Precise Measurement of the Higgs Boson Mass With the CMS Detector

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on behalf of the CMS Collaboration
Introduction

Since CMS announced its discovery in 2012, the focus has been measuring the properties of the Higgs boson:

- $m_H$ is a fundamental parameter whose value is not predicted by the Standard Model (SM);
- SM predictions fully determined once the mass of the boson has been measured;
- Knowing the value of $m_H$ allows to over-constrain electroweak fit (test its self consistency).

Here presented the Higgs boson mass measurement performed with the CMS detector:

- Consider $H \rightarrow ZZ$ and $H \rightarrow \gamma \gamma$ as the decay channels with the best mass resolution (few %);
  - $H \rightarrow \gamma \gamma$ results recently updated;
- Keep excellent mass-resolution in high pileup environment.

The measurement uses the full Run I dataset recorded by CMS of LHC pp collisions:

- $\mathcal{L}_{\text{int}} = 5.1 \text{ fb}^{-1}$ at 7 TeV and $\mathcal{L}_{\text{int}} = 19.7 \text{ fb}^{-1}$ at 8 TeV.
Photon and Electron Energy

To obtain the best energy resolution, photon and electron energies are corrected for several detector effects with regression techniques based on similar sets of input variables:

- Collection of shower-shape variables, cluster $\eta$ and $\phi$-widths, hadronic over EM energy ratio, number of primary vertices…;

- **Photons**: exploited photon-electron similarities (electron EM cluster treated as a photon):
  - Per photon energy resolution prediction ($\frac{E_{\text{true}}}{E_{\text{RECO}}}$);

- **Electrons**: track momentum and corrected cluster energy are combined with a multivariate regression function:
  - Corrected ECAL energy and track momentum estimate with their uncertainties, $E$ over $p$ ratio and electron category based on the amount of emitted bremsstrahlung.

![Graph showing $m_{\text{peak}}$ data vs $m_{\text{MC}}$ over $p_T$ (GeV)]
Final calibration is obtained with two additional steps as follows:

- Energy scale in data is corrected to agree with MC:
  - ET dependent corrections.

- Then MC energy resolution is corrected with a gaussian smearing term to make it match data Z line-shape.

**MC Higgs invariant mass distribution (H → γγ)**

- $\sigma_{HM} = 0.79$ GeV
- $\sigma_{HM} = 2.14$ GeV
Muon momentum

- **Muon $p_T$ resolution** varies between ~1.5% in barrel up to 6.0% in endcaps ($p_T$ range 5 to 70 GeV):
  - Multiple scattering in Tracker dominant effect (detector alignment contribute to lesser extent).

- **Bias in reconstructed muon $p_T$** is determined from **Z peak position** as a function of kinematical variables and validated using Z and low-mass resonances (corrections applied in data accordingly, data/MC agreement 0.1%).

- **Resolution in MC** is corrected from a fit to the Z (and low-mass resonances) mass spectrum (relative data/MC difference 0.5%).
Event parameters:

\[ m_{\gamma\gamma} = 125.9 \text{ GeV} \]
\[ p_{T1} = 89.8 \text{ GeV} \]
\[ p_{T2} = 46.5 \text{ GeV} \]
\[ \eta_{\gamma1} = 0.06 \]
\[ \eta_{\gamma2} = -0.81 \]

\[ \frac{\sigma_m}{m} = 0.89\% \]

See also Matthew Kenzie talk.
Systematic Uncertainties H→γγ (1)

- Per-photon level uncertainties are propagated to the di-photon invariant mass shape.

- **Non linearity in extrapolation of energy scale** (determined with Z electron showers, applied to photons from Higgs decay):
  - Mitigated with $E_T$ dependent scale corrections;
  - Checked Z events in scalar $E_T$ sum and with $E/p$ ratio from W;
  - Linearity assumption checked using parabola;
  - Non linearity up to 0.1%.

See also Federico Ferri talk.
Estimated a deficit of Tracker material in the simulation (up to 10 to 20%):

- Uncertainty (from 0.03 to 0.3%) estimated using modified geometries;
- Checked using double difference of e/γ scales.
Imperfect EM shower simulation:

- Using a simulation with improved shower description changes $e$ and $\gamma$ energy scale;
- Smaller variation in the relative energy scale of electrons and photons with modified G4 is taken as uncertainty on knowledge of correct simulation shower (0.05%);
- Improved simulation considered for next MC production.

Non uniformity of light collection (including radiation-induced transparency losses):

- Unconverted photons on average travel into ECAL crystals one radiation length deeper than electrons;
- Uncertainty estimated as $e/\gamma$ energy scale differences using the nominal MC and a more accurate simulation of the non-uniformity (uncertainty on photon energy scale at most of 0.015%).
Recently updated analysis on Run I dataset:

- Mass measurement uses same analysis as in coupling measurement;
- To get mass estimate less model dependent signal strengths of Higgs production mechanisms are allowed to vary independently.

$$m_H = 124.70 \pm 0.31 \text{ (stat)} \pm 0.15 \text{ (syst)} \text{ GeV}$$

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Uncertainty (GeV)</th>
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</table>
| Energy scale calibration and resolution | - Uncertainty on the correction applied  
- Use $E_T$ dependent corrections  
- Also model stochastic and constant terms in resolution | $\pm 0.05$ |
| Non-linearity in scale extrapolation from $m_Z$ to $m_H$ | - Imperfect modeling in MC of differences between showers from $Z\rightarrow ee$ at $m_Z$ scale and $H\rightarrow \gamma\gamma$ at $m_H$ scale  
- $E_T$ dependent scale corrections mitigates it | $\pm 0.10$ |
| Electron-photon differences not modeled in MC | - Tracker material mis-modeling  
- Variation in scintillation light peak between e and $\gamma$  
- Imperfect EM shower simulation in G4  
- Imperfections in out-of-time PU description | $\pm 0.10$ |
| Other | | $\pm 0.04$ |
H→ZZ→4l

(PhysRevD.89.092007)

See also Adish Vartak talk.
Exploits kinematic variables of the decay products to discriminate between signal and background:

- Mass measured with multi-dimensional (KD, \( m_{4l} \) and per-event mass resolution) unbinned maximum-likelihood fit to the selected events.

\[
m_H = 125.6 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (syst)} \text{ GeV}
\]

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty in ( m_H ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron e-scale</td>
<td>0.3 % (4e), 0.1 % (2e2( \mu ))</td>
</tr>
<tr>
<td>Muon p-scale</td>
<td>0.1 %</td>
</tr>
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</table>
• Signal strength modifiers for (ggH, ttH)→γγ, (VBF, VH)→γγ and H→ZZ are not fixed to the SM expectation to get an estimate of m_H as much as possible model independent:

\[ m_H = 125.03^{+0.26}_{-0.27} \text{ (stat)}^{+0.13}_{-0.15} \text{ (syst)} = 125.03^{+0.29}_{-0.31} \text{ (tot) GeV} \]

- The measurements of the single channels have been checked to agree at the 1.6σ level.
Conclusions

- Properties of the Higgs boson are measured in pp collisions with the CMS detector at the LHC.
  - The data sample collected during Run I corresponds to an integrated luminosity of about 25 fb$^{-1}$.

- From the two highest resolution decay channels ($\gamma\gamma$ and ZZ) the mass of the Higgs boson has been measured to be:

\[ m_H = 125.03^{+0.26}_{-0.27} \text{ (stat)}^{+0.13}_{-0.15} \text{ (syst)} \text{ GeV} \]

the precision of the measurement being dominated by the statistical uncertainty.
Back up
Systematic Uncertainty (HZZ)

- Z, Y and J/ψ events used to set and validate the absolute momentum scale and resolution.

- Electrons: data/MC deviations are used as systematic uncertainty (0.1 to 0.3% mass scale uncertainty in 2e2µ and 4e).

- Muons: systematic uncertainty in momentum scale translates into 0.1% on 4µ mass scale.
Per-event Mass Uncertainty (HZZ)

- Momentum uncertainty for each lepton is propagated into a relative mass uncertainty \( (\sigma_{m4l}/m_{4l}) \) (including FSR photons).

- Line-shapes of \( J/\psi \) and \( Z \) resonances modeled as Breit Wigner \( \otimes \) double-sided Crystal Ball where resolution is estimated as \( \lambda \cdot \sigma_{m4l} \):
  - \( \lambda = 1.2 \) (1.1) for electrons (muons).

- Closure test performed with \( Z \) to leptons:
  - 20\% systematic uncertainty on per-event mass resolution.
ECAL Calibration (1)

Electron/photon energy measured from the energy deposited over several crystals:

\[ E_{e,\gamma} = F_{e,\gamma} \times G \cdot \sum_{xtal} \left[ IC_{xtal} \cdot S(t)_{xtal} \cdot A_{xtal} \right] \]

- \( A_{xtal} \): signal amplitude (ADC counts)
- \( S(t)_{xtal} \): time-dependent corrections for radiation-induced response variations (1 measurement/channel/40 min);
- \( IC_{xtal} \): inter-calibration factor, to equalize the response of all ECAL channels;
- \( G \): ECAL energy scale [GeV/ADC];
- \( F_{e,\gamma} \): particle dependent corrections applied at the clustering level.
ECAL Calibration (2)

- During LHC cycles the single channel response varies depending on the irradiation conditions.
- A light monitoring system is used to track and correct for response changes:
  - Measures the response variation to the laser light.
Pre-calibration performed in 2000-2009 test beams, cosmic rays, radiation source and “beam splashes” during the first LHC runs.

In situ calibration performed combining different techniques:

- Inter-calibration of crystals located within the same $\eta$ ring:
  - $\Phi$-symmetry of the energy flow through the ECAL crystals;
  - $\pi^0/\eta$ invariant mass peak;
  - Electron $E_{(ECAL)}/p(Tk)$.

- Inter-calibration of the $\eta$ rings ($\eta$ scale):
  - Electron $E/p$;
  - $Z$ invariant mass peak.

- Energy scale and resolution:
  - $Z$ invariant mass peak.
Scale Corrections ($H\gamma\gamma$)

- Split data and MC into 59 run ranges, 4x$\eta$ bins and 2xR9 bins.

- Fit Z line shape and find scale corrections for data in runx $|\eta|$ bins.

- Simultaneously fit scale with a Gaussian smearing term for MC $|\eta|$xR9:
  - In barrel (8 TeV) the smearing term has an energy dependence by parametrization through $b/\sqrt{ET} + c$;

- Further residual scale correction in ETx $|\eta|$xR9
Systematic Uncertainty (Scale Corrections $H \rightarrow \gamma\gamma$)

- Uncertainties coming from corrections to the photon energy scale from $Z \rightarrow ee$:
  - Due to:
    - R9 reweight to H photon distribution;
    - Changing electron selection;
    - Invariant mass fit boundary choice.
  - Uncertainty on the correction applied as systematic;
  - Propagated from per-photon level to the di-photon invariant mass shape;
  - Correlates energy scale across analysis categories.
Electron-Photon Differences

- Residual uncertainties due to different detector response to e and γ.

- Uncertainty derived from data/MC differences:
  - Not interested in absolute difference of electron and gamma response;
  - Checked double ratio between the electron and photon energy scales with nominal MC and modified scenarii.

- Imperfect description of material in the Tracker in MC;

- Variation in scintillation light peak between electron and gamma;

- Imperfect EM shower simulation in Geant4;

- Remaining imperfections in out-of-time PU (negligible).
Tracker Material

- Deficit in Tracker material in MC simulation up to 10 to 20%.
- Systematic uncertainty determined by studying different detector geometries:
  - Checked with double difference.

\[
\frac{\langle E_{\text{rec}}/E_{\text{gen}} \rangle_{\text{new, } \gamma} - \langle E_{\text{rec}}/E_{\text{gen}} \rangle_{\text{new, } e}}{\langle E_{\text{rec}}/E_{\text{gen}} \rangle_{\text{std, } \gamma} - \langle E_{\text{rec}}/E_{\text{gen}} \rangle_{\text{std, } e}}
\]
Linearity

- Uncertainty due to extrapolation of energy scales with electrons from Z decay to photon typical of H.

- Checked Z peak position in bins of scalar sum Et and also E/p.
  - Linearity assumption checked using parabola.
Light Collection

- Unconverted photons on average travel into ECAL crystals one radiation length deeper than electrons:
  - Simulation partially includes this non-uniformity (just for rear of the crystal);
  - Non-uniformity in the front part have been measured in test-beam:
    - Effect on the energy scale found to be at most 0.015%;
    - Additional effects due to radiation damage also been studied (found to be smaller).
Mass Uncertainties Summary (H\(\gamma\gamma\))

- Photon energy scale corrections:
  - \(2\times\eta, \ 2\times R9\) (for 7 and 8 TeV);
  - Partially correlated across years;
  - Contributes 0.05 GeV to total mass error.

- Z line shape:
  - \(1\times Z\) mass uncertainty (0.01%);
  - Effect of 10 MeV uncertainty on Z mass;
  - Contributes 0.01 GeV to total mass error.

- Residual non-linearity in scale:
  - \(1\times 7\) and 8 TeV;
  - Partial correlation across years
  - Contributes 0.10 GeV to total mass error.

- E/g differences in MC:
  - \(1\times\)Material (0.07 GeV);
  - \(1\times\)Light Collection (0.02 GeV);
  - \(1\times\)GEANT4 (0.06 GeV);
  - Fully correlated across years;
  - Contributes 0.10 GeV to total mass error.

- Other contribution studied with negligible effects:
  - Residual out-of-time PU mis-modeling.