Calibration of the ATLAS electromagnetic calorimeter and measurement of the couplings of the (Brout-Englert-)Higgs boson in the diphoton channel

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PhD defense

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Introduction

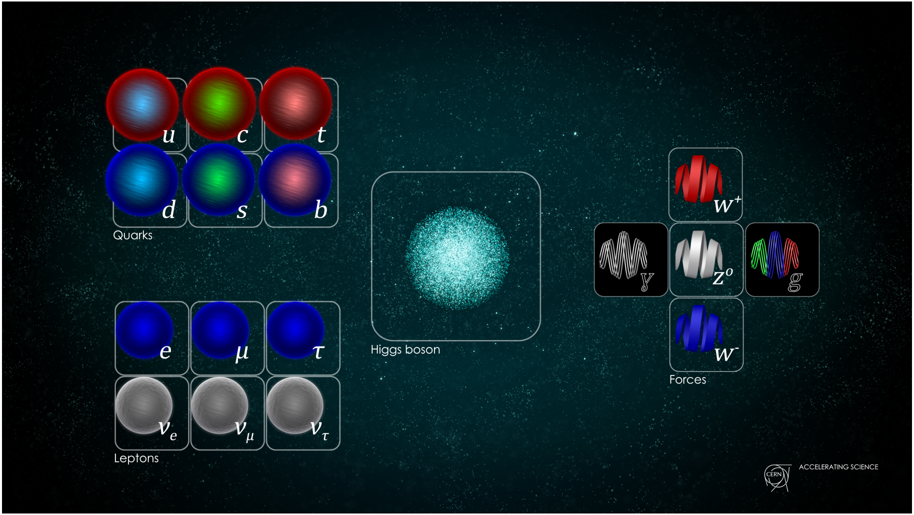
1. The Standard Model of matter

2. Experimental conditions and data processing

3. Measurement of Higgs boson couplings

Particle content of matter

Over the XXth century, elementary particles have been organised into a well structured model.



A mathematical framework

Matter knowledge is embedded into a well defined mathematical framework based on a Lagrangian L.

$$L = \frac{m\dot{\vec{q}}^2}{2} - V(\vec{q}) \tag{1}$$

The dirac lagrangian describes a massive fermion field :

$$L = \bar{\psi}(i\partial\!\!\!/ - m)\psi \tag{2}$$

Imposing least action principle (similar to classical mechanic) lead to equations of motion :

$$\frac{\partial L}{\partial q} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} = 0 \tag{3}$$

Gauge invariance

Symmetries are transformations which leave a system unchanged.
Imposing symmetries on a Lagrangian changes the theory it describes.

$$\psi(x) \to e^{i\alpha(x)}\psi(x) \tag{4}$$

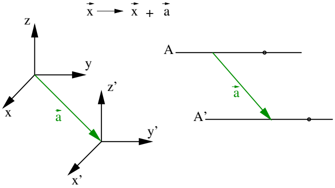
Derivative affects $e^{i\alpha}$

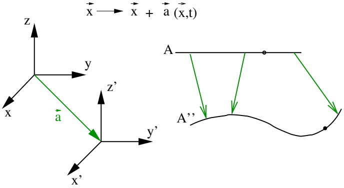
→ **Invariance achieved by adding a field A_μ and changing L.**

→ mass term for A ($m^2 A_\mu A^\mu$) is forbidden by symmetries

$$\partial_\mu \to D_\mu = \partial_\mu + ieA_\mu(x) \tag{5}$$

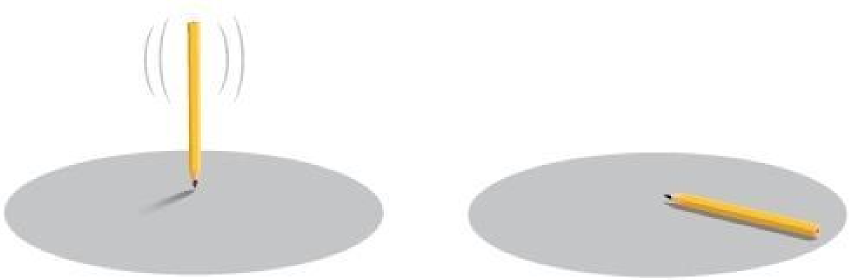
$$A_\mu \to A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x) \tag{6}$$





Spontaneous Symmetry Breaking

SSB describes a system for which its ground state has less symmetry than its Lagrangian.



- Unstable equilibrium has cylindrical symmetry
- Ground state (fallen pen) "has chosen" a direction. The cylindrical symmetry has been broken.

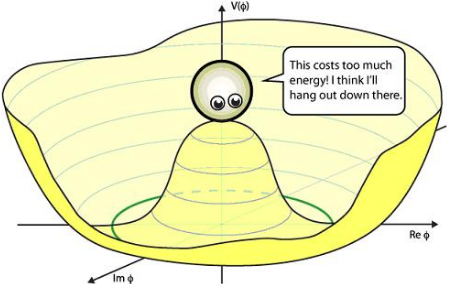
SSB in field theory

SSB is created by imposing a "mexican hat" potential on a field.

$$V(\phi) = \frac{1}{2}\mu^2\phi^*\phi + \frac{1}{4}\lambda(\phi^*\phi)^2 \tag{7}$$

with $\lambda > 0$ and $\mu^2 < 0$.

- Potential has rotational symmetry
- Ground state $|\Phi| = \sqrt{-\frac{\mu^2}{2\lambda^2}} = \frac{v}{\sqrt{2}}$ breaks symmetry.
- Describe a massless and a massive ($m^2 = v^2\lambda$) bosons.



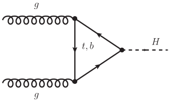
The Standard Model

The SM is composed of :

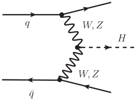
- Local gauge symmetries
  - $SU(3)_c$ for strong interaction. 8 gluons couple to quarks.
  - $SU(2)_L \times U(1)_Y$ for electroweak sector. Bosons $W^\pm$, Z and photon couple to quarks and leptons.
- SSB of $SU(2)_L$ by introduction of scalar field Φ
  - $(D_\mu\Phi)^\dagger(D^\mu\Phi)$ gives mass to $W^\pm$ and Z.
  - A physical and massive degree of freedom : the (Brout-Englert)-Higgs boson H.
  - Yukawa coupling gives mass to fermions.

Higgs boson production

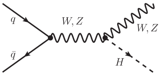
H boson predictions are function of its mass.



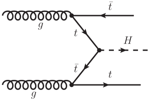
(a) Gluon fusion (ggH)



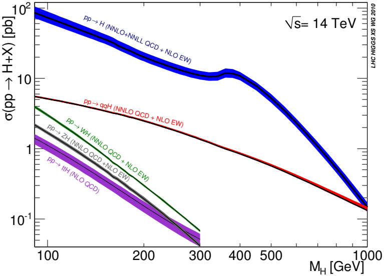
(b) Weak vector boson fusion (VBF)



(c) Higgsstrahung



(d) Associated production with $t\bar{t}$ pair (ttH)

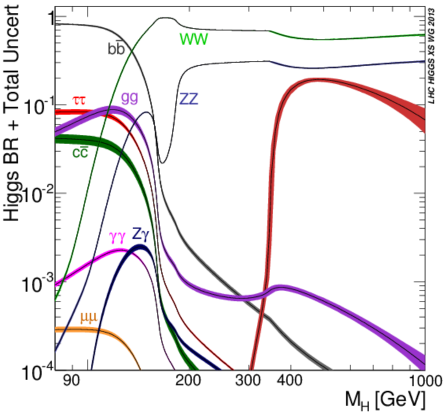


4 dominant production modes

- Gluon fusion ($ggH \simeq 86\%$) probes coupling to gluons through loop.
- Vector Boson Fusion probes direct coupling to electroweak bosons.
- Higgsstrahlung also probes $W\pm$ and Z couplings.
- Associated top production probes couplings to heaviest quark.

Higgs boson decays

A Higgs boson with a mass around 125 GeV opens a wide range of decay channels.



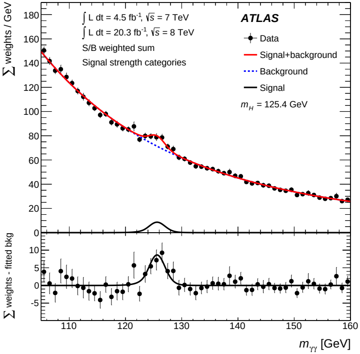
- $H \to bb$ (57 %) probes couplings to b quark. Difficult due to large hadronic background.
- $H \to \tau\tau$ probes couplings to heaviest lepton.
- $H \to VV$ $(V = W, Z)$ probes H boson couplings to EW bosons. Clean signature in leptonic decays of V but low statistics.
- $H \to \gamma\gamma$ probes H boson couplings to photon through loop. Large but smooth background.

H boson Status

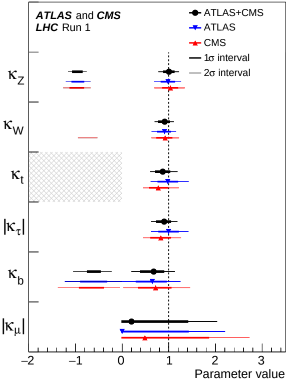
Run 1 of the LHC (2011/2012) allowed the observation of a Higgs like particles and its properties have been measured combining ATLAS+CMS.

mass measurement
PhysRevLett.114.191803

$m_H =$
$125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ GeV



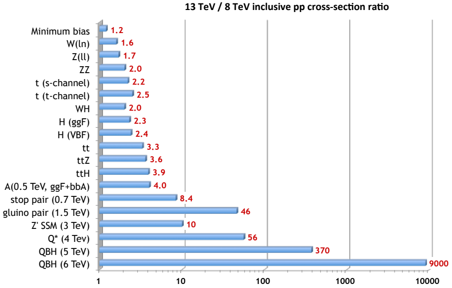
couplings $\kappa_i = \frac{\sigma_i^{exp}}{\sigma_i^{SM}}$
CERN-EP-2016-100



The measured properties are in agreement with the SM H boson.

Run 2 objectives

- LHC energy and luminosity increase
  $\rightarrow$ **30 times more Higgses are expected**
- With reduced statistical uncertainties
  $\rightarrow$ **need to reduce systematic uncertainties**
- Theory uncertainty reduced with ggH N^{3}LO calculation
- Resolution uncertainty dominant at run 1 for couplings
  $\rightarrow$ **Need to improve calibration resolution uncertainty**

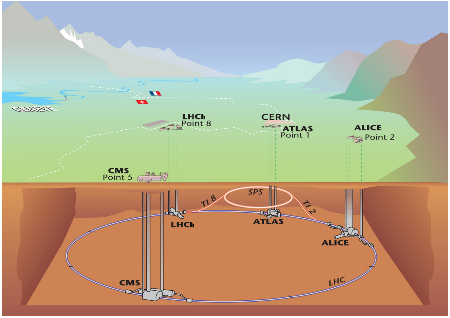


Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

The Large Hadron Collider

The LHC aims at accelerating and colliding protons. Analysing debris of collisions allows to probe SM and/or beyond.

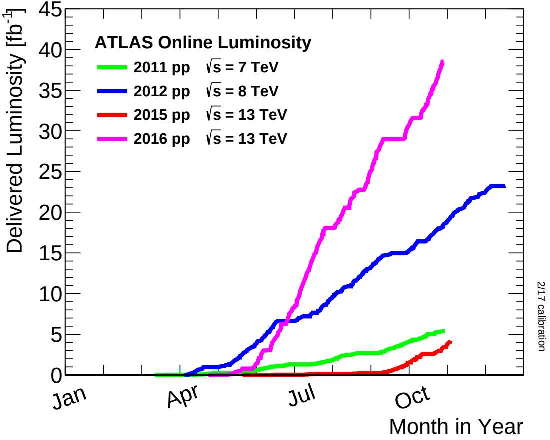
- located at Geneva.
- 27 km long.
- 100 m underground
- collision every 25 ns.
- $\sqrt{s} = 13$ TeV
- 4 collision points equipped with detectors : ALICE, ATLAS, CMS and LHCb.



LHC data taking condition

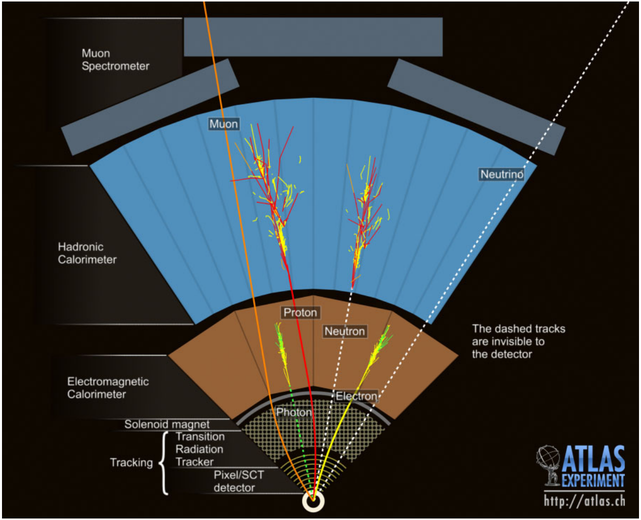
The collision conditions at LHC have significantly changed since its contruction.

- Major increase of integrated luminosity per year.
- Large increase in colliisions per bunch crossing.

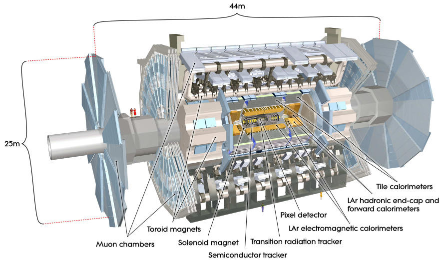


General purpose apparatus

A general purpose particle detector (ATLAS and CMS) is designed as layers with specific measurement goal.



ATLAS experiment



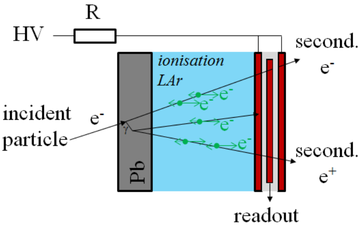
Performance goals of the ATLAS detector

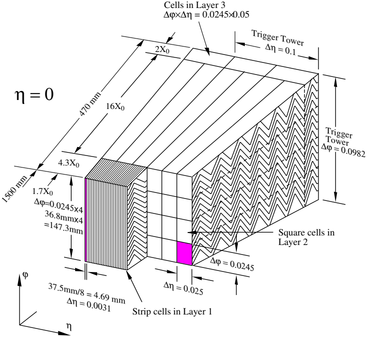
Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

- **Large acceptance**
- **Radiation hard**

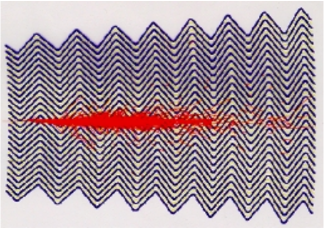
- **Silicon and TRT tracker in 2T magnetic field**
  Measure position and momentum of charged particles
- **Liquid argon electromagnetic calorimeter (LAr)**
  Measure energy of electrons and photons.
- **Scintillating tiles hadronic calorimeter**
  Measure energy of jets
- **Muon chambers**

Electromagnetic calorimeter (LAr)





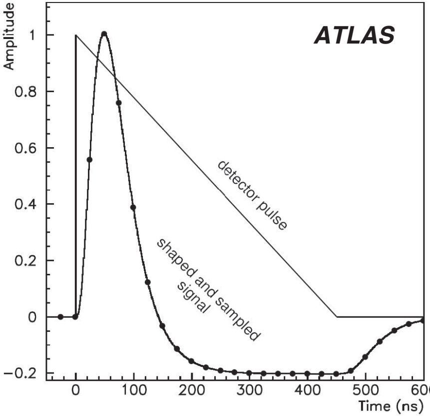
- 1.4m $< r <$ 2m
- Sampling calorimeter :
  - absorber : lead
  - active material : **Liquid Argon** (88K)
- **Accordion geometry** gives uniformity and hermeticity along ϕ.
- **Longitudinally segmented** for pion discrimination



Data recording

- Particle passing through LAr $\rightarrow$ electric signal in electrode.
- Need to collect signal information with limited data size

- Bi-polar filter removes pile-up
- 4 samples (1 per 25ns)
- $A = \sum_{j=1}^{N_{sample}} a_j(s_j - p)$
- $E = F_{\mu\mathrm{A}\rightarrow\mathrm{MeV}}$ $\times F_{\mathrm{DAC}\rightarrow\mu\mathrm{A}}$ $\times \frac{1}{\frac{M_{\mathrm{phys}}}{M_{\mathrm{cali}}}}$ $\times G \times A$



EM object reconstruction

Need to transform the signal in a set of cells into a particle object.

Cluster reconstruction

- Sliding window algorithm
- Search deposit > 2.5 GeV in 3×5 L2 cells towers.
- Energy cluster defined as 3×7.

Track reconstructio

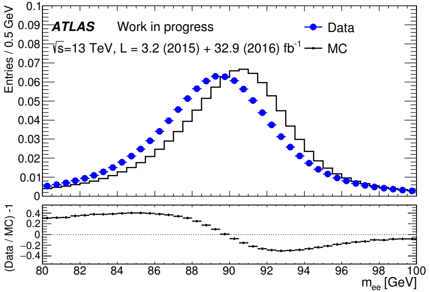
- Search 3 compatible points in Si and propagate track to TRT
- Search 3 compatible points in TRT and propagate track to Si
- Identify conversion vertices

If a track match a cluster $\rightarrow$ electron else if conversion tracks match clusters $\rightarrow$ converted photon else $\rightarrow$ unconverted photon.

EM objects calibration

Energy scale factors

After MVA calibration, mass distribution of $Z \to ee$ for data and MC still have
discrepancy.
A data-driven analysis is performed to match data to MC distribution
(relative matching).



A correction, applied to both electrons of Z decay, is computed to shift the central value of data distribution :

energy scale factor (α)

$$E^{corr} = E^{meas}(1+\alpha)$$

Resolution constant term

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- a : sampling term (10%). Linked to the fluctuations of electromagnetic showers.
  Can be simulated.
- b/E : noise term ($350 cosh(\eta)$ MeV). Measured in dedicated runs.
- **c : constant term (0.7%)**. Must be measured on data.

We observe that data distribution is larger than MC. An **additional constant term (C)** is measure to enlarge MC up to the data width. Both MC electrons undergo the correction :

Resolution constant term (C)

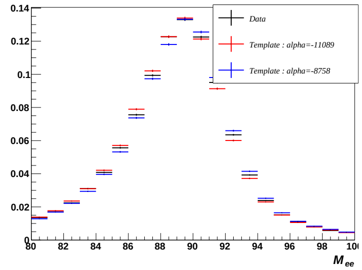
$$E^{corr} = E^{meas}(1 + N(0,1) * C)$$

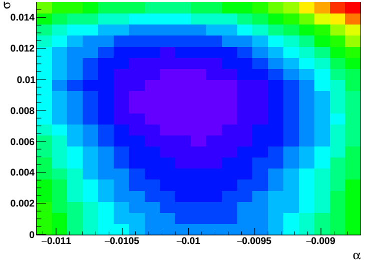
$N(0,1)$: a Gaussian distributed random number

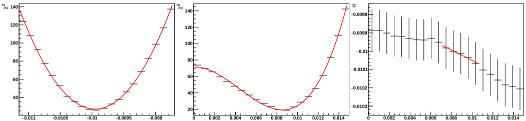
Template method

The template method is used to measure α and C simultaneously.

- Create distorded MC (templates) with test values of α and C.
- **Compute χ^2 between Z mass distribution of data and template**.
- **Fit the minimum of the χ^2 distribution** in the (α, C) plane.
- Fit performed in 2 steps of 1D fits :
  - fit $\chi^2 = f(\alpha)$ at constant C (lines) $\rightarrow (\alpha_{min}, \chi^2_{min})$.
  - fit $\chi^2_{min} = f(C) \rightarrow (C, \Delta C)$
  - project C in $\alpha_{min} = f(C)$, corresponding bin gives $(\alpha, \Delta\alpha)$.

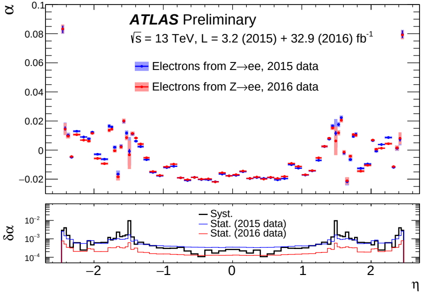


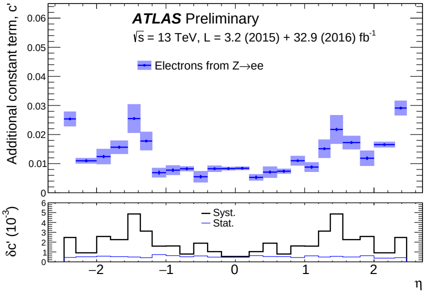




Run 2 results

Scales are measured with 13TeV data at 25ns





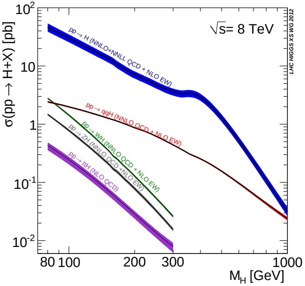
α **discrepancies are below** 0.1% out of the crack $(1.37 < |\eta| < 1.55)$.

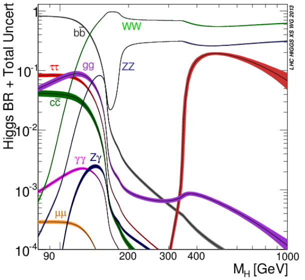
Uncertainties

Runs comparison

Higgs boson at the LHC

- Higgs boson predicted in 1964, discovered in 2012.
- Gives mass to weak boson, and fermions through Yukawa coupling.
- **Several production mode are available at the LHC.**
  - ggH : $gg \rightarrow H$
  - VBF : $qq \rightarrow Hjj$
  - VH : $Z(W) \rightarrow Z(W)H$
  - ttH : $t\bar{t} \rightarrow t\bar{t}H$
- At a mass of 125 GeV, many decay modes available :
  - $H \rightarrow b\bar{b}$: dominant decay mode ($\sim 57\%$) but high background in hadronic machines.
  - $H \rightarrow 4l$: low expected events, almost no background.
  - $H \rightarrow \gamma\gamma$: low branching ratio (0.28%) but clean signature. High but





Likelihood Method

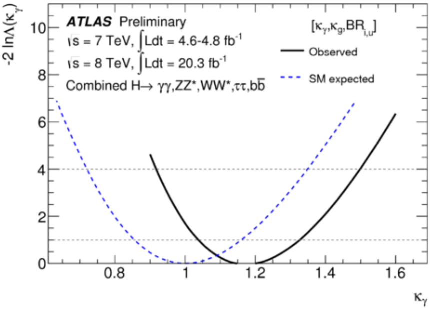
A function (**likelihood**) is built to **evaluate the best set of parameters ($\vec{\mu}$,$\vec{\theta}$)** of a model to agree the best with a dataset in a category.

$$\mathcal{L} = \underbrace{\frac{(n_s(\vec{\mu},\vec{\theta}) + b)^{n_{obs}}}{n_{obs}!} e^{-(n_s(\vec{\mu},\vec{\theta})+b)}}_{(1)} \overbrace{\prod_j^{n_{obs}} \psi(\vec{x_j};\vec{\mu},\vec{\theta})}^{(2)} \underbrace{e^{-\frac{\theta^2}{2}}}_{(3)}$$

(1) **Poissonian law** to evaluate the probability to observe n_{obs}($\equiv$ signal + background) events when $(n_s + b)$ are expected.

(2) **Probability density function** of the observables $\vec{x}$ (diphoton invariant mass for example) for the j^{th} event.

(3) Constraint on the nuisance parameter θ. See next slide.



Nuisance parameters

There are some **external measurements** that contribute to the likelihood and have some **uncertainties**. A **free nuisance parameter** is added for each of these measurements. In order to take into account these external measurements, a **constraint is put on these nuisance parameters**.

For example, the luminosity is re-defined as $L(1 + \delta_L \theta_L)$, with θ_L the nuisance parameter and δ_L the uncertainty on the luminosity (assumed to be Gaussian). In this case, a Gaussian constraint is chosen.
The contribution from luminosity will hence be :

$$L(1 + \delta_L \theta_L) e^{-\theta_L^2/2}$$

Error Estimation

A test statistic is defined as : $t_\mu = -2ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})}$, with $\hat{\theta}$ and $\hat{\mu}$ the best (fitted) parameters, and $\hat{\hat{\theta}}$ the fitted nuisance parameters for a fixed μ.
Uncertainty are given by : $\mathbf{t_{\hat{\mu}\pm 1\sigma} = 1}$ and $\mathbf{t_{\hat{\mu}\pm 2\sigma} = 4}$ in 1D Gaussian limit.

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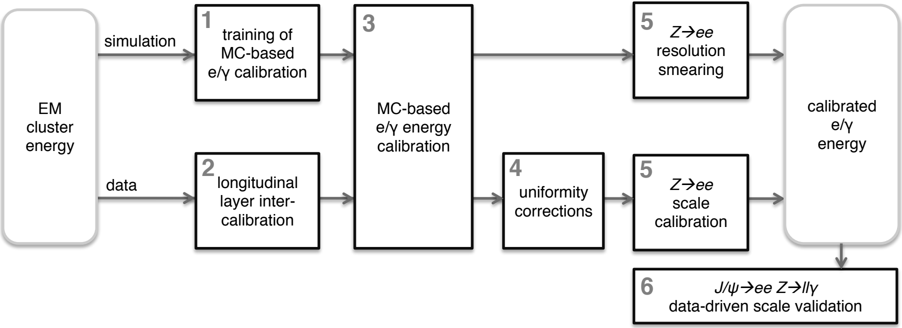
Full calibration

To reach the physics analyses, data and simulated reconstructed events must pass a calibration procedure. This procedures aim to correct the measured energy to **retrieve the true energy of the particle at the interaction point**.



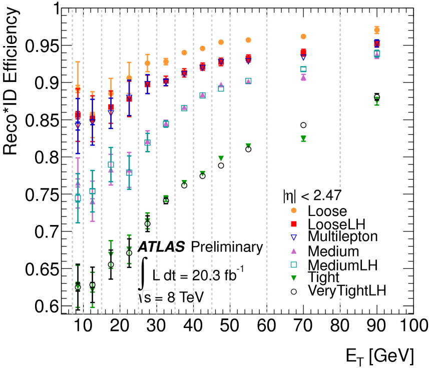
Electrons and photons follow the same steps but with dedicated analyses.

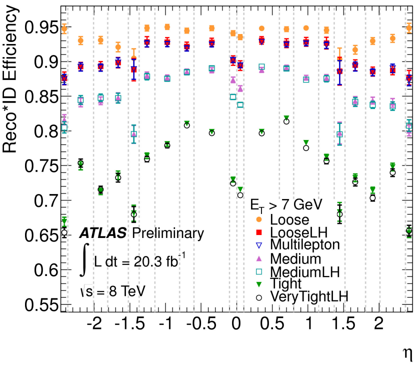
Identification variables

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	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, $\sqrt{(\Sigma E_i (i - i_{\text{max}})^2)/(\Sigma E_i)}$, 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 quality	Number of hits in the B-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	d_0
	Significance of transverse impact parameter defined as the ratio of d_0 and its uncertainty	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	Total number of hits in the TRT	n_{TRT}
	Ratio of the number of high-threshold hits to the total number of hits in the TRT	F_{HT}
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 extrapolated track	$\Delta\phi_2$
	Defined as $\Delta\phi_2$, but the track momentum is rescaled to the cluster energy before extrapolating the track to the middle layer of the calorimeter	$\Delta\phi_{\text{res}}$
	Ratio of the cluster energy to the track momentum	E/p
Conversions	Veto electron candidates matched to reconstructed photon conversions	isConv

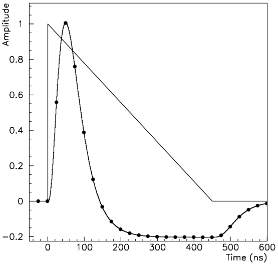
Reconstruction & Identification efficiencies

Not all electrons pass the reconstruction and identification criteria. **3 menus with increasing purity (but deceasing efficiencies) are defined : loose, medium, tight**. The efficiency of these procedures is given as a function of the p_T and $\eta = -ln(tan(\theta/2))$.





Energy measurement in LAr



- **Signal drift time** ($\sim$ 600ns) **too long** for collisions every 25ns (pile-up).
- Analog signal pass through an **bipolar filter** to reduce signal time. Shape optimize signal over pileup and electronic noise.
- ADC sampling every 25ns (4 points are kept).
- Energy computed using **calibration constants and optimal filtering of the samples**.

$$E_{cell} = \underbrace{\sum_{i=1}^{n_{samples}} a_i(s_i - ped)}_{ADC} \cdot G_{ADC\rightarrow DAC} \cdot \left(\frac{M_{phys}}{M_{calib}}\right)^{-1} \cdot F_{DAC\rightarrow\mu A} \cdot F_{\mu A\rightarrow MeV}$$

Reconstruction & Identification

Reconstruction links the energy deposit in detector cells to a **physical particle and its properties**.

- Divide the central part ($|\eta| = |ln(tan(\theta/2))| < 2.47$) into towers of size $\Delta\eta \times \Delta\phi = 0.25 \times 0.25$
- Sum energies from all cells and all layers of the tower
- Sliding window (3×5 towers) algorithm look for 2.5 GeV of transverse energy
- **Track matching and clustering** :
  - no track $\rightarrow$ photon $\rightarrow$ 3×7 cluster
  - track $\rightarrow$ electron $\rightarrow$ 3×7 cluster
  - conversion vertex $\rightarrow$ converted photon $\rightarrow$ 3×7 cluster

Identification is to separate prompt electrons from both jets and other electrons from either hadron decay or photon conversion.
A multivariate likelihood method using 23 variables
of energy deposit and tracking is used.

MVA calibration

- Simulated events are passed through a full GEANT4 simulation of the ATLAS detector.
- Events are then categorized in η and p_T bins, separately for electrons and photons.
- **A multivariate analysis (MVA) is performed to compute the true energy from detector observables**.

Plot shows most probable value (MVP) of E^{corr}/E^{true}.

MVA uses :

- Energies in all layers of the ECAL
- EM shower shape variables
- Barycenters of energy deposits