Rare & BSM decays of the Higgs boson at CMS

Khawla Jaffel

on behalf of the CMS Collaboration

UCLouvain, Center for Cosmology, Particle Physics and Phenomenology (BE).

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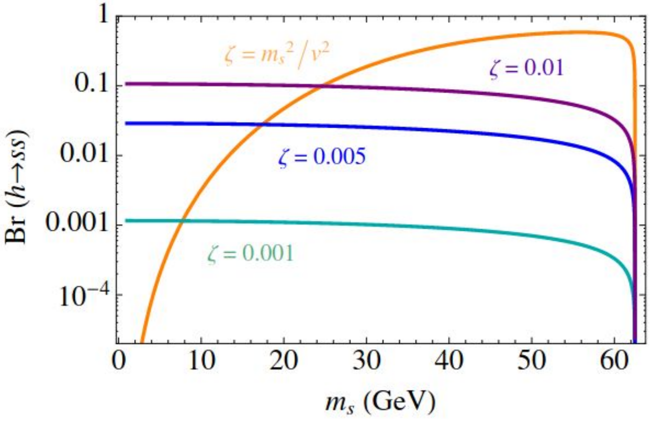
Motivation to search for rare/BSM Higgs decays:

- The SM Higgs has as an extremely narrow width, $\Gamma h \sim 4.07$ MeV, $\Gamma/M = \mathcal{O}(10{-}5)$.
  - The dominant decay, to two b- quarks, is controlled by a coupling with a size of only ~ 0.017.
  - A small coupling to another light state can easily open up additional sizable decay modes.
- The Higgs provides one of only a few "portals" that allow SM matter to interact with hidden-sector matter.
- **The famous/simple Higgs portal:**

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2 \,,$$

  - This interaction allows h → ss after electroweak symmetry breaking (EWSB), and even a coupling as small as $\zeta = 10{-}2$ yields Br(h → BSM) = 10%.
- Possible deviations in rare decay branching fractions could be compatible with existing measurements ⇒ Precision mapping of the couplings is key to understand the nature of the Higgs boson.

arXiv:1312.4992



Coverage and potential of exotic decays:

Decay mode	
$h \to 2$	$h \to$ invisible ($\not{E}_T$)
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to b\bar{b} + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to l^+ l- + \not{E}_T$
	$h \to \gamma + Z(\text{ or} Z')$
$h \to 2 \to 3 \to 4$	$\gamma + \not{E}_T$
	$b\bar{b} + \not{E}_T$
	$\tau^+\tau^- + \not{E}_T$
	$\gamma\gamma + \not{E}_T$
	$l^+l^- + \not{E}_T$ (isolated, collimated)
$h \to 2 \to (1+3)$	$l^+l^- + \not{E}_T$ (isolated)
$h \to 2 \to 4$	$(bb)\ (bb)$
	$(b\bar{b})\ (\tau^+\tau^-)$
	$(b\bar{b})\ (\mu^+\mu^-)$
	$(\tau^+\tau^-)\ (\tau^+\tau^-)$
	$(\tau^+\tau^-)\ (\mu^+\mu^-)$
	$(jj)\ (jj)$
	$(jj)\ (\gamma\gamma)$
	$(l^+l^-)\ (l^+l^-)$ ($h \to Z\ Z_D$, $h \to Z_D\ Z_D$, collimated leptons)
	$(\gamma\gamma)\ (\gamma\gamma)$
	$\gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to 2(ll) + \not{E}_T$ (isolated, collimated)
	$h \to (ll) + \not{E}_T + X$ (isolated, collimated)
$h \to 2 \to 6$	$h \to 2(ll) + \not{E}_T + X$
	$h \to 4(ll) + \not{E}_T$

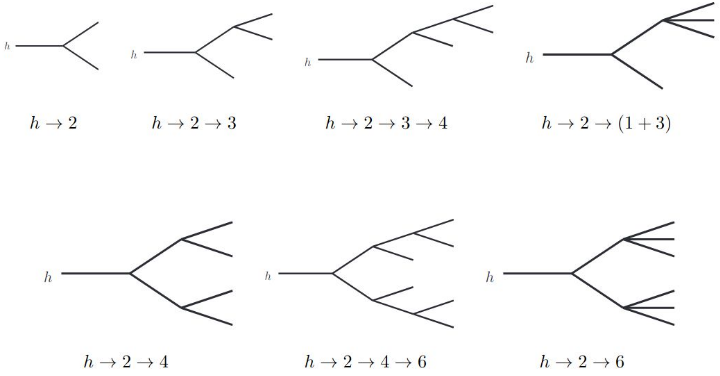
Covered in this talk

Challenging due to missing energy

Challenging due to hadronic decays

Decay topologies

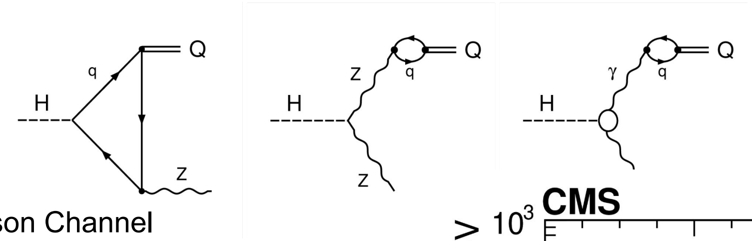
- Intermediate lines represent an *on-shell, neutral* particle, which is either a Z-boson or a BSM particle.



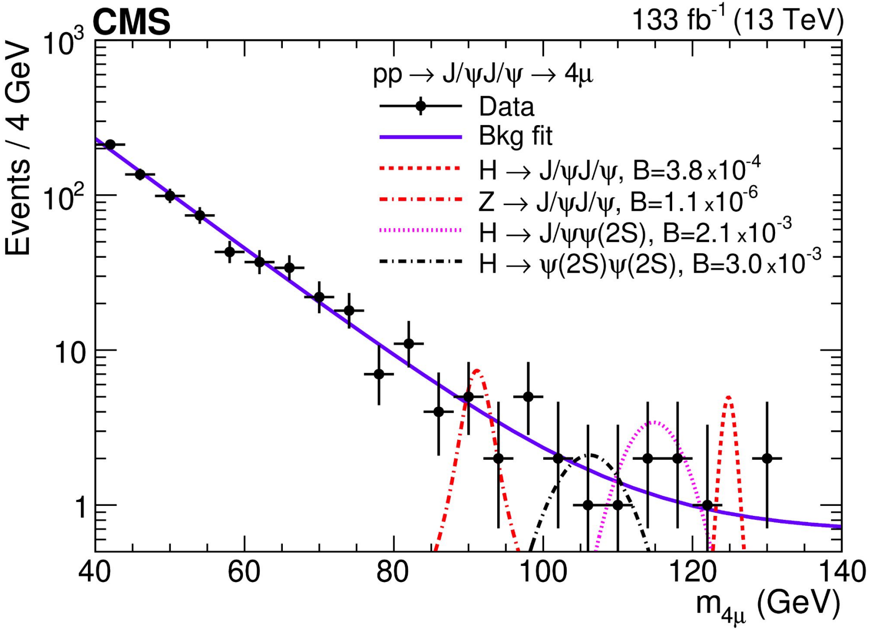
- While this is not the only possible way to make a systematic list of possible exotic decays, it has the advantage that it is well-adapted to a large number of specific models in the literature.

H → Z J/ψ, H→Z ψ(2S)

HIG-20-008
arXiv.2206.03525



- Z boson and a J/ψ meson Channel
  - H → Z J/ψ → 4μ (2μ2e)
- Quarkonium Channels
  - H(Z) →Υ(nS) Υ(mS)→ 4μ
  - H(Z) →J/ψ J/ψ → 4μ
  - H(Z) →Υ(1S) Υ(1S) → 4μ
- Feed-down Channels
  - H →Z ψ(2S) → 4μ (2μ2e)
  - H →ψ(2S) J/ψ → 4μ
  - H →ψ(2S) ψ(2S)→ 4μ



H → Z J/ψ, H→Z ψ(2S)

- Analysis is presented as a upper limit on branching fraction at 95% CL.

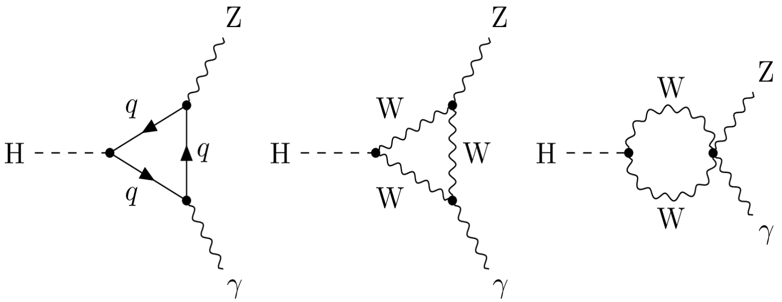
Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(H \to ZJ/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(H \to Z\psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	8.3×10^{-3}	9.4×10^{-3}
$\mathcal{B}(H \to J/\psi J/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$	4.7×10^{-4}	5.2×10^{-4}
$\mathcal{B}(H \to \psi(2S)J/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$	2.6×10^{-3}	2.9×10^{-3}
$\mathcal{B}(H \to \psi(2S)\psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$	3.6×10^{-3}	4.7×10^{-3}
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$	4.3×10^{-4}	4.6×10^{-4}
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$	2.0×10^{-3}	2.2×10^{-3}
Z boson channel				
$\mathcal{B}(Z \to J/\psi J/\psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$	14×10^{-7}	16×10^{-7}
$\mathcal{B}(Z \to \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$	4.9×10^{-7}	5.6×10^{-7}
$\mathcal{B}(Z \to \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$	2.2×10^{-6}	2.4×10^{-6}

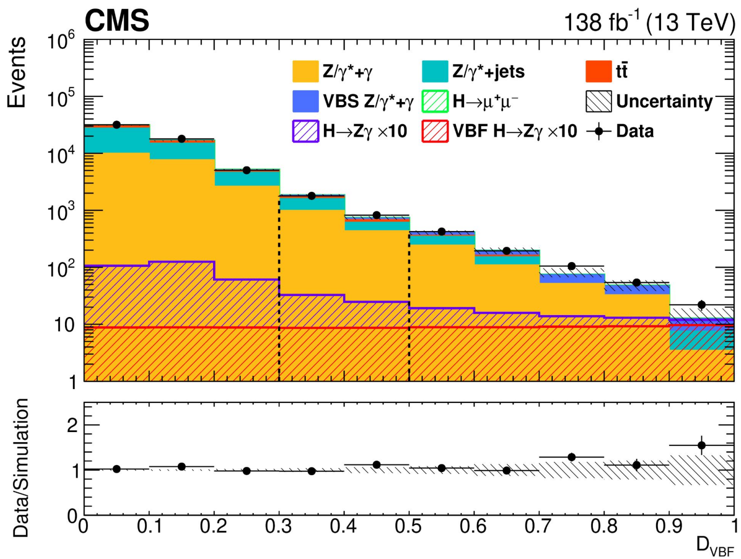
- Upper limits in H→ Z J/ψ in four-lepton final states;
  - The estimates of 95% CL upper limit in BR is about 826 x the SM, and agrees with the expected limit.
  - More than a factor of 1000 lower upper limit than published upper limit Phys. Rev. Lett. 125, 221802.
- H → QQ upper limit;
  - H→YY (unpolarized) channel is 3.2 times better than predicted by Physics Letters B 797 (2019) 134811, and agrees with the expected limits.

H → Zγ

HIG-19-014
arXiv.2204.12945

- Search for γ ℓ+ℓ− final states, with ℓ= e or μ.
  - Cleaner and more sensitive than and hadronic Z decay channels
  - Additional dijet selection to target VBF production
  - Additional lepton selection to target VH and ttH production
- Improve event reconstruction with FSR photon recovery and kinematic fit.
- Categorize events using two BDTs:
  - **Kinematic BDT:** discriminates signal from background.
  - **VBF BDT:** discriminates VBF signal from other signal modes and background
- Fit the spectrum in $m_{\ell+\ell-\gamma}$ search of a resonant peak near the Higgs boson mass.

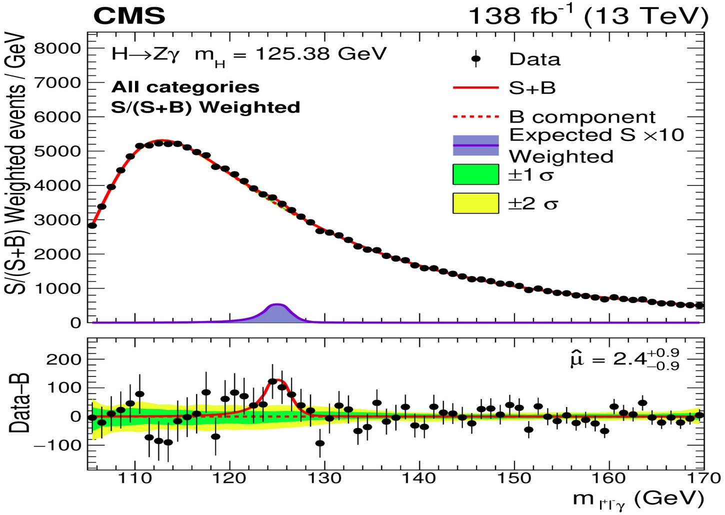


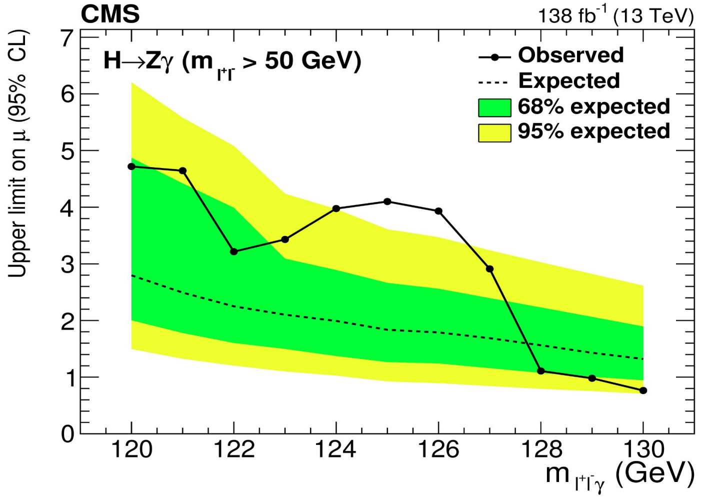


$H \rightarrow Z\gamma$

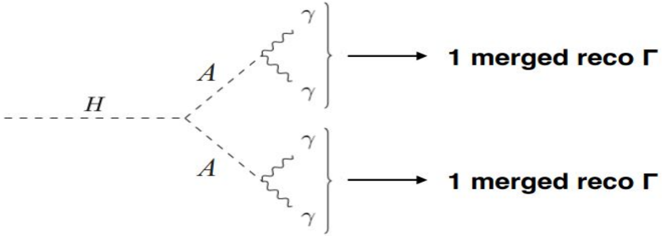
- Analysis improvements, including FSR recovery, kinematic fit, and MVA-based categorization, have significantly improved sensitivity.
- Modeling and fitting the low-mass turn-on has improved reliability of the background estimation.
- Excess **(2.7σ)** observed in data near the Higgs boson mass (125.38 GeV).

  - **Best fit signal strength: μ= 2.4 ± 0.9**
  - **The observed (expected) upper limit at 95% confidence level on *μ* is 4.1 (1.8).**



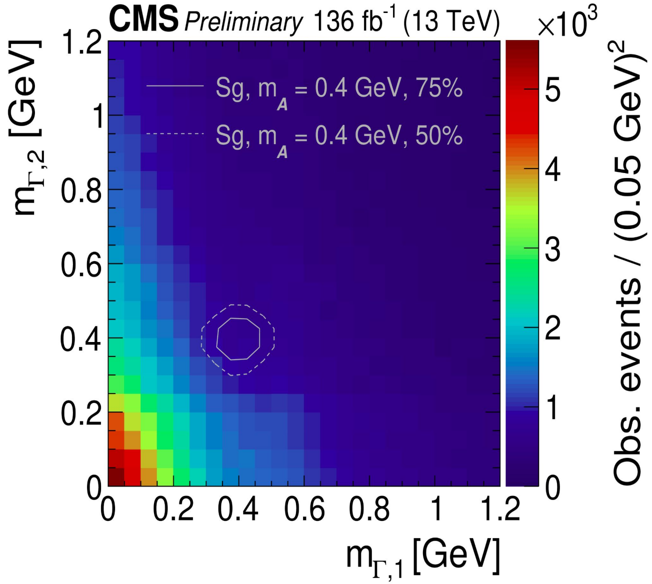


H → AA → 4γ



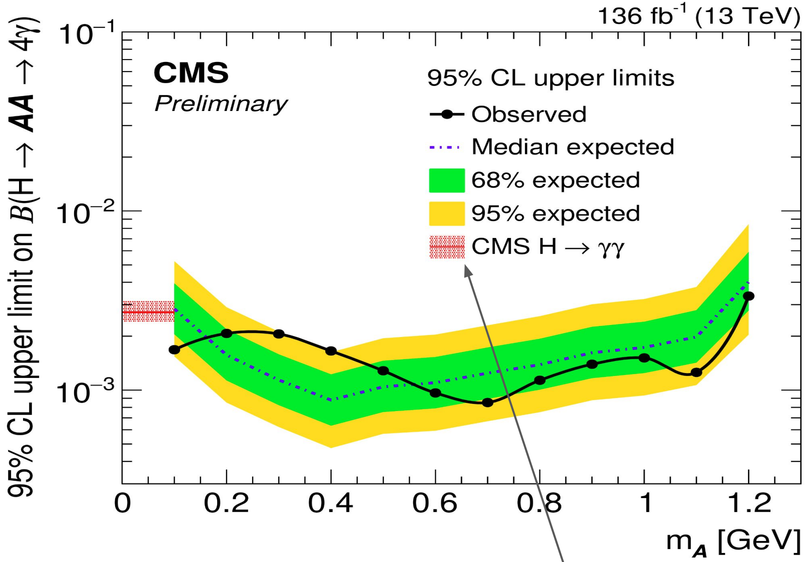
CMS PAS HIG-21-016

- **Exotic Higgs decay to light (pseudo)scalar "A" to photons:**
  - Well-motivated in BSM extensions of Higgs sector (2HDM, NMSSM, ALP)
  - Br(A→γγ) enhanced below mA < 2 x mμ
  - Smaller mA → larger Lorentz boost
- **Search is model-independent :**
  - Fully-merged (2γ) : mA = 0.1–1.2 GeV, each A→γγ leg reconstructed as 1 merged photon object "Γ"
- **Challenging mass spectrum:**
  - The analysis is made possible by a novel particle reconstruction technique that utilizes end-to-end deep learning to estimate the invariant mass of merged photon candidates, mΓ, directly from the information-rich in ECAL energy deposits.



$H \rightarrow AA \rightarrow 4\gamma$

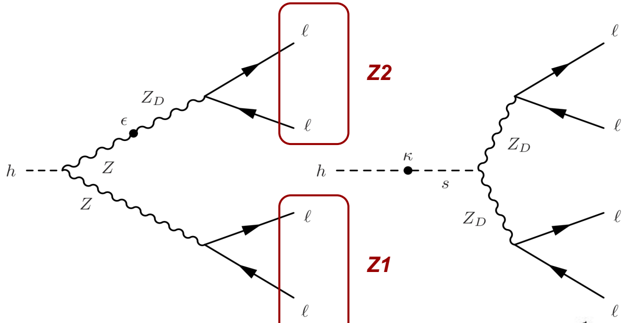
- First CMS H→AA limits below A→μμ threshold (mA < 210 MeV) assuming prompt A decays.
- The upper limits are also valid for models with dissimilar A masses, for mass differences less than the mA-SR window (0.3 GeV).
- Improves indirect constraints from Br(SM H→γγ) for mA ≲ 1.2GeV.
- LHC in unique position to probe A→γγ in ways not possible at lower energy scales, can not be achieved by other experiment for e.g. **GlueX A→γγ search** *arXiv:2109.13439*



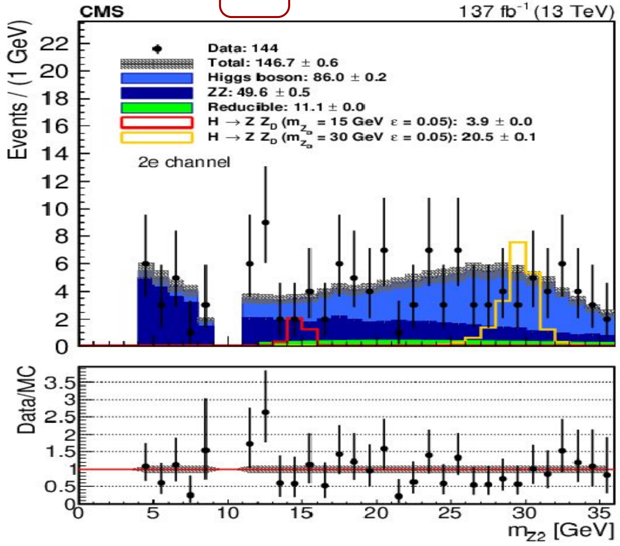
Previous CMS measurement H → γγ *arXiv.1809.10733*

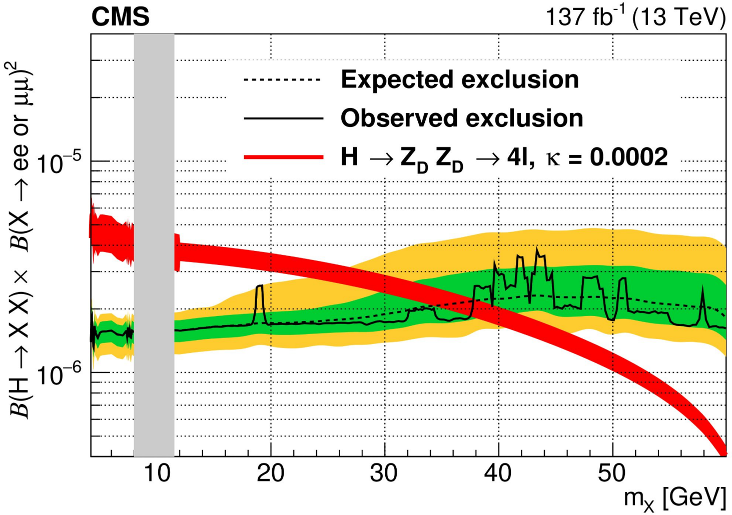
$H \to XX \to 4\ell$, $H \to ZX \to 4\ell$

CMS-HIG-19-007
arXiv:2111.01299



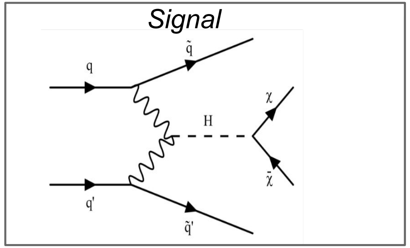
- X = a possible BSM particle.
- Signature 4ℓ = 4μ, 2e2μ, or 4e. Final states with τ leptons are neglected as their contribution to the signal region yield is below 1%.
- Results are interpreted in the context of;
  - Hidden Abelian Higgs model (HAHM)
  - Axion-like particles (ALPs)

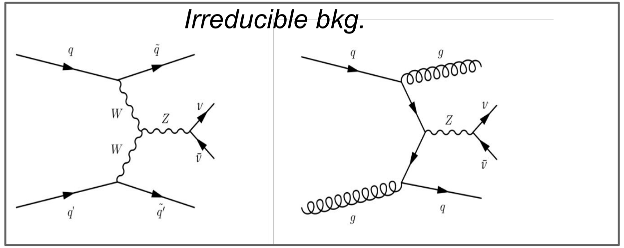




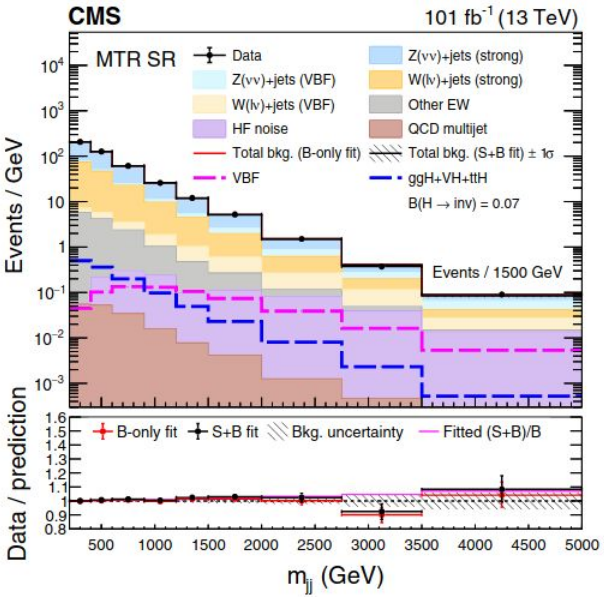
Phys. Rev. D 105 (2022), 092007

VBF(Higgs) → invisible





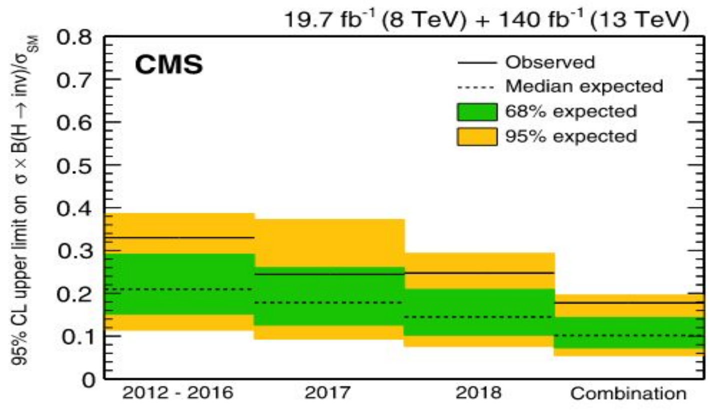
- In the SM, the branching fraction to invisible final states, B(H → inv), is only about 0.1%.
    - In Higgs-portal models, the Higgs boson acts as the mediator between SM particles and dark matter (DM) , strongly enhancing B(H → inv)
- Results are based on (2017+2018) data, further combined with previous 2016 search [arXiv.1809.05937] for a total integrated luminosity of 138 fb−1.
- The sensitivity to the VBF production mechanism is enhanced by using two strategies to construct two analysis categories based on;
    - Missing transverse momentum (MTR-SR)
    - Properties of jets (VTR-SR)
- Mjj, is used as a discriminating variable to separate the signal and the dominant backgrounds arising from vector boson (V= W± or Z) production in association with two jets (V+jets).

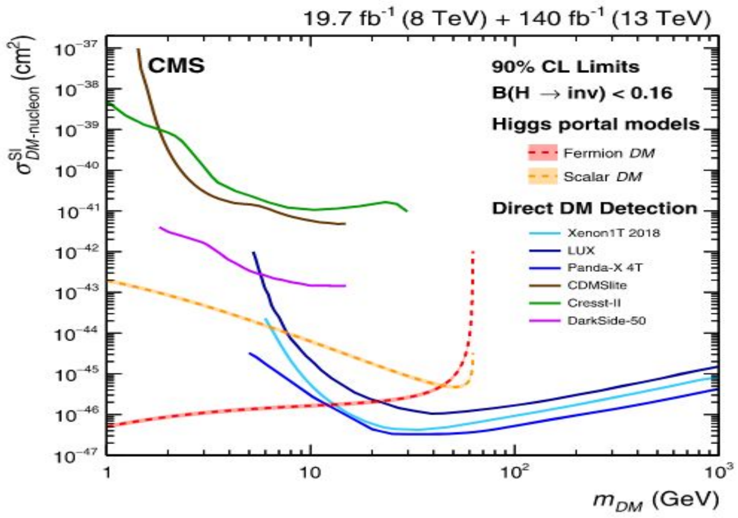


VBF(Higgs) → invisible

Run 2 combination Observed (expected) upper limit
B(H → inv) < 0.17 (0.11) at 95% CL

- The addition of the γ+jets CR (VTR category) improves the expected limits by about 11% (8%) compared to 2016-like analysis, full run 2 overall improvements of 17%.
- 90% CL upper limits on the spin-independent DM-nucleon scattering cross section in Higgs-portal models, assuming a scalar or fermion DM candidate.
    - Limits are compared to results from other experiments .eg. Xenon1T, Cresst-II , CDMSlite , LUX, Panda-X II and DarkSide-50 experiments.
    - CMS results complement the direct-detection experiments in the range mDM smaller than 12 (6) GeV, assuming a fermion (scalar) DM candidate.

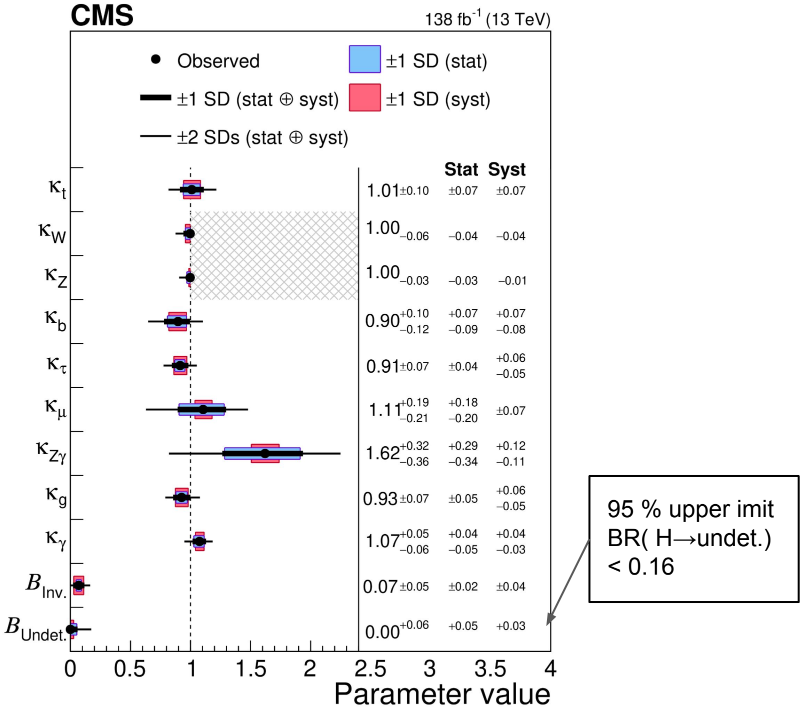




Conclusions:

- Non-standard Higgs decays have always been a well-motivated possibility as evidenced for BSM physics by an extensive experimental searches and growing literature.
- Analyses push boundaries by novel strategies and techniques in the hope to find our window into BSM physics.
- The search for non-standard Higgs decays should form an important component of the experimental program of the LHC and future colliders.
- Branching fractions of O(10%) into exotic decay modes are not only still allowed by existing data but will remain reasonable targets for the duration of the physics program of the LHC.

arXiv.2207.00043

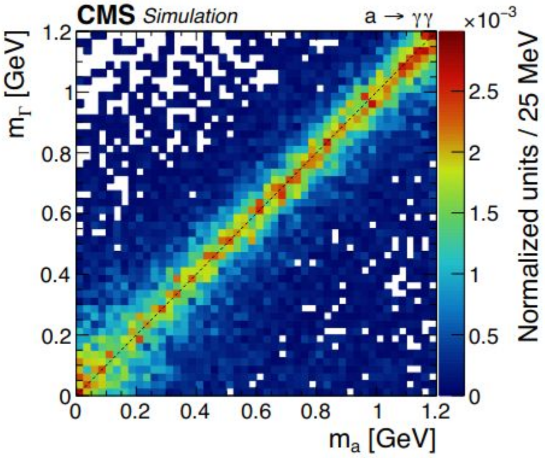


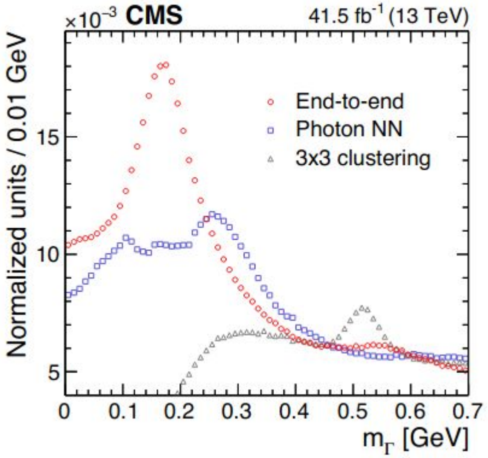
Thanks for listening!

Backup

H → AA → 4γ

- **End-to-End Mass Regression in Particle Decays to Extremely Merged Photons :** train convolutional neural network to estimate parent A mass of merged photons using ECAL detector deposits able to reconstruct Lorentz boosts = 60–600 for 0 < mΓ <1.2 GeV (more details in [EGM-20-001](EGM-20-001)).
  - General technique for regressing near a boundary
  - Left: predicted mΓ vs generated mA
  - Right: data validation using π0→γγ decays contained in hadronic jets





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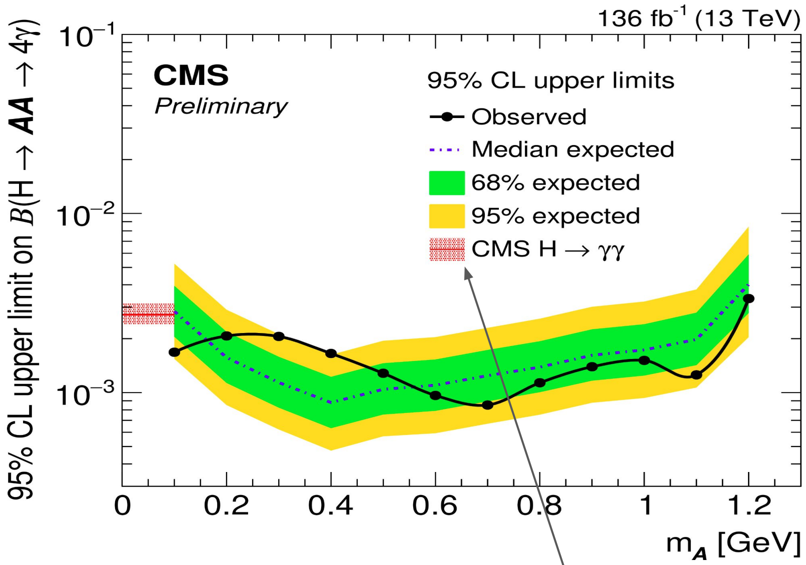
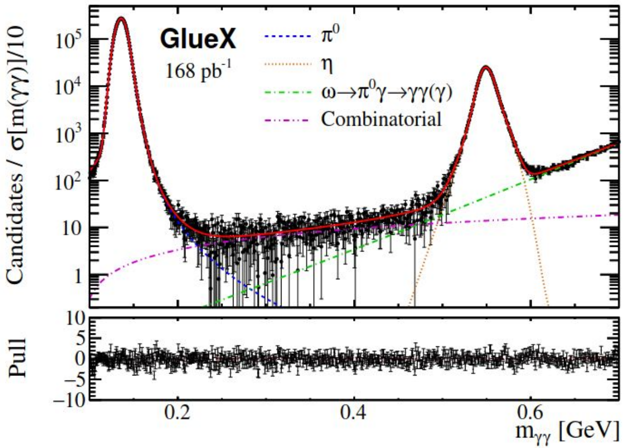
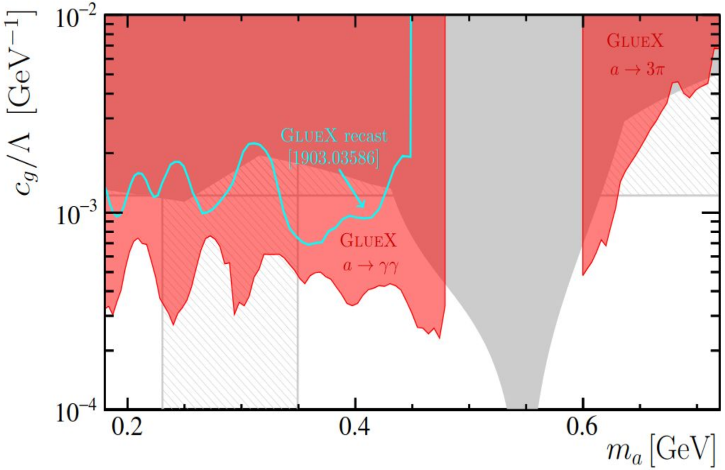


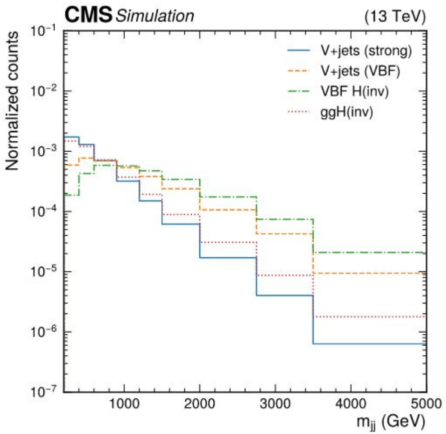
Previous CMS measurement H → γγ arXiv.1809.10733



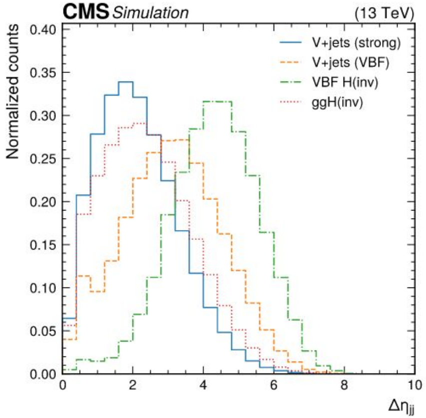


VBF(Higgs) → invisible

- The shape of the Mjj distribution is used to disentangle dijets produced in VBF production from other SM processes.
  - The strong production of the V+jets processes together with the ggH signal dominate at low Mjj,
  - VBF produced V+jets processes populate the high Mjj tail, together with the VBFH signal.



Observable	MTR	VTR
Choice of pair	leading-p_T	leading-M_{jj}
Leading (subleading) jet	$p_T > 80\,(40)$ GeV, $\lvert\eta\rvert < 4.7$	$p_T > 140\,(70)$ GeV, $\lvert\eta\rvert < 4.7$
p_T^{miss}	> 250 GeV	$160 < p_T^{miss} \leq 250$
$\min\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet})$	> 0.5 rad	> 1.8 rad
$\lvert\Delta\phi_{jj}\rvert$	< 1.5 rad	< 1.8 rad
M_{jj}	> 200 GeV	> 900 GeV
$\lvert p_T^{miss} - \text{calo}p_T^{miss}\rvert / p_T^{miss}$	< 0.5	
Leading/subleading jets $\lvert\eta\rvert < 2.5$	NHEF < 0.8, CHEF > 0.1	
HF-noise jet candidates	0 (see Table **??**)	
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 20$ GeV, $\lvert\eta\rvert < 2.3$	
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, DeepCSV Medium	
$\eta_{j1} \times \eta_{j2}$	< 0	
$\lvert\Delta\eta_{jj}\rvert$	> 1	
Muons (electrons)	$N_{\mu,e} = 0$ with $p_T > 10$ GeV, $\lvert\eta\rvert < 2.4\,(2.5)$	
Photons	$N_{\gamma} = 0$ with $p_T > 15$ GeV, $\lvert\eta\rvert < 2.5$	

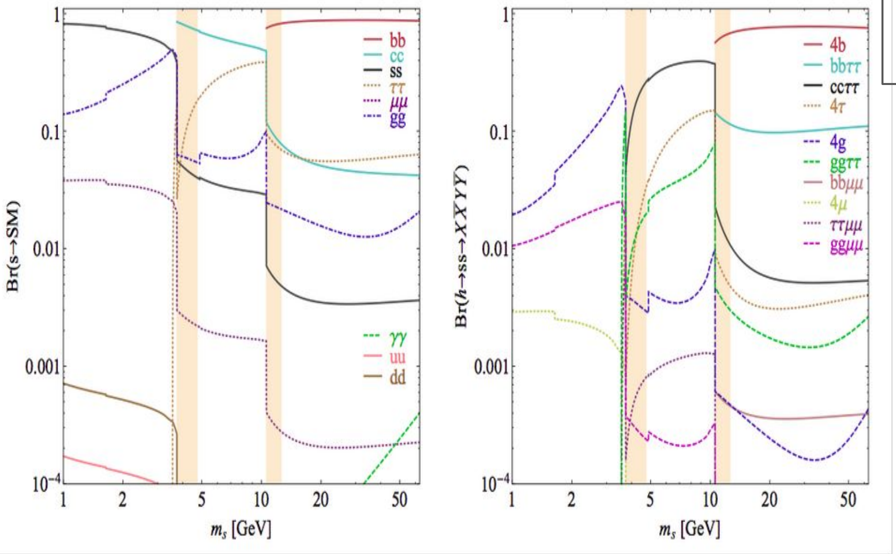


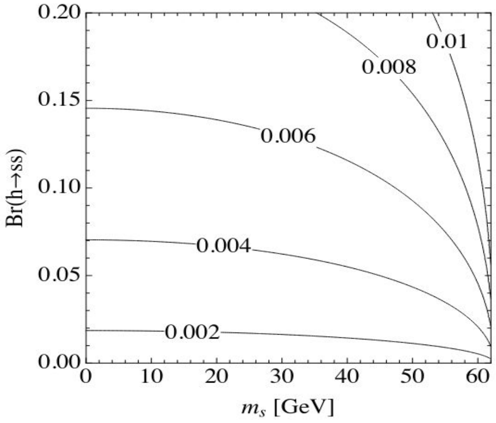
SM +Scalar

- Size of the cubic coupling μv in units of Higgs expectation value v to yield the indicated h → ss branching fraction as a function of singlet mass, is given by;

$$\Gamma(h \to ss) \;=\; \frac{1}{8\pi}\frac{\mu_v^2}{m_h}\sqrt{1-\frac{4m_s^2}{m_h^2}} \;\approx\; \left(\frac{\mu_v/v}{0.015}\right)^2 \Gamma(h \to \mathrm{SM})\,,$$

The individual decay widths of s to SM particles are mostly dominated by decay to heavy fermions for $m_s < m_h/2$ when kinematically allowed.





arXiv:1312.4992

- ***The data collected at the LHC7 and LHC8 may easily contain O(50,000) exotic Higgs decays per experiment***, assuming ~ 10% exotic branching fraction. For those decay modes which pass trigger thresholds with high enough efficiency, dedicated searches represent a tremendous potential for discoveries of new physics.
- *Branching fractions as small as O(10^{-6}) could be detected* at the LHC14 with 300 fb^{-1}, if the decay signature is both visible and clean.

Production	$\sigma_{7\ \text{TeV}}$ (pb)	$N_{ev}^{10\%}$, 5 fb^{-1}	$\sigma_{8\ \text{TeV}}$ (pb)	$N_{ev}^{10\%}$, 20 fb^{-1}	$\sigma_{14\ \text{TeV}}$ (pb)	$N_{ev}^{10\%}$, 300 fb^{-1}
ggF	15.13	7,600	19.27	38,500	49.85	1.5×10^6
VBF	1.22	610	1.58	3,200	4.18	125,000
$hW^\pm$	0.58	290	0.70	1,400	1.5	45,000
$hW^\pm(\ell^\pm\nu)$	$0.58 \cdot 0.21$	62	$0.70 \cdot 0.21$	300	$1.5 \cdot 0.21$	9,600
hZ	0.34	170	0.42	830	0.88	26,500
$hZ(\ell^+\ell^-)$	$0.34 \cdot 0.067$	11	$0.42 \cdot 0.067$	56	$0.88 \cdot 0.067$	1,800
$t\bar{t}h$	0.086	43	0.13	260	0.61	18,300

$H \rightarrow XX \rightarrow 4\ell$, $H \rightarrow ZX \rightarrow 4\ell$

arXiv:2111.01299

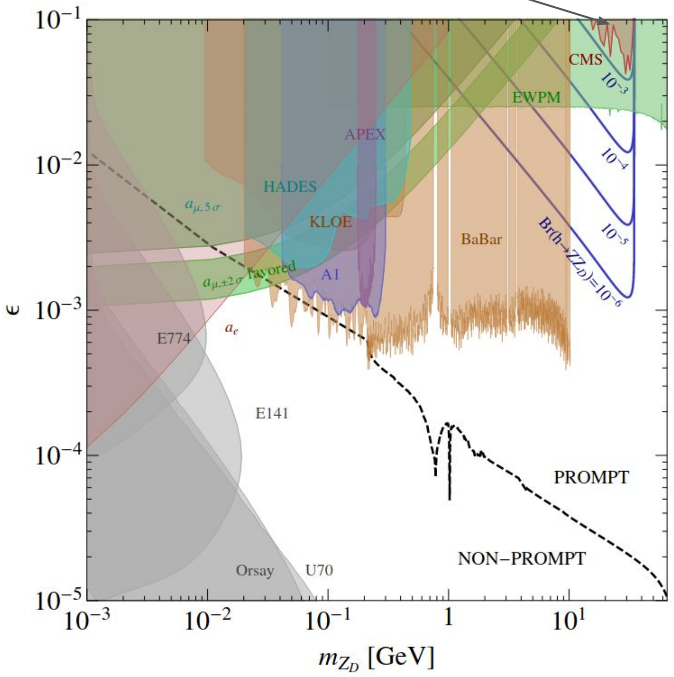
- **Event selection:**
  - At least four well-identified and isolated leptons from the primary vertex are required.
  - The four-lepton invariant mass m4l is required to be within 118 < m4l < 130 GeV.

- **Backgrounds processes with kinematics similar to the signal:**
  - ***Irreducible backgrounds:*** SM Higgs boson, nonresonant production of ZZ via quark-antiquark annihilation or gluon fusion, and rare backgrounds such as tt + Z and triboson production.
  - ***Reducible backgrounds:*** Z+jets, tt, Zγ, and WZ.

$H \rightarrow XX \rightarrow 4\ell$, $H \rightarrow ZX \rightarrow 4\ell$

Derived by recasting the CMS-PAS-HIG-13-002
h →ZZ' → 4l (7+8 TeV) analysis

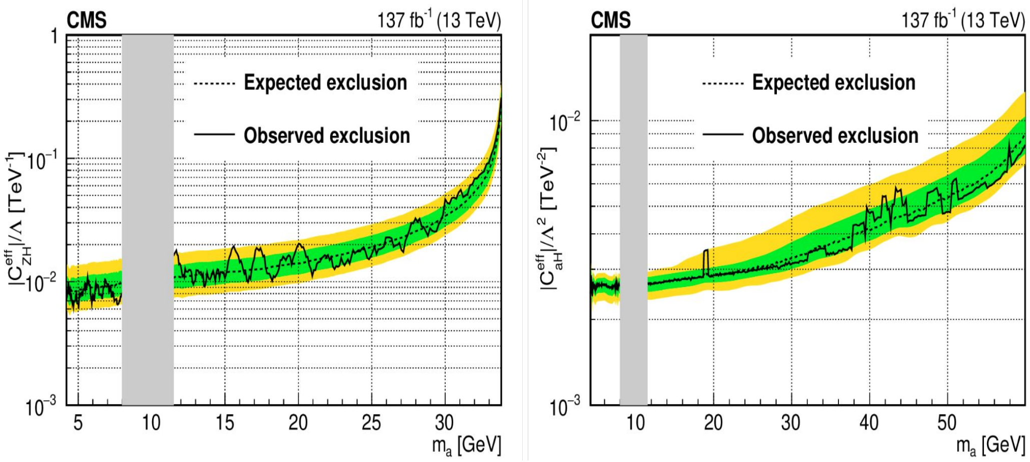
- Existing Experimental Searches and Limits on Higgs portal-mediated Higgs decays:
  - Z_D were previously performed by collider experiments, for example ATLAS arXiv.802.03388 and LHCb arXiv.1710.02867.
  - For m_{Z_D} > 10 GeV, the strongest constraints come from precision electroweak measurements.
  - We expect LHC14 with 300 fb−1 to be sensitive to Br(h → ZZ_D) as low as ~ 10−4 or 10−5. This would make the LHC the best probe of dark vector kinetic mixing for 10 GeV < m_{Z_D} < mh/2 in the foreseeable future.



H → XX→ 4ℓ , H → ZX→ 4ℓ

Limits on the ALP model

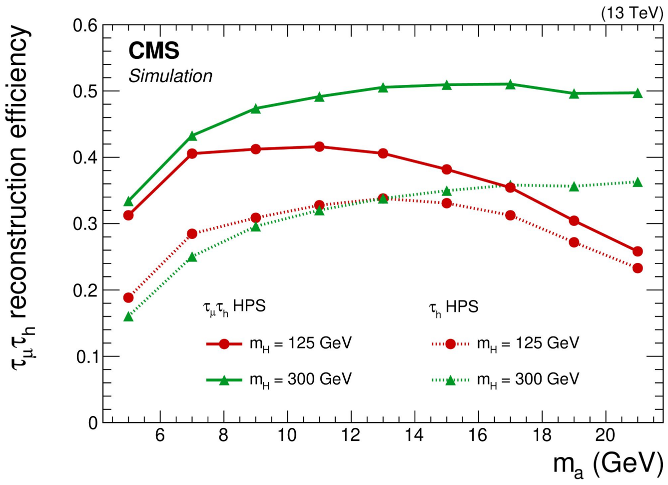
- The theory allows the coupling between the Higgs boson, Z boson, and the ALP field:
    - These couplings are represented by the Wilson coefficients C_{ZH}/Λ and C_{aH}/Λ^2, respectively, where Λ is the decoupling energy scale in the effective field theory, or the mass scale of new physics.



H → aa → μμττ

CMS-HIG-18-024
arXiv:2005.08694

- The light pseudo-scalars (a) decay to μμ and ττ with substantial overlap between the leptons because of the Lorentz boost.
  - Search target mH = 125 (300)GeV and 3.6 (5) < ma < 21 GeV.
  - VBF process increases the expected signal yield by 8 (19)%.
- **Difficult topology motivates the development of a dedicated τμ τh reconstruction method to increase the acceptance.**
  - A specialized τμ τh reconstruction algorithm, based on the hadron-plus-strips (HPS) algorithm with a modified jet seed.
  - The new τ reconstruction technique makes possible the search for the decays of a heavier Higgs boson (mH= 300 GeV) to aa in the μμττ.



H → aa → μμττ

- In general, 2HDMs could allow for exotic decays of the 125 GeV state of the form H → aa.
    - This possibility can be realized in certain corners of parameter space, however 2HDMs are by now too constrained from existing data to allow for a wide variety of exotic Higgs decay phenomenology.
- The 2HDM+S notable example of the so-called next generation of dark matter simplified models.
    - 2HDM+S upper limits on σH x B(H → aa)/σSM
    - The strongest upper limits are obtained from type-III model at tanβ < 1.5 .
    - These results extend current LHC searches for heavier ma bosons that decay to resolved lepton pairs and provide the first such bounds for an H boson with a mass above 125 GeV ([CMS-HIG-17-029](CMS-HIG-17-029)).