$\mathsf{H} \to \mathsf{WW} \to \ell \nu \ \ell \nu$

- BR(H \rightarrow WW \rightarrow lvlv) ~1% for m_H ~ 125 GeV/c²
- Neutrinos \rightarrow no mass peak, \rightarrow use transverse mass
- Large backgrounds: WW, Wt, tt
- Require opposite-charge lepton-pair (ee, μμ, eμ)
- Different background composition depending on nJets and di-lepton flavours
- Split analysis into distinct regions for best overall sensitivity



Difficulties:

(i) need precise knowledge of the backgrounds

Strategy: use control region(s) in data, extrapolation in signal region (ii) jet veto efficiencies need to be understood for signal and background events

$H \rightarrow WW \rightarrow \ell \nu \, \ell \nu$ Analysis Overview







$H \rightarrow WW \rightarrow \ell \nu \, \ell \nu$: Top background

Top (tt+t+Wt) suppression:

- Large background with (two) W→IV
- b-jet veto





Top estimation:

- Normalization in signal regions determined from data b-tag control regions
- Systematic uncertainty in n_{Jet}=0 category: 8%

$H \rightarrow WW \rightarrow \ell \nu \, \ell \nu$: WW background

1

WW suppression:

- Use different spin correlation and m_H < 2×m_W:
 - Reject large di-lepton invariant masses





WW estimation:

- ≤ I Jet: Use high-m_{II} data control region for normalization
- ≥2 Jets: Sub-dominant background; taken from MC

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ \ell\ell} + p_{\mathrm{T}}^{\ \nu\nu}\right)^{2} - \left|\boldsymbol{p}_{\mathrm{T}}^{\ \ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\ \nu\nu}\right|^{2}}$$

$H \rightarrow WW \rightarrow \ell \nu \ell \nu$: gluon-fusion analysis

Signal extraction:

- Maximum-Likelihood Fit in $m_T = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}\right|^2}$
 - For 0/1-jet eµ: categorized in total of 12 signal regions, binned in m_{II}, and flavour and p_T of sub-leading lepton
 - Other channels: global
 - Multiple background control regions in fit



Higgs

lod

$H \rightarrow WW \rightarrow \ell v \, \ell v$: Vektor-boson-fusion analysis

Combine background-discriminating variables into BDT

Events / (15 / 8)

200

180

160E

140

40F

20

120

100

80

60

100

80 60

40 20

0

0.2 0.4 0.6 0.8

ATLAS Simulation

DY(ττ)

 H_{VBF} (×50)

1.5

 ΣC_{I}

1 1.2 1.4 1.6 1.8

Lepton centrality ΣC_{I}

vs = 8 TeV. 20.3 fb⁻¹

n,≥2j VBF,eµ



Fit re-binned BDT distribution

BDT modelling validated in background regions

 $O_{\rm BDT}$

$H \rightarrow WW \rightarrow \ell \nu \, \ell \nu$: gluon-fusion results

Results:

• Clear signal visible in 0/1-jet category

ggF signal significance: 4.3 σ (4.3 σ)
 observed (expected) @m_H = 125.36
 GeV



$H \rightarrow WW \rightarrow \ell v \, \ell v$: Vektor-boson-fusion results

Results:

•BDT outputs in good agreement with data

- •VBF signal significance: 3.2 σ (2.7 σ) observed (expected)
 - ⇒ evidence of Vector-Boson-Fusion production of Higgs bosons in the H → WW* → lvlv decay channel



H → WW → $\ell v \ell v$: combined results Signal significance: 6.1 σ observed (5.8 σ expected) @m_H = 125.36 GeV ⇒ Clear observation of the H → WW* decay mode in the lvlv channel alone!

• Observed value ($@m_H = 125.36 \text{ GeV}$): $\mu = 1.09 + 0.23 - 0.21$





/5

$H \rightarrow \tau\tau$: Overview

180

- BR(H \rightarrow TT) ~6.32% for m_H ~ 125 GeV/c²
- Measure Yukawa coupling to fermions directly
- Currently only accessible leptonic coupling
- Study leptonic and hadronic decay modes of taus

Experimental challenge:

- Identification of hadronic taus
- Good E_T^{miss} resolution $m_{\tau\tau}$ reconstructed with "missing-mass calculator.

(In the past: $\tau\tau$ mass reconstruction in collinear approximation,

i.e. assume that the neutrinos go in the direction of the visible decay products, good approximation for highly boosted taus)

 \rightarrow Higgs mass can be reconstructed

- Dominant background: $Z \rightarrow \tau \tau$ the shape of this background must be controlled in the high mass region
 - \rightarrow use data (Z \rightarrow µµ) to constrain it (embedding)

$H \rightarrow \tau \tau$: Analysis

Event categorization:

Background suppression:

- VBF (loose/tight): two tag jets
- $\boldsymbol{\cdot}$ Boosted: large Higgs-boson \boldsymbol{p}_{T} sd

Signal extraction:

- Maximum likelihood fits
- Fit variable: BDT output
- Various data control regions



Boosted Decision Trees (BDT)

	Variable		VBF		Boosted			
		$\tau_{\rm lep} \tau_{\rm lep}$	$\tau_{\rm lep} \tau_{\rm had}$	$\tau_{\rm had} \tau_{\rm had}$	$\tau_{\rm lep} \tau_{\rm lep}$	$\tau_{\rm lep} \tau_{\rm had}$	$ au_{ m had} au_{ m had}$	
3	$m_{ au au}^{ m MMC}$	•	٠	٠	•	٠	٠	
2	$\Delta R(au_1, au_2)$	•	٠	٠		٠	٠	
	$\Delta\eta(j_1,j_2)$	•	٠	٠				
	m_{j_1,j_2}	•	•	•				
	$\frac{\eta_{j_1} \times \eta_{j_2}}{p_{\rm T}^{\rm Total}}$		•	•				
			•	•				
	$\operatorname{Sum} p_{\mathrm{T}}$					•	•	
	$p_{\mathrm{T}}^{ au_{1}}/p_{\mathrm{T}}^{ au_{2}}$					•	•	
	$E_{\rm T}^{\rm miss}\phi$ centrality		•	•	•	•	•	
	m_{ℓ,ℓ,j_1}				•			
	m_{ℓ_1,ℓ_2}				•			
	$\Delta \phi(\ell_1, \ell_2)$				•			
	Sphericity				•			
	$p_{ ext{T}}^{\ell_1}$				•			
	$p_{\mathrm{T}}^{j_{1}}$				•			
	$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell_2}$				•			
	$m_{ m T}$		•			•		
	$\min(\Delta \eta_{\ell_1 \ell_2, \text{jets}})$	•						
	$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•						
	$C_{\eta_1,\eta_2}(\eta_\ell)$		•					
0	$C_{\eta_1,\eta_2}(\eta_{j_3})$	•						
	$C_{\eta_1,\eta_2}(\eta_{ au_1})$			•				
	$C_{\eta_1,\eta_2}(\eta_{ au_2})$			•				







Run: 209074 Event: 29487501 2012-08-23 15:06:35 UTC

$H \rightarrow \tau\tau$: combined results



$H \rightarrow \tau \tau$: combined results

Significance of result:

- 4.5σ observed
- 3.4 o expected

ATLAS			-σ(statistical)			Total uncertainty		
m _H = 125.36 GeV			−σ(syst. excl. theory) −σ(theory)			$\pm 1\sigma$ on μ		
$\textbf{H} \rightarrow \tau \tau$	$\mu = 1.4^{+0.4}_{-0.4}$	+ 0.3 - 0.3 + 0.3 - 0.2 + 0.1 - 0.1						
Boosted	$\mu = 2.1^{+0.9}_{-0.8}$				-	1		
VBF	$\mu = 1.2^{+0.4}_{-0.4}$	+ 0.3 - 0.3		- i .			:	
7 TeV (Combined	d) $\mu = 0.9^{+1.1}_{-1.1}$	+ 0.8 - 0.8		-		 	:	
8 TeV (Combined	$\mu = 1.5^{+0.5}_{-0.4}$	+ 0.3 - 0.3					· · ·	
$\textbf{H} \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$	$\mu = 2.0^{+1.0}_{-0.9}$	+ 0.7 - 0.7 + 0.6 - 0.5 + 0.1 - 0.1	F		-1			
Boosted	$\mu=3.0^{+2.0}_{-1.7}$	+ 1.4 - 1.3		·				
VBF	$\mu = 1.7^{+1.0}_{-0.9}$	+ 0.8 - 0.8	, L			; 	: : 	
${f H} o au_{ m lep} au_{ m had}$	$\mu = 1.0^{+0.5}_{-0.5}$	+ 0.4 - 0.3 + 0.4 - 0.3 + 0.1 - 0.1		· · · · · · · · · · · · · · · · · · ·			· · ·	
Boosted	$\mu = 0.9^{_{+1.0}}_{_{-0.9}}$	+ 0.6 - 0.6		-		i İ	:	
VBF	$\mu = 1.0^{+0.6}_{-0.5}$	+ 0.5 - 0.4		• <u>;</u>		:	: : :	
${f H} o au_{ m had} au_{ m had}$	$\mu = 2.0^{+0.9}_{-0.7}$	+ 0.5 - 0.5 + 0.8 - 0.5 + 0.1 - 0.1						
Boosted	$\mu = 3.6^{+2.0}_{-1.6}$	+ 1.0 - 0.9		, i ,			: :, ,	
VBF	$\mu = 1.4^{+0.9}_{-0.7}$	+ 0.6 - 0.5		-i.		: 		
0 2 4 $s = 7 \text{ TeV}, 4.5 \text{ fb}^{-1}$ Signal strength $s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$						ר (µ		



Standard	d Model Total Produc			ements Status: March 2015	∫£ dt [fb ^{−1}]	Reference
pp total	$\sigma = 95.35 \pm 0.38 \pm 1.3 \ \mathrm{mb} \ \mathrm{(data)} \\ \mathrm{COMPETE} \ \mathrm{RRpl2u} \ \mathrm{2002} \ \mathrm{(theory)}$		о О			Nucl. Phys. B, 486-548 (2014)
Jets R=0.4 $ y < 3.0$	$\sigma = 563.9 \pm 1.5 + 55.4 - 51.4 \text{ nb} (\text{data}) \\ \text{NLOJet++, CT10} (\text{theory})$		0.1 < p _T < 2 TeV	•	4.5	arXiv:1410.8857 [hep-ex]
Dijets R=0.4 y <3.0, y*<3.0	$\sigma = 86.87 \pm 0.26 + 7.56 - 7.2 \text{ nb} \text{ (data)} \\ \text{NLOJet++, CT10 (theory)}$	0.3 < <i>n</i>	n _{jj} < 5 TeV	0	4.5	JHEP 05, 059 (2014)
W total	$\sigma = 94.51 \pm 0.194 \pm 3.726 \text{ nb} \text{ (data)} \\ \text{FEWZ+HERAPDF1.5 NNLO (theory)}$		¢	4	0.035	PRD 85, 072004 (2012)
Z total	$\sigma = 27.94 \pm 0.178 \pm 1.096 \text{ nb (data)} \\ \text{FEWZ+HERAPDF1.5 NNLO (theory)}$		0	4	0.035	PRD 85, 072004 (2012)
tī total	$ \begin{aligned} \sigma &= 182.9 \pm 3.1 \pm 6.4 \text{ pb (data)} \\ & \text{top++ NNLO+NNLL (theory)} \\ \sigma &= 242.4 \pm 1.7 \pm 10.2 \text{ pb (data)} \\ & \text{top++ NNLO+NNLL (theory)} \end{aligned} $	¢ 4		4	4.6 20.3	Eur. Phys. J. C 74: 3109 (2014) Eur. Phys. J. C 74: 3109 (2014)
t _{t-chan}	$ \begin{aligned} \sigma &= 68.0 \pm 2.0 \pm 8.0 \text{ pb (data)} \\ \text{NLO+NLL (theory)} \\ \sigma &= 82.6 \pm 1.2 \pm 12.0 \text{ pb (data)} \\ \text{NLO+NLL (theory)} \end{aligned} $	¢ 4			4.6 20.3	PRD 90, 112006 (2014) ATLAS-CONF-2014-007
WW+WZ	$\sigma = 68.0 \pm 7.0 \pm 19.0 \text{ pb (data)} \\ \text{MC@NLO (theory)}$	•	LHC pp $\sqrt{s} = 7 \text{ TeV}$ Theory		4.6	JHEP 01, 049 (2015)
WW total	$\sigma = 51.9 \pm 2.0 \pm 4.4 \text{ pb (data)}$ MCFM (theory) $\sigma = 71.4 \pm 1.2 + 5.5 - 4.9 \text{ pb (data)}$ MCFM (theory)	þ A	Observed		4.6 20.3	PRD 87, 112001 (2013) ATLAS-CONF-2014-033
Wt	$ \begin{aligned} \sigma &= 16.8 \pm 2.9 \pm 3.9 \mathrm{pb} \mathrm{(data)} \\ \mathrm{NLO+NLL} \mathrm{(theory)} \\ \sigma &= 27.2 \pm 2.8 \pm 5.4 \mathrm{pb} \mathrm{(data)} \\ \mathrm{NLO+NLL} \mathrm{(theory)} \end{aligned} $		stat stat+syst		2.0 20.3	PLB 716, 142-159 (2012) ATLAS-CONF-2013-100
H ggF total	$\sigma = 23.9 + 3.9 - 3.5 \text{ pb (data)}$ LHC-HXSWG (theory)	4	LHC pp $\sqrt{s} = 8 \text{ TeV}$		20.3	ATLAS-CONF-2015-007
WZ total	$\sigma = 19.0 + 1.4 - 1.3 \pm 1.0 \text{ pb} (\text{data})$ MCFM (theory) $\sigma = 20.3 + 0.8 - 0.7 + 1.4 - 1.3 \text{ pb} (\text{data})$ MCFM (theory)	◊ ↓	Cheory Observed		4.6 13.0	EPJC 72, 2173 (2012) ATLAS-CONF-2013-021
ZZ	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb (data) MCFM (theory) $\sigma = 7.1 + 0.5 - 0.4 \pm 0.4$ pb (data) MCFM (theory)	¢ 4	stat stat+syst		4.6 20.3	JHEP 03, 128 (2013) ATLAS-CONF-2013-020
H vBF total	$\sigma = 2.43 + 0.6 - 0.55 \mathrm{pb} \mathrm{(data)} \\ \mathrm{LHC}\text{-HXSWG} \mathrm{(theory)}$	ATLAS	Preliminary		20.3	ATLAS-CONF-2015-007
t tW	$\sigma = 300.0 + 120.0 - 100.0 + 70.0 - 40.0 \text{ fb} \text{ (data)}$	Run 1	$\sqrt{s} = 7, 8 \text{ TeV}$		20.3	ATLAS-CONF-2014-038
tīZ total	$\sigma = 150.0 + 55.0 - 50.0 \pm 21.0 \text{ fb (data)}$		•		20.3	ATLAS-CONF-2014-038
	$10^{-5} \ 10^{-4} \ 10^{-3} \ 10^{-2} \ 10^{-1} \ 1$					
			σ [pb] $$ (observed/theo	ory	