Splitting function in pp and PbPb collisions at 5.02 TeV

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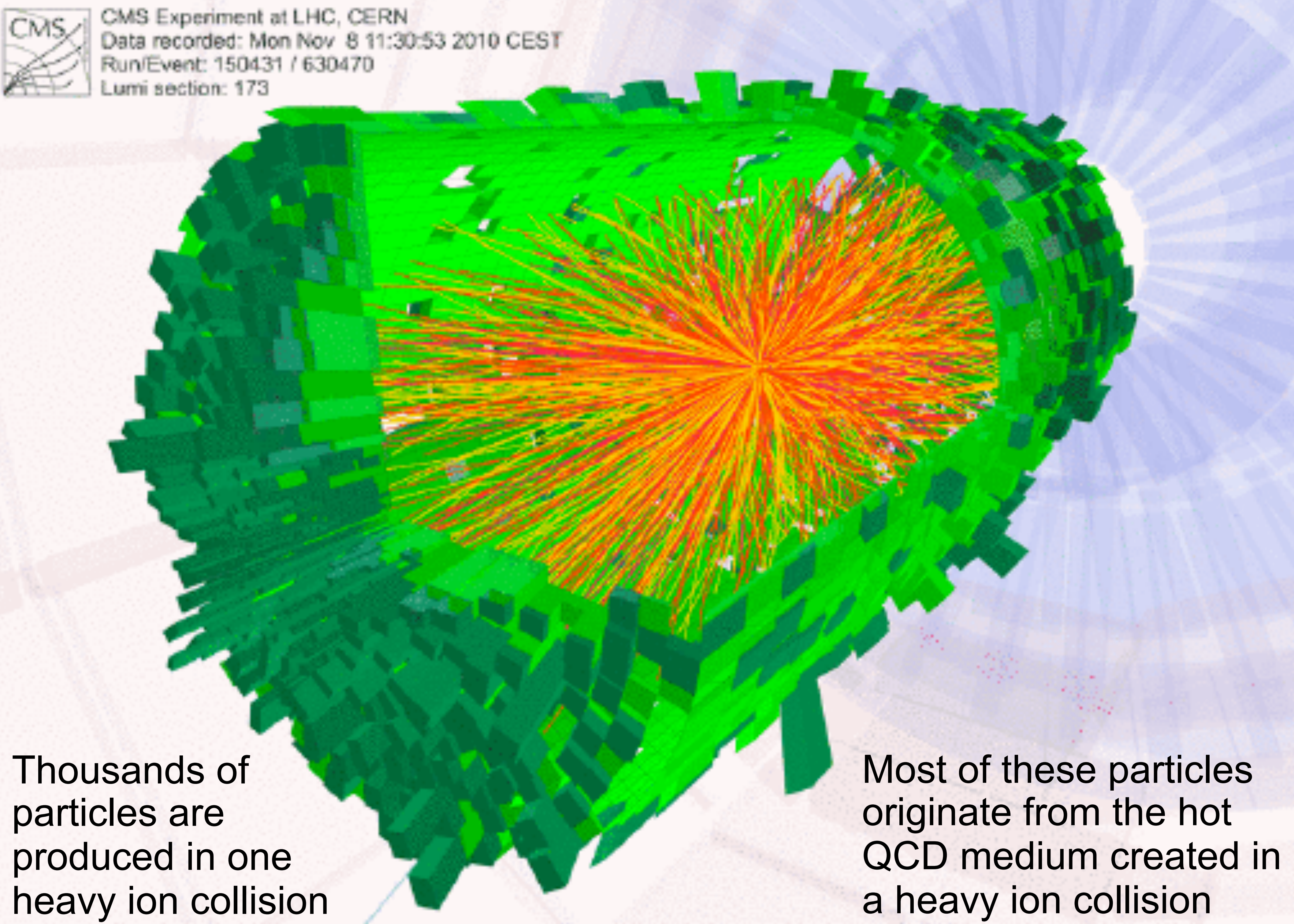
for the CMS collaboration

July 22 2016

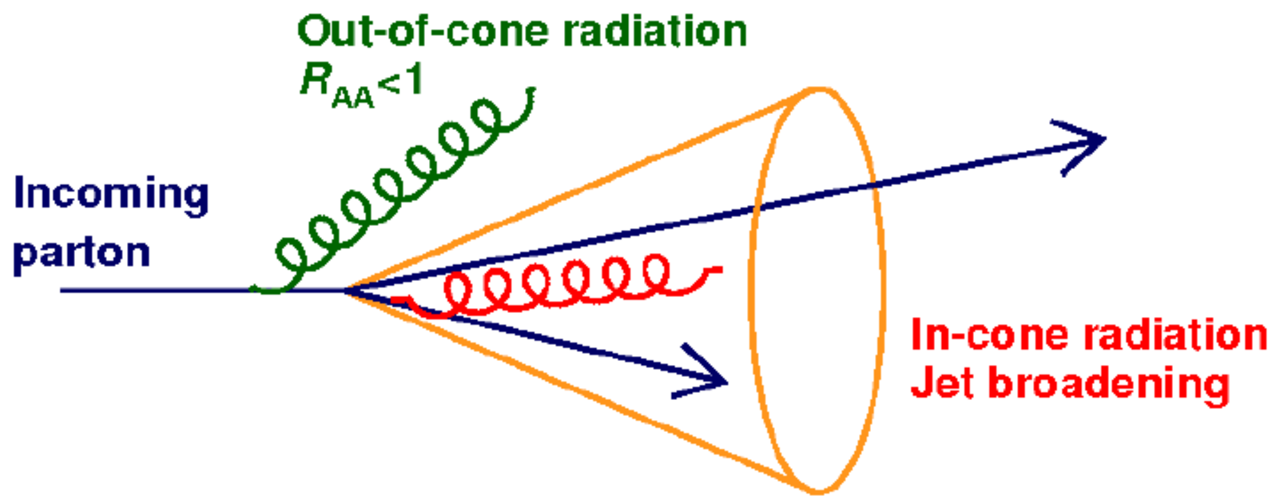


Thousands of particles are produced in one heavy ion collision

Most of these particles originate from the hot QCD medium created in a heavy ion collision

Jets in heavy-ion collisions

- Due to interactions of the hard parton with the medium, the jet is modified relative to pp: Jet Quenching



At RHIC previously studied using 'high p_T' particle production
+ first jet measurements

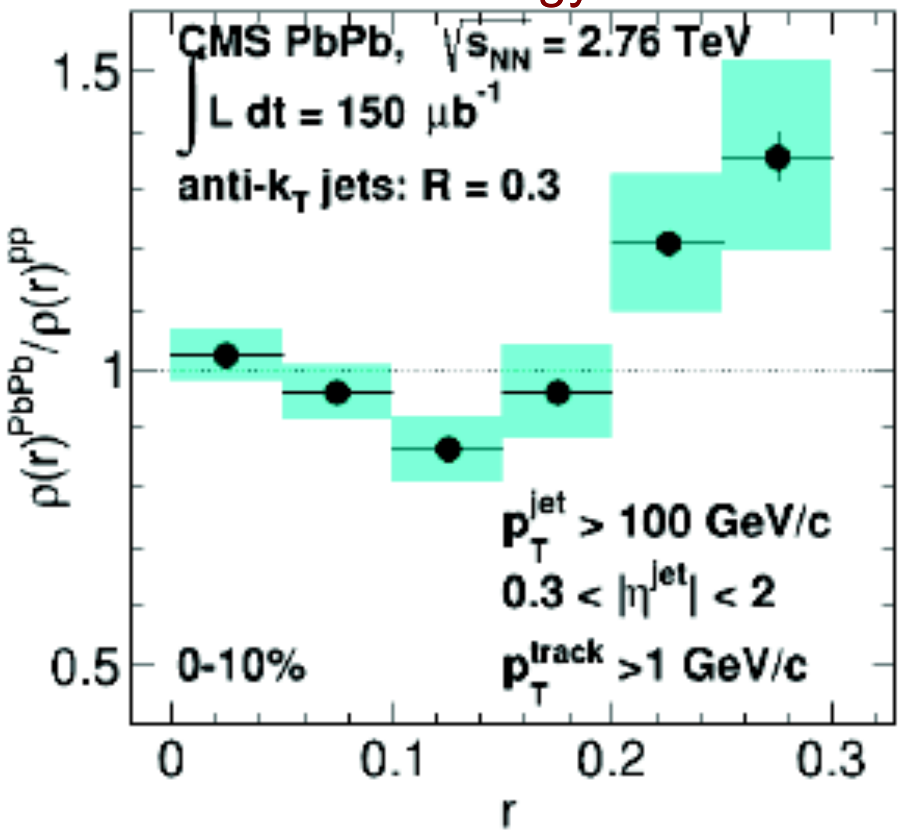
At LHC: larger center-of-mass
→ More hard processes to study the mechanism in detail

Jet shapes and structures Run1

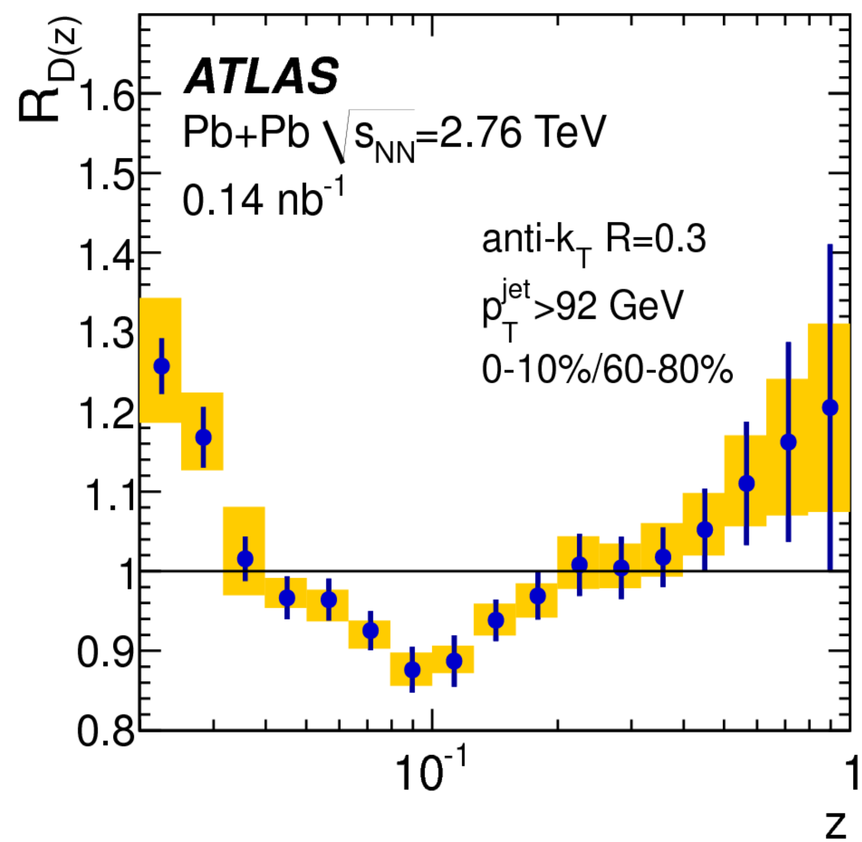
Jet shape observables: energy distribution within a jet
Sensitive to dynamics of parton shower

Radial profile
Transverse fragment distribution
Energy

CMS PLB 730 (2014) 243



'Fragmentation function'
Longitudinal fragment distribution
Multiplicity



ATLAS: PLB 739 (2014) 320–342

Small enhancement at large *R* and small *z:* 1-2 GeV + 2 particles
+ suppression at intermediate *R* and *z*

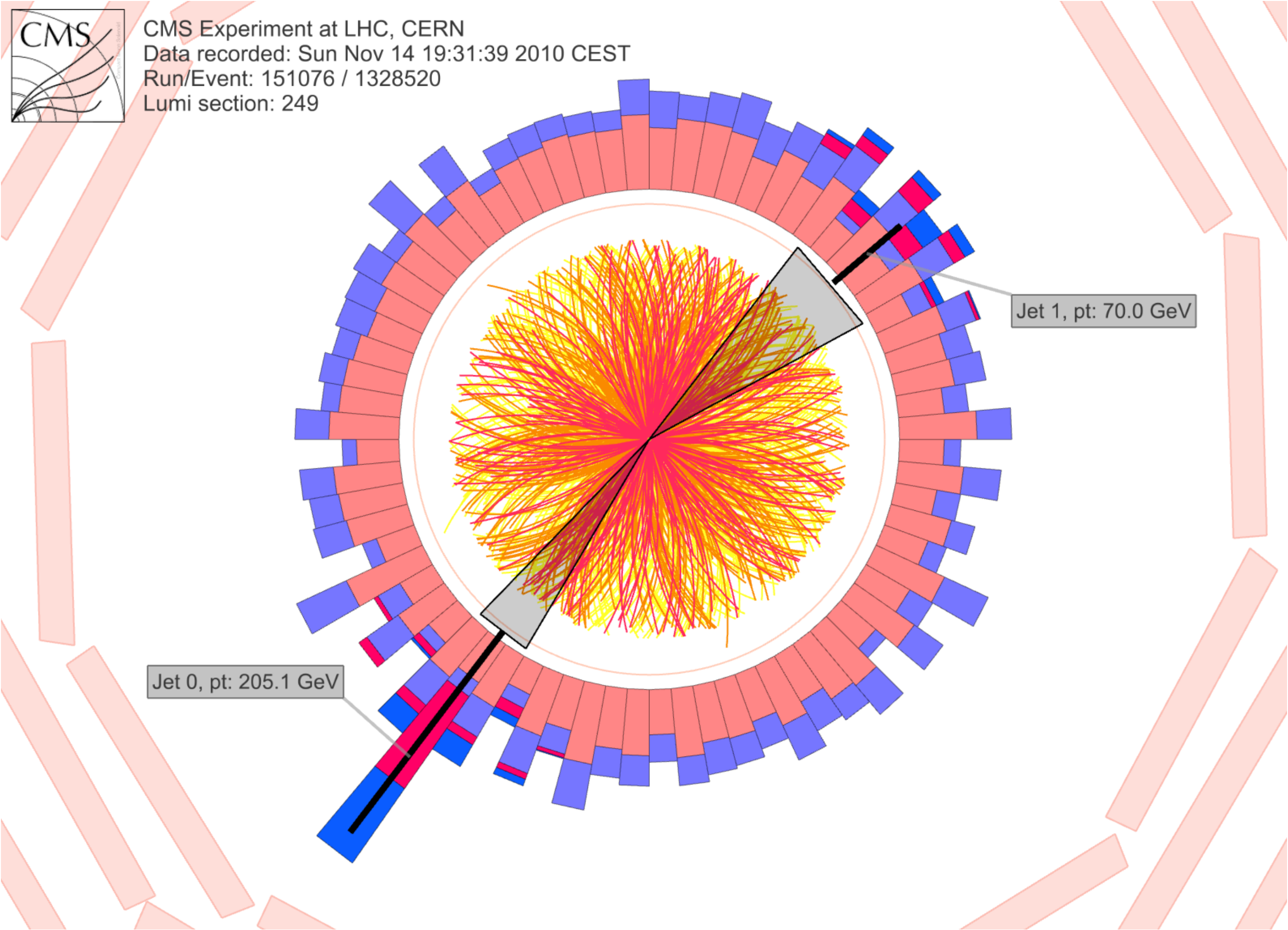
Find the jets

Jets are not so easy to find in a heavy-ion collision

Underlying event needs to be subtracted

→ same as for PU but now everything comes from the same vertex

Particle-by-particle approach: Constituent Subtraction [1]



[1] Berta et al. arXiv:1403.3108

Why measure splitting function?

Goal: understand the evolution of the parton shower in medium

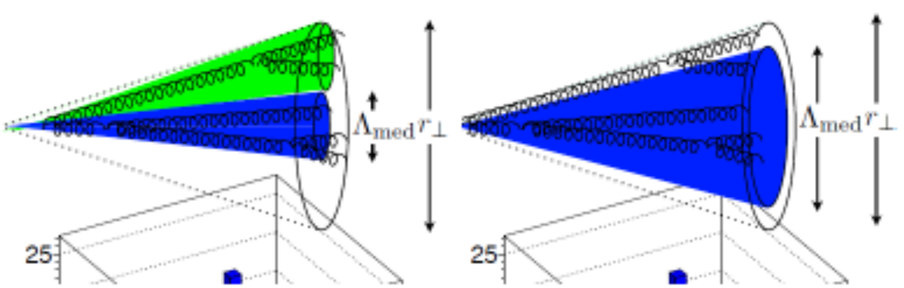
Effect of parton-medium interaction on parton branchings unknown

Several scenarios proposed by theorist.

Here a selection of those that are probed by this measurement:

- Parton gains virtuality due to interaction with medium
  - → increases the gluon radiation probability
  - → modified jet structure
- Antenna picture: role of (de)coherent emitters. Depends on critical angle and therefore temperature of medium

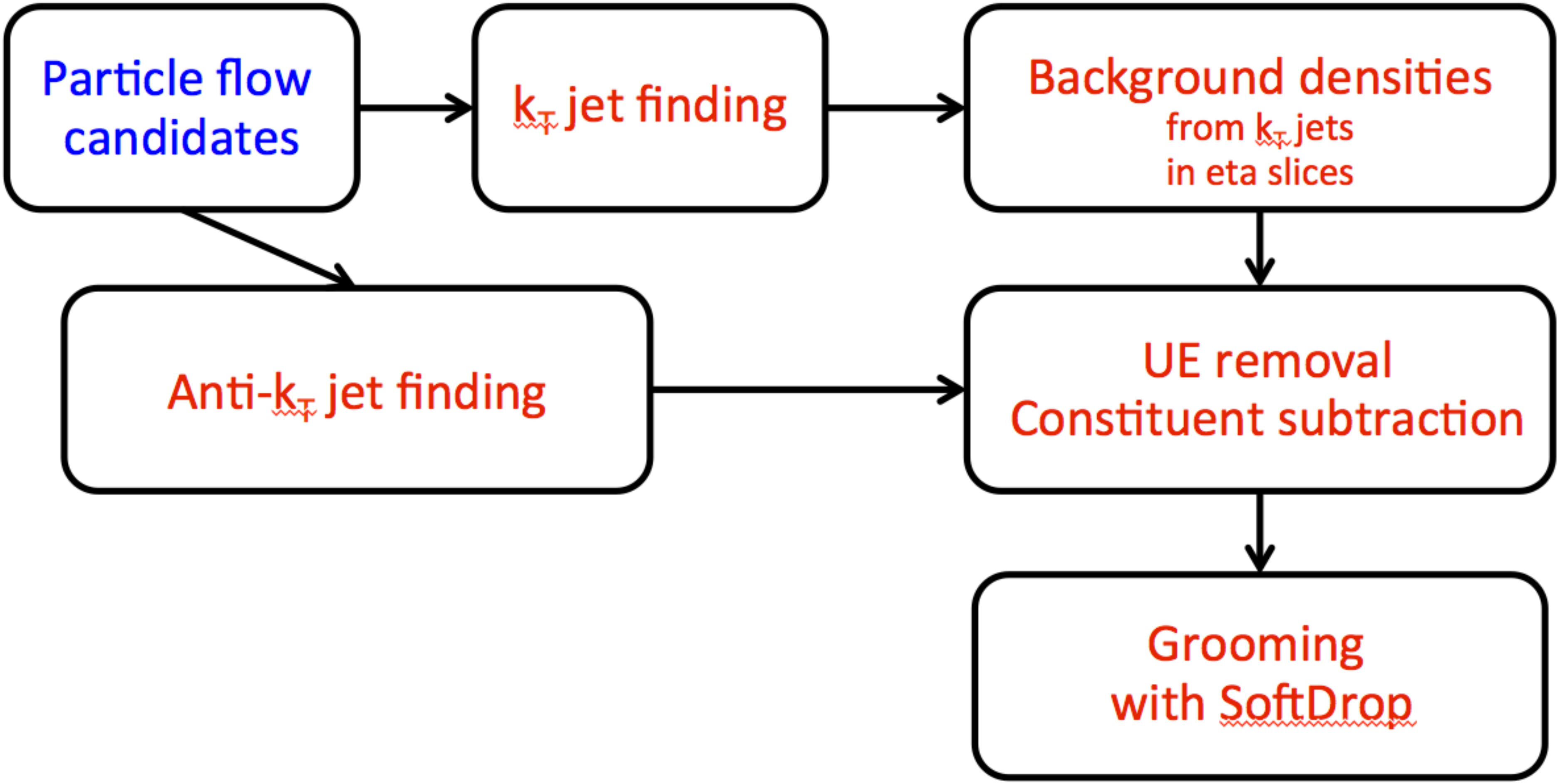
2 coherent emitters: color disconnected subjets



1 coherent emitter: color connected subjets

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

Analysis techniques

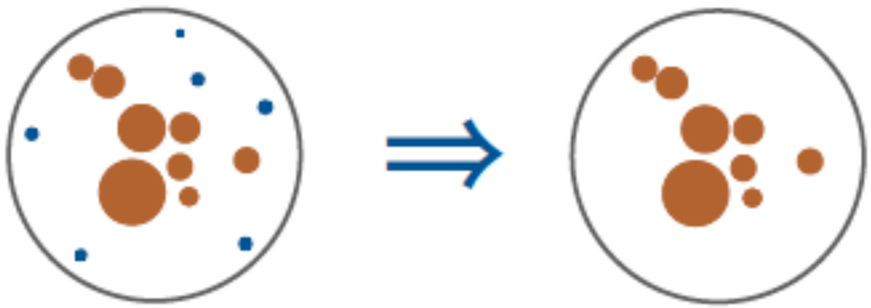


UE removal only for PbPb since
pp data set has low pileup (1.4)

Constituent subtraction
Berta et al. arXiv:1403.3108

Soft Drop

Soft Drop = Jet grooming technique
removes large-angle soft radiation + remaining background



Soft Drop condition

$$z > \underbrace{z_{\mathrm{cut}}}_{\text{energy threshold}}\, \theta^{\overbrace{\beta}^{\text{angular exponent}}}$$

We use $\beta = 0$ and $z_{cut} = 0.1$
All soft emissions are removed
Equivalent to modified Mass Drop

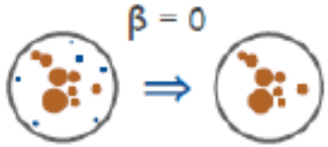
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}},$$

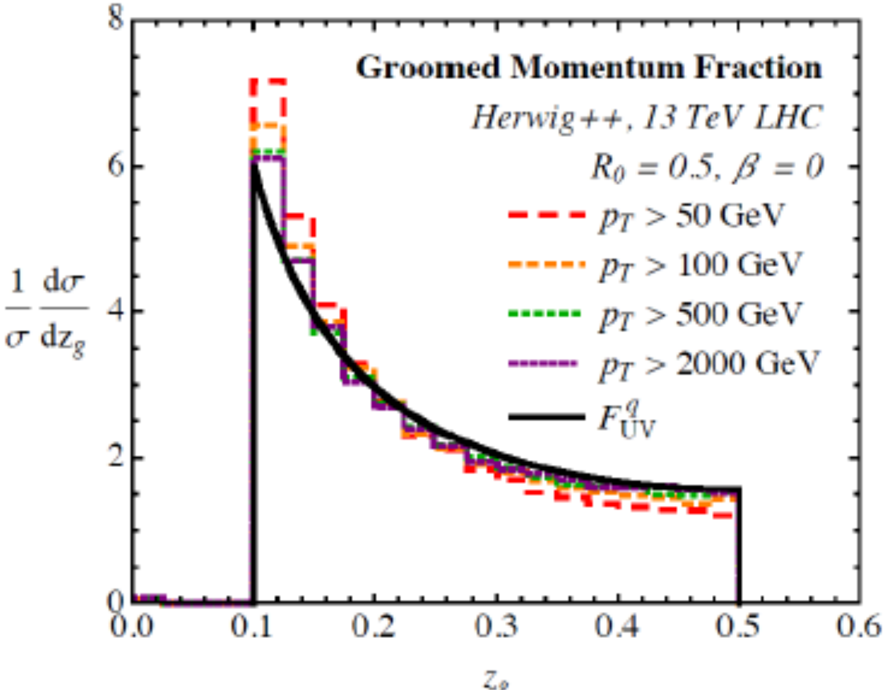
Momentum fraction carried by the subleading branch

[1] Larkoski, Marzani, Thaler
Phys. Rev. D91:111501 (2015)
Soft Drop: JHEP 1405 (2014) 146

Generalized fragmentation function

Measurement of QCD splitting function





Larkoski, Marzain, Thaler
Phys. Rev. D91:111501 (2015)
Soft Drop: JHEP 1405 (2014) 146

Momentum sharing between two leading subjets:

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

Independent of α_s

Moderate dependence on jet p_T

~ same for quarks and gluons

Sensitive to modification of splitting function

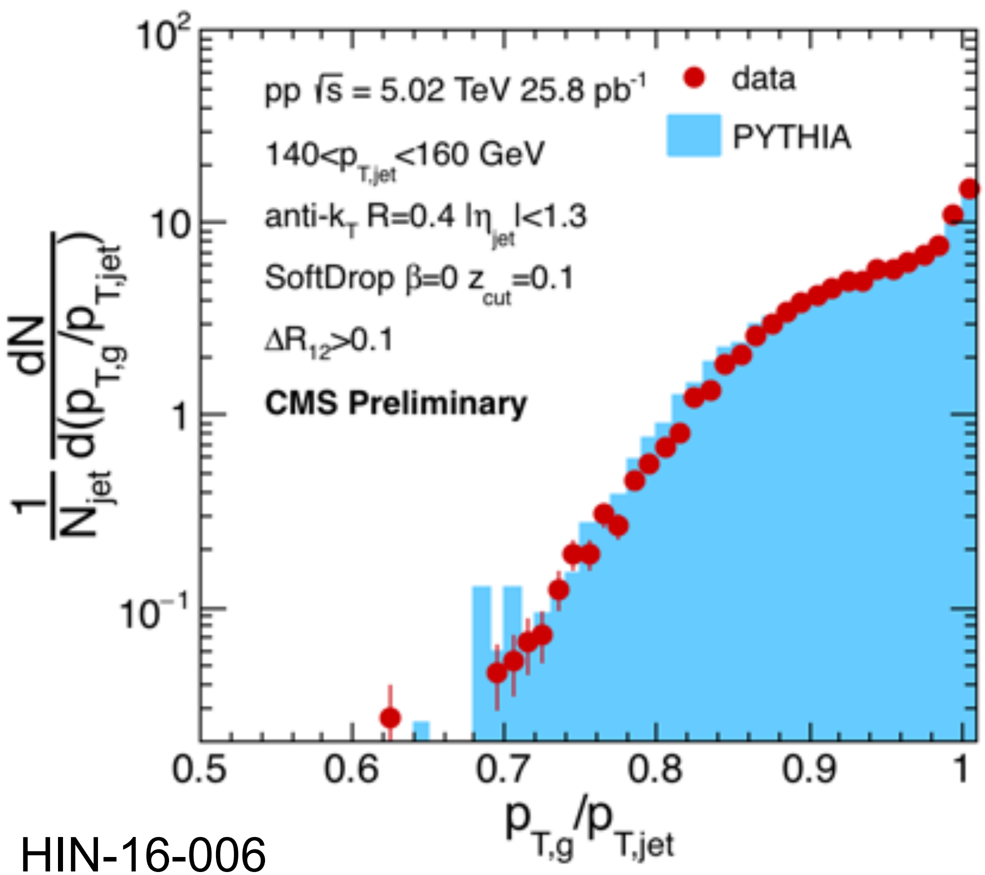
Effect of parton-medium interaction?

Groomed energy fraction

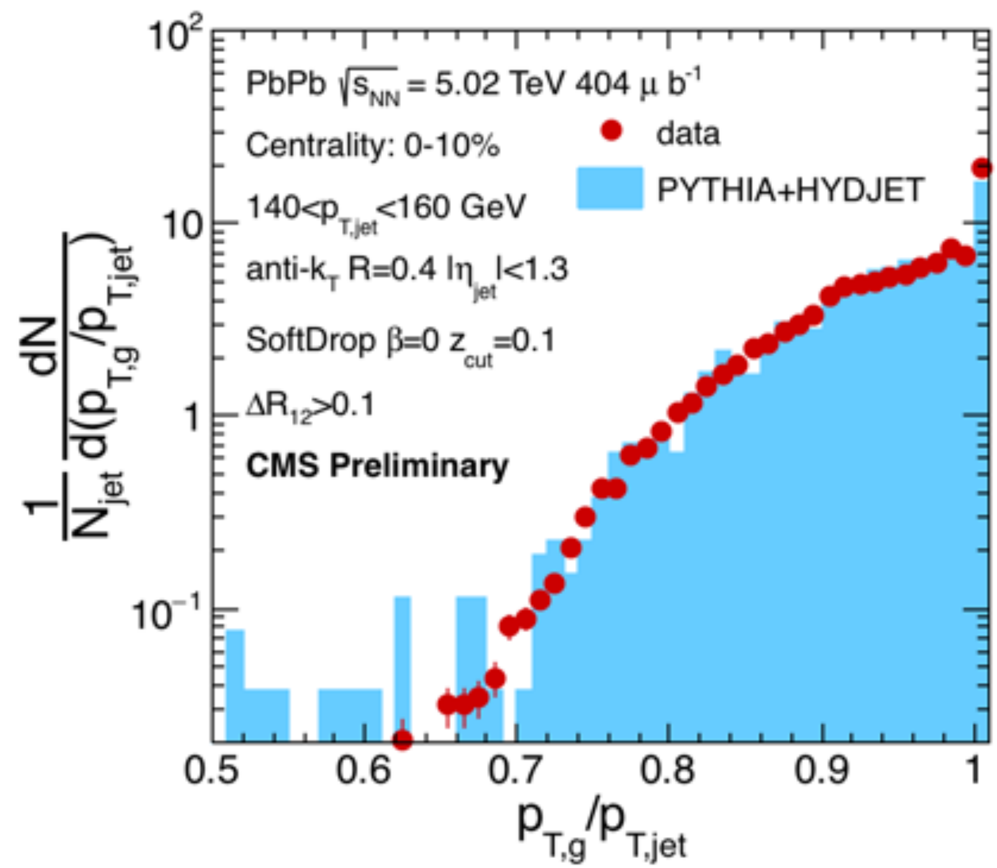
Larger amount of energy gets groomed away in PbPb collisions

Groomed energy fractions well described by MC

pp



PbPb

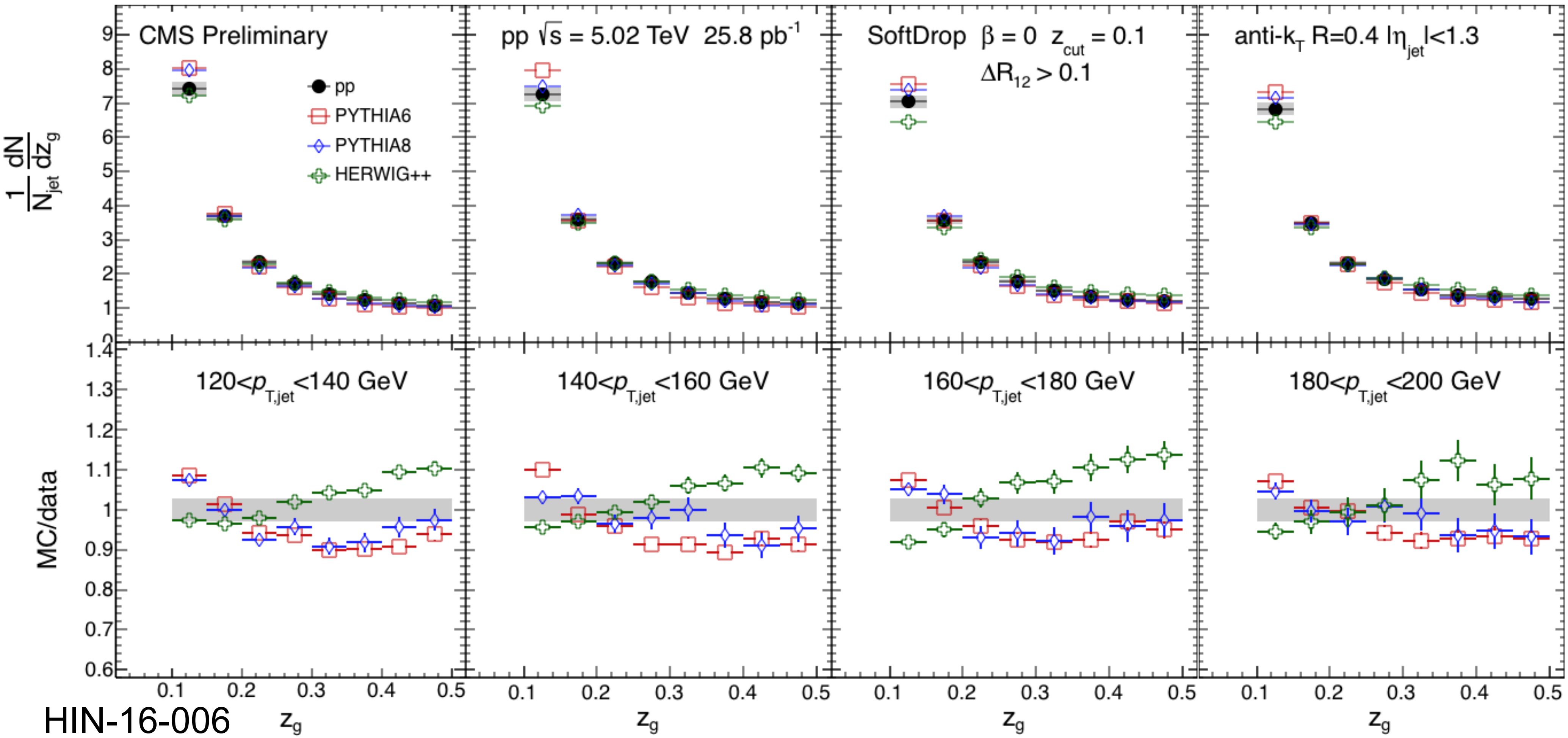


HIN-16-006

Splitting function in pp

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}},$$

PYTHIA8 and HERWIG reproduce the pp data within 5-10%
Opposite trend for PYTHIA and HERWIG



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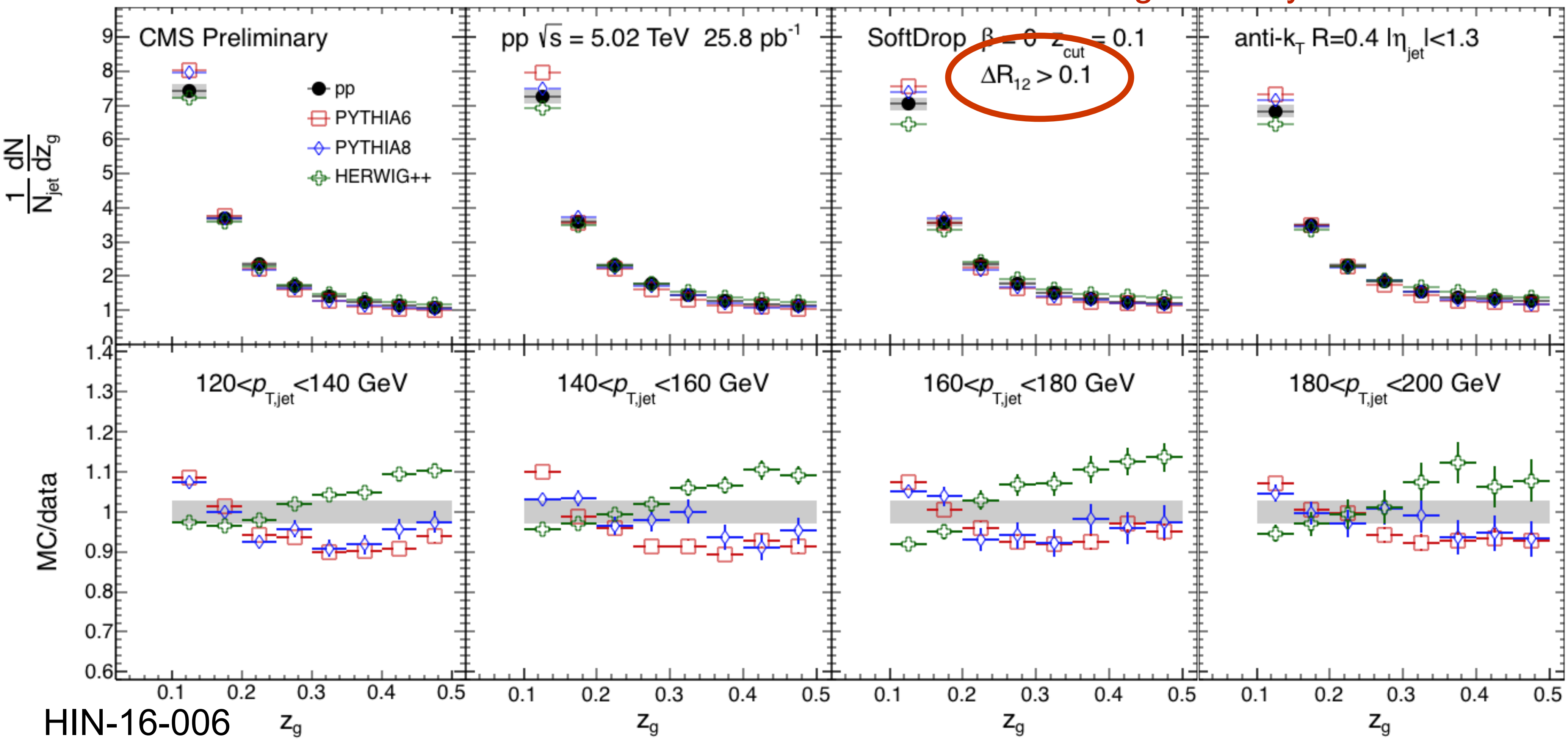
Cannot resolve subjets which are very close due to detector granularity



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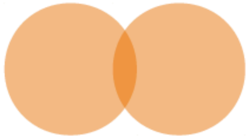
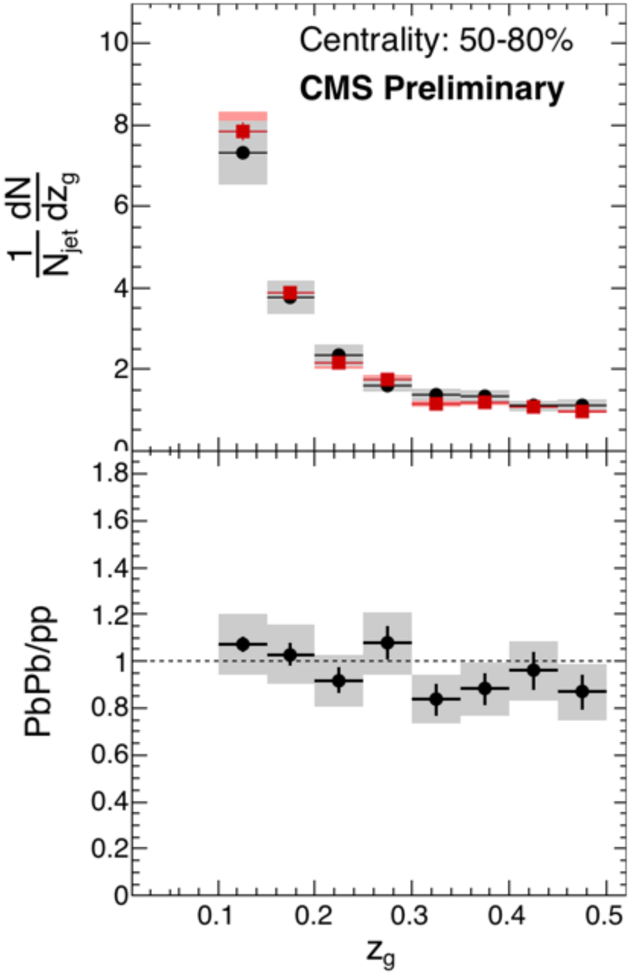
PbPb vs pp

$p_{T,jet}$: 140-160 GeV

Central collisions

Peripheral collisions





Peripheral PbPb and pp very similar

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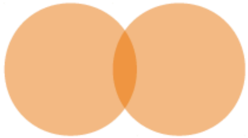
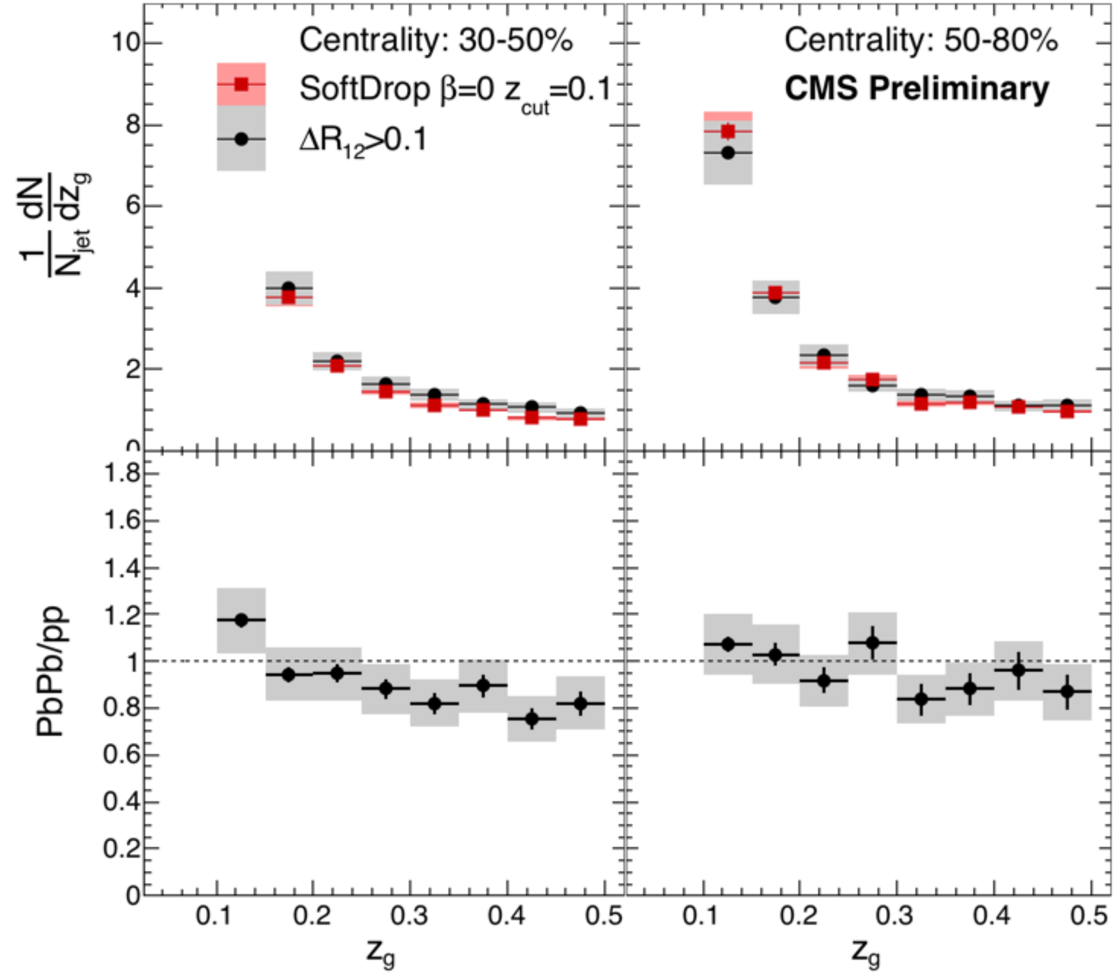
PbPb vs pp

$p_{T,jet}$: 140-160 GeV

Central collisions

Peripheral collisions





Less peripheral PbPb and pp also quite similar

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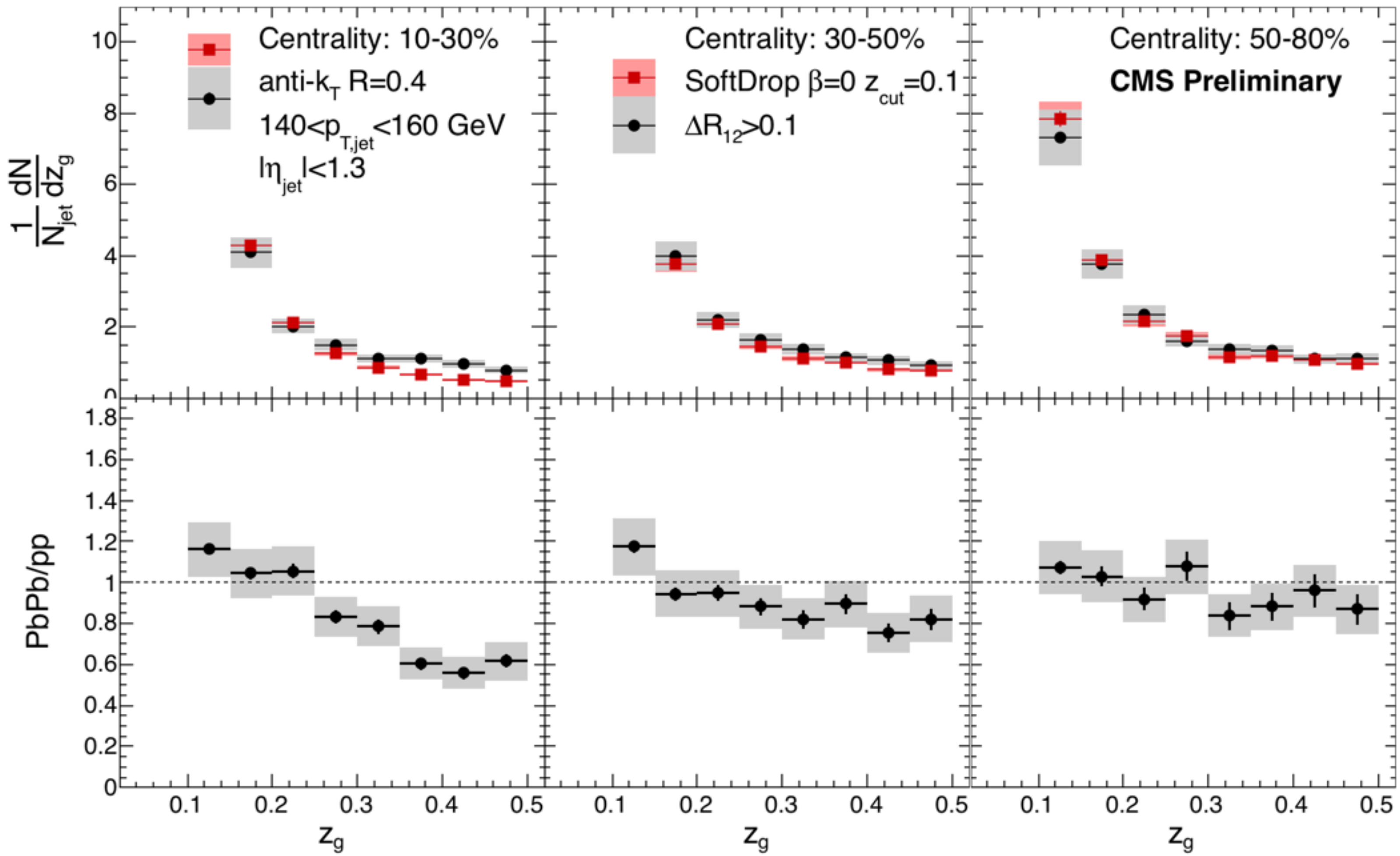
PbPb vs pp

$p_{T,jet}$: 140-160 GeV



Modification of splitting function observed in central PbPb collisions

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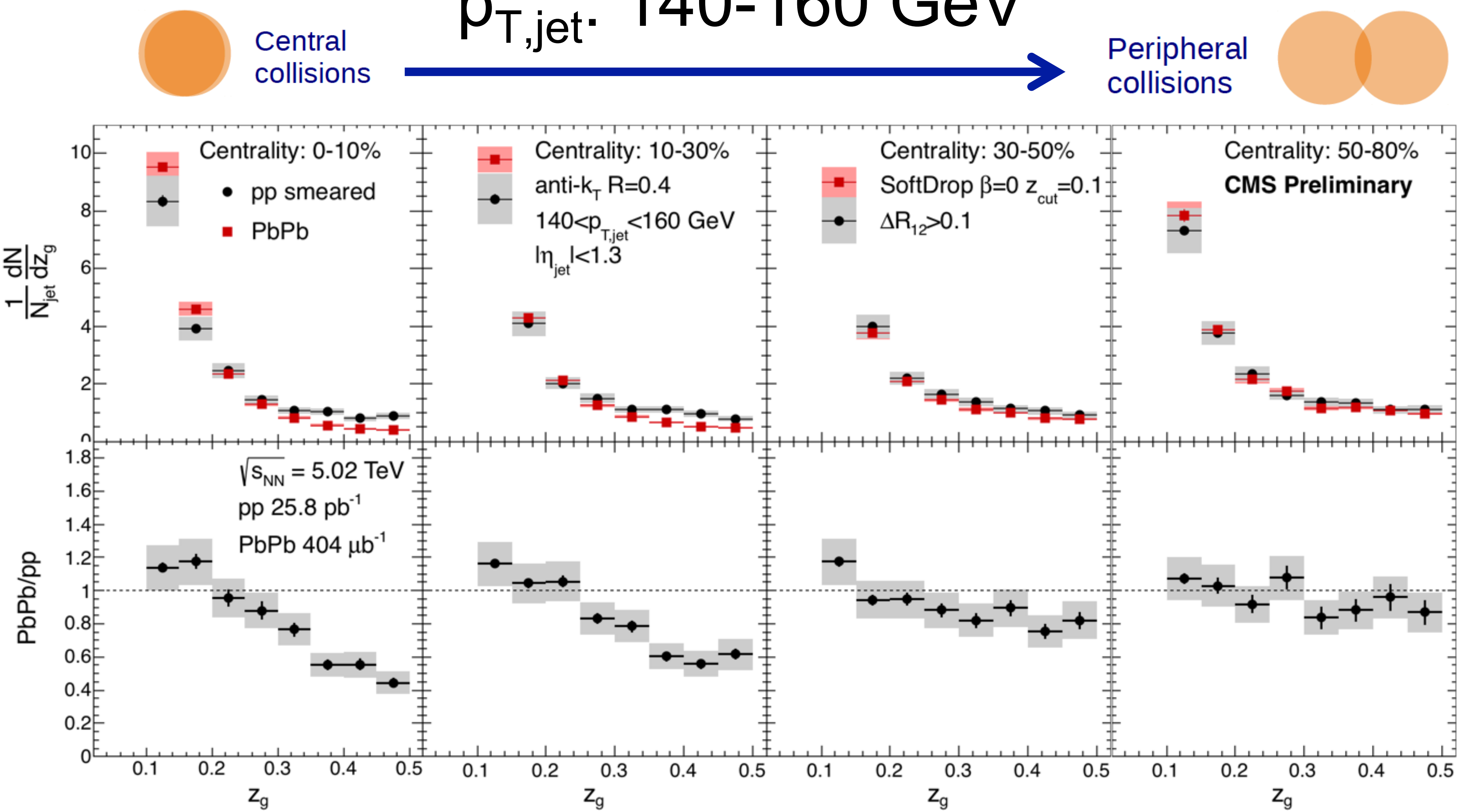
Branching more imbalanced in central PbPb

PbPb vs pp
$p_{T,jet}$: 140-160 GeV



Strong modification of branch splitting observed in central PbPb collisions

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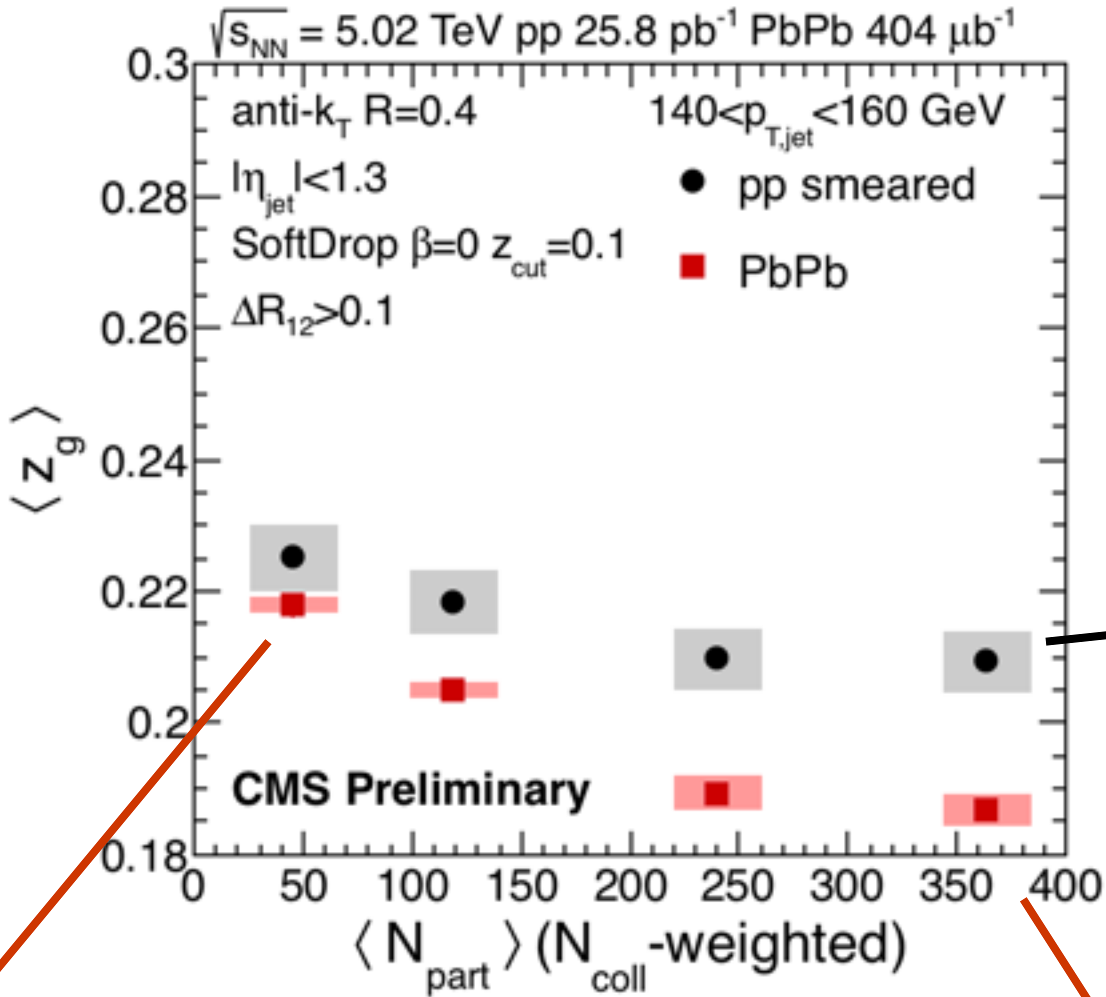
Branching more imbalanced in central PbPb

Evolution with medium density



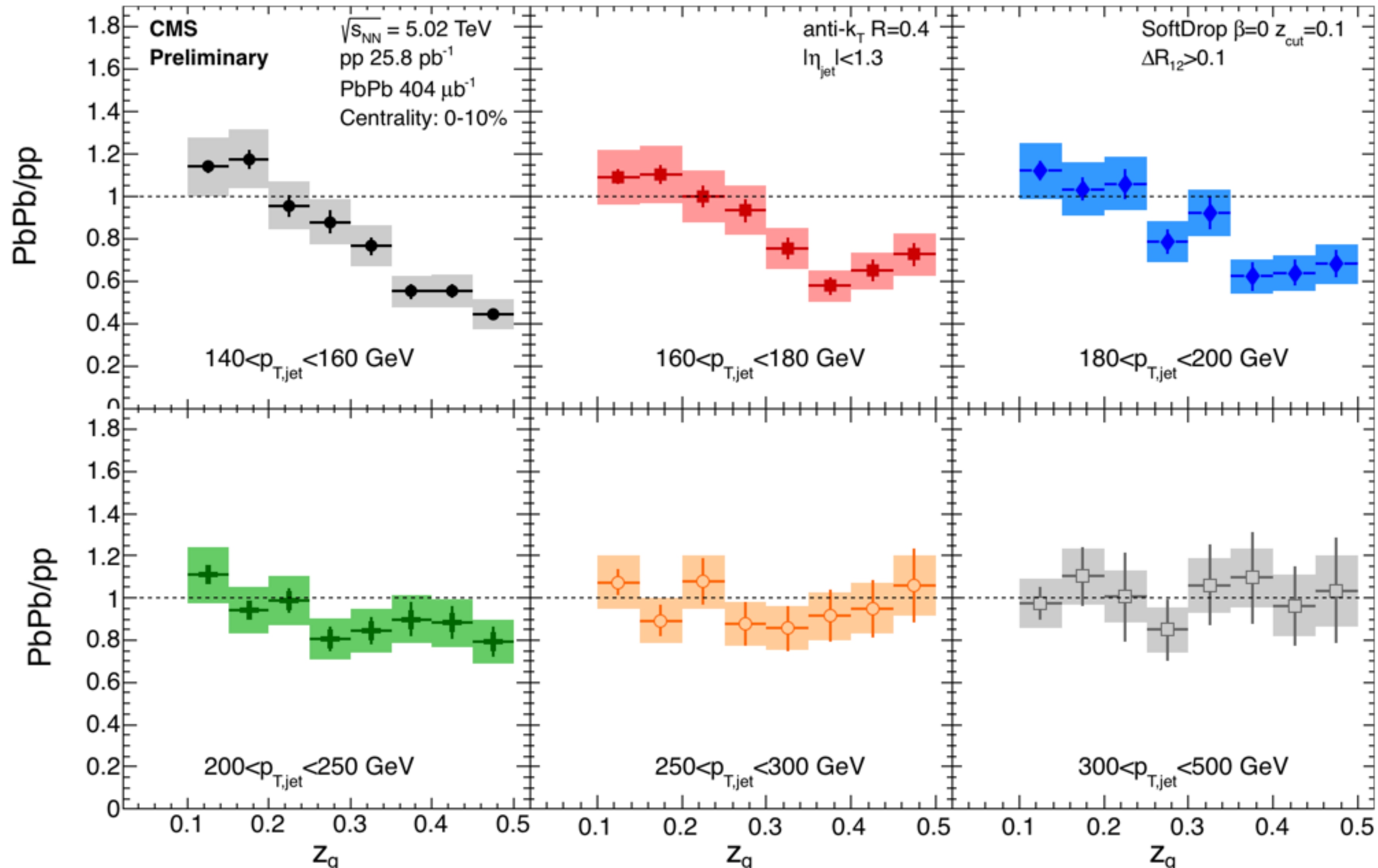
pp reference smeared to PbPb resolution

PbPb in peripheral collisions
'not so hot medium'
pp like → vacuum like

PbPb in most central collisions
'hottest medium'

Jet p_T dependence

Modification gets weaker when increasing jet p_T



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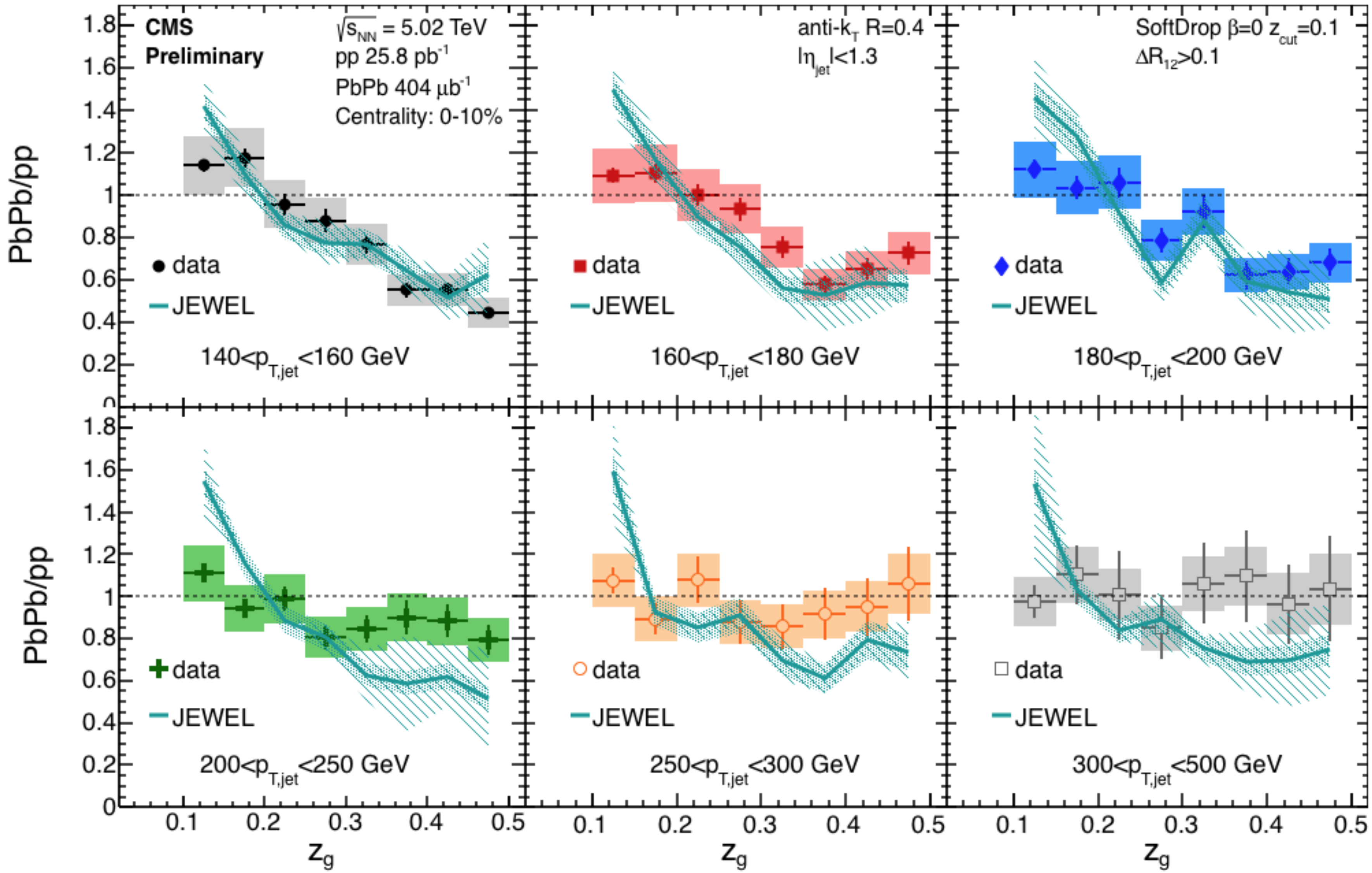
Model comparison

Comparison to jet quenching JEWEL MC event generator

General trend of data is described by JEWEL



JEWEL MC, K. Zapp et al, JHEP03 (2013) 080

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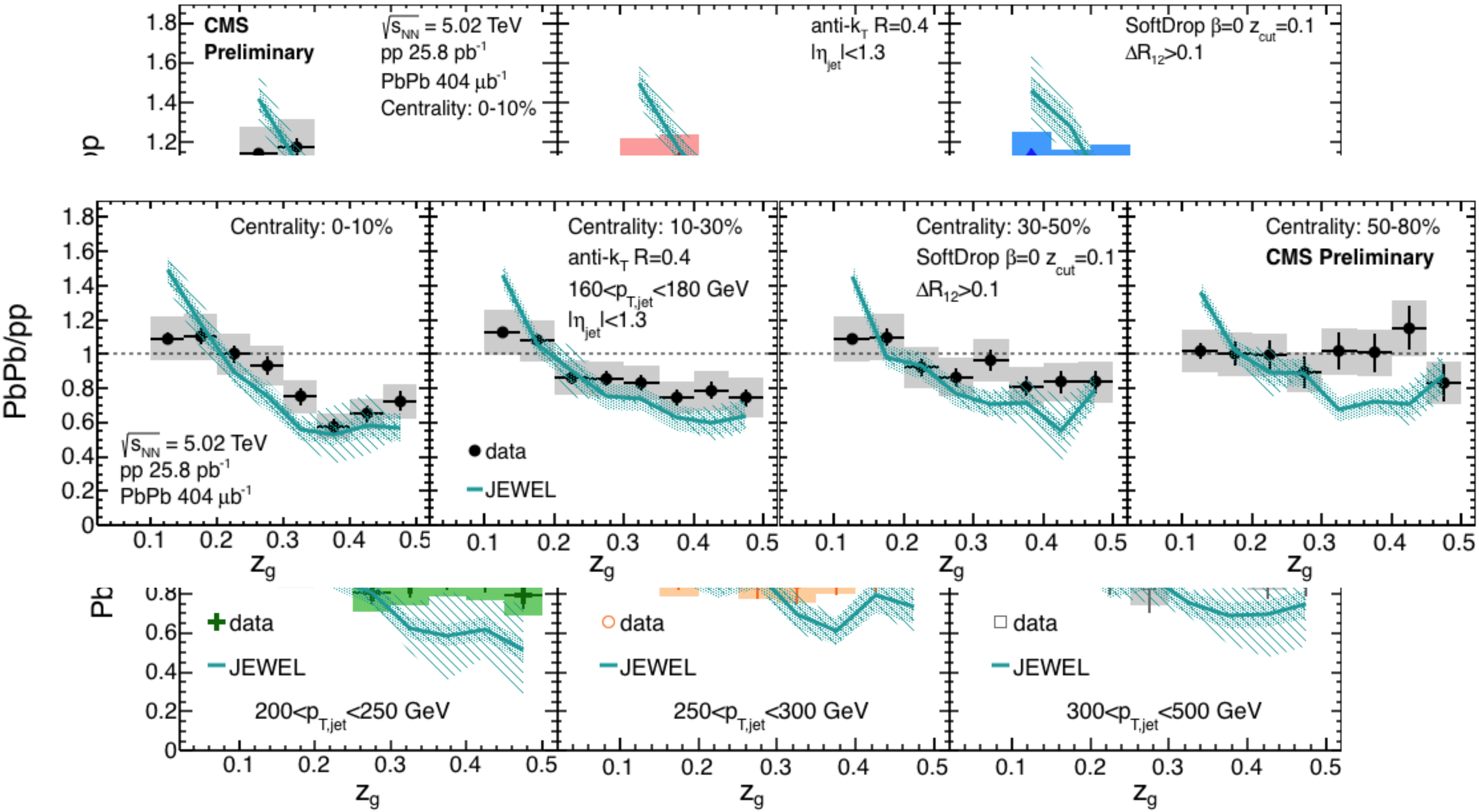


JEWEL MC, K. Zapp et al, JHEP03 (2013) 080

Conclusions

Measurement of splitting function in pp and PbPb collisions at 5.02 TeV presented

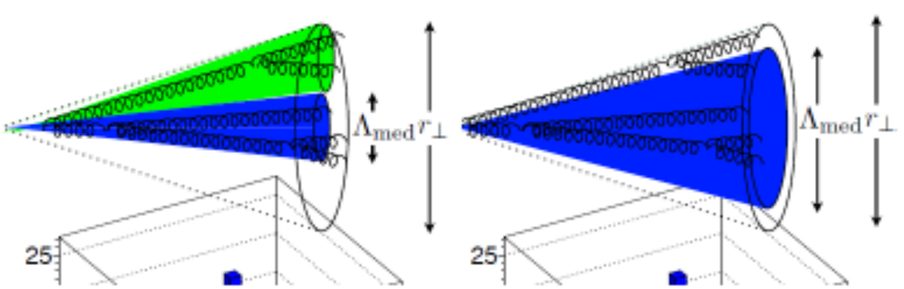
A significant modification of the splitting function is observed in central PbPb collisions.

Physics interpretation:

- Parton picks up (temporarily) virtuality from medium modifying Sudakov evolution
- A jet cannot be **one** coherent emitter

Extensions of measurement to probe the critical opening angle possible

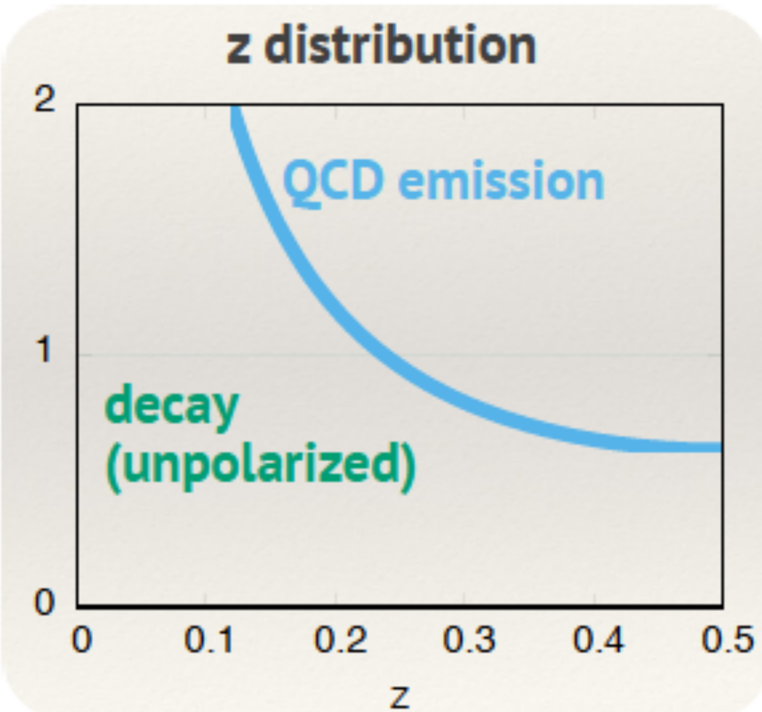
2 coherent emitters: color disconnected subjets



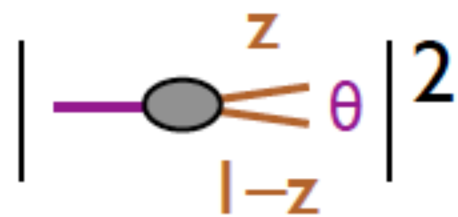
1 coherent emitter: color connected subjets

Bonus slides

QCD Splitting function



[Gavin Salam FCC talk, March 2015]



Splitting Function

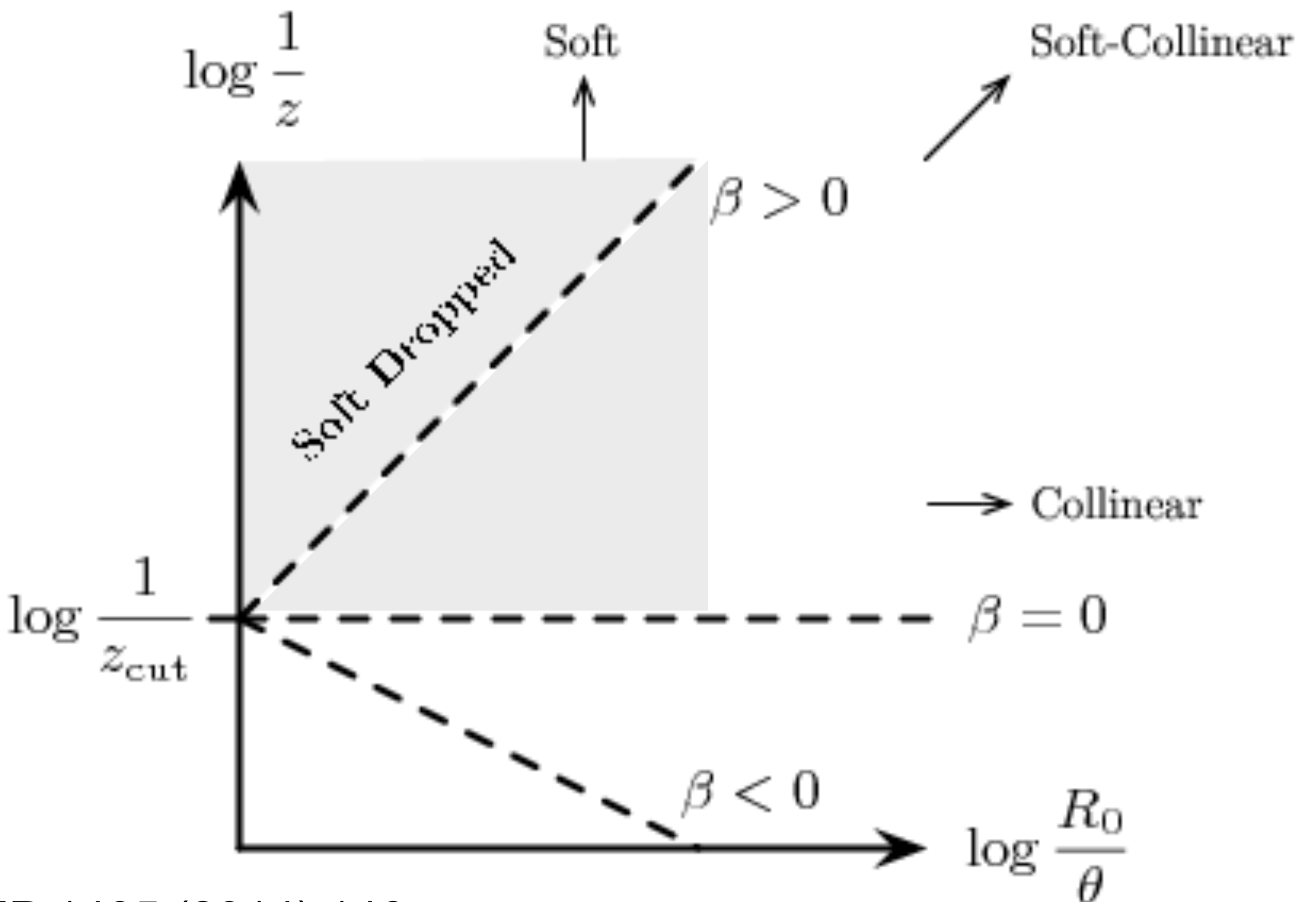
1→2

$$\mathrm{d}P_{i\to jk} = \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}}\,\underbrace{\mathrm{d}z\, P_{i\to jk}(z)}_{\text{Altarelli-Parisi splitting function}}$$

$$\frac{2\alpha_s C_i}{\pi}\,\frac{\mathrm{d}\theta}{\theta}\,\frac{\mathrm{d}z}{z}$$

Feature of QCD: $1/z_g$

Emission phase space



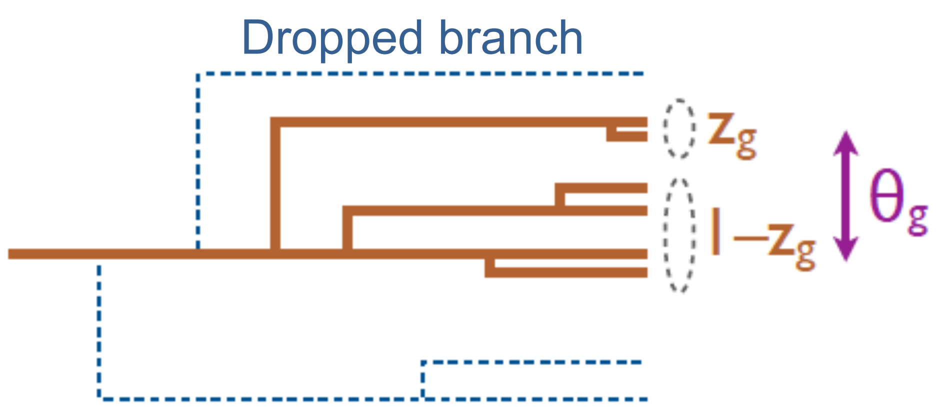
Soft Drop: JHEP 1405 (2014) 146

For beta=0: both soft and soft-collinear emissions are vetoed

Soft Drop

Anti-k_T jet is re-clustered with Cambridge/Aachen (CA)
Then decluster the angular-ordered CA tree
Drop branches until Soft Drop condition is satisfied

Extract the 2 branches after grooming for physics → subjets



Observable is well understood analytically
since all soft divergences are removed

Larkoski, Marzani, Thaler
Phys. Rev. D91:111501 (2015)
Soft Drop: JHEP 1405 (2014) 146

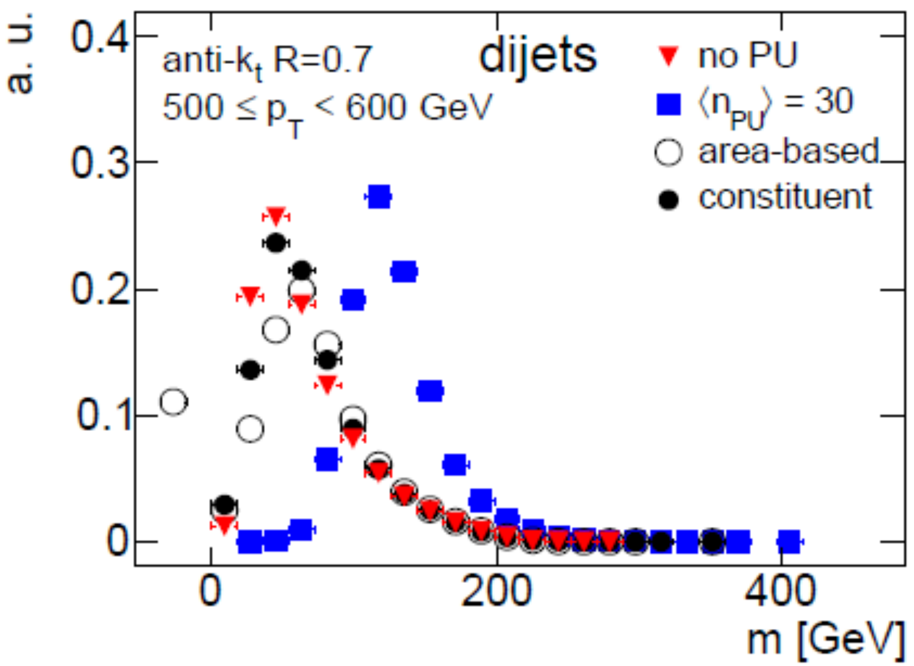
Groomed jet radius determined by dynamics of jet, not from outside

Jets + background subtraction

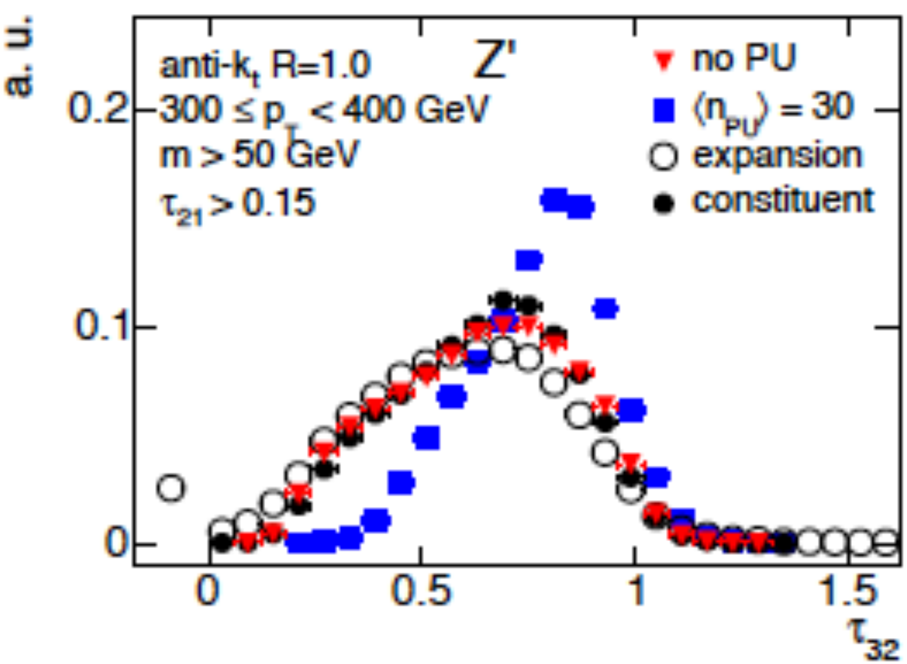
Jets in heavy-ion collisions are contaminated by huge background

Need algorithm which removes background while keeping the true jet constituents → Constituent subtraction method

Jet mass



N-subjettiness (τ_{32})



Constituent subtraction
Berta et al. arXiv:1403.3108

Constituent subtraction

Method was developed to subtract pileup from jets

- Also successfully used in heavy-ions (jet shapes ALICE)

Particle-level approach which removes or corrects jet constituents

Corrects both the 4-momentum of the jet and the substructure

- Ghosts are added to the jet uniformly
  - Ghosts have $p_T=\rho \bullet A_g$ and $m_\delta=\rho_m \bullet A_g$ (A_g = ghost area)
- All jet constituents are correlated with the ghosts: iterative process
- Metric $\Delta R_{i,k}$ (i=particle, k=ghost) determines if order of iterations

$$\Delta R_{i,k} = p_{\mathrm{T}i}^{\alpha} \cdot \sqrt{\left(y_i - y_k^g\right)^2 + \left(\phi_i - \phi_k^g\right)^2}.$$

- p_T and m_δ of particle and ghost are compared: if smaller for ghost, ghost p_T and/or m_δ is subtracted from particle

Advantage of the method:

- corrects some of the local fluctuations;
- doesn't require training;
- one parameter can be tuned (α);

Constituent subtraction for jets: Berta et al. arXiv:1403.3108

Background densities

- ρ and ρ_m are estimated from k_T-clusters
  - k_T-clusters: reconstructed jets with k_T jet algorithm
  - 2 leading k_T clusters are excluded to avoid bias from true jets
  - For ρ p_T and area of the accepted k_T-clusters are used:

$$\rho = \text{median}\left\{\frac{p_{\mathrm{T},i}}{A_i}\right\}$$

  - For ρ_m m_δ and area of the accepted k_T-clusters are used:

$$m_{\delta,k_{\mathrm{T}}^{\mathrm{cluster}}} = \sum_j \left(\sqrt{m_{\mathrm{j}}^2 + p_{\mathrm{T,j}}^2} - p_{\mathrm{T,j}}\right) \qquad \rho_{\mathrm{m}} = \text{median}\left\{\frac{m_{\delta,i}}{A_i}\right\}$$

  - Both densities are estimated in different eta regions:

    [-5,-3,-2.1,-1.3,1.3,2.1,3,5]