Combined Measurement of the Higgs Boson Mass in $pp$ Collisions at $\sqrt{s} = 7$ and $8$ TeV with the ATLAS and CMS Experiments

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Outline

• The SM Higgs Boson: Production and Decay Modes

• The Measurement of the Higgs Boson Mass:
  o The H->γ γ Decay Channel
  o The H->ZZ->4l Decay Channel

• The Combination:
  o Why Combining?
  o How to Combine
  o ATLAS and CMS Combined Mass Results
The SM Higgs Boson: Production and Decay modes
The Measurement of the Higgs Boson Mass

- The Higgs boson mass is a fundamental parameter:
  - not predicted by the theory
  - measured independently by ATLAS and CMS using a simultaneous likelihood-fit on the reconstructed invariant mass and then combined
  - data samples from pp collisions at \( \sqrt{s} = 7 \) and 8 TeV corresponding to 5 fb\(^{-1}\) and 20 fb\(^{-1}\) respectively [RUN 1]
  - only high mass resolution decay channels used for combination:
    - \( H \rightarrow \gamma \gamma \)
    - \( H \rightarrow ZZ \rightarrow 4l \) (with \( l=e, \mu \))
The $H \rightarrow \gamma \gamma$ decay channel

- Main features:
  - Small B.R. ($2.29 \times 10^{-3}$ at $m_H=125$ GeV) but clear signature with two isolated and high-pt photons, excellent mass resolution 1-2 %
  - A narrow resonant signal peak over a large smoothly falling continuum background:
    - Irreducible: prompt di-photon production, $gg \rightarrow \gamma \gamma$, $q\bar{q} \rightarrow \gamma \gamma$ from QCD
    - Reducible: $pp \rightarrow \gamma +$jets (1 prompt $\gamma$ + 1 fake $\gamma$)
    - $pp \rightarrow$ jets (2 fake), $\gamma$ from $\pi^0 \rightarrow \gamma \gamma$
    - Background obtained from a fit to the di-$\gamma$ mass distribution
  - Selection Strategy: events selected via di-photon trigger, categorized according to signal purity, to photon resolution and kinematic discriminants, very good photon reconstruction and identification to improve sensitivity and bkg rejection, CUT-based selection and MVA to reconstruct the peak
  - VBF and VH production modes used to improve sensitivity

Mass Measurements

**ATLAS:** $m_H = 125.98 \pm 0.42$ (stat) $\pm 0.28$ (syst) GeV

**CMS:** $m_H = 124.70 \pm 0.31$ (stat) $\pm 0.15$ (syst) GeV
The $H \rightarrow ZZ \rightarrow 4l$ decay channel

- Main feature:
  - The Golden Channel: Small B.R. ($2.66 \times 10^{-2}$ at $m_H = 125$ GeV) but very clear signature with 4 well-isolated and high-pt leptons ($e, \mu$)
  - A signal mass peak over a small continuum background:
    - Irreducible: $ZZ, Z \gamma^*$ from $ggF$ and $q\bar{q}$ annihilation
    - Reducible: $Z$+jets, $t\bar{t}$, $Z\gamma$+jets, $WW$+jets, $WZ$+jets
  - Excellent mass resolution: 1-2%

- Selection Strategy: reconstruct a $ZZ$ objects made of two di-lepton objects, same flavour and opposite sign. Kinematics discriminants, very good lepton reconstruction and Identification to improve sensitivity and bkg rejection

Mass Measurements

**ATLAS (2D fit):** $m_H = 124.51 \pm 0.52$ (stat) $\pm 0.06$ (syst) GeV

**CMS (3D fit):** $m_H = 125.59 \pm 0.42$ (stat) $\pm 0.17$ (syst) GeV
Why combining?

- Improved precision of $m_H$
  - In SM $m_H$, $m_W$ and $m_t$ related through loop-induced effects:
    - Their comparison used to test the consistency of the SM (evidence of BSM Physics)

- More precise predictions of other Higgs properties

- Combination of other quantities, e.g. COUPLINGS (just completed)
How to combine

• Determination of the Higgs Mass best value and uncertainty maximizing the profile-likelihood ratio function:

\[
\Lambda(\alpha) = \frac{L(\alpha, \theta(\alpha))}{L(\alpha, \theta)}
\]

• Likelihood functions obtained using signal and bkg PDFs depending on the main discriminating variables:
  • Di-photon mass for \( H \rightarrow \gamma \gamma \)
  • Invariant 4l-mass distribution and KD for \( HZZ4l \) (also uncertainty for CMS)

• The parametrization used is approximately the same of the one used by the individual experiment
ATLAS and CMS Combined Mass Results [1/2]

Signal Strength: \( \mu = \frac{\sigma_{\text{exp}} \times B F_{\text{exp}}}{\sigma_{\text{SM}} \times B F_{\text{SM}}} \)

To be more SM independent 3 signal strenght factors defined (same for ATLAS and CMS):

- \( \mu_{\gamma\gamma}^{ggF+gH} \)
- \( \mu_{VBF+VH}^{\gamma\gamma} \)
- \( \mu_{4l} \)

The corresponding profile-likelihood ratio is:

\[
\Lambda(m_H) = \frac{L(m_H, \hat{\mu}_{\gamma\gamma}^{ggF+gH}(m_H), \hat{\mu}_{VBF+VH}^{\gamma\gamma}(m_H), \hat{\mu}_{4l}(m_H), \hat{\theta}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}^{ggF+gH}, \hat{\mu}_{VBF+VH}^{\gamma\gamma}, \hat{\mu}_{4l}, \hat{\theta})}
\]

Combining ATLAS and CMS data using the above procedure:

**Combined Mass Measurement**

\( m_H = 125.09 \pm 0.24 \text{ GeV} \)

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

- Compatibility of the combined ATLAS and CMS mass measurement in \( H \to \gamma \gamma \) and in \( H \to ZZ \to 4l \) is
  \( \Delta m_{\gamma\gamma} = m_H^{\gamma\gamma} - m_H^{4l} = -0.1 \pm 0.5 \text{ GeV} \)

- Compatibility of the ATLAS comb mass meas in the two channels with the CMS one is
  \( \Delta m_H^{\text{exp}} = m_H^{\text{ATLAS}} - m_H^{\text{CMS}} = 0.4 \pm 0.5 \text{ GeV} \)
The signal strengths at the measured value of $m_H$ are:

\[
\begin{align*}
\mu_{\gamma\gamma}^{\gamma\gamma} &= 1.15^{+0.28}_{-0.25} \\
\mu_{VBF+VH}^{\gamma\gamma} &= 1.17^{+0.58}_{-0.53} \\
\mu^{4l} &= 1.40^{+0.30}_{-0.25} \\
\mu_{comb} &= 1.24^{+0.18}_{-0.16}
\end{align*}
\]

The compatibility among signal strengths from ATLAS and CMS evaluated by:

\[
\lambda = \frac{\mu_{ATLAS}}{\mu_{CMS}}
\]

for all signal strengths used (ggF+ttbar, VBF+VH and 4l). It has been calculated to be $\lambda = 1.21_{-0.24}^{+0.30}$. All the values are consistent with unity within 1 $\sigma$. 

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Conclusions

• A combined measurement of the Higgs boson mass has been performed using pp collisions at $\sqrt{s} = 7$ and 8 TeV corresponding to 5 fb$^{-1}$ and 20 fb$^{-1}$ with ATLAS and CMS experiment at LHC

• A maximization of the profile-likelihood ratio $\Lambda (m_H)$ has been performed to determine the best value of $m_H$ and its uncertainty

• The combined measure of the Higgs boson mass has been calculated to be $125.09 \pm 0.21$ (stat.) $\pm 0.11$ (syst.) GeV

• The compatibility of the ATLAS combined mass measurement in the two channels with that of CMS has been evaluated to be $0.4 \pm 0.5$ GeV, definitely compatible with zero within 1 $\sigma$

• The combined signal strength factor has been evaluated to be $\mu_{\text{comb}} = 1.24^{+0.18}_{-0.16}$ and the compatibility among signal strengths from ATLAS and CMS has been calculated to be $\lambda = 1.21^{+0.30}_{-0.24}$, attesting the consistency of the measurements with the Standard Model assumptions
References


The Standard Model Higgs Boson at LHC

- The study of the electroweak symmetry breaking mechanism is one on the main goal of the LHC

- 2012: ATLAS and CMS announced the discovery of a new boson with Higgs-boson-like properties with a mass ~125 GeV

- 2013: more precise measurements of its properties (mass, spin-parity, coupling strengths to SM particles,...) brought to the Nobel prize assignment to Higgs and Englert for its discovery

- The discovery based primarily on mass peaks observed in decay channels H->γγ and H->ZZ->4l
## CMS Detector

### CMS Detector Specifications
- **Total Weight**: 14,000 tonnes
- **Overall Diameter**: 15.0 m
- **Overall Length**: 28.7 m
- **Magnetic Field**: 3.8 T

### Steel Return Yoke
- **Weight**: 12,500 tonnes

### Silicon Trackers
- **Pixel (100x150 μm)**: 16 m² ~66M channels
- **Microstrips (80x180 μm)**: 200 m² ~9.6M channels

### Superconducting Solenoid
- **Niobium titanium coil**: carrying ~18,000A

### Muon Chambers
- **Barrel**: 250 Drift Tube, 480 Resistive Plate Chambers
- **Endcaps**: 468 Cathode Strip, 432 Resistive Plate Chambers

### Preshower
- **Silicon strips**: ~16 m² ~137,000 channels

### Forward Calorimeter
- **Steel + Quartz fibres**: ~2,000 Channels

### Crystal Electromagnetic Calorimeter (ECAL)
- ~76,000 scintillating PWO crystals

### Hadron Calorimeter (HCAL)
- **Brass + Plastic scintillator**: ~7,000 channels
THE CONSTRUCTION OF THE TEST STATISTIC [1/3]

1. How to manage systematics (From bayesian to frequentist approach)

- Assigning a nuisance parameter $\theta_i$ for each independent source of systematic errors (both theoretical and experimental), $\tilde{\theta}_i$ is the best a priori estimate.

- Bayes’ Theorem:

$$\rho(\theta_i \mid \tilde{\theta}_i) \sim p(\tilde{\theta}_i \mid \theta_i) \cdot \pi_\theta(\theta_i)$$

It is related to the degree of belief about the real value of $\theta_i$:

$$\pi_\theta(\theta) \quad \text{a priori probability function for} \tilde{\theta}_i$$

If $\tilde{\theta}_i$ come from real or immaginary measurements and $\pi_\theta(\theta)$ is normally distributed (uniform prior)

$$\rho(\theta_i \mid \tilde{\theta}_i) \quad \text{can be interpreted as an a posteriori probability}$$
2. Choosing a pdf to describe $\theta_i$

If $\theta_i$ is normally distributed

The variation of $\theta_i$ propagates to the observable $O$ in 2 ways:

- **GAUSSIAN ERROR**:
  
  $$O = O_0 (1 + \sigma \cdot \theta) \quad (\text{with } O \text{ negative or positive})$$

- **LOG-NORMAL ERROR**
  
  $$O = O_0 \cdot \kappa^\theta \quad (O \text{ only positive})$$

$O_0 \rightarrow$ observable with no error

$\sigma, \kappa \rightarrow$ contributions to uncertainties
3. Defining a likelihood function

$$L(data \mid \mu, \theta) = \text{Poisson}(data \mid \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta} \mid \theta)$$

Poisson$(data \mid \mu \cdot s(\theta) + b(\theta))$: Poisson probability for data observation

Product of the poissonian probability for observing $n_i$ events in $i$ bins

$$\prod_i \frac{(\mu \cdot s_i + b_i)^{n_i}}{n_i} e^{-\mu s_i - b_i}$$

Not binned likelihood on $k$ events in data samples

$$k^{-1} \prod_i \frac{(\mu S f_s(x_i) + B f_b(x_i))^n}{n_i} e^{-(\mu S - B)}$$

$f_s(x)$ e $f_b(x)$ $\rightarrow$ p.d.f. for signal and bkg for observale $x$

$S$ e $B$ $\rightarrow$ total expected events rate for signal and bkg

$$\mu(\text{"signal strength modifier"}) = \frac{\# \text{observed events}}{\# SM \text{expected events}}$$
Definition of the Test Statistic

\[ q_\mu = -2 \ln \frac{L(data | \mu, \hat{\theta}_\mu)}{L(data | \hat{\mu}, \hat{\theta})} \quad \text{con } 0 \leq \hat{\mu} \leq \mu \]

\( \hat{\theta}_\mu, \hat{\mu}, \hat{\theta} \rightarrow \text{massimizzano num. e den.} \)
\( \mu \rightarrow \text{fissato} \)

Data can be
- Real Data
- Pseudo-dati (toys)

Maximization of \( L \) \( \iff \) Minimization of \( \log \) \( q_\mu \) distributed as \( \chi^2 \)

Signal can’t be negative
Unilateral Confidence

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Summary of $m_H$ measurements with uncertainties
Table of systematic uncertainties for ATLAS and CMS

<table>
<thead>
<tr>
<th>Source</th>
<th>ATLAS $H \rightarrow \gamma\gamma$</th>
<th>ATLAS $H \rightarrow ZZ \rightarrow 4\ell$</th>
<th>CMS $H \rightarrow \gamma\gamma$</th>
<th>CMS $H \rightarrow ZZ \rightarrow 4\ell$</th>
<th>Combined $H \rightarrow \gamma\gamma$</th>
<th>Combined $H \rightarrow ZZ \rightarrow 4\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale uncertainties:</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ATLAS ECAL nonlinearity</td>
<td>0.14 (0.16)</td>
<td>...</td>
<td>0.10 (0.13)</td>
<td>...</td>
<td>0.02 (0.04)</td>
<td>0.05 (0.06)</td>
</tr>
<tr>
<td>or CMS photon nonlinearity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Material in front of ECAL</td>
<td>0.15 (0.13)</td>
<td>...</td>
<td>0.07 (0.07)</td>
<td>...</td>
<td>0.03 (0.03)</td>
<td>0.04 (0.03)</td>
</tr>
<tr>
<td>ECAL longitudinal response</td>
<td>0.12 (0.13)</td>
<td>...</td>
<td>0.02 (0.01)</td>
<td>...</td>
<td>0.02 (0.03)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>ECAL lateral shower shape</td>
<td>0.09 (0.08)</td>
<td>...</td>
<td>0.06 (0.06)</td>
<td>...</td>
<td>0.02 (0.02)</td>
<td>0.03 (0.03)</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.03 (0.01)</td>
<td>...</td>
<td>0.01 (&lt;0.01)</td>
<td>...</td>
<td>0.02 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>ATLAS $H \rightarrow \gamma\gamma$ vertex and conversion reconstruction</td>
<td>0.05 (0.05)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.01 (0.01)</td>
<td>...</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ calibration</td>
<td>0.05 (0.04)</td>
<td>0.03 (0.02)</td>
<td>0.05 (0.05)</td>
<td>...</td>
<td>0.02 (0.01)</td>
<td>0.02 (0.02)</td>
</tr>
<tr>
<td>CMS electron energy scale and resolution</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Muon momentum scale and resolution</td>
<td>...</td>
<td>0.03 (0.04)</td>
<td>...</td>
<td>0.11 (0.10)</td>
<td>...</td>
<td>&lt;0.01 (0.01)</td>
</tr>
<tr>
<td><strong>Other uncertainties:</strong></td>
<td></td>
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<tr>
<td>ATLAS $H \rightarrow \gamma\gamma$ background modeling</td>
<td>0.04 (0.03)</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.01 (0.01)</td>
<td>...</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
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<tr>
<td>Additional experimental systematic uncertainties</td>
<td>0.03 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.02 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
<td>0.01 (&lt;0.01)</td>
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<tr>
<td><strong>Theory uncertainties:</strong></td>
<td></td>
<td></td>
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<tr>
<td>Systematic uncertainty (sum in quadrature)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
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<td>&lt;0.01 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
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<tr>
<td>Statistical uncertainty</td>
<td></td>
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<tr>
<td>Total uncertainty</td>
<td>0.27 (0.27)</td>
<td>0.04 (0.04)</td>
<td>0.15 (0.17)</td>
<td>0.16 (0.13)</td>
<td>0.11 (0.10)</td>
<td></td>
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<tr>
<td><strong>Analysis weights</strong></td>
<td>19% (22%)</td>
<td>18% (14%)</td>
<td>40% (46%)</td>
<td>23% (17%)</td>
<td>...</td>
<td></td>
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</tbody>
</table>
FIG. 3 (color online). The impacts $\delta m_H$ (see text) of the nuisance parameter groups in Table I on the ATLAS (left), CMS (center), and combined (right) mass measurement uncertainty. The observed (expected) results are shown by the solid (empty) bars.
Asimov Data Sets

- Observed uncertainties in the combined measurement compared with the expected ones:
  - The expected calculated by generating 2 ASIMOV datasets:
    - An ASIMOV data: representative event sample that provides:
      - MEDIAN EXPECTATION
      - EXPECTED STATISTIC STATISTICAL VARIATION
    - The first ASIMOV DATA SET is a PRE-FIT sample (generated using \( m_H = 125.0 \) GeV, SM couplings, \( \theta \) fixed to nominal values)
    - The second ASIMOV DATA SET is a POST-FIT sample (\( m_H, \mu^\gamma g_{FF+FH}, \mu^\gamma V_{BF+VH}, \mu^A \) and all \( \theta \) fixed to best-fit estimates from data)

- The expected uncertainties for mass combination are:
  \[
  \delta m_{H_{\text{postfit}}} = \pm 0.22 \text{ GeV} = \pm 0.19(\text{stat}) \pm 0.10(\text{syst}) \text{ GeV} \\
  \delta m_{H_{\text{prefit}}} = \pm 0.24 \text{ GeV} = \pm 0.22(\text{stat}) \pm 0.10(\text{syst}) \text{ GeV}
  \]