The latest results of the measurement of the Higgs boson decaying to a pair of tau leptons

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ICHEP2018, Seoul, Korea
July 5th 2018
Introduction

- Higgs boson in $\tau\tau$ decay mode is the most promising channel to explore the Higgs Yukawa coupling to fermions (decay rate to $\tau\tau$ is less than $bb$, but this channel has much less background).
- Analyzing run1 data, in 4 production modes led to the first evidence of Higgs coupling to fermions (Observed(expected) significance of 3.2(3.7) $\sigma$).
- In this presentation the results for 4 highest production cross section modes will be presented. (ttH results will be presented in a dedicated talk.)
Hadron Plus Strips (HPS) algorithm updated for run2 with dynamic strip reconstruction
Taus are reconstructed either in 1 prong or 3 prong modes
Developed MVA based discriminators to suppress mis-identification of the taus by jets, electrons and muon
DiTau mass is reconstructed using svFit
Part I

$ggH + VBF$ production modes

[CMS-HIG-16-043]
Run 2 categorization

- Event categorization has been changed in Run2
  - 4 different final states (based on tau decays)
  - 3 main categories (mainly) based on the jet multiplicity
  - In each category, events are further split depending on tau decay modes/muon
    \( p_T \) (in 0jet), \( p_T \) of the Higgs boson(in boosted) and mass of the two forward
    jets(in VBF mode)

- 2D distributions are then unrolled to 1D distributions which will be the
  input for the statistical interpretations
Introduce several control regions (i.e. same sign dilepton, high-TransverseMass, ...) to constrain the normalization of the backgrounds.

These control regions are fitted simultaneously with signal region.
Background composition and signal sensitivity varies in each slices
Final distributions

From low $m_{jj}$ to high $m_{jj}$:

Higher S/B & higher purity for VBF production w.r.t ggH production mode

Visible excess of data on top of the SM prediction
Visualizing the excess

- Reorder the bins based on the log(S/S+B)
- Sensitive bins are shifted to the right-side of the distribution and less sensitive to the left-side

- Bins are weighted according to S/S+B
- Higgs signal peaks around 125 GeV
Significance & best fit value

- 4.9 (4.7) $\sigma$ observed (expected) significance
- Combining with run1 we would have 5.9 $\sigma$ (the first observation of the Higgs coupling to tau leptons in a single experiment)
- Signal strength of 1.09 $\pm$ 0.26
- $\tau_h \tau_h$ is the most sensitive channel
- VBF is the most sensitive category
Part II

VH(V→leptons) production mode

[CMS-PAS-HIG-18-007]
8 final states are explored:

- $ee\mu, ee\tau, e\mu\tau, e\tau\tau$
- $\mu\mu\mu, \mu\mu\tau, \mu\tau\tau$

Clean signatures with $ZZ$ as irreducible background. Other are $WZ$ and $Z+\text{jets}$.

$L_T$ (scalar sum of the lepton $p_T$ from H decay) is used to improve the sensitivity:

- $ll\tau\tau$: $L_T = 60\text{GeV}$
- $ll\mu\tau$: $L_T = 60\text{GeV}$
- $ll\tau\tau\tau$: $L_T = 75\text{GeV}$
- $lle\mu$: $L_T = 50\text{GeV}$
High $L_T$ category is more sensitive

The excess of data in most of the bins near Higgs mass

This plot is just for visualization purpose. To extract the limit, all 8 ZH channels are fitted simultaneously
WH semi-leptonic
- $e\mu\tau_h, \mu\mu\tau_h$ channels
- $L_T > 100$ GeV
- $|\Delta \phi(l_1, H)| > 2.0$
- $|\Delta \eta(l_1, H)| < 2.0$
- WZ is the irreducible background. Other backgrounds like $Z+jets$ & $ttbar$ are highly suppressed by requiring 2 leptons to be same sign

WH hadronic
- $e\tau_h\tau_h, \mu\tau_h\tau_h$ channels
- $L_T > 130$ GeV
- $|\Delta \eta(\tau_h, \tau_h)| < 2.0$
- Larger background w.r.t other VH channels
The excess of data in most of the bins near Higgs mass

Similar to ZH, this plot is just for visualization. To extract the limit, all 4 WH channels are fitted simultaneously
Visualizing the excess (VH)

- 2.3 (1.0) $\sigma$ observed (expected) significance
- The signal strength is $2.5\pm1.4$
- ZH and WH production modes have similar sensitivity
Part III

$H \rightarrow \tau \tau$ combination

[CMS-PAS-HIG-18-007]
**Observation of the Higgs boson in $\tau\tau$ final state with 2016 data**

- 5.5 (4.8) $\sigma$ observed (expected) significance

- The combined signal strength is $1.24\pm0.28$

**Higgs couplings to both bosons and fermions are compatible with the SM expectation**

- Higgs boson decays to pairs of $W$ or $Z$ bosons, $H \rightarrow WW$ or $H \rightarrow ZZ$, are considered as part of the signal.
Summary

- First observation of the SM Higgs boson to a pair of tau leptons with a single experiment
  - 5.9 observed significance by combining 2016 (excluding VH) + run 1 data
  - 5.5 observed significance by 2016 data
- The best fit value is consistent with 1.0 within one standard deviation
- The coupling to both fermions and bosons are compatible with those predicted by SM
- Next steps:
  - Measuring the Higgs coupling to tau lepton more precisely, as we accumulate more data
  - Measuring the Higgs anomalous coupling in $\tau\tau$ final state
  - ...
- New results will appear soon!
Backup
Discrimination against jets, electrons and muons

- Whatever comes out of pp collision can fake taus!
- Developed MVA based discriminators to suppress mis-identification of the taus by jets, electrons and muon
- MVA based isolation exploited the tau decay life as well
Final distributions

Abdollah Mohammadi (KSU)
Final distributions

CMS Preliminary

$\tau_+ \tau_-$ Boosted

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

0 $< p_T^{\tau}$ $< 100 \text{ GeV}$
100 $< p_T^{\tau}$ $< 170 \text{ GeV}$
170 $< p_T^{\tau}$ $< 300 \text{ GeV}$
$p_T^{\tau}$ $> 300 \text{ GeV}$

$H \rightarrow \tau \tau$ ($\mu = 1.06$)
$Z \rightarrow \tau \tau$
$Z \rightarrow \mu \mu / \text{ee}$
t$\tau$+jets
W+jets
QCD multijet
Others
Total unc.

Observed
Bkg. unc.

$H \rightarrow \tau \tau$ (Obs. - bkg.)
Bkg. unc.

$M_{\tau \tau}$ (GeV)
Major systematics (Tau Id efficiency and Tau ES)

Tau Id efficiency is measured using Tag&Probe technique (SF=0.95+- 0.05)
W+Jet background estimation

- Subtract all non_w backgrounds from high-MT CR region in data
- Apply a low-MT to high-MT scale factor (driven from simulation)
- Validate the above scale factor from Zmumu selection (data and simulation) when one muon is replaced by a neutrino
Reorder the bins based on the log(S/S+B)

Sensitive bins are shifted to the right-side of the distribution and less sensitive to the left-side
Not possible to make similar weighted-mass plot (money plot) as run 1, due to the different binning.

Weight the distributions in each category and final state based on the S/S +B with similar binnings.
SvFit takes 4 momenta of both tau leptons, MET and and MET uncertainty and develop a likelihood to marginalize the degrees of freedom

- Has a better separation between Htautau and Ztautau
- Shift the Htautau peak to 125 GeV
- Thus, better performance
CRs in the fit

- Introduce several control regions (i.e. SS, high-MT) to constraint the normalization of the backgrounds
- These control regions are fitted simultaneously with signal region in combine
CMS Run1 legacy results: “Evidence”

- Analyzing data in all(6) final states and 3 production modes
- Observed(expected) significance of 3.2(3.7) $\sigma$
- Best fit value of $0.78 \pm 0.27$