MOTIVATION

Since the Higgs boson discovery in 2012, all measurements in agreement with the SM predictions.

- SM Higgs boson width very narrow, $\sim 4$ MeV, much lower than the sensitivity of LHC.
- Current constraints on BSM decays relatively loose, $\mathcal{B}(h \to \text{BSM}) < 34\%$.
- Exotic Higgs decays predicted in many BSM theories with extended Higgs sector.

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**arXiv:1909.02845**

**ATLAS**

- $\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^{-1}$
- $m_H = 125.09$ GeV, $|y_H| < 2.5$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>68% CL</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Z$</td>
<td>$\rho_{\text{inv}} = 88%$</td>
<td>$\kappa_{\text{on}} = 96%$</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>$\rho_{\text{inv}} = 95%$</td>
<td>$\kappa_{\text{on}} = 95%$</td>
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<tr>
<td>$\kappa_t$</td>
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<tr>
<td>$\kappa_b$</td>
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<tr>
<td>$\kappa_{\tau}$</td>
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<td>$\kappa_{g}$</td>
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<tr>
<td>$\kappa_{\gamma}$</td>
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<tr>
<td>$B_{\text{inv}}$</td>
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<td>$B_{\text{undet}}$</td>
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<tr>
<td>$B_{\text{BSM}}$</td>
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<table>
<thead>
<tr>
<th>$B_{\text{BSM}} &lt; 0.34$</th>
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<tbody>
<tr>
<td>$B_{\text{inv}} &lt; 0.30$</td>
</tr>
<tr>
<td>$B_{\text{undet}} &lt; 0.21$</td>
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</tbody>
</table>

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Marina Kolosova 2 of 32 October 3, 2019
MOTIVATION

Search for BSM decays of the Higgs boson though

Rare decays
Predicted by the SM

Lepton flavour violating decays
Forbidden in the SM

Invisible decays
In the SM, only via
H → ZZ* → 4ν, B_{inv} < 0.1%

Decays to light (pseudo-)scalars
h → aa → X̄X ȲȲ
Predicted in many SM extensions
(2HDMs, 2HDM+S)

Search for deviations in the Higgs boson couplings
Precision measurements needed
model-specific approach

Marina Kolosova 3 of 32 October 3, 2019
h(125) → a_1 a_1 → X \bar{X} Y \bar{Y} in ATLAS & CMS

Signatures

a → bb : large BR, low S/B, hard to trigger, low identification efficiency, high \( p_T \) thresholds

a → ττ : large BR, low \( \tau_h \) identification efficiency, high \( p_T \) thresholds

a → µµ : low BR, high S/B, excellent mass resolution, easy to trigger & identify

Challenging final states

- Decay products soft in \( p_T \) and can overlap

- ATLAS & CMS increase sensitivity with sophisticated analysis techniques

SM+S benchmark

arXiv:1312.4992
h(125) → a_1 a_1 → μμbb

☑ Large $B(a → μμ)$ in models with enhanced lepton couplings (Type-III 2HDM)

- $20 < m_{a_1} < 62.5$ (60) GeV for CMS (ATLAS)
- Higgs production via ggF & VBF
- Main background from $Z +$ jets and $t\bar{t}$

Baseline selections
- 2 isolated muons of opposite charge
- 2 b-jets
- $m_{bb} \sim m_{μμ}$ & $m_{bbμμ} \sim m_h$:
  - CMS: $\chi^2 = \chi^2_{bb} + \chi^2_h$
    - $\chi_{bb} = (m_{bb} - m_{μμ})/σ_{bb}$
    - $\chi_h = (m_{μμbb} - m_h)/σ_h$
  - ATLAS: kinematic-likelihood (KL) fit
- $E_{T}^{miss} < 60$ GeV to suppress $t\bar{t}$

- An excess above the SM background is searched in the $m_{μμ}$ distribution
- $\chi^2 < 5$ ensures 64% signal efficiency & 95% background rejection
- Event categorisation (3 categories) based on the b-tagging working points (WPs)
- Unbinned fit to $m_{\mu\mu}$ distribution in data used to model signal & background shape
- Background estimated in data using control regions (CRs) defined by inverting the $\chi^2$ requirement

Inclusive

$$\frac{\sigma_h}{\sigma_{h,SM}} \times B(h \rightarrow a_1a_1 \rightarrow \mu\mu bb)$$

Type-III 2HDM+S

$$B(h \rightarrow a_1a_1 \rightarrow \mu\mu bb) < (1 - 7) \times 10^{-4} \quad \text{(Obs.)}$$

$$B(h \rightarrow a_1a_1 \rightarrow \mu\mu bb) < (1 - 3) \times 10^{-4} \quad \text{(Exp.)}$$
KL fit improves the $m_{bb\mu\mu}$ resolution by a factor of two

- Main background ($Z + \text{jets} \& t\bar{t}$) estimated in data
- Control regions, defined by inverting $E_T^{\text{miss}}$ selection ($t\bar{t}$ CR) and reconstructed $m_{bb\mu\mu}$ window (DY CR), used to constrain the background contribution in the signal region

$m_{\mu\mu}$ in Signal Region

\[ \sigma_H \times B(H \rightarrow a_1 a_1 \rightarrow bb\mu\mu) \]

\begin{align*}
\sigma_H & \leq \sigma_{SM} \\
B(h \rightarrow a_1 a_1 \rightarrow \mu\mu bb) & < 1.2 \times 10^{-4} \quad \text{(Obs.)}
\end{align*}
CMS $h(125) \rightarrow a_1 a_1 \rightarrow \mu \mu \tau \tau / \tau \tau \tau \tau$

- Up to 90% $B(a \rightarrow \tau \tau)$ in Type-II 2HDM+S for large values of $\tan \beta$

- $4 < m_{a_1} < 15$ GeV
- Higgs production via $ggF$, VBF, VH & $t \bar{t}H$
- Identify highly Lorentz-boosted $\mu/\tau$ pairs with overlapping decay products
- Main background from QCD multijet, diboson & top-quark production

Signal searched in events with:
- Two same-sign muons with large angular separation
- Each muon accompanied by a nearby opposite-sign track
- Muon-track systems reconstruct two $a_1$-candidates
Signal extracted with a binned max-likelihood fit to the 2D distribution of \((m_{a_1}^{(1)}, m_{a_1}^{(2)})\)

- Background modelled in data with the use of CRs with modified isolation criteria applied to one or both muon-track systems

\[(m_{a_1}^{(1)}, m_{a_1}^{(2)}) \text{ bins} \]

\[\frac{\sigma_{H}}{\sigma_{SM}} \times B(H \rightarrow a_1 a_1) B^2(a_1 \rightarrow \tau \tau)\]

- Improved limits wrt. 8 TeV analysis (30% at low \(m_{a_1}\), 80% at intermediate \(m_{a_1}\) and new limits for up to 15 GeV)


Many analyses, in both ATLAS & CMS, searching for $h \rightarrow a_1 a_1$, most of them done with Run 2 data.

Observed and expected 95% CL upper limits on $\frac{\sigma_H}{\sigma_{SM}} \times B(H \rightarrow aa)$.
Observed and expected 95% CL upper limits on $\frac{\sigma_H}{\sigma_{SM}} \times \mathcal{B}(H \rightarrow aa)$ in the context of 2HDM+S Type-III scenario for $\tan\beta = 2$ (left) and $m_{a_1} = 40$ GeV (right).
**LFV @ CMS** $H \rightarrow \mu \tau, \ H \rightarrow e \tau$

- Signal searched in events with a prompt $\mu/e$, an oppositely charged $\tau$-lepton and no b-jets

  \[ H^0 \rightarrow \mu \tau_e \]

  \[ H^0 \rightarrow \mu \tau_h \]

  \[ H^0 \rightarrow e \tau_\mu \]

  \[ H^0 \rightarrow e \tau_h \]

- 4 categories per channel based on number of jets (to enhance VBF and $ggF$)
- Boosted decision trees (BDT) approach to distinguish signal from background
- Background $Z \rightarrow \tau\tau$ (QCD multijet) estimated from simulation (data)
- Joint fit to BDT discriminator to derive observed and expected limits

**$H \rightarrow \mu \tau_h$, 0 jets**

**$H \rightarrow e \tau_h$, 2 jets VBF**

**$B(H \rightarrow e\tau)$**

**$B(H \rightarrow \mu\tau)$**
Baseline selection similar to CMS, optimised in each channel for maximum S/B

- 2 categories for each channel ($\mu\tau$, $e\tau$, $\mu\mu$, and $e\mu$): VBF & non-VBF

- BDT variables selection optimised for each channel and category

- CRs, defined by inverting the b-jet veto (top-quark CR) and leading lepton $p_T$ ($Z \rightarrow \tau\tau$ CR) requirements, used to constrain the background normalization

- Events with misidentified objects (jets $\rightarrow$ $\ell$, jets $\rightarrow$ $\tau$, $e \rightarrow \tau$) estimated with data-driven techniques

\[ H \rightarrow \mu\tau \]

\[ H \rightarrow e\tau \]
▶ Strongly constrained by the indirect $\mu \rightarrow e\gamma$ limit, $\mathcal{B}(H \rightarrow e\mu) < O(10^{-9})$
✓ Full Run II data, 139 fb$^{-1}$
▶ Signal searched in events with two opposite charge leptons, no b-jets and low $E_T^{\text{miss}}$
▶ Background is top-quark & diboson production, $W$+jets, multijet events with jets misidentified as leptons
▶ 7 ggF categories based on leptons $p_T$ & $\eta$, 1 VBF category based on number of jets
▶ Background measured with analytical functions constrained by the signal sidebands
✓ 95% CL upper limits on $\mathcal{B}(H \rightarrow e\mu)$ improved by a factor of 6 wrt previous results

![Graph](image_url)
**LFV HIGGS DECAYS**  

**Yukawa couplings**

- Significant improvement on 95% CL upper limits with respect to Run I
- $\mathcal{B}(H \rightarrow \text{LFV})$ constraints can be interpreted in terms of LFV Yukawa couplings:

$$\Gamma(H \rightarrow \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi} \left( |Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2 \right),$$

$$\mathcal{B}(H \rightarrow \ell^\alpha \ell^\beta) = \frac{\Gamma(H \rightarrow \ell^\alpha \ell^\beta)}{\Gamma(H \rightarrow \ell^\alpha \ell^\beta) + \Gamma_{\text{SM}}}$$

<table>
<thead>
<tr>
<th>$\mathcal{B}(H \rightarrow \mu\tau)$</th>
<th>$\mathcal{B}(H \rightarrow \tau\mu)$</th>
<th>$\mathcal{B}(H \rightarrow e\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 0.25%$</td>
<td>$&lt; 0.61%$</td>
<td>$&lt; 0.0061%$</td>
</tr>
<tr>
<td>$&lt; 0.28%$</td>
<td>$&lt; 0.47%$</td>
<td>$&lt; 0.0001%$</td>
</tr>
<tr>
<td>$&lt; 0.25%$</td>
<td>$&lt; 0.61%$</td>
<td>$&lt; 0.0035 %$ (8 TeV)</td>
</tr>
</tbody>
</table>
FUTURE PROSPECTS

High-Lumi LHC
Run 2 analysis $h \rightarrow \alpha \alpha \rightarrow \tau \tau b b$ projected to HL-LHC conditions

Extrapolations done under similar level of detector and triggering performance assumption

3 scenarios for the extrapolation of systematic uncertainties:

1. **Statistical-only**: all systematic uncertainties are neglected
2. **Run-2**: experimental & theoretical unc. same as in Run-2
3. **YR18**: theoretical unc. divided by two, experimental unc. scale inversely with the square root of integrated luminosity with some lower limit

![Graph 1: CMS Projection $h \rightarrow aa \rightarrow 2b2\tau$](image1)

![Graph 2: CMS Projection $h \rightarrow aa \rightarrow 2b2\tau$](image2)
FUTURE PROSPECTS  Triggering at Level-1

- Current trigger bandwidth major handle for BSM analyses
- CMS Phase-2 Tracker upgrade enables tracking information at Level-1 trigger (L1T)
  - Handles for rate suppression & lower thresholds → new phase space for BSM signals

  \[ h(125) \rightarrow \phi\phi \rightarrow 4j \]

  ✓ Negligible SM background when \( \phi \) has a macroscopic decay length
  ✗ Run 2: Majority of such events rejected at L1T due to low H_T thresholds

- New jet clustering algorithm utilises L1 tracking info to reconstruct tracks with impact parameter as large as 5 cm

\( B(h(125) \rightarrow \phi\phi \rightarrow 4j) = 10^{-5} \)
SUMMARY

- ATLAS & CMS working on a broad program of exotic Higgs boson decays searches covering a large variety of 2HDM models
- No significant excess above the SM background found so far
- Limits becoming more stringent with partial or full Run 2 dataset
- More results to come with the full Run 2 dataset!

- Future looks promising as HL – LHC opens new phase space for BSM searches

Thank you for your attention!
BACKUP
Branching fractions (page 22)
CMS (page 24)
ATLAS (page 29)
Projections to HL-LHC (page 32)
**Branching fractions**

Type I

![Graph showing branching fractions for Type I with various signal strengths and mass ranges.](image)

Type II, $\tan \beta = 5$

![Graph showing branching fractions for Type II with $\tan \beta = 5$ and various signal strengths and mass ranges.](image)

Type II, $\tan \beta = 0.5$

![Graph showing branching fractions for Type II with $\tan \beta = 0.5$ and various signal strengths and mass ranges.](image)
BACKUP Branching fractions

Type III, $\tan \beta = 5$

Type III, $\tan \beta = 0.5$

Type IV, $\tan \beta = 0.5$

Type IV, $\tan \beta = 5$
$h \rightarrow a_1 a_1 \rightarrow bb\mu\mu$

- Overlap between $h \rightarrow a_1 a_1 \rightarrow bb\mu\mu$ and $h \rightarrow a_1 a_1 \rightarrow \tau\tau\mu\mu$ final states is checked in Type-III 2HDM+S model, including $\mu\mu\tau\tau$ signal that is misidentified as $\mu\mu bb$

- Contribution from $\mu\mu\tau\tau$ non-negligible

**Graphs**

- **Without $\mu\mu\tau\tau$**
- **With $\mu\mu\tau\tau$**

**References**

- CMS

**ArXiv**

- arXiv:1812.06359
\( h \rightarrow a_1 a_1 \rightarrow \tau \tau bb \)

- \( 15 < m_{a_1} < 60 \) GeV
- 3 final states considered: \( \tau e \tau \mu bb \), \( e \tau h bb \), & \( \mu \tau h bb \) (most sensitive)
- 4 categories per final state, based on \( m_{b\tau\tau}^{\text{vis}} \)
- Background \( t\bar{t}, W+\text{jets} \) (estimated from simulation), jets misidentified as \( \tau h \) (from data)
- Signal extracted from binned maximum-likelihood fit to the \( m_{\tau\tau}^{\text{vis}} \) distribution

**\( \mu \tau h bb \) final state, \( m_{\tau\tau}^{\text{vis}} \)**

\[
\frac{\sigma_h}{\sigma_{SM}} \times B(h \rightarrow aa \rightarrow 2b2\tau)
\]

\[
\frac{\sigma_h}{\sigma_{SM}} \times B(h \rightarrow aa)
\]

**Combining the results**

\( B(h \rightarrow a_1 a_1 \rightarrow 2b2\tau) < 3 - 12\% \) (Obs.)
$h \to a_1a_1 \to \mu\mu\tau\tau$

- $15 < m_{a_1} < 62.5$ GeV
- 4 final states considered: $\mu\mu\mu\mu$, $\mu\mu\tau\tau$, $\mu\mu\mu\tau$ and $\mu\mu\tau\tau$
- Background Z pair production (jets misidentified as leptons) estimated in simulation (data)
- Signal extracted from maximum-likelihood fit to the $m_{\mu\mu}$ distribution
- Improved limits wrt previous results by a factor of 2 or more in all types of 2HDM+S

$m_{\mu\mu}$ in $\mu\mu\mu\mu$ category

- 4 final states considered: $\mu\mu\mu\mu$, $\mu\mu\tau\tau$, $\mu\mu\mu\tau$ and $\mu\mu\tau\tau$
- Background Z pair production (jets misidentified as leptons) estimated in simulation (data)
- Signal extracted from maximum-likelihood fit to the $m_{\mu\mu}$ distribution
- Improved limits wrt previous results by a factor of 2 or more in all types of 2HDM+S
Signal searched in events with two isolated leptons, up to 2 jets, low $E_T^{\text{miss}}$ & no b-jets
- Considering ggF and VBF Higgs production mechanisms
- 9 ggF and 2 VBF categories based on leptons detection area & number of jets
- Background originates from $Z \rightarrow \tau\tau$, $t\bar{t}$, jets misidentified as leptons
- Signal extracted from fit to the $M_{e\mu}$ distribution in the range $110 \text{ GeV} < M_{e\mu} < 160 \text{ GeV}$

$B(H \rightarrow e\mu) < 0.035\%$

$\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 5.4 \times 10^{-4}$
Observed and expected 95% CL upper limits on $\frac{\sigma_H}{\sigma_{SM}} \times B(H \to aa)$ in the context of 2HDM+S Type-II with $\tan\beta = 2$.
H → ZX → 4ℓ & H → XX → 4ℓ (X = a, Zd)

- Final states considered:
  15 < mₓ < 60 GeV: 4e, 2e2µ, 4µ
  1 < mₓ < 15 GeV: 4µ

- Benchmarks considered:
  1. Extended SM with a dark-sector, U(1)d (produces vector boson Zd)
  2. 2HDM with an additional singlet scalar field, 2HDM+S (produces pseudoscalar a)

- Same-flavour opposite sign (SFOS) leptons form quadruplets, m₄ℓ consistent with m_H

- Main background: H → ZZ* → 4ℓ, ZZ* → 4ℓ, triboson, jets misidentified as leptons

- Background estimated using simulation & data-driven techniques

\[
\frac{\sigma_H}{\sigma_{SM}} \mathcal{B}(H \rightarrow Z_dZ_d)
\]

\[
\frac{\sigma_H}{\sigma_{SM}} \mathcal{B}(H \rightarrow ZZ_d)
\]

\[
\frac{\sigma_H}{\sigma_{SM}} \mathcal{B}(H \rightarrow aa)
\]
VH → Vaa → (ℓℓ/ℓν)bbbb

- 20 < m_a < 60 GeV
- b-quarks produced promptly or with cτ_a up to 6 mm
- Signal searched in events with ≥ 1 μ/e, ≥ 2 b – jets
- Background: t ¯t, W/Z+jets, diboson, jets misidentified as leptons
- CRs, defined based on number of leptons, jets & b-jets, used to constrain the background (using simulation & data)
- Boosted Decision Tree (BDT) approach to discriminate signal from background

Prompt, 3.0 - 1.3 pb

best limits for cτ_a ≈ 0.4 mm
First time search for $h \rightarrow aa \rightarrow \gamma\gamma jj$

- Important in models with suppressed fermionic decays
- Considering vector-boson fusion (VBF) Higgs production mechanism
- Signal is searched in events with 2 photons, $\geq 4$ jets. Construct:
  - $m_{jj}^{VBF} > 500$ GeV with VBF jets, $m_{jj}$ with signal jets
  - $m_{\gamma\gamma}$ gives 5 regimes: $|m_{jj} - m_{\gamma\gamma}| > 12 - 24$ GeV
  - $100 < m_{\gamma\gamma jj} < 150$ GeV

- $\gamma\gamma +$ multi jet background estimated from data using sidebands
- No significant excess is observed wrt predicted SM background

\[ F(\sqrt{s} = 13 \text{ TeV}, 36.7 \text{ fb}^{-1}) \]

\[ \frac{\sigma_{h}}{\sigma_{SM}} \times B(h \rightarrow aa \rightarrow \gamma\gamma gg) \]
Upper limits on $B(\eta \to aa \to 2\tau 2b)$ interpreted to $B(\eta \to aa)$ limits in different 2HDM+S models assuming YR18 systematic uncertainties.