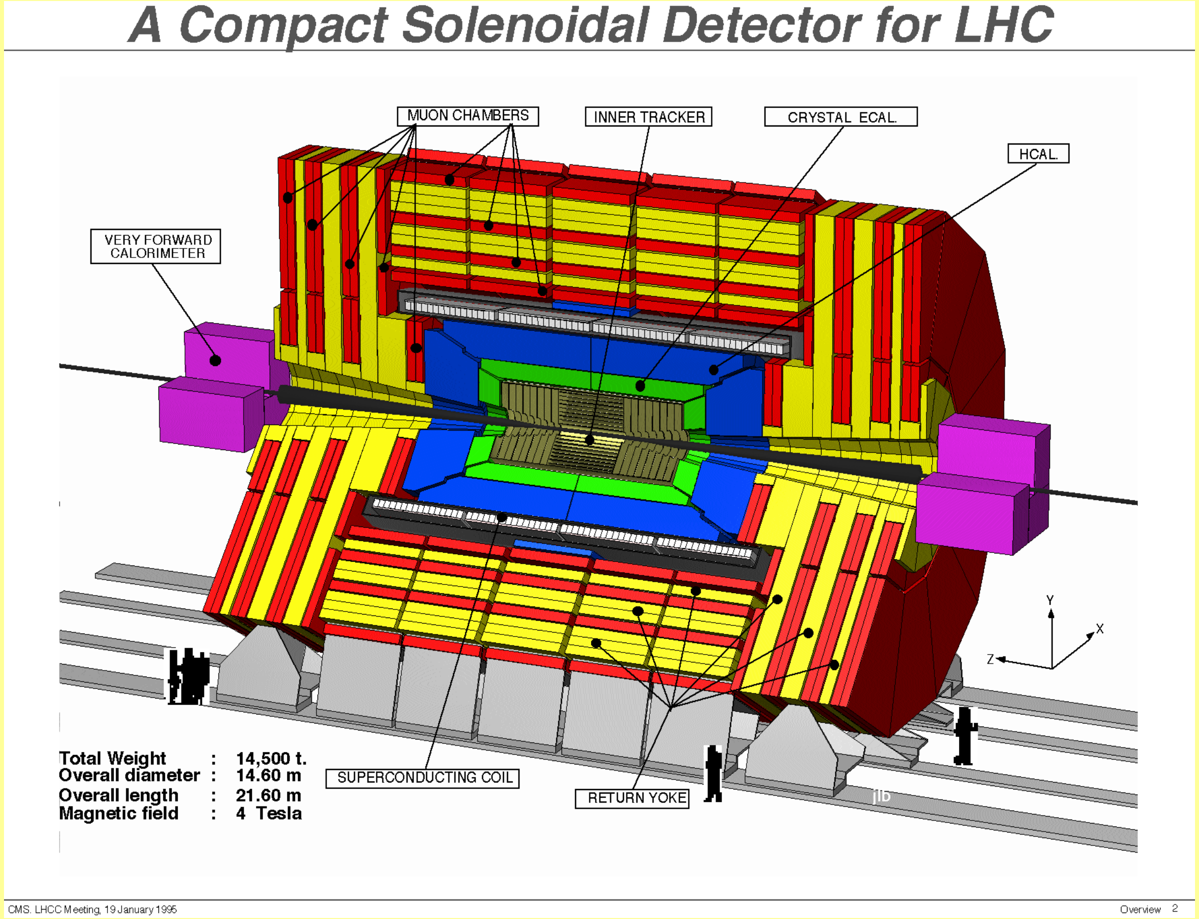
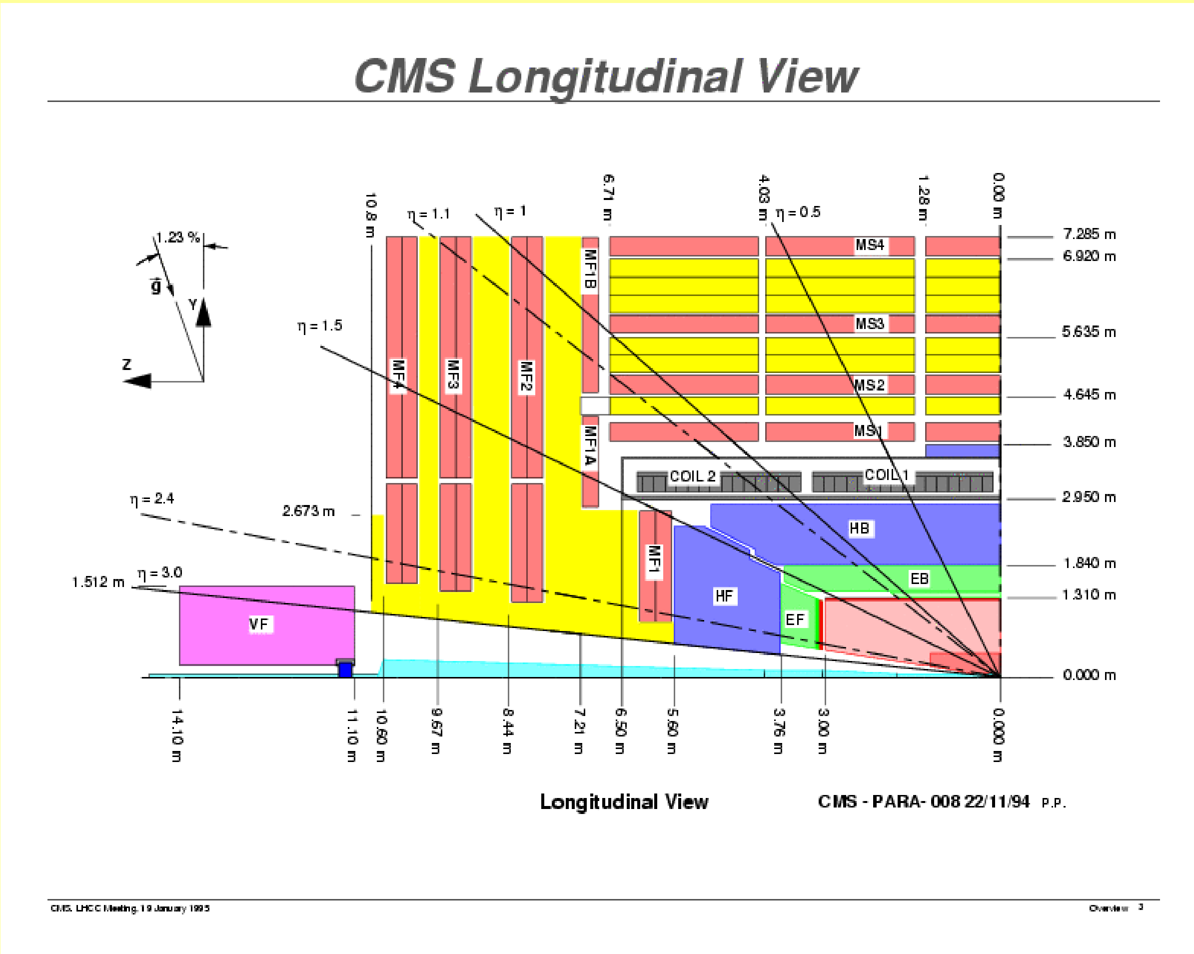
Jets in CMS



Alexei Ulyanov (ITEP)

for CMS Collaboration

CMS detector



Tracker $|\eta|<2.5$

Central calorimeters: $|\eta|<3$

electromagnetic (ECAL)
crystal PbWO4

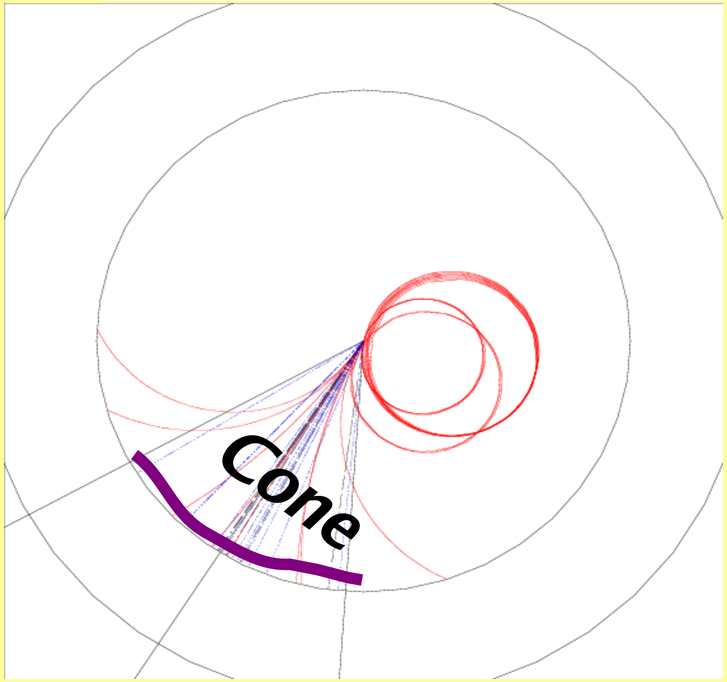
hadronic (HCAL: HB+HE+HO)
sampling calorimeter
scintillator and
brass absorber plates

forward calorimeter $3<|\eta|<5$
quartz fibers and iron

4 Tesla magnetic field

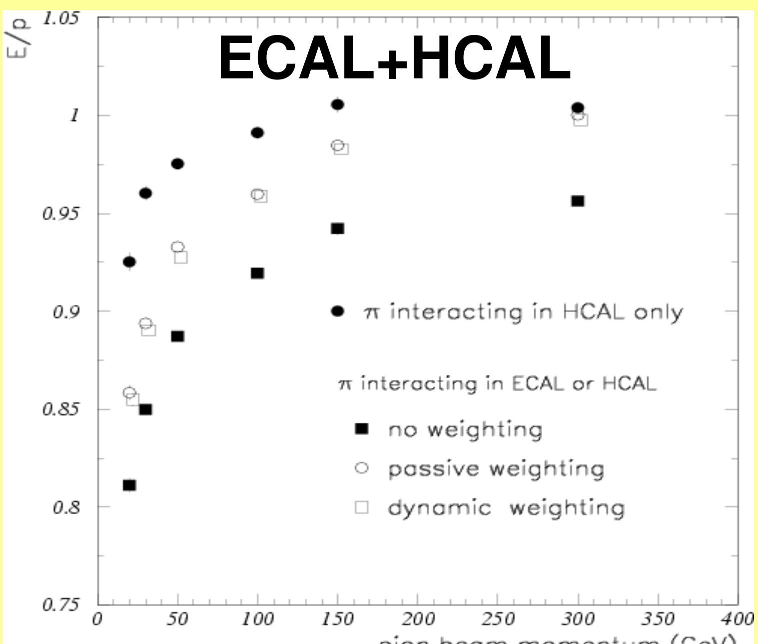
Muon system $|\eta|<2.4$

Detector effects influencing jet reconstruction



Magnetic field effect

Radius of ECAL front face ~1.3m
Charged particles with P_T<0.8 GeV/*c* are loopers in barrel.
Charged particles with P_T<1.6GeV/*c* are deflected by ≥ 0.5 radians.
Silicon tracker and magnetic field allow the precise momentum measurements (dp_T/p_T<2%, p_T<100 GeV).



Nonlinearity of calorimeter response

- **Central calorimetry (|η|<3) consists of two compartments (ECAL and HCAL) and the two have different responses to electrons and hadrons (e/π). Forward calorimeter is a quartz-fiber calorimeter (e/h~5) with very different response to em particles and hadrons.**
- **Jets have both hadronic (charged and neutrals) and electromagnetic components.**

Factors influencing jet reconstruction (summary)

i) From jet physics (from parton to jet at particle level):

- **ISR and FSR**
- **Fragmentation**
- **Underlying event**

Leave for the physics channel study?

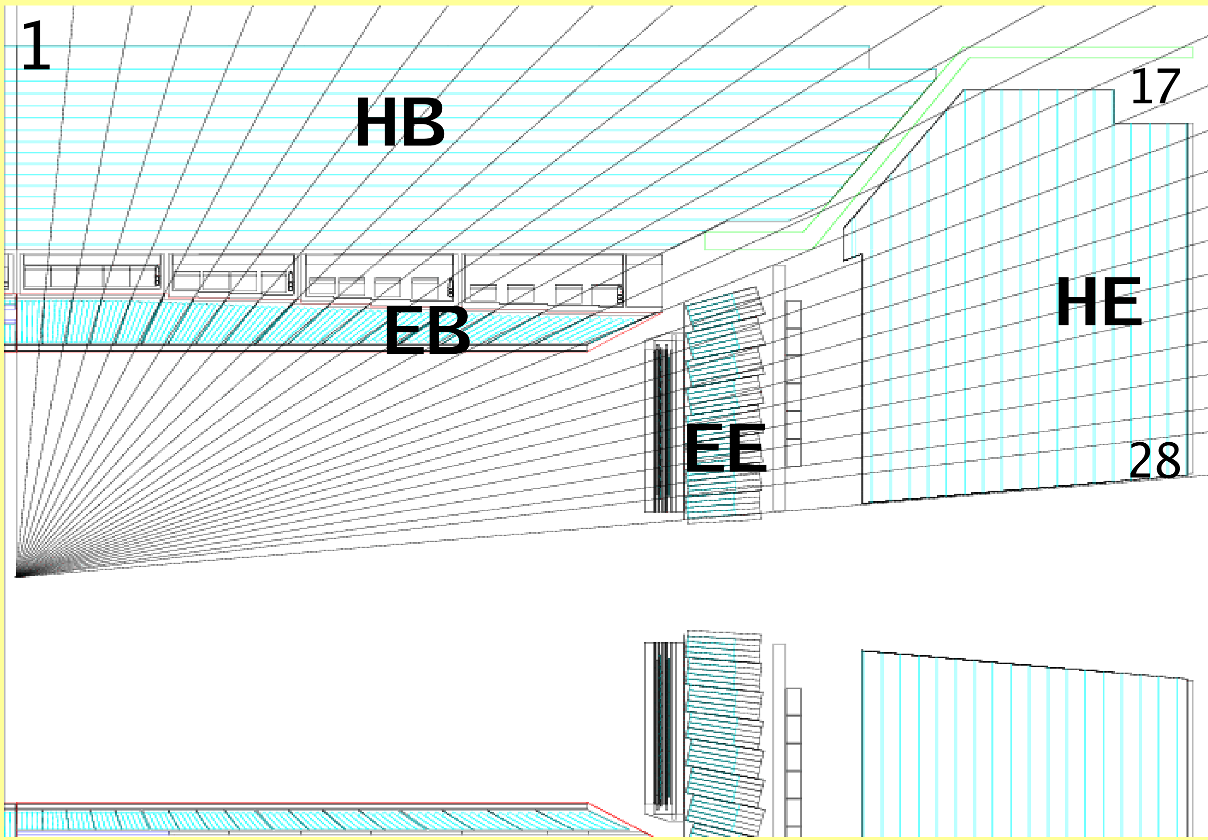
ii) From detector performance (from jet at particle level to calorimeter jet):

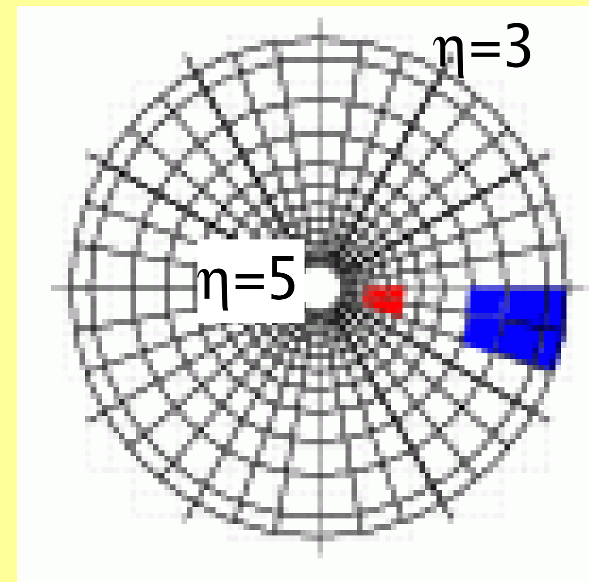
- **Calorimeter response to particles ($e^{\pm}/\gamma$ vs $\pi^{\pm}$)**
- **Magnetic field**
- **Electronic noise/tower thresholds**
- **Dead materials and cracks**
- **Longitudinal leakage for high-Pt jets**
- **Shower size, out of cone loss**
- **Pileup**

Develop common methods?

Jet reconstruction: Input

Input: ECAL+HCAL towers/HF towers





HF: 36 x 13 towers

$\phi \times \eta$: 0.175 x 0.175

ECAL+HCAL tower: HCAL tower + 5x5 crystals

$\lvert\eta\rvert<1.74$	0.087 x 0.087
$1.74<\lvert\eta\rvert<3.0$	tower size ($\eta \times \phi$) increases from 0.087 to 0.175

Jet reconstruction: jet finders

iterative cone algorithm:
- take towers in a cone of radius R around a tower with highest E_T and calculate E_T-weighted η, ϕ
- use the computed direction to seed a new cone
- iterate until the cone position is stable
- a stable cone makes a jet and its towers are removed from the list of input objects
- no jet merging

midpoint cone algorithm:
- use iterative cone procedure to find stable cones starting from all towers with ET above a seed threshold (no tower is removed from the input list)
- for every pair of close objects ($d<2R$) a midpoint is calculated and is used as an additional seed;
- splitting/merging procedure is applied (50% threshold)
- CDF version (reduced cone size in the iterative stage)

Kt algorithm (cluster-based): starts with a list of objects: towers (particles)

$d_i=(P_{T,i})^2 x R^2$; $R=1$

$d_{ij}=\min(P_{T,i}^2, P_{T,j}^2) x R_{ij}^2$; $R_{ij}^2=(y_i-y_j)^2+(\phi_i-\phi_j)^2$

find the minimum of all the d_i and d_{ij} and label it dmin

$dmin=d_{ij}$ -> objects i and j are merged and replaced with a new object

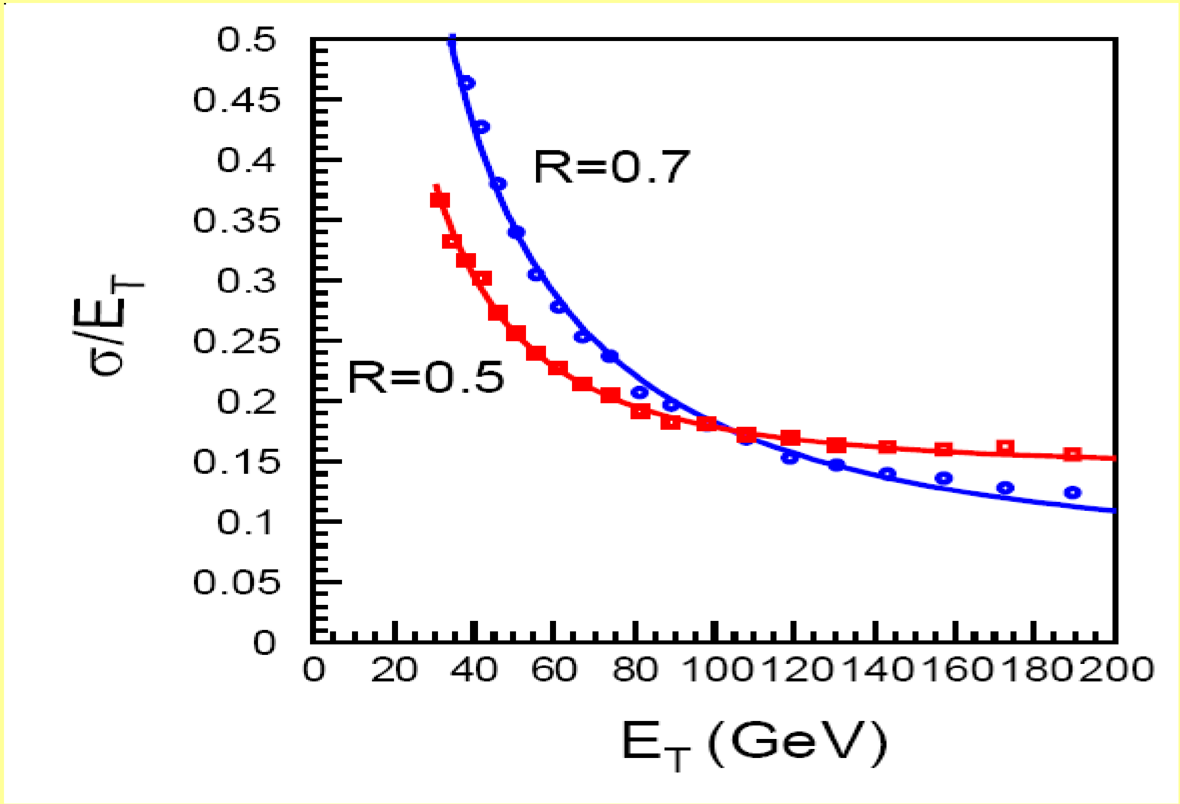
$dmin=d_i$ -> object i is a final jet

Jet finder parameters

Using E-scheme for object recombination (4-vector scheme)

Typical choice for the cone size is R=0.5 or R=0.7

R=1 for the Kt algorithm but it seems to collect too much energy from pile-up and underlying event



Jet resolution at high luminosity for two cone sizes

At particle level cone size R=0.7 was used

Noise and pileup events

CMS will take data with both pp and AA beams.

Electronic noise gives 5 GeV in a cone of 0.5 (η,ϕ) in barrel

pp-beam

In pp running, low luminosity pileup (2 x 10^{33} $cm^{-2}s^{-1}$) gives E_T~2.5 GeV in a cone of 0.5 in pp in barrel region.

In pp running, high luminosity pileup (10^{34} $cm^{-2}s^{-1}$) gives E_T ~10 GeV in a cone of 0.5 in barrel region.

AA beam

Pb-Pb central event gives E_T~200 GeV in cone 0.5 in barrel and even higher in endcap.

The number of pileup min bias events decreases with decreasing luminosity during about (half a day) run.

Noise and pile-up have to be suppressed as a first step before any of jet reconstruction algorithms can be applied.

Noise and pileup suppression:
<u>subtraction based on mean value</u>

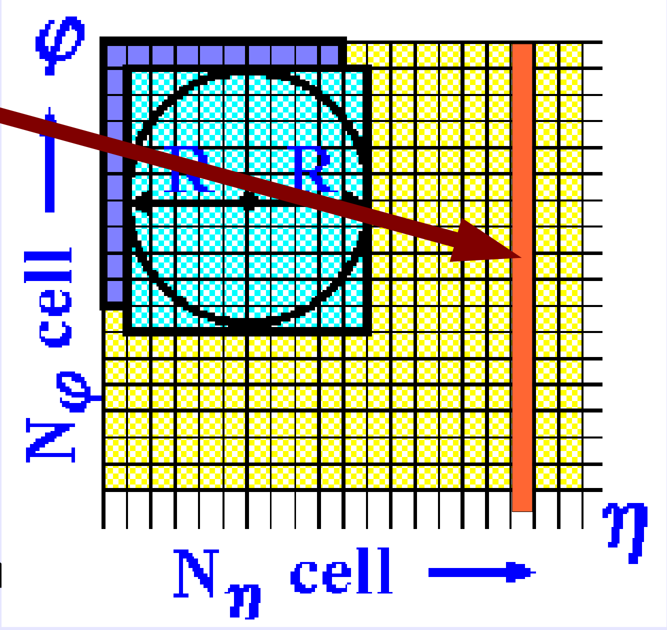
mean value is determined over a large min bias event sample:

- constant cut on tower energy (E cut - noise subtraction)
- constant cut on tower transverse energy (Et cut - noise and pileup subtraction)
- sliding window (E cut depending on pseudorapidity – advanced noise and pileup subtraction, possibly taking into account detector geometry)

mean value is determined on an event-by-event basis: pile-up subtraction algorithm

- calculate average energy and dispersion in tower (in eta rings) for each event
- subtract average energy and dispersion from each tower
- find jets with a jet finder algorithm (any) using the new tower energies
- recalculate average energy and dispersion using towers free of jets
- recalculate jet energies

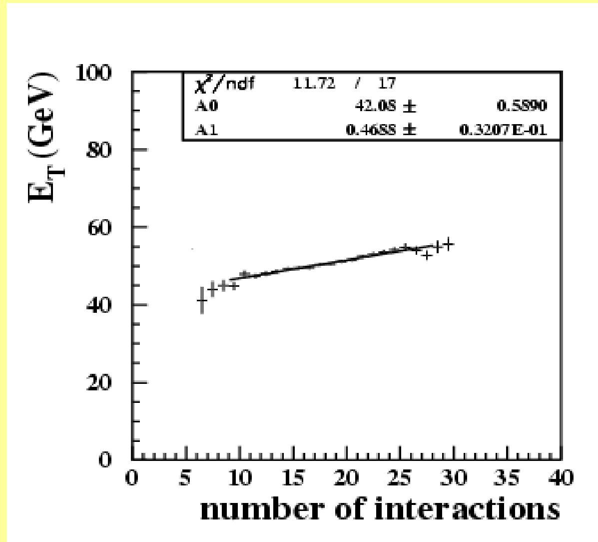
noise, pile-up, geometry are taken into account autom



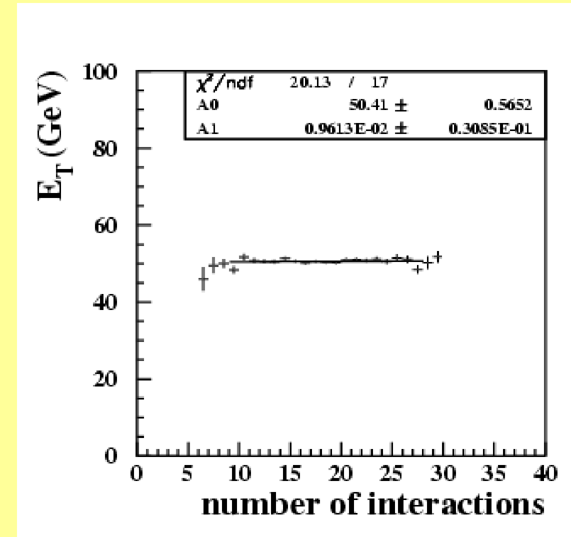
Pileup subtraction algorithm

50 GeV jet
pp, L=10^{34} cm^{-2}s^{-1}

Without pile-up subtr

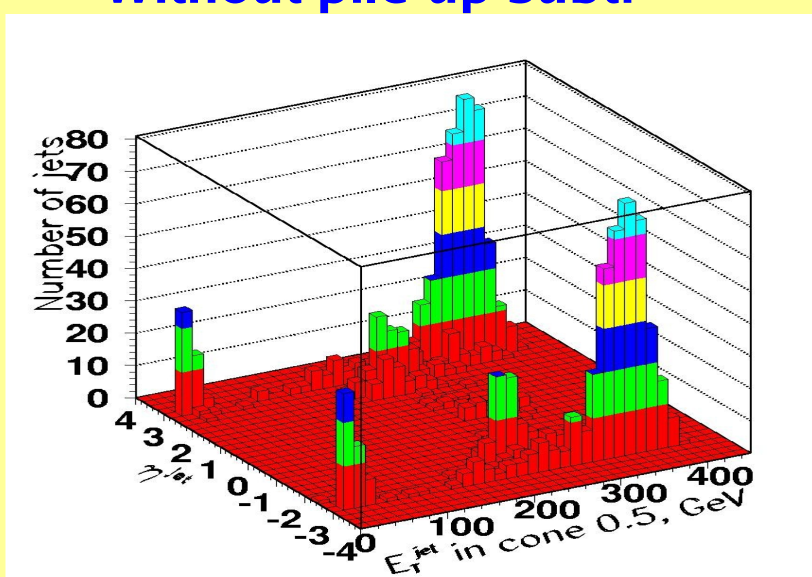


With pile-up subtr

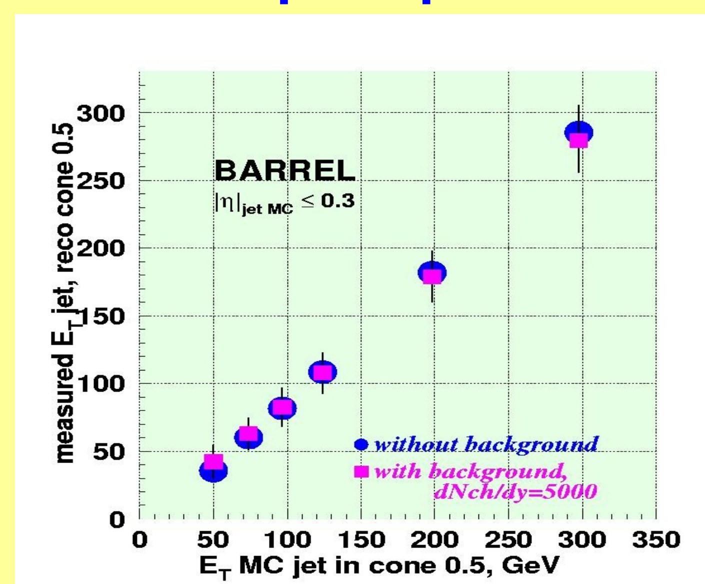


Pb+Pb
dN_{ch}/dy=5000

Without pile-up subtr



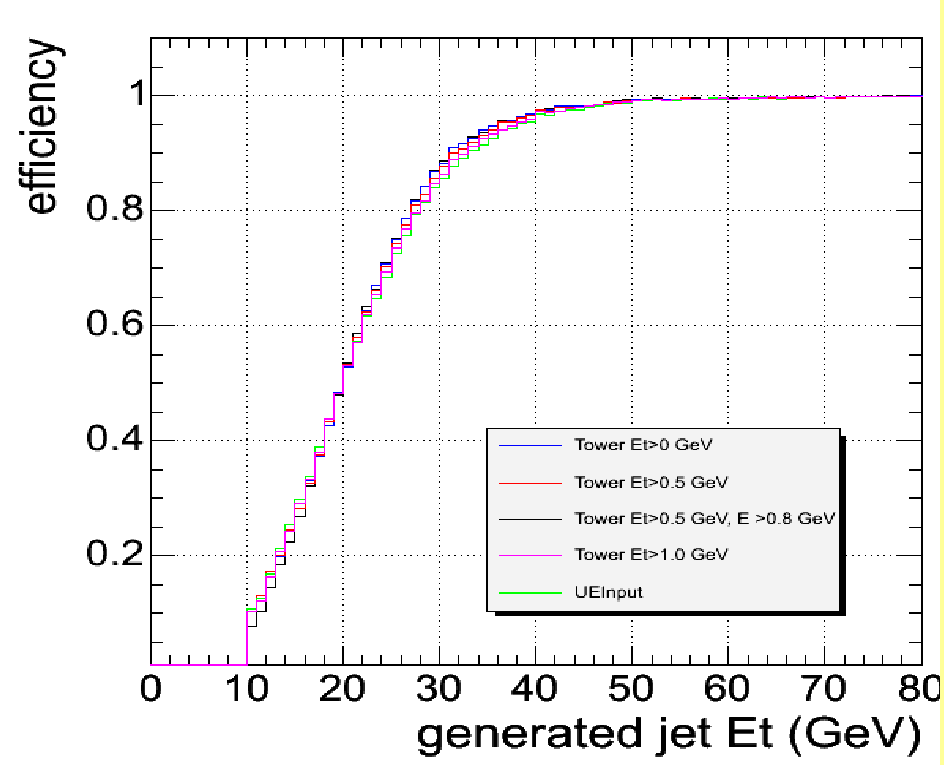
With pile-up subtr



Efficiency and fake jet rate

Cut on the reconstructed E_T is applied depending on the specific choice of calorimeter tower threshold: 50% efficiency for the generated jets with E_T=20 GeV

Tower threshold(GeV)	*ET>0*	*ET>0.5*	*ET>0.5,E>0.8*	*ET>1*	*E>Ecut(η)*
Reconstructed jet ET threshold (GeV)	**15**	**10.1**	**8.46**	**5.86**	**5.6**
Fake rate (jets/event)	**2**	**1.98**	**1.64**	**2.1**	**2.29**



Luminosity=2 x 10^{33} $cm^{-2}s^{-1}$

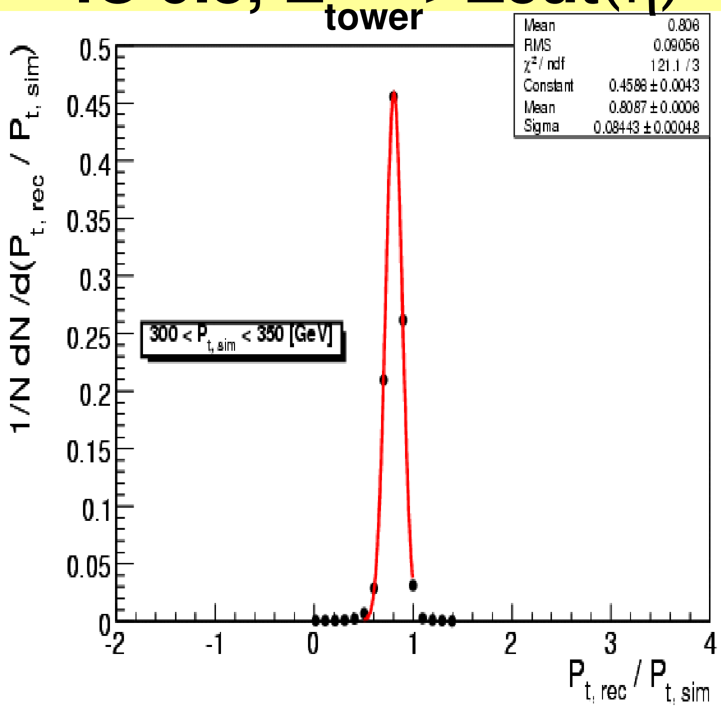
The fake rates are calculated from dijets event samples with 50 GeV< p_{That} <80 GeV

Energy resolution before corrections for different algorithms and parameters

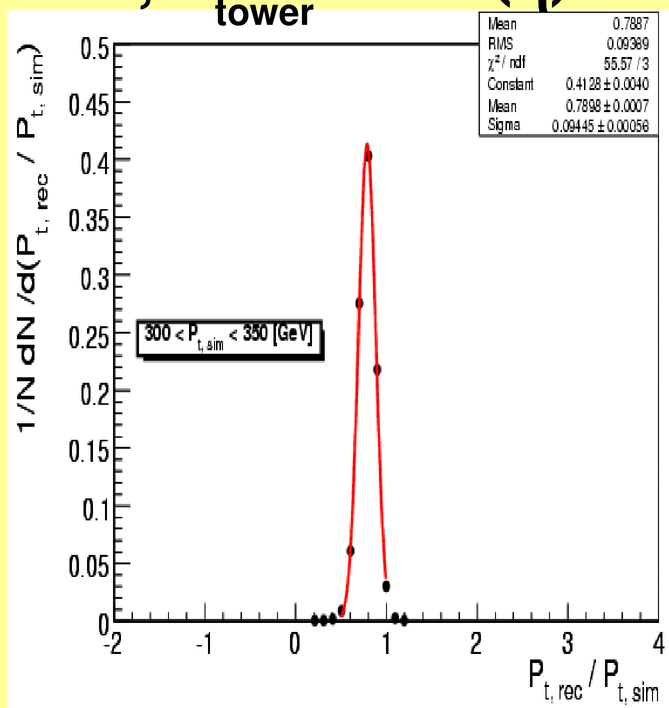
E_T^{tower}>0.5 GeV, E^{tower}>0.8 GeV

Algorithm	*|η|<1.4*	*1.4<|η|<3.0*	*3.0<|η|<5.0*
IC, DR<0.1	$6.6/E_T^{gen}+1.39/\mathrm{sqrt}(E_T^{gen})+0.036$	$7.9/E_T^{gen}+0.7/\mathrm{sqrt}(E_T^{gen})+0.048$	$3.24/E_T^{gen}+0.48/\mathrm{sqrt}(E_T^{gen})+0.077$
IC, DR<0.2	$7.5/E_T^{gen}+1.44/\mathrm{sqrt}(E_T^{gen})+0.034$	$8.5/E_T^{gen}+0.67/\mathrm{sqrt}(E_T^{gen})+0.049$	$4.1/E_T^{gen}+0.2/\mathrm{sqrt}(E_T^{gen})+0.087$
Kt, DR<0.2	$10.6/E_T^{gen}+1.57/\mathrm{sqrt}(E_T^{gen})+0.027$	$13.5/E_T^{gen}+1.06/\mathrm{sqrt}(E_T^{gen})+0.038$	$6.5/E_T^{gen}+0.089$

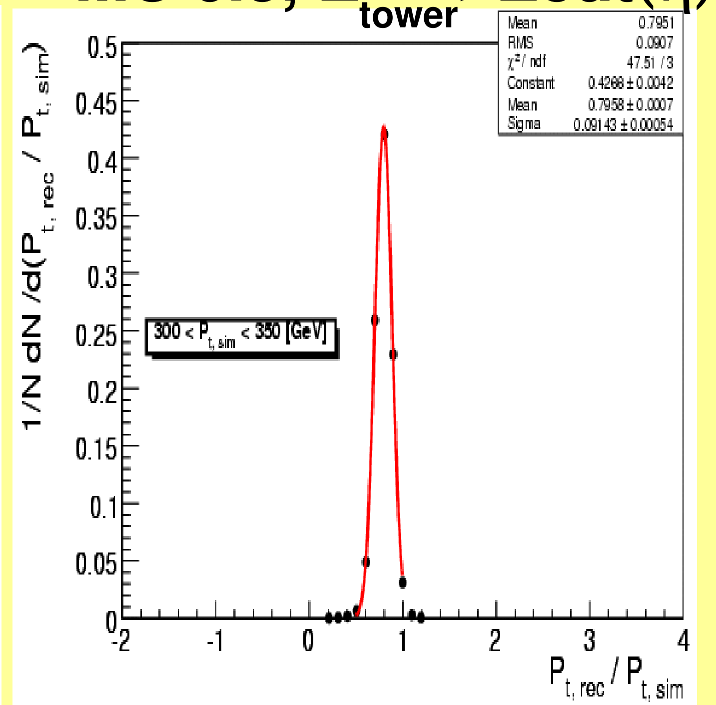
IC 0.5, E_{tower}>Ecut(η)



Kt, E_{tower}>Ecut(η)



MC 0.5, E_{tower}>Ecut(η)



Matching criterion: $DR=\mathrm{sqrt}((\phi_{jet}^{rec}-\phi_{jet}^{gen})^2+(\eta_{jet}^{rec}-\eta_{jet}^{gen})^2) < 0.2$

Jet reconstruction procedure in CMS: II) To apply jet energy correction

Jet based ($|\eta|<4.5$):

1) $E = a \times (EC+HC)$, a depends on jet(E_T,η)

2) $E = a \times EC + b \times HC$, a, b depend on jet($E_T$,$\eta$)

from data: γ/Z+jet, masses (Z,W,...)

from Monte-Carlo generators

Particle based ($|\eta|<4.5$):

3) $E = em + had$ (requires to separate em/had clusters)

$em = a \times EC$ for e/γ

$had = b \times EC + c \times HC$, for hadrons.

b (c) depend on EC (HC)

Use of tracks ($|\eta|<1.9$):

4) $E = E_0$ + (Tracks swept away by 4T field)

5) E = EC(e/γ+neutral) + HC(neutral) + Tracks

Monte-Carlo corrections

At the startup of the experiment we will have to use jet energy corrections derived from simulations.

Response = ET_reconstructed_jet/ET_generated_jet

Correction = 1/Response as a function of E_T and η of jet

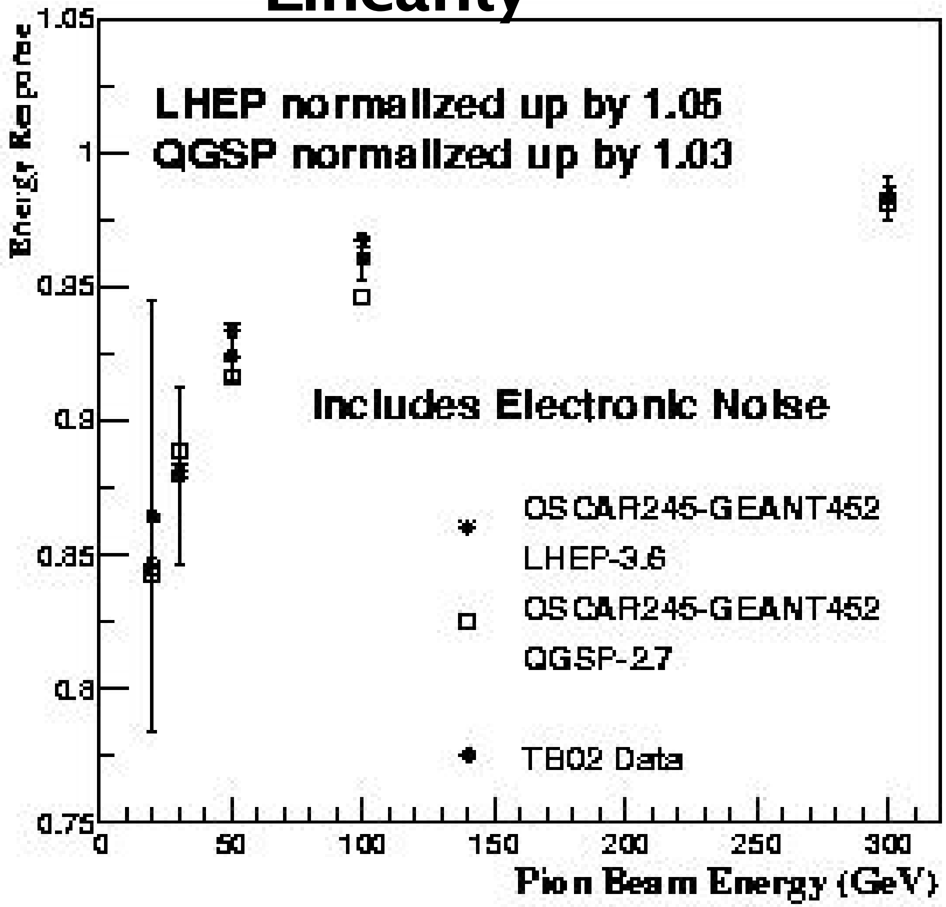
MC jet corrections depend on the jet finding algorithm, on the cone size, on the level of noise and pile-up -> a set of curves vs (P_T,η) is needed

In simulations the observed jet response is different between quark and gluon jets
-> corrections are sensitive to q/g fractions in a jet sample
-> corrections are sensitive to particle multiplicity and momentum distributions in a jet (need to tune MC generator to the experimental data)

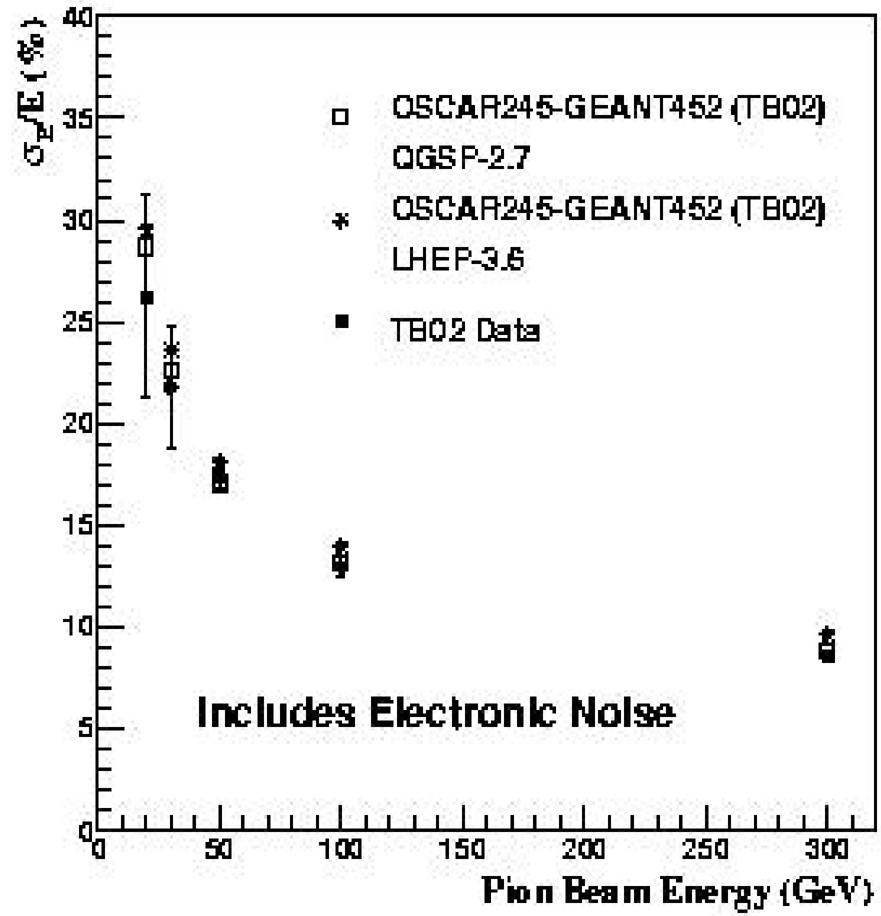
Need to tune and verify the detector simulation with test beam data

Data/Geant4 comparison (pions)

Linearity

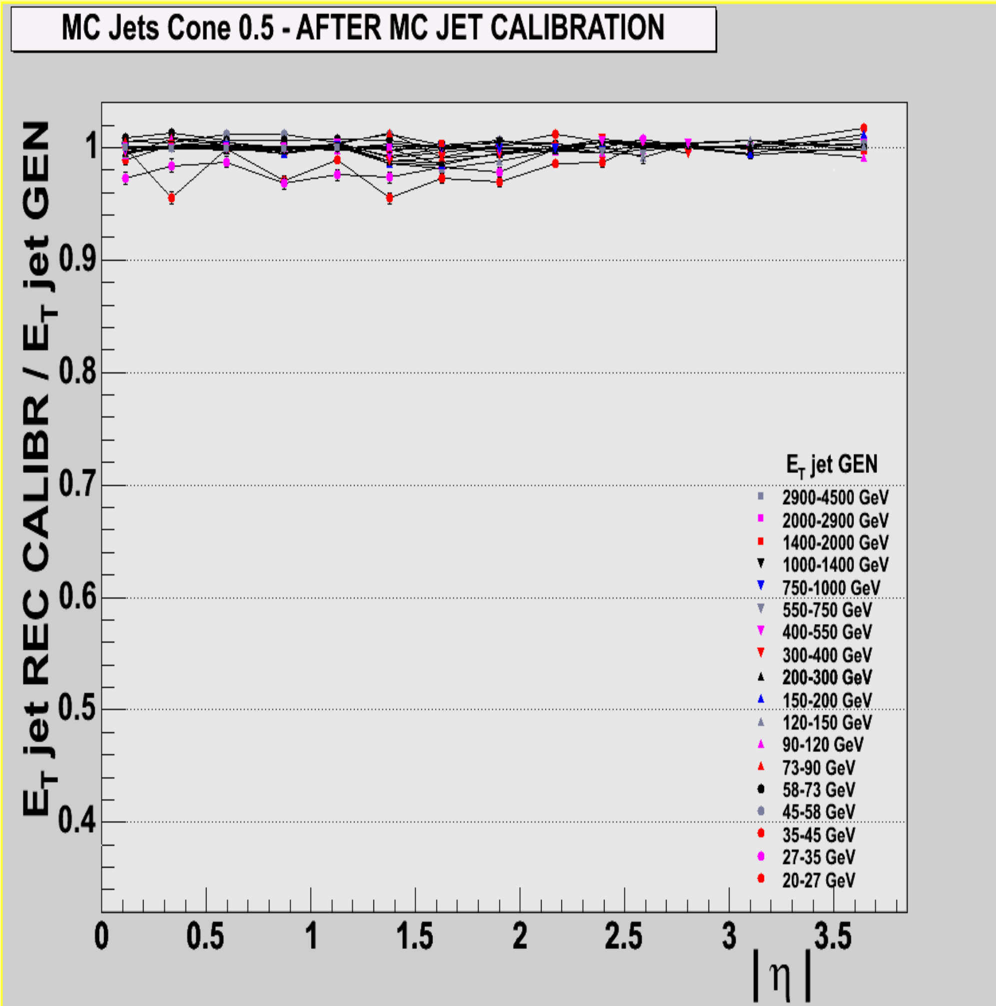


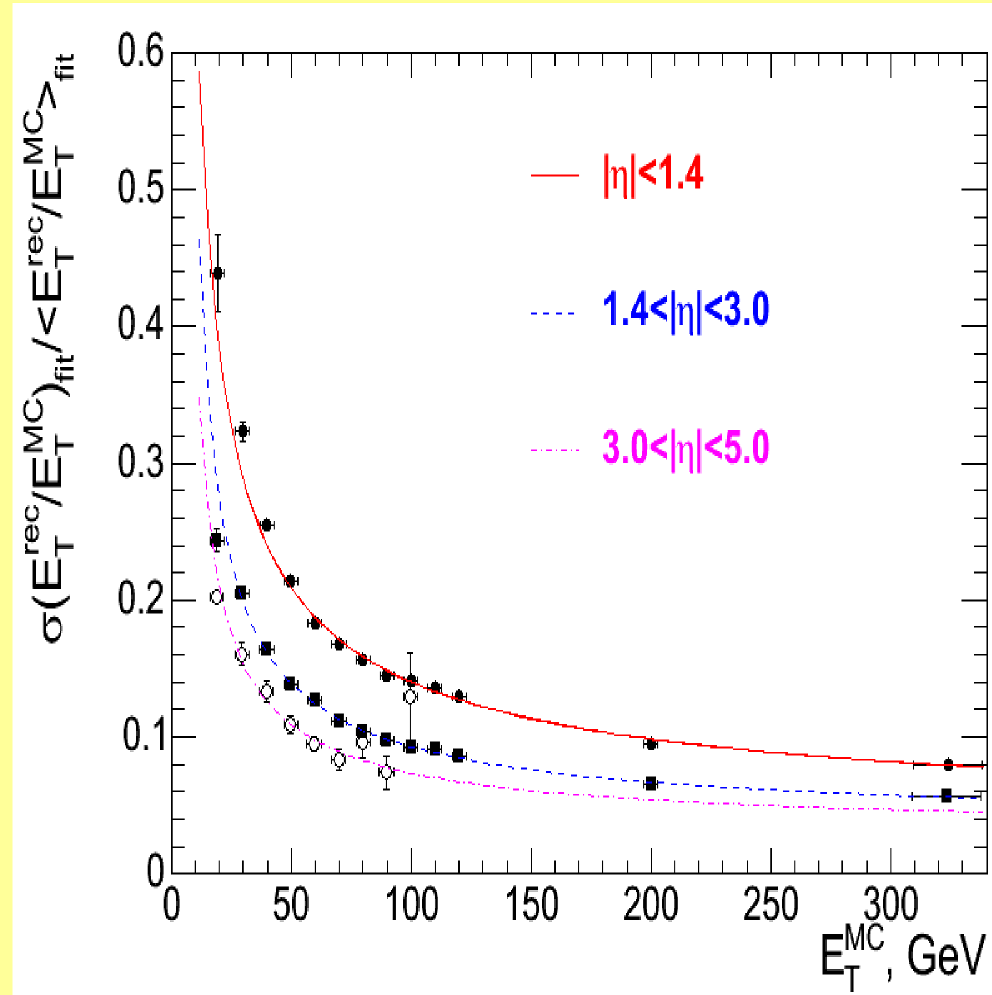
Resolution



Now taking further steps to verify the detector simulation for low energy particles

Jet response linearity and energy resolution after MC corrections



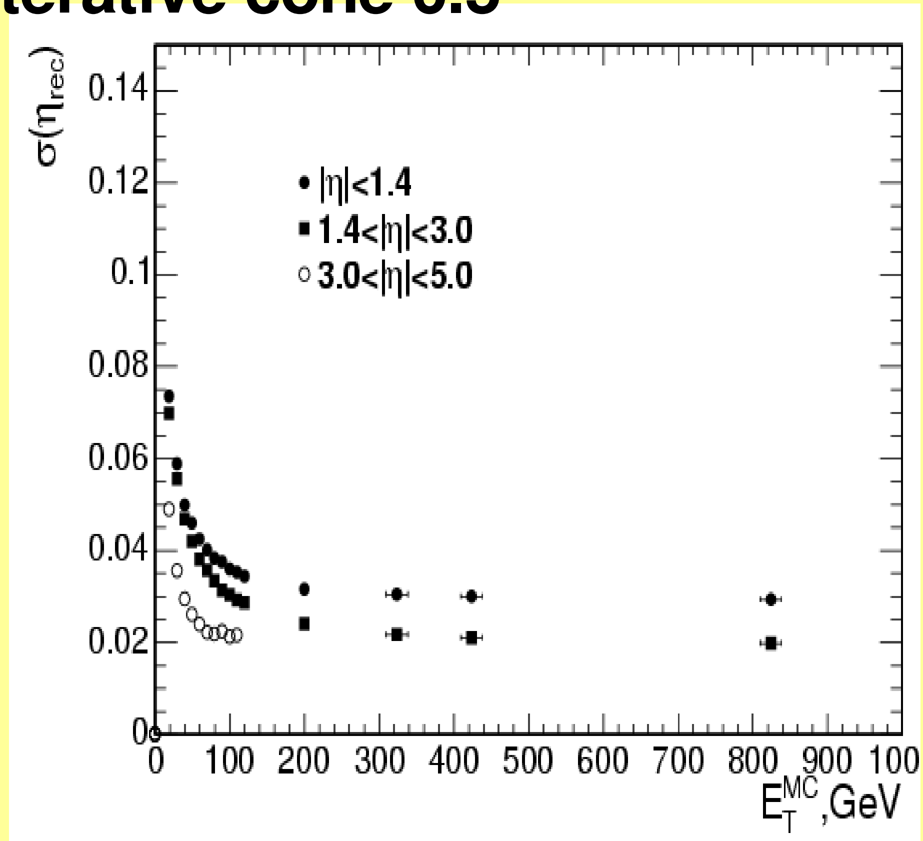


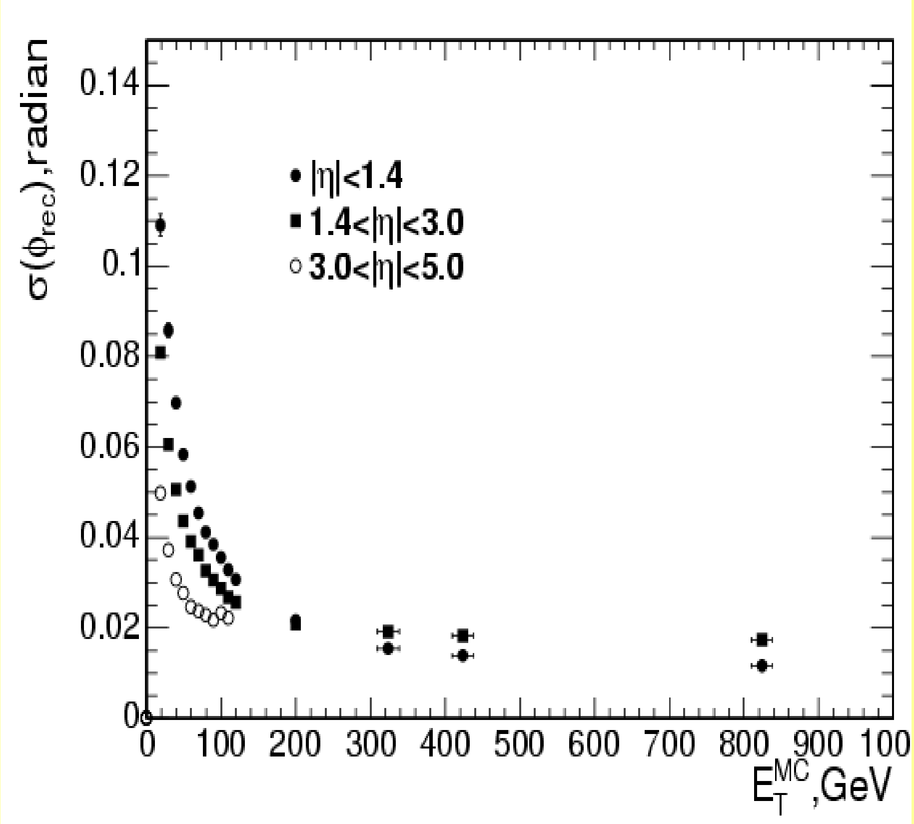
Barrel:

resolution after correction $= 5.6/E_T^{gen} + 1.25/\mathrm{sqrt}(E_T^{gen}) + 0.033$

η and ϕ resolution

Iterative cone 0.5





The sizes of towers (η x ϕ):

$\|\eta\|<1.74$	0.087 x 0.087
$1.74<\|\eta\|<3.0$	the granularity in (η x ϕ) increases from 0.087 to 0.175
$3.0<\|\eta\|<5.191$	0.175 x 0.175

The resolution is less than the size of a tower in the entire eta range

Jet calibration from physics events

γ/Z+jet and W->jj (from ttbar production) samples will give the first estimation of the absolute energy scale. Dijet events can be used to establish the relative energy scale for different rapidities

Application area:

γ+jet correction is applied to parton (direct use of the initial γ-jet E_T balance)

$$E_T^{parton} = E_{Tjet}^{reco} / k_{jet}^{true}, \quad k_{jet}^{true} = E_{Tjet}^{reco} / E_{Tparton}, \quad k_{jet}^{meas} = E_{Tjet}^{reco} / E_{T\gamma/Z}$$

γ+jet correction is applied to particle jet with the additional MC correction taking into account the difference between parton and particle jet:

$$E_{Tjet}^{ptcl} = E_{Tjet}^{parton} \times k_{jet}^{ptcl}$$

Features:

γ+jet correction depends on the jet finding algorithm, on the cone size, on the level of noise and pile-up in event. -> a set of curves vs (P_T,η) is needed

γ+jet correction has systematics connected with parton species and selections to suppress background. In γ+jet sample there are 90% of q and 10% of g jets. There is a background from the dijet events (with leading π^0).

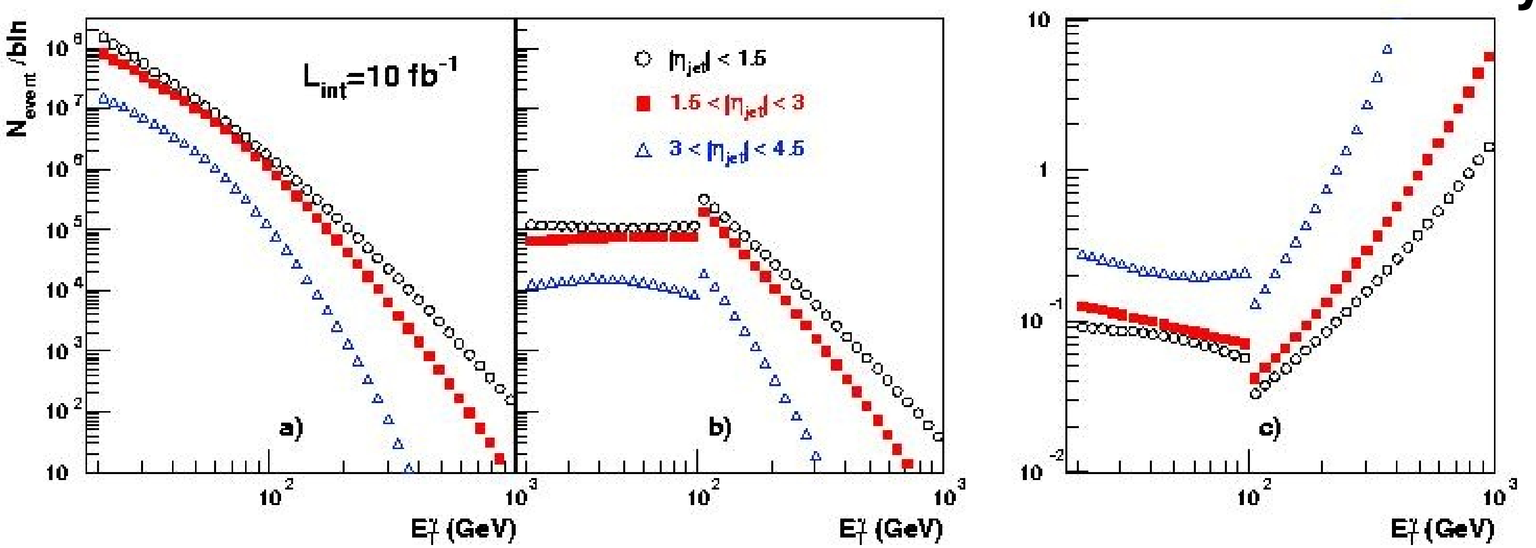
The trigger and rate of γ+jet events

e/γ trigger:

p_T > 80 GeV – all events with isolated e/γ cluster in calorimeters

p_T < 80 GeV - Isolation of e/γ in calorimeters and pixel detector at Level 1-Level2 and rescaling to have rate at the level of a few Hz

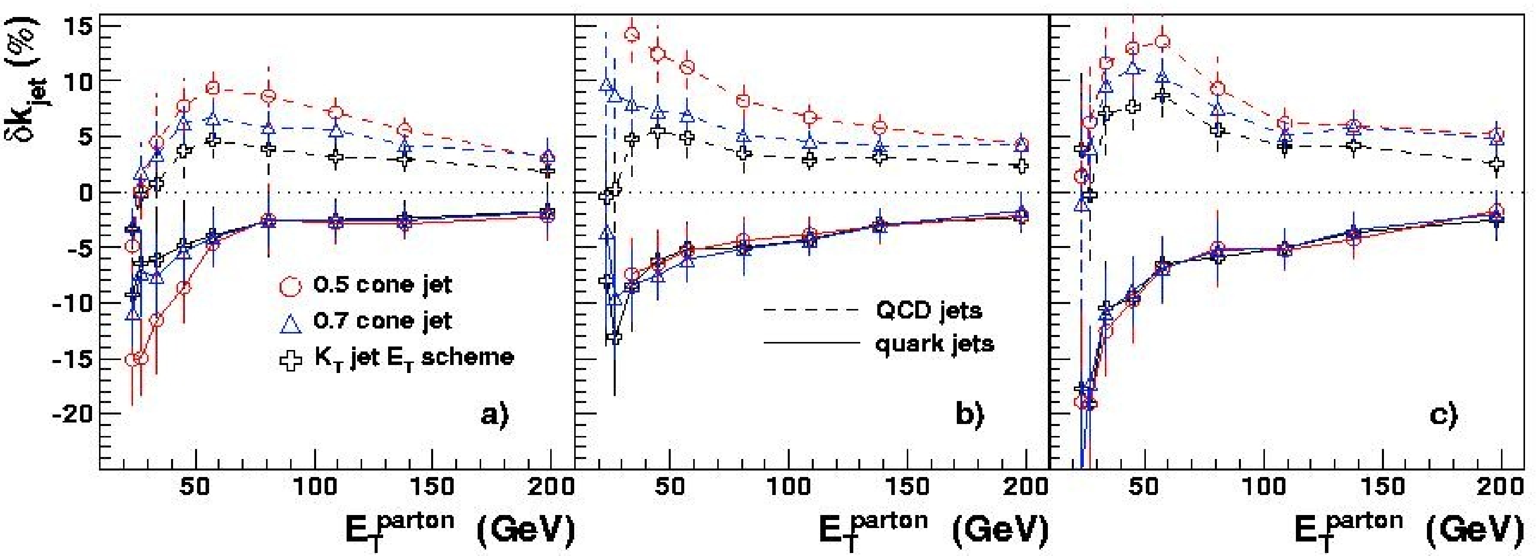
Statistical accuracy (%)



γ+jet calibration

The relative systematic bias for the different samples:($k_{jet}-k_{true})/k_{true}$

$k_{jet} = E_{Tjet}^{reco}/E_{T\gamma}$ $k_{jet}^{true} = E_{Tjet}^{reco}/E_{Tparton}$



The main sources of systematic bias are:

- **bias due to radiation effects**
- **background from QCD dijet events**
- **event selection may bias true energy scale**

Cluster based corrections (energy flow)

- **Fine ECAL granularity allows the reconstruction of energy clusters corresponding to single particles. Depending on the energy deposited in HCAL these clusters can be tagged as hadrons or em particles.**
- **Hadrons that have not interacted in ECAL can be identified as pure HCAL clusters. However, the cluster separation is worse in HCAL.**
- **The energy of "hadronic" clusters can be corrected for non-linear response as**

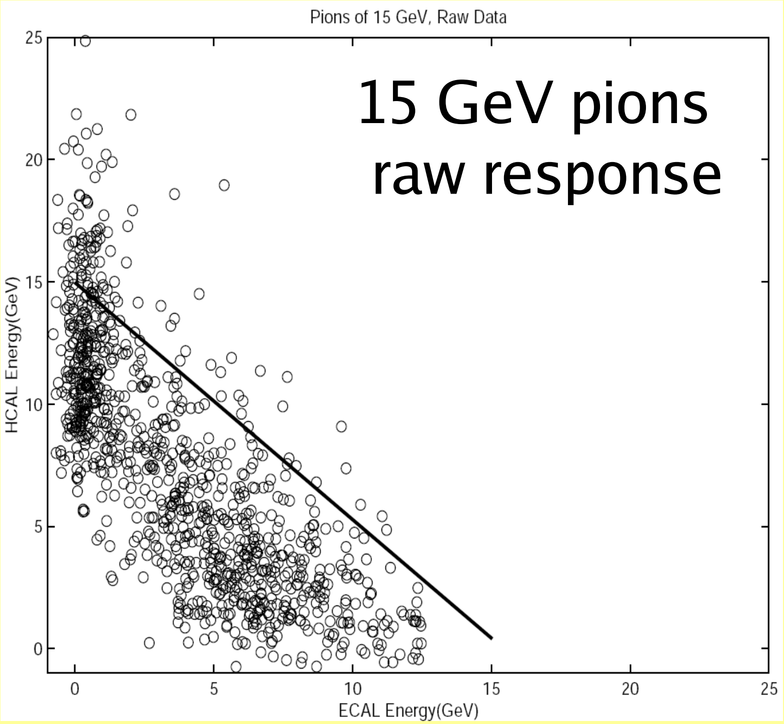
$$E=(e/\pi)_{ecal}E_{ecal}+(e/\pi)_{hcal}E_{hcal},$$

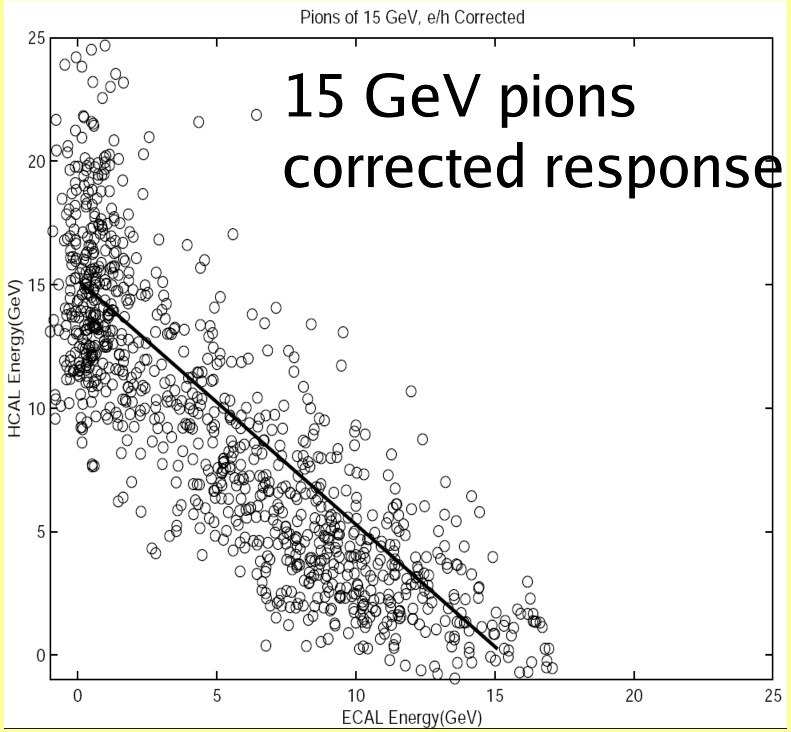
$$(e/\pi)_{(ecal,\,hcal)}=\frac{(e/h)_{(hcal,\,ecal)}}{1+((e/h)_{(hcal,\,ecal)}-1)f_0},$$

$$f_0=a[\log(E_{ecal}+E_{hcal})]^b.$$

Cluster based corrections (cont'd)

- **The (e/π) ratios for ECAL and HCAL parameterized as functions of raw measured ($E_{ecal}+E_{hcal}$) have been fitted to the test beam data.**
- **Single pion response corrected using these parameterizations shows much improved linearity versus particle energy as well as improved energy resolution in the test beam data analysis.**





No results for jets yet

Jet energy correction with charged particle tracks

response subtraction procedure, CMS NOTE 2004/015, published in EPJC:http://dx.doi.org/10.1140/epjcd/s2005-02-004-2

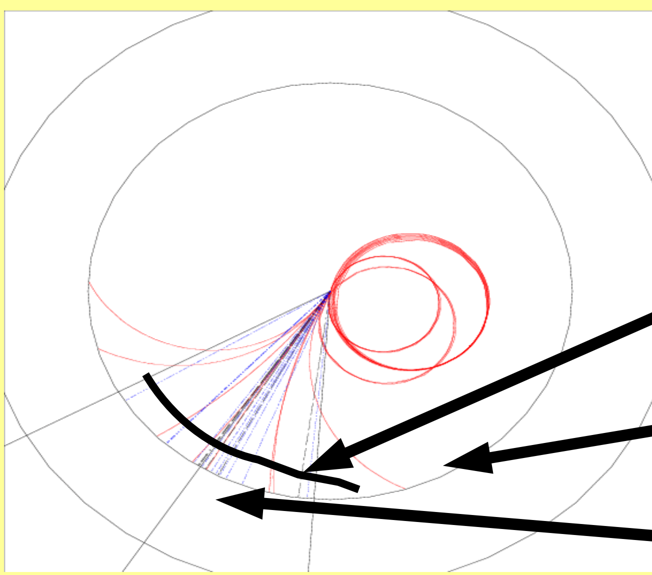
Jet energy=Response to charged+Response (e/γ)+Response (neutrals)

Replace response to charged hadrons of jet in reconstruction cone with energy of charged particle tracks from Tracker.

Jet energy corrected=sum(Pin) + sum(Pout) + Response (e/γ +neutral)_ECAL + Response (neutral)_HCAL

- **Add tracks out of reconstruction cone**

Expected response of charged particles can be calculated in different ways:
e/π technique, library of responses, matched clusters



Track in cone (Pin)

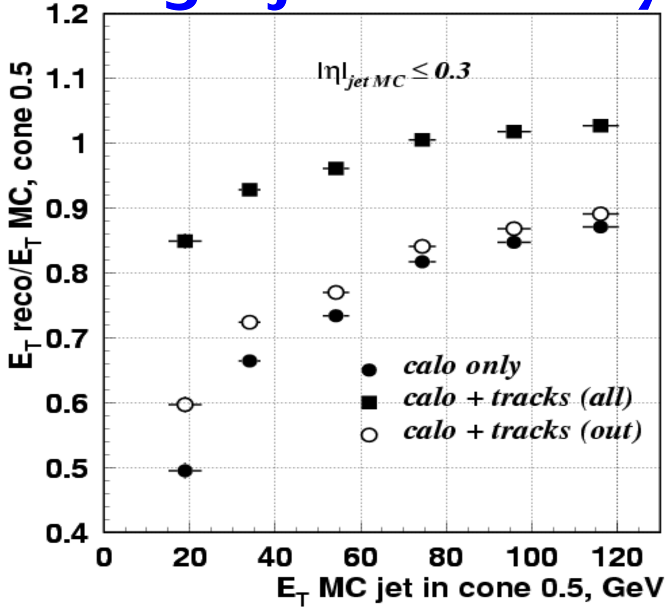
Track out of cone (Pout)

Calorimeter response in cone

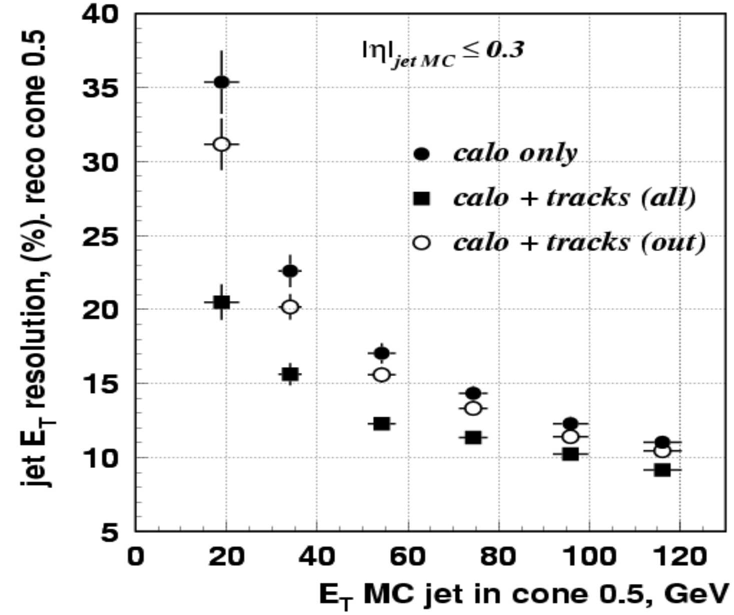
Remark: e/π technique (Dan Green, Energy flow in CMS Calorimetry, Fermilab-FN-0709, V.V.Abramov et al, CMS NOTE 2000/003). TB2002 and TB2006 will be used to estimate the particle response

Jet energy correction with charged particle tracks (example)

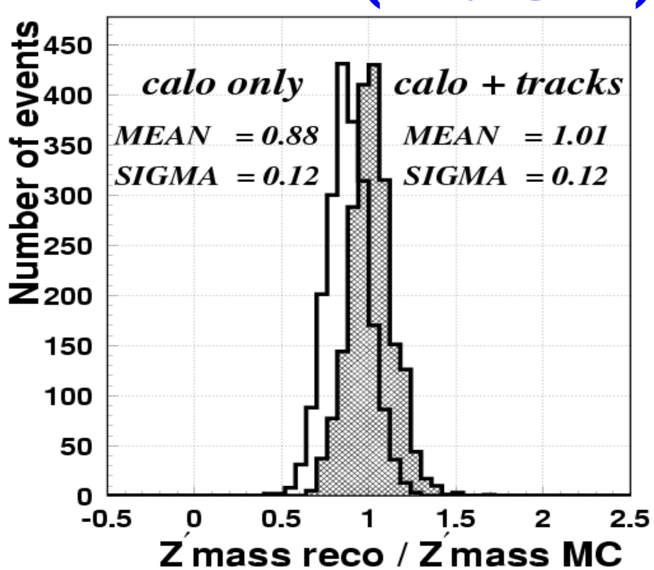
Single jets: linearity



resolution



Mass of Z' (120 GeV)



$\langle M_{rec}/M_{gen} \rangle$ and σ at $L = 2x10^{33}cm^{-2}s^{-1}$

Resonance	***Calo***	***Calo + tracks***
Z' ->jj(120 GeV)	0.88+-0.12	1.01+-0.12
H -> bbbar(125 GeV)	0.84+-0.11	1.006+-0.11

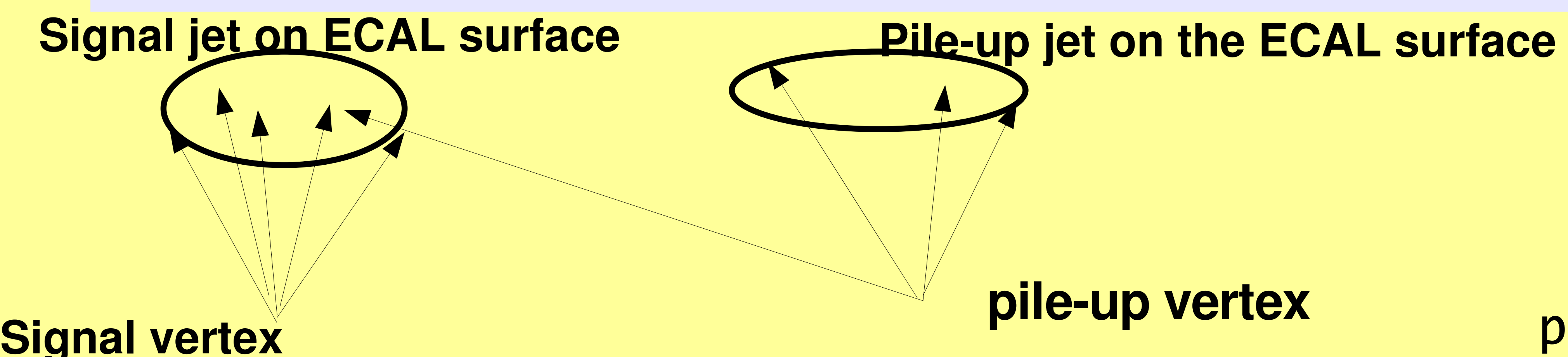
Improvement in fractional resolution ~ 15%

The association of the primary vertex and jet

- Jets are found in calorimeters
- a set of event vertices is found with reconstruction in tracker.
  The signal hard collision/trigger vertex is identified.
- reconstructed tracks from the signal vertex that have impact in
  ECAL within jet cone are identified for each jet.

Criterion α:

- the ratio of the sum of transverse momenta of all tracks found inside the jet cone and coming from the signal vertex to the transverse momentum of jet ($\alpha = \mathrm{sum}(P_{T jet}^{track})/P_T^{jet}$) is calculated.
  The jet vertex should satisfy: $|Z_{vertex}^{track} - Z_{vertex}^{primary}| < dZ$
- the jet is associated with the signal vertex if $\alpha > \alpha_0$



The association of the primary vertex and jet (central jet veto example for qqH)

Central jet veto:

There are no additional jets with $P_T > P_T^{threshold}$ in central rapidity region

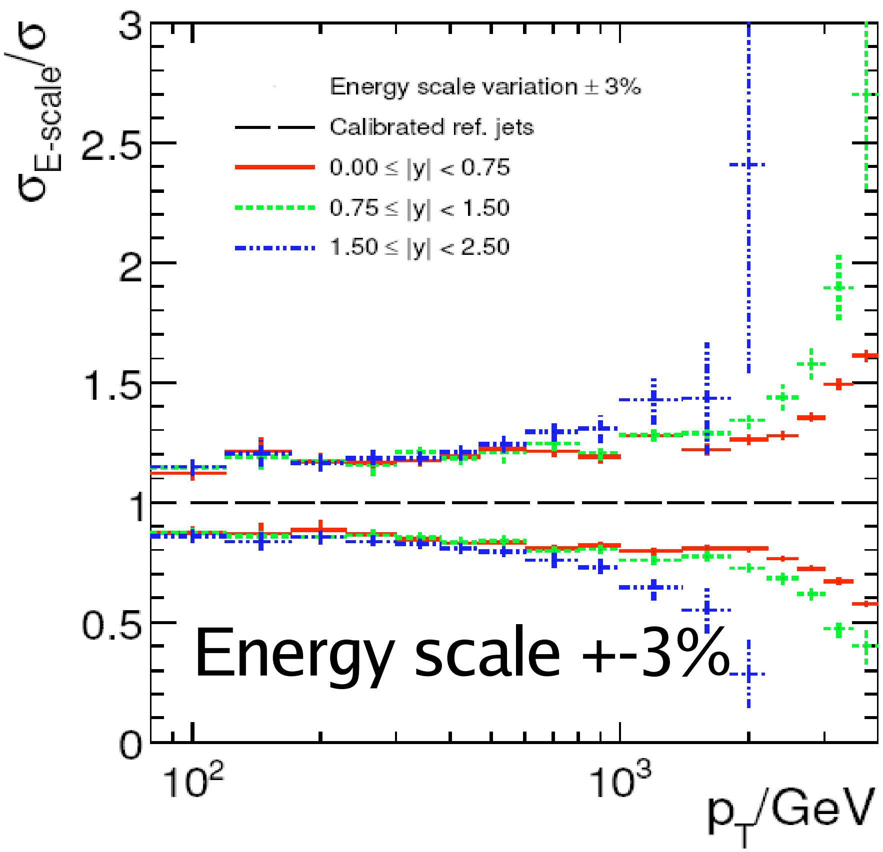
After signal vertex-jet association, the central jet veto is applied only on jets from signal vertex.

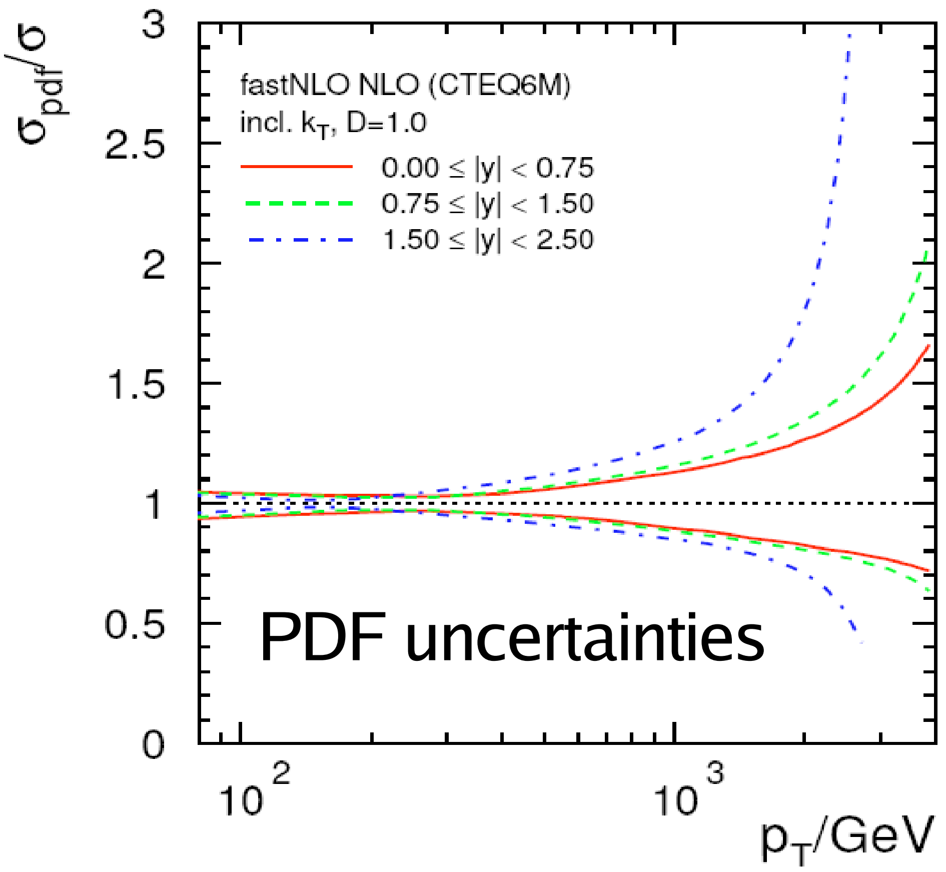
Fraction of signal events passing central jet veto depending on $P_t^{threshold}$, without and with proper signal vertex-jet association applied.

$P_T^{threshold}$	20 GeV	25 GeV	30 GeV	35 GeV	40 GeV	45 GeV
no vertex association	24.00%	60.00%	80.00%	87.00%	90.00%	93.00%
vertex association α=0.2	49.00%	75.00%	87.00%	90.00%	93.00%	94.00%

Uncertainties for the jet cross section

- **An uncertainty of the jet energy scale is expected to dominate the experimental uncertainties for high pT jet cross sections.**
- **Theoretical uncertainties are of the same order of magnitude and dominated by the PDF uncertainties at pT > 500 GeV. At lower momenta other sources of theoretical uncertainties (underlying event, fragmentation) may be significant.**





Summary

Jet measurements include three steps:

- **noise and pile-up suppression**
- **jet finding**
- **jet energy correction and jet direction correction ($|\eta|<2.4$)**

Jet energy and direction corrections are:

- **jet based (γ/Z+jet, W->jj, dijet, Monte-Carlo)**
- **using information from tracker**

Jet measurements requires monitoring and recalibration during data taking:

- **monitoring with off-line processes**
- **recalibration with off-line processes: using isolated particles, γ/Z+jet balancing, min bias for ϕ uniformity, etc**