Jet measurements in LHC

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Outline of the Talk

What is a jet ?

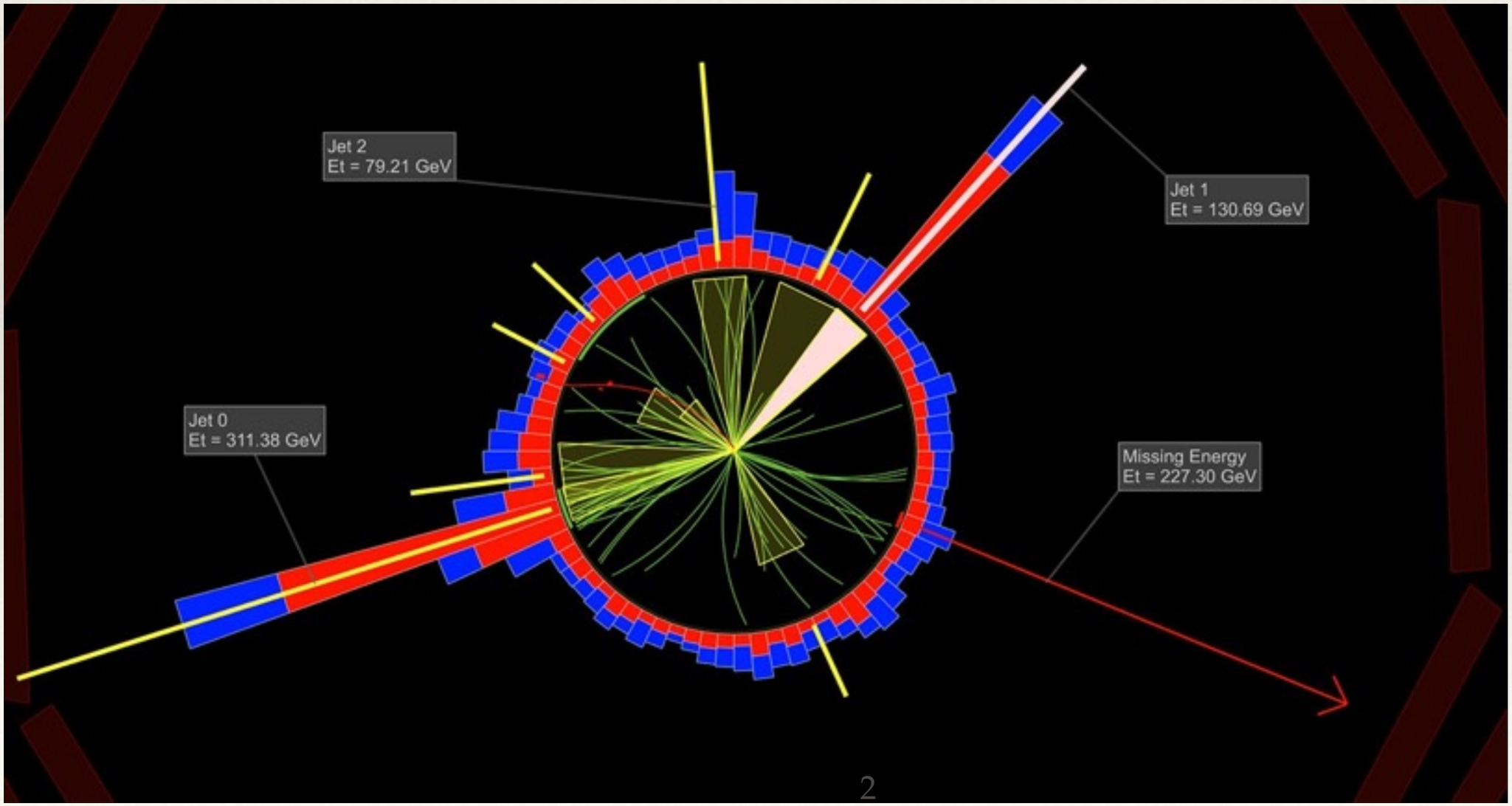
Jets in LHC (jet reconstruction)

Recent jet measurements from LHC

Jets for future

Summary

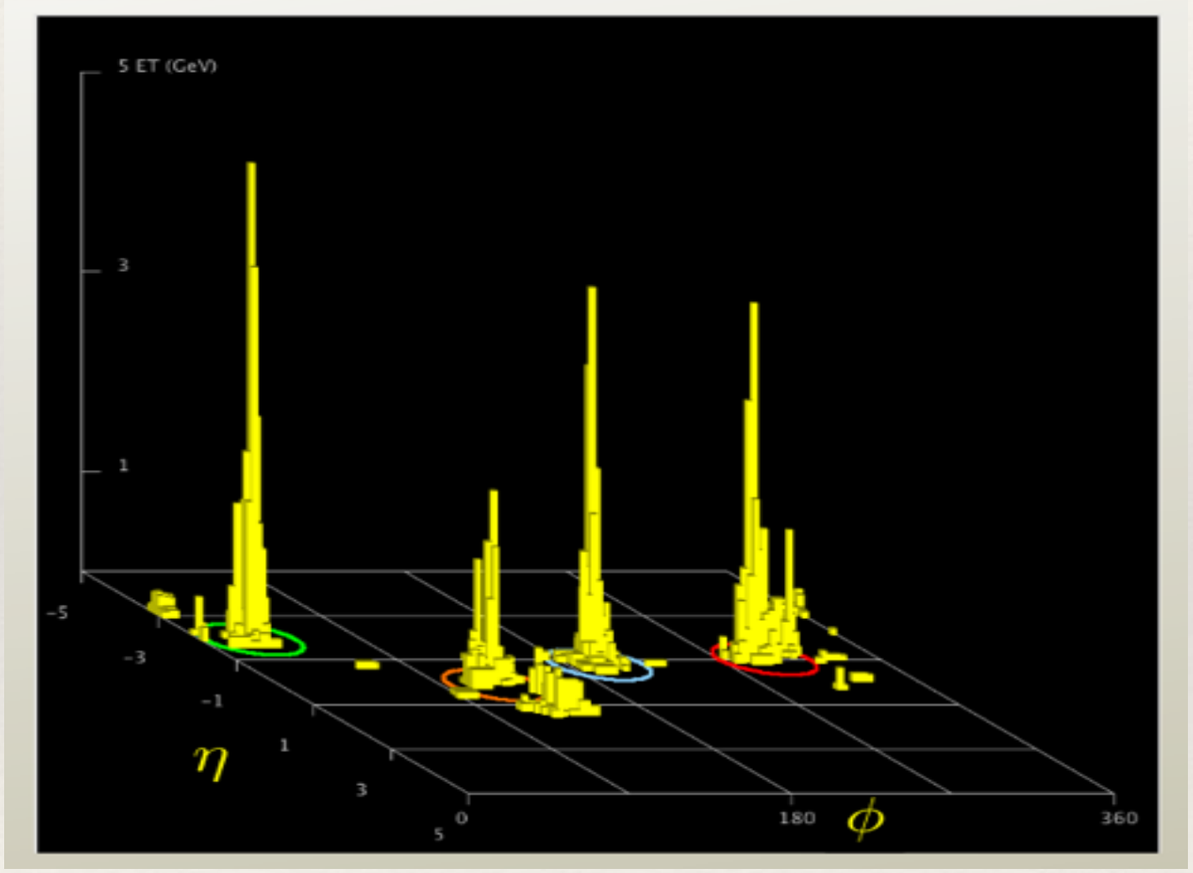
A multi jet event in LHC



What is a jet ?

We use to see Jet Airplanes frequently in the Sky = They use "jets" to fly

A jet : A rapid stream of fluid forced out of a small opening



particle deposits inside jets

In LHC,

A jet is a bunch of particles within a concentrated region.

As a hadron collider, LHC mainly having hadrons as jet constituents.

Most commonly seen, present everywhere !

Motivation : Why study jets ?

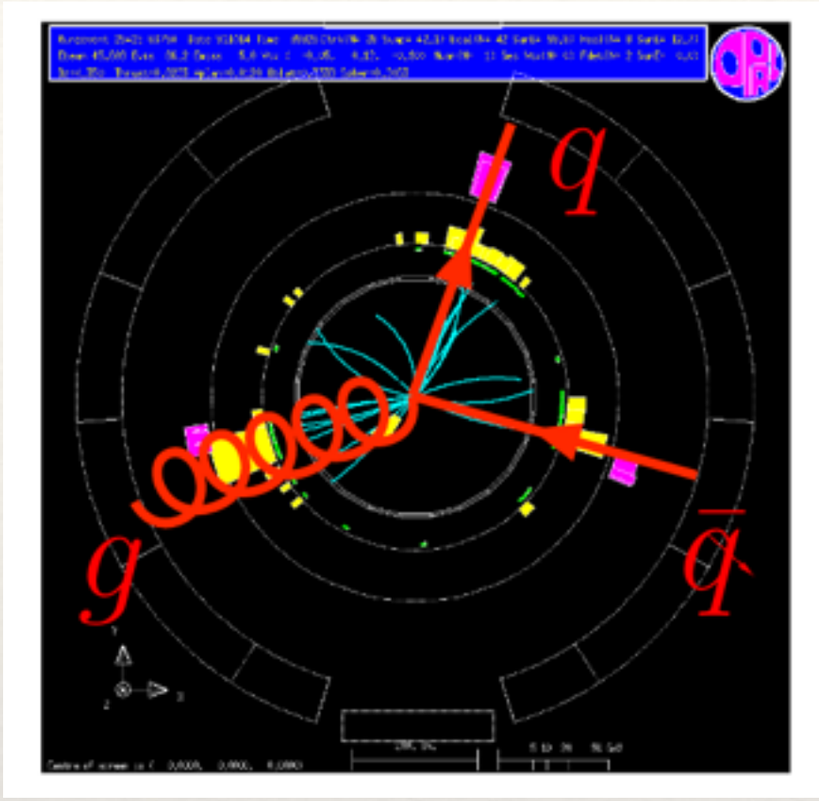
Strongest tool to study strong interaction, strongly interacting particles, prediction/theory for strong interaction.

LHC is a jet factory : Abundance of jets in LHC can be utilised to study the detector.

For any (new/known) particle search frequently jets use to be the background that need to be estimated. Understanding them are important for any search study.

Studies of the internal substructure of jets can discriminate hadronic decay of new heavy particles from other jet background (jet initiated by partons).

Jet Reconstruction :



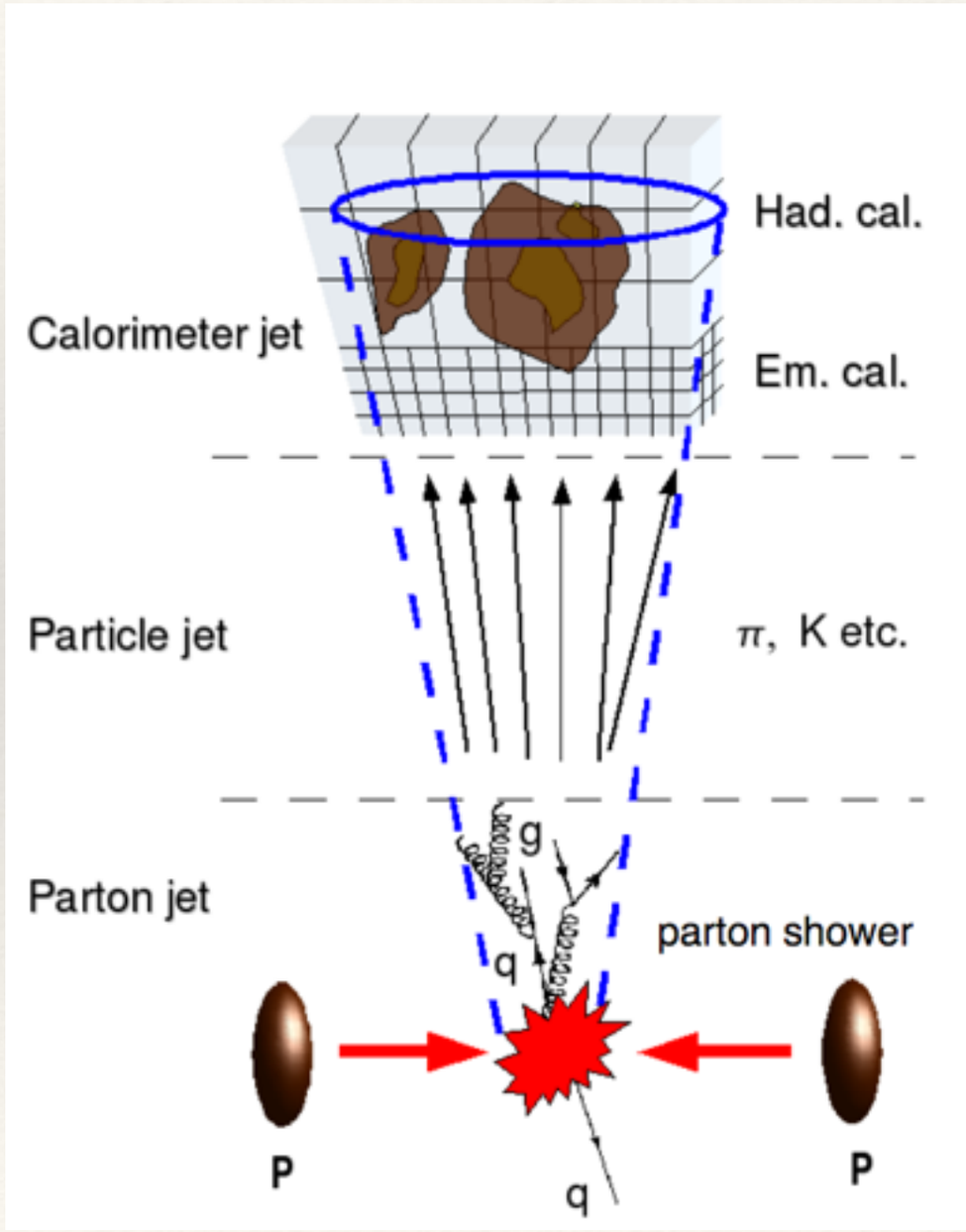
OR, a combined information from all sub detectors used to identify a particle.

These particles (4 momentum vector) are further used as input to a jet reconstruction algorithm to reconstruct a jet.

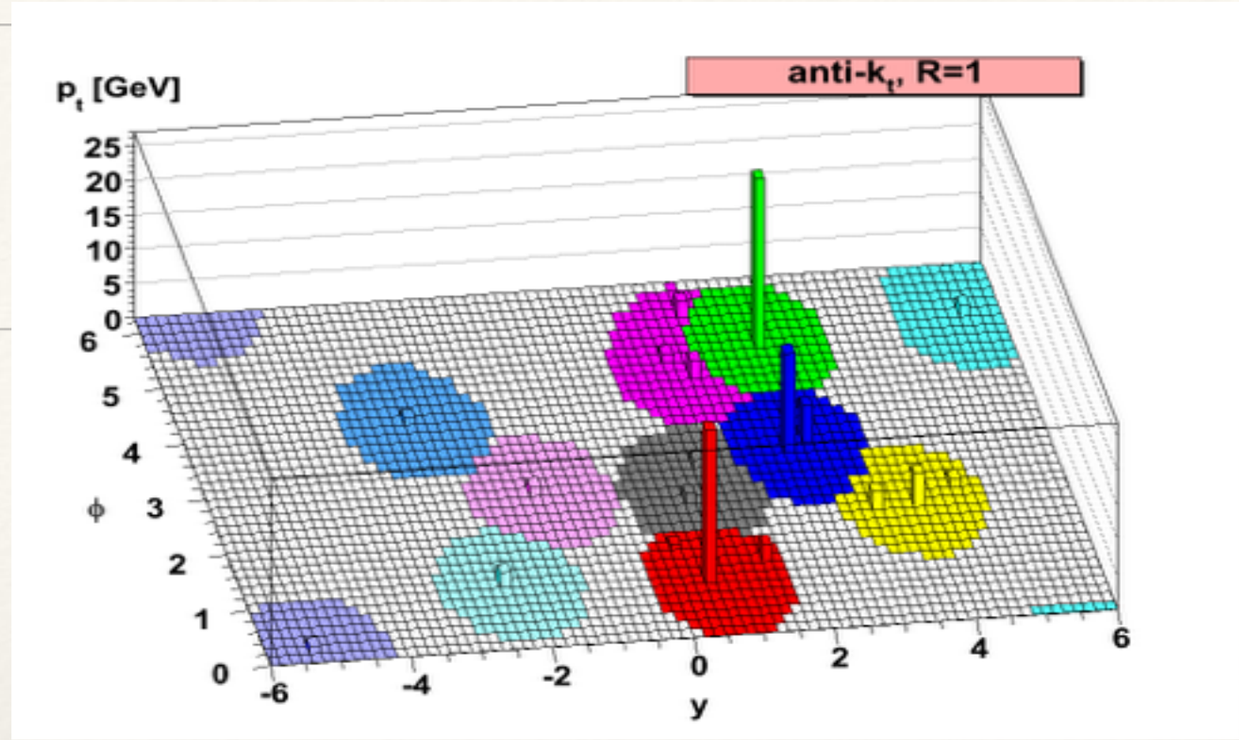
= > Particle Flow (PF) jets

In LHC, A **jet is reconstructed**

Energy clusters in the calorimeters used as input to a jet reconstruction algorithm => calorimeter jets



Jet Algorithm :



Two kinds of approaches are popular :
Cone Algorithm &
Sequential Recombination Algorithm
(commonly used in LHC)

General Flow Chart for 2nd one :

Distance between two input objects — Distance between each input object and beam

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta y^2 + \Delta\phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

Intrinsic transverse momentum — Fixed "radius" parameter

- Find the smallest of all $\{d_{ij}, d_{iB}\}$
- If this is one of the d_{ij} values, inputs i and j are merged.
- If it is one of the d_{iB} values, i^{th} input is considered a jet. & removed

Recent jet measurements from LHC

Measurement of jet charge observable at 8 TeV

Estimator of the electric charge of a jet.

Related to charge of the particle/parton initiating the jet.

Crucial for quark-gluon discrimination.

Useful tool for determining charge quantum number of hadronically decaying particles.

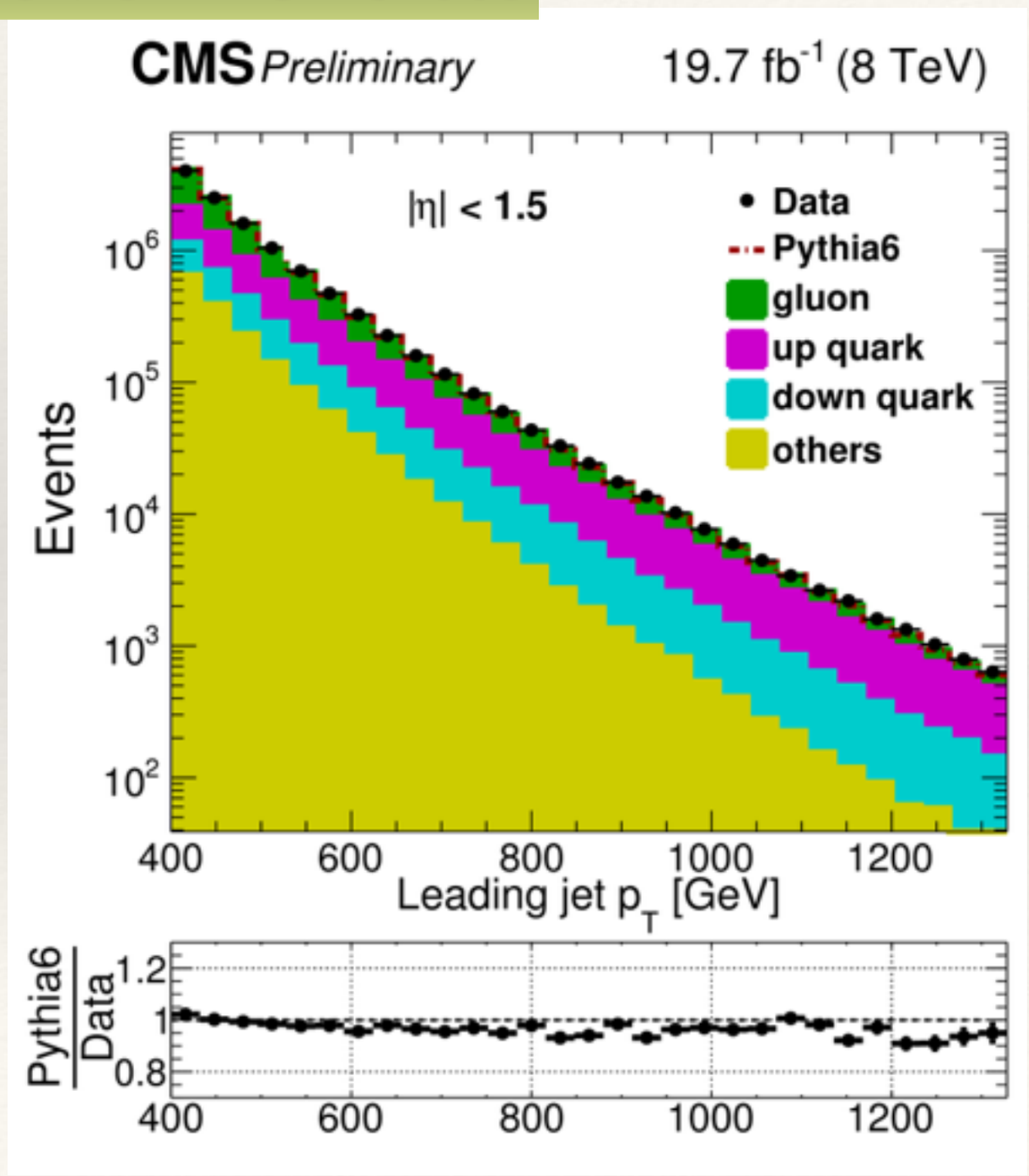
Precise measurements lead to improve MC simulation.

Different definitions are studied !

Measurement of jet charge observable at 8 TeV

Higher the energy more quark jet fraction dominates

CMS-PAS-15-003



Jet charge definitions

Default

$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}})^{\kappa}} \sum_i Q_i (p_{\mathrm{T}}^i)^{\kappa}$$

Parallel

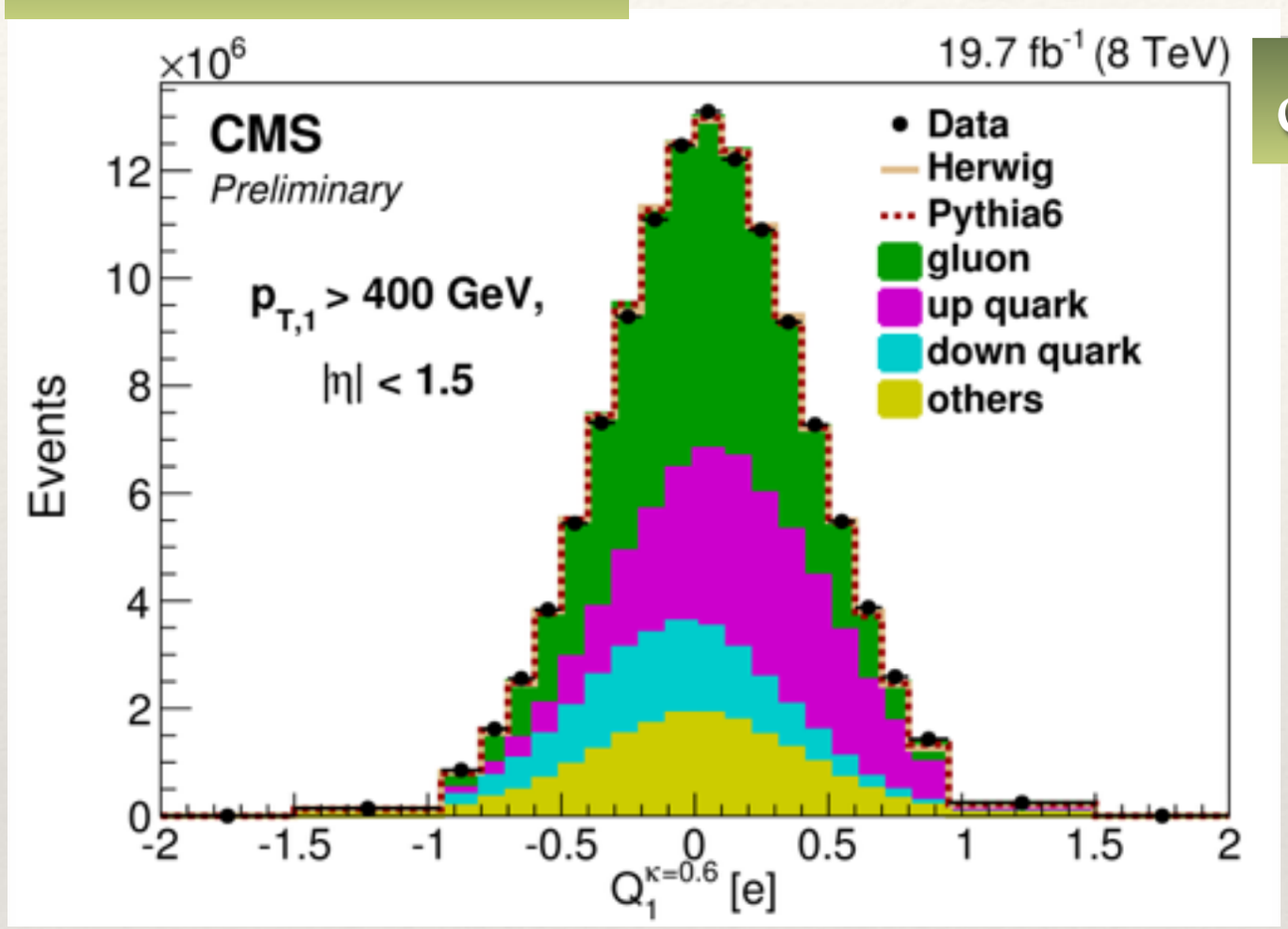
$$Q_L^{\kappa} = \sum_i Q_i \left(p_{\parallel}^i\right)^{\kappa} / \sum_i \left(p_{\parallel}^i\right)^{\kappa}$$

Perpendicular

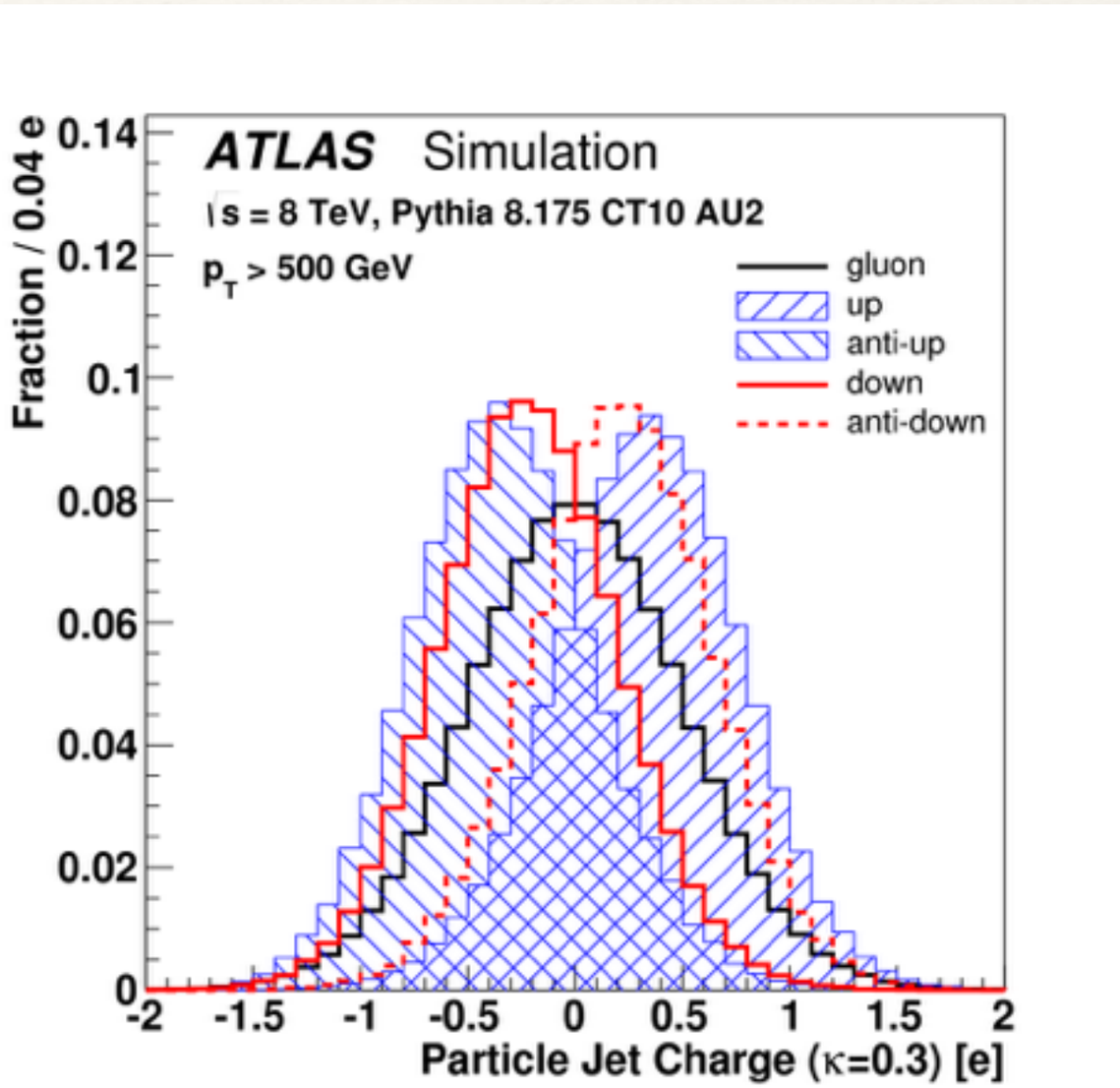
$$Q_T^{\kappa} = \sum_i Q_i \left(p_{\perp}^i\right)^{\kappa} / \sum_i \left(p_{\perp}^i\right)^{\kappa}$$

Jet charge in quark gluon discrimination

CMS-PAS-15-003



quark, anti-quark, gluon category



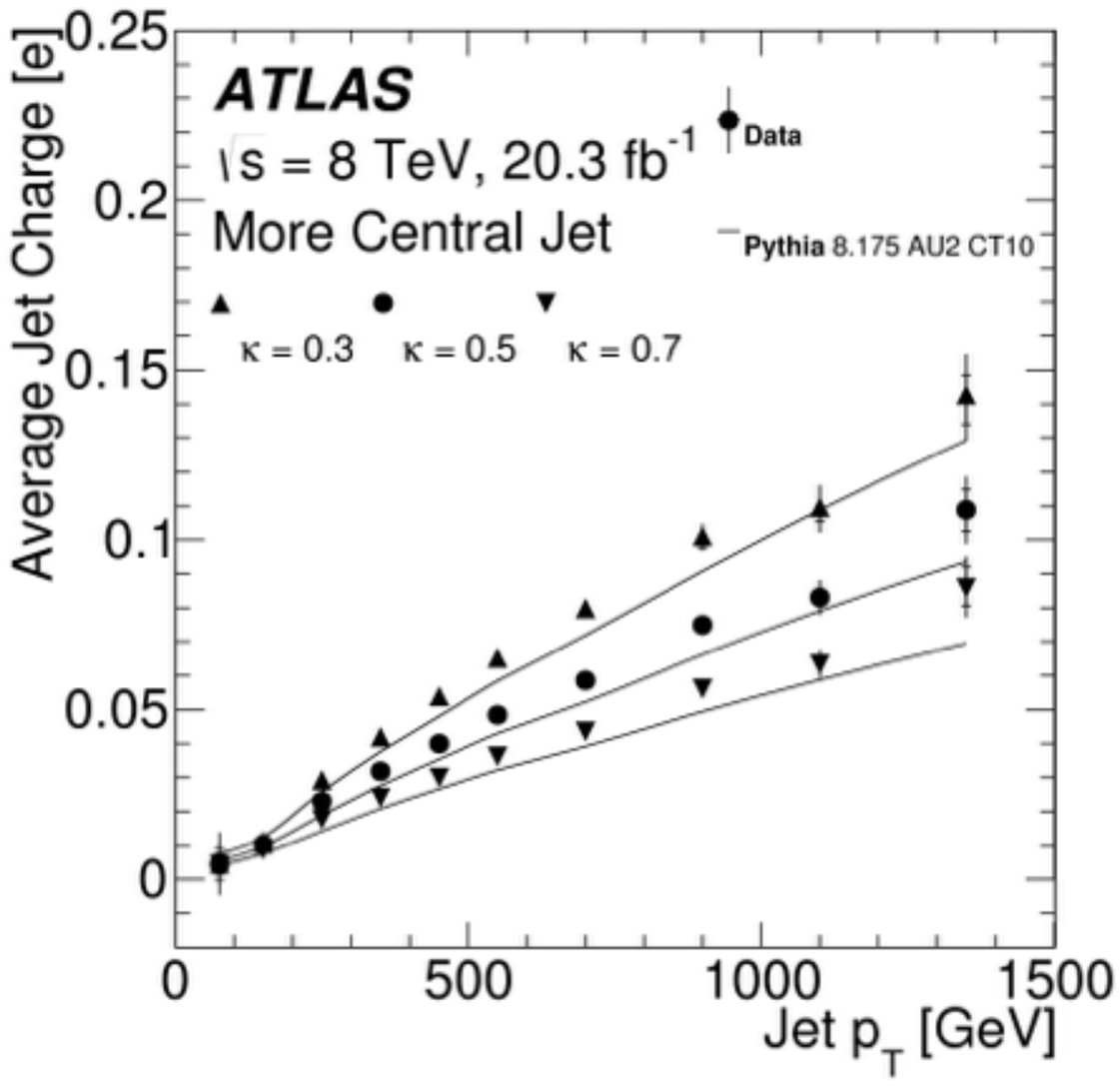
gluon, up , down quark category

Used 2012 pp collision data.
Dijet events selected.
Jet to parton matching carried out with dR.

arXiv:1509.05190

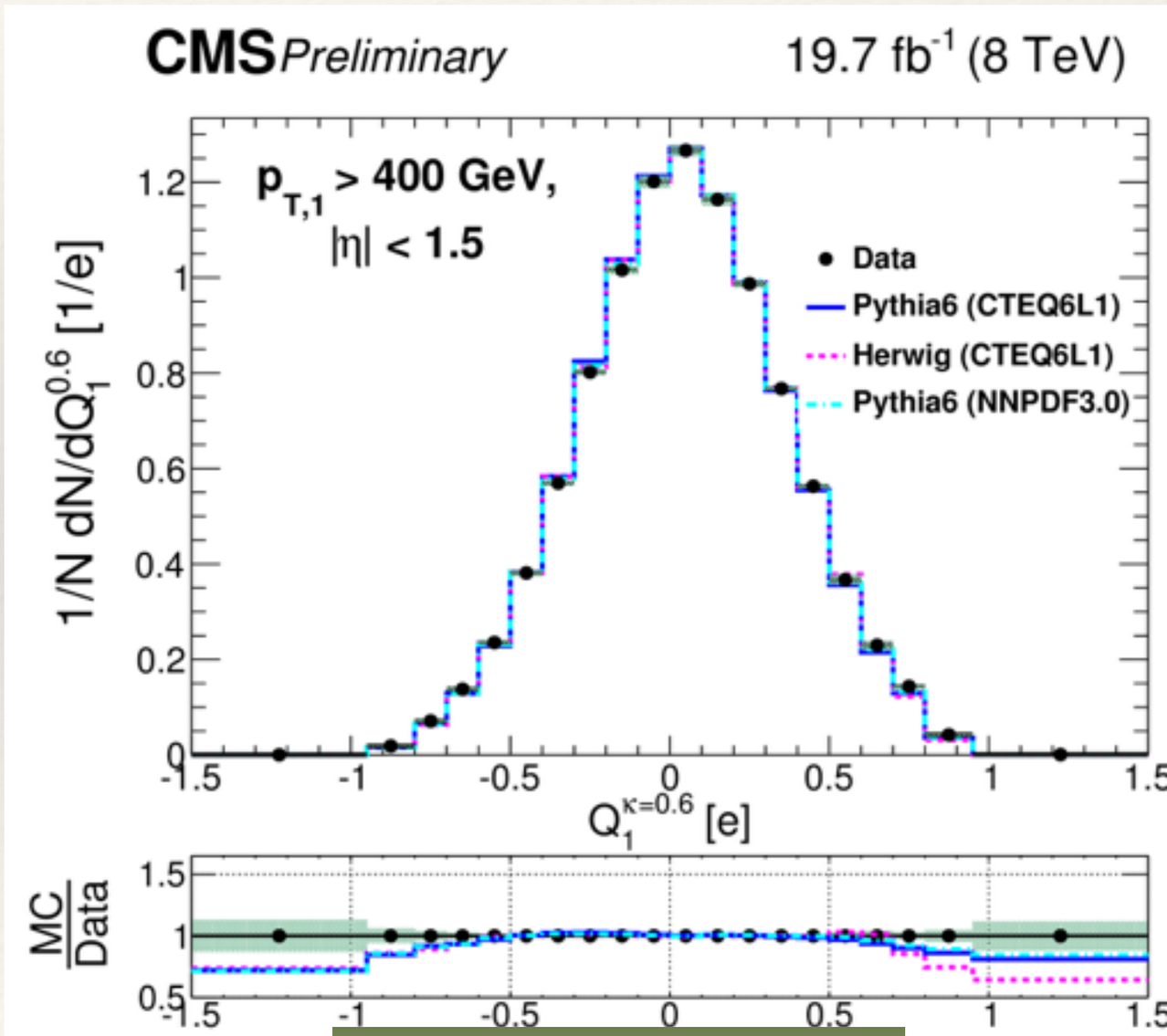
Measurement of jet charge observable at 8 TeV

arXiv:1509.05190



Jet charge value rises with p_T, more p_T more underlying hard partons probed.

More sensitive to fragmentation function than PDF.

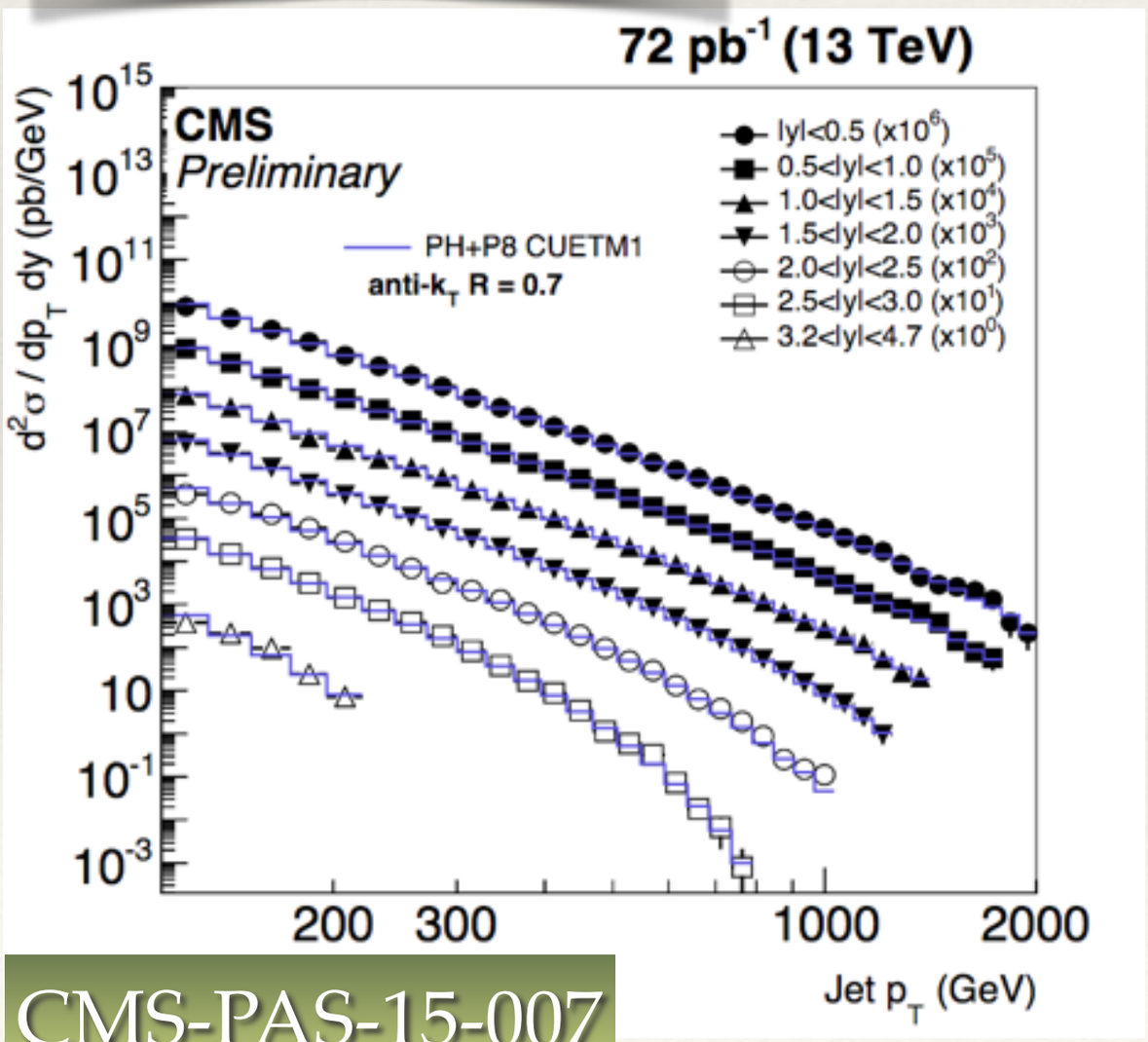


CMS-PAS-15-003

Inclusive jet cross section study at 13 TeV

Measurement of double differential jet cross section covering 114 GeV to 2 TeV jets.
Large jet radius shows better agreement with data within NLO accuracy.
Among LO predictions HPP deviates the most.

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{int,eff}} \frac{N_{jets}}{\Delta p_T \cdot \Delta y}$$



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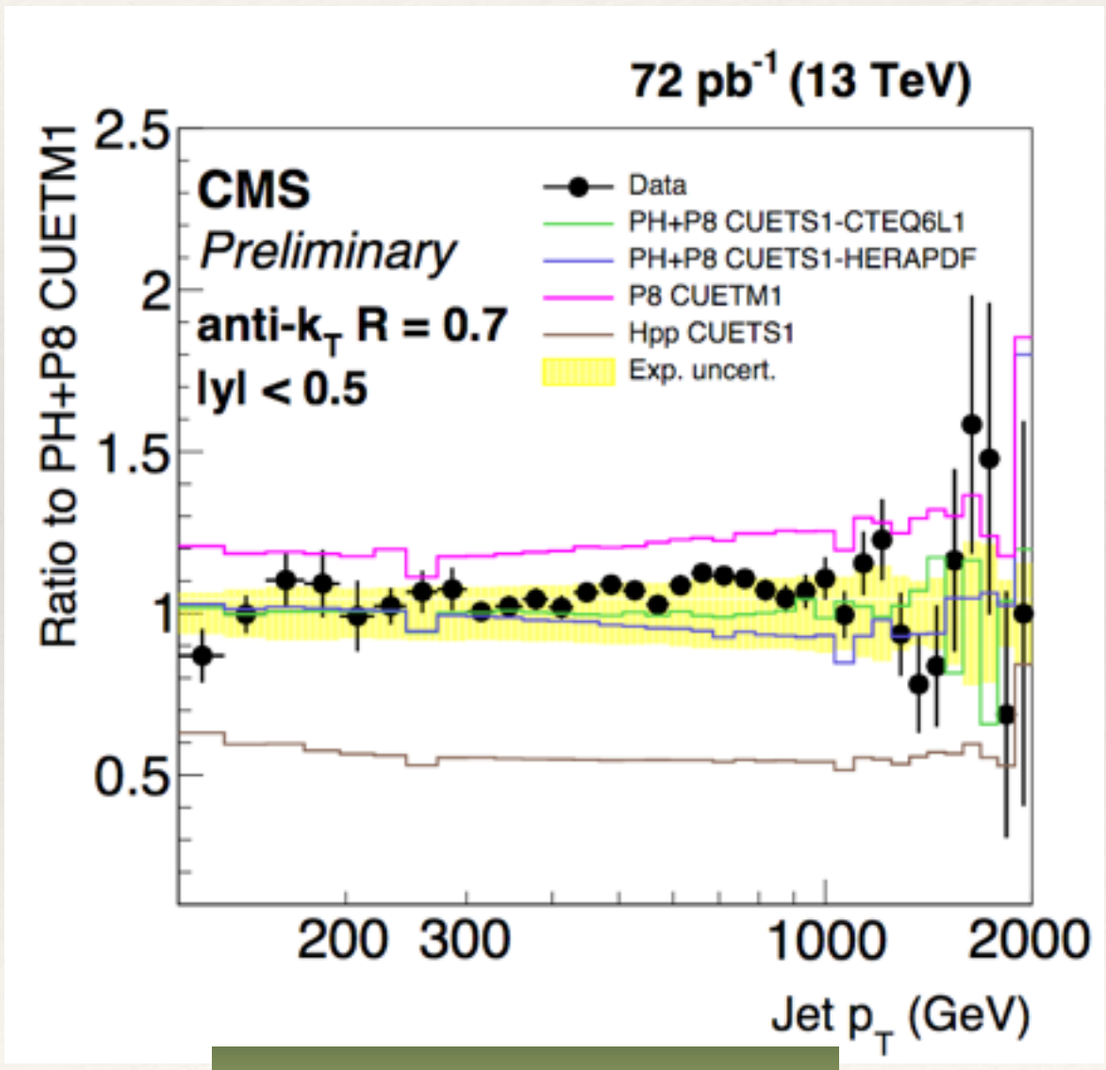
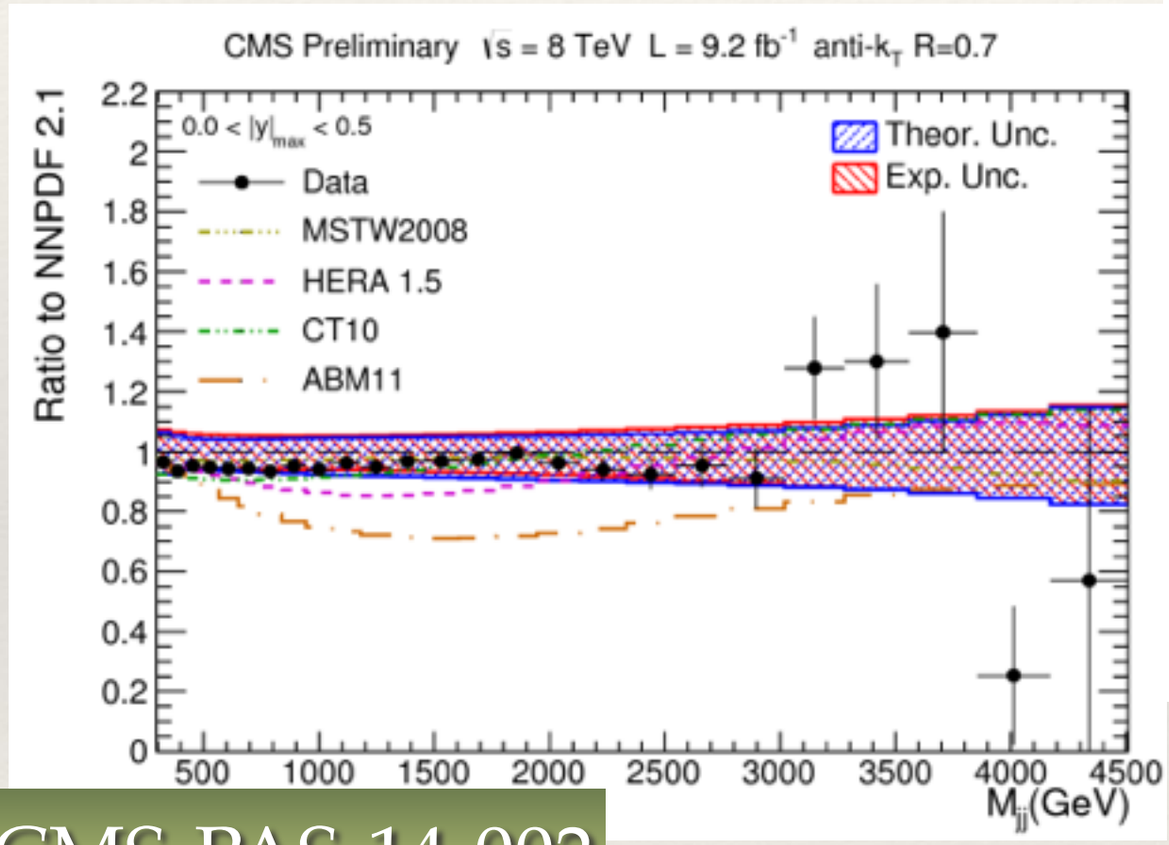


CMS-PAS-15-007

Dijet/Multijet cross section study at 8 TeV

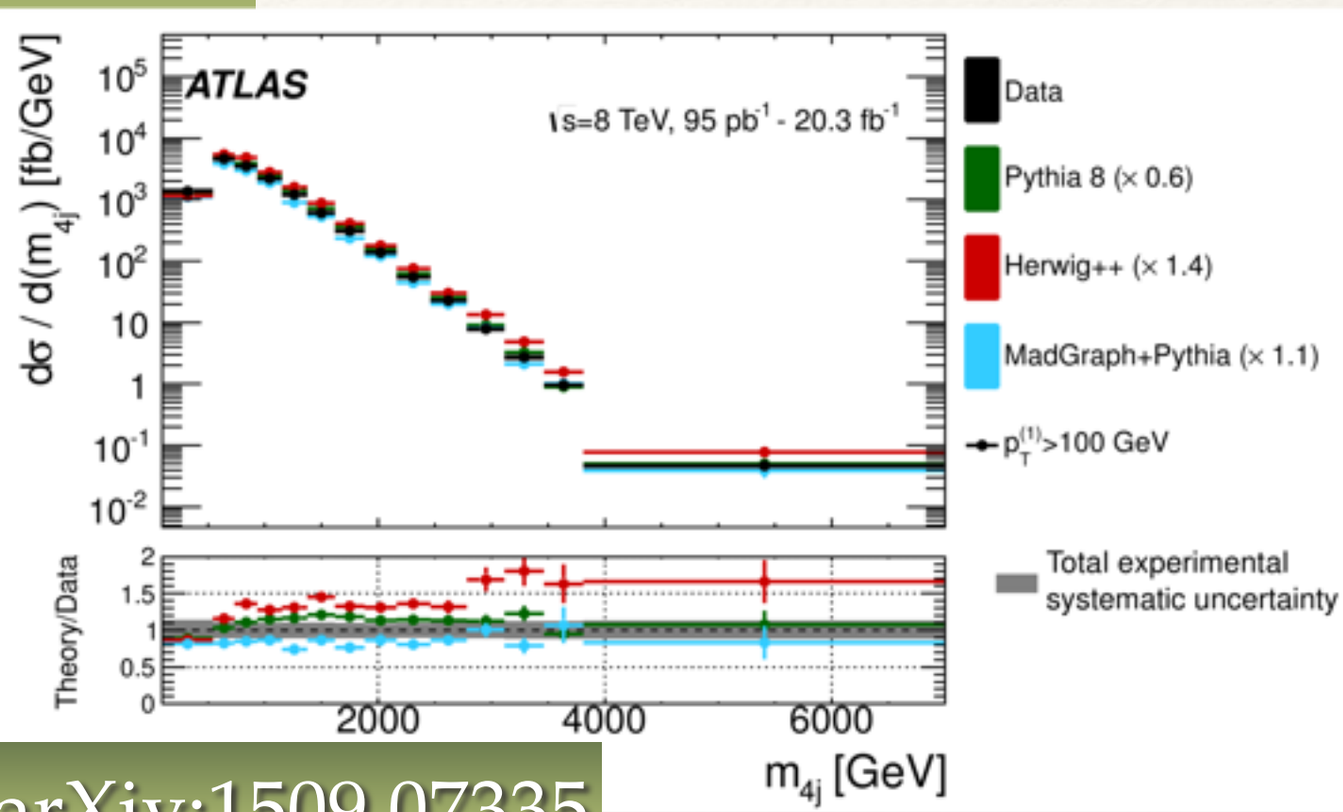
Measurement of dijet cross section as a function of djiet invariant mass and jet rapidity.

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{\mathrm{jj}}\,\mathrm{d}y_{\mathrm{max}}} = \frac{1}{\epsilon \cdot \mathcal{L}_{\mathrm{eff}}} \cdot \frac{N}{\Delta M_{\mathrm{jj}}\ (2 \cdot \Delta|y|_{\mathrm{max}})}$$



CMS-PAS-14-002

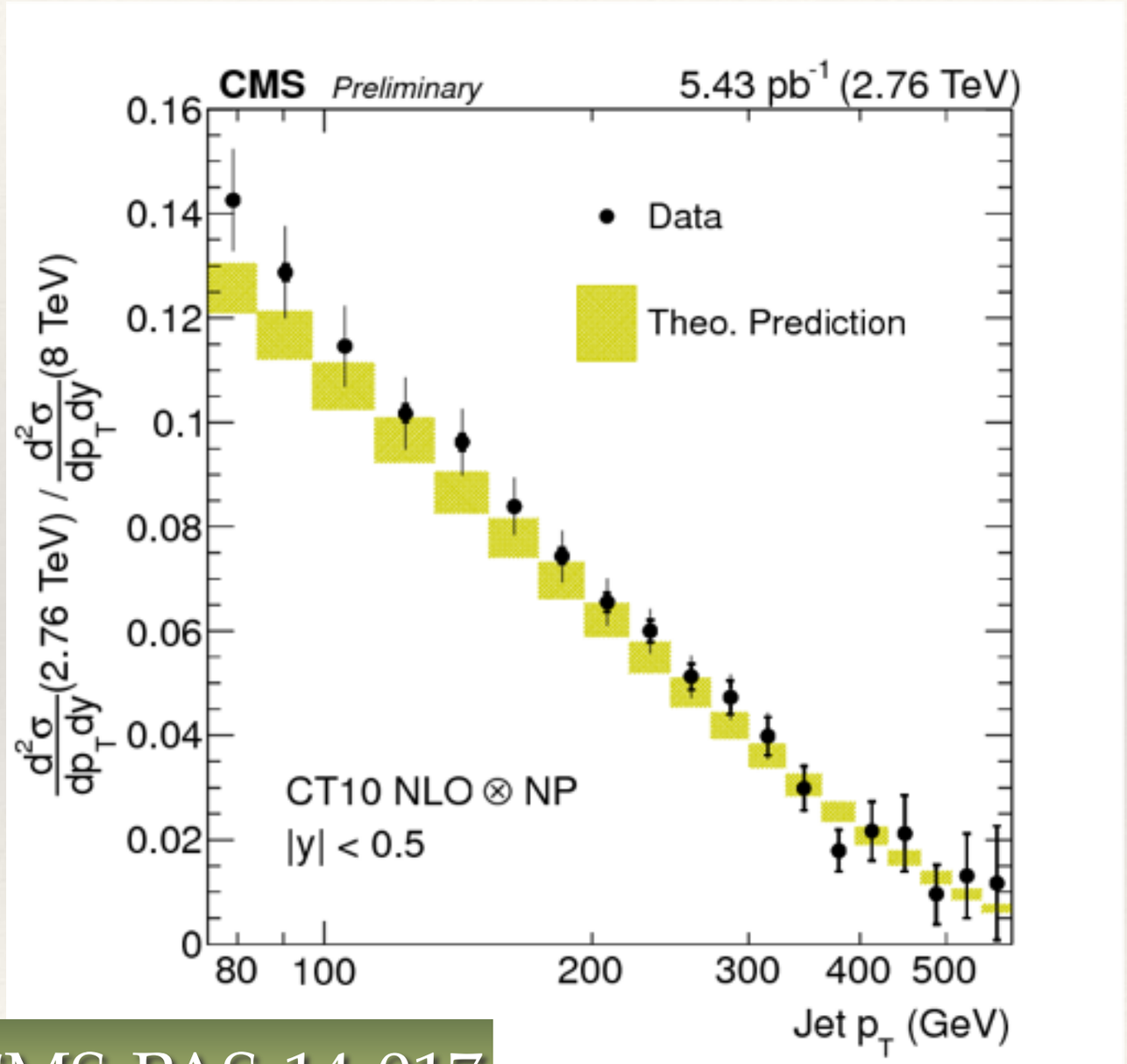
Data, theory are in agreement even at higher mass range within uncertainties.



arXiv:1509.07335

ATLAS performed a 4 jet cross section study, $p_{T(1)} > 100$ GeV, $p_T > 64$ GeV, $|y| < 2.8$.

Jet cross section ratio at 2.76 TeV and 8 TeV



CMS-PAS-14-017

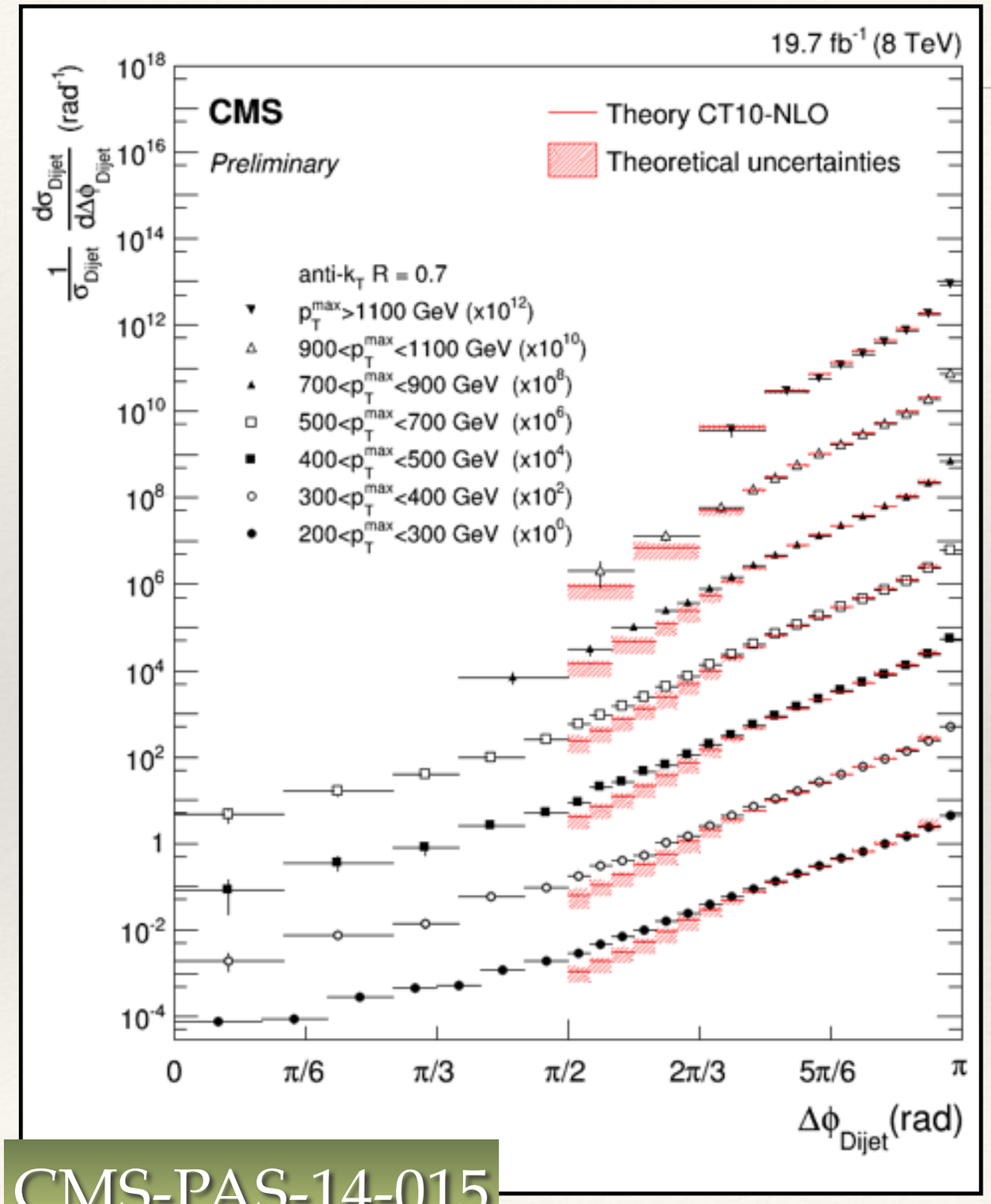
Ratio of inclusive jet cross sections between two centre of mass energies is a potential PDF constraint :

Due to improvement in precision for partial cancellation of uncertainties.

For central region good agreement between data to theory covering the entire jet p_T range (74 to 592 GeV)

Dijet Azimuthal De-correlation at 8 TeV

$$\Delta\phi_{\text{Dijet}} = |\phi_{\text{jet1}} - \phi_{\text{jet2}}|$$



CMS-PAS-14-015

: **Can distinguish dijet to multijet events.**

Dijet cross section as a function of $\Delta\phi_{\text{Dijet}}$, in jet p_T slices, normalized to (σ_{Dijet}).

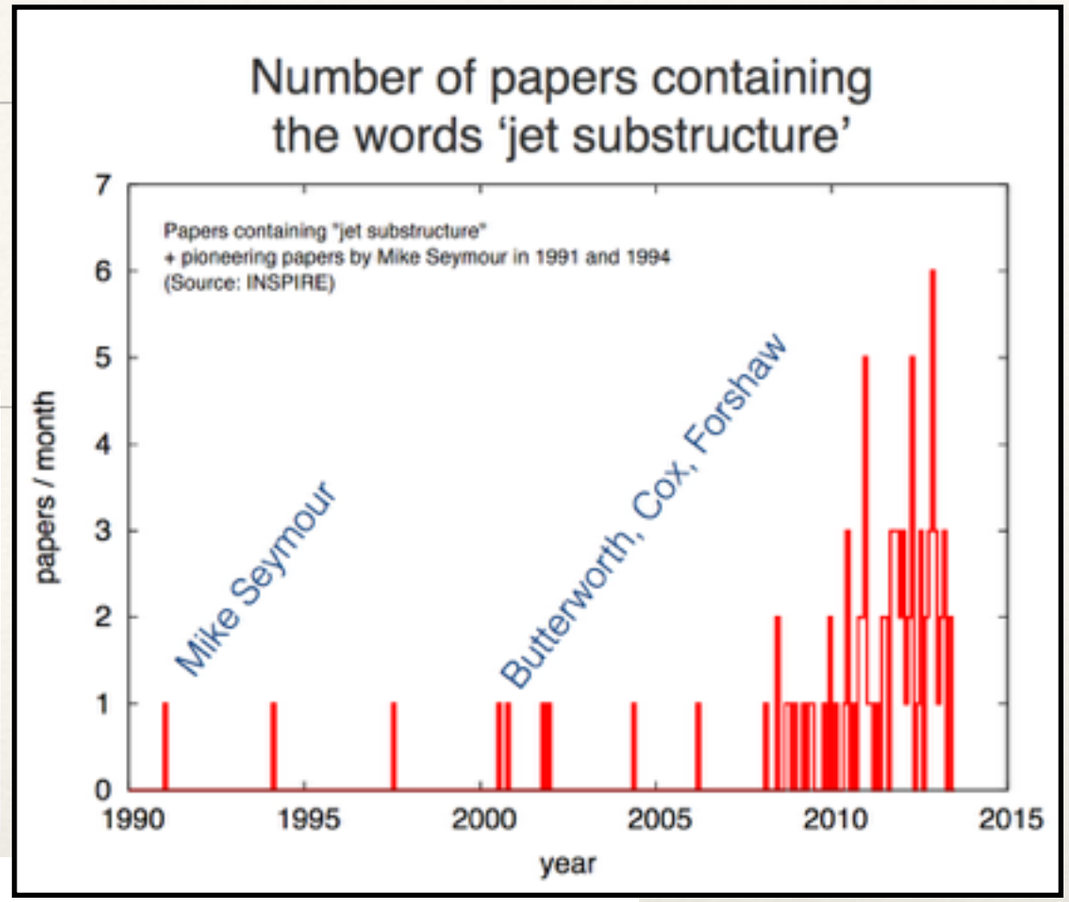
Jet $p_T > 100$ GeV, $|y| < 5$ selected, two leading jets have $|y| < 2.5$.

Leading jet $p_T > 200$ GeV, are chosen.

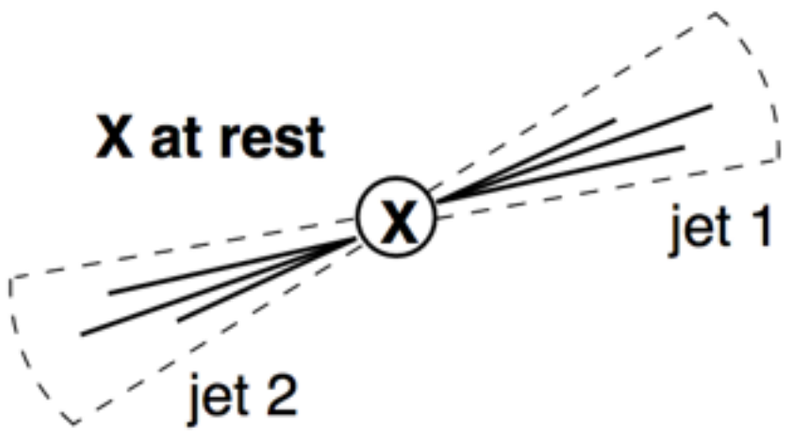
Available theory calculations $\pi/2 < \Delta\phi_{\text{Dijet}} < \pi$

Jets for future : Jet Substructure

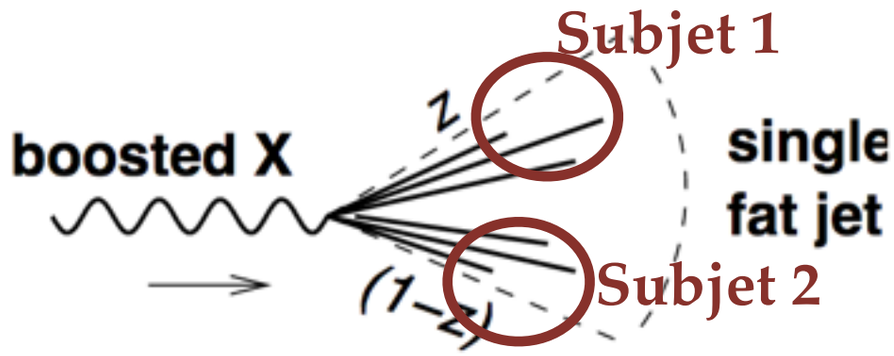
More Energy -> Boosted particles
Jets from hadronic decay of massive boosted particles (such as H, top, W) can be discriminated from other jets !



Normal analyses: two quarks from $X \to q\bar{q}$ reconstructed as two jets



High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$
$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

Detailed description in the next talk..

Summary :

Jet measurements in LHC are extremely useful for understanding and improving QCD.

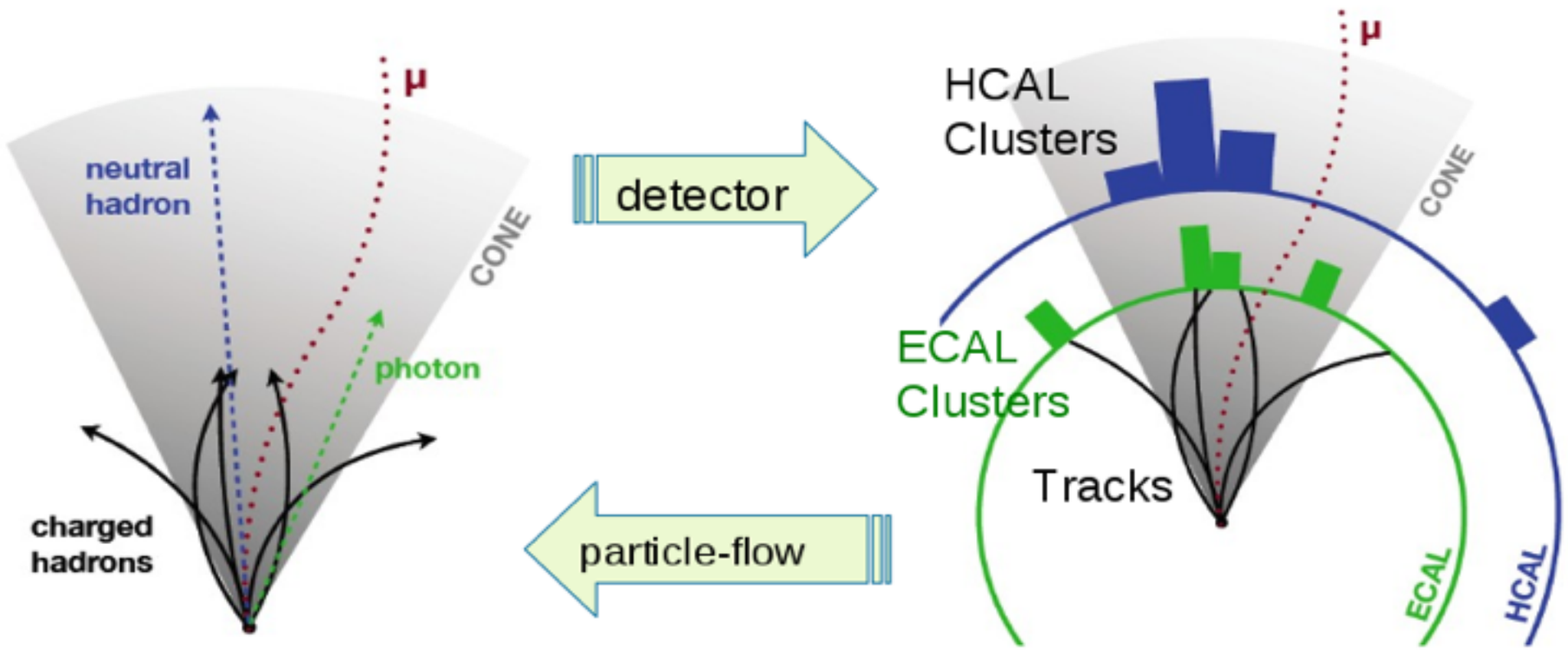
Results corrected for detector effects can be compared with other experiments / theory.

Jets can be used for finding new particles (e.g. jet charge, jet substructure).

Back up

Jets are reconstructed in LHC

Particle Flow (PF) Jets : Reconstructed from particles identified by combining information from sub-detectors : Tracker, ECAL, HCAL.



Calo Jets : Another type of jet used where only calorimeter information utilized for reconstruction.

PF Algorithm :

1. Track reconstruction
2. Calorimeter clustering
3. Extrapolation of tracks, linking the deposits of each particle in the sub detectors

The list of individual particles is then used to build jets

E.g. A set of track + clusters constitute a charged hadron.

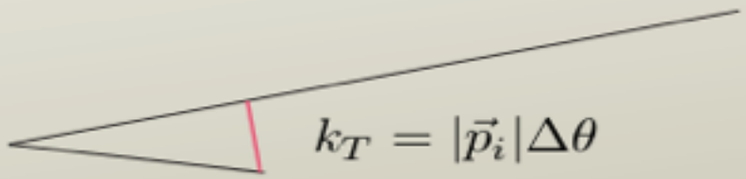
What is k_T?

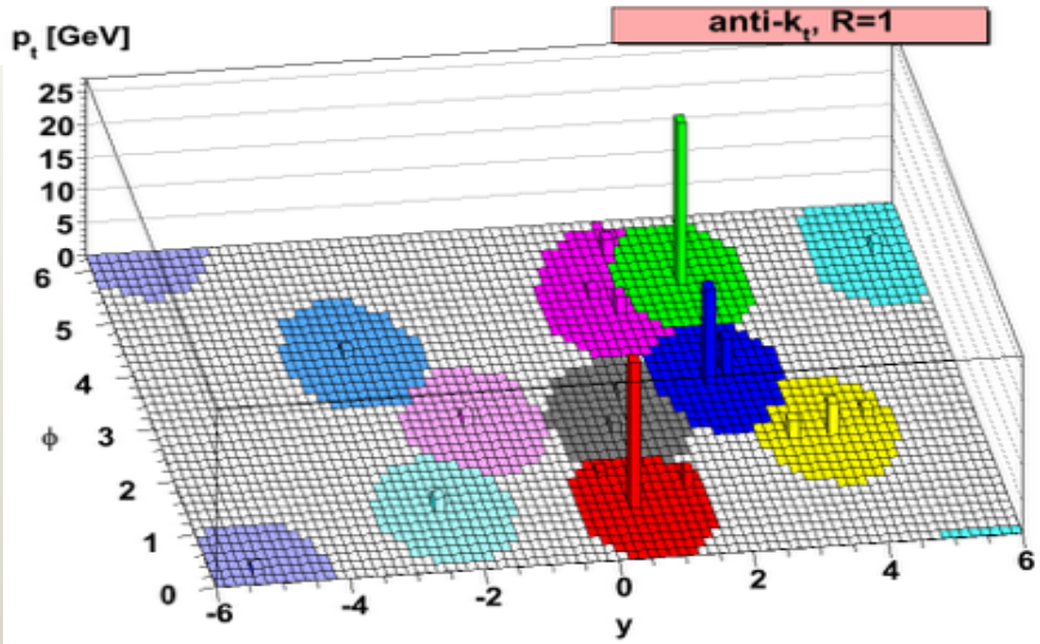
Why the name?

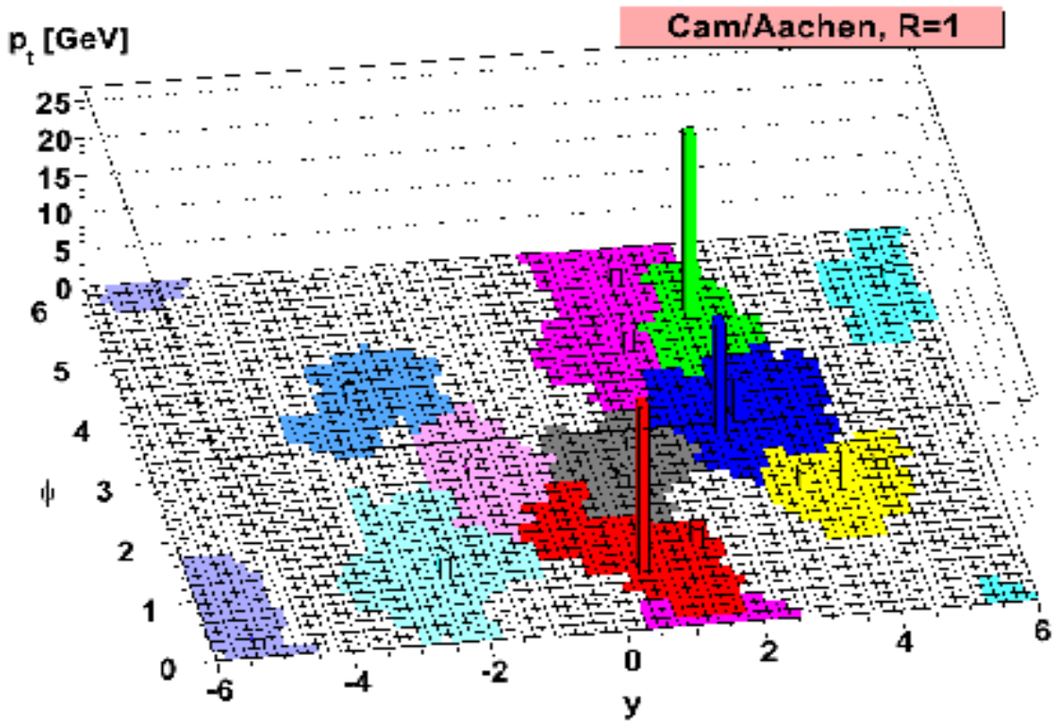
$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2)\,[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2]/R^2$$

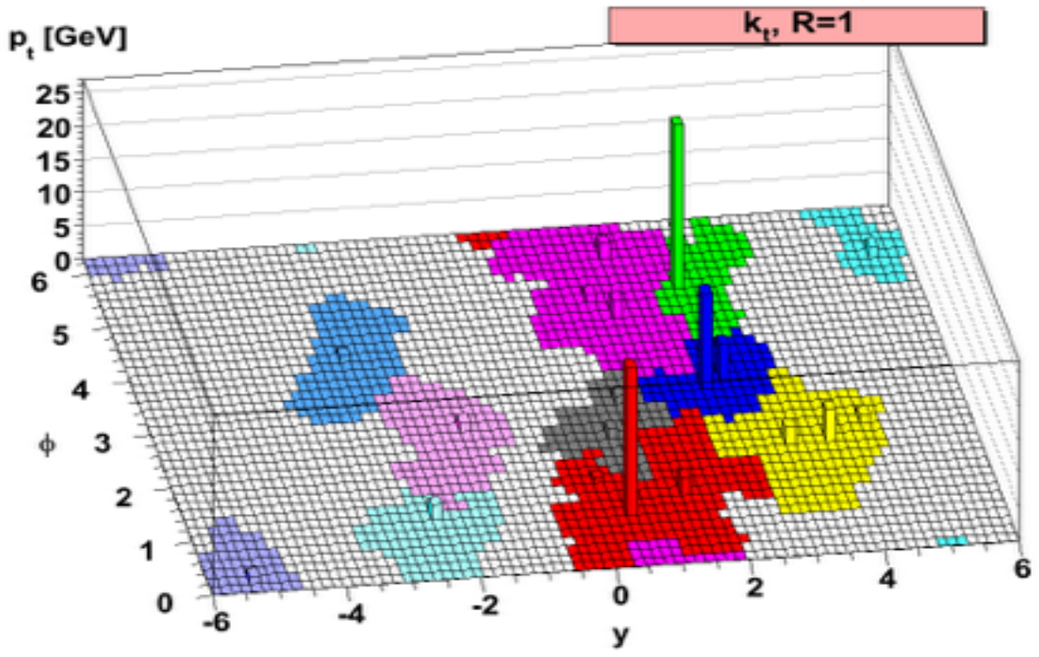
is essentially

$$d_{ij} = k_T^2/R^2$$



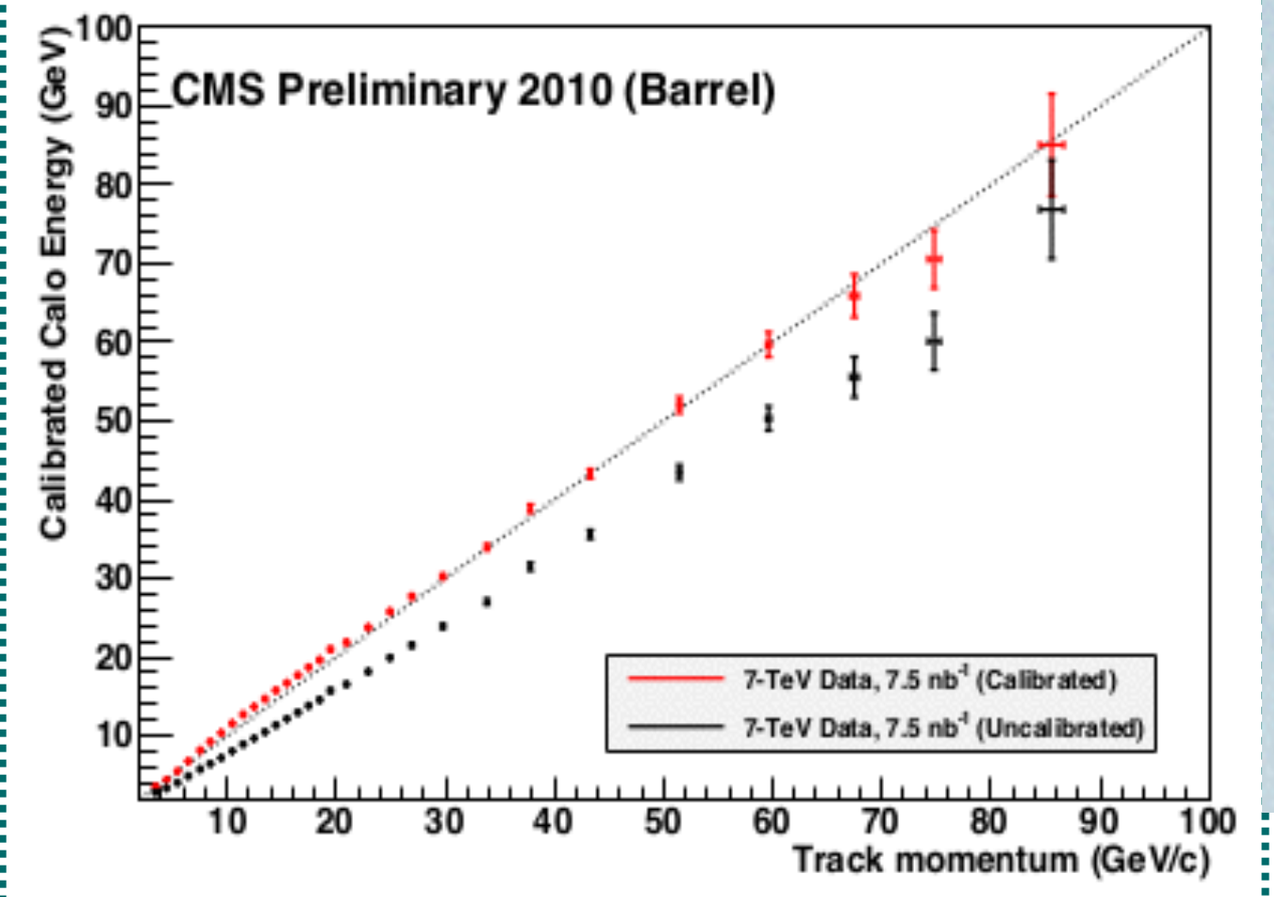


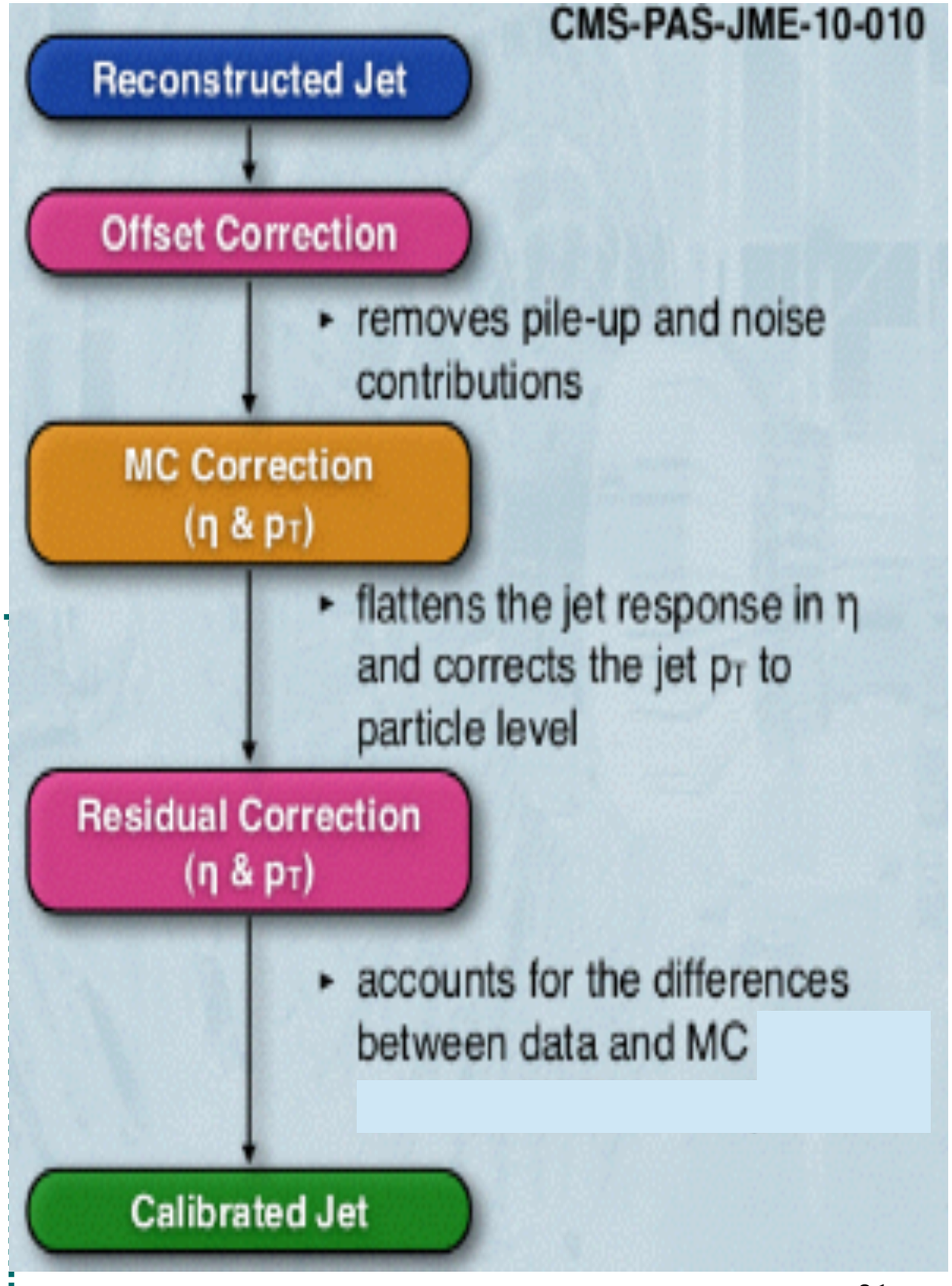




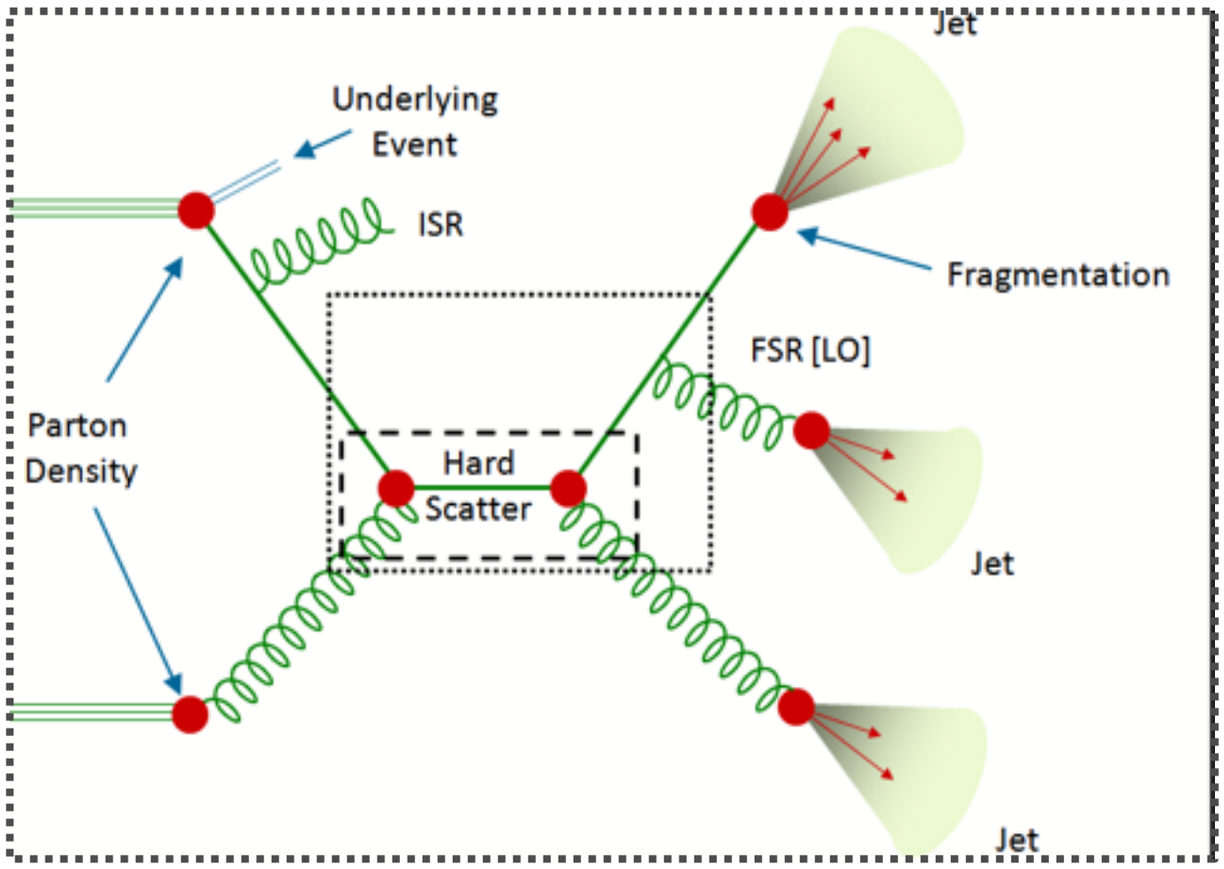
Jet Energy Calibration

It is crucial due to the nonlinear and nonuniform response of the calorimeters.
Also in order to reduce the pile up effect, electronic noise, data-MC mismatch.
A factorized approach is developed by CMS to apply all these corrections.





A simulation example of hard scatter and jet production :



Hard Scatter : Hard interaction with large momentum transfer.

Underlying Event :
All contributions that are not associated to a hard interaction.

PDF (Parton Distribution Function) : Probability of finding a parton with a momentum fraction within a proton depending on the energy scale.

The final state partons produce showers with successively low energy.
After parton showering partons combine to colourless hadrons.

Fragmentation functions model parton showering and hadronization.