Electron, Photon, Muon and Missing Transverse Momentum Reconstruction with the ATLAS detector

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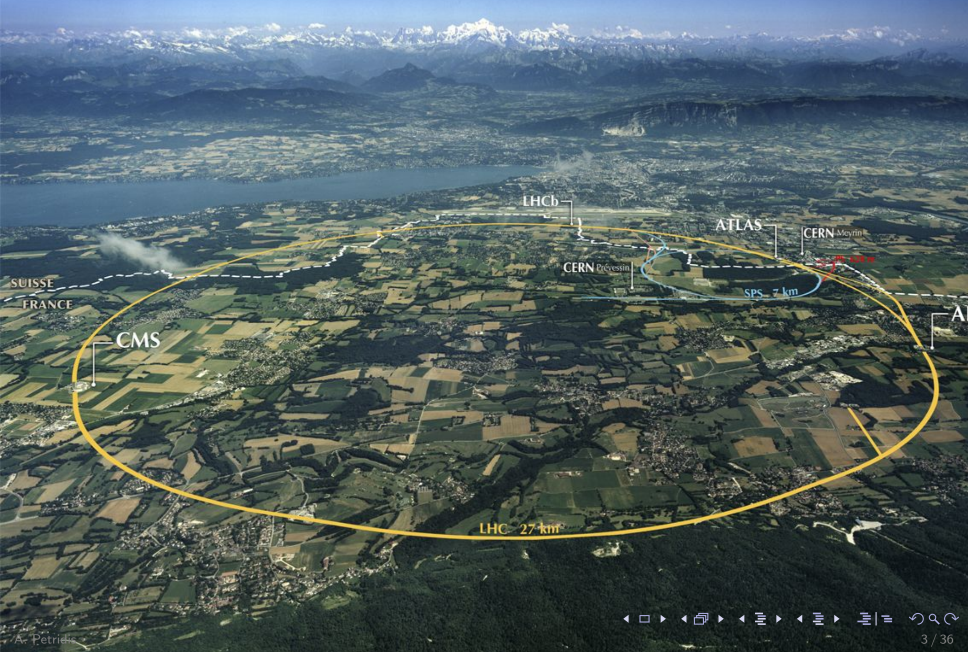
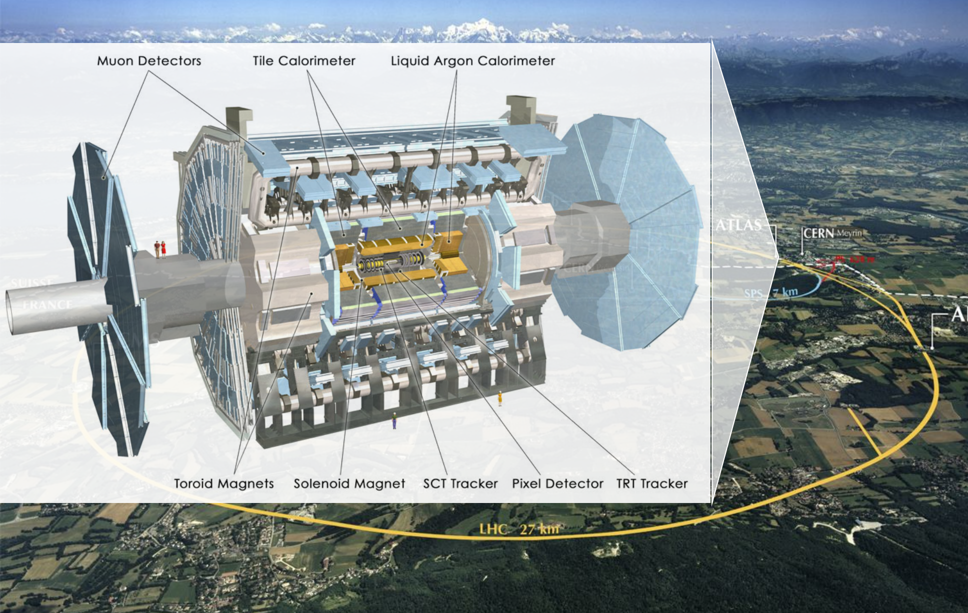
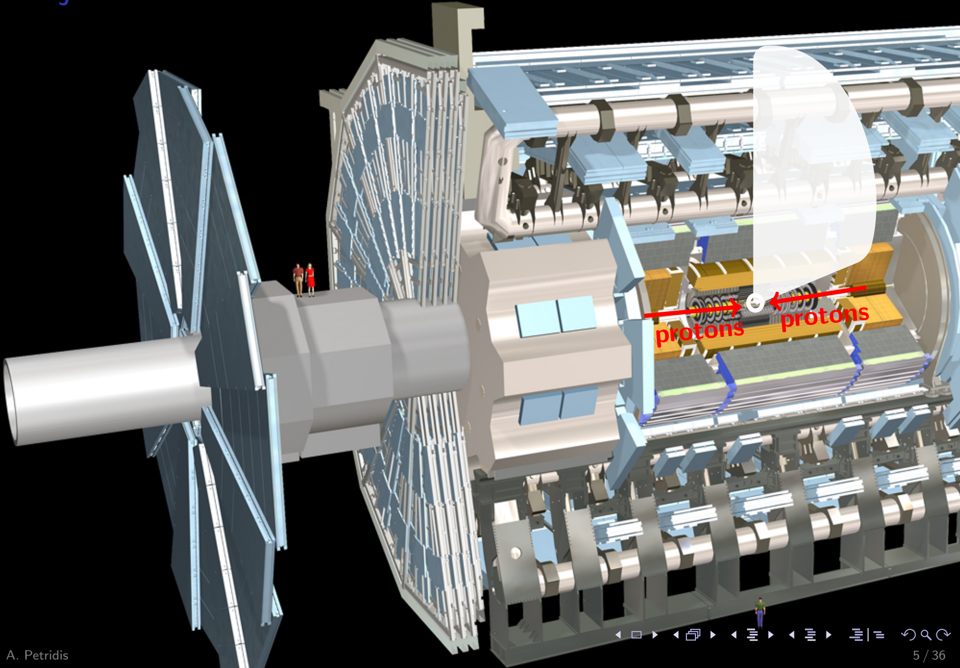
The Large Hadron Collider and the ATLAS experiment



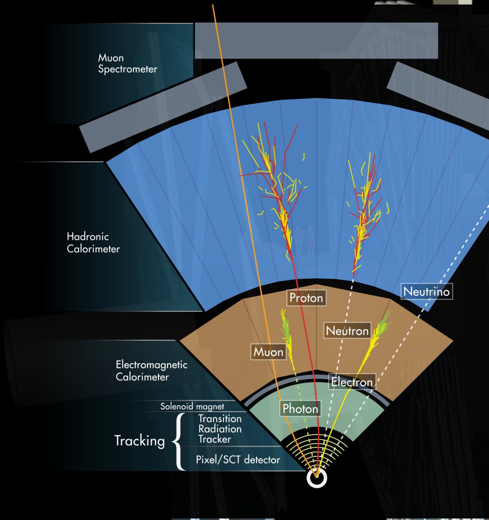
The Large Hadron Collider and the ATLAS experiment



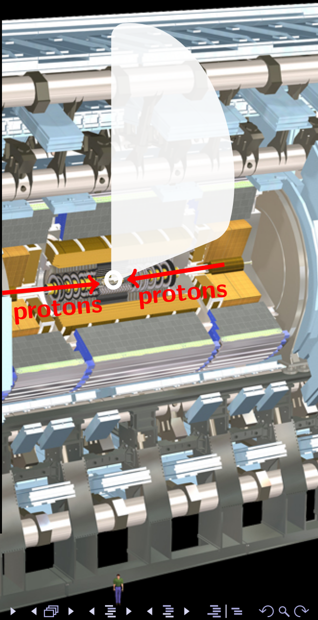
Object identification within the ATLAS detector



Object identification within the ATLAS detector

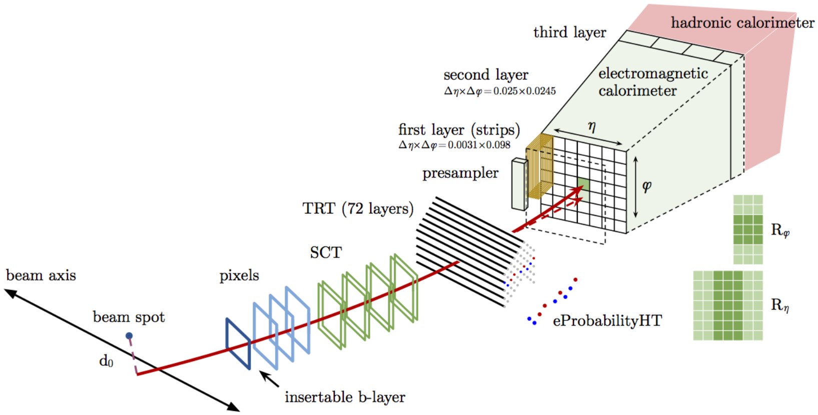


The dashed tracks are invisible to the detector



Electron/Photon Reconstruction

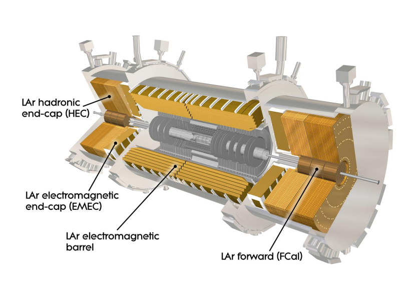
What do we call electron/photon in ATLAS?

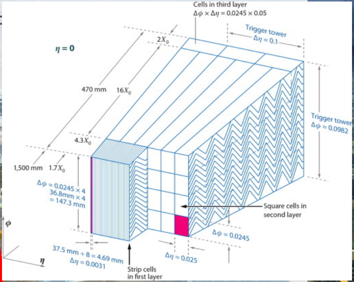


A combination of information from the Inner Detector (**track**) and the Electromagnetic Calorimeter (**energy deposit, cluster**).
If no tracks are associated to an ECAL cluster it is classified as an "unconverted photon"

Electromagnetic Calorimeter

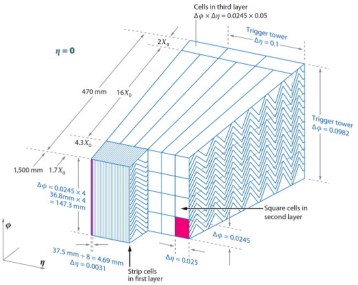
The formation starts with an energy deposit in the EM calorimeter

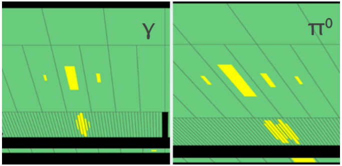




- Liquid Argon as active material
- Lead absorber
- Hermetic coverage, no cracks
- Longidudinal segmentation, "Accordion shape"

Electromagnetic Calorimeter

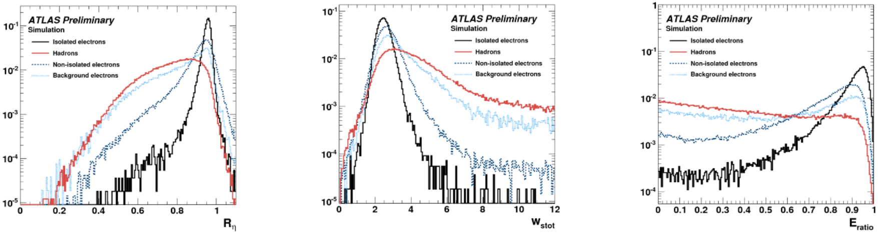




- bremsstrahlung radiation
- pair production of $e^- e^+$

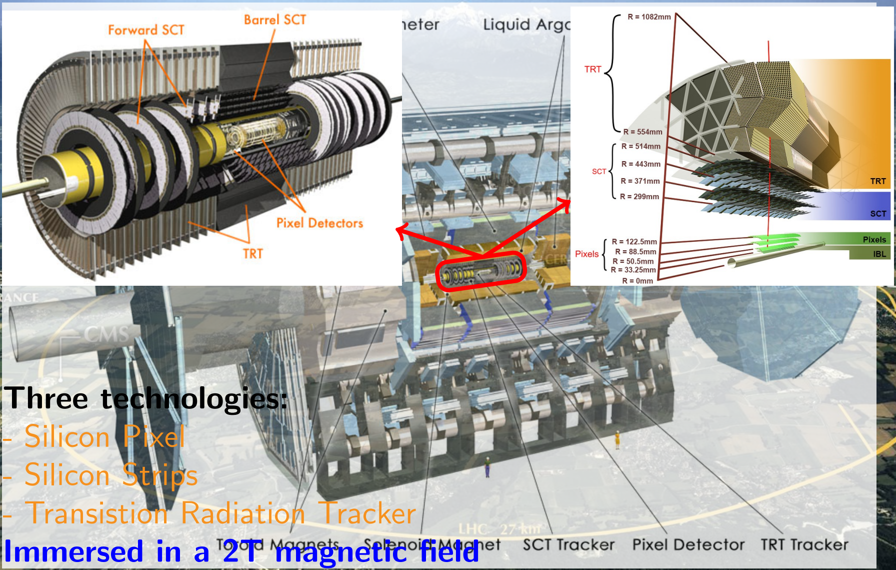
- Consists from three compartments (or layers);
- First layer narrow strips. Acts as preshower detector;
  - Especially useful for seperating π^0 and photons;
  - Precise measurement of direction
- Second layer segmented in squares ($\Delta\eta \times \Delta\phi = 0.025 \times 0.025$)
  - contains the biggest energy deposition of the electron/photon;
- Third layer larger granularity ($\Delta\eta \times \Delta\phi = 0.05 \times 0.025$)
- Energy resolution: $\frac{\sigma_E}{E} = \frac{11\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 0.4\%$
  - First term: stat fluctuations of the sampling method
  - Second term: accounts for inhomogeneities in the responce of the ECAL

Electromagnetic Calorimeter



- **Identification** variables can be extracted by taking adantage of the segmentation and the different layers of ECAL.
    - R_η : Ratio of the energy in 3×7 over the energy in 7×7 cells centered at the electron cluster position (middle layer)
    - w_{stot} : Shower width (first layer)
    - E_{ratio} : Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies (first layer)
- Three sets of selections with an increased rejection power of background have been designed.
    - Loose, Medium, Tight
- Use Multivariate Analysis techniques for the electron classification.

Inner Detector



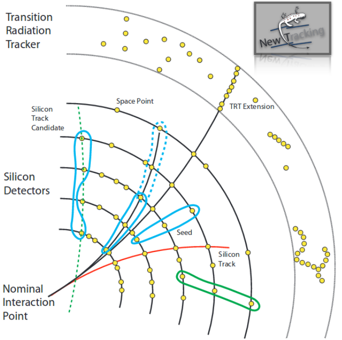
Three technologies:

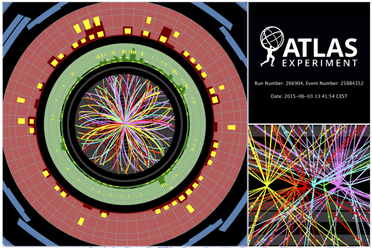
- Silicon Pixel
- Silicon Strips
- Transistion Radiation Tracker

Immersed in a 2T magnetic field

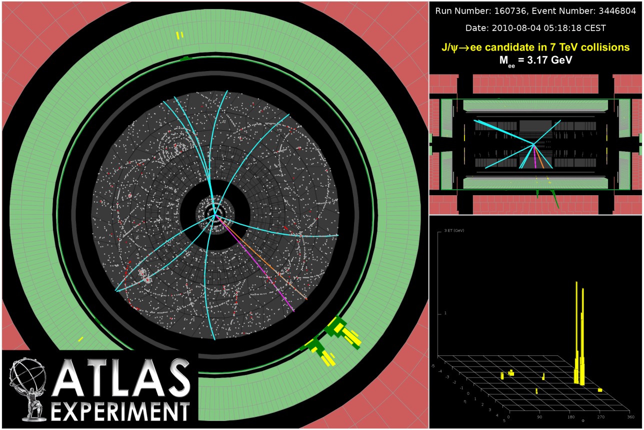
Inner Detector - Identifying a track

- Main task of the inner detector is to idenify the trajectories of the charged particles, “track” (and through this measure the momentum by curvature in magnetic field)
- Cope with the combinatorial explosion of possible hit combinations
- Different techniques can be employed:
    - local method: generate seeds and complete them to track candidates;
    - global method: simultaneous clustering of detector hits into track candidates
- Primary interaction vertex: largest $\sum p_T^2$ over the corresponding tracks



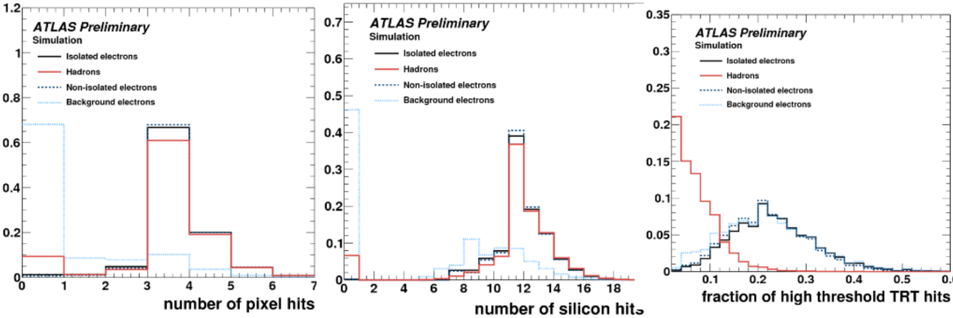


$J/\psi \to ee$



- Tracks are extrapolated to the EM calorimeter to form electrons;
- The energy of the cluster and the direction of the track are used in the defition of the kinematic properties of electrons.

Taking advantage of the Inner Detector



- Additional discrimination of the signal electrons from background processes can be achieved by employing variables from the Inner Detector
- Use Multivariate Analysis techniques for the electron classification.

Electron energy calibration

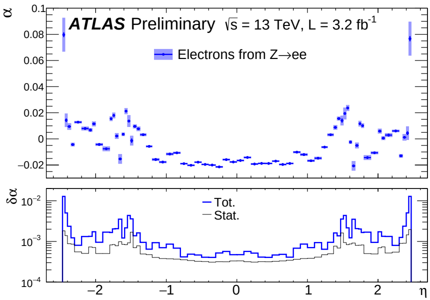
Electrons' energy need to be calibrated to account for the non-uniformity of the detector responce

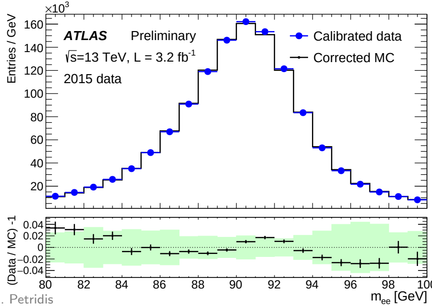
- Energy mis-calibration is defined as the difference in response between data and simulation
  $E_i^{data} = E_i^{MC}(1 + a_i)$, ($a_i$: deviation from optimal calibration, in a given pseudorapidity region i;
- a_i calibration constants are applied to data;
- Energy resolution is parametrised as:
  $$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$
  a : sampling term related to shower fluctuations in the calorimeter and modeled by simulation

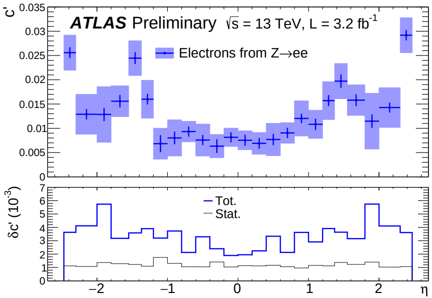
  b : electronic noise term measured in calibration run

  c : constant term
- Difference in energy resolution between data and simulation is modeled by an additional effective constant term:
  $$(\frac{\sigma(E)}{E})_i^{data} = (\frac{\sigma(E)}{E})_i^{MC} \oplus c_i'$$
- c_i constants are applied to MC;
- Both a_i and c_i terms are calculated from $Z \rightarrow ee$ events

Calibration constants





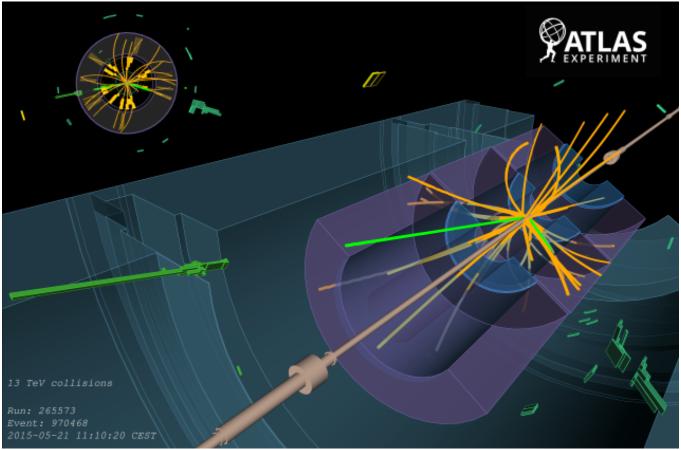


- Scale corrections are larger in the forward region due to more material;

Synopsis for electron reconstruction

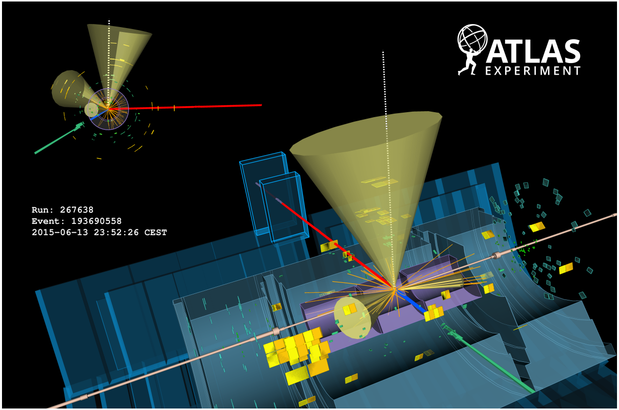
- Find cluster seed with energy > 2.5 GeV
  - Cluster size 3×5 (η/ϕ)- middle layer unit (0.025$\times$0.025)
- Match cluster to track
  - to distinguish $e^{\pm}$ from unconverted γ;
- Match track to a vertex
  - to distinguish $e^{\pm}$ from converted γ;
- Rebuild clusters in optimized cluster sizes
  - $\Delta\eta \times \Delta\phi = 3 \times 7 (5 \times 5)$ barrel (endcap)
- Compute energy measurement summing all the cells in the cluster
- Apply cluster position and energy calibration.

$Z \to ee$



Display of a $p - p$ collision event recorded by ATLAS on 21 May 2015 at a collision energy of $\sqrt{s}$ =13 TeV. Tracks reconstructed from hits in the inner tracking detector are shown as arcs curving in the solenoidal magnetic field and green bars are proportional to the energy deposited in the electromagnetic calorimeter. A high energy electron and positron are identified with an invariant mass consistent with that of a Z boson.

Event Display $t\bar{t}$

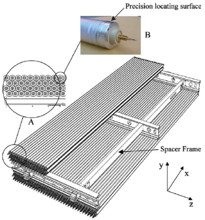


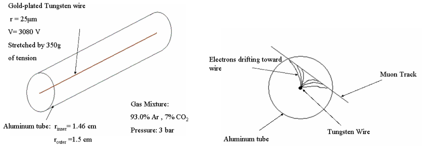
Display of a $t\bar{t}$ candidate event from proton-proton collisions recorded by ATLAS with LHC stable beams at a collision energy of 13 TeV. The red line shows the path of a muon with transverse momentum around 140 GeV through the detector. The green line shows the path of an electron with transverse momentum around 170 GeV through the detector. The green and yellow bars indicate energy deposits in the liquid argon and scintillating-tile calorimeters, from these deposits 3 jets are identified with transverse momenta between 30 and 80 GeV. Two of the jets are identified as having originated from b-quarks. Tracks reconstructed from hits in the inner tracking detector are shown as arcs curving in the solenoidal magnetic field.

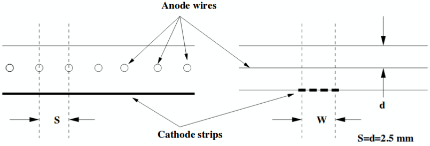
Muon Spectrometer

Precision chambers

- **Monitored Drift Tube (MDT) chambers**
  - 3 cm wide tubes with a wire at the center with an average resolution of 80 μm
  - two separate multi-layers to obtain a better angular resolution
- **Cathode Strip Chambers (CSC)**
  - Located in the forward region;
  - Multiwire proportional chambers
  - Average spatial resolution of 60μm

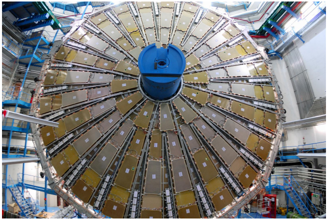


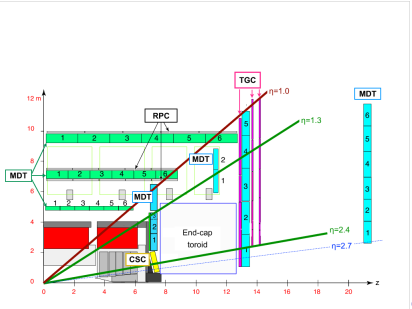




Trigger chambers

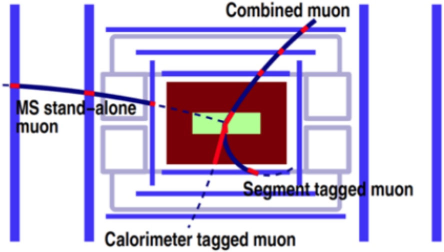
- Two technologies
  - Resistive Plate Chambers (RPC)
    - Located in the Barrel region
  - Thin Gap Chambers (TGC)
    - Located in the Endcap region
- Fast detectors
  - provide the L1 trigger
  - time resolution < 25 ns, important in identifying the Bunch Crossing that the hit corresponds to
- Provide the second coordinate for the MD chambers





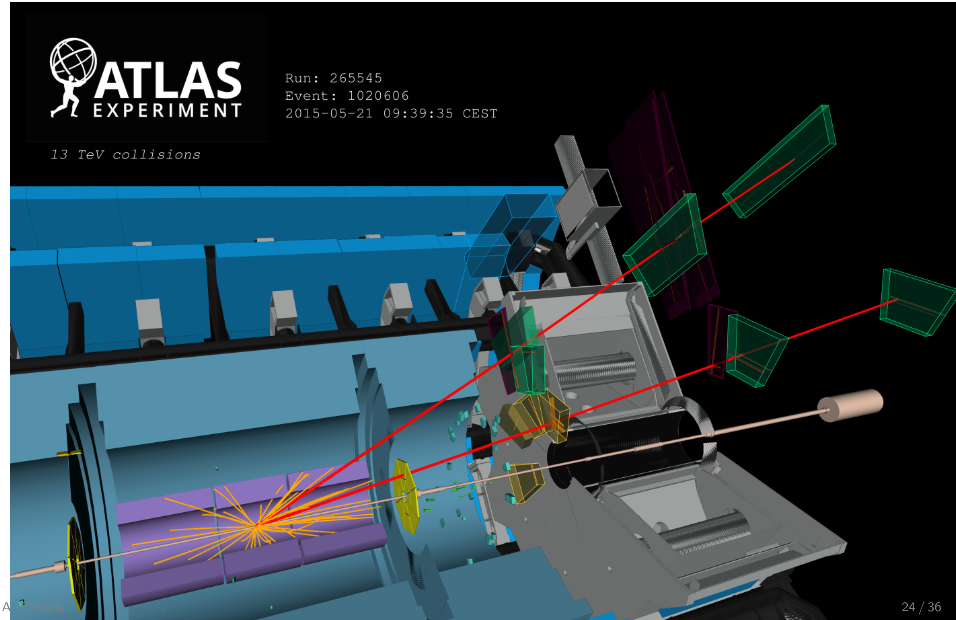
Muon finding algorithms

- Combined muons:
  - ID+MS hits + full track fit
- Standalone muons
  - track in the MS, no associated ID track ($|\eta| > 2.5$)
- Segment tagged muons
  - ID track + matching segment
  - helpful for low p_T muons;
- Calorimeter tagged muons
  - A special category for recovering muons in the hole of ATLAS ($|\eta| < 0.1$)



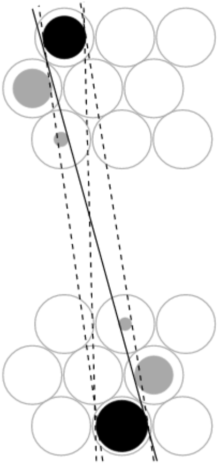
Picture from N. van Eldik

$J/\psi \to \mu\mu$


ATLAS EXPERIMENT
Run: 265545
Event: 1020606
2015-05-21 09:39:35 CEST
13 TeV collisions

Muon reconstruction

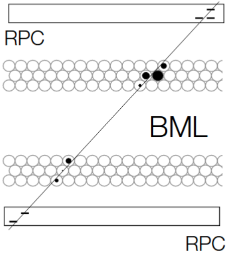
- A collection of hits is available to us when a muon passes through the Muon Spectrometer;
- Additional hits surrounding the real hits from muons are also present and are coming from bacgkround/noise processes.
- Which is the correct combination among the 3000 MDT hits?



Reconstructing the Muon trajectory

- Within the layers of the MS, muon trajectories are in first order straight lines;
- The position in the MDT tubes is measured with the trigger chambers;
- Employ Hough transformation (technique used for resolving combinatorics)
  - Transforms points in the $x, \ y$ space into lines in $R_0, \ \phi$;
  - The lines of all hits from a given line cross in one point in the Hough space
- Easier to start with local segment finding in the individual MDT stations

- Seed selection
  - Calculate tangent lines
  - Associate other hits to the seed lines using a fixed road width
- Segment creation
  - Perform 2D fit to associated hits



Muon identification

- Apply quality requirements to supress background (pion and kaon decays)
  - q/p significance: defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in quadrature of the corresponding uncertainties

$$\left| \frac{(q/p)_{ID} - (q/p)_{MS}}{\sqrt{\sigma(q/p)_{ID}^2 + \sigma(q/p)_{MS}^2}} \right|$$

  - p': defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track

$$\left| \frac{p_T^{ID} - p_T^{MS}}{p_T^{combined}} \right|$$

  - normalised χ^2 of the combined track fit
  - Additional requirements on the number of hits
- Four set of selections: Loose, Medium, Tight, High-p_T

	$4 < p_T < 20$ GeV		$20 < p_T < 100$ GeV	
Selection	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High-p_T	78.1	0.26	80.4	0.13

Muon momentum calibration

- Muons p_T must be calibrated in order to correct for:
  - multiple scattering;
  - local magnetic field distortions;
  - energy loss due to fluctuations in the traversed material;
  - residual misalignments of the detector
- Calibration corrections are extracted by fitting the Z and J/ψ invariant masses

$$p_{\mathrm{T}}^{\mathrm{Cor,Det}} = \frac{p_{\mathrm{T}}^{\mathrm{MC,Det}} + \sum_{n=0}^{1} s_n^{\mathrm{Det}}(\eta,\phi)\left(p_{\mathrm{T}}^{\mathrm{MC,Det}}\right)^n}{1 + \sum_{m=0}^{2} \Delta r_m^{\mathrm{Det}}(\eta,\phi)\left(p_{\mathrm{T}}^{\mathrm{MC,Det}}\right)^{m-1} g_m},$$

Numerator: Describes the momentum scale

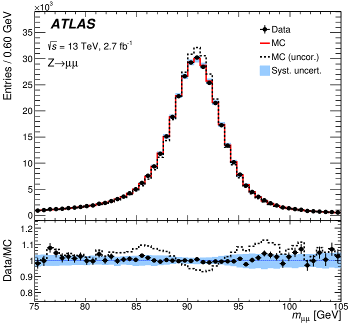
- s_0^{Det}: models the effect on the detector momentum from the inaccuracy in the simulation due to energy loss in the presence of materials between the interaction point and the detectors;
- s_1^{Det}: corrects for inaccuracy in the description of the magnetic field integral.

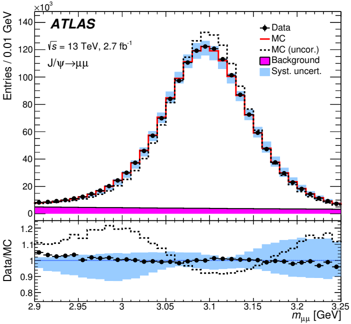
Muon momentum calibration

Denominator: describes the momentum smearing that broadens the relative p_T resolution in simulation

$$\frac{\sigma(p_T)}{p_T} = r_0/p_T \oplus r_1 \oplus r_2.p_T$$

r_0: accounts for fluctuations of the energy loss in the traversed material;
r_1: accounts for multiple scattering, local magnetic field inhomogeneities;
r_2: describes intrinsic resolution effects caused by the spatial resolution of the hit measurements and by residual misalignment of the muon spectrometer





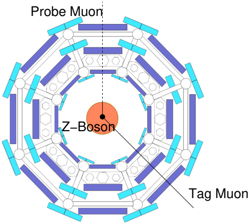
Synopsis for Muon Reconstruction

- Two ways for muon recontruction
  - Outside→in (MS towards ID)
  - Inside→out (ID towards MS)
  - Employ both approaches to maximize efficiency
  - If muon is in the forward region, we have a standalone MS recontruction only
- Keeping combinatorics under control:
  - Find possible roads by employing the Hough transformation
  - Station segment finding
  - Back-extrapolation to the vertex

Efficiency measurements for electrons/muons

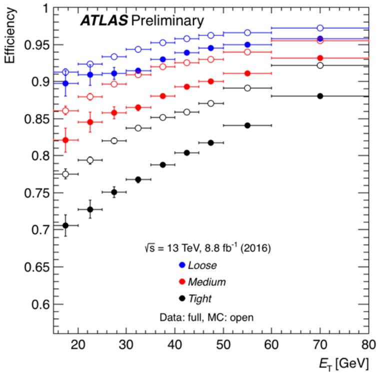
- Efficiency measurements are performed with data
  - Usage of standard candle processes ($Z \rightarrow ee/\mu\mu,\ J/\psi- > ee/\mu\mu$)
  - Based on Tag&Probe method;
    - Tag a lepton (e or μ) with tight selections;
    - Check the probe (with loosen selections) if it passes the seletions under investigation;
    - The efficiency is defined as

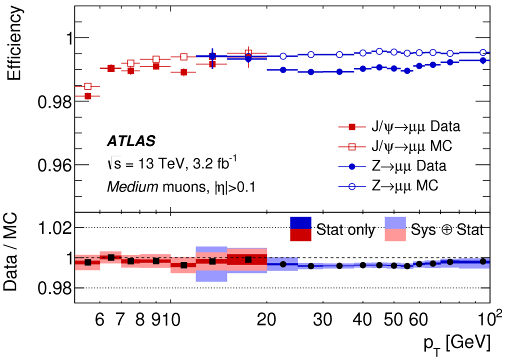
$$Efficiency = \frac{number\ of\ probes\ passing\ a\ specific\ set\ of\ selection}{number\ of\ probes}$$



For the first time in ATLAS we calculated electron efficiencies down to 4.5 GeV
Qualification task assigned to Abhishek Sharma

ID efficiencies





Determining the missing transverse momentum

Contributions: neutrinos(ν), mismeasured momenta or *perhaps new sources* $\tilde{\chi}_1^0$;

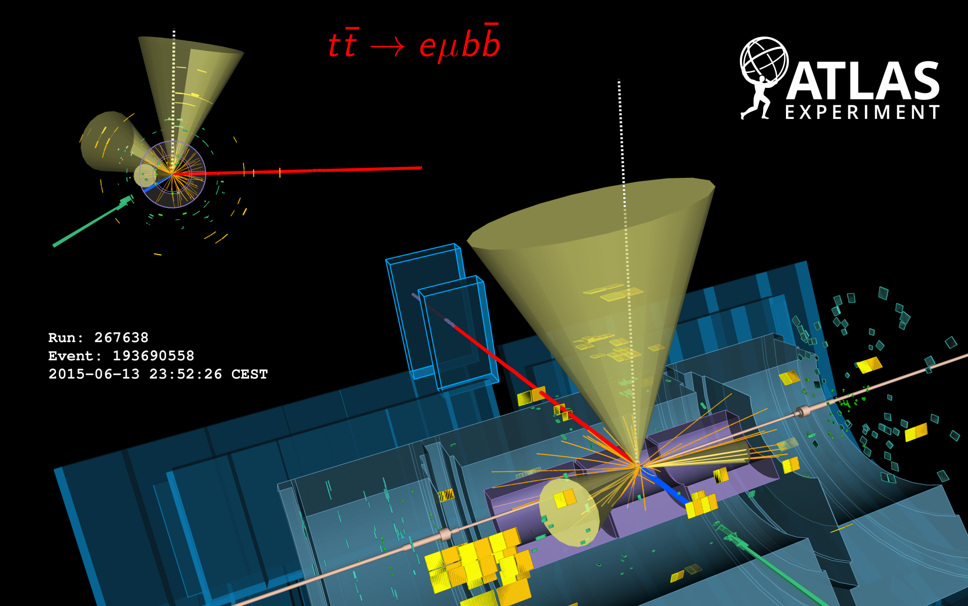
Conservation of momentum in the transverse plane.
$\mathbf{E_T^{miss}}$ is calculated from:

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,\mu} + E_{x(y)}^{miss,SoftTerm}$$

Soft term: clusters of energy in the calorimeters and tracks not associated to high p_T objects;

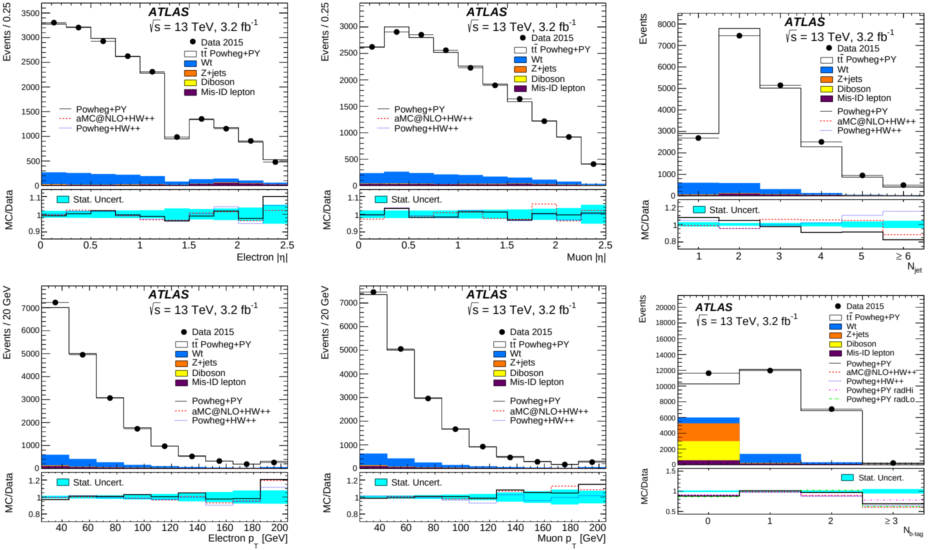
$E_{\mathrm{T}}^{\mathrm{miss}}$: Magnitude of the missing transverse momentum in the event;

$$E_T^{miss} = \sqrt{\left(E_x^{miss}\right)^2 + \left(E_y^{miss}\right)^2}$$



Display of a ttbar candidate event recorded by ATLAS at 13 TeV. The red line shows a muon with p_T=140 GeV. The green line shows an electron with p_T =170 GeV. Two of the jets are identified as having originated from b-quarks.

Modeling of kinematic variables in $t\bar{t}$ events



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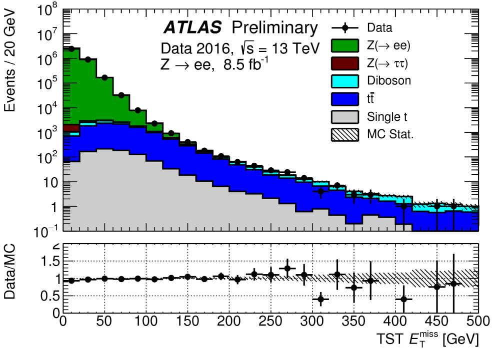
- Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data, ATLAS-CONF-2016-024
- Electron efficiency measurements with the ATLAS detector using 2012 LHC proton-proton collision data, arXiv:1612.01456
- Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data, Eur. Phys. J. C 76 (2016) 666., arXiv:1606.01813
- Performance of algorithms that reconstruct missing transverse momentum in $\sqrt{s}$=8 TeV proton-proton collisions in the ATLAS detector, arXiv:1609.09324

Back-up

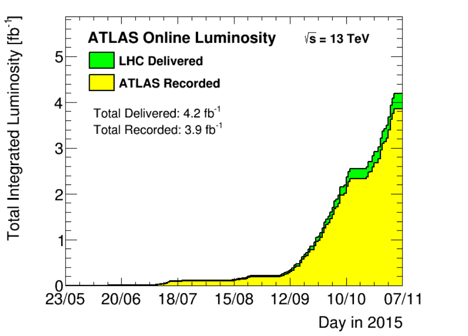
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term modeling



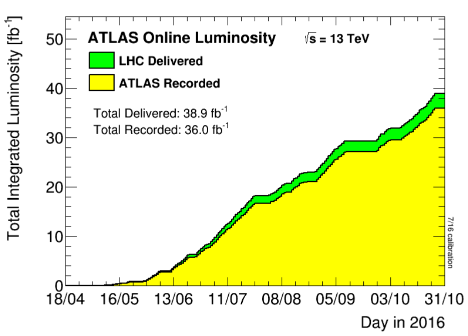
Integrated Luminosity

$$\underbrace{N}_{\#\ of\ events} = \underbrace{\sigma}_{\substack{cross\ section\\ of\ the\ process\ (fb)}} \cdot \underbrace{\int L dt}_{integrated\ luminosity\ (fb^{-1})}$$

2015 @ $\sqrt{s} = 13$ TeV

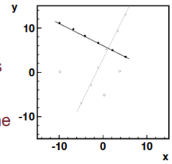


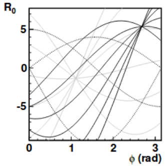
2016 @ $\sqrt{s} = 13$ TeV

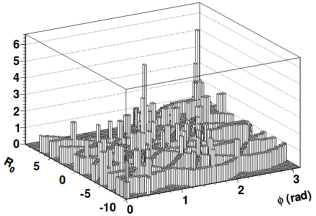


Finding the trajectory in the xy-plane

- Use 2D Hough transform using (R_0, φ)
- The Hough transform
  - transforms points in the x,y space into lines in R_0, φ
  - straight lines in the xy plane are points in the Hough space
    - the lines of all hits from a given line cross in one point in the Hough space
    - when combined with a histogramming technique the problem reduces to finding the bins with the highest value in the histogram
- Advantages of the method
  - very good background rejection properties
  - complexity almost linear with number of hits







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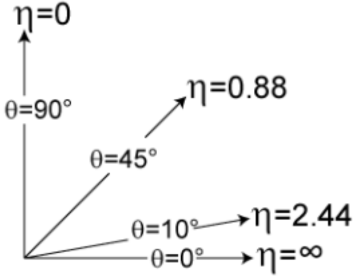
Link to Niel's slides

List of Electron discriminant variables

Type	Description	Name
Hadronic leakage	Ratio of E_{T} in the first layer of the hadronic calorimeter to E_{T} of the EM cluster (used over the range $\lvert\eta\rvert < 0.8$ or $\lvert\eta\rvert > 1.37$)	R_{had1}
	Ratio of E_{T} in the hadronic calorimeter to E_{T} of the EM cluster (used over the range $0.8 < \lvert\eta\rvert < 1.37$)	R_{had}
Back layer of EM calorimeter	Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter. This variable is only used below 100 GeV because it is known to be inefficient at high energies.	f_3
Middle layer of EM calorimeter	Lateral shower width, $\sqrt{(\Sigma E_i \eta_i^2)/(\Sigma E_i) - ((\Sigma E_i \eta_i)/(\Sigma E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_{ϕ}
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	R_{η}
Strip layer of EM calorimeter	Shower width, $\sqrt{(\Sigma E_i (i - i_{\mathrm{max}})^2)/(\Sigma E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in η, and i_{max} is the index of the highest-energy strip	w_{stot}
	Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies	E_{ratio}
	Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter	f_1
Track conditions	Number of hits in the innermost pixel layer; discriminates against photon conversions	n_{Blayer}
	Number of hits in the pixel detector	n_{Pixel}
	Number of total hits in the pixel and SCT detectors	n_{Si}
	Transverse impact parameter with respect to the beam-line	d_0
	Significance of transverse impact parameter defined as the ratio of d_0 and its uncertainty	d_0/σ_{d_0}
	Momentum lost by the track between the perigee and the last measurement point divided by the original momentum	$\Delta p/p$
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT
Track-cluster matching	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track	$\Delta\eta_1$
	$\Delta\phi$ between the cluster position in the middle layer and the track extrapolated from the perigee	$\Delta\phi_2$
	Defined as $\Delta\phi_2$, but the track momentum is rescaled to the cluster energy before extrapolating the track from the perigee to the middle layer of the calorimeter	$\Delta\phi_{\mathrm{res}}$
	Ratio of the cluster energy to the track momentum	E/p

Pseudorapidity definition



$$\eta = -ln\left(tan\left(\frac{\theta}{2}\right)\right)$$

Momentum Measurement

- Moving charged particles are deflected by magnetic fields
  - In a homogeneous ***B*** field particle follows circle with radius ***r***

$$p_t[GeV/c] = 0.3 \cdot B[T] \cdot r[m]$$

measurement of p_t via measuring the radius

Lorentz Force

$$\vec{F}_L = q \cdot \vec{v} \times \vec{B}$$

Centripetal Force

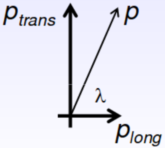
$$F_c = m \cdot v^2 / r$$

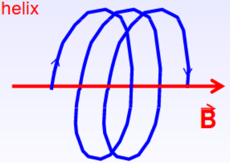
$$p = q \cdot B \cdot r$$

  - p_t is the component of the momentum orthogonal to ***B*** field

p_t : transverse momentum

  - no particle deflection parallel to magnetic field
  - if particle has longitudinal momentum component, the particle will follow a helix





total momentum *p* to be measured via dip angle λ

$$p = \frac{p_t}{\sin \lambda}$$