CMS-PAS-HIN-16-006

Splitting function in pp and PbPb collisions at 5.02 TeV

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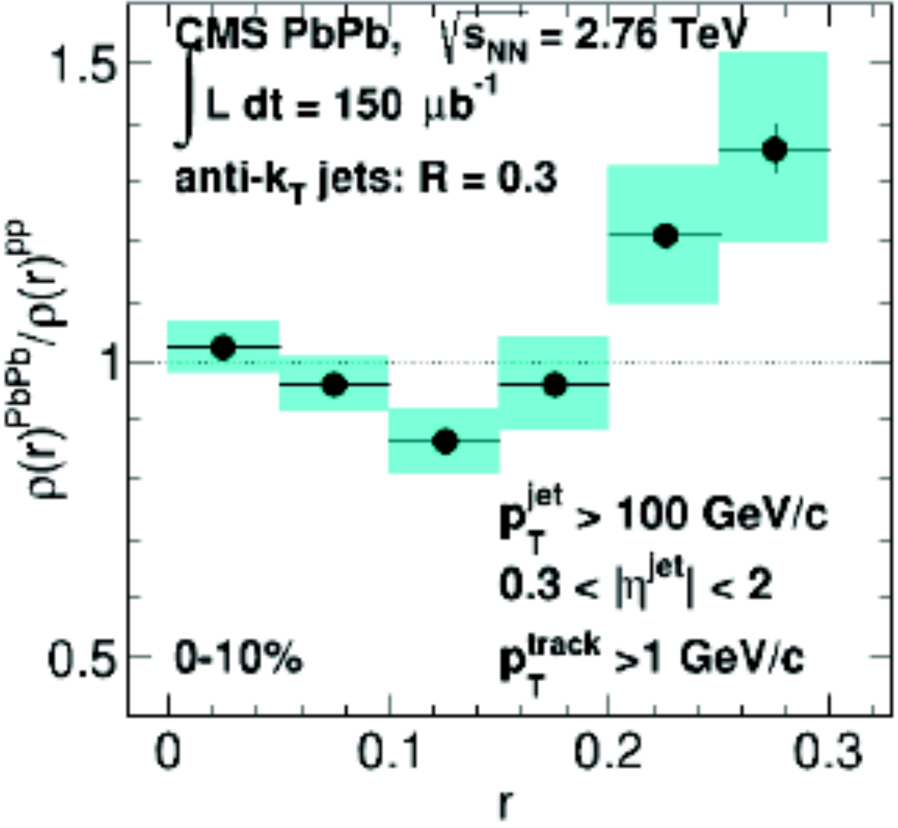
for the CMS collaboration

July 27 2016
HI Jet Workshop, Ecole Polytechnique

Jet shapes and structures Run1

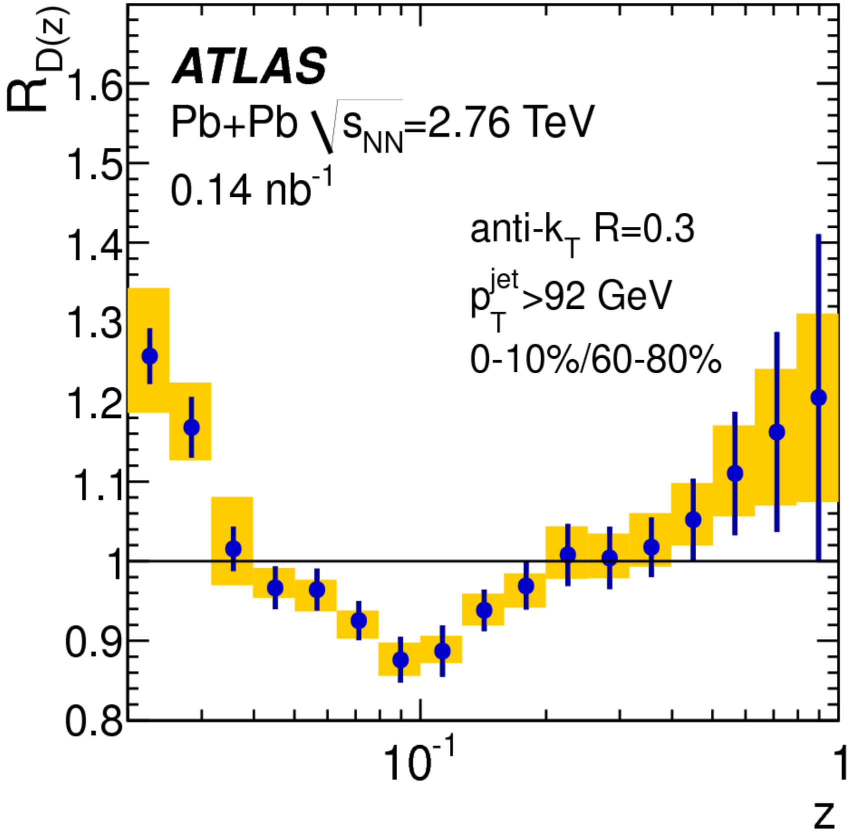
Jet shape observables: energy + multiplicity distributions within a jet
Sensitive to the dynamics of parton shower

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*

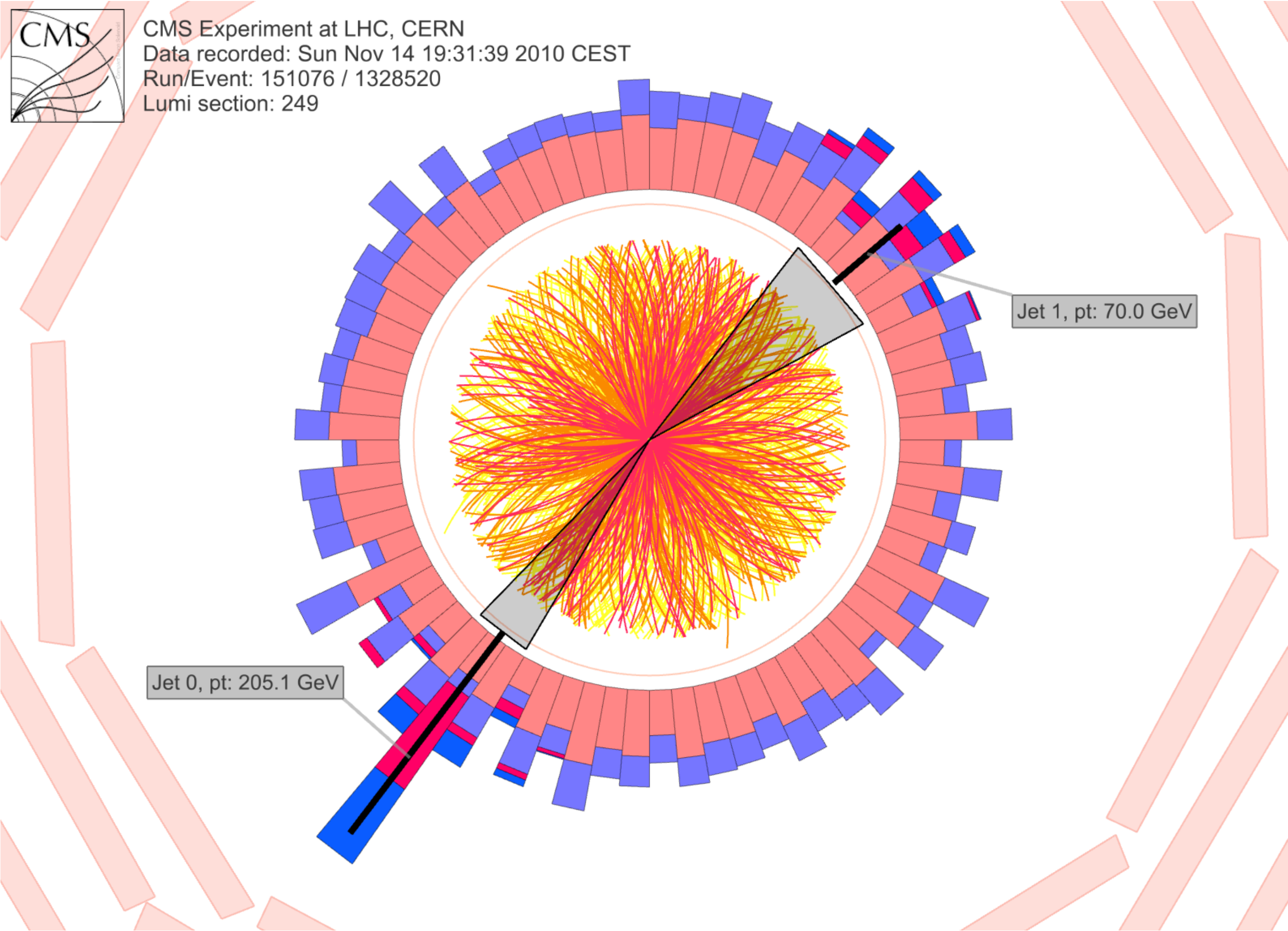
Find the jets

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

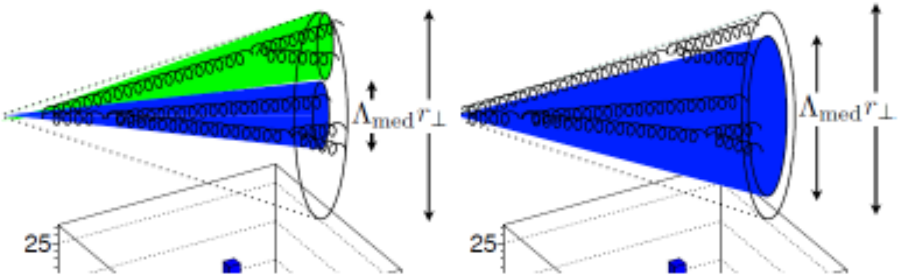
Tool: first splitting in parton shower → only using hard jet components

Several scenarios proposed by theorists.

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

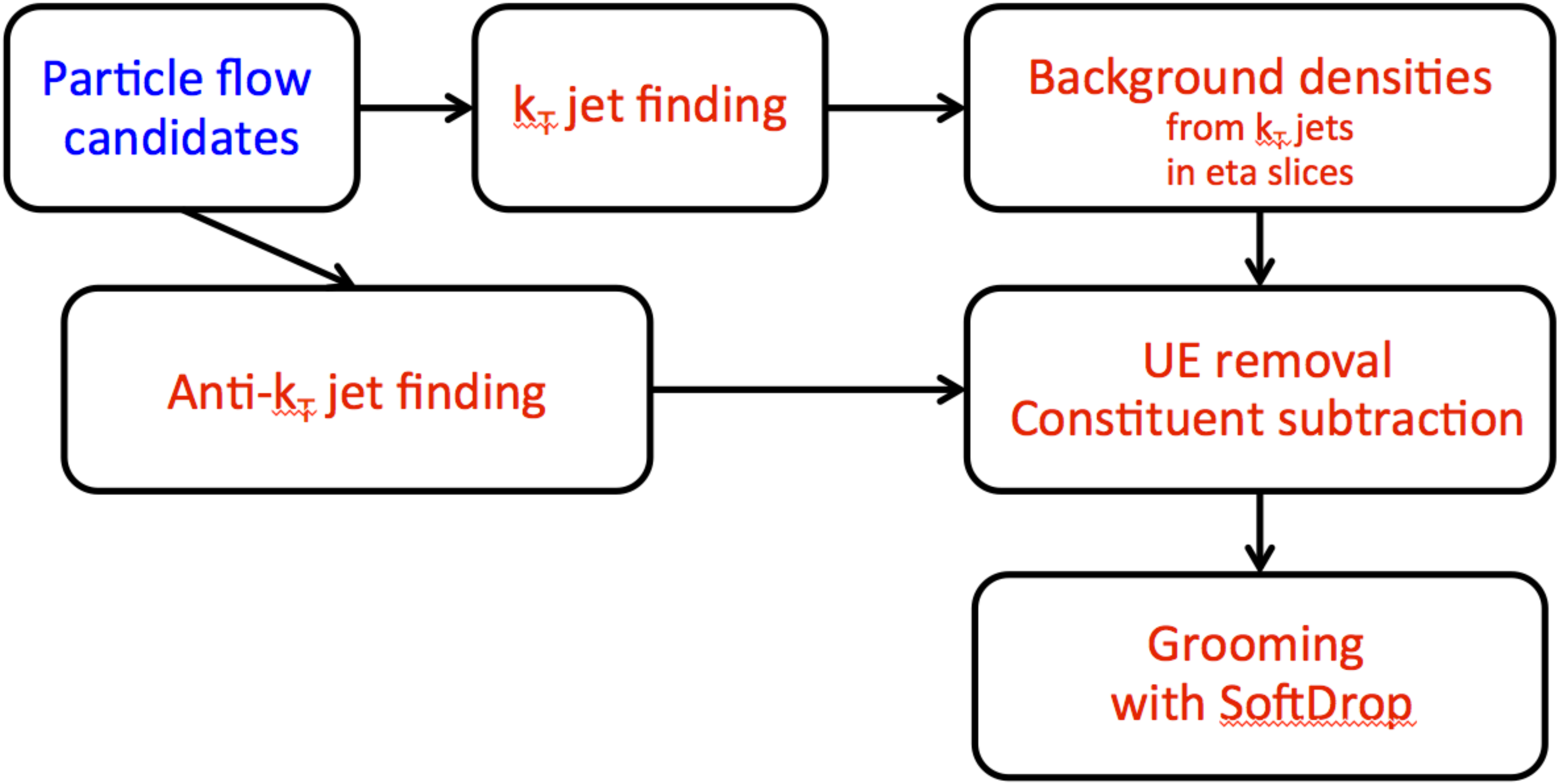
2 coherent emitters: color disconnected subjets



1 coherent emitter: color connected subjets

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

Analysis techniques



Particle flow candidates

k_T jet finding

Background densities from k_T jets in eta slices

Anti-k_T jet finding

UE removal Constituent subtraction

Grooming with SoftDrop

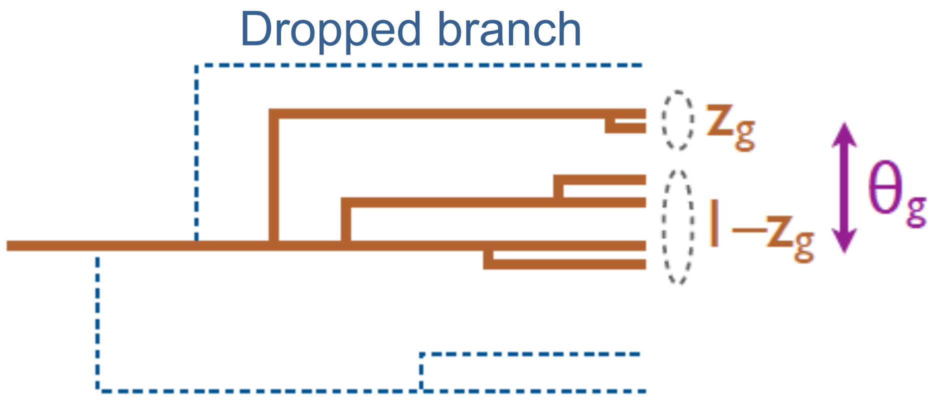
UE removal only for PbPb since
pp data set has low pileup (1.4)

Constituent subtraction
Berta et al. arXiv:1403.3108

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



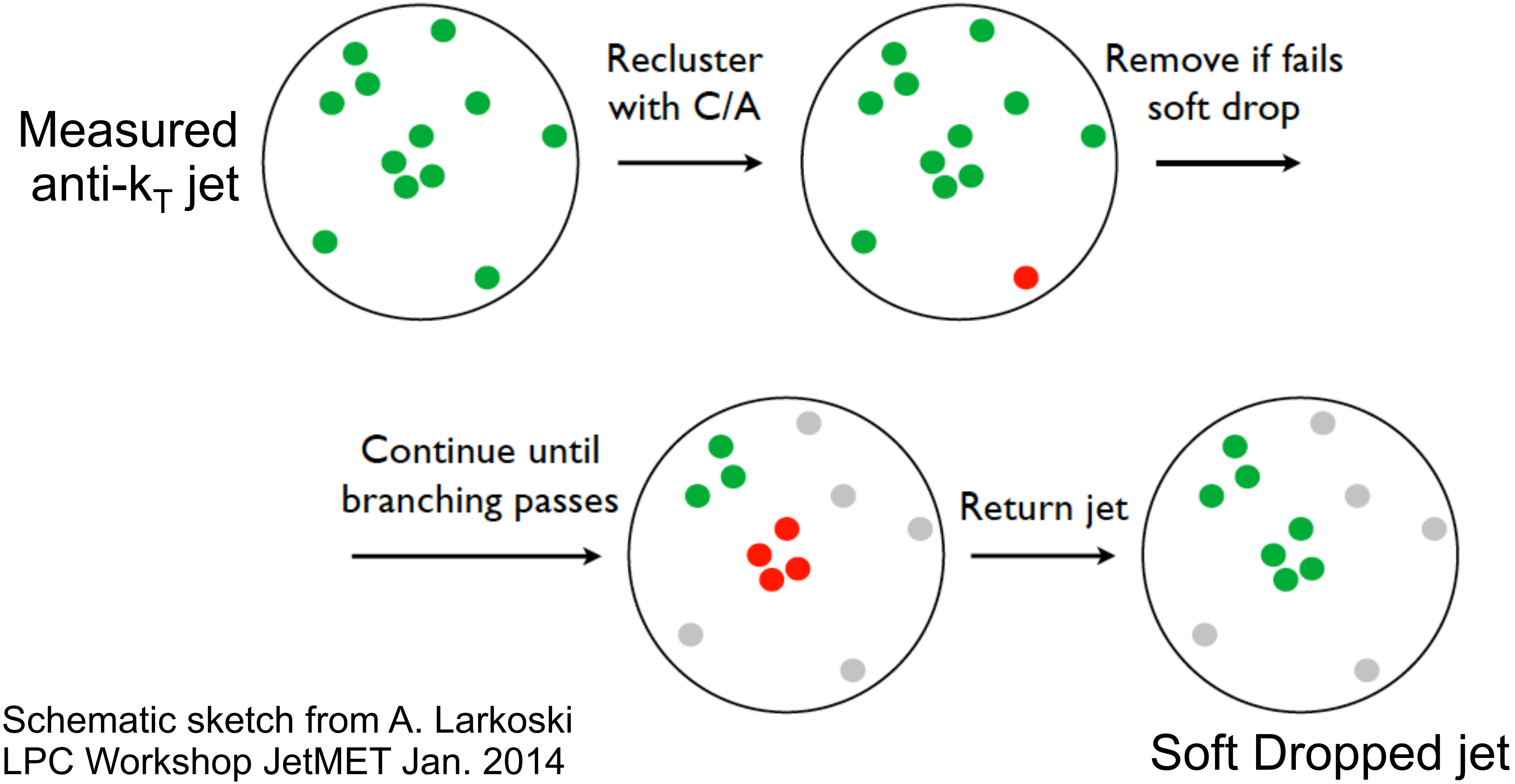
Observable is well understood analytically
since all soft divergences are removed

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

Jet grooming

Jet grooming removes soft divergences and uncorrelated background
Common technique in HEP
This analysis is the first one using jet grooming in heavy ion collisions



Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

Soft Drop

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

Soft Drop condition

$$z > z_{\text{cut}}\, \theta^{\beta}$$

energy threshold

angular exponent

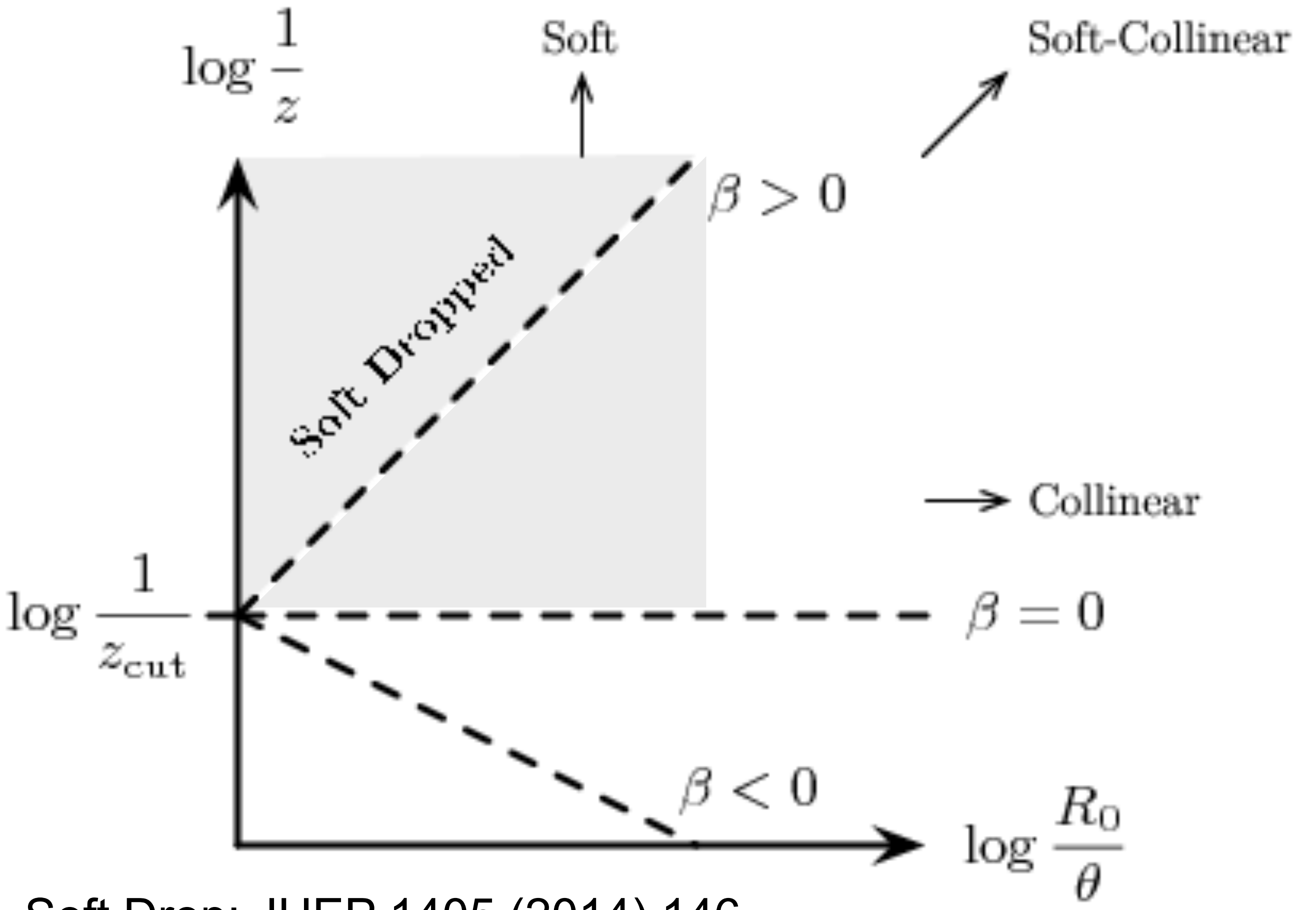
We use $\beta = 0$ and $z_{\text{cut}} = 0.1$
All soft emissions are removed
Equivalent to modified Mass Drop

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

Momentum fraction carried by the subleading branch of first splitting

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

Emission phase space



Soft Drop: JHEP 1405 (2014) 146

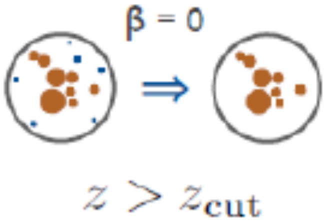
$$\mathrm{d}P_{i\to jk} = \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \mathrm{d}z \underbrace{P_{i\to jk}(z)}_{\text{Altarelli-Parisi splitting function}}$$

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

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

Generalized fragmentation function

Measurement of QCD splitting function



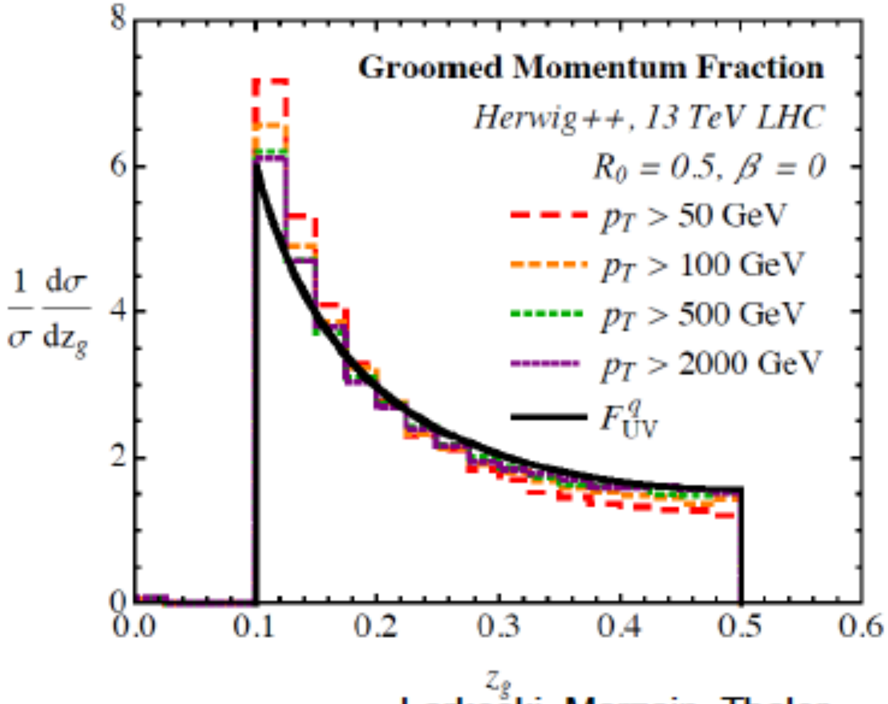
Momentum sharing between two leading subjets:

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

Independent of α_s

Moderate dependence on jet p_T

~ same for quarks and gluons



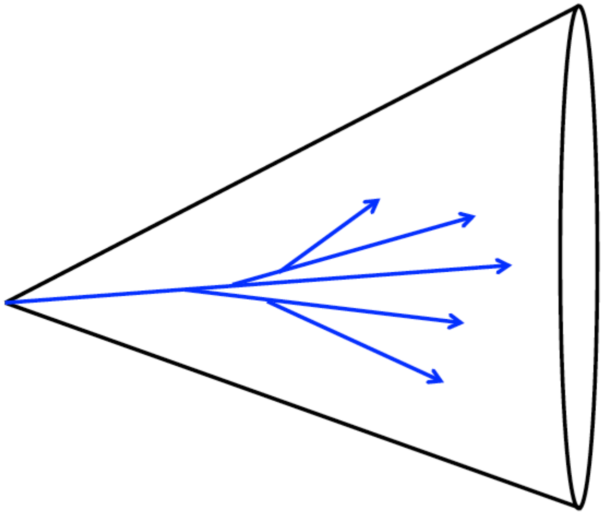
Larkoski, Marzain, Thaler
Phys. Rev. D91:111501 (2015)
Soft Drop: JHEP 1405 (2014) 146

Sensitive to modification of splitting function

Effect of parton-medium interaction?

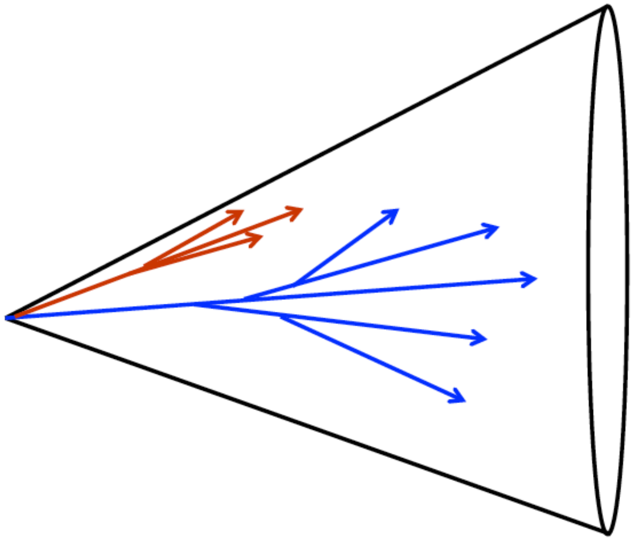
Hard jet substructures

Collimated jet



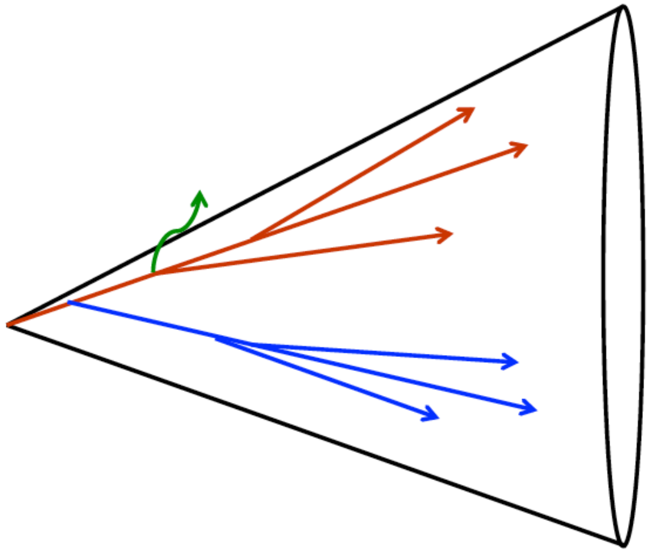
Groomed away
1-4% of total jet
sample independent
of centrality and $p_{T,jet}$

Collimated jet
+ softer 2nd structure



Small z_g

Two hard structures



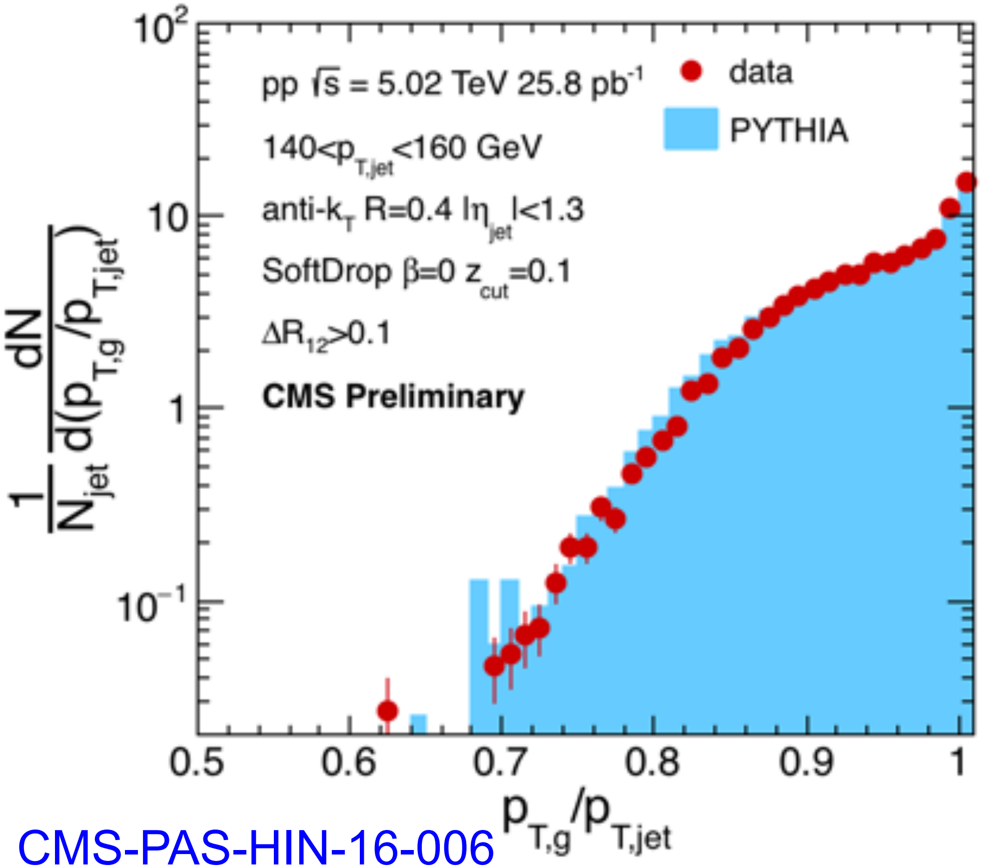
Large z_g

Groomed energy fraction

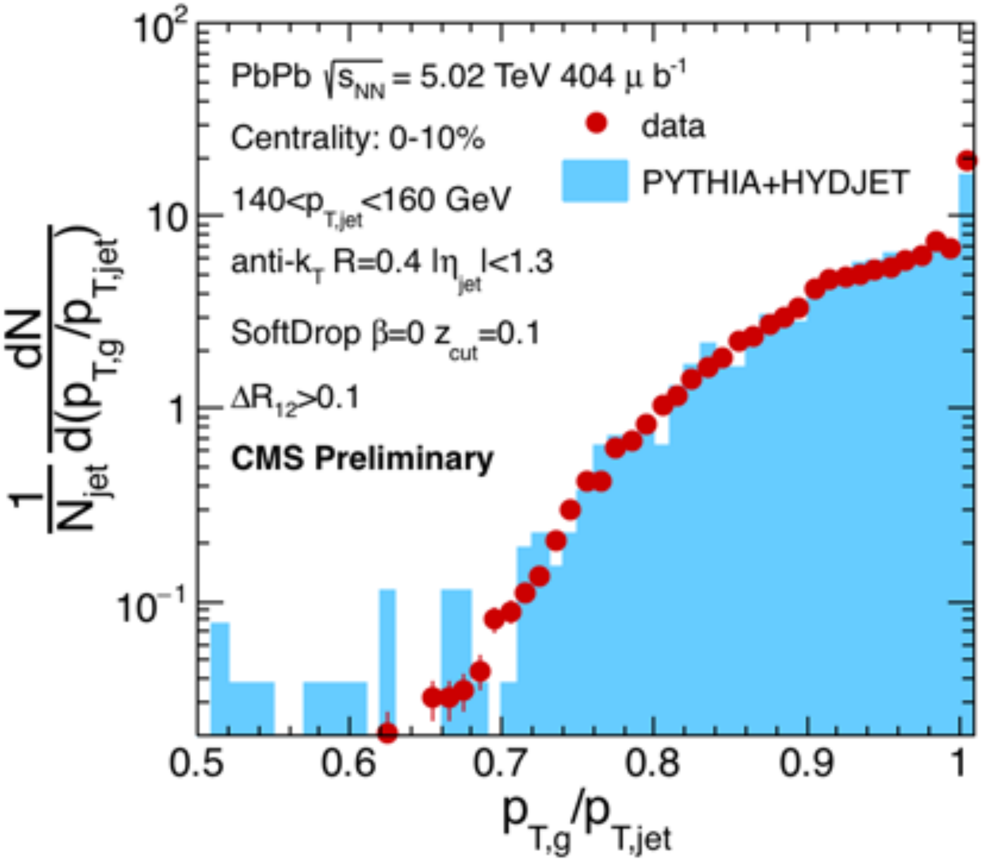
Larger amount of energy gets groomed away in PbPb collisions

Groomed energy fractions well described by MC

pp



PbPb



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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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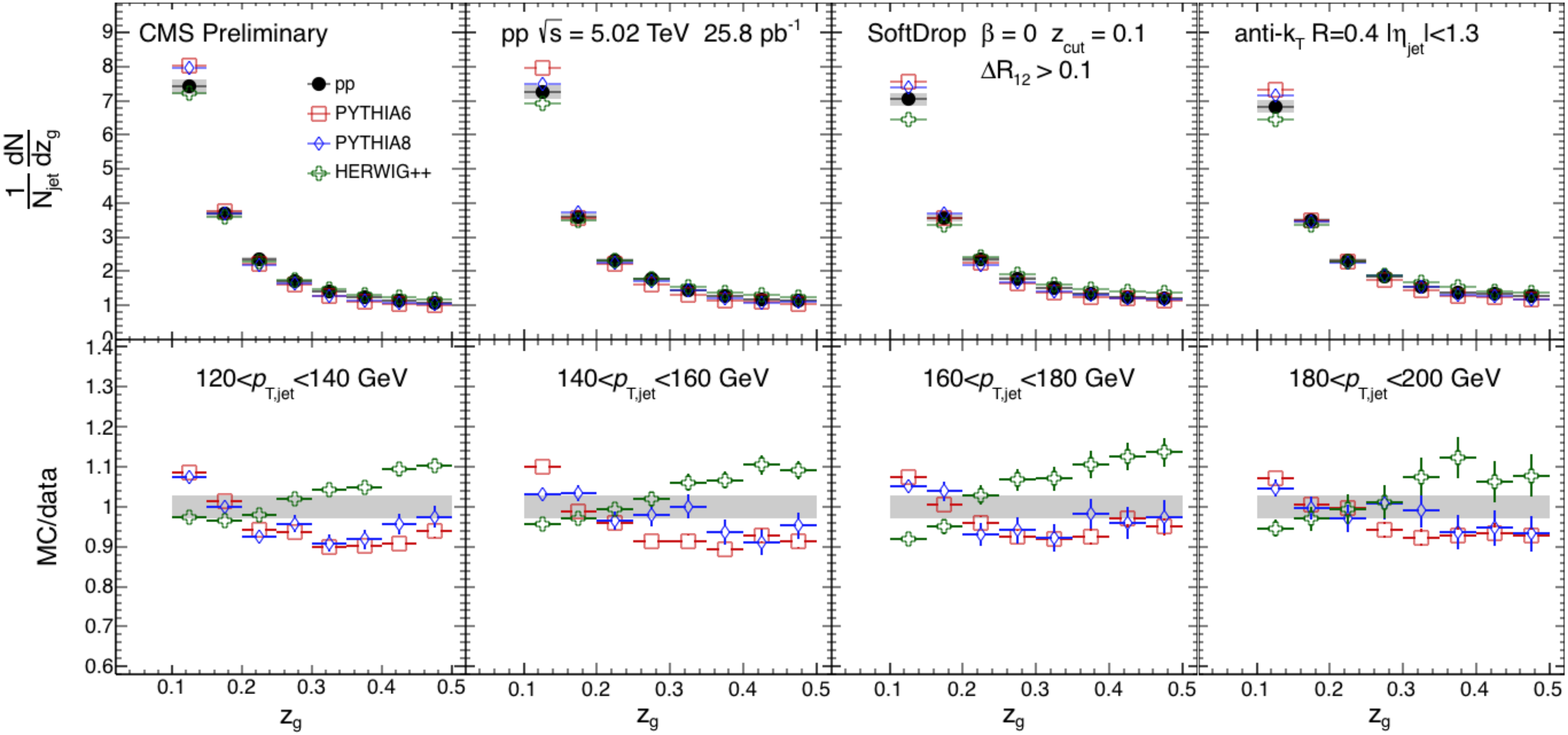

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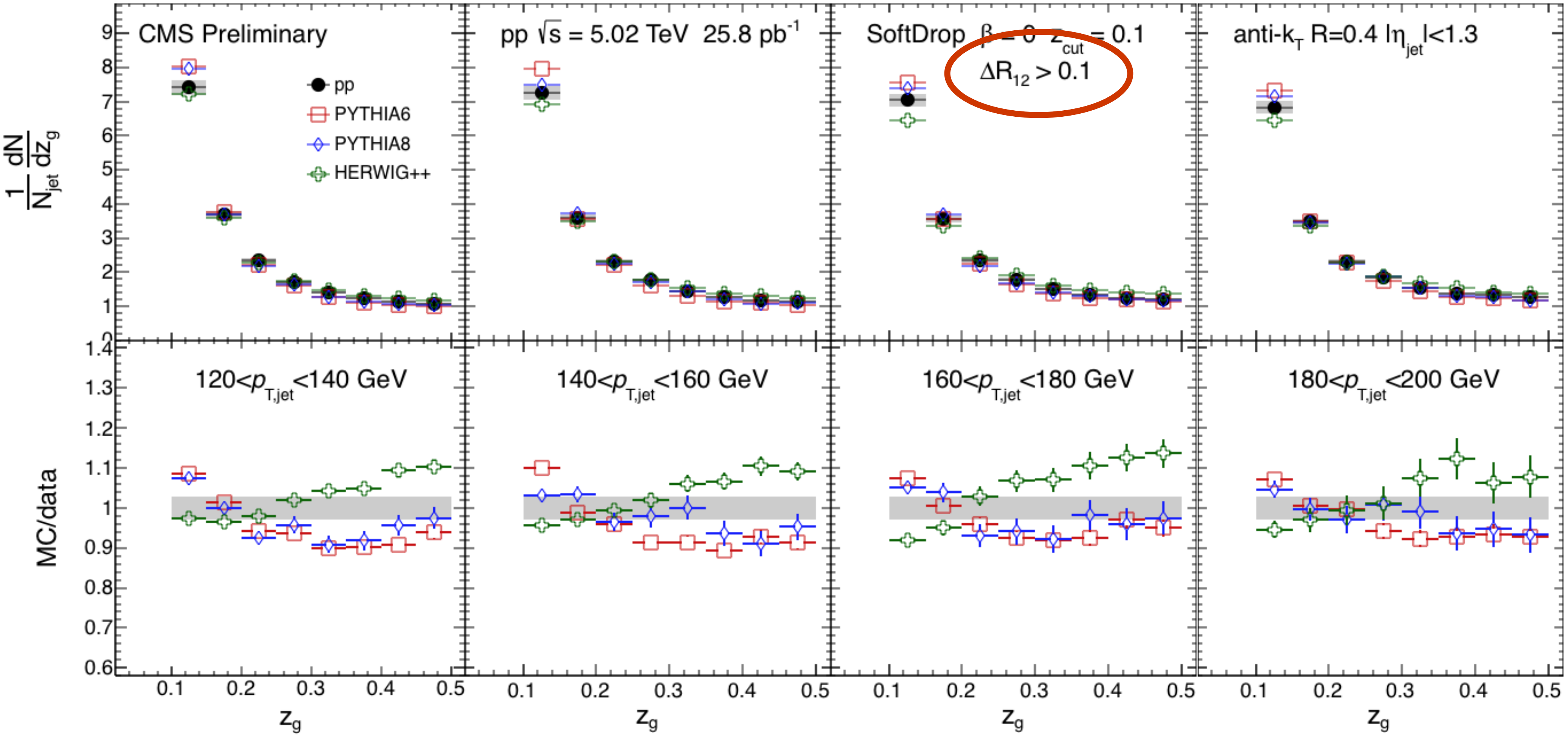
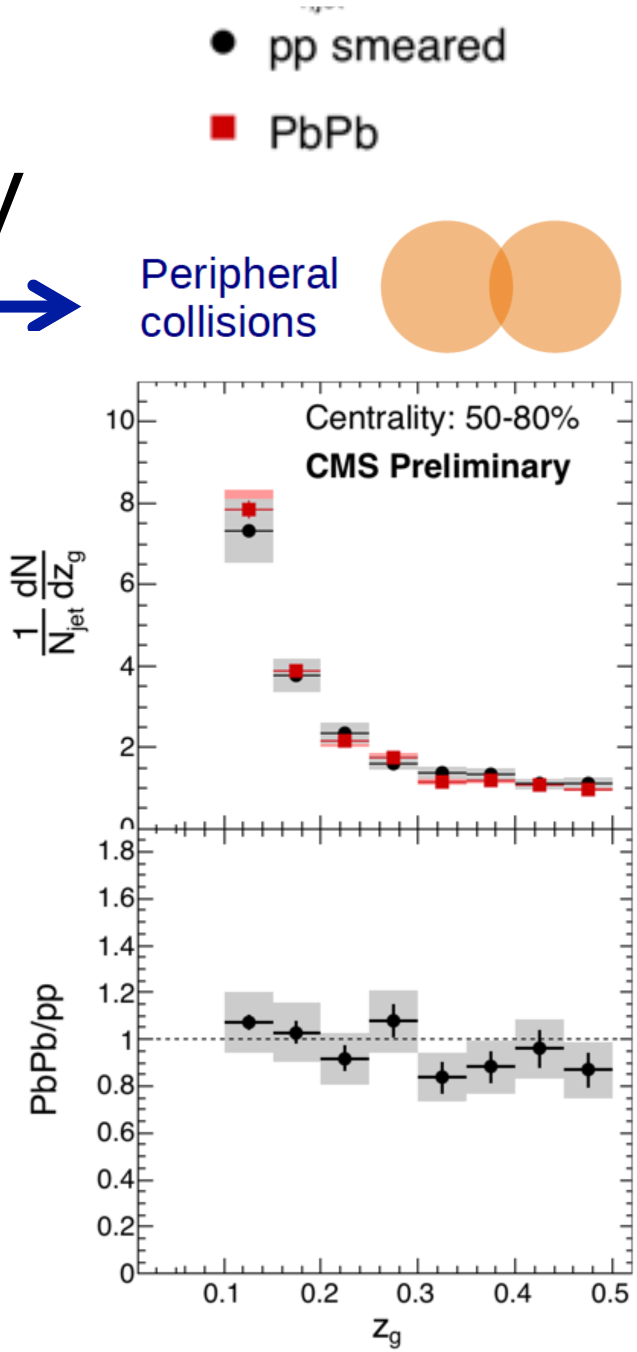
Cannot resolve subjets which are very close due to detector granularity



PbPb vs pp

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

Central collisions → Peripheral collisions



Peripheral PbPb and pp very similar

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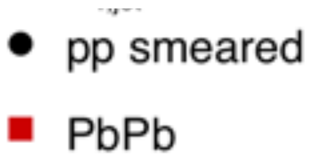
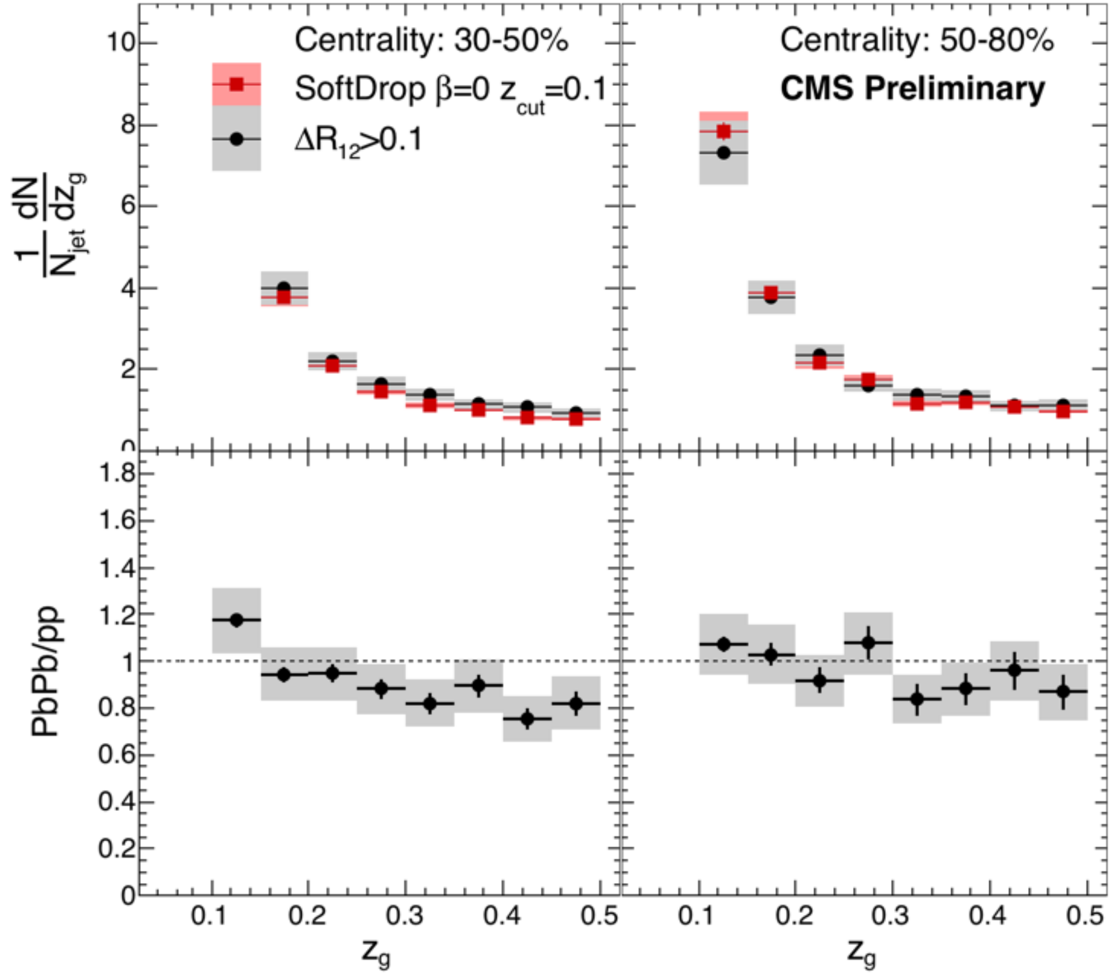
PbPb vs pp

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



Central collisions

Peripheral collisions



Semi-peripheral PbPb and pp also quite similar

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PbPb vs pp

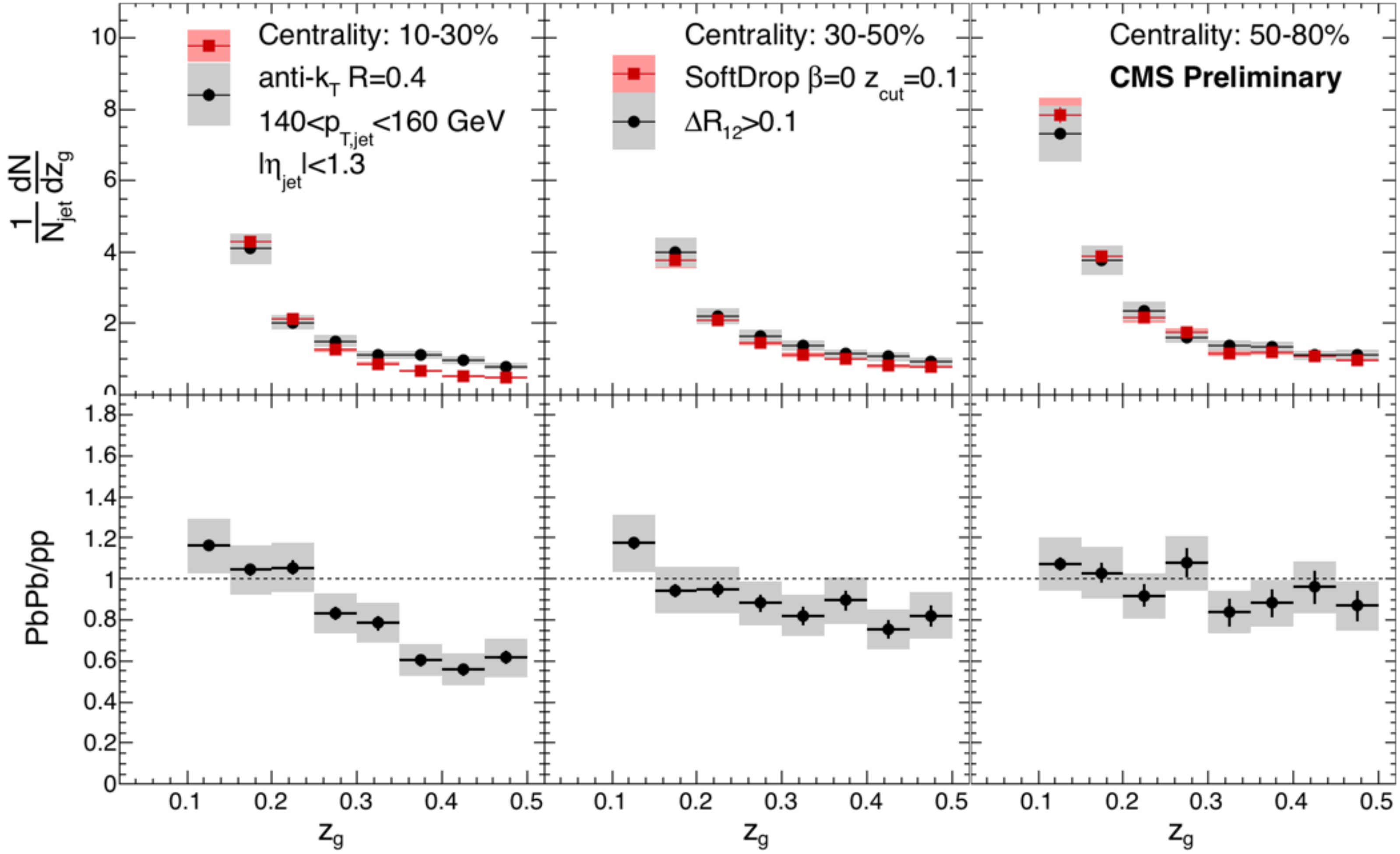
$p_{T,jet}$: 140-160 GeV

● pp smeared

🟥 PbPb

Central collisions

Peripheral collisions



Modification of splitting function observed in central PbPb collisions

Branching more imbalanced in central PbPb

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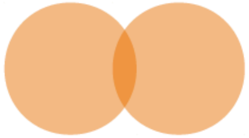
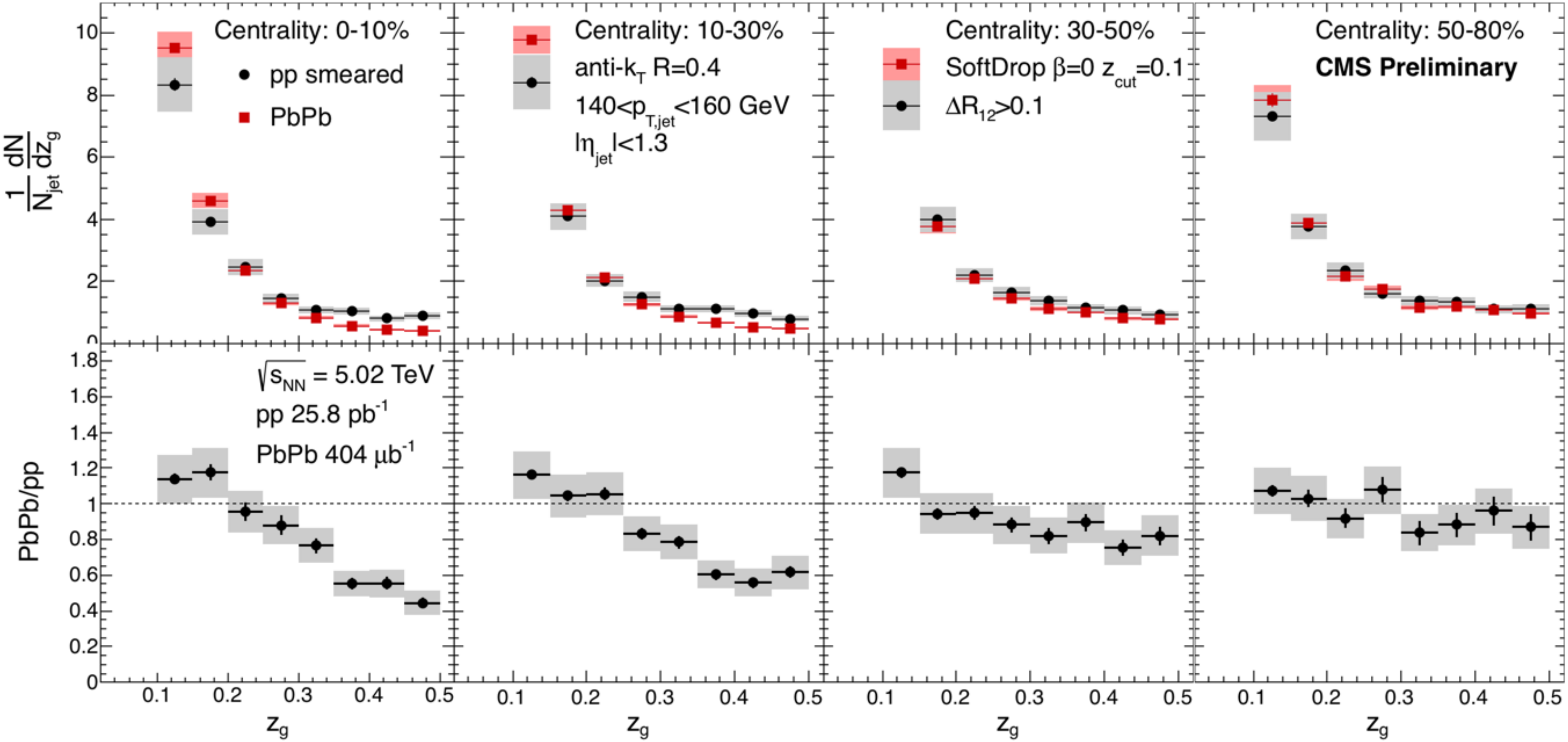
PbPb vs pp

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

Central collisions

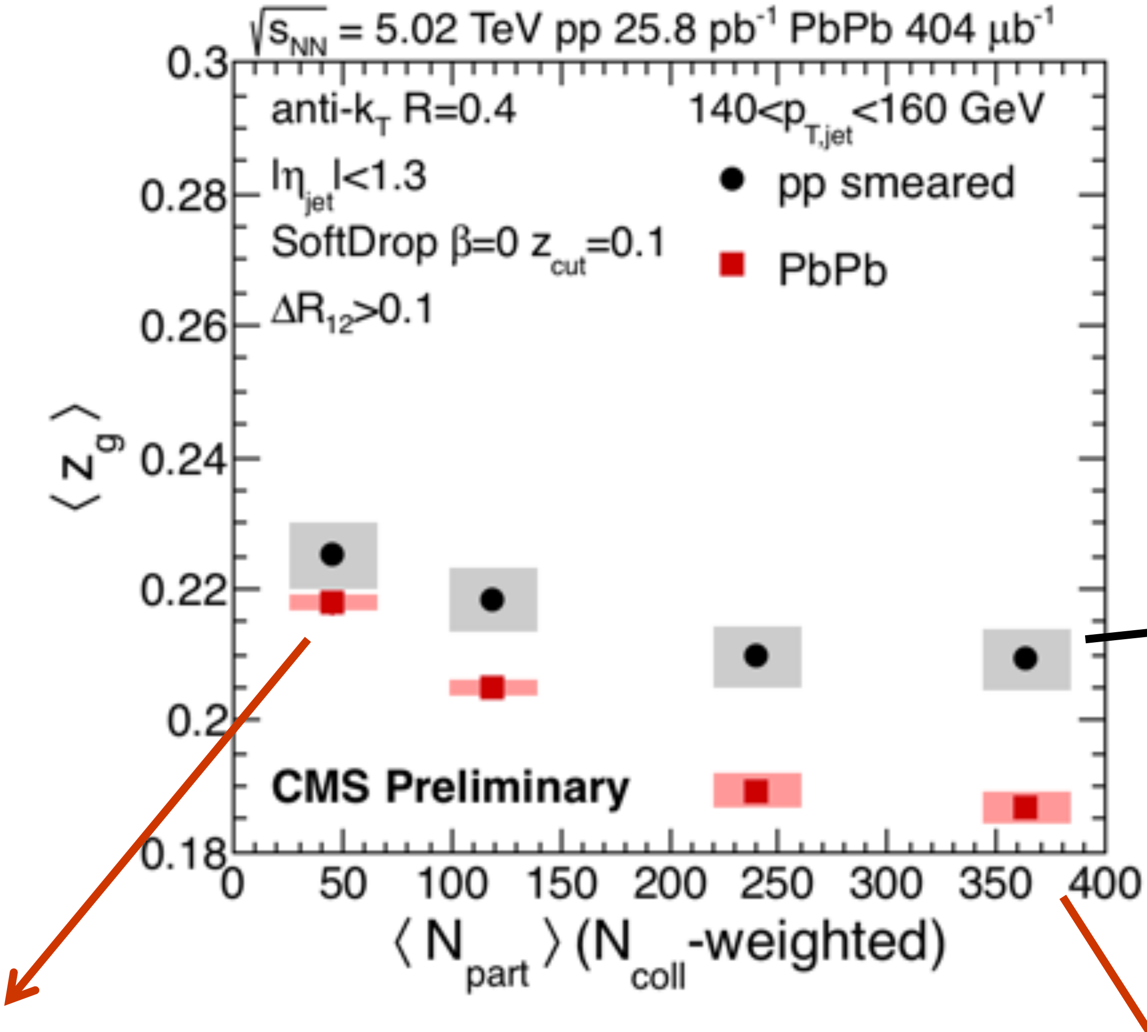
Peripheral collisions





Strong modification of splitting observed in central PbPb collisions
Branching more imbalanced in central PbPb

Evolution with medium density



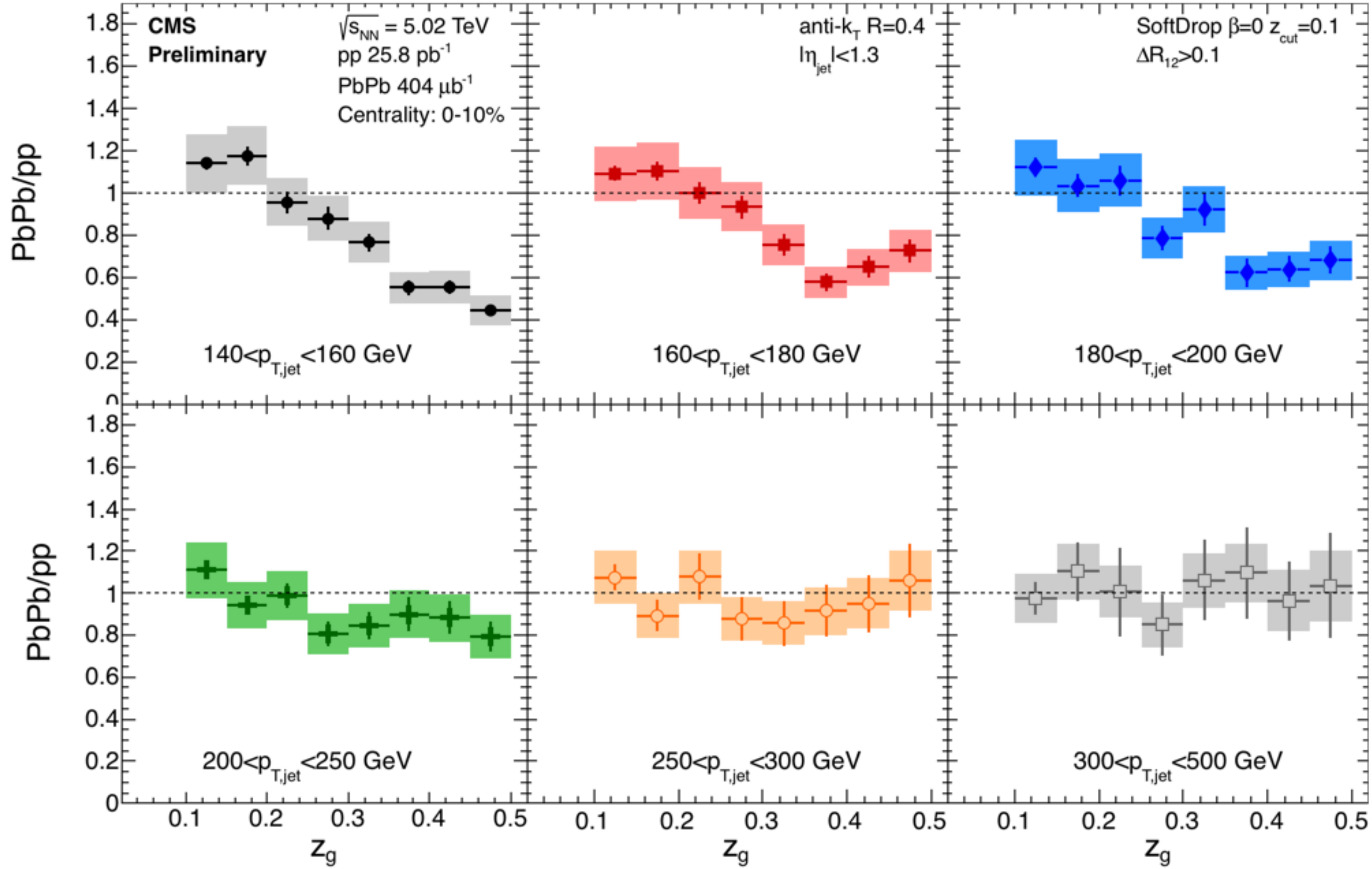
pp reference smeared to PbPb resolution

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

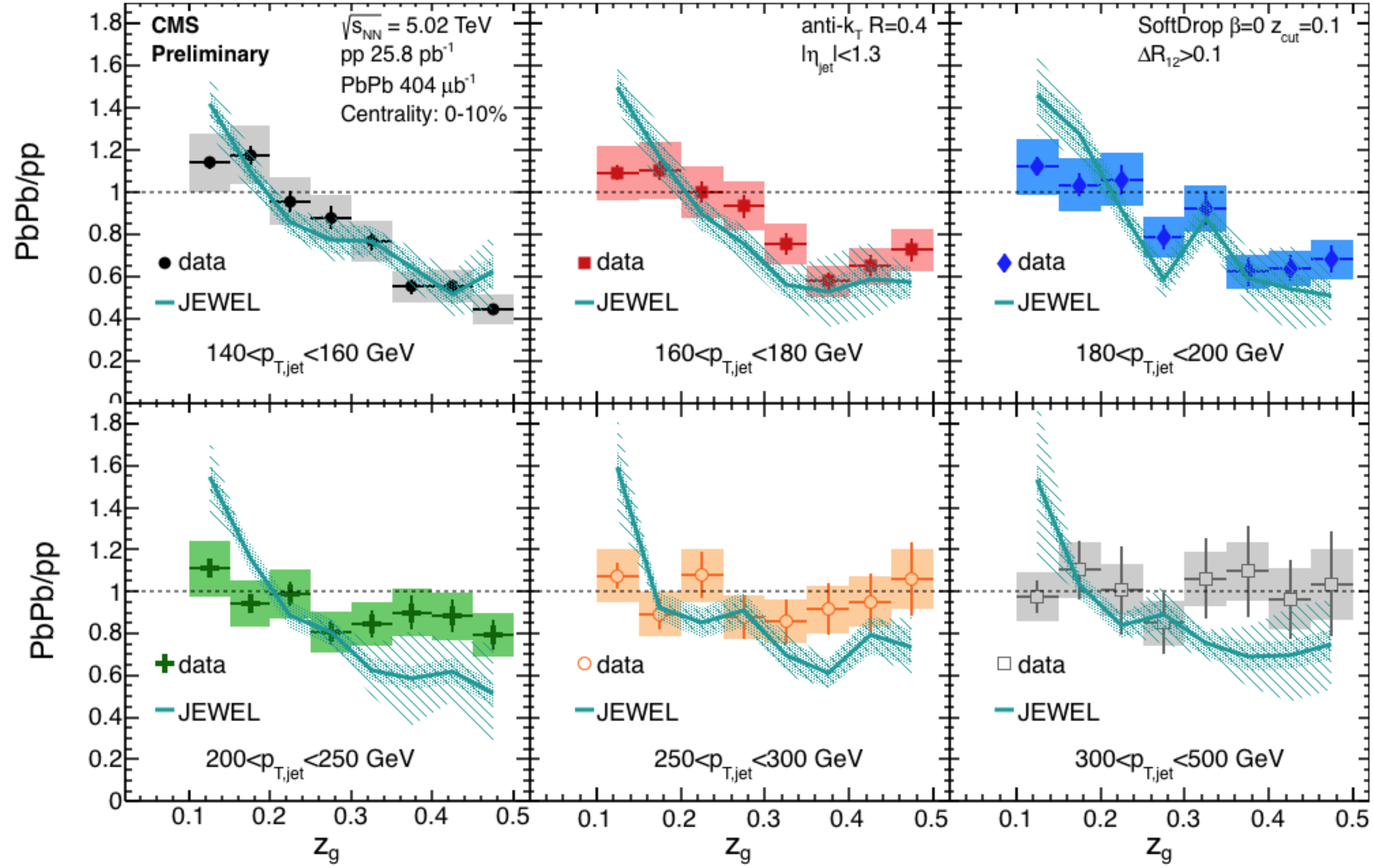


Due to normalization, cannot distinguish between increase at low z_g or suppression at high z_g

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. This calculation: R. Kunnawalkam Elayavalli and K. Zapp in preparation

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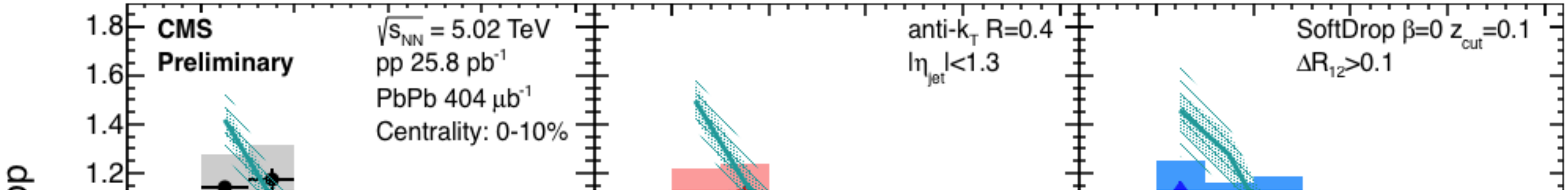
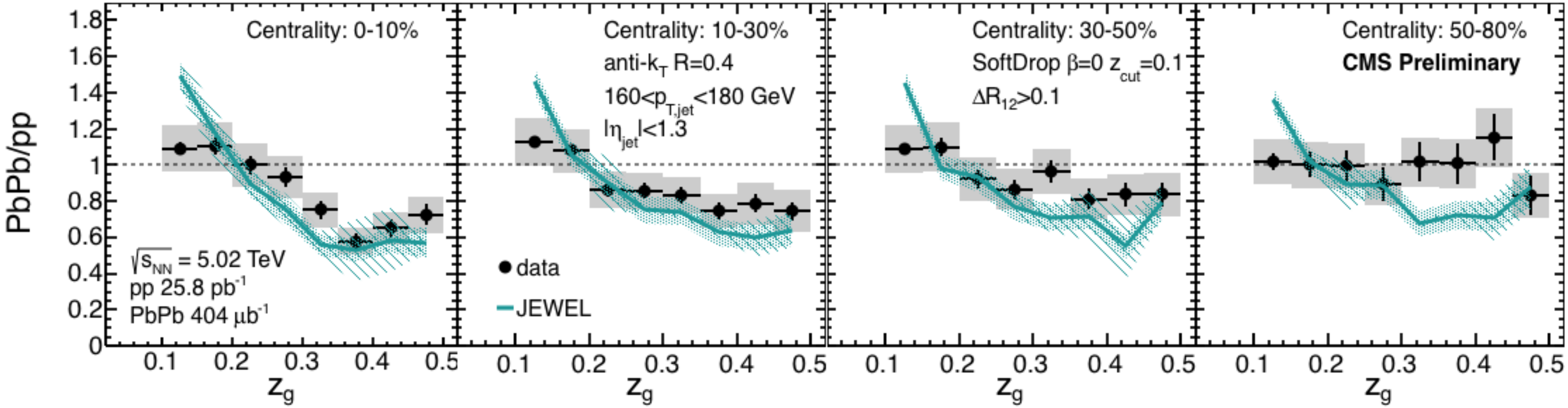
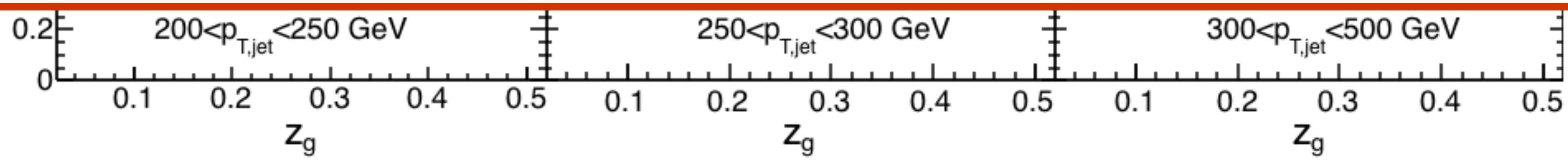




More about JEWEL in Raghav's talk



JEWEL MC, K. Zapp et al, JHEP03 (2013) 080. This calculation: R. Kunnawalkam Elayavalli and K. Zapp in preparation

Conclusions

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

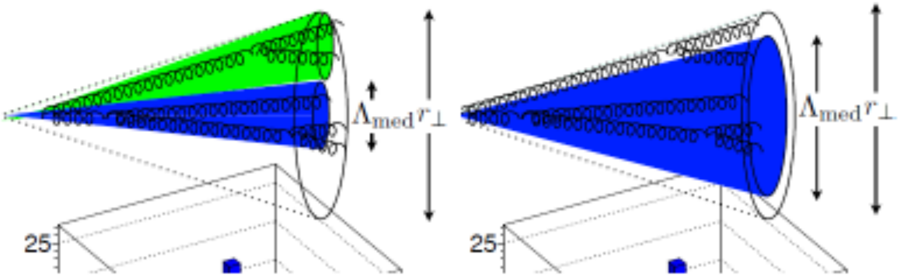
A significant modification of the splitting function is observed in central PbPb collisions

Physics interpretation:

- Coherent vs incoherent emitters
  - If incoherent: energy loss fluctuations? (Guilherme)
- Measure of BDMPS radiation spectrum? (see Yacine's talk)

Extensions of measurement to probe the critical opening angle possible

2 coherent emitters: color disconnected subjets

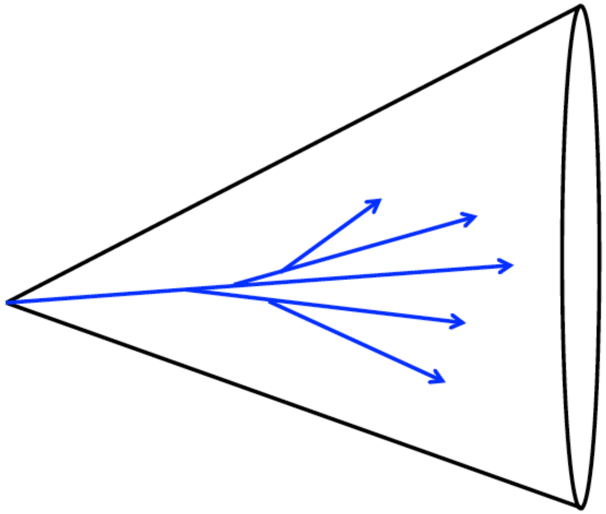


1 coherent emitter: color connected subjets

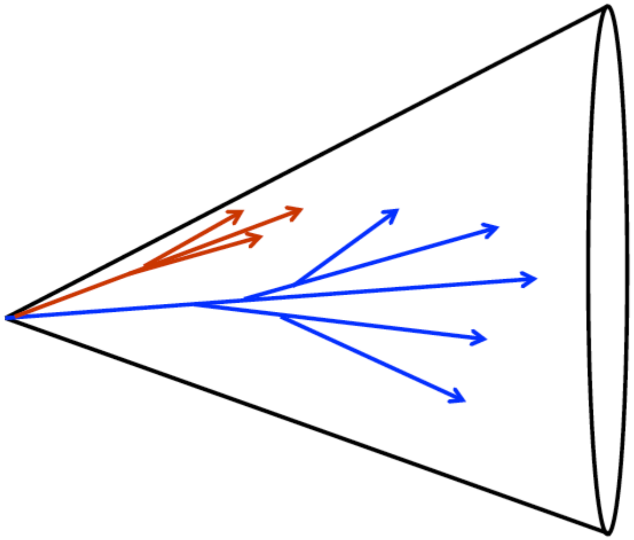
Bonus slides

Hard jet substructures

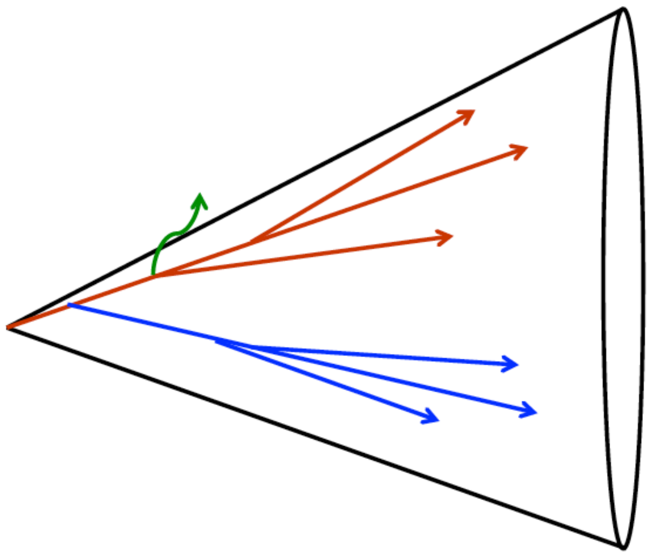
Collimated jet

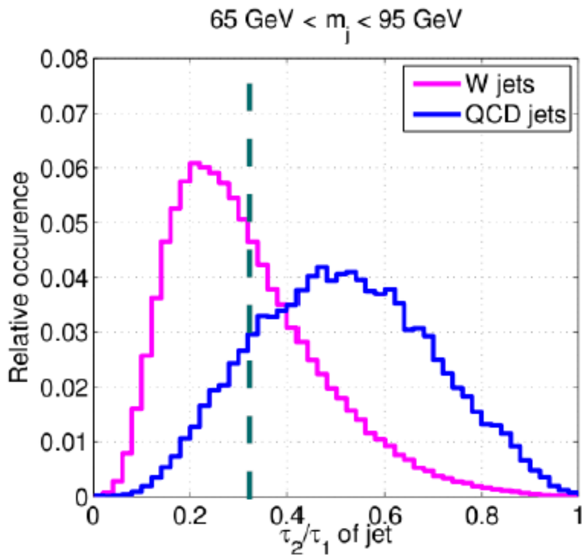


Collimated jet
+ softer 2nd structure



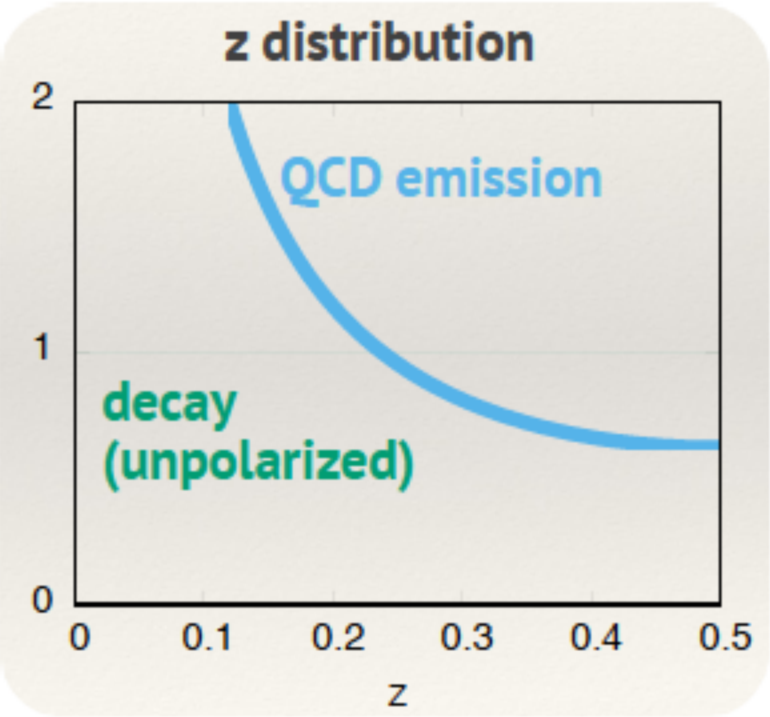
Two hard structures



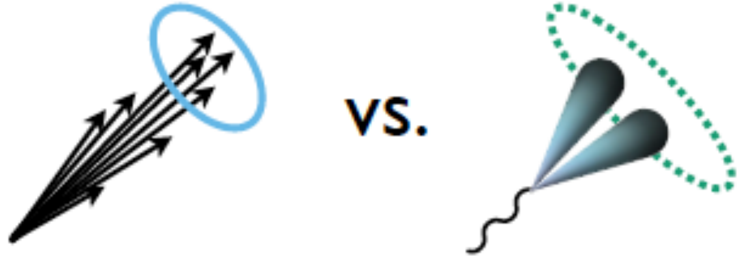


Most QCD jets will be dominated by 1 leading structure + soft radiation

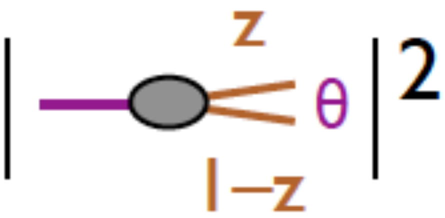
QCD Splitting function



[Gavin Salam FCC talk, March 2015]



Feature of QCD: $1/z_g$



Splitting Function

1→2

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

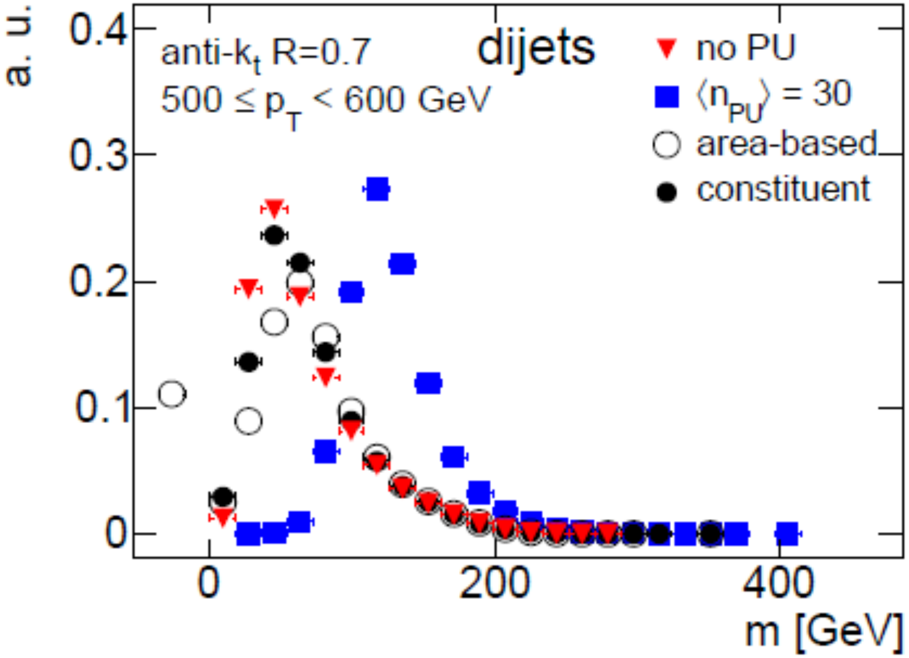
$$\frac{2\alpha_s C_i}{\pi}\,\frac{\mathrm{d}\theta}{\theta}\,\frac{\mathrm{d}z}{z}$$

Jets + background subtraction

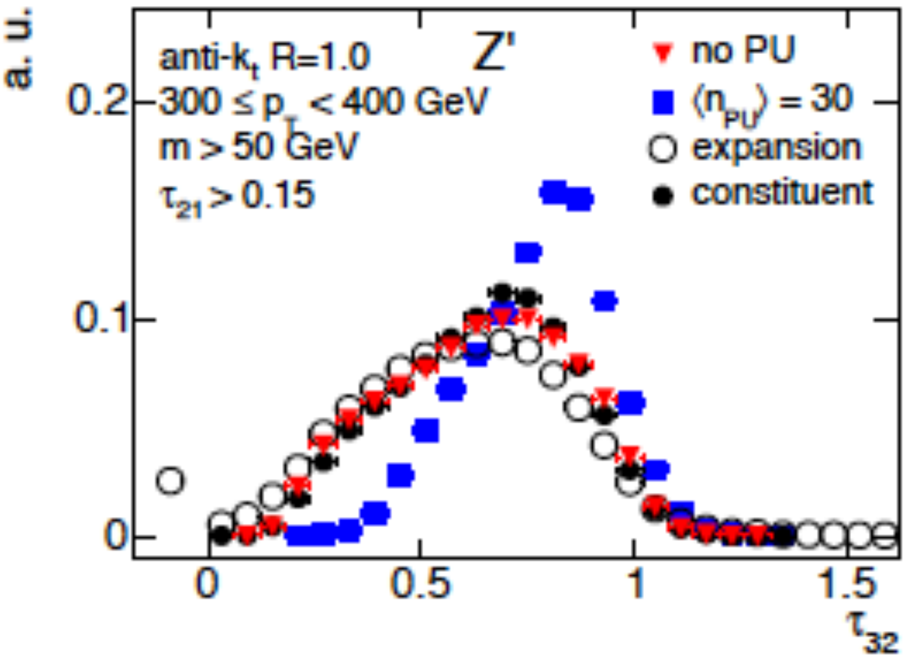
Jets in heavy-ion collisions are contaminated by huge background

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:

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

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

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

  - Both densities are estimated in different eta regions:

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