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

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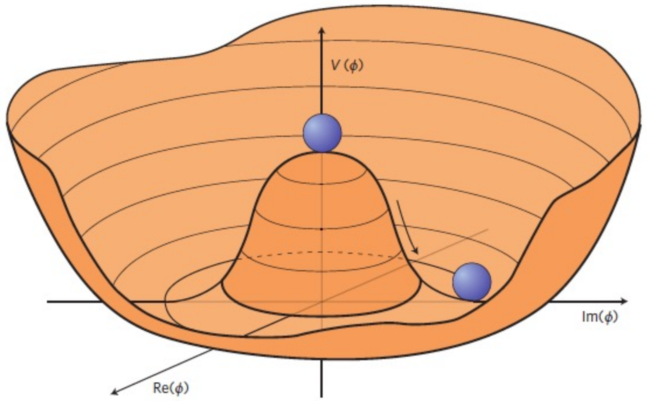
CLHCP

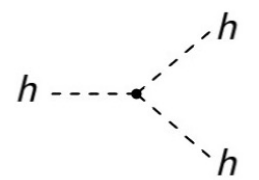
Motivation

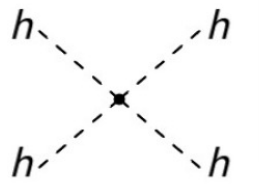
- Standard Model (SM) predicts the self-interaction of the Higgs field



$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$= V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

Massive scalar
$m_H = \sqrt{2\lambda}v$



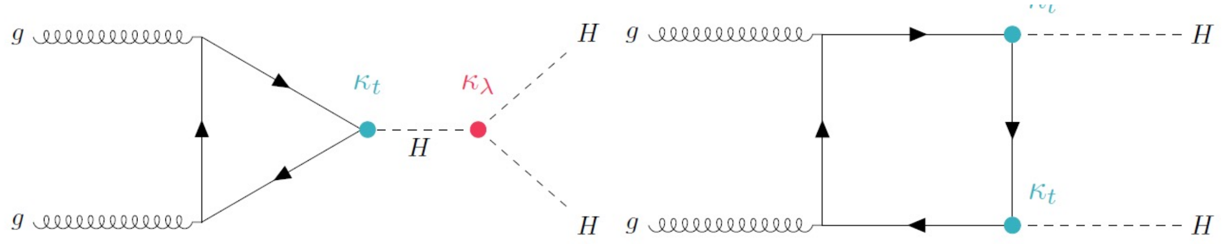


- Made great achievement on Higgs boson mass and coupling measurement.
  - No clear indications for new physics yet…
- Important information: e.g. SM vacuum is meta-stable. SM $m_H \nrightarrow$ FOFT.
- Need to further study the shape of the potential
  - Key to understand nature of EWSB, EWPT and open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

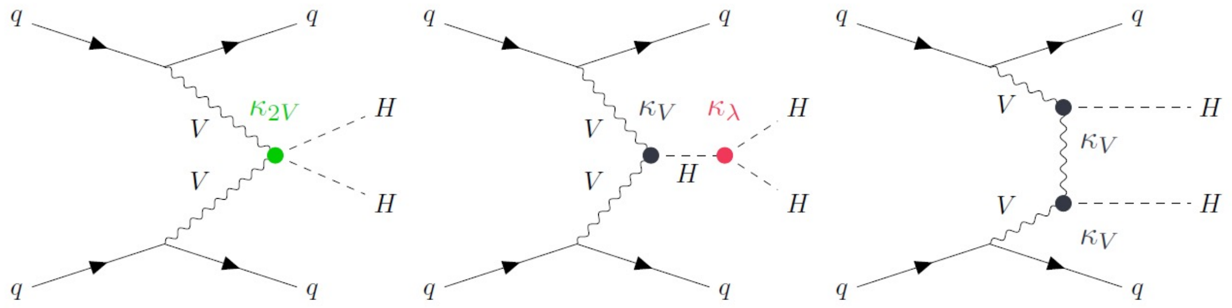
Higgs Boson Pair Production

- Production at the LHC:

Non-resonant



- ➢ SM : mainly by gluon-gluon fusion, small contribution from vector boson fusion
- ➢ Very rare:
  - ➢ σ_{ggF} @ 13 TeV: 31.1fb
  - ➢ σ_{VBF} @ 13 TeV: 1.73 fb

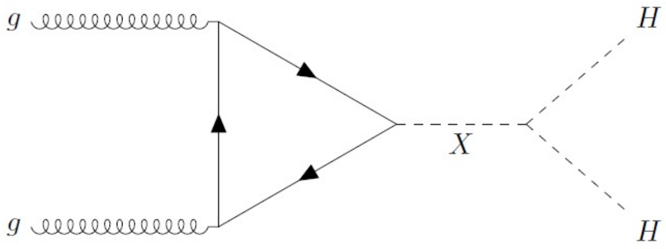


- ➢ BSM models: composite Higgs, anomalous couplings, …

Enhance the rate. Current dataset is already sensitive.

Resonant

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



Overview of Analysis Strategy

- Targeting both non-resonant and resonant production

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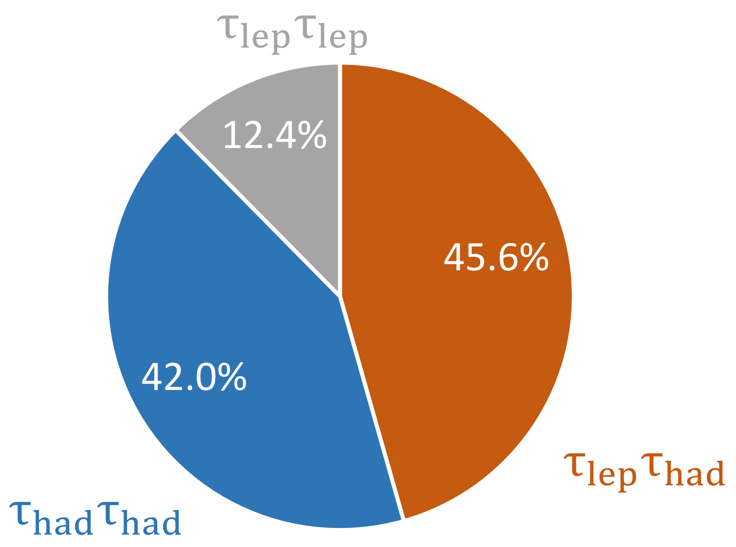
- Medium branching ratio and S/B -> one of the most sensitive channels
- Signal event final state signature contains 2 b-tagged jets and OS τ-leptons
- Focus on $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ di-tau final states using full Run 2 dataset with $L = 139\ \mathrm{fb}^{-1}$ collected by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

Di-Higgs Decay Modes

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%

Di-tau Decay Modes



Overview of Analysis Strategy

- Events further categorized by triggers:

$\tau_{\rm had}\tau_{\rm had}$	Single-τ and di-τ triggers	High purity
$\tau_{\rm lep}\tau_{\rm had}$ SLT	Single-lepton triggers	High acceptance, large $t\bar{t}$ background
$\tau_{\rm lep}\tau_{\rm had}$ 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 $\tau_{\rm had}\tau_{\rm had}$ and $\tau_{\rm lep}\tau_{\rm had}$
  - Upper limits on di-Higgs production cross section.

NN: Neural Network
BDT: Boosted Decision Tree

Physics Objects Definitions

	Electron	Muon	Tau & Anti-Tau	Jet
p_T	p_T > 7 GeV	p_T > 7 GeV	p_T > 20 GeV	p_T > 20 GeV
$\|\eta\|$	$\|\eta\|$ < 2.47 (veto 1.37-1.52)	$\|\eta\|$ < 2.7	$\|\eta\|$ < 2.5 (veto 1.37-1.52)	$\|\eta\|$ < 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			RNN-based Tau-ID (using information of associated tracks and jets)	Anti-k_T R=0.4 jets Particle-flow reconstruction DL1r RNN-based b-tagger Additional b-jet energy corrections

Inverting isolation of e/mu or identification of tau to define control regions

Keys to the improvements of signal efficiency

WP: Working Point
ID: Identification
RNN: Recurrent Neural Network

Selections

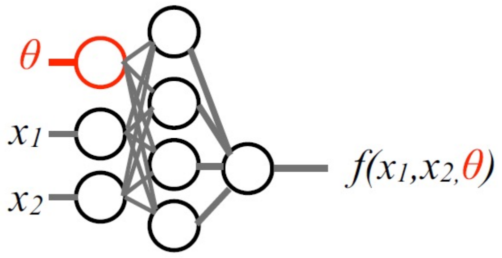
	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Triggers	Single Lepton (e/μ) triggers (SLT)	Single τ_{had} triggers (STT)
	Or Lepton + τ_{had} triggers (LTT)	Or Di-τ_{had} triggers (DTT)
	Offline Requirements Passed	
Event Selection	$m_{\tau\tau}^{MMC}$ [*] > 60 GeV	
	Opposite-sign of $e/\mu/\tau_{had}$ and τ_{had}	
	Exactly two b-tagged jets	
	One (tight) e or (medium) μ	No loose e/μ
	One (loose) τ_{had}	Two (loose) τ_{had}
	M_{bb} < 150 GeV	

[*] likelihood-based di-τ mass reconstruction

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

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_T(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_T		✓	
m_T^W		✓	
E_T^{miss}		✓	
$\mathbf{p}_T^{miss}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_T^{miss})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_T^{miss})$			✓
S_T			✓



Θ is the parameter, here: mass of the resonance
x_i are the feature variables

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Examples of Input Variables

From left to right:

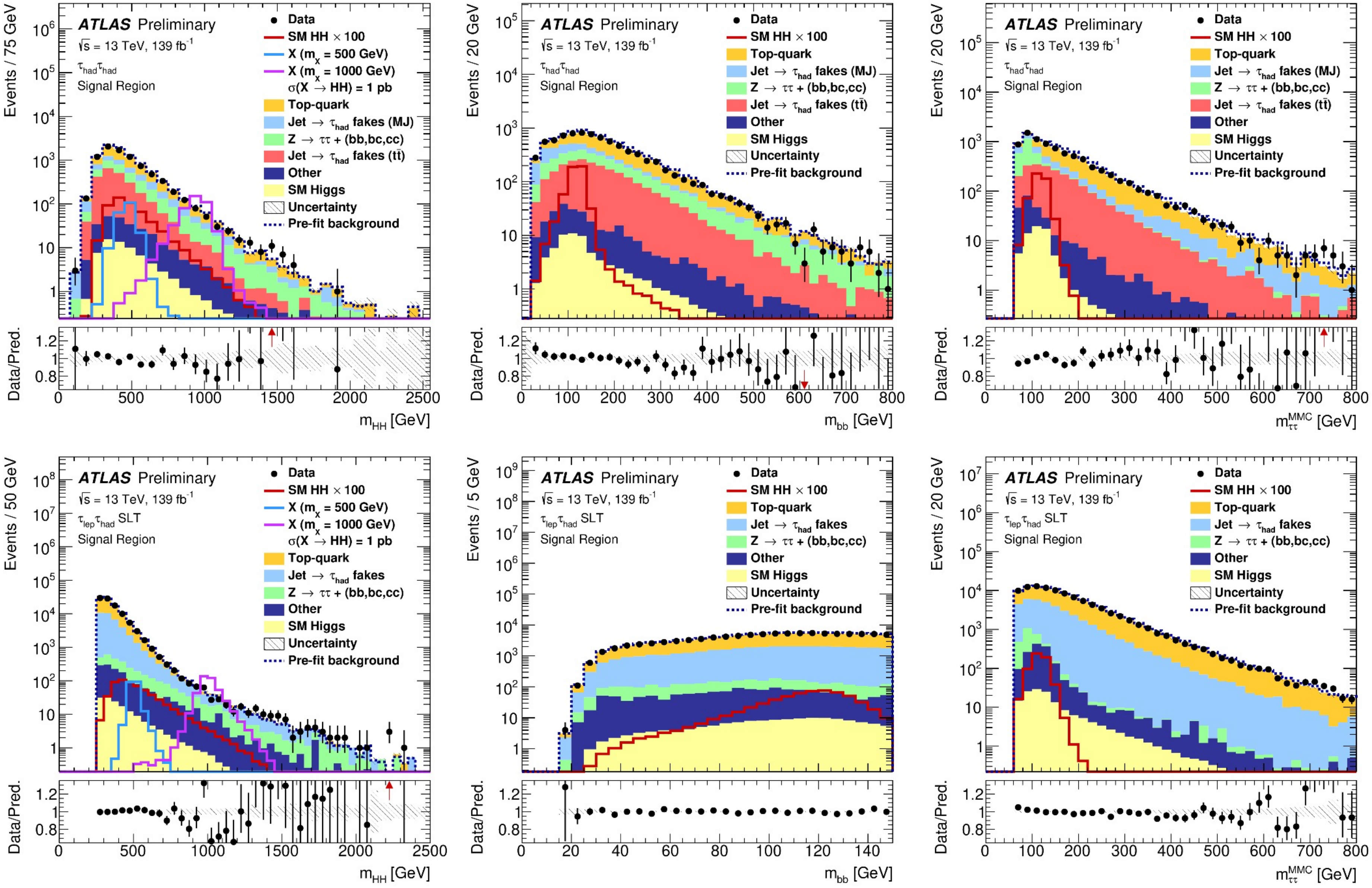
➢ m_{HH}, m_{bb}, $m_{\tau\tau}$

1st row: $\tau_{had}\tau_{had}$

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

After the aforementioned selections

Post-fit (B-only) level plots. Fit results of non-res HH search applied.



Background Estimation

- Main backgrounds:
  - top-quark, Z+jets, W+jets, diboson, single Higgs boson and multi-jet production
  - Backgrounds with τ_{had} mis-identified by quark-/gluon-initiated jet (fake-τ_{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, $m_{\ell\ell}$ window (75-110 GeV)
  - Also provides constraints on the normalisation of the $t\bar{t}$ background
  - Typical norm. factors

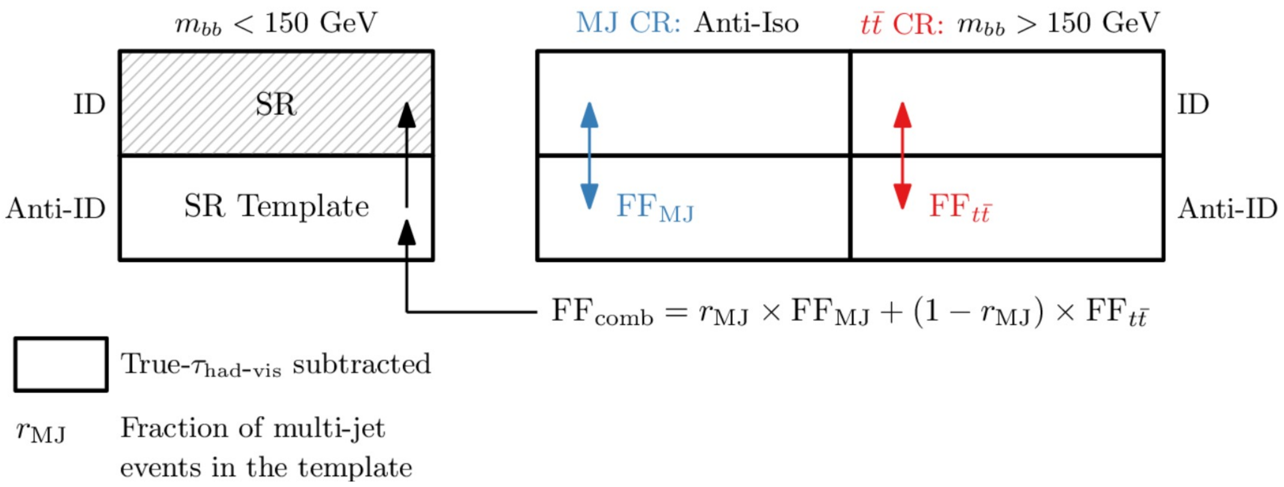
Z+HF	1.39±0.11
$t\bar{t}$	0.96±0.03

SFOS: Same flavour opposite sign

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

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

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



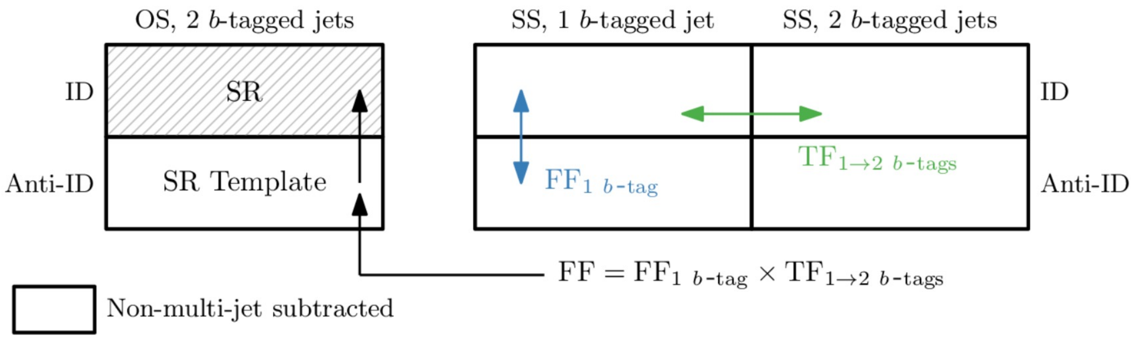
- $\tau_{lep}\tau_{had}$ FFs:
  - Derive in MJ CR (invert lepton isolation) and $t\bar{t}$ CR (m_{bb} > 150 GeV) for multi-jet (MJ) and $t\bar{t}$.
  - Separately for triggers. Parameterised by anti-τ_{had} p_T and prong. (Others are similar)
  - Then combined by fraction in the SR template (quantified by r_{MJ})

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

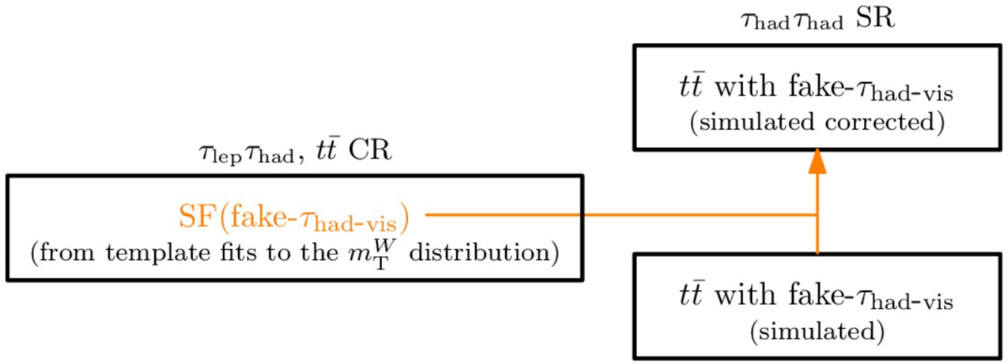
  - In--situ correction on $t\bar{t}$ to improve modelling of templates.

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

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



MVA Output Distributions

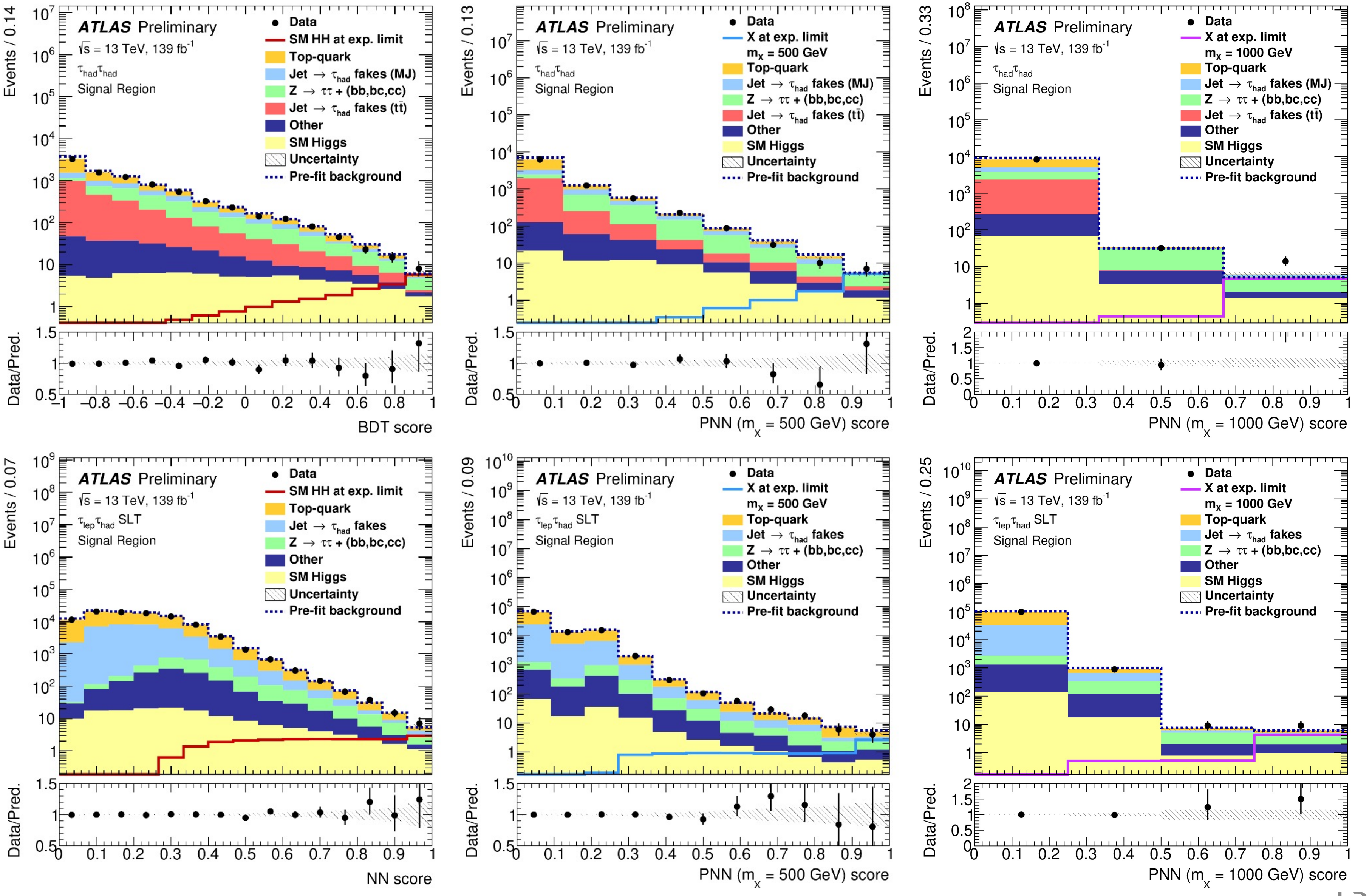
From left to right:

- ➢ BDT output in non-resonant search
- ➢ PNN output m_X = 500 GeV
- ➢ PNN output m_X = 1 TeV

1st row: $\tau_{had}\tau_{had}$

2nd 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.



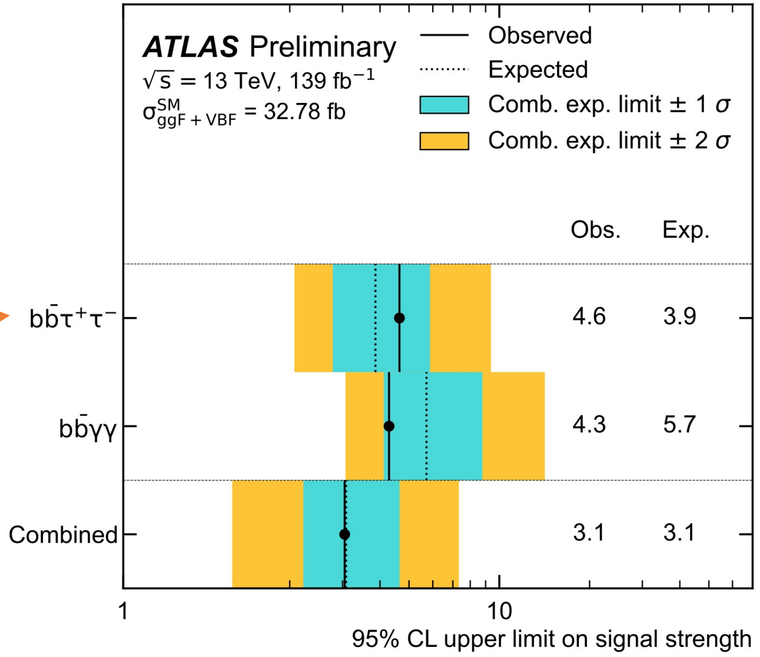
Results: Non-resonant HH

- 95% CL Upper limits on μ = $\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$ -> 4.7 (3.9) observed (expected)

		Observed	$-2\ \sigma$	$-1\ \sigma$	Expected	$+1\ \sigma$	$+2\ \sigma$
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	265	124	167	231	322	432
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.65	2.08	2.79	3.87	5.39	7.22

Combination of $\tau_{had}\tau_{had}$ $\tau_{lep}\tau_{had}$

HH summary ATLAS-CONF-2021-052

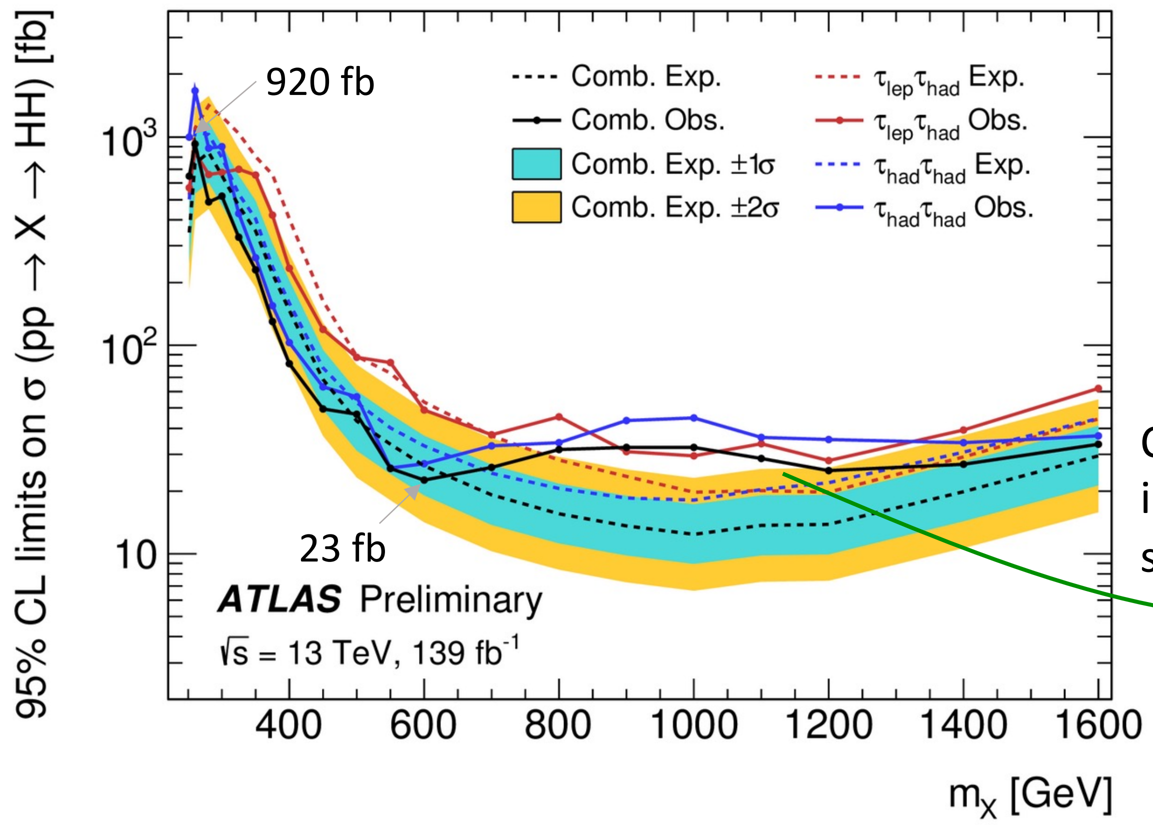


- The most sensitive channel to date

Results: Resonant HH

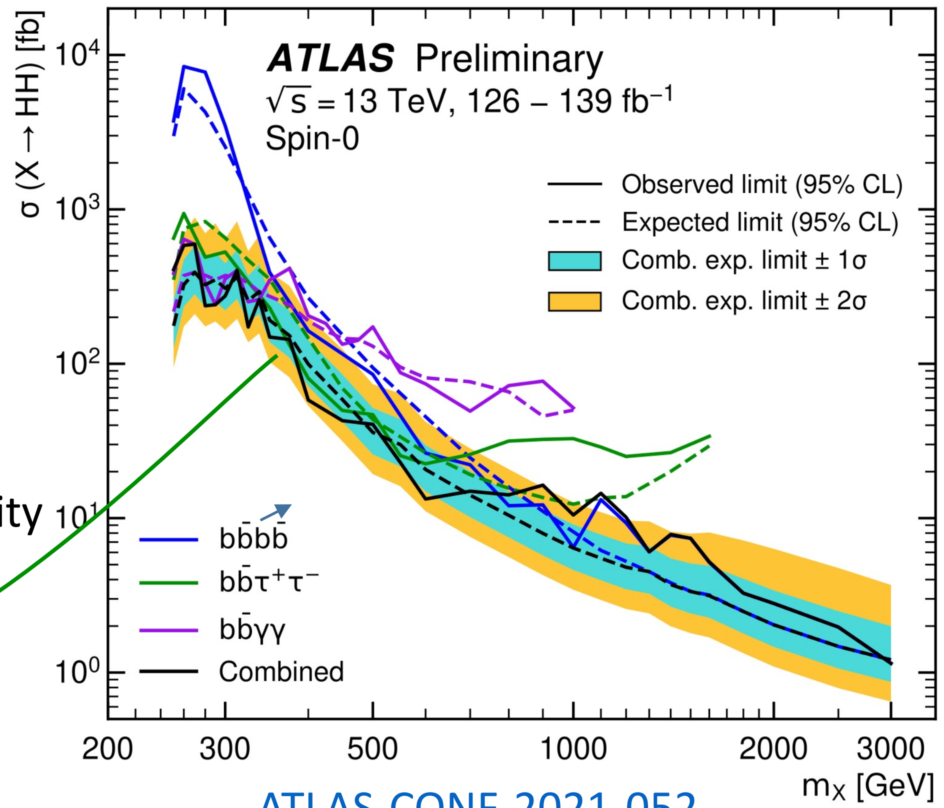
- Broad excess observed from 0.7 to 1.2 TeV
- Maximum local excess significance:
  - Combined: 3.0σ @ 1.0 TeV (Global significance by asymptotic formula $2.0^{+0.4}_{-0.2}\sigma$)
  - $\tau_{\text{lep}}\tau_{\text{had}}$: 1.6σ @ 1.1 TeV, $\tau_{\text{had}}\tau_{\text{had}}$: 2.8σ @ 1.0 TeV

Precise result will be derived using bootstrapping.



Competitive sensitivity in 400 GeV - 1 TeV search range.

Green



ATLAS-CONF-2021-052

HH summary

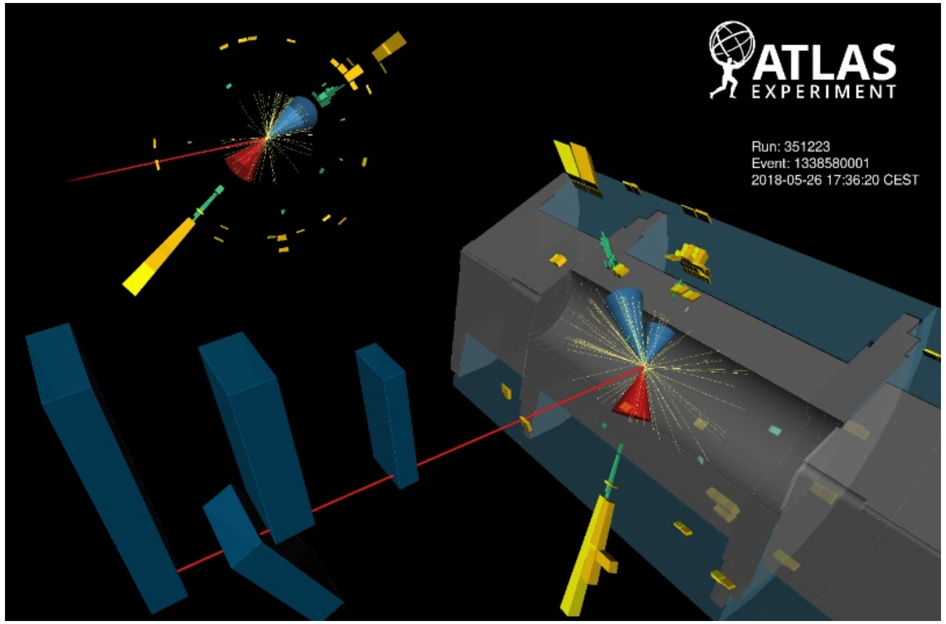
Conclusion

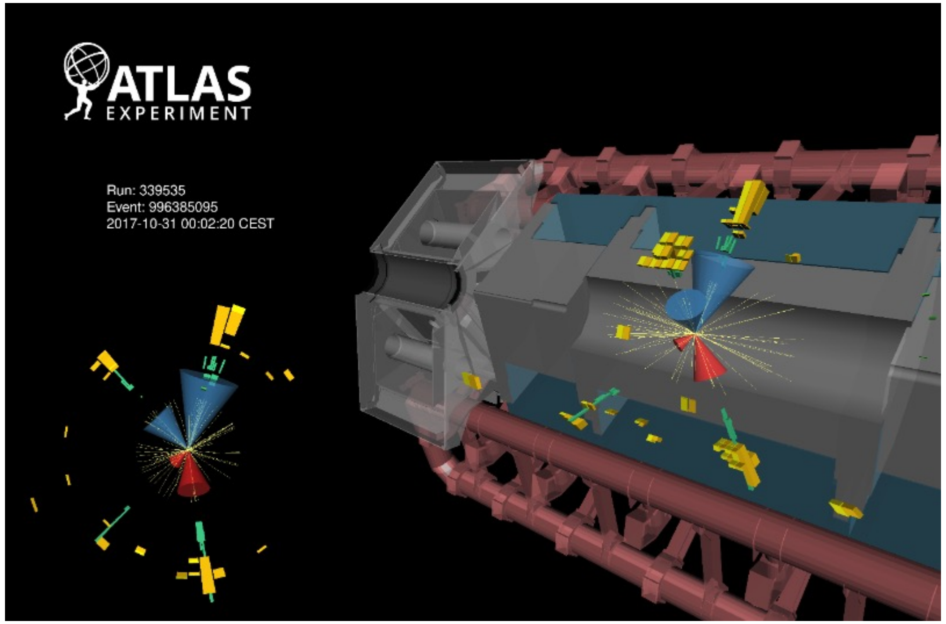
- A search for non-resonant and resonant Higgs boson pair production using $bb\tau\tau$ events
- Data are found to be compatible with the background-only hypothesis
- Largest deviation observed at resonance mass of 1 TeV, local (global) 3.0σ ($2.0^{+0.4}_{-0.2}\sigma$)
- Main results:
  - Upper limits on non-resonant HH production cross-section: obs.(exp.) = 4.7(3.9) x σ_{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 $\tau_{\mu}\tau_{\mathrm{had}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$

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 (α_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 hadronisation	UE model tune	Cross section order
Signal					
non-resonant $gg \to HH$ (ggF)	POWHEG-BOX v2	PDF4LHC15 [73]	PYTHIA 8.244 [68]	A14	NNLO FTApprox [20]
non-resonant $qq \to qqHH$ (VBF)	MADGRAPH	NNPDF3.0NLO [74]	PYTHIA 8.244	A14	N3LO(QCD)
resonant $gg \to X \to HH$	MADGRAPH	NNPDF2.3LO [70]	HERWIG v7.1.3	H7.1-Default	–
Top-quark					
$t\bar{t}$	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NNLO+NNLL [75]
t-channel	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO [76]
s-channel	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO [77]
Wt	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 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	PYTHIA 8.212	AZNLO	N3LO(QCD)+NLO(EW) [79–83]
VBF	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \to WH$	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD)+NLO(EW) [84–90]
$qq \to ZH$	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$gg \to ZH$	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.212	AZNLO	NLO+NLL
ttH	POWHEG-BOX v2	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO

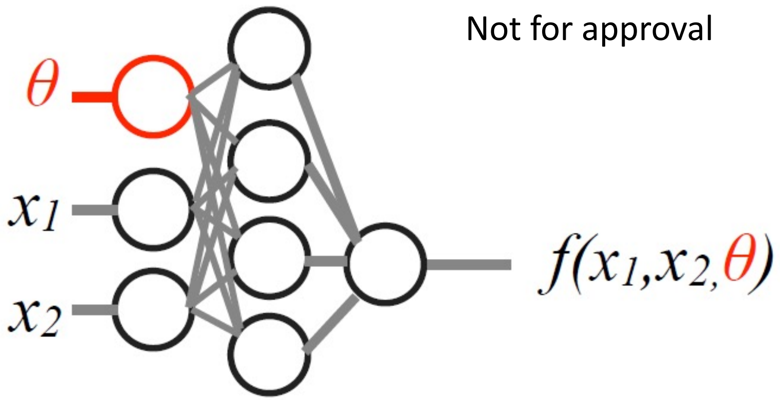
Triggers

Definition of MVA Input Variables

- m_{HH} is the invariant mass of the HH system as reconstructed from the τ_{had} pair (calculated using the MMC) and the b-tagged jet pair;
- $\Delta R(\tau,\tau)$ is evaluated between the two $\tau_{\text{had-vis}}$ (the electron or muon and the $\tau_{\text{had-vis}}$) in the $\tau_{\text{had}}\tau_{\text{had}}$ ($\tau_{\text{lep}}\tau_{\text{had}}$) channel;
- $\Delta R(b,b)$ is evaluated between the b-tagged jets;
- $\Delta p_{\text{T}}(\ell,\tau)$ is the difference between the transverse momenta of the lepton and the $\tau_{\text{had-vis}}$;
- $m_{\text{T}}^{W} = \sqrt{2p_{\text{T}}^{\ell}E_{\text{T}}^{\text{miss}}(1-\cos\Delta\phi_{\ell,E_{\text{T}}^{\text{miss}}})}$ is the transverse mass of the lepton and the $E_{\text{T}}^{\text{miss}}$;
- the $E_{\text{T}}^{\text{miss}}$ ϕ centrality specifies the relative angular position of the E_{T}^{miss} relative to the $\tau_{\text{had-vis}}$ in the transverse plane [126] and is defined as $(A+B)/\sqrt{A^2+B^2}$, where $A = \sin(\phi_{E_{\text{T}}^{\text{miss}}}-\phi_{\tau_2})/\sin(\phi_{\tau_1}-\phi_{\tau_2})$, $B = \sin(\phi_{\tau_1}-\phi_{E_{\text{T}}^{\text{miss}}})/\sin(\phi_{\tau_1}-\phi_{\tau_2})$, and τ_1 and τ_2 represent the two $\tau_{\text{had-vis}}$ (electron or muon and $\tau_{\text{had-vis}}$) in the case of the $\tau_{\text{had}}\tau_{\text{had}}$ ($\tau_{\text{lep}}\tau_{\text{had}}$) channel;
- $\Delta\phi(\tau\tau,bb)$ is the azimuthal angle between the $\tau_{\text{had-vis}}$ pair and the b-tagged jet pair;
- $\Delta\phi(\ell,E_{\text{T}}^{\text{miss}})$ is the azimuthal angle between the lepton and $E_{\text{T}}^{\text{miss}}$;
- $\Delta\phi(\ell\tau,E_{\text{T}}^{\text{miss}})$ is the azimuthal angle between the electron or muon and $\tau_{\text{had-vis}}$ system and the $E_{\text{T}}^{\text{miss}}$;
- S_{T} is the total transverse energy in the event, summed over all jets, $\tau_{\text{had-vis}}$ and leptons in the event and $E_{\text{T}}^{\text{miss}}$.

Parametric Neural Networks

Not for approval

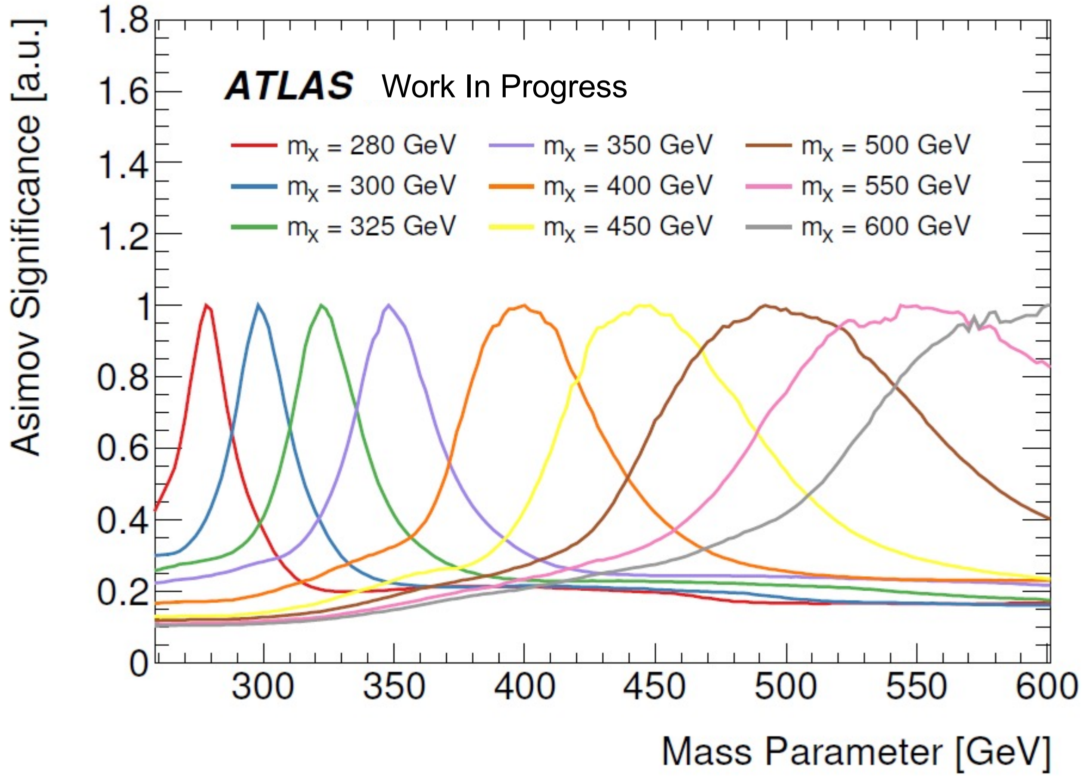


Schematic description of PNN

θ: Parameter

x_i: Discriminating variables

Not for approval



Systematic Uncertainties

- MC statistical uncertainties
- Instrumental uncertainties
  - Luminosity, Pileup Correction, Electrons, Muons, Taus, Jets, Flavour Tagging, …
- Uncertainties on fake-τ_{had} background estimation
  - $\tau_{had}\tau_{had}$ FF for QCD
  - $\tau_{lep}\tau_{had}$ combined FF
  - $\tau_{had}\tau_{had}$ fake SF for $t\bar{t}$
- Uncertainties on normalisation factors for $t\bar{t}$ 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.

<table>
<tr><th>Process</th><th colspan="2">Sources and Variation (N: Norm, S: Shape)</th><th>Comment</th></tr>
<tr><td>$t\bar{t}$</td><td colspan="2">NS: ME, PS, ISR, FSR
N: PDF+α_S</td><td>Normalisation is determined in the fit -> Derive relative acceptance uncertainties. Decorrelate PS unc. to avoid being strongly profiled</td></tr>
<tr><td>Z+HF</td><td colspan="2">NS: μ_R&μ_F scale, ME+PS
N: PDF+α_S, CKKW, QSF, PDF+α_S</td><td>Normalisation is determined in the fit -> Derive relative acceptance uncertainties. Sherpa vs MG5+Py8</td></tr>
<tr><td>Single-top</td><td colspan="2">NS: top interference, FSR
N: Xsec, ME, PS, ISR, FSR, PDF+α_S</td><td>-</td></tr>
<tr><td>Single-Higgs</td><td colspan="2">N: Xsec, ME, PS, ISR, FSR, PDF+α_S, Hbb&H$\tau\tau$ BRs, Higgs+HF</td><td>Higgs+HF: 100% uncertainty on norm of single-Higgs processes without real b-quarks (Higgs + extra HF jets)</td></tr>
<tr><td>Res. HH</td><td rowspan="3">NS: PS, μ_R&μ_F scale, PDF+α_S, Hbb&H$\tau\tau$ BRs</td><td>N: FastSim vs FullSim</td><td>For difference of τ_{had} difference in fast and full sim.</td></tr>
<tr><td>Non-Res. ggF HH</td><td>N: Unc from top mass scheme on Xsec</td><td>Old recommendation was used for draft 1. Recently new recommendation released (link), we have updated results.</td></tr>
<tr><td>Non-Res. VBF HH</td><td>-</td><td>-</td></tr>
</table>

Relative Impact of Uncertainties

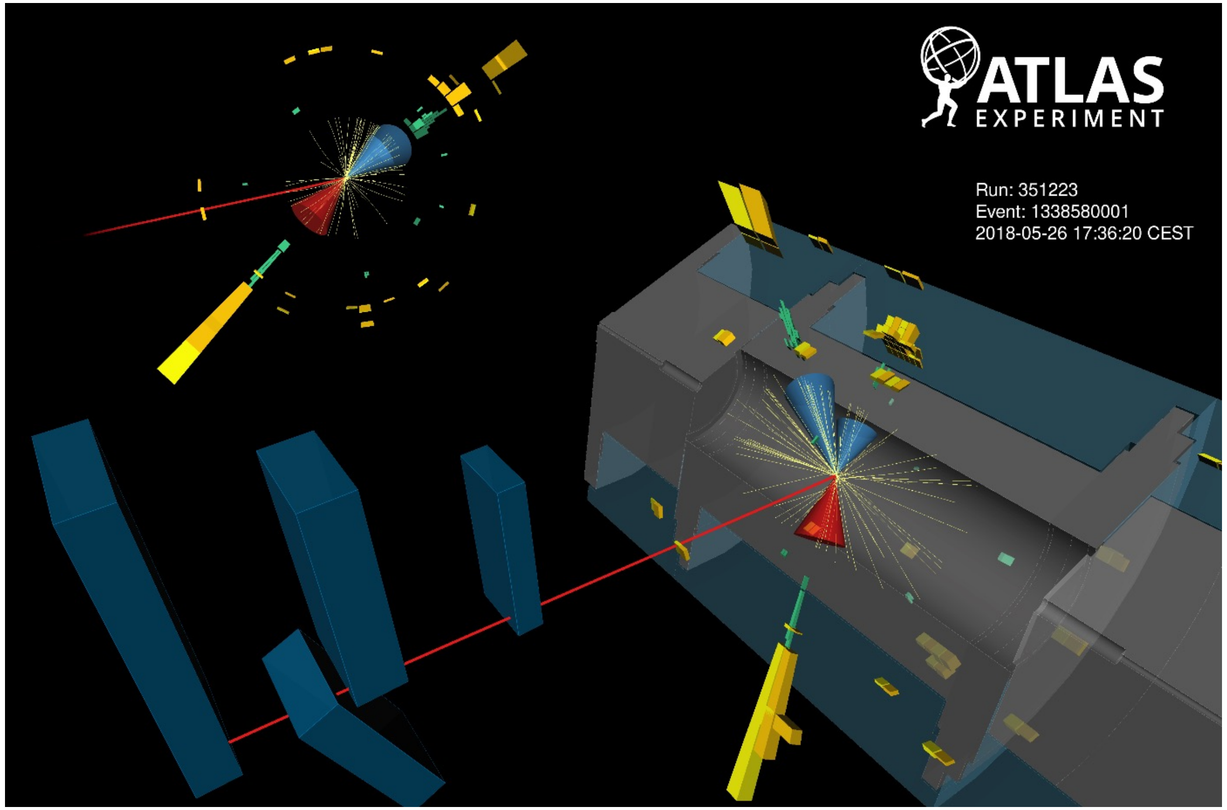
- Relative impact of the various sources of uncertainties (Data stats and Syst. sum in square = 1)

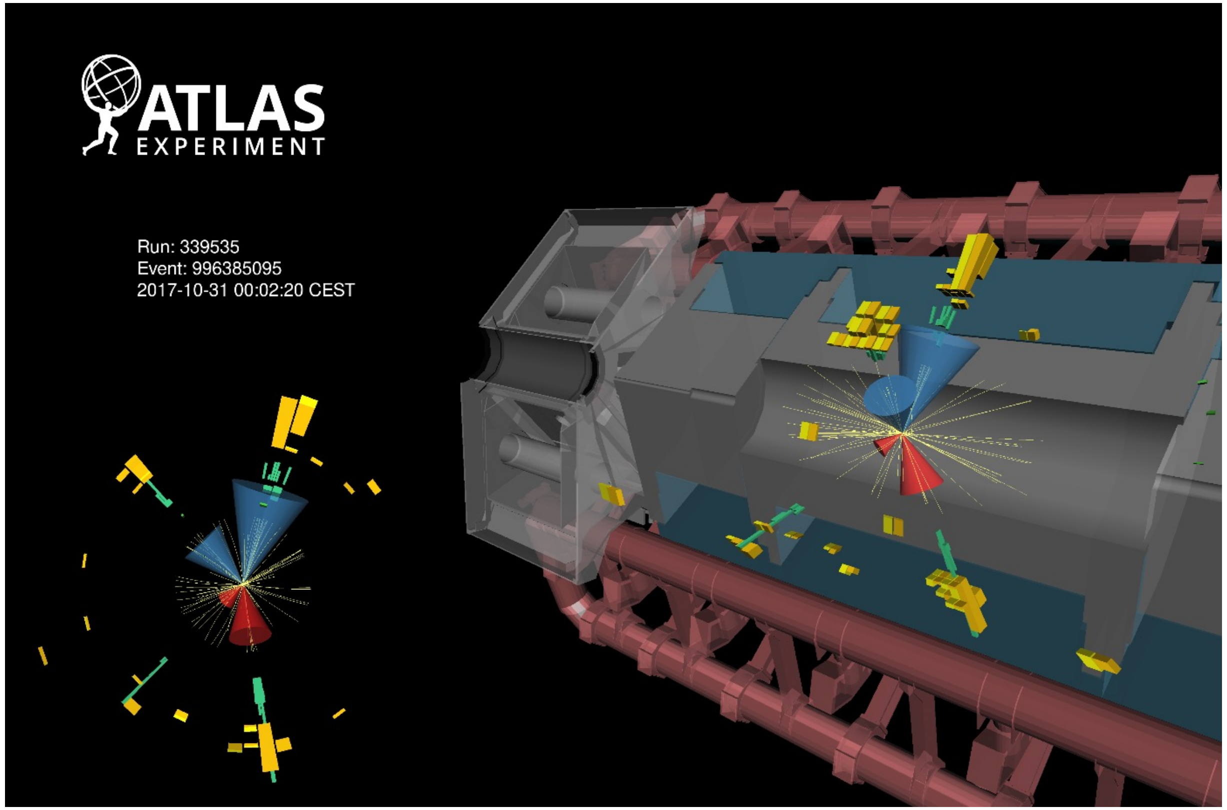
Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	500 GeV	1000 GeV
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and $Z+$HF normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
Experimental				
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	28%	5%	3%
b-jet tagging	3%	6%	3%	3%
$\tau_{\text{had-vis}}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
Fake-$\tau_{\text{had-vis}}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to \tau\tau)+$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 $\tau_\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$





$\boldsymbol{\tau_\mu\tau_{\text{had}}}$

$\boldsymbol{\tau_{\text{had}}\tau_{\text{had}}}$