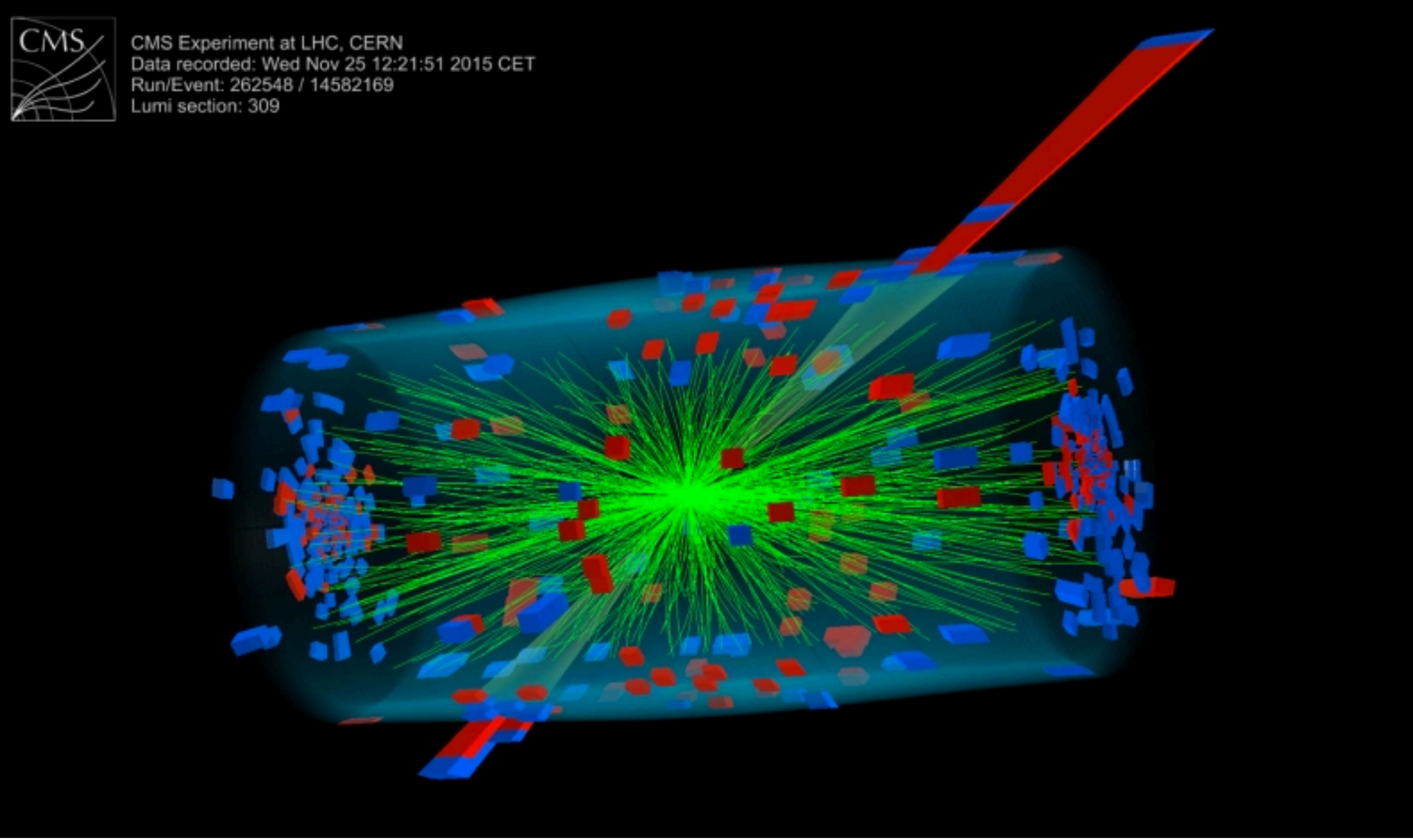
Studies of jet quenching in PbPb collisions at CMS

New run2 results

Marta Verweij (CERN)
for the CMS collaboration

August 5, 2016
ICHEP, Chicago



Run2 heavy-ion data taken in November-December 2015 at 5.02 TeV
pp: 25.8 pb^{-1}
PbPb: 404 μb^{-1}

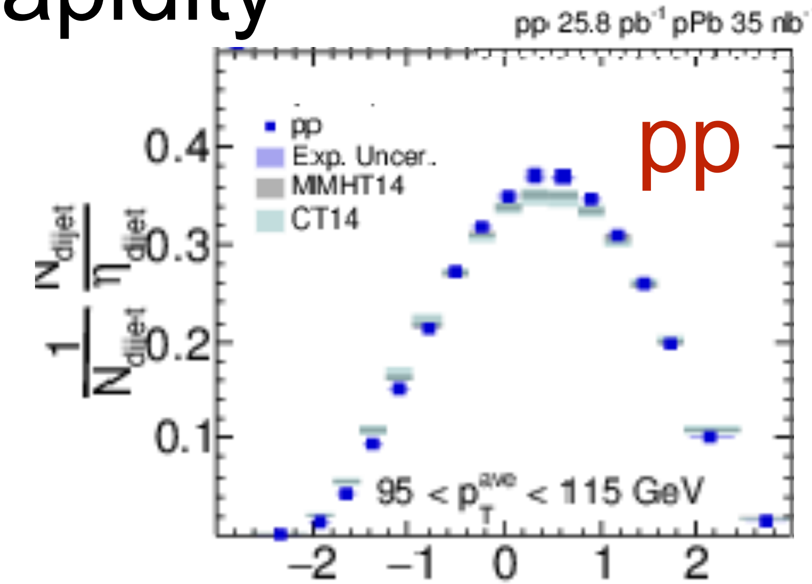
Nuclear PDF
dijet pseudorapidity

[CMS-HIN-16-003](CMS-HIN-16-003)

With pp data at 5 TeV, nuclear PDF can be further constrained

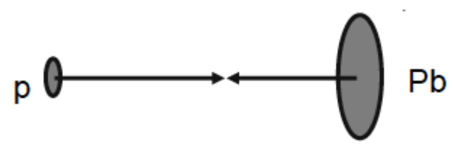
Proton PDF: NLO calculations too wide
→ cancels in pPb-pp difference

pPb-pp: good agreement with EPS09
discrepancy with DSSZ and nCTEQ



Large x
EMC

Small x
Shadowing

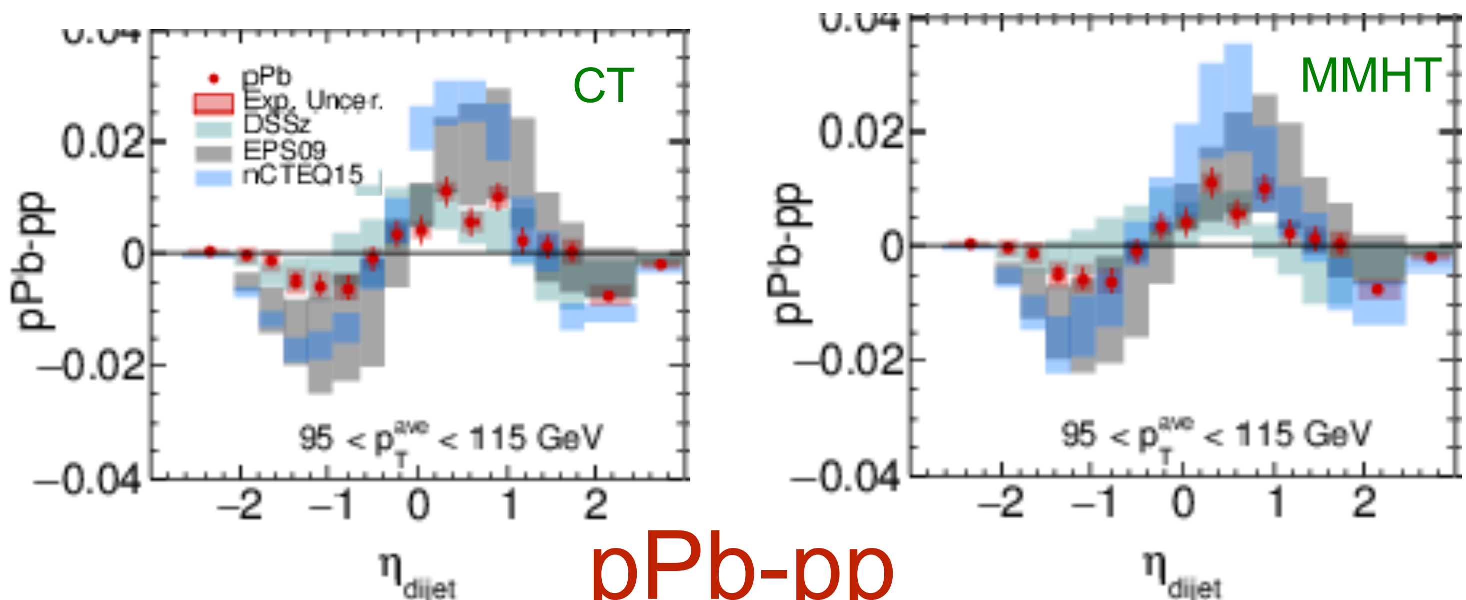


$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

$\sqrt{s_{NN}}$ = 5.02 TeV

$p_{T,1} > 20$, $p_{T,2} > 30$ GeV,

, $\Delta\phi_{1,2} > 2\pi/3$



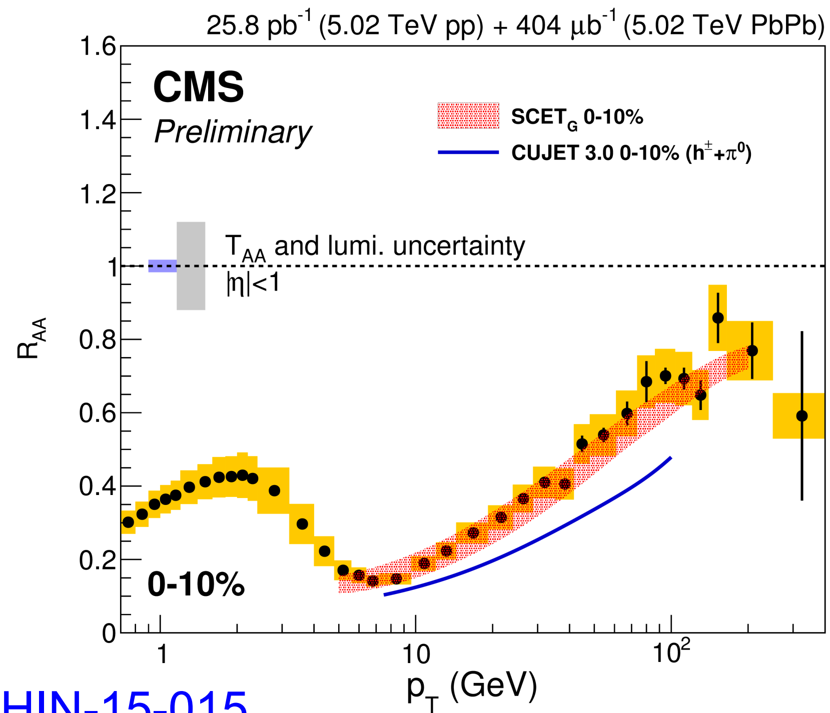
pPb-pp

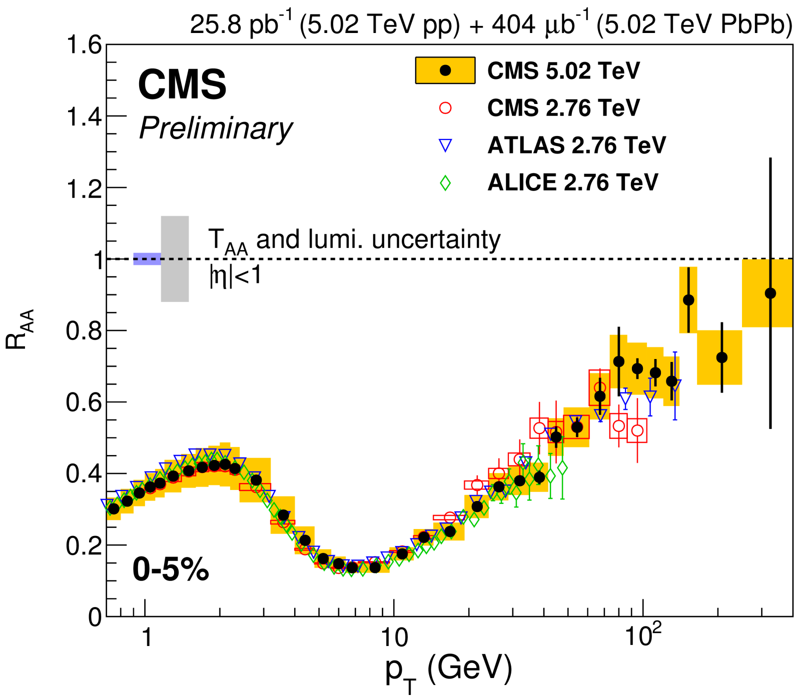
High p_T hadrons

Nuclear modification factor (R_{AA}) measured with high p_T charged hadron production

Strong suppression wrt pp in central heavy ion collisions

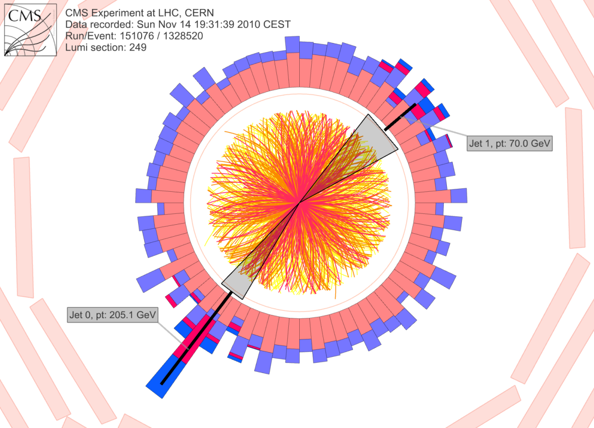
R_{AA} at 5.02 similar to 2.76 TeV
→ does not imply same medium temperature



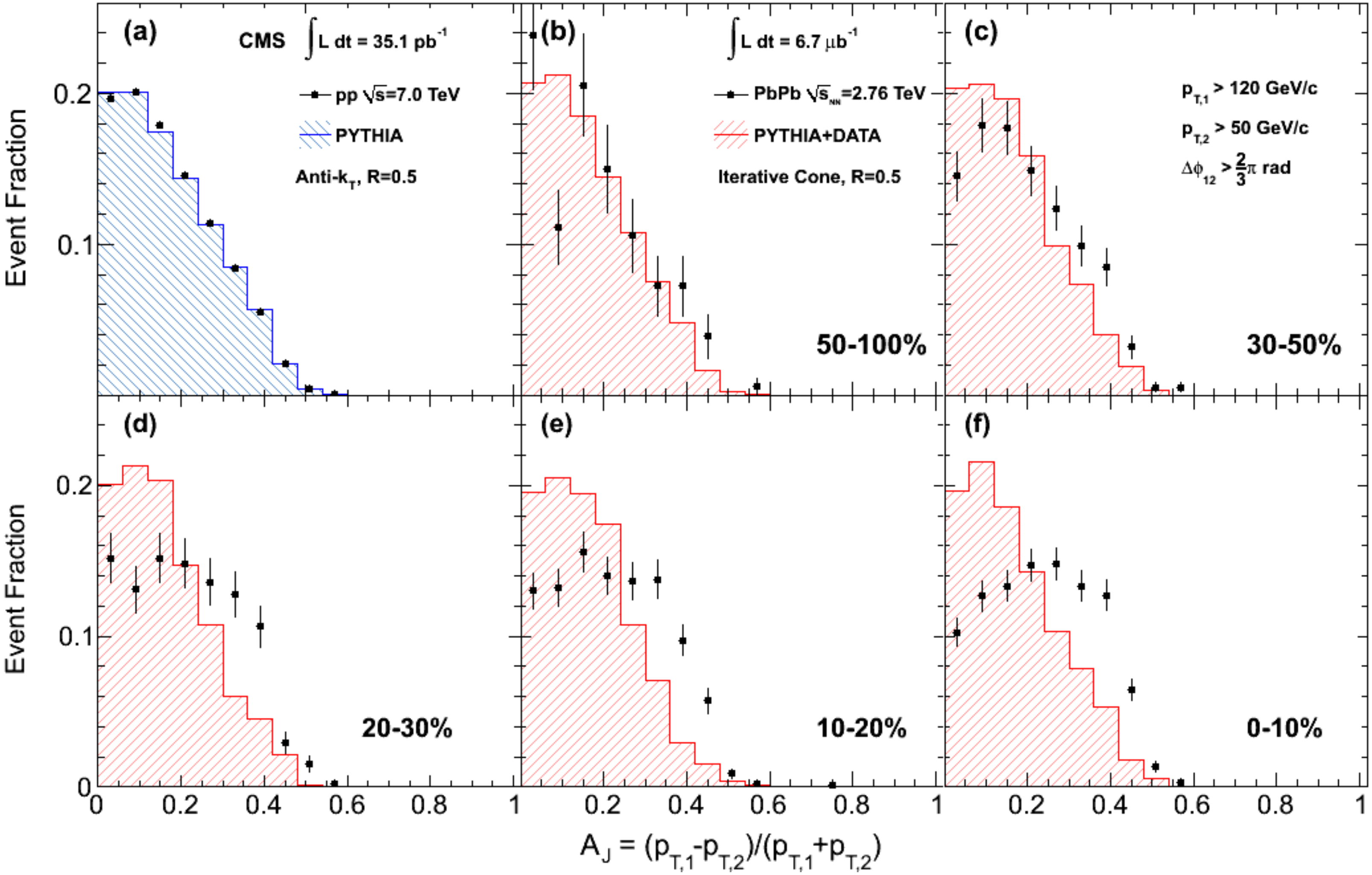


CMS-HIN-15-015

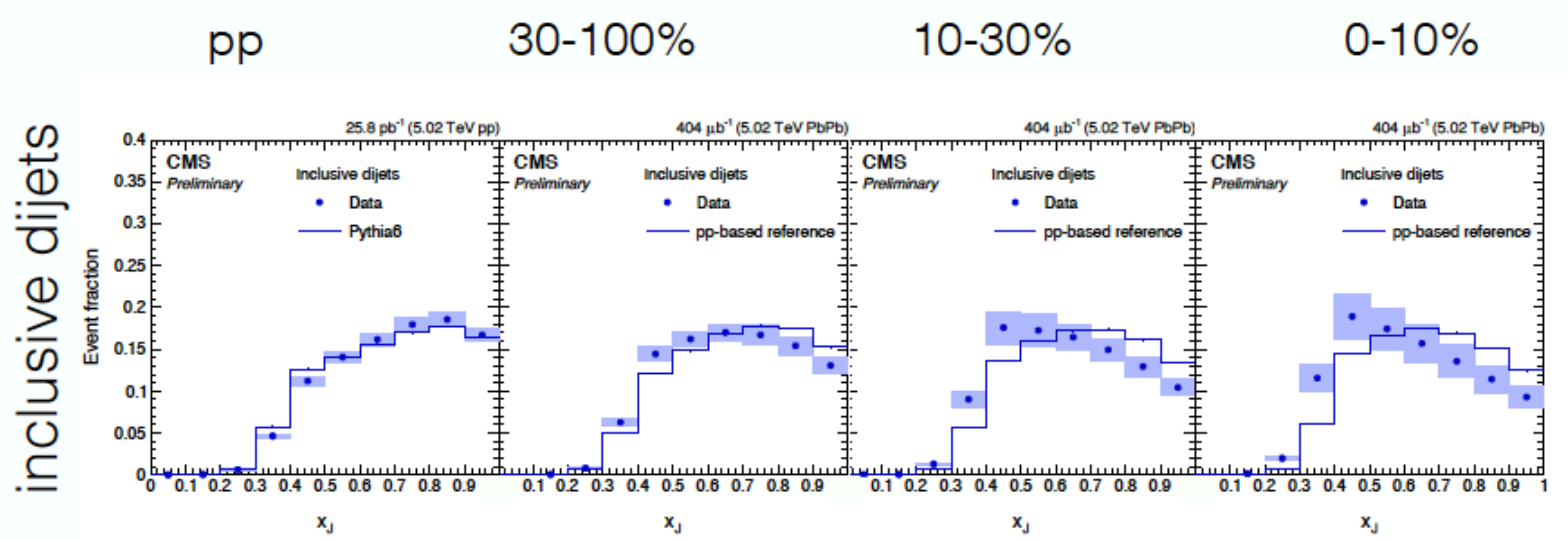
Dijet energy balance



Direct observation of jet quenching during run1: Dijets less balanced in central PbPb collisions due to energy loss



Dijet energy balance at 5.02 TeV



- Dijet selection:

$$|\eta|<1.5$$
$$p_{T,1}>100\ GeV/c$$
$$p_{T,2}>40\ GeV/c$$
$$\Delta\phi_{1,2}>2\pi/3$$

- Dijet imbalance

$$x_J = p_{T,2} / p_{T,1}$$

Also at 5.02 TeV: dijets less balanced in central PbPb collisions

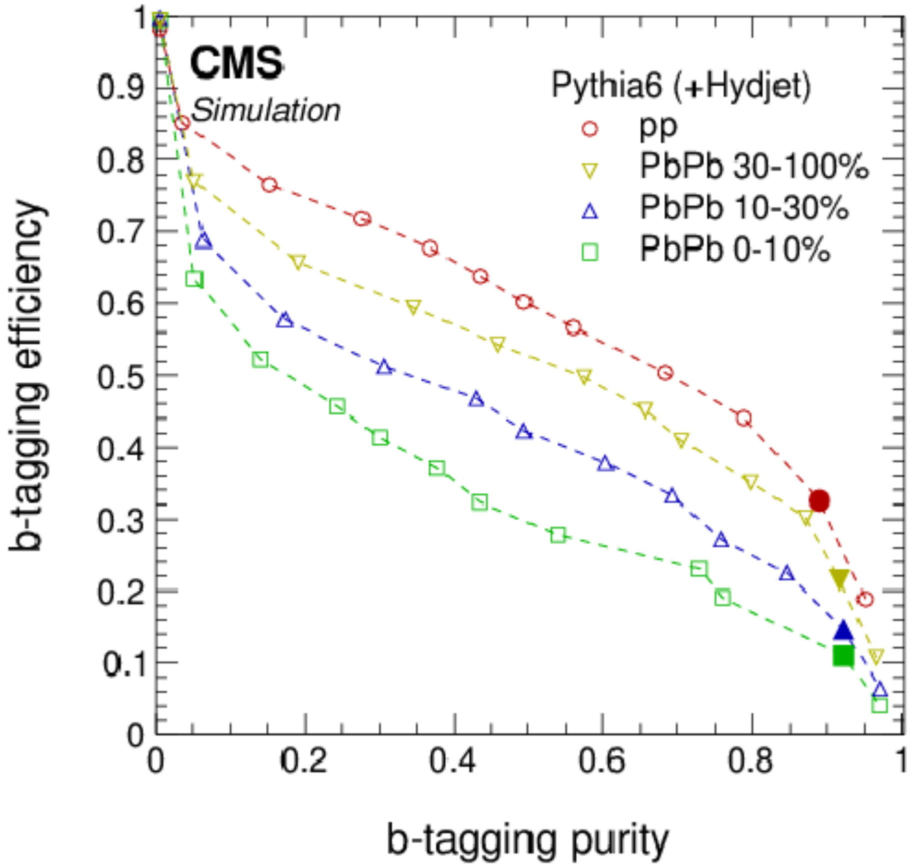
Less pronounced than at 2.76 TeV due to underlying parton spectrum

CMS-HIN-16-005

b-dijets

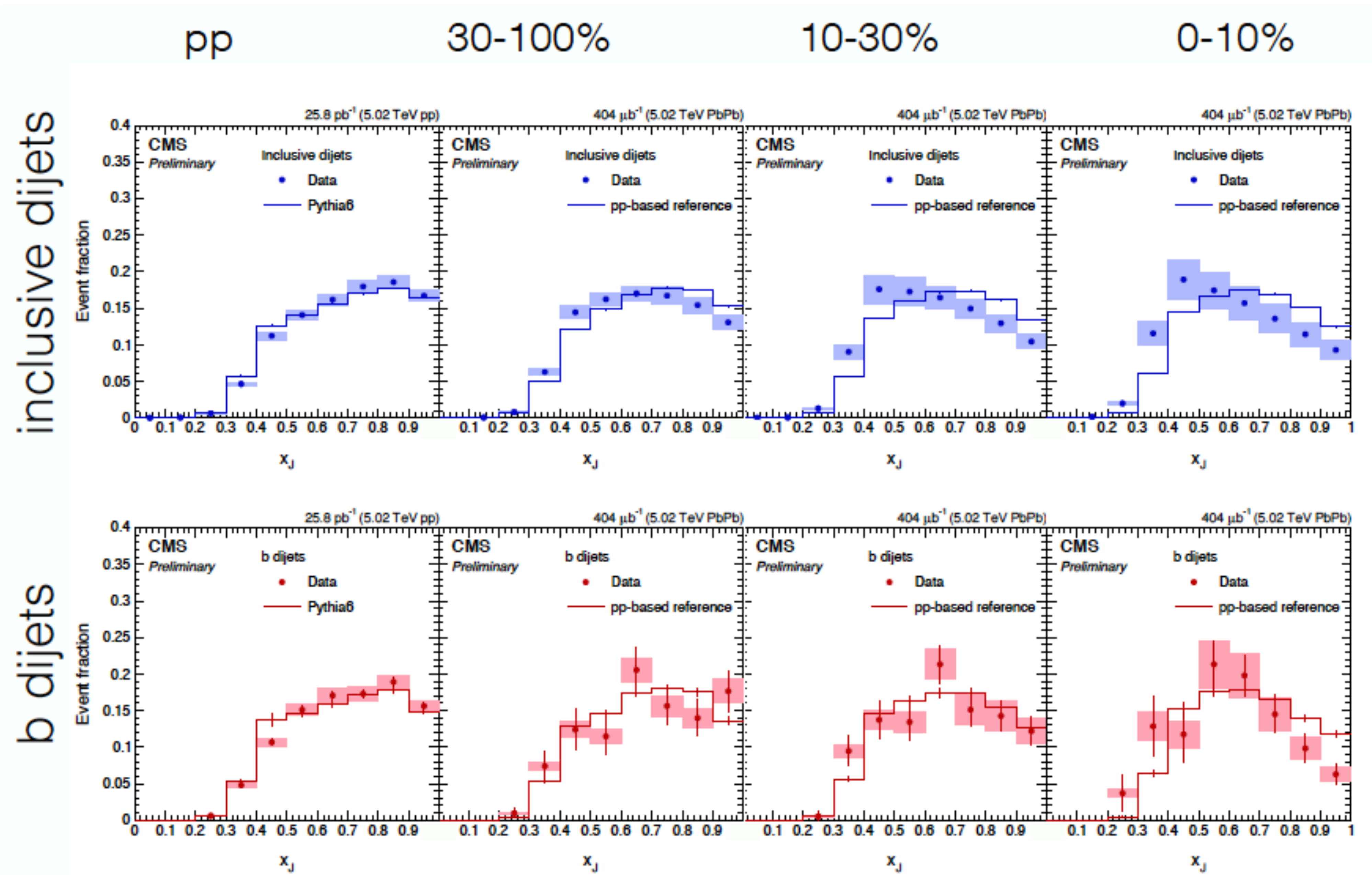
70% from b-dijets from flavor creation
→ mainly probing energy loss of quarks

b-jets are identified using secondary vertex
Efficiency evolves as function of centrality
Tight working points to optimize purity



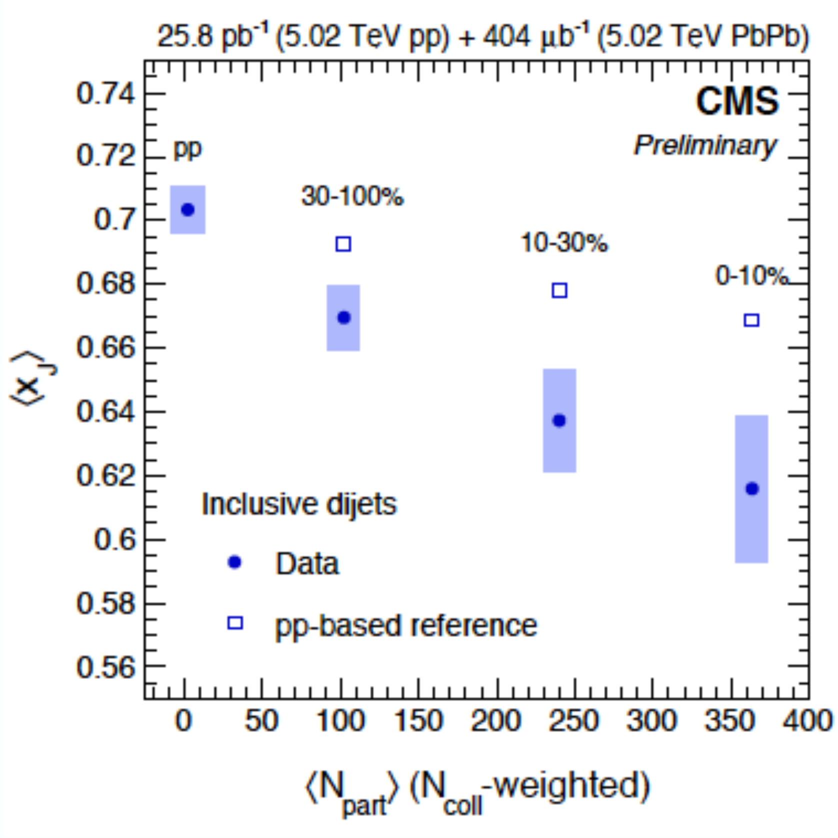
CMS-HIN-16-005

Light vs heavy dijet p_T balance

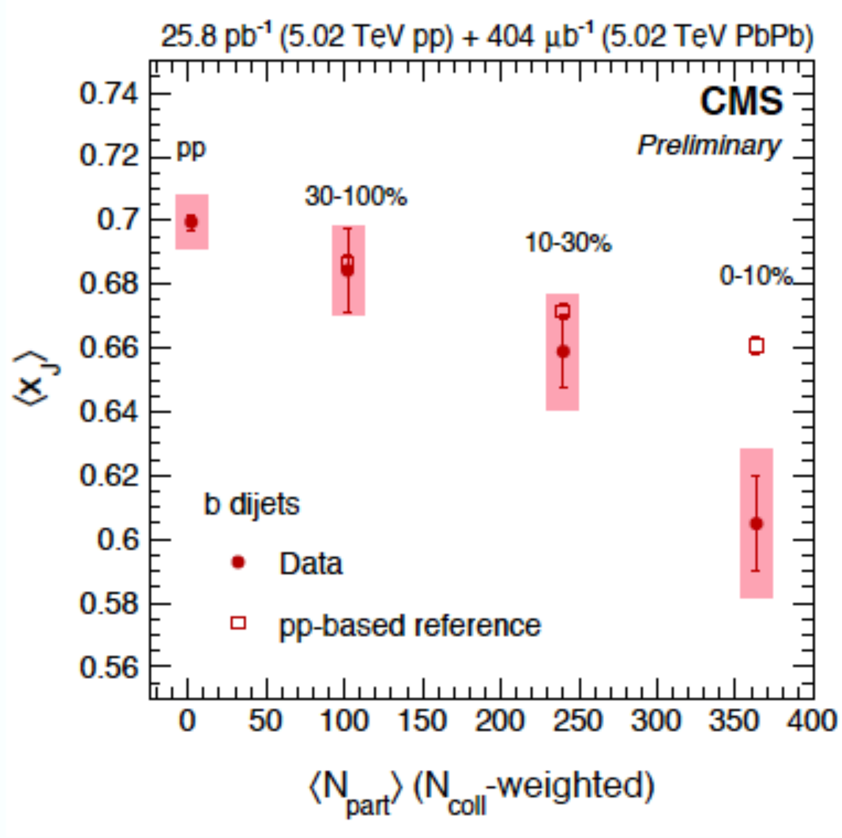


Light vs heavy dijet p_T balance

Inclusive dijets



b-dijets

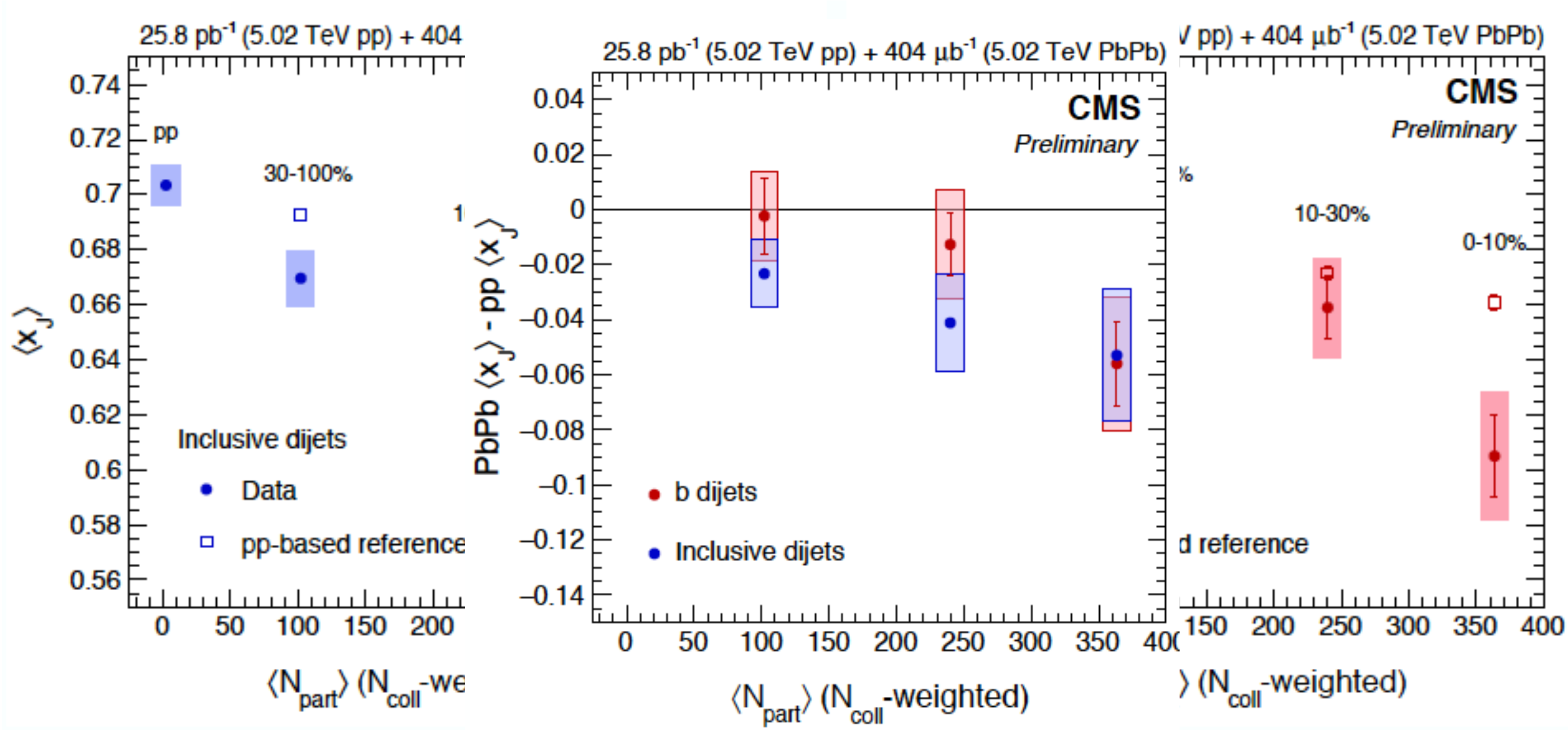


Very similar dijet imbalance for light and heavy quarks

Light vs heavy dijet p_T balance

Inclusive dijets

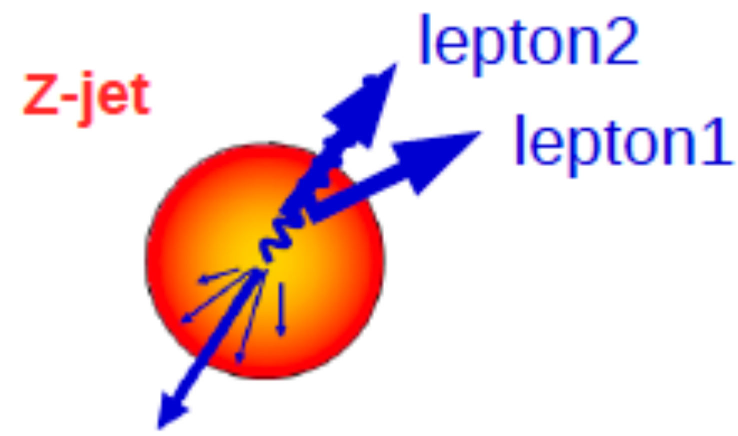
b-dijets

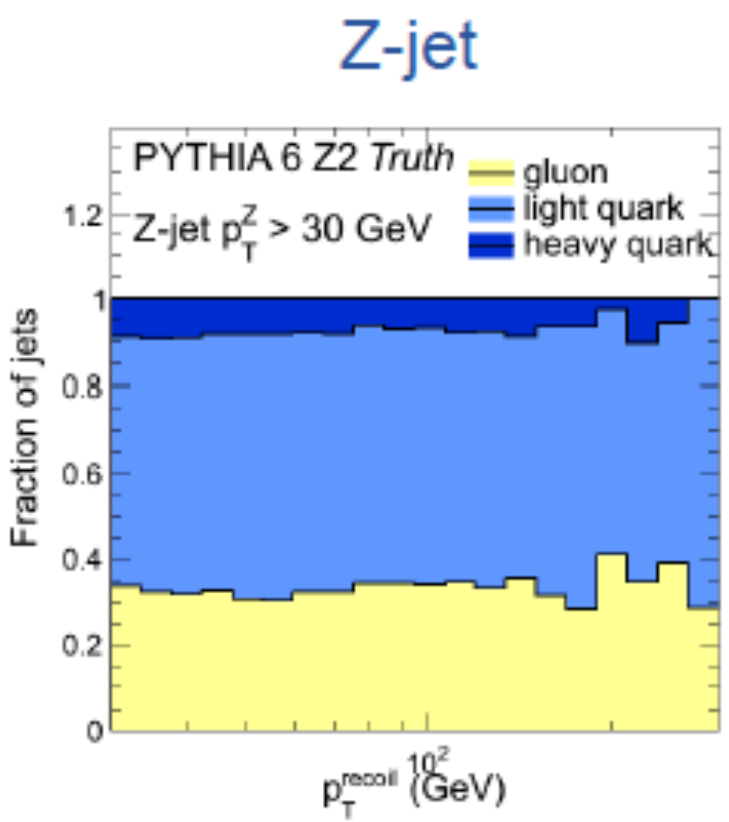


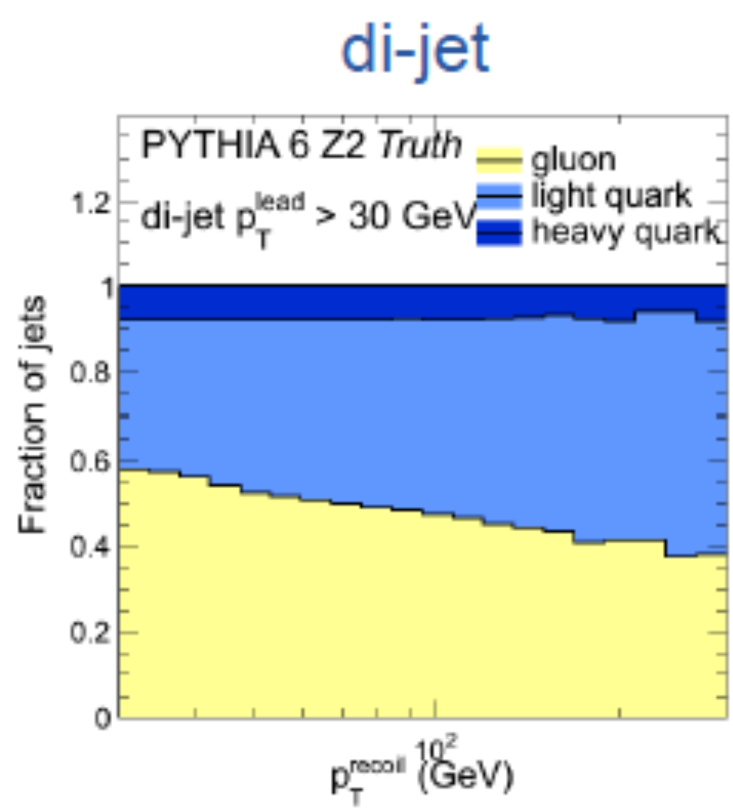
Very similar dijet imbalance for light and heavy quarks

Z-jet correlation

Z doesn't interact with QCD medium
→ Absolute measure of recoiling parton energy
→ Mostly light quarks

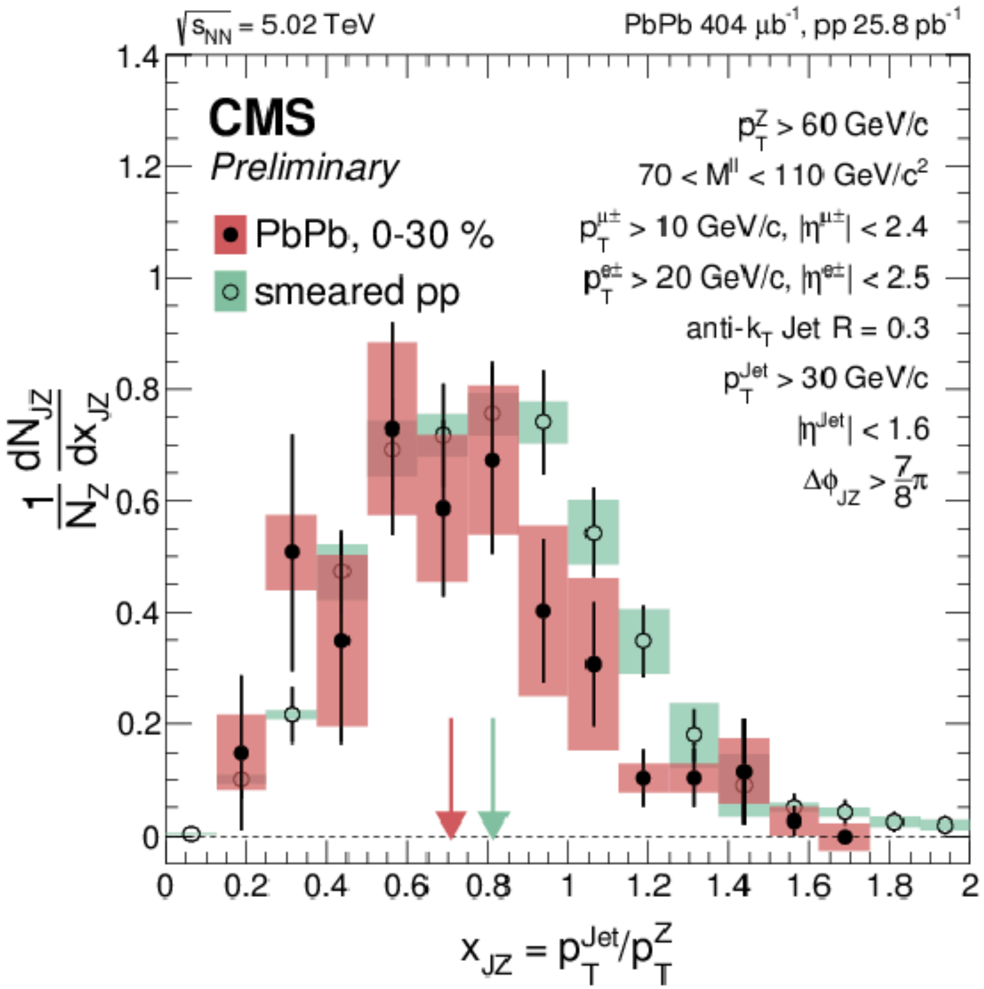






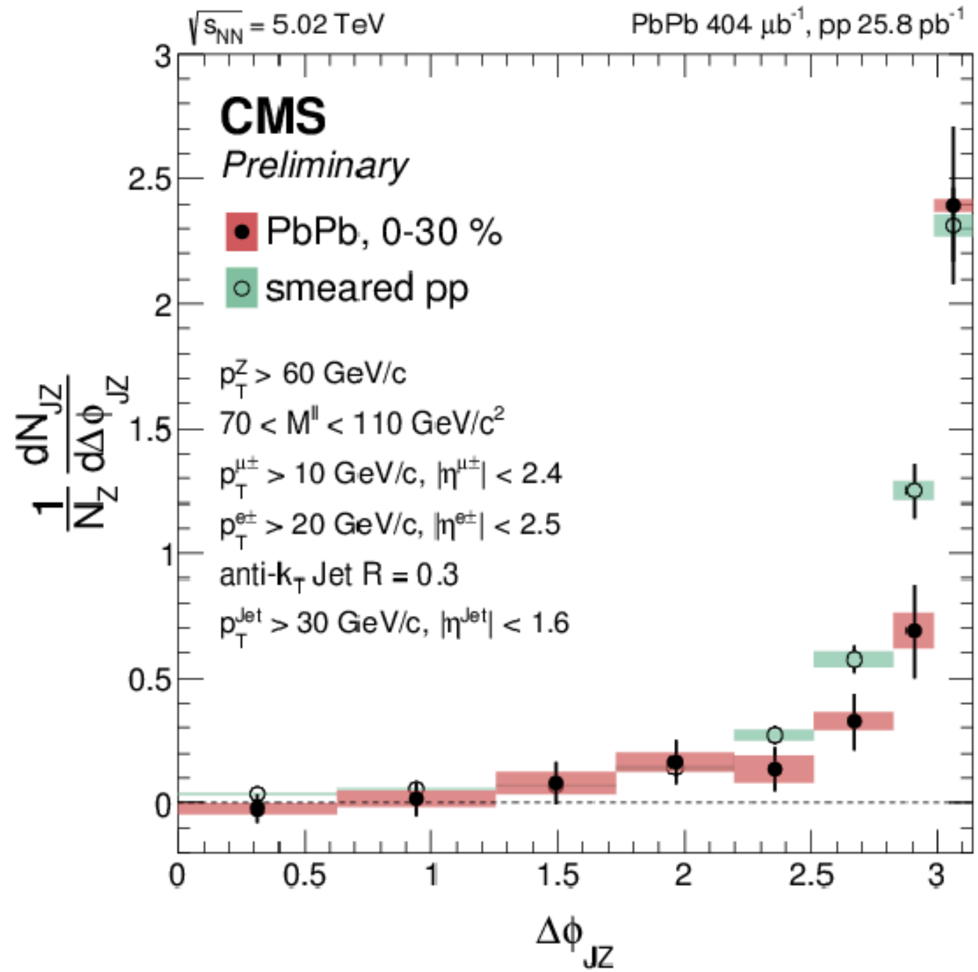
Z-jet measurement

Z-jet energy balance



Less balanced in PbPb compared to pp

Z-jet azimuthal correlation



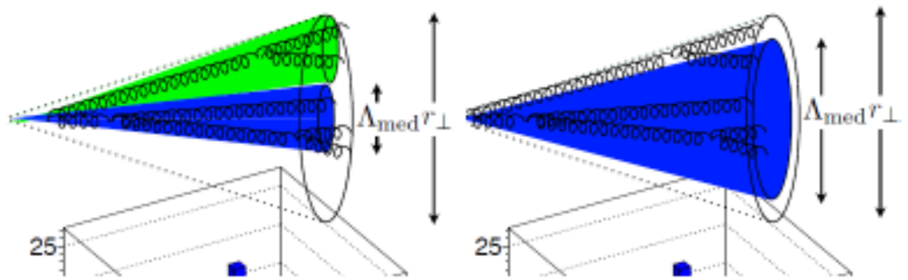
Hint of narrowing
Statistical or physics?

Splitting function

Goal: understand the evolution of the parton shower in medium
Probing the role of color coherence

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

2 coherent emitters: color disconnected subjets



1 coherent emitter: color connected subjets

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

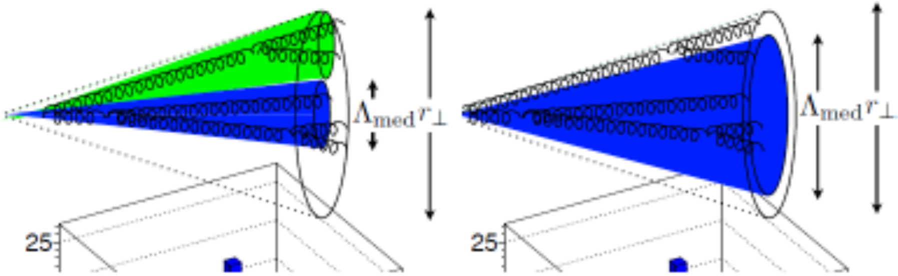
Splitting function

Goal: understand the evolution of the parton shower in medium

Probing the role of color coherence

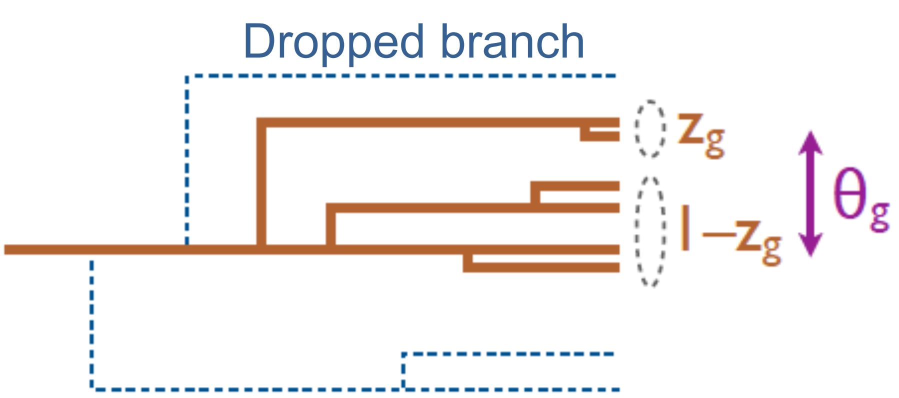
Fig. taken from *Phys.Lett.B* **725** (2013) 357–360

2 coherent emitters: color disconnected subjets



1 coherent emitter: color connected subjets

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

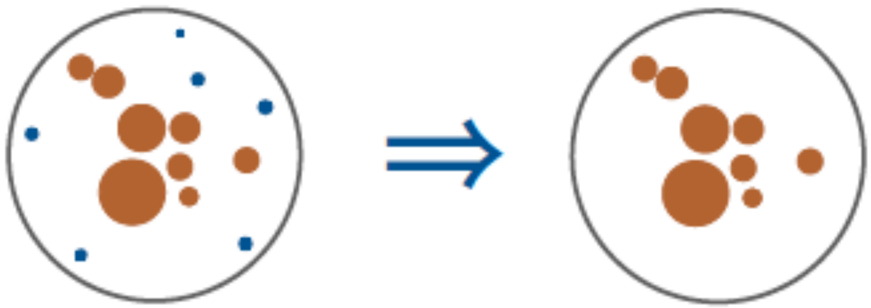


Removes all soft divergences

1) Anti-k_T jet is re-clustered with Cambridge/Aachen (CA)
2) Decluster the angular-ordered CA tree
3) Drop branches until Soft Drop condition is satisfied
4) Extract the 2 branches after grooming for physics → subjets

Softdrop condition

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



Soft Drop condition

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

energy threshold

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 of first splitting

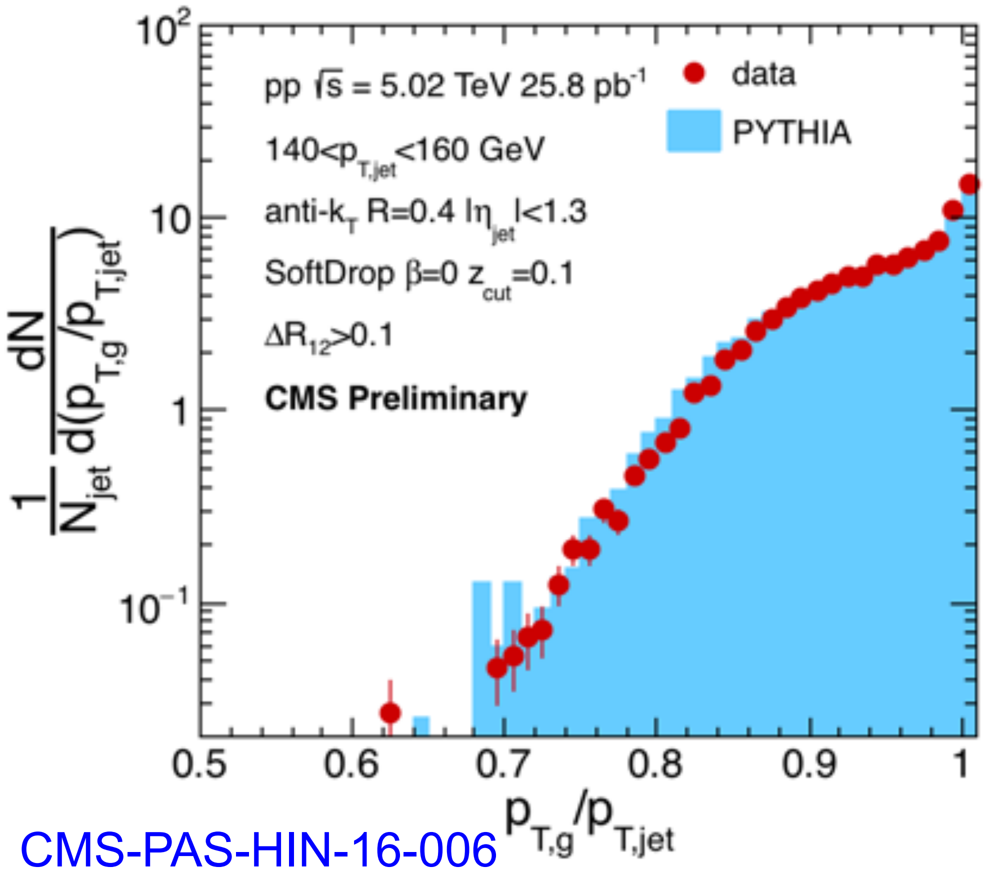
[1] Larkoski, Marzani, Thaler
Phys. Rev. D91:111501 (2015)
Soft Drop: JHEP 1405 (2014) 146

Groomed energy fraction

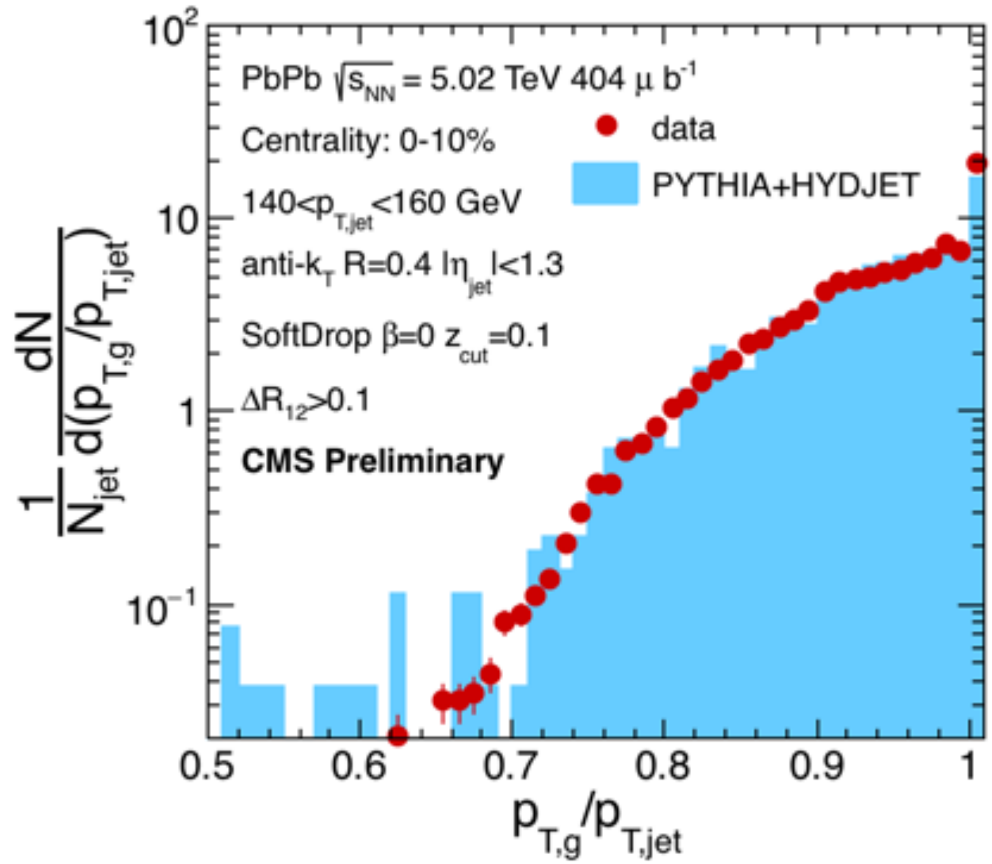
Larger amount of energy gets groomed away in PbPb collisions

Groomed energy fractions well described by MC

pp



PbPb

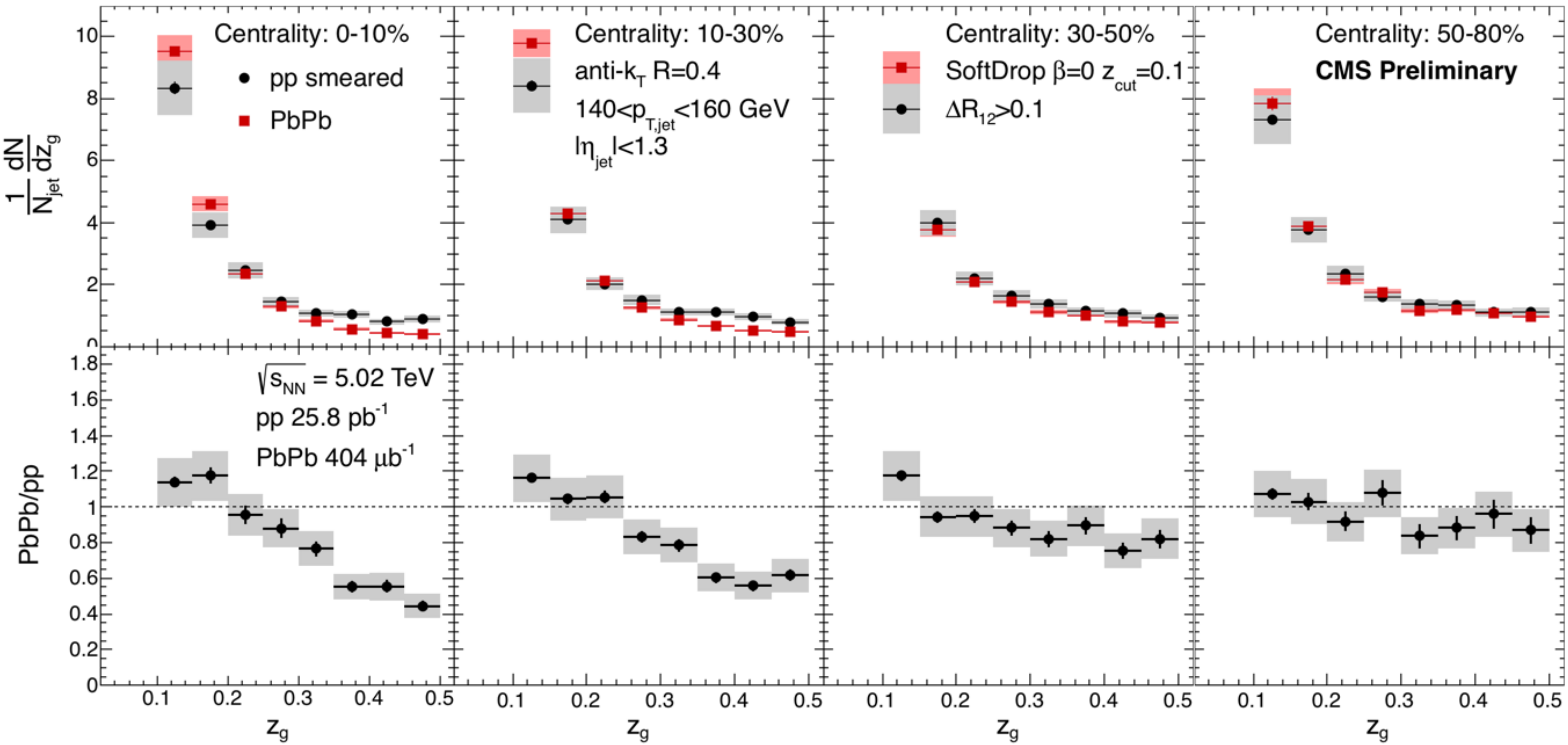


CMS-PAS-HIN-16-006

CMS-PAS-HIN-16-006

PbPb vs pp

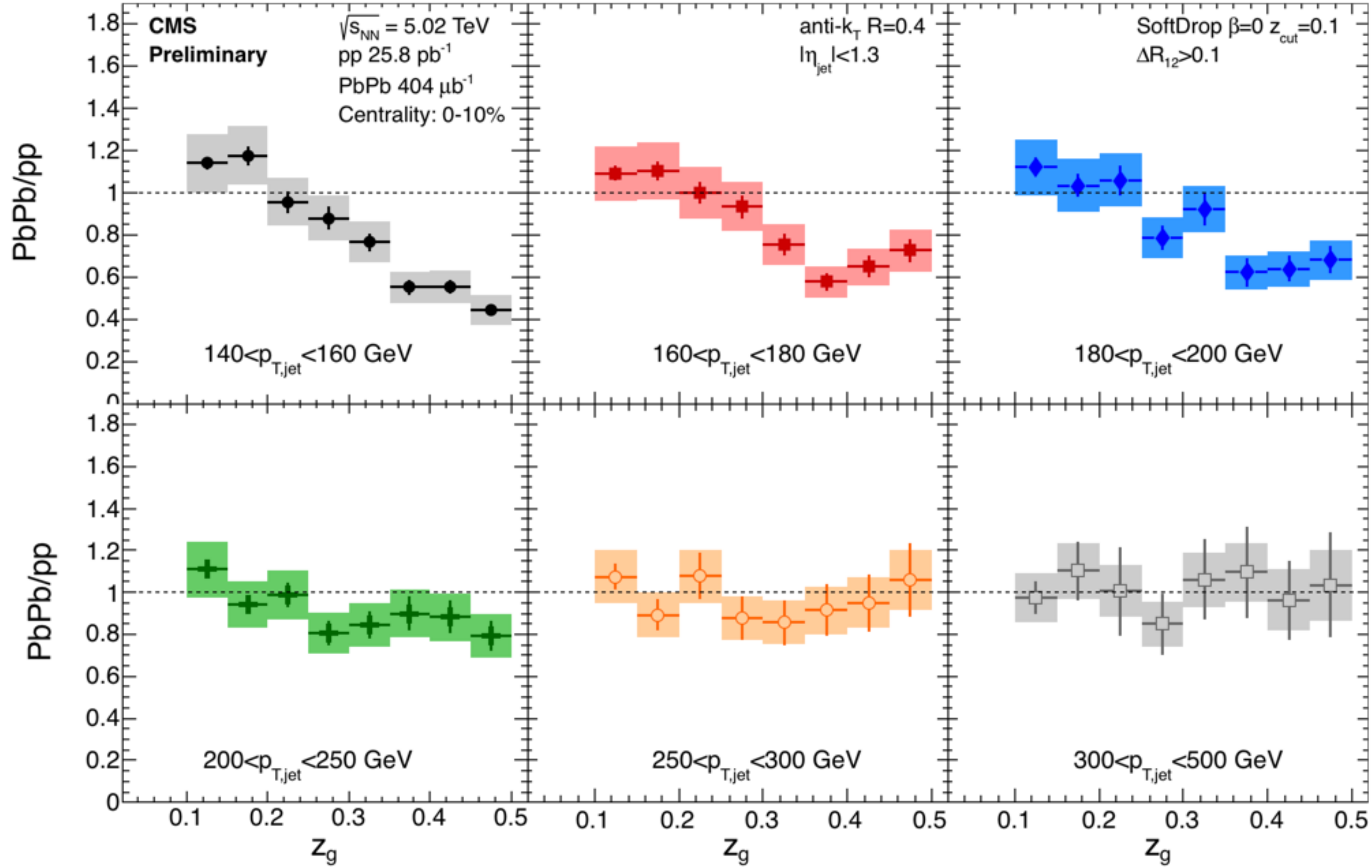
$p_{T,jet}$: 140-160 GeV



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

Jet p_T dependence

Modification gets weaker when increasing jet p_T



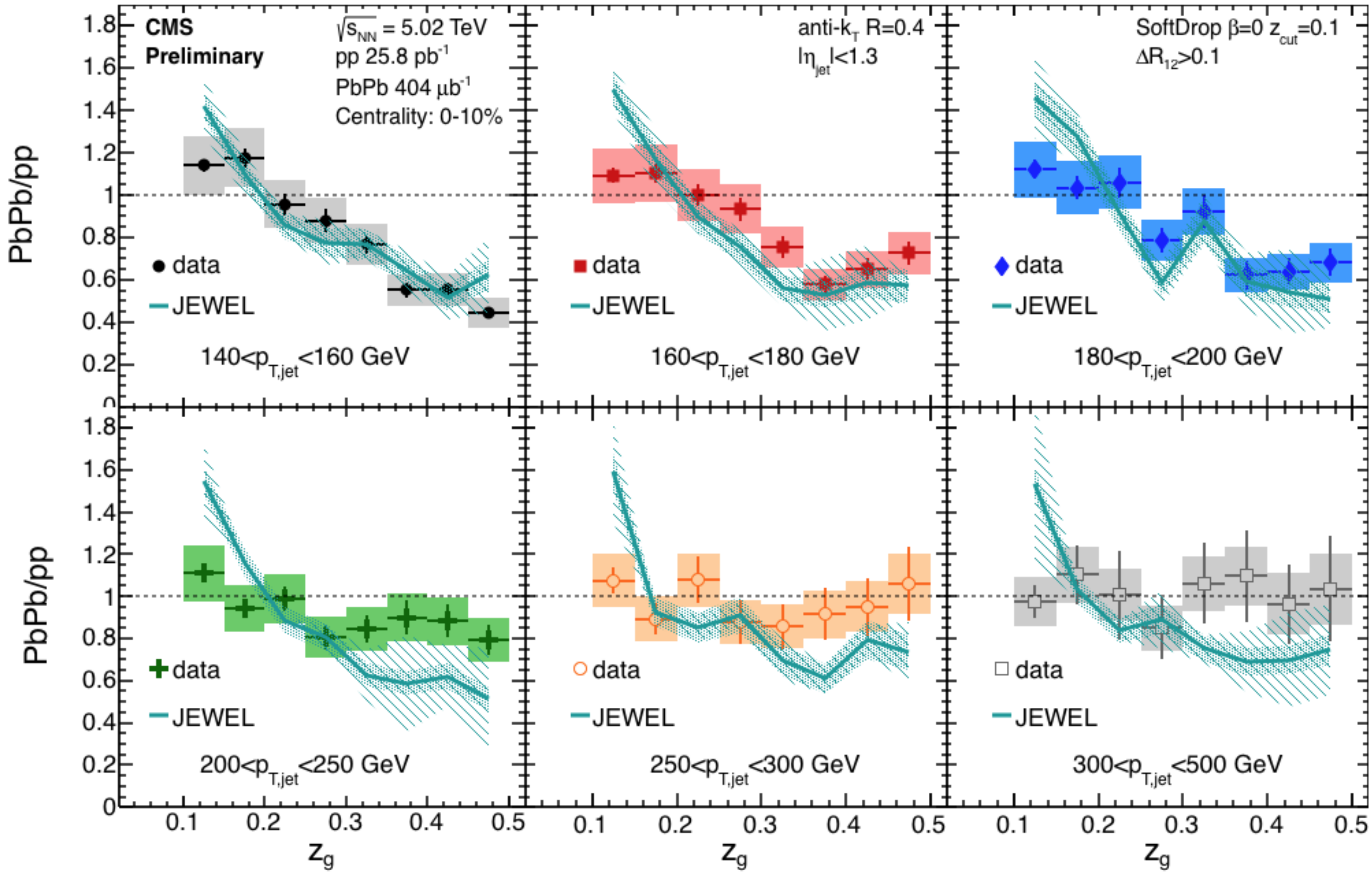
Due to normalization, cannot distinguish between increase at low z_g or suppression at high z_g

CMS-PAS-HIN-16-006

Model comparison

Comparison to jet quenching JEWEL MC event generator

General trend of data is described by JEWEL

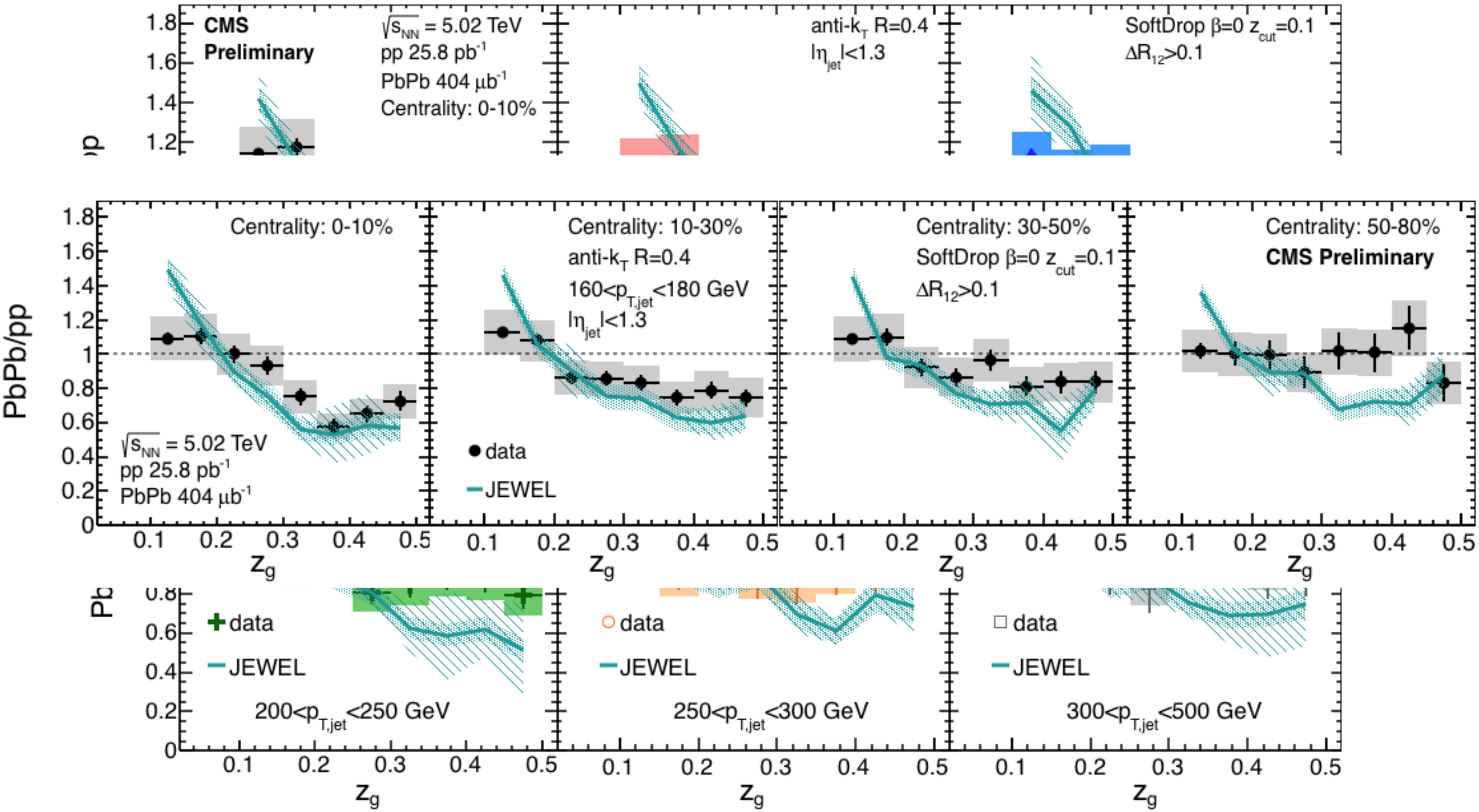


JEWEL MC, K. Zapp et al, JHEP03 (2013) 080. This calculation: R. Kunnawalkam Elayavalli and K. Zapp in preparation

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

Summary

New results probing jet quenching enter unexplored territory at $\sqrt{s_{NN}}$=5.02 TeV :

- High precision measurement (η_{dijet}) to constrain (nuclear) PDFs
- R_{AA} charged particles up to p_T=400 GeV
  → strong suppression which decreases towards higher p_T
- Z-jet events: quark vs color neutral probe
  → smaller energy for recoiling jet
- p_T balance of b-jets
  → similar to light jets
- First measurement of splitting function in pp and PbPb data
  → splitting less balanced for jets in hot QCD medium

All these measurements improve our understanding of parton-medium interactions.

Many more to come… stay tuned

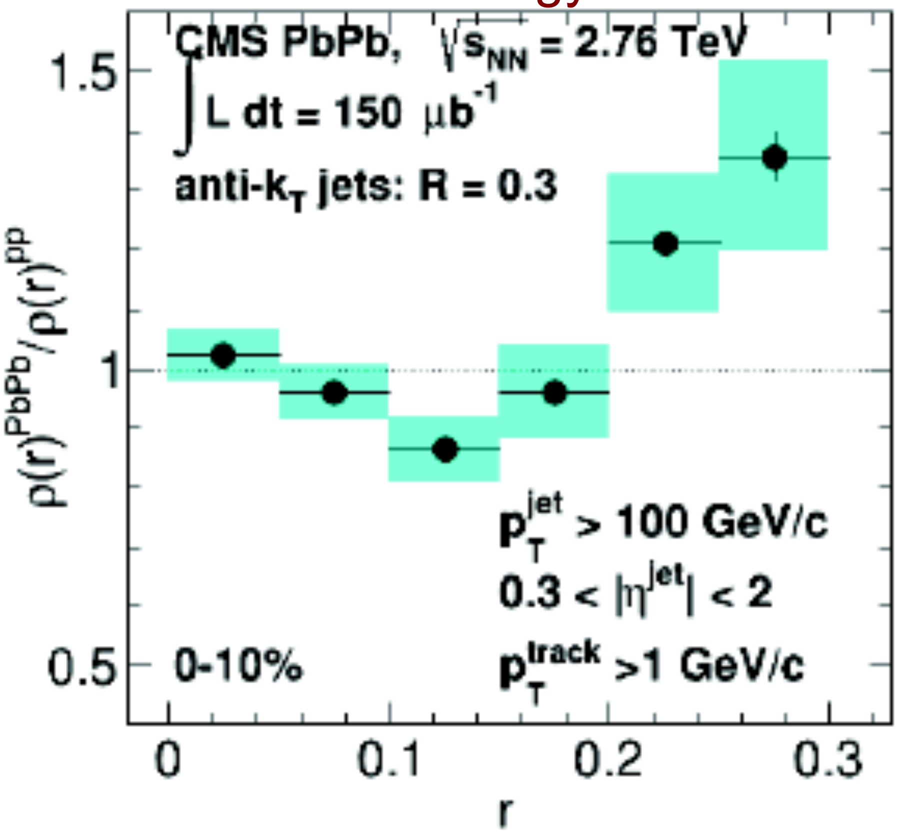
backup

Jet shapes and structures Run1

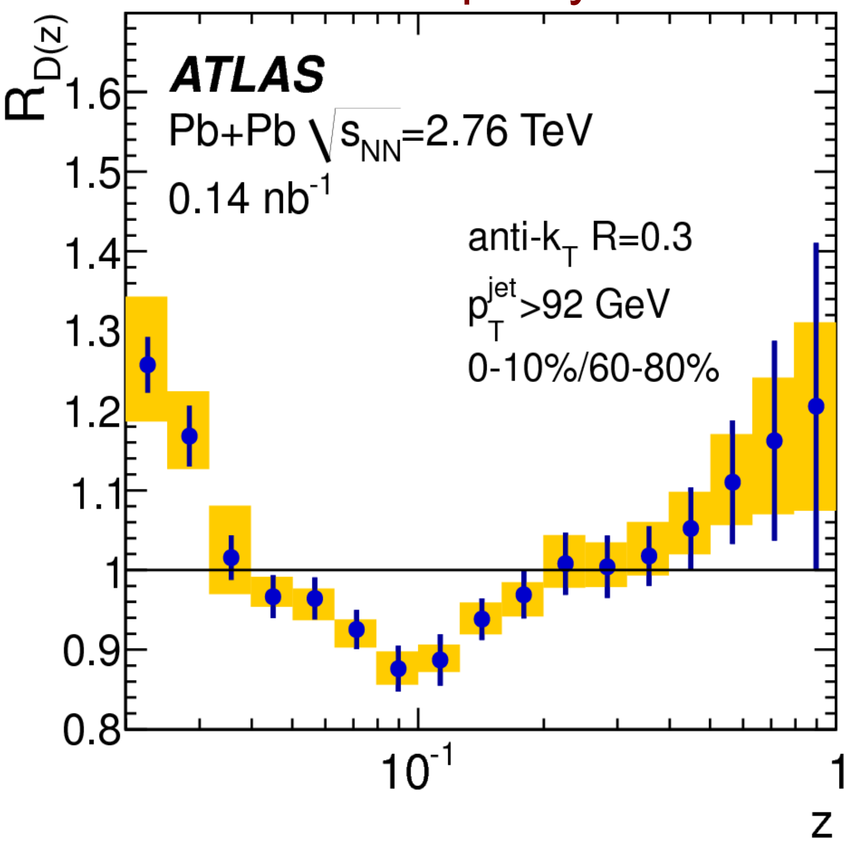
Jet shape observables: energy + multiplicity distributions within a jet
Sensitive to the dynamics of parton shower

Radial profile
Transverse fragment distribution
Energy

CMS PLB 730 (2014) 243



'Fragmentation function'
Longitudinal fragment distribution
Multiplicity



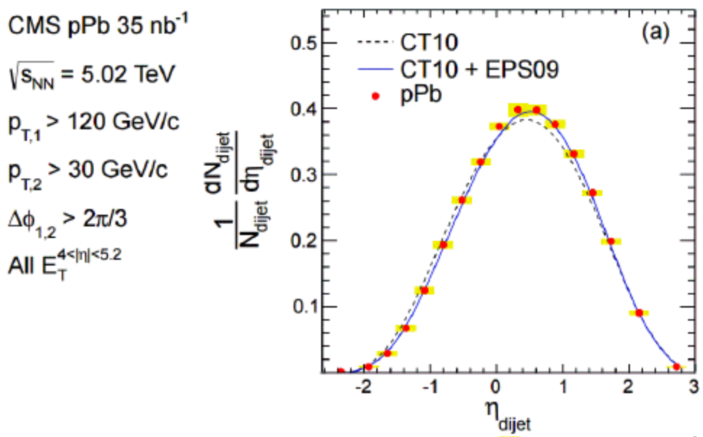
ATLAS: PLB 739 (2014) 320–342

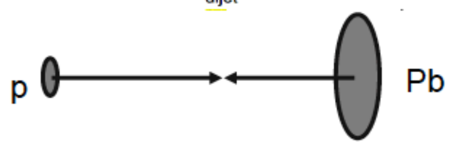
Small enhancement at large *R* and small *z:* 1-2 GeV + ~2 particles + suppression at intermediate *R* and *z*

Nuclear PDFs

With pp data at 5 TeV, nuclear PDF can be further constrained

$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2} \propto 0.5 \log\left(\frac{x_p}{x_{Pb}}\right) + \eta_{CM}$$



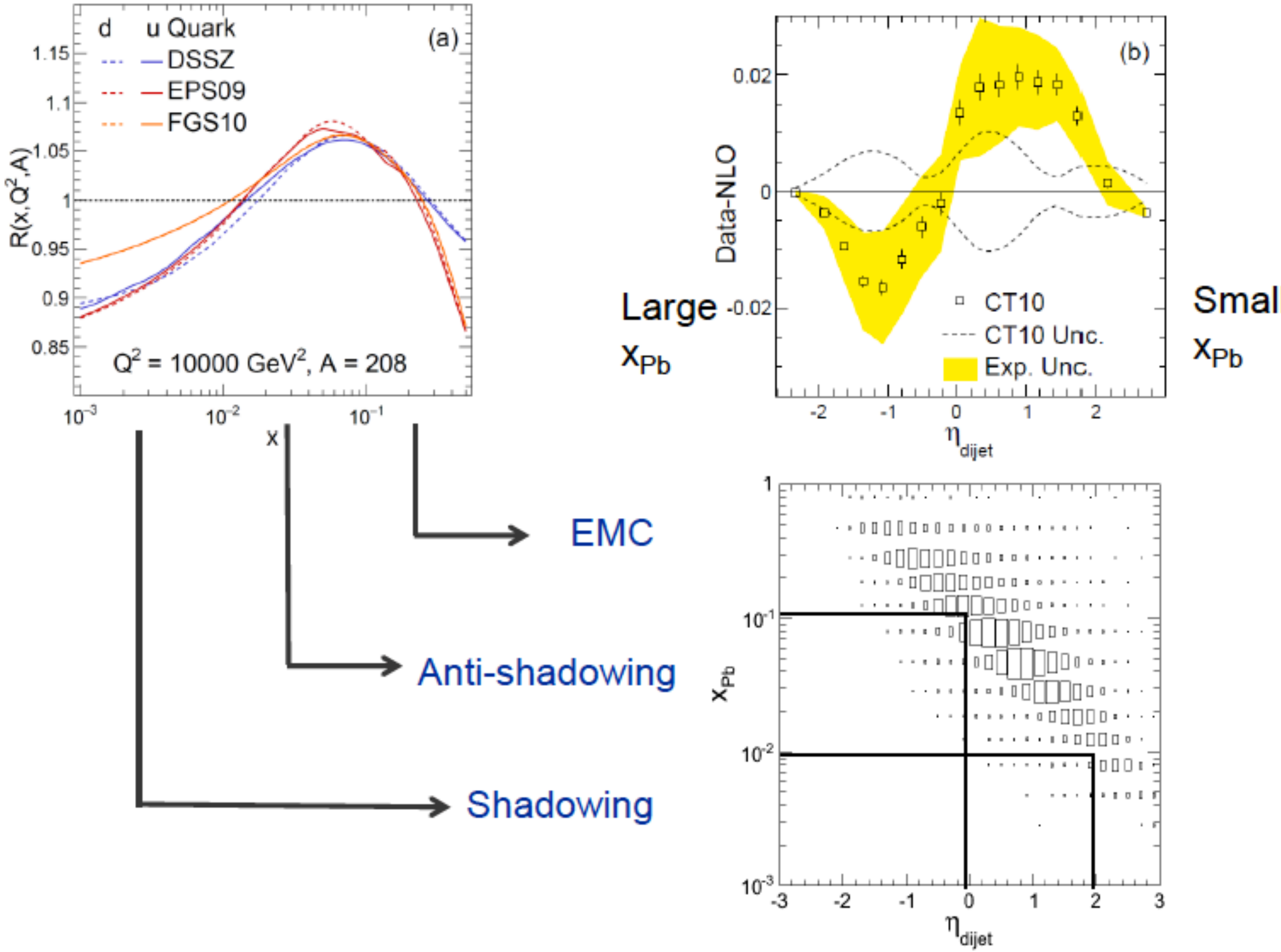


dijet

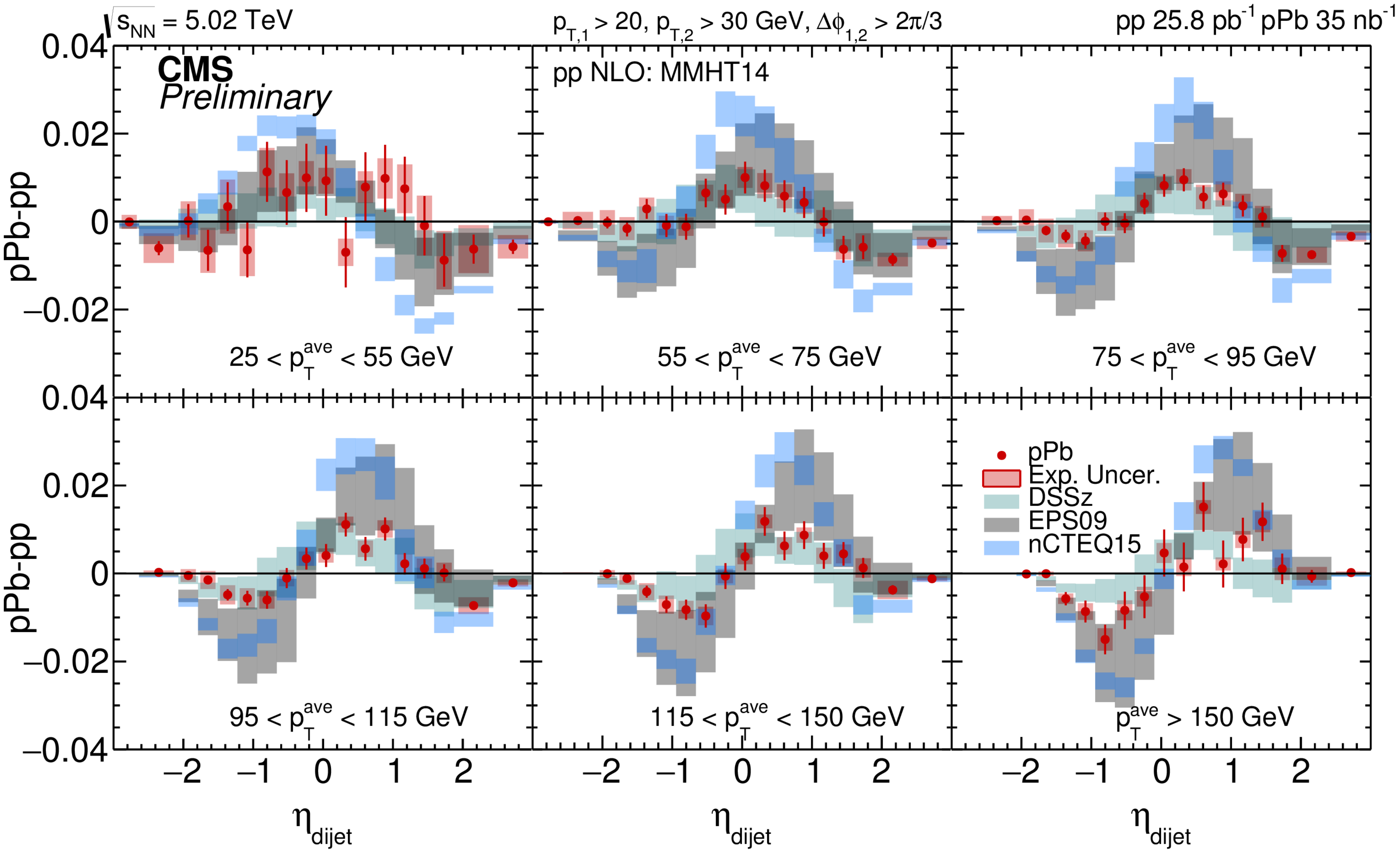
χ^2	1512.01528
PDF + nPDF	dijets$_{\rm CMS}$ (15)
CT10+DSSZ	94.441
CT10+EPS09	10.526
CT10 only	116.187
MSTW2008+DSSZ	56.365
MSTW2008+EPS09	5.522
MSTW2008 only	67.763

Using a different proton PDF changes χ^2 significantly

Mapping onto regions of x_{Pb}



Nuclear PDFs: Q^2 evolution



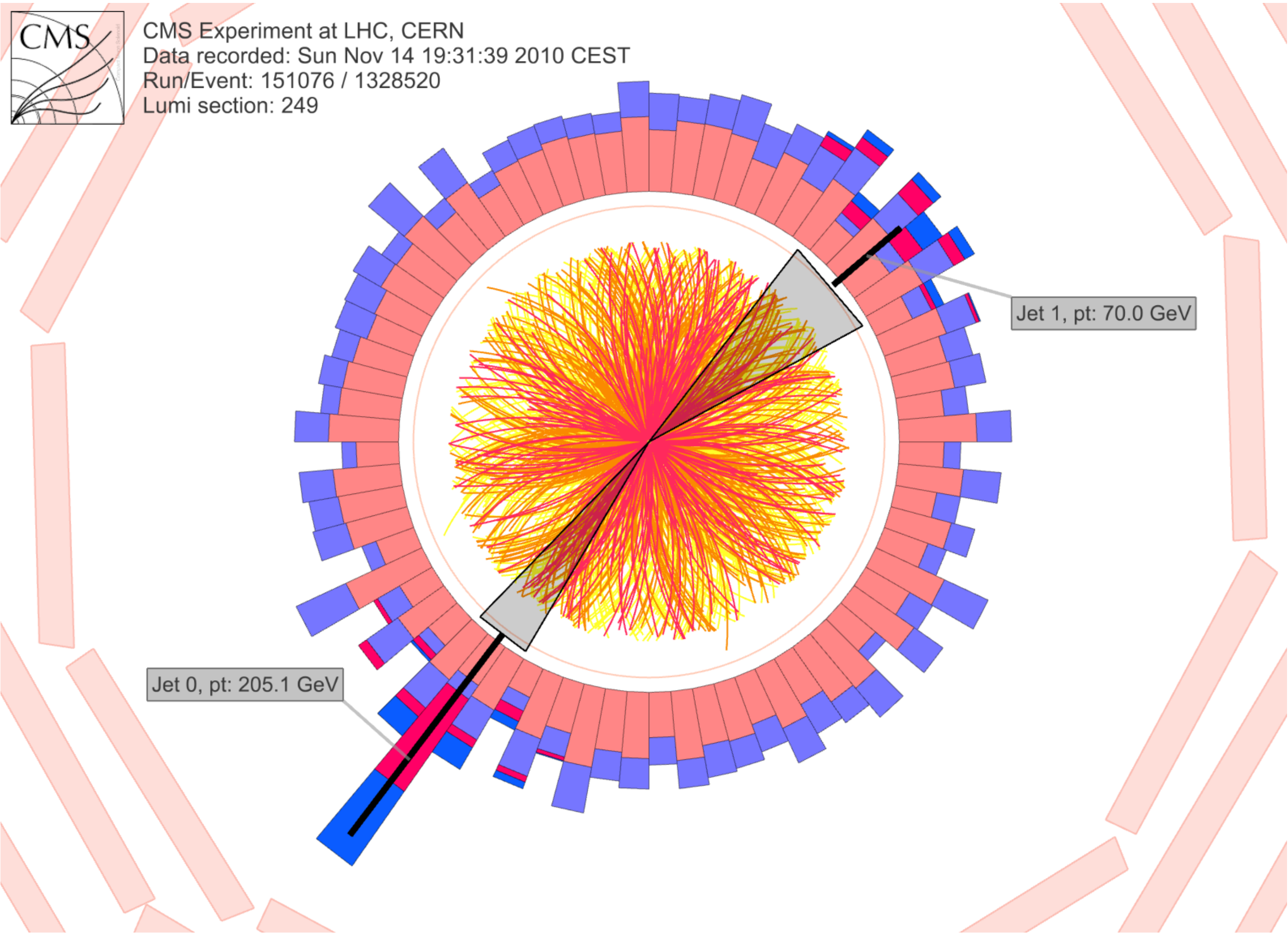
Find the jets

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]



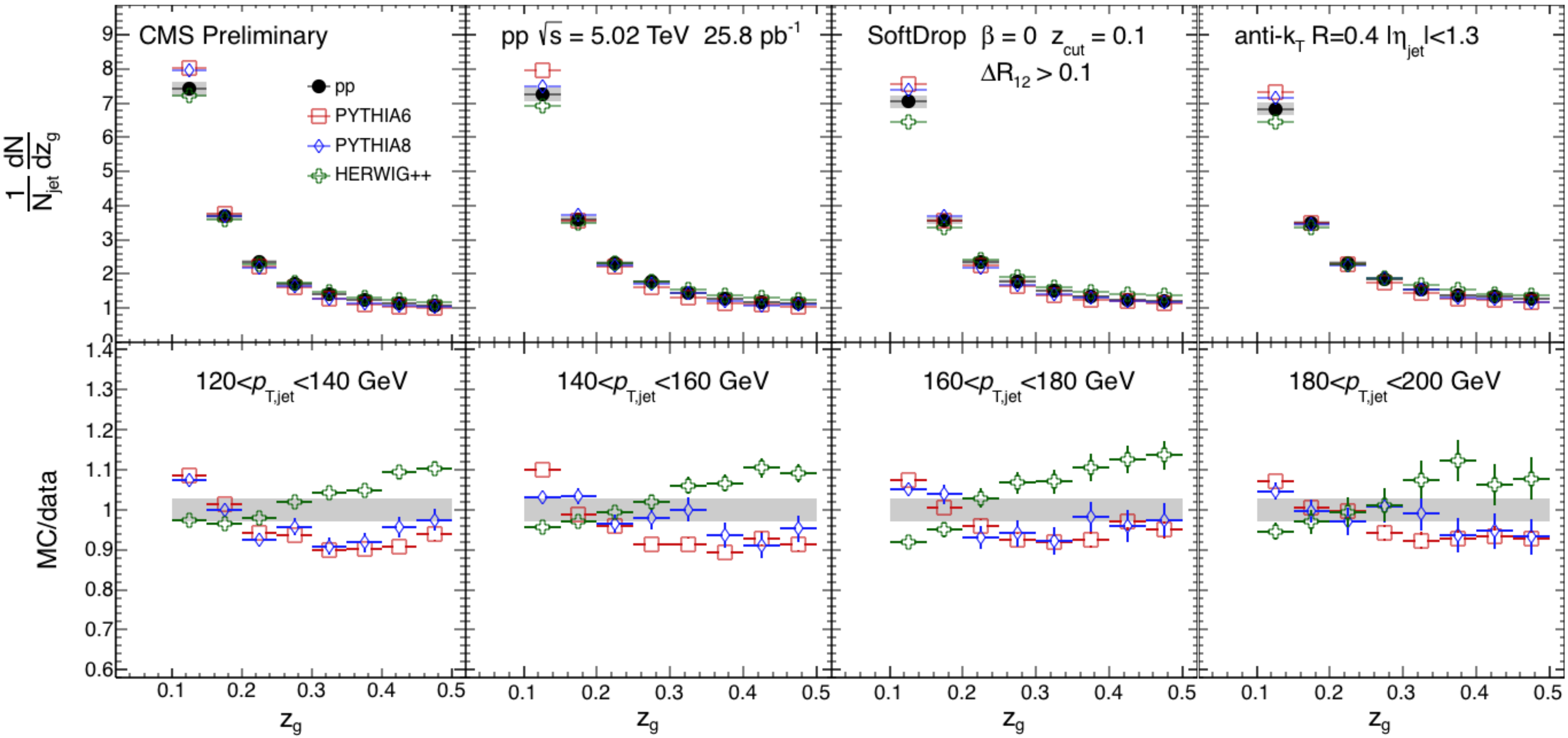
[1] Berta et al.
arXiv:1403.3108

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

CMS-PAS-HIN-16-006



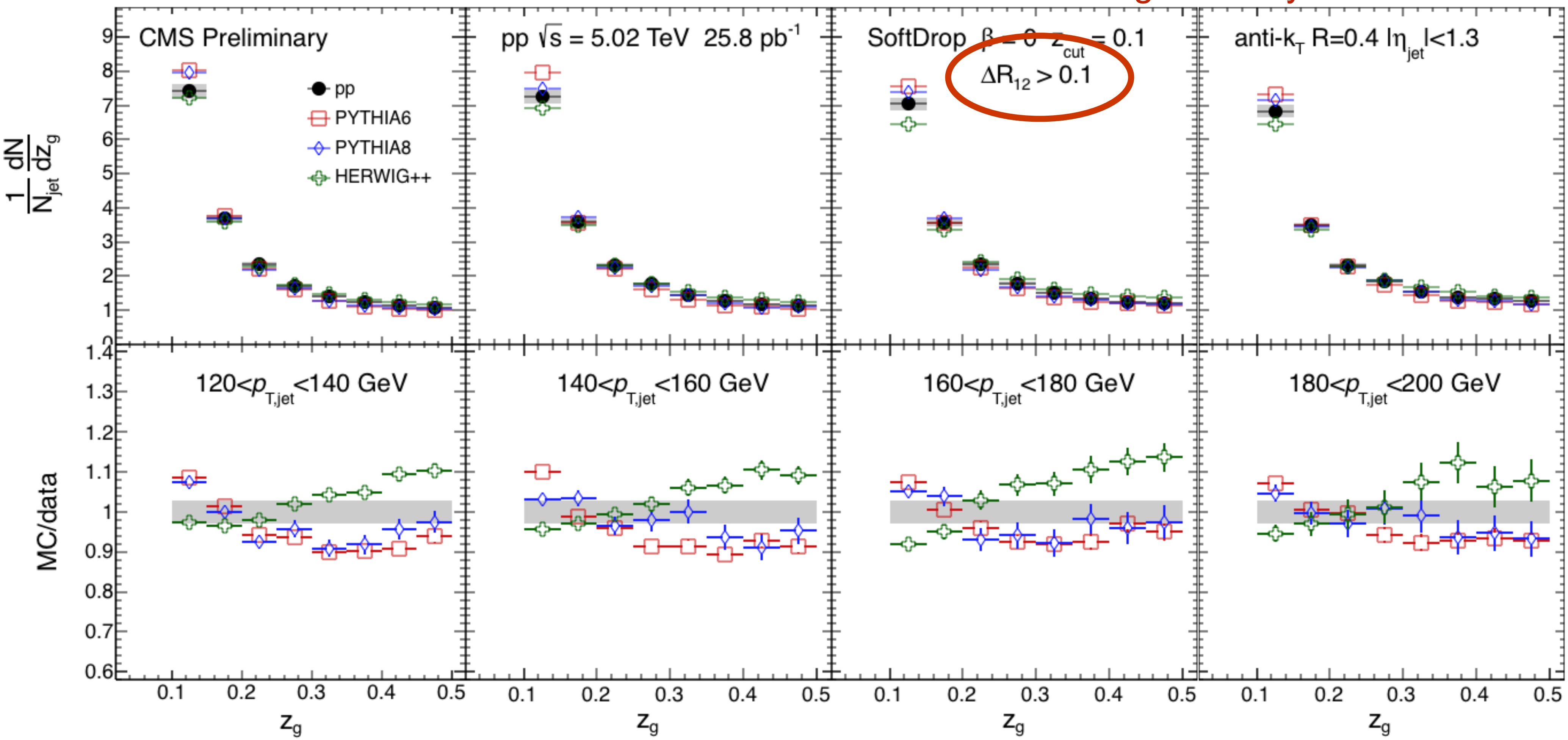
Splitting function in pp

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

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

[CMS-PAS-HIN-16-006]

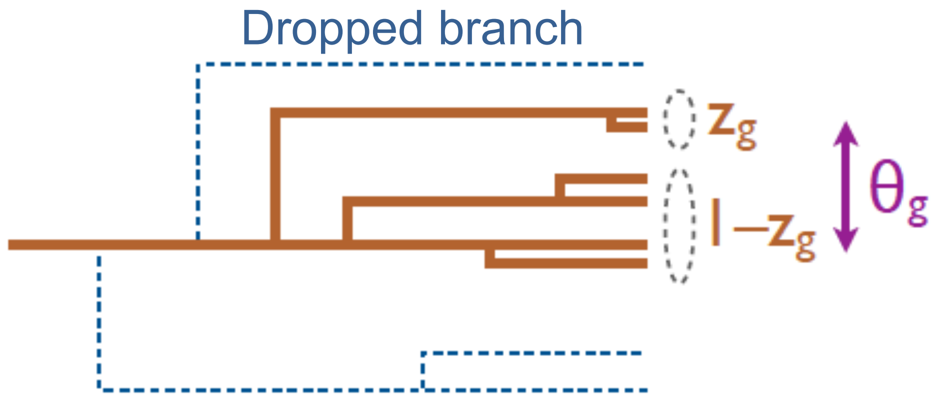
Cannot resolve subjets which are very close due to detector granularity



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



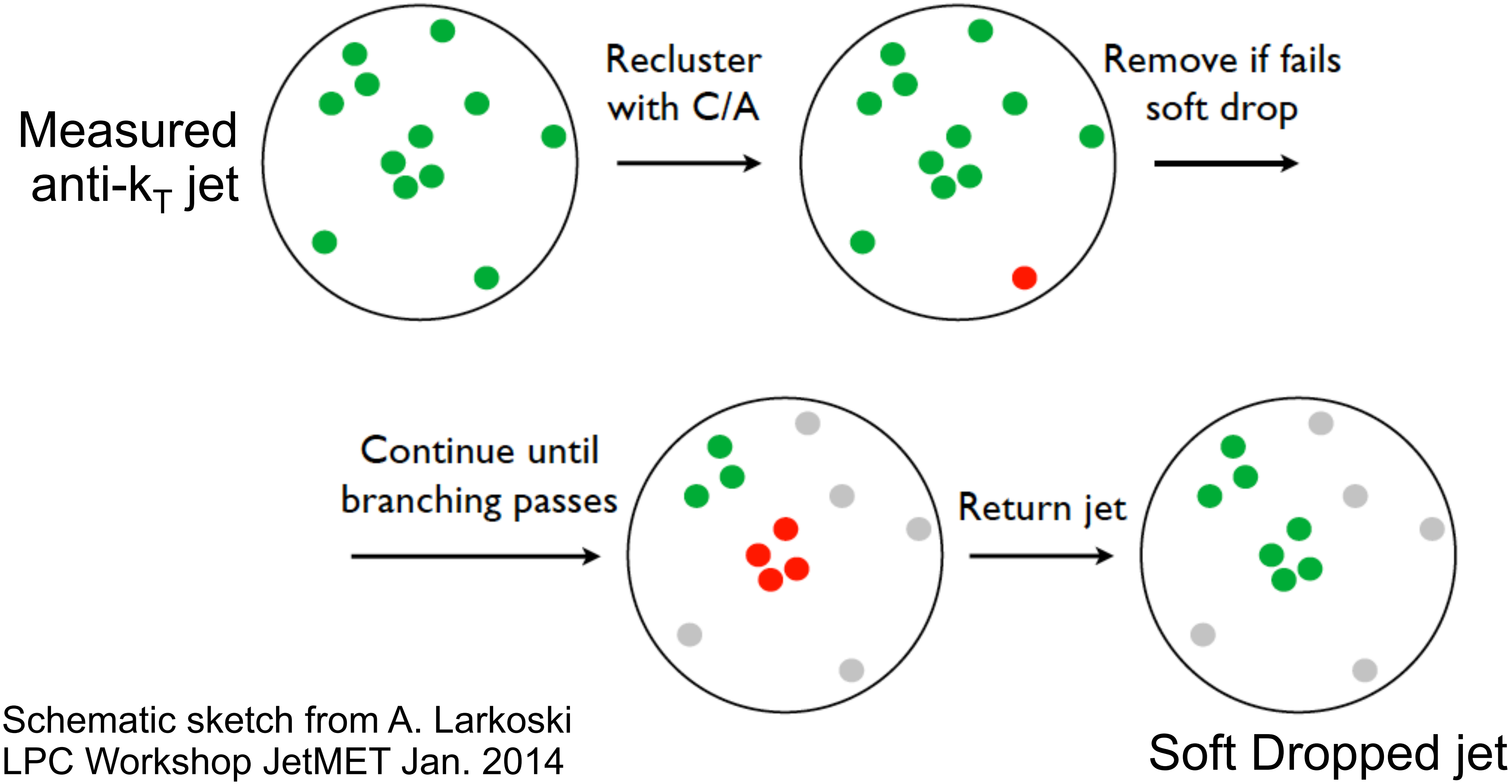
Observable is well understood analytically since all soft divergences are removed

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

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

energy threshold

angular exponent

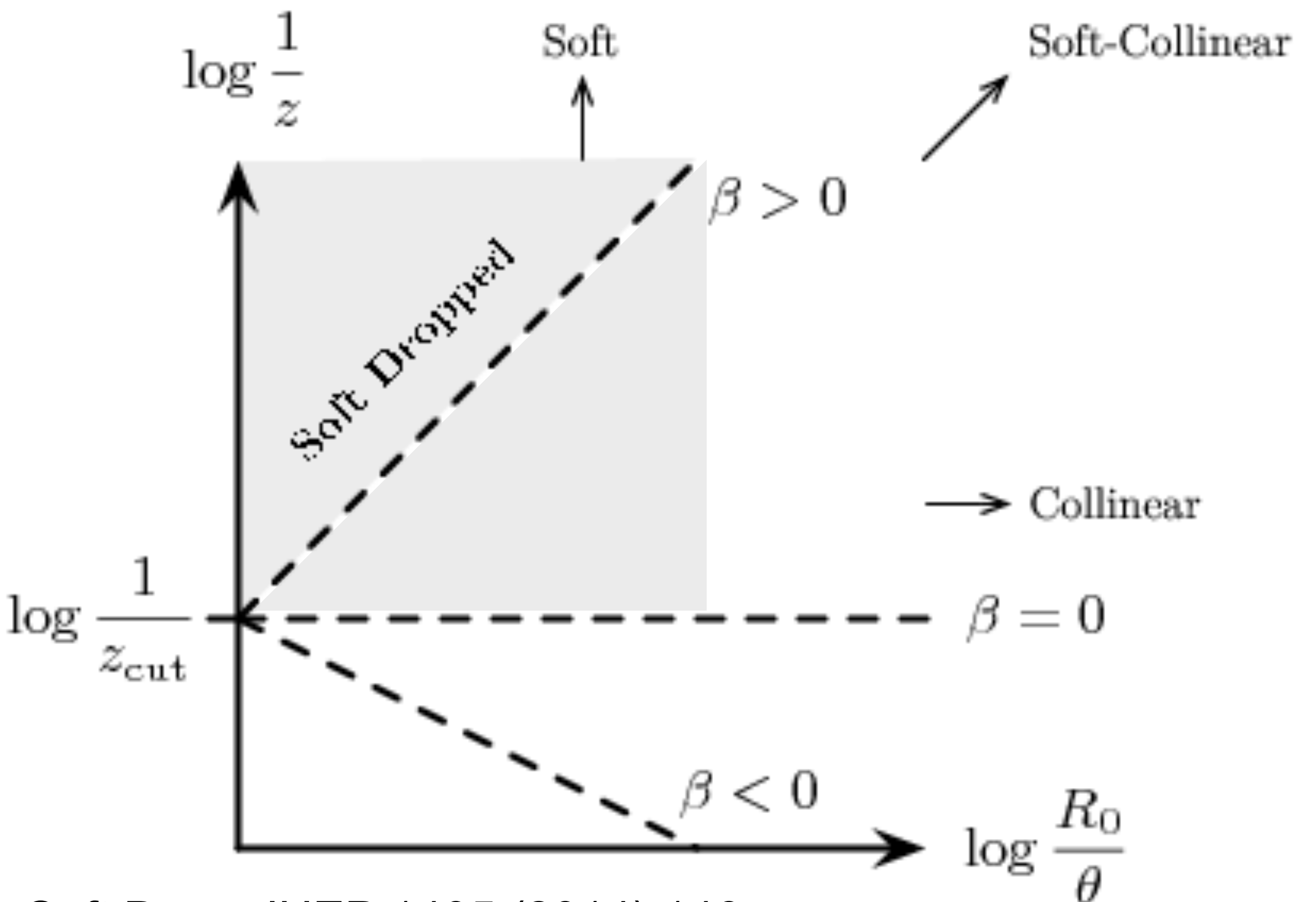
We use $\beta = 0$ and $z_{cut} = 0.1$
All soft emissions are removed
Equivalent to modified Mass Drop

$$z_{\mathrm{g}} = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}.$$

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



$$\mathrm{d}P_{i\to jk} = \frac{\mathrm{d}\theta}{\theta}\,\mathrm{d}z\,P_{i\to jk}(z)$$

Collinear singularity — Altarelli-Parisi splitting function

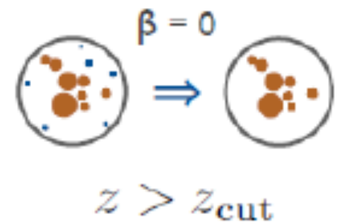
$$\frac{2\alpha_s C_i}{\pi}\,\frac{\mathrm{d}\theta}{\theta}\,\frac{\mathrm{d}z}{z}$$

Soft Drop: JHEP 1405 (2014) 146

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

Generalized fragmentation function

Measurement of QCD splitting function



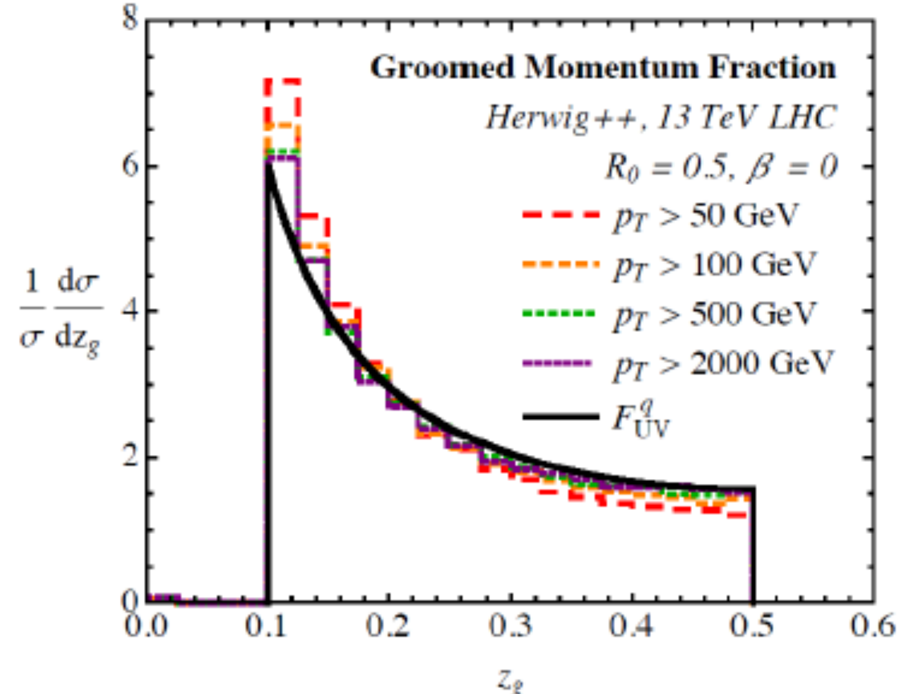
Momentum sharing between two leading subjets:

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

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?