Calorimeters

Showers & Detectors,

Signal Treatment & Commissioning,

Calibration & Reconstruction

Thanks to M. Shapiro, B. Heinemann, N. Hadley, J. Stark, all speakers of CALOR 2006/2008, “Calorimetry for particle physics” C. Fabjan, F. Gianotti - 2003

showers & detectors

- Electron, photons leave em showers in a calorimeter:
  - They are compact:
    - the shower maximum is at ~$6X_0$ longitudinally contained in ~$25\ X_0$,
    - laterally contained to 90% in 1 R_M, > 99% in 3 R_M
  - Measured in homogeneous (crystal) or sampling calorimeters
    - homogenous calorimeter have an excellent intrinsic resolution, but larger non-uniformities, no longitudinal segmentation
    - Sampling calorimeters use either scintillator or liq. Argon as active material, and Pb or Ur as absorber: fine segmentation, large variety of design
    - Intrinsic resolutions 3-20%/√E
- Hadrons produce showers, where the energy contributes
  - **20-30% hadronic cascade**
  - **30-60% electromagnetic cascade**
  - **20-30% of the initial energy is lost in slow nuclear interactions, with large fluctuations**
  - **Intrinsic resolution: 50%-100%/√E**
  - **Hadronic calorimeters complete the em-sections: shower max at ~2λ**
  - **Sampling calorimeters which have to be solid, robust and rather cheap**

Signal treatment & commissioning

- **Testbeams are a very important tool:**
  - Validate R&D of new detectors
  - To determine response of the detector to different particle types
  - To test and calibrate modules of the final detector
- **Online calibration allows to characterize the electonics:**
  - Noise suppresion
  - Linearity and Uniformity
  - Powerful tool for commissioning
- **Cosmic muons are often the first particles seen by the full detector!**
  - Allow to debug the interplay between different subdetecors
  - Give a first “in situ” calibration

Calibration & Reconstruction

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal treatment
  - Online Calibration
  - Commissioning
- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
  - Jets
  - E-flow
  - Simulation

Why calibrate?

- **How to know the energy of the incident particle from ADC counts?**
  - "Absolute calibration"
  - Data/MC comparisons
- **How to improve the resolution?**
  - Is the response linear?
  - Is the response uniform?
  - Is the response stable?

➔ **Online calibration**
  - Measurement of electronics noise
  - Monitoring of calorimeter response

➔ **Test Beam**
  - Test of prototypes
  - Calibration of final modules
  - Measurement of ADC/GeV conversion factors
  - Measurement of e/π

➔ **Offline calibration**
  - Cell level φ intercalibration
  - Clustering
  - Hadronic reweighting
  - Calibration with "physics objects": electrons, jets

Know the reconstructed energies at the percent level!

Cell level calibration

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal treatment
  - Online Calibration
  - Commissioning
- Calibration & Reconstruction
  - Cell level calibration
    - Layer weights
    - Φ intercalibration
    - Offline compensation
  - Electrons/photons
  - Jets
  - E-flow
  - Simulation

Sampling calorimeters: layer weights

For sampling calorimeters, the signal deposited in each active layer has to be multiplied by an adequate factor to get back the “true” energy

Factors are determined by test beam and/or simulation

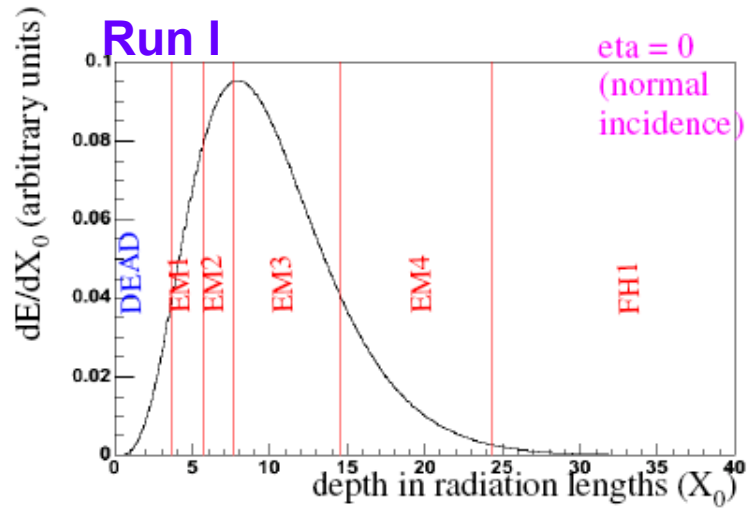
D0 added a solenoide in front of the calorimeter for the Tevatron Run II

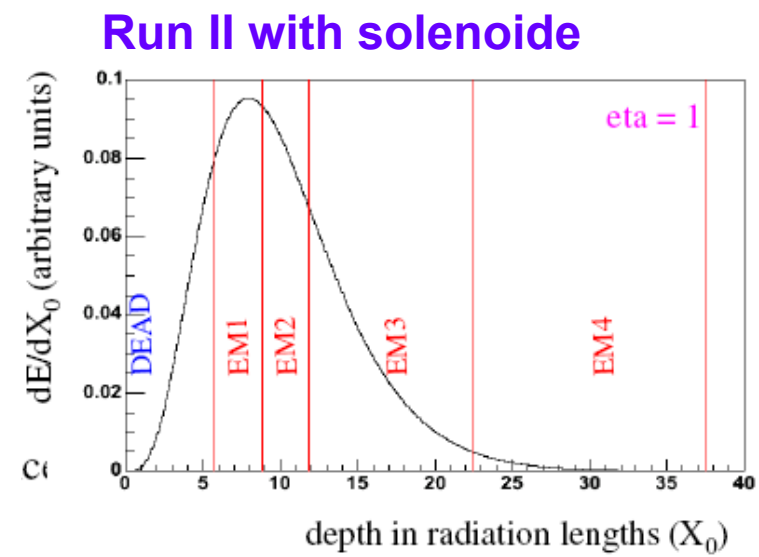
➔increase of dead material

➔➔ the layer weights are increased for the early layers to take the losses into account

According to the angle of the incident particle, the amount of dead material varies

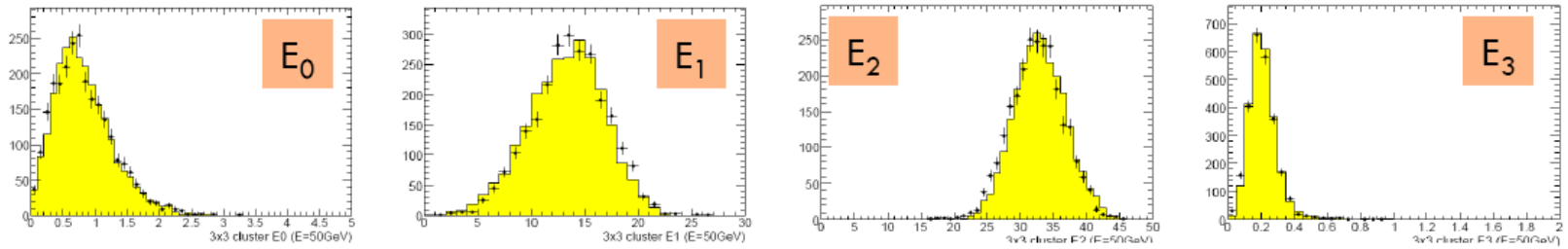
➔ layer weights vary



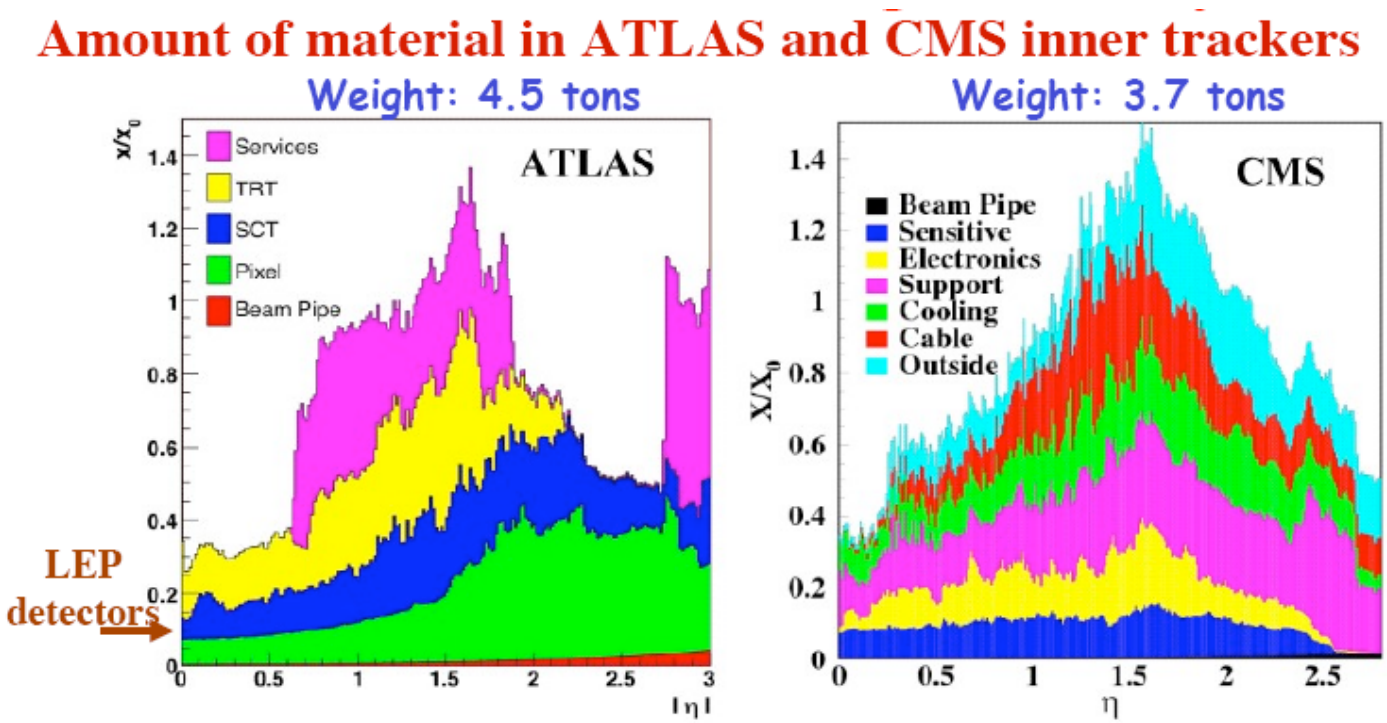


Sampling weights: Data/MC

These sampling weights are determined from test-beam data and simulation



Modeling the amount of dead material in front of the calorimeter is a crucial issue!



Dead material mapping

Detail map of dead material has to be implemented in the Simulation programs – in situ mapping: photon conversions!

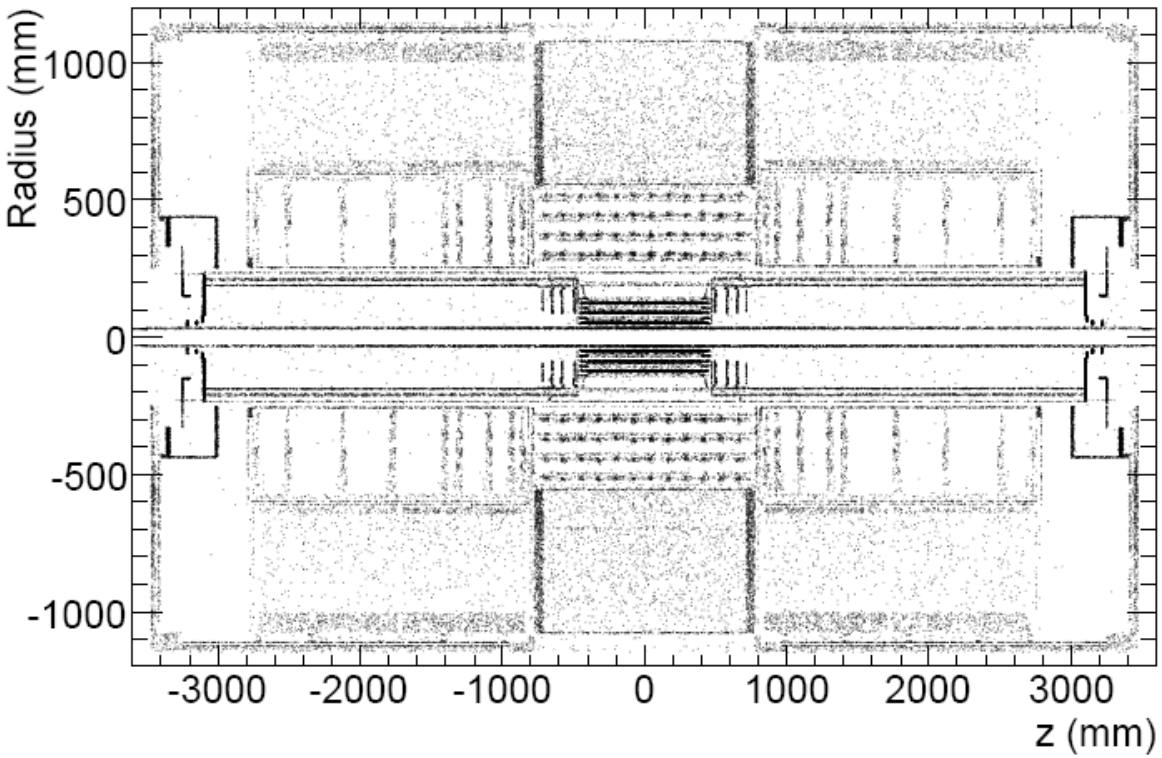


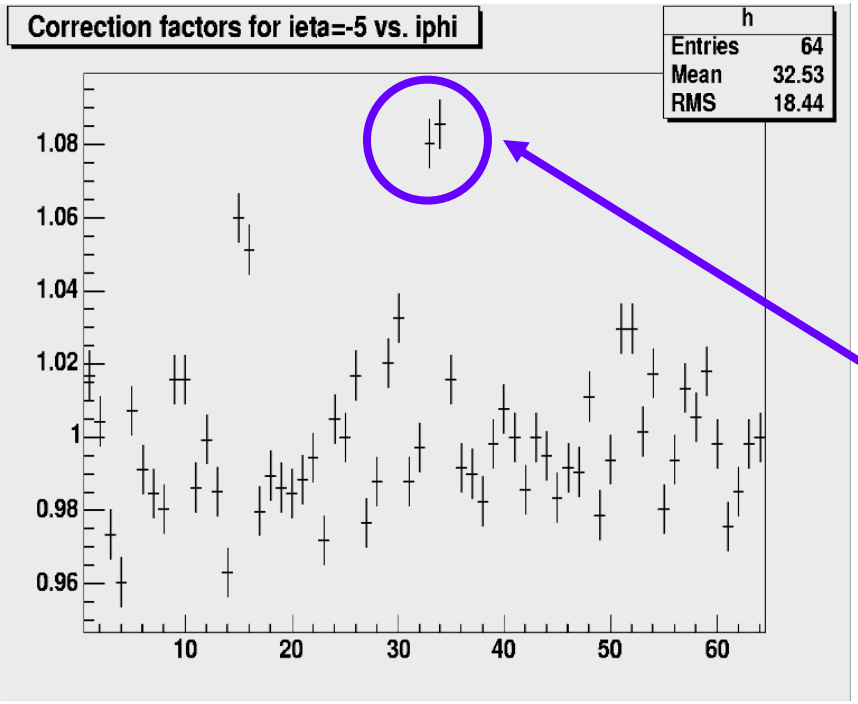
Figure 71. Mapping of photon conversions as a function of z and radius, integrated over ϕ, for the ID. The mapping has been made from 500,000 minimum bias events ($\sim$ 40 minutes of data-taking at 200 Hz), using $\sim$ 90,000 conversion electrons of $p_T > 0.5$ GeV originating from photons from π^0/η decays.

φ intercalibration

Electronics calibration is not sensitive in variations on the calorimeter cells

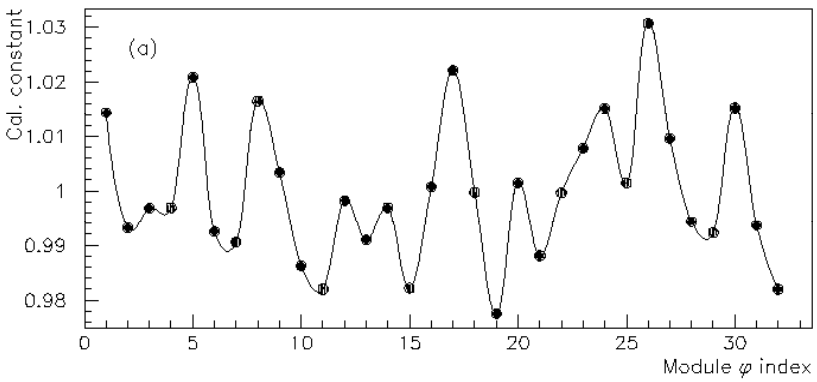
Beams are not polarized, therefore the energy flow should not have any azimuthal dependence ➔ calorimeters are constructed in “rings” ➔ equalize the energy response in one ring (depending on η, cell depth)

Difficulty: trigger should not bias the sample ➔ low L1 trigger threshold



Module 17 dropped during the calorimeter construction in mid 1980’s ➔ stable response over decades!

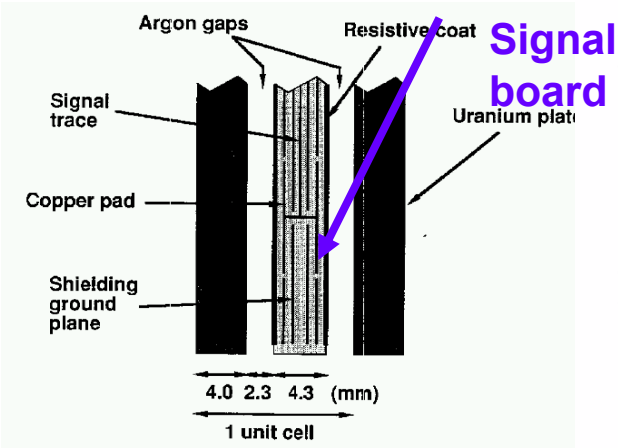
φ intercalibration

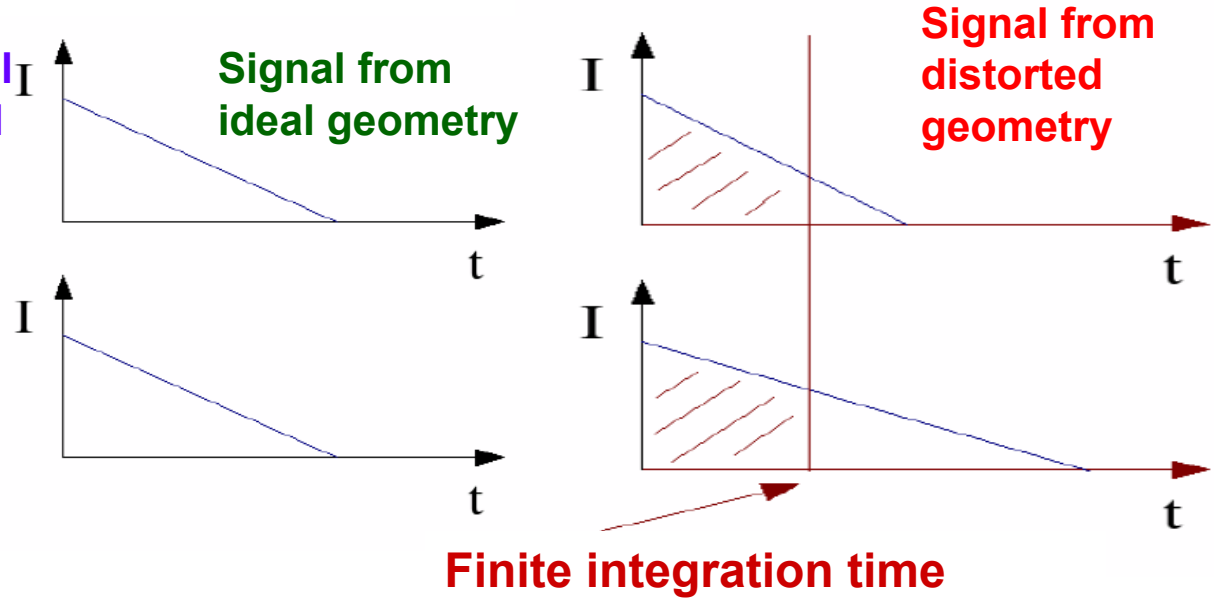


Φ intercalibration from Run I

Effect was less visible – Why?

L. Argon calorimeter made of di-gap cells



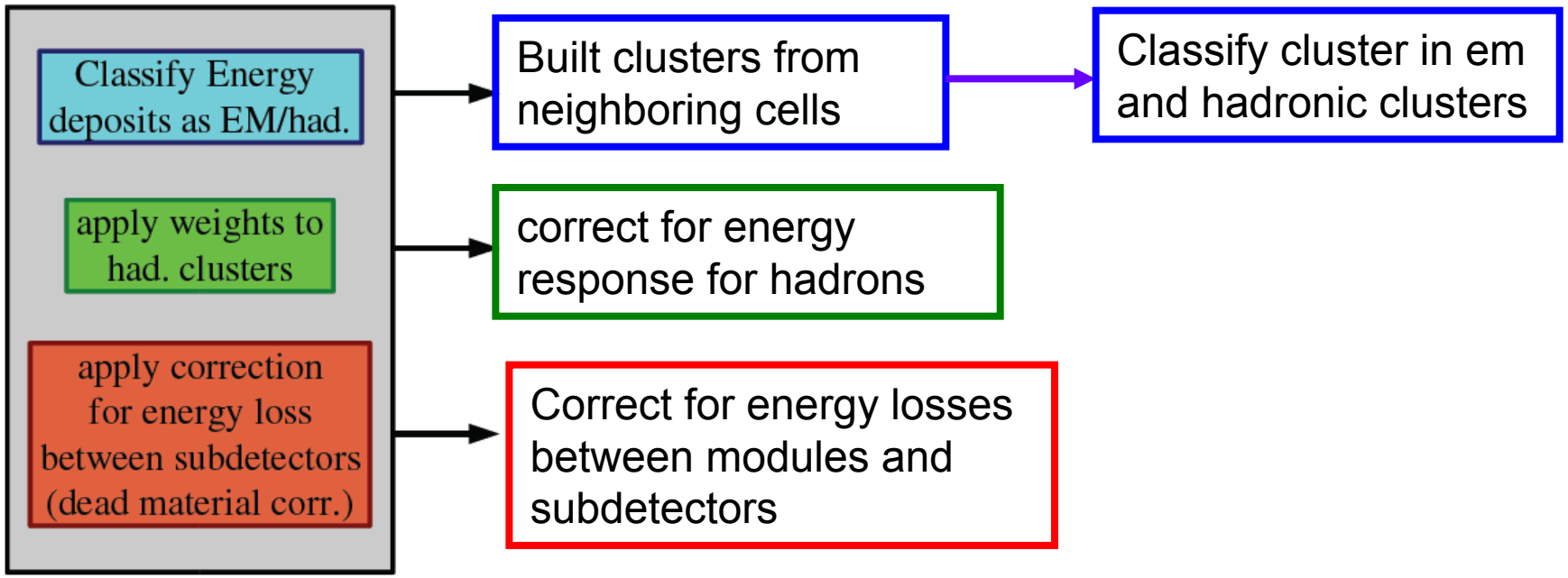


With an infinite integration time we still see the full charge, not with a short integration time!

Integration time went from 3.4μs (>> 450 ns) to 396 ns (85-90% of the signal collected)

Software compensation

Originaly implemented in H1, now also used by Atlas

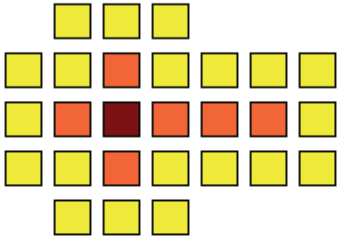


Clusters are reconstructed using "topological algorithm:

- **seeds: highest energy > 4σ**
- **neighbors: energy > 2σ**

Need to take care of overlapping clusters

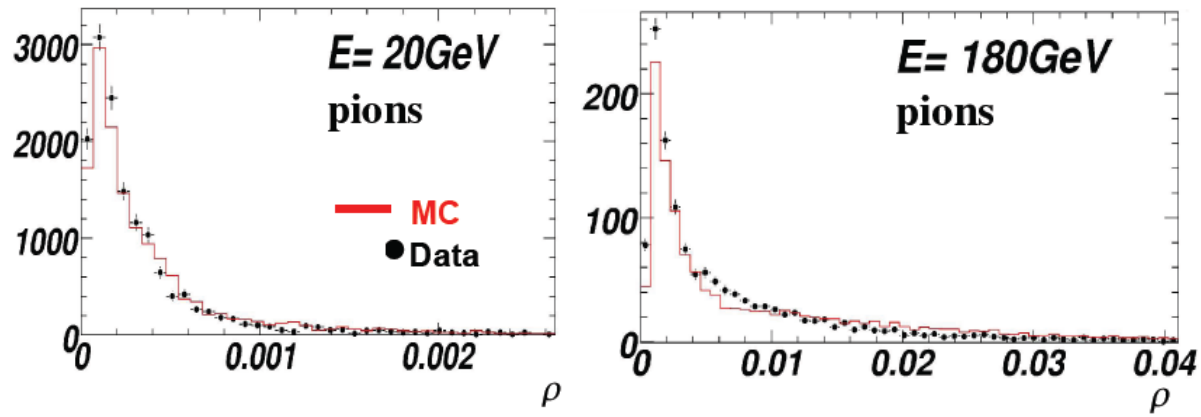
Clusters can span over subdetectors!



Software compensation

Classification based on cluster shape:

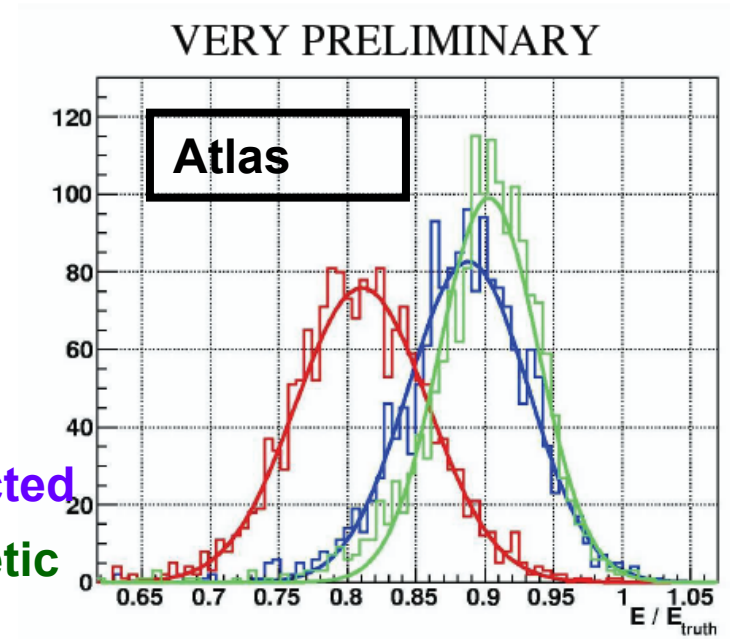
- shower maximum
- average energy density
- electro magnetic fraction



Determine the weights from MC, as function of the cluster position:

$$E_{CELL}^{reco} = w(\vec{x})\, E_{CELL}^{raw}$$

$$w(\vec{x}) = \frac{\langle E_{EM} + E_{non-EM} + E_{invisible} + E_{escaped} \rangle}{\langle E_{EM} + E_{non-EM} \rangle}$$



Preliminary results on improvements:

- Hadron energy scale correct at 98%
- Resolution

raw
corrected
theoretic

em reconstruction

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
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  - Missing ET
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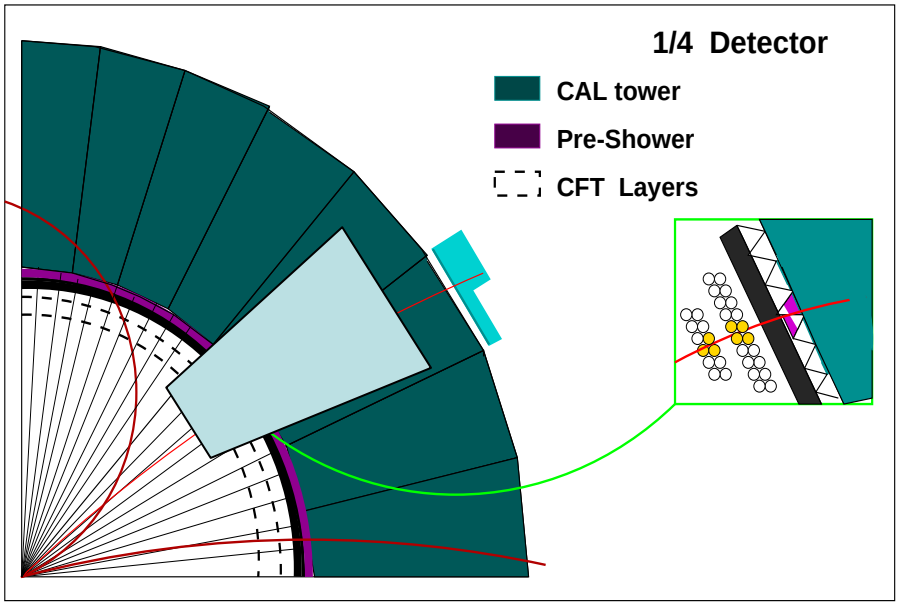
  - Simulation

EM reconstruction

- basically: look for narrow isolated clusters with high EM fraction
  - cone r=0.2
  - $E_{em}/E_{had} > 0.9$
  - isolation:

$$\frac{E_{total}^{cone0.4} - E_{EM}^{cone0.2}}{E_{EM}^{cone0.2}} < 0.2$$

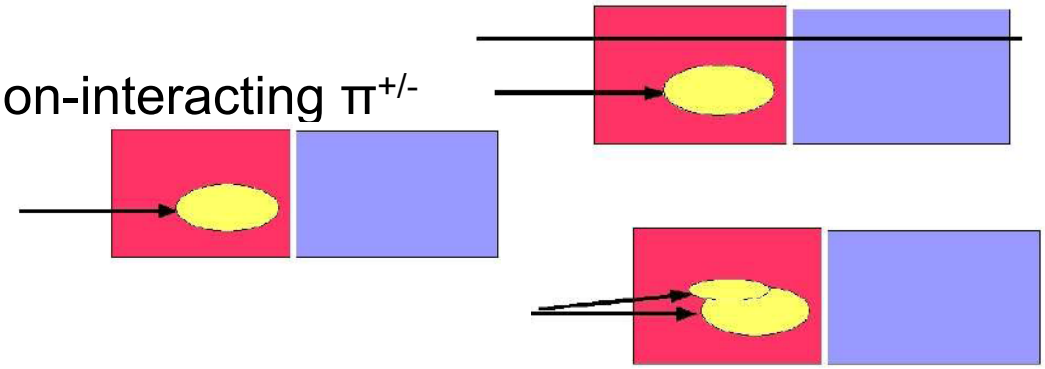


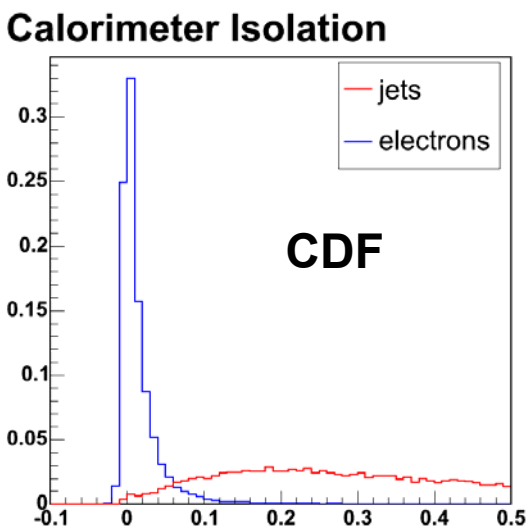
- track match for electrons (spatial and E/p), none for γ:
- matching in preshower detectors

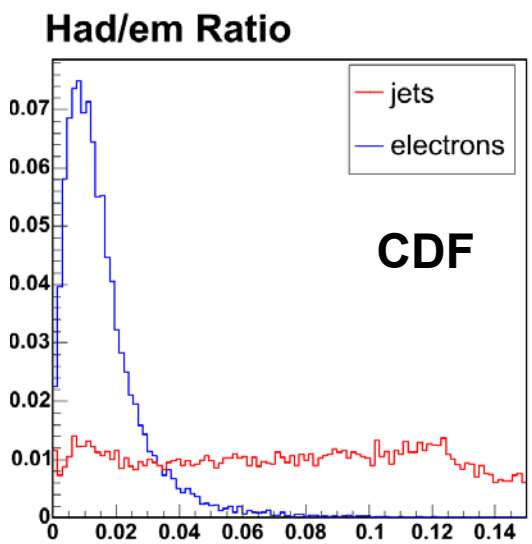
EM identification

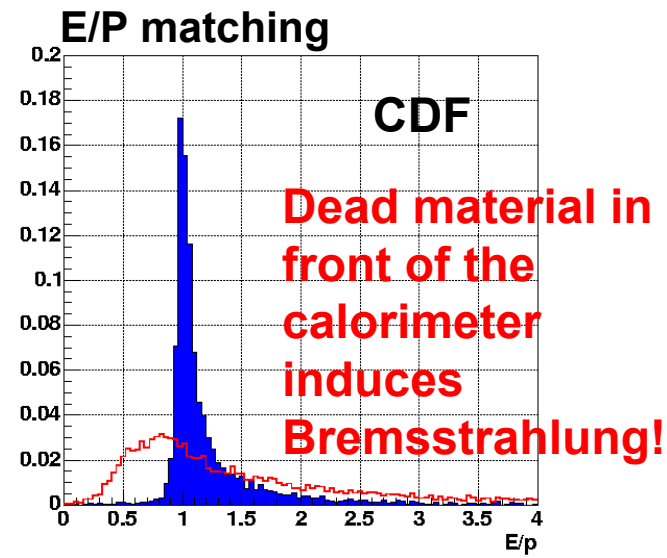
Main backgrounds:

- overlay over a π^0 and a non-interacting $\pi^{+/-}$
- early showering π+/-
- photon conversions







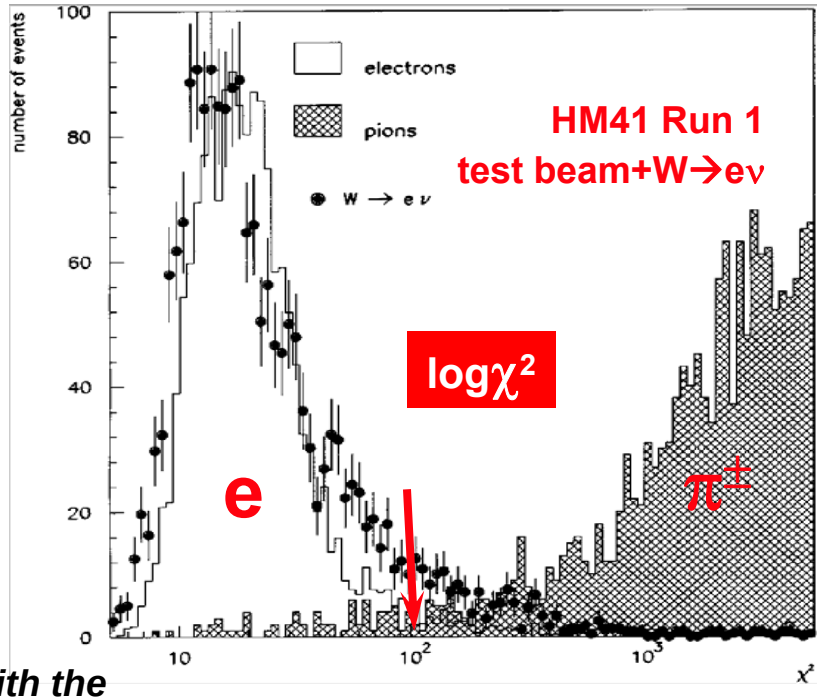


Using shower shapes

H-matrix

- use longitudinal and transverse shower shapes to take into account correlations between energy in cells
- measure compatibility of EM cluster with an electron shower → χ^2
- discriminate against hadronic (π) decays that pass EM fraction and isolation cuts

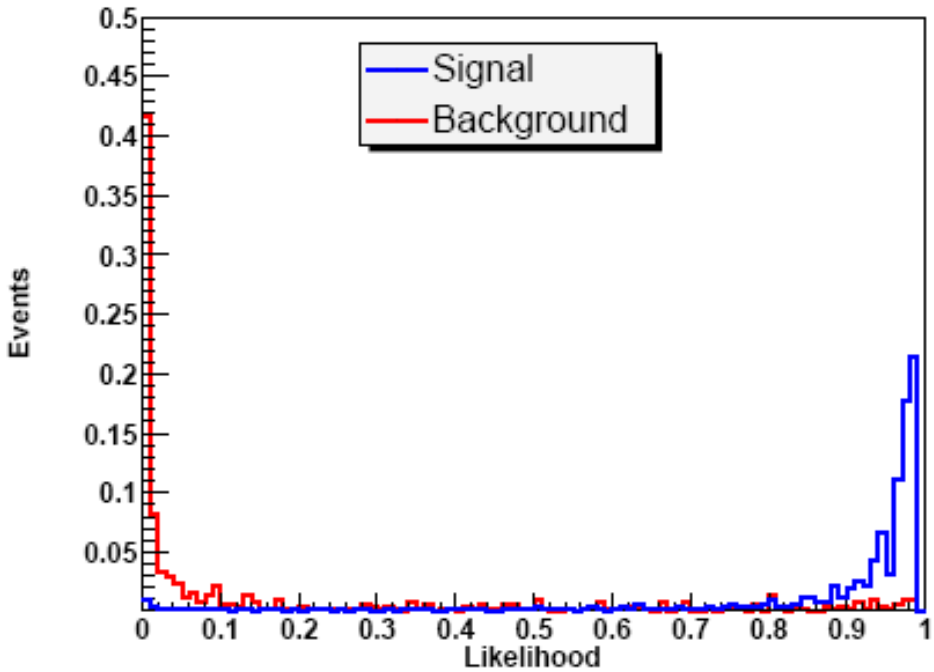
- tuned on MC in $\Delta\eta$ bins of 0.1, $|\eta| < 3.2$ for different energies
- HMx8 / HMx9 / Hmx41
  - energy fractions in each floor (PS), EM1, EM2, EM3, EM4
  - $\Delta\eta$, $\Delta\varphi$ in EM3 → grid (6,6)
  - $\log(E_{tot})$
  - Z/σ_z vertex

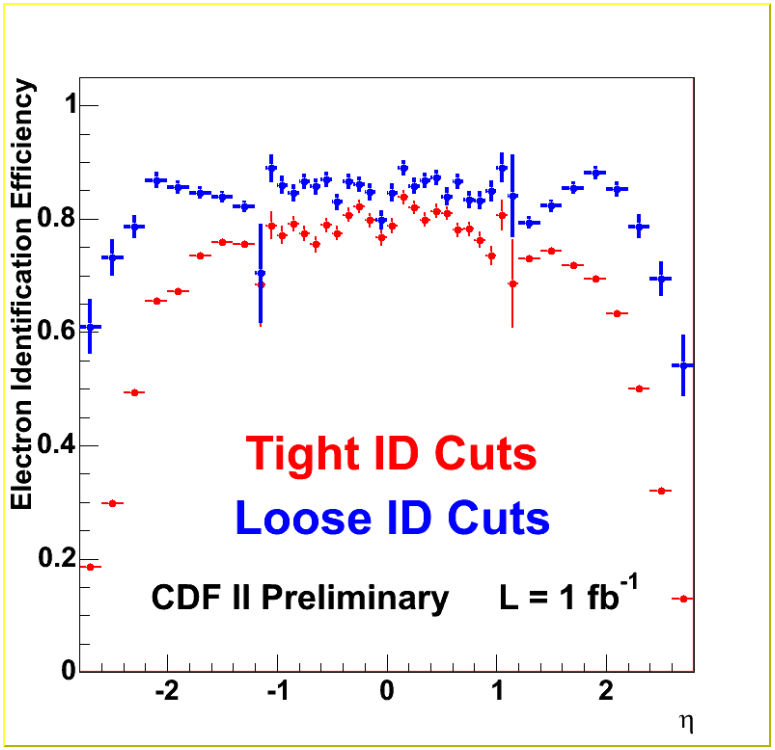


For a description of the H-matrix: "*Top Quark Search with the D0 1992-1993 Data Sample*" Phys. Rev. D52 4877 (1995)

Getting most out of it

- Use those input variables to built a multivariant discriminant:
  - Likelihood function, neural net
- Determine the electron identification efficientcy
  - Determined from Z→ee samples with the “tag and probe” method





Electron calibration

- Absolute scale from Z→ee events, with **E_1, E_2 incoming electron energies, Θ opening angle**

$$m = \sqrt{2E_1E_2 \cdot (1-\cos\theta)}$$

$$E_i = E_i^{\text{raw cluster}} + K(E_i^{\text{raw cluster}}, \vec{\alpha})$$

Raw cluster energy measurement from corrected calorimeter cell energies

parameterized energy loss correction from detailed detector simulation

$$E_i^{raw} = \sum_{j=\text{all cluster cells}} c_\eta(j) \cdot E'_j$$

Cell energies after electronics calibration, φ intercalibration and layer weights

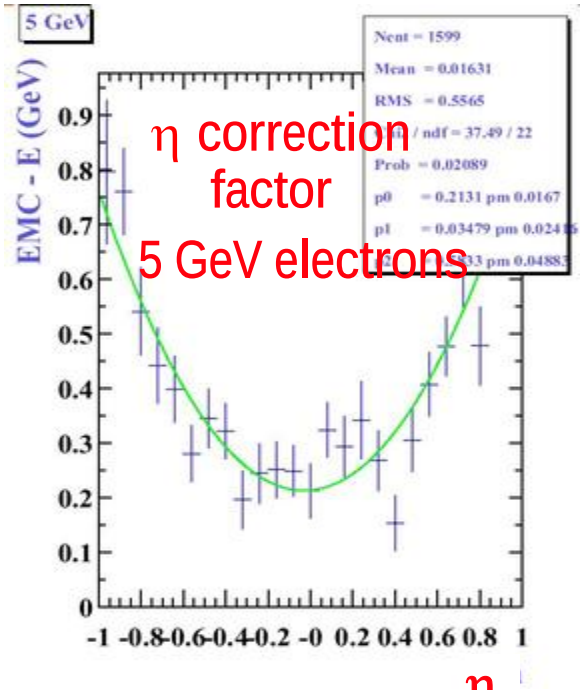
One (unknown) calibration constant per η ring

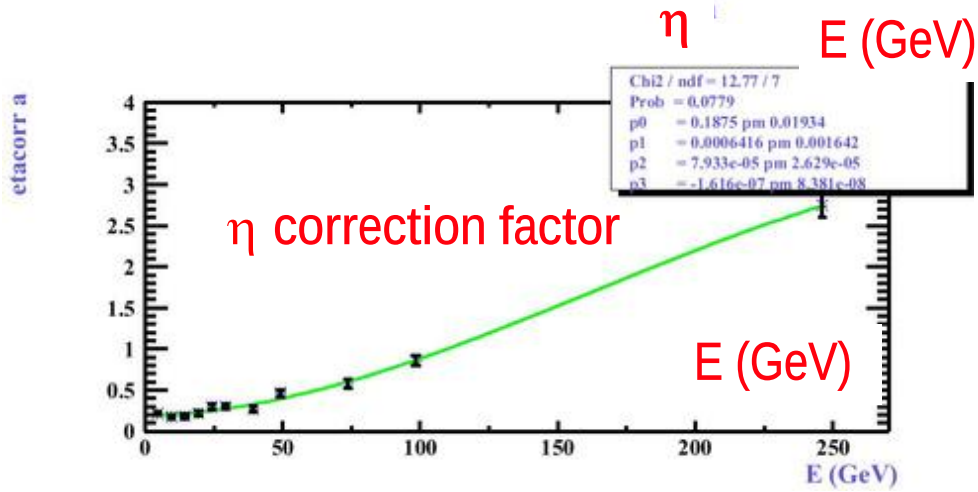
The c_η calibration constants minimize the experimental resolution on m_Z that is given by the very precise LEP measurements

Energy loss parameterization

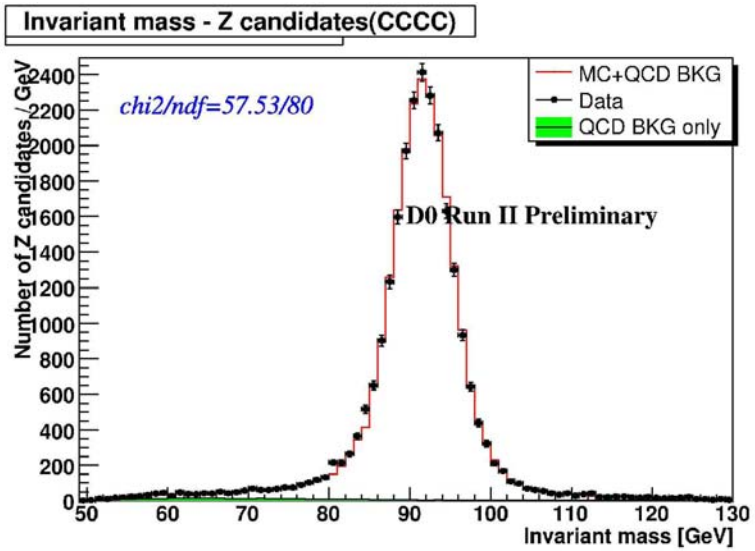
EM Energy Loss Corrections

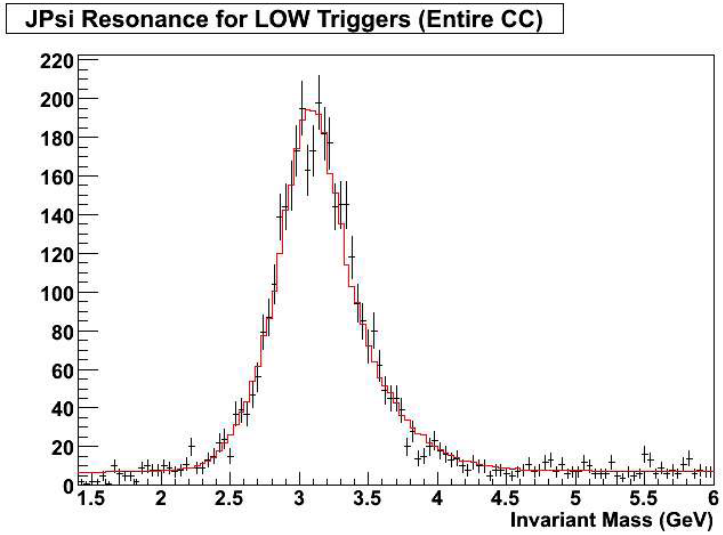
- **energy corrections for geometry dependent effects:**
  φ cracks, η dependence due to dead material in front of calorimeters
- **derived from single electron MC**





Electron energy calibration





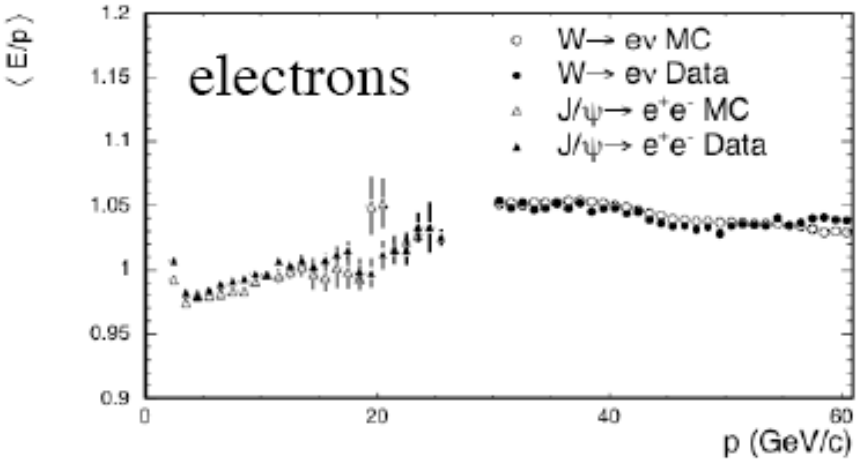
Difficulty: get correct dead material correction from the simulation!

Other calibration methods:

Low energy peaks: J/Ψ

E/p: be aware of bremsstrahlung effects!

Essentially the same corrections apply for photons!



jets

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal treatment
  - Online Calibration
  - Commissioning
- Calibration & Reconstruction
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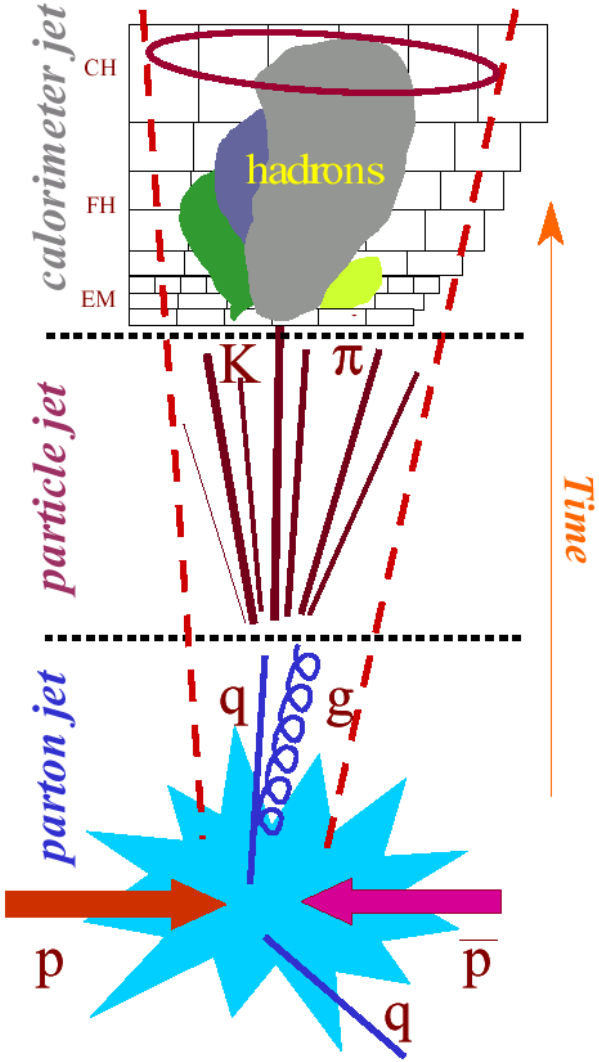
  - Electrons/photons
  - Jets
    - Jet reconstruction
    - Jet Energy Scale
  - Missing ET
  - E-flow
  - Simulation

Jet Finding



- **Calorimeter jet (cone)**
  - jet is a collection of energy deposits with a given cone *R*: $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$
  - cone direction maximizes the total E_T of the jet
  - various clustering algorithms

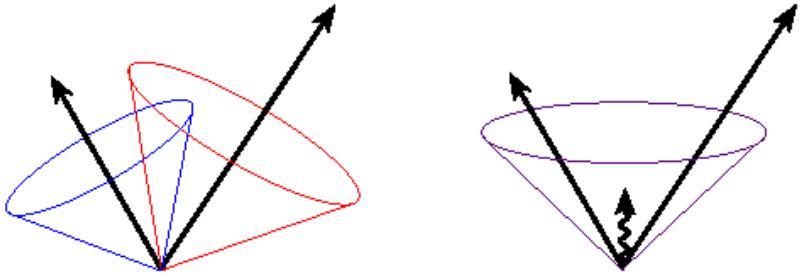
➜ correct for finite energy resolution
➜ subtract underlying event
➜ add out of cone energy

- **Particle jet**
  - a spread of particles running roughly in the same direction as the parton after hadronization

Jet Algorithms: Cone

- **Cone algorithms**
  - **draw a cone of fixed size around a seed**
  - **compute jet axis**
  - **draw a new cone around the new jet axis and recalculate axis and new E_T**
  - **iterate until stable**

  →In addition:
  - **add additional midpoint seeds between pairs of close jets**
  - **split/merge after stable proto-jets found**



Jet Algorithms: k_T

For each object and pair of objects:

$$d_{ii} = k_{T,i}^2$$

$$d_{ij} = \underbrace{\min(k_{T,i}^2, k_{T,j}^2)}_{\text{Soft}} \frac{\Delta R_{ij}^2}{D^2}$$

Collinear (if $\Delta R \ll 1$)

Resolution parameter (D=1)

order all d_{ii} and d_{ij}:

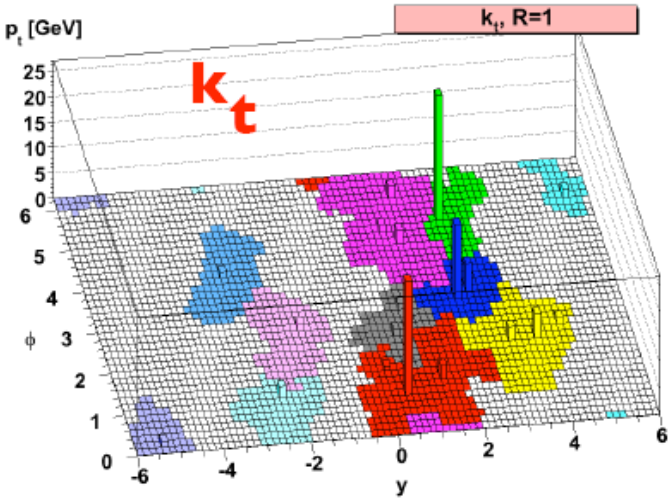
If $d_{min}=d_{ij}$

$\Rightarrow$ merge particles

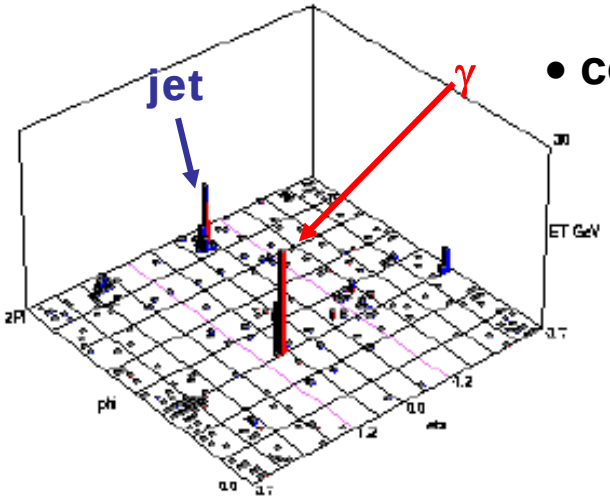
If $d_{min}=d_{ii}$

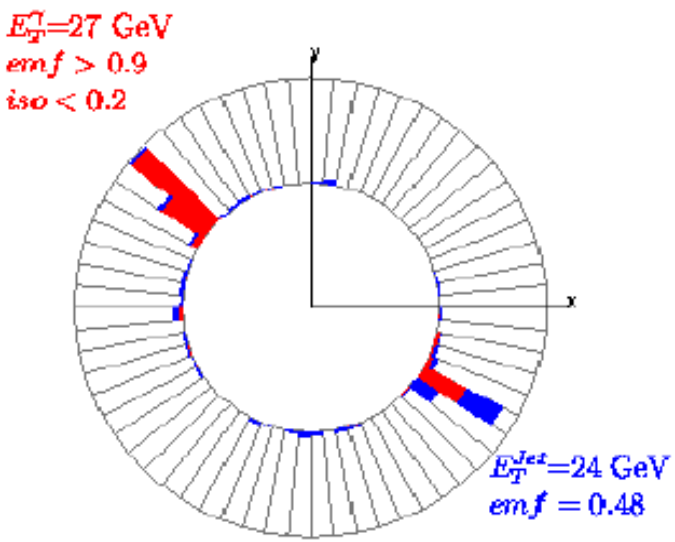
$\Rightarrow$ jet

- **theoretically favored, no split-merge**
- **to reduce computation time, start with 0.2 x 0.2 pre-clusters**



Jet Energy Scale





- **correct Jet Energy to the particle level**

$$E_{jet}^{corr} = \frac{E_{jet}^{raw} - O}{F_\eta R\ S} \qquad P_{T,jet}^{corr} = \frac{P_{T,jet}^{raw} F_\eta - MI}{R}$$

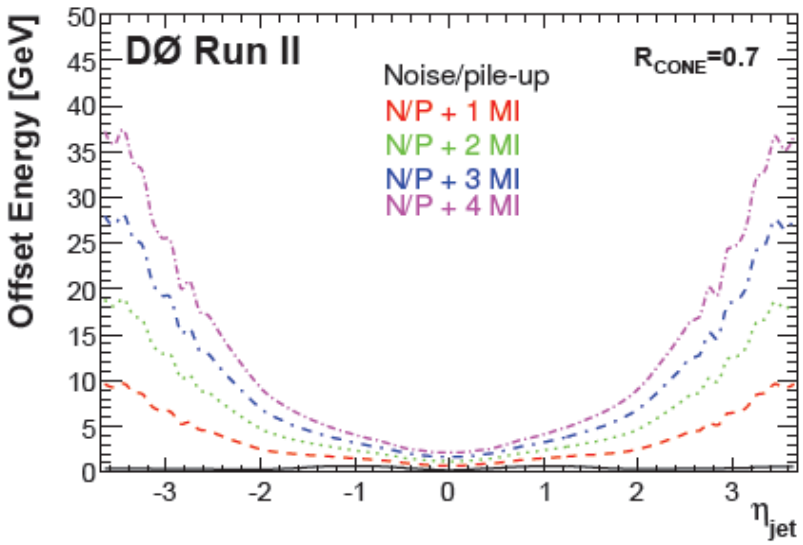
- ***O*: energy offset from underlying event, pile-up, noise, multiple interactions $\mathcal{MI}$**
  determined from Min. Bias Events
- **$\mathcal{R}$: calorimeter response**
  Testbeam, MC, γ-jet events
- **$\mathcal{S}$: energy contained in jet**
  corrections from MC - energy in cones around the jet axis

$\Rightarrow$ ***depending on jet algorithm!***

Offset corrections

Subtract all energy inside the jet cone not related to the hard interaction:

- electronics and uranium noise
- multiple $p\bar{p}$ interactions in the same bunch crossing
- left-overs from previous bunch crossings (pile-up)



Noise/pile-up

Estimated using zero-bias data; data triggered on the presence of bunch crossings and vetoing any hard interactions

Multiple interactions

Measured in minimum-bias data; data triggered using the luminosity monitors to signal potential inelastic scatters. Contribution from additional interactions determined from:

$$\mathrm{MI}(N_{PV}, L) = \mathrm{MinBias}(N_{PV}, L) - \mathrm{MinBias}(N_{PV} = 1, L)$$

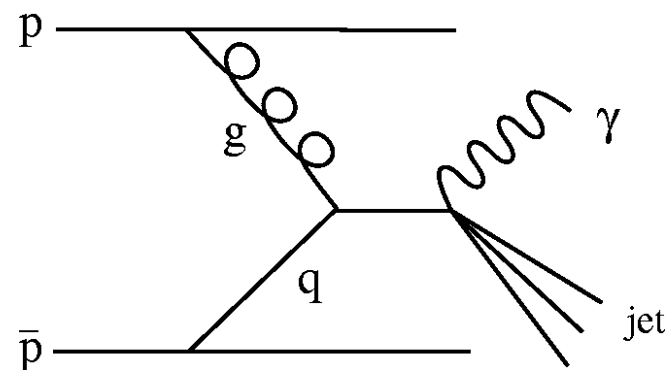
Response correction

One possibility:

use γ+jet events

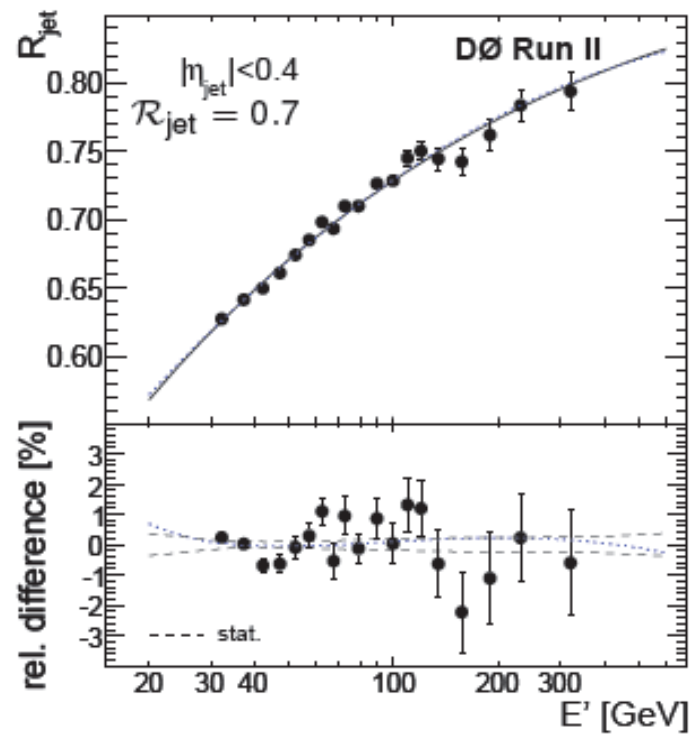
-γ well measured and calibrated

- missing transverse energy projection:



$$R_{\text{had}} = 1 + \frac{\vec{E}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}^{\,2}_{T,\gamma}}$$

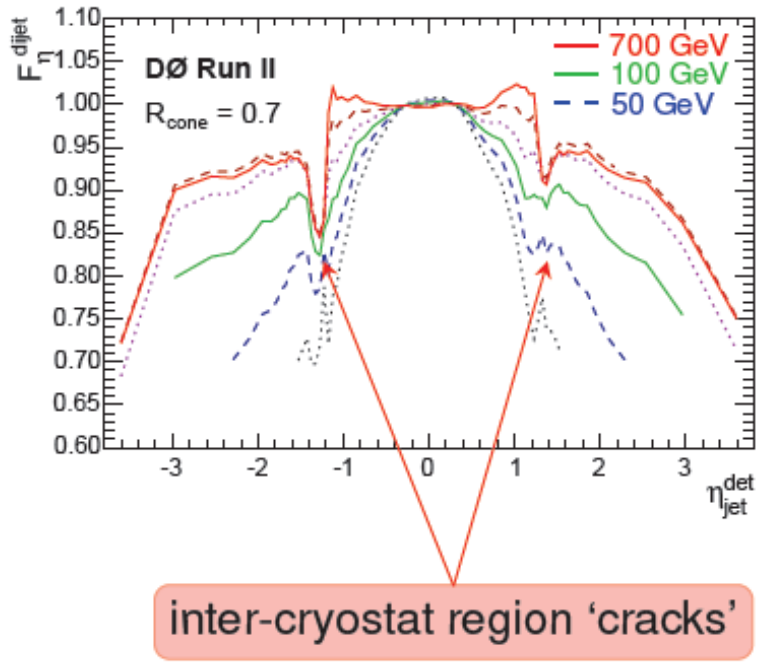
The 25% correction to the response is the largest of all energy scale contributions

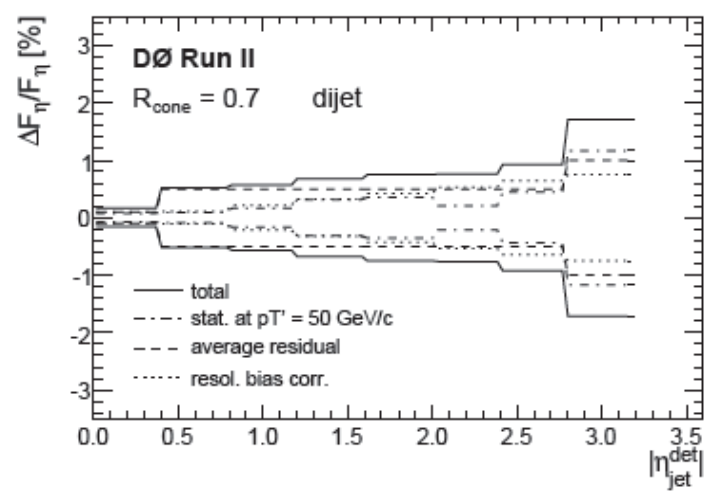


η dependent response correction

Calibrate forward jets with respect to central ones:

- photon+jet one tag photon within |η| < 1.0 contributes to low p_T region
- di-jet one tag jet within |η| < 0.4 contributes to high p_T region

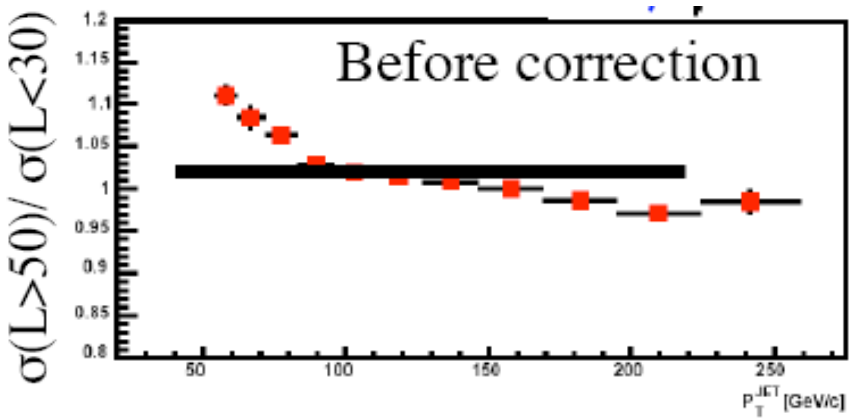


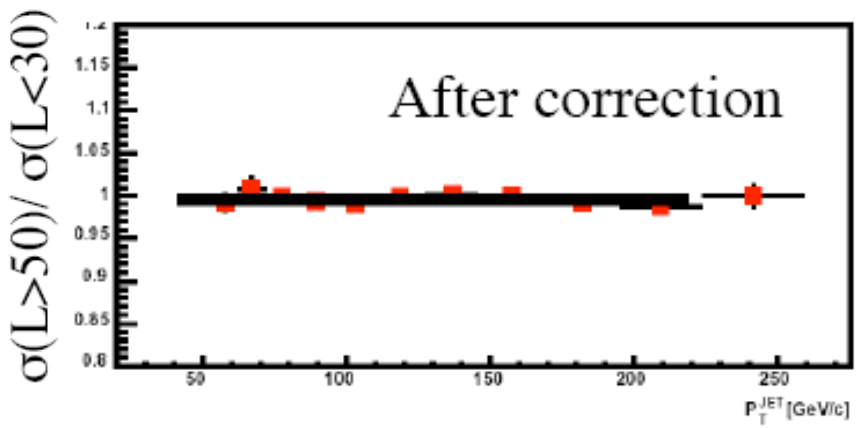


JES for k_T algorithm

Problem of k_T algorithm in hadron colliders: Multiple interactions

- **k_T algorithm is attracted to energy deposits and picks up the energy from MI, UE etc<.**
- **k_T algorithm has now been used by CDF to measure a cross-section for Run2:**
- **emiprical energy correction factor used using the fact that the cross-section is luminosity independent**





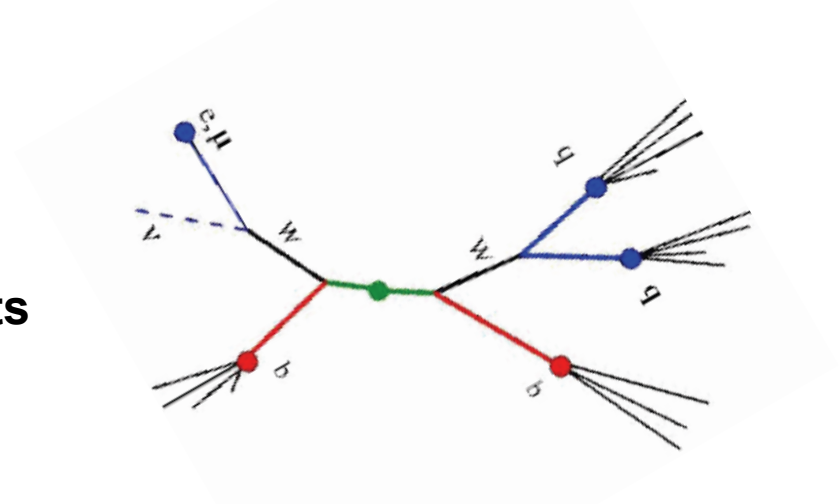
Jet calibration from top events

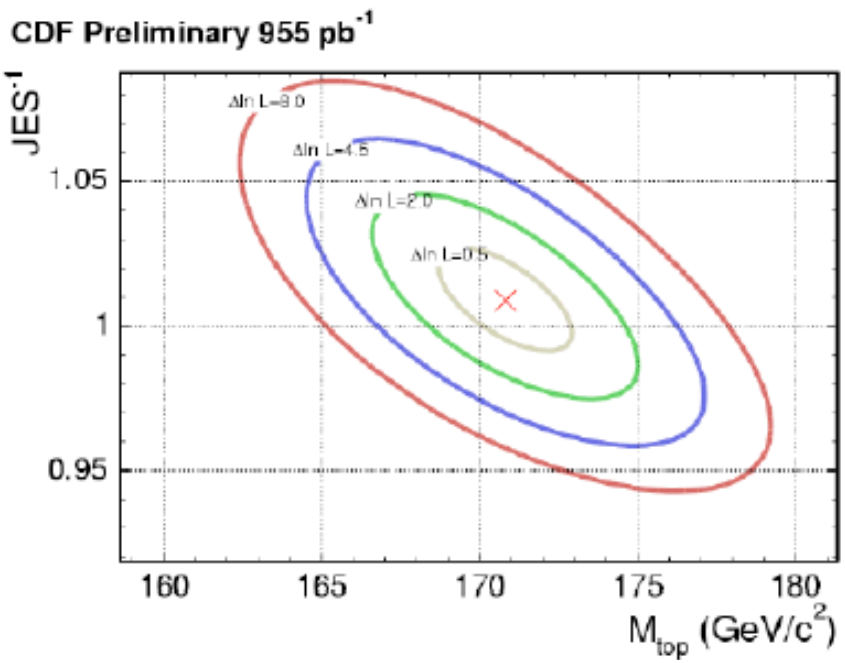
Use the W→ jj decay in top events to calibrate the jet energy scale

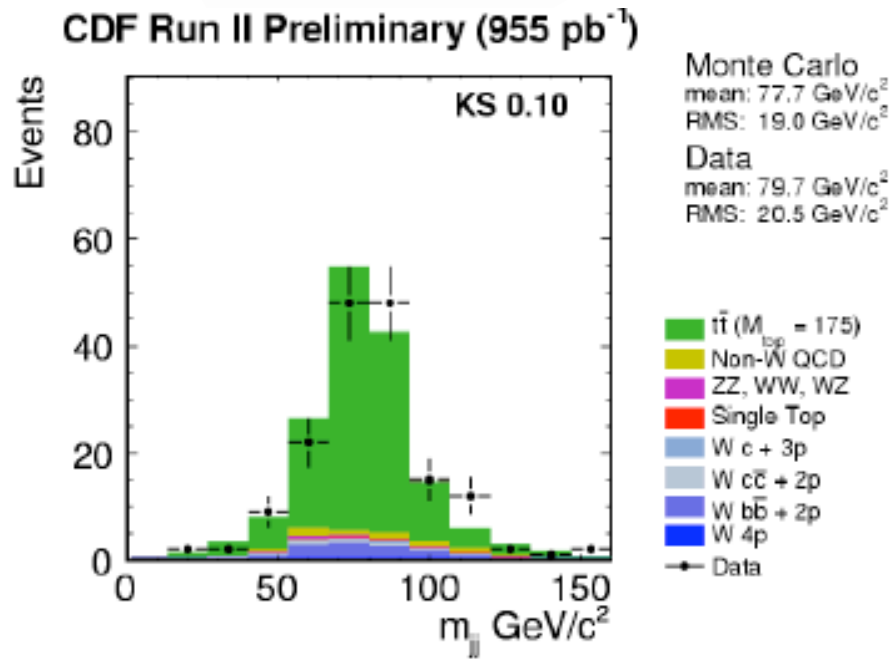
Fit the JES in data an MC

Constraints JES to 2% with 166 evnets

➔ At LHC: 45 000 top events/month!





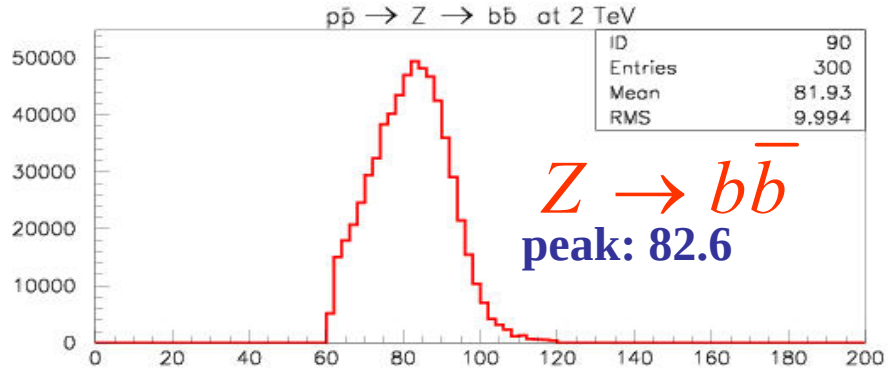


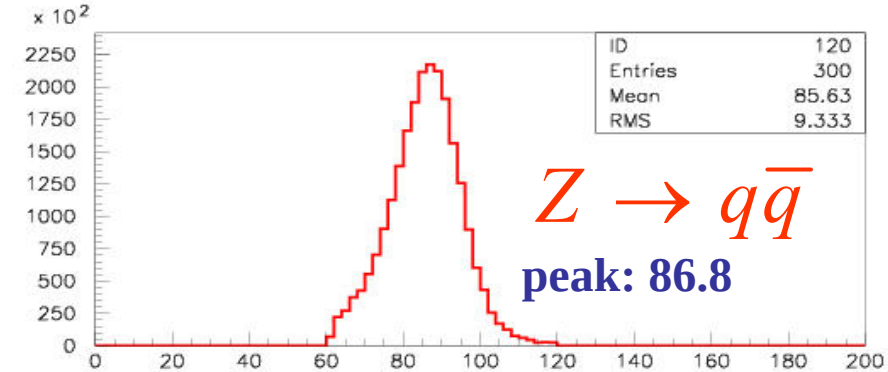
b-jet calibration

- **naïve reconstruction of Z-mass shows a lower mass for selected b-jets than light quark jets.**

⇒ energy losses from semi-leptonic b decays (ν, μ)

⇒ wider b-jets (due to the large b-mass)





Z→ bb

Very difficult to see Z→jj events due to QCD background

except for Z→bb that has a more stringent selection

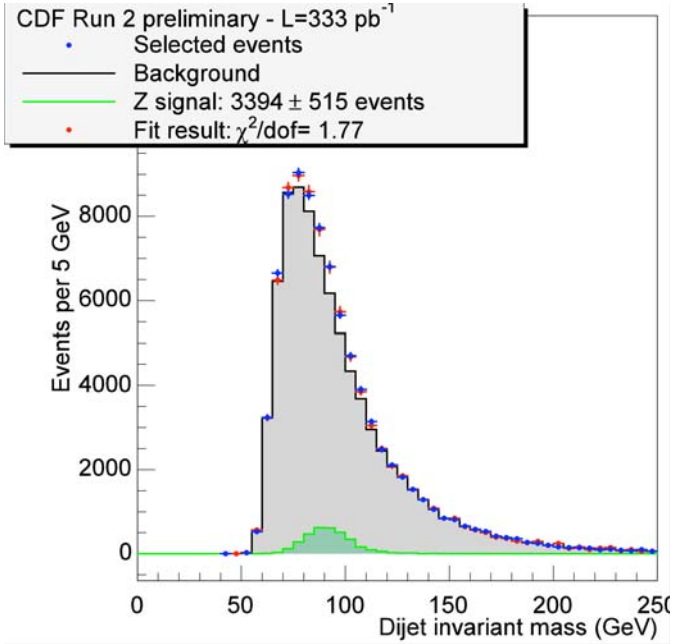
Difficult to trigger:

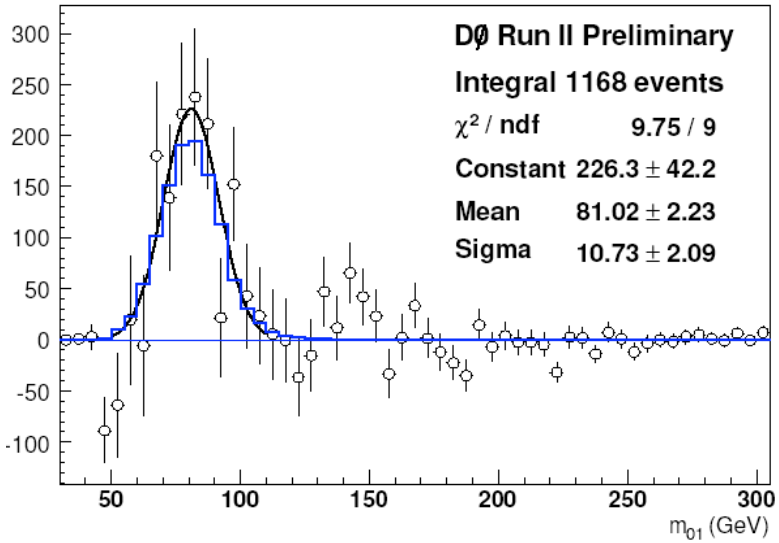
CDF: secondary vertex trigger

D0: events with muons from semi-leptonic decays

Calibration:

- **μ used to estimate energy lost by ν**
- **Data/MC difference**





E-flow

- Showers & Detectors
  - Generalitie
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal treatment
  - Online Calibration
  - Commissioning
- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
  - Jets
  - E-flow
  - Simulation

E-flow

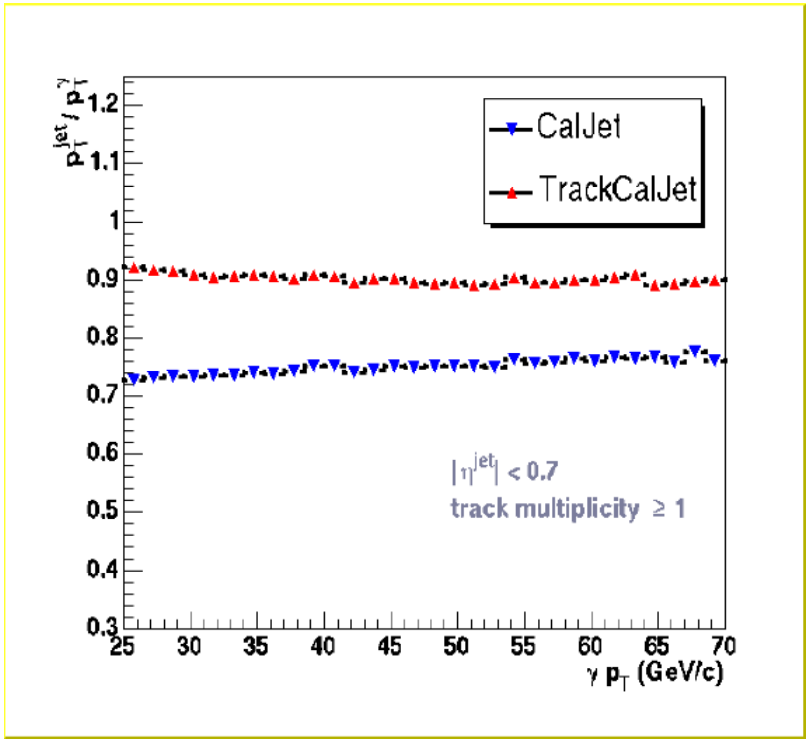
Idea:

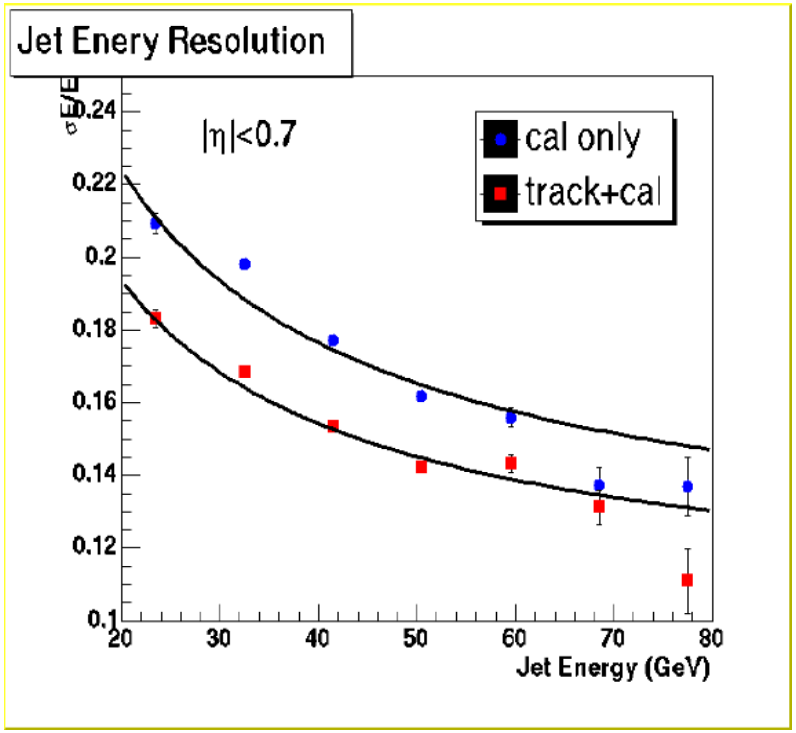
- Combine energy measurement from the calorimeter with the momentum measurement from the tracking:
- To not double count the energy: energy deposited in the calorimeter by the tracks has to be masked

- First algorithms developed by Aleph: clean e^+/e^- environment
- Algorithms also developed by H1 for inclusive measurements, successfully adapted by CDF:
  - extrapolate track to the inner surface of the calorimeter and apply a cone or a cylindrical mask to the calorimeter cells behind the track
  - maximize between the energy in the mask and the track momentum
- Track+calorimeter jet algorithm developed by D0
  - be aware of tracks start in the jet cone, but leak out of it and vice-versa
  - algoritm that prevents masking of too much energy

Calorimeter+track jets

- **Improvements in particular from low momentum tracks**
  - **Better track than calorimeter resolution for low energies**
  - **Threshold for particles to "reach" the calorimeter**





Simulation

- Showers & Detectors
  - Generalities
  - EM Calorimeters
  - Hadronic Calorimeters
- Signal Treatment & Commissioning
  - Signal treatment
  - Online Calibration
  - Commissioning
- Calibration & Reconstruction
  - Cell level calibration
  - Electrons/photons
  - Jets
  - Missing ET
  - E-flow
  - Simulation

Simulation

Many corrections derived for the energy determination, (weighting factors, dead material corrections) depend on the simulation

➔a simulation corresponding in the best possible way to the real world is crucial!

Full and detailed simulation used a lot of computing time:

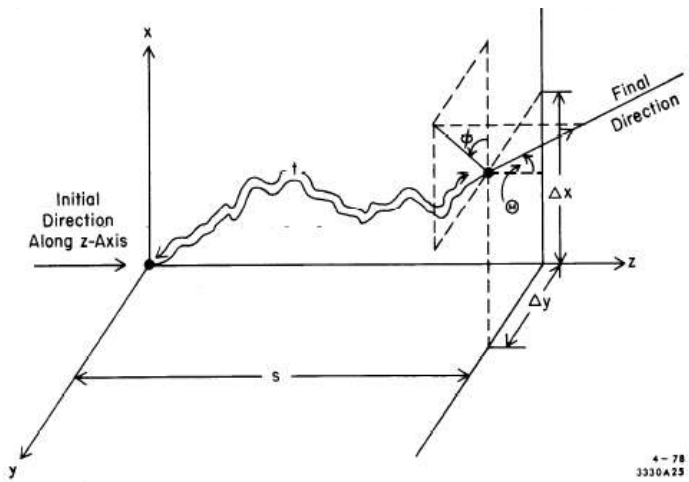
➔"fast simulation" uses only parameterizations in η/φ of resolution, energy losses and efficiencies applied to particles on the generator level.

Those are mostely obtained from the full simulation

Basic Principle of the Geant Simulation:

Track the particles through a precise implementation of the various detector materials

- **CDF/D0 use Geant 3**
- **LHC experiments use Geant 4**



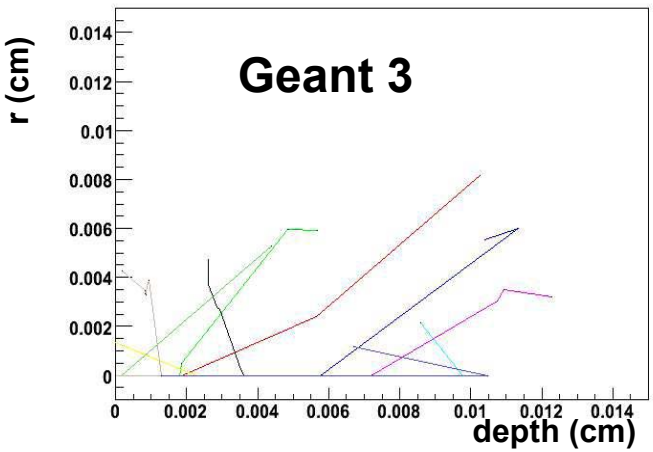
But: several programs to simulate em/had showers exist

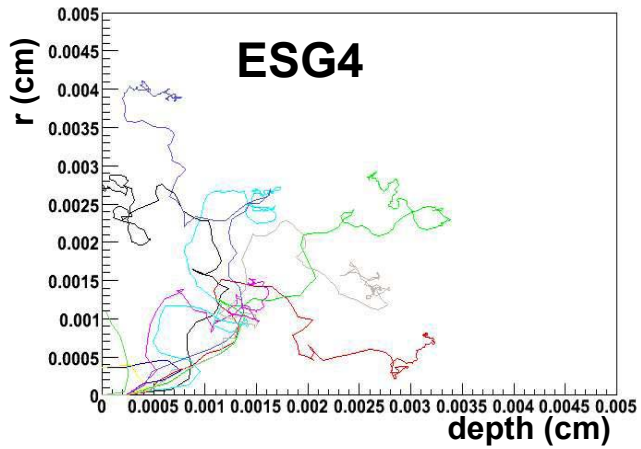
Simulating showers

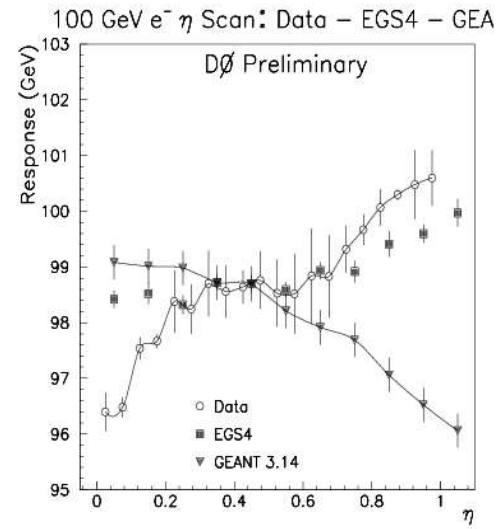
Different approaches to simulate the physics: **None describes the data!**

400 keV electrons in Ur

➔ Factor of 3 difference



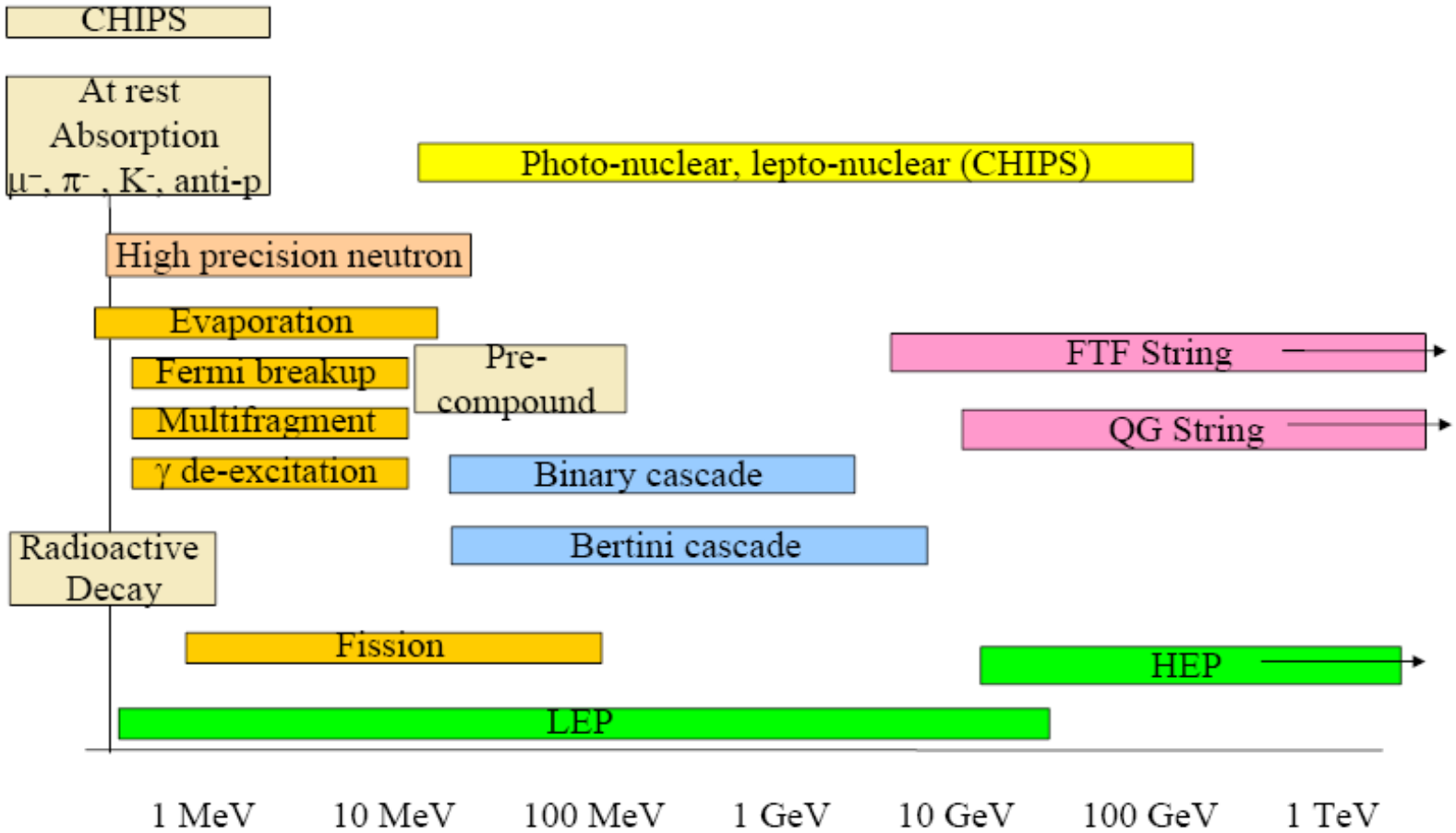




Simulation parameters can be adjusted (maximum step size, maximum fraction energy loss in one step, boudary crossing precision…)

➔ Values of these parameters influence the shower properties and the computing time needed

Hadron showers

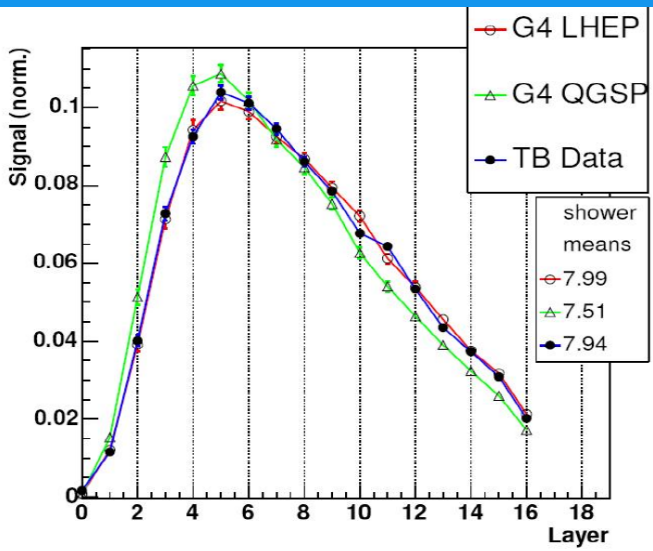


The number of physics processes to be considered is extremely complex!

Geant 4 ingredients

- **A lot of activity in this area since 1997 for LHC purposes**
- **Comparions with LHC test beam data**
- Cross-sections
- Models for interactions
  - Elastic
  - Inelastic **QGSP**
    - String models (~10 GeV – 1 TeV+
      - Quark Gluon String (**QGS**),
      - Complemented by Quasi-elastic
    - Optional : Cascade (from ~0.2 to or 10 GeV): BIC, Bert
    - Pre-equilibrium and equilibrium models: **P**
    - Capture
    - Decay

- **CMS shower shape comparison**

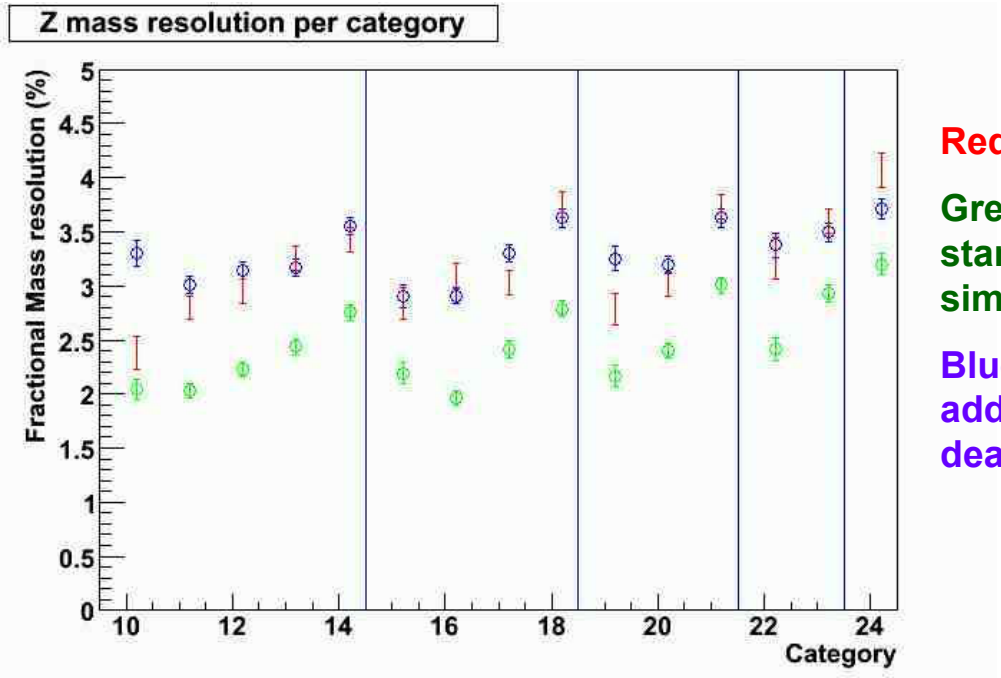


ɔions, leaving MIP in ECAL and L0.

  - Inelastic - **LHEP**
    - **H**igh **E**nergy **P**arameterized (~25GeV -
    - **L**ow **E**nergy **P**arameterized (0- ~55 GeV)
    - Capture
    - Decay

Be precise with dead material!

Energy resolutions depend a lot on the material in front of your calorimeters – not always the knowledge is properly propagated from the pits to the software groups!



Red: data

Green: standard simulation

Blue: with additional dead material

Reconstruction & Calibration

- Understanding and simulating correctly your detector and the showers is fundamental to determine energy corrections
- Try as much as possible to derive correction from data or find estimators to validate the data/mc correspondence
- Calorimeters allow to reconstruct a big variety of objects to do physics analysis with:
  - Electrons/photons
  - Jets
  - (missing E_T and taus)
- Combining tracking and calorimeter measurements can improve results: correct modeling is necessary!