boson + jet

Recent ~~jet~~ results in heavy-ion collisions with CMS

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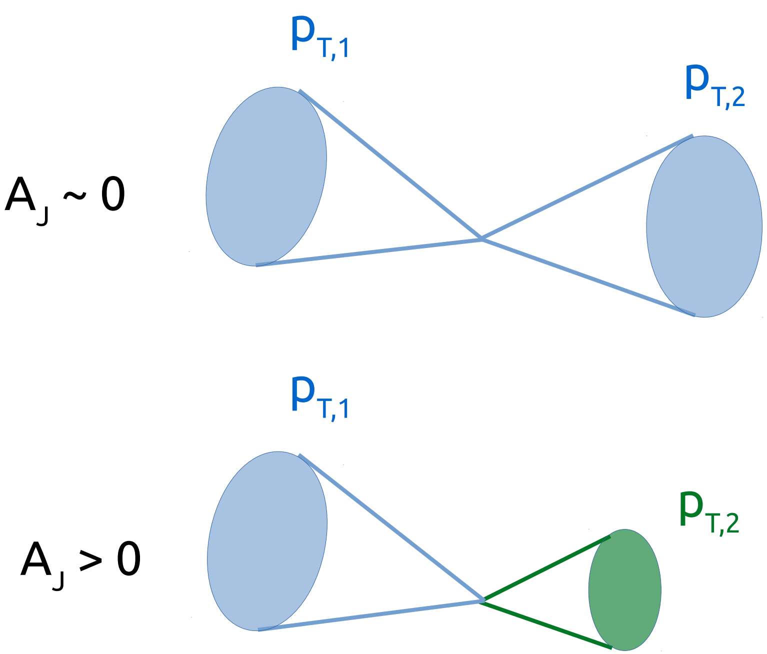
EPS 2019
11 July 2019

Jets as a probe of the QGP

Parton energy loss is related to the thermodynamical and transport properties of the Quark Gluon Plasma

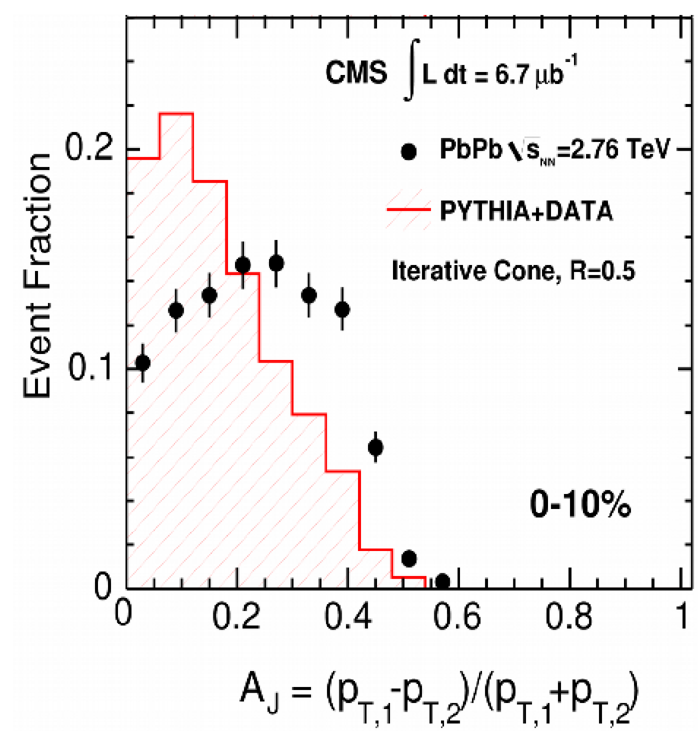
Inclusive and di-jet measurements are good for discovering physics effect :
e.g dijet asymmetry of leading and subleading jets



$p_{T,1} > 120$ GeV, $p_{T,2} > 50$ GeV

$\Delta\phi > 2\pi/3$

CMS, PRC84 (2011) 024906



All jets lose energy while traversing the QGP →
controlled configuration of the initial hard scattering is needed

Boson + jets as a probe of the QGP

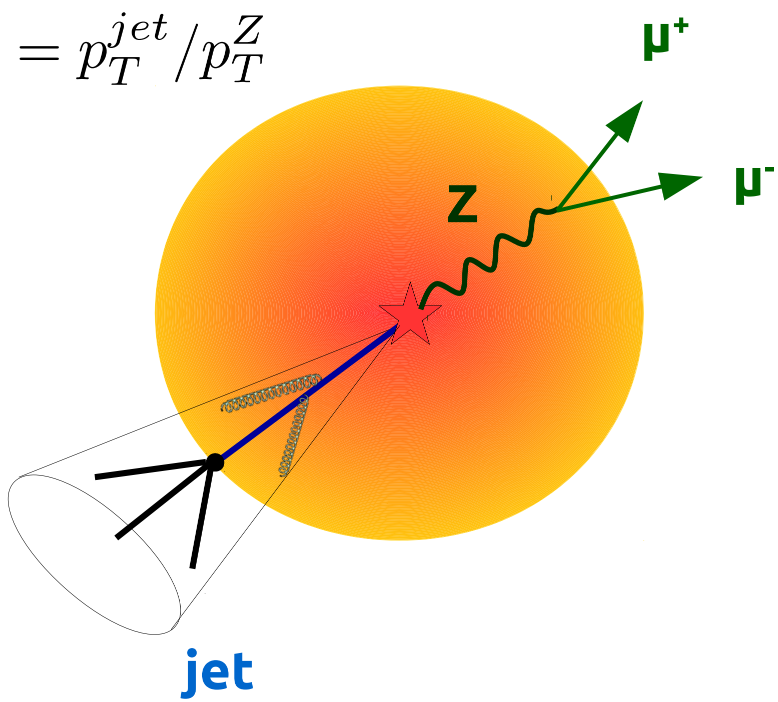
Parton energy loss is related to the thermodynamical and transport properties of the Quark Gluon Plasma

Bosons ($Z \rightarrow l^+l^-/\gamma$) :

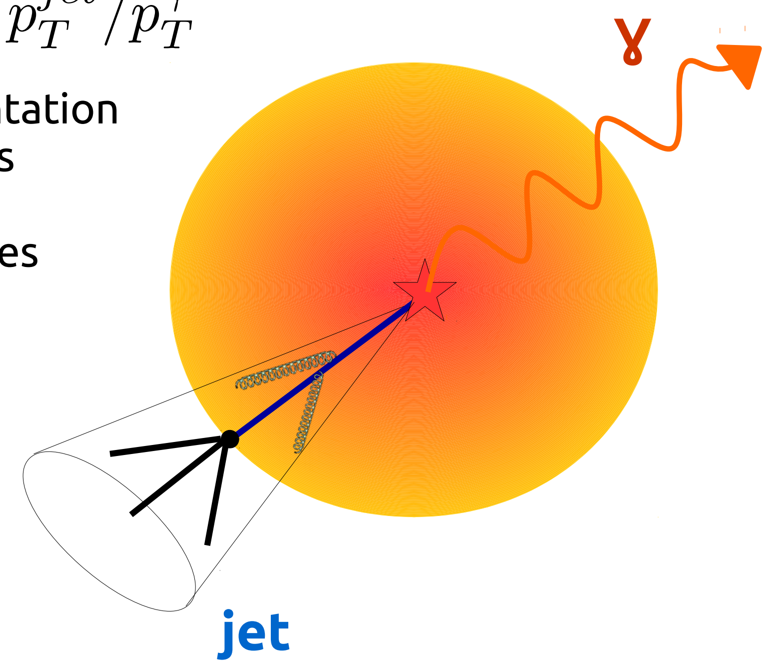
- Do not interact strongly with the QGP
- In "boson + jets" configuration they fix the recoiling jet kinematics (LO)
- At LHC energies enhanced quark jets sample : $q(\bar{q}) + g \rightarrow Z(\gamma) + q(\bar{q})$

CMS measured :

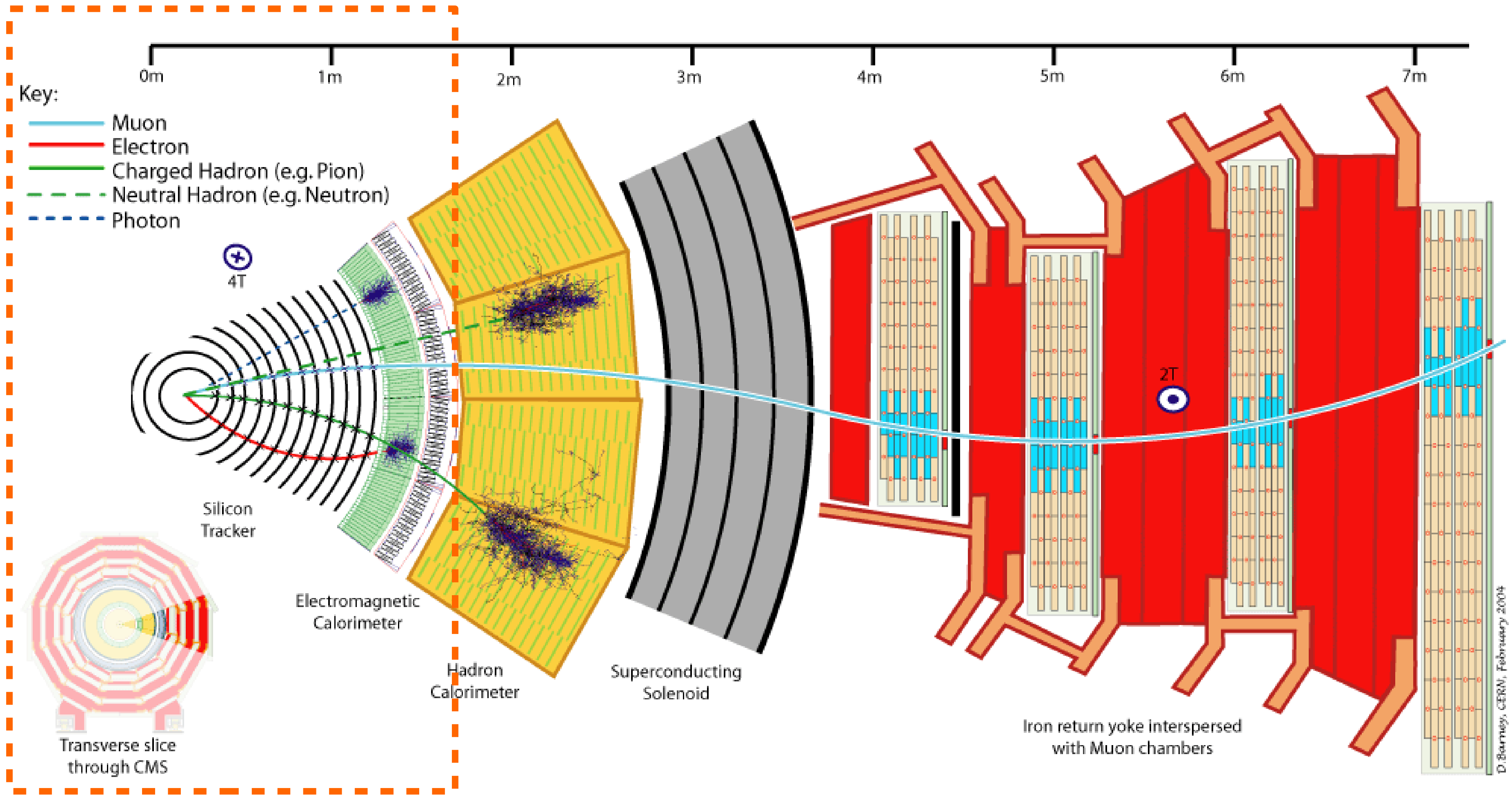
- $X_{jZ} = p_T^{jet}/p_T^Z$



- $X_{j\gamma} = p_T^{jet}/p_T^{\gamma}$
- Fragmentation functions
- Jet shapes



CMS detector : photons and electrons

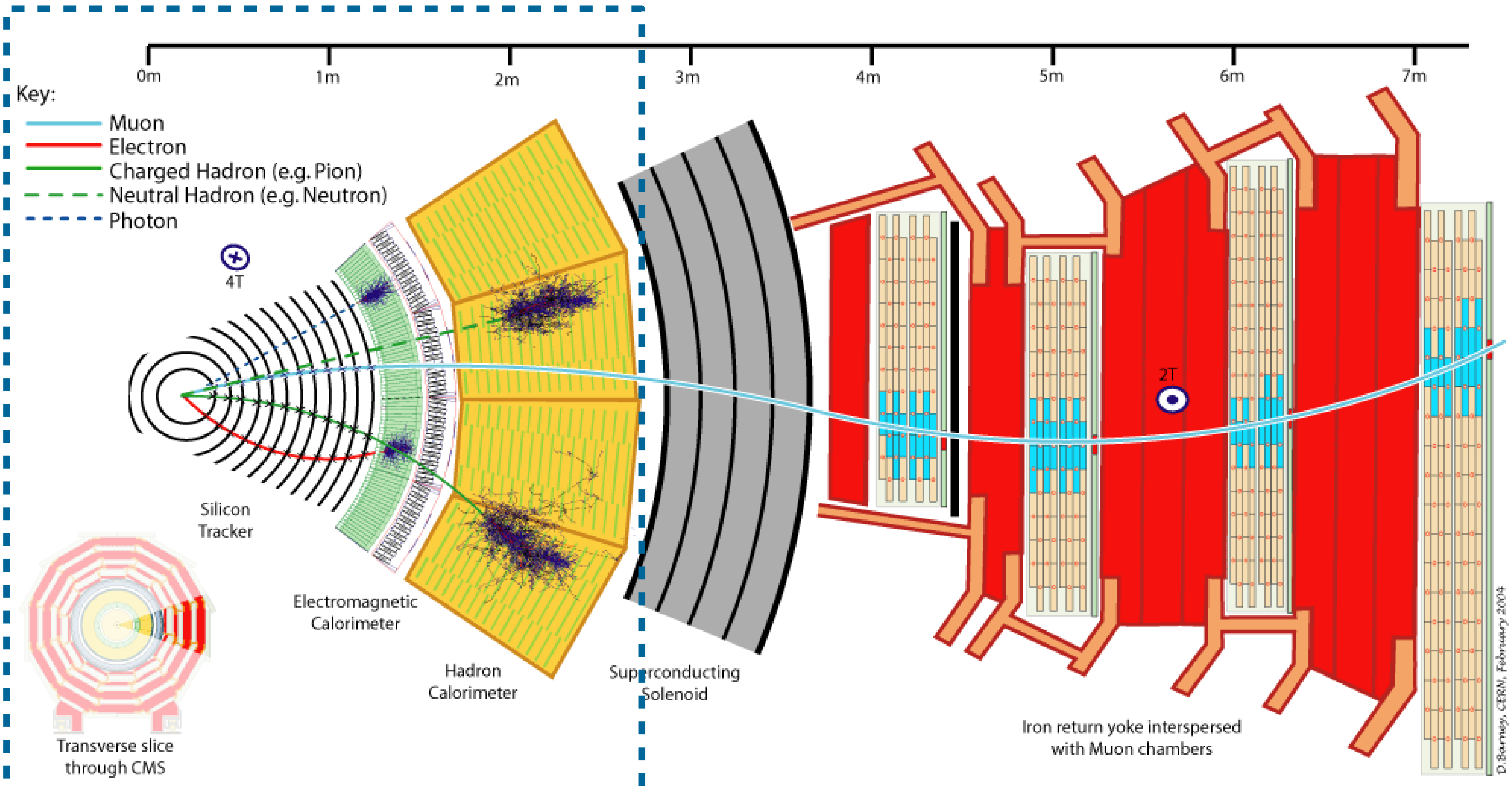


Photons and electrons

Photons* in ECAL barrel : |η| <1.44
Electrons* in ECAL barrel and endcaps : |η| < 2.5

* objects acceptance for the analysis shown in this talk

CMS detector : jets

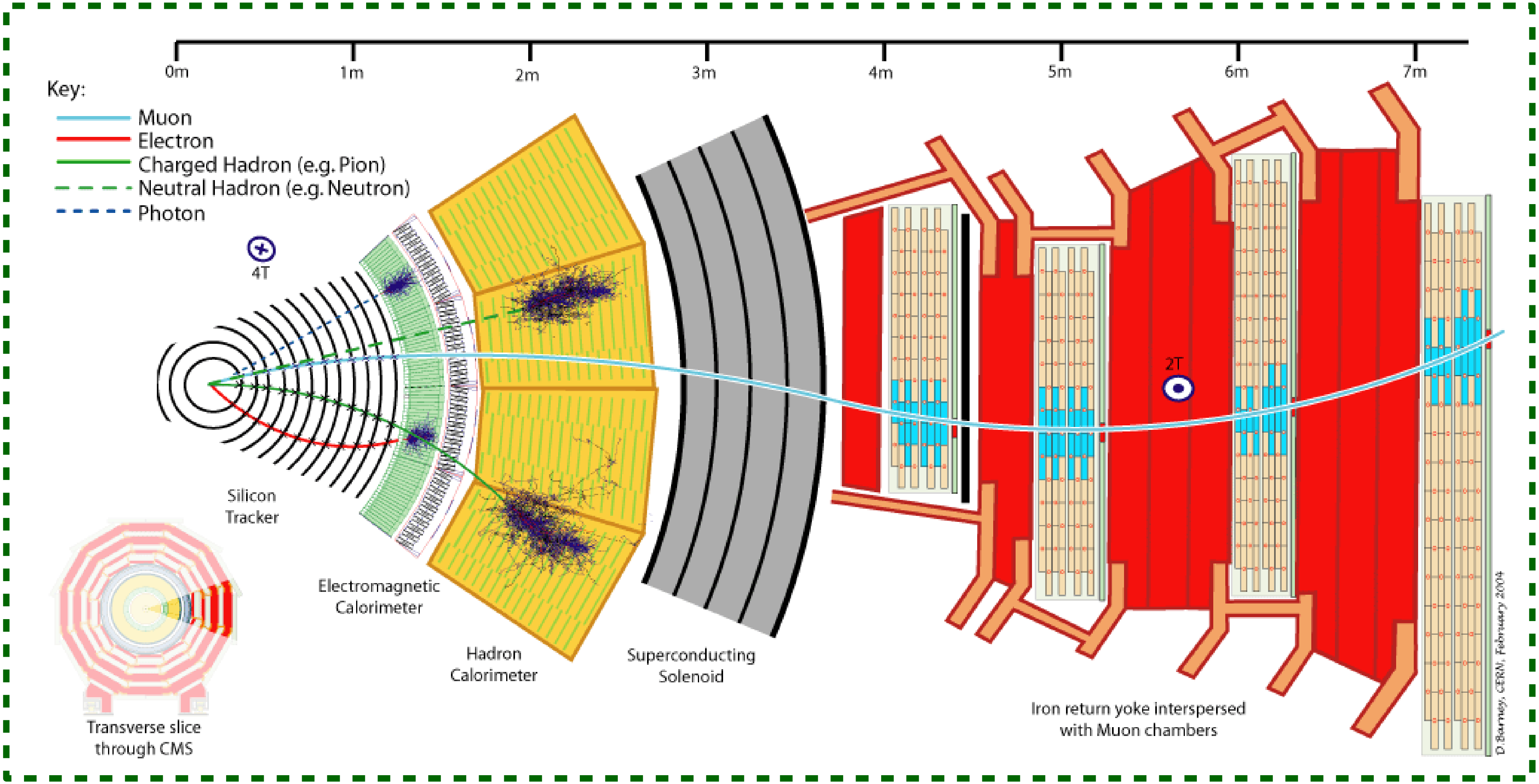


jets

Jets* in |η| < 1.6

* objects acceptance for the analysis shown in this talk

CMS detector : muons

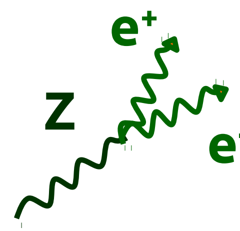


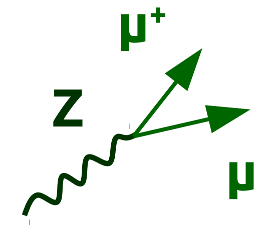
muons

Muons* in |η| <2.4

* objects acceptance for the analysis shown in this talk

Object selections



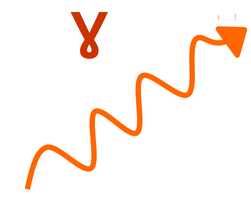


Electrons : $|\eta| < 2.5$, $p_T > 20$ GeV/c,
ECAL barrel-endcap gap excluded

Muons : $|\eta| < 2.4$, $p_T > 10$ GeV/c

Z boson : $e^+e^-/\mu^+\mu^-$ with $p_T > 40$ GeV/c, $70 < M_{inv} < 110$ GeV/c^2

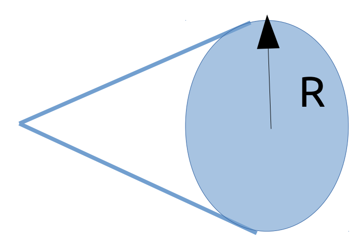
Each Z candidate is paired with all the jets in the event



Photons : $|\eta| < 1.44$, $p_T > 40$ GeV , <u>isolation</u> ($SumIso^{UE\text{-}sub}$) < 1 GeV/c

The highest p_T isolated photon is paired with all the jets in the event

Jets : anti-kT algorithm with R = 0.3, $|\eta| < 1.6$, $p_T > 30$ GeV/c



Jets reconstructed within $\Delta R < 0.4$ from lepton are rejected to eliminate jet energy contamination by leptons coming from Z

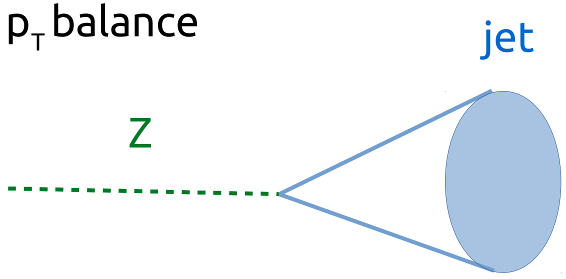
All "boson+jet" pairs are selected , to suppress initial and final state radiation effect → look into back-to-back pairs only $\Delta\phi_{jZ(\gamma)} > 7\pi/8$

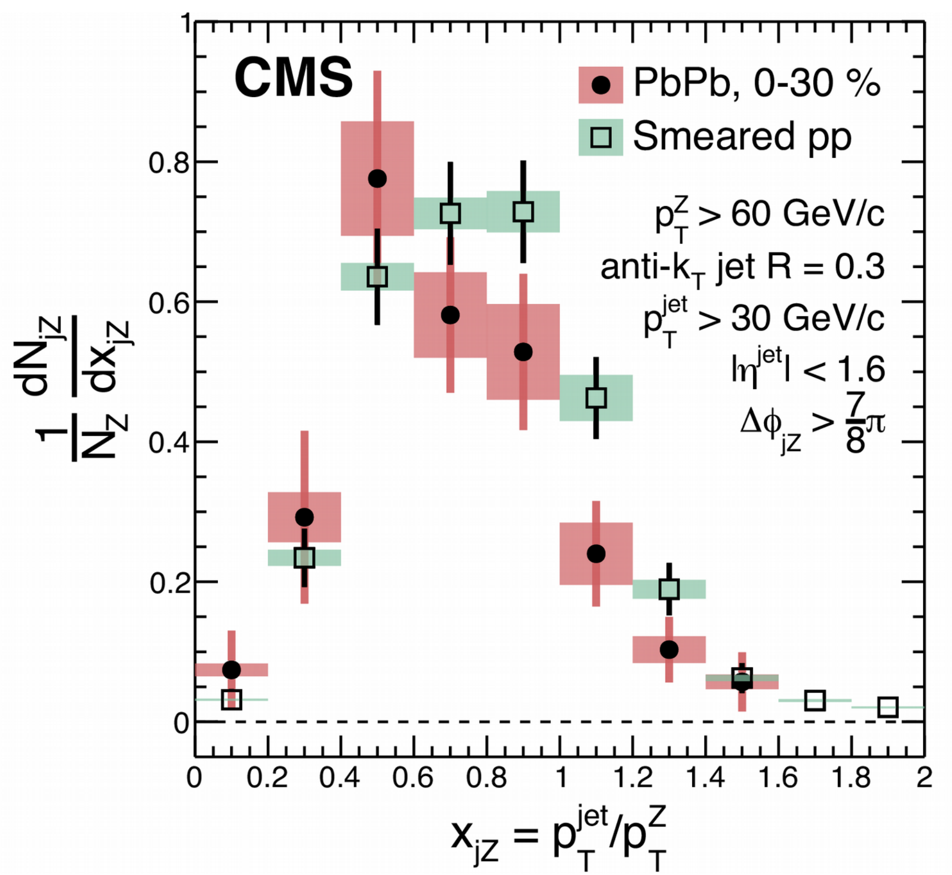
Z+jet correlations

Phys. Rev. Lett. 119 (2017) 082301

What is the amount of energy lost in jet cone? → Z - jet p_T balance

Back-to-back pairs : $\Delta\phi_{jZ} > 7\pi/8$





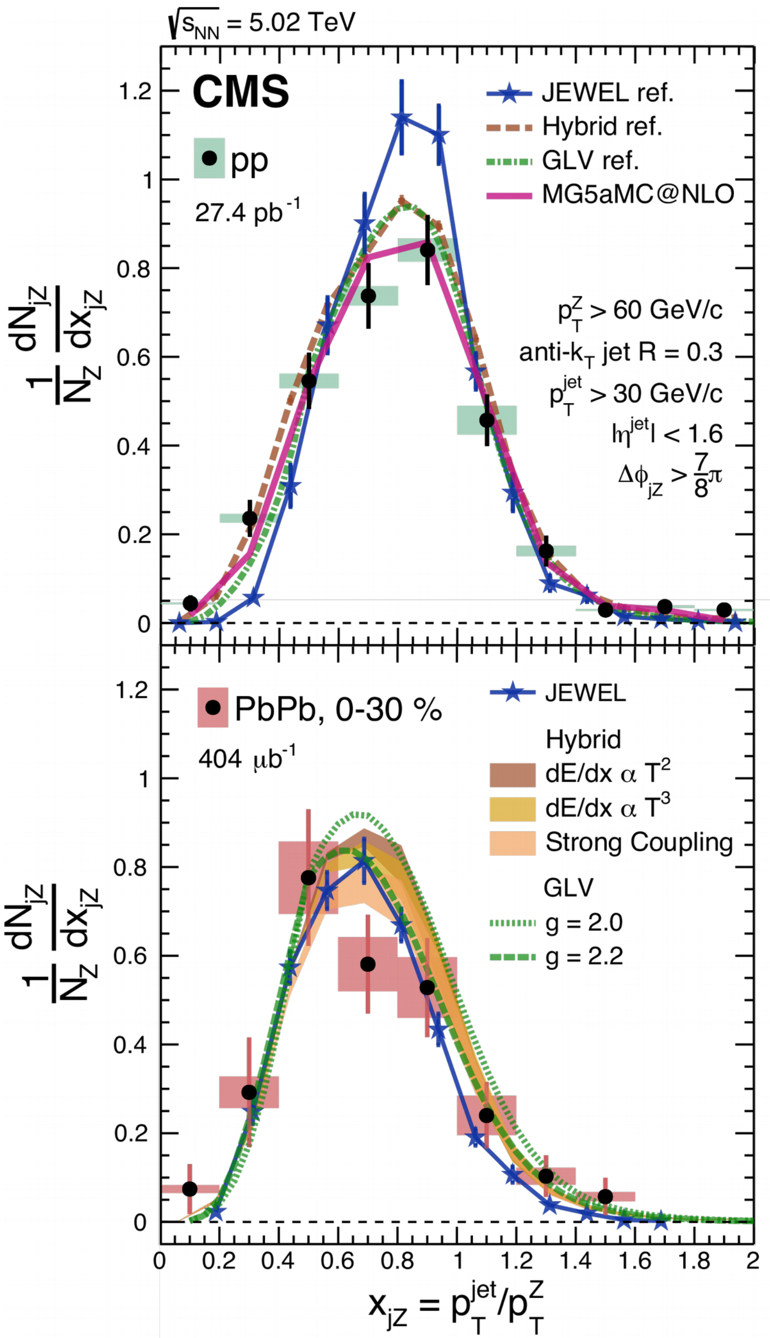
PbPb 0-30% collisions :

balance shifts to lower values wrt pp

The results are not unfolded for detector effects →
pp data are smeared to simulate
poor resolution due to UE fluctuations in PbPb data

Z+jet correlations

Phys. Rev. Lett. 119 (2017) 082301



JEWEL model – perturbative framework for jet quenching :

- No energy loss case (Pythia6): poor agreement with pp
- Energy loss case : consistent with PbPb data

Hybrid model - weak coupling = (high-Q^2) jet evolution, as it would be in vaccum; strong coupling = (low-Q^2) interactions between parton shower and medium :

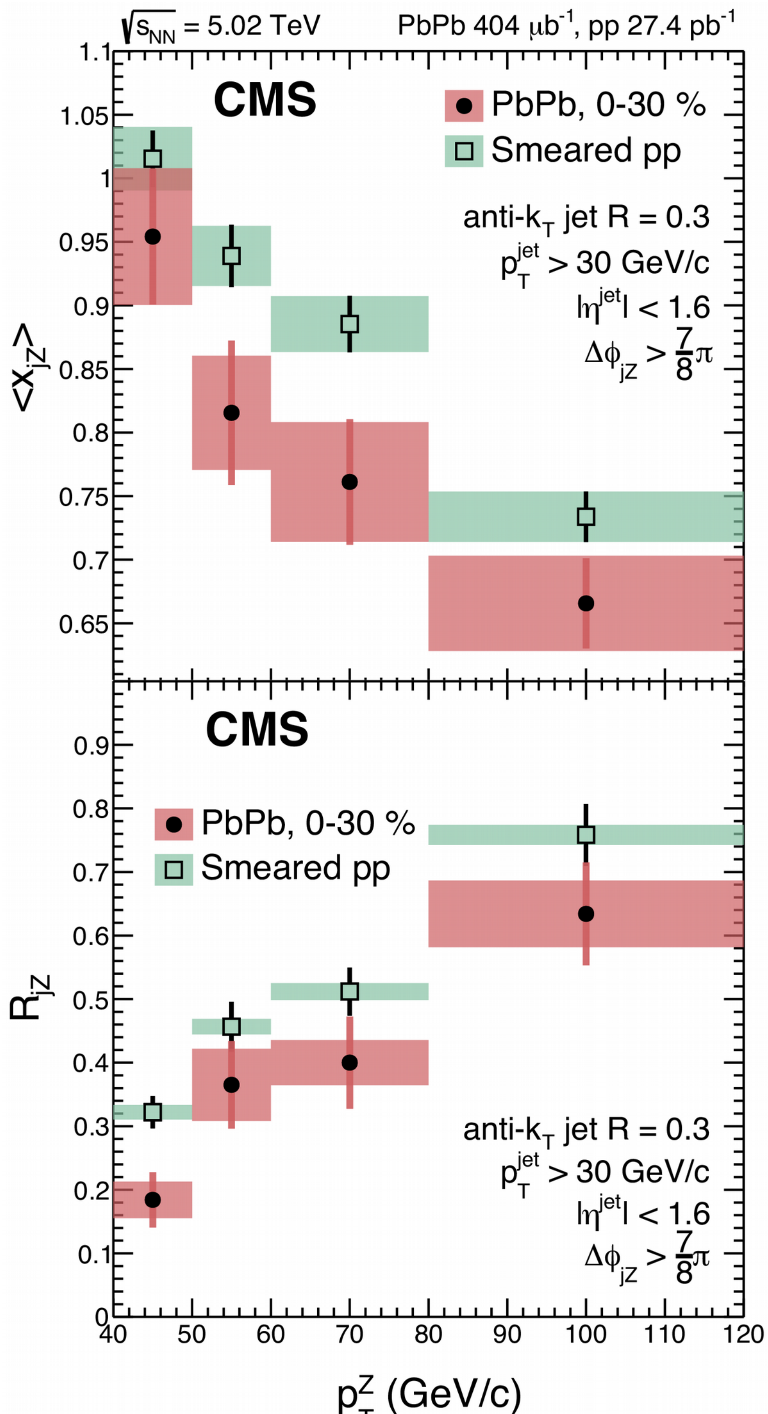
- No energy loss case (Pythia8): describes reasonably well pp
- Energy loss case : strong coupling appears to be the closest to PbPb data

Guylassy-Levai-Vitev (GLV) model – energy loss via out of cone radiation and collisional energy dissipation :

- No energy loss case (Pythia8): describes reasonably well pp
- Energy loss case : strength of the quenching g = 2.2 seems to be favored by PbPb data

Z+jet correlations

Phys. Rev. Lett. 119 (2017) 082301



Mean value of the balance ($< X_{jZ} >$) vs p_T :

→ For full pT range it is lower in PbPb wrt pp

Probability to find an associated jet per Z (R_{jZ}) :

→ Overall decrease in PbPb as jet falls below p_T threshold

→ pp and PbPb difference ~constant with p_T:

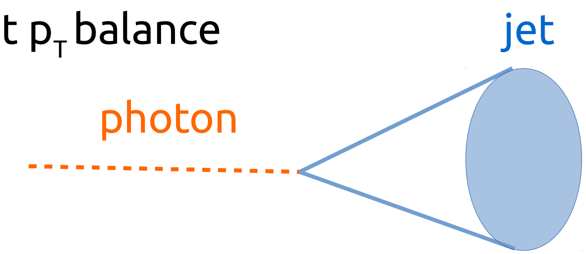
relatively smaller fraction of jets is lost in PbPb for larger initial parton energies

Both are the indication of the jet energy loss in QGP

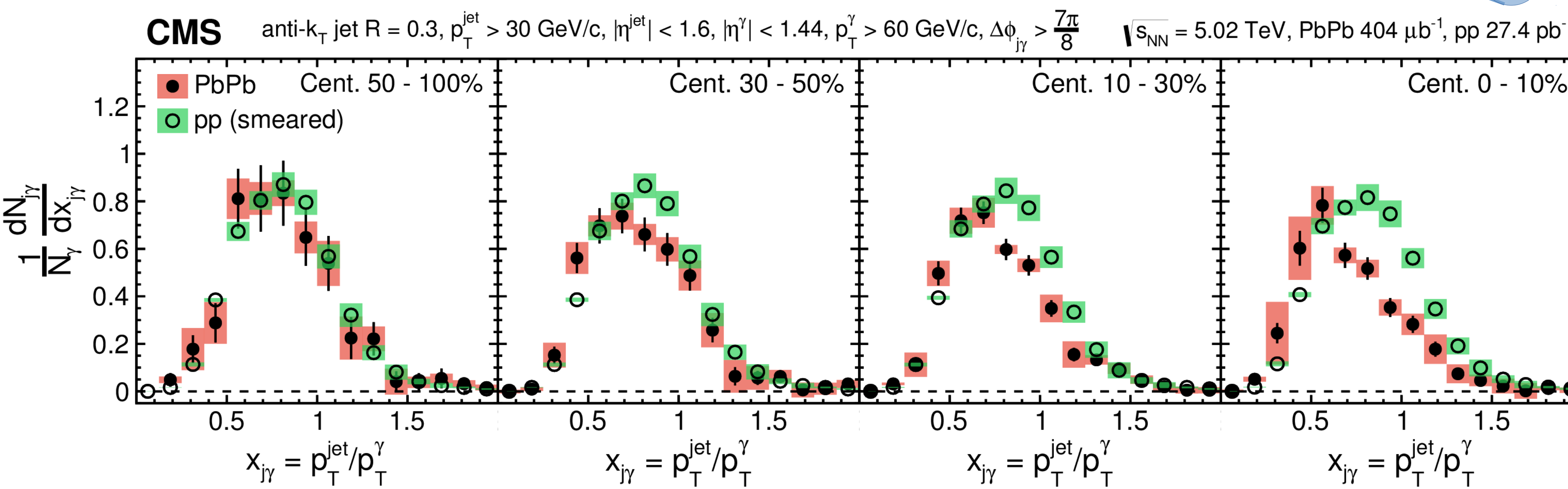
Isolated-photon+jet correlations

Phys. Lett. B 785 (2018) 14

What is the amount of energy lost in jet cone? → ɣ - jet p_T balance



Back-to-back pairs : $\Delta\phi_{j\gamma} > 7\pi/8$

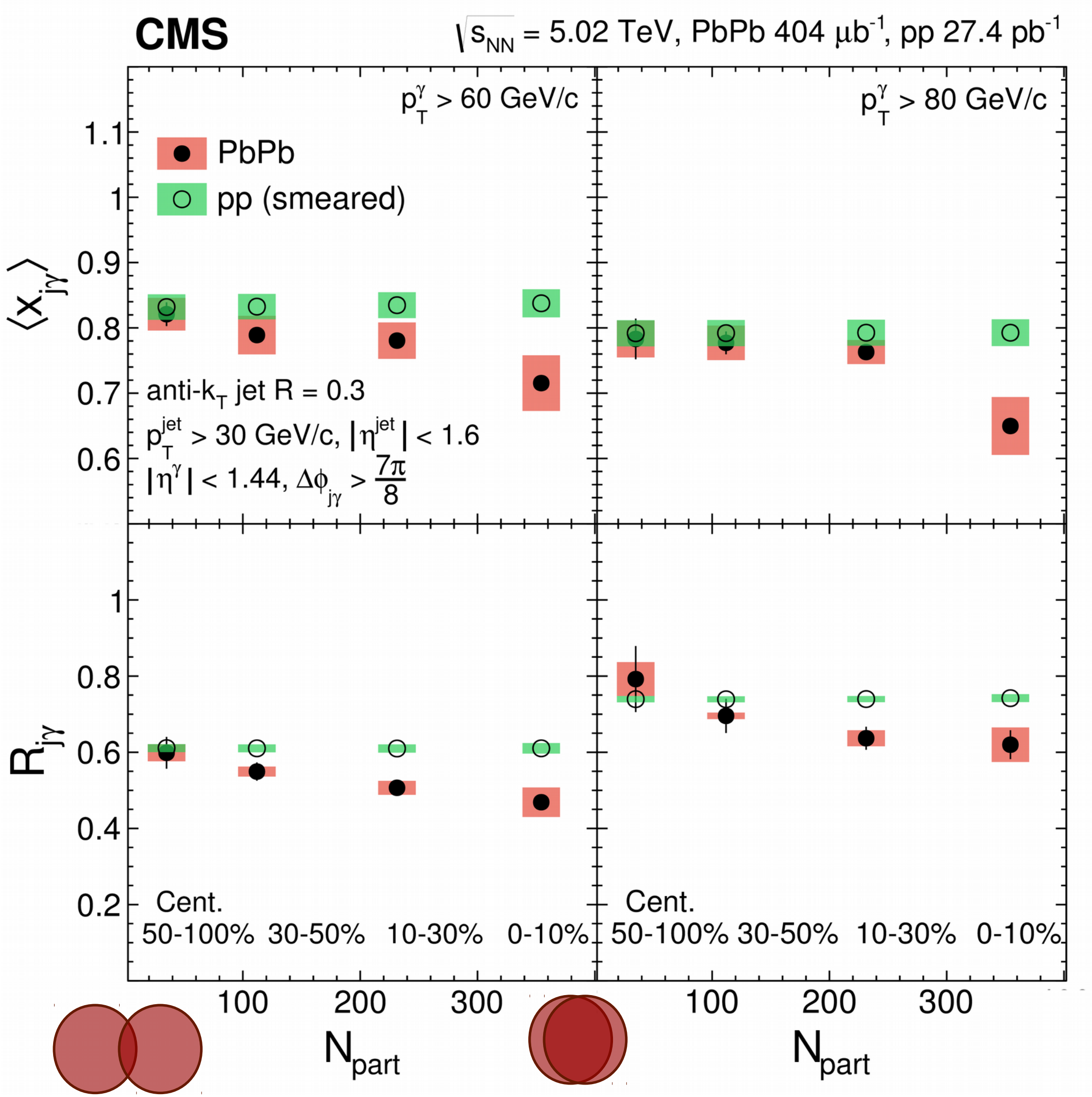


In PbPb central events balance shifts to lower values wrt pp

Consistent with Z-jet measurement

Isolated-photon+jet correlations

Phys. Lett. B 785 (2018) 14



Mean value of the balance (< $X_{j\gamma}$>)

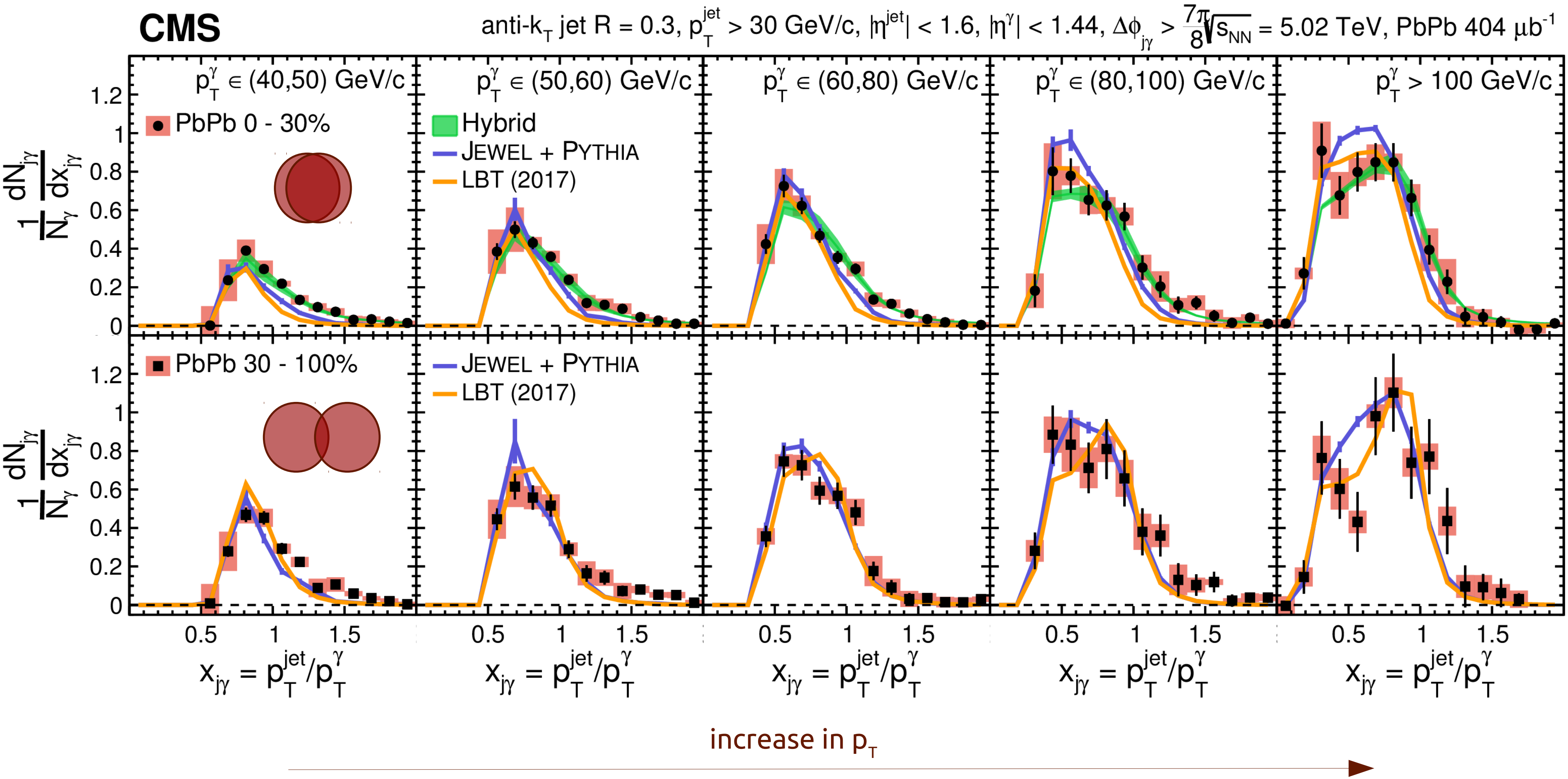
Probability to find a jet partner for photon ($R_{j\gamma}$)

In 0-30% PbPb suppression (compared to smeared pp) of both < X_{jZ}> and R_{jZ} is observed

Consistent with significant in medium energy loss

Isolated-photon+jet correlations

Phys. Lett. B 785 (2018) 14

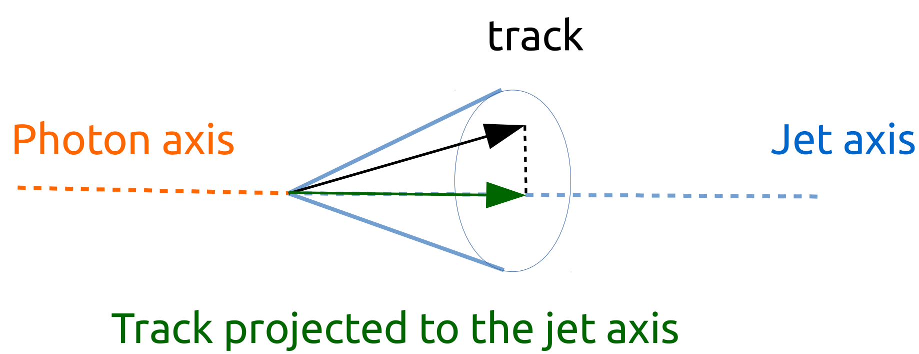


Main features of $x_{J\gamma}$ distributions are reproduced by all models

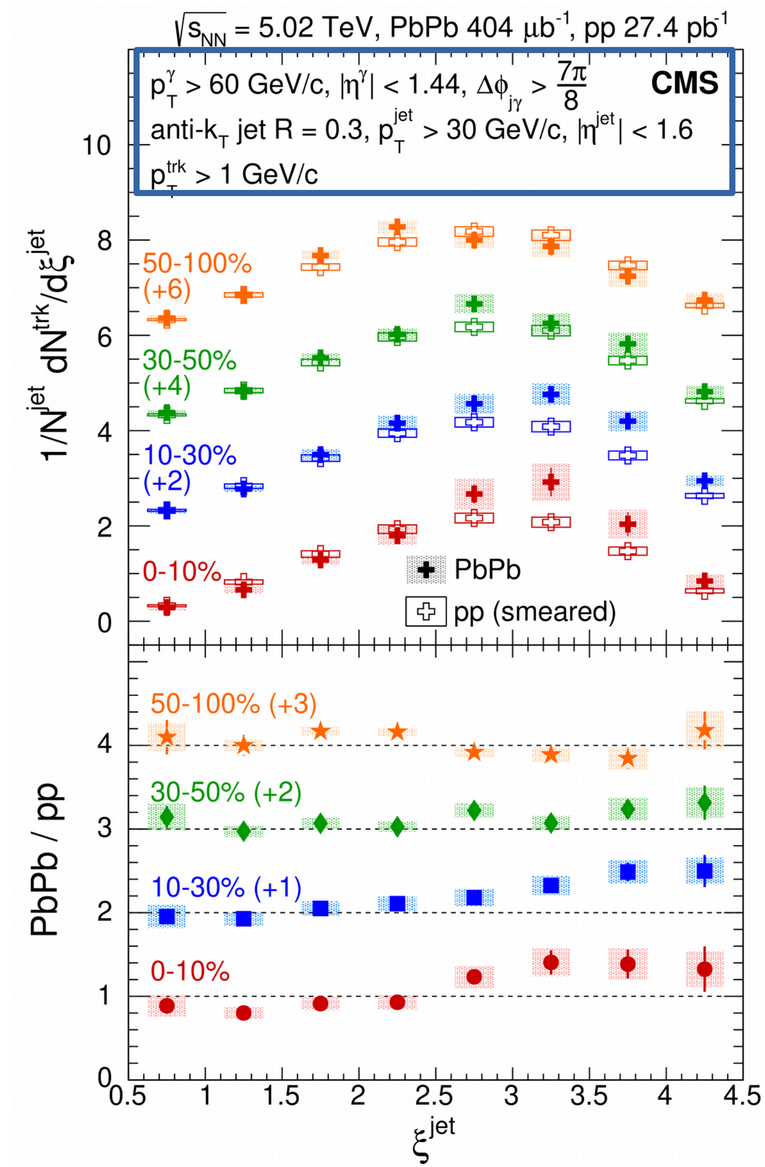
Jet fragmentation

Phys. Rev. Lett. 121 (2018) 242301

Fragmentation pattern wrt p_T of the reconstructed jet
(jet that may have lost energy via interactions with the medium)



$$\xi^{jet} = ln \frac{-|\vec{p}^{\,jet}|^2}{\vec{p}^{\,trk} \cdot \vec{p}^{\,jet}}$$



50-100% PbPb consistent with pp

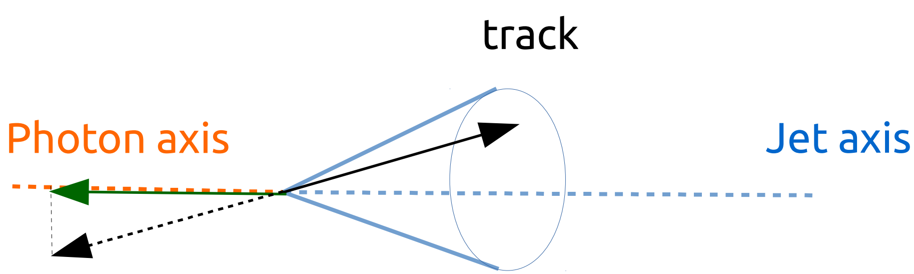
0-10% PbPb :

- **enhancement for ξ_{jet} > 2.5 (p_T^{trk} < 2.5 GeV)**
- **Slight suppression at 0.5 < ξ_{jet} < 2.5 (2.5 < p_T^{trk} < 18 GeV)**

Jet fragmentation

[Phys. Rev. Lett. 121 (2018) 242301](#)

Fragmentation pattern wrt p_T of the initial parton **before energy loss occurred**



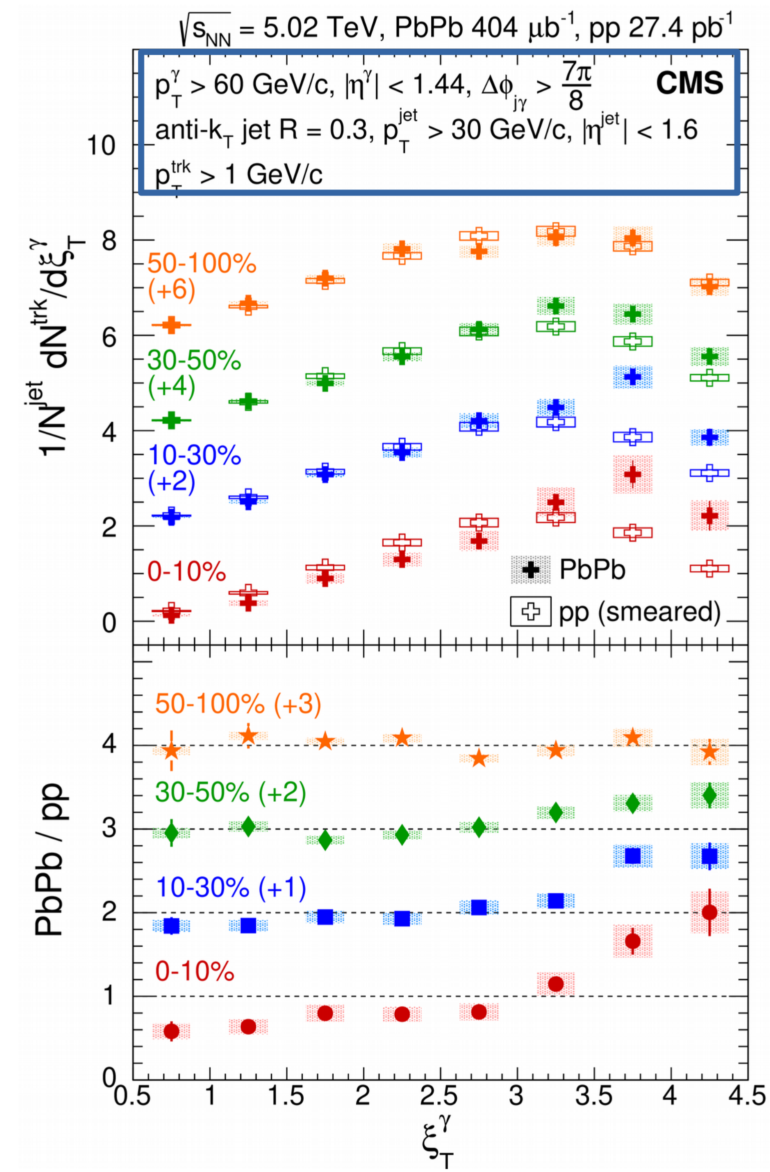
Track projected to the photon axis

$$\xi_T^{\gamma} = ln \frac{-|\vec{p}_T^{\,\gamma}|^2}{\vec{p}_T^{\,trk} \cdot \vec{p}_T^{\,\gamma}}$$

50-100% PbPb consistent with pp

0-10% PbPb :

- **enhancement for $\xi_T^{\gamma} > 3$ ($p_T^{trk} < 3$ GeV)**
- **suppression at $0.5 < \xi_T^{\gamma} < 3$ ($3 < p_T^{trk} < 36$ GeV)**

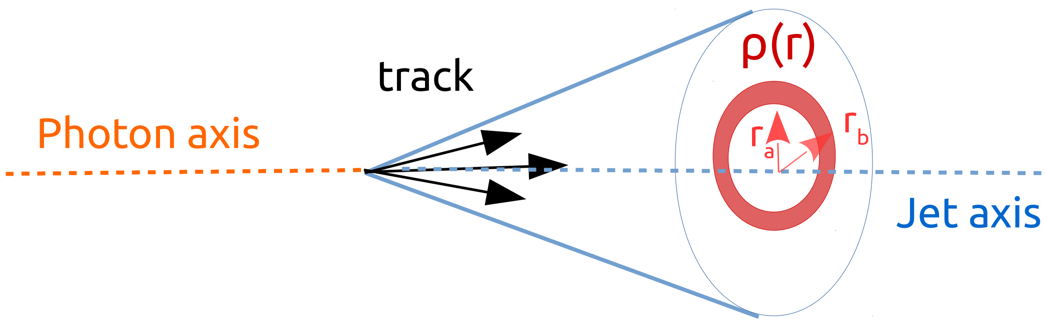


Parton showers emerging from QGP contain more lower energy particles

Jet shapes of isolated photon-tagged jets

Phys. Rev. Lett. 122 (2019) 152001

Jet shapes is an observable for studying distribution of parton energy in radial direction



$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{jets} \sum_{r_a < r < r_b} (p_T^{trk} / p_T^{jet})}{\sum_{jets} \sum_{0 < r < r_f} (p_T^{trk} / p_T^{jet})}$$

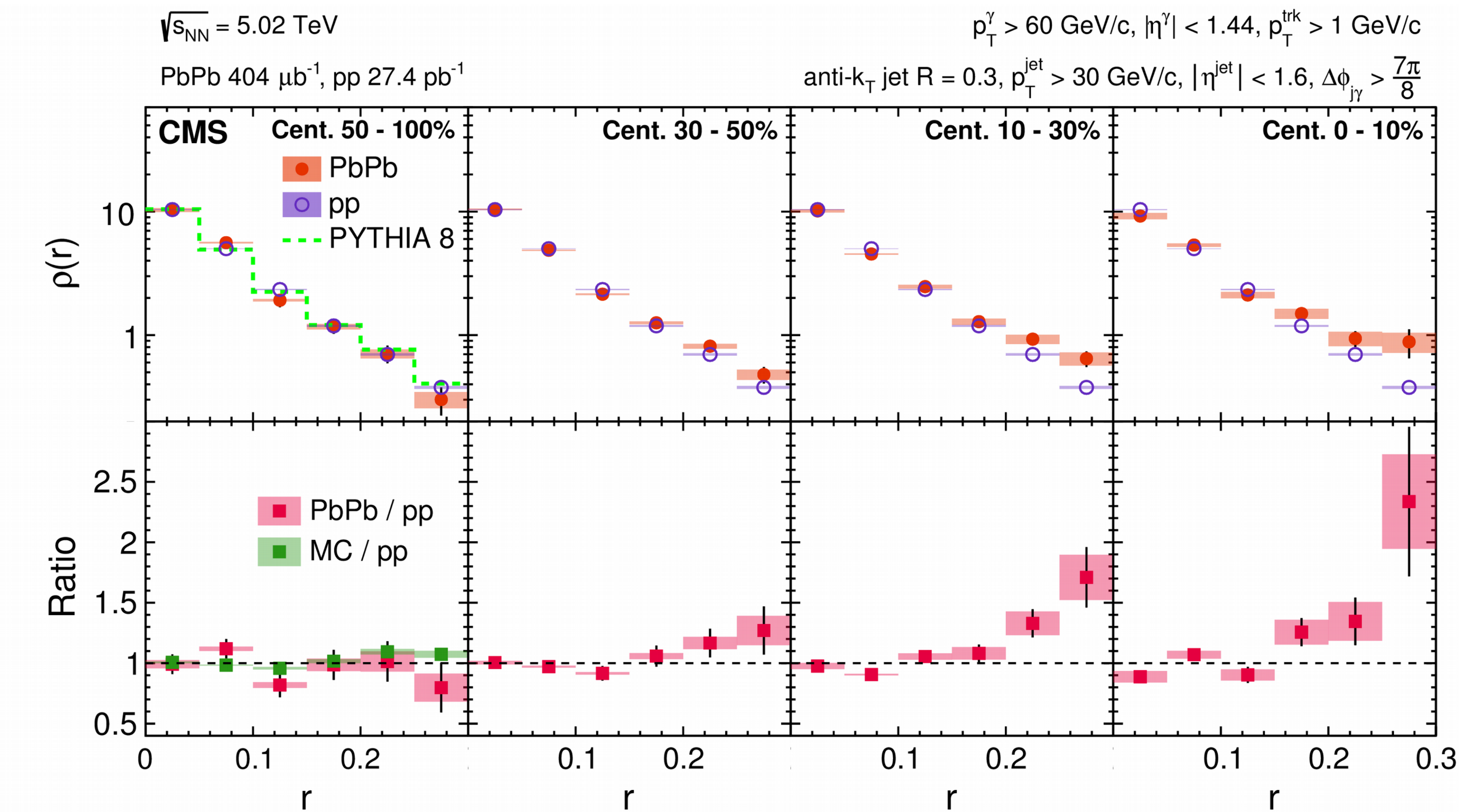
ρ(r) is normalized to unity for r = 0.3

$$r = \sqrt{(\eta^{jet} - \eta^{trk})^2 + (\phi^{jet} - \phi^{trk})^2}$$

How the jet p_T is distributed in a direction transverse to the jet axis ?

Jet shapes of isolated photon-tagged jets

Phys. Rev. Lett. 122 (2019) 152001

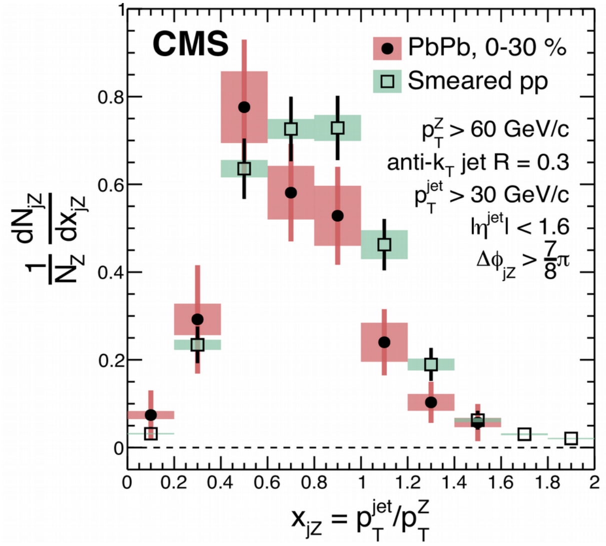


increase in centrality

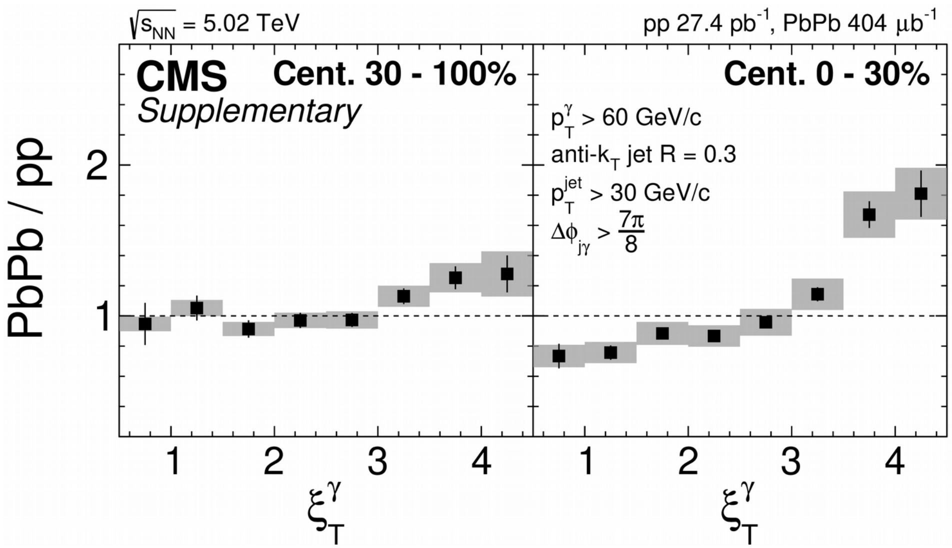
Direct observation of jet broadening in the QGP

Summary

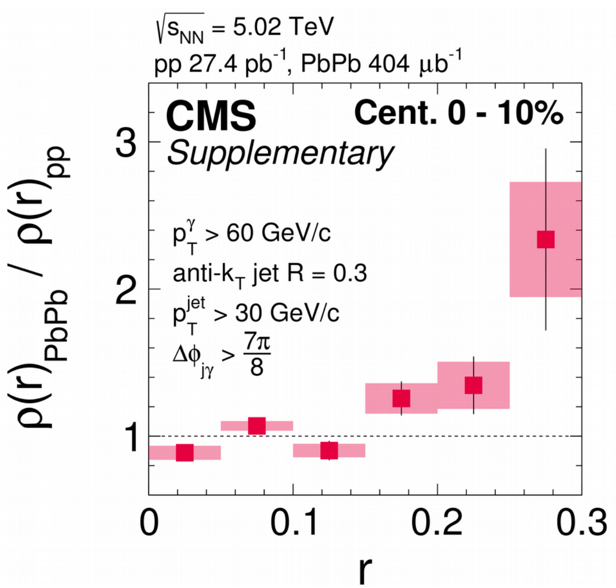
- Energy loss manifests itself in the balance shift to lower values and overall decrease of “Z/γ + jet” pairs



- “γ + jet” fragmentation functions : parton showers emerging from the QGP contain more lower-energy particles



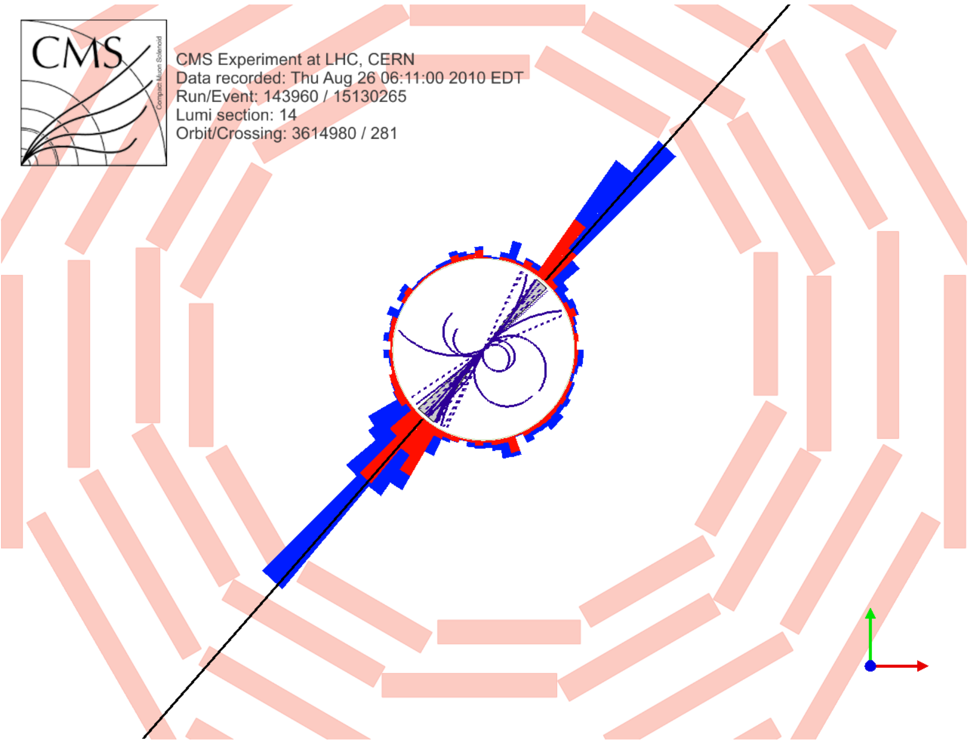
- “γ + jet” jet shapes : a direct observation of the jet broadening in the QGP



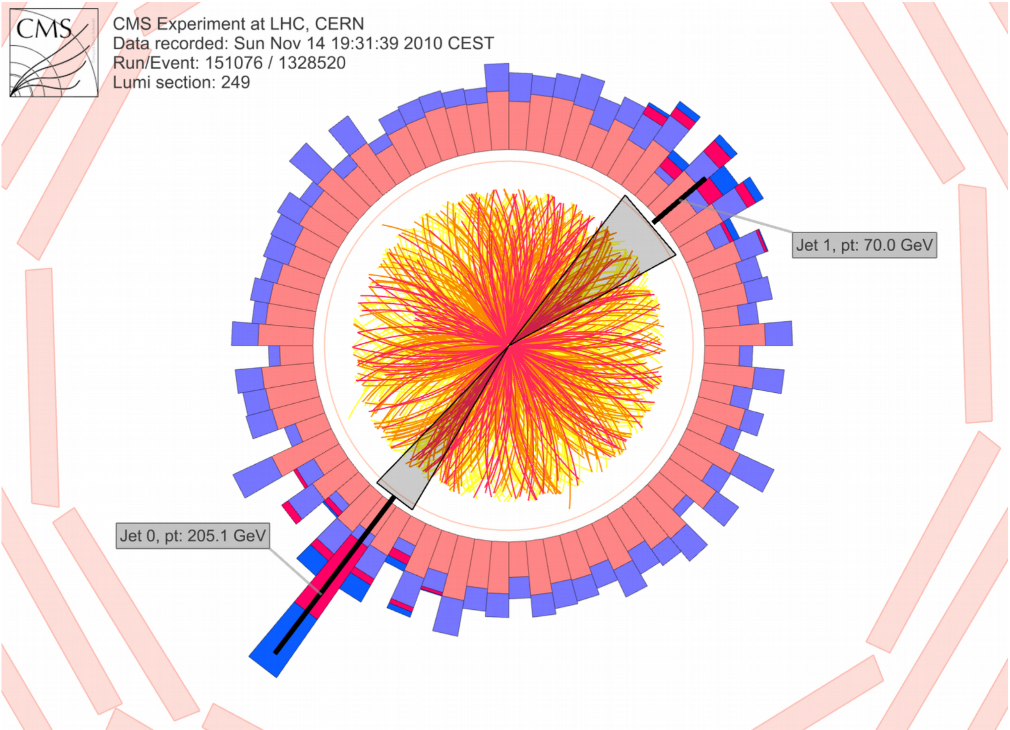
Backup slides

Dijet p_T balance

If **no energy loss**, typically two jets have equal pT wrt the beam axis → ~ **back-to-back**



In PbPb more typical picture is **highly unbalanced dijets**

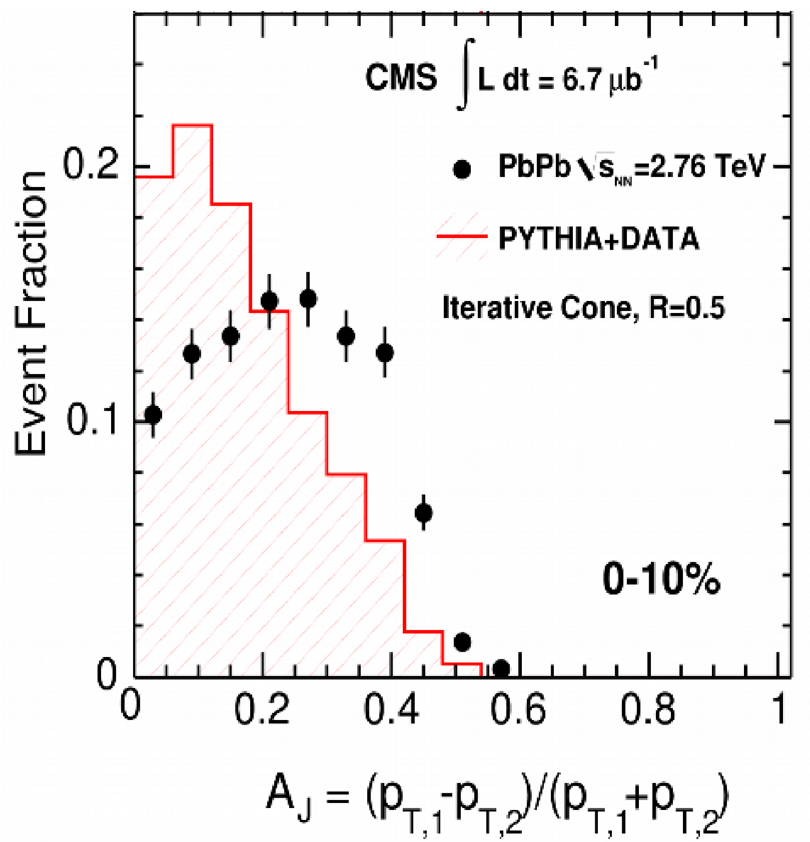


How to quantify the effect?

Dijet asymmetry in CMS

Dijet asymmetry of leading and subleading jets

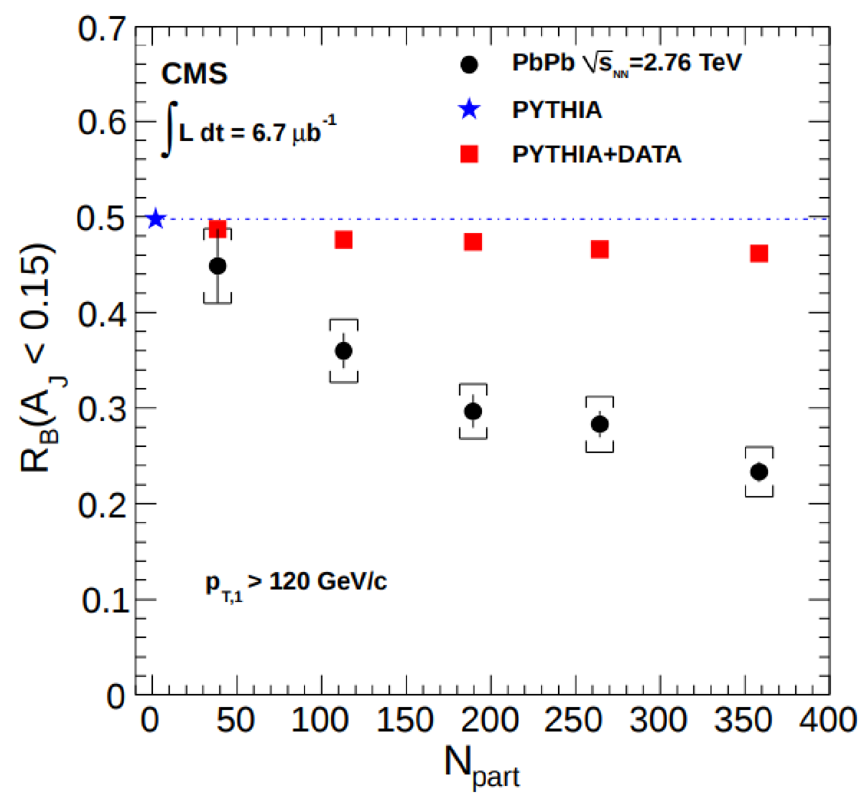
$p_{T,1} > 120\ \mathrm{GeV},\ p_{T,2} > 50\ \mathrm{GeV}$
$\Delta\phi > 2\pi/3$



"no energy loss" : peak ~ 0.1
PbPb data : peak ~ 0.3

Fraction of all events with "balanced" jets

CMS, PRC84 (2011) 024906

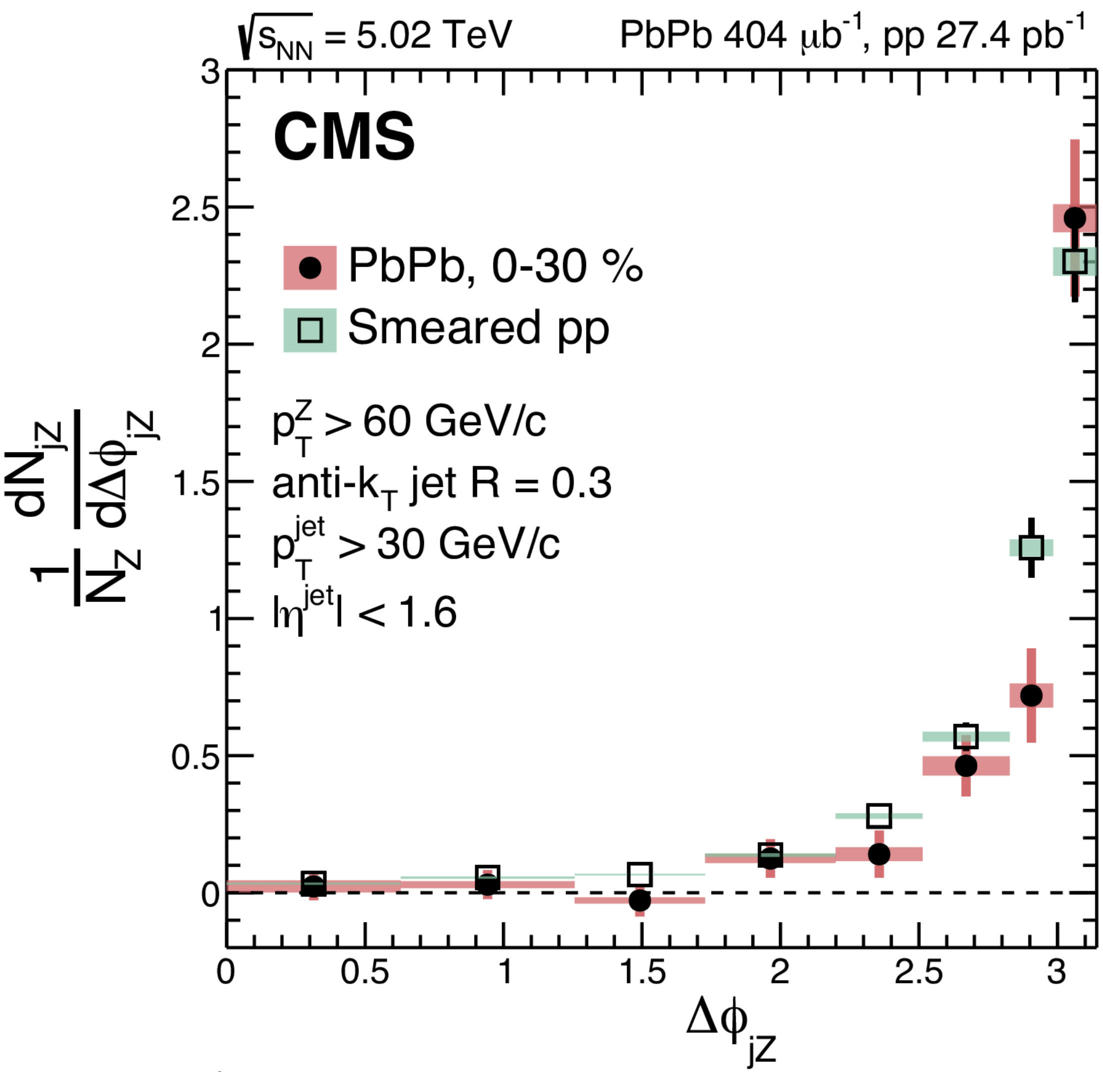


In the most central PbPb ~ 2 times less "balanced" dijets

High degree of jet quenching

Z-jet correlations

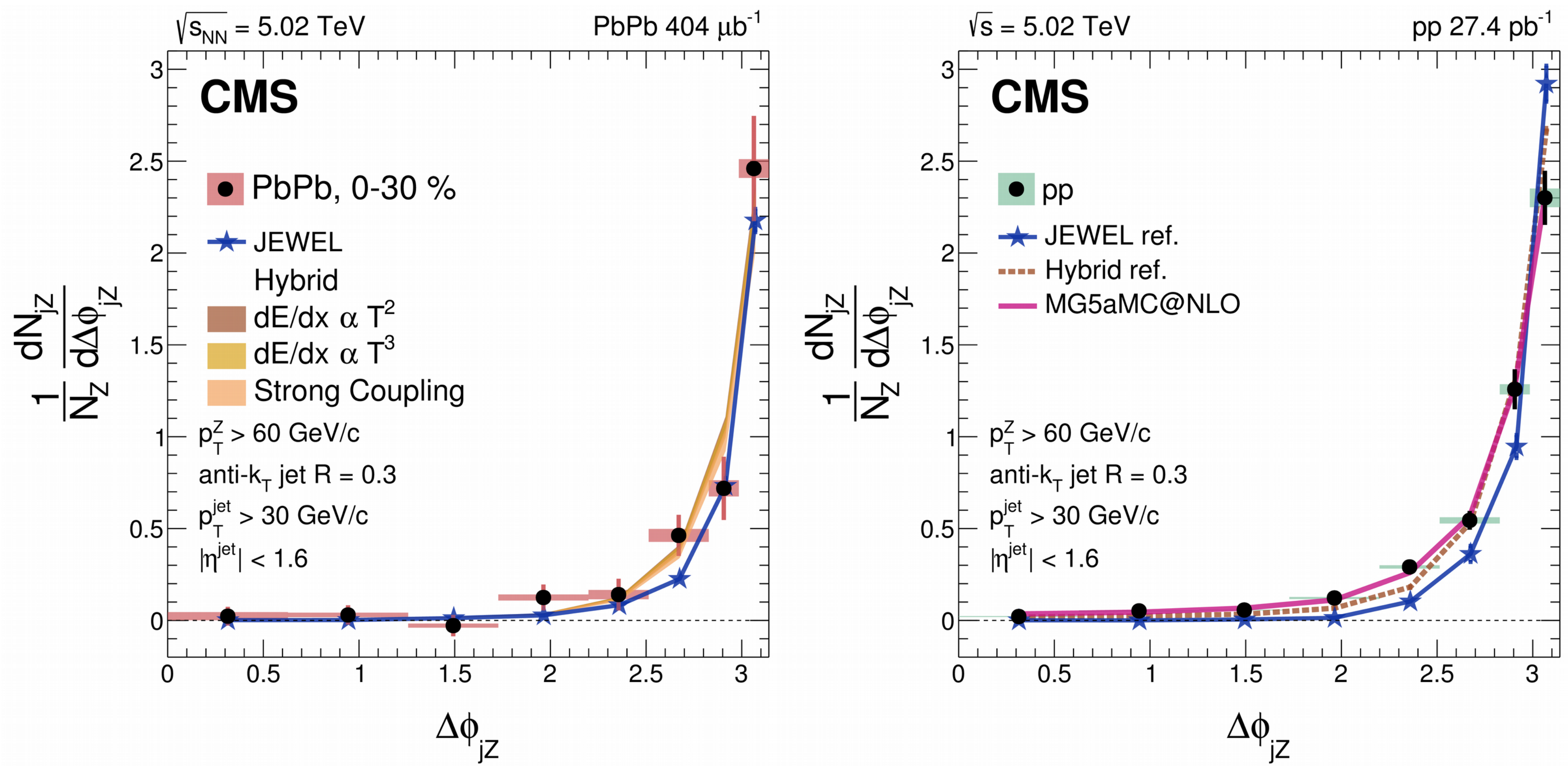
Distributions of the azimuthal angle difference $\Delta\varphi_{jZ}$ between the Z boson and the jet



No difference in the angular difference between PbPb and pp

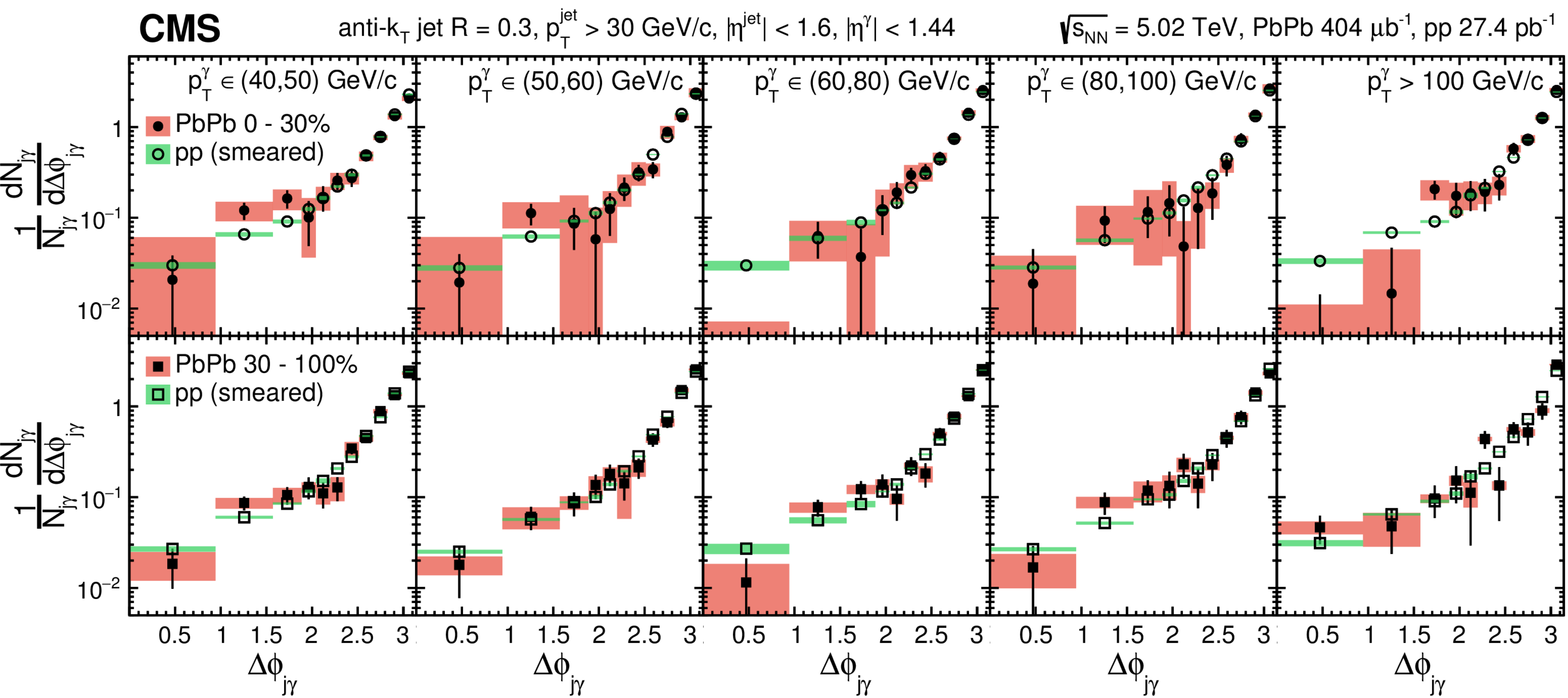
Z-jet correlations

Comparison pp and PbPb to models :



Photon-jet correlations

Distributions of the azimuthal angle difference $\Delta\varphi_{j\gamma}$ between the photon and the jet



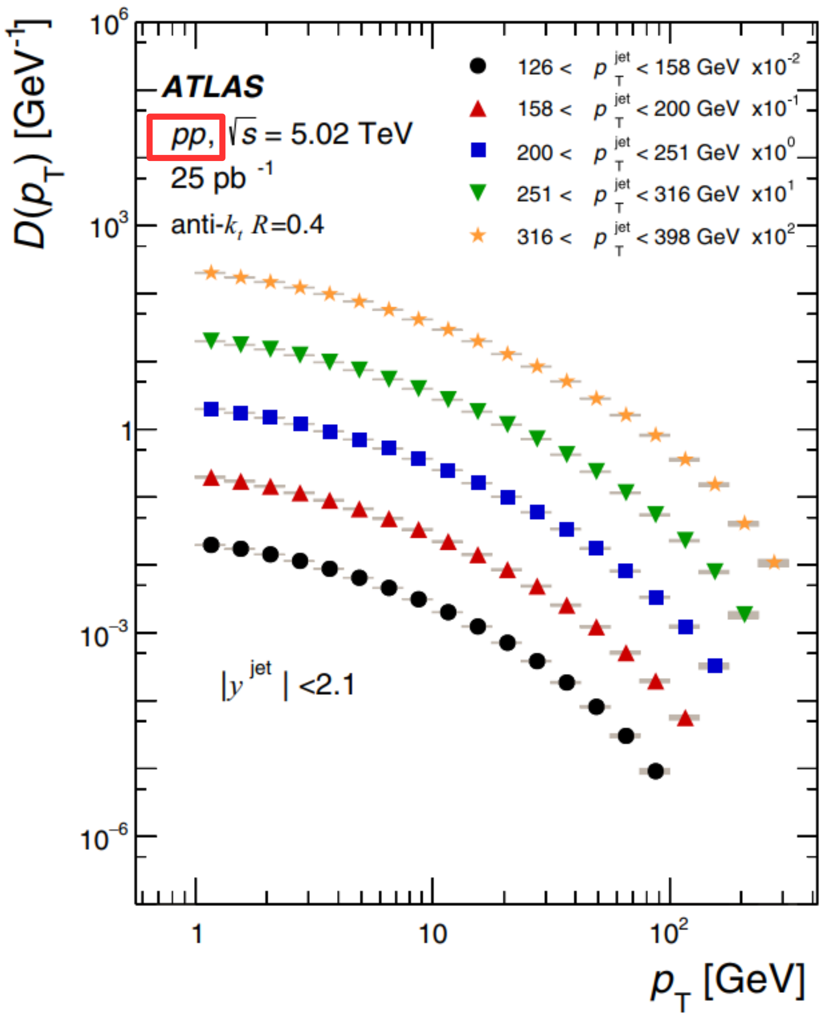
No difference in the angular difference between PbPb and pp

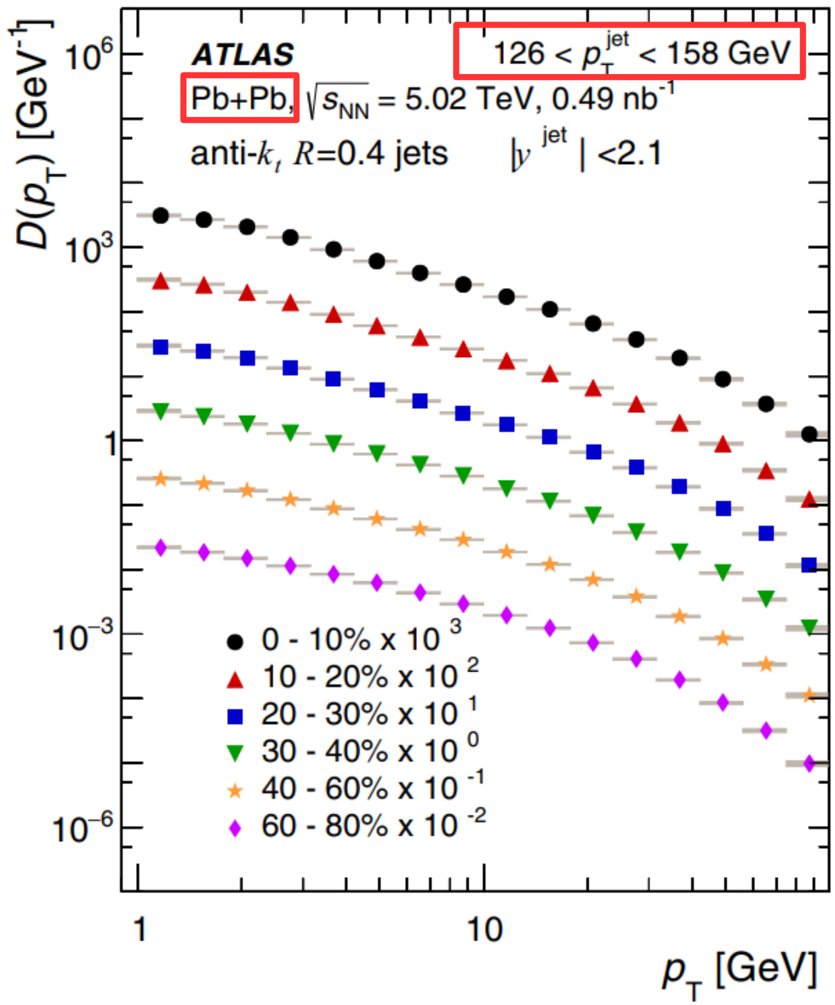
Jet fragmentation function in ATLAS

Distribution of charged-particle p_T inside the jet (fragmentation function) :

$$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$

ATLAS, Phys. Rev. C 98 (2018) 024908





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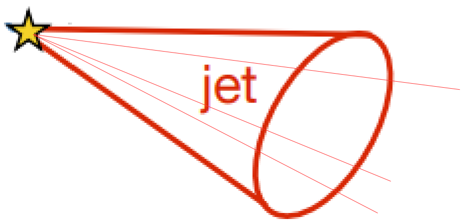


ATLAS, Phys. Rev. C 98 (2018) 024908

How much is the jet structure modified ?

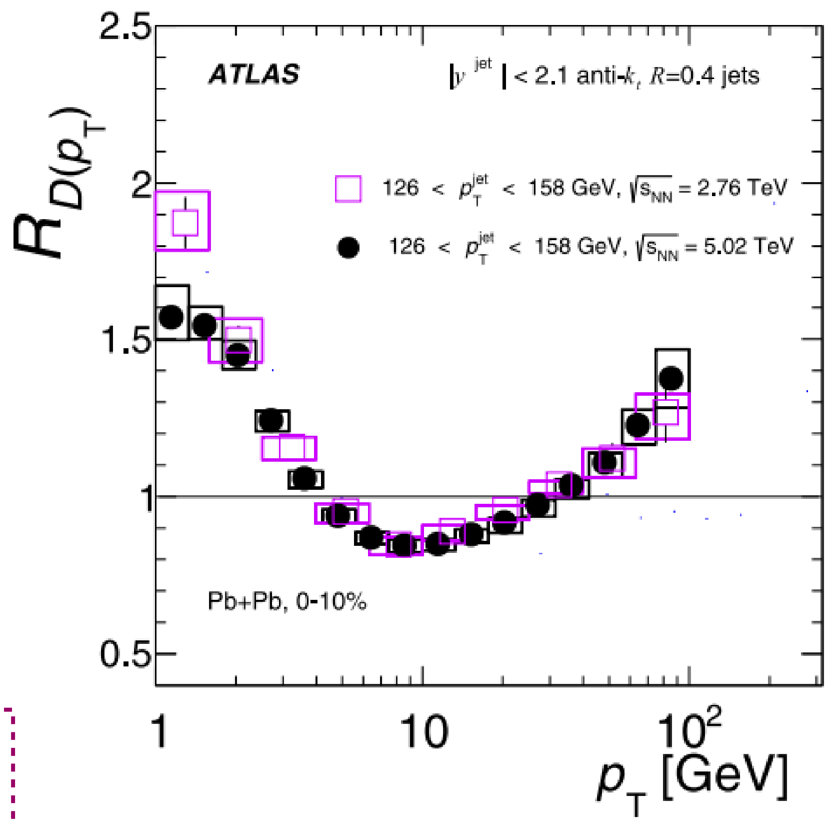
$$R_{D(p_T)} = \frac{D(p_T)_{PbPb}}{D(p_T)_{pp}}$$

PbPb compared to pp :

→ more soft particles due to interaction with the medium

→ suppression at mid p_T

→ enhancement at high p_T : consistent with quenching dependence on quark/gluon initiated jets



Gluon vs quark jet:

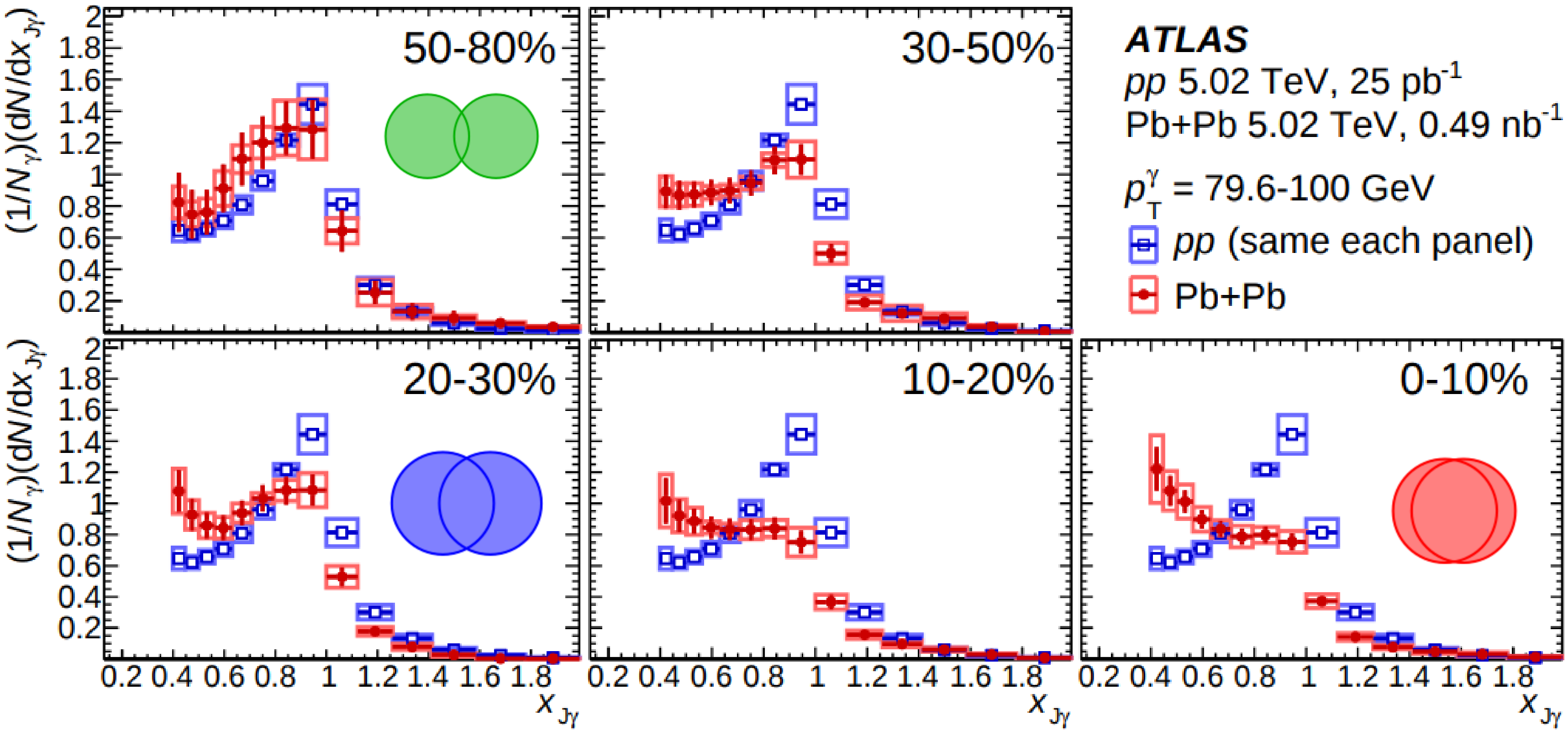
→ larger charged hadron multiplicity
→ contain more softer particle
→ wider

Photon+jet pT balance in ATLAS

What is the amount of energy lost by the jet?

Balance : $X_{J\gamma} = \frac{p_{T,jet}}{p_T^{\gamma}}$

ATLAS, Phys. Lett. B 789 (2019) 167



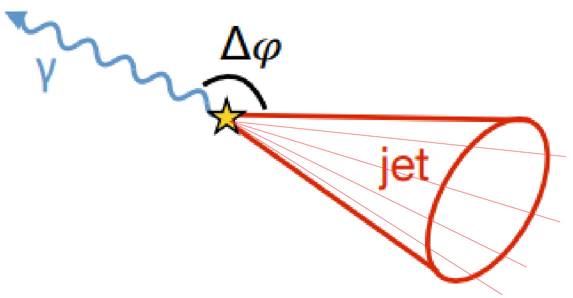
The jet energy decrease with centrality

- in peripheral events : a peak-like structure is present in the same position as in pp
- in the most central events : strongly modified, no peak, jet energy decrease

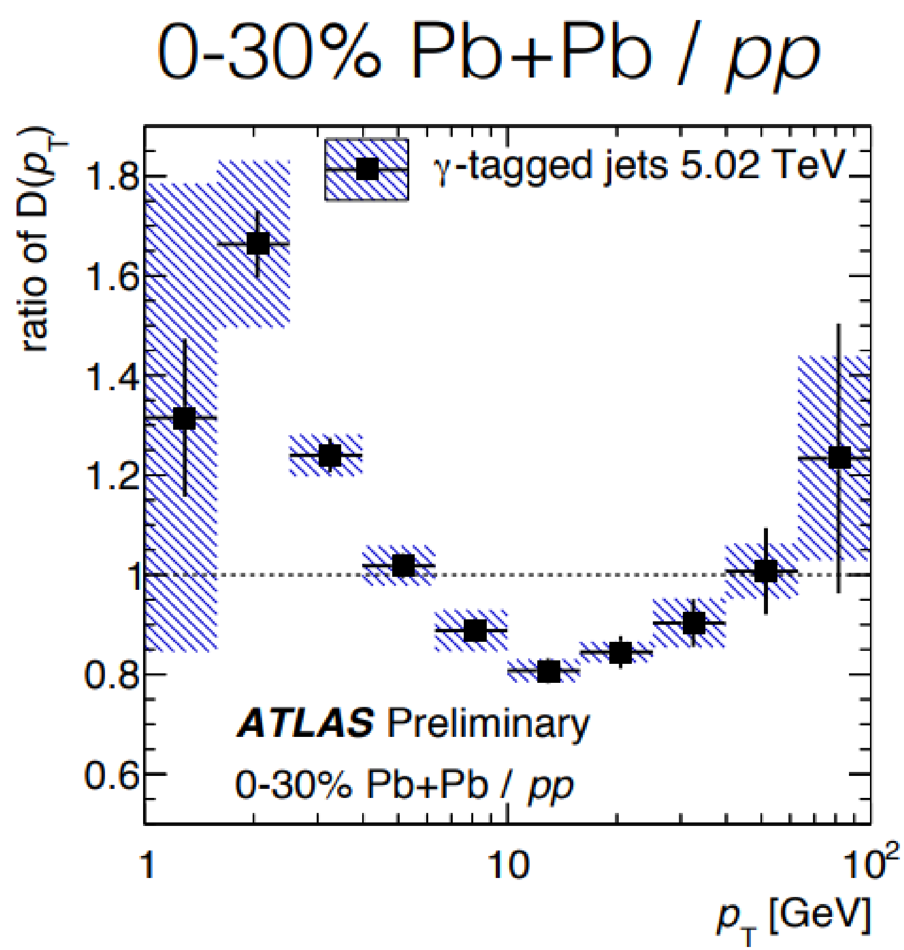
Photon+jet fragmentation function in ATLAS

How is substructure modified by medium?

Fragmentation function : $$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$



ATLAS-CONF-2017-074



Modifications compared to pp :

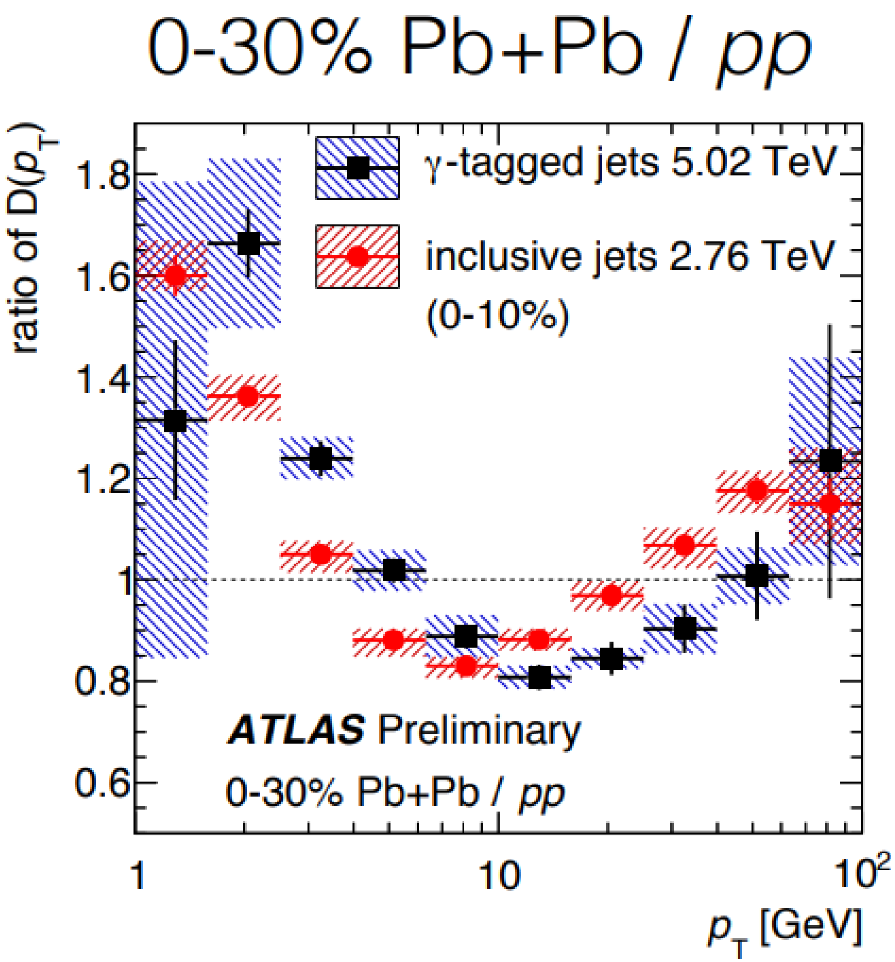
- → more soft particles due to interaction with the medium
- → suppression at mid p_T
- → no modification at high p_T

Photon+jet fragmentation function in ATLAS

How is substructure modified by medium?

Fragmentation function : $D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$

ATLAS-CONF-2017-074



$\gamma + \mathrm{jet}$ vs inclusive jets :

→ more enhancement at low p_T

→ shift of mid p_T minimum

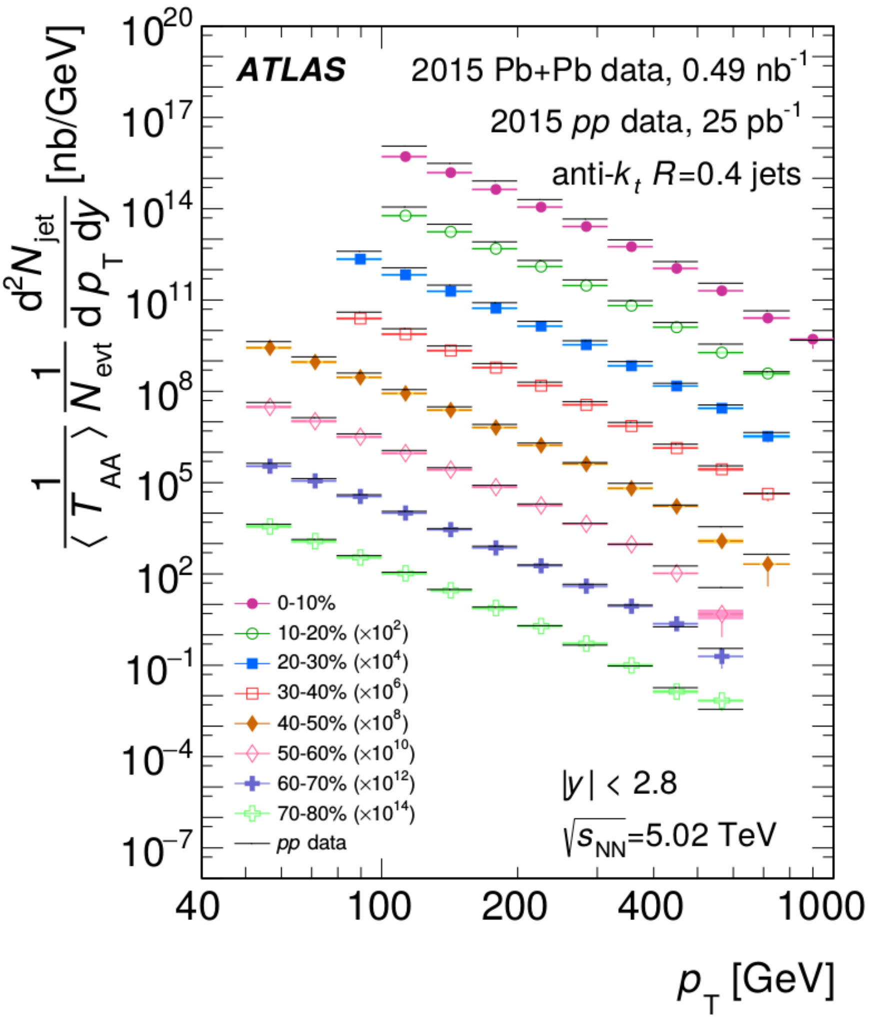
→ no enhancement at high p_T

Indication : quark initiated jets are modified differently

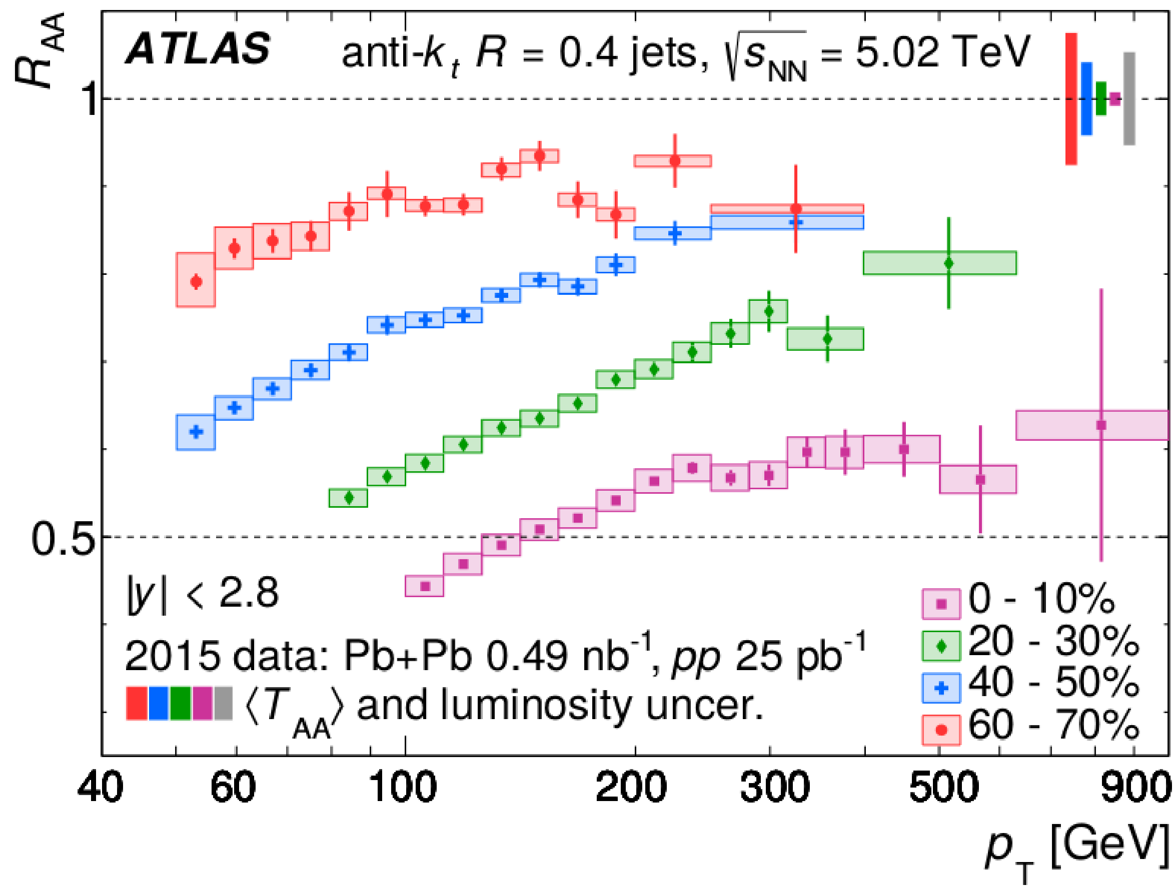
Jet suppression in ATLAS

Inclusive jet cross-sections are measured in pp and PbPb up to 1 TeV

Phys. Lett. B 790 (2019) 108



$$R_{AA} = \frac{\text{per-event yield}_{AA}}{\text{number of binary collisions} \times \text{per-event yield}_{pp}}$$



At large pT : flat suppression in central collisions

Jet reconstruction at the LHC

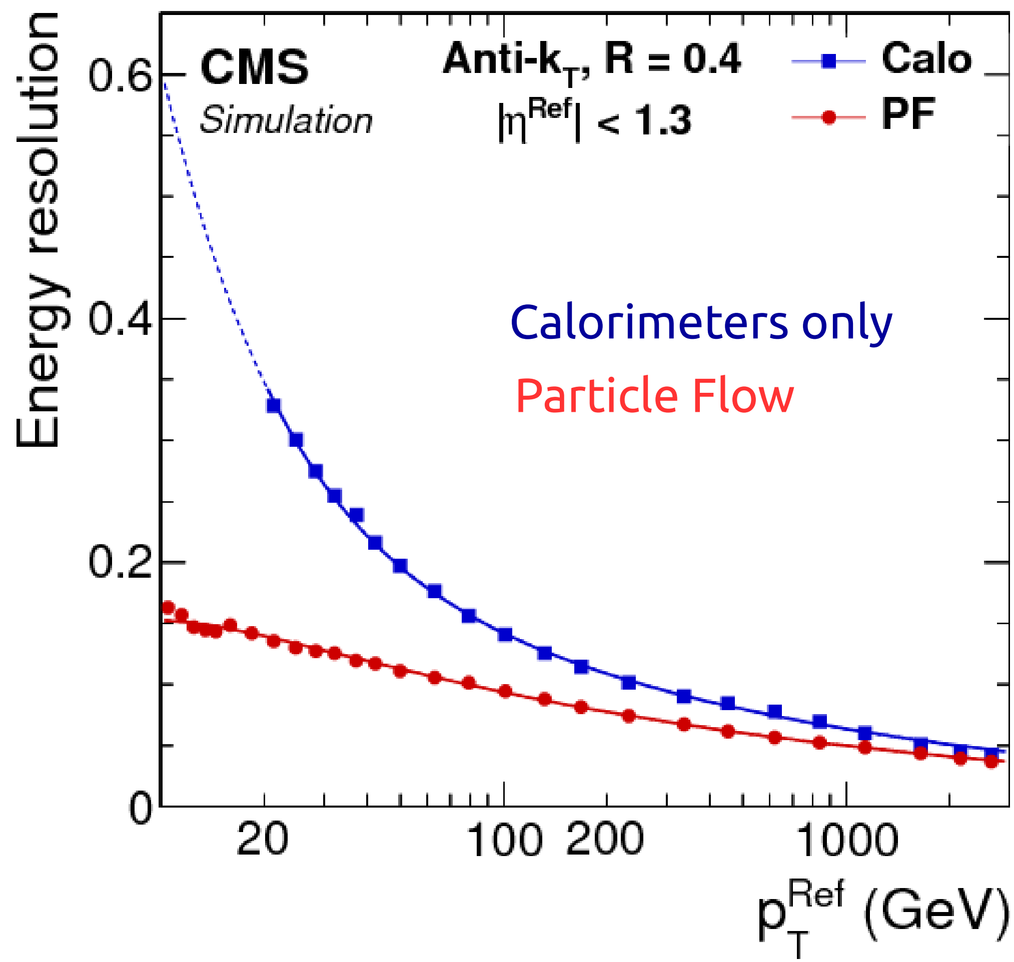
Jets consist of hadrons and photons → energy can be measured by the calorimeters only

Particle Flow in CMS (JINST 12 (2017) P10003)
ATLAS (Eur. Phys. J. C 77 (2017) 466)

Particle Flow reconstruction :
Combine tracks and calorimeter clusters

Particle Flow jet composition :

→ 65% charged hadrons
→ 25% photons
→ 10% neutral hadrons



Jet energy resolution improves by factor 2 at lower p_T thanks to the tracker resolution

Jet clustering

Jet clustering : reverse-engineering of the fragmentation and hadronization

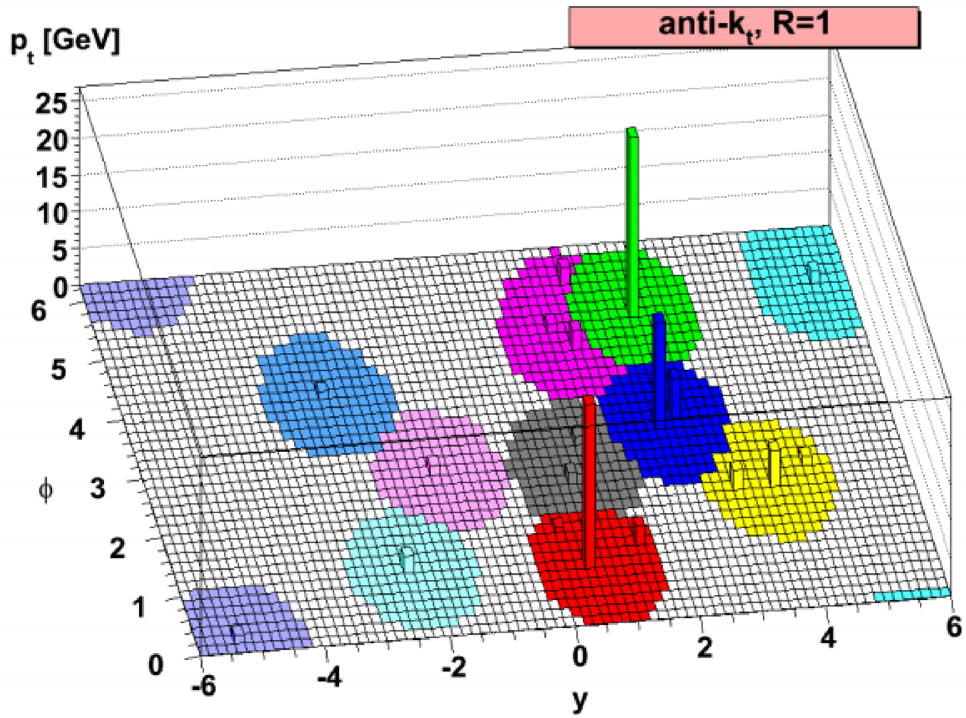
Sequential clustering : combines the closest particles into jets

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

- p = 1 : kt
- p = 0 : C/A
- p = -1: anti-kt

Distance between pairs of particles — Jet radius — Distance to the beam

JHEP 0804:063,2008

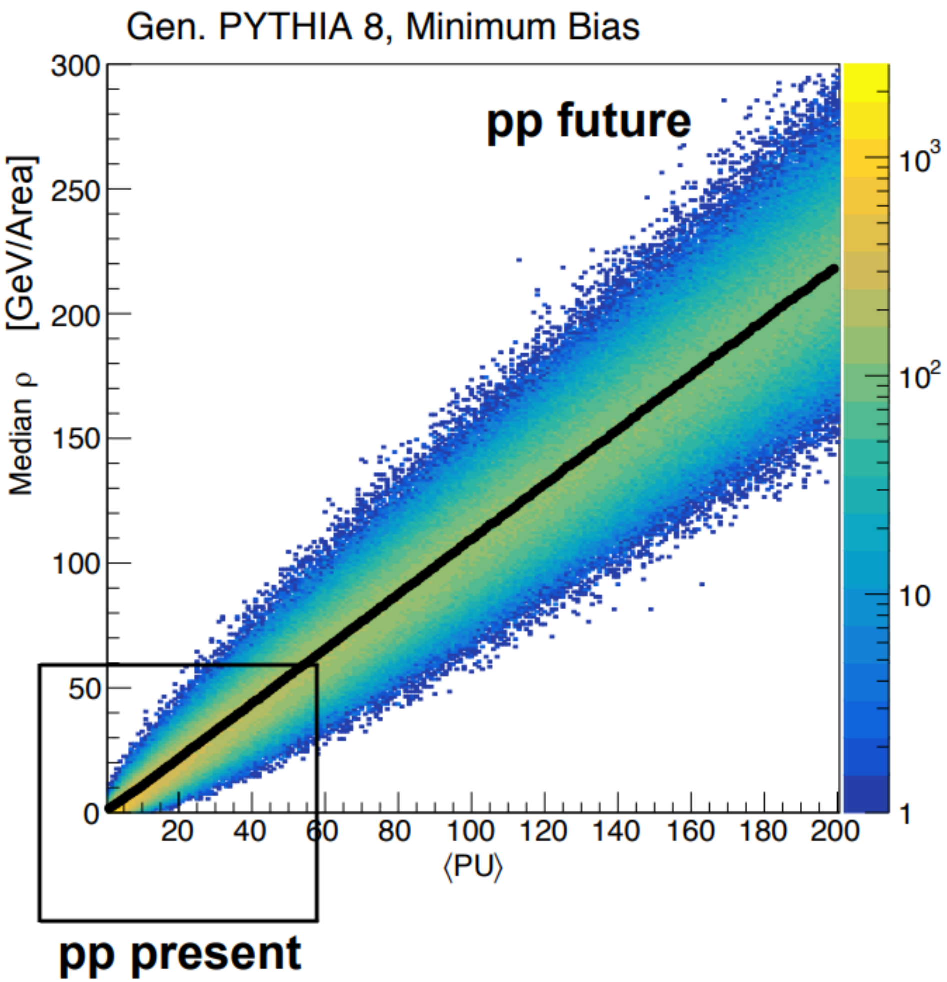


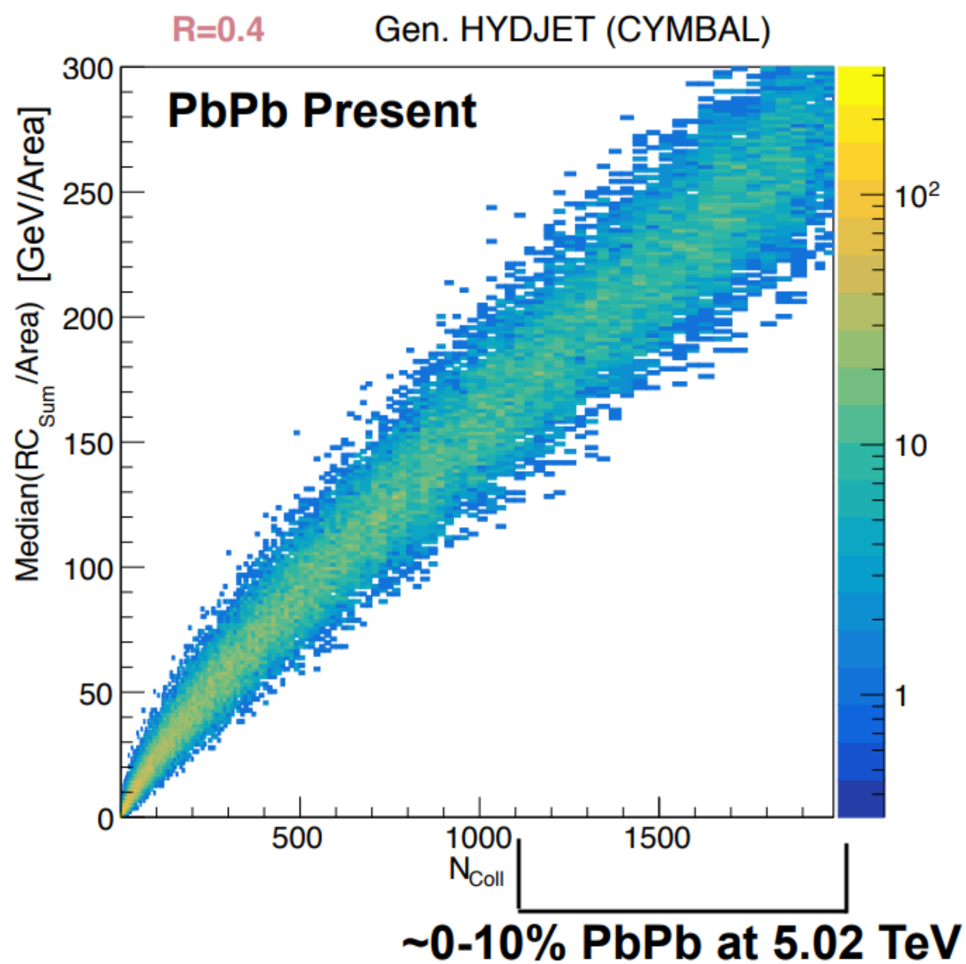
Underlying event in pp and PbPb collisions

Underlying Event (UE) - particles not associated with the hardest parton-parton process quantified as transverse momentum density (ρ)

PileUp (PU) – concurrent interactions coming from the same bunch crossing

BNL jet workshop '18, C.McGinn talk

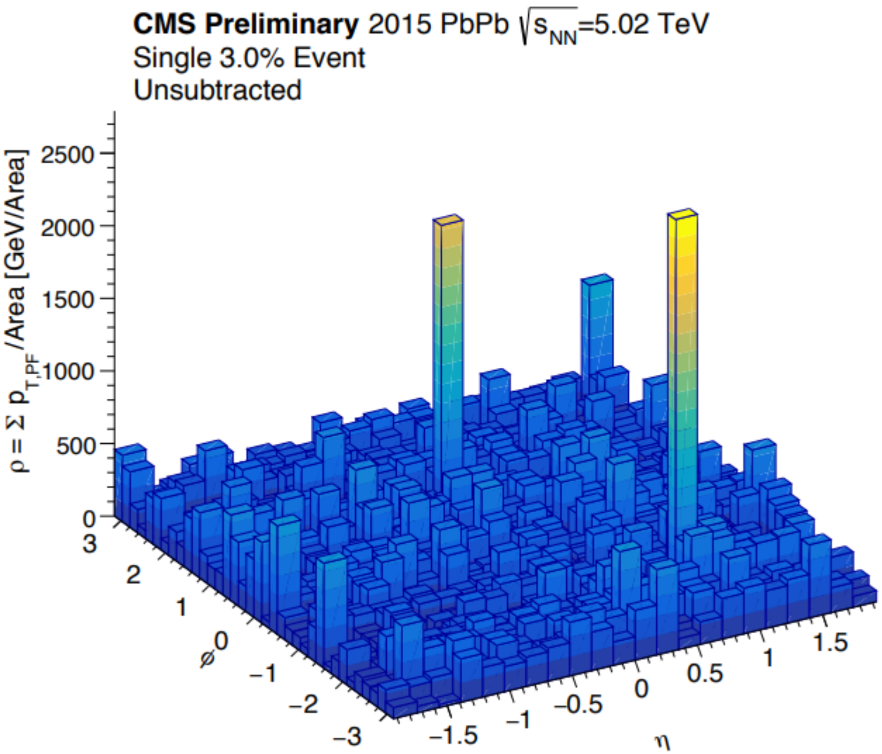




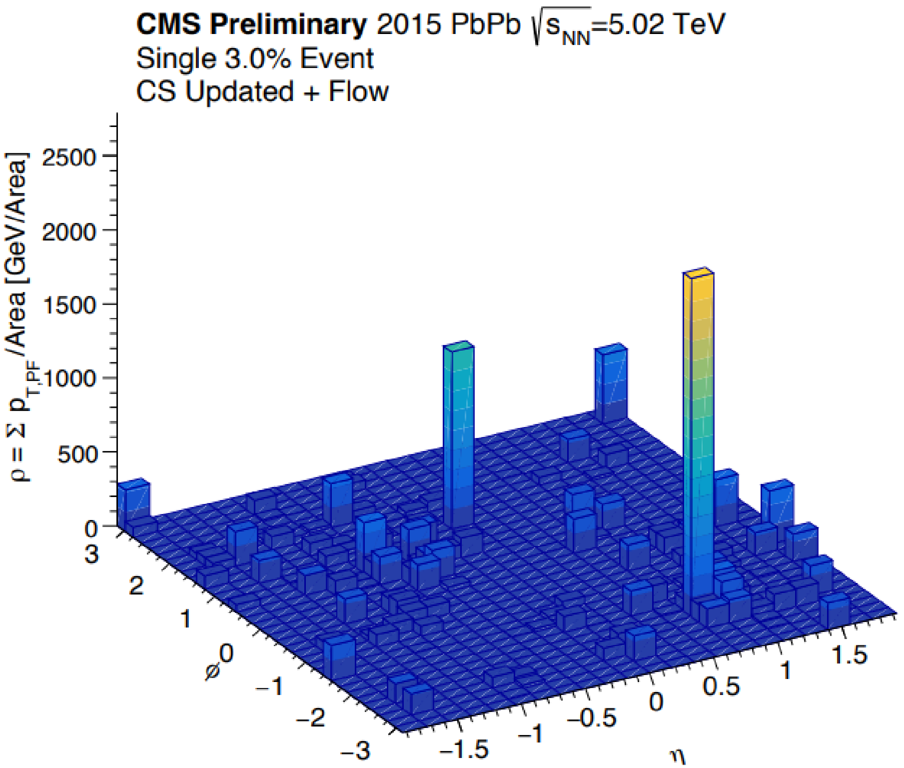
UE in pp with <PU> ~ 200 looks like central PbPb

Jets in PbPb collisions

Before UE subtraction



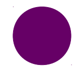
After UE subtraction

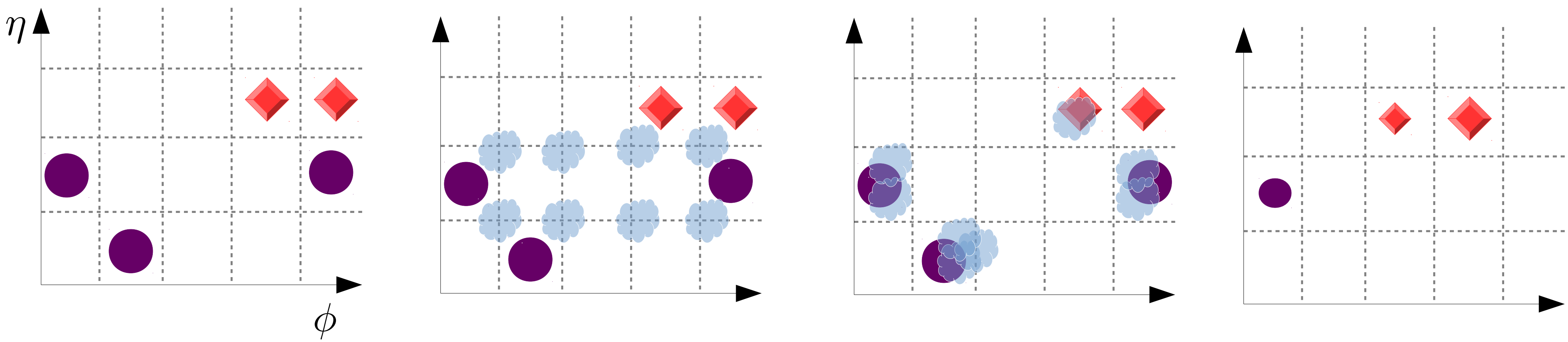


What amount of UE to subtract? How?

UE subtraction in CMS : constituent subtraction

Particle-by-particle: correct the 4-momentum of a jet and substructure

 - signal  - underlying event - ghost (artificial particles)



Add ghosts with $p_T^{ghost} = A_{ghost} \cdot \rho$ in random locations;

A_{ghost} - area occupied

Combine them with the closest real particle

$p_T^{particle} > p_T^{ghost}$

$p_T^{particle} < p_T^{ghost}$

The largest pT particle/ghost survives

$p_T^{particle} = p_T^{particle} - p_T^{ghost}$

$p_T^{ghost} = p_T^{ghost} - p_{T\,particle}$

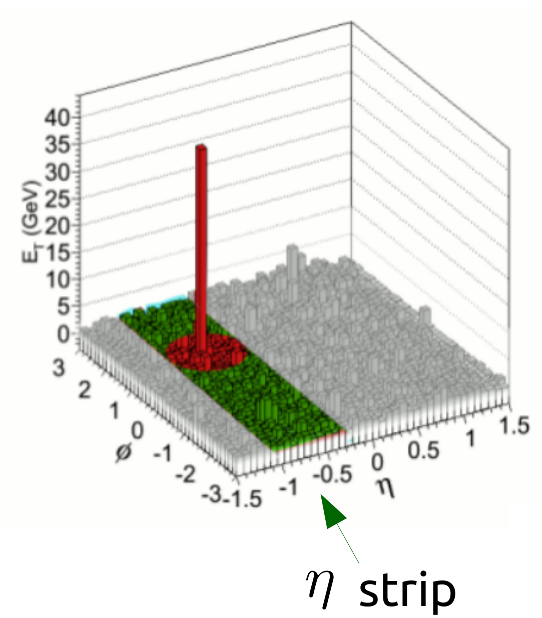
Repeat until no ghosts/particles left

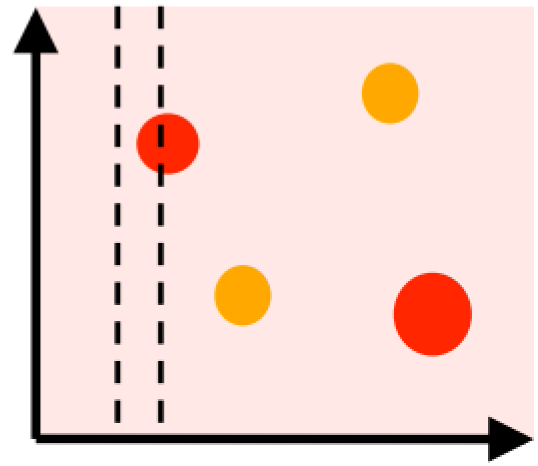
Remaining particles get clustered into a jet

UE subtraction in CMS : iterative pedestal

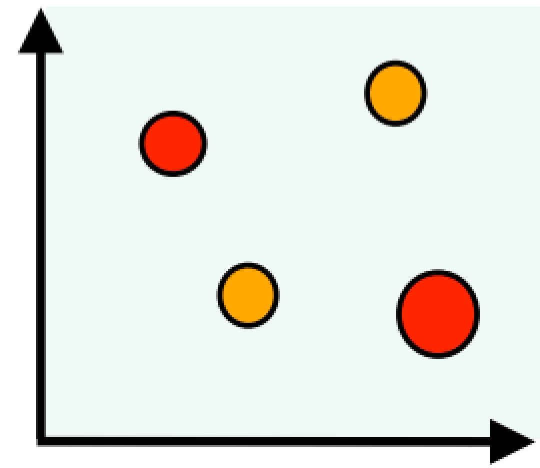
What amount to subtract? How?

CMS, EPJC 50 (2007) 117

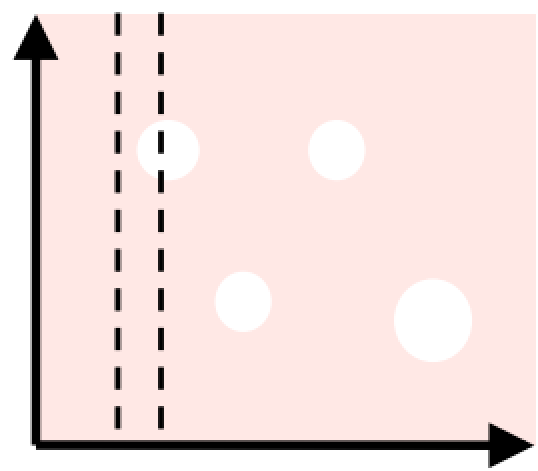




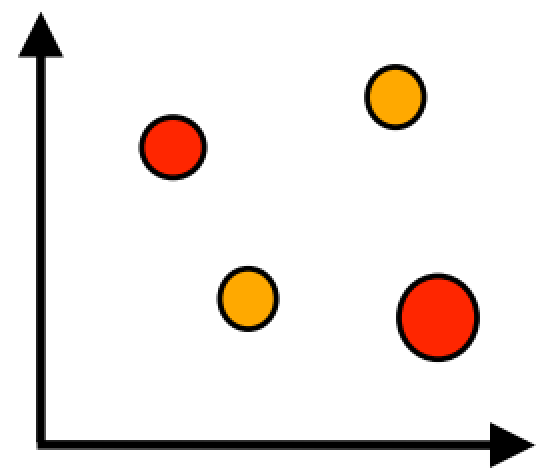
1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$



2. Run anti-k_T algorithm on background-subtracted towers



3. Exclude reconstructed jets and re-estimate background

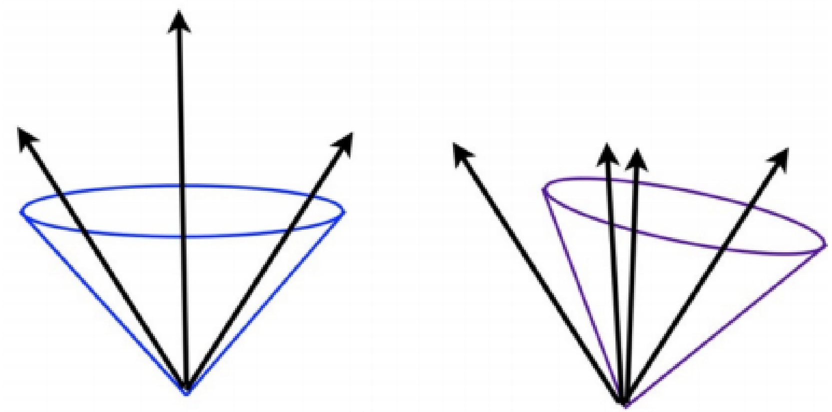


4. Re-run anti-k_T algorithm to get final jets

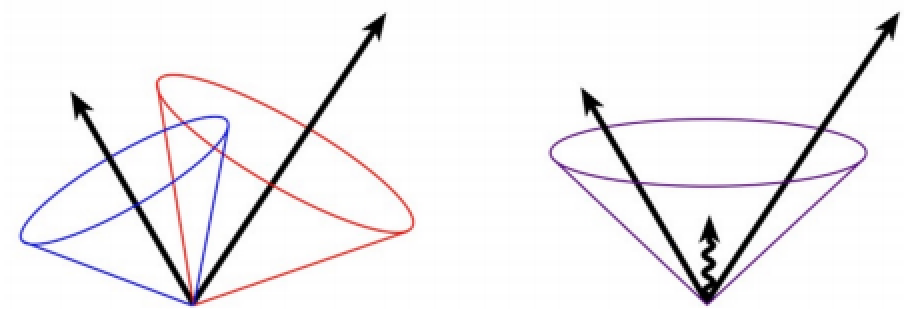
Jet clustering algorithms : requirements

Collinear and IR safety :

→ Collinear splittings should not bias jet finding
→ Soft radiation should not effect jet configuration



Collinear



Infra-red

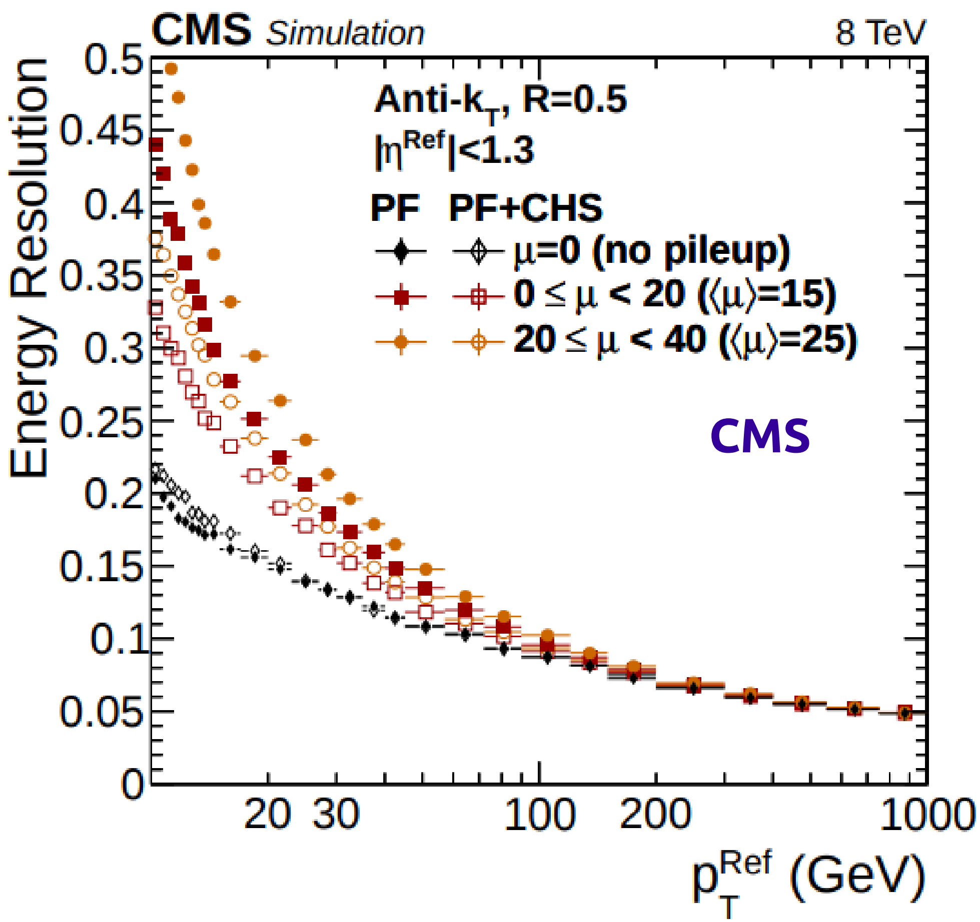
Minimal sensitivity to hadronization, underlying event (UE), Pile-Up(PU)

Applicable at detector-level :

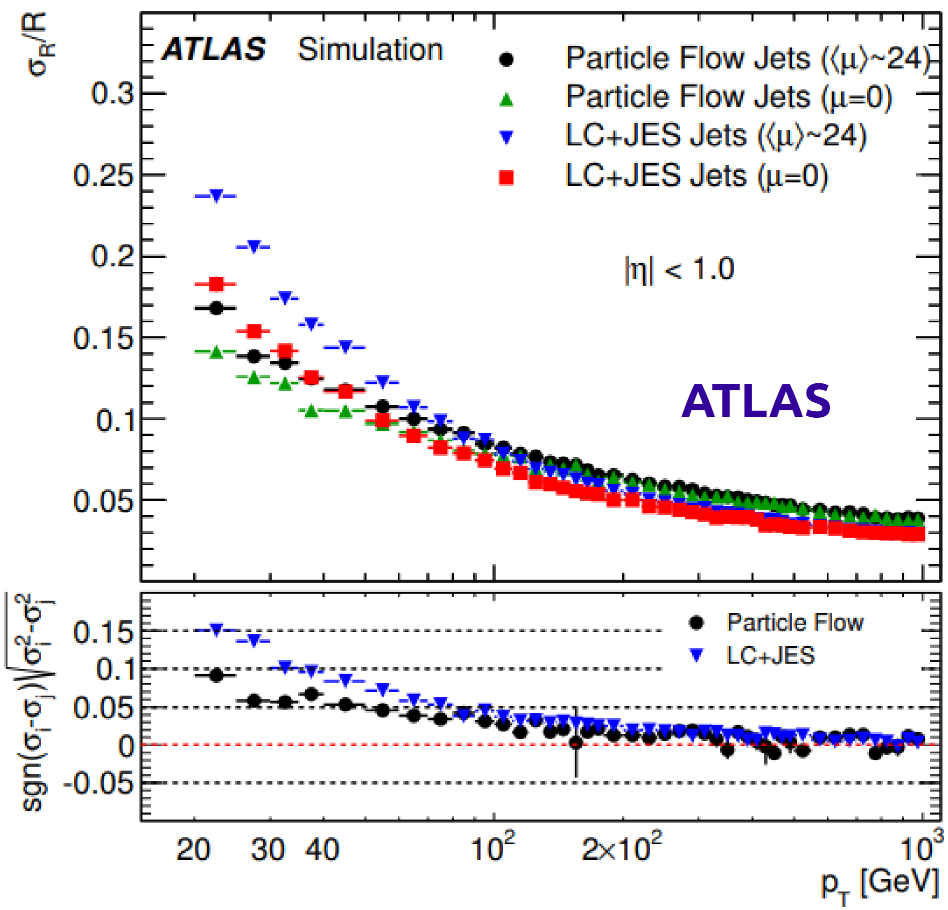
→ good computational performance
→ not to complex to correct

Jet performance in pp collisions

JINST 12 (2017) P10003



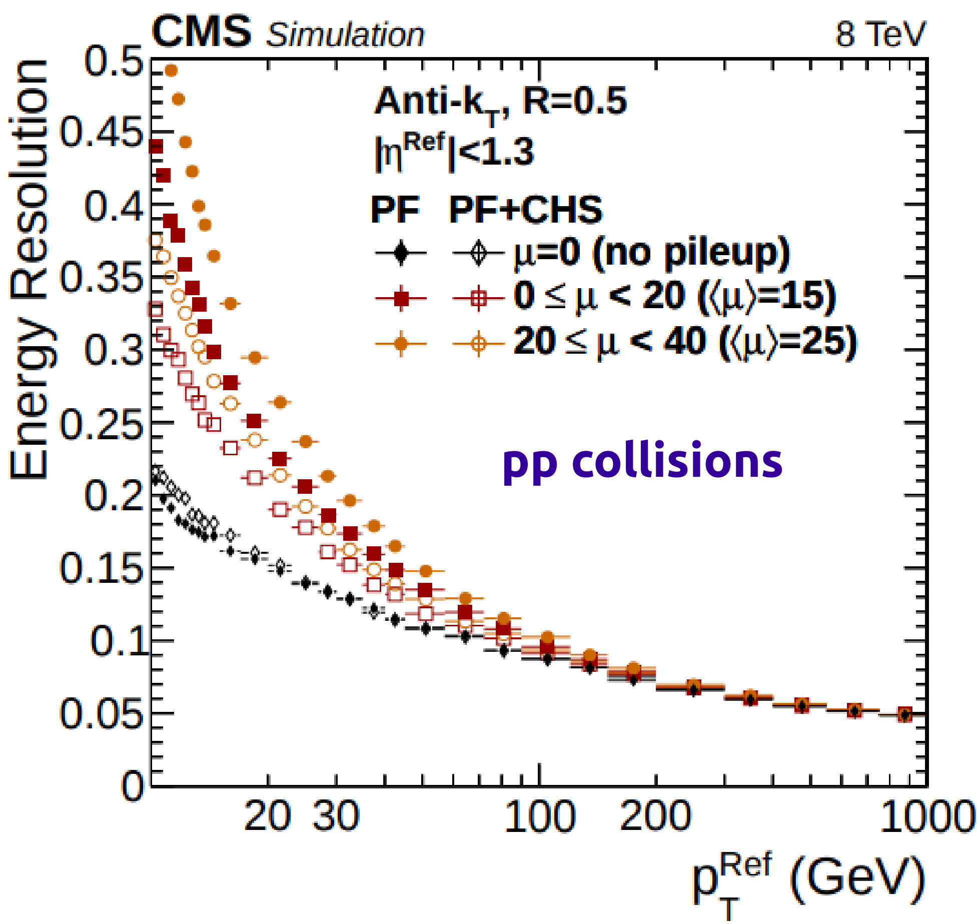
Eur. Phys. J. C 77 (2017) 466



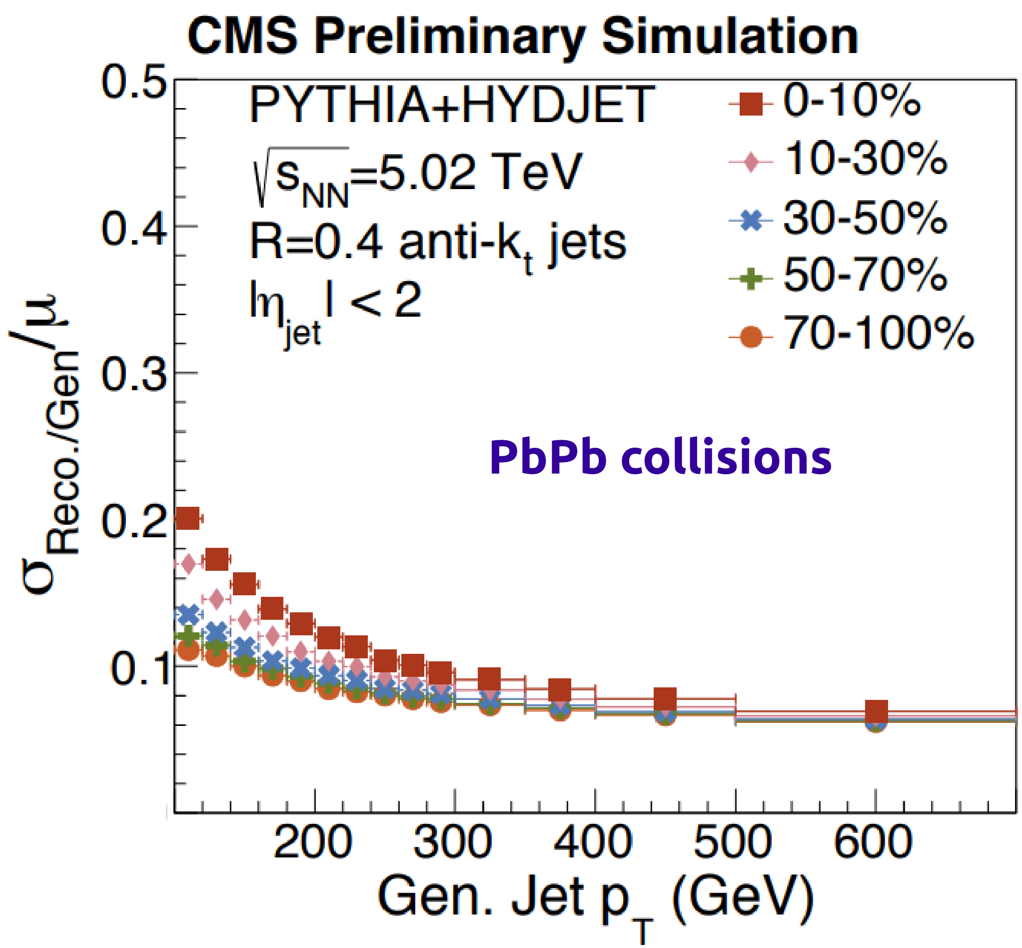
Very good resolution in ATLAS and CMS in pp collisions

Jet performance in PbPb collisions

JINST 12 (2017) P10003



CMS-DP-2018-024



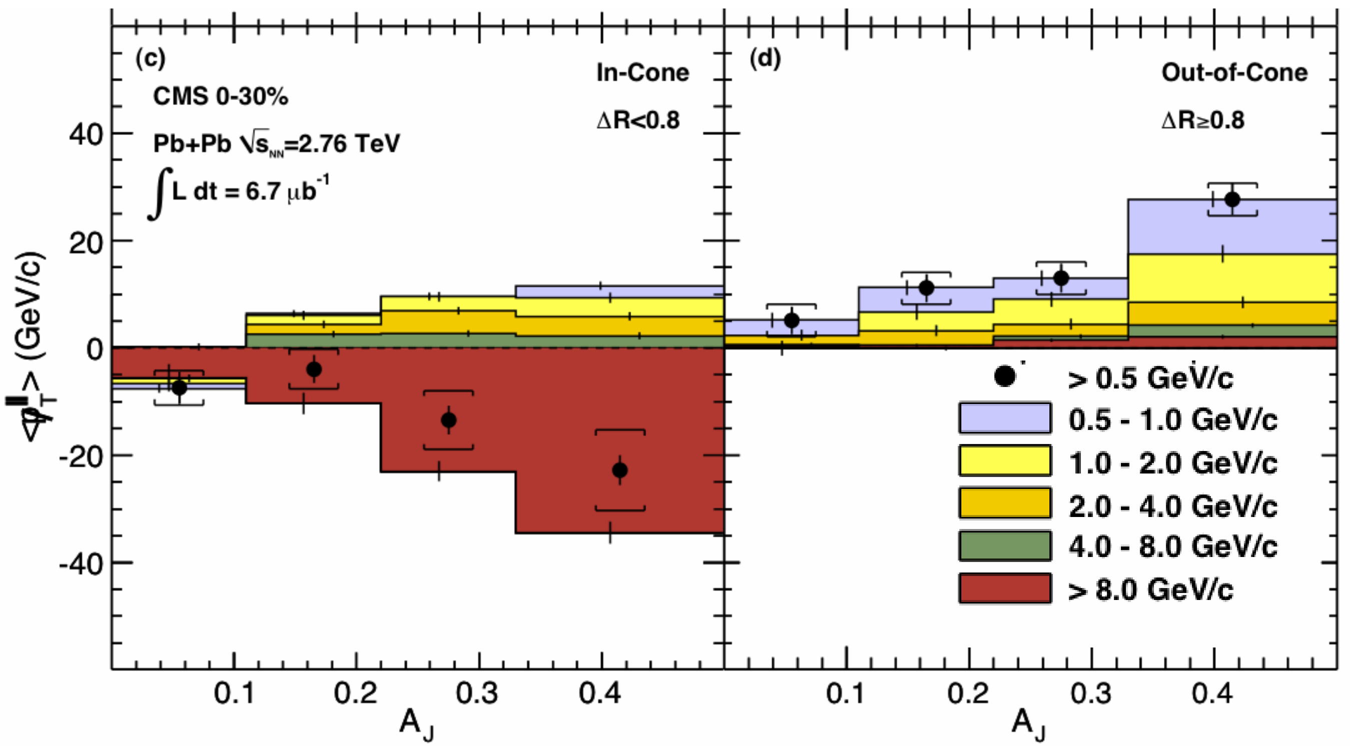
Very good resolution in PbPb collisions for jets with R = 0.4

Dijet asymmetry in CMS

Complementary information about the overall momentum balance in the dijet events: the projection of missing pT of reconstructed charged tracks onto the leading jet axis

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{i}} -p_{\mathrm{T}}^{\mathrm{i}} \cos\left(\phi_{\mathrm{i}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

CMS, PRC84 (2011) 024906



Subleading jet energy is moved from high pT to lower pT and from small to large angles