Measurements of Higgs Anomalous Couplings at ATLAS and CMS (LFV, FCNC)

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On behalf of the ATLAS and CMS Collaborations
Introduction

- The 125 GeV Higgs boson discovered by CMS and ATLAS experiments in 2012
- Data collected during Run 1 and Run 2 of the LHC used for experimental measurements of the Higgs signal strength compared to the Standard Model (SM)

- Higgs appears to be that of the SM
- SM is a highly successful theory but it has several shortcomings
  - Absence of gravity
  - Absence of explanation for Dark Matter
  - CP violation
  - the Hierarchy problem
  - .....
Higgs as a probe for new physics

- Search for decays highly suppressed in the SM
- Observation would point to the physics beyond the Standard Model (BSM)
  - Flavour changing neutral currents (FCNC)
  - Lepton flavour violating (LFV) decays of the Higgs

Results Based on data analyses from ATLAS and CMS with LHC pp collisions at 13 TeV

- In many cases full Run 2 statistics: 140 fb	extsuperscript{-1} from results released in the last year
- Due to time constraints can only show a selection of results with a focus on the most recent ones

  - FCNC
    - FCNC of the top quark and Higgs final states to 2 photons. CMS, Run 2, 137 fb	extsuperscript{-1}. New submitted 3\textsuperscript{rd} November 2021 arXiv:2111.02219
    - Search for FCNC $t \rightarrow qH$ using $H \rightarrow bb, H \rightarrow \tau_{l,h}, H \rightarrow WW^{*}, \tau_{l} \tau_{l}, ZZ^{*}$, $H \rightarrow \gamma\gamma$ ATLAS, Run 2, 36 fb	extsuperscript{-1} JHEP 05 (2019) 123

  - LFV
    - $H \rightarrow \tau\mu$, CMS, Run 2, 137 fb	extsuperscript{-1} Phys. Rev. D 104 (2021) 032013
    - $H \rightarrow \tau\mu$, ATLAS, Run 2, 36 fb	extsuperscript{-1} Phys. Lett. B 800 (2020) 135069
    - $H \rightarrow e\mu$, ATLAS, Run 2, 139 fb	extsuperscript{-1} Phys. Lett. B 801 (2020) 135148
Flavour Changing Neutral Currents

- Flavour changing quark decays mediated by neutral currents are forbidden at tree level in the Standard Model.
- Can proceed at higher orders but heavily suppressed by GIM mechanism or CKM unitary constraints.
- Decay of a top quark (t) into a Higgs boson (H) and up quark (u), \( t \rightarrow Hu \), or charm quark (c), \( t \rightarrow Hc \), are expected to be \( O(10^{-17}) \) and \( O(10^{-15}) \).
- Any observation of \( t \rightarrow Hq \) would be indication of new physics.
- Example single \( t \) (ST) and \( tt \) production (TT) with \( H \rightarrow \gamma\gamma \) decay.
- Full Run 2 data analysis from CMS using H→γγ decays
- The Higgs decay follows a similar strategy to H→γγ analyses
- Background and signal (for t →Hu and t →Hc) separated using BDTs
- With BDTs trained for the two dominant SM backgrounds
  - resonant
  - non-resonant
- Divided into exclusive categories for top decay
  - Leptonic (3 BDT score sub-categories)
  - Hadronic (4 BDT score sub-categories)
- Invariant mass for $H \rightarrow \gamma \gamma$ decay candidates $m_{\gamma \gamma}$
- Expected signal and resonant background $m_{\gamma \gamma}$ distributions modelled using the sum of a double-sided Crystal Ball function and Gaussian
- The non-resonant background is modelled directly from data, using the discrete profiling method
- No excess observed above background observed in data
- Use to place limits of FCNC branching ratios
FCNC, $t \rightarrow Hq$, $H \rightarrow \gamma\gamma$  

- Observed (expected) 95% CL upper limits on $B(t \rightarrow Hu)$ and $B(t \rightarrow Hc)$ are 0.019 (0.031)% and 0.073 (0.051)%

- Use to place limits on coupling
  - Observed (expected) 95% CL upper limits on $|\kappa_{Hut}|$ and $|\kappa_{Hct}|$ are 0.037 (0.047) and 0.071 (0.060)
**FCNC Combination**

- ATLAS combination using $H \rightarrow bb$, $H \rightarrow \tau_l, \tau_h$, $H \rightarrow WW^*, \tau_l \tau_l, ZZ^*$, $H \rightarrow \gamma \gamma$ for 36 fb$^{-1}$ of Run 2 data

- Results of best fit to data for $B(t \rightarrow Hu)$ and $B(t \rightarrow Hc)$

- All analyses (except $H \rightarrow bb$) are statistically limited
Observed (expected) 95% CL upper limits on $B(t \to Hu)$ and $B(t \to Hc)$ are 0.12 (0.083)% and 0.11 (0.083)%

Observed (expected) 95% CL upper limits on $|\kappa_{Hut}|$ and $|\kappa_{Hct}|$ are 0.066 (0.055) and 0.064 (0.055)
Lepton Flavour Violating Higgs Decays

- Lepton flavour violation is not allowed in the SM. However, the observation of neutrino oscillations indicates that LFV occurs in nature!
- Many BSM models include them e.g. SUSY and some composite Higgs model allow LFV Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$
- ATLAS and CMS searches have been performed in the $e\tau$ and $\mu\tau$ channel, with ATLAS additionally in the $e\mu$ channel
- $H \to e\tau/\mu\tau$, CMS, Run 2, 137 fb$^{-1}$ [Phys. Rev. D 104 (2021) 032013]
- $H \to e\tau/\mu\tau$, ATLAS, Run 2, 36 fb$^{-1}$ [Phys. Lett. B 800 (2020) 135069]
- $H \to e\mu$, ATLAS, Run 2, 139 fb$^{-1}$ [Phys. Lett. B 801 (2020) 135148]
LFV decays: $H \to e\tau/\mu\tau$

- Channels and final states $H \to \mu\tau_h$, $H \to \mu\tau_e$, $H \to e\tau_h$, $H \to e\tau_\mu$:
- Categories:
  - $gg \to H$: 0 jet, 1 jet, 2 jets
  - $qq \to H$: 2 jets ($m_{jj} > 500(550)$ GeV $e\tau(\mu\tau)$)
- $Z \to \tau\tau$, top quark processes, mis-identified objects are the major backgrounds
  - Background estimation using data driven techniques + simulation
- BDTs trained in each channel separately
  - Maximum likelihood fit to BDT output discriminators
  - Simultaneously over all channels and categories
LFV decays: $H \rightarrow e\tau/\mu\tau$

- No significant excesses over the SM prediction are found
- Upper limits on LFV branching fractions at 95% CL: $\text{BR}(H \rightarrow \mu\tau) < 0.15(0.15)\%$, $\text{BR}(H \rightarrow e\tau) < 0.22(0.16)\%$

Previous results based on 36 fb$^{-1}$:
- CMS: $B(H \rightarrow \mu\tau) > 0.25(0.25)\%$ and $B(H \rightarrow e\tau) > 0.61(0.37)\%$
- ATLAS: $B(H \rightarrow \mu\tau) > 0.28(0.37)\%$ and $B(H \rightarrow e\tau) > 0.47(0.34)\%$

Paul Thompson  Anomalous Higgs Couplings at CMS and ATLAS
Branching fraction limits converted to limits on off-diagonal Yukawa couplings

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

\[ \mathcal{B} \left( H \rightarrow \ell^\alpha \ell^\beta \right) = \frac{\Gamma \left( H \rightarrow \ell^\alpha \ell^\beta \right)}{\Gamma \left( H \rightarrow \ell^\alpha \ell^\beta \right) + \Gamma_{SM}} \]

here, \( \ell^\alpha, \ell^\beta \) are different flavored leptons

Most stringent limits on branching fractions and couplings from LHC
The $H \rightarrow e\mu$ analysis follows a similar strategy to $H \rightarrow \mu\mu$ analyses.

Events are selected with one electron and one muon and are categorized.

Eight categories are defined (S/B):

- A low-$p_T$ category in which one of the selected leptons has $p_T < 27$ GeV.
- A VBF category for events with two jets with $|\Delta \eta_{jj}| > 3$ and $m_{jj} > 500$ GeV.
- Remaining events are categorized as central if both leptons have $|\eta| < 1$, otherwise they are categorized as non-central.
- These events are then classified based on $p_T^{ll}$ as low ($p_T^{ll} \leq 15$), mid ($15 < p_T^{ll} \leq 50$) or high-$p_T$ ($p_T^{ll} > 50$).

No excess above background only fit.

Use to set limits on LFV branching ratio. Statistical uncertainties dominate.
LFV Higgs Decays

- Upper limits on LFV branching fractions at 95% CL
  - $B(H \rightarrow \mu \tau) < 0.28\%$
  - $B(H \rightarrow e \tau) < 0.47\%$
  - $B(H \rightarrow e \mu) < 0.0062\%$ (0.0059%)  
    

- Branching fraction limits converted to limits on off-diagonal Yukawa couplings
Summary

- Searches by ATLAS and CMS for FCNC decays involving Higgs boson decays
- Searches have also been performed for LFV Higgs boson decays
- No evidence has yet been found and so limits have been set

- Some analyses yet to exploit full Run 2 data
- The start of LHC Run 3 is in 2022
- Looking forward to more results from ATLAS and CMS on the search for Anomalous Higgs production...
Back-up