Calibration of the ATLAS electromagnetic calorimeter and measurement of the couplings of the (Brout-Englert-)Higgs boson in the diphoton channel using run 2 data

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PhD defense
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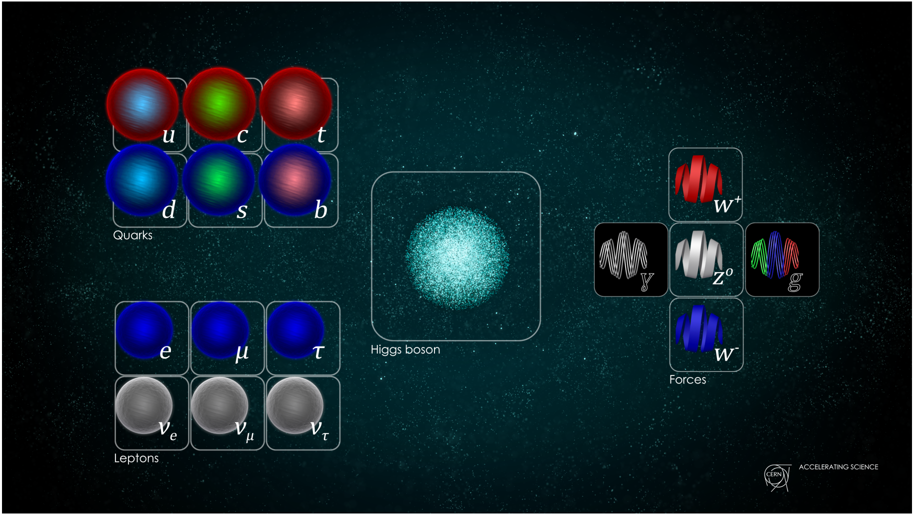
Introduction

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

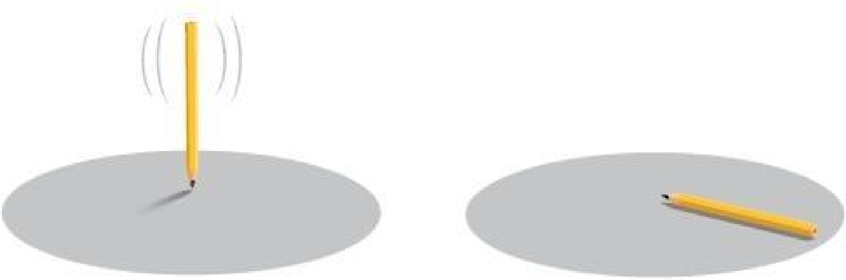
Particle content of matter

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



Spontaneous Symmetry Breaking (SSB)

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.

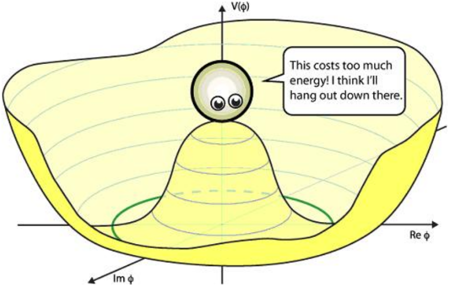
SSB in field theory

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

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

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

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



The Standard Model

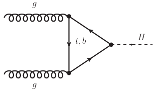
The SM is composed of :

- 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.

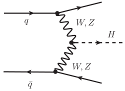
- SSB of $SU(2)_L \times U(1)_Y$ by introduction of scalar field Φ
  - gives mass to $W^\pm$ and Z.
  - A physical and massive degree of freedom : the (Brout-Englert)-Higgs boson H.
  - Yukawa coupling gives mass to fermions.

Higgs boson production

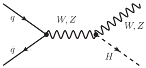
H boson predictions are function of its mass.



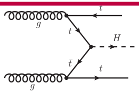
(a) Gluon fusion (ggH)



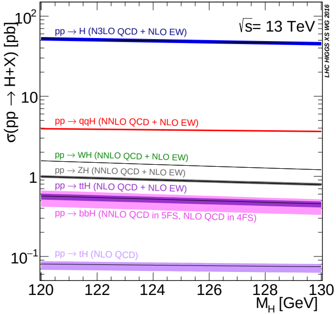
(b) Weak vector boson fusion (VBF)



(c) Higgsstrahung



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

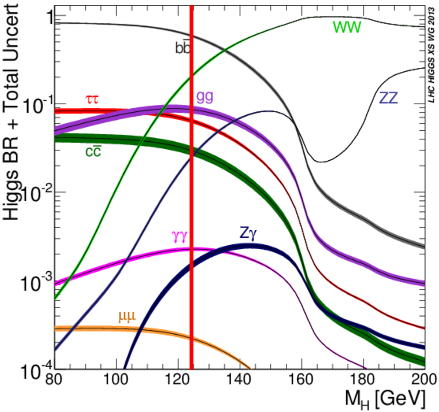


4 dominant production modes

- 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.



- $H \to bb$ (58 %) 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. Good energy resolution.

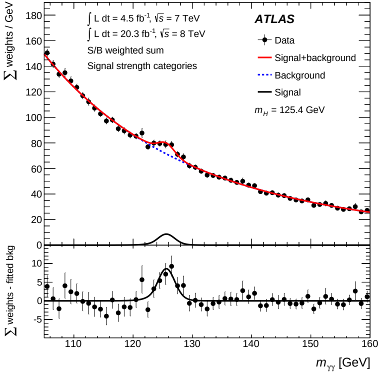
$$\kappa_\gamma^2 \to 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

H boson Status

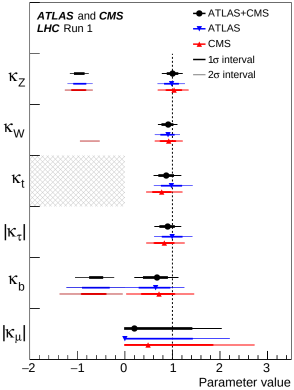
Run 1 of the LHC (2011/2012) allowed the observation of a Higgs like particles and its properties have been measured combining ATLAS+CMS.

mass measurement
Phys.Rev.Lett.114.191803

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



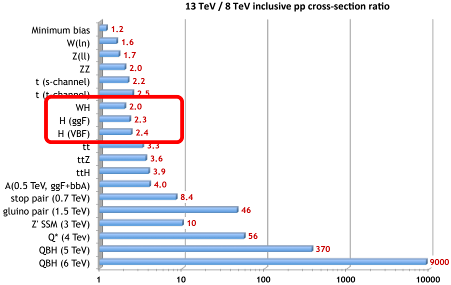
couplings $\kappa_i = \frac{g^{exp}_{Hii}}{g^{SM}_{Hii}}$
CERN-EP-2016-100



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

Run 2 objectives

- LHC energy and luminosity increase
  → **10 times more Higgses are expected**
- With reduced statistical uncertainties
  → **need to reduce systematic uncertainties**
- Theory uncertainty reduced with ggH N^{3}LO calculation
- Resolution uncertainty dominant at Run 1 for couplings
  → **Need to improve calibration resolution uncertainty**

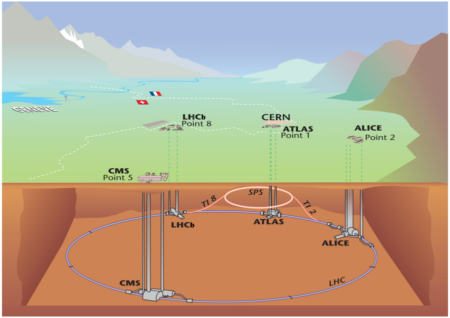


Uncertainty group	Run 1 $\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

The Large Hadron Collider (LHC)

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

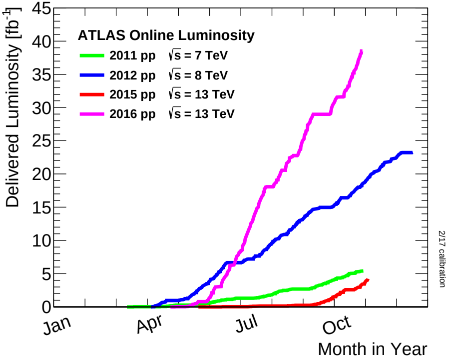
- located at Geneva.
- 27 km circonference.
- 100 m underground
- collision every 25 ns.
- nominal luminosity of 10^{34} cm^{-2}s^{-1}.
- $\sqrt{s} = 13$ TeV.
- 4 collision points with detectors : ALICE, ATLAS, CMS and LHCb.

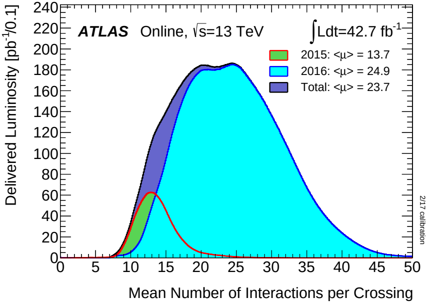


LHC data taking condition

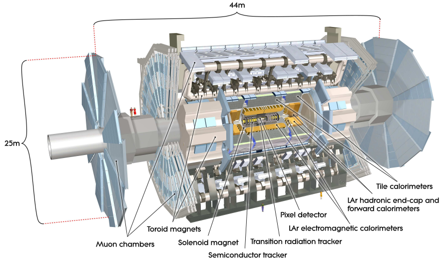
The collision conditions at LHC have significantly changed since its contruction.

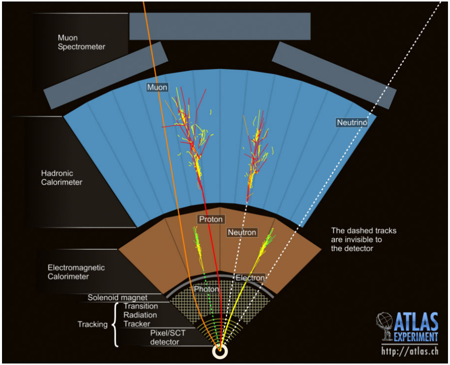
- Major increase of integrated luminosity per year.
- Large increase in collisions per bunch crossing.





ATLAS experiment

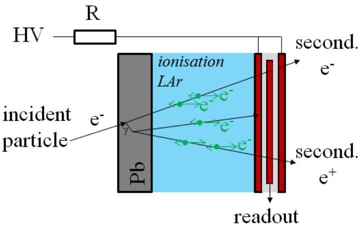


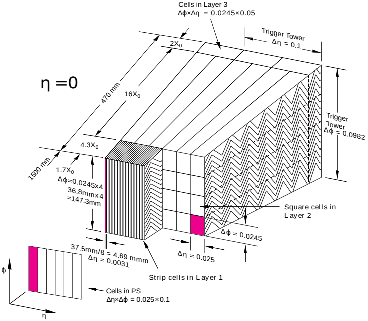


- **Large acceptance**
- **Radiation hard**

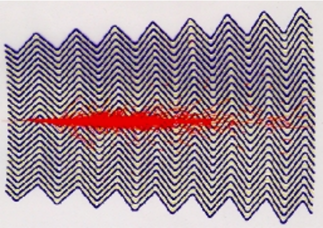
- **Silicon and TRT tracker in 2T magnetic field**
  Measure position and momentum of charged particles. IBL added for Run 2.
- **Liquid argon electromagnetic calorimeter (LAr)**
  Measure energy of electrons and photons.
- **Scintillating tiles (+ HEC + FCAL) hadronic calorimeter**
  Measure energy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

Electromagnetic calorimeter (ECAL)

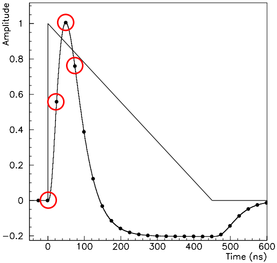




- $1.4\text{m} < r < 2\text{m}$
- Sampling calorimeter :
  - absorber : lead
  - active material : **Liquid Argon** (88K)
- **Accordion geometry** gives uniformity and hermeticity along ϕ.
- **Longitudinally and transversally segmented**
- Layer 1 used for jet discrimination



Energy measurement in LAr



- **Signal drift time** ($\sim$ 450 ns) **too long** for collisions every 25 ns (pile-up).
- Analog signal pass through an **bipolar filter** to reduce signal time. Shape optimize signal over pileup and electronic noise.
- ADC sampling every 25 ns (4 points are kept).
- Energy computed using **calibration constants and optimal filtering of the samples**.

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

Reconstruction & Identification of electrons and photons

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

- Sum energy from all layers in towers of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
- Sliding window ($\Delta\eta \times \Delta\phi = 3 \times 5$ towers) algorithm look for 2.5 GeV of transverse energy

Track matching

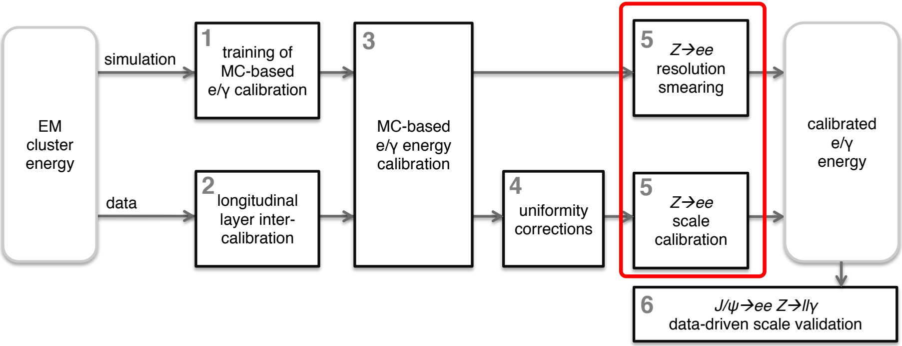
- no track $\rightarrow$ photon
- track $\rightarrow$ electron
- conversion vertex $\rightarrow$ converted photon

Clustering

- 3×7 cluster in barrel
- 5×5 cluster in end-cap

Full calibration

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

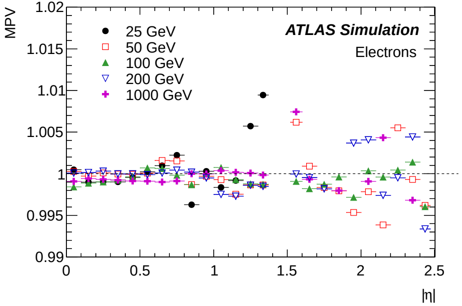


Electrons and photons follow the same steps but with dedicated analyses.

MVA calibration

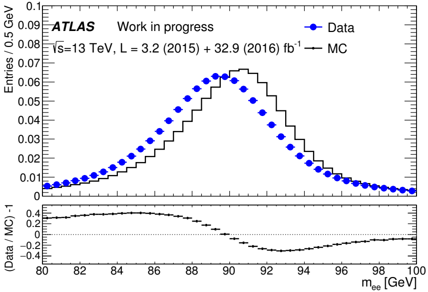
- Simulated events are passed through a full GEANT4 simulation of the ATLAS detector.
- Events are then categorized in η and p_T bins, separately for electrons and photons.
- **A multivariate analysis (MVA), using ECAL variables, is performed to compute the true energy from detector observables**.

Most probable value (MPV) of E^{corr}/E^{true}.



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

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

- a : sampling term (10%). Linked to the fluctuations of electromagnetic showers.
  Can be simulated.
- b : noise ($\sim 350\ cosh(\eta)$ MeV) + pile-up term. Measured in dedicated runs.
- c' : simulated constant term
- c **: in-situ additional constant term (**0.7%**)**

We observe that data distribution is larger than MC. c is measured to enlarge MC up to the data width. Both MC electrons undergo the correction :

Resolution constant term (c**)**

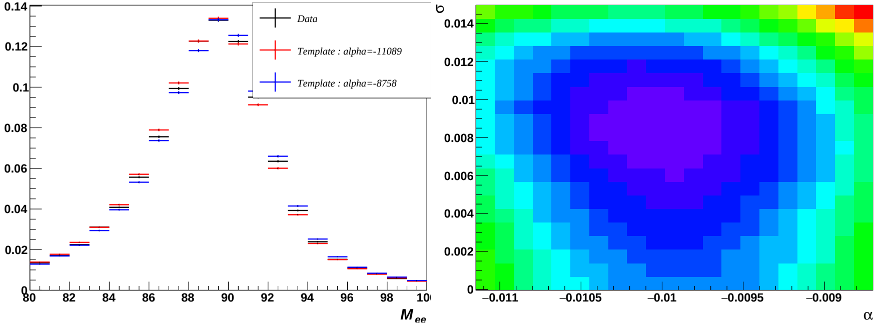
$$E^{corr} = E^{meas}(1 + N(0,1) * c)$$

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

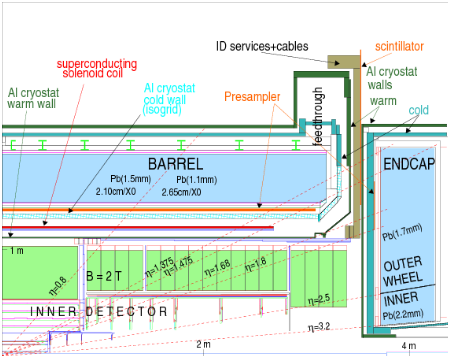
Template method

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

- Create distorded MC (templates) with test values of α and c
- **Compute $\chi^2(M_Z;$ data, template$)$**
- **Fit the minimum of the χ^2 distribution** in the (α, c) plane.



η dependence of correction factor



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

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

Inversion Procedure

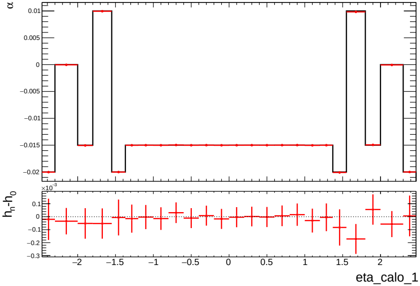
Obtaining **electron scales (α_i) from Z scales ($\alpha_{ij} \pm \Delta\alpha_{ij}$)** need the minimizations of the following χ^2's.

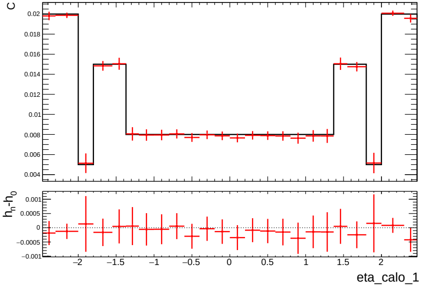
$$\alpha_{ij} = \frac{\alpha_i + \alpha_j}{2}$$

$$c_{ij}^2 = \frac{c_i^2 + c_j^2}{2}$$

$$\chi^2 = \sum_{i,j \le i} \frac{(\alpha_i + \alpha_j - 2\alpha_{ij})^2}{(\Delta\alpha_{ij})^2}$$

$$\chi^2 = \sum_{i,j \le i} \frac{\left(\sqrt{\frac{c_i^2 + c_j^2}{2}} - c_{ij}\right)^2}{\Delta^2 c_{ij}}$$

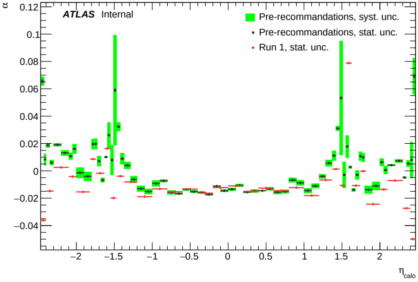




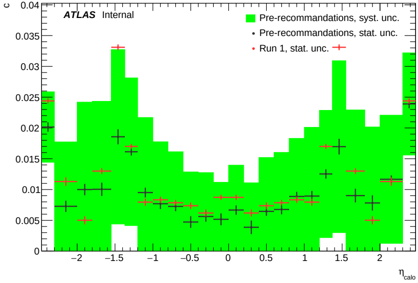
Run 2 pre-recommandations

Run 2 early analyses need scales factors for 13 TeV but not enough were available. Need to **estimate Run 2 scales from Run 1 data**.
Pre-recommandations are computed using 8 TeV data reprocessed with :

- new detector geometry (IBL)
- new reconstruction algorithm (4 samples)
- new calibration machine learning



Energy Scale Factors α



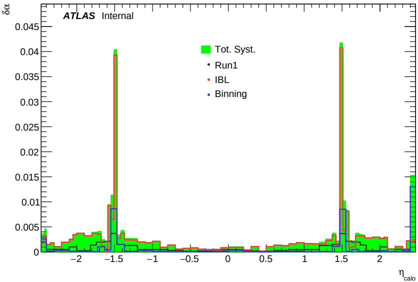
Resolution constant term c

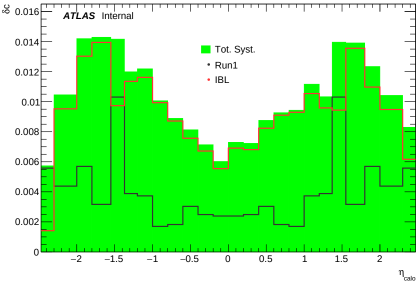
Calibration in-situ : Run 2 pre-recommandations systematics

2012 systematics are used for the pre-recommandations.

Two more systematics are added in quadrature :

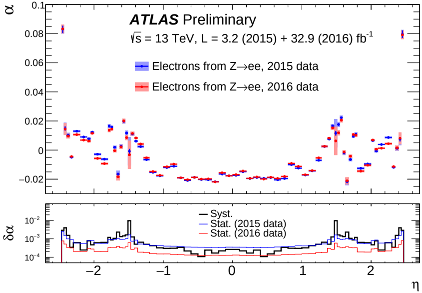
- Increasing the number of bin for α shows sub-patterns. Systematic is defined as difference between a bin value and the average of its sub-bins.
- Pre-recommandations being computed with 8TeV datasets, one needs to evaluate the impact of the center of mass energy. Systematic is defined as the scale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

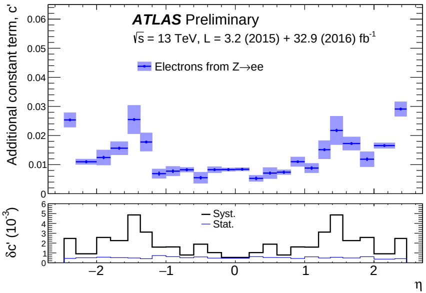




Run 2 results

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



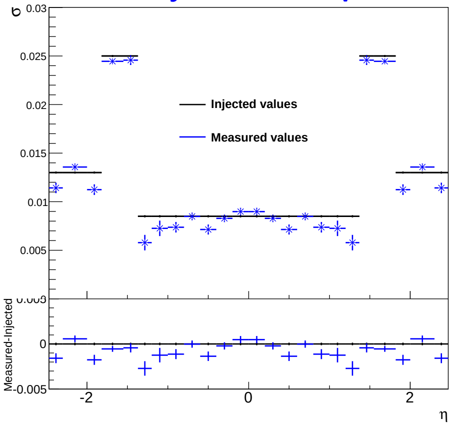


Main sources of uncertainty

- Diff. btw tight and medium electrons
- Closure : difference between injected and measured values
- Bremsstrahlung impact on electron momentum

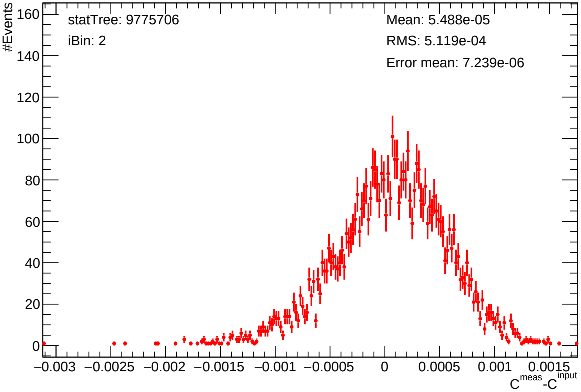
Closure uncertainty

- Run 1 closure systematic defined on single measurement
- Run 2 cross-checks favoured opposite sign effect
- **Dominant resolution systematic requires more care**



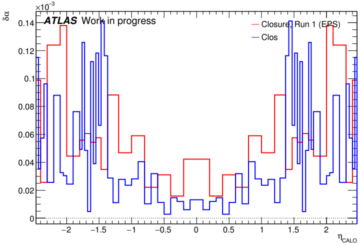
Run 2 closure uncertainty

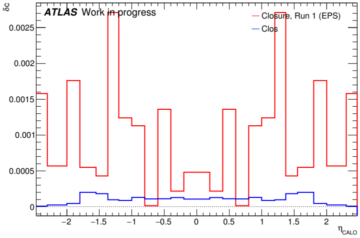
- Pseudo experiments have been performed
- Average over all sources of statistical fluctuations
- **New closure defined as average of distribution in each bin.**



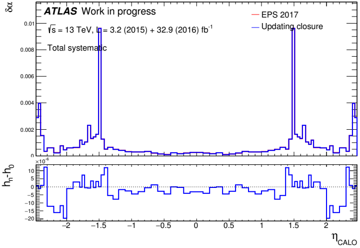
Comparing closure uncertainties

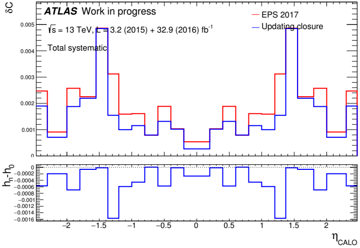
Closure uncertainty





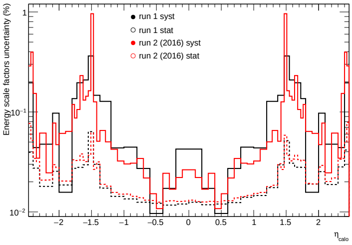
Total uncertainty

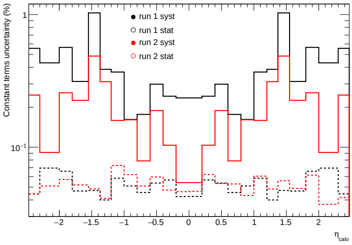


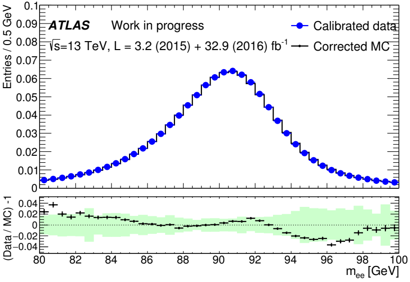


Runs comparison

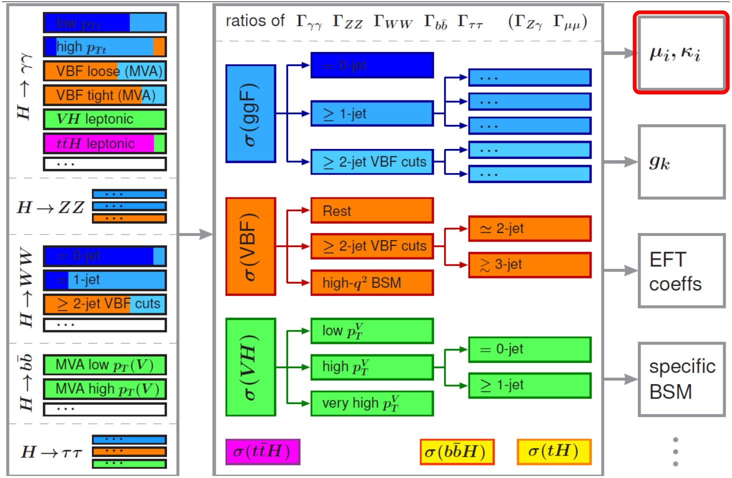
Performances of Run 2 in-situ calibration better than Run 1. Cross-checks performed on photons from $Z \to ll\gamma$.







Simplified Template Cross (X) Section (STXS) framework



Cross-sections in exclusive phase space regions (truth bins) allows to measure signal strengths ($\mu = \frac{\sigma^{exp}}{\sigma^{th}}$).

Couplings measurement strategy

Inclusive selection

- 2 tight isolated photons
- $\frac{p_T^{\gamma_{1(2)}}}{m_{\gamma\gamma}} > 0.35\ (0.25)$
- $|\eta| \in [0, 1.37] \cup [1.52, 2.37]$
- $m_{\gamma\gamma} \in [105, 160]$ GeV

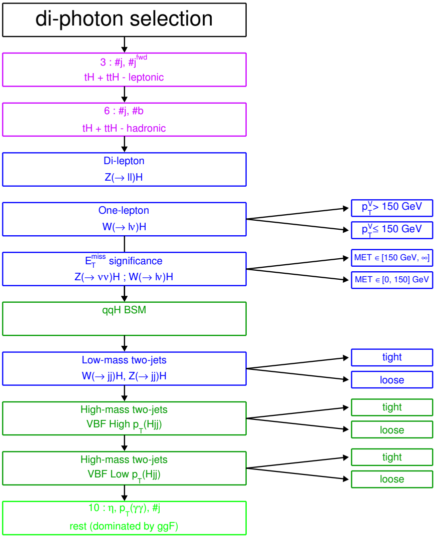
Dataset properties

- $\sim$ 330k events
- 42% signal efficiency
- $\simeq$ 1730 SM expected signal yield

Analysis strategy

- Define reconstructed categories targetting specific truth bin.
- Measure acceptance of each category wrt truth bins.
- Evaluate systematics effects on signal model.
- Combined fit of $m_{\gamma\gamma}$ distribution with signal+bkg model.

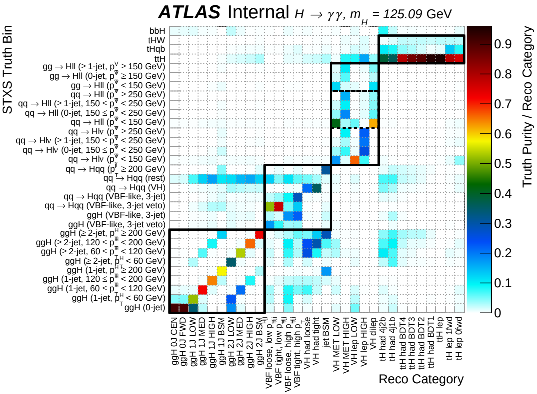
Reconstructed categories



Optimised sensitivity to :

- rare processes
- truth bins
- detector resolution

Signal events distribution over truth bins per category



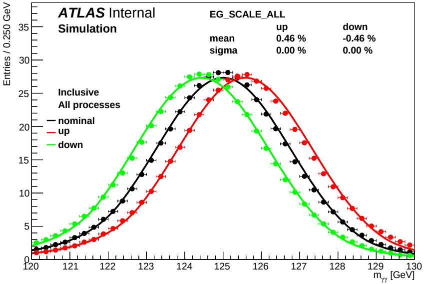
- Columns : distribution of events of a given category over the truth bins.
- Rectangles : process optimised categories

Good performances of process targetting

Calibration uncertainties methodology

For each systematic sources (energy scale for example) and each category :

- Create distributions of :
  - $m^{\text{nom}} = m^{rec}\sqrt{(1+\alpha_1)(1+\alpha_2)}$
  - $m^{\text{up}} = m^{rec}\sqrt{(1+\alpha_1+\Delta\alpha_1)(1+\alpha_2+\Delta\alpha_2)}$
  - $m^{\text{down}} = m^{rec}\sqrt{(1+\alpha_1-\Delta\alpha_1)(1+\alpha_2-\Delta\alpha_2)}$
- Fit distributions using signal model (Double Sided Crystal Ball)
- Define systematic variation : $\Delta X = \frac{X^{fluct}}{X^{nom}} - 1$
  $X \in$ mean, RMS, yield



1 source of uncertainty = 1 nuisance parameter (NP)

Correlation models

Two correlation models :

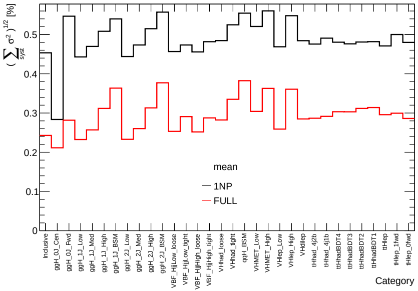
1NP

- 2NP (scale + resolution)
- Fully correlated
- Conservative
- Faster

FULL

- 86 NP (77 scale + 9 resolution)
- True correlation

Total Scale Uncertainty (%)	1NP	FULL
Measurement with $H \to \gamma\gamma$ MC	0.46	0.27
Formula	0.47	0.26



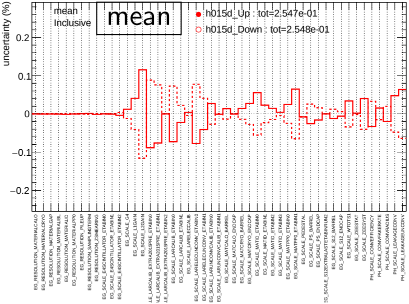
Calibration uncertainties results

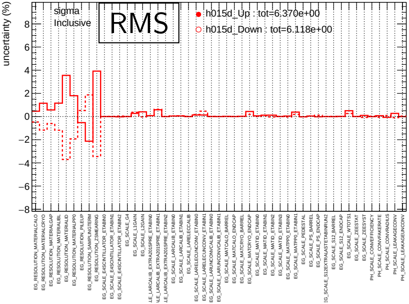
Merged Model : 49 NP

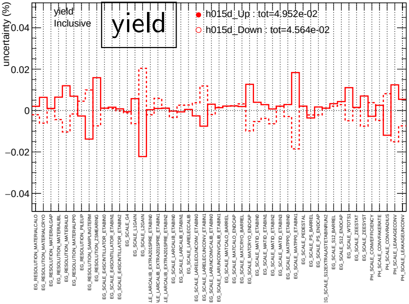
- 9 for resolution
- 40 for scale

impacting

- resolution
- mass
- yield per category

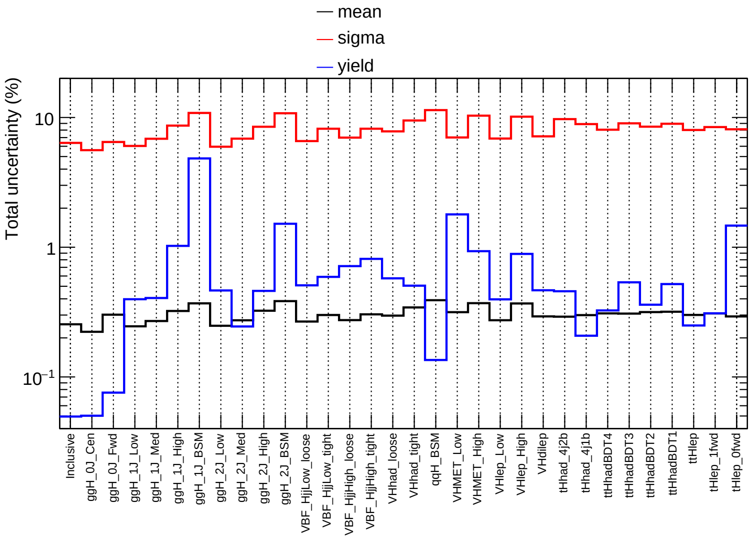






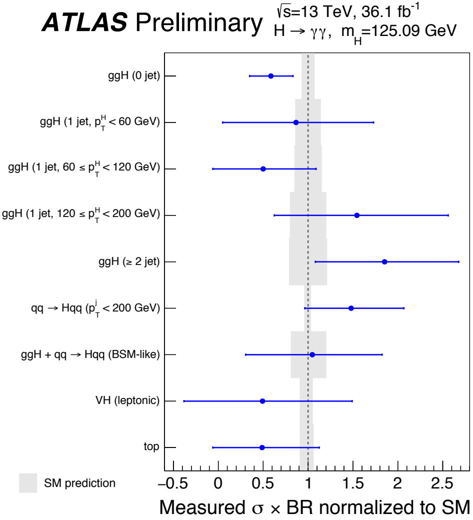
Total uncertainty

Total calibration uncertainty as a function of reconstructed category.



Run 2 $H \to \gamma\gamma$ couplings results

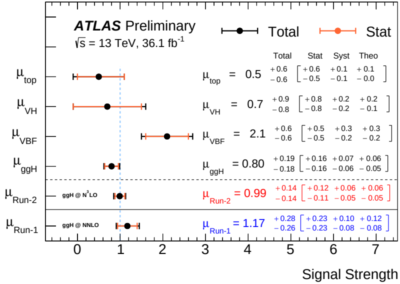
Due to lack of statistics, some truth bins have been merged. Grey area represents theory uncertainty (not included in measurement).



Run 2 $H \to \gamma\gamma$ signal strength results

STXS difficult to interpret directly.

Measurement of signal strengths $\mu_i = \frac{\sigma_i^{exp}}{\sigma_i^{SM}}$ performed ($\mu = 1 = $ SM).



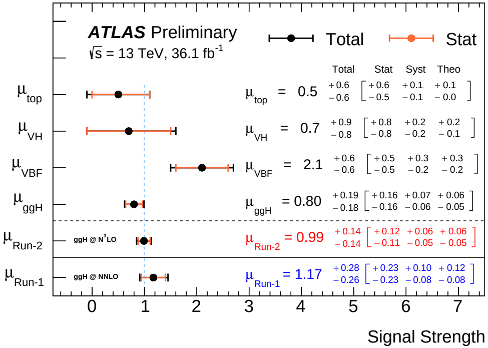
Uncertainty Group	$\sigma_\mu^{\text{syst.}}$
Theory (yield)	0.03
Experimental (yield)	0.02
Luminosity	0.03
Theory (migrations)	0.05
Experimental (migrations)	0.01
Mass resolution	0.03
Mass scale	0.04
Background shape	0.03

- Major theory improvement wrt Run 1
- Major resolution improvement wrt Run 1
- Increase of mass scale impact
- **No deviation from SM**

Conclusion

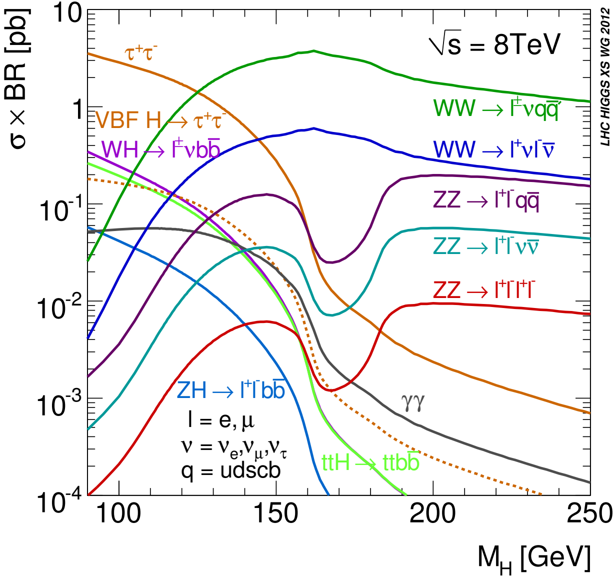
- Outstanding LHC performance $\rightarrow$ large statistics available
- Major improvement of calibration uncertainties
  resolution uncertainties no longer dominant on μ
- Couplings measurement performed with 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV
- **No significant deviation from standard model**

- Much more data expected until end of run 2
- **Work on experimental systematics required**



Back-up

Effective H events production



Mass dependence of BR

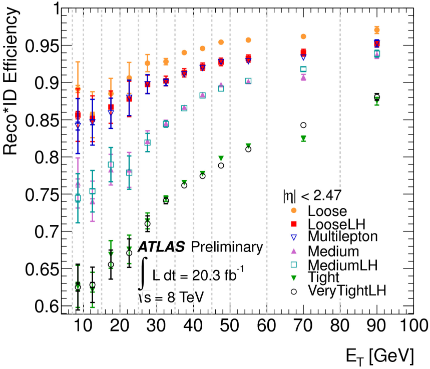
BR (%)	124.8	125.1	125.4	$\frac{\Delta \mathrm{BR}}{\mathrm{BR}}$
$H \to b\bar{b}$	58.0	57.5	57.1	3.2
$H \to ZZ$	2.59	2.67	2.74	4.2
$H \to \gamma\gamma$	0.228	0.228	0.228	4.9

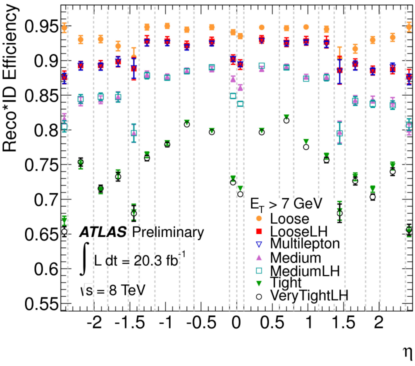
Identification variables

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 η.

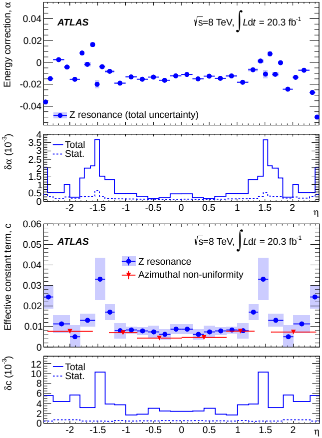




Calibration in-situ : run 1 results and uncertainties

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

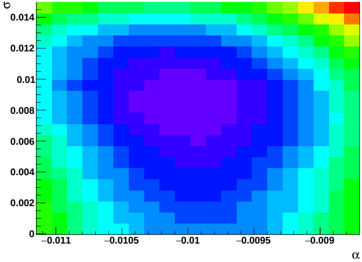
- electron identification quality from medium to tight.
- Z mass window
- electron p_T cut
- uncertainties on efficiencies scale factors
- energy loss through bremshtrahlung
- background
- pile-up
- measurement method



Calibration MVA variables

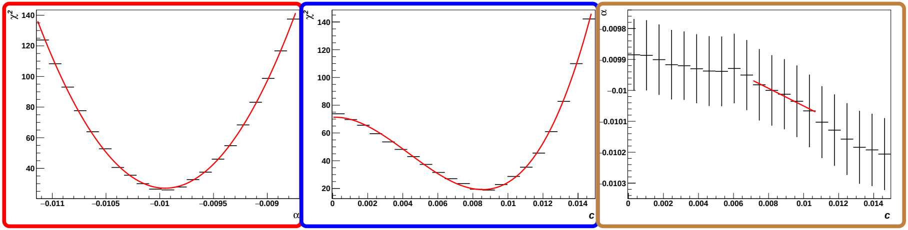
- $\mathrm{E_{acc}}$: sum of uncalibrated energies measured in the accordion.
- $\mathrm{E_0/E_{acc}}$: ratio of the energy in the presampler over the energy in the accordion.
- E_1/E_2 : ratio of the uncalibrated energy in the first over the second layer (E_1/E_2).
- η_{cluster} : pseudo rapidity in the ATLAS frame.
- Cell index : an integer number defined as the integer part of the division ($\eta_{\mathrm{calo}}/\Delta\eta$) where η_{calo} is the cluster pseudo rapidity in the calorimeter frame with $\Delta\eta$ as the size of one cell in the middle layer.
- η position of the cluster with respect to the cell edge.
- ϕ with respect to the lead absorber. This variable is sensitive to the modulation of the thickness of the absorber as a function of ϕ.

Template method



Minimum of χ^2 distribution fitted in 2 steps of 1D fits :

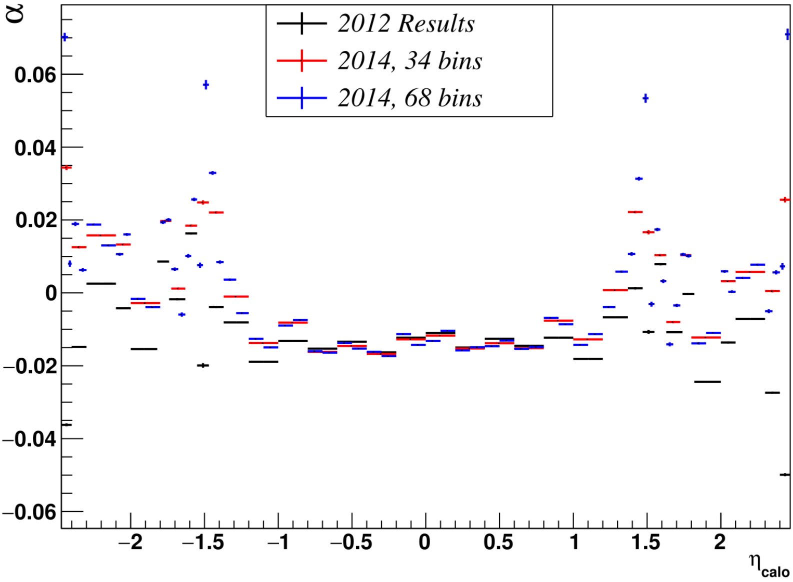
- fit $\chi^2 = f(\alpha)$ at constant c (lines) $\rightarrow (\alpha_{min}, \chi^2_{min})$.
- fit $\chi^2_{min} = f(c) \rightarrow (c, \Delta c)$
- project c in $\alpha_{min} = f(c)$, corresponding bin gives $(\alpha, \Delta\alpha)$.



In situ calibration η_{calo} bin frontiers

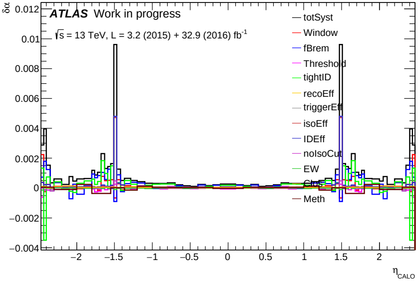
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.285 1.37 1.42 1.47 1.51 1.55 1.59 1.63 1.6775 1.725 1.7625 1.8 1.9 2 2.05 2.1 2.2 2.3 2.35 2.4 2.435 2.47

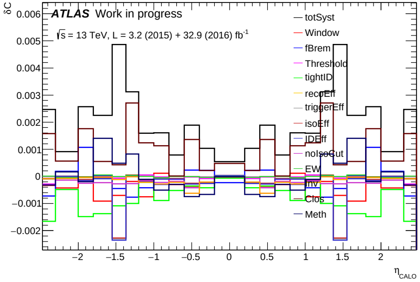
In-situ 2015 pre-recommandations : binning uncertainty



In situ scale uncertainties uncertainties

12 (13) sources of uncertainties have been evaluated for α (c).

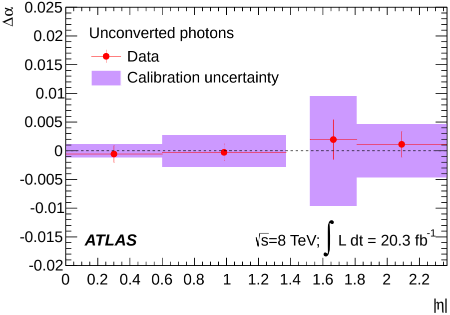


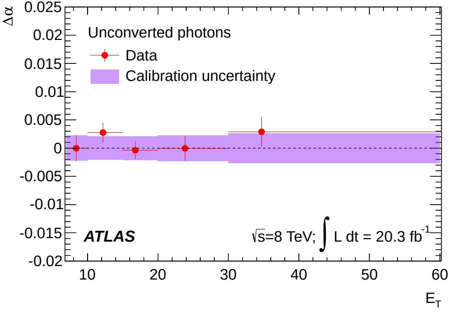


Photon correction

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

No significant deviation observed.

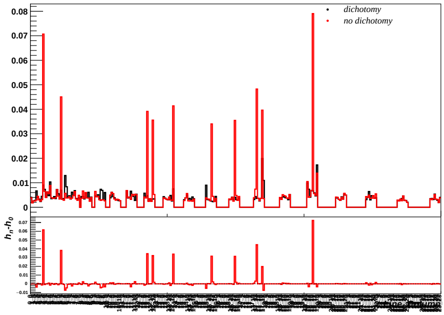


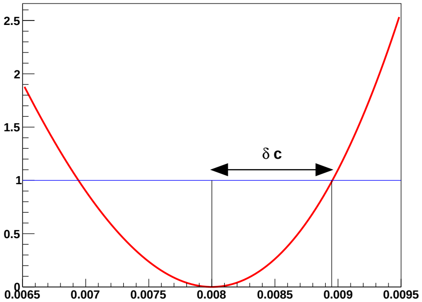


c fit

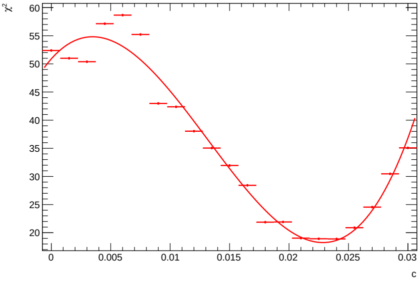
$$a_0(c) = b_0 + \frac{(c-\hat{c})^2}{{b_2}^2} + b_1 . \frac{(c-\hat{c})^3}{{b_2}^3}$$

$$P(\hat{c} + \delta c) = 1 \qquad (2)$$

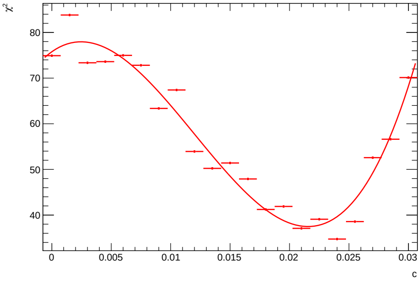




Z mass distribution binning



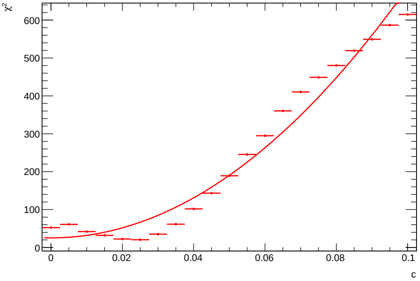
(a) 20 bins

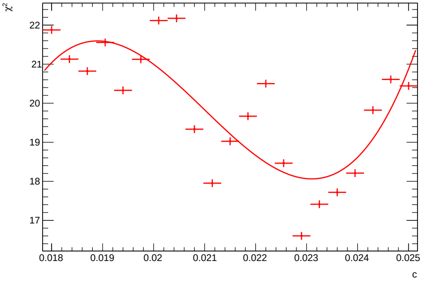


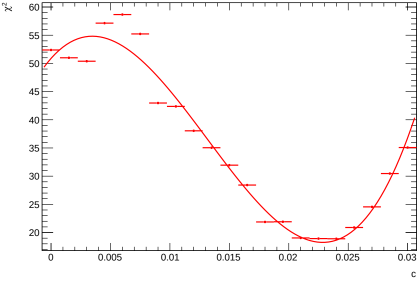
(b) 40 bins

Comparison of χ^2 distributions for different Z mass distribution binnings.

Scale range optimisation

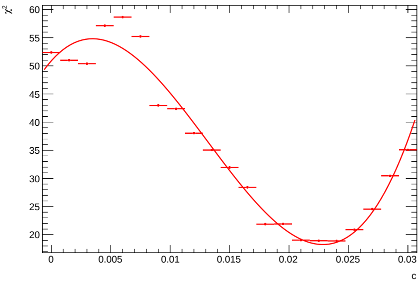




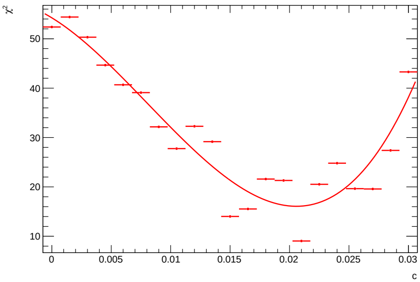


- top left : arbitrary conservative values
- top right : 1σ range
- bottom left : 5σ

Template correlation



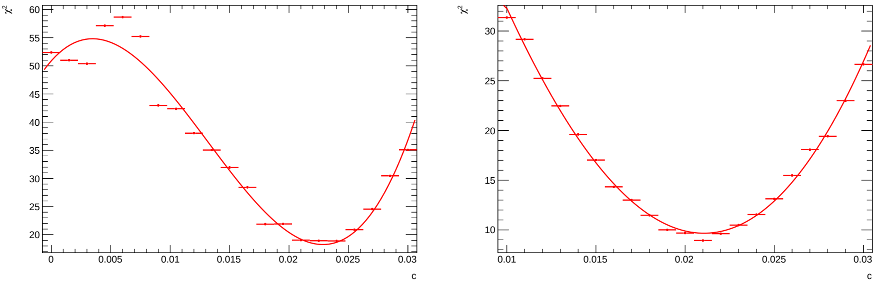
(a) correlated



(b) uncorrelated

Comparison of χ^2 distribution between a correlated and uncorrelated MC template smearing. Uncorrelated supposes that mass smearings in two different templates use different random numbers.

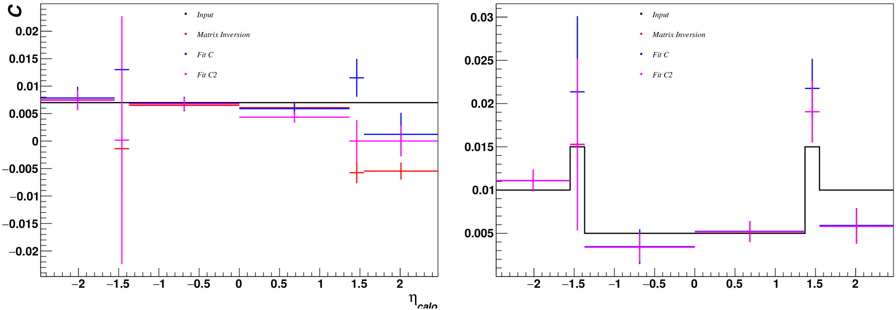
N_{useEl}



(a) $N_{\text{useEl}} = 1$ (b) $N_{\text{useEl}} = 10$

χ^2 distribution for a typical configuration for different values of N_{useEl}. In both cases, pseudo-data corresponds to the same dataset as the MC in which a constant term has been injected.

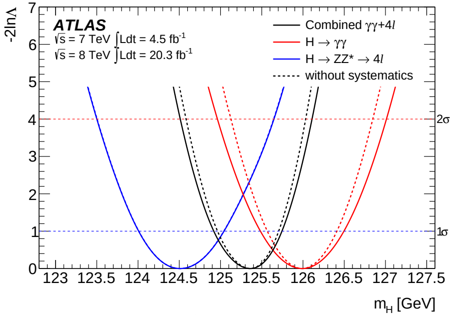
Inversion



Comparison of closures for different inversion procedures.

ATLAS run 1 H boson mass measurement

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



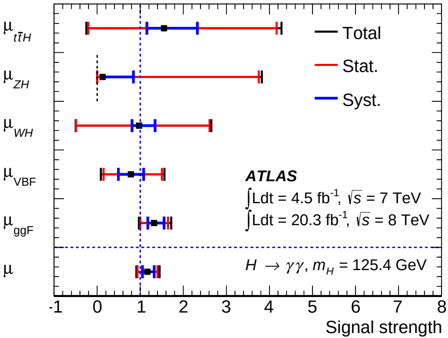
Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_T)	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

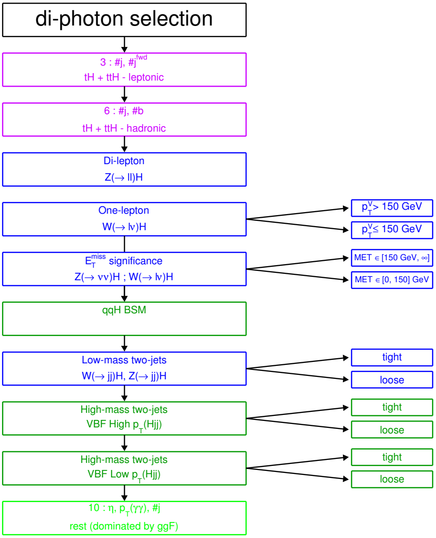
$$\mu_{\gamma\gamma} = \frac{(\sigma \times BR)^{meas}}{(\sigma \times BR)^{SM}} = 1.17 \pm 0.23(\text{stat}) \,^{+0.10}_{-0.08}(\text{syst}) \,^{+0.12}_{-0.08}(\text{theory})$$



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**.

Reconstructed categories

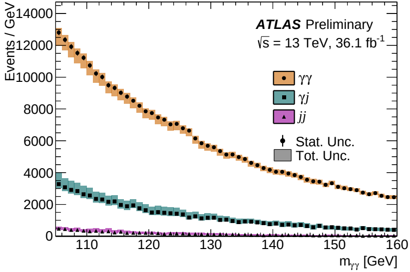


Optimised sensitivity to :

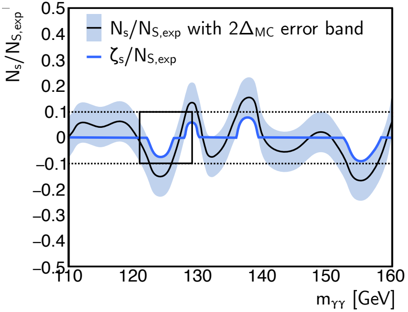
- rare processes
- truth bins

Category	Selection
tH lep 0fwd	$N_{\text{lep}} = 1$, $N_{\text{jets}}^{\text{cen}} \leq 3$, $N_{\text{b-tag}} \geq 1$, $N_{\text{jets}}^{\text{fwd}} = 0$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
tH lep 1fwd	$N_{\text{lep}} = 1$, $N_{\text{jets}}^{\text{cen}} \leq 4$, $N_{\text{b-tag}} \geq 1$, $N_{\text{jets}}^{\text{fwd}} \geq 1$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
ttH lep	$N_{\text{lep}} \geq 1$, $N_{\text{jets}}^{\text{cen}} \geq 2$, $N_{\text{b-tag}} \geq 1$, $Z_{\ell\ell}$ veto ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
ttH had BDT1	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{b-tag}} \geq 1$, $\text{BDT}_{\text{ttH}} > 0.92$
ttH had BDT2	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{b-tag}} \geq 1$, $0.83 < \text{BDT}_{\text{ttH}} < 0.92$
ttH had BDT3	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{b-tag}} \geq 1$, $0.79 < \text{BDT}_{\text{ttH}} < 0.83$
ttH had BDT4	$N_{\text{lep}} = 0$, $N_{\text{jets}} \geq 3$, $N_{\text{b-tag}} \geq 1$, $0.52 < \text{BDT}_{\text{ttH}} < 0.79$
tH had 4j1b	$N_{\text{lep}} = 0$, $N_{\text{jets}}^{\text{cen}} = 4$, $N_{\text{b-tag}} = 1$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
tH had 4j2b	$N_{\text{lep}} = 0$, $N_{\text{jets}}^{\text{cen}} = 4$, $N_{\text{b-tag}} \geq 2$ ($p_{\text{T}}^{\text{jet}} > 25$ GeV)
VH dilep	$N_{\text{lep}} \geq 2$, $70\,\text{GeV} \leq m_{\ell\ell} \leq 110\,\text{GeV}$
VH lep HIGH	$N_{\text{lep}} = 1$, $\lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV}$, $p_{\text{T}}^{l+E_{\text{T}}^{\text{miss}}} > 150\,\text{GeV}$
VH lep LOW	$N_{\text{lep}} = 1$, $\lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV}$, $p_{\text{T}}^{l+E_{\text{T}}^{\text{miss}}} < 150\,\text{GeV}$, $E_{\text{T}}^{\text{miss}}$ significance > 1
VH MET HIGH	$150\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 250\,\text{GeV}$, $E_{\text{T}}^{\text{miss}}$ significance > 9 or $E_{\text{T}}^{\text{miss}} > 250\,\text{GeV}$
VH MET LOW	$80\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 150\,\text{GeV}$, $E_{\text{T}}^{\text{miss}}$ significance > 8
jet BSM	$p_{\text{T,j1}} > 200\,\text{GeV}$
VH had tight	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV}$, $\text{BDT}_{\text{VH}} > 0.78$
VH had loose	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV}$, $0.35 < \text{BDT}_{\text{VH}} < 0.78$
VBF tight, high p_T^{Hjj}	$\Delta\eta_{\text{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_T^{Hjj} > 25\,\text{GeV}$, $\text{BDT}_{\text{VBF}} > 0.47$
VBF loose, high p_T^{Hjj}	$\Delta\eta_{\text{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_T^{Hjj} > 25\,\text{GeV}$, $-0.32 < \text{BDT}_{\text{VBF}} < 0.47$
VBF tight, low p_T^{Hjj}	$\Delta\eta_{\text{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_T^{Hjj} < 25\,\text{GeV}$, $\text{BDT}_{\text{VBF}} > 0.87$
VBF loose, low p_T^{Hjj}	$\Delta\eta_{\text{jj}} > 2$, $\lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5$, $p_T^{Hjj} < 25\,\text{GeV}$, $0.26 < \text{BDT}_{\text{VBF}} < 0.87$
ggH 2J BSM	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \geq 200\,\text{GeV}$
ggH 2J HIGH	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \in [120, 200]$ GeV
ggH 2J MED	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \in [60, 120]$ GeV
ggH 2J LOW	≥ 2 jets, $p_{\text{T}}^{\gamma\gamma} \in [0, 60]$ GeV
ggH 1J BSM	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \geq 200\,\text{GeV}$
ggH 1J HIGH	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \in [120, 200]$ GeV
ggH 1J MED	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \in [60, 120]$ GeV
ggH 1J LOW	$= 1$ jet, $p_{\text{T}}^{\gamma\gamma} \in [0, 60]$ GeV
ggH 0J FWD	$= 0$ jets, one photon with $\lvert\eta\rvert > 0.95$
ggH 0J CEN	$= 0$ jets, two photons with $\lvert\eta\rvert \leq 0.95$

Background parametrization



- MC not reliable for background description
- Shape fitted on data
- Spurious signal (signal measured on background only sample) evaluated for selection of functional form.

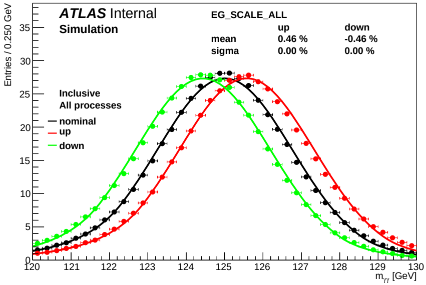


$$\zeta_s = \begin{cases} (N_s+2\Delta_{MC}), & N_s+2\Delta_{MC} < 0 \\ (N_s-2\Delta_{MC}), & N_s-2\Delta_{MC} > 0 \\ 0, & \text{otherwise} \end{cases}$$

Calibration uncertainties methodology

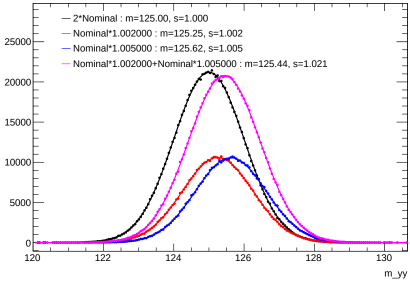
For a given systematic source :

- Create distributions of $m_{\gamma\gamma}^{nom}$, $m_{\gamma\gamma}^{up}$, $m_{\gamma\gamma}^{down}$
- Fit main parameter of the systematic with DSCB :
  - Fit $m_{\gamma\gamma} \in [105, 160]$GeV
  - Fixing $n_{high} = 5$ and $n_{low} = 9$
  - Fixing $\alpha_{high} = \hat{\alpha}_{high}^{nom}$, $\alpha_{low}^{nom} = \hat{\alpha}_{low}^{nom}$, $X = \hat{X}^{nom}$
- Systematic variation : $\frac{X^{fluct}}{X^{nom}} - 1$, $X \in \{\mu, \sigma\}$



$$CB(m_{\gamma\gamma}) = \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{low} \leq t \leq \alpha_{high} \\ \dfrac{e^{-\frac{1}{2}\alpha_{low}^2}}{\left[\frac{1}{R_{low}}\left(R_{low} - \alpha_{low} - t\right)\right]^{n_{low}}} & \text{if } t < -\alpha_{low} \\ \dfrac{e^{-\frac{1}{2}\alpha_{high}^2}}{\left[\frac{1}{R_{high}}\left(R_{high} - \alpha_{high} + t\right)\right]^{n_{high}}} & \text{if } t > \alpha_{high} \\ t = (m_{\gamma\gamma} - \mu)/\sigma,\ R_{low} = \dfrac{\alpha_{low}}{n_{low}},\ R_{high} = \dfrac{\alpha_{high}}{n_{high}} \end{cases} \quad (3)$$

Scale impact on width

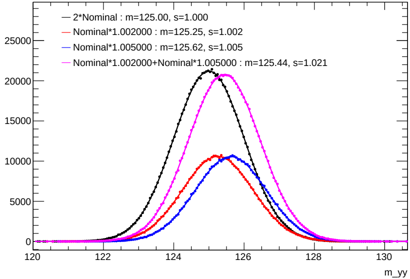


1M random numbers generated on a Gaussian($\mu = 125, \sigma = 1$).

- Initial numbers distribution.
- Half events multiplied by 1.002.
- Remaining events multiplied by 1.005.
- Combined distribution of red and blue.

Mean (m) and RMS (s) of a fitted gaussians are given in the legend.
Interpretationof the curve in the next slides.

μ/σ scale correlation



Lets assume a gaussian distributed energy distribution. Applying energy scale correction gives :

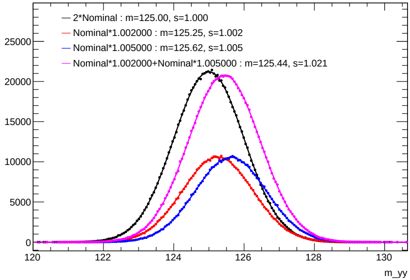
$$E \rightarrow E(1+a)$$

Hence the distribution will be changed to :

$$exp(-\frac{(E-\mu)^2}{2\sigma^2} \rightarrow exp(-\frac{(\frac{E}{1+a}-\mu)^2}{2\sigma^2}) = exp(-\frac{(E-\mu(1+a))^2}{2\sigma^2(1+a)^2}) \quad (4)$$

The new distribution is a shifted gaussian with scaled RMS.
Given the medium shift of EG_SCALE_ALL, we expect ${}^{+0.4}_{-0.4}\%$ change in resolution.

Inhomegenous scale



The RMS of two points separated by d is $d/4$.
If d is the difference between two scale factors,

$$d \sim 3.10^{-3} \cdot E_\gamma = 0.18$$

$$\frac{\text{RMS}}{\text{Resolution}} = \frac{d/4}{1.5\text{GeV}} = 3\%$$

The inhomogeneity of the scale factors uncertainties changes the width of the distribution at the percent level. This effect will always increase the width.

Black and pink distribution show an illustration of this effect.

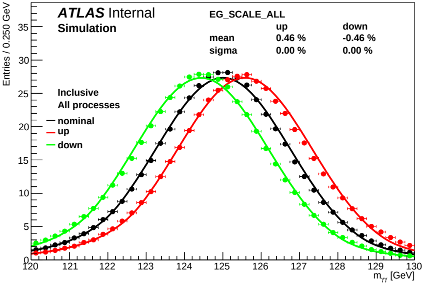
Scale factors interpretation

Assume the up fluctuation (red) as data and nominal distribution (black) as MC in the template method. One has

$$m_H^{up} = m_H^{nom}(1+\alpha)$$

Hence

$$\delta_{m_H} = \alpha$$



Furthermore :

$$\sigma_H^{up} = \sigma_H^{nom} \oplus cE$$

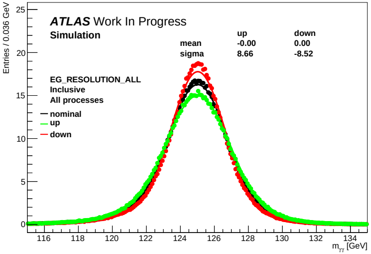
Hence

$$\delta_{\sigma_H} = \sqrt{1 + \frac{c^2 E^2}{\sigma_H^2}} - 1$$

One has to be carefull with resolution uncertainty as the template method is weak to measure small differences.

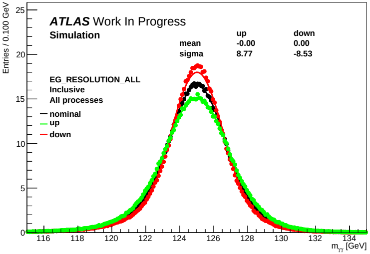
Method comparison

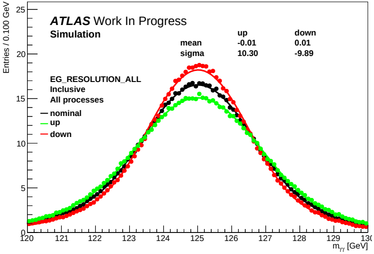
4 different fitting methods are compared : fitting in 3 different ranges and template method cross-check within $[122, 128]$GeV. Methods compared on h013 simplified model (2NP).



$\leftarrow$ $[105, 160]$

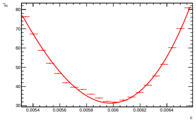
$\rightarrow$ $[115, 135]$





$\leftarrow$ $[120, 130]$

$\rightarrow$ $[122, 128]$

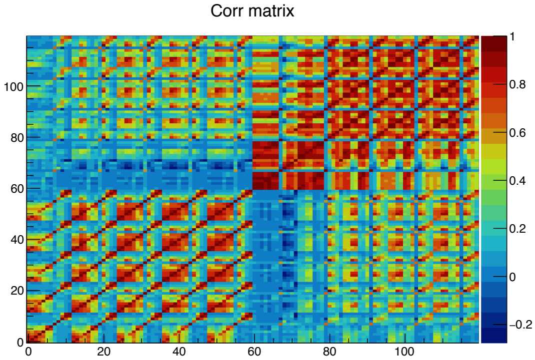


$$c = (0.598 \pm 0.009)\%$$

$$\rightarrow \delta_{\sigma_H} = (8.82 \pm 0.25)\%$$

Uncertainty correlation formula

$$\frac{\sigma(M)}{M} = \frac{1}{N_\gamma}\sqrt{\sum_{ij} N_i N_j V_{ij}}. \qquad (5)$$



Total Scale Uncertainty (%)	1NP	FULL
Measurement with $H \to \gamma\gamma$ MC	0.46	0.27
Formula	0.47	0.26

Likelihood Method

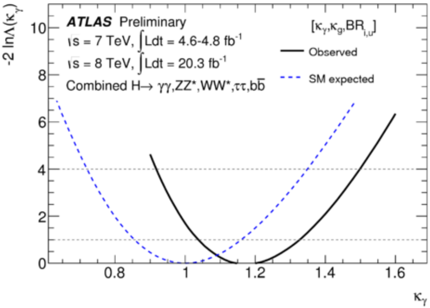
A function (**likelihood**) is built to **evaluate the best set of parameters ($\vec{\mu}$,$\vec{\theta}$)** of a model to agree the best with a dataset in a category.

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

(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 :

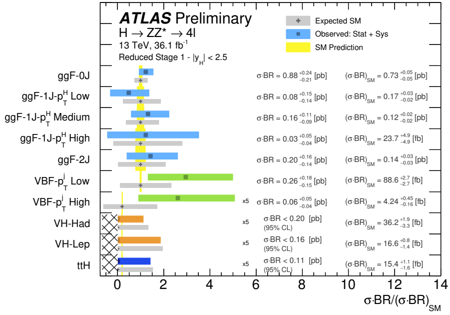
$$L(1 + \delta_L \theta_L) e^{-\theta_L^2/2}$$

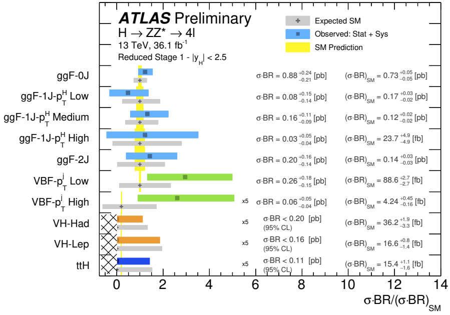
Error Estimation

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.

ATLAS $H \to 4l$ couplings measurement

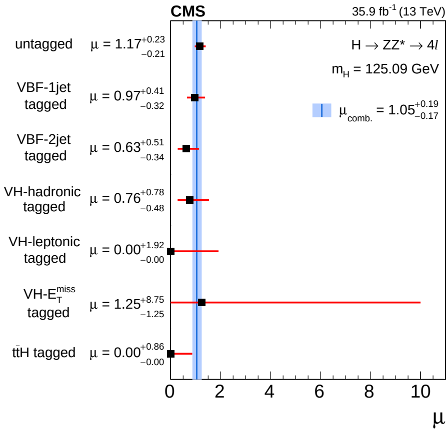
ATLAS-CONF-2017-043

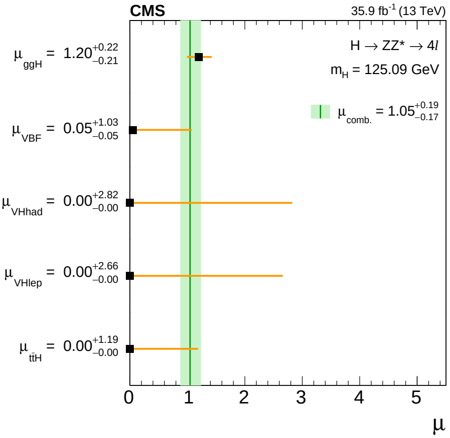




CMS $H \to 4l$ couplings measurement

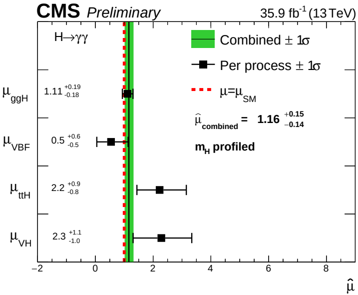
CMS-HIG-16-041

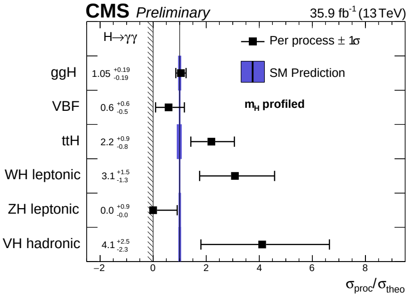




CMS $H \to \gamma\gamma$ couplings measurement

CMS-PAS-HIG-16-040





Run 2 H boson mass measurement

ATLAS

Channel	Mass measurement [GeV]
$H \to ZZ^* \to 4\ell$	124.88 ± 0.37 (stat) ± 0.05 (syst) $= 124.88 \pm 0.37$
$H \to \gamma\gamma$	125.11 ± 0.21 (stat) ± 0.36 (syst) $= 125.11 \pm 0.42$
Combined	124.98 ± 0.19 (stat) ± 0.21 (syst) $= 124.98 \pm 0.28$

CMS

$$H \to 4l : 125.26 \pm 0.20(\text{stat.}) \pm 0.08(\text{syst})$$

$$H \to \gamma\gamma : 125.4 \pm 0.15(\text{stat.}) \pm \sim 0.3(\text{syst})$$