Analysis of LHC data

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Data Flow in Collider experiments (1)

Data Collection

Theory

Particles, couplings

Hard Interaction

Partons

PDF, UE,
QCD/QED Radiation
Fragmentation/Hadronisation

pp interactions

LHC

Data Analysis

X-section measurement
Mass measurement

Kinematic acceptance
Particle ID efficiency
Background subtraction

Signal selection

Data Flow in Collider experiments (2)

Data Collection

LHC

Particles

Detectors

Tracks, clustered energy deposits
Space points, cell energy deposits

Readout

Electrical signals

Digitisation

Byte stream

DAQ/Trigger

Events

Mass storage

Data Analysis

Momentum/energy measurement
Particle id
Combined Object reconstruction

Pattern Recognition
Detector calibration
Alignmnent

Electronics calibration

Efficiency correction

Diagram is a simplified view: in reality some of the parts proceed in parallel: e.g. some physics signals ($Z \to \ell\ell$) are also used for increase of detector understanding

Lectures will be based going up an down this data flow diagram:

- Discussion of how the physics aim influenced the requirements on the performance of the LHC and of the general purpose detectors
- Basic issues and limitation the detection and reconstrution of different objects in LHC detectors
- Description of the basic steps needed for the commissioning and undertanding of a few detector subsystems
- Description of the steps for some example analyses:
  - $W \to \ell\nu$ cross-section
  - SUSY searches

LHC: pp Collider $\sqrt{s}$=14 TeV   Startup: end 2009 with $\sqrt{s}$=7 TeV

Main motivations:

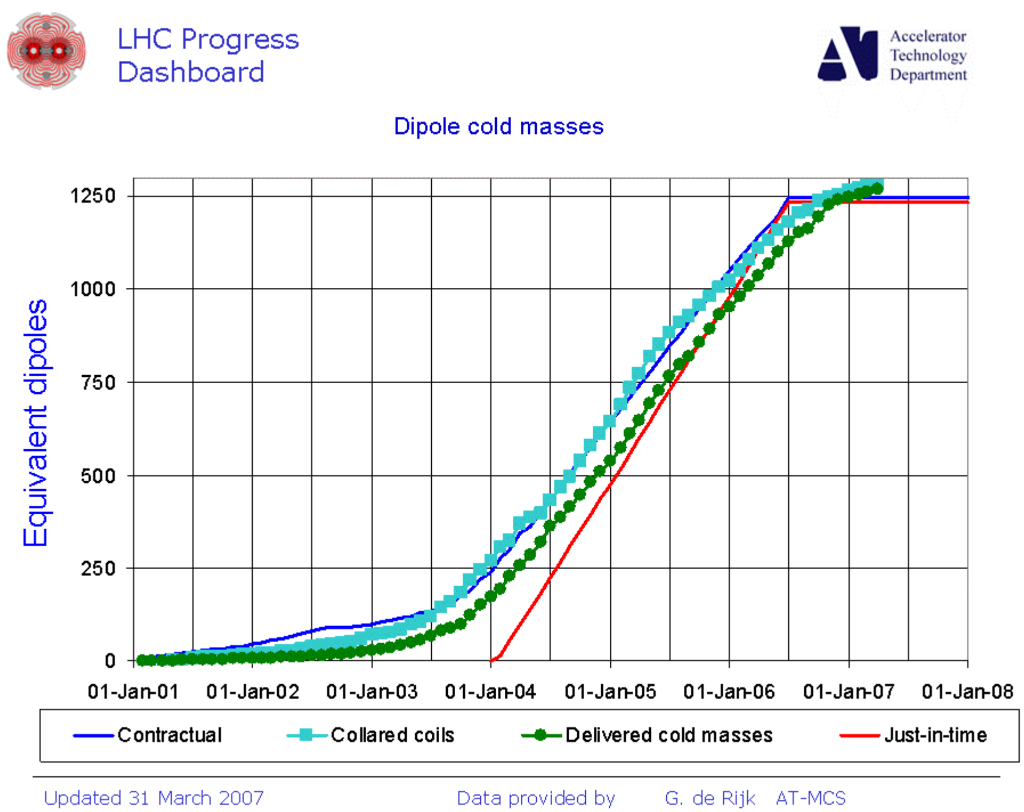
- Elucidate the mechanism of ElectroWeak Symmetry breaking:
  - Look for Higgs boson in allowed interval 100 GeV-1 TeV
  - In absence of low mass Higgs, study production of longitudinal gauge boson pairs.
- Find evidence for possible deviation from the Standard Model
  - Strong theoretical motivations to think that SM is only effective theory
  - In order to solve some of the theoretical difficulties with SM, deviations should be observable at $\sim$TeV scale

LHC Energy

$\sqrt{s} = 14$ TeV: explore the TeV scale, search for new massive particles up to 5 TeV

Maximum energy limited by the bending power needed to fit ring in 27 Km circumference LEP tunnel

$$p(\text{TeV}) = 0.3\text{B (T) R(km)}$$



LHC: $B = 8.4$ T:

$\sim$1300 superconducting dipoles working at 1.9 K

All magnets were produced and tested in time!

Luminosity:

$$\mathcal{L} = \frac{N}{\sigma}$$

with $\mathcal{L}$: Luminosity $\quad N$: event frequency, $\quad \sigma$: cross-section

Two luminosity scenarios:

- peak$\sim 10^{33}$ cm^{-2}s^{-1} - initial "low luminosity": $\int \mathcal{L}\mathrm{dt} = 10 \text{ f}b^{-1}$ per year
- peak$\sim 10^{34}$ cm^{-2}s^{-1} - design "high luminosity": $\int \mathcal{L}\mathrm{dt} = 100 \text{ f}b^{-1}$ per year

Benchmark: ensure detection of Higgs boson in the range 100 GeV-1 TeV

$m(H) \sim 100 - 150$ GeV	$H \to \gamma\gamma$	$\sigma \times BR \times \epsilon \sim 10 - 20$ fb	$S/B \sim 1/50$
$m(H) = 1$ TeV	$H \to WW \to \ell\nu jj$	$\sigma \times BR \times \epsilon \sim 2 - 3$ fb	$S/B \sim 1/2$

Discovery when statistical significance for signal $S/\sqrt{B} > 5 \to$

Required integrated luminosity for discovery (no K-factors):

- $H \to \gamma\gamma$: $\sim$1000 events ~ 100 fb^{-1}
- $H \to WW$: $\sim$50 events ~ 20 fb^{-1}

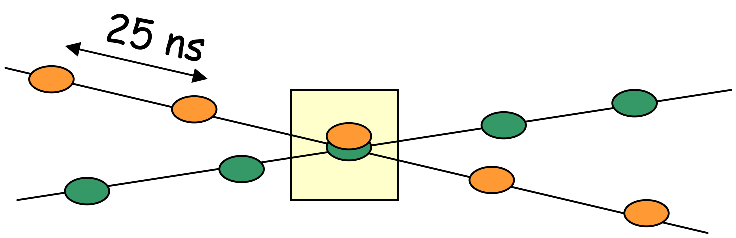
How is luminosity $\mathcal{L}$ achieved?

If two beams containing n_1 and n_2 particles collide with a frequency f:

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma^2_{beam}}$$

with σ_{beam} gaussian transverse beam profile

LHC values: $n_1 = n_2 = 10^{11}$, and $\sigma_{beam} \sim 16 \times 10^{-6}$ m, determined by the physics of colliding beams.



To achieve $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}, LHC has to run with a bunch crossing every 25 ns

Inelastic proton-proton cross-section at $\sqrt{s} = 14$ TeV is ~ 70 mb $\Rightarrow$

LHC interaction rate at high luminosity: $\sim 7 \times 10^{-2} \times 10^{-24} \times 10^{34} = 7 \times 10^8$ Hz

40 MHz crossing frequency: $\Rightarrow \sim 25$ superimposed interactions per crossing (pile-up)

Characteristics of pile-up interactions

Soft partonic interactions: describe with non-perturbative phenomenological models

Collider jargon: "Minimum bias": experimental definition: depends on experiment's trigger. Usually associated to non-single diffractive events

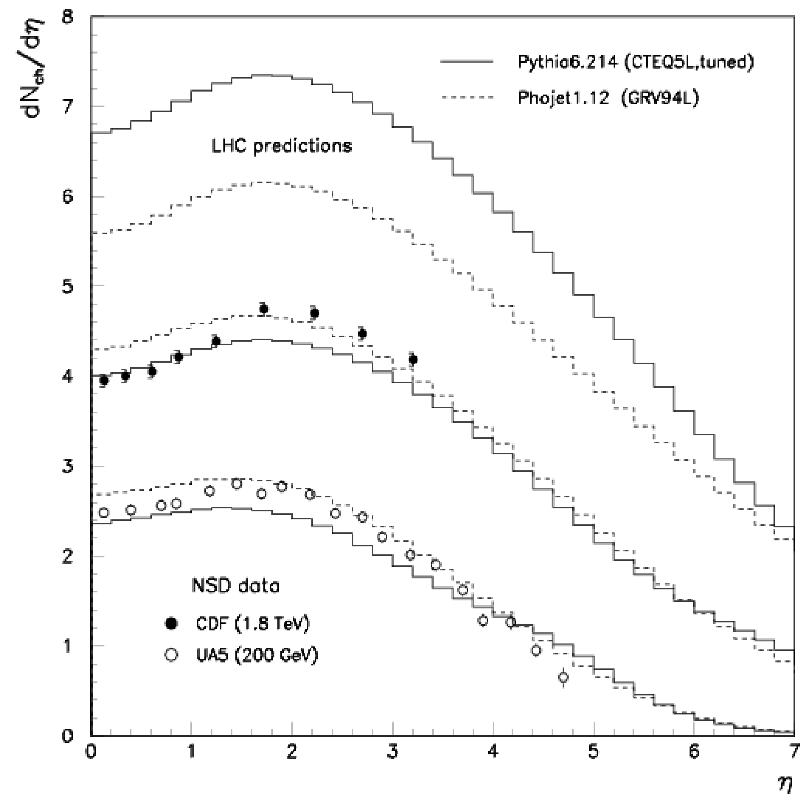
Measured at $S\bar{p}pS$ and Tevatron, large uncertainties in extrapolation to LHC

Main features:

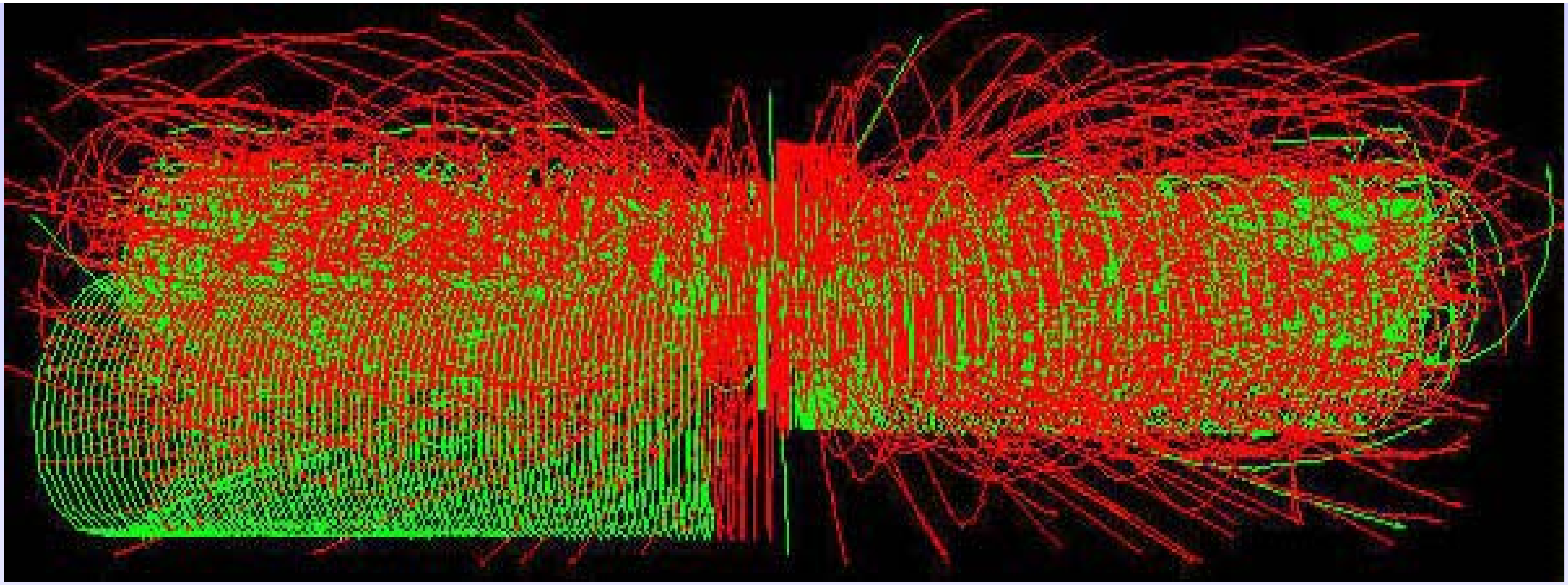
~7 charged particles per unit of rapidity⇒ ~ 100 charged particles over $|\eta| < 2.5$ per crossing at low luminosity

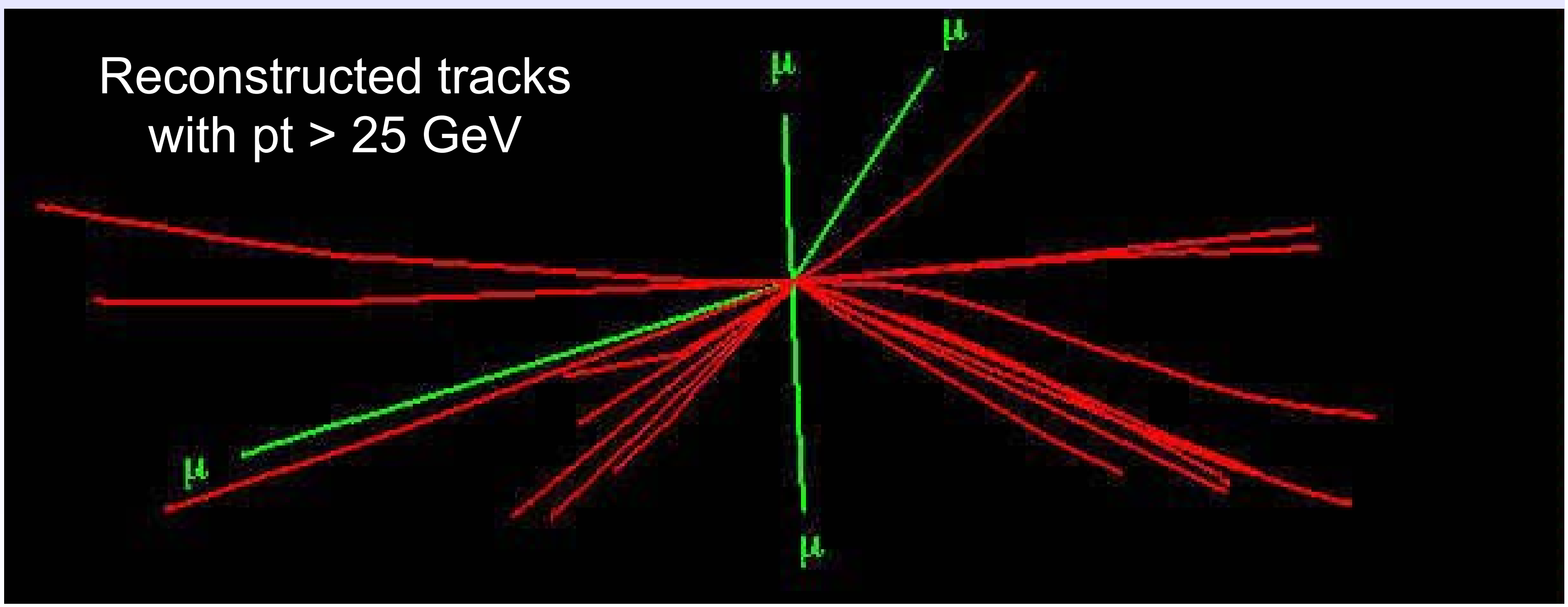
Significant radiation damage from interaction!

$< p_T > \sim 500$ MeV ⇒ can select interesting particles by cut in p_T



Example: $h \to 4\mu$ event in CMS at high luminosity





Large impact on detector design:

- ## Speed:

  LHC detectors must have fast response otherwise integrate over too many bunch crossings

  Typical response time: 20-50 ns$\longrightarrow$ integrate over 1-2 bunch crossings

  $\Rightarrow$ very challenging readout electronics

- ## Granularity:

  LHC detectors must be highly granular to minimise probability that pile-up particles in same detector element as interesting object

  $\Rightarrow$ Large number of electronics channels

- ## Radiation hardness:

  High flux of particles from pp collisions $\Rightarrow$ high radiation environment

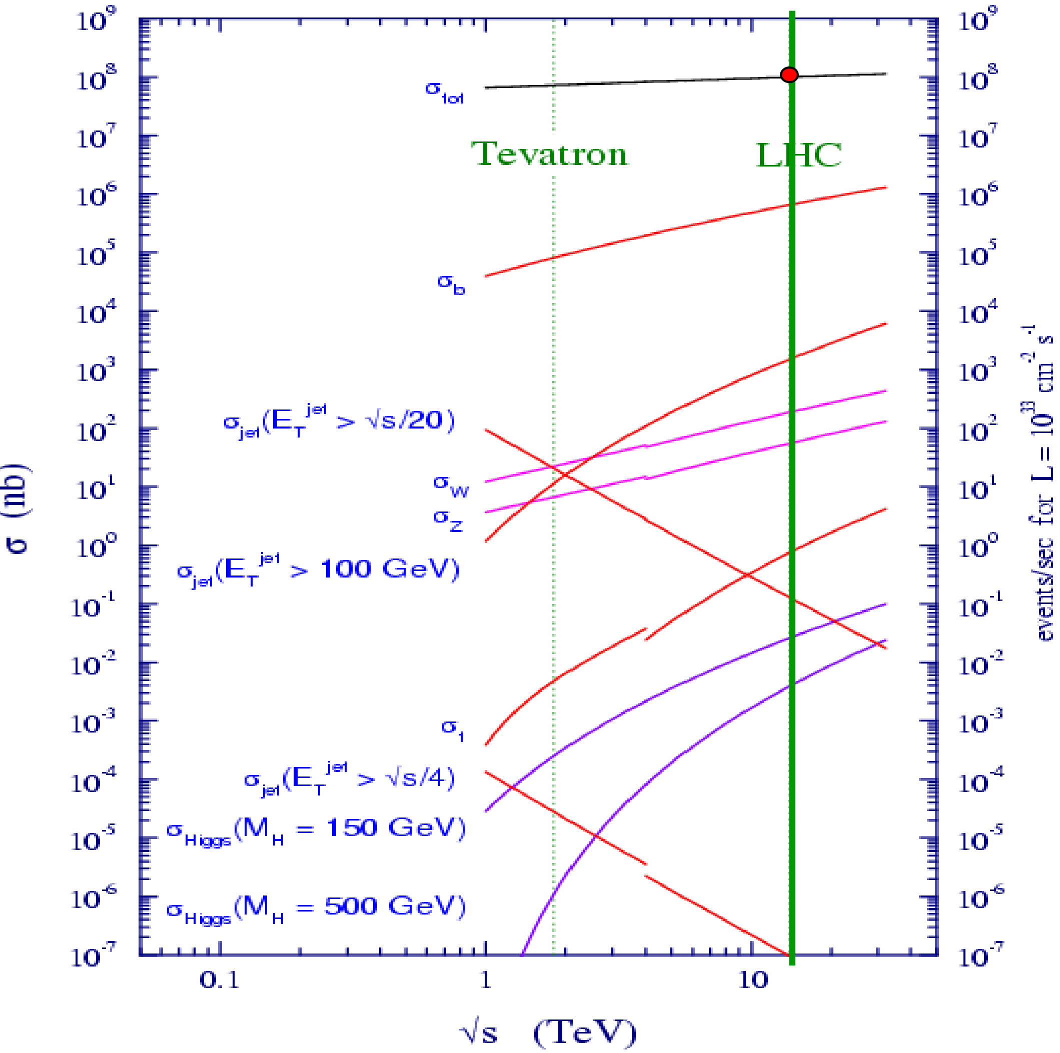
  In 10 years of LHC data: up to $10^{17} n$ cm^{-2}, up to 10^{7}Gy

  Radiation decrease like d^2 from beam: detectors near beam pipe mostly affected

  $\Rightarrow$ Need radiation resistant detector technologies especially at high $|\eta|$

  $\Rightarrow$ Need also radiation hard electronics

Backgrounds to discovery physics



High p_T events dominated by QCD jet production:

- Strong production
- Many contributing diagrams

$\sigma_{jet}(E_T^{jet} > 100$ GeV$) \sim \mu$b

Signal processes rare:

- Involve heavy particles:

$\sigma_{\tilde{q}\tilde{q}}(m(\tilde{q}) \sim 1$ TeV$) \sim$ pb

- Have weak cross-section

$\sigma_{Higgs}(m(Higgs) = 100$ GeV$) \sim 30$ pb

QCD background from 5-6 orders of magnitude larger than signals

Overwhelming QCD backgrounds in exclusively hadronic channels

$\Rightarrow$ rely on final states involving γ, leptons, $\not{E}_T$, b-jets $\Rightarrow$ pay additional price in BR

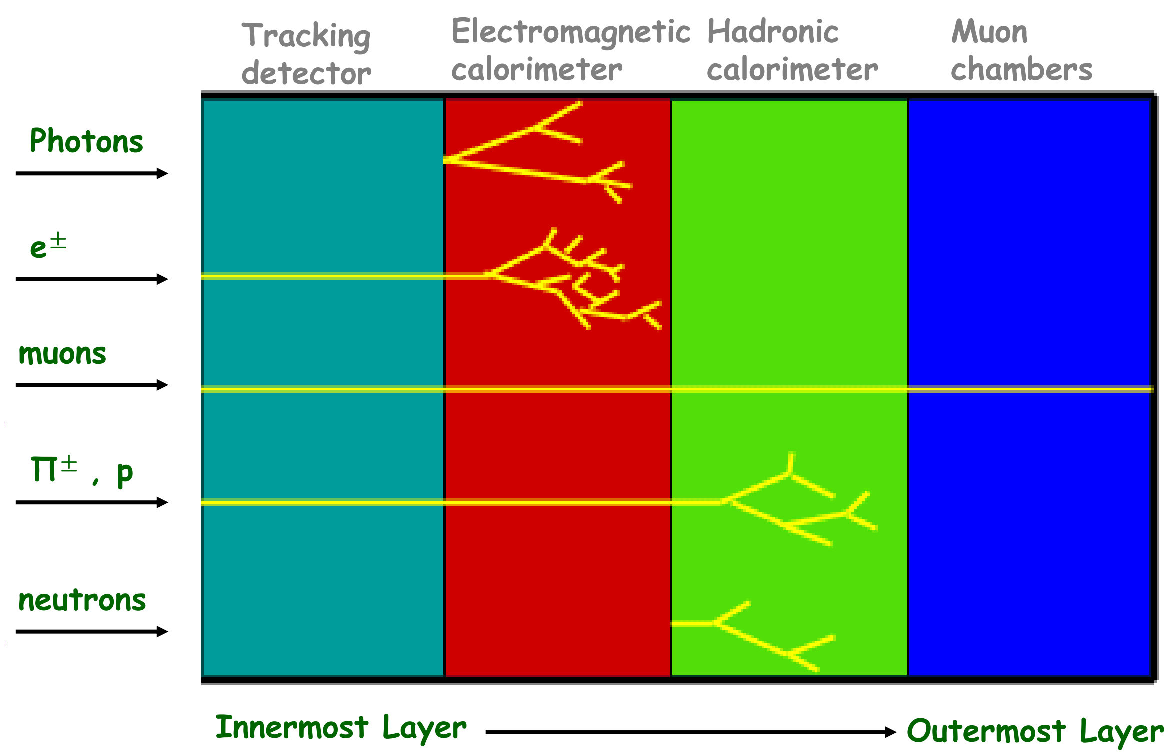
Generic Collider detector

Do not know how new physics will manifest itself:

$\Rightarrow$ Detectors must be sensitive to as many particles and signatures as possible:

$$e,\ \mu,\ \tau,\ \nu,\ \gamma,\ \text{jets},\ b-\text{quarks}$$

Implement this through a layered structure of subdetectors round the beam pipe



ATLAS and CMS detectors

Schema of previous page implemented in both detetors:

- Momentum/charge of tracks and secondary vertices (e.g. from b-quark decays) measured in central tracker. Excellent momentum and position resolution required
- Energy and position of electrons and photons measured in electromagnetic calorimeters. Excellent position and energy resolution required
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters. Good coverage and granularity required
- Muons identified and momentum measured in external muon spectrometer (+ central tracker). Excellent resolution required.
- Neutrinos "detected and measured" through measurement of missing transverse energy $\not{E}_T$. Calorimeter coverage over $|\eta| < 5$ needed

Difference between detectors is in choice of technologies for different subcomponents and in configuration of magnetic field

ATLAS detector

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(\mathrm{GeV})} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \to \gamma\gamma$)

Precision Muon Spectrometer,

$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \to \mu\mu$, $H \to 4\mu$)

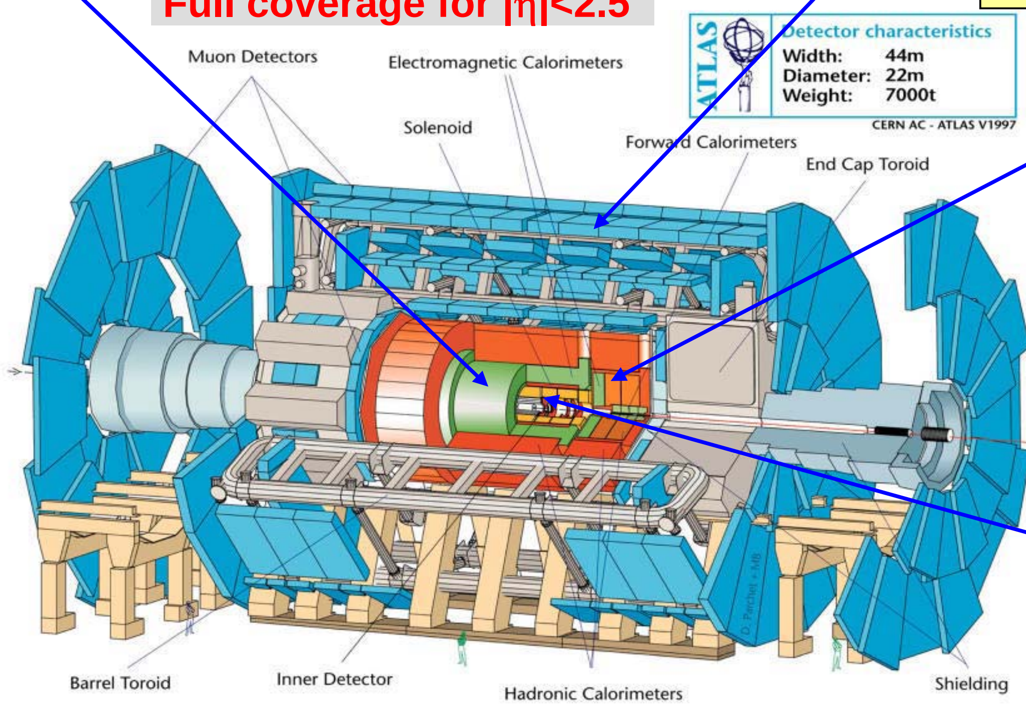
Full coverage for $|\eta|<2.5$

Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(\mathrm{GeV})} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \to \tau\tau$)



Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

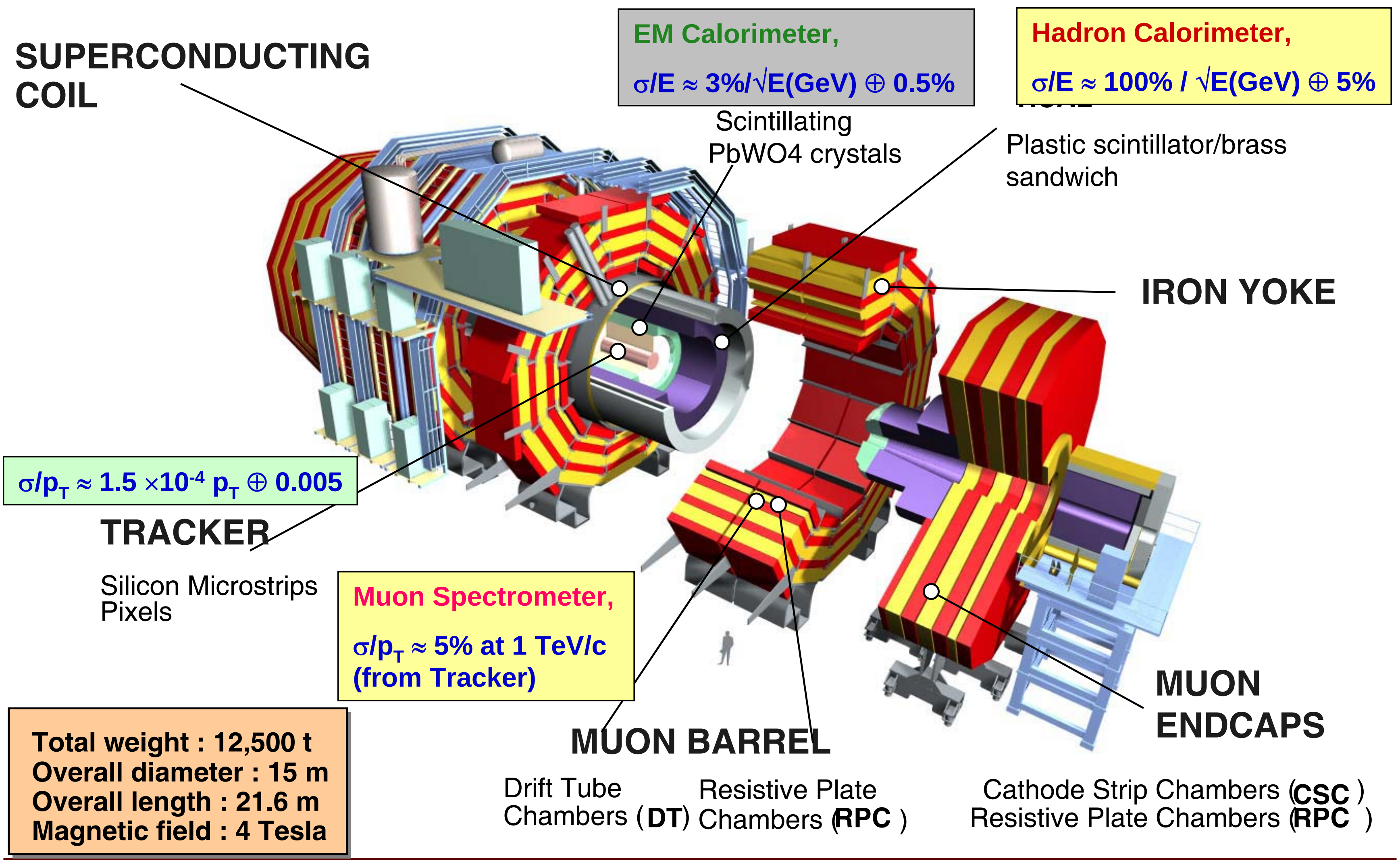
$\sigma/p_T \approx 5 \times 10^{-4}\, p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)$=15μm@20GeV (e.g. $H \to bb$)

Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

CMS detector



	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixel + strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\ p_T \oplus 0.01$	Si pixel + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb - liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scintillator + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ + catcher) $\sigma/E \sim 65\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ $\sigma/p_T \sim 7\ \%$ at 1 TeV standalone	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

A few examples of required performance:

- Lepton measurement: $p_T \sim \mathrm{GeV} \rightarrow 5\mathrm{TeV}$ ($b \rightarrow lX$, W', Z')
- Mass Resolution (m~ 100 GeV):

  $\sim 1\%$ $(H \rightarrow \gamma\gamma, 4l)$

  $\sim 10\%$ ($W \rightarrow jj$, $H \rightarrow bb$)

- Calorimeter coverage: $|\eta| < 5$ (E_T^{miss}, forward jet tag)
- Particle identification :

  $\epsilon_b \sim 50\%$ $R_j \sim 100$ ($H \rightarrow bb$, SUSY)

  $\epsilon_\tau \sim 50\%$ $R_j \sim 100$ $(A/H \rightarrow \tau\tau)$

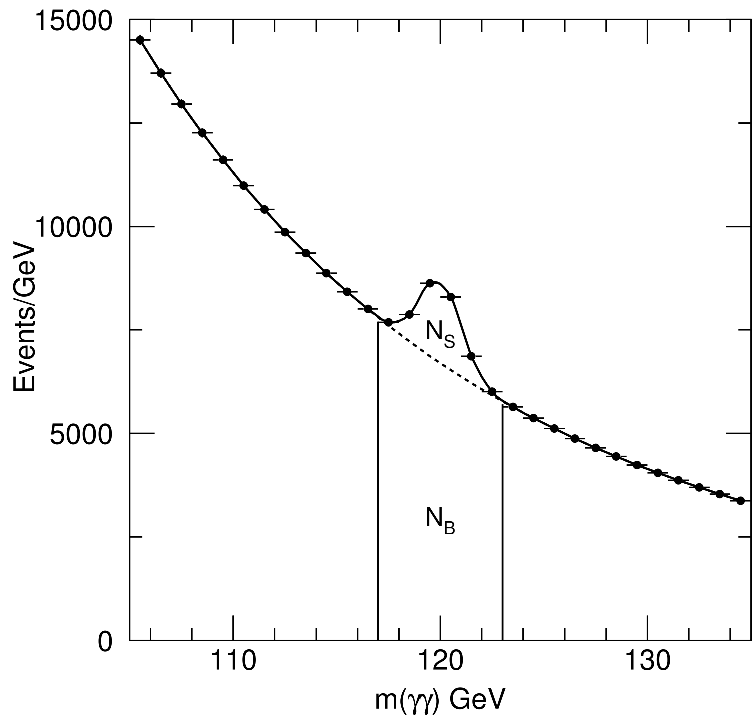
  $\epsilon_\gamma \sim 80\%$ $R_j \sim 10^3$ $(H \rightarrow \gamma\gamma)$

  $\epsilon_e > 50\%$ $R_j \sim 10^5$

- Trigger: 40 MHz$\rightarrow$ 100 Hz reduction

Example of optimisation of discovery potential

Suppose a narrow particle $X \rightarrow \gamma\gamma$ is produced:



Signal significance:

$$S = \frac{N_s}{\sqrt{N_B}}$$

N_s= number signal events

N_B= number of background events

$\sqrt{N_B}$= error on number of background events for large numbers

Otherwise use Poisson statistics

$S > 5$: signal is larger than 5 times the error on background.

Gaussian probability that background fluctuates up by more than 5σ: 10^{-7}

LHC detector performance optimised for case of $H \rightarrow \gamma\gamma$

Parameters for maximising significance

- Detector resolution (σ_m):

  If σ_m increases, need to correspondingly enlarge peak region to keep same number of signal events $\Rightarrow N_B$ increases by same factor $(B \sim flat)$

  $\Rightarrow S = N_s/\sqrt{N_B}$ decreases $\Rightarrow S \sim 1/\sqrt{\sigma_m}$

  This is only valid for $\Gamma_H \ll \sigma_m$ If Higgs broad, detector resolution not relevant

- Integrated luminosity L:

  $N_s \sim L \qquad N_B \sim L \qquad \Rightarrow S \sim \sqrt{L}$

- Signal selection efficiency ϵ

  $N_s \sim \epsilon$. If background rejection constant: $S \sim \epsilon$

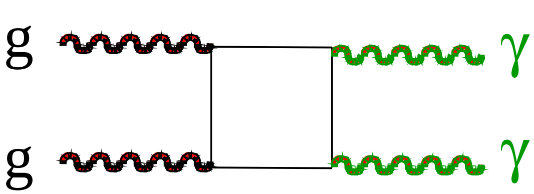
- Rejection of reducible backgrounds R.

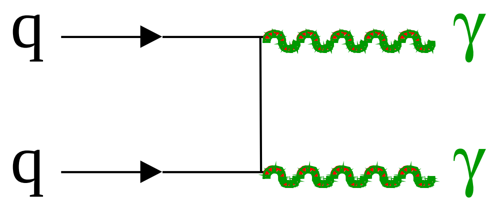
  If they dominate and N_s constant : $S \sim \sqrt{R}$.

  Typically try to acheve R such that reducible backgrounds $\ll$ irreducible ones

$H \to \gamma\gamma$: backgrounds

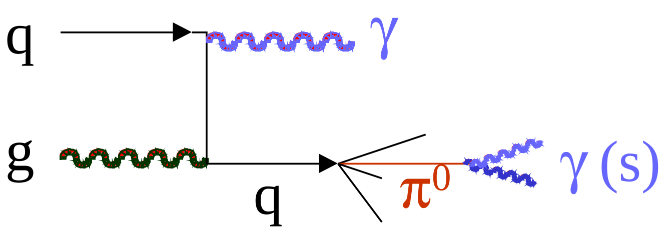
- $\gamma\gamma$ production, irreducible (same final state as signal)





$$\frac{\sigma_{\gamma\gamma}}{\sigma(H \to \gamma\gamma)} \sim 60$$

- γ+Jet, Jet+Jet where one or both jets fake a photon, reducible



$$\frac{\sigma_{\gamma j}}{\sigma_{\gamma\gamma}} \sim 10^3 \quad \frac{\sigma_{jj}}{\sigma_{\gamma\gamma}} \sim 10^6$$

Need rejection factor of $\sim 10^3$ on jets for $\epsilon_\gamma = 80\%$ in order to bring reducible background below $\gamma\gamma$ background

Fake photons dominated by π^0, design EM calo with excellent granularity to achieve desired γ/π^0 rejection

$H \to \gamma\gamma$: irreducible background

Irreducible background: can not be suppressed with detector cuts

$\sigma_{\gamma\gamma} = 2\ \mathrm{fb/GeV}$ for $m_{\gamma\gamma} = 100$ GeV; $\Gamma_H < 1$ MeV $\Rightarrow$ Significance $\sim 1/\sqrt{\sigma_m}$

$\sigma_m^2 = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$ Two contributions to σ_m: σ_E and σ_θ

ATLAS

Lead-liquid argon sampling calorimeter:

$$\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}}$$

Longitudinal segmentation: measure γ direction

$$\sigma(\theta) \sim \frac{50\mathrm{mrad}}{\sqrt{E}}$$

When available use reconstructed conversions or reconstructed primary vertex

CMS

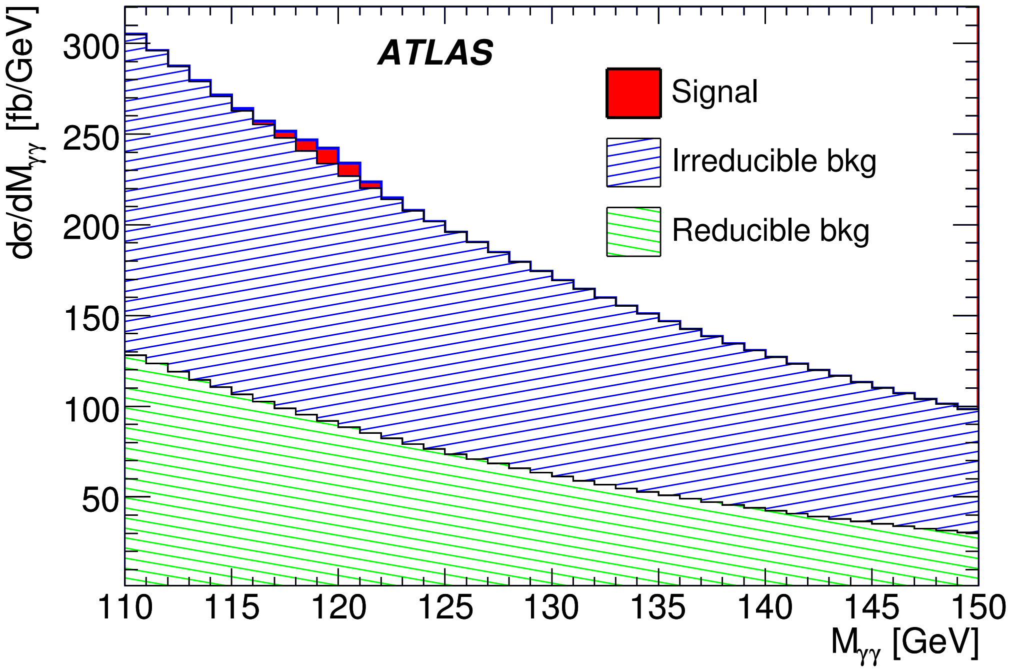
Cristal calorimeter:

$$\frac{\sigma(E)}{E} \sim \frac{2 - 5\%}{\sqrt{E}}$$

No longitudinal segmentation: vertex measured from secondary tracks from spectator partons, difficult at high L, available only for 80% of events

ATLAS result for $m_H \sim 120$ GeV: $\sigma_m = 1.46$ GeV

$H \rightarrow \gamma\gamma$: resulting ATLAS performance



Two isolated photons

$P_t(\gamma_1) > 40$ GeV

$P_t(\gamma_2) > 25$ GeV

$|\eta| < 2.37$, excluding crack region

Signal efficiency within $\pm 1.4\sigma_m$ of the peak is 26%, contributions from:

- Kinematic cuts
- Photon Id and isolation cuts ($\sim 80\%$ per leg)
- Mass bin ($\sim 73\%$)

For $m(H) = 120$ GeV, 1 fb^{-1}, 25.4 ev. signal, 947 bg. ($N_s/N_B \sim 2.5\%$)

Background dominated by $\gamma\gamma$ events, can be determined from sidebands

Improved sensitivity by combining with analyses on exclusive channels with 1 or more jets.

Electron-photon identification (ATLAS)

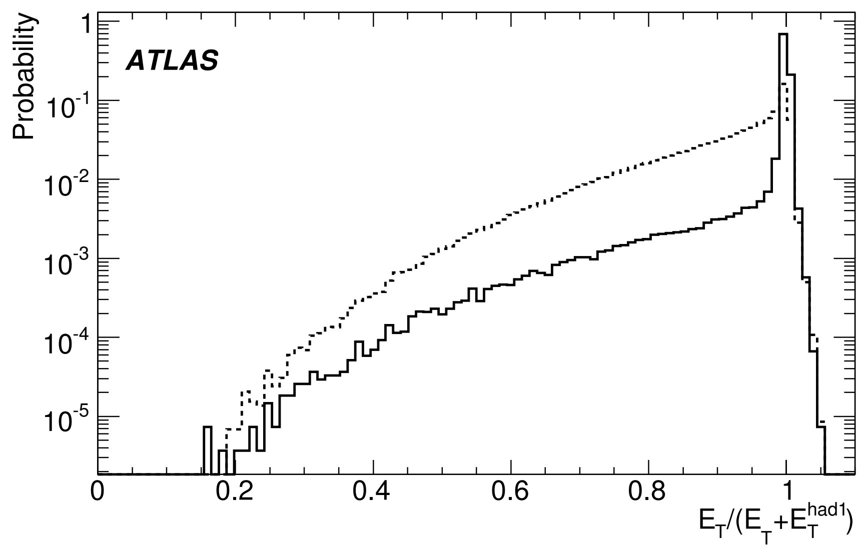
Separate electrons/photons from the overwhelming background of QCD jets

Reject charged hadrons in jets through longitudinal and lateral energy deposition pattern (lateral and longitudinal segmentation). Identify EM object

Example: show ratio of energy in EM compartment to sum of energy in EM compartment and in first hadronic compartment.

Electrons: full line

Jets: dotted line



Main remaining background : fragmentation of quarks/gluons where a π^0 carries away most of the momentum, with the decay $\pi^0 \rightarrow \gamma\gamma$

Distinguish two photons from π^0 decay from single photon through detailed study of EM shower in Calorimeter: High EM calo granularity to separate two photons

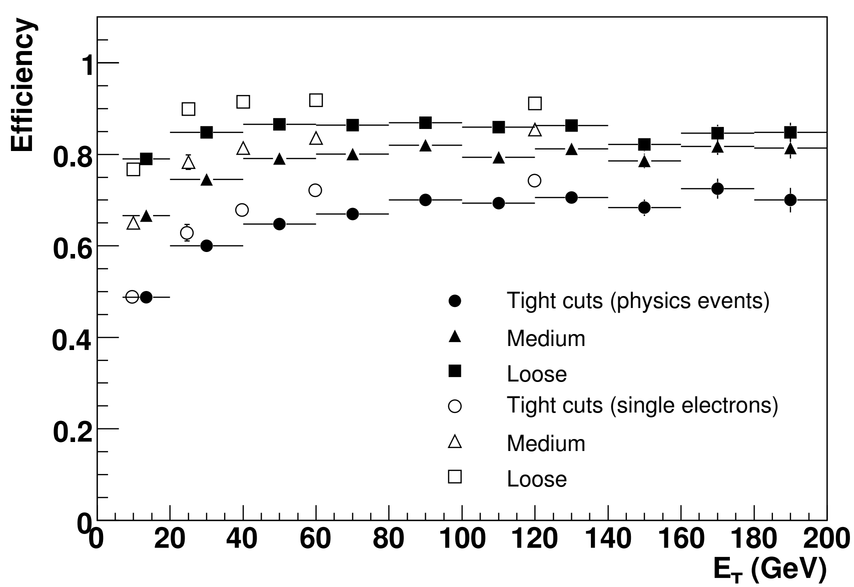
Electron identification (2)

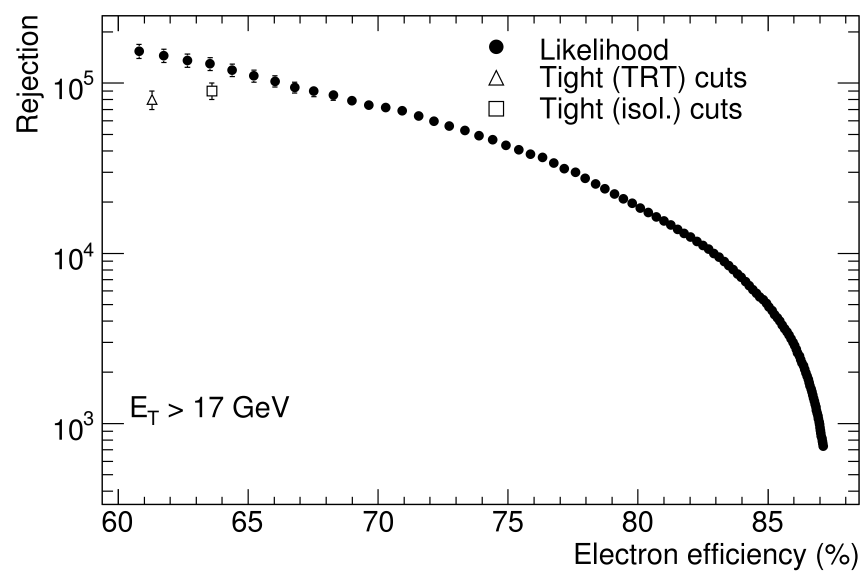
If track from $\pi^{\pm}$ superimposed to EM cluster can fake electron

Use matching between position/momentum of track and position/energy of EM cluster to reject fake electrons: Require excellent EM energy and position resolution

Further cuts include an isolation request, which suppresses electrons from B decays, and a Transition Radiation Signal

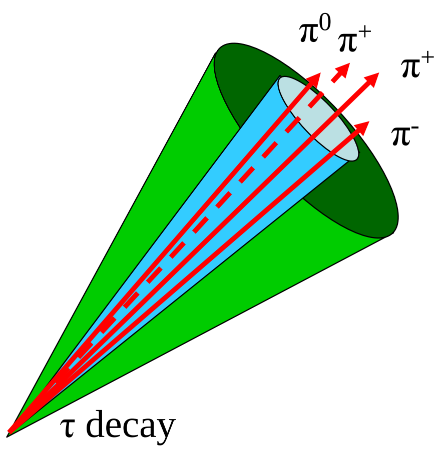
In ATLAS defined three default sets of requirements, based on combination of the above curts, yielding different efficiencies





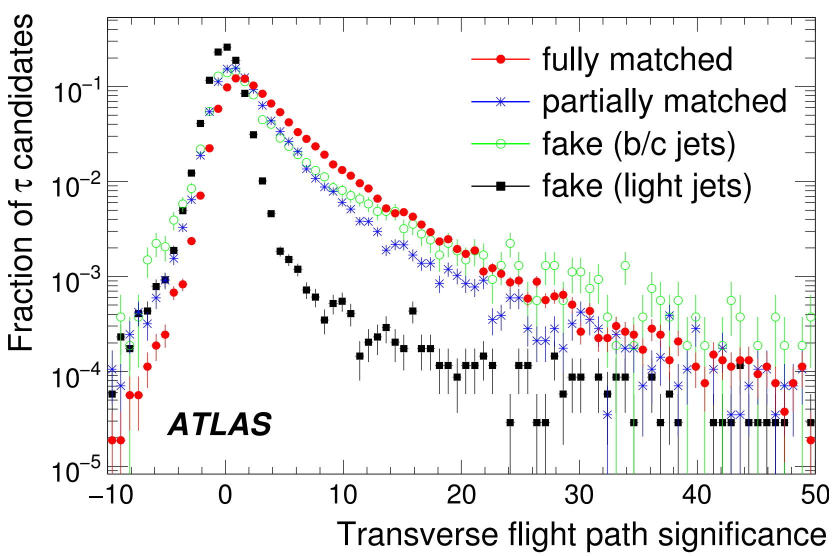
Identification of τ hadronic decays

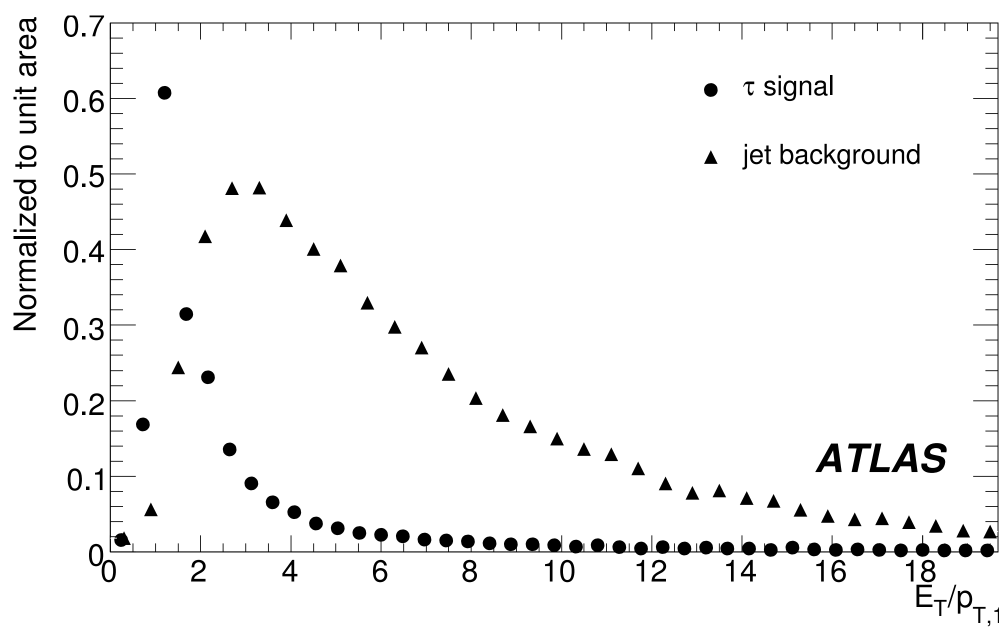
Taus decay hadronically into one or three $\pi^{\pm}$ plus π^{0} and ν_{τ}



Exploit difference between hadronic τ decays and QCD jets:

- Low track multiplicity $(1 < N_{tr} < 3)$
- Collimated track topology for 3-prong decays
- Narrow jet in calo
- Large fraction of energy carried by leading track (right plot)
- Non zero Impact parameter (left plot)

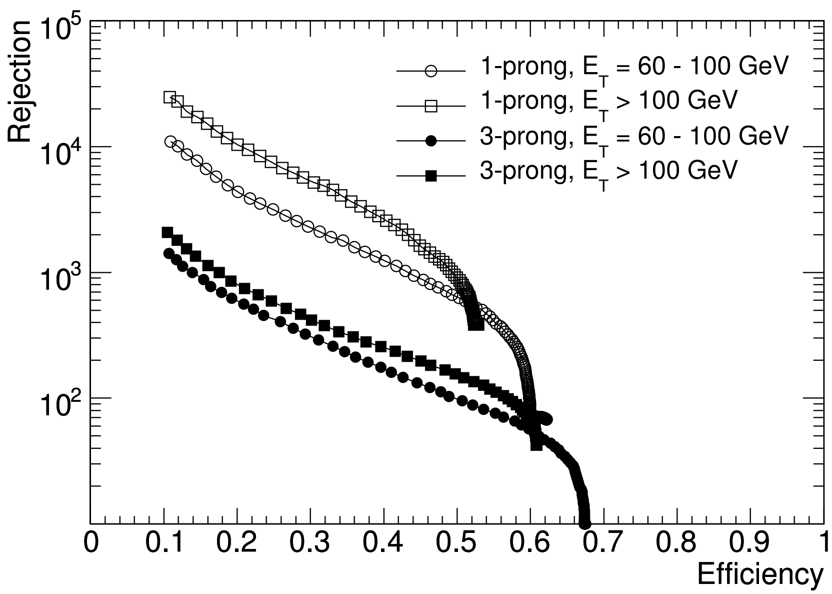


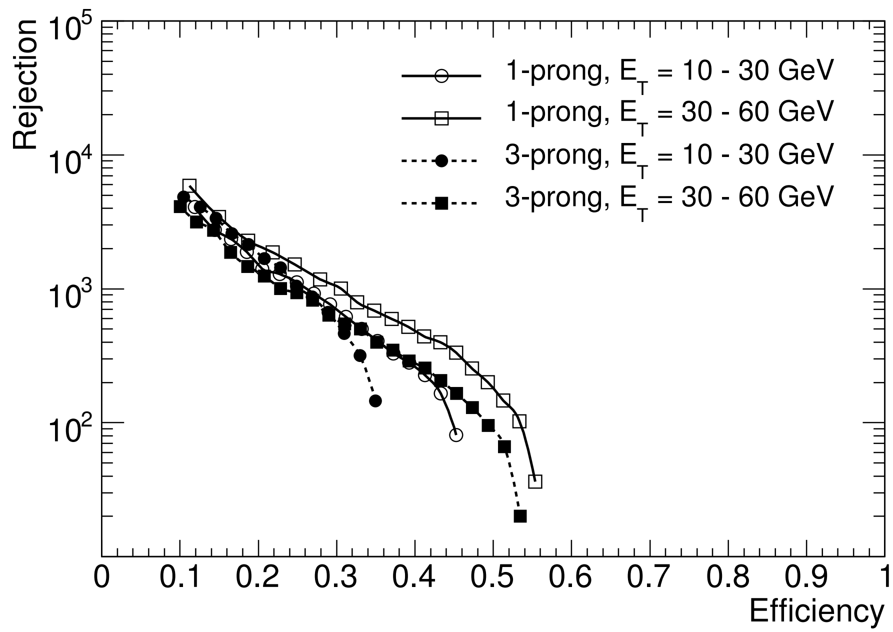


τ identification (2)

Two complementary approaches in ATLAS:

- Calo-based, seeded by calorimeter cluster, build likelihood on discriminat variables (right)
- Track-based, seeded by tracks in inner detector, energy is recostructed from tracks and EM energy deposit. Perform discrimination based on a NN (left)



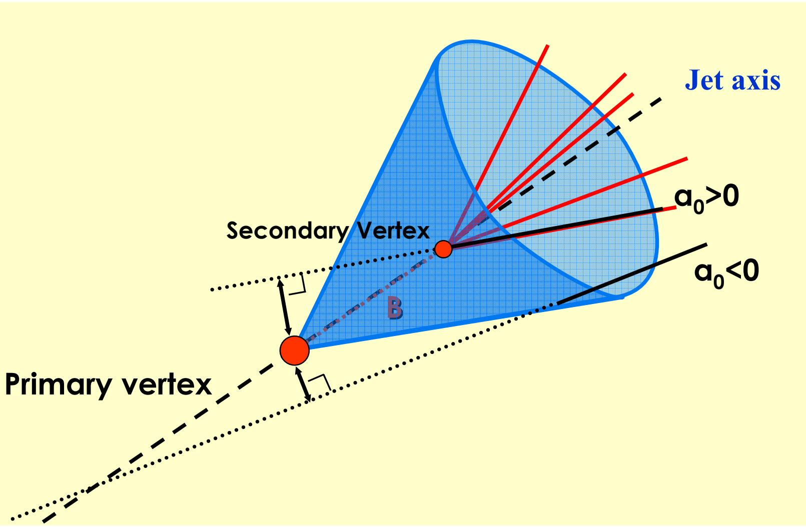


Track-based method effective for low-p_T τ, calo-based at high p_T

Strong difference between 1 and 3-prong decays dor calo method

For 50% efficiency achieve rejection between 100 and 1000

B-tagging



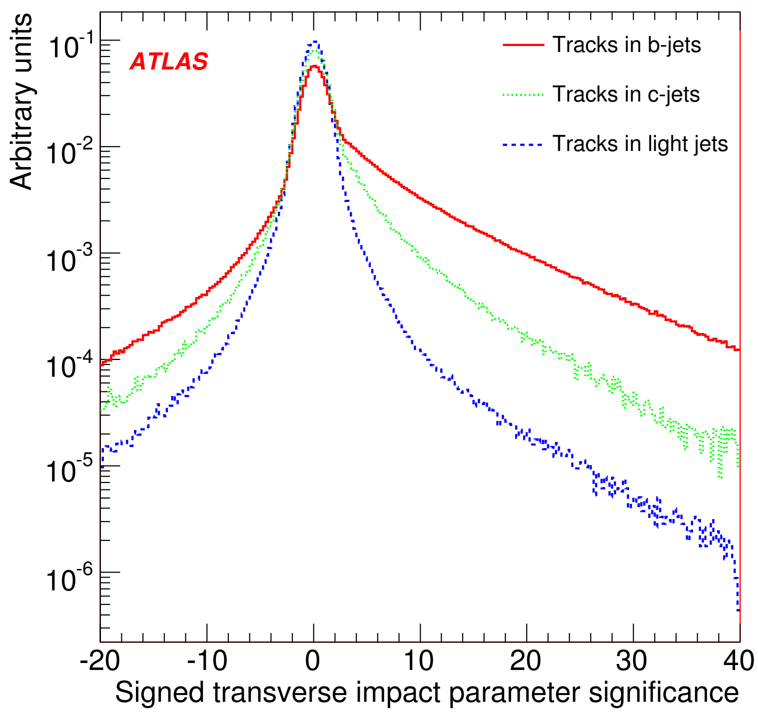
b-hadrons decay a a few mm away from interaction vertex. Two main features:

- Long decay path
- Secondary vertex inside jet

Decay path measured through impact parameter: minimum distance from primary vertex

Distribution of significance of impact parameter: symmetric for tracks from fragmentation of light quarks

Ehancement on positive side for tracks from b-hadron decays

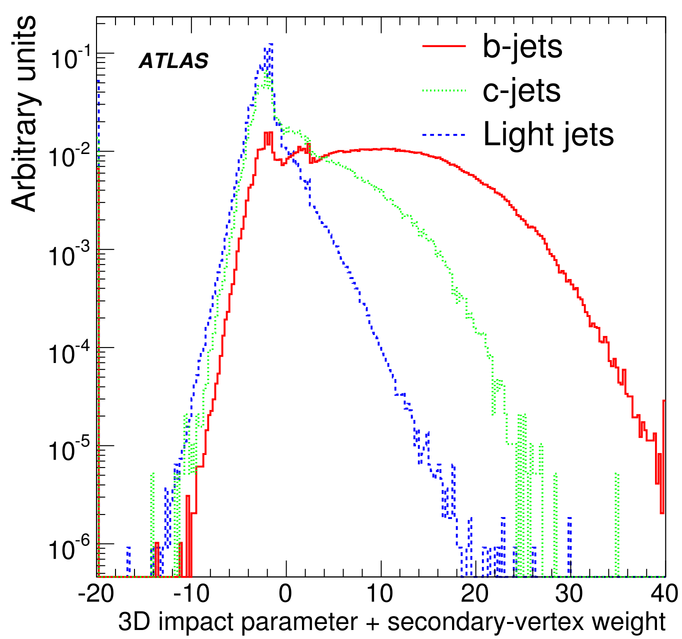


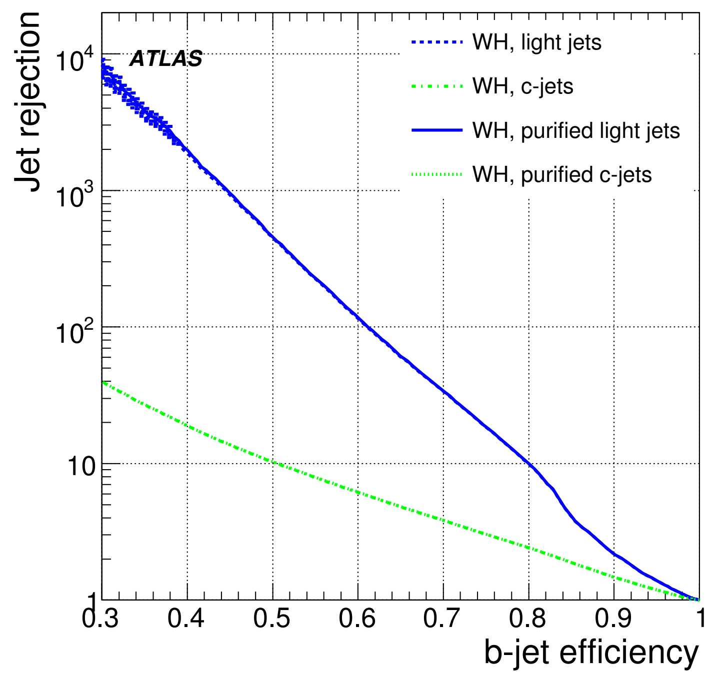
B-tagging (cont)

For a jet, build likelihood function from the impact parameter of the tracks associated to it and from variables for secondary vertex

ATLAS: Study samples of fully simulated WH, ttH, $\bar{t}t$ events

Measure rejection on QCD jets as a function of tagging efficiency

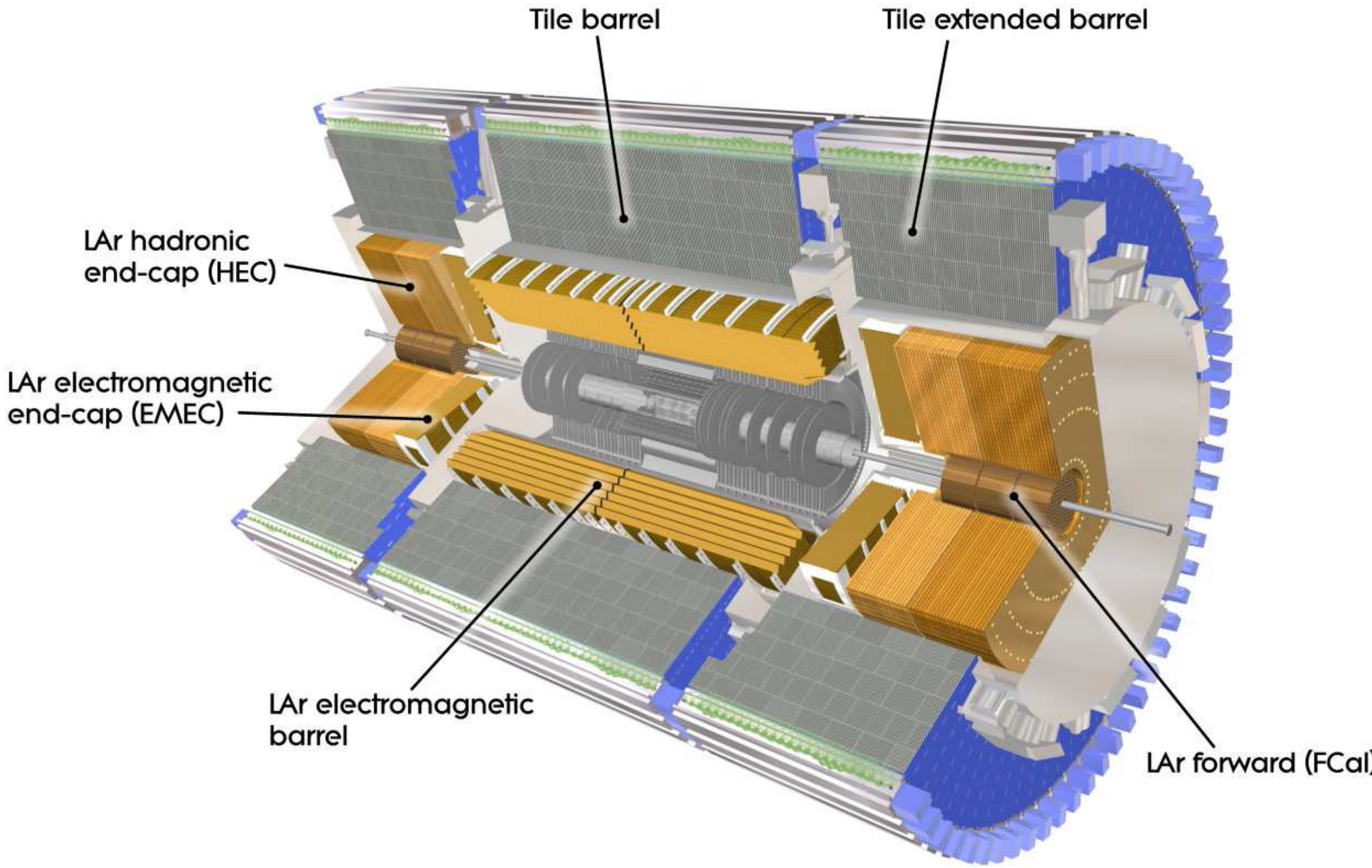




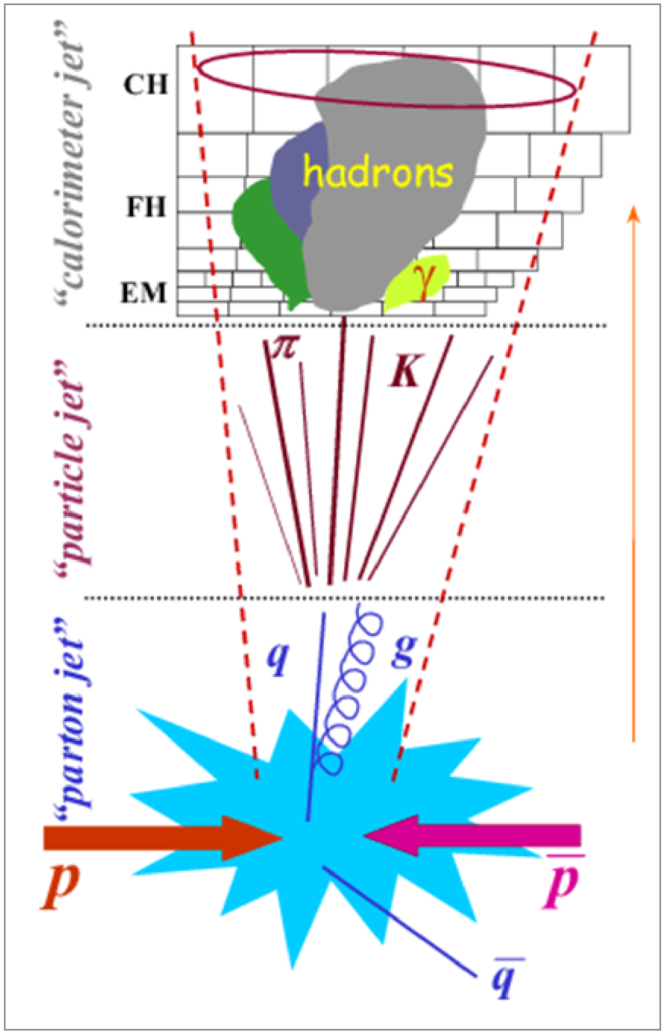
For WH sample observe rejection factor of 100 on light jets for $\epsilon_b = 60\%$

The efficiency/rejection curve is a function of the used sample.

ATLAS Calorimeter system



Jet reconstruction

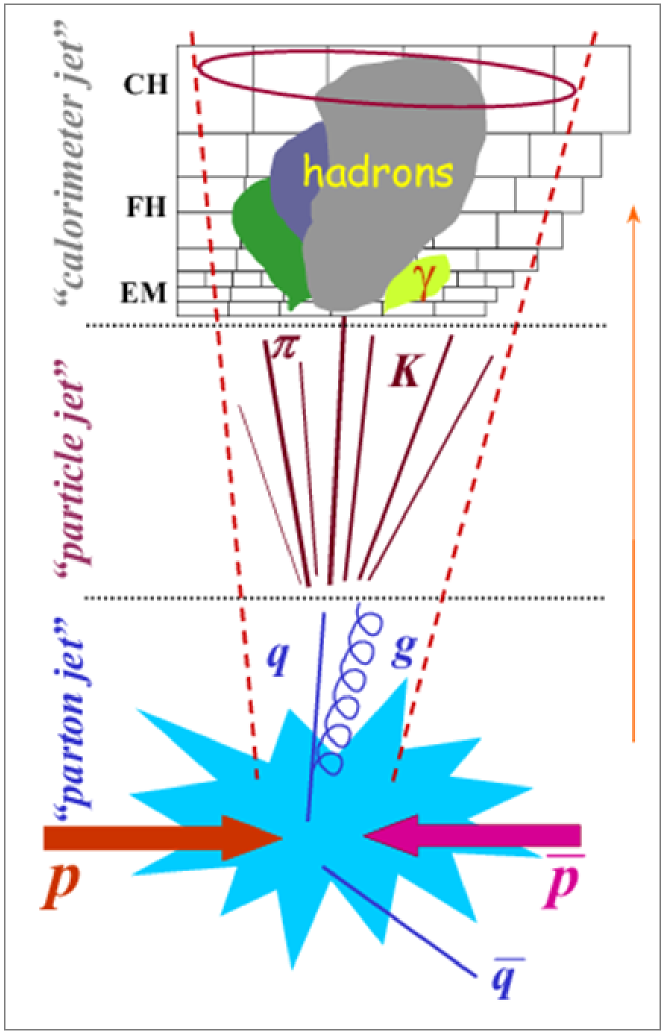


Jet reconstruction: starting from from the calorimeter signals obtain the kinematics of the particle jet or of the parton jet, depending on where we want to perform Data-Theory comparison

Calorimeter jet and Particle jet obtained running the same jet algorithm on calo cell or on stable particles

Crucial element in Data-Theory comparison, needs to satisfy theoretical requirements (infrared-safe) and experimental requirements (e.g. low sensitivity to soft part of event)

Jet reconstruction phase 1: the Calorimeter jet



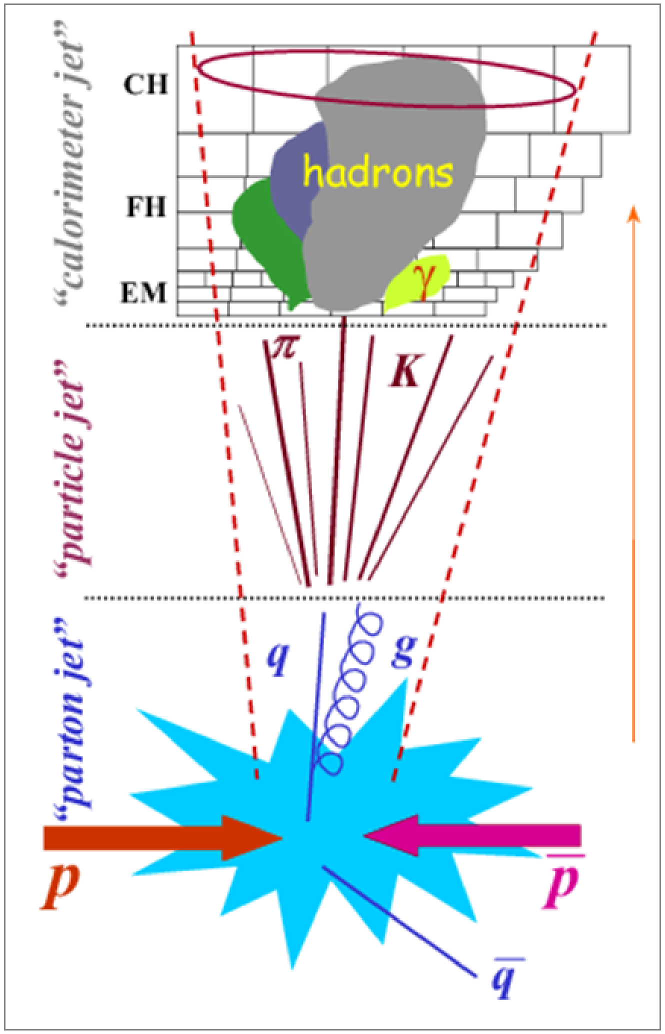
Hadronic signal definition: cell energy deposits are clusterized to build the base objects for jet reconstruction

Algorithms for suppression of electronic and pile-up niose are appied at this stage

In ATLAS two types of base objects:

- Towers of dimension $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- 3D energy blobs

Jet reconstruction phase2: to Particle jet

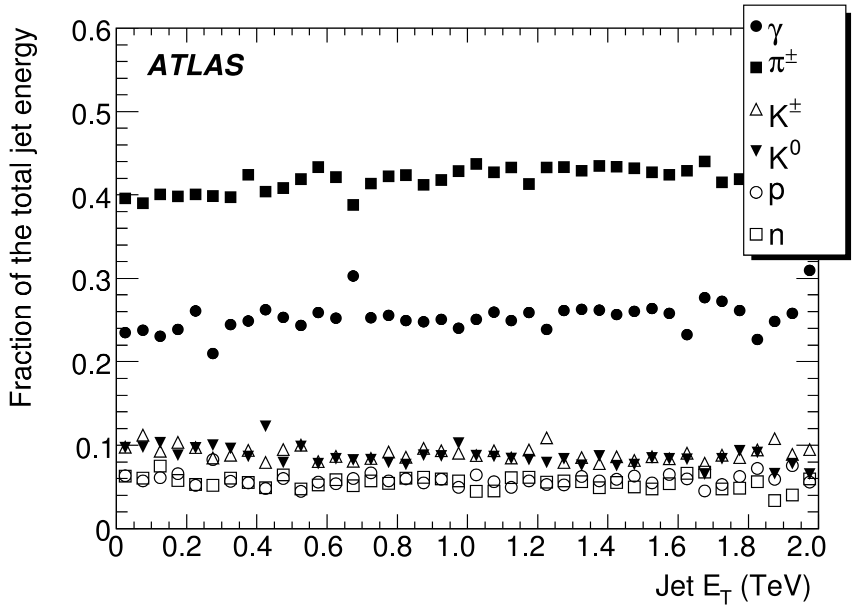


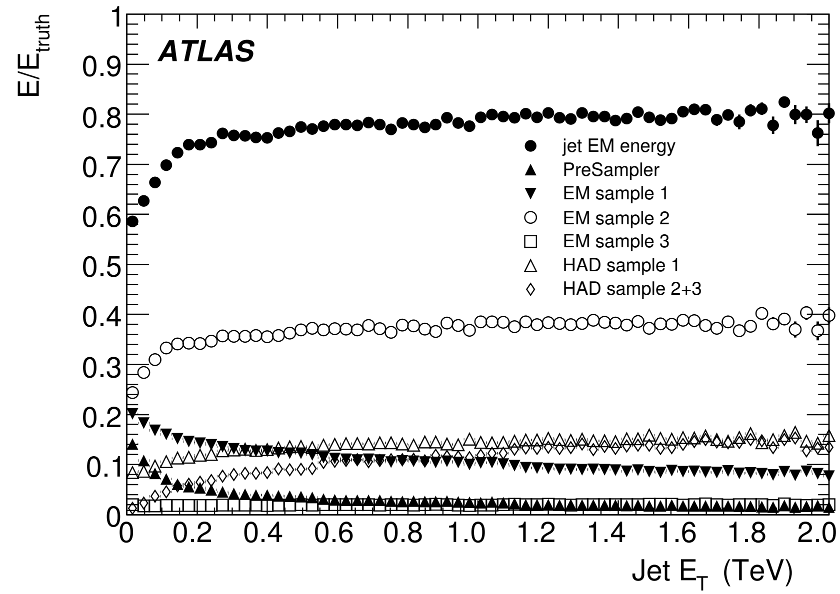
Correct for detector effects to get from calorimeter jet to particle jet:

- Non compensation of calorimeters (response to hadrons $\neq$ response to electrons)
- Effects of cracks, dead material, losses in material in front of calorimeters
- Longitudinal leakage
- Magnetic field effect

This step relies on excellent MC simulation of calorimeter response validated on test beam

Jets: Composition and Energy deposit LAR/Tile





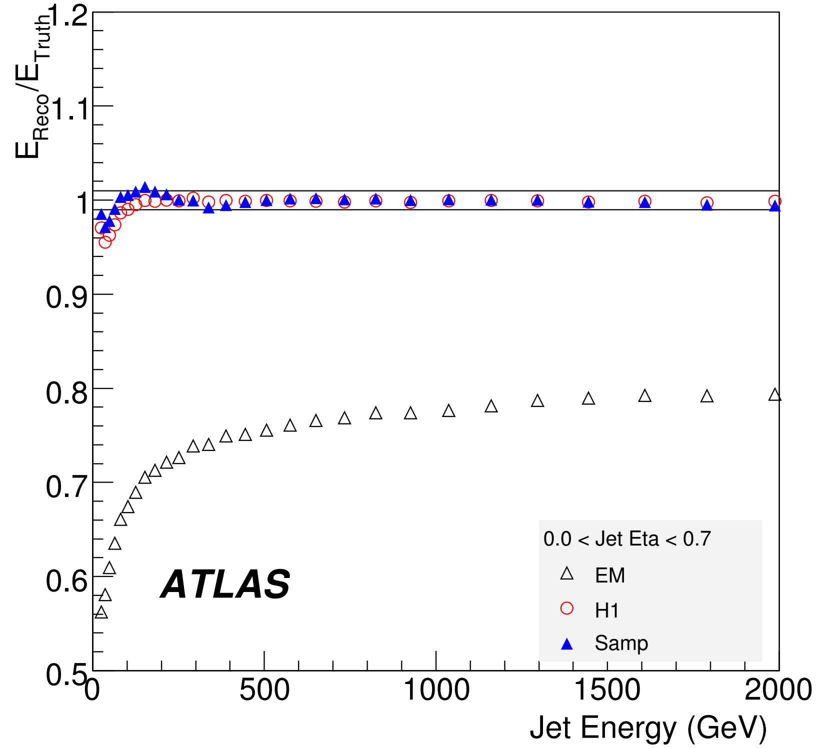
Jet energy carried by particle types

e.g. 40% $\pi^{\pm}$, 25% γ

60-80% of true jet energy in LArg EM calorimeter, for $|\eta| < 0.7$ central region

Calorimeter Calibration

- Lar and TileCal non-compensating ($e/h \neq 1$)
- Must apply a calibration scheme
- Example: cell weighting
- Electromagnetic showers: high energy density, no weighting
- Hadronic showers: lower energy density, weight to scale up energy

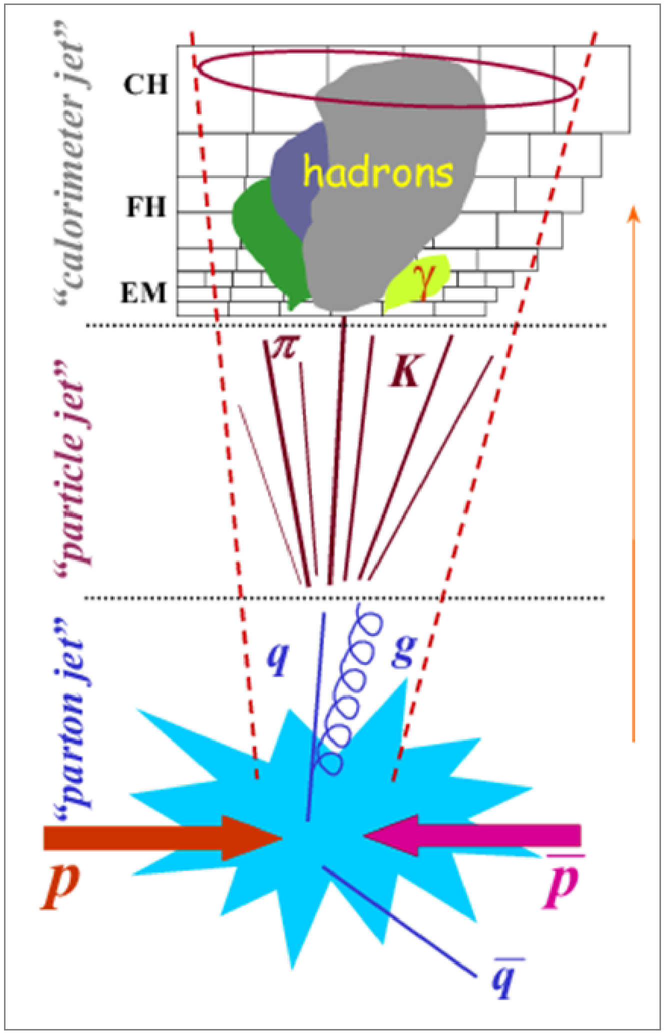


$$E_{jet} = \sum_{cells} E_i \times W_i(\rho_i)$$

$$\rho_i = E_i/V_i$$

Jet response before and after cell weighting

Jet reconstruction phase 3: go to partonic energy



Theoretically not well defined, but need this step e.g. when one wants to measure the mass of a heavy resonande decaying to jet-jet

Correct for:

- Energy loss outside of jet clustering
- Added energy from underlying event

This step will be performed with the data, using processes where a jet recoils against a well measured object: W, Z, γ, or $W \rightarrow jj$ in top decays. Goal is 1% precision on jet energy scale

The $\not\!\!E_T$ variable

Total energy and momentum in final and initial state equal: $(E_f, \vec{p}_f)$=$(E_i, \vec{p}_i)$.

Initial state in collider: $E_i = \sqrt{s}$, $\vec{p}_i = 0$

For e^+e^- collider all final state particles in detector acceptance $\vec{p}_f = 0$, if non-interacting particle with momentun $\vec{p}^\nu$ produced $(\nu, \tilde{\chi}^0_1)$, then $\vec{p}_f \neq 0$, and

$$\vec{p}^\nu = \vec{p}^{miss} = -\sum_j \vec{p}_j = -\vec{p}_f$$

With j running on all the detected particles

For hadron collider: particles from spectator quarks undetected in the beam pipe, $\vec{p}_f \neq 0$

$\Sigma_k\,(\vec{p}_T)_k \sim 0$ for particles k outside acceptance $\Rightarrow \Sigma_j\,(\vec{p}_T)_j = 0$ for particles j in acceptance.

If non-interacting particle with momentun $\vec{p}^\nu_T$ produced:

$$\vec{p}^\nu_T = \vec{p}^{miss}_T = -\sum_j\,(\vec{p}_T)_j$$

Approximate $\vec{p}^{miss}_T$ by $\not\!\!E_T$, vector sum of energy deposition in calorimeter cells:

$$E^{miss}_x = \sum_j E_j \sin\theta_j \cos\phi_j \quad E^{miss}_y = \sum_j E_j \sin\theta_j \sin\phi_j$$

j runs on cells with energy deposition and $\phi_j(\theta_j)$ respectively azimuthal and polar angle of cell j

Experimental measurement of $\not\!\!E_T$

Based on assumption that all the energy is measured in the calorimeters or seen as muons in the spectrometers

Multi-step procedure correcting for experimental effects:

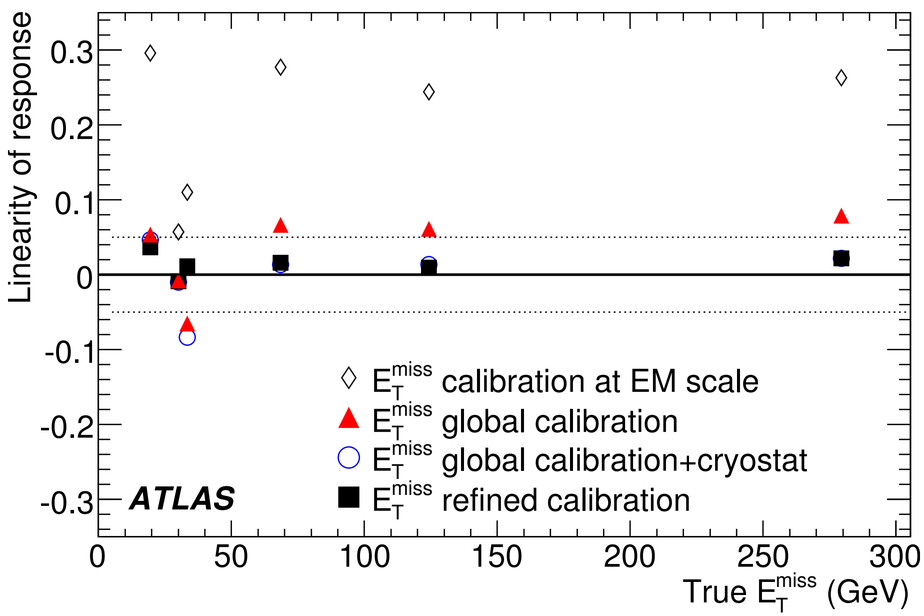
- Consider all cells calibrated at EM scale surviving an electronic noise suppression procedure
- Calibrate using global calibration weights based on energy density in cells, and perform vector sum
- Apply corrections for energy lost in cryostats
- Apply correction for detected muons
- Perform final refinement recalibrating cells depending on the reconstructed object they are assigned to

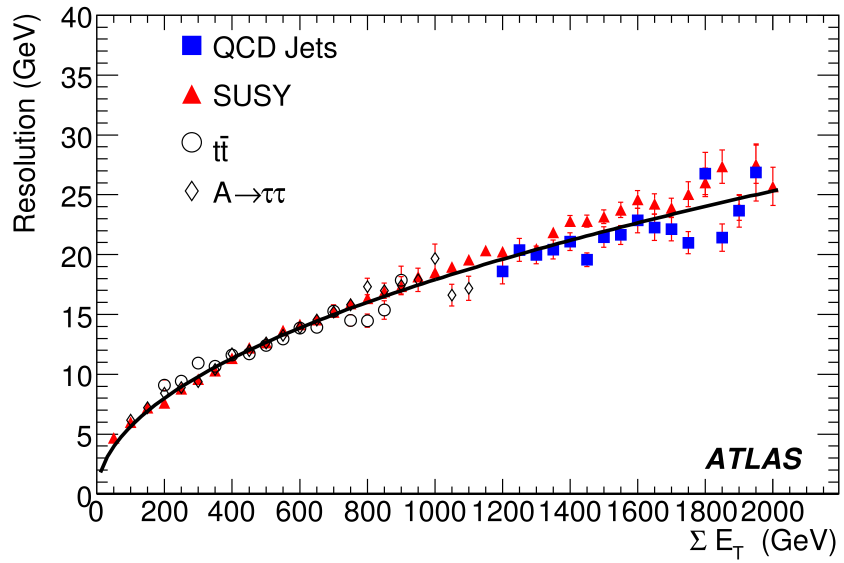
ATLAS procedure, very similar procedure for CMS. Additional step in CMS is improvement of resolution by using information from tracks

$\not\!\!E_T$ performance

Measurement resolution estimated on MC by plotting the difference between true and extimated $\not\!\!E_T$ separately on each of the components

Resolution can be fitted as $0.57 \cdot \sqrt{\Sigma\, E_T}$





Backup

Analysis of LHC data - Lecture 2

Giacomo Polesello

INFN, Sezione di Pavia

Procedures for detector understanding

Ambitious performance goals driven by very precise requirements from physics

Complex and new detectors with hundreds of millions of electronics channels

Many months of work for commissioning and understanding the detector.

- Setting the timing of the detector channels with respect to each other and to the beam crossing
- Detecting and correcting for various malfunctioning: electronic noise, dead channels (below 1-2%)
- Controlling the stability of the detector response with time/environmental conditions, e.g. temperature, humidity
- Controlling the spatial uniformity of response of the detector
- Calibrate/align the sub detectors, and evaluate resolution and absolute scale
- Tune the performance of the reconstruction software both at subdetector and at the combined system level
- Evaluate efficiency/ background rejection for the different particle building algorithms

Final understanding of detectors only achievable with real collisions in LHC environment

Procedure with data faster if already good understanding achieved with pre-collision studies

	Initial	Final	Data Samples
e/γ energy scale	2%	0.1%	$Z, J/\psi, \Upsilon, \pi^0$
e/γ uniformity	1-4%	0.5%	Z
jet energy scale	5-10%	1-2%	W from $\bar{t}t$, $\gamma/Z+$ jets
tracking alignment	10-100 μm	$\leq 10\mu\mathrm{m}$	tracks, Z, J/ψ, Υ
muon alignment	30-50 $\mu\mathrm{m}$	30 $\mu\mathrm{m}$	inclusive muon, Z, J/ψ, Υ

Long term strategy for detector understanding

- Last few years: extensive test-beam activities with final detector components
  - Standalone Detector test beams: Basic calibration of calorimeter modules, test of electronics and alignment procedures
  - ATLAS combined test-beam of full slice of detector: test in real life particle ID algorithms, procedures of inter-detector alignment, validation of detailed simulation
- Now, extending up to the arrival of beam:
  - Cosmics data taking: Study detector timing and alignment. Examples:

    Have $\sim$ 0.5 Hz of Through-going muons passing near origin

    Can study EM calorimeter response variations versus η to 0.5%

    May achieve statistical precision on alignment of 10μm in part of Pixels/SCT

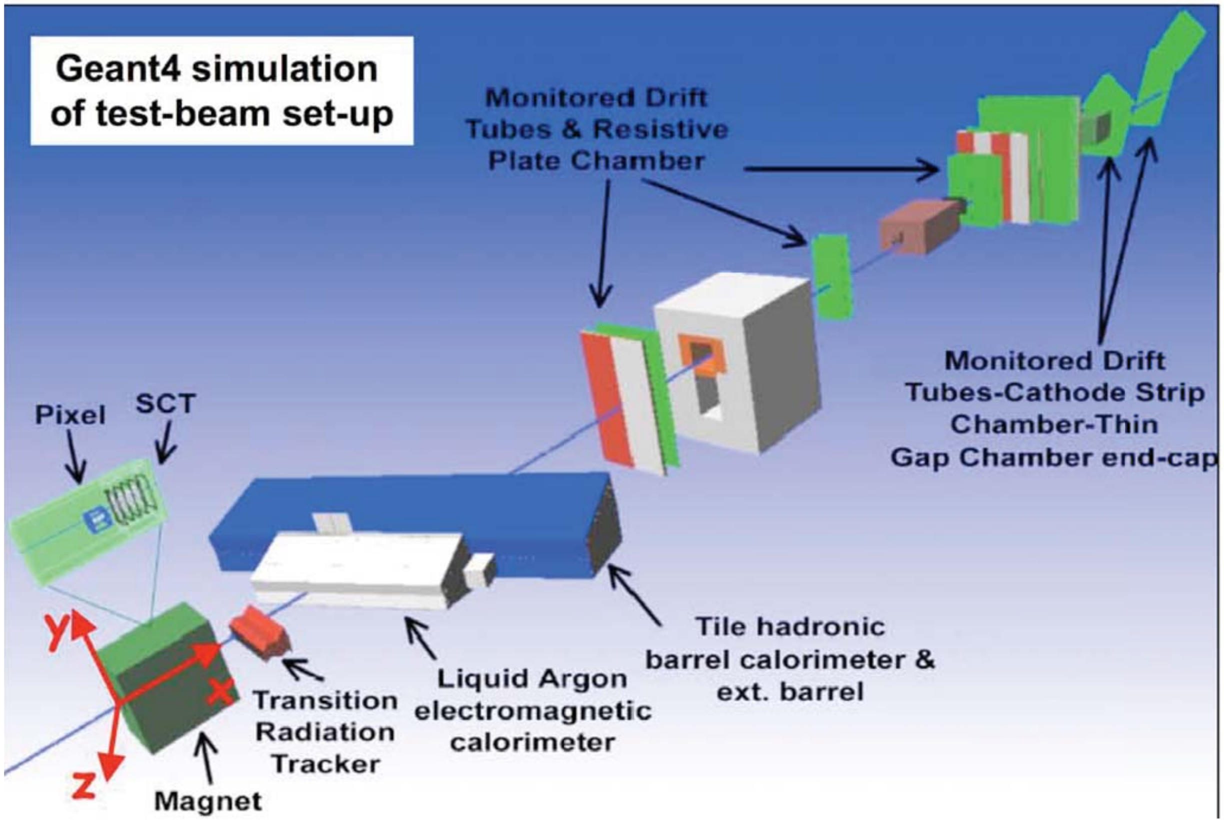
    May achieve 30-40 μm alignment precision for muon chambers within $\pm 60^\circ$ to vertical

When beam arrives

- From first injections: beam-halo and beam-gas interactions. More specialised alignment work
- Goal for first 14 TeV interactions:
  - Understand and calibrate detector and trigger in situ using well-known physics samples: $Z/W \rightarrow$leptons, semileptionic tt
  - Understand basic SM physics at 14 TeV: first measurements and publications
    - jets and W, Z cross-section top mass and cross-section
    - Event features: Min. bias, jet distributions, PDF constraints
  - Understand tails of SM processes as backgrounds (tt, W/Z + jets), go for discovery: Z', SUSY, Higgs

Mandatory to demonstrate that we understand LHC physics through SM measurements before going for discovery physics

The 2004 combined test beam



- All sub-detectors, LVL1 trigger integrated and running together with common DAQ
- Data analyzed with common ATLAS SW, DataBases

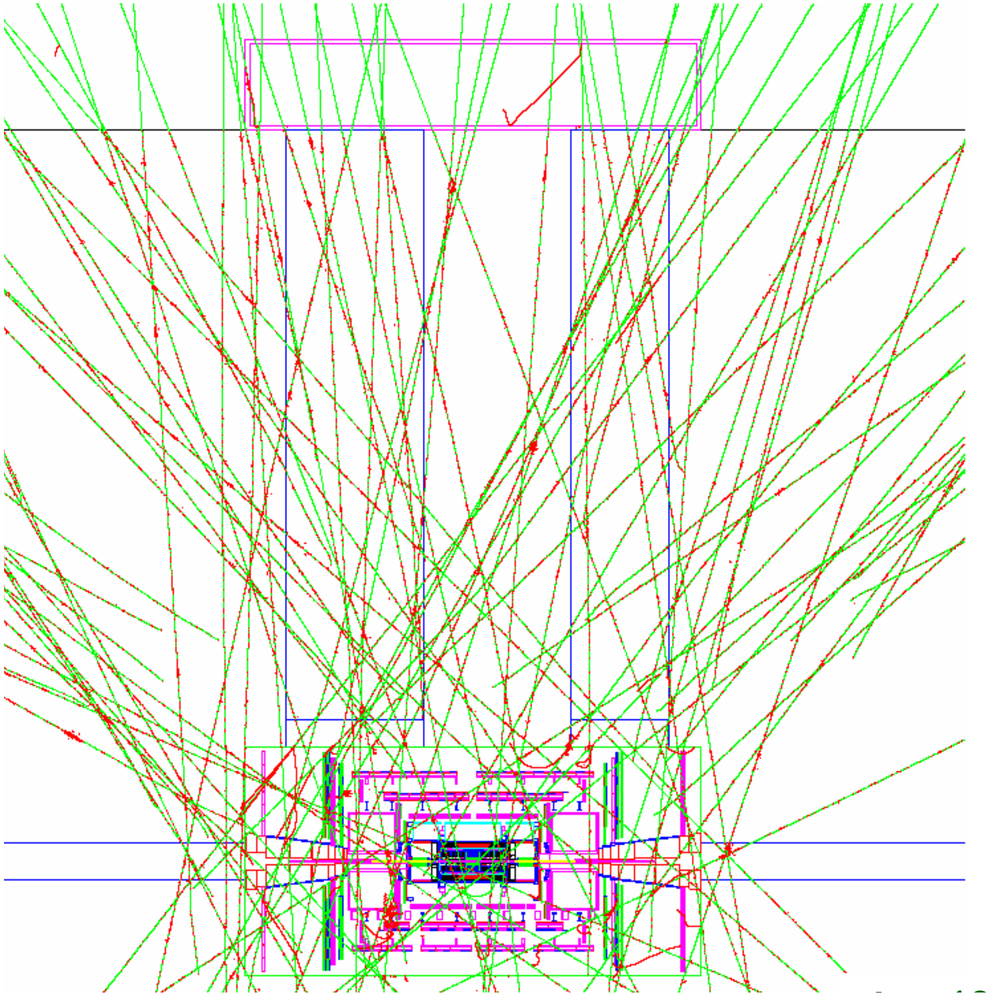
~ 90 million events collected

$e\pm$, $p\pm$	1 -> 250 GeV
$\mu^{\pm}$, $\pi^{\pm}$, π^0	up to 350 GeV
γ	20-100 GeV

B-field = 0 -> 1.4 T

Many configurations (e.g. additional material in ID, 25 ns runs, …)

Cosmics

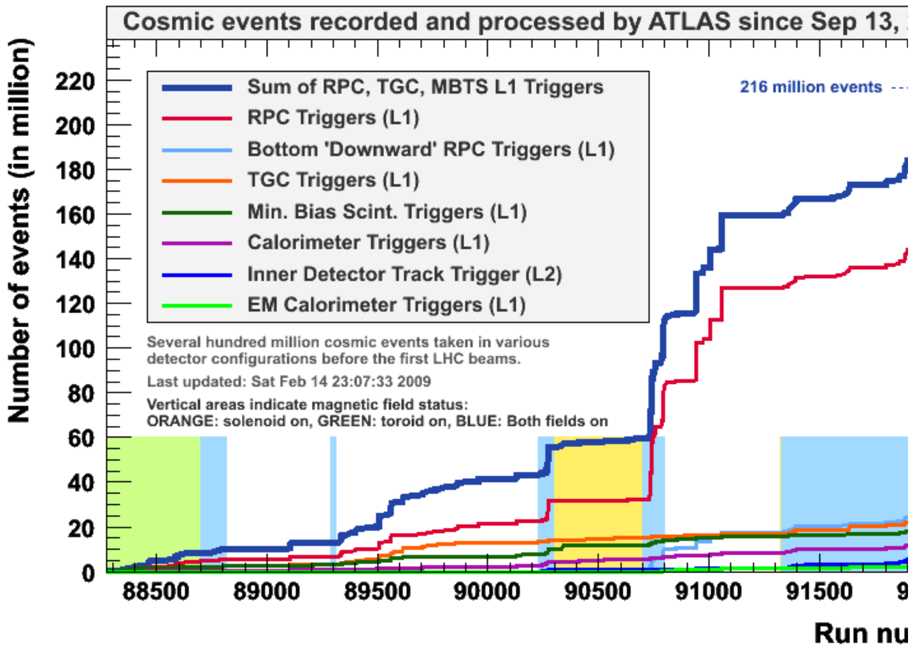


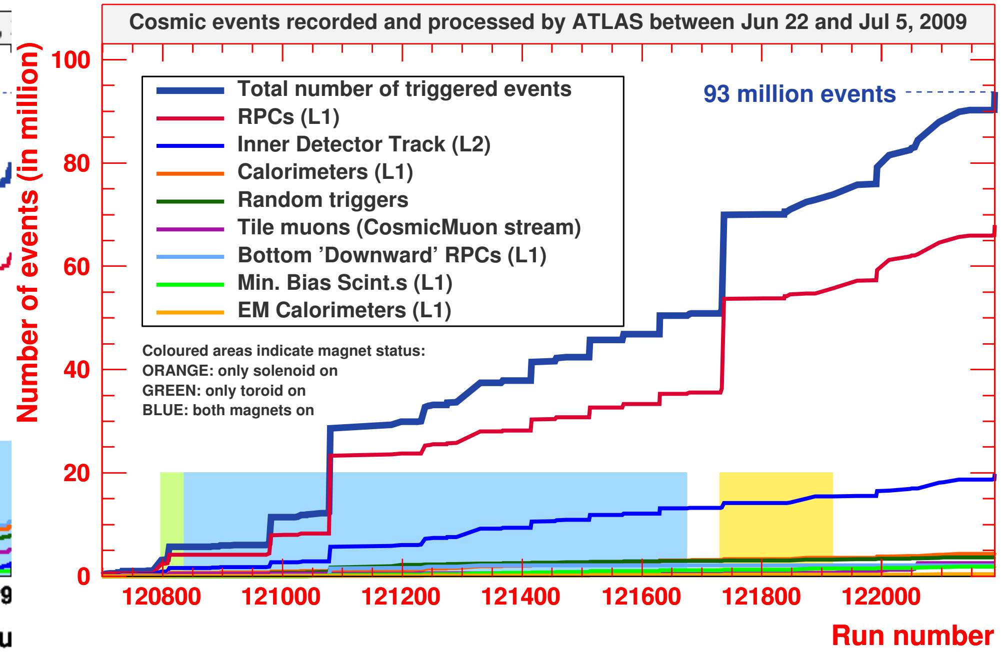
Simulation of 10 ms of cosmics

trigger rate 1-500 Hz depending on cuts,

trigger type, enabled detectors

ATLAS Cosmics runs in 2008 and 2009



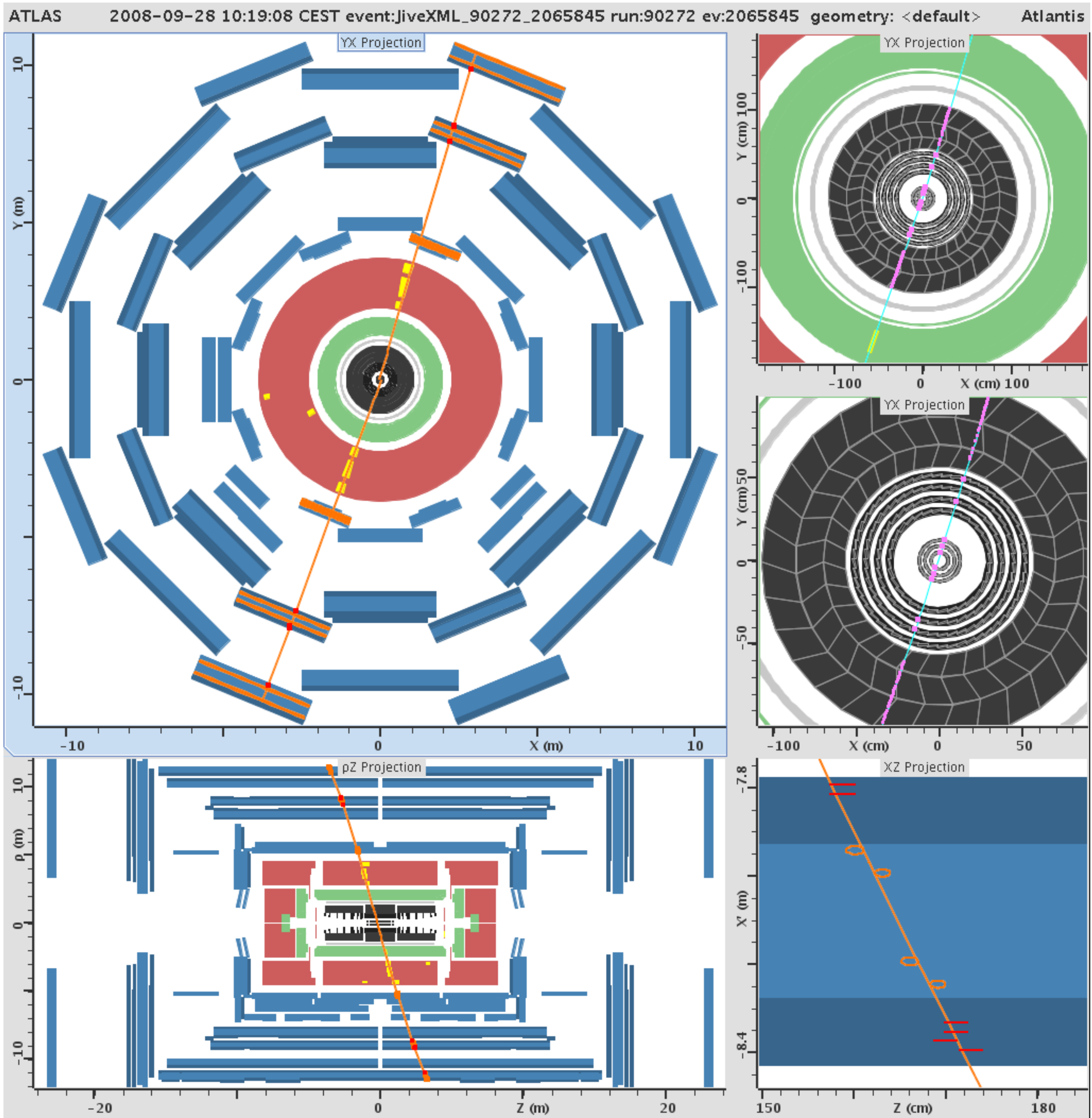


Many hundreds of million events with various detectors and magnetic field configurations

Sample dominated by cosmic muons collected with the RPC trigger

Several million inner detector tracks collected with dedicated second level trigger

Example of cosmic muons crossing all of barrel detectors



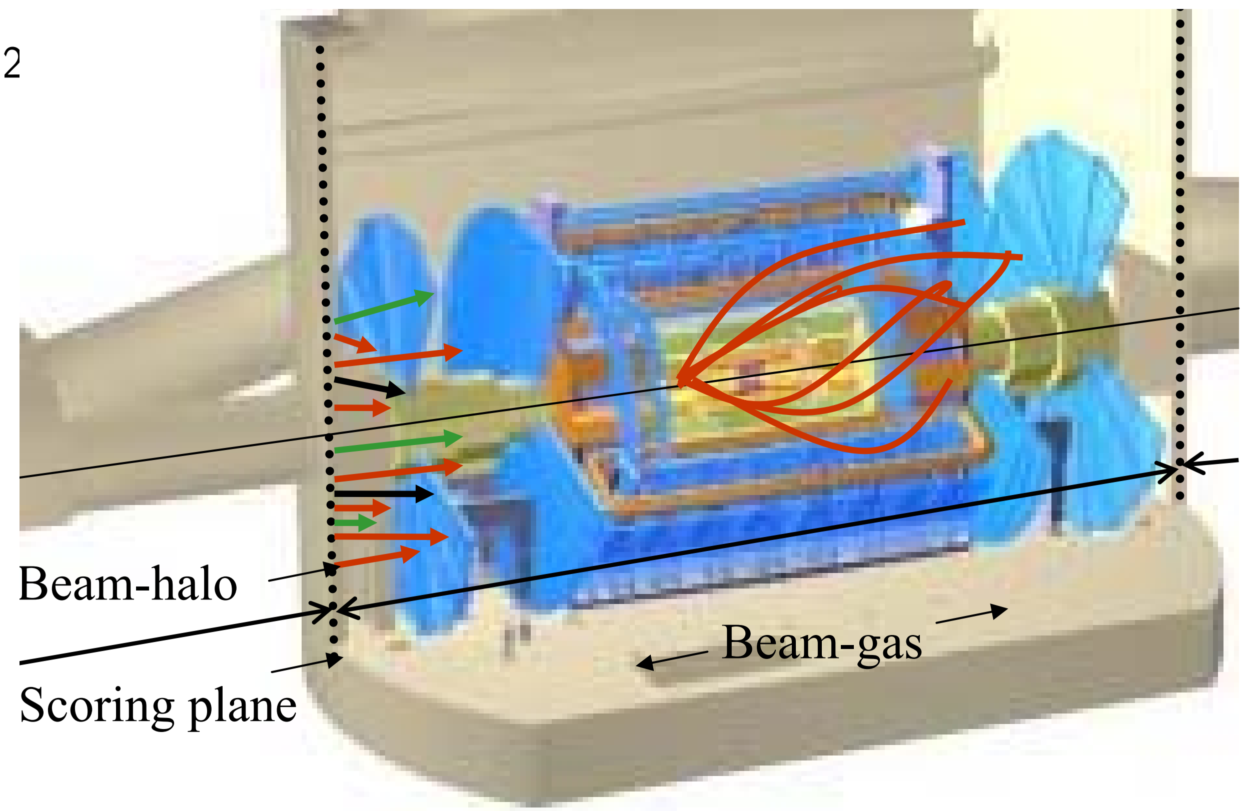
Single beam period

Beam halo/collimator splashes

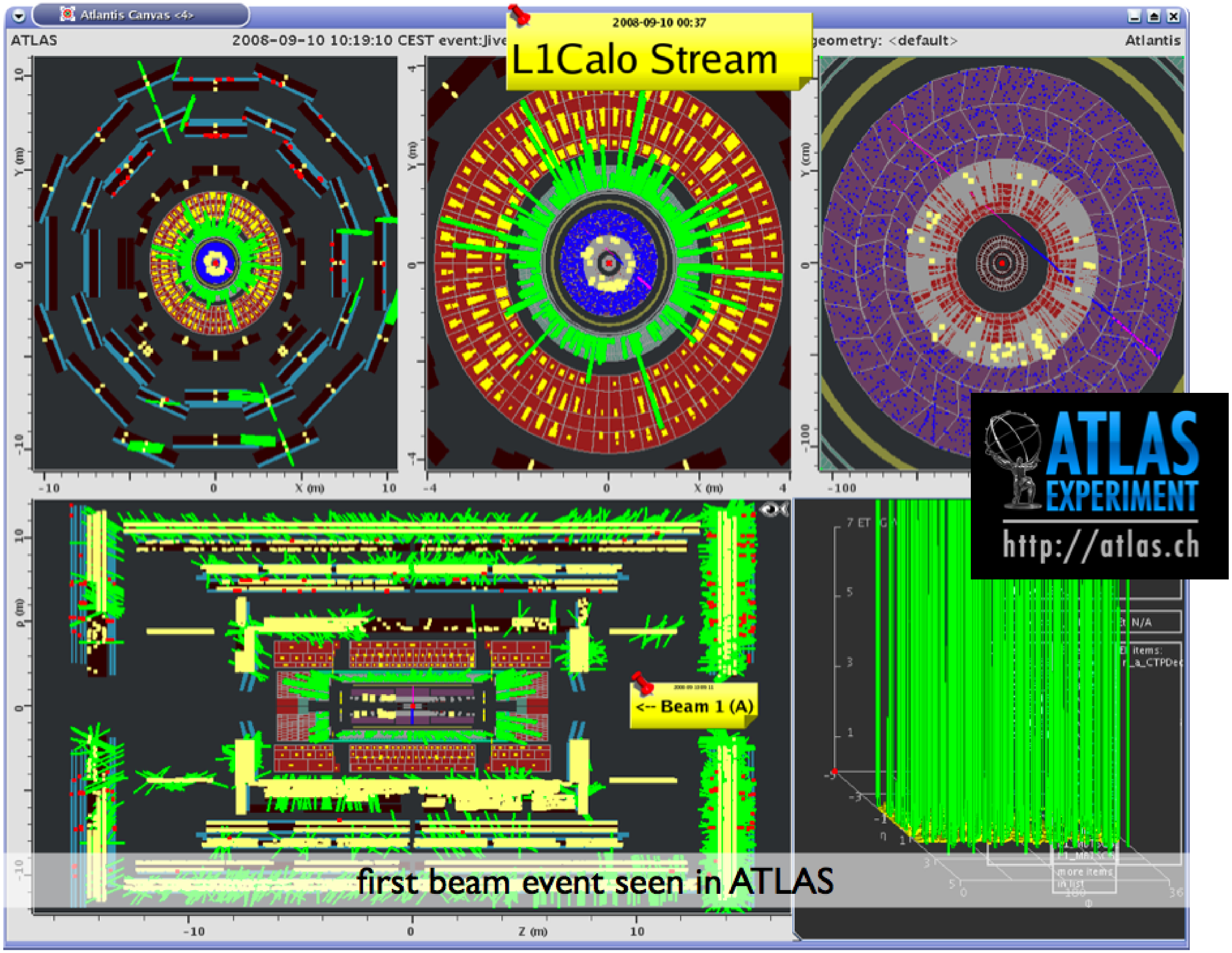
- Low p_T particles from the machine straight into detecotr
- Use for alignment and calibration in endcaps
- A few runs in period 10-13/09/2

Beam-gas

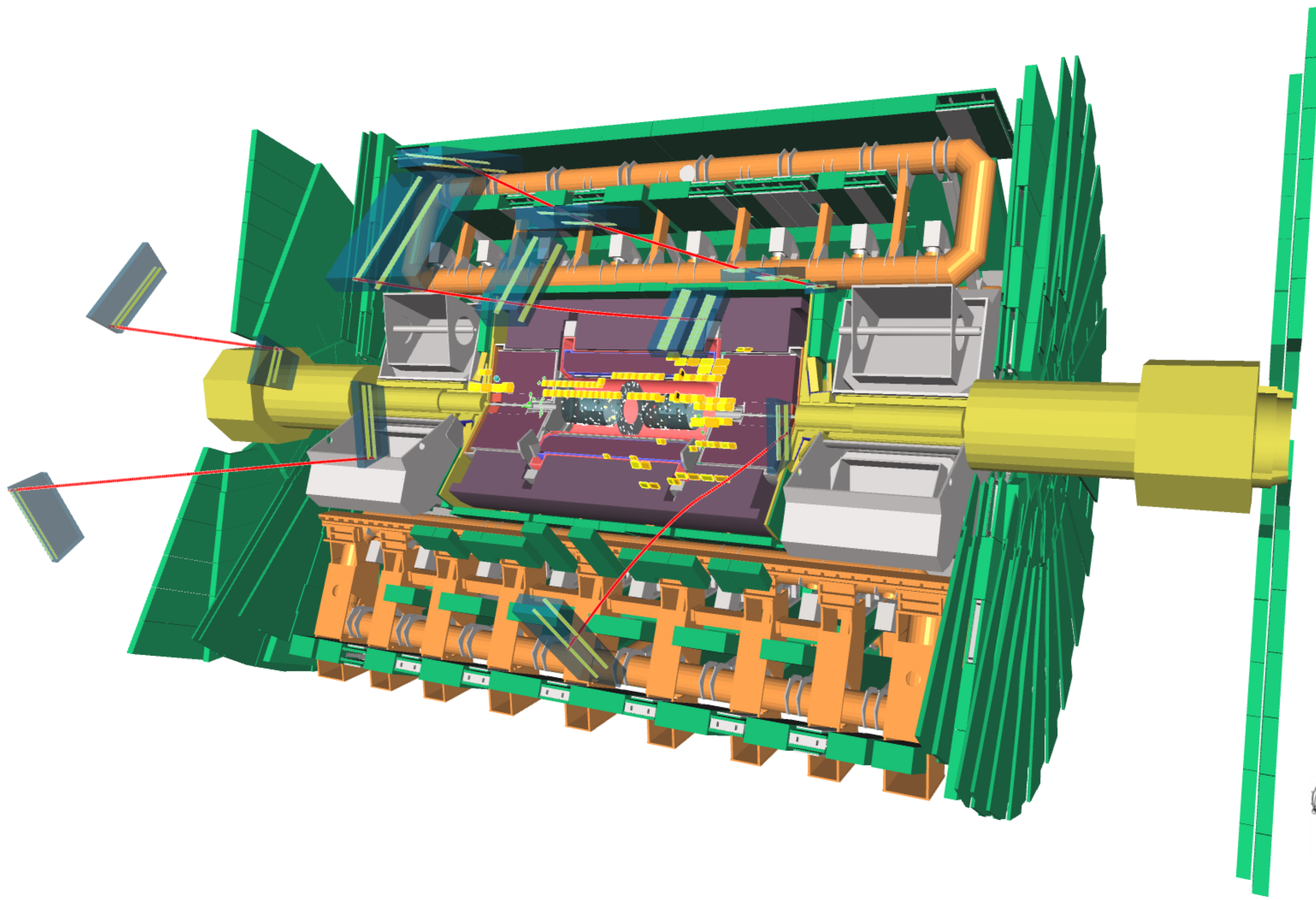
- Vacuum not perfect 3×10^{-8} Torr
- Proton-nucleon p(7 TeV)+p(rest)
- Resemble collision events but with soft spectrum



Famous beam splash event on 10/09/08

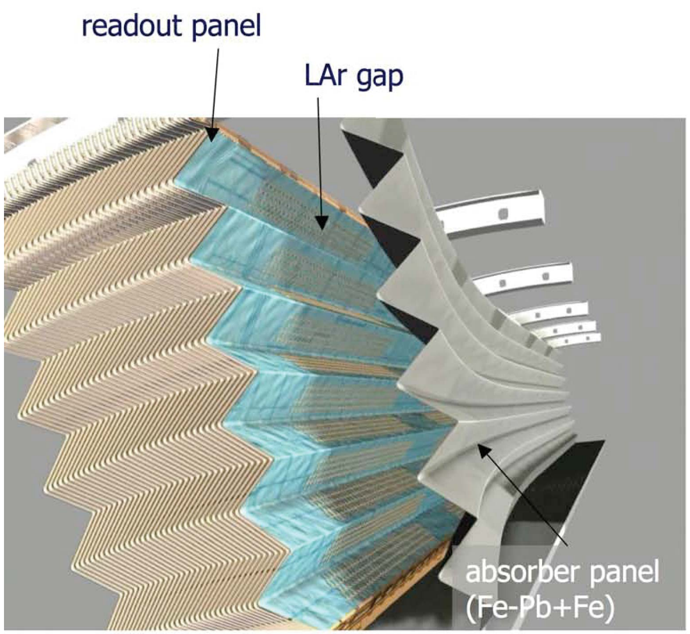


Clean beam halo event with stable beam evening 10/09/08



Example 1: ATLAS EM calorimeter

Pb-liquid argon sampling calorimeter with Accordion shape



Why?

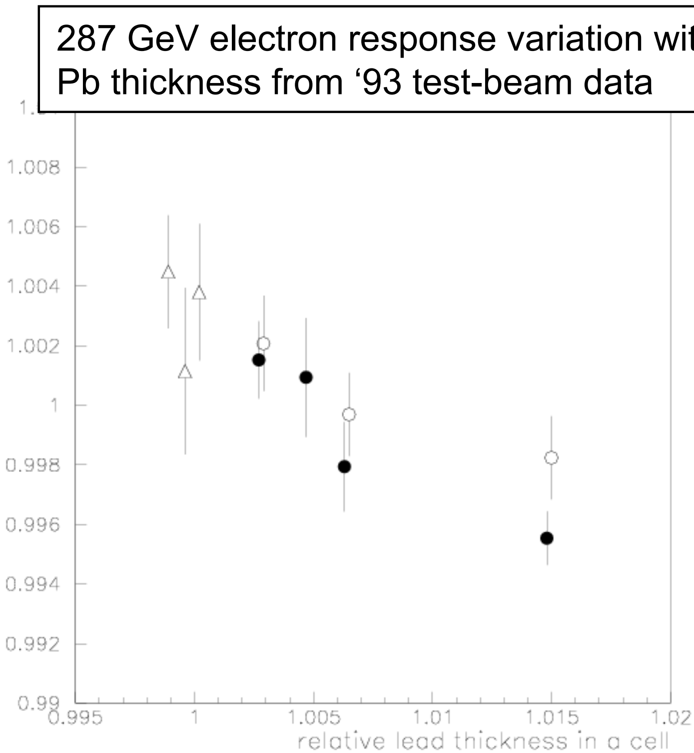
- Readout speed
- Radiation hard
- Electronically intercalibrated
- Allows longitudinal segmentation
- Hermetic in phi
- Good energy, angular resolution

Most difficult experimental issue: achieve a response uniformity $\leq 0.7\%$ over $|\eta| < 2.5$ driven by $h \to \gamma\gamma$ search

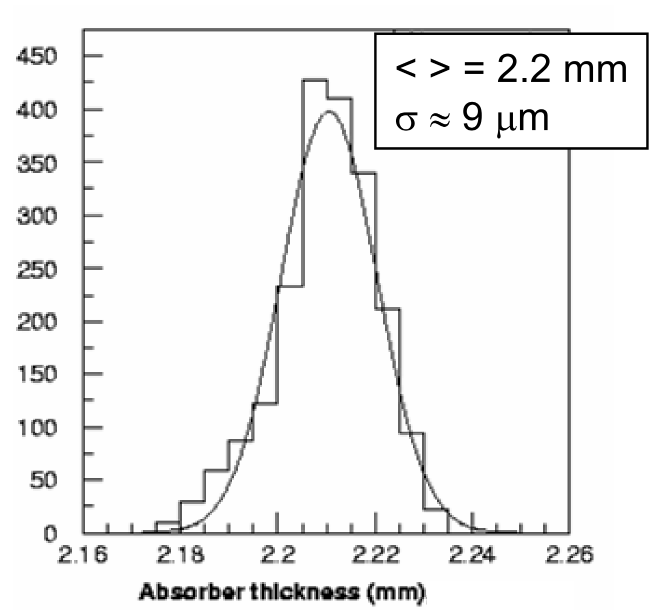
Requires very detailed work starting from the constructon phase

Step 1: Tight control of mechanical tolerances

1% more lead in cell leads to response drop of 0.7% $\Rightarrow$ control plate thickness to 0.5% ($\sim 1\mu$m)

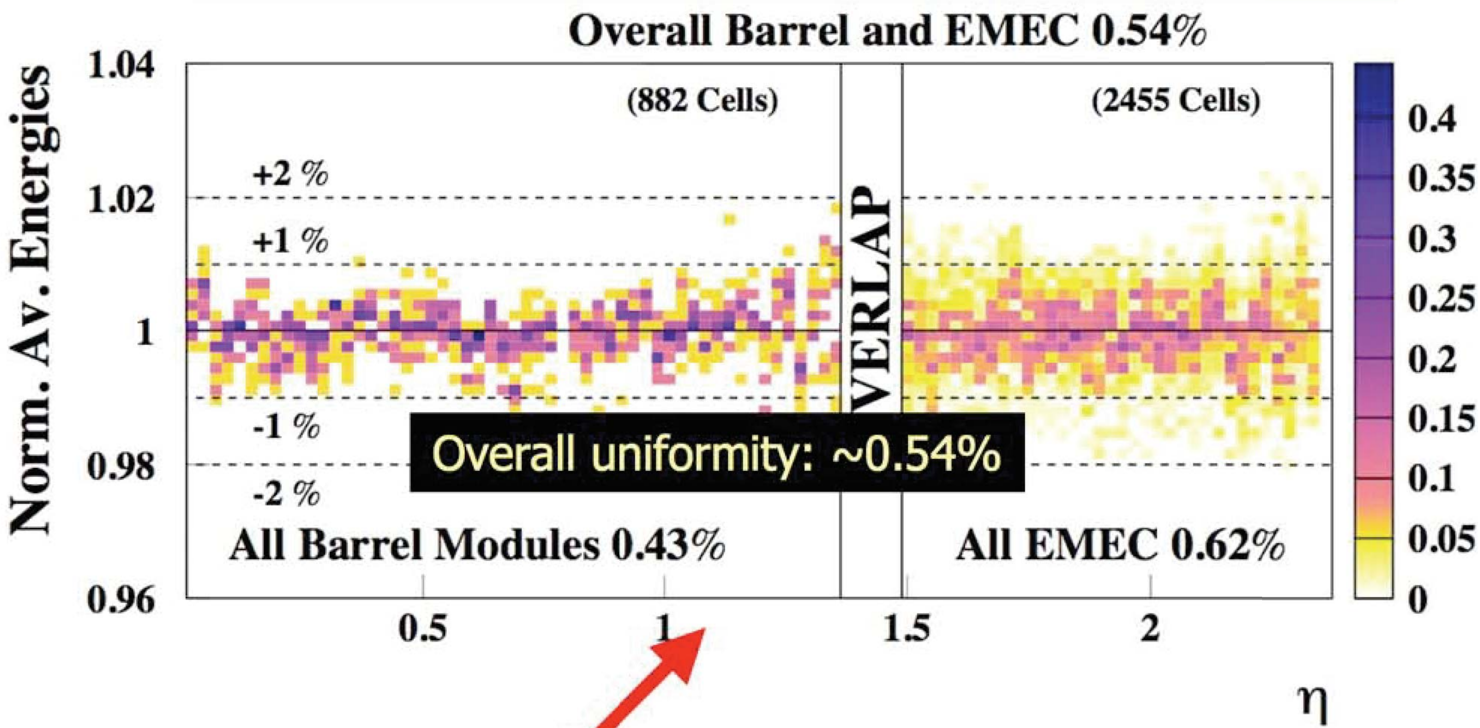


Thickness measurement of 1536 absorber plates



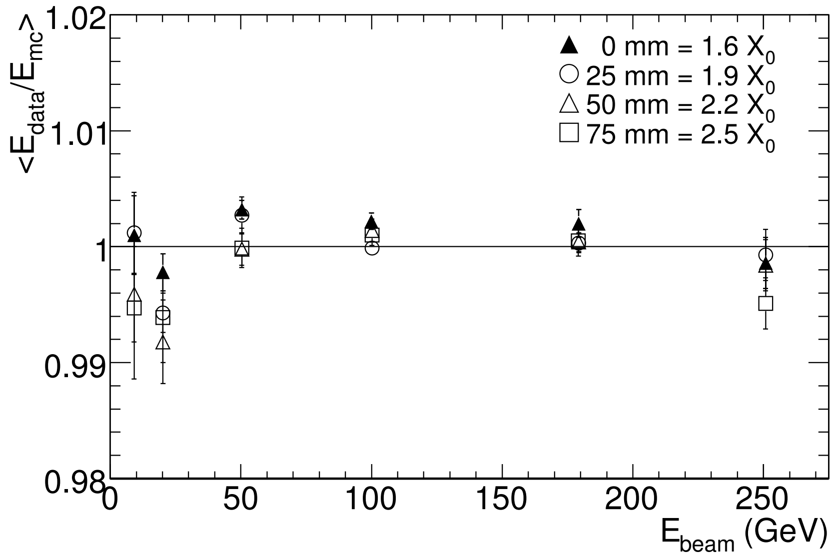
Step 2: Test beam uniformity studies

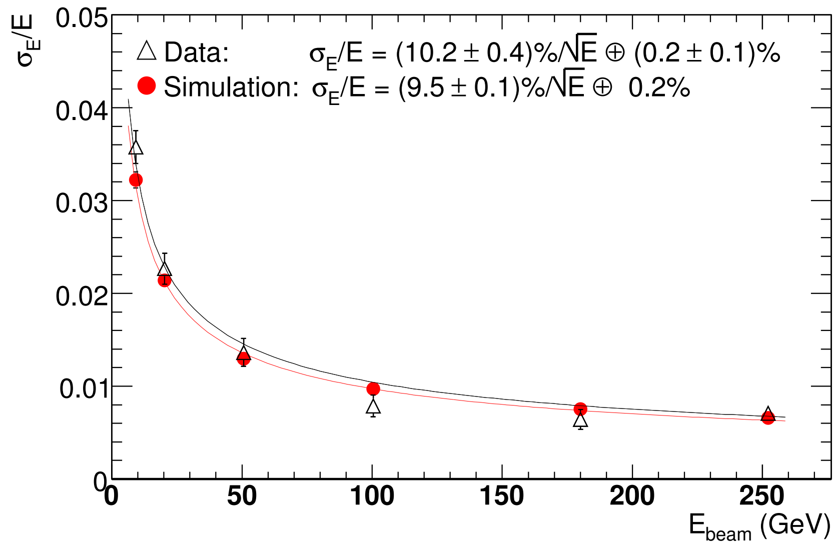
Scans with 120-245 GeV electrons (all 7 tested modules)



4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

Step 3: Performance measurement in combined test beam





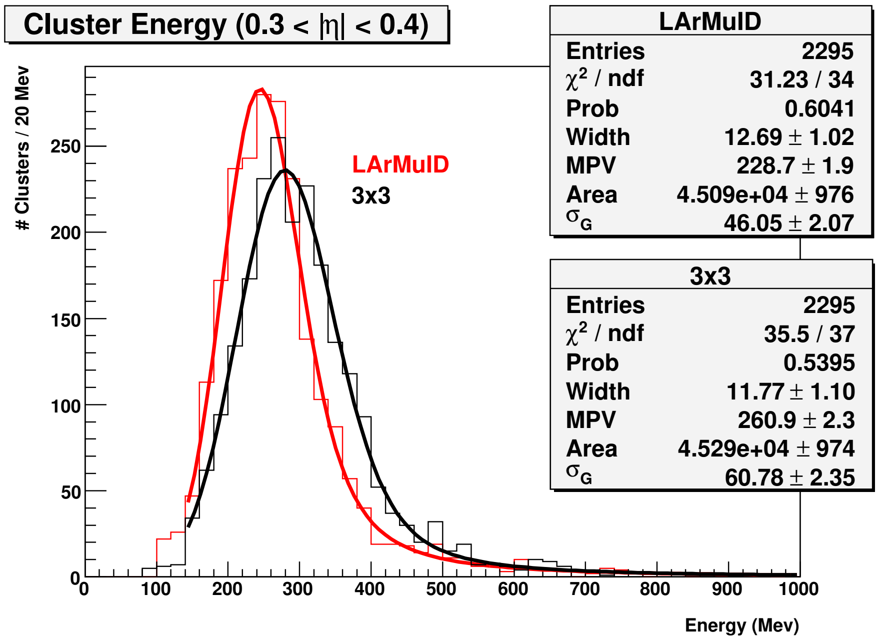
Measure linearity and resolution for electrons between 5 and 250 GeV

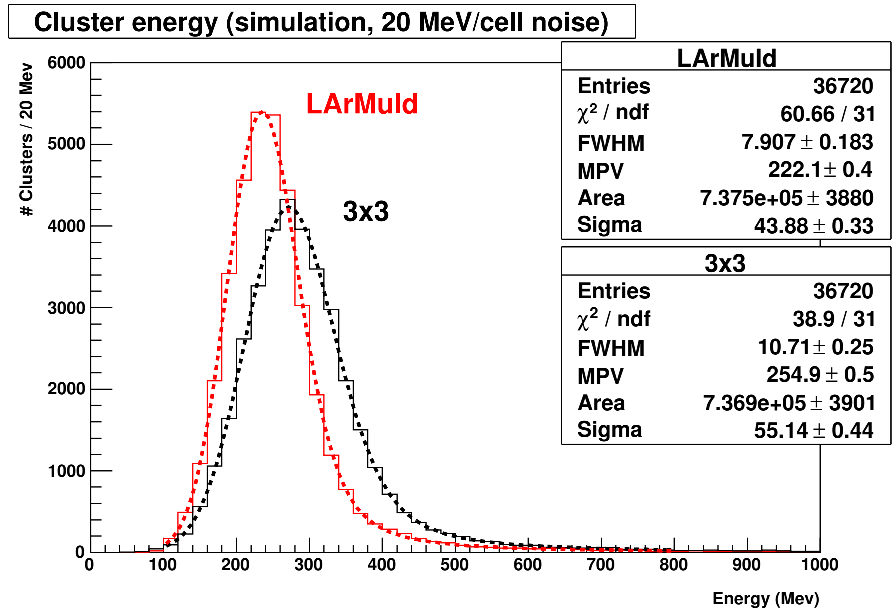
Material in beam tuned to reproduce material in real detector

Energy measurement linear to much better than 1%

Excellent agreement of measured resolution with MC predictions. Design stochastic and constant terms achieved

Step 5: Cosmic muons: response check



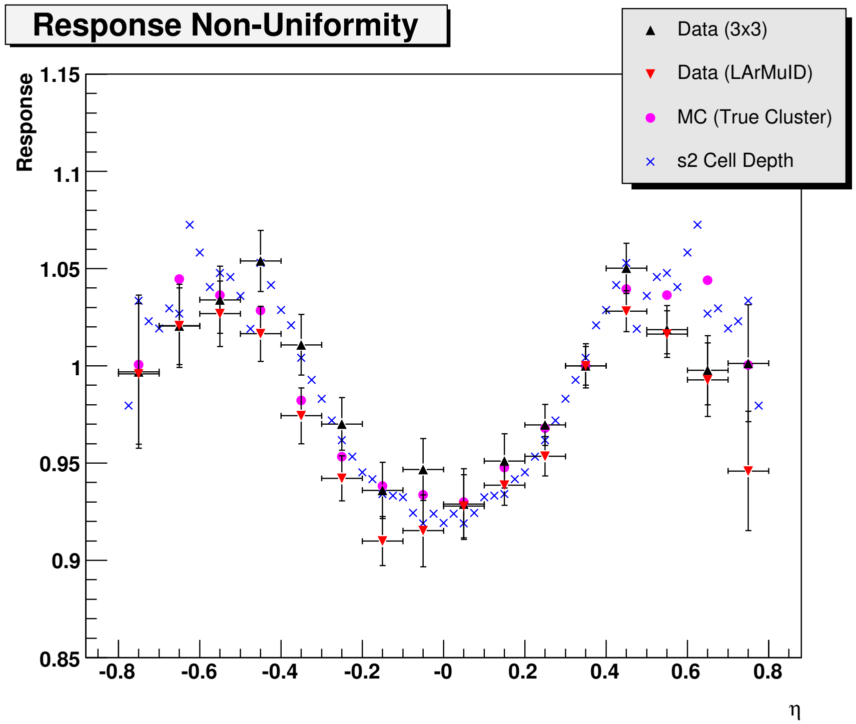


Use events with a loose requirement of projectivity for the muon track

For two different clustering algorithm plot the shape of muon energy deposition for second sampling layer

The shape agrees well with MC predictions at very low energies (2-300 MeV)

Step 5: Cosmics muons: uniformity study



Plot MPV of landau fit to energy distribution as a function of η

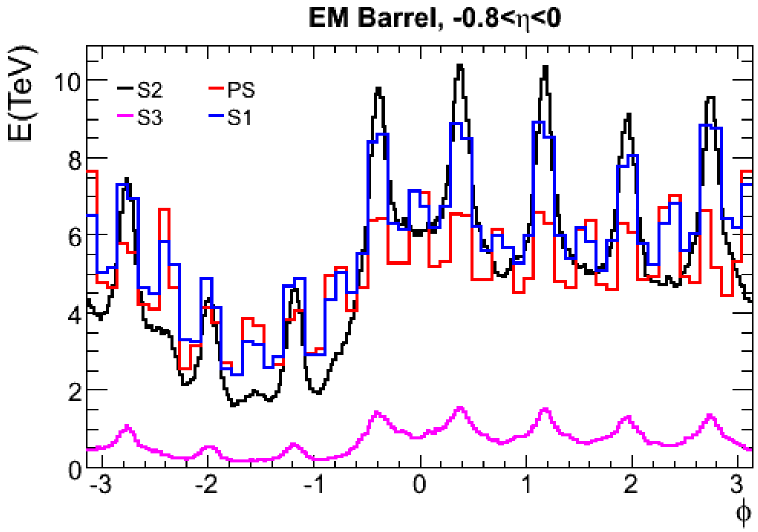
Energy response variation in eta follows nicely the MC expectations

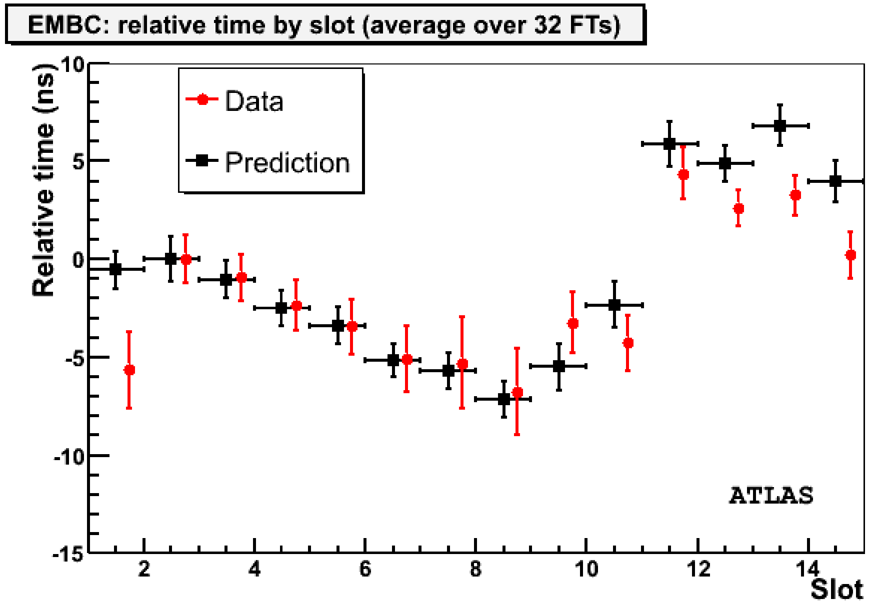
Analysis on $\sim$10k events collected in the ATLAS cavern in 2006-2007

With this statistics achieve control at the level of 2% of response variation in η in bins of 0.1

Work is ongoing on higher statistics cosmics samples.

Step 6: Beam splash: check the timing of the calorimeter





With ∼100 events fom beam splash large energy deposit in calo cells

Can use these deposits to measure the timing of each of the front-end boards from the position of the signal pulse

These can be compared to the predictions from the calibration pulses and the readout path

The agreement between measured and predicted time is at the level of 2 ns except in the presampler

Step 7: Equalization with $Z \to e^+e^-$

Constant term $c_{tot} = c_L + c_{LR}$ composed of two terms:

- c_L: local term. $c_L \simeq 0.5\%$ demonstrated at the test-beam over units of $\Delta\eta \times \Delta\phi = 0.2 \times 0.4$
- c_{LR} long-range response non-uniformities from unit to unit (400 in total): from module-to-module variations, different upstream material, etc.

Use $Z \to ee$ and Z mass constraint to correct for long-range uniformities

From full simulation: $\sim 250\ e^\pm$ per unit to achieve $c_{LR} \leq 0.5\%$

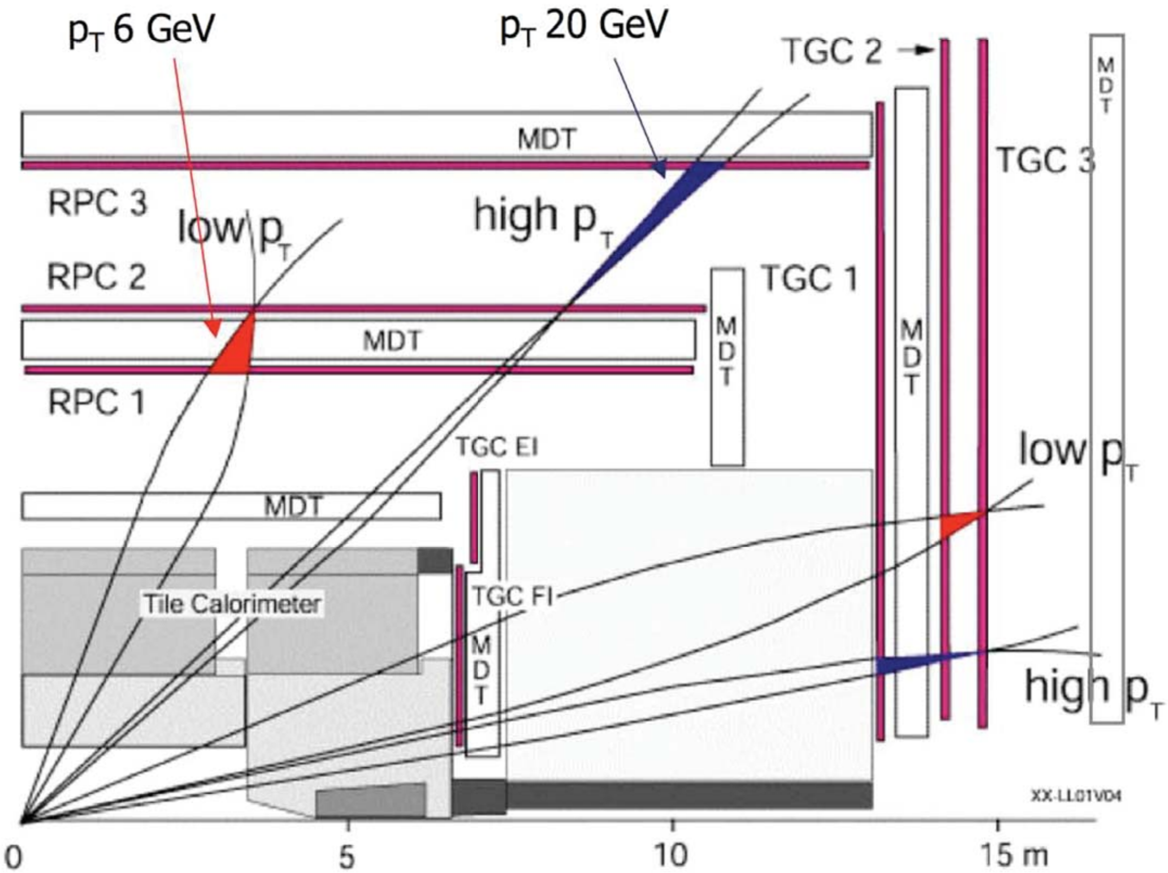
$\Rightarrow \sim 10^5\ Z \to ee$ events, few days of data-taking at 10^{33}

Worst case scenario: no corrections applied

$c_L = 1.3\%$ "on-line" non uniformity of individual modules

$c_{LR} = 1.5\%$ no $Z \to ee$ corrections, poor knowledge of upstream material

Example 2: the muon spectrometers



$\Delta p_T/p_T \sim 3\%$ for p_T = 10–100 GeV
in standalone mode

Precision chambers :

MDT : monitored drift tubes

1108 chambers, 339 k channels

CSC : cathode strip chambers

32 chambers, 31 k channels

Trigger chambers (LVL1):

RPC : resistive plate chambers

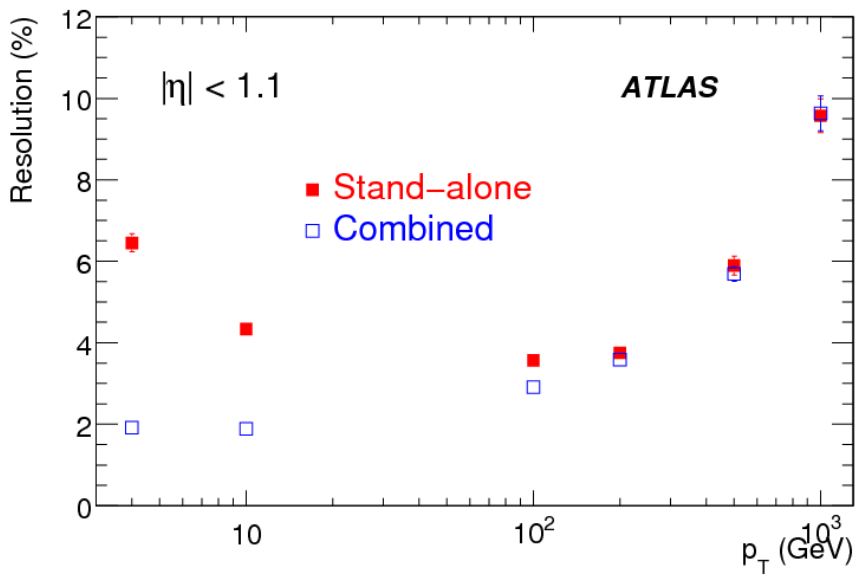
560 chambers, 359 k channels

TGC : thin gap chambers

3588 chambers, 318 k channels

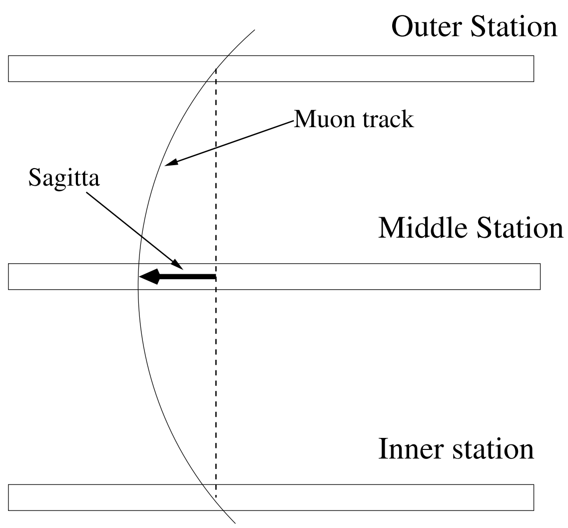
Total : ~12’000 m^2, ~ 1.1 M channels

The muon measurement strategy



Muon p_T is measured through combination of measurement in inner detector and in muon spectrometer

Contribution of muon spectrometer dominant for $P_T > 100$ GeV



p_T is determined through measurement of track sagitta S .

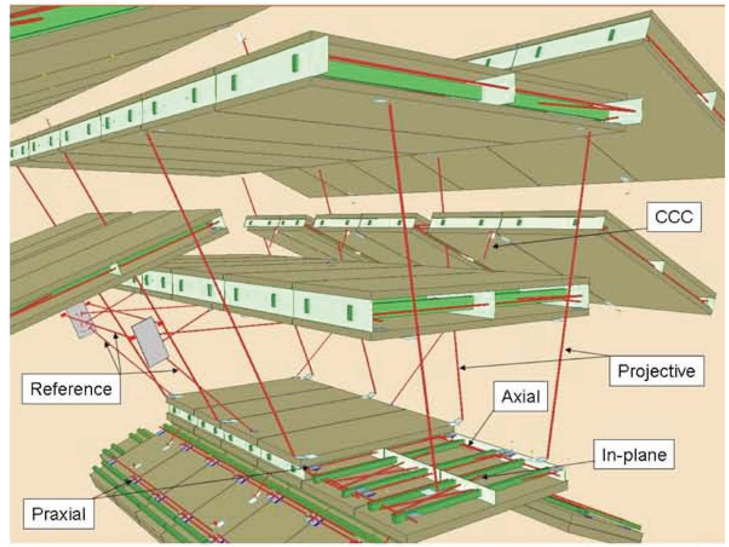
σ(S)$\propto$ $\sigma(1/p_T)$ For a 1 TeV muon S ~500 μm

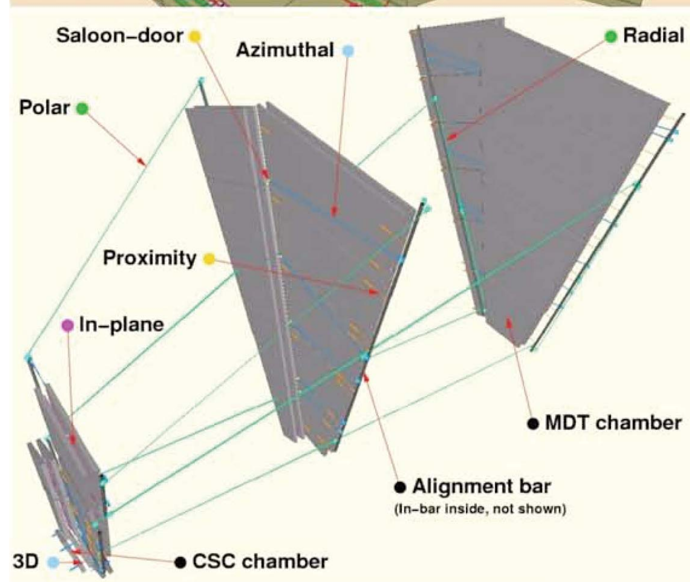
Goal: $\sigma(S)$ ~50 μm. Require:

- Precision of chamber measurement: ~30 μm
- Relative chamber alignment alignment to ~30 μm

Muon alignment system

Need to know the geometrical position of all chambers in time to 30 μm over several tens of meters





Sophisticated system based on i.r light sources projecting a mask onto a CCD sensor

Alignment precision of ± 20 μm already demonstrated in 2004 test beam

Final alignment/calibataion obtained in-situ with straight tracks from collisions

Tested with cosmics data in 2008/2009

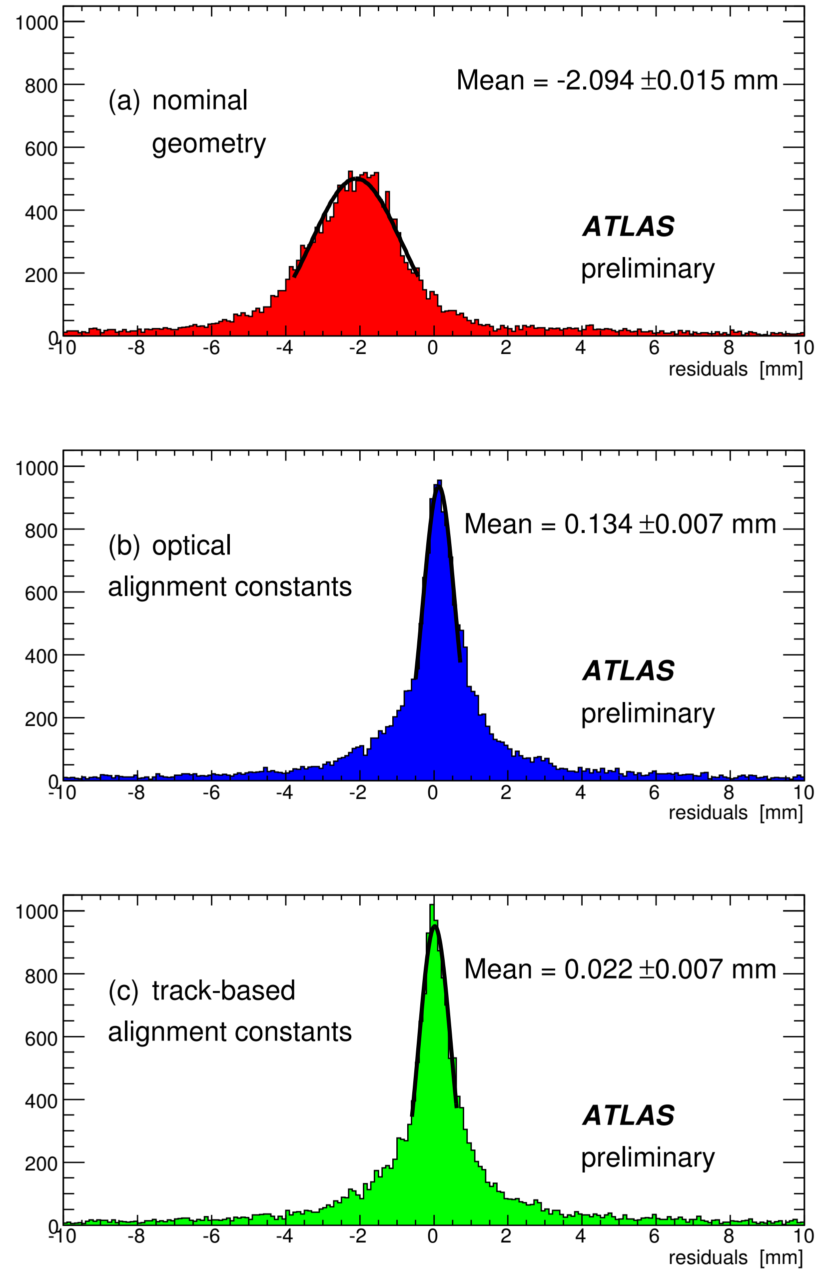
Muon system alignment: cosmic ray test

Sagitta distribution for cosmics taken without magnetic field in the middle barrel chamber

For proper alignment sagitta should be with in 30 μm from zero

Shown for three geometries:

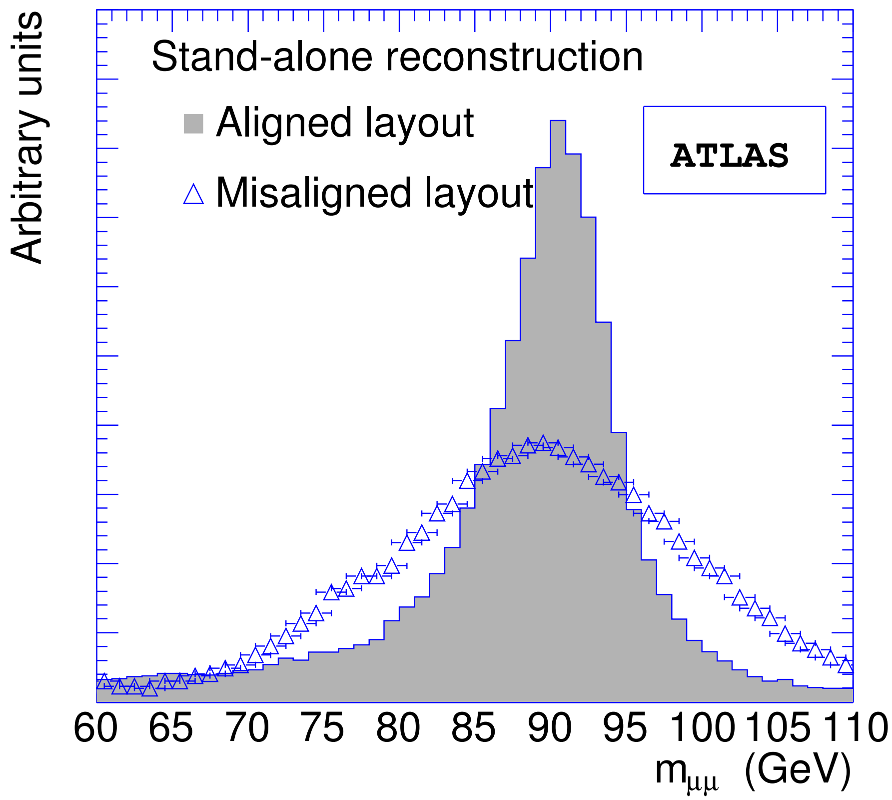
- Nominal geometry
- Geometry based on optical alignment constraints
- Geometry obtained after alignment with straight tracks



Impact of alignment on physics performance

Reconstruct MC data using a geometry different than the one used for simulation

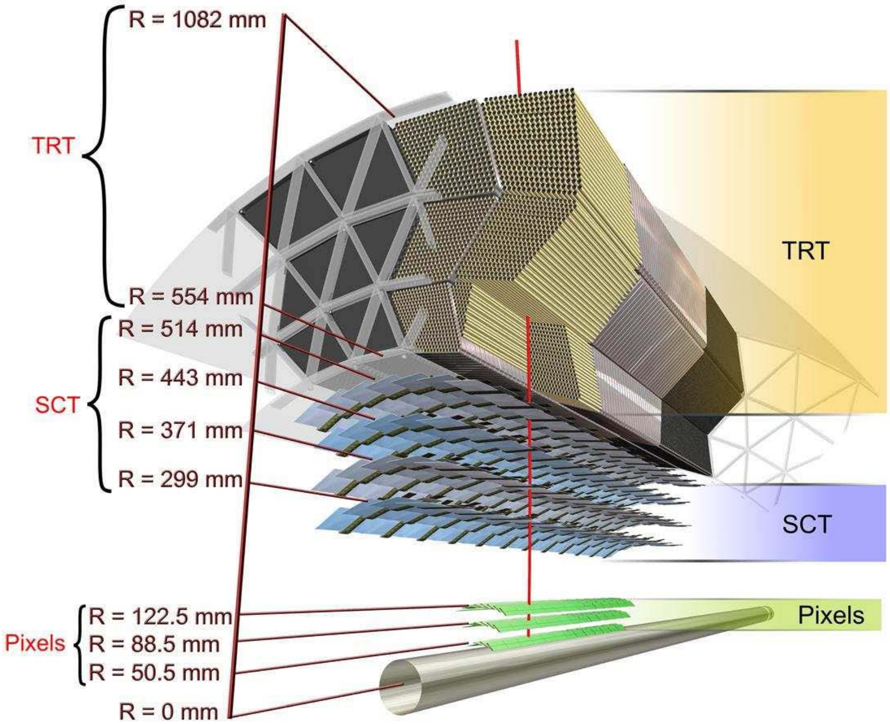
In reconstruction, shift chambers randomly with a gaussian distribution centeredat zero and with $\sigma = 1$ mm, and apply random rotations with $\sigma = 1$ mrad



Peak from $Z \to \mu\mu$ reconstructed using only muon spectrometer measurement (no inner detector)

No effect on overall scale, but large broadening of peak

Example 3: ATLAS Inner detector



Tracking based on 7 high precision points:

- 3 pixel layers:
- 4 Silicon strip layers

Plus continuous tracking in Transition Radiation tracker

Item	Intrinsic accuracy (μm)	Alignment tolerances (μm)		
		Radial	Axial z	Azimuth Rϕ
Pixel				
Layer 0	10 ($R\phi$) 115 (z)	10	20	7
Layers 1 and 2	10 ($R\phi$) 115 (z)	20	20	7
Disks	10 ($R\phi$) 115 (R)	20	100	7
SCT				
Barrel	17 ($R\phi$) 580 (z)[1]	100	50	12
Disks	17 ($R\phi$) 580 (R)[1]	50	200	12
TRT	130 (drift time)			30[2]

Strict requirements on alignment to exploit intrinsic resolution of detectors

Module positioning on support to 17-100 μm, supports positioned to 20-200 μm

Use tracks for final aligment. First tests with cosmics

Inner detector alignment

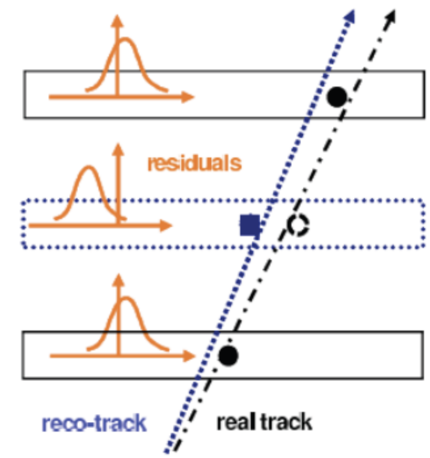
Put together all ID subsystems by minimizing track residuals.

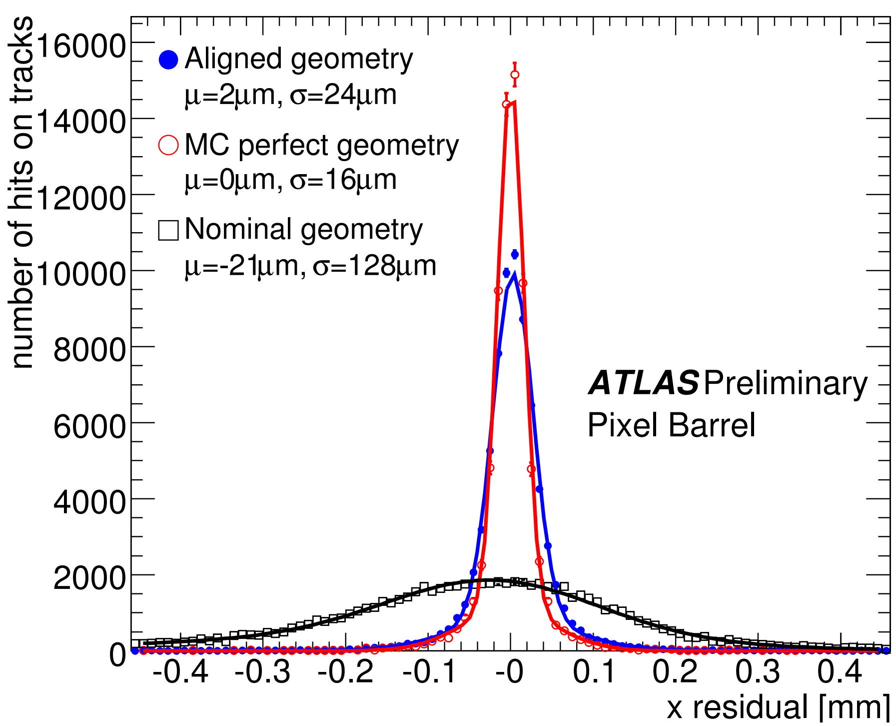
For pixel: perfect alignment: $\sigma = 16\ \mu$m

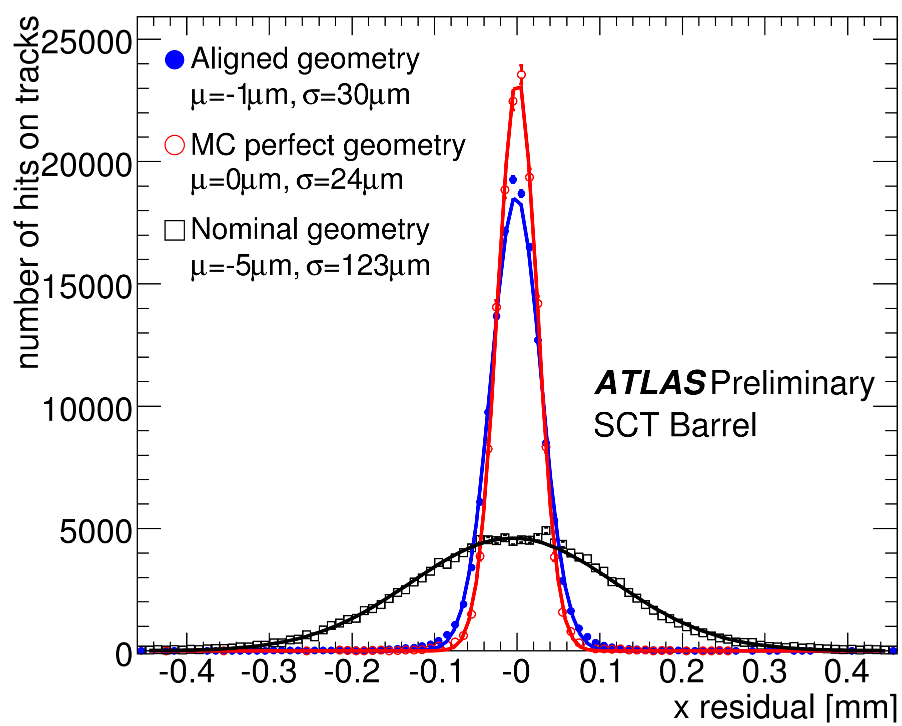
Cosmics alignment: $\sigma = 24\ \mu$m

For SCT: perfect alignment: $\sigma = 24\ \mu$m

Cosmics alignment: $\sigma = 30\ \mu$m





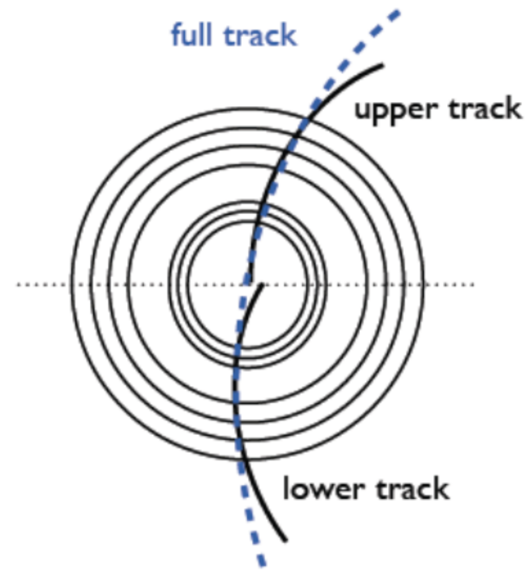


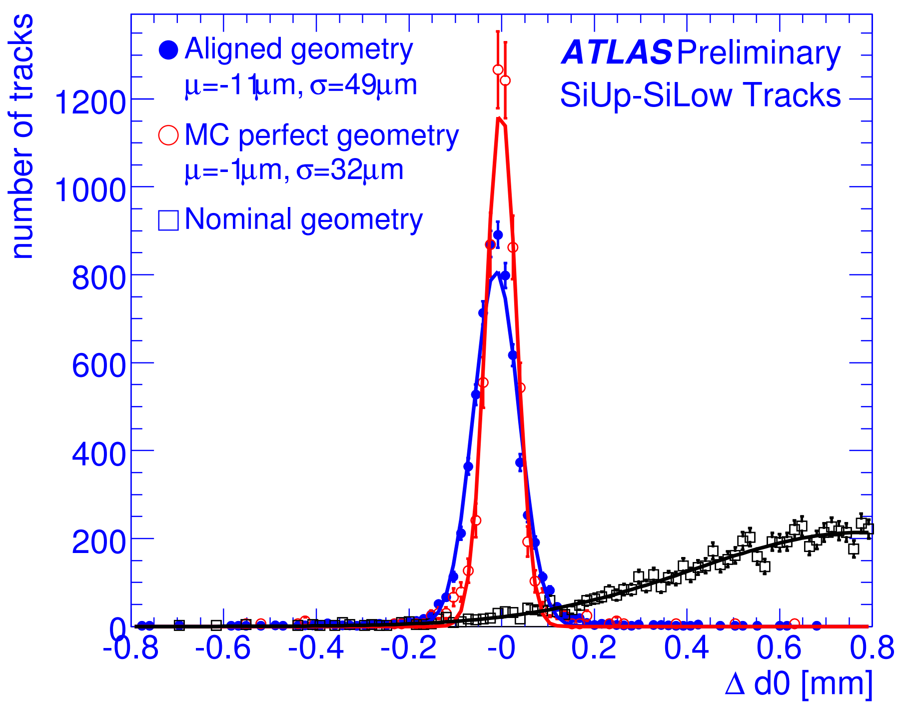
Track parameter resolution

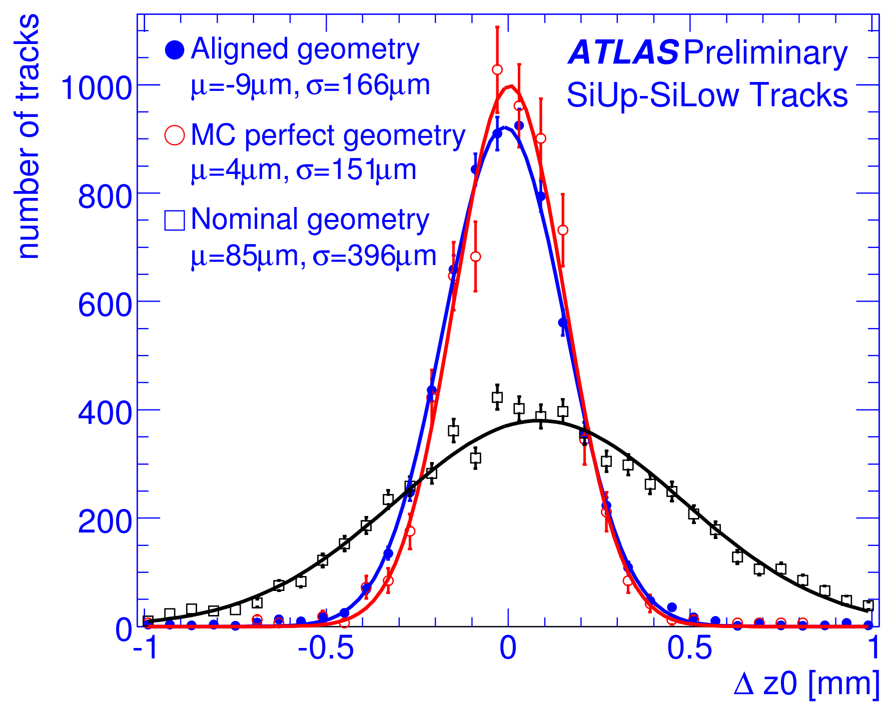
Measure precision on determination of track paramter on cosmics:

- Split track into two segments
- Compare extrapolation at interaction points of segments

Resolution already acceptable for LHC startup





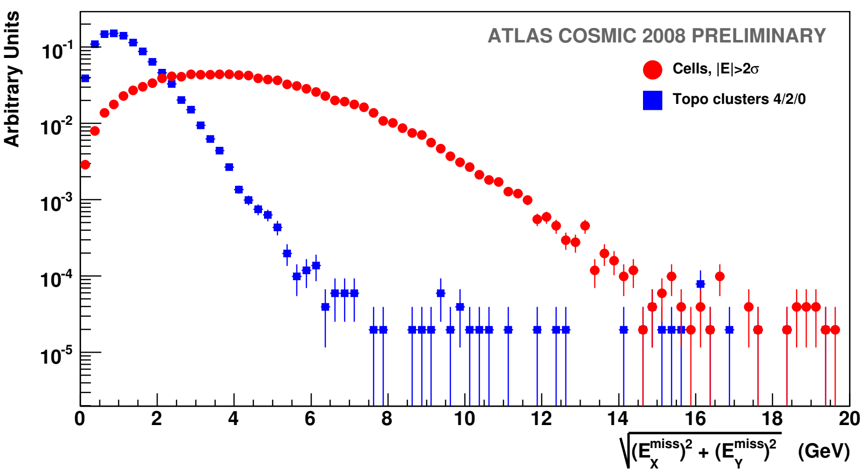


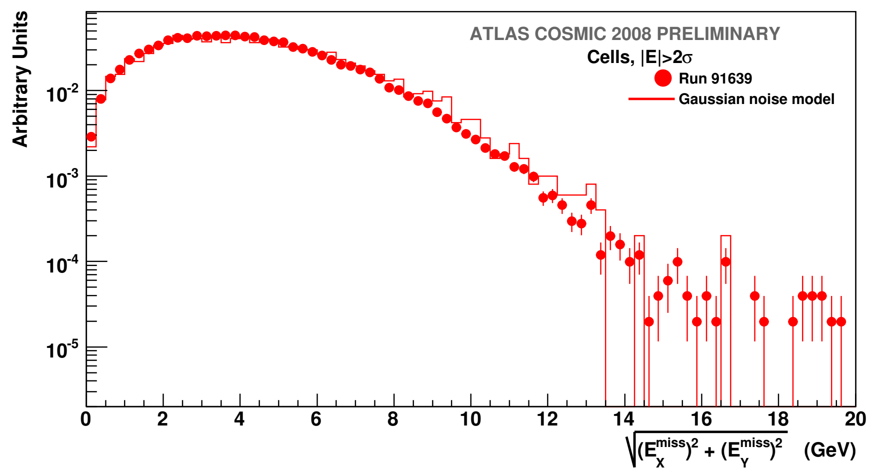
Example: Etmiss commissioning

Basic check: look at random triggers, and plot $\not\!\!E_T$ distribution

Use two different algorithms for cell noise subtraction: simple cut at 2σ, 3-D energy clusters (topcolusters)

Much narrower distribution for topoclusters

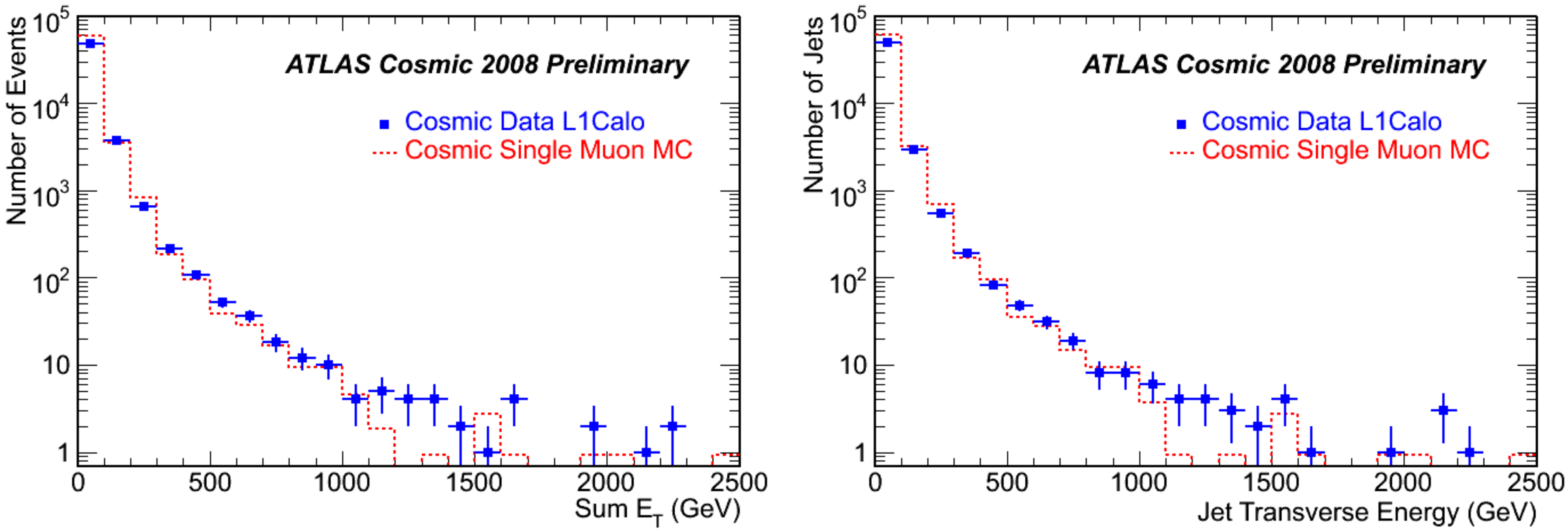




Observe excellent agreement between measured $\not\!\!E_T$ and simple gaussian model of noise in calo cells

Good stability observed over 1.5 months period

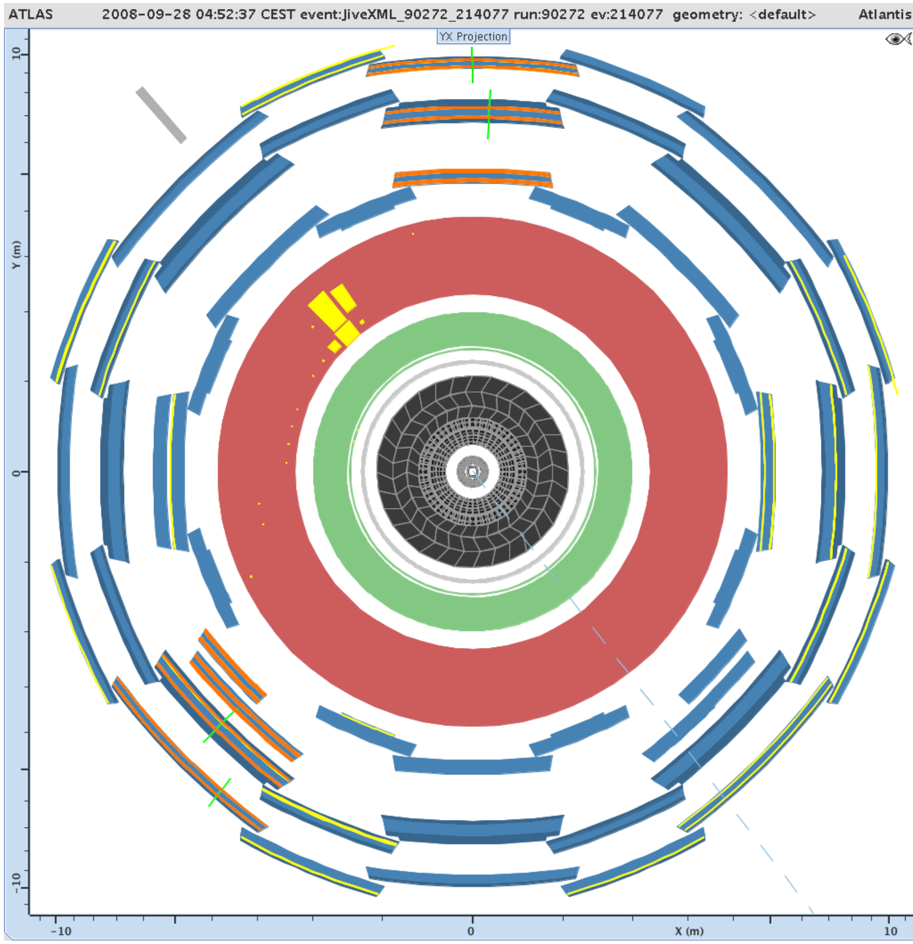
Fake Etmiss: cosmic rays

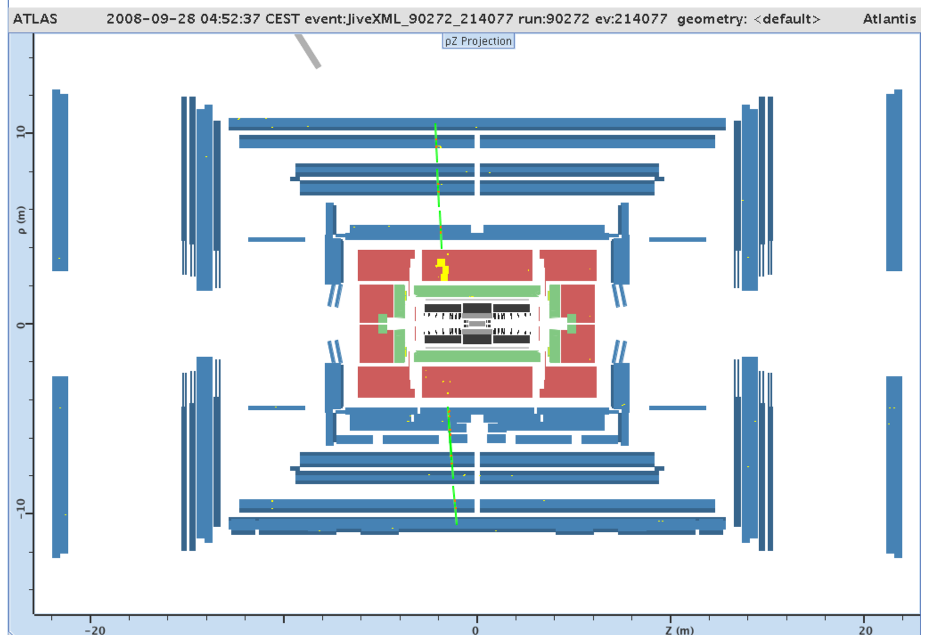


High energy cosmic ray muons undergoing hard brehmsstrashlung can generate fake $\not{E}_T$

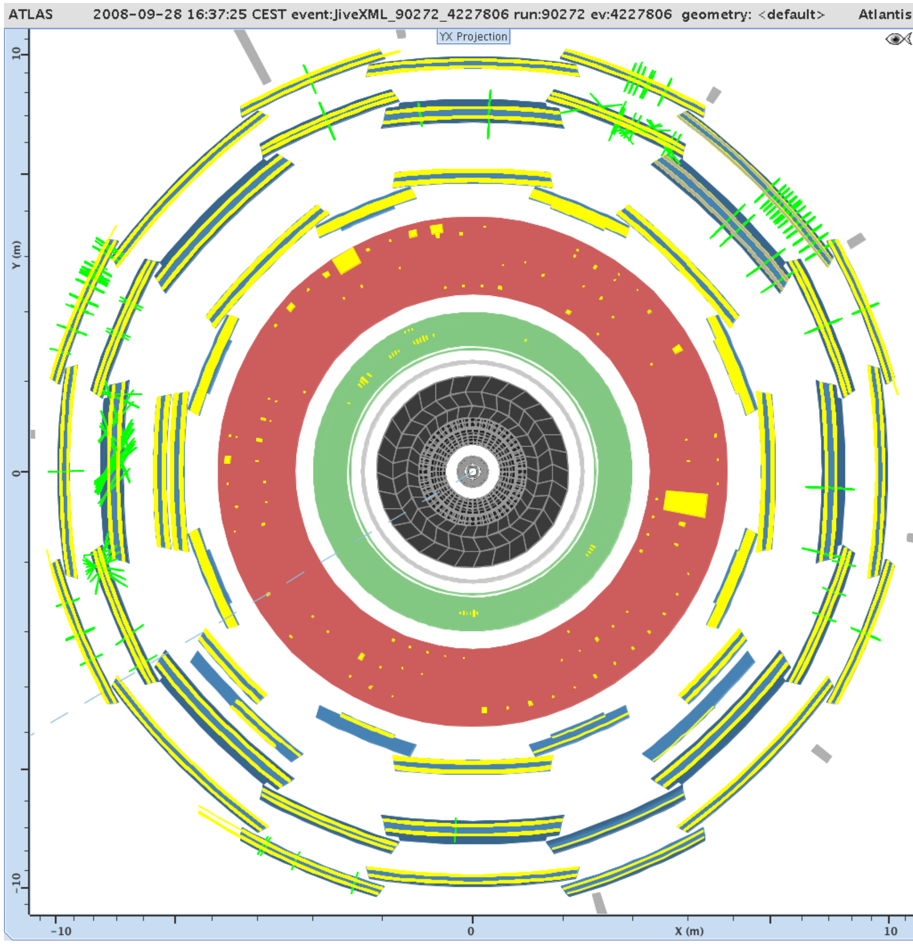
Discrepancy in tails due to MC statisitcs and from cosmic ray air showers (not modelled in MC

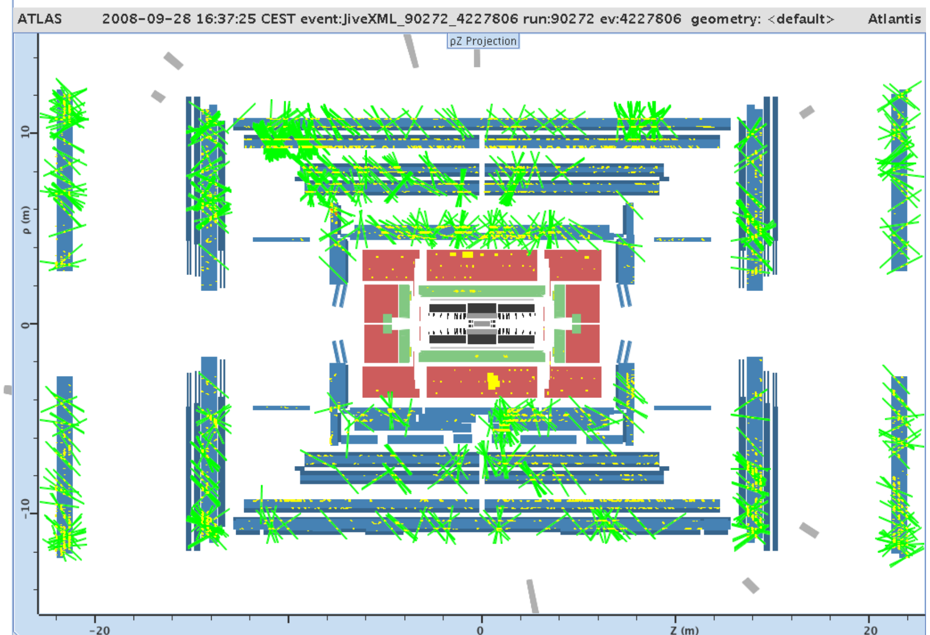
TeV event from single cosmic ray muon



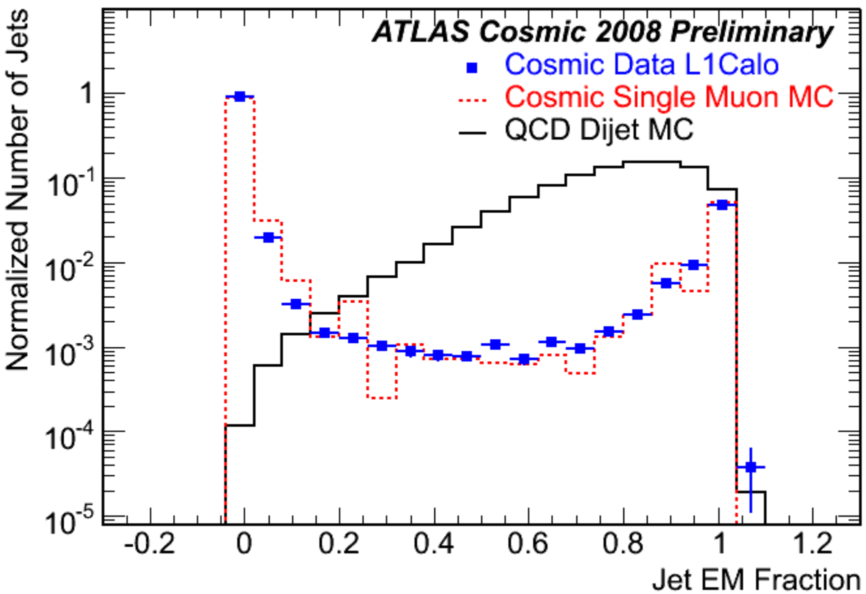


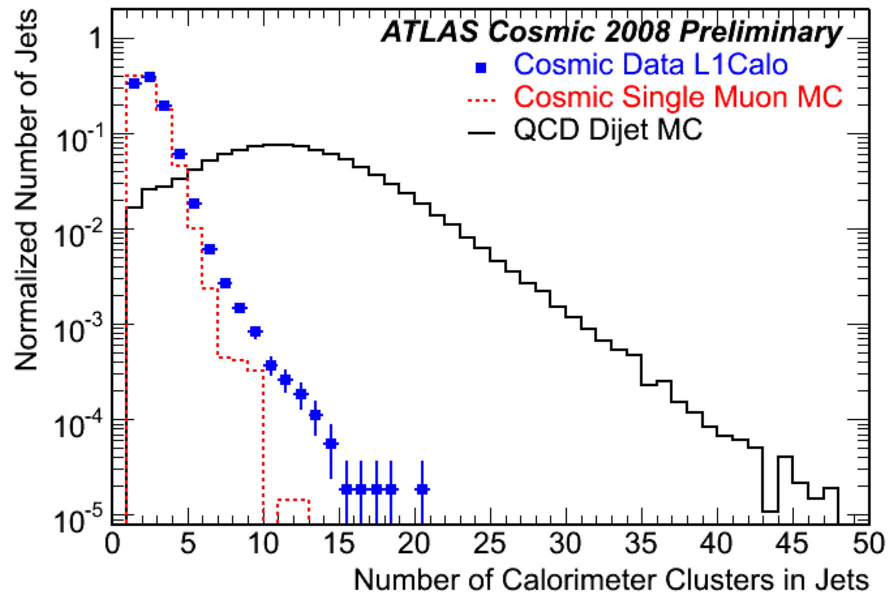
TeV event from cosmic ray air shower





Cleaning cuts



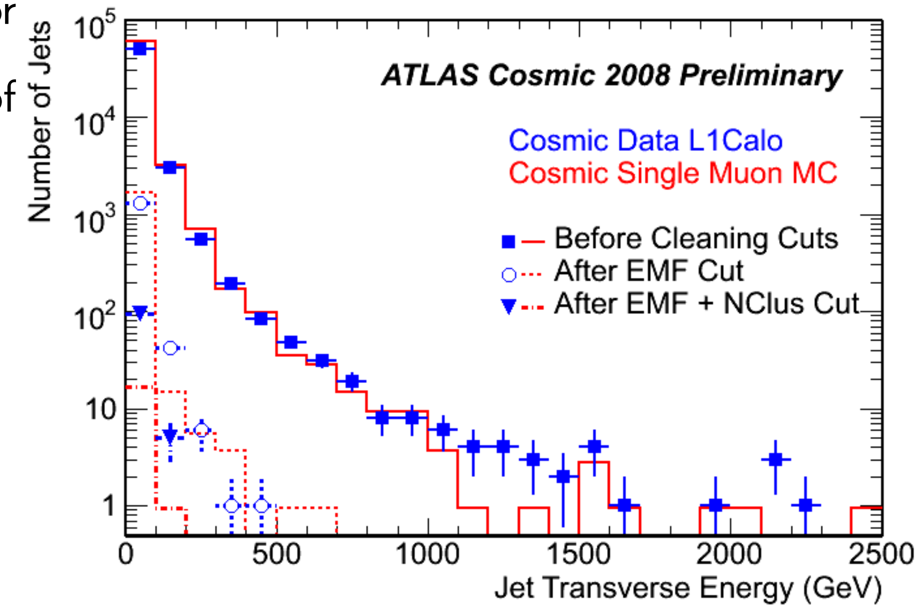


Jet EM fraction (F_{EM}) : Typically 0 or 1 for muons undergoing bremsstrahlung in Tilecal of LARG

Number of clusters (N_{clus}) : lower for cosmics

Resulting rejection after requiring:

- $0.2 < F_{EM} < 0.97$
- $N_{clus} \geq 7$



Backup