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Joint ICTP-INFN-SISSA Conference: Topical Issues in LHC Physics

29 June - 2 July, 2009

Jet Studies in CMS / ATLAS

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Jets in CMS

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Joint ICTP-INFN-SISSA Conference: Topical Issues in LHC Physics
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Outline

- Introduction
- Jet Algorithms
- Jet Reconstruction
- Jet Energy Scale
- Jet Resolution
- Prelude to Jet Physics
- Summary

The public CMS results can be found here:
https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

The public ATLAS results can be found here:
https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults

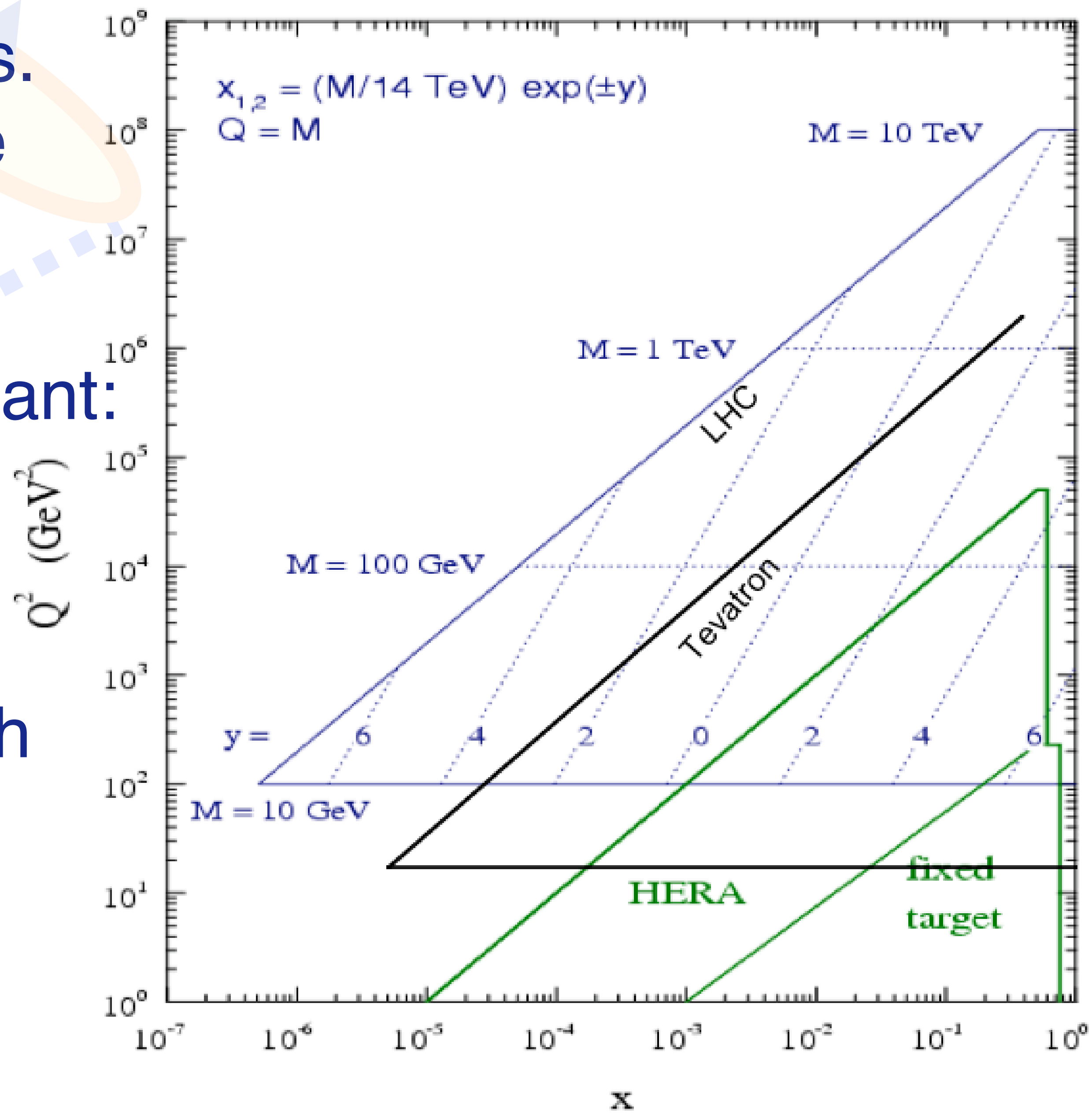
PART I: Introductory Elements

✦ Physics processes with jet final states will be dominant in the LHC experiments.

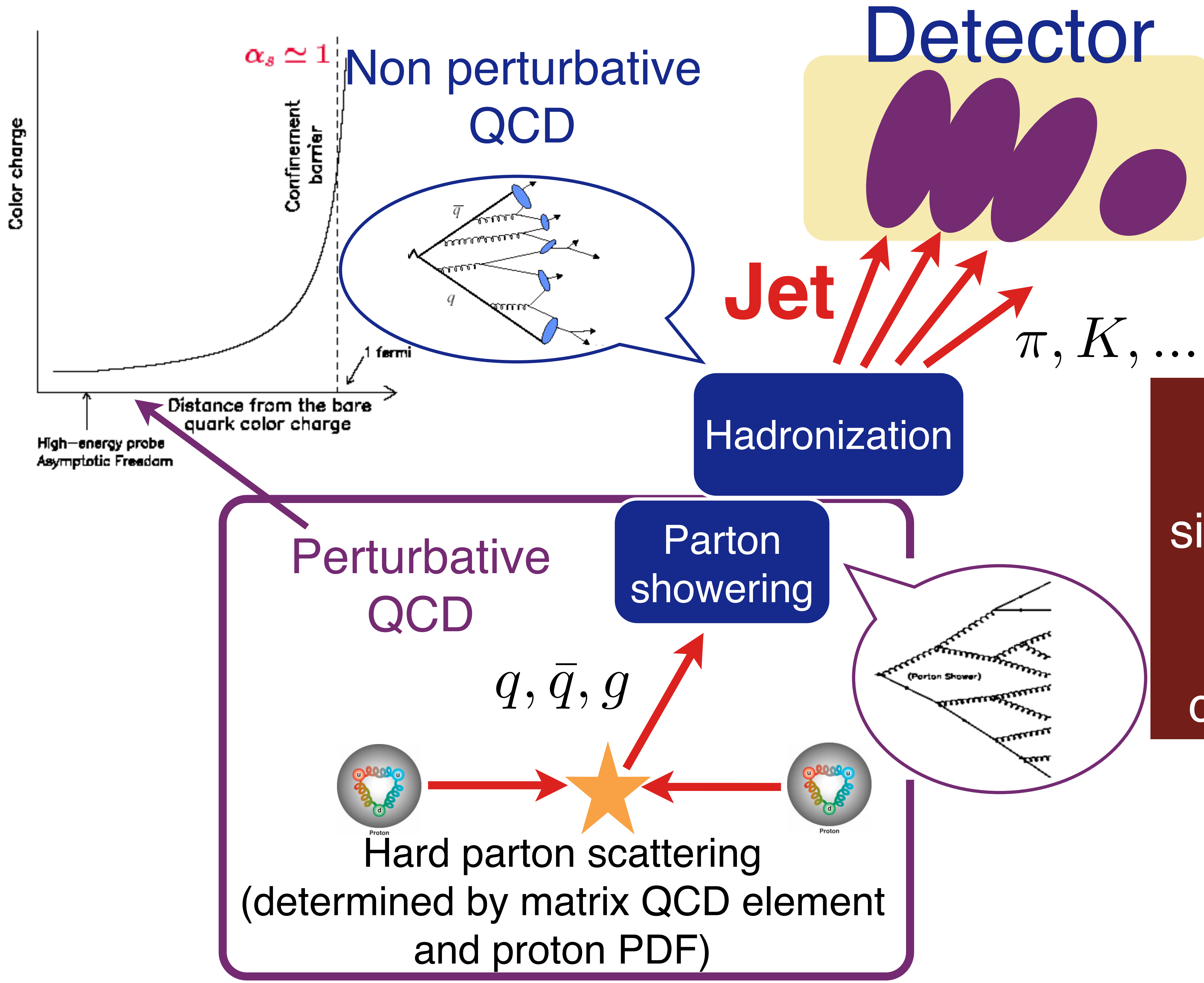
✦ The LHC detectors' rapidity coverage allows probing a large ***Q^2 vs x*** phase space.

✦ Jet measurements at LHC are important:

- understanding QCD
- sensitivity to new physics, strongly interacting
- constrain PDFs (far in the future, with large amount of data)
- hadronic SUSY
- top measurements (all hadronic, semileptonic)
- Electroweak W,Z+jets measurements
- .....

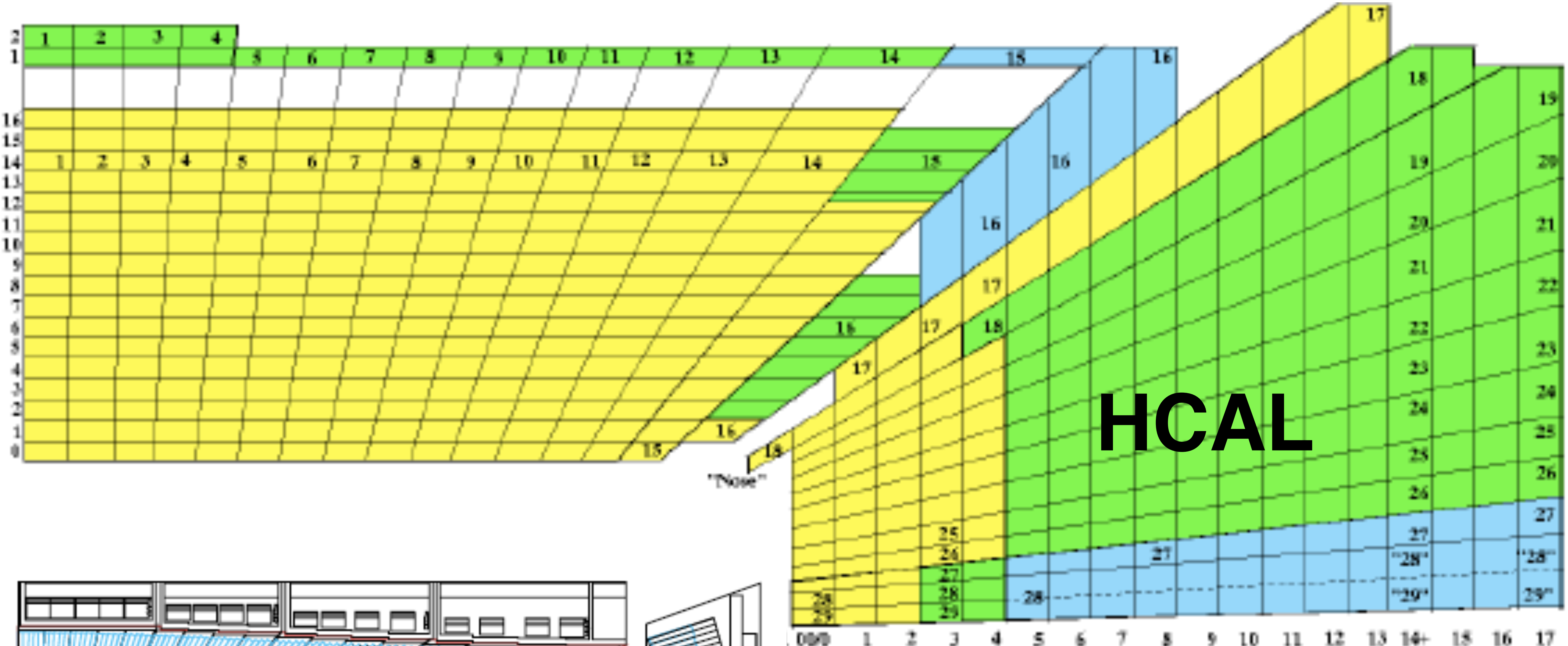


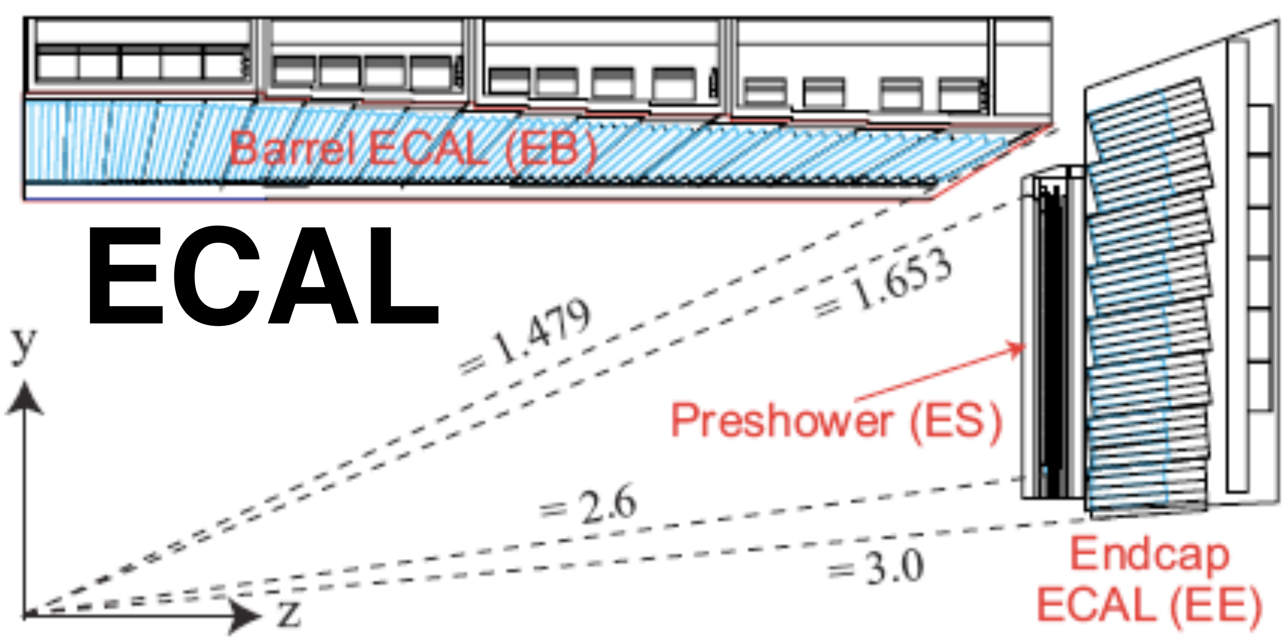
What are the Jets?



A jet is the experimental signature of a parton, materialized as a spray of highly collimated hadrons.

The CMS Calorimeters

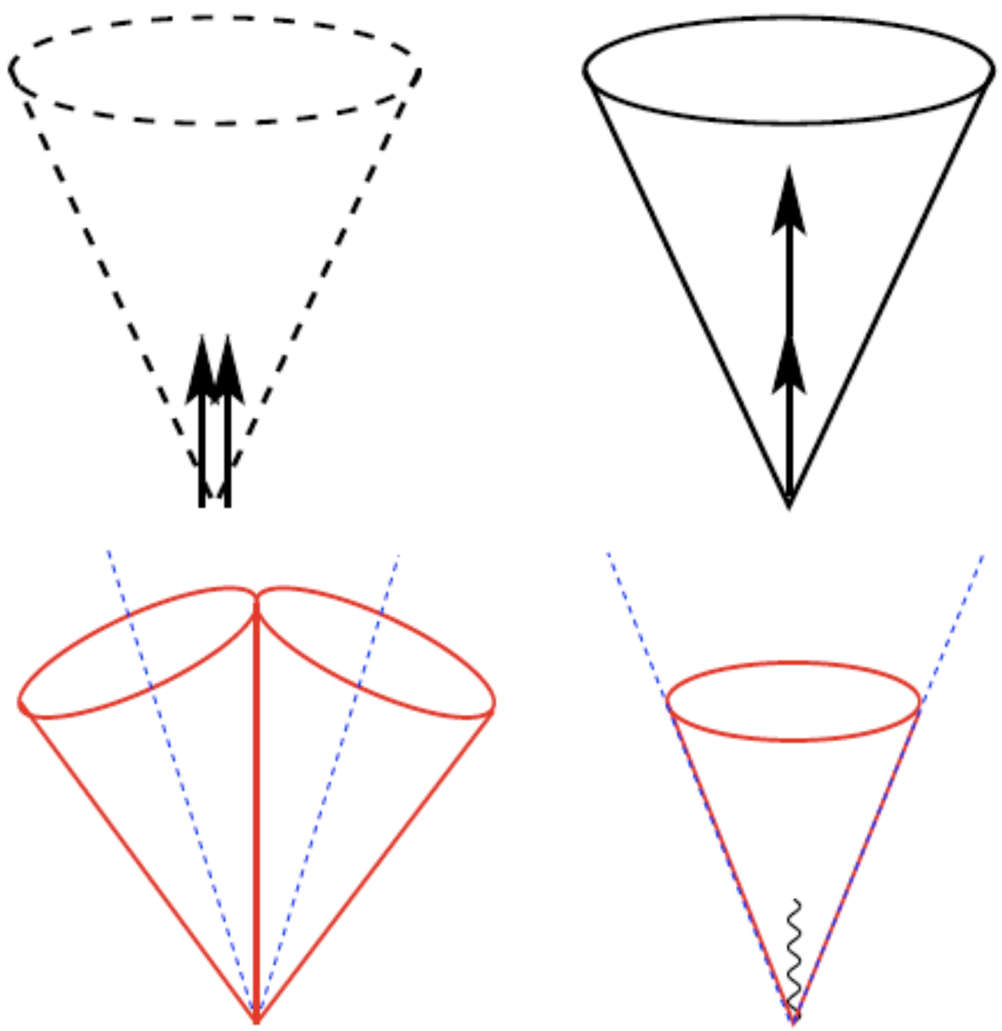




From the experimental point of view, the calorimeters are the principle instruments for detecting jets.

Principles of Jet Reconstruction

A jet reconstruction algorithm is a set of mathematical rules that reconstruct unambiguously the properties of a jet.



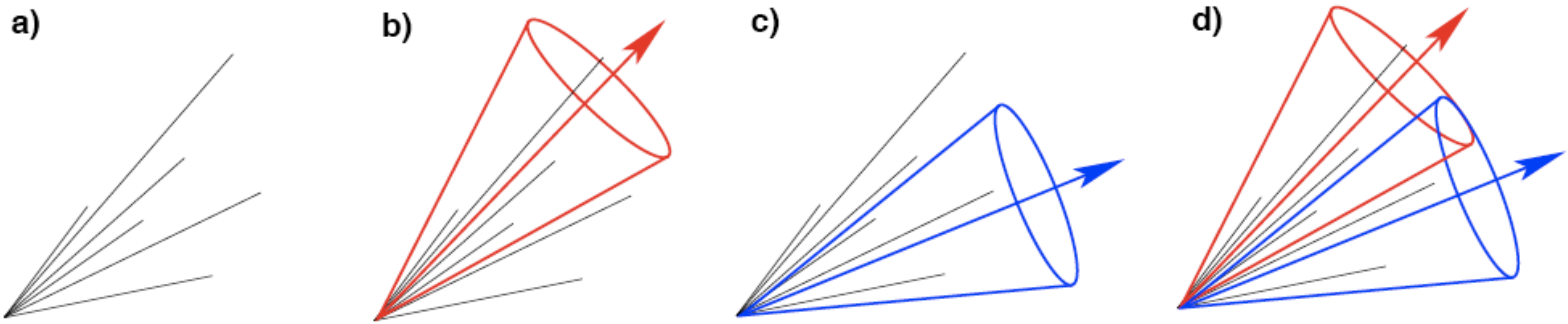
1. Simplicity
required by experimental analyses and theoretical calculations.

2. Collinear safety
The output of the jet algorithm should remain the same if the energy of a particle is distributed among two collinear particles.

3. Infrared safety
The output of the jet algorithm should be stable against addition of soft particles.

4. Robustness against pile-up and underlying event contamination
very relevant for the LHC experiments.

Fixed Cone Algorithms



Iterative Cone

- searching for stable cones of fixed radius R in η-ϕ space.
- all particles above an E_T threshold act as seeds.
- collinear and infrared unsafe to all orders.

Midpoint Cone

- searching for stable cones of fixed radius R in η-ϕ space (proto-jets).
- all particles above an E_T threshold act as seeds.
- the midpoints between proto-jets which are closer than 2R are used as additional seeds.
- Merge-Split mechanism for overlapping proto-jets. Ordering parameter: p_T^{jet}.
- collinear and infrared safe up to NLO.

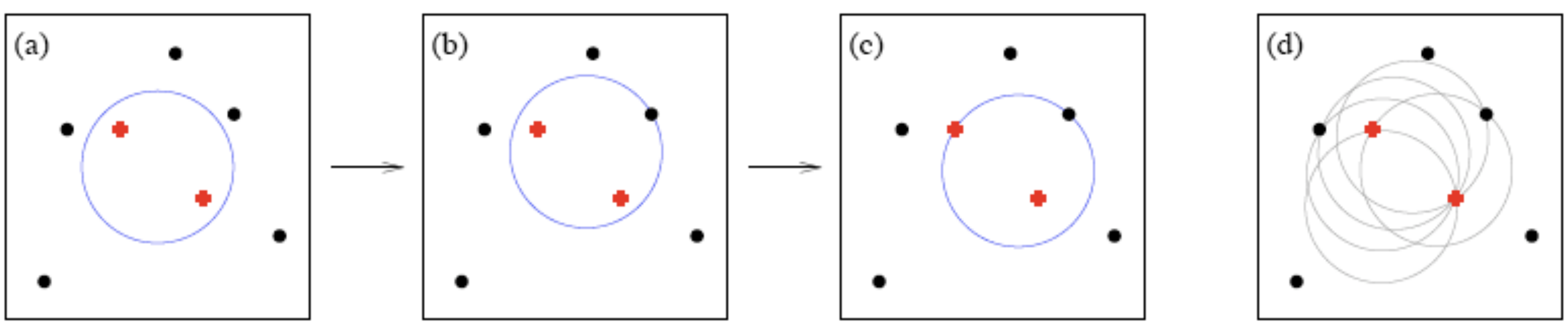
SISCone Algorithm

Seedless Infrared-Safe Cone

✦ searching for stable cones of fixed radius R in y-ϕ space (proto-jets).
✦ no seeds are applied. All stable cones are sought for (proto-jets).
✦ has been made computationally possible thanks to an innovative implementation. It reduces the execution time from $N \cdot 2^N$ to $N^2 \ln N$.
✦ Merge-Split mechanism for overlapping proto-jets. Ordering parameter: $\sum |p_T^{constituents}|$.
✦ collinear and infrared safe to all orders.

JHEP 0705:086,2007

Illustration of the implementation concept
(finding all the circles whose circumference lie on 2 points)



Sequential Recombination Algorithms

$$d_{ij} = \min\left(k_{T,i}^{n}, k_{T,j}^{n}\right)\frac{\Delta R_{ij}^2}{D^2}$$

$$d_{iB} = k_{T,i}^{n}$$

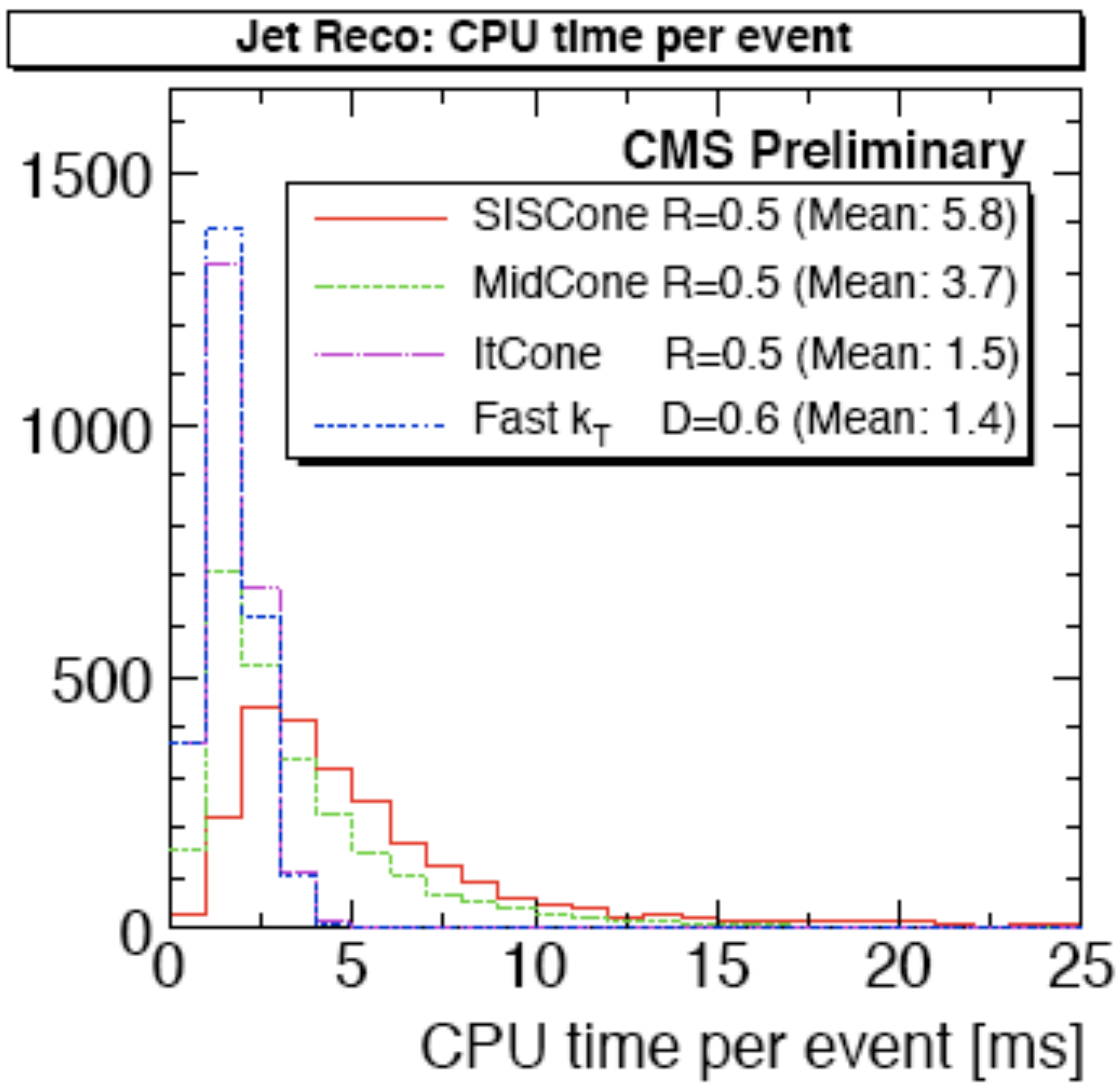
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

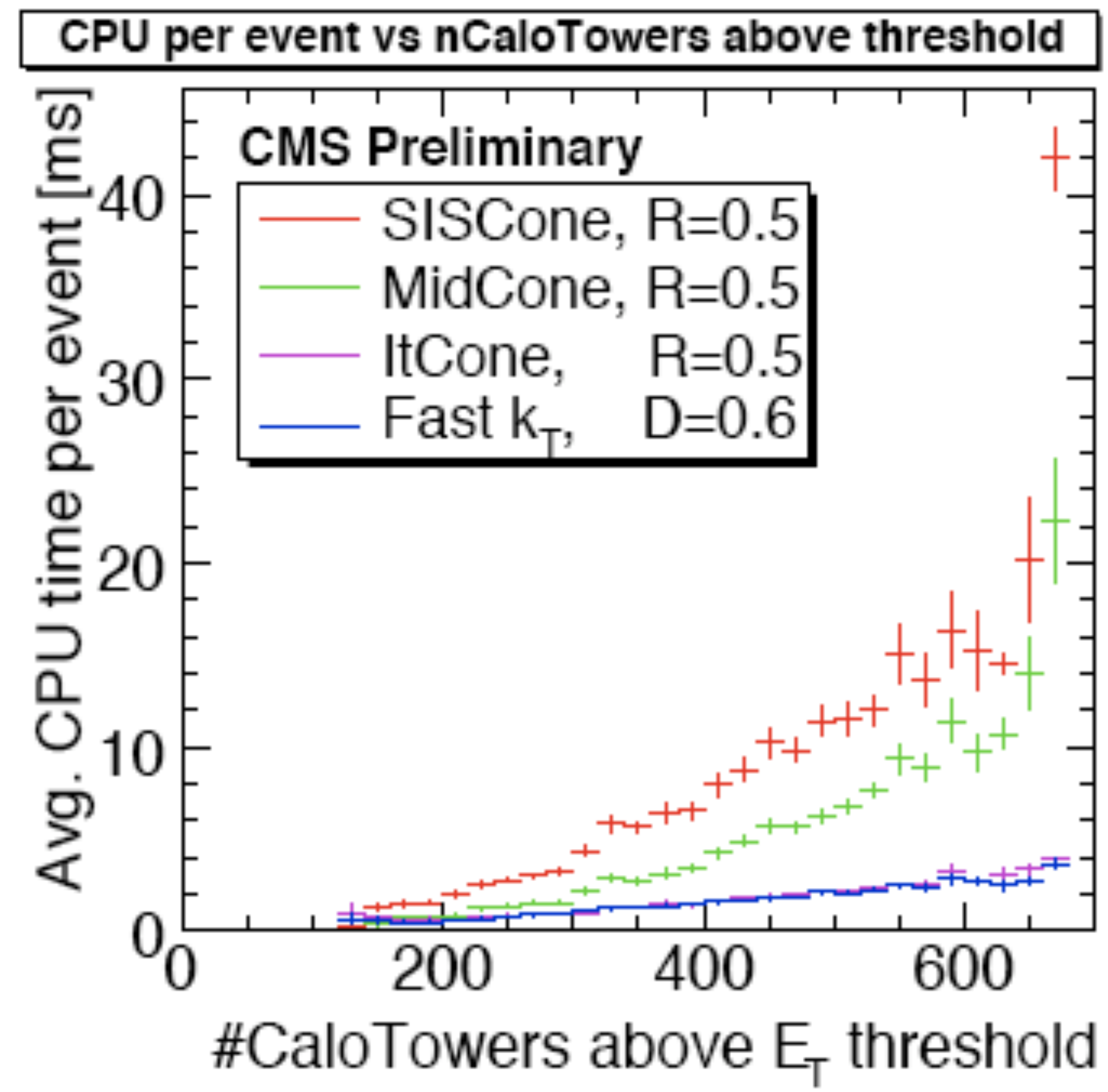
if $d_{ij} < d_{iB}$ the particles are merged.

- **n=2**: "***k*$_T$**" (favours clustering of low p_T particles)
- **n=0**: "***Cambridge-Aachen***" (no p_T weighting)
- **n=-2**: "***anti-k*$_T$**" (favours clustering of high p_T particles)

✦ merging of 4-vector pairs based on transverse momentum weighted distance in y-ϕ plane.
✦ the clustering terminates when the weighted distance between particles is greater than a specific value **D** (resolution parameter).
✦ the quantity **D** is of the order of unity.
✦ infrared and collinear safe.
✦ no unclustered energy.
✦ the jet area is not well defined.

Timing





✦ The SISCone algorithm is the most CPU intensive.
✦ The "fast" implementation of the k_T algorithm is comparable to the iterative-cone performance.

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Jet Flavours & Types

The jet algorithms take as input sets of 4-vectors:

1. GenJets
Stable simulated particles (after hadronization and before interaction with the detector).

2. CaloJets
Calorimeter energy depositions grouped in CaloTowers.

3. JetPlusTrack
Calorimeter jets whose energy has been corrected with jet-track association.

4. PFJets
Individually reconstructed particles by combination of multiple detector inputs (particle flow objects).

5. TrackJets
Tracks

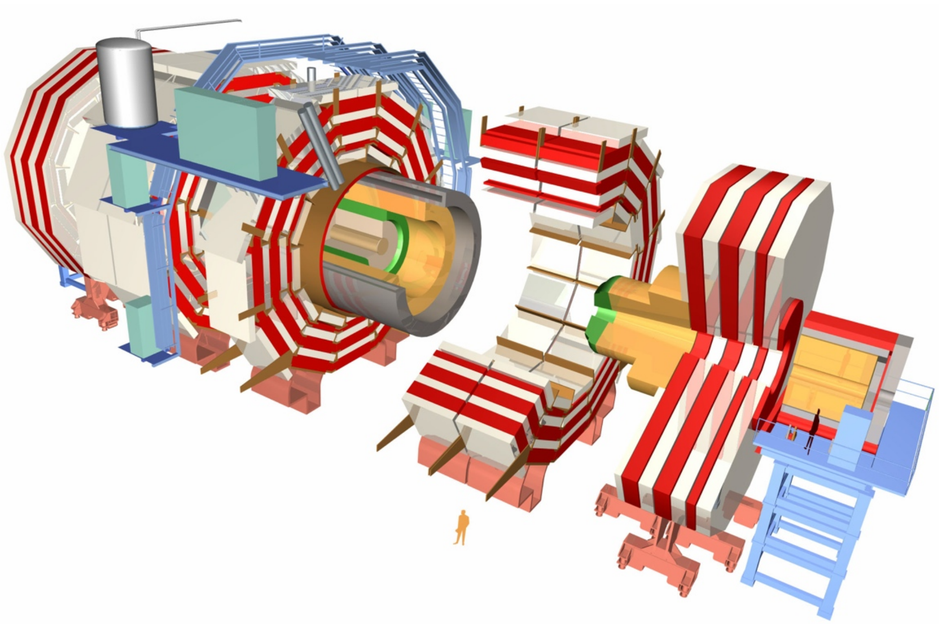
Particles, CaloTowers, PF, Tracks → **Jet Algorithm** → GenJets, CaloJets, PFJets, TrackJets, JetPlusTrack

Summary of Jets in CMS & ATLAS

CMS

✦ **Jet algorithms:**
- Seedless Cone, R=0.5, 0.7
- K_T, D=0.4, 0.6
- Iterative Cone, R=0.5 (used in the trigger)

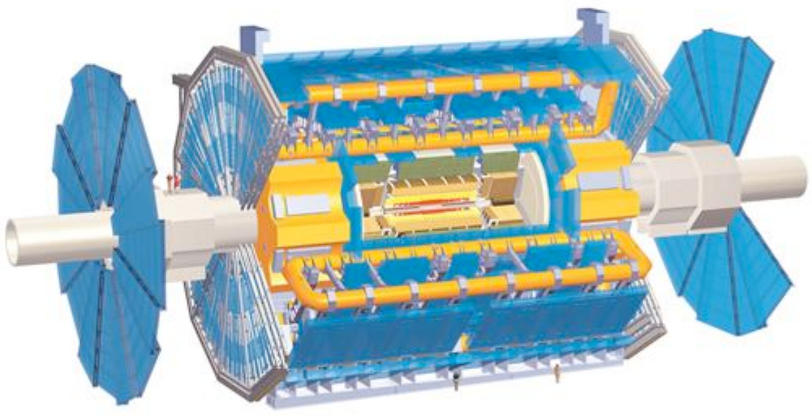
✦ **Jet types:**
- Calorimeter jets (towers input).
- Track jets (tracks input).
- JetPlusTrack (combined calorimeter and tracker information).
- Particle Flow jets (particles input).



ATLAS

✦ **Jet algorithms:**
- Seeded Cone, R=0.4, 0.7
- K_T, D=0.4, 0.6
- Recently adopted the *anti-k_T* algorithm as the default one.

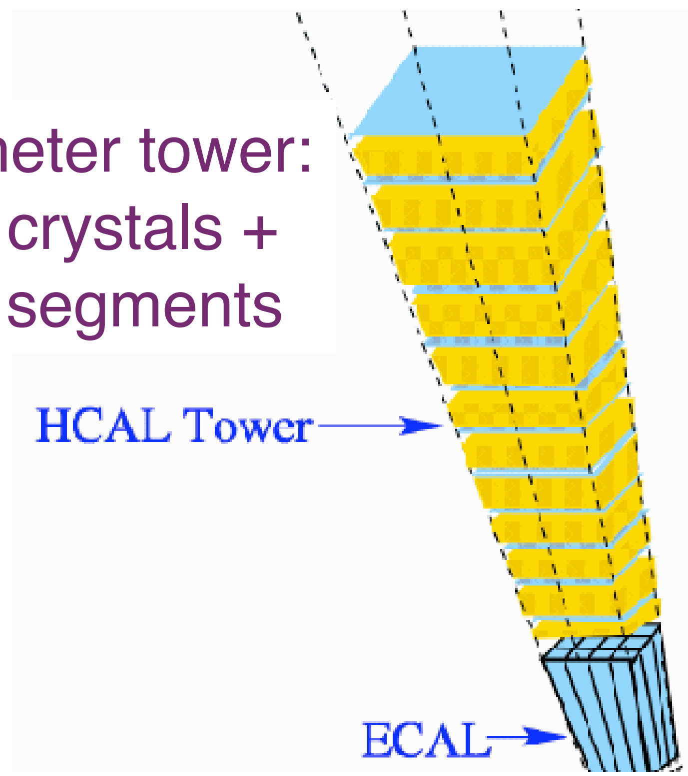
✦ **Jet types:**
- Calorimeter jets (towers or topological cell clusters input).
- Track jets (tracks input).
- Energy Flow jets (combined calorimeter and tracker information).



PART II: Jet Performance in CMS

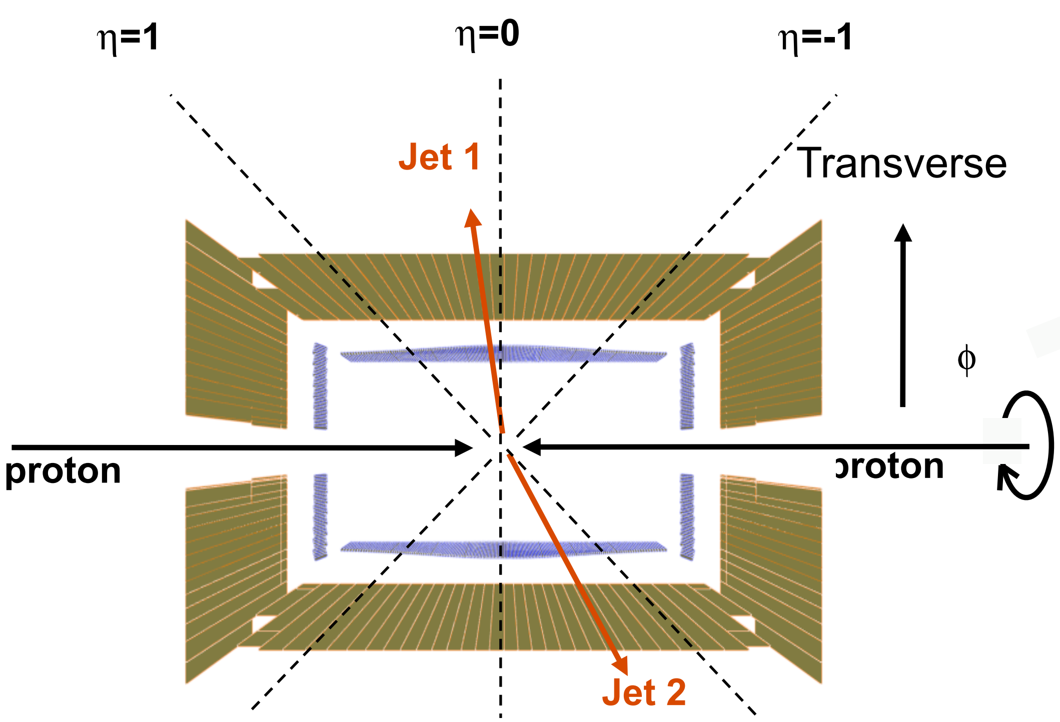
Calorimeter Jets

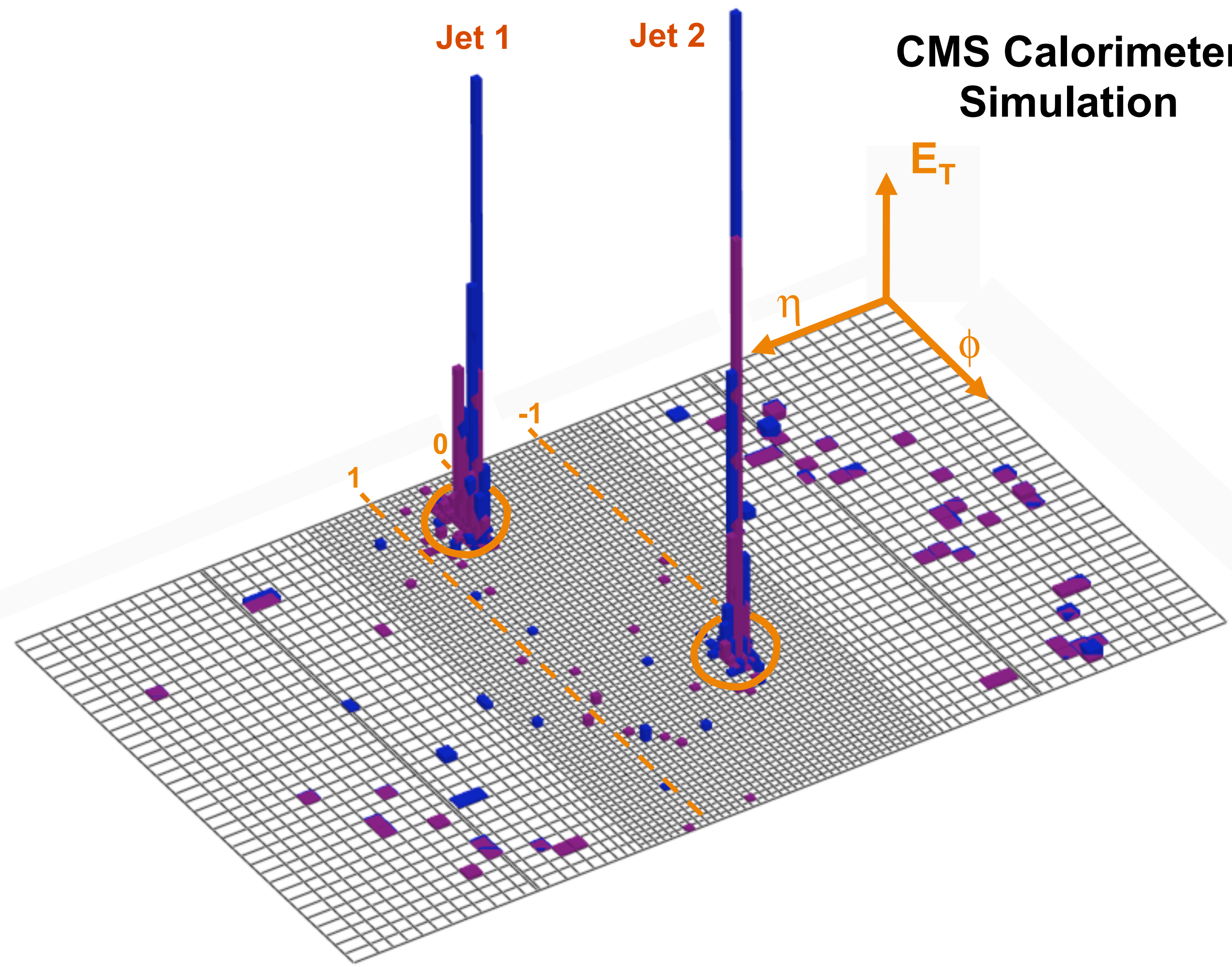
Calorimeter tower:
ECAL crystals +
HCAL segments



✦ A calorimeter jet is the output of the jet finding algorithm when applied to the CaloTowers.

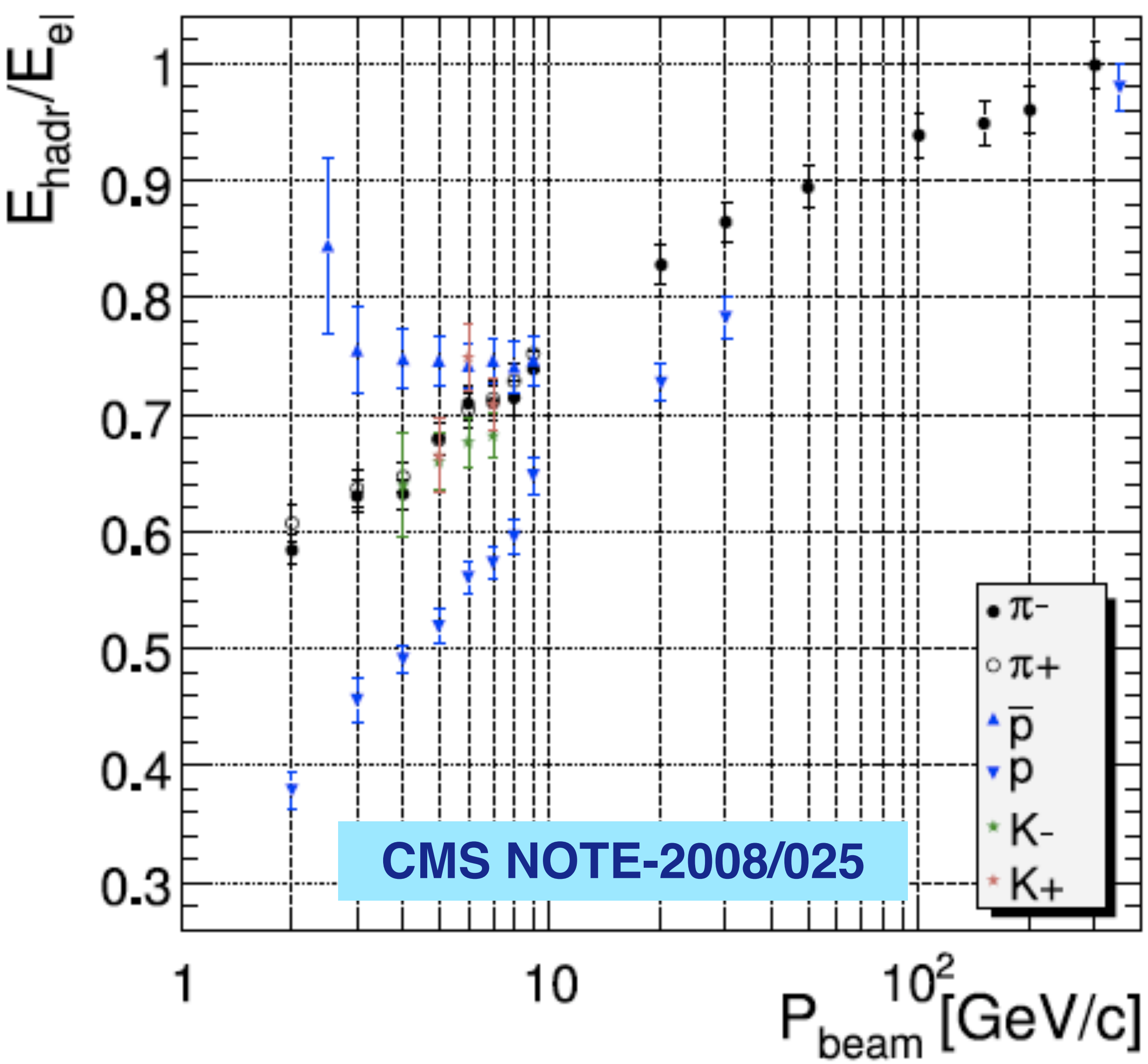
✦ The calorimeter jets are the baseline jet definition.





Calorimeter Calibration

Single particle response from TB2006

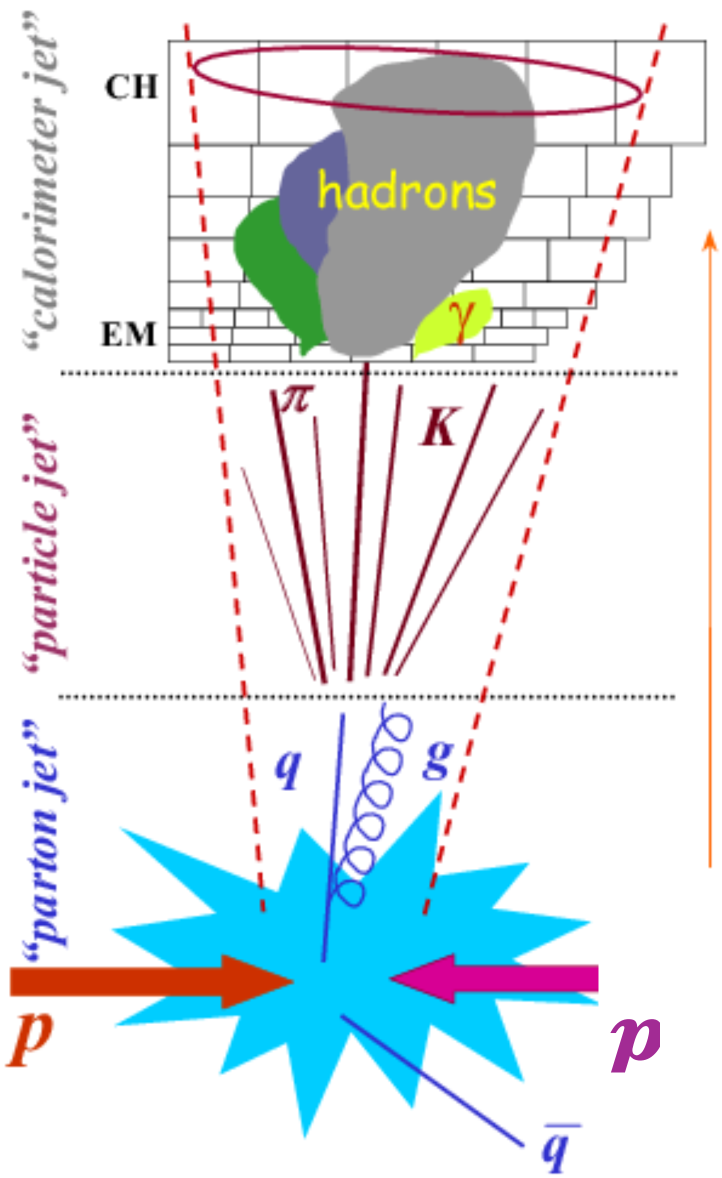


- ✦ **HCAL:**
  - ▶ **pre-calibration**
    - Test Beam measurements with 50 GeV pions.
  - ▶ **"in-situ" calibration**
    - ϕ inter-calibration with Zero Bias and Min Bias events.
    - absolute energy scale with isolated tracks.
- ✦ **ECAL:**
  - ▶ **pre-calibration**
    - Test Beam measurements with electrons.
  - ▶ **"in-situ" calibration**
    - ϕ inter-calibration with $\pi^0 \rightarrow \gamma\gamma$ events.
    - absolute energy scale with $Z \rightarrow e^+e^-$ events.

Jet Energy Calibration *(the CMS plan)*

Required → Optional →

Reconstructed Jet	Offset	Rel: η	Abs: p_T	EMF	Flavour	UE	Parton	Calibrated Jet



Why do we need to calibrate jets?

✦ Because the calorimeter response is non-linear in p_T and non-uniform across the detector.

✦ **The jet energy scale is the most important uncertainty related to jets.**

Why a multi-step approach?

✦ Each sub-correction corrects for a different effect.

✦ Each sub-correction can be separately studied and optimised.

✦ Easier to develop data driven methods.

✦ Systematic uncertainties are easier to estimate.

✦ The approach has been used by both D0 and CDF with success.

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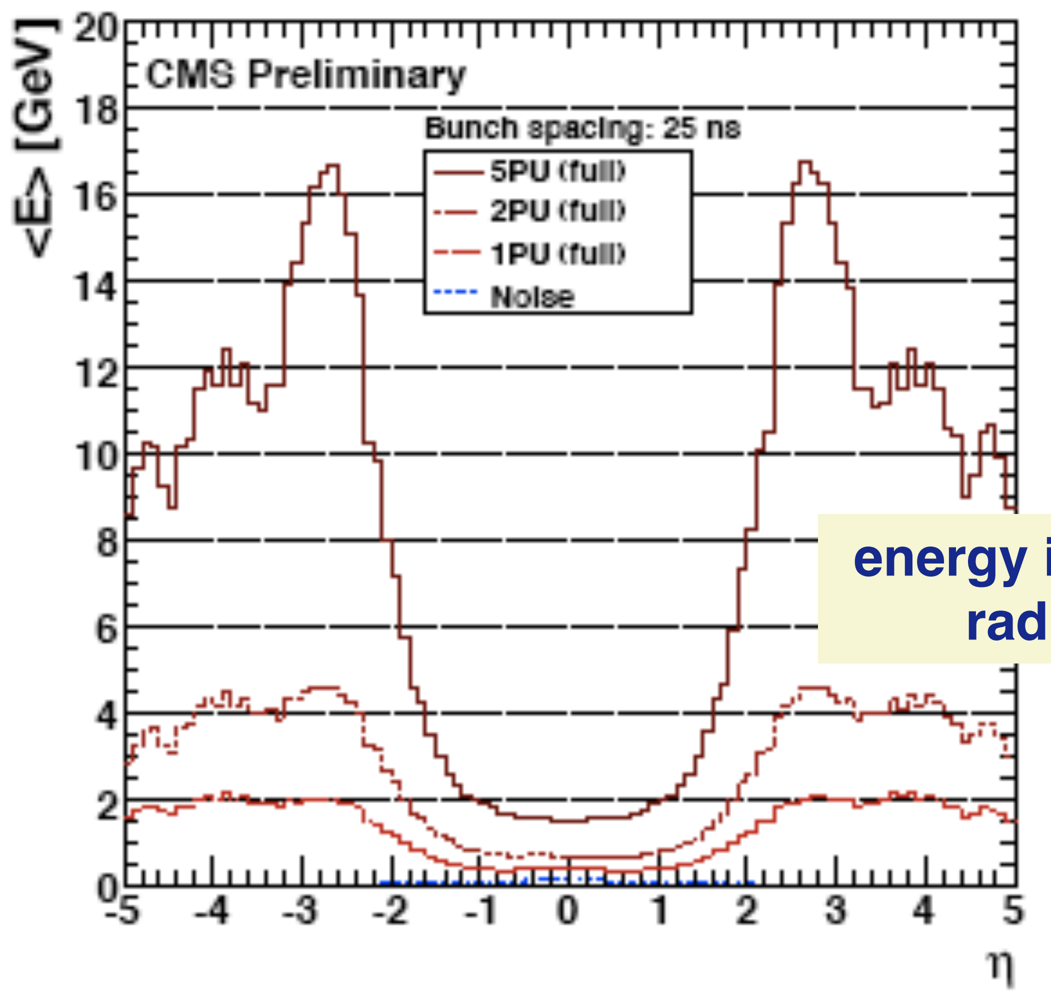
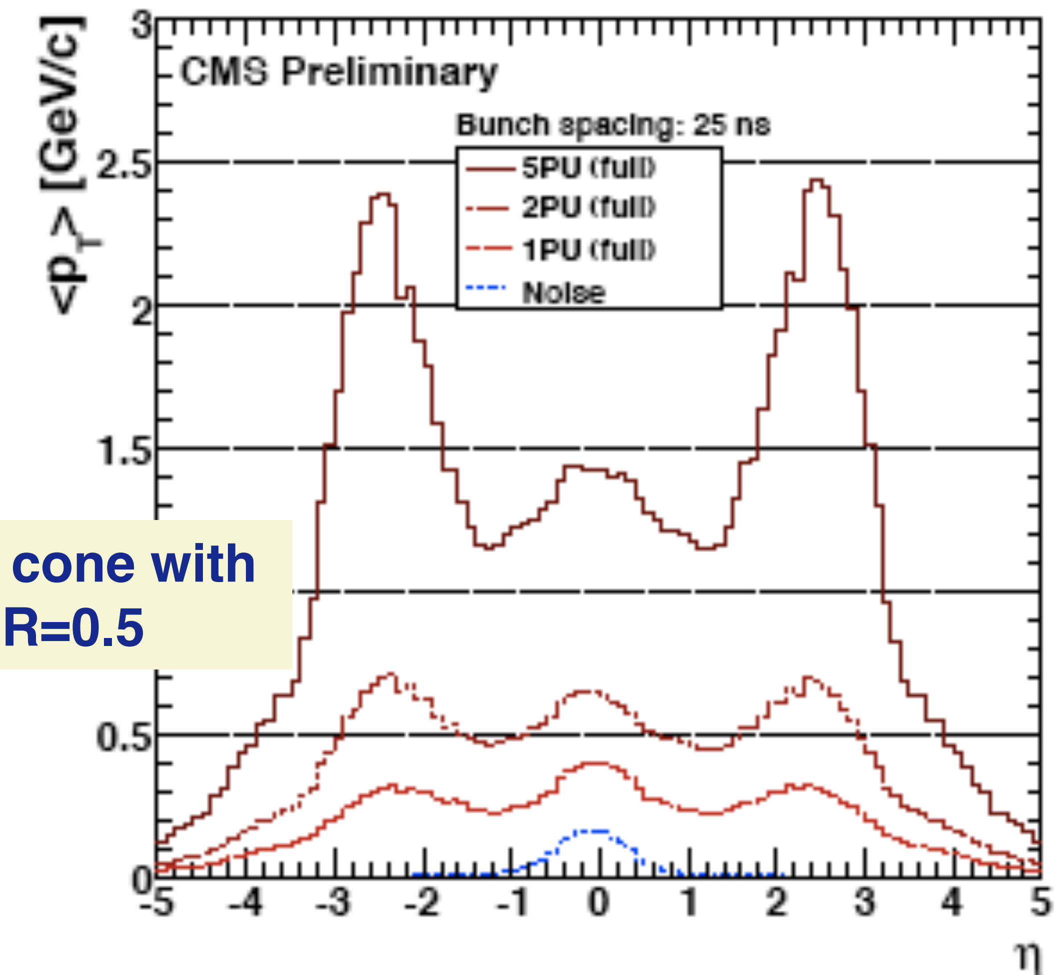
Jet Energy Calibration *(offset)*





energy in a cone with radius R=0.5

- ✦ The ***offset correction*** removes from each jet the energy due to noise and pile-up, on average. It will be measured from data with non zero-suppressed data.
- ✦ The noise contribution is more significant in the barrel region (|η|<1.3).
- ✦ The pile-up contribution is more significant in the endcaps.

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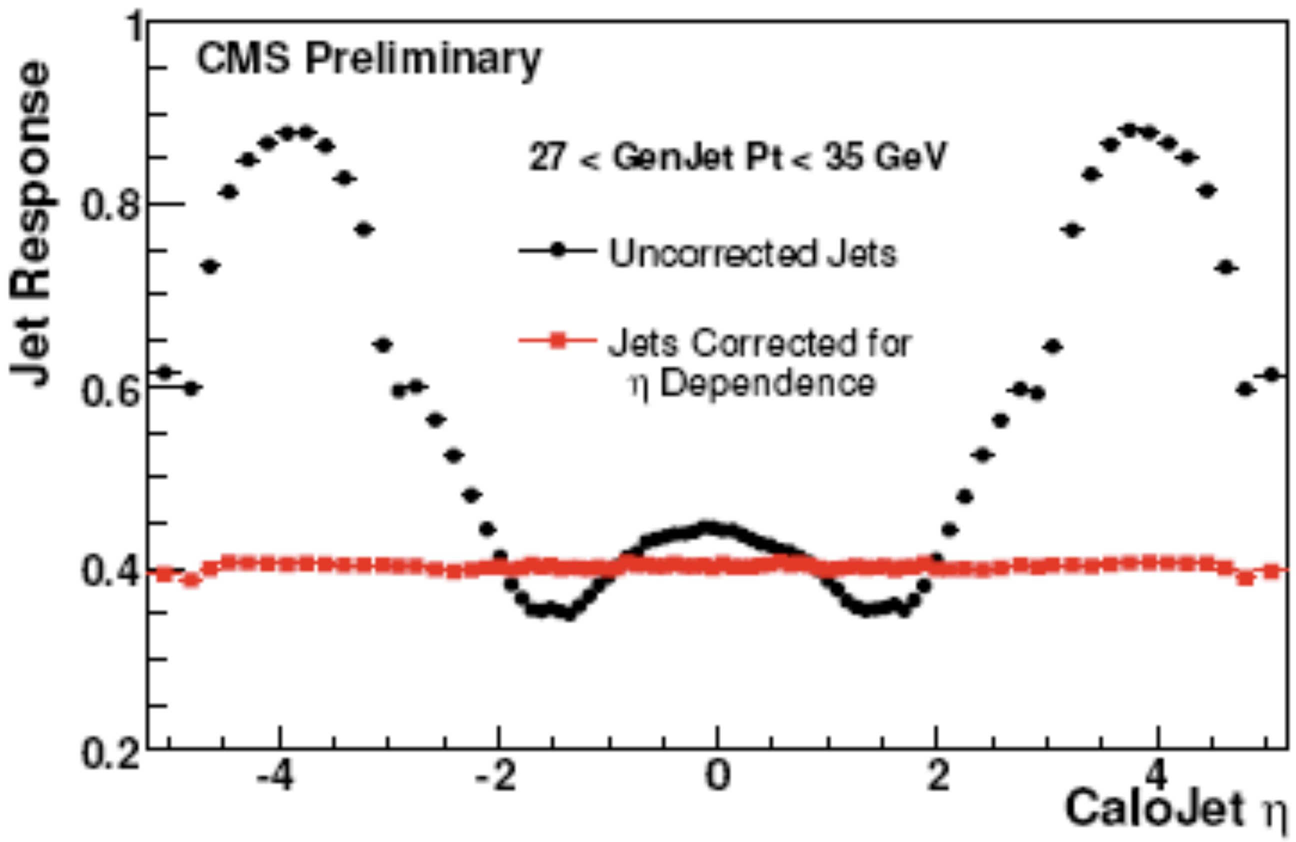
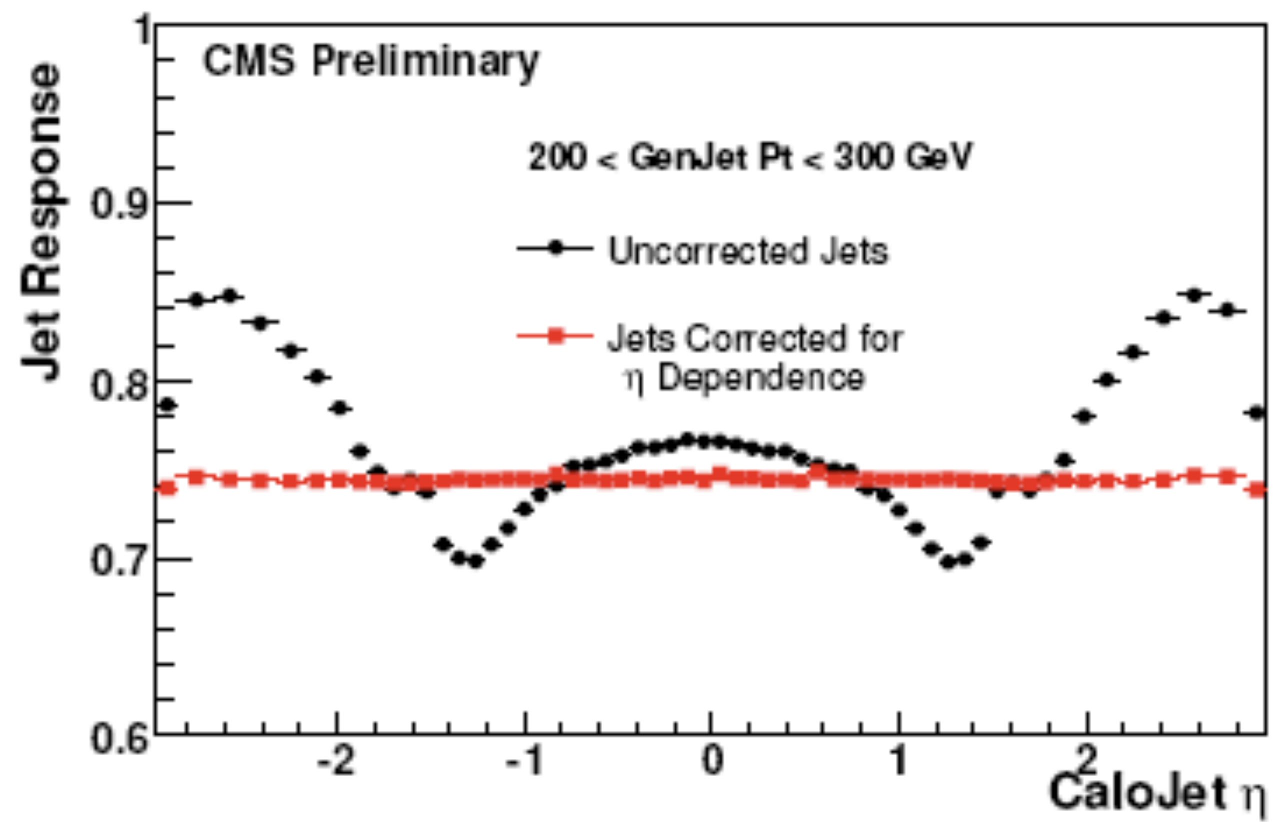
Jet Energy Calibration *(relative)*





✦ The ***relative correction*** removes the pseudorapidity dependence of the jet response.

✦ It will be measured from data with the *dijet balance* method (p_T balance between a jet in the barrel and the other jet at arbitrary η).

✦ $1pb^{-1}$ of data should be enough to derive this correction.

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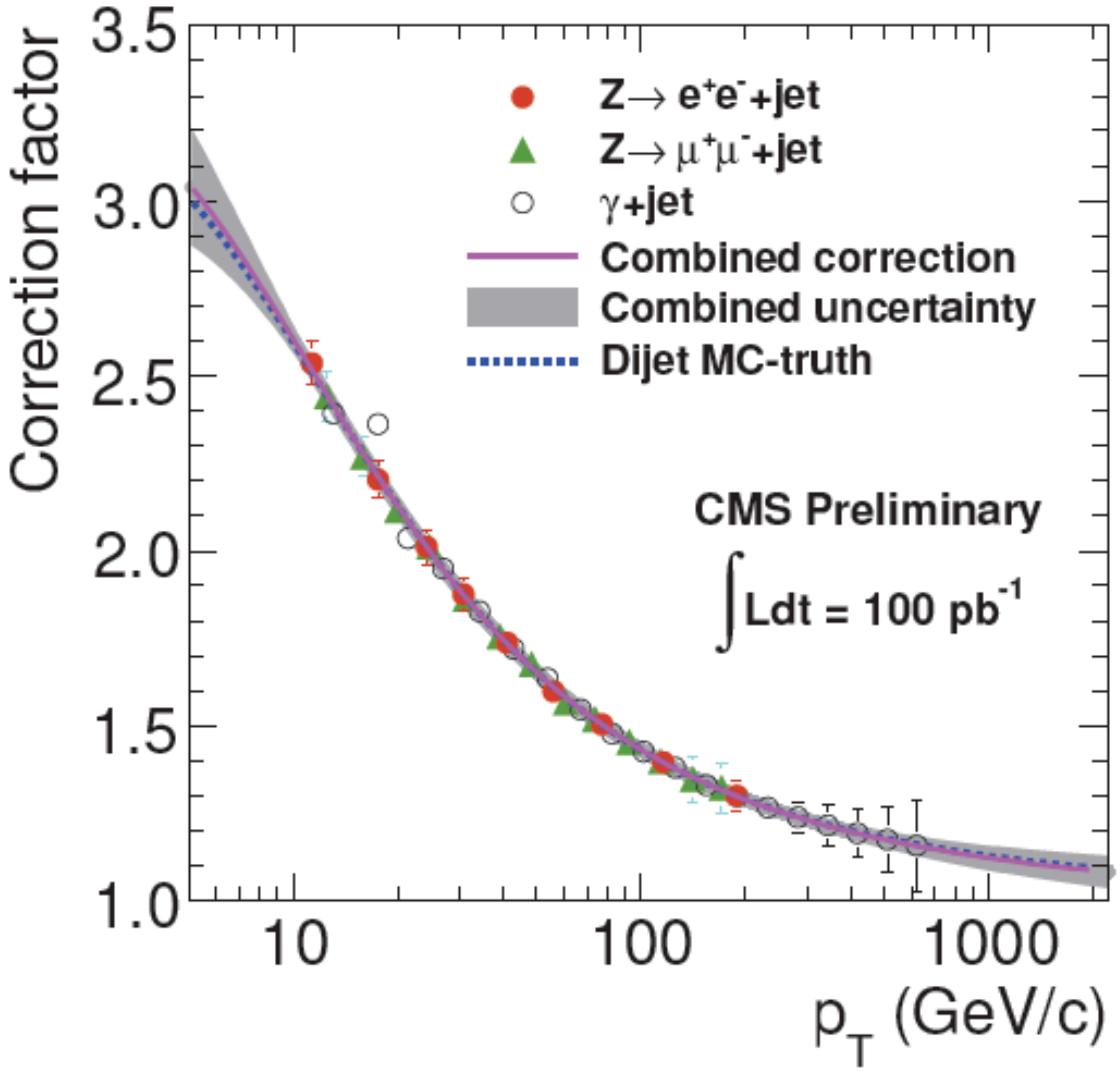
Jet Energy Calibration *(absolute)*



- The ***absolute correction*** removes the p_T dependence of the jet response.
- It will be measured from data with *p_T balancing* in events with γ/Z+jet.
- The results of the three individual measurements (γ+jet, $Z \rightarrow e^+e^-$+jet, $Z \rightarrow \mu^+\mu^-$+jet) will be combined into a single one.
- The MC will be used to extrapolate in the high p_T region, where data are not available for direct calibration.

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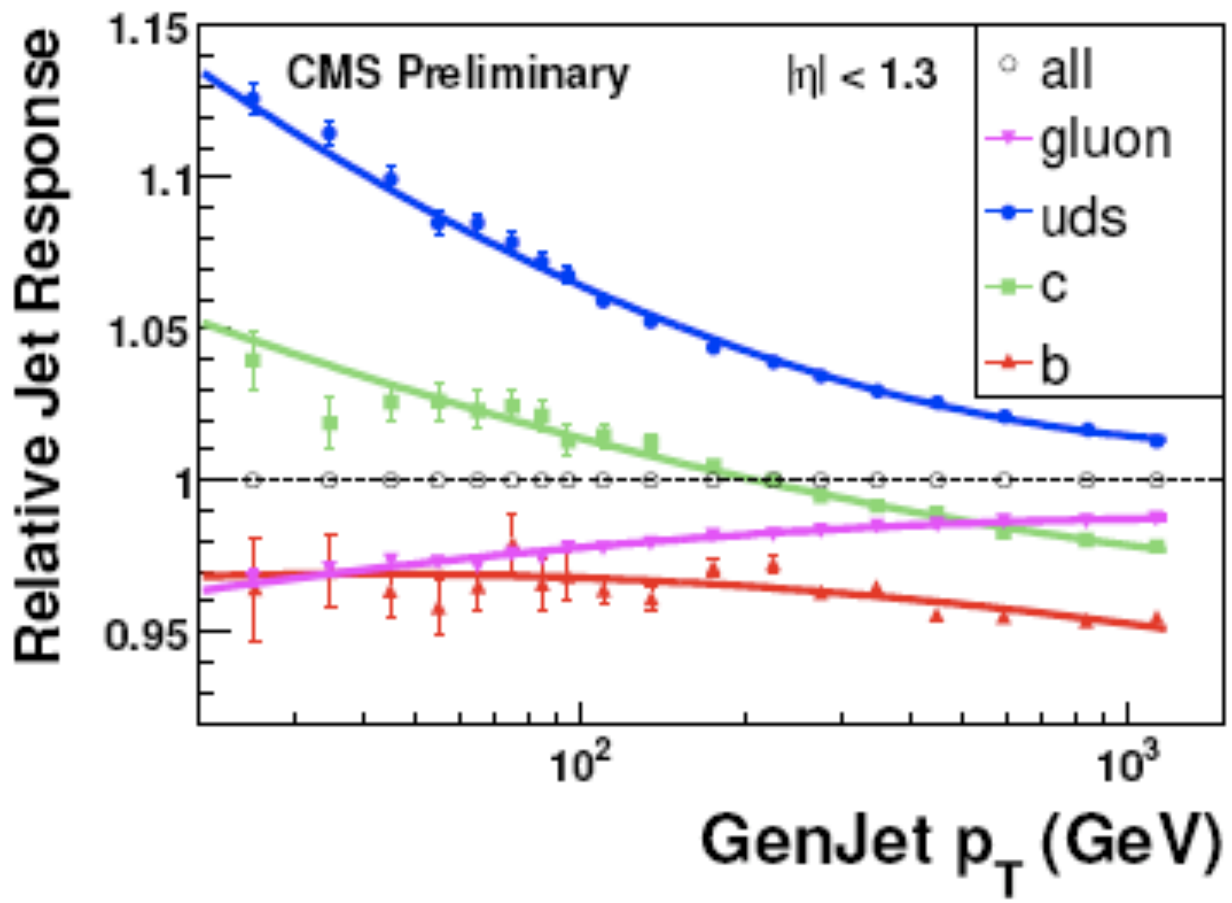
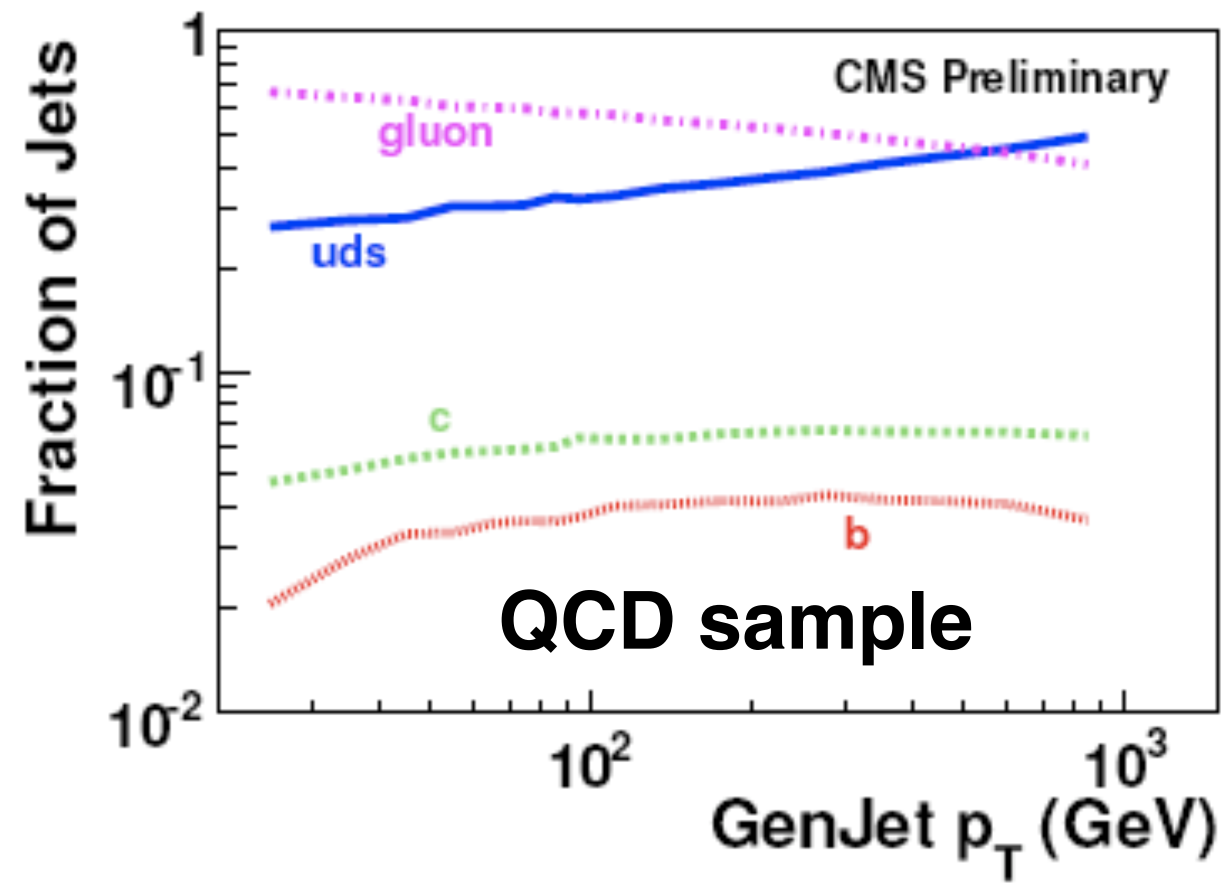
Jet Energy Calibration *(flavour)*





- ✦ The ***flavour correction*** corrects for the flavour dependence of the jet response.
- ✦ It will be derived from MC.
- ✦ It works under a given flavour assumption.
- ✦ There is a significant difference between the quark and gluon initiated jet response.

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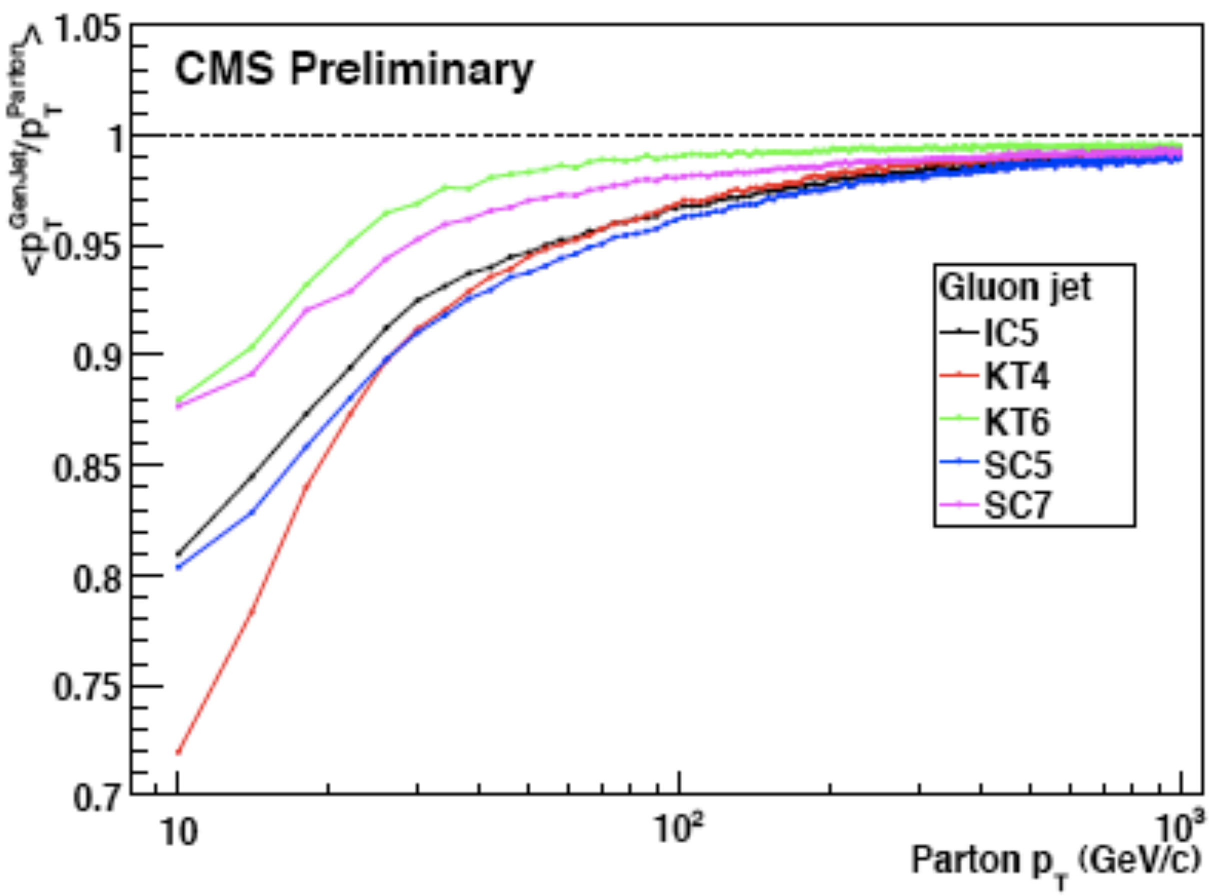
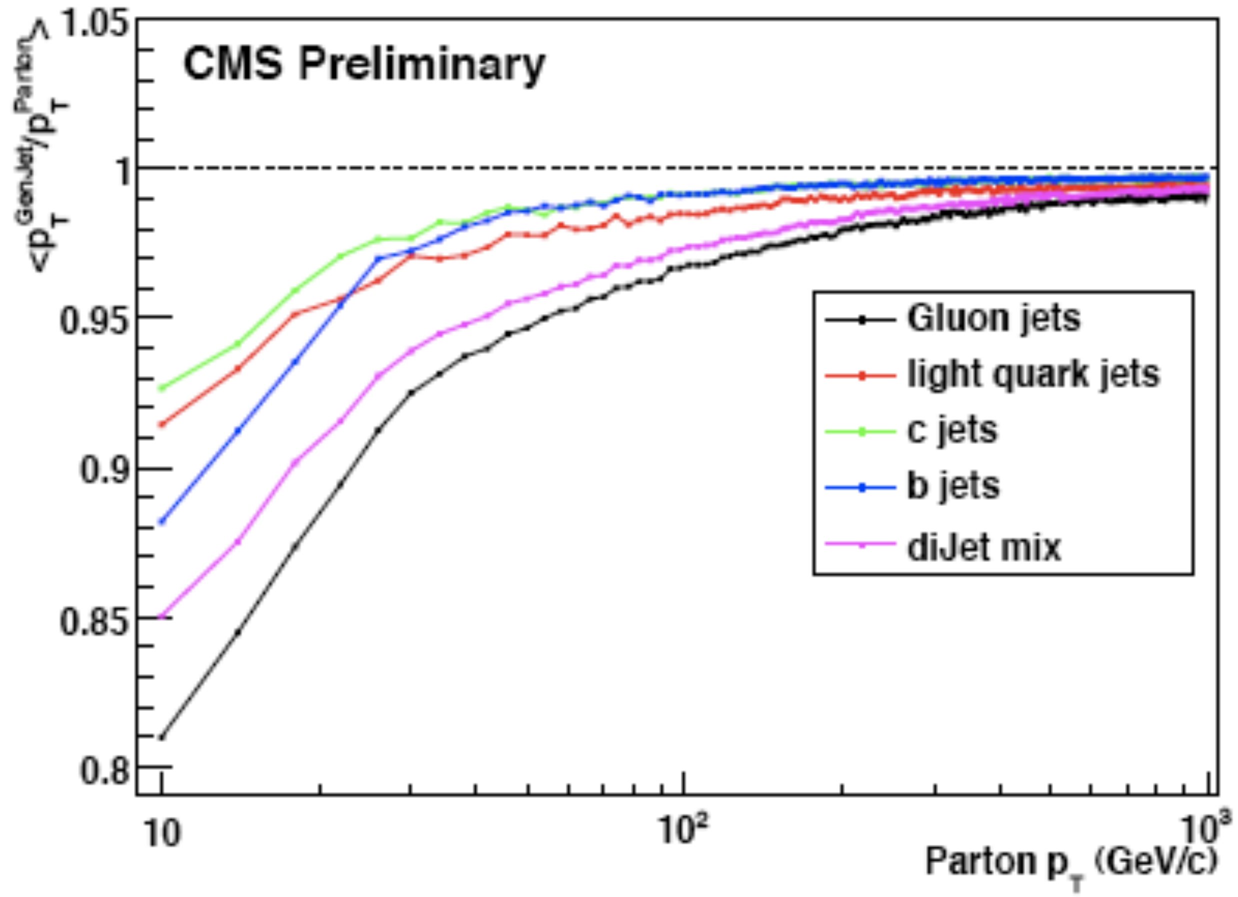
Jet Energy Calibration *(parton)*





- ✦ The ***parton correction*** corrects the energy of a particle jet to the parton level.
- ✦ It will be derived from MC.
- ✦ It works under a given parton assumption.
- ✦ The parton correction should be used with caution because it depends on the algorithm and the sample used to derive it.

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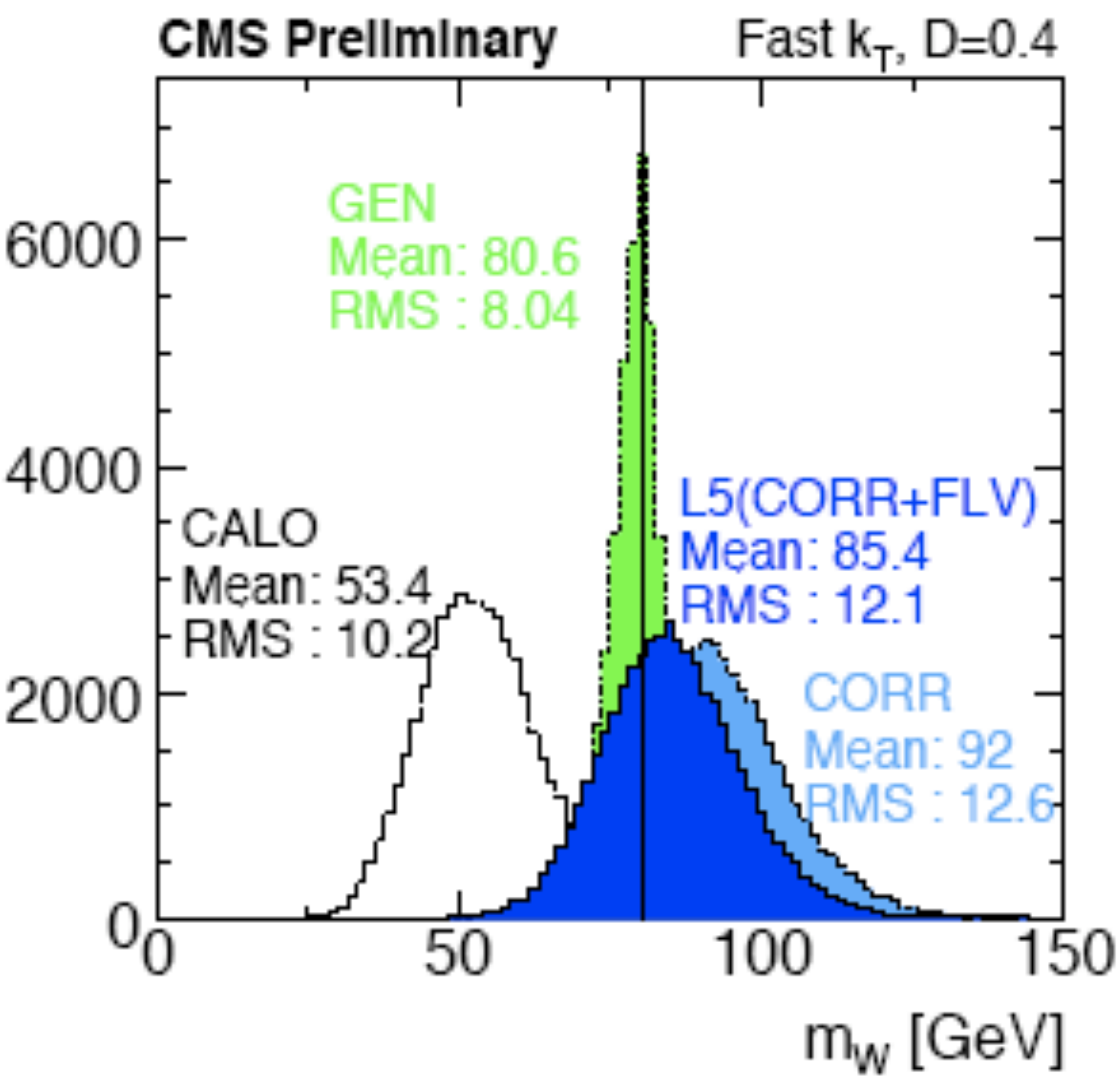
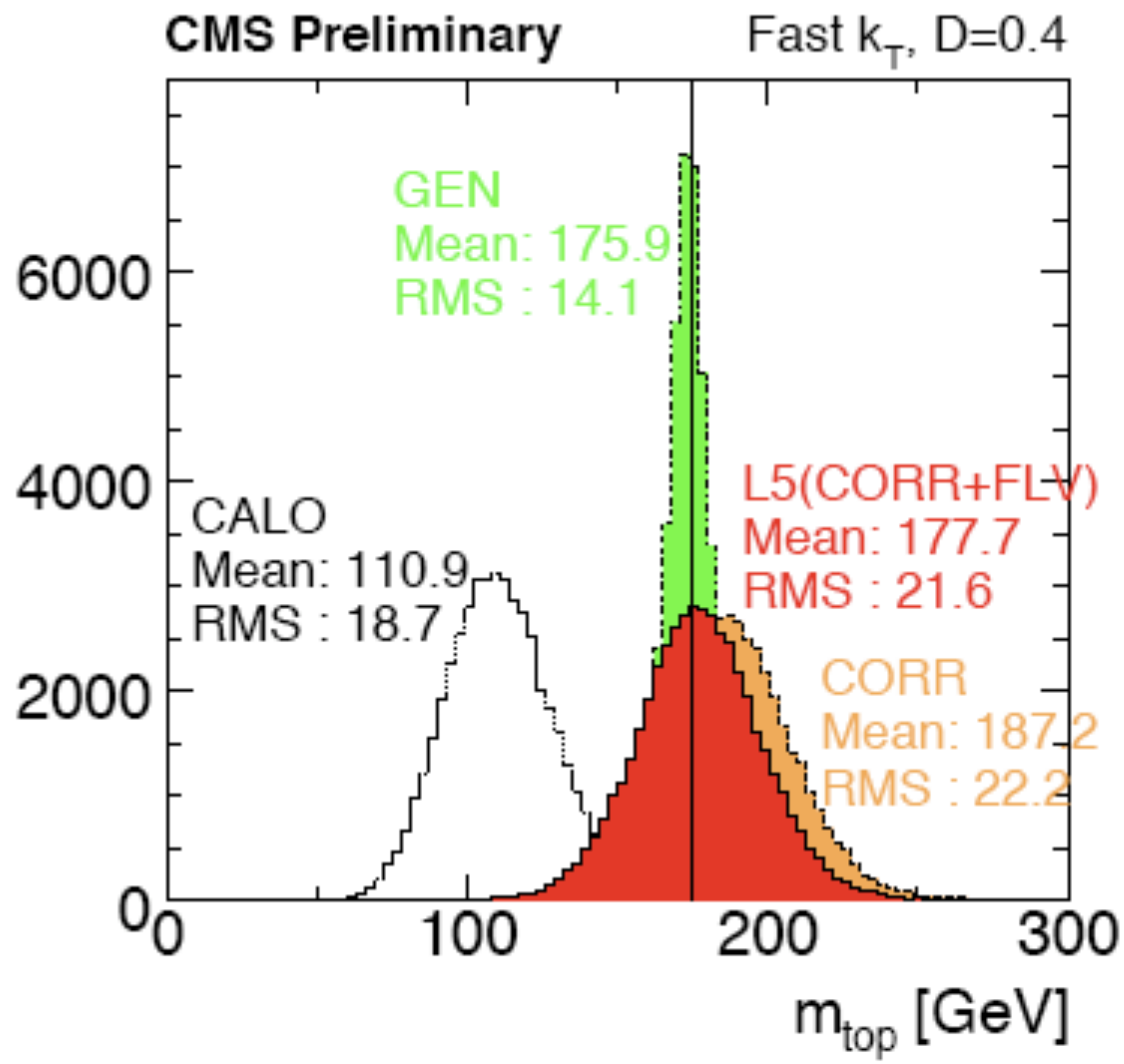
Does the Jet Energy Calibration work?





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Jet Energy Calibration in ATLAS

✦ **Default correction to particle level** (removes the detector effects).

✦ **Foresees similar approach to CMS (data driven) in particular for early data.**

✦ **Additional methods to improve resolution:**

▶ **global approach**

- global mc truth matching.
- cell signal weighting.
- weights are calculated by optimizing jet energy resolution.

▶ **local approach**

- compensation weights and dead material correction calculated using simulation for single pions on calorimeter clusters.
- jet algorithms use as input calibrated calorimeter clusters.

✦ **Performance of the jet energy calibration will be tested with in-situ measurements and MC.**

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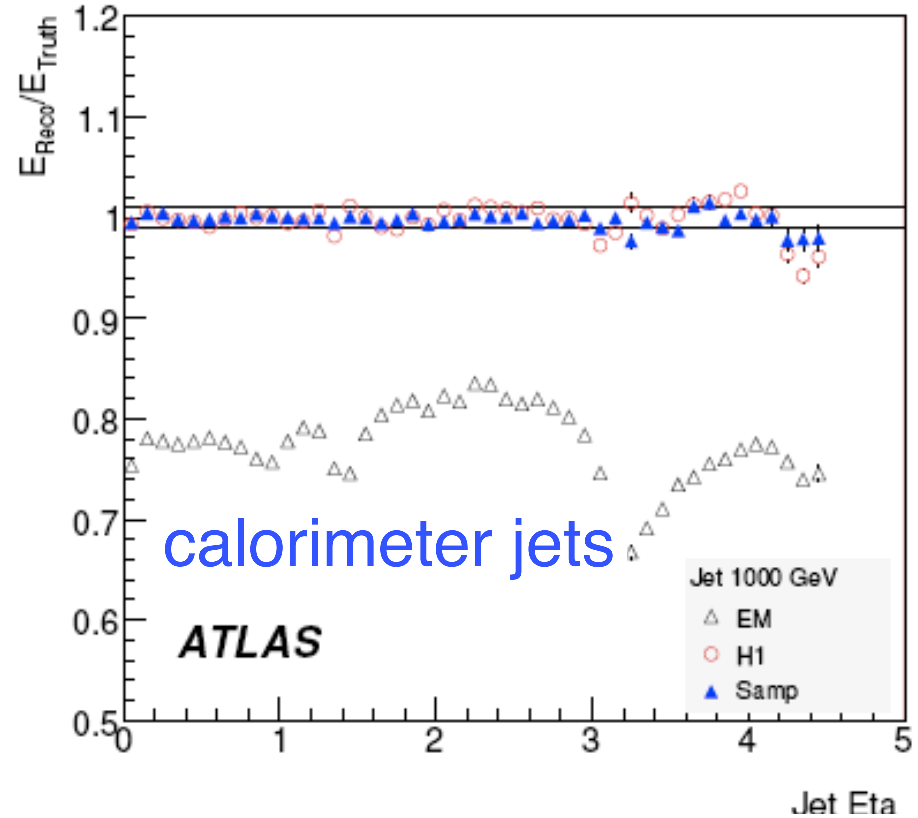
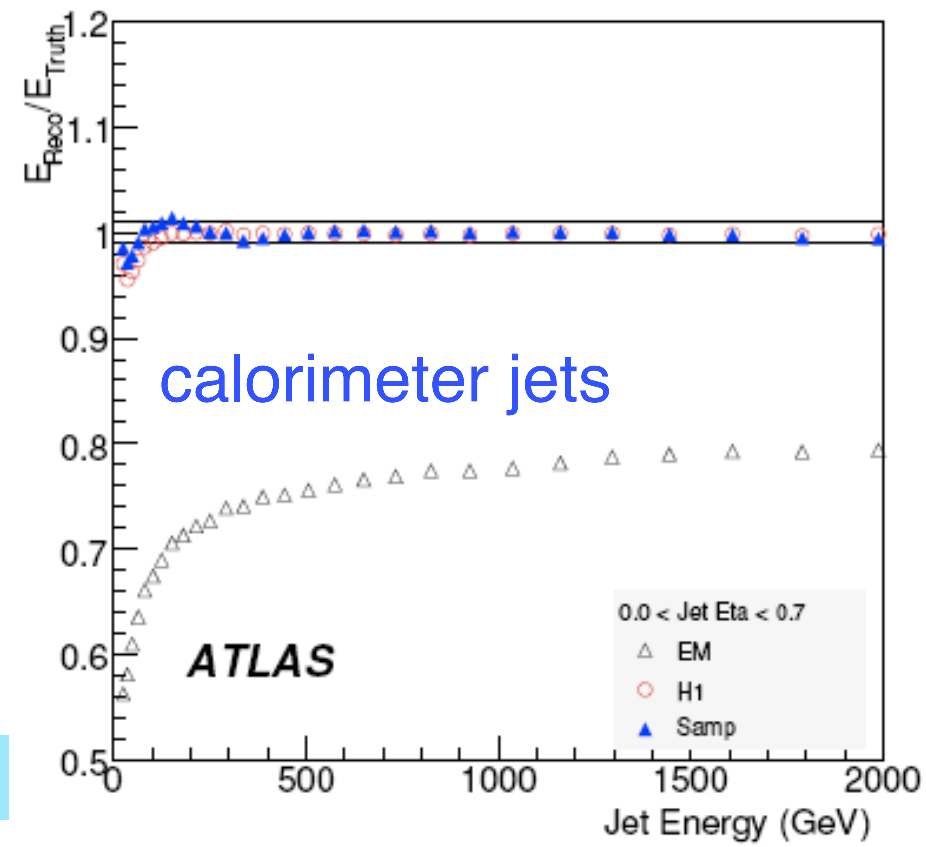
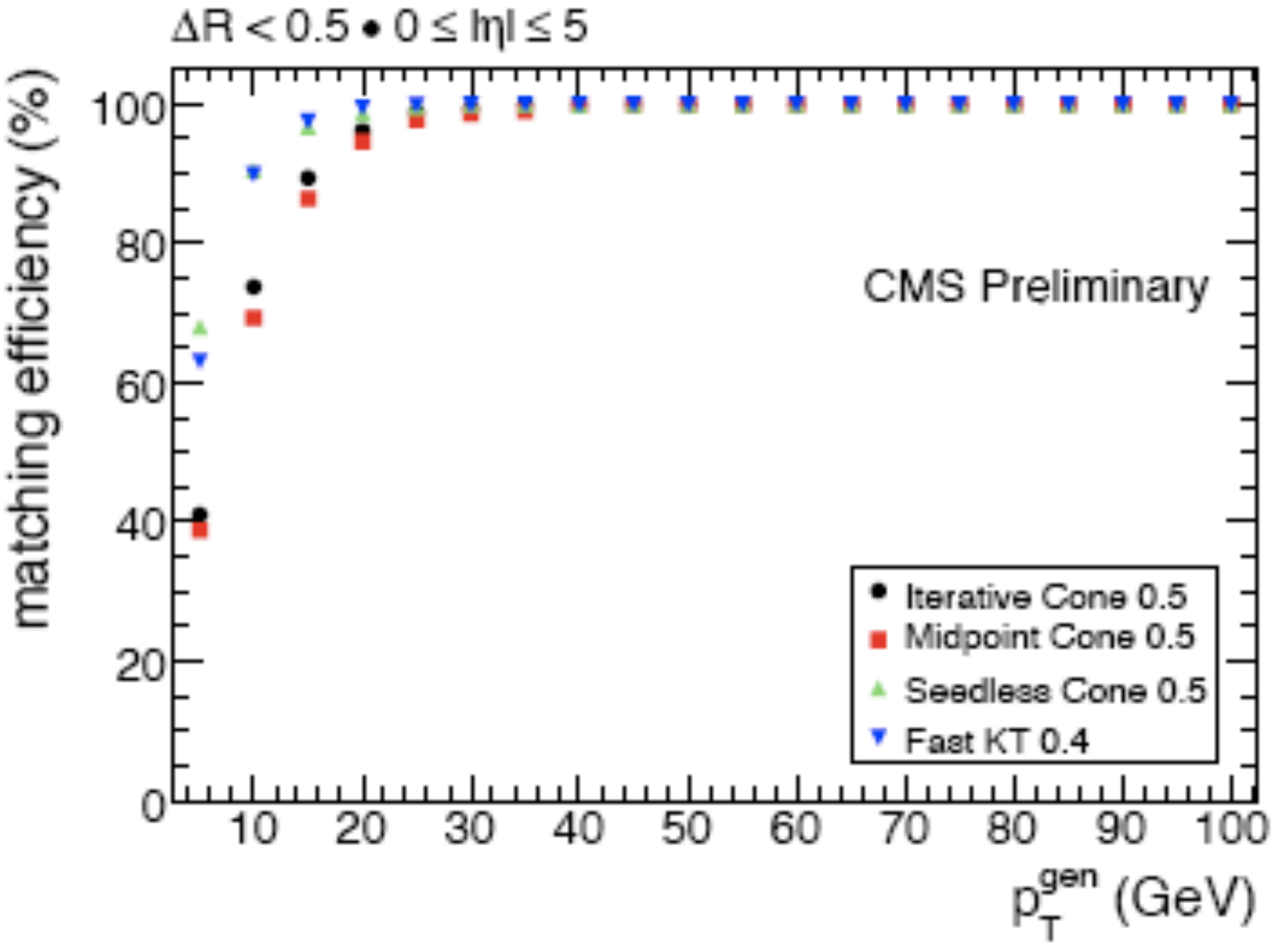
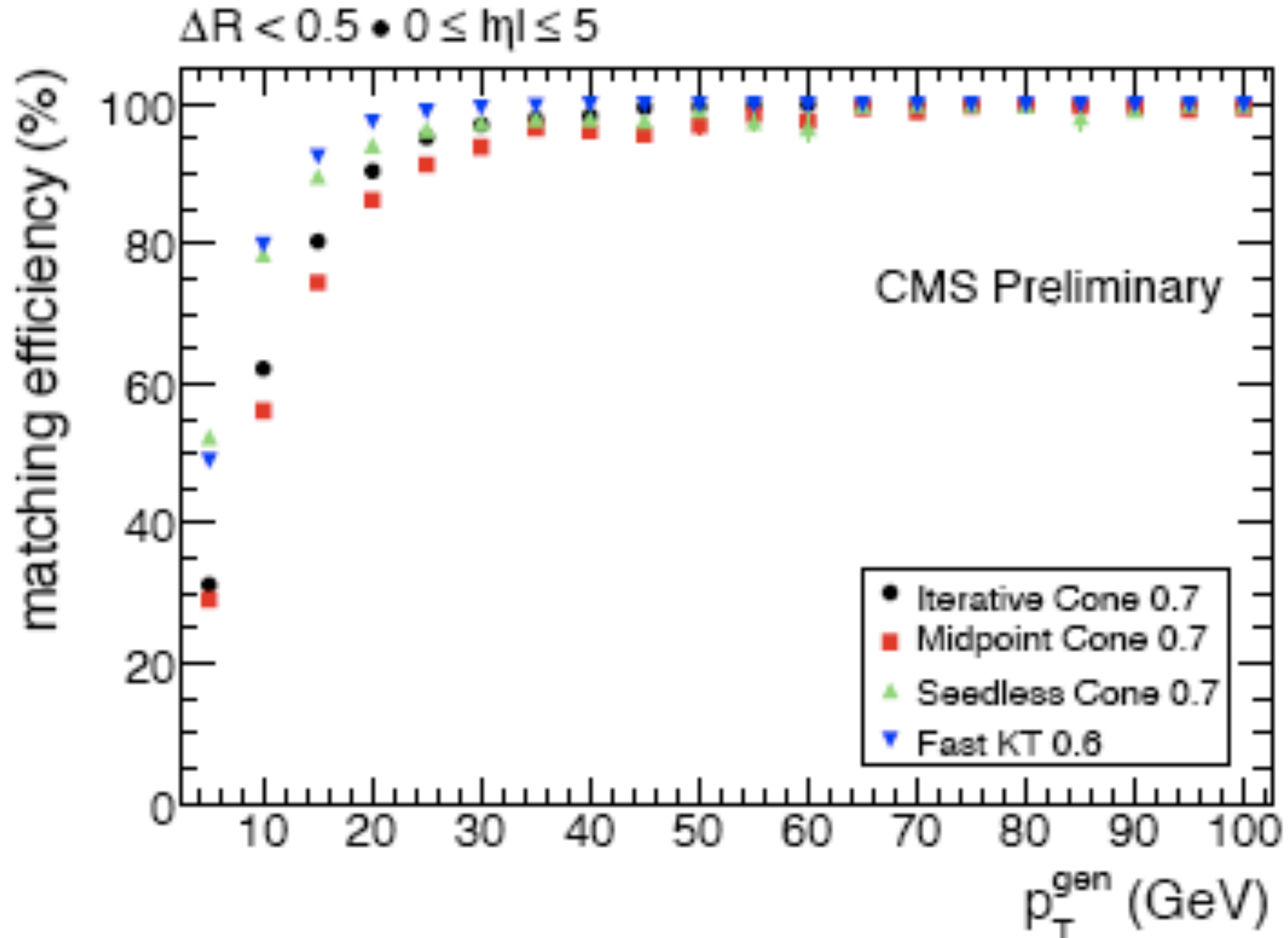




Matching Efficiency





✦ Matching efficiency is the probability to find a reconstructed jet, within a given radius R in η-φ space, from a generated jet.

✦ The matching efficiency is NOT equal to the reconstruction efficiency because it is affected by the finite angular resolution.

✦ The matching efficiencies of SISCone and k_T algorithms are comparable but clearly higher than the simpler cone algorithms.

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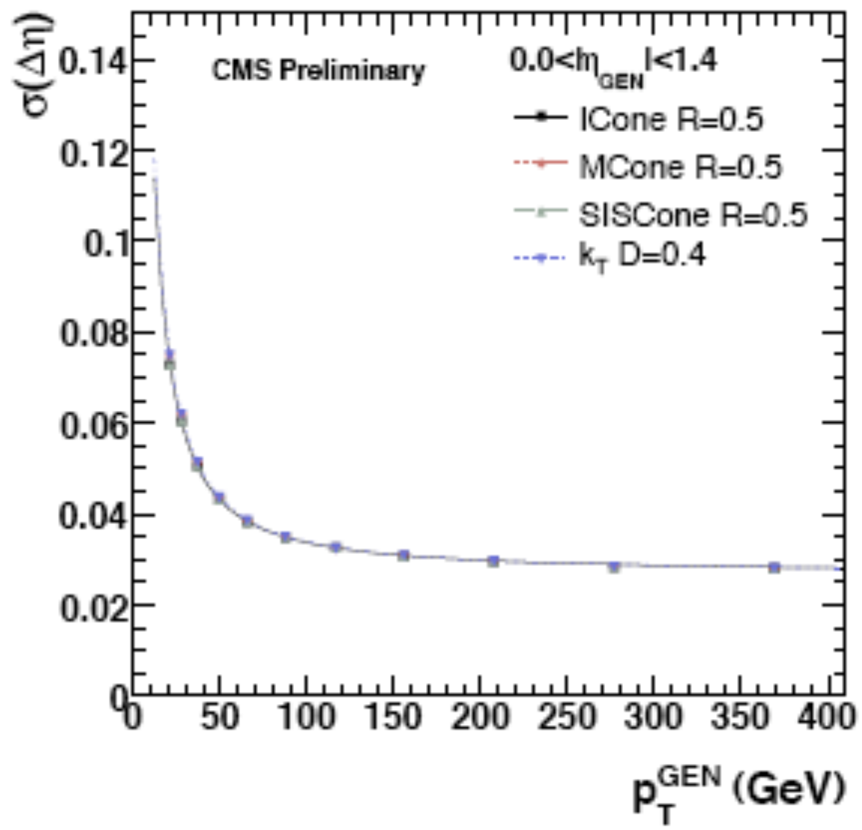
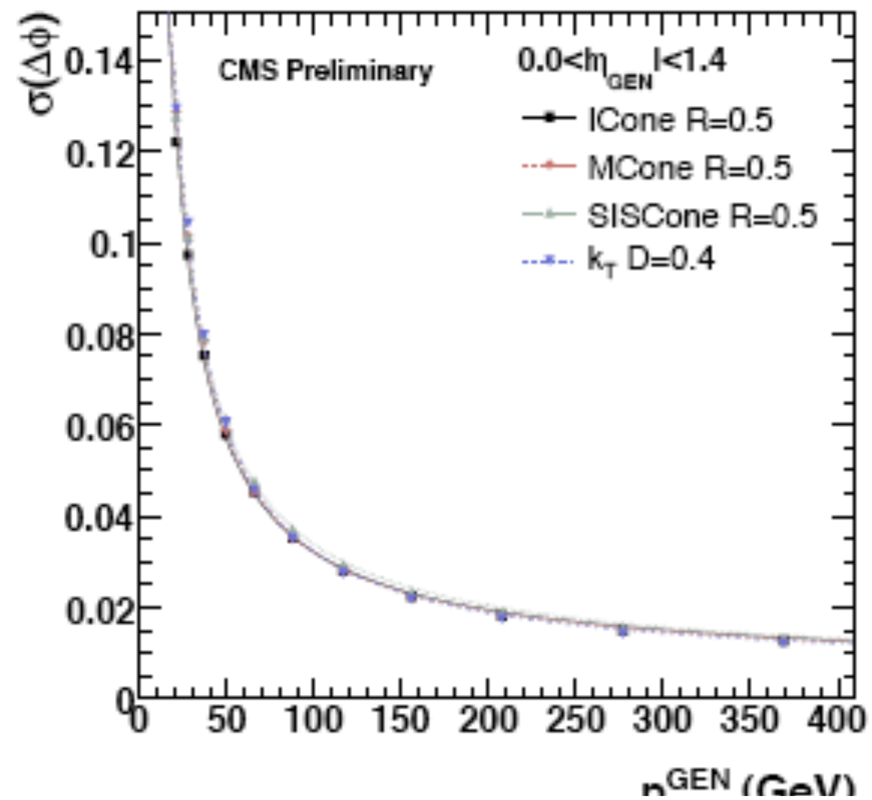
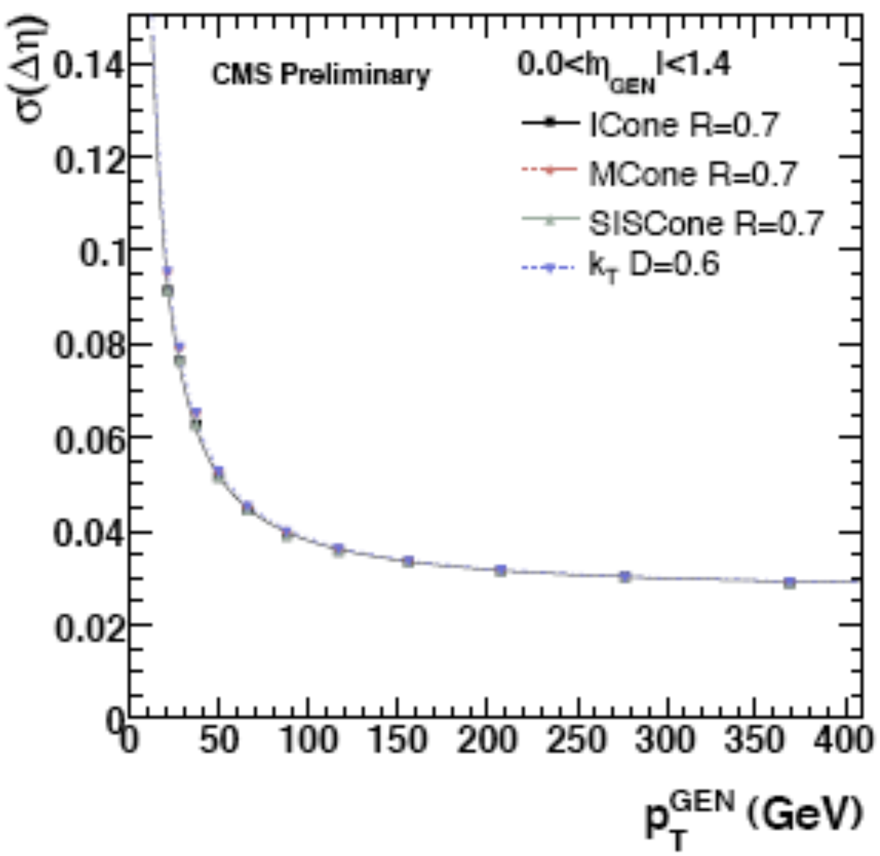
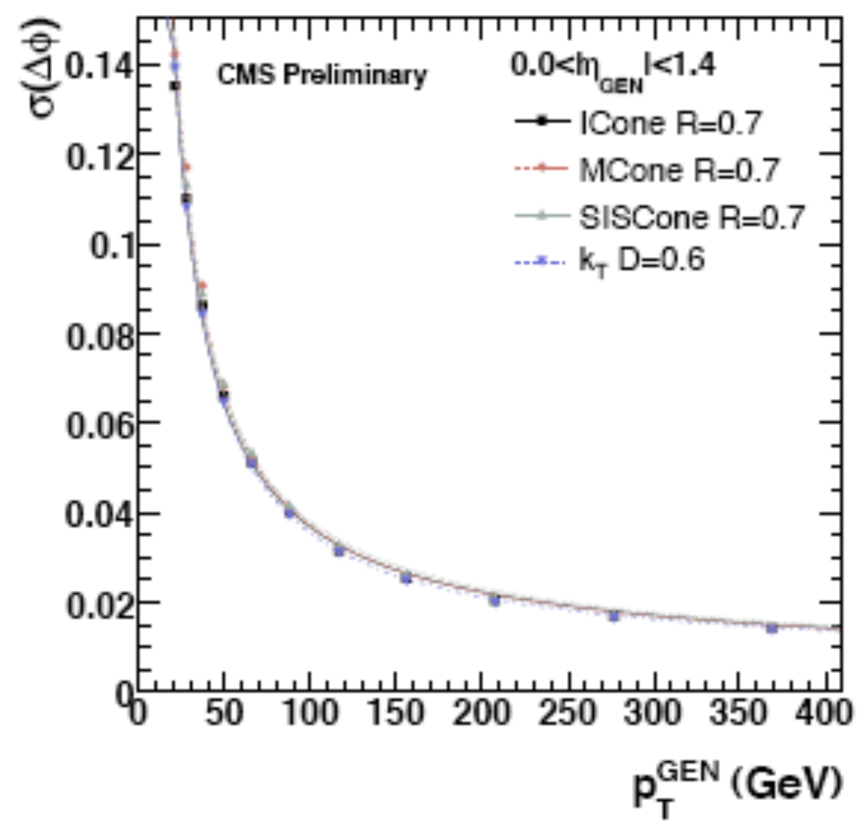
Angular Resolution









No difference observed in the angular resolution of the various jet algorithms.

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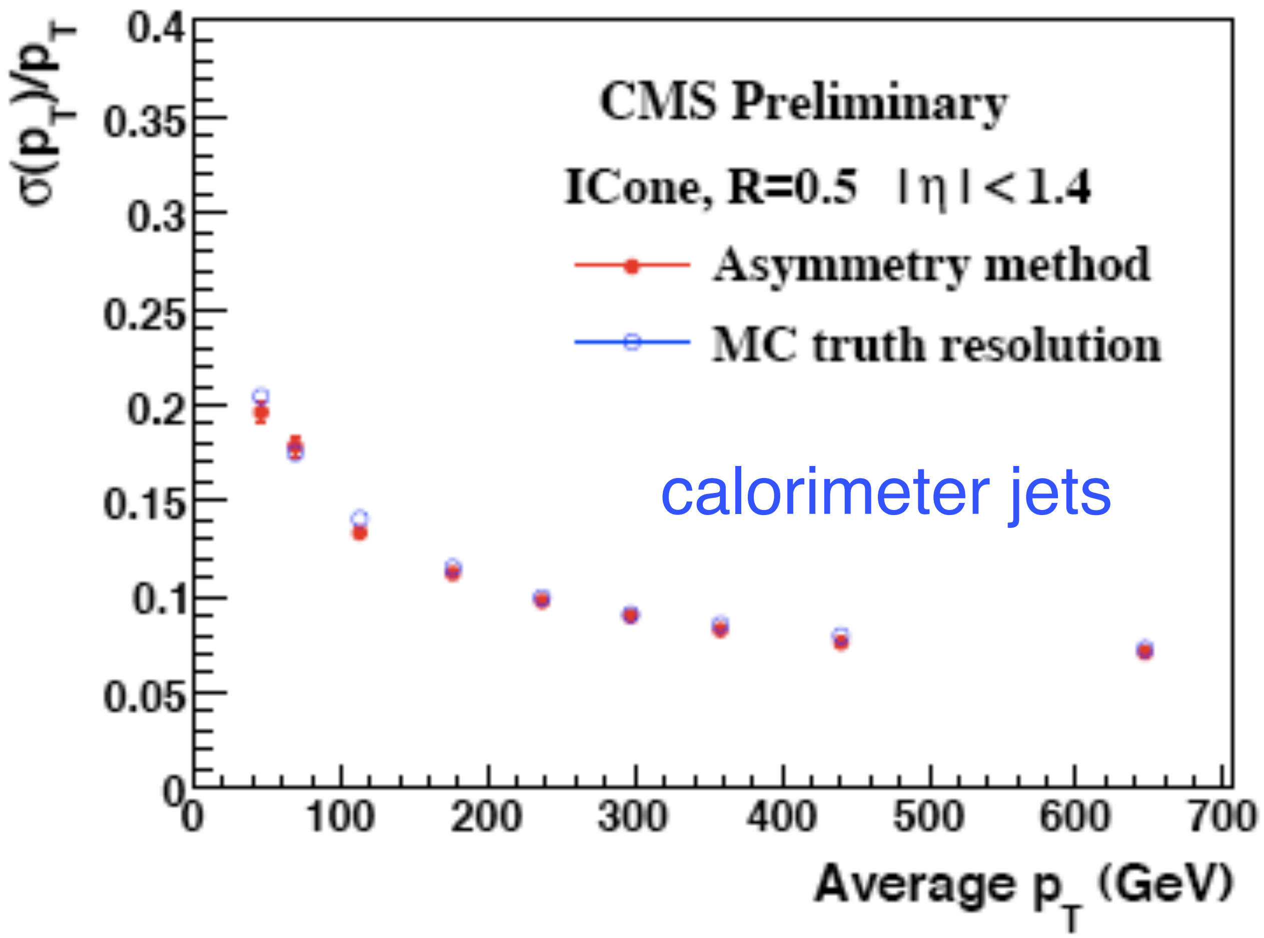
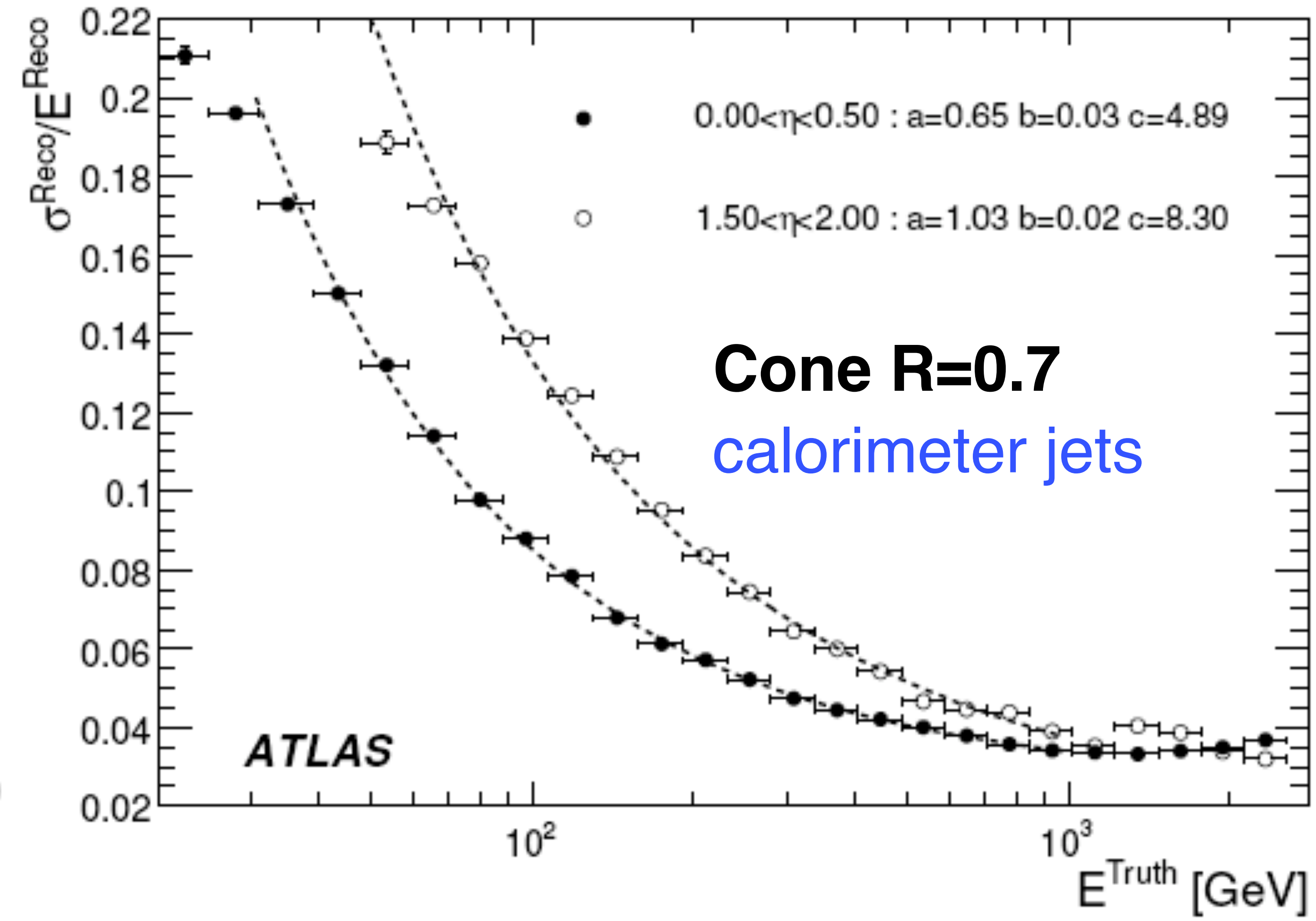
Energy Resolution





✦ The jet energy resolution will be measured with data using the *asymmetry method* (balancing between two calibrated jets, observed in the same detector region).

✦ Preliminary studies indicate that the data driven approach is in good agreement with the MC truth results.

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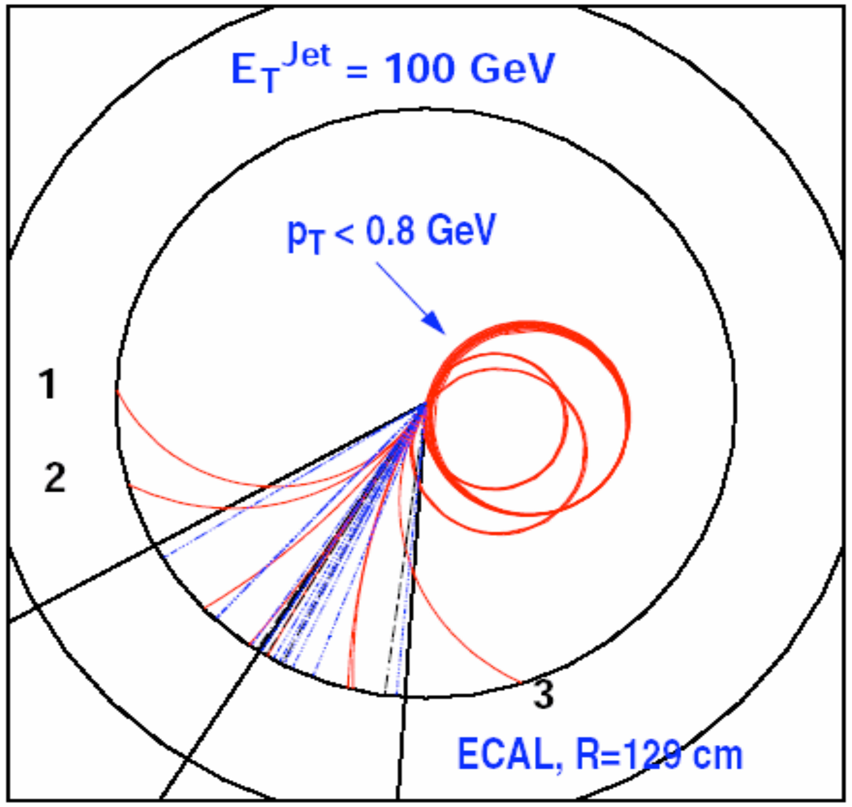
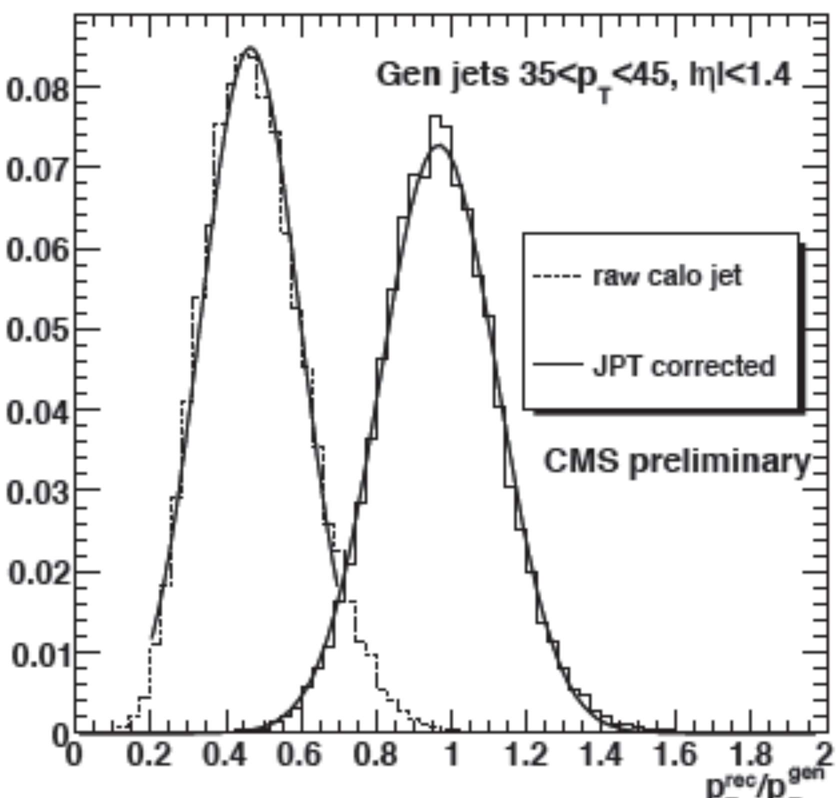
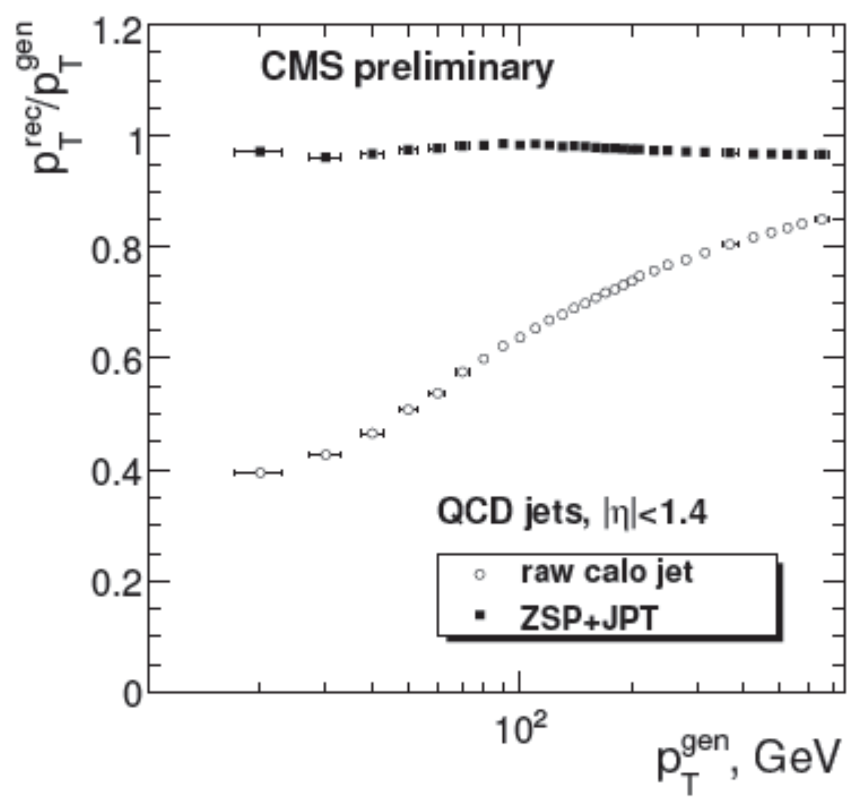
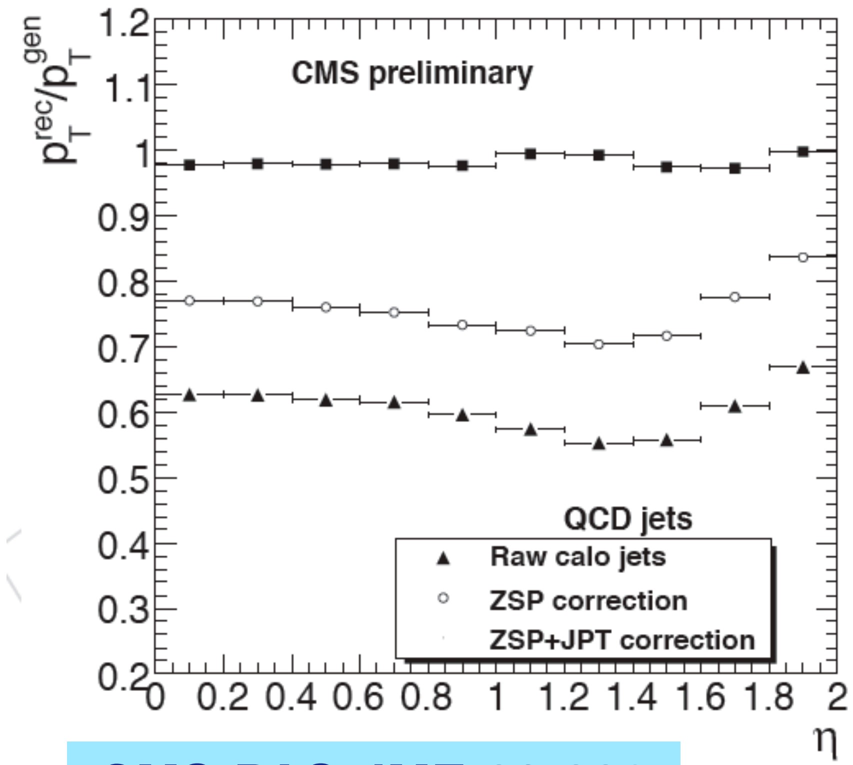
JetPlusTrack Algorithm (I)



- The JetPlusTrack algorithm improves the resolution of the calorimeter jets by using the momentum of the tracks associated to a jet.
- Basic idea: for each track associated with a jet, remove the average expected energy from the observed calorimeter energy and replace it with the track momentum.
- The key element for the commissioning of the JPT algorithm is the single particle response. This has been measured with test beam studies and will be determined by data, using isolated tracks.







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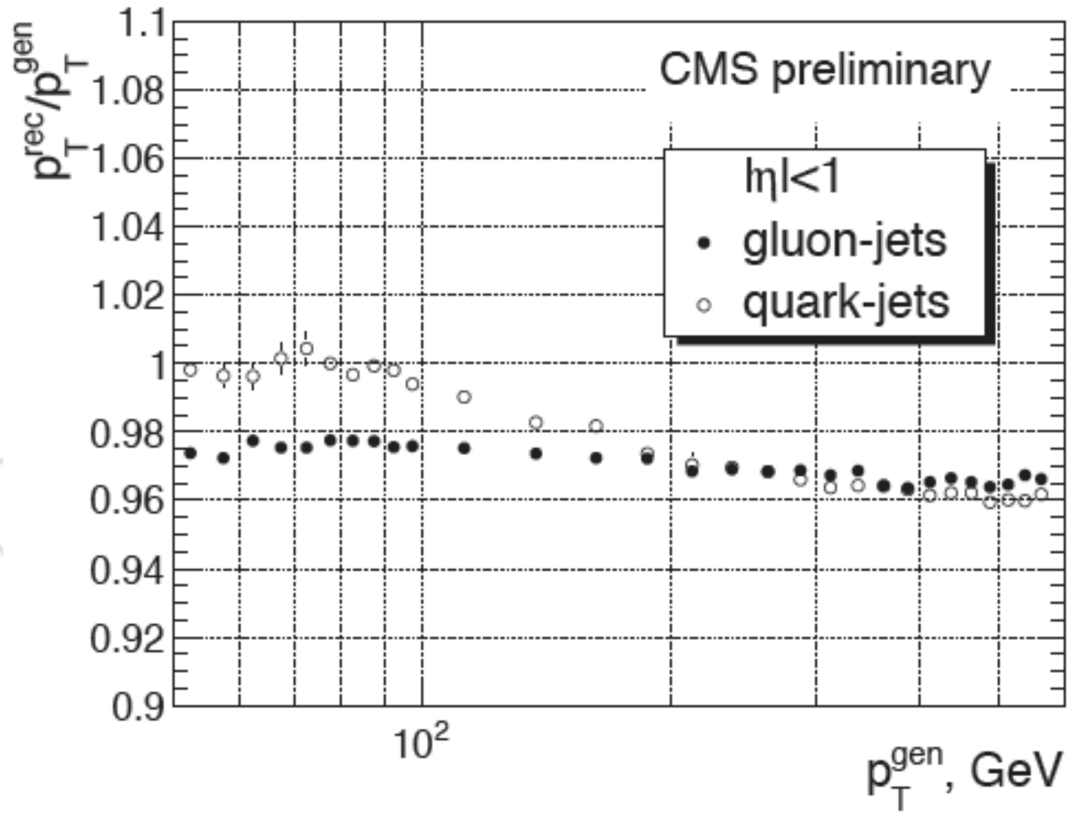
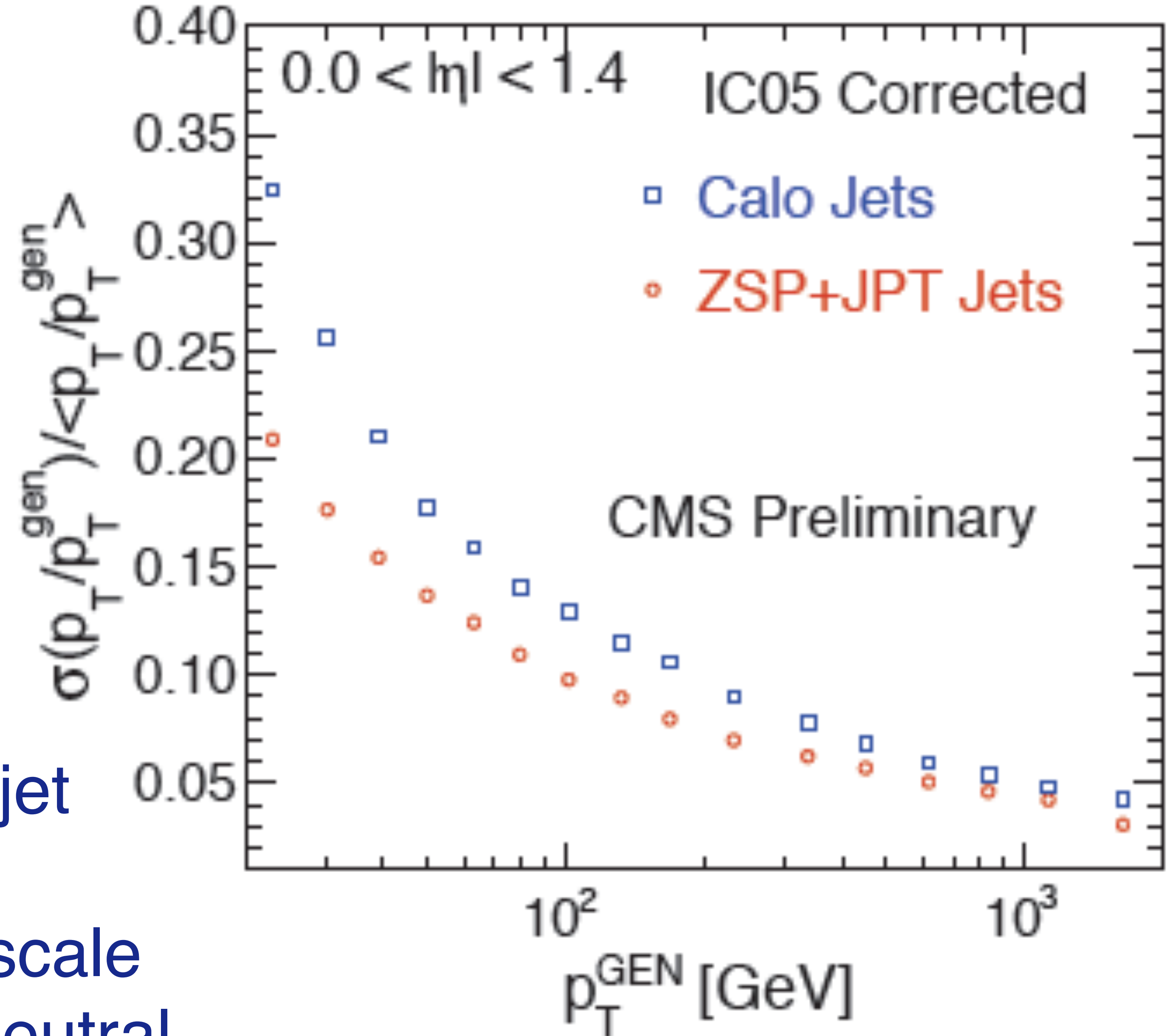
JetPlusTrack Algorithm (II)





- ✦ Significant improvement of the jet energy resolution.
- ✦ Almost restores the jet energy scale (the JPT can not account for the neutral hadrons and the photons).
- ✦ Almost insensitive to the jet flavour composition.

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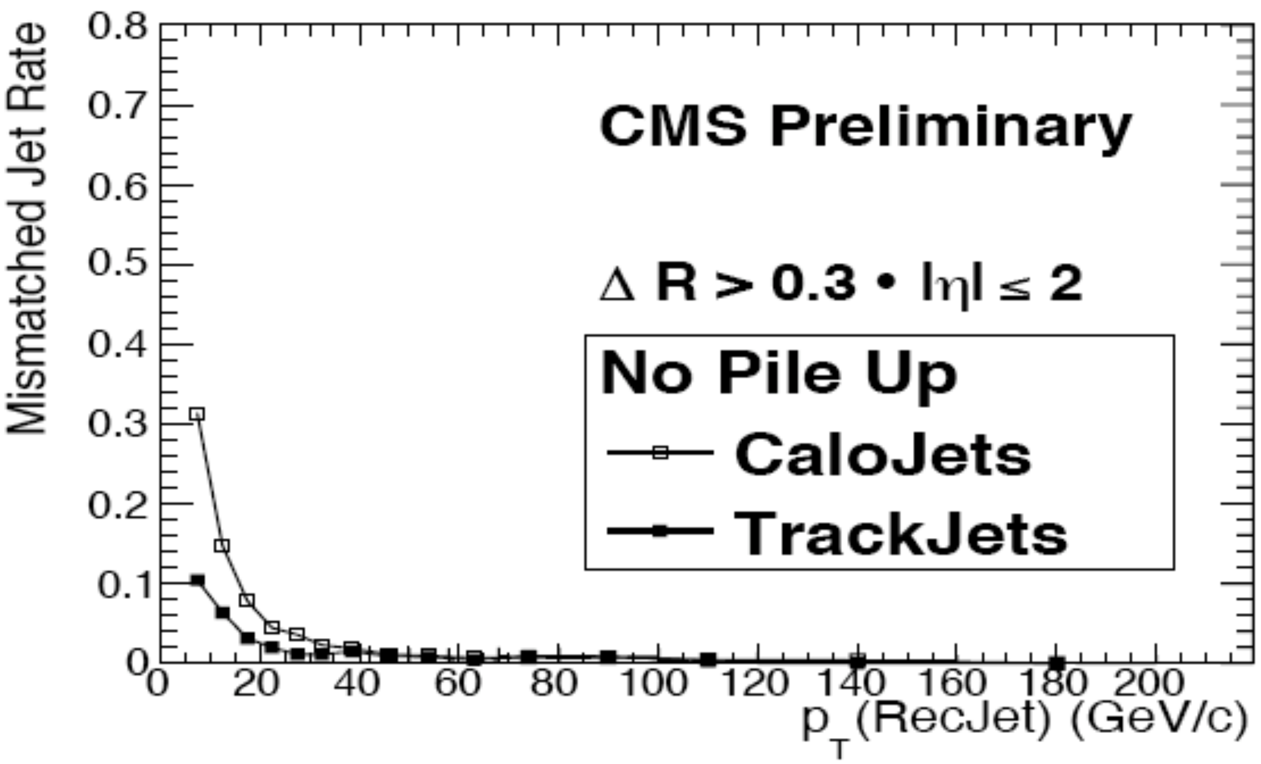
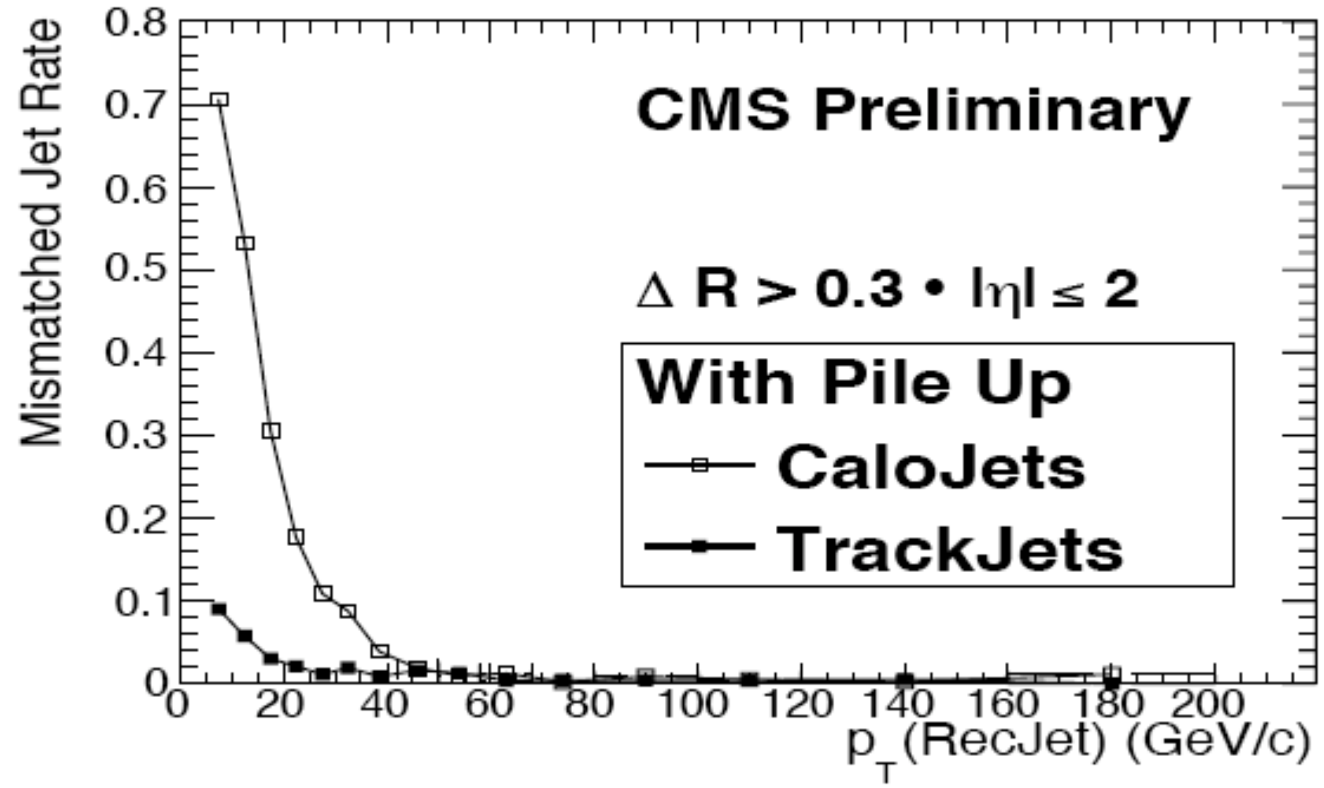
Track Jets





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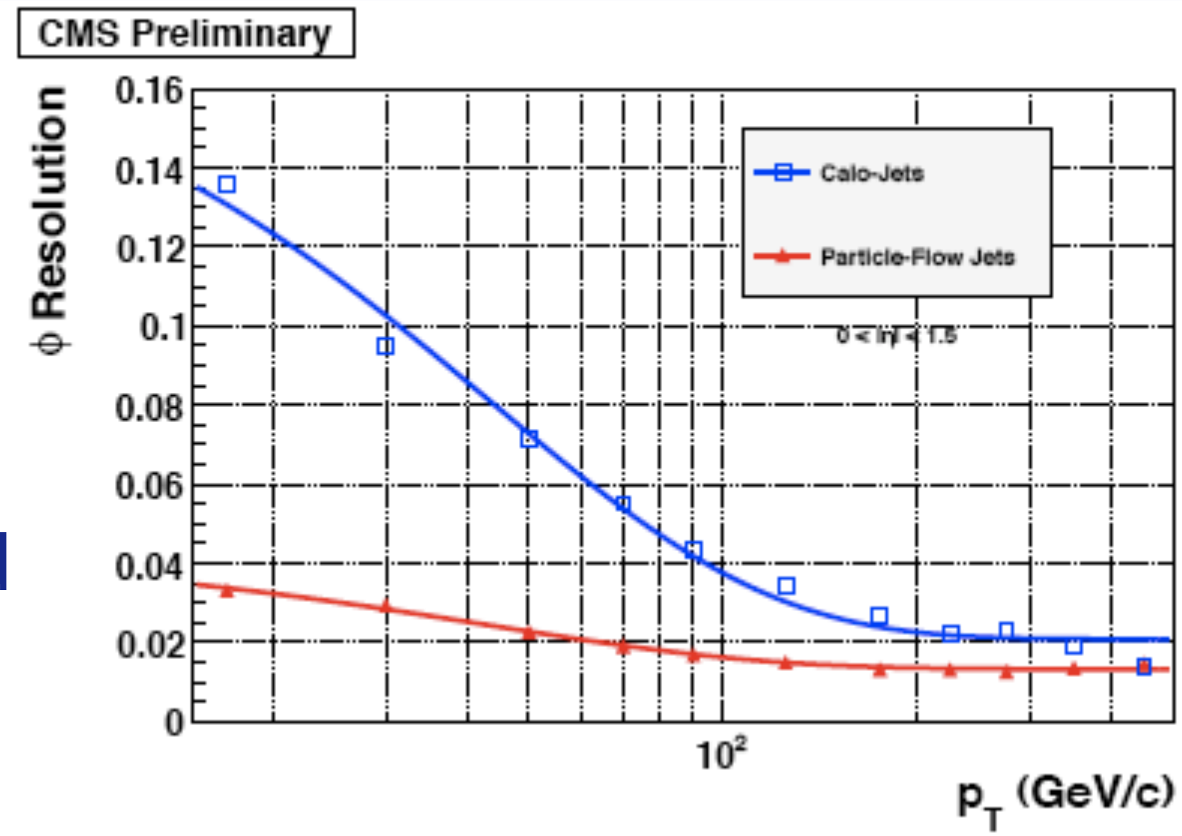
✦ The track jets are the output of the jet algorithm on reconstructed tracks.

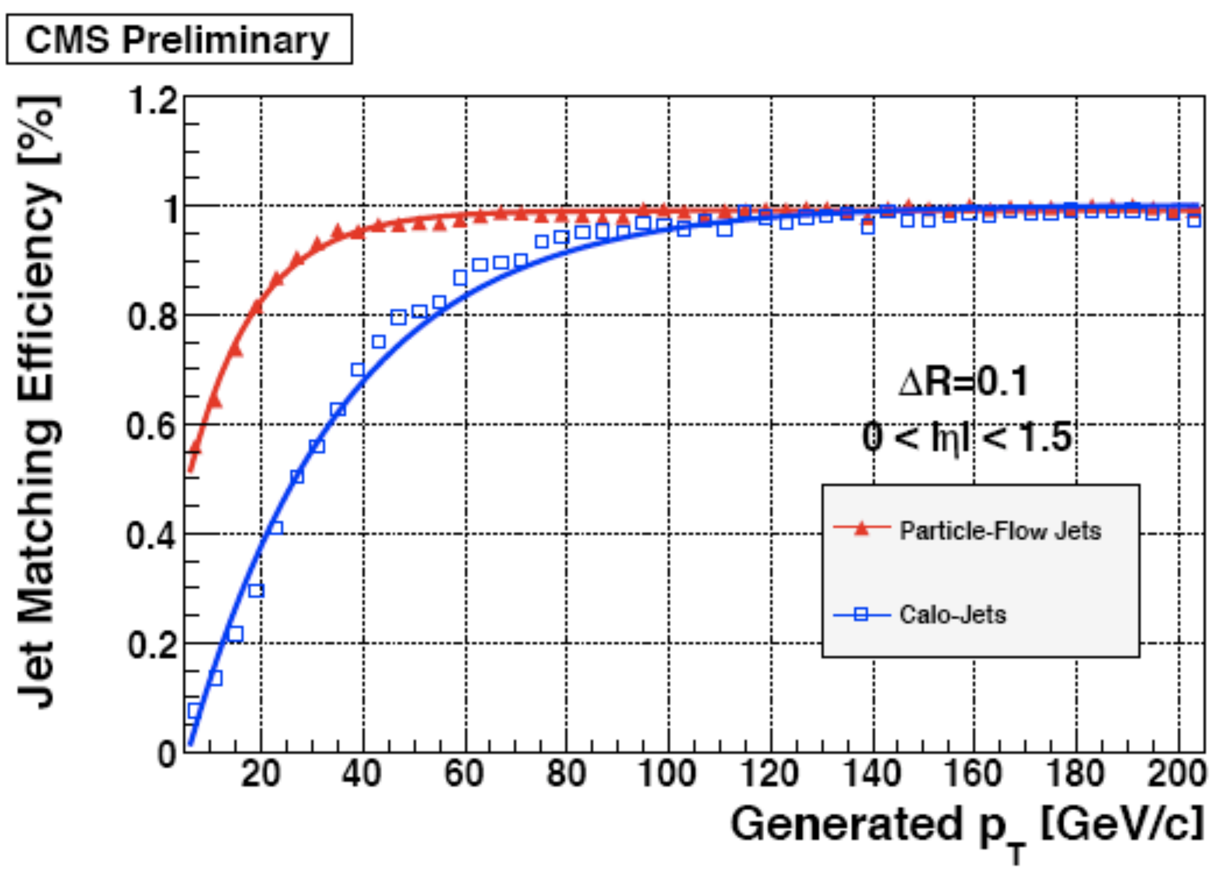
✦ Due to the high reconstruction efficiency end the low fake rate, track jets can be used for jet counting or jet tagging.

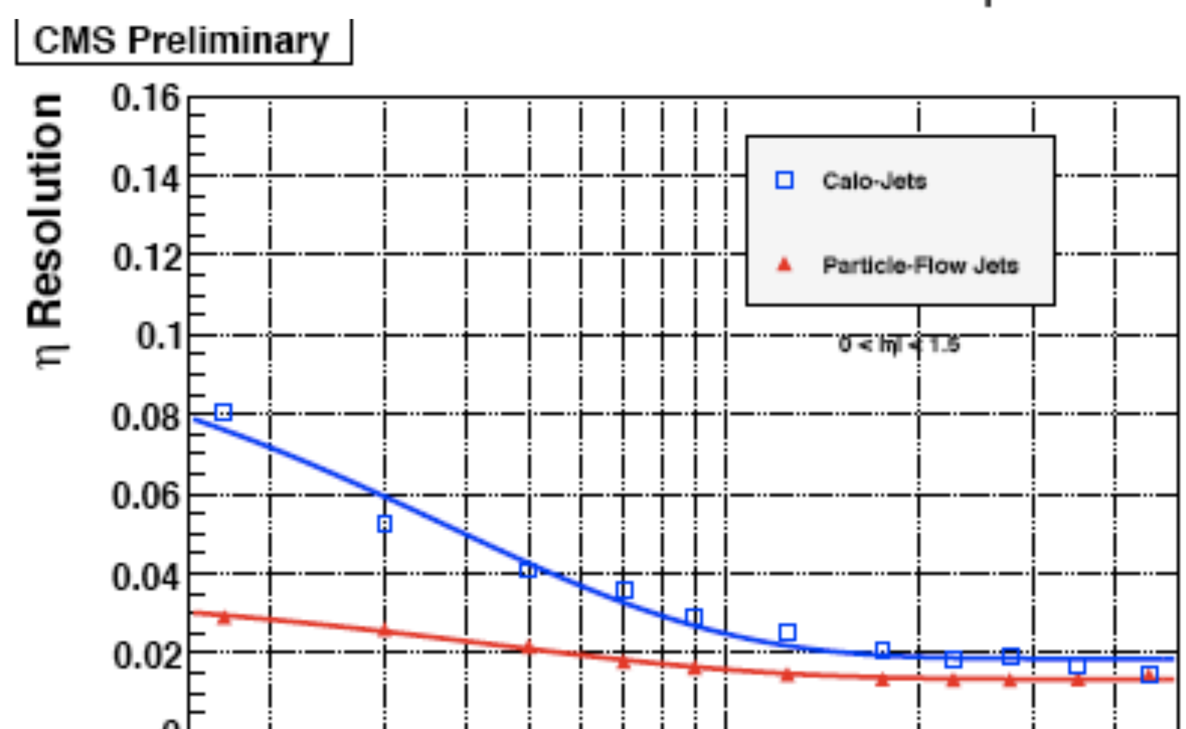
Particle Flow Jets (I)

✦ The particle flow algorithm attempts to reconstruct all stable particles in the event ($\pi^{\pm}$,π^0,γ,Ks, etc) by combining the information from many sub-detectors.

✦ The particle flow jets are the output of the jet algorithm on the reconstructed particles.







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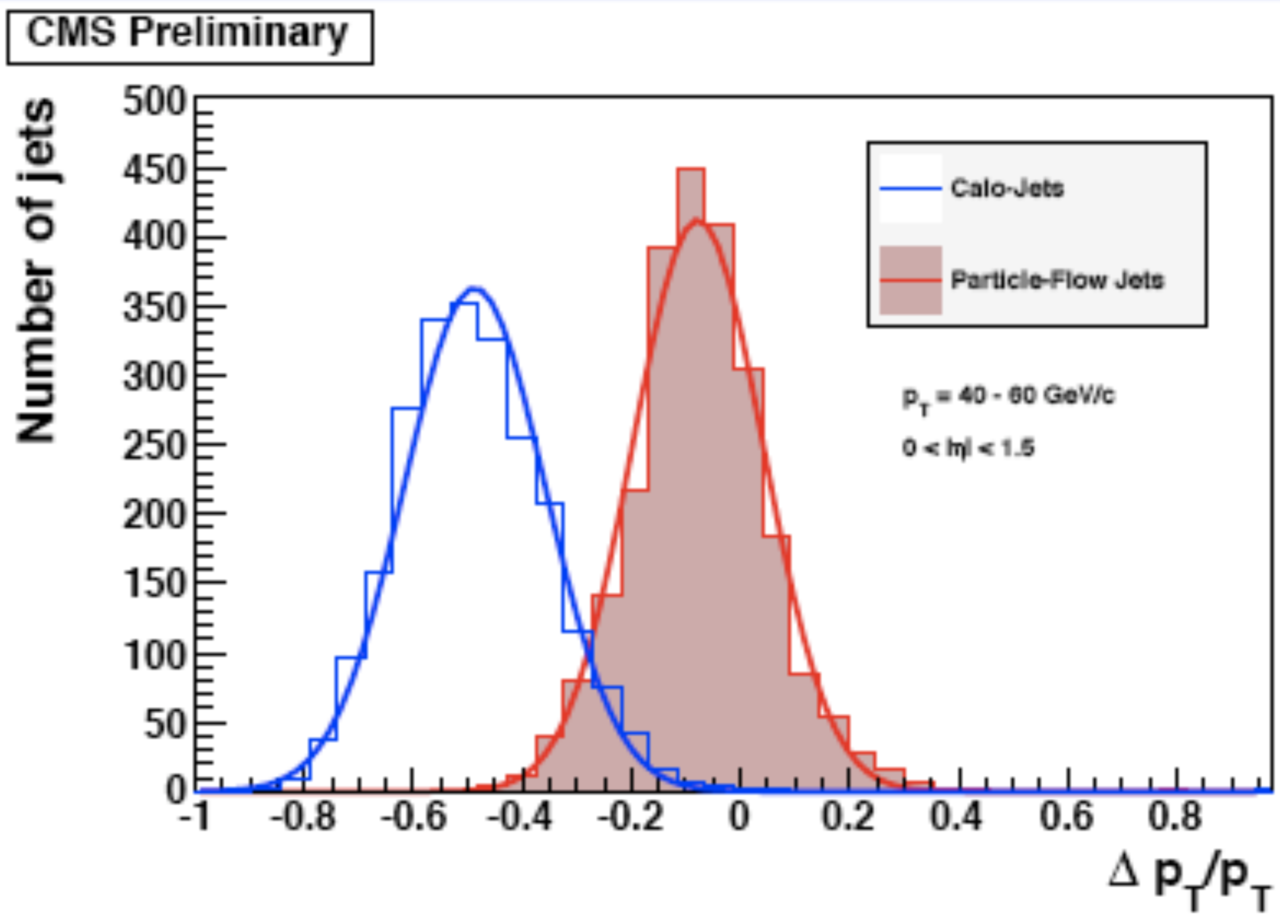
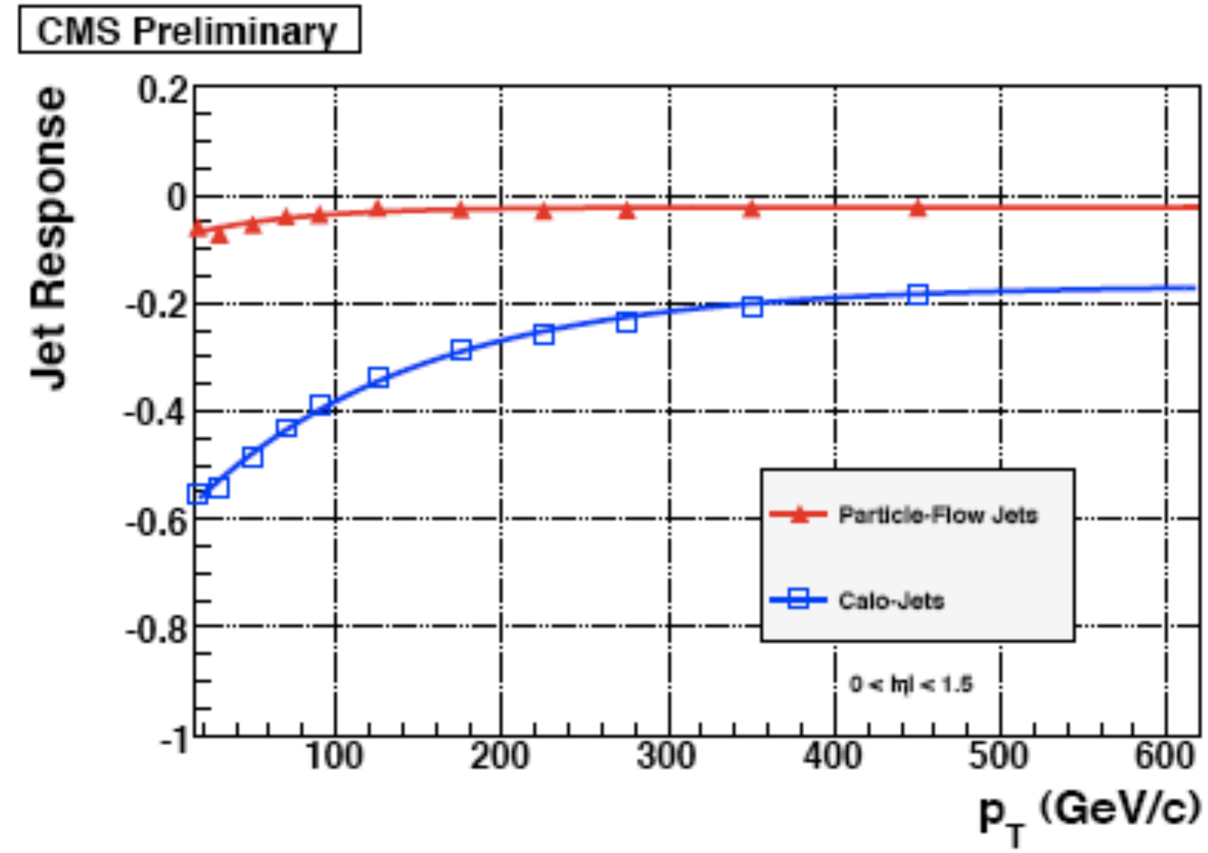
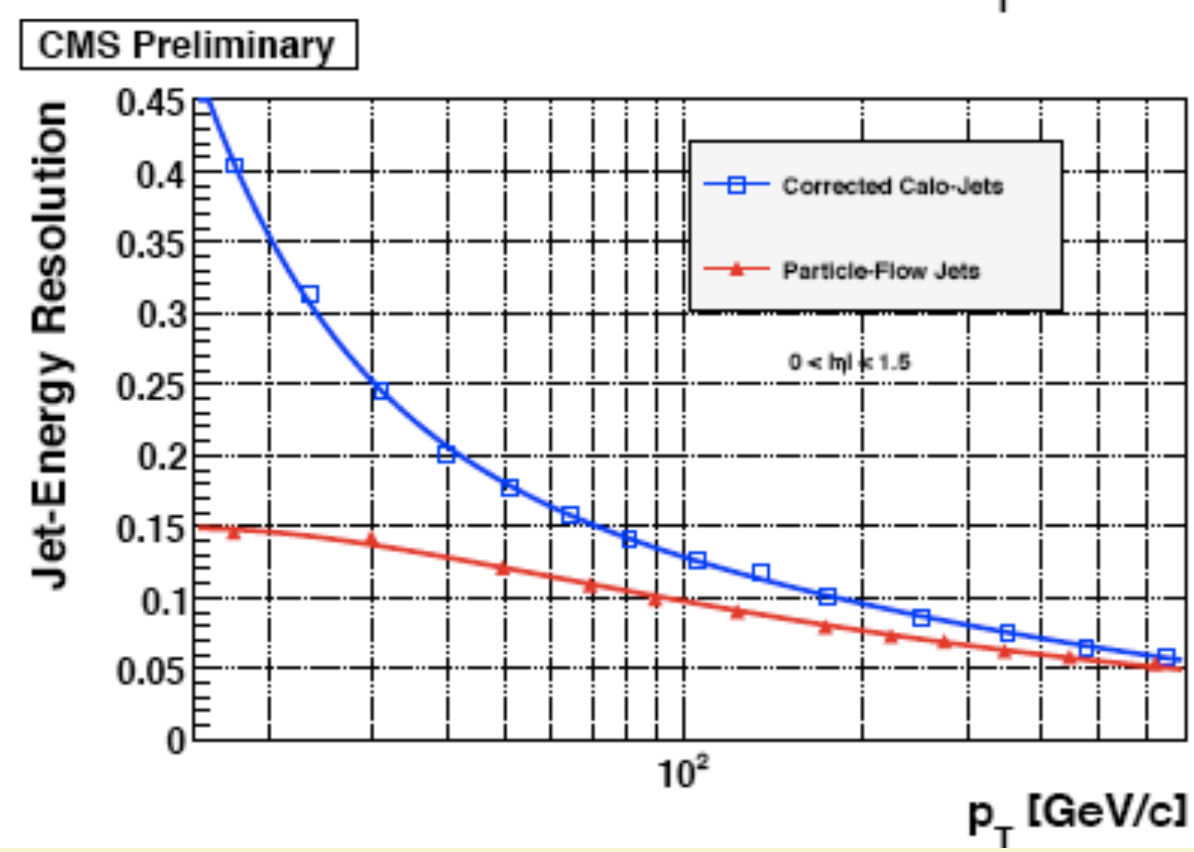
Particle Flow Jets (II)







- ✦ Better reconstruction efficiency and smaller fake rate.
- ✦ Significant improvement of the jet energy and angular resolutions.
- ✦ Small residual jet energy calibration needed.
- ✦ Very promising signs in MC. Needs to be validated with data.

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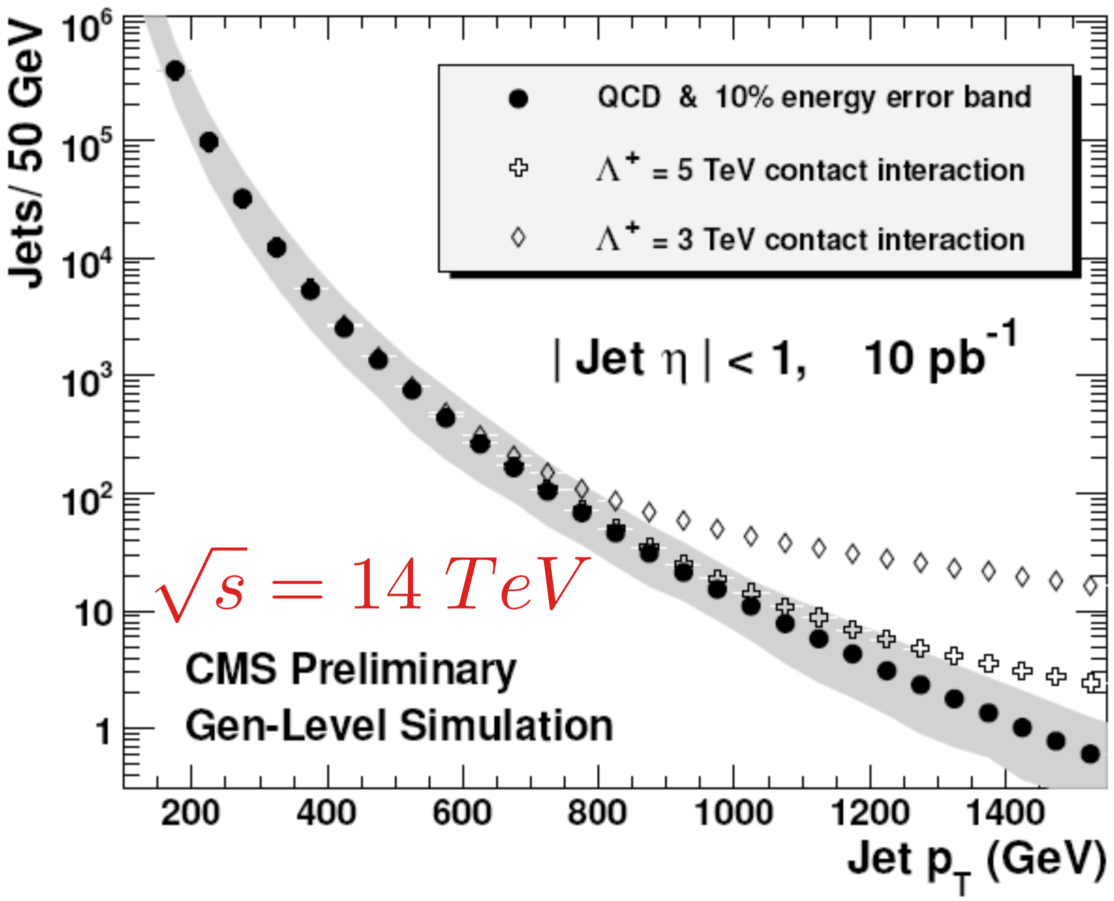
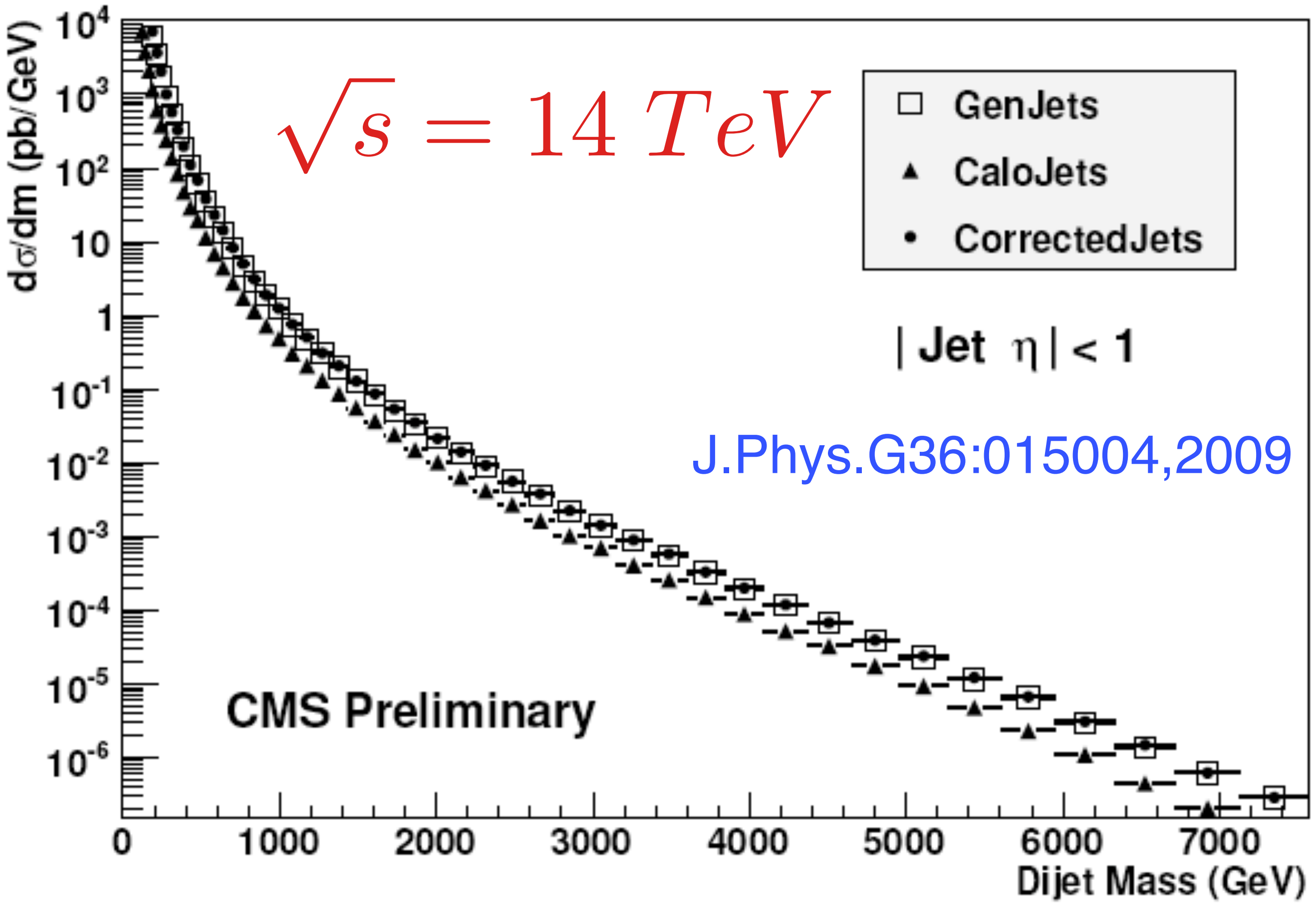
PART III: Prelude to Jet Physics

QCD Studies: Cross-sections





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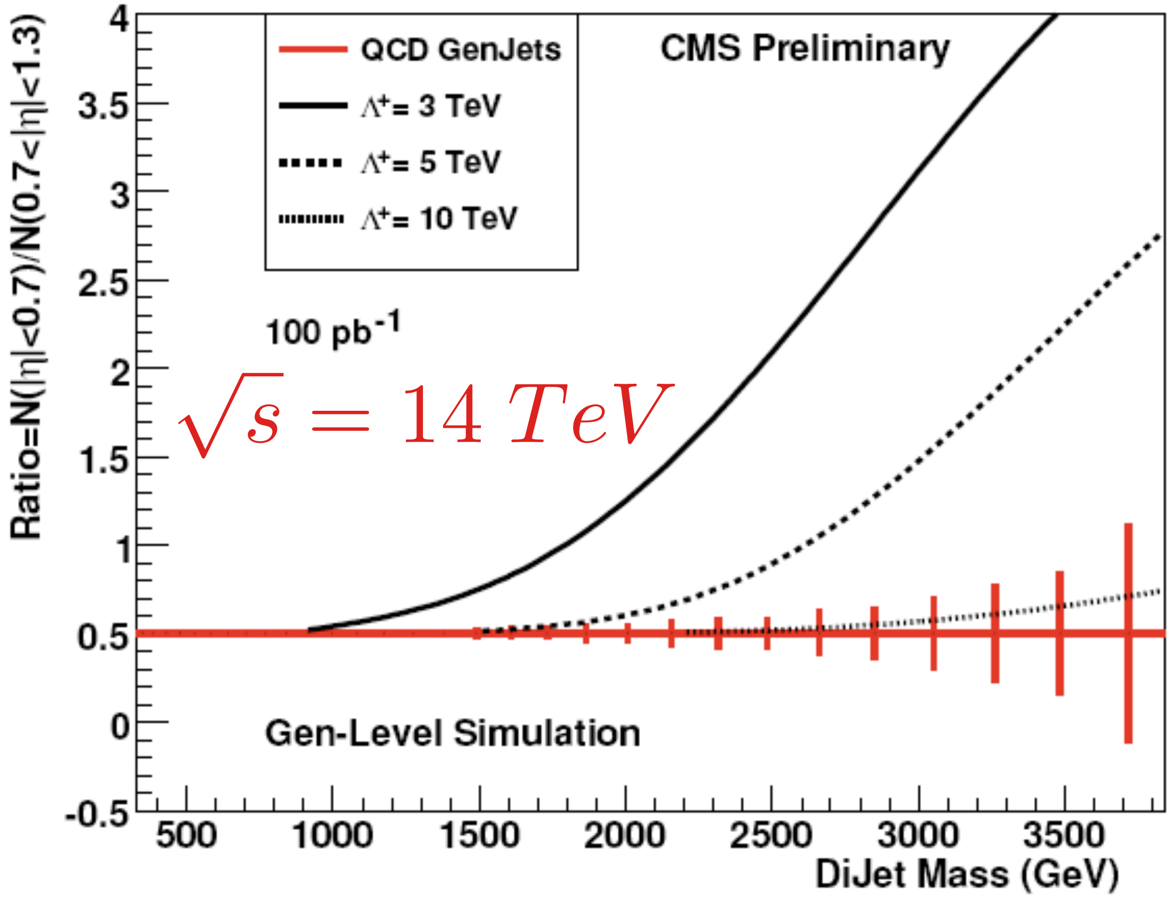
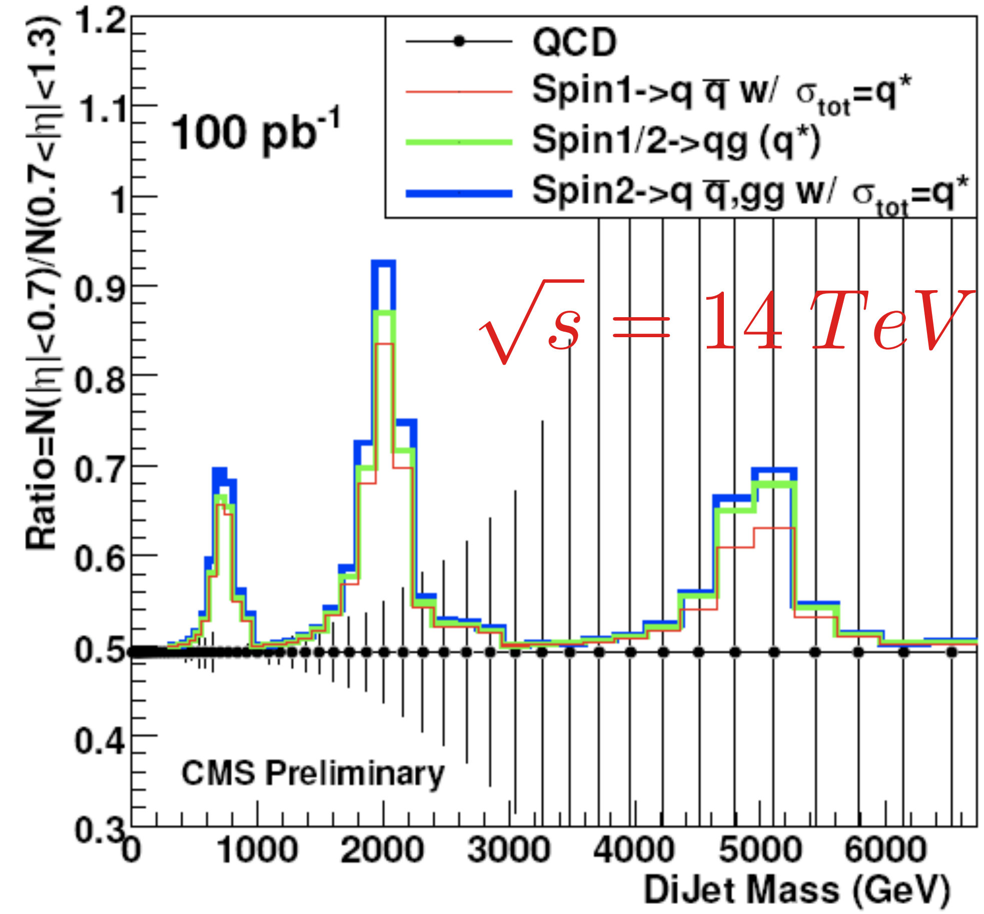
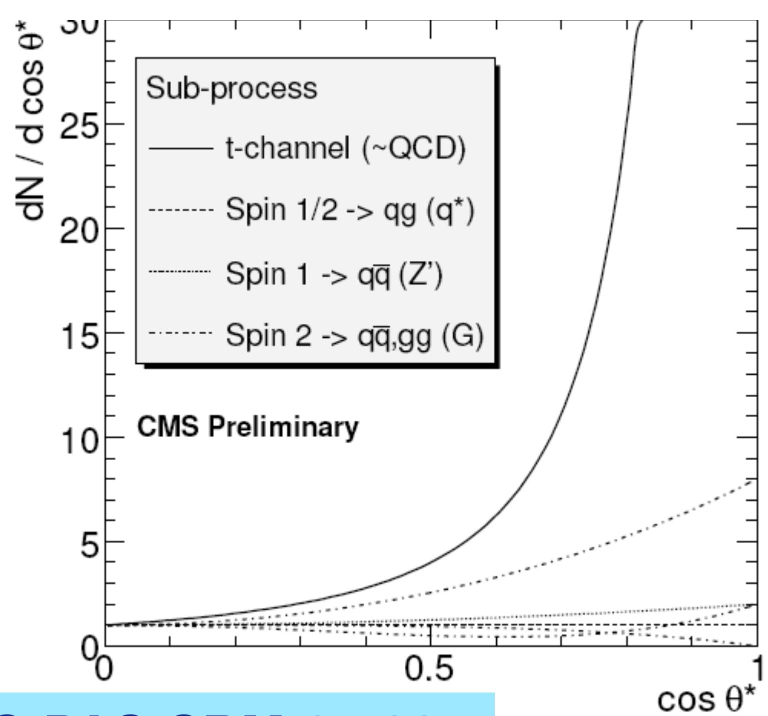
- ✦ The jet cross-sections (inclusive jet p_T spectrum, dijet mass spectrum) are important jet commissioning measurements.
- ✦ They can be used to confront QCD predictions.
- ✦ They are sensitive to new physics (e.g. contact interactions or heavy objects decaying to two jets).
- ✦ They are dominated by the jet energy scale systematic uncertainty.

QCD Studies: Angular Distributions







- ✦ The jet angular distributions are sensitive to new physics. QCD favours scattering at small angle in contrast to other processes which favour more uniform scattering.
- ✦ The dijet ratio (number of dijet events in |η|<0.7 over number of dijet events in 0.7<|η|<1.3) is a robust way to look for deviations from QCD in early data.
- ✦ The full dijet angular distribution measurement will follow when we have better understanding of the detector.

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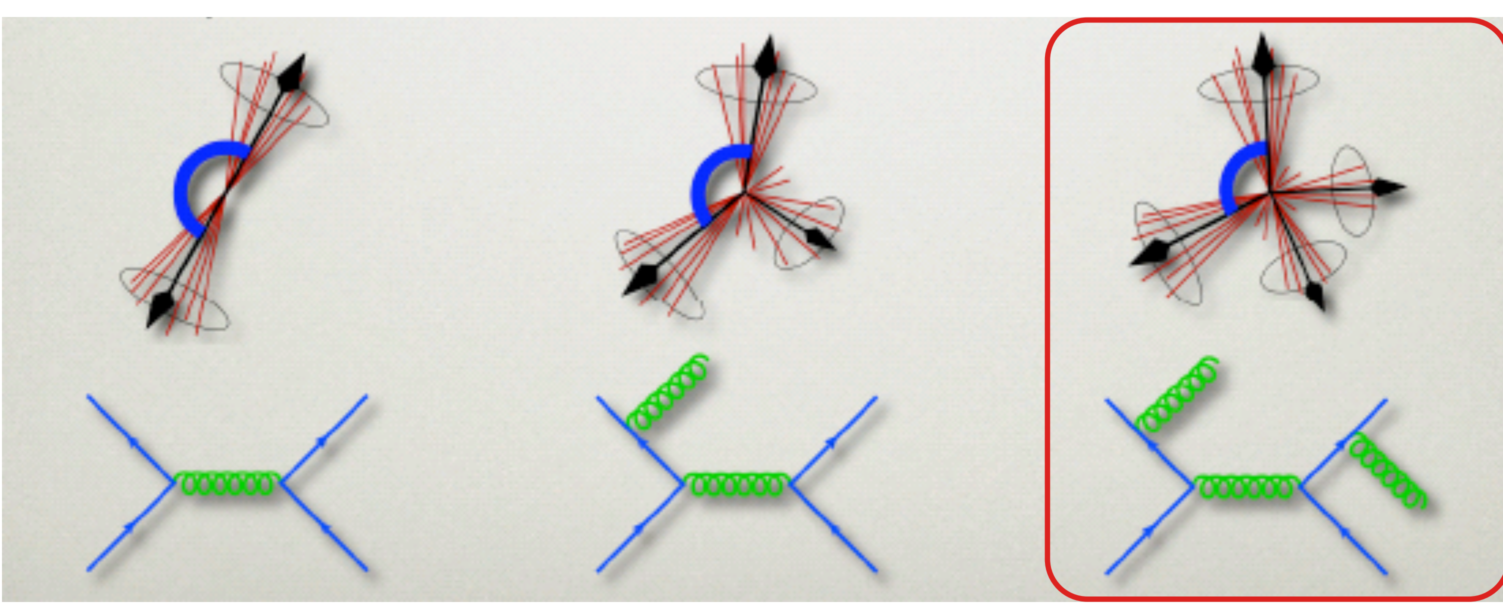
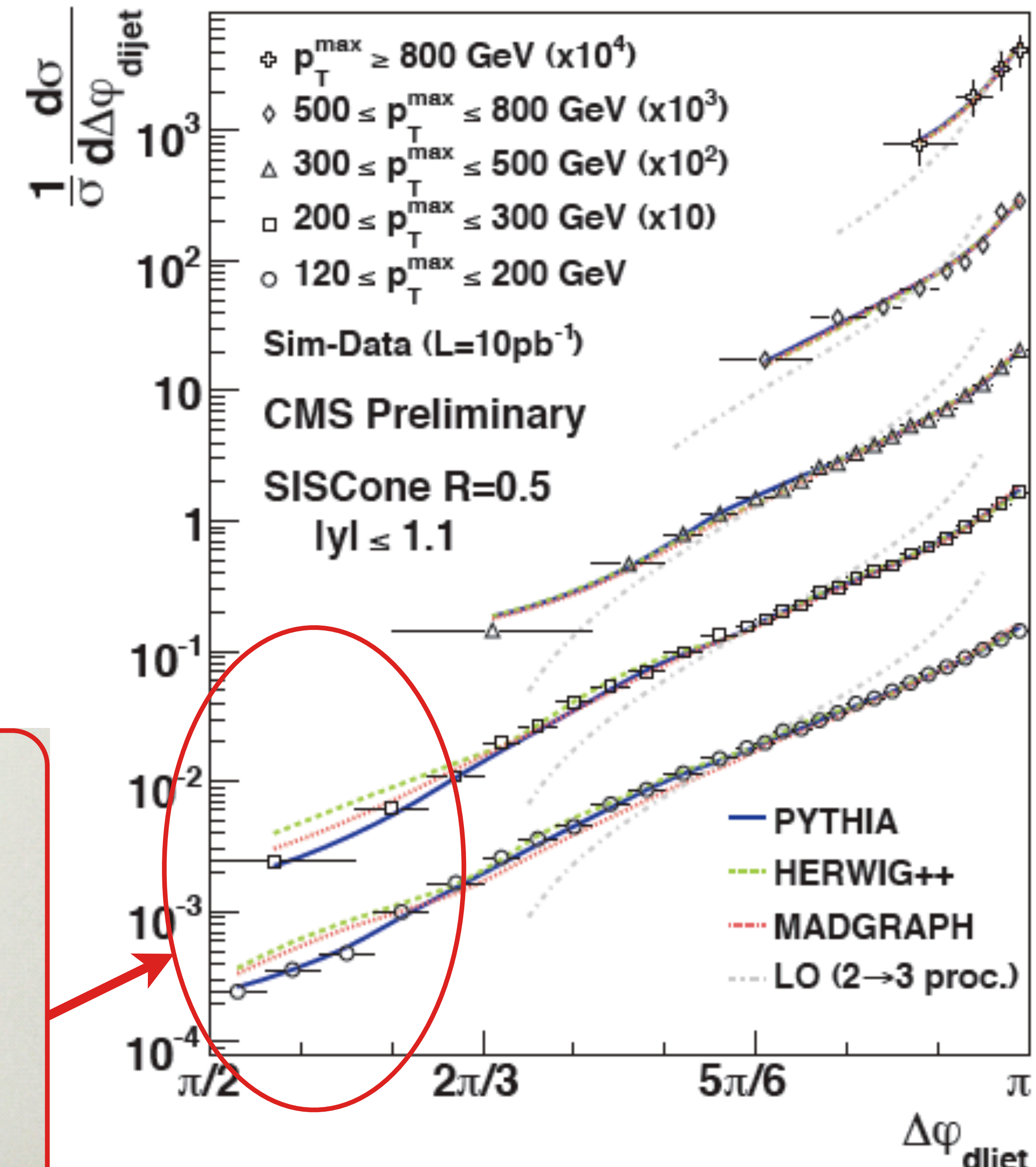
QCD Studies: Dijet Azimuthal Decorrelation

✦ Measurement of the azimuthal angle between the two leading jets.
✦ Confrontation of the pQCD calculations.
✦ Sensitivity to gluon radiation modelling. Can help tune MC generators.
✦ Not affected by the major jet related uncertainties (JES).

Observable: $$\frac{1}{N}\frac{dN}{d\Delta\phi}$$

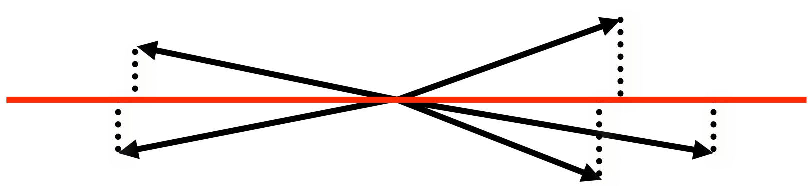




CMS-PAS-QCD-09-003

QCD Studies: Event Shapes

- ✦ Study of the kinematic variables (e.g ***central transverse thrust***) that probe the structure of the hadronic final state.
- ✦ Test of QCD dynamics.
- ✦ Not affected by the JES uncertainty.
- ✦ Can help tune MC generators.
- ✦ Can be used to measure a_S.

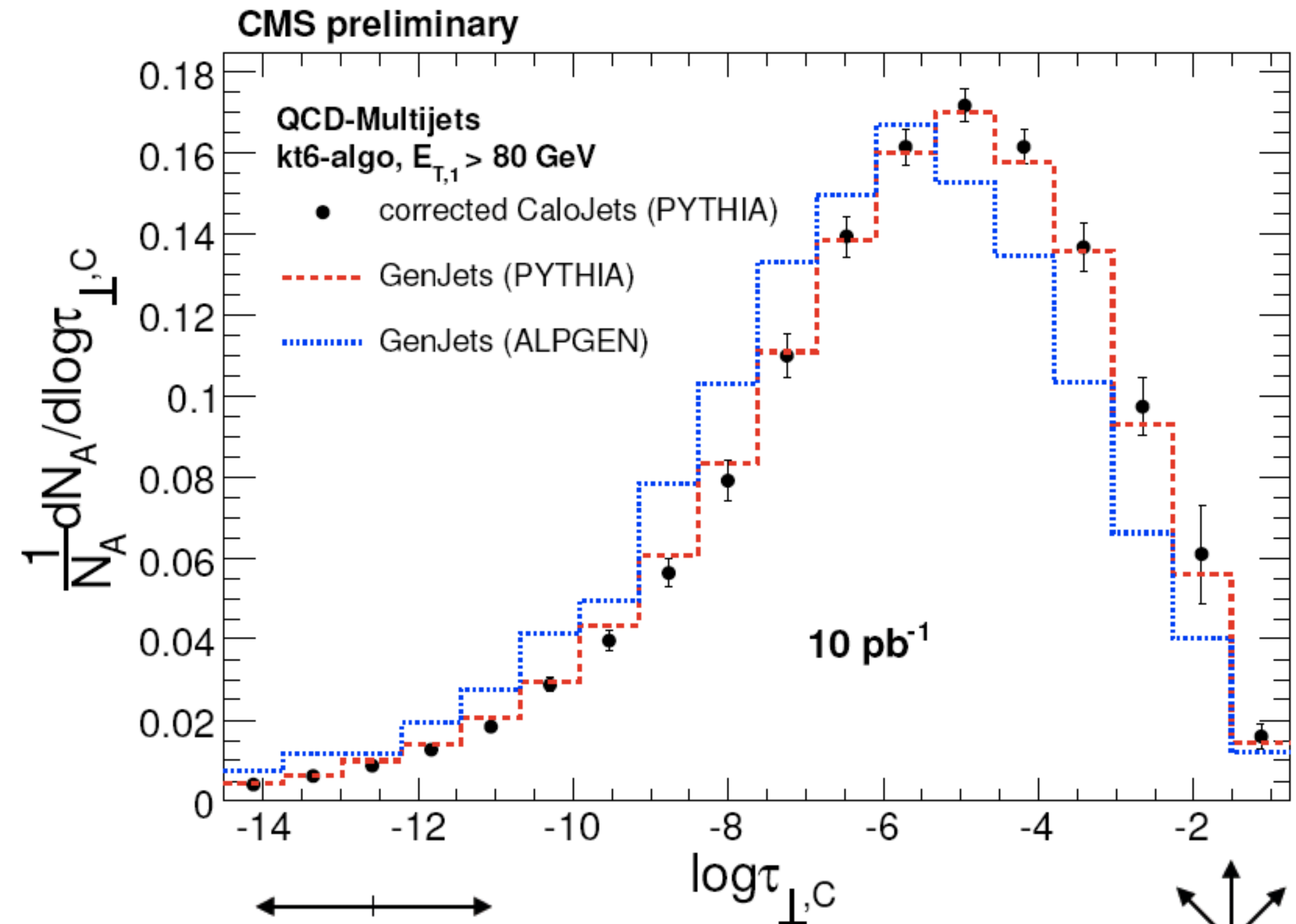


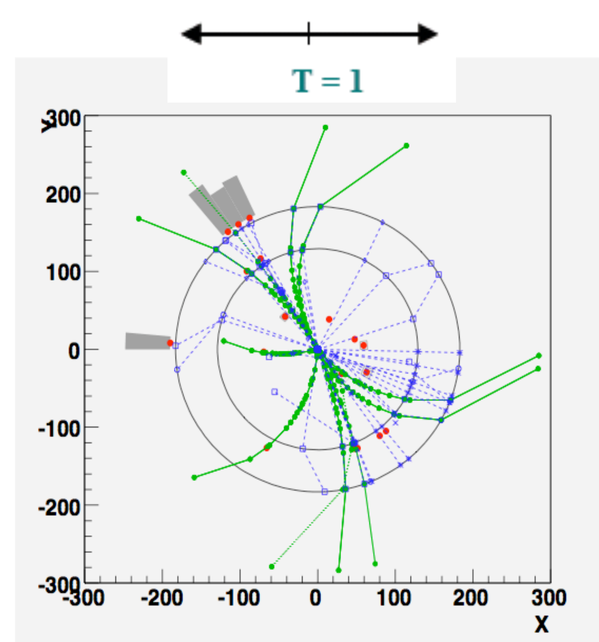
$$\tau_{\perp,C} \equiv 1 - T_{\perp,C}$$

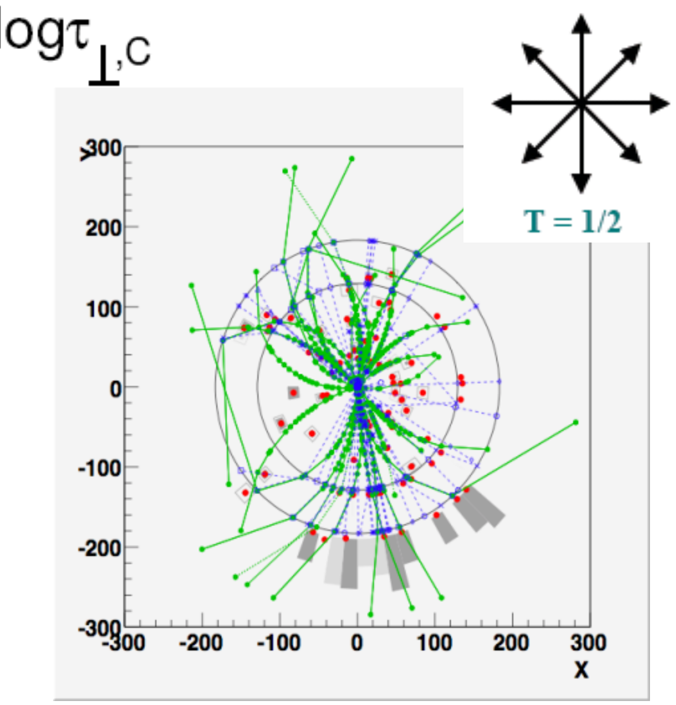
$$T_{\perp,C} \equiv \max_{\vec{\eta}_T} \frac{\sum_i \left| \vec{p}_{\perp,i} \bullet \vec{\eta}_T \right|}{\sum_i p_{\perp,i}}$$

Observable: $$\frac{1}{N} \frac{dN}{d \log(\tau_{\perp,C})}$$

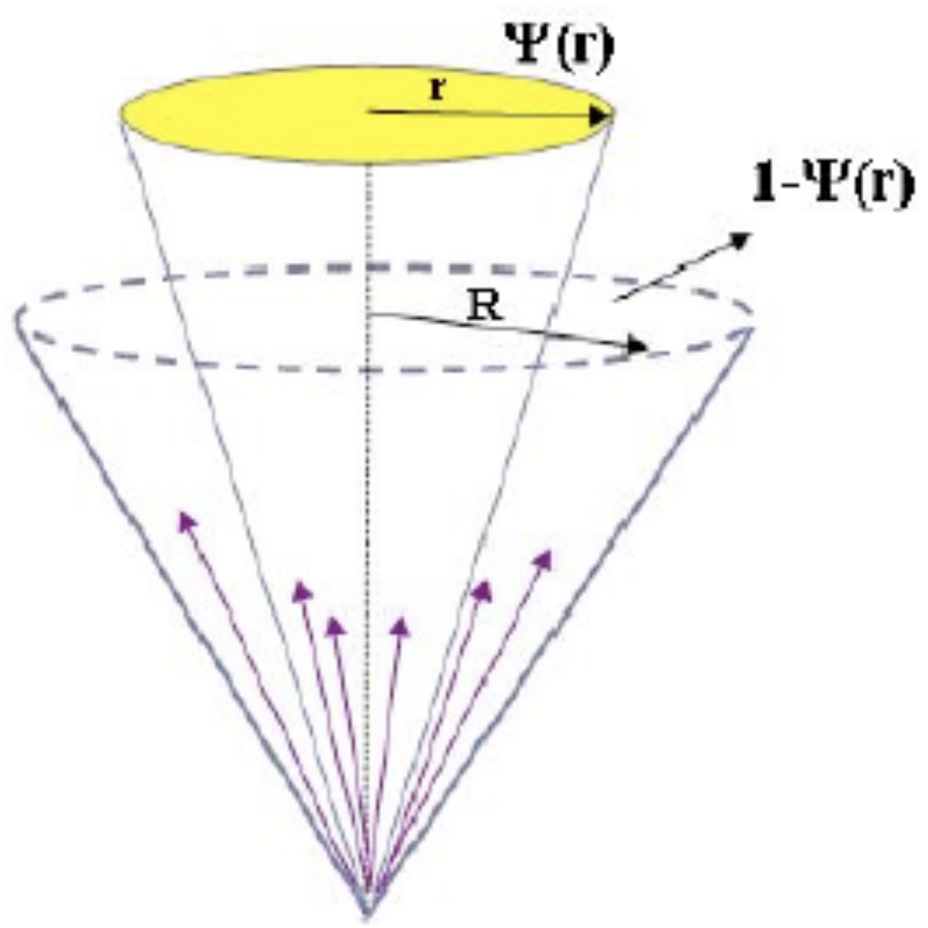
CMS-PAS-QCD-08-003







QCD Studies: Jet Structure



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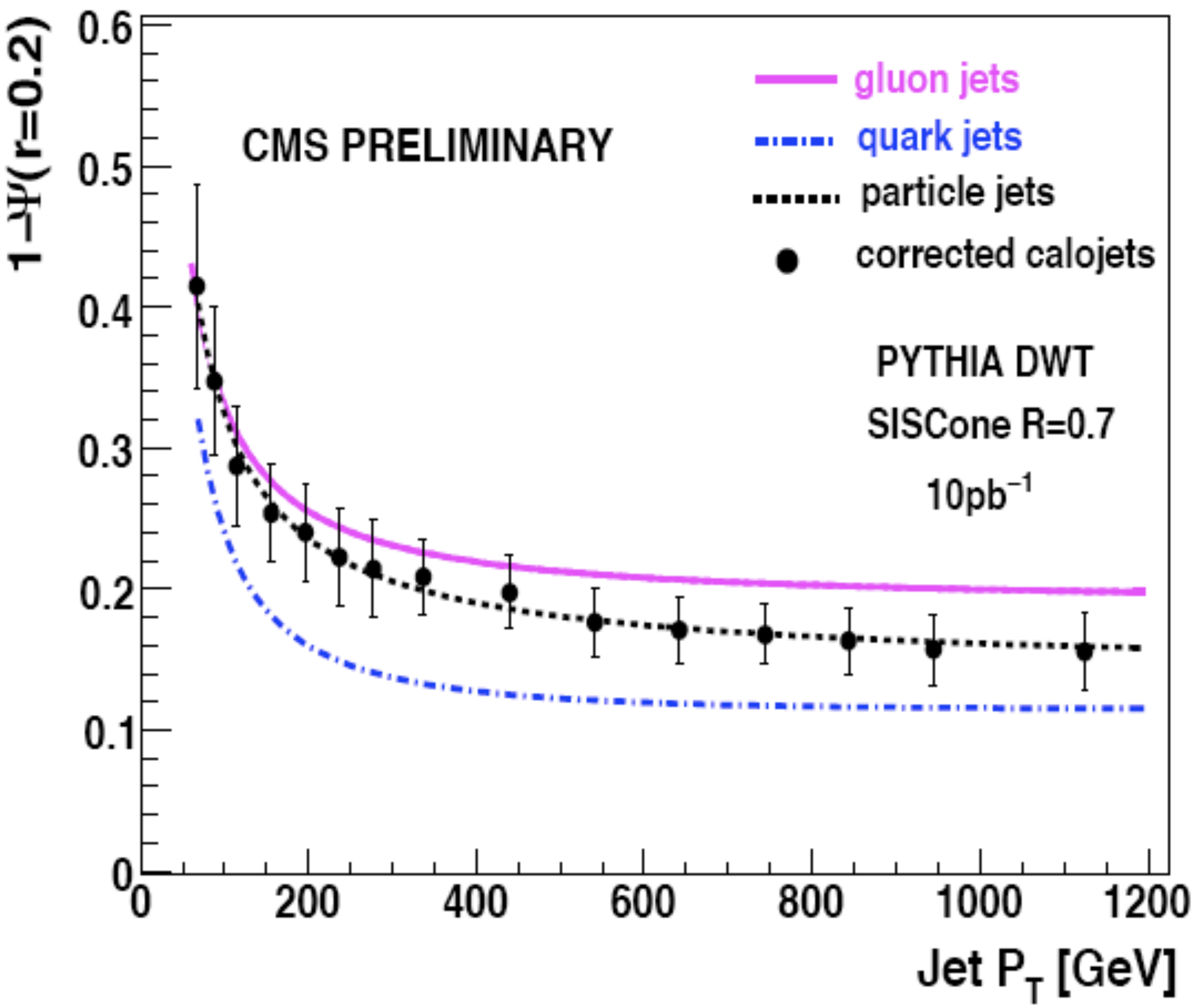

✦ Measurement of the energy flow inside jets.
✦ Jet structure measurements can be used to test the showering models in the MC generators.
✦ Can be used to distinguish gluon originated jets from quark jets.

Summary

✦ Jet final states are important both for understanding the detectors' performance and for the "re-discovery" of the Standard Model at the LHC experiments.

✦ Jets can be reconstructed with many types of algorithms and detector inputs. The experiments are strongly supporting the theoretically sound algorithms.

✦ Different jet definitions are optimal for different analyses. No single jet definition can be optimal for 3 orders of magnitude in transverse momentum. At low p_T, the combination of multiple detector information (e.g. tracker and calorimeter) seems to be more appropriate. At high p_T, the performance of the calorimeters is superior.

✦ The most challenging task related to jets is the establishment of the energy scale. This can be achieved through "in-situ" measurements and careful tuning of the simulation.

✦ The numerous preliminary MC studies and the Tevatron experience give us confidence that we can achieve the commissioning of jets in LHC. That needs to be proven however in the real collision environment.