Properties of the Higgs boson (mass, width)

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On behalf of the ATLAS and CMS experiments

Higgs2022, Pisa, 7 November 2022

The H boson mass

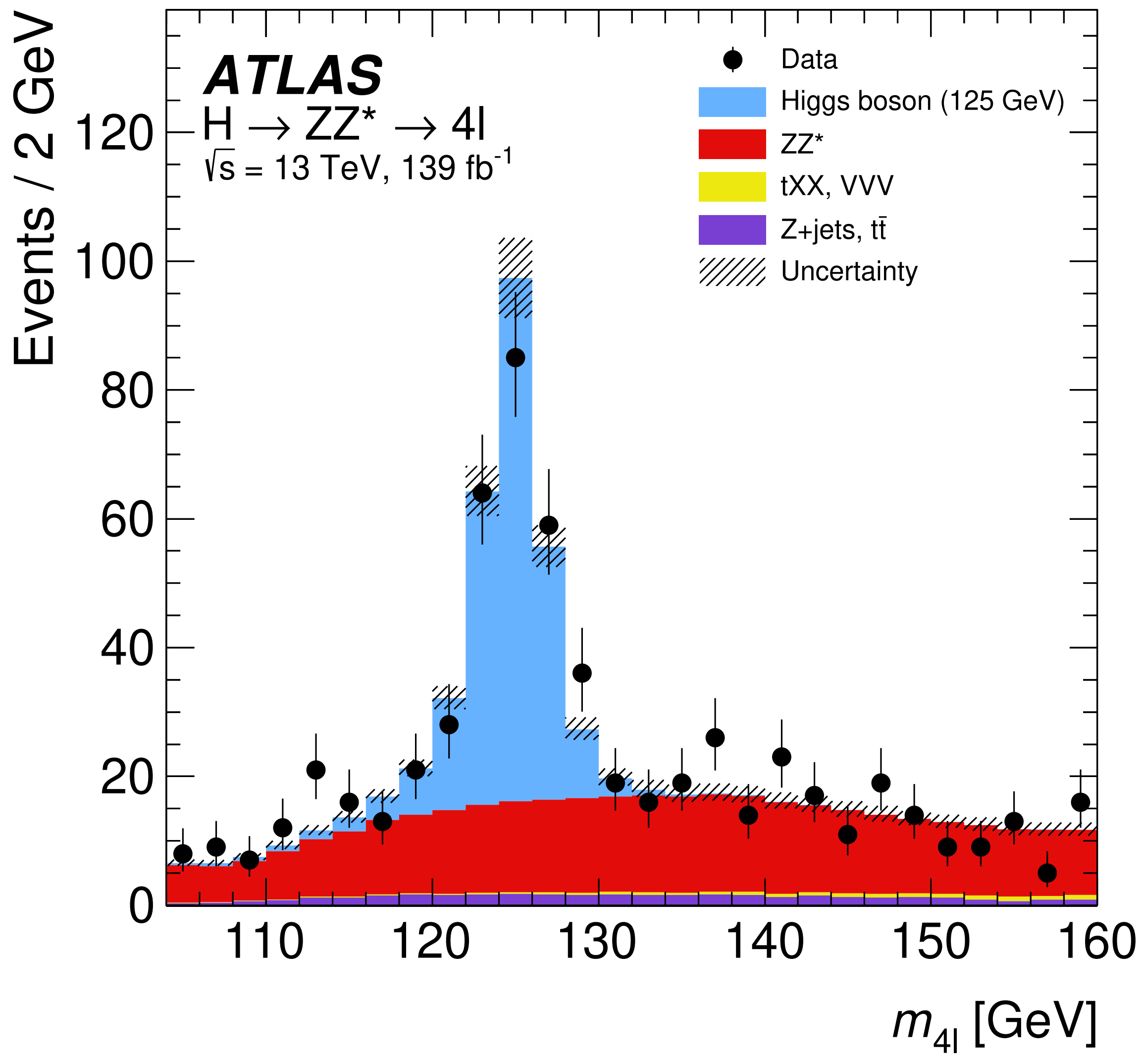
- m_H is a free parameter of the standard model

- It is measured in fully-reconstructed final states involving $\mu^{\pm}$, $e^{\pm}$ or γ
  - $H \rightarrow ZZ \rightarrow 4l; H \rightarrow \gamma\gamma$

- The main principles of the measurement are
  - To calibrate precisely the energy/momentum of leptons and photons in data
  - To make optimal use of available information
  - To minimize the differences between simulation and data that would lead to a biased m_H value when fitting data with a simulated model
  - And… to collect a large sample ☺

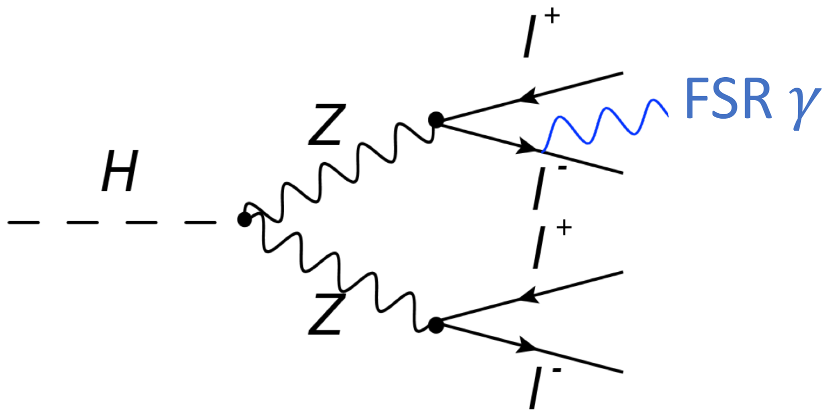
m_H in $H \to ZZ \to 4l$ in ATLAS arXiv:2207.00320

- Improvements
  - Full Run 2 sample (139fb^{-1})
  - Improved muon momentum scale calibration
  - Event-by-event estimate of the m_{4l} resolution
  - Discrimination between signal and ZZ background using deep neural net
- Event selection
  - $p_{T,\ lepton}$ > 20, 15, 10, 7 (e) or 5 (μ) GeV
  - 313 events with m_{4l} in [115,130] GeV interval
- Four event categories: 4μ, 2e2μ, 2μ2e, 4e



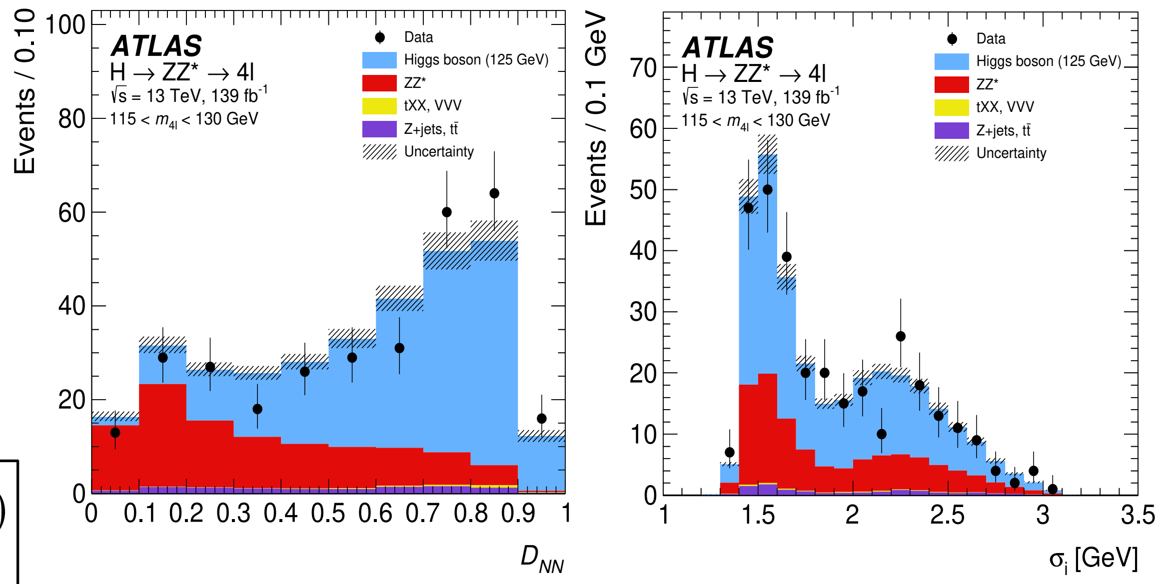
m_H in $H \to ZZ \to 4l$ in ATLAS

- How to get a sharp peak
  - Optimize μ and electron momentum scale calibration
  - Recover final-state radiation photons
  - Make use of kinematic constraint from mass of leading Z



- How to use information optimally
  - Discriminate between S and B
    - D_{NN} computed by neural net using matrix-element based HZZ/ZZ decay discriminant and (p_T, η) of 4-lepton system
  - Account for per-event expected mass resolution σ_i
    - Estimated by a quantile regression neural net using lepton momenta and resolutions as inputs
  - Perform joint fit of three observables $(m_{4l}, D_{NN}, \sigma_i)$

$$\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i | m_H) = \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | \sigma_i, m_H) \cdot \mathcal{P}(\sigma_i | m_H)$$
$$\simeq \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | m_H),$$

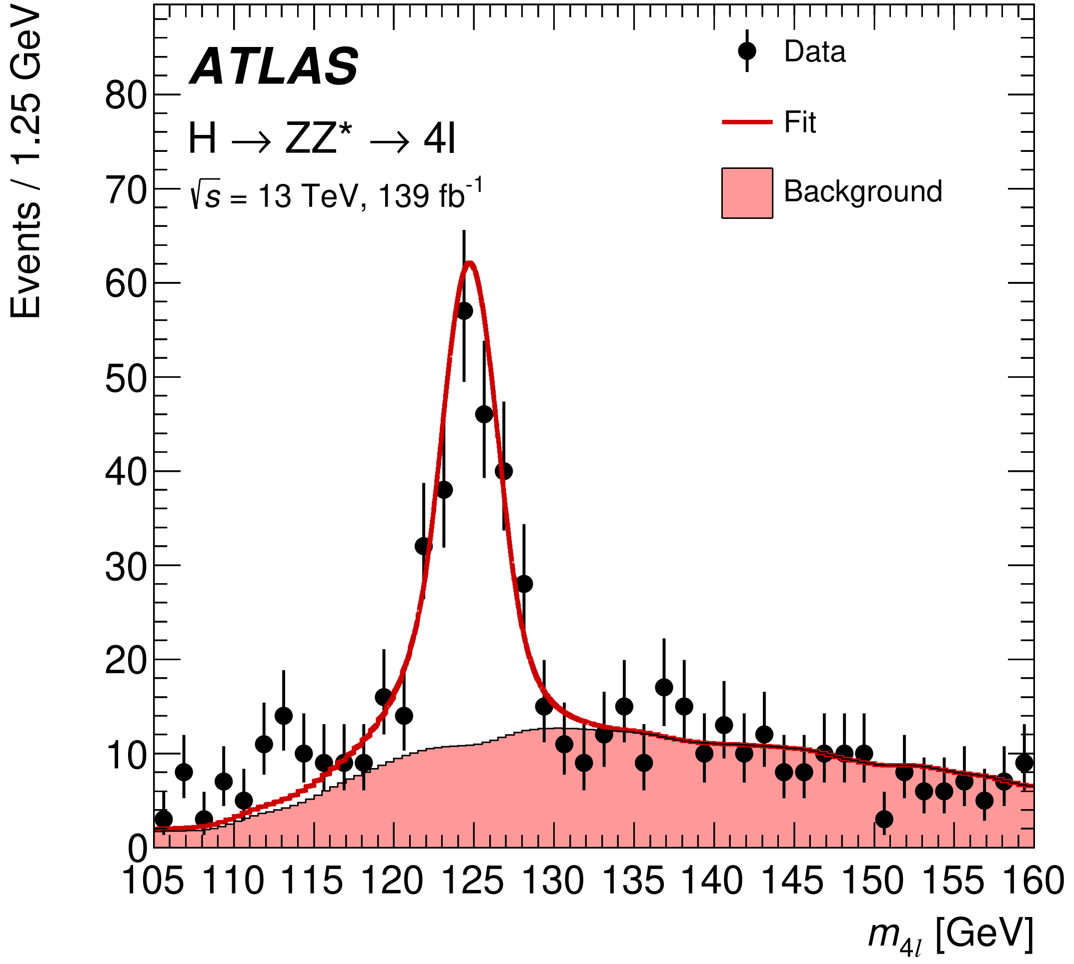


m_H in $H \to ZZ \to 4l$ in ATLAS

- Signal model $\boxed{\mathcal{P}(m_{4\ell}|D_{NN}, \sigma_i, m_H)}$
  - Double-sided Crystal-Ball function with Gaussian core and two exponential tails
  - Dependence of parameters on D_{NN}, σ_i and m_H obtained from fits to samples with different m_H values
  - One model per category

- Background model
  - ZZ and $tXX + VVV$ shapes modelled from MC simulation
  - Fake or non-prompt leptons: data-driven
  - Smoothing using Gaussian kernel

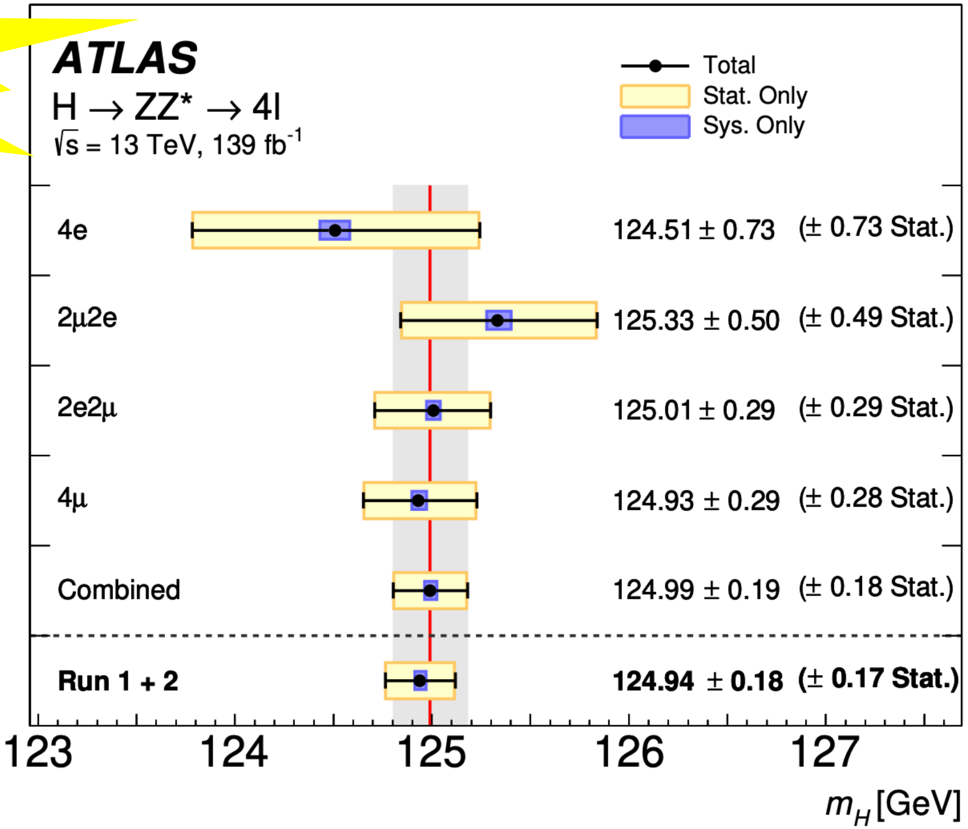
- Signal and ZZ background normalizations left free



Results

See also talk by Giacomo Artoni (Tuesday)

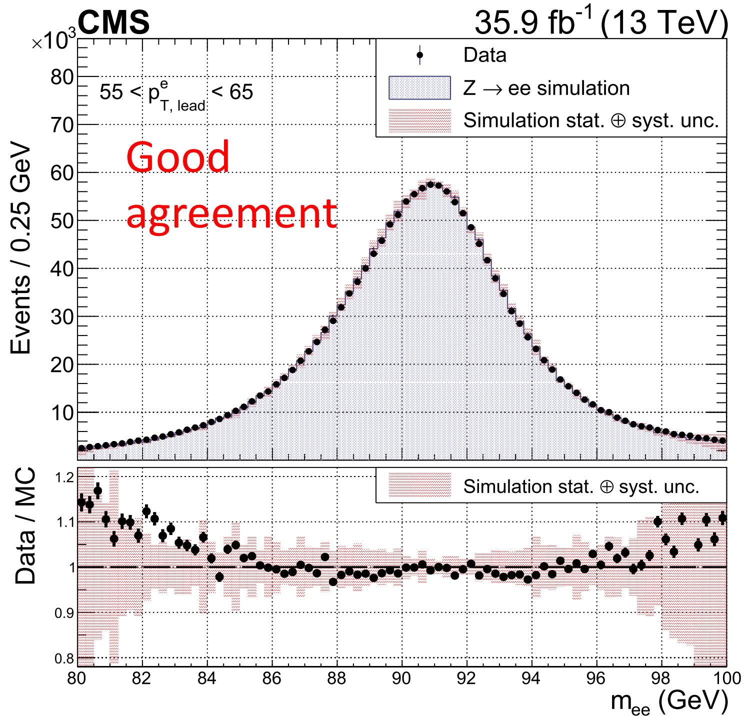
- Run 2 measurement
  - $m_H = 124.99 \pm 0.18(stat.) \pm 0.04(syst.)GeV$
  - Most precise single-channel measurement so far
  - Uncertainty value cross-checked with pseudo-experiments
    - *p*-value of observed uncertainty = 0.28
  - All four categories yield consistent values
- Statistical uncertainty largely dominates
- Lepton momentum scale is the main source of systematic uncertainty
  - Small theory uncertainty, driven by FSR modelling
- Combined ATLAS Run 1 + Run 2 measurement
  - $m_H = 124.94 \pm 0.17(stat.) \pm 0.03(syst.)GeV$

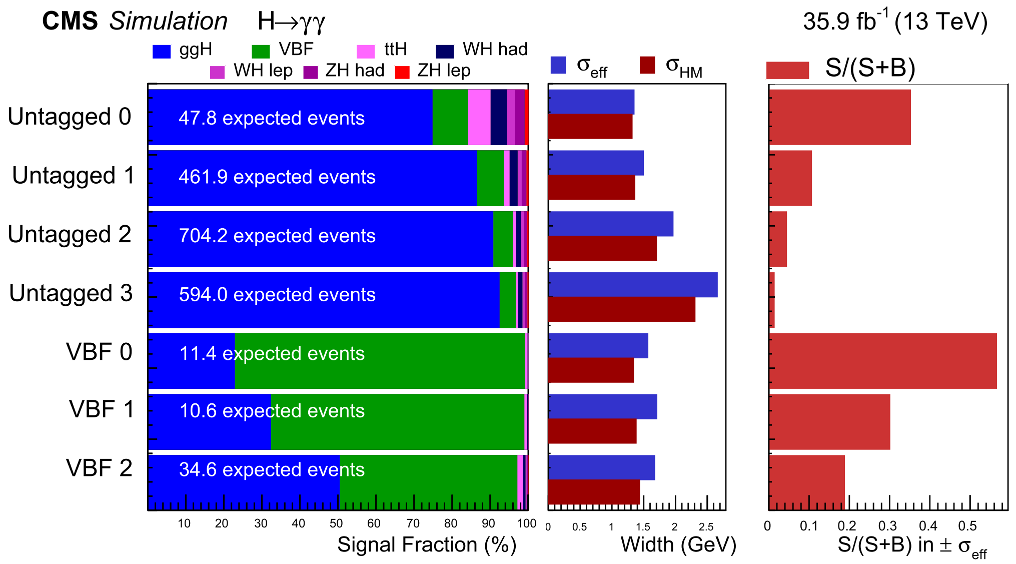


Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

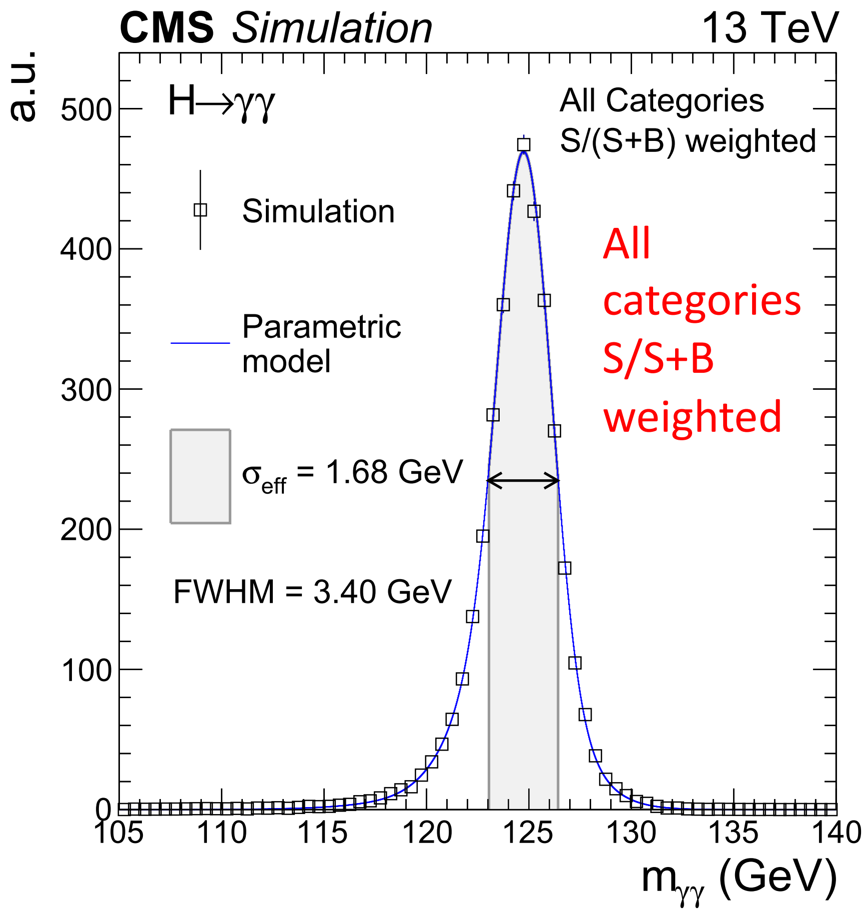
m_H in $H \to \gamma\gamma$ in CMS
2016 data; 35.9fb^{-1} Physics Letters B 805 (2020) 135425

- γ energy calibration
  - both scale correction to data, and per-photon resolution, are estimated using a regression MVA trained on simulation
    - inputs: shower shape variables; preshower data; pileup-sensitive observables
  - further corrections computed using $Z \to ee$ events, with e reconstructed as photon
- Event categories
  - VBF category split in 3 based on MVA output
    - inputs: VBF tagger, diphoton BDT, diphoton $p_T^{\gamma\gamma}/m_{\gamma\gamma}$
  - Untagged category split in 4 according to diphoton BDT output

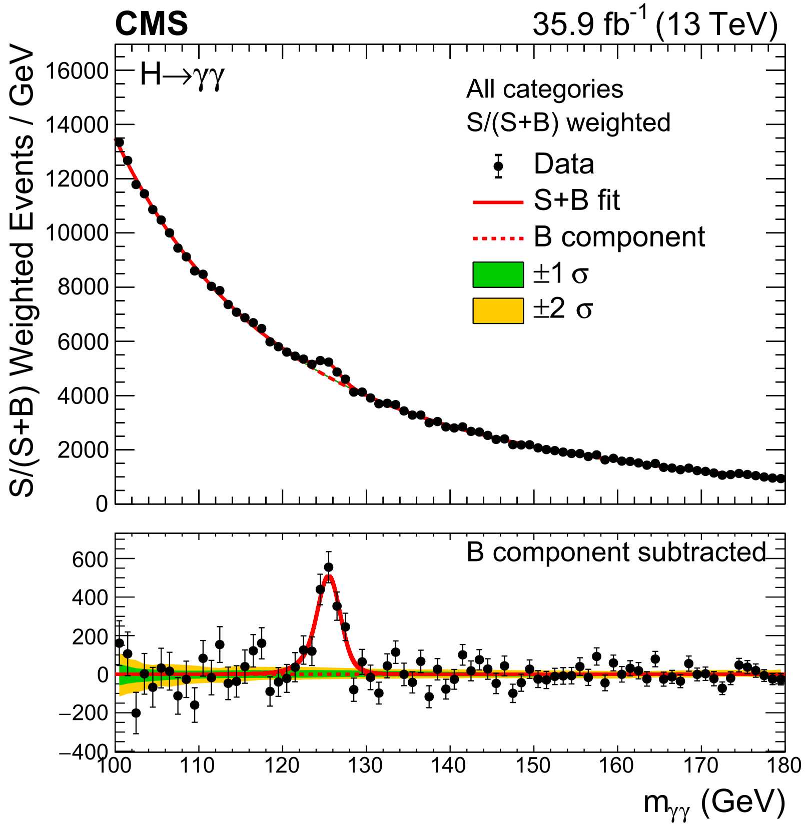




- Signal model: for each category,
  - Lineshapes are computed for each production mode and for each vertex scenario (right or wrong choice of $H \to \gamma\gamma$ vertex)
  - Summed according to the expected fractions of each production mode and of each vertex scenario
  - Up to 4 Gaussian components per lineshape; polynomial dependence of parameters on m_H



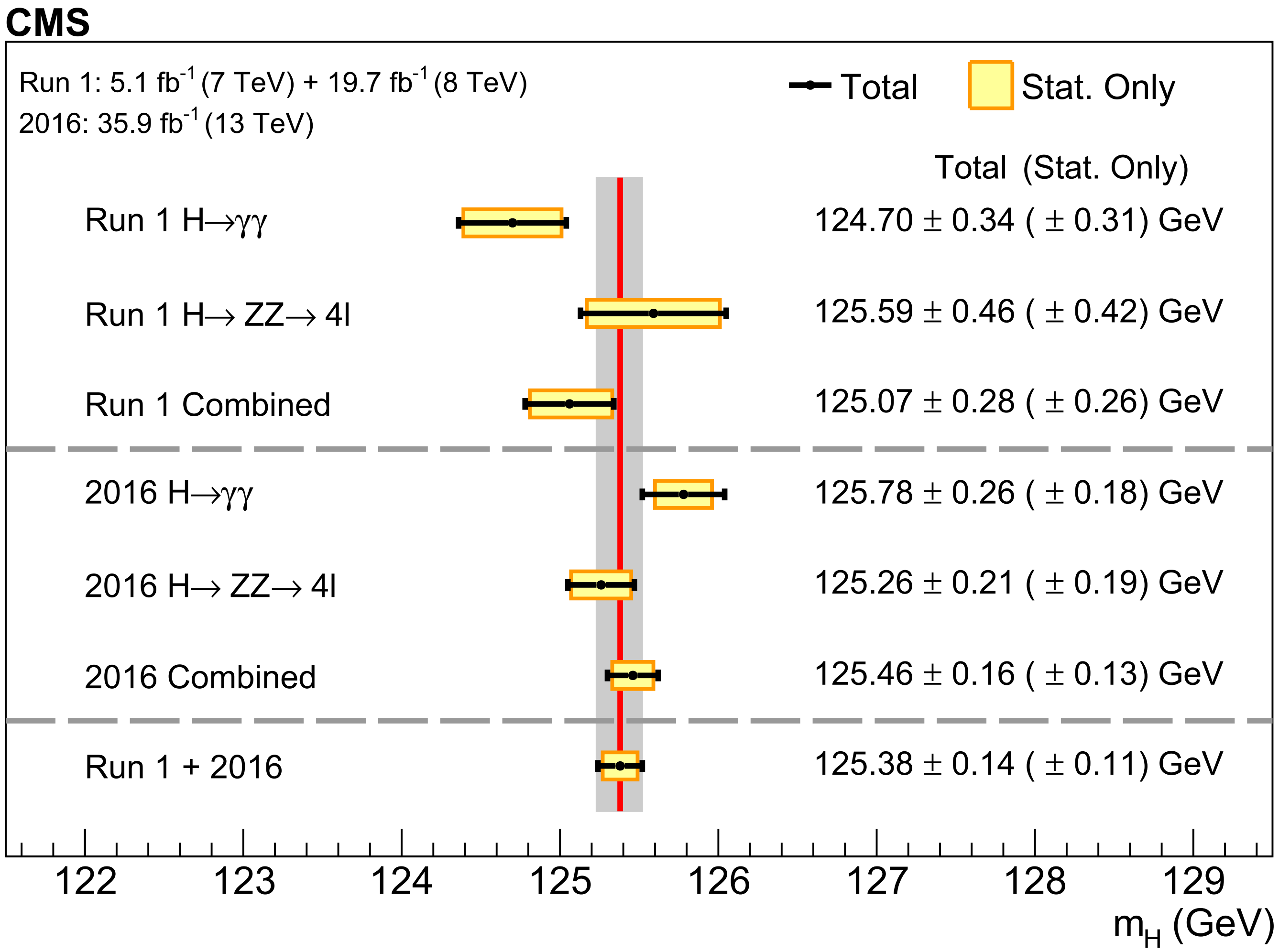
All categories S/S+B weighted



- Background model
  - Several families of parametrizations fit to $m_{\gamma\gamma}$ data

Combining $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ Run 1 + 2016 datasets

$$m_H = 125.38 \pm 0.14\ GeV$$



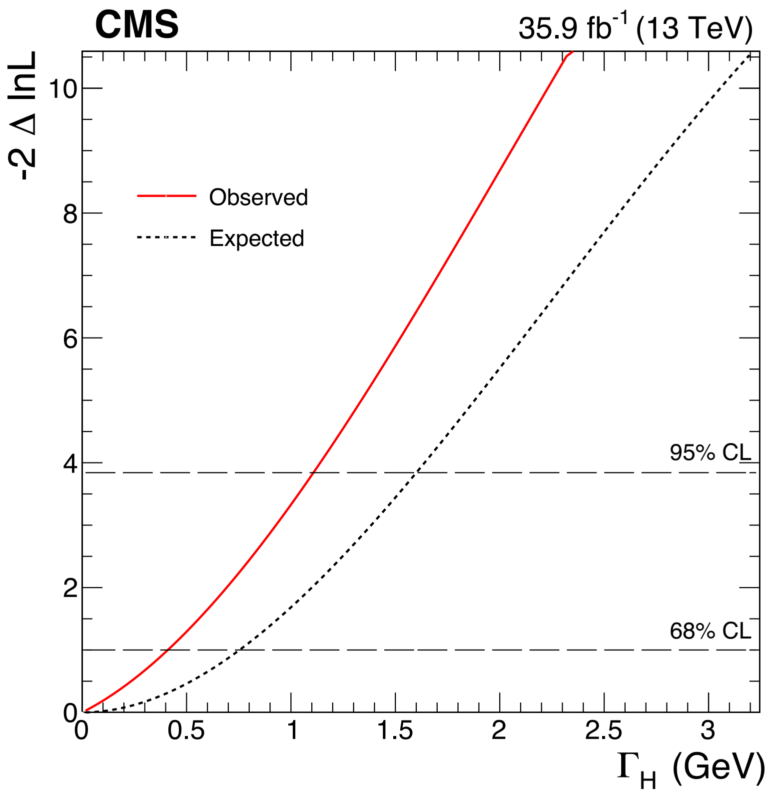
Perspectives on m_H measurement

- The huge effort to calibrate leptons and photons in Run 2 leads to an impressive reduction of the systematic uncertainty on m_H
  - To the extent that the statistical component remains dominant, as in Run 1
- A more precise m_H value can be expected
  - From using full Run 2 dataset, if not already done
  - From combining channels and experiments
- Currently, no prediction requires a more accurate m_H measurement
  - Precise calibration will be motivated by other physics (search for narrow resonances,…)

The H boson total decay width Γ_H

- Once m_H is known, Γ_H is predicted
  - In the standard model, $\Gamma_H = 4.1MeV$ for $m_H = 125GeV$
- A non-standard Γ_H would mean new physics
  - Direct searches or global fits: $\Gamma_{invis/undet} < \sim 10\%$ at 95% C.L.
- The extraction of H couplings requires making an assumption on Γ_H
  - E.g. no BSM decays, and Γ_H computed as a function of all coupling modifiers
  - Or, invisible or undetected decays allowed, but $\kappa_{W,Z} < 1$
- A Γ_H measurement adresses both questions directly
  - but expected Γ_H is much smaller than detector resolution ($\sim GeV$)

On-shell $H \to ZZ \to 4l$ (35.9fb^{-1})
$\Gamma_H < 1.10GeV$ @95% C.L.
JHEP11 (2017) 047



Γ_H from off-shell data

- In the standard model, ~10% of s-channel $H \rightarrow ZZ$ cross section is off-shell $(m_{ZZ} > 220 GeV)$
- The ratio of off-shell to on-shell cross sections is sensitive to Γ_H

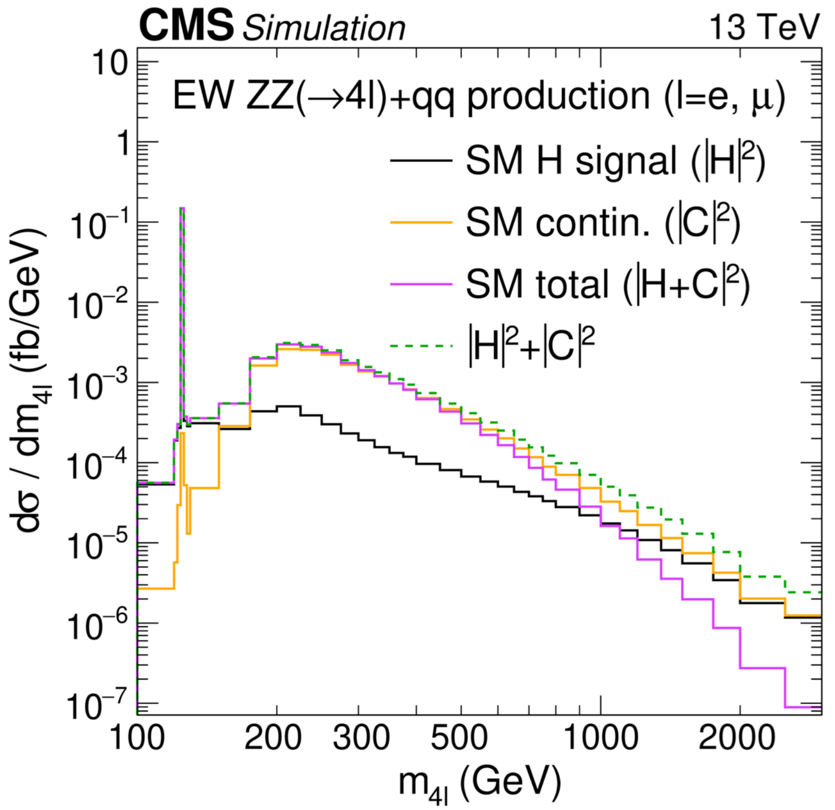
$$\sigma = \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2 + m_{\mathrm{H}}^2 \Gamma_{\mathrm{H}}^2} \dots dm^2$$

On-shell

$$\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_{\mathrm{H}}} \propto \mu_{prod}$$

Off-shell

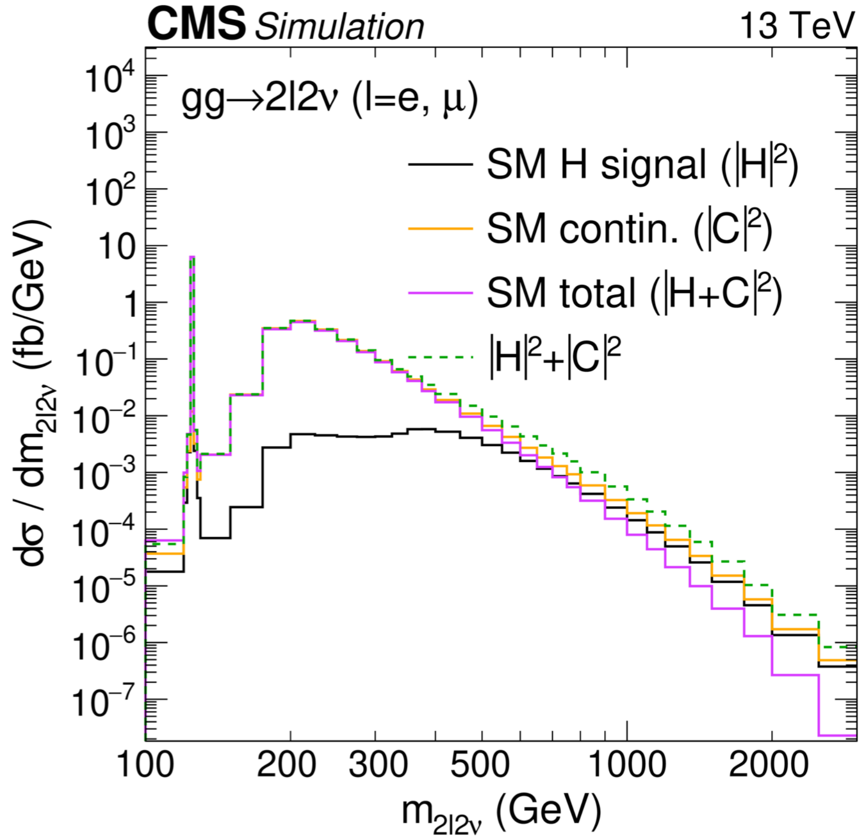
$$\sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2} \dots dm^2 \propto \underbrace{\mu_{prod} \cdot \Gamma_{\mathrm{H}}}_{\mu_{prod}^{off-shell}}$$



- The interference with the standard-model ZZ background is destructive (unitarity)
  - We look for a reduction of what the standard model would predict in the absence of a H boson
- Good signal and background modelling across a wide m_{ZZ} range is needed

$H \to ZZ \to 2l2\upsilon$ off-shell analysis NP (2022) 01682

- $H \to ZZ \to 2l2\upsilon$ and $\to 4l$ bring comparable sensitivity to off-shell production
  - While on-shell $H \to ZZ \to 2l2\upsilon$ is not visible due to background
- CMS analysis recently published
  - $2l2\upsilon$ off-shell 13 TeV data (138fb^{-1})
  - combined with $4l$ off-shell (78fb^{-1}) and on-shell (140fb^{-1})
- Signal and interfering background
  - Modelled at approximate NLO
    - POWHEG NLO fixed-pole mass samples reweighted to S, B, SBI hypotheses using LO matrix-element computation from MELA (details in CMS NOTE-2022/010)
  - ggH process:
    - NNLO differential k-factor applied as a function of m_{ZZ}
    - N^{3}LO normalization
    - 10% extra uncertainty on $gg \to ZZ$ background



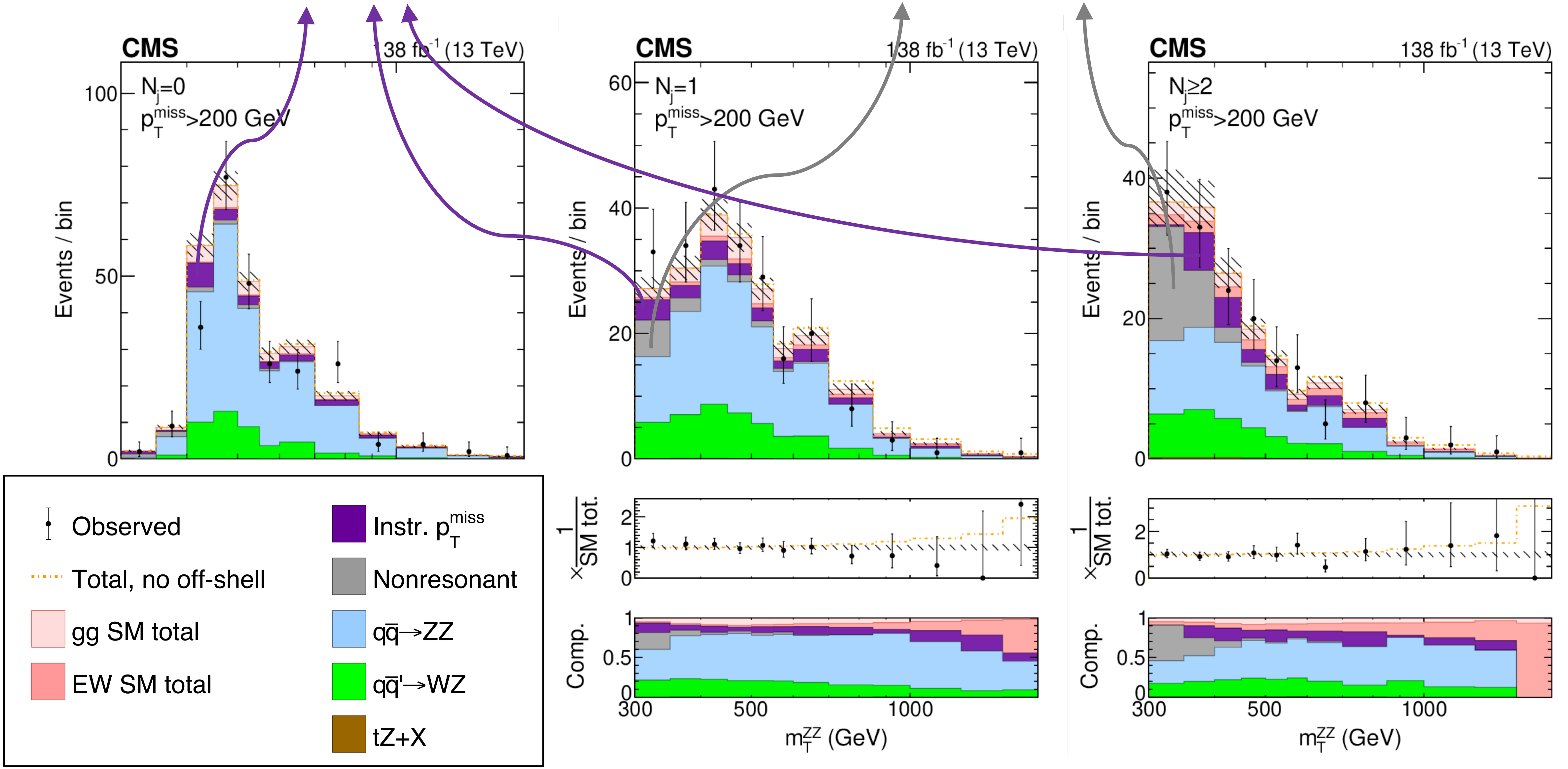
Event selection

- μμ/ee + p_T^{miss} final state
  - $p_{T,l} > 25GeV$
  - $m_{ll} \in m_Z \pm 15GeV; p_{T,ll} > 55GeV$
  - Jet categories: 0, 1 and $\geq$ 2 jets with $p_{T,j} > 30GeV$
  - p_T^{miss} > $125GeV$ in $N_j = 0{,}1$ and > $140GeV$ in $N_j \geq 2$
  - B-jet veto

- Observables ($N_j = 0{,}1$ categories)
  - p_T^{miss}
  - Transverse mass: $m_{\mathrm{T}}^{\mathrm{ZZ}^2} = \left(\sqrt{p_{\mathrm{T}}^{\ell\ell^2} + m_{\ell\ell}^2} + \sqrt{p_{\mathrm{T}}^{\mathrm{miss}^2} + m_{\mathrm{Z}}^2} \right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\mathrm{miss}} \right)^2$

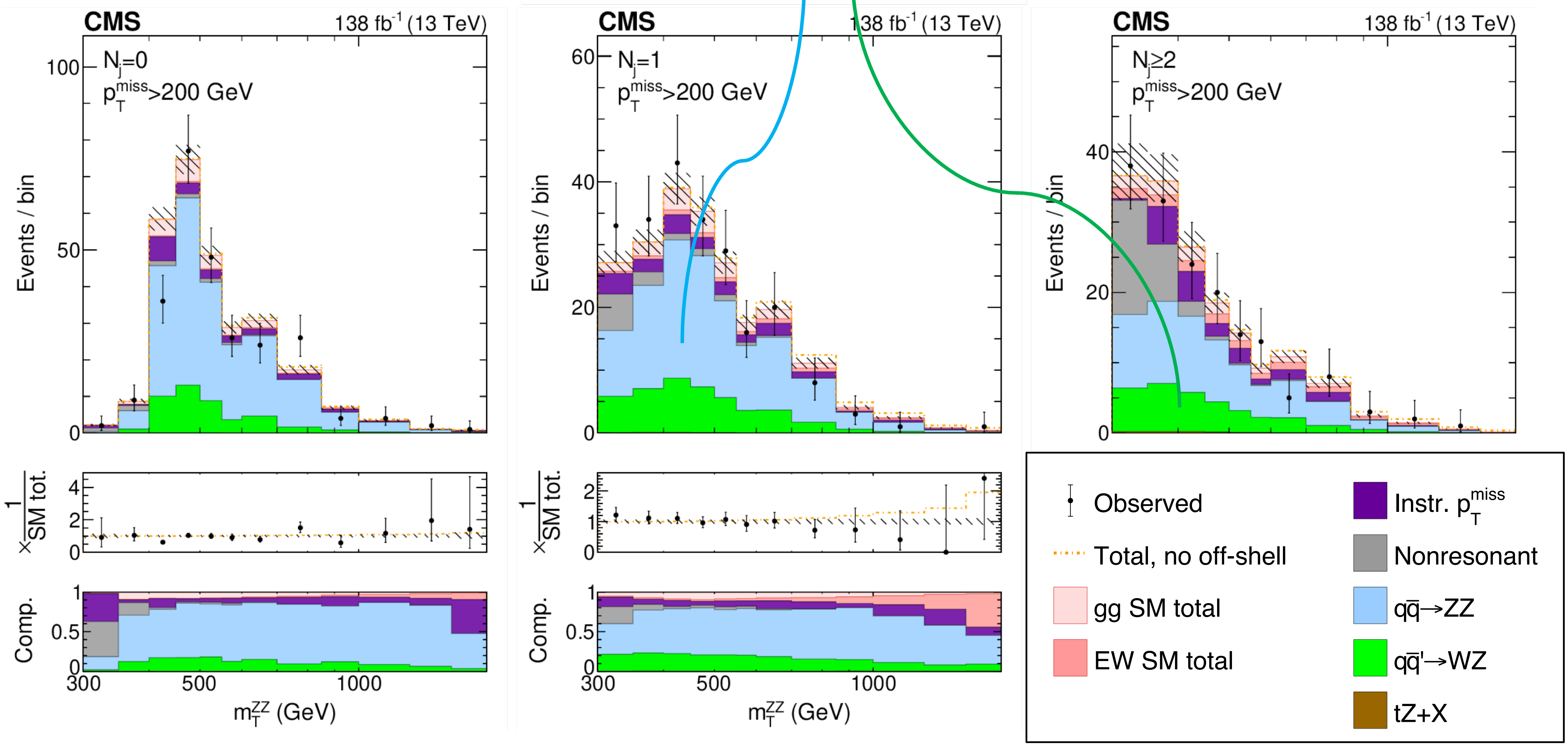
Instrumental p_T^{miss} from $Z + jet$ events
Data-driven using $\gamma + jet$ events

Non-resonant: $t\bar{t}, W^+W^-$
Data-driven using unlike-flavor (eμ) events



Irreducible: ZZ, WZ

From simulations; constrained by joint fit with 3-lepton control region



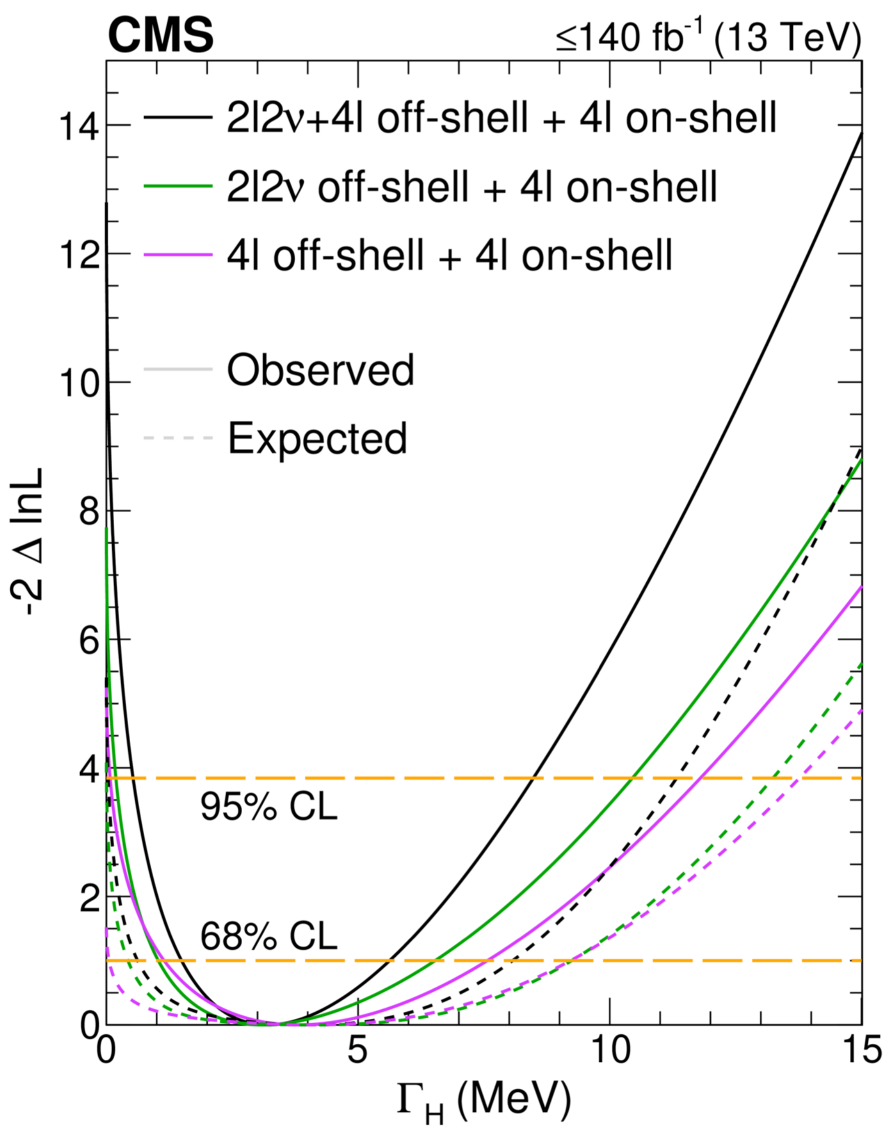
VBF-sensitive observables

- Kinematic discriminant $D_{2jet}^{VBF} = \frac{P_{VBF}}{P_{VBF}+P_{ggH+2jet}}$ computed with MELA
  - "Production-side" discriminant; H boson momentum approximated assuming $\eta_{Z\rightarrow\upsilon\upsilon} = \eta_{Z\rightarrow ll}$
- Kinematic discriminant $D_{2jet}^{VBF,ai} = \frac{P_{VBF}^{ai}}{P_{VBF}^{ai}+P_{ggH+2jet}^{SM}}$
  - One version for each anomalous coupling ai

Parameters of interest fitted to histograms of two ($N_j = 0,1$) or four ($N_j \geq 2$) observables:

Interpretation parameters	$N_j < 2$	$N_j \geq 2$
$\mu_F^{\text{off-shell}}, \mu_V^{\text{off-shell}}, \mu^{\text{off-shell}}$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{\text{2jet}}^{\text{VBF},a2}$
$\Gamma_H\ (f_{ai} = 0)$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{\text{2jet}}^{\text{VBF},a2}$
$\Gamma_H, \bar{f}_{a2}$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{\text{2jet}}^{\text{VBF},a2}$
$\Gamma_H, \bar{f}_{a3}$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{\text{2jet}}^{\text{VBF},a3}$
$\Gamma_H, \bar{f}_{\Lambda1}$	$m_T^{ZZ}, p_T^{\text{miss}}$	$m_T^{ZZ}, p_T^{\text{miss}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{\text{2jet}}^{\text{VBF},\Lambda1}$

Results



Param.	Cond.	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
$\mu_F^{\text{off-shell}}$	$\mu_V^{\text{off-shell}}$ (u)	$0.62^{+0.68}_{-0.45}$	$^{+1.38}_{-0.614}$	$^{+1.1}_{-0.99998}$	< 3.0
$\mu_V^{\text{off-shell}}$	$\mu_F^{\text{off-shell}}$ (u)	$0.90^{+0.9}_{-0.59}$	$^{+2.0}_{-0.849}$	$^{+2.0}_{-0.89}$	< 4.5
$\mu^{\text{off-shell}}$	$R_{V,F}^{\text{off-shell}} = 1$	$0.74^{+0.56}_{-0.38}$	$^{+1.06}_{-0.61}$	$^{+1.0}_{-0.84}$	$^{+1.7}_{-0.9914}$
	$R_{V,F}^{\text{off-shell}}$ (u)	$0.62^{+0.68}_{-0.45}$	$^{+1.38}_{-0.6139}$	$^{+1.1}_{-0.99996}$	$^{+2.0}_{-0.99999}$
Γ_H	$2\ell 2\nu + 4\ell$	$3.2^{+2.4}_{-1.7}$	$^{+5.3}_{-2.7}$	$^{+4.0}_{-3.5}$	$^{+7.2}_{-4.07}$
Γ_H	$2\ell 2\nu$	$3.1^{+3.4}_{-2.1}$	$^{+7.3}_{-2.9}$	$^{+5.1}_{-3.7}$	$^{+9.1}_{-4.099}$
Γ_H	4ℓ	$3.8^{+3.8}_{-2.7}$	$^{+8.0}_{-3.73}$	$^{+5.1}_{-4.05}$	< 13.8

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\, MeV$$

$\mu^{off-shell} = 0$ excluded at 3.6σ

Good sensitivity to off-shell VBF production

Leading systematic uncertainties on $\mu^{off-shell}$

- NLO electroweak corrections on ZZ background
- $ggH + 2jet$ modelling
- $gg \to ZZ$ background k-factor

Perspectives on Γ_H measurement

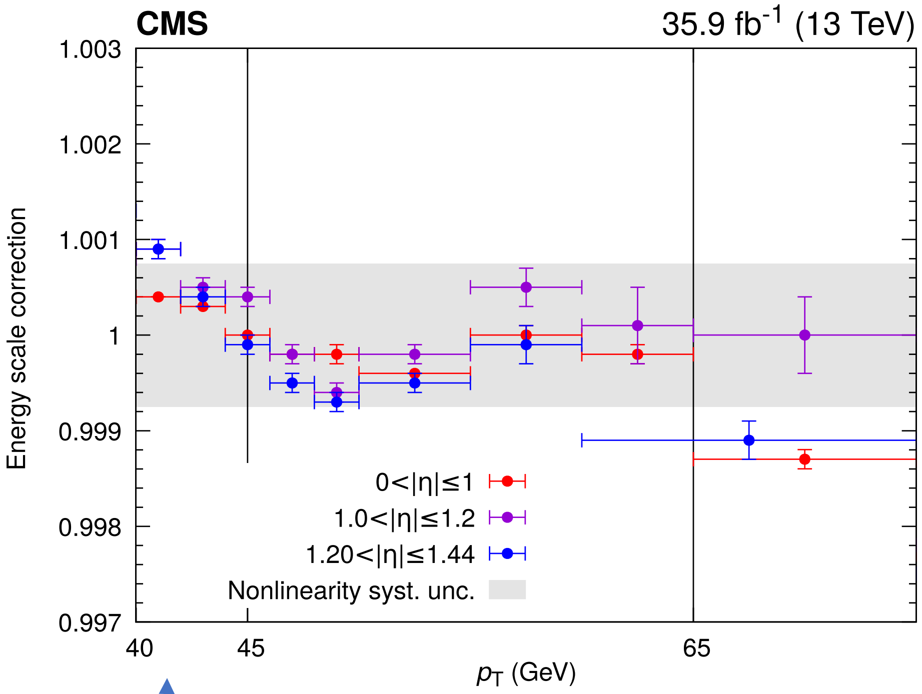
- There is still plenty of room for new physics in Γ_H
- Off-shell data brings a constraint with a precision that becomes relevant
- Systematic uncertainties can still improve e.g. on ZZ background
- Statistical uncertainties on off-shell yields are still large, e.g. in the VBF channel
  - These will for sure improve

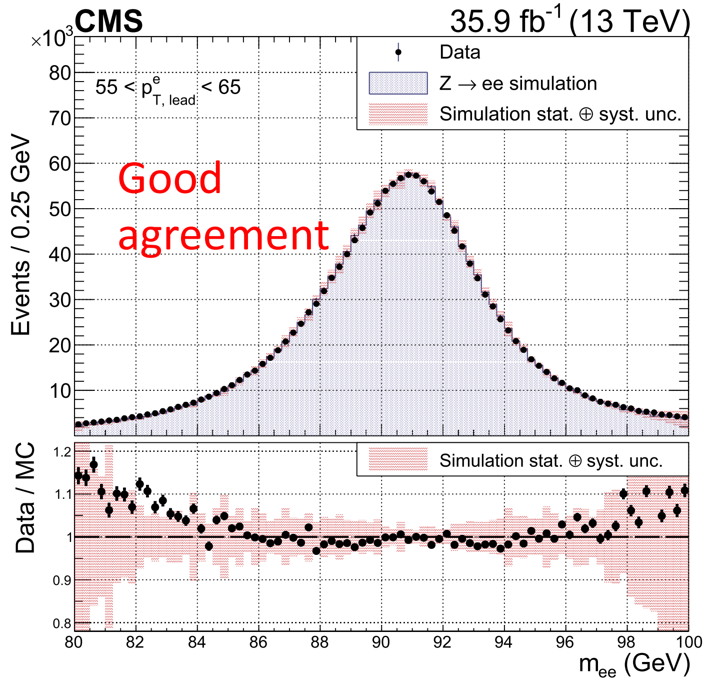
See also new ATLAS result in Michiel Jan Veen's highlight talk (Wednesday)

backup

m_H in $H \to \gamma\gamma$ in CMS
2016 data; 35.9fb^{-1} Physics Letters B 805 (2020) 135425

- γ energy calibration
  - both scale correction to data, and per-photon resolution, are estimated using a regression MVA trained on simulation
    - inputs: shower shape variables; preshower data; pileup-sensitive observables
  - further corrections computed using $Z \to ee$ events, with e reconstructed as photon
    - smearing correction to simulation, as a fct of η and shower shape variable (R_9)
    - scale correction to data, as a fct of η and R_9
    - scale correction to data, in bins of p_T and η to cover difference in p_T range bw. $Z \to ee$ and $H \to \gamma\gamma$





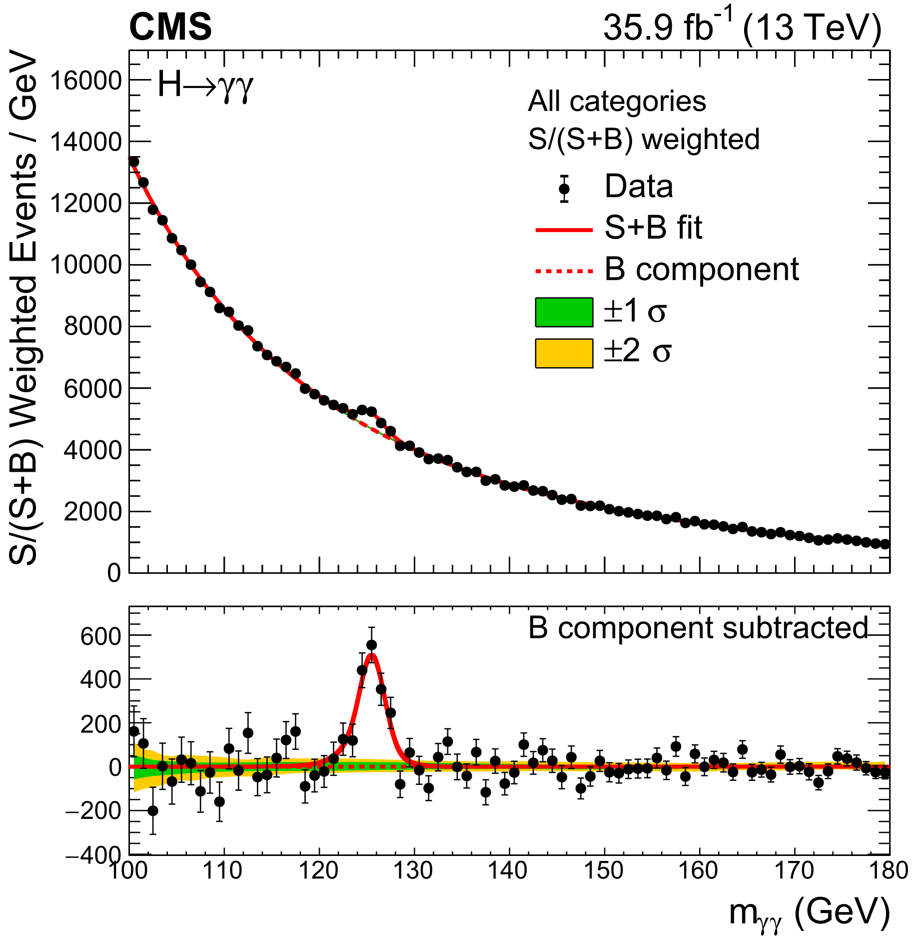
Results

2016 dataset measurement

$$m_H = 125.78 \pm 0.18(stat.) \pm 0.18(syst.) GeV$$

The observed impact of the different uncertainties on the measurement of m_{H}.

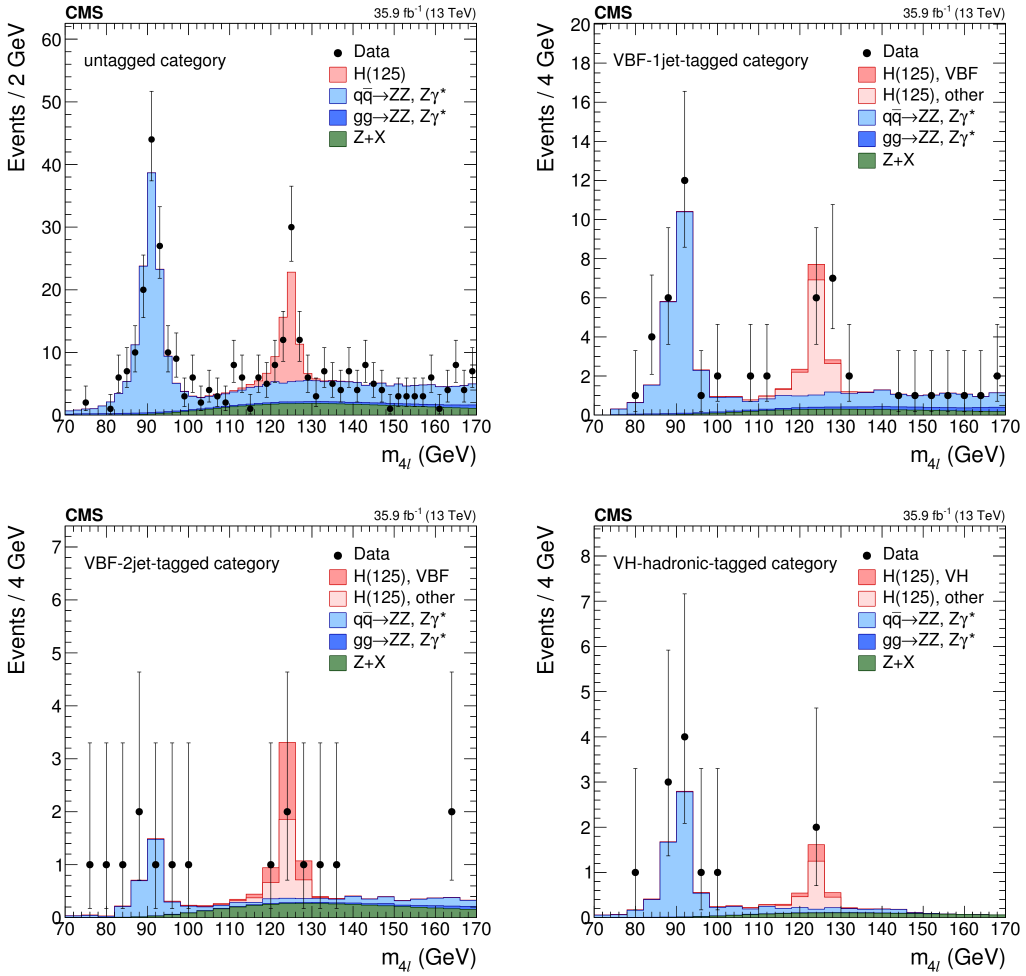
Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_{T} dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26



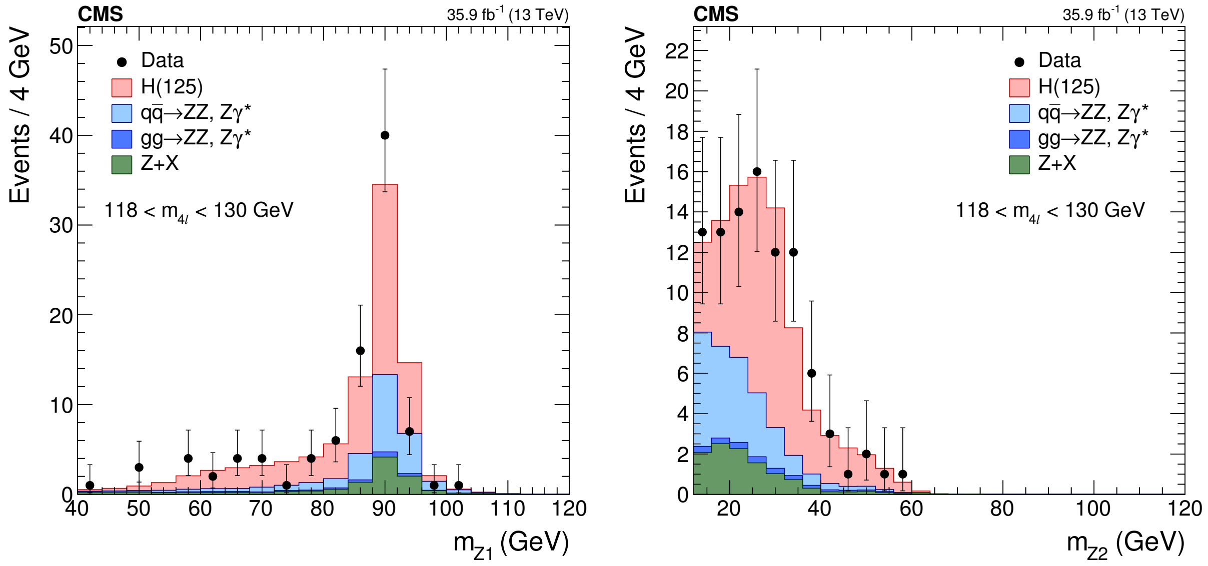
m_H and Γ_H from on-shell $H \to ZZ \to 4l$ in CMS 2016 data, 35.9fb^{-1}

- Mass measurement
  - Lepton momentum corrections from $Z \to ll$ and $J/\psi \to ll$ events
  - FSR photon recovery
  - 3 lepton combinations 4e, 4μ, 2e2μ
  - 7 categories targeting different production modes (ggF, VBF, VH, ttH)
  - Use of per-event m_{4l} uncertainty D_{mass}
    - Computed by propagating lepton momentum uncertainties and corrected for using $Z \to ll$ samples
  - Kinematic constraint from mass of leading Z
  - Background discrimination using matrix-element based decay discriminant D_{bkg}^{kin}
  - Double-sided Crystal Ball signal shape
  - 3D fit to $(m_{4l}, D_{mass}, D_{bkg}^{kin})$
- Onshell width measurement
  - Events grouped into 2 categories: VBF 2-jet and others
  - 1D fit to m_{4l} with m_H and Γ_H left free

Examples of m_{4l} distributions in four categories



Z_1 and Z_2 mass distributions



$H \to ZZ \to 4l$ off-shell

- 3 categories: VBF-tagged; VH-tagged; untagged
  - On the basis of kinematic discriminants $D_{2jet}^{VBF,VH} = \frac{P_{VBF,VH}}{P_{VBF,VH} + P_{ggF+2jet}}$

- 3 observables
  - m_{4l}
  - $D_{bkg}^{VBF+dec}$ or D_{bkg}^{VH+dec} or D_{bkg}^{kin} likelihood ratio computed against main background for each category
  - $D_{bsi}^{VBF+dec}$ or D_{bsi}^{VH+dec} or $D_{bsi}^{gg,dec}$ complementing the above with interference information, e.g.

$$D_{bsi}^{gg,dec} = \frac{P_{ggH}}{2\sqrt{P_{ggH} . P_{ggZZ\ box}}}$$

Off-shell event distributions