Energy calibration and Higgs couplings measurement in the diphoton channel with the ATLAS detector

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Pheniics Days
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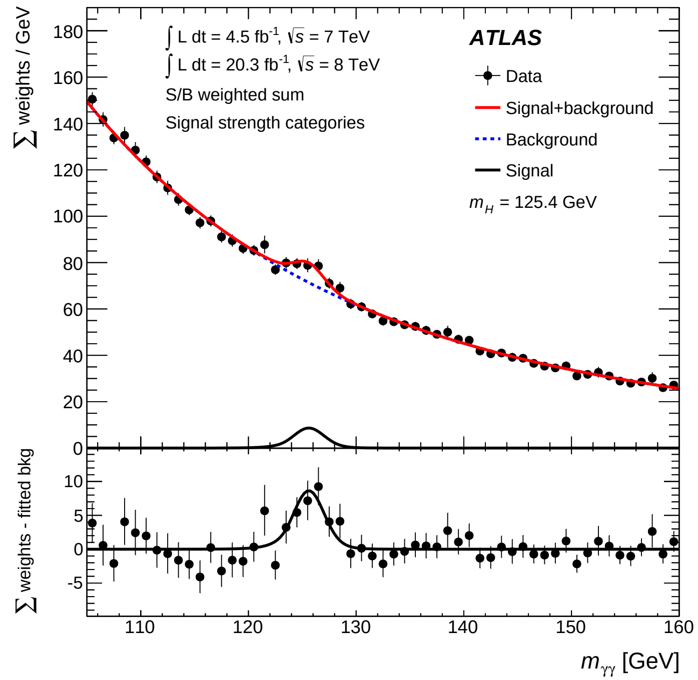
Introduction

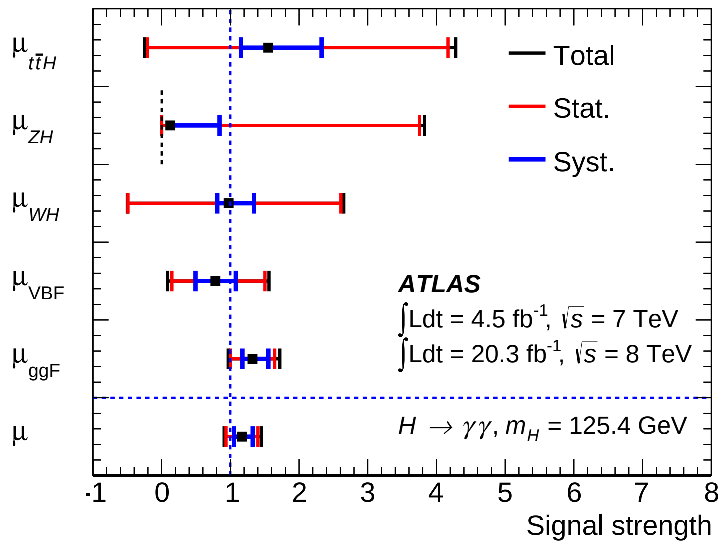
- **Higgs precision measurement led by electrons and photons** (and muons) .

  $$m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})\ \text{GeV}$$
  (ATLAS+CMS) PhysRevLett.114.191803
- Run 2 ongoing at an increased center of mass energy of 13 TeV. **30 times more Higgses are expected**
- Higgs couplings may bring hints of new physics :

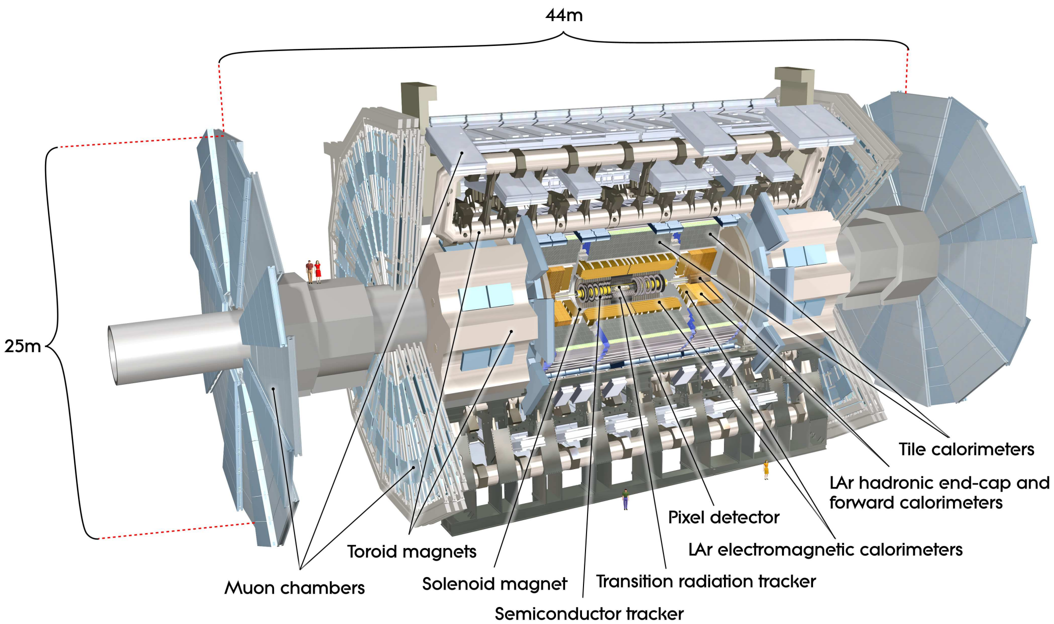
$$\mu = \frac{\sigma^{meas}}{\sigma^{SM}}$$

- With reduced statistical uncertainties $\rightarrow$ **need to reduce systematic uncertainties**.
- Calibration is a important source of systematic. Needs to be improved in Run 2.





ATLAS experiment



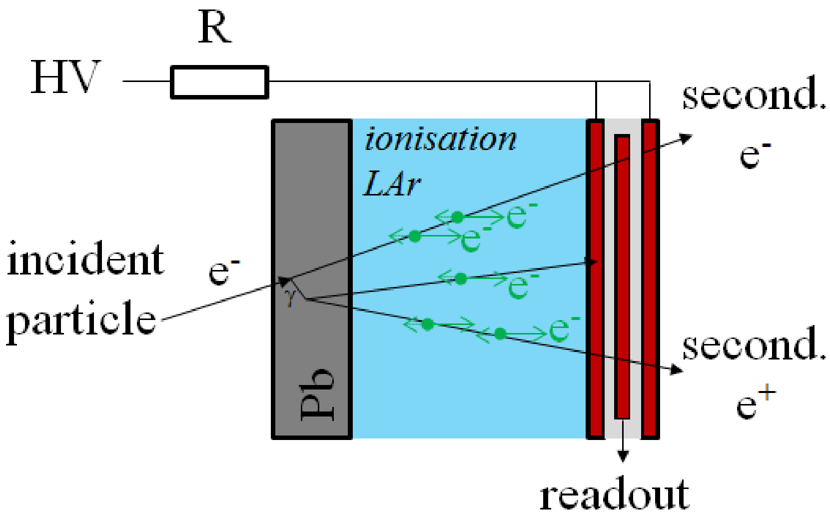
Performance goals of the ATLAS detector

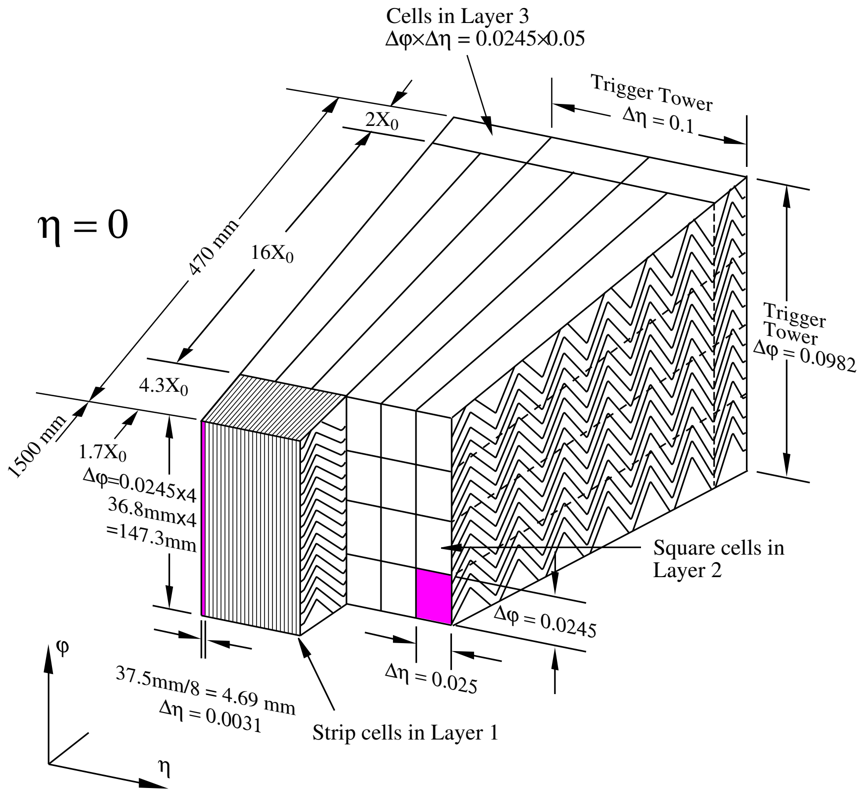
Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2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

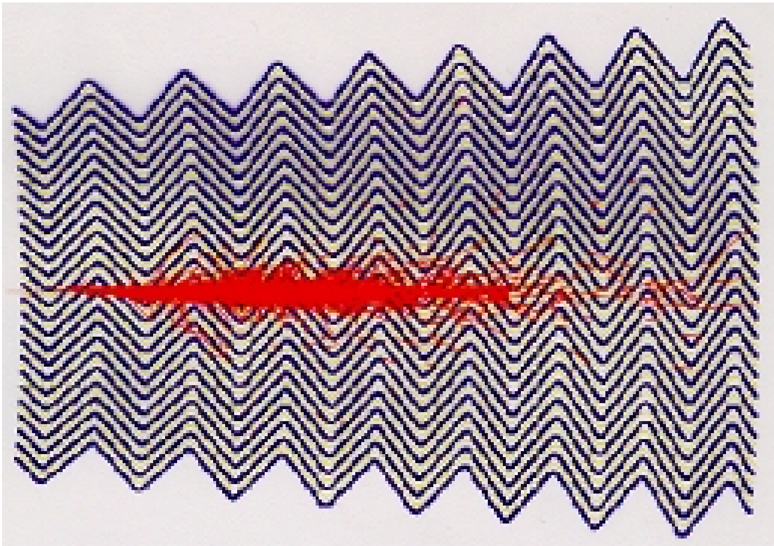
- **Silicon and TRT tracker in 2T magnetic field**
  Measure position and momentum of charged particles
- **Liquid argon electromagnetic calorimeter (LAr)**
  Measure energy of electrons and photons.
- **Scintillating tiles hadronic calorimeter**
  Measure energy of jets
- **Muon chambers**

Electromagnetic calorimeter (LAr)



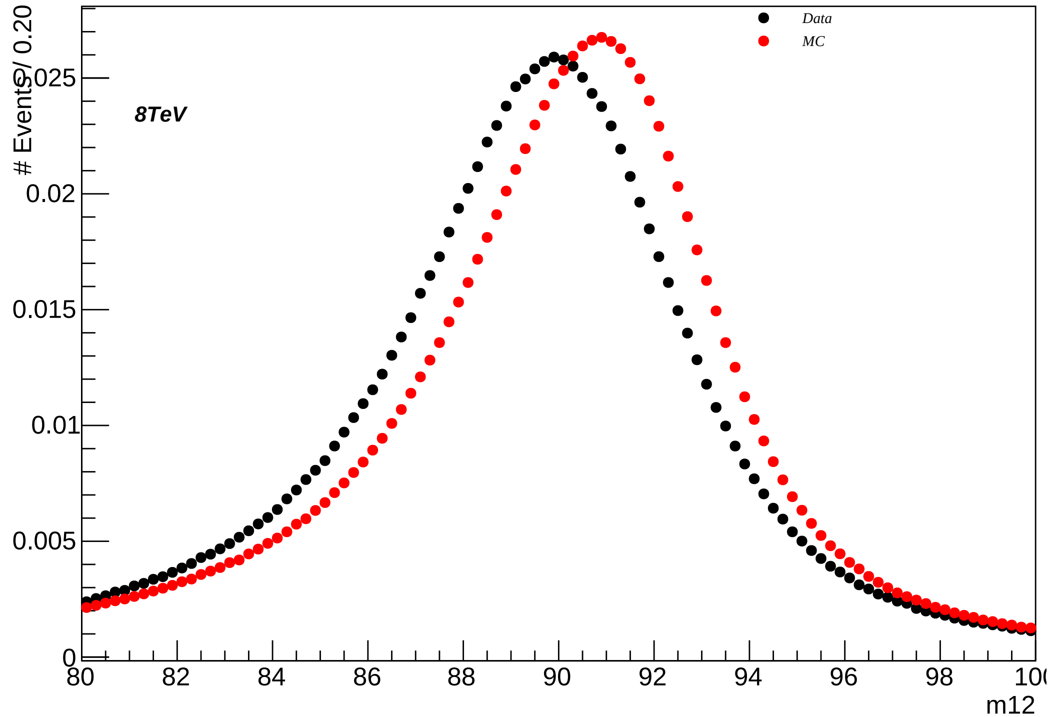


- $1.4\text{m} < r < 2\text{m}$
- Sampling calorimeter :
  - absorber : lead
  - active material : **Liquid Argon** (88K)
- **Accordion geometry** gives uniformity and hermeticity along ϕ.
- **Longitudinally segmented** for pion discrimination



Energy 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)

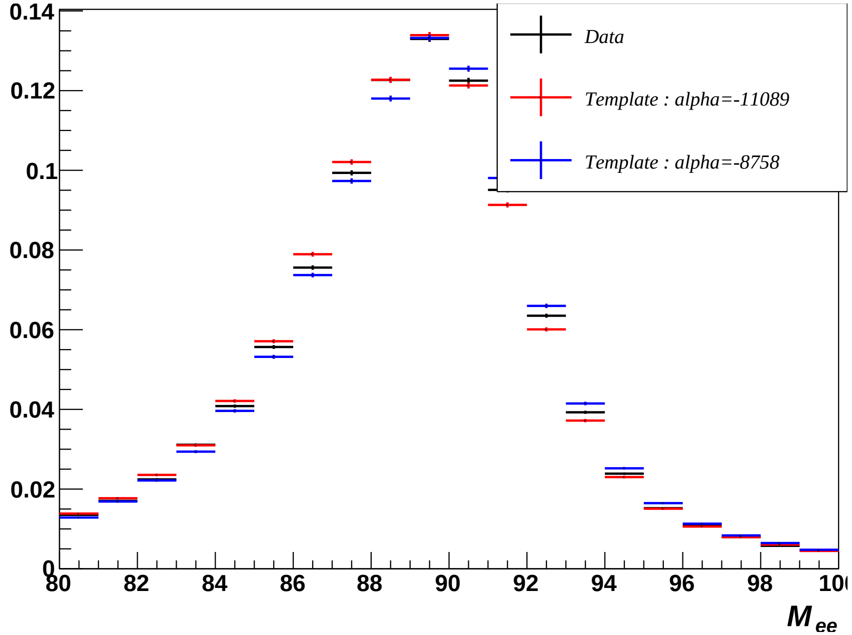
$$E^{corr} = E^{meas}(1 + N(0,1) * C)$$

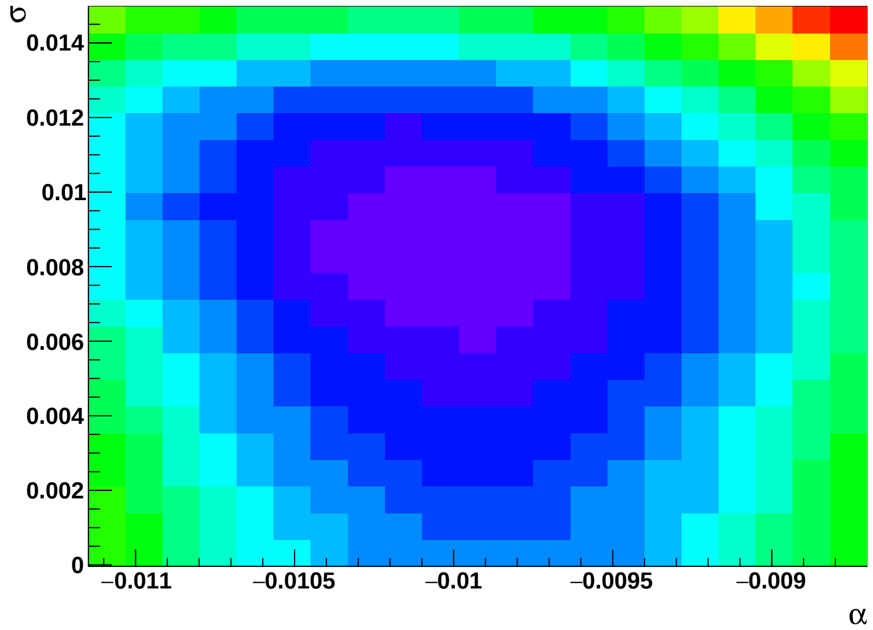
$N(0,1)$: a Gaussian distributed random number

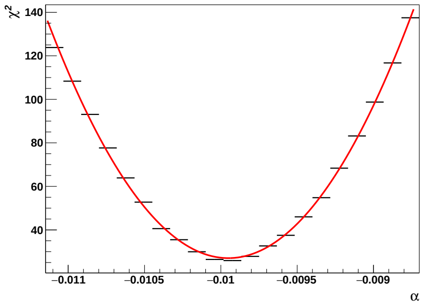
Template method

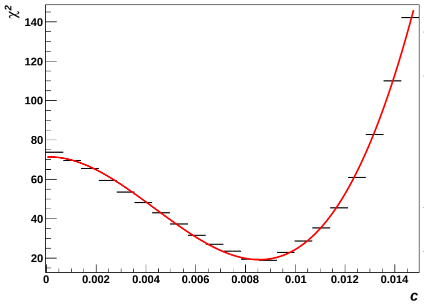
The template method is used to measure α and C simultaneously.

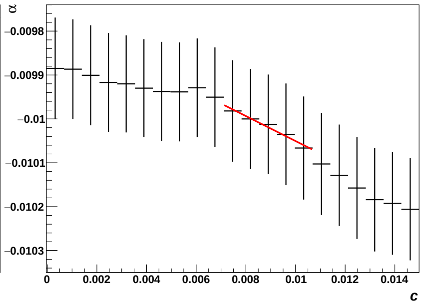
- Create distorded MC (templates) with test values of α and C.
- **Compute χ^2 between Z mass distribution of data and template**.
- **Fit the minimum of the χ^2 distribution** in the (α, C) plane.
- Fit performed in 2 steps of 1D fits :
  - fit $\chi^2 = f(\alpha)$ at constant C (lines) $\rightarrow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





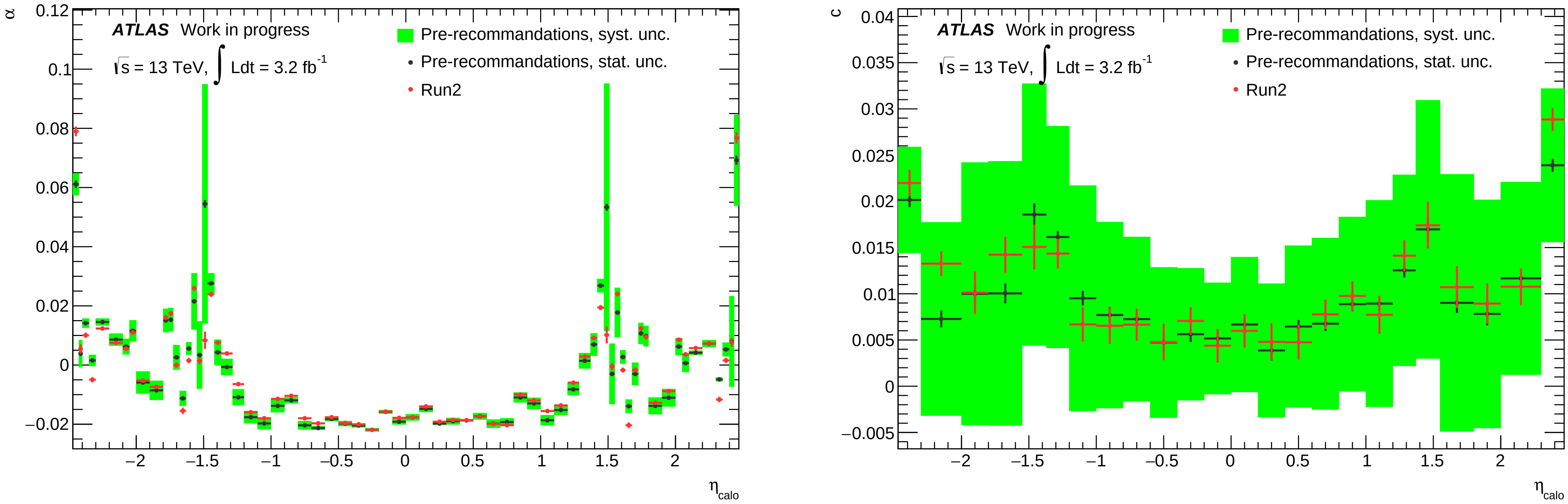






Run 2 results

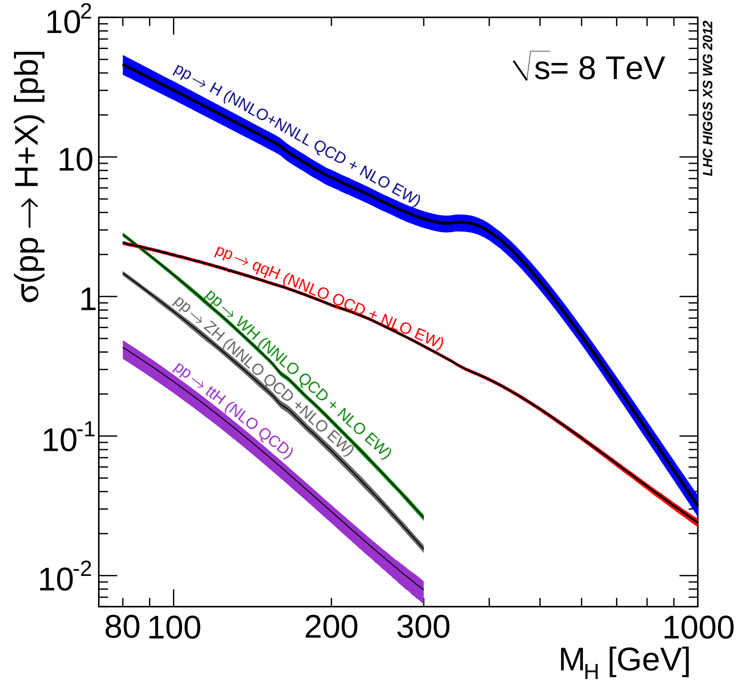
Scales are measured with 13TeV data at 25ns

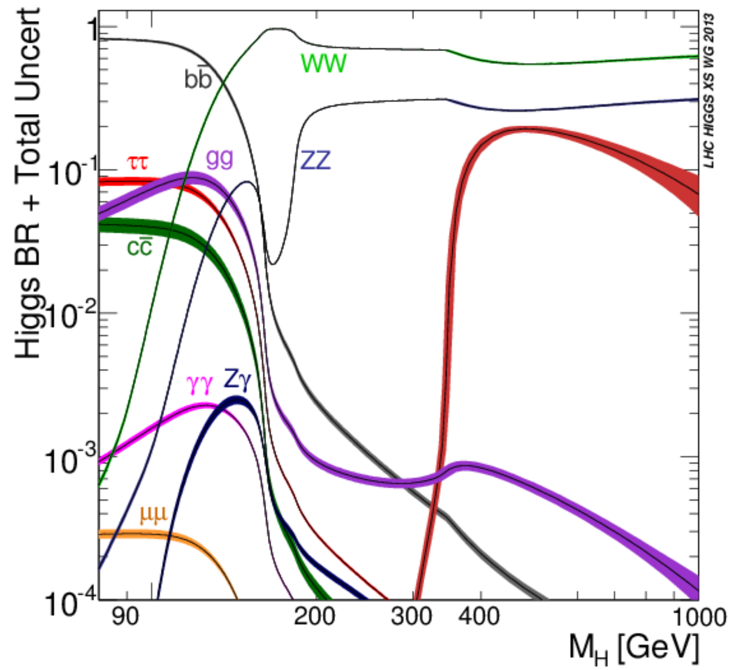


α **discrepancies are below** 0.1% out of the crack $(1.37 < |\eta| < 1.55)$.

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 : $gg \to H$
  - VBF : $qq \to Hjj$
  - VH : $Z(W) \to Z(W)H$
  - ttH : $t\bar{t} \to t\bar{t}H$
- At a mass of 125 GeV, many decay modes available :
  - $H \to b\bar{b}$: dominant decay mode ($\sim 57\%$) but high background in hadronic machines.
  - $H \to 4l$: low expected events, almost no background.
  - $H \to \gamma\gamma$: low branching ratio (0.28%) but clean signature. High but smooth background.





Likelihood Method

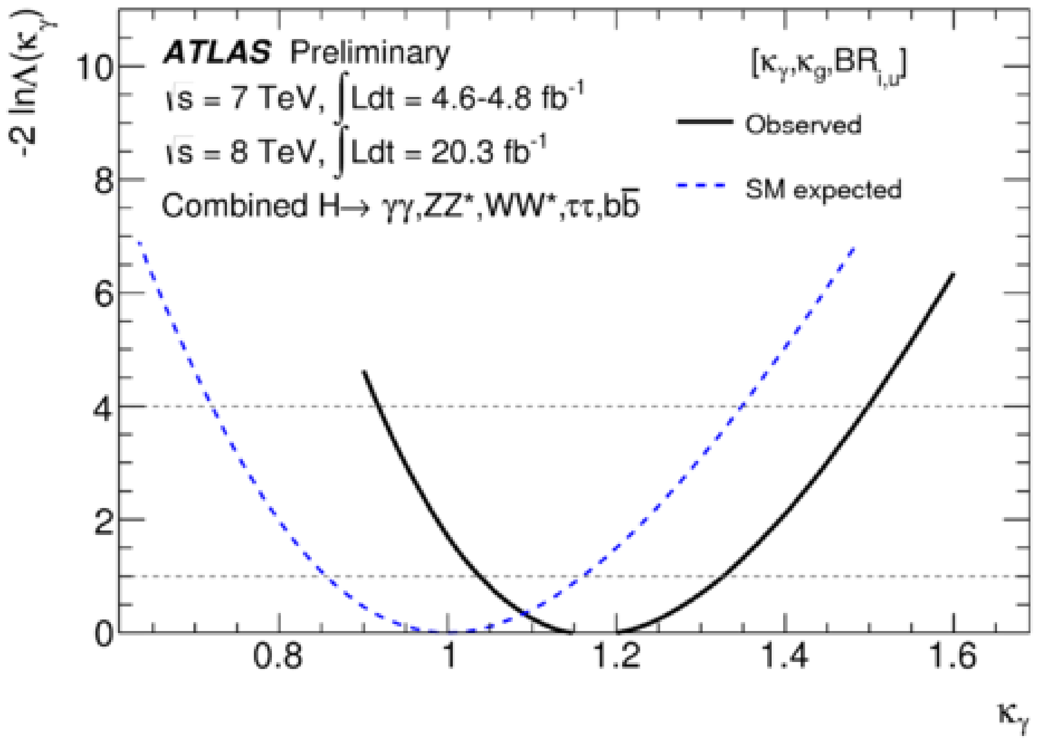
A function (**likelihood**) is built to **evaluate the best set of parameters ($\vec{\mu}$,$\vec{\theta}$)** of a model to agree the best with a dataset in a category.

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

(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 :

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

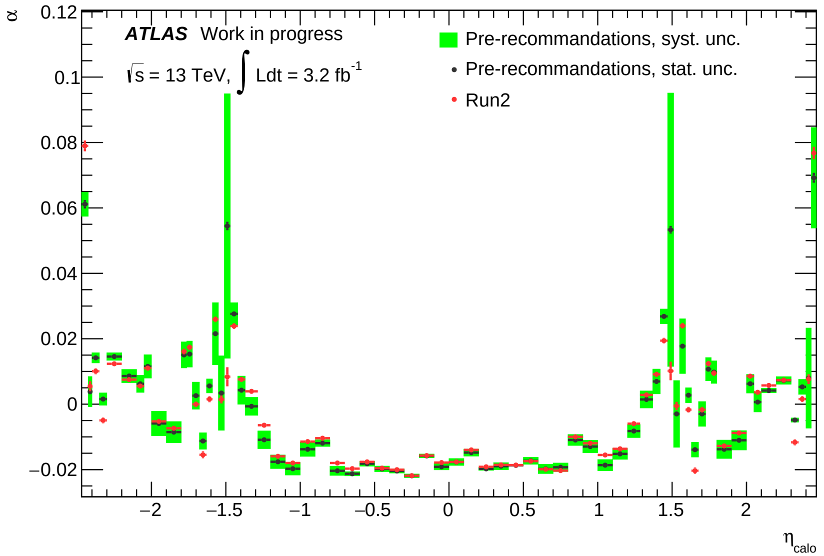
Error Estimation

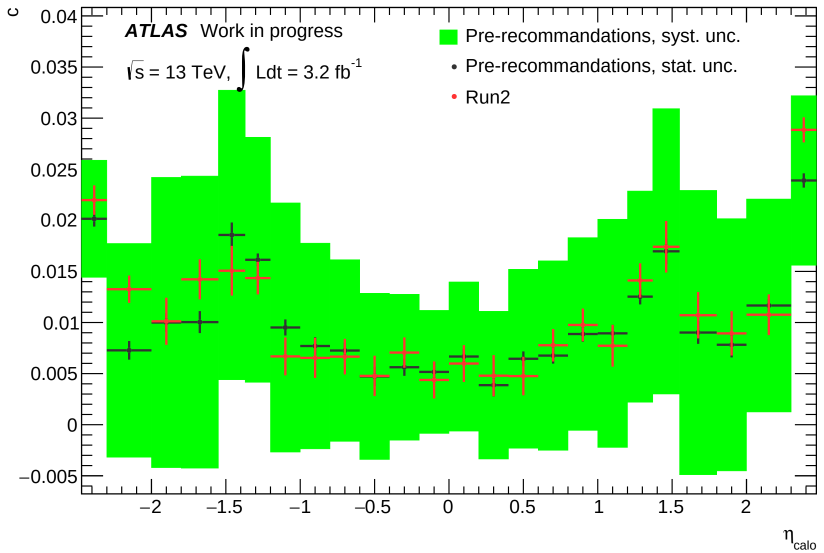
A test statistic is defined as : $t_\mu = -2ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})}$, with $\hat{\theta}$ and $\hat{\mu}$ the best (fitted) parameters, and $\hat{\hat{\theta}}$ the fitted nuisance parameters for a fixed μ.
Uncertainty are given by : $\mathbf{t_{\hat{\mu}\pm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

Conclusion

- Higgs measurement uncertainties are dominated by statistics : **new challenges ahead to keep it that way with 30× more stat.**
- **Electron calibration under control.** Calibration systematics (dominant in Higgs measurements) need improvement to use the full potential of new statistics.
- Stronger constraints on Higgs couplings may bring hints of BSM physics.

Stay tuned !





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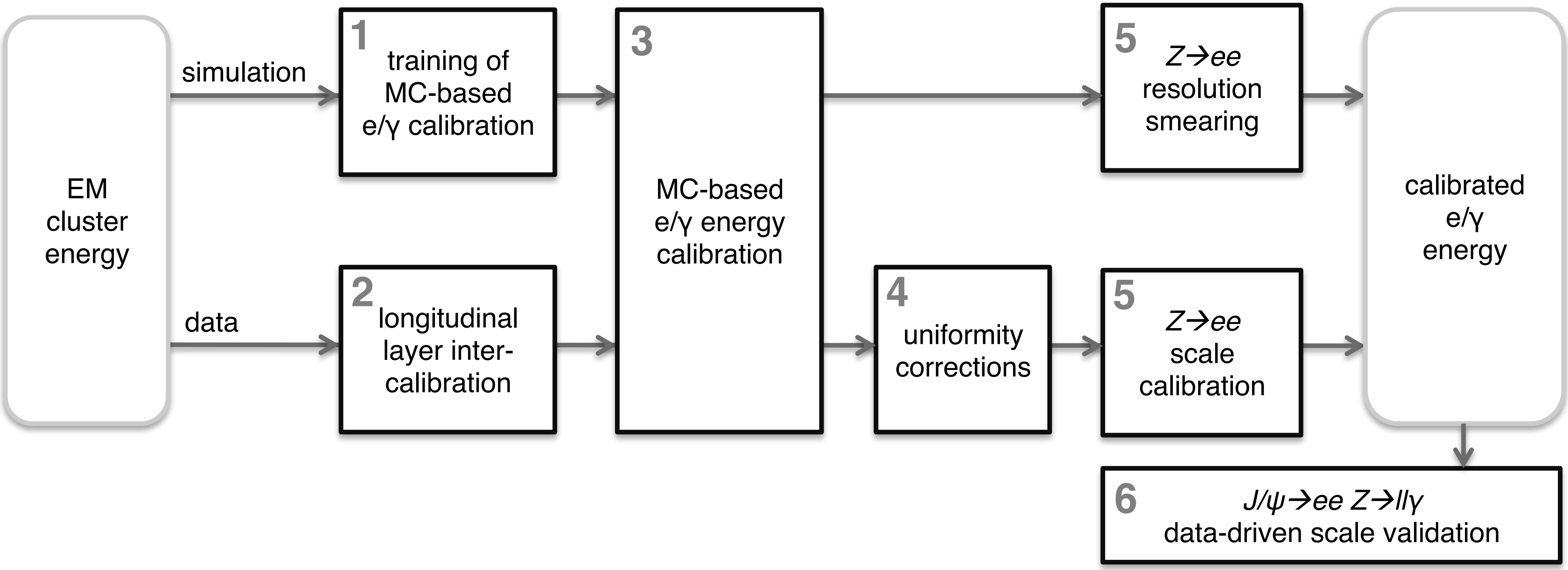
Full calibration

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**.



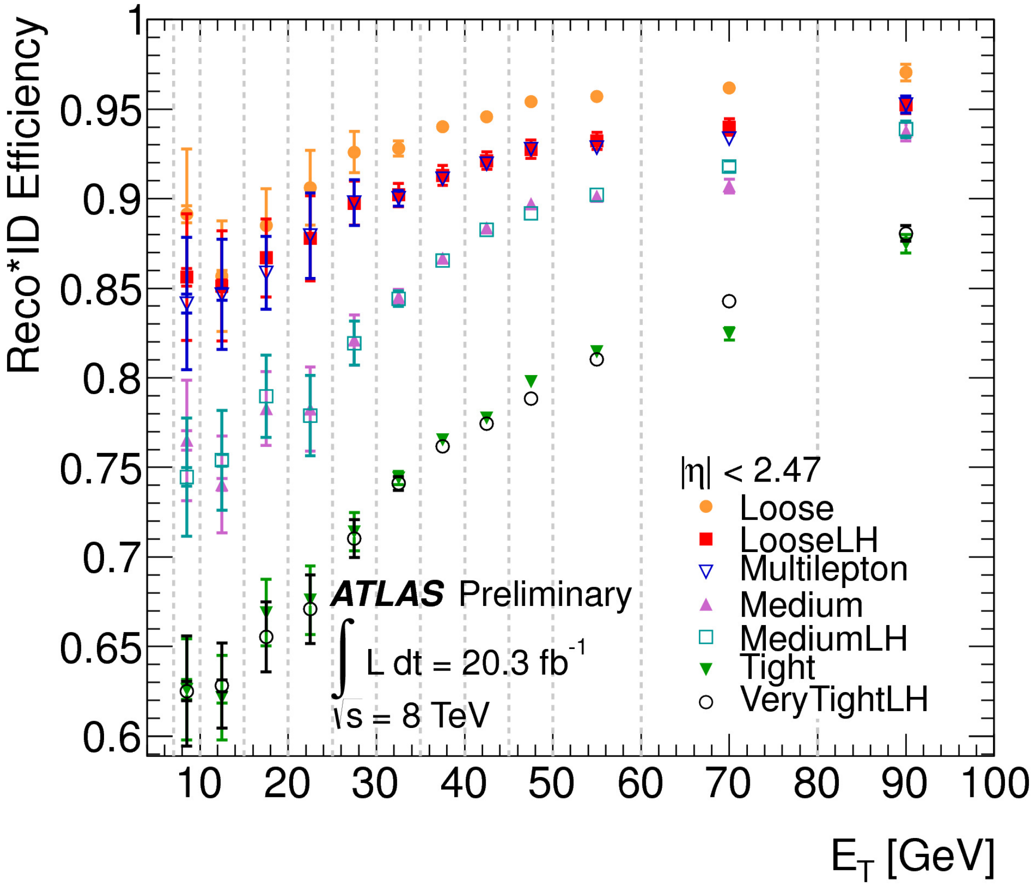
Electrons and photons follow the same steps but with dedicated analyses.

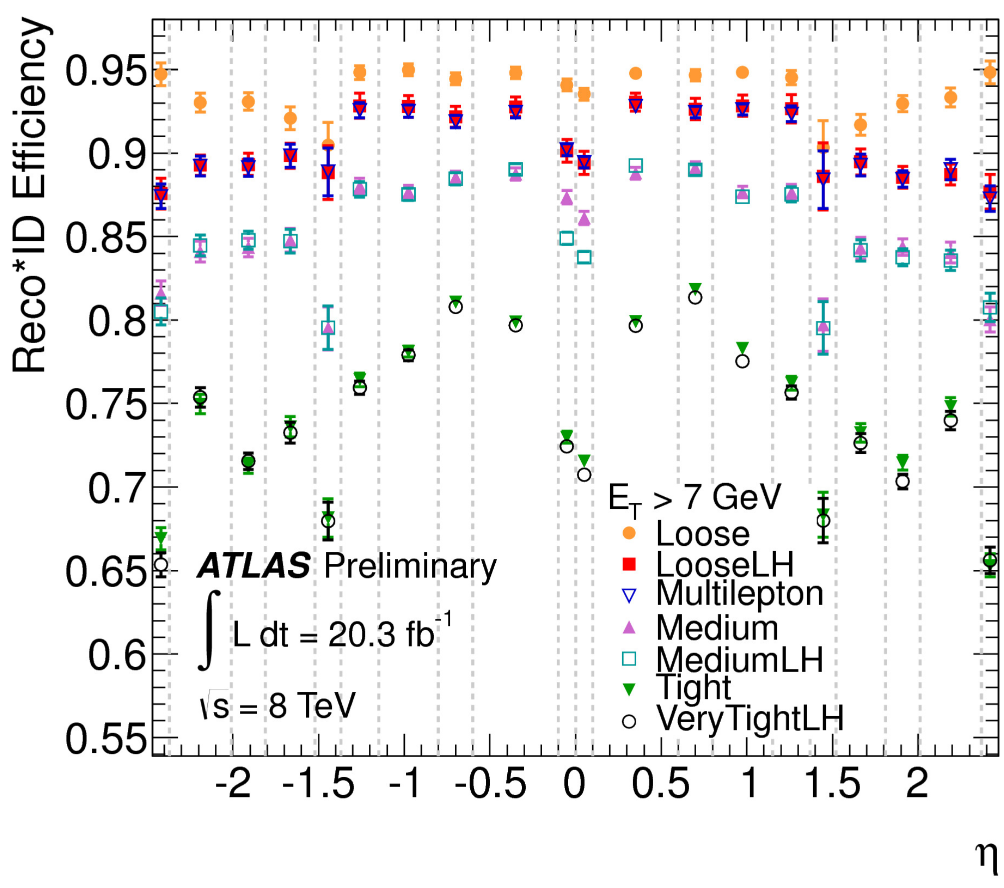
Identification variables

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 $\|\eta\| < 0.8$ or $\|\eta\| > 1.37$)	R_{Had1}
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	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, $\sqrt{(\Sigma E_i \eta_i^2)/(\Sigma E_i) - ((\Sigma E_i \eta_i)/(\Sigma E_i))^2}$, 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 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	$\Delta\phi_{\mathrm{res}}$
	Ratio of the cluster energy to the track momentum	E/p
Conversions	Veto electron candidates matched to reconstructed photon conversions	isConv

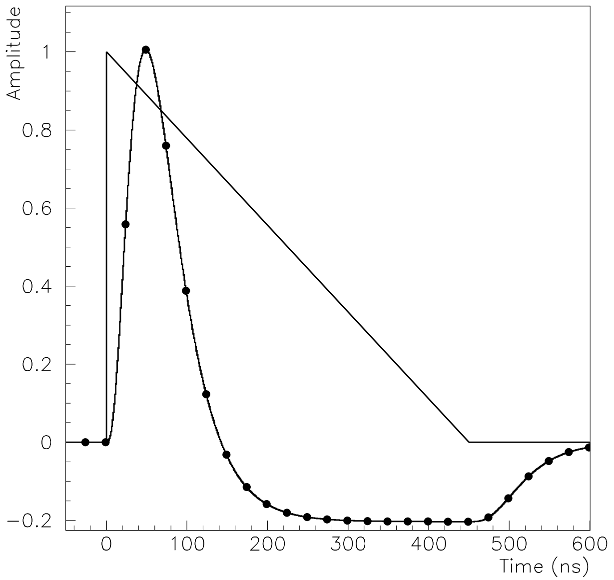
Reconstruction & Identification efficiencies

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 (3×5 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.

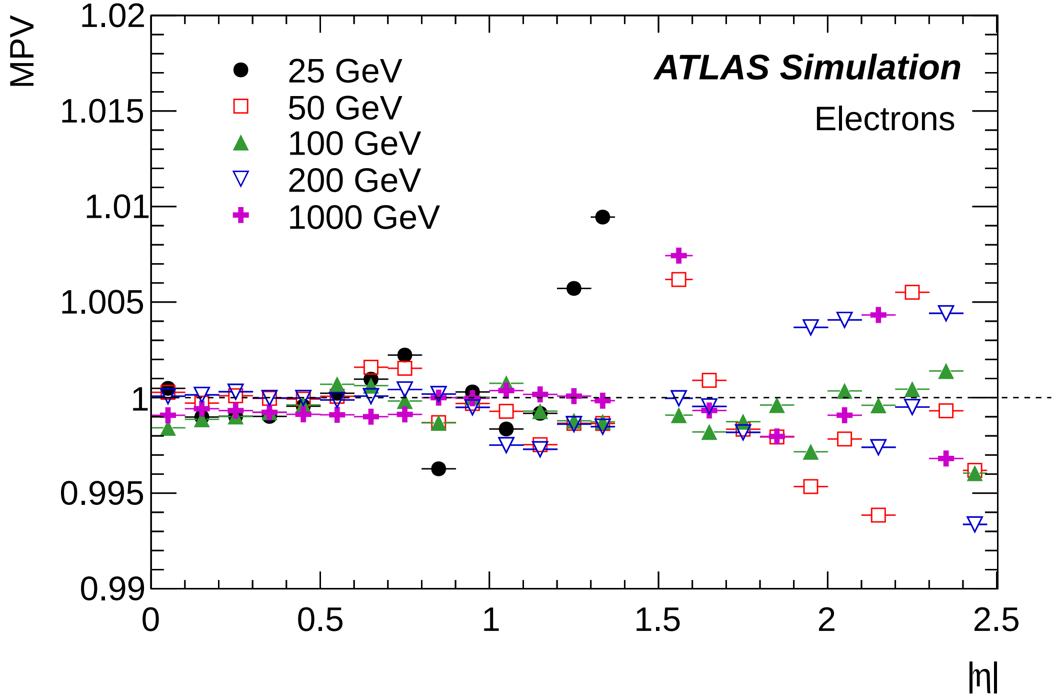
MVA calibration

- 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 :

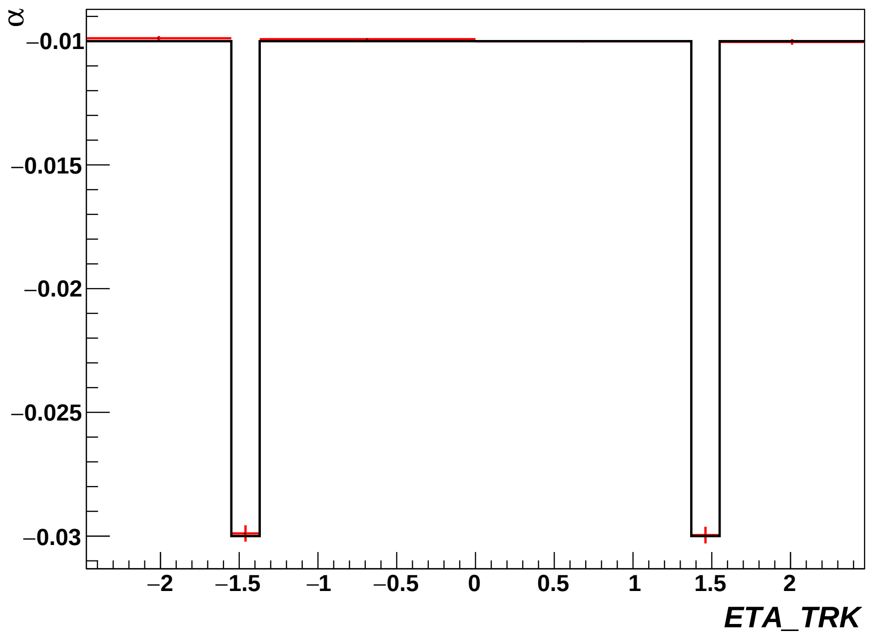
- Energies in all layers of the ECAL
- EM shower shape variables
- Barycenters of energy deposits

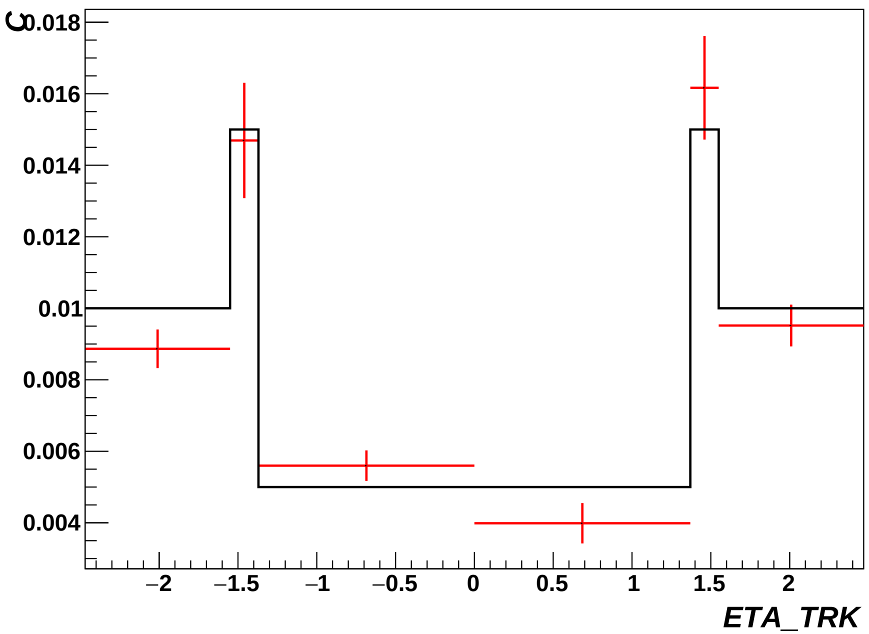


Inversion Procedure

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

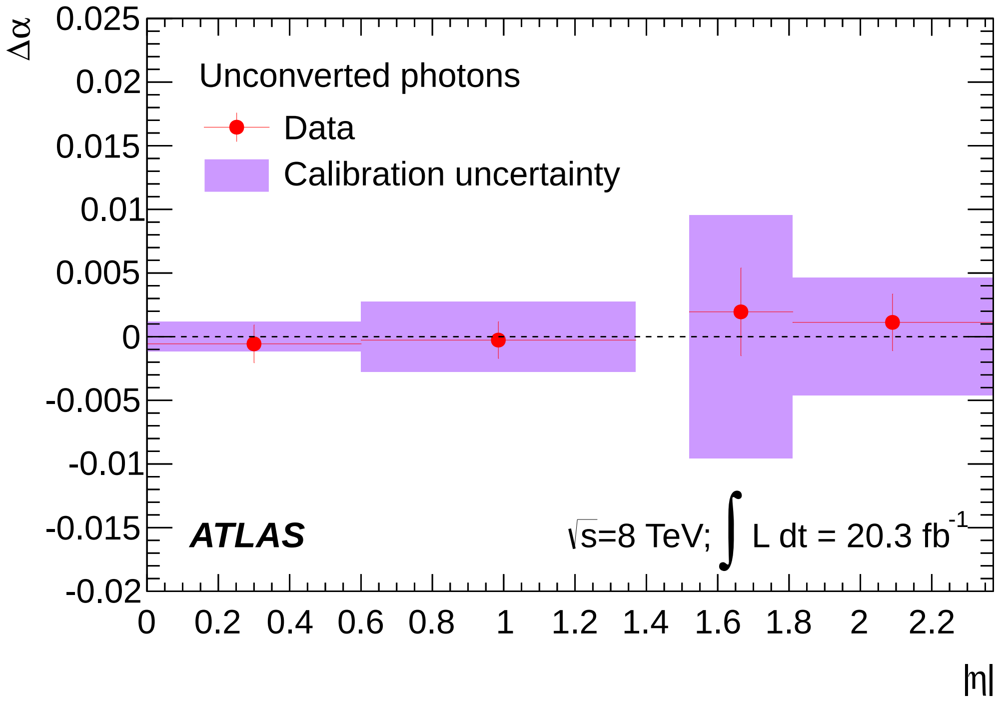
$$\chi^2 = \sum_{i,j\leq i} \frac{(\alpha_i+\alpha_j-2\alpha_{ij})^2}{(\Delta\alpha_{ij})^2}$$
$$\chi^2 = \sum_{i,j\leq i} \frac{(\sqrt{\frac{c_i^2+c_j^2}{2}}-c_{ij})^2}{\Delta^2 c_{ij}} \tag{1}$$

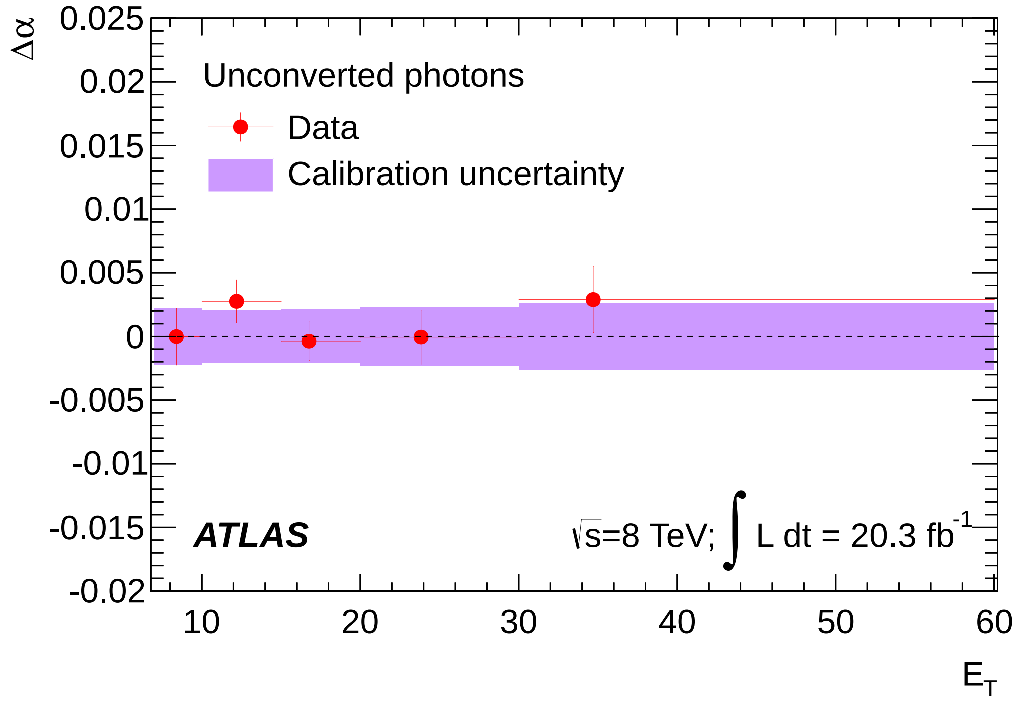




Photon correction

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



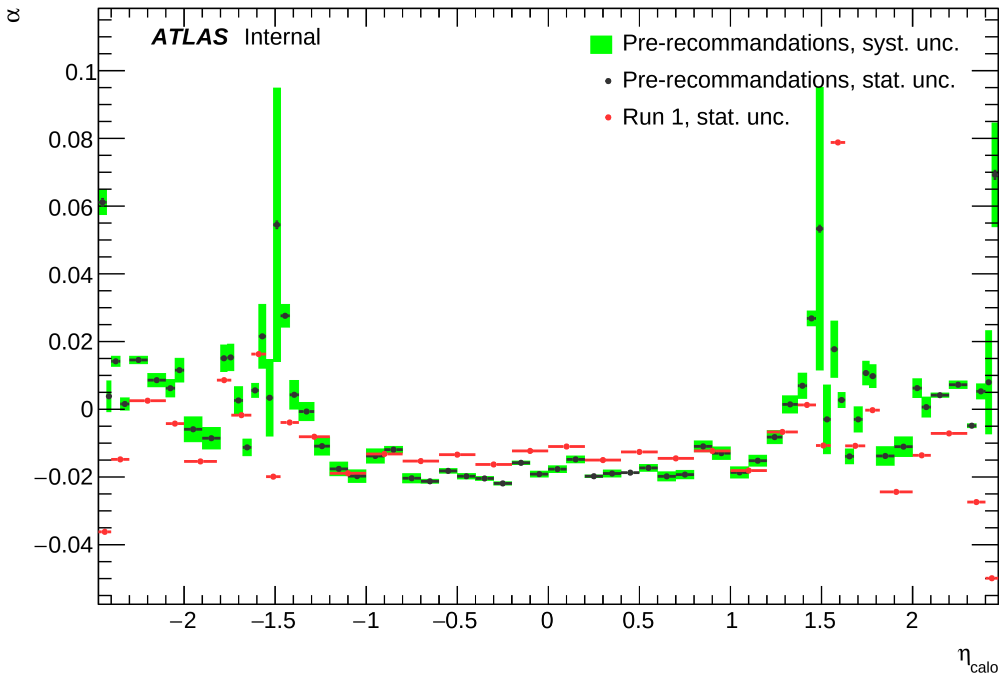


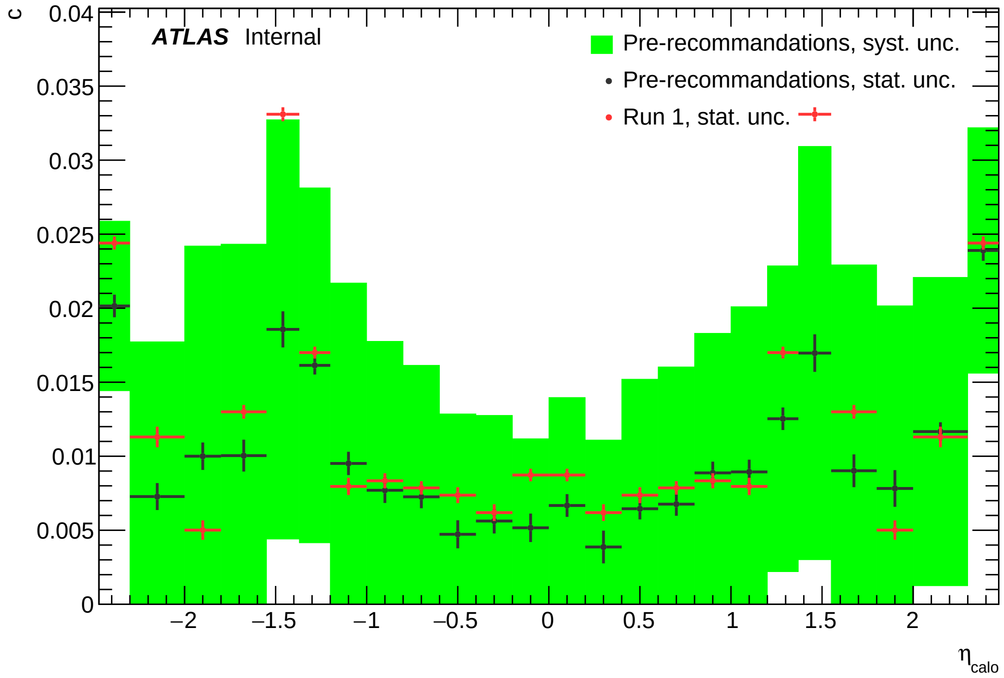
Run 2 prerecommandations

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



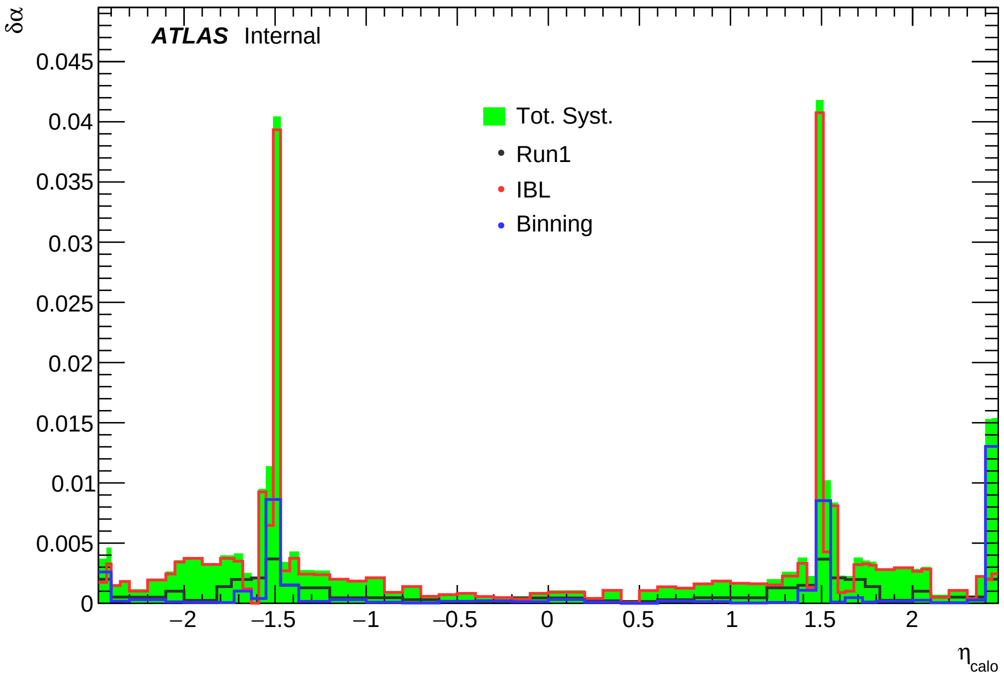


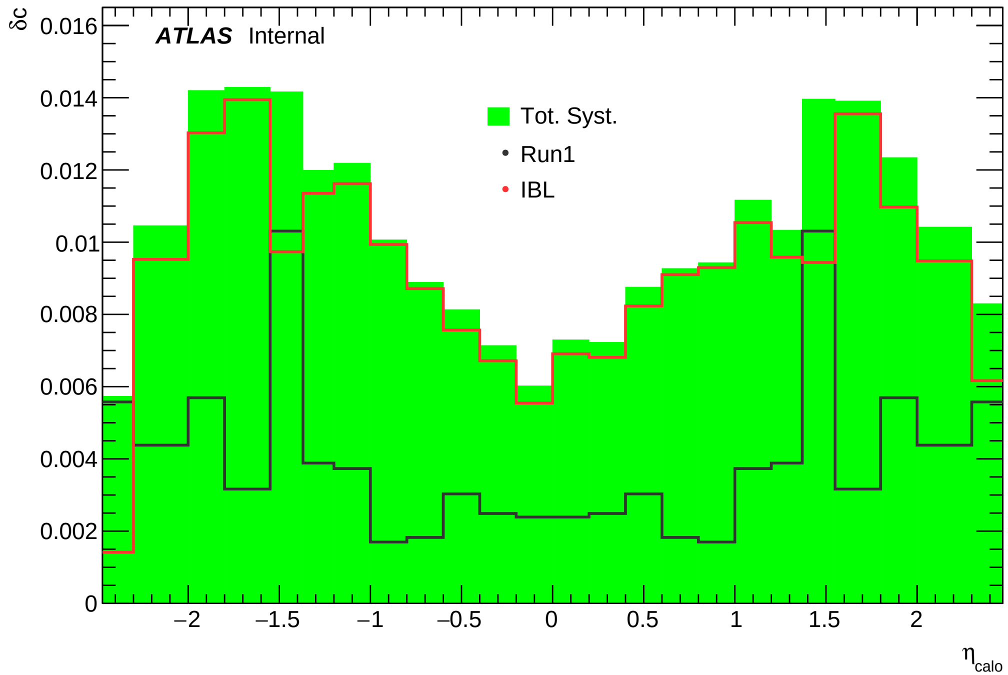
Run 2 pre-recommandations systematics

2012 systematics are used for the pre-recommandations.

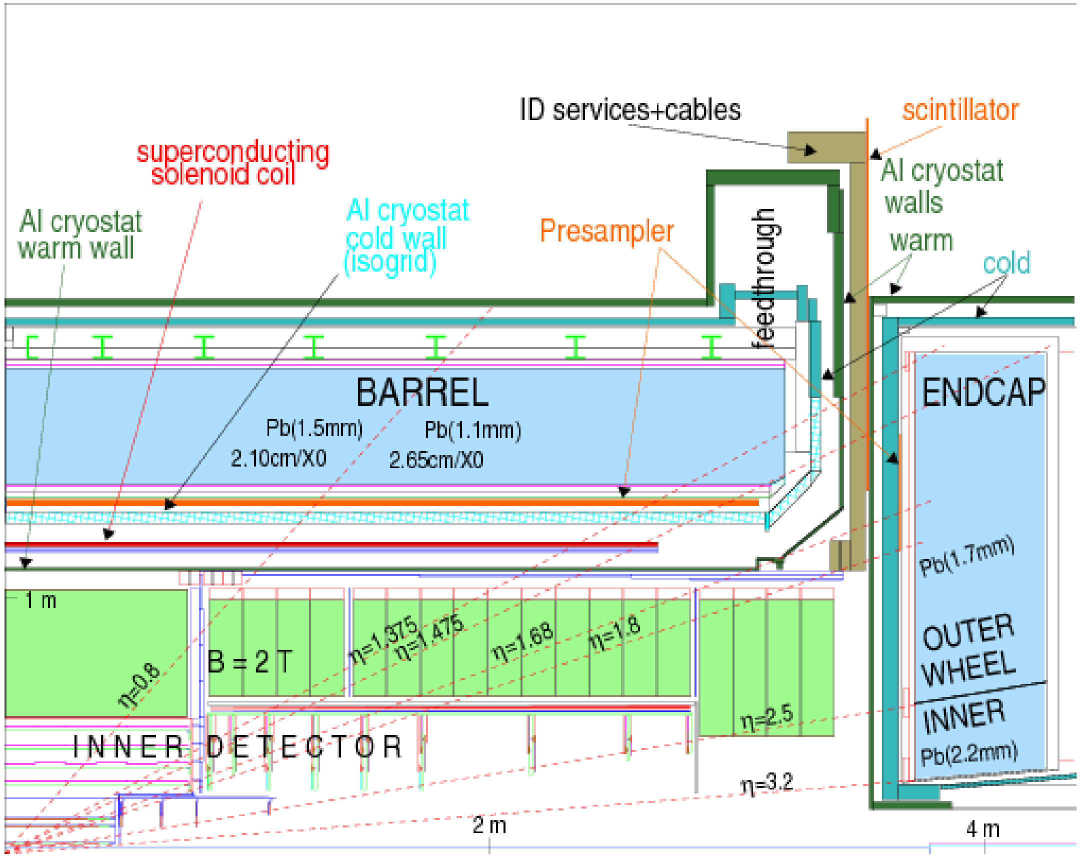
Two more systematics are added in quadrature :

- 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-recommandations 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.





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.

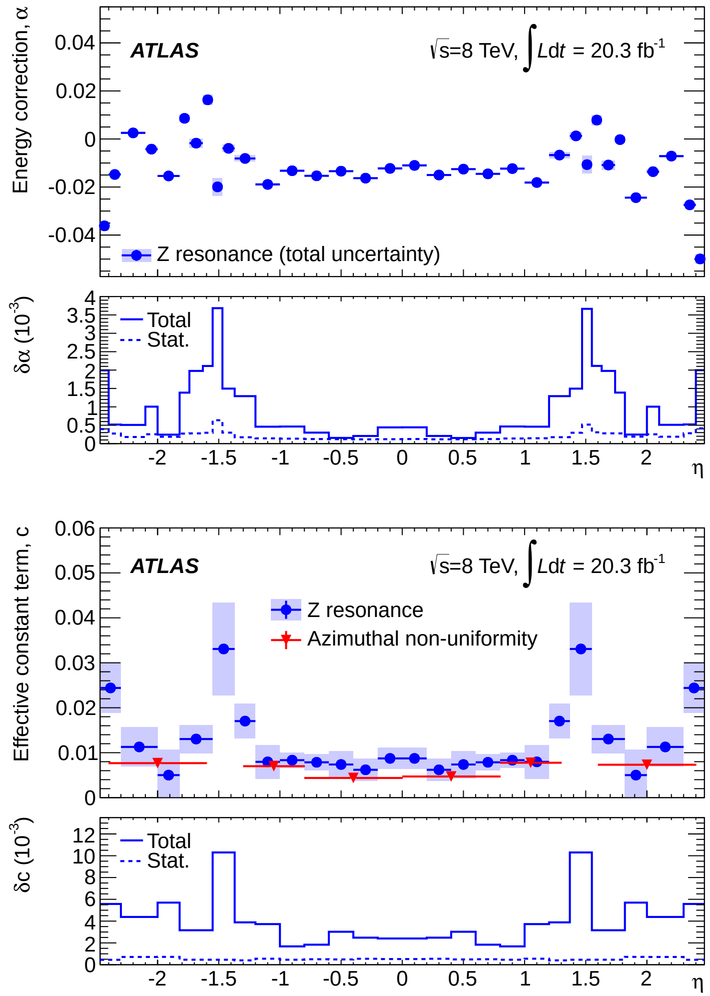
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.285 1.37 1.42 1.47 1.51 1.55 1.59 1.63 1.6775 1.725 1.7625 1.8 1.9 2 2.05 2.1 2.2 2.3 2.35 2.4 2.435 2.47

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

Run 1 : results and uncertainties

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

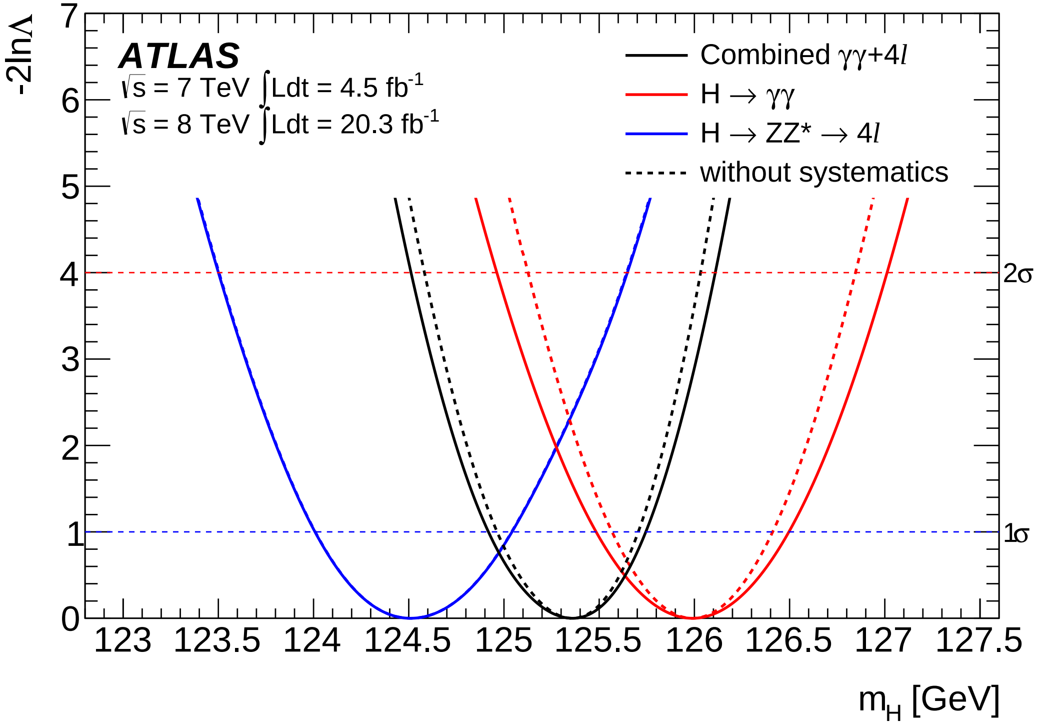
- electron identification quality from medium to tight.
- Z mass window
- electron p_T cut
- uncertainties on efficiencies scale factors
- energy loss through bremshtrahlung
- background
- pile-up
- measurement method



Mass measurement

Higgs mass is the **last unknown parameter of the standard model** :

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



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
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

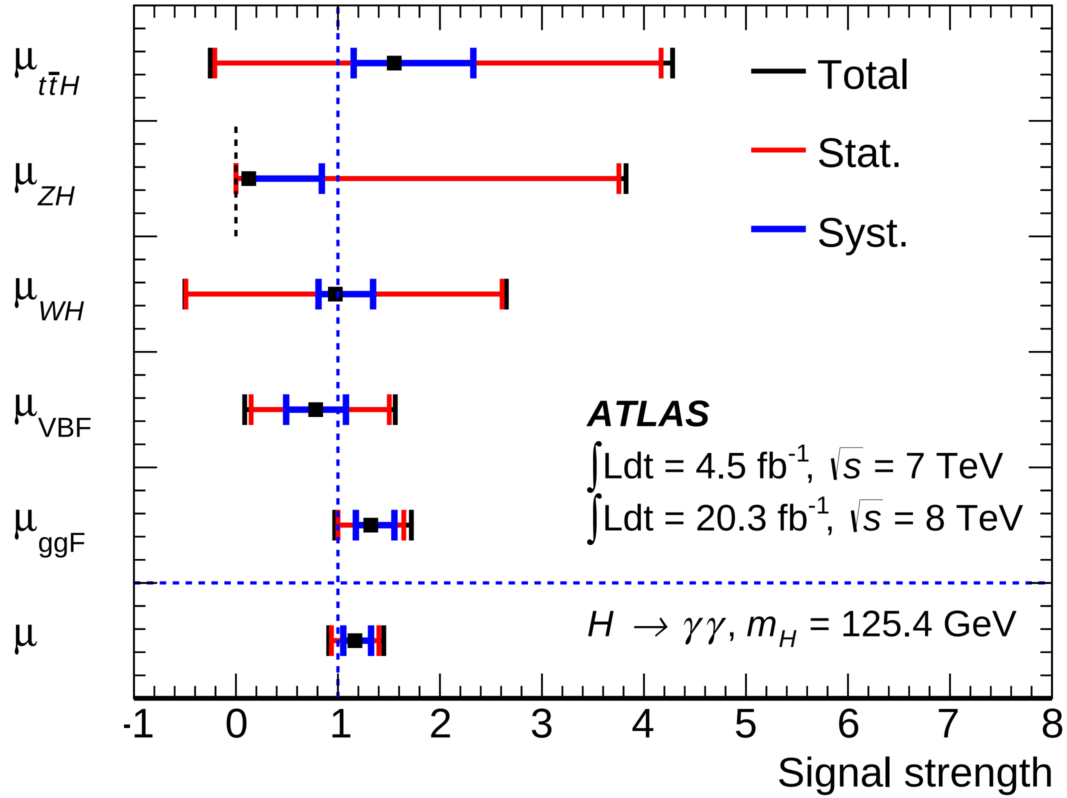
Statistical uncertainties highly dominant.

Run 2 will increase sensitivity to systematics.

$\mu_{\gamma\gamma}$ measurement

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

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



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**.