Searches for rare Higgs boson processes with the CMS detector

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on behalf of the
CMS Collaboration

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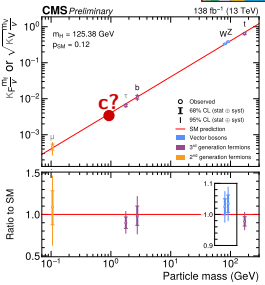
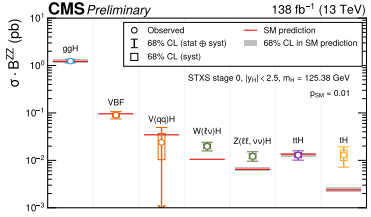
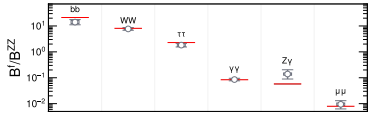
Introduction

- The increase in the integrated luminosity makes **rare Higgs boson processes** more and more accessible
- **Rare Higgs boson processes** are a test for the SM Higgs sector, e.g. light fermion Yukawa coupling:
  - the charm quark coupling $y_c = \sqrt{2}m_c/v$ is the next target (see Felix Heyen's poster)
  - even smaller are y_u, y_d, y_s, which far exceed the current LHC sensitivity
  - the Higgs trilinear coupling c_λ is on track for HL-LHC
- Deviations from SM expectations may indicate **New Physics** beyond the SM
- This talk will focus on two types of Higgs boson rare processes:





- **rare production** of a H produced via Vector Boson Scattering (VBS) [HIG-24-003] **NEW FOR EPS**

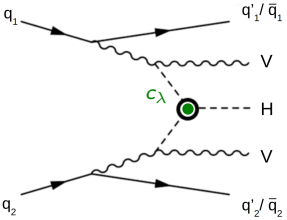


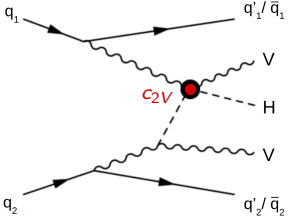
- **rare decays** of a H to a ρ, ϕ, or K^* meson and a photon [PLB862(2025)139296], and a Ψ(nS) meson and a photon [PLB865(2025)139462]
- **rare decays** of a H to Zγ [PRL132(2024)021803]
- **rare decays** of a H to $\mu\mu$ [JHEP01(2021)148]

VBS VVH production

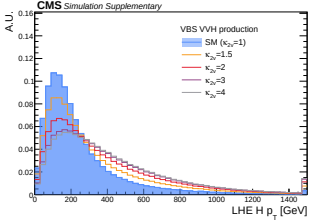
CMS-PAS-HIG-24-003 **NEW FOR EPS**

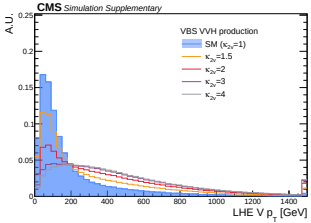
- Vector Boson Scattering with VVH production is sensitive to:
  - c_λ Higgs self-coupling, foreseen for HL-LHC
  - c_{2V} quartic gauge coupling





- Distinctive experimental signature (H + 2×(V = W,Z) + 2 VBS jets), but small cross section expected from the SM: 1.77 fb at LO
- However, deviations from the SM may result in:
  - rapid **increase in the cross section**, proportional to k_{2V}^2
  - generally **larger Lorentz boost** of the W and Z bosons
- As a result, the sensitivity to k_{2V} is competitive with double Higgs channels





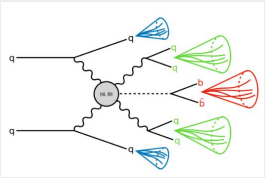
p_T spectra of the Higgs boson (top) and the vector boson (bottom) at generator level as a fuction of k_{2V}

VBS VVH production

CMS-PAS-HIG-24-003 **NEW FOR EPS**

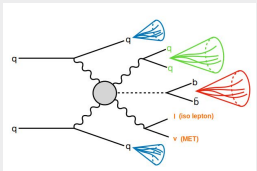
- Events divided into 5 exclusive categories, covering final states with:
  - 0 leptons (all hadronic)
    - splitting full-boosted (with AK8 jets) and partially-boosted (AK8 and AK4 jets)
  - 1 lepton (from one W)
  - 2 opposite-sign leptons (from WW or Z)
    - separating events with $m_{\ell\ell}$ close to the Z boson ($\ell\ell$ from Z) or not ($\ell\ell$ from WW)
- Higgs boson always considered in $H \to bb$ decay, reavealed by a boosted AK8 jet
- $H \to bb$ and $V \to qq$ jets identified with `ParticleNet` tagger [Phys. Rev. D 101, 056019 (2020)]
- Two VBS jets taken as the narrow jets with largest $\Delta\eta_{jj}$

all-hadronic



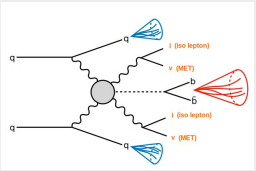
- 2 AK8 jets from V (all-hadronic)
- 1 AK8 jet from V + 2 AK4 jets (semi-boosted)

1 lepton



- 1ℓ from $W \to \ell\nu$ decay

2 leptons

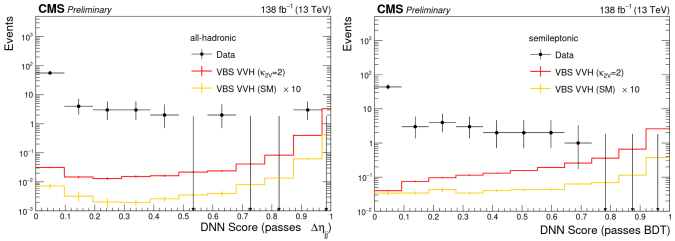


- $m_{\ell\ell}$ close to $m_Z \to \ell\ell$ from Z
- $m_{\ell\ell}$ not compatible with $m_Z \to \ell\ell$ from WW

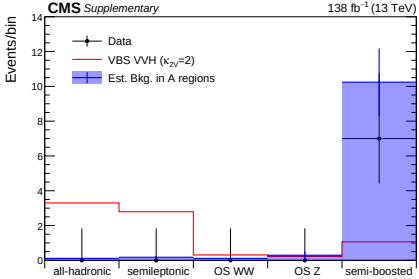
VBS VVH production

CMS-PAS-HIG-24-003 **NEW FOR EPS**

- Background estimation is fully data driven, and based on the automated ABCD method
- The two variables used to the define the A (signal) and BCD regions are:
  - a variable that is related to the VBS jet system, $|\Delta\eta_{jj}|$ or a dedicated BDT
  - a Deep NN (DNN) based on the kinematic variables of the bosons, trained to be uncorrelated from the previous variable



DNN score of the all hadronic (left) and semileptonic categories (right) that is used to determine the A region



Events in the signal region (A) of the 5 categories

- The number of events in 4 ABCD regions $\times$ 5 categories are simultaneously fitted in a combined S+B fit
- Uncertainties are derived from a "closure test" of the method on data
- **Good agreement** of the data with the estimated background

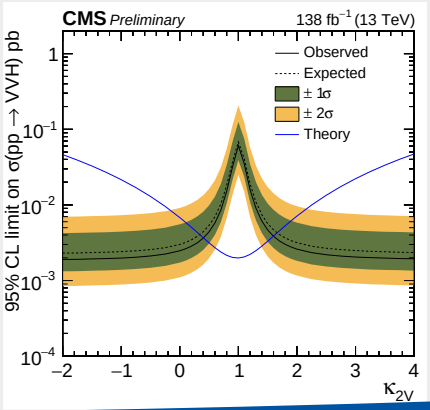
VBS VVH production

CMS-PAS-HIG-24-003 **NEW FOR EPS**

- Statistical combination with the parallel channel explored by HIG-24-001 (with two same-sign leptons)

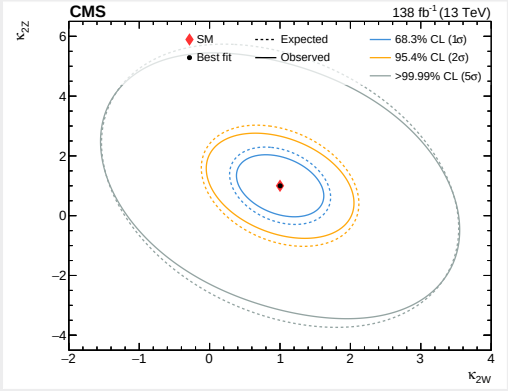
1D limit

- 1D scan assumes $k_{2V} = k_{2W} = k_{2Z}$
- Data constrains **$0.40 < k_{2V} < 1.60$**



2D limit

- k_{2W} and k_{2Z} are varied independently in a 2D scan

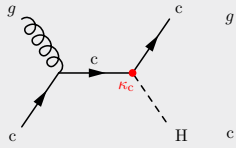


Rare Higgs production modes ($cH, \gamma H$)

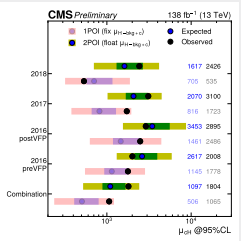
HIG-24-009, HIG-23-011

$cH, H \to WW \to e\nu\mu\nu$ [HIG-24-009]

Search for H in single charm associated production

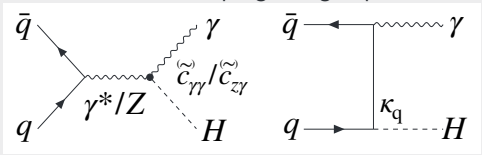


- The observed upper limit on σ/σ_{SM} is 1065 (506 expected)
- Constraint on the Yukawa coupling of the Higgs boson to the charm quark: $|k_c| < 211$ (95 expected) $\times$ SM expectation
- Check also Daina's talk this morning!



γH production [HIG-23-011]

H production in association with a γ and constraints on the Yukawa couplings of light quarks



- boosted Higgs boson (H to $b\bar{b}$ or ZZ $\to 4\ell$) recoiling against a high-energy photon
- Potentially sensitive to effective HZγ and H$\gamma\gamma$ anomalous couplings
- Constraints on k_q (assuming the other couplings are SM):

k_u	$(0.0 \pm 1.5) \cdot 10^3$
k_d	$(0.0 \pm 7.1) \cdot 10^2$
k_s	0^{+33}_{-34}

H decay to a ρ, ϕ, or K^{0*} meson $+\gamma$

Phys. Lett. B 862 (2025) 139296

$H \to (\rho, \phi, K^{0*})\gamma$

- the $\phi\gamma$ ($\rho\gamma$) involve (in some diagrams) the coupling of the H with the s (u, d) quarks, which are still unexplored
- the $K^{*0}\gamma$ diagram features a FCNC and is therefore strongly suppressed in the SM

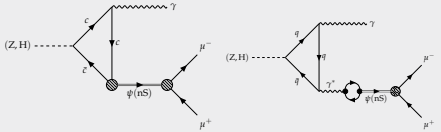
	$\mathcal{B}$
$H \to \rho^0(770)\gamma$	$(1.68 \pm 0.08) \cdot 10^{-5}$
$H \to \phi(1020)\gamma$	$(2.31 \pm 0.11) \cdot 10^{-6}$
$H \to K^{*0}(770)\gamma$	$1.19 \cdot 10^{-11}$

- Common final state constituted by a $\gamma + 2$ hadronic tracks $\to$ experimental challenge
  - $\mathcal{B}(\rho^0 \to \pi^+\pi^-) \sim 100\%$
  - $\mathcal{B}(\phi \to K^+K^-) \sim 49\%$
  - $\mathcal{B}(K^{*0} \to K^\pm\pi^\mp) \sim 100\%$

H decay to a $\Psi(nS) + \gamma$

Phys. Lett. B 865 (2025) 139462

$H \to \Psi(nS)\gamma$



- Loop of c quark in direct process $\to$ probe for $Hc\bar{c}$ coupling
- $\mathcal{B}(H \to \Psi(nS)\gamma) \sim 10^{-6}$, $\mathcal{B}(Z \to \Psi(nS)\gamma) \sim 10^{-8}$
- Final state with γ and pair of μ from meson decay ($\mathcal{B}(\Psi(1S) \to \mu\mu) \approx 6\%$): clean experimental signature
- Z decay as benchmark for $\mathcal{B}$ prediction

- Both searches maximize sensitivity to the Higgs boson production modes defining specific categories:

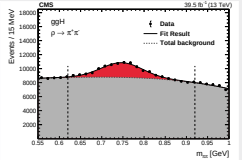
VBF: at least two additional jets with large m_{jj}
VH, ttH: at least one additional isolated lepton
ttH, bbH: at least one additional b tagged jet
ggF: all the events not passing the previous selections

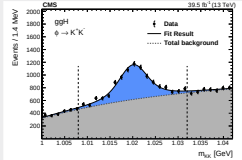
H decay to a ρ, ϕ, or K^{0*} meson $+\gamma$

Phys. Lett. B 862 (2025) 139296

$H \to (\rho, \phi, K^{0*})\gamma$

- Events collected with specifically-designed trigger algorithms:
  - one photon + a jet mimicking a two-pronged τ (2018)
  - one photon + a pair of VBF-like jets
  - one photon + one lepton, or single and double lepton
- The track pair with invariant mass closest to the meson candidate is used to define the signal region and the sidebands
- A BDT classifier, trained on the mass sidebands with event and angualr variables, is used to define two categories depending on $S/\sqrt{B}$

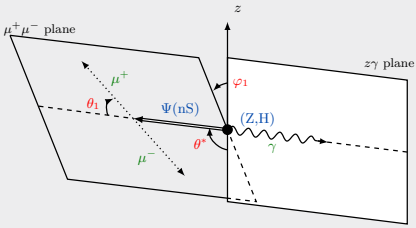




H decay to a Ψ(nS) $+\gamma$

Phys. Lett. B 865 (2025) 139462

$H \to \Psi(nS)\gamma$



- Exploit the signal spin correlations to perform an angular analysis of the events
- One production angle ($cos(\theta^*)$) and two decay angles ($cos(\theta_1), \Phi_1$) are used as basis for a MELA-like discriminator
- Define an high- and low-purity categories depending on the Likelihood discriminator score

H decay to a ρ, ϕ, or K^{0*} meson $+\gamma$

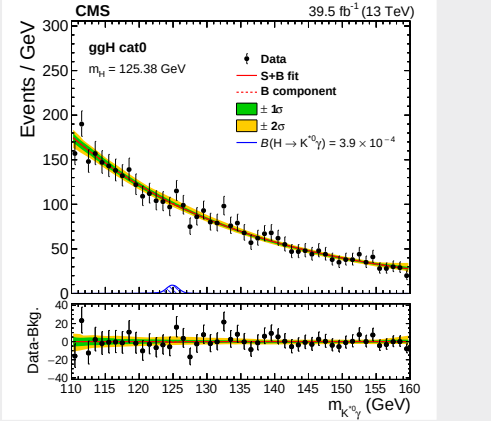
Phys. Lett. B 862 (2025) 139296

H decay to a $\Psi(nS) + \gamma$

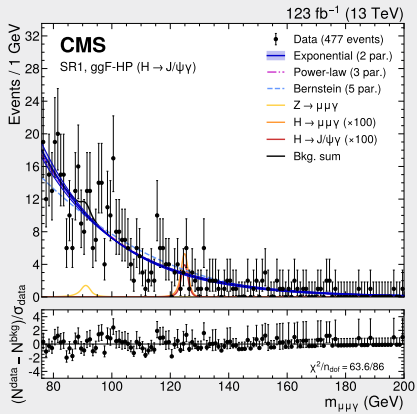
Phys. Lett. B 865 (2025) 139462

- Fit to the data with different families of parametric functions (power laws, exp., polynomials) for the bkg + peaking shape for the signal ($1 \sim 2\%$ resolution)
- Account for the assumption on the choice of the bkg. function with a penalty term in the Likelihood of the fit [Discrete Profiling method]

$H \to (\rho, \phi, K^{0*})\gamma$

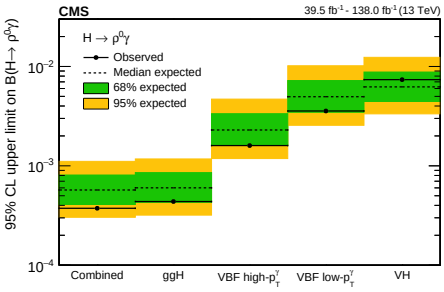


$H \to \Psi(nS)\gamma$



H decay to a ρ, ϕ, or K^{0*} meson $+\gamma$

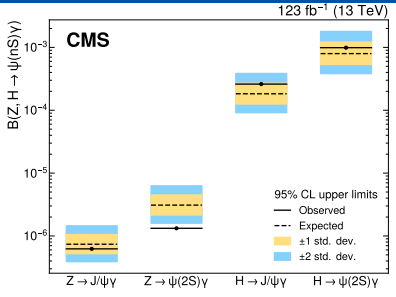
Phys. Lett. B 862 (2025) 139296



	$\mathcal{B}(\mathrm{H} \to \mathcal{M}\gamma)$		
	Expected	Observed	SM
$\mathrm{H} \to \rho^0\gamma$	$5.71^{+2.37}_{-1.63} \cdot 10^{-4}$	$3.74 \cdot 10^{-4}$	$1.68 \cdot 10^{-5}$
$\mathrm{H} \to \phi\gamma$	$2.88^{+1.33}_{-0.83} \cdot 10^{-4}$	$2.97 \cdot 10^{-4}$	$2.31 \cdot 10^{-6}$
$\mathrm{H} \to K^{*0}\gamma$	$2.10^{+0.90}_{-0.58} \cdot 10^{-4}$	$1.71 \cdot 10^{-4}$	$1.19 \cdot 10^{-11}$

H decay to a Ψ(nS) $+\gamma$

Phys. Lett. B 865 (2025) 139462



	$\mathcal{B}(\mathrm{H} \to \mathcal{M}\gamma)$		
	Expected	Observed	SM
$\mathrm{H} \to \Psi(1S)\gamma$	$1.8^{+0.9}_{-0.6} \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	$3.0 \cdot 10^{-6}$
$\mathrm{H} \to \Psi(2S)\gamma$	$8.0^{+4.2}_{-2.6} \cdot 10^{-4}$	$9.9 \cdot 10^{-4}$	$1.0 \cdot 10^{-6}$
$\mathrm{Z} \to \Psi(1S)\gamma$	$0.7^{+0.3}_{-0.2} \cdot 10^{-6}$	$0.6 \cdot 10^{-6}$	$9.0 \cdot 10^{-8}$
$\mathrm{Z} \to \Psi(2S)\gamma$	$3.1^{+1.4}_{-0.9} \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$	$4.8 \cdot 10^{-8}$

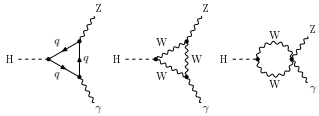
- Significant improvement in the previous searches of H decays to a ρ, ϕ, or K^{0*}
- $\mathrm{H} \to \Psi(\mathrm{nS})\gamma$ sets constraints on k_c: $-166 < k_c < +208$
- Closing to the sensitivity needed for the rare $\mathrm{Z} \to \Psi(1S)\gamma$ decay

H decay to Z + γ

PRL 132 (2024) 021803

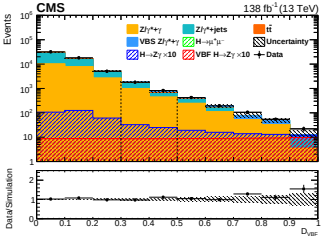
Purely loop induced process predicted by the SM:

- Final state with a photon and a pair of e or μ from Z decay
- New Physics might enter in loops
  - $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (1.57 \pm 0.09) \cdot 10^{-3}$
    - but additional factor 10 reduction accounting for $\mathcal{B}(\mathrm{Z} \to \ell\ell)$

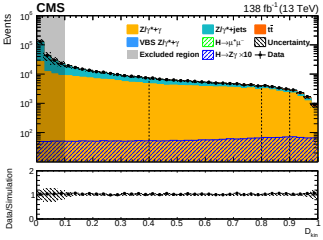


Full Run-2 analysis with 138 fb^{-1}:

- Events required to satisfy the trigger requirements for at least one of the dielectron or dimuon triggers
- Backgrounds: Drell-Yan with ISR γ or with jets
- Signal: narrow peak around the Higgs boson mass in $m_{\ell\ell\gamma}$
- 8 mutually exclusive categories according to:
  1. Presence of an additional lepton (ZH or WH Higgs boson production)
  3. Multivariate discriminant $\mathcal{D}_{\mathrm{VBF}}$ for VBF topology (2 jets)
  4. Multivariate discriminant $\mathcal{D}_{\mathrm{kin}}$ that exploits differences in the kinematic properties between signal and background for ggF (untagged) topology



(a) $\mathcal{D}_{\mathrm{VBF}}$ multivariate discriminant

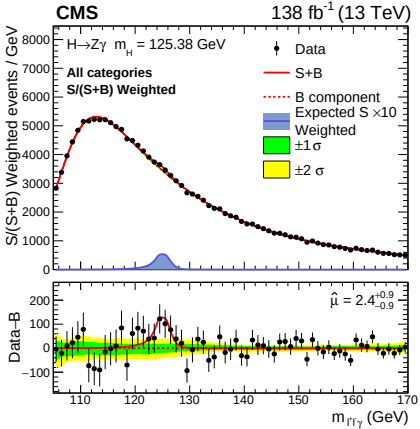


(b) $\mathcal{D}_{\mathrm{kin}}$ multivariate discriminant

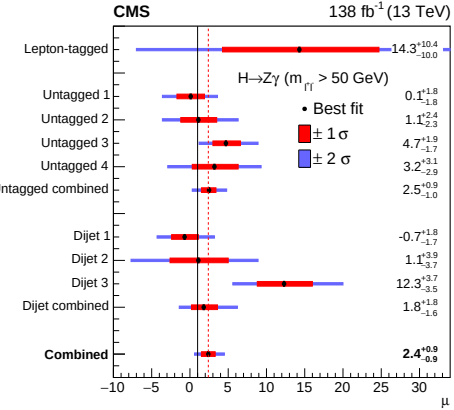
H decay to $Z + \gamma$

PRL 132 (2024) 021803

Best fit value for all categories combined: $\mu = 2.4 \pm 0.9$



Sum over all categories of the data points and signal-plus-background model after the simultaneous fit to each $m_{\ell\ell\gamma}$ distribution.

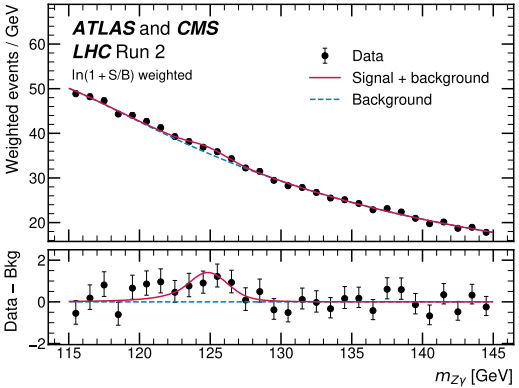


Observed signal strength μ for a SM Higgs boson with $m_{\ell\ell\gamma} = 125.38$ GeV.

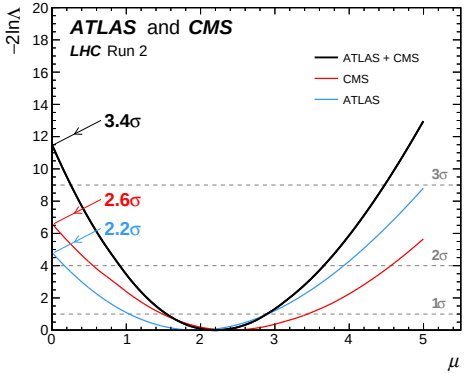
H decay to $Z + \gamma$

PRL 132 (2024) 021803

- **Combined Significance of 3.4 std dev. Combined Observed signal yield: $\mu = 2.2 \pm 0.7$**
- **Measured $\mathcal{B}(H \to Z\gamma) = (3.4 \pm 1.1) \cdot 10^{-3}$ (1.9 std dev within SM pred)**



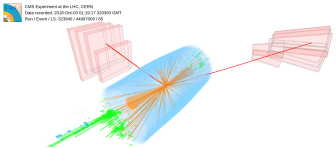
The $Z\gamma$ invariant mass distribution of events from all ATLAS and CMS analysis categories



Negative profile log-likelihood scan of the signal strength μ

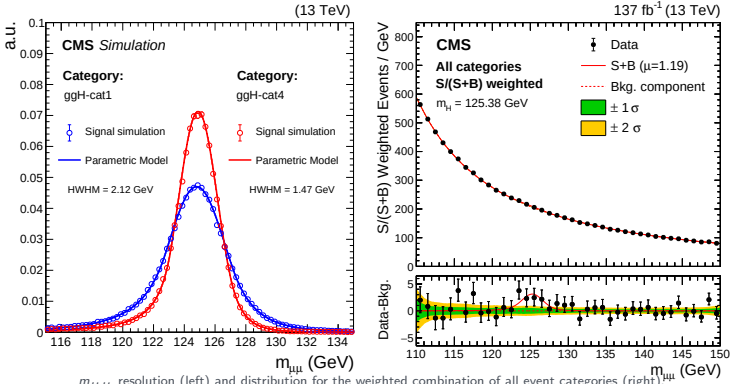
H decay to $\mu\mu$

JHEP 01 (2021) 148



$H \to \mu\mu$ decay search with 137fb^{-1}:

- **Sensitivity about Yukawa couplings between H and muons**
- $\mathcal{B}(H \to \mu\mu) = 2.18 \cdot 10^{-4}$ ($\pm 1.7\%$)
- Multiple categories targeting different Higgs production modes
- Excellent $m_{\mu\mu}$ resolution, with recovery for FSR photons



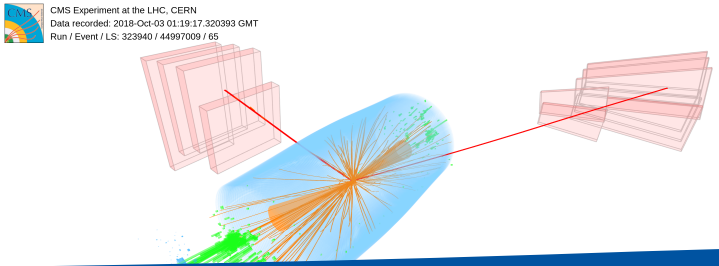
$m_{\mu\mu}$ resolution (left) and distribution for the weighted combination of all event categories (right).

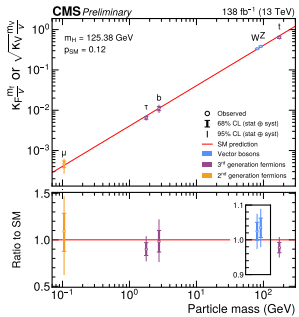
Upper limits on $\mathcal{B}$ set at 95% CL:

- Measured $\sigma/\sigma_{SM} = 1.19^{+0.44}_{-0.42}$ after combination
- Constrain on the coupling constant $0.85 < k_\mu < 1.29$
- **First evidence of decay (3.0 standard deviations)**

Concluding remarks

- With the increase in integrated luminosity, the Higgs frontier will move to rare and rarer processes
- So far, the Higgs boson still looks like the SM predicted
  - coupling to the muon is perfectly compatible with SM
  - close to measurement of the couplings to the charm quark
  - small tension in the H $\rightarrow$ Zγ channel, to be confirmed with new Run 3 data
- New Run 3 data (to date, 200fb^{-1}and counting) will shed more light on many measurements
- In rare process searches, the reach is still limited by statistics
- More data, in many cases, would also decrease systematic uncertainties (e.g. background estimation), further aiding progress
- Stay tuned for the next round of results with Run 3 data!





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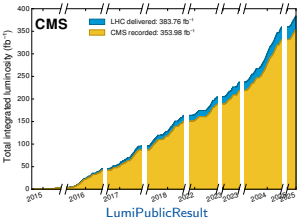

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