

# Search for exotic Higgs productions and decays with ATLAS

Xin Chen

*Tsinghua University*



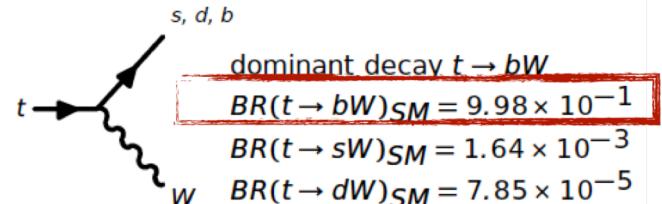
希格斯物理小型研讨会  
中国高等科学技术中心，03/23/2023

# Outline

- As LHC is accumulating more data, the Higgs physics is entering a era of precision measurements
- It is actually strange that the Higgs we found is very much like what the SM predicts it to be – fine tuning problem
- Looking for new physics associated with Higgs is always a vigorous program at LHC, in the belief that this particle is a portal to yet unknown beyond SM physics (such as the dark sector)
- In this talk, I will cover the following topics
  - Higgs Flavor Changing Neutral Current (FCNC) interaction with the top quark
  - Higgs Lepton Flavor Violation (LFV) decays
  - Heavy Higgs production and decay with EFT

# FCNC – Why Top?

- Top is the heaviest (short lifetime) known fundamental particle
  - it is the only quark that decays before hadronizing
  - spin information passes to decay products
- Dominant decay mode:  $t \rightarrow Wb$ 
  - all other couplings can be considered rare => FCNC decay
- Many SM extensions predict the new particles that couple to top quarks
- LHC is a Top quark factory
  - Large top production allows many precision measurements/searches for many SM and BSM analyses
  - FCNC involving lighter quark covered by B and Charm factories  
[1204.0735 ATL-PHYS-PROC-2016-136](https://arxiv.org/abs/1204.0735)



# Why FCNC?

- Flavor-changing neutral currents (FCNC) decays
  - are forbidden at tree level
  - occur at one-loop level but are strongly suppressed by the **GIM mechanism**
  - significantly enhanced in BSM extensions (maximum up to  $\sim 10^{-3}$ )
  - Any observation of top FCNC = BSM physics

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \rightarrow Zu$	$7 \times 10^{-17}$	—	—	$\leq 10^{-7}$	$\leq 10^{-6}$	
$t \rightarrow Zc$	$1 \times 10^{-14}$	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \rightarrow gu$	$4 \times 10^{-14}$	—	—	$\leq 10^{-7}$	$\leq 10^{-6}$	—
$t \rightarrow gc$	$5 \times 10^{-12}$	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \rightarrow \gamma u$	$4 \times 10^{-16}$	—	—	$\leq 10^{-8}$	$\leq 10^{-9}$	—
$t \rightarrow \gamma c$	$5 \times 10^{-14}$	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \rightarrow hu$	$2 \times 10^{-17}$	$6 \times 10^{-6}$	—	$\leq 10^{-5}$	$\leq 10^{-9}$	—
$t \rightarrow hc$	$3 \times 10^{-15}$	$2 \times 10^{-3}$	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

[1311.2028](#)

# Top SMEFT

- Model independent approach => effective field theory
  - $L_{EFT} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \dots$
- $\Lambda$ : new physics energy scale (usually set to 1 TeV)
- $O_i$ : dimension six operators (15 are relevant for top quark physics)
- dim-5 operators: introduce lepton flavor violation, not considered in top FCNC studies

$$O_{\phi q}^{(3,i+3)} = i \left( \phi^\dagger \overleftrightarrow{D}_\mu^I \phi \right) (\bar{q}_i \gamma^\mu \tau^I Q)$$

$$O_{\phi q}^{(1,i+3)} = i \left( \phi^\dagger \overleftrightarrow{D}_\mu^I \phi \right) (\bar{q}_i \gamma^\mu Q)$$

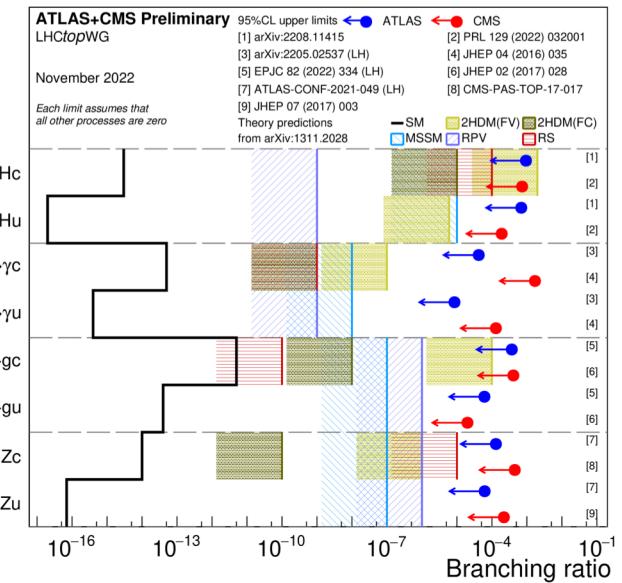
**tqZ/tqy**

$$O_{\phi u}^{(i+3)} = i \left( \phi^\dagger \overleftrightarrow{D}_\mu^I \phi \right) (\bar{u}_i \gamma^\mu t)$$

$$O_{uB}^{(i3)} = g_Y (\bar{q}_i \sigma^{\mu\nu} t) \tilde{\phi} B_{\mu\nu}, \quad O_{uW}^{(i3)} = g_W (\bar{q}_i \sigma^{\mu\nu} \tau^I t) \tilde{\phi} W_{\mu\nu}^I$$

$$O_{uG}^{(i3)} = g_s (\bar{q}_i \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A, \quad O_{u\phi}^{(i3)} = (\phi^\dagger \phi) (\bar{q}_i t) \tilde{\phi}$$

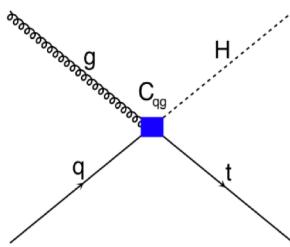
**tqH/tqg**



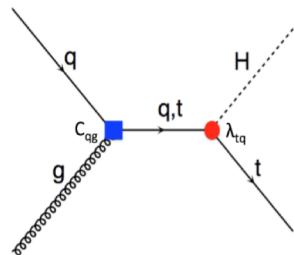
# tqH interaction

- Higgs as a neutral current involves flavor change interactions in top SMEFT

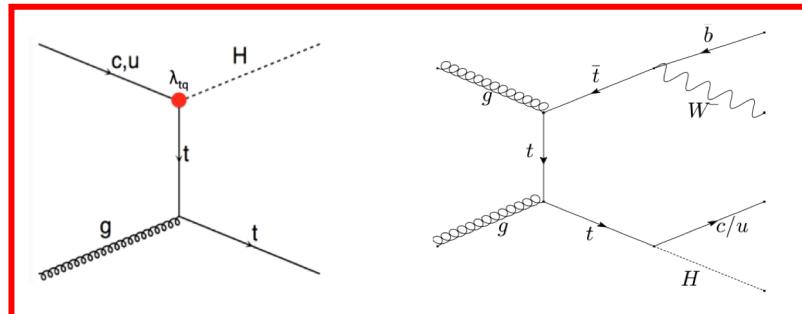
$$\mathcal{L}_{EFT} = \frac{C_{u\phi}^{i3}}{\Lambda^2} (\phi^\dagger \phi) (\bar{q}_i t) \tilde{\phi} + \frac{C_{u\phi}^{3i}}{\Lambda^2} (\phi^\dagger \phi) (\bar{t}_i q) \tilde{\phi}$$



FCNC tqg



FCNC tqH+tqg



FCNC tqH

Summary for searching for FCNC tqH in different decay modes

		$\mathcal{L} [\text{fb}^{-1}]$	95% CL observed upper limits	
			on $\mathcal{B}(t \rightarrow cH)$	on $\mathcal{B}(t \rightarrow uH)$
ATLAS	$H \rightarrow b\bar{b}$ [32]	36.1	$4.2 \times 10^{-3}$	$5.2 \times 10^{-3}$
	$H \rightarrow \gamma\gamma$ [33]	36.1	$2.2 \times 10^{-3}$	$2.4 \times 10^{-3}$
	$H \rightarrow \tau\tau$ ( $\tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$ ) [32]	36.1	$1.9 \times 10^{-3}$	$1.7 \times 10^{-3}$
	$H \rightarrow WW^*, \tau\tau, ZZ^*$ ( $2\ell\text{SS}, 3\ell$ ) [34]	36.1	$1.6 \times 10^{-3}$	$1.9 \times 10^{-3}$
	Combination [32]	36.1	$1.1 \times 10^{-3}$	$1.2 \times 10^{-3}$
CMS	$H \rightarrow b\bar{b}$ [35]	35.9	$4.7 \times 10^{-3}$	$4.7 \times 10^{-3}$
	$H \rightarrow b\bar{b}$ [36]	137	$9.4 \times 10^{-4}$	$7.9 \times 10^{-4}$
	$H \rightarrow \gamma\gamma$ [37]	137	$7.3 \times 10^{-4}$	$1.9 \times 10^{-4}$

# Samples

- Data: collected by ATLAS with an integrated luminosity of  $139 \text{ fb}^{-1}$
- MC Signal: FCNC production and decay sample
  - generated from the TopFCNC model using MADGRAPH5\_aMC@NLO at NLO in QCD
  - The parton shower and hadronization are held by Pythia8 with A14 tune
  - NNPDF30NLO parton distribution functions is used
  - Left handed (LH) operator and right handed operator (RH) shows no difference. So the two sets of samples are merged together for higher statistics
- Background: ttbar, Ztautau, diboson, single top...

Process	Generator		PDF set		Tune	Order
	ME	PS	ME	PS		
$t\bar{t}(qH)$ Signal	POWHEG-BOX	PYTHIA 8	NNPDF30NLO	NNPDF23LO	A14	NLO
$t\bar{H}$ Signal	MADGRAPH5_aMC@NLO	PYTHIA 8	NNPDF30NLO	NNPDF23LO	A14	NLO
$W/Z+jets$	SHERPA 2.2.1		NNPDF30NNLO		SHERPA	NLO/LO
$t\bar{t}$	POWHEG-BOX	PYTHIA 8	NNPDF30NLO	NNPDF23LO	A14	NLO
Single top	POWHEG-BOX	PYTHIA 8	NNPDF30NLO	NNPDF23LO	A14	NLO
$t\bar{t}X$	MADGRAPH5_aMC@NLO	PYTHIA 8	NNPDF30NLO	NNPDF23LO	A14	NLO
$VH$	POWHEG-BOX	PYTHIA 8	PDF4LHC15	CTEQ6L1	AZNLO	NLO
$tH$	MADGRAPH5_aMC@NLO	PYTHIA 8	CT10PDF		A14	NLO
Diboson	SHERPA 2.2.1		NNPDF30NNLO		SHERPA	NLO/LO

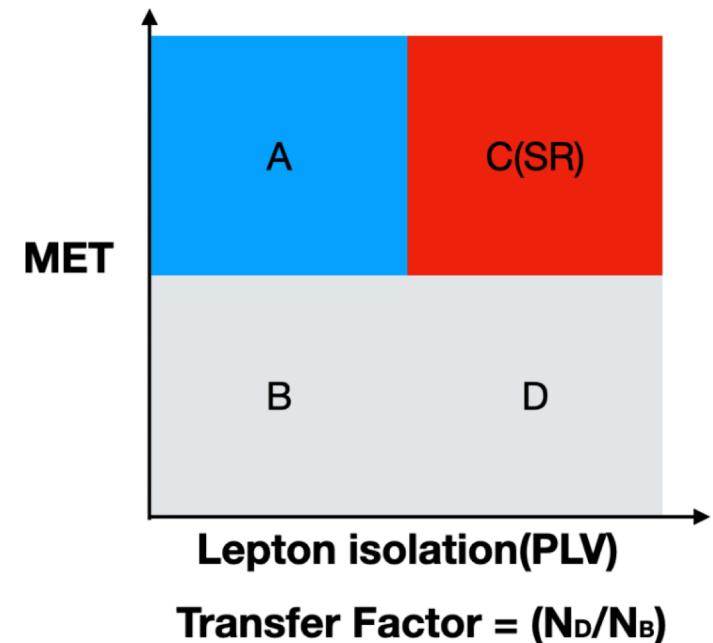
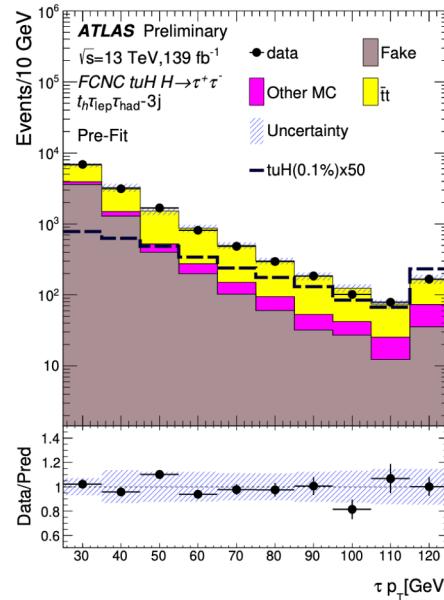
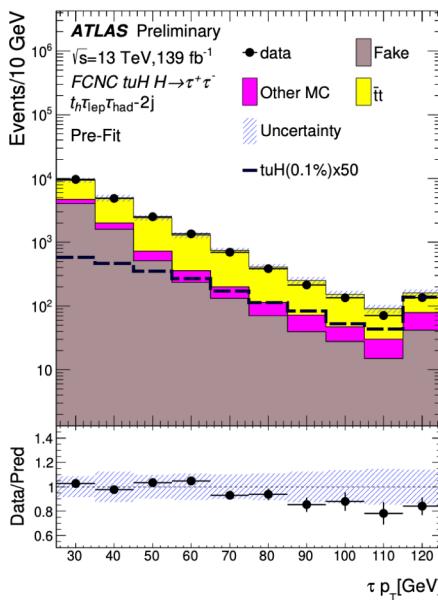
# Selections

- Object selection
  - Jets
    - AntiKt4EMPFlow
    - DL1r 70%
    - $P_T > 25\text{GeV}, |\eta| < 4.5$
  - Muons
    - Loose ID
    - Loose Isolation
    - $P_T > 10\text{GeV}, |\eta| < 2.5$
  - Electrons
    - Loose ID
    - Loose Isolation
    - $P_T > 15\text{GeV}, |\eta| < 2.5$
  - $\tau_{had-vis}$ 
    - RNN medium
    - eVeto Medium
    - $P_T > 25\text{GeV}, |\eta| < 2.5$
- Signal Region Definitions

Requirement	leptonic channel			hadronic channel $t_h \tau_{had} \tau_{had}$
	$t_h \tau_{lep} \tau_{had}$	$t_l \tau_{had} \tau_{had}$	$t_l \tau_{had}$	
Trigger		single-lepton trigger		di- $\tau$ trigger
Leptons		=1 isolated $e$ or $\mu$		no isolated $e$ or $\mu$
$\tau_{had}$	=1 $\tau_{had}$	$\geq 2 \tau_{had}$	=1 $\tau_{had}$	$\geq 2 \tau_{had}$
Electric charge ( $Q$ )	$Q_\ell \times Q_{\tau_{had,1}} < 0$	$Q_{\tau_{had,1}} \times Q_{\tau_{had,2}} < 0$	$Q_\ell \times Q_{\tau_{had,1}} > 0$	$Q_{\tau_{had,1}} \times Q_{\tau_{had,2}} < 0$
Jets	3, $\geq 4$ jets	$\geq 1$ jets	2, $\geq 3$ jets	3, $\geq 4$ jets
$b$ -tagging		=1 $b$ -tagged jets		=1 $b$ -tagged jets

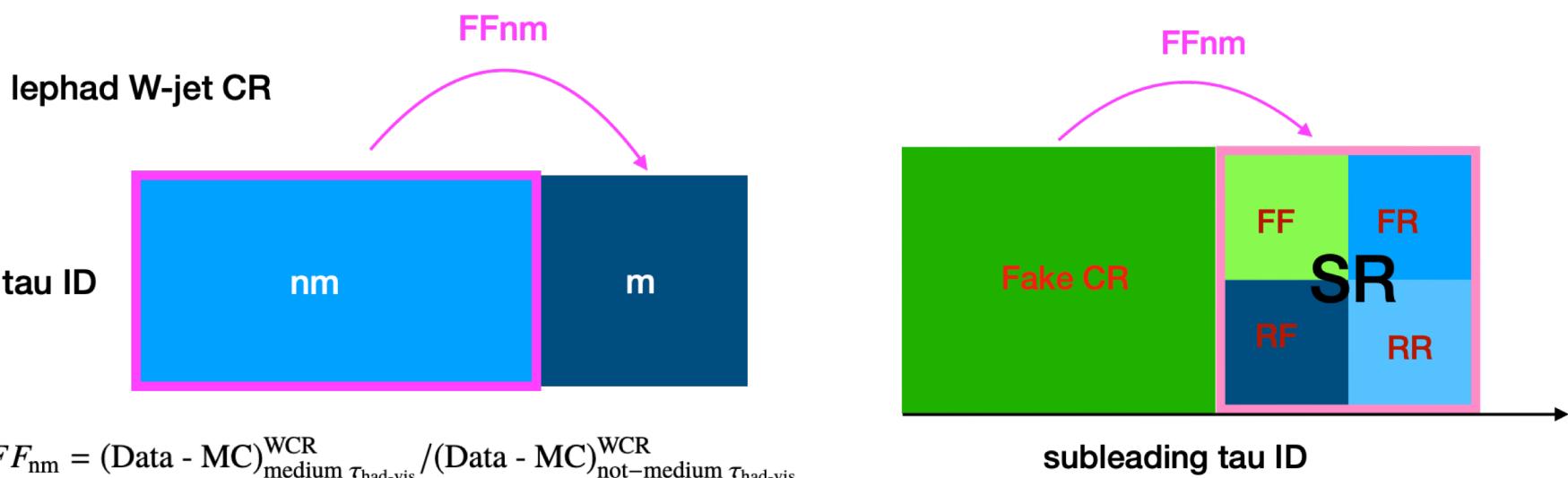
# Background estimation

- Derive different scale factors for each fake source in the following CRtts:
- Four types of fake tau:
  - w-jet faking taus with opposite charge to the lepton ( $t_\ell t_h 2b\tau_{had} 2jOS$   $t_\ell t_h 2b\tau_{had} 3jOS$ )
  - w-jet faking taus with same charge to the lepton ( $t_\ell t_h 2b\tau_{had} 2jSS$   $t_\ell t_h 2b\tau_{had} 3jSS$ )
  - b-jet faking tau ( $t_\ell t_\ell 1b\tau_{had}$ )
  - other faking tau ( $t_\ell t_\ell 2b\tau_{had}$ )
- QCD contribution is estimated by ABCD method



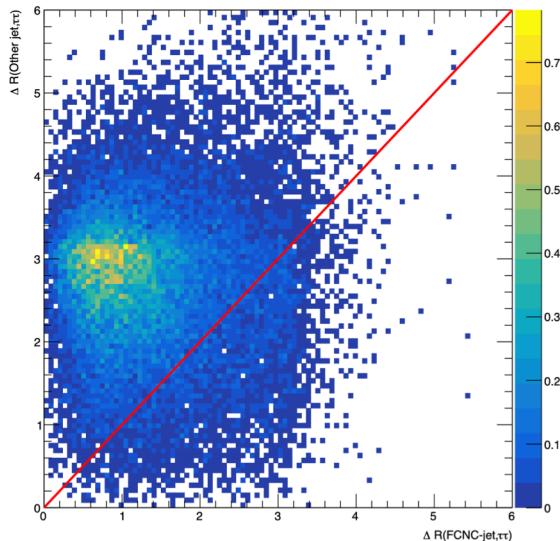
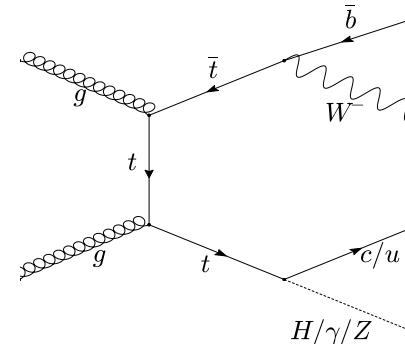
# Background estimation

- Fake Factor Method (data driven), derived fake factor in different n-tracks, pt, and eta.
- Fake CR: 2 os  $\tau_{had}$  with leading one passing RNN medium, subleading one failing the RNN medium, other requirements are the same as SR.
- Signal region contribution:
  - RR: Both taus are real (MC)
  - FR: Leading tau is fake, sub-leading tau is real (MC, uncertainty:50%)
  - RF: Leading tau is real, sub-leading tau is fake (Fake Factor Method)
  - FF: Both taus are fake (Fake Factor Method)



# Signal reconstruction

- If W decays hadronically:
  - tau + tau -> Higgs mass
  - c/u + H -> top mass
  - q+q -> W mass
  - q+q+b -> top mass
- Problems to be solved:
  - Which jet is c/u from FCNC top decay
  - How to treat neutrino from tau decay?
- The jet closest to ditau candidates is chosen as FCNC-jet ( reconstruction rate is 70%-85%)
- Using collinear approximation fit. Two constraints are from MET and one from Higgs mass. The floating parameter is the energy ratio of the tau visible decay product.

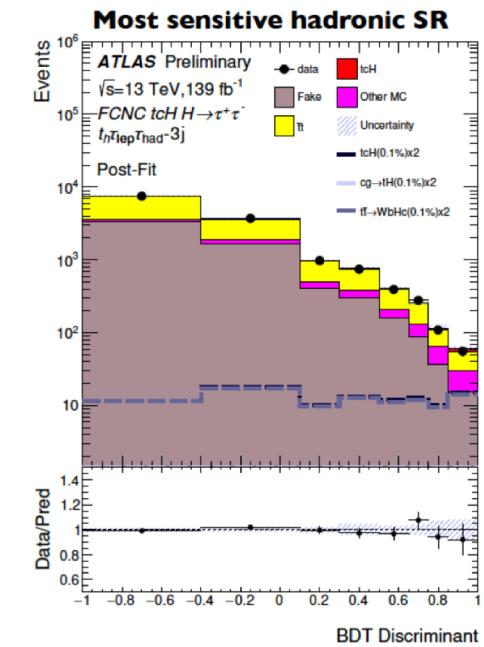
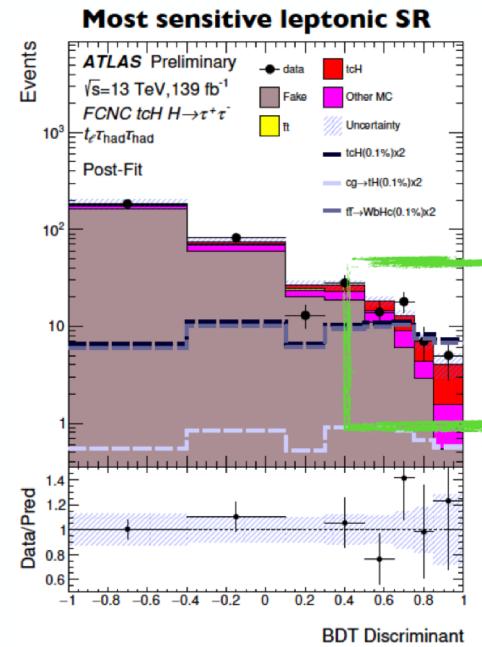
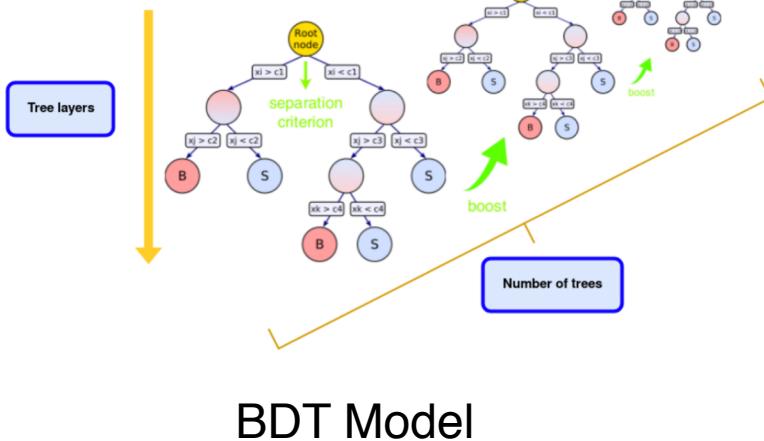


$$\chi^2 = \left( \frac{m_H^{\text{fit}} - 125}{\sigma_{\text{Higgs}}} \right)^2 + \left( \frac{E_{x,\text{miss}}^{\text{fit}} - E_{x,\text{miss}}}{\sigma_{\text{miss}}} \right)^2 + \left( \frac{E_{y,\text{miss}}^{\text{fit}} - E_{y,\text{miss}}}{\sigma_{\text{miss}}} \right)^2$$

from fit to FCNC signal MC

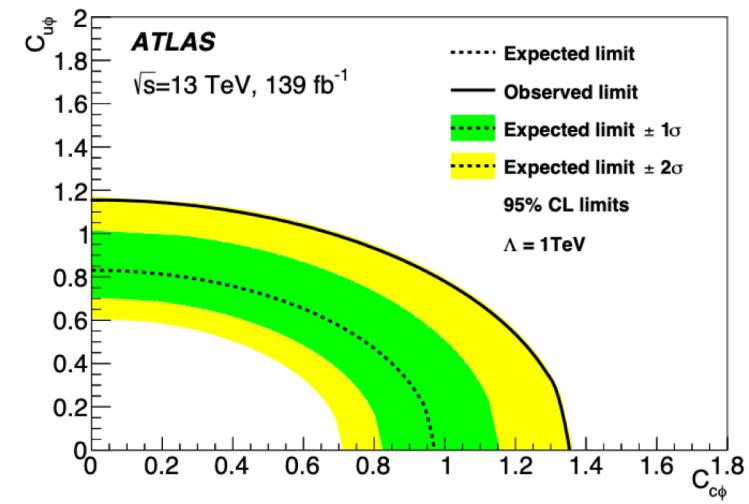
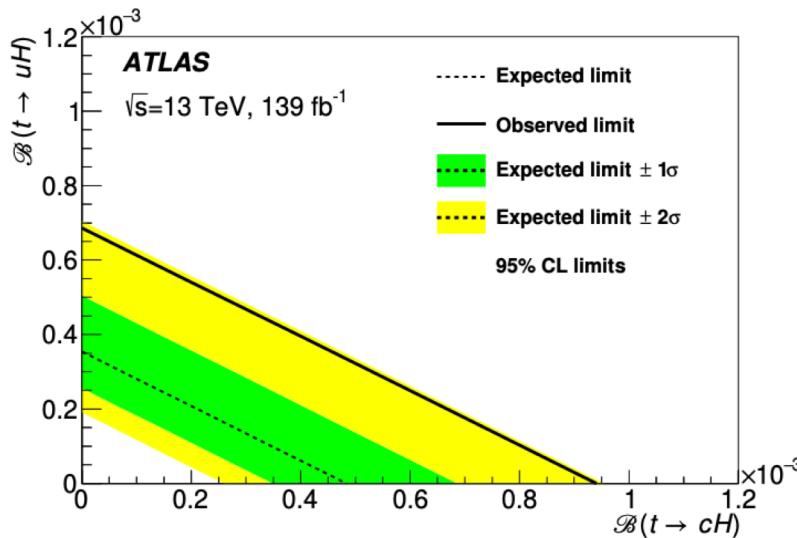
# Signal and background separation

- Separation of both signal modes from background using GBDT method
- BDT hyper-parameters are obtained from the alternative signal PS samples.
- Train BDT separately for decay and production processes, tch and tuH, but it gives similar sensitivity.
  - One BDT per signal region with 12-17 kinematic input features
- BDT output score as an input to the final fit.



# Results

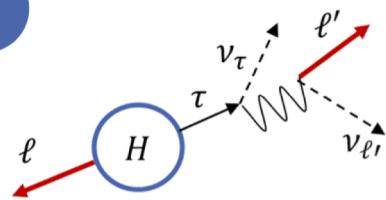
- Data are compatible with background prediction in most SRs
  - slight excess of 2.3 sigma in  $t_\ell \tau_{had} \tau_{had}$  SR
- Upper limits at 95% CL set on branching ratios
- Improvements of factor **2(observed)-4(expected)** in limits on BRs compared with partial run-2 analysis



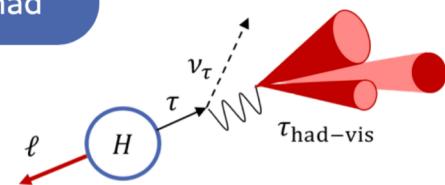
# LFV - introduction

- Search for  $H \rightarrow e\tau$  and  $H \rightarrow \mu\tau$ , two independent signals. Analysis targets leptonic tau decays (two different bckg. estimation methods) and hadronic tau decays.

leplep



lephad



**Lep-lep** final states with one electron and one muon.

Channel classification ( $e\tau_\mu$  or  $\mu\tau_e$ ) based on  $p_T$  ordering in the Higgs frame:  $p_T(l_H) > p_T(l_\tau)$ .

Two background estimation method:

- **Symmetry based leplep**

Fake background data-driven. Other backgrounds estimated mainly data-driven via symmetry method

- **MC-template leplep**

Fake background data-driven. Other backgrounds estimated with MC templates and normalization of main backgrounds data-driven from CRs

**Lep-Had** final states with one lepton and one hadronic tau (ethad or muthad):

Only one background estimation is used:

- **MC-template lephad**

Fake background data-driven. Other backgrounds estimated through MC

# Analysis strategy

Main Higgs boson production modes considered for LFV signal (ggH, VBF, VH).

Categorization: loose preselection (baseline) and further split into **VBF and non-VBF** regions.

**MVA** used to enhance sensitivity. Final discriminants are the MVA scores.

Statistical analysis for signal strength  $\mu = B(H \rightarrow l\tau)$  extraction with Maximum Binned Likelihood fit combining VBF and Non-VBF regions:

- **1 POI fit: independent fit** for each signal,  $B(H \rightarrow e\tau) = 0$  when fitting  $B(H \rightarrow \mu\tau)$  and vice versa.
  - For lep-lep final states, either MC-template or Symmetry is used based on the expected sensitivity of each category, MC-template is used for non-VBF and Symmetry for VBF in both final states.
- **2 POI fit: simultaneous fit** of  $B(H \rightarrow e\tau)$  and  $B(H \rightarrow \mu\tau)$ .
  - Only MC-template method is used, Symmetry method is sensitive only to the difference  $B(H \rightarrow \mu\tau) - B(H \rightarrow e\tau)$ .
- **Fit of the  $B(H \rightarrow \mu\tau) - B(H \rightarrow e\tau)$  difference.**
  - 1 POI fit setup of the lep-lep channel using the Symmetry method
  - Measurement also used to evaluate compatibility with MC-template lep-lep.

# Categories

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
	exactly 1e and 1 $\mu$ , OS $\tau_{\text{had-veto}}$	exactly 1 $\ell$ and 1 $\tau_{\text{had-vis}}$ , OS $\tau_{\text{had}} \text{Tight ID}$
<i>Baseline</i>	<i>b</i> -veto $p_T^{\ell_1} > 45$ (35) GeV MC-template (Symmetry method) $p_T^{\ell_2} > 15$ GeV $30 \text{ GeV} < m_{\ell_1\ell_2} < 150$ GeV $0.2 < p_T^{\text{track}}(\ell_2 = e)/p_T^{\text{cluster}}(\ell_2 = e) < 1.25$ (MC-template) track $d_0$ significance requirement (see text) $ z_0 \sin \theta  < 0.5$ mm	Medium eBDT ( $e\tau_{\text{had}}$ ) <i>b</i> -veto $p_T^{\ell} > 27.3$ GeV $p_T^{\tau_{\text{had-vis}}} > 25$ GeV, $ \eta^{\tau_{\text{had-vis}}}  < 2.4$ $\sum_{i=\ell, \tau_{\text{had-vis}}} \cos \Delta\phi(i, E_T^{\text{miss}}) > -0.35$ $ \Delta\eta(\ell, \tau_{\text{had-vis}})  < 2$
<i>VBF</i>	<i>Baseline</i>	
	$\geq 2$ jets, $p_T^{j_1} > 40$ GeV, $p_T^{j_2} > 30$ GeV $ \Delta\eta_{jj}  > 3$ , $m_{jj} > 400$ GeV	
<i>non-VBF</i>	<i>Baseline</i> plus fail VBF categorisation	
	–	veto events if $90 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 100$ GeV

- VBF and non-VBF categories as well as lep-lep and lep-had channels are mutually exclusive
- Selection is as similar as possible between MC-template and Symmetry, differences related to the symmetry assumption and definition of CRs.

# Background estimation Symmetry method

- Data-driven method where the main backgrounds in one channel are estimated using the data yields in the other channel
- SM processes are symmetric ( $e\mu$  exchange). LFV H decays break this symmetry if  $B(H \rightarrow \mu\tau) \neq B(H \rightarrow e\tau)$ .
- Data of each of the two channels can serve as background prediction for the other channel.
- The Symmetry method measures the difference of LFV signal strengths. If one of the signal is assumed to be zero, then it becomes an absolute measurement.

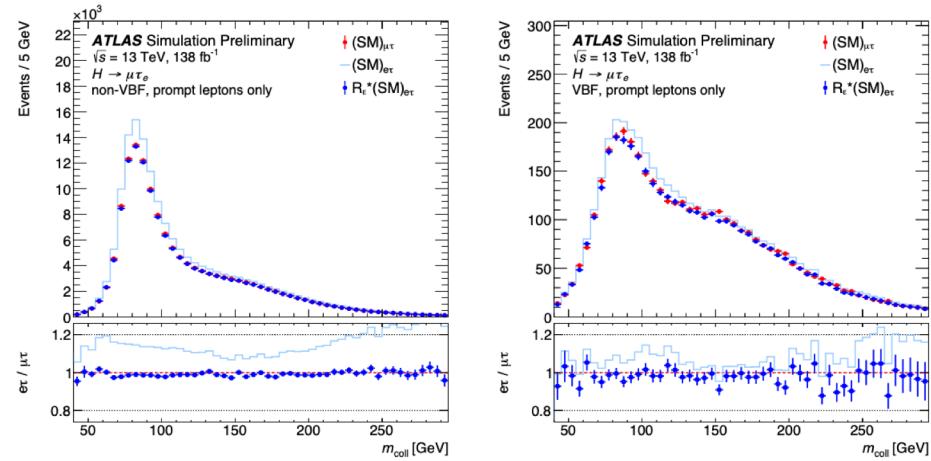
**Induced asymmetries:** mainly due to differences in lepton efficiencies and fake rates

$$n_{\text{det}}^{\mu\tau} = \frac{\epsilon^{\mu\tau}}{\epsilon^{e\tau}} (n_{\text{det}}^{e\tau} - f^{e\tau}) + f^{\mu\tau}$$

## Fakes estimation:

Fake Factor method is used, FF computed in Z+jets CR for  $j \rightarrow \text{lep}$ .

$\gamma \rightarrow e, \mu$  and  $\tau_{\text{had}} \rightarrow \text{lep}$  with MC, via MC-truth info.



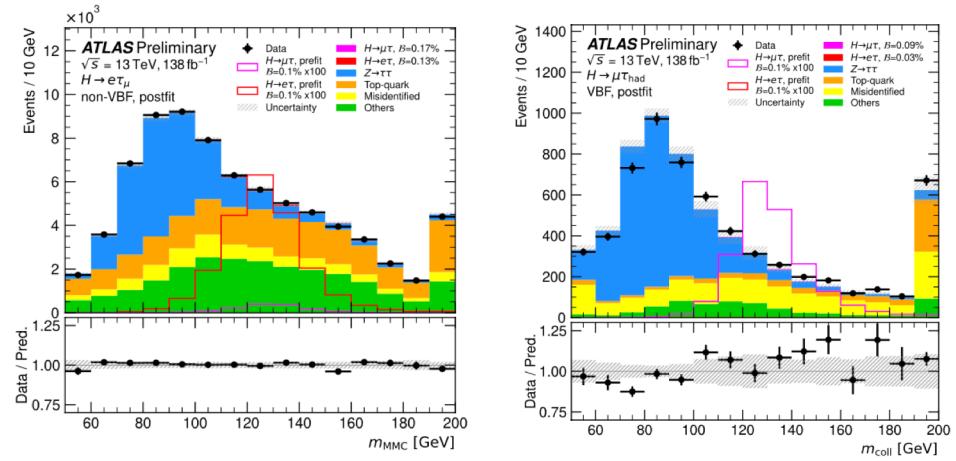
# Background estimation MC-template method

## Lep-lep channel

- **Z $\rightarrow\tau\tau$  and top:** Normalisation factors (NF) is extracted from 1-bin CRs separately for VBF and non-VBF. Top CR defined inverting b-veto. Z $\rightarrow\tau\tau$  CR is defined by  $35 < p_T(l_1) < 45$  GeV
- **Z $\rightarrow\mu\mu$ :** ( $\mu \rightarrow e$  fake) NF is extracted from dedicated CR at prefit level and normalization uncertainty included in the fit.
- **Diboson:** Modelling checked in a dedicated Validation region
- **SM Higgs:** mainly H $\rightarrow\tau\tau$  and H $\rightarrow WW$ , estimated from MC
- **Fakes:** Data-driven estimate for j $\rightarrow$ lep,  $\gamma \rightarrow e, \tau_{had} \rightarrow$ lep
- CRs are included in fit for each category where lep-lep MC-template is used.

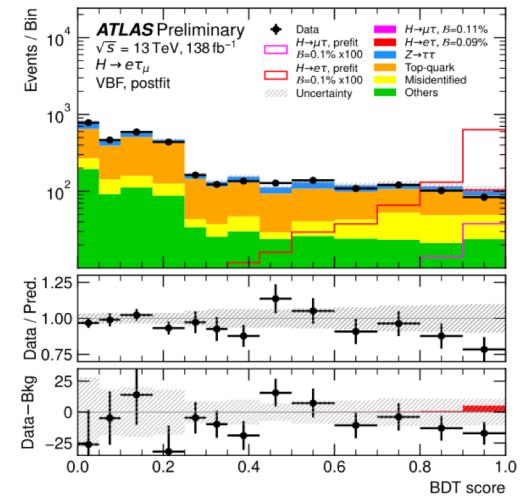
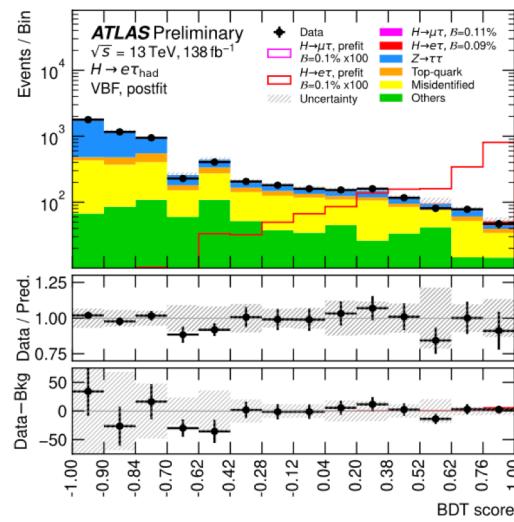
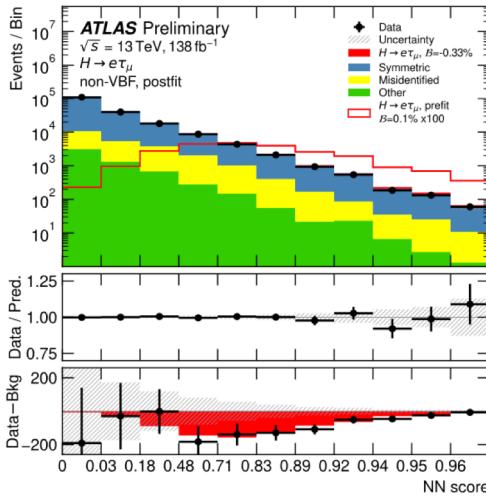
## Lep-had channel

- **Z $\rightarrow\tau\tau$ :** different NF for VBF and non-VBF in the fit.
- **Top:** NF shared with lep-lep for categories where the MC-template is used for lep-had. Otherwise top normalization fixed from MC and corresponding theory uncertainties included.
- **Z $\rightarrow\mu\mu$ :** uncertainties on the normalisation are extracted from dedicated VR.
- **Diboson, SM Higgs, others:** estimated from MC.
- **Fakes:** estimate of j $\rightarrow \tau_{had}$  with fake-factor. Main sources are W+jets and multijets.



# MVA Analysis

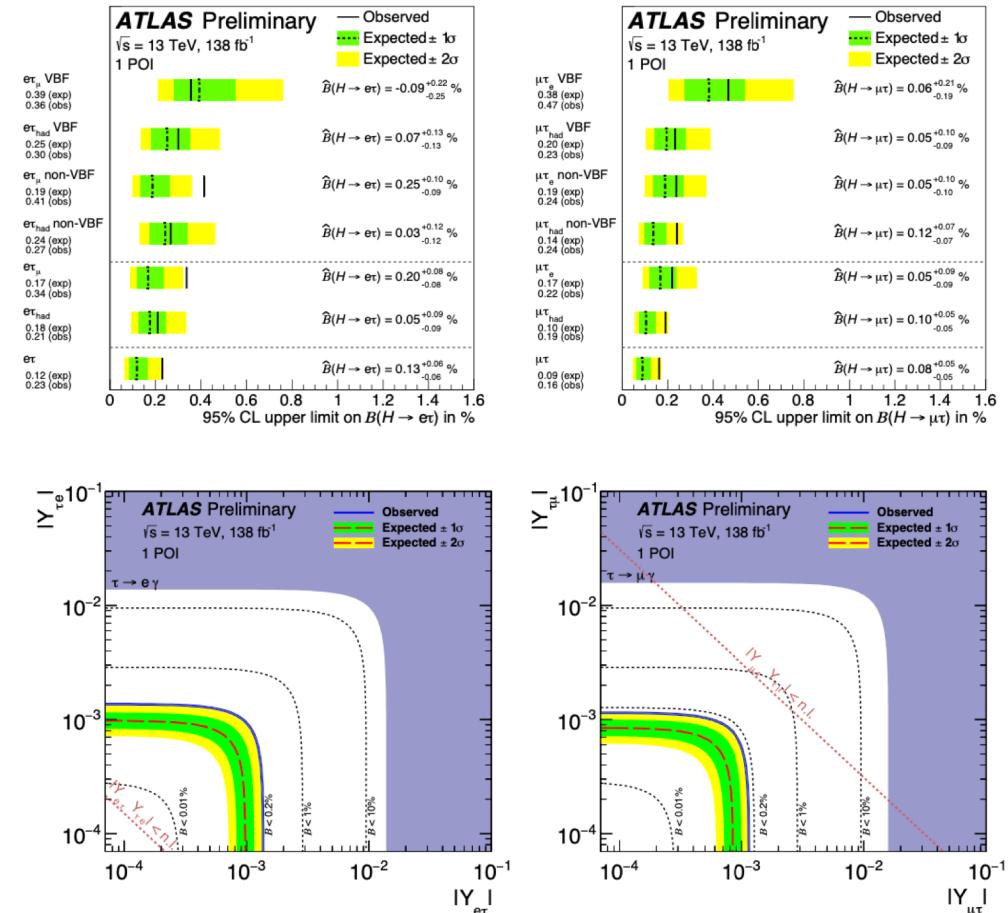
- **Symmetry method, leplep:** **NNs trained with Keras**, Separate training for non-VBF and VBF, but common for  $e\tau_\mu$  and  $\mu\tau_e$ 
  - Non-VBF: 1 Multiclassifier NN with 3 output nodes. Signal node is used for fit.
  - VBF: 3 NNs, combined linearly. LFV vs  $(Z\tau\tau + H\tau\tau + \text{MC fakes}) / (\text{Top} + \text{VV} + \text{HWW}) / \text{Fakes}$
- **MC-template method, leplep:** **BDTs with TMVA**, Separate training for non-VBF and VBF, but common for  $e\tau_\mu$  and  $\mu\tau_e$ 
  - Non-VBF and VBF: 3 BDTs, combined linearly. LFV vs  $(Z\tau\tau + H\tau\tau + Z\text{leplep}) / (\text{Top} + \text{VV} + \text{HWW}) / \text{Fakes}$
- **MC-template method, lephad:** **BDTs with TMVA**, Separate training for non-VBF and VBF and for  $e\tau_{\text{had}}$  and  $\mu\tau_{\text{had}}$ 
  - Non-VBF  $e\tau_{\text{had}}$ : 3 BDTs, combined linearly. LFV vs  $Z\tau\tau$  / Fakes / rest of bkg
  - VBF and non-VBF  $\mu\tau_{\text{had}}$ : 2 BDTs, combined linearly for non-VBF  $\mu\tau_{\text{had}}$  and quadratically for VBF. LFV vs  $Z\tau\tau$  / rest of bkg



# 1 POI Fit results

arXiv:2302.05225

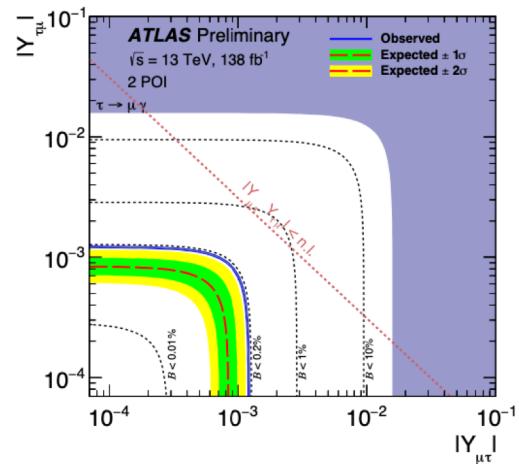
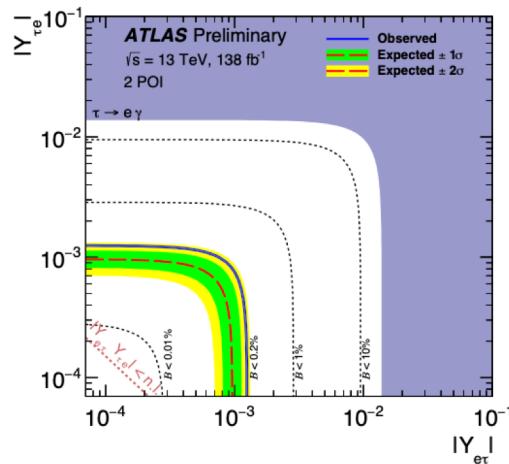
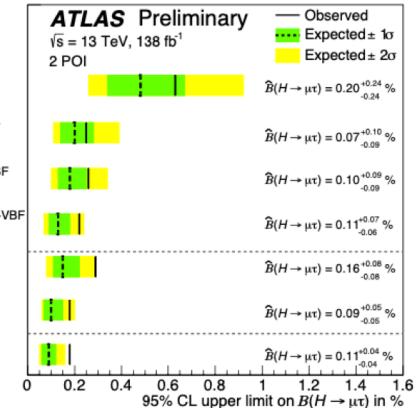
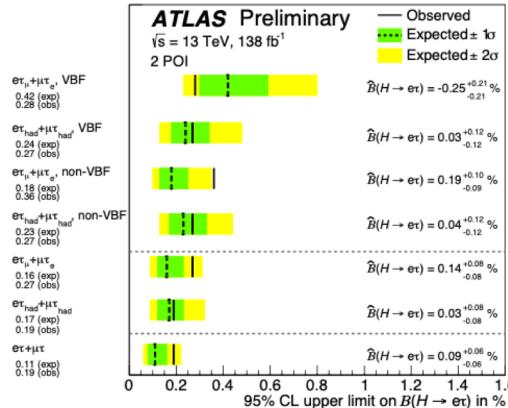
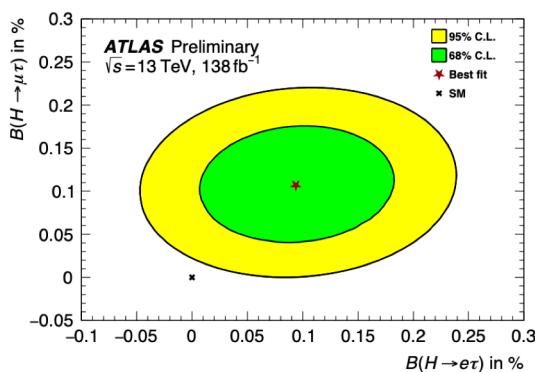
- $B(H \rightarrow e\tau) = 0$  when fitting  $B(H \rightarrow \mu\tau)$  and viceversa.
- Combination **6 regions** in total for each fit:
  - Symmetry:  $|\tau|$  VBF SR.
  - MC template:  $|\tau|$  non-VBF SR+Top+Ztt CRs.
  - MC template:  $|\tau|_{had}$  VBF+non-VBF SRs.
- Observed limits are above expected ones.
- **$2.2\sigma$**  excess seen for  $B(H \rightarrow e\tau)$  and  **$1.9\sigma$**  for  $B(H \rightarrow \mu\tau)$ .



$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}(H \rightarrow \ell\tau)}{1 - \mathcal{B}(H \rightarrow \ell\tau)} \Gamma_H(\text{SM})$$

# 2 POI Fit results

- Combination of:
  - MC template:  $\text{lt}_\tau$  VBF+non-VBF of SR+Top+Ztt CRs.
  - MC template:  $\text{lt}_{\text{had}}$  VBF+non-VBF SRs.
- 1.6 $\sigma$**  excess seen for  $B(H \rightarrow e\tau)$  and **2.5 $\sigma$**  for  $B(H \rightarrow \mu\tau)$ .
- Compatibility with SM within **2.17 $\sigma$** .



$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}(H \rightarrow \ell\tau)}{1 - \mathcal{B}(H \rightarrow \ell\tau)} \Gamma_H(\text{SM})$$

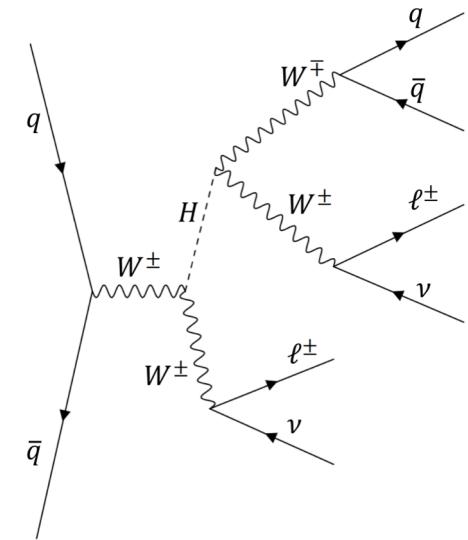
# EFT search for a heavy Higgs - motivation

[arXiv:2211.02617](https://arxiv.org/abs/2211.02617)

- No hint of existence of CP even heavy Higgs bosons from previous search with specific models [PRD.98.052008](#).

## New Ideas!

- Model-independent search for a Generic Heavy Higgs boson ( $H$ ) having both dim-4 and dim-6 interactions with SM particles
  - Phenomenology study ([PLB 804 \(2020\) 135358](#)) shows the same-sign di-lepton final state (**SS2L**) of associated production with vector boson (VH) channel dominates the sensitivity.



dim-6 effective operator Lagrangian

$$\mathcal{L}_{HVV}^{(6)} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n, \quad \Lambda = 5TeV$$

dim-4 operator Lagrangian

Light Higgs

$$\mathcal{L}_{hWW}^{(4)} = \rho_h g m_W h W^\mu W_\mu$$

$$\mathcal{L}_{hZZ}^{(4)} = \rho_h \frac{g m_W}{2 \cos^2 \theta_W} h Z^\mu Z_\mu$$

heavy Higgs

$$\mathcal{L}_{HWW}^{(4)} = \rho_H g m_W H W^\mu W_\mu$$

$$\mathcal{L}_{HZZ}^{(4)} = \rho_H \frac{g m_W}{2 \cos^2 \theta_W} H Z^\mu Z_\mu$$

$$\mathcal{L}_{HWW}^{(6)} = \rho_H g m_W \frac{f_W}{2\Lambda^2} (W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + h.c.)$$

$$- \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W_{\mu\nu}^+ W^{-\mu\nu} H$$

$$\mathcal{L}_{HZZ}^{(6)} = \rho_H g m_W \frac{c^2 f_W + s^2 f_B}{2c^2 \Lambda^2} Z_{\mu\nu} Z^\mu \partial^\nu H$$

$$- \rho_H h m_W \frac{c^4 f_{WW} + s^4 f_{BB}}{2c^2 \Lambda^2} Z_{\mu\nu} Z^{\mu\nu} H$$

$$s = \sin \theta_W, \quad c = \cos \theta_W$$

$$f_B = f_{BB} = 0,$$

$$\rho_h = 1, \rho_H = 0.05$$

Only  $f_W, f_{WW}, m_H$  are free parameters

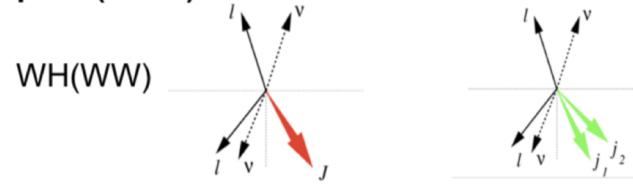
# Analysis strategy

- Signal signature: two same-sign leptons ( $e$  or  $\mu$ ) in association with one large-R jet ( $J$ ) or two small-R jets ( $j$ ), and  $E_T^{miss}$ .

- Boosted SR:** leading large-R jet passing LCTopo W-tagger

- Resolved SR:** invariant mass of two leading small-R jets consistent with a hadronically decaying W-boson

## Same-sign 2 lepton (SS2L)



Observable:  $M_{eff} = \sum p_T^{Lepton} + \sum p_T^{V-jets} + E_T^{miss}$

- Dominant Backgrounds:**

- WZ and same-sign WW (ssWW):**  
MC driven with normalization from data using dedicated CRs.

: MC driven

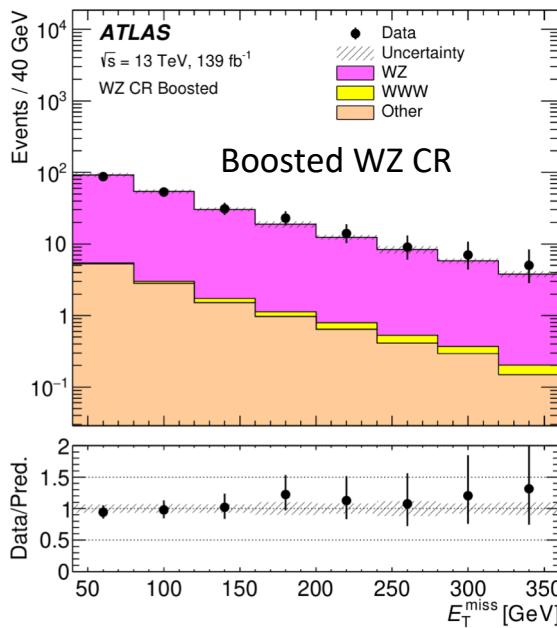
- Non-prompt:** data driven

Selections	Boosted SR	Resolved SR	ssWW CR	Boosted WZ CR	Resolved WZ CR
Trigger			Single lepton		
Leptons	two same-sign leptons with $p_T > 27, 20$ GeV		zero additional veto leptons	three leptons with $p_T > 27, 20, 20$ GeV at least one SFOS lepton pair	
$m_{ee}$		$> 100$ GeV			-
$m_{\ell\ell\ell}$		-			$> 100$ GeV
$b$ -jets			zero $b$ -tagged small- $R$ jets		
$E_T^{miss}$	$> 80$ GeV	$> 60$ GeV		$> 40$ GeV	
Large- $R$ jets	at least one large- $R$ jet with $p_T > 200$ GeV, $ \eta  < 2.0$ $50$ GeV $< m_J < 200$ GeV and pass 80% W-tagger WP	zero large- $R$ jets with $p_T > 200$ GeV, $ \eta  < 2.0$ $50$ GeV $< m_J < 200$ GeV and pass 80% W-tagger WP	at least one large- $R$ jet with $p_T > 200$ GeV, $ \eta  < 2.0$ $50$ GeV $< m_J < 200$ GeV and pass 80% W-tagger WP	zero large- $R$ jets with $p_T > 200$ GeV, $ \eta  < 2.0$ $50$ GeV $< m_J < 200$ GeV and pass 80% W-tagger WP	
Small- $R$ jets	-	at least two small- $R$ jets with $p_T > 20$ GeV and $ \eta  < 2.5$	-		at least two small- $R$ jets with $p_T > 20$ GeV and $ \eta  < 2.5$
$m_{jj}$	-	$50$ GeV $< m_{jj} < 110$ GeV	$> 200$ GeV	-	-

# Control regions

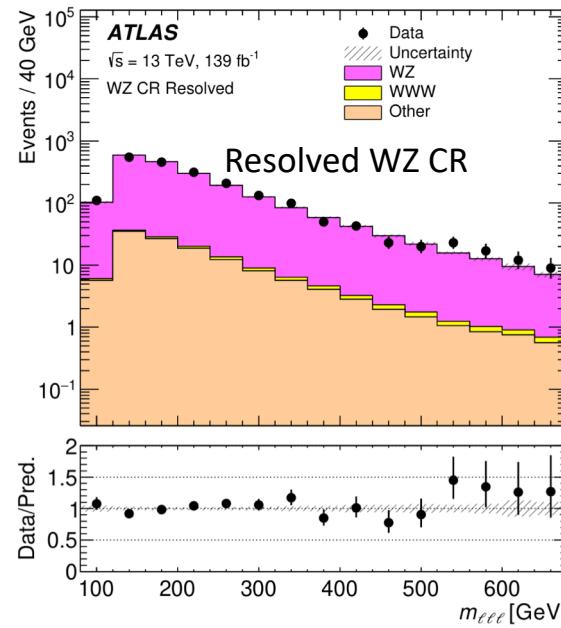
- WZ and ssWW backgrounds are the dominant background in SR.
- Corresponding CRs are defined to constrain WZ/ssWW in the final fit:
  - Take the shape from MC simulation
  - Normalisation factor (NF) is one of the free parameters

Plots with NFs applied

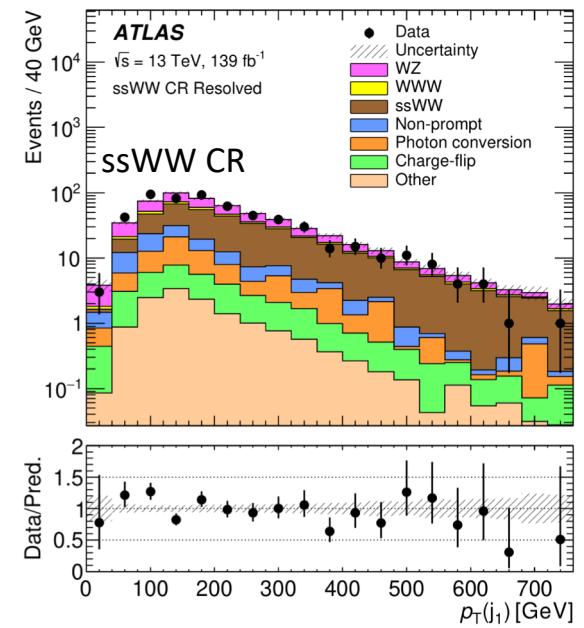


$$\mu_{\text{BoostedWZ}} = 0.93 \pm 0.07$$

NF of X = (data - other backgrounds) / X



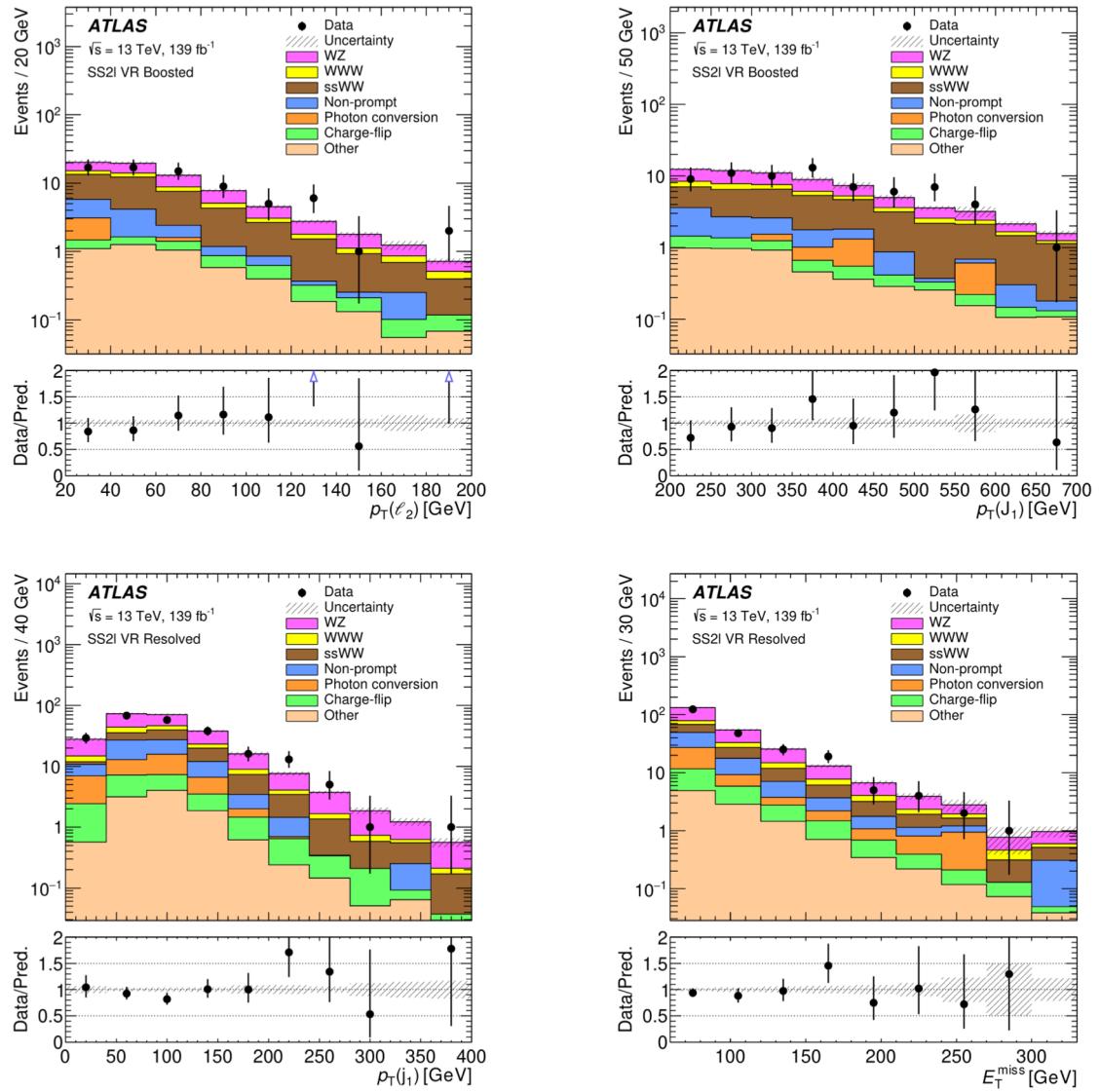
$$\mu_{\text{ResolvedWZ}} = 0.83 \pm 0.03$$



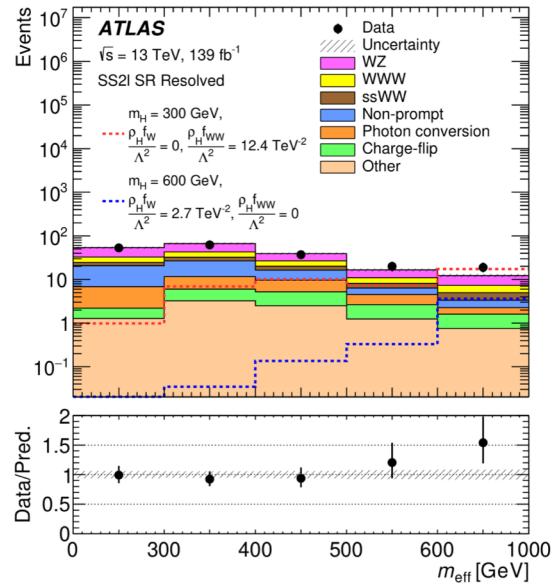
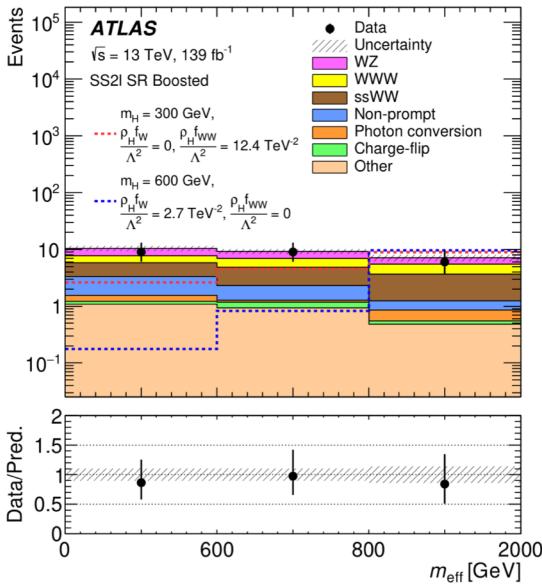
$$\mu_{\text{ssWW}} = 1.54 \pm 0.18$$

# Validation regions

- Reverse the W tagger in boosted and  $m_{jj}$  in resolved to obtain the validation regions
- Check background estimation of ssWW, WZ and WWW.
- Data-driven backgrounds and NFs are applied



# Fit result in signal region

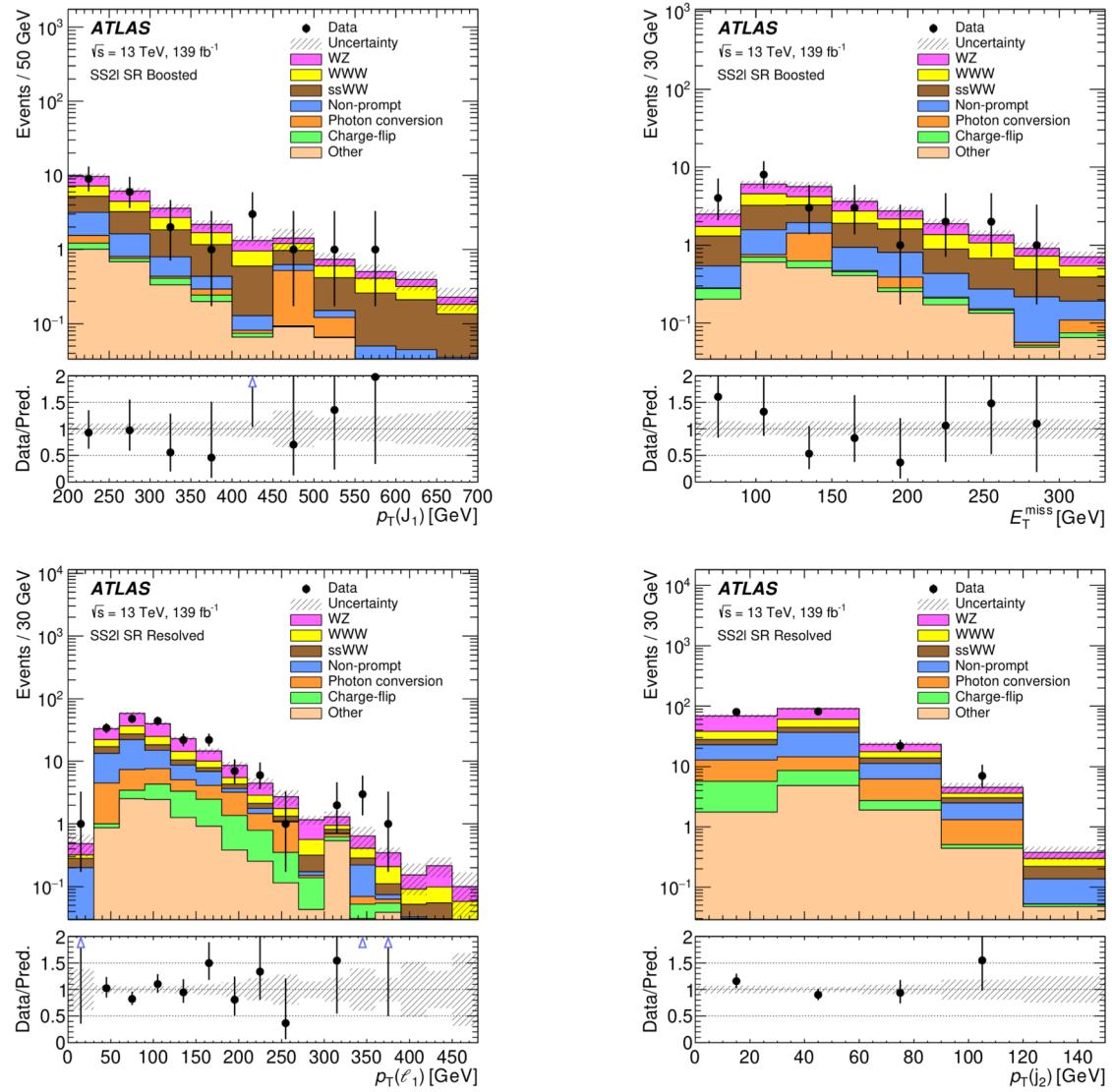


Yields	Boosted SR	Resolved SR
Observed events	24	191
Fitted bkg events	$26.8 \pm 2.7$	$189.0 \pm 7.8$
WWW	$5.8 \pm 1.0$	$30.4 \pm 2.9$
ssWW	$7.5 \pm 2.3$	$16.5 \pm 1.9$
WZ	$6.71 \pm 0.76$	$68.7 \pm 5.0$
Non-prompt	$3.20 \pm 0.36$	$39.6 \pm 6.3$
Charge-flip	$0.43 \pm 0.03$	$8.61 \pm 0.57$
Photon conversion	$0.73 \pm 0.07$	$17.2 \pm 1.7$
Other	$2.50 \pm 0.45$	$9.0 \pm 1.5$

- Post-fit distributions for boosted SR and resolved SR with **background-only fit**
- ssWW is the dominant background in boosted SR, while WZ dominates the resolved SR.
- Good agreement between data and expected background.

# Fit result in signal region

- Distributions of other kinematic variables in SRs are shown.
- Good agreement between data and expected background are observed

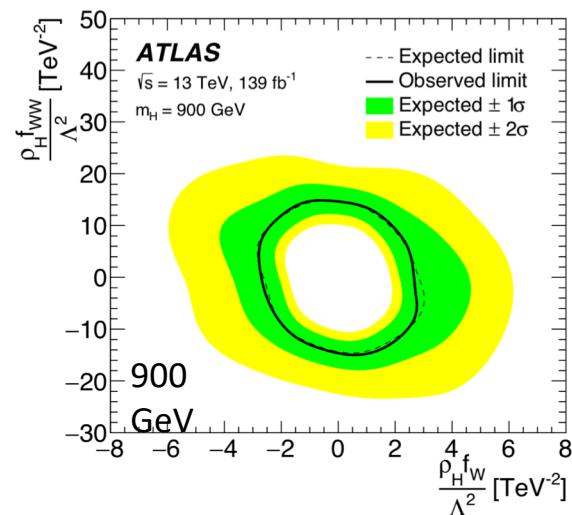
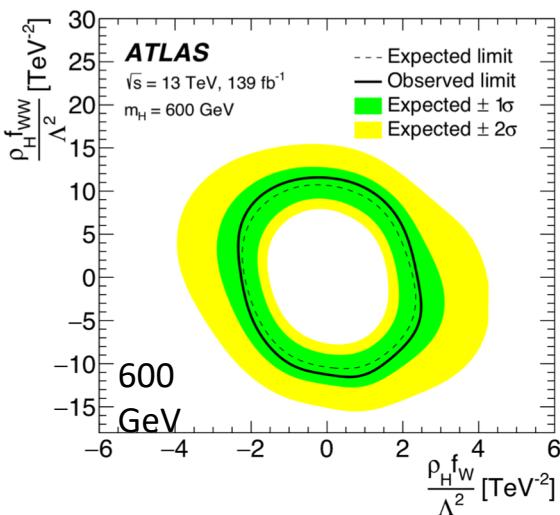
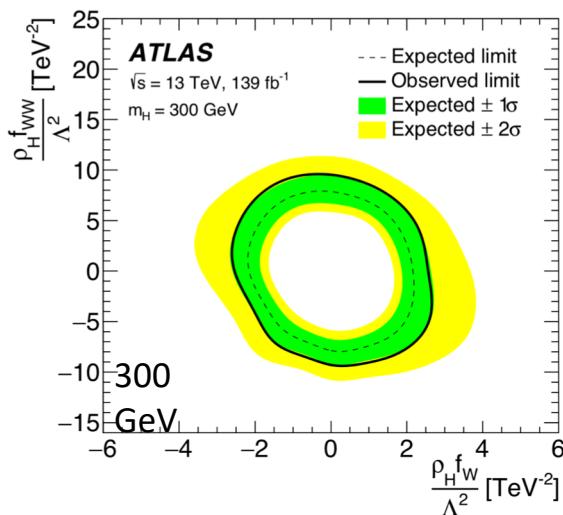


# Systematics

- Systematics:
  - Experimental systematics: lumi, jet, muon, electron...
  - Theoretical systematics: PDF, scale, parton shower.
  - Systematics from data-driven background
- Theoretical systematics have the largest impact in boosted SR, while systematics of non-prompt background estimation have the largest impact in resolved SR.

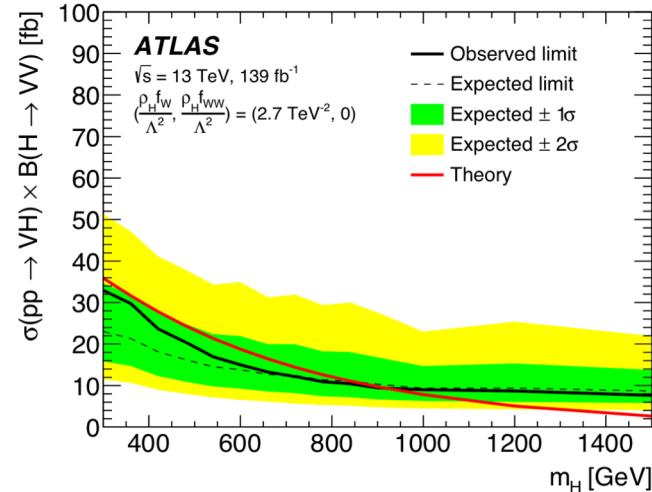
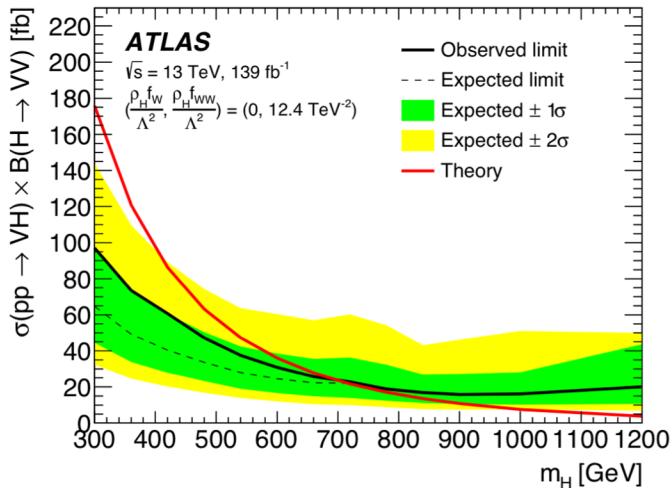
Uncertainty of channel	Boosted SR	Resolved SR
Total systematic uncertainties	10.0%	4.1%
Data driven non-prompt	1.3%	3.3%
Theoretical uncertainties	8.9%	2.6%
MC statistical uncertainties	3.0%	1.9%
Floating normalizations	3.5%	1.2%
Small- $R$ jet	-	1.1%
Data driven photon conversion	0.2%	0.9%
$E_T^{\text{miss}}$	0.2%	0.7%
$b$ -tagging	0.8%	0.5%
Data driven charge-flip	0.1%	0.3%
Electron	0.5%	0.2%
Muon	0.6%	0.2%
Pile-up reweighting	0.2%	0.2%
Large- $R$ jet	1.1%	0.2%
$W$ -tagger	3.7%	-

# Sensitivity

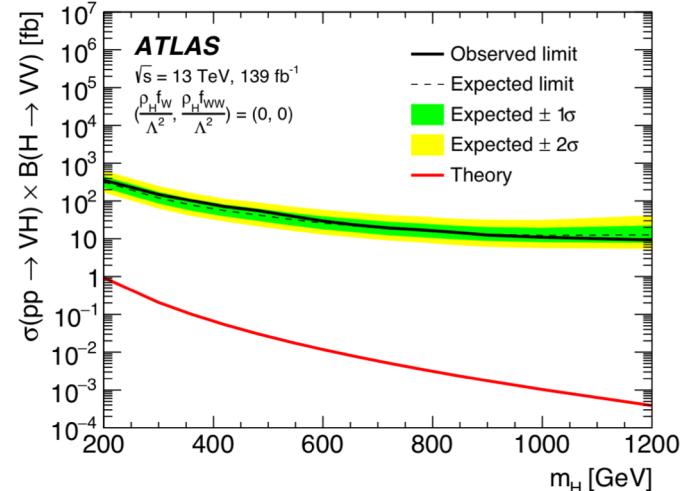


- Observed and expected exclusion contours at 95% confidence level in  $(\frac{\rho_H f_W}{\Lambda^2}, \frac{\rho_H f_{WW}}{\Lambda^2})$  parameter space.
- With  $m_H = 300 \text{ GeV}$ ,  $|\frac{\rho_H f_W}{\Lambda^2}| > 2.7 \text{ TeV}^{-2}$  and  $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 10 \text{ TeV}^{-2}$  can be excluded.
- With  $m_H = 600 \text{ GeV}$ ,  $|\frac{\rho_H f_W}{\Lambda^2}| > 2.5 \text{ TeV}^{-2}$  and  $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 12 \text{ TeV}^{-2}$  can be excluded.
- With  $m_H = 900 \text{ GeV}$ ,  $|\frac{\rho_H f_W}{\Lambda^2}| > 2.9 \text{ TeV}^{-2}$  and  $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 15 \text{ TeV}^{-2}$  can be excluded.

# Upper limits



- Upper limit on heavy Higgs production ( $pp \rightarrow VH$ ) cross section as a function of  $m_H$  at 95% confidence level with 3 sets of fixed  $(f_W, f_{WW})$ :  $(0, 6200)$ ,  $(1350, 0)$ ,  $(0, 0)$ .
- With  $(f_W, f_{WW}) = (0, 6200)$ , heavy Higgs boson with mass up to **700** GeV can be excluded, while with  $(f_W, f_{WW}) = (1350, 0)$ , heavy Higgs boson with mass up to **900** GeV can be excluded.



# Summary

Higgs, a special particle that gives mass to all other massive particles, may act as a portal between SM and the unknown new physics. Looking for exotic Higgs interactions, or for new Higgs-like particle directly, is an active program at LHC

More LHC data allows more precise measurements of Higgs properties and new physics search potential. State-of-the-art background estimation techniques have been devised at ATLAS ensures reliable and optimal results

Topics covered in this talk (Higgs FCNC, LFV and EFT searches) are just some interesting ones among many others. New ideas are being developed to look at new channels or suppress more background, so that a signal may come up

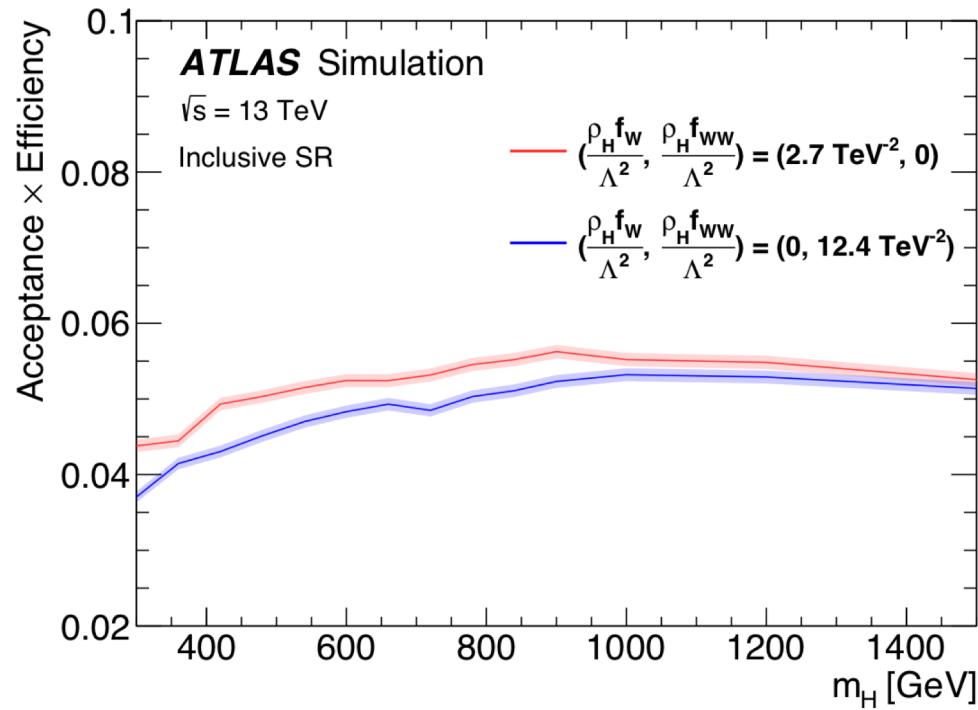
So far there is no deviations observed in the Higgs sector. We have to re-hone our search techniques for run-2, and include more data from run-3 and later.

# Backup Slides

# EFT analysis – event selection

Selections	Boosted SR	Resolved SR	$ssWW$ CR	Boosted $WZ$ CR	Resolved $WZ$ CR
Trigger			Single lepton		
Leptons	two same-sign leptons with $p_T > 27, 20$ GeV			three leptons with $p_T > 27, 20, 20$ GeV at least one SFOS lepton pair	
		zero additional veto leptons			
$m_{\ell\ell}$		$> 100$ GeV			-
$m_{\ell\ell\ell}$		-			$> 100$ GeV
$b$ -jets			zero $b$ -tagged small- $R$ jets		
$E_T^{\text{miss}}$	$> 80$ GeV	$> 60$ GeV		$> 40$ GeV	
Large- $R$ jets	at least one large- $R$ jet with $p_T > 200$ GeV, $ \eta  < 2.0$ $50 \text{ GeV} < m_J < 200 \text{ GeV}$ and pass 80% $W$ -tagger WP	zero large- $R$ jets with $p_T > 200$ GeV, $ \eta  < 2.0$ $50 \text{ GeV} < m_J < 200 \text{ GeV}$	at least one large- $R$ jet with $p_T > 200$ GeV, $ \eta  < 2.0$ $50 \text{ GeV} < m_J < 200 \text{ GeV}$ and pass 80% $W$ -tagger WP	zero large- $R$ jets with $p_T > 200$ GeV, $ \eta  < 2.0$ $50 \text{ GeV} < m_J < 200 \text{ GeV}$	
Small- $R$ jets	-	at least two small- $R$ jets with $p_T > 20$ GeV and $ \eta  < 2.5$		-	at least two small- $R$ jets with $p_T > 20$ GeV and $ \eta  < 2.5$
$m_{jj}$	-	$50 \text{ GeV} < m_{jj} < 110 \text{ GeV}$	$> 200$ GeV	-	-

# EFT analysis – signal efficiency



# EFT analysis – event yields

<b>Yields</b>	Boosted SR	Resolved SR	Boosted WZ CR	Resolved WZ CR	$ssWW$ CR
Observed events	24	191	236	2094	567
Fitted bkg events	$26.8 \pm 2.7$	$189.0 \pm 7.8$	$235 \pm 15$	$2095 \pm 46$	$566 \pm 24$
$WWW$	$5.8 \pm 1.0$	$30.4 \pm 2.9$	$1.30 \pm 0.31$	$11.2 \pm 2.1$	$28.5 \pm 5.5$
$ssWW$	$7.5 \pm 2.3$	$16.5 \pm 1.9$	–	–	$254 \pm 27$
$WZ$	$6.71 \pm 0.76$	$68.7 \pm 5.0$	$221 \pm 15$	$1956 \pm 50$	$150.6 \pm 5.7$
Non-prompt	$3.20 \pm 0.36$	$39.6 \pm 6.3$	–	–	$48.6 \pm 8.8$
Charge-flip	$0.43 \pm 0.03$	$8.61 \pm 0.57$	–	–	$22.8 \pm 1.3$
Photon conversion	$0.73 \pm 0.07$	$17.2 \pm 1.7$	–	–	$46.7 \pm 4.7$
Other	$2.50 \pm 0.45$	$9.0 \pm 1.5$	$12.3 \pm 1.6$	$130 \pm 20$	$14.3 \pm 2.0$

# EFT analysis – systematics

Uncertainty of channel	Boosted SR	Resolved SR
Total systematic uncertainties	10.0%	4.1%
Data driven non-prompt	1.3%	3.3%
Theoretical uncertainties	8.9%	2.6%
MC statistical uncertainties	3.0%	1.9%
Floating normalizations	3.5%	1.2%
Small- $R$ jet	-	1.1%
Data driven photon conversion	0.2%	0.9%
$E_T^{\text{miss}}$	0.2%	0.7%
$b$ -tagging	0.8%	0.5%
Data driven charge-flip	0.1%	0.3%
Electron	0.5%	0.2%
Muon	0.6%	0.2%
Pile-up reweighting	0.2%	0.2%
Large- $R$ jet	1.1%	0.2%
$W$ -tagger	3.7%	-