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

Christophe Goudet

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

PhD defense

Orsay, September 11, 2017

# Introduction

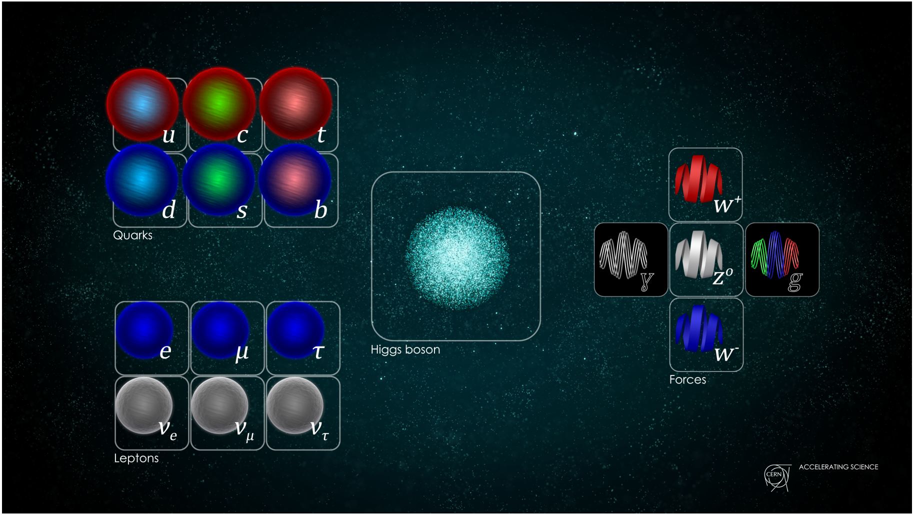
1. The Standard Model of matter

2. Experimental conditions and data processing

3. Measurement of Higgs boson couplings

# Particle content of matter

Over the XX$^{th}$ 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

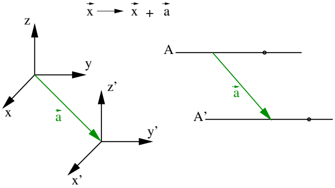
Symmetries are transformations which leave a system unchanged.
Imposing symmetries on a Lagrangian changes the theory it describes.

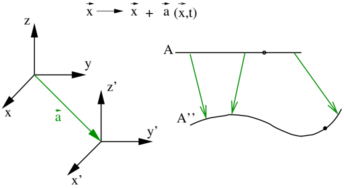
$$\psi(x) \to e^{i\alpha(x)}\psi(x) \tag{4}$$

Derivative affects $e^{i\alpha}$
$\to$ **Invariance achieved by adding a field $A_\mu$ and changing $L$.**

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

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



# Spontaneous symmetry breaking

# The Standard Model

list of properties plot de particle content

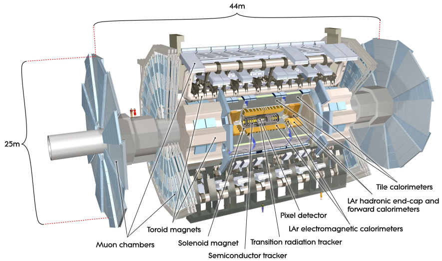
# Higgs measurement

# Run 2 objectives

# The LHC

# General purpose apparatus

# ATLAS experiment



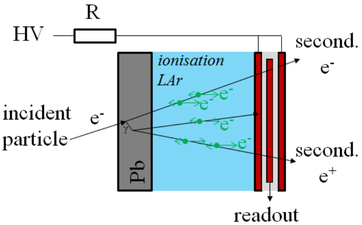

Performance goals of the ATLAS detector

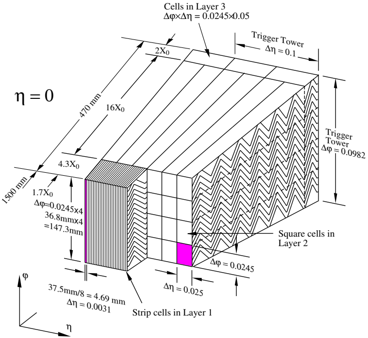
| Detector component | Required resolution | $\eta$ coverage | |
|---|---|---|---|
| | | Measurement | Trigger |
| Tracking | $\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$ | $\pm 2.5$ | |
| EM calorimetry | $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$ | $\pm 3.2$ | $\pm 2.5$ |
| Hadronic calorimetry (jets) | | | |
| barrel and end-cap | $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ | $\pm 3.2$ | $\pm 3.2$ |
| 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 | $\sigma_{p_T}/p_T$=10% at $p_T$ = 1 TeV | $\pm 2.7$ | $\pm 2.4$ |

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

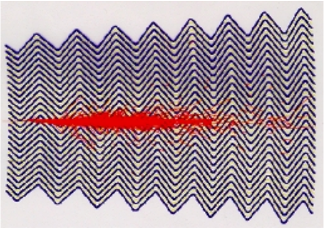
- **Silicon and TRT tracker in 2T magnetic field**
  Measure position and momentum of charged particles
- **Liquid argon electromagnetic calorimeter (LAr)**
  Measure energy of electrons and photons.
- **Scintillating tiles hadronic calorimeter**
  Measure energy of jets
- **Muon chambers**

# Electromagnetic calorimeter (LAr)




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



# Data recording

speak of OFC to transform electric signa to

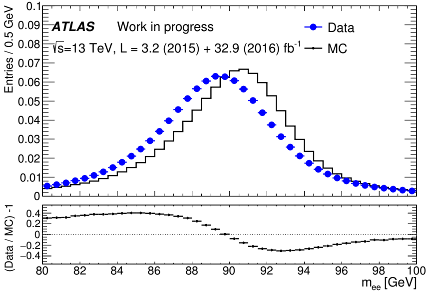
# EM object reconstruction

track reconstruction and EM clusters

# EM objects calibration

# Energy scale factors

After MVA calibration, mass distribution of $Z \rightarrow ee$ 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 ($\alpha$)**

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

# 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)**

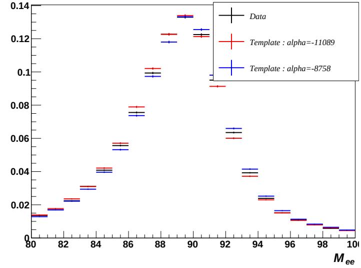
$$E^{corr} = E^{meas}(1 + N(0,1) * C)$$

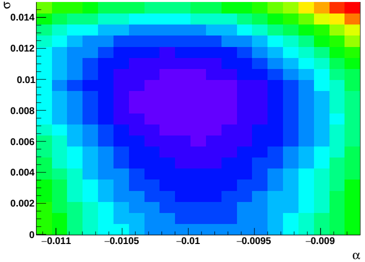
$N(0,1)$ : a Gaussian distributed random number

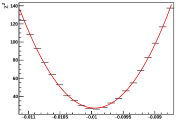
# Template method

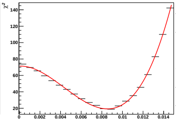
The template method is used to measure $\alpha$ and $C$ simultaneously.

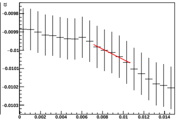
- Create distorded MC (templates) with test values of $\alpha$ and $C$.
- **Compute $\chi^2$ between Z mass distribution of data and template**.
- **Fit the minimum of the $\chi^2$ distribution** in the $(\alpha, C)$ plane.
- Fit performed in 2 steps of 1D fits :
  - fit $\chi^2 = f(\alpha)$ at constant $C$ (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 $(\alpha, \Delta\alpha)$.



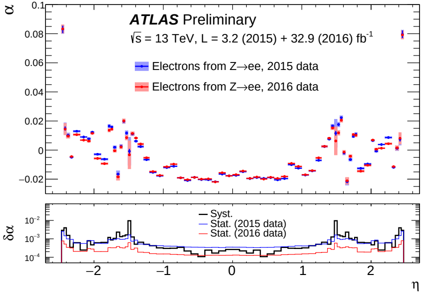



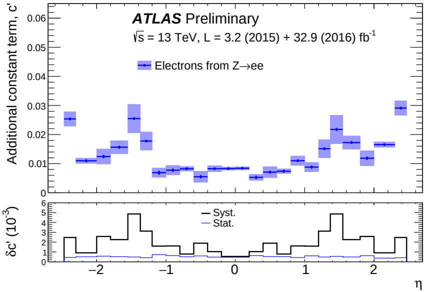



# Run 2 results

Scales are measured with 13TeV data at 25ns



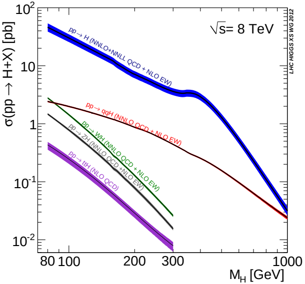

$\alpha$ **discrepancies are below** $0.1\%$ out of the crack $(1.37 < |\eta| < 1.55)$.

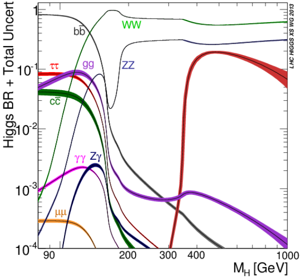
# Uncertainties

# 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

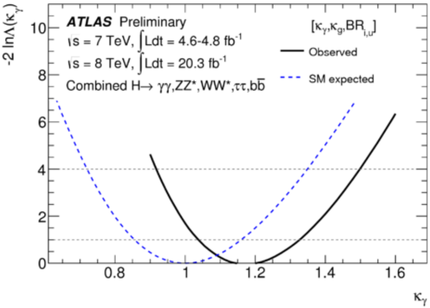
A function (**likelihood**) is built to **evaluate the best set of parameters ($\vec{\mu}$,$\vec{\theta}$)** of a model to agree the best with a dataset in a category.

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

(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 $\theta$. 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 $\theta_L$ the nuisance parameter and $\delta_L$ 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 $\mu$.
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.

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

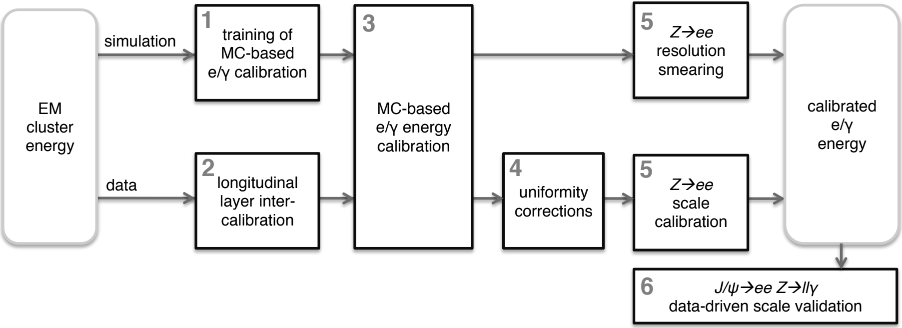
Christophe Goudet

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

PhD defense
Orsay, September 11, 2017

# 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**.



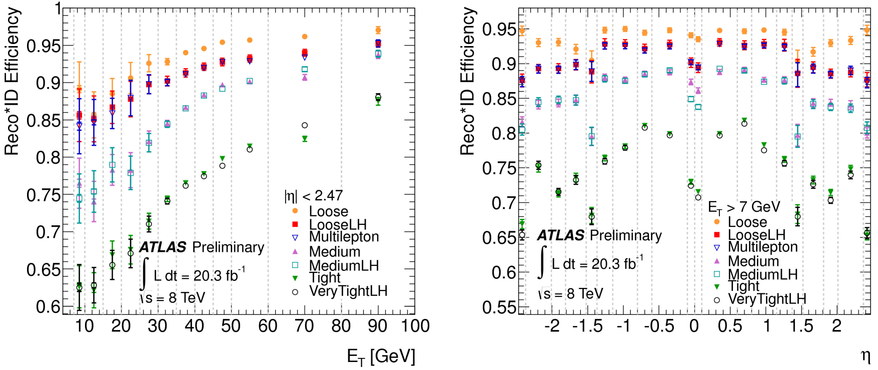

Electrons and photons follow the same steps but with dedicated analyses.

# Identification variables

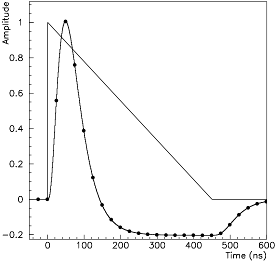
| Type | Description | Name |
|---|---|---|
| Hadronic leakage | Ratio of $E_T$ in the first layer of the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $\|\eta\| < 0.8$ or $\|\eta\| > 1.37$) | $R_{\mathrm{Had1}}$ |
| | Ratio of $E_T$ in the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$) | $R_{\mathrm{Had}}$ |
| 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 $\eta_i$ is the pseudorapidity of cell $i$ and the sum is calculated within a window of $3 \times 5$ 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 | $R_\phi$ |
| | Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position | $R_\eta$ |
| 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 $\eta$, and $i_{\mathrm{max}}$ is the index of the highest-energy strip | $w_{\mathrm{stot}}$ |
| | Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies | $E_{\mathrm{ratio}}$ |
| | 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) | $n_{\mathrm{Blayer}}$ |
| | Number of hits in the pixel detector | $n_{\mathrm{Pixel}}$ |
| | Number of total hits in the pixel and SCT detectors | $n_{\mathrm{Si}}$ |
| | Transverse impact parameter | $d_0$ |
| | Significance of transverse impact parameter defined as the ratio of $d_0$ and its uncertainty | $\sigma_{d_0}$ |
| | 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 | $n_{\mathrm{TRT}}$ |
| | Ratio of the number of high-threshold hits to the total number of hits in the TRT | $F_{\mathrm{HT}}$ |
| 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 | $\Delta\phi_{\mathrm{res}}$ |
| | 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**.

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

# 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 ($3 \times 5$ towers ) algorithm look for 2.5 GeV of transverse energy
- **Track matching and clustering** :
  - no track $\rightarrow$ photon $\rightarrow$ $3 \times 7$ cluster
  - track $\rightarrow$ electron $\rightarrow$ $3 \times 7$ cluster
  - conversion vertex $\rightarrow$ converted photon $\rightarrow$ $3 \times 7$ 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 $\eta$ 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