Higgs mass measurement at CMS

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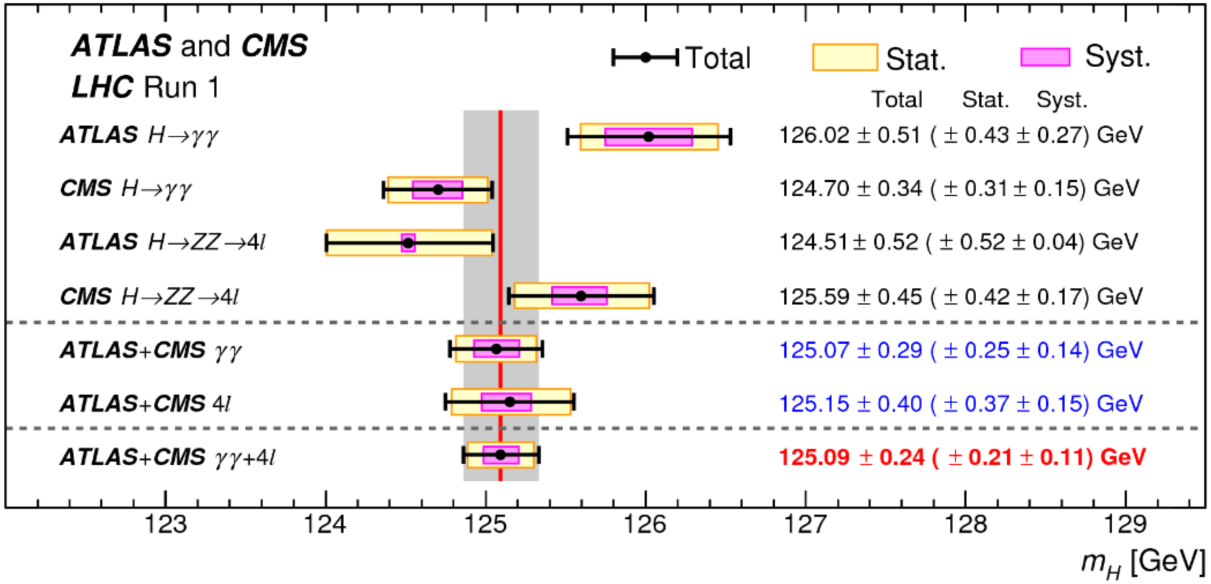
On behalf of the CMS collaboration

Introduction

- **The only free fundamental parameter of the Higgs sector in SM**
  - **Completely determines the SM Higgs properties**

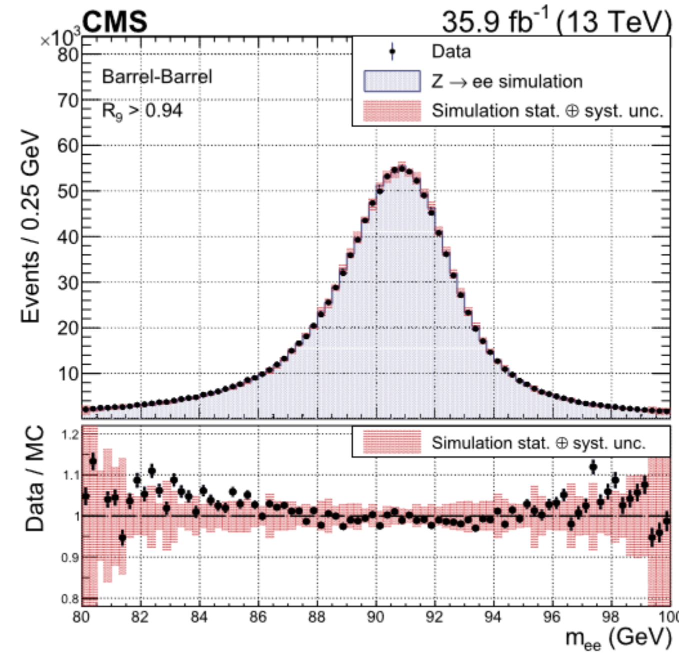
- **Measured from the mass peak in the two high resolution channels: H→ZZ → 4ℓ and H → $\gamma\gamma$**

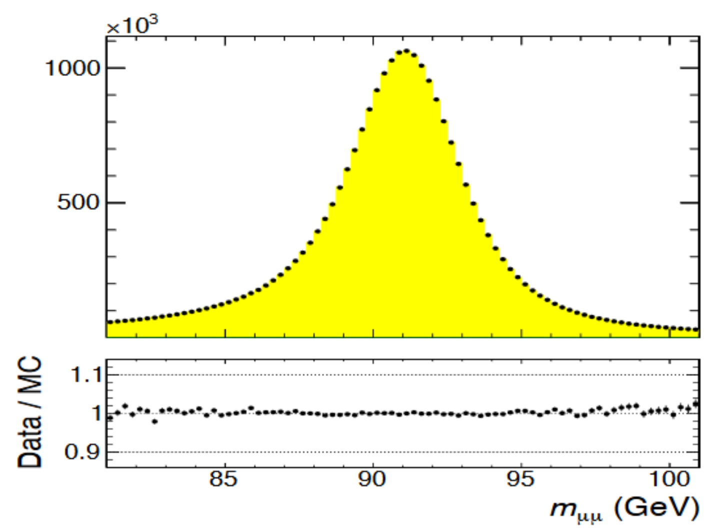


- **Already ~0.2% precision by ATLAS+CMS Run 1 combination**

m_H measurement

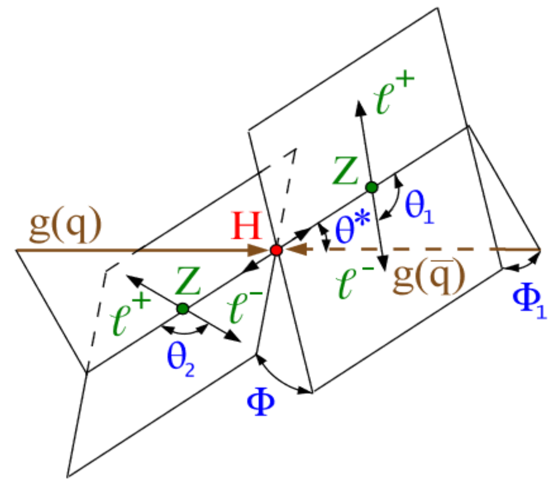
- Involves fitting m_H-dependent model to data
  - Model developed from simulation
- Requires precise understanding of particle response in the detector
  - Simulation must accurately reflect data
  - Mass resolution limited by resolution of Higgs boson decay products

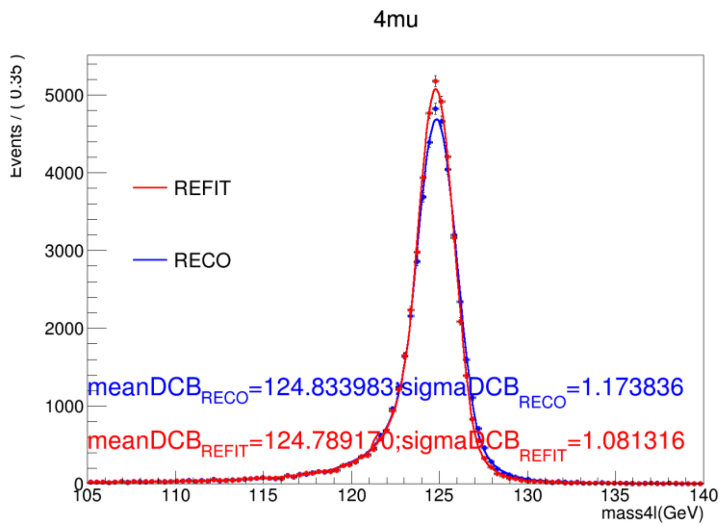




Analysis strategy (H→ZZ → 4ℓ)

- Three event categories: 4μ, 4e and 2e2μ
- Fit is performed for m_H in 3D space:
  - $pdf(m_{4l}, D_{bkg}^{kin}, \sigma_{m4l}|m_H)$
  - σ_{m4l}, per-evet mass uncertainty, improve the sensitivity by 8%
  - D_{bkg}^{kin}, discriminate signal events to background, improve the sensitivity by 3%
- Z1 mass constraint
  - $L(p_T^1, p_T^2|p_T^{reco1}, p_T^{reco2}, \sigma_{pT}^1, \sigma_{pT}^2) = Gauss(p_T^{reco1}|p_T^1, \sigma_{pT}^1) * Gauss(p_T^{reco2}|p_T^2, \sigma_{pT}^2) * L(m_{12}|m_Z, m_H)$
  - $L(m_{12}|m_Z, m_H)$ is a constraint item, improve the sensitivity by 10%





Results with 2016 dataset (H→ZZ → 4ℓ)

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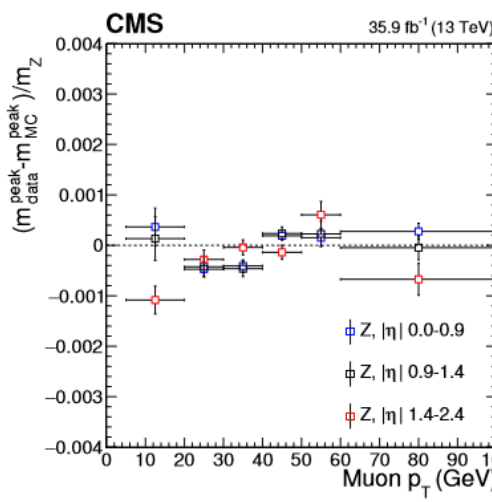
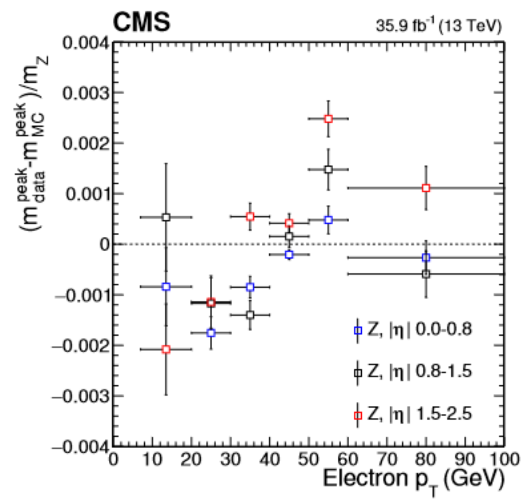
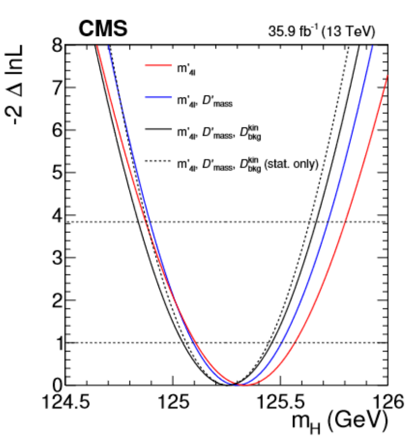
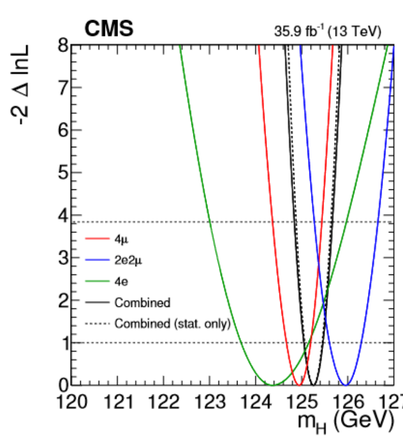
- **3D fit, nuisances are allowed to be float**
- **Lepton energy scale dominates the systematic uncertainties**
  - **4μ ~0.04%**
  - **4e ~0.3%**
- **4μ: 124.94±0.25(stat) ±0.08(syst)GeV**
- **4e: 123.37±0.62(stat) ±0.38(syst)GeV**
- **2e2μ: 125.95±0.32(stat)±0.14(syst)GeV**
- **Combination: 125.26±0.19(stat)±0.08(syst)GeV**









Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.6 %
Lepton identification/reconstruction efficiencies	2.5 – 9 %
Background related uncertainties	
Reducible background (Z+X)	36 – 43 %
Signal related uncertainties	
Lepton energy scale	0.04 – 0.3 %
Lepton energy resolution	20 %

Analysis strategy (H → γγ)

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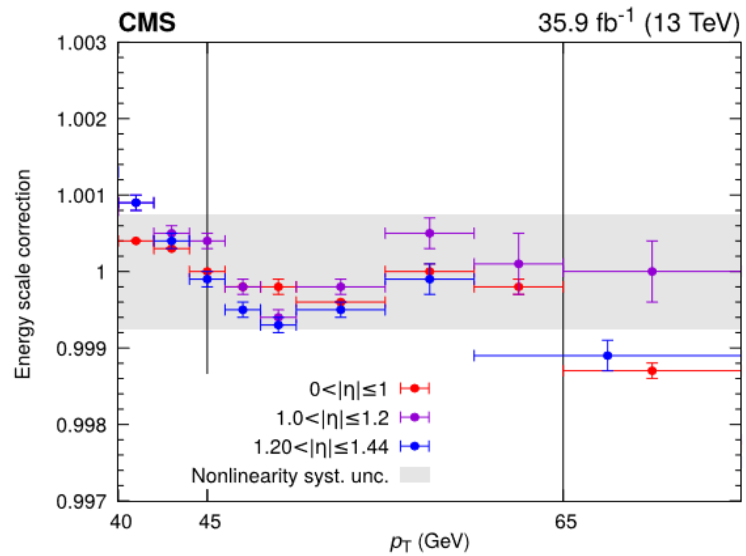
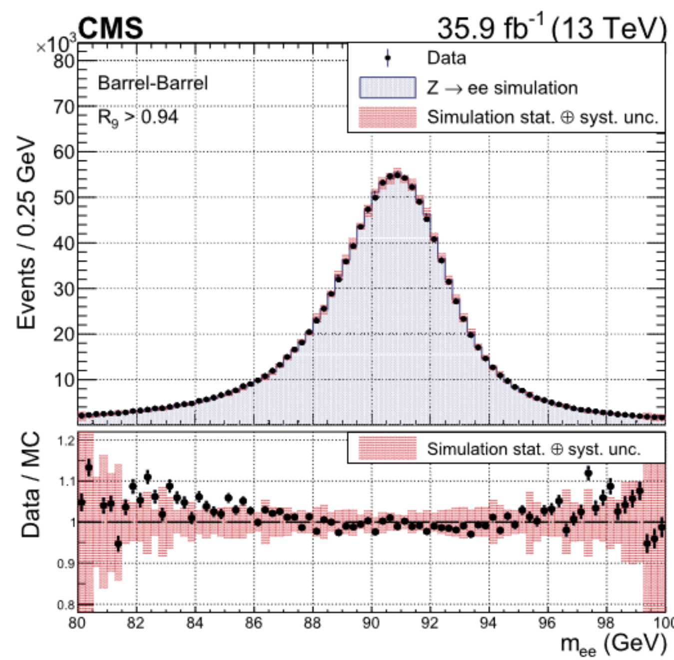
- Diphoton vertex chosen using dedicated BDT
- Individual photon identified with a dedicated photon ID BDT
- A dedicated BDT used to select di-photon pairs
- Events are categorized into 3VBF and 4 Untagged(pick up mainly ggH and other events) categories
- Special efforts made to correct the energy scale more precisely than before
    - Improved detector calibration ->good agreement of the input variables to energy regression correction
    - More granular Run-η-R9-pt dependent scale correction





Results with 2016 dataset ($H \to \gamma\gamma$)

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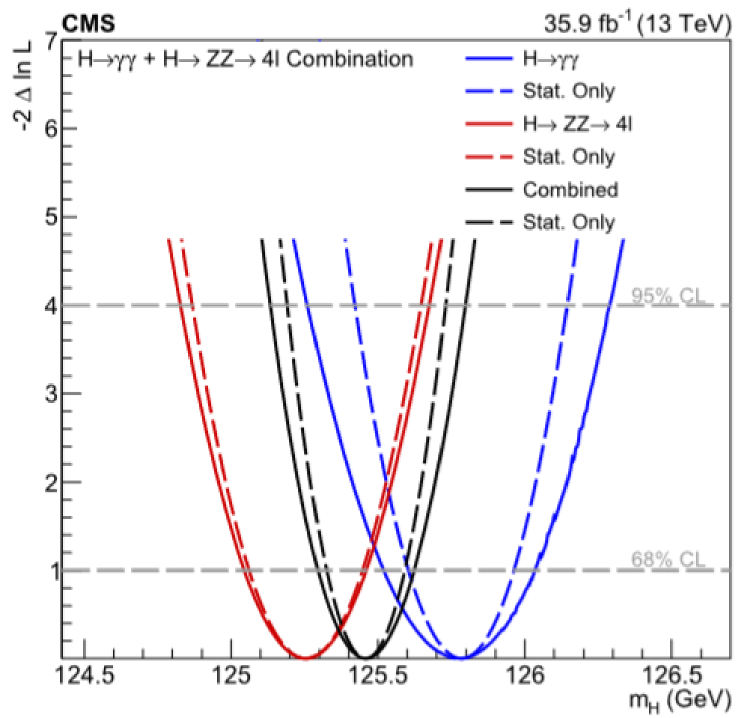
- Likelihood fit is performed simultaneously to seven categories in the range 100-180GeV
- Systematic uncertainties are included in the form nuisances
  - The electron energy scale uncertainties are propagated directly to the photon energy scale
  - Additional uncertainties assigned to deal with e-γ differences

- **The best fit value:**
  125.78±0.18(stat) ±0.18(syst)GeV

Table 1
The observed impact of the different uncertainties on the measurement of m_H.

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26



Combination (H $\rightarrow \gamma\gamma$ & H$\rightarrow$ZZ $\rightarrow 4\ell$)

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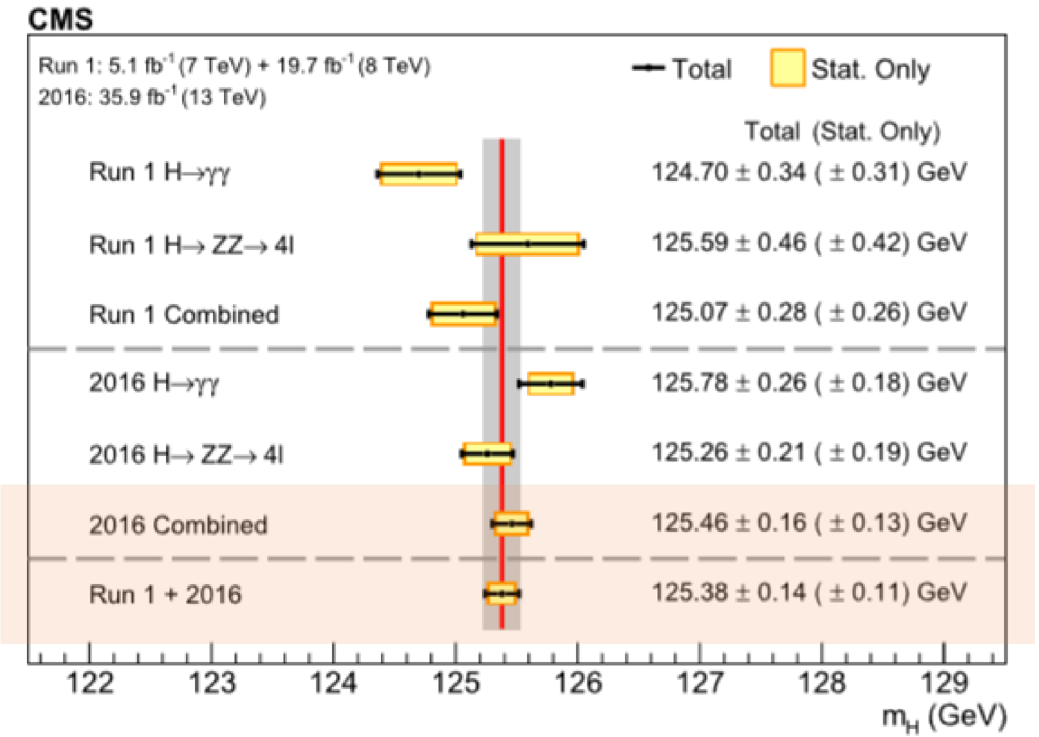
- We treat the electron scale and photon scale to be uncorrelated between two channels
  - In the H $\rightarrow \boldsymbol{\gamma\gamma}$, the largest uncertainty on the photon energy scale is due to the different ECAL response to electron and photon, which is only applied to the H $\rightarrow \boldsymbol{\gamma\gamma}$
  - Energy scale corrections used in two channels are different
  - Average energy of electrons in H$\rightarrow$ZZ $\rightarrow 4\ell$ is much lower than the photon energy in H $\rightarrow \boldsymbol{\gamma\gamma}$
- Same procedure is used to combine this result(2016) with the same measurement from Run 1



- With Run 1+ 2016 data, CMS m_H =125.35$\pm$0.11(stat) $\pm$0.08(syst)GeV
- Compatible with Run 1 LHC combination
- Most precise m_H measurement to date ~0.11%

Summary

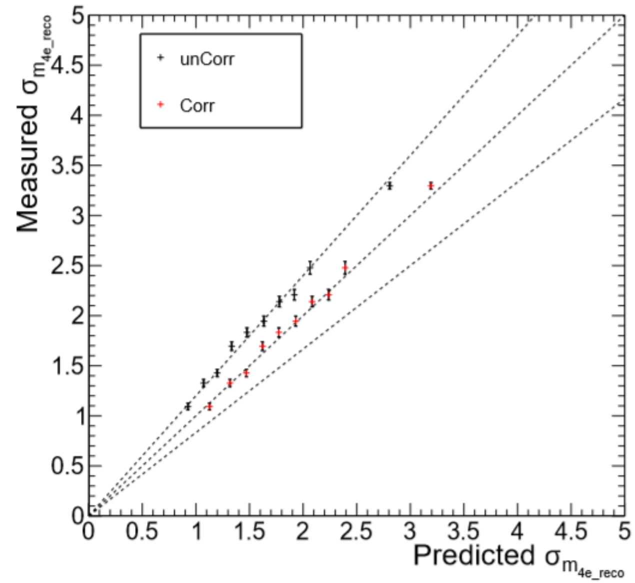
- **Higgs mass measurement have entered a precision era at LHC**
  - **Higgs boson mass measurement with 0.11% accuracy**

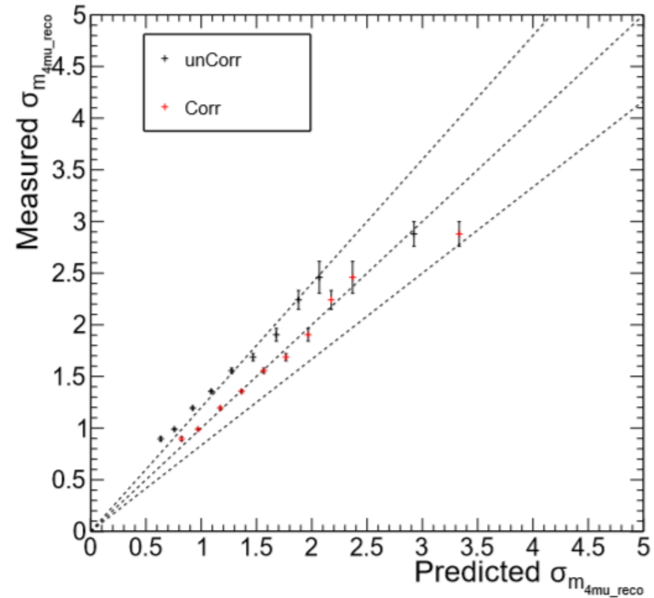
- **Updates are ongoing within CMS using LHC full Run 2 dataset together with further refinements on the detector calibration and energy corrections**

backup

Per-event mass uncertainty

- The uncertainty in the pt can be predicted for each lepton.
- Per-lepton pt uncertainty is propagated to four-lepton mass to predict the per-event mass uncertainty
- The per-lepton pt uncertainty is corrected in data and MC using Z boson events



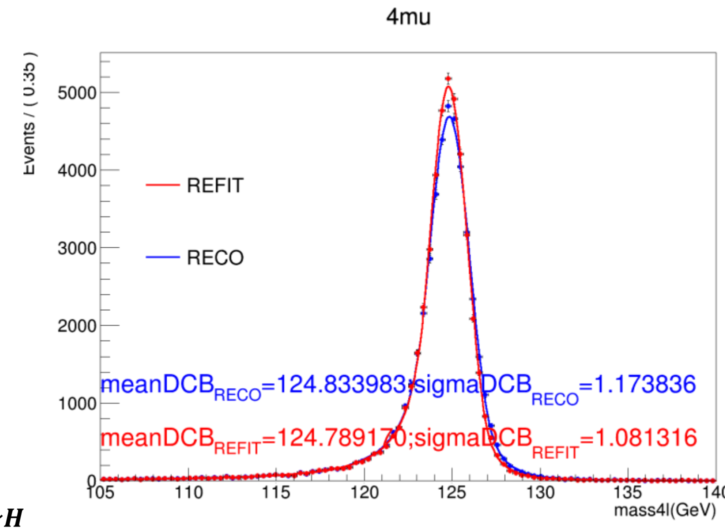


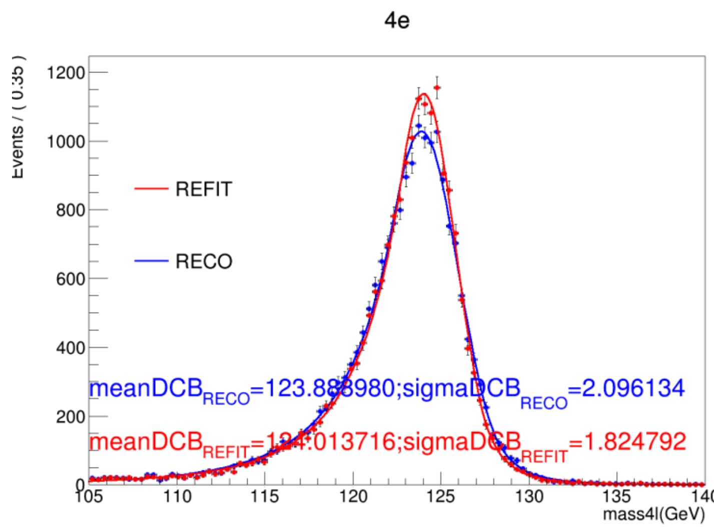
Z1 mass constraint

- Input
  - p_T^{reco1},p_T^{reco2}: reconstructed lepton pT
  - σ_{pT}^1,σ_{pT}^2: lepton pT resolution, after per-lepton pT resolution rescale
- Construct likelihood with Z_1 mass as constraint term

$$\boldsymbol{L(p_T^1, p_T^2 | p_T^{reco1}, p_T^{reco2}, \sigma_{pT}^1, \sigma_{pT}^2)}$$
$$\boldsymbol{= Gauss(p_T^{reco1} | p_T^1, \sigma_{pT}^1) Gauss(p_T^{reco2} | p_T^2, \sigma_{pT}^2) L(m_{12} | m_Z, m_H}$$

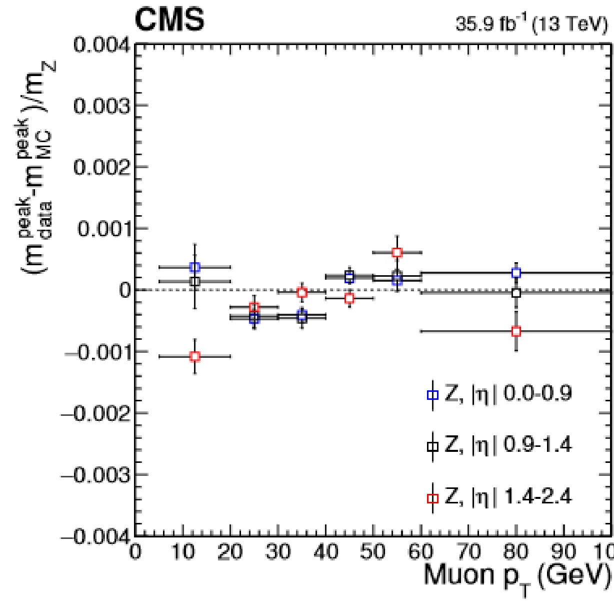
- Output
  - p_T^1, p_T^2: refitted lepton pT
  - $\sigma(p_T^1)$,$\sigma(p_T^2)$: error of refitted lepton pT
- Constraint
  - $L(m_{12}|m_Z, m_H)$: Z_1 line shape at generator level from SM Higgs sample with m_H=125GeV
  - m_{12} is calculated from p_T^1, p_T^2

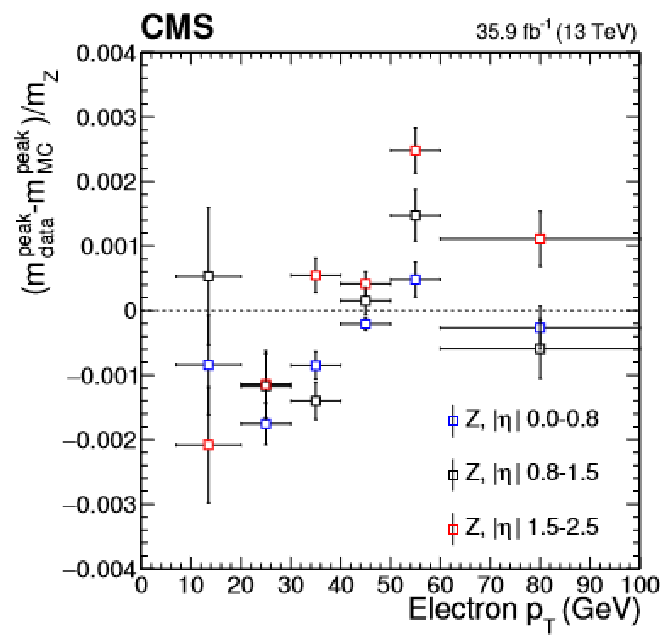




Lepton energy scale uncertainty

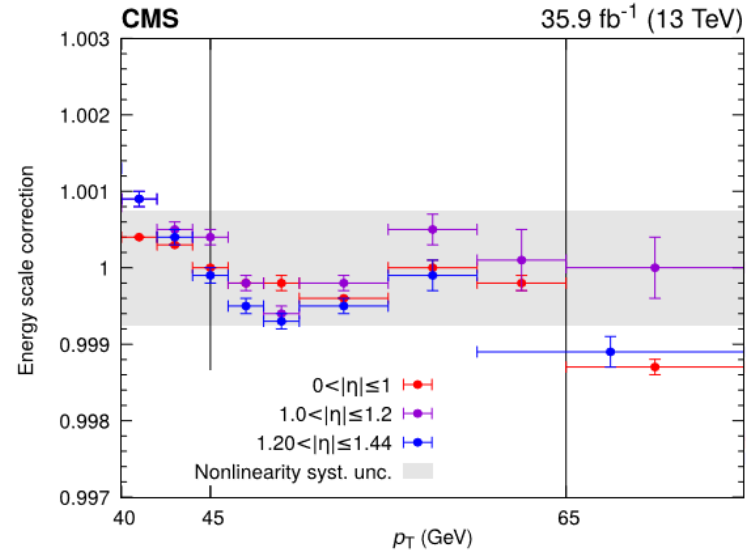
- The uncertainty in lepton energy scale is the dominant system uncertainty in the mass measurement
- It is determined by considering the Z→ 2ℓ mass distributions in data and MC.
  - Events are separate into categories based on the pt and eta of one of two leptons and integrating over the other.
  - Fit DCB∗BW to dilepton mass distribution.
  - The offset in the measured peak position are extracted
  - The relative difference between data and MC is propagated to four-lepton mass to determine the scale uncertainty
  - The uncertainty is determined to be 0.04% , 0.3% and 0.1% for 4mu, 4e and 2e2mu channel.



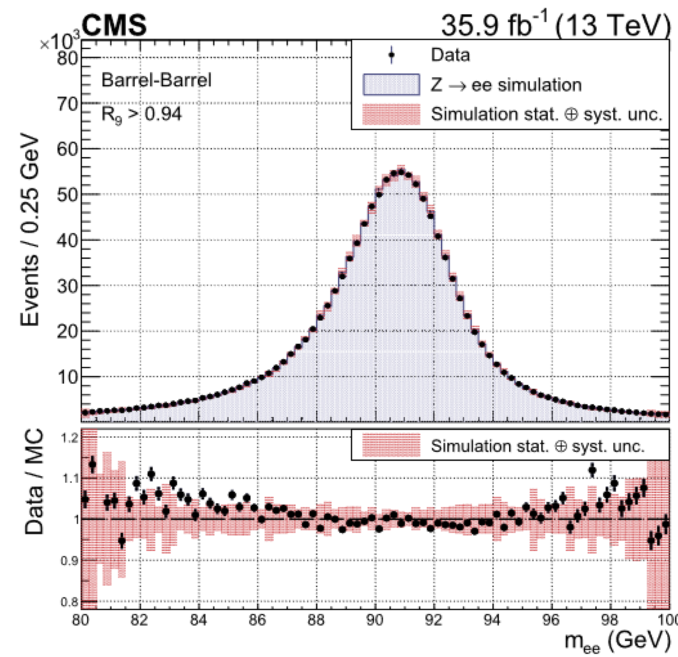


Photon energy calibration

- Correction using MVA regression technique is derived by EGammaPOG
  - The lack of containment of the shower in the clustered crystals
  - The energy lost by photons that convert upstream of the ECAL.

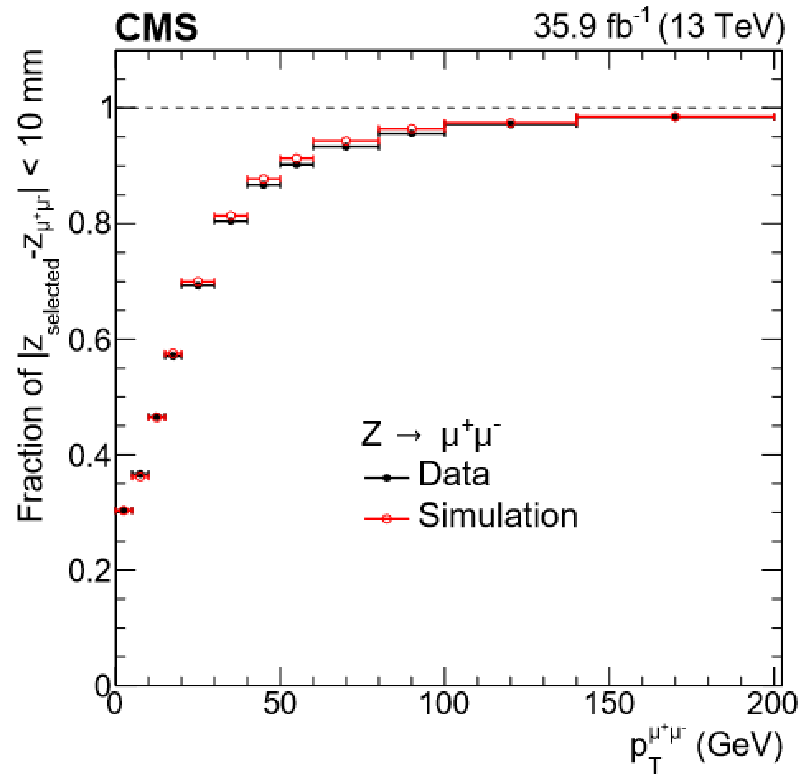


- After apply above correction. A multistep procedure is used to correct the data MC residual disagreement.
  - Run-eta dependent correction
  - Eta-R9 dependent correction
  - Pt dependent correction



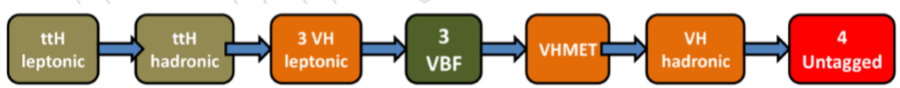
Diphoton vertex identification

- The diphoton mass resolution has contributions from measurement of energy and the angle between two photons
- If the diphoton is associated with the charged particle vertex, the mass resolution can be improved
- Two BDT frameworks are design
  - Vertex identification BDT is used to identify the most likely vertex
  - Vertex probability BDT is used to estimate the probability of correctly choosing that vertex.



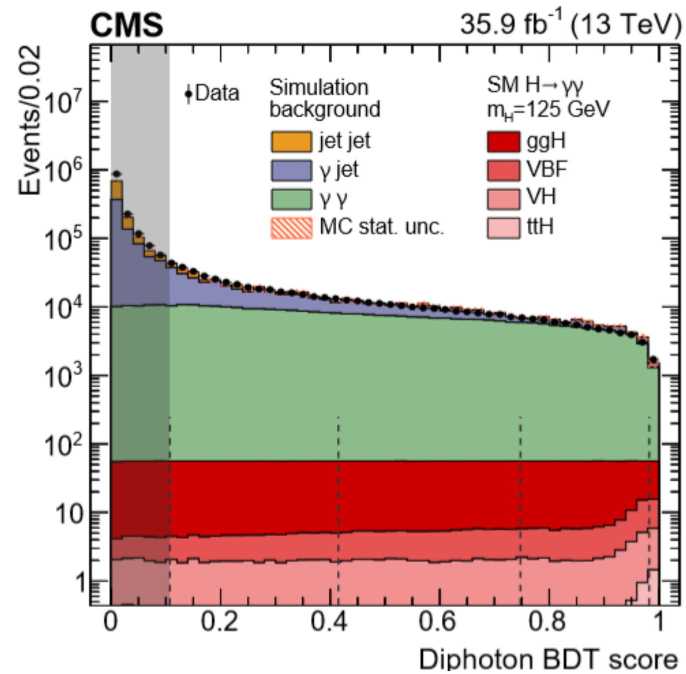
Event classification

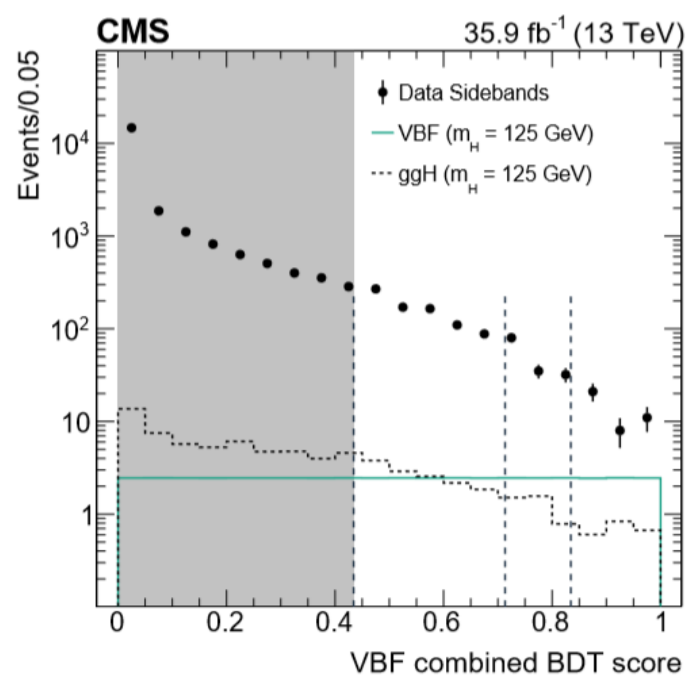
- To improve the sensitivity of this analysis, events are classified targeting different production mechanism and according to their mass resolution and their predicted signal-to-background ratio.



- Untagged events are further divided into 4 categories diphoton BDT
  - Diphoton BDT is used to discriminate signal and background events

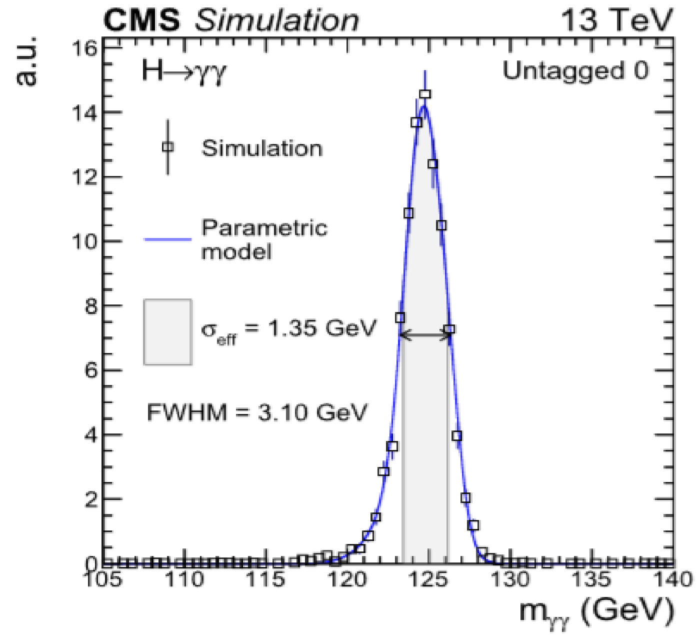
- VBF combined BDT is used to separate VBF events to 3 categories
- ttH and VH categories are not considered in this analysis



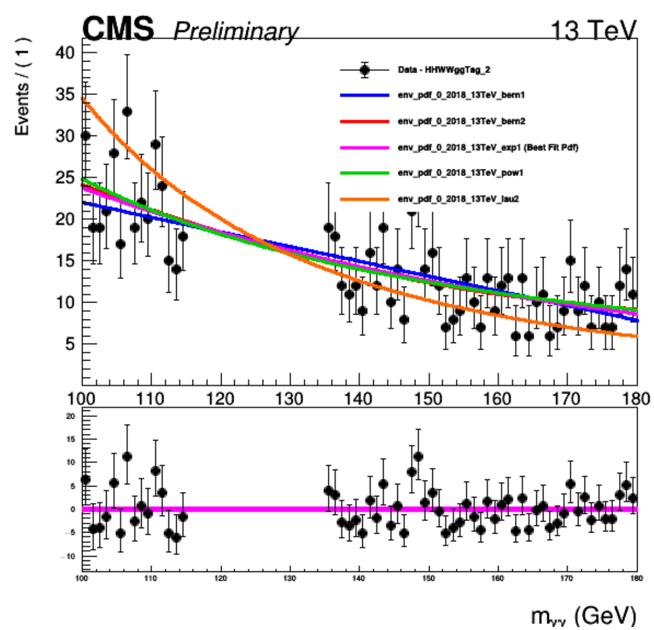


Signal and background models

- Signal mode is parametrized using a sum up to five Gaussian functions for each category
- A simultaneous fit of all different MH samples is performed, where individual parameters of the function form are themselves polynomials of MH



- Background model, the discrete profiling method is used



muon

- Resolution and pt scale measured in Z J/ψ decays
  - Simulation momenta corrected and smeared to match data

- Z->$\mu\mu$ mass resolution
  - ~1%(barrel) ~1.5%(endcap)

- Scale uncertainty
  - ~0.04%

electron

- MVA based energy correction for e/γ
  - Trained on simulation samples
  - Correction for energy loss in material in front of ECAL, variation of cluster response, effects of pileup, etc.

- Z->ee decays used for energy scale and resolution correction
  - Correct for the residual differences between data and MC, after applying the MVA based correction from the first step

- Uncertainties on scale
  - ~0.1% for e, ~0.15% for γ