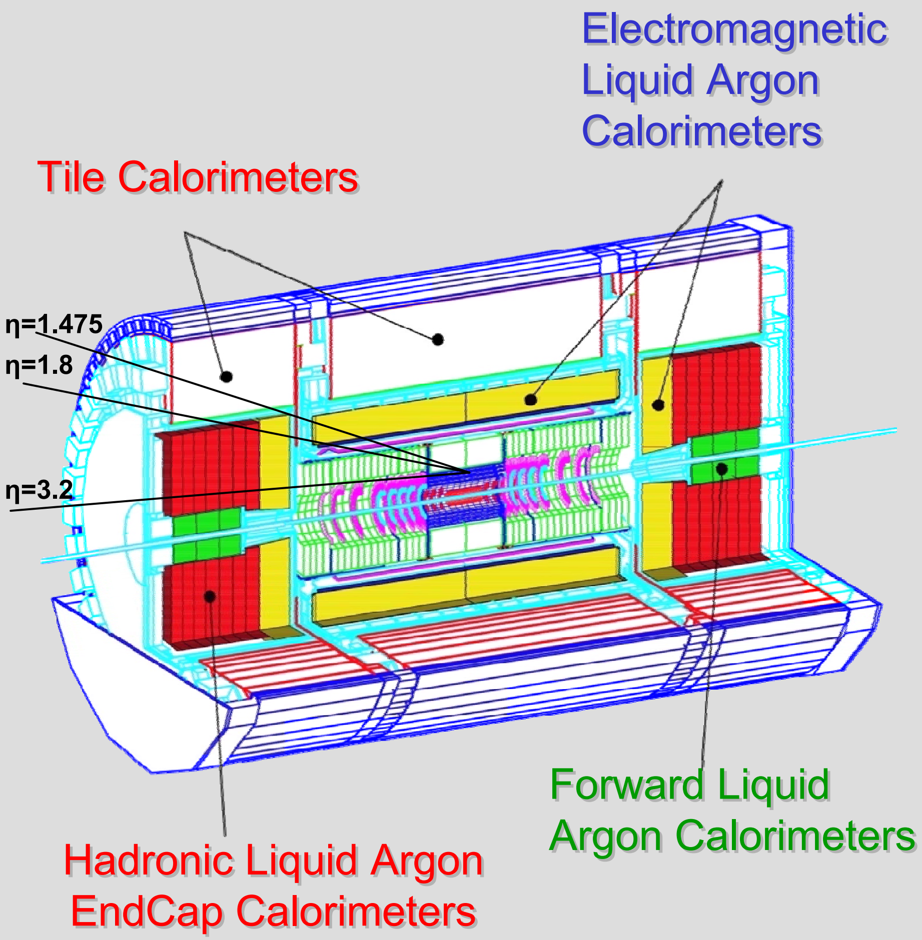
# Overview of Jet measurement at ATLAS

- Calorimeters of  ATLAS Jet reconstruction
- Jet energy measurement
- In situ energy calibration
- Conclusions

# The ATLAS calorimeter

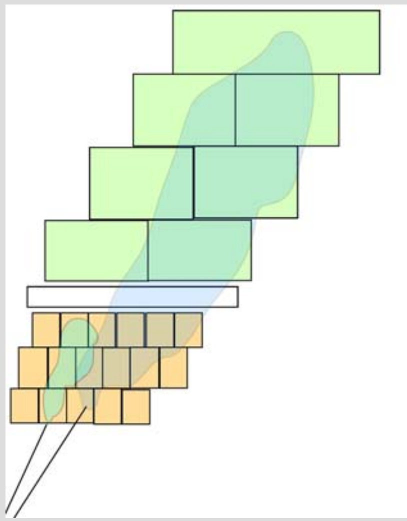



**EM accordion** 3 long. sections

**Central Hadronic** 3 long. sections

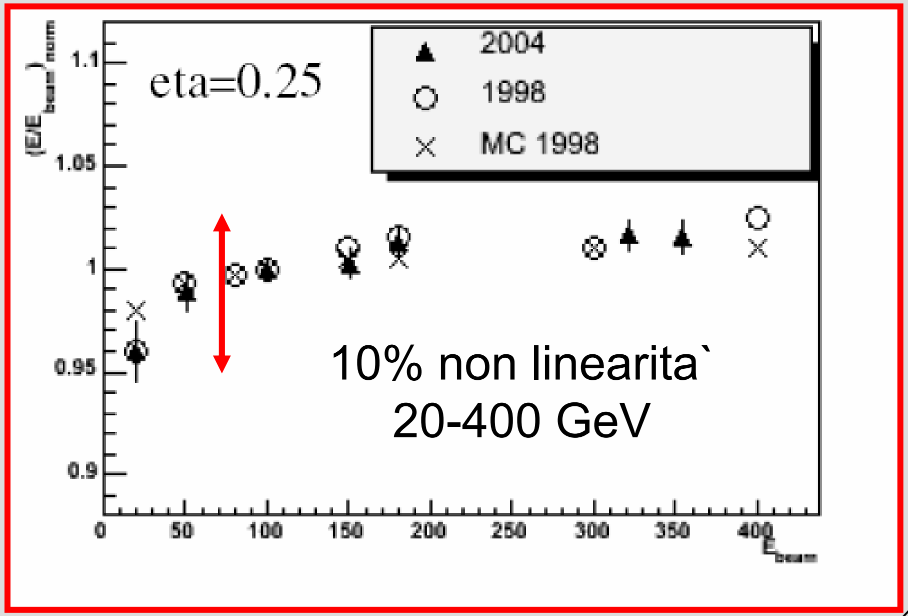
**End Cap Hadronic** 4 long. sections

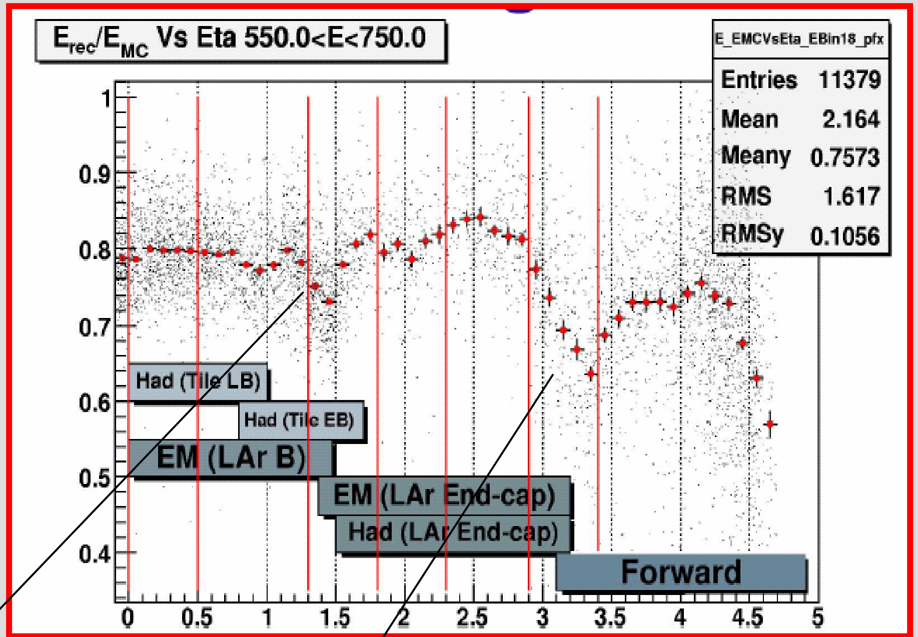
**Forward calorimeter** 3 long. sections

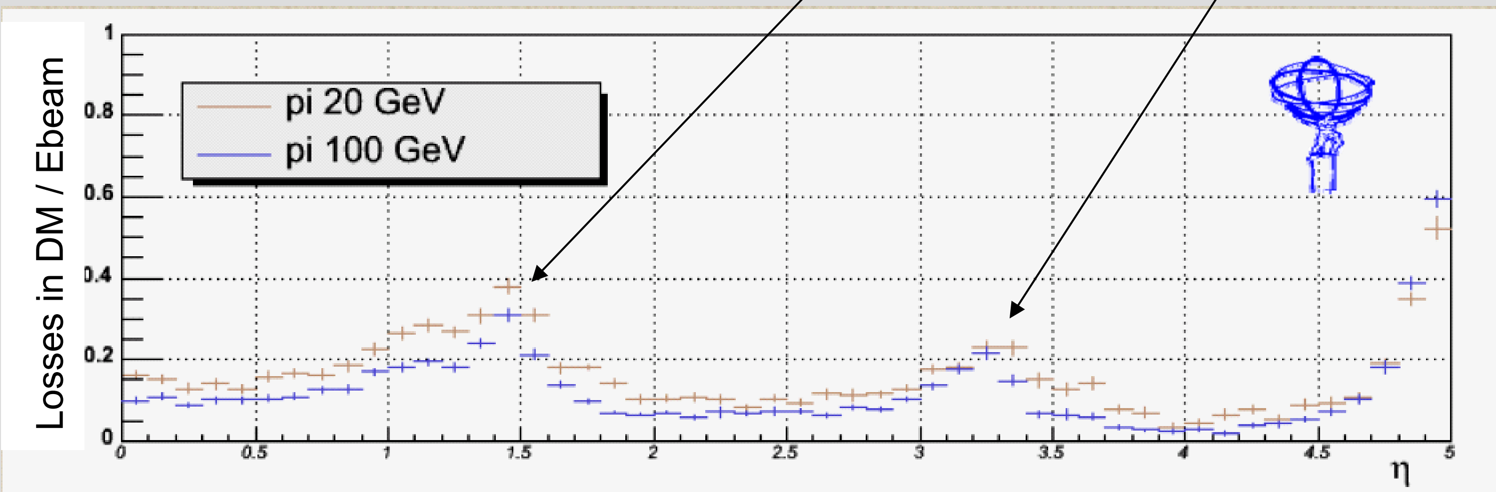


Fine longitudinal and lateral segmentation. Fundamental for recovering compensation.

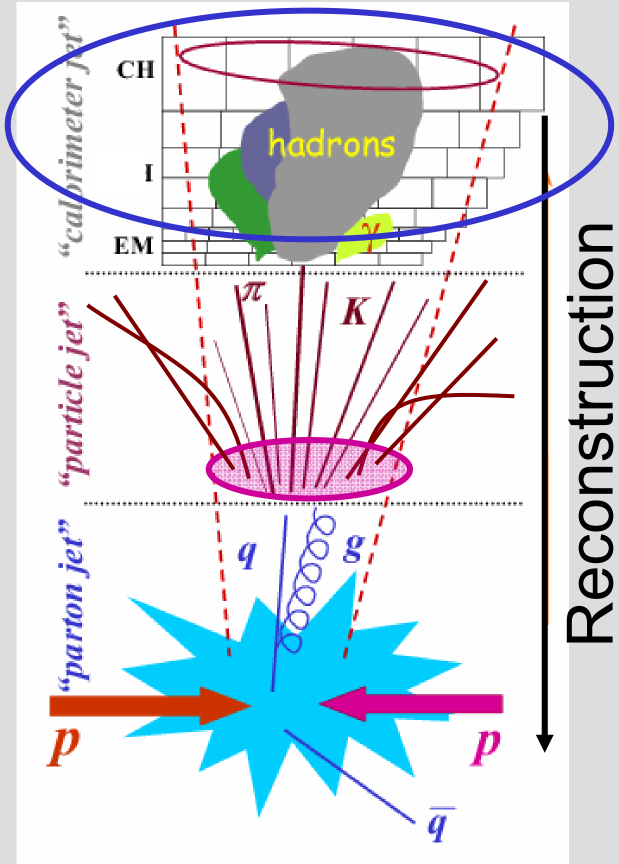
# Detector effects: e/h and cracks



# Jet reconstruction phase 1: the calorimeter jet




The cell energy deposits are clusterized to obtain the base objects for jet reconstruction.

Noise (electronic noise and pile-up) suppression algorithms are applied at this stage

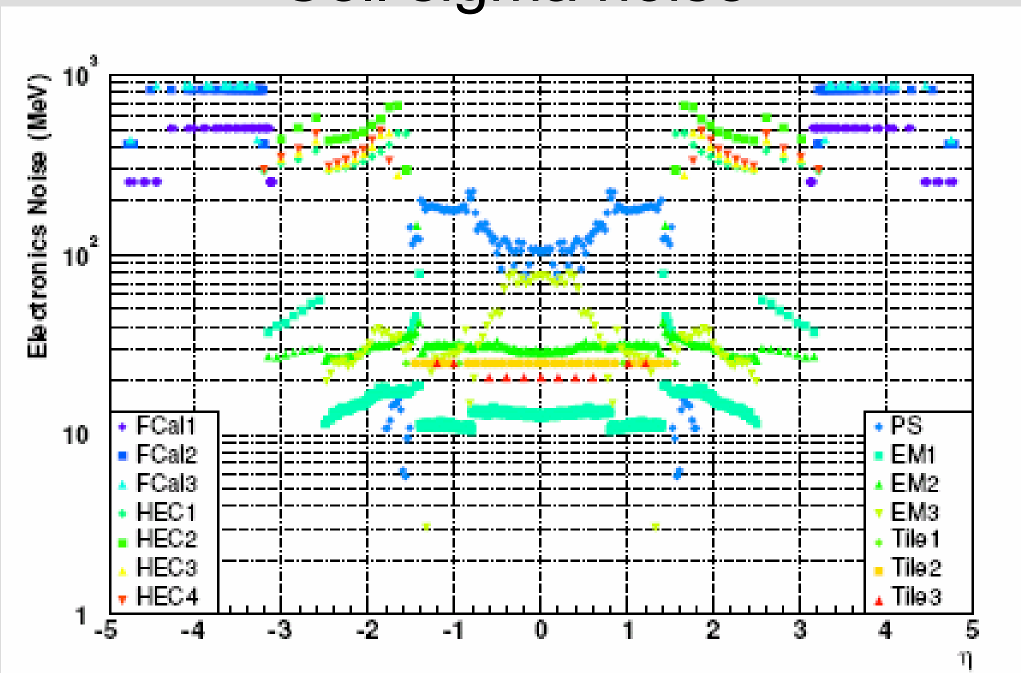
Jet reconstruction algorithms are applied and recombination scheme is used to obtain jet kinematics

# Cell energy clusterization

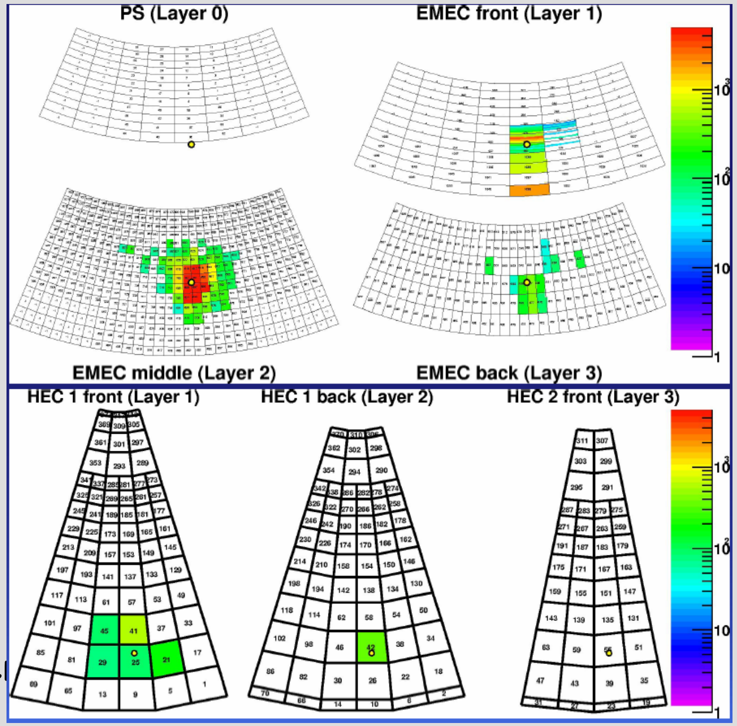
Two objects may be used as input for the jet reconstruction algorithms:

- Calorimeter Towers of dimension $\Delta\eta\times\Delta\varphi = 0.1 \times 0.1$
- 3D Energy blobs – Topological Clusters: 3 levels of $E/\sigma$ thresholds are used for seed cells – neighbour cells - final expansion (4-2-0)
- TopoClusters give a better noise suppression

Cell sigma noise




Cluster for 120 GeV pion in EMEC and HEC (2002 Test Beam data)



# Jet reconstruction algorithms

## Iterative cone

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

| | $\Delta$R | $E_T$seed | $\Delta$S |
|---|---|---|---|
| ATLAS | 0.7/0.4 | 2 GeV | 50% |
| CMS | 0.5 | 2 GeV | - |

Split and merge procedure ($\Delta$S) for ATLAS

CMS exclude jet algorithm input objects as soon as they belong to a built jet

E Recombination scheme: 4 vector sum of object components to obtain jet kinematics

Cone algorithm is the most widely used for physics analysis in ATLAS up to recently: cone 0.4 for top physics and cone 0.7 for all other analysis.

Calibrations are tuned on cone 0.7 jets.

In last year a lot of activity has started also on other jet algorithms.

# Jet reconstruction algorithms

## Midpoint Algorithm

Implementation based on CDF approach.

0 Seed Et > 2 GeV

1 Cone precluster with radius 0.5x$\Delta$R

2 Add midpoints if preclusters i,j are separated < 2 x$\Delta$R

3 Cone jets of radius $\Delta$R are searched

4 Merge if >50% of $p_T$ of lowest jet is shared, else split

## $K_T$ algorithm

Preclusters objects with $\Delta R<0.2$

For each object i of transverse impulse $k_T$ calculate:

$$d = \begin{cases} d_{ii} = k_{T,i}^2 \\ d_{ij} = \min(k_{T,i}^2, k_{T,j}^2)\dfrac{\Delta R_{ij}^2}{D^2} \end{cases}$$

If $d_{min} = d_{ii}$ $\Rightarrow$ jet

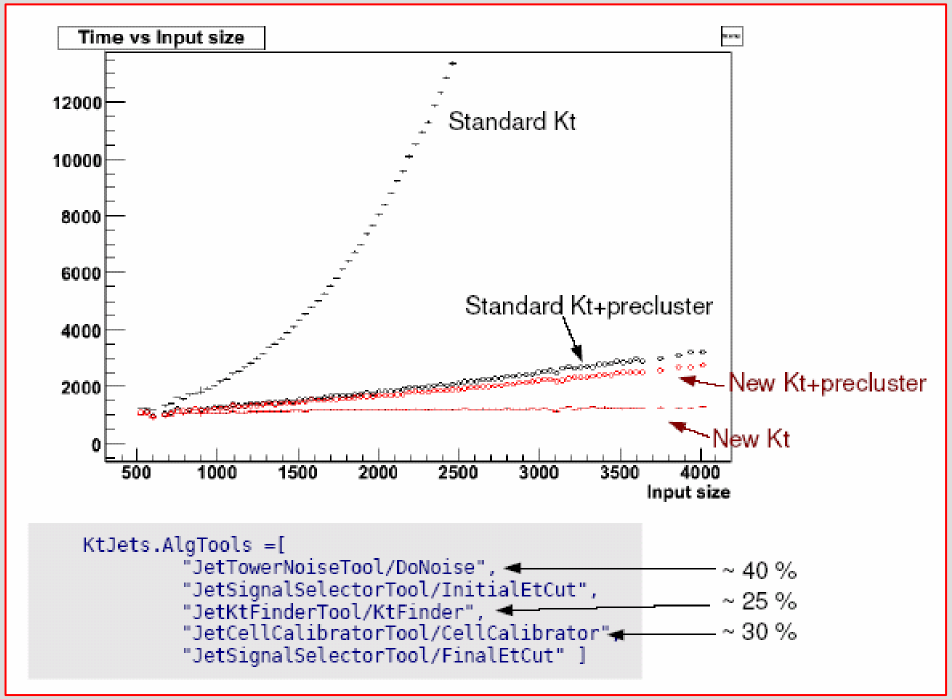
else if $d_{min} = d_{ij}$ $\Rightarrow$ ij (4-vector sum) in a new $d_{ii}$

D = 1 is default – more later

E Recombination scheme: 4 vector sum of object components to obtain jet kinematics

# Fast $K_T$

- KT algorithms are typically slow since speed scales with $O(N^3)$
- It has been shown that they can be made faster by using nearest neighbour information (Cacciari, Salam hep-ph/0512210)
- FastKT has been implemented in ATLAS and it also allows to skip the preclustering phase.



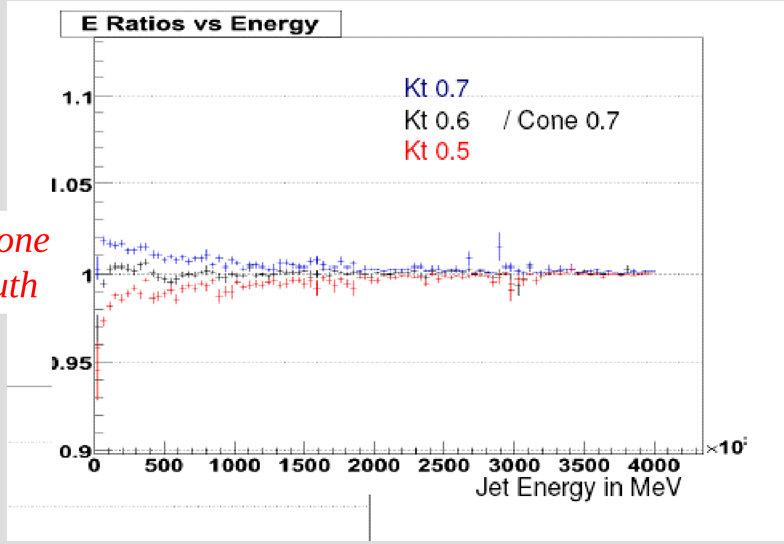
# Choice of jet algorithm and parameters

What is the best way to choose a jet algorithm for my analysis and the value of jet algorithm parameters ?

Some examples from what has been done in ATLAS.

Look at MC particles jets reconstructed with Cone and Kt and compare the reconstructed energy.

$$E_{truth}^{KT} \,/\, E_{truth}^{Cone}$$




With this "recepy" we obtain:

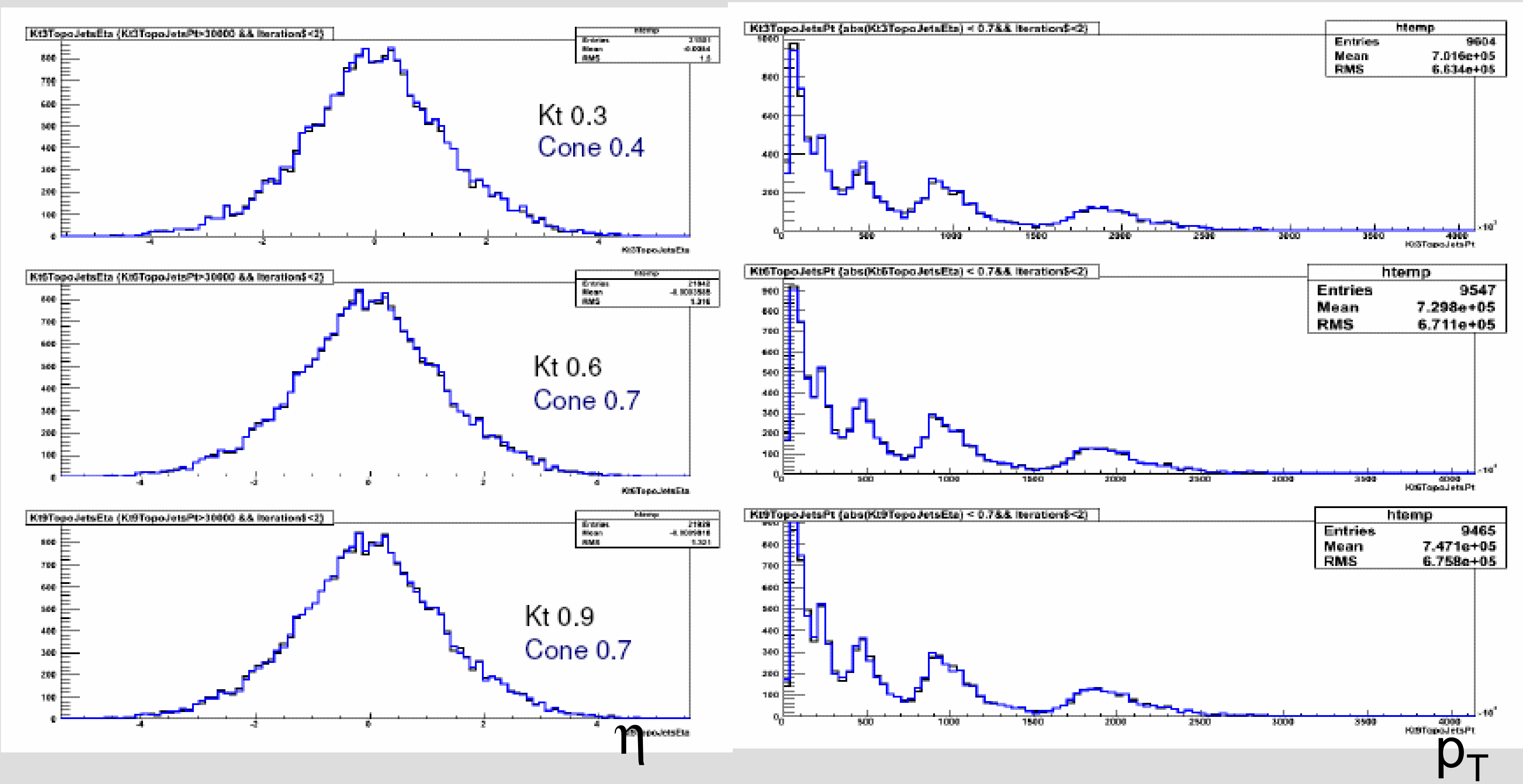
D = 0.6 for Cone 0.7
D = 0.3 for Cone 0.4

In Ellis-Soper article (PRD 48, 3160–3166 (1993)) in order to have the same inclusive one-jet cross section dependance on renormalization and factorization scale for cone KT indicates D=1.35x$\Delta$R

Are these two results inconsistent ?

# Cone vs $K_T$

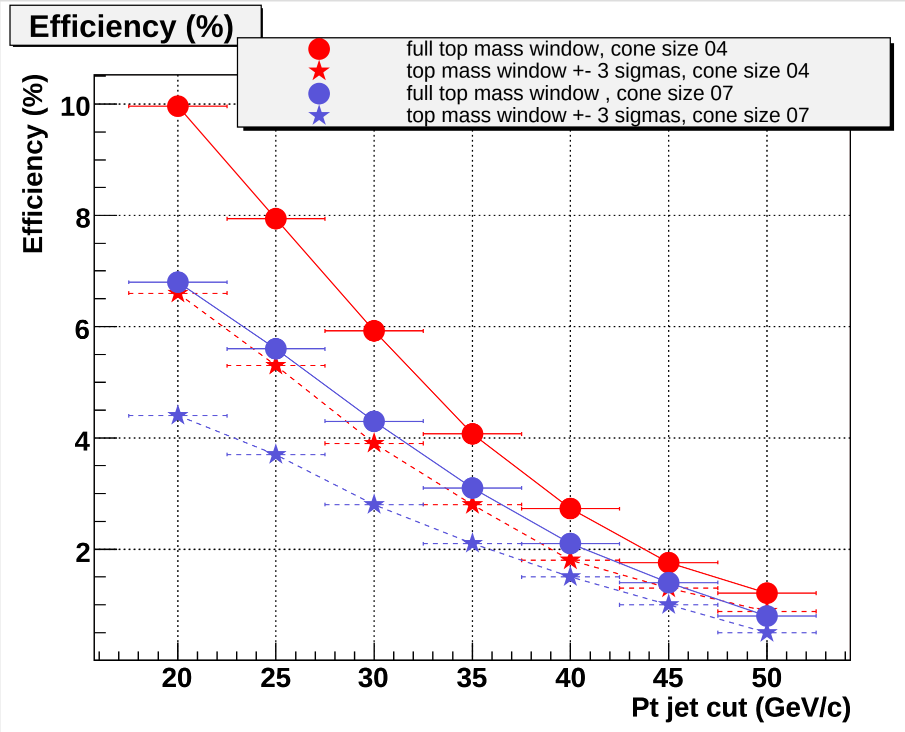
Looking at the 2 highest pt jet

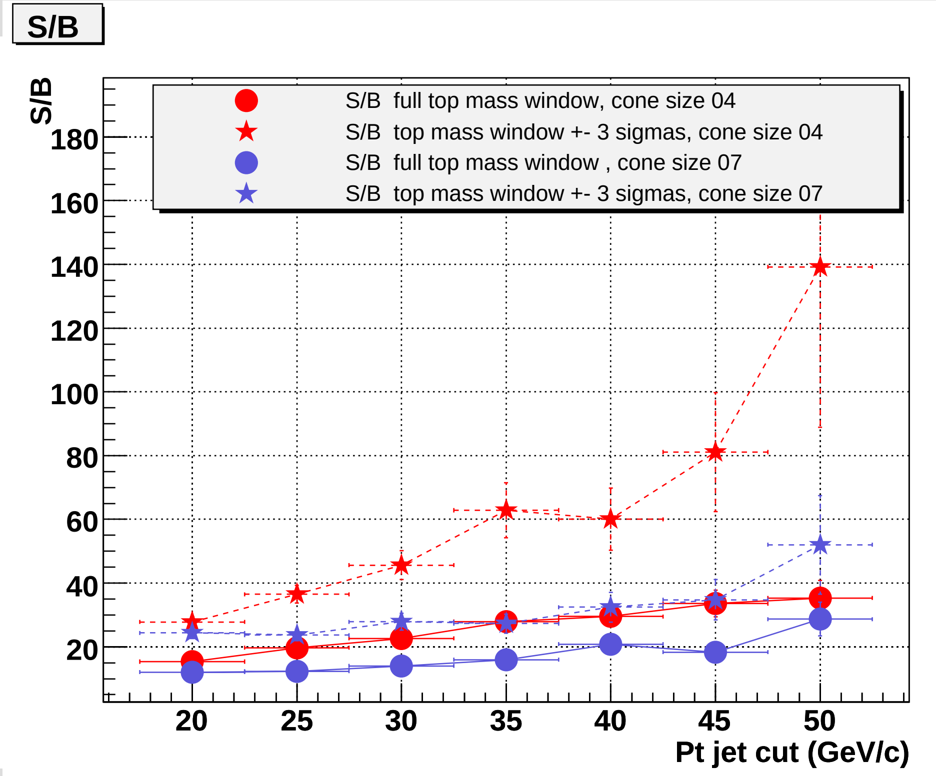


# Tuning cone algorithm on top events

Studied for top mass measurement in lnb jjb channel
Looked at efficiency, S/B, W and top « purity » (correct jets taken)

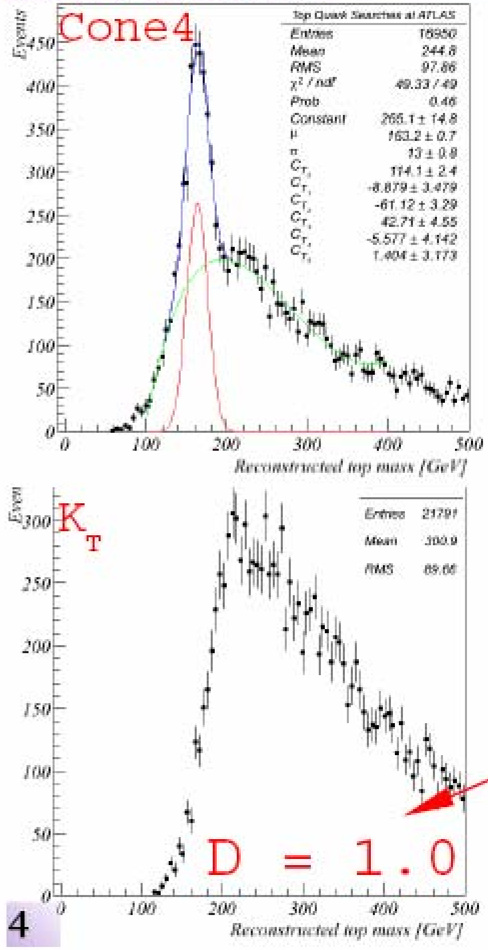
→ Cone 0.4 (much) better than cone 0.7



# Tuning KT algorithm on top data

## Introduction




**$K_T$ ALGORITHM (inclusive)**

Ellis & Soper, PRD48, 3160, (1993)

Start from a set of objects:

$\{p_1, p_2, \ldots, p_i, p_j, \ldots, p_n\}$

For each object pair ij:

Define $d_i$ and $d_{ij}$ in the $\Delta R$ scheme:

$d_i = (p_{T_i})^2$

$d_{ij} = \mathrm{Min}((p_{T_i})^2, (p_{T_j})^2) * \Delta R_{ij}^2 / \mathbf{D}^2$

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

if $d_{ij} < d_i$, merge objects i and j:

by several recombination schemes

($E$, $p_t$, $p_t^2$, $E_t$ or $E_t^2$).

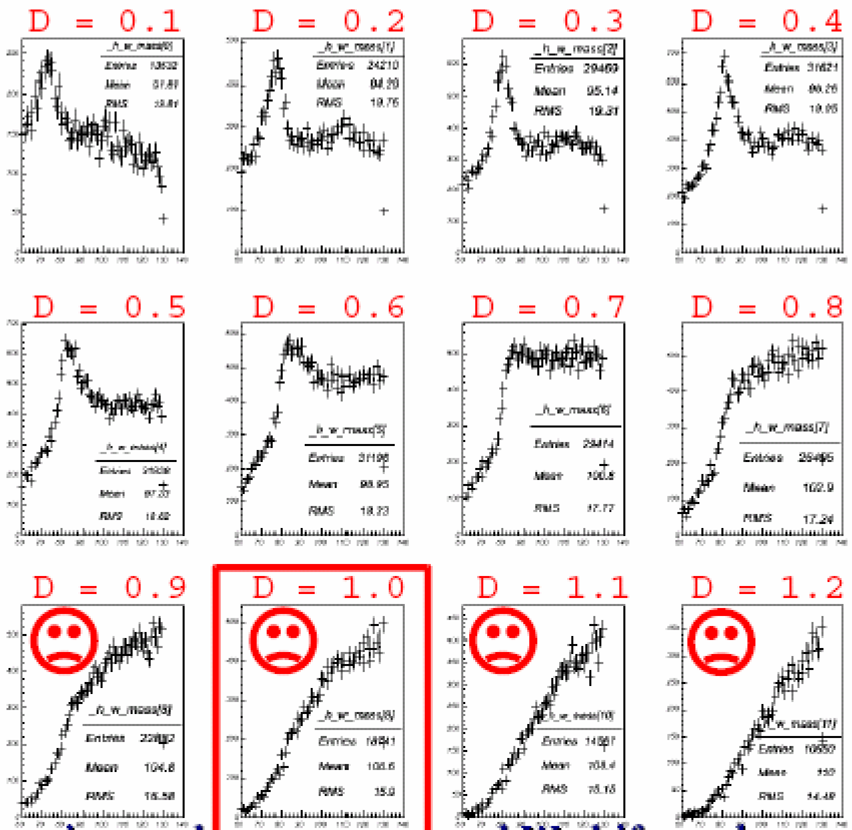
For instance, the E scheme:

$p_{ij} = p_i + p_j$

if $d_i < d_{ij}$, object i is a jet

# Tunining the KT algorithm

*W mass reconstruction: e.g. ΔR , E scheme [Default]*




**Increasing D, the reconstructed W shifts to larger mass values, but D should not be too large...**

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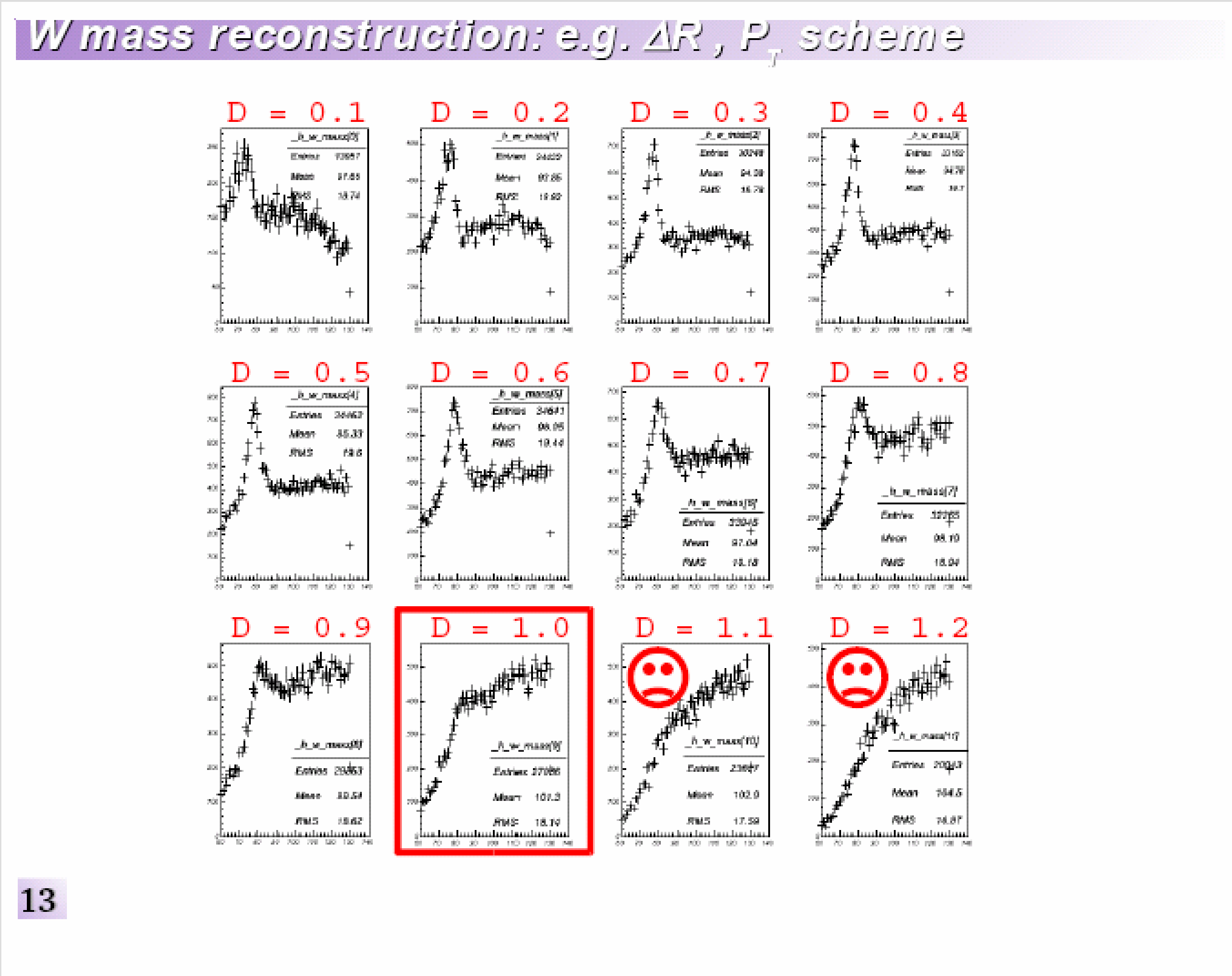
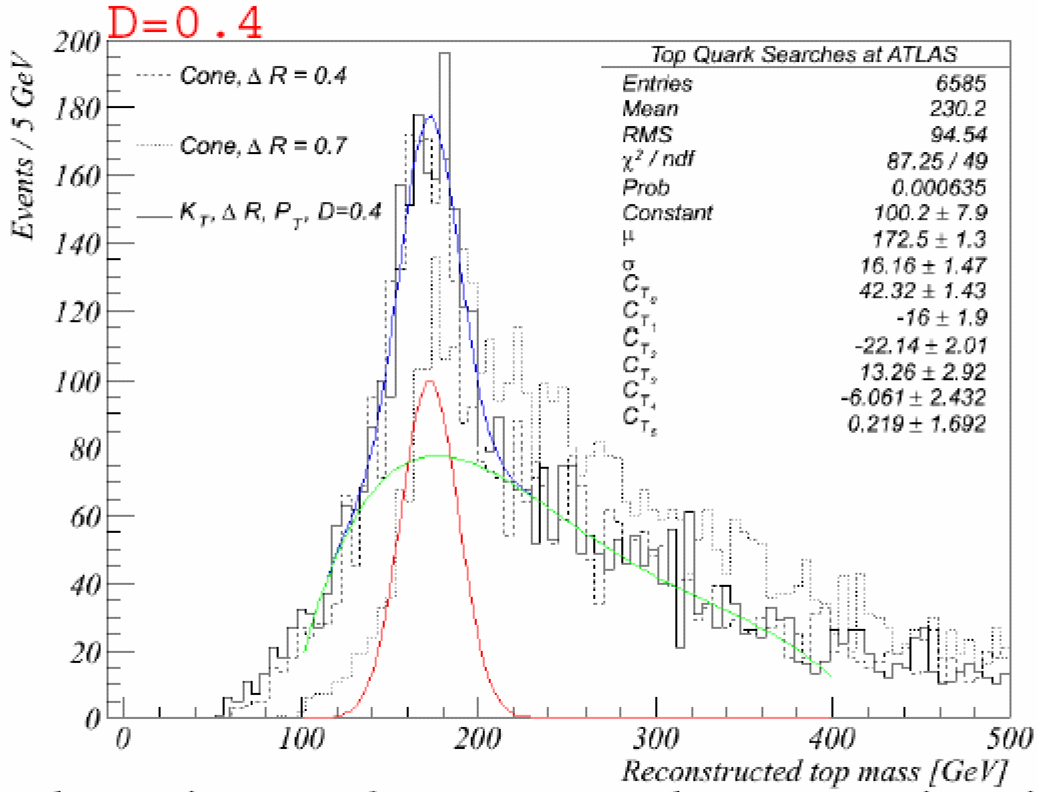
# Which recombination scheme…



# W mass with tuned KT

**T1- 4100: full simulation using ΔR , $P_T$ scheme**



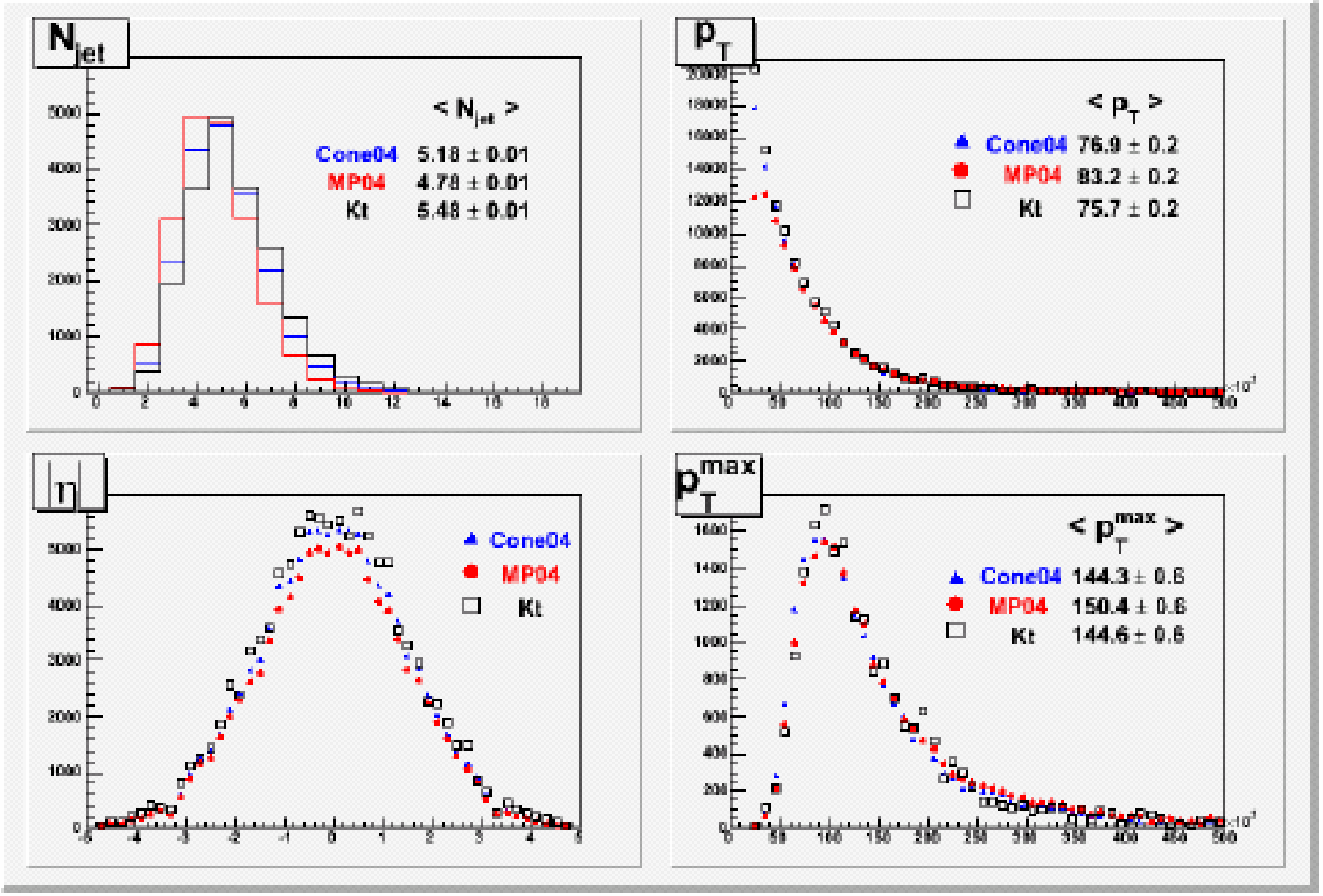

**Clearly, we improve the top mass peak reconstruction with a reasonable D value of the $K_T$ algorithm.**

# Midpoint first comparison

Cone 0.4

Midpoint 0.4

KT 0.45

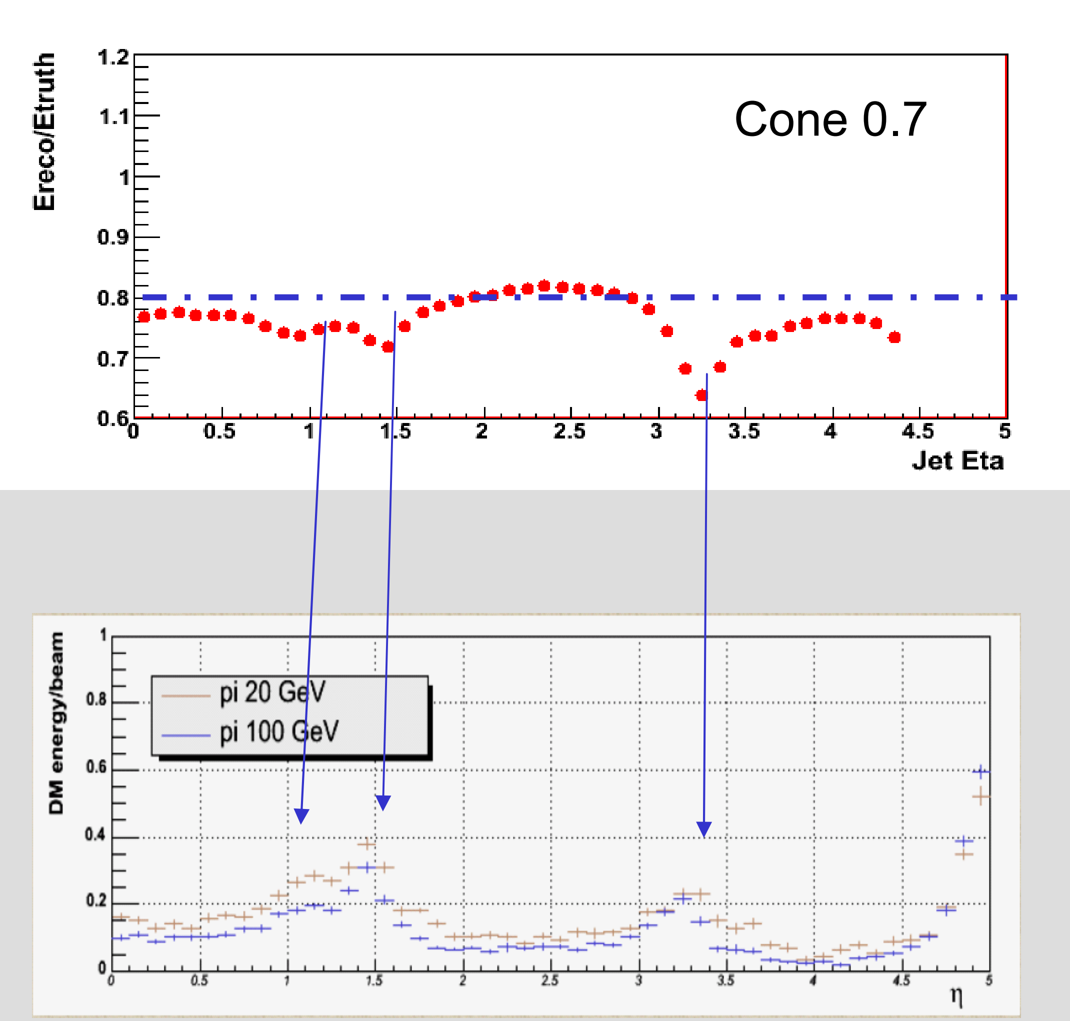



- *Excess of low-pT jets (20 GeV<pT< 50 GeV) for Cone and Kt*
- *MidPoint tends to merge low-pT jets*

# Choosing and tuning

- Various methods to tune the favorite algorithm
- Proliferation of jet collections, we need to find a well defined path to make the choice and to define the parameter tuning
- Calibration and UE, pileup subtraction will have to be understood in detail and it will not be straightforward to generalize it to any clustering algorithm
- So a deciding on benchmark jet clustering would help a lot since
- Now we go to calibration …

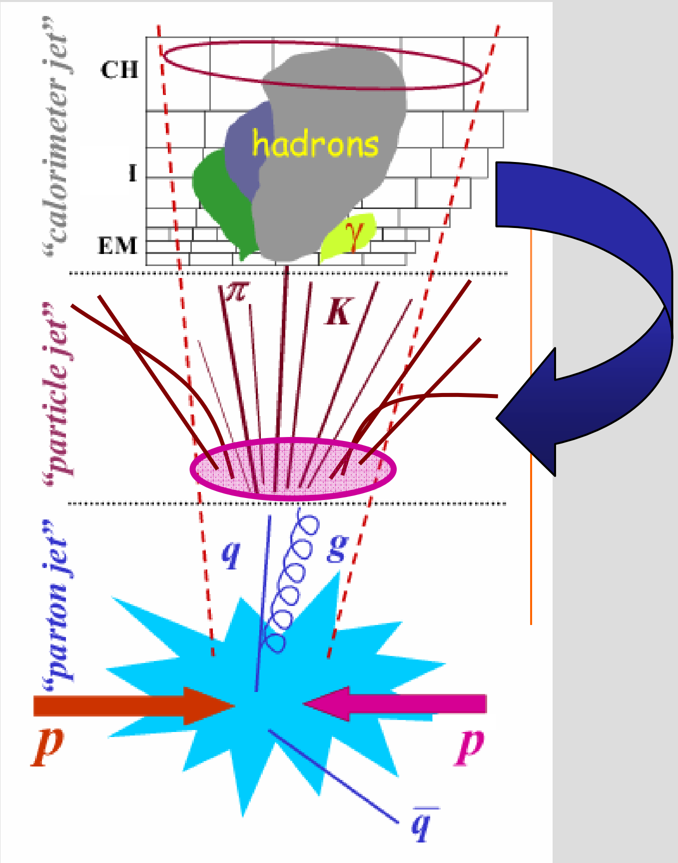
# Uncalibrated reconstructed Jets:detector effects at work…




Detector effects are clearly seen on E_reconstructed/E_truth:

Cracks, e/h, B field (tracks with pT< 350 MeV do not reach the calorimeter)

# Phase 2: calibrating to the particle jet




Phase 2 : the detector effects are corrected calibrating the reconstructed jet to the particle jet

Truth:

- Particle Jets are reconstructed applying jet algorithm to stable particles (excluding neutrinos and muons) and are matched to Calorimeter Jet (ATLAS)
- All particle falling in the angular region of calorimeter jet (only for cone) (ATLAS)

Both truths contain the particles swept off from B field:

ATLAS $p_T$<350 MeV

# Calibrating to Particle Jet

2 step procedure

1. Calibrated energy is calculated as:

$$E_{Raw} = \sum_s Ecell_s$$

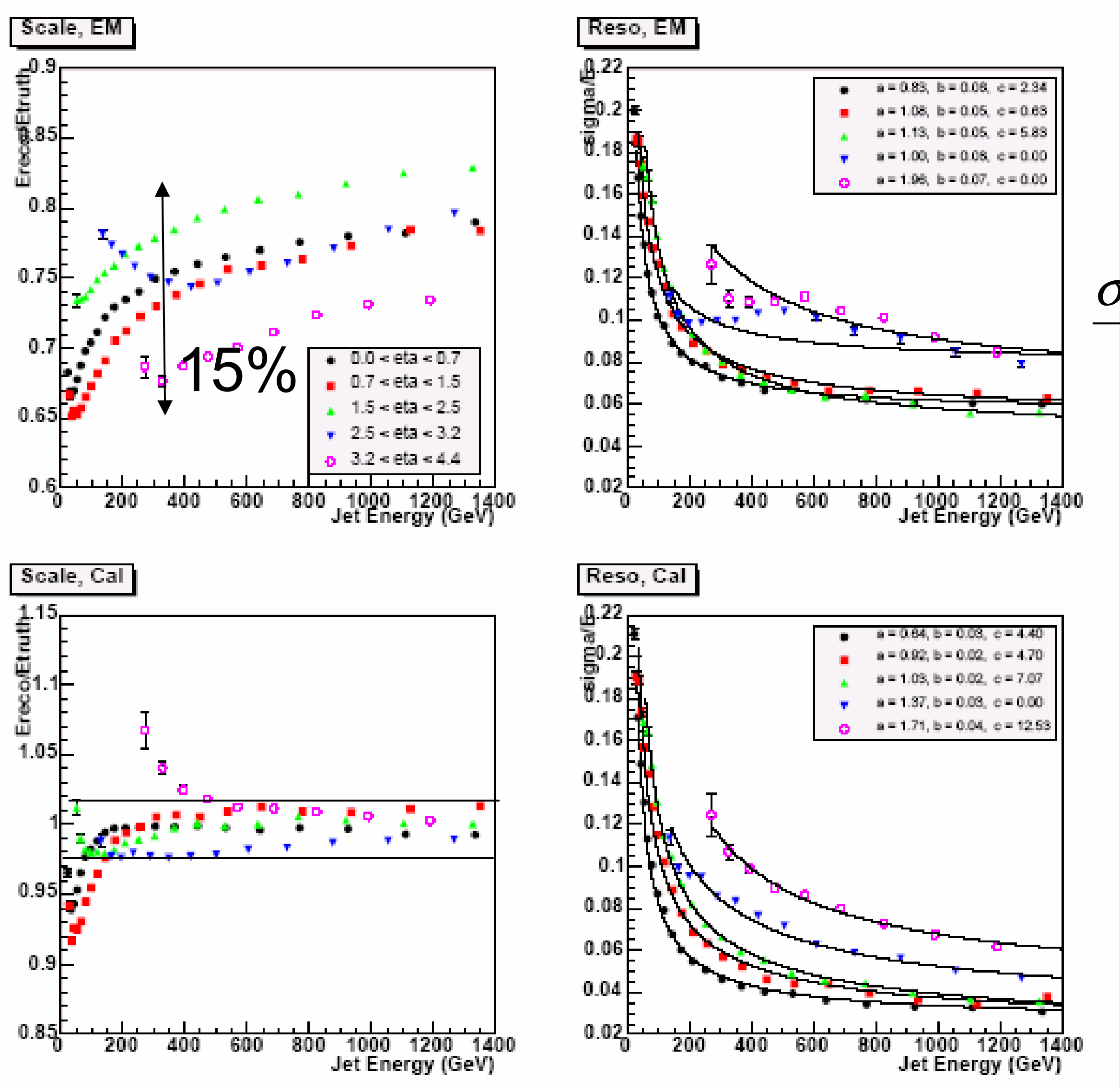
$$E_{Rec} = \sum_s w(Ecell, CellPosition)Ecell_s$$

} Cell weighting

the *w(Ecell,CellPosition)* coefficients are obtained by minimizing the energy resolution to the MC truth with the linearity constraint. Same weights are used for different algorithms.

2. A factor $R(E_T,\eta) = E_T rec/E_T MC$ is applied to correct for residual non linearities and for algorithm effects.

# From the Calorimeter jet to the Particle Jet




QCD – 0.7 cone jet built from calorimeter towers

Uncalibrated $|\eta|<0.7$

$$\frac{\sigma(E)}{E} = \frac{0.83}{\sqrt{E(GeV)}} \oplus 0.05 \oplus \frac{2.3}{E(GeV)}$$

Calibrated $|\eta|<0.7$

$$\frac{\sigma(E)}{E} = \frac{0.67}{\sqrt{E(GeV)}} \oplus 0.02 \oplus \frac{4.4}{E(GeV)}$$

Linearity ±2% $E_T$>20 GeV

However changing the jet algorithms requires new tuning of calibration….what we are trying to do to generalize the calibration approach

# Local hadron calibration

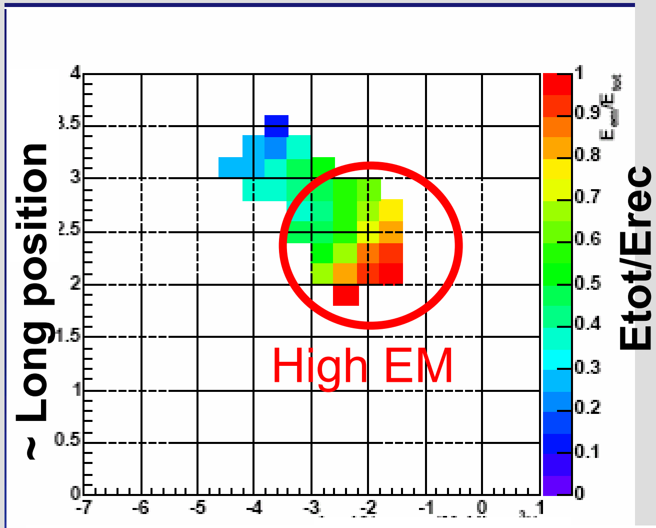
The aim is to Calibrate the TopoClusters before reconstructing the jets. The calibration is based on MC information: for each cell EM energy, Escaped energy, Invisible energy, Non EM energy.

This information are used to:

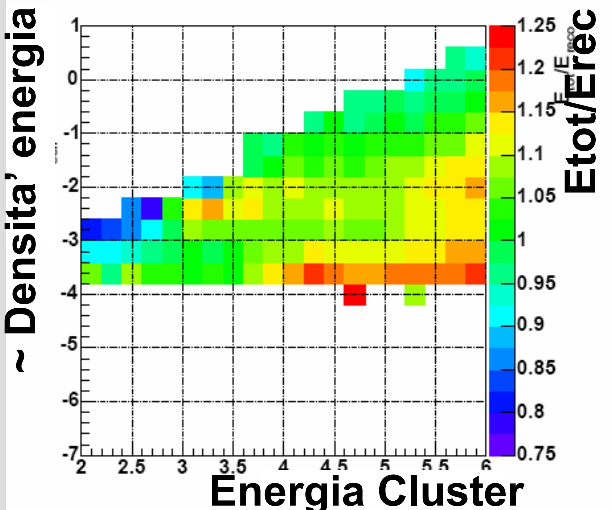
1 – Classify the calorimetric deposit: EM not weighted, NonEM to be weighted

2 – Calbration: topoclusters characteristics are used to define the calibration weights

3 – Dead Material Correction



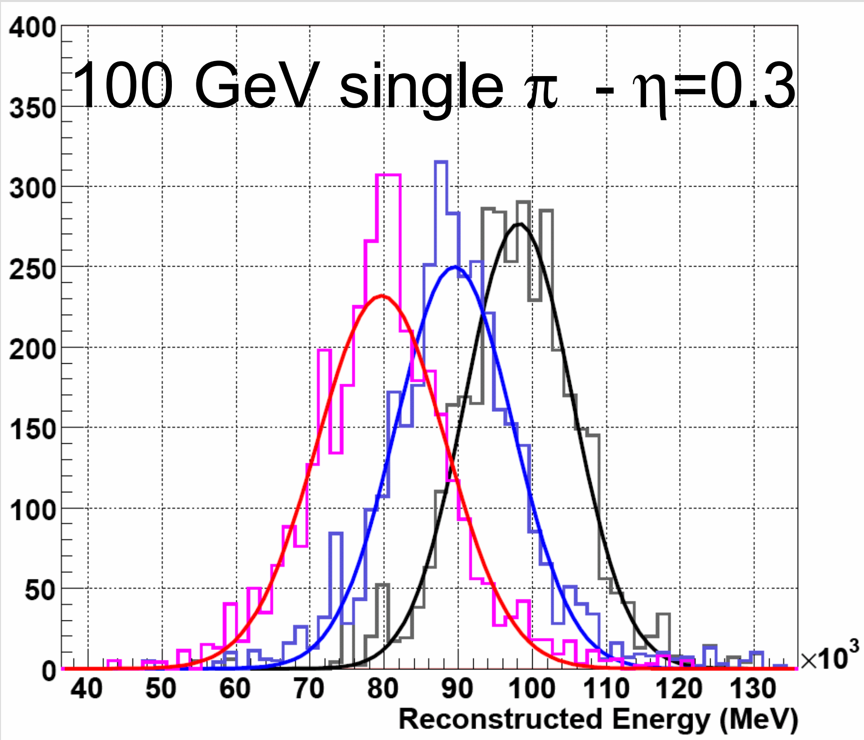

~ energy weighted cell density



# Local Hadron Calibration

Example of how the three step works on single pions: TopoCluster classification (EM or not); weighting to correct e/h; dead material correction

F.Spano talk at Overview week




EM scale
Classified + Weighted
Classified +Weighted +Dead Material corr.

Linearity is recovered and resolution is comparable to what we obtain with different methods

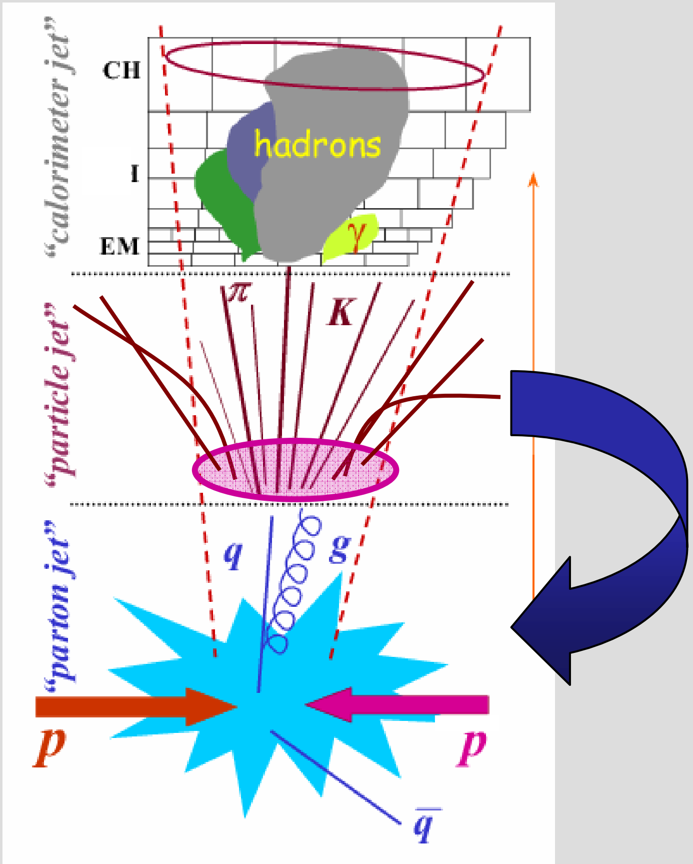
# Local calibration

Local calibration would allow to:

- better understand the contribution of each factor to calibration, it relies on a deep understanding of our data
- Start jet reconstruction at a calibrated scale
- Obtain reconstructed and calibrated jets with any algorithm. Calibration would include the corrections for e/h and dead material
- Corrections for B swept tracks, out of cone … would be added on top of this calibration

Local calibration is being developed and it still needs testing and validation before being used for physics analysis.

# Phase 3: back to the parton energy




Phase 3: absolute energy measurement of parton energy. Goal precision 1%....

- correct for energy losses out of jet clustering
- correct for energy physics effect such as: underlying event, ISR, FSR

# Back to the parton energy

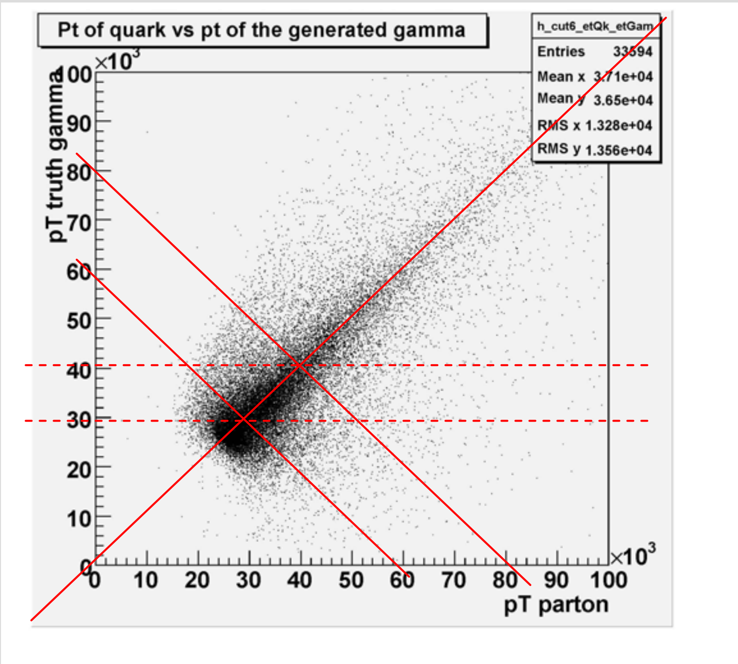
From data sample (in-situ):

- W $\rightarrow$ jj : imposing W mass. Maximum Energy $\approx$ 200 GeV, jet overlapping. Events from ttbar with 1 lepton used to trigger.
- $Z(e^+e^-, \mu^+\mu^-)$ + jet: $p_T$ balance or Etmiss projection method. Useable for light and b jets, about 5% of the total event rate. $p_T$ range ~ 40-400 GeV.
- $\gamma$+j : $p_T$ balance or Etmiss projection method. Higher statistics but high QCD background. More on next slides…

# Calibration using data: Gamma + jet

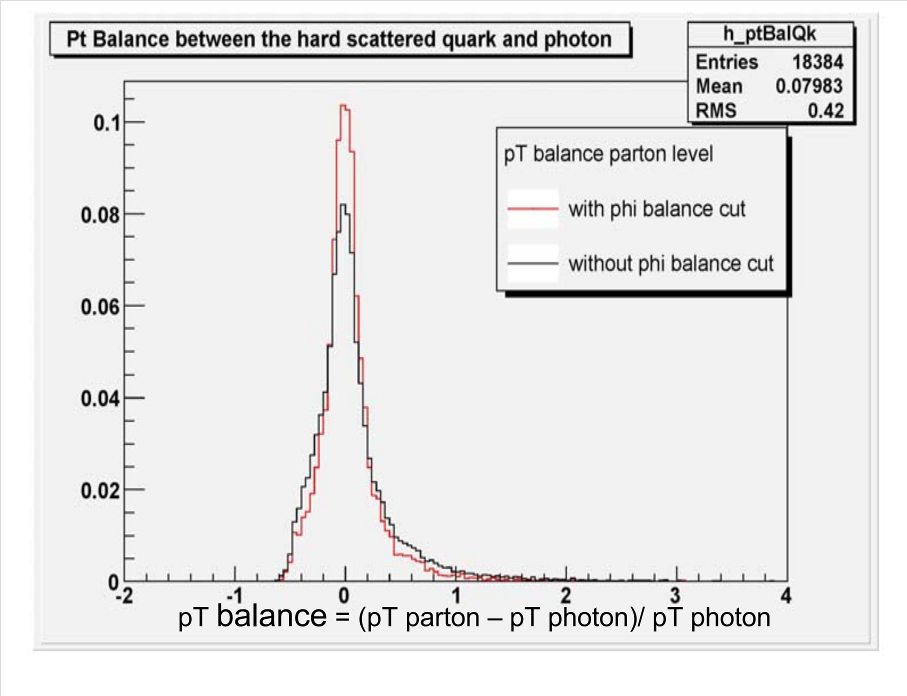
Direct photon production: qg → qγ (90%) qqbar → g γ (10%)

PtJet = PtGamma → kjet = $p_T$Jet/$p_T$ γ




Gamma selection isolation & $E_T$>30 GeV
Select Highest pT jet
apply phi back-to-back cut Δϕ > 175⁰

# Calibration with Gamma+jet events




$$p_T balance = \frac{p_T Jet - p_T Photon}{p_T Photon}$$

Fit peak region iterating a gaussian fit between ±σ around the most probable value

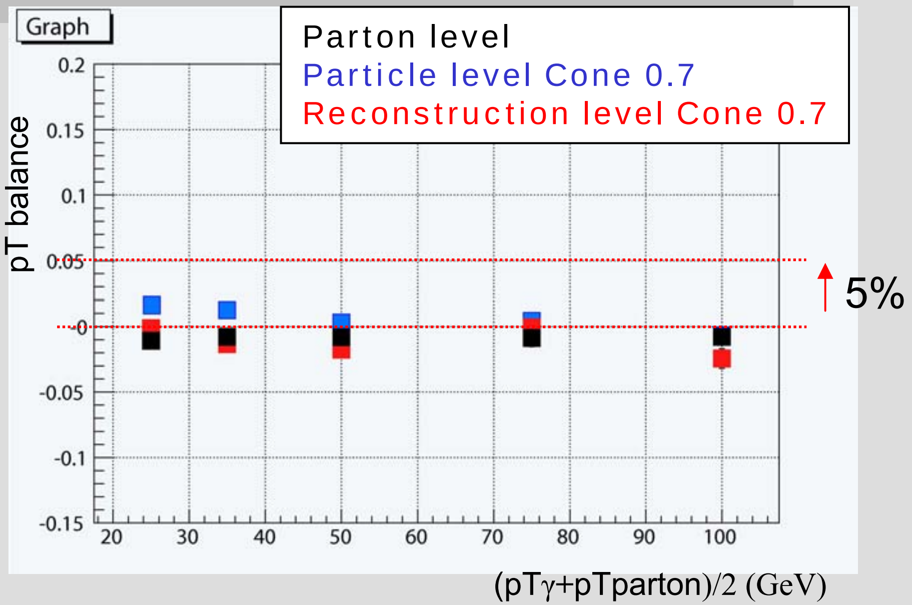
# Calibration using data: Gamma + jet

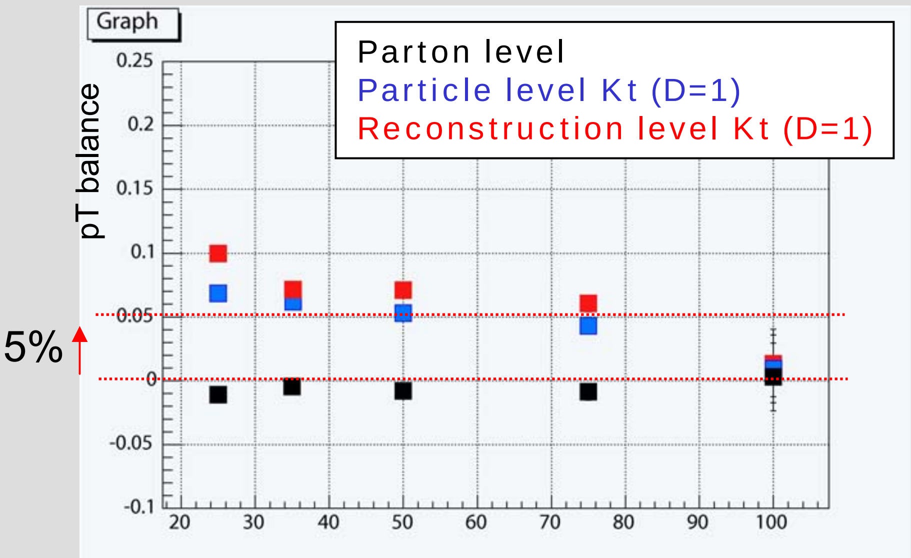
Comparing balance at reconstruction, MC jet and parton level gives indication on:

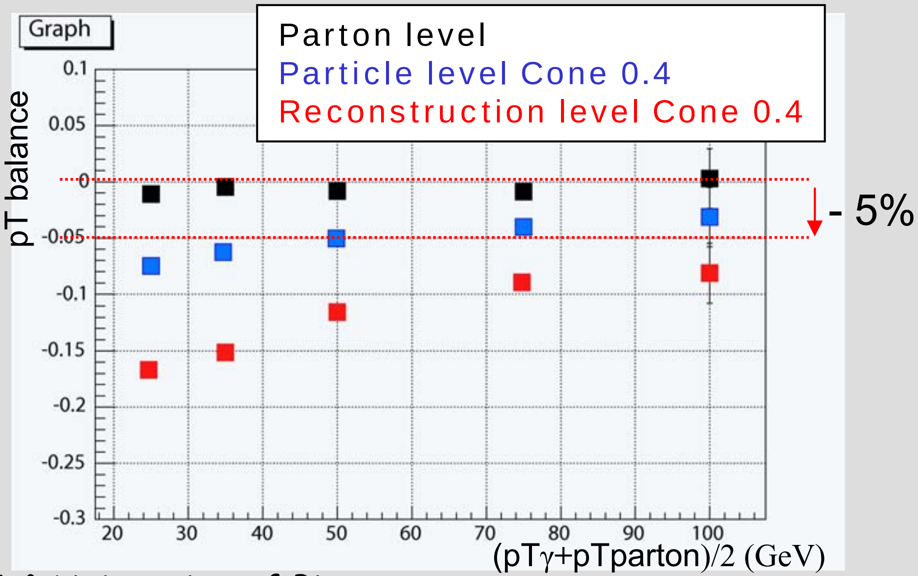
1.calibration biases

2.contribution of UE event, contribution of Out of cone energy, 3. effect of ISR contribution.

More work needed to disentagle UE from Out of cone. Work is in progress.

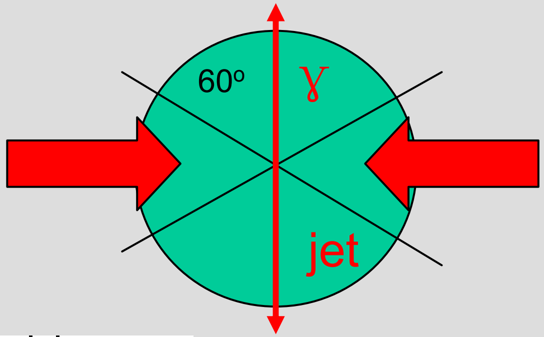


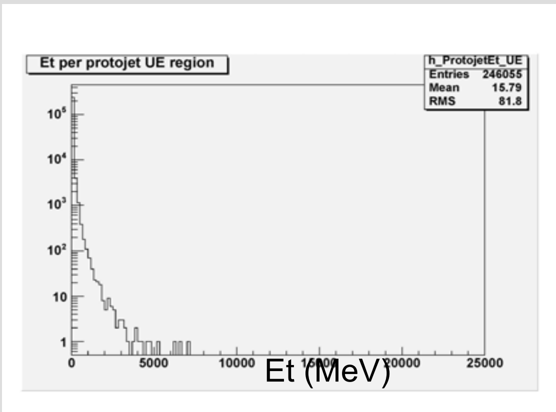
# Estimating the UE event contribution

To find the mean Et for UE, we consider the transverse region of the event: avoiding 60 degrees on both sides of photon and jet

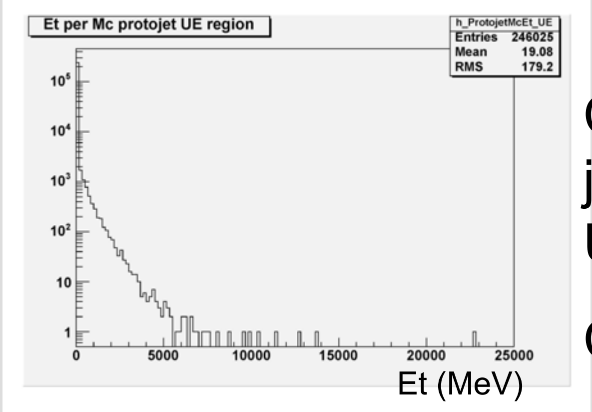



Transverse region

Protojet recon lvl




Protojet particle lvl




Mean transverse energy

| | |
|---|---|
| Recon protojet | 15.8 ± 0.2 MeV |
| Particle protojet | 19.1 ± 0.4 MeV |

Considering the number of jet components we estimate UE contribution to reco jets:

Cone 0.4 - 2.7 GeV

Cone 0.7 – 1.2 GeV

KT (D=1) – 5.1 GeV

Very preliminar results … work in progress.

# A candle for jet energy: top mass

Top at detector commissioning: no b tagging, only calibration for detector effects. Realistic scenario for first data taking phase. Search for ttbar → lnubbjj.

Selection cut:

Etmiss > 20 GeV

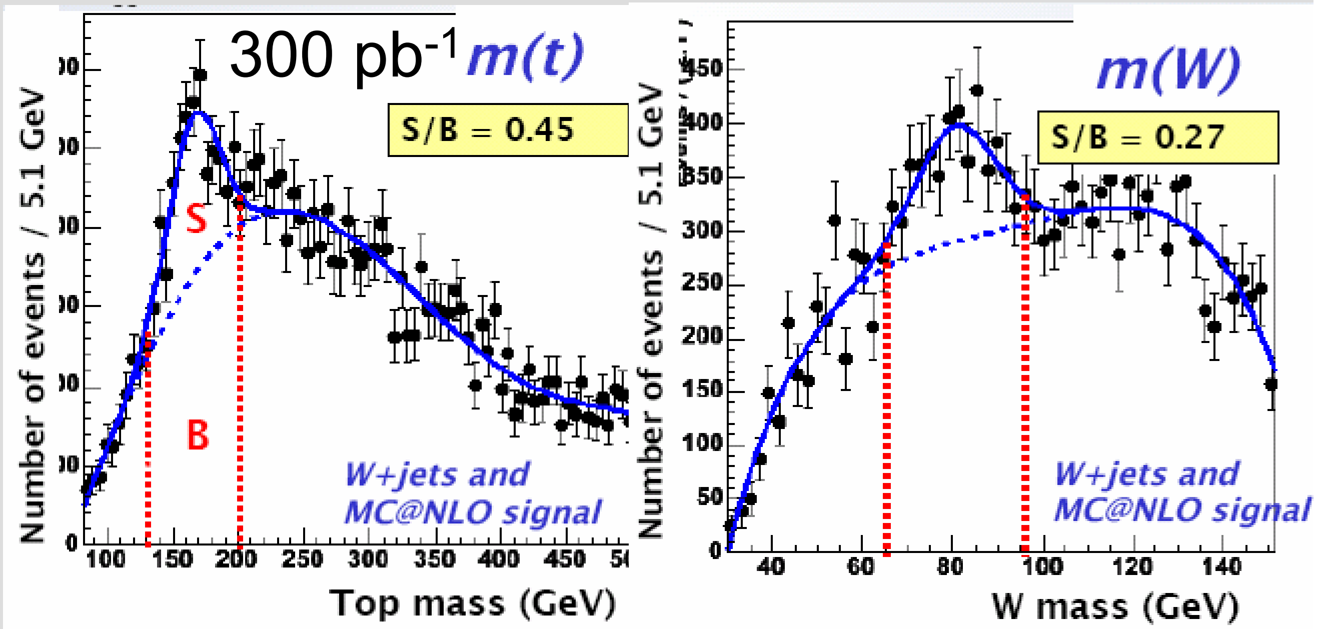
1 lepton $P_T$ > 20 GeV

4 jet $P_T$ > 40 GeV

Reconstruction:

W → jj selection: 2 highest pT jet in CM of jjj

Third jet giving highest pT top




W+4j background increased by three times to consider W+3/5j and uncertainty

Peak and width can be used to understand MC/data agreement and calibration performance

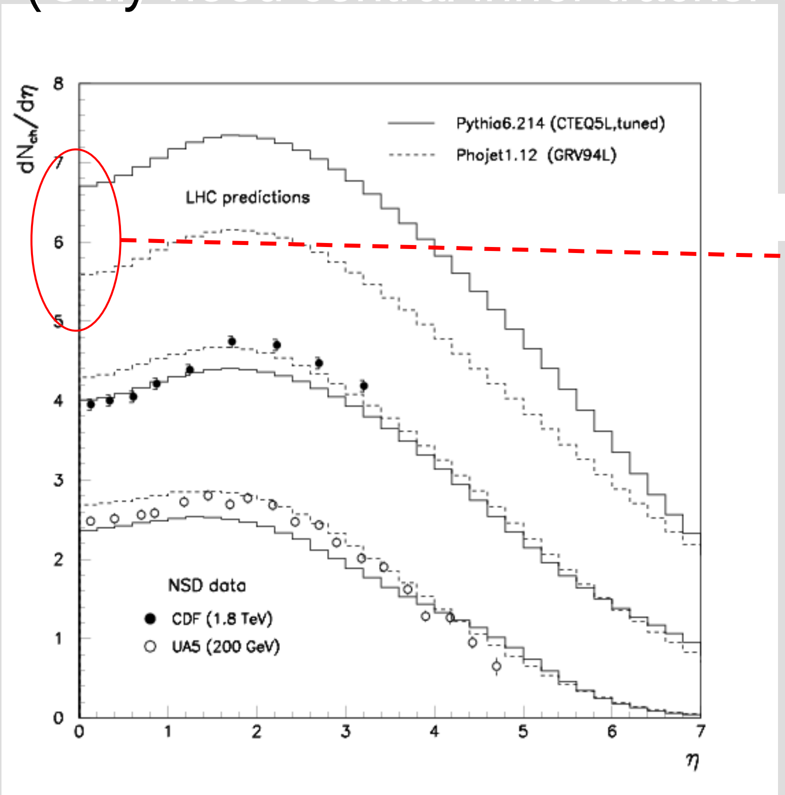
# Summary

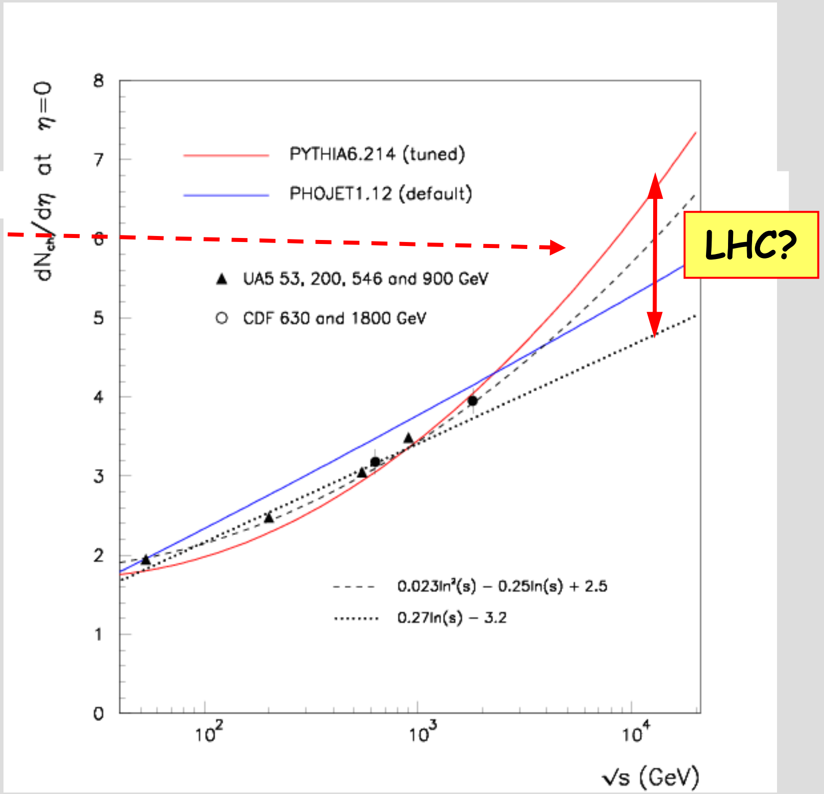
- Cone, KT and midpoint algorithms have been implemented
- They can take as input MC particles, CaloTowers, TopoClusters
- Tuning of various algorithm to various analysis needs is under going
- Calibration to correct for detector effects has been developed and possible alternatives are being studied
- Study on UE and pileup subtraction are just starting (re-starting)
- My personal opinion is that we should at the beginning concentrate on a well defined and justified jet algorithm in order to understand all the issuse about jet reconstruction and energy scale and than we can move to more general scheme.
- Which is the best way to define the jet algorithm to become the benchmark has to be understood.

# Back up slides

# Charged particle density at $\eta = 0$

(Only need central inner tracker and a few thousand pp events)




Multiple interaction model in PHOJET predicts a ln(s) rise in energy dependence. PYTHIA suggests a rise dominated by the $\ln^2(s)$ term.

# The Underlying Event in jet physics

- The underlying event in charged jet evolution:

*Phys. Rev. D, 65 092002 (2002)*

*CDF analysis:*

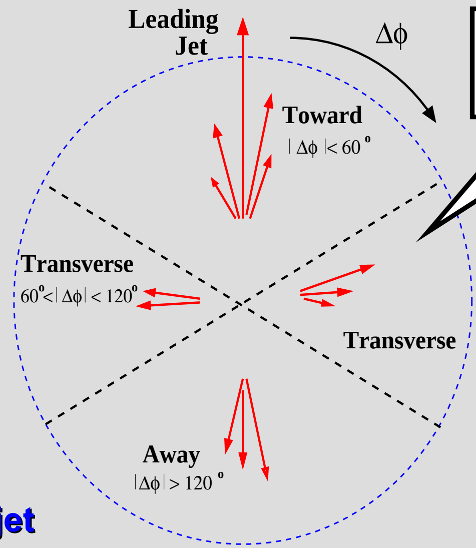
- charged particles:

$p_t$>0.5 GeV and $|\eta|$<1

- cone jet finder:

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$$

$$\Delta\phi = \phi - \phi_{ljet}$$




UE is defined as the Transverse Region

➢ The underlying event is defined as *everything in the collision except the hard process* .

➢ *It is not* a minimum bias event!

➢ The underlying event has ***hard*** (multiple “semi-hard” parton scatterings) and ***soft*** components (beam-beam remnants).

# LHC predictions: pp collisions at $\sqrt{s}$ = 14 TeV

*ATL-PHYS-PUB-2005-007*

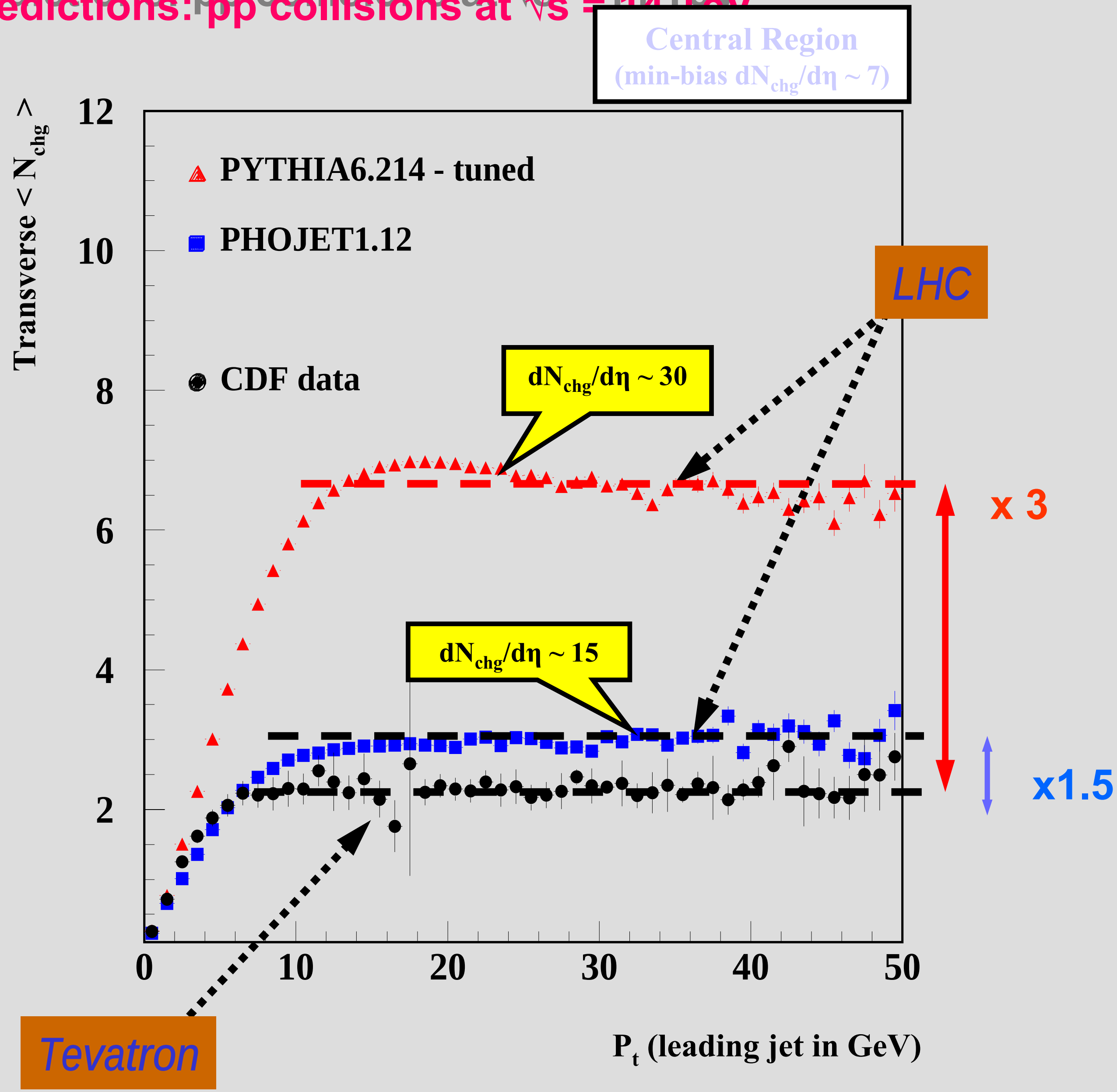
Charged particles:

$p_t$>0.5 GeV and |η|<1

Cone jet finder:

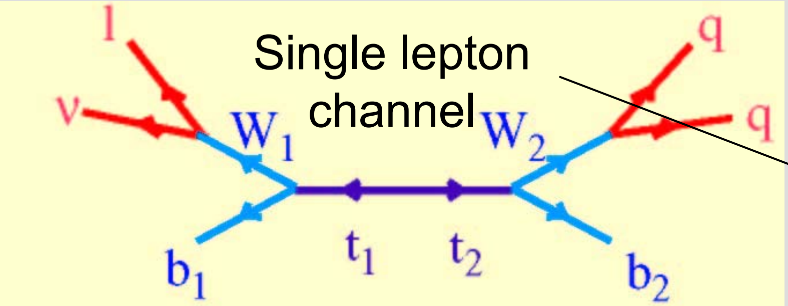
$$R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}=0.7$$

UE particles come from region transverse to the leading jet.



# Systematic on $m_{top}$

$10^{33} cm^{-2} sec^{-1}$



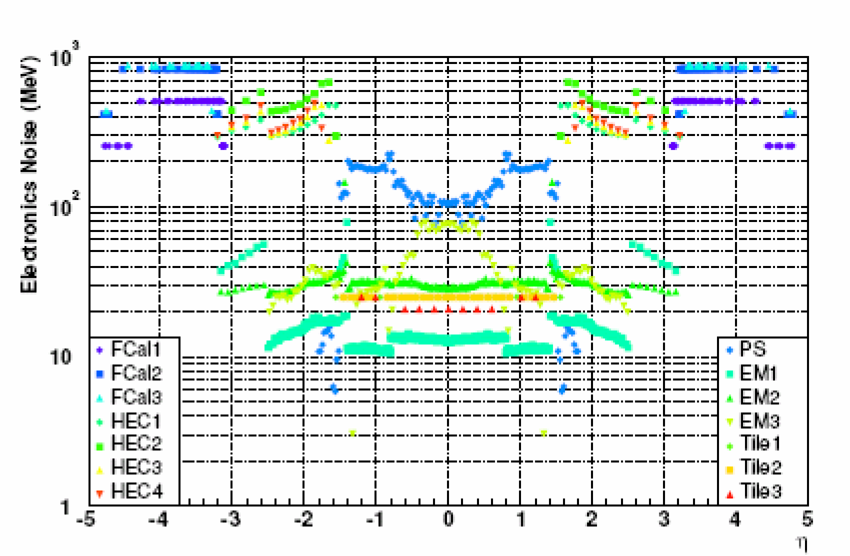

| Period | evts | $dM_{top}(stat)$ |
|---|---|---|
| 1 year | $3x10^5$ | 0.1 GeV |
| 1 week | $1.9x10^3$ | 0.4 GeV |

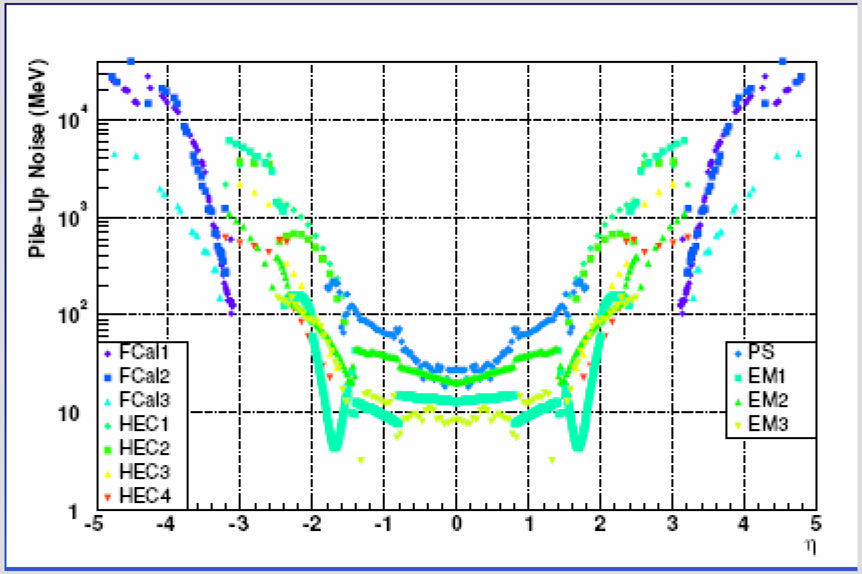
Events in top mass window

Systematic error on top mass from light and bjet energy scale uncertainty

| jet unc. | $\Delta M_{top}(jet)$ | $\Delta M_{top}(bjet)$ |
|---|---|---|
| 1% | 0.9 GeV | 0.7 GeV |
| 5% | 11 GeV | 3.5 GeV |

# Noise level

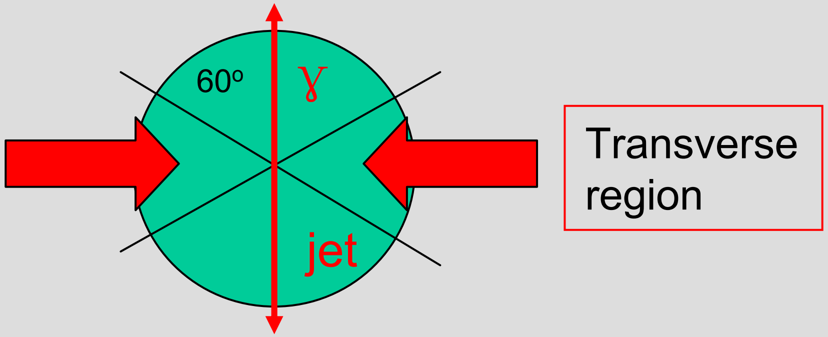

Electronics Noise (MeV)
FCal1
FCal2
FCal3
HEC1
HEC2
HEC3
HEC4
PS
EM1
EM2
EM3
Tile1
Tile2
Tile3
η


Pile-Up Noise (MeV)
FCal1
FCal2
FCal3
HEC1
HEC2
HEC3
HEC4
PS
EM1
EM2
EM3
η

# Gamma + jet and Underlying event

Try to measure the mean ET of UE from the event sample

Select the “transverse region” of the event: avoiding 60 degrees in Phi arround both photon and the jet.




Mean transverse energy per $\eta \times \varphi = 0.1 \times 0.1$

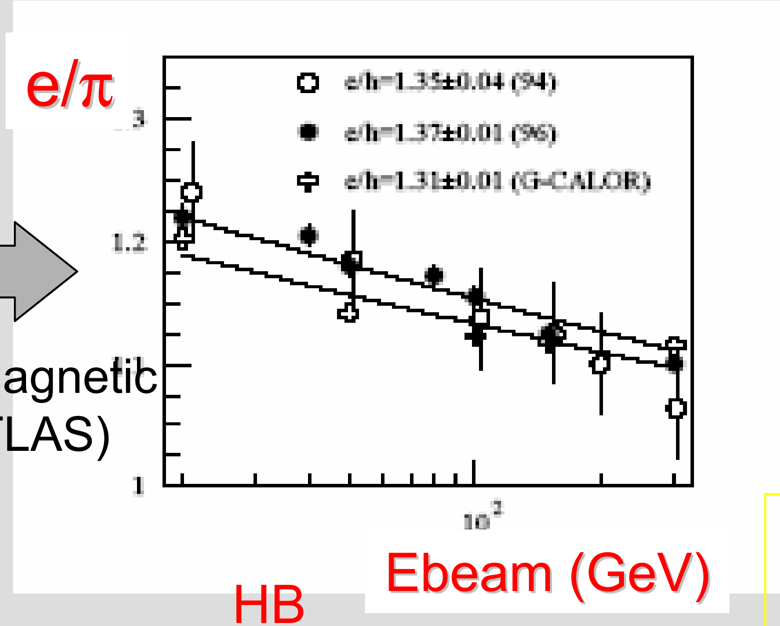
| | |
|---|---|
| Tower (RMS of el.noise ~140 MeV) | 15.1 ± 0.2 MeV |
| Particle protojet (Σ particles per tower) | 19.1 ± 0.4 MeV |

3 GeV in cone 0.7

Average UE level ~10% RMS of el.noise (very sensitive to noise suppression)

Subtraction algorithm and biases introduced are under study.

# Compensation




e/π elettromagnetic scale (ATLAS)

CMS e/h = 1.4
ATLAS e/h = 1.36/1.5
} Had. Cal.

ΔS = 15%-12% per Eπ 20-300 GeV

HB

**CMS**

$\mathbf{E_{rec} = E_{EM} + (\alpha \times H1 + H2 + H3)}$

A high signal H1 indicates hadronic signal thus the EM scale is too low and $\alpha > 1$ corrects for e/h < 1. The correction may or not depend on energy.

**ATLAS**

- benchmark
- H1 [NIM-A1809(1981)429] :

$\mathbf{E_{rec} = \Sigma\, W_{EM}(Ecell,Epart)Ecell +}$

$\mathbf{\Sigma\, W_{HAD}(Ecell,Epart)Ecell}$

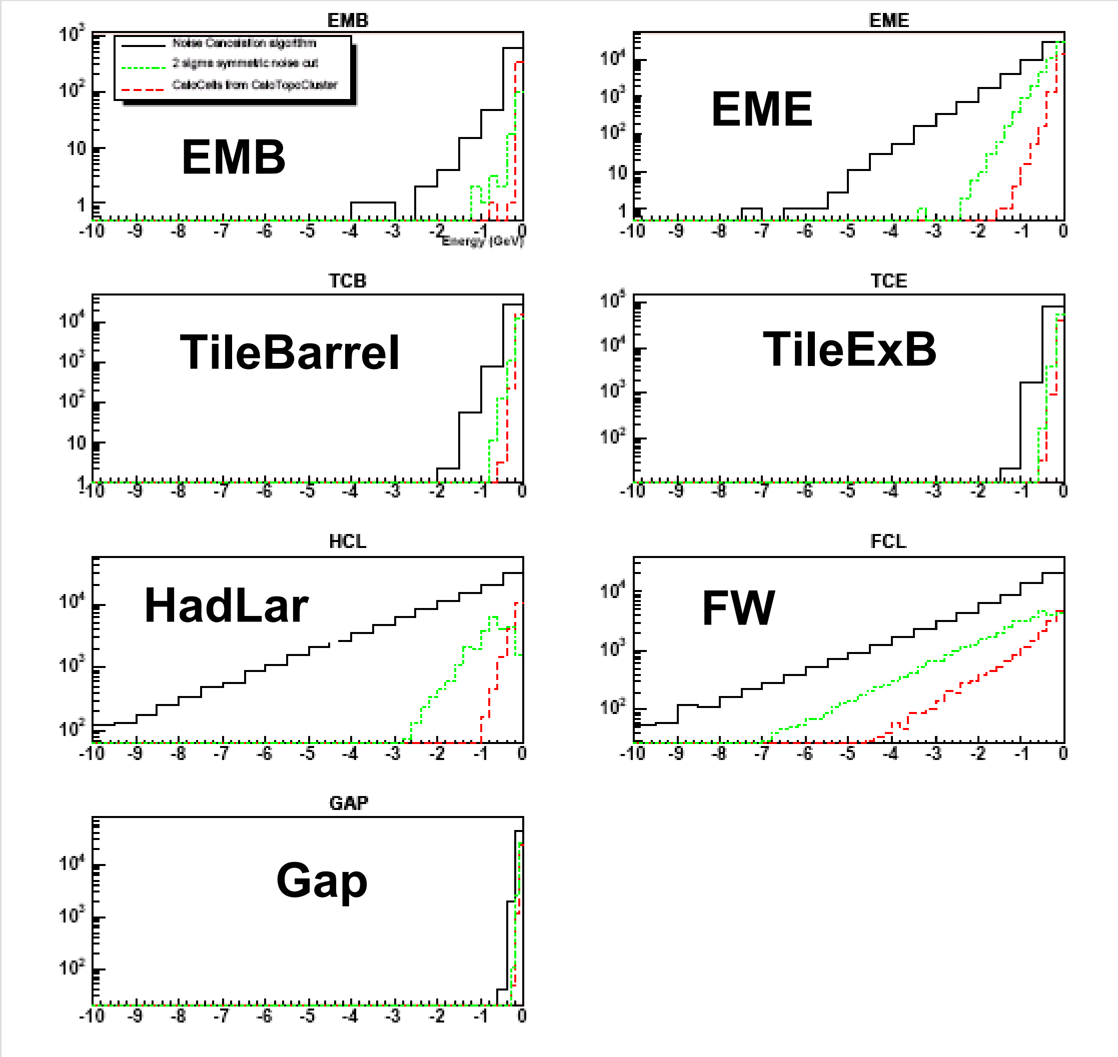
W obtained by minimizing resolution

# Noise suppression performance

Zero suppression

2 sigma symmetric

CaloTopoCluster




Plots show how much negative enegy is left in jets after noise cancellation/subtraction algorithm is applied in each calorimeter region.

Topological Cluster < 2 sigma symmetric < Zero suppresion