Higgs Boson Mass Measurements

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on behalf of the CMS Collaboration

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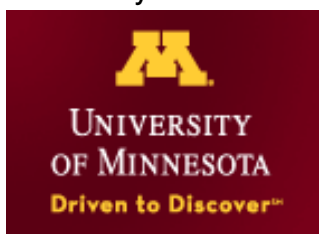
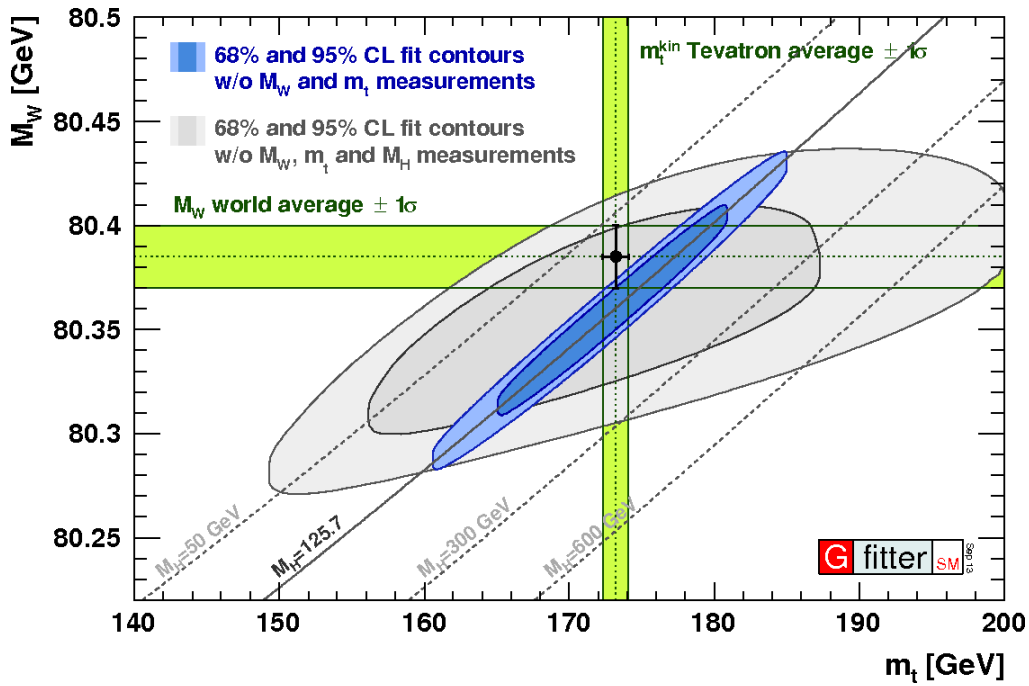


Higgs Hunting 2014
July 22, 2014

Introduction

- Higgs boson discovered (04 Jul 2012)
- Property studies ongoing: couplings, mass, spin, parity



Precise mass measurement (m_H):

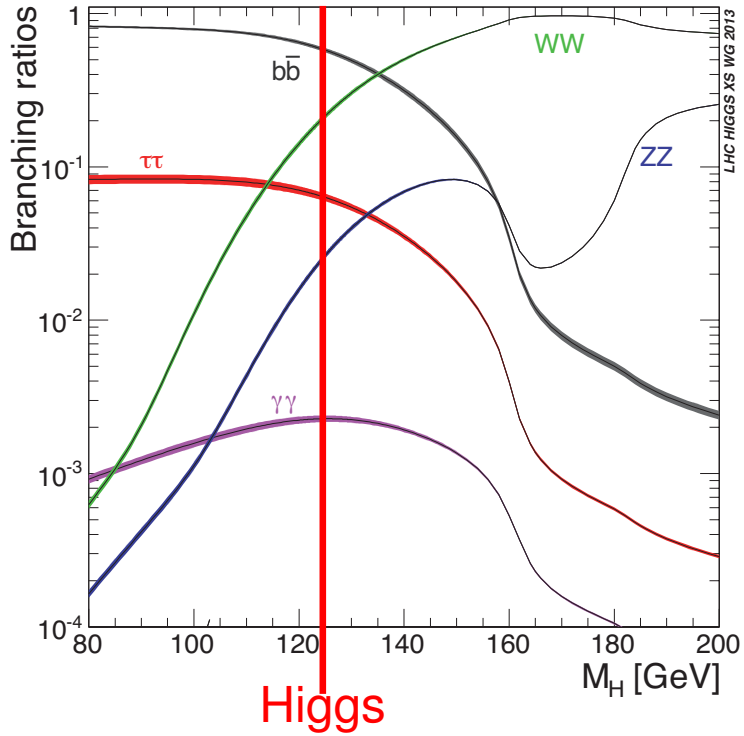
- Not predicted by Standard Model (SM)
- SM predictions fully determined once m_H measured
- Self-consistency of the model (electro-weak fit)
- Vacuum stability

Mass measurement with the CMS detector

Higgs studied in several decay channels:

channel	fully reconstructed final state	high energy resolution
$H \to WW$	☹	☹
$H \to \tau\tau$	☹	☹
$H \to bb$	✓	☹
$H \to ZZ \to !4\ell$	✓	☹
$H \to ZZ^* \to 4\ell$	✓	✓
$H \to \gamma\gamma$	✓	✓

$\ell = \mu, e$



Used full Run I data recorded by CMS in pp collisions:

- $L_{int} = 5.1\,\mathrm{fb}^{-1}\,(@7\ \mathrm{TeV}) + 19.7\,\mathrm{fb}^{-1}\,(@8\ \mathrm{TeV})$
- $H \to \gamma\gamma$ analysis recently updated
  - Improved calibration 7 TeV and 8 TeV data
  - Improved background estimation technique
  - Additional exclusive categories
  - Re-optimized selection and categorization

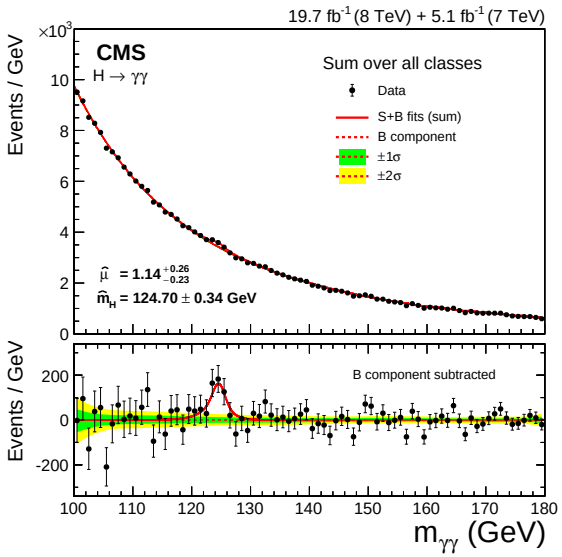
Strategy of the analyses

$H \to \gamma\gamma$

- Two isolated, high p_T photons
- Events categorized by $m_{\gamma\gamma}$ resolution, kinematics and production mode
- Same as measurement of the couplings
- Simultaneous S+B fit to all categories.
- Background from fit to data
- Analytic signal model accounting for data/MC corrections and associated uncertainties

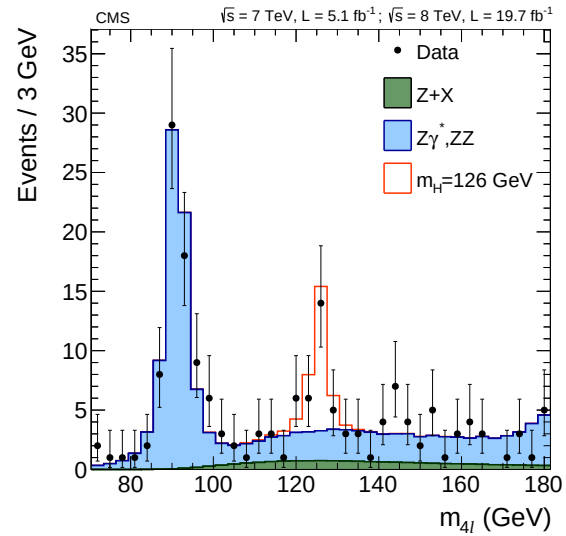
$H \to ZZ^* \to 4\ell$

- Four isolated leptons
- Only lepton flavor categorization (4e, 4μ, 2e2μ)
- Unbinned maximum likelihood fit
- Use $m_{4\ell}$ vs kin. Discriminant (KD) for S/B separation
- Use information on event-by-event mass resolution



Signal width dominated by experimental invariant mass resolution:

- energy resolution (μ, e, γ)



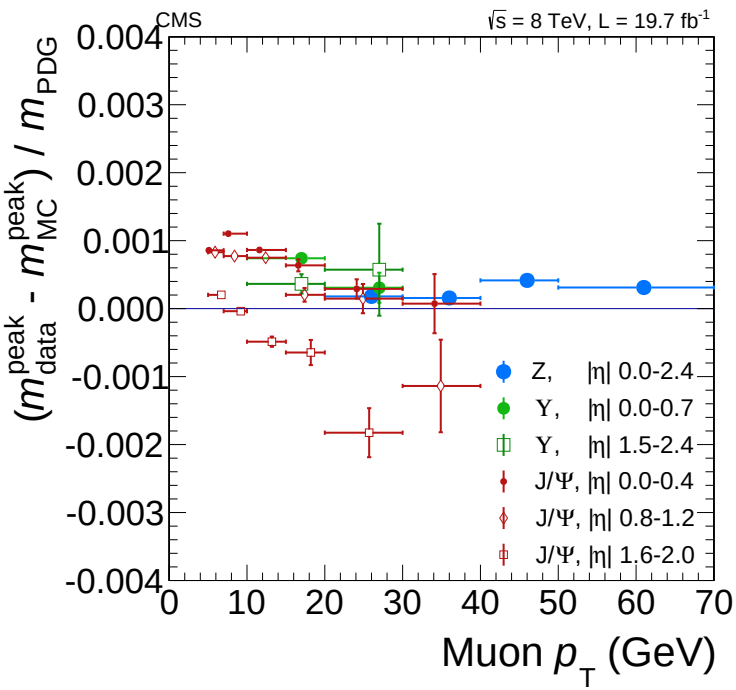
Energy scale systematics dominates mass measurement

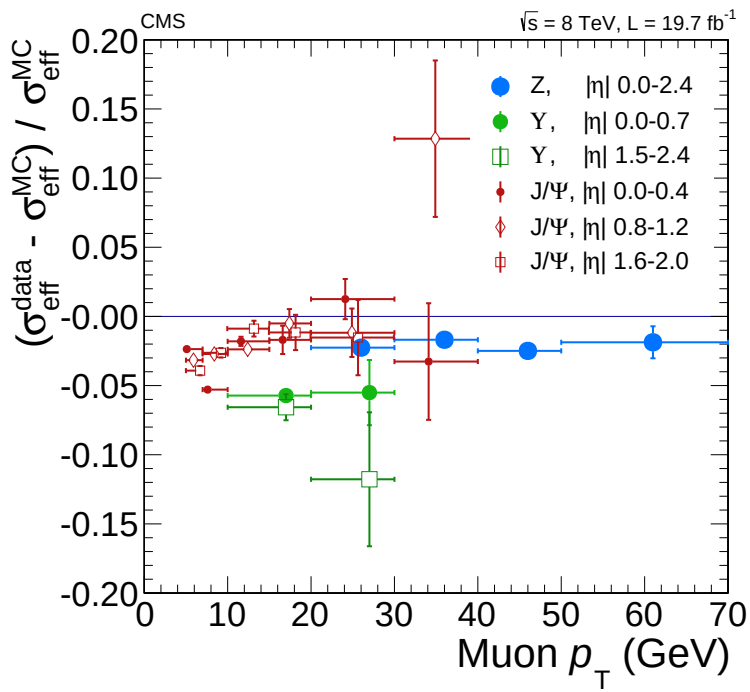
Outline

- Muon energy scale corrections and systematics
- Electron/photon energy corrections (for best resolution)
- Electron energy scale and systematics
- Photon energy scale
- Photon energy scale systematics
- Results

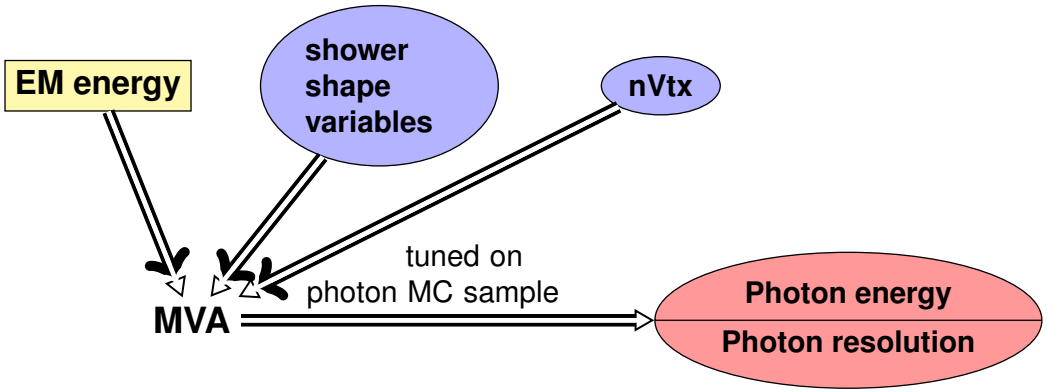
Muon momentum corrections and uncertainties

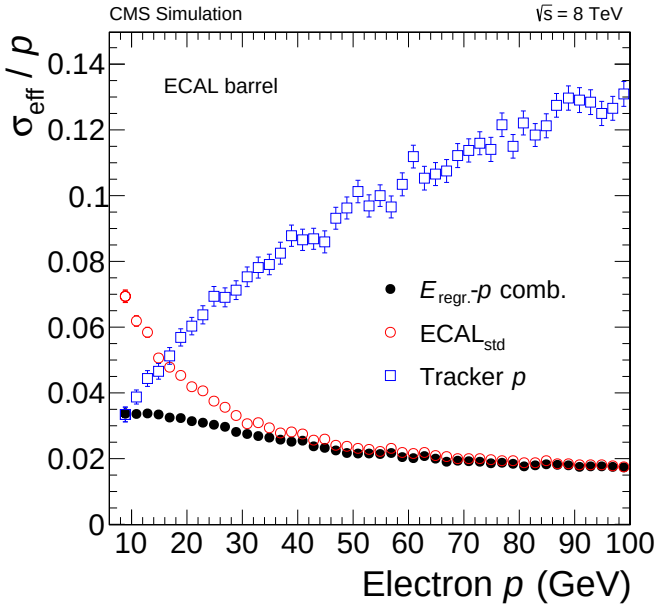
- Bias in reconstructed muon p_T determined from Z peak position as a function of kinematical variables
  - validated using Z and low-mass resonances (corrections applied in data accordingly, data/MC agreement 0.1%)
- Conservative systematics at single muon level: same order of the corrections
  - Muon momentum scale uncertainty (propagated to $m_{4\mu}$) = 0.1%
- p_T resolution from ~ 1.5% in barrel up to 6% in endcaps ($5 < p_T < 70$ GeV):
  - Dominant effect: multiple scattering in Tracker
- Resolution in MC is corrected from fit to the Z (and low-mass resonances) mass spectrum (relative data/MC difference 0.5%)



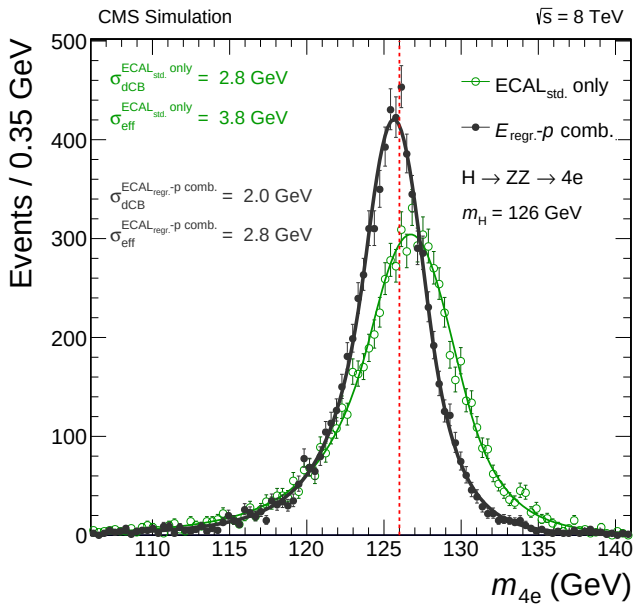


Photon and electron energy measurement





- Multivariate technique (MVA) for best EM energy resolution



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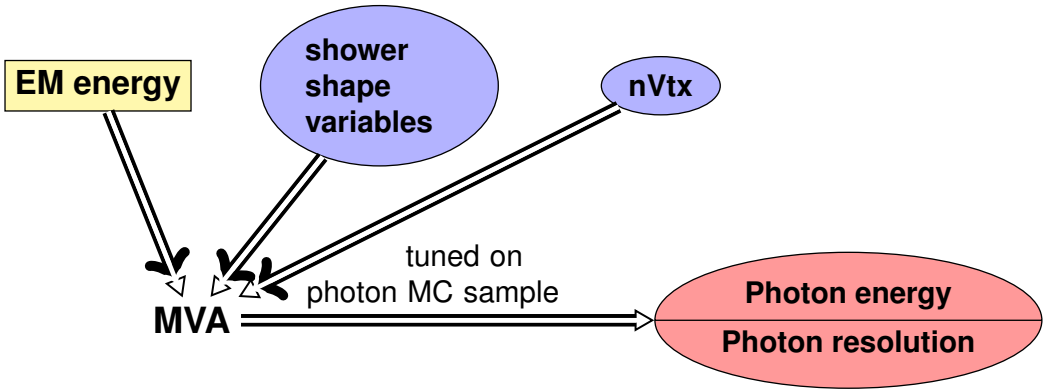
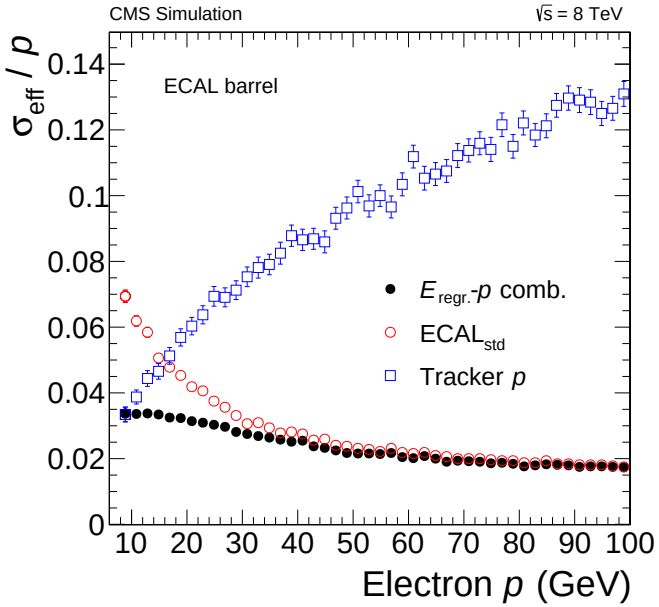
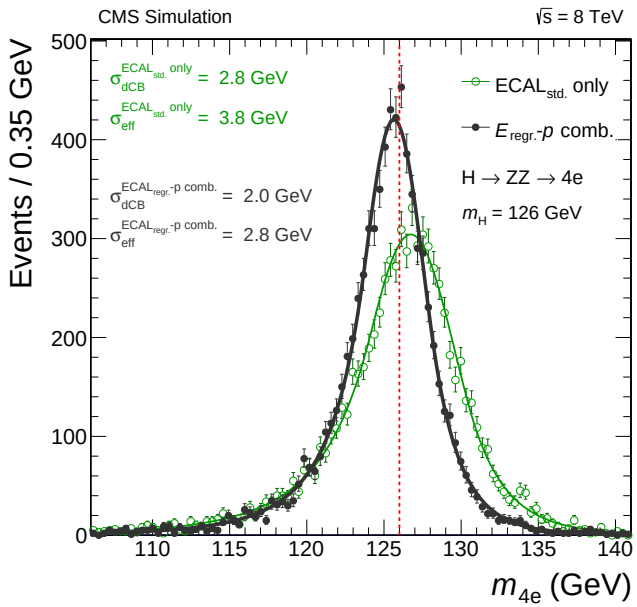




- Multivariate technique (MVA) for best EM energy resolution
- Per-photon/per-electron energy resolution estimation



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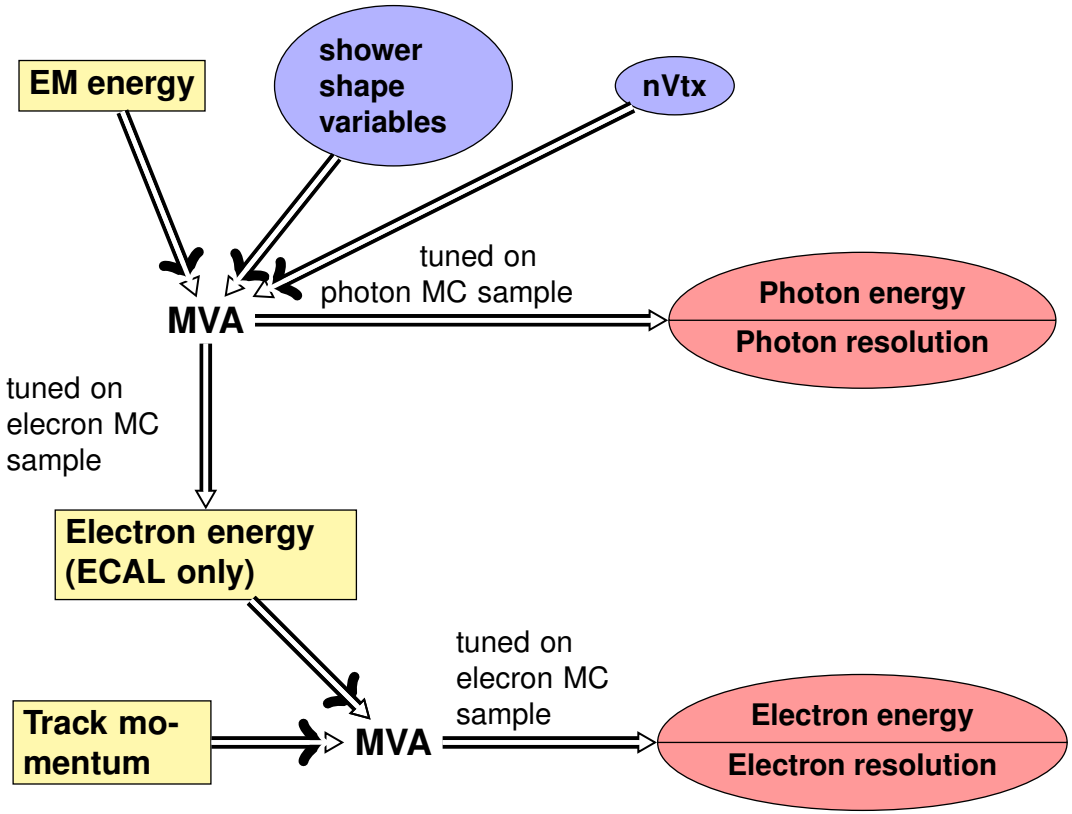
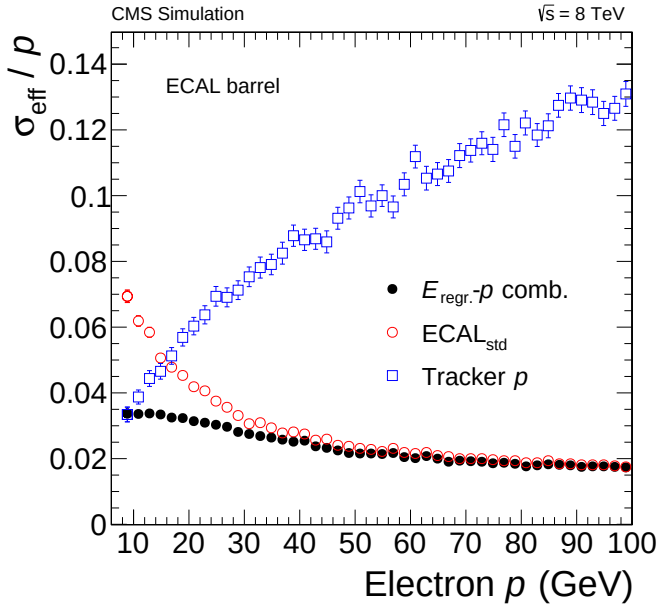
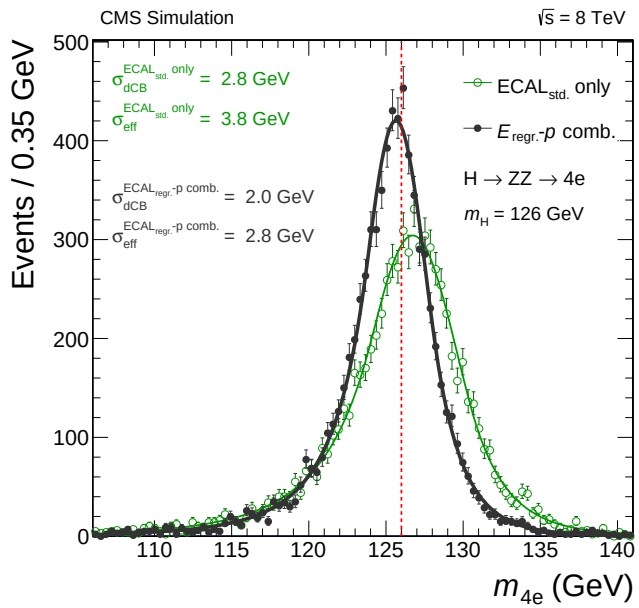


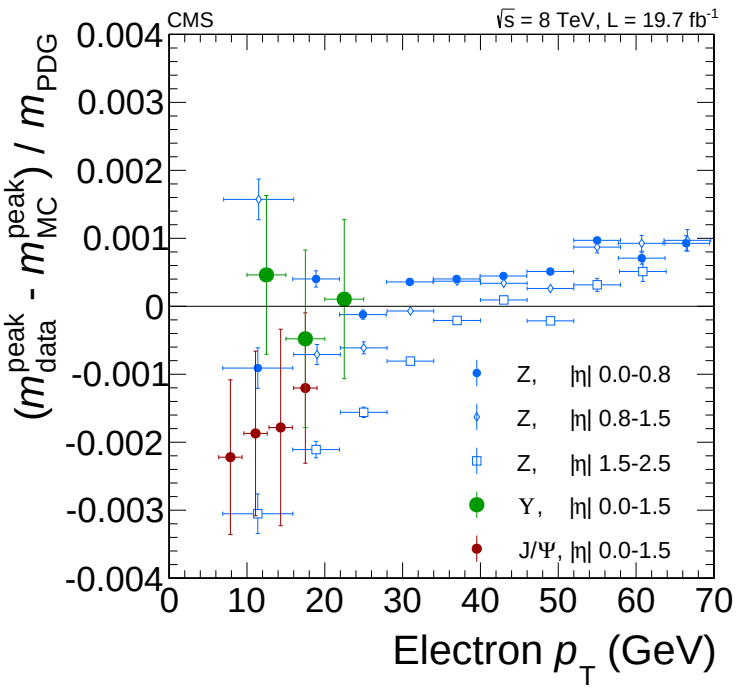




- Multivariate technique (MVA) for best EM energy resolution
- Per-photon/per-electron energy resolution estimation
- Electron energy: combination of track momentum and EM shower energy

Electron momentum uncertainties

- Energy scale verified with $Z \to e^+ e^-$ and low mass resonances (J/Ψ, Υ)
- Systematic uncertainty on energy scale dominated by linearity
- Momentum scale consistent within 0.2% in the central barrel and up to $\sim 0.3\%$ in the forward part of the ECAL end caps after corrections



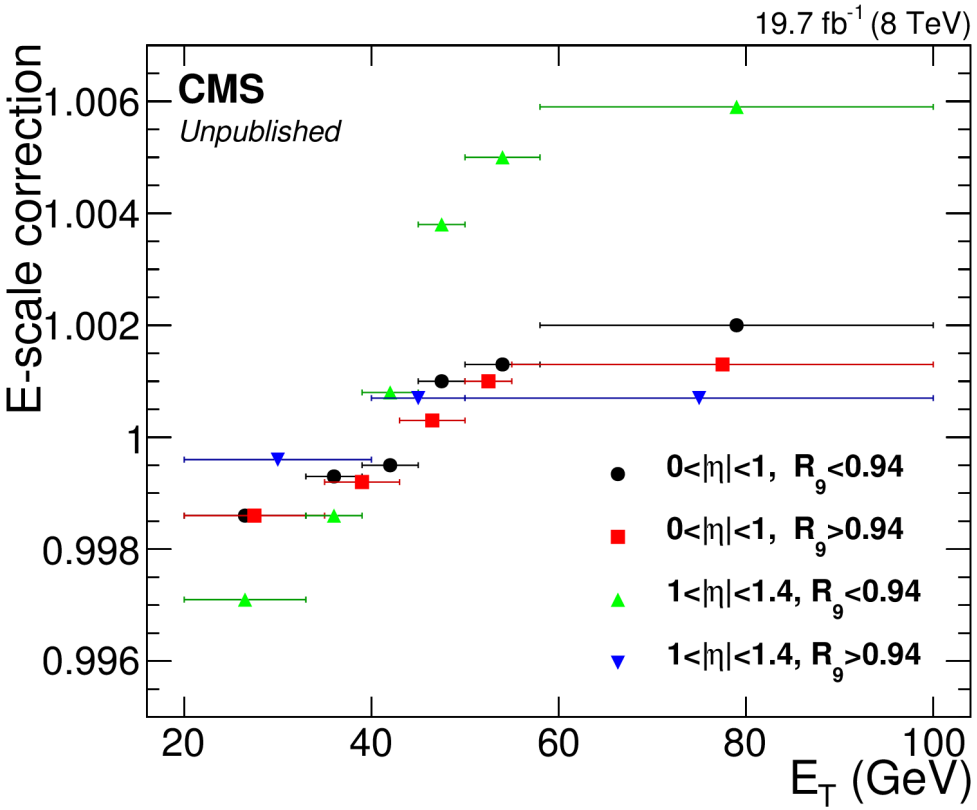
- Conservative systematics: same order of the corrections:
  - 0.6% in the central barrel
  - up to 1.5% in the endcap
- Scale systematic propagated to
  - m_{4e}: 0.3%
  - $m_{2e2\mu}$: 0.1%

Photon data-mc corrections

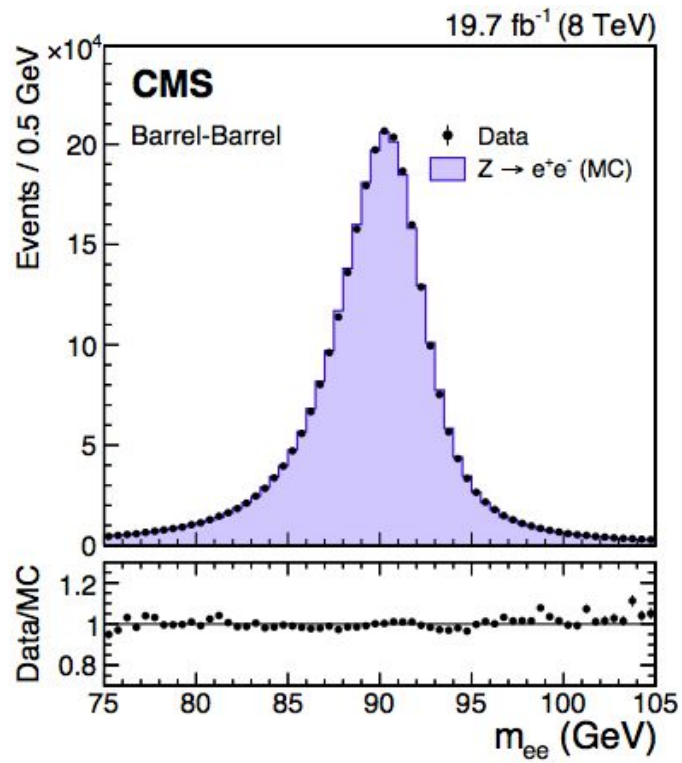
Further corrections for data-MC discrepancies derived with $Z \to e^+ e^-$ sample

- Energy scale (data): E_T dependent corrections (only 8 TeV, barrel)
  - Corrections of few per mille
- Energy resolution (MC) to match resolution in data: gaussian smearing

$H \to \gamma\gamma$



$H \to \gamma\gamma$



$H \to \gamma\gamma$ systematic uncertainties

	Description	Uncer. (GeV)
Energy scale and resolution corrections ($Z \to e^+e^-$)	■ Per-photon uncertainty propagated to the di-photon invariant mass shape	±0.05
$M_Z \to M_H$: non linearity in extrapolation	■ Imperfect modelling in MC of differences between showers from $Z \to e^+e^-$ at M_Z scale and $H \to \gamma\gamma$ at M_H scale ■ Mitigated by E_T dependent scale corrections	±0.10
Electron to photon differences	■ Tracker material mis-modeling (at most 0.3%) ■ Variation in scintillation light peak between e and γ (at most of 0.015%) ■ Imperfect EM shower simulation in G4 (0.05%) ■ Imperfections in out-of-time pileup description	±0.10
Other		±0.04

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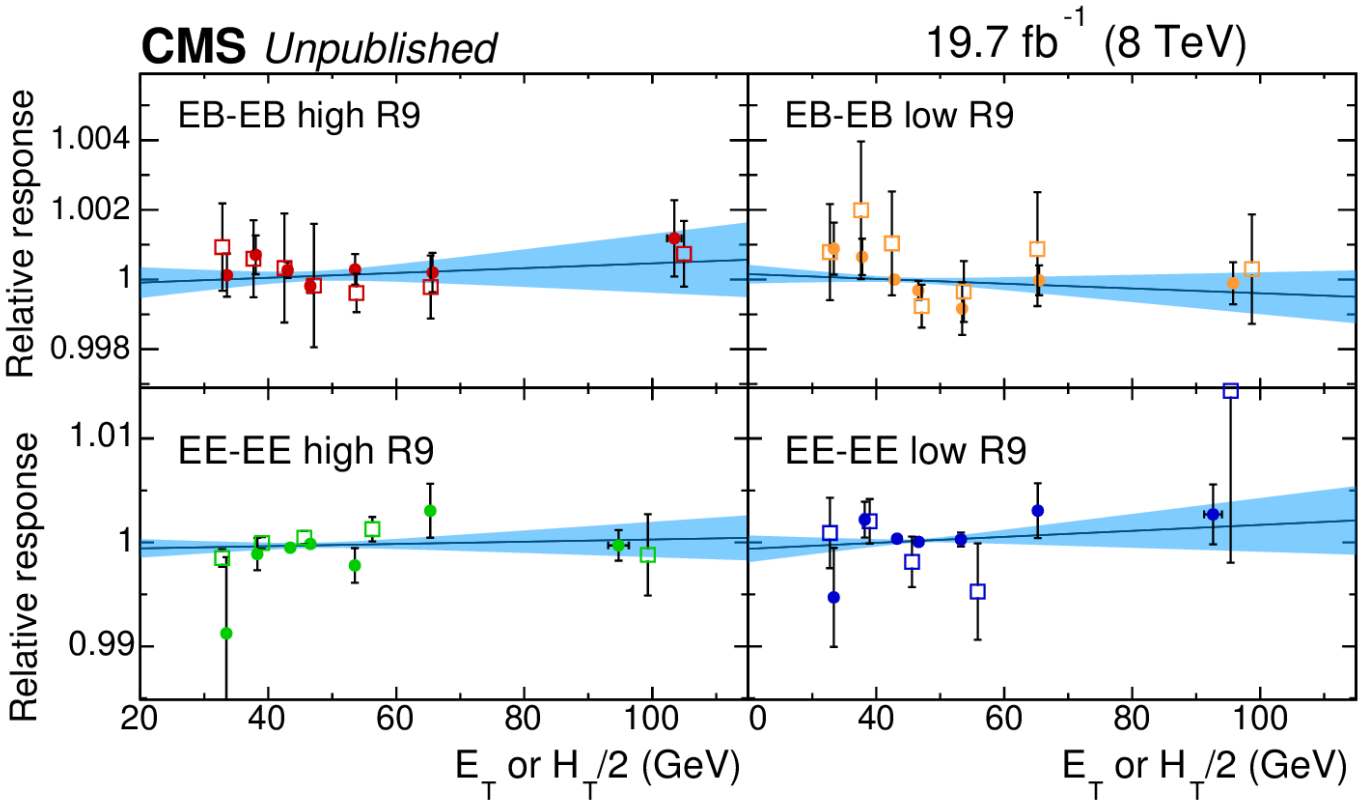
Other		±0.04

Non linearity in scale extrapolation from M_Z to M_H

$H \to \gamma\gamma$



Checked with:

- M_{ee} data/MC ratio ($Z \to e^+e^-$)
- E/p data/MC ratio ($W \to e\nu$)

$$R_9 = E_{3\times3}/E_{ECAL}$$

$R_9 > 0.94$ unconverted photons or electrons with little amount of brem emission

$R_9 < 0.94$ converted photons or electrons with high amount of brem emission

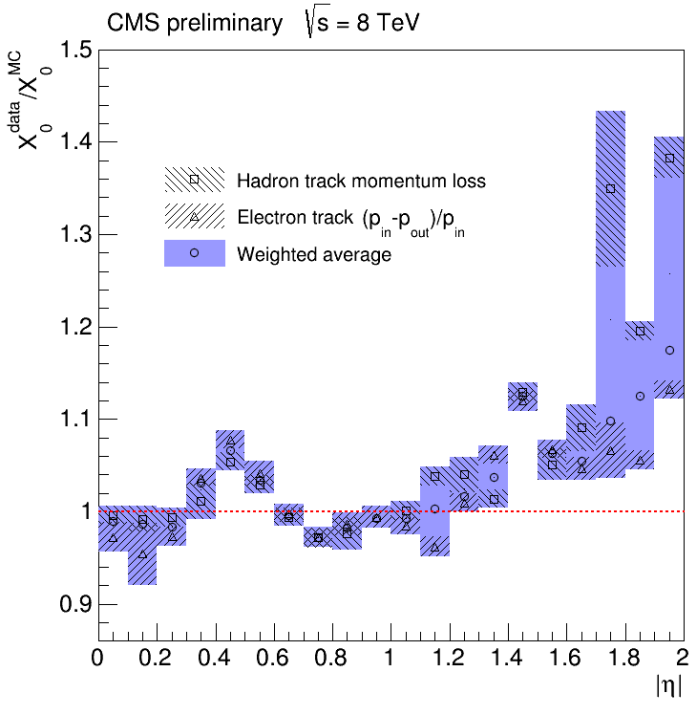
Tracker material mis-modeling

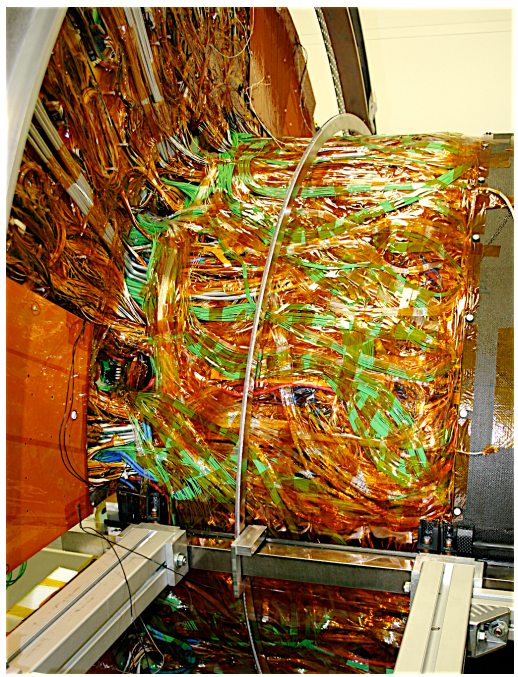
$H \to \gamma\gamma$

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

$$\frac{\langle E_{rec}/E_{gen}\rangle^{\gamma}_{new} - \langle E_{rec}/E_{gen}\rangle^{e}_{new}}{\langle E_{rec}/E_{gen}\rangle^{\gamma}_{std} - \langle E_{rec}/E_{gen}\rangle^{e}_{std}}$$

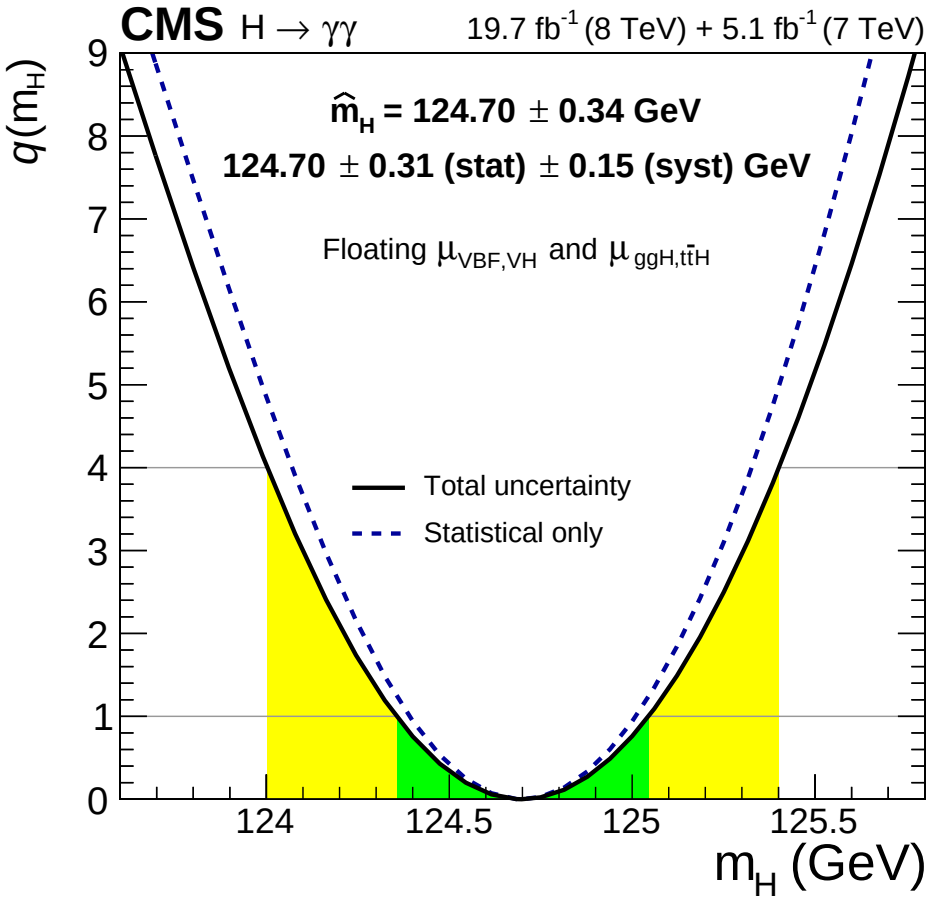
- Systematics at most 0.3%





$H \to \gamma\gamma$ mass measurement

CMS-HIG-13-001



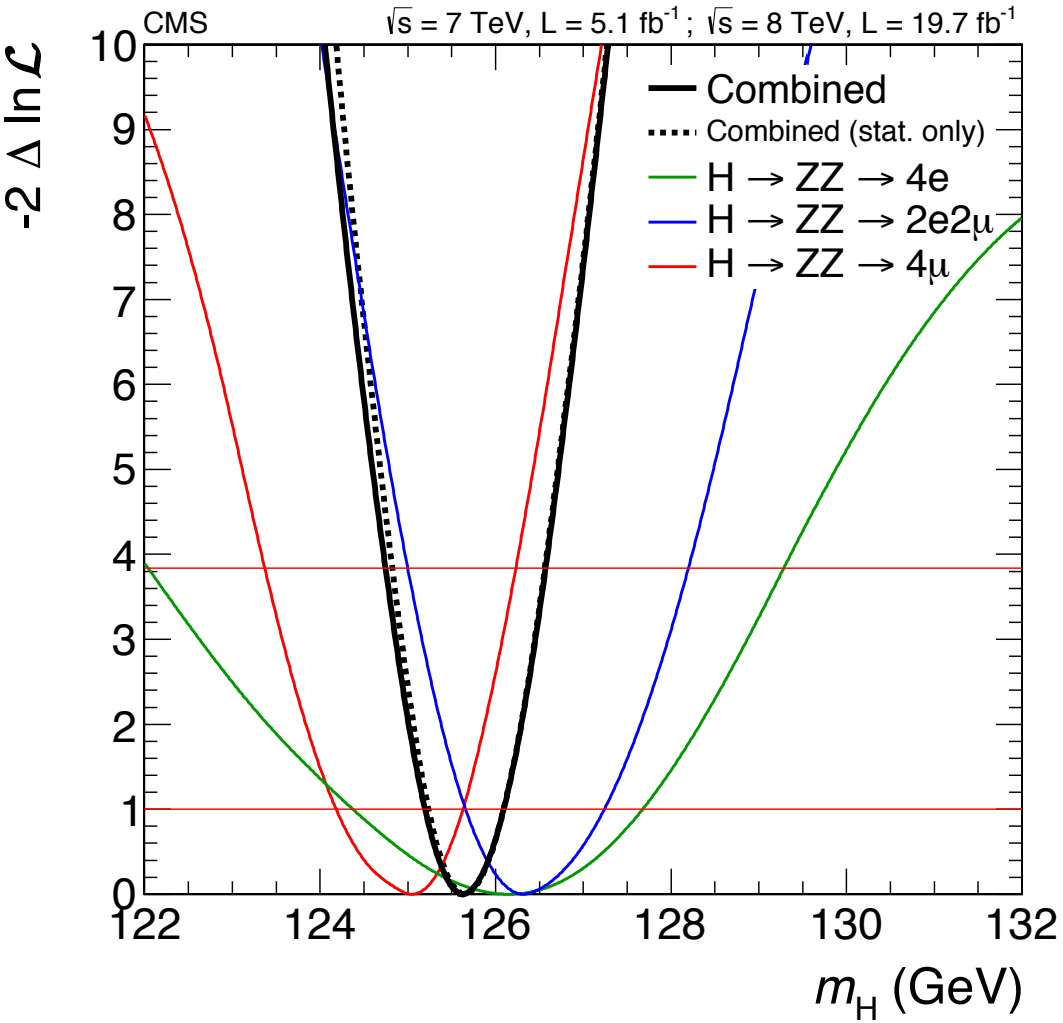
Recently updated analysis on Run I dataset

- 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.

$$m_H = 124.70 \pm 0.34\,[\pm 0.31(stat) \pm 0.15(syst)]\ \text{GeV}$$

$H \to ZZ^* \to 4\ell$ mass measurement

PhysRevD.89.092007



Channel	Measured mass (GeV)
4e	$126.2^{+1.5}_{-1.8}$
$2e2\mu$	$126.3^{+0.9}_{-0.7}$
4μ	$125.1^{+0.6}_{-0.9}$

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

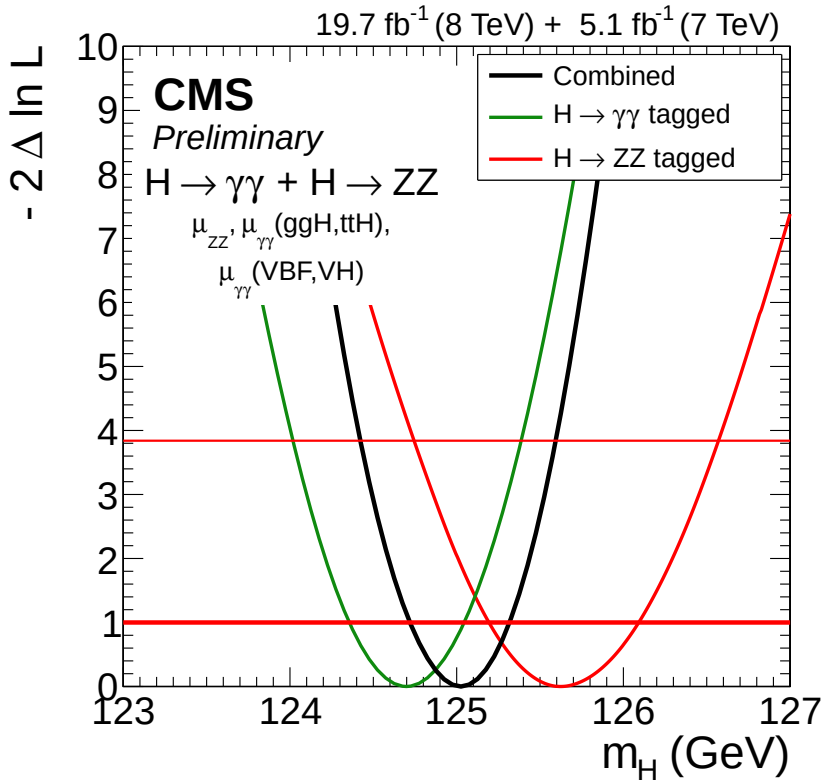
Combination

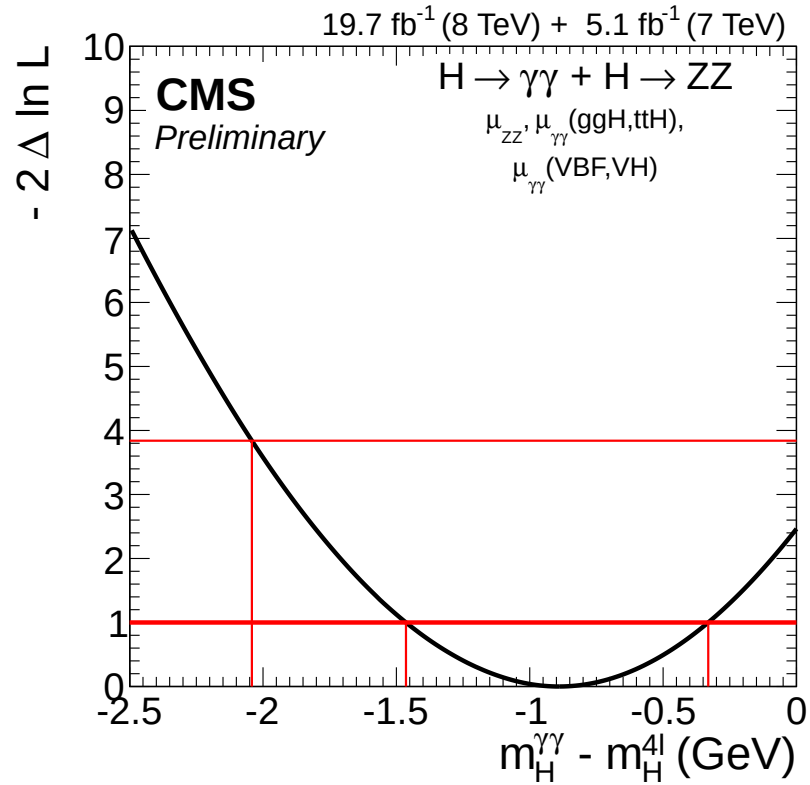
CMS-PAS-HIG-14-009

Signal strength modifiers for $\mu_{ZZ}, \mu_{\gamma\gamma}(ggH, ttH)$, $\mu_{\gamma\gamma}(VBF, VH)$ are not fixed to the SM expectation to get an estimate of m_H as much as possible model independent:

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

$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ results compatible at the 1.6σ level.





Conclusions

- $H \to \gamma\gamma$ analysis recently updated
- Full Run I dataset analyzed
  ($L_{int} = 5.1\,\mathrm{fb}^{-1}(@7\ \mathrm{TeV}) + 19.7\,\mathrm{fb}^{-1}(@8\ \mathrm{TeV})$)
- Higgs mass measured in the two highest resolution decay channels ($H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$):

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

- Mass measurement still dominated by statistical uncertainty

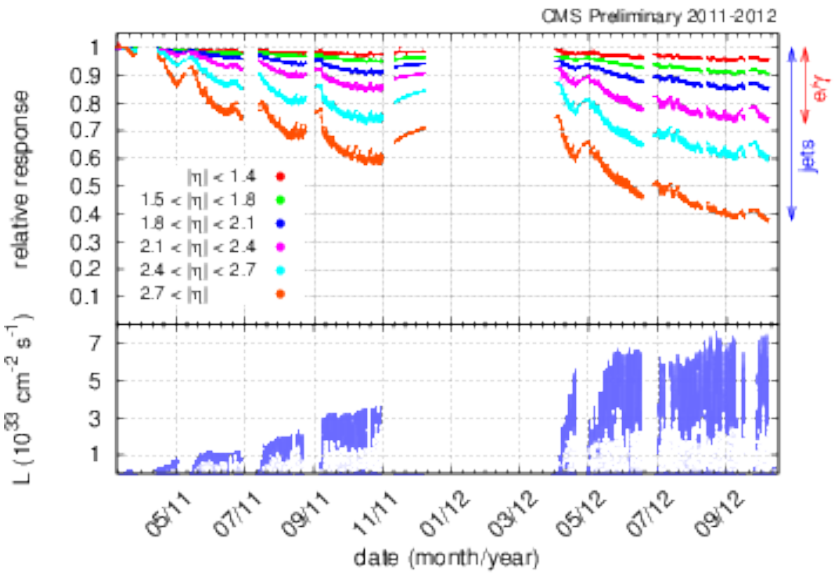
. . . preparing for Run II

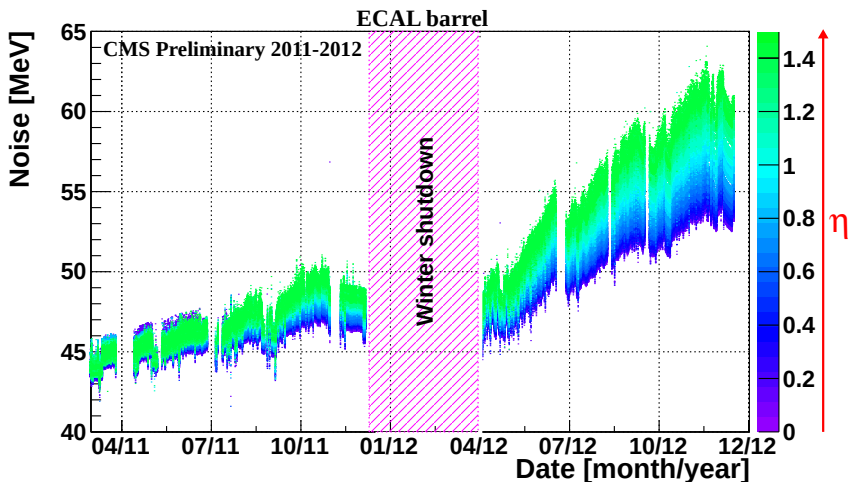
Backup

Improved ECAL simulation

Huge effort in understanding better data and the CMS detector:

- MC with 3 sets of conditions matching 3 periods of data taking: condition evolution with time taken into account
  - Increasing energy equivalent noise in ECAL barrel vs time
  - Matching pileup evolution vs time
- Extended Out-of-time pileup window simulation (-300ns:50ns)

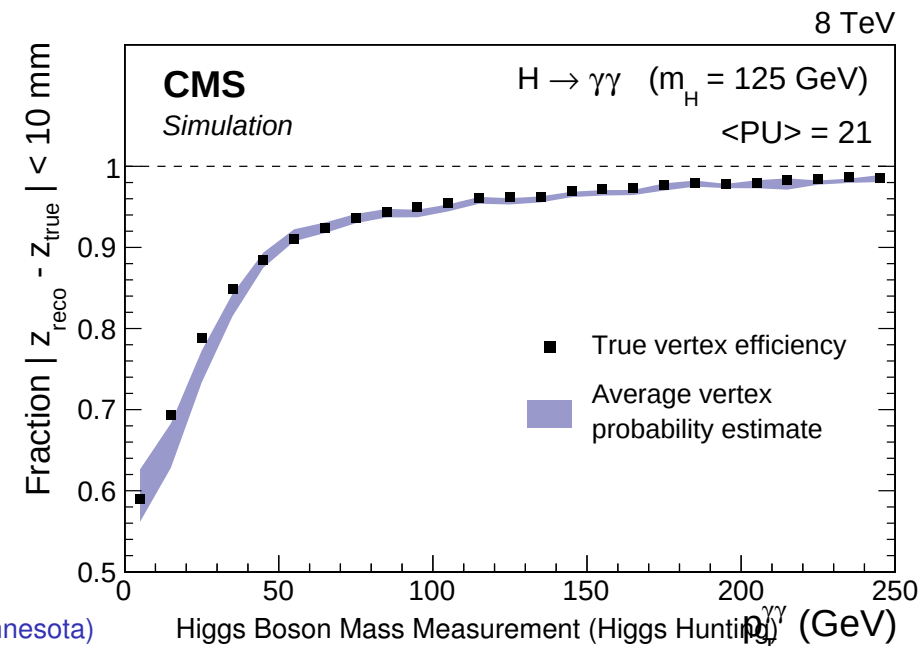




Photon vertex determination

$H \to \gamma\gamma$

- Di-photon opening angle resolution affects the $m_{\gamma\gamma}$ resolution
- Di-photon vertex selected by Boosted Decision Tree (BDT):
  - sum p_T of tracks
  - balance between tracks p_T and di-photon p_T
- $P(|Z_{reco} - Z_{true}| < 10\text{mm})$ estimated event-by-event by second BDT:
  - vertex identification BDT output (three most likely vertices)
  - total number of reconstructed vertices in the event
  - $p_T^{\gamma\gamma}$
  - distances between the three high score vertices,
- event-by-event $m_{\gamma\gamma}$ resolution (used in event categorization) from:
  - per-photon energy resolution → dominant if $|Z_{reco} - Z_{true}| < 10\text{mm}$
  - $P(|Z_{reco} - Z_{true}| < 10\text{mm})$

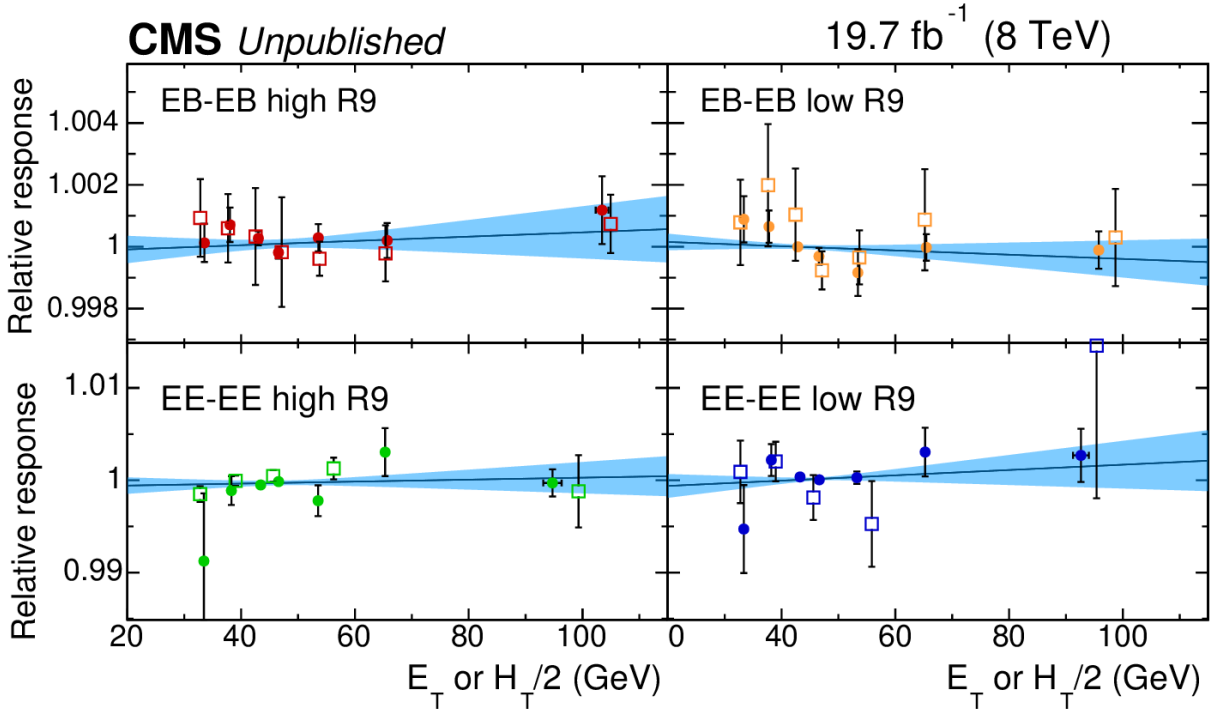


Energy scale and resolution correction uncertainties

- Due to:
  - R_9 reweight to H photon distribution;
  - Changing electron selection;
  - Invariant mass fit boundary choice.
- Uncertainty on the correction applied;
- Propagated from per-photon level to the di-photon invariant mass shape;

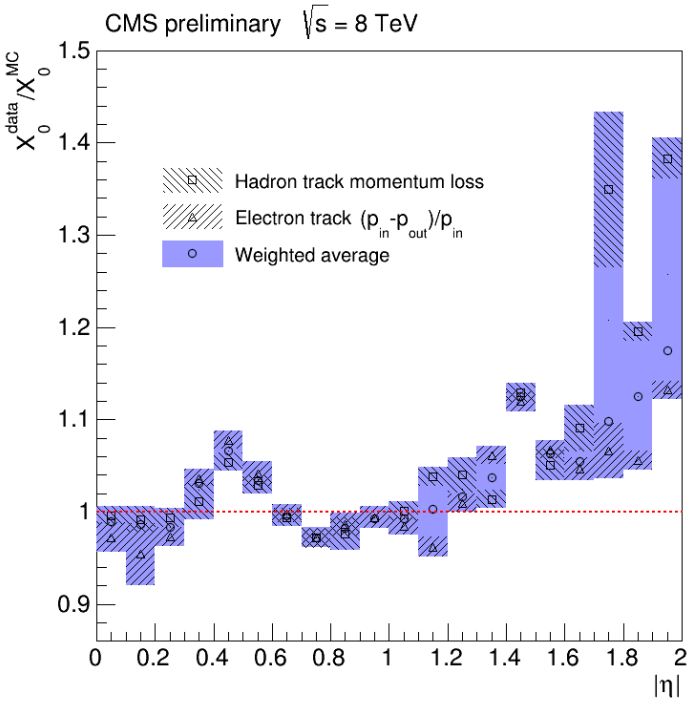
$H \to \gamma\gamma$ systematic uncertainties

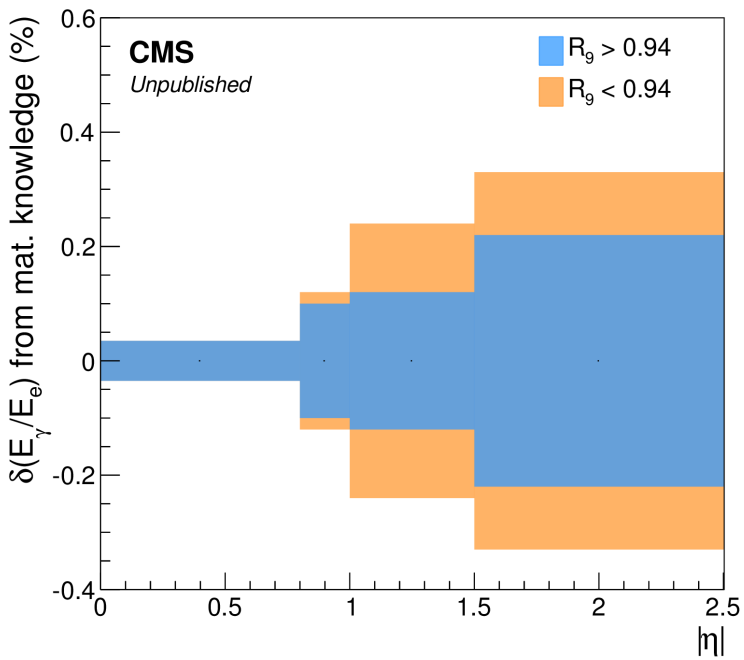
	Description	Uncer. (GeV)
$M_Z \to M_H$: non linearity in extrapolation	■ Imperfect modelling in MC of differences between showers from $Z \to e^+ e^-$ at M_Z scale and $H \to \gamma\gamma$ at M_H scale ■ Mitigated by E_T dependent scale corrections	± 0.10



$H \to \gamma\gamma$ systematic uncertainties

	Description	Uncer. (GeV)
Electron to photon differences	■ Tracker material mis-modeling (at most 0.3%) ■ Variation in scintillation light peak between e and γ (at most of 0.015%) ■ Imperfect EM shower simulation in G4 (0.05%) ■ Imperfections in out-of-time pileup description	±0.10





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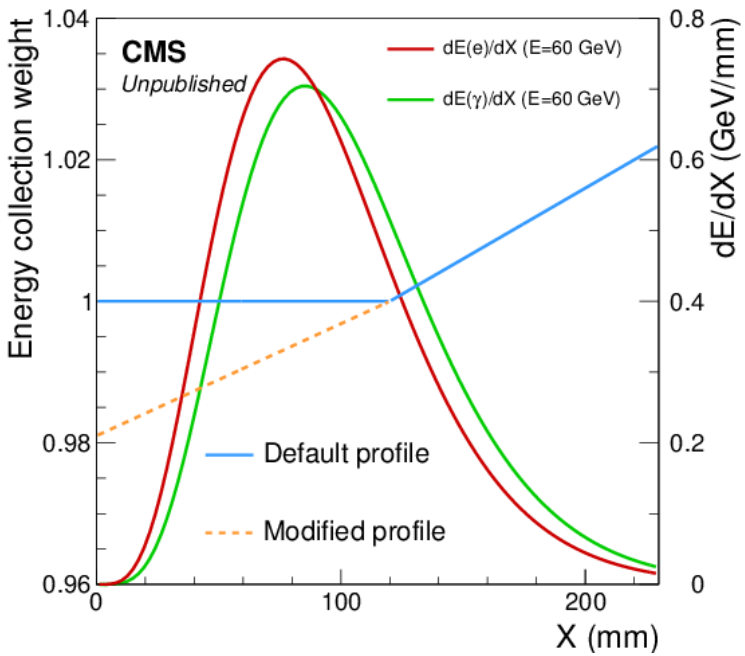

- Unconverted photons on average travel into ECAL crystals one radiation legth deeper than electrons
- Uncertainty estimated as e/γ energy scale differences using the nominal MC and a more accurate simulation of the non-uniformity (uncertainty on the photon energy scale at most of 0.015%)
- radiation-induced transparency loss included

$H \to \gamma\gamma$ systematic uncertainties

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

$$\frac{E^{\gamma}_{stdG4}/E^{e}_{stdG4}}{E^{gamma}_{modG4}/E^{e}_{modG4}}$$

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Other		±0.04