Higgs τ -lepton Yukawa coupling measurement and the τ embedding method for background estimation

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We Found it!

$$M_H = (125.09 \pm 0.21 \pm 0.11) \text{ GeV}$$

preliminary

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Motivation

- from the above results we can't say anything about the new particle coupling to fermions
hence, to determine whether it is SM H , it is so important to measure it.

To establish the mass generation mechanism for fermions as implemented in the SM, we need to measure the direct coupling of the Higgs boson to fermions.

$$\mathcal{L} \supset - \left(1 + 2a \frac{h}{v} \right) \left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) - \sum_\psi \left(1 + c_\psi \frac{h}{v} \right) m_\psi \bar{\psi} \psi$$

Controls the hWW, hZZ couplings

Controls the $h\psi\psi$ coupling

in Standard Model:

- $c_\psi = 1$
- $a = 1$

Why $H \rightarrow \tau\tau$

- heaviest lepton $\rightarrow$ strongest coupling: **couplings are proportional to masses**
- lower background than in $b\bar{b}$ (*leptonic versus hadronic channels*)

to find signal of new physics we need to know all SM and QCD processes $\Rightarrow$ background, as precisely as we can.

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Signal ($m_H = 125$ GeV)	MC generator	$\sigma \times \mathcal{B}$ [pb]	
		$\sqrt{s} = 8$ TeV	
ggF, $H \rightarrow \tau\tau$	POWHEG [42–45] + PYTHIA8 [46]	1.22	NNLO+NNLL [48–53, 84]
VBF, $H \rightarrow \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO [57–59, 84]
WH, $H \rightarrow \tau\tau$	PYTHIA8	0.0445	NNLO [62, 84]
ZH, $H \rightarrow \tau\tau$	PYTHIA8	0.0262	NNLO [62, 84]
Background	MC generator	$\sigma \times \mathcal{B}$ [pb]	
		$\sqrt{s} = 8$ TeV	
$W(\rightarrow \ell\nu)$, ($\ell = e, \mu, \tau$)	ALPGEN [77]+PYTHIA8	36800	NNLO [85, 86]
$Z/\gamma^*(\rightarrow \ell\ell)$,	ALPGEN+PYTHIA8	3910	NNLO [85, 86]
$60 \text{ GeV} < m_{\ell\ell} < 2 \text{ TeV}$			
$Z/\gamma^*(\rightarrow \ell\ell)$,	ALPGEN+HERWIG [87]	13000	NNLO [85, 86]
$10 \text{ GeV} < m_{\ell\ell} < 60 \text{ GeV}$			
VBF $Z/\gamma^*(\rightarrow \ell\ell)$	SHERPA [88]	1.1	LO [88]
$t\bar{t}$	POWHEG + PYTHIA8	253 [†]	NNLO+NNLL [89–94]
Single top : Wt	POWHEG + PYTHIA8	22 [†]	NNLO [95]
Single top : s -channel	POWHEG + PYTHIA8	5.6 [†]	NNLO [96]
Single top : t -channel	AcerMC [80]+PYTHIA6 [73]	87.8 [†]	NNLO [97]
$q\bar{q} \rightarrow WW$	ALPGEN+HERWIG	54 [†]	NLO [98]
$gg \rightarrow WW$	GG2WW [79]+HERWIG	1.4 [†]	NLO [79]
WZ, ZZ	HERWIG	30 [†]	NLO [98]
$H \rightarrow WW$	same as for $H \rightarrow \tau\tau$ signal	4.7 [†]	

$Z/\gamma^* \rightarrow \tau\tau$ main and large irreducible background

EMBEDDING:: data-driven method to estimate it.

- for $\tau_{lep}\tau_{lep}$ and $\tau_{lep}\tau_{had} \Rightarrow W$ +jets contributions are determined by inverting the isolation requirements or fake-factor method,
- for $\tau_{had}\tau_{had} \Rightarrow$ multijet background is modelled using a template extracted from data.
- for $\tau_{lep}\tau_{lep}$ and $\tau_{lep}\tau_{had} \Rightarrow$ normalisation for background contributions from $t\bar{t}$ is obtained from data control regions.

⇒ embedding:

- *kinematics of Z boson, Jets and underlying events as well as contributions from pile-up are taken from data*
- *Only τ decays and the detector response to the τ decay products are based on simulation*

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- distribution of the calorimeter isolation energy, within $\Delta R = 0.3$ around muons in $Z \rightarrow \mu\mu$ events from data, before and after embedding of simulated muons.

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- p_T of the leading lepton → checking the influence of input muon radiation and reconstruction effects on embedded mini event

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- reconstructed invariant $\tau\tau$ mass: comparison between kinematic distribution of the embedded sample to the fully simulated one.

results

- ⇒ an excess of events over the expected background is found with an observed significance of 4.5 standard deviations
- ⇒ it provides evidence for the direct coupling of the Higgs to fermions.

$$\bullet \mu = 1.43_{-0.26}^{+0.27}(\text{stat.})_{-0.25}^{+0.32}(\text{syst.}) \pm 0.09 \text{ (theory syst.)}$$

The measured signal strength, normalised to the Standard Model expectation, is consistent with the predicted Yukawa coupling strength in SM.

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ATLAS

$m_H = 125.36$ GeV

$\sqrt{s} = 7$ TeV, 4.5 fb $^{-1}$
 $\sqrt{s} = 8$ TeV, 20.3 fb $^{-1}$

Signal strength (μ)

$\mu = 1.43^{+0.43}_{-0.37}$

ATLAS-CONF-2015-044

Decay channel	ATLAS+CMS
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

Measured significance (σ)

$H \rightarrow \tau\tau$	5.5
$H \rightarrow bb$	2.6

footnote

embedding was also used in Run-1 in searches for charged Higgs in $H \rightarrow \tau\nu$ channel JHEP03 (2015) 088.

- It is hard to distinguish the signatures of the $H^\pm \rightarrow \tau^\pm \nu$ from the ones of SM $W^\pm \rightarrow \tau^\pm \nu$: the dominant part of the irreducible background in $\bar{t} \rightarrow bH(\tau\nu)\bar{b}W$ ch.

- comparison of the backgrounds obtained through embedding (black points) with simulation (histogram) for m_T ,
- statistical and systematical errors of the embedding method are given by the black error bars, while of the simulation by gray hashed area.

Conclusion

- evidence for decays of H boson into $\tau\tau$ pairs
- measured signal strength, normalised to SM expectation, is found to be

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{syst.}) \pm 0.09(\text{theory syst.}),$$

which is consistent with the predicted Yukawa coupling in SM.

- embedding method helps to determine it with such precision,
- embedding as a largely data-driven method to set background.

Thank you for your attention

BACKUP

Impact of systematic uncertainties on the fitted signal-strength parameter μ for the combined fit for all channels and both centre-of-mass energies. The systematic uncertainties are listed in decreasing order of their impact on μ on the y-axis.

Summary of the triggers used to select events for the different analysis channels at the two centre-of-mass energies. When more than one trigger is used, a logical OR is taken and the trigger efficiencies are calculated accordingly.

$\sqrt{s} = 7$ TeV				
Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV]		
		$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
Single electron	20–22	$e\mu$: $p_T^e > 22 - 24$ $p_T^\mu > 10$	$e\tau$: $p_T^e > 25$ $p_T^\tau > 20$	–
Single muon	18	$\mu\mu$: $p_T^{\mu 1} > 20$ $p_T^{\mu 2} > 10$ $e\mu$: $p_T^e > 20$ $p_T^\mu > 15$	$\mu\tau$: $p_T^\mu > 22$ $p_T^\tau > 20$	–
Di-electron	12/12	ee : $p_T^{e1} > 15$ $p_T^{e2} > 15$	–	–
Di- τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau 1} > 35$ $p_T^{\tau 2} > 25$
$\sqrt{s} = 8$ TeV				
Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV]		
		$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
Single electron	24	$e\mu$: $p_T^e > 26$ $p_T^\mu > 10$ ee : $p_T^{e1} > 26$ $p_T^{e2} > 15$	$e\tau$: $p_T^e > 26$ $p_T^\tau > 20$	–
Single muon	24	–	$\mu\tau$: $p_T^\mu > 26$ $p_T^\tau > 20$	–
Di-electron	12/12	ee : $p_T^{e1} > 15$ $p_T^{e2} > 15$	–	–
Di-muon	18/8	$\mu\mu$: $p_T^{\mu 1} > 20$ $p_T^{\mu 2} > 10$	–	–
Electron+muon	12/8	$e\mu$: $p_T^e > 15$ $p_T^\mu > 10$	–	–
Di- τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau 1} > 35$ $p_T^{\tau 2} > 25$

Discriminating variables used in the training of the BDT for each channel and category at $\sqrt{s} = 8$ TeV. The filled circles indicate which variables are used in each case.

Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1, j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\text{T}}^{\text{Total}}$		•	•			
Sum p_{T}					•	•
$p_{\text{T}}^{\tau_1} / p_{\text{T}}^{\tau_2}$					•	•
$E_{\text{T}}^{\text{miss}} \phi$ centrality		•	•	•	•	•
m_{ℓ, ℓ, j_1}				•		
m_{ℓ_1, ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\text{T}}^{\ell_1}$				•		
$p_{\text{T}}^{j_1}$				•		
$E_{\text{T}}^{\text{miss}} / p_{\text{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1 \ell_2, \text{jets}})$	•					
$C_{\eta_1, \eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1, \eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1, \eta_2}(\eta_{\ell})$		•				
$C_{\eta_1, \eta_2}(\eta_{j_3})$	•					
$C_{\eta_1, \eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1, \eta_2}(\eta_{\tau_2})$			•			

**The scale factors calculated in control regions (CR) for background normalisation.
Only the statistical uncertainties are given.**

Channel	Background	Scale factors (CR)	
		VBF	Boosted
$\tau_{\text{lep}}\tau_{\text{lep}}$	Top	0.99 ± 0.07	1.01 ± 0.05
	$Z \rightarrow ee$	0.91 ± 0.16	0.98 ± 0.10
	$Z \rightarrow \mu\mu$	0.97 ± 0.13	0.96 ± 0.08
$\tau_{\text{lep}}\tau_{\text{had}}$	Top	0.84 ± 0.08	0.96 ± 0.04