Exotic production and decays of the 125 GeV Higgs in the CMS experiment

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Introduction

The discovery of the Higgs boson 10 years ago [1, 2] established the theory of the SM

→ But many questions remain!

- Several BSM theories which can explain Dark Matter origin, Hierarchy Problem, etc. and also predict a Higgs Resonance
  → New physics particles preferentially couple to the Higgs boson

- Extended Higgs sector (MSSM, NMSSM etc.) allows the SM Higgs boson to act as a portal to a “hidden sector” of new physics interactions

- Run 2 focused on measuring the Higgs properties, including probes to BSM physics [3, 4]

New exotic phase space to be explored with additional data from Run 3

- Various SM Higgs couplings have only been constrained → new physics couplings may still be present

**LFV decays of the Higgs boson**

- SM forbids flavour violating Higgs couplings to leptons and quarks → Allowed in several new physics scenarios, e.g., 2HDM, extra dimensions, composite Higgs…

- Indirect limits:
  - BR(H→eμ): upper limit on μ→eγ at < 10^{-8}, albeit with several assumptions on Higgs couplings and FCNC interactions
  - BR(H→eτ/μτ): from rare τ decays and measurement of e and μ magnetic moments

\[ Y = \begin{bmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{bmatrix} \]

LFV Higgs couplings can contribute to anomalous muon magnetic moment g-2

- Direct searches performed using full Run-2 luminosity
H → eµ

Search for both SM and BSM Higgs boson X → eµ, where 110 < m_X < 160, following a bump hunt strategy

- Categorised based on ggH and VBF Higgs production modes
- Completely data driven background estimation
- Signal m_{eµ} distributions fit with a parametric model and compared to background

The two signal categories further optimised using boosted decision tree (BDT) and split according to signal purity

**Observed upper limit on the SM Higgs BR is determined to be 4.4 \times 10^{-5} at 95% CL**

The LFV Yukawa coupling is evaluated to be \sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 1.9 \times 10^{-4}
Overview:

- Multiple signal region categories based on $\tau$ decay and jet multiplicity to enhance sensitivity
- Construct collinear mass variable $m_{col} = m_{vis} / \sqrt{x_{vis}}$ to estimate $m_H$

A BDT is trained in each channel and the discriminant distribution is used in a maximum likelihood fit to extract the upper limits on the Higgs BR.

Analysis constrains BR($H \rightarrow \mu\tau$) < 0.15 and BR($H \rightarrow e\tau$) < 0.16 at 95% CL.

Also provides upper limits on LFV Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$ and $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$ 

Phys. Rev. D 104 (2021) 032013
Higgs to pseudoscalar decays

- Viable decay in 2HDM+S: two scalar doublets and one scalar singlet, leading to seven scalars or pseudoscalars

- Assuming the singlet state has no direct Yukawa couplings, decays to fermions are a result of mixing with the Higgs sector

- Mixing is small enough to preserve the SM couplings of the Higgs, branching fractions of the pseudoscalars depend on the model and model parameters
  
  → Different BSM models can be tested considering $H \rightarrow aa$ but special interest is in constraining 2HDM+S that conserve observed features of the SM

Predicted decay branching ratios of $H$ to a decoupled singlet state $(s)$ in 2HDM+S

[Graph showing predicted decay branching ratios]

Full Run-2 results

arxiv:1312.4992
Search for very low mass pseudoscalars in the diphoton decay mode

- Investigate $0.1 < m_a < 1.2$
- Diphoton decay is boosted and reconstructed as a single photon-like object “$\Gamma$”
- Probe merged $\Gamma$ candidates in the SM $H \rightarrow \gamma\gamma$ final state using novel photon reconstruction technique of end-to-end deep learning [5]

Fit 2D distribution of invariant masses $m_{\Gamma 1}$ and $m_{\Gamma 2}$

- **Signal region:** $110 < m_{\Gamma\Gamma} < 140$ around Higgs resonance
- **Sideband regions:** $100 < m_{\Gamma\Gamma} < 110$ and $140 < m_{\Gamma\Gamma} < 180$ used to estimate non-resonant background

Search is also sensitive to long-lived decays: For $0.1 < m_a < 0.4$, upper limits are 0.9 to 1.8 times larger for $c\tau = 1$ mm and 3 to 30 times larger for $c\tau = 10$ mm

*First search in this topology*

arxiv:2209.06197
Search for SM-like $H \rightarrow aa \rightarrow 4\gamma$ where the four photons are well isolated:

- Probes the mass range $15 < m_a < 62$
- Identifies the primary vertex using a BDT is trained using variables related to tracks recoiling against the well reconstructed four-photon system → improves Higgs mass resolution

Train a event classifier using variables uncorrelated to $m_{\gamma\gamma\gamma\gamma}$ and look for a 125 GeV resonance in the $m_{\gamma\gamma\gamma\gamma}$ spectrum of the signal-like events

Observed upper limits on cross section range between 0.80-0.26 fb, compared to Higgs production cross section of 52 pb

Both $H \rightarrow aa \rightarrow 4\gamma$ analyses are statistically limited and no significant deviation from SM background is observed
H → aa → 2µ2b

Clean signature with a precise mass resolution from mµµ and large BR from bb

- Search for a masses within $15 < m_a < 60$
- Bump hunt analysis using the dimuon invariant mass mµµ
- Completely data-driven background estimation
- Thorough study of the signal to use a single discriminating variable to suppress background

Parametric fit of the signal model in different categories based on b-jet properties

Most stringent observed upper limit till date in this final state, slightly better than ATLAS results

No significant deviations from SM prediction, analysis is limited by statistics

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CMS-PAS-HIG-22-007

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Relatively larger BR to $bb$ and $\tau\tau$, improved $\tau$ lepton reconstruction techniques

- Search for a masses within $12 < m_a < 60$
- Three final states explored: $\mu\tau_h$, $e\tau_h$, $e\mu$
- $SVfit$ algorithm to reconstruct $m_{\tau\tau}$ including neutrino energies

Deep neural network training in final states with 1 b-jet and 2 b-jets separately for three channels: used in event categorization to improve signal sensitivity

Type-independent upper limits on BR($H \rightarrow aa \rightarrow llbb$) in the context of 2HDM+S are derived combining with $2\mu2b$ as a function of $m_a$

$2\mu2b$ and $2\tau2b$ combination: BR($H \rightarrow aa$) values excluded above 23% (Type II tan$\beta > 1$), 7% (Type III tan$\beta = 2.0$) and 15% (Type IV tan$\beta = 0.5$)
Higgs decay to Axion-like particle

First search in LHC for Axion-like particles (ALPs) produced via $H \rightarrow Za$

- ALPs are predicted in extended SM theories addressing strong CP problem
- They are dark matter candidates decaying into photons
- Exploit merged photon reconstruction technique \([5]\) to explore the mass range $1 < m_a < 30$

A BDT event classifier is used to select the signal region maximising significance across the invariant mass distribution $m_{\gamma\gamma}$

No significant deviation from SM background is observed, analysis limited by statistical uncertainty

Also constrain effective coupling between $H$, $Z$ and $a$ within $\sim 0.015$ to $0.1$ in this mass range

See poster by Zebing
Invisible Higgs decays

- In the SM the $H \rightarrow$ invisible BR is $\sim 0.1\%$, however much higher values are predicted by several BSM theories
  → Enhanced decay in Higgs portal models where dark matter particle mass $m_{\text{DM}} < m_{H}/2$

- VBF production mode is the most sensitive channel: allows suppression of SM backgrounds

Recent search performed in $ttH$ and $VH$ production modes in hadronic final states

Signal is extracted from a fit to the hadron recoil distribution, equivalent to missing transverse momentum ($p_{T,\text{miss}}$), in $ttH$ and $VH$ channels

Results are combined with earlier searches for $H \rightarrow$ invisible decays yielding a combined upper limit of $15\%$ on BR($H \rightarrow$ invisible) at 95\% CL

arxiv.org:2303.01214
Exotic Higgs production

Dark matter at colliders: pairs of WIMPs resulting in $p_T^{\text{miss}}$

- Final state radiation of DM particle or a new physics interaction with the Higgs results in the final state $H+p_T^{\text{miss}}$ or mono-Higgs events
  - Two main models: (1) $Z’$-2HDM (2) Baryonic-$Z’$

- Several Higgs decay channels are investigated: $b\bar{b}$, $\tau\tau$, $\gamma\gamma$, $WW$ and $ZZ$

All five decay modes are combined to place exclusion limits on the DM production cross section as a function of the $Z’$ mass

JHEP 03 (2020) 025
Higgs portal to hidden BSM sector being explored by CMS analyses in different final states

→ First look at many full Run-2 results, some still to be updated

- Improved sensitivity compared to previous searches using novel analysis techniques and machine learning

- Stringent upper limits placed on the explored phase spaces of mono-Higgs production, $H \rightarrow \text{LFV}$ decays and $H \rightarrow \text{invisible}$ final states

- For $H \rightarrow a a$, no significant excess over SM prediction just yet, many other channels remain to be explored
  - Asymmetric pseudoscalar masses unexplored
  - Signals with low pseudoscalar mass to be analysed using boosted reconstruction techniques, similar to boosted $H \rightarrow a a \rightarrow 4 \gamma$ and $H \rightarrow Z a$ searches

Direct searches benefit the most with increase in luminosity: exciting times ahead with the onset of LHC Run-3!

Also tune in to talks by Ram and Toyoko for more BSM results! Summary is covered by Maxwell

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Thank You
Backup
**H→aa→4µ**

Analysis targets very low mass pseudoscalars:

- Interpreted in terms of **dark SUSY model** ($0.25 < m_a < 8.5$ GeV) and **NMSSM** ($0.25 < m_a < 3.55$ GeV)
- Limits derived as a function of dark photon mass and $m_a$ respectively in the two scenarios

Two dimuon pairs per event are chosen, where $m_{(µµ)1} \sim m_{(µµ)2} < 9$ GeV, satisfying stringent reconstruction requirements that eliminate most of the background

In the context of $H→2a+X→4µ+X$, the search results in:

- **95% CL upper limit on $\sigma(H→2a+X)xBR^2(a→2µ)$**, constrained within 0.15 and 0.39 fb

- **90% CL upper limit on BR($H→2γ_D+X$)**, constrained within 0.1 to 40%
Overview:

- **2µ2τ final state:** Target low mass \((3.6 < m_a < 21)\) and high mass \((15 < m_a < 62.5)\) pseudoscalars
- **2µ2τ and 4τ final states:** combined in the mass range \(4 < m_a < 15\)

Boosted τ pairs for very low \(m_a\) require specialized reconstruction and isolation algorithms to avoid overlap, standard μ identification algorithm used even in boosted topologies

A boosted topology with two well separated same-charged muons is also targeted, where one \(a \rightarrow 2\mu\) and the other \(a \rightarrow \tau \mu\) one-prong

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**Graphs:**

1. **Low mass 2µ2τ**
2. **High mass 2µ2τ**
3. **Combined 2µ2τ and 4τ combination**

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**References:**

- JHEP 08 (2020) 139
- JHEP 11 (2018) 018

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