Jets and energy loss

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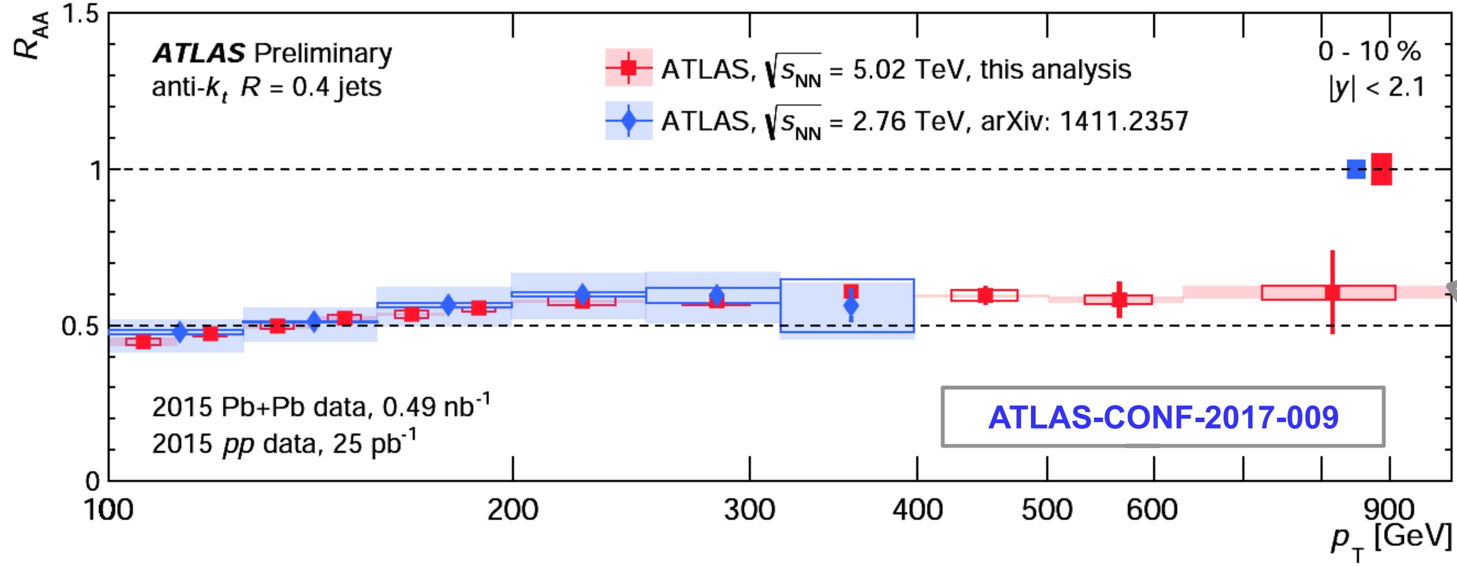
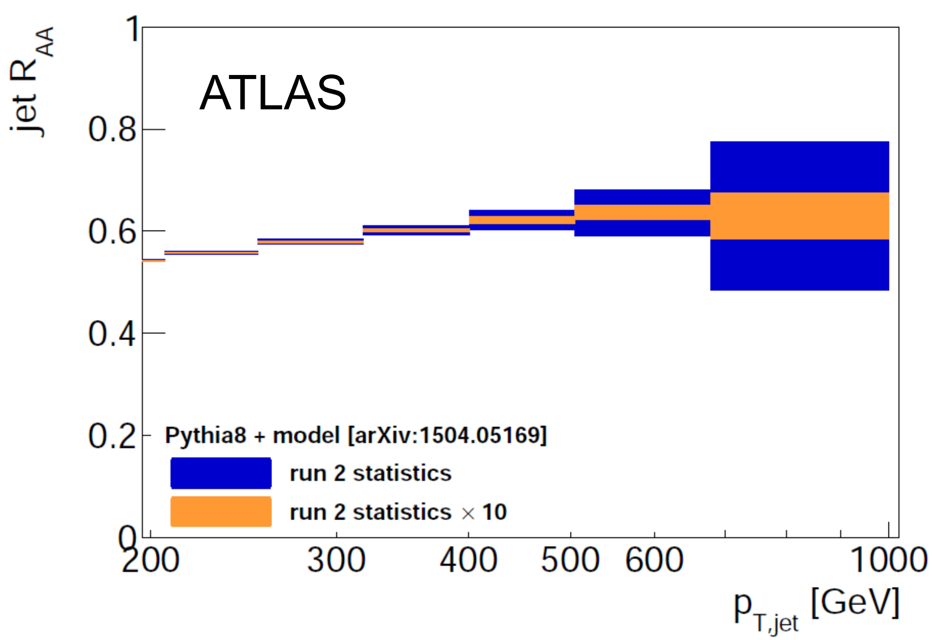
on behalf of ALICE, ATLAS, CMS and LHCb

October 2017
CERN
HLHE-LHC workshop

Jet R_{AA} at high-p_T

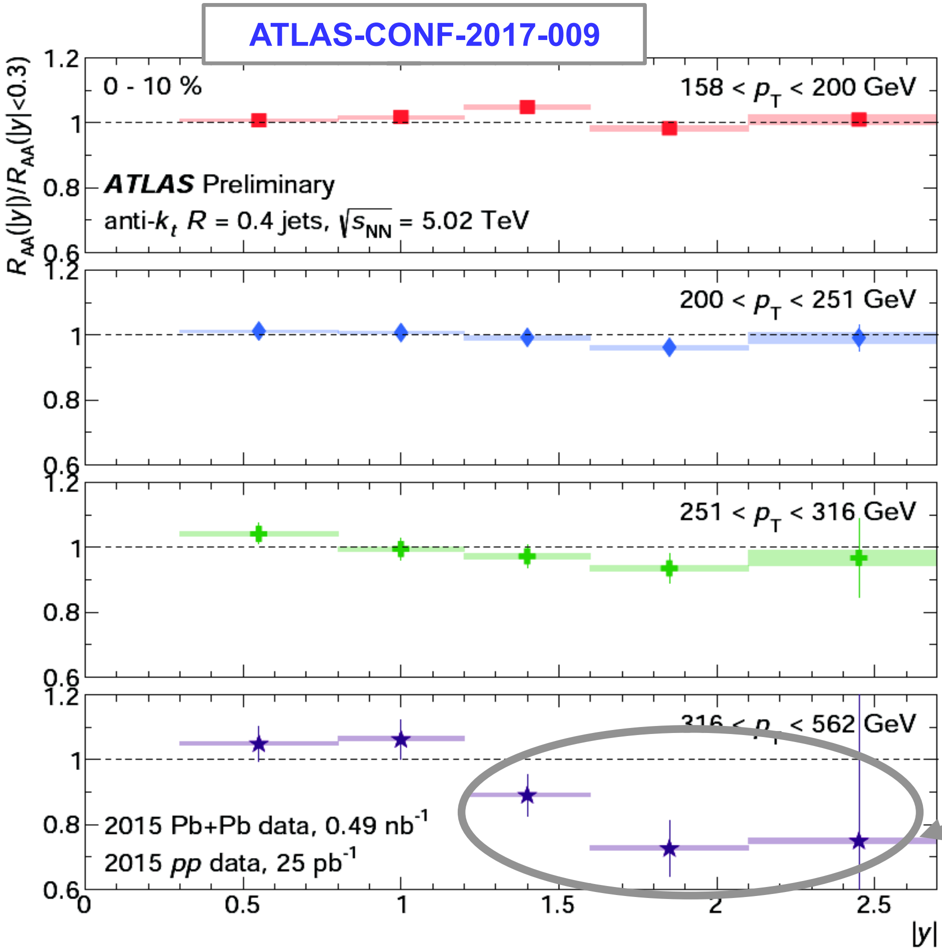


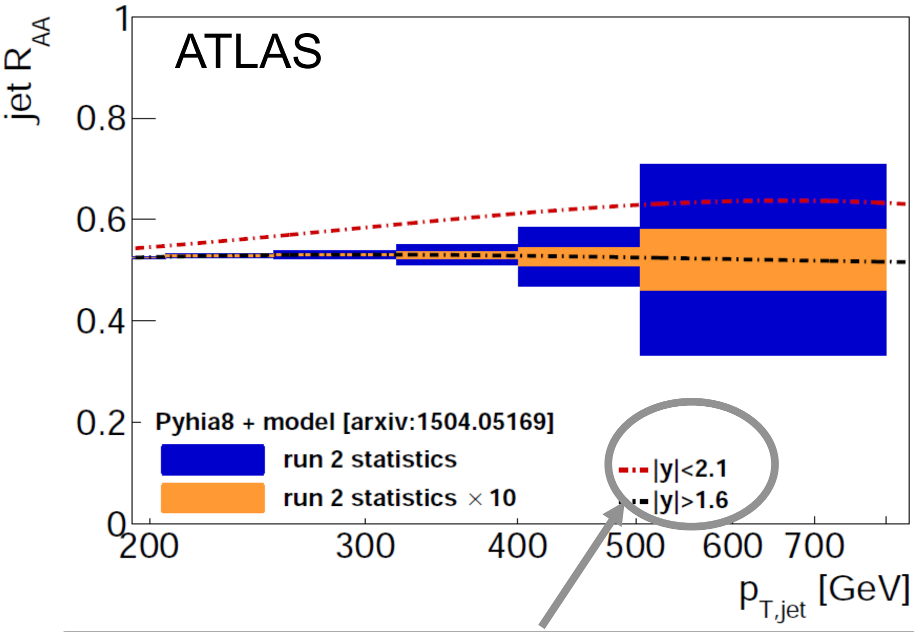
Significant jet suppression seen at the TeV scale



- Jet R_{AA} high-p_T:
  - the role of color coherence
  - flavor dependence of energy loss
  - overall strength of the energy loss
  - and more
- Significant improvement in precision expected

Jet R_{AA} in the forward region





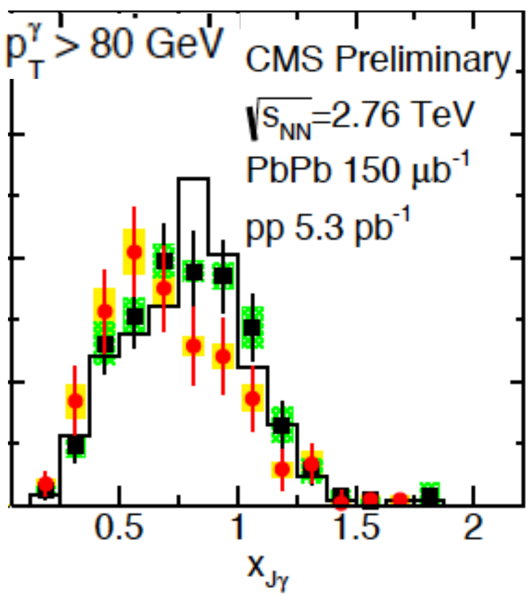
Suppression different in the forward region at high-pt

- Forward high-p_T:
  interplay between flavor and spectral steepness, path length.
- Future runs allow to access higher p_T where the rapidity dependence is stronger.

Precision energy loss: γ-jets

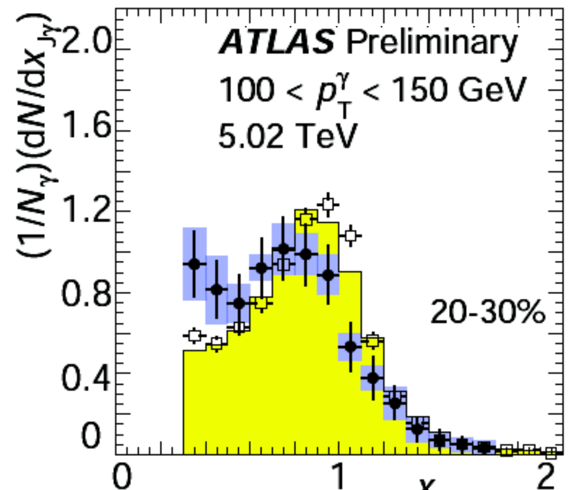
How much energy gets radiated out of the jet cone?

Run1 ~0.15/nb



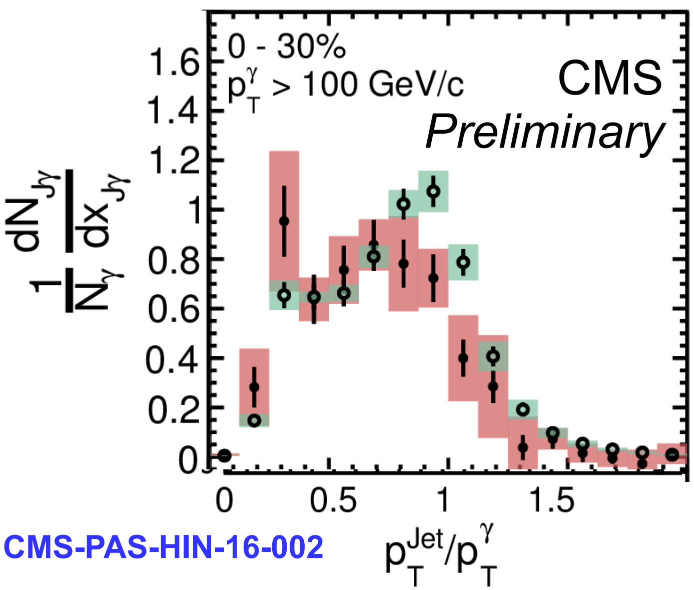
arXiv:1205.0206
CMS-PAS-HIN-13-006

Run2 ~0.5/nb



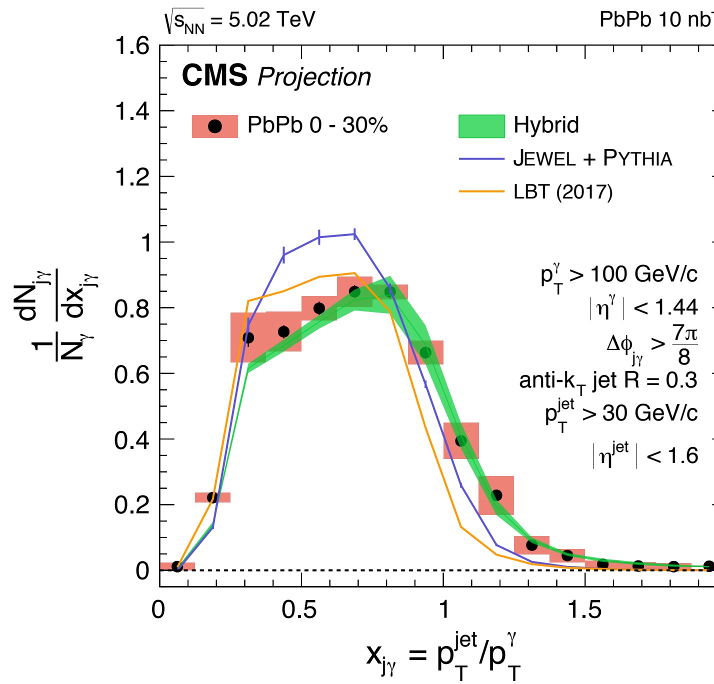
ATLAS-CONF-2016-110

PbPb 404 μb^{-1}, pp 25.8 pb^{-1}



CMS-PAS-HIN-16-002

HL-LHC ~10/nb



CMS-PAS-FTR-17-002

With HL-LHC statistics:

- Precise energy loss measurement
- Distinguish between theories / models

Precision energy loss: γ-jets

What is the optimal cone size? TBD

How low in p_T should we measure?

→ Ideally cover full phase space

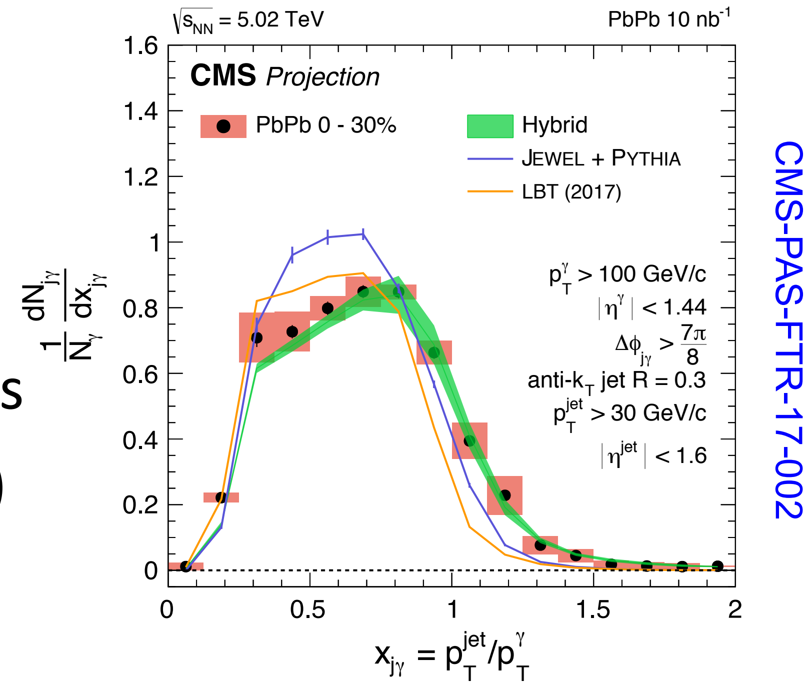
Try to measure ALL the recoiling energy

- Photon + multijet: NLO + semi hard emissions
- Photon + hadrons (missing p_T, radial profiles)

Go differential:

- medium path length
- centrality dependence

HL-LHC ~10/nb



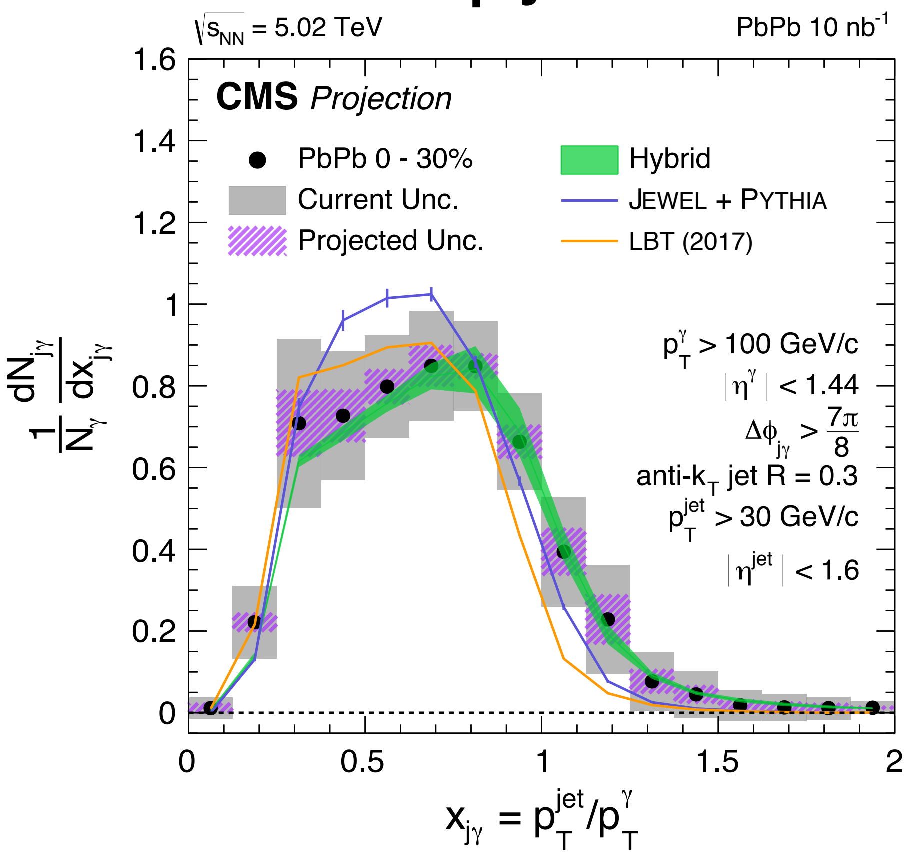
CMS-PAS-FTR-17-002

Experimentally: minimize jet energy scale and resolution uncertainties

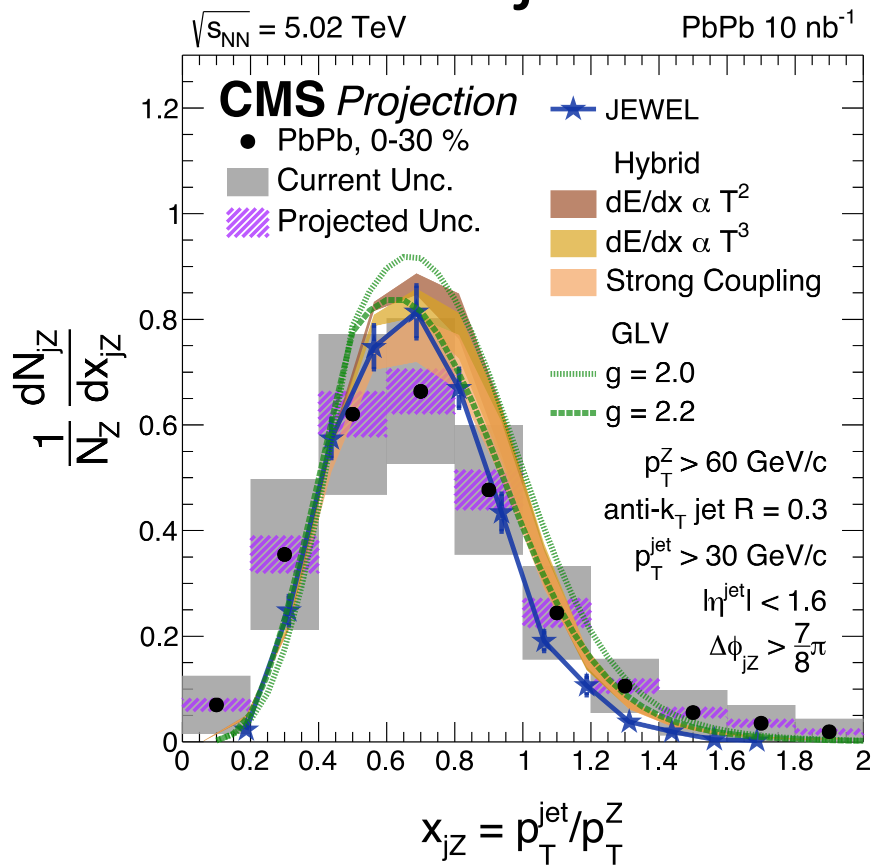
→ again, you have to measure all the energy

Precision energy loss: X + jets

γ-jet



Z-jet



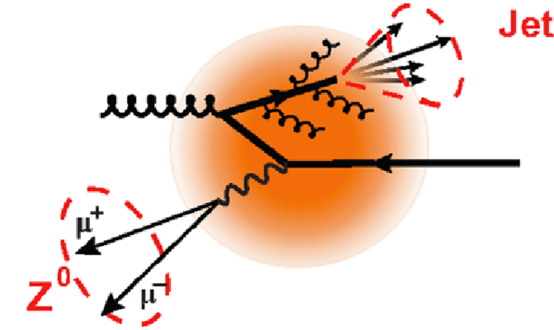
CMS-PAS-FTR-17-002

Projection for γ-jet and Z-jet energy balance measurements

Significant reduction of statistical and systematic uncertainties

Hadron-jet / jet-jet: initial parton kinematics less well known
but larger statistics allow for more differential precision measurements

Jet Deflection



Angular distribution of recoil jet relative to trigger axis

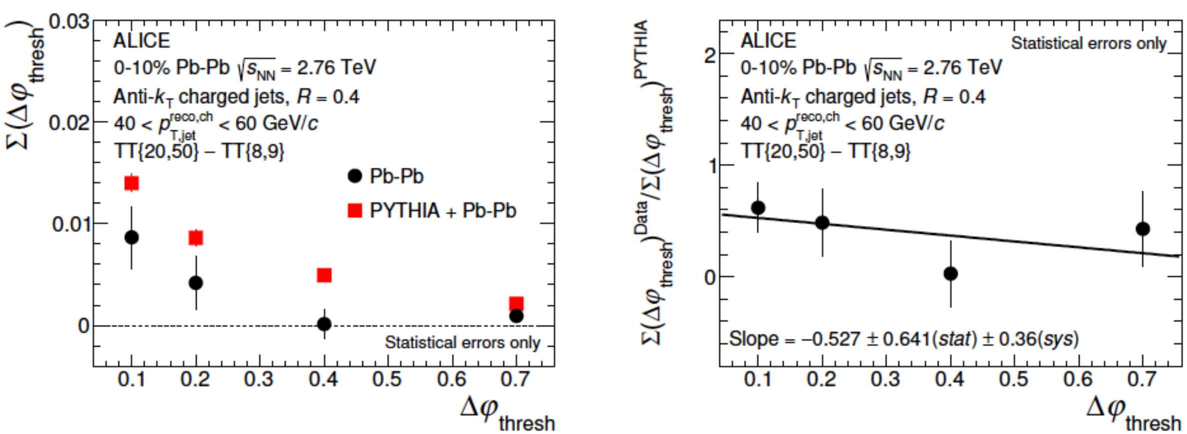
- Trigger: hadron, jet, boson (γ, Z, W)
  - Boson cleanest since it isn't affected by the medium
  - Hadron and jet much higher statistics + tool to probe geometry

Coherent scattering of recoil jet

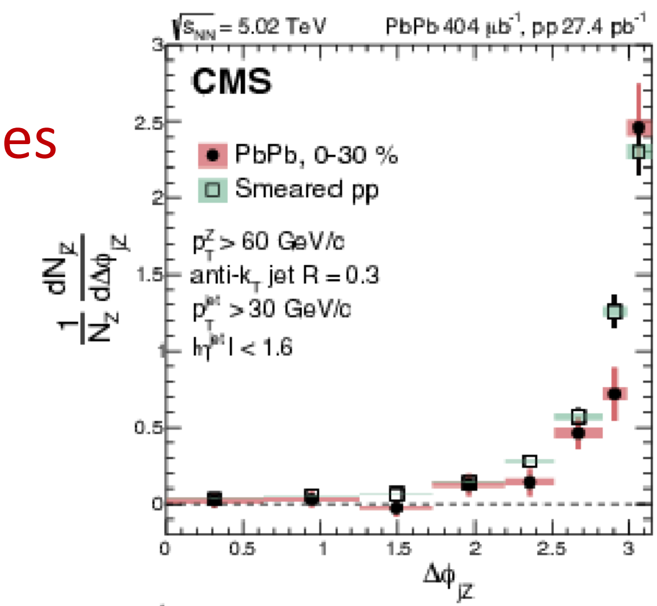
- In competition with shower broadening
- Significant if early in-medium

No evidence for jet deflection within uncertainties

→ Rule out or not with run3+4 data?



JHEP 09 (2015) 170



PRL119 (2017) 082301

It is very unlikely the distributions are different p-value > 0.4

Jet substructure

Different type of jet shapes and substructure sensitive to different dynamics of the parton shower.

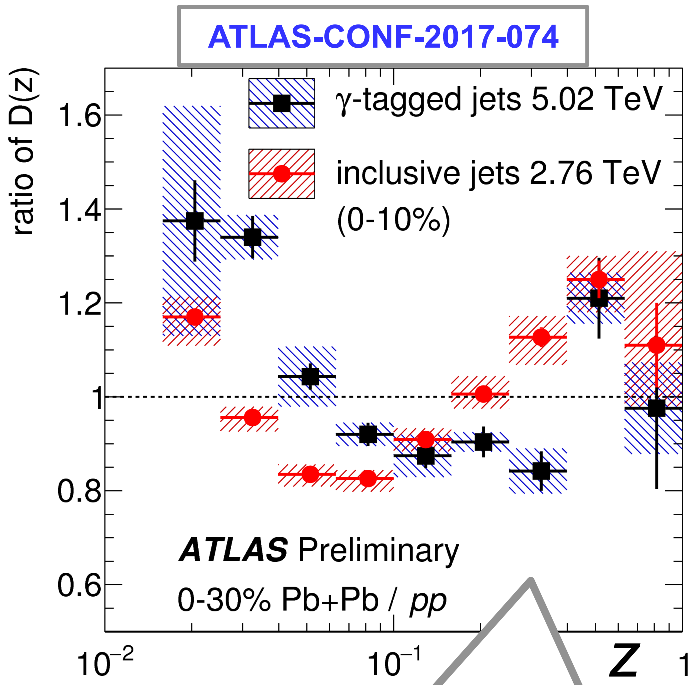
Alternatively: jet-jet correlations to study larger opening angle

LHC run1 and 2 PbPb data show modification of the jet substructure

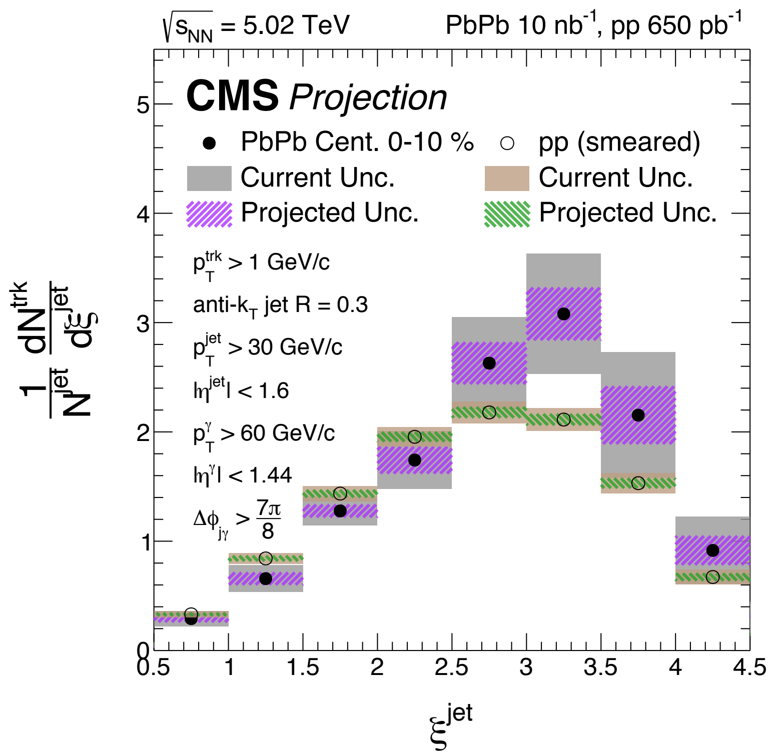
Jet fragmentation functions

Is the jet fragmentation function modified by the medium? Yes

What is the flavor dependence of this modification?



γ-jet fragmentation: tagging flavor



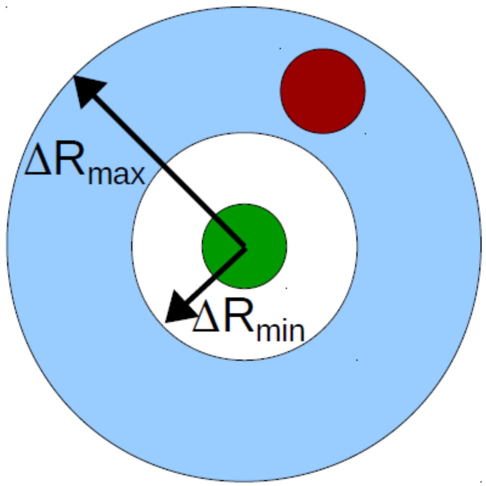
CMS-PAS-FTR-17-002

Increased statistics needed for the fragmentation at the highest fragment's momentum fractions (high z, low xi)

+ fragmentation function of c and b quark initiated jets.

b quarks might also be selected in top quark events

Neighboring jet studies

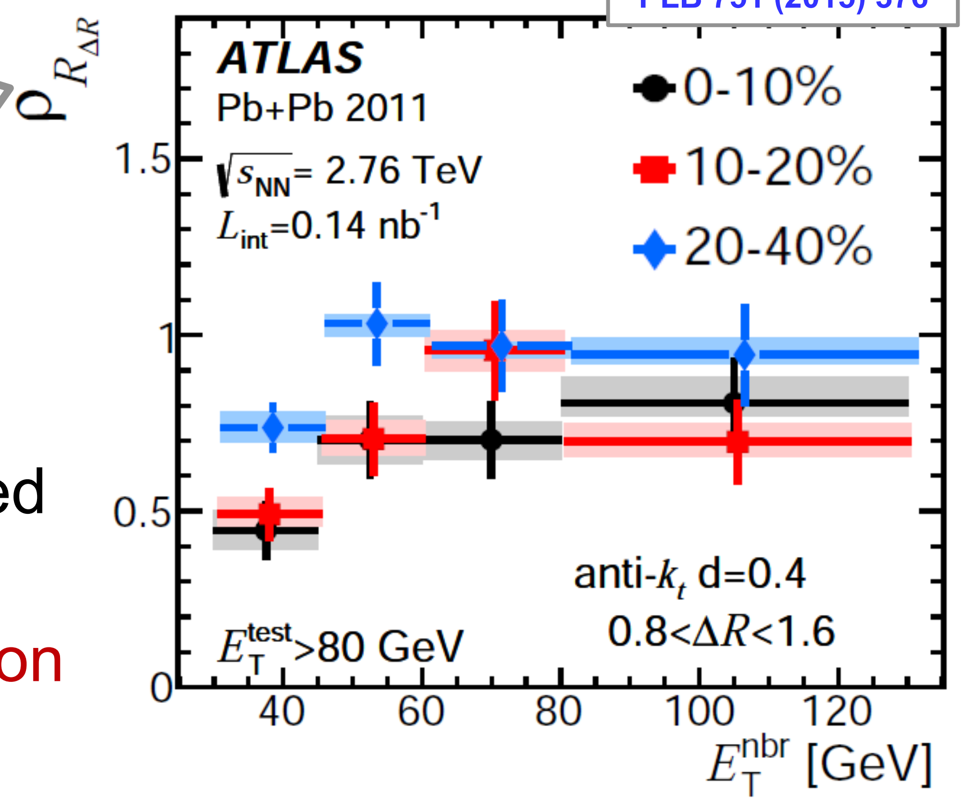


$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}}, \Delta R)$$

… rate of nearby jets = rate of subleading subjets in the interval $\Delta R_{min} - \Delta R_{max}$

ratio of $R_{\Delta R}$ = conditional R_{AA} for subjets

PLB 751 (2015) 376

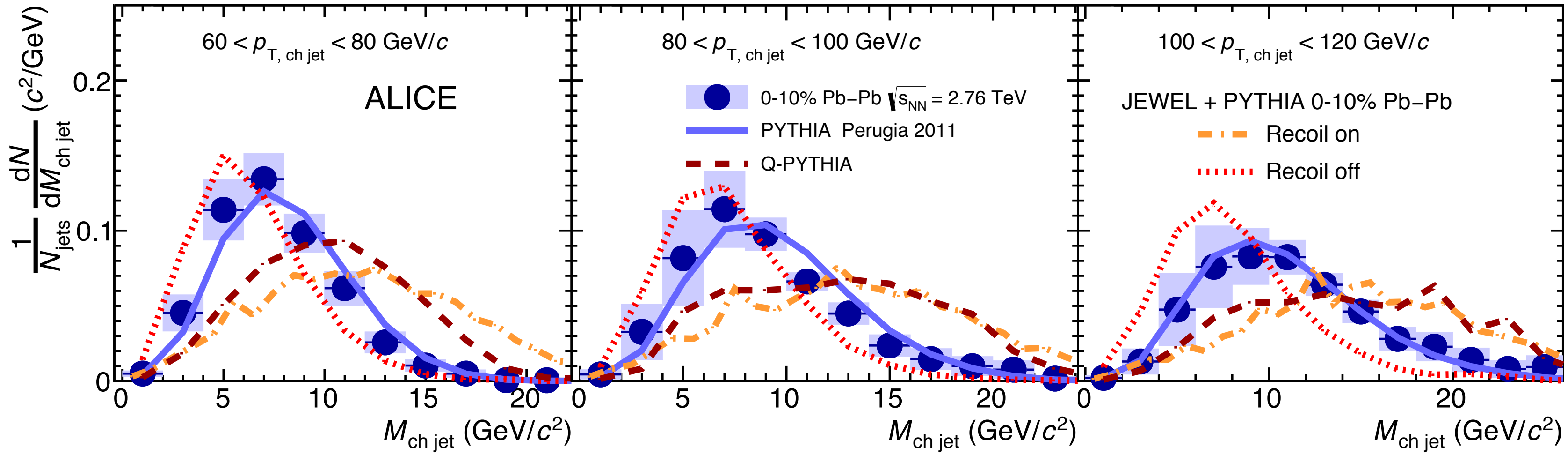


- Hard gluon emission, jet substructure
- Alternative to important but complicated substructure techniques
- Increased statistics implies the precision

Jet mass

Jet mass is sensitive to jet broadening

Example of a measurement which is systematics limited

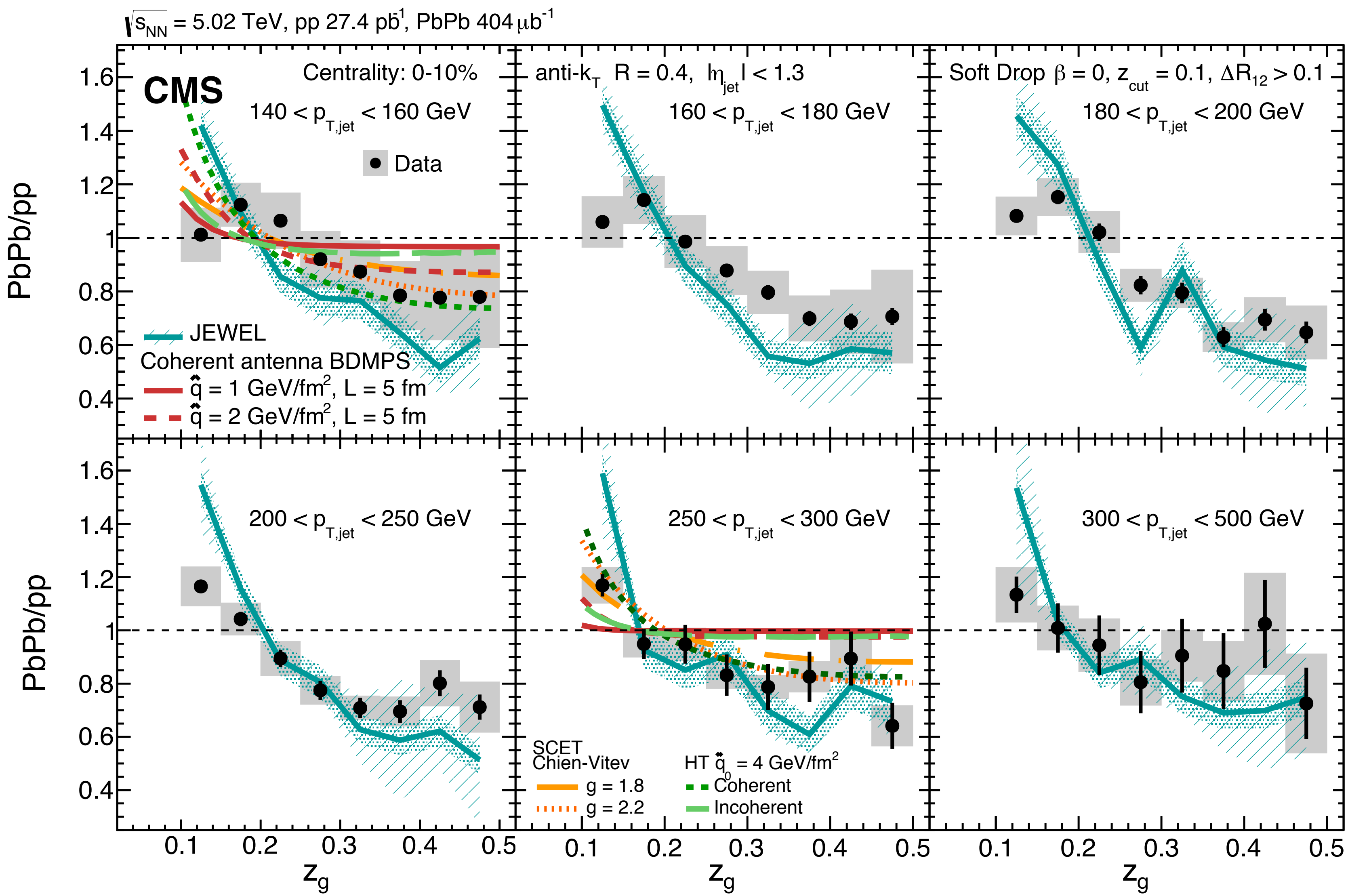


For ALICE

- *TPC tracking efficiency uncertainties:*
  significant reduction already in progress
- *Background estimate:*
  Realistic quenching models and further theoretical improvements will reduce the systematic uncertainty

Groomed substructure

1^{st} measurements with LHC run2 data show clear modifications of the jet substructure. Jet p_T dependence statistically limited



arXiv:1708.09429

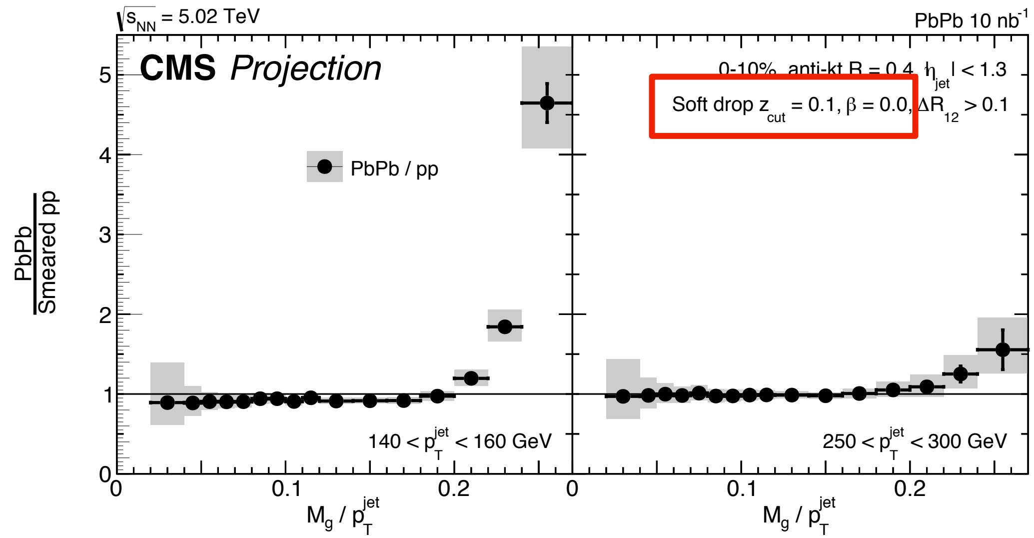
Groomed substructure

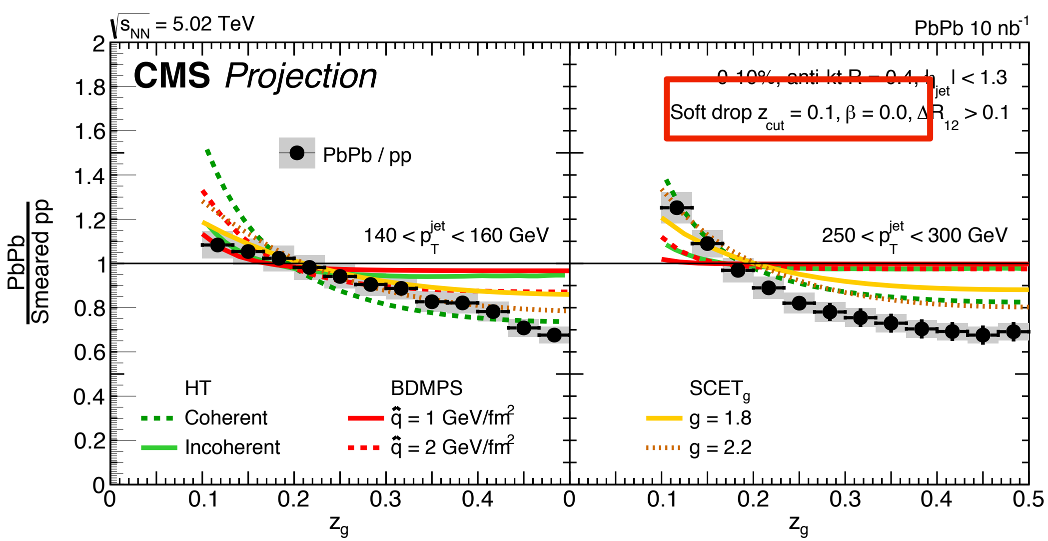
1[st] measurements with LHC run2 data show clear modifications of the jet substructure. Jet p_T dependence statistically limited

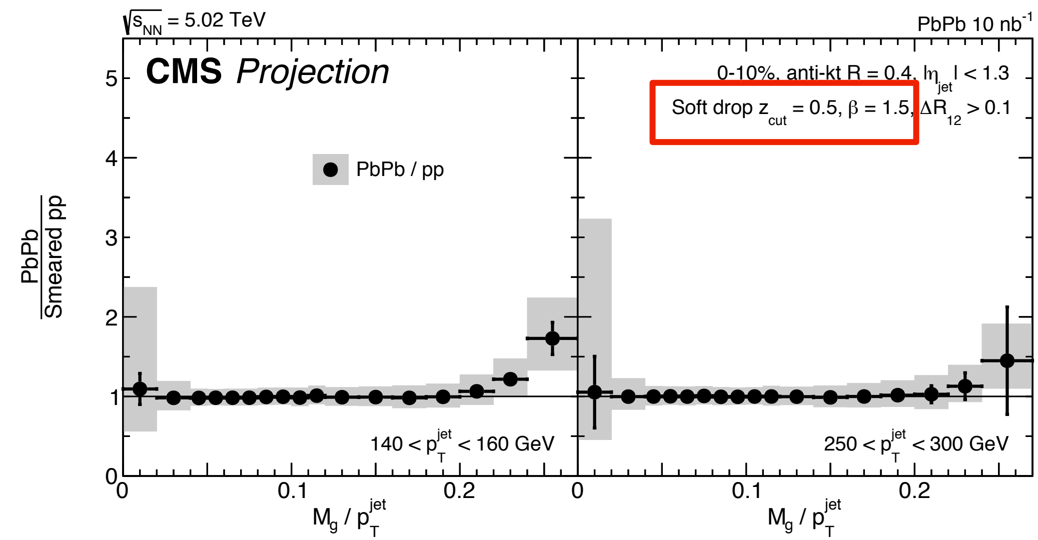
HL-LHC: unprecedented accuracy

By choosing observables carefully physics effects can be isolated

- Semi-hard emissions
- Medium response
- Role of color coherence

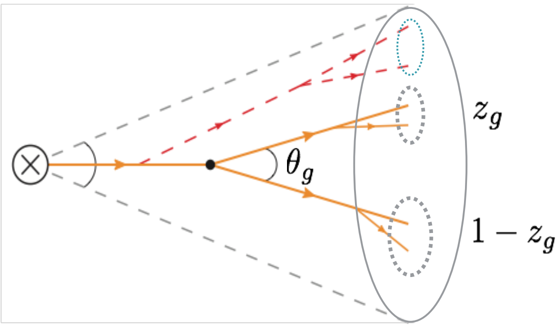






z_g CMS-PAS-FTR-17-002 $M_g/p_{T,jet}$

Substructure correlations



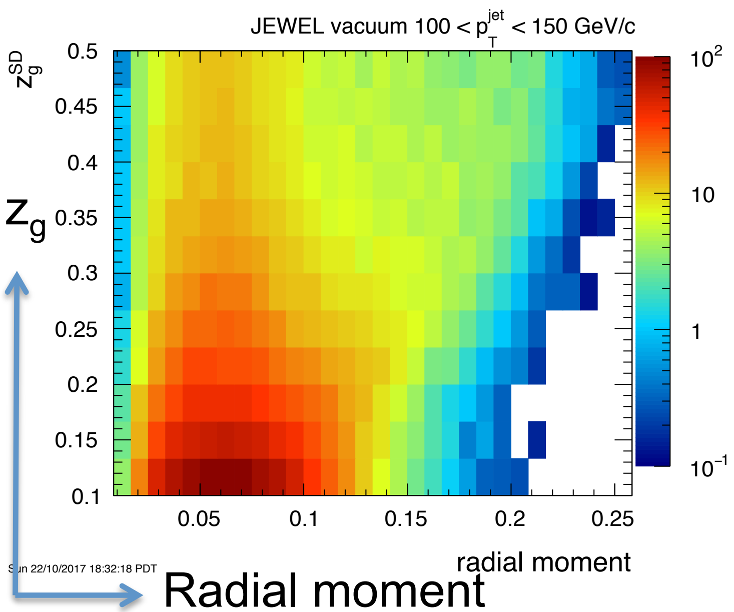
Correlations may suppress background effects

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

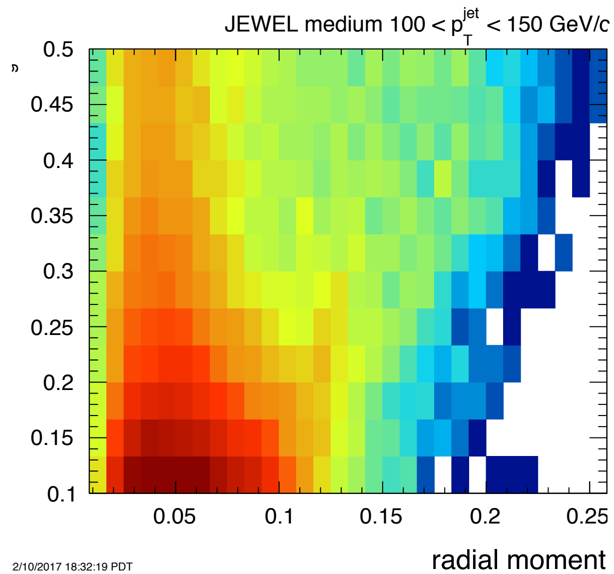
Example: JEWEL, p_T^{jet}= 100 GeV; recoil off
z_g (std SoftDrop b=0, z>0.1) vs. radial moment

$$g = \sum_{i \in \mathrm{jet}} \frac{p_T^i}{p_T^{\mathrm{jet}}} |r_i|$$

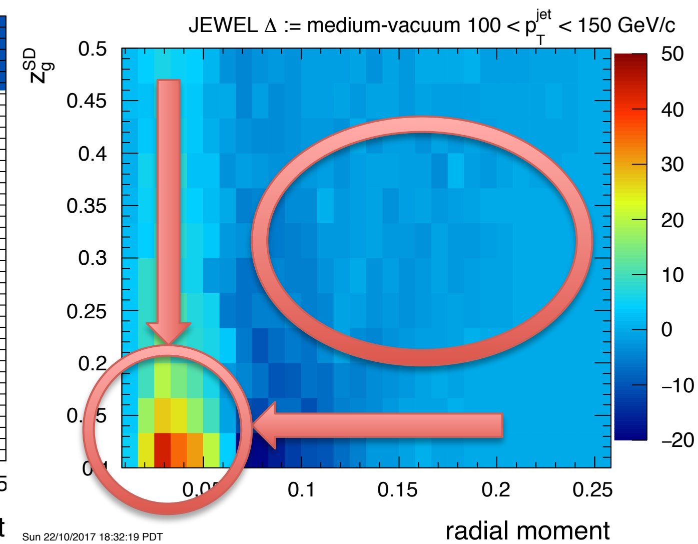
JEWEL VACUUM (pp)



JEWEL (10% central PbPb) - MEDIUM



MEDIUM-VACUUM
Subtraction – not a ratio!

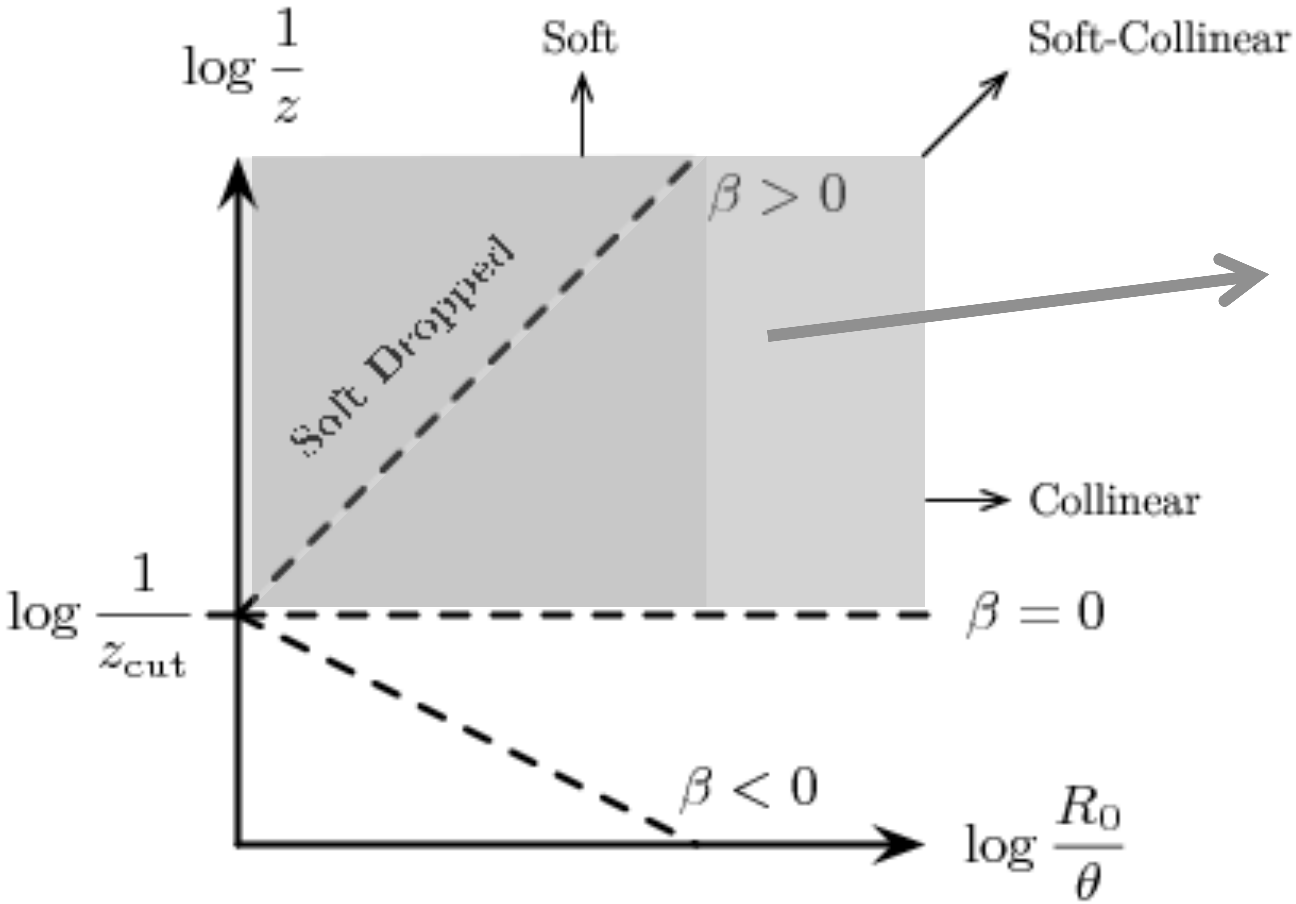


Observations (a per jet observable – shape studies):

Study by ALICE

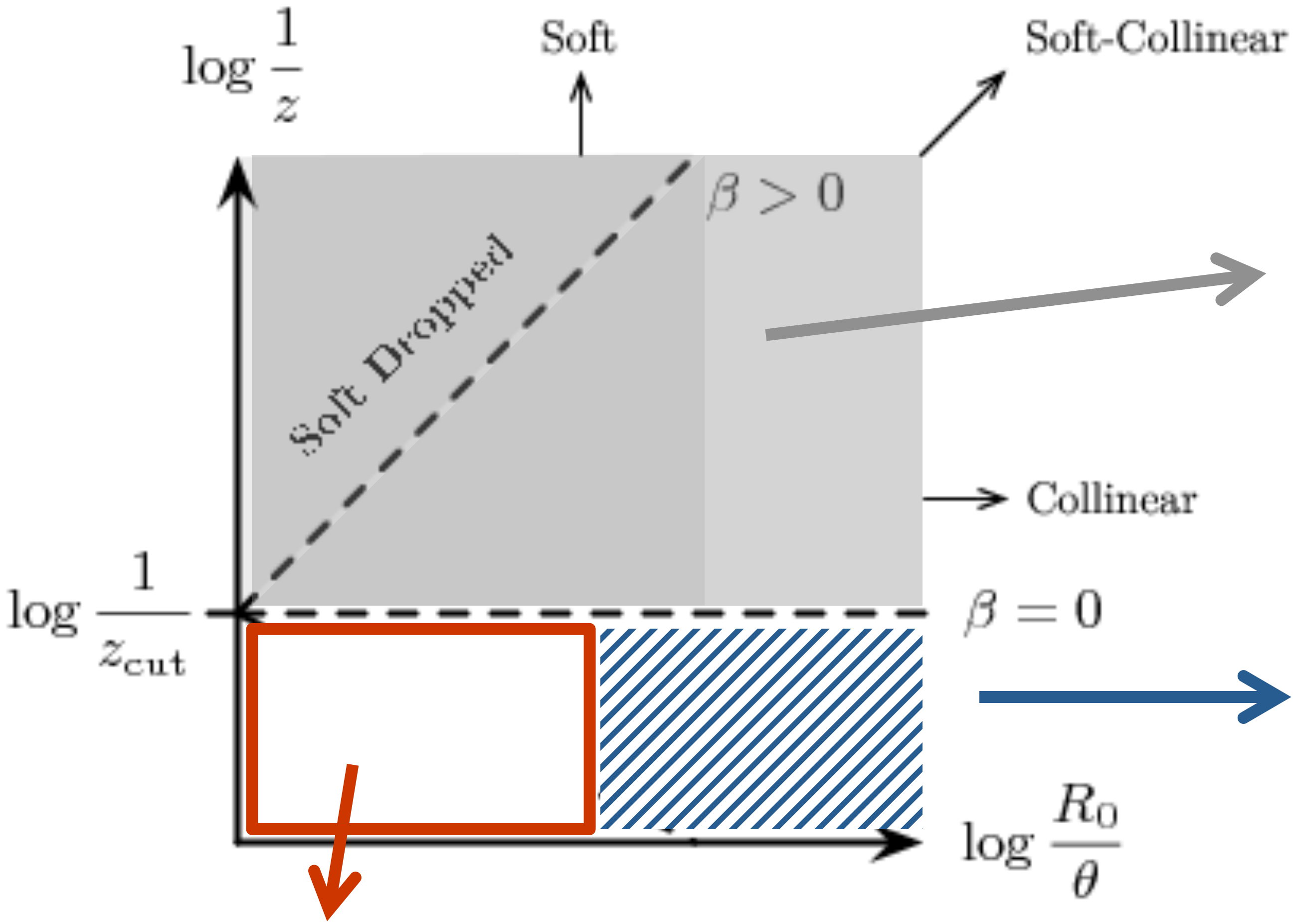
- Known effect: JEWEL "collimates" jets in medium
- Medium: => enhances low z_g
- Medium: => small radial moment preferred

Emission phase space



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

Emission phase space



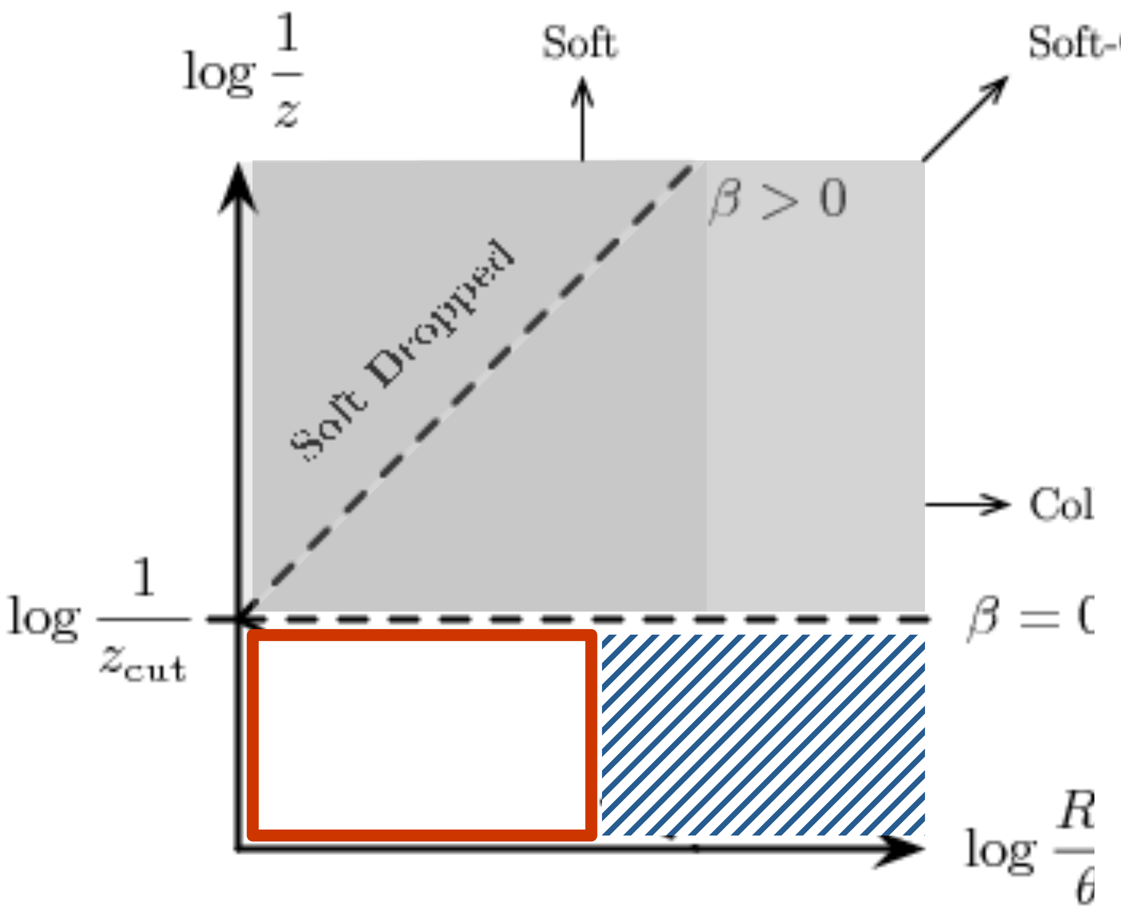
For β=0: both soft and soft-collinear emissions are vetoed

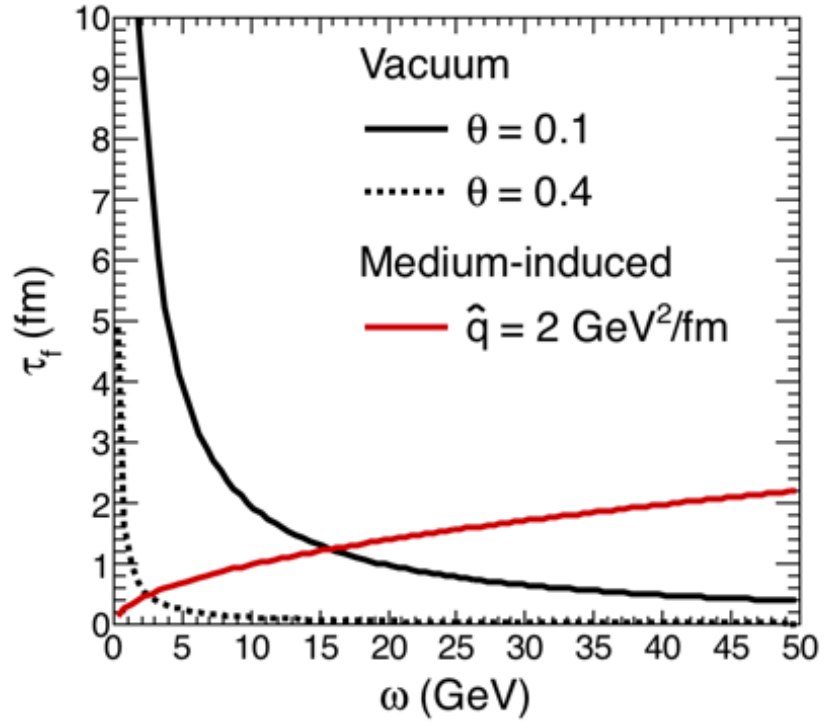
CMS also removes jets with $\Delta R_{12}<0.1$ (ΔR_{12} = η-φ separation between the two subjets)

With splitting function analysis we explore this region of phase space

Earliest vacuum splittings: lower left corner

Emission phase space

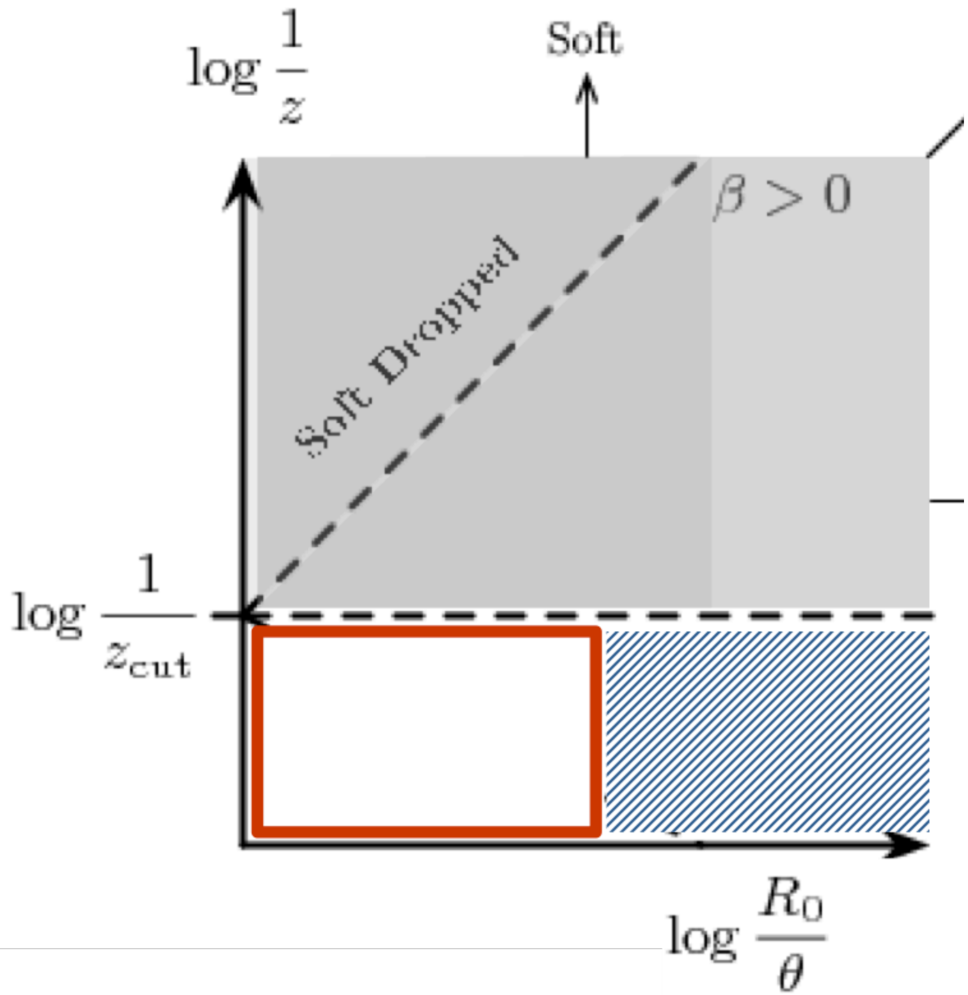




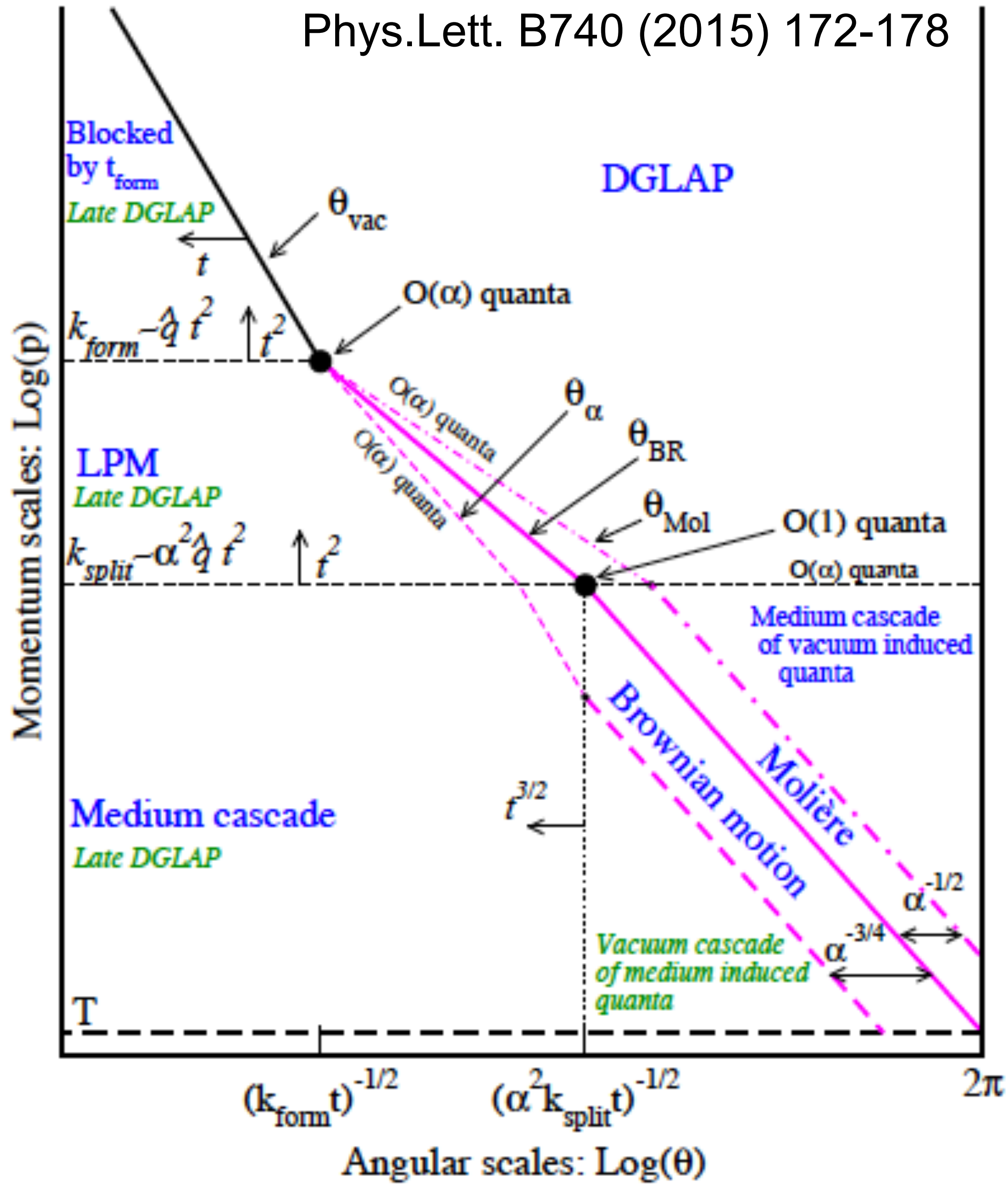
$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega} \qquad \tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

Can vary formation time by varying opening angle and p_T of subleading subjet

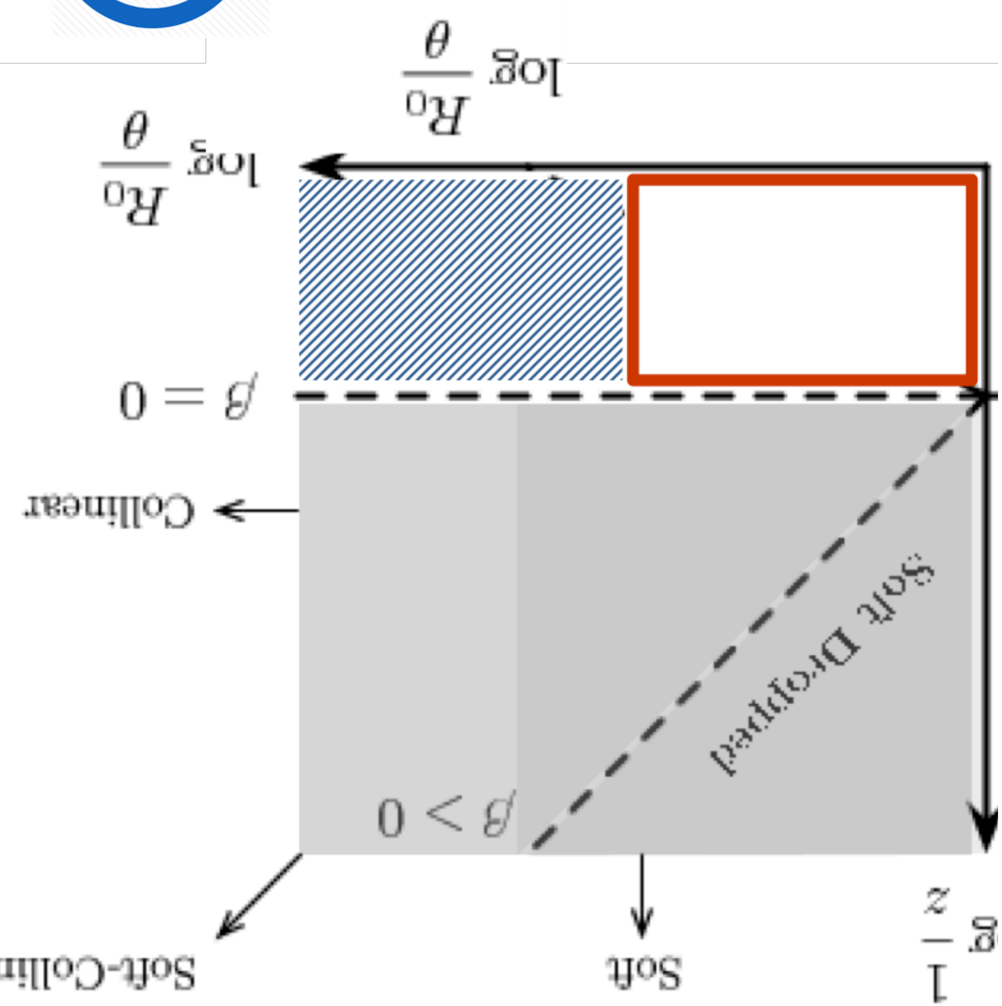
Radiation diagram



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



Radiation diagram



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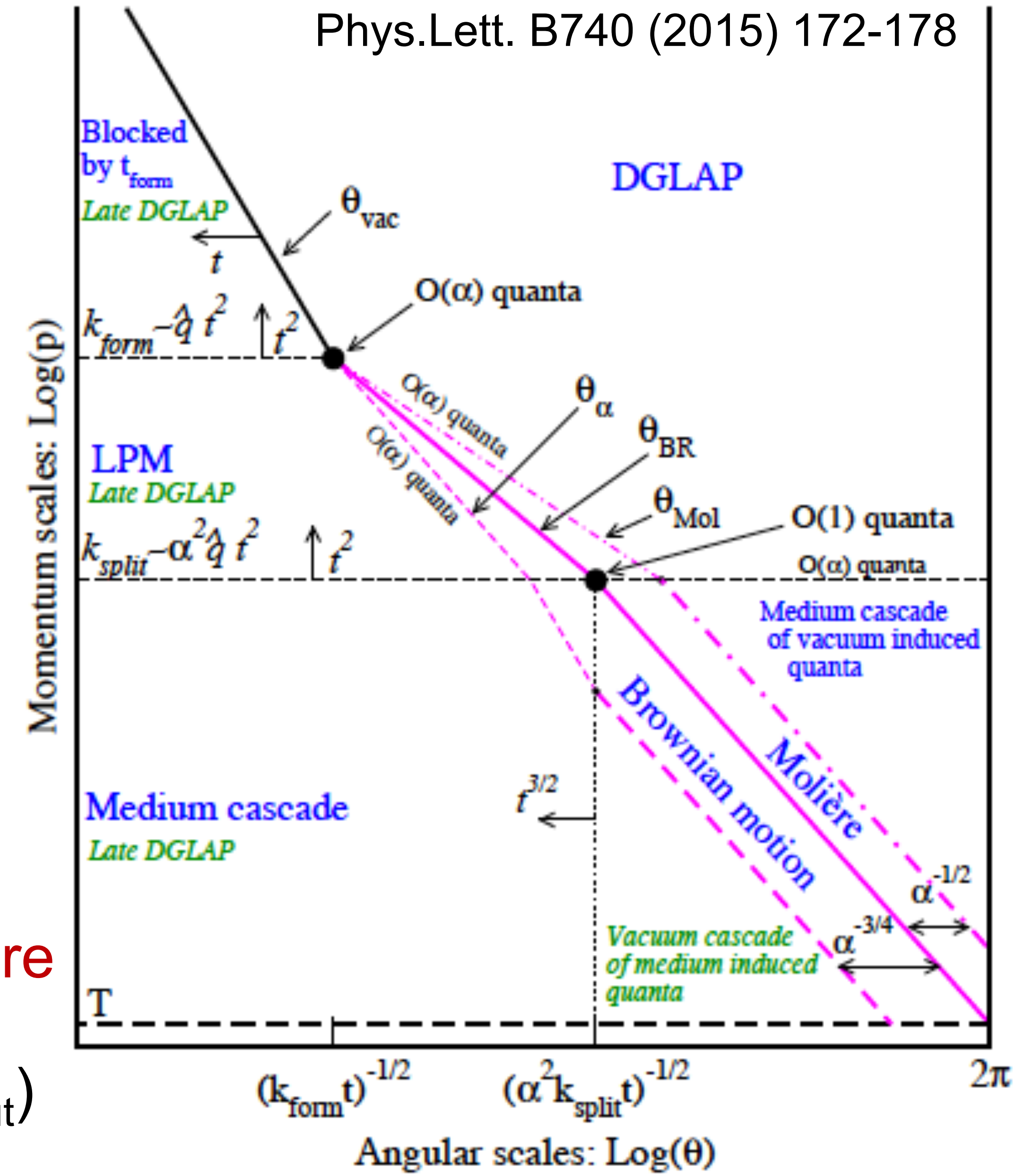
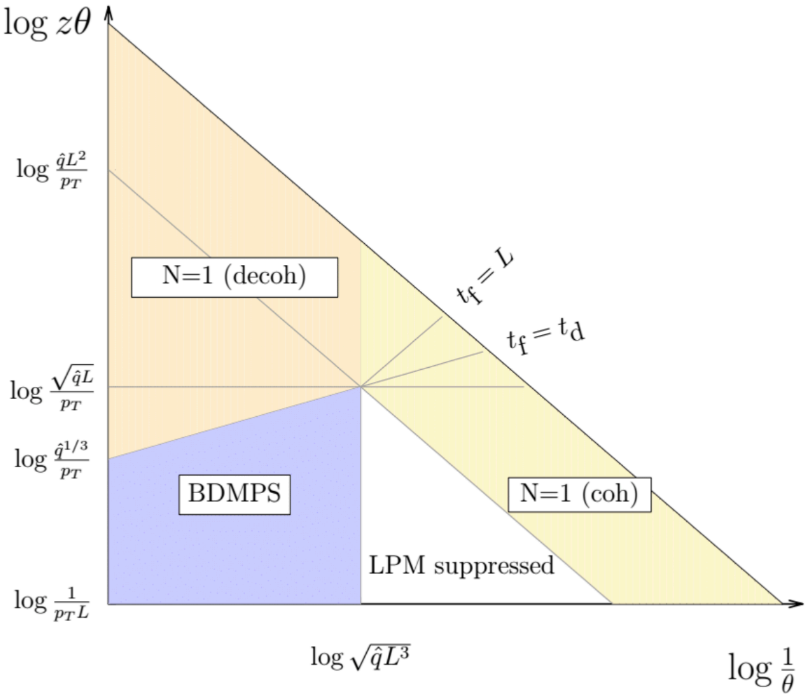


Which part of the parton cascade are we seeing?

Varying SoftDrop parameters (β,z_{cut}) allows us to move through

Radiation diagram



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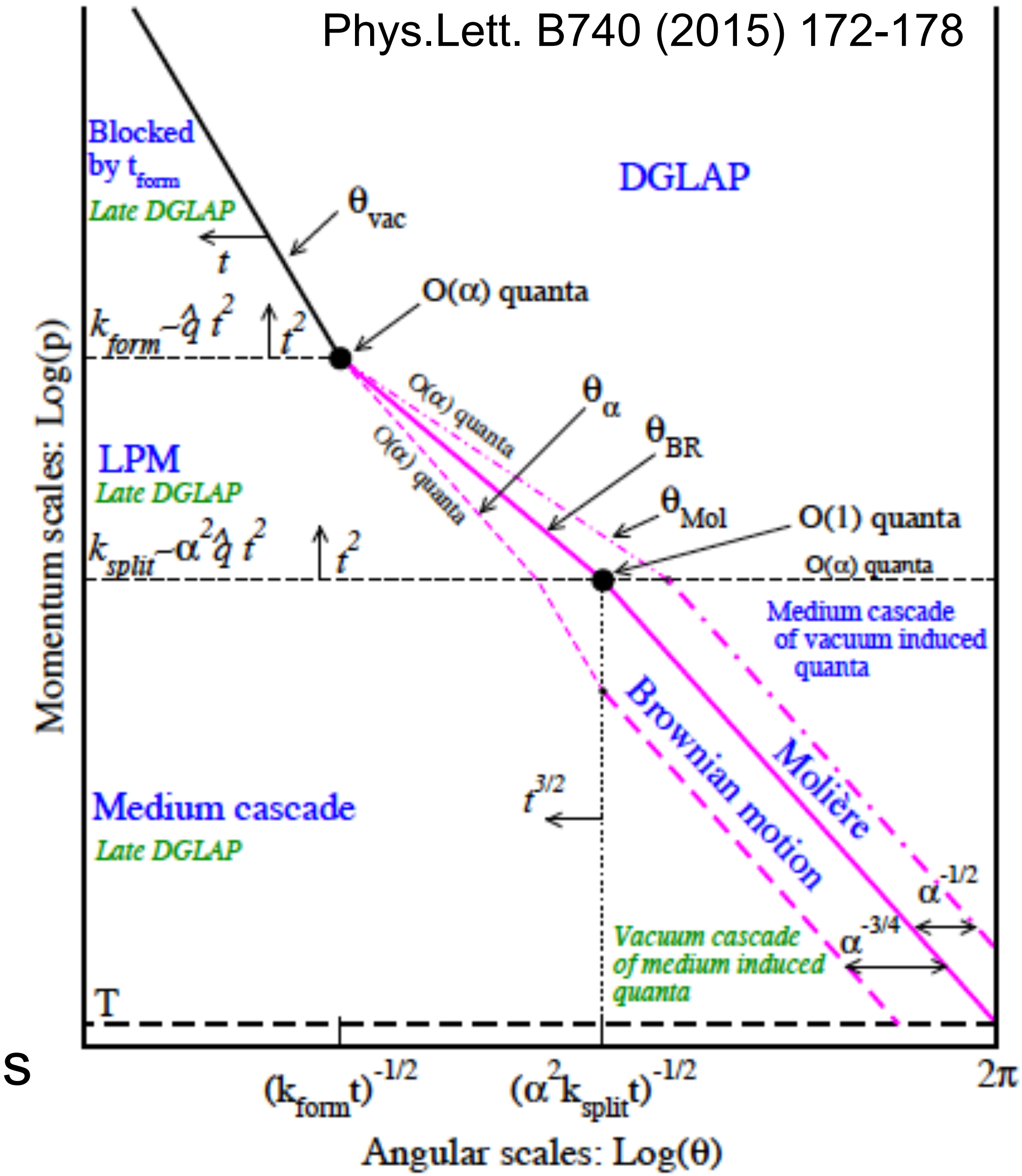


CERN jet workshop Aug. 2017:

"With substructure one can probe different regions of radiation phase space:

- semi-hard medium radiations
- Multiple soft radiations
- Regulate which vacuum splittings are probed

"

Summary

Goal for HL-LHC: Measure the microscopic structure of the QGP

Large statistics of jets up to p_T=1 TeV for ATLAS+CMS
and p_T=200 GeV for ALICE

Precision energy loss and jet deflection measurement with X+jet

Dynamics of parton shower accessible through
- Jet correlations
- Jet shape observables
- Jet substructure with subjets

Probe different regimes of the radiation phase space to
1) Understand the mechanism responsible for jet quenching
2) Map out the properties of the QGP

Not discussed but important:
Is there jet quenching in small systems?
Can we measure the jet quenching turnon?

backup

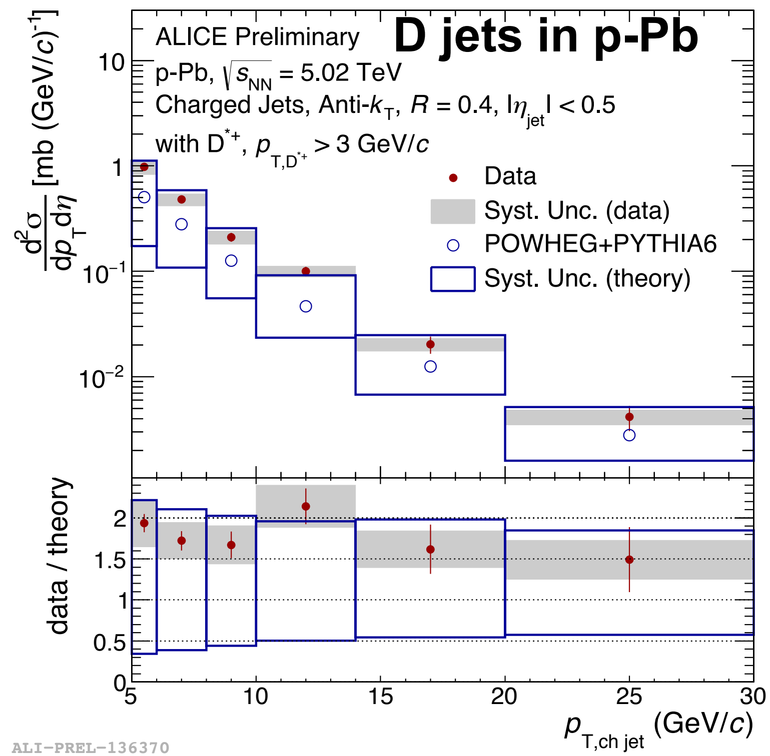
Opportunities with HF jets in ALICE

Can HF-jets extend what we learn with jets?

- **Mass dependence** of energy loss at low jet p_T (mass effects for b-jets expected to be relevant for p_T<75 GeV/c) J. Huang et al., PLB 726, 1–3, 251-256 (2013)
- **Different fragmentation** pattern (also in vacuum)
- (Heavy) "**quark tagging**"
    - jet shape for heavy-flavour jets
- Push jet measurements at **lower p_T?**

"Hard scattering" tagging

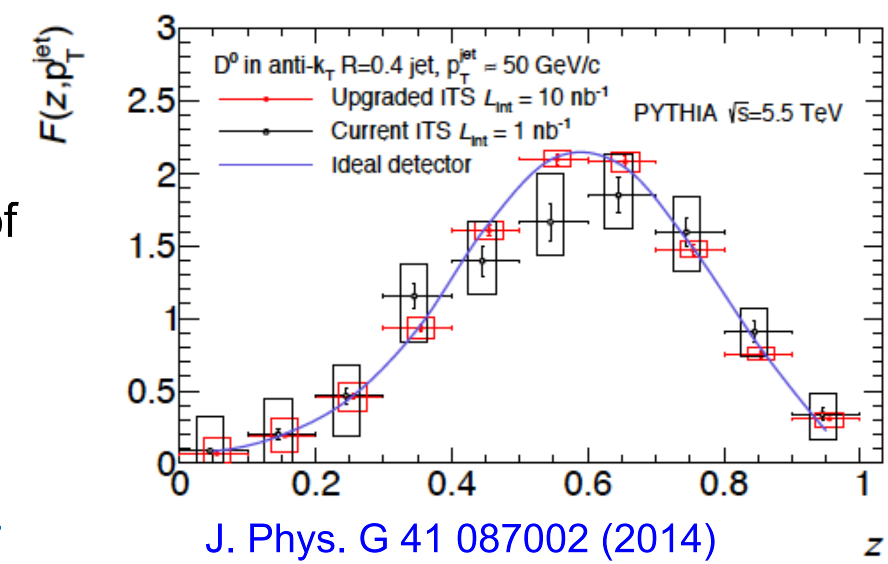
- **D meson-tagged jets**: uniqueness in the study of parton shower and jet shape in the medium



ALICE HF-jet measurements Run 3/4

- D-tagged jets (with full D mesons)
- b-tagged jets
- Heavy-flavour jets with HF-electron tagging
- Production as well as measurements of correlation of heavy-flavour signals with jets

Performance for low p_T jets is under study



J. Phys. G 41 087002 (2014)