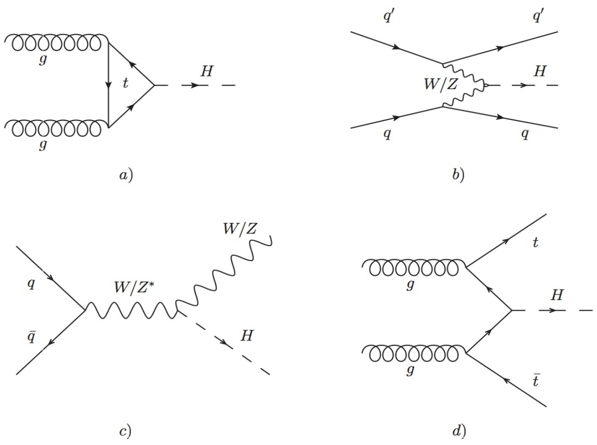
Lorenzo Russo,
on behalf of the ATLAS and the CMS collaborations
Università di Siena & INFN di Firenze

Higgs to WW measurements at ATLAS and CMS

Debrecen, QCD@LHC 27 Ago 2017 – 1 Set 2017

Introduction

Since the observation of a new particle in 2012, mass, spin and CP violation have been measured by ATLAS and CMS experiments.



One of the most sensitive decay channel is $H \rightarrow WW \rightarrow \ell\upsilon\ell\upsilon$.

ATLAS and CMS preliminary 2015-2016 results.

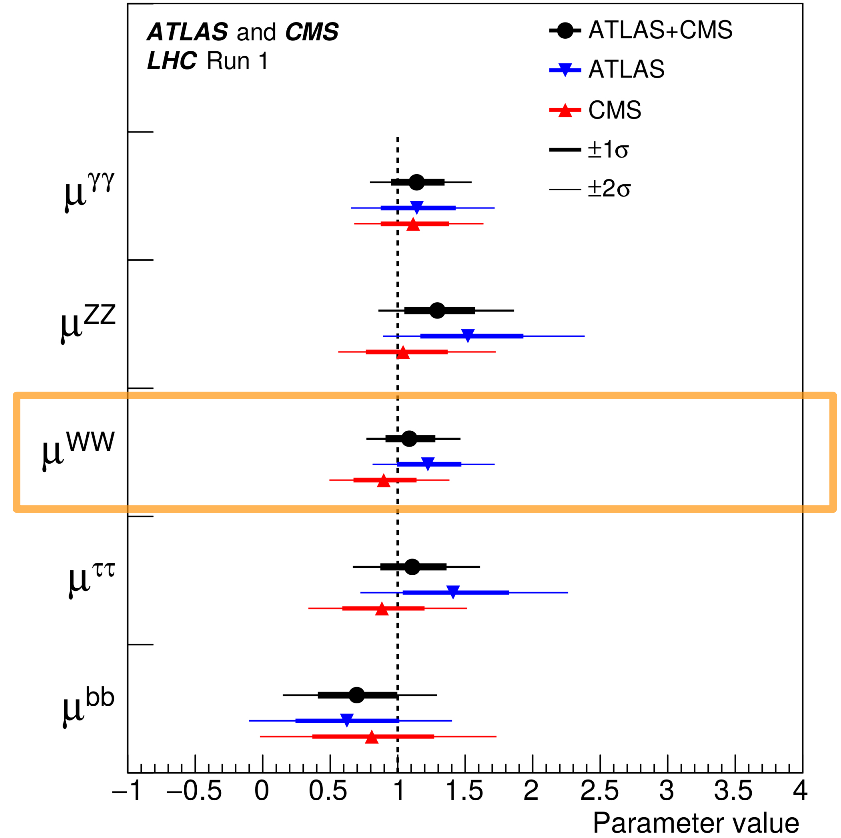
Extended Higgs sector: motivated in many beyond SM scenarios.

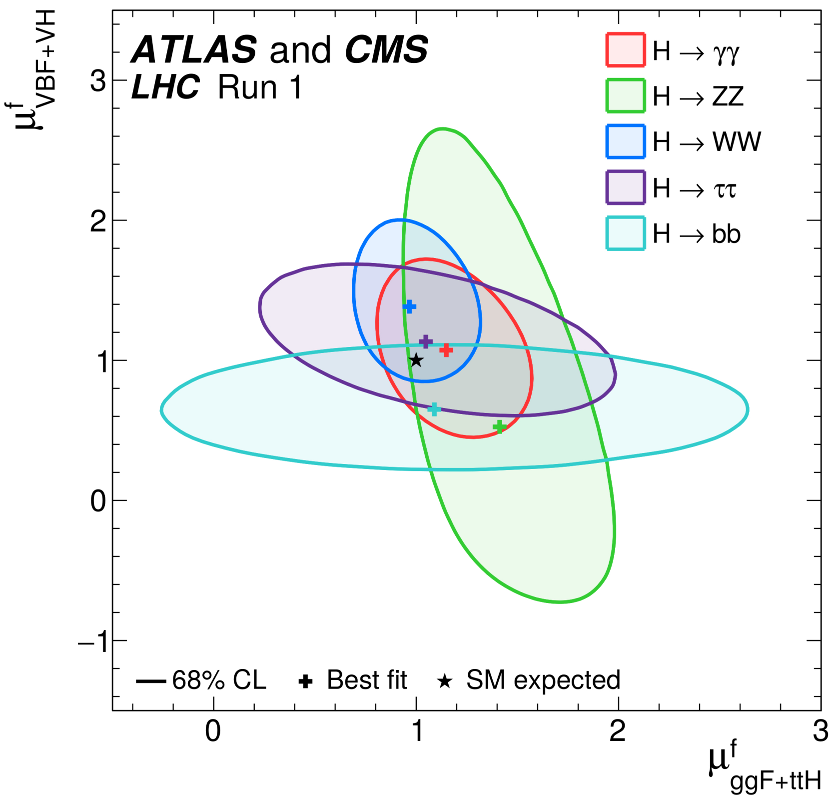
The search for heavy neutral scalar particle, X, decaying to two W boson with two lepton and two neutrinos in the final state, is carried out by ATLAS and CMS with LHC Run-II data.

Run-I H → WW results

The ATLAS and CMS Collaborations -JHEP 1608 (2016) 045-

- **ATLAS**: obs (exp) 6.8σ (5.8σ) and $\mu = 1.22^{+0.23}_{-0.21}$
- **CMS**: obs (exp) 4.8σ (5.6σ) and $\mu = 0.90^{+0.23}_{-0.21}$
- **ATLAS + CMS**: $\mu = 1.09^{+0.18}_{-0.16}$
- Excellent agreement with data in WW channel.

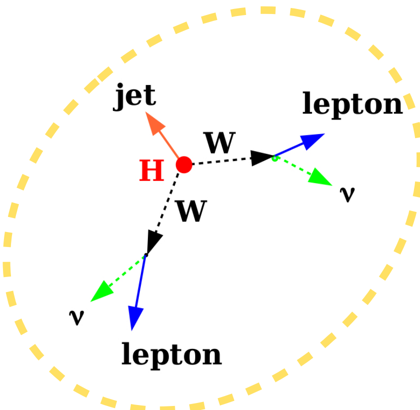




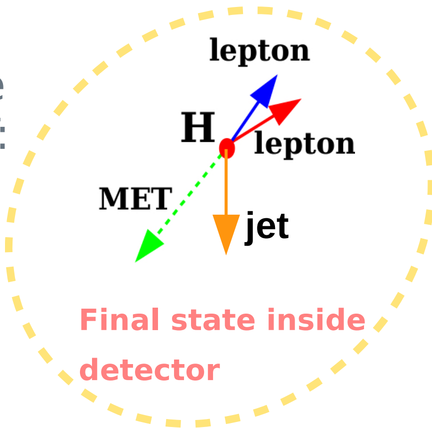
- WW channel gives one of the most precise measurement of the Higgs boson coupling.

Signal and backgrounds for the Higgs boson

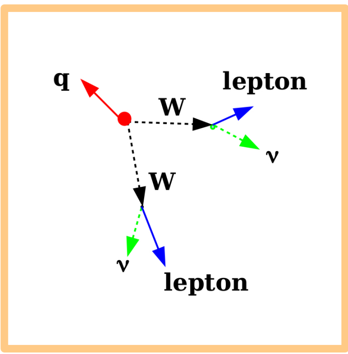
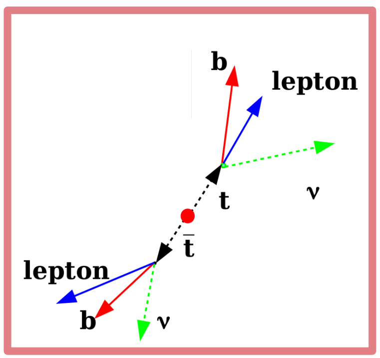
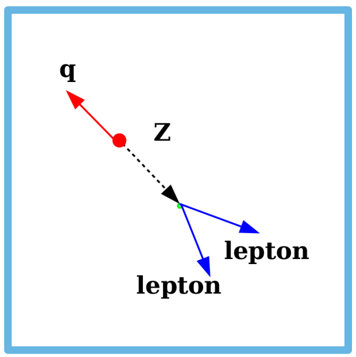
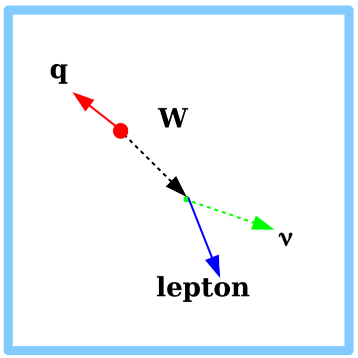
- **Signal**:



The neutrinos in the final state escape direct detection and lead to large MET: impossible to reconstruct the Higgs invariant mass spectrum.



- **Main backgrounds**: several processes can lead to the similar event properties.

$\mathbf{WW} \rightarrow \ell\upsilon\ell\upsilon$	$\mathbf{tt} \rightarrow \mathbf{WWbb} \rightarrow \ell\upsilon\ell\upsilon\mathbf{bb}$	$\mathbf{DY} \rightarrow \ell\ell$	$\mathbf{W}$ +jets $\rightarrow \ell\upsilon$ +jets
			
Irriducible backgrounds	**Characterized by b-jets**	**Mismeasured MET**	**Fake lepton from a misidentified jet**

- Other background processes with Z bosons, such as WZ/Wγ^*, ZZ* with a misidentified lepton and Zγ with γ conversion are relevant in WH production mode.

SM Higgs boson in CMS

CMS PAS HIG-16-021

- Update of the preliminary 2015 results with $\mathcal{L}$= 2.3 fb^{-1}: in this analysis is used a $\mathcal{L}$= 12.9 fb^{-1} of 2016 data, collected up to August 2016.

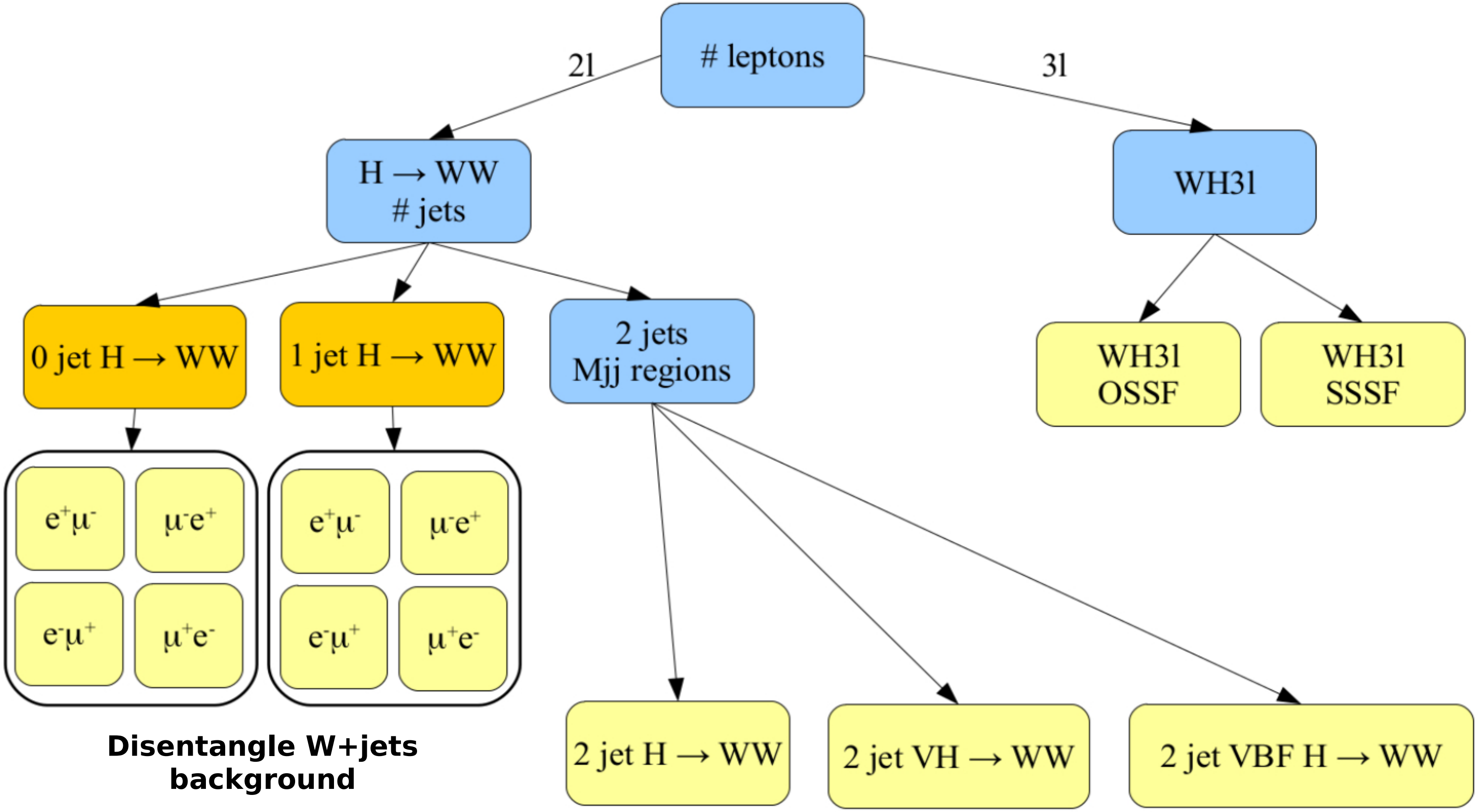
- Main production mode **ggF** is studied.
  - Also **VBF** and **VH** is taken in account for precision coupling measurements.

- The invariant mass of the Higgs boson can not be reconstructed (neutrinos presence). Introduced the Higgs transverse mass:

$$m_{\mathrm{T}}^{\mathrm{H}} = \sqrt{2 p_{\mathrm{T}}^{\ell\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi(\ell\ell, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}))}$$

Events categorization

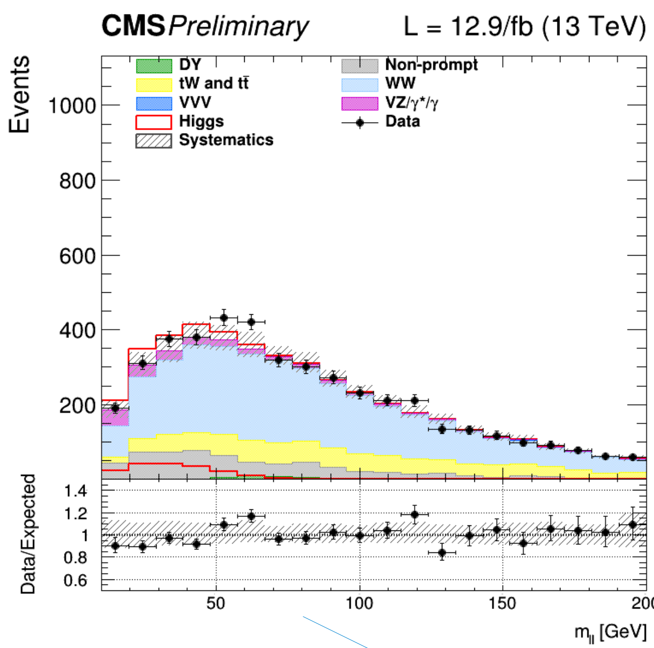
- Events categorized according to the number of **leptons**, the number of **jets** and the **kinematics** of the jets.
  - **0** and **1-jet** categories are split in lepton-flavour charge: significance improved 15%.

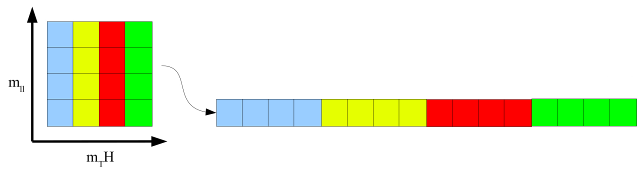


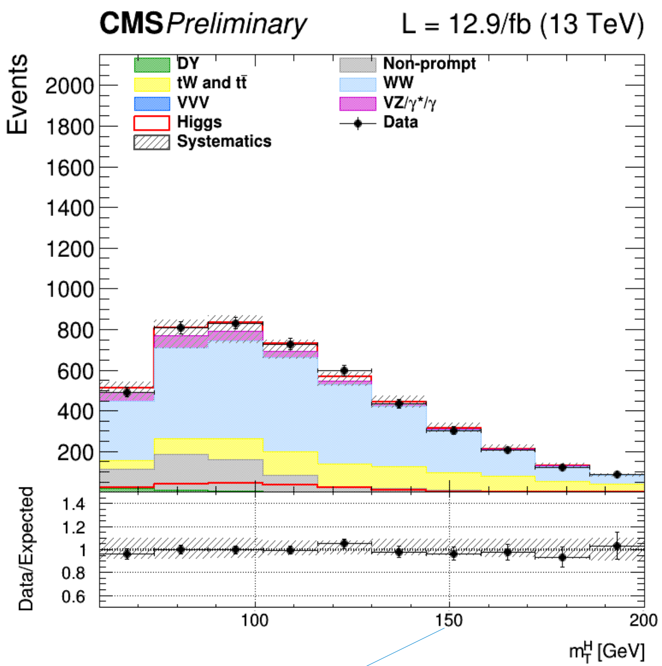
Disentangle W+jets background

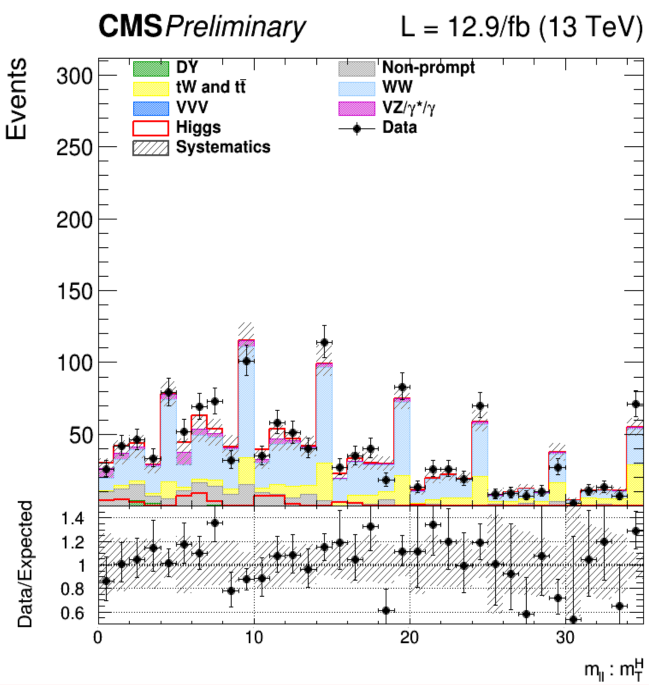
Gluon Fusion categories

- The analysis is based on bi-dimensional templates of $m_{\ell\ell}$ vs m^H_T: the distributions are used for the signal extraction.









- Un-rolled 2D distribution with 5 $m_{\ell\ell}$ bins and 7 bins in m^H_T.

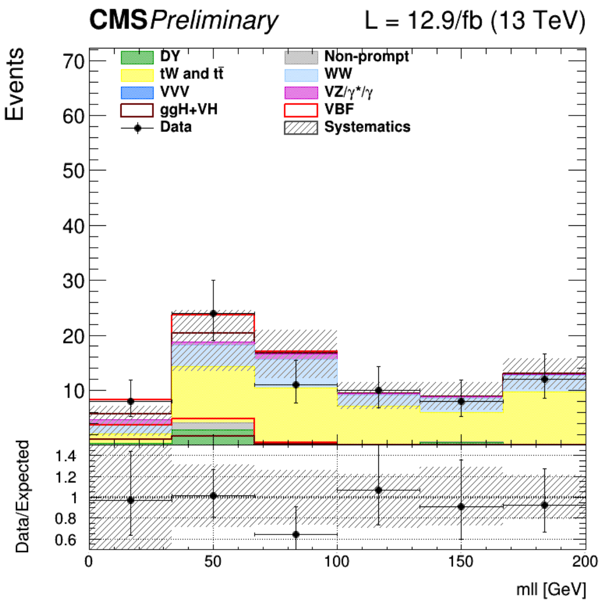
Vector Boson Fusion, VH and WH categories

- **VBF**: characterized by pair of forward-backward jets. The analysis based is on m$\ell\ell$ distribution.

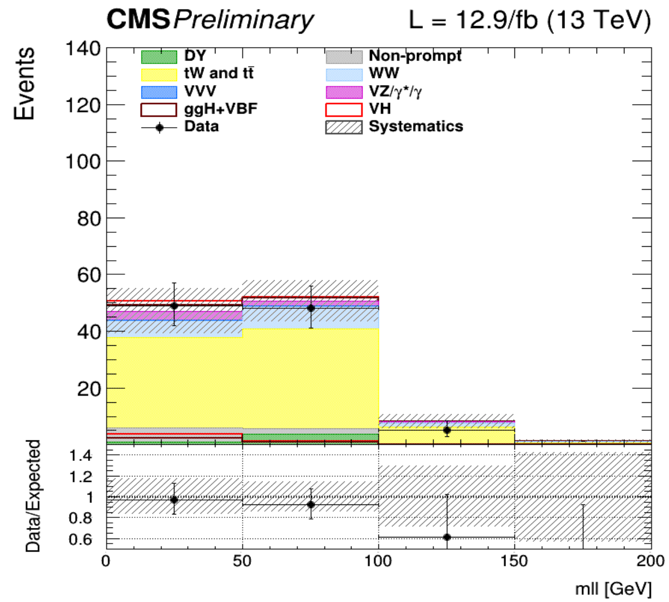
- **VH with 2 jets**: W or Z decays in two resolved jets. Two jets invariant mass in [65,105] GeV. Analysis based on m$\ell\ell$ distribution.

- **WH with 3 leptons**: fourth lepton veto. Two sub-categories: Same-Sign-Same-Flavour $\mu^{\pm}\mu^{\pm}e^{\mp}/e^{\pm}e^{\pm}\mu^{\mp}$ and Opposite-Sign-Same-Flavour $\mu^{\mp}\mu^{\pm}e^{\mp}/e^{\mp}e^{\pm}\mu^{\mp}$. Template fit on minimum ΔR between opposite-charged leptons.

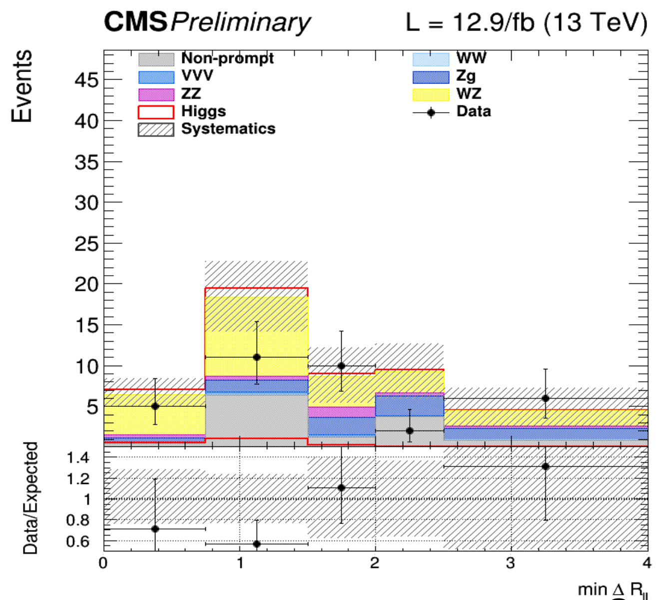
VBF



VH+2jets



WH



Results

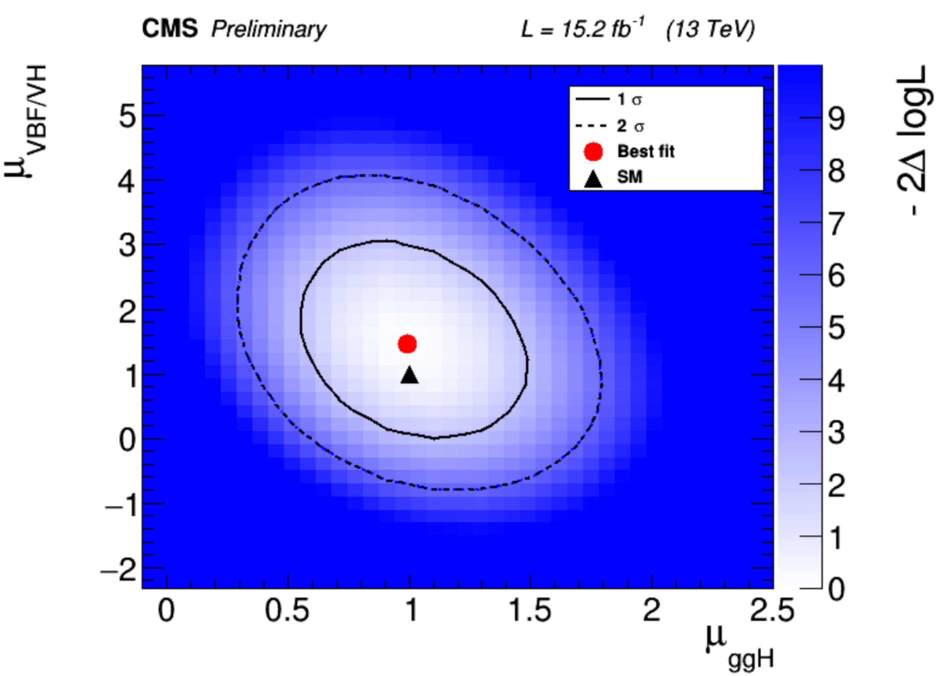
- **Observed and Expected Significance**

category	significance	σ/σ_{SM}
0-jet	2.7 (2.9)	$0.9\,^{+0.4}_{-0.3}$
1-jet	2.1 (2.5)	$1.1\,^{+0.4}_{-0.4}$
2-jet	2.0 (1.0)	$1.3\,^{+1.0}_{-1.0}$
VBF 2-jet	2.2 (1.5)	$1.4\,^{+0.8}_{-0.8}$
VH 2-jet	1.0 (0.4)	$2.1\,^{+2.3}_{-2.2}$
WH 3-lep	0.0 (0.5)	$-1.4\,^{+1.5}_{-1.5}$
combination	4.3 (4.1)	$1.05\,^{+0.27}_{-0.25}$

$$\mu = \sigma/\sigma_{SM} = 1.05 \pm 0.26$$

CMS **Run-I** significance results for VFB and ggF separately	
$\mu^{WW}_{VBF} = 1.08^{+0.65}_{-0.58}$	$\mu^{WW}_{ggF} = 0.84^{+0.25}_{-0.21}$

CMS Run-II Likelihood scan



- To explore Higgs boson couplings is necessary to separate between ggF and the other contribution.

  -In ggF, the Higgs boson's coupling to fermions is involved by virtual loop.

  -In the other mechanism, the tree level coupling to vector boson play a central role.

SM Higgs boson in ATLAS

ATLAS-CONF-2016-112

- Vector Boson Fusion (**VBF**) and associated **WH** production processes are considered in the analysis:
  - **VBF**: one e and one μ, and at least two jets.
  - **WH**: three identified leptons with total charge $\pm e$.

  Mutually orthogonal

  - The ggF and the ZH are considered as background.
  - Contributions from ttH and bbH are negligible.
- Data correspond to $\mathcal{L}$= 5.8 fb^{-1} recorded in 2015 and 2016 at 13 TeV.

The VBF analysis

- **VBF signature**: two high-rapidity energetic jets (p_T> 25 GeV) with large rapidity separation and N_{jet} ≥ 2 and *b-jet* veto.
- **BDT** is developed to improve the statistic with 8 variables: $\Delta\phi_{\ell\ell}, m_{\ell\ell}, m_T, \Delta y_{jj}, m_{jj}, p_T^{tot}, \sum_{\ell,j} m_{\ell j}$, and $\eta_\ell^{centrality}$

  $\boxed{\boldsymbol{p}_T^{\ell_1}+\boldsymbol{p}_T^{\ell_2}+\boldsymbol{E}_T^{miss}+\sum \boldsymbol{p}_T^{jets}}$

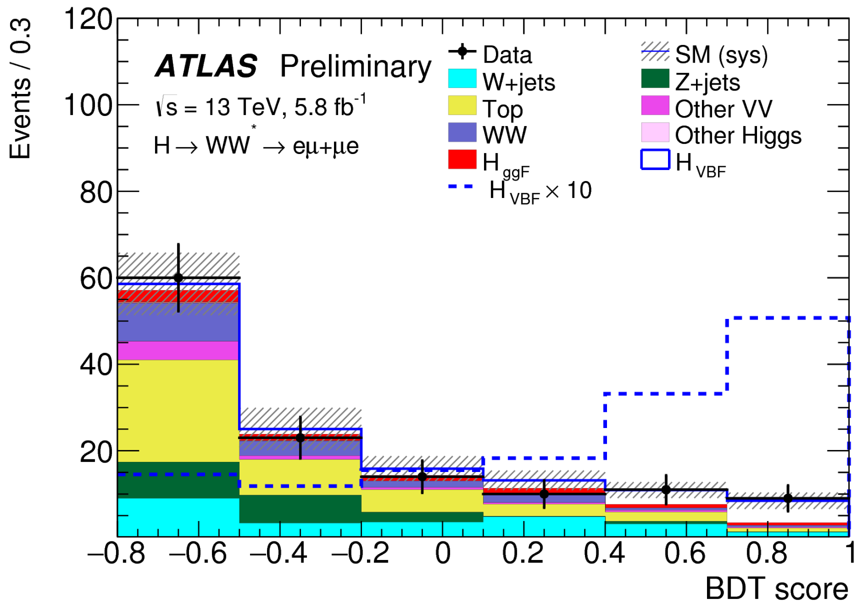
  $\boxed{\eta_\ell^{centrality} = |\eta_\ell - \frac{\sum \eta_{jj}}{2}|/\frac{\Delta\eta_{jj}}{2}}$

  The score is defined in range [-1,1]. Three different categories:
  - **BDT score [-1, -0.8]**, dominated by Top background.
  - **BDT score [-0.8, 0.7]**, signal region 1 (SR1).
  - **BDT score [0.7, 1]**, signal region 2 (SR2).

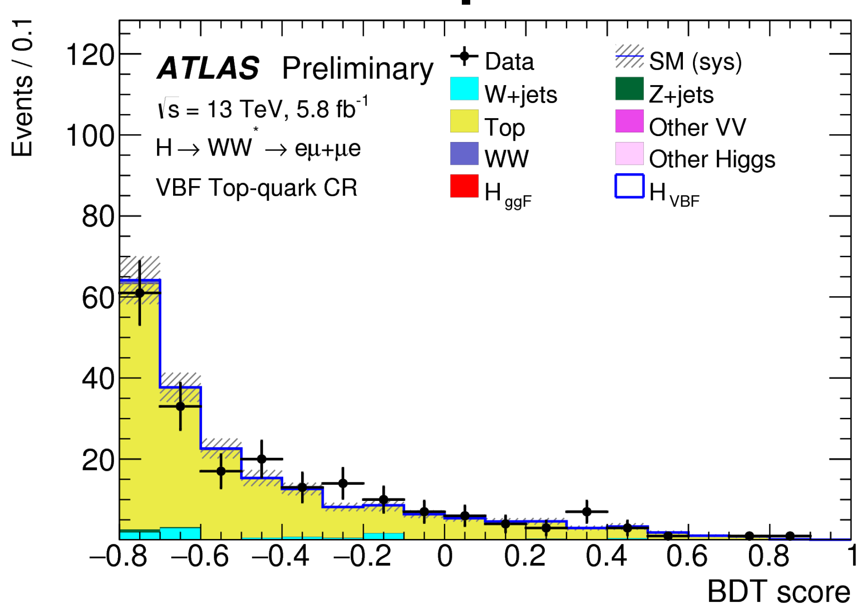
  $\left.\begin{array}{l} \text{[-0.8, 0.7]} \\ \text{[0.7, 1]} \end{array}\right\}$ **BDT > -0.8**

- **Control regions**:
  - Top: exaclty one b-tag jet
  - Z → $\tau\tau$ defined as: $|m_{\tau\tau} - m_Z| < 25\text{GeV}$, $m_{\ell\ell} < 80\text{GeV}$

SRs



Top CR

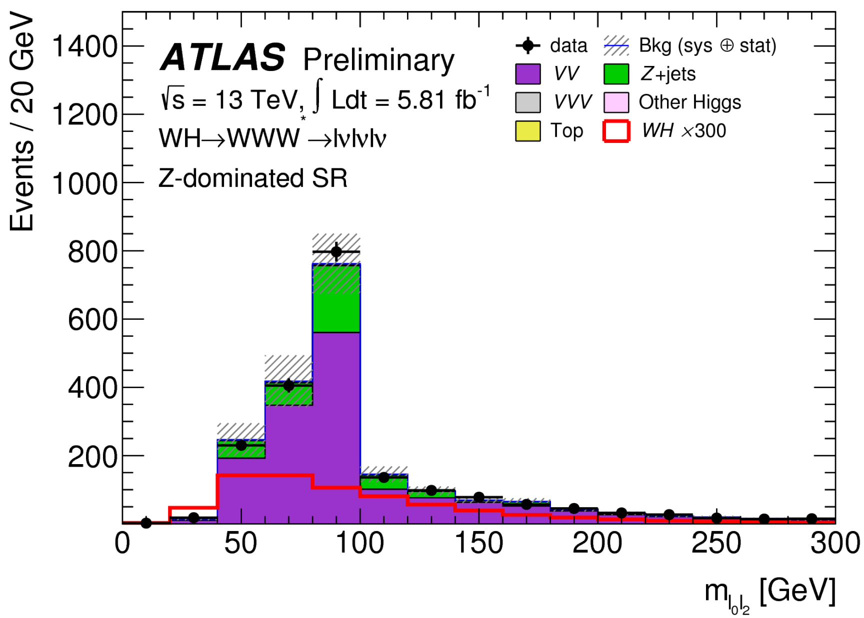


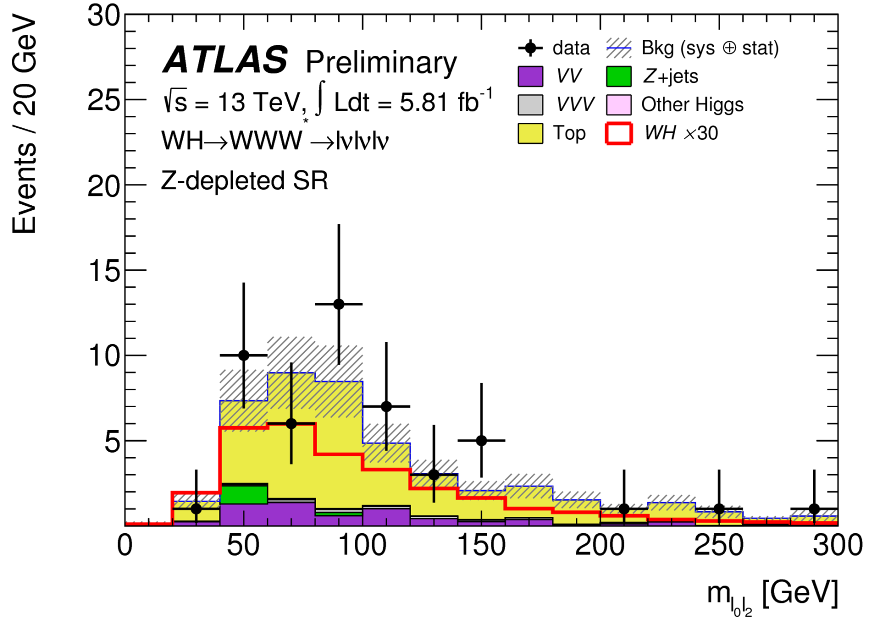
The WH analysis

- **WH signature**: exactly 3 leptons with total charge $\pm e$. The fakes arise from Top and Z+jets production.

- **Same-Flavour-Opposite-Sign leptons categorization**:
  - ≥ 1 SFOS pair, ¾ signal but Z-boson irriducible background (SR Z-dominated).
  - No SFOS pair, ¼ signal, reducible background (SR Z-depleted).

Opposite charge leptons invariant mass



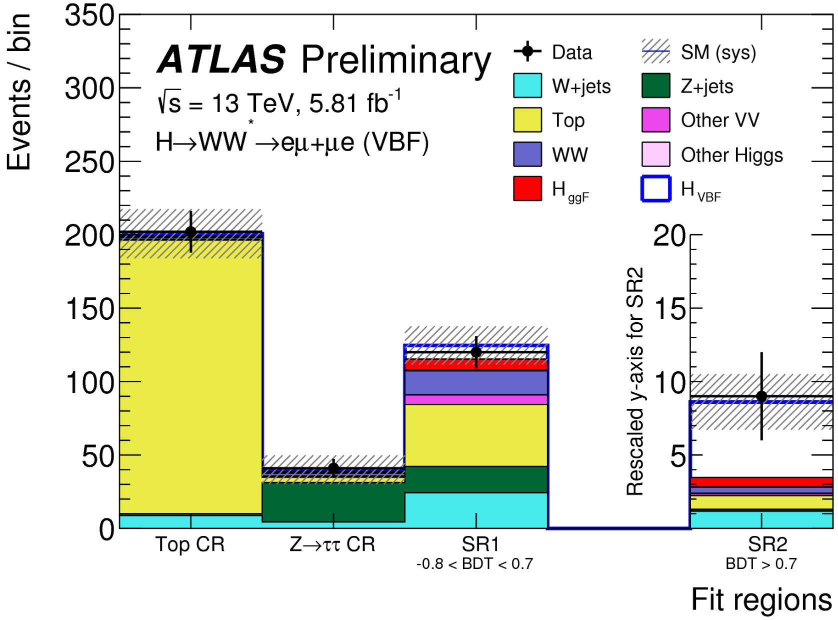


- **Control Regions**: several CRs for WZ/Wγ*, Zγ , Z+jets and top quark.

Signal extraction and Results

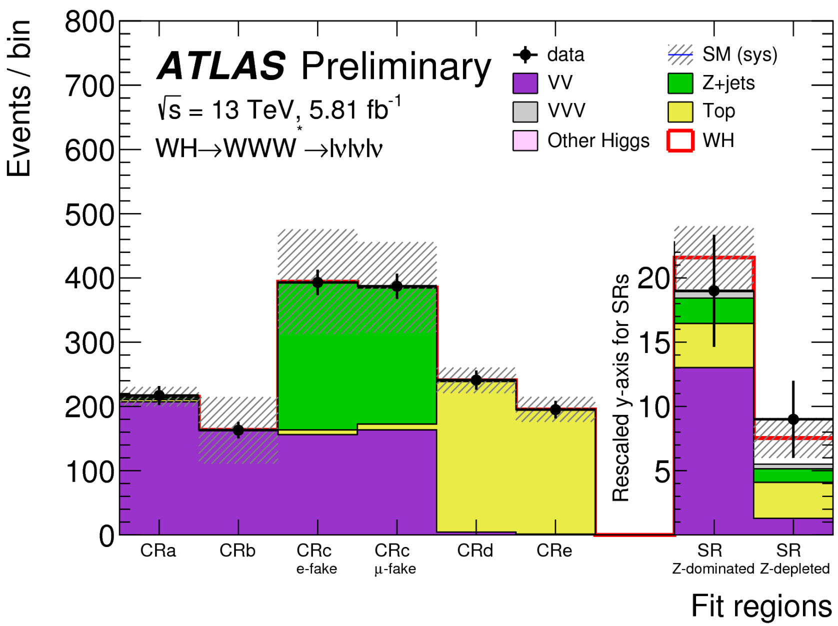
- **VBF**: fit is performed in the two SRs (most significant bin of BDT), in the Top and in the $Z \rightarrow \tau\tau$ CRs.

Obs (Exp) Significance is 1.9σ (1.2σ)



- **WH**: simultaneous fit in the Z-dominated, Z-depleted SRs and in the CRs.

Obs (Exp) Significance is 0.77σ (0.24σ)



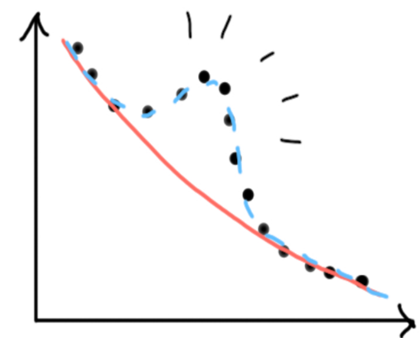
- **Signal strength** for VBF and WH:

$$\mu_{\text{VBF}} = 1.7^{+1.0}_{-0.8}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$$
$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(\text{stat})^{+2.3}_{-2.7}(\text{sys})$$

ATLAS **Run-I** results: $\mu_{\text{VBF+VH}} = 1.56^{+0..52}_{-0.46}$

Strategy for *high-mass* Higgs boson

- Search for *heavy neutral scalar* Higgs boson decaying in two W boson is carried out by ATLAS and CMS experiment.



- Motivated in many BSM, two-Higgs-doublet or in WW unitarization scattering scenario (**See T. Williams's talk**).
- The preselection for the searches are similar to the SM analyses. Analysis strategies between the experiments are also similar, but have a few differences:
  - $\mathcal{L}_{\text{ATLAS}}$ = 13.2 fb^{-1} in 2015+2016 and $\mathcal{L}_{\text{CMS}}$ = 2.3 fb^{-1} in 2015
  - Both use only **ggF** and **VBF** production mode.
  - Three categories in ATLAS (**ggF, VBF 1jet, VBF ≥2jet**) and CMS (**0jet, 1jet, VBF**).
  - High-Higgs masses **range**: ALTAS=[300 GeV, 3 TeV] and CMS=[200 GeV, 1 TeV] .
  - Different width hypotheses (**NWA or LWA**).
  - Slight difference in discriminant-fit variable:

Sum of the two four-momenta

ATLAS

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$$

CMS

$$m_{\mathrm{T,i}} = \sqrt{(p_{ll} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{ll} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2}.$$

High-Mass Higgs boson in ATLAS

ATLAS-CONF-2016-074

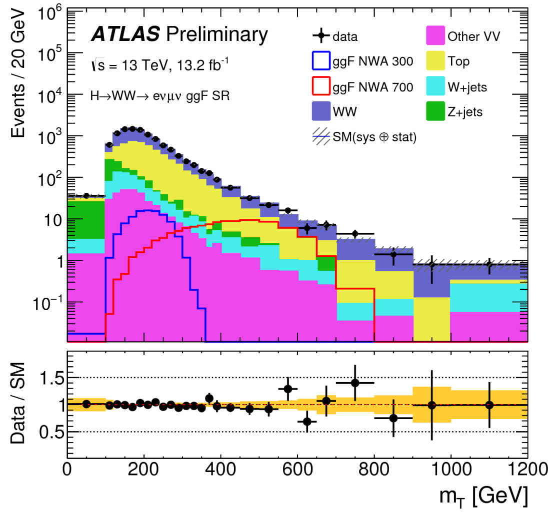
- Thee different signal regions:

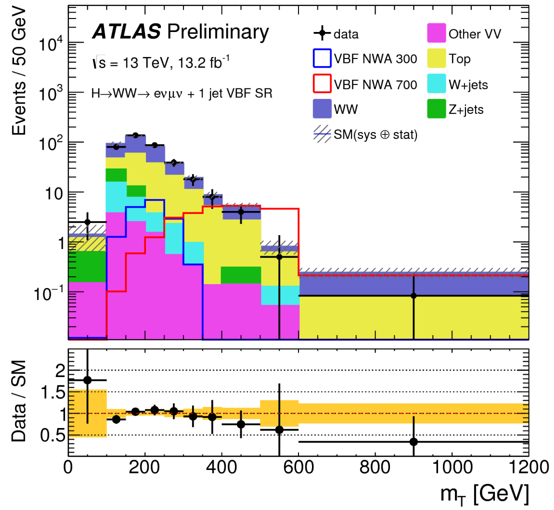
SR ggF | **SR VBF1j** | **SR VBF2j**

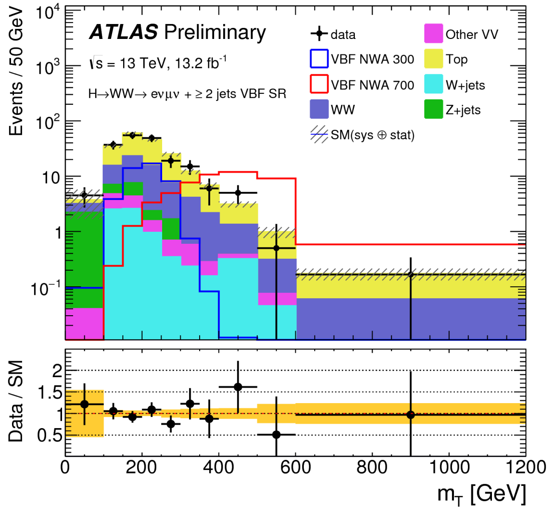
ggF predominantly
Njet=0

ggF and VBF contribute
Njet =1

VBF predominantly,
Njet ≥2



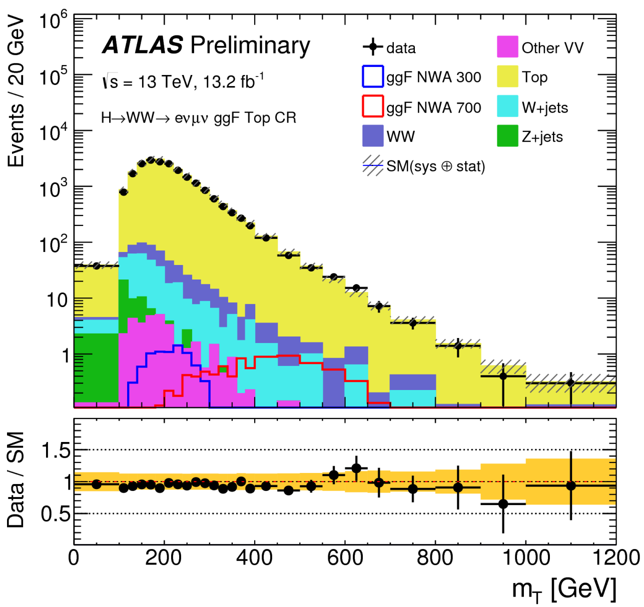




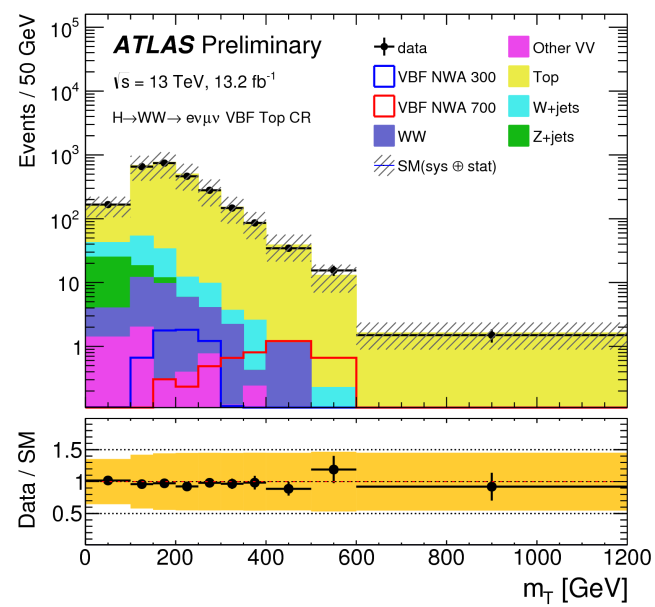
Backgrounds and Uncertainties

- Main backgrounds **Top-quark** and **WW.** Both normalized to data in the control regions.

WW CR in ggF



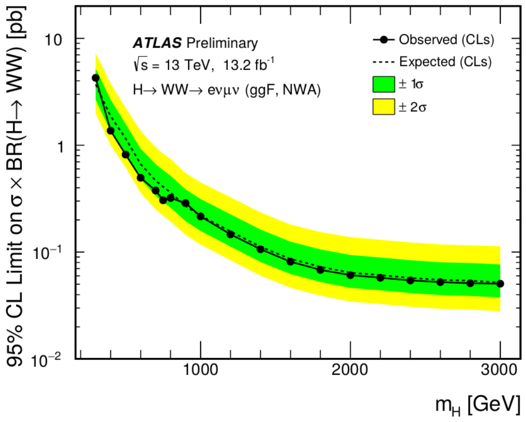
Top CR in VBF2J



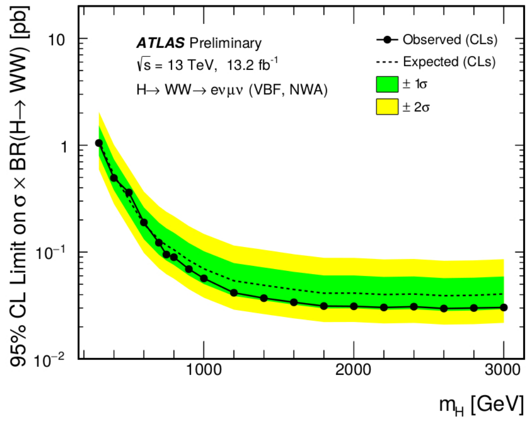
- **Systematic uncertainies**
  - **Experimental**: jet-energy scale, b-tagging efficiency, lepton reconstruction and identification, MET.
  - **Theoretical**:Impact or missing higher-order correction, PDF variation in MC modelling.

Results

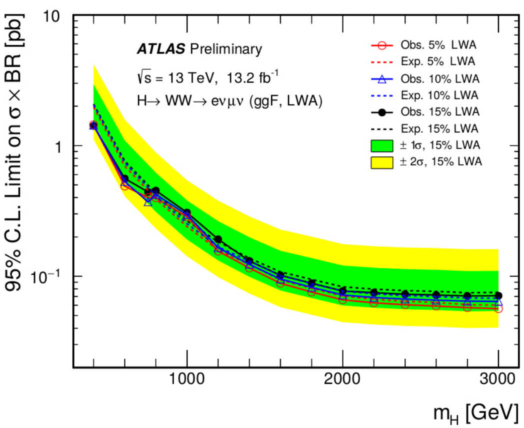
- Limits are obtained separately for ggF and VBF in NWA signal hypothesis
- Only for ggF in the LWA hypothesis.



(a) NWA, ggF



(b) NWA, VBF



(c) LWA, ggF

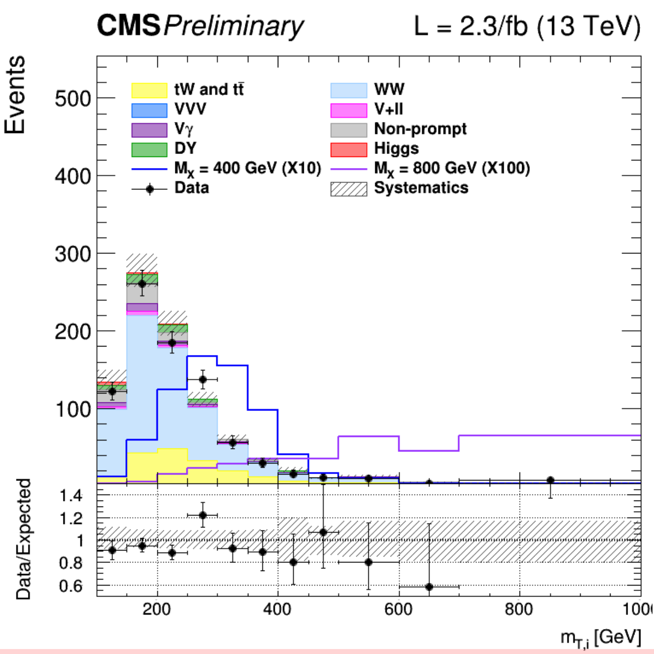
- Values above 4.3 pb at 300 GeV and 0.051 pb at 3 TeV are excluded in NWA for ggF.
- Values above 1.4 pb at 400 GeV and 0.071 pb at 3 TeV are excluded in LWA (15%) for ggF.
- The limits don't depend to width hypothesis.

High-Mass Higgs boson in CMS

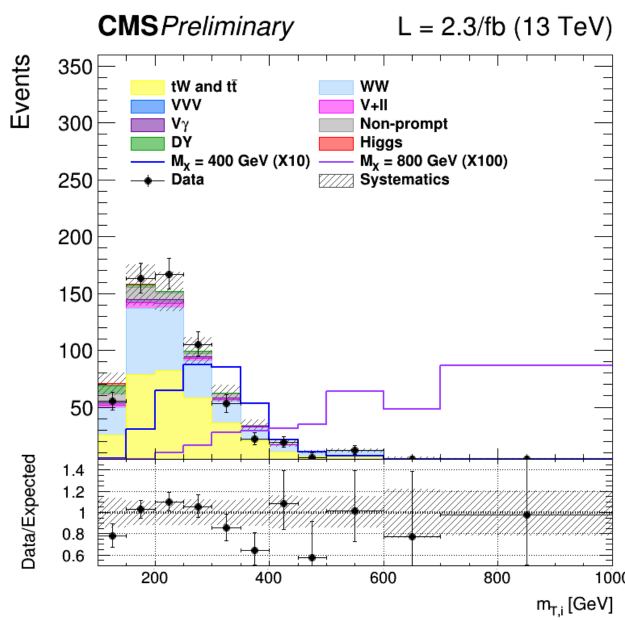
CMS PAS HIG-16-023

- $m_{T,i}$ allows a better distinction among different signal mass hypothesis than m_T^H

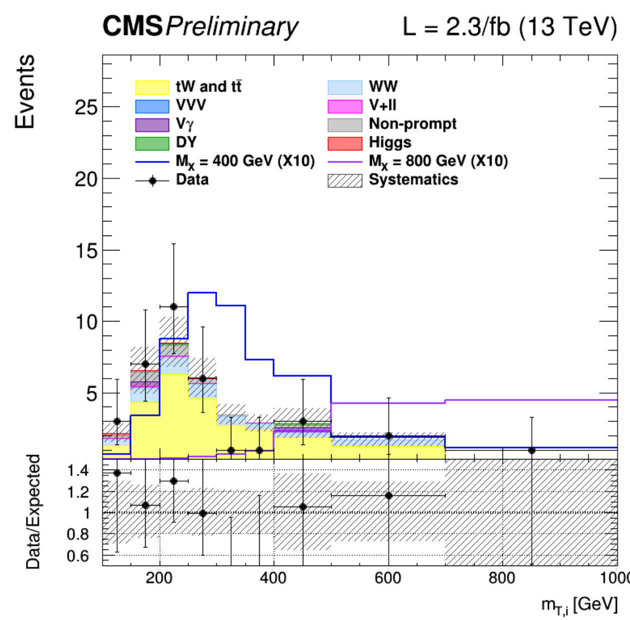
0 jet



1 jet

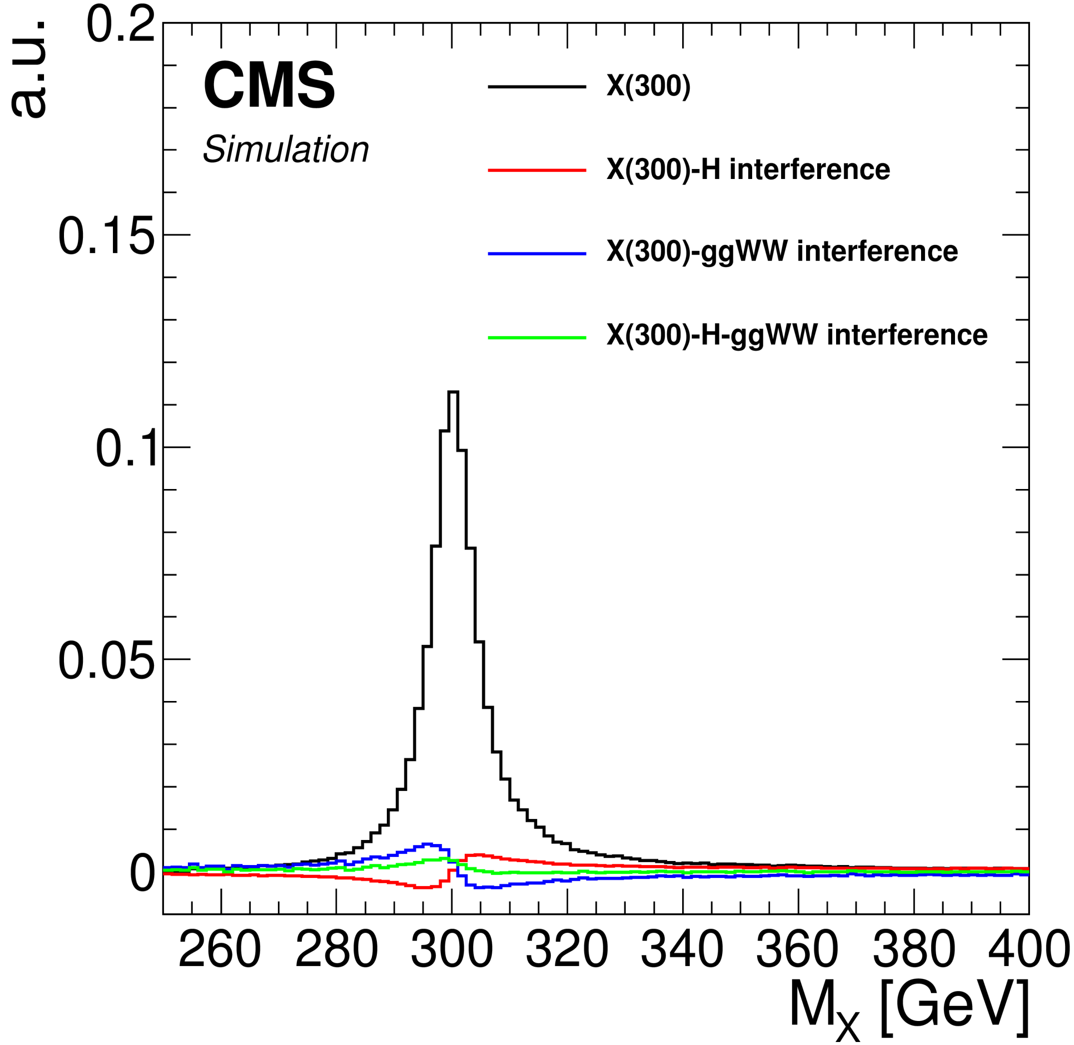


VBF



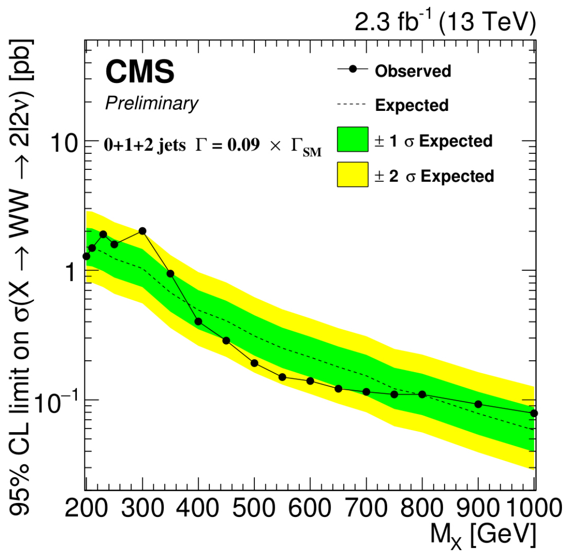
Signal model and Interference

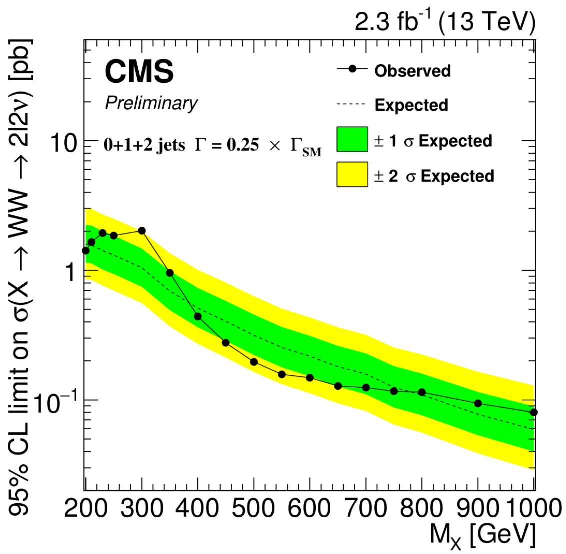
- The signal model includes the terms of interference between the gg→X→WW and the gg→WW processes, as well as the term that arises from the interference with the off-shell tail of the gg→H→WW contribution. The two interference terms partially **cancel out** and the total contribution is ~1-10% with respect to the signal.

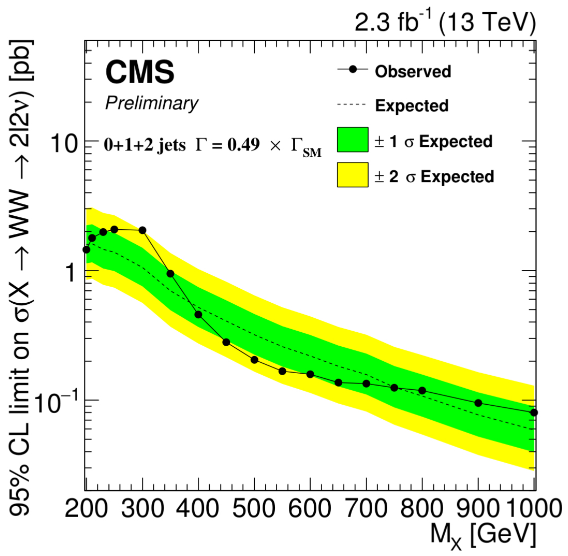


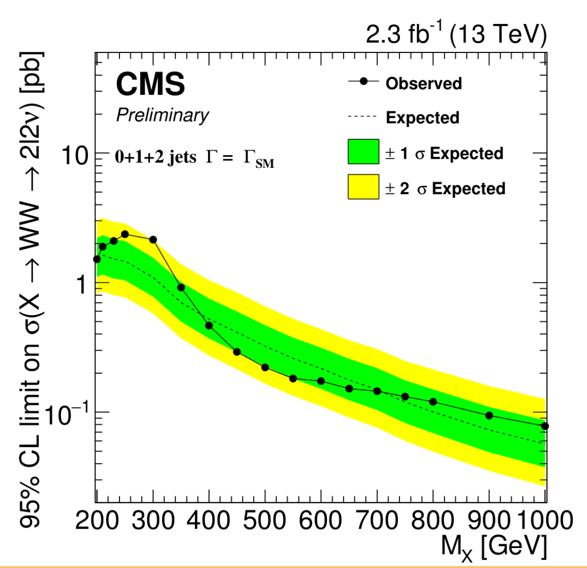
Expected and observed limits

- Expected and observed exclusion limit for the combination of the three jets categories for different widths. The limits don't depend to width hypothesis.
- No significant excess with respect to the SM background has been observed.









Conclusion

- Studies on the Higgs boson properties are essential to understand the nature of the Higgs boson.
  - ATLAS preliminary results with $\mathcal{L}$= 5.8 fb^{-1} for VBF and WH production mode.
  - CMS preliminary results with $\mathcal{L}$= 12.9 fb^{-1} for ggF, VBF and WH production mechanisms.

  - ATLAS RUN-I $\mu_{VBF+VH}= 1.56\,^{+0..52}_{-0.46}$, Run-II $\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$ $\mu_{WH} = 3.2^{+3.7}_{-3.2}(\mathrm{stat})^{+2.3}_{-2.7}(\mathrm{sys})$

  - CMS Run-I $\mu = 0.90^{+0.23}_{-0.21}$

    Run-II 1.05±0.26 (0.25 ± 0.03 (theory) ± 0.07 (systematic))

    CMS results in Run-I and Run-II are very similar.

- All measurements are in agreement with the SM prediction.
- Stay tuned for full 2016 statistics results.

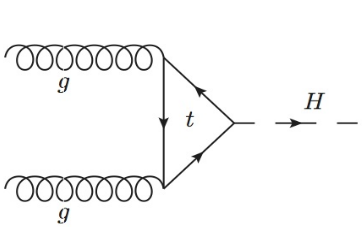
Conclusion

- The high-mass Higgs boson like particle search is important to confirm/deny the SM prediction.
- Preliminary ATLAS and CMS analsis.
    - Similar results between ATLAS and CMS with Run-II data.
    - New results coming soon.

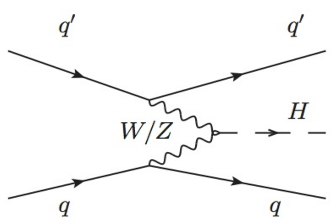
backup

The Higgs boson in the Standard Model

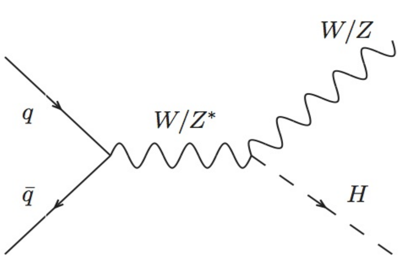
Higgs boson production processes



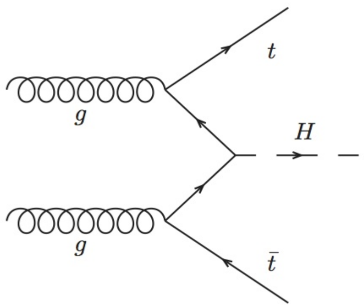
ggH 48.58 pb



qqH 3.78 pb



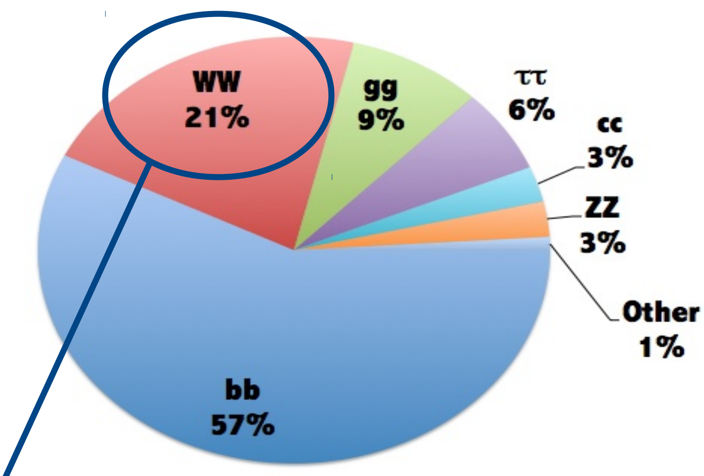
WH+ZH 2.38 pb



ttH+bbH 1.0 pb

xsec @ 13 TeV

Higgs boson decays



WW channel has the second largest **Branching Ratio** and a reasonable level of irreducible background.

SM Higgs boson in ATLAS

ATLAS-CONF-2016-112

$$\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$$
$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(\mathrm{stat})^{+2.3}_{-2.7}(\mathrm{sys})$$

Since the contribution of the ggF production process to the background in the VBF analysis is not negligible, the impact of a beyond-SM contribution to ggF production on the μ_{VBF} result has been assessed. A scan of μ_{VBF} as a function of μ_{ggF} was performed changing μ_{ggF} up and down by one hundred percent, i.e. from the SM $\mu_{\mathrm{ggF}} = 1$ to $\mu_{\mathrm{ggF}} = 0$ or to $\mu_{\mathrm{ggF}} = 2$. This results in a variation of μ_{VBF} of 25% which is well below the precision of the given measurement.

The measured signal strength, μ_{VBF} (μ_{WH}), can be used to evaluate the product $\sigma_{\mathrm{VBF}(WH)} \cdot \mathcal{B}_{H\to WW^*}$ for the VBF (associated WH) production mode, respectively. The central value is the product of μ and the predicted cross section used to define it. The uncertainties are similarly scaled, except for the theoretical uncertainties related to the total predicted signal yield, which do not apply to this measurement. Since these uncertainties are small compared to leading uncertainties in both signal strength measurements, the cross sections are calculated to be:

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 1.4^{+0.8}_{-0.6}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})\ \mathrm{pb}$$

$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.9^{+1.1}_{-0.9}(\mathrm{stat})^{+0.7}_{-0.8}(\mathrm{sys})\ \mathrm{pb}$$

SM Higgs boson in ATLAS

ATLAS-CONF-2016-074

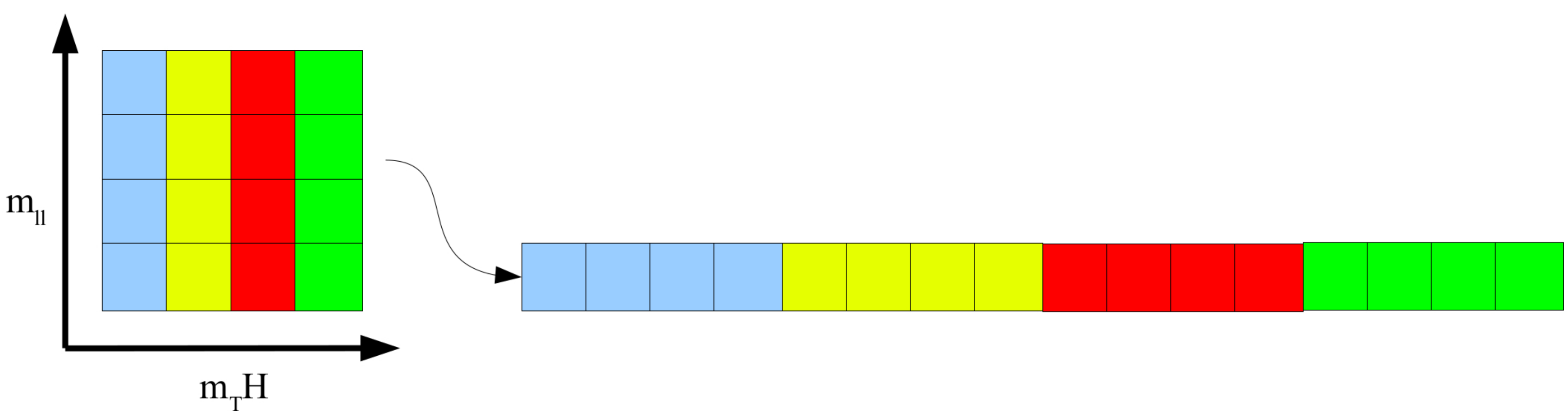
Table 1: Selection cuts used in the ggF and VBF signal regions. The VBF1J phase space corresponds to $N_{\text{jet}} = 1$, $|\eta_j| > 2.4$ and $\min(|\Delta\eta_{j\ell}|) > 1.75$ while the VBF2J phase space corresponds to $N_{\text{jet}} \geq 2$, $m_{jj} > 500$ GeV and $|\Delta y_{jj}| > 4$. These sets of cuts ensure the orthogonality with respect to the SR_{ggF} category.

SR_{ggF}	SR_{VBF1J}	SR_{VBF2J}
Preselection cuts: $p_{\text{T}}^{\text{lead}} > 25$ GeV, $p_{\text{T}}^{\text{sublead}} > 15$ GeV, 3rd lepton veto, $m_{\ell\ell} > 10$ GeV		
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55$ GeV $p_{\text{T}}^{\text{lead}} > 45$ GeV $p_{\text{T}}^{\text{sublead}} > 30$ GeV $\max(m_{\text{T}}^{W}) > 50$ GeV		
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{\text{jet}} = 1$ $\lvert\eta_j\rvert > 2.4$ $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{\text{jet}} \geq 2$ $m_{jj} > 500$ GeV $\lvert\Delta y_{jj}\rvert > 4$

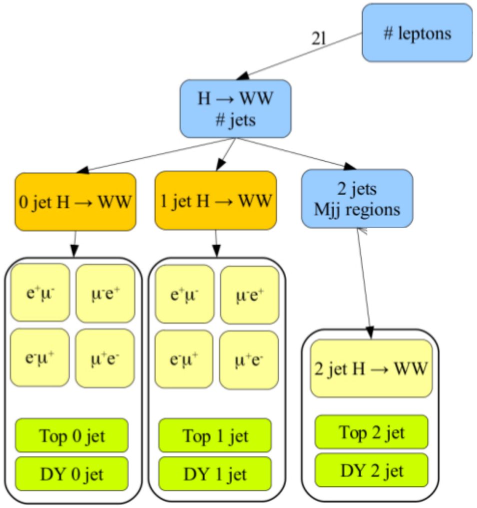
SM Higgs boson in CMS

CMS PAS HIG-16-021

To extract the Higgs boson signal a binned fit is performed using 2-D distributions of the and $\mathbf{m}_T^H$ for signal and all backgrounds processes in four categories.



Gluon Fusion categories



- Gluon fusion phase space is split in jets-number. Due to low statatistic the 2-jet case is not split in charge-flavour.
- The invariant mass of the Higgs boson can not be reconstructed (neutrinos presence): is introduced the Higgs transverse mass.

$$m_T^H = \sqrt{2 p_T^{\ell\ell} E_T^{\text{miss}} (1 - \cos \Delta\phi(\ell\ell, \vec{E}_T^{\text{miss}}))},$$

- Strategy of selection:

Preselection

$m_{\ell\ell} > 12 GeV$, $p_{T1} > 25 GeV$, $p_{T2} > 10(13) GeV$ for μ(ele),
$E_T^{\text{miss}} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $p_{T3} < 10$ GeV
electron and muon with opposite charge

0-jet

$m_T^H > 60$ GeV, $m_T^{H\ell 2-met} > 30$ GeV
no b-jets with p_T between 20 and 30 GeV

1-jet

$m_T^H > 60$ GeV, $m_T^{H\ell 2-met} > 30$ GeV
no b-jets with $p_T > 20$ GeV

2-jet (orthogonal to VBF and VH)

at least 2 jets
$m_T^{H\ell 2-met} > 30$ 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

SM Higgs boson in CMS

CMS PAS HIG-16-021

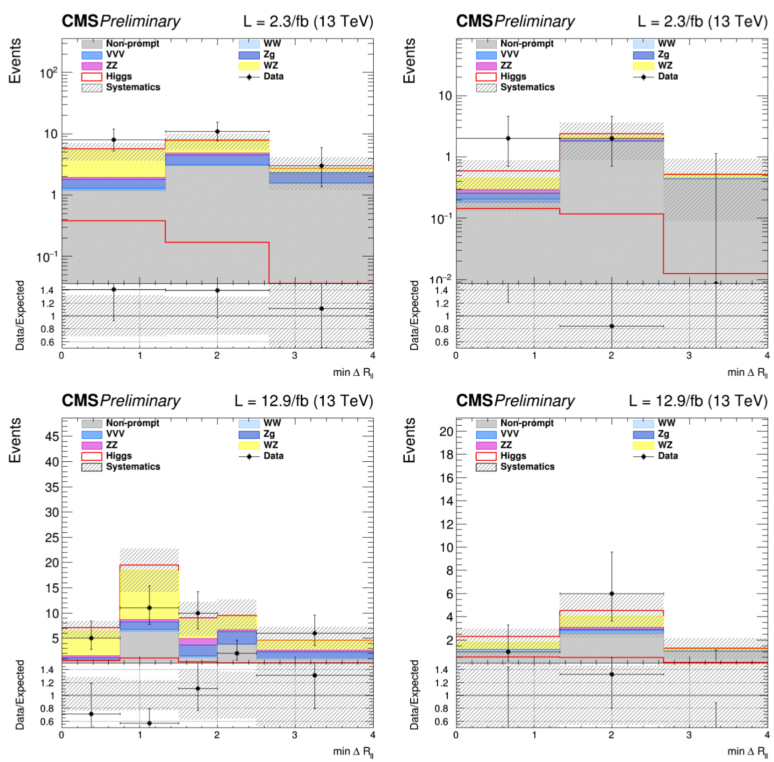
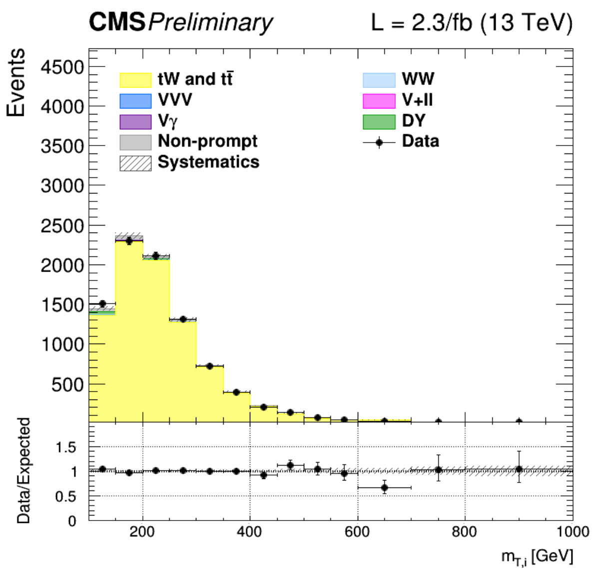


Figure 8: ΔR template for OSSF (left) and SSSF (right) event categories for 2015 (upper row) and 2016 (lower row) data.

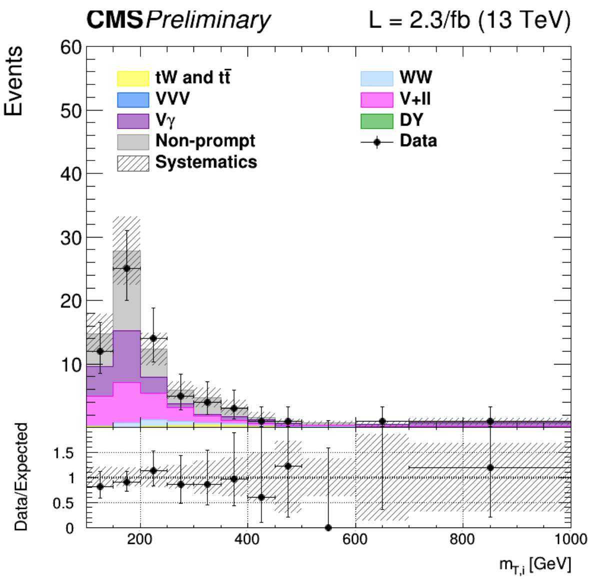
Backgrounds estimation

- **Non-resonant WW**: populates the entire phase space in $m_{T,i}$, while the high-mass signal is concentrated at high values of this variables (especially for m_{Sig} >400 GeV).



- **Top**: backgrounds estimation performed in two steps.
  -SF is computed to take in account the b-tag efficiencies and mistagging rate in data and MC.
  -Top cross-section normalization with data using data-driven approach.

- **Jet induced**: events with W+jets when a jet is misidentified as a lepton. This background is relevant at low leptons p_T.



- **Drell Yan**: the normalization of the simulated sample is estimated in data and the normalization SFs are extracted.