

Search for rare decays and lepton-flavor-violating decays of Higgs boson at the ATLAS experiment

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Getting to know the 125 GeV scalar



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years

discovery

HIGGS boson

p2

Menu of the talk – 125 GeV Higgs rare decays

Rare loop-induced or Yukawa-suppressed radiative decays $(\sim 140 \text{ fb}^{-1})$ \succ H \rightarrow Z γ , H \rightarrow $\gamma\gamma^* \not\leftarrow$ (Z, $\gamma^* \rightarrow ll$) \succ H \rightarrow J/ $\psi\gamma$, $\psi\gamma$ or $\Upsilon\gamma$ (J/ ψ , ψ , $\Upsilon \rightarrow \mu\mu$) **NEW** \succ H $\rightarrow \omega \gamma$, $K^* \gamma$ ATLAS data Is the Higgs sector responsible for LFV? **NEW** > $H \rightarrow e\tau$, $H \rightarrow \mu\tau$ \rightarrow $> H \rightarrow e\mu$, 2 Can we observe Higgs decays to 1st and 2nd generation? Full Run \rightarrow H \rightarrow ee \succ H \rightarrow µµ \bigstar

The searches mainly statistically limited ($\sigma \times BR \sim O(\text{fb})$ or less) Dominant systematic unc. come from limited MC stats.

- \Rightarrow analysis strategy & results
- \Rightarrow systematic uncertainties

Search for rare loop-induced or Yukawa-suppressed decays (with a prompt photon)

- Extra contributions to the fermionic/bosonic loops?
- Modified fermion couplings?



 $H \rightarrow Z\gamma \ (Z \rightarrow ll, l=e,\mu)$

- Six mutually exclusive SR categories Simultaneous profile ML fit of the S+B model in the six regions.
- Kinematic fit of m_{ll}
 FSR correction in μμ channel
- Observed (expected) bkg. only fit *p*-value 1.3% (12.3%)
- Observed (expected) significance 2.2σ (1.2σ)

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Fitted signal strength: $2.0 \pm 0.9(\text{stat.}) \stackrel{+0.4}{_{-0.3}}(\text{syst.}) = 2.0 \stackrel{+1.0}{_{-0.9}}(\text{tot.})$ 95% CL upper limit on signal strength $3.6 \times \text{SM} (0.55\% \text{ on } B(H \rightarrow Z\gamma))$



- Three categories of *ll* pairs:
 - 1. $\mu\mu (p_T > 3 \text{ GeV})$
 - 2. resolved $ee (p_T > 4.5 \text{ GeV})$
 - 3. merged $ee (p_T(ee) > 20 \text{ GeV})$
- Merged electrons distinguished from jets or single electrons using MVA methods
- 9 mutually orthogonal SR categories defined based on VBF/non-VBF, high/low p_{Tt}

Fitted signal strength: 1.5 ± 0.5 (stat.) $^{+0.2}_{-0.1}$ (syst.) = 1.5 ± 0.5 (tot.)

 \Rightarrow observed (expected) significance: 3.2 σ (2.1 σ)

 $\Rightarrow \sigma \times B(H \rightarrow ll\gamma) = 8.7 \pm 2.7(\text{stat.}) \stackrel{+0.7}{_{-0.6}}(\text{syst.}) \text{ fb}$

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 \bigstar



arXiv:2208.03122 arXiv:2301.09938

<u>(JHEP 07 (2018) 127)</u>



 $H \rightarrow J/\psi\gamma, \psi(2S)\gamma, \Upsilon(1S, 2S, 3S)\gamma$

- indirect and direct diagrams!
- ♦ $B(H\rightarrow J/\psi\gamma) \sim 10^{-6}$, $B(H\rightarrow \Upsilon\gamma) \sim 10^{-9} 10^{-8}$
- ♦ $B(H \rightarrow \omega \gamma) \sim 10^{-6}$, $B(H \rightarrow K^* \gamma) << 10^{-11}$

- Inclusive background (all except for DY+ FSR γ) from 'generation region' (SR with relaxed isolation) in data. Correlated sampling, normalisation from the fit. (arXiv: <u>2112.00650</u> [hep-ex])
- The search is performed for both H and Z decays to $Q\gamma$ (except K^*)
- Data remain consistent with the background only hypothesis.
- ♦ 95% CL limits on $B(H \rightarrow Q\gamma)$ are set
- ♦ 95% CL limits on $B(Z \rightarrow Q\gamma) \sim O(10^{-6})$

Search for Lepton Flavour Violation in the Higgs sector

- Neutrinos oscillate: lepton flavour is not an exact symmetry
- Is the Higgs sector responsible?
- Naturally occurs in >1 HDM, composite Higgs, Randall-Sundrum warped ED, etc.

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 $\bar{\nu}_{\ell'}$



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$H \rightarrow e\tau, H \rightarrow \mu\tau \ (\tau_{l}, \tau_{had})$

arXiv:2302.05225

- For each decay two channels considered: $l\tau_l, l\tau_{had}$
- For $l\tau_l$ different flavours only
- VBF and non-VBF categories
- Lepton p_T in the approx. H rest frame used to resolve the ambiguity (5-7%)
- ↔ dominant backgrounds: $Z \rightarrow \tau \tau$, top
- MC-template (all channels) & Symmetry
 (*l*τ_l) background estimation methods









$H \rightarrow e\tau, H \rightarrow \mu\tau \ (\tau_{l}, \tau_{had})$





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Н→еµ

- OS lepton pairs $p_T > 27(15)$ GeV
- Veto on identified *b*-jets (suppress top background)
- $\bigstar E_T^{miss}/\sqrt{H_T} < 1.75 \text{ GeV}^{1/2}$
- Categorisation:
 - VBF and non-VBF
 - Central ($\left|\eta^{l}
 ight|<1$) and Non-central
 - Low, Medium and High p_T^{ll}
- Simultaneous binned ML fits to the observed m_{ll} distributions in the range $110 < m_{ll} < 160 \text{ GeV}$

Н→еµ

✤ Main bkg.: DY Z/γ*→ττ, top, diboson, misidentified leptons

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Observed (expected) 95% CL upper limits on $B(H \rightarrow e\mu)$: 6.2×10⁻⁵ (5.9×10⁻⁵)

H→ee

- OS lepton pairs $p_T > 27(15)$ GeV
- Veto on identified *b*-jets (suppress top background)
- $\bigstar E_T^{miss}/\sqrt{H_T} < 3.5 \text{ GeV}^{1/2}$
- Categorisation:
 - VBF and non-VBF
 - Central ($\left|\eta^{l}
 ight|<1$) and Non-central
 - Low, Medium and High p_T^{ll}
- Simultaneous binned ML fits to the observed m_{ll} distributions in the range $110 < m_{ll} < 160 \text{ GeV}$

H→ee

♦ Main bkg.: DY $Z/\gamma^* \rightarrow ee$

Phys. Lett. B 801 (2020) 135148



Observed (expected) 95% CL upper limits on $B(H \rightarrow ee)$: 3.6×10⁻⁴ (3.5×10⁻⁴)

Can we observe Higgs decays to 1st and 2nd generation leptons?

- B(H→ee)_{SM}~5×10⁻⁹
- $B(H \rightarrow \mu\mu)_{SM} \sim 2 \times 10^{-4}$
- Can we confirm SM couplings?
- Any indication of BSM-induced enhancement?



$H \rightarrow \mu \mu$

- ✤ OS muon pairs p_T > 27(15) GeV
 ✤ Veto on identified *b*-jets (except ttH)
- 20 mutually exclusive categories:
 - S/B from dedicated BDT's go of A
 - VBF
 - ggF
 - VH
 - ttH



Simultaneous binned ML fits to the observed m_{µµ} distributions in the range 110 < m_{µµ} < 160 GeV
 Main bkg.: DY Z/γ*→µµ

Obs. (exp.) significance: $S=2.0\sigma$ (1.7 σ)

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SUMMARY

- Rich program of ATLAS searches for rare and forbidden
 SM Higgs decays
- Targeting loop-induced radiative decays, couplings to 1st and 2nd generation fermions and potential LFV in the Higgs sector
- SM holds strong but some discrepancies are to be followed up (e.g. $H \rightarrow l\tau$)
- Stay tuned for what Run 3 data reveals...

THANK YOU



$H \rightarrow Z\gamma \ (Z \rightarrow ll)$

- Single or di-lepton trigger
- OSSF lepton pair (>10 GeV) + photon (>10 GeV)
- Kinematic fit of m_{ll} after FSR correction
- Six mutually exclusive SR categories:
 - 1. VBF-enriched (BDT classification)
 - 2. High relative $p_T \left(p_T^{\gamma} / m_{Z\gamma} > 0.4 \right)$
 - 3. High $p_{Tt} ee$
 - 4. Low $p_{Tt} ee$
 - 5. High $p_{Tt} \mu \mu$
 - 6. Low $p_{Tt} \mu \mu$

 $p_{\mathrm{T}t} = |\vec{p}_{\mathrm{T}}^{Z\gamma} \times \hat{t}|, \text{ where } \hat{t} = (\vec{p}_{\mathrm{T}}^{Z} - \vec{p}_{\mathrm{T}}^{\gamma})/|\vec{p}_{\mathrm{T}}^{Z} - \vec{p}_{\mathrm{T}}^{\gamma}|$

- Signal shape parameterised by DSCB, background in each category by an analytic function (polynomial or power function)
- Z+jets reducible background estimated from data and re-constructed from simulated Zγ multiplied by the fitted ratio function.
- MC statistics second largest source of uncertainty (spurious signal) DIS2023 28/03/2023

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H→(*ll*)_{Im}γ m_{*ll*}<30 GeV

- Combination of single-lepton, dilepton, diphoton, and lepton+photon triggers
- OSSF lepton pair + photon (>20 GeV)
- Three categories of *ll* pairs:
 - 1. $\mu\mu (p_T > 3 \text{ GeV})$
 - 2. resolved $ee (p_T > 4.5 \text{ GeV})$
 - 3. merged $ee (p_T(ee) > 20 \text{ GeV})$
- Merged electrons distinguished from jets or single electrons using multivariate methods
- 9 mutually orthogonal SR categories defined based on VBF/non-VBF, high/low p_{Tt} , $\mu\mu$, ee resolved/merged
- Dominant background comes from nonresonant *llγ* events
- MC statistics second largest source of uncertainty (spurious signal)

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$H \rightarrow J/\psi\gamma, \psi(2S)\gamma, \Upsilon(1S,2S,3S)\gamma$ $H \rightarrow \omega\gamma, K^*\gamma$ (flavour changing)

arXiv:2208.03122 arXiv:2301.09938

(JHEP 07 (2018) 127)



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$H \rightarrow e\tau, H \rightarrow \mu\tau \ (\tau_{\nu}, \tau_{had})$

arXiv:2302.05225

Selection	$\ell au_{\ell'}$	$\ell au_{ m had}$		
	exactly 1 <i>e</i> and 1 μ , OS	exactly 1ℓ and $1\tau_{had-vis}$, OS		
Baseline	$ au_{ m had}$ -veto	$ au_{ m had}{ m Tight~ID}$		
		Medium eBDT ($e\tau_{had}$)		
	<i>b</i> -veto	<i>b</i> -veto		
	$p_{\rm T}^{\ell_1} > 45 (35) {\rm GeV} {\rm MC}$ -template (Symmetry method)	$p_{\rm T}^\ell > 27.3 {\rm GeV}$		
	$p_{\mathrm{T}}^{\ell_2} > 15 \mathrm{GeV}$	$p_{\rm T}^{\tau_{\rm had-vis}} > 25 {\rm GeV}, \eta^{\tau_{\rm had-vis}} < 2.4$		
	$30 \text{GeV} < m_{\ell_1 \ell_2} < 150 \text{GeV}$	$\sum \cos \Delta \phi(i, E_{\rm T}^{\rm miss}) > -0.35$		
	$0.2 \leq \operatorname{strack}(\ell_{1})/\operatorname{scluster}(\ell_{1}) \leq 1.25$ (MC town late)	$i=\ell, \tau_{\text{had-vis}}$		
	$0.2 < p_{\rm T}^{\rm min}(t_2 = e)/p_{\rm T}^{\rm min}(t_2 = e) < 1.25$ (MC-template)	$ \Delta\eta(t, \tau_{\rm had-vis}) < 2$		
	track a_0 significance requirement (see text)			
	$ z_0 \sin \theta < 0.5 \mathrm{mm}$			
	Baseline			
VBF	≥ 2 jets, $p_{T}^{j_{1}} > 40$ GeV, $p_{T}^{j_{2}} > 30$ GeV			
	$ \Delta \eta_{jj} > 3, m_{jj} > 400 \text{GeV}$			
non-VBF	Baseline plus fail VBF categorisation			
	-	veto events if		
	-	$90 < m_{\rm vis}(e, \tau_{\rm had-vis}) < 100 {\rm GeV}$		

Selection	$\ell au_{\ell'}$	$\ell au_{ m had}$	
misidentified background CR	<i>non-VBF</i> (or <i>VBF</i>) category with statistically independent lepton (ℓ or $\tau_{\text{had-vis}}$) selection, see text		
$Z \rightarrow \mu \mu \operatorname{CR/VR} \left(\ell \tau_{\ell'} / \ell \tau_{\text{had}} \right)$	$\begin{array}{l} \textit{Baseline with 35 GeV} < p_{\rm T}^{\ell_1} < 45 \ {\rm GeV} \\ 75 \ {\rm GeV} < m_{\ell_1 \ell_2} < 100 \ {\rm GeV} \\ \Delta \phi(\ell_2, E_{\rm T}^{\rm miss}) < 1.5 \\ 1.25 < p_{\rm T}^{\rm rack}(\ell_2)/p_{\rm T}^{\rm cluster}(\ell_2) < 3 \end{array}$	$Baseline \\ \eta(\tau) < 0.1 \\ 90 \text{ GeV} < m_{\text{coll}}(\mu, \tau) < 110 \text{ GeV}$	
top-quark CR	<i>non-VBF</i> (or <i>VBF</i>) selection with inverted <i>b</i> -veto requirement	_	
$Z \rightarrow \tau \tau \ \mathrm{CR}$	<i>non-VBF</i> (or <i>VBF</i>) selection with 35 GeV $< p_{T}^{\ell_1} < 45$ GeV	-	
Diboson VR	Baseline $p_T^{\ell_2} > 30 \text{ GeV}$ $100 \text{ GeV} < m_{\ell_1 \ell_2} < 150 \text{ GeV}$ $m_T > 30 \text{ GeV}$ veto events with jets with $p_T > 30 \text{ GeV}$	-	



Method	Channel	Category	Region	1 POI fit	2 POI fit
	$\ell au_{\ell'}$	non-VBF	SR	\checkmark	\checkmark
			$Z \rightarrow \tau \tau \ \mathrm{CR}$	\checkmark	\checkmark
MC-template			Top-quark CR	\checkmark	\checkmark
ine template		VBF	SR		\checkmark
			$Z \rightarrow \tau \tau \ \mathrm{CR}$		\checkmark
			Top-quark CR		\checkmark
MC template	$\ell au_{ m had}$	non-VBF	SR	\checkmark	\checkmark
		VBF	SR	\checkmark	\checkmark
Summatry	$\ell au_{\ell'}$	non-VBF	SR		
		VBF	SR	\checkmark	

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$H \rightarrow \mu \mu$

VBF category

Two jets

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- Veto: b-jets & additional leptons
- BDT (O_{VBF}) based on 17 variables which include μμ and *jj* kinematics
- 4 categories with S/B ranging from 18% to 2.8%



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ggF category

- Three jet cathegories (0-2),
- BDT (O_{ggF}⁽⁰⁻²⁾) based on up to 17 variables which include μμ and optionally jet kinematics
- 3x4 categories with S/B ranging from 1.7% to 0.07%



$H \rightarrow \mu \mu$

VH category

- Veto: b-jets
- Additional isolated $\mu(e) p_T > 10(15)$
- Two separate BDT's targeting WH and ZH final states
- 2 WH and 1 ZH signal categories defined with S/B ranging from 3.7% to 0.8%

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ttH category

- At least one b-jet (85% WP)
- Additional isolated $\mu(e) p_T > 15 \text{ GeV}$
- BDT taking 12 inputs, including multiplicity of *b*-jets
- ttH category optimizes expected significance, with S/B of 8%





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Corresponding CMS results

HIG-20-009

HIG-20-009

HIG-22-002

- $H \to Z\gamma \ (Z \to ll)$ HIG-19-014 $\mu = 2.0 \pm 0.9 (tot.)$ sign.=2.7 σ
- $H \rightarrow \gamma^*(ll)_{Im}\gamma$ HIG-17-007 95% CL limit: 3.9 (2.0) x SM (36 fb⁻¹)
 - 95% CL limit: $B(H \rightarrow e\tau)$: 0.22% (0.16%) 95% CL limit: $B(H \rightarrow \mu\tau)$: 0.15% (0.15%)



H→*ee* HIG-21-015

NEW

 $H \rightarrow \mu \mu$ HIG-19-006

95% CL limit: $B(H \rightarrow ee)$: 3.0×10⁻⁴ (3.0×10⁻⁴)

Obs. (exp.) significance: $S=3.0\sigma$ (2.5 σ) 95% CL: $0.8 \times 10^{-4} < B(H \rightarrow \mu\mu) < 4.5 \times 10^{-4}$

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 $H \rightarrow e\tau$

 $H \rightarrow \mu \tau$

 $H \rightarrow e\mu$