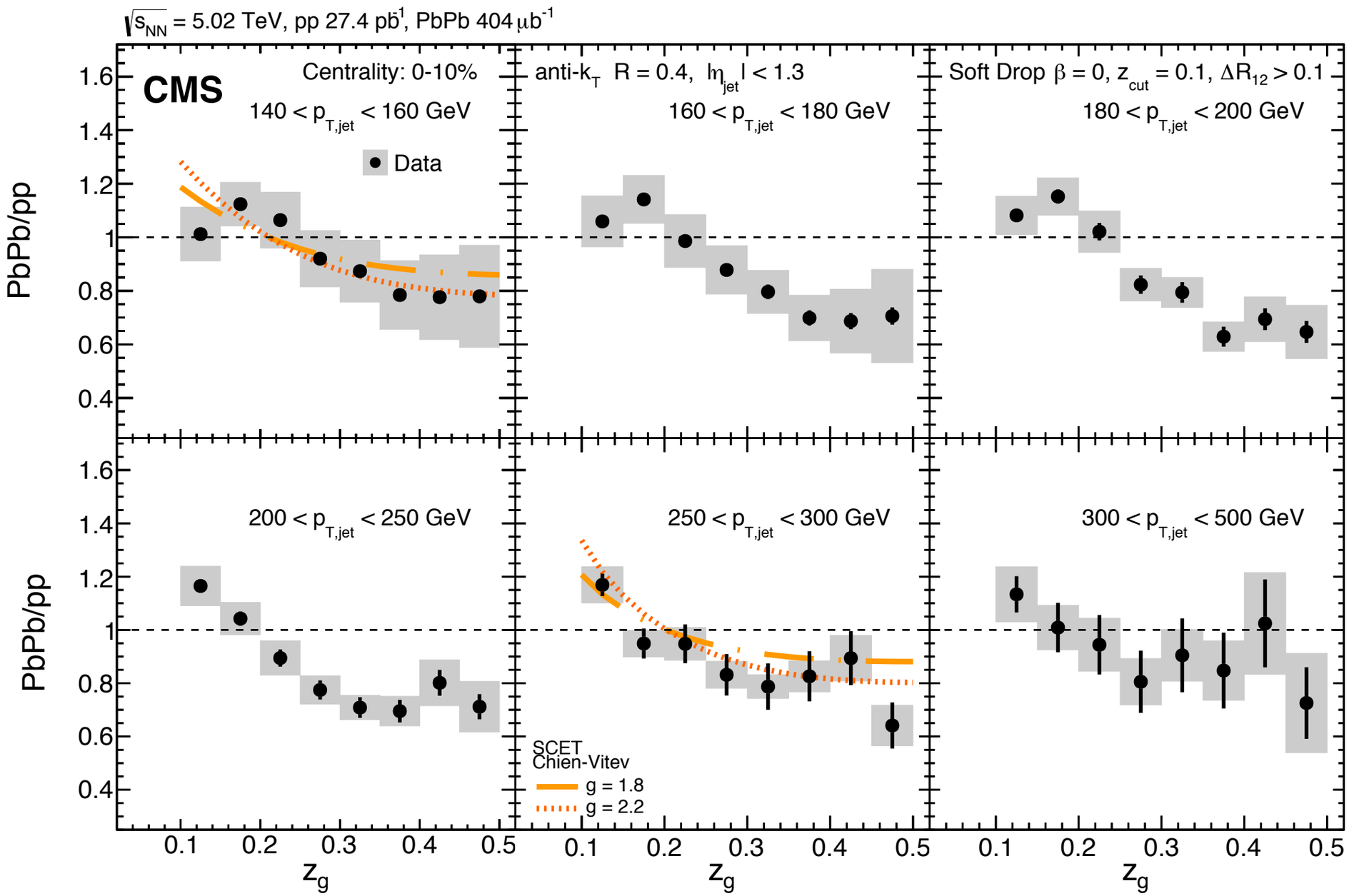
10% most central events




**Modified splitting function**

**Soft collinear effective theory:**
arXiv:1608.07283

- Increased modification with higher coupling constant

# Groomed Jet Mass (centrality bins)

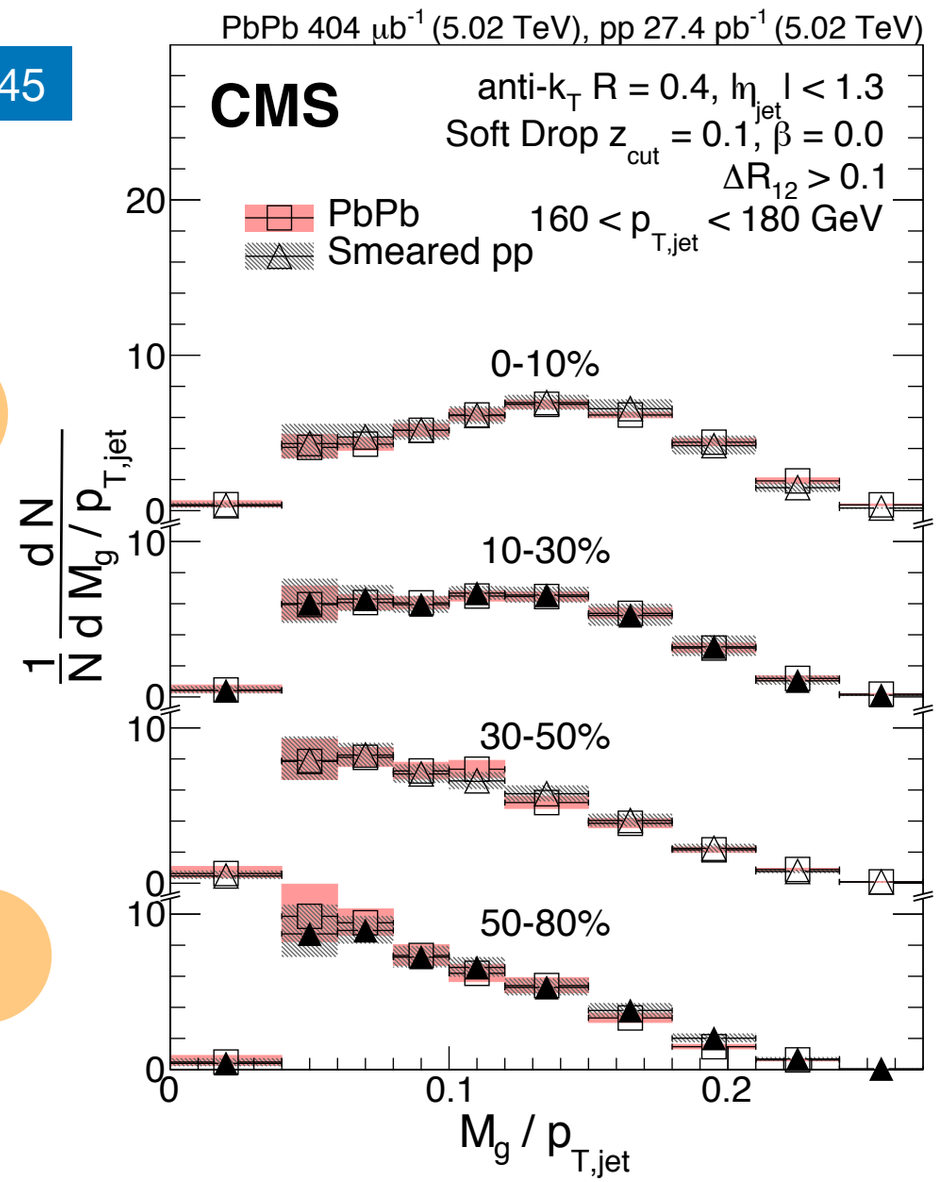
## ( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming

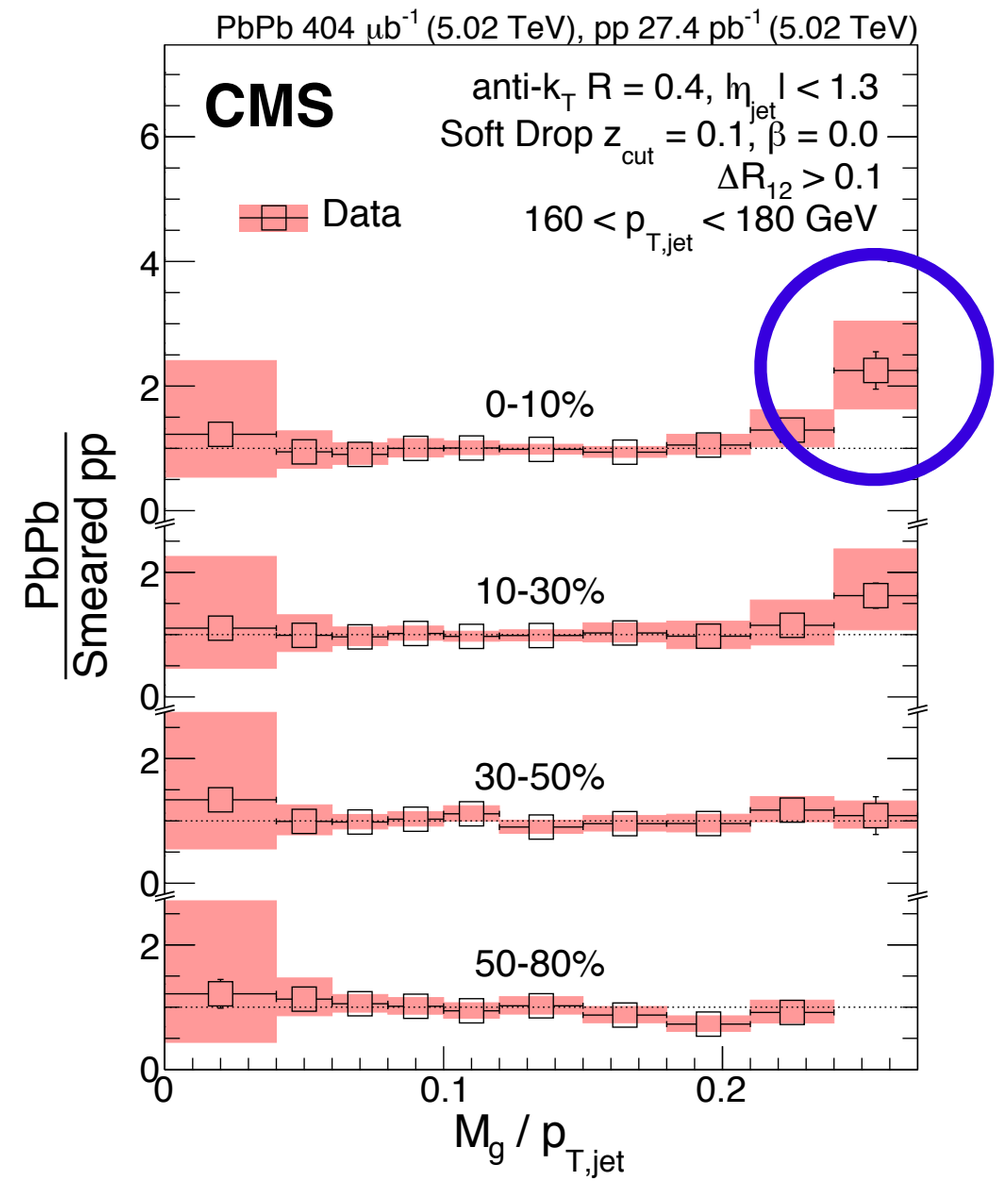
## $p_{T,jet}$ : 160 -180 GeV

arXiv:1805.05145

Central Collisions

Peripheral Collisions




- Enhancement of $M_g/p_{T,jet}$ observed in central PbPb collisions relative to pp collisions

# Groomed Jet Mass (centrality bins)

## ( $z_{cut}$ = 0.5, $\beta$ = 1.5 ) : jet core

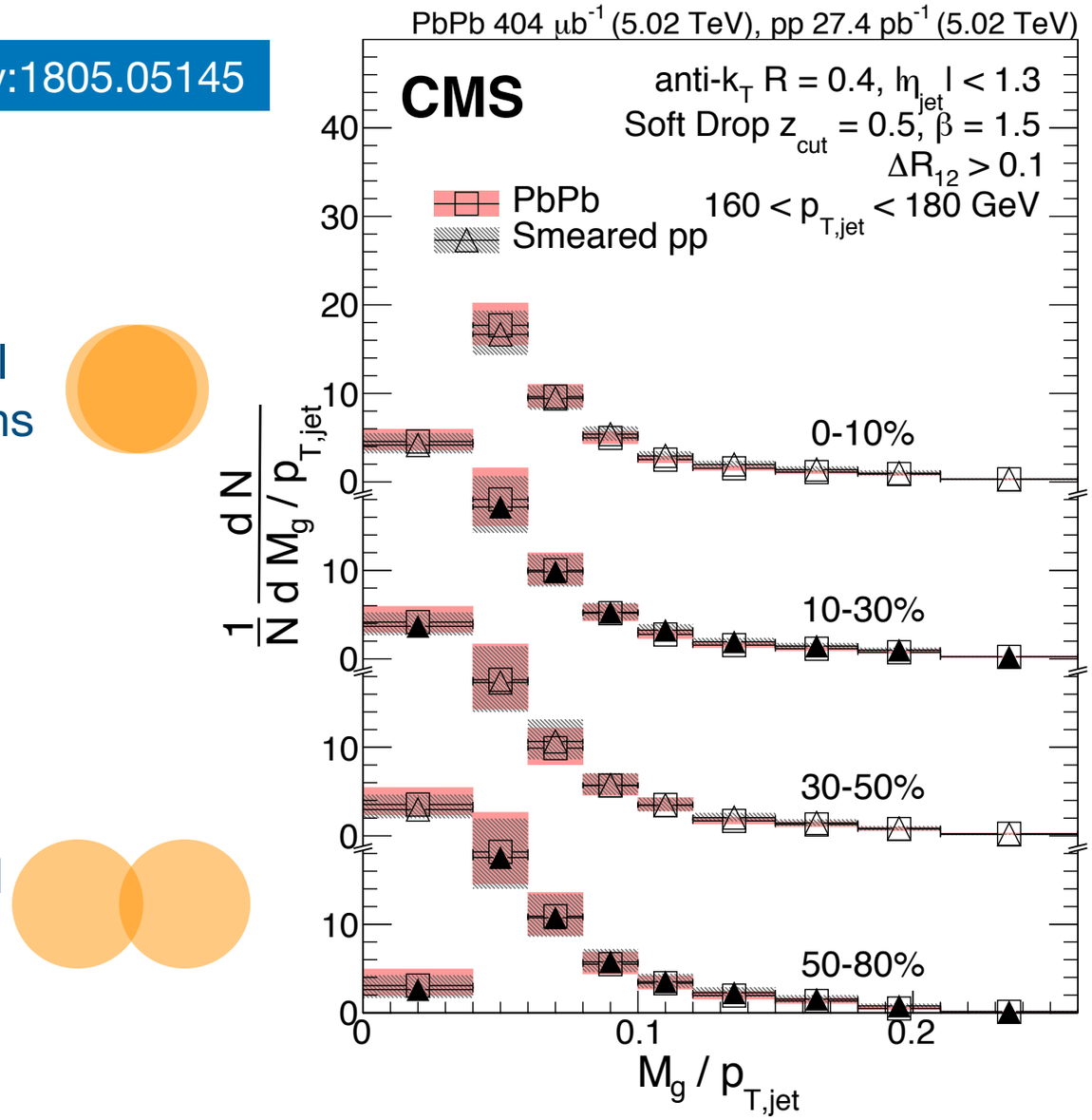
## $p_{T,\,jet}$ : 160 -180 GeV

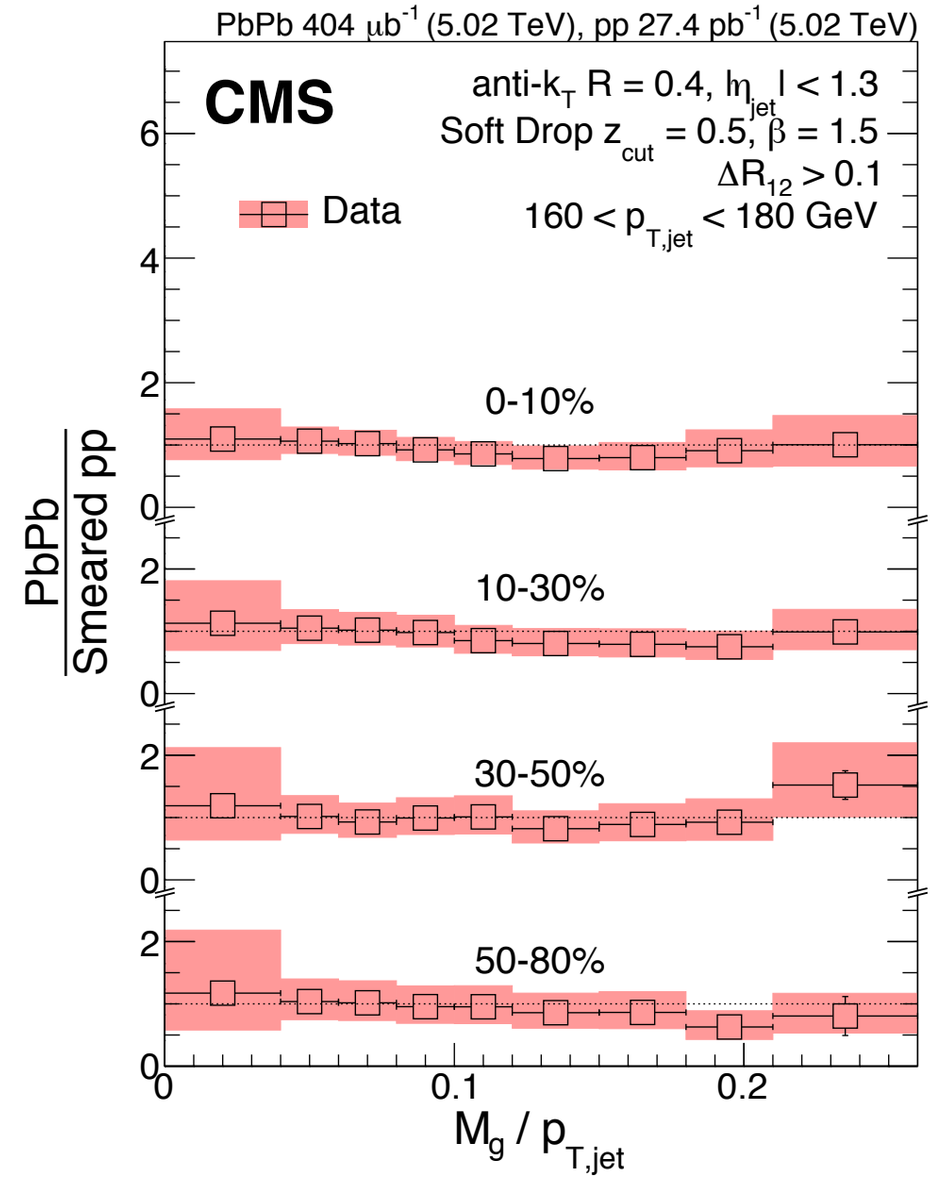
arXiv:1805.05145

Central Collisions



Peripheral Collisions



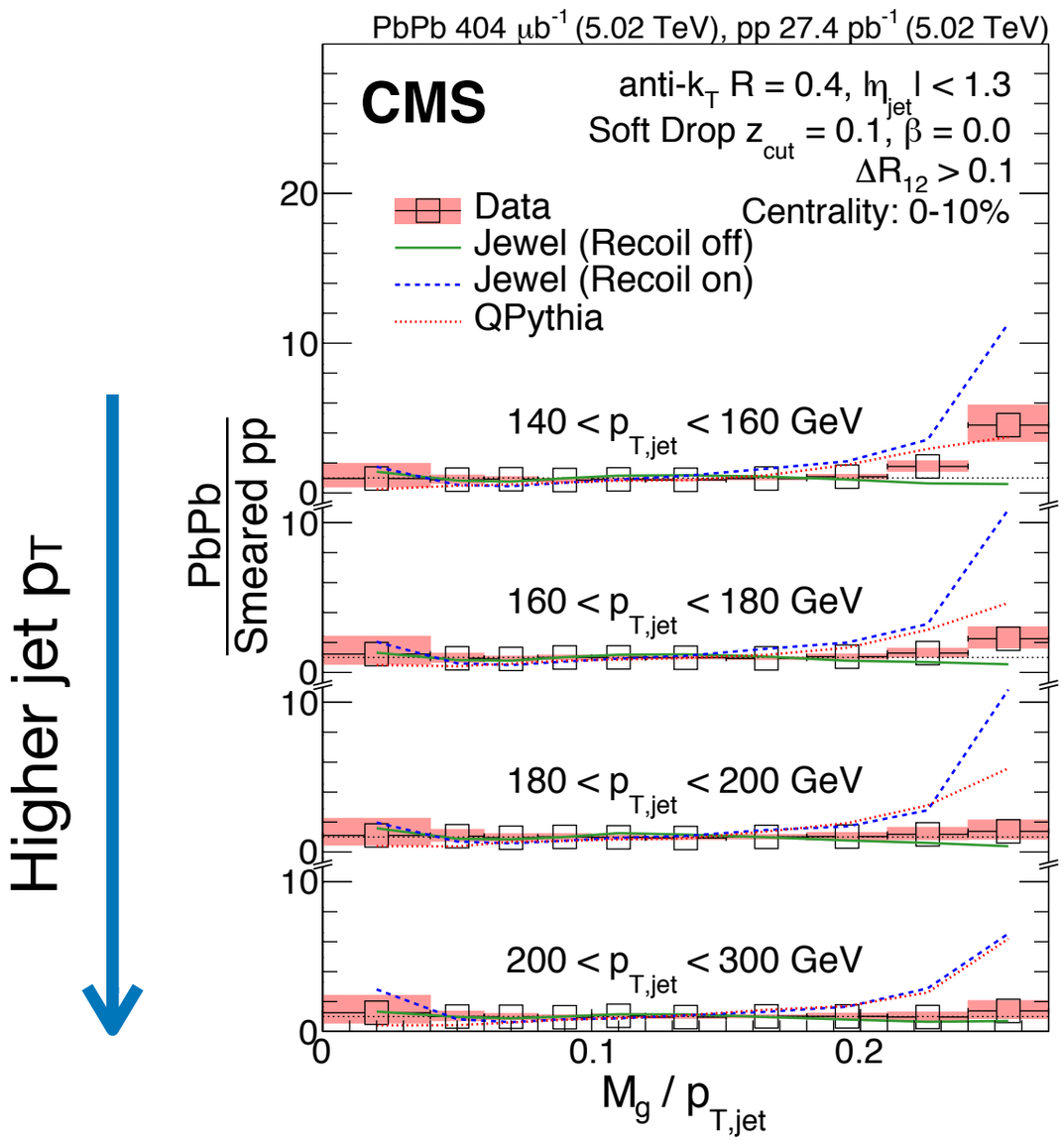

- No significant modifications to the core of the jet observed

# Groomed Jet Mass ($p_{T,jet}$ bins)

arXiv:1805.05145

## 10% most central events

**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**




**JEWEL:**
EPJC (2014) 74: 2762

**Q-PYTHIA:**
EPJC (2009) 63: 679

# Groomed Jet Mass ($p_{T,jet}$ bins)

arXiv:1805.05145

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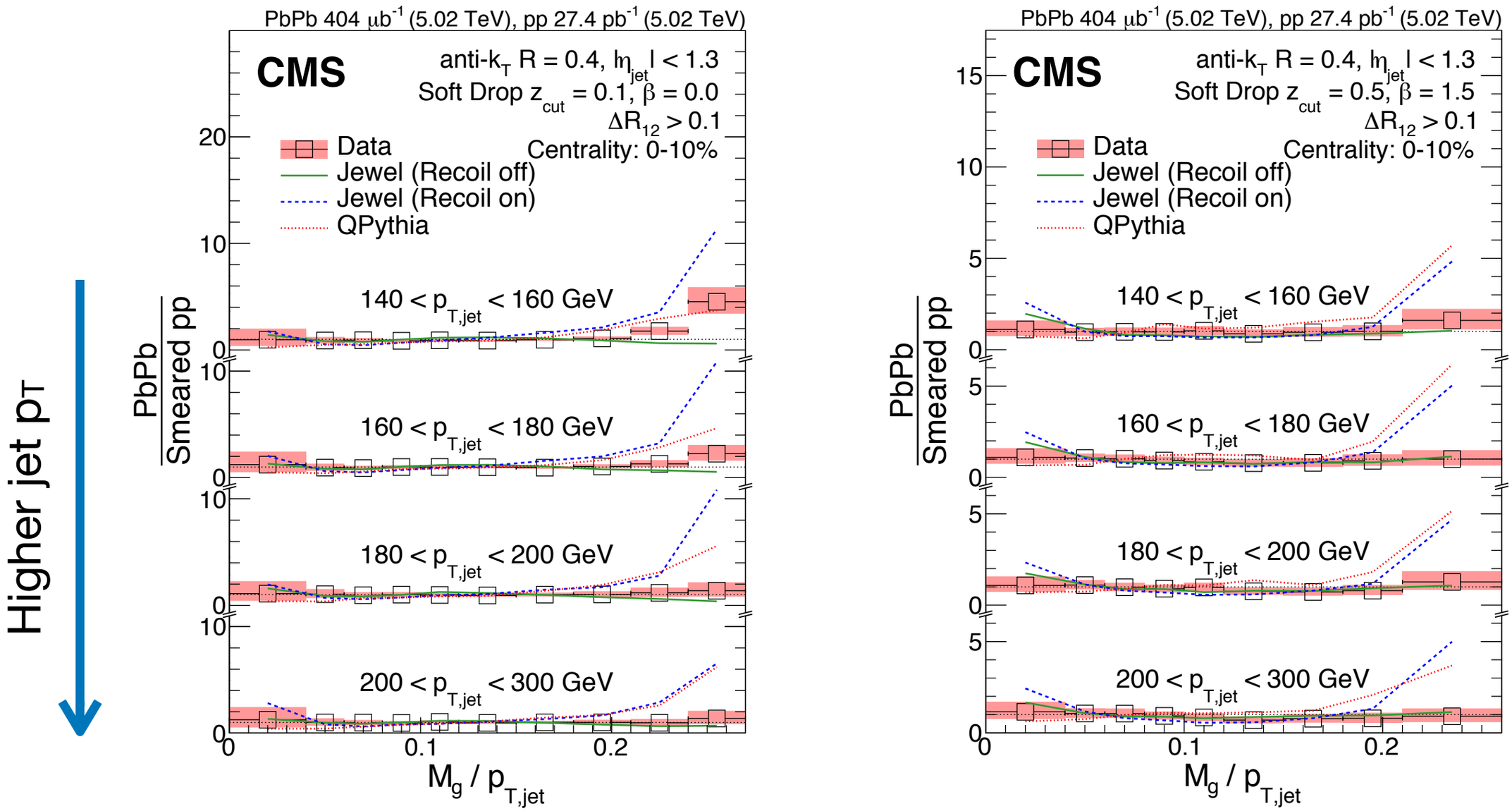
**( $z_{cut}$ = 0.5, $\beta$ = 1.5 ) : jet core**




**JEWEL:**
EPJC (2014) 74: 2762

**Q-PYTHIA:**
EPJC (2009) 63: 679

- Of the models compared to data here, none describe the jet mass measurements for the flat and jet core grooming settings simultaneously

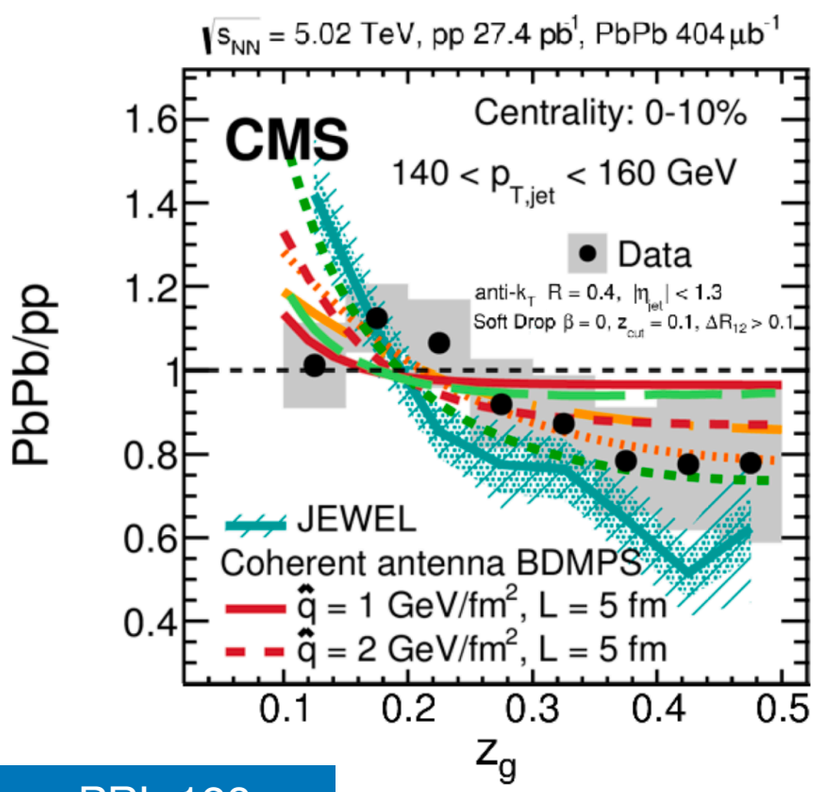
# Summary

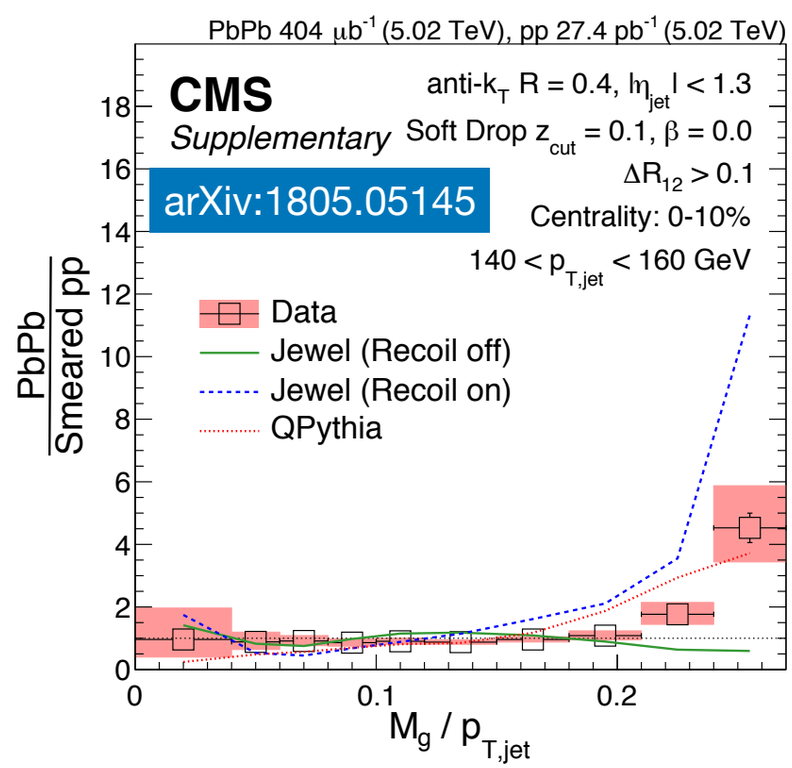
- Jet mass and shared momentum fraction measurements in pp and PbPb collisions with the CMS detector at the LHC are presented using 5.02 TeV data

- **Flat grooming setting**: Subjets less balanced in PbPb + enhancement of large mass jets in PbPb

**Centrality 0-10% ; 140 < $p_{T,jet}$ < 160 GeV**

**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**



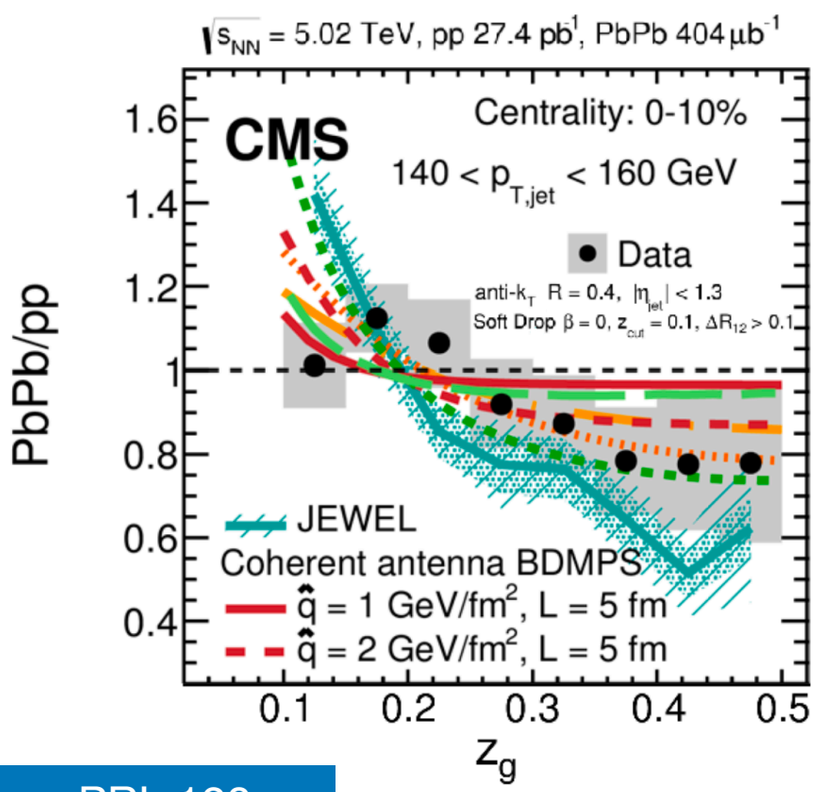

PRL 120 (2018) 142302

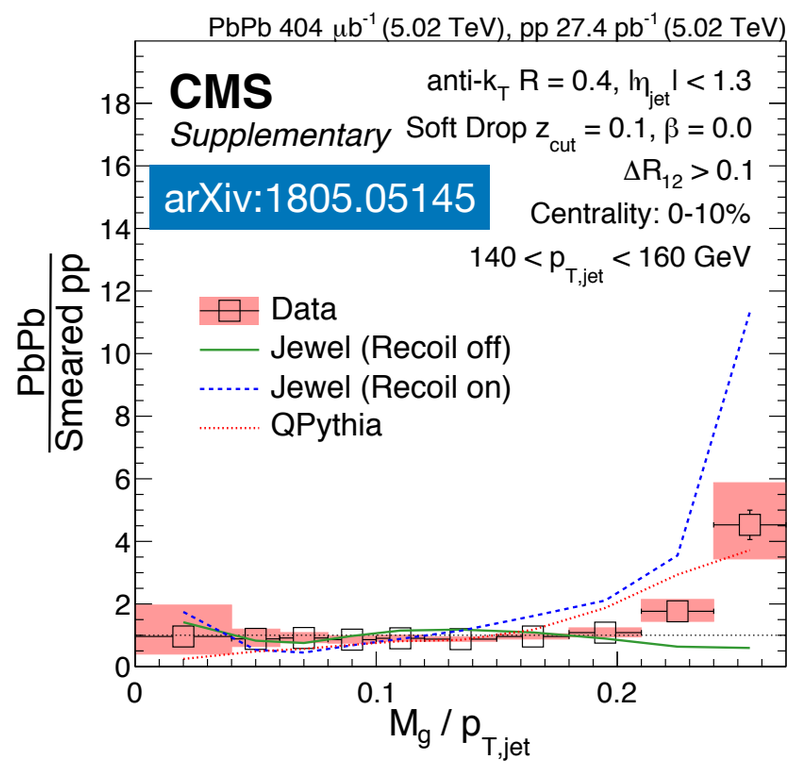
# Summary

- Jet mass and shared momentum fraction measurements in pp and PbPb collisions with the CMS detector at the LHC are presented using 5.02 TeV data
- **Flat grooming setting**: Subjets less balanced in PbPb + enhancement of large mass jets in PbPb
- **Jet core setting**: No modification observed in jet mass

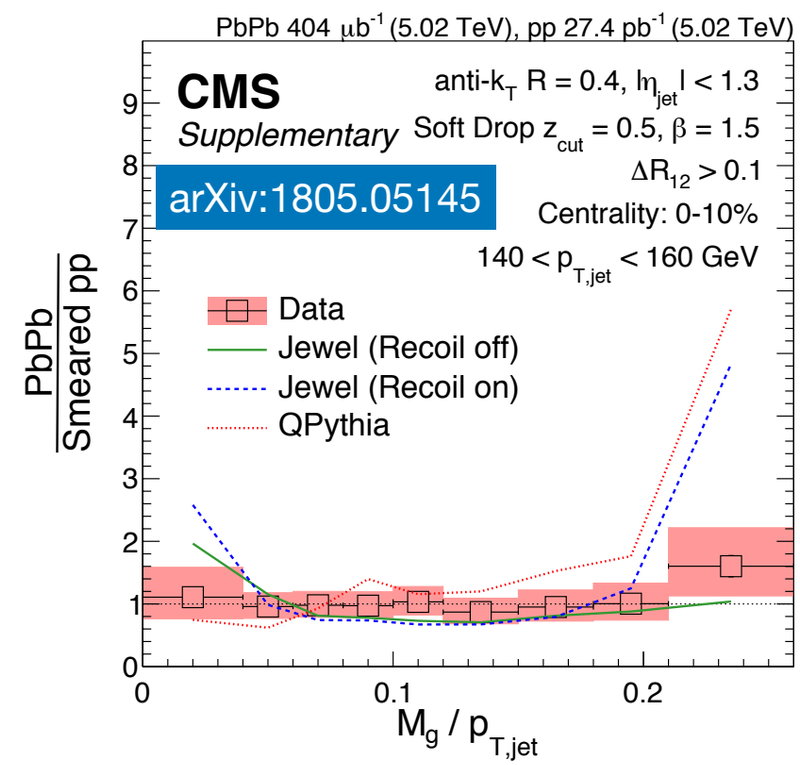
**Centrality 0-10% ; 140 < $p_{T,jet}$ < 160 GeV**

**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming**




**( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : jet core**

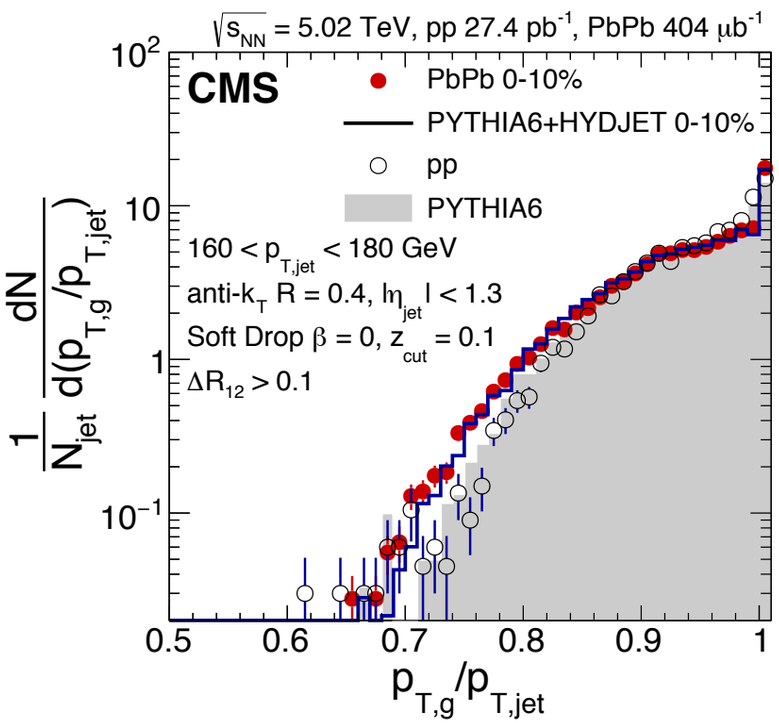



PRL 120 (2018) 142302

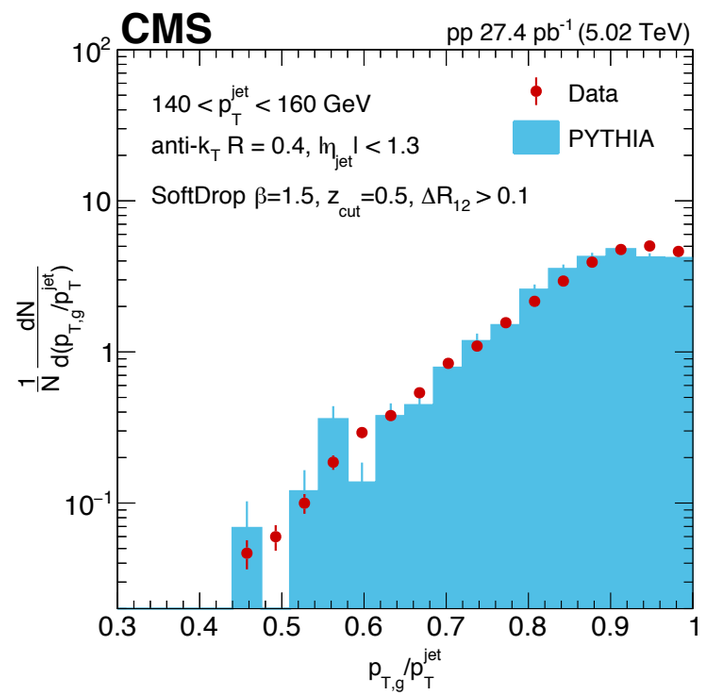
# Backup Slides

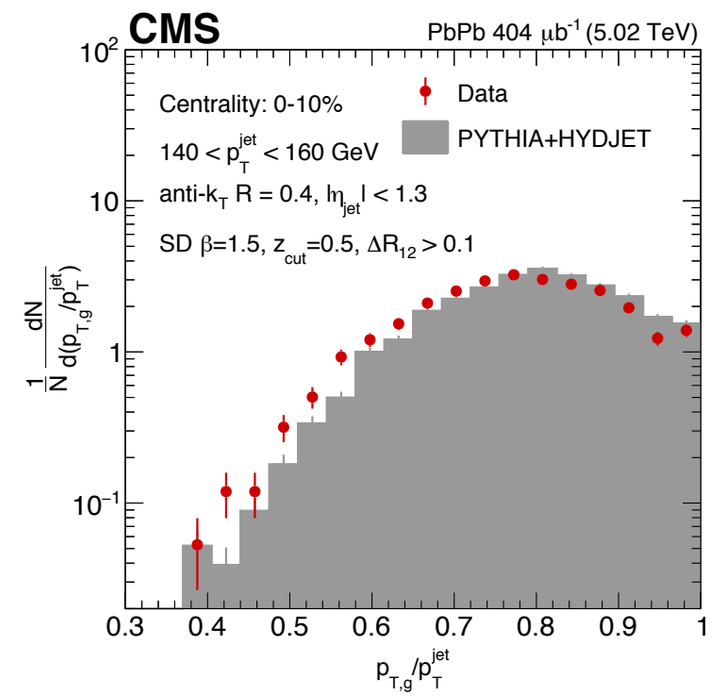
# Groomed Energy Fraction

## Momentum sharing result




## Groomed jet mass result

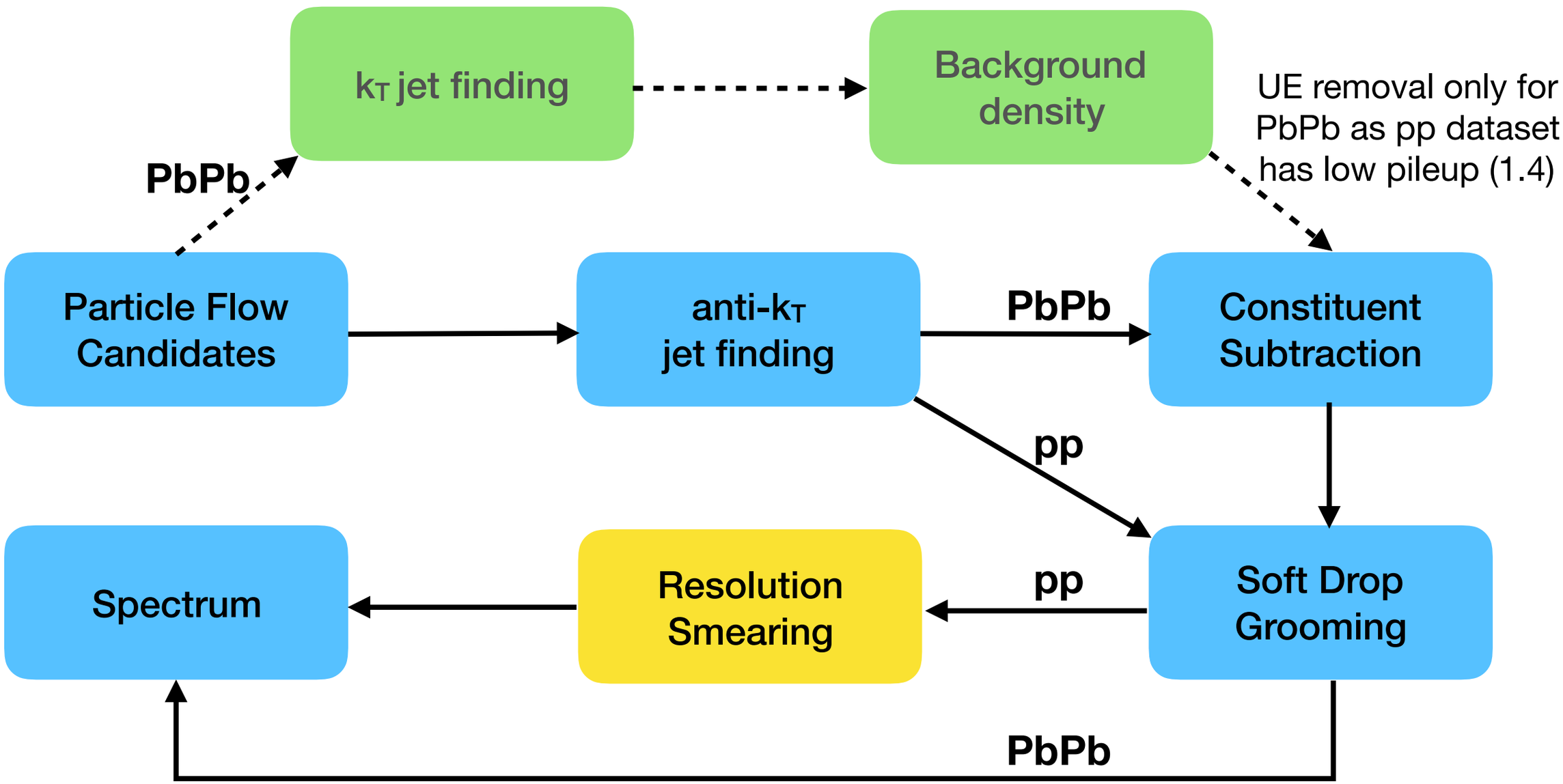



- Larger amount of energy gets groomed away in PbPb collisions
- Groomed energy fractions well described by MC

# Analysis Flow (momentum sharing and jet mass)

- We use **Particle Flow jets** clustered with the anti-$k_T$ algorithm and radius **$R_{jet}$ = 0.4, jet $|\eta|$ < 1.3, jet $p_T$ > 140 GeV**
- Particle level Constituent Subtraction[1] is performed in PbPb to remove contribution from underlying event activity




[1] : Berta et al. arXiv:1403.3108

# PbPb vs. smeared pp

- Smearing procedure applied to pp data to account for UE and reconstruction differences between pp and PbPb collisions
- Different methods used for this purpose in the two analyses.

**Shared Momentum Fraction ( $z_g$ )**

pp vs. embedded pp
↓
Smearing matrix
↓
Apply on data

**Groomed Mass ( $M_g/p_{T,jet}$ )**

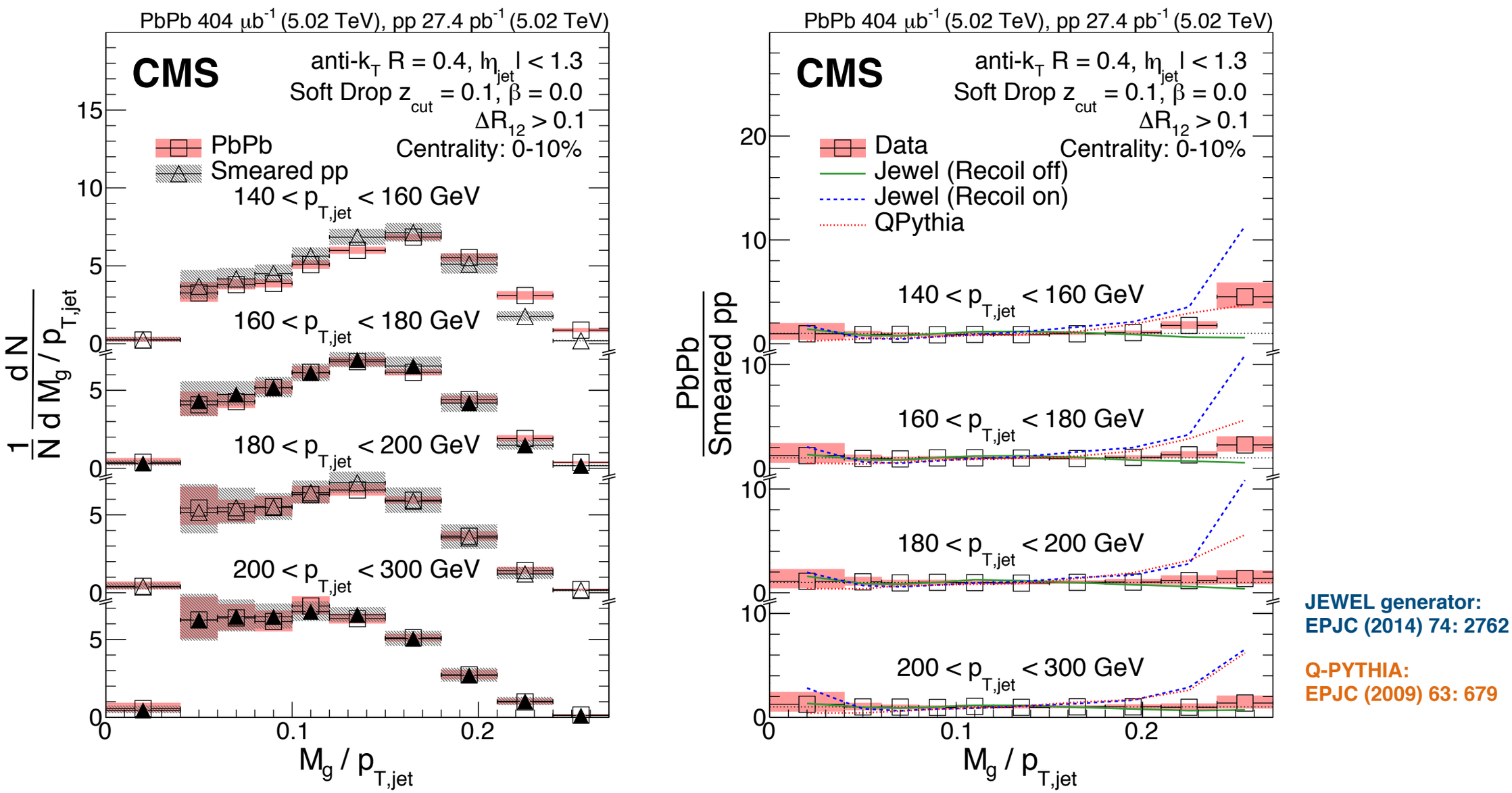
Event mixing:
pp + PbPb background
↓
Subtraction and Grooming

**Internal cross check : The two methods give consistent $z_g$ result**

# Groomed Jet Mass ($p_{T,jet}$ bins)

## ( $z_{cut}$ = 0.1, $\beta$ = 0.0 ) : flat grooming

10% most central events




JEWEL generator:
EPJC (2014) 74: 2762

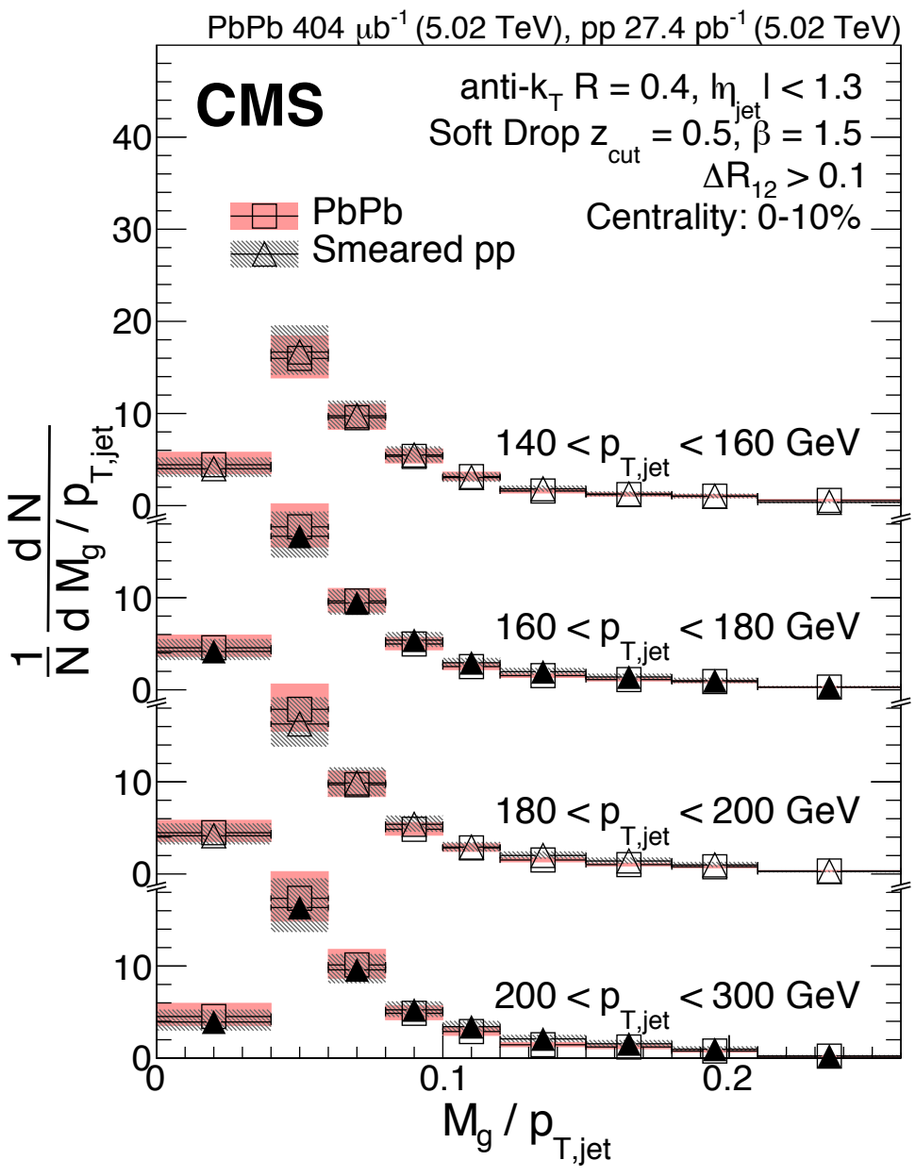
Q-PYTHIA:
EPJC (2009) 63: 679

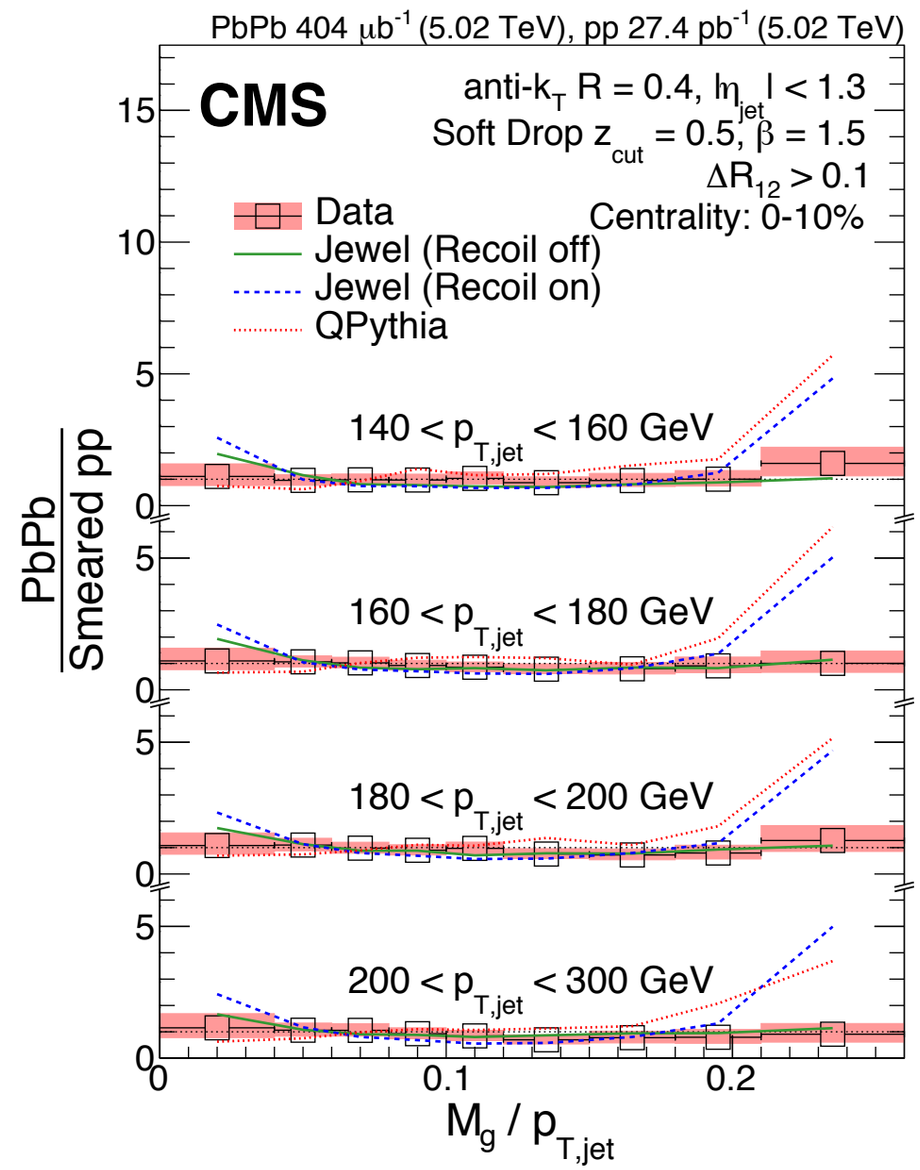
- Generators JEWEL (recoil on) and Q-PYTHIA tend to predict large modification
- Modification gets weaker with increasing jet $p_T$

# Groomed Jet Mass ($p_{T,jet}$ bins)

## ( $z_{cut}$ = 0.5, $\beta$ = 1.5 ) : jet core

10% most central events



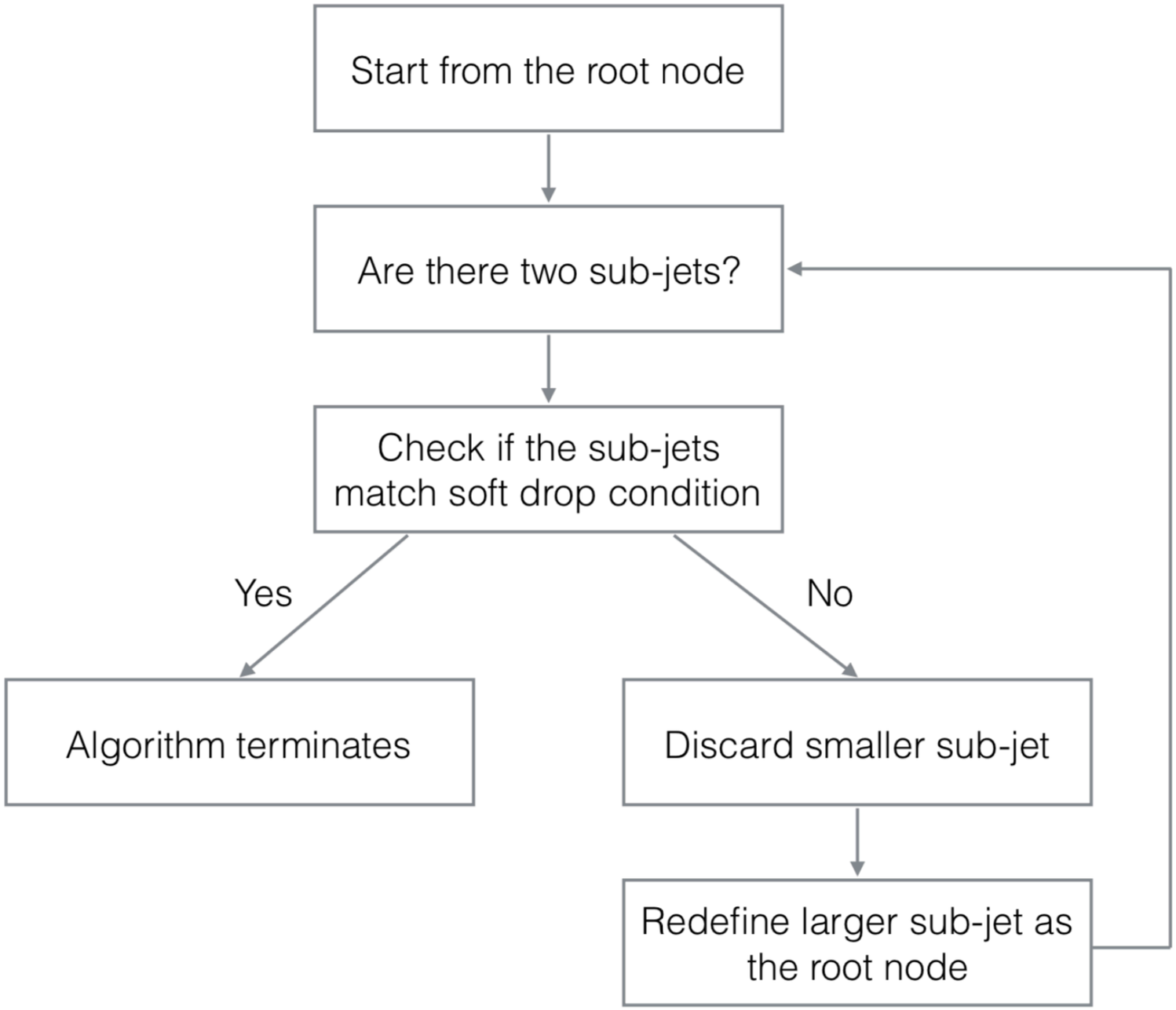




**JEWEL generator:**
**EPJC (2014) 74: 2762**

**Q-PYTHIA:**
**EPJC (2009) 63: 679**

- Generators JEWEL (recoil on) and Q-PYTHIA tend to predict large modification
- No significant modifications to the core of the jet

# Soft Drop flow chart



# Constituent Subtraction