UNIVERSITÀ DEGLI STUDI FIRENZE

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
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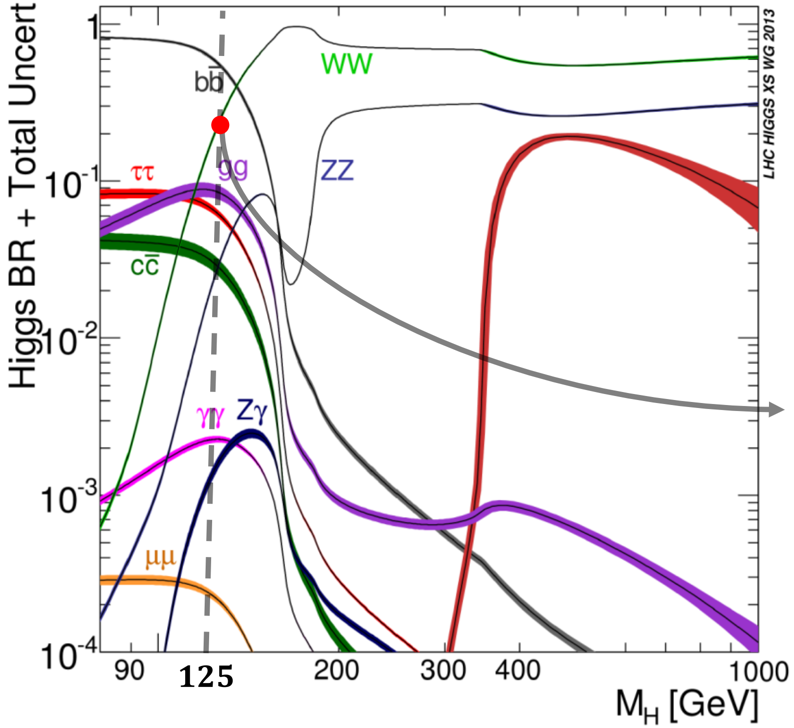
Recent $H \to WW$ results using CMS data

MATTIA LIZZO – UNIVERSITÀ DEGLI STUDI DI FIRENZE

On behalf of the CMS Collaboration

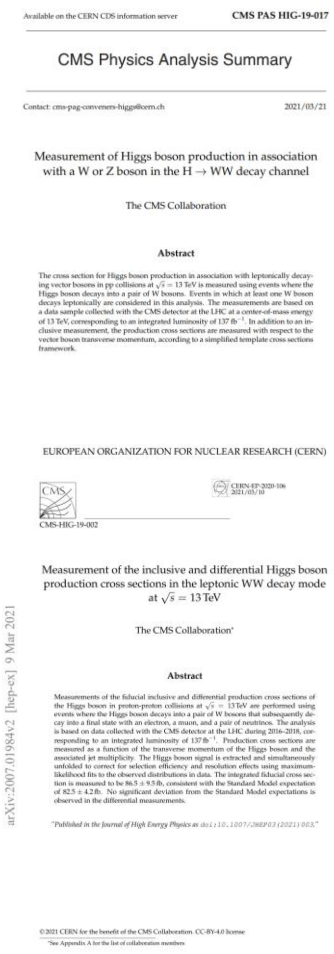
Introduction

- The $H \rightarrow WW$ decay channel is suitable for measuring rare Higgs production modes and differential cross sections
- Several Higgs boson's properties in this channel have been extensively studied with $\sqrt{s} = 13$ TeV results in CMS-HIG-16-042



Second most probable BR ($M_H = 125$ GeV)

RESULTS COVERED


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

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-HIG-19-002

Measurement of the inclusive and differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

CMS-PAS-HIG-19-017

- *Measurement of Higgs boson production in association with a W or Z boson in the $H \rightarrow WW$ decay channel*

CMS-HIG-19-002

- *Measurements of differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s} = 13$ TeV*

HIG-19-017

Motivation

- HIG-19-017 targets the $VH(H \rightarrow W^{+}W^{-})$ production mode, also known as $Higgs - stralhung$, where only associated vector bosons decaying leptonically are considered $(V \rightarrow leptons)$

- This process provides a direct probe to measure the coupling of the Higgs boson to vector bosons and is particularly sensitive to possible BSM operators, thus being an important test for the SM Higgs sector

- For the extreme rarity of this channel, the analysis benefits from the use of the full Run2 CMS data set $(137\ \mathrm{fb}^{-1})$ although the error on this measurement is still dominated by the statistical component

4 final states are considered:

- $WH \rightarrow 2\ell 2\nu qq\ (WHSS)$
- $WH \rightarrow 3\ell 3\nu\ (WH3\ell)$
- $ZH \rightarrow 3\ell \nu qq\ (ZH3\ell)$
- $ZH \rightarrow 4\ell 2\nu\ (ZH4\ell)$

$\otimes$ **2 results**

- **Inclusive cross section** (as a signal strength modifier $\hat{\mu}$)
- **STXS** (**S**implified **T**emplate **XS**ection)

Main backgrounds

- Background contamination strongly depends on the considered final state, defined by different number of leptons and jets

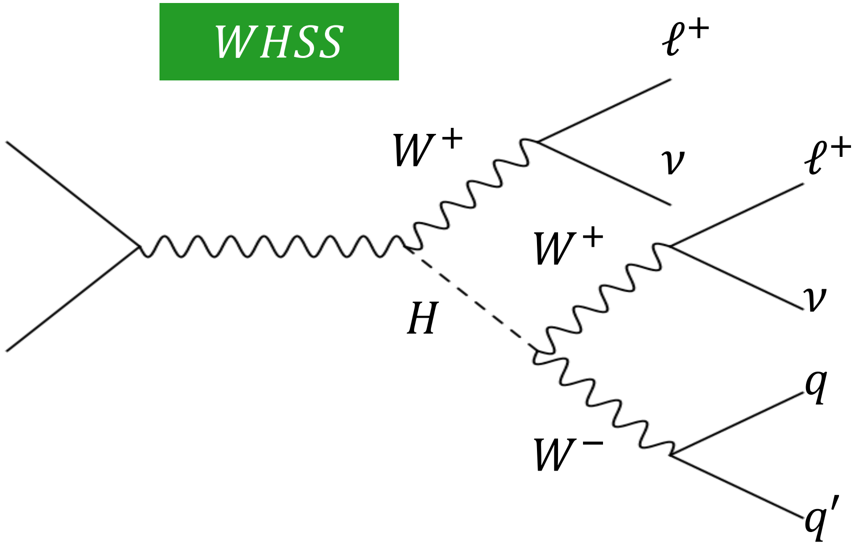
- Di-boson production mechanisms such as $WZ,\ Z\gamma(Z\gamma^{*})$ and ZZ are directly measured in data through dedicated control regions

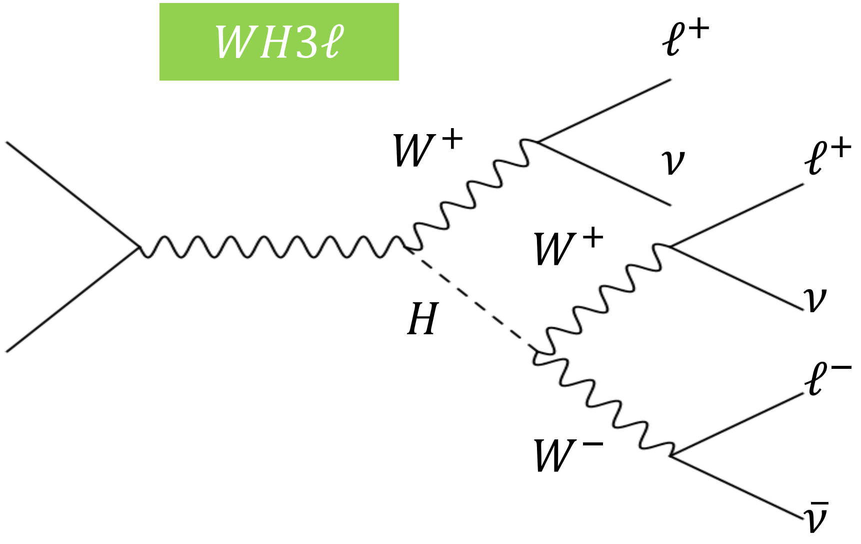
- Non prompt leptons are also estimated from data, applying a transfer function to loose leptons that do not pass the tight isolation and identification criteria of the analysis. Such events mainly originate from leptonic decays of heavy hadrons and are primarily due to:

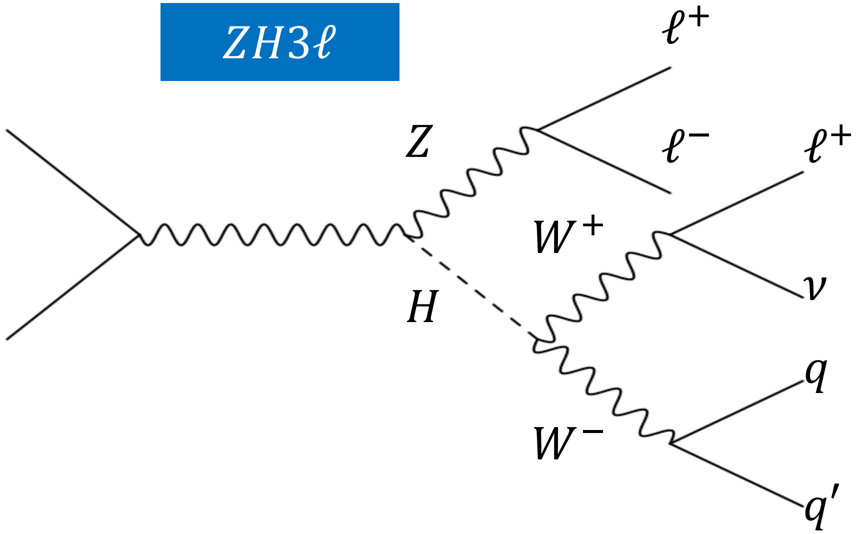
  - $W + jets$ in 2ℓ channel
  - $Z + jets$ in 3ℓ channel
  - Negligible in 4ℓ channel

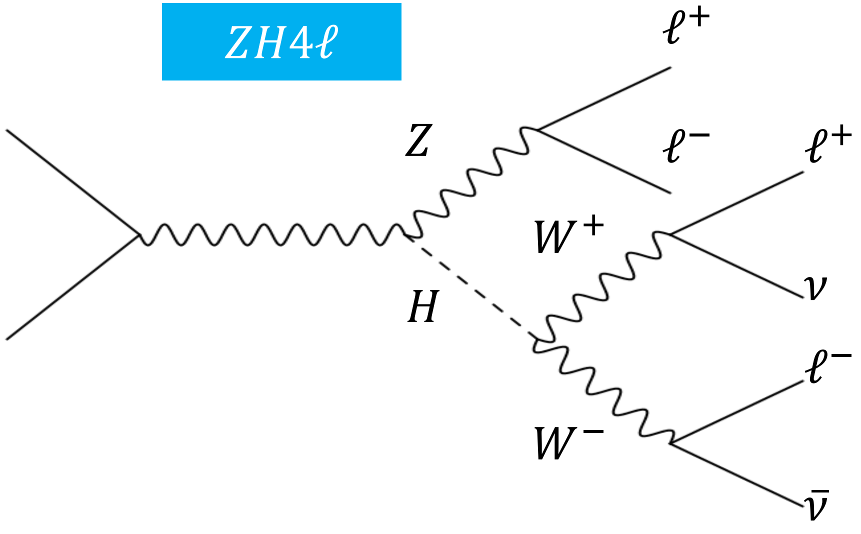
- Other minor backgrounds $(t\bar{t} + tW, DY, WW, VVV \ldots)$ are estimated from MC simulation

Analysis strategy – Inclusive XSec

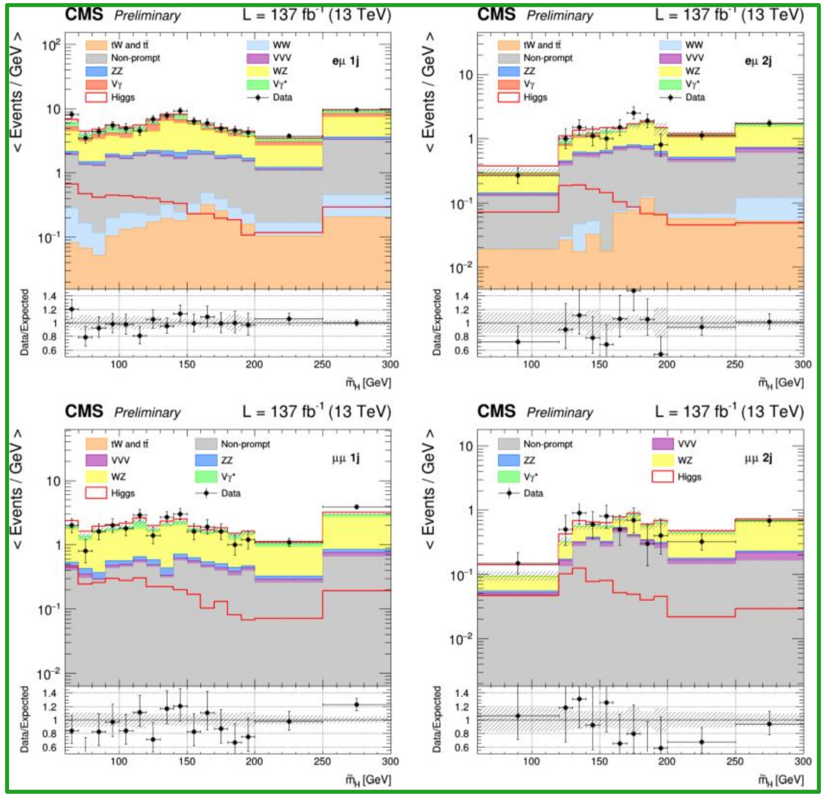








Signal extraction – Inclusive XSec



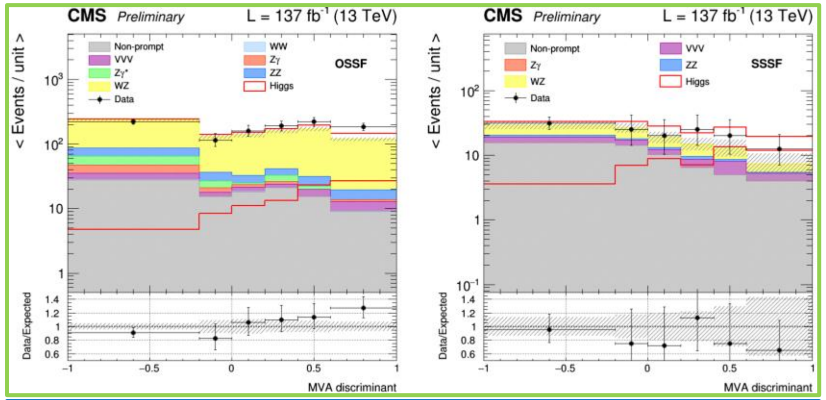
$WHSS$

$$\widetilde{m}_H{}^2 \equiv (p_{jj} + 2p_\ell)^\mu (p_{jj} + 2p_\ell)_\mu$$

- It serves as a proxy of the Higgs mass ($2p_\ell$ mimics $p_\ell + p_\nu$)

$WH3\ell$

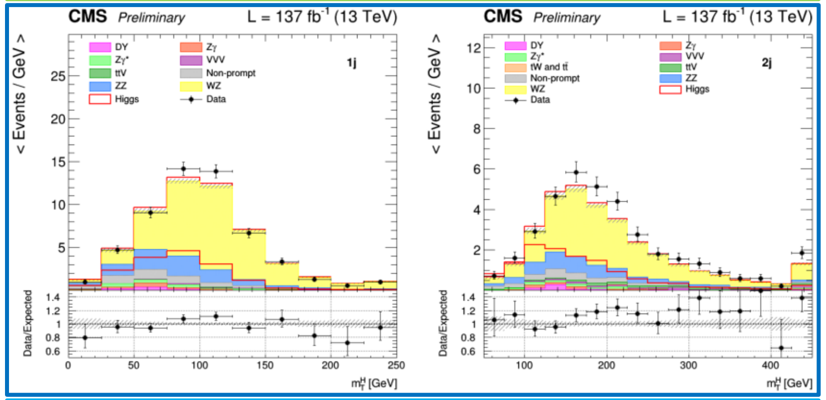
An MVA discriminant is fitted in the SR, trained from a BDT algorithm



$ZH3\ell$

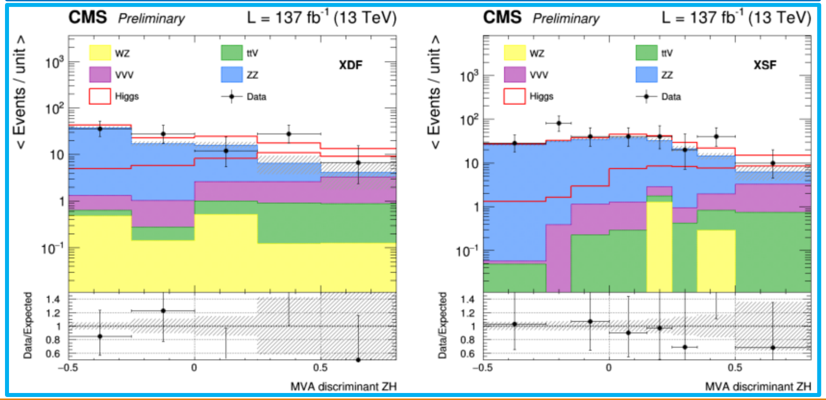
$$m_T^H \equiv m_T(p_\ell + p_T^{miss}, p_{j(j)})$$

- It represents the transverse mass between the 2 W bosons, i.e. is the Higgs transverse mass

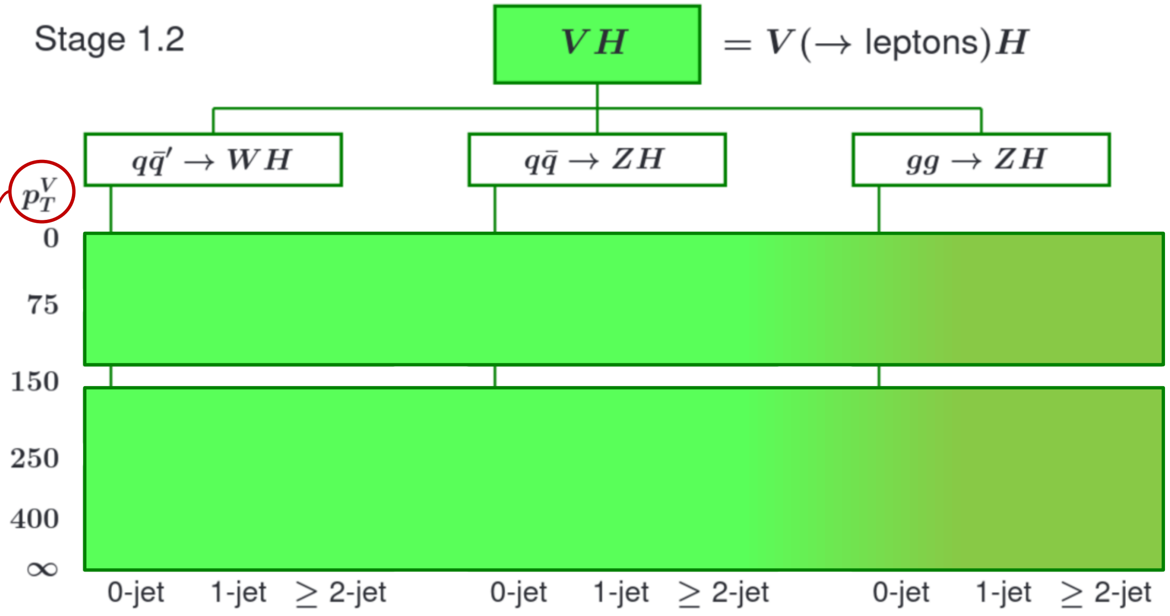


$ZH4\ell$

An MVA discriminant is fitted in the SR, trained from a BDT algorithm



Signal extraction – STXS



WH channel:

$$\vec{p}_T^{\,W} \equiv \vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu}$$

$$\vec{p}_T^{\,\nu} \equiv \vec{p}_T^{\,miss} - \vec{p}_T^{\,\nu,H} \simeq \vec{p}_T^{\,miss} - \vec{p}_T^{\,\ell,H}\left(\frac{125}{||\vec{p}^{\,\ell}+\vec{p}^{\,jj}||} - 1\right)$$

ZH channel:

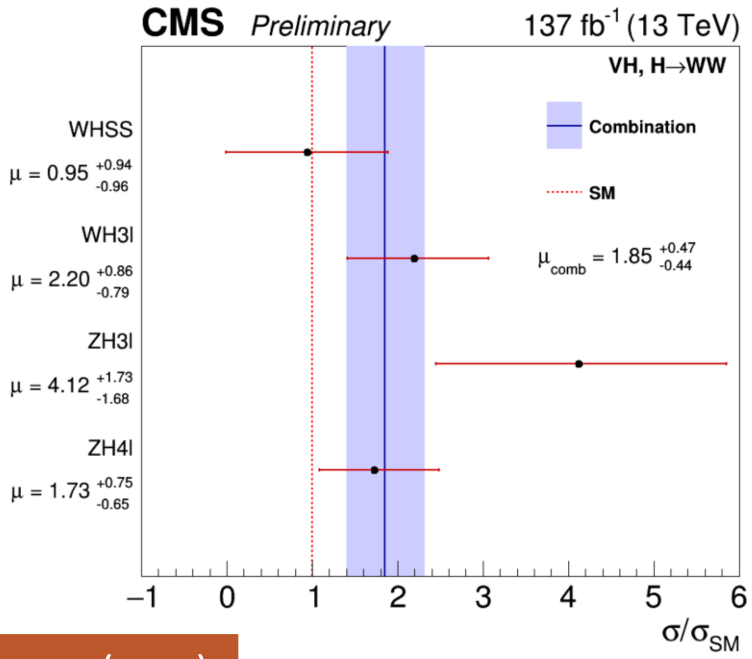
$$\vec{p}_T^{\,Z} \equiv \vec{p}_T^{\,\ell^\pm} + \vec{p}_T^{\,\ell^\mp}\text{, with } m^Z_{\ell^\pm\ell^\mp} \simeq m_Z$$

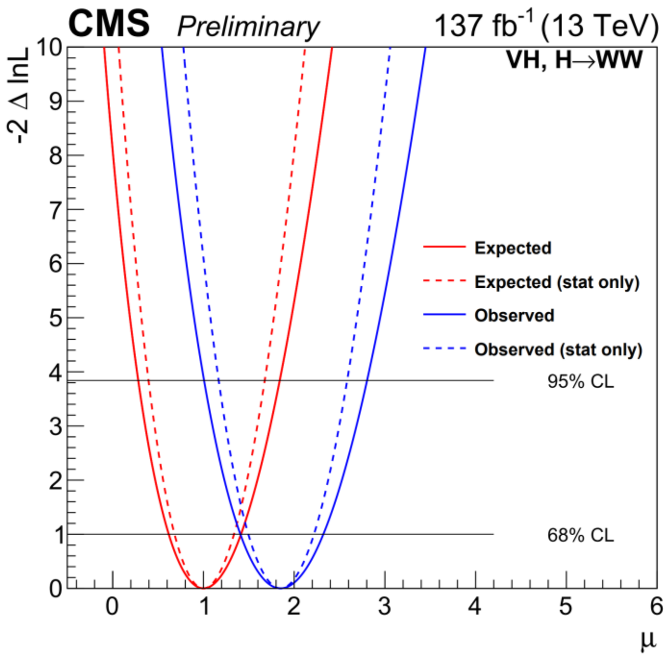
- The **STXS** framework has been developed as an evolution of signal strength measurements
- Its purpose is to provide pre-defined kinematic bins to measure Higgs production modes and reduce theoretical uncertainties
- In the $VH(H \to WW)$ analysis only two bins have been considered due to the limited statistical precision of this channel

The fit procedure used to extract the STXS binned cross section uses same background CRs, SR categorization and discriminating observables as those of the inclusive measurement

Results – Inclusive XSec

- The signal strength modifier $\hat{\mu}$ is extracted by a simultaneous fit to all categories
- The fit assumes that the relative rates of the different Higgs boson's production mechanisms are as the SM ones
- An additional fit has been performed scaling the signal process with a different signal strength modifier in each category



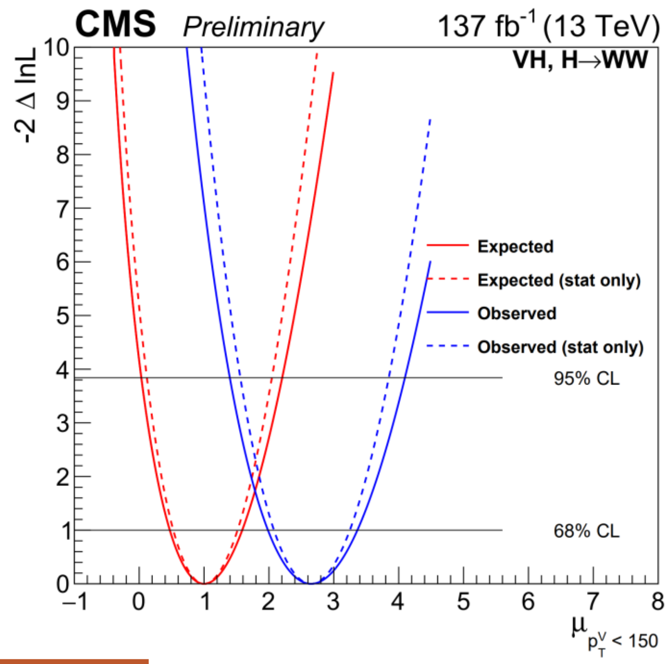


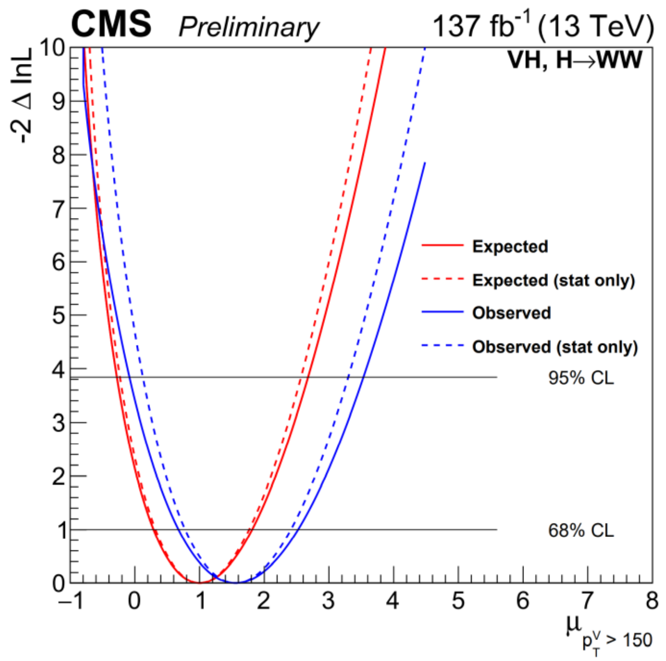
	$\hat{\mu}$	Significance (exp.)
$WHSS$	$0.95^{+0.94}_{-0.96}$	$1.0\ \sigma\ (1.1\ \sigma)$
$WH3\ell$	$2.20^{+0.86}_{-0.79}$	$3.0\ \sigma\ (1.6\ \sigma)$
$ZH3\ell$	$4.12^{+1.73}_{-1.68}$	$2.5\ \sigma\ (0.6\ \sigma)$
$ZH4\ell$	$1.73^{+0.75}_{-0.65}$	$3.1\ \sigma\ (2.1\ \sigma)$
Combination	$1.85^{+0.47}_{-0.44}$	$4.7\ \sigma\ (2.8\ \sigma)$

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

Results – STXS

- The signal strength modifier $\hat{\mu}$ is extracted by a simultaneous fit to all categories
- All production modes are scaled together in the $H \to WW$ channel assuming SM relative rates, while the $H \to \tau\tau$ decay is kept fixed to its SM cross section
- An additional fit has been performed scaling each VH production mode with a different signal strength modifier in each $p_T^V \gtrless 150$ GeV bin





	$\hat{\mu}$	Significance (exp.)
$WH\ p_T^W < 150$ GeV	$1.5^{+1.0}_{-0.9}$	$1.64\ \sigma\ (1.24\ \sigma)$
$WH\ p_T^W > 150$ GeV	$3.6^{+1.8}_{-1.6}$	$2.23\ \sigma\ (0.83\ \sigma)$
$ZH\ p_T^Z < 150$ GeV	$3.4^{+1.1}_{-1.6}$	$4.37\ \sigma\ (1.59\ \sigma)$
$ZH\ p_T^Z > 150$ GeV	$0.8^{+1.2}_{-0.9}$	$0.83\ \sigma\ (1.18\ \sigma)$

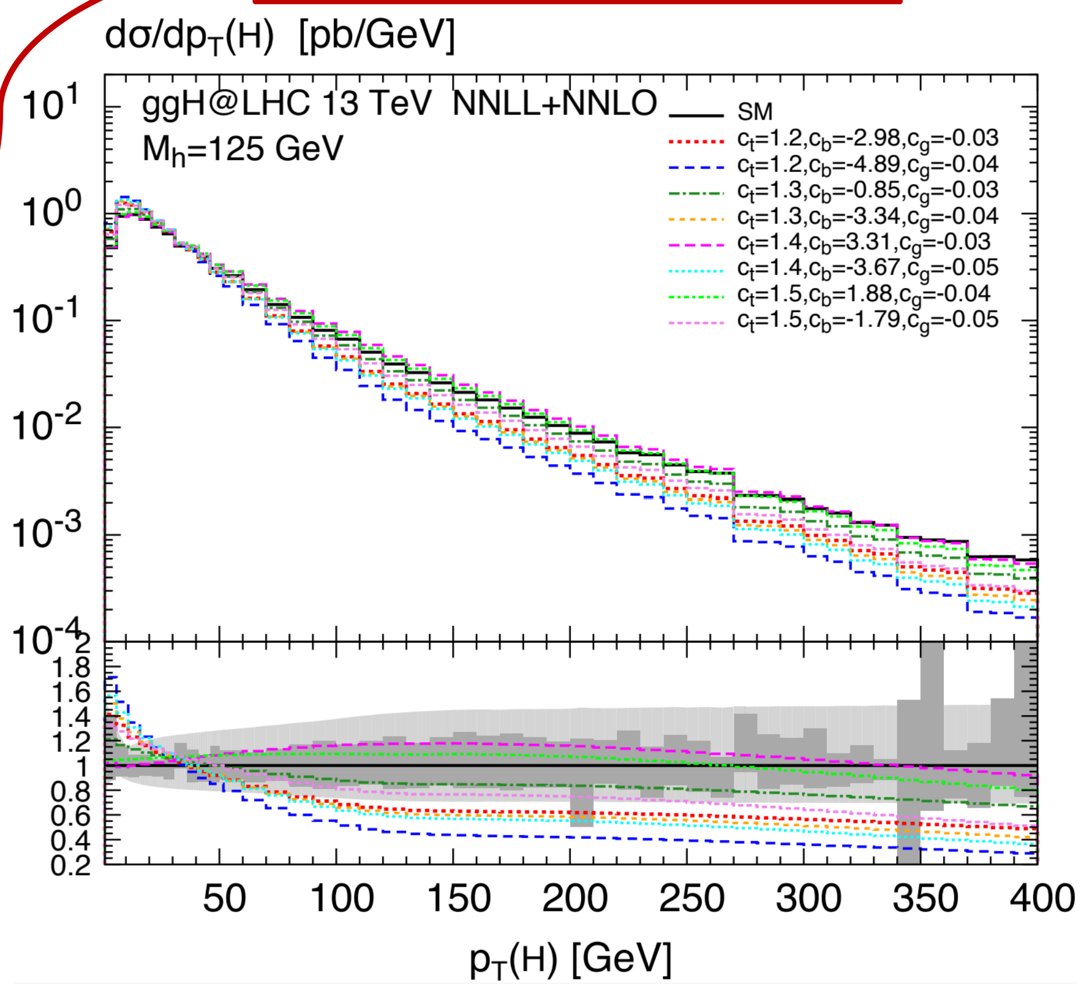
$$\hat{\mu}_{p_T^V < 150GeV} = 2.65^{+0.57}_{-0.55}(stat)^{+0.38}_{-0.32}(exp)^{+0.08}_{-0.07}(theo)$$
$$\hat{\mu}_{p_T^V > 150GeV} = 1.56^{+0.85}_{-0.77}(stat)^{+0.43}_{-0.40}(exp)^{+0.11}_{-0.09}(theo)$$

HIG-19-002

Motivation

- **Differential production cross section** for the Higgs boson can be predicted theoretically with high precision, such as $\frac{d\sigma}{dp_T^H}$ and $\frac{d\sigma}{dN_{jets}}$
- Variations of the Higgs boson's couplings to quarks and to other gauge bosons w.r.t. SM values may be observed through p_T^H spectrum
- $\sigma(pp \to H + N_{jets})$ is sensitive to relative contributions from different production modes per jet bin

Indirect search for new physics

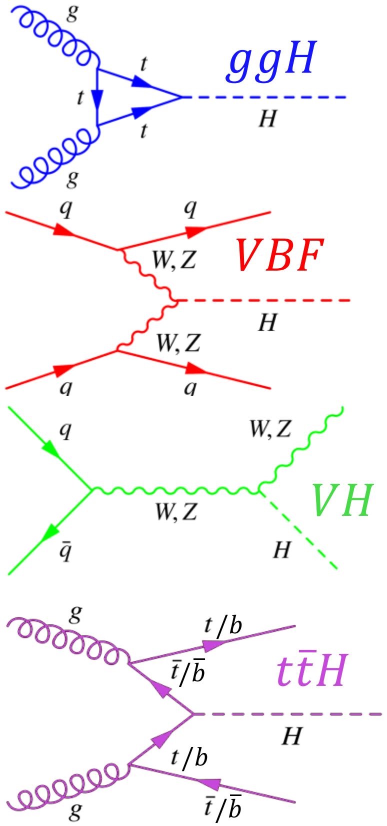


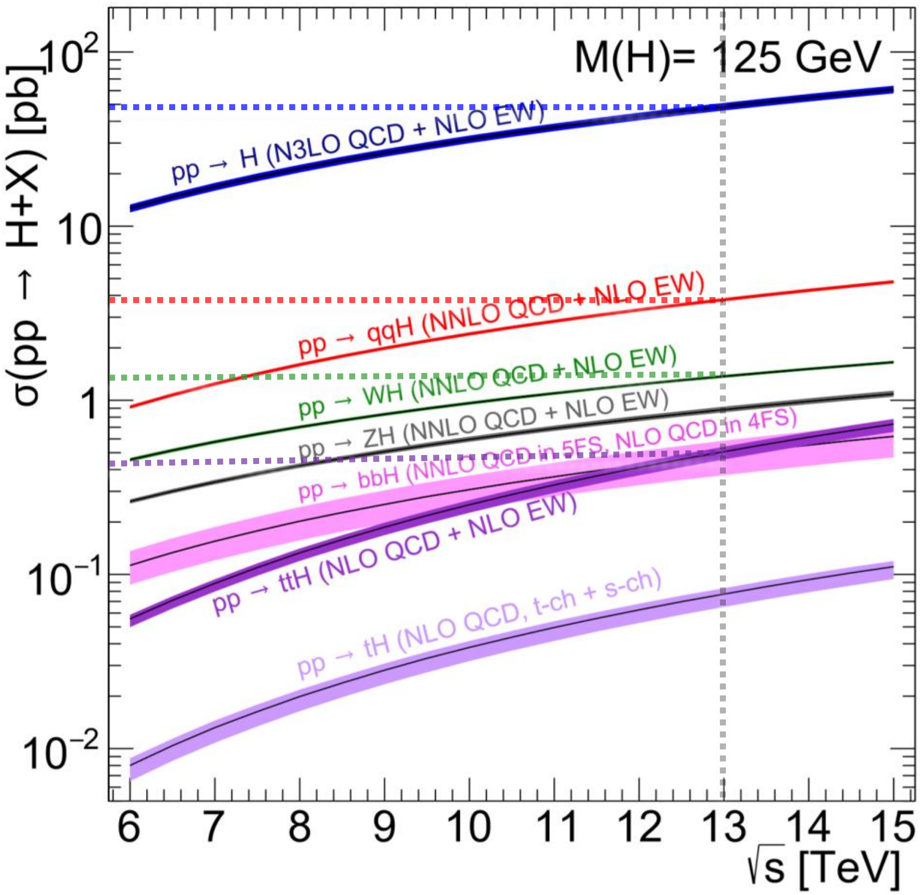
$H \to WW$ has enough statistics to tackle all the main production mechanisms

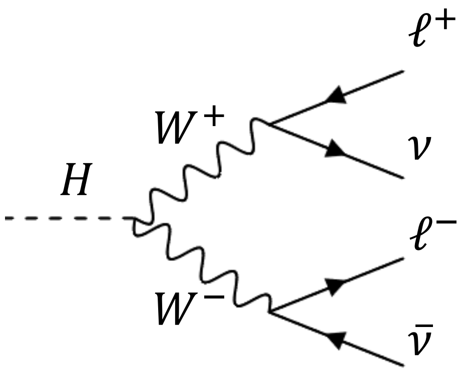
Signal candidates are binned in p_T^H and N_{jets}, which are referred to as **differential basis observables**

$H \to WW \to 2\ell 2\nu$

- **Fully leptonic final state** is the cleanest channel to detect the Higgs signal



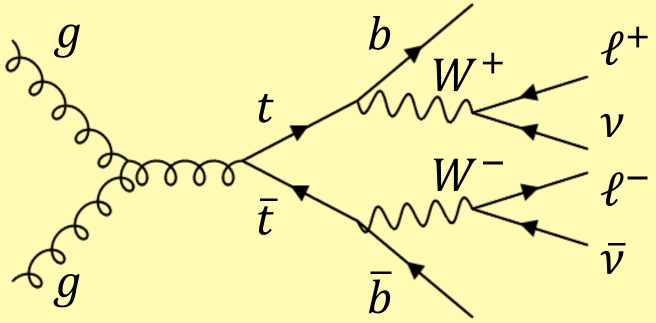




- **2 isolated leptons $(e\mu)$ with opposite charge**
- **Leptons emitted close to each other (spin correlation with the Higgs boson)**
- **Large signal yield and relatively clean signature**
- ***MET* presence due to the escaping neutrinos (Higgs mass is not reconstructed)**

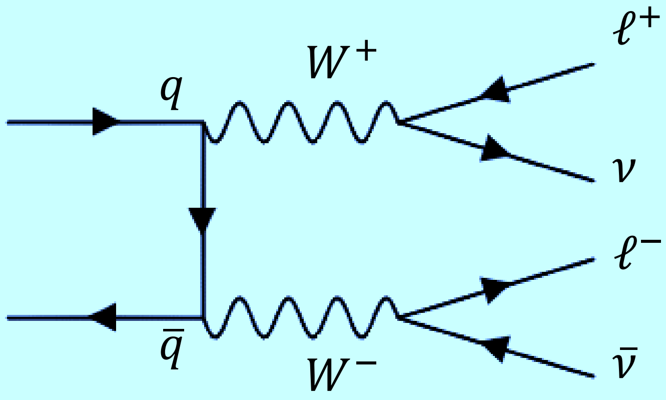
Main backgrounds

$t\bar{t}$ pair production



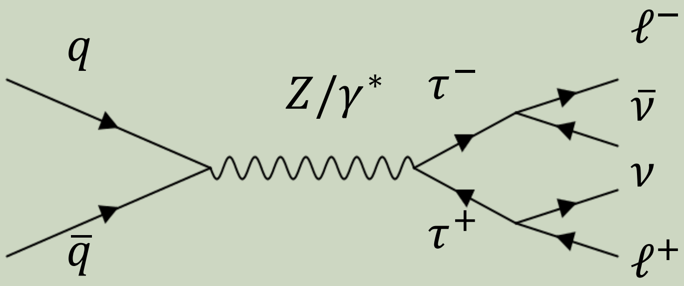
- Large cross section
- b-veto applied
- Normalization taken from data

Non-resonant W^+W^-



- No spin correlation
- Different kinematics
- Normalization taken from data

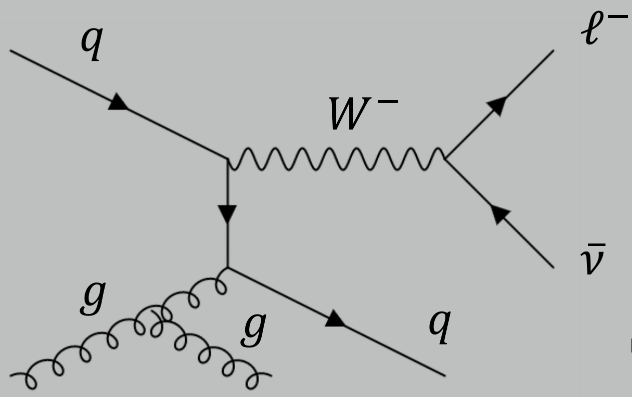
Drell-Yan $\tau^+\tau^-$



- Suppresed with $m_T > 60$ GeV $(*)$
- Normalization taken from data

$(*)\ m_T = \sqrt{2p_T^{\ell\ell}p_T^{miss}[1-\cos\Delta\phi(\vec{p}_T^{\ell\ell},\vec{p}_T^{miss})]}$

Non-prompt leptons



- Jet misidentified as a lepton
- Mainly comes from $W + jets$ events
- Fake rate estimated from data

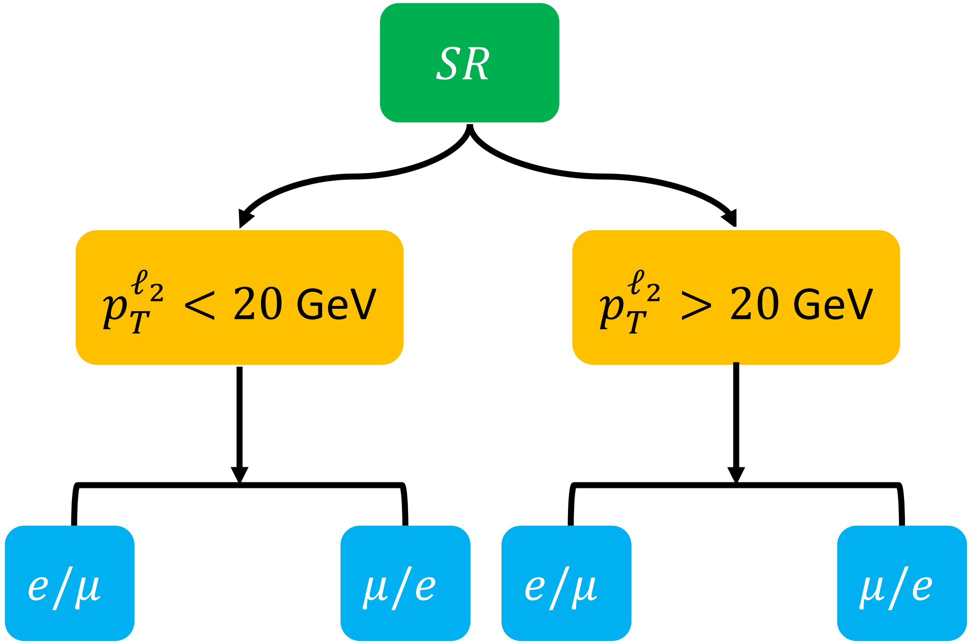
Analysis strategy

PRE-SELECTION:

- 2 opposite charged leptons $(e\mu)$
  $p_T^{\ell_1} > 25$ GeV, $p_T^{\ell_2} > 13$ GeV
- $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV
- Third lepton veto

- Signal candidates are selected applying the pre-selection and further cuts on top of that
  - $m_T > 60$ GeV
  - $m_T^{\ell_2} > 30$ GeV
  - No b-tagged jets

All Higgs production modes are regarded as signal processes



$\boldsymbol{N_{jets}}$ binning:
$[0, 1, 2, 3, \geq 4]$

$\boldsymbol{p_T^H}$ binning:
$[0, 20, 45, 80, 120, 200, \infty]$

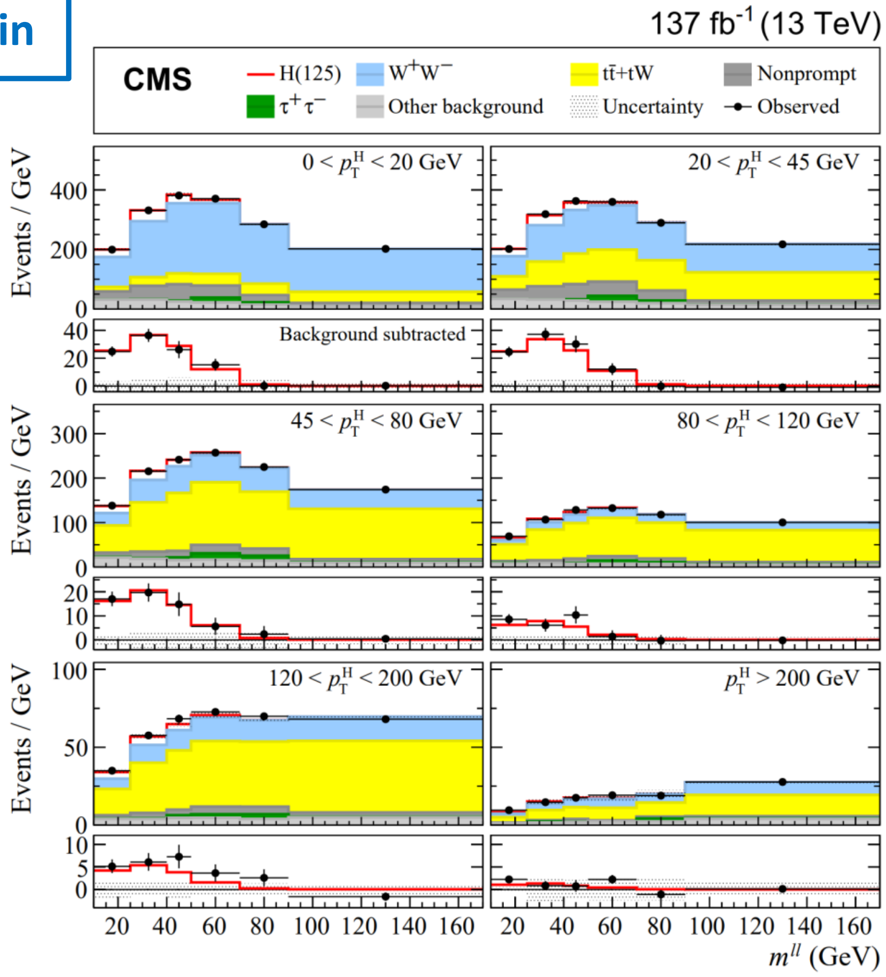
Categories are merged in high p_T^H and N_{jets} bins due to lack of statistics

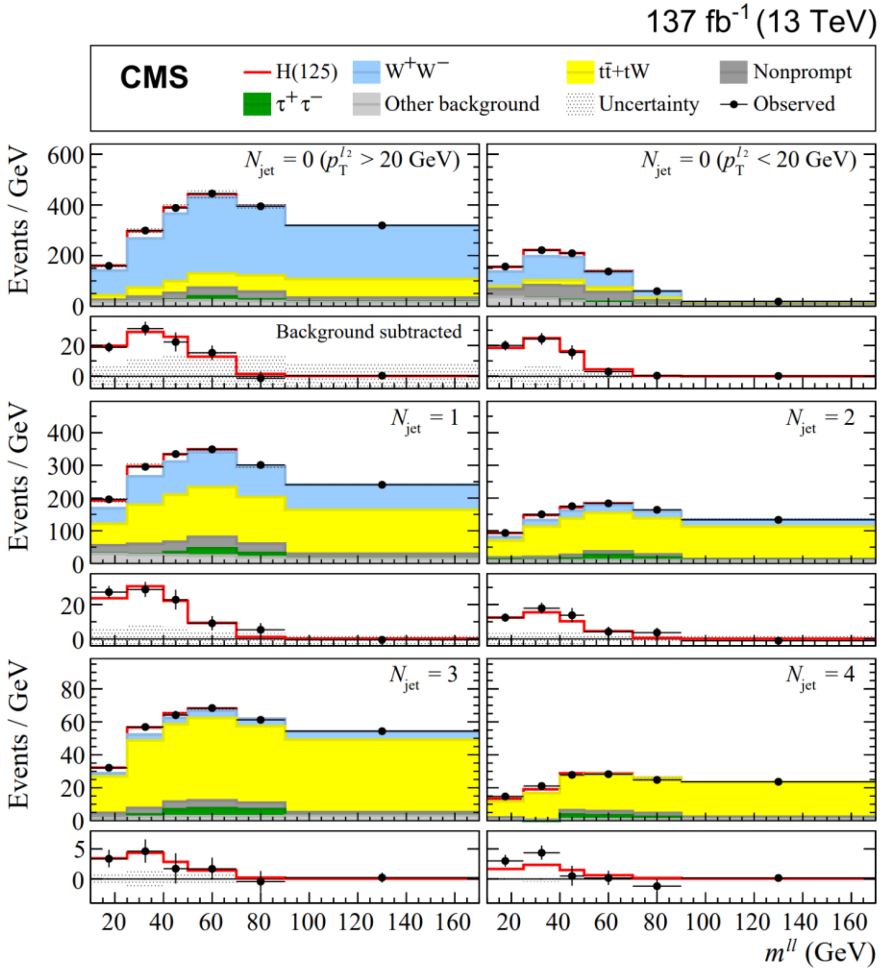
Post-fit distributions

2D $(m_{\ell\ell}, m_T)$ histrogram is fitted to data in each N_{jets} and p_T^H bin

- $m_{\ell\ell}$ distribution is obtained integrating over all the m_T range and combining full Run2 dataset

- The Higgs signal is measured in a fiducial phase space, defined with a similar selection as the one of the ggH-tagged category





Correlation matrices

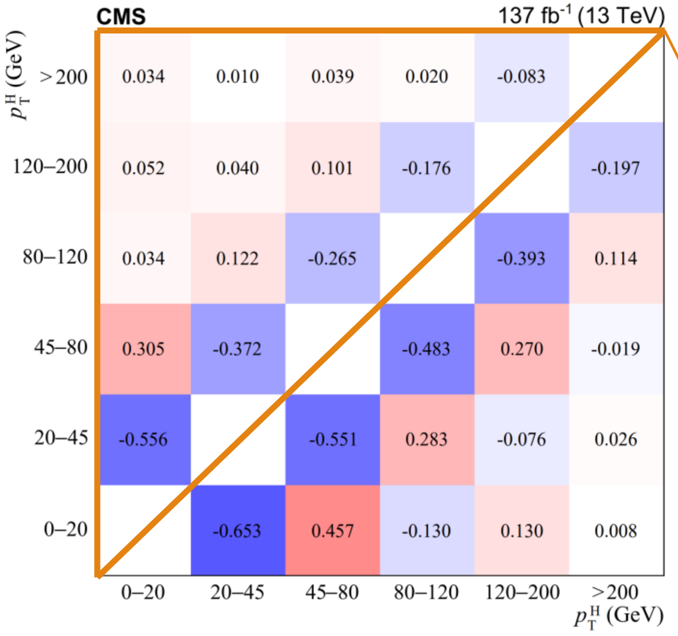
- These matrices quantify correlation between signal strength modifiers in the fiducial phase space

- Each element has been extracted by the fit to the full Run2 combined data sets (integrated luminosity 137 fb^{-1})

REGULARIZATION TERM

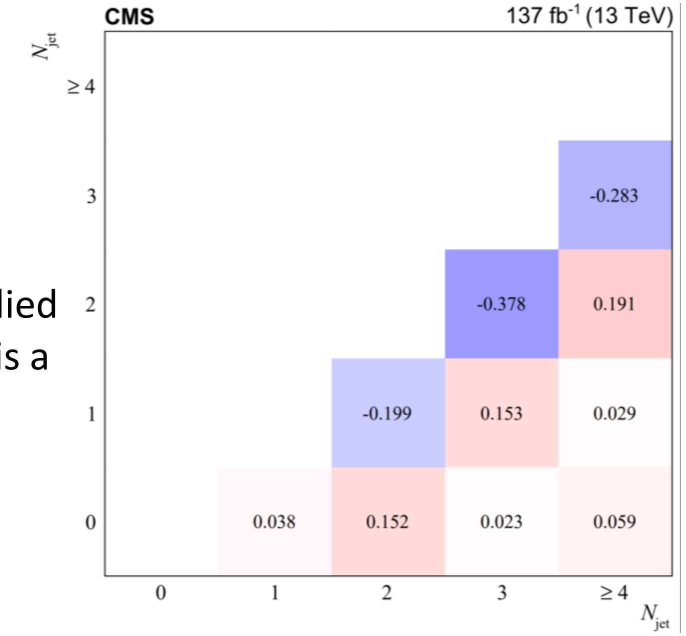
$$\mathcal{K}(\vec{\mu}) = \prod_i \exp\left(-\frac{[(\mu_{i+1}-\mu_i)^2-(\mu_i-\mu_{i-1})^2]}{2\delta^2}\right)$$

- δ is called the **regularization strength** parameter and controls the intensity of the regularization procedure

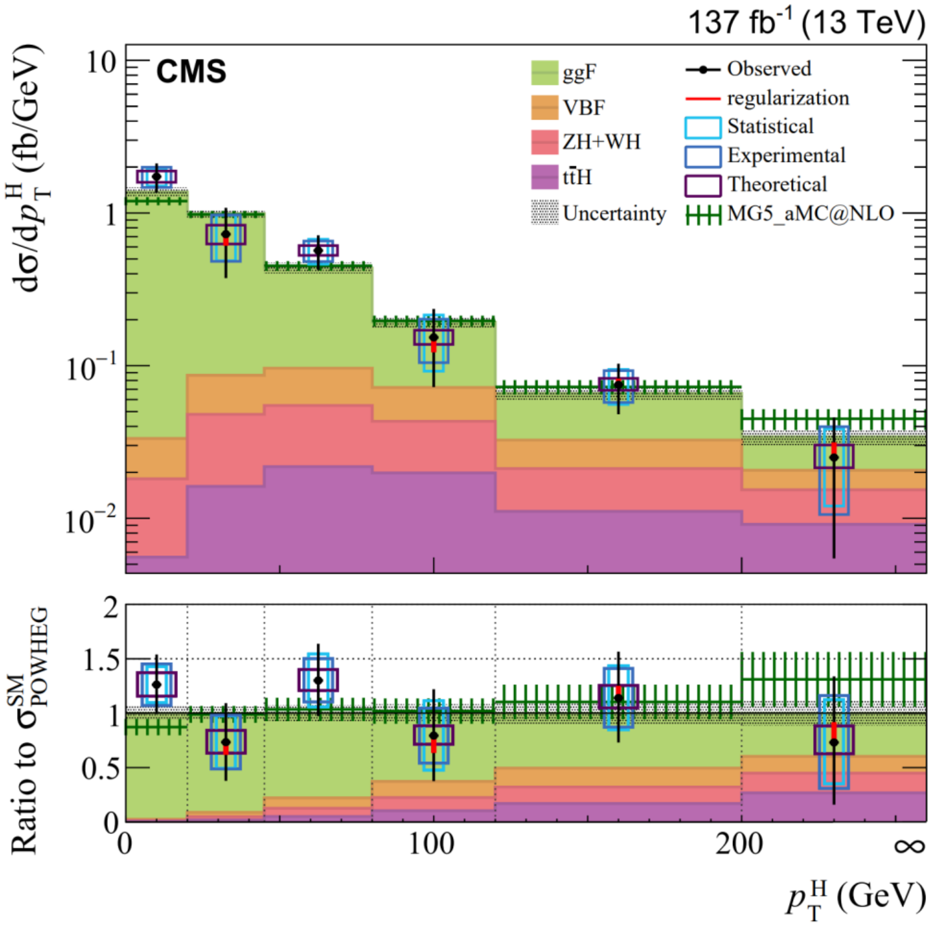


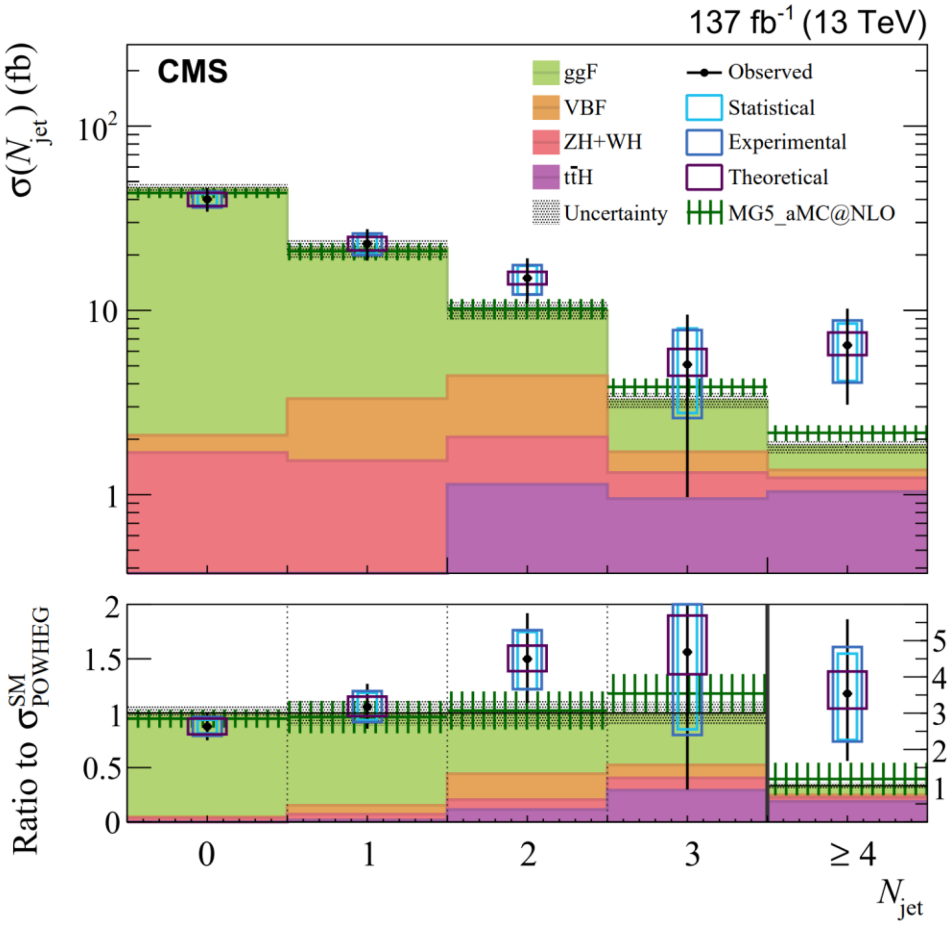
The p_T^H correlation matrix above the diagonal shows the effect of the regularization procedure: $\boldsymbol{\delta = 2.50}$ has been found minimizing the mean of the global correlation coefficient

No regularization has been applied to the N_{jet} distribution since it is a discrete variable



Results – unfolded distributions





$\mu^{fid} = 1.05 \pm 0.12\ (\pm 0.05(\text{stat}) \pm 0.07(\text{exp}) \pm 0.01(\text{signal}) \pm 0.07(\text{bkg}) \pm 0.03(\text{lumi}))$

$\sigma^{fid} = 86.5 \pm 9.5$ fb **consistent with** $\sigma^{SM} = 82.5 \pm 4.2$ fb

Conclusions

- **The $H \rightarrow WW$ decay channel** led to important results using Run2 CMS data
- **Higgs boson production in association with either a W or Z boson** has been measured, quoting both the **inclusive cross section** (as a signal strength modifier) and the **STXS measurement**
- Results are consistent with SM predictions within 2σ
- **Differential cross section measurement** w.r.t. Higgs transverse momentum and number of associated hadronic jets have been performed
- **Signal strength modifiers** have been measured at generator level using a regularized unfolding procedure and no deviations from SM have been observed
- **More analyses** are currently ongoing and brand new results with full Run2 CMS data are expected to give more insight on the Higgs boson properties

BACKUP

VH strategy – Inclusive XSec

$WH \to 2\ell 2\nu qq$ ($WHSS$)

$p_T^{\ell_1} > 25$ GeV ; $p_T^{\ell_2} > 20$ GeV ; $p_T^{\ell_3} < 10$ GeV

$m_{\ell\ell} > 12$ GeV ; $\Delta\eta_{\ell\ell} < 2$

$b-jet\ veto$

$p_T^{miss} > 30$ GeV ; $\widetilde{m}_H > 50$ GeV

$1j\ e\mu\ SR$	$\geq 2j\ e\mu\ SR$
$1\ jet\ \ p_T > 30$ GeV	$\geq 2\ jets\ p_T > 30$ GeV $m_{jj} < 100$ GeV

$1j\ \mu\mu\ SR$	$\geq 2j\ \mu\mu\ SR$
$1\ jet\ p^T > 30$ GeV $\lvert m_{\ell\ell} - m_Z \rvert > 15$ GeV	$\geq 2\ jets\ p^T > 30$ GeV $\lvert m_{\ell\ell} - m_Z \rvert > 15$ GeV $m_{jj} < 100$ GeV

$WH \to 3\ell 3\nu$ ($WH3\ell$)

$p_T^{\ell_1} > 25$ GeV ; $p_T^{\ell_2} > 20$ GeV ; $p_T^{\ell_3} > 15$ GeV ; $p_T^{\ell_4} < 10$ GeV

$q(\ell\ell\ell) = \pm 1$; $\min(m_{\ell\ell}) > 12$ GeV

$b-jet\ veto$

$no\ jet\ with\ p^T > 30$ GeV

$\ell^+\ell^-\ SF\ SR$	$\ell^\pm\ell^\pm\ SF\ SR$
$\lvert m_{\ell\ell} - m_Z \rvert > 20$ GeV $p_T^{miss} > 40$ GeV	

$0j\ WZ\ CR$	$Z\gamma\ CR$
$\ell^+\ell^- pair$; $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV $p_T^{miss} > 45$ GeV $m_{\ell\ell\ell} > 100$ GeV	$\ell^+\ell^- pair$; $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV $p_T^{miss} < 40$ GeV 80 GeV $< m_{\ell\ell\ell} < 100$ GeV

VH strategy – Inclusive XSec

$ZH \to 3\ell\nu qq\ (ZH3\ell)$

$p_T^{\ell_1} > 25$ GeV ; $p_T^{\ell_2} > 20$ GeV ; $p_T^{\ell_3} > 15$ GeV ; $p_T^{\ell_4} < 10$ GeV

$q(\ell\ell\ell) = \pm 1$; $\min(m_{\ell\ell}) > 12$ GeV

$b - jet\ veto$

$|m_{\ell\ell} - m_Z| < 25$ GeV ; $|m_{\ell\ell\ell} - m_Z| > 20$ GeV

$1j\ SR$	$\geq 2j\ SR$
$1\ jet\ \ p_T > 30$ GeV	$\geq 2\ jets\ p_T > 30$ GeV
$\Delta\phi(W, j(j)) < \pi/2$	$\Delta\phi(W, j(j)) < \pi/2$

$1j\ WZ\ CR$	$\geq 2j\ WZ\ CR$
$1\ jet\ p_T > 30$ GeV	$\geq 2\ jets\ p_T > 30$ GeV
$\Delta\phi(W, j(j)) > \pi/2$	$\Delta\phi(W, j(j)) > \pi/2$

$ZH \to 4\ell 2\nu\ (ZH4\ell)$

$p_T^{\ell_1} > 25$ GeV ; $p_T^{\ell_2} > 20$ GeV ; $p_T^{\ell_3}, p_T^{\ell_4} > 10$ GeV ; $p_T^{\ell_5} < 10$ GeV

$q(\ell\ell\ell\ell) = 0$; $\min(m_{\ell\ell}) > 12$ GeV

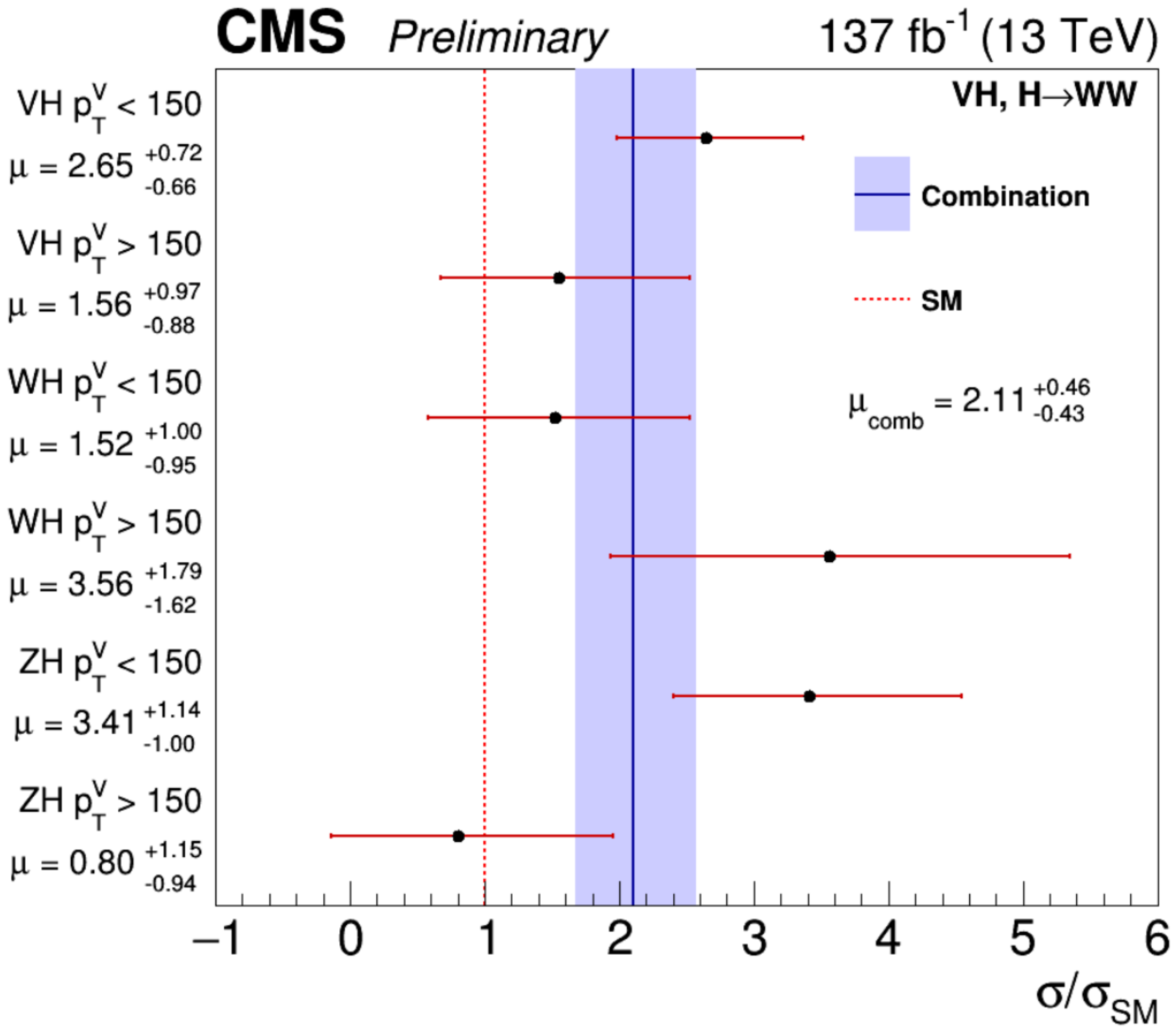
$b - jet\ veto$

$|m_{\ell\ell}^Z - m_Z| < 15$ GeV

$XSF\ SR$	$XDF\ SR$
$m_{\ell\ell\ell\ell} > 140$ GeV	$10\text{ GeV} < m_{\ell\ell}^X < 70$ GeV
$10\text{ GeV} < m_{\ell\ell}^X < 60$ GeV	$p_T^{miss} > 20$ GeV
$p_T^{miss} > 35$ GeV	

$ZZ\ CR$
$75\text{ GeV} < m_{\ell\ell}^X < 105$ GeV
$p_T^{miss} < 35$ GeV

VH analysis - STXS results



Signal composition – VH analysis

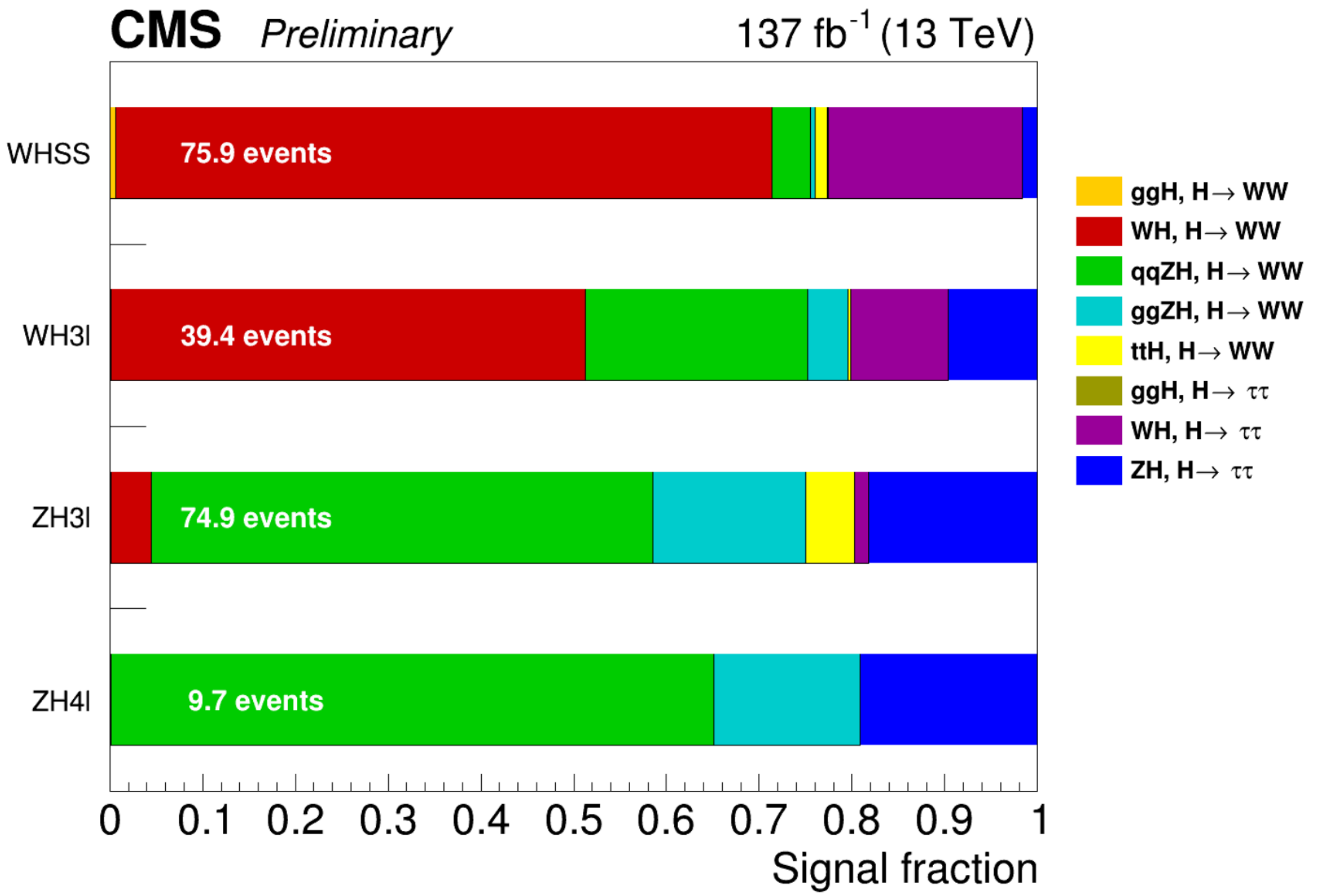
- Different signal composition in each category

$$WH(H\to WW) + WH(H\to\tau\tau) \simeq 95\%$$
$$ZH(H\to WW) + ZH(H\to\tau\tau) \simeq 5\%$$
$$other < 1\%$$

$$WH(H\to WW) + WH(H\to\tau\tau) \simeq 60\%$$
$$ZH(H\to WW) + ZH(H\to\tau\tau) \simeq 40\%$$
$$other \ll 1\%$$

$$WH(H\to WW) + WH(H\to\tau\tau) \simeq 5\%$$
$$ZH(H\to WW) + ZH(H\to\tau\tau) \simeq 90\%$$
$$other \simeq 5\%$$

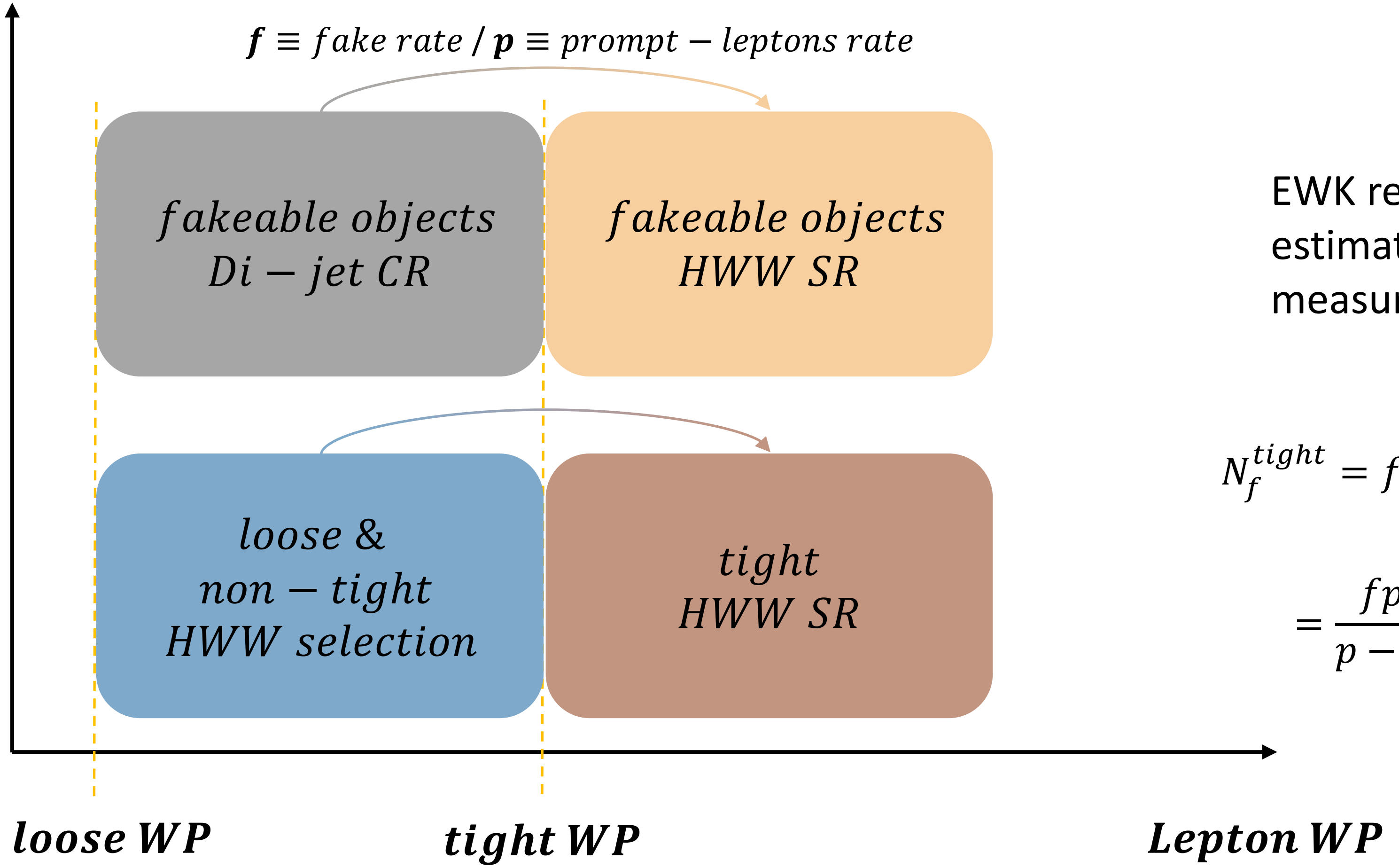
$$WH(H\to WW) + WH(H\to\tau\tau) \ll 1\%$$
$$ZH(H\to WW) + ZH(H\to\tau\tau) \simeq 100\%$$
$$other \ll 1\%$$



- The fit is performed scaling all production modes with a unique signal strength, i.e. assuming SM relative rates

Non-prompt leptons estimation

- The estimation of the non-prompt lepton contribution (or *fake leptons*) is based on the "fakeable object" method data-driven technique, with no applicability restrictions: the basic idea is to estimate this background in a dedicated CR and then extrapolate it to the signal region with the usage of a transfer function



EWK residual contribution in the dijet CR is estimated in MC samples and also used to measure the **prompt leptons rate**

$$N_f^{tight} = f \times N_f^{loose} = \frac{f}{1-f} \times N_f^{loose\,\&\,non-tight} =$$

$$\ldots$$

$$= \frac{fp}{p-f}\left[N^{loose\,\&\,non-tight} - \frac{1-p}{p} N^{tight}\right]$$

Full differential cross sections

p_T^H (GeV)	σ^{SM} (fb)	μ	Regularized μ Value	stat	exp	signal	bkg	lumi	Bias	σ^{obs} (fb)
0–20	27.45	1.37 ± 0.30	1.26 ± 0.27	± 0.17	± 0.19	± 0.01	± 0.10	± 0.03	$+0.00$	34.6 ± 7.5
20–45	24.76	0.52 ± 0.42	0.73 ± 0.36	± 0.24	± 0.25	± 0.01	± 0.10	± 0.03	-0.12	18.2 ± 8.9
45–80	15.28	1.55 ± 0.41	1.30 ± 0.33	± 0.24	± 0.20	± 0.03	± 0.09	± 0.03	-0.03	19.9 ± 5.2
80–120	7.72	0.49 ± 0.52	0.79 ± 0.42	± 0.32	± 0.25	± 0.02	± 0.08	± 0.03	-0.16	6.1 ± 3.3
120–200	5.26	$1.34^{+0.51}_{-0.48}$	1.14 ± 0.41	± 0.29	± 0.27	± 0.04	± 0.08	± 0.03	$+0.11$	6.0 ± 2.2
>200	2.05	$0.64^{+0.63}_{-0.60}$	$0.73^{+0.61}_{-0.57}$	± 0.38	± 0.42	$^{+0.09}_{-0.03}$	± 0.10	± 0.03	$+0.19$	1.5 ± 1.2

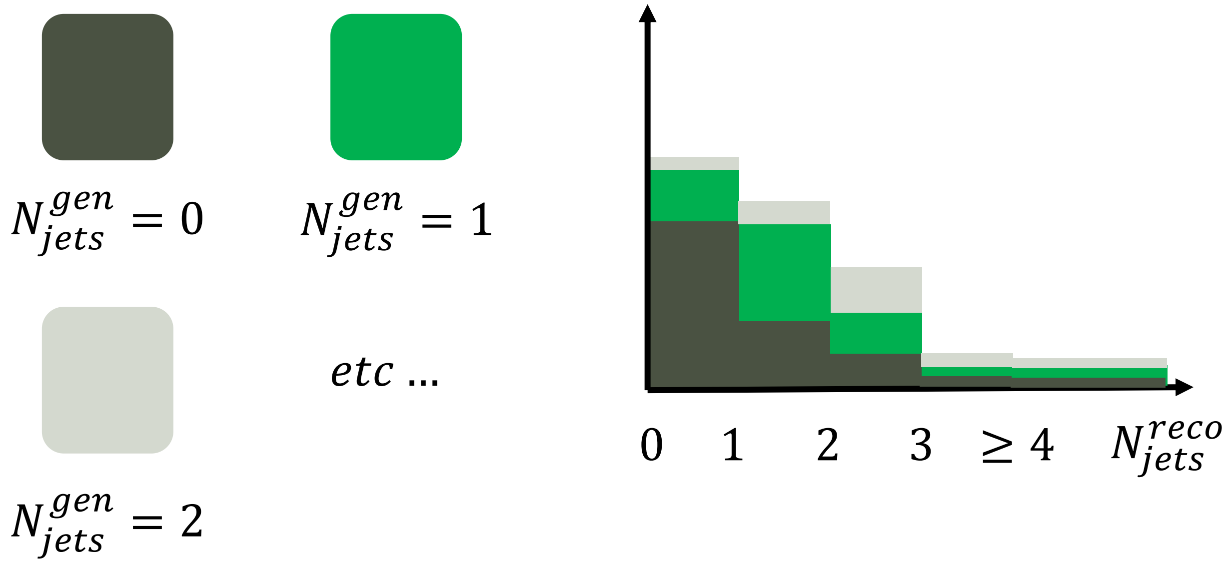
N_{jet}	σ^{SM} (fb)	μ Value	stat	exp	signal	bkg	lumi	σ^{obs} (fb)
0	45.70	0.88 ± 0.13	± 0.06	± 0.08	± 0.01	± 0.07	± 0.03	40.1 ± 6.0
1	21.74	1.06 ± 0.20	± 0.12	± 0.14	± 0.01	± 0.08	± 0.03	23.0 ± 4.6
2	9.99	1.50 ± 0.40	$^{+0.25}_{-0.28}$	± 0.28	± 0.04	± 0.11	± 0.03	15.0 ± 4.2
3	3.26	$1.56^{+1.35}_{-1.26}$	$^{+0.89}_{-0.71}$	$^{+0.84}_{-0.76}$	$^{+0.17}_{-0.07}$	$^{+0.29}_{-0.19}$	$^{+0.07}_{-0.04}$	$5.1^{+4.4}_{-4.1}$
≥ 4	1.83	$3.54^{+2.05}_{-1.86}$	$^{+1.10}_{-1.28}$	$^{+1.28}_{-1.32}$	$^{+0.40}_{-0.20}$	$^{+0.38}_{-0.34}$	$^{+0.10}_{-0.07}$	$6.5^{+3.8}_{-3.4}$

Systematic uncertainties

Nuisance parameter	Type	Effect
Lepton reconstruction and identification efficency	Experimental	shape & normalization
Trigger efficiency	Experimental	shape & normalization
Integrated luminosity	Experimental	normalization
Lepton momentum scale	Experimental	shape & normalization
Jet energy scale (JES)	Experimental	shape & normalization
Unclustered energy scale	Experimental	shape & normalization
b-tagging scale factors	Experimental	shape
Pileup	Experimental	normalization
Non-prompt leptons estimation	Experimental	shape & normalization
PDF	Theoretical	normalization
Renormalization and factorization scale	Theoretical	shape & normalization
Parton shower modeling	Theoretical	shape
Underlying event modeling	Theoretical	normalization

Unfolding procedure

- MC samples are binned at **gen-level** in the differential basis observables
- Bins are treated as independent signal sources that might contribute in each **reco-level** category
- Embedding these templates within the likelihood function is equivalent fitting reco-level yields and inverting the **response matrix**



A **fiducial phase space** similar to the signal region is defined for gen-level samples → Signal in the j-th bin at reco-level is also determined by events coming from the **non-fiducial** region → Non-fiducial cross section is **scaled together** with the fiducial component, due to its large contribution

Signal extraction – Differential

- Two additional control regions are defined to contrain top and DY normalization during the fit procedure

- $m_{\ell\ell} > 50$ GeV
- At least one b-tagged jet

- 40 GeV $< m_{\ell\ell} <$ 80 GeV
- $m_T < 60$ GeV

- $\boldsymbol{m_{\ell\ell}}$ and $\boldsymbol{m_T}$ are found to have good discrimination power between signal and background

2D template shape is fitted to data in each bin of each signal sub-category

$$\mathcal{L}_{unreg}(\vec{\mu},\vec{\theta}) = \prod_{j=1}^{N_{bins}^{reco}} Poisson\left(n_j; s_j(\vec{\mu},\vec{\theta}) + b_j(\vec{\theta})\right) \cdot \mathcal{N}(\vec{\theta})$$

$\vec{\boldsymbol{\mu}}$ = **signal strength modifiers vector**

$\vec{\boldsymbol{\theta}}$ = **nuisance parameters**

$\mathcal{N}(\vec{\theta})$ = nuisance constraints

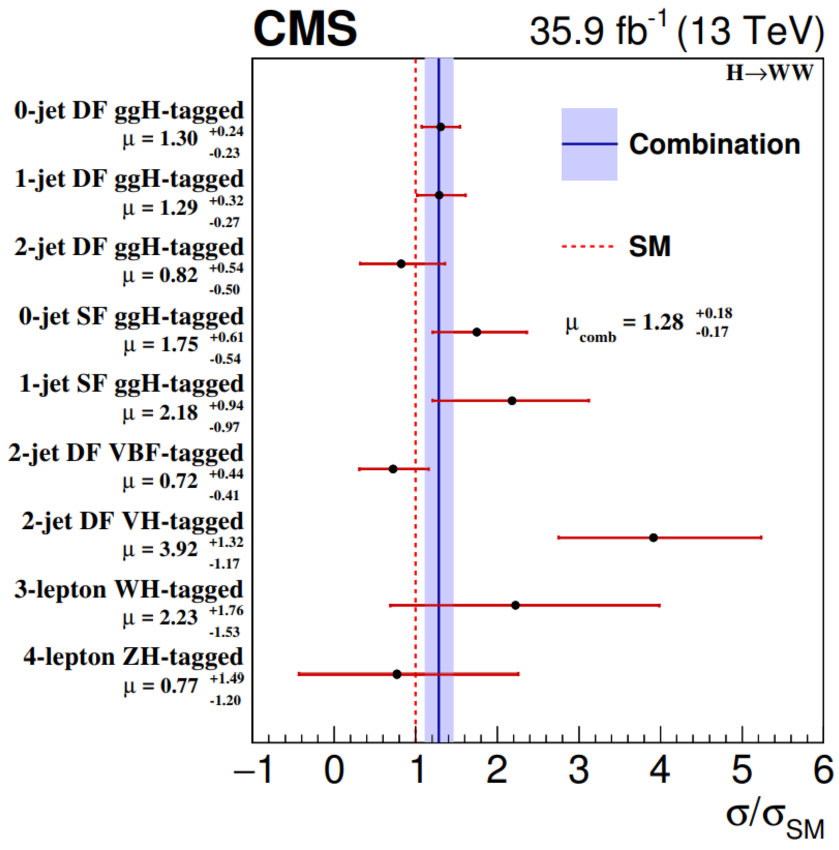
Regularization factor is added to penalize changes in the second derivative of $\boldsymbol{\mu}$

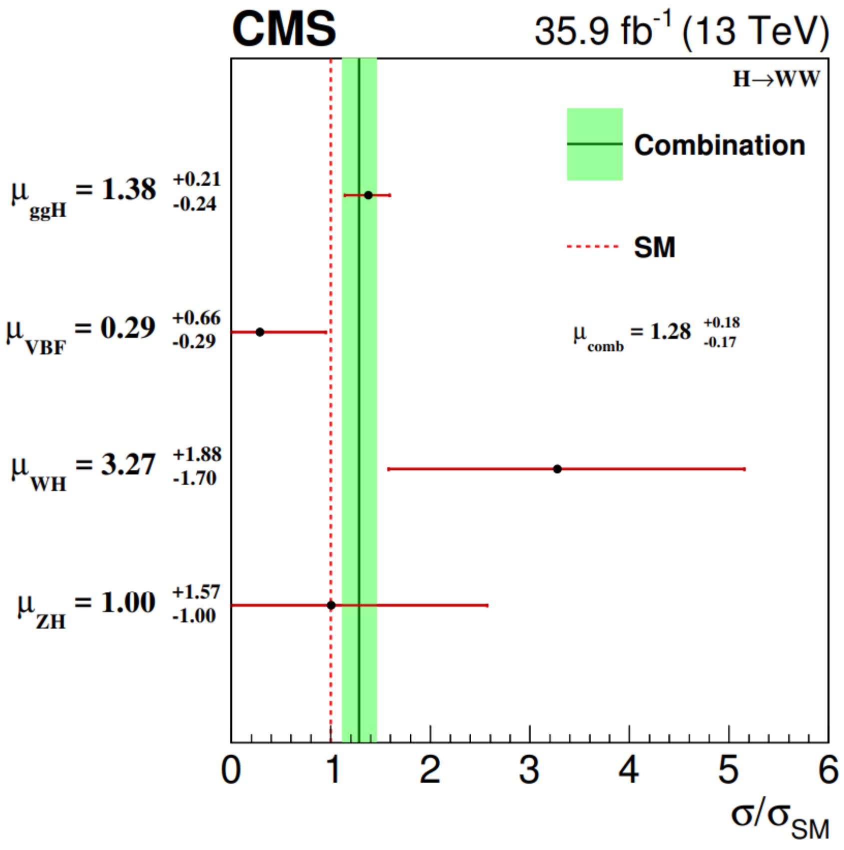
$$\mathcal{L}_{reg}(\vec{\mu},\vec{\theta}) = \mathcal{L}_{unreg}(\vec{\mu},\vec{\theta}) \cdot \mathcal{K}(\vec{\mu})$$

$$s_j(\vec{\mu},\vec{\theta}) = \sum_{i=1}^{N_{bins}^{gen}} \left[R_{ji}(\vec{\theta})\mu_i L_j \cdot \left(\sigma_i^{fid} + \sigma_i^{non-fid}\right)\right]$$

HIG-16-042 results

- Results obtained using the 2016 CMS data set ($\mathcal{L} = 35.9\ \text{fb}^{-1}$)





$$\mu = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10\,(\text{stat}) \pm 0.11\,(\text{syst})^{+0.10}_{-0.07}\,(\text{theo})$$