Measurements of Higgs Boson Properties in the H→WW Channel in CMS

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CMS
Compact Muon Solenoid

INFN

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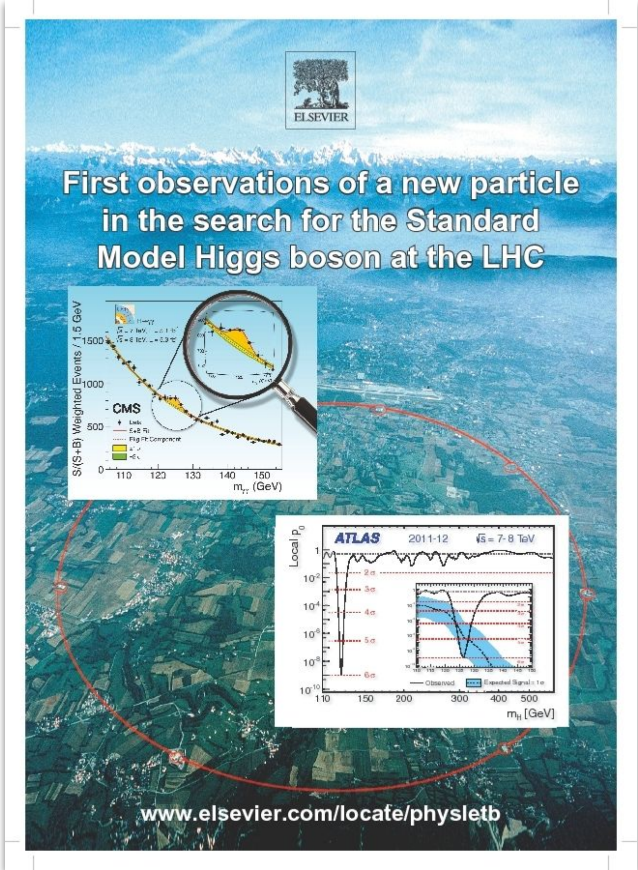
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

10 years after the Higgs boson discovery…

… what have we learned?

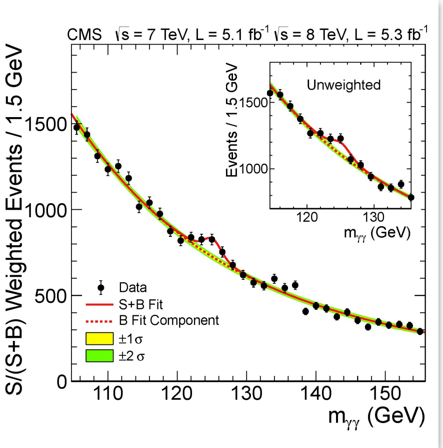


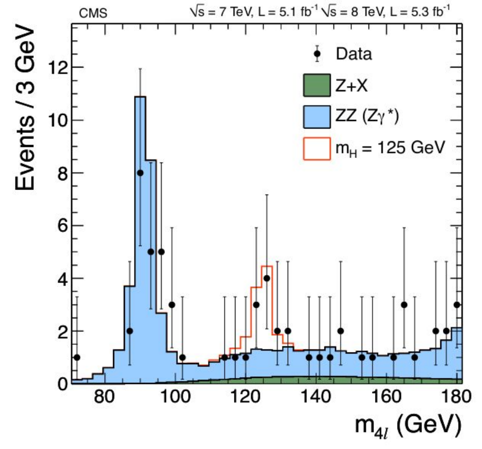
ELSEVIER

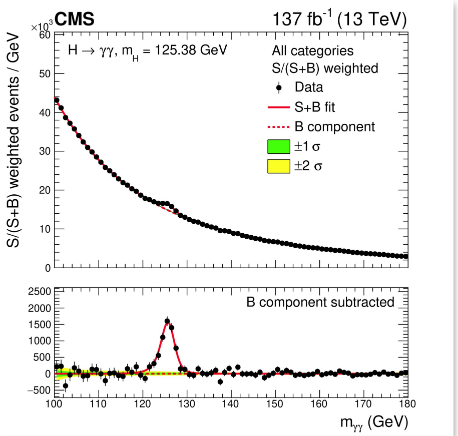
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

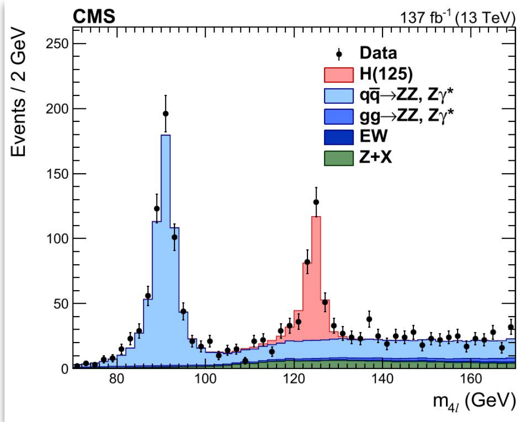
www.elsevier.com/locate/physletb

From discovery to precision









2012

Today

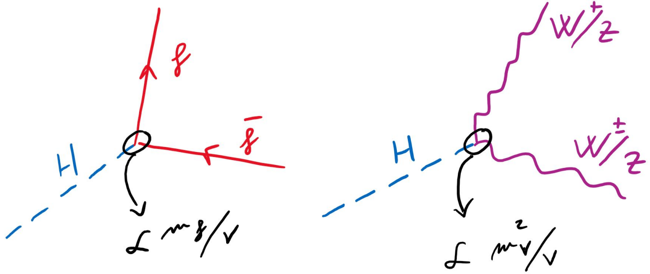
In 10 years the paradigm has changed…

From searching for a new particle to precision measurements!

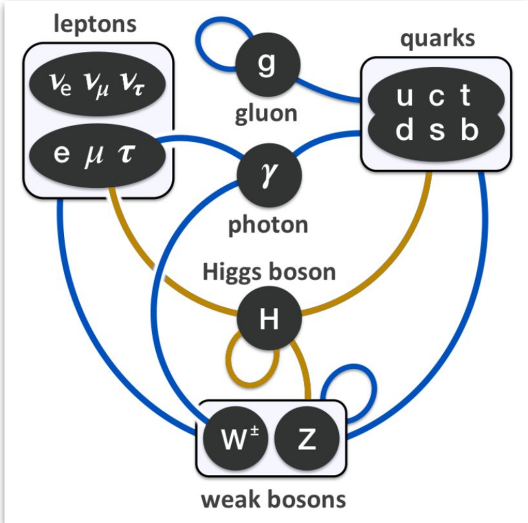
But let’s start from the beginning...

The role of the Higgs boson in the Standard Model

- The interaction of the Higgs boson with the particles provides thei a mass.
- The Higgs boson couplings with bosons and fermions are proportional to their mass.



Courtesy of R. Seidita (all cartoon diagrams)



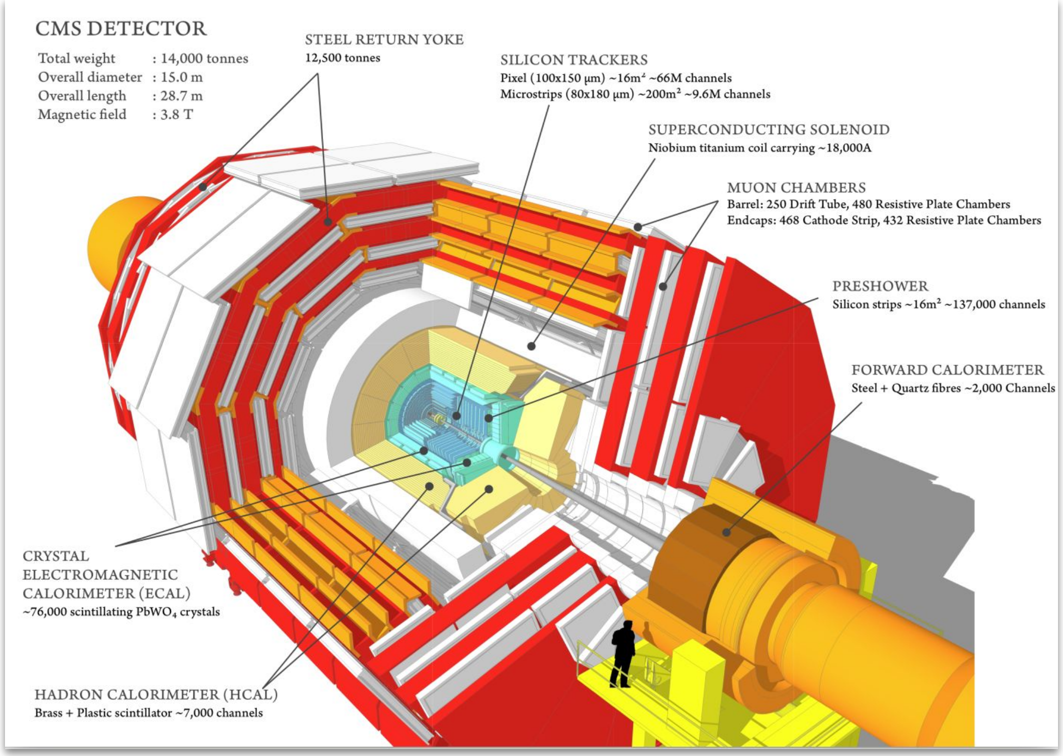
What are the needed ingredients to produce the Higgs boson?

A big machine! The CERN Large Hadron Collider!

- Collides protons at $\sqrt{s} = 13$ TeV (soon 13.6 TeV), but also heavy ions.
- Reaches nominal instantaneous luminosities of $1\text{x}10^{34}$ fb^{-1}.
- 4 interaction points, where 4 experiments are placed:
    - ALICE
    - ATLAS
    - CMS
    - LHCb

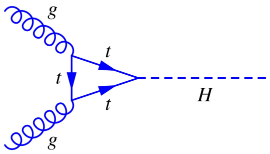
What are the needed ingredients to produce the Higgs boson?

A big particle detector! The Compact Muon Solenoid (CMS) experiment

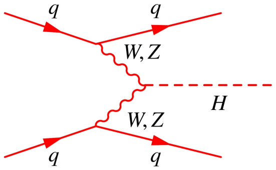


- **General purpose detector with hermetic design.**
- **A complex system of particle detectors:**
  - Silicon pixel tracker
  - Silicon strip tracker
  - PbWO 4 crystal EM calorimeter
  - Hadron calorimeter
  - Muon system
- **3.8 T solenoid** to bend charged particles tracks

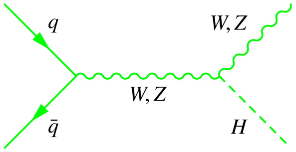
Higgs boson production



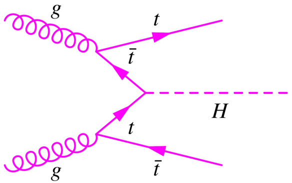
ggH
σ = 48.5 pb



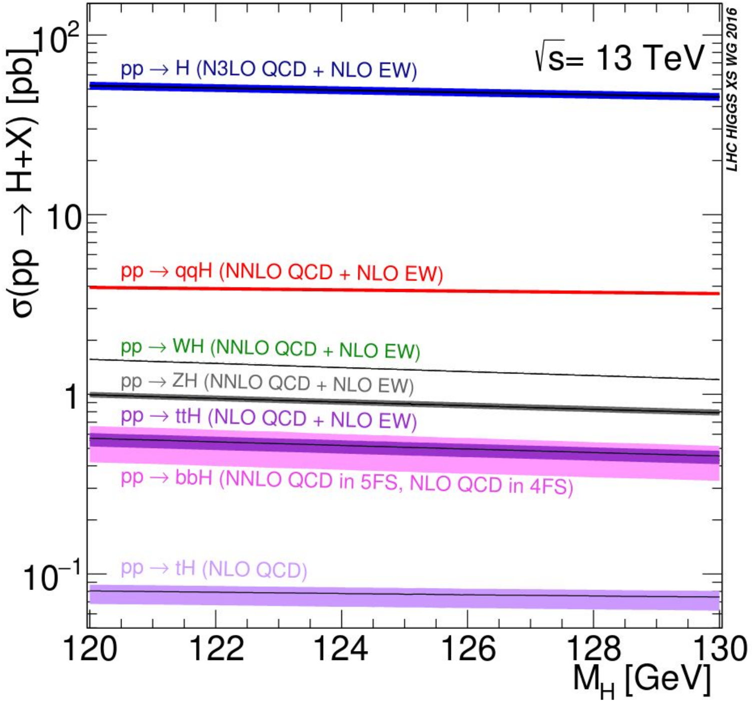
VBF
σ = 3.8 pb



VH
σ = 2.3 pb



ttH
σ = 0.5 pb



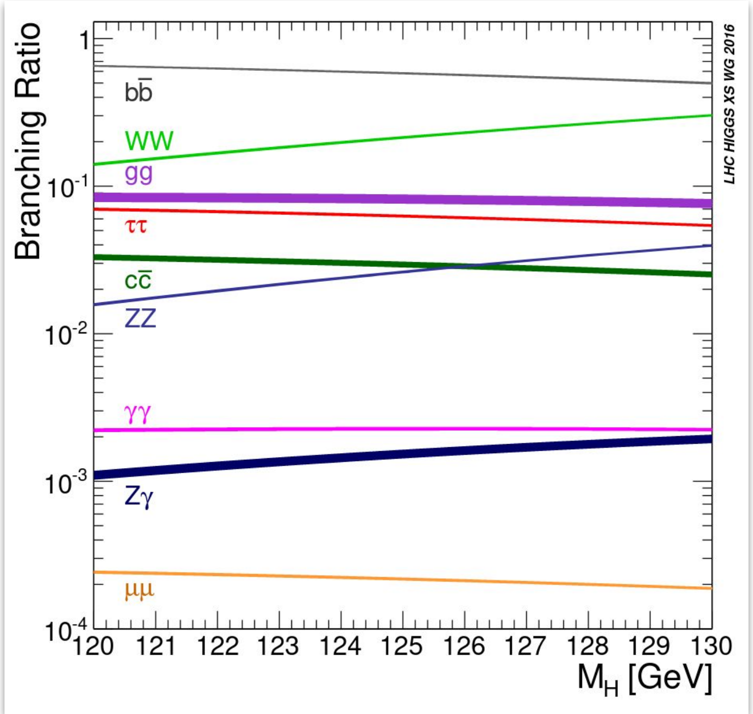
Total cross-section of ~55pb

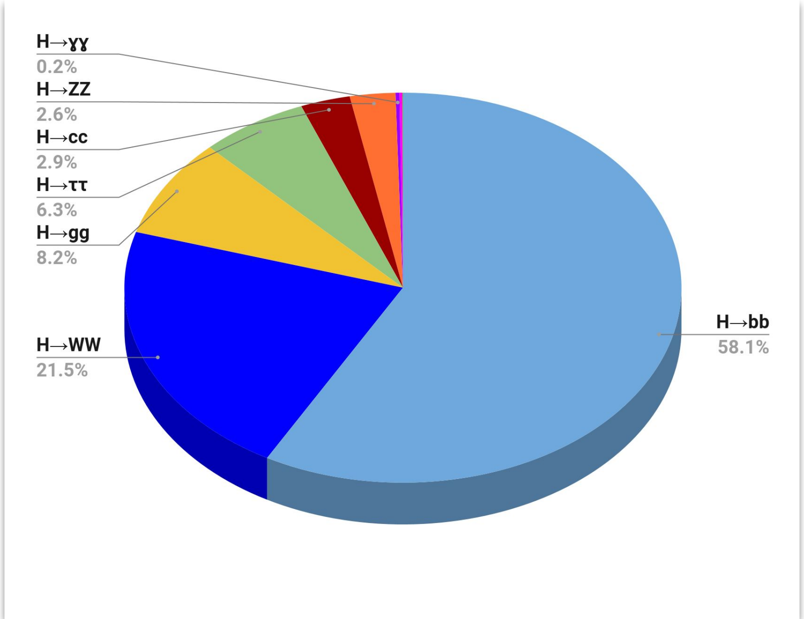
At the LHC we produce O(1) Higgs boson per second!

From the start of the LHC Run 2 (138 fb^{-1}) we have produced 7 million Higgs bosons!

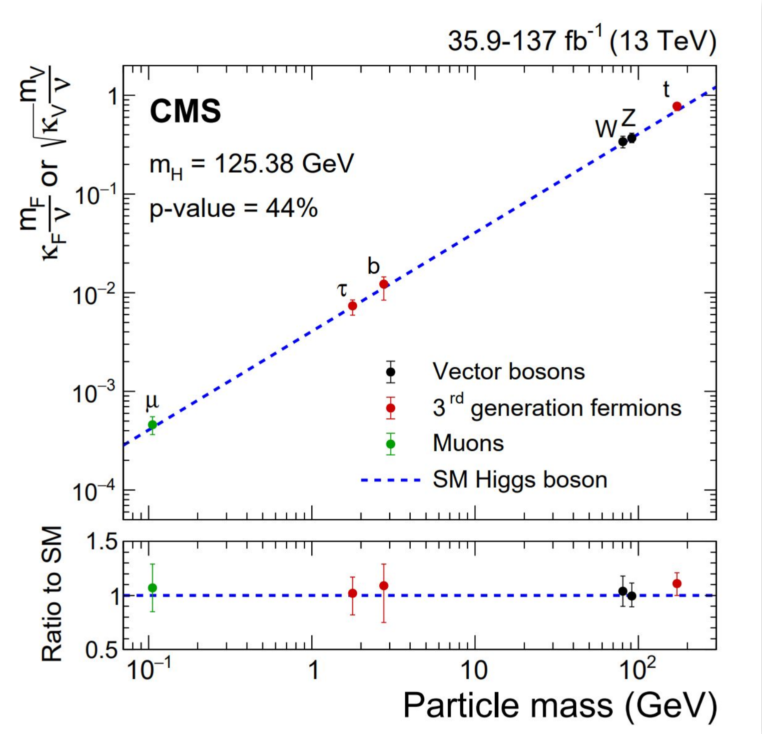
Higgs boson decay

- Main bosonic decay modes: WW, ZZ, γγ
- Main fermionic decay modes: bb, ττ



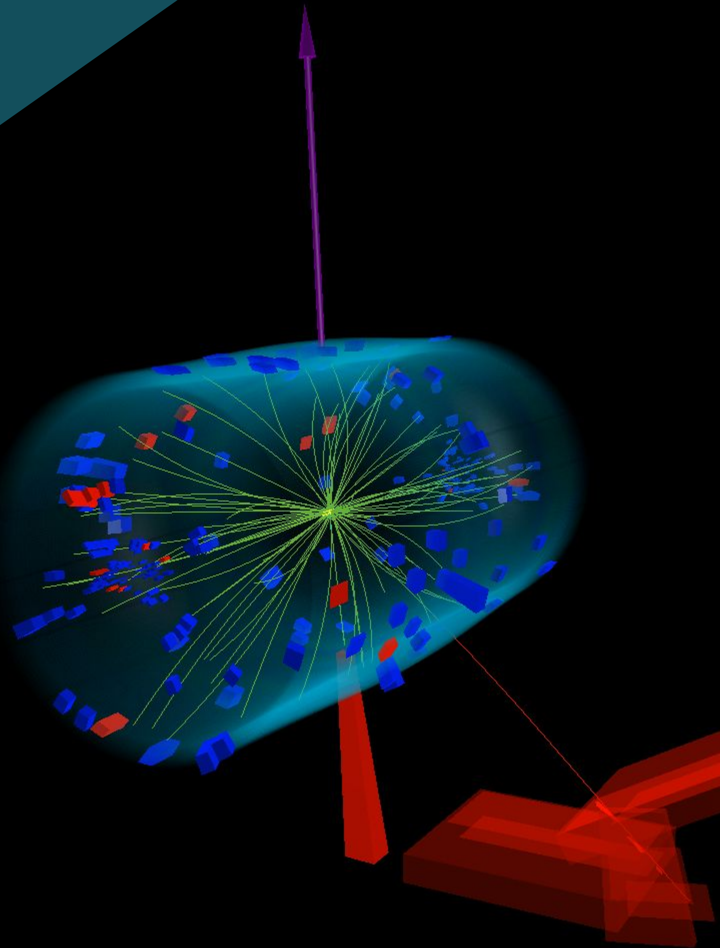


The Run 2 of the LHC

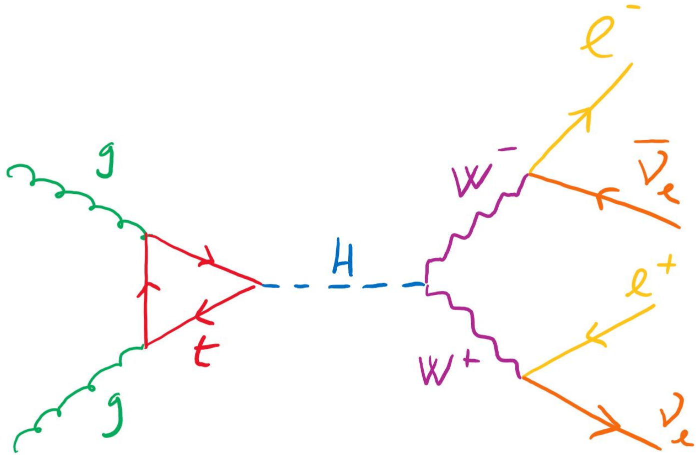


- A huge physics program was explored in Run2, spanning energies from O(GeV) to O(TeV).
- An unprecedented data sample of 138 fb^{-1} was collected in pp collisions at $\sqrt{s}$=13 TeV.
- Highlights:
  - All the main Higgs boson production modes observed with >5 σ either in single channels or in the combinations.
  - H→**μμ** direct evidence.
  - m_H = 125.38 ± 0.14 GeV
  - Differential measurements in all the main channels

The H→WW decay channel



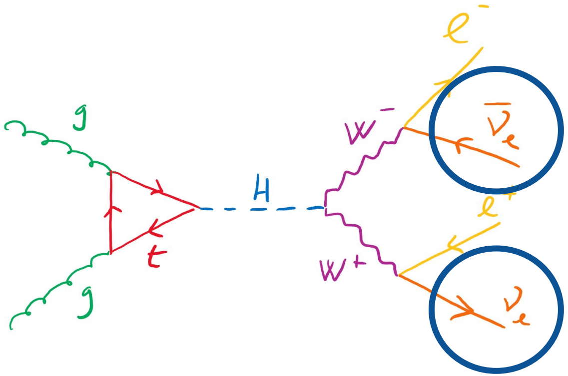
The H→WW decay channel



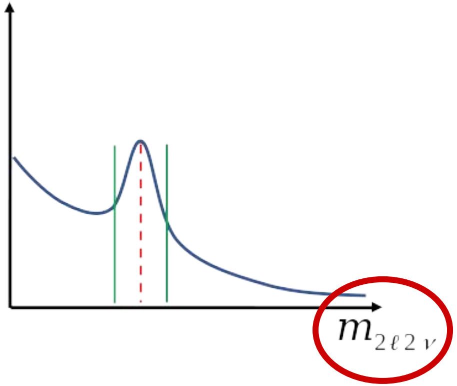
- One of the main channels for cross-section and coupling measurements.
- Several features characterize the sensitivity of a particular channel:
  - the cross section times branching ratio, i.e. σ (ggH)xBR(HWW);
  - the final state signature;
  - the background discrimination power.

- BR(W→hadrons)~70% ⇒ a lot of signal, but huge QCD background at hadron colliders.
- BR(W→lν)~10% ⇒ smaller signal but “clean” final state and less background.

The H→WW→2l2ν signature



Ok there are backgrounds, but we have a resonant Higgs boson here… shouldn't we see a peak?



Yes! But in practice no… 🙁

We can't measure the neutrinos 4-momenta because our experiments can't detect neutrinos.

We don't have the full information to reconstruct this invariant mass.

What we can measure is the missing momentum in the transverse plane with respect to the proton beams.

$$\vec{p}_T^{\,miss} = -\sum_{obj} \vec{p}_T^{\,obj}$$

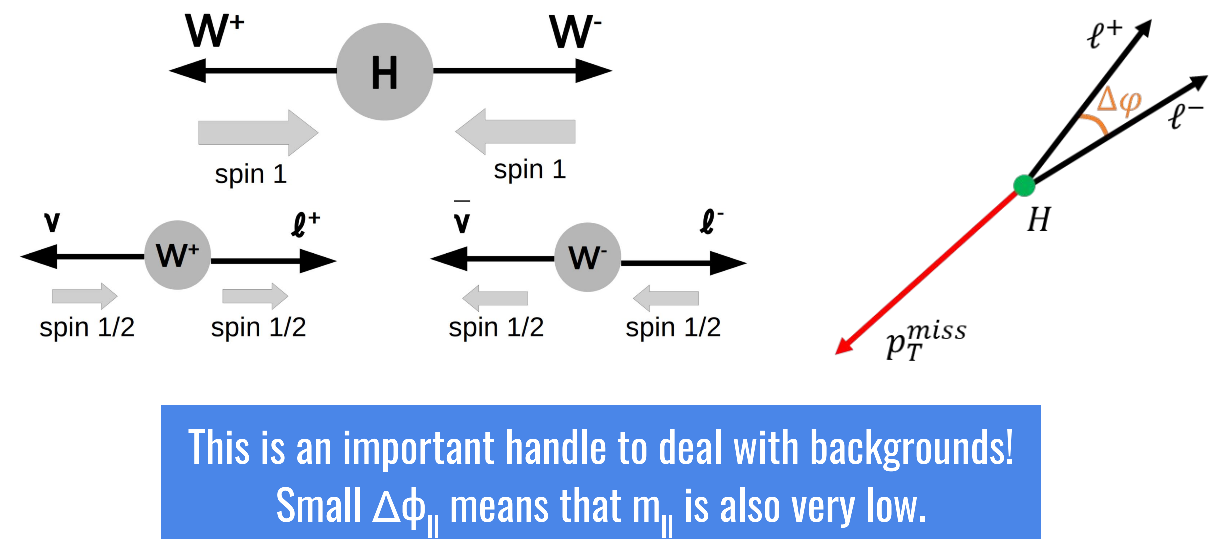
So no peak, no party?

What do physics books tell us about this channel?

- m_H=125 GeV and m_W=80 GeV → one of the 2 Ws must be off-shell
- Higgs and W spins play a role!

Does not help with backgrounds, but it means that one of the 2 leptons will have very low pT

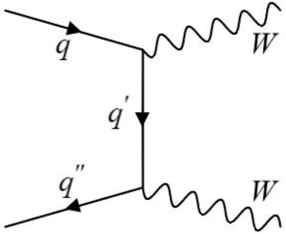
We need dilepton triggers with low pT thresholds



This is an important handle to deal with backgrounds!
Small $\Delta\phi_{ll}$ means that m_{ll} is also very low.

Background processes

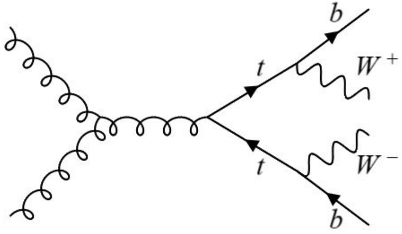
Non-resonant WW production



No spin correlation and both Ws are on-shell.

Data-driven normalization.

Top quark processes

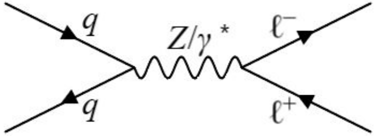


Large cross section and similar signature except for the 2 b-jets.

B-jets can be identified (and suppressed) using b-tagging algorithms.

Data-driven normalization.

Drell-Yan processes



Huge cross-section, dominant when looking at leptons with same flavor.

Enters also the eμ final state via the leptonic tau decays.

Fully data-driven (tau embedding method for emu final states).

Depending on the channel, other backgrounds can be important.
Such as the nonprompt lepton production, i.e. jets faking prompt leptons (fully data-driven).

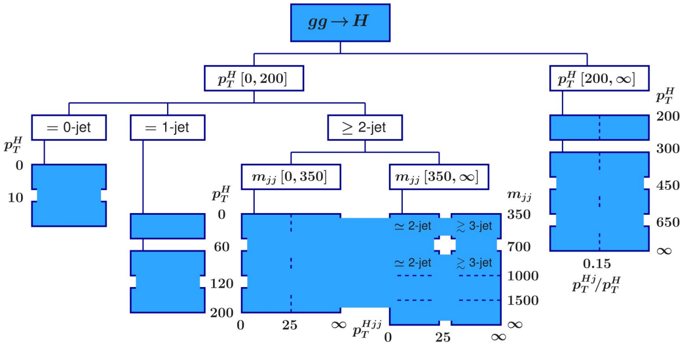
Let’s dig into the real analysis now

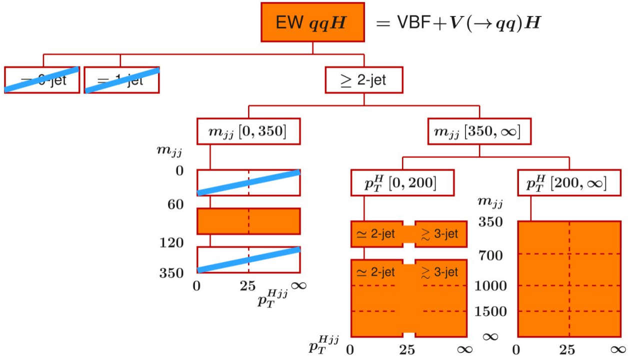
CMS-PAS-HIG-20-013

New for Moriond/EW 22

Analysis goals - cross sections

- Cross section measurements of different production mechanisms.
- Cross section measurement in the Simplified Template Cross Section (STXS) framework.



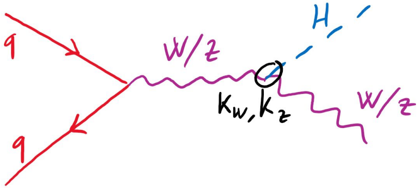


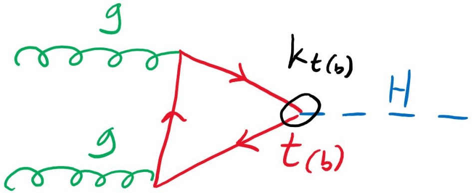
- Measure cross sections in pre-defined template bins per production mode with the goal of:
  - minimizing theory dependence;
  - maximizing experimental sensitivity;
  - isolating possible BSM effects.

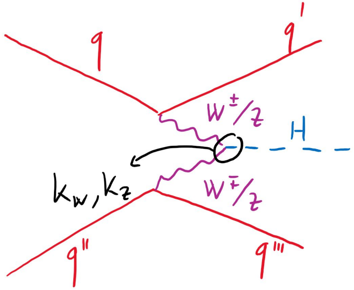
- No fiducial phase space (only $|y_H|<2.5$):
  - ✓ Possible to combine different decay channels.
  - X Larger extrapolation uncertainties.

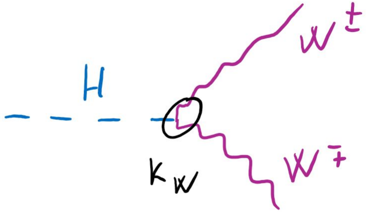
Analysis goals - couplings

- The H→WW decay provides direct access to the Higgs coupling with W bosons.
- But measuring different production mechanisms simultaneously allows constraining the couplings with Z and top









- Couplings are constrained by a parameterization of σxBR in terms of the k-framework, e.g.:

$$(\sigma \times \mathcal{BR})_{gg\rightarrow H\rightarrow WW} \propto \kappa_t^2 \kappa_W^2$$

$$(\sigma \times \mathcal{BR})_{VBF\rightarrow H\rightarrow WW} \propto (0.73\kappa_W^2 + 0.27\kappa_Z^2) \cdot k_W^2$$

Analysis overview

Category	Number of leptons	Number of jets	Sub-categorization
ggH	2	-	$(\mathrm{DF}, \mathrm{SF}) \times (0 \text{ jets}, 1 \text{ jet}, \geq 2 \text{ jets})$
VBF	2	≥ 2	$(\mathrm{DF}, \mathrm{SF})$
VH2j	2	≥ 2	$(\mathrm{DF}, \mathrm{SF})$
WHSS	2	≥ 1	$(\mathrm{DF}, \mathrm{SF}) \times (0 \text{ jets}, 1 \text{ jet})$
WH3ℓ	3	0	SF lepton pair with opposite or same sign
ZH3ℓ	3	≥ 1	$(1 \text{ jet}, 2 \text{ jets})$
ZH4ℓ	4	-	$(\mathrm{DF}, \mathrm{SF})$

- The analysis targets ggH, VBF, WH and ZH production mechanisms exploring a variety of final states.

- **ggH:** gg→H(WW→2l2ν)
- **VBF:** qq→qqH(WW→2l2ν)
- **VH2j:** V(qq) H(WW→2l2ν)

New measurements with the full Run2 dataset!

- **WHSS:** W(lν) H(W(lν) W(qq))
- **WH3l:** W(lν) H(WW→2l2ν)
- **ZH3l:** Z(ll) H(W(lν) W(qq))
- **ZH4l:** Z(ll) H(WW->2l2ν)

Reload of the measurements already reported in CMS-PAS-HIG-19-017

Ingredients

Low pT triggers

- eμ triggers with pT>23, 12 GeV
- Single lepton triggers to recover efficiency

Efficient b-tagging

- Needed to veto events containing a b-tagged jet

High performance electron/muon identification

- Requiring lepton isolation is fundamental to tackle nonprompt lepton backgrounds.
- Extensive use of MVA techniques.

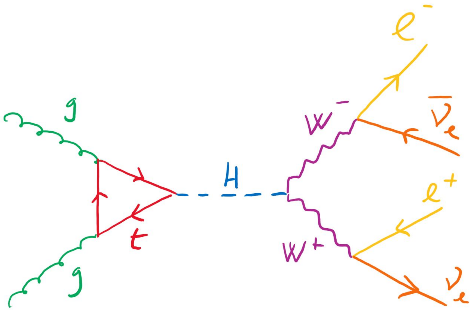
State of the art Monte Carlo simulations

- Background modelling is important for processes estimated from simulations.
- Using Powheg, Madgraph5_aMC@NLO, etc.

And much more....

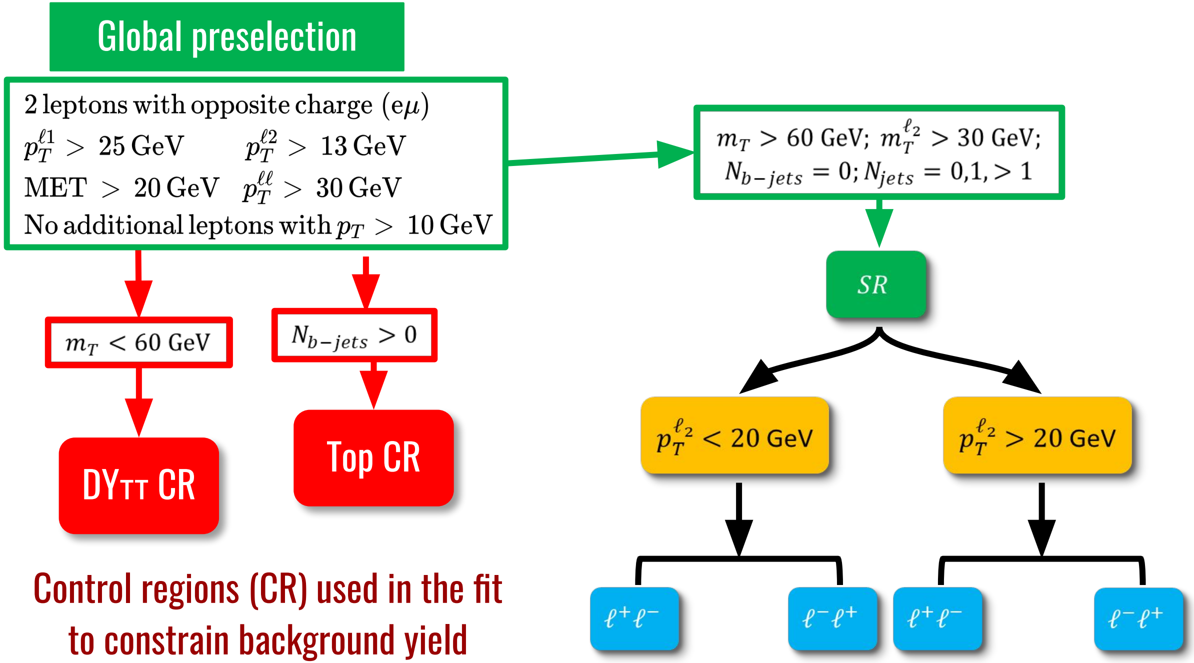
- anti-kT (DR=4) jets; PUPPI MET; pileup jet ID; a variety of corrections, scale-factors, k-factors, calibrations, validations, ...

ggH channels - categories



Key aspects:

- Most sensitive channels.
- Different flavor (DF) channels have better performance, but same flavor (SF) are also taken into account.
- For SF the DY background is fully data-driven.



Global preselection

2 leptons with opposite charge ($e\mu$)
$p_T^{\ell 1} > 25$ GeV $p_T^{\ell 2} > 13$ GeV
MET > 20 GeV $p_T^{\ell\ell} > 30$ GeV
No additional leptons with $p_T > 10$ GeV

$m_T < 60$ GeV → **DYττ CR**

$N_{b-jets} > 0$ → **Top CR**

$m_T > 60$ GeV; $m_T^{\ell_2} > 30$ GeV;
$N_{b-jets} = 0; N_{jets} = 0,1,>1$

SR

$p_T^{\ell_2} < 20$ GeV: $\ell^+\ell^-$, $\ell^-\ell^+$

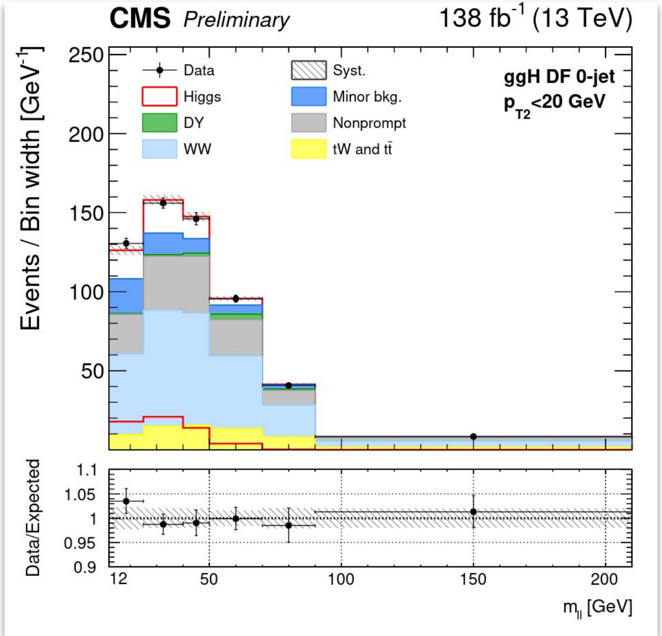
$p_T^{\ell_2} > 20$ GeV: $\ell^+\ell^-$, $\ell^-\ell^+$

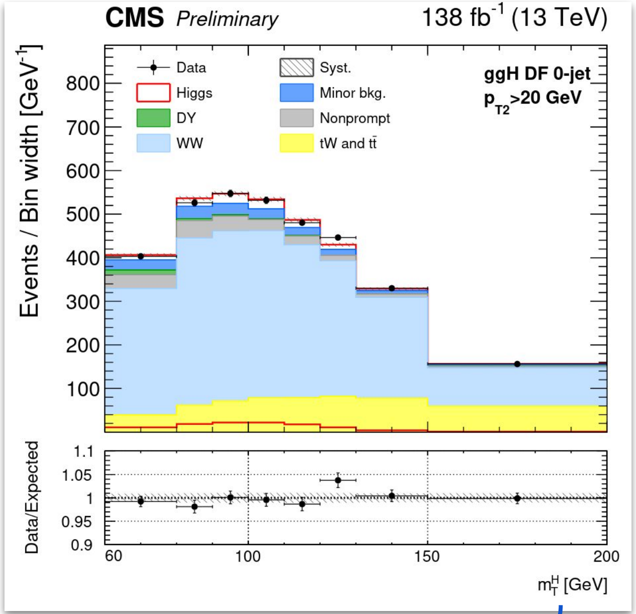
Control regions (CR) used in the fit to constrain background yield

Similar control regions are present for all channels

ggH channels - fit variables

2-dimensional template fit using these observables



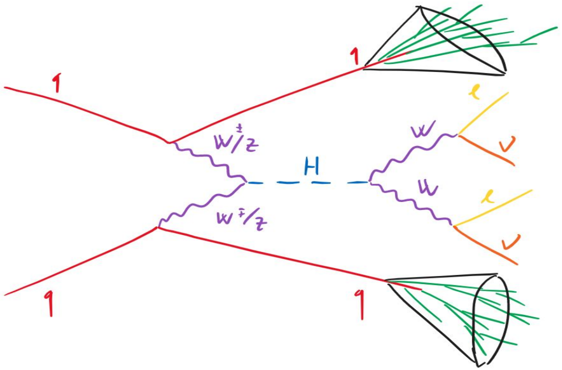


$$m_{\mathrm{T}}^{\mathrm{H}} = \sqrt{2\, p_{\mathrm{T}}^{\ell\ell}\, p_{\mathrm{T}}^{miss}\, (1 - \cos\Delta\phi(\ell\ell, \mathrm{MET}))}$$

Do not need dedicated WW control regions.

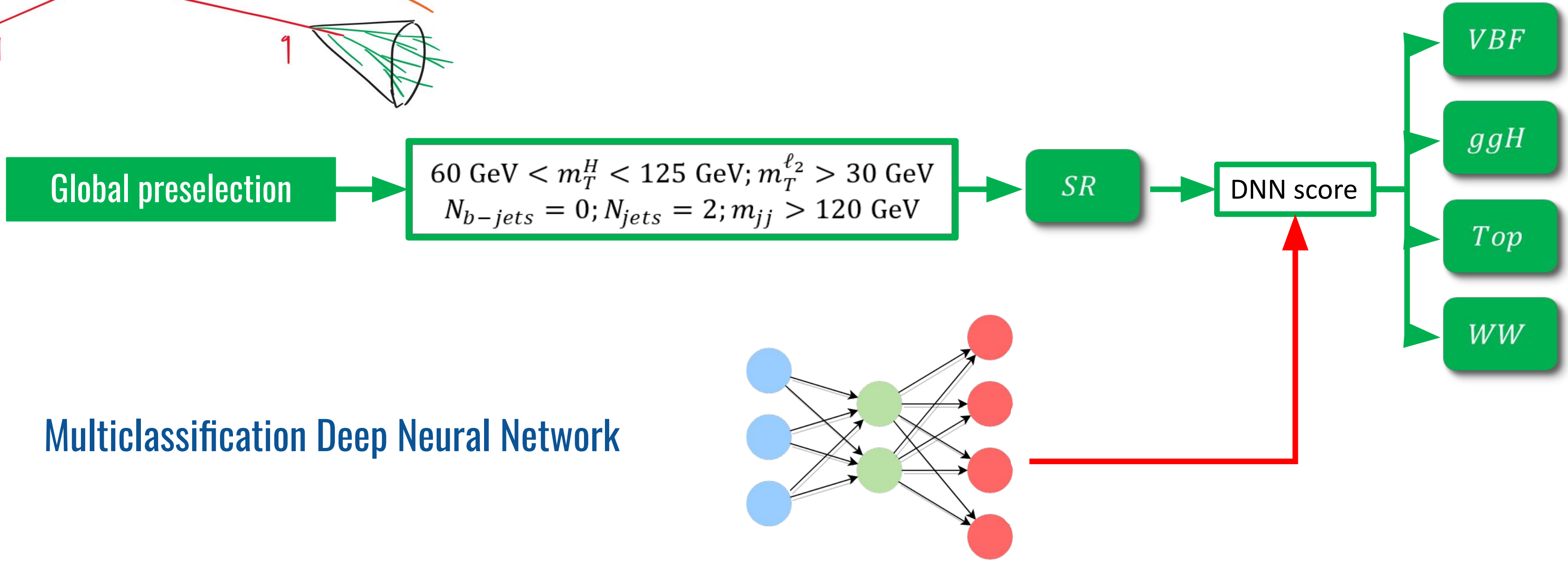
WW yield constrained using data directly in the signal region.

VBF channels - categories



Key aspects:

- VBF is a rare process;
- 2 VBF jets with high invariant mass and pseudorapidity gap;
- important to distinguish VBF and ggH.

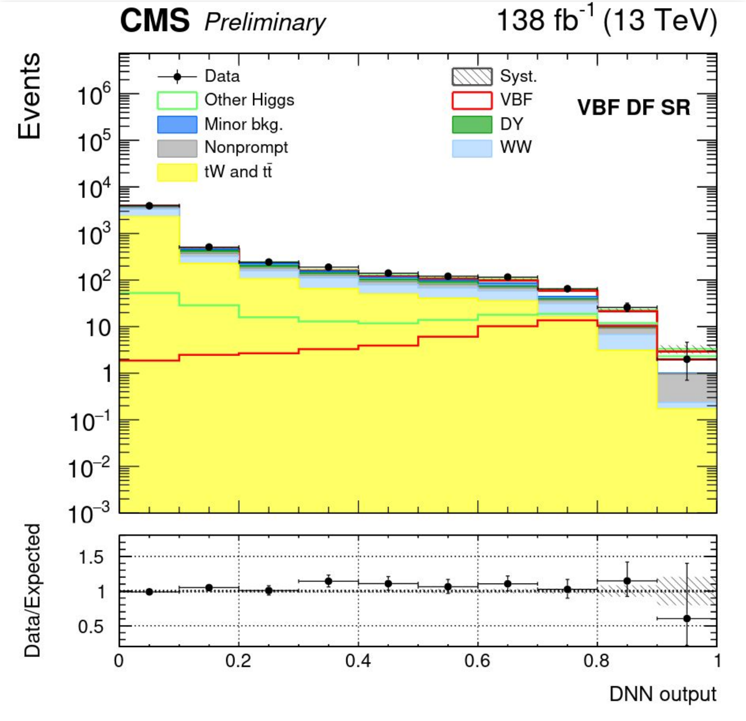


$60\ \text{GeV} < m_T^H < 125\ \text{GeV}; m_T^{\ell_2} > 30\ \text{GeV}$
$N_{b-jets} = 0; N_{jets} = 2; m_{jj} > 120\ \text{GeV}$

Multiclassification Deep Neural Network

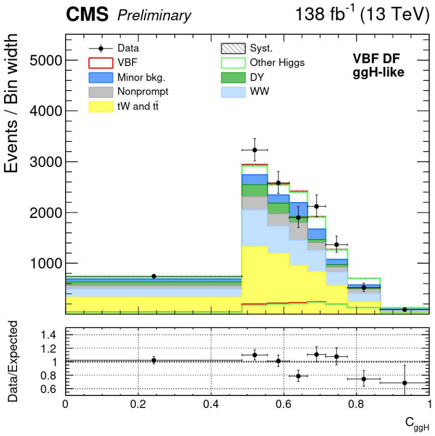
VBF channels - fit variables

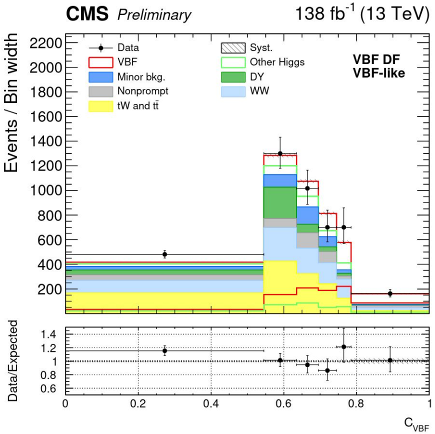
The fit variables are the DNN output discriminators



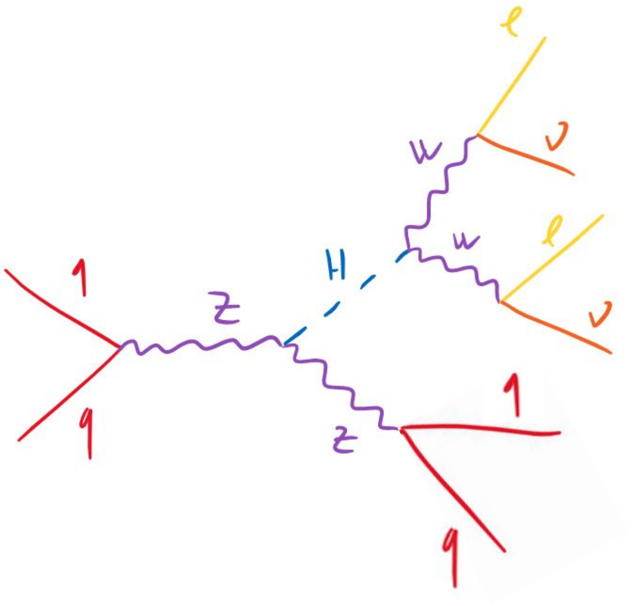
ggH node has the highest score

VBF node has the highest score



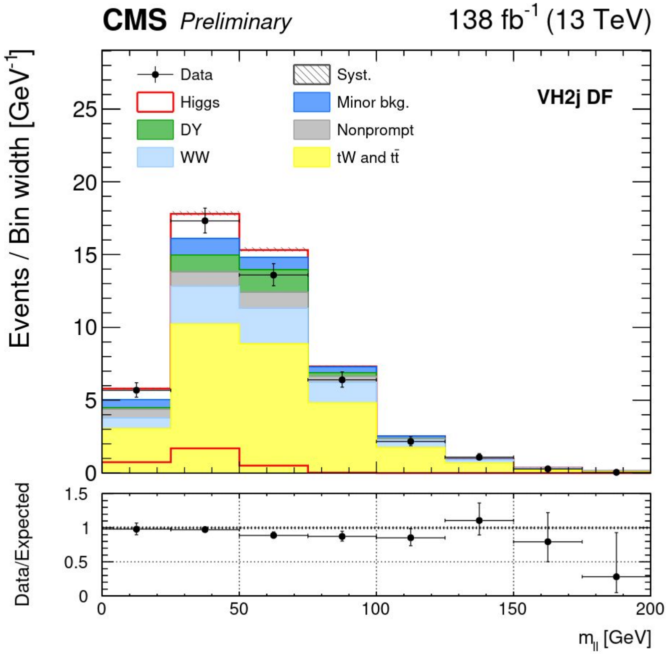


VH hadronic channel

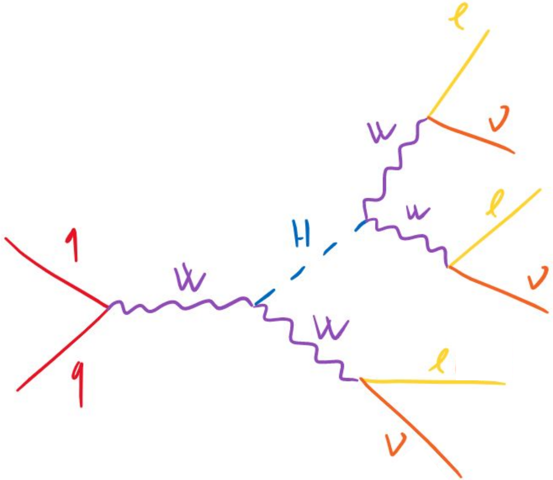


Key aspects:

- Contributions from both ZH and WH (impossible to distinguish them).
- The dijet mass peaks at the Z/W mass.
- Large ggH contamination.

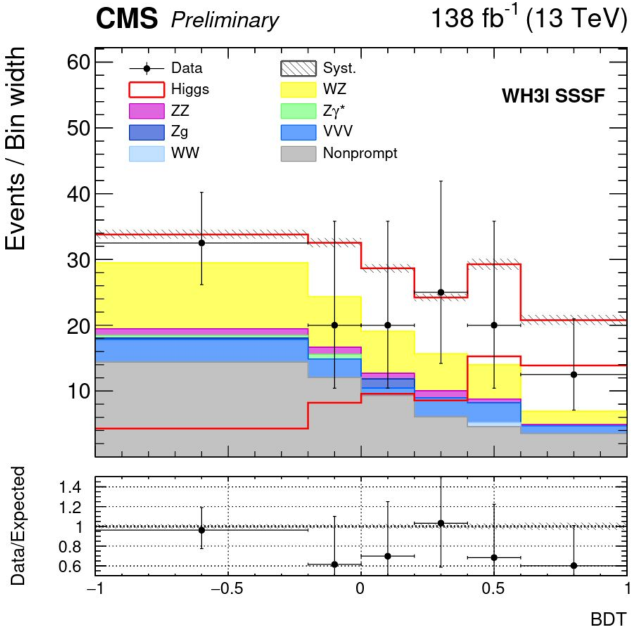


WH 3 leptons

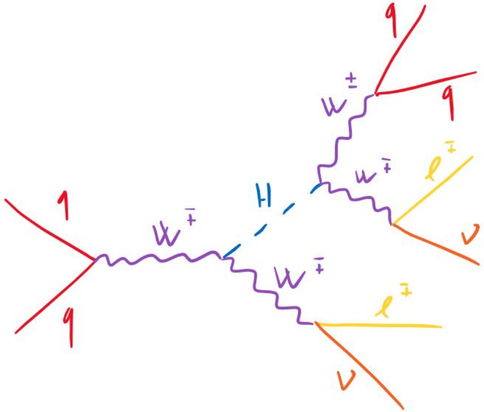


Key aspects:

- Consider the combinatorics of lepton charge and flavor.
- Main backgrounds are WZ and Nonprompt lepton production.
- BDT trained to maximize the signal-to-background separation.
- BDT used as fit variable.



WH 2 same-sign leptons

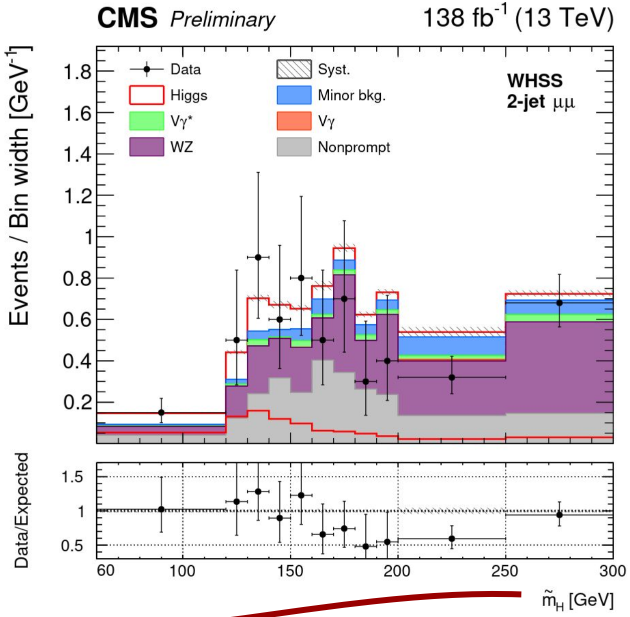


Key aspects:

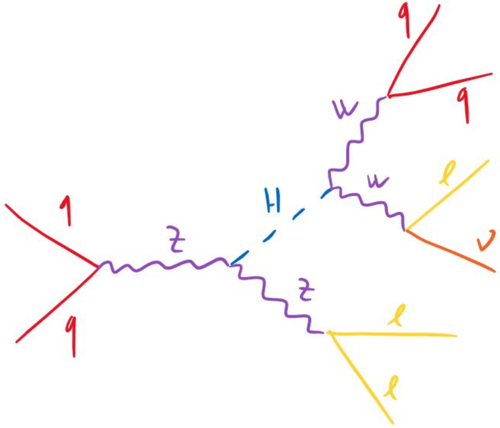
- Target hadronic decays of one of the W arising from the Higgs boson.
- Require the other 2 leptons to have same-sign to reduce backgrounds.
- Main remaining backgrounds are WZ and Nonprompt.

This is a reasonably good proxy for the true Higgs boson mass

$$\tilde{m}_{\mathrm{H}} = \sqrt{(p_{jj} + 2p_{\ell})^2}$$

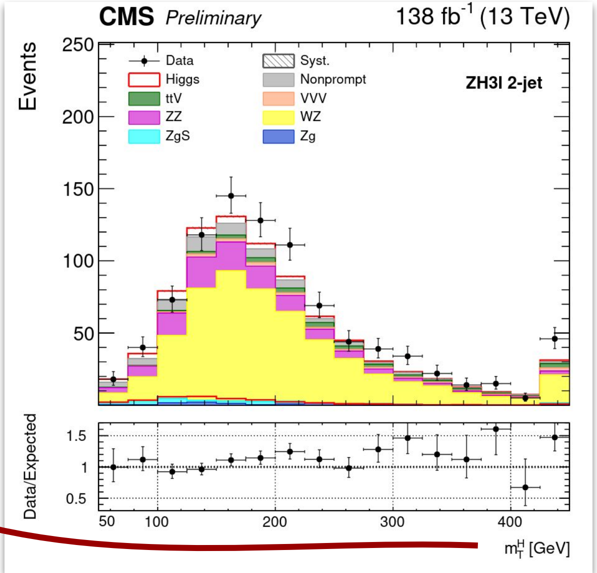


ZH 3 leptons



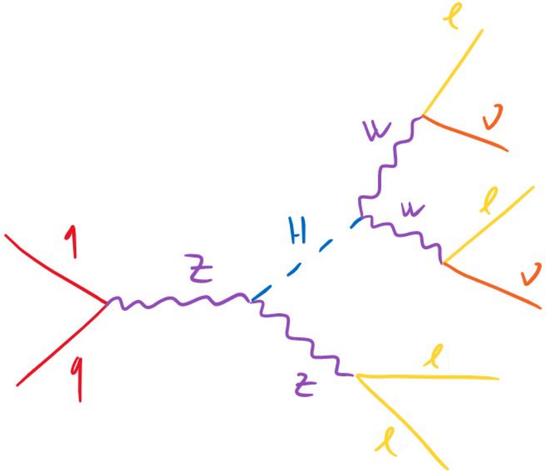
Key aspects:

- Similar to WHSS, but for the ZH production mechanism.
- The lep+MET and jj systems are close-by in the transverse plane (remember the spins!).
- The main background is WZ.



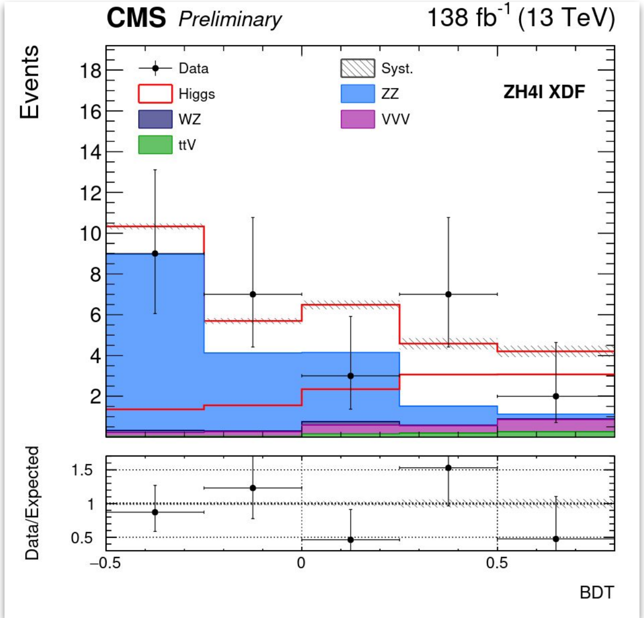
Transverse mass of the full system of leptons, MET and jets.

ZH 4 leptons



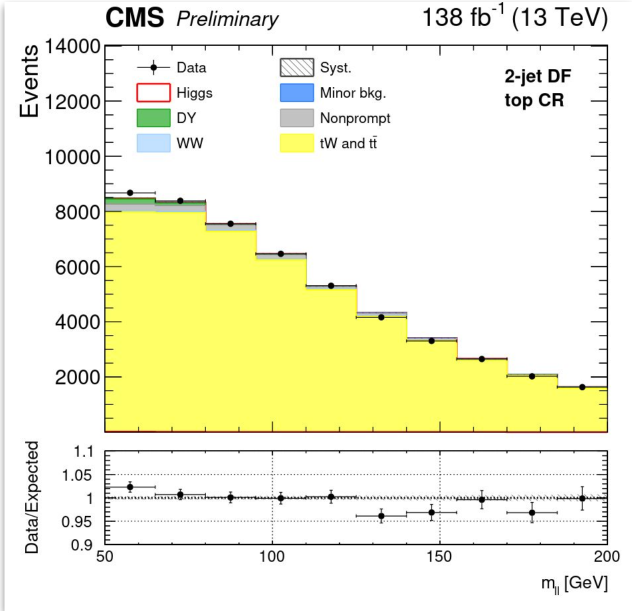
Key aspects:

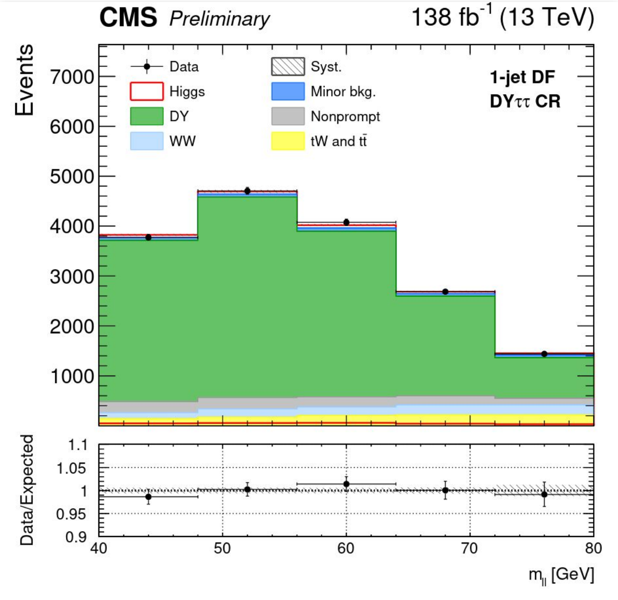
- 4 leptons makes this a very clean channel, the signal is small though.
- 2 sub-categories according to lepton flavor and charge.
- The only background is ZZ.
- Train a BDT to optimize the signal-to-background separation and use it as fit variable.



Control regions

- Important to use control regions for a few reasons:
  - use them in the fit to constrain background yields directly from data;
  - use them to check the shape agreement between data and simulation.





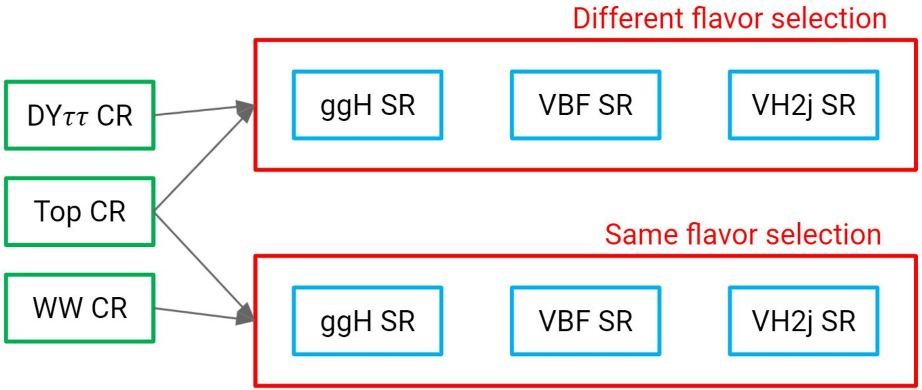
Let’s now put all the ingredients together…

The fit structure

- Simultaneous maximum likelihood template fit to all signal and control regions.
    - 207 categories
    - 1974 bins

$$\boxed{\mu = \sigma / \sigma_{\mathrm{SM}}}$$

$$\mathcal{L}(\vec{v},\mu) = \left(\prod_{j=1}^{N_{bins}} \mathcal{P}\left(n_j; \mu \cdot s_j(\vec{v}) + b_j(\vec{v})\right)\right) \cdot \mathcal{N}(\vec{v})$$



Different flavor selection

DY$\tau\tau$ CR

Top CR

WW CR

ggH SR

VBF SR

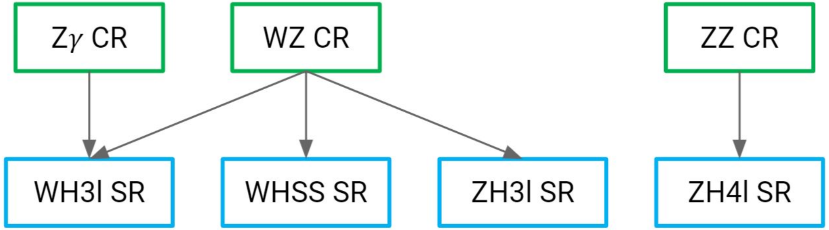
VH2j SR

Same flavor selection

ggH SR

VBF SR

VH2j SR



Zγ CR

WZ CR

ZZ CR

WH3l SR

WHSS SR

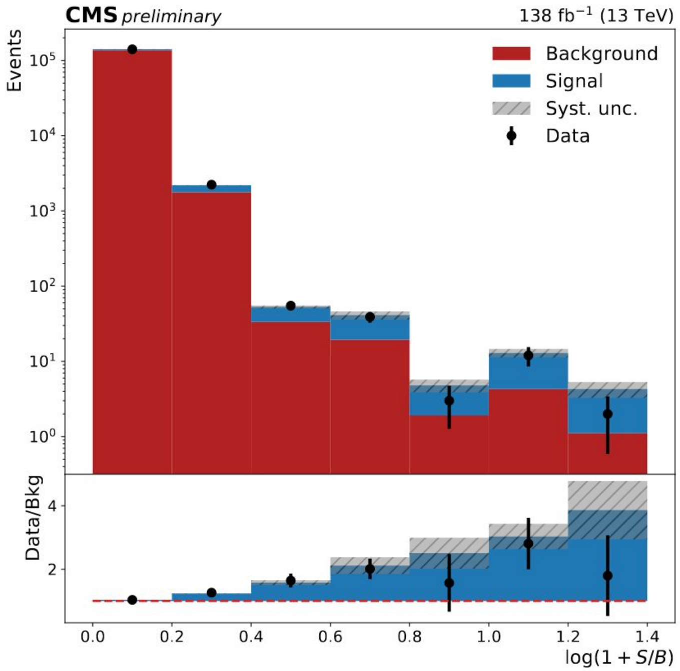
ZH3l SR

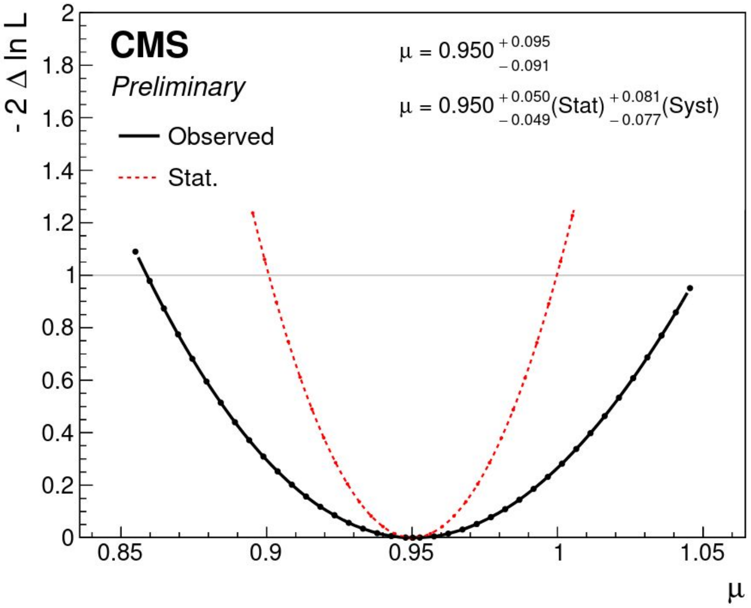
ZH4l SR

- Different fits are performed according to different signal models:
    - 1 μ scaling all Higgs signals;
    - 1 μ per production mode;
    - 1 μ per STXS bin;
    - kappa-framework.

Inclusive results

Distribution of events as a function of the statistical significance of their corresponding bin in the analysis templates



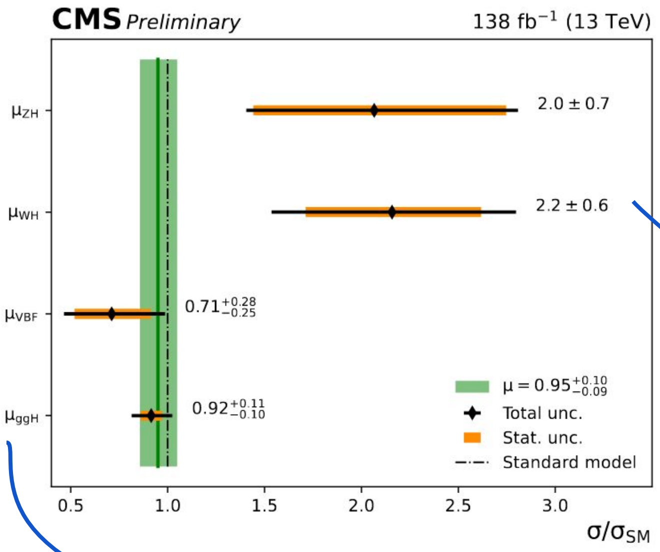


Precision on the inclusive signal-strength measurement is below 10%!
Dominant contribution of systematic uncertainties.

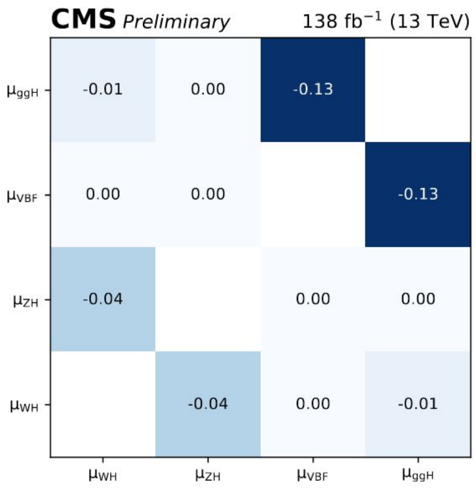
Production mode results

- Signal strength measurement precision:
  - ~11% (ggH), ~35% (VBF and VH);

- μ_{ggH} measurement is systematics-limited.
- Similar size of stat and syst for μ_{VBF} and μ_{WH}.
- μ_{ZH} limited by statistical uncertainties.



Amongst the most precise μ_{ggH} and μ_{WH} measurements from a single decay channel



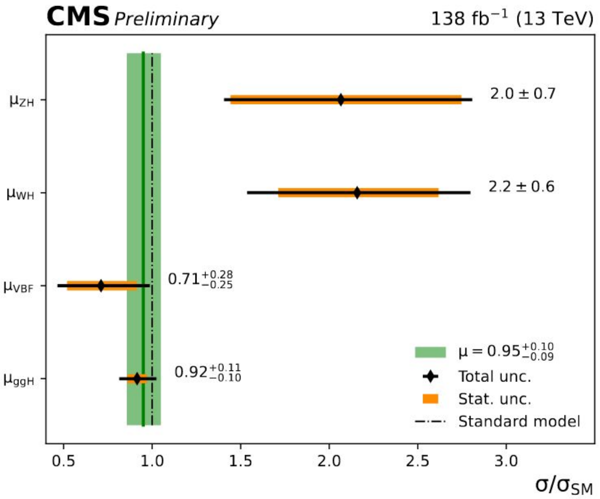
CMS Preliminary 138 fb^{-1} (13 TeV)

	μ_{WH}	μ_{ZH}	μ_{VBF}	μ_{ggH}
μ_{ggH}	-0.01	0.00	-0.13	
μ_{VBF}	0.00	0.00		-0.13
μ_{ZH}	-0.04		0.00	0.00
μ_{WH}		-0.04	0.00	-0.01

Correlations are fairly small

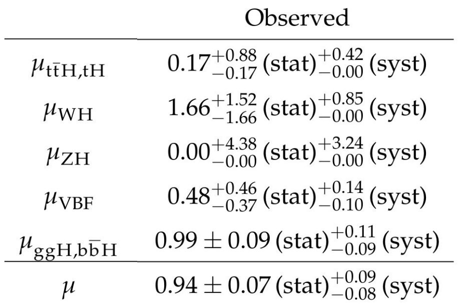
Observed(expected) significances:
ggH: 10.5(11.8)σ
VBF: 3.15(4.74)σ
WH: 3.61(1.82)σ
ZH: 3.73(2.19)σ

How do we compare with other channels?



CMS H→ZZ

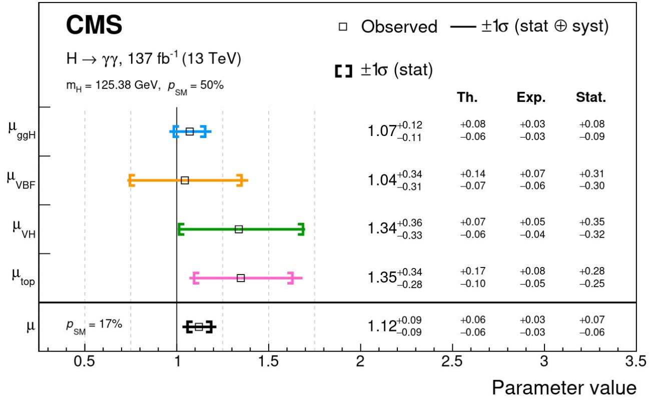
EPJC, 81 (2021) 488



	Observed
$\mu_{t\bar{t}H,tH}$	$0.17^{+0.88}_{-0.17}$ (stat) $^{+0.42}_{-0.00}$ (syst)
μ_{WH}	$1.66^{+1.52}_{-1.66}$ (stat) $^{+0.85}_{-0.00}$ (syst)
μ_{ZH}	$0.00^{+4.38}_{-0.00}$ (stat) $^{+3.24}_{-0.00}$ (syst)
μ_{VBF}	$0.48^{+0.46}_{-0.37}$ (stat) $^{+0.14}_{-0.10}$ (syst)
$\mu_{ggH,b\bar{b}H}$	0.99 ± 0.09 (stat) $^{+0.11}_{-0.09}$ (syst)
μ	0.94 ± 0.07 (stat) $^{+0.09}_{-0.08}$ (syst)

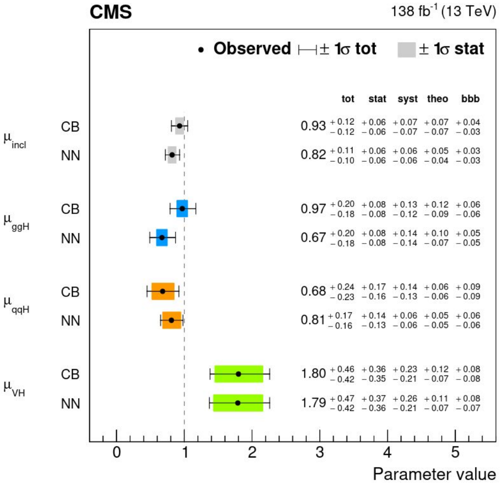
CMS H→γγ

JHEP, 07 (2021) 027



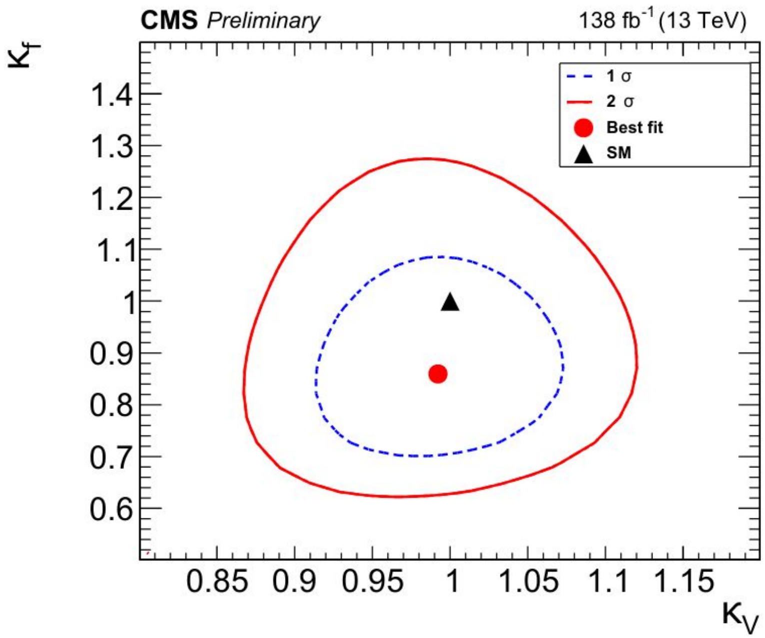
CMS H→ττ

arXiv:2204.12957



k-framework interpretation

- We assume the same scaling k for bosons (k_V) and for fermions (k_f).



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

HWW CMS

$$\kappa_V = 0.99 \pm 0.05$$
$$\kappa_f = 0.86^{+0.14}_{-0.11}$$

ATLAS full Run 2 combination

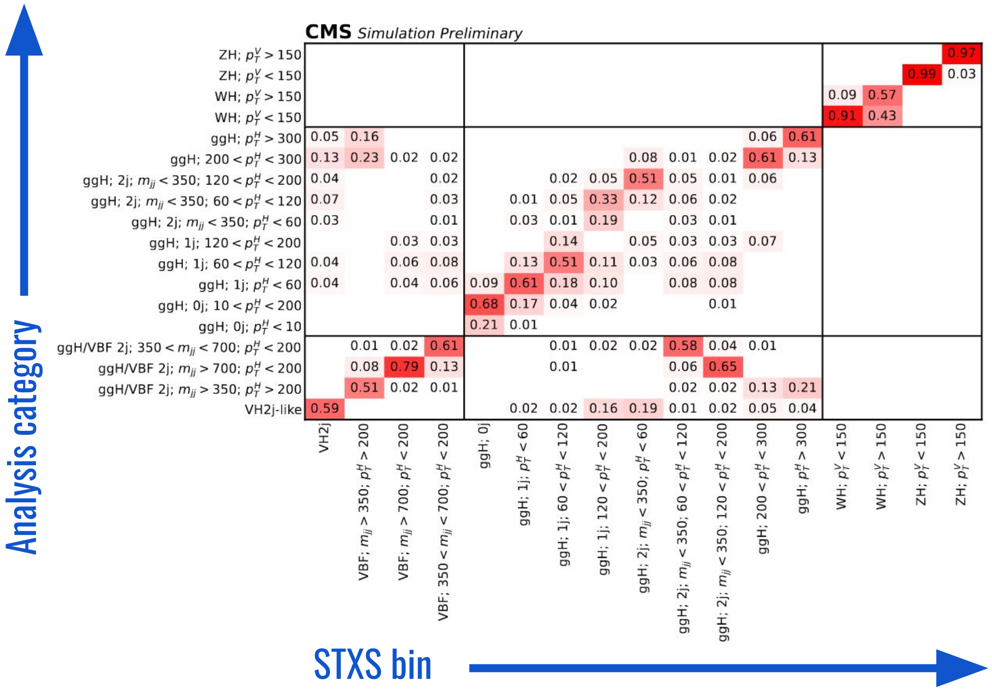
ATLAS-CONF-2021-053

$$\kappa_V = 1.039^{+0.031}_{-0.030}$$
$$\kappa_F = 0.93 \pm 0.05$$

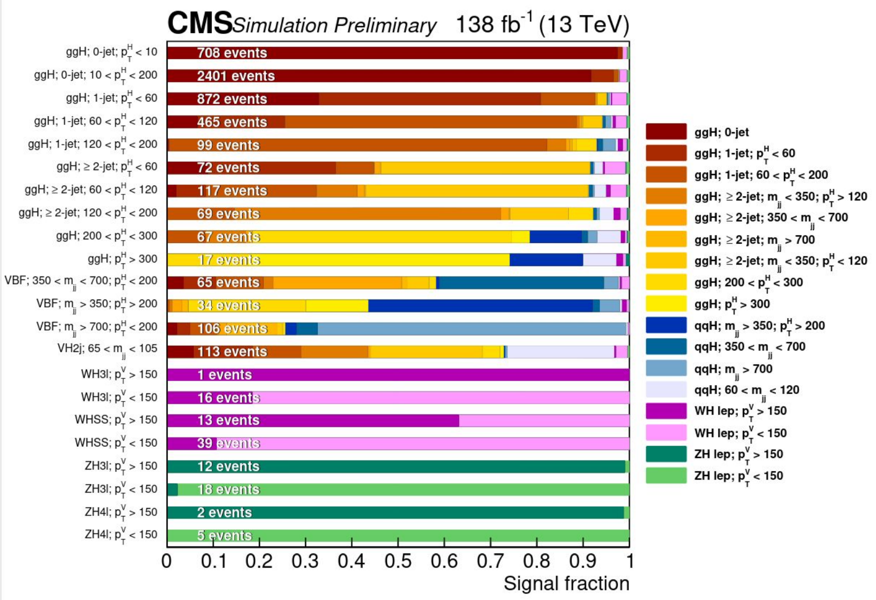
- Extremely good precision for k_V!
  - And competitive measurement of k_f.
- Comparable with ATLAS full Run 2 combination of all Higgs decay channels!

STXS measurements

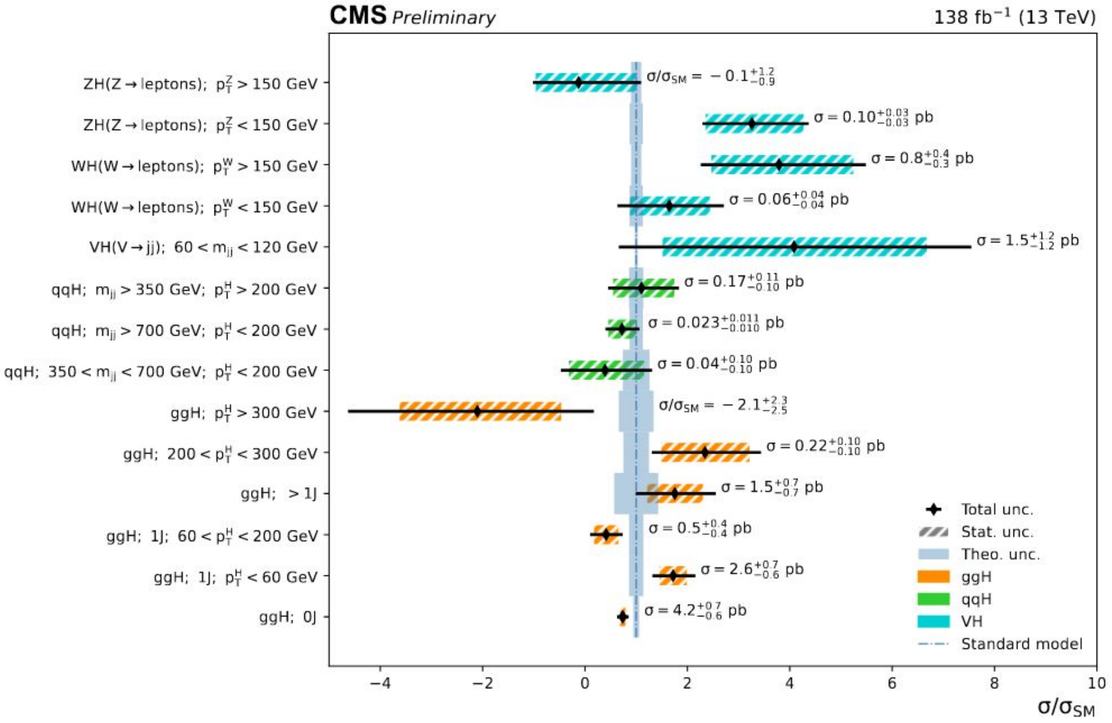
- STXS is a differential measurement unfolded to particle-level.
- The analysis categories at reconstructed-level are adapted to match the particle-level STXS bin definitions.



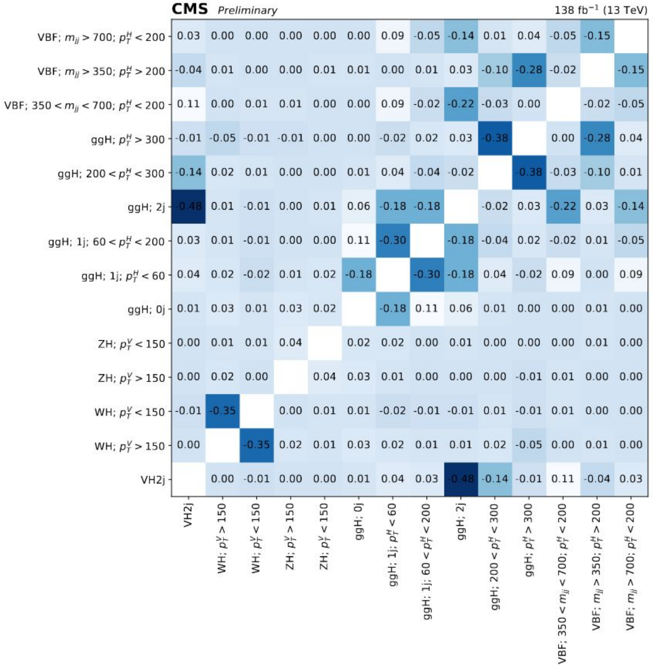
	VH2j	VBF; $m_{jj} > 350$; $p_T^H > 200$	VBF; $m_{jj} > 700$; $p_T^H < 200$	VBF; $350 < m_{jj} < 700$; $p_T^H < 200$	ggH; 0j	ggH; 1j; $p_T^H < 60$	ggH; 1j; $60 < p_T^H < 120$	ggH; 1j; $120 < p_T^H < 200$	ggH; 2j; $m_{jj} < 350$; $p_T^H < 60$	ggH; 2j; $m_{jj} < 350$; $60 < p_T^H < 120$	ggH; 2j; $m_{jj} < 350$; $120 < p_T^H < 200$	ggH; $200 < p_T^H < 300$	ggH; $p_T^H > 300$	WH; $p_T^V < 150$	WH; $p_T^V > 150$	ZH; $p_T^V < 150$	ZH; $p_T^V > 150$
ZH; $p_T^V > 150$																	0.97
ZH; $p_T^V < 150$																0.99	0.03
WH; $p_T^V > 150$														0.09	0.57		
WH; $p_T^V < 150$														0.91	0.43		
ggH; $p_T^H > 300$	0.05	0.16										0.06	0.61				
ggH; $200 < p_T^H < 300$	0.13	0.23	0.02	0.02					0.08	0.01	0.02	0.61	0.13				
ggH; 2j; $m_{jj} < 350$; $120 < p_T^H < 200$	0.04			0.02			0.02	0.05	0.51	0.05	0.01	0.06					
ggH; 2j; $m_{jj} < 350$; $60 < p_T^H < 120$	0.07			0.03		0.01	0.05	0.33	0.12	0.06	0.02						
ggH; 2j; $m_{jj} < 350$; $p_T^H < 60$	0.03			0.01		0.03	0.01	0.19		0.03	0.01						
ggH; 1j; $120 < p_T^H < 200$			0.03	0.03			0.14		0.05	0.03	0.03	0.07					
ggH; 1j; $60 < p_T^H < 120$	0.04		0.06	0.08		0.13	0.51	0.11	0.03	0.06	0.08						
ggH; 1j; $p_T^H < 60$	0.04		0.04	0.06	0.09	0.61	0.18	0.10		0.08	0.08						
ggH; 0j; $10 < p_T^H < 200$					0.68	0.17	0.04	0.02			0.01						
ggH; 0j; $p_T^H < 10$					0.21	0.01											
ggH/VBF 2j; $350 < m_{jj} < 700$; $p_T^H < 200$		0.01	0.02	0.61			0.01	0.02	0.02	0.58	0.04	0.01					
ggH/VBF 2j; $m_{jj} > 700$; $p_T^H < 200$		0.08	0.79	0.13			0.01			0.06	0.65						
ggH/VBF 2j; $m_{jj} > 350$; $p_T^H > 200$		0.51	0.02	0.01						0.02	0.02	0.13	0.21				
VH2j-like	0.59					0.02	0.02	0.16	0.19	0.01	0.02	0.05	0.04				



STXS results



- The current LHC dataset allowed the simultaneous measurement of 14 STXS bins.
- NB: Correlations between some measurements can be sizeable because of event migrations between nearby categories.

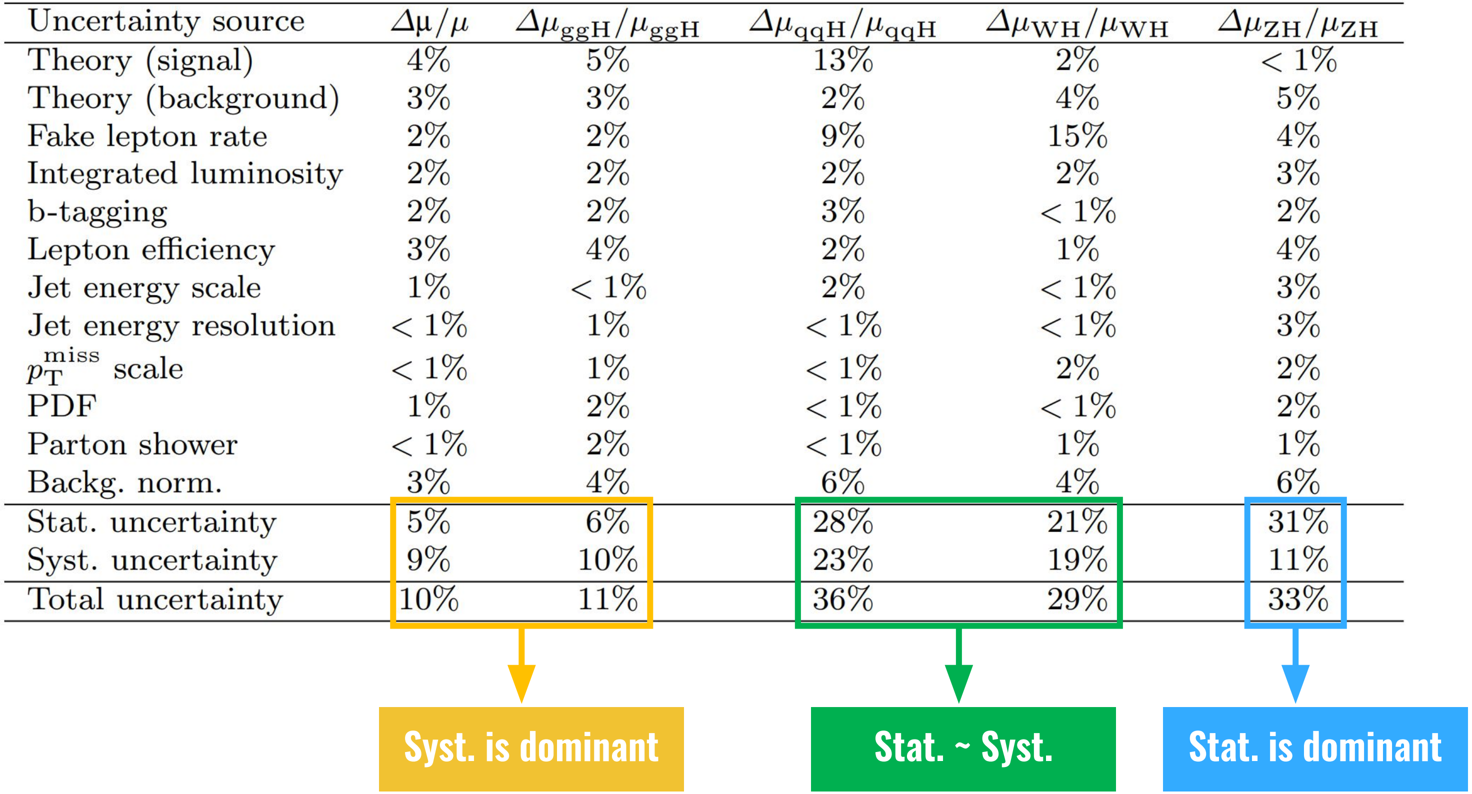


	VH2j	WH; $p_T^V > 150$	WH; $p_T^V < 150$	ZH; $p_T^V > 150$	ZH; $p_T^V < 150$	ggH; 0j	ggH; 1j; $p_T^H < 60$	ggH; 1j; $60 < p_T^H < 200$	ggH; 2j	ggH; $200 < p_T^H < 300$	ggH; $p_T^H > 300$	VBF; $350 < m_{jj} < 700$; $p_T^H < 200$	VBF; $m_{jj} > 350$; $p_T^H > 200$	VBF; $m_{jj} > 700$; $p_T^H < 200$
VBF; $m_{jj} > 700$; $p_T^H < 200$	0.03	0.00	0.00	0.00	0.00	0.00	0.09	-0.05	-0.14	0.01	0.04	-0.05	-0.15	
VBF; $m_{jj} > 350$; $p_T^H > 200$	-0.04	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.03	-0.10	-0.28	-0.02		-0.15
VBF; $350 < m_{jj} < 700$; $p_T^H < 200$	0.11	0.00	0.01	0.01	0.00	0.00	0.09	-0.02	-0.22	-0.03	0.00		-0.02	-0.05
ggH; $p_T^H > 300$	-0.01	-0.05	-0.01	-0.01	0.00	0.00	-0.02	0.02	0.03	-0.38		0.00	-0.28	0.04
ggH; $200 < p_T^H < 300$	-0.14	0.02	0.01	0.00	0.00	0.01	0.04	-0.04	-0.02		-0.38	-0.03	-0.10	0.01
ggH; 2j	-0.48	0.01	-0.01	0.00	0.01	0.06	-0.18	-0.18		-0.02	0.03	-0.22	0.03	-0.14
ggH; 1j; $60 < p_T^H < 200$	0.03	0.01	-0.01	0.00	0.00	0.11	-0.30		-0.18	-0.04	0.02	-0.02	0.01	-0.05
ggH; 1j; $p_T^H < 60$	0.04	0.02	-0.02	0.01	0.02	-0.18		-0.30	-0.18	0.04	-0.02	0.09	0.00	0.09
ggH; 0j	0.01	0.03	0.01	0.03	0.02		-0.18	0.11	0.06	0.01	0.00	0.00	0.01	0.00
ZH; $p_T^V < 150$	0.00	0.01	0.01	0.04		0.02	0.02	0.00	0.01	0.00	0.00	0.00	0.01	0.00
ZH; $p_T^V > 150$	0.00	0.02	0.00		0.04	0.03	0.01	0.00	0.00	0.00	-0.01	0.01	0.00	0.00
WH; $p_T^V < 150$	-0.01	-0.35		0.00	0.01	0.01	-0.02	-0.01	-0.01	0.01	-0.01	0.01	0.00	0.00
WH; $p_T^V > 150$	0.00		-0.35	0.02	0.01	0.03	0.02	0.01	0.01	0.02	-0.05	0.00	0.01	0.00
VH2j		0.00	-0.01	0.00	0.00	0.01	0.04	0.03	-0.48	-0.14	-0.01	0.11	-0.04	0.03

Precisions at low #jets and low p_T^H comparable to/better than other single decay channels!

Also nice precision for mildly boosted ggH and VH STXS categories!

Discussion on uncertainties



Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{\mathrm{ggH}}/\mu_{\mathrm{ggH}}$	$\Delta\mu_{\mathrm{qqH}}/\mu_{\mathrm{qqH}}$	$\Delta\mu_{\mathrm{WH}}/\mu_{\mathrm{WH}}$	$\Delta\mu_{\mathrm{ZH}}/\mu_{\mathrm{ZH}}$
Theory (signal)	4%	5%	13%	2%	< 1%
Theory (background)	3%	3%	2%	4%	5%
Fake lepton rate	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
b-tagging	2%	2%	3%	< 1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	< 1%	2%	< 1%	3%
Jet energy resolution	< 1%	1%	< 1%	< 1%	3%
$p_{\mathrm{T}}^{\mathrm{miss}}$ scale	< 1%	1%	< 1%	2%	2%
PDF	1%	2%	< 1%	< 1%	2%
Parton shower	< 1%	2%	< 1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

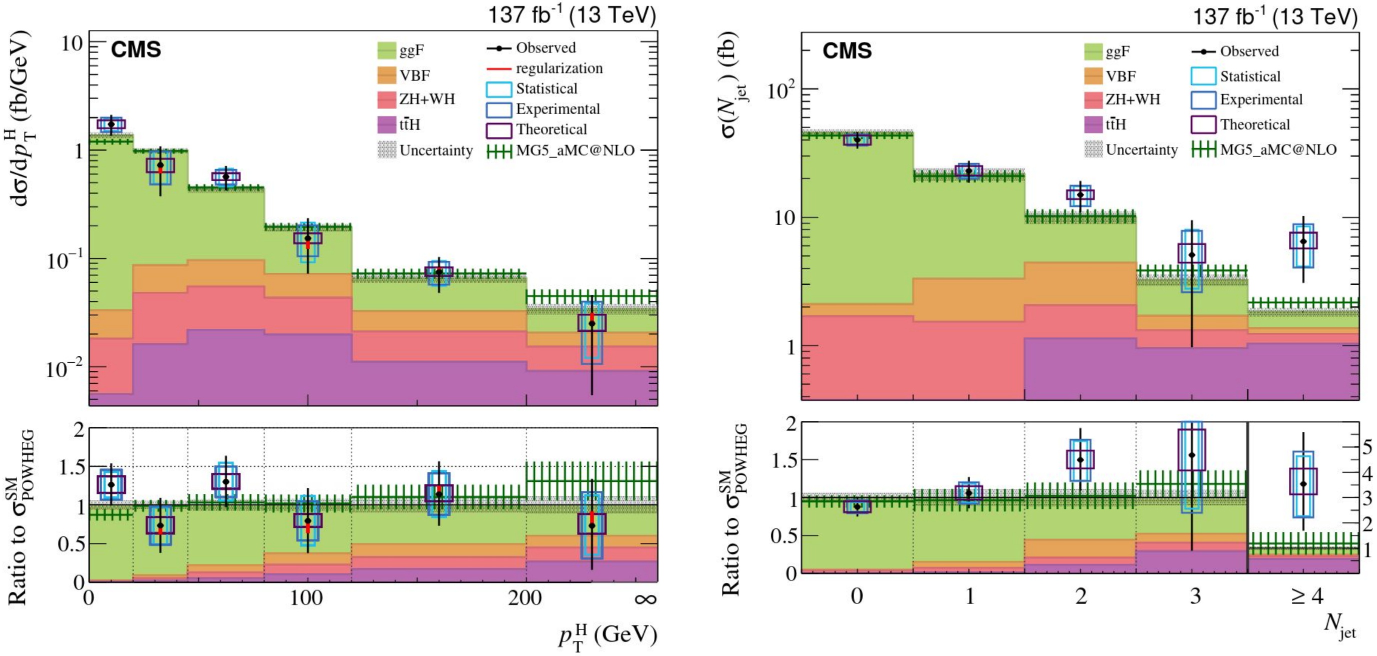
Syst. is dominant

Stat. ~ Syst.

Stat. is dominant

What else can we do in this channel?

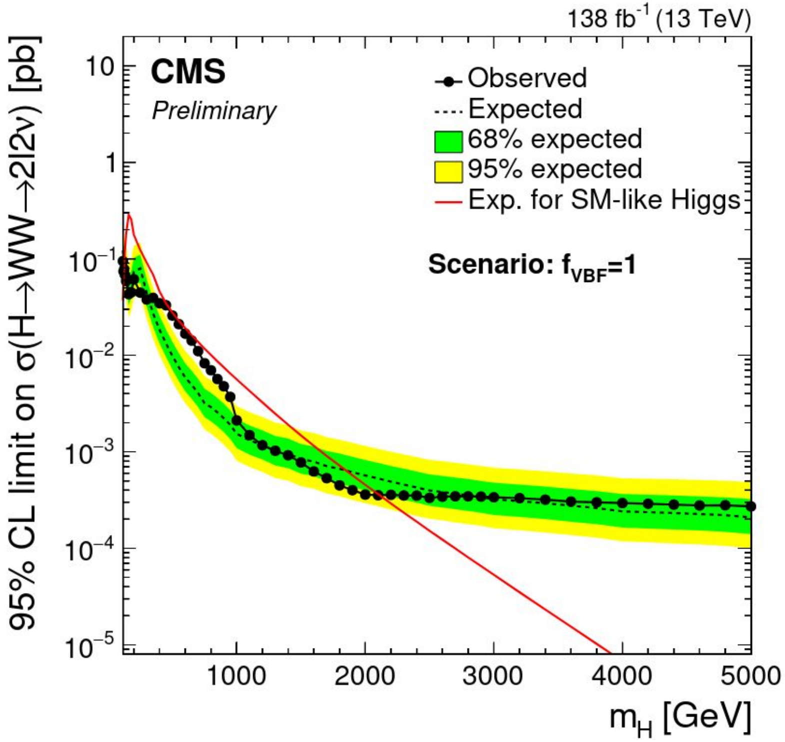
Go differential



JHEP03(2021)003

Fiducial differential measurement of the H→WW production cross section as function of the Higgs boson pT and number of associated jets.

Search for high mass resonances



- Search for high mass resonances decaying to WW→2l2ν:
  - signal interpreted as an additional heavy Higgs boson with SM-like properties (EW singlet), with different widths and ggH/VBF fraction assumptions;
  - large number of additional interpretations based on 2HDM and MSSM scenarios;
  - Broad excess above 2 **σ** observed around 650 GeV!

CMS-PAS-HIG-20-016

New result for Moriond/EW 2022

Conclusions & Takeaways

Conclusions/takeaways

- A lot has been learned from the Higgs boson discovery 10 years ago!

- The paradigm has changed: from searching for a new particle to the precision measurement of its properties.

- Up to now everything seems very SM-like, but much more is yet to come:
  - Run2 data analysis is not over yet!
  - The Run3 of the LHC is right around the corner.
  - And HL-LHC awaits in the future.

Conclusions/takeaways

- H→WW is one of the most promising channels for cross section and couplings measurements.
    - Given the extreme complexity, this analysis was also a huge effort in terms of time and personpower!
    - 6 PhD students + a number of postdocs and seniors.
- Several measurements start to be limited by the impact of systematic uncertainties.
    - We will need to improve objects/backgrounds/strategy to perform even better in Run3.
- Stay tuned for more Run2 and new Run3 results to come!

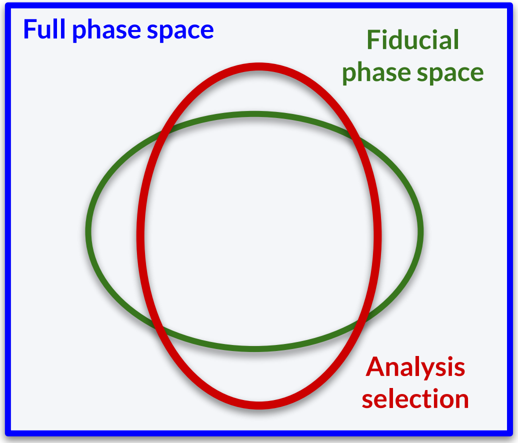
Thanks for your attention!

Supplementary slides

Next step: go differential

- Fiducial differential cross section measurements provide:
  - fundamental test of the SM predictions;
  - a probe of phase spaces sensitive to BSM effects.

- **Differential**: measure cross section in bins of some observables (p_T^H, #jets, …).
- **Fiducial**: extrapolate the measurement to a restricted phase space that matches as closely as possible the experimental selections.



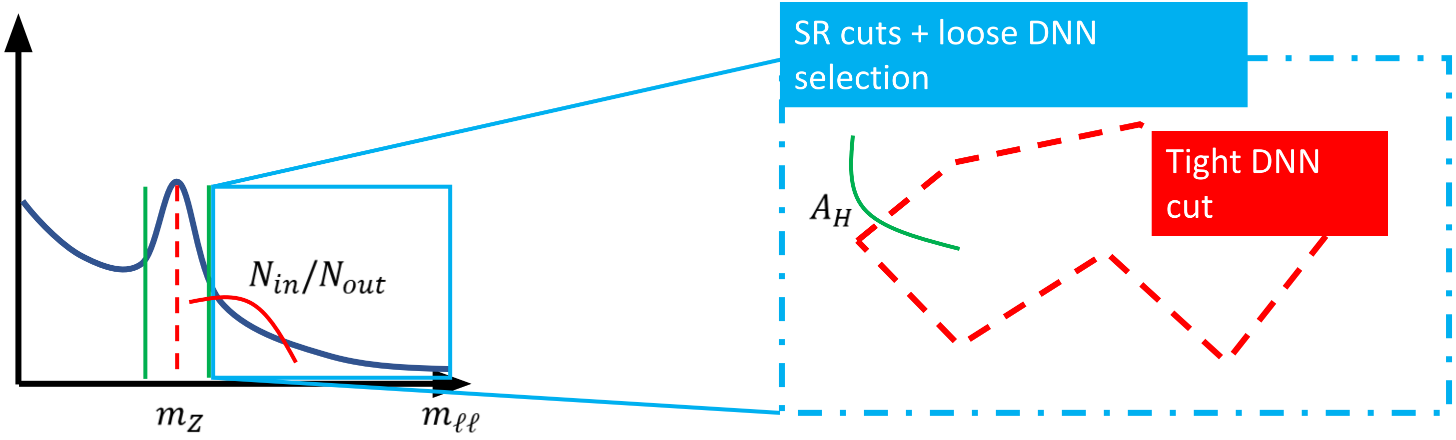
✓ Reduce model dependence by avoiding the extrapolation to the full phase space.
✓ Long measurement lifetime and easy comparison with different theories.

X Limited to few variables at the same time.
X Hard to combine different channels without extrapolating to the full phase space.
X Non trivial to include complex variables (e.g. DNNs) in the fiducial phase space.

SF channels – signature and backgrounds

- Many of the same considerations as DF channels apply, with one important difference
- When selecting leptons with the same flavor (ee, μμ) by far the largest background contribution comes from $qq \rightarrow Z \rightarrow \ell\ell$ processes (DY)
- In order to extract the signal, a DNN discriminant is trained, with a tight cut on its output
- **Problem:**
  - In $qq \rightarrow Z \rightarrow \ell\ell$ events E_T^{miss} comes from detector inefficiencies
  - The phase space region with best S/B is at high E_T^{miss}
  - Very hard to correctly model in MC
- Once we cut on the DNN's output, we end up with a badly modeled background
- To circumvent this, a data driven technique is used (next slide)
- In all SF channels only the number of events enters the fit

SF channels – DY background estimation



- N_{in}/N_{out} is calculated directly from data as the signal contribution in the loose DNN selection can be safely neglected
- The loose-to-tight transfer factor A_H is taken from MC

Background estimation setup

Top

$$\left(N_{jets}=0{,}1\right)\times(\mu e,ee,\mu\mu)\times(2016,2017+2018)$$

$$\left(N_{jets}>1\right)\times(\mu e,ee,\mu\mu)\times(2016,2017+2018)\times\left(\underbrace{m_{jj}\in[0{,}65]\cup[120,\infty)}_{\text{ggH2j}};\underbrace{m_{jj}>120}_{\text{VBF}};\underbrace{m_{jj}\in[65{,}120]}_{\text{VH2j}}\right)$$

WW

$$\left(N_{jets}=0{,}1{,}2\right)\times(ee,\mu\mu)\times(2016,2017+2018)$$

DYττ

$$\left(N_{jets}=0{,}1{,}2\right)\times(\mu e)\times(2016,2017,2018)$$

WZ

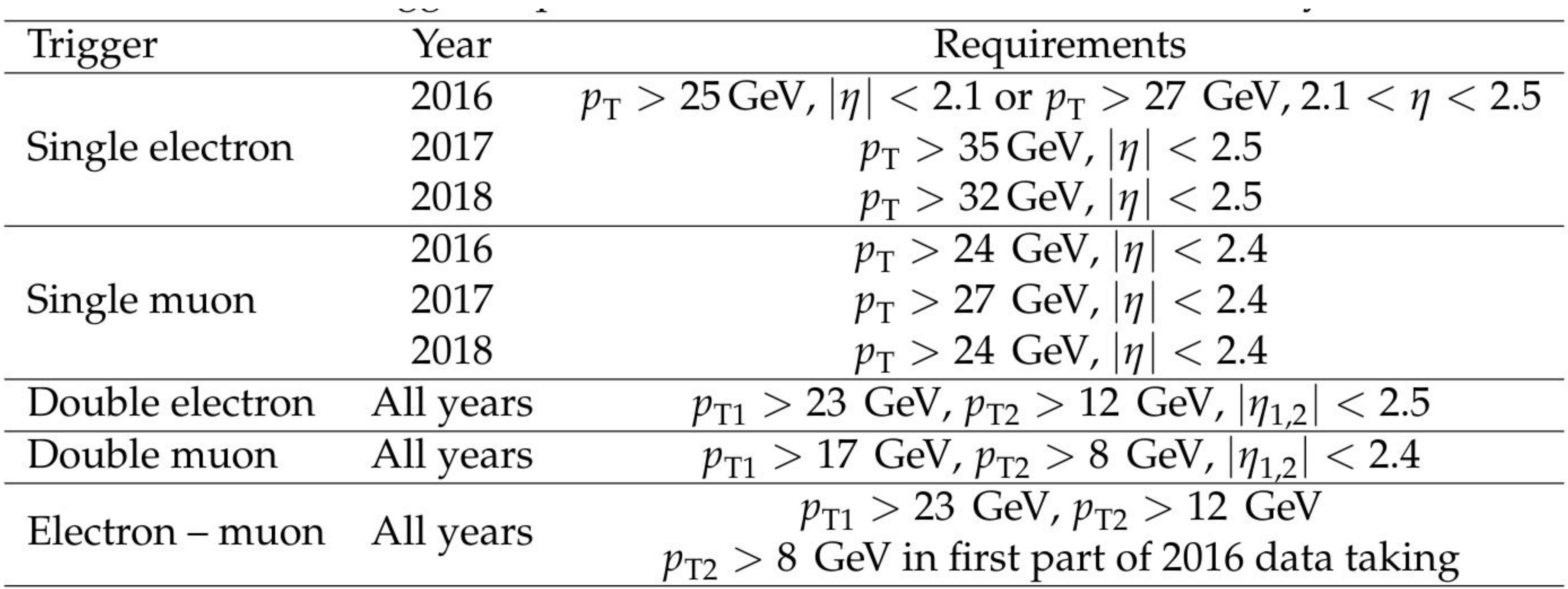
$$\left(N_{jets}=0{,}1{,}2\right)\times(2016,2017+2018)$$

Zγ, ZZ

$$\left(N_{jets}=0\right)\times(2016,2017+2018)$$

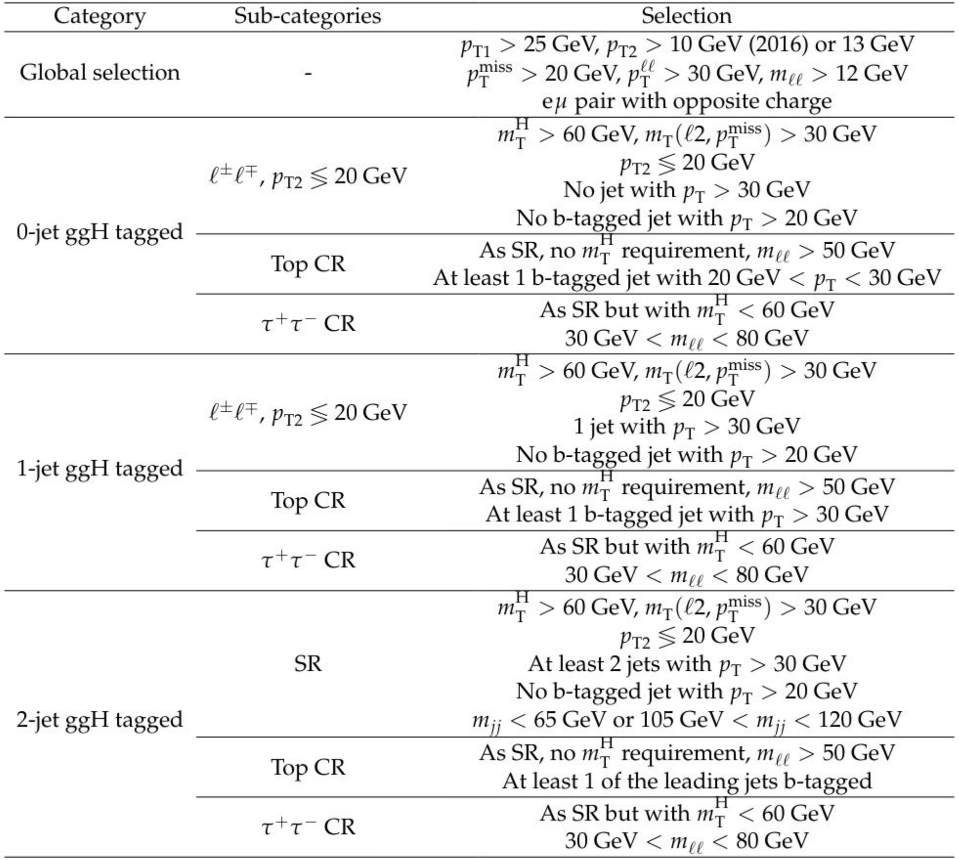
2016 rates kept independent because of differing MC setup; Dyττ rates split per year because embedded samples (i.e., data) are used

Triggers



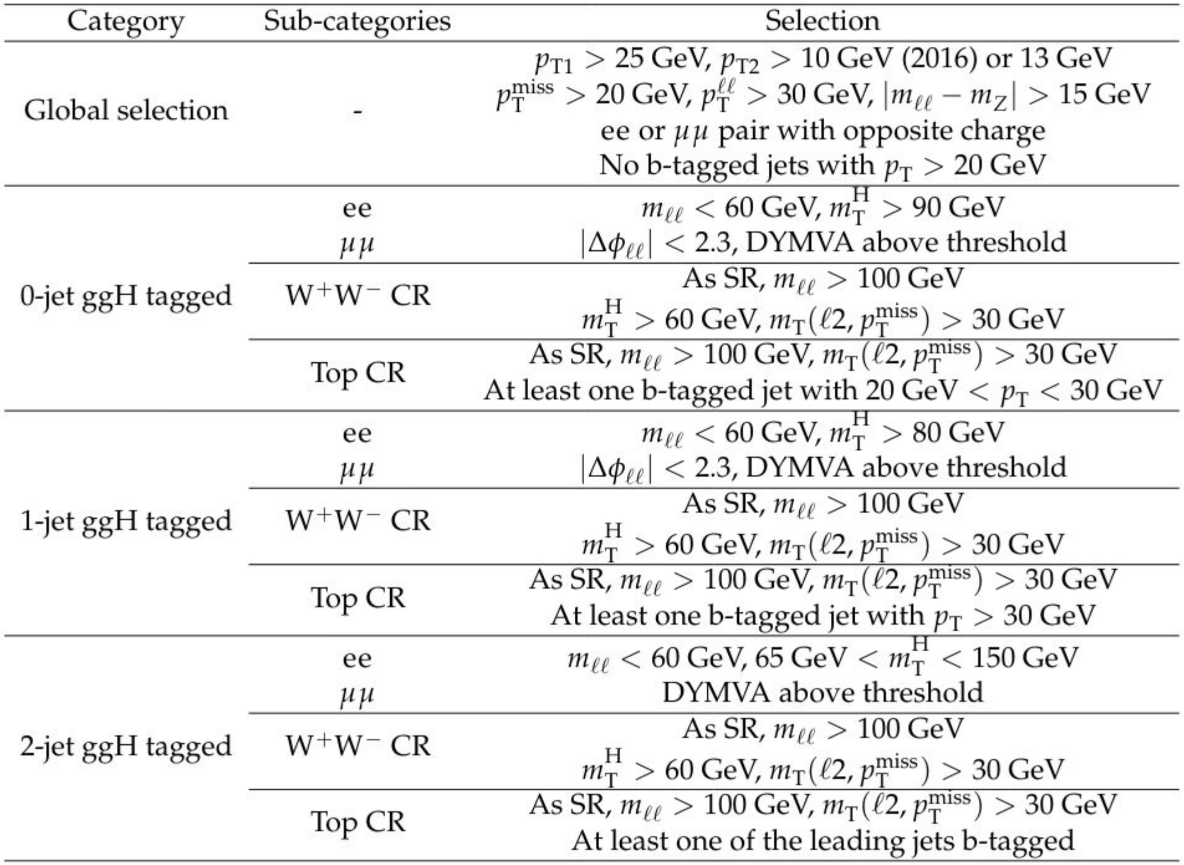
Trigger	Year	Requirements
Single electron	2016	$p_{\mathrm{T}} > 25\,\mathrm{GeV}, \lvert\eta\rvert < 2.1$ or $p_{\mathrm{T}} > 27\ \mathrm{GeV}, 2.1 < \eta < 2.5$
	2017	$p_{\mathrm{T}} > 35\,\mathrm{GeV}, \lvert\eta\rvert < 2.5$
	2018	$p_{\mathrm{T}} > 32\,\mathrm{GeV}, \lvert\eta\rvert < 2.5$
Single muon	2016	$p_{\mathrm{T}} > 24\ \mathrm{GeV}, \lvert\eta\rvert < 2.4$
	2017	$p_{\mathrm{T}} > 27\ \mathrm{GeV}, \lvert\eta\rvert < 2.4$
	2018	$p_{\mathrm{T}} > 24\ \mathrm{GeV}, \lvert\eta\rvert < 2.4$
Double electron	All years	$p_{\mathrm{T1}} > 23\ \mathrm{GeV}, p_{\mathrm{T2}} > 12\ \mathrm{GeV}, \lvert\eta_{1,2}\rvert < 2.5$
Double muon	All years	$p_{\mathrm{T1}} > 17\ \mathrm{GeV}, p_{\mathrm{T2}} > 8\ \mathrm{GeV}, \lvert\eta_{1,2}\rvert < 2.4$
Electron – muon	All years	$p_{\mathrm{T1}} > 23\ \mathrm{GeV}, p_{\mathrm{T2}} > 12\ \mathrm{GeV}$ $p_{\mathrm{T2}} > 8\ \mathrm{GeV}$ in first part of 2016 data taking

ggH DF event requirements



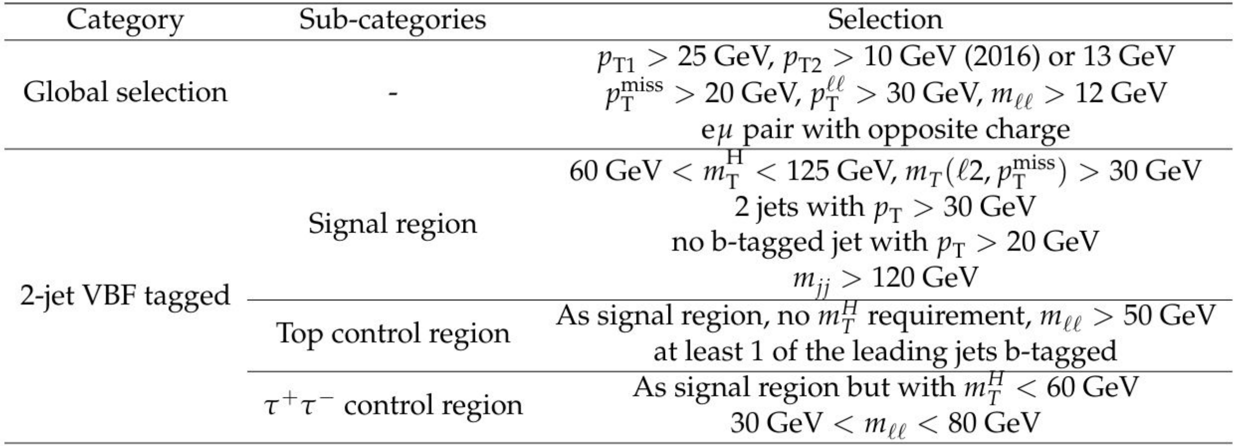
Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 10$ GeV (2016) or 13 GeV $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 12$ GeV $e\mu$ pair with opposite charge
0-jet ggH tagged	$\ell^{\pm}\ell^{\mp}$, $p_{T2} \lessgtr 20$ GeV	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \lessgtr 20$ GeV No jet with $p_T > 30$ GeV No b-tagged jet with $p_T > 20$ GeV
	Top CR	As SR, no m_T^H requirement, $m_{\ell\ell} > 50$ GeV At least 1 b-tagged jet with 20 GeV $< p_T <$ 30 GeV
	$\tau^+\tau^-$ CR	As SR but with $m_T^H < 60$ GeV 30 GeV $< m_{\ell\ell} <$ 80 GeV
1-jet ggH tagged	$\ell^{\pm}\ell^{\mp}$, $p_{T2} \lessgtr 20$ GeV	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \lessgtr 20$ GeV 1 jet with $p_T > 30$ GeV No b-tagged jet with $p_T > 20$ GeV
	Top CR	As SR, 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 30 GeV $< m_{\ell\ell} <$ 80 GeV
2-jet ggH tagged	SR	$m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV $p_{T2} \lessgtr 20$ 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 GeV $< m_{jj} <$ 120 GeV
	Top CR	As SR, no m_T^H requirement, $m_{\ell\ell} > 50$ GeV At least 1 of the leading jets b-tagged
	$\tau^+\tau^-$ CR	As SR but with $m_T^H < 60$ GeV 30 GeV $< m_{\ell\ell} <$ 80 GeV

ggH SF event requirements

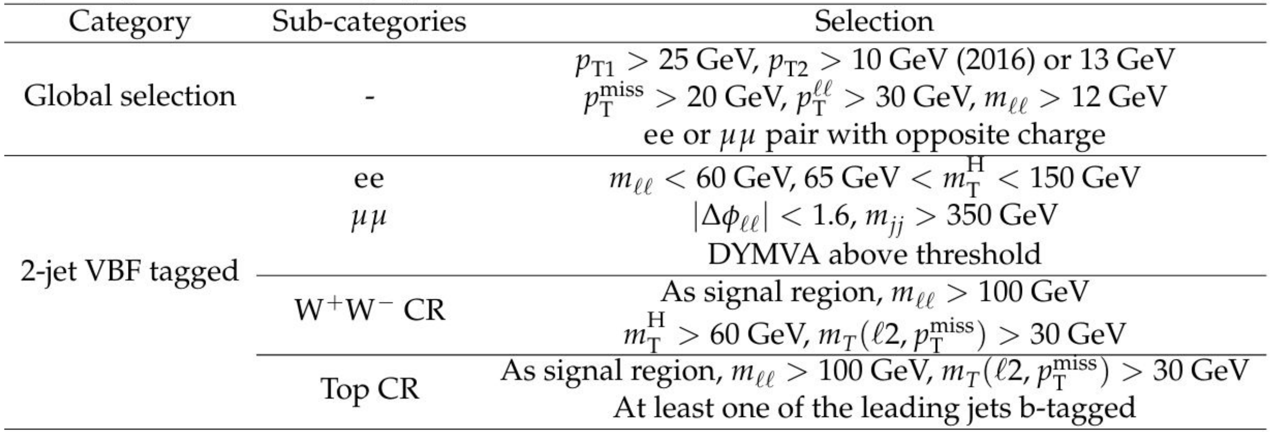


Category	Sub-categories	Selection
Global selection	-	$p_{\mathrm{T}1} > 25$ GeV, $p_{\mathrm{T}2} > 10$ GeV (2016) or 13 GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $p_{\mathrm{T}}^{\ell\ell} > 30$ GeV, $\lvert m_{\ell\ell} - m_{\mathrm{Z}}\rvert > 15$ GeV ee or $\mu\mu$ pair with opposite charge No b-tagged jets with $p_{\mathrm{T}} > 20$ GeV
0-jet ggH tagged	ee $\mu\mu$	$m_{\ell\ell} < 60$ GeV, $m_{\mathrm{T}}^{\mathrm{H}} > 90$ GeV $\lvert\Delta\phi_{\ell\ell}\rvert < 2.3$, DYMVA above threshold
	$\mathrm{W}^{+}\mathrm{W}^{-}$ CR	As SR, $m_{\ell\ell} > 100$ GeV $m_{\mathrm{T}}^{\mathrm{H}} > 60$ GeV, $m_{\mathrm{T}}(\ell 2, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV
	Top CR	As SR, $m_{\ell\ell} > 100$ GeV, $m_{\mathrm{T}}(\ell 2, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV At least one b-tagged jet with 20 GeV $< p_{\mathrm{T}} <$ 30 GeV
1-jet ggH tagged	ee $\mu\mu$	$m_{\ell\ell} < 60$ GeV, $m_{\mathrm{T}}^{\mathrm{H}} > 80$ GeV $\lvert\Delta\phi_{\ell\ell}\rvert < 2.3$, DYMVA above threshold
	$\mathrm{W}^{+}\mathrm{W}^{-}$ CR	As SR, $m_{\ell\ell} > 100$ GeV $m_{\mathrm{T}}^{\mathrm{H}} > 60$ GeV, $m_{\mathrm{T}}(\ell 2, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV
	Top CR	As SR, $m_{\ell\ell} > 100$ GeV, $m_{\mathrm{T}}(\ell 2, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV At least one b-tagged jet with $p_{\mathrm{T}} > 30$ GeV
2-jet ggH tagged	ee $\mu\mu$	$m_{\ell\ell} < 60$ GeV, 65 GeV $< m_{\mathrm{T}}^{\mathrm{H}} <$ 150 GeV DYMVA above threshold
	$\mathrm{W}^{+}\mathrm{W}^{-}$ CR	As SR, $m_{\ell\ell} > 100$ GeV $m_{\mathrm{T}}^{\mathrm{H}} > 60$ GeV, $m_{\mathrm{T}}(\ell 2, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV
	Top CR	As SR, $m_{\ell\ell} > 100$ GeV, $m_{\mathrm{T}}(\ell 2, p_{\mathrm{T}}^{\mathrm{miss}}) > 30$ GeV At least one of the leading jets b-tagged

VBF DF/SF event requirements

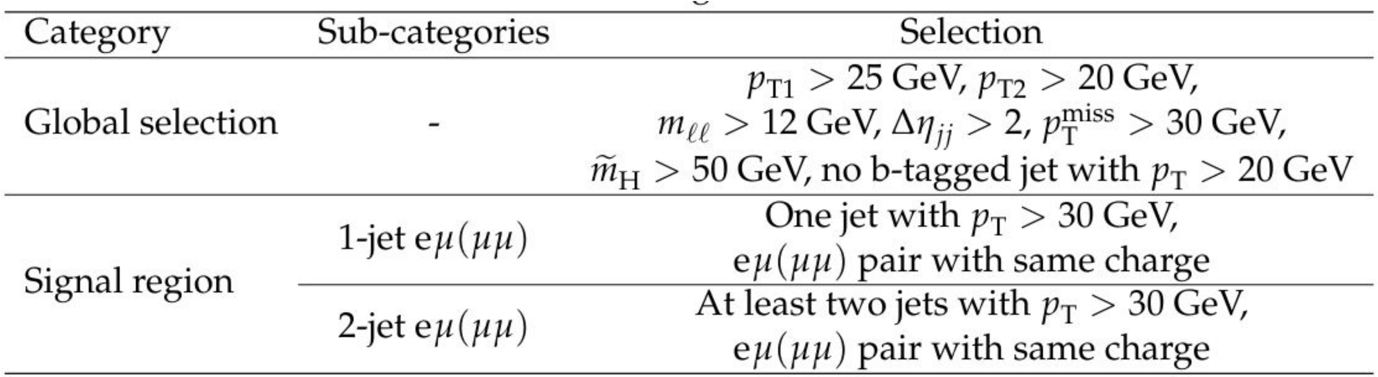


Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 10$ GeV (2016) or 13 GeV $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 12$ GeV eμ pair with opposite charge
2-jet VBF tagged	Signal region	60 GeV $< m_T^H <$ 125 GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV 2 jets with $p_T > 30$ GeV no b-tagged jet with $p_T > 20$ GeV $m_{jj} > 120$ GeV
	Top control region	As signal region, no m_T^H requirement, $m_{\ell\ell} > 50$ GeV at least 1 of the leading jets b-tagged
	$\tau^+\tau^-$ control region	As signal region but with $m_T^H < 60$ GeV 30 GeV $< m_{\ell\ell} <$ 80 GeV

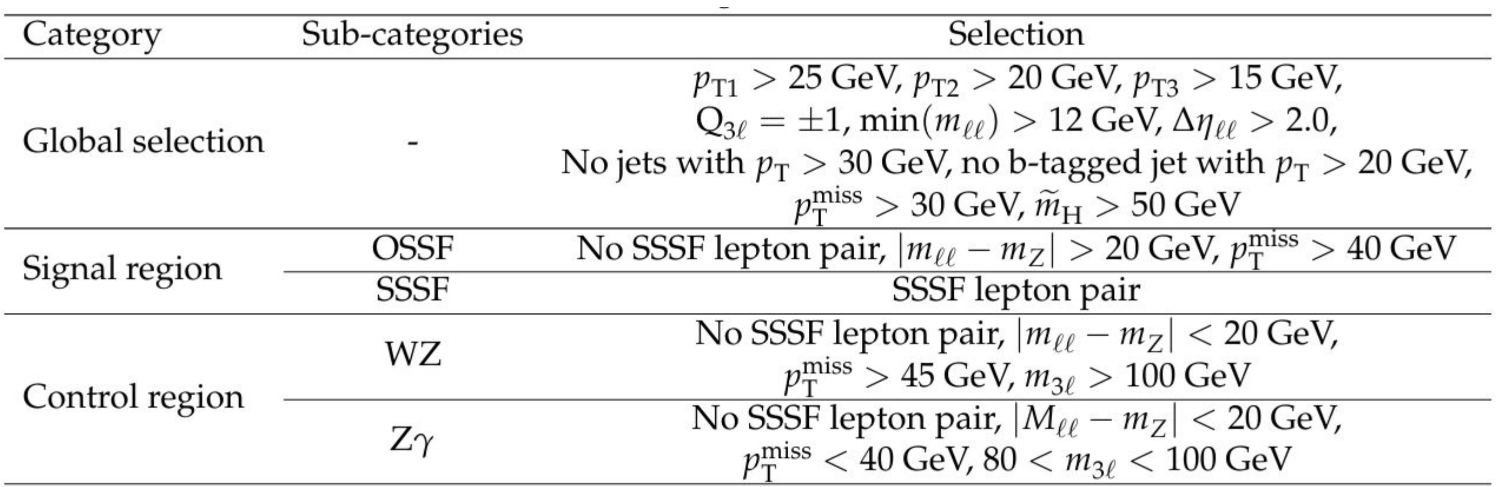


Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 10$ GeV (2016) or 13 GeV $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $m_{\ell\ell} > 12$ GeV ee or $\mu\mu$ pair with opposite charge
2-jet VBF tagged	ee $\mu\mu$	$m_{\ell\ell} < 60$ GeV, 65 GeV $< m_T^H <$ 150 GeV $\|\Delta\phi_{\ell\ell}\| < 1.6$, $m_{jj} > 350$ GeV DYMVA above threshold
	W$^+$W$^-$ CR	As signal region, $m_{\ell\ell} > 100$ GeV $m_T^H > 60$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV
	Top CR	As signal region, $m_{\ell\ell} > 100$ GeV, $m_T(\ell 2, p_T^{miss}) > 30$ GeV At least one of the leading jets b-tagged

WHSS/WH3l event requirements

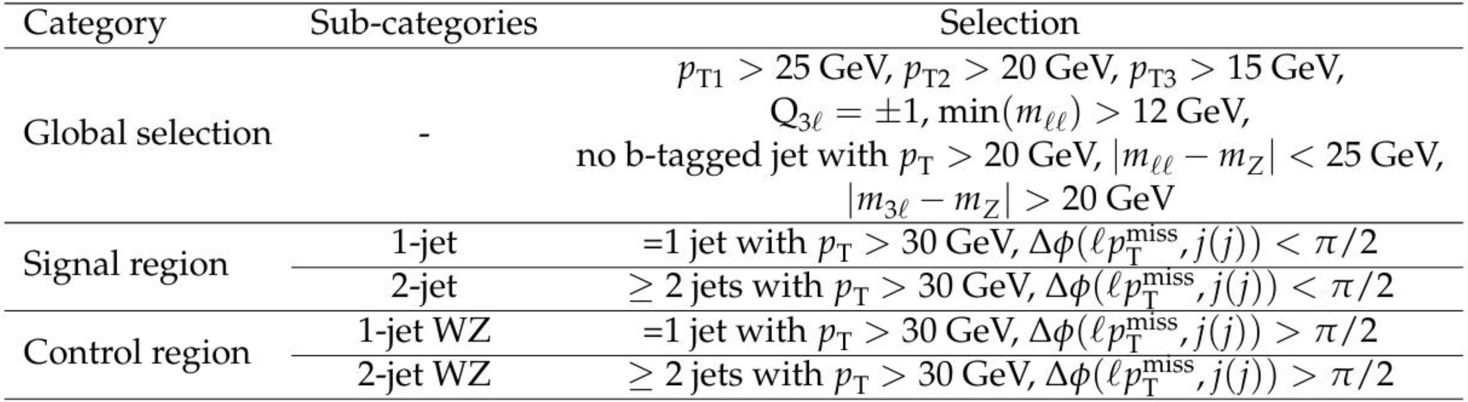


Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $m_{\ell\ell} > 12$ GeV, $\Delta\eta_{jj} > 2$, $p_T^{miss} > 30$ GeV, $\widetilde{m}_H > 50$ GeV, no b-tagged jet with $p_T > 20$ GeV
Signal region	1-jet eμ($\mu\mu$)	One jet with $p_T > 30$ GeV, eμ($\mu\mu$) pair with same charge
	2-jet eμ($\mu\mu$)	At least two jets with $p_T > 30$ GeV, eμ($\mu\mu$) pair with same charge

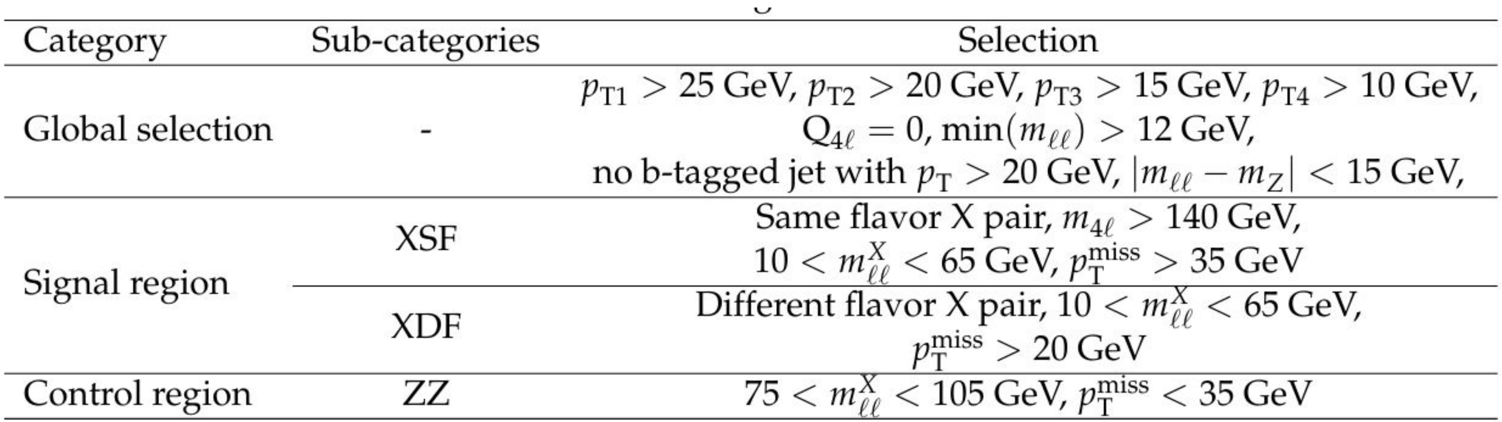


Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $p_{T3} > 15$ GeV, $Q_{3\ell} = \pm 1$, $\min(m_{\ell\ell}) > 12$ GeV, $\Delta\eta_{\ell\ell} > 2.0$, No jets with $p_T > 30$ GeV, no b-tagged jet with $p_T > 20$ GeV, $p_T^{miss} > 30$ GeV, $\widetilde{m}_H >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

ZH3l/ZH4l event requirements

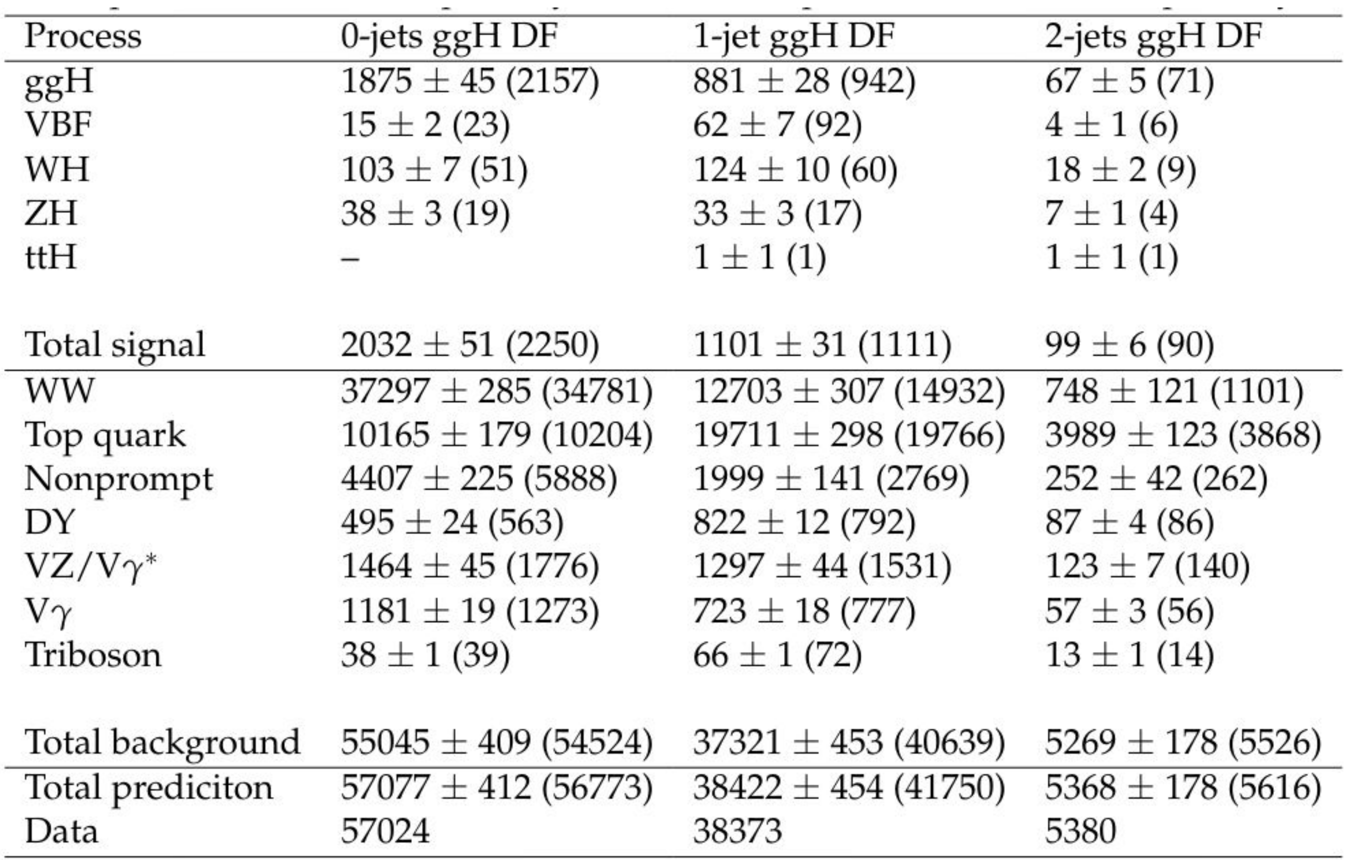


Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $p_{T3} > 15$ GeV, $Q_{3\ell} = \pm 1$, $\min(m_{\ell\ell}) > 12$ GeV, no b-tagged jet with $p_T > 20$ GeV, $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV, $\lvert m_{3\ell} - m_Z \rvert > 20$ GeV
Signal region	1-jet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



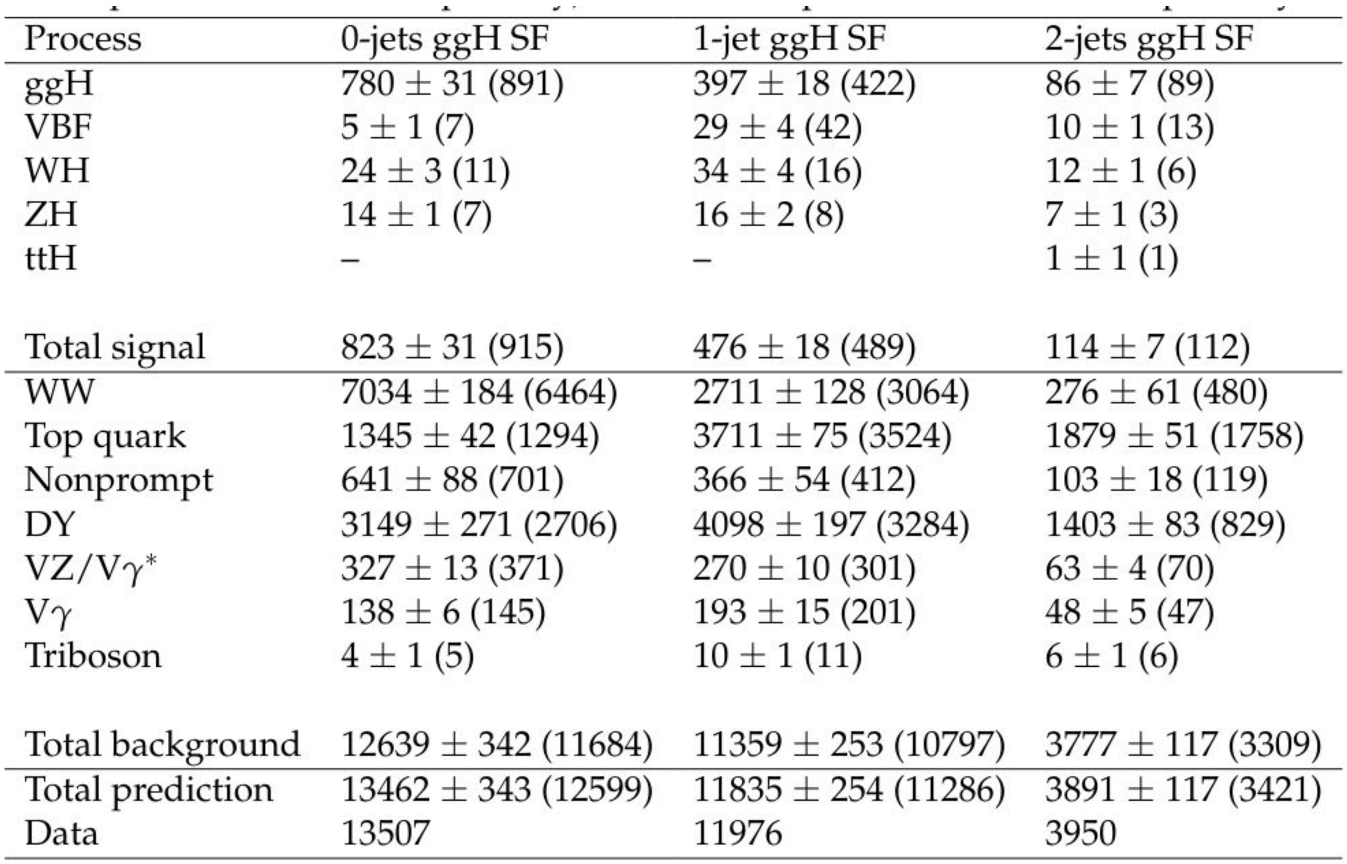
Category	Sub-categories	Selection
Global selection	-	$p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $p_{T3} > 15$ GeV, $p_{T4} > 10$ GeV, $Q_{4\ell} = 0$, $\min(m_{\ell\ell}) > 12$ GeV, no b-tagged jet with $p_T > 20$ GeV, $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV,
Signal region	XSF	Same flavor X pair, $m_{4\ell} > 140$ GeV, $10 < m_{\ell\ell}^X < 65$ GeV, $p_T^{miss} > 35$ GeV
	XDF	Different flavor X pair, $10 < m_{\ell\ell}^X < 65$ GeV, $p_T^{miss} > 20$ GeV
Control region	ZZ	$75 < m_{\ell\ell}^X < 105$ GeV, $p_T^{miss} < 35$ GeV

ggH DF yields



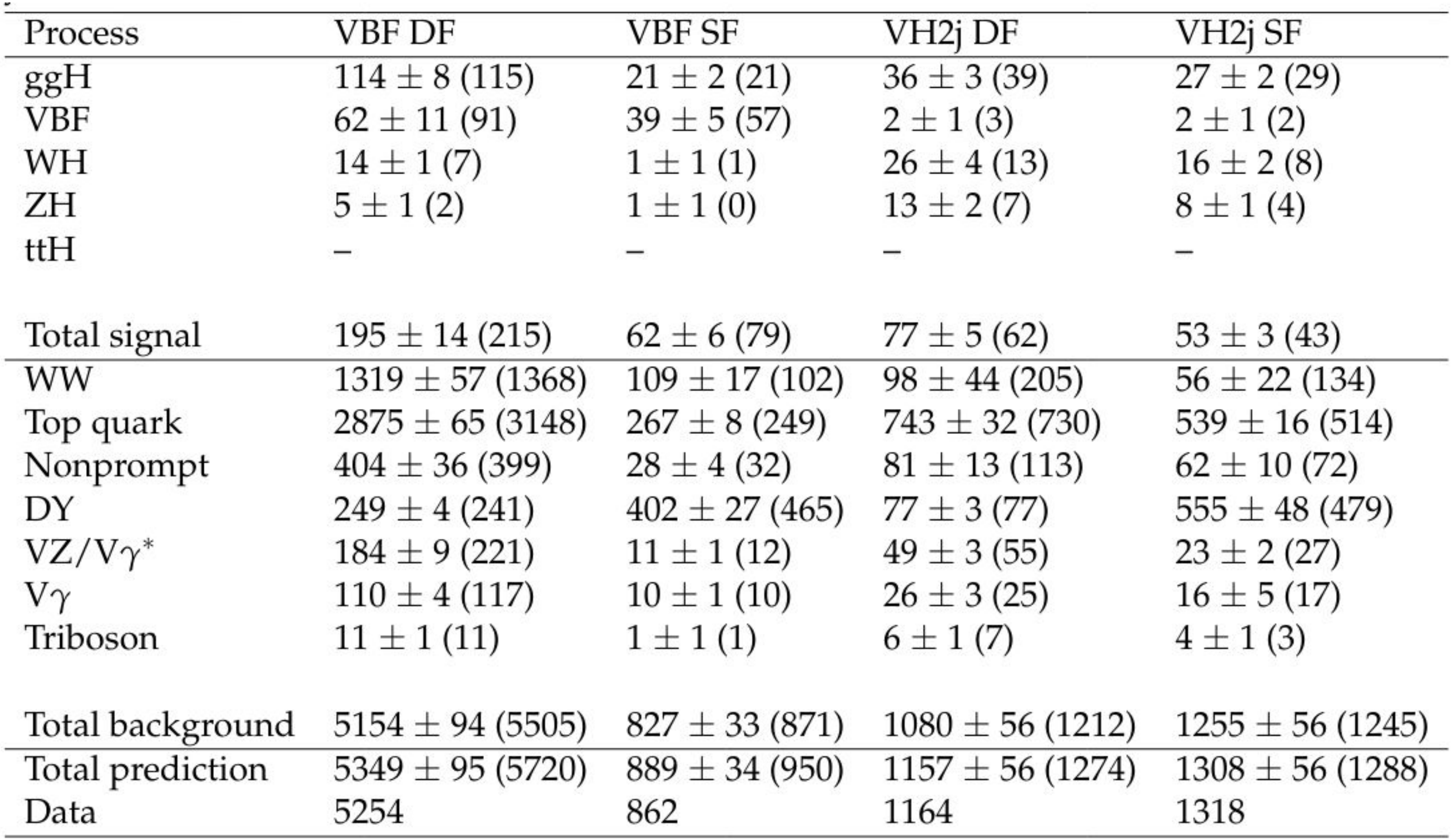
Process	0-jets ggH DF	1-jet ggH DF	2-jets ggH DF
ggH	1875 ± 45 (2157)	881 ± 28 (942)	67 ± 5 (71)
VBF	15 ± 2 (23)	62 ± 7 (92)	4 ± 1 (6)
WH	103 ± 7 (51)	124 ± 10 (60)	18 ± 2 (9)
ZH	38 ± 3 (19)	33 ± 3 (17)	7 ± 1 (4)
ttH	–	1 ± 1 (1)	1 ± 1 (1)
Total signal	2032 ± 51 (2250)	1101 ± 31 (1111)	99 ± 6 (90)
WW	37297 ± 285 (34781)	12703 ± 307 (14932)	748 ± 121 (1101)
Top quark	10165 ± 179 (10204)	19711 ± 298 (19766)	3989 ± 123 (3868)
Nonprompt	4407 ± 225 (5888)	1999 ± 141 (2769)	252 ± 42 (262)
DY	495 ± 24 (563)	822 ± 12 (792)	87 ± 4 (86)
$VZ/V\gamma^*$	1464 ± 45 (1776)	1297 ± 44 (1531)	123 ± 7 (140)
$V\gamma$	1181 ± 19 (1273)	723 ± 18 (777)	57 ± 3 (56)
Triboson	38 ± 1 (39)	66 ± 1 (72)	13 ± 1 (14)
Total background	55045 ± 409 (54524)	37321 ± 453 (40639)	5269 ± 178 (5526)
Total prediciton	57077 ± 412 (56773)	38422 ± 454 (41750)	5368 ± 178 (5616)
Data	57024	38373	5380

ggH SF yields



Process	0-jets ggH SF	1-jet ggH SF	2-jets ggH SF
ggH	780 ± 31 (891)	397 ± 18 (422)	86 ± 7 (89)
VBF	5 ± 1 (7)	29 ± 4 (42)	10 ± 1 (13)
WH	24 ± 3 (11)	34 ± 4 (16)	12 ± 1 (6)
ZH	14 ± 1 (7)	16 ± 2 (8)	7 ± 1 (3)
ttH	–	–	1 ± 1 (1)
Total signal	823 ± 31 (915)	476 ± 18 (489)	114 ± 7 (112)
WW	7034 ± 184 (6464)	2711 ± 128 (3064)	276 ± 61 (480)
Top quark	1345 ± 42 (1294)	3711 ± 75 (3524)	1879 ± 51 (1758)
Nonprompt	641 ± 88 (701)	366 ± 54 (412)	103 ± 18 (119)
DY	3149 ± 271 (2706)	4098 ± 197 (3284)	1403 ± 83 (829)
VZ/Vγ^*	327 ± 13 (371)	270 ± 10 (301)	63 ± 4 (70)
Vγ	138 ± 6 (145)	193 ± 15 (201)	48 ± 5 (47)
Triboson	4 ± 1 (5)	10 ± 1 (11)	6 ± 1 (6)
Total background	12639 ± 342 (11684)	11359 ± 253 (10797)	3777 ± 117 (3309)
Total prediction	13462 ± 343 (12599)	11835 ± 254 (11286)	3891 ± 117 (3421)
Data	13507	11976	3950

VBF/VH2j yields



Process	VBF DF	VBF SF	VH2j DF	VH2j SF
ggH	114 ± 8 (115)	21 ± 2 (21)	36 ± 3 (39)	27 ± 2 (29)
VBF	62 ± 11 (91)	39 ± 5 (57)	2 ± 1 (3)	2 ± 1 (2)
WH	14 ± 1 (7)	1 ± 1 (1)	26 ± 4 (13)	16 ± 2 (8)
ZH	5 ± 1 (2)	1 ± 1 (0)	13 ± 2 (7)	8 ± 1 (4)
ttH	–	–	–	–
Total signal	195 ± 14 (215)	62 ± 6 (79)	77 ± 5 (62)	53 ± 3 (43)
WW	1319 ± 57 (1368)	109 ± 17 (102)	98 ± 44 (205)	56 ± 22 (134)
Top quark	2875 ± 65 (3148)	267 ± 8 (249)	743 ± 32 (730)	539 ± 16 (514)
Nonprompt	404 ± 36 (399)	28 ± 4 (32)	81 ± 13 (113)	62 ± 10 (72)
DY	249 ± 4 (241)	402 ± 27 (465)	77 ± 3 (77)	555 ± 48 (479)
VZ/Vγ^*	184 ± 9 (221)	11 ± 1 (12)	49 ± 3 (55)	23 ± 2 (27)
Vγ	110 ± 4 (117)	10 ± 1 (10)	26 ± 3 (25)	16 ± 5 (17)
Triboson	11 ± 1 (11)	1 ± 1 (1)	6 ± 1 (7)	4 ± 1 (3)
Total background	5154 ± 94 (5505)	827 ± 33 (871)	1080 ± 56 (1212)	1255 ± 56 (1245)
Total prediction	5349 ± 95 (5720)	889 ± 34 (950)	1157 ± 56 (1274)	1308 ± 56 (1288)
Data	5254	862	1164	1318

VH leptonic yields

Process	WHSS	WH3ℓ	ZH3ℓ	ZH4ℓ
ggH	1 ± 1 (1)	–	–	–
VBF	–	–	–	–
WH	148 ± 12 (69)	44 ± 5 (20)	2 ± 1 (1)	–
ZH	10 ± 11 (5)	3 ± 1 (2)	74 ± 7 (36)	19 ± 2 (10)
ttH	1 ± 1 (1)	–	1 ± 1 (1)	–
Total signal	159 ± 12 (76)	48 ± 5 (22)	76 ± 7 (38)	19 ± 2 (10)
WW	40 ± 1 (39)	–	–	–
Top quark	62 ± 1 (62)	–	–	–
Nonprompt	596 ± 37 (805)	55 ± 6 (85)	166 ± 16 (215)	–
DY	28 ± 7 (35)	–	30 ± 1 (29)	1 ± 1 (1)
VZ/Vγ^*	1309 ± 26 (1355)	311 ± 10 (276)	1905 ± 25 (1796)	45 ± 1 (39)
Vγ	135 ± 11 (162)	14 ± 3 (20)	36 ± 6 (40)	–
Triboson	41 ± 1 (41)	15 ± 1 (15)	30 ± 1 (30)	3 ± 1 (3)
Total background	2211 ± 47 (2498)	396 ± 12 (397)	2167 ± 30 (2110)	50 ± 1 (44)
Total prediciton	2370 ± 49 (2574)	444 ± 13 (419)	2243 ± 31 (2148)	69 ± 2 (54)
Data	2359	423	2315	69