CMS

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Higgs mass and width measurement in ZZ to 4-leptons final state with CMS full Run2 data

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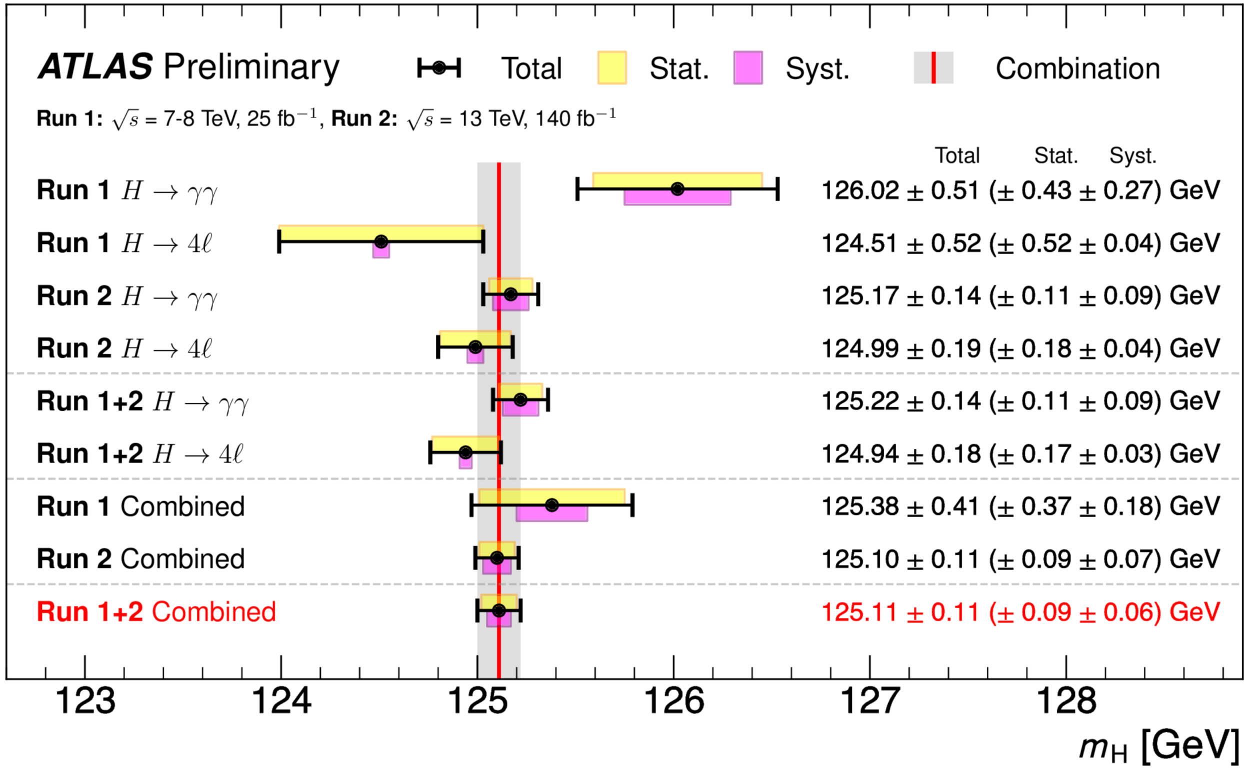
Introduction

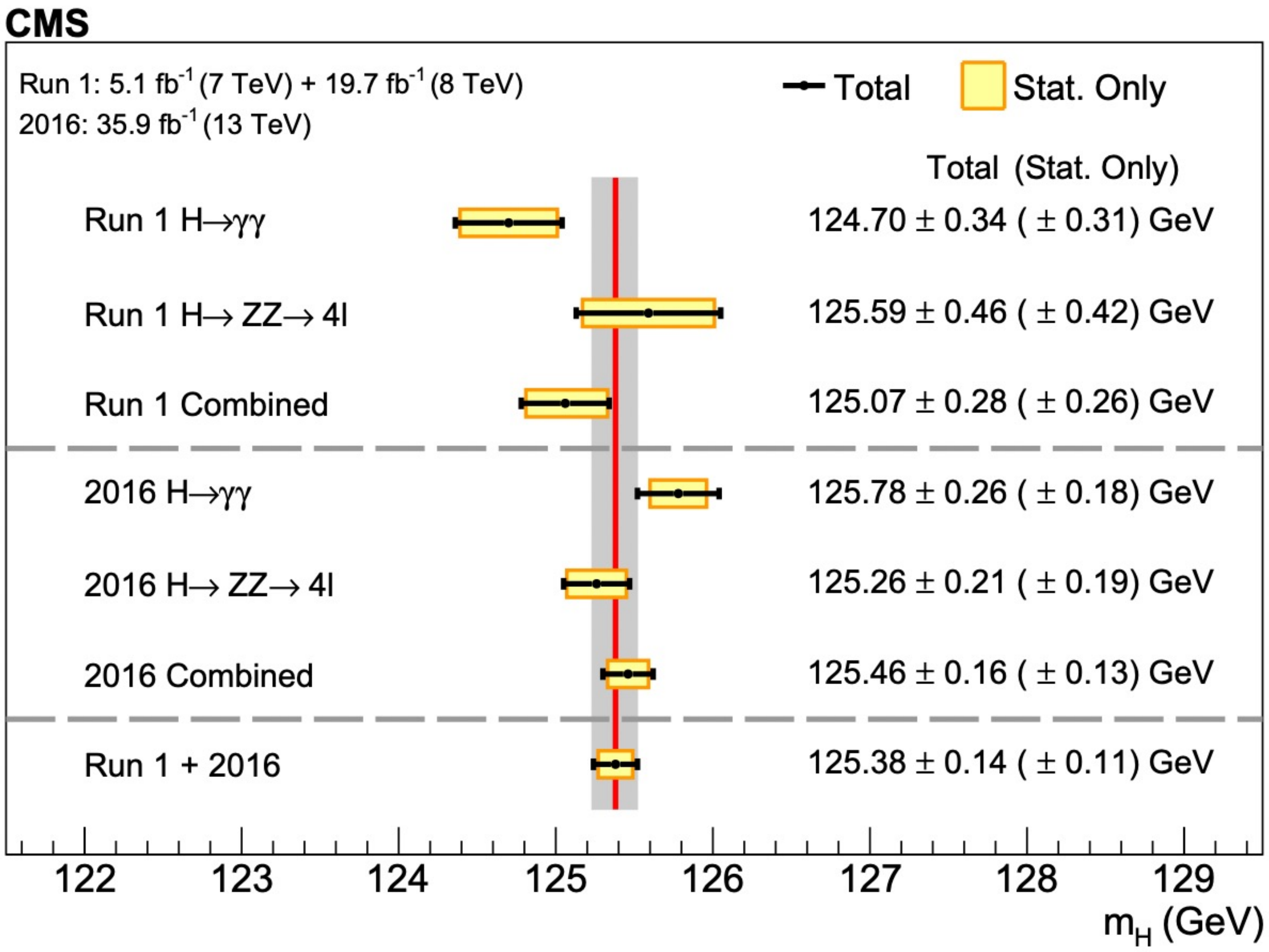
- The Higgs boson mass is one of the most important free parameters of the Standard Model.
  - Its value should be measured precisely since it determines all other Higgs boson properties.
- The two mass peaks formed by 4ℓ and $\gamma\gamma$ have good resolution.
- Already ~0.1% precision by ATLAS Run1+Run2 combination.

ATLAS-CONF-2023-037



Introduction

- Before this measurement from CMS ~0.1% precision



PLB 805 (2020) 135425

CMS m_H measurement in $H \to ZZ \to 4\ell$

- Run2 Ultra-Legacy data (138 fb^{-1})
  - Event selection Inherits from HIG-21-009

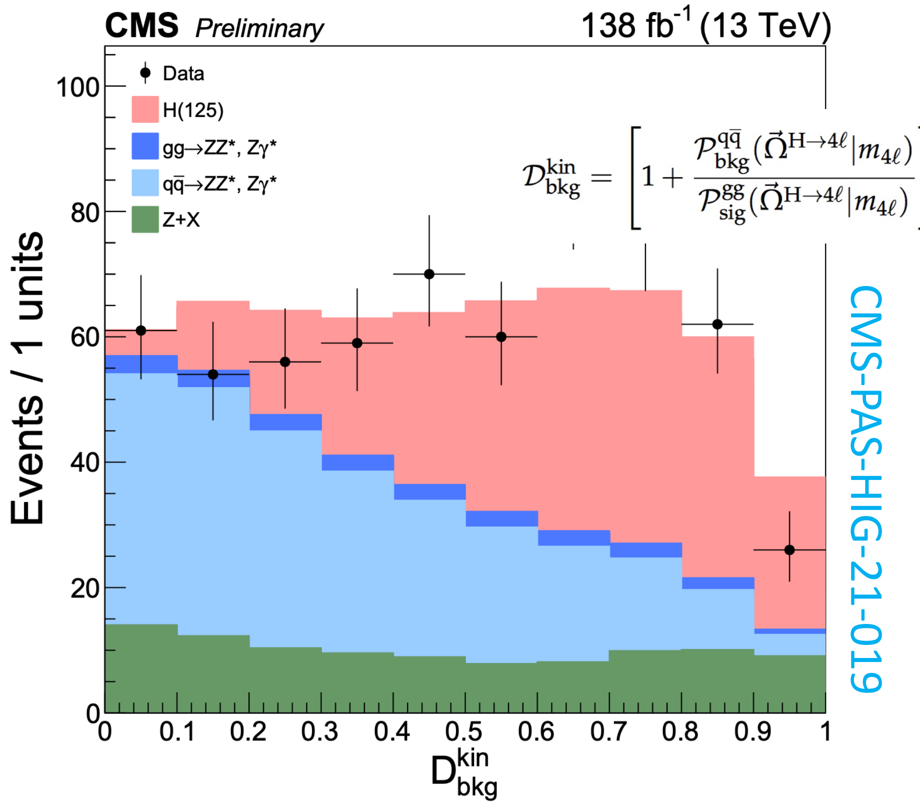
Table 2: The observed number of events and the post-fit expected yields for the H boson signal and background contributions in the on-shell region $105 < m_{4\ell} < 140$ GeV.

	4μ	4e	$2e2\mu$	$2\mu 2e$	Total
$q\bar{q}$ background	89.2	38.9	64.4	42.1	234.6
gg background	9.7	4.9	4.9	3.8	23.4
Z+X background	32.4	12.2	28.2	18.6	91.3
Total signal	90.9	48.7	65.5	53.3	258.4
Total expected	222.2	104.6	163.0	117.8	607.7
Observed	230	94	170	107	601

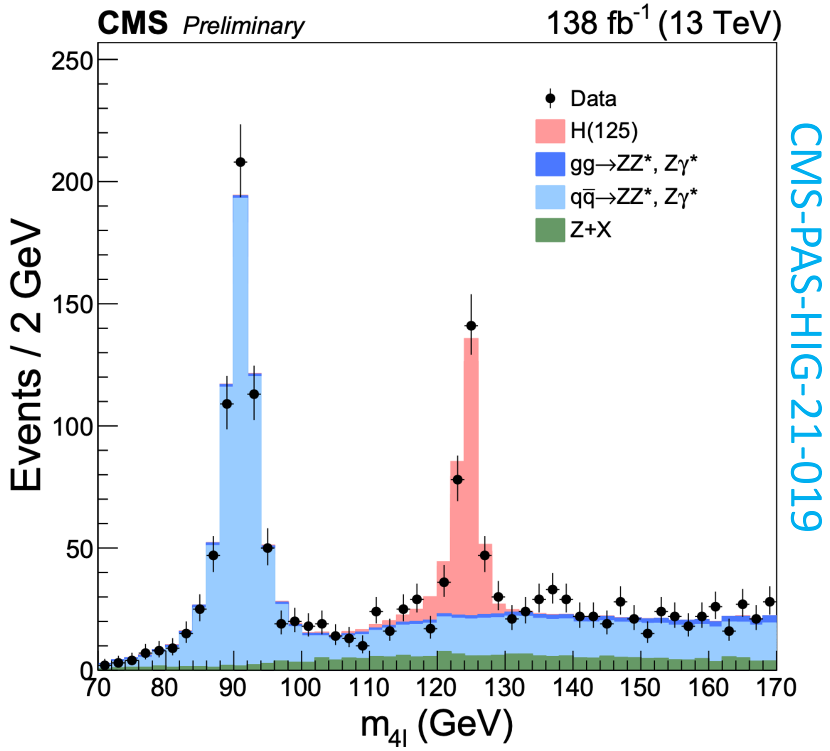
CMS-PAS-HIG-21-019

CMS $\mathrm{m_H}$ measurement in $H \to ZZ \to 4\ell$

- Observables
  - 4-lepton invariant mass (m_{4l})
  - Kinematic discriminant (D_{bkg}^{kin})
  - Per-event mass uncertainty (D_{mass})



$$\mathcal{D}_{\rm bkg}^{\rm kin} = \left[1 + \frac{\mathcal{P}_{\rm bkg}^{q\bar{q}}(\vec{\Omega}^{\rm H\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\rm sig}^{gg}(\vec{\Omega}^{\rm H\to 4\ell}|m_{4\ell})}\right]^{-1}$$



- Signal line shape: double-side crystal ball
  - Treat all parameters as function of $\mathrm{m_H}$
  - $k_i = a + b * (125 - \mathrm{m_H})$
- ZZ backgrounds: from simulations
- Z+X: data-driven

CMS m_H measurement in $H \to ZZ \to 4\ell$

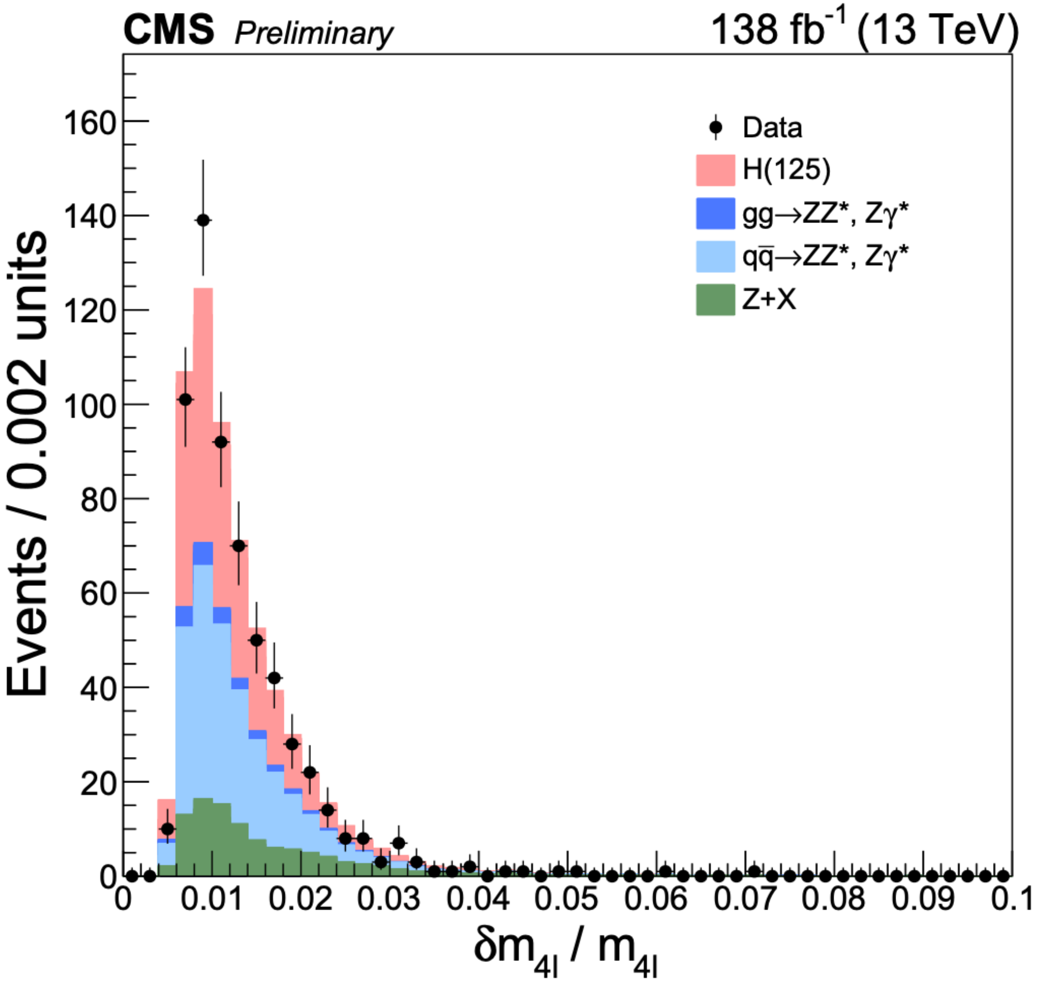
- Per-event mass uncertainty
  - Lepton kinematics uncertainty is propagated to the 2/4-lepton event to predict the mass uncertainty on an event-by-event basis

$$m_0 = F(p_{T1}, \phi_1, \eta_1;\ p_{T2}, \phi_2, \eta_2;\ p_{T3}, \phi_3, \eta_3;\ p_{T4}, \phi_4, \eta_4)$$

$$\delta m_i = F(\ldots;\ p_{Ti} + \delta p_{Ti}, \phi_i, \eta_i;\ \ldots) - m_0$$

$$\delta m = \sqrt{\delta m_1^2 + \delta m_2^2 + \delta m_3^2 + \delta m_4^2}$$

  - The per-lepton momentum uncertainties are corrected in data and simulation using Z boson events
    - Asking $\overline{\delta m} = \sigma$ of the Z peak
  - After corrections are derived, a closure test of the agreement between the predicted and fitted 4-lepton mass resolution is performed.
    - Measured σ : the σ from the fit function
    - Predicted σ : arithmetic mean of predicted per-event mass error



CMS-PAS-HIG-21-019

CMS $\mathrm{m_H}$ measurement in $H \rightarrow ZZ \rightarrow 4\ell$

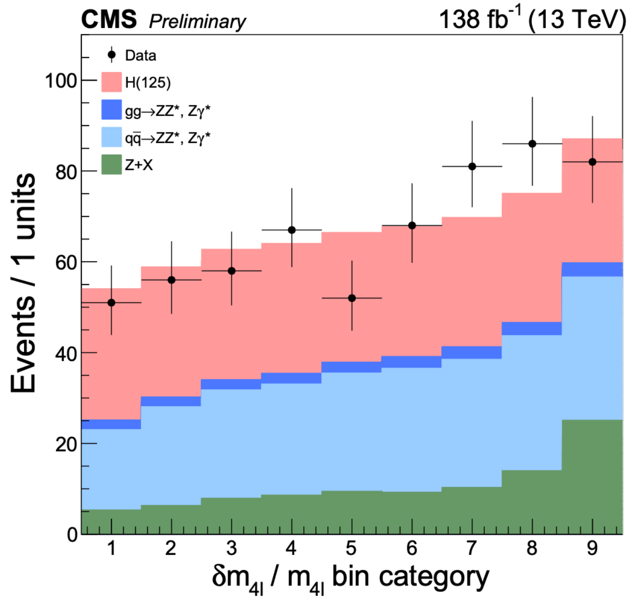
- New technique, beam-spot constraint for muon **(new w.r.t HIG-16-041)**
  - Once the 4-lepton system selected, muons are constrained to beam spot
  - This method improves Higgs boson mass resolution by roughly 5-8% (depending on year) in the 4μ final state
  - Smaller impact (<3%) in $2\mu 2e$ and $2e2\mu$ final state
  - No improvement in 4e final state, because electron momentum measurement is dominated by ECAL system
- Z1 mass constraint
  - To improve the mass resolution, a kinematic fit is also performed using a mass constraint on the intermediate on-shell Z resonance
  - The basic idea is to re-evaluate P_T of two leptons forming the Z1 boson of the Higgs candidate, with a constraint on the reconstructed Z mass to follow the Z boson true line shape

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

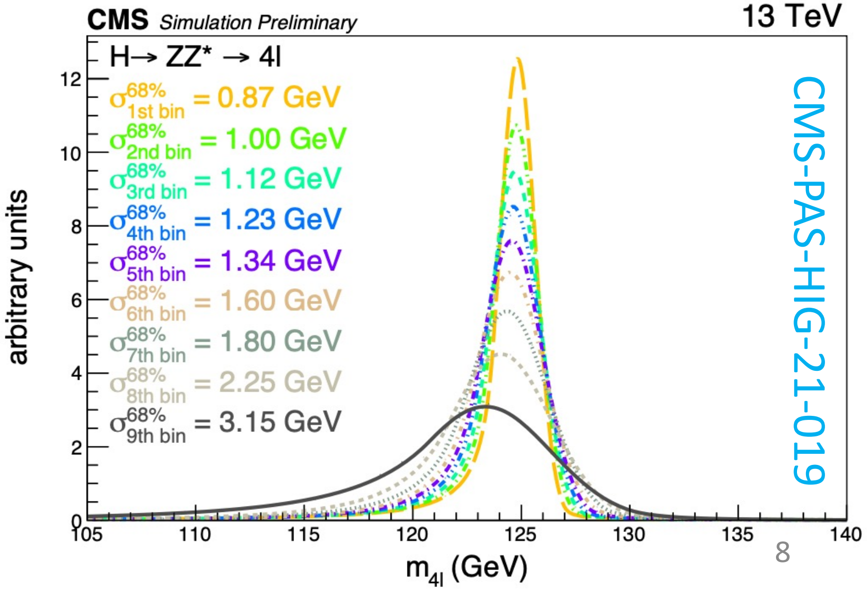
CMS m_H measurement in $H \rightarrow ZZ \rightarrow 4\ell$

- Per-event mass uncertainty **(new w.r.t HIG-16-041)**
  - In 2016, 3D likelihood $\mathcal{L}(m_{4l}, D_{mass}, D_{bkg}^{kin})$
  - Currently, mass error for categorisation
  - $\mathcal{N} \times \mathcal{L}(m_{4l}, D_{bkg}^{kin})$
  - Events are classified into 9 categories based on their $\sigma_{m4l}/\ m_{4l}$
  - Ranges are found by splitting ggH (at 125GeV) sample evenly
  - The new approach deal with the correlation between σ_{m4l} and D_{bkg}^{kin}
- Better systematic uncertainties treatment

Difference(%)	4μ	4e	$2e2\mu$	$2\mu 2e$
Muon momentum scale	0.03%	-	0.03%	0.03%
Electron energy scale	-	0.15%	0.15%	0.15%
Muon momentum resoltuon	3%	-	3%	3%
Electron energy resolution	-	10%	10%	10%



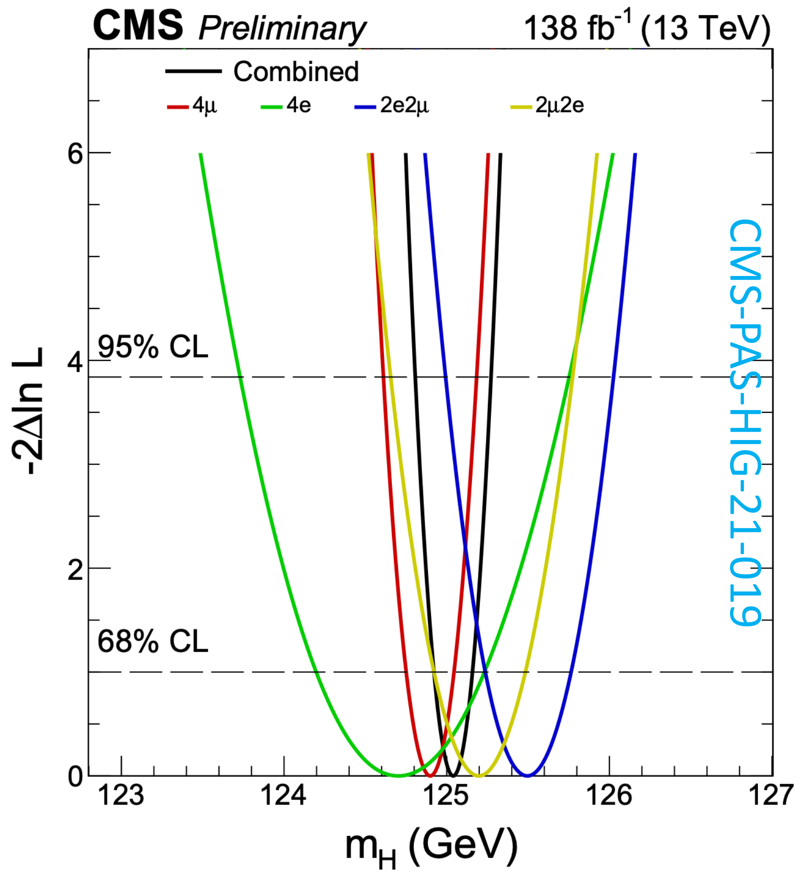
CMS-PAS-HIG-21-019

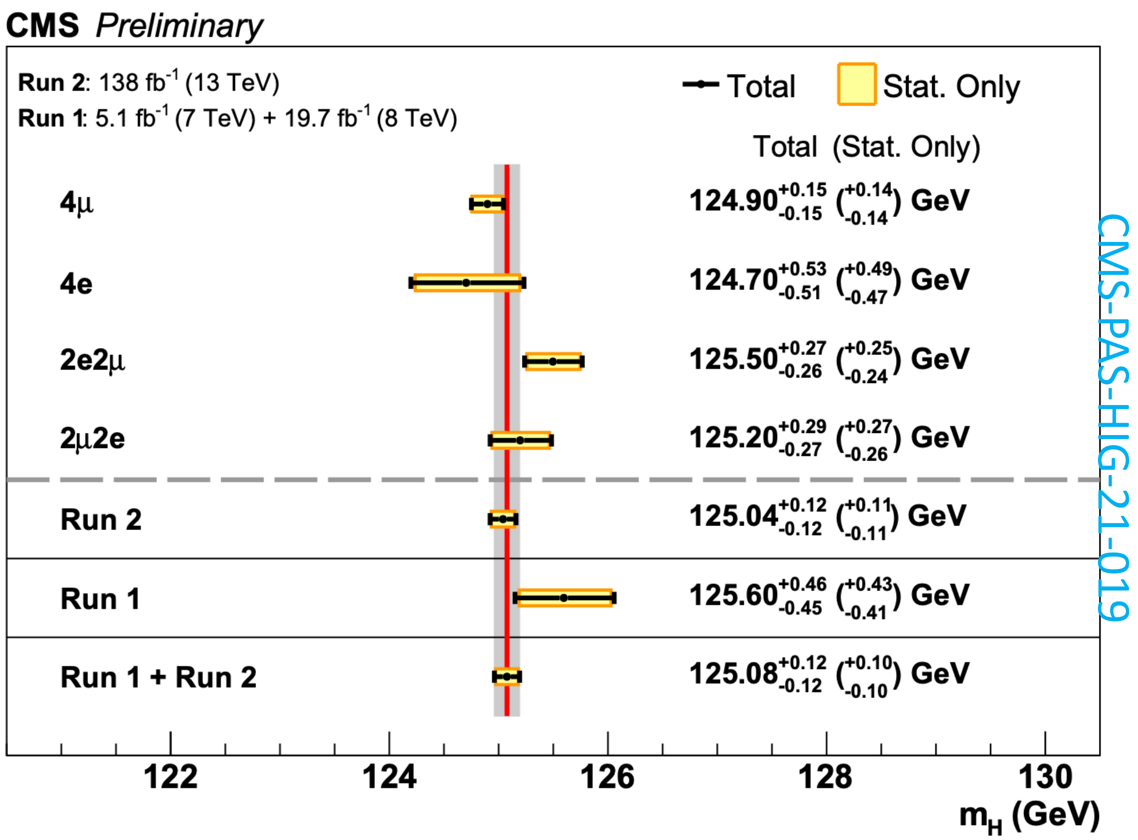


CMS-PAS-HIG-21-019

CMS m_H measurement in $H \to ZZ \to 4\ell$

- Full Run2 and Run1+Run2 results



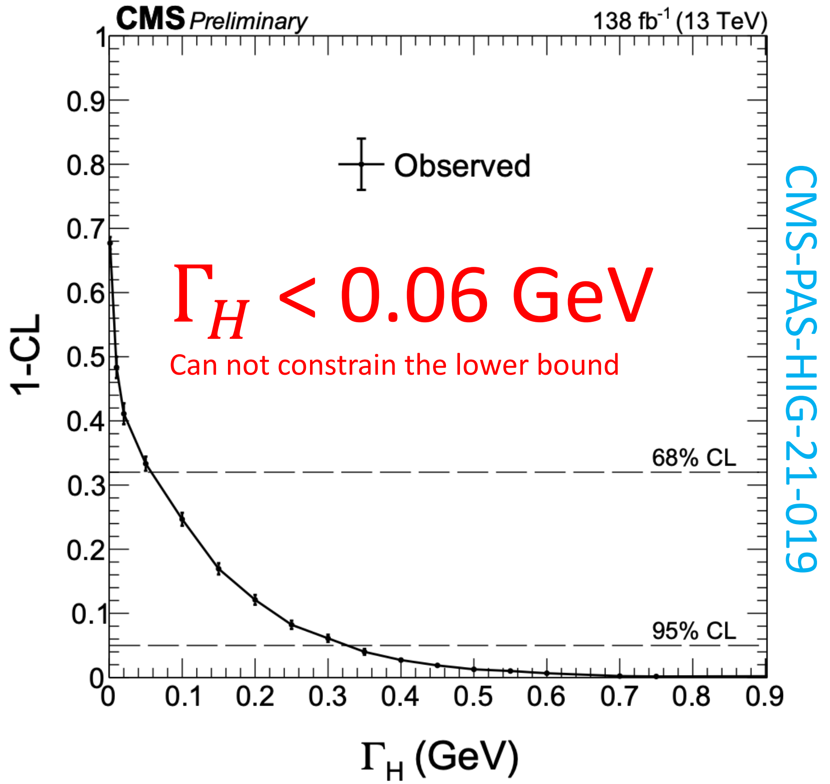


$$m_H = 125.08 \pm 0.12(\pm 0.10)\ GeV$$

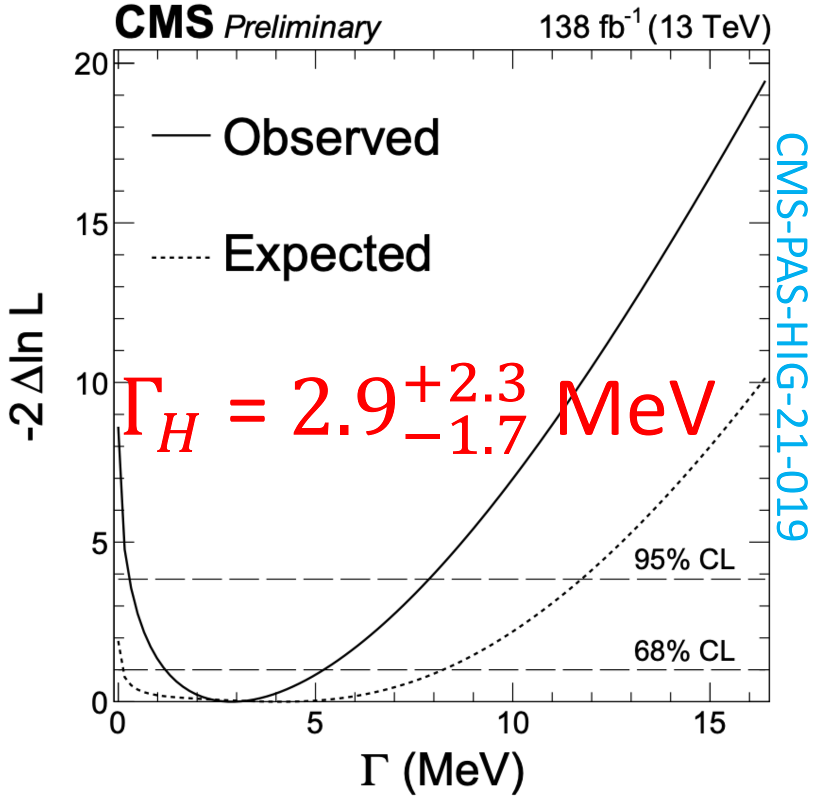
Expected: 0.12 GeV

CMS $\boldsymbol{\Gamma_H}$ measurement in $H \to ZZ \to 4\ell$

- On-shell
  - Same as the mass procedure, treat Γ_H as POI, 1D model only
  - Bounded parameter, Feldman-Cousins algorithm



- Off-shell
  - Aim to measure width from the ratio of off-shell and on-shell yields
  - Mass range > 220 GeV
  - Categorisation based on MELA and jet info.



Summary

- m_H measurement using CMS full Run2 data in 4-lepton final state has been presented
- m_H from HZZ

	Run1	Run1 (ATLAS+CMS)	2016	Run2	Run1+2
ATLAS	124.51 ± 0.52	125.15 ± 0.40	124.79 ± 0.37	124.99 ± 0.19	124.94 ± 0.18
CMS	125.59 ± 0.46		125.26 ± 0.21	125.04 ± 0.12	125.08 ± 0.12

- Γ_H from HZZ
  - Off-shell, $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV
  - On-shell, $\Gamma_H < 0.06$ GeV

Thank you for your attention

Objects

Objects definition is inherited from HIG-19-001 and HIG-21-009

AN

Electrons
$p_T^e > 7\,GeV \quad \lvert\eta^e\rvert < 2.5$
$d_{xy} < 0.5\,cm \quad d_z < 1\,cm$
$\lvert SIP_{3D}\rvert < 4$
BDT ID with isolation with cuts

Muons
Global or Tracker Muon
Discard Standalone Muon tracks if reconstructed in muon system only
Discard muons with muonBestTrackType==2 even if they are global or tracker muons
$p_T^\mu > 5$ GeV $\quad \lvert\eta^\mu\rvert < 2.4$
$d_{xy} < 0.5$ cm $\quad d_z < 1\,cm$
$\lvert SIP_{3D}\rvert < 4$
PF muon ID if $p_T < 200$ GeV, PF muon ID or High-p_T muon ID if $p_T > 200$ GeV
$\mathcal{I}_{PF}^{\mu} < 0.35$

FSR photons
$p_T^\gamma > 2\,GeV \quad \lvert\eta^\gamma\rvert < 2.4$
$\mathcal{I}_{PF}^{\gamma} < 1.8$
$\Delta R(\ell,\gamma) < 0.5 \quad \frac{\Delta R(\ell,\gamma)}{(p_T^\gamma)^2} < 0.012\,GeV^{-2}$

Event Selection

Event selection is inherited from HIG-19-001 and HIG-21-009

- **Z Candidates**
  - Any OS-SF pair that satisfies 12 < m_{ll} < 120 GeV
- Build all possible **ZZ candidates** defined as pairs of non-overlapping Z candidate; define Z_1 candidate with m_{ll} closest to the PDG m_z
  - m_{z1} > 40GeV; $P_T(l1)$ > 20GeV; $P_T(l2)$ > 10GeV
  - ΔR > 0.02 between each of the four leptons
  - m_{ll} > 4GeV for OS pairs (regardless of flavor)
  - Reject 4μ and 4e candidates where the alternative pair $Z_a Z_b$ satisfies $|m_{za} - m_z| < |m_{z1} - m_z|$ AND m_{zb} < 12GeV
  - m_{4l} > 70GeV
- If more than one ZZ candidate is left, take the one with m_{z1} mass closest to m_z and the Z_2 from the candidates whose lepton give higher P_T sum.