Experimental opportunities with jet structure measurements

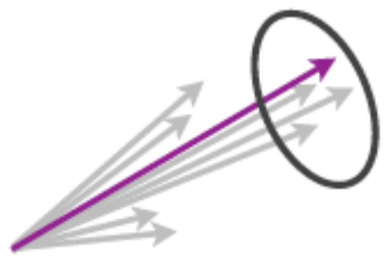
Marta Verweij (CERN)

October 2016
Boston
Heavy ions in the 2020s

The Broader Lesson

By Jesse Thaler

Fragmentation Functions



Single hadron

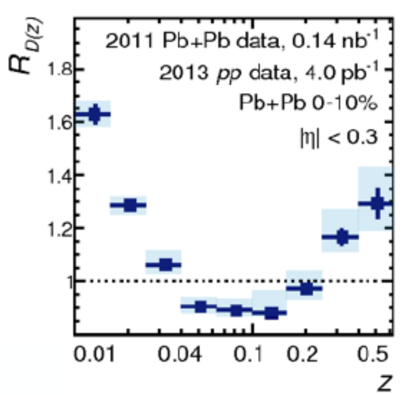
Classic Jet Shapes

All hadrons

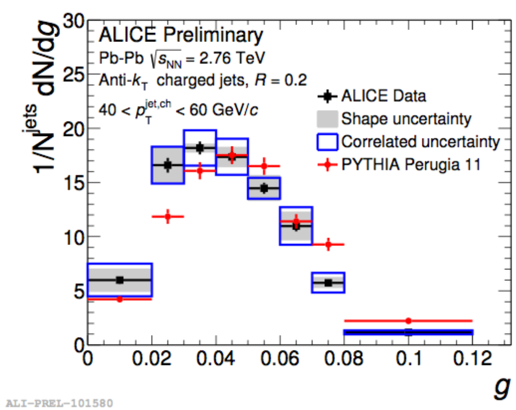
Groomed Observables

Subset of hadrons

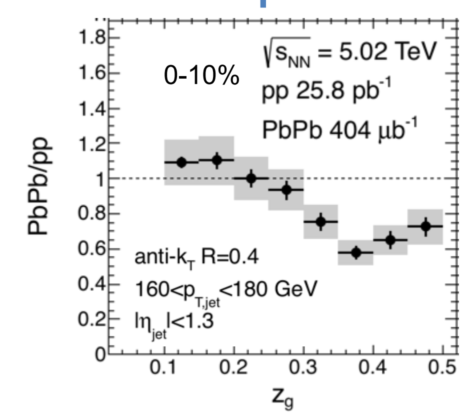
Done in AA



Some done in AA



First steps taken

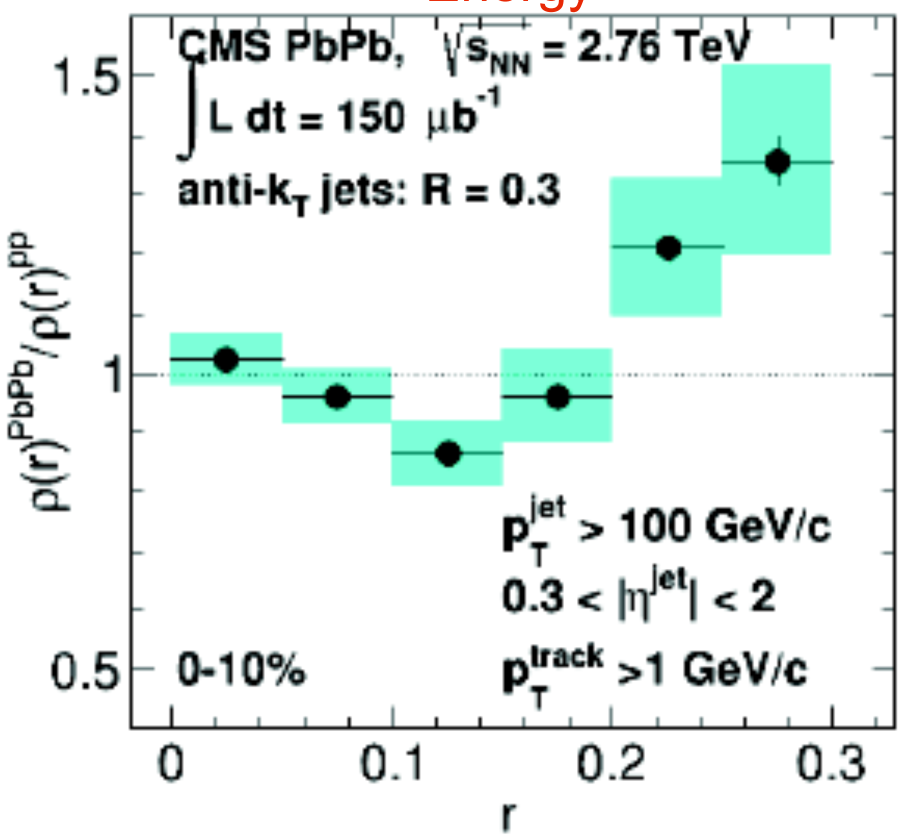


Looking inside the jet

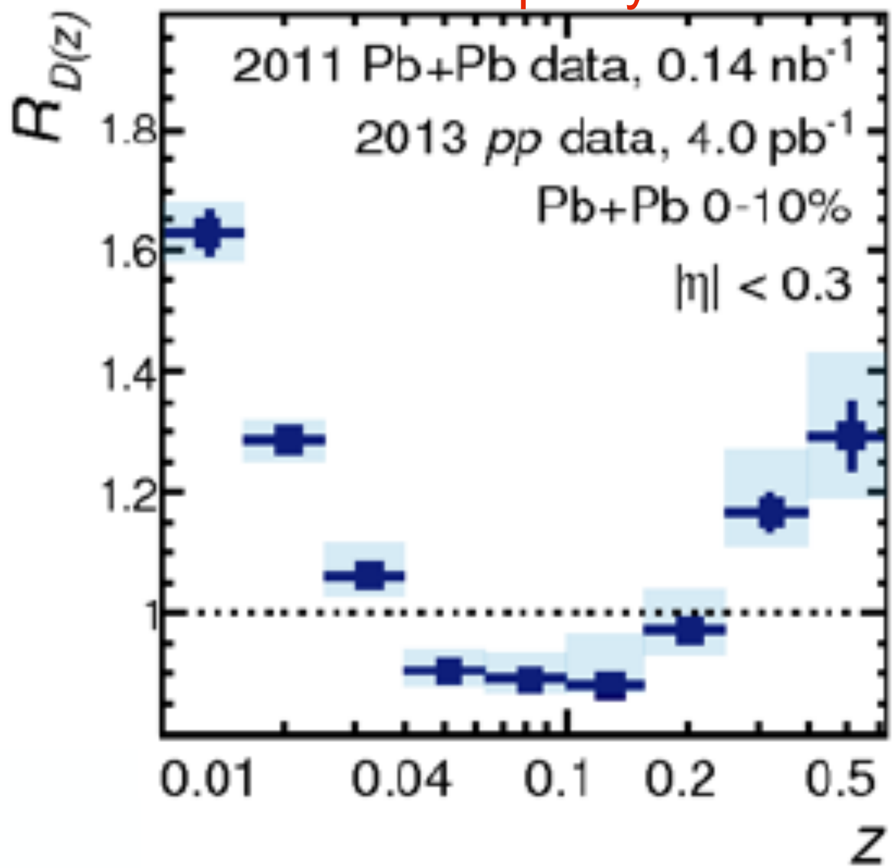
Jet shape observables: energy + multiplicity distributions within a jet
Sensitive to the dynamics of parton shower

Radial profile
Transverse fragment distribution
Energy

CMS PLB 730 (2014) 243



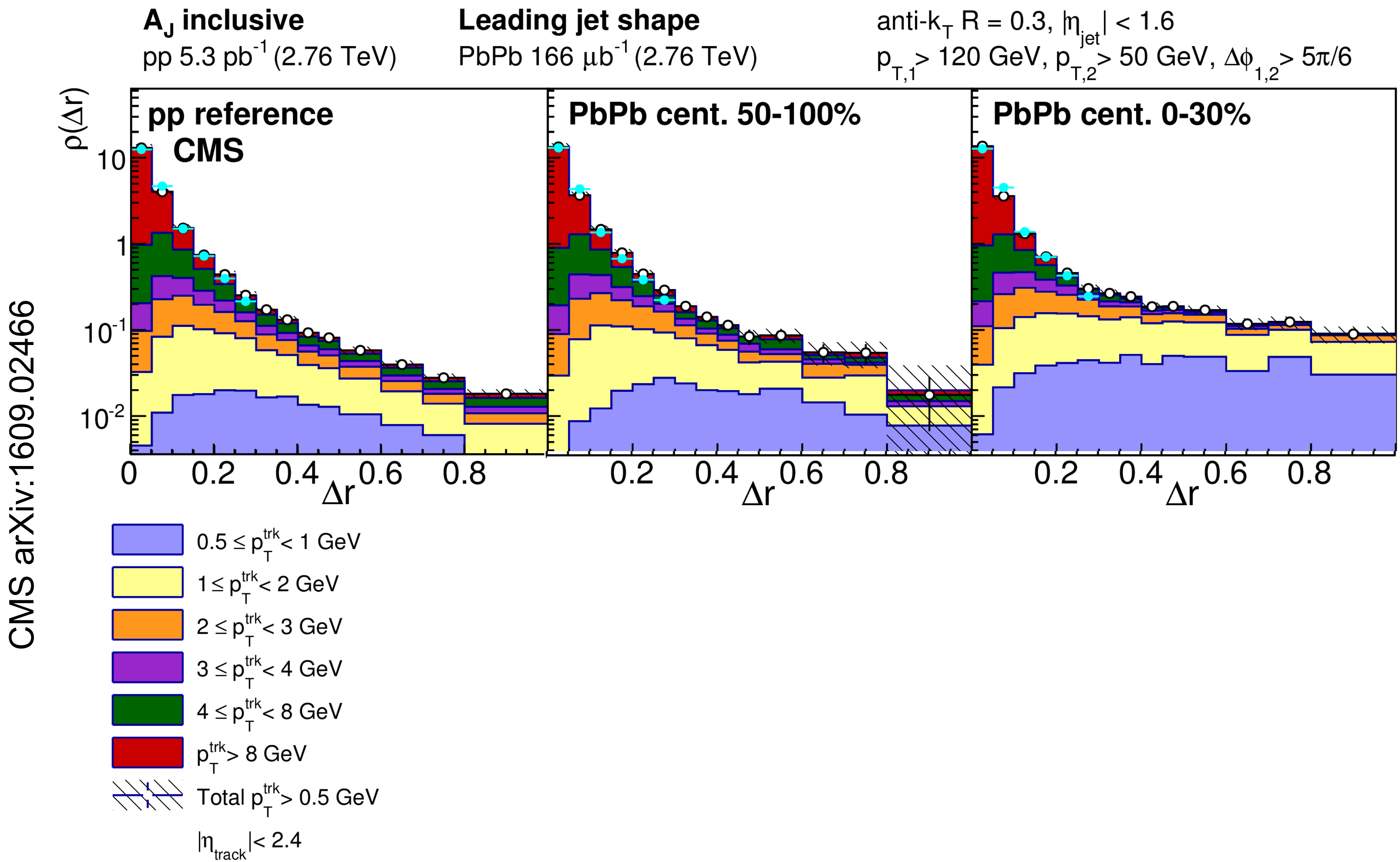
'Fragmentation function'
Longitudinal fragment distribution
Multiplicity



ATLAS-CONF-2015-055

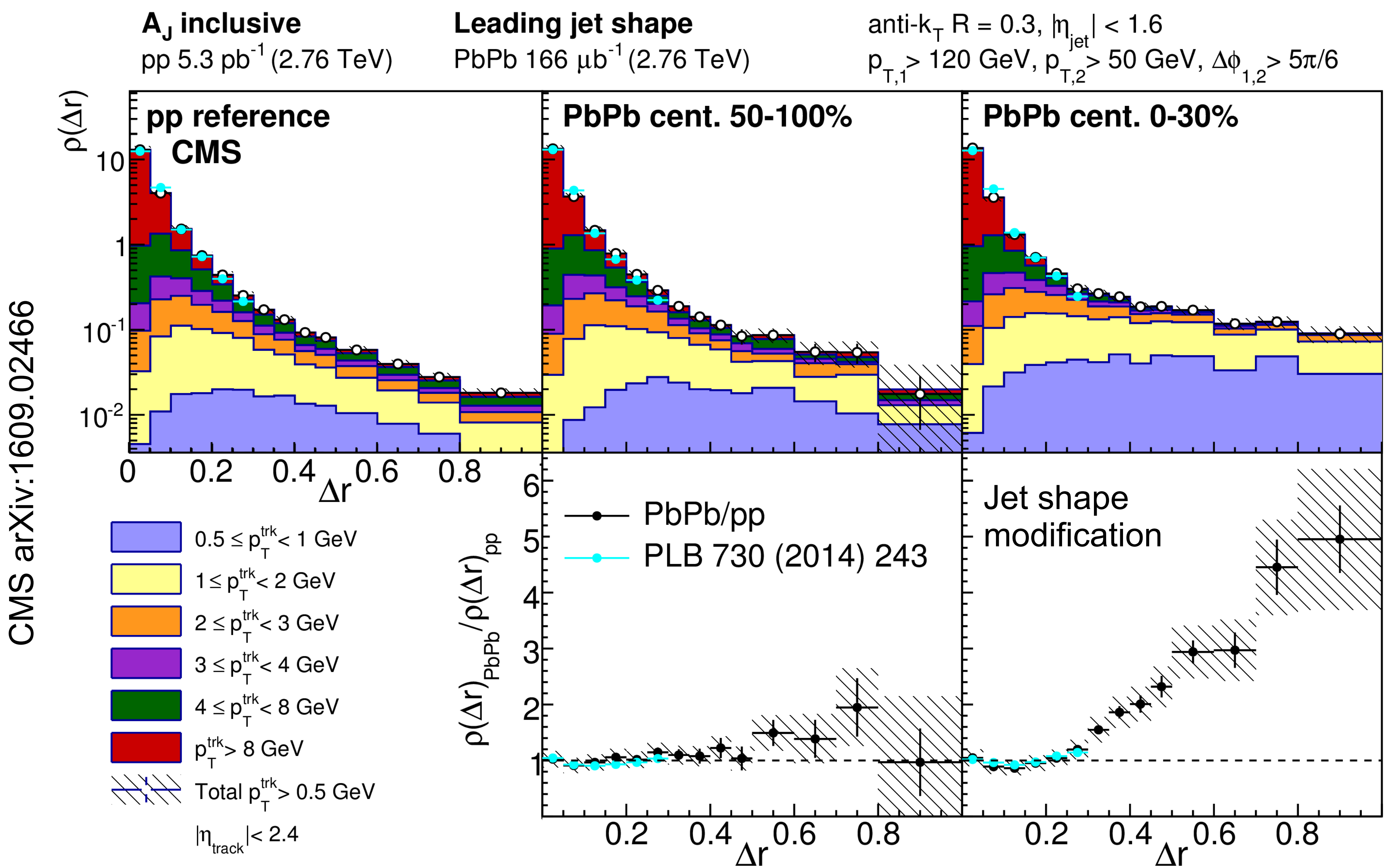
Small enhancement at large *R* and small ξ: 1-2 GeV + ~2 particles
+ suppression at intermediate *R* and ξ

Jet shape at large angle



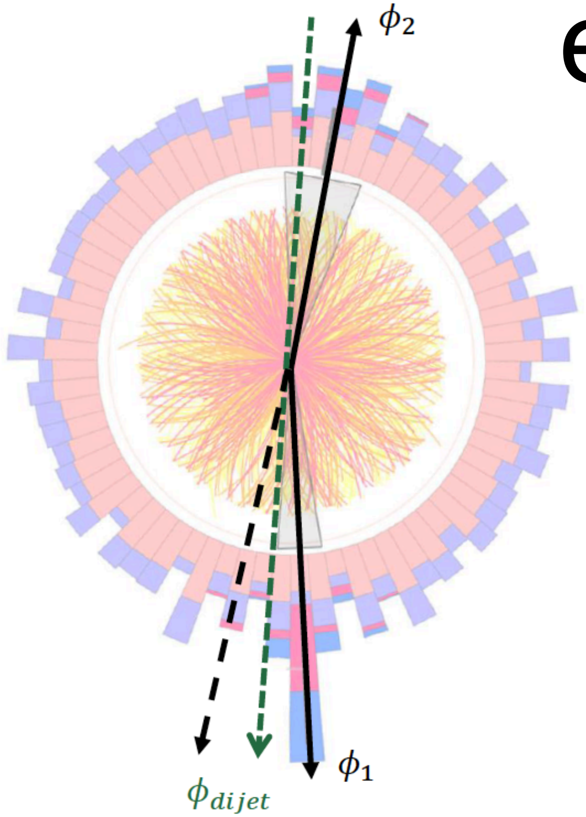
Missing energy from jet is recovered at very large distance from jet

Jet shape at large angle



Missing energy from jet is recovered at very large distance from jet

Jet superstructure and global event shapes



Missing p_T

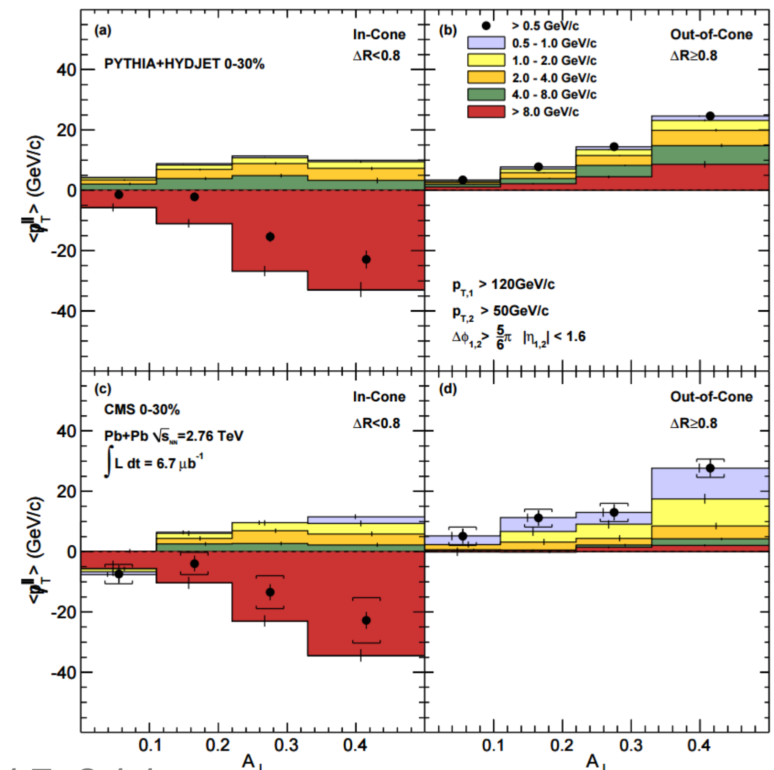
projection of the p_T of charged particles onto the azimuthal dijet axis

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\rm Dijet}\right)$$

In-cone $\Delta<0.8$ | Out-of-cone $\Delta>0.8$

MC

Data



The effects of jet quenching persist up to large angles

The global event shape is modified and not only inner-jet properties

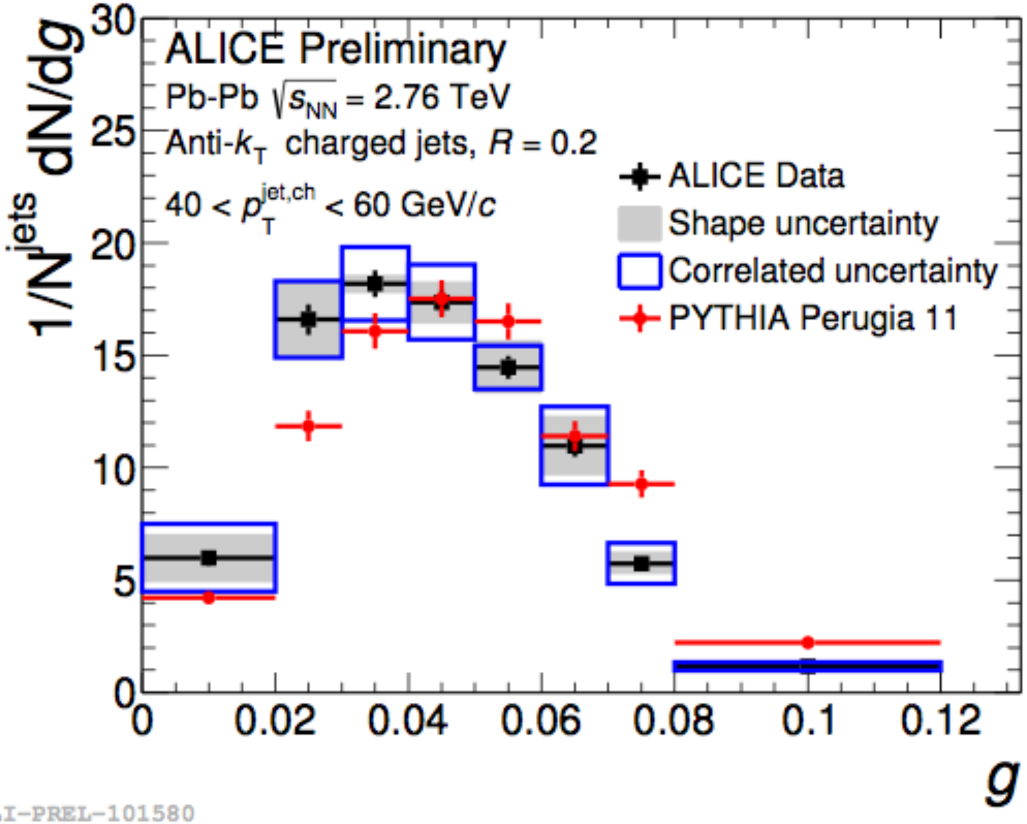
More detailed studies: HIN-14-010, HIN-14-016, HIN-15-011

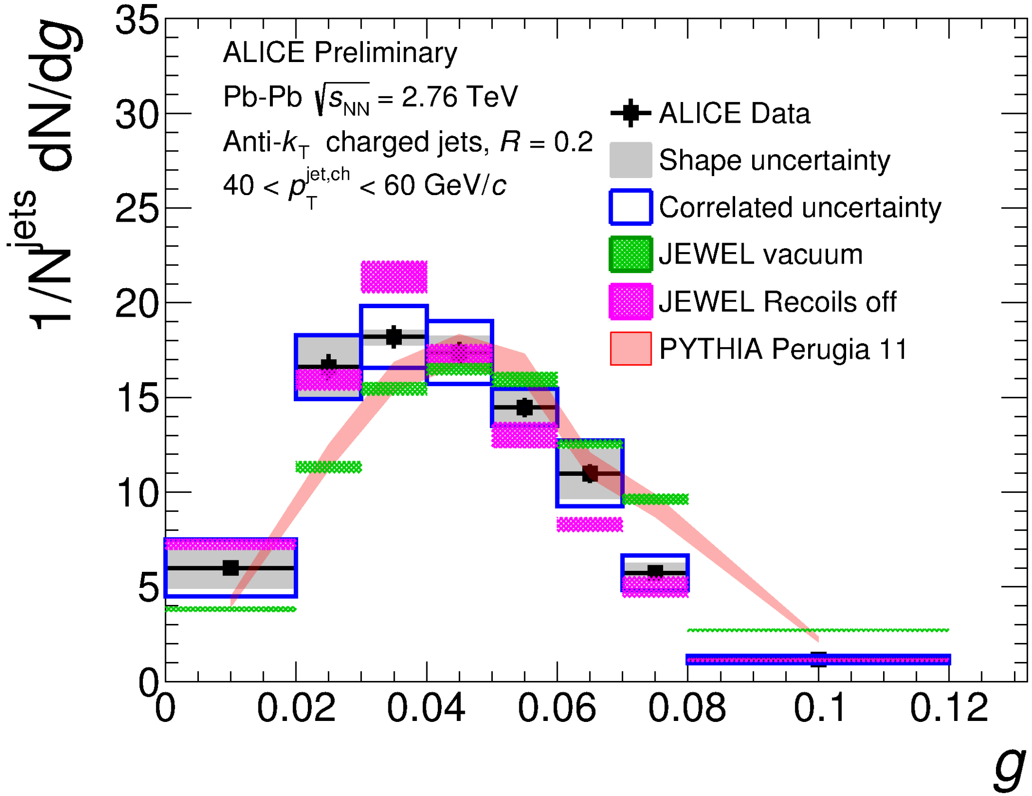
arXiv:1102.1957

Jet shapes: jet width

p_T-weighted jet width $\quad g \equiv \frac{\sum_{\text{tracks}} p_{T,i}\, r}{p_{T,\text{jet}}}$

Small jets: R=0.2





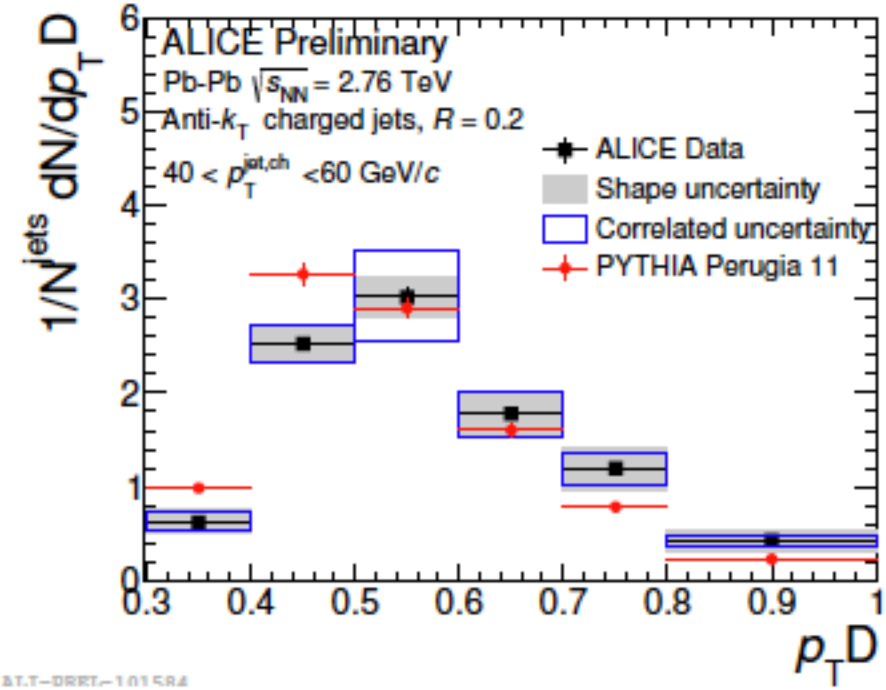
Jet width smaller in Pb+Pb than pp (PYTHIA)

JEWEL model shows similar trend

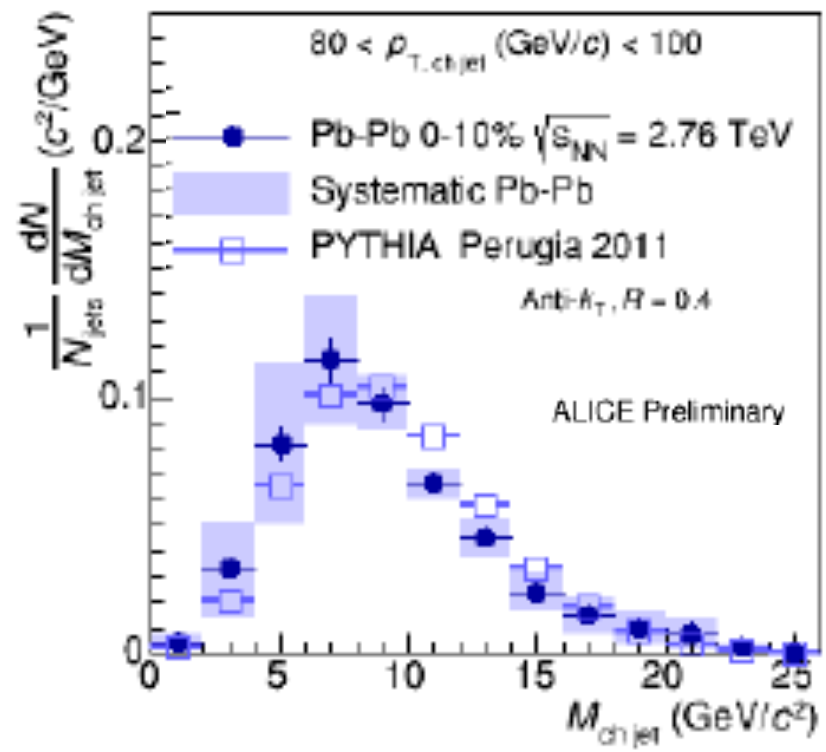
Jets in medium narrower than in vacuum
But… comparing at same jet p_T – after energy loss

Jet shapes: mass and p_{TD}

p_{TD}
R=0.2



Jet mass
R=0.4



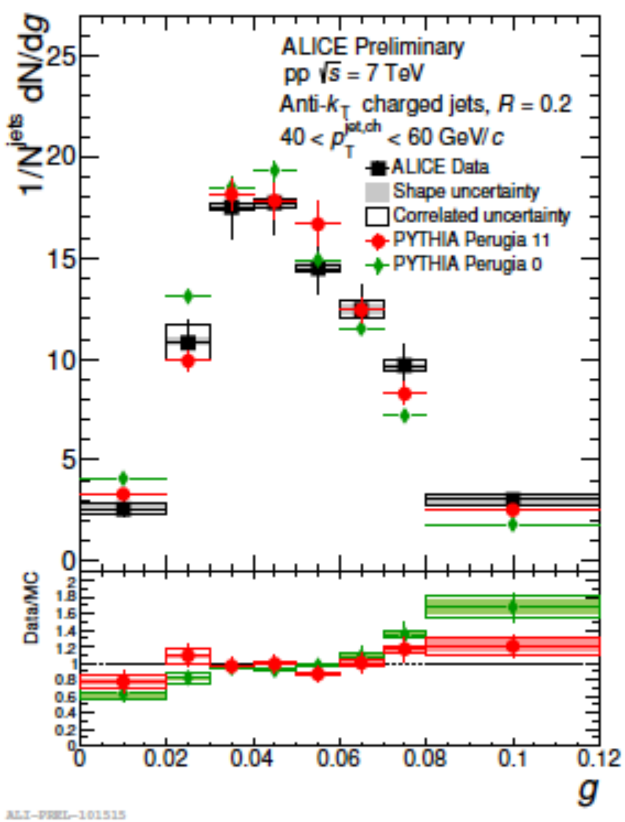
$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

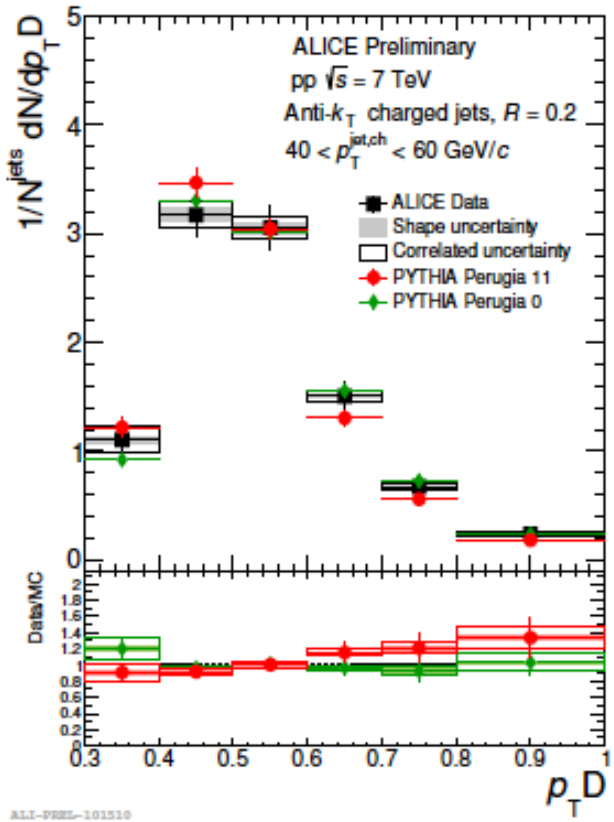
Also p_{TD} and mass consistent with collimation of jet core

All wrt PYTHIA with PYTHIA validation using pp/pPb data at different √s

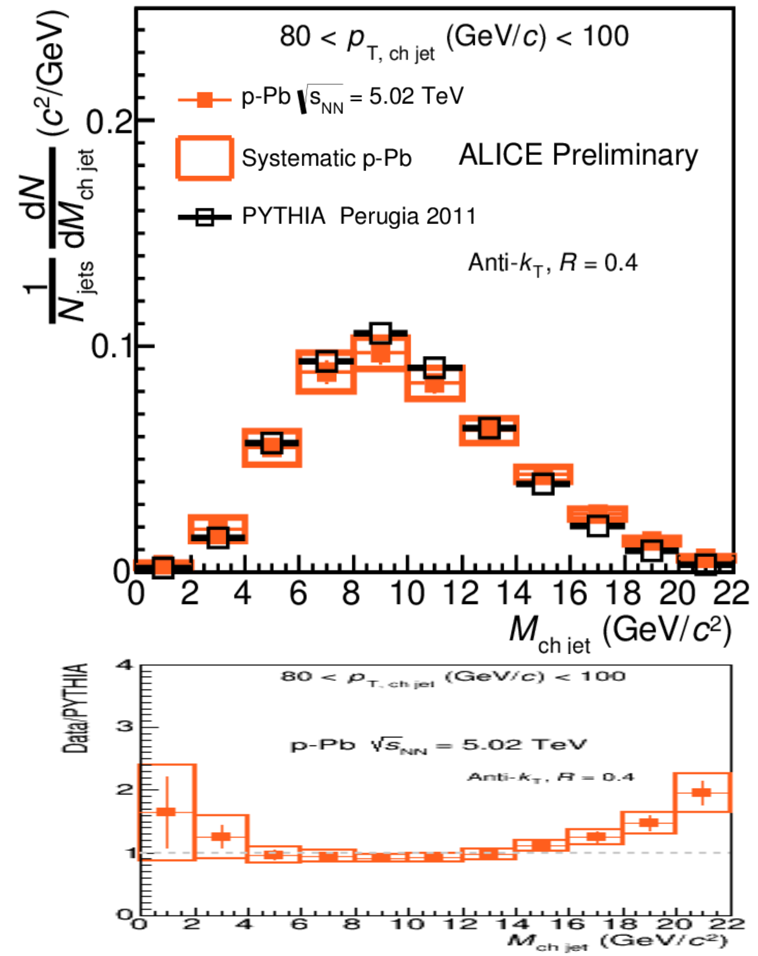
Jet shapes in reference data

Jet width and p_{TD} in 7 TeV pp





Jet mass in 5.02 TeV pPb



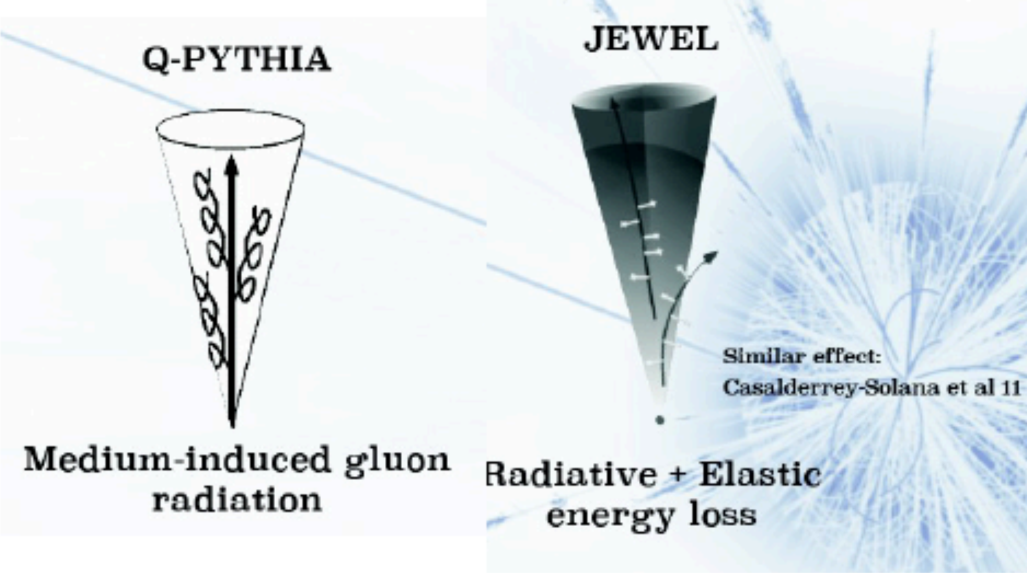
The agreement isn’t great

PYTHIA is actually closer to PbPb data
than what you would observe with a measured pp reference

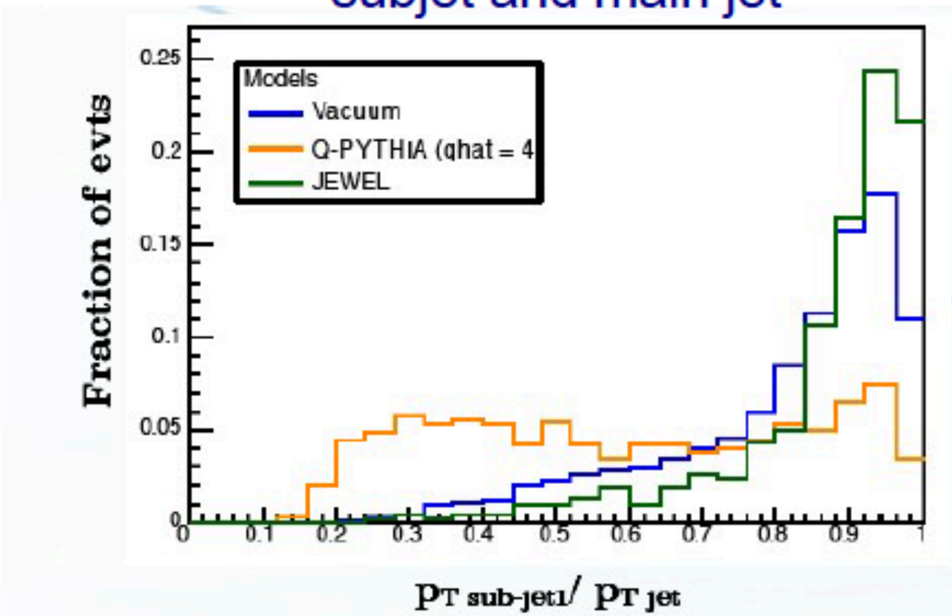
Subjets

Sensitive to jet quenching
Different model predictions
→ as for all jet structures

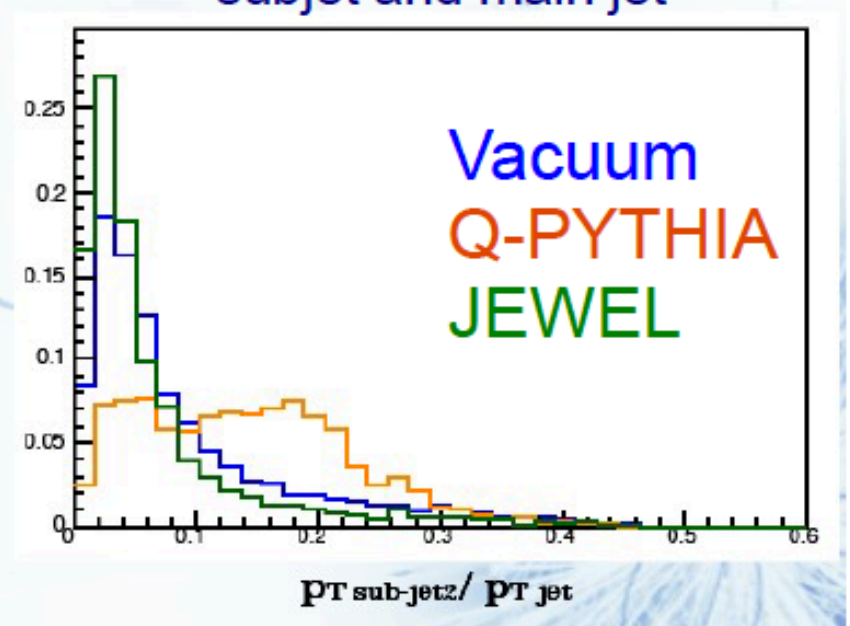
Can be used to validate models
and tag quenched jets



Ratio between p_T of leading subjet and main jet



Ratio between p_T of subleading subjet and main jet



L. Apolinario, X. Zhang, Quark Matter 2014

Subjets: reclustered in the big jet. Very different from groomed jets

Groomed jet observables

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

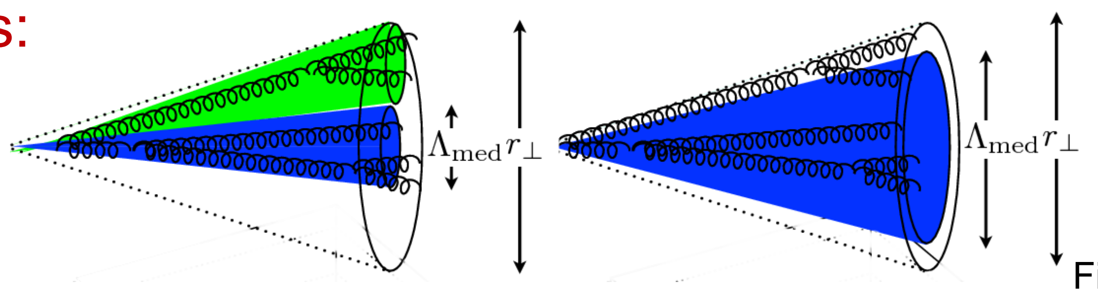
Goal: understand the evolution of the parton shower in medium

Several scenarios proposed by theorists before measurement was done

Examples:

- 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



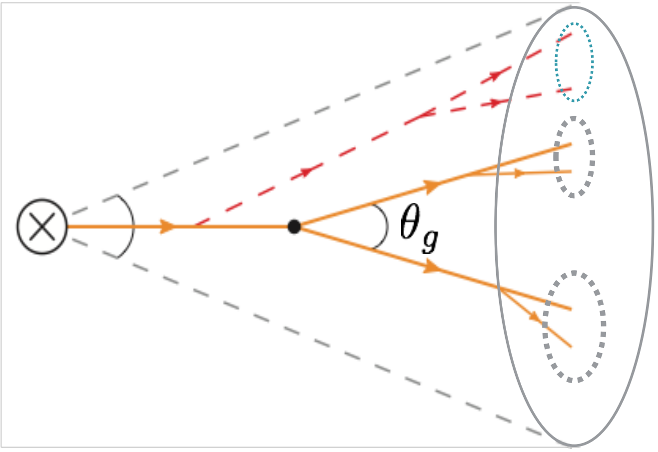
1 coherent emitter: color connected subjets

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

Jet splitting function

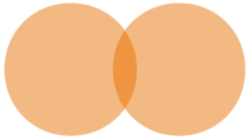
$$d\sigma^{vac}_{DGLAP} \sim \frac{\alpha_s}{z}$$

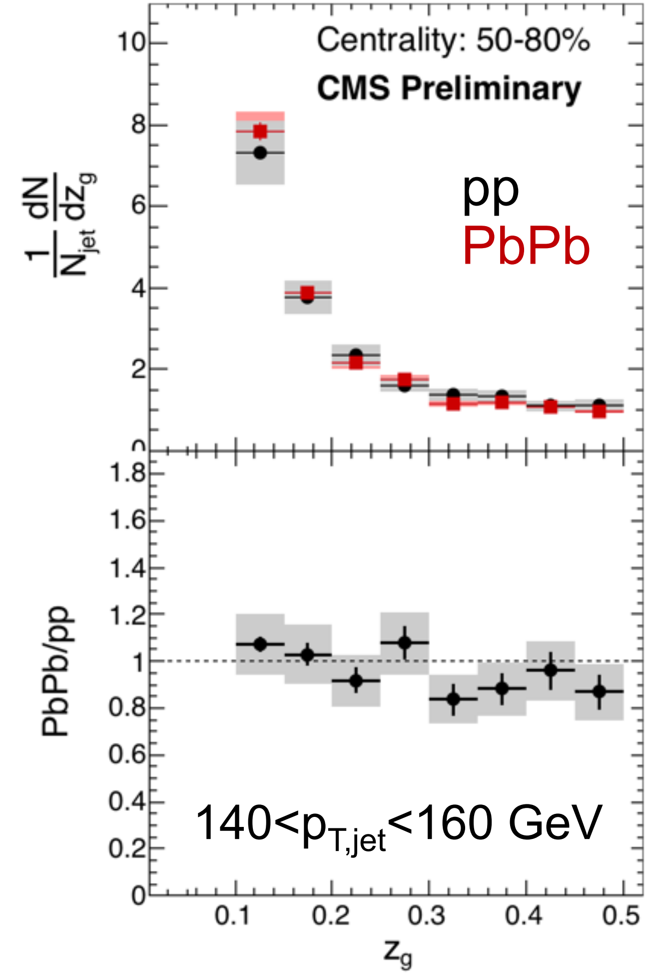
With groomed jets (SoftDrop): soft large angle radiation removed to define the hardest splitting



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

Peripheral collisions





Observable: Momentum fraction carried by the subleading branch of first splitting

Weak dependence on α_s

Weak dependence on jet p_T

The same for quarks and gluons
→ Energy loss changing q/g fraction irrelevant

Peripheral PbPb and pp very similar

Larkoski, Marzani, Thaler
Phys. Rev. D91:111501 (2015)

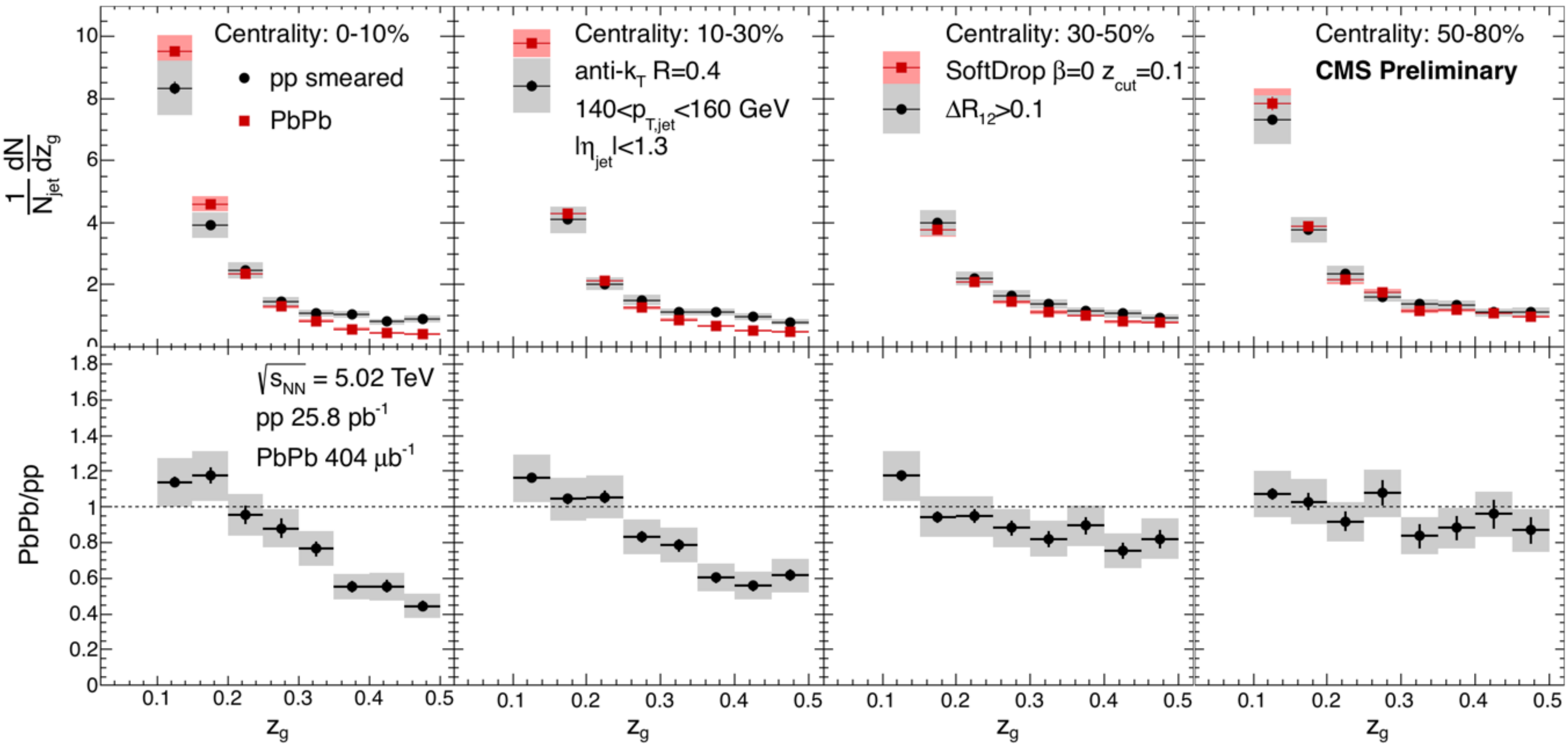
CMS-PAS-HIN-16-006

CMS-PAS-HIN-16-006

PbPb vs pp

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

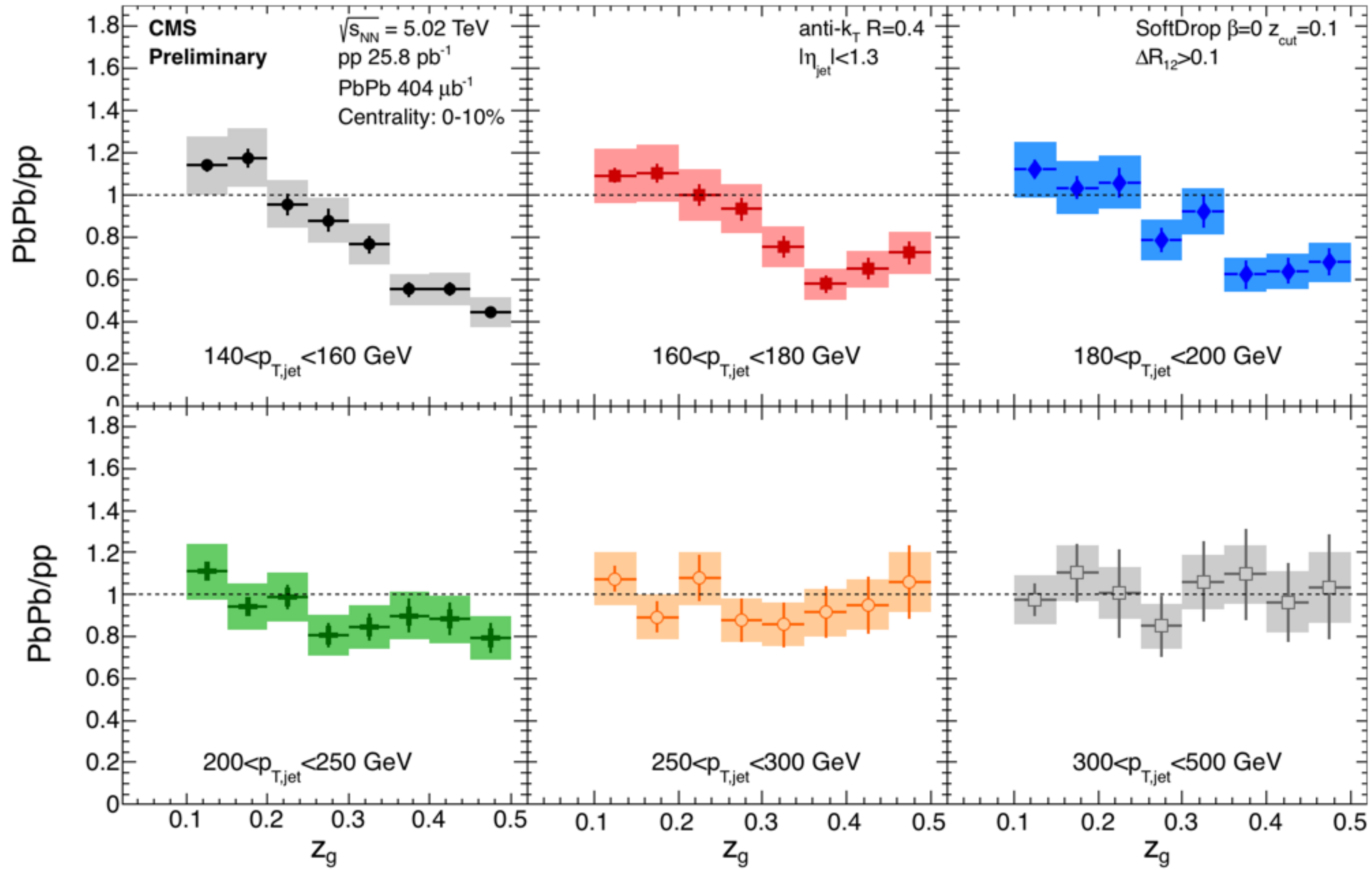
Central collisions → Peripheral collisions



Modification of subjet balance 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

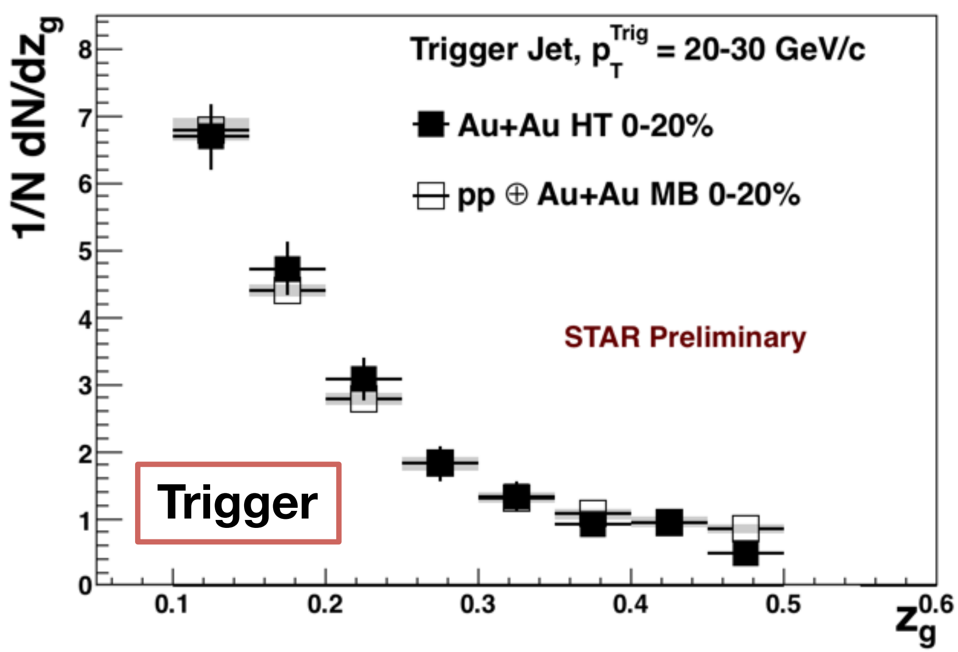
STAR z_g

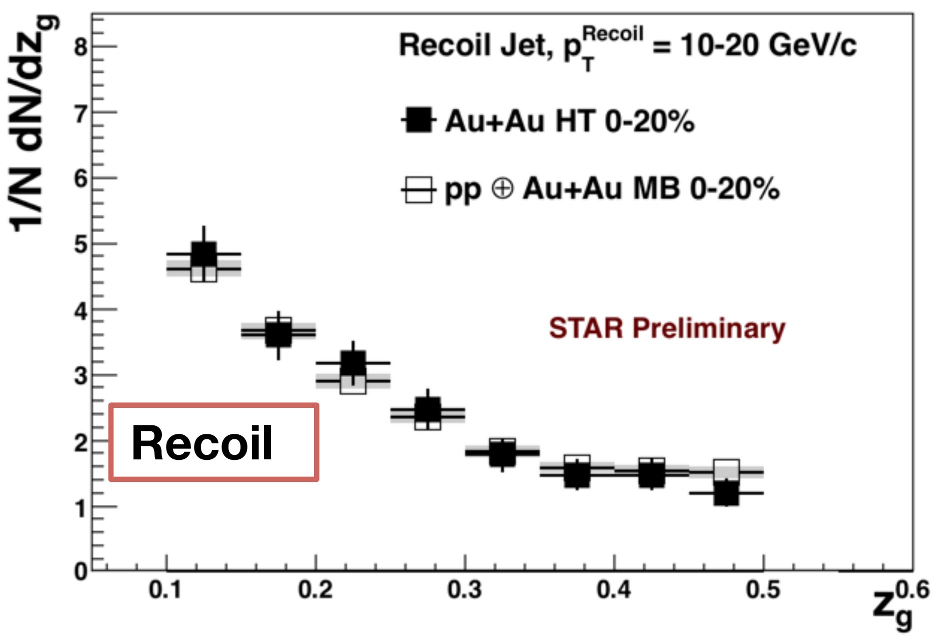
No difference between AuAu and pp!

Inconsistent with CMS? No, very different measurement

Low p_T jets, biased by trigger requirement

Large vacuum formation time (~10 fm, outside medium)



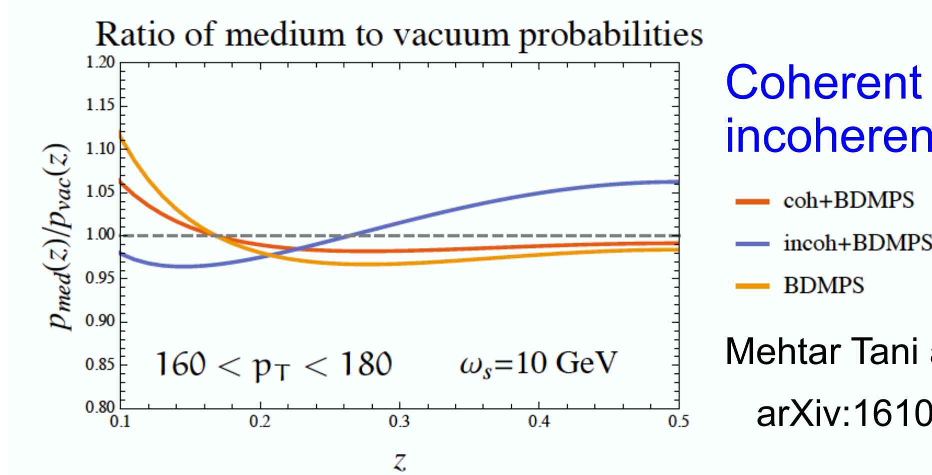


z_g – theory response

A lot of excitement

Grooming jets has potential

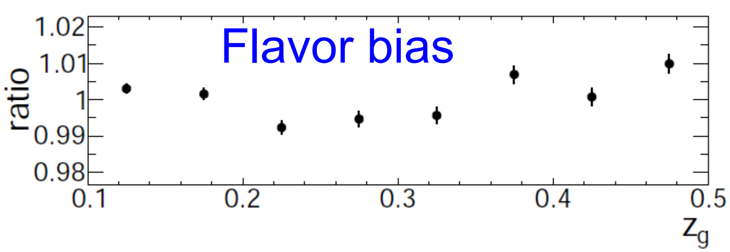
To be seen how it constrains the medium properties



Coherent vs incoherent emitters

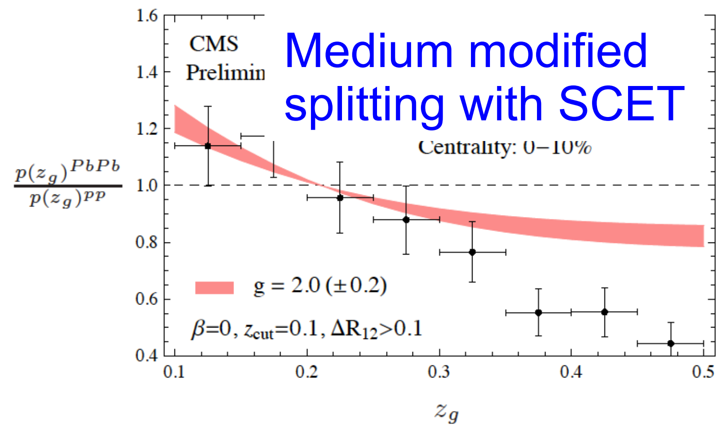
Mehtar Tani and Tywoniuk arXiv:1610.08930

M Spousta

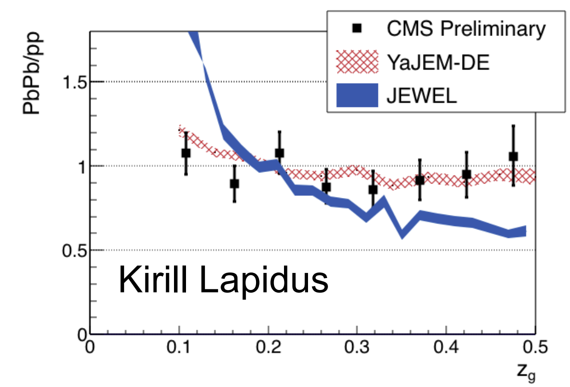


Flavor bias

Chien and Vitev. arXiv:1608.07283

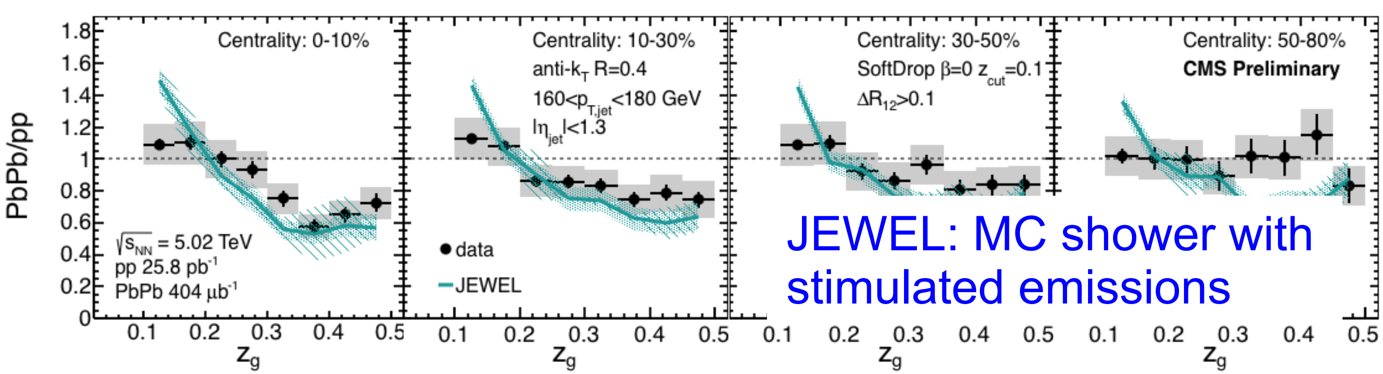


Medium modified splitting with SCET

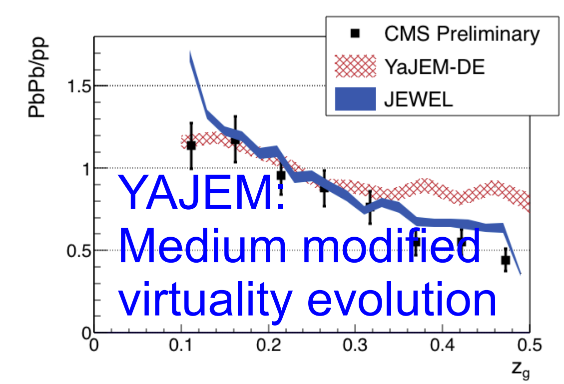


Kirill Lapidus

R. Kunnawalkam Elayavalli and K. Zapp

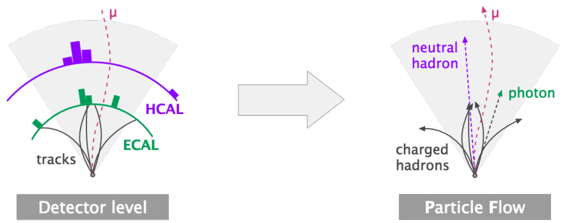


JEWEL: MC shower with stimulated emissions



YAJEM! Medium modified virtuality evolution

Analysis techniques: CMS z_g



UE removal before grooming to reduce the probability that you pick up a background blob

Particle flow candidates

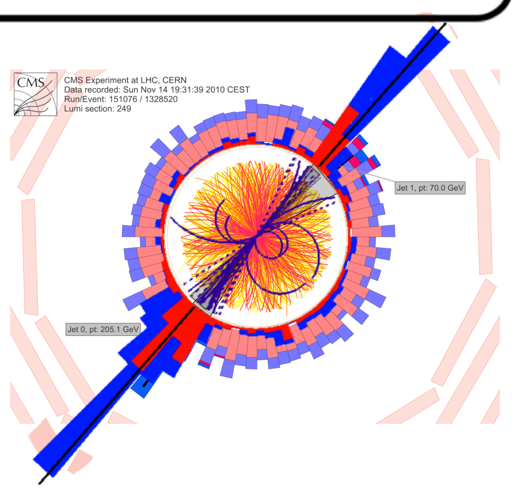
k_T jet finding

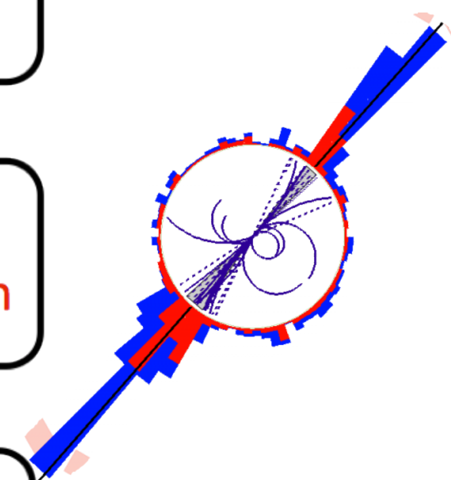
Background densities
from k_T jets
in eta slices

Anti-k_T jet finding

UE removal
Constituent subtraction

Grooming
with SoftDrop

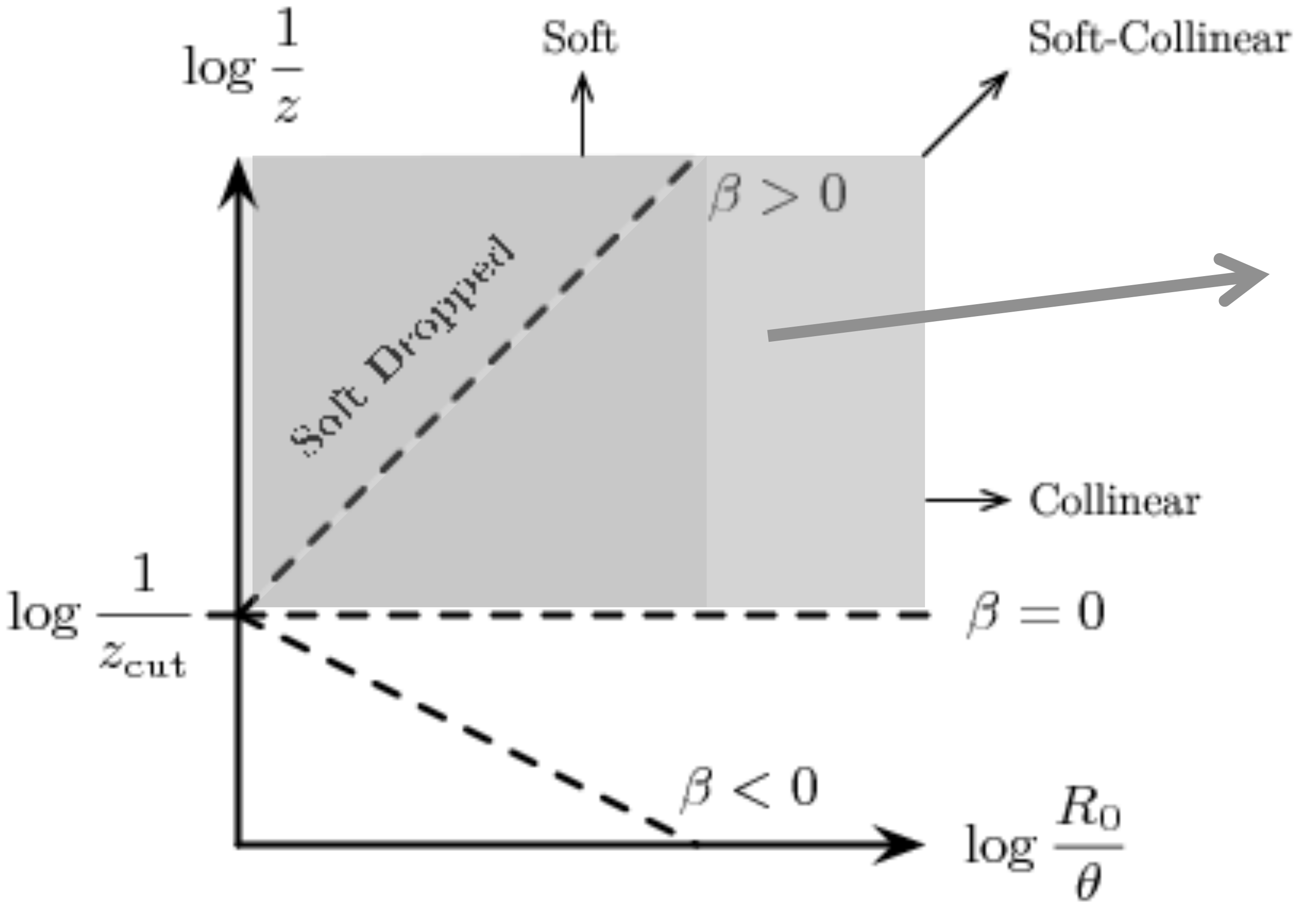




UE removal only for PbPb since pp data set has low pileup (1.4)

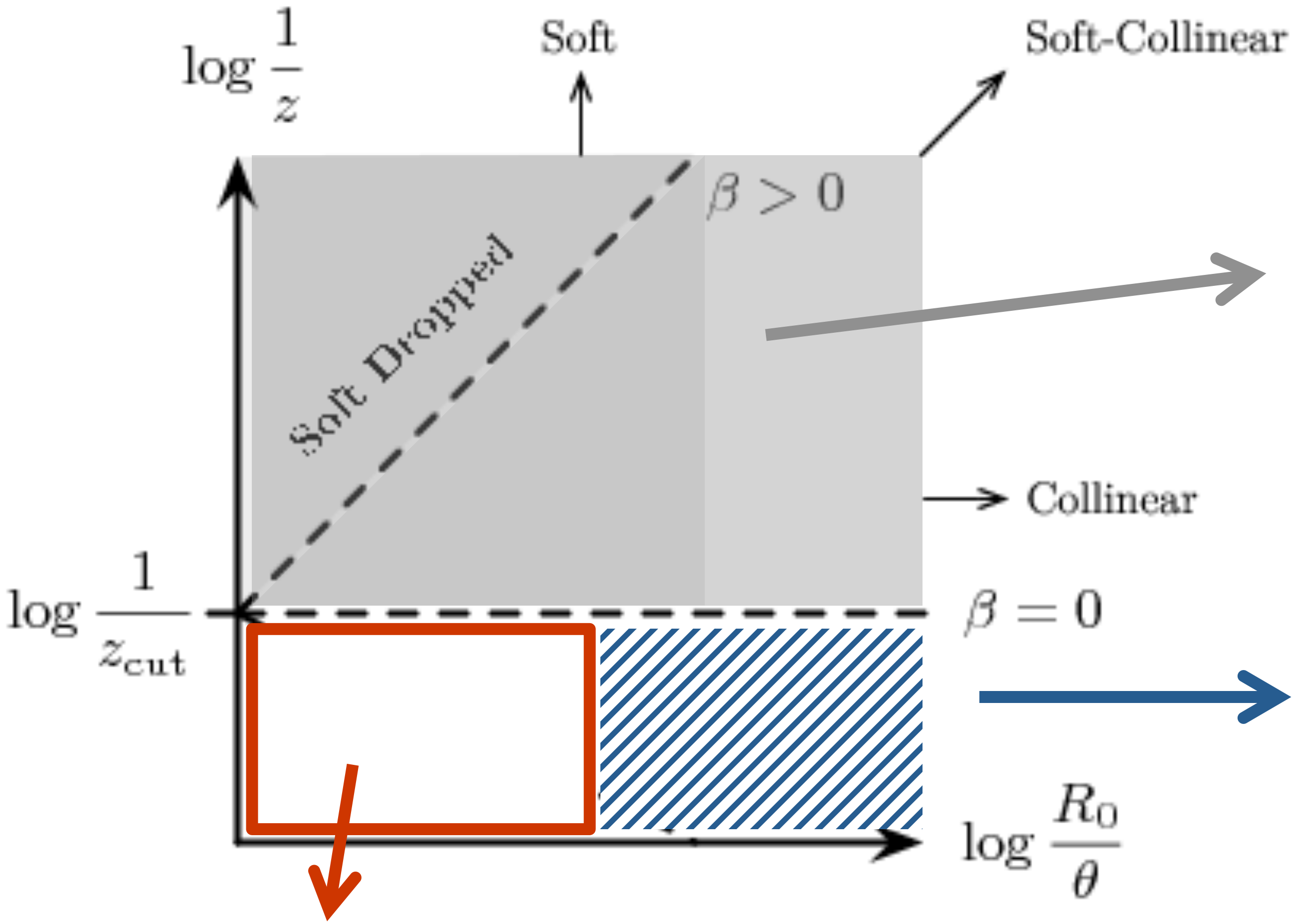
Constituent subtraction
Berta et al. arXiv:1403.3108

Emission phase space



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

Emission phase space



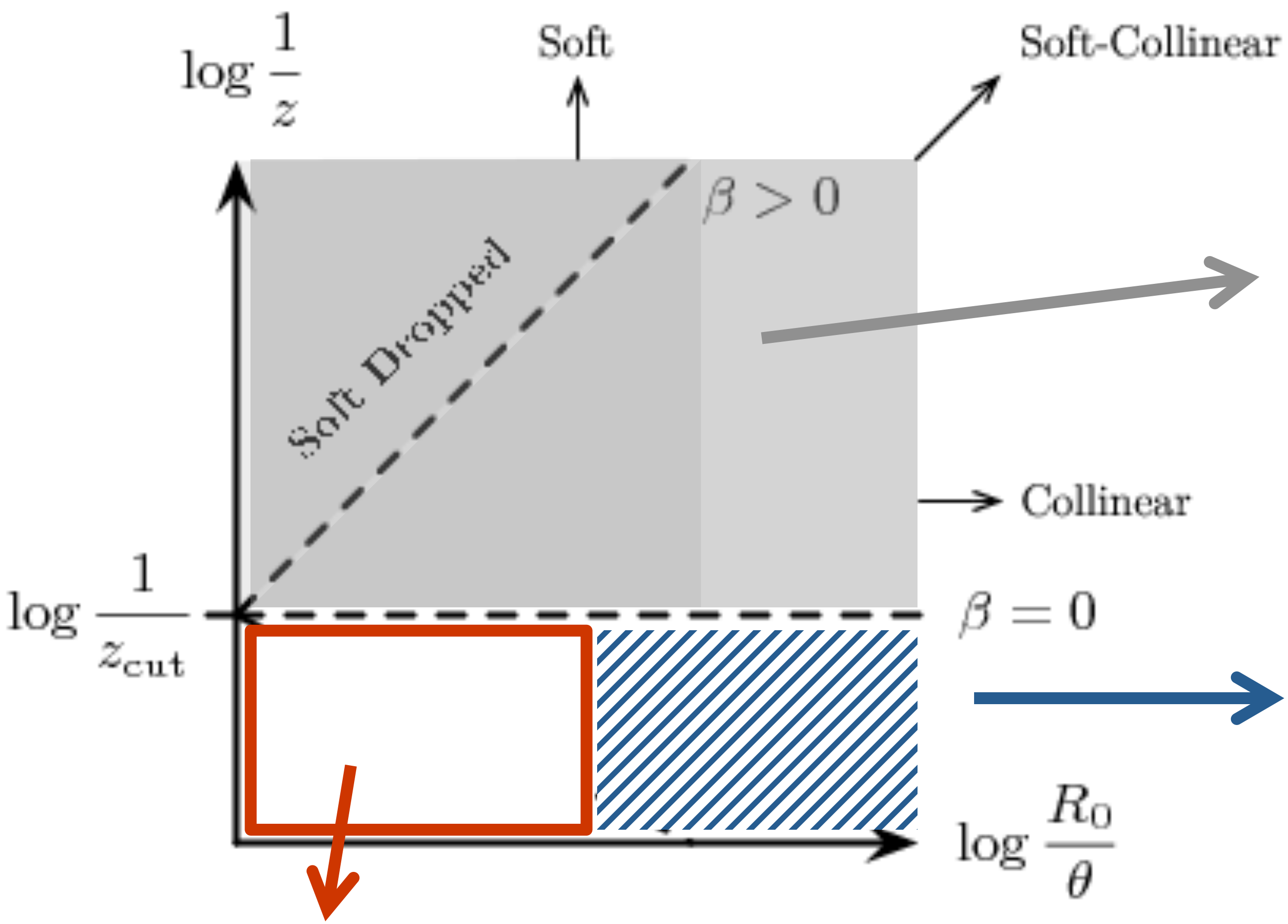
For β=0: both soft and soft-collinear emissions are vetoed

CMS also removes jets with $\Delta R_{12} < 0.1$ (ΔR_{12} = η-φ separation between the two subjets)

With splitting function analysis we explore this region of phase space

Earliest vacuum splittings: lower left corner

Emission phase space



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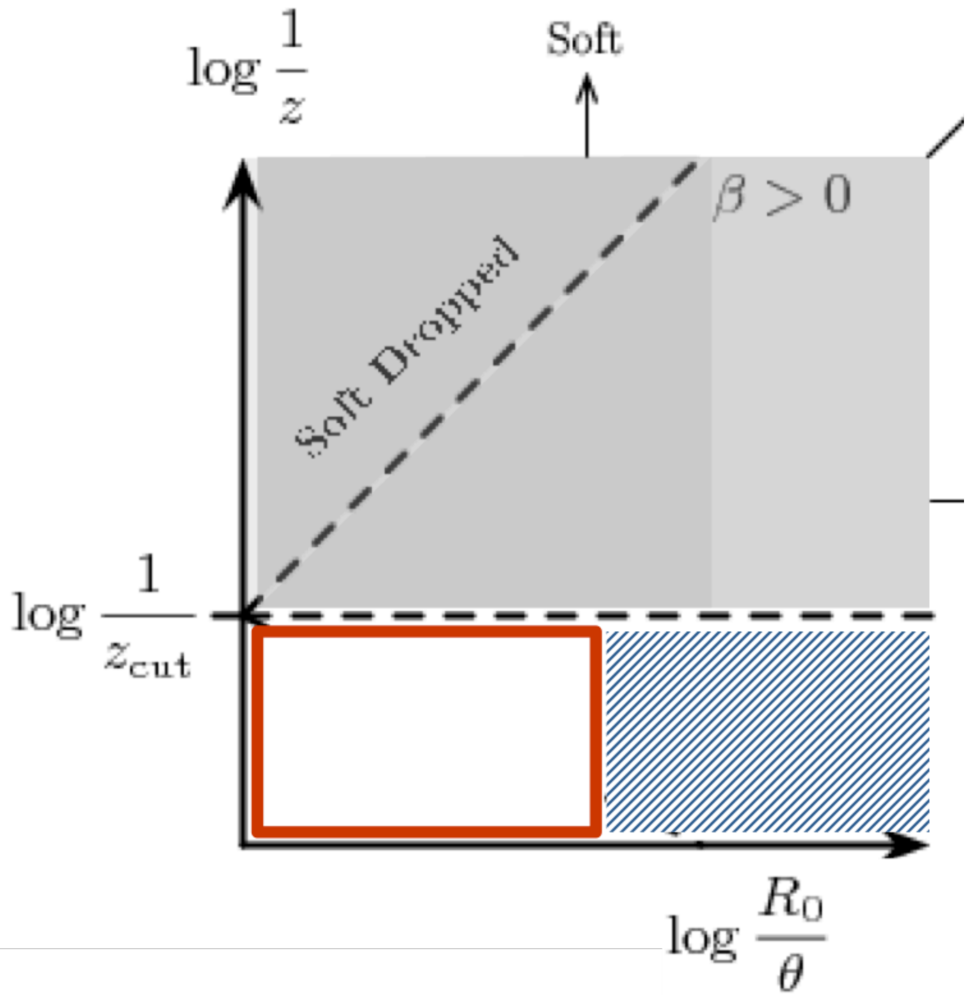
With splitting function analysis we explore this region of phase space

Earliest vacuum splittings: lower left corner

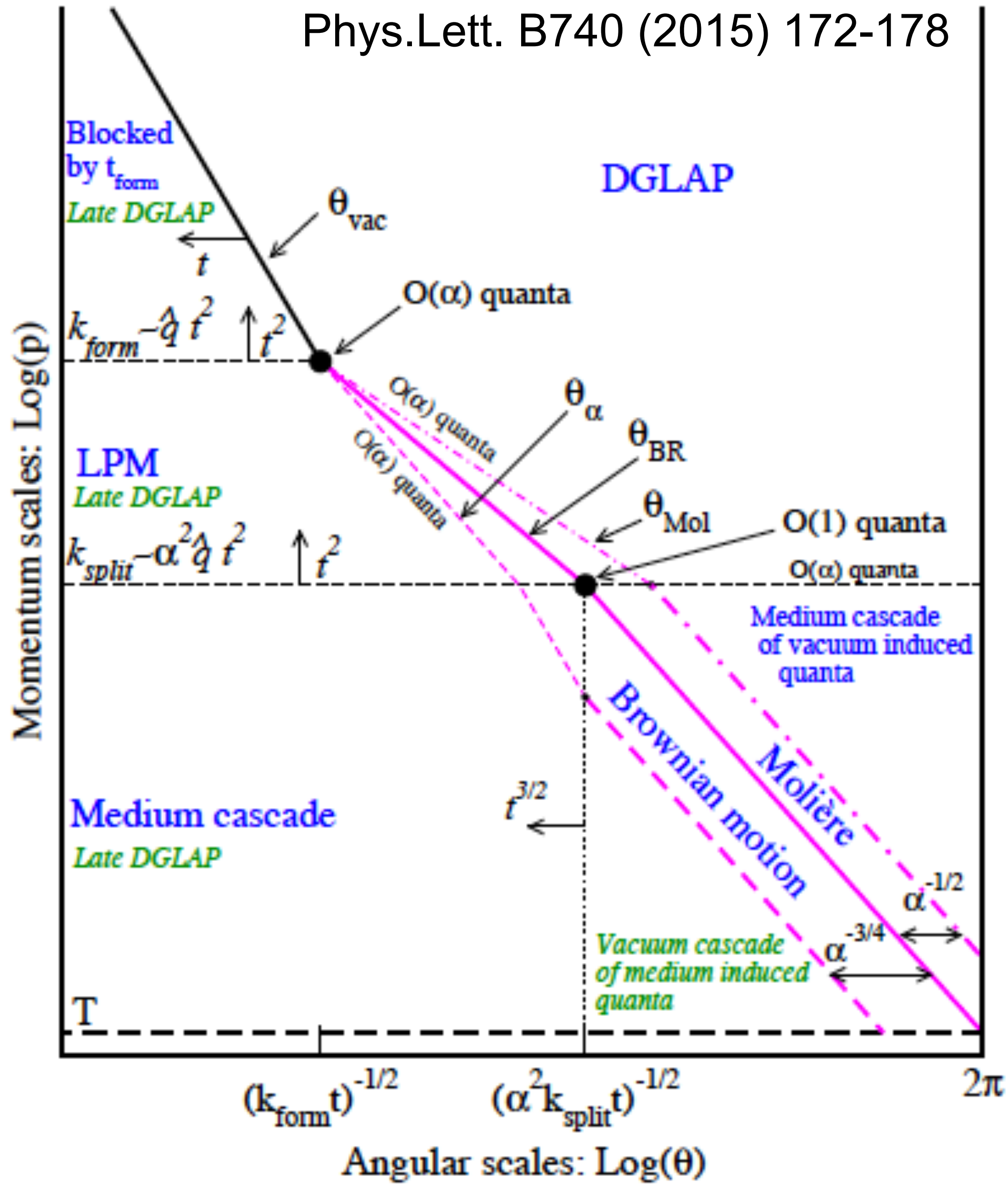
$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2\omega} \qquad \tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

For CMS measurement: τ_f^{vac} ~ 1.4 fm
For STAR measurement: τ_f^{vac} ~ 6-10 fm

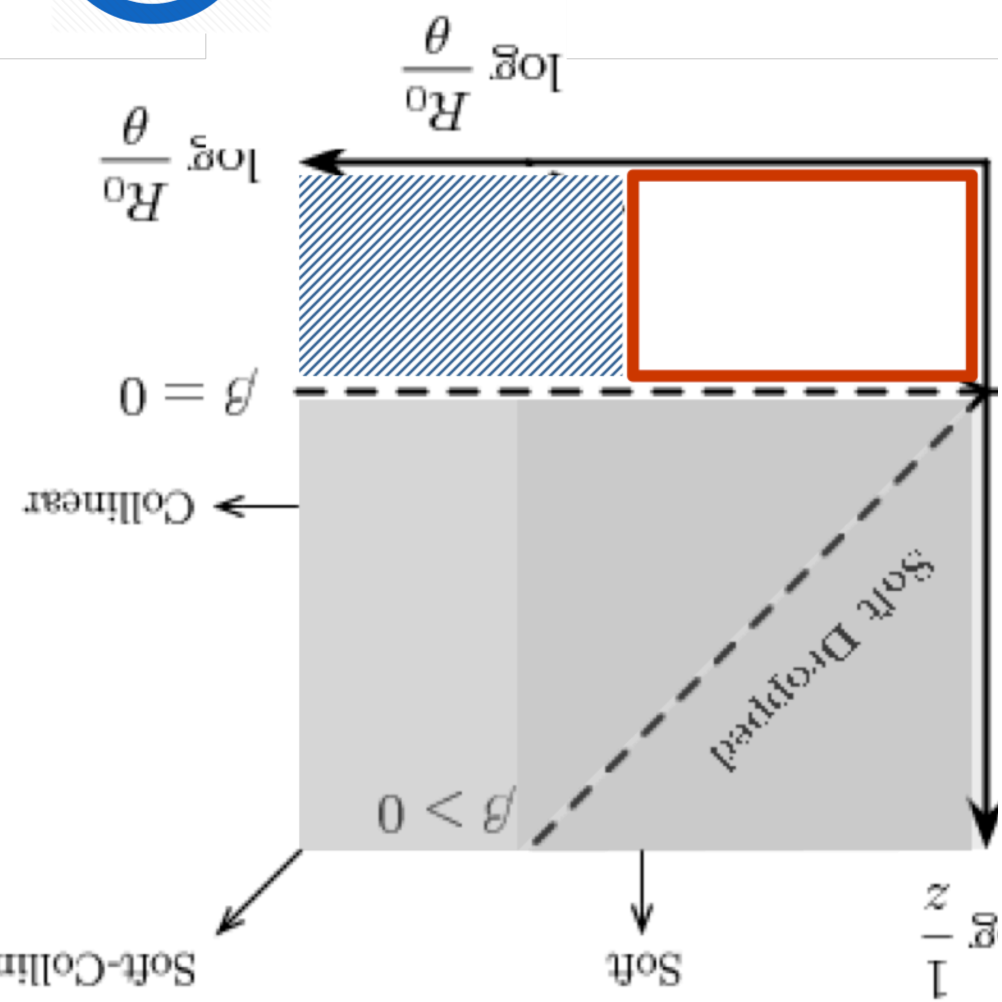
Radiation diagram



Kurkela and Wiedemann
Phys.Lett. B740 (2015) 172-178



Radiation diagram



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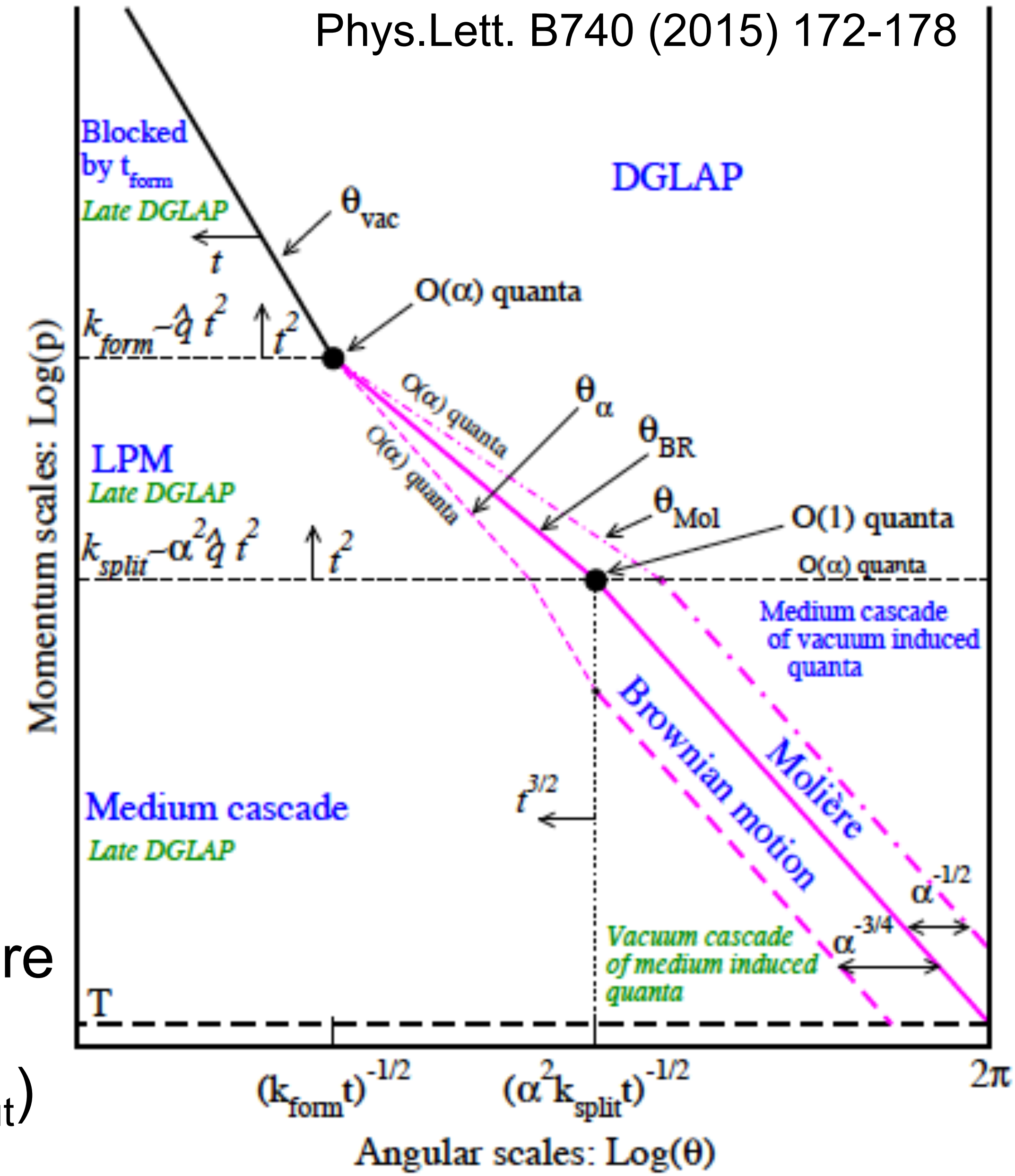
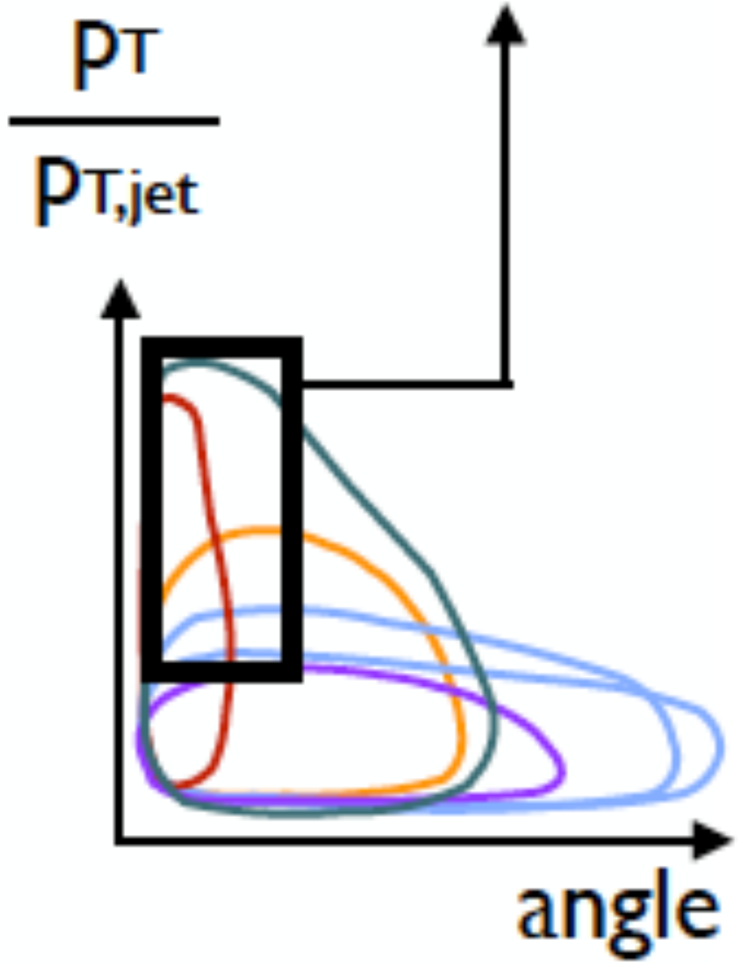


Which part of the parton cascade are we seeing?
Varying SoftDrop parameters (β,z_{cut}) allows us to move through

Radiation diagram



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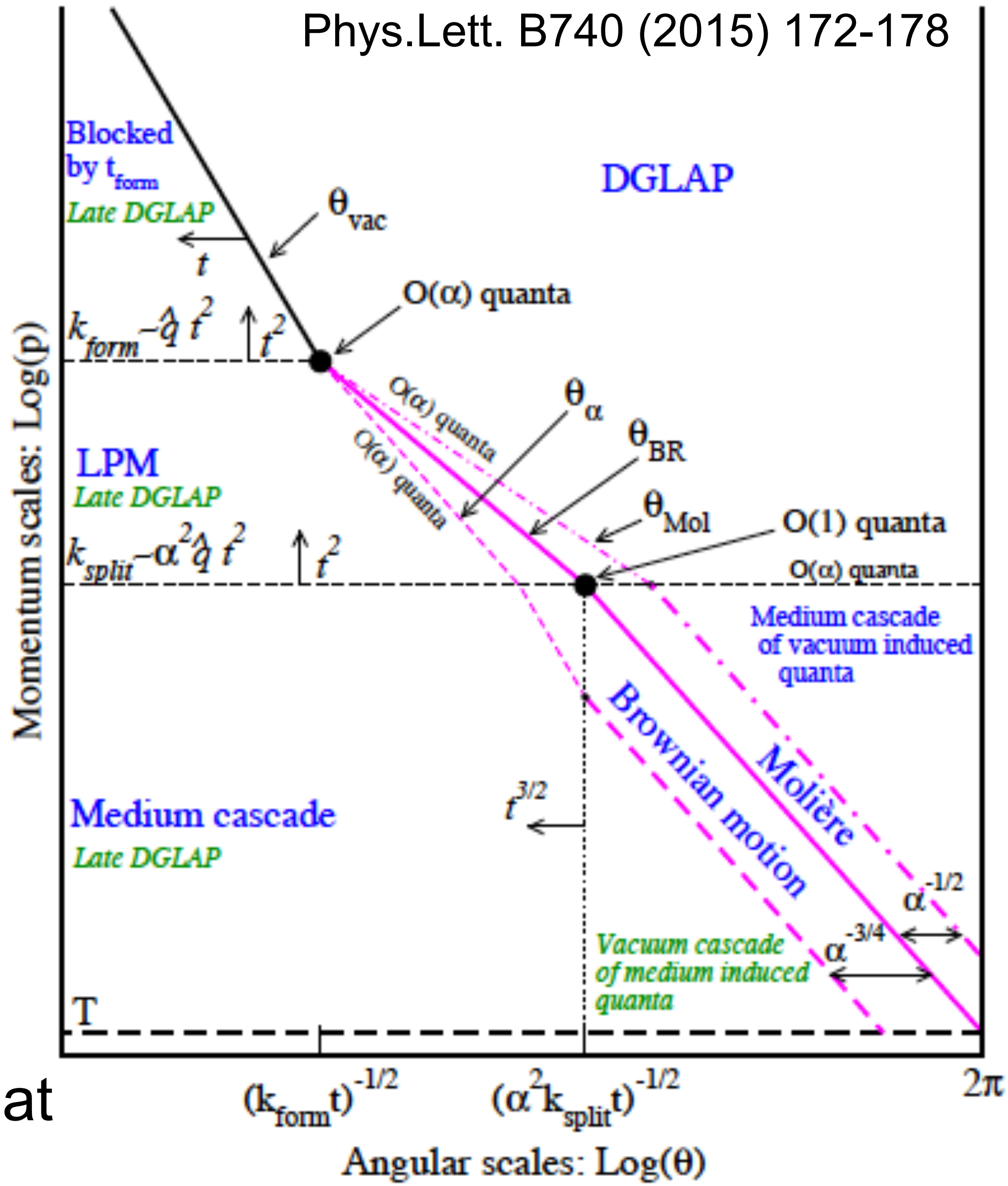


Doga was thinking the same thing

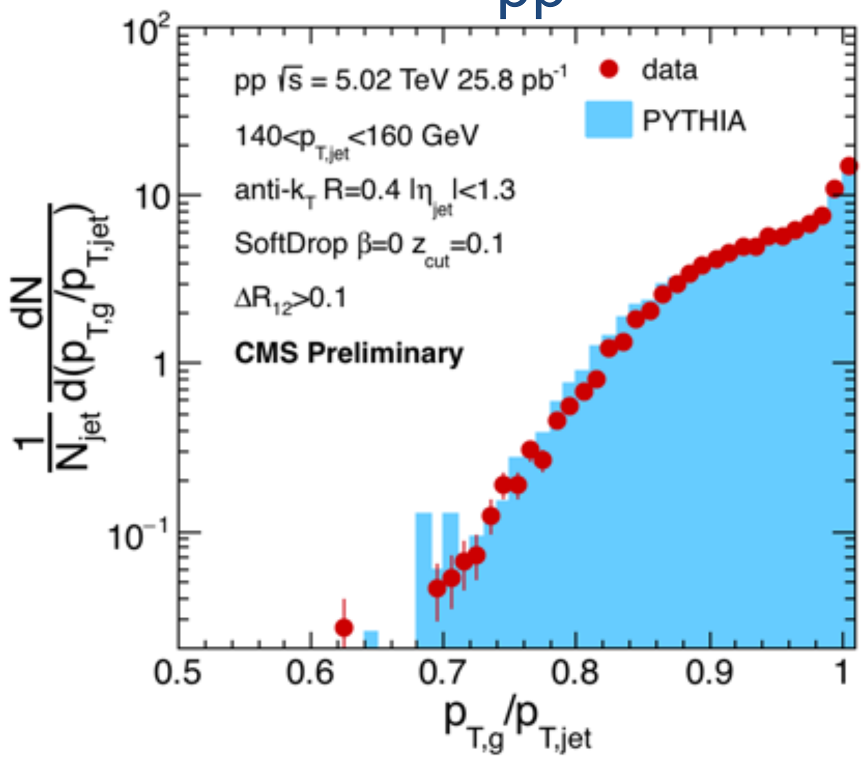
But we don't know where to draw that square

The groomed-away energy

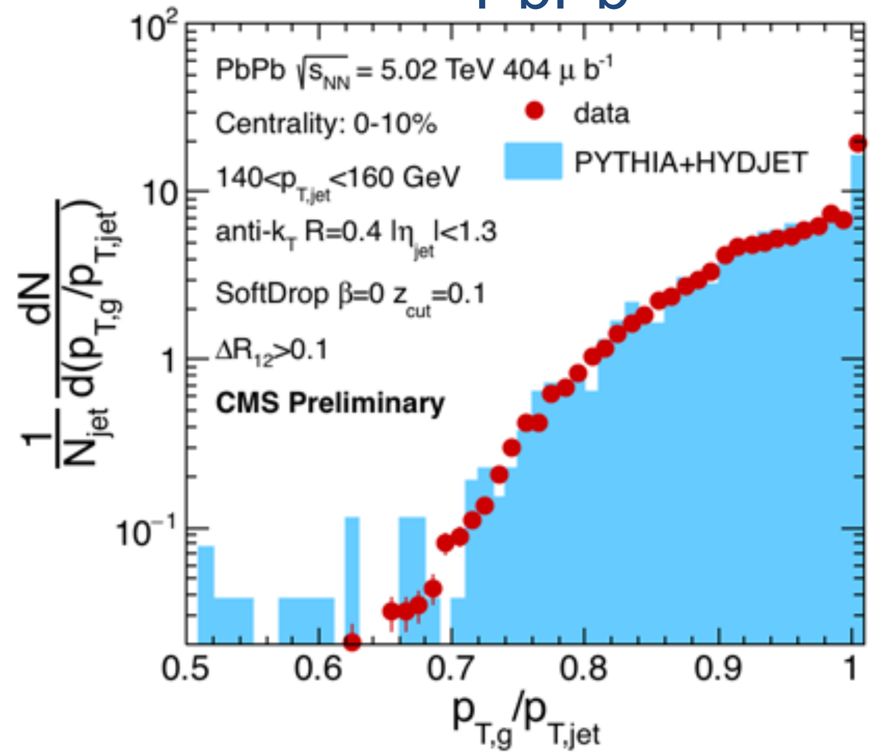
Larger amount of energy gets groomed away in PbPb collisions

Groomed energy fractions well described by MC
→ Dominated by vacuum-like radiation
Can we use the groomed-away energy to map out the medium cascade?
RHIC vs LHC?

pp



PbPb



CMS-PAS-HIN-16-006

The groomed-away energy

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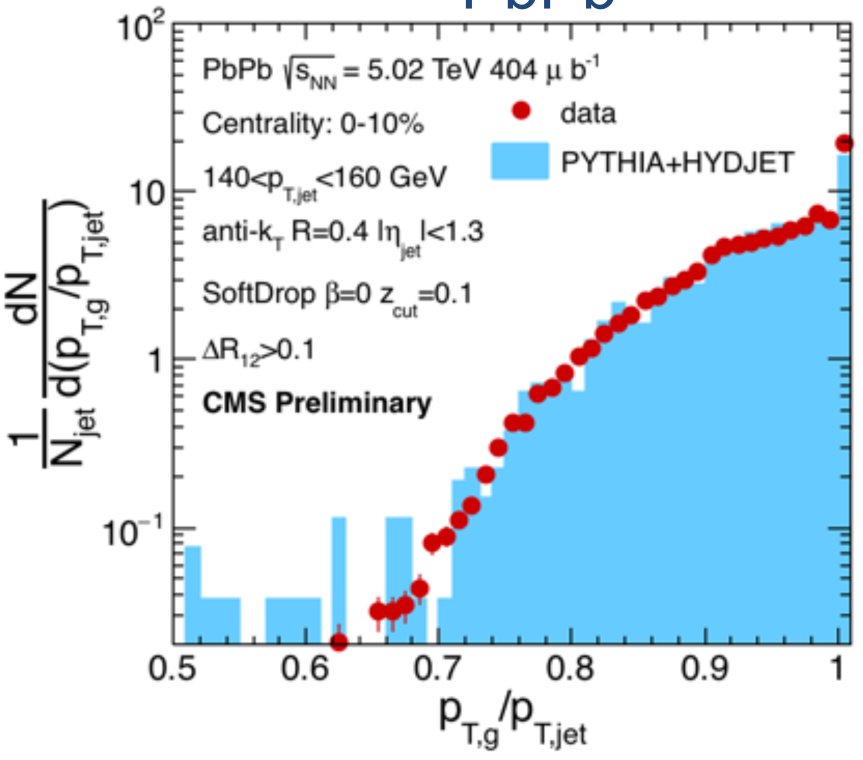
Groomed energy fractions well described by MC
→ Dominated by vacuum-like radiation
Can we use the groomed-away energy to map out the medium cascade?
RHIC vs LHC?

Need more differential approach than just looking at total groomed-away energy

→How many branches got dropped?
→What is their energy and angle?

PbPb



CMS-PAS-HIN-16-006

Future

Jet shapes with larger R + measured pp reference

Full exploration of groomed jet observables: M_g, θ_g, Δ_g

Unexplored observables: N-subjettiness, jet pull, jet charge, etc

Jet substructure for jets recoiling from photon/Z

RHIC + LHC

Boosted topologies (top, W)

LHC

Bonus slides

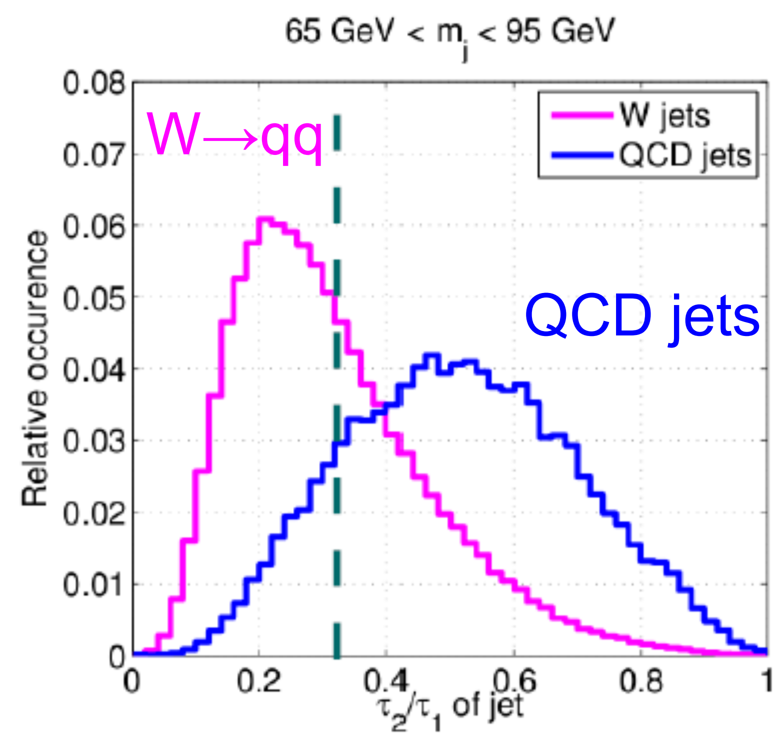
N-subjettiness

Thaler, van Tilburg [arXiv:1011.2268](https://arxiv.org/abs/1011.2268)

A measure of how consistent a jet is with having N subjets (τ_N)

Used to find boosted W, Z, Higgs (2-prong), boosted top (3-prong) in pp

$$\tau_N = \frac{1}{d_0} \underbrace{\sum_k p_{T,k}}_{\text{Sum over all particles}} \underbrace{\min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}}_{\text{Minimize distance of each particle to subjets}}$$



N-subjettiness

Thaler, van Tilburg arXiv:1011.2268

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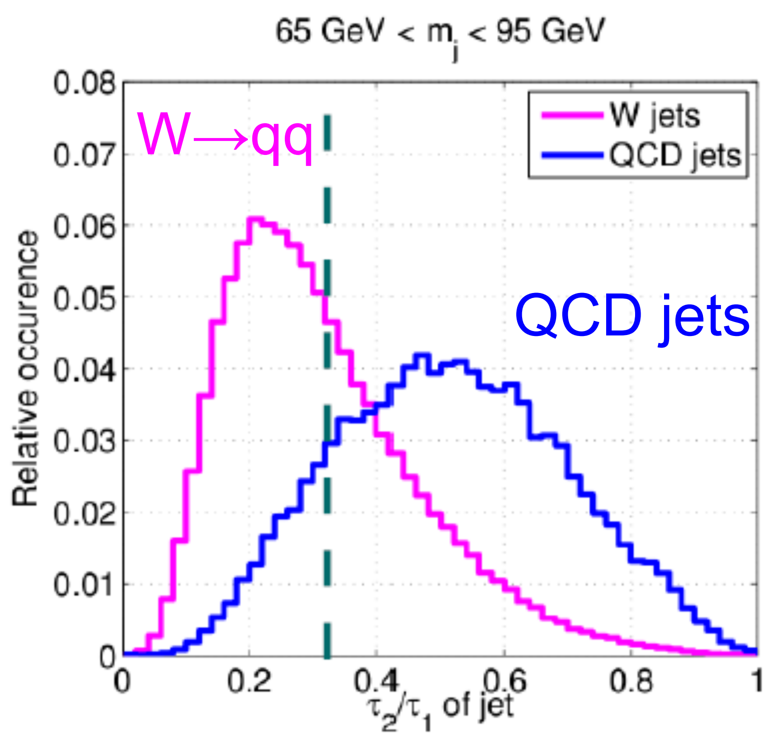
QCD jets with 2 cores: small τ_2/τ_1

Does the medium absorb one of the substructures?
- Test by measuring rate

Modified in AA?
- subjet observables for $\tau_2/\tau_1 < 0.2$-0.4



Color (dis)connected partons

Does the medium destroy color connections?

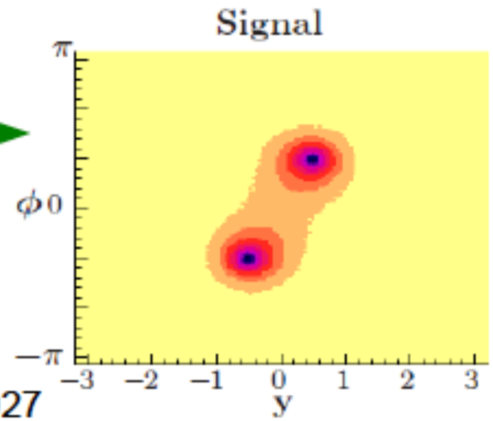
Can we probe the color connection, or lack of color connection experimentally?

One possibility: jet pull angle of subjets / x-cone jets

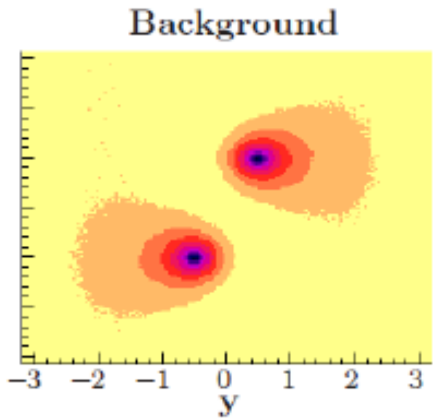
Energy flow of color connected partons points to each other.

Quantify with pull angle, θ_p = angle between pull vector and vector between jet axises

Gallicchio, Schwartz arXiv:1001.5027
CMS-PAS-JME-14-002
ATLAS: arXiv:1506.05629



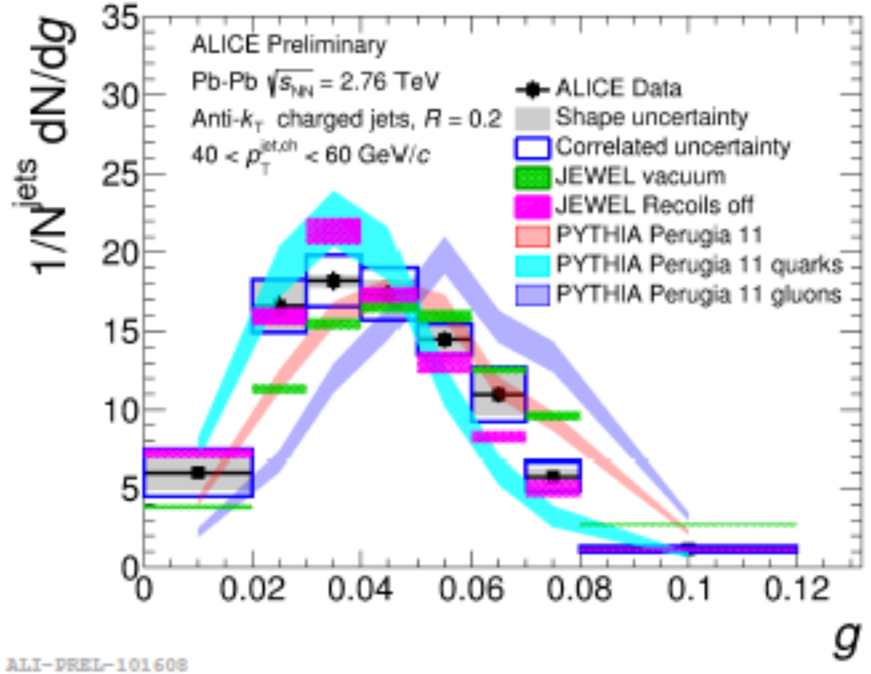
Color connected

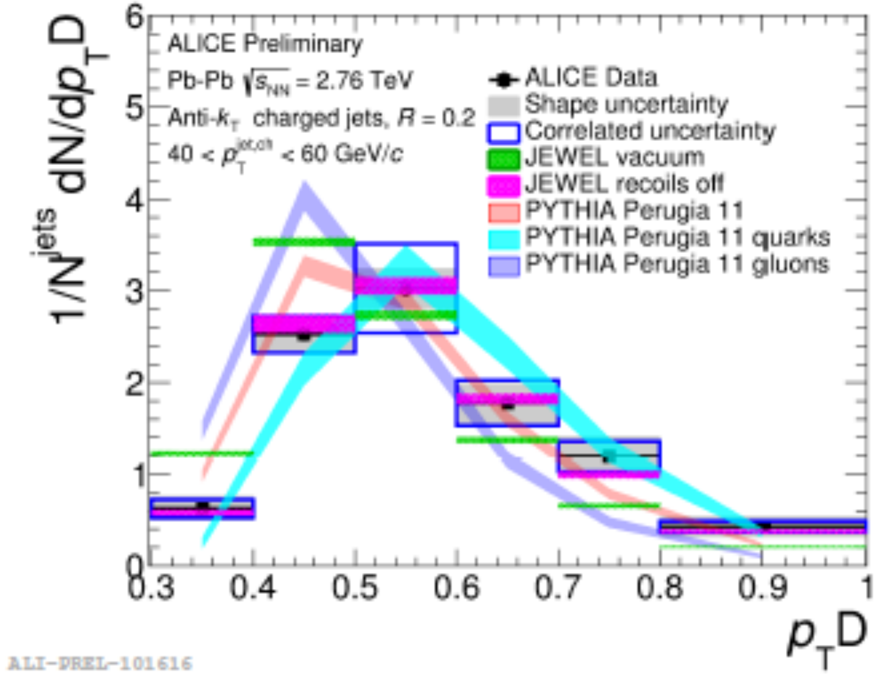


Color disconnected

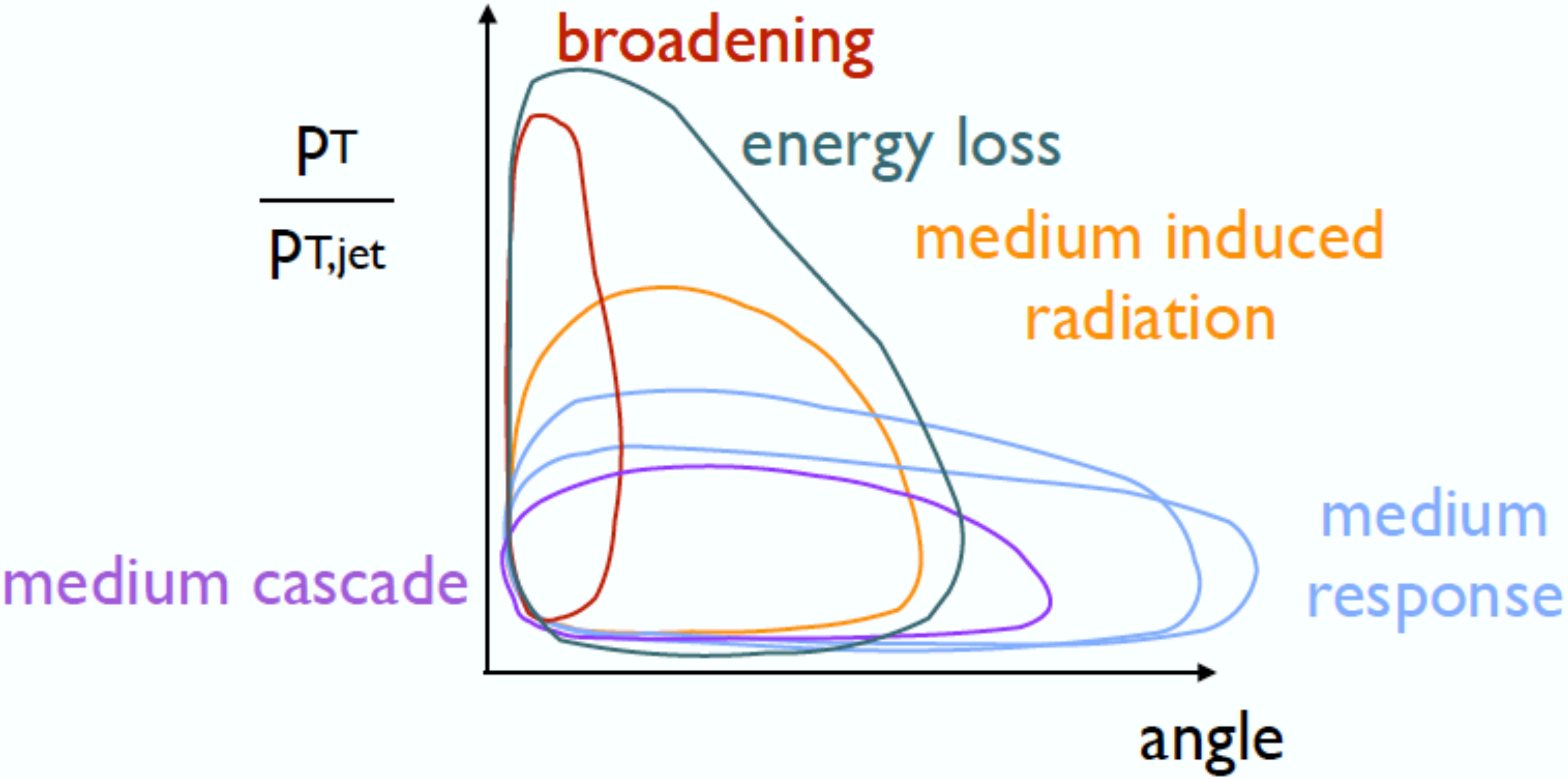
ALICE jet shapes data vs theory

Looks like quarks





Doga's map

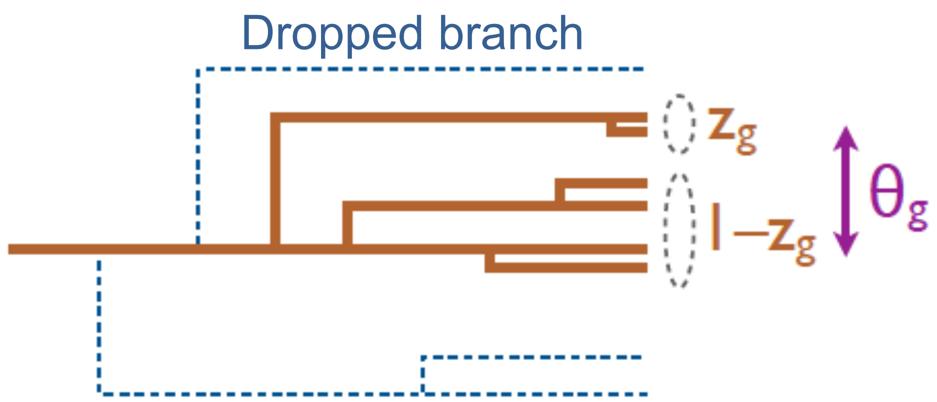


broadening
energy loss
medium induced radiation
medium response
medium cascade
$\frac{p_T}{p_{T,jet}}$
angle

Jet grooming with SoftDrop

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

Extract the 2 branches after grooming for physics → subjets



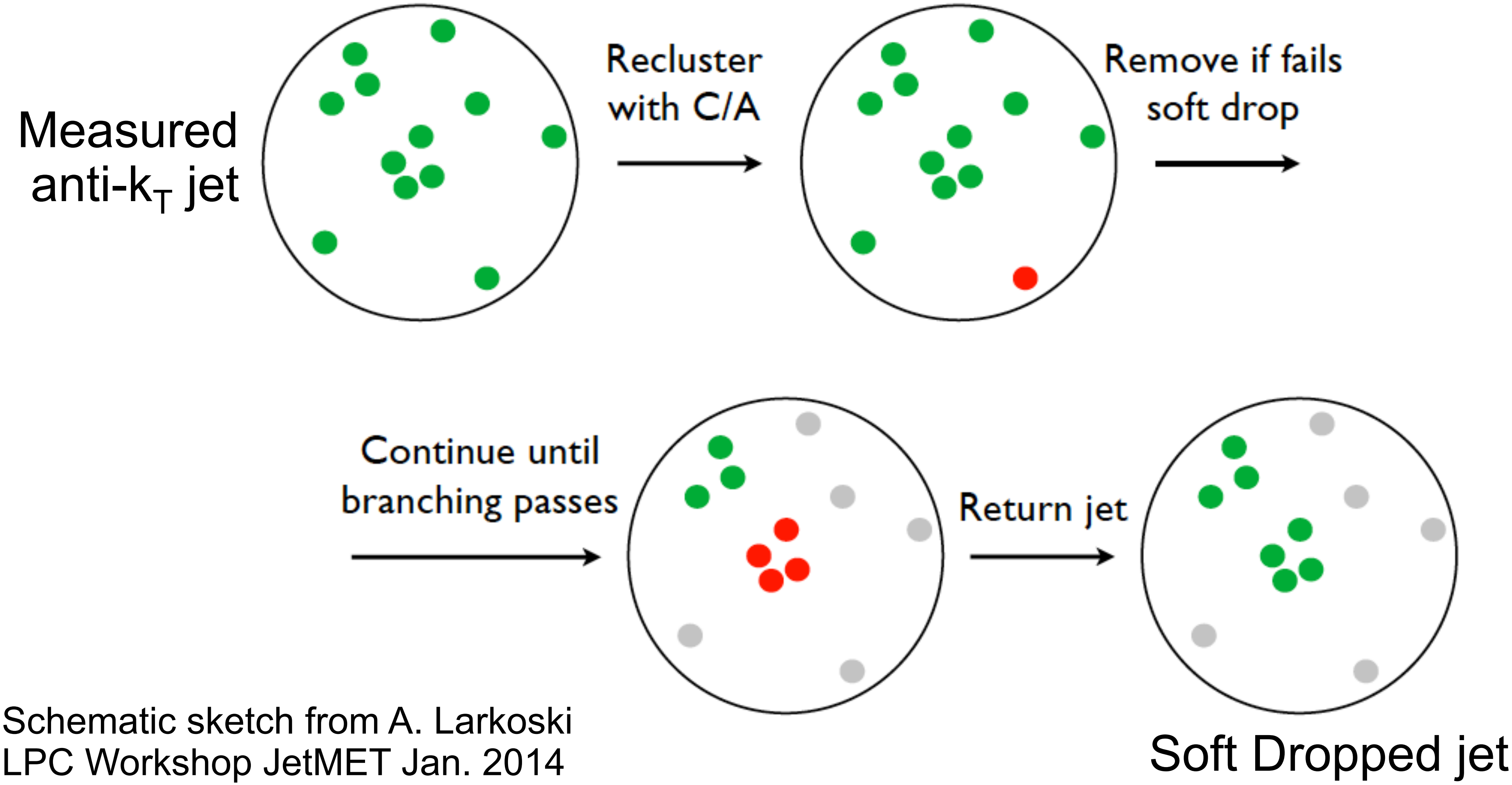
Observable is well understood analytically since all soft divergences are removed

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

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

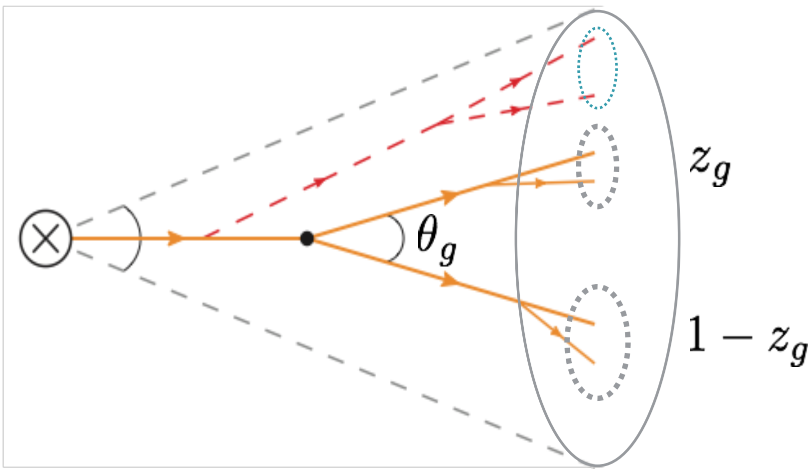
Jet grooming

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

Shared momentum fraction



Soft Drop condition

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

energy threshold

angular exponent

We use $\beta = 0$ and $z_{cut} = 0.1$
Large-angle soft radiation + background is removed

[1] Larkoski, Marzani, Thaler
Phys. Rev. D91:111501 (2015)
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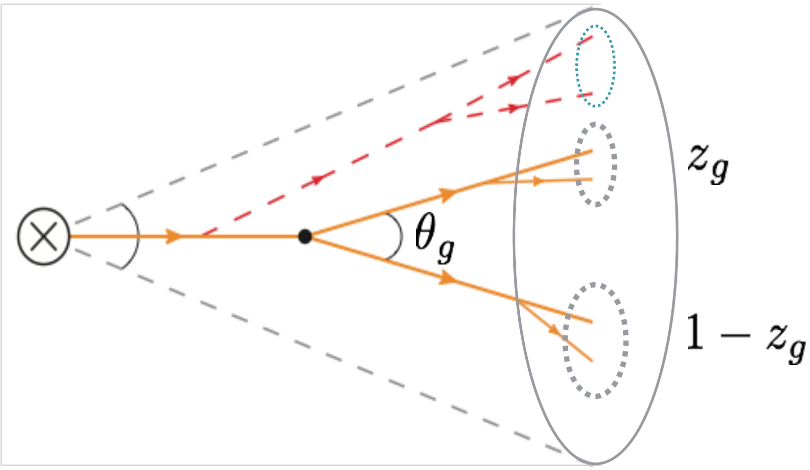
Shared momentum fraction



Soft Drop condition

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

energy threshold

angular exponent

We use $\beta = 0$ and $z_{cut} = 0.1$
Large-angle soft radiation + background is removed

Observable:
Momentum balance between the two subjets as defined by grooming procedure

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

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

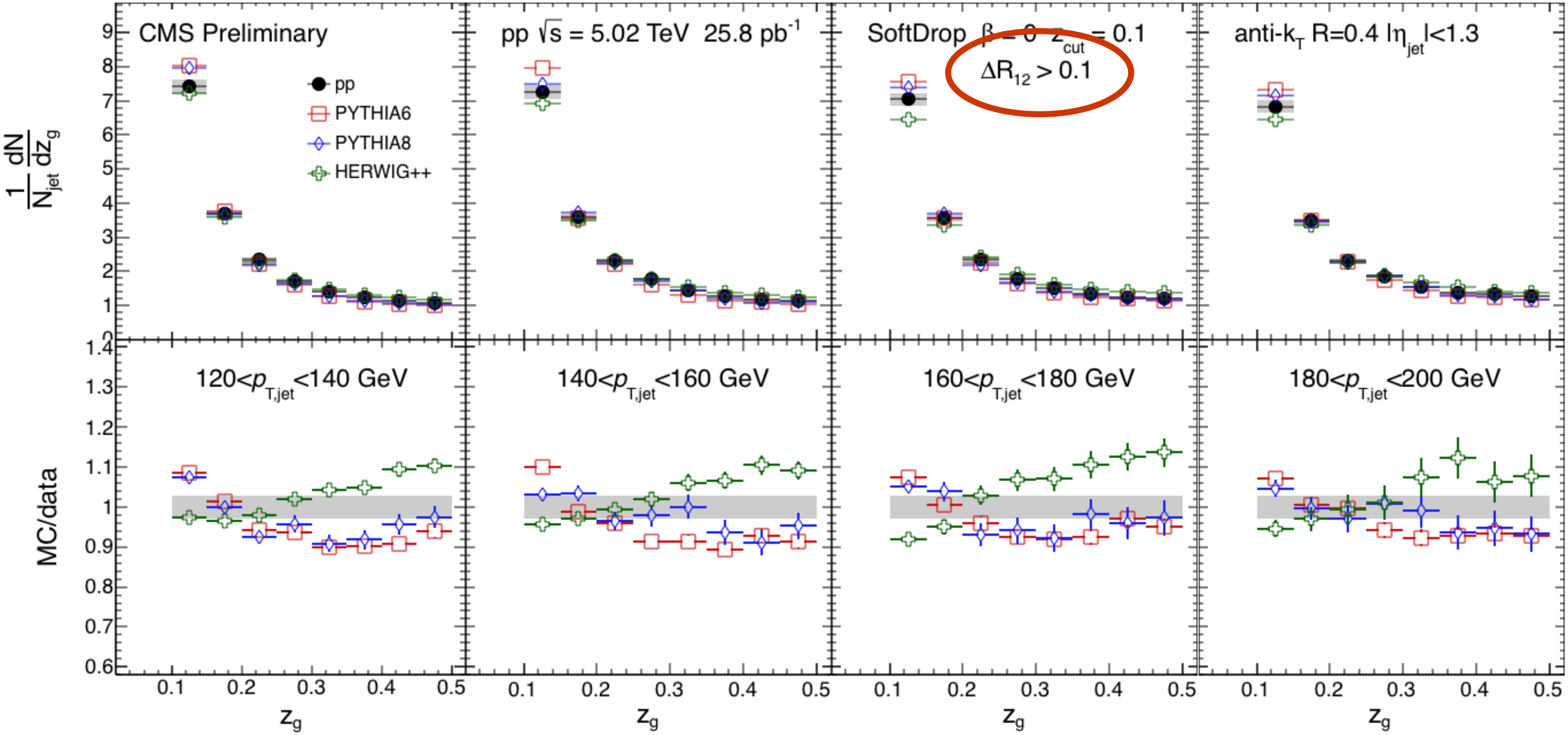
Splitting function in pp

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

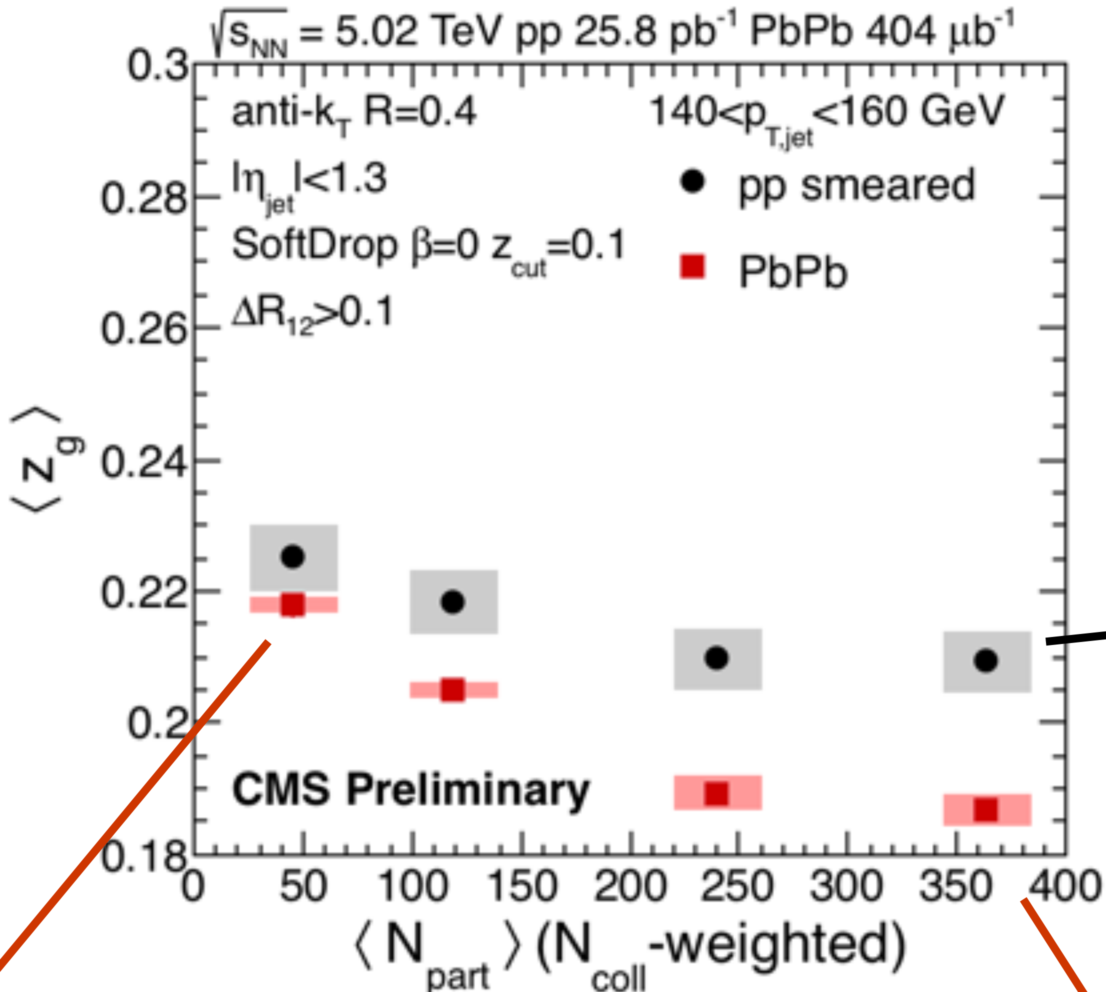
PYTHIA8 and HERWIG reproduce the pp data within 5-10%
Opposite trend for PYTHIA and HERWIG

CMS-PAS-HIN-16-006

Cannot resolve subjets which are very close due to detector granularity



Evolution with medium density



pp reference smeared to PbPb resolution

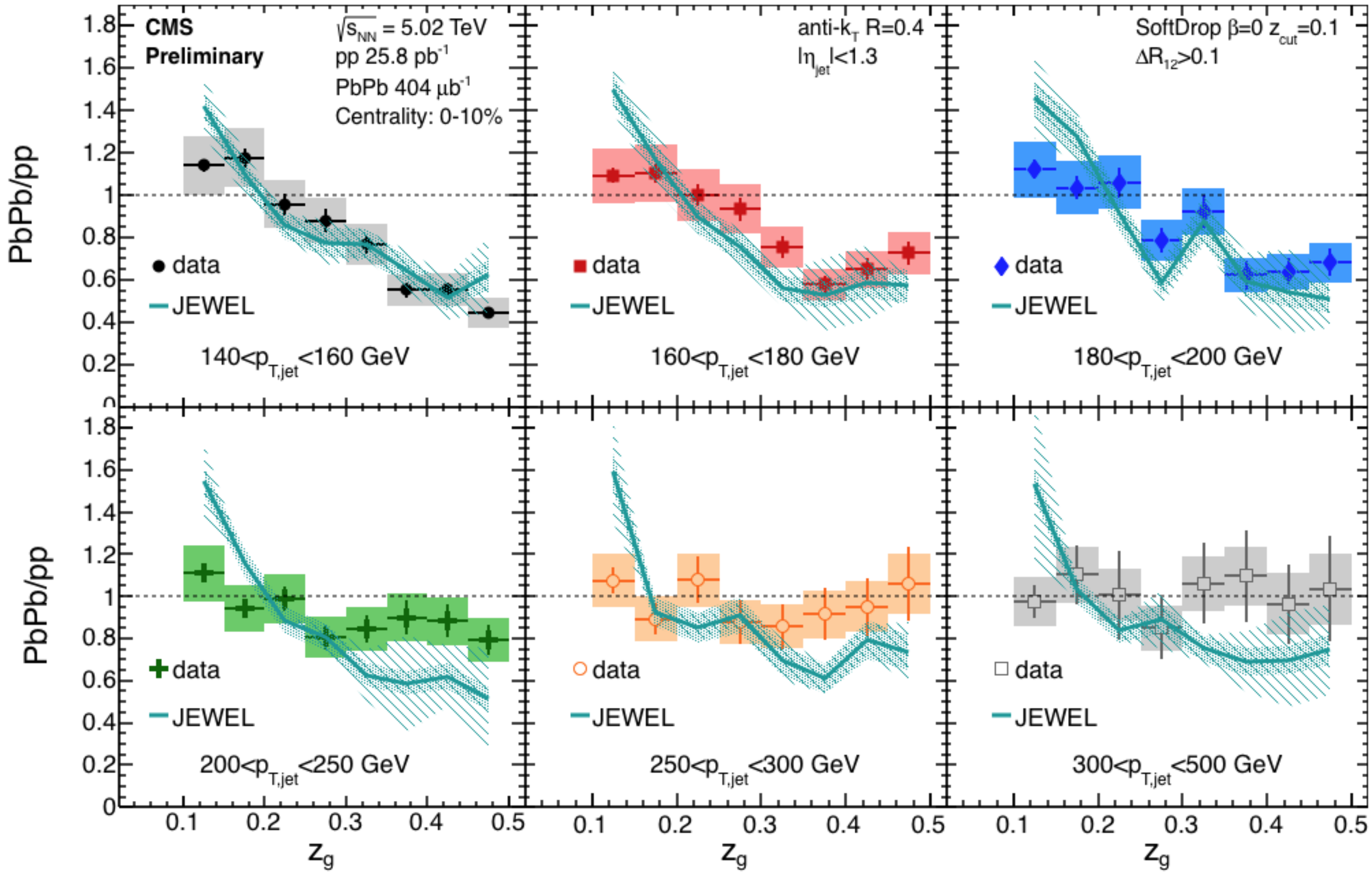
PbPb in peripheral collisions
'not so hot medium'
pp like → vacuum like

PbPb in most central collisions
'hottest medium'

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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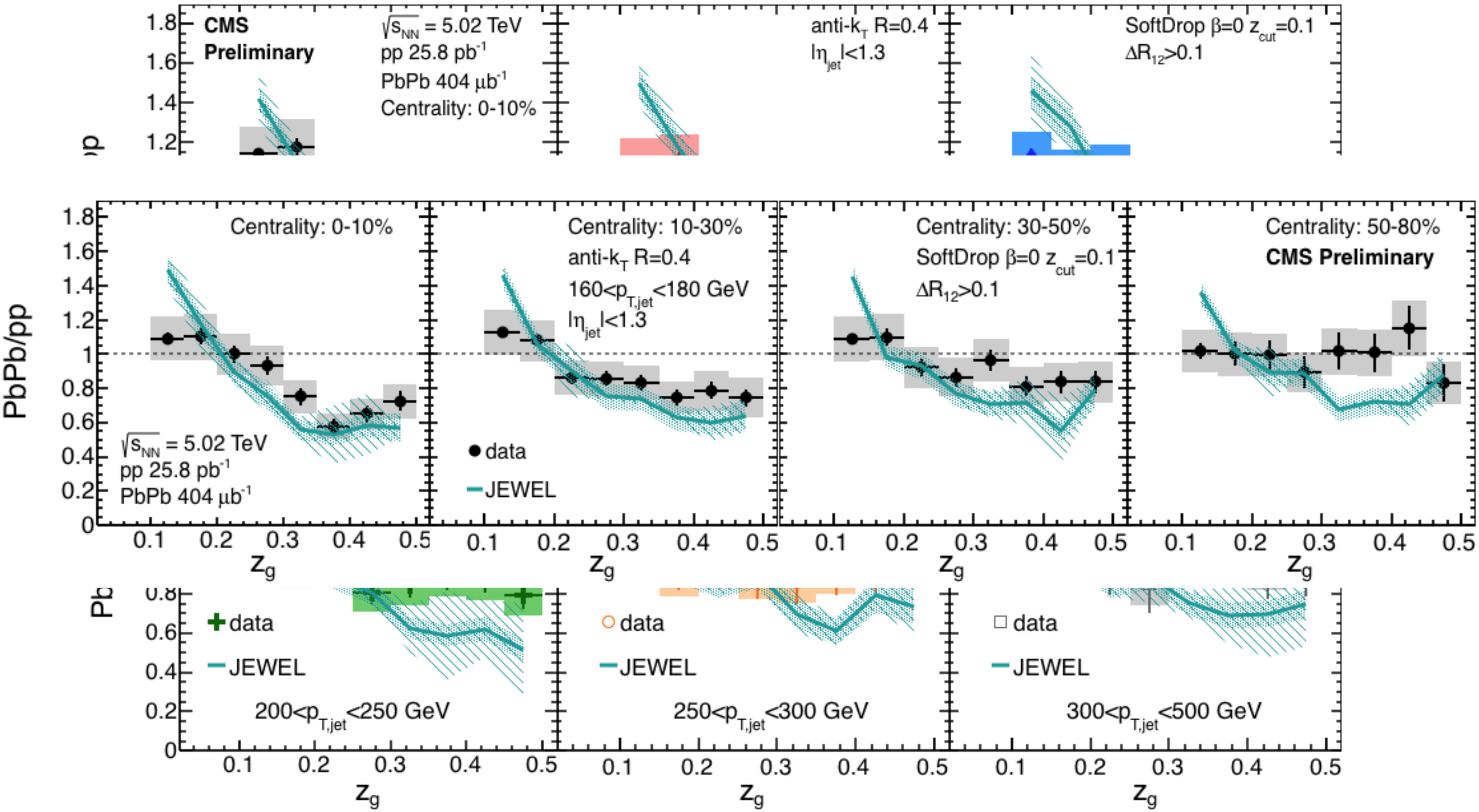

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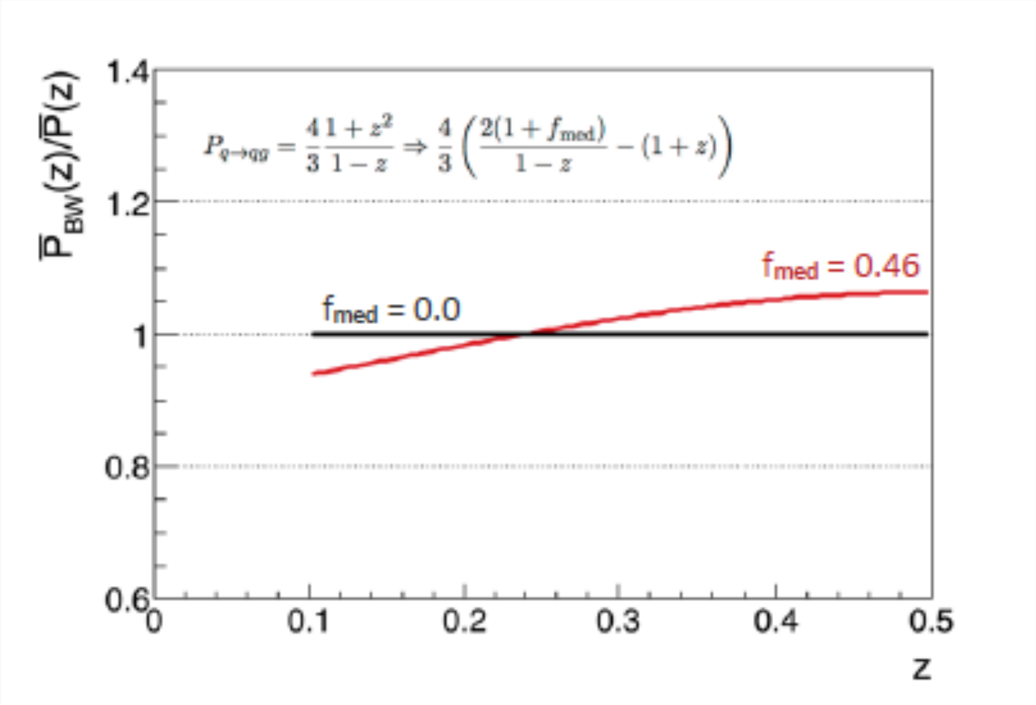
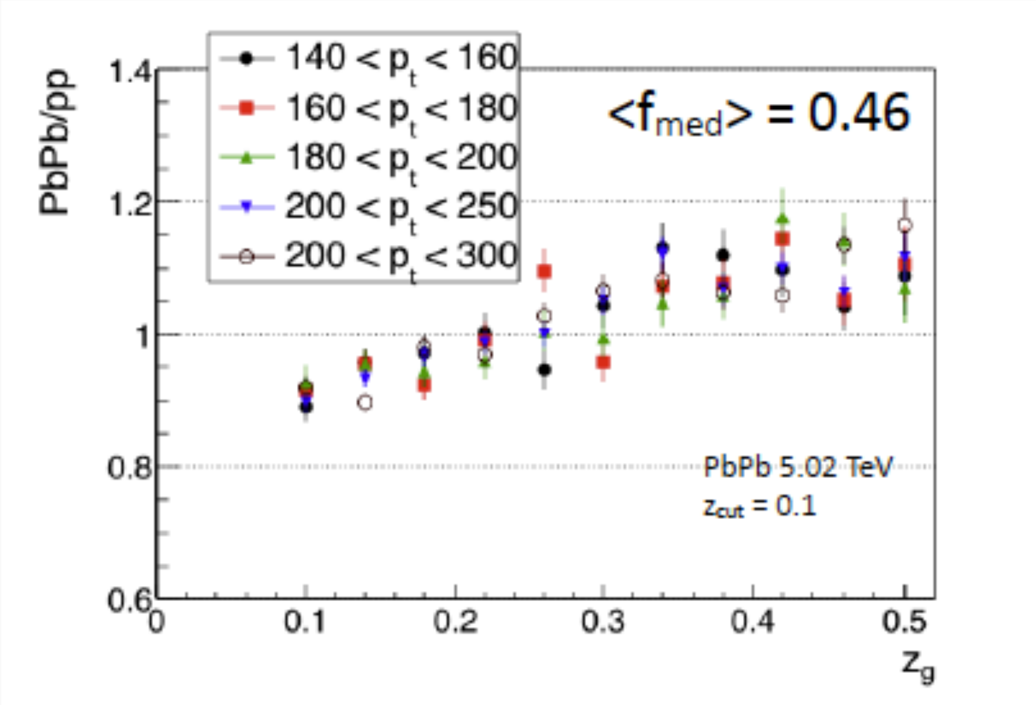
MC with modified splitting function

MC input: modified P(z)



MC output: modified $p(z_g)$



- YaJEM-BW: modification of the P(z) is directly propagated to the measurable z_g

Ref: talk by Kirill Lapidus on Saturday