Run 1 results on the scalar boson:
mass and couplings

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for the ATLAS & CMS collaborations
Introduction

• The discovery of a Higgs-like boson in 2012 has set new goals for the LHC experiments:
  – measure precisely the mass of the boson (the last free parameter in the Standard Model)
  – test if the particle is indeed a scalar boson → *topic of next talk*
  – test if its couplings are compatible with SM predictions (several BSM theories can contain Higgs-like particles)
  – search for rare or more challenging production or decay modes → *see talks in monday's BEH session*
Mass measurement

• The mass of the boson is directly accessible through the $H \rightarrow \gamma \gamma$ and $H \rightarrow 4\ell$ decays:
  – the kinematic of the decay is fully reconstructed
  – all final state objects can be precisely measured
  – theoretical issues negligible at the current precision

• Indeed, a mass measurement at 0.5% accuracy was available on the very day of the discovery!

• Improved analyses of the full Run 1 dataset have allowed gaining a factor 2 in precision
Analyses

• LHC experiments have released the final run 1 mass measurement papers in both final states:
  – CMS: 4ℓ and γγ papers [arXiv:1312.5353, 1407.0558], preliminary combination [HIG-14-009]

• Fundamental ingredient: excellent lepton and photon efficiency, resolution and energy scale calibration
  → see talks in monday’s LHC Run 1 legacy session
H → γγ analysis strategy

1. Fit narrow mass peak over smooth background
2. Enhance the sensitivity by categorizing events by purity and mass resolution.
Categorization

- **ATLAS**: dedicated event categorization for the mass measurement analysis:
  - Categorization by photon $\eta$ and quality (unconverted vs converted), and by diphoton $p_T$ ($p_T$ rel. to trust axis)
- **CMS**: same analysis used for mass and couplings (and optimized for the latter)
  - Tagged categories for VBF, VH, $ttH$ production modes: 7 topologies, based on jets, $E_T^{\text{miss}}$, leptons, $b$-tags
  - Untagged events categorized using a BDT classifier relying on photon $p_T$, $\eta$, purity, and $m(\gamma\gamma)$ resolution
- Larger variation of $m(\gamma\gamma)$ resolution in CMS categories compared to ATLAS ones
$H \rightarrow ZZ \rightarrow 4\ell$
H → ZZ → 4ℓ strategy

- Extremely clean signature, but challenging due to very low BR ($10^{-4}$) and soft lepton $p_T$ spectrum
H → ZZ → 4ℓ strategy

• Extremely clean signature, but challenging due to very low BR (10^{-4}) and soft lepton p_T spectrum

• Fully reconstructed final state optimal for exploiting matrix element methods
  – Now included also in ATLAS analysis, combined in a BDT together with Higgs p_T and rapidity
Improving further $4\ell$ mass

- In $\sim 75\%$ of the $H \to ZZ \to 4\ell$ events, one $Z$ boson is on mass shell:
  - a kinematic fit of the $Z$ decay improves the $m(4\ell)$ resolution event by event, and reduces the energy scale systematic.
  - used by ATLAS only, $\sim 15\%$ gain on $\sigma(m)$
Improving further $4\ell$ mass

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- Lepton momentum resolution dependent on $p_T$, $\eta$, and quality (esp. for electrons)
  - $m_H$ fit can be performed using the individual $m(4\ell)$ resolutions of each observed event
  - now used also by ATLAS (as cross-check)

- Identification of photons from final state radiation recovers signal tail at low $m(4\ell)$, and improves isolation efficiency
  - now implemented also in ATLAS analysis
Systematics: muon momentum scale

- Muon momentum scale calibrated and validated on Z, J/ψ, Υ decays
Systematics: muon momentum scale

- Muon momentum scale calibrated and validated on $Z, J/\psi, \Upsilon$ decays
- After calibration, the systematic uncertainty on $m_H$ from the muon scale is negligible with respect to the statistical uncertainty:
  - ATLAS: 0.04%
  - CMS: 0.1% (conservative)
    (stat. uncertainty: $\sim$0.4%)
Systematics: electrons energy scale

• Similar approaches as for muons at Z peak, but more challenging at low \( p_T \):
  – smaller calibration samples of \( J/\psi, \Upsilon \) (due to trigger)
  – relative weight of calo & tracker changes with \( p_T \)
• Scale uncertainty on \( m(4e) \): 0.3% (CMS), 0.04% (ATLAS)
• Impact on \( m_H \) reduced by the smaller weight of 4e and 2\( \mu \)2e states wrt 4\( \mu \), 2e2\( \mu \) in comb.
  – also by Z1 refit for ATLAS
Systematics: photons

- Energy scale calibrated on $Z \rightarrow ee$ in data, then extrapolated to $H \rightarrow \gamma\gamma$ using MC. Main challenges:
  - Linearity: harder $p_T$ spectrum in $H(125) \text{ vs } Z(91.2)$
  - Photon to electron differences in data vs MC: from uncertainties in material description, longitudinal calibration, shower modelling.

- The scale uncertainty drives the systematic on the $m_H$ measurement in $\gamma\gamma$ channel.
  - ATLAS vs CMS difference, due to more challenging response calibration for ATLAS detector (see backup)

<table>
<thead>
<tr>
<th></th>
<th>stat.</th>
<th>syst.</th>
<th>comb.</th>
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</thead>
<tbody>
<tr>
<td><strong>ATLAS $\gamma\gamma$</strong></td>
<td>0.42 GeV</td>
<td>0.28 GeV</td>
<td>0.50 GeV</td>
</tr>
<tr>
<td><strong>CMS $\gamma\gamma$</strong></td>
<td>0.31 GeV</td>
<td>0.15 GeV</td>
<td>0.35 GeV</td>
</tr>
</tbody>
</table>
Results

\begin{center}
\begin{tabular}{|l|l|l|}
\hline
 & ATLAS fit ± stat. ± syst & CMS fit ± stat. ± syst \\
\hline
\gamma\gamma & 125.98 ± 0.42 ± 0.28 GeV & 124.70 ± 0.31 ± 0.15 GeV \\
\hline
4\ell & 124.51 ± 0.52 ± 0.06 GeV & 125.8 ± 0.4 ± 0.2 GeV \\
\hline
comb & 125.36 ± 0.37 ± 0.18 GeV & 125.03 ± 0.26 ± 0.14 GeV \\
\hline
\end{tabular}
\end{center}
Rencontres du Vietnam 2014:
Physics at LHC and beyond

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(CERN)

COUPLINGS

\[ \lambda \text{ or } (g/2\nu)_{10} \]

\[ \text{CERN preliminary} \]

\[ 9.7 \pm (0.1 \text{ stat}) \pm (0.1 \text{ sys}) \text{ TeV} \]

\[ \text{EM Higgs} \]

\[ 95\% \text{ CL} \]

\[ 0.1 \text{ TeV} \]
Testing compatibility with the SM

- Probing for the Higgs boson in many final states allows testing compatibility with the SM predictions, but:
  - sensitivity in many individual final states is limited
  - contributions from different production or decay modes hard to disentangle in some topologies (e.g. H+jets), making results harder to interpret in BSM models
Why couplings?

• Analyzing the combined data in terms of couplings helps overcoming these limitations:
  – harvests all information on the same coupling from both production and decay, in all experimental final states
  – allows direct comparison with BSM predictions without requiring theorists to simulate our experimental analyses

\[ ggH, \ H \rightarrow ZZ \]

\[ VBF, \ H \rightarrow \gamma\gamma \]

\[ ZH, \ H \rightarrow bb \]
Input analyses

<table>
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<tr>
<th>decay</th>
<th>production mode tags</th>
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<tr>
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<tr>
<td>γγ</td>
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<tr>
<td>bb</td>
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<tr>
<td>ττ</td>
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</table>

- CMS: preliminary combination [HIG-14-009], but all included inputs are now submitted as final run 1 papers
- ATLAS: preliminary combination [ATLAS-CONF-2014-009] of *in itinere* papers on WW, ZZ, γγ and preliminary bb, ττ
- Direct H→invis, Zγ, μμ searches exist but are not included

(*) Not a dedicated category, but the di-jet discriminant can separate VH(V→jj) from ggH+jets and VBF

= Included in comb. (full 8 TeV dataset)

= Full 8 TeV analyzed, but not yet in comb.
Testing couplings

- Framework set within LHC Higgs XS WG [CERN YR3].
- Assume a single, narrow width, scalar boson:
  \[ \sigma(xx \rightarrow H \rightarrow yy) = \sigma(xx) \times \frac{\Gamma_{yy}}{\Gamma_{tot}} \]
- Parameterize deviations of \( \sigma \) and \( \Gamma \) from their SM values in terms of coupling modifiers \( \kappa_i \) (or ratios \( \lambda_{ij} := \frac{\kappa_i}{\kappa_j} \)).
Approximations and assumptions

- We account for deviations only in expected yields, not in the kinematics of individual processes
  - limitation of experimental analyses and of used theory inputs
- We don’t have higher order corrections in theory predictions except for the SM case ($\kappa = 1$)
  - limitation of theoretical predictions
- Assumptions are needed on unmeasured couplings, (e.g. same relative deviations for charm and top)
  - limitation of the hadron collider environment
- We assume no beyond SM Higgs production modes, and that backgrounds are only from SM
General fits

- Full Run 1 dataset allows testing fairly general models, which can be constructed as following:
  1. Start introduce modifiers for tree-level couplings to $W$, $Z$, $t$, $b$, $\tau$: $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_{\tau}$ (or use a common $\kappa_V$)
  2. Two choices for loop-level contributions (e.g. $\sigma_{ggH}$, $\Gamma_{\gamma\gamma}$):
     A. Assume only SM particles in the loop: contribution can be computed in terms of $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_{\tau}$
General fits

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     B. Be agnostic: introduce effective $\kappa_g, \kappa_\gamma$ parameters
General fits

• Full Run 1 dataset allows testing fairly general models, which can be constructed as following:
  1. Start introduce modifiers for tree-level couplings to \( W, Z, t, b, \tau \): \( K_W, K_Z, K_t, K_b, K_\tau \) (or use a common \( K_V \))
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     B. Be agnostic: introduce effective \( K_g, K_\gamma \) parameters

• An alternative paradigm is instead to parameterize everything in terms of coupling ratios \( \lambda_{XY} \), except for one reference process setting the overall scale (by convention taken to be \( ggH, H \to ZZ \))
Vector bosons

- $W$ and $Z$ couplings tested at the 15-20% level.
- Good compatibility with SM predictions

**CMS, tree & loop $\kappa$'s, $\kappa_W = \kappa_Z$**

**ATLAS, tree-level only $\kappa$'s**

- $W$ and $Z$ couplings tested at the 15-20% level.
- Good compatibility with SM predictions.
Bottom, Tau

- Coupling probed at the 30-40% level
  - Agreement with SM, with some preference for smaller $\kappa$ values
- Deviations on $b$ couplings also affect strongly the yields in other modes through $\Gamma_{bb}$ in $\Gamma_{tot}$ at denominator
  - and cancellation $\Gamma_{bb}/\Gamma_{tot}$ in makes $VH\to bb$ yield not so sensitive to $\kappa_b$

ATLAS, tree-level only $\kappa$'s: interference in $\gamma\gamma$ and $gg$ loops sensitive to sign of $\kappa$

CMS, tree & loop $\kappa$'s: assume $\kappa > 0$
Top

- Can be probed directly via $t\bar{t}H$ production: 
  $\rightarrow$ dedicated talk on $t\bar{t}H$ in Monday’s BEH session
- Also probed indirectly via loops in gluon fusion production and $H \rightarrow \gamma\gamma$ partial decay width:
  - Requires the assumption of no BSM particles in loop

CMS, $t\bar{t}H$ only:  
$\Delta \kappa/\kappa \sim 40-50\%$

ALAS, loop only:  
$\Delta \kappa/\kappa \sim 30\%$  
($t\bar{t}H$ not in this combination)

CMS, loops & $t\bar{t}H$:  
$\Delta \kappa/\kappa \sim 25\%$
Loop-induced couplings

- Effective couplings to gluons and photons are good probes for new physics beyond the SM:
  - Extra coloured particles can affect gluon fusion
  - Extra charged particles can affect $H \rightarrow \gamma \gamma$ decay
- BSM extensions like top partners give correlated deviations in the two

A qualitative sketch of possible deviations in $\kappa_g, \kappa_\gamma$
Loop-induced couplings

- Effective couplings to gluons and photons are good probes for new physics beyond the SM:
  - Extra coloured particles can affect gluon fusion
  - Extra charged particles can affect $H \rightarrow \gamma\gamma$ decay
- BSM extensions like top partners give correlated deviations in the two

ATLAS & CMS: simplified model with only loop couplings floating

contours redrawn for clarity from
ATLAS CONF-HIGG-14-009
CMS PAS-HIG-14-009
Loop-induced couplings

- In more general fits, deviations in couplings to photons tested at 15-20%, gluons at 20–30%
- Hard to constrain correlated shift in $\sigma(ggH)$ and $\Gamma_{\text{tot}}$ (e.g. from $\kappa_b$):
  - cancellation in $ggH \rightarrow VV$, $\gamma\gamma$ yields

CMS, $\kappa_g$ and $\kappa_\gamma$ from full tree+loop model

ATLAS, $g/Z$ and $\gamma/Z$ from full coupling ratio model
Probing BSM decays

- New physics can introduce new Higgs decay modes not detected at LHC.
  \[ \Gamma_{\text{tot}} = \Gamma_{\text{SM}}(\kappa_i) + \Gamma_{\text{BSM}} \]
- A larger \( \Gamma_{\text{tot}} \) can be resolved from a deviation in the \( \kappa \)'s if we have some assumption.

\[ \sigma(xx) \sim \kappa_x^2 \]
\[ \Gamma_{yy} \sim \kappa_y^2 \]
\[ \Gamma_{\text{tot}} = \kappa^2 \Gamma_{\text{SM}} + \Gamma_{\text{BSM}} \]

\[ \sigma \cdot BR \sim \frac{\kappa^2 \cdot \kappa^2}{\kappa^2 \Gamma_{\text{SM}} + \Gamma_{\text{BSM}}} \]
Probing BSM decays

- New physics can introduce new Higgs decay modes not detected at LHC.
  \[ \Gamma_{\text{tot}} = \Gamma_{\text{SM}}(\kappa_i) + \Gamma_{\text{BSM}} \]
- A larger \( \Gamma_{\text{tot}} \) can be resolved from a deviation in the \( \kappa \)'s if we have some assumption.
- Two scenarios considered:
  1. tree level couplings as in SM (assume new physics entering only in loops and decays)
  2. \( \kappa_V \leq 1 \) (EWSB motivated)
Overall picture

- Couplings to vector bosons and 3\textsuperscript{rd} generation fermions probed at ATLAS & CMS with 15-50% precision
  - Fair compatibility with SM predictions overall
Conclusions

• Final LHC Run 1 mass measurements available:
  – already in the realm of precision measurements: discussing sub-per-mille systematics in calibrations
  – work ongoing on ATLAS+CMS mass combination

• For couplings, the books are still quite open:
  – Current constraints at 10-50%: still room for almost-but-not-quite-SM-like Higgs bosons
  – Expect some further improvement already on Run 1 data, e.g. from final ATLAS analyses
  – Improving these constraints will be one of the main goals for Run 2 and beyond (incl. future machines)
BACKUP
Systematics: photon differences

- Some reasons for the difference in systematics:
  - Larger uncertainty from non-linearity in ATLAS (0.1% vs 0.08%): LAr gain switch at energies between Z and H
  - ATLAS has ~0.1% extra systematics from the material in between the inner detector and the calorimeter
  - CMS homogeneous crystal calorimeter reduces impact of longitudinal calibration systematic (0.02% vs 0.1%)
  - CMS synchronous categorization of photons and electrons by shower compactness mitigates the effects of the uncertainty on the material budget:
    - calibrate unconverted photons with golden electrons
    - calibrate converted photons with showering electrons
Theoretical systematics

• For overall $\mu$ and for $\mu_{ggH}$ experimental uncertainties are comparable to theoretical uncertainties.

CMS $\mu = 1.00^{+0.09}_{-0.09} \text{(stat)}^{+0.08}_{-0.07} \text{(theo)}^{+0.07}_{-0.07} \text{(exp)}$

$\mu_{ggH} = 0.85^{+0.11}_{-0.09} \text{(stat)}^{+0.11}_{-0.08} \text{(theo)}^{+0.10}_{-0.09} \text{(exp)}$

ATLAS $\mu = 1.30^{+0.12}_{-0.12} \text{(stat)}^{+0.10}_{-0.08} \text{(theo)}^{+0.10}_{-0.08} \text{(exp)}$

• For the tests of couplings, experimental uncertainties are still expected to be dominant.

• Their evaluation and treatment, also for backgrounds and differential distributions, will be very important for analysis of Run 2 and beyond.
Compatibility of $4\ell$, $\gamma\gamma$

Statistical compatibility two mass measurements evaluated by looking at $\Delta m = m(\gamma\gamma) - m(4\ell)$

$\Delta m = +1.5 \pm 0.7^{(\text{stat})} \pm 0.3^{(\text{syst})}$ GeV (1.6$\sigma$)

$\Delta m = -0.9 \pm 0.6$ GeV (1.6$\sigma$)
Probing custodial symmetry

- Couplings to $W$ & $Z$ closely related in SM and most BSM alternatives with a doublet field.
- Tested in many different ways, two examples here:
  - CMS: from $H \rightarrow VV$ alone, in ggH-dominated final states
  - ATLAS: from most general coupling fit
m_H combination & model independency

- An effort is made to make the mass measurement more model independent.
- In designing the analysis:
  - ATLAS: don’t use tagged categories for mass measurement, both in H → γγ and H → 4ℓ
  - CMS H → ZZ: don’t use dijet category and p_T(H)
- In parametrizing the signal in the combination:
  - Separately floating signal strengths for H → 4ℓ, H → γγ
  - CMS H → γγ: float separately μ(VBF,VH) vs μ(ggH,ttH)
  - Both experiments checked independency of result on assumptions made on signal strengths.
Signal and background modelling

• Both experiments rely on a parametric modelling for the Higgs boson signal shape:
  – Parameters determined from fitting MC samples, after applying all data/mc corrections & smearings

• Backgrounds modelled with arbitrary smooth functions: polynomials, exponentials, power laws
  – Studies to determine the biases from assumed bkg parameterization done with toy MC or fast sim.
  – ATLAS: include bias as extra systematic on signal yield
  – CMS: profile likelihood over the choice of bkg shape
Minimal benchmark model

- Assume universal deviations in couplings to fermions ($\kappa_f$) and to vector boson ($\kappa_V$)
- Shows consistency across the 5 decay channels
Untagged $\gamma\gamma$ categories, 8 TeV

<table>
<thead>
<tr>
<th>ATLAS Category</th>
<th>$n_{\text{Sig}}$</th>
<th>$\sigma_{\text{eff}}$ (GeV)</th>
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<tbody>
<tr>
<td>unconv central high $p_T$</td>
<td>7.1</td>
<td>1.21</td>
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<td>unconv central low $p_T$</td>
<td>59.3</td>
<td>1.35</td>
</tr>
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<td>unconv rest high $p_T$</td>
<td>10.4</td>
<td>1.36</td>
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<td>96.2</td>
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<td>4.5</td>
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<td>conv central low $p_T$</td>
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<td>conv rest low $p_T$</td>
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<td>conv transition</td>
<td>42.1</td>
<td>2.41</td>
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<table>
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<th>CMS Category</th>
<th>$n_{\text{Sig}}$</th>
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<tr>
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<td>Untag 3</td>
<td>153</td>
<td>2.04</td>
</tr>
<tr>
<td>Untag 4</td>
<td>121</td>
<td>2.62</td>
</tr>
</tbody>
</table>

Notes:

- CMS numbers for $m_H = 125$ GeV, ATLAS ones for $m_H = 126$ GeV.
- ATLAS $\sigma_{\text{eff}}$ 5-10% better at 7 TeV; CMS instead ~5% worse at 7 TeV.
The $p_{Tt}$ variable

The thrust axis

$$\hat{t} = \frac{\vec{p}_{\gamma^1} - \vec{p}_{\gamma^2}}{|\vec{p}_{\gamma^1} - \vec{p}_{\gamma^2}|}$$

**ATLAS Simulation Preliminary**

$\sqrt{s} = 7$ TeV

Entries / 5 GeV (normalized to unity)
CMS Simulation \( H \rightarrow \gamma\gamma \) (\( m_H = 125 \text{ GeV}/c^2 \))

- Untagged 0: 8.0 total expected signal
- Untagged 1: 50.5 total expected signal
- Untagged 2: 117.2 total expected signal
- Untagged 3: 153.1 total expected signal
- Untagged 4: 121.4 total expected signal
- Dijet Tag 0: 4.5 total expected signal
- Dijet Tag 1: 5.6 total expected signal
- Dijet Tag 2: 13.7 total expected signal
- VH Lepton Tight: 1.4 total expected signal
- VH Lepton Loose: 0.9 total expected signal
- VH MET Tag: 1.8 total expected signal
- VH Dijet Tag: 1.6 total expected signal
- ttH Leptonic Tag: 0.5 total expected signal
- ttH Multijet Tag: 0.6 total expected signal

- Signal Fraction (%)
- Width (GeV)
- \( S/(S+B) \) in ± \( \sigma_{\text{eff}} \)
# Systematics on ATLAS $m_H$

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Uncertainty on $m_H$ [MeV]</th>
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<tr>
<td>LAr syst on material before presampler (barrel)</td>
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</tr>
<tr>
<td>LAr syst on material after presampler (barrel)</td>
<td>20</td>
</tr>
<tr>
<td>LAr cell non-linearity (layer 2)</td>
<td>60</td>
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<tr>
<td>LAr cell non-linearity (layer 1)</td>
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<tr>
<td>LAr layer calibration (barrel)</td>
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<tr>
<td>Lateral shower shape (conv)</td>
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<td>Lateral shower shape (unconv)</td>
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<td>Presampler energy scale (barrel)</td>
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<td>ID material model ($</td>
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<td>$H \rightarrow \gamma\gamma$ background model (unconv rest low $p_T$)</td>
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<td>$Z \rightarrow ee$ calibration</td>
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<td>Primary vertex effect on mass scale</td>
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<td>Muon momentum scale</td>
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<td>Remaining systematic uncertainties</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>180</strong></td>
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Material before ECAL

Inner Tracker + Services

All
# Comparison of systematics on $m_{\gamma\gamma}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Name</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
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<td>In situ calib</td>
<td>$Z \rightarrow ee$ calibration</td>
<td>0.04%</td>
<td>0.04%</td>
</tr>
<tr>
<td>$e/\gamma$ diff</td>
<td>Material tracker</td>
<td>0.07% (5% ID unc)</td>
<td>0.06% (10-20% ID unc)</td>
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<tr>
<td></td>
<td>Other material</td>
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<td></td>
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<tr>
<td></td>
<td>Longitudinal calib</td>
<td>0.1%</td>
<td>0.02%</td>
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<td></td>
<td>Lateral shower shape</td>
<td>0.06%</td>
<td>0.07%</td>
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<td>Linearity</td>
<td></td>
<td>0.12% (MG/HG full effect)</td>
<td>0.08% (after corr)</td>
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<td>-</td>
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<td>&lt; 0.01%</td>
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<tr>
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### Source of uncertainty

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty in $\hat{m}_H$ (GeV)</th>
</tr>
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<tbody>
<tr>
<td>Imperfect simulation of electron-photon differences</td>
<td>0.10</td>
</tr>
<tr>
<td>Linearity of the energy scale</td>
<td>0.10</td>
</tr>
<tr>
<td>Energy scale calibration and resolution</td>
<td>0.05</td>
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<tr>
<td>Other</td>
<td>0.04</td>
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<tr>
<td>All systematic uncertainties in the signal model</td>
<td>0.15</td>
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### Statistical Total

<table>
<thead>
<tr>
<th></th>
<th>Uncertainty in $\hat{m}_H$ (GeV)</th>
</tr>
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<tbody>
<tr>
<td>Statistical</td>
<td>0.31</td>
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<tr>
<td>Total</td>
<td>0.35</td>
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</tbody>
</table>

### ATLAS

<table>
<thead>
<tr>
<th>Class</th>
<th>Central $p_T$</th>
<th>Unconverted $p_T$</th>
<th>Converted $p_T$</th>
<th>Trans. $p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\to e^+e^-$ calibration</td>
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<td></td>
</tr>
<tr>
<td>LAr cell non-linearity</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Layer calibration</td>
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<tr>
<td>ID material</td>
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<tr>
<td>Other material</td>
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<tr>
<td>Conversion reconstruction</td>
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<td></td>
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<tr>
<td>Lateral shower shape</td>
<td></td>
<td></td>
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<tr>
<td>Background modeling</td>
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<tr>
<td>Vertex measurement</td>
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<tr>
<td>Total</td>
<td>0.23</td>
<td>0.28</td>
<td>0.24</td>
<td>0.30</td>
</tr>
</tbody>
</table>

**Note:** The values are given in units of GeV and are based on the ATLAS experiment's analysis of the $Z\to e^+e^-$ channel.
H → γγ signal models (inclusive)

- The CMS signal model has narrower core, larger tails compared to ATLAS one

**Graphs:**
- CMS Unpublished
- Simulation
- Parametric model
- σ_{eff} = 1.87 GeV
- FWHM = 3.10 GeV
- ATLAS Simulation
  - √s = 8 TeV
  - H → γγ, m_H = 125 GeV
  - Inclusive
  - FWHM = 3.69 GeV

**Note:** Same X axis scale in the two plots.
## CMS m\(\gamma\gamma\): cross-checks

<table>
<thead>
<tr>
<th></th>
<th>(\hat{\mu})</th>
<th>(\hat{m}_H) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>2.22(^{+0.62}_{-0.55})</td>
<td>124.2</td>
</tr>
<tr>
<td>8 TeV</td>
<td>0.90(^{+0.26}_{-0.23})</td>
<td>124.9</td>
</tr>
<tr>
<td>Combined</td>
<td>1.14(^{+0.26}_{-0.23})</td>
<td>124.7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Expected</th>
<th>Observed</th>
<th>(m(H))</th>
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<tbody>
<tr>
<td>Main analysis</td>
<td>1.00(^{+0.24}_{-0.22})</td>
<td>1.14(^{+0.26}_{-0.23})</td>
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<tr>
<td>Cut-based analysis</td>
<td>1.00(^{+0.26}_{-0.24})</td>
<td>1.29(^{+0.29}_{-0.26})</td>
<td>124.6</td>
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<tr>
<td>Sideband bkg. model analysis</td>
<td>1.00(^{+0.25}_{-0.22})</td>
<td>1.06(^{+0.26}_{-0.23})</td>
<td>124.7</td>
</tr>
</tbody>
</table>
ATLAS $H \rightarrow \gamma\gamma$ cross-checks

- Mass re-measured splitting datasets in categories to test for possible biases

\[ \int L dt = 4.5 \text{ fb}^{-1} \ \ \ \ \ \int L dt = 20.3 \text{ fb}^{-1} \ \ \ s = 7 \text{ TeV} \ \ \ s = 8 \text{ TeV} \]

- Converted vs unconverted
- High vs low pile-up
- Barrel vs endcaps
<table>
<thead>
<tr>
<th>Category</th>
<th>$n_{\text{sig}}$</th>
<th>FWHM [GeV]</th>
<th>$\sigma_{\text{eff}}$ [GeV]</th>
<th>$b$ in $\pm\sigma_{\text{eff}90}$</th>
<th>$s/b$ [%]</th>
<th>$s/\sqrt{b}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s}=8$ TeV</td>
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<tr>
<td>Inclusive</td>
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<tr>
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<td>2.81</td>
<td>1.21</td>
<td>26.0</td>
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<td>1.26</td>
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<tr>
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<tr>
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<td>26.0</td>
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<td>1.51</td>
<td>24.7</td>
<td>7.98</td>
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<td>4.81</td>
<td>2.23</td>
<td>365</td>
<td>2.00</td>
<td>0.38</td>
</tr>
</tbody>
</table>
ATLAS Calibration scheme

SIMULATION

1. training of MVA e/γ calibration

EM cluster energy

2. equalization of uniformity response
   - HV
   - IMW
   - Gain
   - E₀
   - E₁/E₂

3. equalization of longitudinal layer response

MC-based e/γ response calibration

4. e/γ energy

DATA

5. Z→ee data-driven resolution smearing and scale calibration

calibrated e/γ energy

6. J/ψ→ee Z→eeγ data-driven scale validation