Evidence for off-shell Higgs boson production and the measurement of its width

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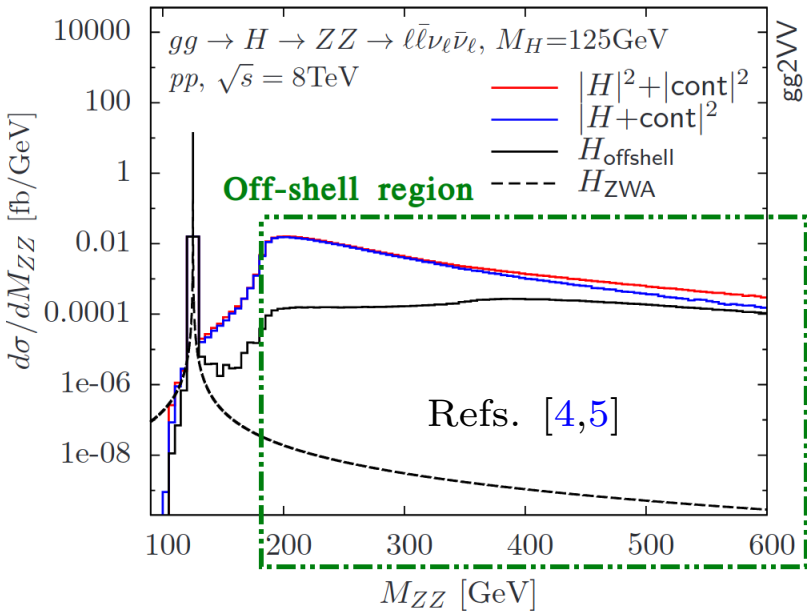
H → ZZ → $2\ell 2\nu$ analysis (HIG-21-013)

- In this analysis (Analysis PAS: HIG-21-013) we study the off-shell Higgs production in H → ZZ → $2\ell 2\nu$ signal channel (ggH and VBF) where $\ell = e, \mu$. The analysis is based on Data collected by CMS experiment during LHC run 2 (2016-2018) at $\sqrt{s} = 13$ TeV and with integrated luminosity of $\sim 138\text{fb}^{-1}$.

- Goals:
  - Measuring of signal strength parameters ($\mu^{\text{off-shell}}, \mu_{\text{F}}^{\text{off-shell}}, \mu_{\text{V}}^{\text{off-shell}}$) ⇒ off-shell $2\ell 2\nu$ results are combined with 4ℓ off-shell analysis [1]
  - Measuring Γ_{H} and constraining anomalous couplings strengths (f_{ai}) ⇒ off-shell $2\ell 2\nu$ results are combined with 4ℓ on-shell analyses [2,3].

- Signal and interfering backgrounds (MELA reweighting)
- qq → ZZ(WZ) backgrounds (simulation + 3ℓ WZ CR)
- Instrumental $p_{\text{T}}^{\text{miss}}$ from DY (data-driven + γ CR)
- Nonresonant backgrounds (data-driven + $e\mu$ CR)
- Other minor backgrounds (simulation)



*** MELA = Matrix Element Likelihood Analysis, CR = Control Region, DY = Drell-Yan ***

Likelihood scans of signal strengths and Γ_H

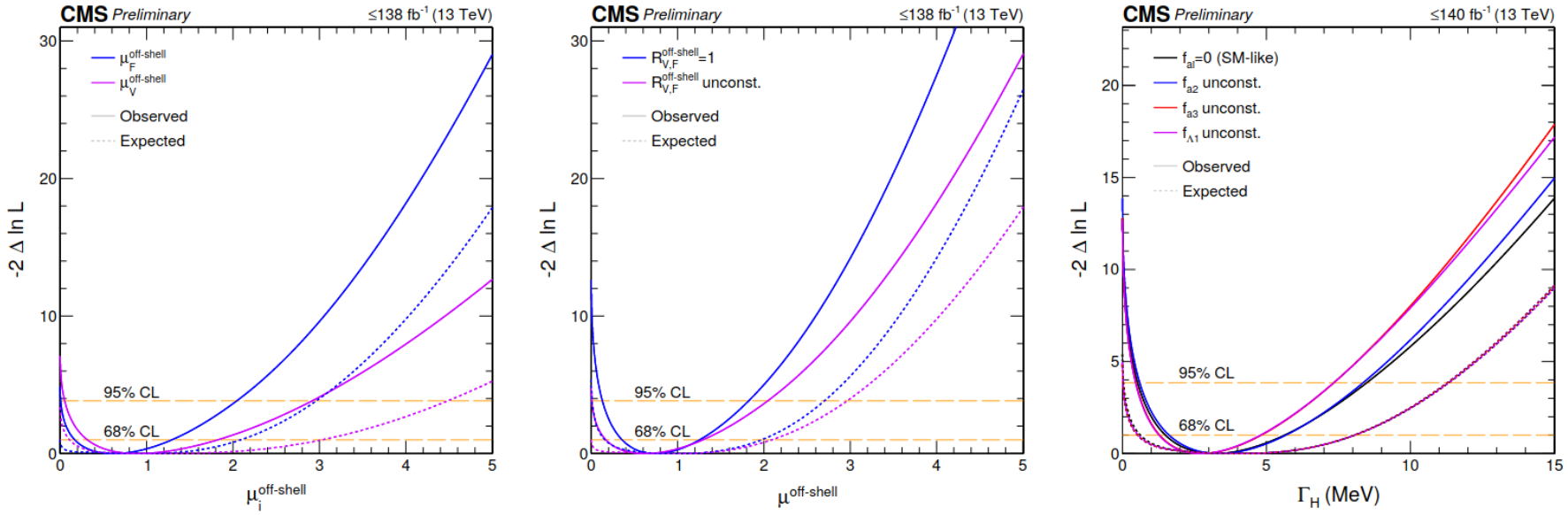


Figure 1: Observed (solid) and expected (dashed) likelihood scans for $\mu_F^{\text{off-shell}}$ or $\mu_V^{\text{off-shell}}$ (left), $\mu^{\text{off-shell}}$ (middle), and Γ_H (right). Scans for $\mu_F^{\text{off-shell}}$ (blue) and $\mu_V^{\text{off-shell}}$ (magenta) are obtained with the other parameter unconstrained. Those for $\mu^{\text{off-shell}}$ are shown with (blue) and without (magenta) the constraint $R_{V,F}^{\text{off-shell}} = 1$. Constraints on Γ_H are shown with and without anomalous HVV couplings. The horizontal lines indicate the 68% and 95% CL regions.

Summary of results

Table 1: Summary of results on the off-shell signal strength and Γ_H. Results for $\mu^{\text{off-shell}}$ are with $R_{V,F}^{\text{off-shell}}$ either unconstrained or $= 1$. Constraints on $\mu_F^{\text{off-shell}}$ and $\mu_V^{\text{off-shell}}$ are shown with the other signal strength unconstrained. Results for Γ_H (in units of MeV) are obtained with the on-shell signal strengths unconstrained. Tests with anomalous HVV couplings are distinguished by the denoted on-shell cross section fractions. The expected values (not shown) are either unity or $\Gamma_H = 4.1$ MeV. The abbreviation 'c.v.' stands for 'central value', and the abbreviation '(u)' stands for 'unconstrained'.

Param.	Cond.	Observed		Expected
		c.v.	68% | 95% CL	68% | 95% CL
$\mu_F^{\text{off.}}$	$\mu_V^{\text{off.}}$ (u)	0.62	$[0.17, 1.3] \mid [0.0060, 2.0]$	$[2 \cdot 10^{-5}, 2.1] \mid < 3.0$
$\mu_V^{\text{off.}}$	$\mu_F^{\text{off.}}$ (u)	0.90	$[0.31, 1.8] \mid [0.051, 2.9]$	$[0.11, 3.0] \mid < 4.5$
$\mu^{\text{off.}}$	$R_{V,F}^{\text{off.}} = 1$	0.74	$[0.36, 1.3] \mid [0.13, 1.8]$	$[0.16, 2.0] \mid [0.0086, 2.7]$
	$R_{V,F}^{\text{off.}}$ (u)	0.62	$[0.17, 1.3] \mid [0.0061, 2.0]$	$[4 \cdot 10^{-5}, 2.1] \mid [1 \cdot 10^{-5}, 3.0]$
Γ_H	SM-like	3.2	$[1.5, 5.6] \mid [0.53, 8.5]$	$[0.62, 8.1] \mid [0.035, 11.3]$
Γ_H	f_{a2} (u)	3.4	$[1.6, 5.7] \mid [0.60, 8.4]$	$[0.52, 8.0] \mid [0.015, 11.3]$
Γ_H	f_{a3} (u)	2.7	$[1.3, 4.8] \mid [0.47, 7.3]$	$[0.53, 8.0] \mid [0.015, 11.3]$
Γ_H	$f_{\Lambda 1}$ (u)	2.7	$[1.3, 4.8] \mid [0.46, 7.2]$	$[0.55, 8.1] \mid [0.019, 11.3]$

Results interpretations on BSM HVV couplings

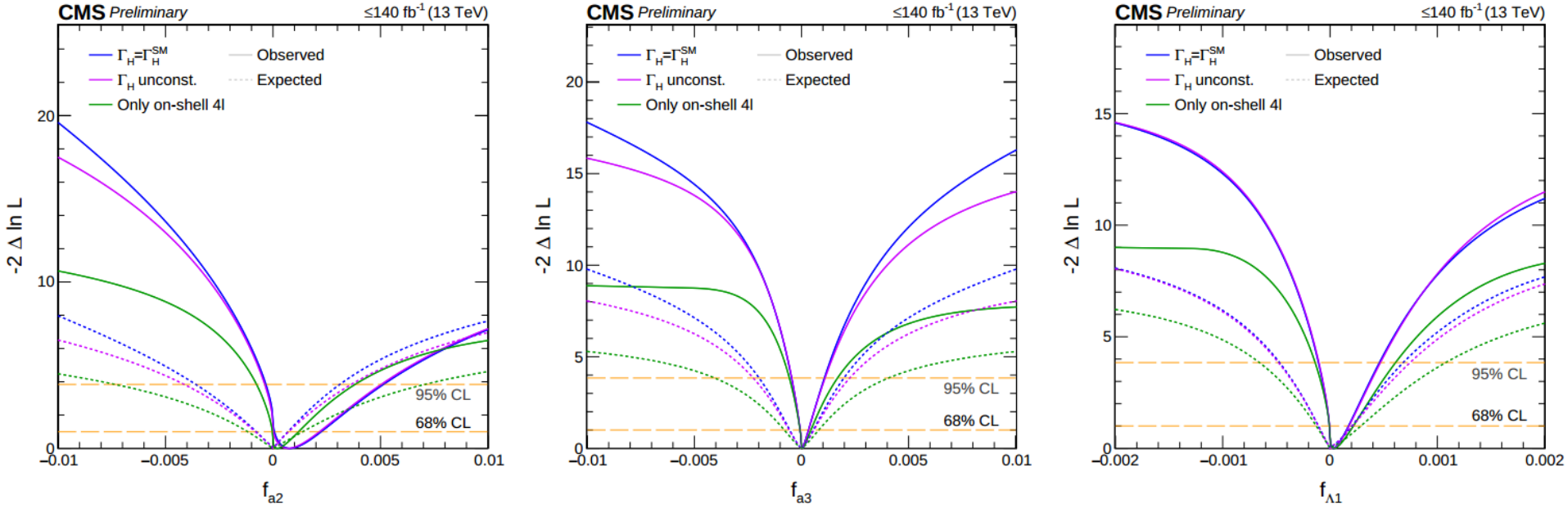


Figure 6: Shows the likelihood scans of f_{a2} (left), f_a3 (middle), and f_{Λ_1} (right) are shown with the constraint $\Gamma_{\mathrm{H}} = \Gamma_{\mathrm{H}}^{\mathrm{SM}}$ (blue), Γ_{H} unconstrained (violet), or based on on-shell 4ℓ only (green). Observed (expected) scans are shown with solid (dashed) curves. The horizontal lines indicate the 68% and 95% CL regions.

Backup

Event yields

Table 2: Comparisons between the number of observed events in the $2\ell 2\nu$ channel with expectations from the SM and no–off-shell scenarios as a function of N_j for low and high $m_{\mathrm{T}}^{\mathrm{ZZ}}$. An additional requirement of $p_{\mathrm{T}}^{\mathrm{miss}} \geq 200\,\mathrm{GeV}$ has been imposed for $N_j \geq 2$.

	$m_{\mathrm{T}}^{\mathrm{ZZ}}$	$N_j = 0$	$Nj = 1$	$N_j \geq 2$
SM	$< 450\,\mathrm{GeV}$	1118^{+45}_{-49}	660^{+31}_{-40}	92^{+7}_{-8}
No off.	$< 450\,\mathrm{GeV}$	1127^{+46}_{-49}	666^{+31}_{-40}	93^{+7}_{-8}
Data	$< 450\,\mathrm{GeV}$	989	643	95
SM	$\geq 450\,\mathrm{GeV}$	241^{+13}_{-14}	166^{+10}_{-12}	68^{+5}_{-6}
No off.	$\geq 450\,\mathrm{GeV}$	252^{+14}_{-14}	178^{+10}_{-13}	75^{+5}_{-6}
Data	$\geq 450\,\mathrm{GeV}$	217	151	66

Sensitivity of off-shell $2\ell 2\nu$ channel, CMS

Table 4: Constraints on the $\mu_F^{off-shell}$, $\mu_V^{off-shell}$, and $\mu^{off-shell}$ parameters are summarized. The constraints on $\mu^{off-shell}$ are obtained with $R_{V,F}^{off-shell}$ unconstrained or $= 1$. The measurements are presented using the $2\ell 2\nu$ analysis alone, or with the inclusion of off-shell 4ℓ events. The designation 'c.v.' stands for the central value obtained in the likelihood scan, and the expected central value is always unity, so it is not quoted explicitly.

Parameter	Condition	Observed		Expected
		c.v.	68% | 95% CL	68% | 95% CL
$\mu_F^{off-shell}$ $(2\ell 2\nu + 4\ell)$	$\mu_V^{off-shell}$ unconst.	0.62	$[0.17, 1.3] \mid [0.0060, 2.0]$	$[2 \cdot 10^{-5}, 2.1] \mid < 3.0$
$\mu_F^{off-shell}$ $(2\ell 2\nu)$	$\mu_V^{off-shell}$ unconst.	0.41	$[0.014, 1.4] \mid < 2.6$	$< 2.5 \mid < 3.7$
$\mu_V^{off-shell}$ $(2\ell 2\nu + 4\ell)$	$\mu_F^{off-shell}$ unconst.	0.90	$[0.31, 1.8] \mid [0.051, 2.9]$	$[0.11, 3.0] \mid < 4.5$
$\mu_V^{off-shell}$ $(2\ell 2\nu)$	$\mu_F^{off-shell}$ unconst.	1.1	$[0.28, 2.4] \mid [0.016, 3.8]$	$[0.07, 3.2] \mid < 4.8$
$\mu^{off-shell}$ $(2\ell 2\nu + 4\ell)$	$R_{V,F}^{off-shell} = 1$	0.74	$[0.36, 1.3] \mid [0.13, 1.8]$	$[0.16, 2.0] \mid [0.0086, 2.7]$
	$R_{V,F}^{off-shell}$ unconst.	0.62	$[0.17, 1.3] \mid [0.0061, 2.0]$	$[4 \cdot 10^{-5}, 2.1] \mid [1 \cdot 10^{-5}, 3.0]$
$\mu^{off-shell}$ $(2\ell 2\nu)$	$R_{V,F}^{off-shell} = 1$	0.74	$[0.25, 1.5] \mid [0.043, 2.3]$	$[0.11, 2.3] \mid [2 \cdot 10^{-4}, 3.2]$
	$R_{V,F}^{off-shell}$ unconst.	0.41	$[0.014, 1.4] \mid [2 \cdot 10^{-5}, 2.6]$	$[3 \cdot 10^{-5}, 2.5] \mid [6 \cdot 10^{-6}, 3.7]$

Sensitivity of off-shell 4ℓ channel, CMS

Table 10: Summary of allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) intervals for $\mu^{\text{off-shell}}$, $\mu_{\text{F}}^{\text{off-shell}}$, and $\mu_{\text{V}}^{\text{off-shell}}$ obtained from the analysis of the combination of Run 1 and Run 2 off-shell data sets.

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.78^{+0.72}_{-0.53}$ $[0.02, 2.28]$	$1.00^{+1.20}_{-0.99}$ $[0.0, 3.2]$
$\mu_{\text{F}}^{\text{off-shell}}$	$0.86^{+0.92}_{-0.68}$ $[0.0, 2.7]$	$1.0^{+1.3}_{-1.0}$ $[0.0, 3.5]$
$\mu_{\text{V}}^{\text{off-shell}}$	$0.67^{+1.26}_{-0.61}$ $[0.0, 3.6]$	$1.0^{+3.8}_{-1.0}$ $[0.0, 8.4]$

arXiv:1901.00174

ATLAS latest results

Table 2: The 95% CL upper limits on $\mu_{\text{off-shell}}$, $\Gamma_H/\Gamma_H^{\text{SM}}$ and R_{gg}. Both the observed and expected limits are given. The 1σ (2σ) uncertainties represent 68% (95%) confidence intervals for the expected limit. The upper limits are evaluated using the CL_s method, with the SM values as the alternative hypothesis for each interpretation.

		Observed	Expected		
			Median	$\pm 1\ \sigma$	$\pm 2\ \sigma$
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \to 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
$\Gamma_H/\Gamma_H^{\text{SM}}$	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]
R_{gg}	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]

arXiv:1808.01191v2

Systematic uncertainties

Most of the systematics affect both the shape and normalization

- Theoretical uncertainties:
  - Renormalization scale and Factorization scale (up to 30%)
  - $\alpha_S(m_Z)$ and PDF variations (up to 20%)
  - Simulation of the second jet in gg samples (up to 20%)
  - Scale and tune variations of PYTHIA
  - NLO EW correction ($q\bar{q} \to ZZ, WZ$)
  - Uncorrelated uncertainties on $N_j = 0$ (2.7%), $N_j = 1$ (6.0%) and $N_j \geq 2$ (7.6%) in $q\bar{q} \to ZZ, WZ$ derived from the 3ℓ CR

- Instrumental uncertainties on the simulations:
  - Luminosity (between 1.2% and 2.5%, depending on the data taking period)
  - L1 prefiring scale
  - Pile-up, JES, JER and p_T^{miss} resolution correction
  - Uncertainties in lepton, trigger, pile-up jet identification, and b-tagging efficiencies (typically 1% per lepton)

Statistical uncertainties on simulations are also taken into account.