HVV, Higgs Mass, CP

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Outline

- Introduction
- Higgs property of HVV
  - Production and decay
  - Mass
  - Width
  - Cross section
  - CP and Anomalous couplings
- Summary

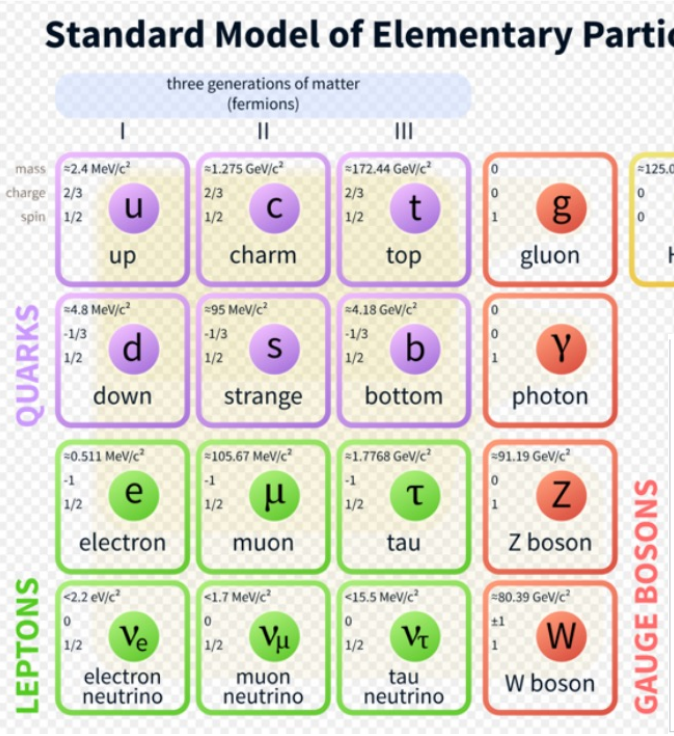
Introduction

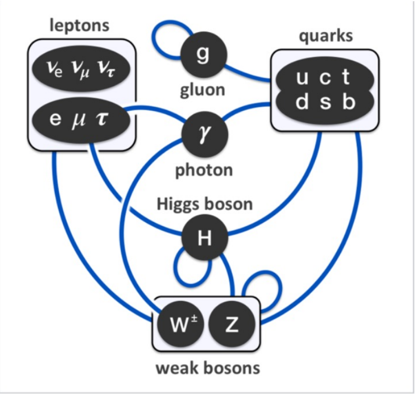
➤Standard model

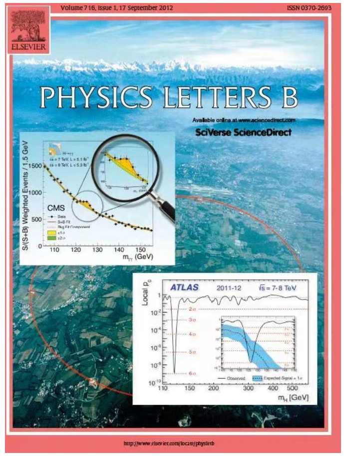
- Describe elementary particles and interactions
- Introduce Higgs mechanism in1960s
- Predict a scalar field responsible for mass origin

➤Higgs boson

- Particle corresponding to excitation of the predicted scalar field
- Key to verify the current understanding of boson/fermion mass generation
- A new probe to new physics after its experimental observation
- Crucial to measure its properties

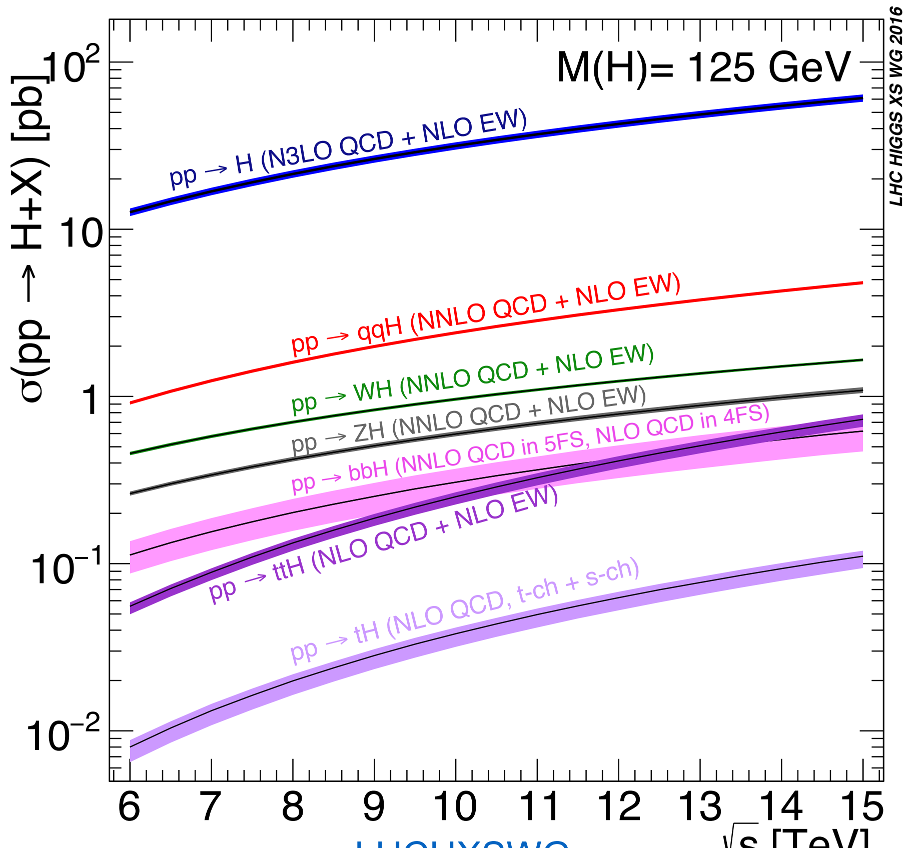






Observed in 2012

Higgs production at LHC



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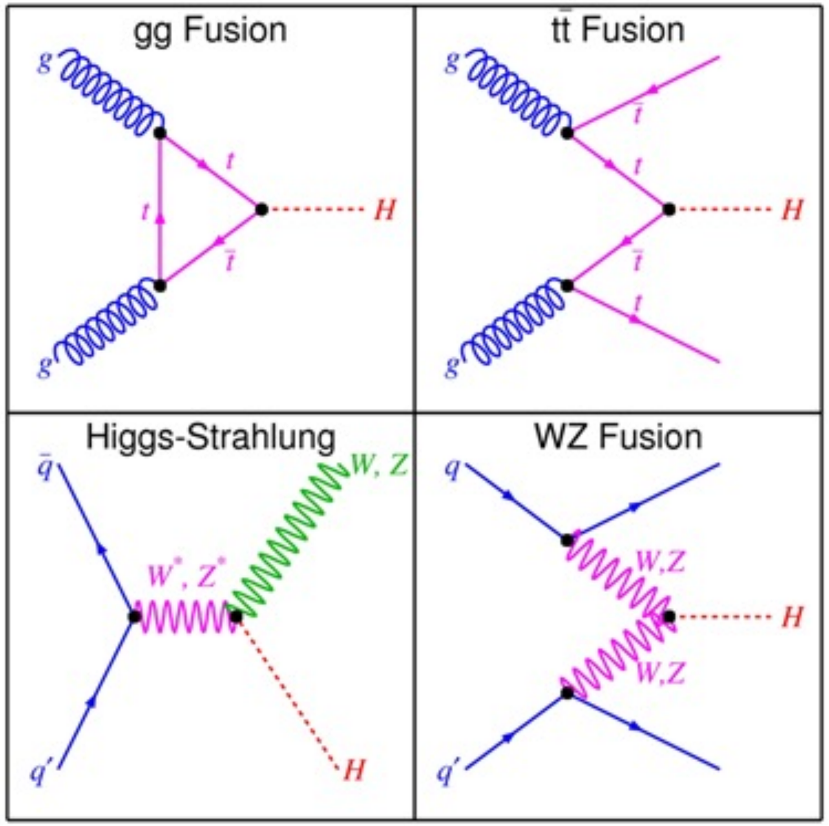
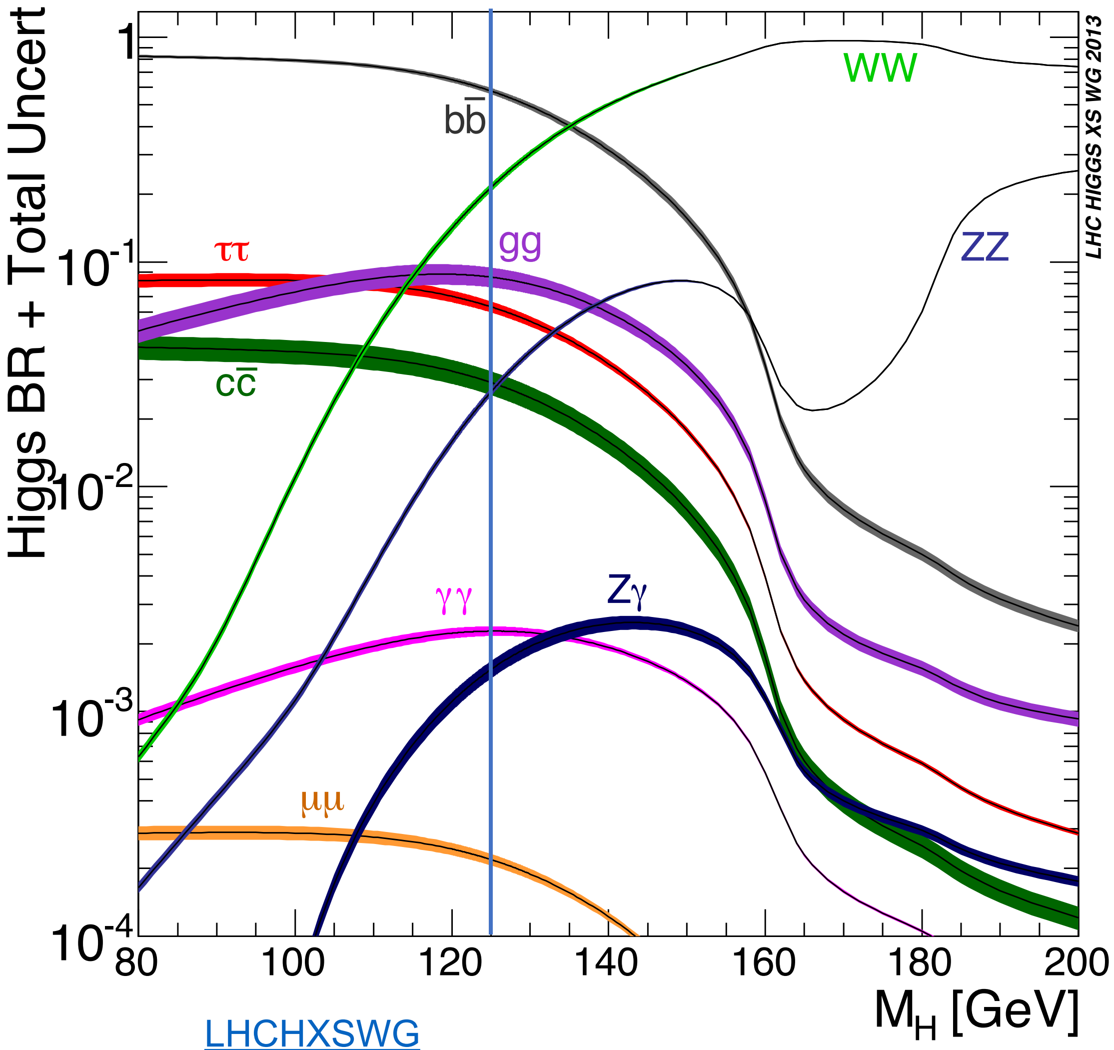


Fig. Feynman diagram of each production model

- Main production model and its cross section at 13TeV and Higgs mass of 125GeV
- Gluon-Gluon Fusion: 48.58 pb
- VBF: 3.782pb
- VH: 1.373pb(WH); 0.8839pb(ZH)
- ttH: 0.5071pb

Higgs decay at LHC



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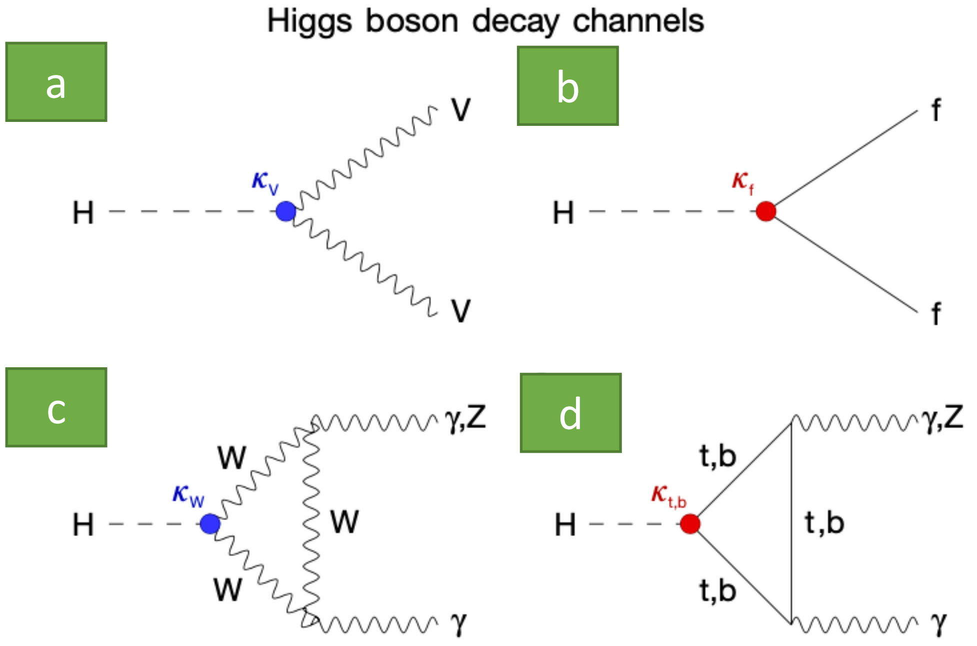
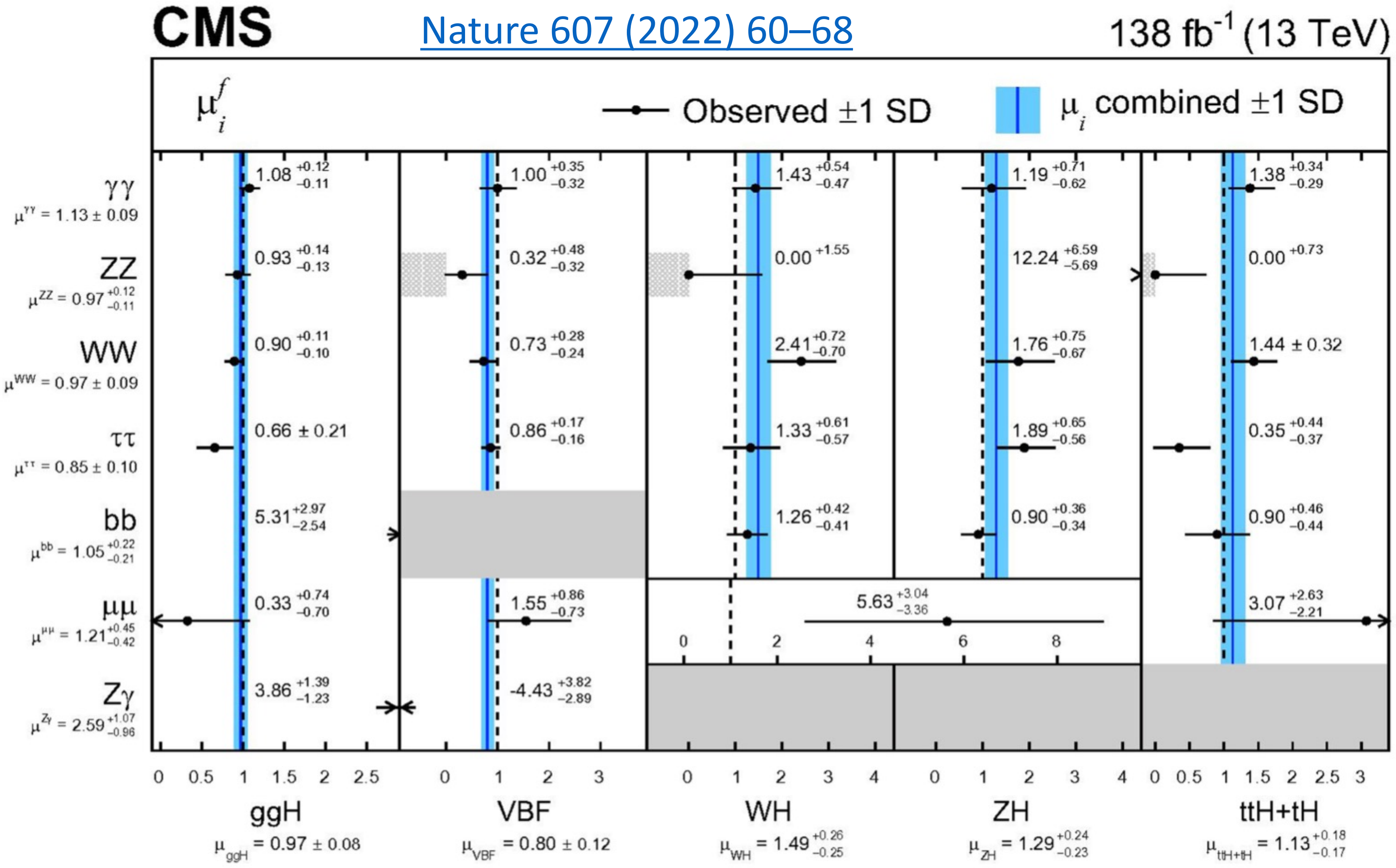


- Higgs boson decays into Nature 607 (2022) 60–68
  - Heavy vector boson pairs (**a**)
  - Fermion–antifermion pairs (**b**)
  - Photon pairs or Zγ (**c**,**d**)

Experimental measurements at CMS

[Nature 607 (2022) 60–68]



$$\mu = 1.002 \pm 0.057$$

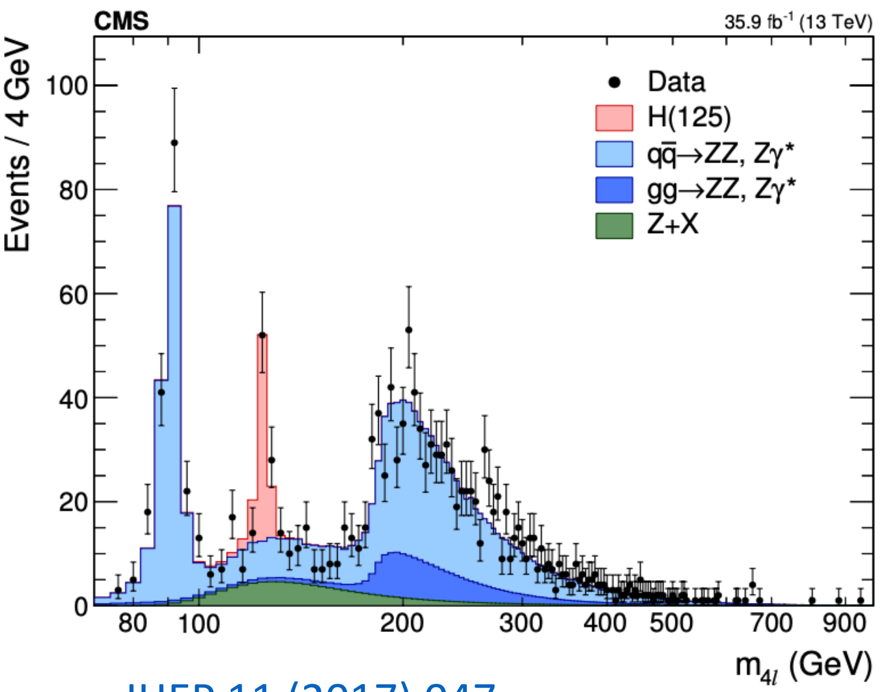
- Uncertainty improvement by a factor of *4.5* in precision compared with Higgs discovery

- HWW
  - arXiv: 2206.09466 submitted to EPJC
- HZZ
  - Eur. Phys. J. C 81 (2021) 488
  - arXiv: 2305.07532 submitted to JHEP
- H$\gamma\gamma$
  - JHEP 07 (2021) 027
- HZγ
  - JHEP 05 (2023) 233
  - CMS-PAS-HIG-23-002

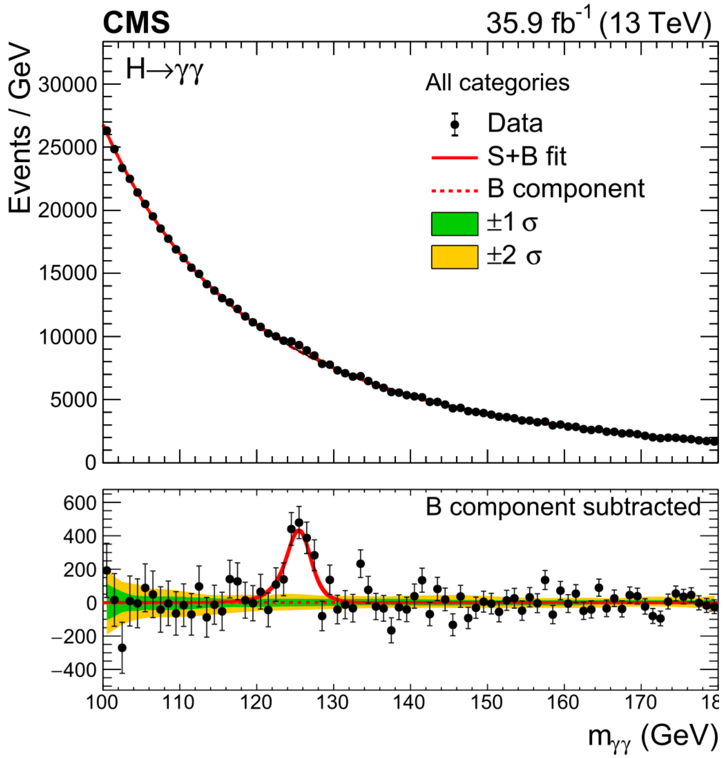
- Signal strength: $\mu_i = \sigma_i/\sigma_i^{SM}$ and $\mu^f = B_f/B_f^{SM}$ for given initial (i) and final (f) states, $i \rightarrow H \rightarrow f$
- Excellent agreement with the SM expectation

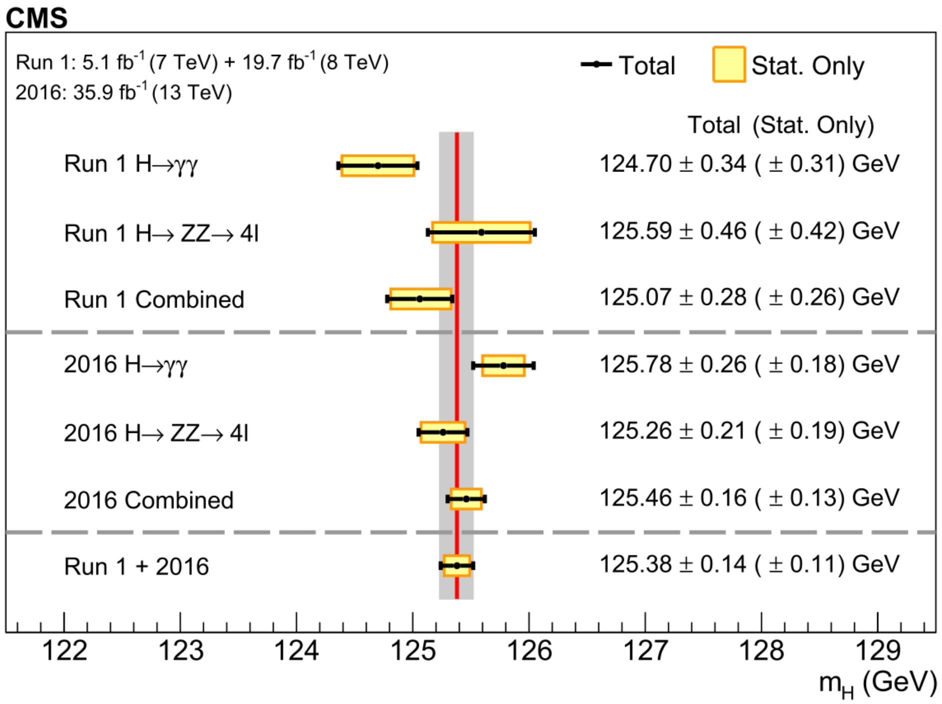
Higgs Mass

- One of the most important free parameter of the standard model
  - Couplings of Higgs to other elementary particles can be predicted by SM once its mass is known.
- Measured in so-called golden channel $4l, \gamma\gamma$ with a precision of 0.11%: $\boldsymbol{m_H = 125.38 \pm 0.14\ (\pm 0.11)\ GeV}$



[JHEP 11 (2017) 047]

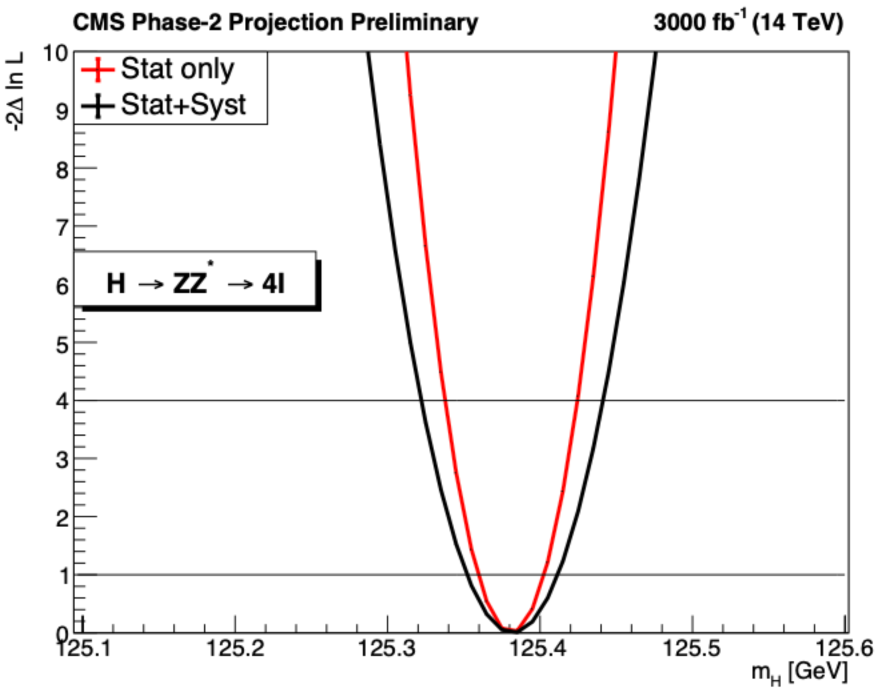




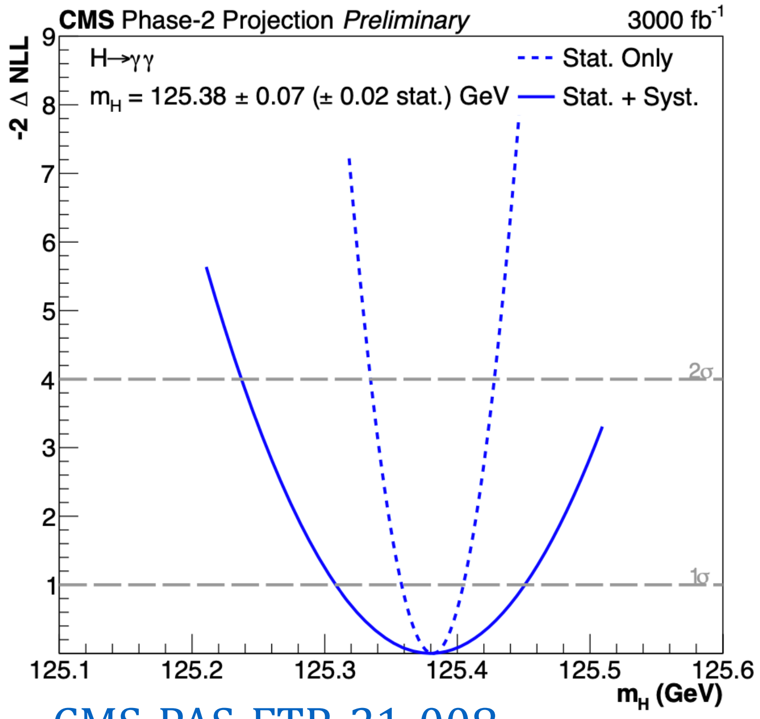
[Phys. Lett. B 805 (2020) 135425]

Higgs Mass of HL-LHC Projection

- Assumption that the same performance of Phase 2 detector as Run2
- Significantly increased pileup (Expected up to 200)
- Signal cross sections scaled to 14 TeV
- Background scaled according to the parton luminosity
- Further fine tuned photon energy calibration and better resolution for e, μ



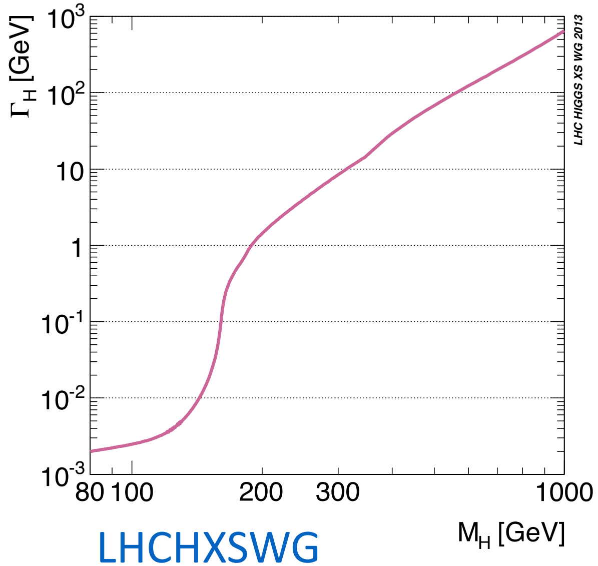
CMS-PAS-FTR-21-007



CMS-PAS-FTR-21-008

Higgs Width

- SM prediction $\Gamma_H = 4.1\ MeV$
- Direct measurement
  - Line shape limited by detector resolution
    - Limited mass resolution of order 1 GeV of LHC detectors
  - Lifetime too short
    - $\Gamma_H = \frac{\hbar}{2\pi\tau_H}, \tau_H = 1.6\times10^{-22}s$
    - Experimental limit $\tau_H < 1.9\times10^{-13}s$ at 95% CL
- Indirect measurement:
  - On-shell and off-shell cross section:
    - $\sigma^{on-shell} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_p$
    - $\sigma^{off-shell} \propto g_p^2 g_d^2 \propto \mu_p \Gamma_H$
  - $\frac{\Gamma_H}{\Gamma_{SM}} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$



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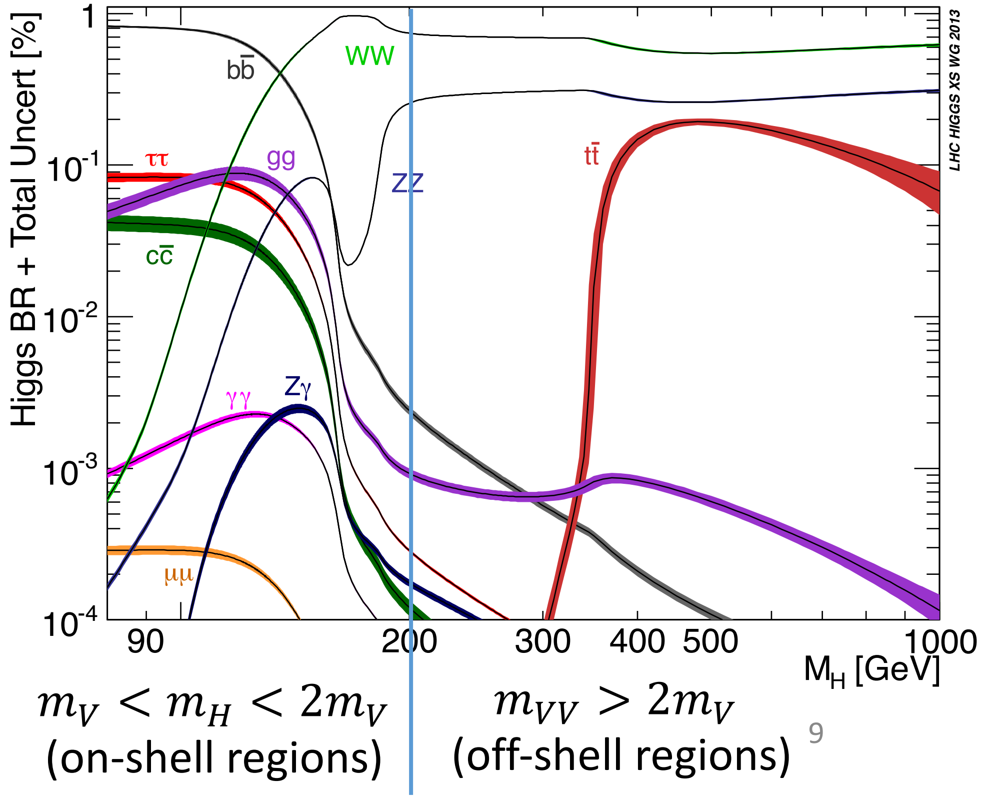
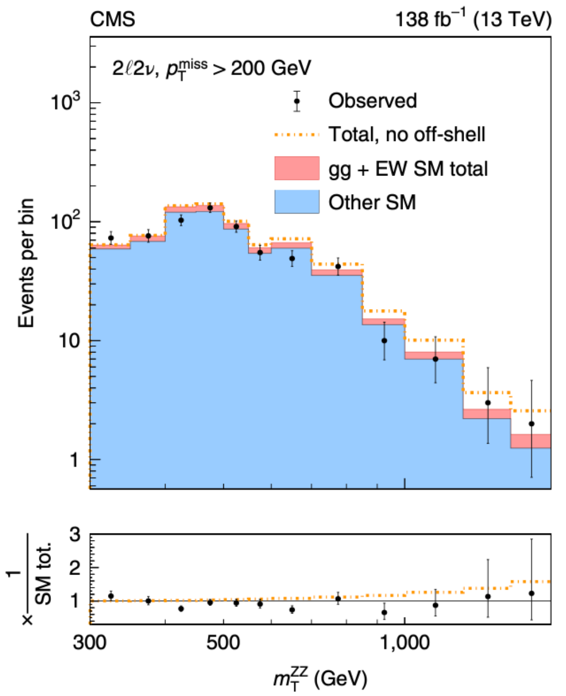
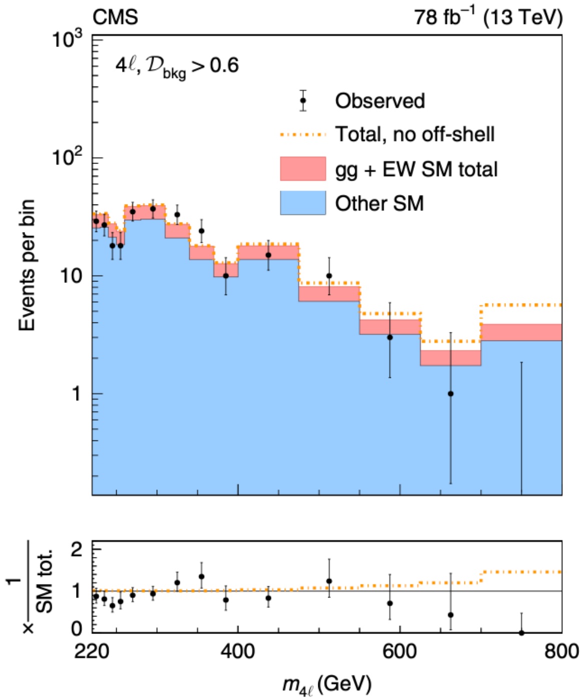
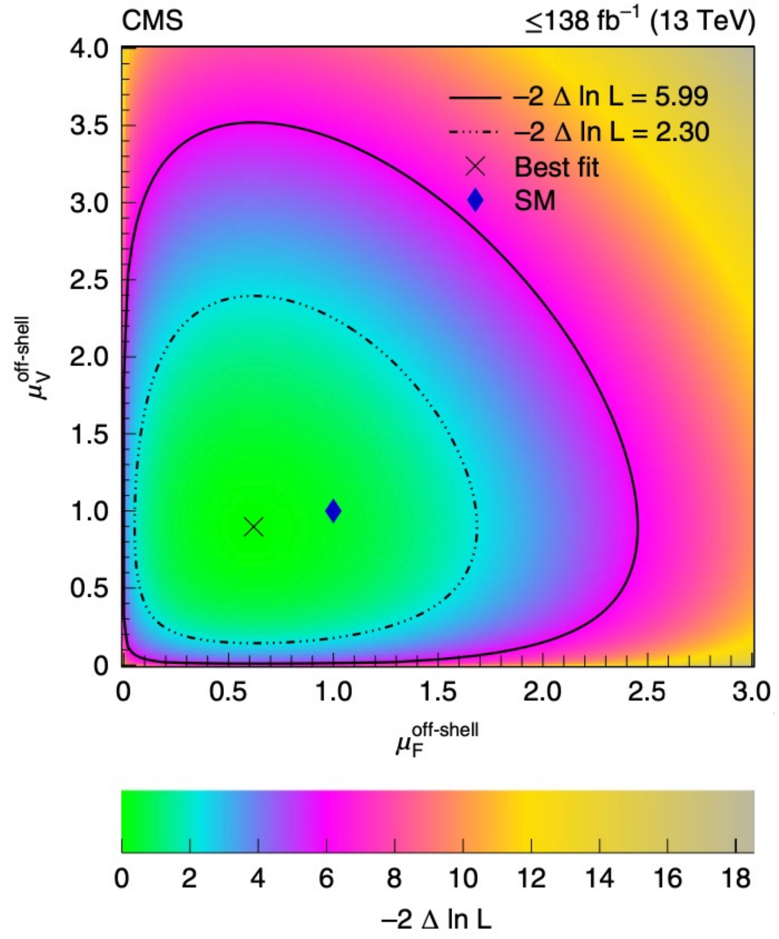
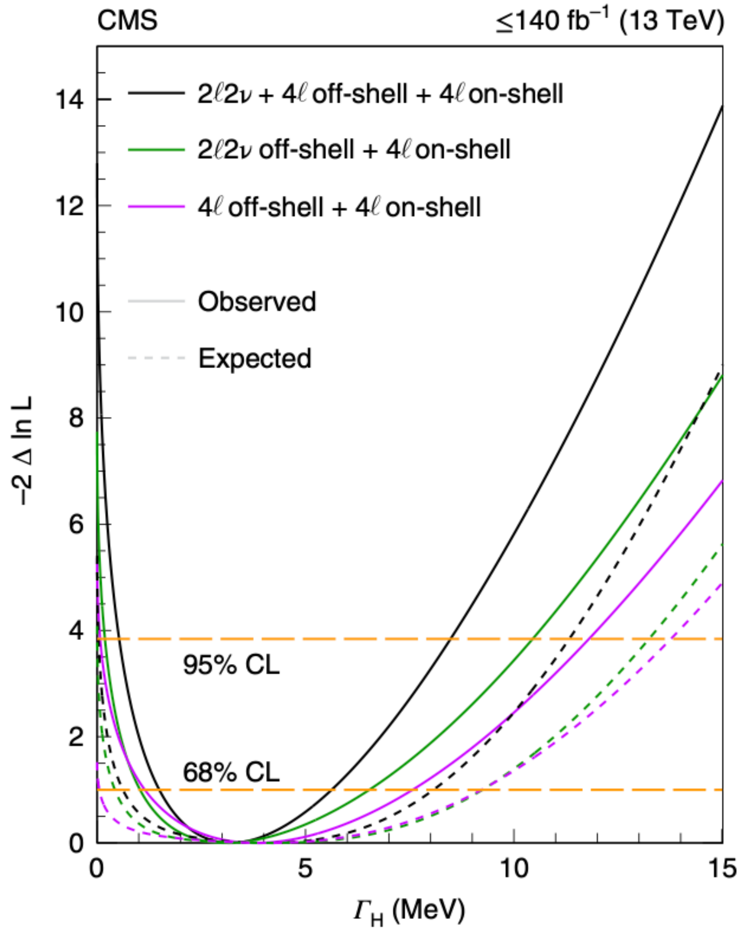


Off-shell Higgs and Width measurement









[*Nature Phys. 18 (2022) 1329*]

- Distributions of ZZ invariant mass observables in off-shell signal regions
- Off-shell Higgs is observed with 3.6σ
- $\Gamma_H = 3.2^{+2.4}_{-1.7}\ MeV$

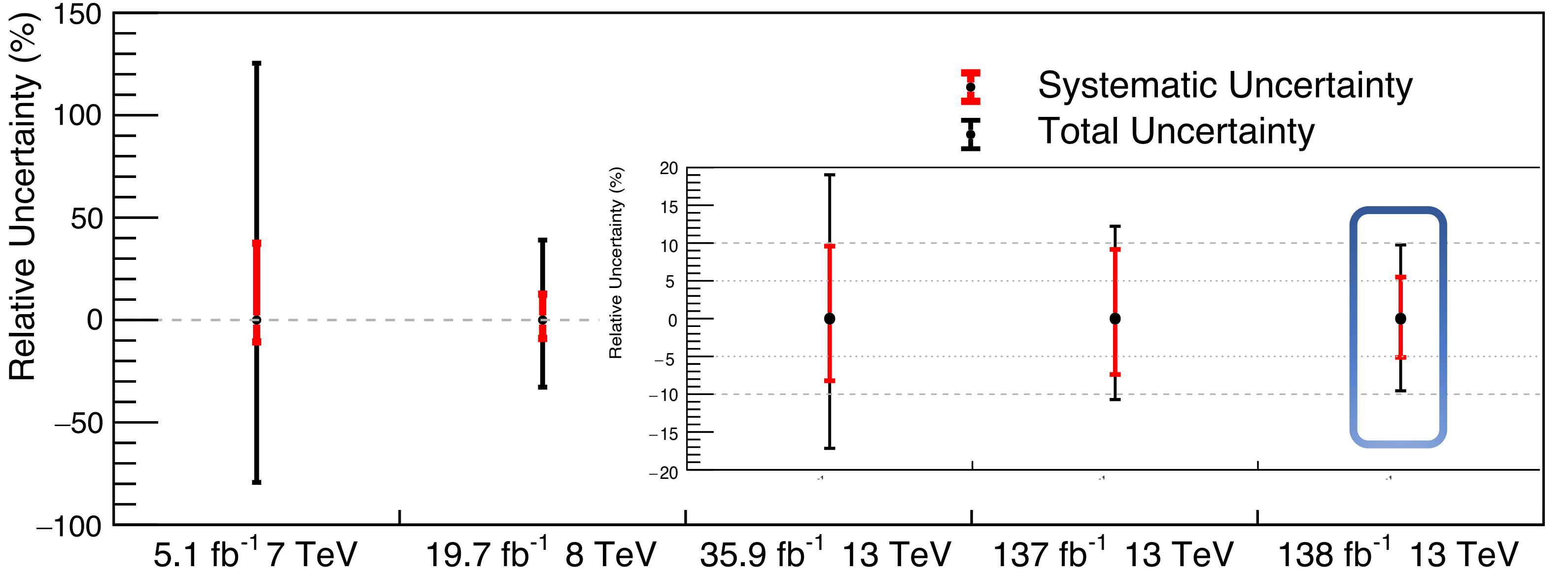
Higgs Cross Section

- Fiducial/Differential cross section:
  - **Minimal** ***dependence*** on the assumptions of the relative fraction or kinematic distributions of the separate production ***modes***
  - Fiducial cross section = **cross section in fiducial volume** (cuts applied to generated events)

$$\sigma_i = \frac{N_{reco,i}}{C_i * A_i * L * B} \quad \Longrightarrow \quad \sigma_{fid,i} * B = \frac{N_{reco,i}}{C_i * L}$$

- Simplified template cross section:
  - **Maximize** the ***sensitivity*** of the measurements while at the same time to **minimize** their ***dependence*** on the ***theory*** predictions
  - The events are further binned within ggH, VBF, and VH in order to study deeper structure within each production mechanisms

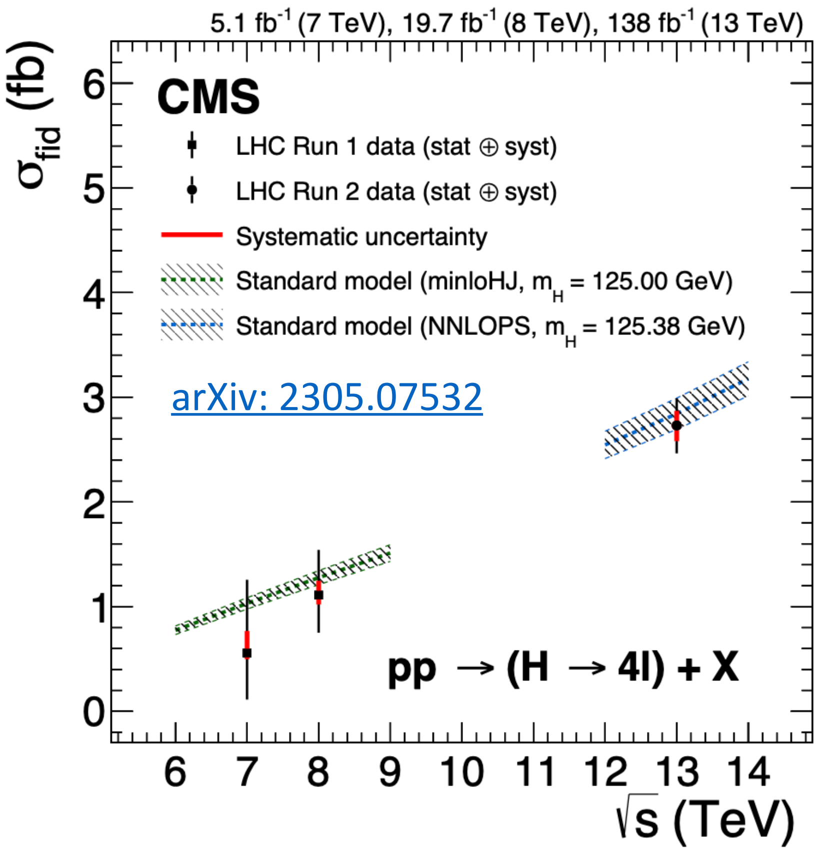
Fiducial cross section of $H \rightarrow ZZ \rightarrow 4l$



JHEP04(2016)005 JHEP04(2016)005 JHEP11(2017)047 EPJC81(2021)488 CMS-PAS-HIG-21-009

10% precision

$$\sigma^{\text{fid}} = 2.73^{+0.22}_{-0.22}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})\,\text{fb}$$
$$= 2.73^{+0.22}_{-0.22}\,(\text{stat})^{+0.12}_{-0.12}(\text{electrons})^{+0.06}_{-0.05}(\text{lumi})^{+0.04}_{-0.04}(\text{bkg})^{+0.03}_{-0.02}(\text{muons})\,\text{fb}$$

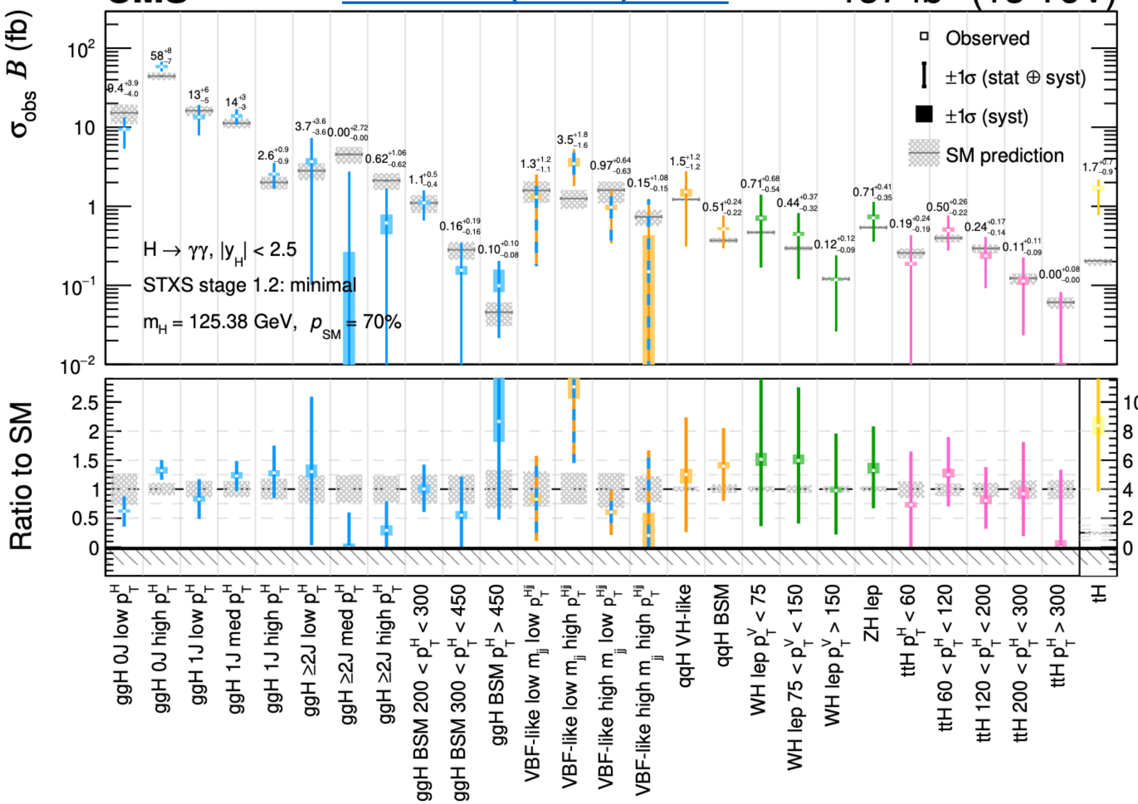


Fiducial cross section as a function of center of mass

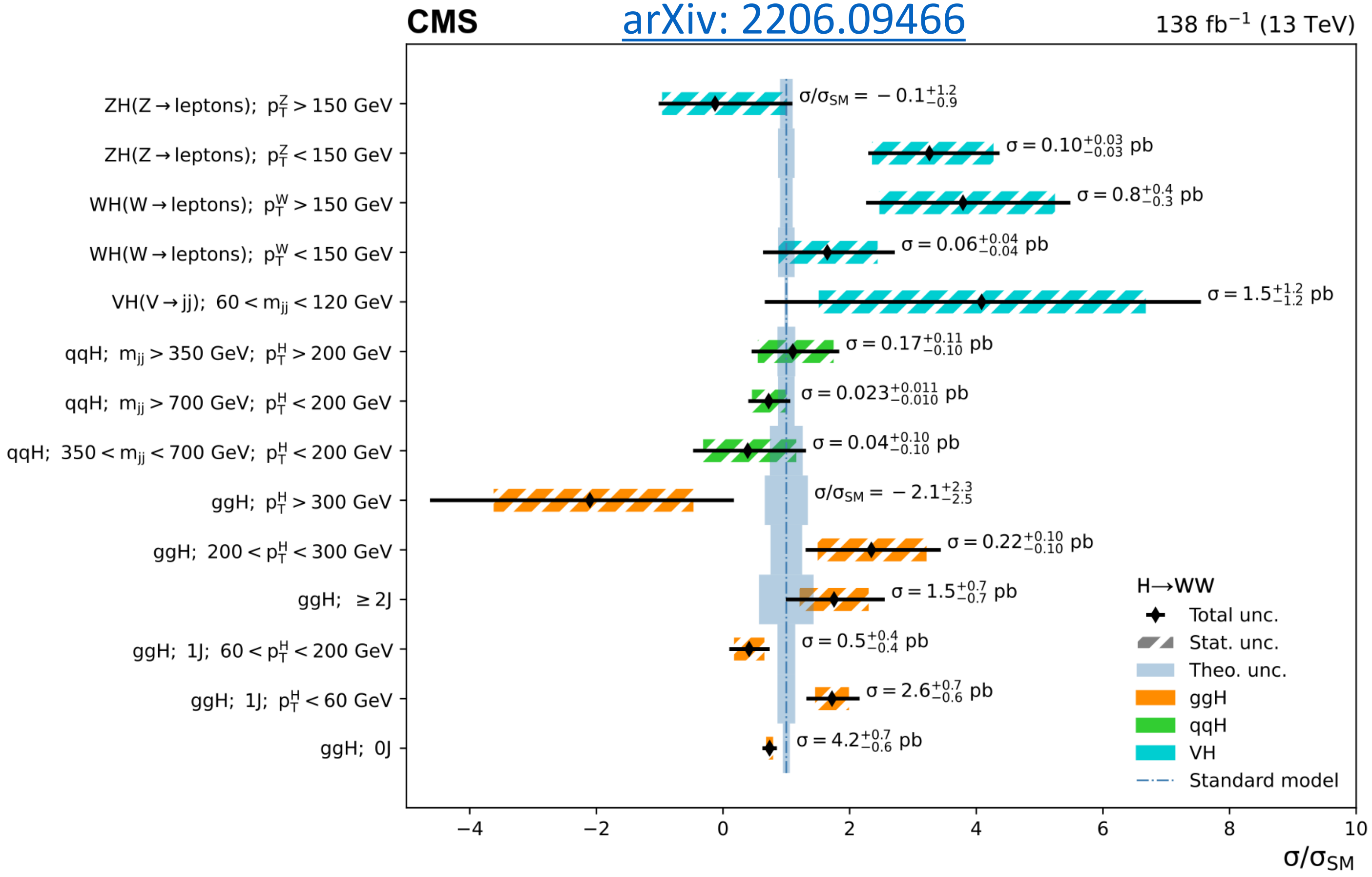
- Systematic uncertainty dominated by
  - Electrons-related nuisances,
  - Especially electron reconstruction efficiency
- **Reduction of the systematic component** due to the reduction of the main lepton nuisances

Simplified template cross section

JHEP 07 (2021) 027



arXiv: 2206.09466



- Observed cross sections in each STXS bin of Stage 1.2 framework, normalized to the SM expectation of (Left) $H \rightarrow \gamma\gamma$ and (Right) $H \rightarrow WW$ decay channel.

Higgs CP and anomalous couplings

- SM Higgs is CP even $J^{CP} = 0^{++}$
- Angular distributions of leptons in bosonic decay channels, spin (J) and parity were also found to be compatible with SM
- A large number of alternative spin–parity hypotheses ruled out at the >99.9% confidence level (CL) with Run 1 data Phys. Rev. D 92 (2015) 012004
- HVV scattering amplitude of a spin-0 boson H and two spin-one gauge bosons (ZZ, WW, Zγ, $\gamma\gamma$, gg) and effective fractional cross sections

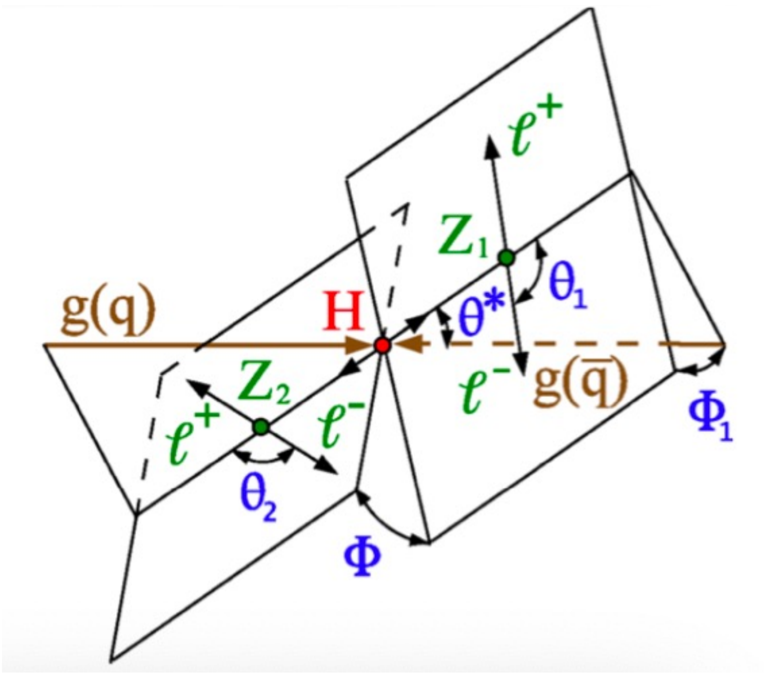
$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

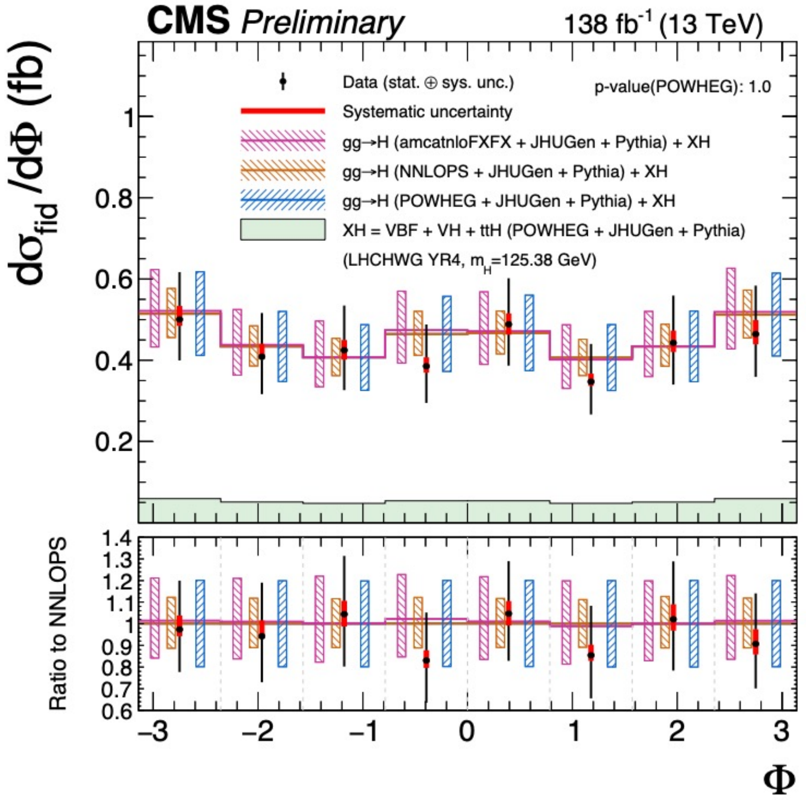
CP even
- SM-like spin-zero 0^+: $a_1^{ZZ}=a_1^{WW}=2$
- Higher order spin-zero 0_h^+: a_2

CP odd
- Pseudoscalar spin-zero 0^- : a_3

Scales of BSM physics

Differential Cross Section --- CP relevant



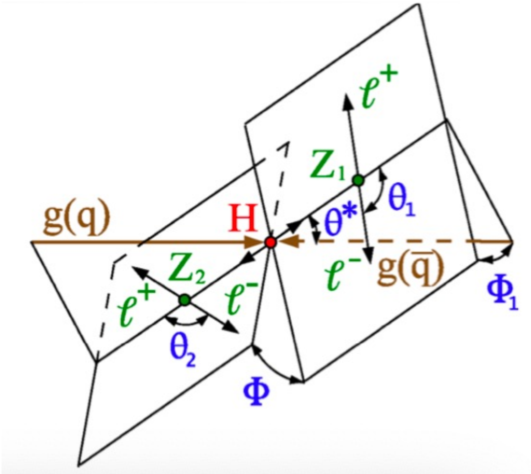


arXiv: 2305.07532
submitted to JHEP

- Differential observables of **Higgs decay**
  - Angular observables: $\Phi \quad \Phi_1 \quad \cos\theta \quad \cos\theta_1 \quad \cos\theta^*$
  - Describe angle between the plane of Higgs, Z_1, Z_2 decay and the beam direction
  - Sensitive to the **spin and charge conjugation and parity properties of the Higgs**

Differential Cross Section --- CP relevant

- Higgs **Decay** in 4l final states could be characterized by the following seven parameters:
  - m_{Z1}, m_{Z2}
  - Φ , Φ_1 , $\cos\theta$, $\cos\theta_1$, $\cos\theta^*$



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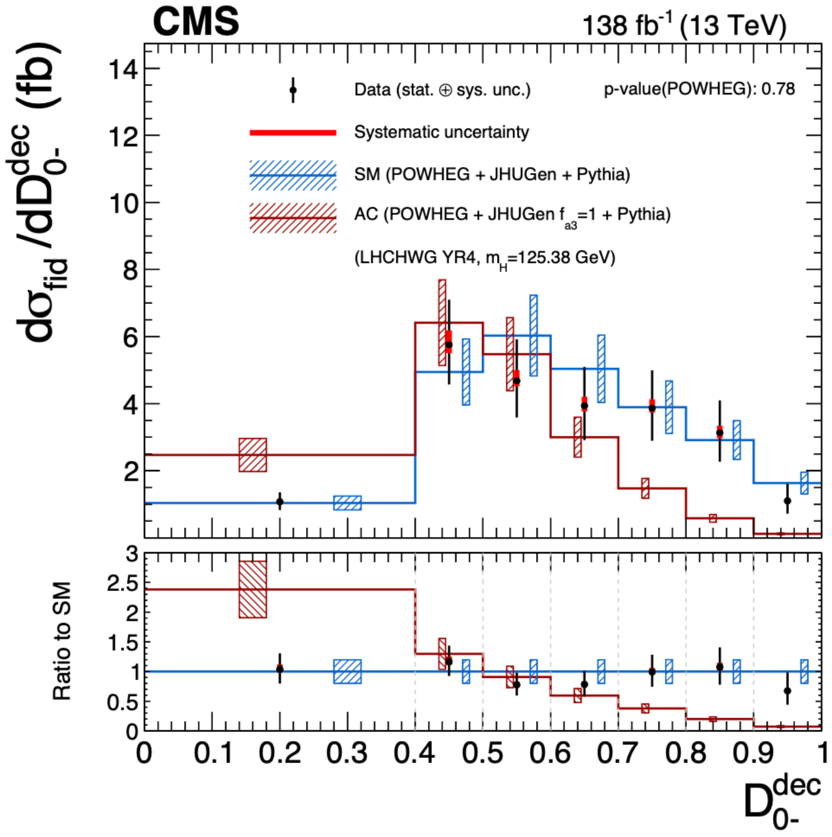
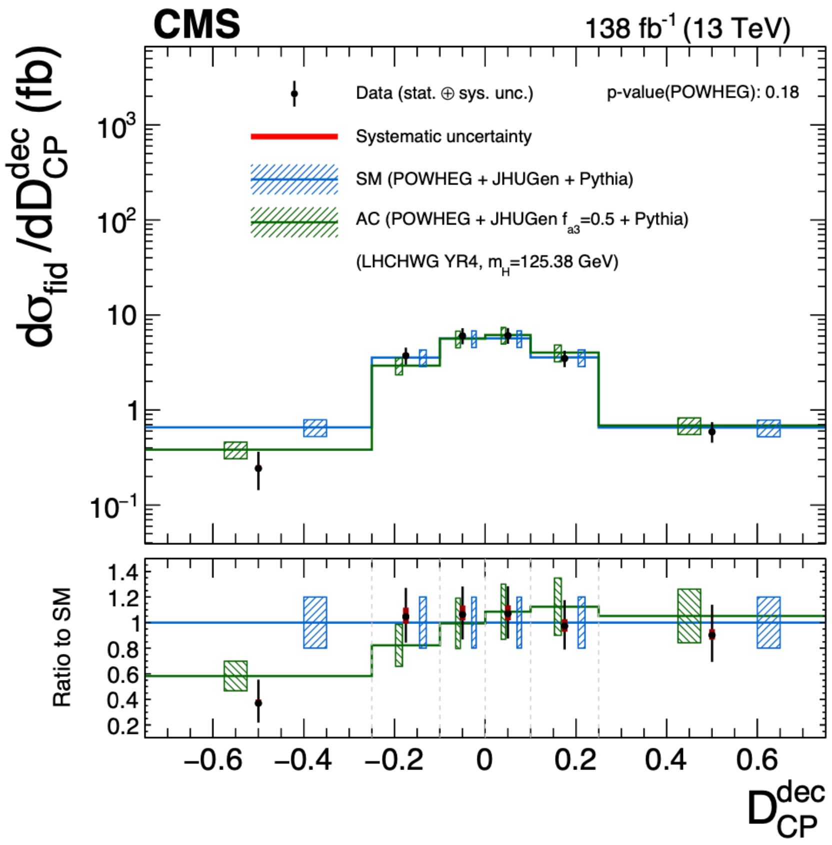
	$\mathcal{D}_{\rm alt}$				$\mathcal{D}_{\rm int}$	
	Coupling					
	a_3	a_2	κ_1	$\kappa_2^{Z,\gamma}$	a_3	a_2
Discriminant	$\mathcal{D}_{0-}$	$\mathcal{D}_{0h+}$	$\mathcal{D}_{\Lambda1}$	$\mathcal{D}_{\Lambda1}^{Z,\gamma}$	$\mathcal{D}_{CP}$	$\mathcal{D}_{\rm int}$

$$\mathcal{D}_{\rm alt} = \frac{\mathcal{P}_{\rm sig}(\vec{\Omega})}{\mathcal{P}_{\rm sig}(\vec{\Omega}) + \mathcal{P}_{\rm alt}(\vec{\Omega})} \quad \mathcal{D}_{\rm int} = \frac{\mathcal{P}_{\rm int}(\vec{\Omega})}{2\cdot\sqrt{\mathcal{P}_{\rm sig}(\vec{\Omega})\cdot\mathcal{P}_{\rm alt}(\vec{\Omega})}},$$

- Observables sensitive to **HVV anomalous couplings**
  - D_{0-} and D_{CP}
  - Pseudoscalar spin-zero 0⁻: a_3
    sensitive to possible BSM contributions from CP violation

Differential Cross Section --- CP relevant





arXiv: 2305.07532
submitted to JHEP

- Differential cross sections as a function of
  - Matrix-element discriminants
    - Built based on the two hypotheses for which the discriminant is designed for
      - Standard Model prediction ggH (POWHEG) + XH
      - Anomalous Coupling prediction ggH AC samples normalized to the ggH+XH SM cross section
  - Probe **HZZ vertex** and sensitive to BSM physics

Anomalous Higgs couplings to vector bosons in H->4l

$$A(HV_1V_2) = \frac{1}{v}\left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV}(q_{V1}+q_{V2})^2}{(\Lambda_Q^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$(a_1^{ZZ}, \kappa_1^{ZZ}, a_2^{ZZ}, a_3^{ZZ})$
$(a_1^{WW}, \kappa_1^{WW}, a_2^{WW}, a_3^{WW})$
$(\kappa_2^{Z\gamma}, a_2^{Z\gamma}, a_3^{Z\gamma})$
$(a_2^{\gamma\gamma}, a_3^{\gamma\gamma})$

- 13 coupling considering symmetry and gauge invariance
- 9: Four loop-induced couplings $a_{2,3}^{\gamma\gamma}$ and $a_{2,3}^{Z\gamma}$ are constrained by $H \to \gamma\gamma$ and $Z\gamma$
  - EW production and H → 4l decay, we set these four couplings to zero

- Two approach:
  - 5: Set $a_i^{WW} = a_i^{ZZ}$ → $\boldsymbol{a_1}$: $\boldsymbol{a_2, a_3, \kappa_1/(\Lambda_1)^2, \kappa_2^{Z\gamma}/(\Lambda_1^{Z\gamma})^2}$
  - 4: Equivalent to Higgs basis Lagrangian parametrization with dim-4 and dim-6 operators. $SU(2)\times U(1)$ symmetry, 5 correlation constraints
    → $\boldsymbol{a_1}$: $\boldsymbol{a_2, a_3, \kappa_1/(\Lambda_1)^2}$

Anomalous Higgs couplings to vector bosons in H->4l

- Parametrization of cross sections

$$\sigma(j \to H \to f) \propto \frac{(\sum_{il}\alpha_{il}^{(j)} a_i a_l)(\sum_{mn}\alpha_{mn}^{(f)} a_m a_n)}{\Gamma_H}$$

α_{il}^{k}: coefficients and model with simulation
a_i: real couplings describing the HVV interactions
Γ_H: depends on the couplings a_i

- Parametrization of the signal strength and cross section fractions

$$f_{ai}^{VV} = \frac{|a_i^{ZZ}|^2 \alpha_{ii}^{dec}}{\sum_j |a_j^{VV}|^2 \alpha_{jj}^{dec}} sign(\frac{a_i^{VV}}{a_1})$$

f_{ai}: measure xsec contribution of a_i in decay, Γ_H is absorbed in μ

Phys. Rev. D 104 (2021) 052004

- Coupling ratio

$$\frac{a_i^{VV}}{a_j^{VV}} = \sqrt{\frac{|f_{ai}^{VV}|\alpha_{jj}^{(2e2\mu)}}{|f_{aj}^{VV}|\alpha_{ii}^{(2e2\mu)}}} \mathrm{sign}(f_{ai}^{VV} f_{aj}^{VV})$$

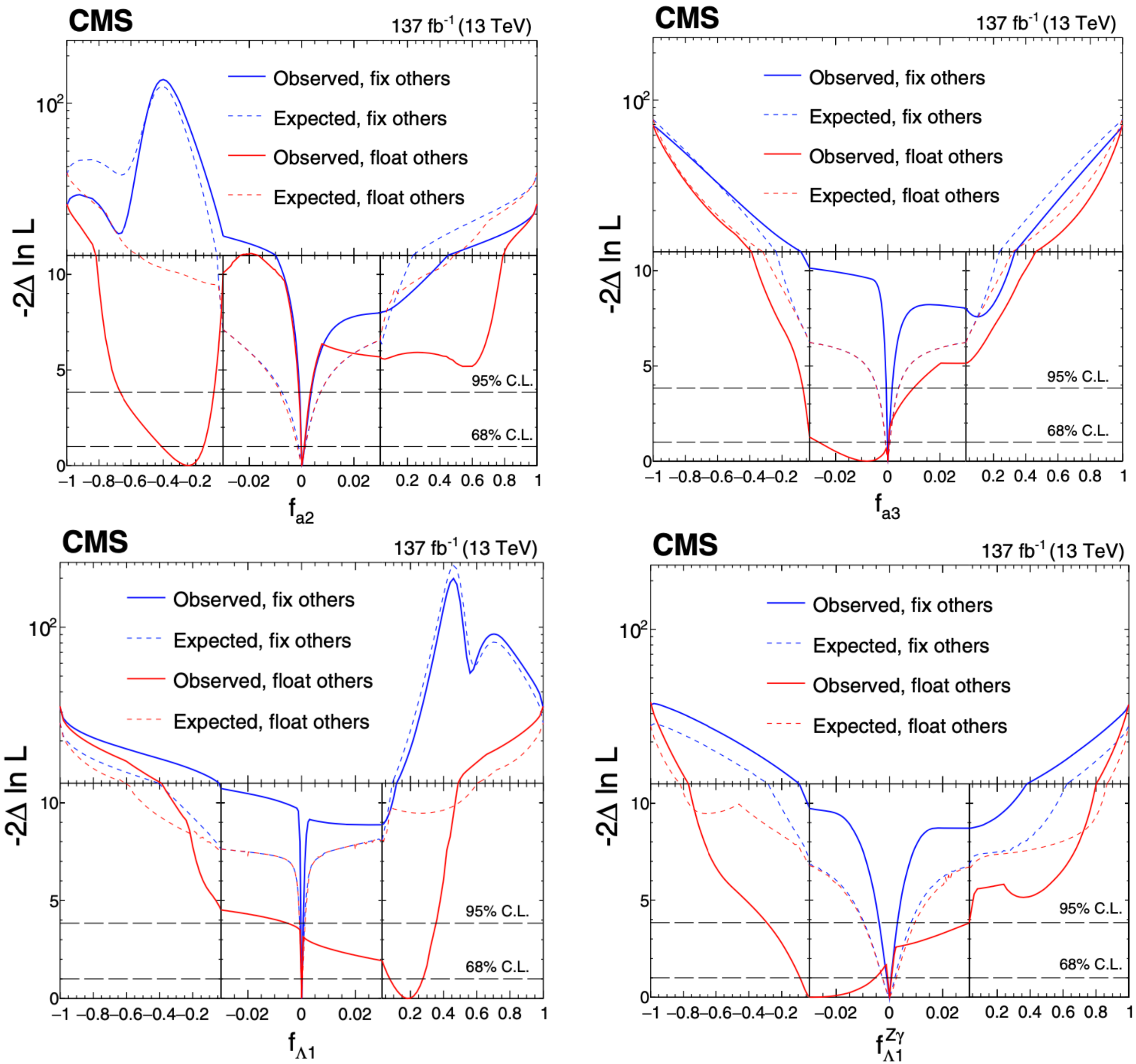
Coupling	Fraction	Approach 1	Approach 2
a_i^{VV}	f_{ai}^{VV}	α_{ii}/α_{11}	α_{ii}/α_{11}
a_3	f_{a3}	0.153	0.153
a_2	f_{a2}	0.361	6.376
$-\kappa_1$	$f_{\Lambda 1}$	0.682	5.241
$-\kappa_2^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	1.746	---

Measured values of μ_j and f_{ai} should be sufficient

Constraints on HVV couplings

- Approach 1:
  - $a_i = a_i^{WW}$, 4 constraints, measure 5 couplings: $a_1, \kappa_1, a_2, a_3, \kappa_2^{Z\gamma}$
  - $(f_{a3}, f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}) = (-0.00805, -0.24679, 0.18629, -0.02884)$

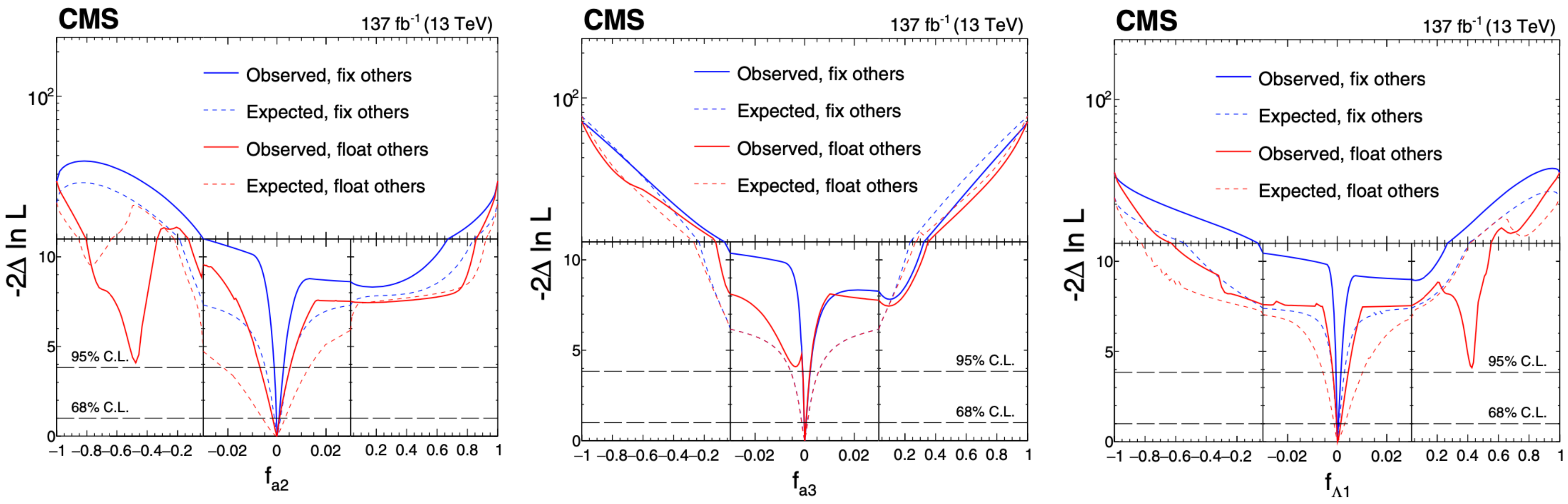
[Phys. Rev. D 104 (2021) 052004]



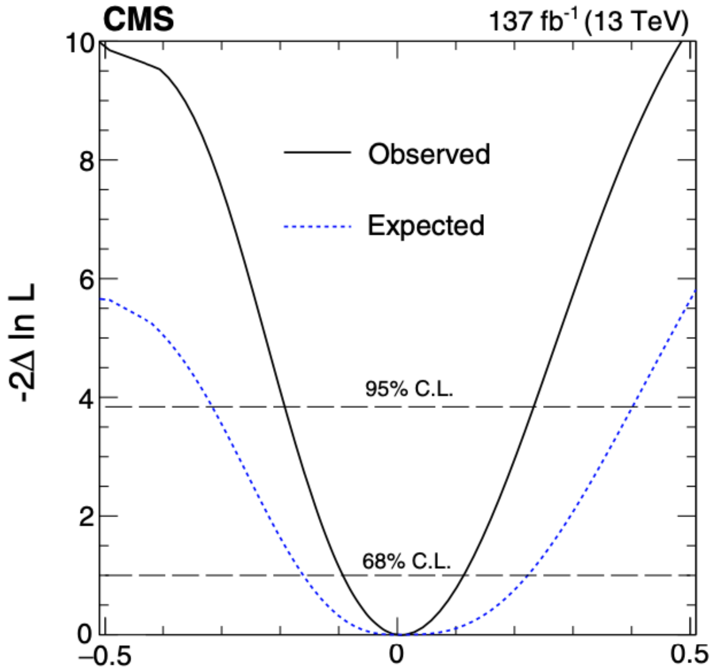
Constraints on HVV couplings within SU(2) × U(1) symmetry

[Phys. Rev. D 104 (2021) 052004]

- Approach 2:
  - Higgs basis EFT, $SU(2)\times U(1)$ symmetry, 5 correlation constraints,
  - Measure 4 couplings, a_1: κ_1, a_2, a_3



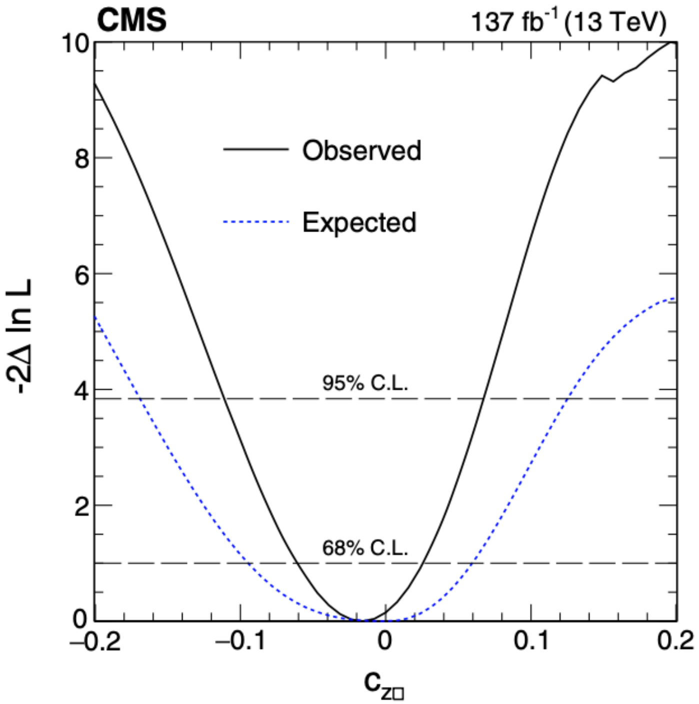
Constraints on HVV couplings within SU(2) × U(1) symmetry

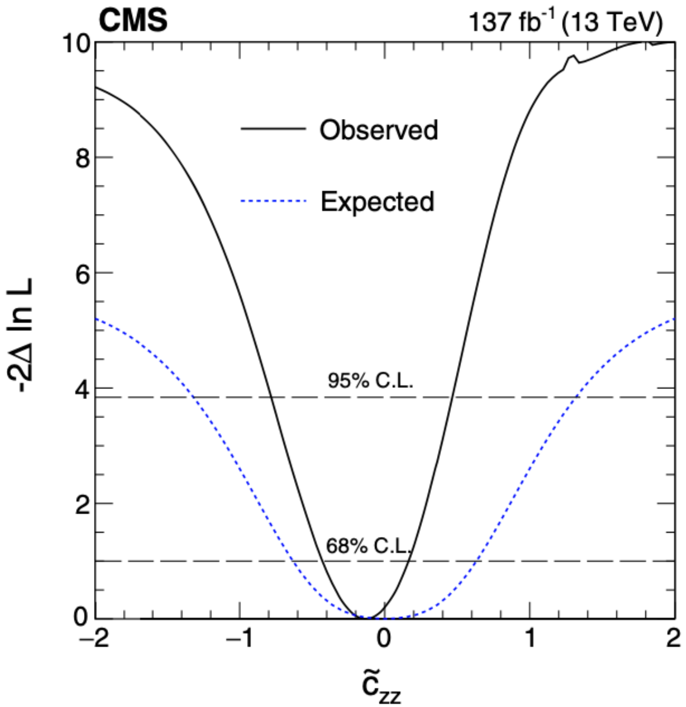


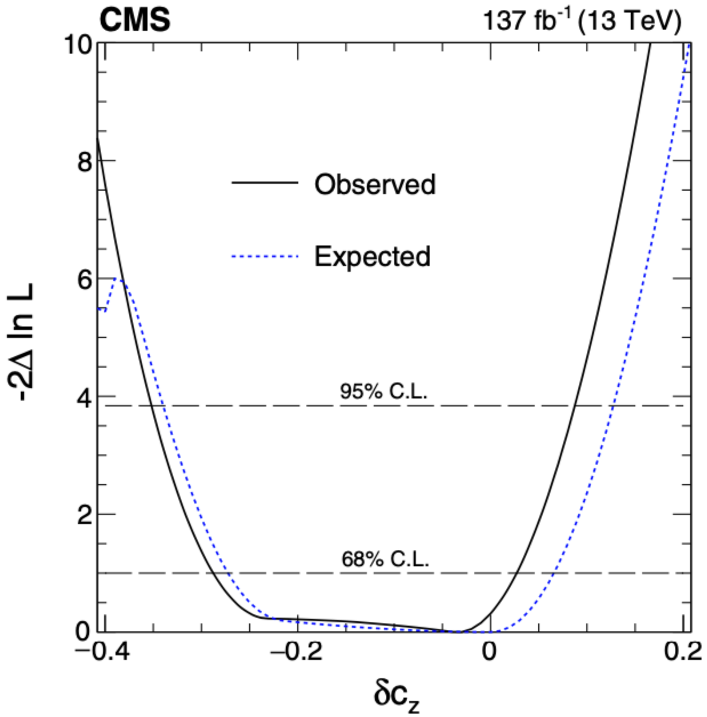
- A linear one-to-one relationship between the amplitude couplings and the EFT couplings in the Higgs basis

$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2, \qquad \delta c_z = \frac{1}{2} a_1 - 1,$$

$$\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3. \qquad c_{z\Box} = \frac{m_Z^2 s_w^2}{4\pi\alpha} \frac{\kappa_1}{(\Lambda_1)^2},$$



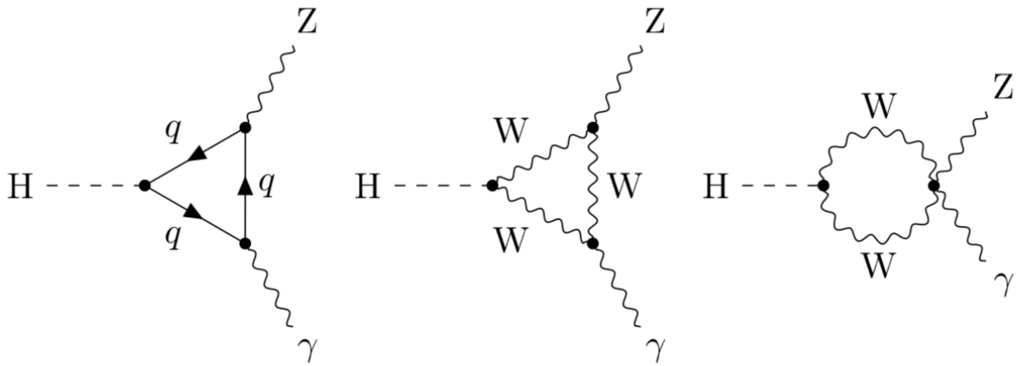




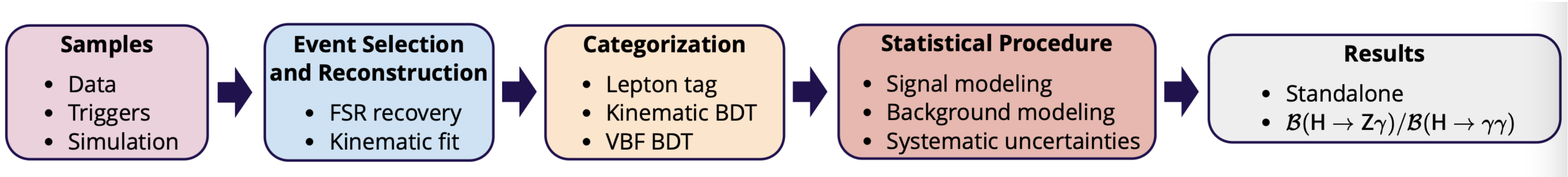
Phys. Rev. D 104 (2021) 052004

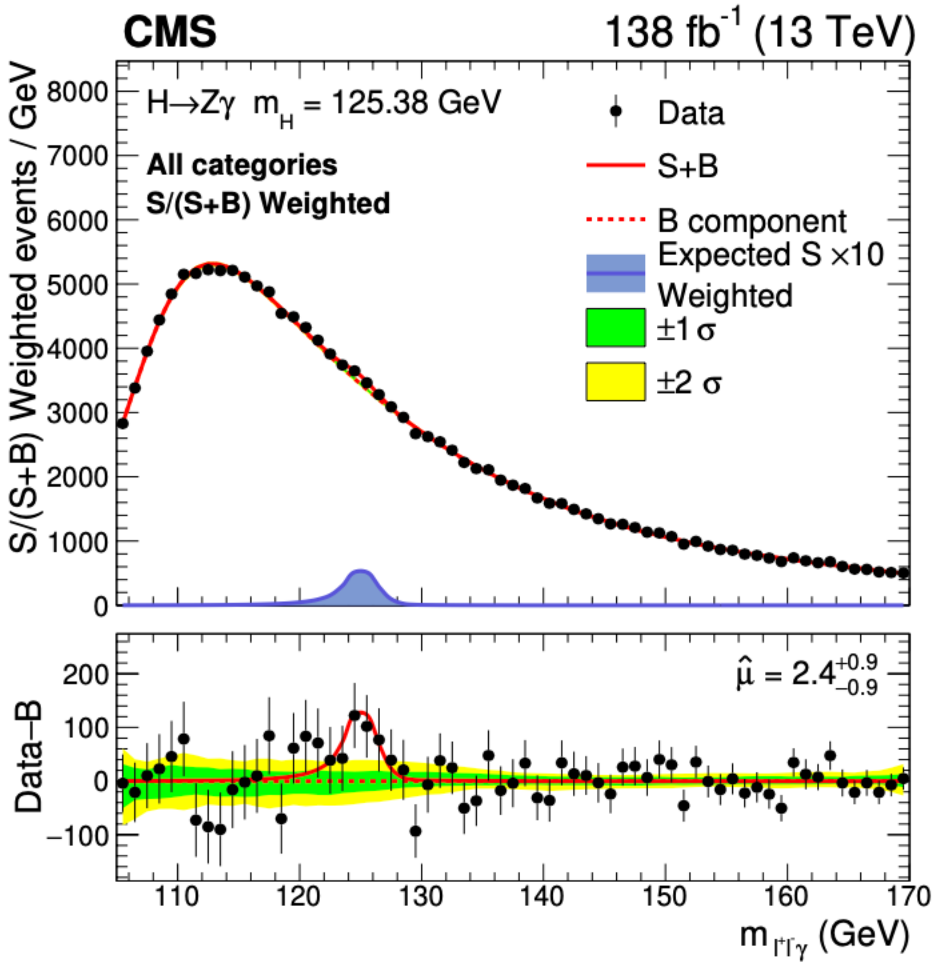
$\mathrm{H} \rightarrow Z\gamma$

- SM $\mathrm{B}(H \rightarrow Z\gamma) = (1.57 \pm 0.09)\times 10^{-3}$ ($\mathrm{m_H} = 125.38 \pm 0.14$ GeV)
- SM $\mathrm{B}(H \rightarrow Z\gamma)/B(H \rightarrow \gamma\gamma) = 0.69 \pm 0.04$
- Loop nature makes it sensitive to potential BSM physics models
    - Supersymmetry and extended Higgs sectors
    - Ratio $\mathrm{B}(H \rightarrow Z\gamma)/B(H \rightarrow \gamma\gamma)$
        - Its Shift by different amounts with impact on the ratio of O(10%)
        - $B(H \rightarrow Z\gamma)$ sensitive to a potential anomalous trilinear Higgs self-coupling



$\mathrm{H} \rightarrow Z\gamma$



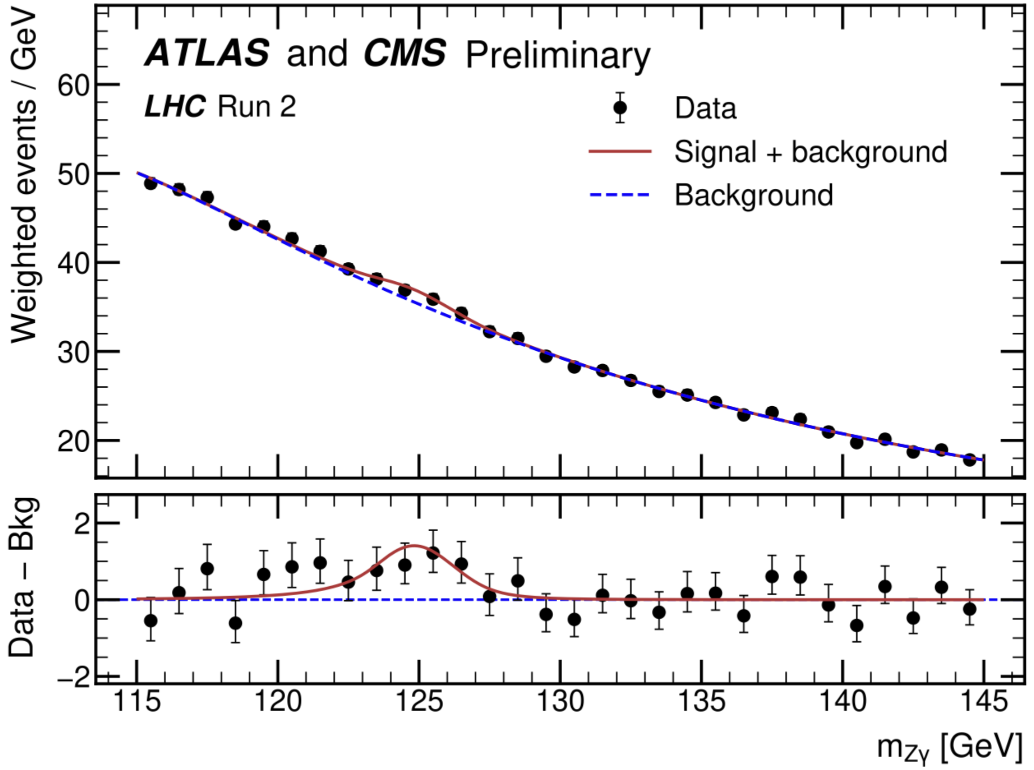


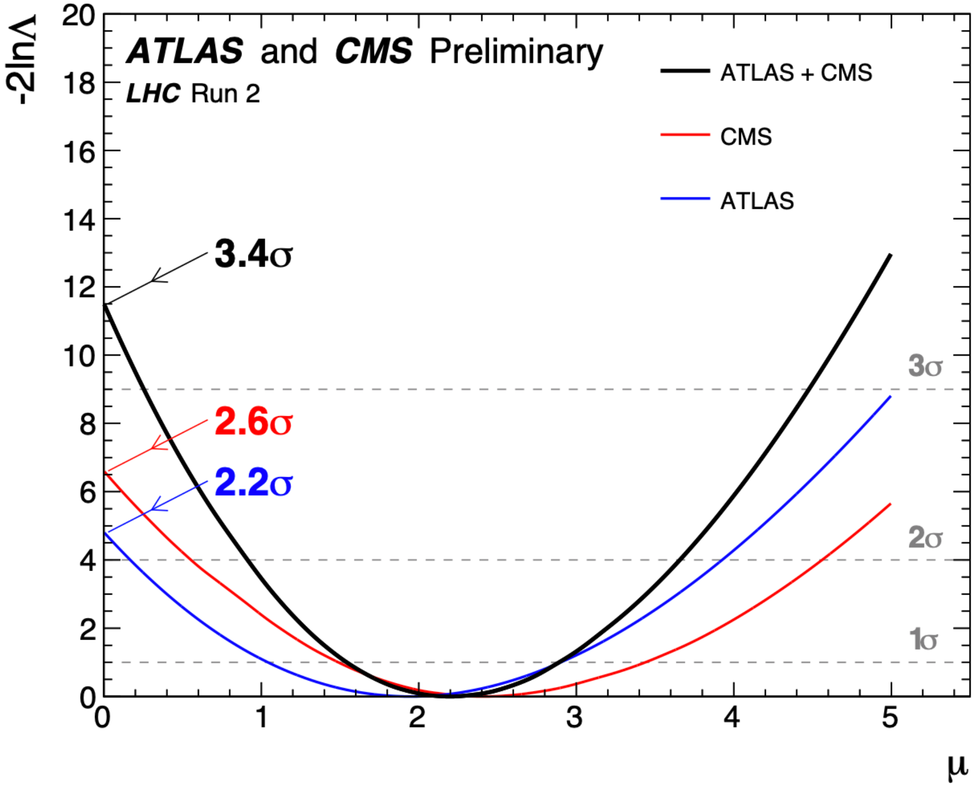
JHEP 05 (2023) 233

- Sig: $H \rightarrow Z\gamma \rightarrow l^+l^-\gamma$
- Bkg: QCD $(Z/\gamma^* + \gamma) \rightarrow l^+l^-\gamma$; $Z/\gamma^* \rightarrow l^+l^- + jets$; $\bar{t}t$; EWK $(Z/\gamma^* + \gamma) \rightarrow l^+l^-\gamma$; $H \rightarrow \mu^+\mu^-$
- Categorize events using two BDTs
  - Kinematic BDT: discriminates signal from background
  - VBF BDT: discriminates VBF signal from other signal modes and background
- Fit the $m_{l^+l^-\gamma}$ spectrum in search of a resonant peak near the Higgs boson mass
  - Model signal with a Crystal Ball function plus a Gaussian function
  - Background function choice determined by envelope method
- Local significance under background-only hypothesis: 2.7(1.2)σ observed (expected)

H → $Z\gamma$

CMS-PAS-HIG-23-002
ATLAS-CONF-2023-025





- Combination of the ATLAS and CMS with Run2 data
- **First** Evidence for the H → $Z\gamma$ decay
  - a significance of 3.4σ and the signal strength of 2.2 $\pm$ 0.7
  - Branching fraction is measured to be (3.4 $\pm$ 1.1) $\times$ 10^{-3}

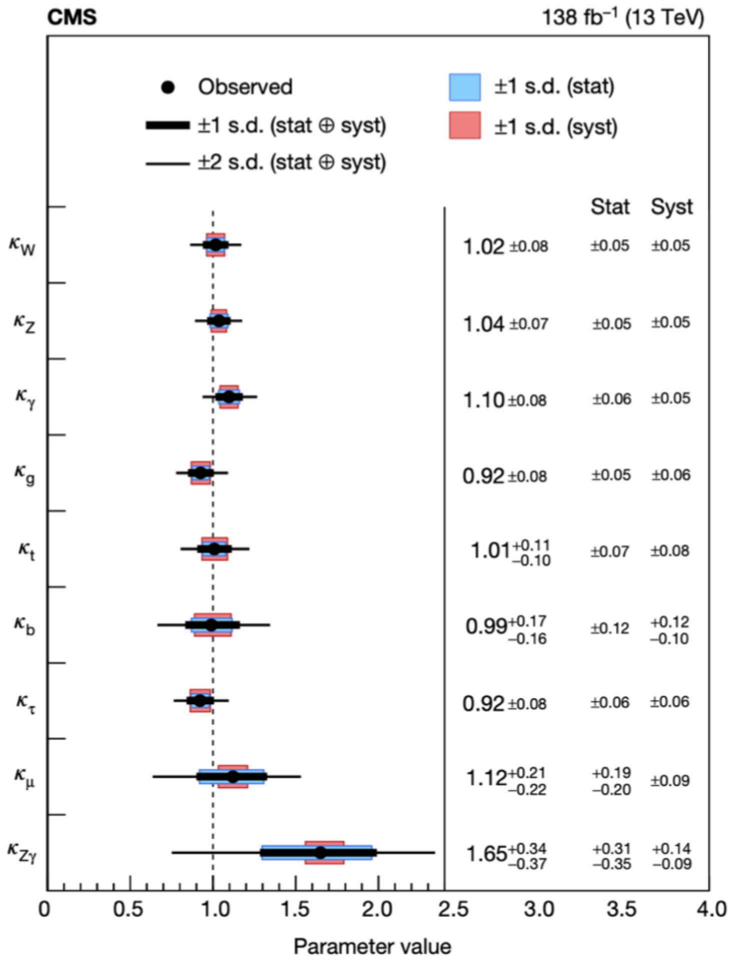
Summary

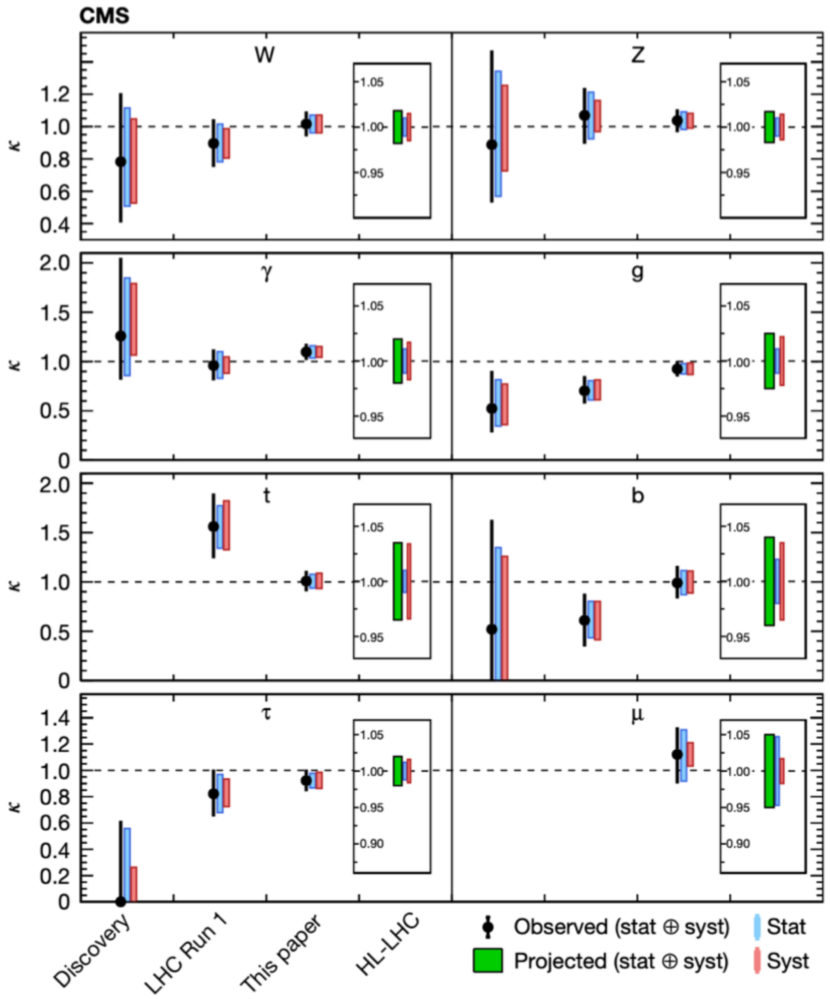
- Higgs Mass: $m_H = 125.38 \pm 0.14\ (\pm 0.11)\ GeV$
- Higgs Width: $\Gamma_H = 3.2^{+2.4}_{-1.7}\ MeV$
- First observed off-shell Higgs production at LHC with 3.6σ
- Limit on HVV anomalous couplings
- First evidence of $\mathrm{H} \rightarrow Z\gamma$ channel with 3.4σ combined with ATLAS and CMS
- All results are consistent, within their uncertainties, with the expectations for the Standard Model H boson

Thanks for your attention!

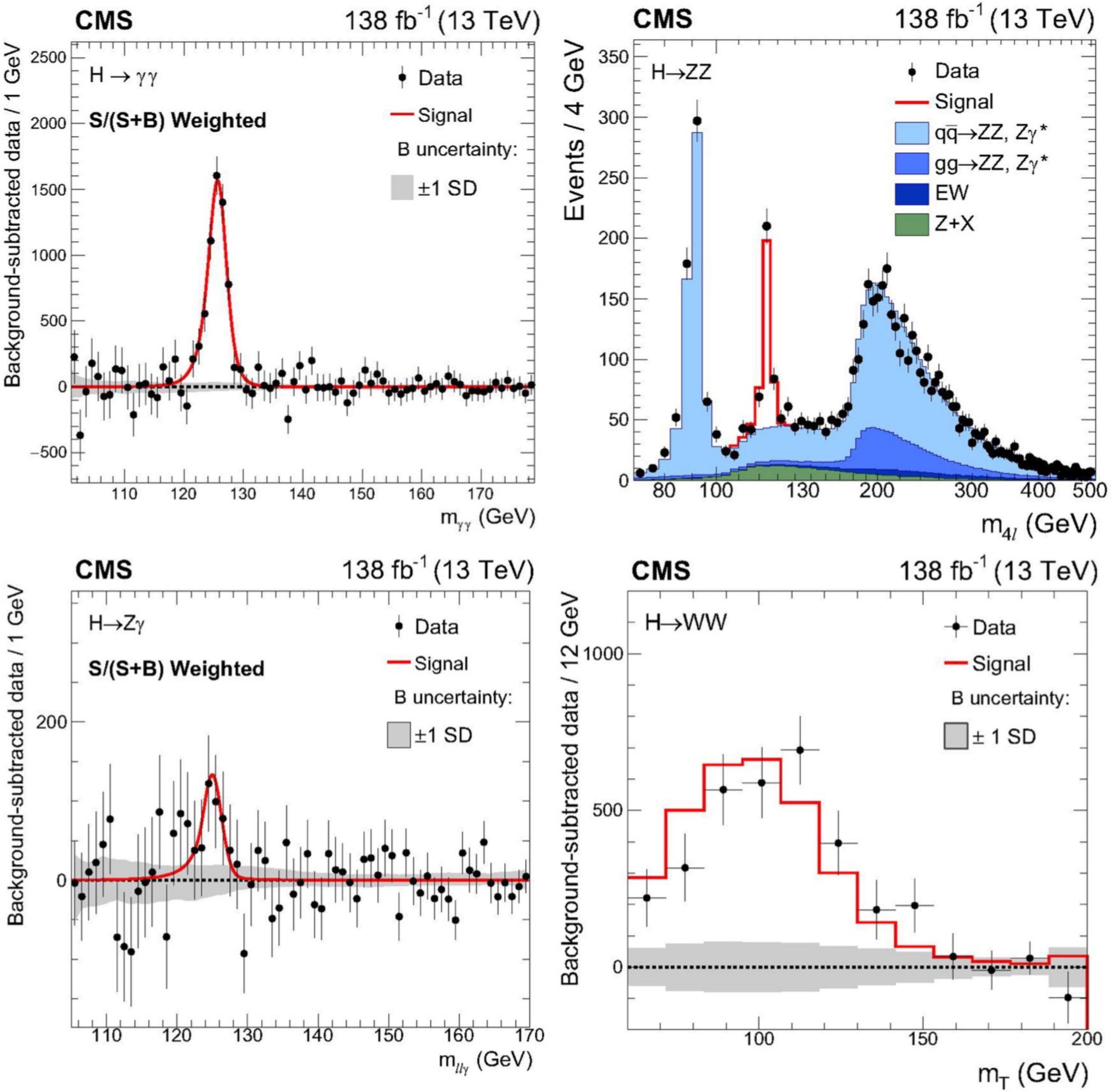
Backup

Experimental measurements





[Nature 607 (2022) 60–68]

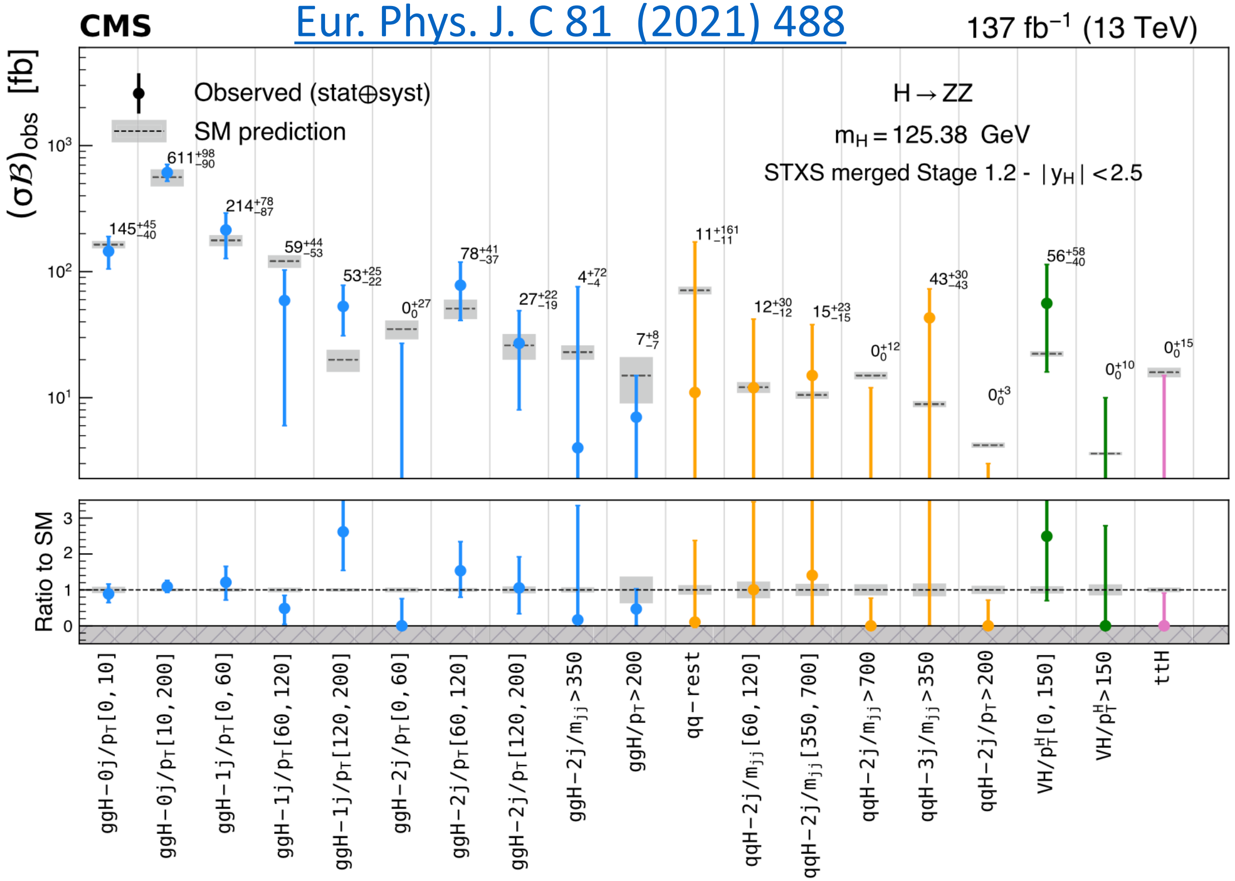


Higgs boson mass peak in diboson decay channel

[Nature 607 (2022) 60–68]

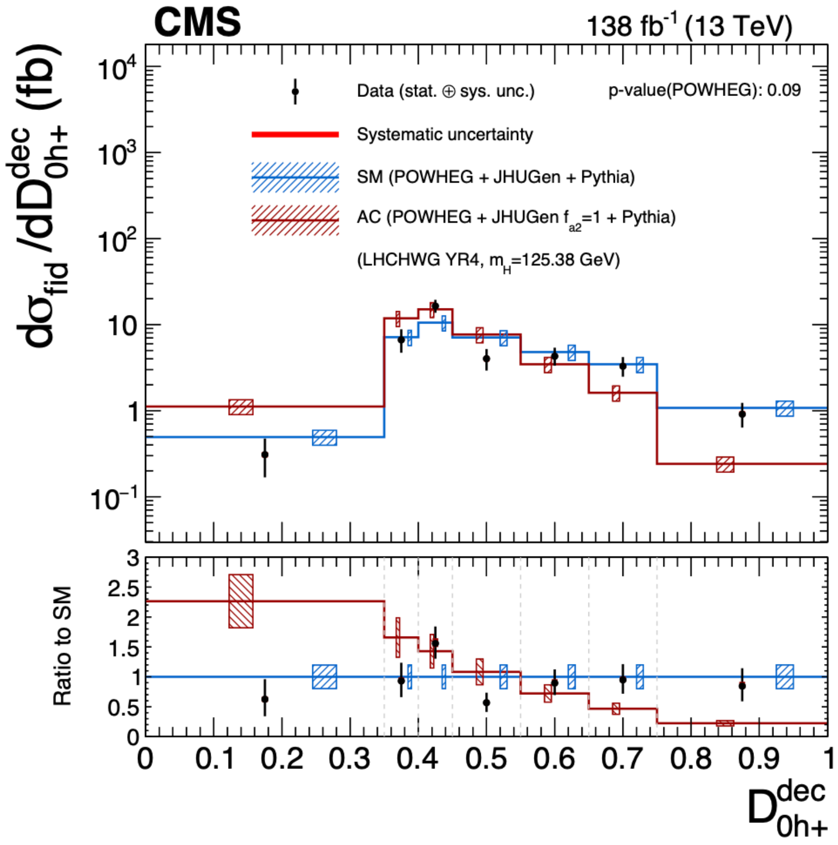
Higgs Cross Section Measurement

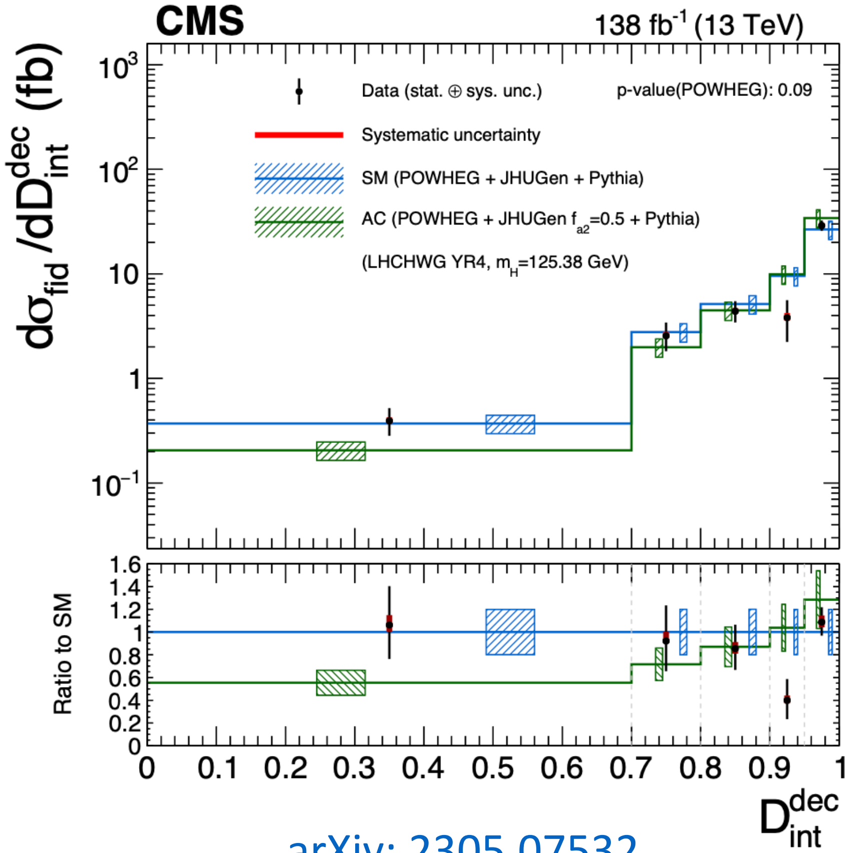
[Eur. Phys. J. C 81 (2021) 488]



- Observed cross sections in each STXS bin of Stage 1.2 framework, normalized to the SM expectation of $H \rightarrow ZZ$ channel

1D Differential Cross Section --- CP relevant

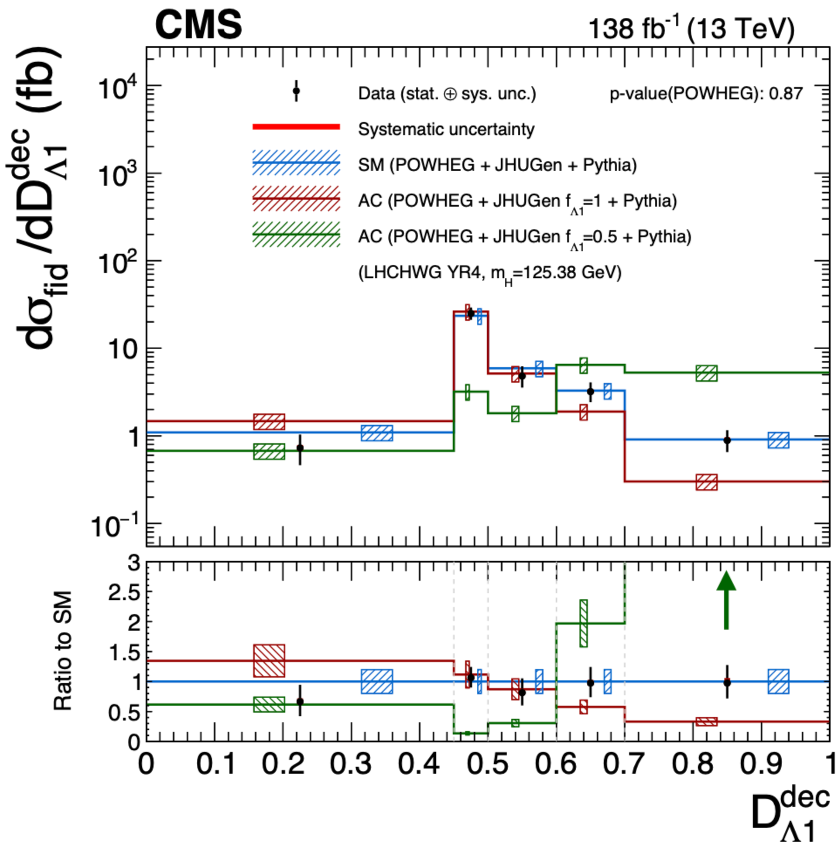


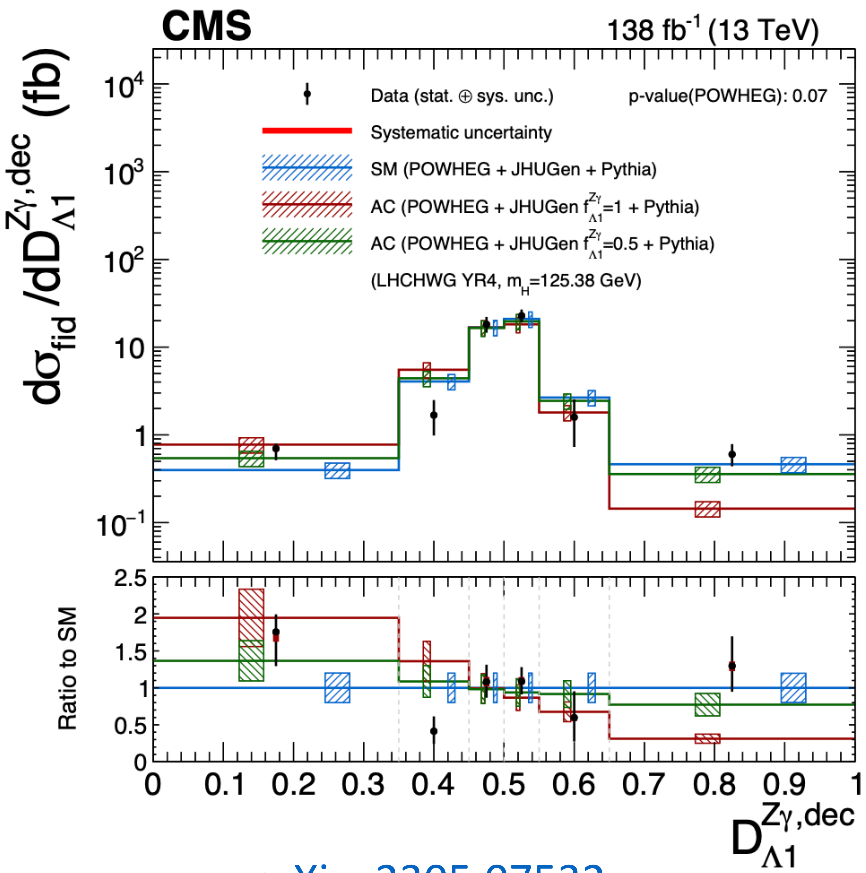


arXiv: 2305.07532
submitted to JHEP

- Differential cross sections as a function of
  - Matrix-element discriminants
    - Built based on the two hypotheses for which the discriminant is designed for
      - Standard Model prediction ggH (POWHEG) + XH
      - Anomalous Coupling prediction ggH AC samples normalized to the ggH+XH SM cross section
  - Probe **HZZ vertex** and sensitive to BSM physics

1D Differential Cross Section --- CP relevant





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Anomalous coupling in HZZ4l

$$a_1^{WW} = a_1^{ZZ} + \frac{\Delta m_W}{m_W},$$

$$a_2^{WW} = c_w^2 a_2^{ZZ} + s_w^2 a_2^{\gamma\gamma} + 2 s_w c_w a_2^{Z\gamma},$$

$$a_3^{WW} = c_w^2 a_3^{ZZ} + s_w^2 a_3^{\gamma\gamma} + 2 s_w c_w a_3^{Z\gamma},$$

$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{a_2^{\gamma\gamma} - a_2^{ZZ}}{m_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{a_2^{Z\gamma}}{m_Z^2},$$

$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{a_2^{\gamma\gamma} - a_2^{ZZ}}{m_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{a_2^{Z\gamma}}{m_Z^2},$$

Phys. Rev. D 104 (2021) 052004

- The parametrization in Eq (HVV scattering amplitude) is the most general one, and we apply $SU(2)\times U(1)$ symmetry in the relationships of anomalous couplings

Anomalous coupling in HZZ4l

- Summary of constraints on the anomalous HVV coupling parameters with the best fit values and allowed 68 and 95% CL intervals.

[Phys. Rev. D 104 (2021) 052004]

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	[−0.00007, 0.00044]	[−0.00081, 0.00081]
		95% CL	[−0.00055, 0.00168]	[−0.00412, 0.00412]
	Approach 1	best fit	−0.00805	0.00000
	float f_{a2}, $f_{\Lambda 1}$, $f_{\Lambda 1}^{Z\gamma}$	68% CL	[−0.02656, 0.00034]	[−0.00086, 0.00086]
		95% CL	[−0.07191, 0.00990]	[−0.00423, 0.00422]
	Approach 2	best fit	0.00005	0.0000
	float f_{a2}, $f_{\Lambda 1}$	68% CL	[−0.00010, 0.00061]	[−0.0012, 0.0012]
		95% CL	[−0.00072, 0.00218]	[−0.0057, 0.0057]
f_{a2}	Approach 1	best fit	0.00020	0.0000
	$f_{a3} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	[−0.00010, 0.00109]	[−0.0012, 0.0014]
		95% CL	[−0.00078, 0.00368]	[−0.0075, 0.0073]
	Approach 1	best fit	−0.24679	0.0000
	float f_{a3}, $f_{\Lambda 1}$, $f_{\Lambda 1}^{Z\gamma}$	68% CL	[−0.41087, −0.15149] ∪ [−0.00008, 0.00065]	[−0.0017, 0.0014]
		95% CL	[−0.66842, −0.08754] ∪ [−0.00091, 0.00309]	[−0.0082, 0.0073]
	Approach 2	best fit	−0.00002	0.0000
	float f_{a3}, $f_{\Lambda 1}$	68% CL	[−0.00178, 0.00103]	[−0.0060, 0.0033]
		95% CL	[−0.00694, 0.00536]	[−0.0206, 0.0131]
$f_{\Lambda 1}$	Approach 1	best fit	0.00004	0.00000
	$f_{a3} = f_{a2} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	[−0.00002, 0.00022]	[−0.00016, 0.00026]
		95% CL	[−0.00014, 0.00060]	[−0.00069, 0.00110]
	Approach 1	best fit	0.18629	0.00000
	float f_{a3}, f_{a2}, $f_{\Lambda 1}^{Z\gamma}$	68% CL	[−0.00002, 0.00019] ∪ [0.07631, 0.27515]	[−0.00017, 0.00036]
		95% CL	[−0.00523, 0.35567]	[−0.00076, 0.00134]
	Approach 2	best fit	0.00012	0.0000
	float f_{a3}, f_{a2}	68% CL	[−0.00021, 0.00141]	[−0.0013, 0.0030]
		95% CL	[−0.00184, 0.00443]	[−0.0056, 0.0102]
$f_{\Lambda 1}^{Z\gamma}$	Approach 1	best fit	−0.00001	0.0000
	$f_{a3} = f_{a2} = f_{\Lambda 1} = 0$	68% CL	[−0.00099, 0.00057]	[−0.0026, 0.0020]
		95% CL	[−0.00387, 0.00301]	[−0.0096, 0.0082]
	Approach 1	best fit	−0.02884	0.0000
	float f_{a3}, f_{a2}, $f_{\Lambda 1}$	68% CL	[−0.09000, −0.00534] ∪ [−0.00068, 0.00078]	[−0.0027, 0.0026]
		95% CL	[−0.29091, 0.03034]	[−0.0099, 0.0096]

$\mathrm{H} \to Z\gamma$ of CMS

- Observe an excess in the data near the Higgs boson mass ($m_H = 125.38\ GeV$)
  - Best fit signal strength: $\mu = 2.4 \pm 0.9$
  - Measured $\sigma(pp \to H) \times B(H \to Z\gamma) = 0.21 \pm 0.08\ pb$
    - consistent with SM prediction at 1.6σ level
  - Local significance under background-only hypothesis: 2.7(1.2)σ observed (expected)
- Used a combined fit with $H \to \gamma\gamma$ to measure $\frac{\mathrm{B}(H \to Z\gamma)}{B(H \to \gamma\gamma)} = 1.54 + 0.65$
  - Consistent with SM value (0.69 $\pm$ 0.04) at the 1.5σ level.

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Constraints on the H boson self-coupling

Probing κ_λ via single-Higgs decay

arXiv: 2305.07532
submitted to JHEP

- Differential XS measurement as a function of p_T^H ⇨ extract limits on H boson self coupling.

production — decay

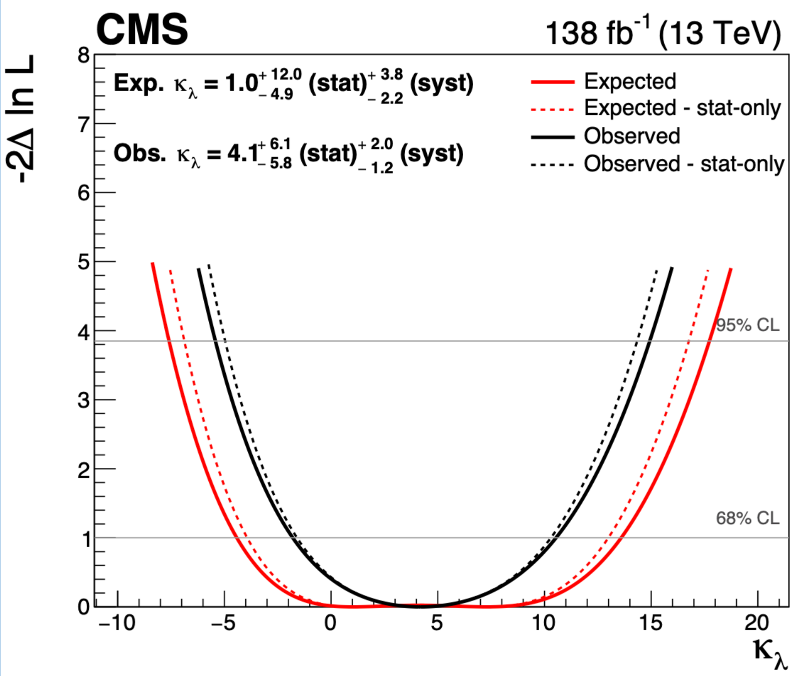
$$\mu_i^f = \mu_i \times \mu^f = \frac{\sigma^{NLO}}{\sigma_{SM}^{NLO}} \frac{BR(H\to ZZ)}{BR^{SM}(H\to ZZ)} = \frac{1+\kappa_\lambda C_{1,i}+\delta Z_H}{(1-(\kappa_\lambda^2-1)\delta Z_H)(1+C_{1,i}+\delta Z_H)} \times \left[1+\frac{(\kappa_\lambda-1)(C_1^{\Gamma ZZ}-C_1^{\Gamma tot})}{1+(\kappa_\lambda-1)C_1^{\Gamma tot}}\right]$$

- Cross sections of different production mechanisms of H boson is parameterized as a function of

$$\kappa_\lambda = \lambda_3/\lambda_3^{SM}$$

- The corresponding observed (expected) excluded κ_λ range at 95% CL

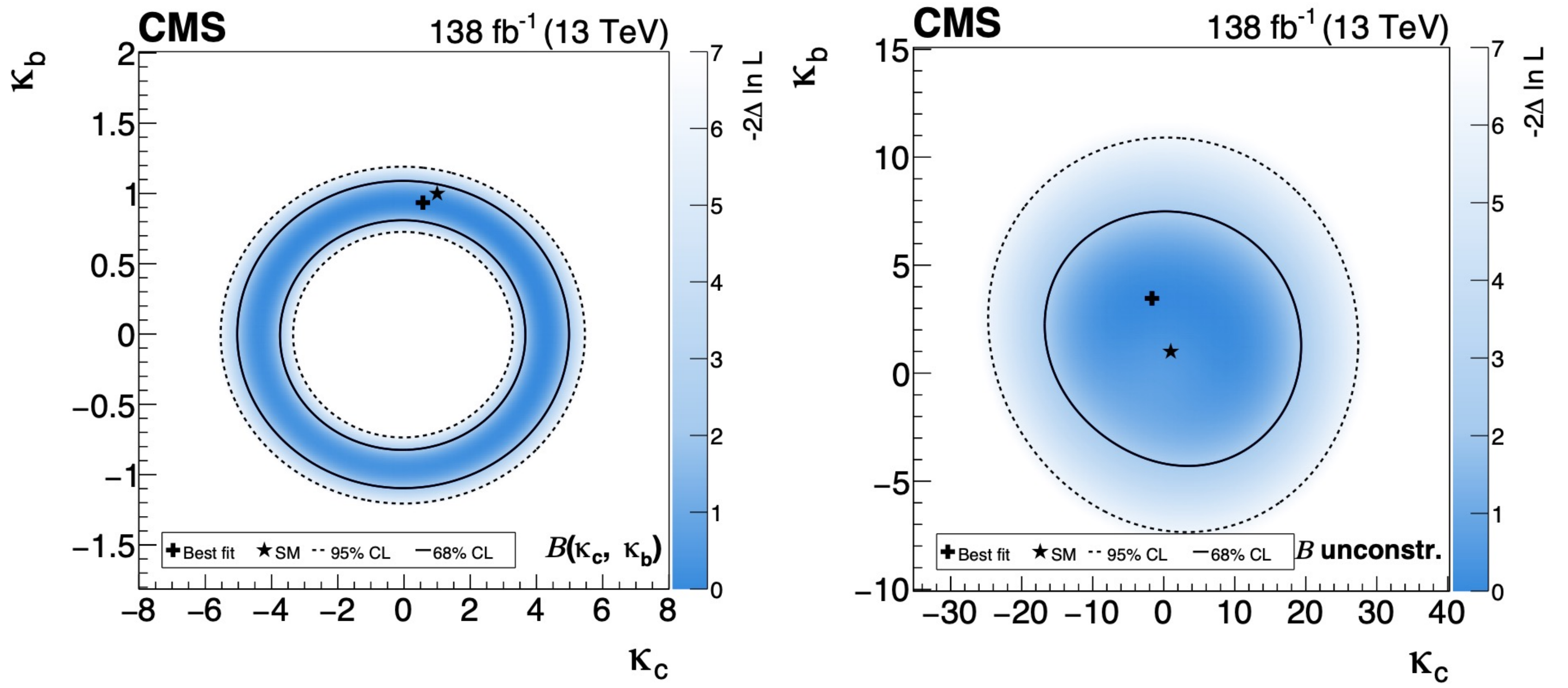
$$-5.5(-7.7) < \kappa_\lambda < 15.1(17.9)$$



Constraints on Higgs boson couplings modifier

Probing κ_b, κ_c via p_T^H differential cross section

[arXiv: 2305.07532](https://arxiv.org/abs/2305.07532)
submitted to JHEP



HIG-21-009		Full Run2 Ultra Legacy Floating κ_b κ_c Observed 95% confidence interval	Expected 95% confidence interval
Shape-Only	κ_b	[-5.6, 8.9]	[-5.5, 7.4]
	κ_c	[-20, 23]	[-19, 20]
Shape+ normalization	κ_b	[-1.1, 1.1]	[-1.3, 1.2]
	κ_c	[-5.3, 5.2]	[-5.7, 5.7]

- Simultaneous fit for coupling modifier κ_b, κ_c assuming
  - (left) coupling dependence of the branching fractions (*shape+normalization*)
  - (right)branching fractions implemented as nuisance parameters with no prior constraint (*shape-only*)
- Observed and expected 95% confidence intervals for the Yukawa coupling modifiers

Fiducial/Differential Cross Section

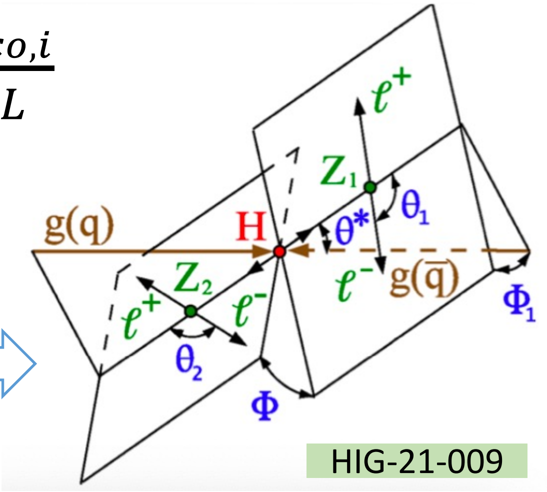
- An alternative approach to study the properties of the Higgs boson
- Cross section of bin i is defined as:

$$\sigma_i = \frac{N_{reco,i}}{C_i * A_i * L * B}$$

- **Fiducial cross section** = cross section in fiducial volume (cuts applied to generated events)

$$\sigma_{fid,i} * B = \frac{N_{reco,i}}{C_i * L}$$

- **Higgs boson kinematics**:
  - P_T^H: probes the perturbative QCD modelling of this production mechanism
  - $|\eta^H|$: sensitive to the gluon fusion production mechanism and PDFs



- **Jet activity:** N_{jets}; P_T and η of leading (sub) jet; $\mathcal{T}_B, \mathcal{T}_C$ …
  - sensitive to the theoretical modelling and relative Higgs production.
- **Spin and CP quantum numbers:** Angular observables, such as $\Phi, \Phi_1, \cos\theta_1, \cos\theta_2$, $|cos\theta^*|$:
  - sensitive to the spin and charge conjugation and parity properties of the Higgs
- **Higgs boson production mechanisms**
  - specific fiducial regions may be constructed