Measurement of the Higgs boson production cross sections in bosonic channels with the CMS experiment

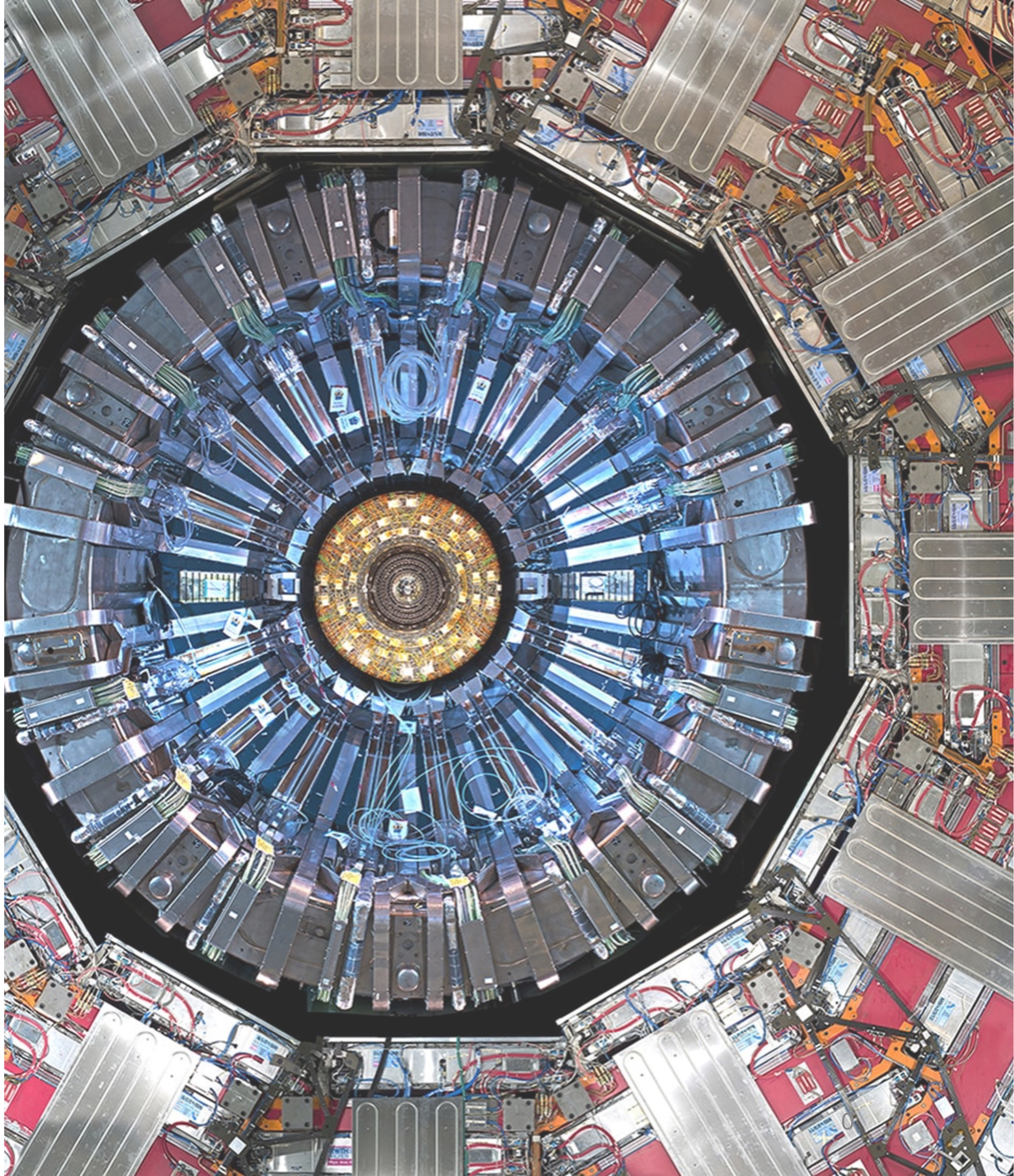
Higgs 2023

Sergio Blanco Fernandez on behalf of the CMS Collaboration

IFCA (CSIC – University of Cantabria)

29/11/2023

Research supported by PID2020-113304RB-100



Introduction and motivation

We have moved from the discovery to the **precision era** of Higgs measurements

There is still room for new measurements, the Higgs sector must be precisely investigated

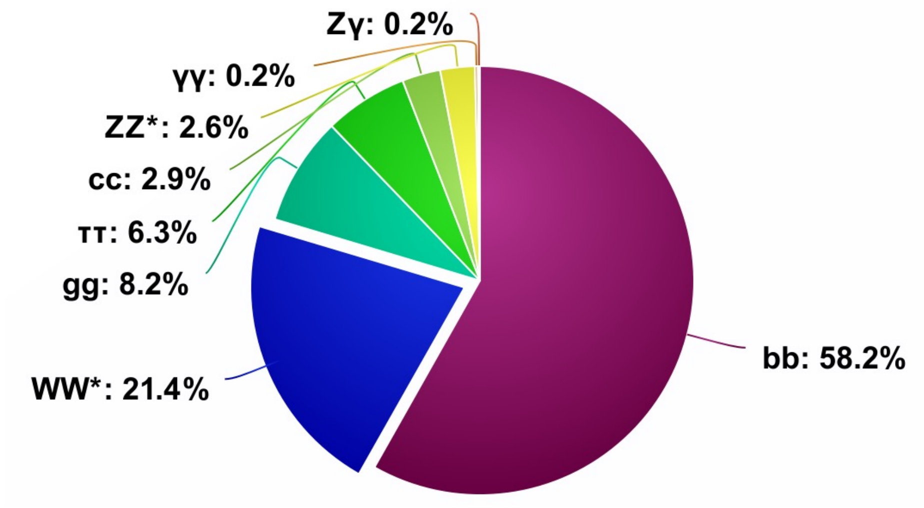
Bosonic decays of the Higgs boson are covered in this talk, including both differential and inclusive results

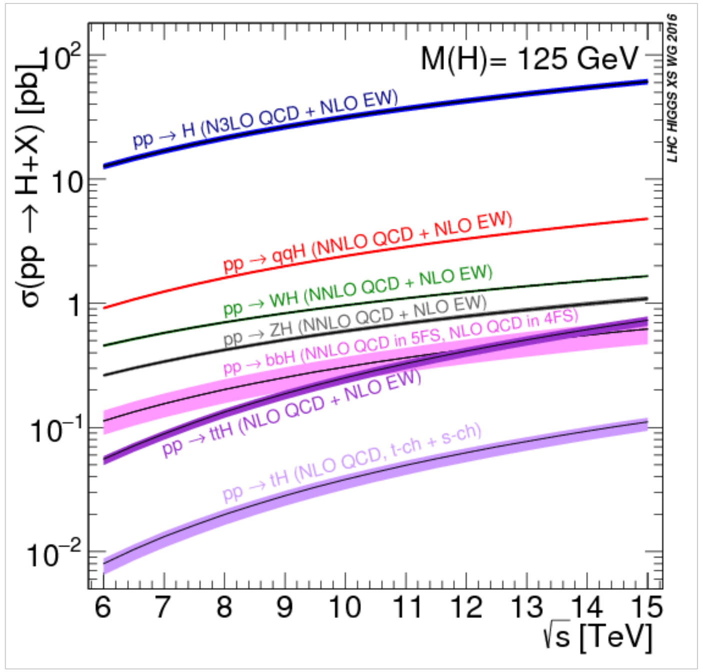
All the main decays of the Higgs boson have been observed. Here, we focus on the decay to bosons:

- $\gamma\gamma$
- **WW**
- **ZZ**

A lot of different results are produced at CMS:

Inclusive and differential cross-sections, STXS, off-shell, AC, …





Higgs results at CMS

ZZ

- Inclusive
- Differential

[JHEP 08(2023)040](https://doi.org/)

- STXS

Eur. Phys. J. C 81, 488 (2021)

$\gamma\gamma$

- Inclusive
- Differential

JHEP 07(2023)091

- STXS

JHEP 07(2021)027

WW

- Differential
- Inclusive

JHEP 03(2021)003

- STXS

Eur. Phys. J. C 83, 667 (2023)

Eur. Phys. J. C 81, 378 (2021)*

STXS 1.2	ggH	VBF	VH	ttH	tH
$\gamma\gamma$	×	×	×	×	×
ZZ	×	×	×	×	
WW	×	×	×	×*	

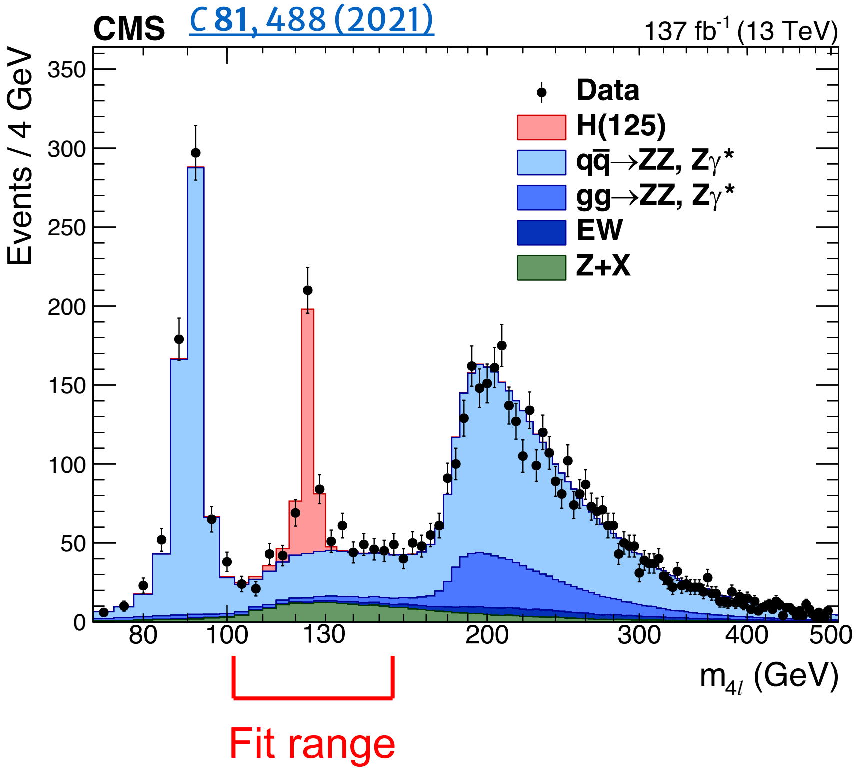
* ttH and tH productions targeted in a different analysis using WW, ZZ, and $\tau\tau$ decays

Higgs → ZZ inclusive, differential and STXS

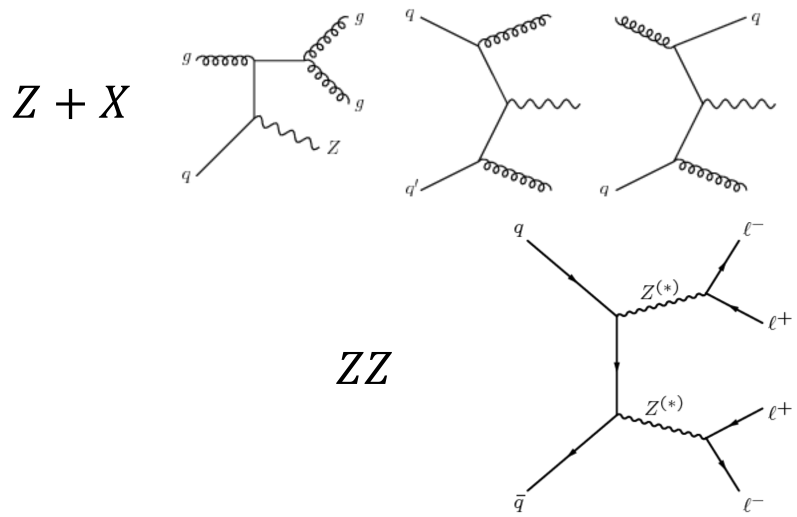
- The $\mathbf{H \rightarrow ZZ}$ represents one of the golden channels for the Higgs studies
- Look for **4 well-identified leptons** in the final state
- qqZZ and ggZZ, mitigated in the **fit to the Higgs peak** $(105 < m_{4l} < 160 \text{ GeV})$

Fiducial phase space
$p_{T,l_1} > 20$ GeV
$p_{T,l_2} > 10$ GeV
$p_{T,3,4}(muon) > 7(5)$ GeV
$\lvert\eta\rvert(muon) < 2.5\ (2.4)$
$\sum p_T(\Delta R < 0.3) < 0.35 p_T^{lep}$
$40 < m_{Z1} < 120$ GeV
$12 < m_{Z2} < 120$ GeV
$\Delta R_{l_i,l_j} > 0.02$ for $i \neq j$
$m_{ll} > 4$ GeV

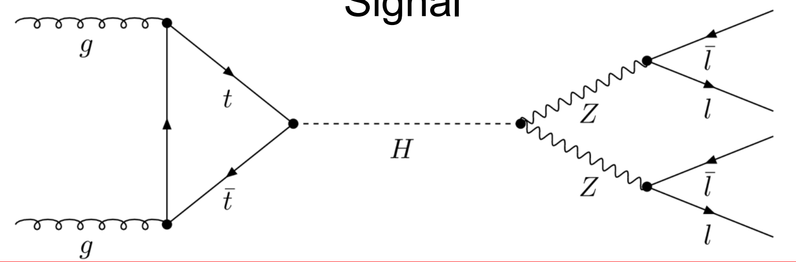
Eur. Phys. J. C 81, 488 (2021)



Backgrounds

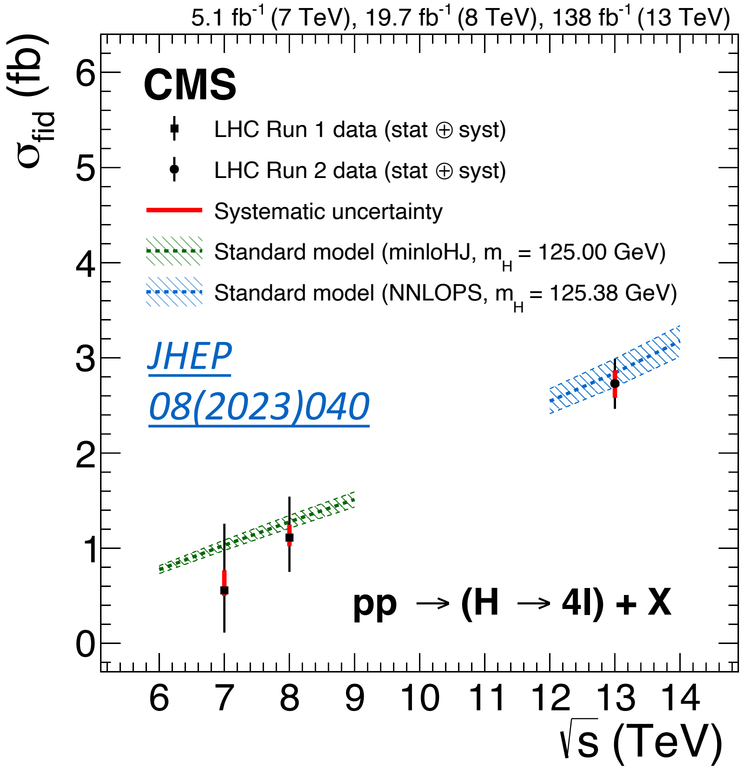


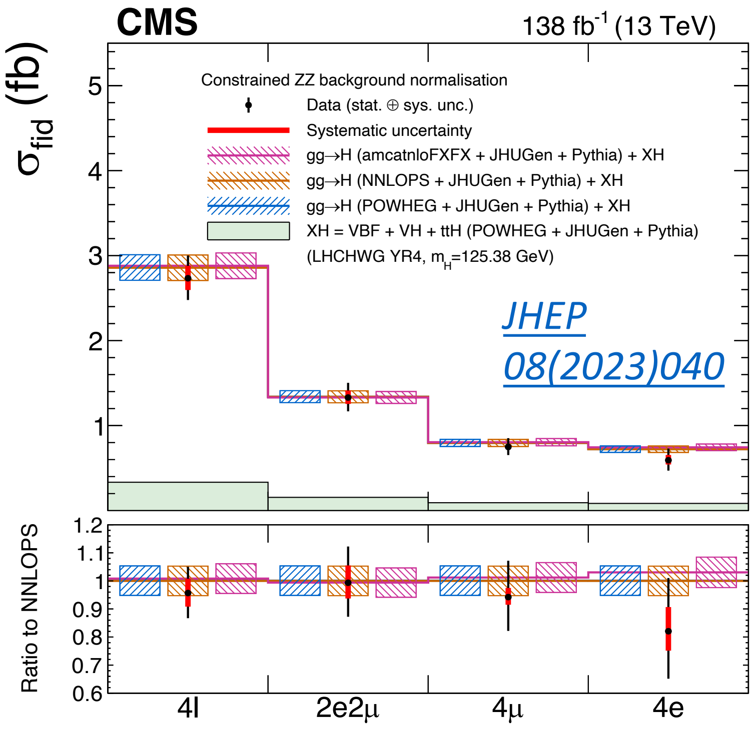
Signal

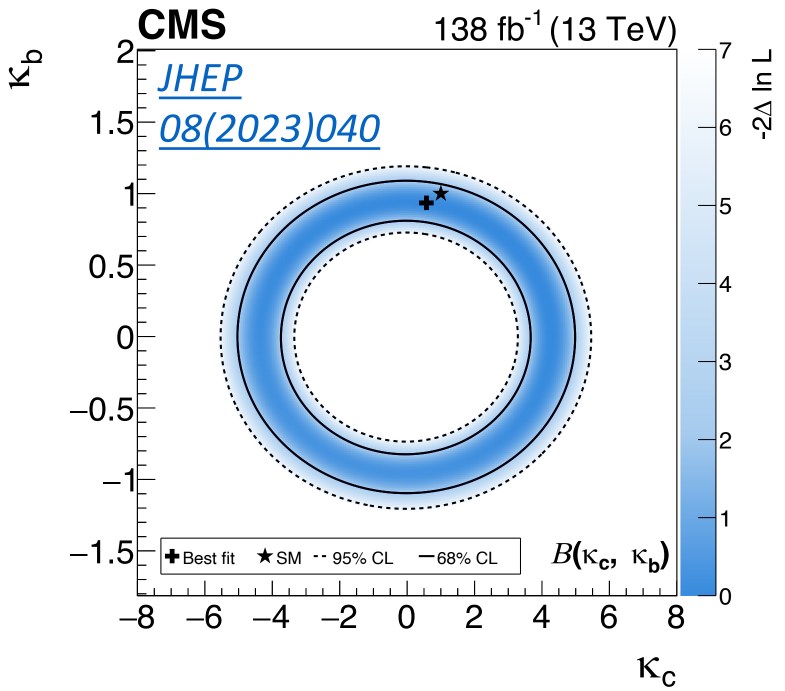


Higgs → ZZ inclusive, differential and STXS

- **Full reconstruction of the Higgs kinematics**
- The statistics from the Run 2 data-taking period allow for **high precision** on inclusive and differential results
- The **inclusive fiducial cross-section** results in: $\sigma^{fid} = 2.73 \pm 0.22(stat) \pm 0.15(syst)$ fb



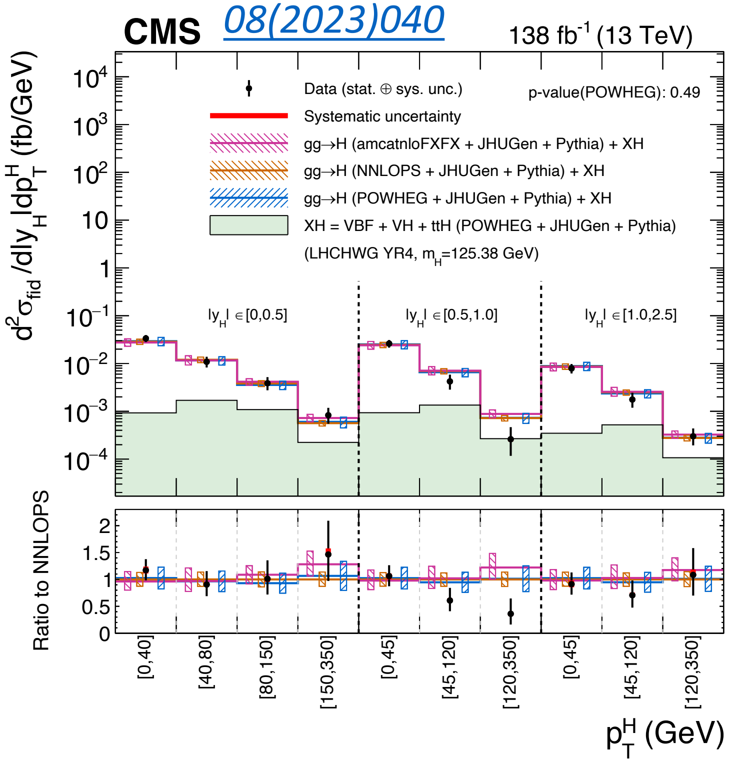




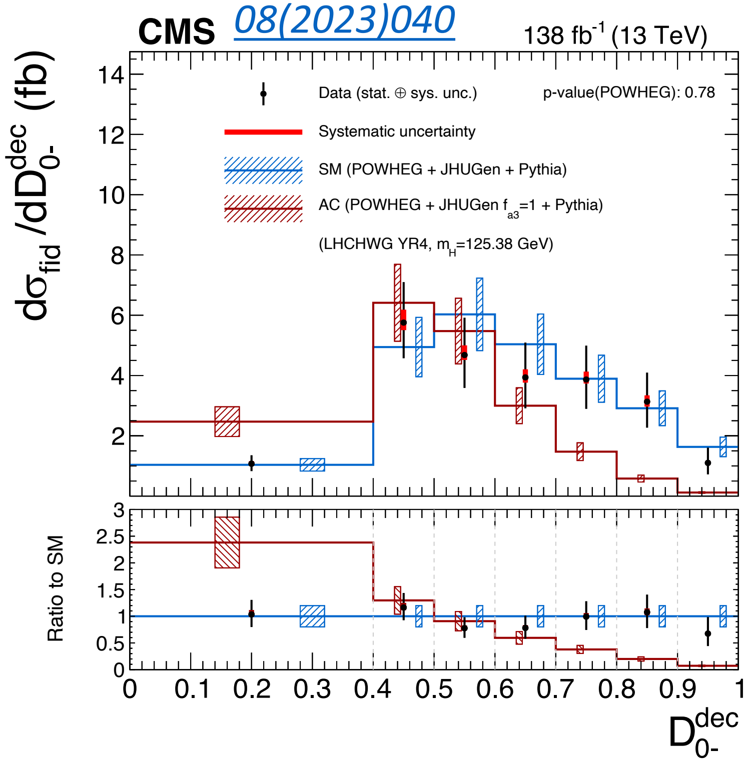
Higgs → ZZ inclusive, differential and STXS

- Signal extraction performed via a **fit to the total m_{4l}** invariant mass
- Differential on **32 distributions**. Production and decays kinematics + Matrix elements (BSM effects)
- A **likelihood-based unfolding** is performed to resolve detector effects. Multiple MC predictions are compared here

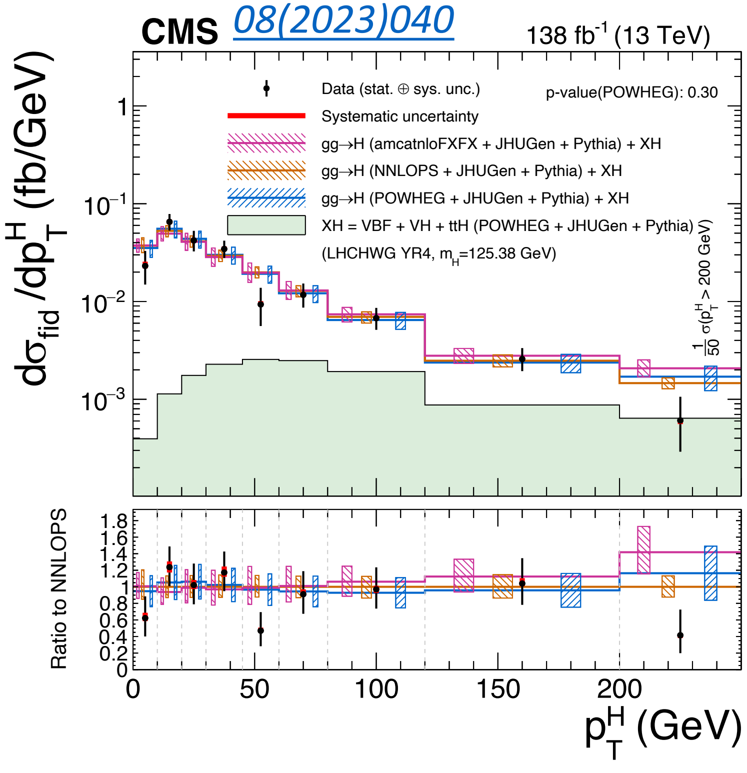
JHEP 08(2023)040



JHEP 08(2023)040



JHEP 08(2023)040



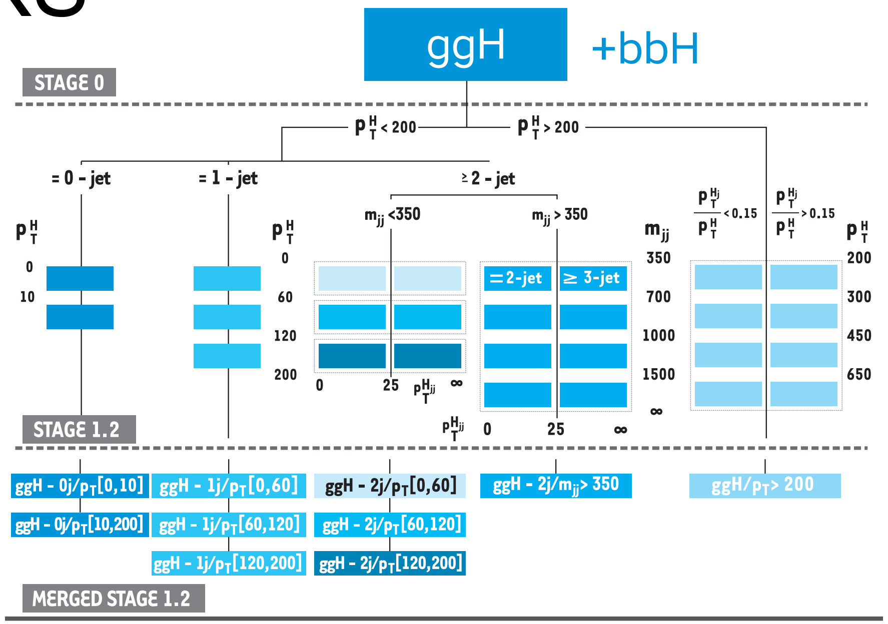
Higgs → ZZ inclusive, differential and STXS

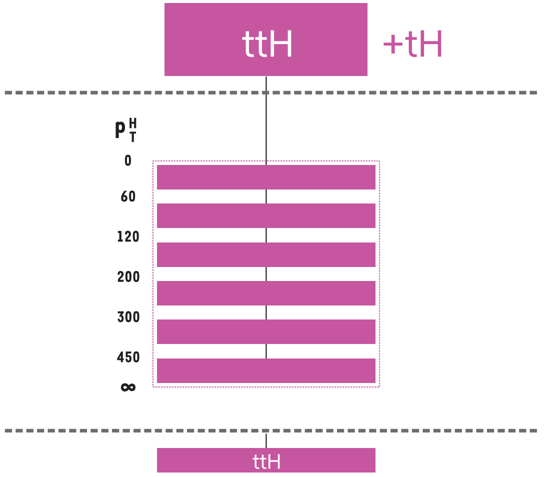
The **STXS framework** is adopted by LHC experiments to:

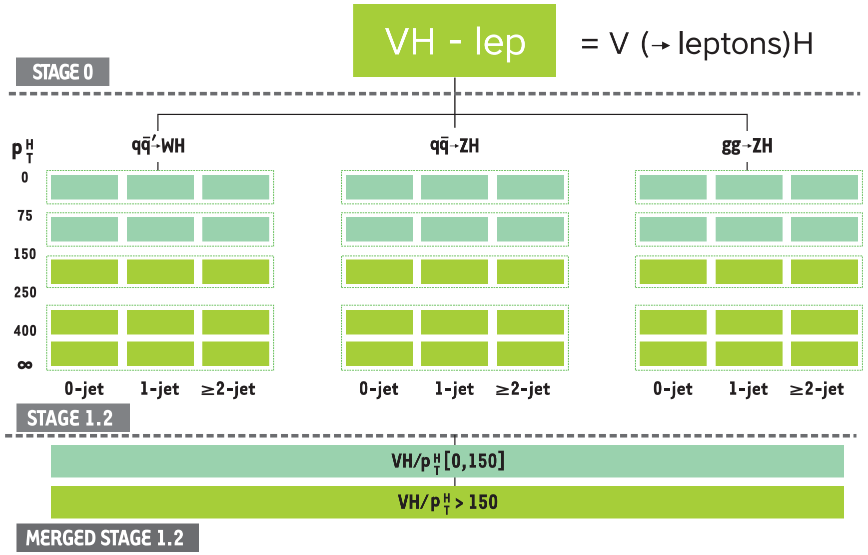
- Reduce theoretical dependence
- Combine different channels
- Increase sensitivity to BSM effects

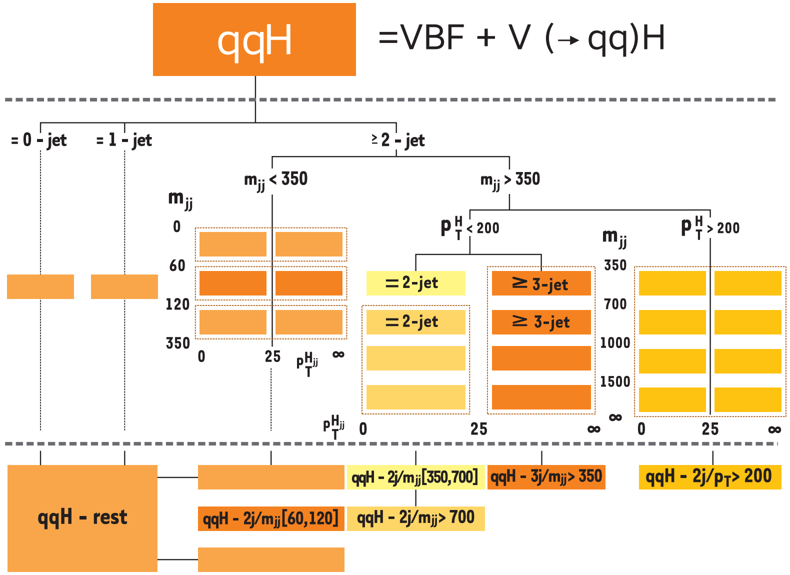
- It's not a fiducial phase space. Possible larger extrapolations

STXS stage 1.2 is used by the analysis presented here







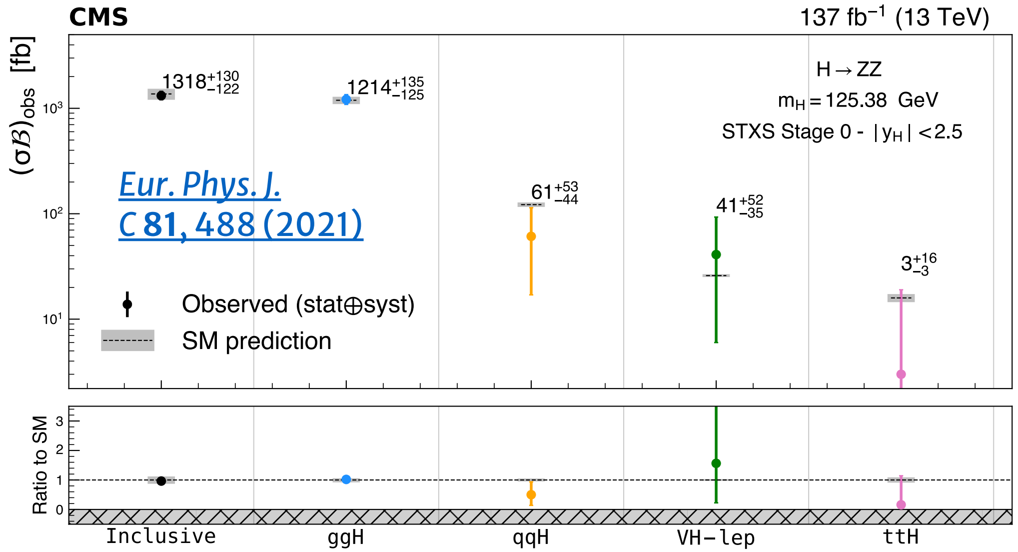


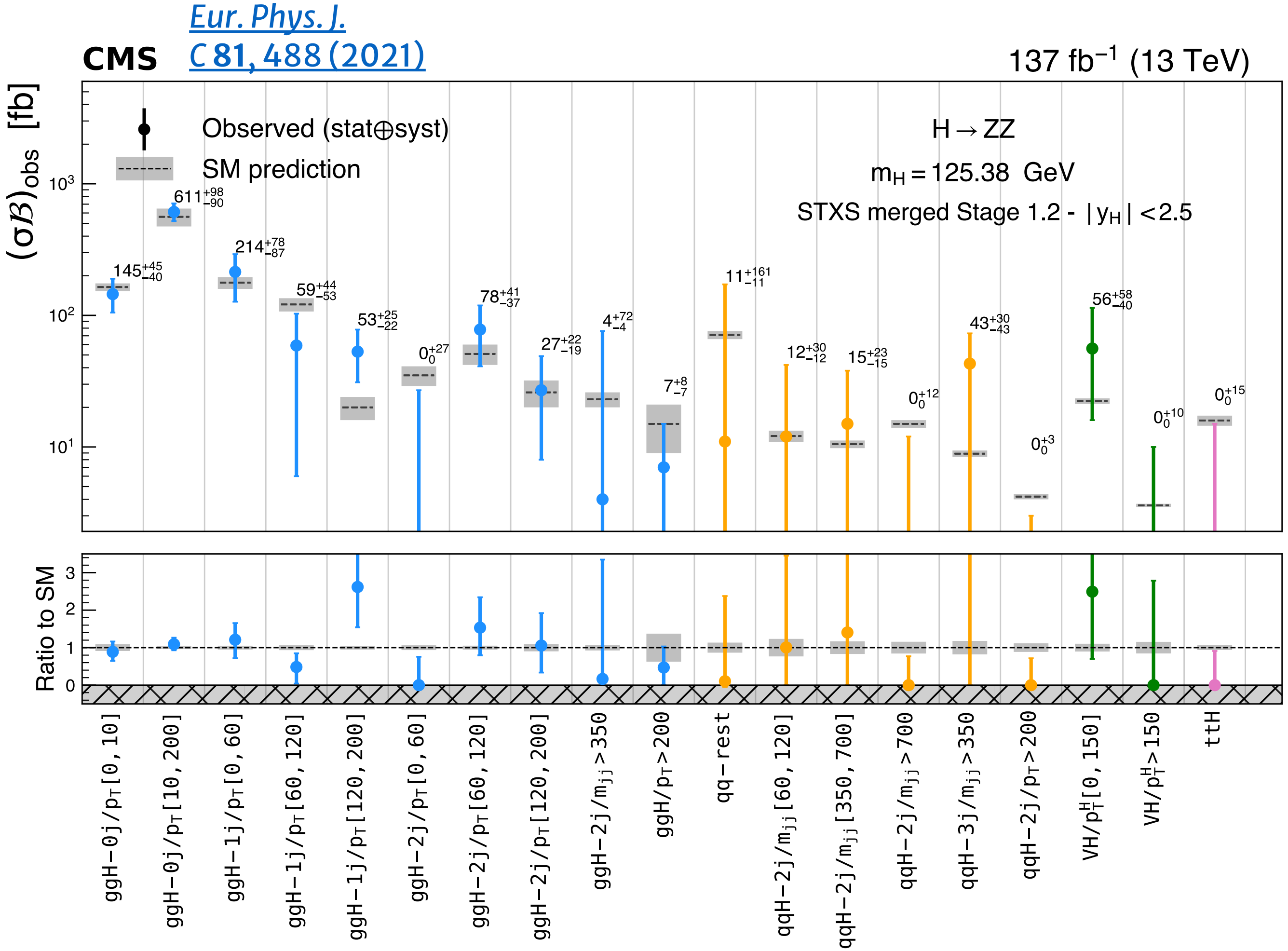
Higgs → ZZ inclusive, differential and STXS

The **STXS stage 1.2** splitting is used by the analysis presented here

All the **main productions** of the Higgs boson are targeted

Good agreement was found in all the categories





Higgs → $\gamma\gamma$ inclusive, differential and STXS

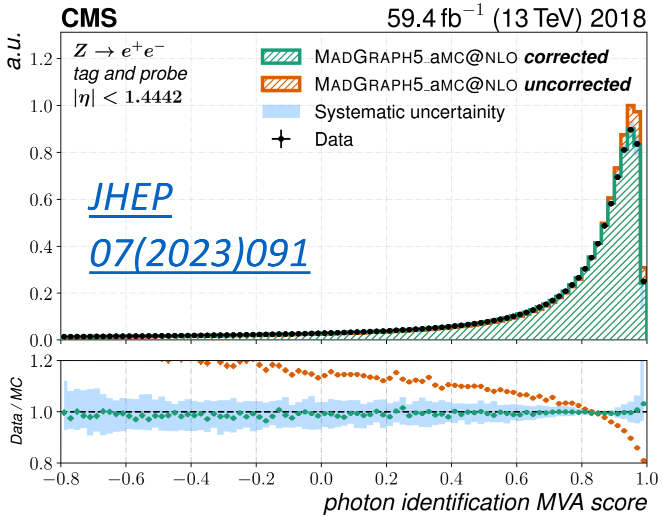
The $\mathrm{H} \rightarrow \gamma\gamma$:
- **Clean final state** topology, even with a low branching ratio
- The invariant mass can be **precisely reconstructed**

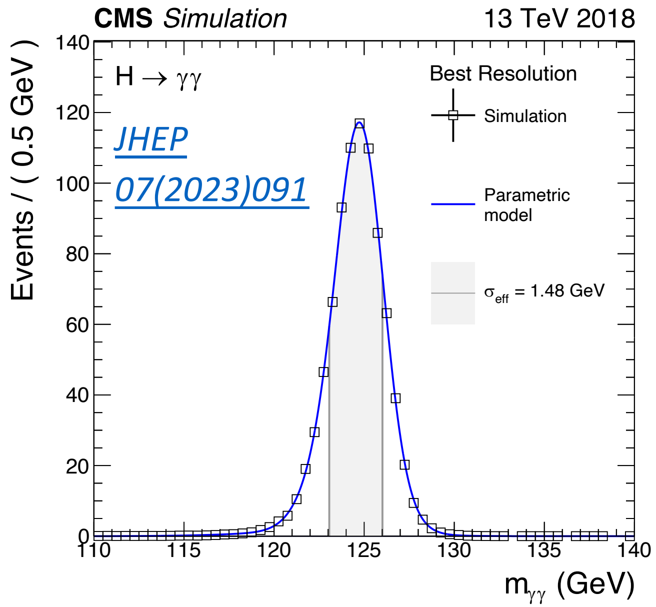
Several improvements to photons:
- **Photon MVA identification**
- **Photon energy regressor**

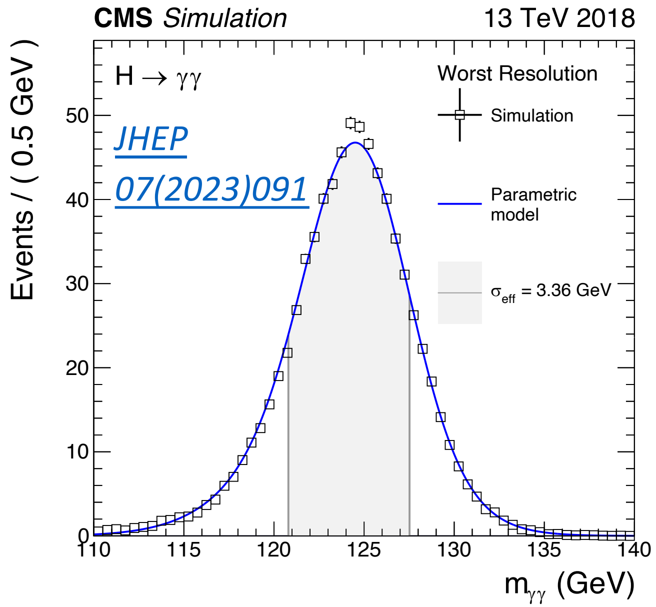
Signal region binned as a function of decorrelated mass energy resolution estimator

Extra leptons, jets, b-jets, MET, etc. for different production mechanisms

Fiducial phase space
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$
$\mathcal{I}_{\text{gen}}^{\gamma} < 10$ GeV
$\lvert\eta\rvert < 2.5$



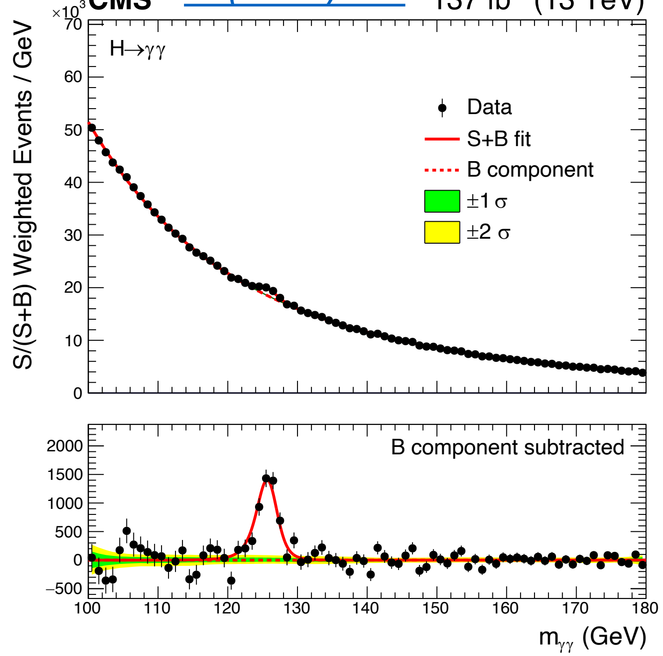




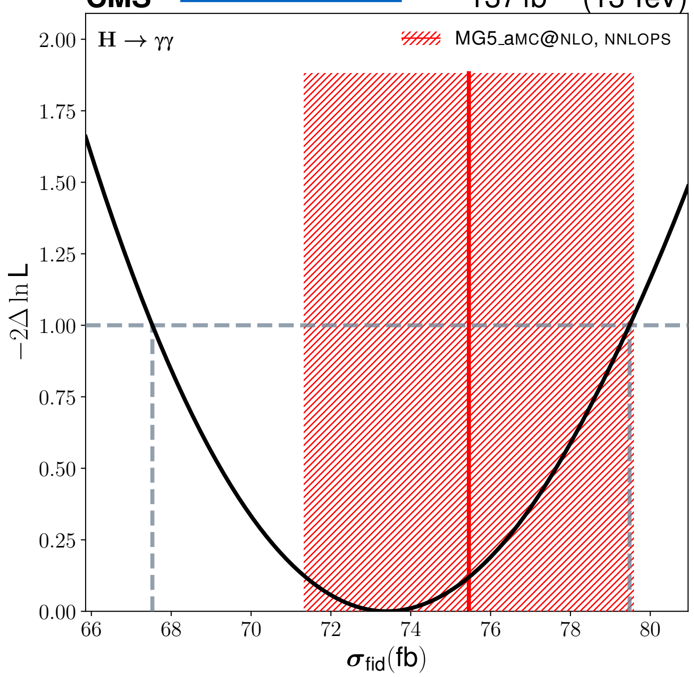
Higgs → $\gamma\gamma$ inclusive, differential and STXS

- Dominant background from **QCD diphoton production**. The background shape is fit using monotonically falling shapes through the discrete profiling method
- **Very precise results** for the Higgs cross-section, including all the main production mechanisms
- The signal strength is extracted via **fit to the diphoton mass**: $\sigma^{fid} = 73.4^{+6.1}_{-5.9} = 73.4^{+5.4}_{-5.3}(stat)^{+2.4}_{-2.2}(syst)$ fb

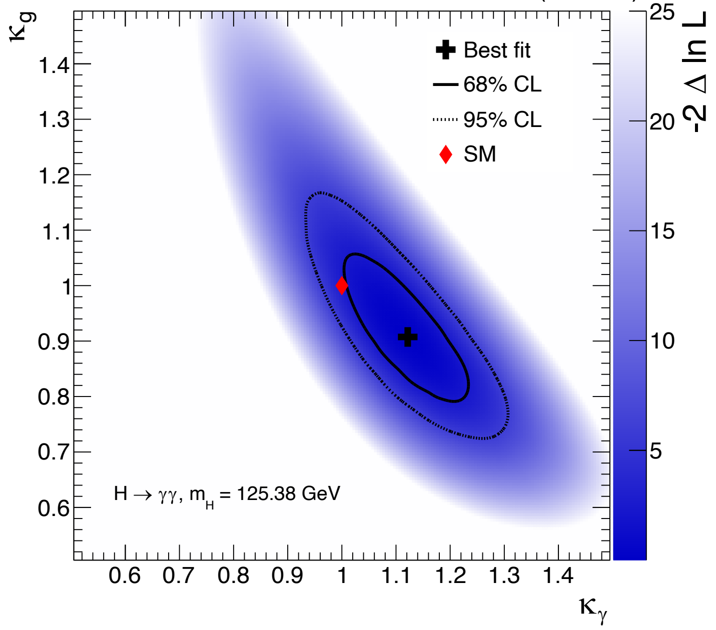
JHEP 07(2023)091



JHEP 07(2023)091



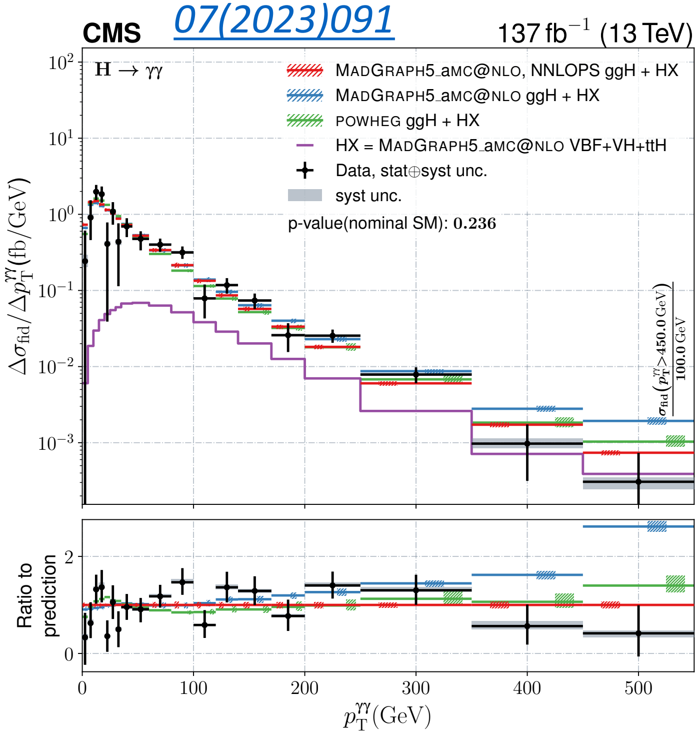
JHEP 07(2021)027



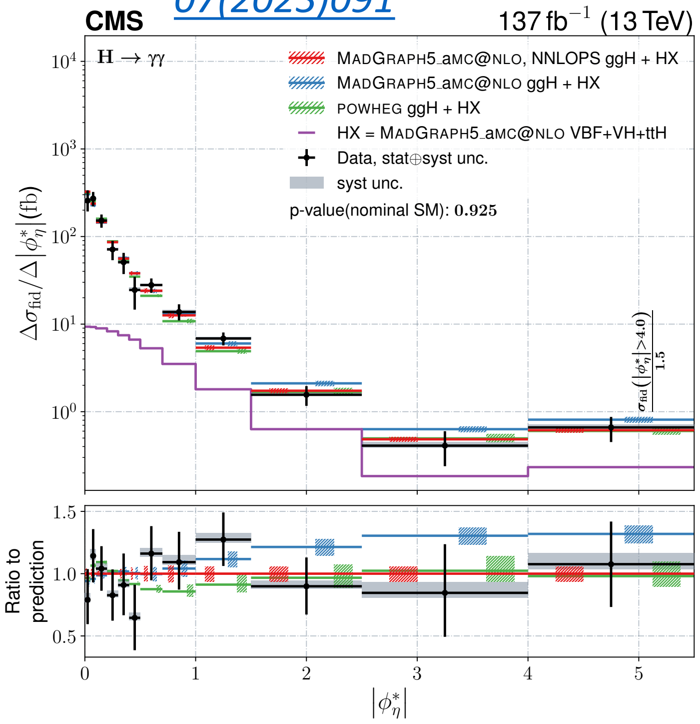
Higgs → $\gamma\gamma$ inclusive, differential and STXS

- **High granularity and precision** are reached in the **differential analysis**
- **26 differential measurements:** 24 one-dimensional and 2 two-dimensional distributions from different kinematic variables
- Good agreement with the SM predictions is found in all cases. Multiple MC predictions are compared here

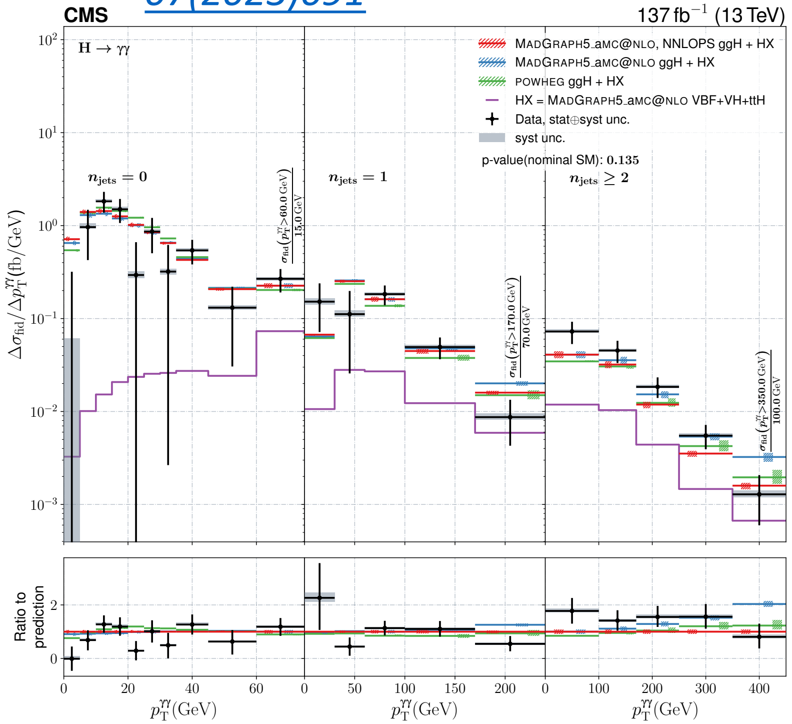
JHEP 07(2023)091



JHEP 07(2023)091

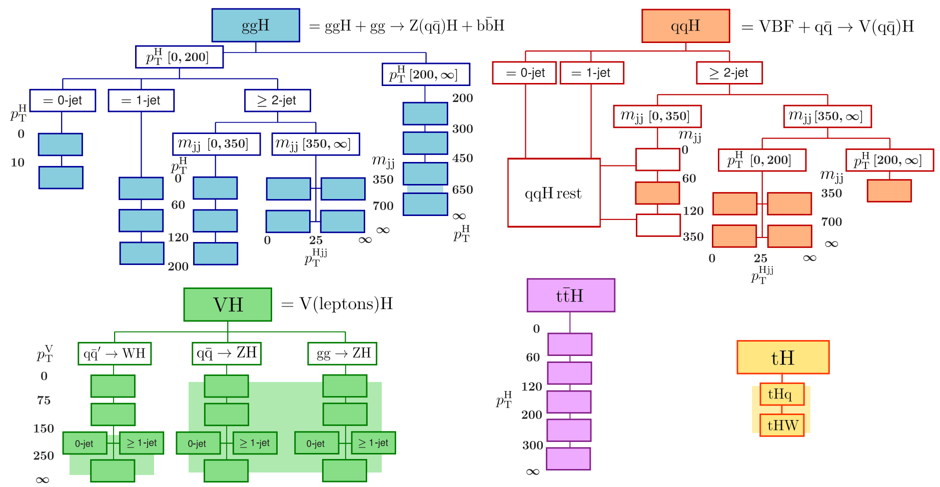


JHEP 07(2023)091

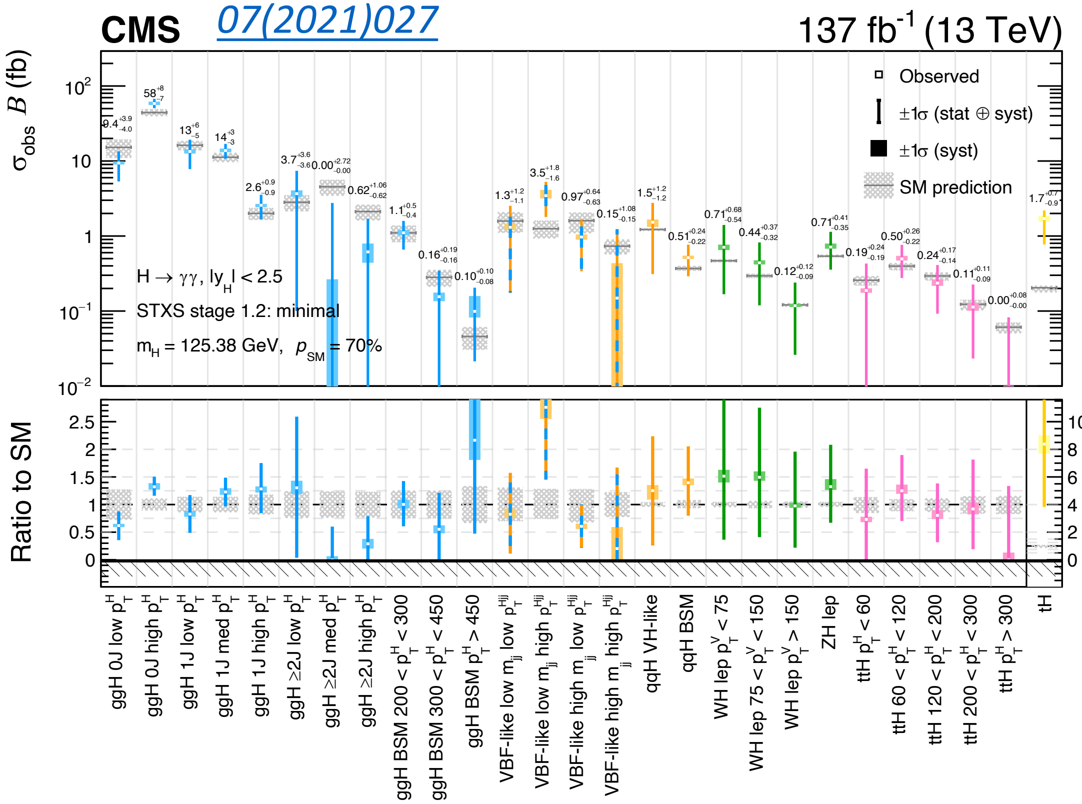


Higgs → $\gamma\gamma$ inclusive, differential and STXS

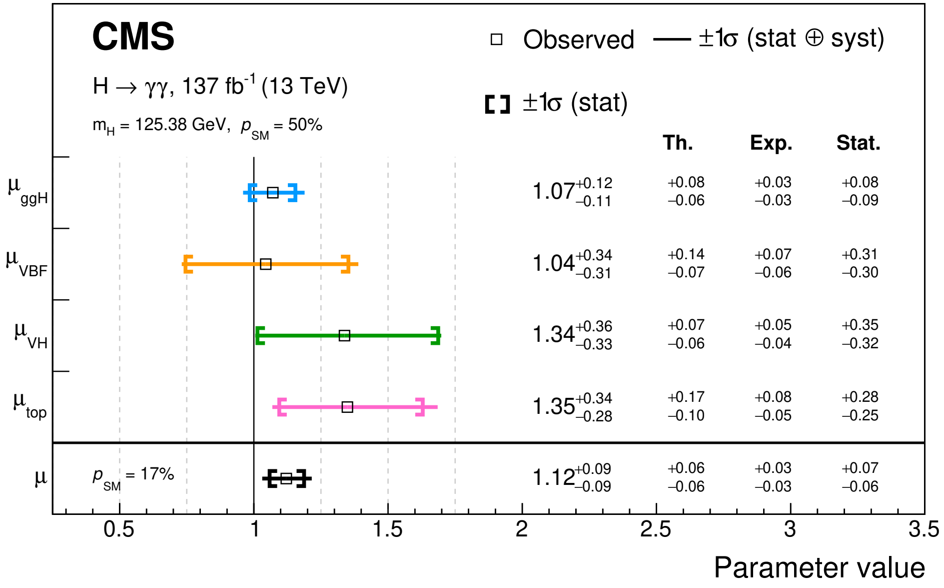
- The **STXS stage 1.2** measured with the highest precision in CMS
- 17(27) **independent kinematic regions** fit simultaneously for the 4 main production modes in 2 independent measurements
- An upper limit is set for **tH production mode**



JHEP 07(2021)027



JHEP 07(2021)027



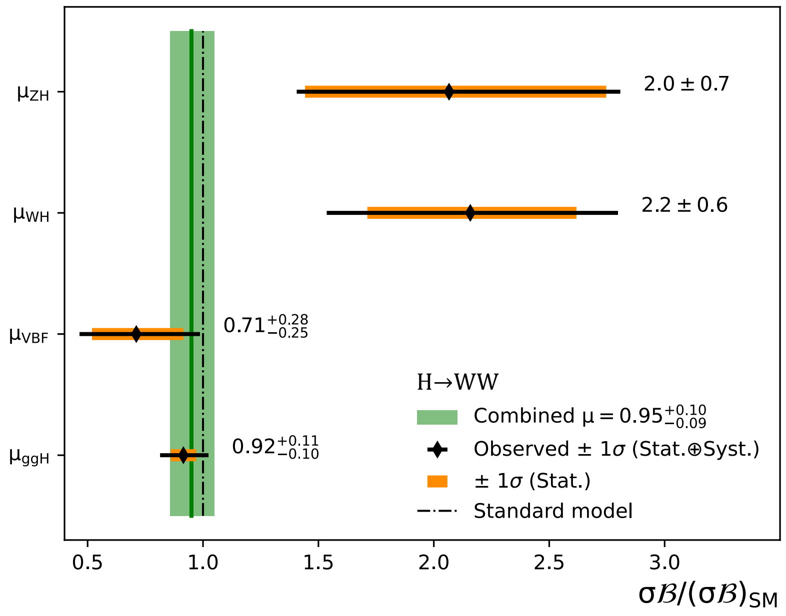
Higgs → WW inclusive, differential and STXS

- The $H \to WW$ benefits from the **second-largest branching ratio**. No possible reconstruction of the Higgs mass. Large backgrounds. Huge variety of final state topologies, always targeting at least **2 leptons**
- In particular, affected by **top, DY, WW,** and **non-prompt lepton** contaminations. Define different **Control Regions** to constraint/control the main backgrounds from data

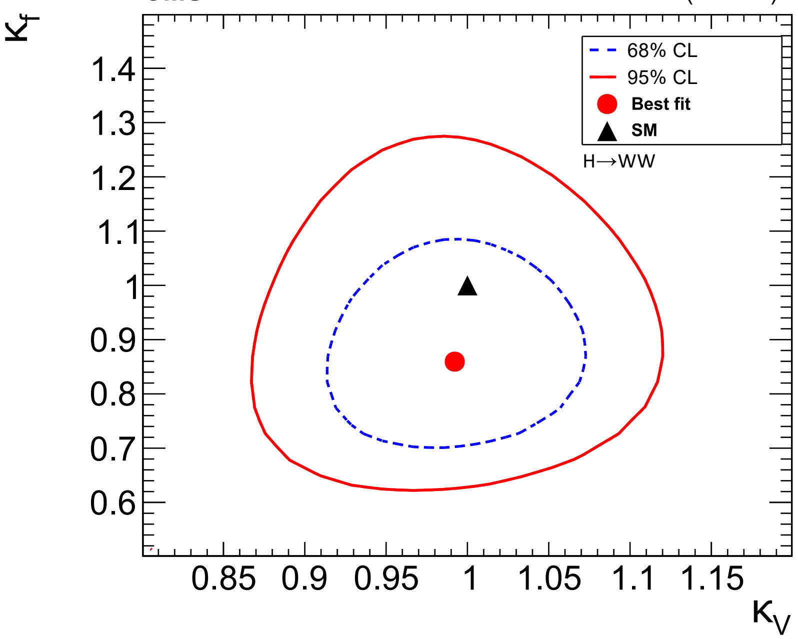
$$\mu_{inc} = 0.95^{+0.10}_{-0.09} = 0.95 \pm 0.05(stat) \pm 0.08(syst)$$

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

Eur. Phys. J. C 83, 667 (2023)



Eur. Phys. J. C 83, 667 (2023)

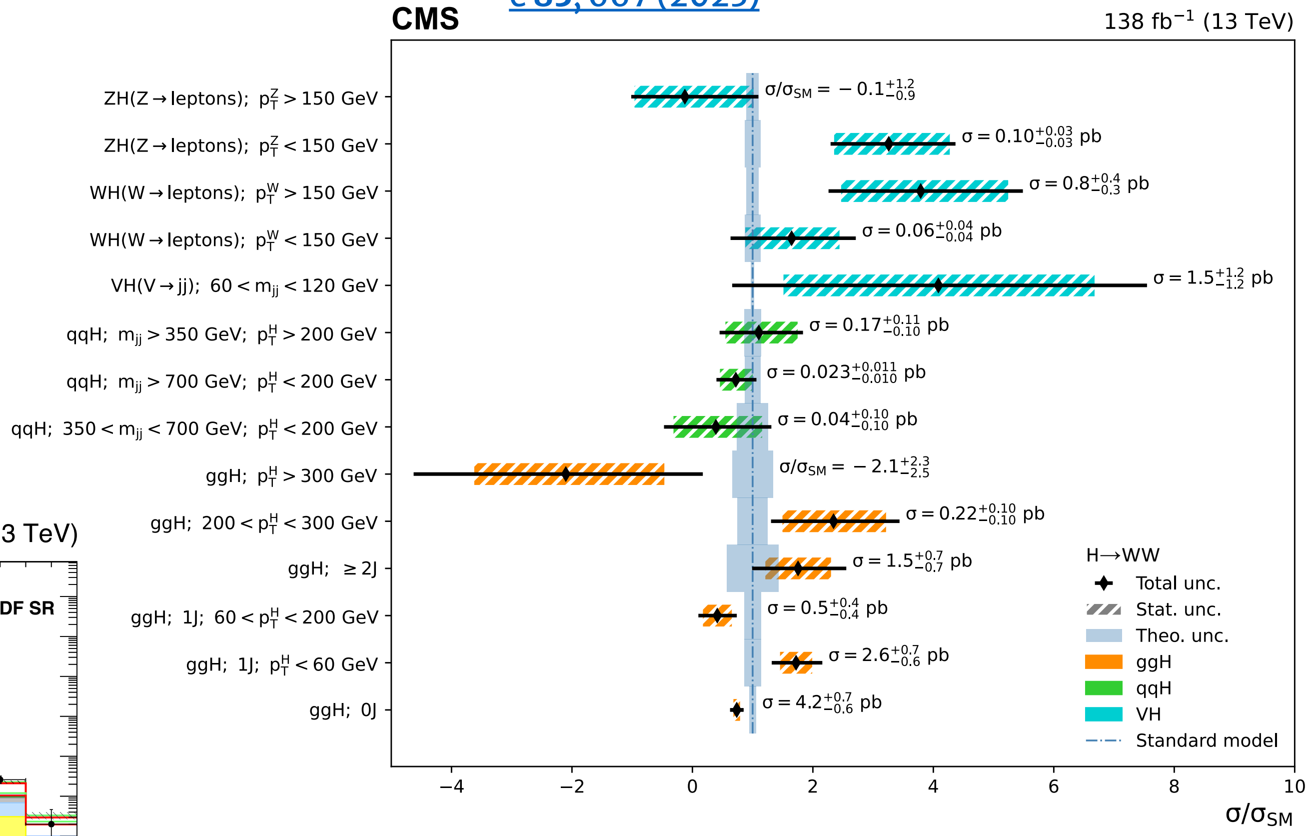


Fiducial phase space
$p_{T,l_1} > 25$ GeV
$p_{T,l_2} > 13$ GeV
$\lvert\eta\rvert < 2.5$
$m_{ll} > 12$ GeV
$p_T^{ll} > 30$ GeV
$m_T^{l2} > 30$ GeV
$m_T^H > 60$ GeV

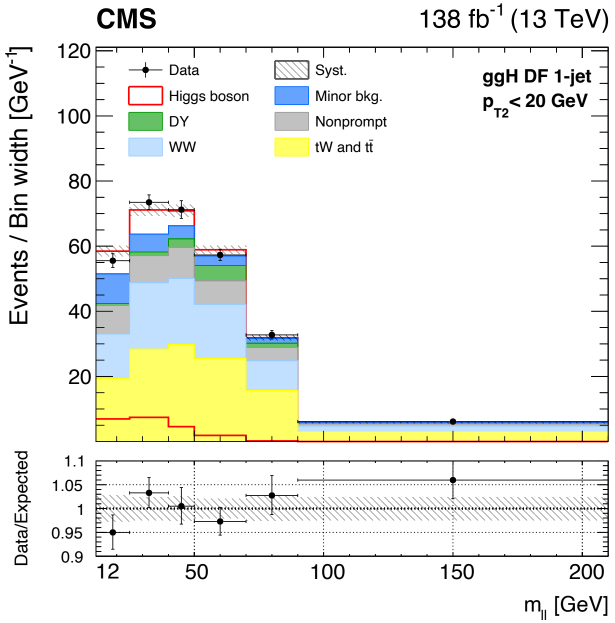
Higgs → WW inclusive, differential and STXS

- The **STXS stage 1.2** is targeted in this analysis
- Some bins are **merged** because of the lack of statistics
- **Different observables** are used to extract the signal strength modifiers, such as kinematic variables, BDTs or DNNs

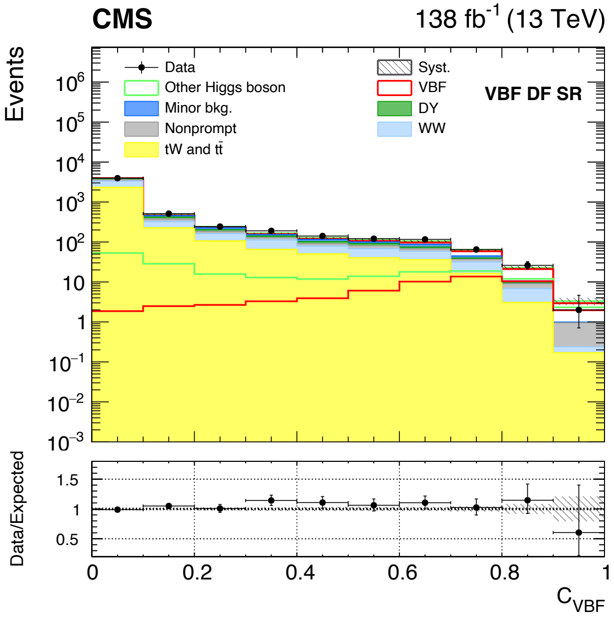
Eur. Phys. J. C 83, 667 (2023)



Eur. Phys. J. C 83, 667 (2023)

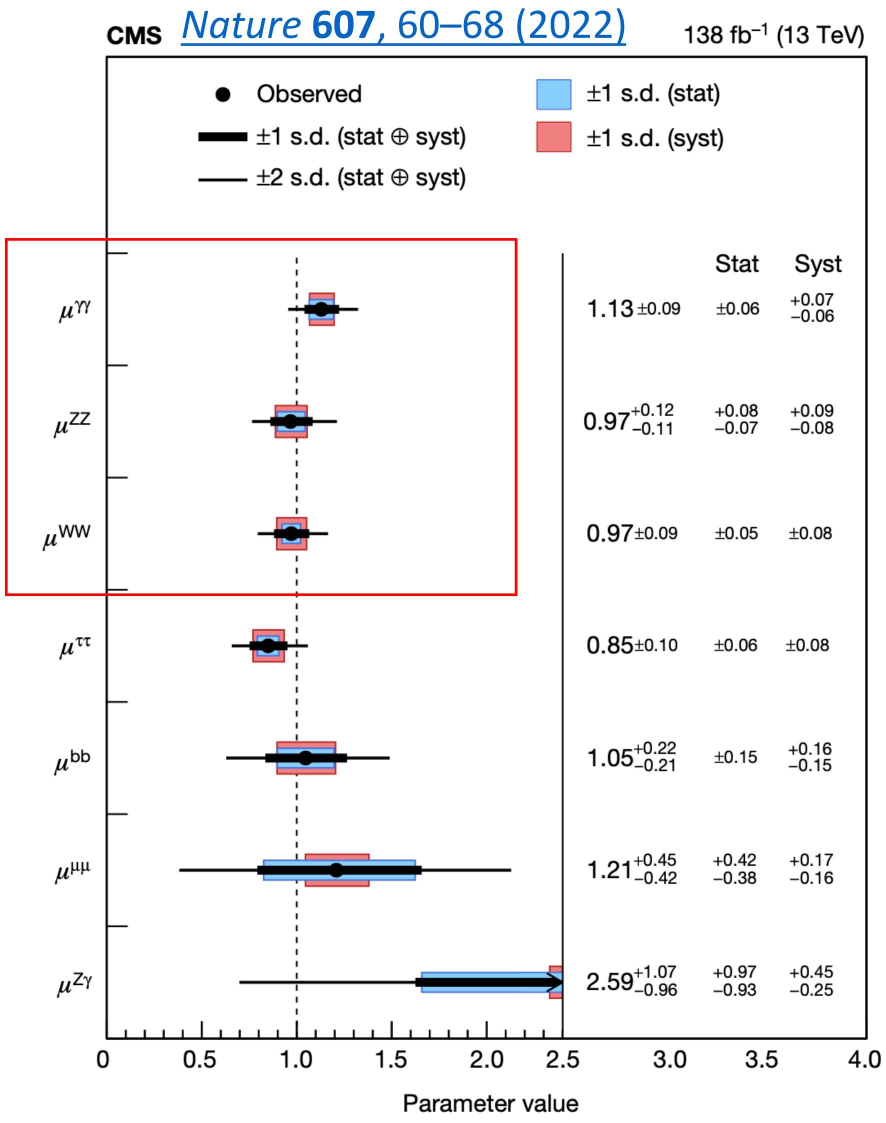


Eur. Phys. J. C 83, 667 (2023)



Summary

- In a few years, the Higgs boson physics has moved from discovery to precision measurements, **what's next?**
  - Higgs boson self couplings
  - Double Higgs production
  - Anomalous couplings
  - …
- All the data show an **excellent agreement** with the standard model predictions
- And **more statistics** to complete the most statistically limited analysis



BACKUP

Higgs boson production modes

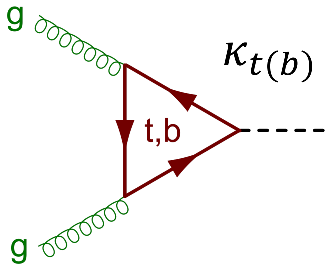
Run 2 legacy precision allows us to probe the coupling structure of the Higgs boson.

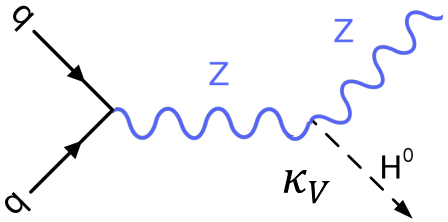
The analyses are divided into different classes by production mode so we can measure:

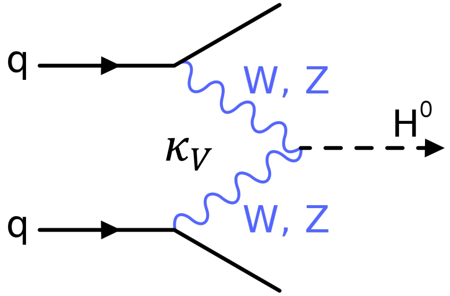
$$\mu = \frac{\sigma(\times BR)}{\sigma(\times BR)_{SM}}$$ **Signal strength**

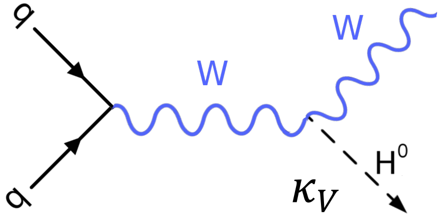
$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H}$$ **Couplings**

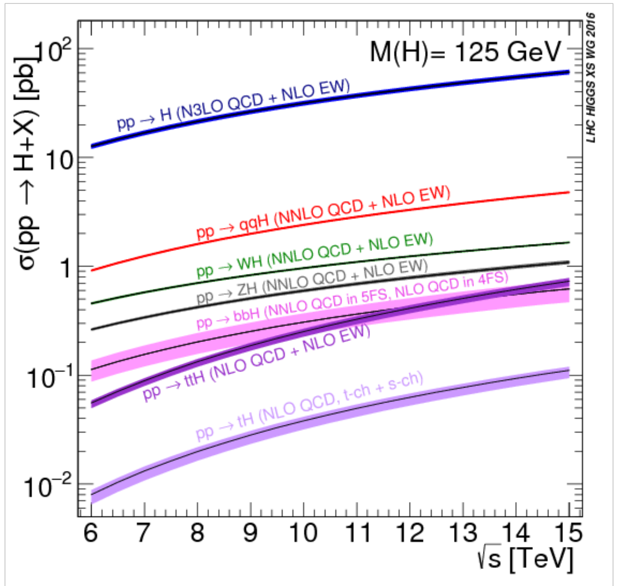
STXS 1.2 (with merged bins due to statistics)









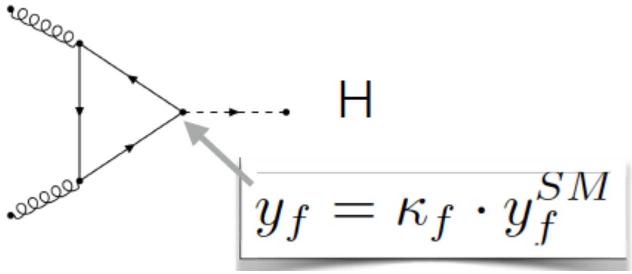


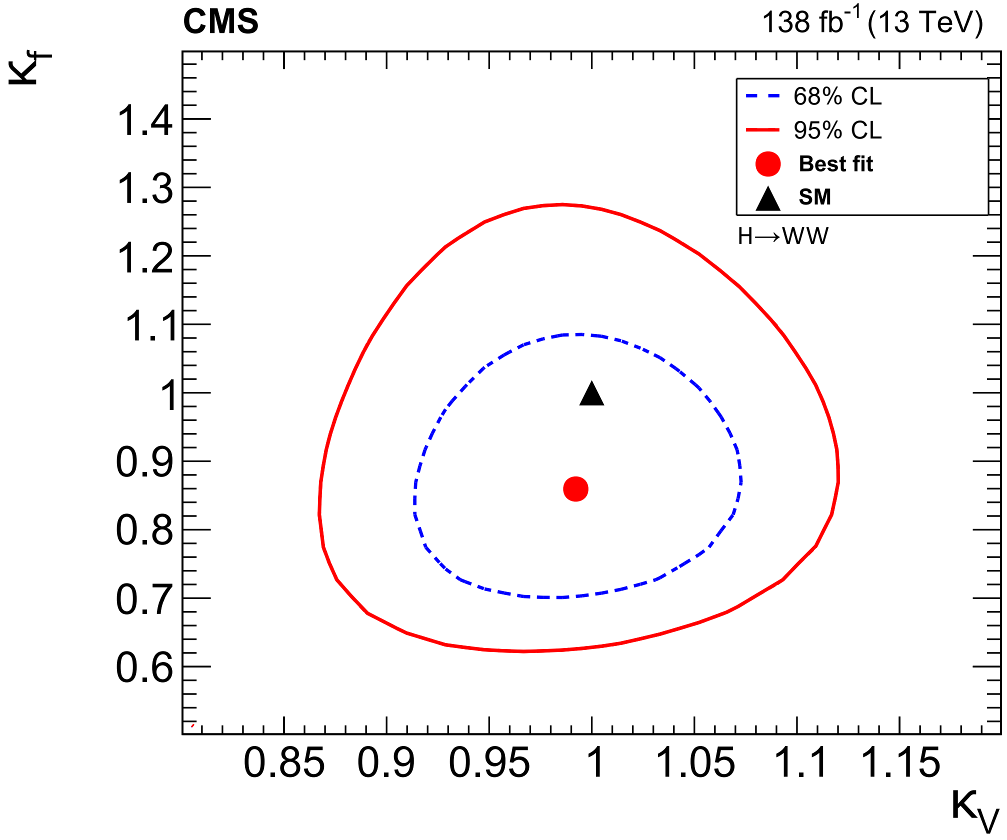
Signal strength and couplings

The results on the fermion and boson couplings of the Higgs boson are obtained scaling the signal according to:

$$\sigma B(X_i \to H \to WW) = \kappa_i^2 \frac{\kappa_V^2}{\kappa_H^2(\kappa_V, \kappa_f)} \sigma_{SM} B_{SM}(X_i \to H \to WW)$$

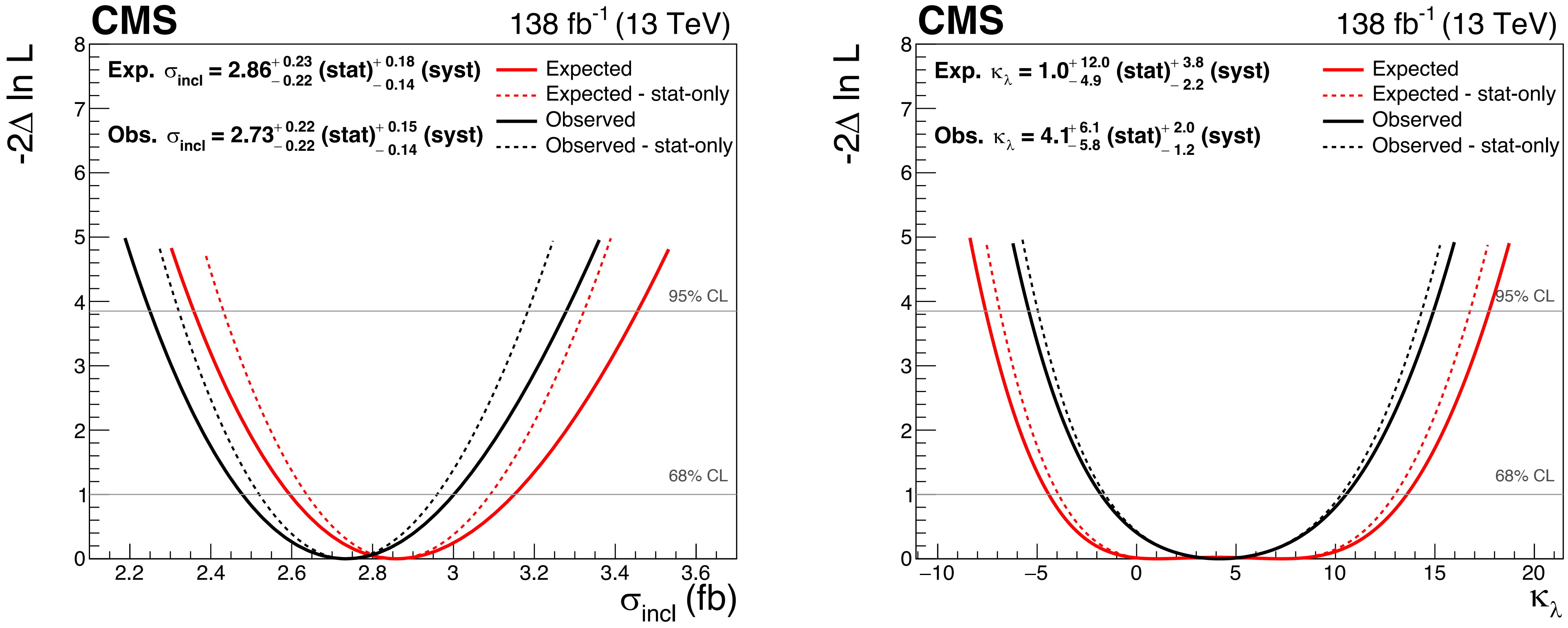
Where κ_H is the modifier of the total Higgs width, and X_i the different production modes





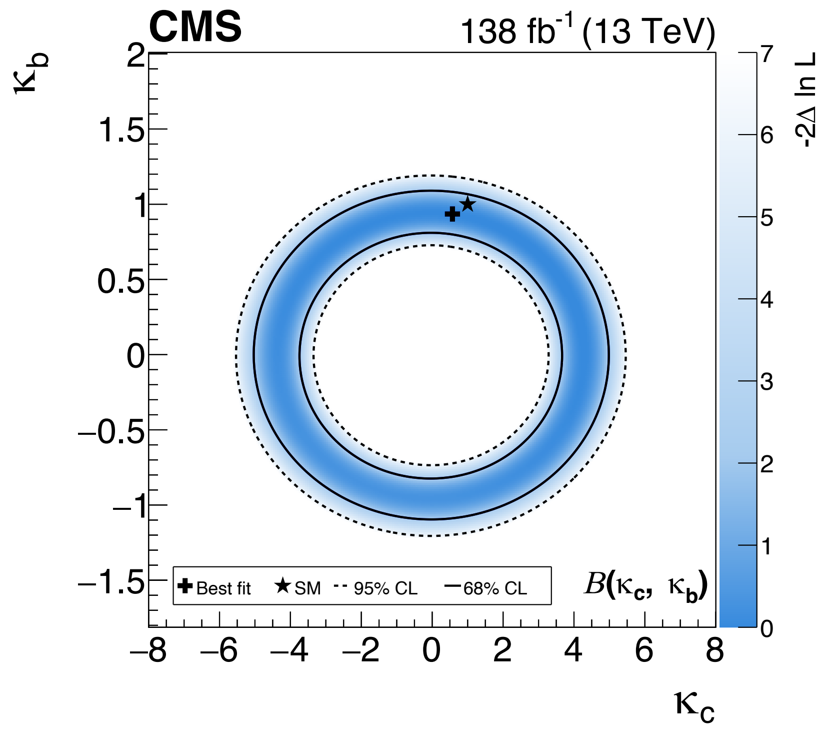
Higgs → ZZ inclusive, differential and STXS

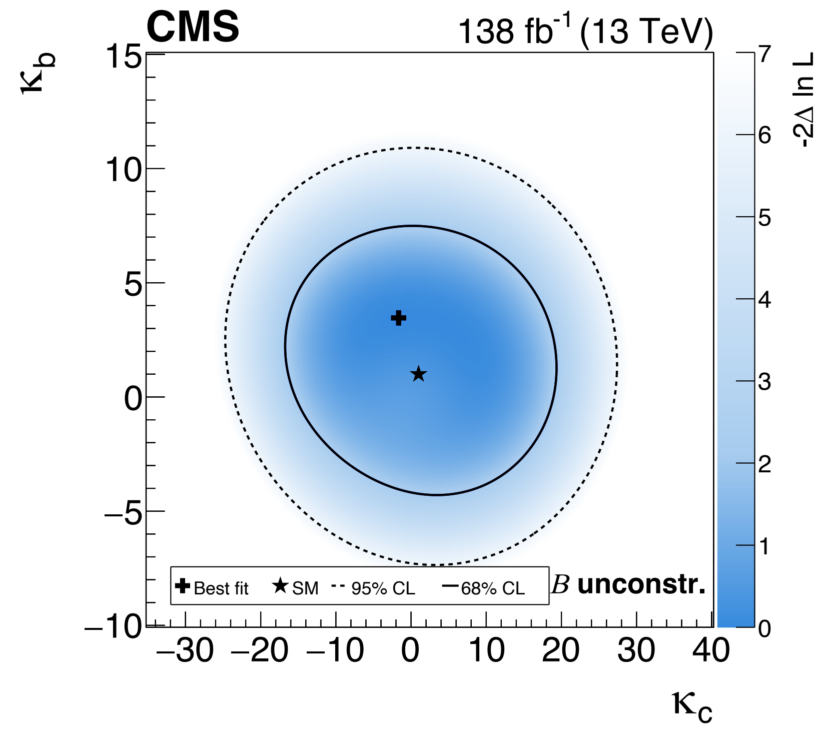
Results on inclusive cross section and couplings



Higgs → ZZ inclusive, differential and STXS

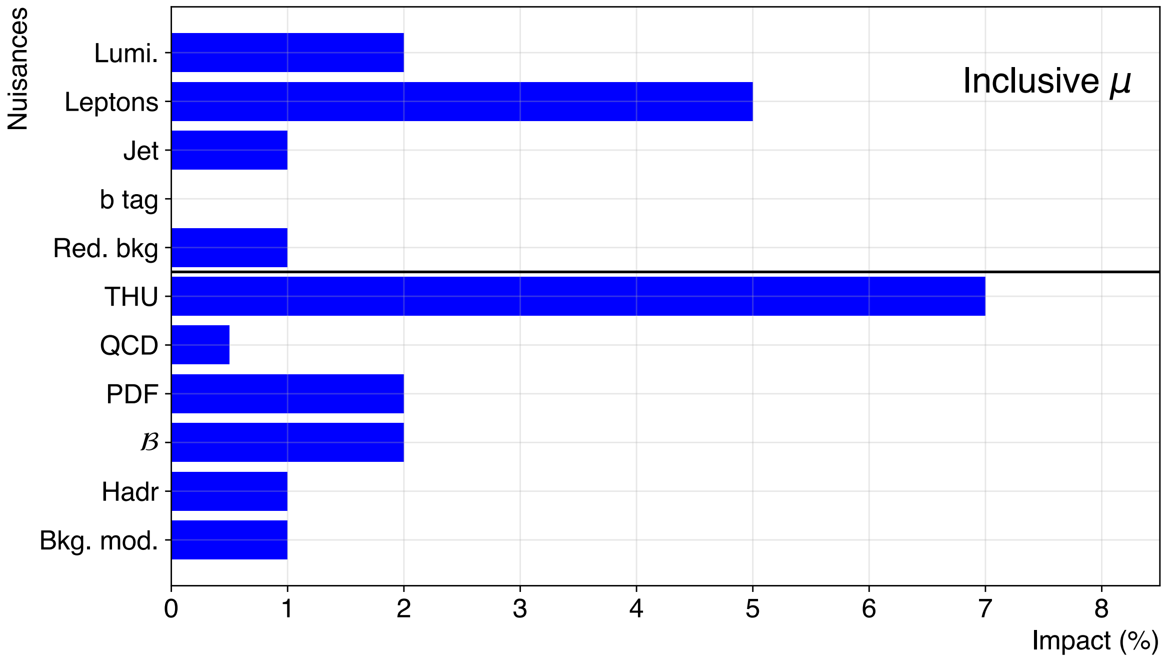
Result on couplings for constrained and unconstrained branching fraction

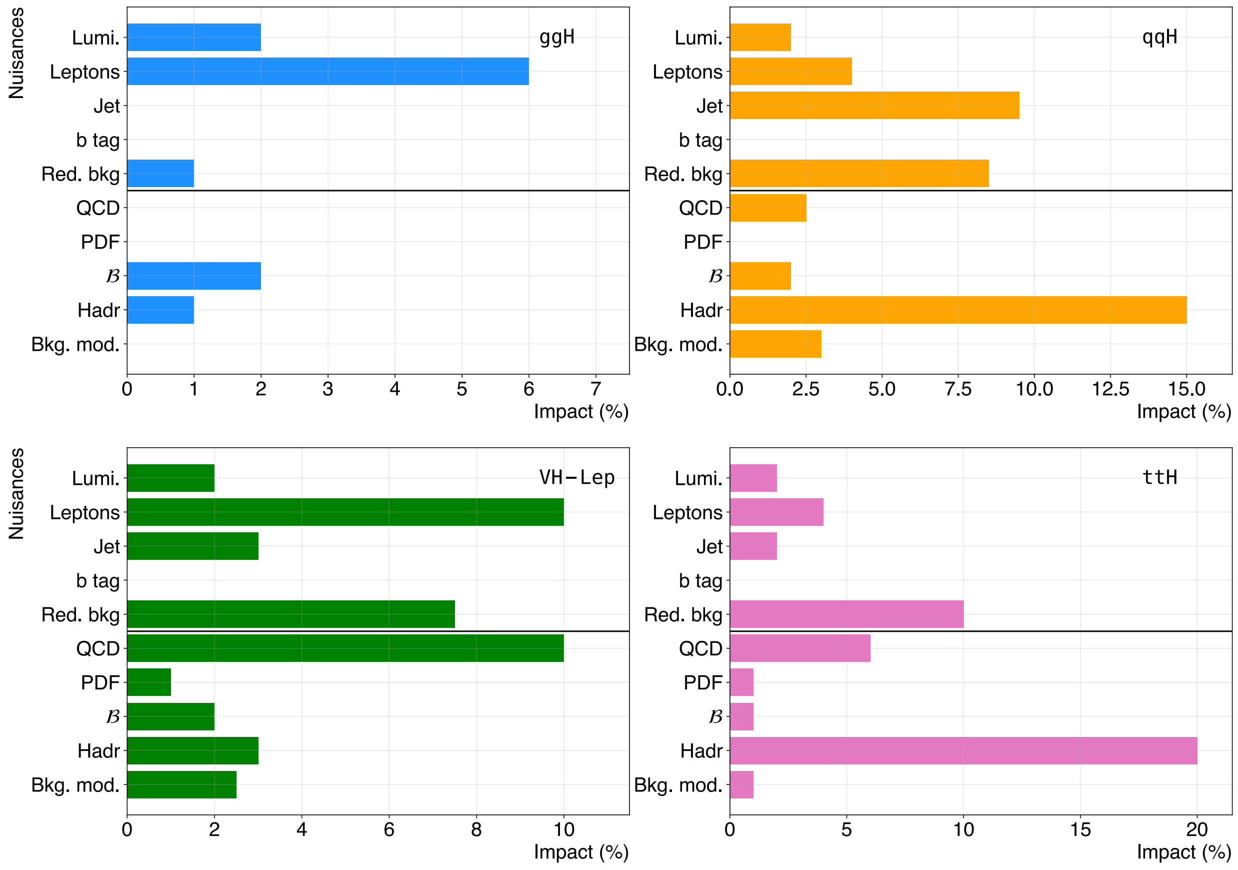




Higgs → ZZ inclusive, differential and STXS

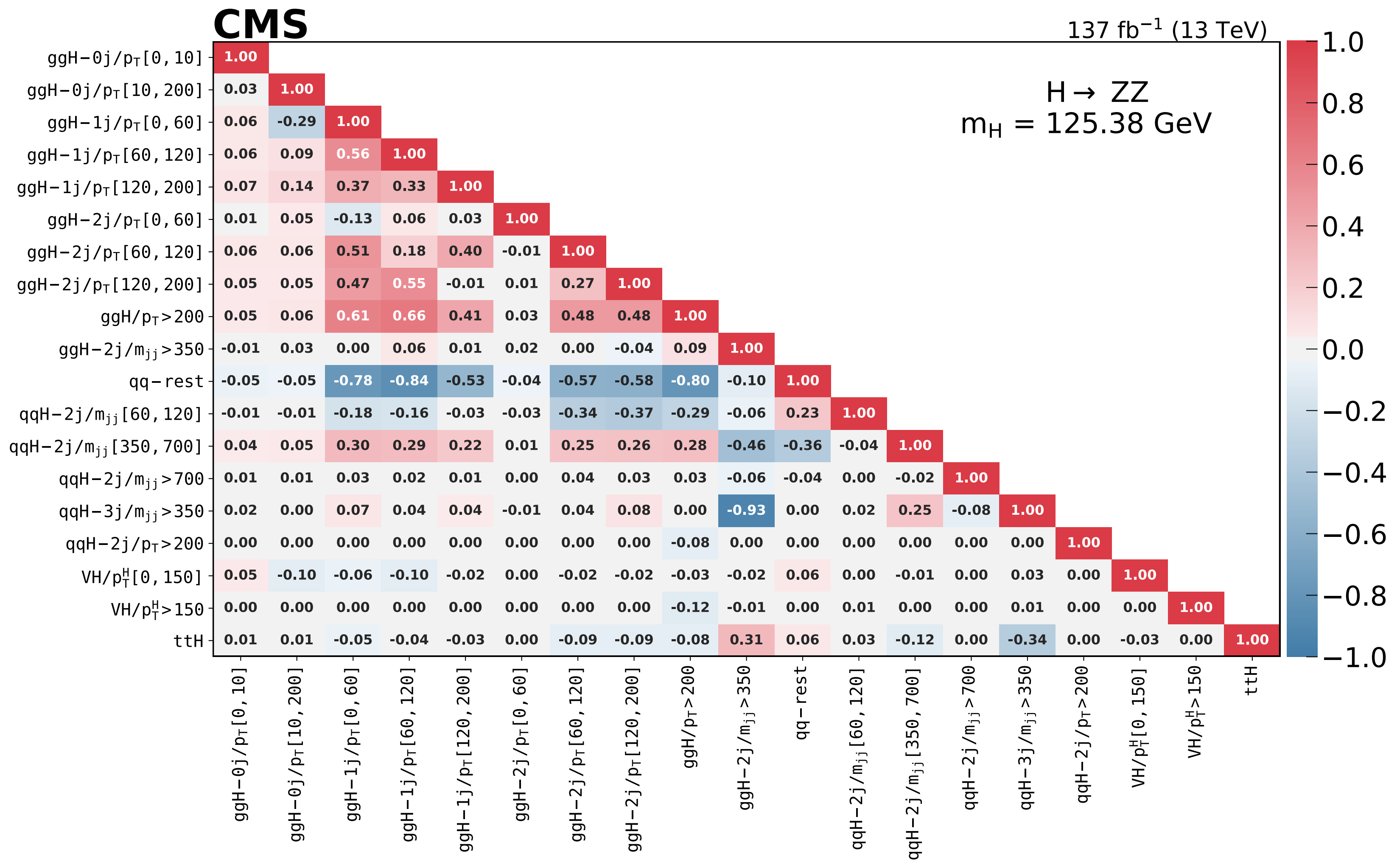
Matrix element discriminants are used to separate the different production modes in the STXS HZZ analysis. For ttH, b-tagged jets are targeted





Higgs → ZZ inclusive, differential and STXS

Matrix element discriminants are used to separate the different production modes in the STXS HZZ analysis. For ttH, b-tagged jets are targeted



Higgs → $\gamma\gamma$ inclusive, differential and STXS

Photon identification and reconstruction

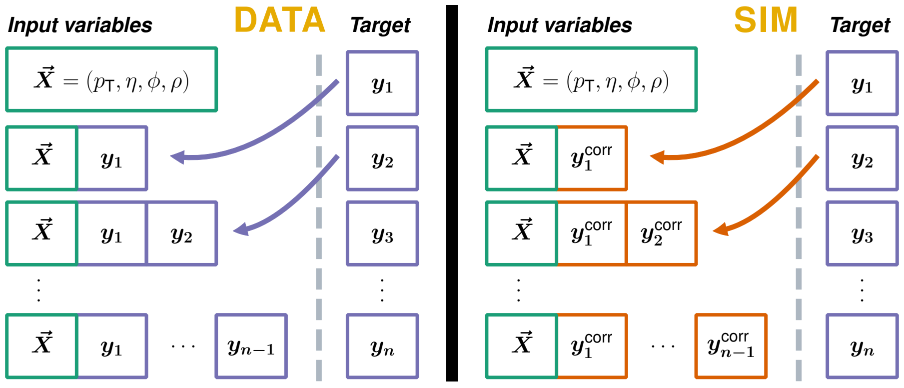
MVA is designed to reject non-prompt photons from hadronic activity

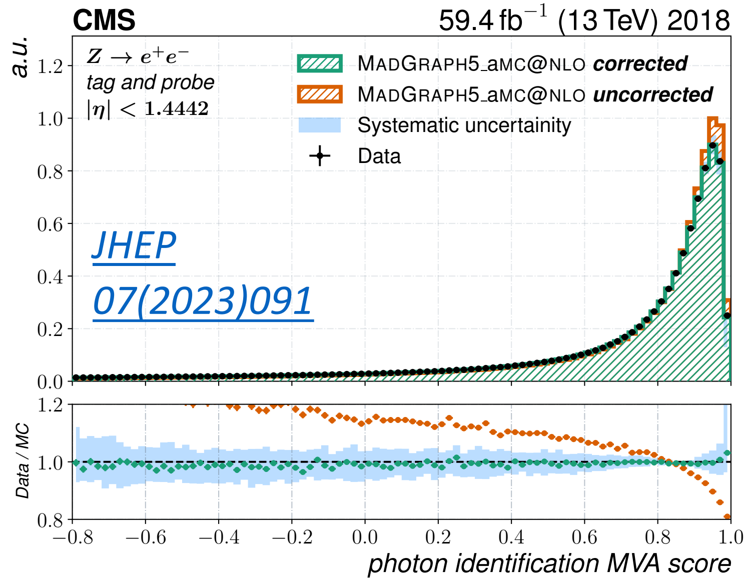
A method called quantile regression is used to correct the MC input distributions to match the data.

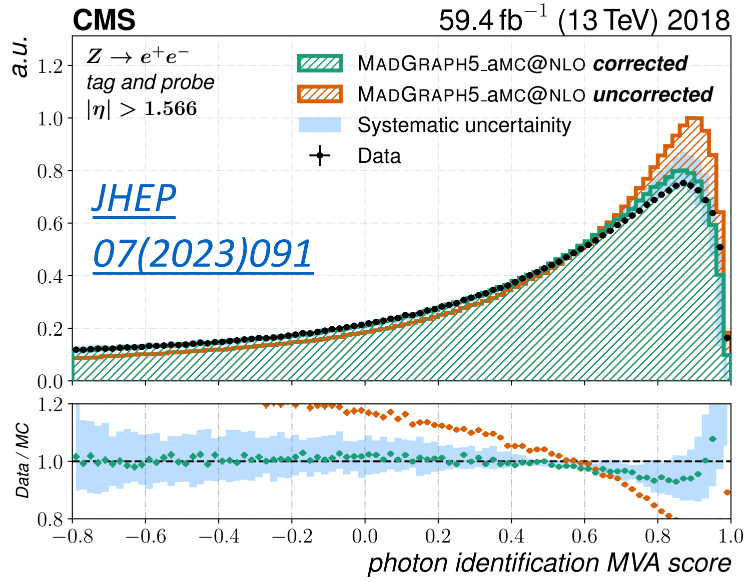
Photon energy regressor

An MVA is also used to estimate the photon energy with a higher accuracy. However, there is a proportional correlation between the energy resolution and the invariant mass of the diphoton system. This may lead into undesired background shapes when you bin the signal region as a function of the mass resolution

Then, a quantile morphing algorithm is used to decorrelate the variables

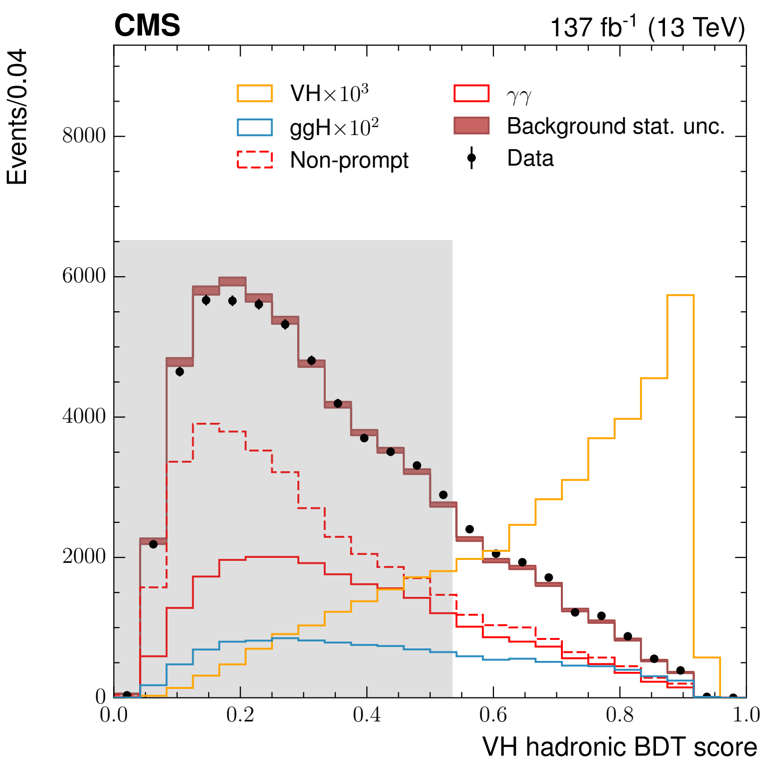




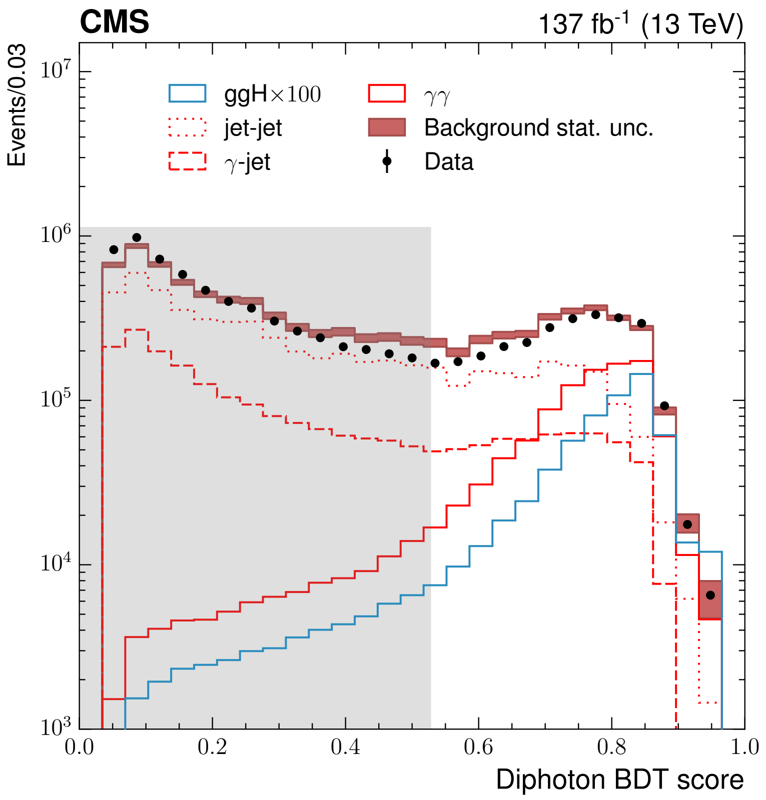


Higgs → $\gamma\gamma$ inclusive, differential and STXS

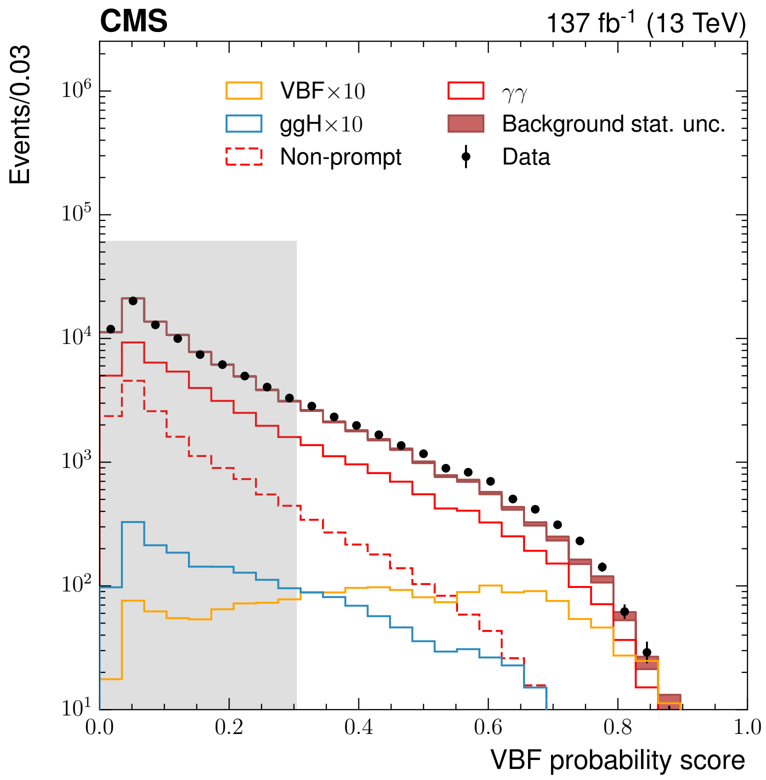
VH hadronic



ggH

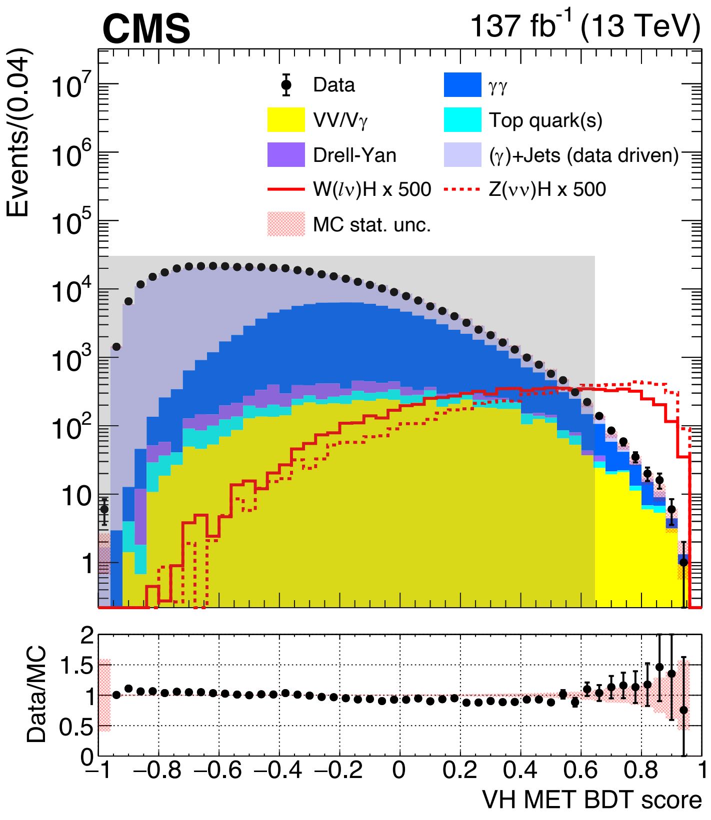


VBF hadronic

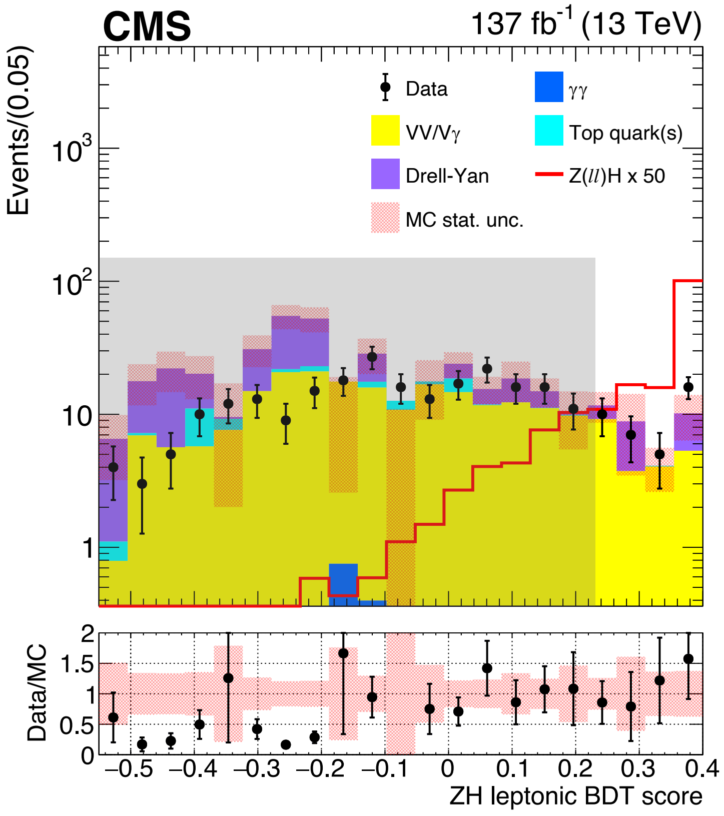


Higgs → $\gamma\gamma$ inclusive, differential and STXS

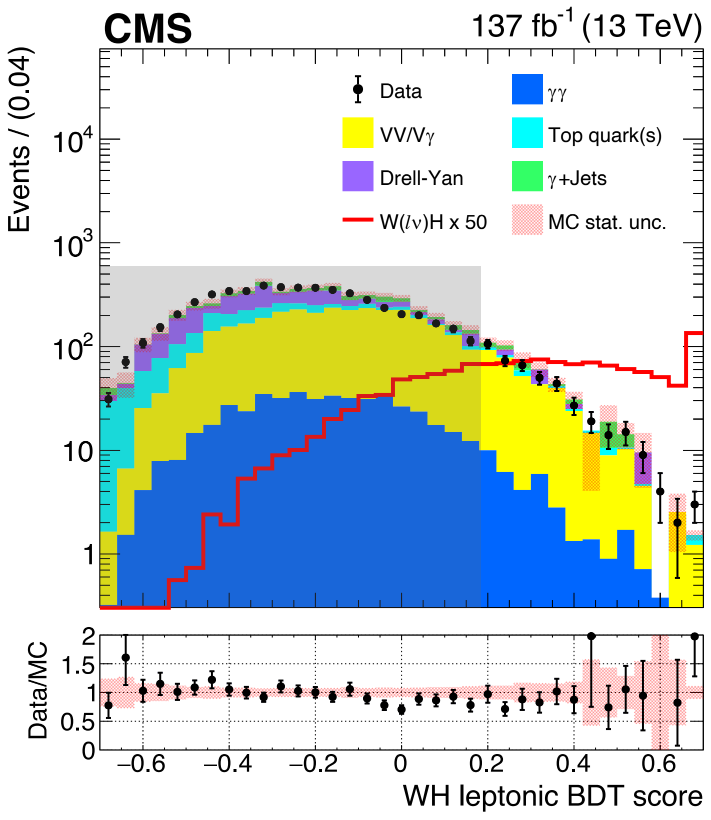
VH MET



ZH MET

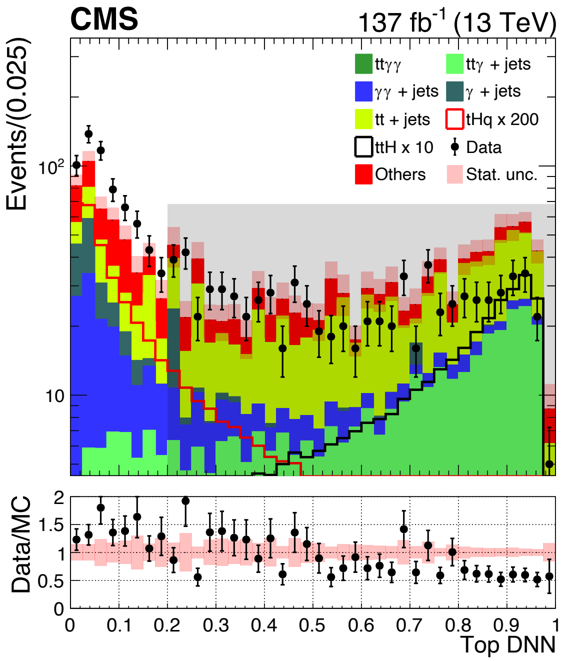


WH MET

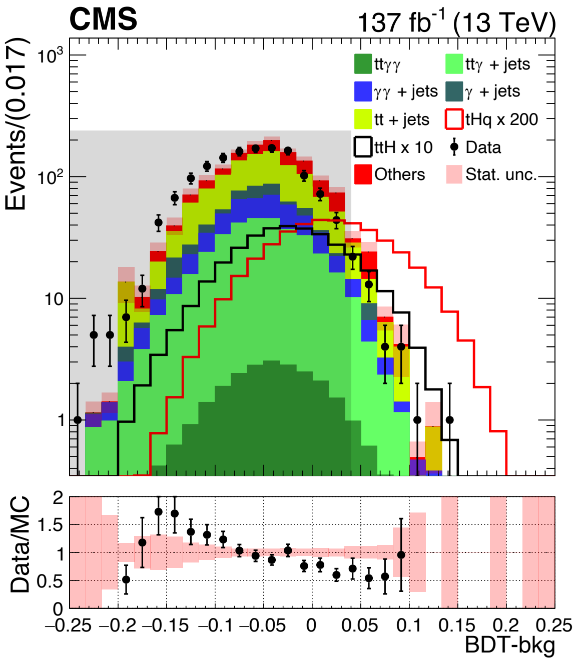


Higgs → $\gamma\gamma$ inclusive, differential and STXS

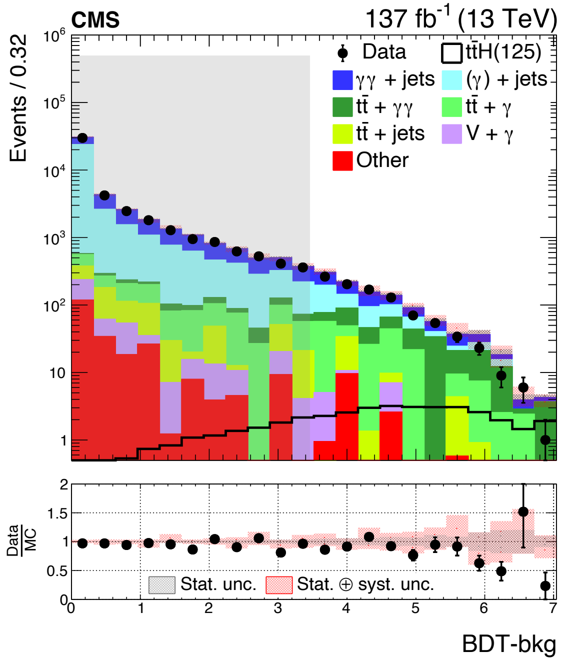
ttH vs tHq



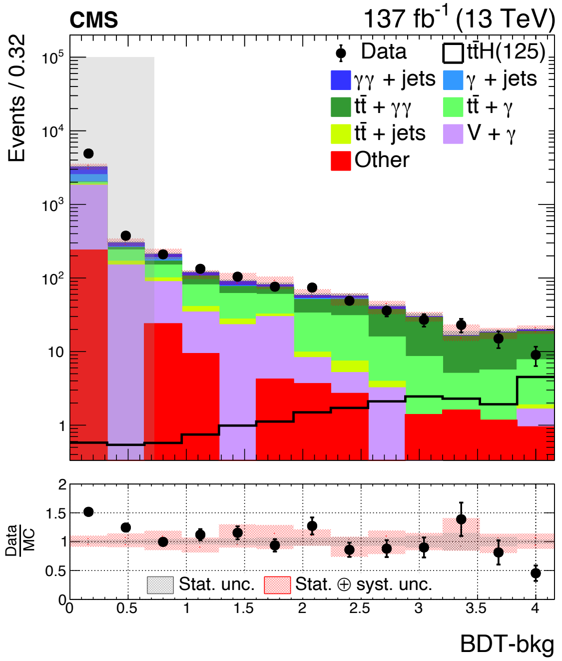
ttH+tHq vs Bkg



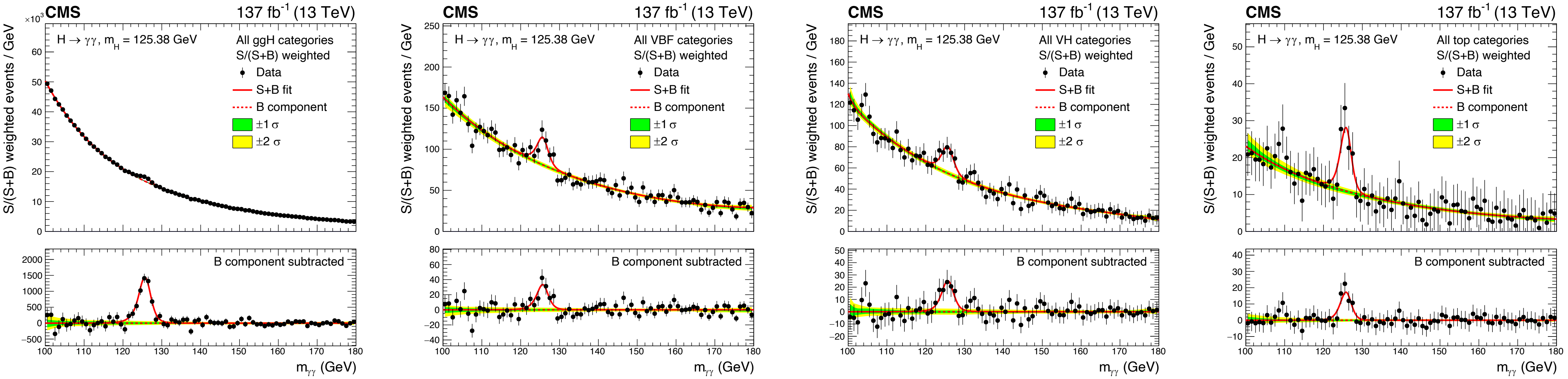
ttH hadronic



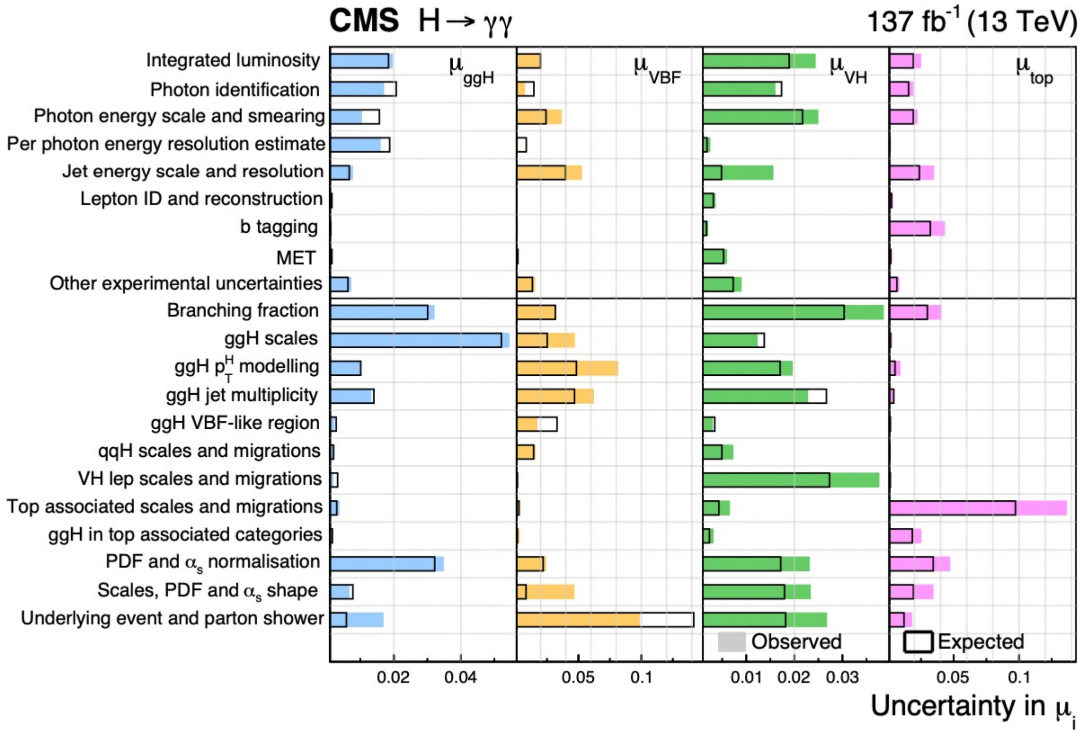
ttH leptonic

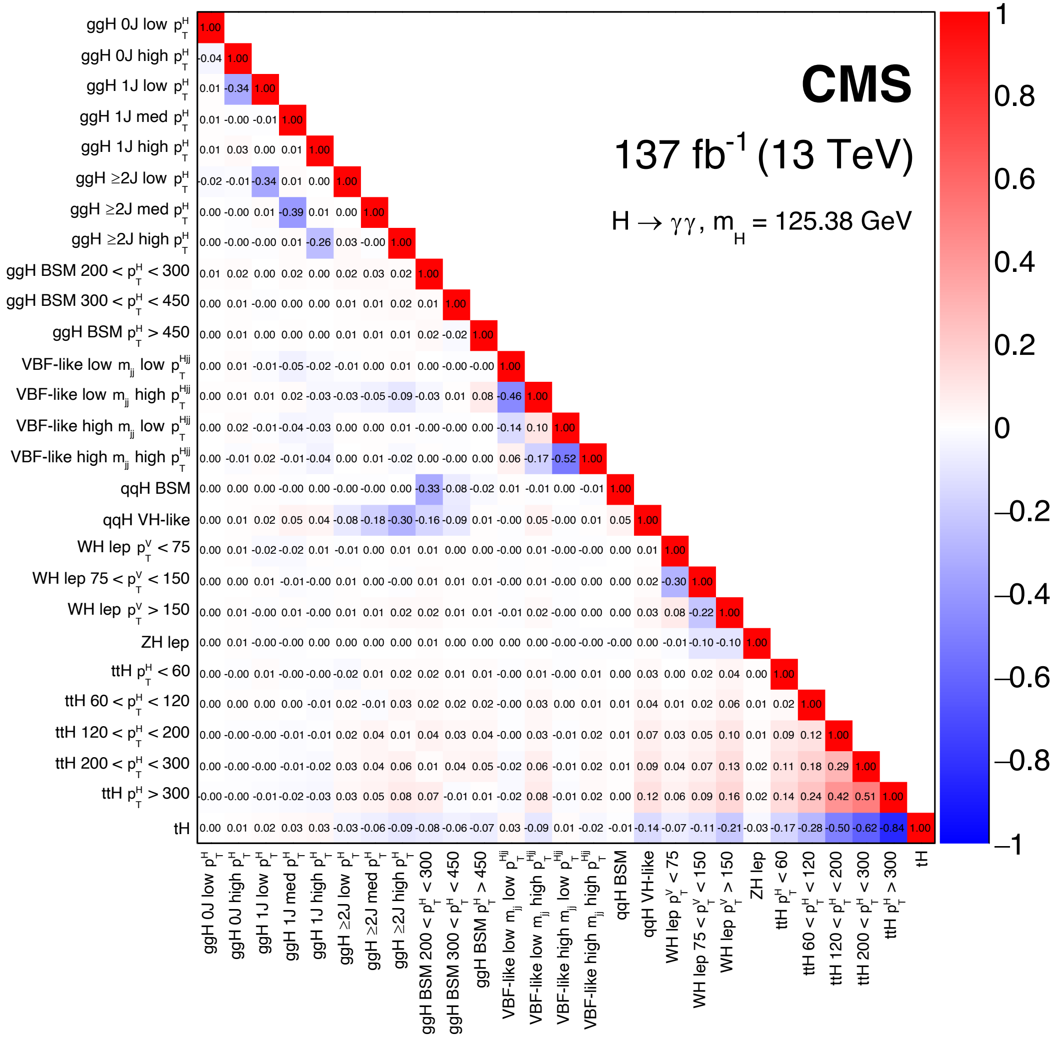


Higgs → $\gamma\gamma$ inclusive, differential and STXS

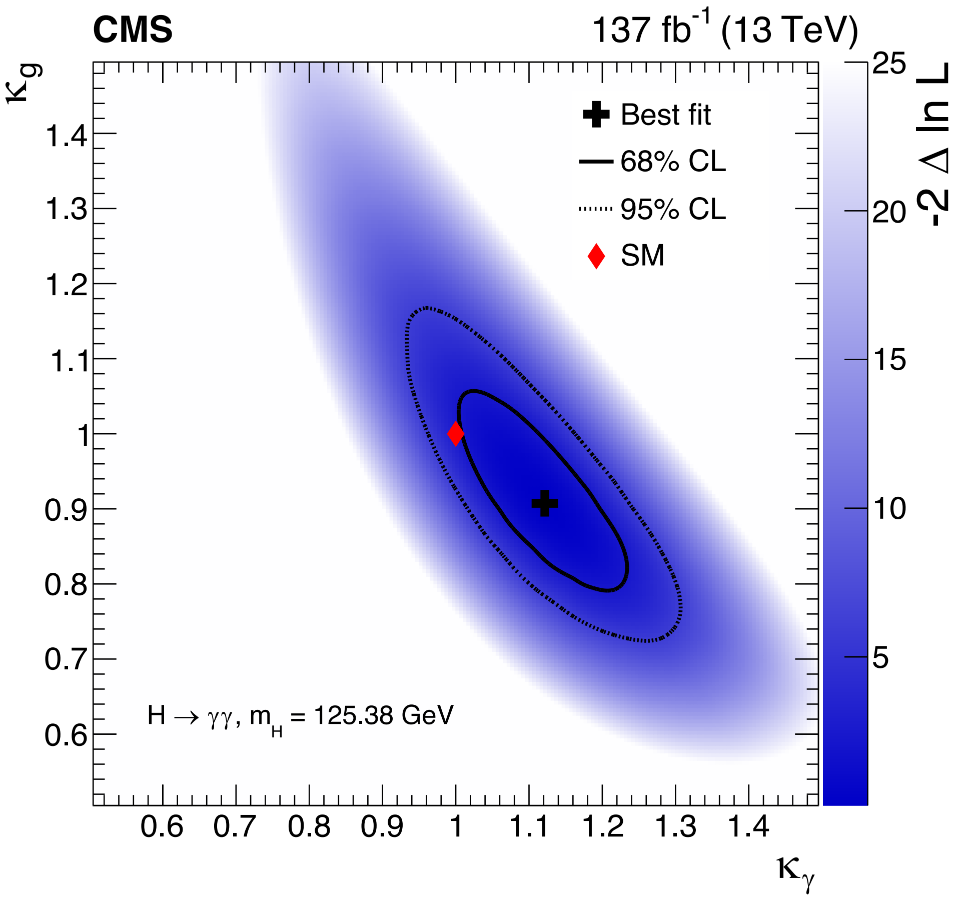


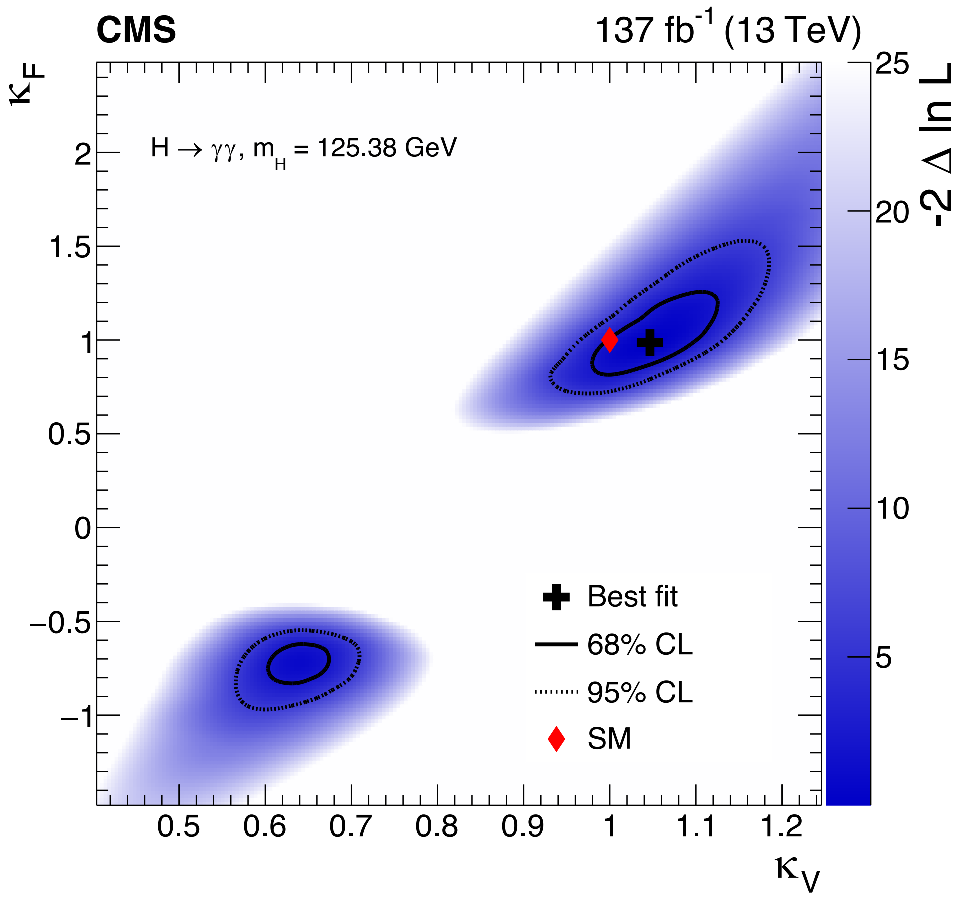
Higgs → $\gamma\gamma$ inclusive, differential and STXS





Higgs → $\gamma\gamma$ inclusive, differential and STXS



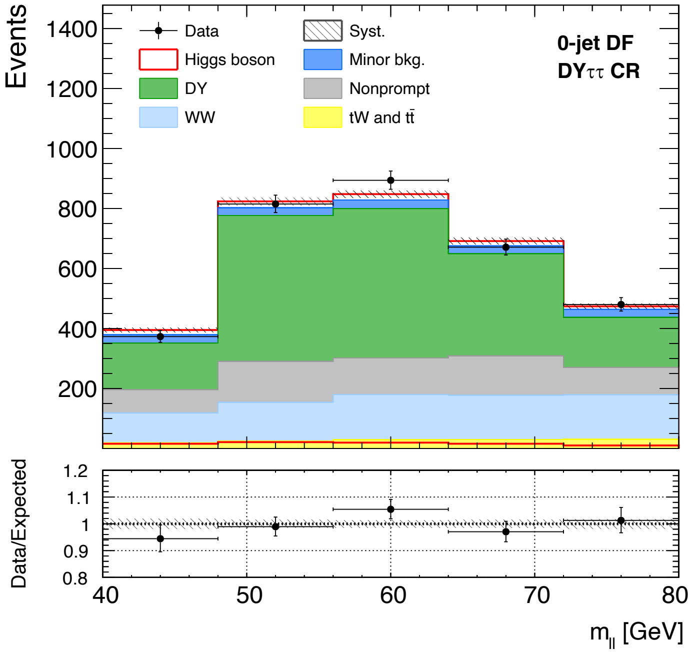


Higgs → WW inclusive, differential and STXS

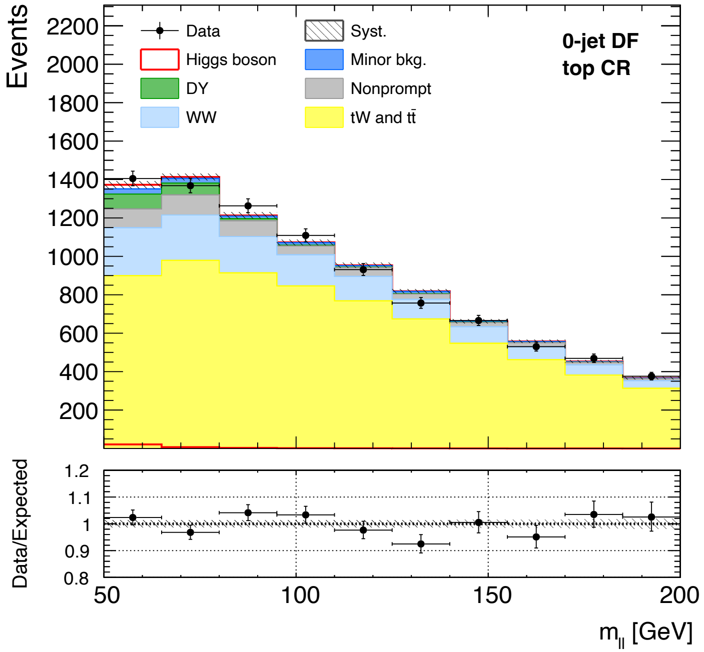
- The $H \rightarrow WW$ benefits from the **second-largest branching ratio**. No possible reconstruction of the Higgs mass. Large backgrounds
- Huge variety of final state topologies, always targeting at least **2 leptons**
- **Control regions** are constructed to estimate their effect from data
- In particular, affected by **top, DY, WW,** and **non-prompt lepton** contaminations

Fiducial phase space
$p_{T,l_1} > 25$ GeV
$p_{T,l_2} > 13$ GeV
$\lvert\eta\rvert < 2.5$
$m_{ll} > 12$ GeV
$p_T^{ll} > 30$ GeV
$m_T^{l2} > 30$ GeV
$m_T^H > 60$ GeV

Eur. Phys. J. C 83, 667 (2023)



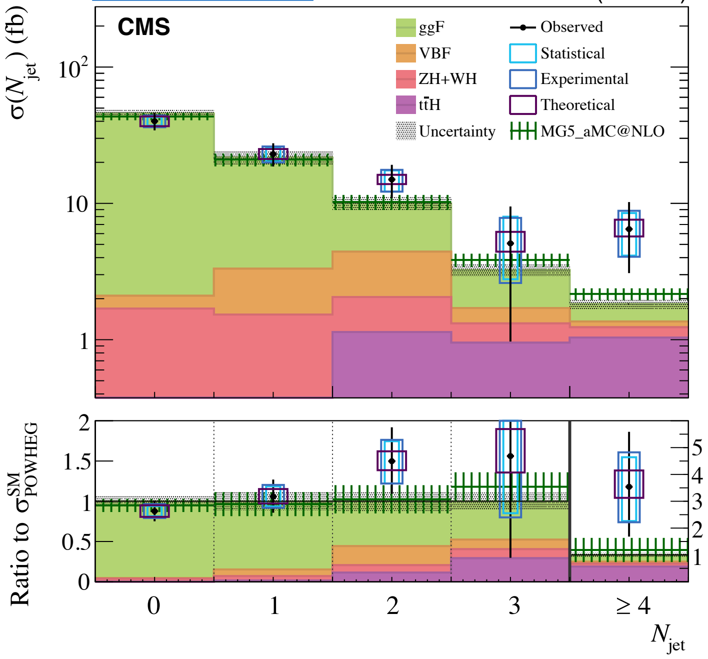
Eur. Phys. J. C 83, 667 (2023)



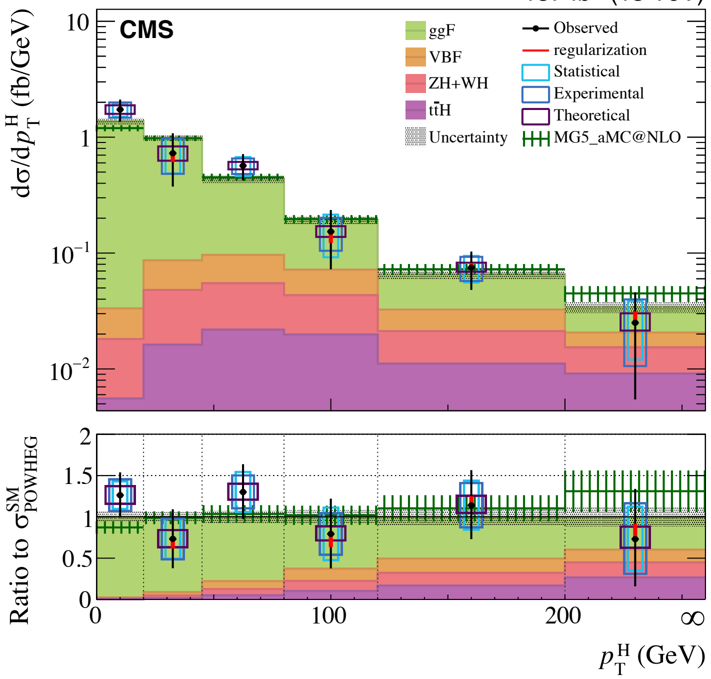
Higgs → WW inclusive, differential and STXS

- **Fiducial inclusive and differential cross-sections** measured
- 2 differential distributions: $\boldsymbol{p_T^H}$ and **the number of jets** $(\boldsymbol{n_{jet}})$
- Simultaneous fit over the signal and control regions to extract the signal strength modifiers. **2-D $\boldsymbol{m_{ll} - m_T^H}$ distribution is fit**
- The signal extraction, unfolding, and regularization are included in the fit

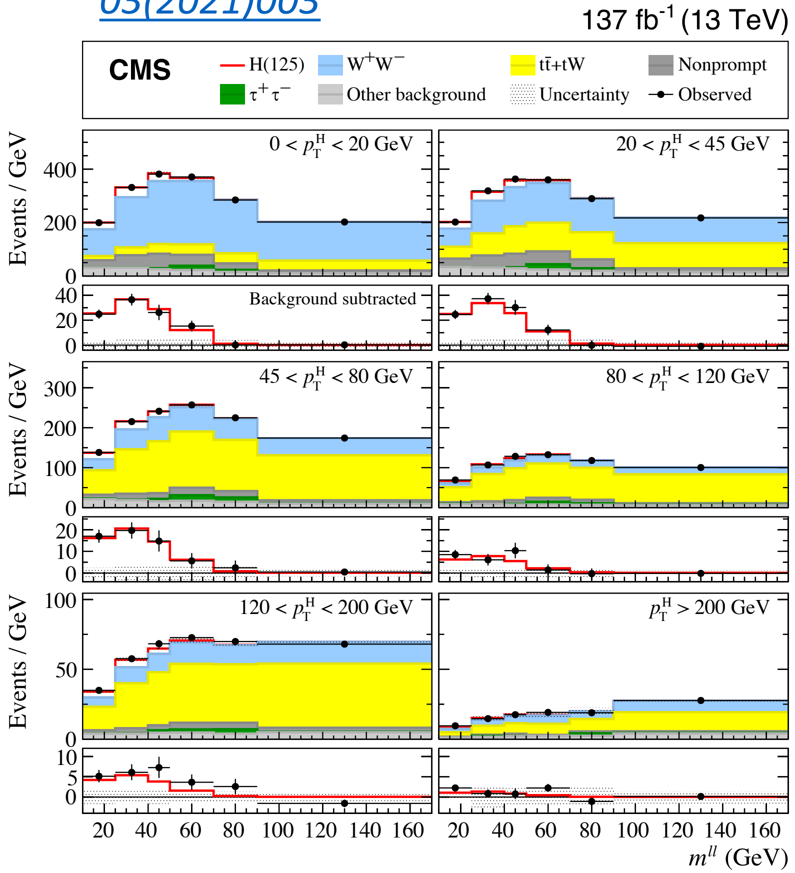
JHEP 03(2021)003



JHEP 03(2021)003



JHEP 03(2021)003



Higgs → WW inclusive, differential and STXS

The analysis relies on simulations to model our signal and background processes.

PDFs: NNPDF 3.0 at NLO in 2016 and NNLO in 2017,2018

CMS detector: The CMS detector response is simulated using **GEANT4**

Signals

POWHEG v2 at NLO for ggH,VBF and VH

MINLO Hjj extension used to match NLO accuracy for VH and ggH when $N_{jet} \geq 2$ and LO for $N_{jet} \geq 3$

POWHEG+MINLO reweight for ggH signal to match NNLOPS accuracy

JHUGen for the decay of the Higgs boson to WW

Backgrounds

POWHEG v2 at NLO for qqWW, reweight to match NNLO+NNLL accuracy

MCFM v7.0 for ggWW at LO and normalized to match the NLO cross-section

MadGraph5_aMC@NLO v2.4.2 for VBS WW production at LO

POWHEG v2 for top quark production processes ($t\bar{t}, tW, \ldots$)

MadGraph5_aMC@NLO v2.4.2 for DY production at NLO

The **DY** ($\boldsymbol{Z \to \tau\tau}$) is estimated using an data-driven embedded technique

Other dibosonic processes involving a Z boson simulated with **POWHEG v2**

Processes involving an initial state radiation photon use **MadGraph5_aMC@NLO v2.4.2 and PYTHIA**

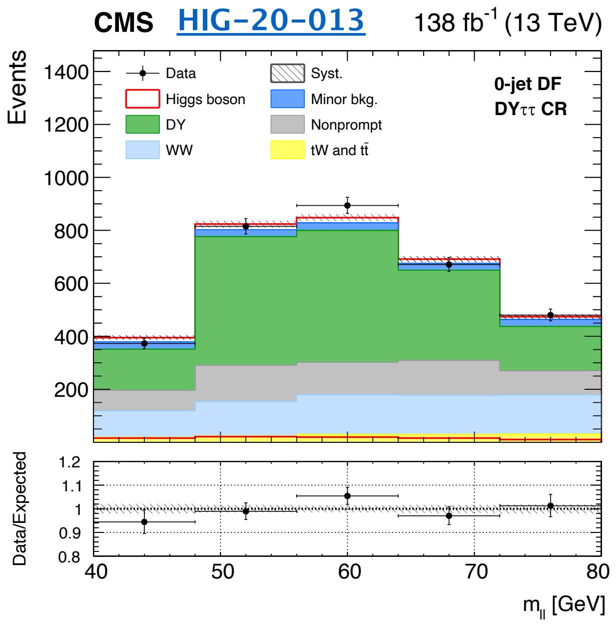
Higgs → WW inclusive, differential and STXS

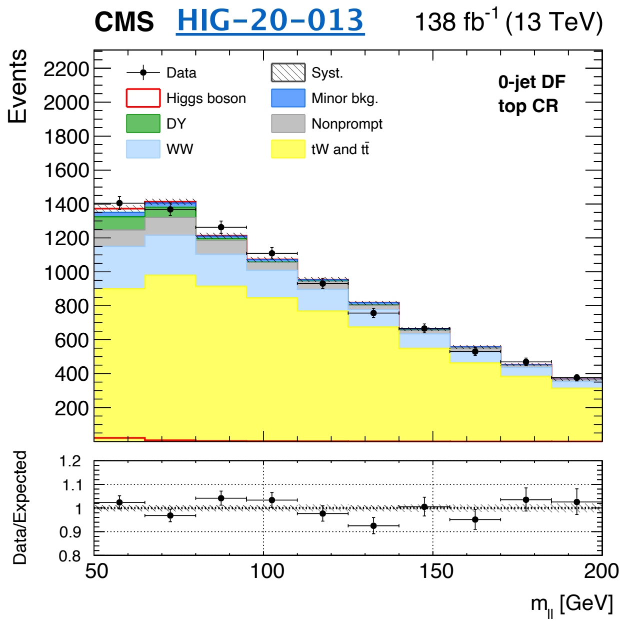
The main backgrounds that affect the ggF and VBF categories are:

- **Top** $(t\bar{t}, tW, \ldots)$
- **DY** $pp \to Z \to l^{\pm}l^{\mp}$
- **Non-resonant WW**
- **Non-prompt background** (at low lepton p_T)

For the VH categories, it also affects:

- **WZ**
- **V**$\boldsymbol{\gamma}$ $(\mathrm{V} = \mathrm{W}, \mathrm{Z})$
- **ZZ**





Several background-enriched control regions are designed to obtain normalization factors to the MC from data

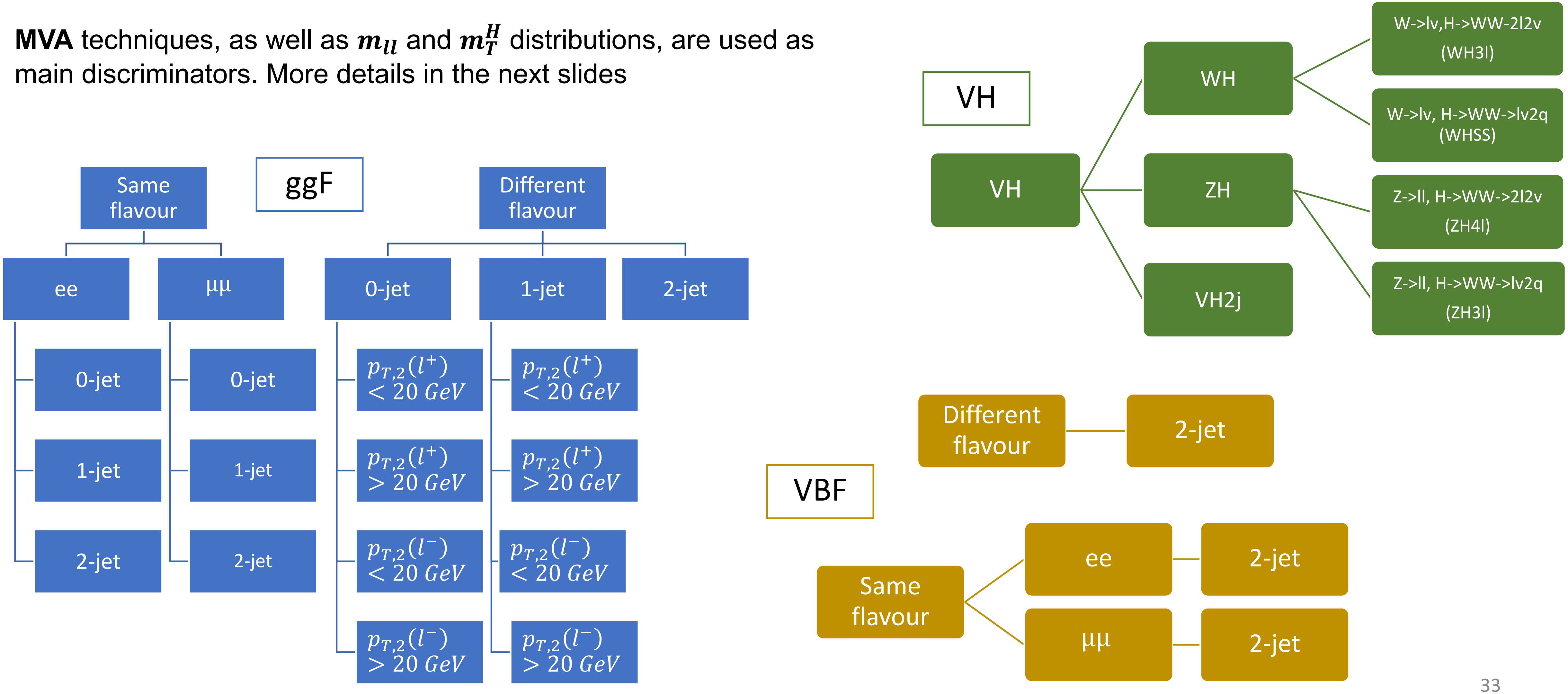
Backgrounds

POWHEG v2 at NLO for qqWW, reweight to match NNLO+NNLL accuracy
MCFM v7.0 for ggWW at LO and normalized to match the NLO cross-section
MadGraph5_aMC@NLO v2.4.2 for VBS WW production at LO
POWHEG v2 for top quark production processes $(t\bar{t}, tW, \ldots)$
MadGraph5_aMC@NLO v2.4.2 for DY production at NLO
The **DY** $(\boldsymbol{Z \to \tau\tau})$ is estimated using an data-driven embedded technique
Other dibosonic processes involving a Z boson simulated with **POWHEG v2**
Processes involving an initial state radiation photon use **MadGraph5_aMC@NLO v2.4.2 and PYTHIA**

Higgs → WW inclusive, differential and STXS

There are several categorizations of the signal regions as a function of the production mode and final state topology. There is a basic common selection that consists of **2 opposite-sign leptons and MET ($p_T^{miss} > 20$ GeV)**

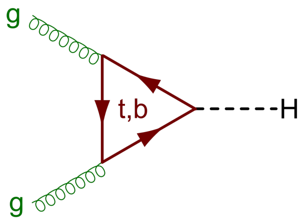
MVA techniques, as well as m_{ll} and m_T^H distributions, are used as main discriminators. More details in the next slides



Higgs → WW inclusive, differential and STXS

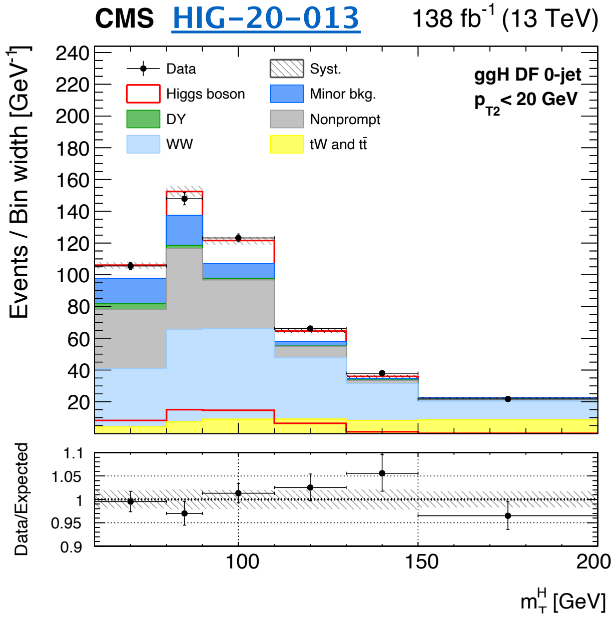
$$m_T^H = \sqrt{2p_T^{ll} \cdot p_T^{miss}\left[1 - \cos\Delta\phi\left(ll, \overrightarrow{p_T^{miss}}\right)\right]}$$

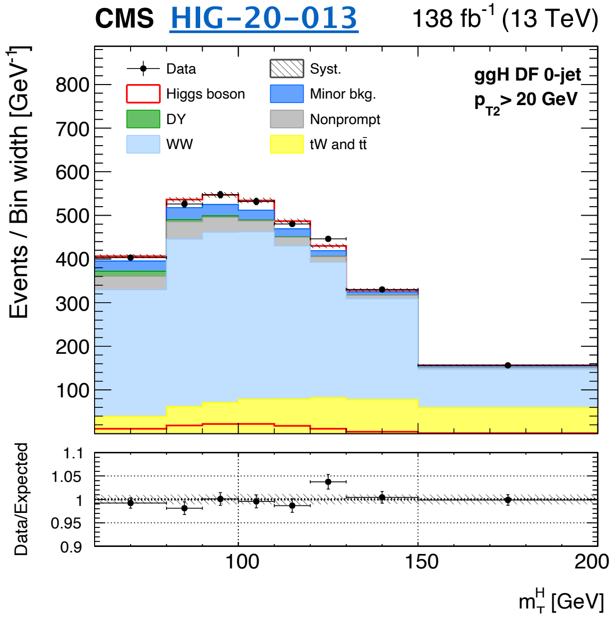
ggF

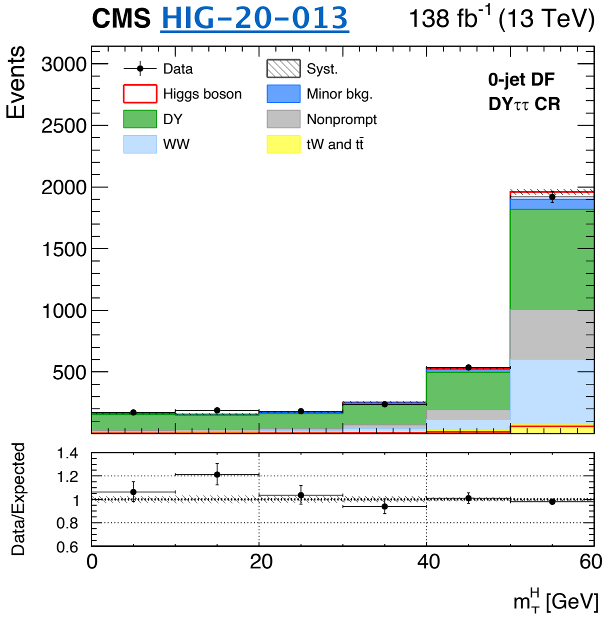


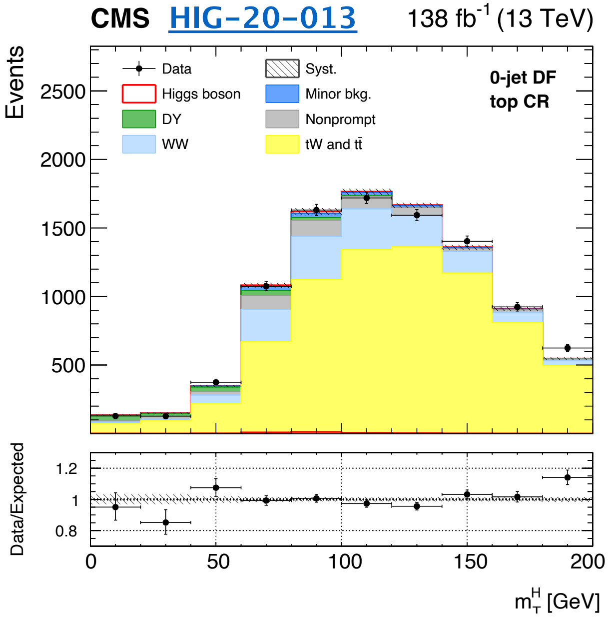
This category targets the gluon-gluon fusion production of the Higgs boson
Divided into categories by final state:

- Same flavour dominated by the **DY** background
- Different flavour dominated by $\mathbf{t\bar{t}}$ and **WW** backgrounds
- **Two control regions** for $\mathbf{t\bar{t}}$ and **DY**
- Divided in trailing lepton p_T subregions ($p_T \lessgtr 20$GeV) to control systematics from non-prompt background
- Divided in 0, 1 and 2 jets
- **DYMVA NN** used to supress DY background in the same flavour region
- **B-tagging** identification algorithms are used to reject top quark decays





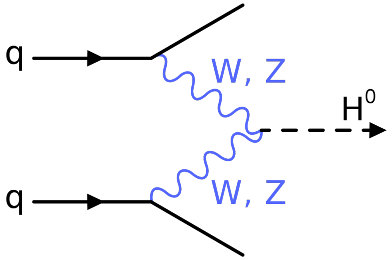




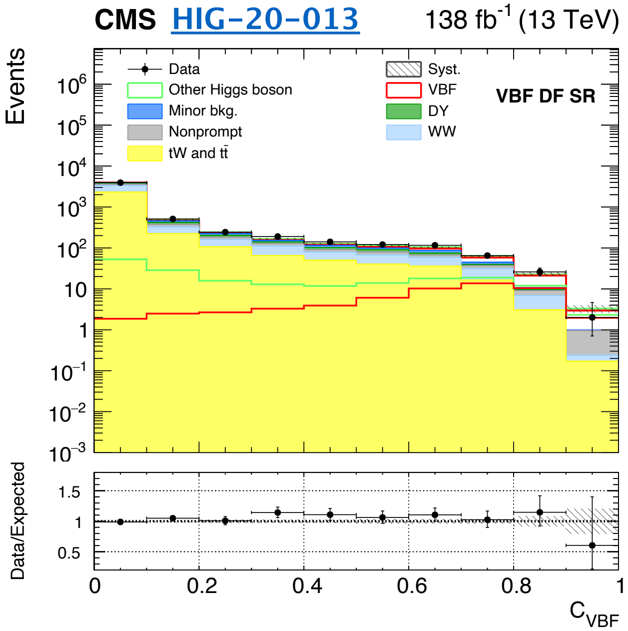
Higgs → WW inclusive, differential and STXS

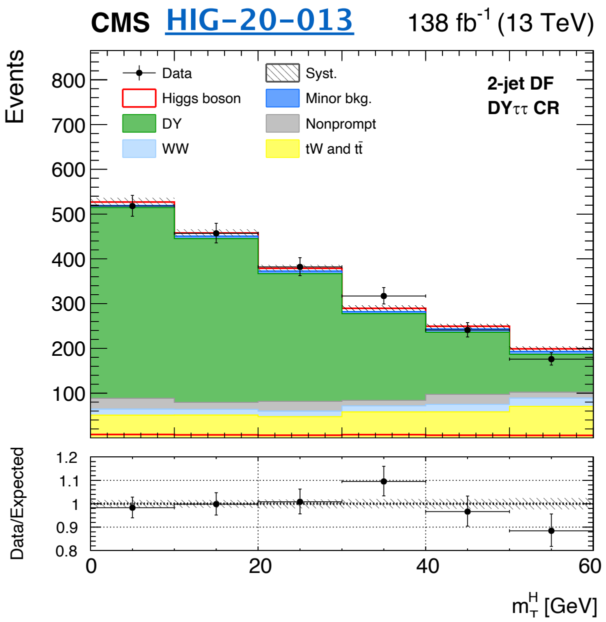
VBF

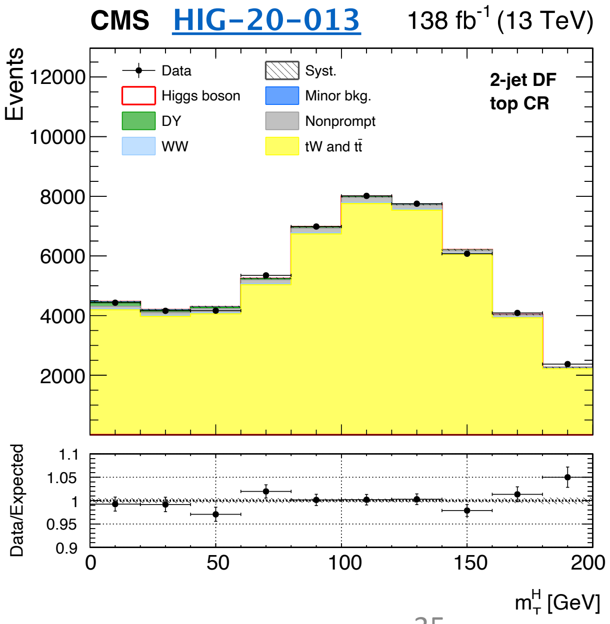
This category targets the Vector Boson Fusion production of the Higgs boson
Divided into categories by final state:



- The VBF topology is characterized by two forward-backward jets with large m_{jj}
- Cuts on m_{jj} and $\Delta\eta_{jj}$ to supress **ggF 2j background**
- Same flavour dominated by the **DY** background
- Different flavour dominated by $\mathbf{t\bar{t}}$ and **WW** backgrounds
- **Two control regions** for $\mathbf{t\bar{t}}$ and **DY**
- **Categorical NN** constructed to identify and separate 4 categories in DF (VBF, ggF, Top, WW)
- **DYMVA NN** is used to supress DY background in the SF region





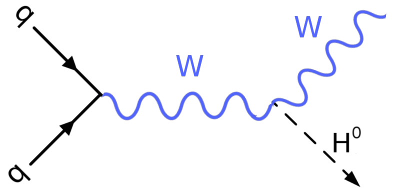


Higgs → WW inclusive, differential and STXS

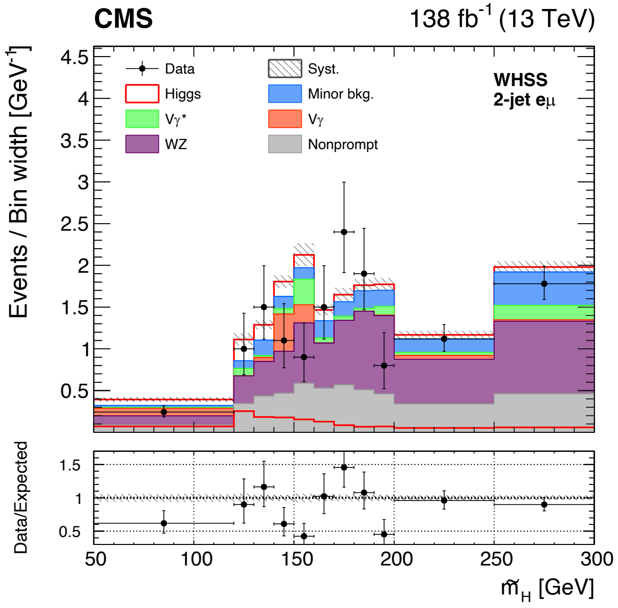
$$\widetilde{m}_H = \sqrt{(P_{jj} + 2P_l)^2}$$

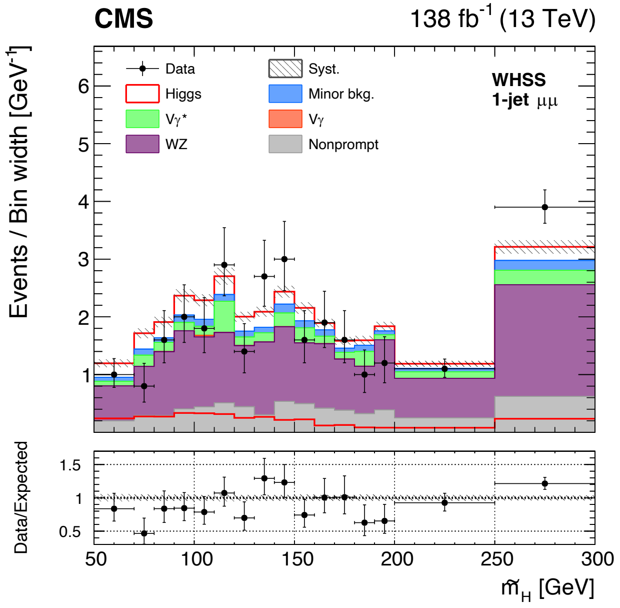
WH

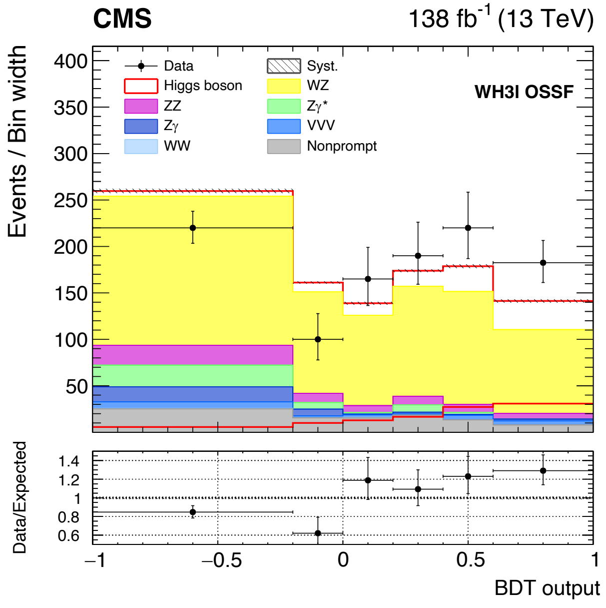
This category targets the vector boson associated production of the Higgs boson (VH)
Divided into categories by final state:

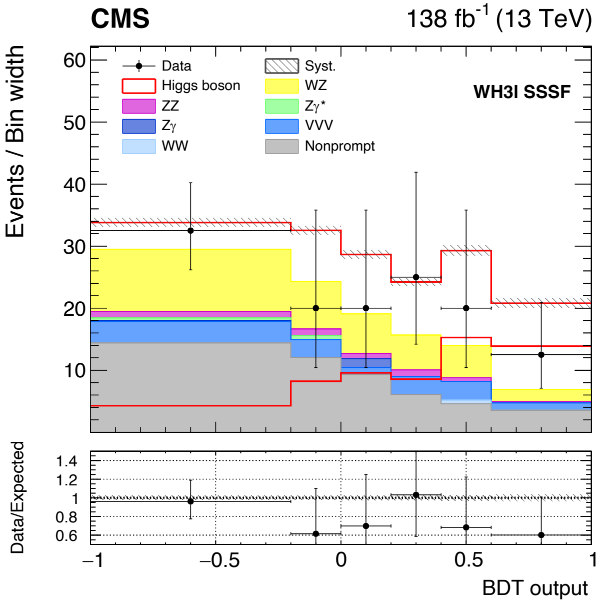


- **WHSS**: $pp \rightarrow WH, W \rightarrow l\nu, H \rightarrow WW \rightarrow l\nu qq$
- Also divided into Different Flavour ($e^{\pm}\mu^{\mp}$) and Same Flavour ($\mu^{\pm}\mu^{\mp}$)
- **WH3l**: $pp \rightarrow WH, W \rightarrow l\nu, H \rightarrow WW \rightarrow 2l2\nu$
- Two regions: Opposite Sign Same Flavour (**OSSF**) or Same Sign Same Flavour (**SSSF**) leptons
- **One control region for WZ**, the main background
- One **BDT** for each category in the WH3l case





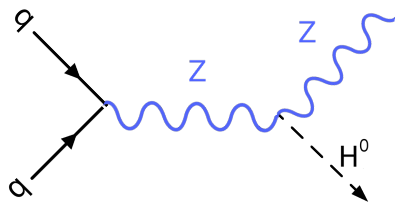




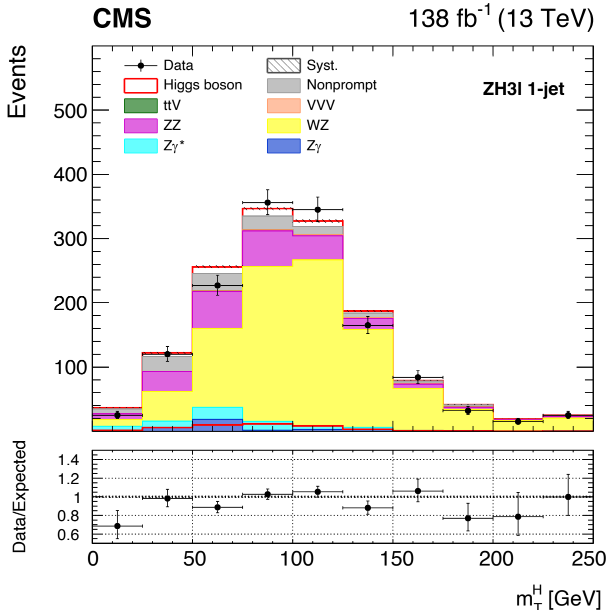
Higgs → WW inclusive, differential and STXS

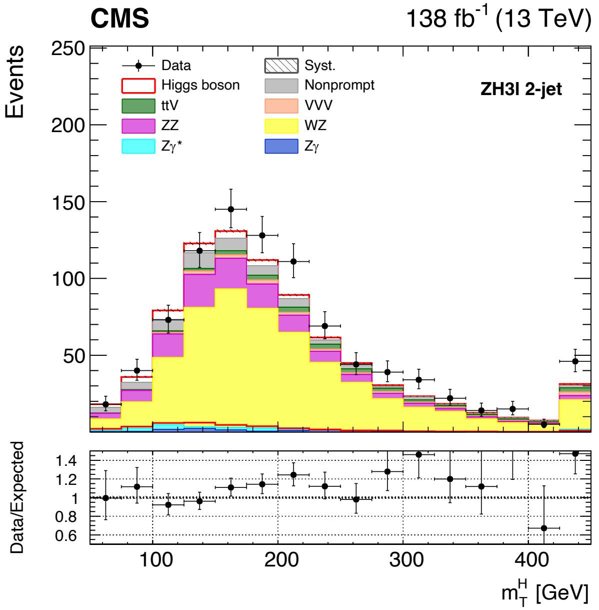
ZH

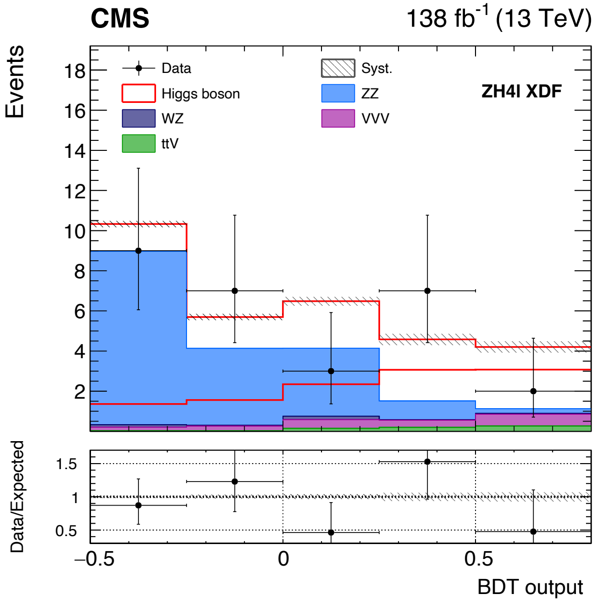
This category targets the vector boson associated production of the Higgs boson (VH)
Divided into categories by final state:

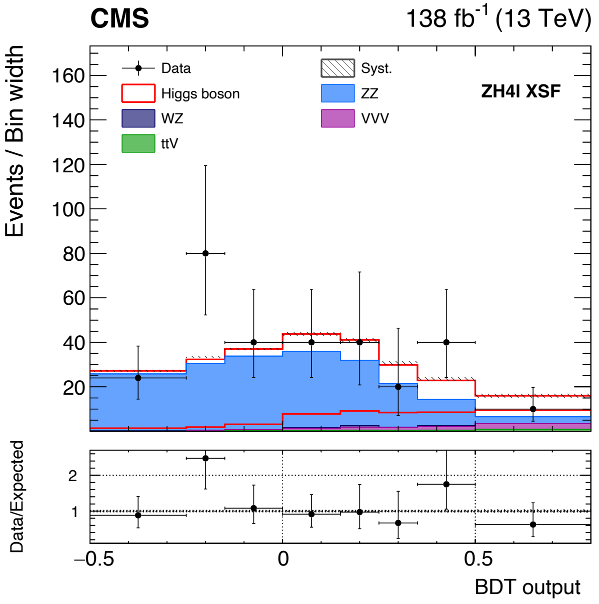


- **ZH3l**: $pp \rightarrow ZH, Z \rightarrow ll, H \rightarrow WW \rightarrow l\nu qq$
- At least one lepton pair is compatible with a Z decay. One or two jets non b-tagged jets
- **One control region for WZ**, the main background
- **ZH4l**: $pp \rightarrow ZH, Z \rightarrow ll, H \rightarrow WW \rightarrow 2l2\nu$
- Categorized by the decay of the WW pair: Same or Different flavour (SF or DF)
- Dedicated **control region for ZZ** background







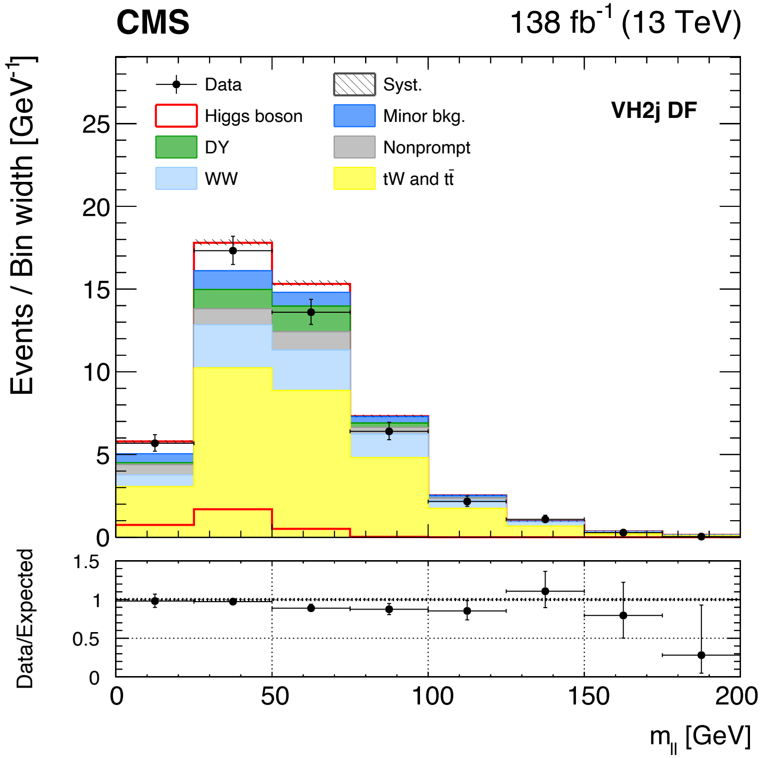


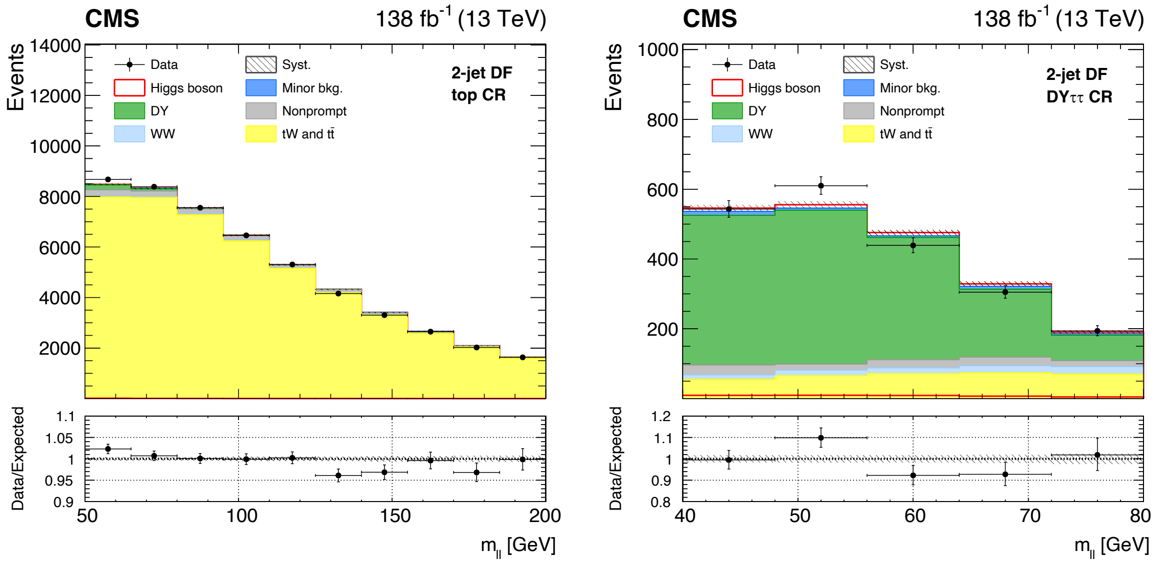
Higgs → WW inclusive, differential and STXS

VH2j

This category targets the vector boson associated production of the Higgs boson (VH)
Divided into categories by final state:

- **VH2j**: $pp \to VH, V \to q\bar{q}, H \to WW \to 2l2\nu$
- It's not possible to distinguish between Z or W associated boson
- Different and Same Flavour categories (**DF or SF**)
- Cuts on the kinematics of the jets to separate the VH contribution from ggF 2j and VBF
- Similar background sources as ggF 2j and VBF
- **Top and DY control regions**





Higgs → WW inclusive, differential and STXS

The ggF channel is the unique one dominated by systematics. The rest are largely dominated by the statistical uncertainty

	ggF	VBF	WH	ZH
Statistical	6%	28%	21%	31%
Systematics	10%	23%	19%	11%
1º Syst	**Theoretical modeling** of the signal process (5%)	**Theoretical signal modelling** (13%)	**Lepton misidentification** (non-prompt background) (15%)	**Background normalization** (6%)
2º Syst	**Lepton identification** (4%)	**Lepton misidentification** (non-prompt background) (9%)	**Background normalization** (4%)	**Background theoretical modeling** (5%)
3º Syst	**Background normalization** (4%)	**Background normalization** (6%)	**Background modeling** (4%)	**Lepton misidentification** (4%)

Higgs → WW inclusive, differential and STXS

The total combined result for the signal strength modifier is:

$$\boldsymbol{\mu = 0.95^{+0.10}_{-0.09} = 0.95 \pm 0.05(stat) \pm 0.08(syst)}$$

The results are **dominated by the ggF** channel, the unique observed in the $\mathrm{H} \to \mathrm{WW}$ decay channel at CMS. We need Run 3 statistics to improve the results for more differential cross-sections, higher significances, etc.

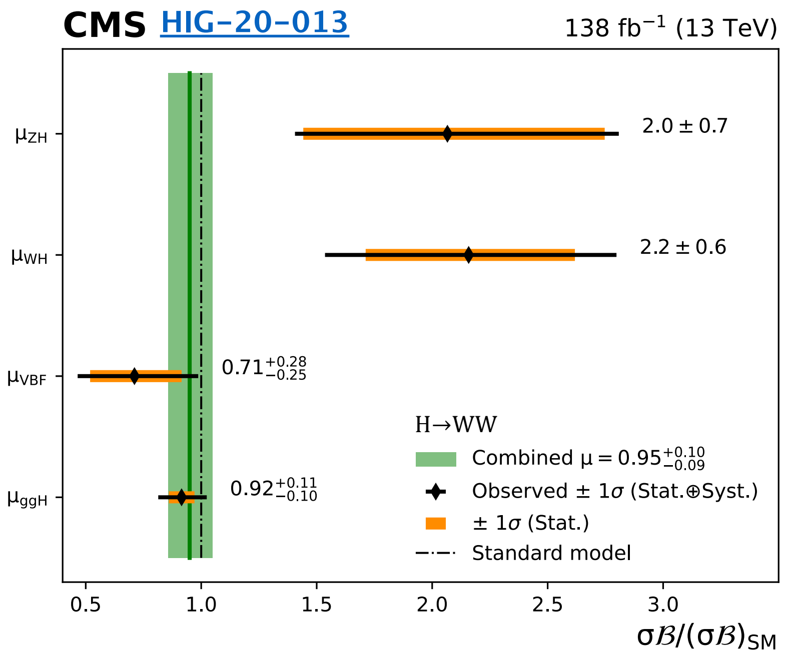
Significance per mode

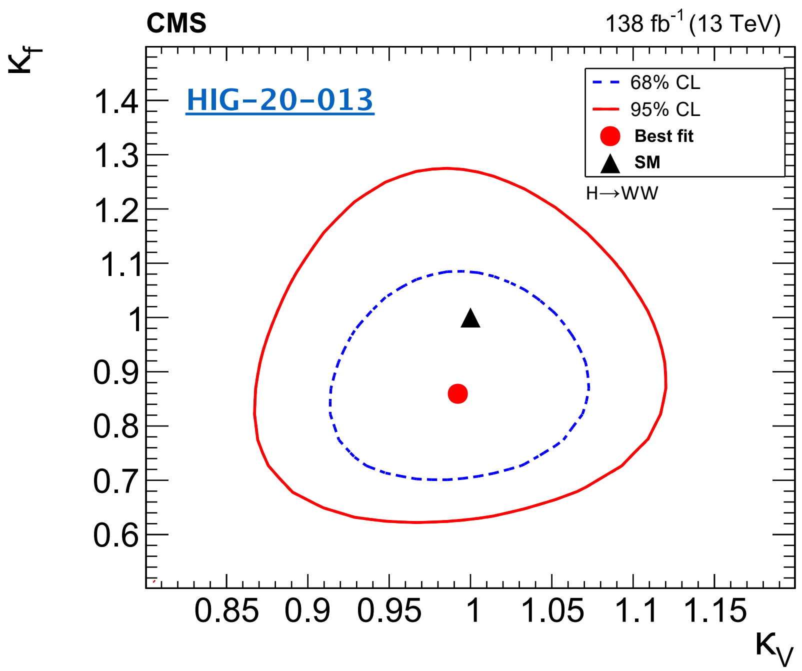
$3.73\,\sigma$

$3.61\,\sigma$

$3.51\,\sigma$

$10.5\,\sigma$





The largest uncertainty on the combination comes from the **theoretical modeling of the ggH** signal. The subleading one corresponds to the **electron reconstruction and identification**

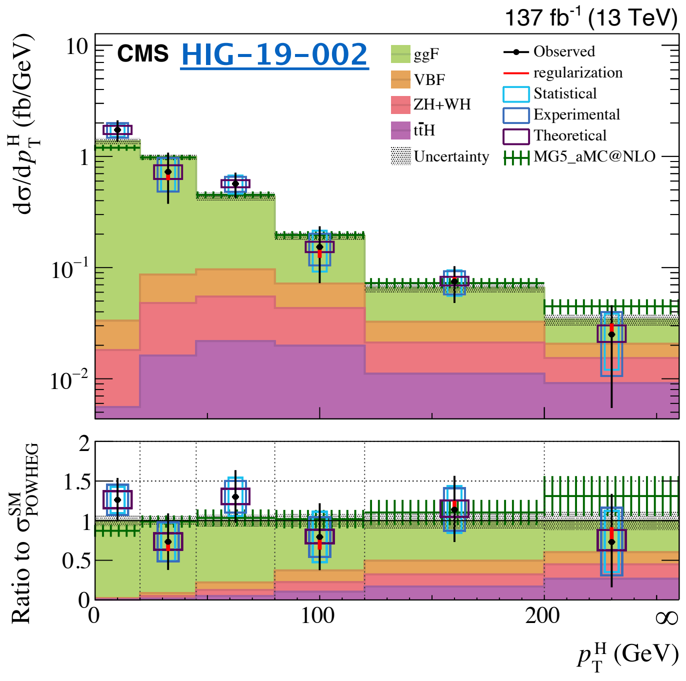
Higgs → WW inclusive, differential and STXS

The lack of statistics has forced to merge some of the bins in the STXS 1.2 into 14 bins, mostly as a function of p_T^H

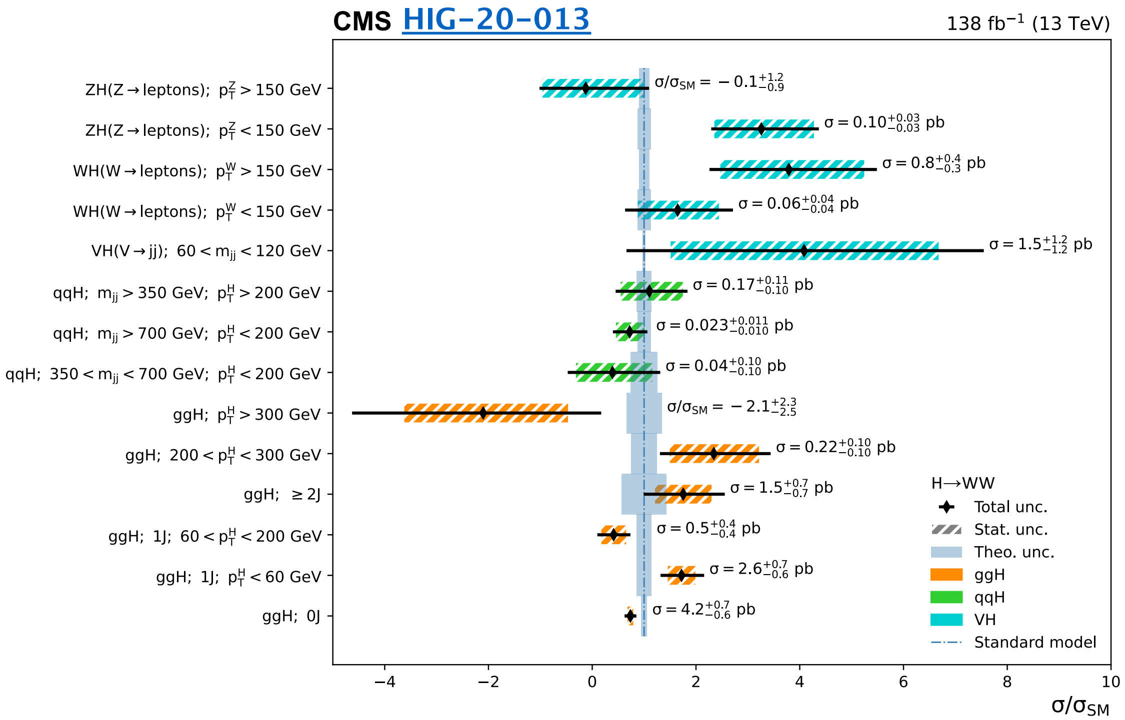
Everything is **consistent with standard model predictions**. However, the most sensitive bins to new physics are still limited by statistics.

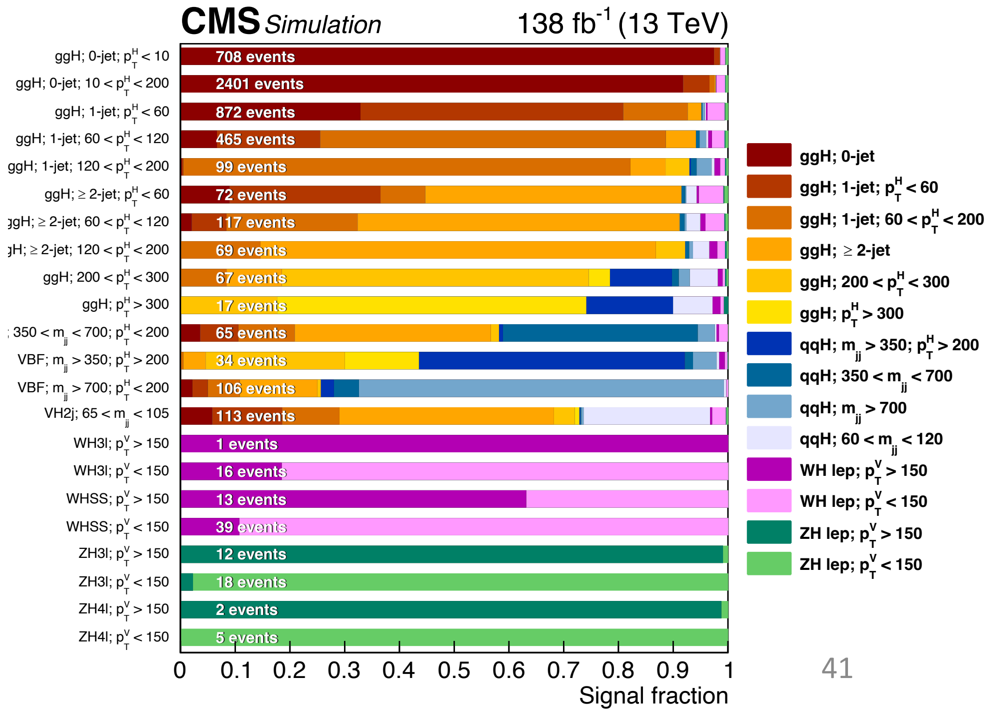
Let's wait for Run 3 results to improve the results on all STXS bins

Differential cross section



STXS 1.2

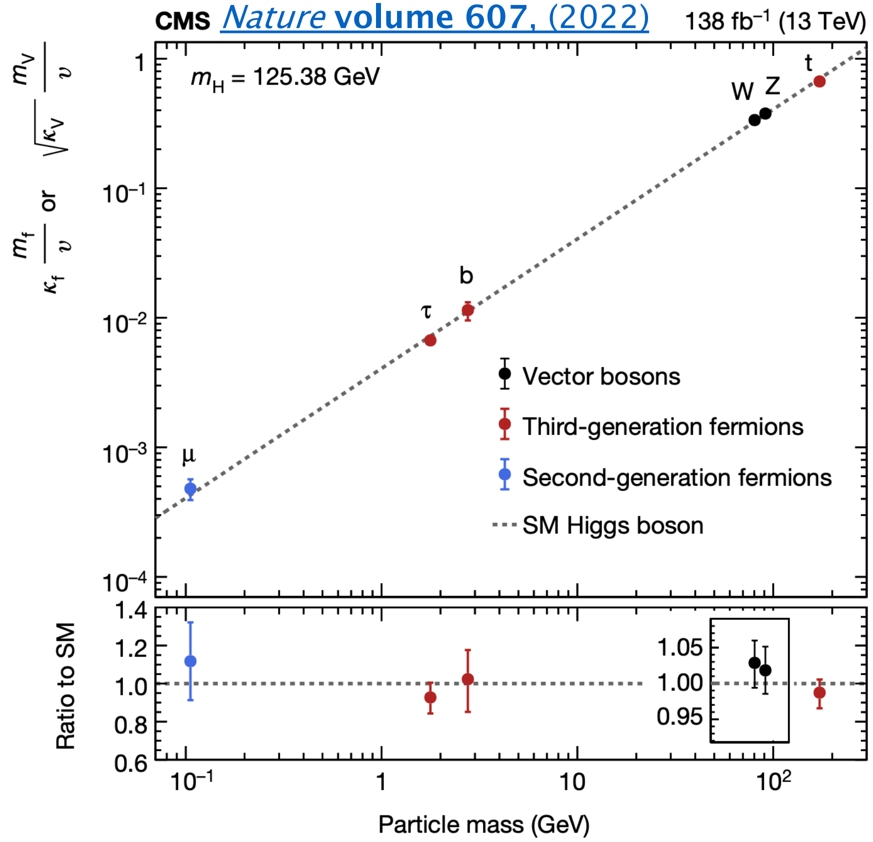




Final combination

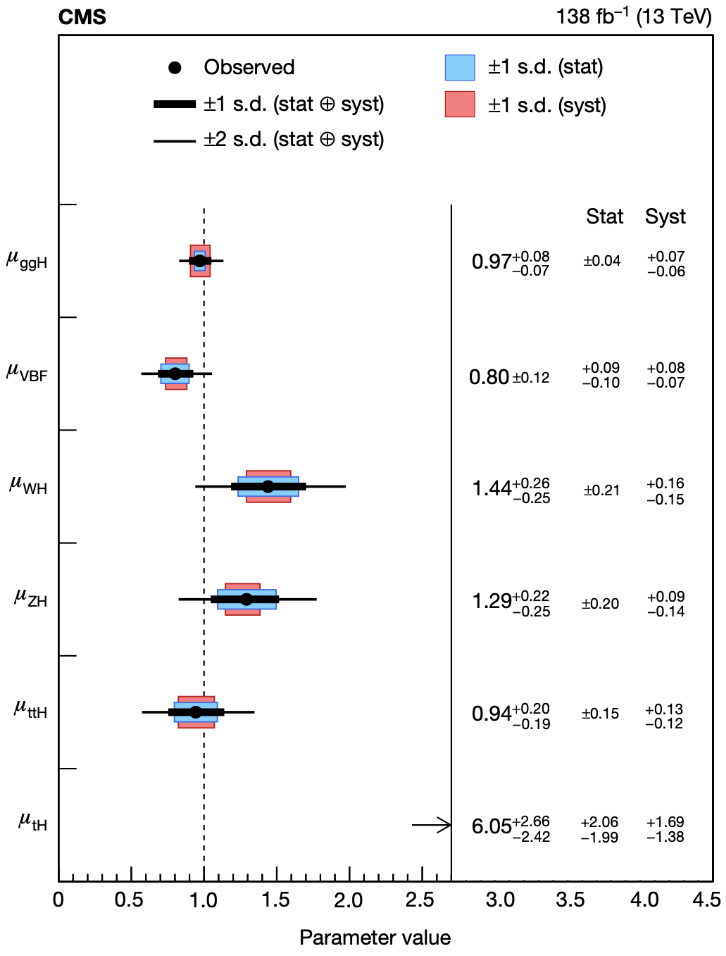
Combined results published in Nature
[*Nature* **volume 607**, pages 60–68 (2022)]
for the 10 years from the Higgs discovery

Excellent agreement is found with the standard model!



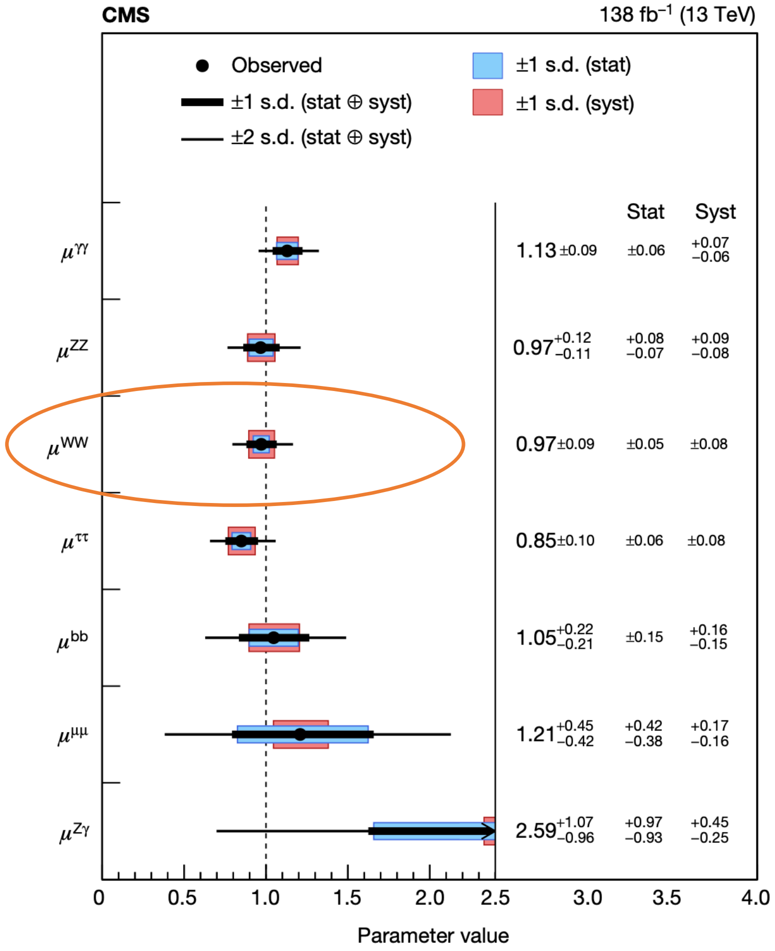
Production

Nature **volume 607**, (2022)



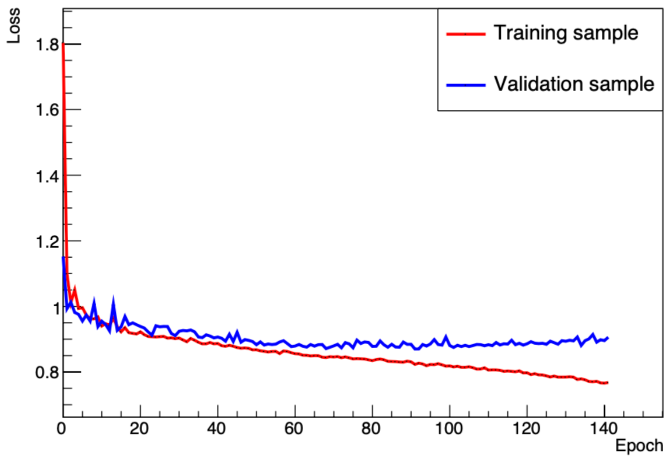
Decay

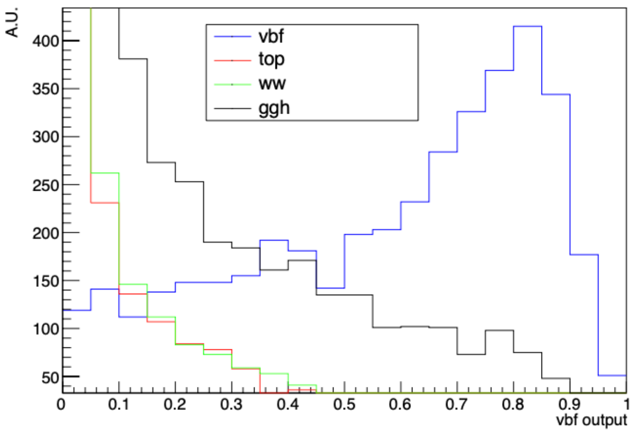
Nature **volume 607**, (2022)

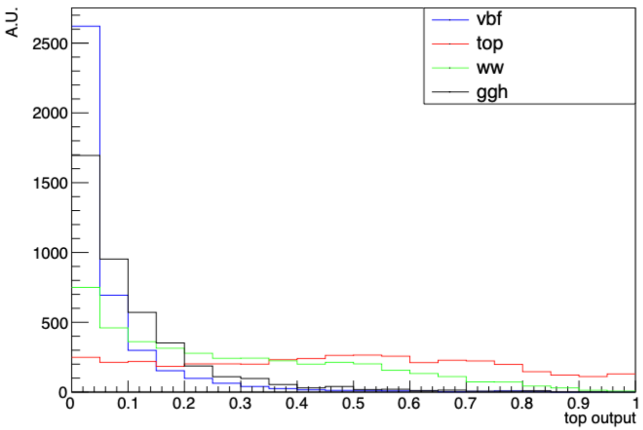


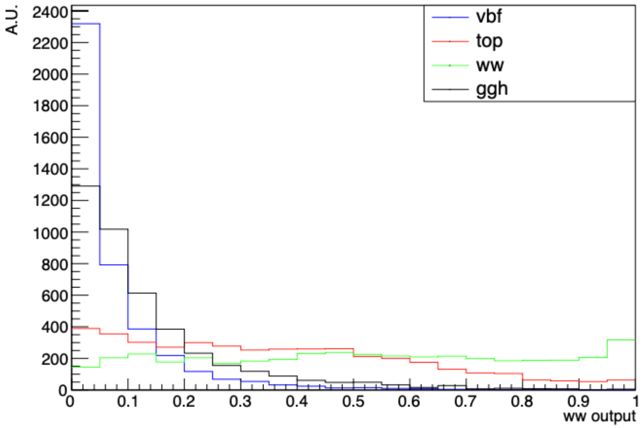
Higgs → WW inclusive, differential and STXS

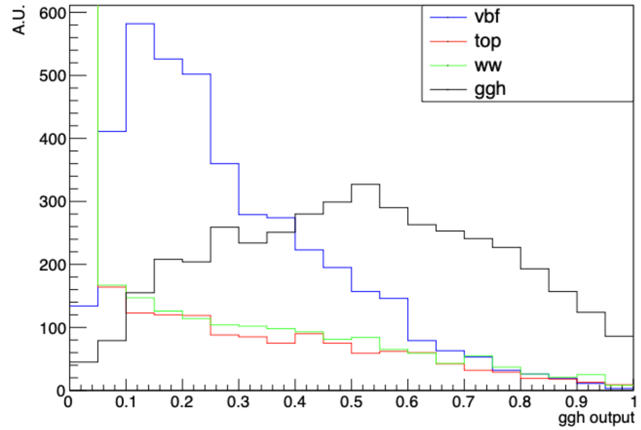
The categorical neural network has been constructed with Keras, using 26 input variables corresponding to the kinematics of the leptons, jets and the quark-gluon likelihood estimators.











Higgs → WW inclusive, differential and STXS

ggF DF

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,GeV$, $p_{T2} > 10\,GeV$ (2016) or $13\,GeV$ $p_T^{miss} > 20\,GeV$, $p_T^{\ell\ell} > 30\,GeV$, $m_{\ell\ell} > 12\,GeV$ eμ pair with opposite charge
0-jet ggH category	
$\ell^\pm\ell^\mp$, $p_{T2} \lesseqgtr 20\,GeV$	$m_T^H > 60\,GeV$, $m_T(\ell_2, p_T^{miss}) > 30\,GeV$ $p_{T2} \lesseqgtr 20\,GeV$ No jet with $p_T > 30\,GeV$ No b-tagged jet with $p_T > 20\,GeV$
Top quark CR	As SR but with no m_T^H requirement, $m_{\ell\ell} > 50\,GeV$ At least 1 b-tagged jet with $20 < p_T < 30\,GeV$
$\tau\tau$ CR	As SR but with $m_T^H < 60\,GeV$ $40 < m_{\ell\ell} < 80\,GeV$
1-jet ggH category	
$\ell^\pm\ell^\mp$, $p_{T2} \lesseqgtr 20\,GeV$	$m_T^H > 60\,GeV$, $m_T(\ell_2, p_T^{miss}) > 30\,GeV$ $p_{T2} \lesseqgtr 20\,GeV$ 1 jet with $p_T > 30\,GeV$ No b-tagged jet with $p_T > 20\,GeV$
Top quark CR	As SR but with no m_T^H requirement, $m_{\ell\ell} > 50\,GeV$ At least 1 b-tagged jet with $p_T > 30\,GeV$
$\tau\tau$ CR	As SR but with $m_T^H < 60\,GeV$ $40 < m_{\ell\ell} < 80\,GeV$
2-jet ggH category	
SR	$m_T^H > 60\,GeV$, $m_T(\ell_2, p_T^{miss}) > 30\,GeV$ $p_{T2} \lesseqgtr 20\,GeV$ At least 2 jets with $p_T > 30\,GeV$ No b-tagged jet with $p_T > 20\,GeV$ $m_{jj} < 65\,GeV$ or $105 < m_{jj} < 120\,GeV$
Top quark CR	As SR but with no m_T^H requirement, $m_{\ell\ell} > 50\,GeV$ At least one b-tagged jet with $p_T > 30\,GeV$
$\tau\tau$ CR	As SR but with $m_T^H < 60\,GeV$ $40 < m_{\ell\ell} < 80\,GeV$

Higgs → WW inclusive, differential and STXS

ggF SF

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\text{GeV}$, $p_{T2} > 10\,\text{GeV}$ (2016) or $13\,\text{GeV}$ $p_T^{miss} > 20\,\text{GeV}$, $p_T^{\ell\ell} > 30\,\text{GeV}$ ee or $\mu\mu$ pair with opposite charge $m_{\ell\ell} > 12\,\text{GeV}$, $\lvert m_{\ell\ell} - m_Z\rvert > 15\,\text{GeV}$
0-jet ggH category	
ee, $\mu\mu$	$m_{\ell\ell} < 60\,\text{GeV}$, $m_T^H > 90\,\text{GeV}$, $\lvert\Delta\phi_{\ell\ell}\rvert < 2.3$ No b-tagged jets with $p_T > 20\,\text{GeV}$ DYMVA above threshold
WW CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$ $m_T^H > 60\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$
Top quark CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$ At least one b-tagged jet with $20 < p_T < 30\,\text{GeV}$
1-jet ggH category	
ee, $\mu\mu$	$m_{\ell\ell} < 60\,\text{GeV}$, $m_T^H > 80\,\text{GeV}$, $\lvert\Delta\phi_{\ell\ell}\rvert < 2.3$ No b-tagged jets with $p_T > 20\,\text{GeV}$ DYMVA above threshold
WW CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$ $m_T^H > 60\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$
Top quark CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$ At least one b-tagged jet with $p_T > 30\,\text{GeV}$
2-jet ggH category	
ee, $\mu\mu$	$m_{\ell\ell} < 60\,\text{GeV}$, $65 < m_T^H < 150\,\text{GeV}$ No b-tagged jets with $p_T > 20\,\text{GeV}$ DYMVA above threshold
WW CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$ $m_T^H > 60\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$
Top quark CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$ At least one b-tagged jet with $p_T > 30\,\text{GeV}$

Higgs → WW inclusive, differential and STXS

VBF

Different Flavour

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\text{GeV}$, $p_{T2} > 10\,\text{GeV}$ (2016) or $13\,\text{GeV}$ $p_T^{miss} > 20\,\text{GeV}$, $p_T^{\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 12\,\text{GeV}$ eμ pair with opposite charge
2-jet VBF category	
SR	$60 < m_T^H < 125\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$ 2 jets with $p_T > 30\,\text{GeV}$, $m_{jj} > 120\,\text{GeV}$ No b-tagged jet with $p_T > 20\,\text{GeV}$
Top quark CR	As SR but with no m_T^H requirement, $m_{\ell\ell} > 50\,\text{GeV}$ At least one b-tagged jet with $p_T > 30\,\text{GeV}$
$\tau\tau$ CR	As SR but with $m_T^H < 60\,\text{GeV}$ $40 < m_{\ell\ell} < 80\,\text{GeV}$

Same Flavour

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\text{GeV}$, $p_{T2} > 10\,\text{GeV}$ (2016) or $13\,\text{GeV}$ $p_T^{miss} > 20\,\text{GeV}$, $p_T^{\ell\ell} > 30\,\text{GeV}$ ee or $\mu\mu$ pair with opposite charge $m_{\ell\ell} > 12\,\text{GeV}$, $\lvert m_{\ell\ell} - m_Z\rvert > 15\,\text{GeV}$
2-jet VBF category	
ee, $\mu\mu$	$m_{\ell\ell} < 60\,\text{GeV}$, $65 < m_T^H < 150\,\text{GeV}$ At least 2 jets with $p_T > 30\,\text{GeV}$ $\lvert\Delta\phi_{\ell\ell}\rvert < 1.6$, $m_{jj} > 350\,\text{GeV}$ No b-tagged jets with $p_T > 20\,\text{GeV}$ DYMVA above threshold
WW CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$ $m_T^H > 60\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$
Top quark CR	As SR but with $m_{\ell\ell} > 100\,\text{GeV}$, $m_T(\ell_2, p_T^{miss}) > 30\,\text{GeV}$ At least one of the leading jets b-tagged

Higgs → WW inclusive, differential and STXS

WH

WHSS

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\mathrm{GeV}$, $p_{T2} > 20\,\mathrm{GeV}$ $m_{\ell\ell} > 12\,\mathrm{GeV}$, $\lvert\Delta\eta_{\ell\ell}\rvert < 2$, $p_T^{miss} > 30\,\mathrm{GeV}$ $\widetilde{m}_H > 50\,\mathrm{GeV}$, no b-tagged jet with $p_T > 20\,\mathrm{GeV}$
Signal region	
1-jet $e\mu(\mu\mu)$	One jet with $p_T > 30\,\mathrm{GeV}$ $e\mu(\mu\mu)$ pair with same charge
2-jet $e\mu(\mu\mu)$	At least two jets with $p_T > 30\,\mathrm{GeV}$, $m_{jj} < 100\,\mathrm{GeV}$ $e\mu(\mu\mu)$ pair with same charge
Control region	
WZ	Shared with ZH3ℓ

WH3l

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\mathrm{GeV}$, $p_{T2} > 20\,\mathrm{GeV}$, $p_{T3} > 15\,\mathrm{GeV}$ $Q_{3\ell} = \pm 1$, $\min(m_{\ell\ell}) > 12\,\mathrm{GeV}$, $\Delta\eta_{\ell\ell} > 2.0$ $p_T^{miss} > 30\,\mathrm{GeV}$, $\widetilde{m}_H > 50\,\mathrm{GeV}$ No jets with $p_T > 30\,\mathrm{GeV}$, no b-tagged jet with $p_T > 20\,\mathrm{GeV}$
Signal region	
OSSF	OSSF lepton pair, $\lvert m_{\ell\ell} - m_Z\rvert > 20\,\mathrm{GeV}$, $p_T^{miss} > 40\,\mathrm{GeV}$
SSSF	No OSSF lepton pair
Control region	
WZ	OSSF lepton pair, $\lvert m_{\ell\ell} - m_Z\rvert < 20\,\mathrm{GeV}$ $p_T^{miss} > 45\,\mathrm{GeV}$, $m_{3\ell} > 100\,\mathrm{GeV}$
Zγ	OSSF lepton pair, $\lvert m_{\ell\ell} - m_Z\rvert < 20\,\mathrm{GeV}$ $p_T^{miss} < 40\,\mathrm{GeV}$, $80 < m_{3\ell} < 100\,\mathrm{GeV}$

Higgs → WW inclusive, differential and STXS

ZH

ZH3l

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\mathrm{GeV}$, $p_{T2} > 20\,\mathrm{GeV}$, $p_{T3} > 15\,\mathrm{GeV}$ $Q_{3\ell} = \pm 1$, $\min(m_{\ell\ell}) > 12\,\mathrm{GeV}$ $\lvert m_{\ell\ell} - m_Z\rvert < 25\,\mathrm{GeV}$, $\lvert m_{3\ell} - m_Z\rvert > 20\,\mathrm{GeV}$ No b-tagged jet with $p_T > 20\,\mathrm{GeV}$
Signal region	
1-jet	$=1$ jet with $p_T > 30\,\mathrm{GeV}$, $\Delta\phi(\ell p_T^{miss}, j(j)) < \pi/2$
2-jet	≥ 2 jets with $p_T > 30\,\mathrm{GeV}$, $\Delta\phi(\ell p_T^{miss}, j(j)) < \pi/2$
Control region	
1-jet WZ	$=1$ jet with $p_T > 30\,\mathrm{GeV}$, $\Delta\phi(\ell p_T^{miss}, j(j)) > \pi/2$
2-jet WZ	≥ 2 jets with $p_T > 30\,\mathrm{GeV}$, $\Delta\phi(\ell p_T^{miss}, j(j)) > \pi/2$

ZH4l

Subcategories	Selection
Global selection	
—	$p_{T1} > 25\,\mathrm{GeV}$, $p_{T2} > 15\,\mathrm{GeV}$, $p_{T3} > 10\,\mathrm{GeV}$, $p_{T4} > 10\,\mathrm{GeV}$ $Q_{4\ell} = 0$, $\min(m_{\ell\ell}) > 12\,\mathrm{GeV}$, $\lvert m_{\ell\ell} - m_Z\rvert < 15\,\mathrm{GeV}$ No b-tagged jet with $p_T > 20\,\mathrm{GeV}$
Signal region	
XSF	Same-flavor X pair, $m_{4\ell} > 140\,\mathrm{GeV}$ $10 < m_{\ell\ell}^{X} < 60\,\mathrm{GeV}$, $p_T^{miss} > 35\,\mathrm{GeV}$
XDF	Different-flavor X pair, $10 < m_{\ell\ell}^{X} < 70\,\mathrm{GeV}$ $p_T^{miss} > 20\,\mathrm{GeV}$
Control region	
ZZ	$75 < m_{\ell\ell}^{X} < 105\,\mathrm{GeV}$, $p_T^{miss} < 35\,\mathrm{GeV}$

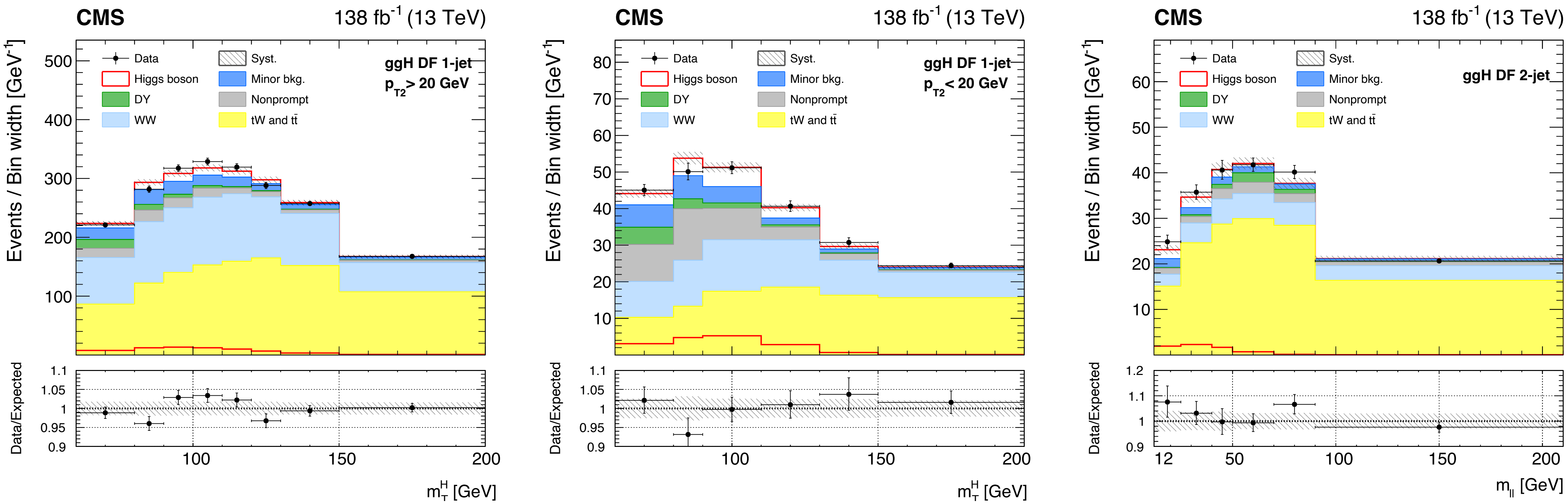
Higgs → WW inclusive, differential and STXS

VH2j

Subcategory	Selection
Global selection	
—	$p_{T1} > 25\,GeV$, $p_{T2} > 10\,GeV$ (2016) or $13\,GeV$ $p_T^{miss} > 20\,GeV$, $p_T^{\ell\ell} > 30\,GeV$, $m_{\ell\ell} > 12\,GeV$ eμ pair with opposite charge
Signal region	
—	At least 2 jets with $p_T > 30\,GeV$, $\|\eta_{j1}\|, \|\eta_{j2}\| < 2.5$ $\Delta\eta_{jj} < 3.5$, $65 < m_{jj} < 105\,GeV$ $60\,GeV < m_T^H < 125\,GeV$, $\Delta R_{\ell\ell} < 2$ No b-tagged jet with $p_T > 20\,GeV$
Control region	
Top quark CR	As SR but with no m_T^H requirement, $m_{\ell\ell} > 50\,GeV$ At least 1 b-tagged jet with $p_T > 30\,GeV$
$\tau\tau$ CR	As signal region but with $m_T^H < 60\,GeV$ $40 < m_{\ell\ell} < 80\,GeV$

Higgs → WW inclusive, differential and STXS

ggF



Higgs → WW inclusive, differential and STXS

CR