From Raw Data to Physics Results

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CERN Summer Student Lectures 2011
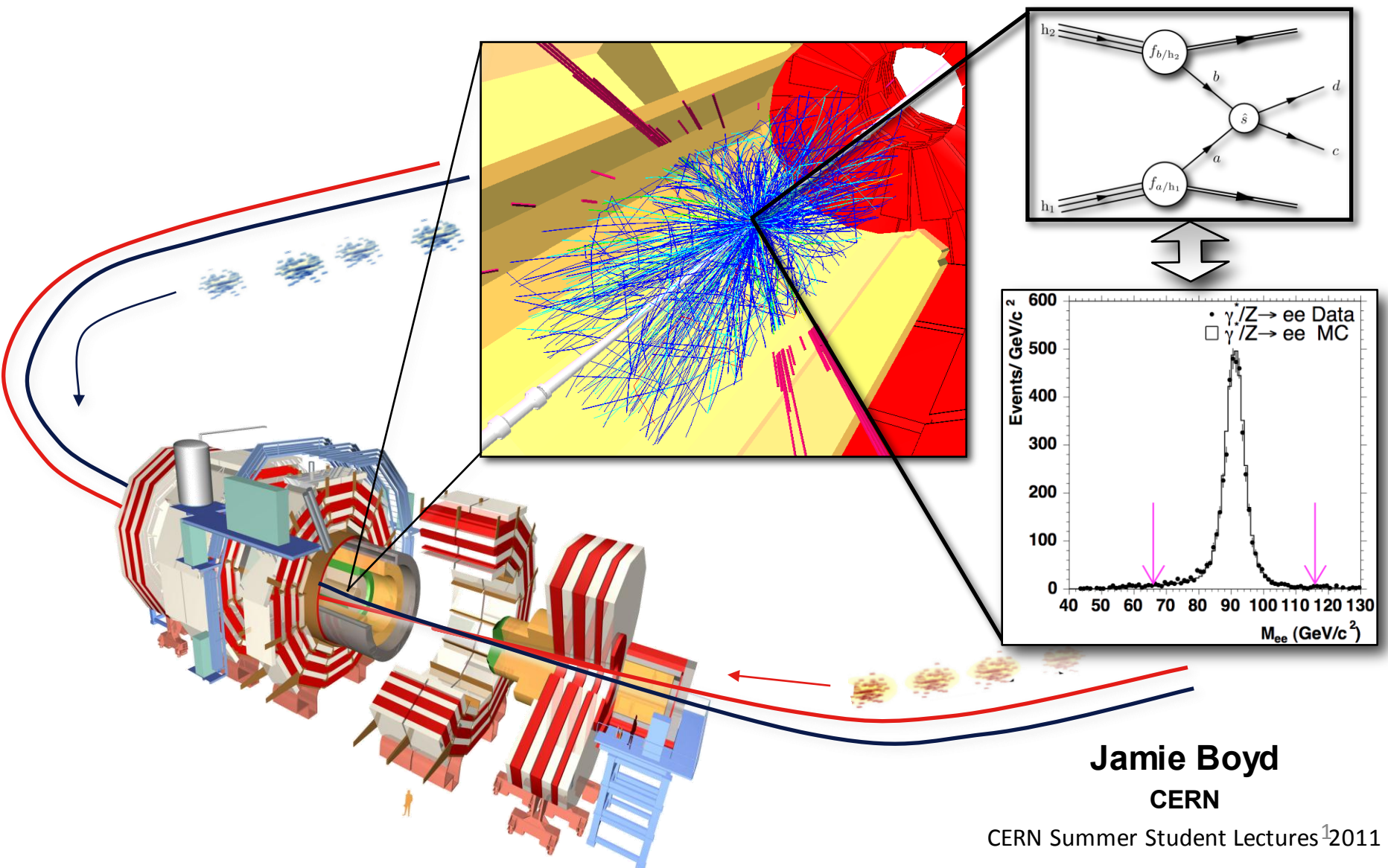
Outline

- Summary
  - Brief overview of the full lecture course
- A simple example
  - Measuring the Z^0 cross-section
- Reconstruction & Simulation
  - Track reconstruction
  - Calorimeter recostruction
  - Physics object reconstruction
  - Simulation
- Physics Analysis
  - Data Quality
  - Z'->ll
  - H->γγ
  - H->ZZ->4l
- Computing infrastructure
- The End!

Yesterdays Lecture

Todays Lecture

Disclaimer : Much of the content based on previous years lectures Thanks to G. Dissertori

Section 3: Reconstruction
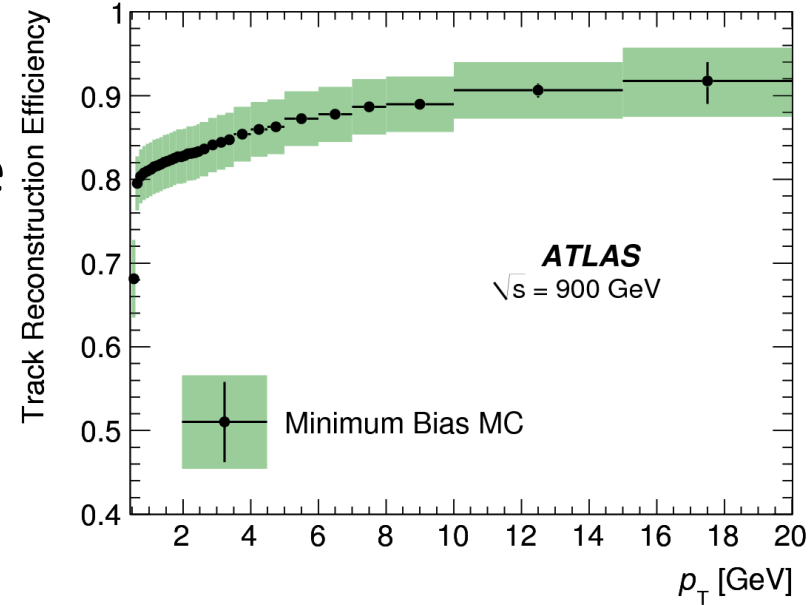
Reconstruction

- Detector reconstruction
  - Tracking
    - finding path of charged particles through the detector
  - Calorimeter reconstruction
    - finding energy deposits in calorimeters from charged and neutral particles
- Combined reconstruction
  - Electron/Photon identification
  - Muon identification
  - Jet finding
- Calibrations and alignments applied at nearly every step
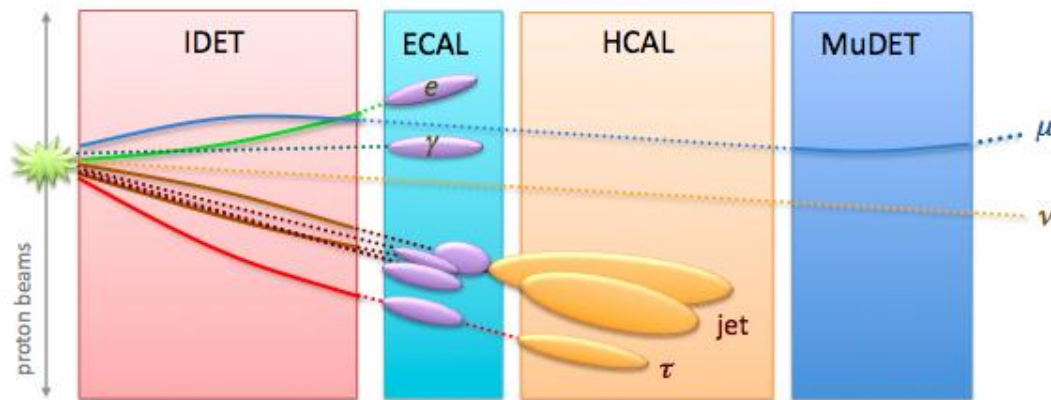
Important figures of merit for reconstructed objects

- **Efficiency**

  – how often do we reconstruct the object – e.g. tracking efficiency

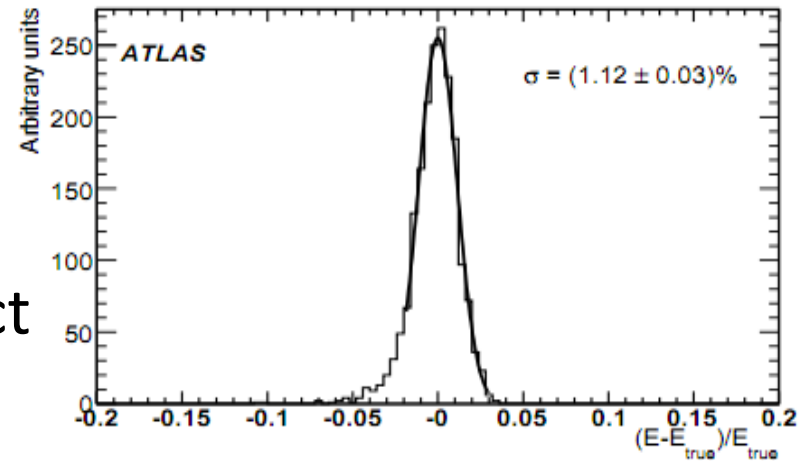Efficiency = (Number of Reconstructed Tracks) / (Number of True Tracks)

Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency

- **Resolution**
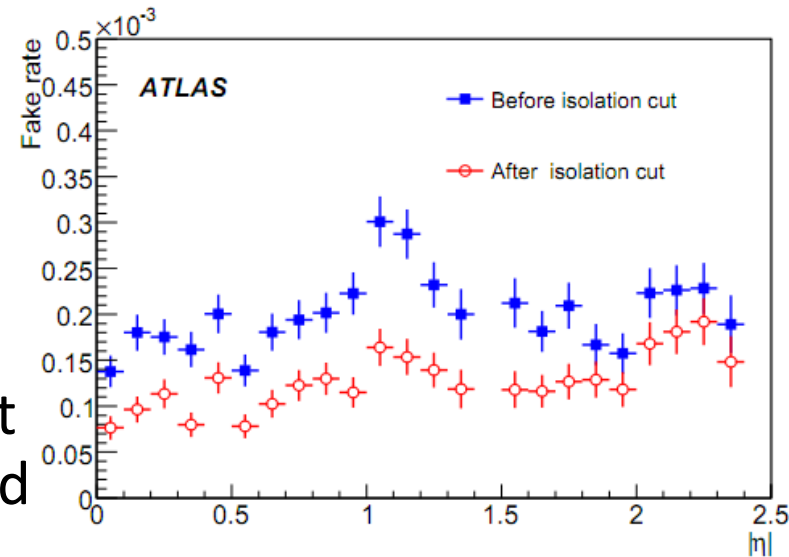 - how accurately do we reconstruct it – e.g. energy resolution

Electron energy resolution from simulation

Energy resolution = (Measured_Energy – True_Energy) / True_Energy

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Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency

- **Resolution**
  - how accurately do we reconstruct a quantity – e.g. energy resolution

- **Fake rate**
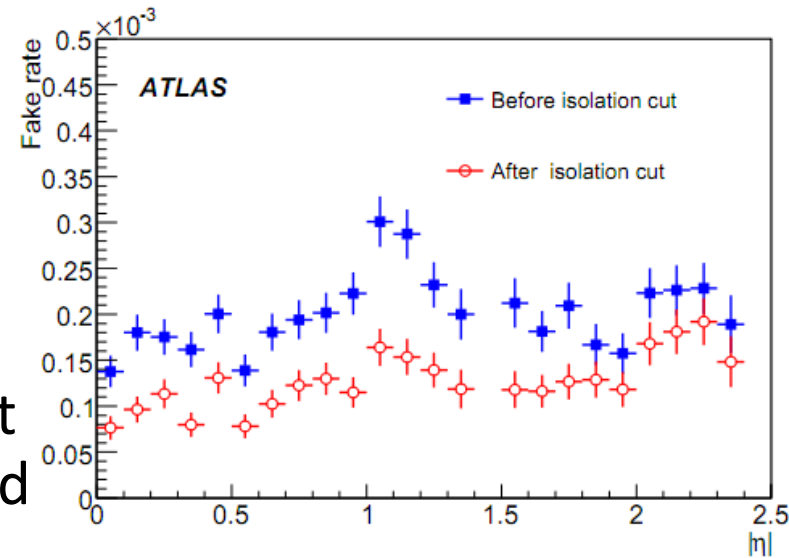 - how often we reconstruct a different object as the object we are interested in – e.g. a jet faking a electron

Fake rate = (Number of jets reconstructed as an electron) / (Number of jets)

Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency

- **Resolution**
  - how accurately do we reconstruct a quantity – e.g. energy resolution

- **Fake rate**
  - how often we reconstruct a different object as the object we are interested in – e.g. a jet faking a electron


These quantities depend on the detector, but also on the reconstruction and calibrations and alignment!

Important figures of merit for reconstructed objects

- **Efficiency**
  - how often do we reconstruct the object – e.g. tracking efficiency

- **Resolution**
  - how accurately do we reconstruct a quantity – e.g. energy resolution

- **Fake rate**
  - how often we reconstruct a different object as the object we are interested in – e.g. a jet faking a electron
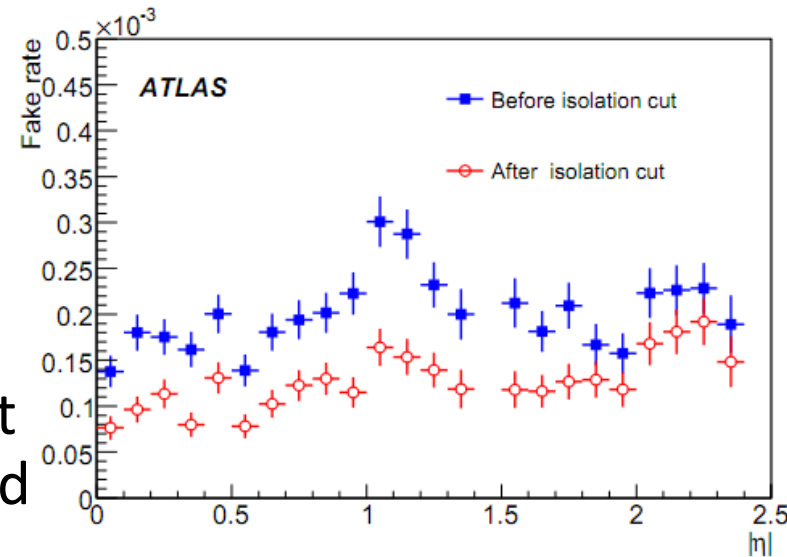
For physics analysis it is important
i)   to have high efficiency, good resolution, and low fake rates
ii)   to be able to measure the efficiencies, resolutions and fake rates and their uncertainties (not easy)

Reconstruction Goals

- High efficiency
- Good resolution
- Low fake rate
- Robust against detector problems
  - Noise
  - Dead regions of the detector
- Be able to run within the computing resource limitations
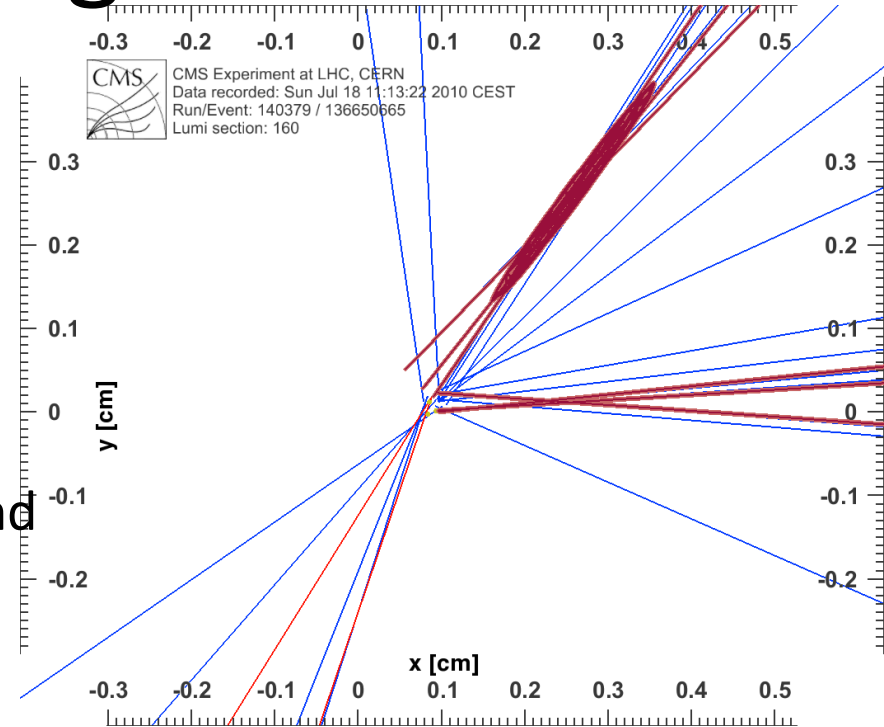 - CPU time per event
  - Memory use

Track finding

Tracking

- Track finding very important for analysis
- Tracks are used directly in the reconstruction of
  - Electrons
  - Muons
  - And to a lesser extent in Tau, Jet and photon reconstruction
- For reconstructed tracks we know
  - Momentum
    - straighter the track the higher momentum it is
  - Charge
  - Point of closest approach to the interaction point

  (important to identify particles such as b-quarks which have a long lifetime and so travel a measurable distance before they decay)
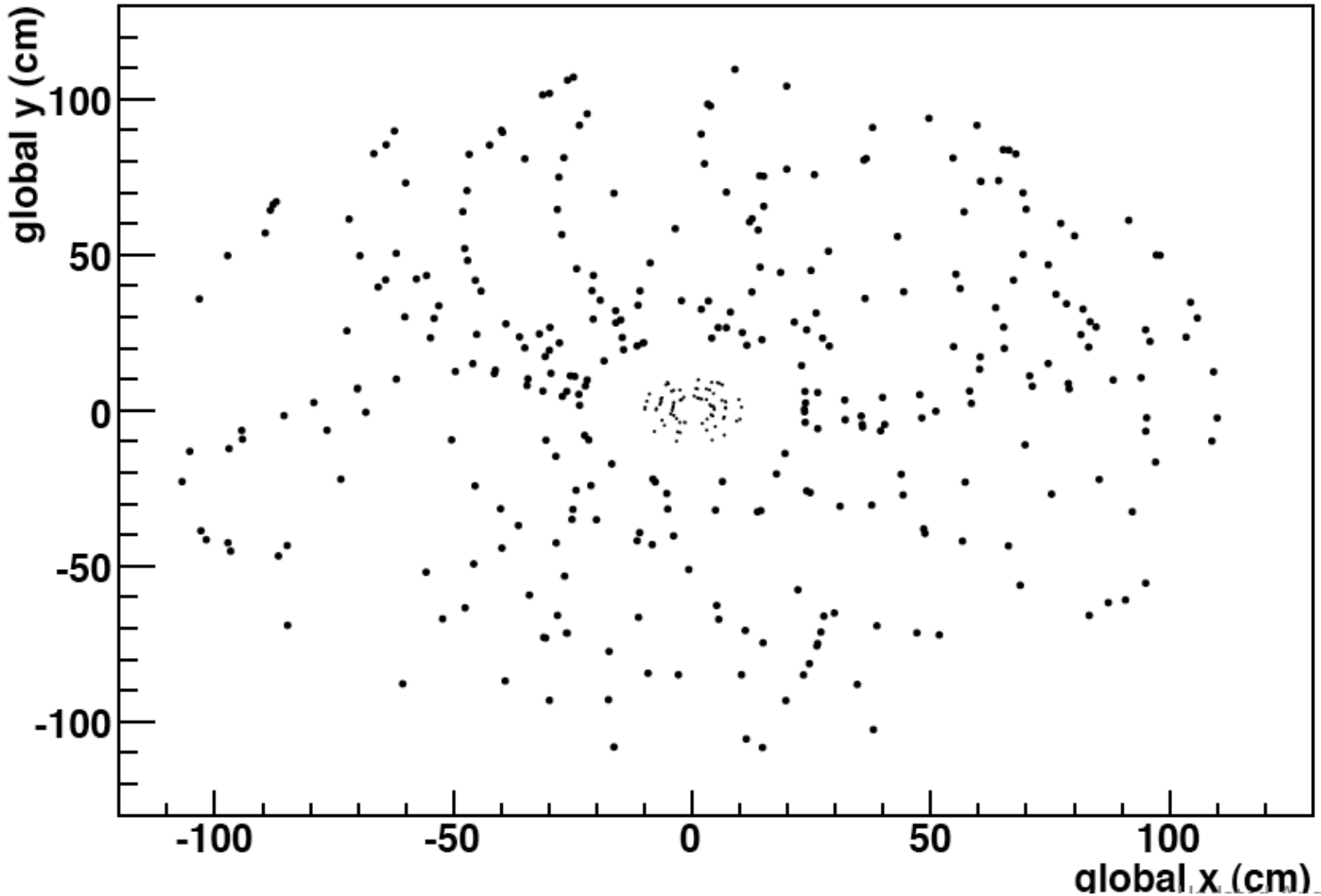

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 18 11:13:22 2010 CEST
Run/Event: 140379 / 136650665
Lumi section: 160

Quiz: Tracking by eye - Can you find the 50 GeV Track?

cf Aaron Dominguez

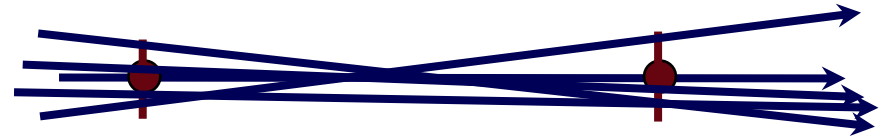# Track Fitting

- 1D straight line fit as simple case
- Two perfect measurements
  - away from interaction point
  - no measurement uncertainty
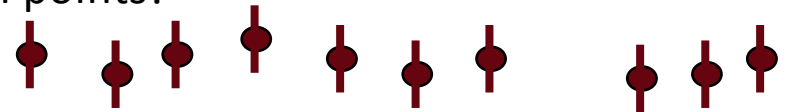 - just draw a straight line through them and extrapolate

- Imperfect measurements give less precise results
  - the farther you extrapolate, the less you know

- Smaller errors and more points help to constrain the possibilities.
  But how to find the best point from a large set of points?

- Quantitatively
  - parameterize a track:
  - In case of straight line $y(x) = \theta\,x + d$ or, eg., helix in case of magnetic field present

  predicted track position at i^{th} hit

  position of ith hit

  - Find track parameters by Least-Squares-Minimization

  - Obtain also uncertainties on track parameters

  $$\chi^2 = \sum_{i=1}^{n_{\text{hits}}} \frac{(y_i - y(x_i))^2}{\sigma_i^2}$$

  $\delta\theta \qquad \delta d$

  uncertainty of ith measurement
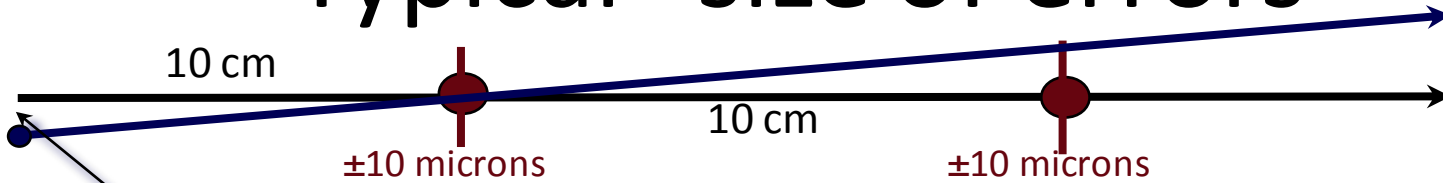
14

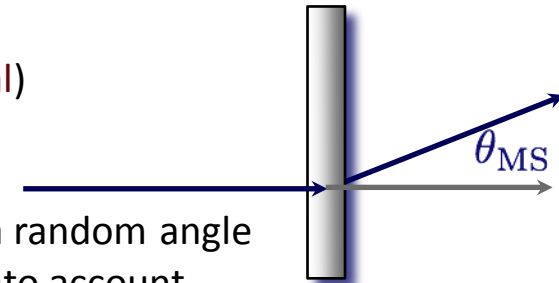# "Typical" size of errors

10 cm

±10 microns   10 cm   ±10 microns

- Error δd on position is about ±10 microns
- Error $\delta\theta$ on angle is about ±0.1 milliradians (±0.002 degrees)
- Satisfyingly small errors
  - allows separation of tracks that come from different particle decays (which can be separated at the order of mm)

- Problem 1:
  - we "see" particles by interaction with a detector (=material)
  - interaction leads to : energy loss, change in direction
  - This is **Multiple Scattering**
    Charged particles passing through matter "scatter" by a random angle
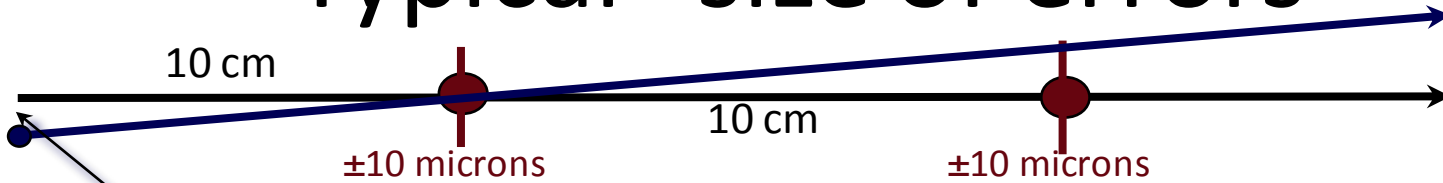 Need more sophisticated algorithms to be able to take this into account

θ_{MS}

$$\sqrt{\langle\theta_{\mathrm{MS}}^2\rangle} = \frac{15\,\mathrm{MeV}/c}{\beta p}\sqrt{\frac{\mathrm{thickness}}{X_{\mathrm{rad}}}}$$

examples:

300 micron Si : RMS = 0.9 mrad $/\beta p$
1 mm Be   : RMS = 0.8 mrad $/\beta p$
❾ leads to additional position errors

# "Typical" size of errors

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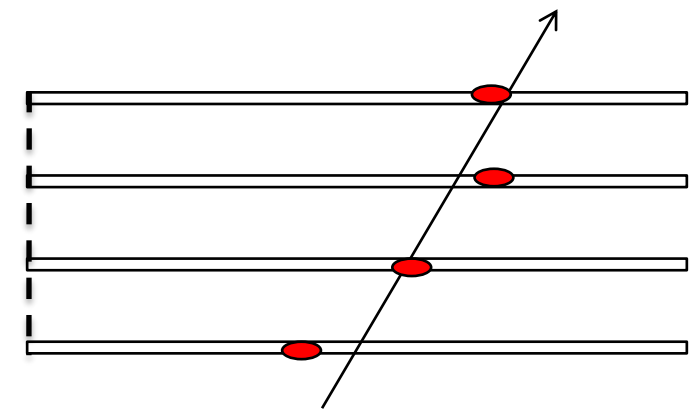
- Problem 2:
    - Tracking detector elements are not positioned in space with perfect accuracy
    - Can be misaligned with respect to each other by upto ~100 microns
    - Needs to be taken into account by the track finding software
    - Need to derive alignment corrections from the data and apply these in track reconstruction

much exaggerated misalignment
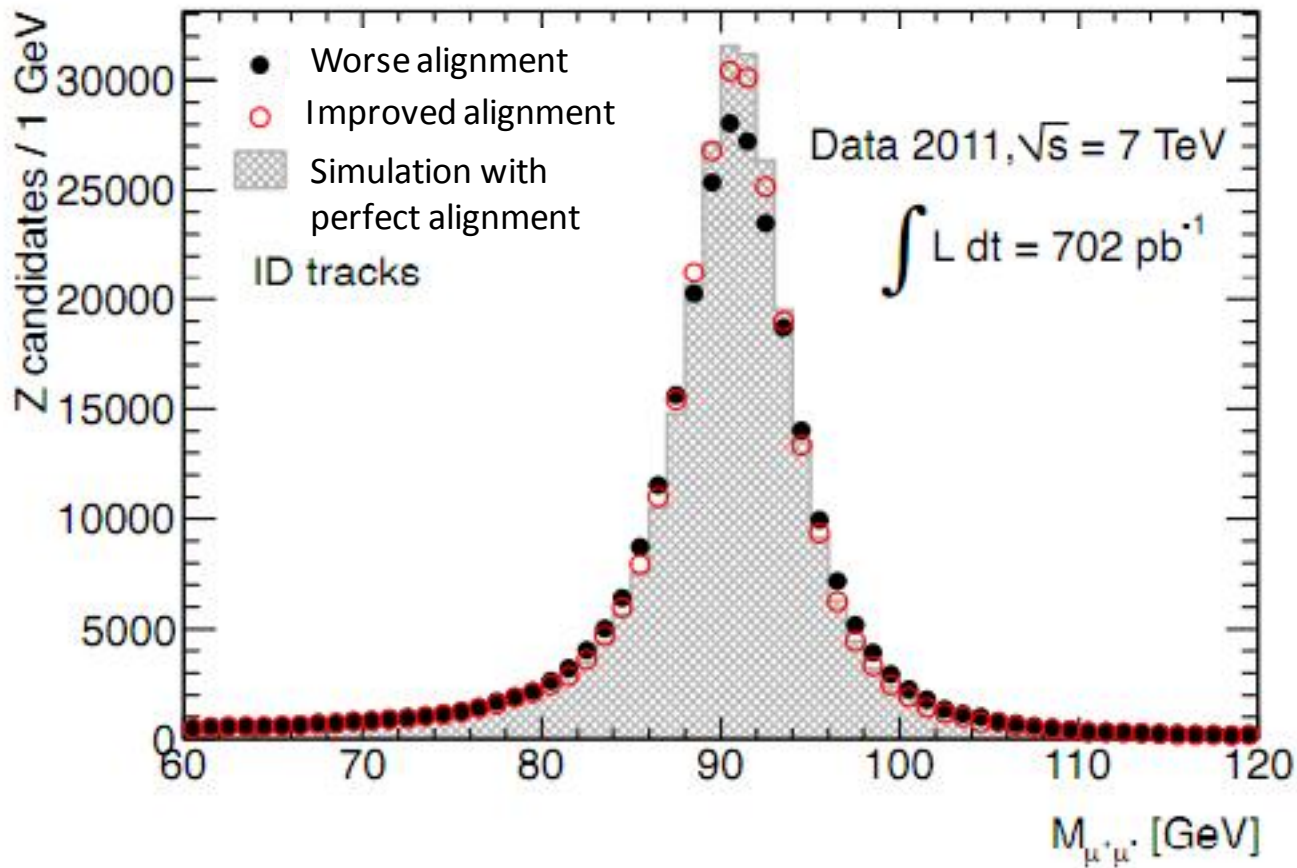
16
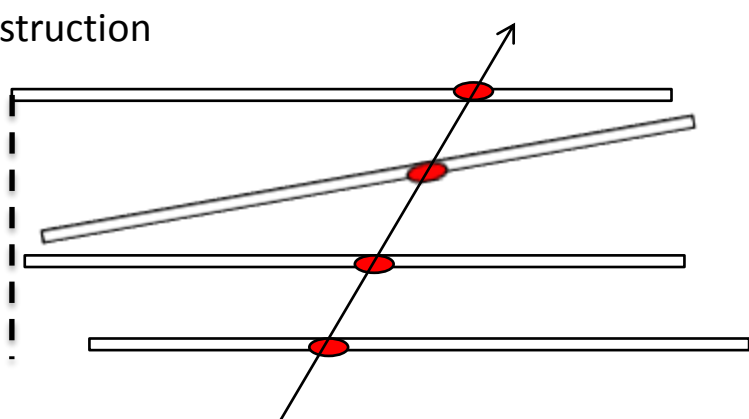
misaligned real detector   perfect alignment

Tracker Alignment

- Improving the tracker alignment description in the reconstruction gives better track momentum resolution which leads to better mass resolution.
- Can see the reconstructed Z width gets narrower if we use better alignment constants. Very important for physics analysis to have good alignment.
- Alignment of detector elements can change with time for example when the detector is opened for repair, or when the magnetic field is turned on and off.
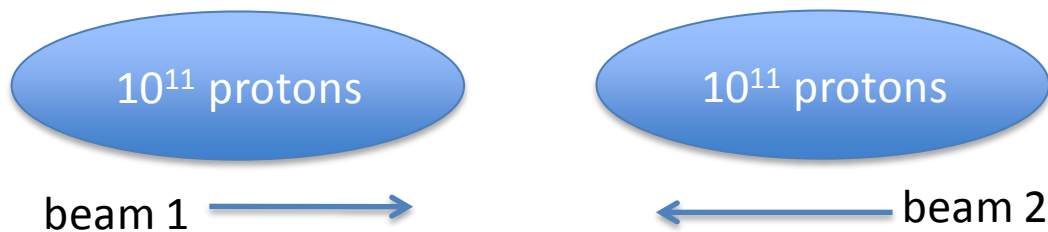
17

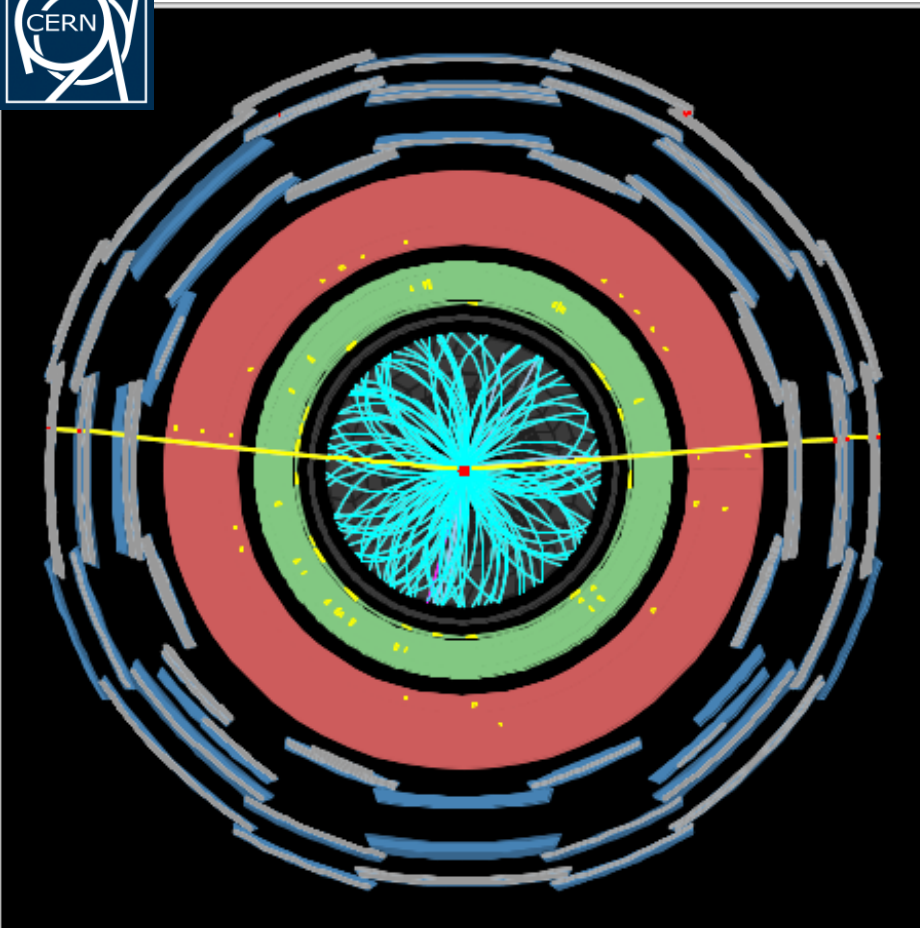# Tracking by eye - Can you find the 50 GeV Track?

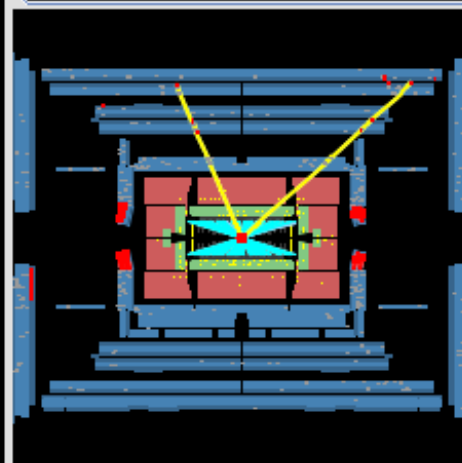cf Aaron Dominguez
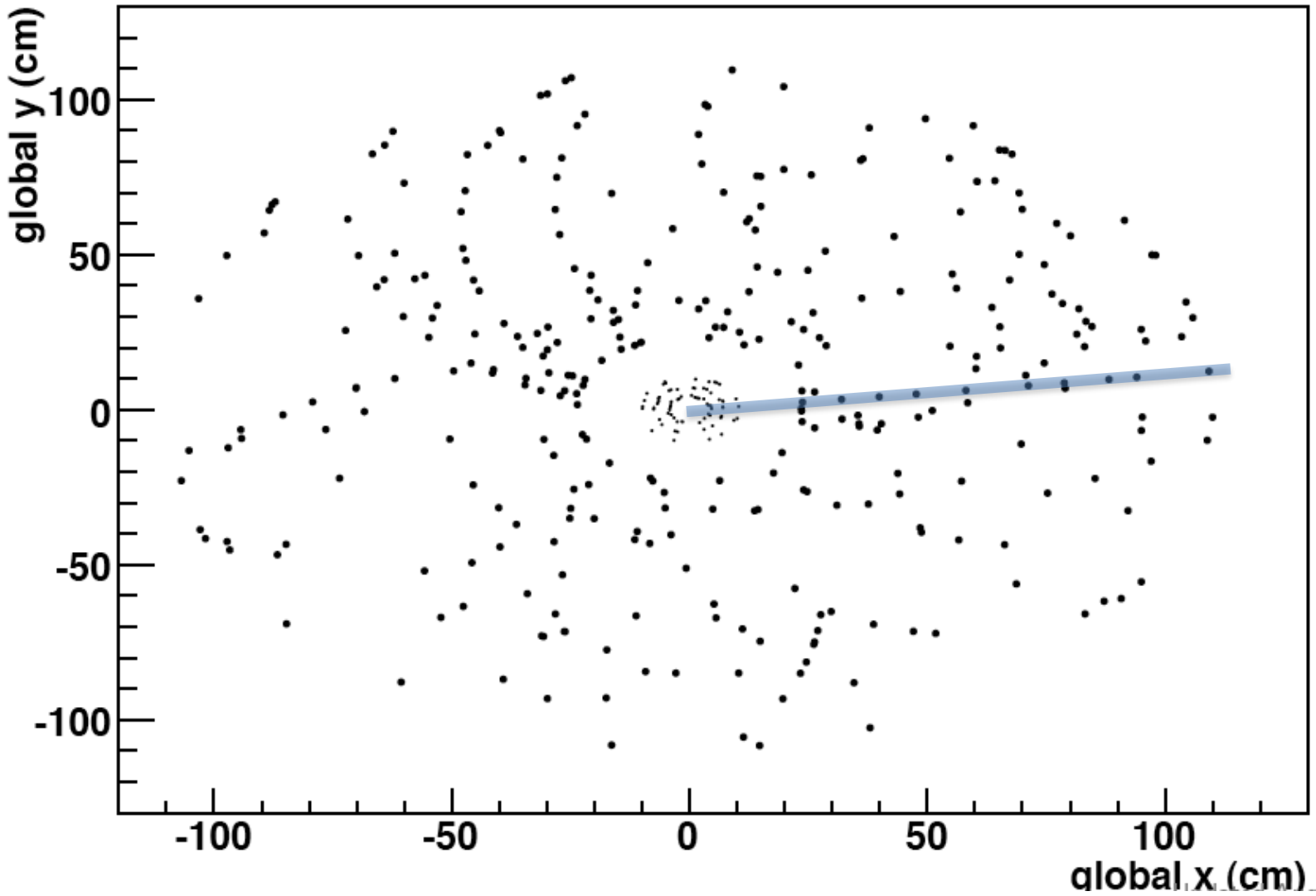
(aside) Pileup

- When the LHC collides bunches of protons we can get more than one p-p interaction – this is called pileup
- The number of pileup interactions depends on the LHC parameters
  - How many protons per bunch
  - How small the bunches have been squeezed
- For this year we have on average 6 interactions every time the bunches cross
- These pileup interactions give lots of low momentum tracks
- We can usually identify which tracks are from which interactions by combining tracks that come from the same vertex
- Pileup can cause difficulties for some physics analyses
  - Also causes reconstruction to need more computing power
- But allows us to get more luminosity
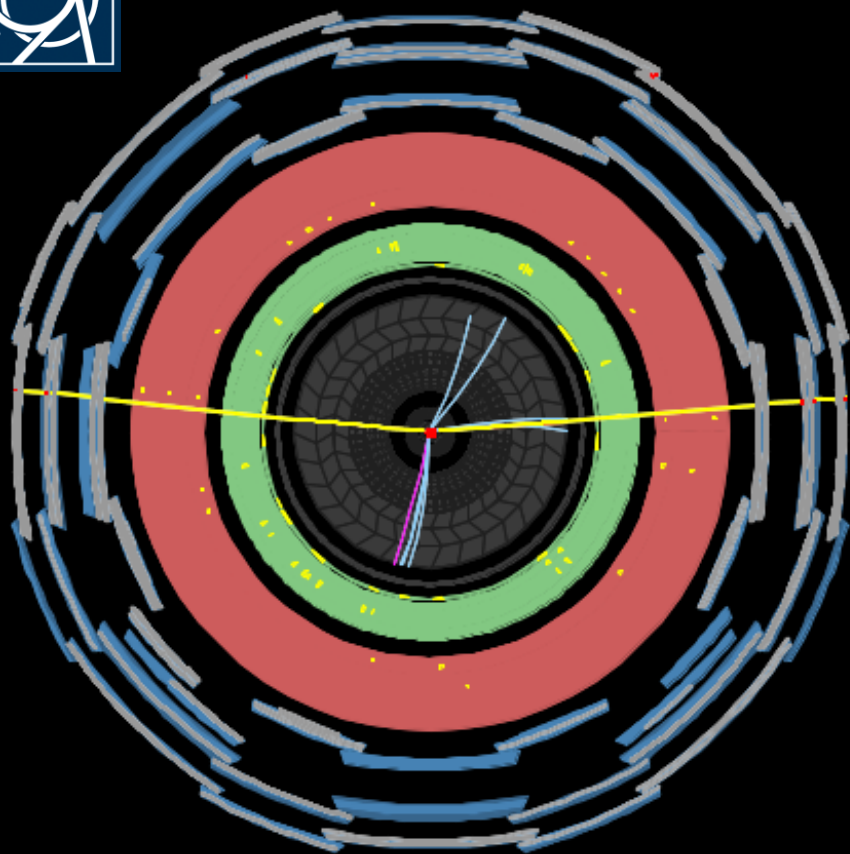
10^{11} protons 10^{11} protons

beam 1 →   ← beam 2

Recent Z->μμ event in ATLAS.
With 11 reconstructed vertices.
Tracks with transverse momentum above 500MeV are shown (P_T>0.5GeV).

How can we do physics analysis with such a mess of tracks in the detector?

Recent Z->μμ event in ATLAS.
With 11 reconstructed vertices.
Tracks with transverse momentum above 2.0GeV are shown (P_T>2.0GeV).

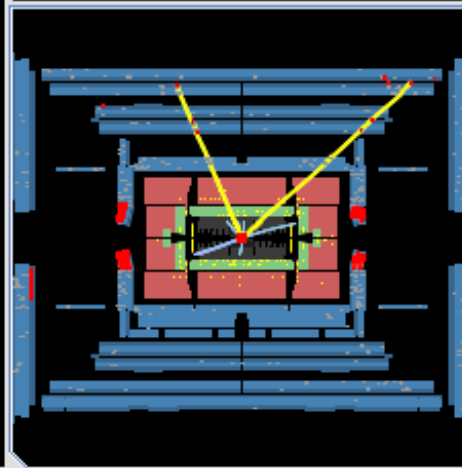How can we do physics analysis with such a mess of tracks in the detector?
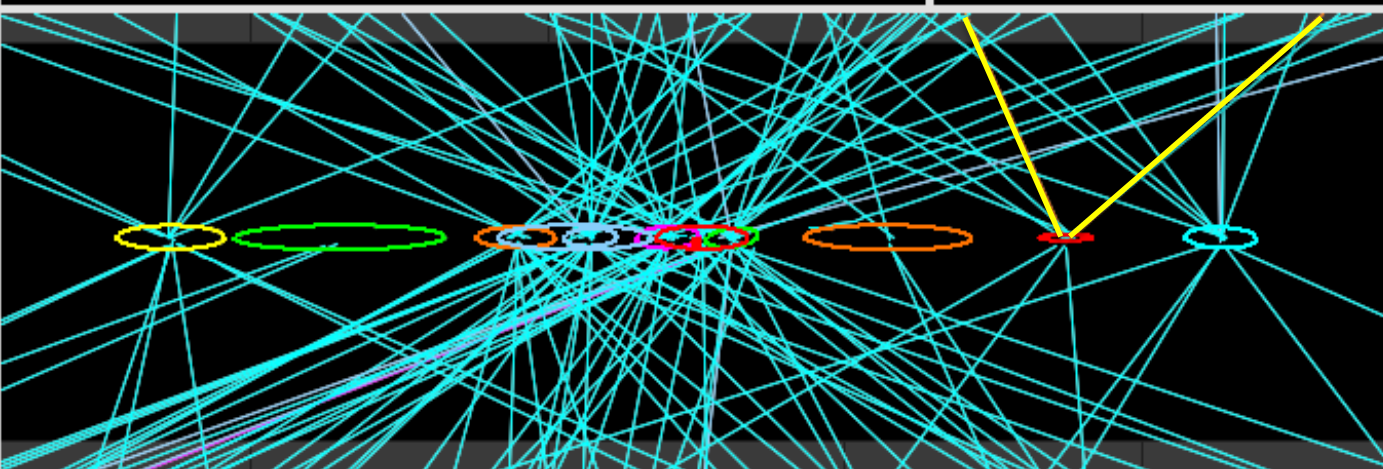
ATLAS EXPERIMENT

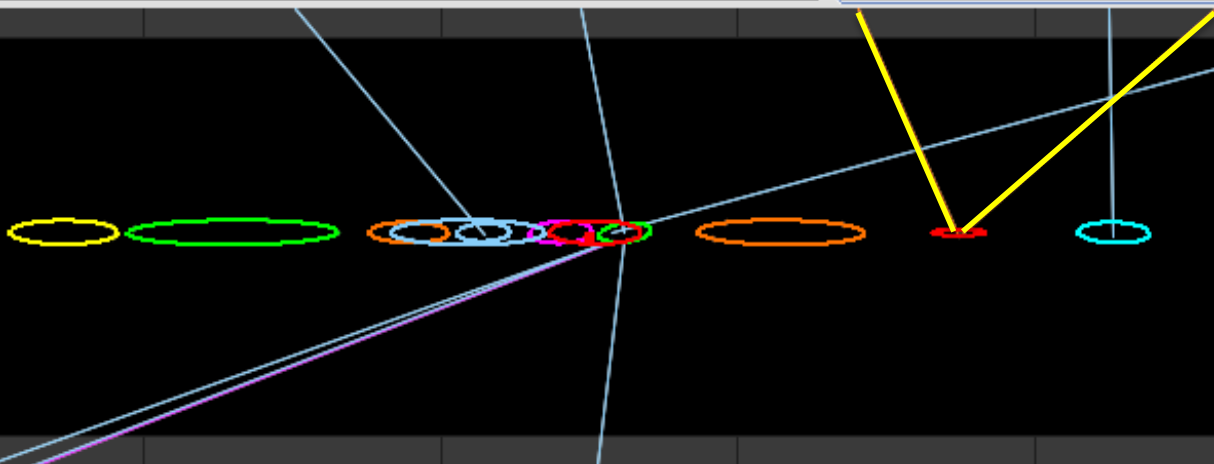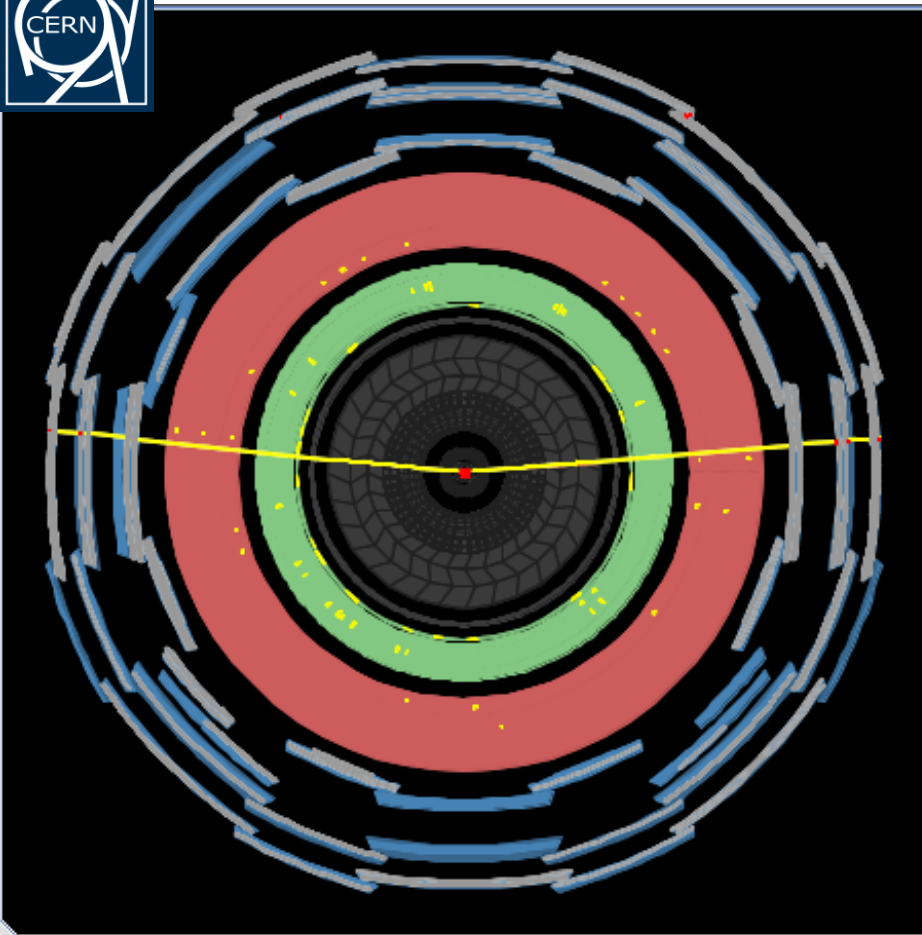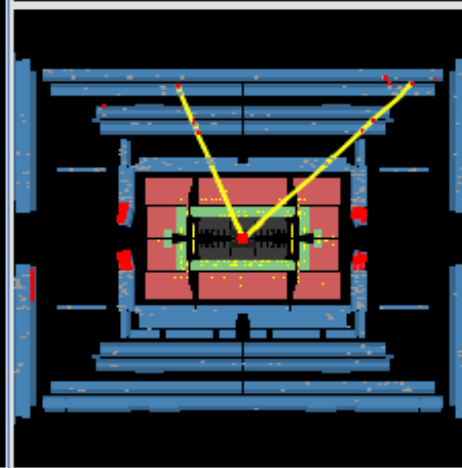Run Number: 180164, Event Number: 146351094

Date: 2011-04-24 01:43:39 CEST

Recent Z->μμ event in ATLAS.
With 11 reconstructed vertices.
Tracks with transverse momentum above 10GeV are shown (P_T>10GeV).

How can we do physics analysis with such a mess of tracks in the detector?
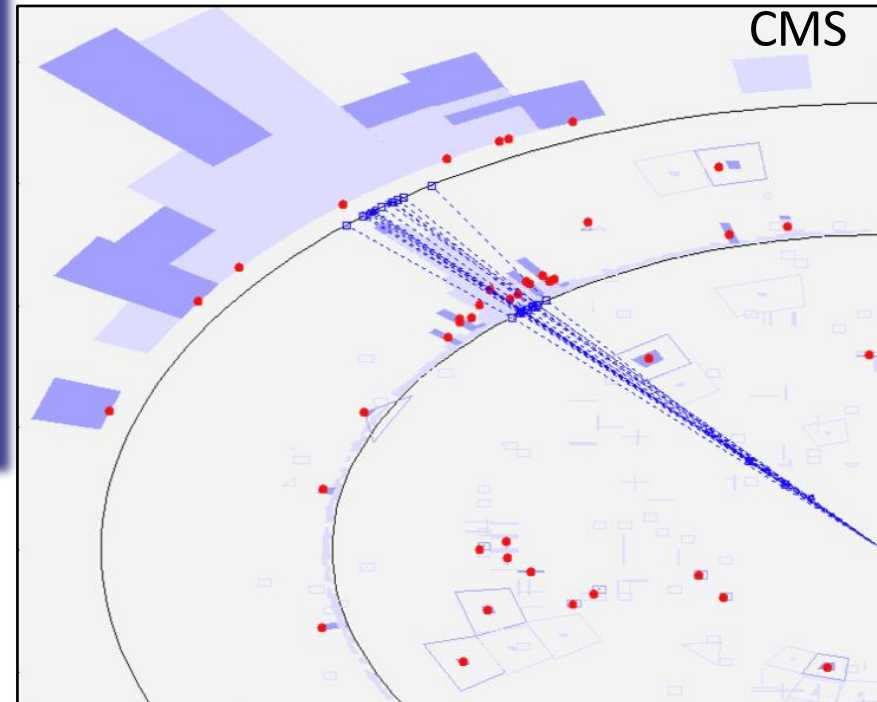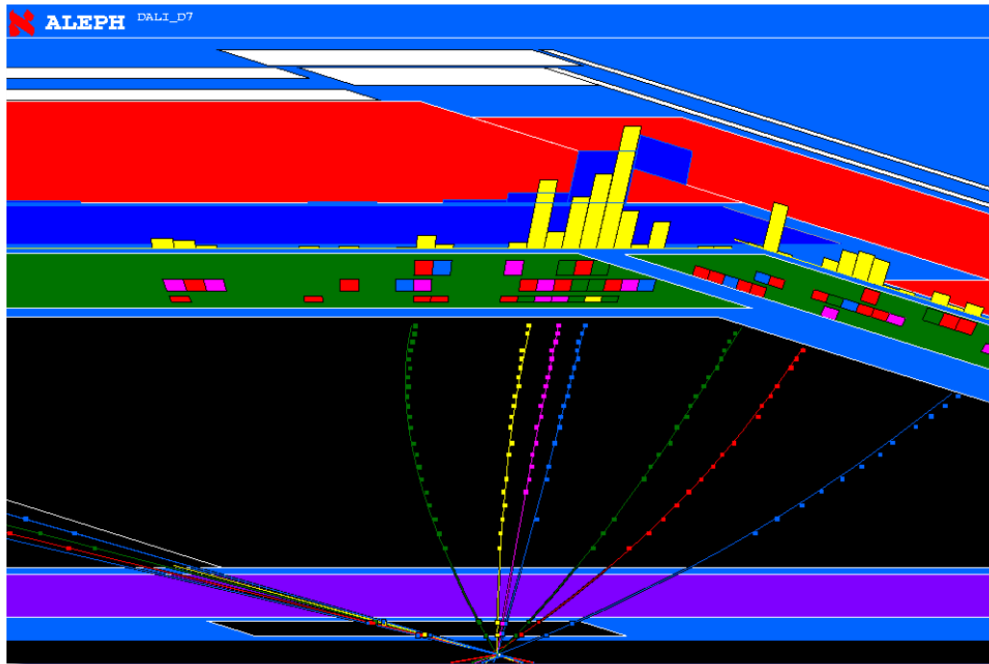
By applying a cut on the object momentum the event becomes much cleaner and easier to analyze 22

Calorimeter energy reconstruction

Goals

- Reconstruct energy deposited by charged and neutral particles
- Determine position of deposit, direction of incident particles
- Be insensitive to noise and "un-wanted" (un-correlated) energy (pileup)

- and obtain the best possible resolution!

Clusters of energy

- Calorimeters are segmented in cells
- Typically a shower extends over several cells
    - Useful to reconstruct precisely the impact point from the "center-of-gravity" of the deposits in the various cells
- Example CMS Crystal Calorimeter:
    - electron energy in central crystal ~ 80 %, in 5x5 matrix around it ~ 96 %
- So task is : identify these clusters and reconstruct the energy they contain

front view

side view

view in (φ,η) cells
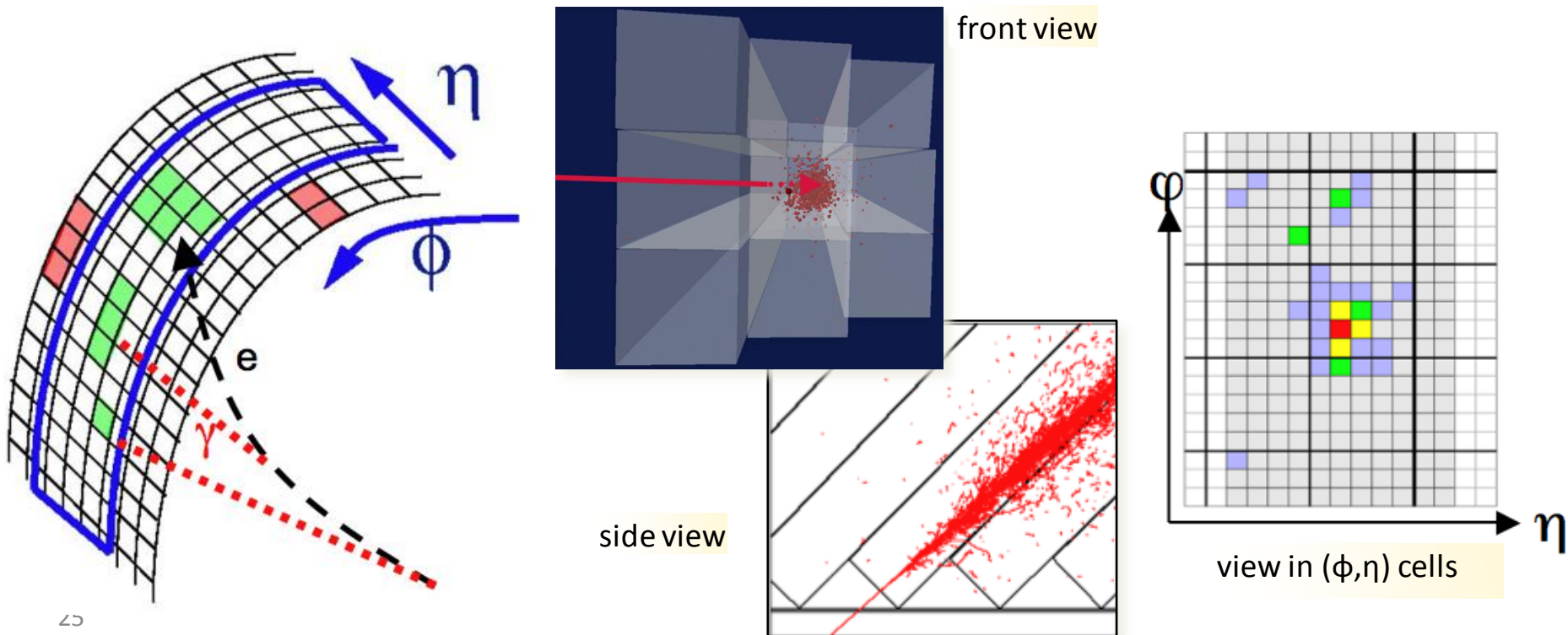
Cluster Finding

- Clusters of energy in a calorimeter are due to the original particles
  - Clustering algorithm groups individual channel energies
  - Don't want to miss any; don't want to pick up fakes

Projection →

high threshold, for seed finding

low threshold, against noise
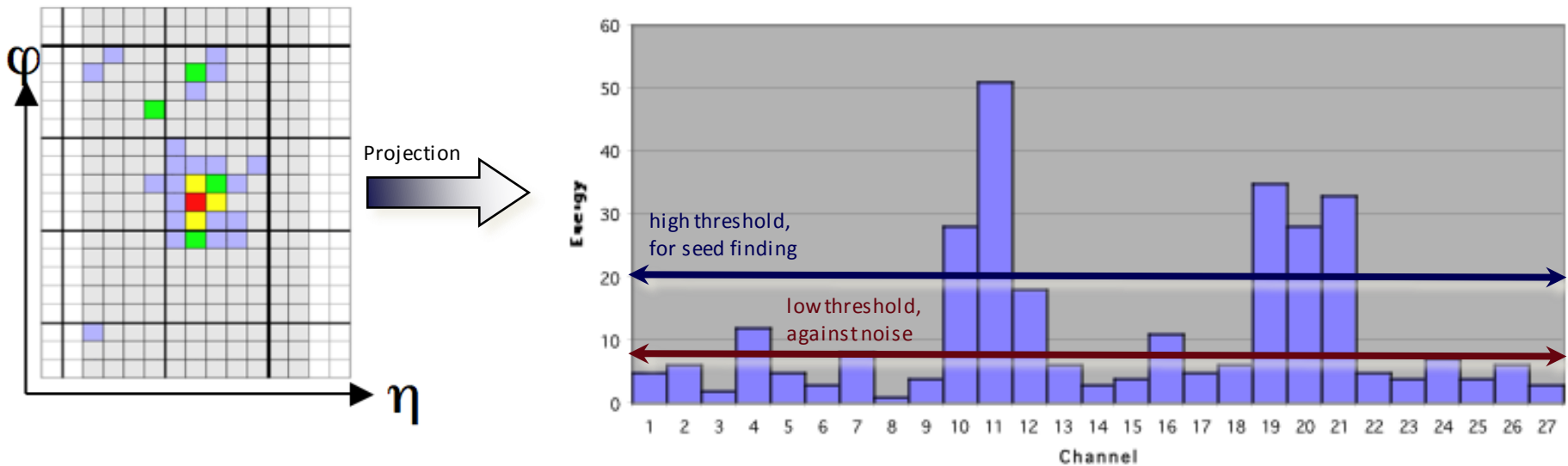
Simple example of an algorithm

- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are **added to the cluster if**
1. The crystal's energy is above the noise level (lower threshold)
2. The crystal has not been assigned to another cluster already
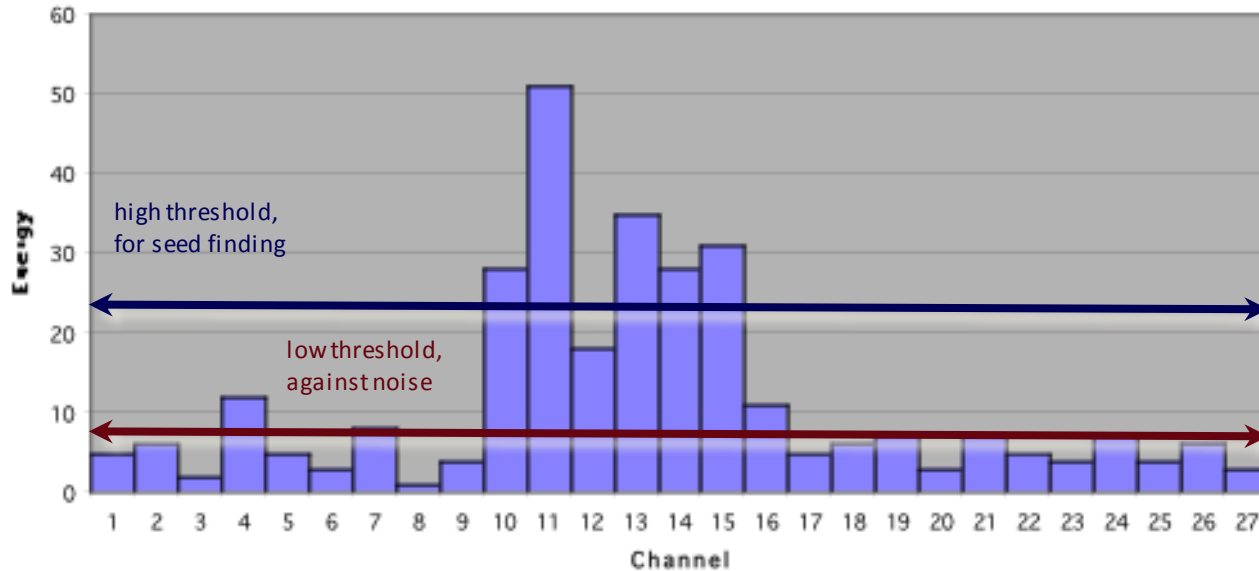
Difficulties

- Careful tuning of thresholds needed
  - needs usually learning phase
  - adapt to noise conditions
  - too low : pick up too much unwanted energy
  - too high : loose too much of "real" energy. Corrections/Calibrations will be larger

example : one lump or two?

Energy Calibration

$$E^{reco} = F(E_{acc}^{reco}, \eta) \cdot E_{ps}^{cl\,LAr} + S_{acc}(X, \eta) \cdot \left(\sum_{i=1,3} E_i^{cl\,LAr}\right) \cdot (1 + C_{out}(X, \eta)) \cdot (1 + f_{leak}(X, \eta))$$
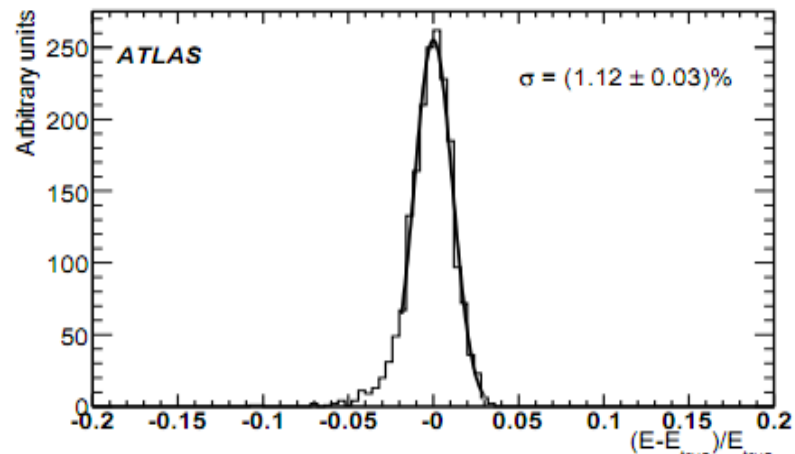
Energy deposited in front of calo

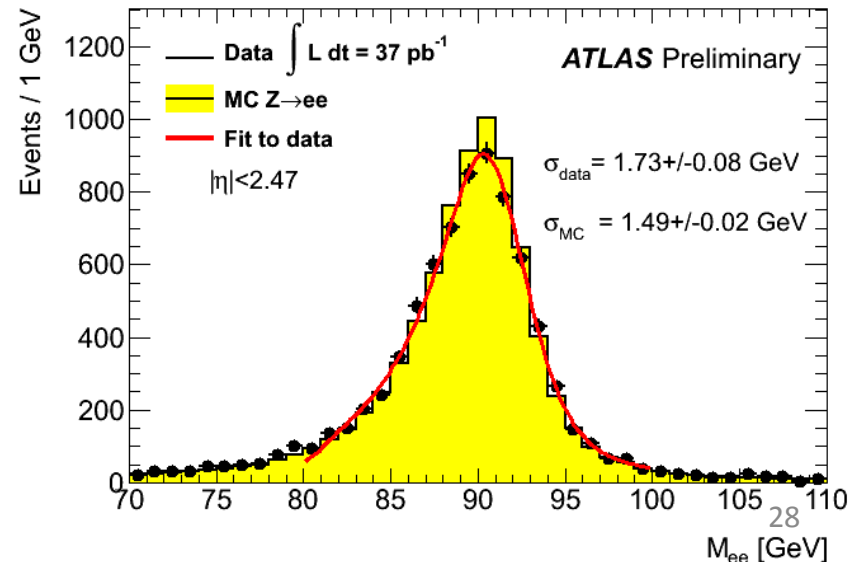**Energy deposited into the cluster**

Energy deposited out of cluster

Energy deposited behind calo

- Calibration constants can be complex functions of the position and energy of the cluster
  - $E^{CALIB} = f(E^{MEASURED}, \eta, \phi, ...)$, f includes various calibration constants
- Calibration very important to get the best energy resolution


Electron energy resolution from simulation

Physics objects reconstruction

Electron/Photon Identification

- Electron/Photon reconstruction takes as input the tracks and calorimeter clusters already produced
- Electron/Photon leave narrow clusters in the electromagnetic calorimeter
  - Apply selection on the cluster shape to reduce background from jets
- Electron has track pointing at cluster
  - Requires aligning the calorimeter with the tracker
- Photon has no track pointing at it
- Final Electron momentum measurement can come from tracking or calorimeter information (or a combination of both)
  - Often have a final calibration to give the best electron energy
- Often want isolated electrons
 - Require little calorimeter energy or tracks in the region around the electron
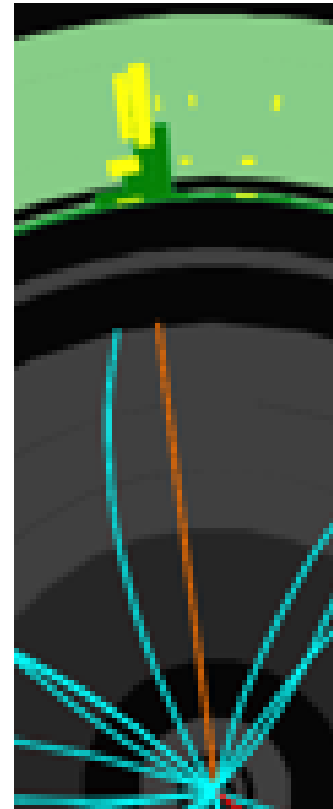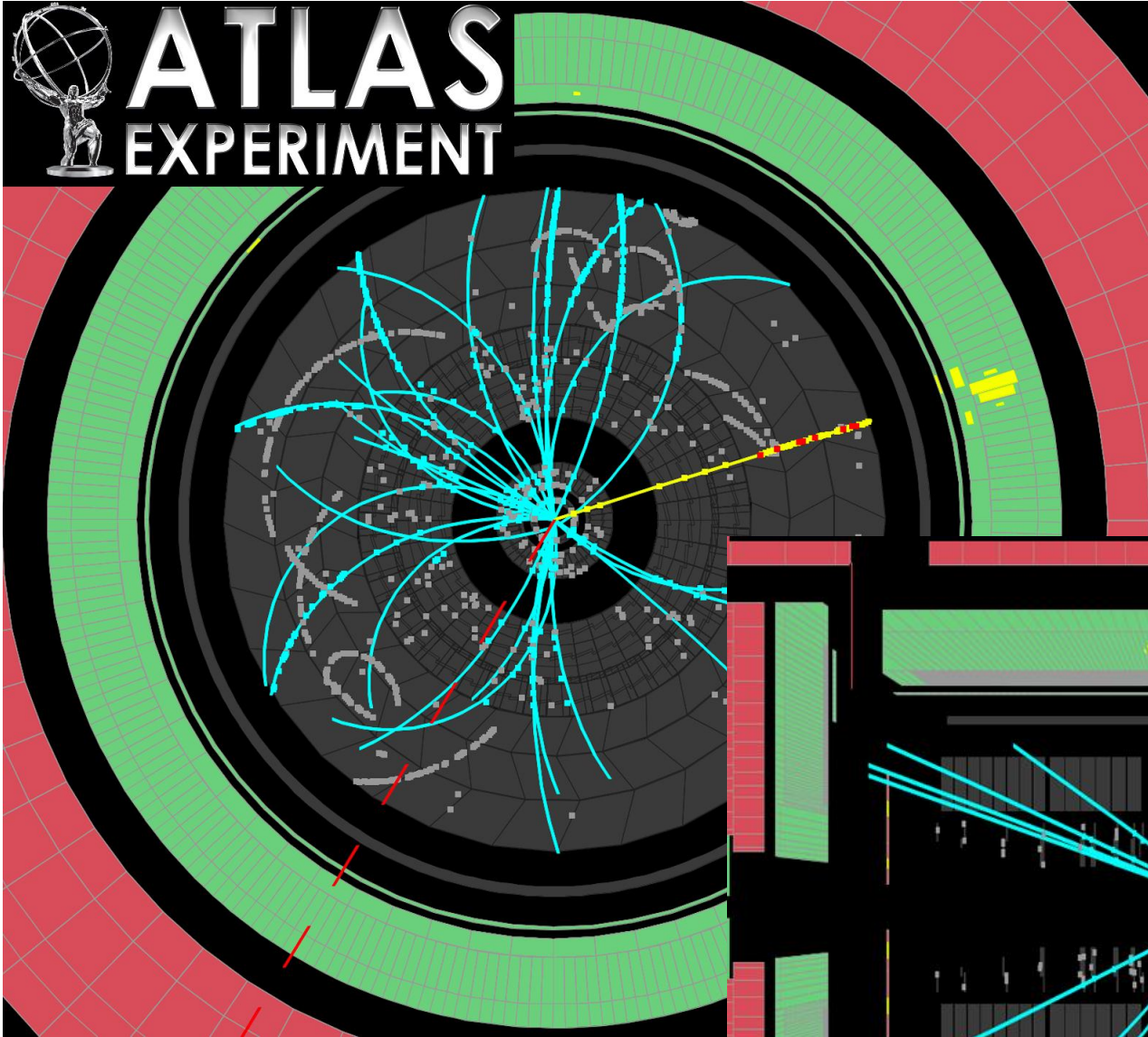
An electron in ATLAS
1. Narrow cluster in electromagnetic calorimeter
2. No energy in the hadronic calorimeter behind
2. High momentum track pointing at cluster
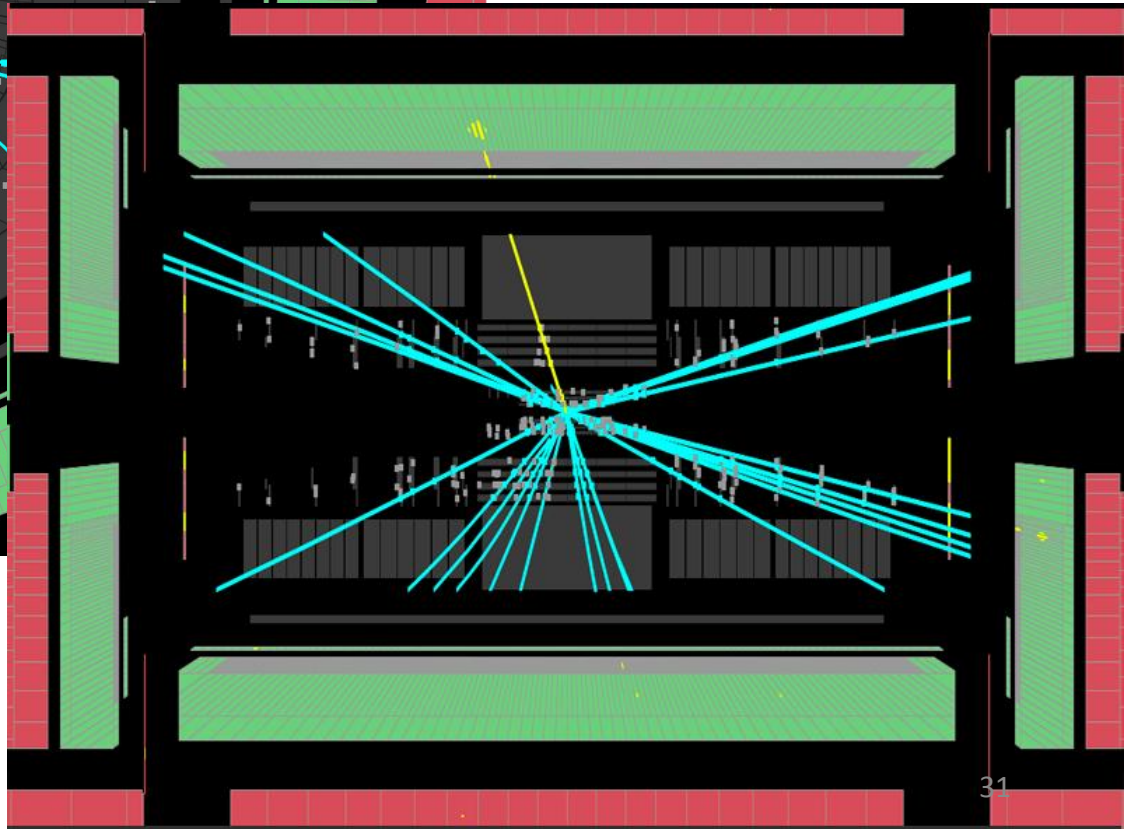
Electron/Photon Backgrounds

- Hadronic jets leave energy in the calorimeter which can fake electrons or photons
- Usually a Jet produces energy in the hadronic calorimeter as well as the electromagnetic calorimeter
- Usually the calorimeter cluster is much wider for jets than for electrons/photons
- So it should be easy to separate electrons from jets
- However have many thousands more jets than electrons, so need the rate of jets faking an electron to be very small ~10^{-4}
- Need complex identification algorithms to give the rejection whilst keeping a high efficiency
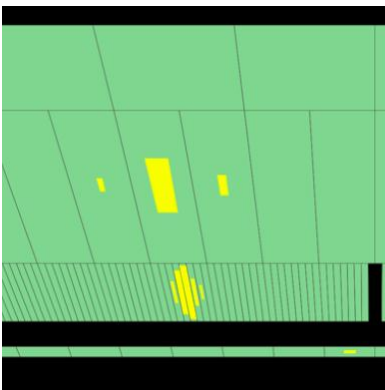
Example of an electron energy deposit in the electromagnetic calorimeter in ATLAS.
Use shower shape variables based on size of cluster in the radial and longitudinal directions to distinguish from hadronic showers (see next slide)

Electrons / Jets
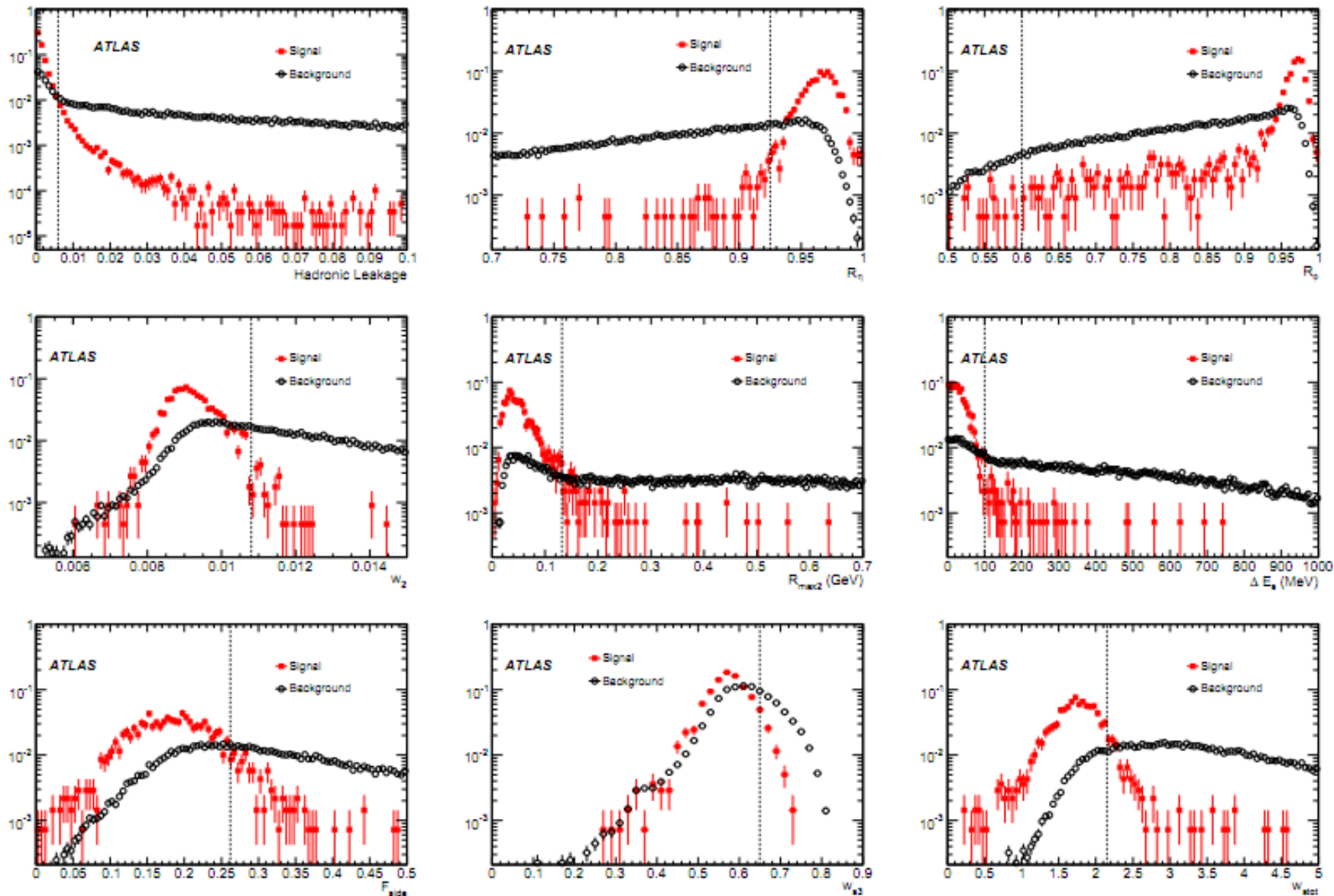
Example of different calorimeter shower shape variables used to distinguish electron showers from jets in ATLAS
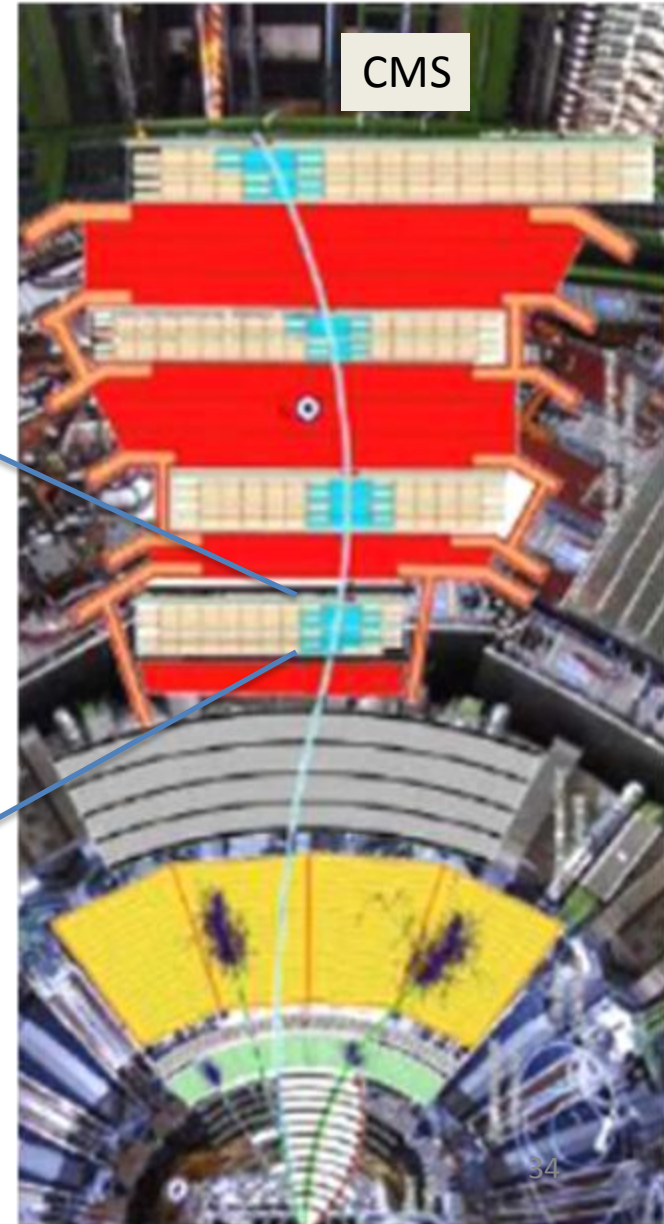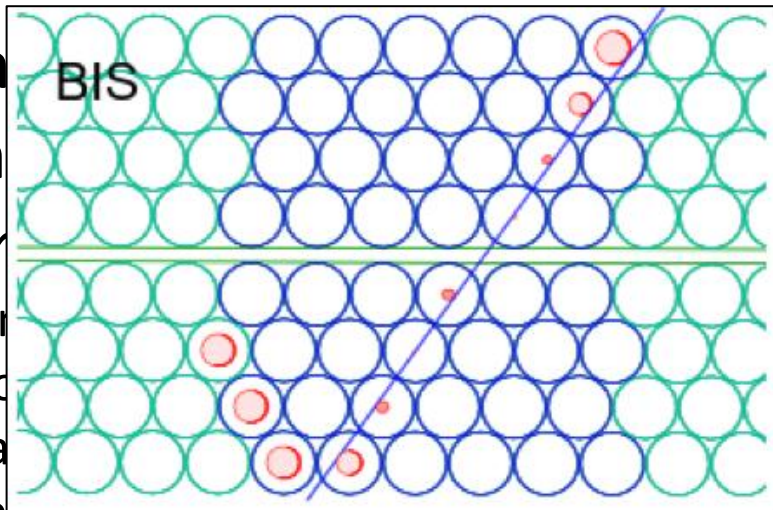
Muon identification

- Combine the muon segments found in the muon detector with tracks from the tracking detector

- Momentum measured from bending in the field in tracker

Muon segment in drift tubes

- Combine resolution
- Need alignment in the reconstruction software
- Alignment of the muon detectors also very important to get best momentum resolution

CMS

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Simulation

Simulation

- Simulated data samples needed for
  - Designing experiments
  - Tuning analysis selections
  - Background estimation
  - Efficiency and fake-rate estimation
- To get best physics outputs from the experiment it is essential to have an accurate simulation of the detector
  - Lots of work goes into tuning the simulation to give best description of the data
  - Test beam studies from construction period of the detector used to tune simulation (test beam allows to study detector response to known particle types and momenta – e.g. 20GeV electrons)
- Very detailed simulation of the detector
  - Detailed description of the detector geometry
  - Accurate simulation of the detector electronics response
  - Include detector 'noise' in the simulation
- Keep the 'truth' information
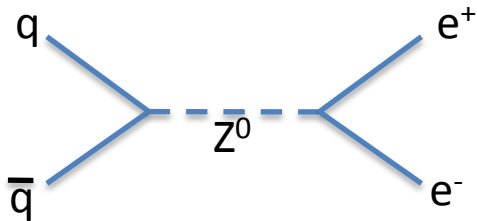 - Allows efficiency and fake rates to be estimated

Simulation workflow

Physics simulation

Simulate the physics interaction (set in the simulation configuration)
Output of this part is the 4-vector's of the produced particles.
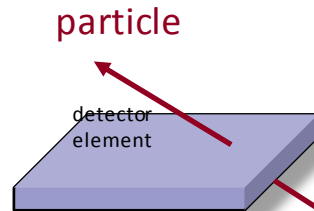In this case the 4-vector's of the 2 electrons from the Z decay.

Detector Simulation

Simulate the propagation of the electrons through the detector.
Including:
-bending in the magnetic field
-leaving hits in the tracking detector elements
-interacting with the material in the detector
-interacting in the calorimeter (detailed description of the EM shower)

Electronics Simulation

Simulate the response of the detector elements to the 'hits' from the electron.
Simulate the voltage pulse on the detector and how the detector electronics works.
The output of this stage is very similar to the raw data from the detector.
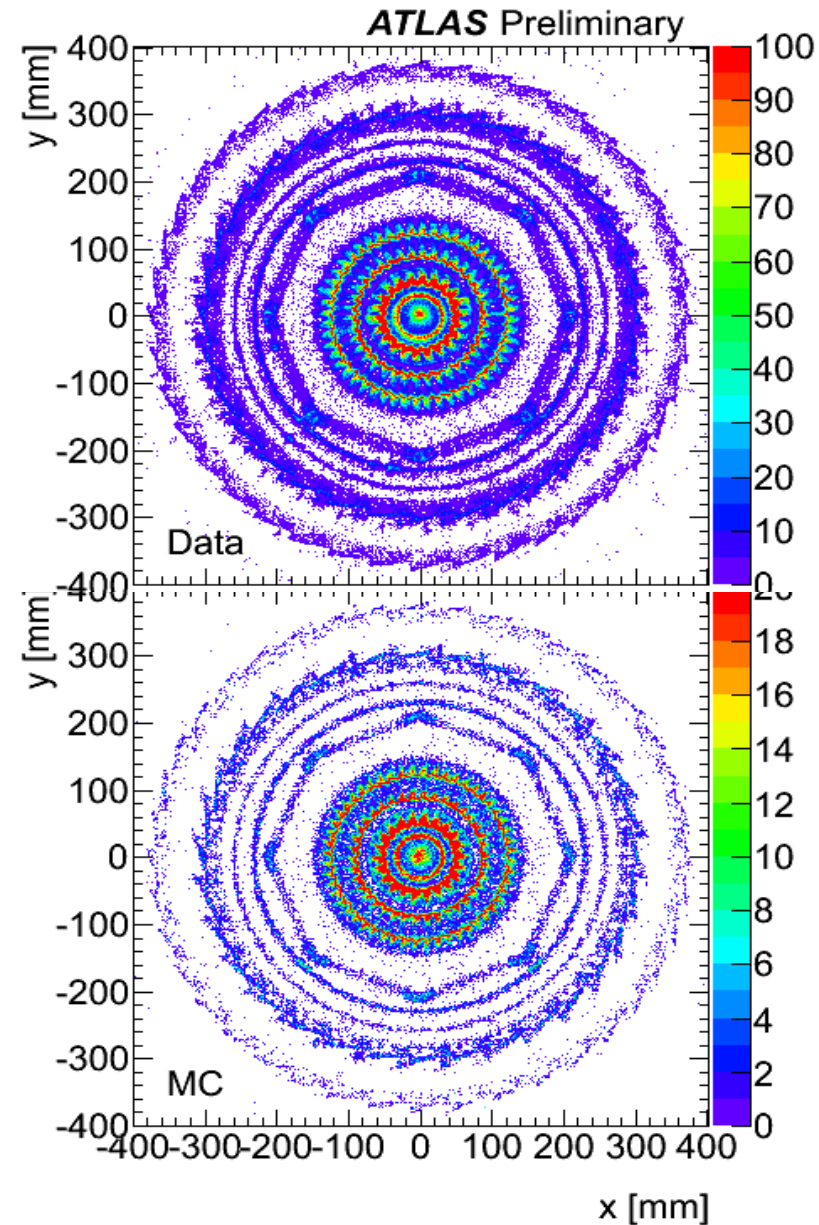(but we keep the truth information)
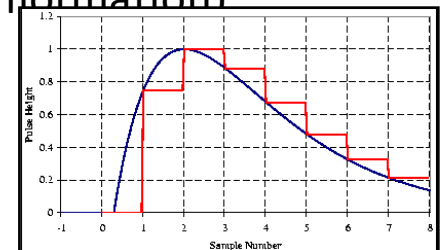
Detector simulation step is very CPU intensive. Requires huge computing resources.

Detector Geometry in the Simulation

Use a very detailed geometry of the detector in the simulation program.
Need to correctly model the interaction of the particles with the detector material.

Can use photon conversions to map out the material in the detector.
Doing this is both the real data and the simulation allows you to check the material description of the detector in the simulation.

Summary

- Reconstruction split into two parts
  - Detector reconstruction
  - Physics object reconstruction
- Sophisticated algorithms used to give best performance
  - Complex calibrations and alignments
- Detailed simulation very important for physics analysis
  - Including detailed geometry of the detector
- Tomorrow – Physics Analysis….

Tracking at the LHC experiments

- Need to cope with
  - Multiple scattering
    - Tracking detectors at the LHC have a lot of material in them compared to previous experiments
  - Mis-alignments
- Track finding at LHC difficult because many tracks produced in LHC interactions
  - Lots of hits in the tracker
  - Lots of combinatorics (need to keep the CPU time spent in tracking under control)
- Want very high track finding efficiency
- Want good track momentum and impact parameter resolution