Higgs properties: Mass, width, CP, EFT …

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on behalf of the ATLAS and CMS Collaborations

59th Rencontres de Moriond on
"Electroweak Interactions & Unified Theories"
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The Higgs boson

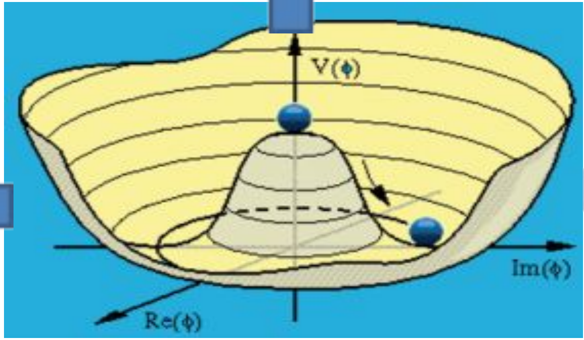
In the decade since the discovery of the SM-like Higgs boson, ATLAS and CMS collaborations have a diverse portfolio of precision measurements of its properties.

Spin and CP

- Scalar : Spin 0, CP even

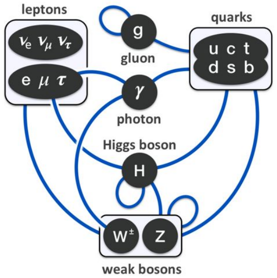
Width

- Mass dependent
- ~4.1 MeV @ m_H of 125 GeV



Couplings

- H—Boson: gauge interactions
- H—fermions: Yukawa interactions
- H—H: Self Coupling



See talk by R. Hayes for the latest status on the Higgs couplings

The SM Higgs sector is **fully predictive once m_H is known**, experimentally:

- This measurement is carried out in the **"high resolution" H→γγ and the H→ZZ→4l channels**

Is this the Higgs boson of the Standard Model?

Two complementary approaches available

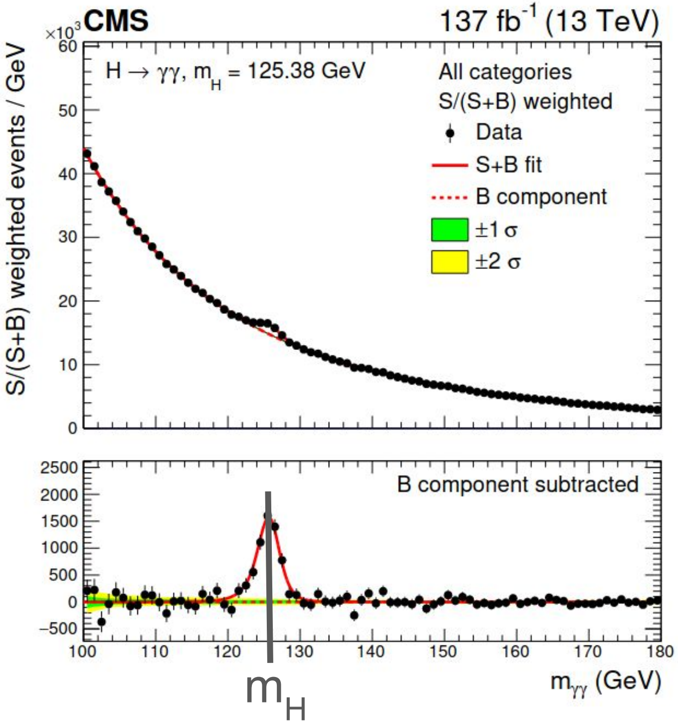
Direct searches for new phenomena

- Additional “Higgs” boson(s)
- Exotic decays of the current Higgs boson
- Search for anomalous couplings or EFT searches

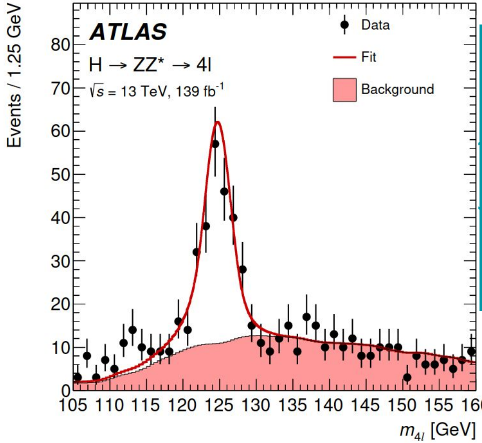
Indirect approach

- Precision measurements of an extensive set of properties of the current Higgs boson and compare with the predictions from SM

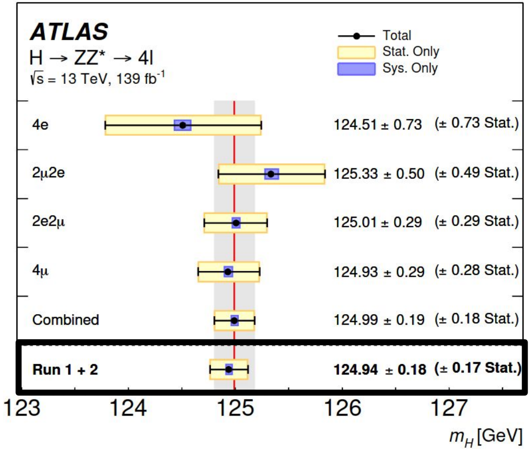
Measurements of the mass of the Higgs boson



Summary of m_H measurements in H→ZZ→ 4l



PLB 843 (2023) 137880



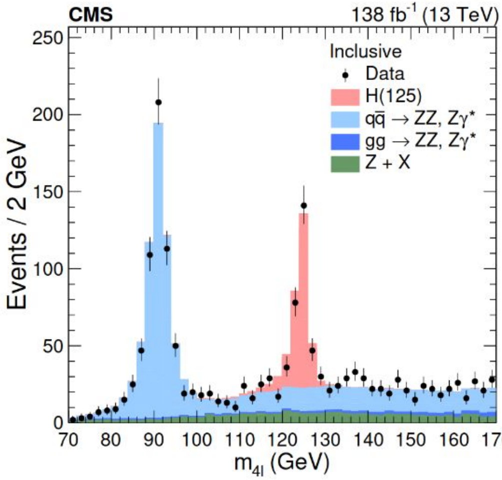
Similar analysis strategies in 4 channels : 4μ/2e2μ/2μ2e/4e

→Improved lepton energy scale calibrations

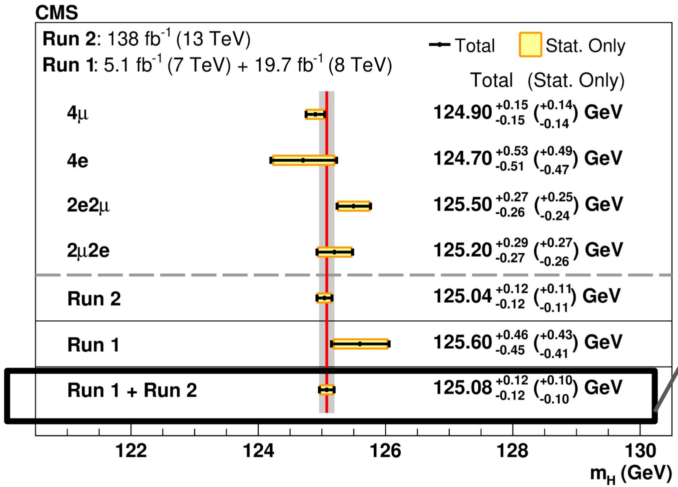
→ δm/m aware categorization, improved S vs B discriminants, FSR recovery, Z Mass constraint …

→ Additionally in CMS a beam-spot constraint on the 4 lepton tracks to originate from a common vertex (--> 3-8 % better **σ**$_m$)

→ Results are STAT. limited

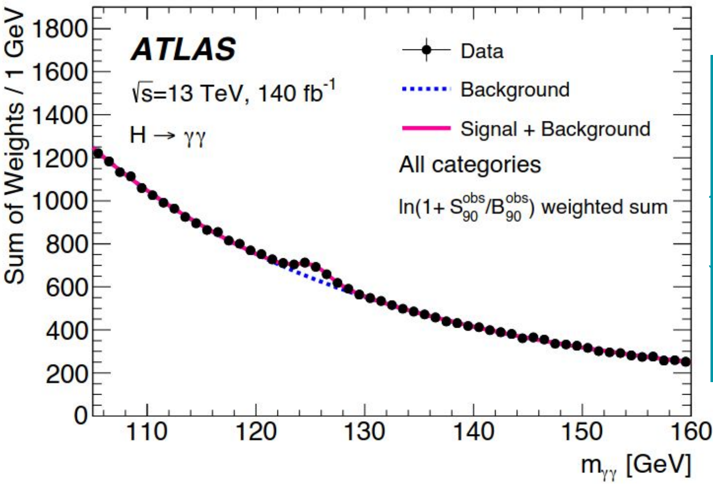


HIG-21-019, submitted to PRD



Most precise single channel measurement

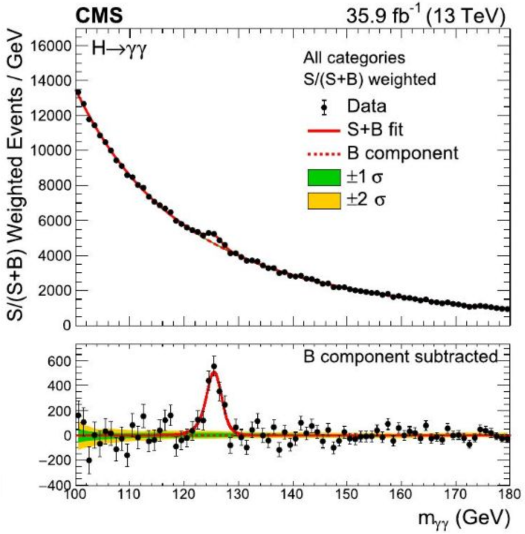
Summary of m_H measurements in H→γγ



PLB 847 (2023) 138315

Core challenge in this measurement is to **extrapolate the energy scale correction from electrons from Z→ee [~45 GeV] to photon from H→γγ [~60 GeV]**

Mitigate the photon energy scale uncertainties using **granular photon reco. and calibration.**



PLB 805 (2020) 135425

Full Run 2 measurement

m_H = 125.17 ± 0.14 (0.11(stat) ± 0.09(syst)) GeV

– Effect due to the gain switch in the EM calorimeter [at E_T ~ 50-60 GeV] calibrated with dedicated runs (This paper)

– Achieved a 4x reduction in the photon scale related systematic uncertainty from **~320 MeV (Run 1) → 80 MeV**

Run 1 + Run 2 combination of H→ZZ and H→γγ

m_H = 125.11 ± 0.11 (0.09(stat) ± 0.06(syst)) GeV

Measurement with the 2016 dataset

m_H = 125.78 ± 0.26 (0.18(stat) ± 0.18(syst)) GeV

– Largest uncertainty due to impact of radiation damage of the CMS ECAL crystals (110 MeV on m_H)

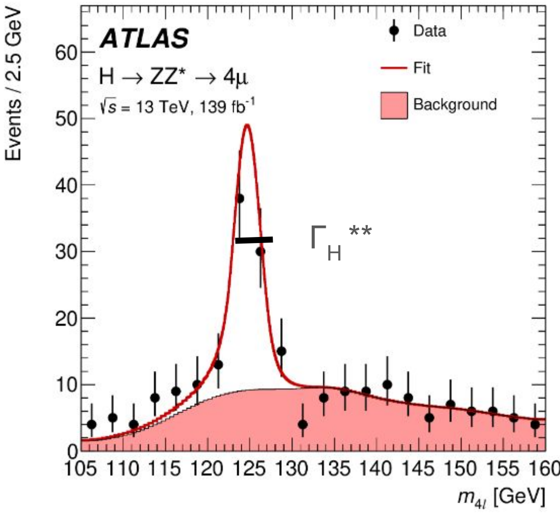
– Correction methodology developed to correct for this in the full Run 2 measurement (CMS-DP-24-004) → significantly reduce its impact.

Natural width of the Higgs boson

- For a Higgs boson of mass ~ 125 GeV its natural width is ~ 4.1 MeV. In the best categories the diphoton or 4 lepton mass resolution we obtain is around 1 GeV **. Hence **direct measurements** of the Higgs boson width will always have limited reach
    - **Γ_H < 50 (330) MeV at 68 (95) % C.L from CMS H→ZZ→ 4l**

- In the H→$\gamma\gamma$ (**on-shell**) channel **interference between gluon fusion (signal) and the QCD continuum (bkg)** results in a shift in the measured m_H (Γ_H dependent)
    - **-26 MeV effect** in the Run 2 ATLAS m_H from H→$\gamma\gamma$
    - Can invert this, with optimized event categorization, to better constrain Γ_H (**< ~100 MeV in Run 2**)

- **From indirect measurements there are 2 options:**
    - Can infer constraints on Γ_H from combined Higgs coupling measurements
    - **Off-shell HVV measurements**



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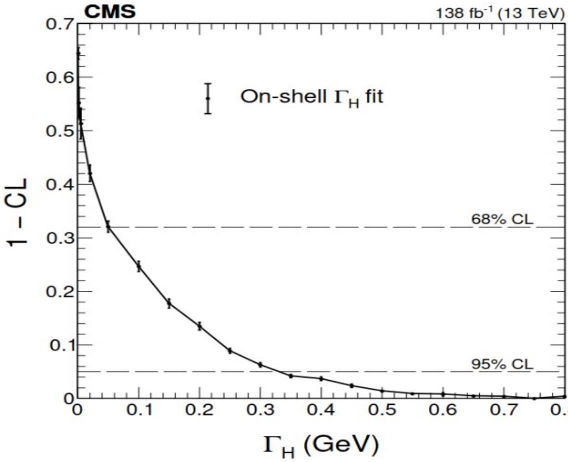
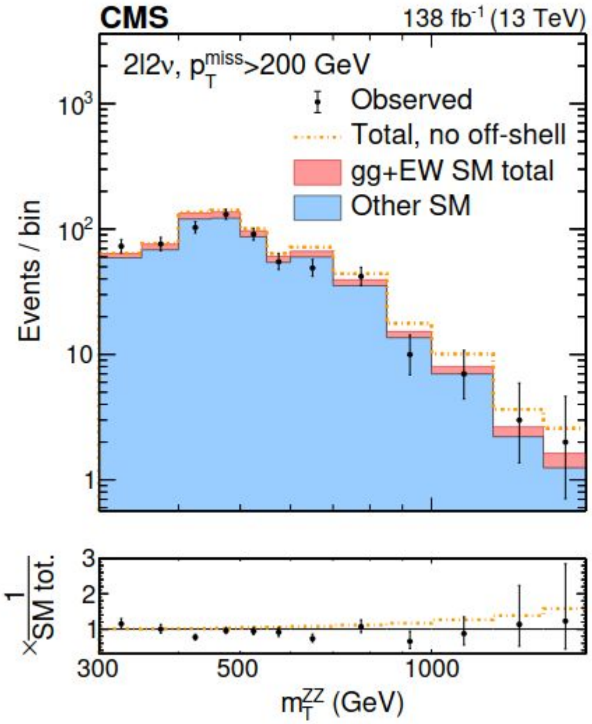


HIG-21-019, submitted to PRD

Constraining Γ_H from off-shell measurements

Basic idea is to use the cross-section ratio of off-shell/on-shell H→VV production (eg. below V=Z)

$$\sigma^{on-shell}_{gg\to H\to VV}\sim \frac{g_g^2 g_V^2}{m_H\Gamma_H} \;||\; \sigma^{off-shell}_{gg\to H^*\to VV}\sim \frac{g_g^2 g_V^2}{4.m_V^2}$$

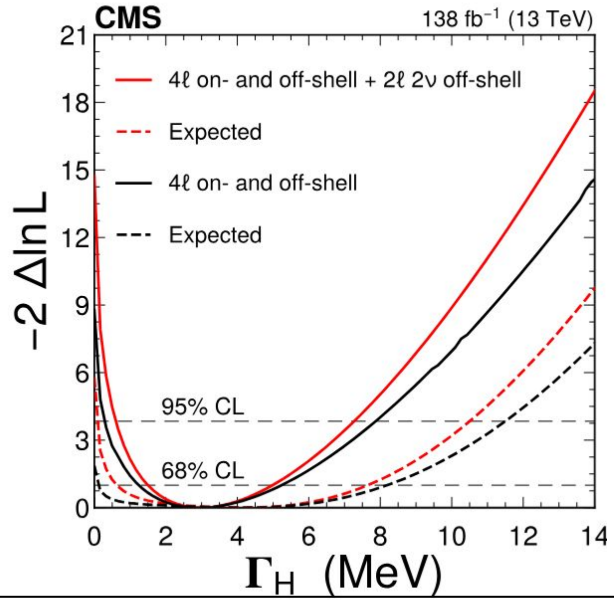


To constrain the width with this method ($\sigma^{off-shell} / \sigma^{on-shell} \sim \Gamma_H \rightarrow \mu^{off-shell} / \mu^{on-shell} \sim \Gamma_H$) requires strong theoretical assumptions in particular that **the coupling modifiers are identical for on-shell and off-shell production.**

Significant **destructive interference** between the Higgs boson production signal and the continuum EW VV production.

Constraints on Γ_H from off-shell measurements in the H→ZZ channel

Both collaborations have performed the analysis with the 4l and 2l2v



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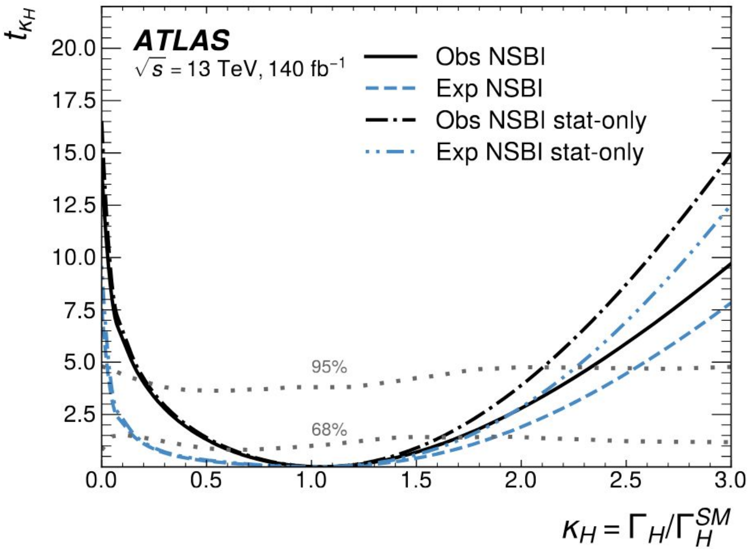


ATLAS-CONF-2024-016 submitted to RPP

Event selection based on Untagged, VBF and VH categories with two additional kinematical discriminants to tag Interference and backgrounds

$\Gamma_H = 3.0_{-1.5}^{+2.0}$ MeV

Evidence of off-shell prod. @ **3.8 σ(2.4 σ Exp.)**

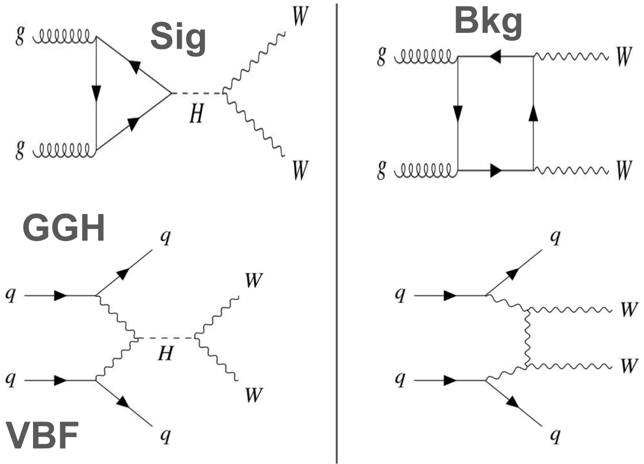
Signal region defined using a DNN based 5 class, multi classifier followed by a neural simulation-based statistical inference (NSBI) strategy→ **~20% better precision**

$\Gamma_H = 4.3_{-1.9}^{+2.7}$ MeV

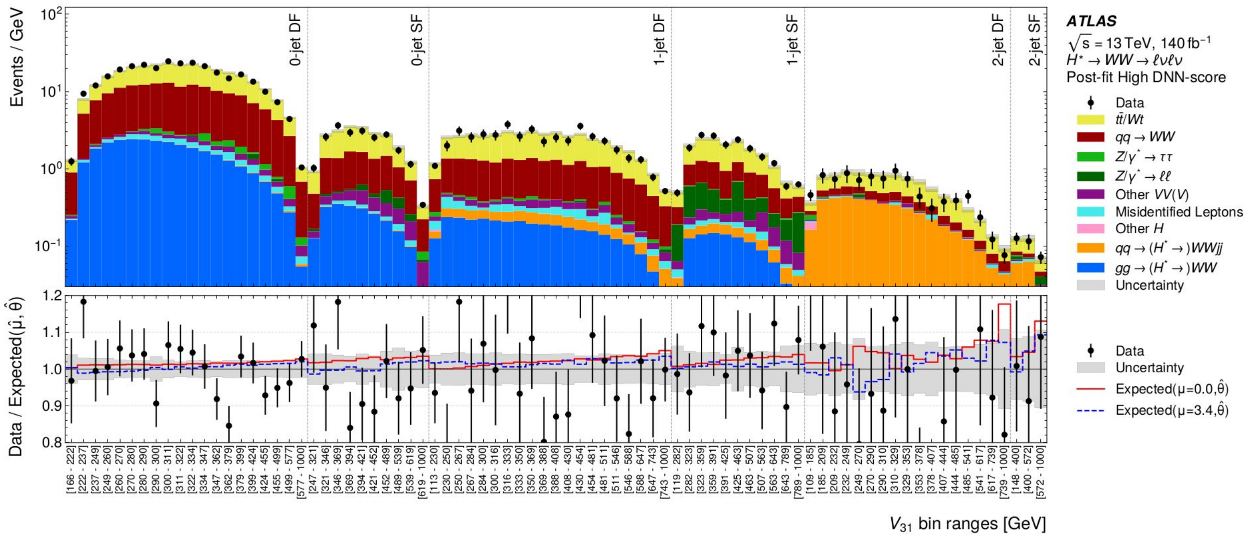
Evidence of off-shell prod. @ **3.7 σ(2.4 σ Exp.)**

NEW: Constraints on Γ_H from off-shell measurements in the H→WW channel

Paper



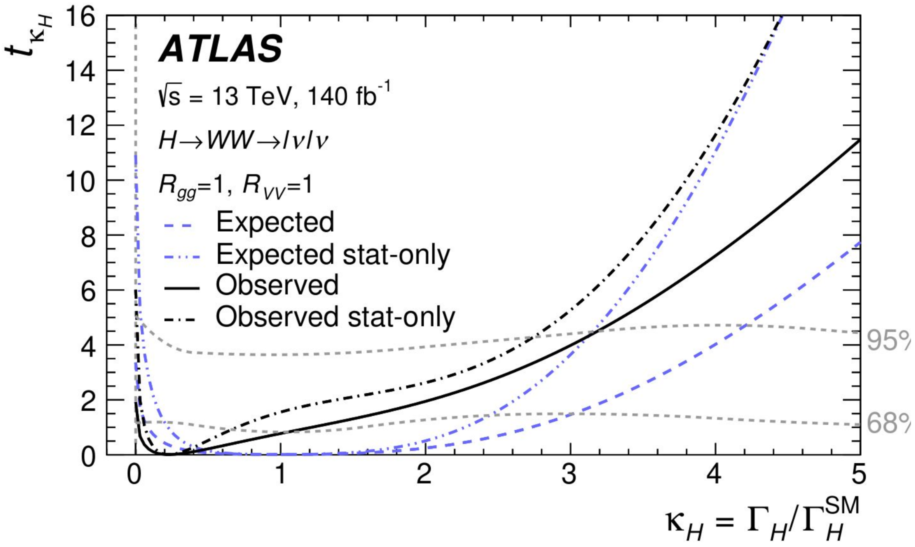
See talk by Z. Wolffs for details

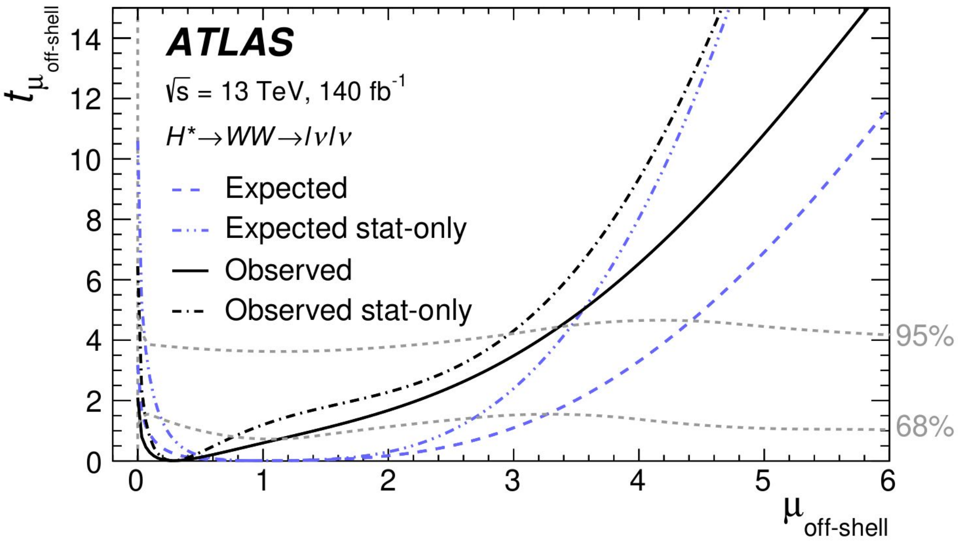


- Analysis performed in the fully lep. final states with the full Run 2 dataset. This is the first interpretation of the width from the off-shell H*→WW process.
- Presence of off-shell production is characterized by a deficit of events w.r.t the bkg. only hypothesis. The statistical analysis takes into account the signal, bkg. and the interference.
- The analysis is performed in bins of a variable V_{31} in categories: [(DF, SF) of leptons *(0, 1, >= 2) jets] * [3 DNN cats. for each lep/jet combination]

NEW: Constraints on Γ_H from off-shell measurements in the H→WW channel

Paper





The off-shell production signal strength has been constrained to be below 3.4 (4.4) at 95% CL, nearly a 5x improvement over the Run 1 result.

Obs(Exp) $\Gamma_H = 0.9_{-0.9}^{+3.4}(4.1_{-3.8}^{+8.3})$ MeV; $\Gamma_H < 13.1\ (17.3)$ MeV at 95% CL

Anomalous couplings and EFT

Individual analyses optimized for particular phase spaces :
Typically carried out in particular production channels and decay modes to derive sensitivity to a set of EFT observables, often with dedicated discriminants to enhance the sensitivity to detect EFT/anomalous coupling[AC] specific observables.

- CMS AC in H→ZZ [PRD 104, 052004 (2021)]
- **ATLAS CP properties in H→ZZ [JHEP 05 (2024) 105]**
- CMS AC in H→$\tau\tau$ and comb. [PRD 108 (2023) 032013]
- ATLAS SMEFT interpretation H→$\tau\tau$ diff. Xsec [**JHEP 03 (2025) 010**]
- **ATLAS off-shell H→4l + 2l2ν EFT analysis [ATL-PHYS-PUB-2023-012]**
- **CMS VH(bb) EFT analysis [JHEP 03 (2025) 114]**
- **CMS AC and EFT interpretation in H→WW [Eur. Phys. J. C 84 (2024) 779]**

Reinterpretations from combined measurements:
Start from existing measurements that are optimized for SM Higgs properties→ Fair sensitivity to a larger set of EFT operators

- ATLAS STXS + fiducial combination of Higgs channels [ANA-HIGG-2022-17-PAPER]

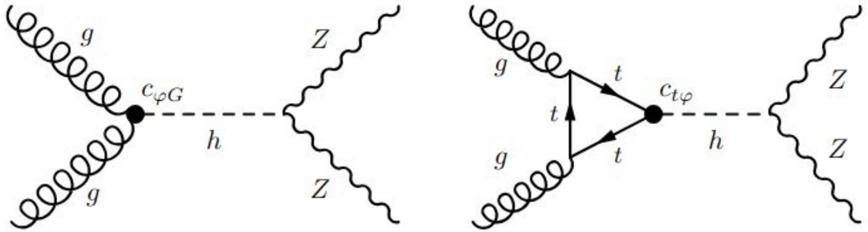
- **CMS Higgs diff. Combination [CMS-HIG-23-013]**

- ATLAS Higgs + EWK [ATL-PHYS-PUB-2022-037]

- CMS Higgs + EWK + Top [SMP-24-003]

EFT analysis in off-shell H→4l + H→2l2ν I (ATLAS)

In on-shell measurements H-t and H-g couplings have a degeneracy. To decouple this off-shell H→ZZ (4l/2l2ν) is used.

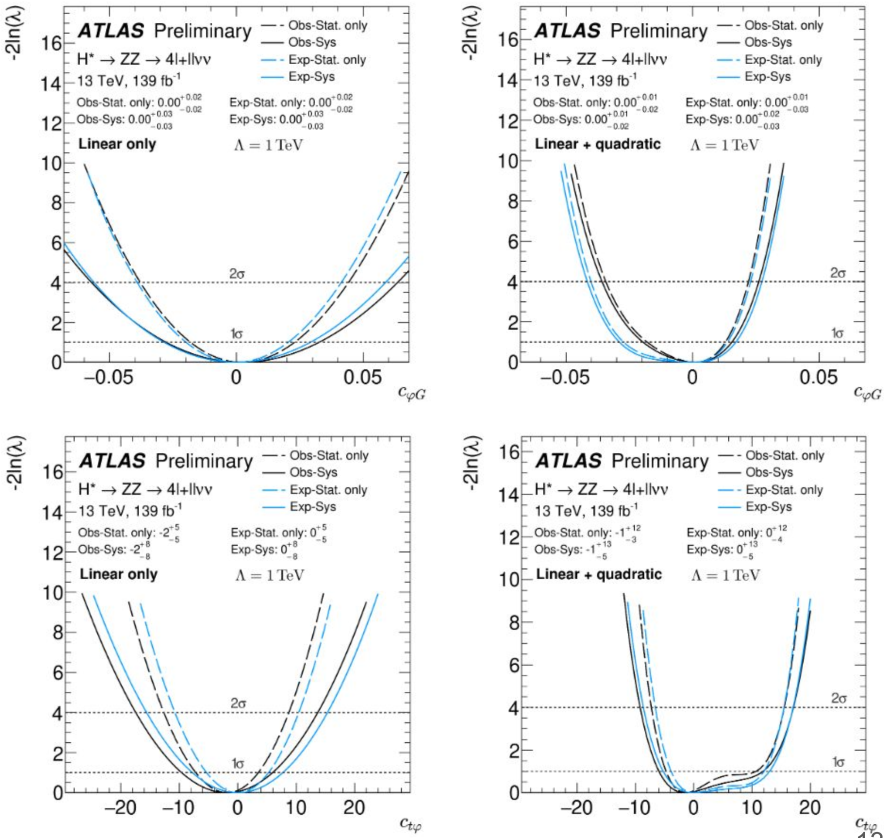


In the 4l channel a DNN based observable was used.

In the 2l2ν channel the transverse mass of the 2 Z bosons is used as the observable

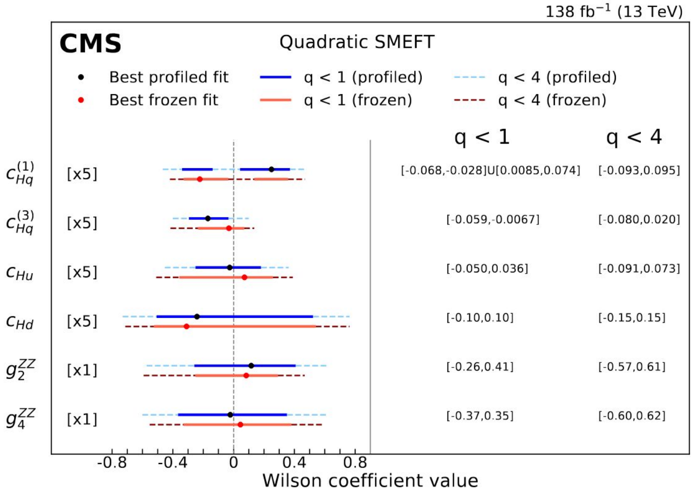
$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

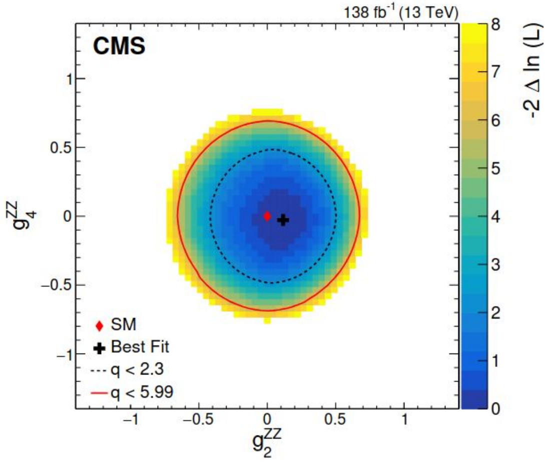
ATLAS-PHYS-PUB-2023-012

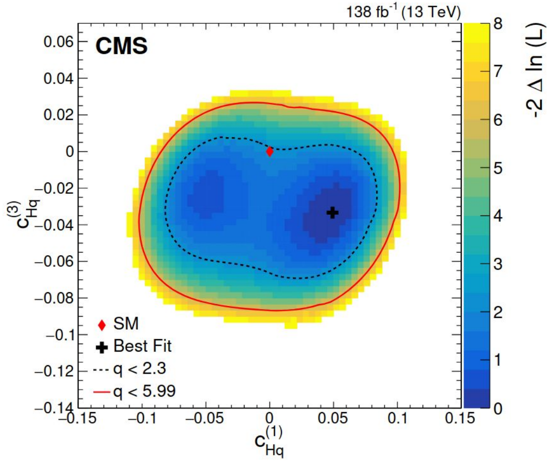


EFT analysis in the VH(→bb) channel (CMS)

JHEP 03 (2025) 114







Analysis performed with the Run 2 dataset targeting :

– The WCs $c^{(3)}_{Hq}$, $c^{(1)}_{Hq}$, c_{Hu} and c_{Hd}

– The couplings g_2^{ZZ} and g_4^{ZZ} ~ linear combinations of c_{HW}, c_{HWB}, c_{HB} (+ CP odd terms)

Use angular information to better discriminate between CP-even vs. CP-odd HVV couplings (g_2^{ZZ} and g_4^{ZZ})

“Boosted Information Tree” based regression method used to obtain optimal observables for each WC

CP properties of the Higgs couplings

So far we have found the Higgs boson to be consistent with the SM : $J^{CP} = 0^{++}$

From the current level of precision achieved in CP measurements, a small CP violating anomalous coupling is still permissible.

The CP properties of Hff and HVV couplings have been studied across a wide range of H production modes and decay channels. For eg. to study the HVV couplings :

$$A(HVV) \sim \left[\underset{\substack{\uparrow \\ \boxed{\text{SM : VV = ZZ,WW}}}}{a_1^{VV}} + \underset{\substack{\uparrow \\ \text{CP Even (higher order couplings)} \\ (\Lambda_1 = 1TeV)}}{\frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \underset{\substack{\uparrow \\ \text{CP Even}}}{a_2^{VV}} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + \underset{\substack{\nwarrow \\ \text{CP Odd}}}{a_3^{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)} \quad *$$

Events categorized based on matrix-element discriminants (MELA method) or Machine Learning techniques.

Results usually expressed in terms of cross-section ratios f_{ai} , depending on the AC a_i

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \operatorname{sign}\left(\frac{a_i}{a_1}\right)$$

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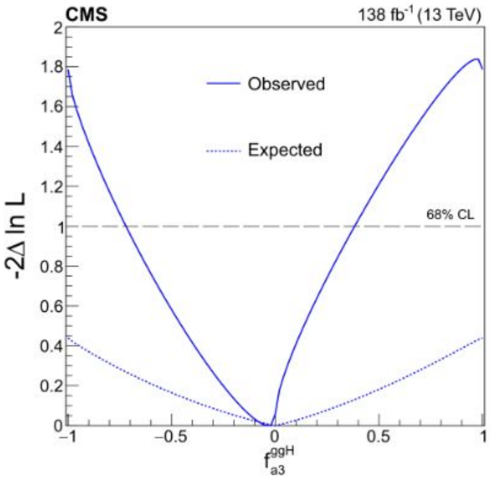
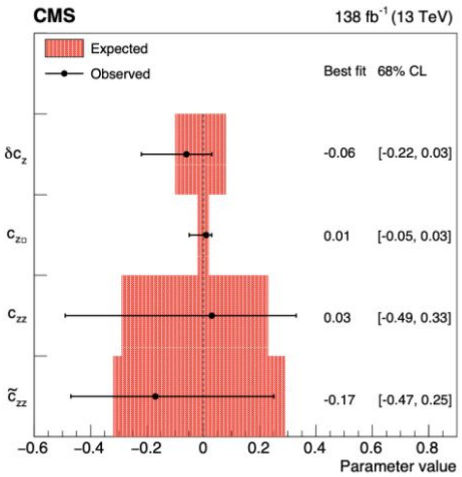
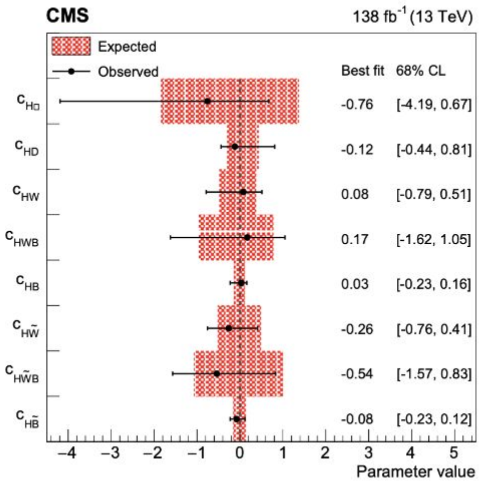
H→ WW CP properties and EFT constraints (CMS)







Eur. Phys. J. C 84 (2024) 779

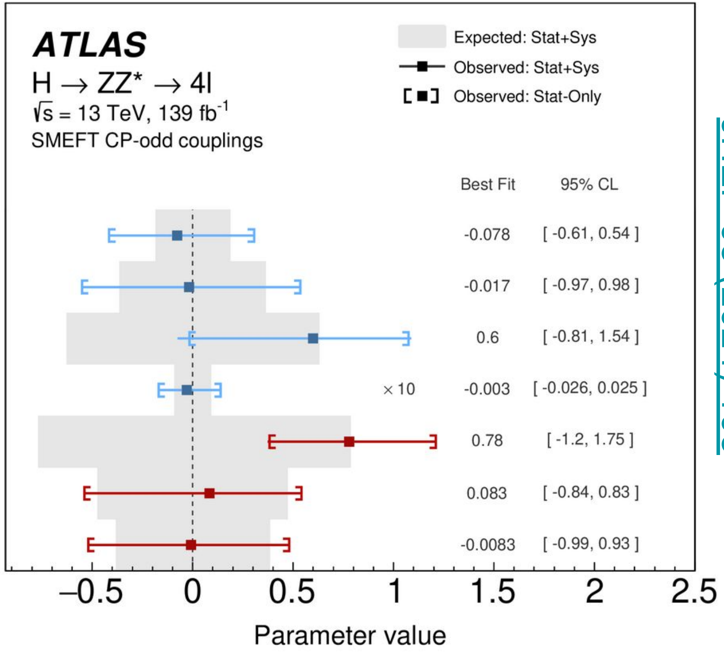
Used MELA method to determine observables sensitive to the different types of the HVV anomalous coupling.

Three discriminants : D_{VBF}→optimized for VBF production; D_{0-} → CP odd/even sensitive; and m_{ll}→ sensitive to the decay vertex.

The AC results are the most stringent till date. Also translated to the SMEFT Higgs and Warsaw basis →found to be in agreement with the SM.

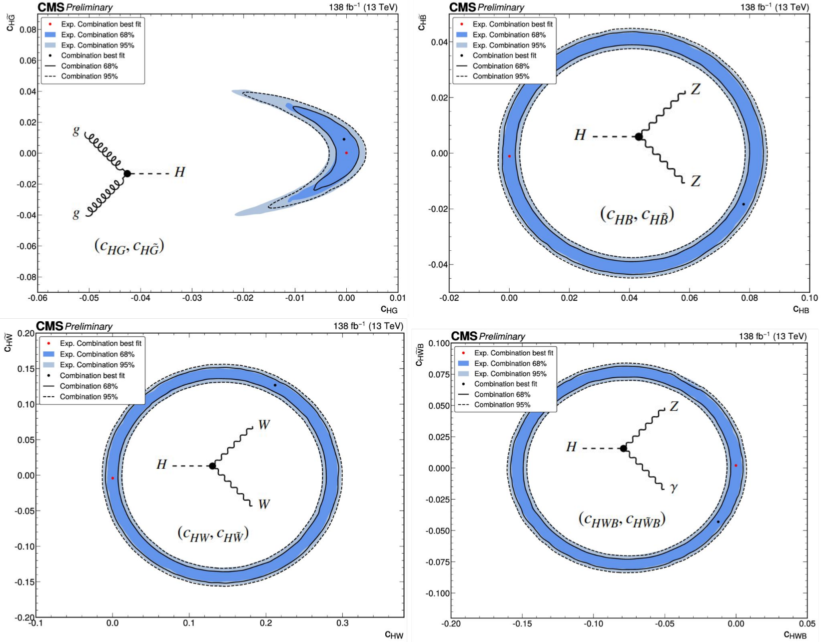
Probe the CP structure of HVV interaction with SMEFT

3 CP odd operators probed in VBF H→ZZ production & decay with the SMEFT framework



JHEP 05 (2024) 105

CMS-HIG-23-013



Combining H→ɣɣ, H→ZZ, H→ WW and H→𝝉𝝉

No significant non-SM CP component found in any of the measurements.

Cross-section (STXS) measurements can also constrain EFT parameters.

This talk by A. Nigamova covers the latest from STXS combinations in CMS.

Summary

- The Run 2 m_H measurements are **approaching the 0.1% precision level**
  - In the **4l channel the measurements are still stat. limited** while **tending to be syst. limited in the $\gamma\gamma$ channel.**
  - Over the horizon of the **HL-LHC a precision of ~30 MeV is projected** dominated by the 4l channel.

- The best constraints on Γ_H come from the **off-shell measurements in the H→ZZ channel, already reaching a precision of ~50%** of the SM prediction.
  - **A first ever interpretation of the width from off-shell H→WW measurements from ATLAS constrains the width to be below 13.1 MeV at 95% CL.**
  - Over the horizon of the **HL-LHC a precision of better than 25% has been projected.**

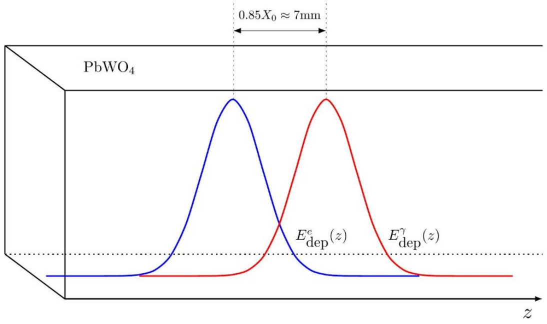
- No indication of any deviation of Higgs boson properties from SM. **Imperative to carry out both channel optimized and global EFT measurements to see if we have missed any hints of deviations from SM.**

Additional Content

Account for the impact of radiation damage to the ɣ-energy scale

Photon energy scale (derived from Z→ee) is affected by the non-uniform radiation damage along the ECAL crystal.

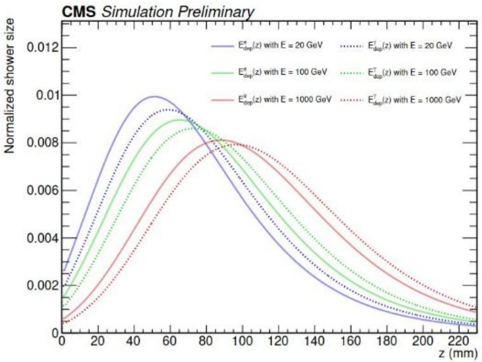
Soln: Correction for this effect using a light collection efficiency (LCE) modelling that accounts for radiation damage (**CMS-DP-24-004**)



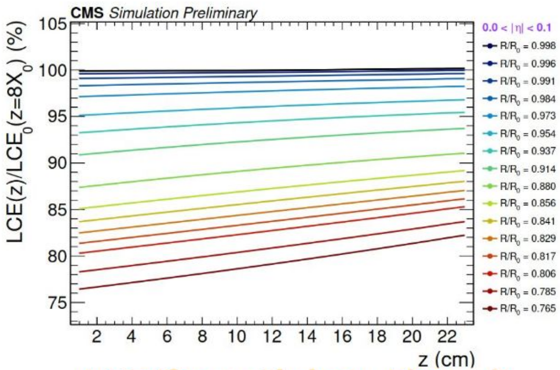
$$F = \frac{S^e}{S^\gamma} = \frac{\dfrac{\int E^e_{\mathrm{dep}}(z) \times \mathrm{LCE}(z;\, \mathrm{R/R_0}, \eta)\, \mathrm{d}z}{\int E^e_{\mathrm{dep}}(z)\, \mathrm{d}z}}{\dfrac{\int E^\gamma_{\mathrm{dep}}(z) \times \mathrm{LCE}(z;\, \mathrm{R/R_0}, \eta)\, \mathrm{d}z}{\int E^\gamma_{\mathrm{dep}}(z)\, \mathrm{d}z}}$$

Collected energy for damaged crystal

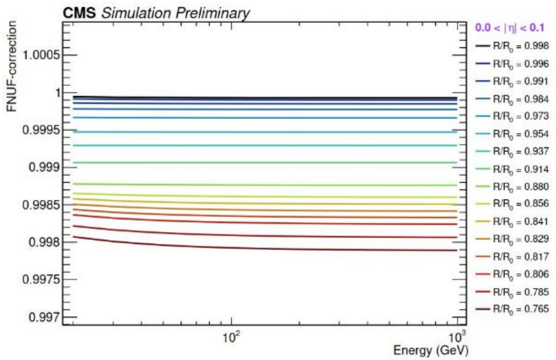
Collected energy for undamaged crystal



E_{dep} (from Geant4)



LCE (from Fluka + Litrani)



Correction

Expected to strongly reduce the impact of this source of uncertainty in the full Run 2 measurement from CMS

Can we do any better from on-shell mass measurements

It was pointed out by Dixon and Li back in 2013, that in the diphoton decay channel **interference between gluon fusion Higgs production and the QCD continuum** results in a **shift in the measured m_H**

This shift is dependent on Γ_H **.** ATLAS in fact estimated this **shift in the Run 2 mass measurement to be around - 26 MeV** where it is accounted for as a systematic uncertainty.

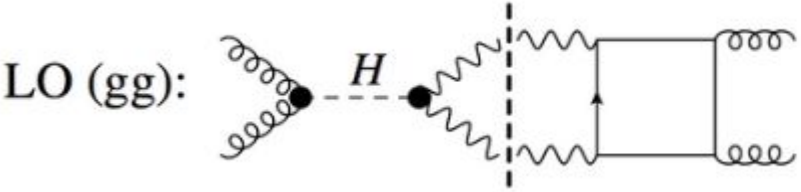
It is possible to turn this around and use this mass shift due to interference as an observable and use it to constrain Γ_H

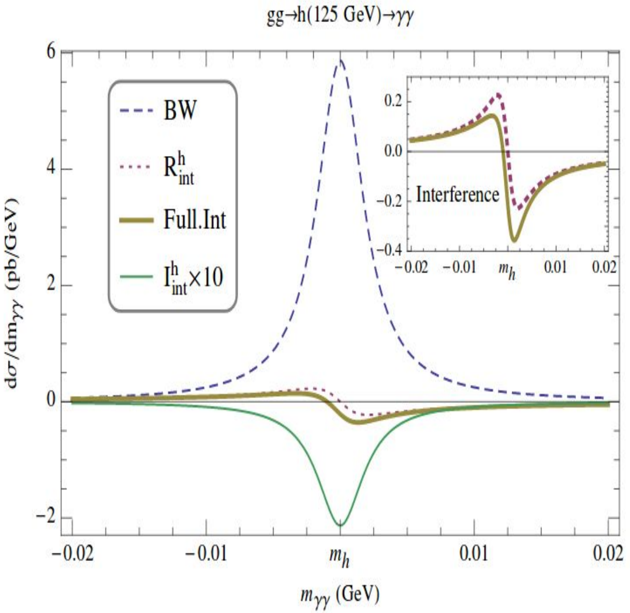
For optimal sensitivity a **dedicated event categorization is needed** : low p_T^H events have a higher mass shift compared to high p_T^H events.

ATLAS had described a strategy with 8 TeV data to carry out such a measurement (ATL-PHYS-PUB-2016-009)

→ **Expect a constraint < ~100 MeV** with such a method with the full Run 2 dataset

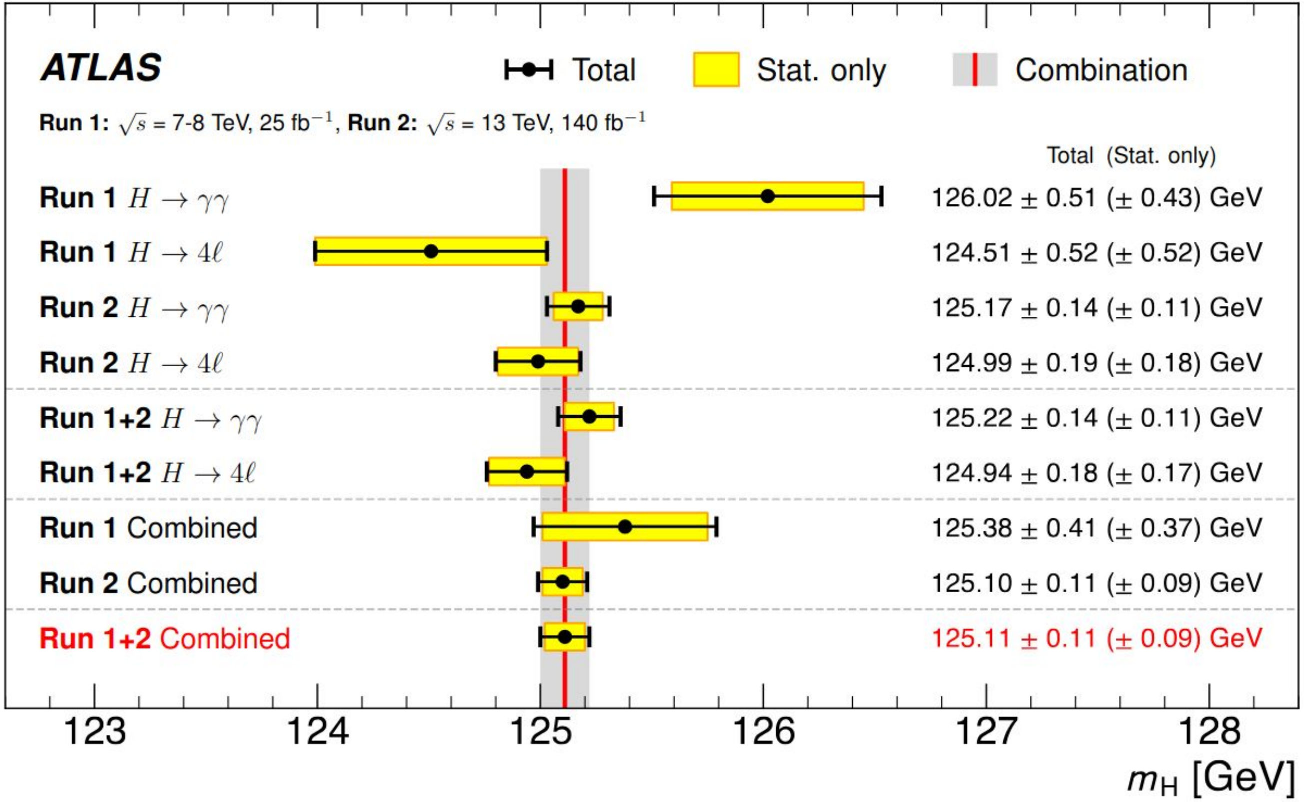
Dixon, Li et. al. Phys. Rev. Lett. 111, 111802





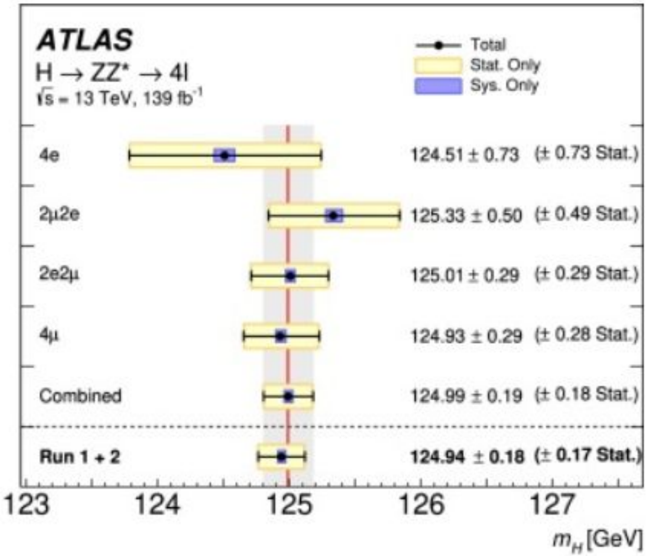
ATLAS Run 1 + Run 2 m_H grand combination

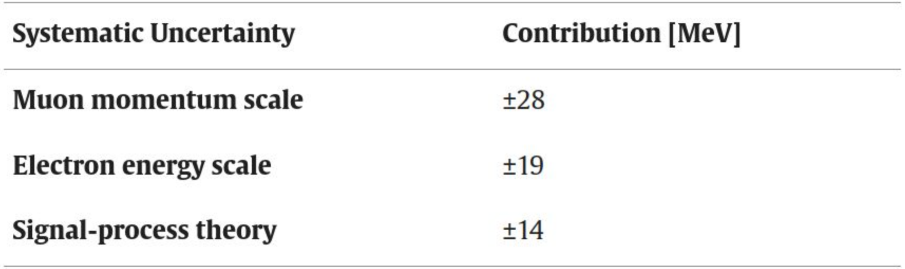
PRL 131 (2023) 251802



Systematic uncertainties in m_H measurements in H→ZZ->4l

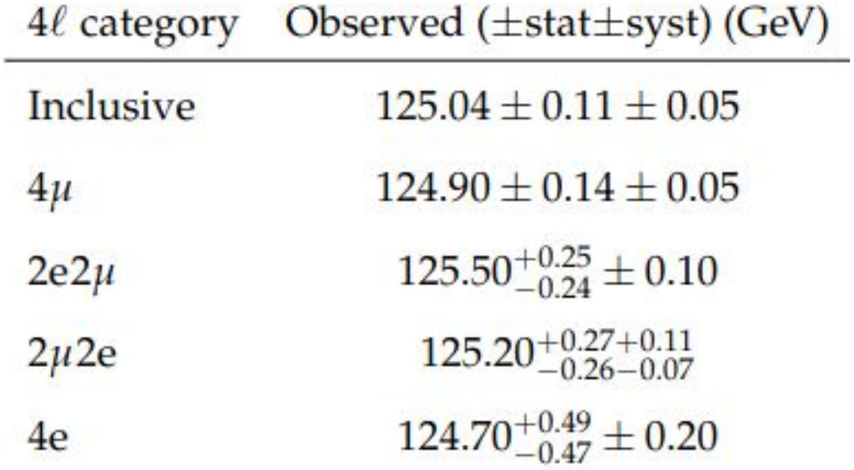
ATLAS full Run 2





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

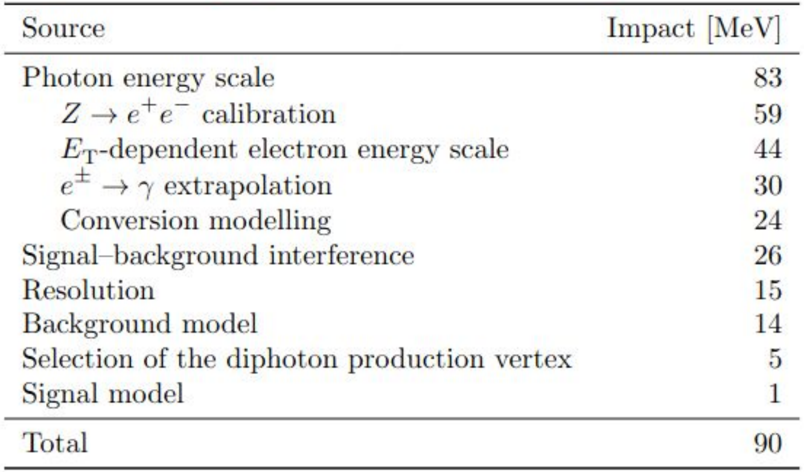
CMS full Run 2



4ℓ category	Observed (±stat±syst) (GeV)
Inclusive	$125.04 \pm 0.11 \pm 0.05$
4μ	$124.90 \pm 0.14 \pm 0.05$
$2e2\mu$	$125.50^{+0.25}_{-0.24} \pm 0.10$
$2\mu 2e$	$125.20^{+0.27+0.11}_{-0.26-0.07}$
4e	$124.70^{+0.49}_{-0.47} \pm 0.20$

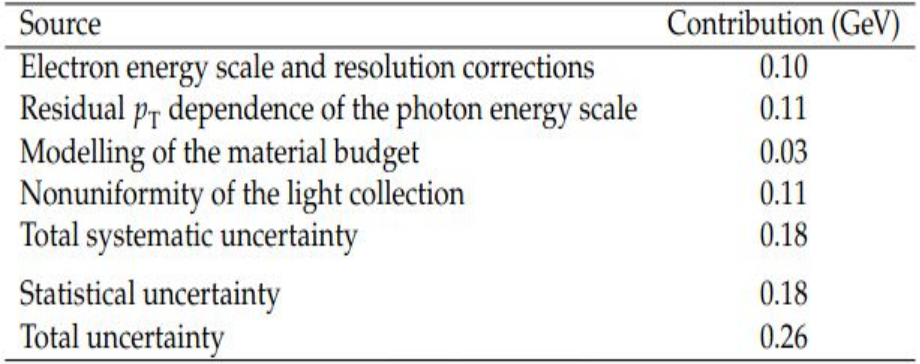
Systematic uncertainties in m_H measurements in $H\rightarrow\gamma\gamma$

ATLAS full Run 2



Source	Impact [MeV]
Photon energy scale	83
$Z \rightarrow e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \rightarrow \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

CMS 2016

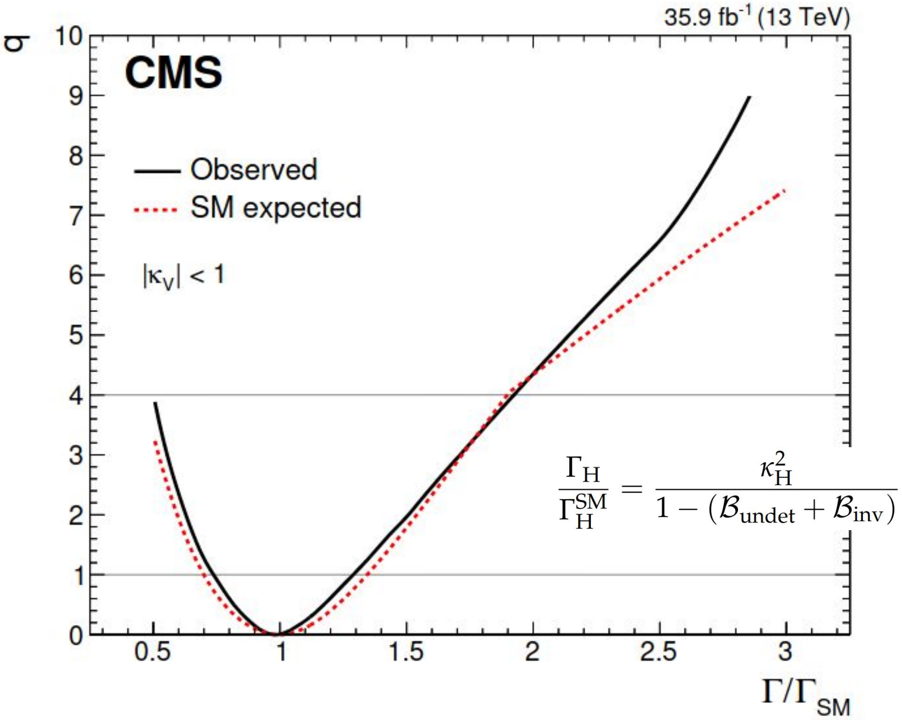


Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Γ_H from combination of coupling measurements

CMS HIG-17-031

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\mathrm{WH})$	—	—		κ_W^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	—	—		κ_Z^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	—	—		κ_t^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{BSM} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 +$ $+ 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 +$ $+ 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 +$ $+ 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$



$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{1 - (\mathcal{B}_{undet} + \mathcal{B}_{inv})}$$

CMS 2016 Higgs combination : $\mathbf{\Gamma_H/\Gamma_{SM} = 0.98_{-0.25}^{+0.31}}$ (ATLAS Run 1 : $\mathbf{\Gamma_H/\Gamma_{SM} = 0.64_{-0.25}^{+0.40}}$)