Measurement of Higgs to WW in association with a vector boson using the full Run II dataset at CMS

<u>Amandeep Kaur</u> – Panjab University India

SM@LHC 2021

On behalf of the CMS Collaboration

28 April 2021

Outline

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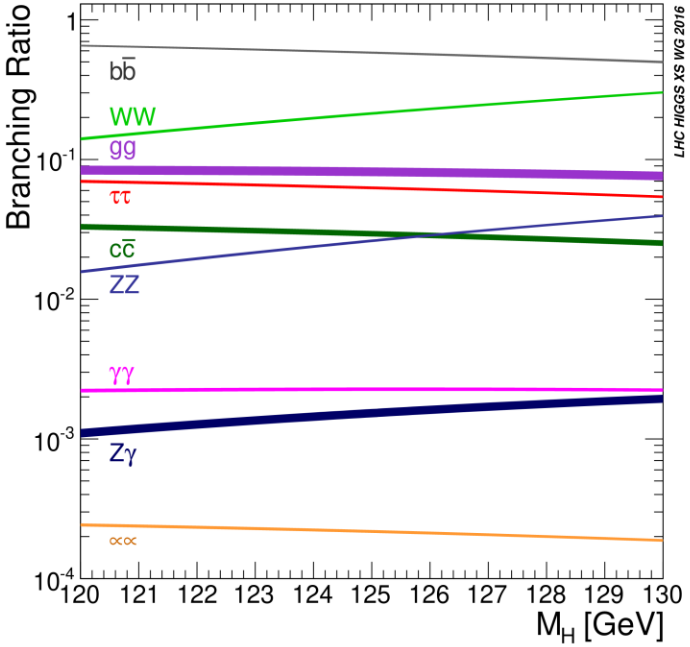
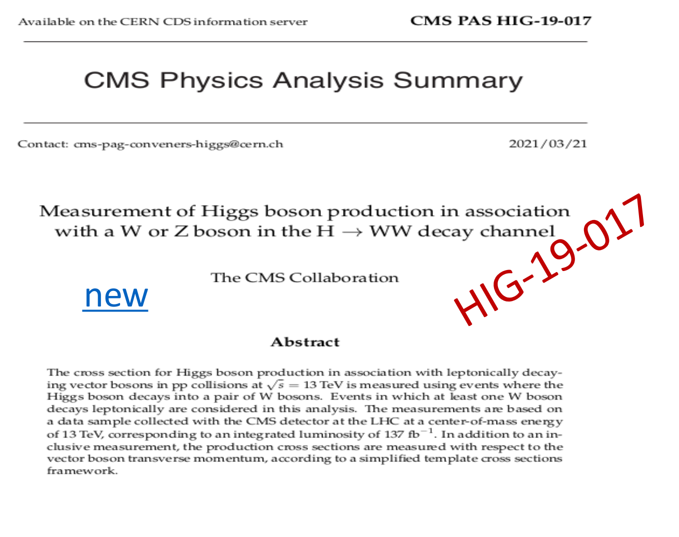
Summary

Introduction

- The large Higgs boson branching ratio to a W boson pair --> most suitable for the precision measurement of the Higgs boson production cross section .
- Direct handle on Higgs boson coupling to vector bosons .
- This analysis benefit from the data collected in Run II by the CMS experiment ; possible to probe various decay channels .



Documentation


Available on the CERN CDS information server CMS PAS HIG-19-017

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2021/03/21

Measurement of Higgs boson production in association with a W or Z boson in the H → WW decay channel

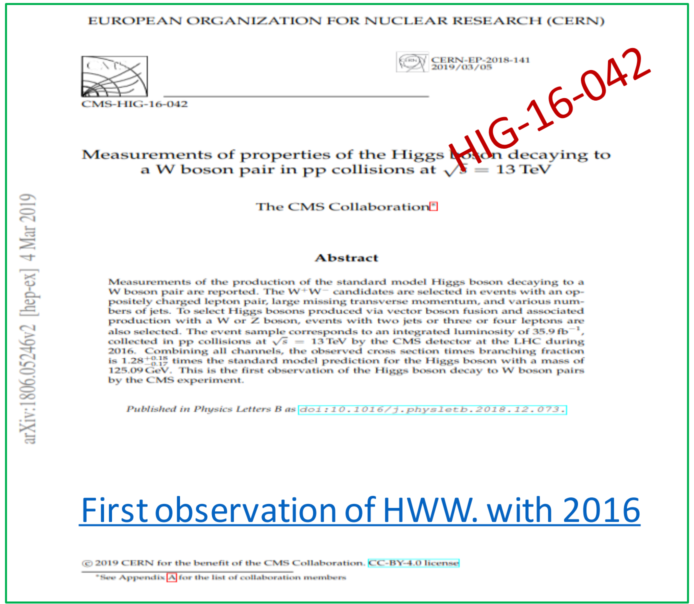
The CMS Collaboration

Abstract

The cross section for Higgs boson production in association with leptonically decaying vector bosons in pp collisions at $\sqrt{s} = 13$ TeV is measured using events where the Higgs boson decays into a pair of W bosons. Events in which at least one W boson decays leptonically are considered in this analysis. The measurements are based on a data sample collected with the CMS detector at the LHC at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 137 fb^{-1}. In addition to an inclusive measurement, the production cross sections are measured with respect to the vector boson transverse momentum, according to a simplified template cross sections framework.

new

HIG-19-017


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-141
2019/03/05

CMS-HIG-16-042

Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Measurements of the production of the standard model Higgs boson decaying to a W boson pair are reported. The W^+W^- candidates are selected in events with an oppositely charged lepton pair, large missing transverse momentum, and various numbers of jets. To select Higgs bosons produced via vector boson fusion and associated production with a W or Z boson, events with two jets or three or four leptons are also selected. The event sample corresponds to an integrated luminosity of 35.9 fb^{-1}, collected in pp collisions at $\sqrt{s} = 13$ TeV by the CMS detector at the LHC during 2016. Combining all channels, the observed cross section times branching fraction is $1.28^{+0.18}_{-0.17}$ times the standard model prediction for the Higgs boson with a mass of 125.09 GeV. This is the first observation of the Higgs boson decay to W boson pairs by the CMS experiment.

Published in Physics Letters B as doi:10.1016/j.physletb.2018.12.073.

arXiv:1806.05246v2 [hep-ex] 4 Mar 2019

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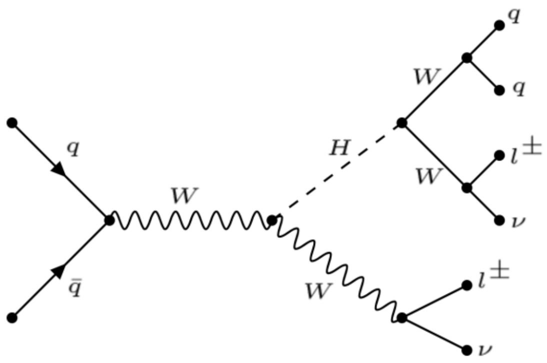
*See Appendix A for the list of collaboration members

HIG-16-042

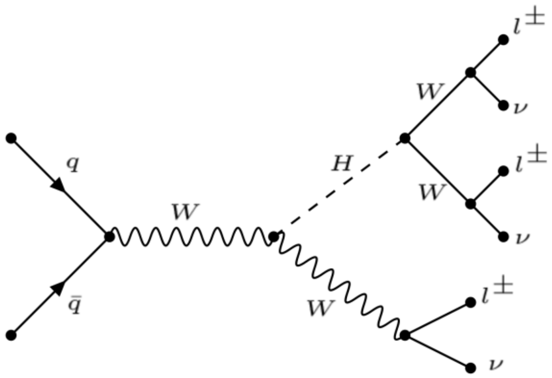
First observation of HWW. with 2016

Analysis Overview

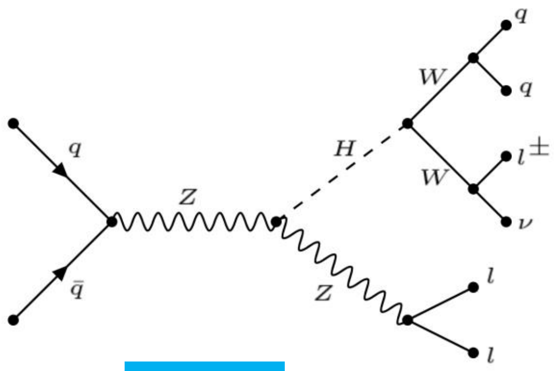
- Leptonic decay of associated boson is considered. Along with inclusive measurement, the production cross sections are measured according to a simplified template cross sections framework (STXS).
- Four different final states ; WHSS and ZH3l are new channels (were not considered in HIG-16-042).
- There are different challenges in each channel depending upon the dominating backgrounds , hence different approaches .
- Analysis is performed with the full Run II data collected by the CMS experiment at the center-of-mass energy 13 TeV , which corresponds to luminosity of $137\ fb^{-1}$.



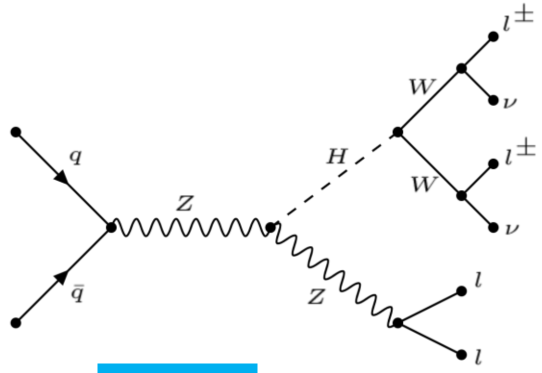
WHSS



WH3l



ZH3l



ZH4l

WHSS

Backgrounds

Major : WZ, W + jets, and Vγ (∗)
Minor : WW, ZZ, VVV

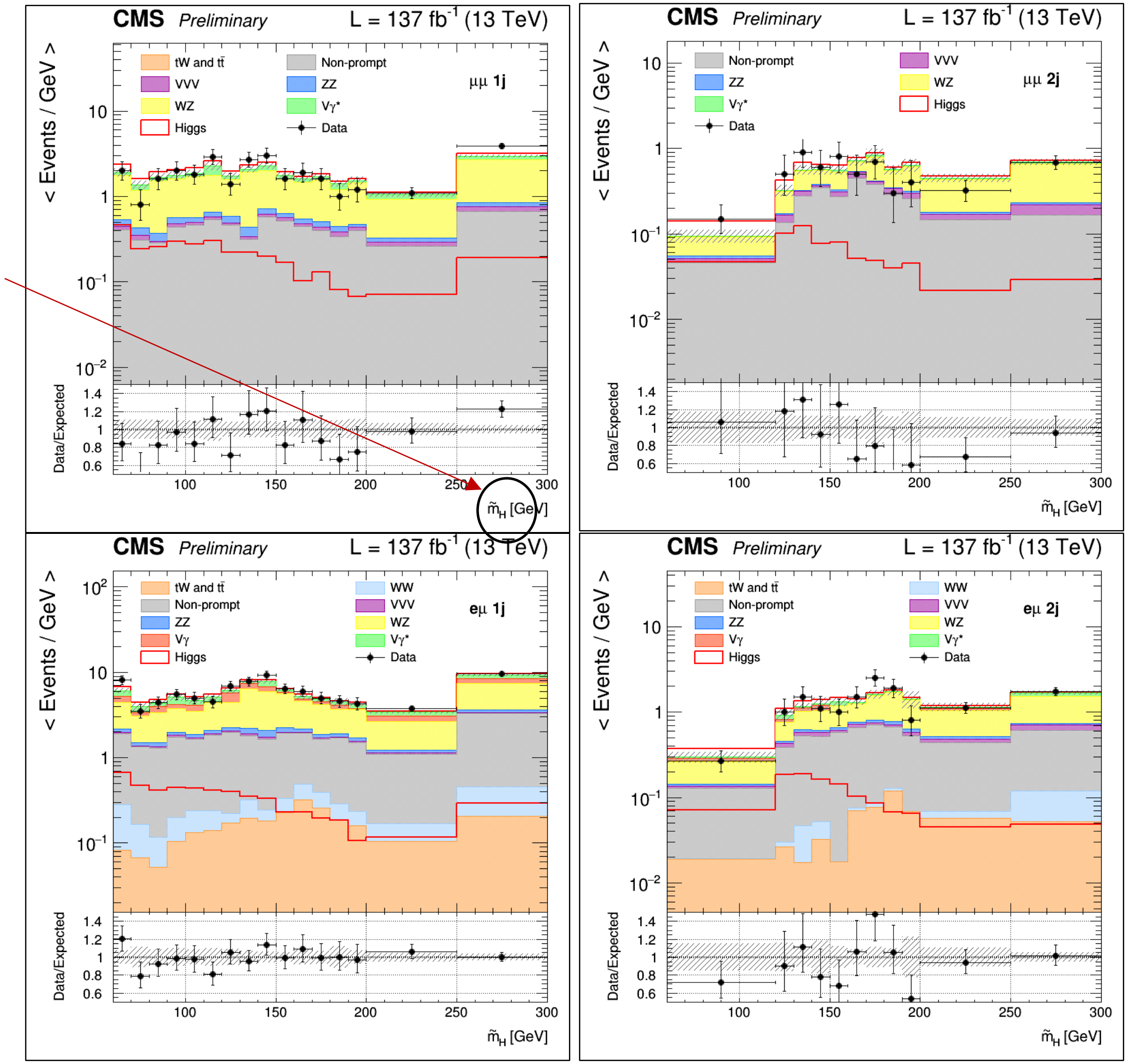
- SR : (μμ, eμ) x (1j, 2j)
- CR : WZ (1j , 2j)

$\tilde{m}_H$: Invariant mass of dijet and 2 x lepton— Proxy for Higgs mass

chosen lepton is the one closest to the di-jet (for 2j cat) or single-jet (for 1-jet cat) system.

	Preselection			
Lepton p_T (GeV)	$> 25, 20$			
Third lepton veto	Yes			
$m_{\ell\ell}$ (GeV)	> 12			
$\Delta\eta_{\ell\ell}$	< 2.0			
B jet veto	DeepCSV, medium WP, applied to all jets with $p_T > 20$ GeV			
p_T^{miss} (GeV)	> 30			
$\tilde{m}_H$ (GeV)	> 50			
	1j $e\mu$ SR	2j $e\mu$ SR	1j $\mu\mu$ SR	2j $\mu\mu$ SR
Jets with $p_T > 30$ GeV	==1	≥ 2	==1	≥ 2
m_{jj} (GeV)		< 100		< 100
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)			> 15	> 15

Main uncertainties: non-prompt, statistical, background modeling



WH3l

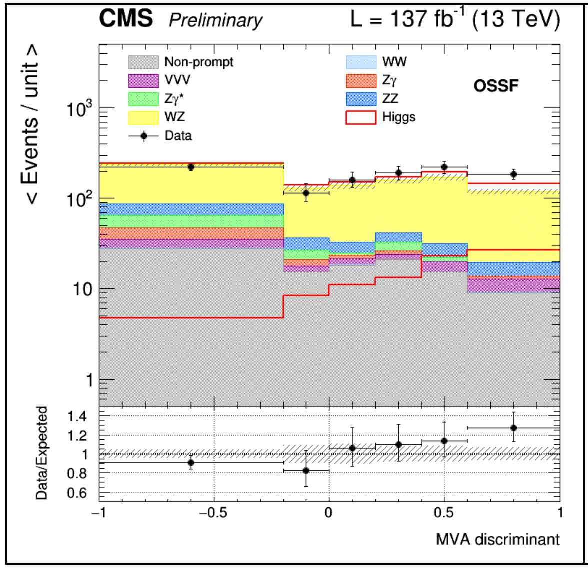
Backgrounds

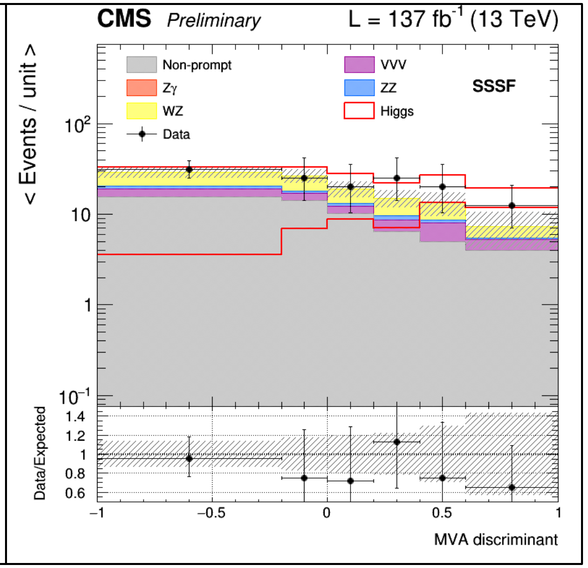
Major : Non-prompt (Z+jets, top) , WZ, ZZ, Vγ
Minor : VVV, WW, Vγ*

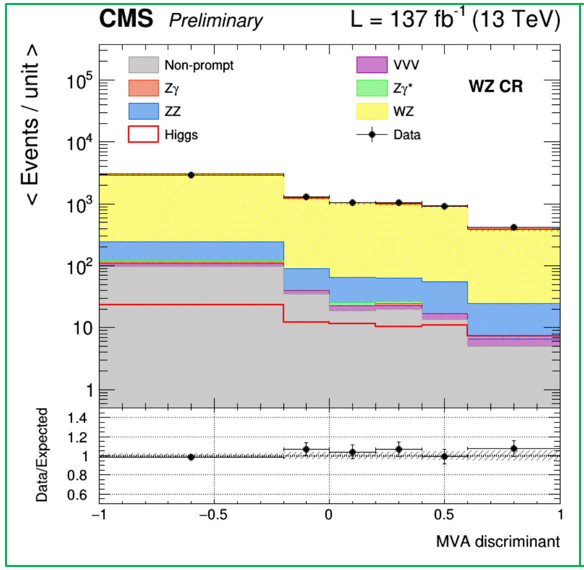
Final state	Name	Signal fraction
$(\mu/e)^{\pm} + (\mu/e)^{\mp} + (l)^{\mp}$	opposite-sign same-flavor (OSSF)	~3/4
$(\mu/e)^{\pm} + (\mu/e)^{\pm} + (e/\mu)^{\mp}$	same-sign same-flavor (SSSF)	~1/4

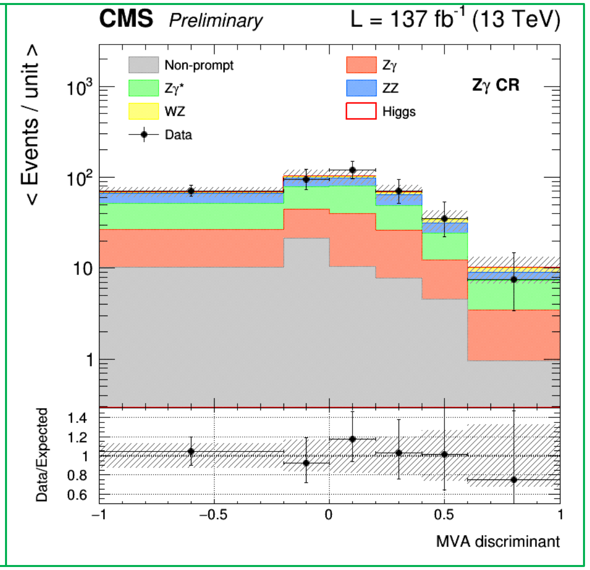
- CR : WZ and Zγ
- To separate signal and background : multivariate Boosted Decision Tree (BDT) is used ; fit is performed to the BDT discriminant .

	Preselection			
Lepton p_T (GeV)	$> 25, 20, 15$			
Fourth lepton p_T (GeV)	< 10			
$ch_{\ell\ell\ell}$	± 1			
$\min(m_{\ell\ell})$ (GeV)	> 12			
Jets with $p_T > 30$ GeV	0			
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV			
	OSSF SR	SSSF SR	WZ CR	$Z\gamma$ CR
OSSF lepton pair	Yes	No	Yes	Yes
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)	> 20		< 20	< 20
p_T^{miss} (GeV)	> 40		> 45	< 40
$m_{\ell\ell\ell}$ (GeV)			> 100	$[80, 100]$









Main uncertainties: non-prompt, statistical, background modeling

WH3l

Backgrounds

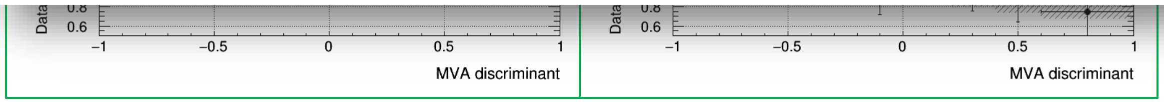
Major : Non-prompt (Z+jets, top) , WZ, ZZ, Vγ
Minor : VVV, WW, Vγ*

Final state	Name	Signal fraction
$(\mu/e)^{\pm} + (\mu/e)^{\mp} + (l)^{\mp}$	opposite-sign same-flavor (OSSF)	~3/4
$(\mu/e)^{\pm} + (\mu/e)^{\pm} + (e/\mu)^{\mp}$	same-sign same-flavor (SSSF)	~1/4

- CR : WZ and Zγ
- To separate signal and background : multivariate Boosted Decision Tree (BDT) is used ; fit is performed to the BDT discriminant .

	Preselection			
Lepton p_T (GeV)	$> 25, 20, 15$			
Fourth lepton p_T (GeV)	< 10			
$ch_{\ell\ell\ell}$	± 1			
$\min(m_{\ell\ell})$ (GeV)	> 12			
Jets with $p_T > 30$ GeV	0			
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV			
	OSSF SR	SSSF SR	WZ CR	$Z\gamma$ CR
OSSF lepton pair	Yes	No	Yes	Yes
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)	> 20		< 20	< 20
p_T^{miss} (GeV)	> 40		> 45	< 40
$m_{\ell\ell\ell}$ (GeV)			> 100	$[80, 100]$

- Train BDT to discriminate signal from background
  - Background: WZ, ZZ, $V\gamma^{(*)}$, top, Drell-Yan
- Selection: OSSF and SSSF categories, without Z veto in OSSF
- Input variables:
  - MET
  - $p_T(\ell)$, $\Delta\phi(\ell,MET)$, $m_T(\ell,MET)$ for each lepton
  - $m(\ell\ell\ell)$, $p_T(\ell\ell\ell)$
  - $m_T(\ell\ell\ell+MET)$, $p_T(\ell\ell\ell+MET)$, $\Delta\phi(\ell\ell\ell, MET)$
  - Minimum $\lvert m_{\ell\ell} - m_Z \rvert$, $m_{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta R_{\ell\ell}$ for all OSSF lepton pairs
  - b tag score of leading, subleading jets
- Separate trainings for 2016, 2017+2018



WH3l

Backgrounds

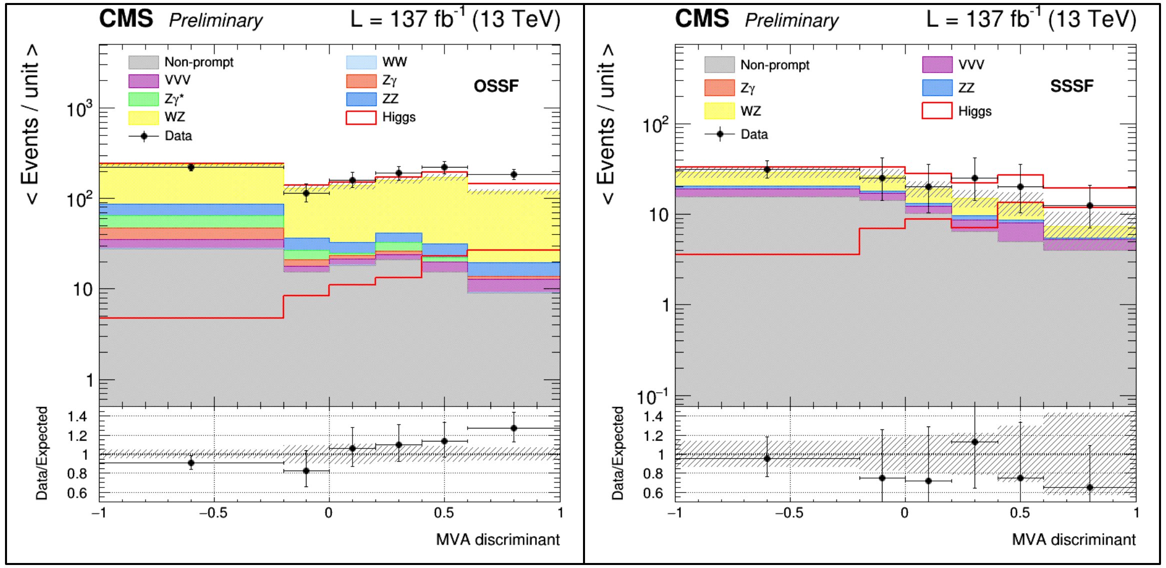
Major : Non-prompt (Z+jets, top) , WZ, ZZ, Vγ
Minor : VVV, WW, Vγ*

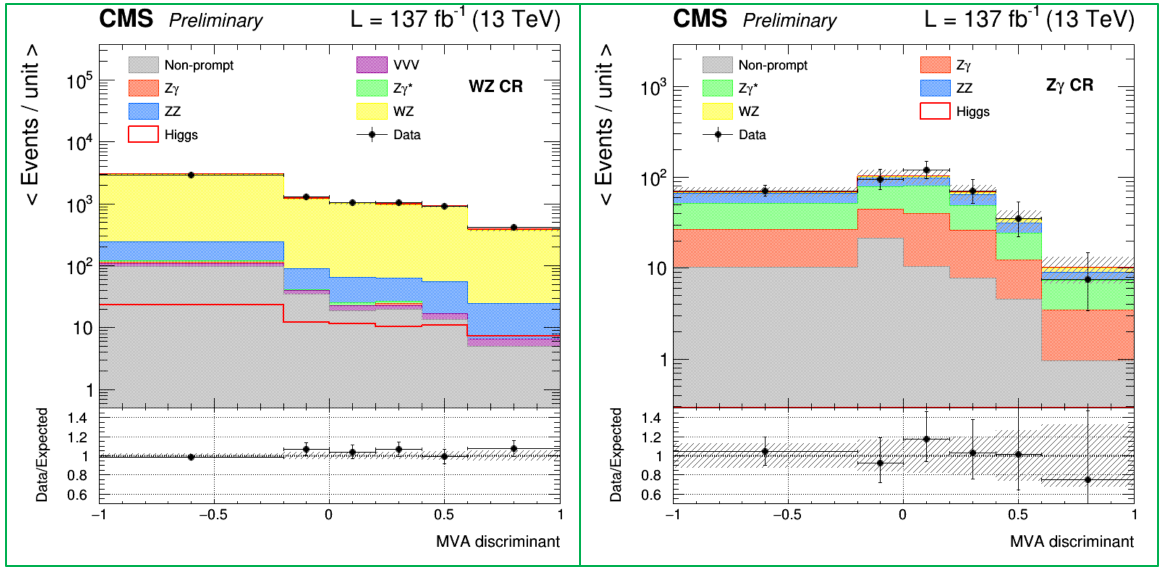
Final state	Name	Signal fraction
$(\mu/e)^{\pm} + (\mu/e)^{\mp} + (l)^{\mp}$	opposite-sign same-flavor (OSSF)	~3/4
$(\mu/e)^{\pm} + (\mu/e)^{\pm} + (e/\mu)^{\mp}$	same-sign same-flavor (SSSF)	~1/4

- CR : WZ and Zγ
- To separate signal and background : multivariate Boosted Decision Tree (BDT) is used ; fit is performed to the BDT discriminant .

	Preselection			
Lepton p_T (GeV)	$> 25, 20, 15$			
Fourth lepton p_T (GeV)	< 10			
$ch_{\ell\ell\ell}$	± 1			
$\min(m_{\ell\ell})$ (GeV)	> 12			
Jets with $p_T > 30$ GeV	0			
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV			
	OSSF SR	SSSF SR	WZ CR	$Z\gamma$ CR
OSSF lepton pair	Yes	No	Yes	Yes
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)	> 20		< 20	< 20
p_T^{miss} (GeV)	> 40		> 45	< 40
$m_{\ell\ell\ell}$ (GeV)			> 100	$[80, 100]$

Main uncertainties: non-prompt, statistical, background modeling





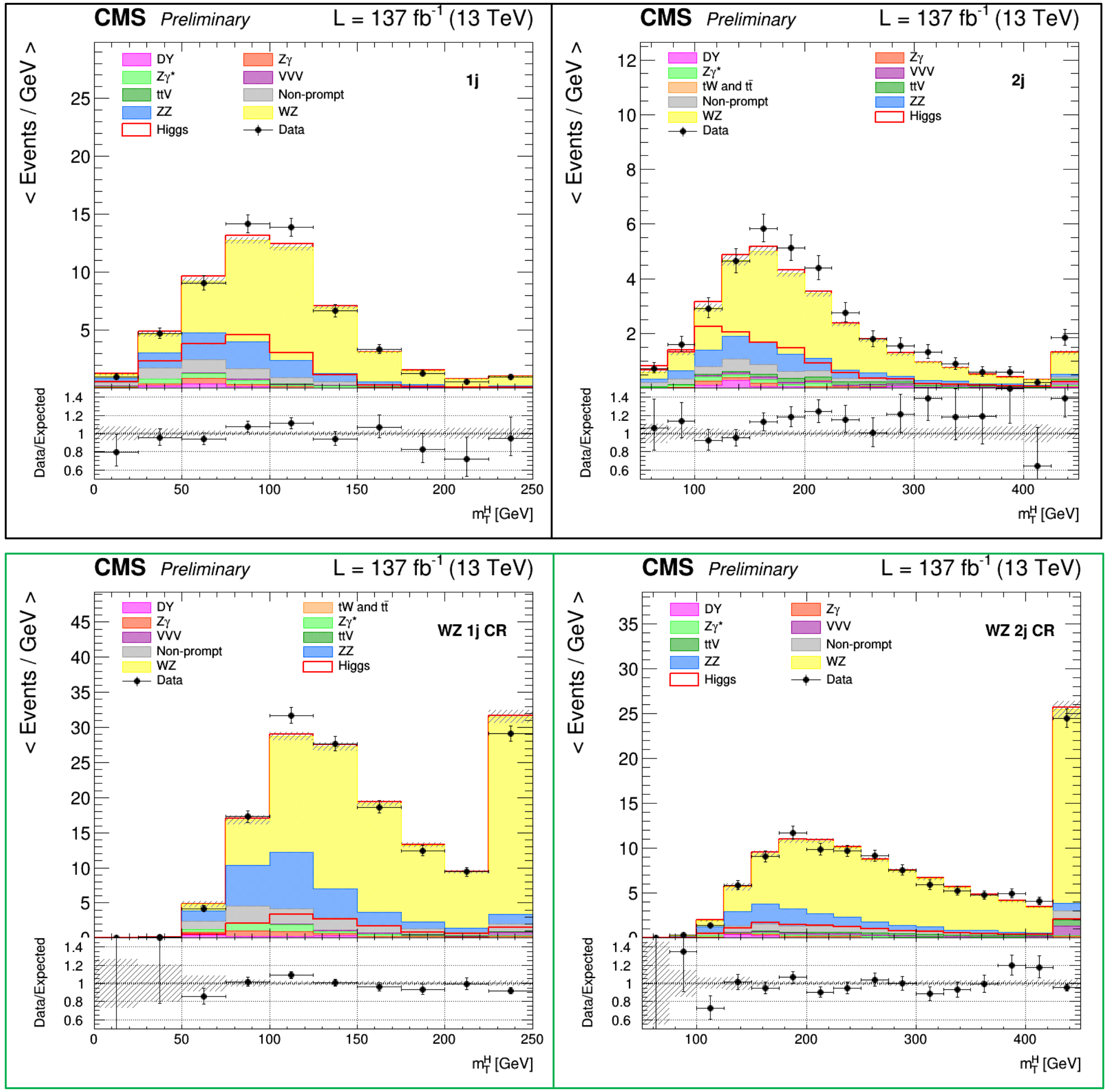
ZH3l

Backgrounds

Major : WZ, Zγ, Non-prompt (Z+jets)
Minor : ZZ, VVV, ttZ

- Events are categorized based on the number of jets in the event, hence 1j , 2j signal region .
- CR : WZ (1j , 2j)
- fit is performed to the m_T^H ; where $m_T^H = m_T$ (l + MET , j(j))

	Preselection			
Lepton p_T (GeV)	$> 25, 20, 15$			
Fourth lepton p_T (GeV)	< 10			
$ch_{\ell\ell\ell}$	± 1			
$\min(m_{\ell\ell})$ (GeV)	> 12			
b jet veto	DeepCSV, medium WP, applied to all jets with $p_T > 20$ GeV			
$\lvert m_{\ell\ell} - m_Z \rvert$ (GeV)	< 25			
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ (GeV)	> 20			
	1j SR	2j SR	1j WZ CR	2j WZ CR
Jets with $p_T > 30$ GeV	==1	≥ 2	==1	≥ 2
$\Delta\varphi(\ell p_T^{miss}, j(j))$	$< \pi/2$	$< \pi/2$	$> \pi/2$	$> \pi/2$



Main uncertainties: non-prompt, (all) background modeling

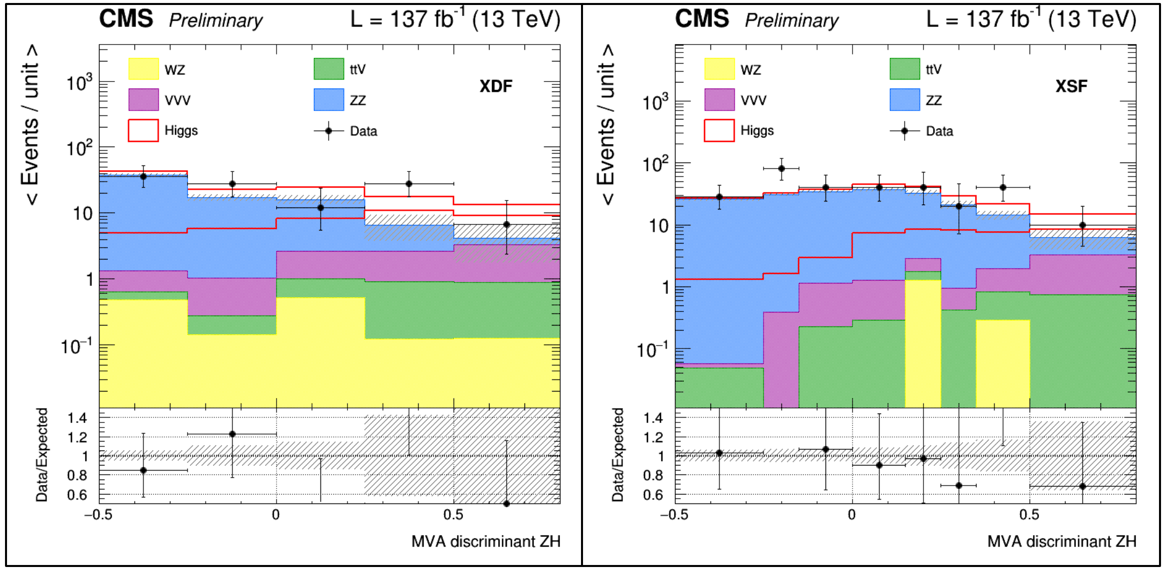
ZH4l

Backgrounds

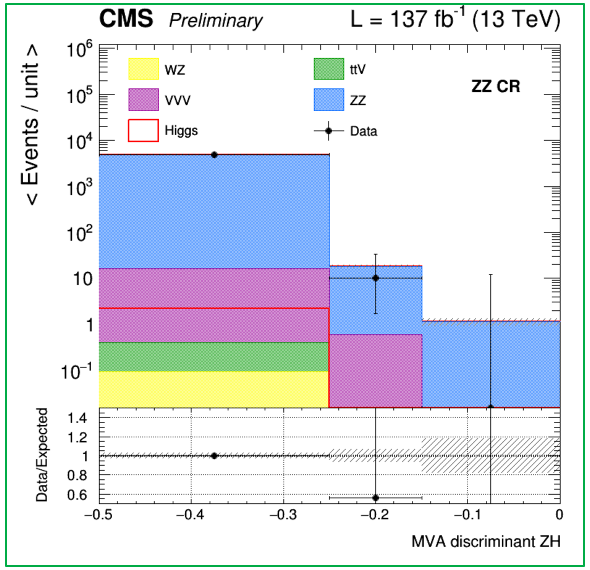
Major : qqZZ , ggZZ
Minor : WZ, WW, Vγ, top, ttV, VVV

- SR : XSF : same-flavor X lepton pair ; XDF : different-flavor X lepton pair (where X = lepton pair from the Higgs boson)
- CR : ZZ

- To separate signal and background : multivariate Boosted Decision Tree (BDT) is used ; fit is performed to the BDT discriminant .



	Preselection		
Lepton p_T (GeV)	$> 25, 15, 10, 10$		
Fifth lepton p_T (GeV)	< 10		
$ch_{\ell\ell\ell\ell}$	0		
$\min(m_{\ell\ell})$ (GeV)	> 12		
$\lvert m^Z_{\ell\ell} - m_Z \rvert$ (GeV)	< 15		
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV		
	XSF SR	XDF SR	ZZ CR
X pair flavor	Same	Different	
$m_{\ell\ell\ell\ell}$ (GeV)	> 140		
$m^X_{\ell\ell}$ (GeV)	[10,60]	[10,70]	[75,105]
PUPPI p_T^{miss} (GeV)	> 35	> 20	< 35



Main uncertainties: QCD scale, lepton efficiencies, statistical, MET

ZH4l

Backgrounds

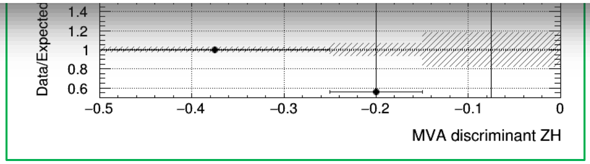
Major : qqZZ , ggZZ
Minor : WZ, WW, Vγ, top, ttV, VVV

- SR : XSF : same-flavor X lepton pair ; XDF : different-flavor X lepton pair (where X = lepton pair from the Higgs boson)
- CR : ZZ

- To separate signal and background : multivariate Boosted Decision Tree (BDT) is used ; fit is performed to the BDT discriminant .

	Preselection		
Lepton p_T (GeV)	$> 25, 15, 10, 10$		
Fifth lepton p_T (GeV)	< 10		
$ch_{\ell\ell\ell\ell}$	0		
min($m_{\ell\ell}$) (GeV)	> 12		
$\lvert m^Z_{\ell\ell} - m_Z \rvert$ (GeV)	< 15		
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV		
	XSF SR	XDF SR	ZZ CR
X pair flavor	Same	Different	
$m_{\ell\ell\ell\ell}$ (GeV)	> 140		
$m^X_{\ell\ell}$ (GeV)	[10,60]	[10,70]	[75,105]
PUPPI p_T^{miss} (GeV)	> 35	> 20	< 35

- Train BDT to discriminate signal (qqZH) from background (ZZ)
- Selection: preselection + MET > 20 + 10 GeV < $m_{\ell\ell}^X$ < 70 GeV
- Input variables:
  - MET
  - $m_T(\ell$,MET) for leading and trailing lepton .
  - ΔR, $\Delta\phi$ between X lepton pair; ΔR between Z lepton pair
  - $m_{\ell\ell}$ for X lepton pair
  - m_T(X,MET)
- Combined training for all years



ZH4l

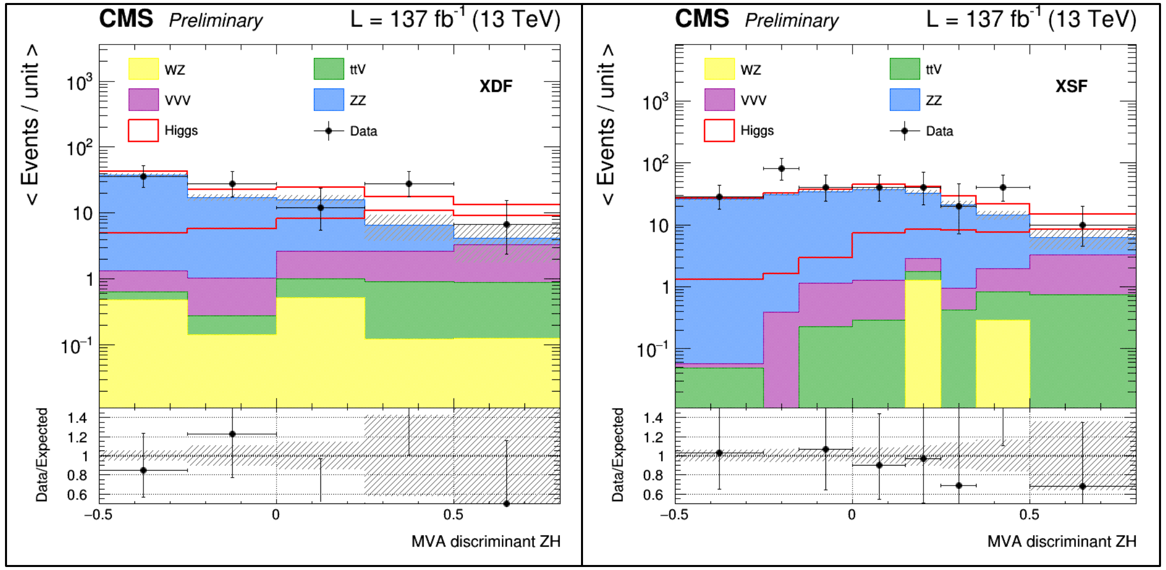
Backgrounds

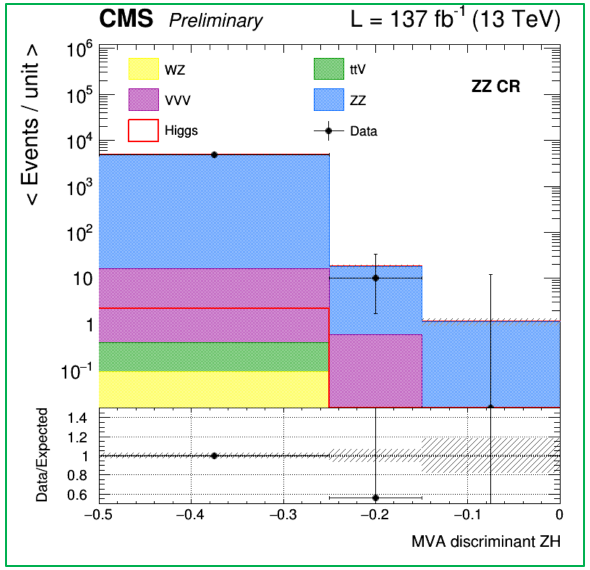
Major : qqZZ , ggZZ
Minor : WZ, WW, Vγ, top, ttV, VVV

- SR : XSF : same-flavor X lepton pair ; XDF : different-flavor X lepton pair (where X = lepton pair from the Higgs boson)
- CR : ZZ

- To separate signal and background : multivariate Boosted Decision Tree (BDT) is used ; fit is performed to the BDT discriminant .

	Preselection		
Lepton p_T (GeV)	$> 25, 15, 10, 10$		
Fifth lepton p_T (GeV)	< 10		
$ch_{\ell\ell\ell\ell}$	0		
$\min(m_{\ell\ell})$ (GeV)	> 12		
$\lvert m^Z_{\ell\ell} - m_Z \rvert$ (GeV)	< 15		
B jet veto	DeepCSV, loose WP, applied to all jets with $p_T > 20$ GeV		
	XSF SR	XDF SR	ZZ CR
X pair flavor	Same	Different	
$m_{\ell\ell\ell\ell}$ (GeV)	> 140		
$m^X_{\ell\ell}$ (GeV)	[10,60]	[10,70]	[75,105]
PUPPI p_T^{miss} (GeV)	> 35	> 20	< 35





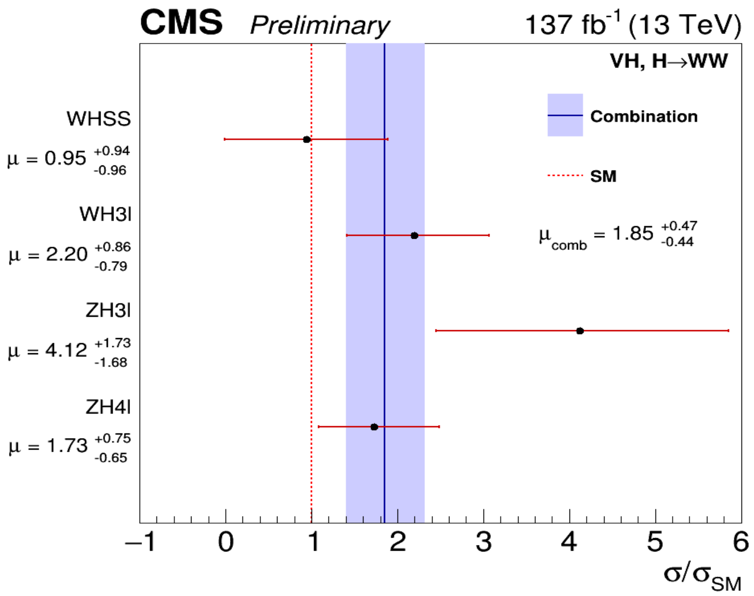
Main uncertainties: QCD scale, lepton efficiencies, statistical, MET

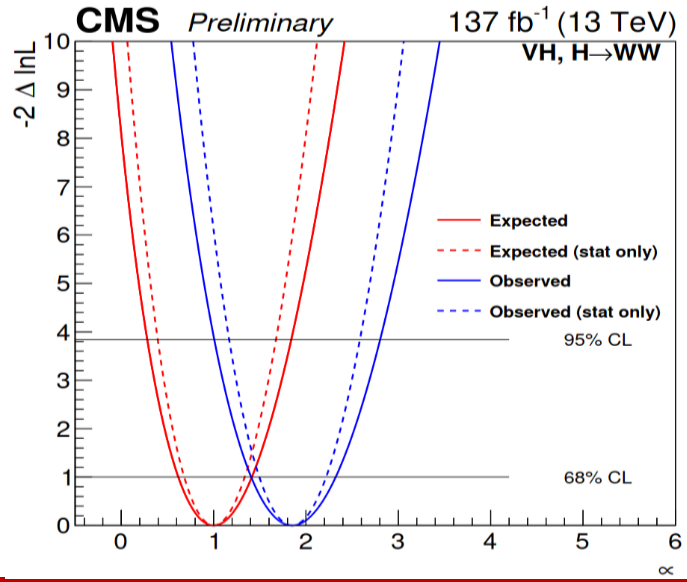
Results(Inclusive)

Signal strength and Significance for separate channel and combined .

Category	μ	Significance
WHSS	$0.95^{+0.94}_{-0.96}$	1.0 σ (1.1 σ expected)
WH3l	$2.20^{+0.86}_{-0.79}$	3.0 σ (1.6 σ expected)
ZH3l	$4.12^{+1.73}_{-1.68}$	2.5 σ (0.6 σ expected)
ZH4l	$1.73^{+0.75}_{-0.65}$	3.1 σ (2.1 σ expected)
Combination	$1.85^{+0.47}_{-0.44}$	4.7 σ (2.8 σ expected)

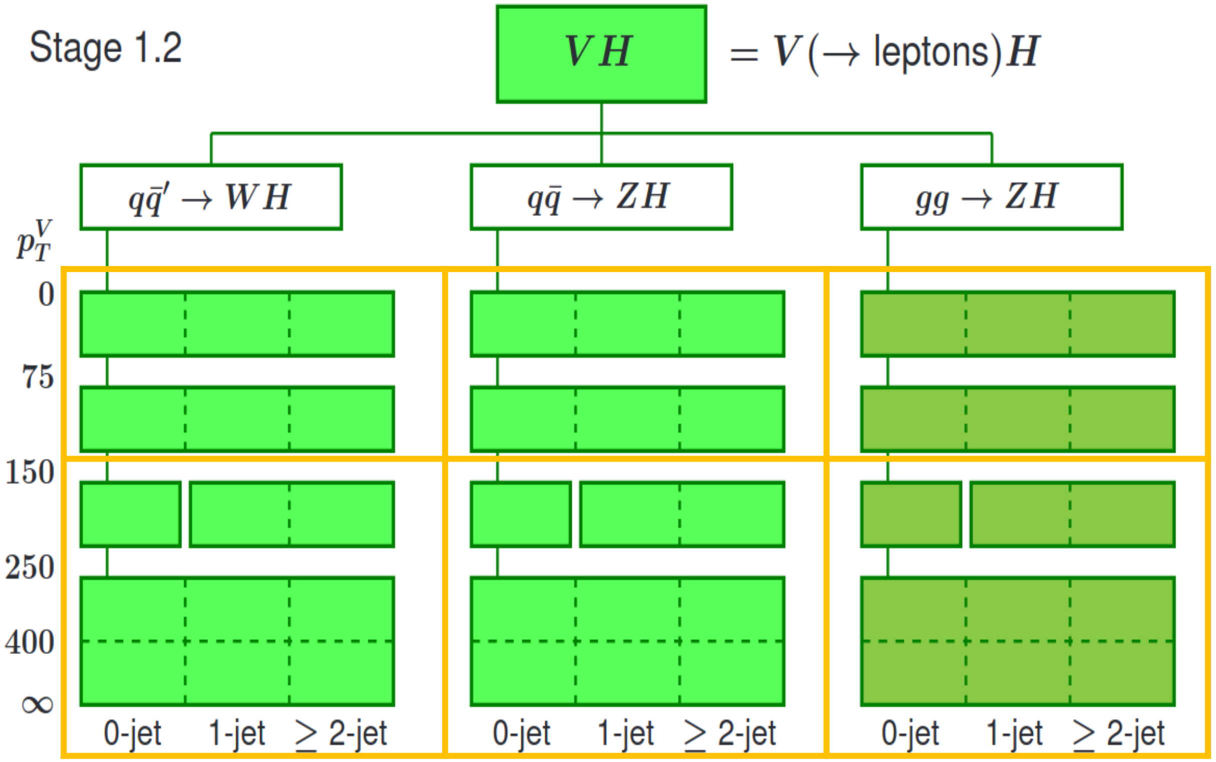
$$\hat{\mu} = 1.85^{+0.33}_{-0.32}\,(stat)\,^{+0.27}_{-0.25}\,(exp)\,^{+0.10}_{-0.07}\,(theo)$$





Simplified Template Cross Sections (STXS)

- The primary goals of the STXS framework are to maximize the sensitivity of the measurements and to minimize their theory dependence at the same time .
- Not sensitive to all bins, due to limited statistical precision --> merged , considered p_T^V <(>) 150 GeV for WH and ZH .



Definition of p_T^V

- **WHSS :**

$$\vec{p}_T^W = \vec{p}_T(\ell_W) + \vec{p}_T(\nu_W)$$
$$= \vec{p}_T(\ell_W) + \vec{E}_T^{miss} - \vec{p}_T(\nu_H)$$
$$\vec{p}_T(\nu_H) = \vec{p}_T(\ell_H) \times \left(\frac{125}{||\vec{p}_T(\ell_H) + \vec{p}_T(jj)||} - 1 \right)$$

- **WH3l :**

For W p_T , $p_T(l_W)$ is used as a proxy .

- **ZH3l , ZH4l :**

Z p_T is p_T of OSSF lepton pair ; $m_{ll} \sim m_Z$

N.B. : The fit to extract STXS uses the same background CRs , signal region categories and signal-discriminating kinematical observables as of inclusive measurement .

Results (STXS)

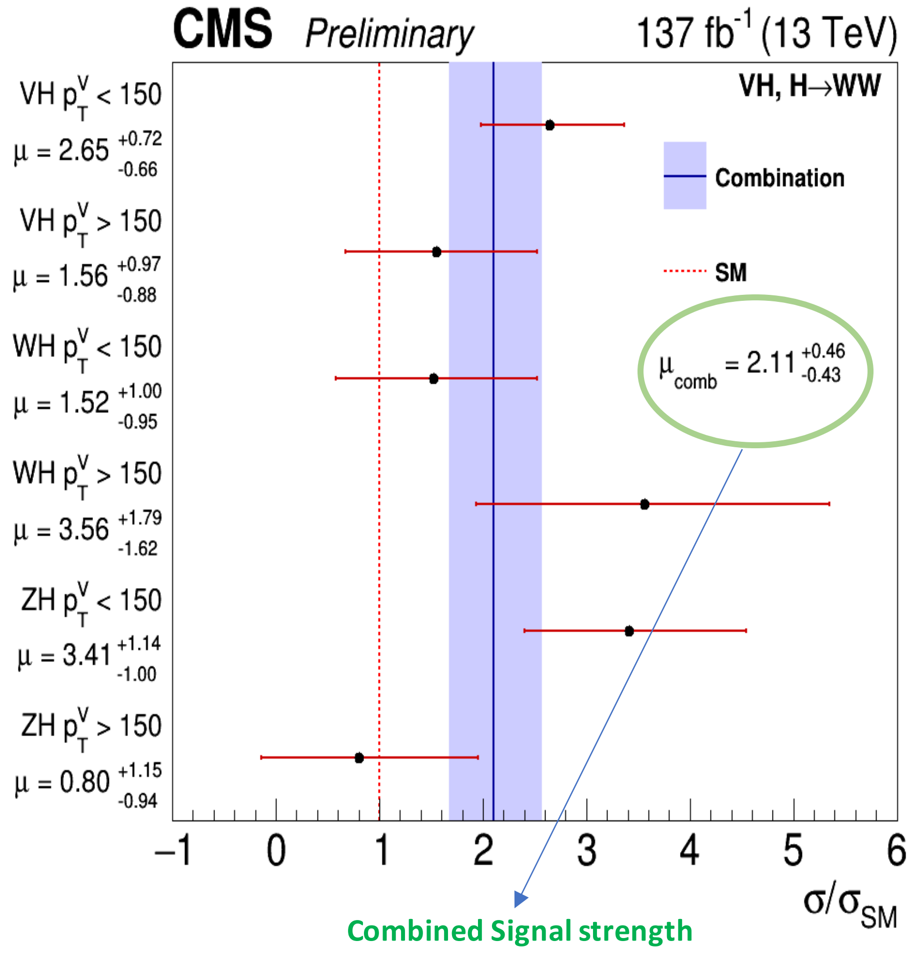
Signal strength and Significance in each production mode

Category	μ	Significance
$WH\ p_T^V$ < 150 GeV	$1.5^{+1.0}_{-0.9}$	1.64 σ (1.24 σ expected)
$WH\ p_T^V$ > 150 GeV	$3.6^{+1.8}_{-1.6}$	2.23 σ (0.83 σ expected)
$ZH\ p_T^V$ < 150 GeV	$3.4^{+1.1}_{-1.0}$	4.37 σ (1.59 σ expected)
$ZH\ p_T^V$ > 150 GeV	$0.8^{+1.2}_{-0.9}$	0.83 σ (1.18 σ expected)

Signal strength and Significance combining the production modes

$$\hat{\mu}_{p_T^V < 150} = 2.65^{+0.57}_{-0.55}\,(stat)\ ^{+0.38}_{-0.32}\,(exp)\ ^{+0.08}_{-0.07}\,(theo)$$ 4.7σ (2.0 expected)

$$\hat{\mu}_{p_T^V > 150} = 1.56^{+0.85}_{-0.77}\,(stat)\ ^{+0.43}_{-0.40}\,(exp)\ ^{+0.11}_{-0.09}\,(theo)$$ 1.8σ (1.5 expected)



Summary

- Presented the latest results in Higgs boson decaying to WW channel , where the associated boson is decaying leptonically is considered .

- Along with inclusive measurement , STXS measurements have been performed .The observed significance of the inclusive VH production cross section is 4.7σ, while the observed significance of the VH production cross section for $p_T^V < 150$ (> 150) is 4.7σ(1.8σ).

- The combined signal strength of STXS differs from the inclusive result due to the STXS event categorization, although the two results agree within uncertainties.

Thanks for your attention !

Backup

Objects	2016	2017/2018
Electrons	mva_90p_Iso2016 + relIso + *ttHMVA > 0.7	Fall17V1Iso_WP90 + relIso + *ttHMVA > 0.7
Muons	Tight ID + Rochester corrections + dz/dxy cuts + *ttHMVA > 0.8	Tight + dz/dxy cuts + *ttHMVA > 0.8
Jets	Tight AK4 jets + lepton cleaning + loose PU ID + JECs	
b tag	deepCSV (medium for WHSS/ZH3l, loose for WH3l/ZH4l)	
MET	PuppiMET	

* not applied in ZH4l .

Data

2016

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_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
		HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*
	[278273,284044]	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*

2018

Data Set	Run range	HLT path
SingleMuon	[315252,325175]	HLT_IsoMu24_v*
		HLT_Mu50_v*
	[314859,325175]	HLT_IsoMu27_v*
DoubleMuon	[315252,325172]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8_v*
		HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8_v*
EGamma	[315252,325172]	HLT_Ele32_WPTight_Gsf_v*
		HLT_Ele35_WPTight_Gsf_v*
		HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_v*
MuonEG	[315252,325172]	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*

2017

Data Set	Run range	HLT path
SingleMuon	[297020,306462]	HLT_IsoMu27_v*
SingleElectron	[297020,306462]	HLT_Ele35_WPTight_Gsf_v*
DoubleMuon	[297020,299329]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
	[299337,306462]	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass8_v*
DoubleEG	[297020,306462]	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_v*
MuonEG	[297020,306462]	HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v*
	[297020,299329]	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
	[299337,306462]	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*

MC

2016	RunIISummer16NanoAODv5-PUMoriond17_Nano1June2019_102X_mcRun2_asymptotic_v7-v1
2017	RunIIFall17NanoAODv5-PU2017_12Apr2018_Nano1June2019_102X_mc2017_realistic_v7-v1
2018	RunIIAutumn18NanoAODv6-Nano25Oct2019_102X_upgrade2018_realistic_v20-v1

Impacts of sources of systematic uncertainty on signal strength

Type	Source	Impact (%)
Theoretical	Renormalization and factorization scale	3
	Parton distribution function	2
	Parton shower, underlying event	2
Experimental	Nonprompt	9
	Sample size of simulation data	8
	Electron	3
	b tag	3
	Jet	2
	Luminosity	2
	WZ normalization	2
	$Z\gamma$ normalization	2
	ZZ normalization	1
	Muon	1