Measurement of productions of Higgs boson in $H \to W^+W^- \to l^+\nu l^-\nu$ decay mode at $\sqrt{S} = 13$Tev in CMS experiment

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On behalf of CMS collaboration

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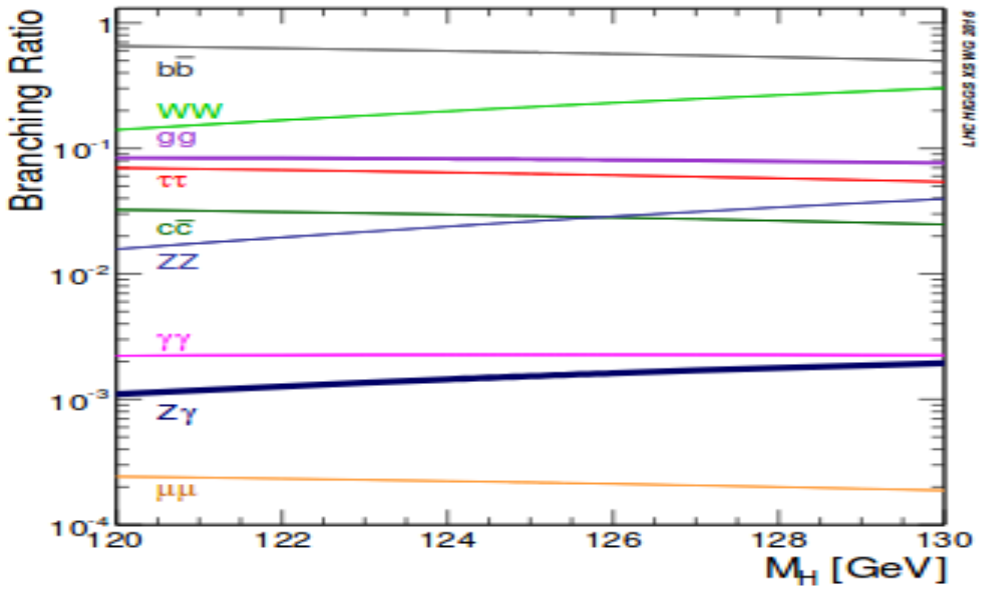
Outline

Introduction

- Higgs boson is discovered in ICHEP2012 in CMS and ATLAS experiment.
- Excess of events observed at 125 GeV.
- The probability that only background fluctuating up to this limit is only one in 3 million.
- A number of other features reinforce confidence in the results.



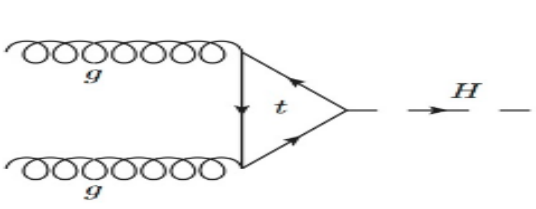
Motivation

- Higgs boson is discovered in $H \to \gamma\gamma$ and $H \to ZZ$ so $H \to WW$ decay was still away from Higgs discovery during Run 1.
- $H \to WW$ has second largest branching ratio at mH$\simeq$ 125GeV
- Neutrinos are present in final state so there is no signal peak.
- Any deviation from expectations would be a clear sign of new physics.
- WW enters as background too so by use of kinematics, it can be differentiate from signal.

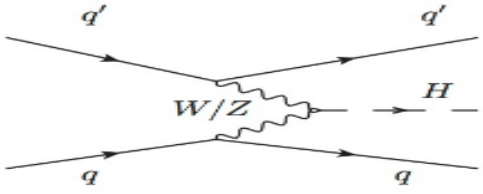
There are four main production mode of Higgs boson at mass $\simeq$ 125.09GeV-

a) **gluon fusion mode(ggH)** b) **VBH(Vector boson fusion)**

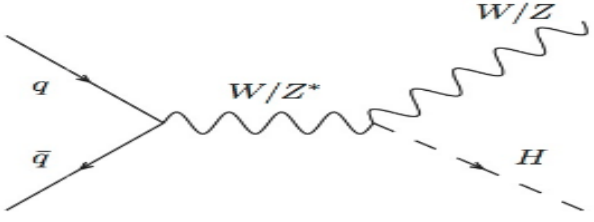
c) **VH(associated Higgs production)** d) **ttH Mode**



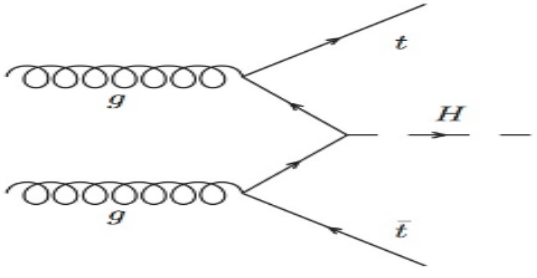
a)



b)



c)



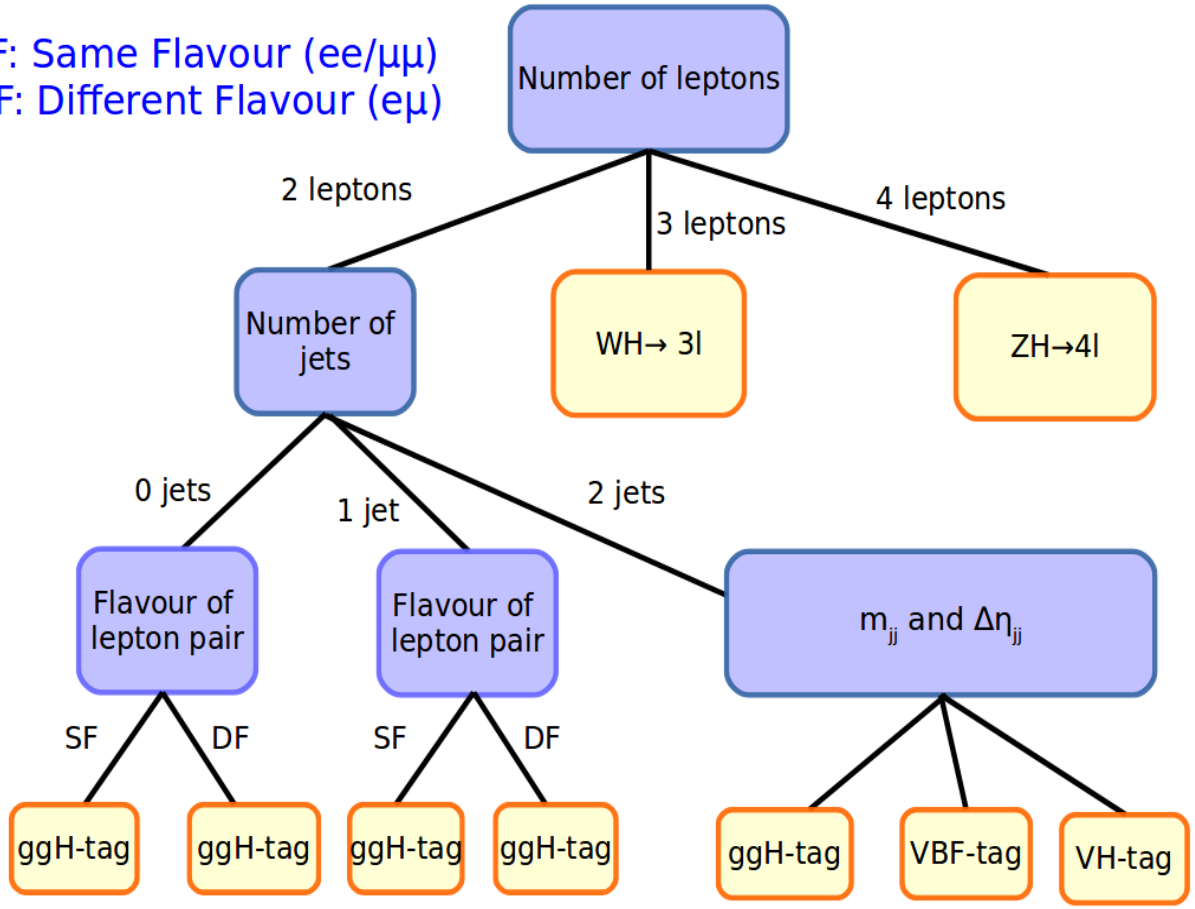
d)

Analysis Strategy

- Final state has -
  - 2 leptons(e,μ) with opposite charge.
  - Missing transeverse enegy due to presence of neutrinos.
- Presence of $\nu's$ in final state gives distribution, instead of peak of final state object mass.
- Analysis is categorize on the basis of number of leptons, number of jets and kinematics of jets.

Categorization

SF: Same Flavour (ee/μμ)
DF: Different Flavour (eμ)



0 and 1 jet ggH-tagged are rich in signal hence it can be studied in detail.

0 **and** 1 **jet**

Different flavour ggH

- Split into other categories based on -
  - flavour of leading and trailing lepton
  - charge of leading and trailing lepton
  - pT of trailing lepton either greater than 20 GeV or less than 20 GeV

Same flavour

- 3 reigon based on cut based : WW, signal and Top
- Dominated by DY$\to$ *ee*/$\mu\mu$*background*

- Final state is fully leptonic with presence of ν.

Variables: Analysis uses mainly two variable
m_{ll} : Invariant mass of di lepton
m_T : Transverse mass of final state object whcih scale with Higgs boson.
Transverse mass defined as:

$$m_T = \sqrt{2p_T^{ll} * E_T^{miss}[1 - \cos\Delta\phi]}$$

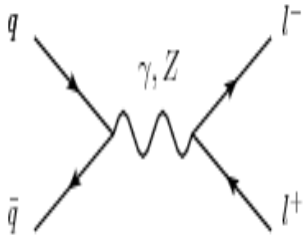
where p_T^{ll} : di lepton transverse momentum
$\Delta\phi$: angle between di lepton momentum and E_T^{miss}
E_T^{miss} : Transverse missing energy due to presence of ν (neutrino)

Selections for 0 and 1 jet ggH

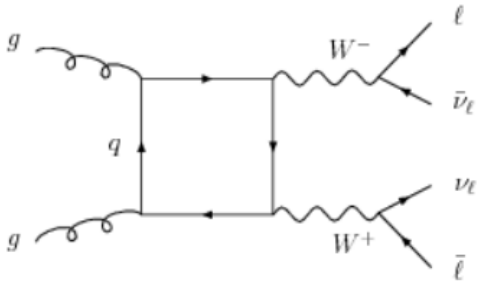
category	sub-category	cuts
preselection everywhere	-	$m_{\ell\ell} > 12$ GeV, $p_{T1} > 25$ GeV, $p_{T2} > 10$ (13) GeV for μ (e), $E_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $p_{T3} < 10$ GeV electron and muon with opposite charge
0 jet ggH-tagged	$e^+ \mu^- p_{T2} > 20$ GeV $e^- \mu^+ p_{T2} > 20$ GeV $\mu^+ e^- p_{T2} > 20$ GeV $\mu^- e^+ p_{T2} > 20$ GeV	$m_T^H > 60$ GeV, $m_T^{\ell 2-met} > 30$ GeV subleading lepton $p_T > 20$ GeV no jets with $p_T > 30$ GeV no b-jets with p_T between 20 and 30 GeV
	$e^+ \mu^- p_{T2} < 20$ GeV $e^- \mu^+ p_{T2} < 20$ GeV $\mu^+ e^- p_{T2} < 20$ GeV $\mu^- e^+ p_{T2} < 20$ GeV	$m_T^H > 60$ GeV, $m_T^{\ell 2-met} > 30$ GeV subleading lepton $p_T < 20$ GeV no jets with $p_T > 30$ GeV no b-jets with p_T between 20 and 30 GeV
	Top eμ	as nominal but without m_T^H cut, with $m_{\ell\ell} > 50$ GeV and at least one b-jet with p_T between 20 and 30 GeV
	DY$\tau\tau$	as nominal but with $m_T^H < 60$ GeV and 30 GeV $< m_{\ell\ell} < 80$ GeV
1 jet ggH-tagged	$e^+ \mu^- p_{T2} > 20$ GeV $e^- \mu^+ p_{T2} > 20$ GeV $\mu^+ e^- p_{T2} > 20$ GeV $\mu^- e^+ p_{T2} > 20$ GeV	$m_T^H > 60$ GeV, $m_T^{\ell 2-met} > 30$ GeV subleading lepton $p_T > 20$ GeV exactly one jet with $p_T > 30$ GeV no b-jets with $p_T > 20$ GeV
	$e^+ \mu^- p_{T2} < 20$ GeV $e^- \mu^+ p_{T2} < 20$ GeV $\mu^+ e^- p_{T2} < 20$ GeV $\mu^- e^+ p_{T2} < 20$ GeV	$m_T^H > 60$ GeV, $m_T^{\ell 2-met} > 30$ GeV subleading lepton $p_T < 20$ GeV exactly one jet with $p_T > 30$ GeV no b-jets with $p_T > 20$ GeV
	Top eμ	as nominal but without m_T^H cut, with $m_{\ell\ell} > 50$ GeV and one b-jet with $p_T > 30$ GeV
	DY$\tau\tau$	as nominal but $m_T^H < 60$ GeV and 30 GeV $< m_{\ell\ell} < 80$ GeV and no b-jet with $p_T > 30$ GeV

Main Background

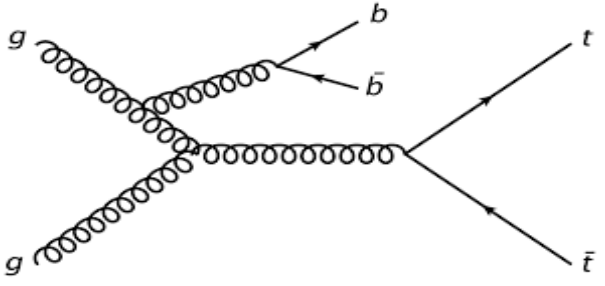
$DY \to ee/\mu\mu$



WW backgrounds



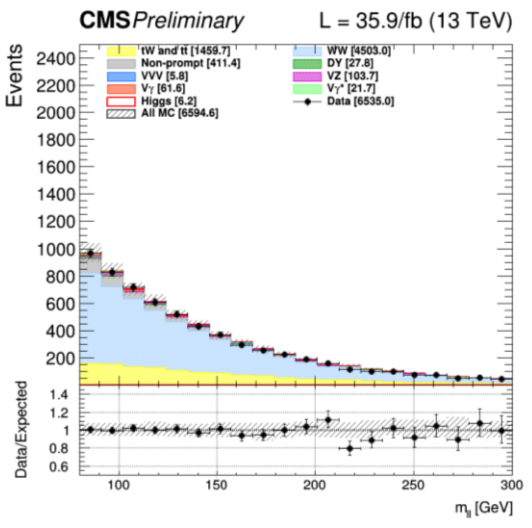
Top backgrounds



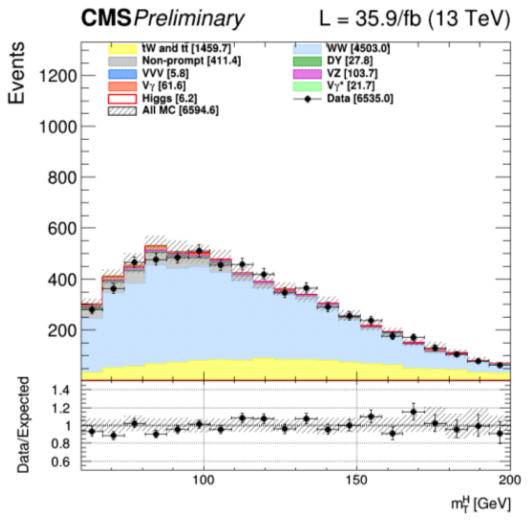
Uncertainities

1. *Experimental Uncertainities:*sources are - luminosity(2.3%),muon momentum(0.2%) and electron energy scale($0.6 - 1\%$),jet energy scale uncertainty($<$10%),Trigger efficiency($<$1%)
2. Theoretical Uncertainities:sources are - ggH theory uncertainties, Parton Shower, QCD scale uncertainty

Distribution of variables in WW selection level and superimposed with $mH \simeq 125.09 GeV$ after applying addtion cut $m_{ll} > 80 GeV$ to remove Higgs contribution and $m_H^T > 60 GeV$ to supress $DY \to \tau\tau$



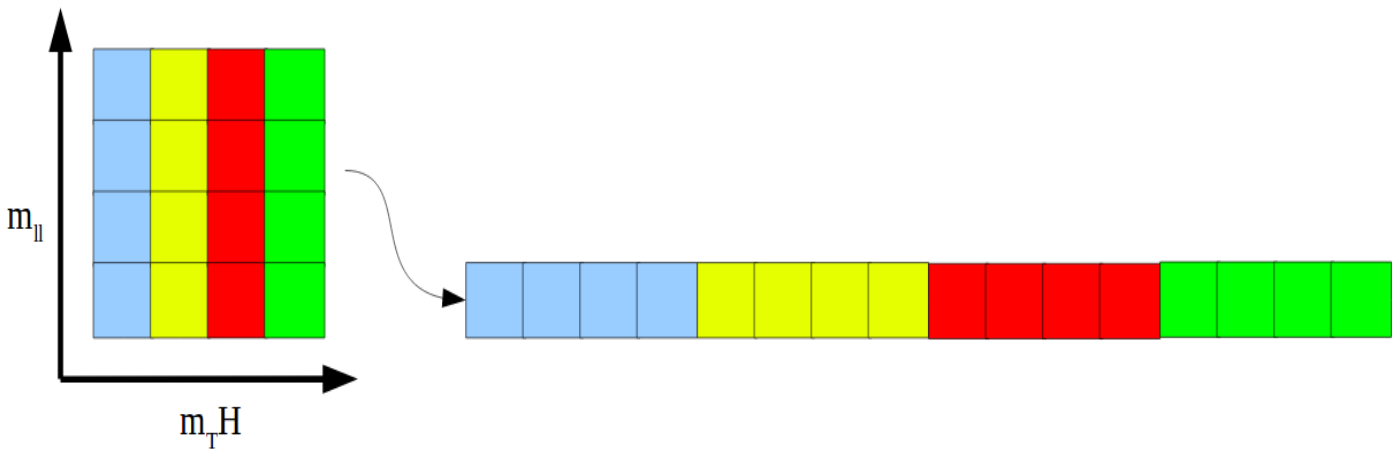
(c) $m_{\ell\ell}$ in the 0-jet category



(d) m_{T} in the 0-jet category

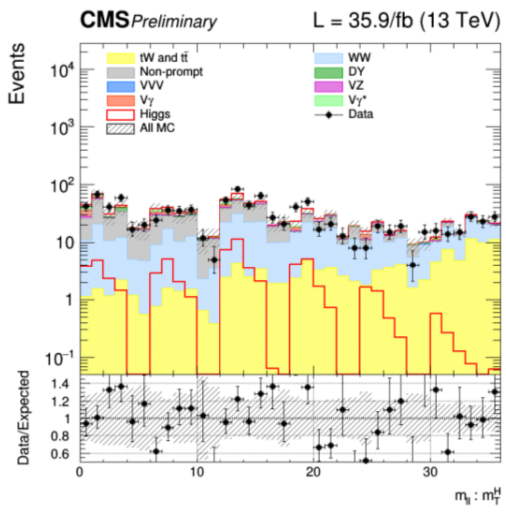
2D to 1D Plot

these histograms can be arranged in a way such that if we choose:
10 bins in m_T^H : 0 - 200 Gev [20 GeV width]
5 bins in m_{ll} : 10 - 110 Gev[20 GeV width]
2 D histogram can be convert in 1 D after picking

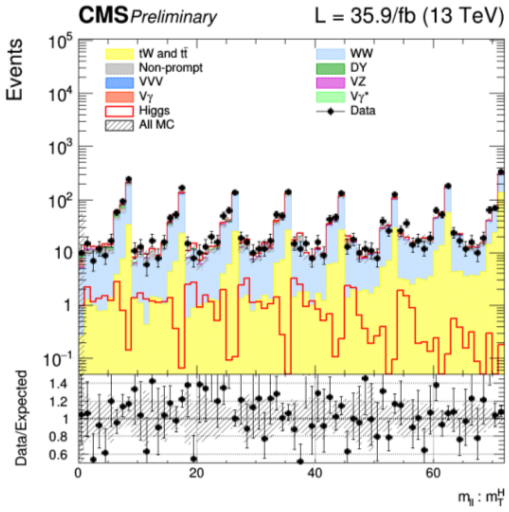


Signal and background

Signal and background can be seen by using number of events with respect to unrolled m_{ll} and m_T^H on Y axis.

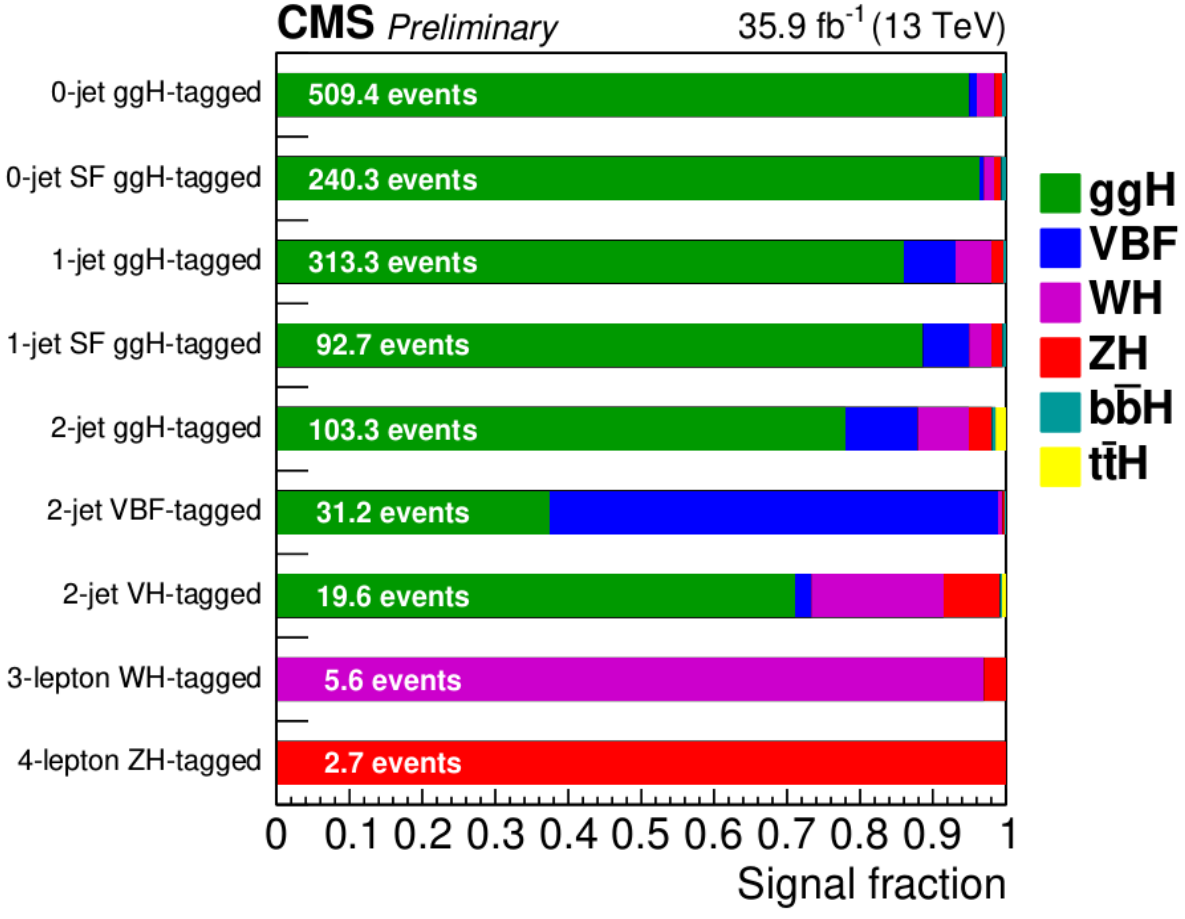


(a) prefit $e^-\mu^+ p_{T2} < 20\,\text{GeV}$ 0 jet ggH-tagged



(b) prefit $e^-\mu^+ p_{T2} > 20\,\text{GeV}$ 0 jet ggH-tagged

Signal fraction in different categories



Results of all category can be seen here-

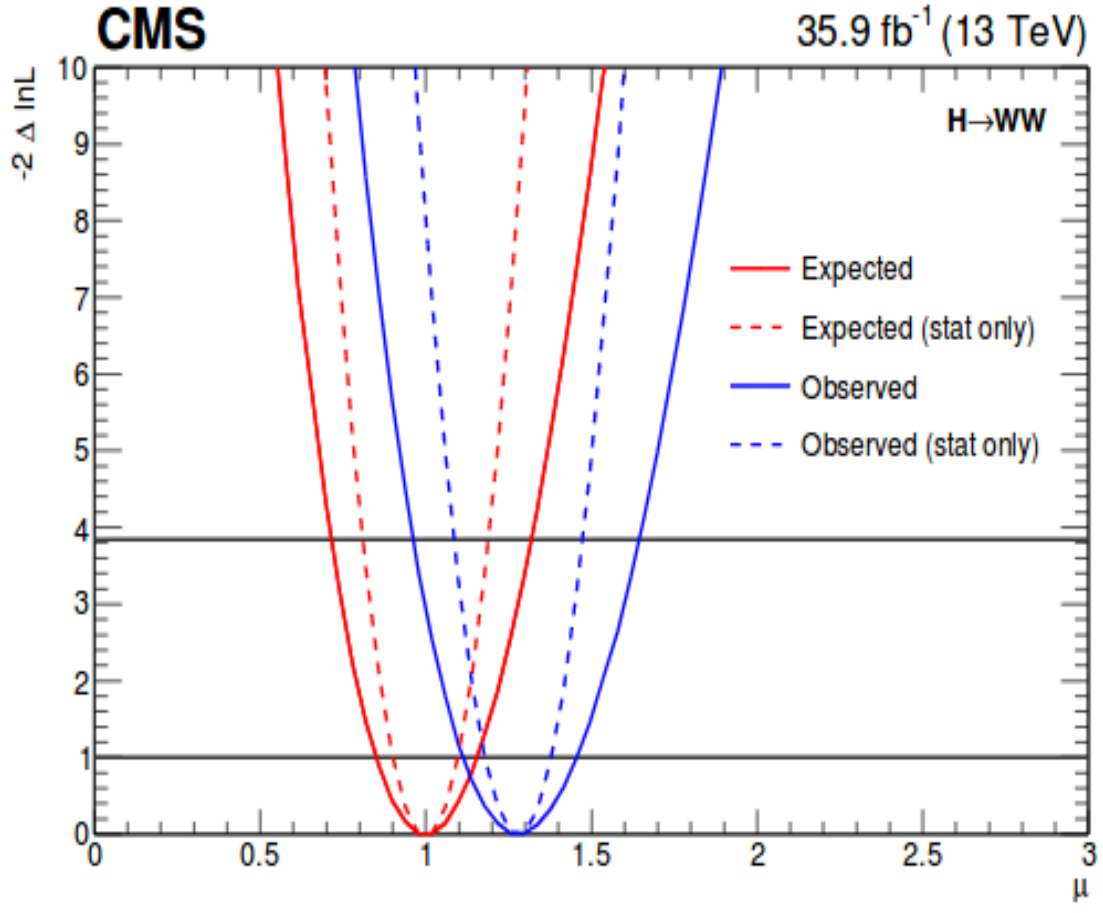
Results

Category	Observed (expected) significance	Observed σ/σ_{SM} (68% CL)
0-jet ggH-tag	$6.5\,\sigma$ ($4.8\,\sigma$)	$1.31^{+0.24}_{-0.23}$
1-jet ggH-tag	$5.2\,\sigma$ ($4.0\,\sigma$)	$1.29^{+0.32}_{-0.27}$
2-jet ggH-tag	$1.5\,\sigma$ ($1.7\,\sigma$)	$0.82^{+0.54}_{-0.50}$
2-jet VBF-tag	$1.7\,\sigma$ ($2.3\,\sigma$)	$0.72^{+0.44}_{-0.41}$
2-jet VH-tag	$3.2\,\sigma$ ($0.7\,\sigma$)	$3.92^{+1.32}_{-1.17}$
0-jet SF ggH-tag	$2.9\,\sigma$ ($1.6\,\sigma$)	$1.75^{+0.61}_{-0.54}$
1-jet SF ggH-tag	$1.9\,\sigma$ ($1.0\,\sigma$)	$2.18^{+0.94}_{-0.97}$
3 leptons WH-tag	$1.5\,\sigma$ ($0.9\,\sigma$)	$2.23^{+1.76}_{-1.54}$
4 leptons ZH-tag	$0.7\,\sigma$ ($0.8\,\sigma$)	$0.77^{+1.49}_{-1.20}$
Combination	$9.1\,\sigma$ ($7.1\,\sigma$)	$1.28^{+0.18}_{-0.17}$

Results

Observed significance for the combination of all categories is 9.1σ and expected significance is 7.1σ

This is the first observation of Higgs boson decay to W boson pairs.



Conclusion

- Analysis is presented using full 2016 dataset
- It is first observation of Higgs boson in $H \to WW$ decay mode.
- Analysis is divided on the basis of differnt Higgs production mode(ggH,VBF,WH and ZH)
- The observed significance is found to be $9.1\sigma(7.1\sigma$ expected), and the global signal strength modifier is $1.29^{+0.18}_{-0.17}$

Thank You

BACK-UP

Trigger path used in the analysis

Data Set	Run range	HLT path
SingleMuon	[273158,284044]	HLT_IsoMu24_v* HLT_IsoTkMu24_v*
SingleElectron	[273158,284044]	HLT_Ele27_WPTight_Gsf_v* HLT_Ele25_eta2p1_WPTight_Gsf_v*
DoubleMuon	[273158,281612]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v* HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v*
	[281613,284044]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v* HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
DoubleEG	[273158,284044]	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
MuonEG	[273158,278272]	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v* HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
	[278273,284044]	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v* HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*

- Analysis is based on 2016 dataset corresponding luminosity $35.9 fb^{-}$
- Dataset used in the analysis are - SingleMuon, SingleElectron, DoubleMuon, DoubleEG, MuonEG
- Muons and electrons ID/ISO based on the tight working points, with extra cuts to reduce contamination from nonprompt leptons.
- Jets, b-tagging (CMVAv2) and MET definition based on the POGs official recipes.
- Data/MC scale factors are applied to correct simulation for:
  - Lepton ID/ISO
  - Reconstruction efficiency
  - Trigger efficiency
  - B-tagging efficiency
  - PU reweighting

Top background

- B-tagged jet veto used to reduce it.
- Controlled by splitting the analysis according to the number of jets (counted jets have pT$>$ 30 GeV).

WW bg

- Same final state as the signal process, but different lepton kinematic distributions
- Measured from data leaving the normalization free to float in the fit

Non-prompt

- Fully data driven using the fake rate method.
- Can be reduced exploiting the charge and flavor asymmetry of this process

  Different categories depending on the charge and flavor combination of the lepton pair
- Particularly important in the phase space with low pT leptons
- Further splitting based on the subleading lepton pT.

DY

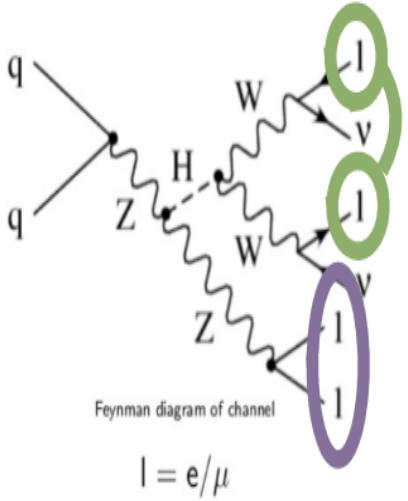
- Fully data driven in categories with a same flavor lepton pair (ee and $\mu\mu$).

2 **jet DF**

- 2 jets different flavor categories are split in sub-categories targeting ggH, VBF and VH production modes.
- Splitting based on $m_{jj} and \Delta\eta_{jj}$

WH-tag

- Events with exact charged high $p_T(25,20,15 GeV) are selected. Min p_T of leptons is 12 GeV$. After preselection,further divided based on same sign and same flavour(SSSF) and opposite sign same flavour(OSSF).



X is the left dilepton system after Z_0 is chosen.

Z_0 is the OSSF lepton pair with closest mass to Z.

ZH-tag

- Event categorized by the flavour of lepton coming from Higgs.
- Cut and count analysis.

selections for 2 jet

2 jet ggH-tagged	$e\mu$	at least 2 jets with $p_T > 30$ GeV $m_T^{\ell 2-met} > 30$ GeV and $m_T^H > 60$ GeV no b-jets with $p_T > 20$ GeV $m_{jj} < 65$ GeV or 105 GeV $< m_{jj} < 400$ GeV
	Top $e\mu$	as nominal but without m_T^H cut, with $m_{\ell\ell} > 50$ GeV and at least one of the two leading jets b-tagged
	DY$\tau\tau$	as nominal but $m_T^H < 60$ GeV and 30 GeV $< m_{\ell\ell} < 80$ GeV and no b-jet with $p_T > 30$ GeV

VBF 2j	$e\mu$ low m_{jj}	only 2 jets ($p_T > 30$ GeV) 60 GeV $< m_T^H < 125$ GeV leptons η between the two leading jets 400 GeV $< m_{jj} < 700$ GeV and $\Delta\eta_{jj} > 3.5$ no b-jets with $p_T > 20$ GeV
	$e\mu$ high m_{jj}	only 2 jets ($p_T > 30$ GeV) 60 GeV $< m_T^H < 125$ GeV leptons η between the two leading jets $m_{jj} > 700$ GeV and $\Delta\eta_{jj} > 3.5$ no b-jets with $p_T > 20$ GeV
	Top $e\mu$	as nominal but with $m_{\ell\ell} > 50$ GeV and one b-jet with $p_T > 30$ GeV
	DY$\tau\tau$	as nominal but $m_T^H < 60$ GeV and 30 GeV $< m_{\ell\ell} < 80$ GeV and no b-jet with $p_T > 30$ GeV
VH 2j	$e\mu$	at least 2 jets two leading jets $\lvert\eta\rvert < 2.5$ and $m_T^H > 60$ GeV 60 GeV $< m_T^H < 125$ GeV and $\Delta R_{ll} < 2$ no b-jets with $p_T > 20$ GeV 65 GeV $< m_{jj} < 105$ GeV and $\Delta\eta_{jj} < 3.5$
	Top $e\mu$	as nominal but without m_T^H cut, with $m_{\ell\ell} > 50$ GeV and at least one of the two leading jets b-tagged
	DY$\tau\tau$	as nominal but $m_T^H < 60$ GeV and 30 GeV $< m_{\ell\ell} < 80$ GeV and no b-jet with $p_T > 30$ GeV

Selections for ZH4l

category	sub-category	cuts
preselection everywhere	-	Four tight and isolated leptons, and no charge in total $p_T > 25$ GeV for the leading lepton $p_T > 15$ GeV for the second leading lepton $p_T > 10$ GeV for the rest 2 leptons No fifth lepton Four letpon mass larger than 140 GeV (Only for XSF region) Z_0 dilepton mass larger than 4 GeV X dilepton mass larger than 4 GeV
4-leptons	XSF	A 15 GeV mass window of Z candidate A 10 to 60 GeV mass window of X candidate E_T^{miss} cut larger than 35 GeV < 100 GeV
	XDF	A 15 GeV mass window of Z candidate A 10 to 70 GeV mass window of X candidate E_T^{miss} cut larger than 20 GeV b-jet veto
	ZZ	Preselection category A 15 GeV mass window of Z candidate A 75 GeV to 105 GeV mass window of X candidate E_T^{miss} cut smaller than 35 GeV