SM Higgs to a pair of tau leptons with LHC Run-2 data at CMS

Yiwen Wen
on behalf of the CMS Collaboration
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SM Higgs -> tau tau: overview

- Higgs to tau tau is very promising channel to study the **Yukawa couplings** to explore the mass generation mechanism for fermions

- **advantage**: higher event rate than other Higgs leptonic decays and less backgrounds than Higgs to bb

- in CMS Run-1 observed $3.2\sigma$ [JHEP 05 (2014) 104], CMS+ATLAS observed $5.5\sigma$ [JHEP 08 (2016) 045]

- **4 channels** ($e\mu, \mu\tau_h, e\tau_h, \tau_h\tau_h$) ~ 95% of di-tau decay is covered

- 89% involving hadronic taus, **identify** and **trigger** hadronic taus in a high pile-up environment
tau reconstruction in CMS

- leptonic decay -> 35%: standard electron ID or muon ID

- hadronic decay -> 65%: hadron-plus-strip (HPS) algorithm

- hadronic taus reconstructed from a combination of charged hadrons and strips of cluster of e/\(\gamma\) candidates

- identify three main decay modes
  - hadron: \(\rho^\pm \rightarrow \pi^\pm \pi^0\)
  - hadron-plus-strip: \(a_1 \rightarrow \pi^\pm \pi^0\pi^0\)
  - three hadrons: \(a_1 \rightarrow \pi^\pm \pi^0\pi^+\)

- tau mass reconstructed should be compatible with tau decay modes

- new feature: in run-2, strip size adjusted dynamically
tau reconstruction in CMS

dynamic strip reconstruction
> in Run-2, strip size adjusted dynamically as a function of the pT of e/γ
  • better acceptance at low pT
  • better jet rejection at high pT

MVA-based discriminator rejecting jet faking tau
> using variables related to:
  • isolation variables (pT sums)
  • τ decay length information (track impact parameters, SV decay length)
  • etc..

measurement of tau-id efficiency
> using likelihood fit to visible mass in μτh channel
> data/MC scale factor of 0.95 ± 0.05
tau trigger in CMS Run-2

> with the more critical Run-2 pile-up condition, efficiency of Run-1 like L1 trigger would have reduced by more than a factor of 2

> in Run-2: **major upgrade of L1 trigger system:**
  
  • increases the algorithm complexity and the readout granularity
  • improving $T_h$ identification with dynamic clustering technique at the hardware level

> in high-level trigger:
  
  • despite the high pile-up, kept same nominal pT thresholds as Run-1(35 GeV) for di-$T_h$ trigger but improved turn-on and efficiency
background estimations

$Z \to \tau\tau$: shapes from Monte-Carlo (MC), corrections (DY mass, $p_T$, $m_{jj}$) derived from $Z \to \mu\mu$ sideband

$W+\text{Jets}$: shapes from MC, normalization constrained in high $m_T$ sideband region.

$VV+\text{SingleTop}$: MC

$QCD$: fully data-driven in sideband region of same-sign pair events

leptons to $\tau$ fakes: same as $Z \to \tau\tau$, with addition fake rate and energy scale data/MC corrections

top pair: shapes from MC normalization and shape is constrained in a $e\mu$ + jets sideband region
to further suppress background

> to reduce **W+Jets** in $e\tau_h, \mu\tau_h$ channel

\[
m_T = \sqrt{2 p_T^{e,\mu} E_T^{miss} (1 - \cos \Delta \phi)} < 50 \text{GeV}
\]

> to reduce **top pair production** in $e\mu$ channel

\[
D_{\zeta} = P_{\zeta} - 1.85 \cdot P_{\zeta}^{\text{vis}} > -35 \text{GeV}
\]

$\vec{\zeta}$ is axis bisecting directions $\vec{p}_T^e$ and $\vec{p}_T^\mu$

\[
P_{\zeta} = (p_T^e + p_T^\mu + p_T^{\text{miss}}) \cdot \frac{\vec{\zeta}}{|\vec{\zeta}|}
\]

\[
P_{\zeta}^{\text{vis}} = (p_T^e + p_T^\mu) \cdot \frac{\vec{\zeta}}{|\vec{\zeta}|}
\]
event categorization

> 3 categories focused on two most sensitive production mode \( \text{ggH} \) and \( \text{qqH} \):

- **0-jet**: targeting \( \text{ggH} \) and allowing for systematics to be constrained in other categories
- **VBF**: targeting \( \text{qqH} \) events pass the di-jet cuts
- **boosted**: targeting \( \text{ggH} \) events with a Higgs boson recoiling against a jet, and \( \text{qqH} \) events that fail the di-jet cut

> extracting the signal in 2D: one is **di-tau mass** (visible mass or SVFit mass) and the other is chosen targeting specific production modes

<table>
<thead>
<tr>
<th>Selection</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0-jet</strong></td>
<td>VBF</td>
</tr>
<tr>
<td>( e\mu )</td>
<td>No jet</td>
</tr>
<tr>
<td>( \mu\tau_h )</td>
<td>No jet</td>
</tr>
<tr>
<td>( e\tau_h )</td>
<td>No jet</td>
</tr>
<tr>
<td>( \tau_h\tau_h )</td>
<td>No jet</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e\mu )</td>
</tr>
<tr>
<td>( \mu\tau_h )</td>
</tr>
<tr>
<td>( e\tau_h )</td>
</tr>
<tr>
<td>( \tau_h\tau_h )</td>
</tr>
</tbody>
</table>

The signal/background increases as a function of **di-jet invariant mass**

The signal/background increases as a function of **di-tau pT**

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example of 2D distributions

(signals, top) and (backgrounds, bottom) have different signatures
un-rolled 2D distribution

“boosted $\tau_h \tau_h$ di-tau mass unrolled in di-tau pT”

CMS Preliminary

$\tau_h \tau_h$, Boosted

35.9 fb$^{-1}$ (13 TeV)

Events/bin

10^4

10^3

10^2

10^1

0 < $p_T^{\tau\tau}$ < 100 GeV

100 < $p_T^{\tau\tau}$ < 170 GeV

170 < $p_T^{\tau\tau}$ < 300 GeV

$p_T^{\tau\tau}$ > 300 GeV

(Obs. - bkg.)

Bkg. unc.

4

2

0

-2

0-40

40-80

80-120

120-160

160-200

200-250

m_{\tau\tau} (GeV)

black dot shows significance per bin
red line shows expected significance of SM Higgs(125) per bin

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systematics

- refined uncertainty model
  - split jet energy scale into 27 different sources
  - more detailed tau ID and scale uncertainties
  - control regions in fit

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Prefit Magnitude</th>
<th>Postfit Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_h$ energy scale</td>
<td>1.2% on energy scale</td>
<td>0.2-0.3%</td>
</tr>
<tr>
<td>$e$ energy scale</td>
<td>1-2.5% on energy scale</td>
<td>0.2-0.5%</td>
</tr>
<tr>
<td>$e$ misidentified as $\tau_h$ energy scale</td>
<td>3% on energy scale</td>
<td>0.6-0.8%</td>
</tr>
<tr>
<td>$\mu$ misidentified as $\tau_h$ energy scale</td>
<td>1.5% on energy scale</td>
<td>0.3-1.0%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>27 sources, event-by-event</td>
<td>-</td>
</tr>
<tr>
<td>$E_{T}^{miss}$ energy scale</td>
<td>Event-by-event</td>
<td>-</td>
</tr>
<tr>
<td>$\tau_h$ ID &amp; isolation</td>
<td>5% per $\tau_h$</td>
<td>3.5%</td>
</tr>
<tr>
<td>$\tau_h$ trigger</td>
<td>5% per $\tau_h$</td>
<td>3%</td>
</tr>
<tr>
<td>$\tau_h$ reconstruction per decay mode</td>
<td>3% migration between decay modes</td>
<td>2%</td>
</tr>
<tr>
<td>$e$ ID &amp; isolation &amp; trigger</td>
<td>2%</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$ ID &amp; isolation &amp; trigger</td>
<td>2%</td>
<td>-</td>
</tr>
<tr>
<td>$e$ misidentified as $\tau_h$ rate</td>
<td>12% per $\tau_h$ decay mode</td>
<td>5%</td>
</tr>
<tr>
<td>$\mu$ misidentified as $\tau_h$ rate</td>
<td>25% per $\tau_h$ decay mode</td>
<td>3-8%</td>
</tr>
<tr>
<td>Jet misidentified as $\tau_h$ rate</td>
<td>20% per 100 GeV $\tau_h$ $p_T$</td>
<td>15%</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau/\ell\ell$ estimation</td>
<td>Normalization: 7-15%</td>
<td>3-15%</td>
</tr>
<tr>
<td>$W +$ jets estimation</td>
<td>Uncertainty on $m_{\ell\ell/\tau\tau}$, $p_T(\ell\ell/\tau\tau)$, and $m_{\ell}$ corrections</td>
<td>-</td>
</tr>
<tr>
<td>QCD multijet estimation</td>
<td>Normalization, $e\mu$ and $\tau_h\tau_h$: 4-20%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Extrap. from high-$m_T$ region, $e\tau_h$ and $\mu\tau_h$: 5-10%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Unc. from CR, $e\tau_h$ and $\mu\tau_h$: $\gamma$ 5-15%</td>
<td>-</td>
</tr>
<tr>
<td>Diboson normalization</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>Single-top normalization</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>tt estimation</td>
<td>Normalization from CR: $\gamma$ 5%</td>
<td>-</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.5%</td>
<td>-</td>
</tr>
<tr>
<td>b-tagged jet veto ($e\mu$)</td>
<td>3.5-5.0%</td>
<td>-</td>
</tr>
<tr>
<td>Limited number of events</td>
<td>Statistical uncertainty in every bin</td>
<td>-</td>
</tr>
<tr>
<td>Signal theoretical uncertainty</td>
<td>Up to 20%</td>
<td>-</td>
</tr>
</tbody>
</table>
only $H \rightarrow \tau \tau$ decays treated as signal

- statistical uncertainties are largest
- significant contributions from all other sources, in particular also from bin-by-bin uncertainties (MC statistics)
visualizing the excess

> rearranged in a histogram based on the decimal logarithm of the ratio of the signal (S) to signal-plus-background (S+B) in each bin

> signal is clearly visible
we have observation for Higgs -> tau tau in CMS experiment (CMS-PAS-HIG-16-043):

- 4.9 $\sigma$ at Run-2 13 TeV
- 5.9 $\sigma$ in the combination with the CMS Run-1 analysis (7+8+13 TeV)

results are compatible with SM predictions

first direct observation of the tau Yukawa coupling in a single experiment!
Back-up
challenges in the analysis

> $\mu\tau_{h}/e\tau_{h}$

> electron faking tau looks just like $H \rightarrow \tau \tau$ signal

> require anti-electron(muon) discriminator works well

> $\tau_{h}\tau_{h}$

> With two hadronic tau, challenge of jet background in both the trigger and the tau ID

> new L1 trigger (run 2 trigger upgrade) helped keeping low rates and Pt threshold

> well working discriminator against jet, any improvement of it will be twice better

> the most sensitive channel

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tau energy scale correction

- Tau energy scale (TES) correction is determined by fitting visible mass and tau mass distribution, using $Z/\gamma^* \rightarrow \mu \tau$ events.

- TES is measured per decay mode: 1prong, 1prong+1 $\pi_0$, and 3 prongs.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1prong</td>
<td>-1.8%</td>
</tr>
<tr>
<td>1prong + $\pi_0$</td>
<td>+1.0%</td>
</tr>
<tr>
<td>3 prongs</td>
<td>+0.4%</td>
</tr>
</tbody>
</table>

Uncertainty for all 3 decay modes: +/- 1.2%
Event bin 

data/MC corrections: e/µ -> tau fake rate scale factor

- **anti-electron(muon) discriminator** is used to reject e(µ) faking tau events
- tau POG provides SF to correct data/MC difference
- applied on background when reco tau is matched at GEN-level to a prompt electron(muon)
- fake rates measured using tag-and-probe on Z->eτ_h (Z->µτ_h) events when τ_h matched to GEN-level e(µ)
- **tag**: identified electron(muon) 
  **probe**: τ candidate which either passes or fails anti-e(µ) discriminant

| Tau discriminator          | | range           | Scale factor |
|-----------------------------||--|----------------|
| againstElectronMVAVLoose    | | | 1.21 ± 0.07 |
| againstElectronMVLose       | | | 1.32 ± 0.04 |
| againstElectronMVAMedium    | | | 1.40 ± 0.11 |
| againstElectronMVATight     | | | 1.40 ± 0.18 |
| againstElectronMVAVLoose    | | | 1.37 ± 0.05 |
| againstElectronMVLose       | | | 1.38 ± 0.04 |
| againstElectronMVAMedium    | | | 1.52 ± 0.13 |
| againstElectronMVATight     | | | 1.90 ± 0.30 |
| againstElectronMVAVLoose    | | | 1.96 ± 0.46 |
| againstMuonLoose3           | | | 1.01 ± 0.02 |
| againstMuonTight3           | | | 1.26 ± 0.07 |
| againstMuonLoose3           | 0.4 < | 0.8 | | 1.00 ± 0.03 |
| againstMuonTight3           | 0.4 < | 0.8 | | 1.36 ± 0.28 |
| againstMuonLoose3           | 0.8 < | 1.2 | | 0.87 ± 0.03 |
| againstMuonTight3           | 0.8 < | 1.2 | | 0.85 ± 0.04 |
| againstMuonLoose3           | 1.2 < | 1.7 | | 1.15 ± 0.13 |
| againstMuonTight3           | 1.2 < | 1.7 | | 1.71 ± 0.5 |
| againstMuonLoose3           | 1.7 < | 2.3 | | 2.28 ± 0.26 |
| againstMuonTight3           | 1.7 < | 2.3 | | 2.32 ± 0.5 |

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observation of SM Higgs decays to tau tau

- local p-value using a profile likelihood ratio test statistic
- for 125 GeV SM Higgs
- expected significance is $4.7 \sigma$
- observed significance is $4.9 \sigma$
- first observation in a single experiment!

- combined with 7, 8 TeV and 13 TeV data
- the combination give observed and expected significance of $5.9 \sigma$!
expected limits and log(S/(S+B)) distribution

> rearranged in a histogram based on the the
decimal logarithm of the ratio of the signal (S)
to signal-plus-background (S + B) in each bin

> signal is clearly visible

ττ channel is the most sensitive
\[ \mu = 1.06^{+0.11}_{-0.09}(th.)^{+0.12}_{-0.12}(bbb.)^{+0.13}_{-0.12}(syst.)^{+0.15}_{-0.15}(stat.) \]

The combined best-fit signal strength is \( \mu = 1.06 \pm 0.25 \)
combined observed and predicted m_{\tau\tau} distributions

> to visualize the excess
> m_{\tau\tau} mass distribution weighted S/(S + B)
> the signal is normalized to its best-fit signal strength
> data in good agreement with 125 GeV Higgs signal
Observed $= 1.06 \mu$, $\tau \tau \rightarrow H \tau \tau \rightarrow Z W + \text{jets}$, $QCD \text{ multijet}$, $\text{Others}$, $Bkg. \text{ unc.}$ $35.9 \text{ fb}^{-1} (13 \text{ TeV})$
observation of SM Higgs decays to tau tau (HIG-16-043)

significant excess centered near 125 GeV
The combined best-fit signal strength is $\mu = 1.06 \pm 0.25$
The observed likelihood contour is consistent with the SM expectation of $\kappa_V$ and $\kappa_f$ equal to unity.