

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

Christophe Goudet



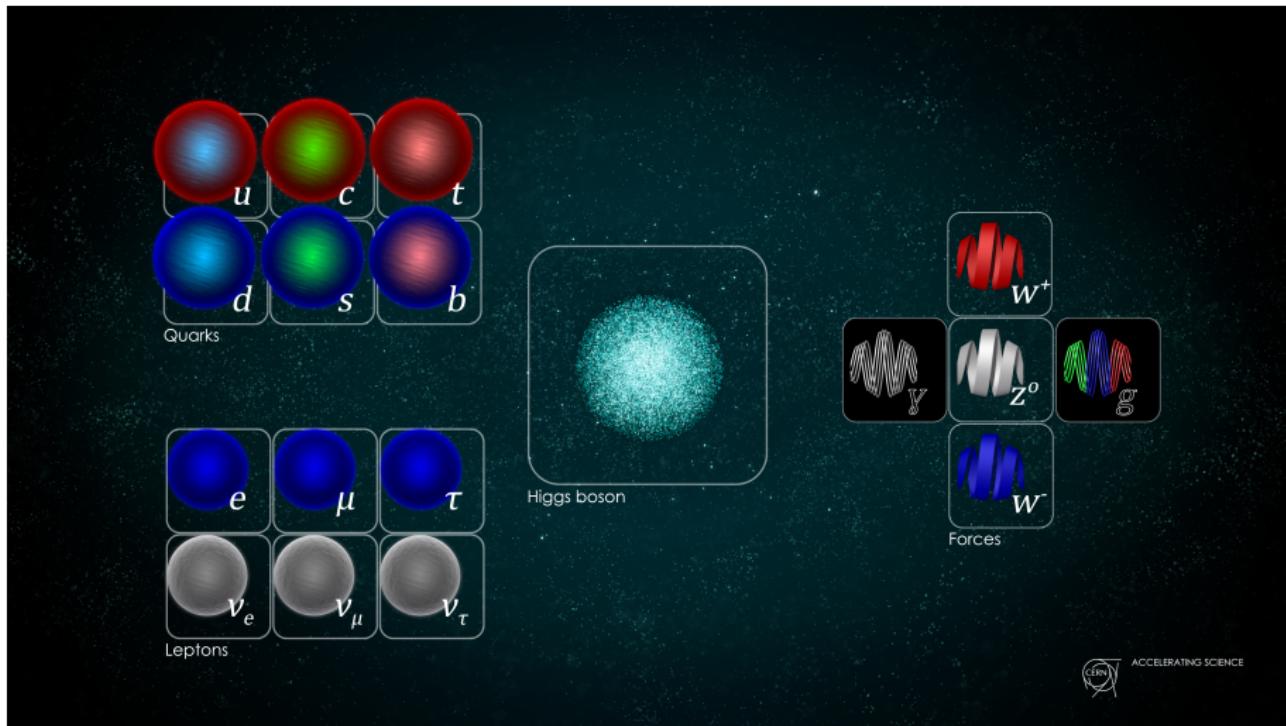
PhD defense
Orsay, September 12, 2017

Introduction

- 1 The Standard Model of matter
- 2 Experimental conditions and data processing
- 3 Calibration of electromagnetic objects
- 4 Measurement of Higgs boson couplings

Particle content of matter

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



ACCELERATING SCIENCE

A mathematical framework

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

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

The dirac lagrangian describes a massive fermion field :

$$L = \bar{\psi}(i\not{\partial} - m)\psi \quad (2)$$

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

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

Gauge invariance

Symmetries are transformations which leave a system unchanged.

Imposing symmetries on a Lagrangian changes the theory it describes.

$$\psi(x) \rightarrow e^{i\alpha(x)}\psi(x) \quad (4)$$

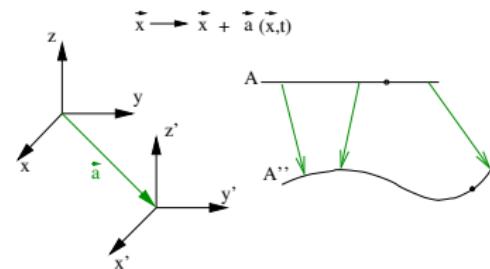
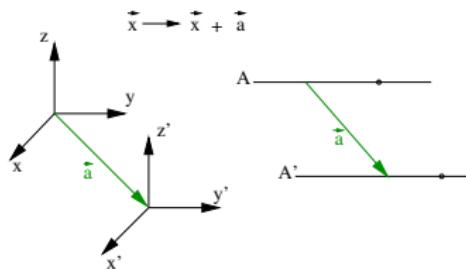
Derivative affects $e^{i\alpha}$

→ 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

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ieA_\mu(x) \quad (5)$$

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



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.

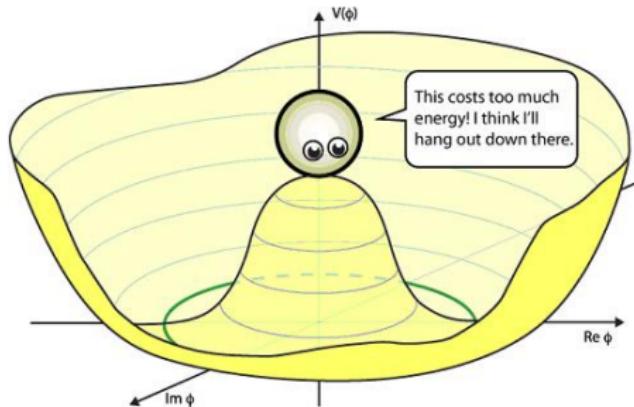
SSB in field theory

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

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

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.



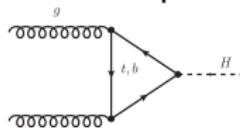
The Standard Model

The SM is composed :

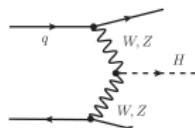
- Local gauge symmetries
 - ▶ $SU(3)_c$ for strong interaction. 8 gluons couple to quarks.
 - ▶ $SU(2)_L \times U(1)_Y$ for electroweak sector. Bosons W^\pm , Z and photon couple to quarks and leptons.
- SSB of $SU(2)_L$ by introduction of scalar field Φ
 - ▶ $(D_\mu \Phi)^\dagger (D^\mu \Phi)$ gives 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

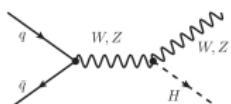
H boson predictions are function of its mass.



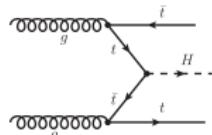
(a) Gluon fusion (ggH)



(b) Weak vector boson fusion (VBF)



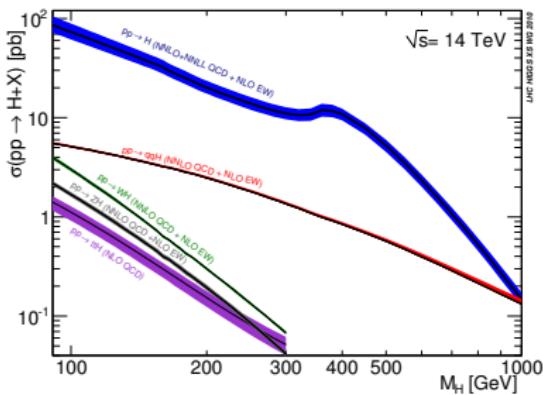
(c) Higgsstrahlung



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

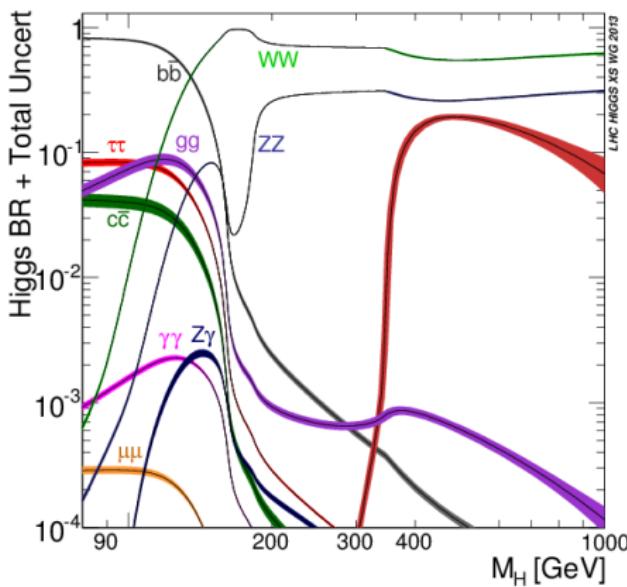
4 dominant production modes

- 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.



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

H boson Status

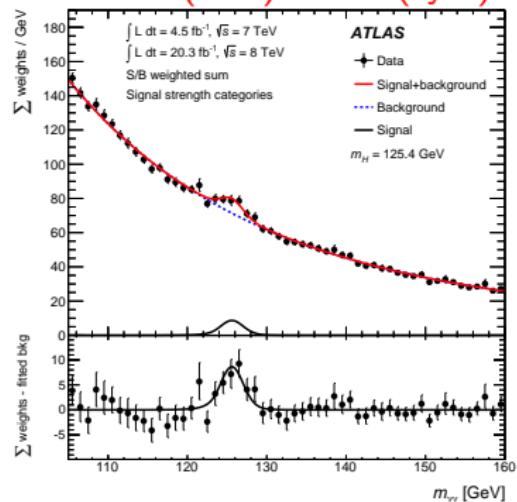
Run 1 of the LHC (2011/2012) allowed the observation of a Higgs like particles and its properties have been measured combining ATLAS+CMS.

mass measurement

PhysRevLett.114.191803

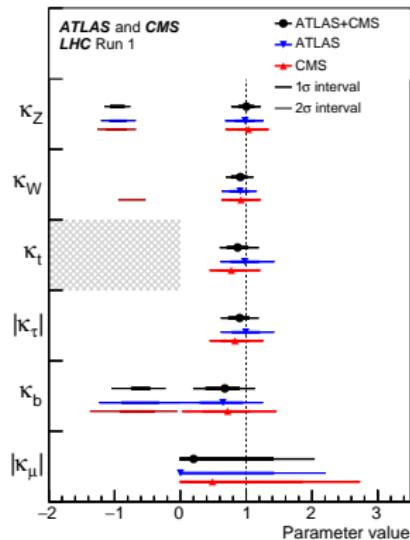
$$m_H =$$

$$125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}) \text{ GeV}$$



$$\text{couplings } \kappa_i = \frac{\sigma_i^{\text{exp}}}{\sigma_i^{\text{SM}}}$$

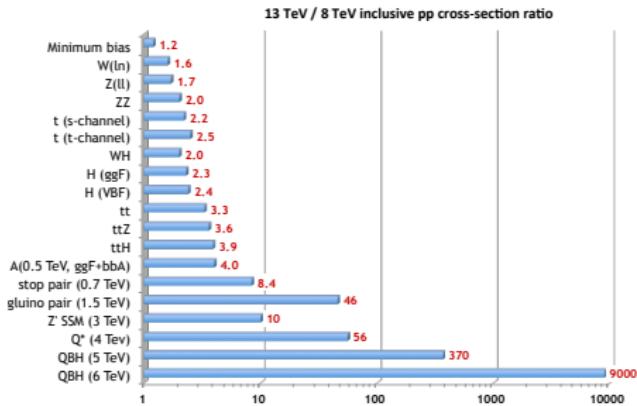
CERN-EP-2016-100



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

Run 2 objectives

- LHC energy and luminosity increase
→ **30 times more Higgses are expected**
- With reduced statistical uncertainties
→ **need to reduce systematic uncertainties**
- Theory uncertainty reduced with ggH N³LO calculation
- Resolution uncertainty dominant at run 1 for couplings
→ **Need to improve calibration resolution uncertainty**



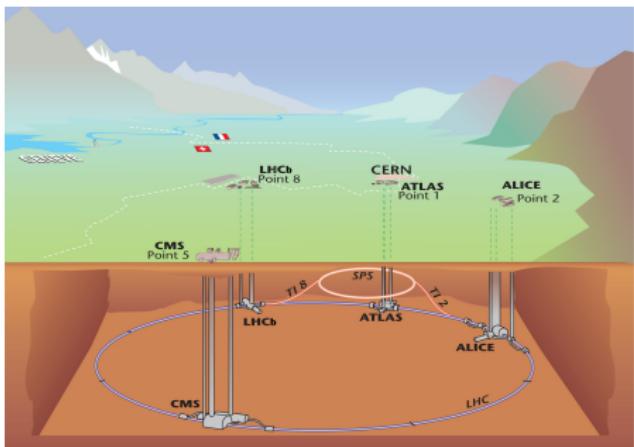
Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

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The Large Hadron Collider

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

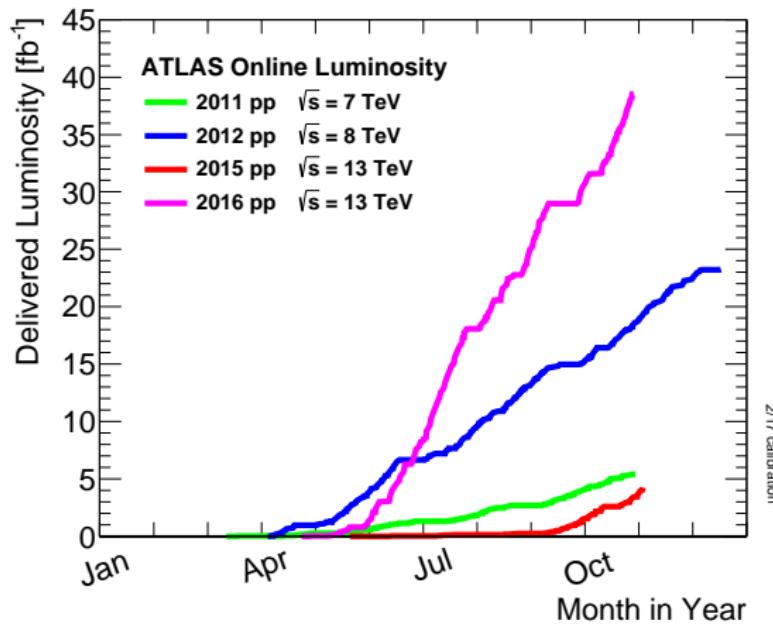
- located at Geneva.
- 27 km long.
- 100 m underground
- collision every 25 ns.
- $\sqrt{s} = 13 \text{ TeV}$
- 4 collision points equipped with detectors : ALICE, ATLAS, CMS and LHCb.



LHC data taking condition

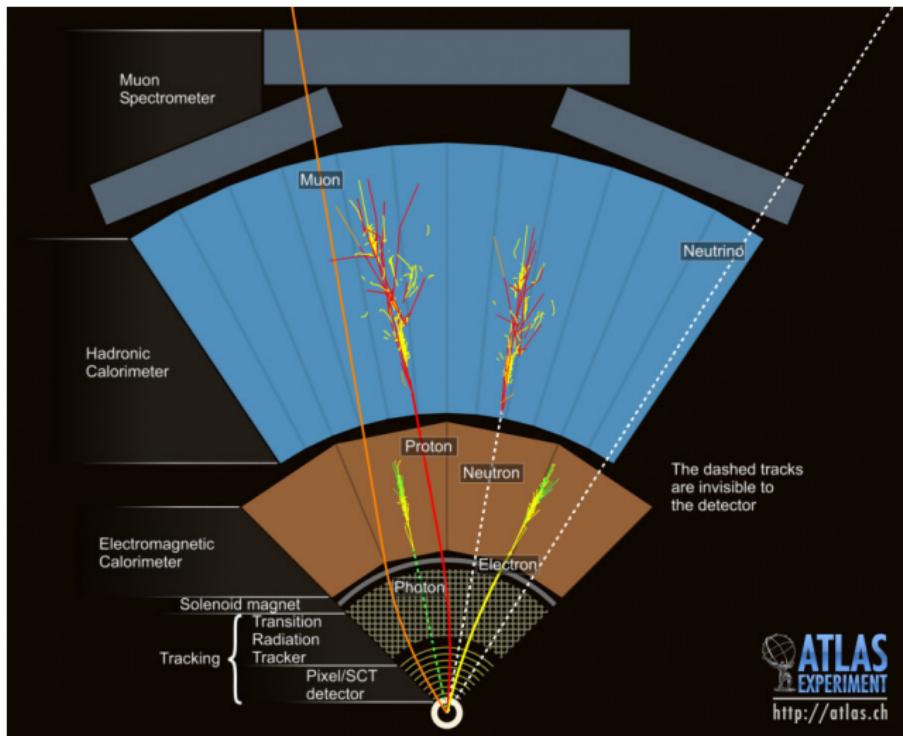
The collision conditions at LHC have significantly changed since its construction.

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

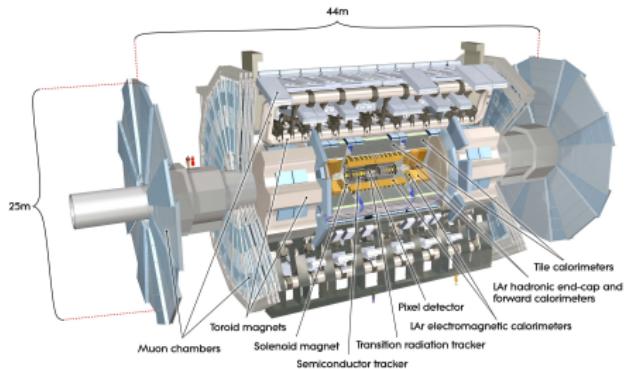


General purpose apparatus

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



ATLAS experiment

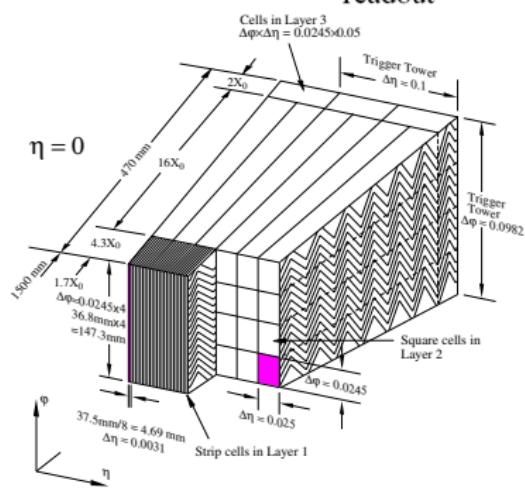
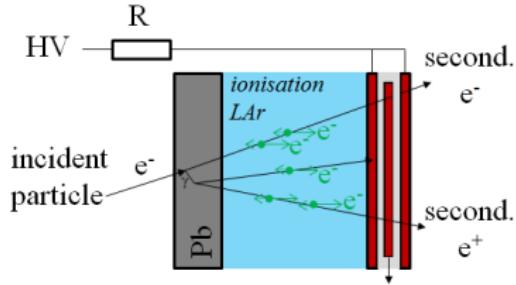


Performance goals of the ATLAS detector

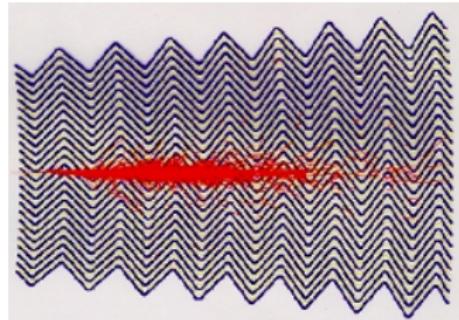
Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets) barrel and end-cap forward	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ $\sigma_E/E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

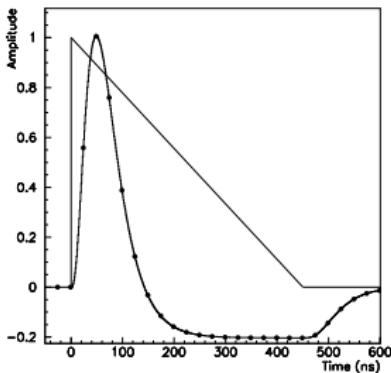
Electromagnetic calorimeter (LAr)



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



Energy measurement in LAr



- **Signal drift time** ($\sim 600\text{ns}$) **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 $\rightarrow 3 \times 7$ cluster
 - ▶ track \rightarrow electron $\rightarrow 3 \times 7$ cluster
 - ▶ conversion vertex \rightarrow converted photon $\rightarrow 3 \times 7$ cluster

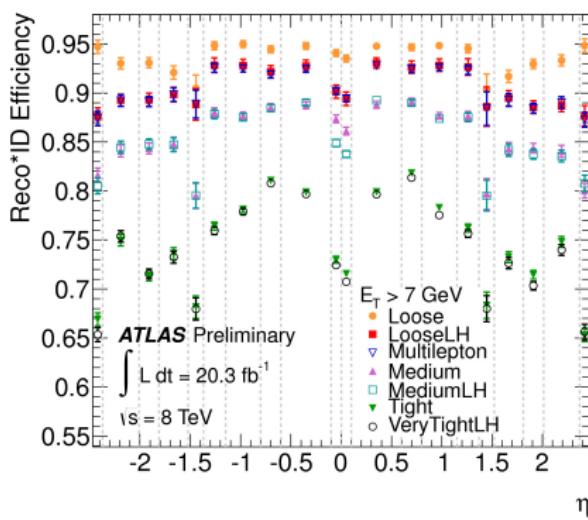
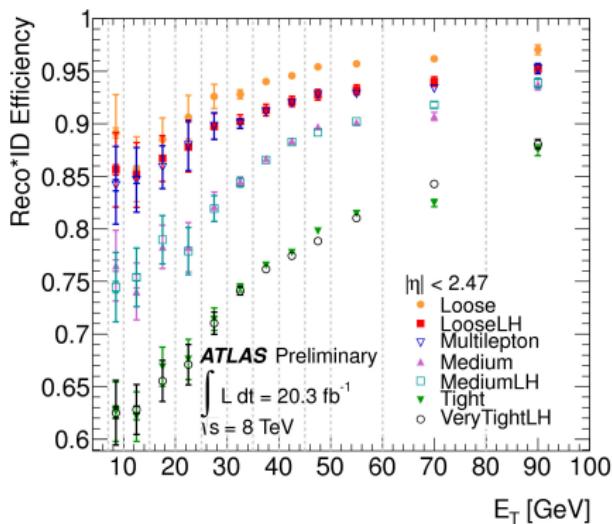
Identification is to separate prompt electrons from both jets and other electrons from either hadron decay or photon conversion.

A multivariate likelihood method using 23 variables
of energy deposit and tracking is used.

Reconstruction & Identification efficiencies

Not all electrons pass the reconstruction and identification criteria.

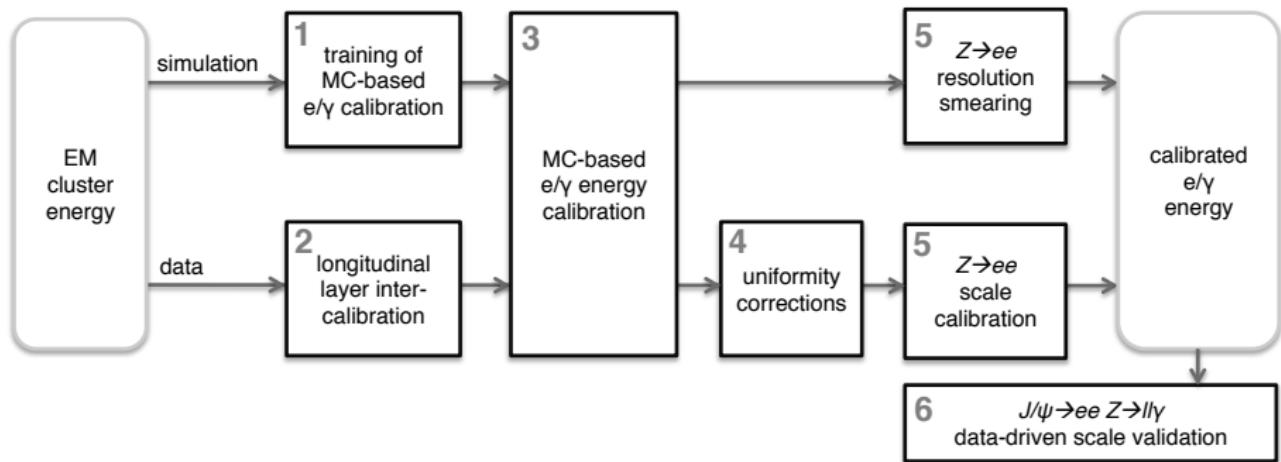
3 menus with increasing purity (but deceasing efficiencies) are defined : loose, medium, tight. The efficiency of these procedures is given as a function of the p_T and $\eta = -\ln(\tan(\theta/2))$.



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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.

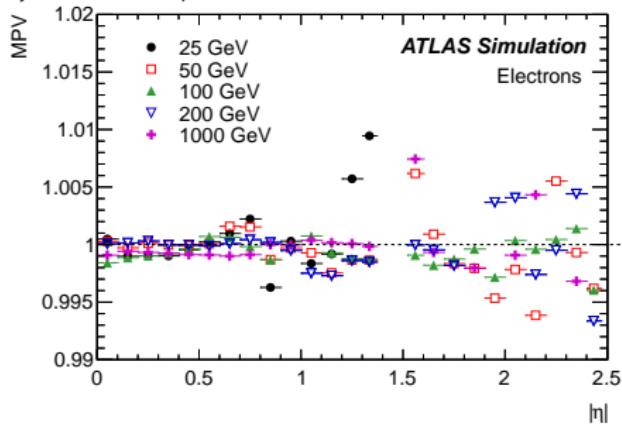
MVA calibration

- 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



Energy scale factors

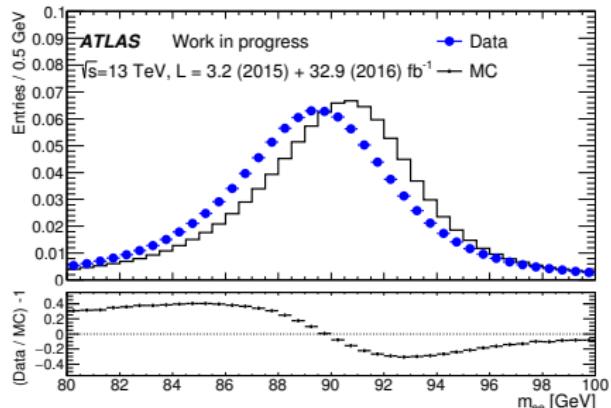
After MVA calibration, mass distribution of $Z \rightarrow ee$ for data and MC still have discrepancy.

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 (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)

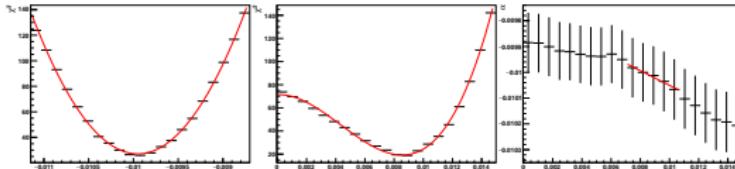
$$E^{corr} = E^{meas}(1 + N(0, 1) * C)$$

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

Template method

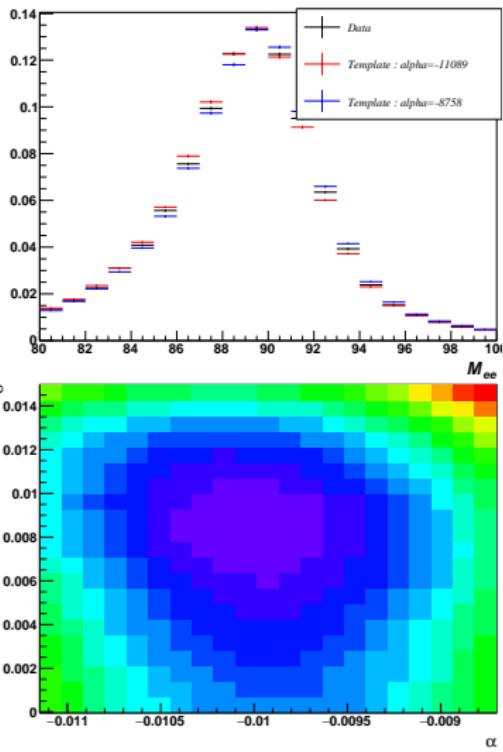
The template method is used to measure α and C simultaneously.

- Create distorted 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 $(\alpha, \Delta\alpha)$.



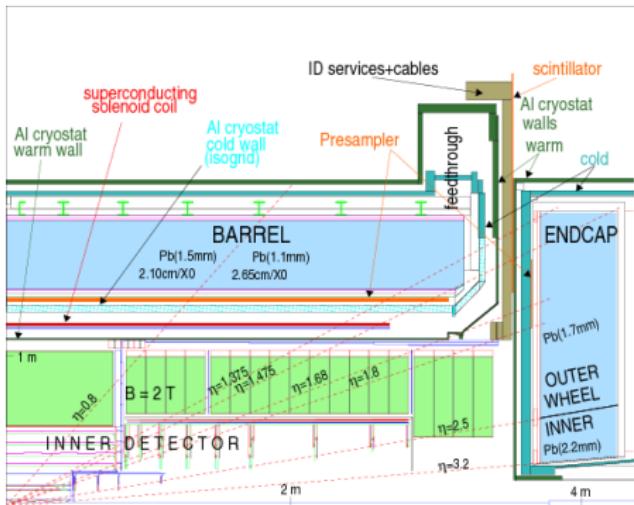
Goudet (LAL)

Energy calibration & Higgs couplings



Orsay, September 12, 2017

Detector splitting



- Detector is not uniform along η .
- To improve resolution, **calibration is performed in bin of η_{calo} .**
- 68 and 24 bins are used respectively for α and C .

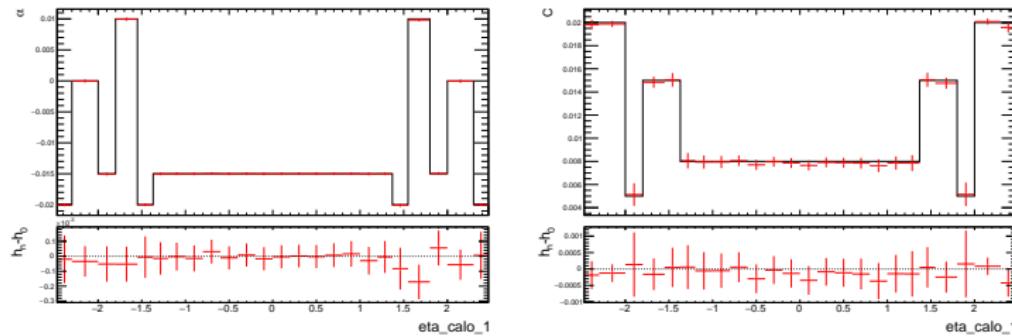
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.285
1.37 1.42 1.47 1.51 1.55 1.59 1.63 1.6775 1.725
1.7625 1.8 1.9 2 2.05 2.1 2.2 2.3 2.35 2.4 2.435 2.47

Electrons are labelled by their η bin, hence Z are labeled by the combination of electrons bins. **Scales are computed for each combination.**

Inversion Procedure

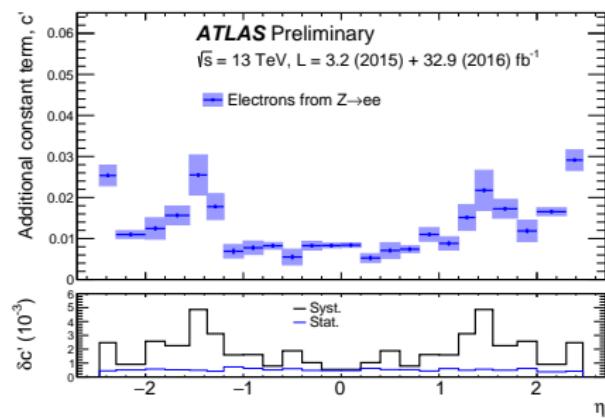
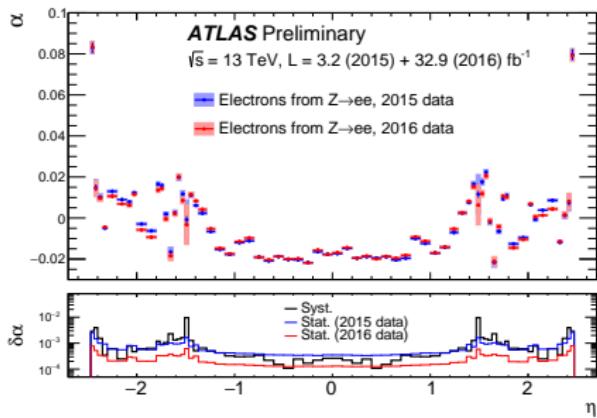
Obtaining **electron scales from Z scales** need the minimizations of the following χ^2 's

$$\chi^2 = \sum_{i,j \leq i} \frac{(\alpha_i + \alpha_j - 2\alpha_{ij})^2}{(\Delta\alpha_{ij})^2}$$
$$\chi^2 = \sum_{i,j \leq i} \frac{(\sqrt{\frac{c_i^2 + c_j^2}{2}} - c_{ij})^2}{\Delta^2 c_{ij}} \quad (8)$$



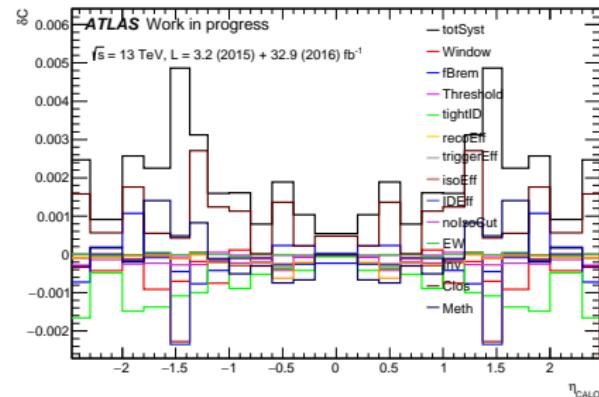
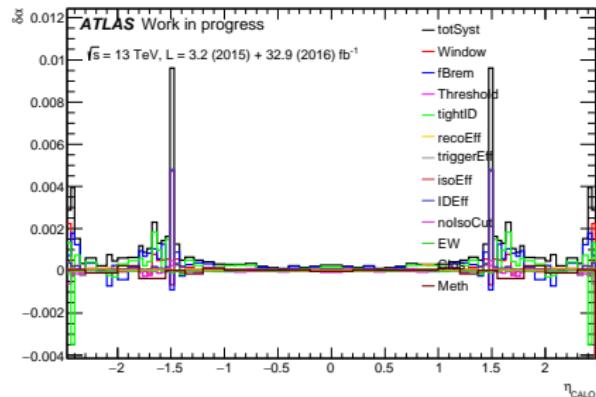
Run 2 results

- α measured independently for each year.
- c measured on combined data.



Uncertainties

12 (13) sources of uncertainties have been evaluated for $\alpha (c)$.

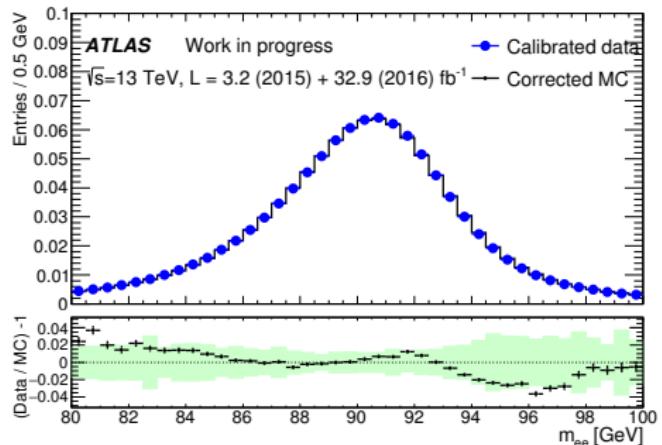
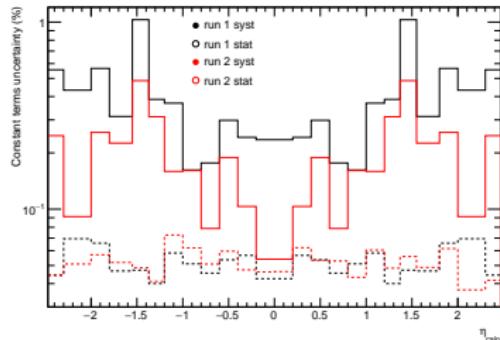
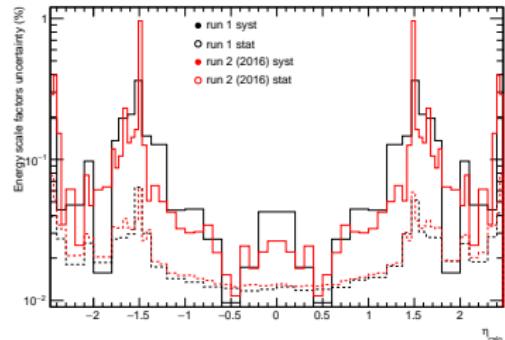


Main sources

- Diff. btw tight and medium electrons
- Closure
- Bremsstrahlung impact on electron momentum

Runs comparison

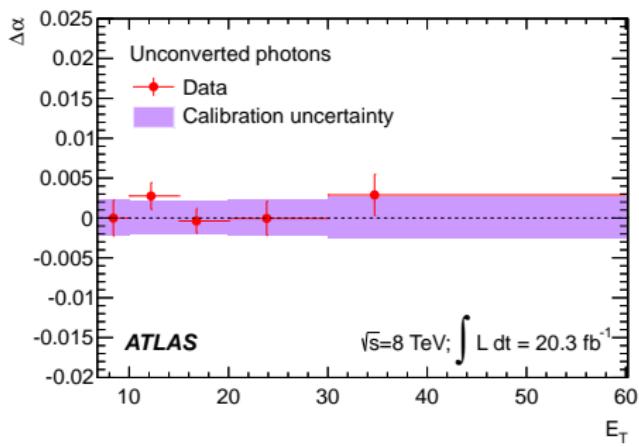
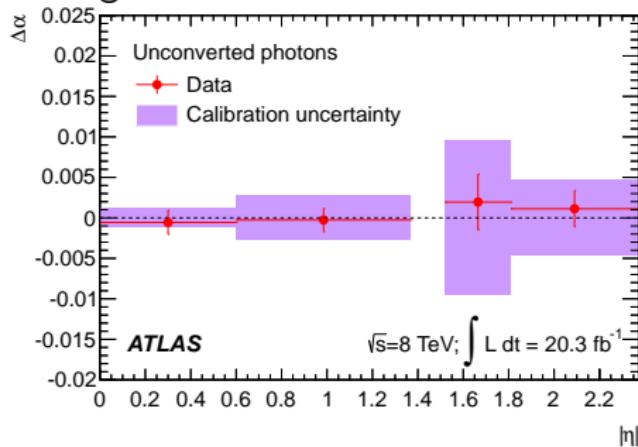
Performances of run 2 in-situ calibration surpass run 1 results.



Photon correction

Electrons scale factors are also applied to photons. A residual scale factor ($\Delta\alpha$) is measured from $Z \rightarrow ll\gamma$.

No significant deviation observed.

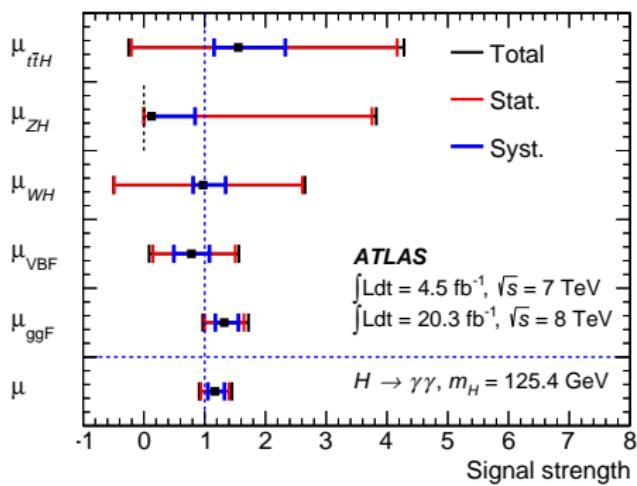


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$\mu_{\gamma\gamma}$ measurement

$\mu_{\gamma\gamma}$ is a main variable to measure. It is related to the cross section (production probability) :

$$\mu_{\gamma\gamma} = \frac{(\sigma \times BR)^{\text{meas}}}{(\sigma \times BR)^{\text{SM}}} = 1.17 \pm 0.23(\text{stat}) \begin{array}{l} +0.10 \\ -0.08 \end{array} (\text{syst}) \begin{array}{l} +0.12 \\ -0.08 \end{array} (\text{theory})$$



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

If no improvements, **calibration uncertainty will be dominant in run 2.**

Likelihood Method

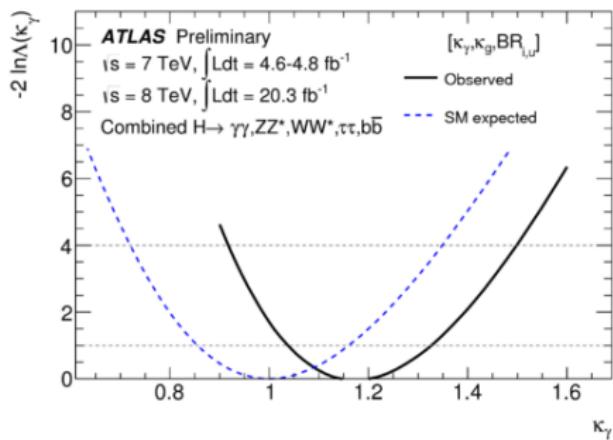
A function (**likelihood**) is built to **evaluate the best set of parameters** $(\vec{\mu}, \vec{\theta})$ of a model to agree the best with a dataset in a category.

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

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

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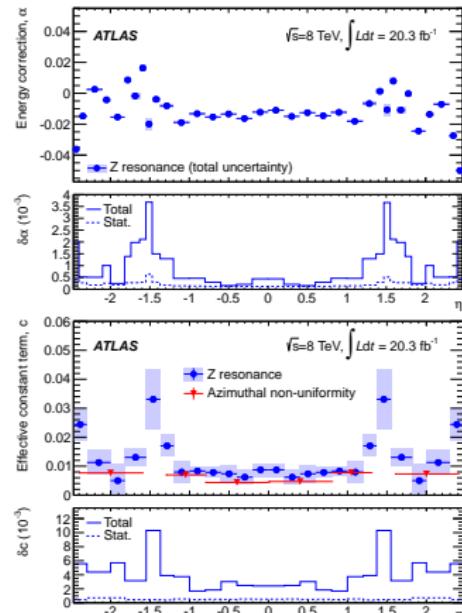
Identification variables

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_{Had}
	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_{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, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, 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_{η^2}
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_θ
	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, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, 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_{stat}
	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_{TRT}
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	<code>isConv</code>

Calibration in-situ : run 1 results and uncertainties

Uncertainties are evaluated as the difference between official scales and the ones measured with a changed parameter. They include :

- electron identification quality from medium to tight.
- Z mass window
- electron p_T cut
- uncertainties on efficiencies scale factors
- energy loss through bremsstrahlung
- background
- pile-up
- measurement method

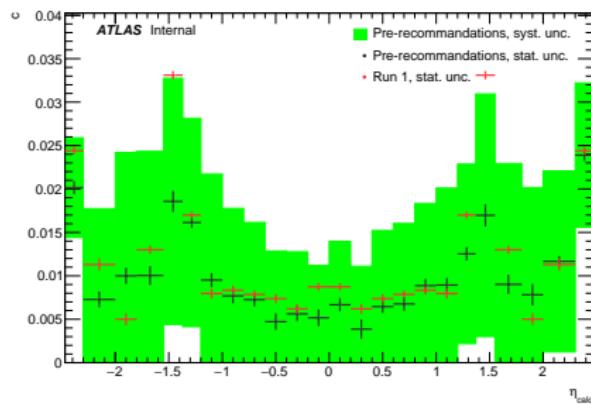
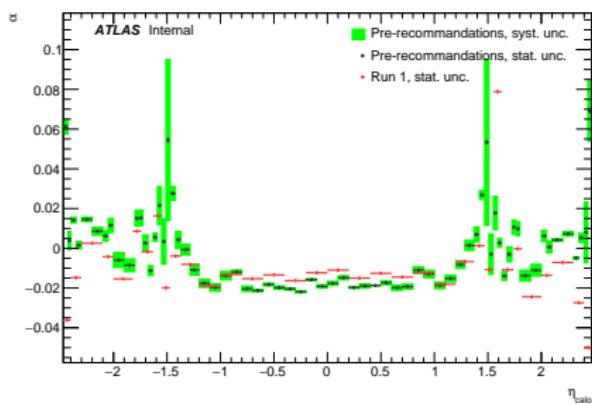


Run 2 prerecommandations

Run 2 early analyses need scales factors for 13TeV but not enough data will be available. Need to **estimate run 2 scales from run 1 data**.

Pre-recommandations are computed using 8 TeV data reprocessed with :

- new detector geometry
- new reconstruction algorithm
- new calibration machine learning

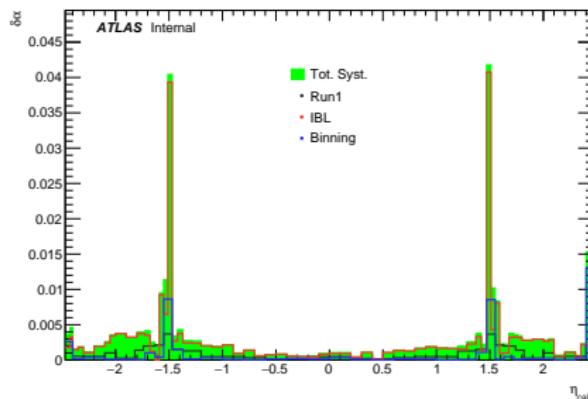


Calibration in-situ : run 2 pre-recommendations systematics

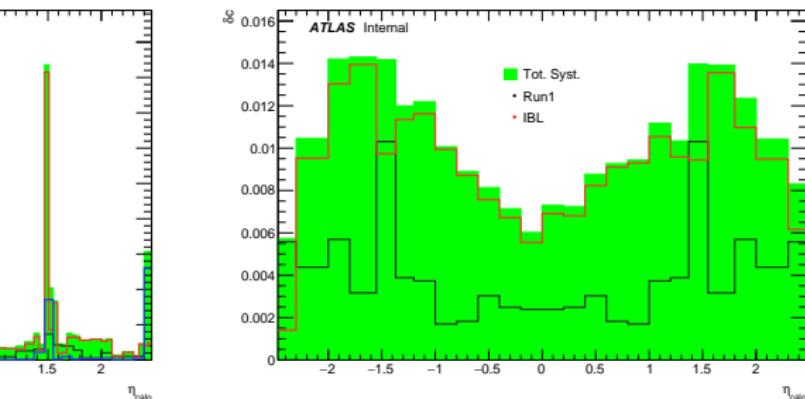
2012 systematics are used for the pre-recommendations.

Two more systematics are added in quadrature :

- Increasing the number of bin for α shows sub-patterns. Systematic is defined as difference between a bin value and the average of its sub-bins.
- Pre-recommendations being computed with 8TeV datasets, one needs to evaluate the impact of the center of mass energy. Systematic is defined as the scale measured from 13 TeV MC on 8 TeV templates.



Goudet (LAL)

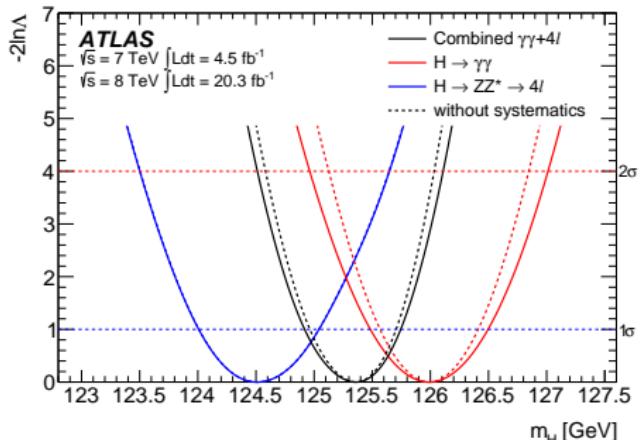


Energy calibration & Higgs couplings

Orsay, September 12, 2017

ATLAS run 1 H boson mass measurement

$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})$$



Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($ \eta < 1.1$)	50
$H \rightarrow \gamma\gamma$ background model (unconv rest low p_T)	40
$Z \rightarrow ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

Statistical uncertainties highly dominant.

Run 2 will increase sensitivity to systematics.