Recent results in the $\mathbf{H \rightarrow WW}$ channel from CMS

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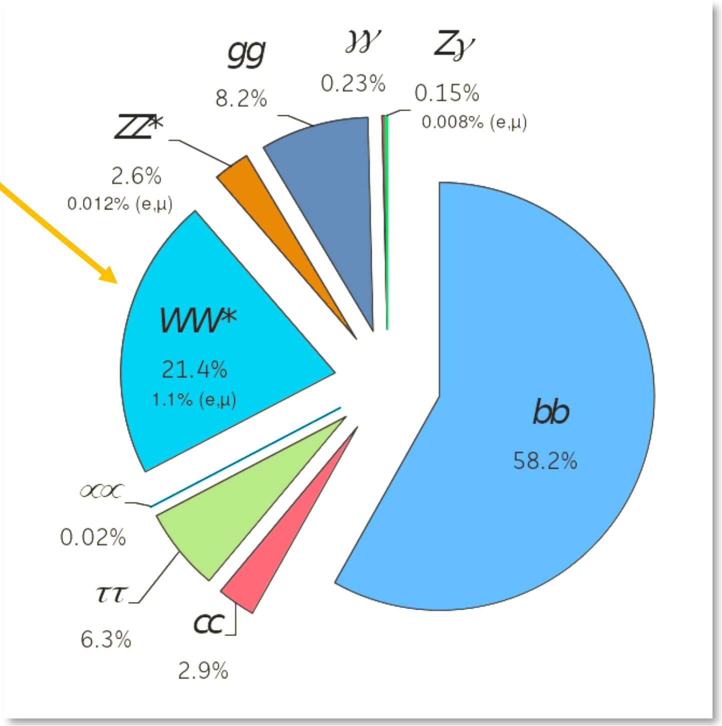
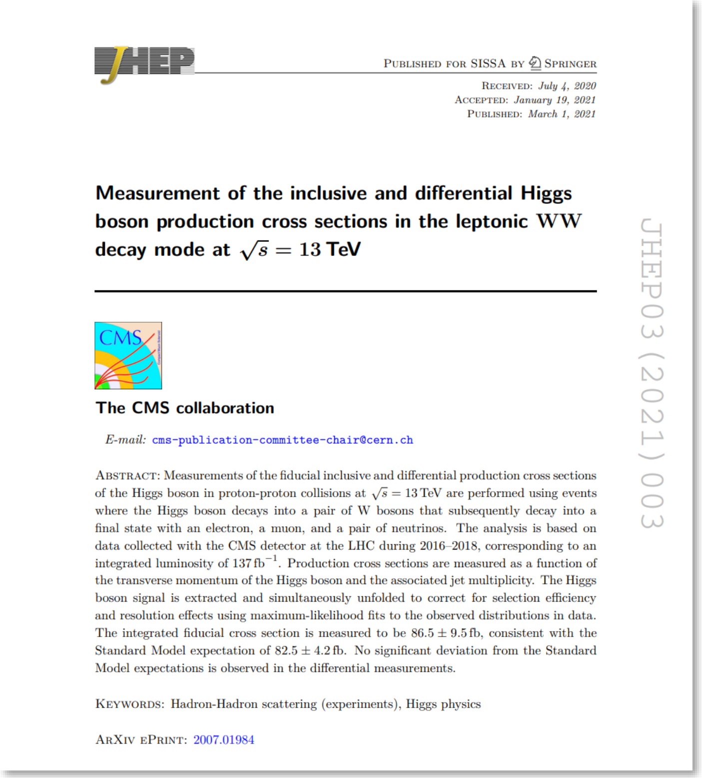
ON BEHALF OF THE CMS COLLABORATION

Introduction

- H → WW channel: second highest branching ratio, highest to a leptonic final state
- Suitable for measuring rare Higgs production modes and differential cross sections
- Full 137 fb^{-1} LHC Run 2 dataset





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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

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Abstract: Measurements of the fiducial inclusive and differential production cross sections of the Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV are performed using events where the Higgs boson decays into a pair of W bosons that subsequently decay into a final state with an electron, a muon, and a pair of neutrinos. The analysis is based on data collected with the CMS detector at the LHC during 2016–2018, corresponding to an integrated luminosity of 137 fb^{-1}. Production cross sections are measured as a function of the transverse momentum of the Higgs boson and the associated jet multiplicity. The Higgs boson signal is extracted and simultaneously unfolded to correct for selection efficiency and resolution effects using maximum-likelihood fits to the observed distributions in data. The integrated fiducial cross section is measured to be 86.5 ± 9.5 fb, consistent with the Standard Model expectation of 82.5 ± 4.2 fb. No significant deviation from the Standard Model expectations is observed in the differential measurements.

Keywords: Hadron-Hadron scattering (experiments), Higgs physics

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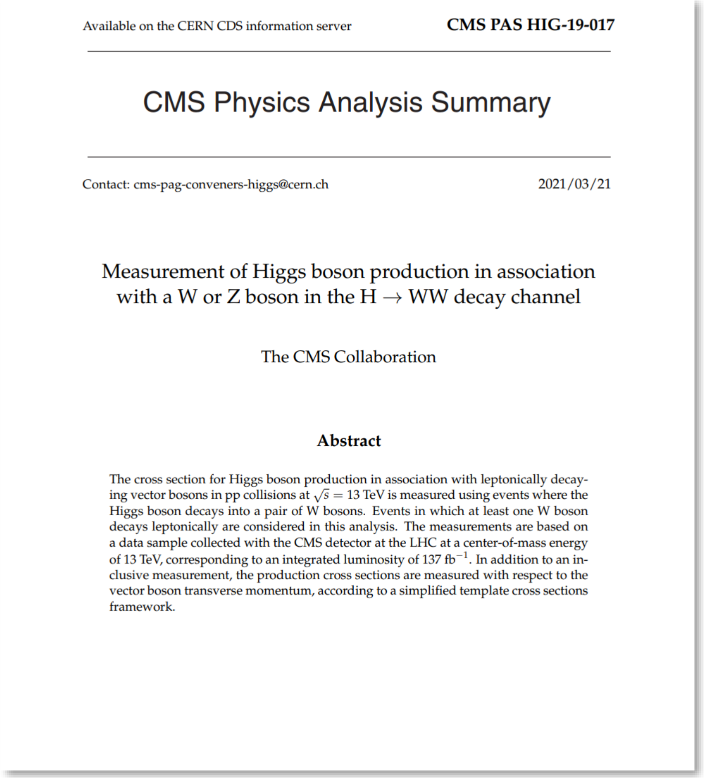


Available on the CERN CDS information server

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.

CMS-PAS-HIG-19-017

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

CMS-PAS-HIG-19-017

Motivation

- The analysis targets the $VH(H \rightarrow W^{+}W^{-})$ production mode, also known as $Higgsstralhung$
- Only associated vector bosons decaying leptonically are considered ($V \rightarrow leptons$)
- Sensitive to the coupling structure of the Higgs boson to vector bosons
- Precision benchmark for the SM and probe for possible BSM effects

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

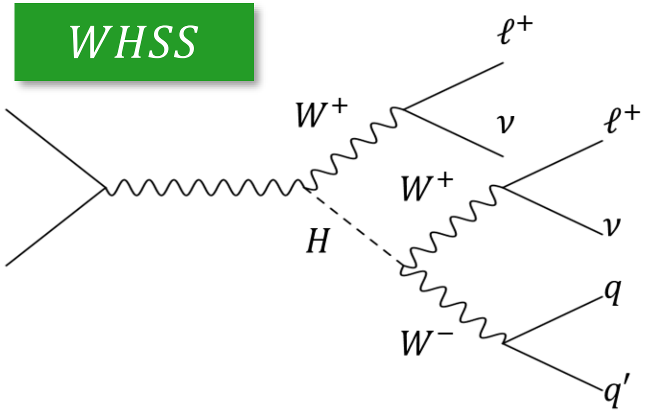
- **Inclusive cross section** (as a signal strength modifier $\hat{\mu}$)
- **STXS** (**S**implified **T**emplate **XS**ection)

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 directly measured in data through dedicated control regions
- Non prompt leptons also estimated from data
  - Applying a transfer function to loose leptons i.e., not passing tight isolation and identification criteria of the analysis
- Jet misidentification primarily from leptonic decays of heavy hadrons:
  - $W + jets$ 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

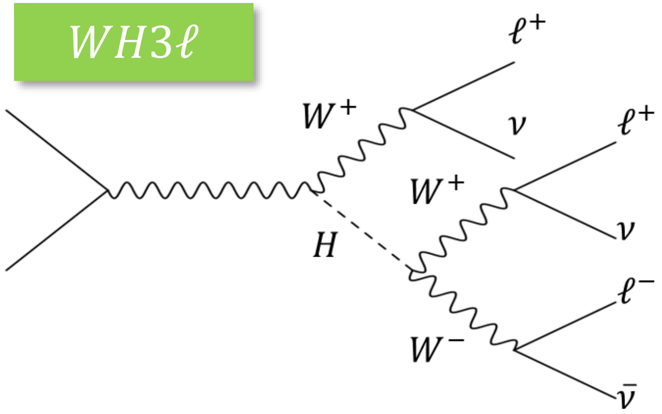
Analysis strategy – inclusive Xsec

$WHSS$



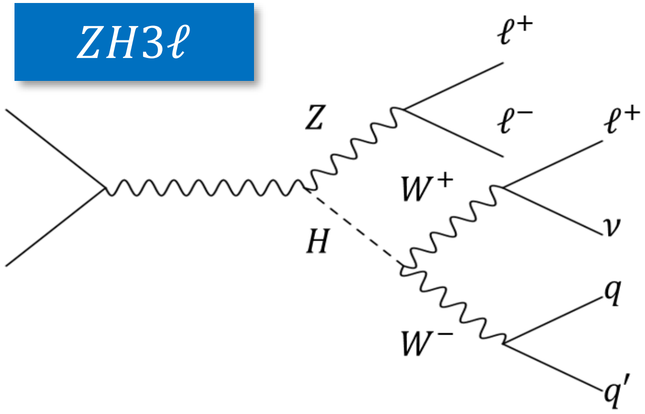
- Divided by N_{jets} and $\{e\mu, \mu\mu\}$
- WZ background measured in CRs

$WH3\ell$



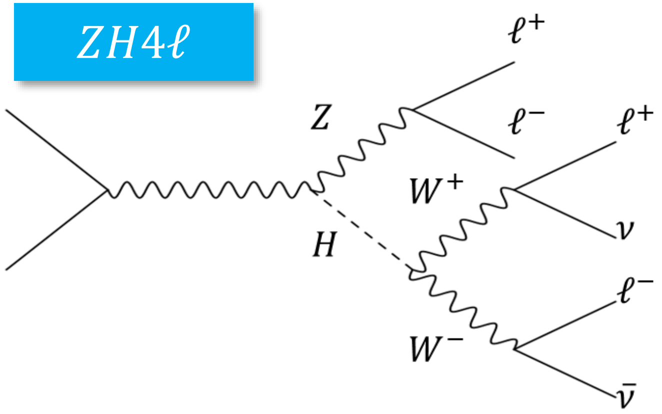
- Divided based on presence or not of an OSSF lepton pair
- WZ, Zγ backgrounds measured in CR

$ZH3\ell$



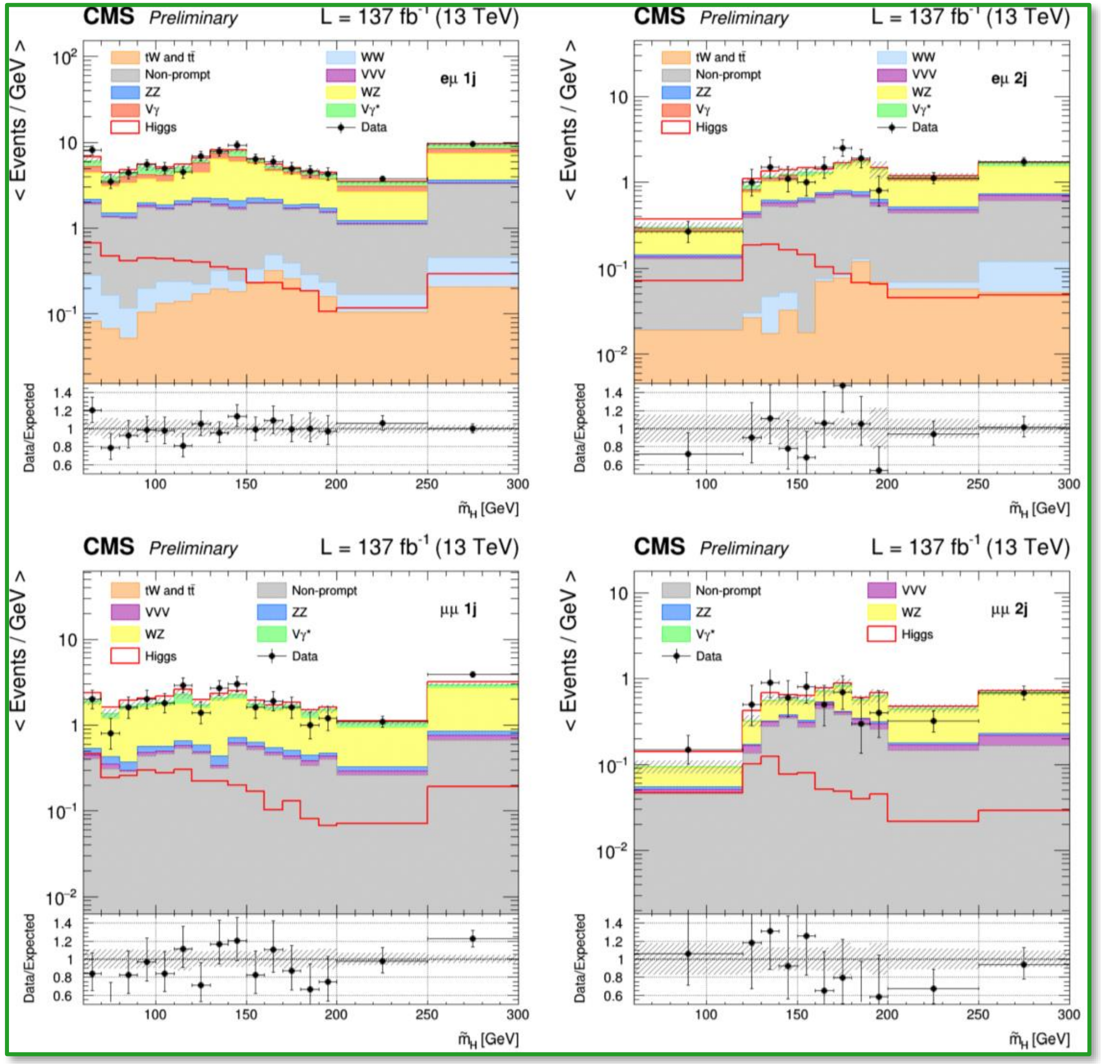
- Divided by N_{jets}
- WZ background measured in CRs shared w/ WHSS

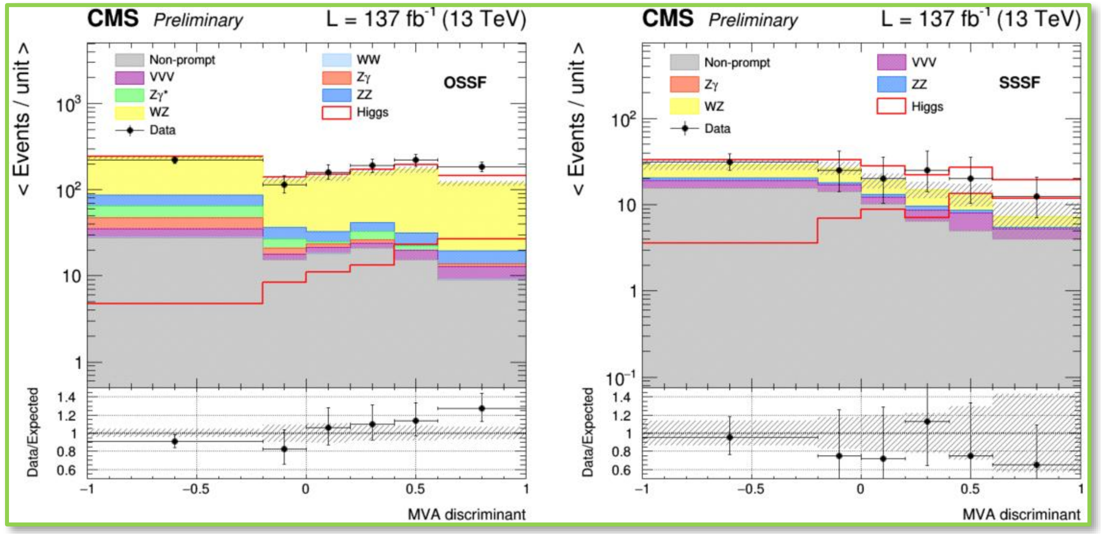
$ZH4\ell$



- Divided in DF ad SF Higgs decays
- ZZ background measured in CR

Signal extraction – inclusive Xsec (1)





An MVA discriminant is fitted in the SR, based on a BDT algorithm

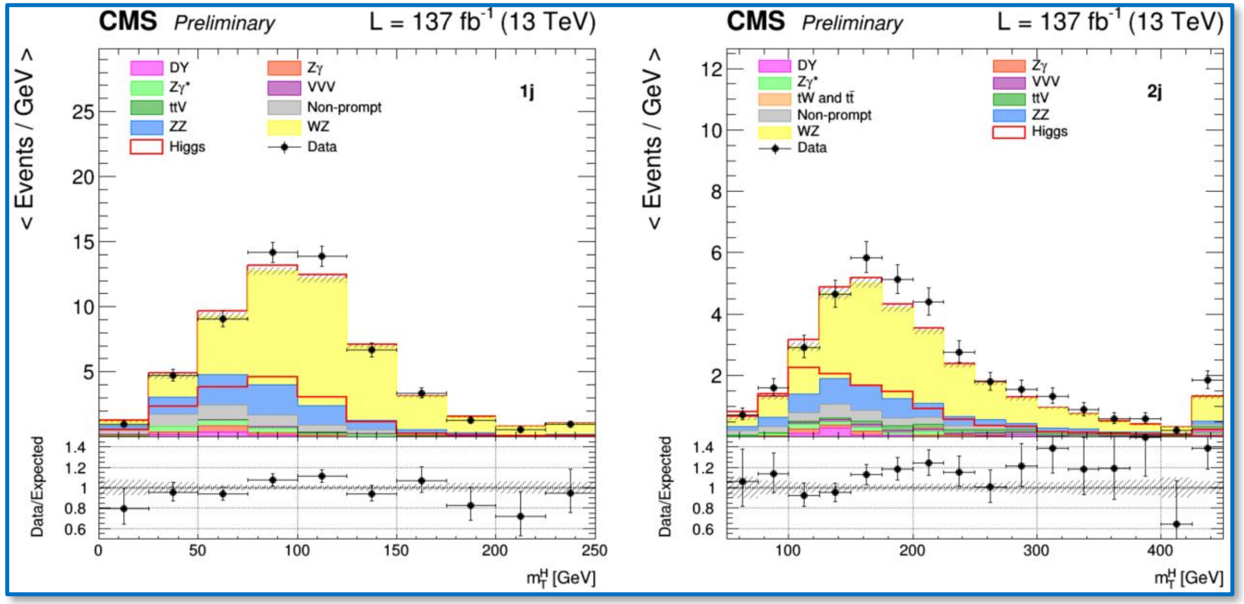
$WH3\ell$

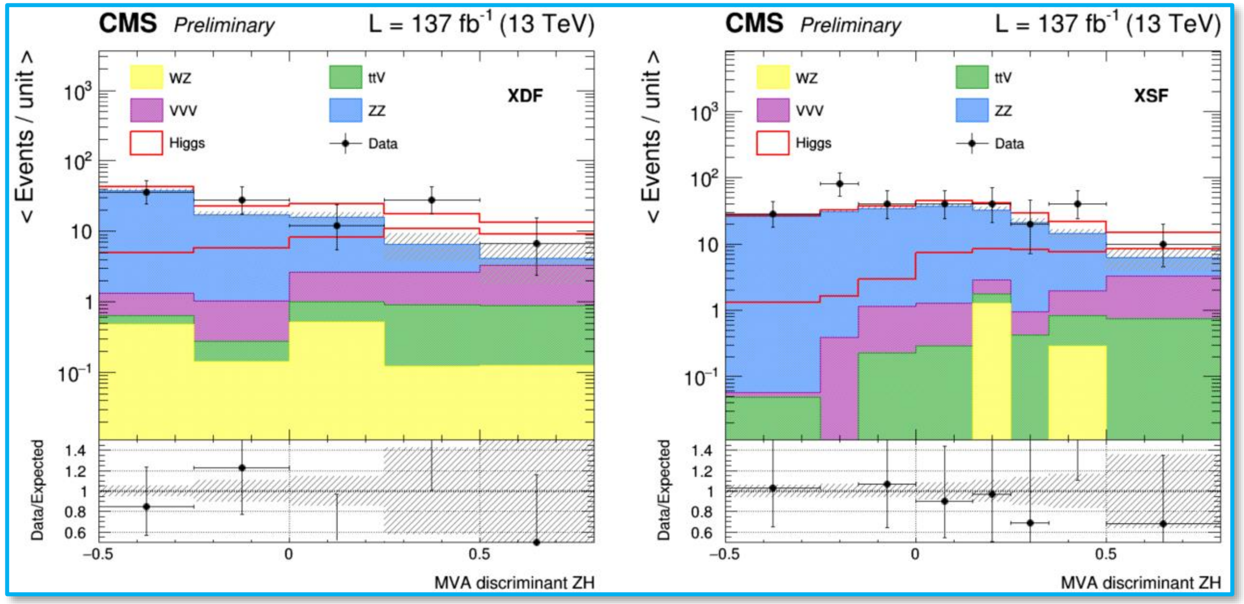
$WHSS$

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

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

Signal extraction – inclusive Xsec (2)





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

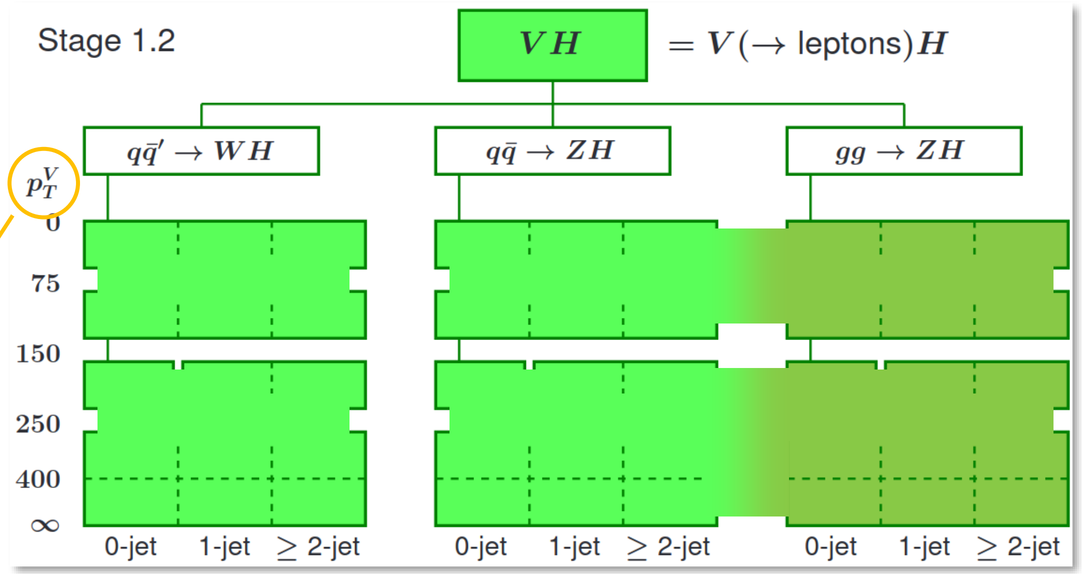
It represents the transverse mass of the 2 W bosons i.e., the Higgs transverse mass

$ZH3\ell$

$ZH4\ell$

An MVA discriminant is fitted in the SR, based on a BDT algorithm

Signal extraction – STXS



- Framework developed as an extension of signal strength measurements
- Provides 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 statistics currently available

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

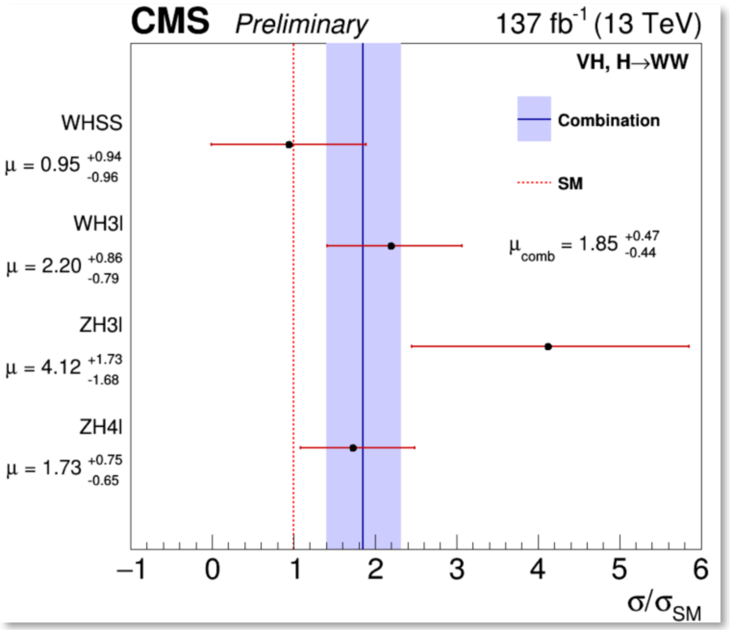
ZH:
$\vec{p}_T^{W} \equiv \vec{p}_T^{\ell} + \vec{p}_T^{\nu}$

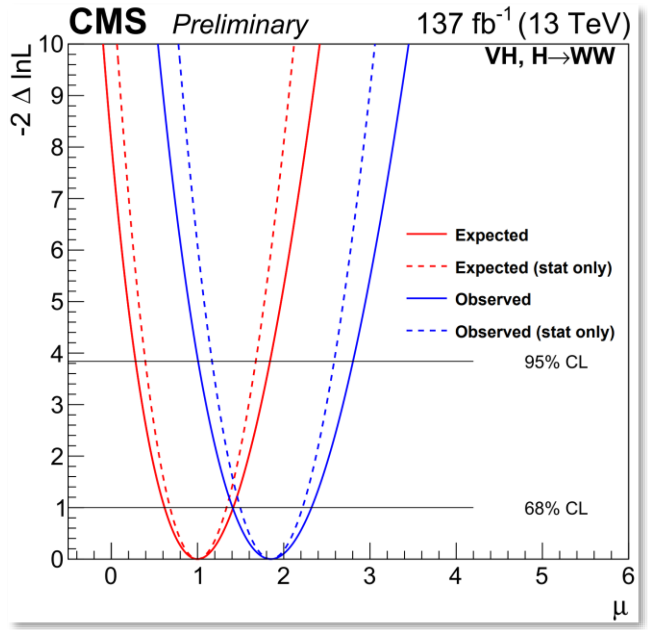
$\vec{p}_T^{\nu} \equiv \vec{p}_T^{miss} - \vec{p}_T^{\nu,H} \simeq \vec{p}_T^{miss} - \vec{p}_T^{\ell,H}\left(\frac{125}{||\vec{p}^{\ell}+\vec{p}^{jj}||} - 1\right)$

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

- Signal strength modifier μ extracted by a simultaneous fit to all categories
- The fit assumes relative rates of the different Higgs boson's production mechanisms are as in the SM
- Additional fit scaling the signal processes with a different signal strength modifier in each category



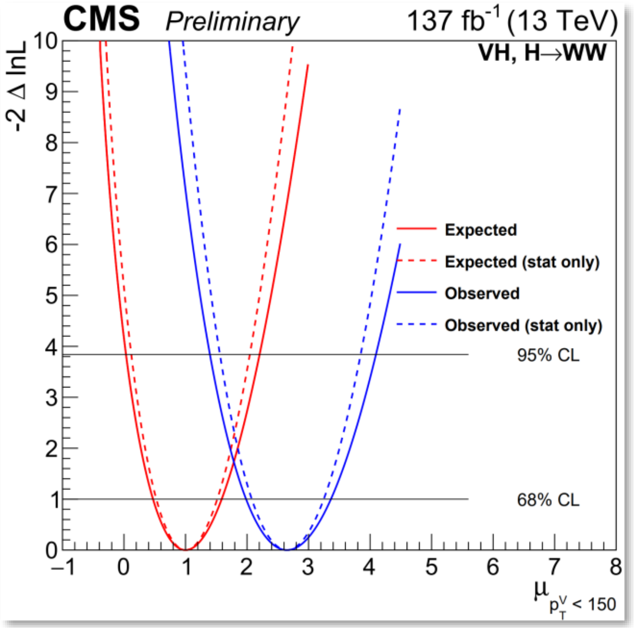


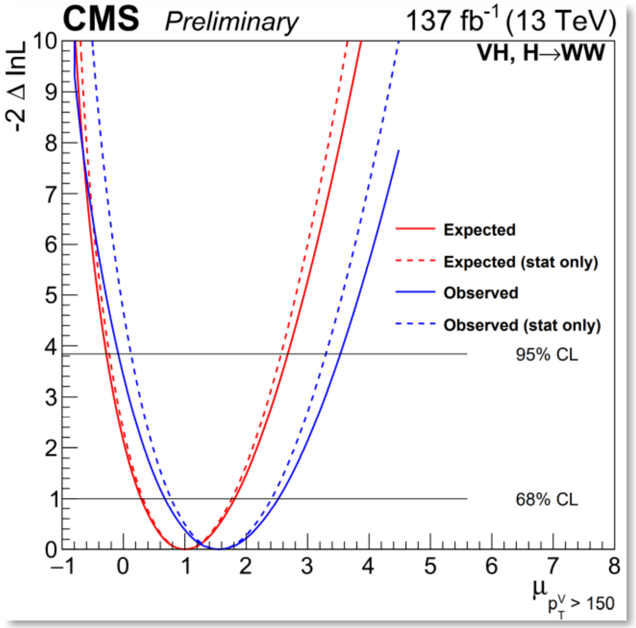
	μ	Significance (exp.)
$WHSS$	$0.95^{+0.94}_{-0.96}$	$1.0\ \sigma\ (1.1\ \sigma)$
$WH3\ell$	$2.20^{+0.86}_{-0.79}$	$3.0\ \sigma\ (1.6\ \sigma)$
$ZH3\ell$	$4.12^{+1.73}_{-1.68}$	$2.5\ \sigma\ (0.6\ \sigma)$
$ZH4\ell$	$1.73^{+0.75}_{-0.65}$	$3.1\ \sigma\ (2.1\ \sigma)$
Combination	$1.85^{+0.47}_{-0.44}$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

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

Results – STXS

- $H \rightarrow \tau\tau$ events are treated as background and fixed to the SM expectation
- Additional fit 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	$0.8^{+1.2}_{-0.9}$	$0.83\ \sigma\ (1.18\ \sigma)$

$$\mu_{p_T^V < 150\ \text{GeV}} = 2.65^{+0.57}_{-0.55}(stat)^{+0.38}_{-0.32}(exp)^{+0.08}_{-0.07}(theo)$$

$$\mu_{p_T^V > 150\ \text{GeV}} = 1.56^{+0.85}_{-0.77}(stat)^{+0.43}_{-0.40}(exp)^{+0.11}_{-0.09}(theo)$$

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

JHEP03(2021)003

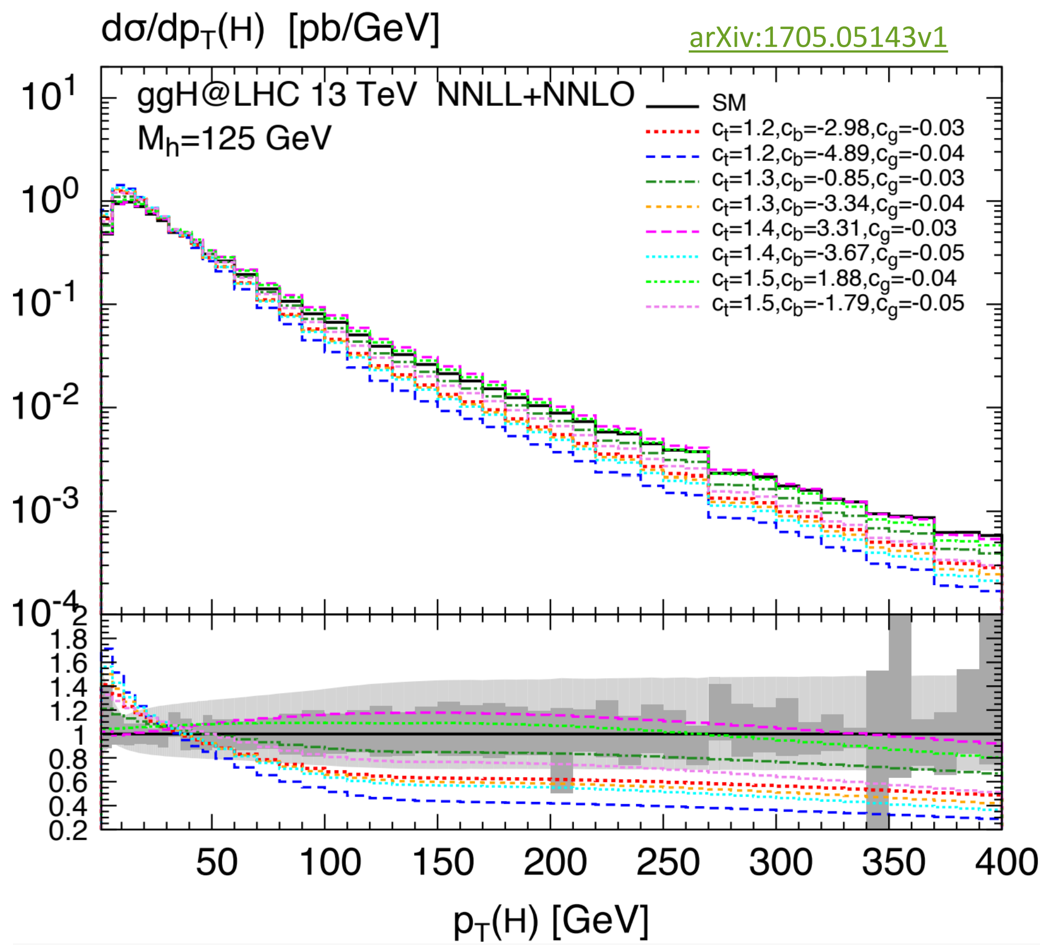
Motivation

- **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 affect the p_T^H spectrum
- $\sigma(pp \rightarrow H + N_{jets})$ sensitive to relative contributions from different production modes per jet bin

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

Main backgrounds: non-resonant WW, top, DY $\rightarrow \tau\tau$, non-prompt leptons

arXiv:1705.05143v1



Analysis strategy

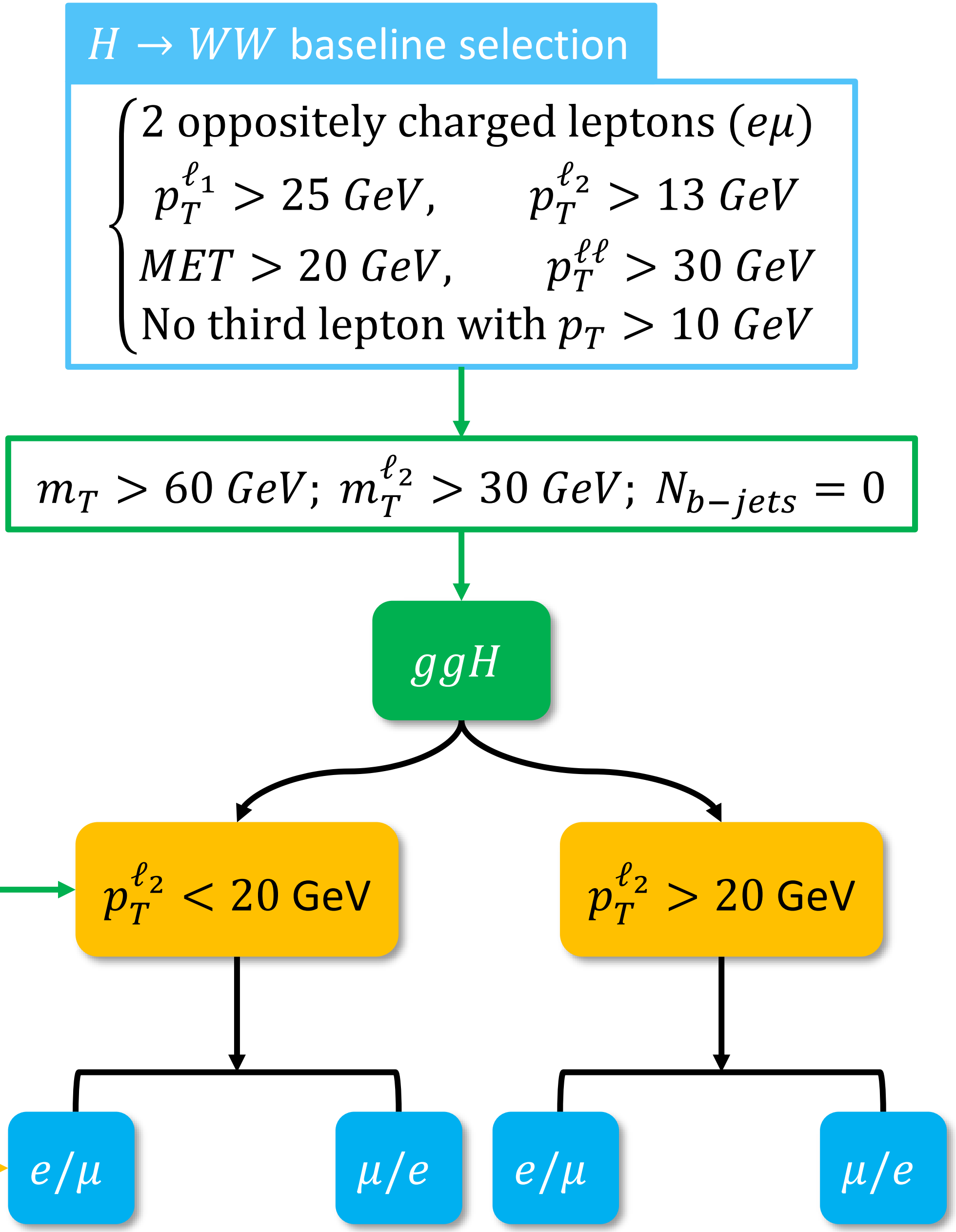
- Main target is the ggH production mode
- Further subcategorization to enhance sensitivity, gradually relaxed for higher p_T^H/N_{jets} bins (lower statistics)
- $Z \rightarrow \tau\tau,\ t\bar{t}$ backgrounds normalized from data in dedicated phase space regions; WW normalized in signal region
- Both reconstructed and particle level phase space binned in p_T^H/N_{jets}, **simultaneous regularized unfolding within fit**
- Low p_T^H binning driven by MET resolution

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

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

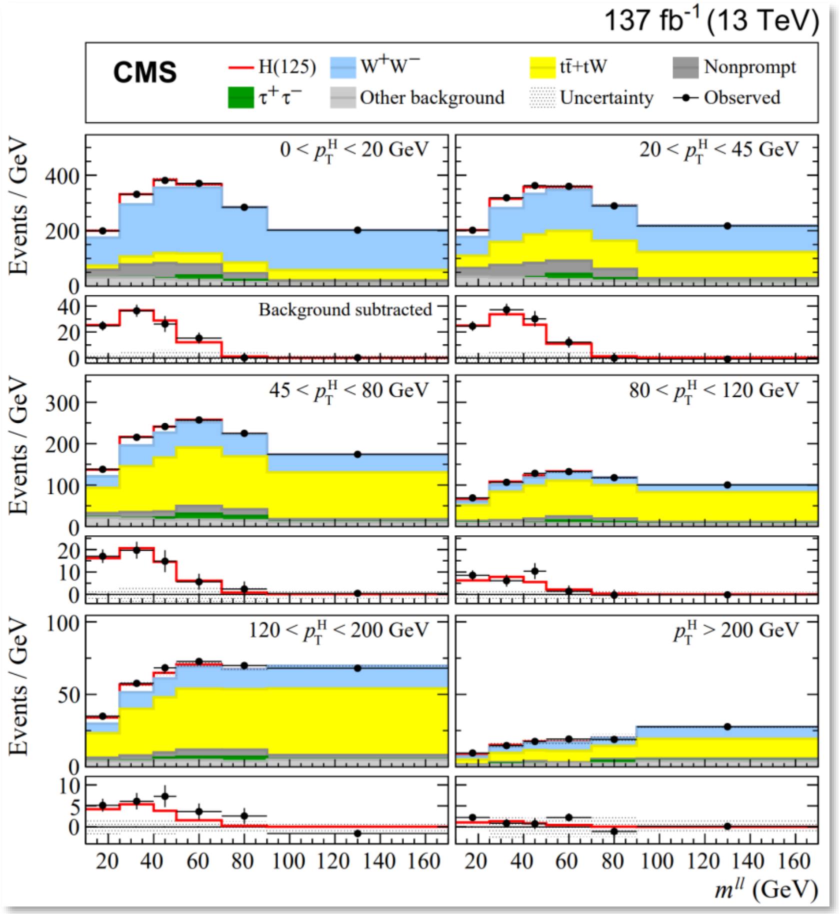
Low $p_T^{\ell_2}$ regions have less WW, $t\bar{t}$ contamination $\Longrightarrow$ higher S/B

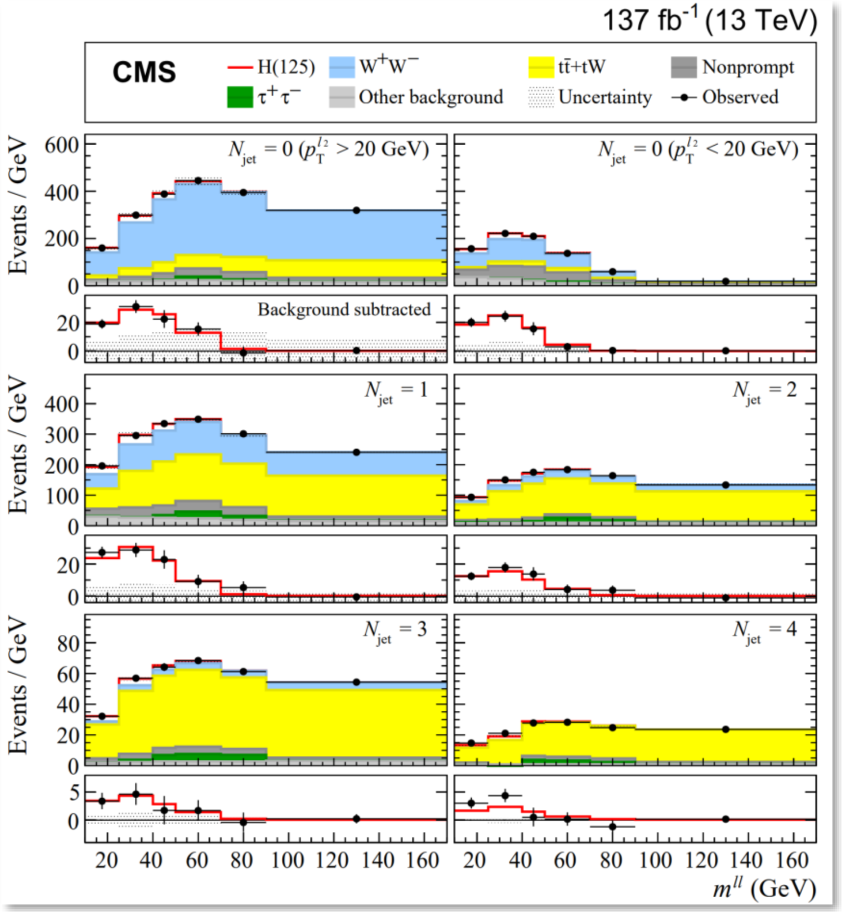
Non-prompt leptons primarily from mis-id of electrons



Signal extraction

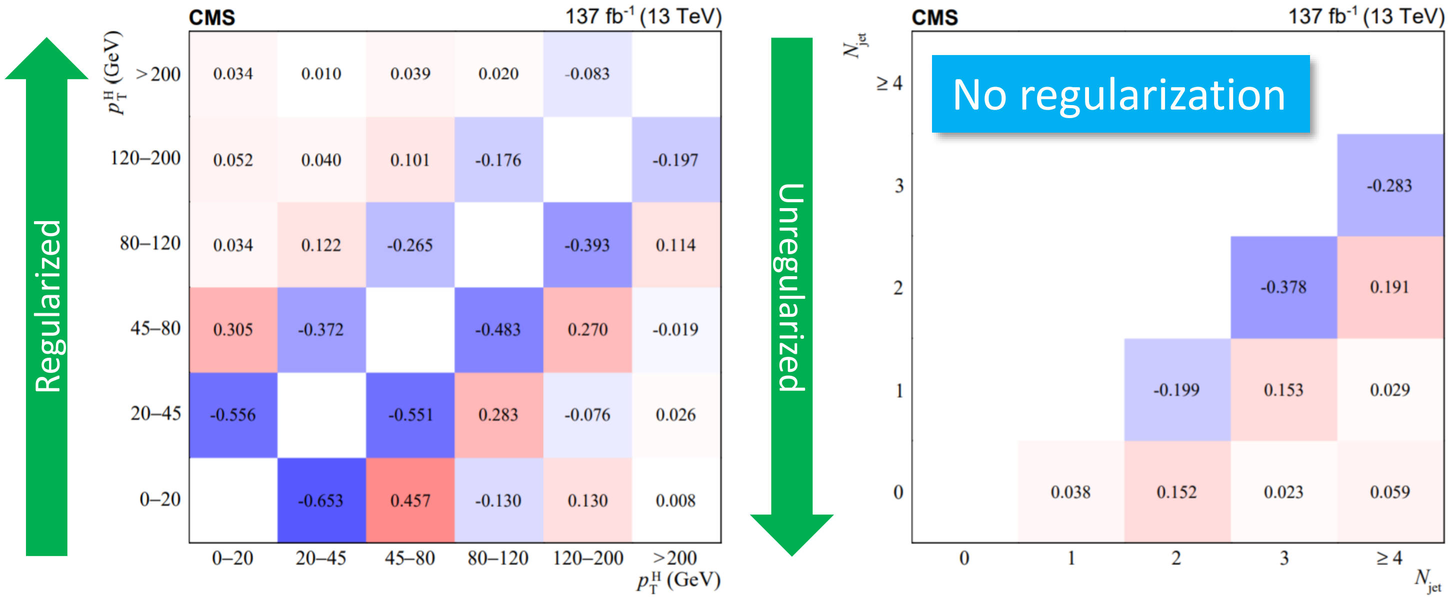
- 2D $(m_{\ell\ell}, m_T)$ template is fitted to data in each N_{jets} and p_T^H bin
- Showing $m_{\ell\ell}$ projection for clarity





Unfolding

- Higgs signal unfolded to a fiducial phase space
- Defined to match the experimental selection as closely as possible
- Done directly in the fit by embedding the response matrix in the likelihood
- Natural propagation of systematic uncertainties to unfolded result



$$\mathcal{L} = \prod_i Poisson\left(n_i; \sum_j R_{ij}(\theta)\,\mu_j + b_i\right)\cdot \mathcal{C}(\theta)\cdot \mathcal{K}(\mu)$$

Migration matrix

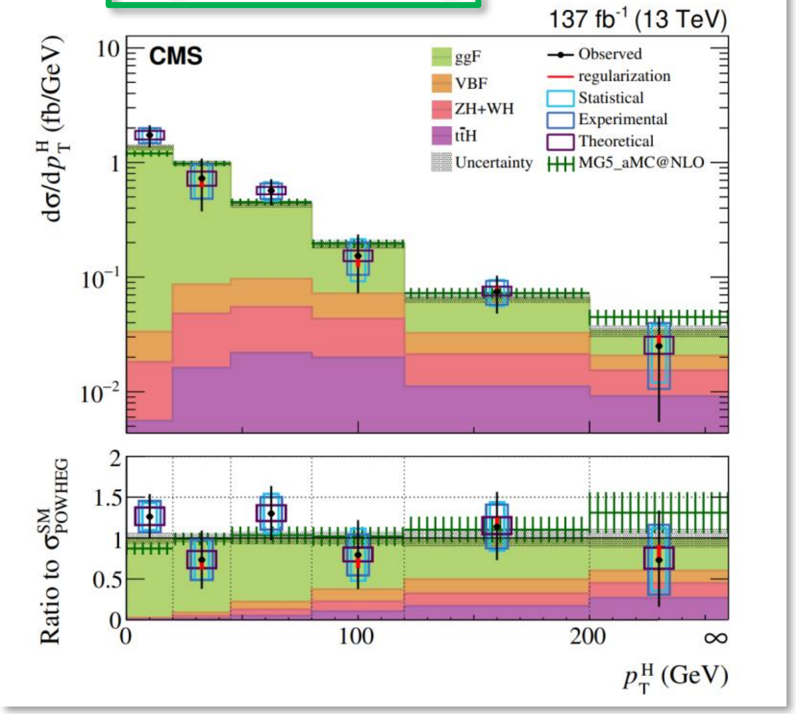
Particle level signal strength

Regularization term (optional), Tikhonov scheme in this analysis

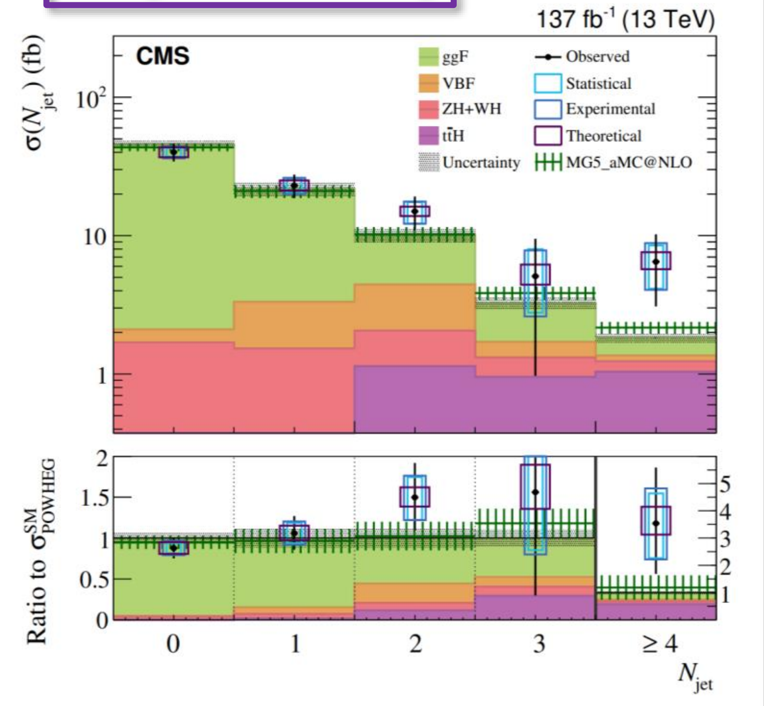
Results

- Fiducial and differential (p_T^H, N_{jets}) cross sections
- All production modes are considered
- Nominal prediction form POWHEGv2 at NLO, ggH reweighted to NNLOPS
- Results also compared to MG5@NLO
- Good agreement to SM, highest excess for $N_{jets} \geq 4$ at 1.4σ

Regularized unfolding



Unregularized unfolding



- Total fiducial cross section obtained from fit on p_T^H
- Good agreement with SM prediction obtained from POWHEGv2

$\sigma^{fid} = 86.5 \pm 9.5$ fb

$\sigma^{fid}_{SM} = 82.5 \pm 4.2$ fb

$\mu^{fid} = 1.03^{+0.12}_{-0.11}(\pm 0.05(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.03(\text{lumi.}) \pm 0.07(\text{exp.}))$

Conclusions

- **The $\mathbf{H \to WW}$ channel is at the forefront of the precision era of Higgs physics**
- **Due to its high branching fraction and clean signature, it allows to effectively measure rare processes and differential cross sections**
- **The agreement with the SM is found to be good overall**
- **This class of measurements will greatly benefit from the increased statistical power of the LHC Run 3 dataset and beyond, opening new possibilities**
- **Many more interesting $\mathbf{H \to WW}$ analyses in the works with Run 2 data!**

Thank you for your attention

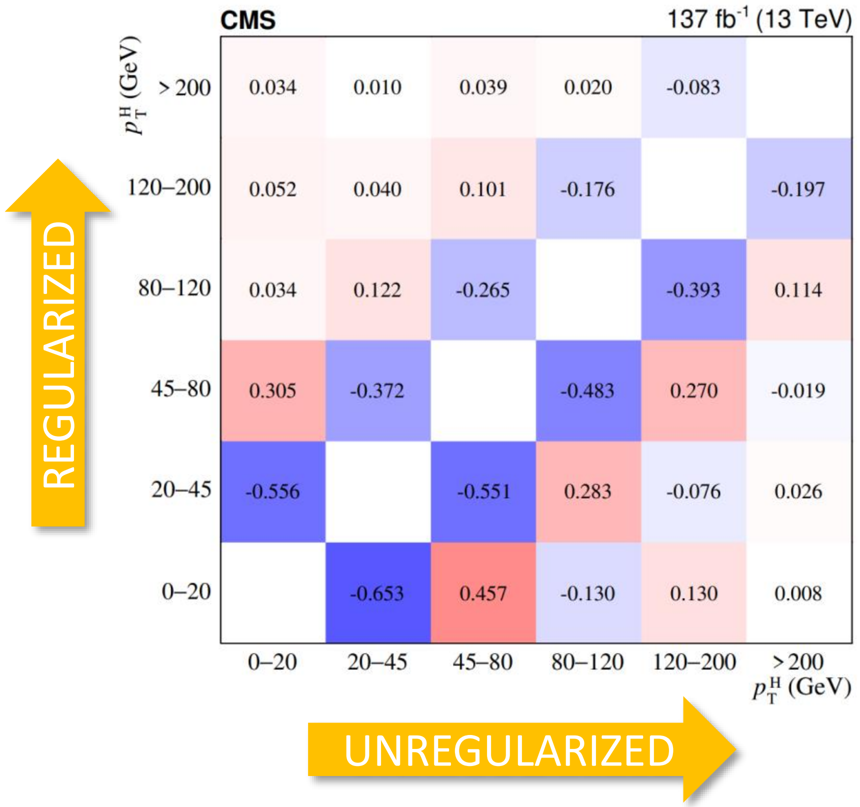
Backup

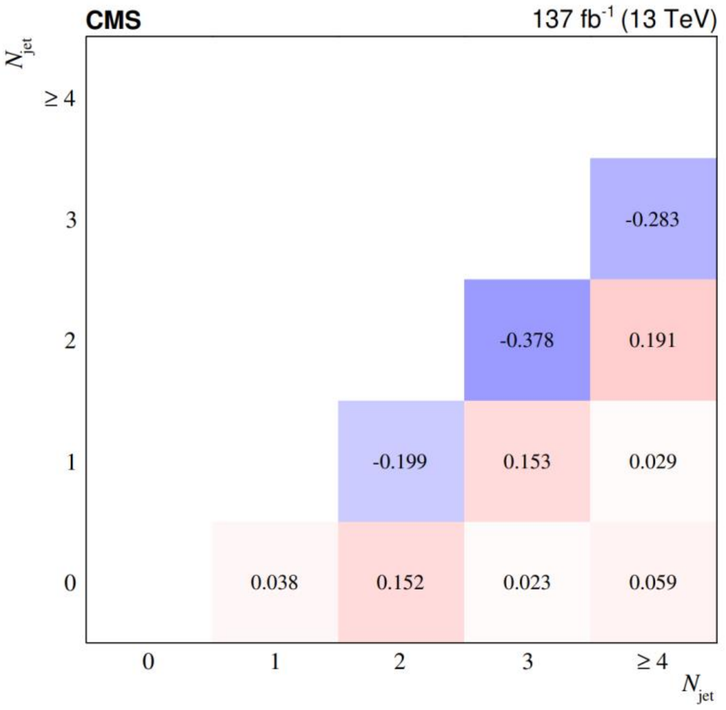
Fiducial volume definition – differential

Observable	Condition
Lepton origin	Direct decay of $H \to W^+W^-$
Lepton flavors; lepton charge	e μ (not from τ decay); opposite
Leading lepton p_T	$p_T^{l_1} > 25$ GeV
Trailing lepton p_T	$p_T^{l_2} > 13$ GeV
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{ll} > 12$ GeV
p_T of the dilepton system	$p_T^{ll} > 30$ GeV
Transverse mass using trailing lepton	$m_T^{l_2} > 30$ GeV
Higgs boson transverse mass	$m_T^{H} > 60$ GeV

Momenta of photons radiated within $\Delta R = 0.1$ of a lepton are added to the lepton's momentum

Correlation matrices - H → WW





Correlations among the unfolded signal strength modifiers