CMS rare and BSM Higgs decays

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Motivation

- Higgs discovery was a great achievement for LHC
- Measurements of Higgs couplings and properties in the main decay channels show good compatibility with the SM predictions

Room for new Physics: $B(H \rightarrow BSM) < 34\%$ from Run-I as in JHEP08(2016)045

CMS Higgs BSM investigations:
- Direct searches of BSM processes:
  - $H \rightarrow aa$
  - LFV decays
- Deviation from SM prediction for rare decays:
  - $H \rightarrow \mu\mu$
  - $H \rightarrow$ invisible
  - $H \rightarrow ll\gamma, H \rightarrow J/\psi\gamma$
**Motivation:**
- Not allowed either in SM or MSSM
- allowed in other BSM theories
  - 2HDM+S foresees a scalar (compatible with the observed SM Higgs) and a pseudoscalar light enough for $h \to aa$
- $B(H \to aa)$ can be of several percent

- CMS performed many searches of the Higgs ($M_h=125$ GeV) decaying to new light resonances
  - Shown last year:
    - $h \to aa \to 2\mu 2b$ (8 TeV)
    - $h \to aa \to 4\mu$ (7, 8, 13 TeV)
    - $h \to aa \to 2\mu 2\tau$ (8 TeV)
    - $h \to aa \to 4\tau$ (8 TeV)

- New results since HH2017
  - $h \to aa \to 2\mu 2\tau$ arxiv:1805.04865
  - $h \to aa \to 2b 2\tau$ arxiv:1805.10191
  - $h \to 4\mu$ HIG-18-003

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**status at HH2017**
from **JHEP 10 (2017) 076**

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47: PLB 752 (2016) 146
48: JHEP 01 (2016) 079
**$h \to aa \to 2\mu 2\tau$**

- 4 different final states: $\mu\mu + e\mu$, $\mu\mu + e\tau_h$, $\mu\mu + \mu\tau_h$, $\mu\mu + \tau_h\tau_h$
- events from $H \to aa \to 4\tau$ are considered in the signal

- probed masses $15.0 < m_a < 62.5$ GeV
  - cannot go below 15 GeV: decay products are too boosted and result non-isolated

- Unbinned maximum likelihood to $M(\mu\mu)$
- combined obs limit for $M_a = 60$ GeV: $\sigma_h x B(H \to aa \to 2\mu 2\tau) < 1.2 \times 10^{-4} \times \sigma_{SM}$

**arxiv:1805.04865**

CMS result improved (w.r.t 8 TeV) by at least a factor of 2 in all four types of 2HDM+S
$h \rightarrow aa \rightarrow 2b2\tau$

- signature: 1 b-jet + 1 lepton and 1 $\tau$ or 2 leptons
  - 3 different $\tau\tau$ final states: $e\mu$, $e\tau_h$, $\mu\tau_h$
- 4 $m_{\text{vis}}^{\tau\tau}$ categories
- probed masses $15 < m_a < 60$ GeV
- binned maximum likelihood to $M^{\text{vis}}(\tau\tau)$

  - No excess observed
  - combined obs limit varies from 3% to 12%
  - highest sensitivity in intermediate mass region

[arxiv:1805.10191]
**h → 4μ**

- clear signature: 4 muons
- Can be interpreted in many models:
  - NMSSM: $90 < m(h_{1,2}) < 150$ GeV, $0.25 < m(a_1) < 3.55$ GeV
  - Dark SUSY: $0.25 < m(\gamma_D) < 8.5$ GeV, $m(n_I) = 10$ GeV, $0 < c\tau(\gamma_D) < 100$mm, $m(n_D) = 1$ GeV

13 events are observed.
SM background expectation: $9.90 \pm 1.24$ (stat.) $\pm 1.84$ (syst.)

No event above 3 GeV

- Improvement $m_{a_1}=3.55$ GeV: ~20%
- Improvement $m_{a_1}=0.25$ GeV: ~50%

- Improvement $\varepsilon$: factor 10
- Improvement $m_{\gamma_D}$: factor 5
LFV: $\mathcal{H} \rightarrow e/\mu + \tau$

- Forbidden in SM but allowed in several beyond the Standard Model theories
- CMS recently updated the search for LFV decays of the Higgs ($m_H = 125$)
  - 2 Higgs decay channels
    - 2 $\tau$ decay channels: $\tau_{\text{had}}$ or $\tau_{\mu/e}$
    - 4 categories: 0 jet, 1 jet, 2 jets (ggH), 2 jets (qqH)
    - BDT classifier (collinear mass fit as cross check)
- $\mathcal{H} \rightarrow e\mu$ not investigated: indirect limit $B(\mathcal{H} \rightarrow e\mu) < 10^{-8}$. CMS RunI observed limit is $B(\mathcal{H} \rightarrow e\mu) < 0.035\%$
**LFV: H→e/\mu + \tau**

Most stringent limits up to date

8 TeV CMS results
- obs (exp) \( B(H\to\mu\tau) < 1.51 \(1.33) \%
- obs (exp) \( B(H\to\eta\tau) < 0.69 \(0.75) \%

\[
\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} = 2.26 \times 10^{-3}
\]

\[
\sqrt{|Y_{e\tau}|^2 + |Y_{\tau\epsilon}|^2} = 2.26 \times 10^{-3}
\]
**H → μμ**

- Very rare decay, \( B = 2.18 \times 10^{-4} \)
- Clean and narrow peak on top of smoothly falling \( DY \rightarrow \mu \mu \) background
- Only SM \( H \) decay to 2nd generation expected to be seen at LHC
  - Could be enhanced by new physics

- 15 event categories (based on BDT and mass resolution) used to enhance sensitivity
- Maximum likelihood signal+background fit to \( M(\mu \mu) \)

**More details in yesterday’s talk by Artur Kalinowski**

**arxiv:1807.06325**
Combining Run1 and 2016 data, limit less than a factor of 3 away from SM rate for \( M_H = 125.09 \) GeV

- best fit signal strength:
  \[
  obs \ \mu_{125}^{\text{comb}} = 1.0 \pm 1.0 (\text{stat})^{+0.1}_{-0.1} (\text{syst}), \quad exp \ \mu_{125}^{\text{comb}} = 1.0^{+1.1}_{-1.0}
  \]

- obs (exp) significance: 0.9 (1.0) \( \sigma \)
- \( B(H \rightarrow \mu \mu) < 6.4E-4 \) (obs)

More details in yesterday talk by Artur Kalinowski
H → invisible

- Events with high MET
- SM $B(H \rightarrow ZZ \rightarrow 4\nu) \sim 0.12\%$

- Many possible extensions of the SM would allow enhance the rate: decays to dark matter, hidden valleys / portals, ...

- CMS use combination of
  - VBF-tagged
  - associated W/Z (including boosted W/Z → quarks!)
  - ISR/mono-jet

CMS HIG-17-023

Clear VBF signature: dijet system with large rapidity gap $\Delta\eta(j_1, j_2)$ and large dijet mass $M(j_1, j_2)$

10.1140/epjc/s10052-018-5740-1
10.1103/PhysRevD.97.092005

Z-→ OS/SF leptons close to $M_Z$
Smallest BR, Higher S/B

W-→ qq: resolved or boosted

Largest $\sigma$, lowest S/B
H → invisible

- Different approaches uses:
  - VBF-tagged: cut-and-count + shapes analysis
  - Z(II)-tagged: BDT Classifier
  - background estimated from simulation and CR

- Relative contributions between the different production mechanisms consistent with SM predictions

- BR(H → invisible) < 24 (18) % (at 95% CL)
• Present in the SM, but very small rate:

\[
\frac{B(H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma)}{B(H \rightarrow \gamma\gamma)} = (1.69 \pm 0.10)\%,
\frac{B(H \rightarrow Z\gamma \rightarrow e^+e^-\gamma/\mu\mu\gamma)}{B(H \rightarrow \gamma\gamma)} = (2.27 \pm 0.14)\%.
\]

• loop-induced decay $\rightarrow$ sensitive to new physics

• Multiple lepton flavours:
  – $M_{ll} > 50$ GeV: $H \rightarrow Z(\rightarrow ee/\mu\mu)\gamma$
  – $M_{ll} < 50$ GeV: $H \rightarrow \gamma^*(\rightarrow \mu\mu)\gamma$

• Multiple (7) event categories used to enhance signal sensitivity by 11-18%  
  – presence of additional lepton or jets
    • lepton tag, di-jet tag
  – boosting
    • boosted tag: $p_T^{ll\gamma} > 60$ GeV,
  – 4 untagged categories to enhance $ll\gamma$ mass resolution and S/B
    • photon and leptons $\eta$, shower-shape
combined exp (obs) $\sigma < 3.9$ (2.0) $\sigma_{SM}$ for $M_H=125$ GeV
**H → J/ψγ**

- **Motivation:** search for $H \rightarrow J/\psi \gamma$ decays used to couplings to the second generation of quarks

$$B_{SM}(H \rightarrow J/\psi \gamma) = (3.0^{+0.2}_{-0.2}) \times 10^{-6}$$

- **very small decay rate → few signal events expected priori to selections with Run-II statistics**

- **$J/\psi \rightarrow \mu\mu$: clean signature w.r.t. direct searches for H(cc) decays and $H \rightarrow \gamma^* \gamma \rightarrow \mu\mu\gamma$**
H$\rightarrow$J/$\psi$γ

• Analysis strategy: very similar to those of the H$\rightarrow$γ$^*$γ → µµγ search + m(µµ) requirement

• No categories based on production modes or mass resolution

• Fit to M_{llγ} mass
  • Bernstein polynomial used to fit the background

13 TeV obs. (exp.) limit:
B(H$\rightarrow$J/$\psi$γ) < 7.6 (5.2) x 10^{-4}, 260 (170) times the SM expectation

13 + 8 TeV combination obs. (exp.) limit on B(H$\rightarrow$J/$\psi$γ) is 220 (160) x B_{SM} (H$\rightarrow$J/$\psi$γ)
Summary

- Extensive, on-going program at CMS searching for Higgs rare and BSM decays:
  - Searching for decays to new light pseudoscalars foreseen in BSM theories
  - Probing off-diagonal Yukawa couplings
  - Probing coupling of the Higgs boson to second generation of leptons and quarks

- Enhancements from the SM prediction would directly point to BSM physics
  - So far, no significant deviations from SM predictions are observed

- Limits on decays to new light pseudoscalars
  - improved by (at least) a factor of 2 in the four types 2HDM+S in 2µ2τ channel
  - First limits in 2b2τ channel
  - Best direct limit of H→eτ and H→µτ branching ratios.

- Run-II sensitivity for Higgs invisible decays stronger than Run-I despite higher p_T^miss thresholds
  - VBF H→inv the most sensitive channel
  - VBF H→inv sensitivity improved by means of a m_jj shape fit

- H → µµ search sensitivity around 2 x SM → goal would be reach SM sensitivity with full Run-II data
- H → llγ final states give access to BR(H→Zγ) and BR(H→J/ψγ)
  - Sensitivity still far from the SM prediction → it will not be reached by the end of Run-II
ADDITIONAL MATERIAL
Dominant diagrams contributing to $H \rightarrow \ell^+ \ell^-$
$H \rightarrow J/\psi \gamma$