Search for resonant and non-resonant Higgs boson pair production in the bbττ decay channel using 13 TeV pp collision data from the ATLAS detector

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#### Motivation

• Standard Model (SM) predicts the self-interaction of the Higgs field





- Made great achievement on Higgs boson mass and coupling measurement.
   ➢No clear indications for new physics yet...
- Important information: e.g. SM vacuum is meta-stable. SM m<sub>H</sub> → FOFT.
- Need to further study the shape of the potential
   Key to understand nature of EWSB, EWPT and open the opportunity for new physics.
   Self-interaction: direct access by studying Higgs pair production at LHC

## **Higgs Boson Pair Production**

• Production at the LHC:

#### Non-resonant

- SM : mainly by gluon-gluon fusion, small contribution from vector boson fusion
- > Very rare:
  - ➤ σ<sub>ggF</sub> @ 13 TeV: 31.1fb
  - σ<sub>VBF</sub> @ 13 TeV: 1.73 fb
- BSM models: composite Higgs, anomalous couplings, ...

Resonant

Enhance the rate. Current dataset is already sensitive.

BSM resonance decaying to pair of Higgs: Two Higgs doublet models (2HDMs), spin-2 gravitons in Randall-Sundrum model, supersymmetry models, ...



#### **Overview of Analysis Strategy**

• Targeting both non-resonant and resonant production

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- Medium branching ratio and S/B -> one of the most sensitive channels
- Signal event final state signature contains 2 b-tagged jets and OS  $\tau$ -leptons
- Focus on  $\tau_{had}\tau_{had}$  and  $\tau_{lep}\tau_{had}$  di-tau final states using full Run 2 dataset with  $L = 139 \text{ fb}^{-1}$  collected by ATLAS detector

Di-Higg	s Decay				
Higgs Decay	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	<0.001%



## **Overview of Analysis Strategy**

• Events further categorized by triggers:

$\tau_{had} \tau_{had}$	Single- $\tau$ and di- $\tau$ triggers	High purity
$\tau_{lep} \tau_{had}$ SLT	Single-lepton triggers	High acceptance, large $tar{t}$ background
$\tau_{lep} \tau_{had} \ LTT$	Lepton+τ triggers	Lower $p_T^l$ increases low-mass sensitivity

- Signal extraction:
  - MVA-based analysis based on kinematic inputs
- Main backgrounds:
  - Top-quark, Z boson + jets (heavy flavours), multi-jet, single Higgs boson
- Results:
  - Combine  $\tau_{had}\tau_{had}$  and  $\tau_{lep}\tau_{had}$
  - Upper limits on di-Higgs production cross section.

	Electron	Muon	Tau & Anti-Tau	Jet
$p_T$	$p_T$ > 7 GeV	$p_T$ > 7 GeV	$p_T$ > 20 GeV	$p_T$ > 20 GeV
$ \eta $	η  < 2.47 (veto 1.37-1.52)	$ \eta  < 2.7$	η  < 2.5 (veto 1.37-1.52)	<b> η  &lt;</b> 2.5
Quality	Loose ID Loose isolation	Loose ID Loose isolation	Tau: Loose ID Anti-Tau: Fail Loose ID but pass 99% WP Loose electron-veto	B-tagging: 77% efficiency WP
Other	Inverting isola or identification define control	tion of e/mu on of tau to regions	RNN-based Tau-ID (using information of associated tracks and jets)	Anti-k <sub>T</sub> R=0.4 jets Particle-flow reconstruction <b>DL1r RNN-based b-tagger</b> Additional b-jet energy corrections
			Keys to the improvements of signal efficiency	WP: Working Point

RNN: Recurrent Neural Network

#### Selections

#### $\tau_{lep}\tau_{had}$

#### $\tau_{had}\tau_{had}$

Single Lepton ( $e/\mu$ ) triggers (SLT) Single  $au_{had}$  triggers (STT)

Or Lepton +  $au_{had}$  triggers (LTT) Or Di- $au_{had}$  triggers (DTT)

Offline Requirements Passed

**Event Selection** 

Triggers

$$\begin{split} m_{\tau\tau}^{\text{MMC} [*]} &> 60 \text{ GeV} \\ & \text{Opposite-sign of } e/\mu/\tau_{\text{had}} \text{ and } \tau_{\text{had}} \\ & \text{Exactly two b-tagged jets} \\ & \text{One (tight) } e \text{ or (medium) } \mu & \text{No loose } e/\mu \\ & \text{One (loose) } \tau_{\text{had}} & \text{Two (loose) } \tau_{\text{had}} \\ & \text{M}_{\text{bb}} < 150 \text{ GeV} \end{split}$$

## Multi-Variable Signal Extraction

- MVA classifiers evaluated on events passing the above selections are used to extract possible signals
- Using variables constructed by 4-vectors
  - Detailed definitions can be found in <u>backup</u>

• MVAs:

- Non-res: NN for  $\tau_{lep}\tau_{had},$  BDT for  $\tau_{had}\tau_{had}$
- Resonance: Parametric NN (PNN) -> discriminants parametrised by m<sub>x</sub> (near-optimal sensitivity across continuous mass search range)



 $\Theta$  is the parameter, here: mass of the resonance  $x_i$  are the feature variables

Variable	$ au_{ m had} au_{ m had}$	$\tau_{\text{lep}} \tau_{\text{had}} \text{ SLT}$	$ au_{\mathrm{lep}} au_{\mathrm{had}} \mathrm{LTT}$
<i>m<sub>HH</sub></i>	✓	✓	1
$m_{\tau\tau}^{\rm MMC}$	$\checkmark$	$\checkmark$	$\checkmark$
m <sub>bb</sub>	$\checkmark$	$\checkmark$	$\checkmark$
$\Delta R(\tau, \tau)$	$\checkmark$	1	$\checkmark$
$\Delta R(b,b)$	$\checkmark$	1	
$\Delta p_{\mathrm{T}}(\ell, au)$		1	$\checkmark$
Sub-leading <i>b</i> -tagged jet <i>p</i> <sub>T</sub>		$\checkmark$	
$m_{\mathrm{T}}^W$		$\checkmark$	
$E_{\mathrm{T}}^{\mathrm{miss}}$		$\checkmark$	
$\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} \phi$ centrality		$\checkmark$	
$\Delta \phi(\ell  au, bb)$		$\checkmark$	
$\Delta \phi(\ell, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$			$\checkmark$
$\Delta \phi(\ell \tau, \mathbf{\hat{p}}_{\mathrm{T}}^{\mathrm{miss}})$			$\checkmark$
ST			<i>✓</i>

### **Examples of Input Variables**

0.8E

500



0.8Ē

2500

m<sub>HH</sub> [GeV]

2000



300

400

Data

SM HH × 100

Top-quark

Jet  $\rightarrow \tau_{had}$  fakes (MJ)

 $Z \rightarrow \tau \tau$  + (bb,bc,cc)

ATLAS Preliminary

Signal Region

140

m<sub>bb</sub> [GeV]

120

700

m<sup>MMC</sup><sub>TT</sub> [GeV]

## **Background Estimation**

- Main backgrounds:
  - top-quark, Z+jets, W+jets, diboson, single Higgs boson and multi-jet production
  - Backgrounds with  $\tau_{had}$  mis-identified by quark-/gluon-initiated jet (fake- $\tau_{had}$ ) are estimated from data-driven, Other backgrounds are estimated by MC simulation
- Normalisations of simulated  $t\bar{t}$  and Z+HF are determined by data in the fits
  - Dedicated ZCR: Lepton triggers, 2 leptons (SFOS), 2 b-tags, m<sub>ee</sub> window (75-110 GeV)
  - Also provides constraints on the normalisation of the  $t\bar{t}$  background
  - Typical norm. factors

Z+HF	$1.39 \pm 0.11$
$t\overline{t}$	$0.96 \pm 0.03$

# Fake- $\tau_{had}$ background in $\tau_{lep}\tau_{had}$

- Fake Factor (FF) method:
  - Inverting  $\tau_{had}\text{-}\text{ID}$  to define fake- $\tau_{had}$  CRs
  - FF derived separately for different processes

$$FF = \frac{N_{ID}}{N_{Anti-ID}}$$
,  $N = N(data) - N(non - Fake)$ 



#### • $\tau_{lep}\tau_{had}$ FFs:

- Derive in MJ CR (invert lepton isolation) and  $t\overline{t}$  CR (m<sub>bb</sub> > 150 GeV) for multi-jet (MJ) and  $t\overline{t}$ .
- Separately for triggers. Parameterised by anti- $au_{
  m had}$   $p_T$  and prong. (Others are similar)
- Then combined by fraction in the SR template (quantified by  $r_{MJ}$ )

 $r_{MJ} = \frac{N(data) - N(true + fake \tau_{had}, MC)}{N(data) - N(true \tau_{had}, MC)}$ 

• In--situ correction on  $t\overline{t}$  to improve modelling of templates.

# Fake- $\tau_{had}$ background in $\tau_{had}\tau_{had}$

- Fake- $\tau_{had}$  from multi-jet: FF method
  - FFs are derived in 1 b-tag SS control region
  - Extrapolate to 2 b-tag regions by transfer factors (TFs)



- Fake- $\tau_{had}$  from t $\overline{t}$ : fake scale factors
  - Fake- $\tau_{had}$  efficiency correction factors
  - Measure in  $\tau_{lep}\tau_{had}$   $t\overline{t}$  CR by fitting  $m_T^W$  to data
  - Applied to simulated fake- $\tau_{had} t \overline{t}$  in SR.



### **MVA Output Distributions**

From left to right:

- BDT output in non-resonant search
- > PNN output  $m_x = 500 \text{ GeV}$
- > PNN output  $m_x = 1$  TeV

 $1^{st}$  row:  $\tau_{had}\tau_{had}$  $2^{nd}$  row:  $\tau_{lep}\tau_{had}$  SLT

- Simultaneous fit of the MVA scores in  $\tau_{had}\tau_{had}$  and  $\tau_{lep}\tau_{had}$  and  $m_{\ell\ell}$  distribution in Z+HF CR
- Edges of bins are determined by algorithms to optimise sensitivity while ensuring valid background stats.



#### Results: Non-resonant HH

• 95% CL Upper limits on  $\mu = \sigma_{ggF+VBF} / \sigma_{ggF+VBF}^{SM} \rightarrow 4.7$  (3.9) observed (expected)

		Observed	$-2 \sigma$	$-1 \sigma$	Expected	+1 $\sigma$	$+2 \sigma$		
τ τ	$\sigma_{\rm ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245		
'had 'had	$\sigma_{ m ggF+VBF}/\sigma_{ m ggF+VBF}^{ m SM}$	4.95	2.38	3.19	4.43	6.17	8.27	Combination of $\tau_{ha}$	$d^{T}_{had} \tau_{lep} \tau_{had}$
$\tau_1 = \tau_1 = 1$	$\sigma_{\rm ggF+VBF}$ [fb]	265	124	167	231	322	432		
'lep'had	$\sigma_{ m ggF+VBF}/\sigma_{ m ggF+VBF}^{ m SM}$	9.16	4.22	5.66	7.86	10.9	14.7		
Combined	$\sigma_{\rm ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213	HH summary	ATL-PHYS-PUB-2021-031
	$\sigma_{ m ggF+VBF}/\sigma_{ m ggF+VBF}^{ m SM}$	4.65	2.08	2.79	3.87	5.39	7.22		
								<b>ATLAS</b> Preliminary	Observed     Expected
							With all	HH decay	Expected $\pm 2 \sigma$
							channel	s in early Run2	Expected $\pm 1 \sigma$
Outperf	forms the co	mbina <sup>.</sup>	tion	resu	ults in			<b>N</b>	Obs. Exp.
early Ru	u <b>n2</b> (27.5-36.	1 fb <sup>-1</sup> )					27.5	Combined 5-36.1 fb <sup>-1</sup>	6.9 10 Normalised to $\sigma_{ggF}$ — Phys. Lett. B 800 (2020) 135103
The most sensitive channel to date							bbl+vl-v 139 fb <sup>-1</sup>	♦ 40 29 Normalised to σ <sub>99</sub> F Phys. Lett. B 801 (2020) 135145	
								bbγγ 139 fb <sup>-1</sup>	4.1 5.5 Normalised to $\sigma_{39F+VBF}$ - ATLAS-CONF-2021-016
								bbt+t	4.7 3.9 Normalised to <i>Group</i> + VIRE

139 fb

2

10

5

20

50

95% CL upper limit on  $\sigma$  (pp  $\rightarrow$  HH) normalised to  $\sigma_{SM}$ 

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#### **Results: Resonant HH**

- Broad excess observed from 0.7 to 1.2 TeV
- Maximum local excess significance:
  - Combined: 3.0 $\sigma$  @ 1.0 TeV (Global significance by asymptotic formula  $2.0^{+0.4}_{-0.2}\sigma$ )
  - $\tau_{lep} \tau_{had}$ : 1.50 @ 1.1 TeV,  $\tau_{had} \tau_{had}$ : 2.80 @ 1.0 TeV

→ HH) [fb] → HH) [fb Combined 27.5–36.1 fb<sup>-1</sup> 10 ATLAS Preliminary [Phys. Lett. B 800 (2020) 135103] 920 fb ---- Comb. Exp.  $\tau_{lep} \tau_{had} Exp.$  $\sqrt{s} = 13 \text{ TeV}, 27.5 - 139 \text{ fb}^{-1}$ bbbb 126-139 fb<sup>-1</sup>  $\tau_{\text{lep}}\tau_{\text{had}}$  Obs. Comb. Obs.  $10^{3}$ Spin-0 [ATLAS-CONF-2021-035] Comb. Exp. ±1 $\sigma$ × ↑  $\tau_{had} \tau_{had} Exp.$  $b\bar{b}\tau^{+}\tau^{-}$  (resolved) 139 fb<sup>-1</sup> 10<sup>4</sup> [ATLAS-CONF-2021-030] Comb. Exp.  $\pm 2\sigma$ -  $\tau_{had}\tau_{had}$  Obs. - (bp -95% CL limits on  $\sigma$  (pp  $\rightarrow$  X  $b\bar{b}\tau^{+}\tau^{-}$  (boosted) 139 fb<sup>-1</sup> [JHEP 11 (2020) 163] bbyy 139 fb<sup>-1</sup>  $10^{3}$ [ATLAS-CONF-2021-016] 10<sup>2</sup> Competitive sensitivity<sup>10<sup>-</sup></sup> in 400 GeV - 1 TeV 23 fb 10 <del>|</del> search range. **ATLAS** Preliminary Observed  $\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$ --- Expected Cyan 10 400 600 800 1000 1200 1600 1400 200 300 500 1000 2000 3000 m<sub>x</sub> [GeV] m<sub>x</sub> [GeV] HH summary 15

Precise result will be derived

ATL-PHYS-PUB-2021-031

using bootstrapping.

## Conclusion

- A search for non-resonant and resonant Higgs boson pair production using bbττ events
- Data are found to be compatible with the background-only hypothesis
- Largest deviation observed at resonance mass of 1 TeV, local (global)  $3.0\sigma (2.0^{+0.4}_{-0.2}\sigma)$
- Main results:
  - Upper limits on non-resonant HH production cross-section: obs.(exp.) = 4.7(3.9) x  $\sigma_{SM}$
  - Upper limits on resonant HH production cross-section: obs.(exp.) = 23-920 fb (12-840 fb)
- Looking forward to results from more channels and further studies dedicated to Higgs boson self coupling and HHVV coupling constants.

Publications: ATLAS-CONF-2021-030

Physics briefing: link

#### Thanks for listening!



Data with highest non-resonant SM/NN score in  $\tau_{\mu}\tau_{had}$  and  $\tau_{had}\tau_{had}$ 

#### Extra Materials

Table 1: The generators used for the simulation of the signal and background processes. If not specified, the order of the cross-section calculation refers to the expansion in the strong coupling constant ( $\alpha_S$ ). The acronyms ME, PS and UE are used for matrix element, parton shower and underlying event, respectively.

Process	ME generator	ME PDF	PS and	UE model	Cross section
	_		hadronisation	tune	order
Signal					
non-resonant $gg \rightarrow HH$ (ggF)	Powheg-Box v2	PDF4LHC15 [73]	Рутніа 8.244 [ <mark>68</mark> ]	A14	NNLO FTApprox [20]
non-resonant $qq \rightarrow qqHH$ (VBF)	MadGraph	NNPDF3.0NLO [74]	Рутнія 8.244	A14	N3LO(QCD)
resonant $gg \to X \to HH$	MadGraph	NNPDF2.3LO [70]	Herwig v7.1.3	H7.1-Default	-
Top-quark					
tī	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.230	A14	NNLO+NNLL [75]
<i>t</i> -channel	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.230	A14	NLO [76]
s-channel	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.230	A14	NLO [77]
Wt	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.230	A14	NLO [78]
$t\bar{t}V\ (V=W,Z)$	Sherpa 2.2.1	NNPDF3.0NNLO [74]	Sherpa 2.2.1	Default	NLO
Vector boson + jets					
W+jets	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Z+jets	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
WW	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
WZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
ZZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
Single Higgs boson					
ggF	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.212	AZNLO	N3LO(QCD)+NLO(EW) [79-83]
VBF	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \rightarrow WH$	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.212	AZNLO	NNLO(QCD)+NLO(EW) [84-90]
$qq \rightarrow ZH$	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$gg \rightarrow ZH$	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.212	AZNLO	NLO+NLL
tt H	Powheg-Box v2	NNPDF3.0NLO	Рутніа 8.230	A14	NLO



#### Definition of MVA Input Variables

- $m_{HH}$  is the invariant mass of the *HH* system as reconstructed from the  $\tau_{had}$  pair (calculated using the MMC) and the *b*-tagged jet pair;
- $\Delta R(\tau,\tau)$  is evaluated between the two  $\tau_{had-vis}$  (the electron or muon and the  $\tau_{had-vis}$ ) in the  $\tau_{had}\tau_{had}$  ( $\tau_{lep}\tau_{had}$ ) channel;
- $\Delta R(b, b)$  is evaluated between the *b*-tagged jets;
- $\Delta p_{\rm T}(\ell,\tau)$  is the difference between the transverse momenta of the lepton and the  $\tau_{\rm had-vis}$ ;
- $m_{\rm T}^W = \sqrt{2p_{\rm T}^\ell E_{\rm T}^{\rm miss}(1 \cos \Delta \phi_{\ell, E_{\rm T}^{\rm miss}})}$  is the transverse mass of the lepton and the  $E_{\rm T}^{\rm miss}$ ;
- the  $E_{\rm T}^{\rm miss} \phi$  centrality specifies the relative angular position of the  $E_{T}^{\rm miss}$  relative to the  $\tau_{\rm had-vis}$  in the transverse plane [126] and is defined as  $(A+B)/\sqrt{A^2+B^2}$ , where  $A = \sin(\phi_{E_{\rm T}^{\rm miss}} \phi_{\tau_2})/\sin(\phi_{\tau_1} \phi_{\tau_2})$ ,  $B = \sin(\phi_{\tau_1} \phi_{E_{\rm T}^{\rm miss}})/\sin(\phi_{\tau_1} \phi_{\tau_2})$ , and  $\tau_1$  and  $\tau_2$  represent the two  $\tau_{\rm had-vis}$  (electron or muon and  $\tau_{\rm had-vis}$ ) in the case of the  $\tau_{\rm had}\tau_{\rm had}$  ( $\tau_{\rm lep}\tau_{\rm had}$ ) channel;
- $\Delta \phi(\tau \tau, bb)$  is the azimuthal angle between the  $\tau_{had-vis}$  pair and the *b*-tagged jet pair;
- $\Delta \phi(\ell, E_{\rm T}^{\rm miss})$  is the azimuthal angle between the lepton and  $E_{\rm T}^{\rm miss}$ ;
- $\Delta \phi(\ell \tau, E_{\rm T}^{\rm miss})$  is the azimuthal angle between the electron or muon and  $\tau_{\rm had-vis}$  system and the  $E_{\rm T}^{\rm miss}$ ;
- $S_{\rm T}$  is the total transverse energy in the event, summed over all jets,  $\tau_{\rm had-vis}$  and leptons in the event and  $E_{\rm T}^{\rm miss}$ .



Schematic description of PNN

- $\theta$ : Parameter
- *x<sub>i</sub>*: Discriminating variables



#### Systematic Uncertainties

- MC statistical uncertainties
- Instrumental uncertainties
  - Luminosity, Pileup Correction, Electrons, Muons, Taus, Jets, Flavour Tagging, ...
- Uncertainties on fake- $\tau_{\text{had}}$  background estimation
  - $\tau_{had}\tau_{had}$  FF for QCD
  - $\tau_{lep}\tau_{had}$  combined FF
  - $\tau_{had}\tau_{had}$  fake SF for  $t\overline{t}$
- Uncertainties on normalisation factors for  $\ensuremath{t\overline{t}}\xspace$  and Z+HF
- Theoretical uncertainties on signals and backgrounds.
- Most significant impact comes from:
  - MC statistical uncertainties
  - Top, Z+HF and Single Higgs theoretical uncertainties

#### Theoretical Uncertainties

- Theoretical uncertainties on signal and background:
  - Major processes with rough description here.

Process	Sources and Var	iation (N: Norm, S: Shape)	Comment
tī	NS: N	ME, PS, ISR, FSR N: PDF+α <sub>s</sub>	Normalisation is determined in the fit -> Derive relative acceptance uncertainties. Decorrelate PS unc. to avoid being strongly profiled
Z+HF	NS: μ <sub>R</sub> N: PDF+α <sub>s</sub>	&μ <sub>F</sub> scale, ME+PS , CKKW, QSF, PDF+α <sub>s</sub>	Normalisation is determined in the fit -> Derive relative acceptance uncertainties. Sherpa vs MG5+Py8
Single-top	NS: top N: Xsec, ME	interference, FSR E, PS, ISR, FSR, PDF+α <sub>s</sub>	_
Single-Higgs	N: Xsec, ME, PS, ISR, FSR, PDF+α <sub>s</sub> , Hbb&Ηττ BRs, Higgs+HF		Higgs+HF: 100% uncertainty on norm of single-Higgs processes without real b-quarks (Higgs + extra HF jets)
Res. HH	N: FastSim vs FullSim		For difference of $ au_{had}$ difference in fast and full sim.
Non-Res. ggF HH	NS: PS, μ <sub>R</sub> &μ <sub>F</sub> scale, PDF+α <sub>s</sub> ,	N: Unc from top mass scheme on Xsec	Old recommendation was used for draft 1. Recently new recommendation released ( <u>link</u> ), we have updated results.
Non-Res. VBF HH		-	_

#### **Relative Impact of Uncertainties**

• Relative impact of the various sources of uncertainties (Data stats and Syst. sum in square = 1)

Uncertainty source	Non-resonant <i>HH</i>		Resonant $X \to HH$	
encortainty source		$300  {\rm GeV}$	$500  { m GeV}$	$1000  {\rm GeV}$
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and $Z + HF$ normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
$\mathbf{Experimental}$				
Jet and $E_{\rm T}^{\rm miss}$	7%	28%	5%	3%
<i>b</i> -jet tagging	3%	6%	3%	3%
$ au_{ m had-vis}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
$Fake-\tau_{had-vis}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to  au  au) + \mathrm{HF}$	9%	17%	9%	15%
Single Higgs boson	29%	2%	15%	14%
Other backgrounds	3%	2%	5%	3%
Signal	5%	15%	13%	34%

- Still dominated by data statistical uncertainty.
- MC statistical uncertainty, top-quark and single Higgs boson modelling uncertainties have the largest impacts, for non-resonant HH search.

### **Event Displays**

#### Data with highest non-resonant SM/NN score in $\tau_{\mu}\tau_{had}$ and $\tau_{had}\tau_{had}$

