Higgs to WW measurements with CMS

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On behalf of the CMS Collaboration

INFN of Florence (Italy)

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Seoul (Korea)

Higgs boson properties

- The measurement of the Higgs boson properties is one of the main goals of the LHC Run2.
  - Optimal test of Standard Model (SM) predictions.
  - Beyond the Standard Model (BSM) contributions can have effects of about 1-10% on the Higgs boson couplings.

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

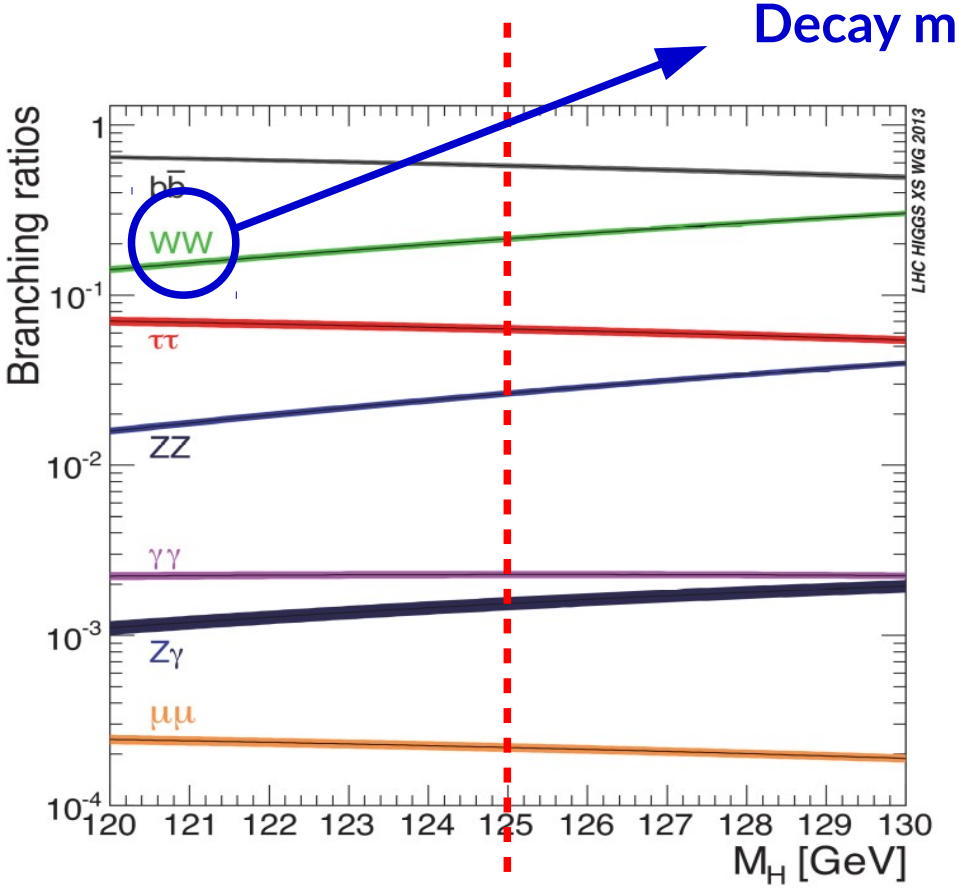
arXiv:1310.8361 – m_{NP}~1 TeV

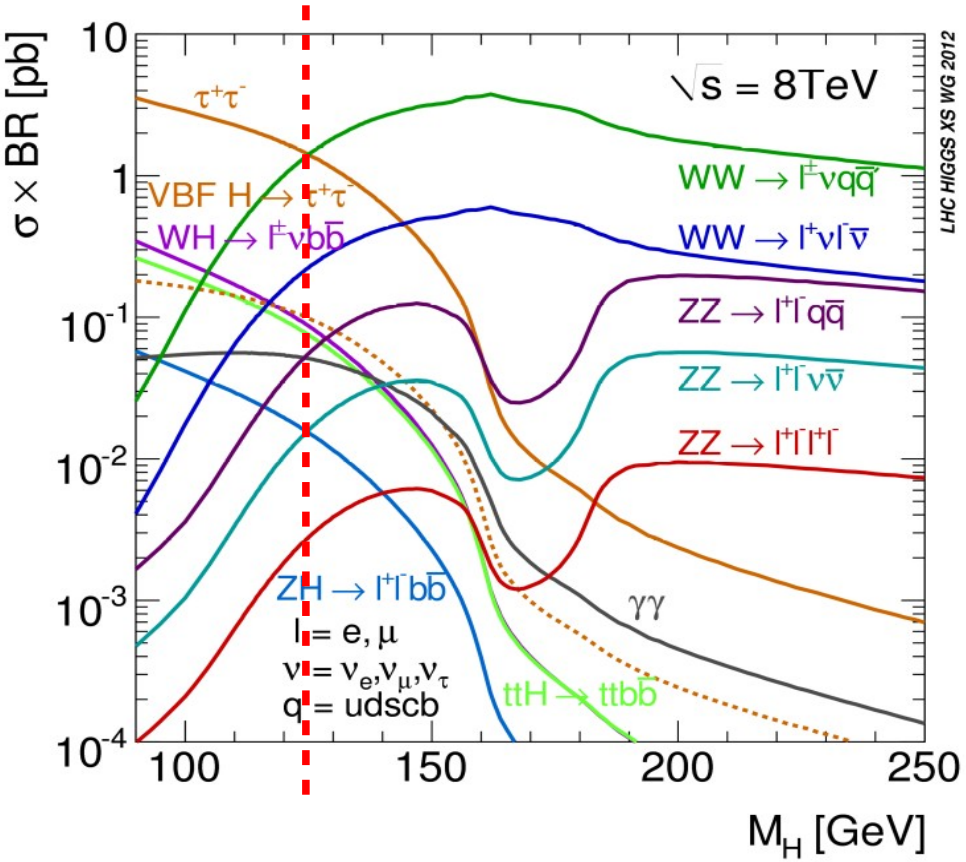
Effects of some BSM models on the Higgs boson couplings

- H→WW is a key channel for the measurement of the Higgs boson couplings and properties.

Introduction

Decay mode with second largest BR

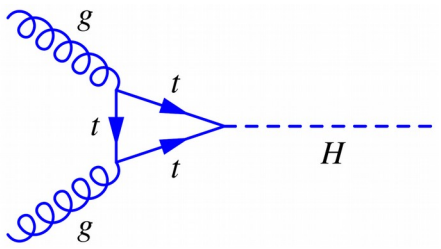




- **In this talk:**
  - Focus on the fully leptonic final state
  - New 13 TeV results based on an integrated luminosity of 35.9 fb^{-1}.
  - CMS-HIG-16-042 – arXiv:1806.05246 – submitted to PLB

Higgs boson production at LHC

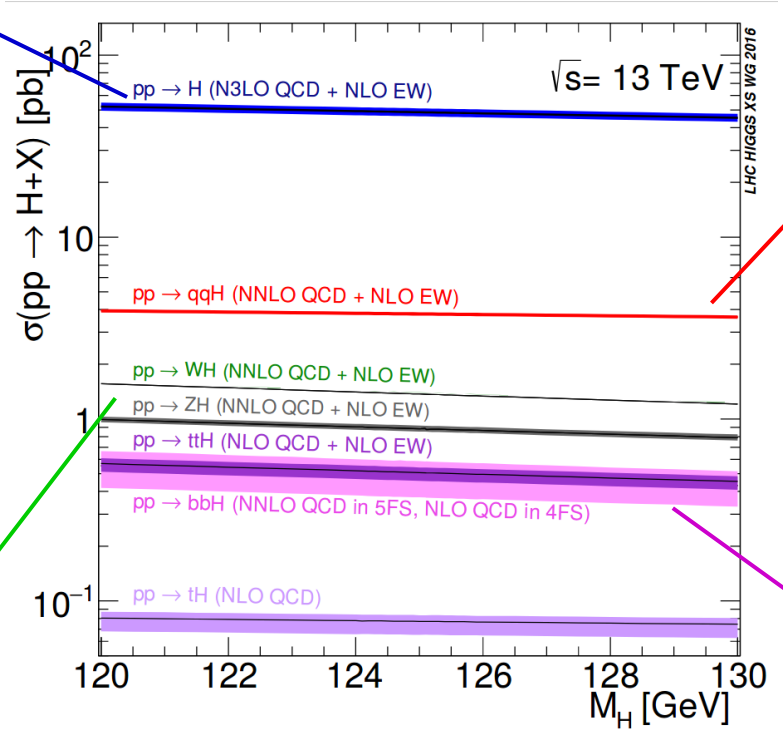
Enough statistics to tackle all the main production modes.



Gluon fusion (ggH)

- Sensitive to Higgs couplings with fermions (t, b quarks).

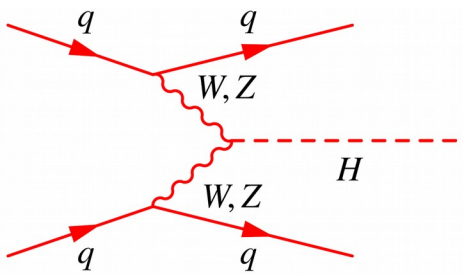
$$\sigma \times \mathcal{B}(\mathrm{H} \to \mathrm{WW}) = 9.5 \text{ pb}$$



Vector boson fusion (VBF)

- Sensitive to the coupling with W and Z.

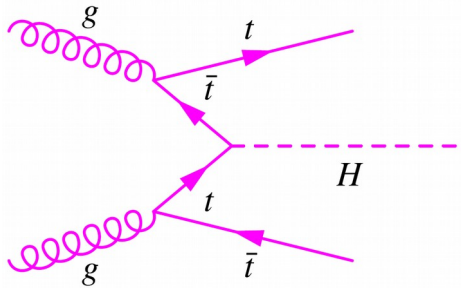
$$\sigma \times \mathcal{B}(\mathrm{H} \to \mathrm{WW}) = 0.8 \text{ pb}$$



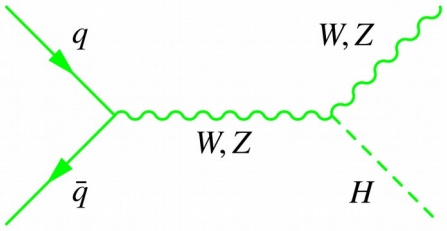
Top associated production (ttH)

- Sensitive to the direct coupling with top quark.

$$\sigma \times \mathcal{B}(\mathrm{H} \to \mathrm{WW}) = 0.1 \text{ pb}$$



See C. Pardo's talk



Vector boson associated prod. (VH)

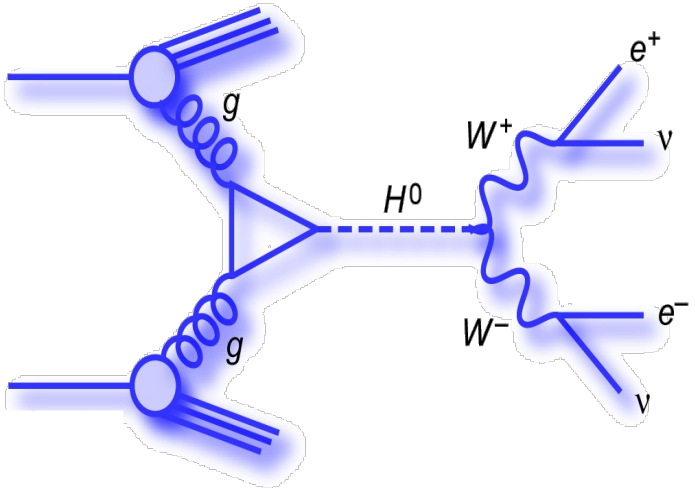
- Sensitive to the coupling with W and Z.

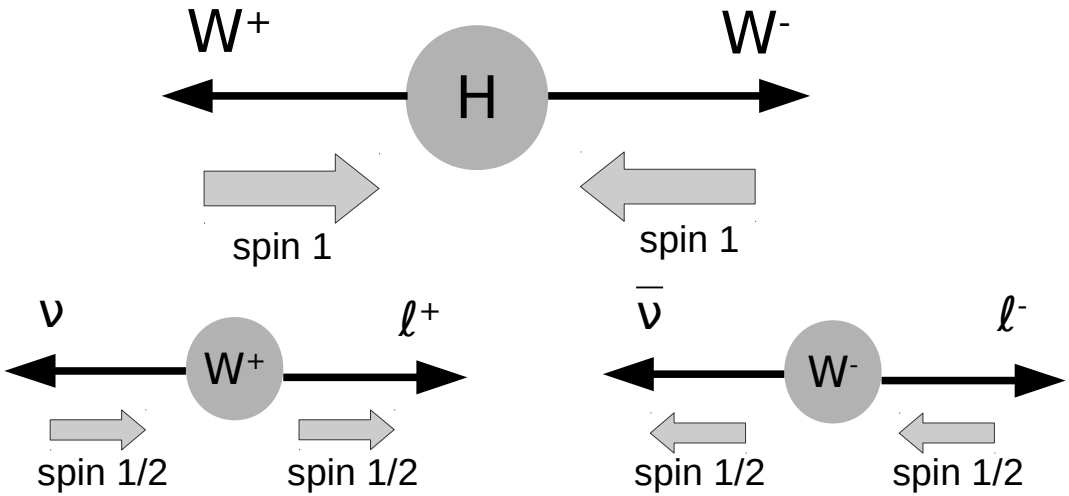
$$\sigma \times \mathcal{B}(\mathrm{H} \to \mathrm{WW}) = 0.5 \text{ pb}$$

The H→WW→2ℓ2ν channel

- 2 isolated leptons (electrons or muons) with opposite charge.
- Moderate MET.
- Number of jets depending on the production mode.

- Large signal yield.
- Good sensitivity to the Higgs boson couplings.
- Clean experimental signature.
- The presence of two neutrinos prevents the reconstruction of the Higgs boson mass.

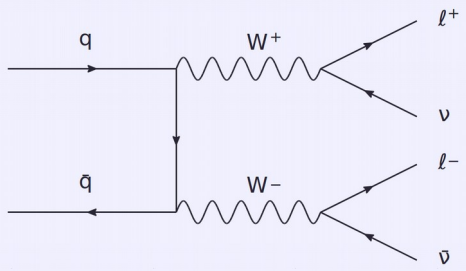




- Higgs boson has spin 0:
  - → the leptons are preferentially emitted close to each other.
  - → Small dilepton mass (m_{ll}).

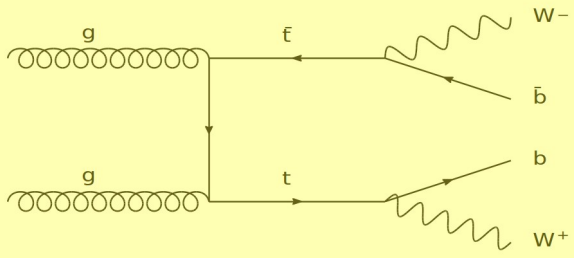
Main backgrounds

Non-resonant WW



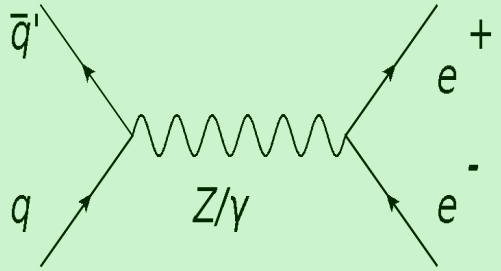
Same final state as the signal process.

tt̄



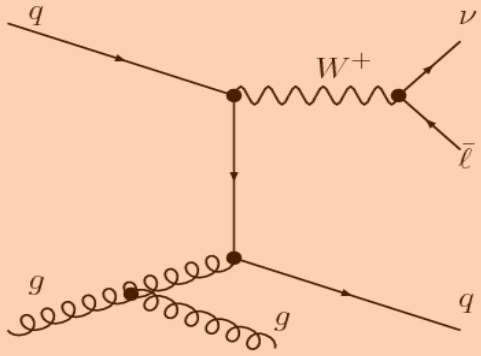
Very large cross section.
Same final state as the signal process + 2 b-jets.
Reduced vetoing b-jets

Drell-Yan



Very large in the same flavour final state.

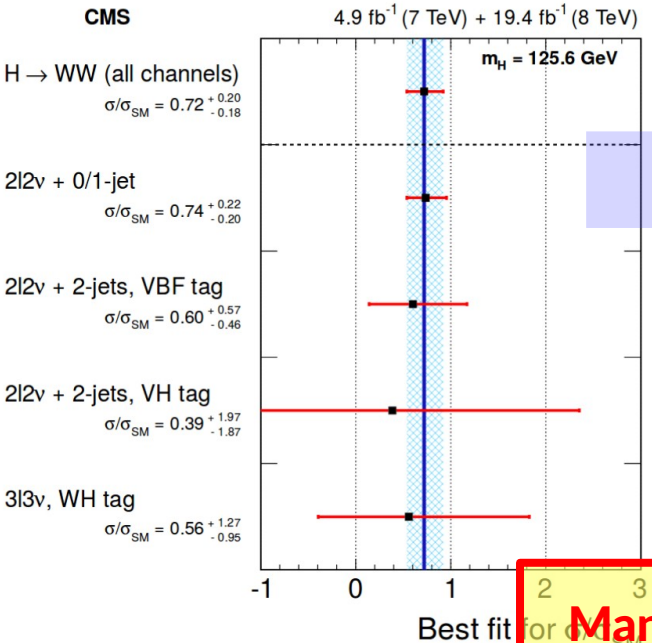
Nonprompt



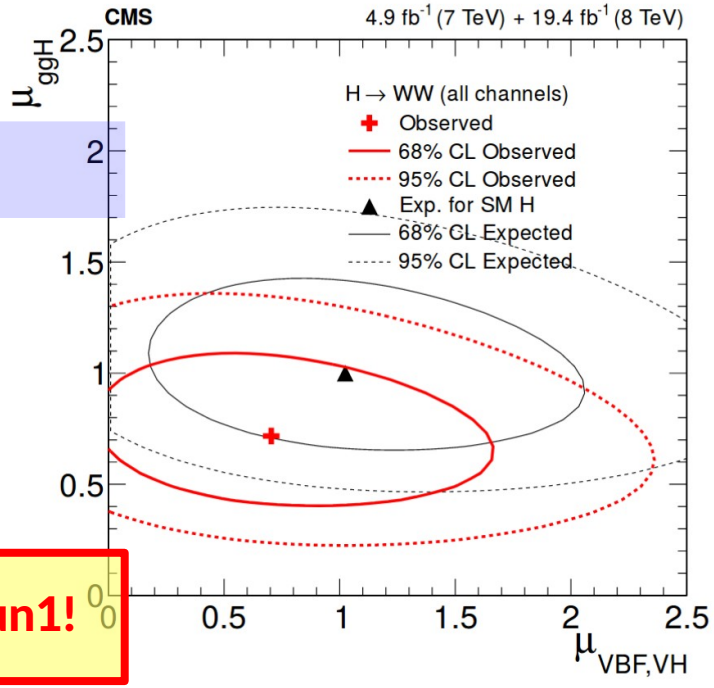
One jet can be misidentified as a lepton. Reduced with lepton ID and isolation.
Contribution also from semi-leptonic tt̄.
Totally data-driven with fake rate method.

- **Other backgrounds**: single-top, gg→WW, Wγ(*), WZ, ZZ, VVV (V=W,Z).
- Top quark and DY background normalization taken from data using dedicated control regions.
- WW background normalization free-floating in the fit.
  - signal and WW have different kinematic distributions.

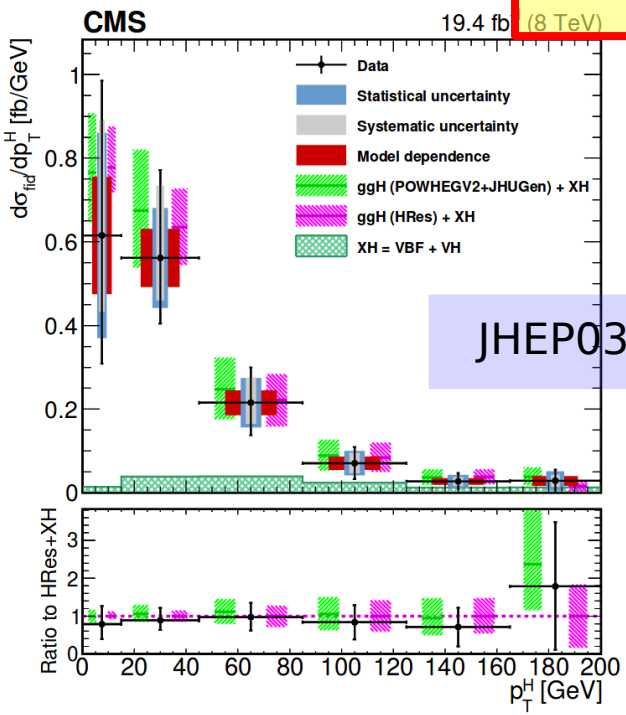
Highlights from Run1



JHEP01(2014)096

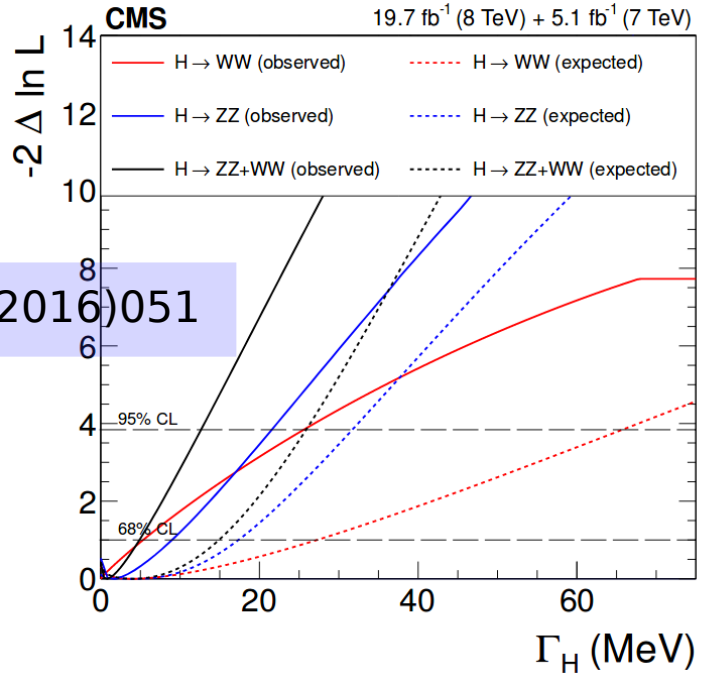


Many interesting results from Run1!



JHEP03(2017)032

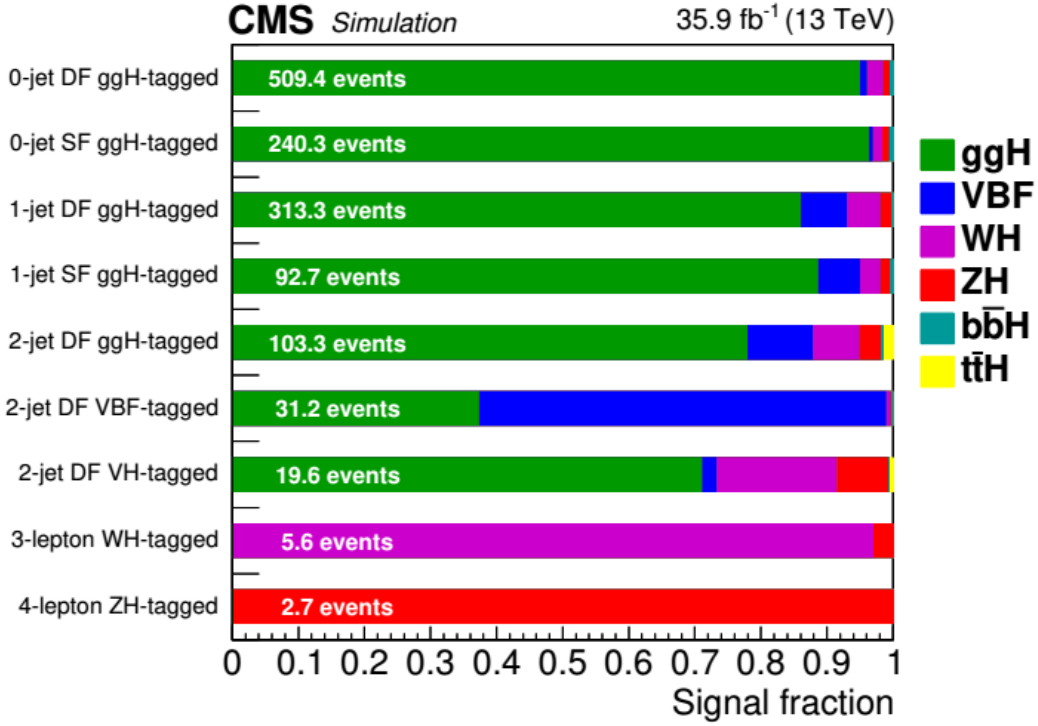
JHEP09(2016)051



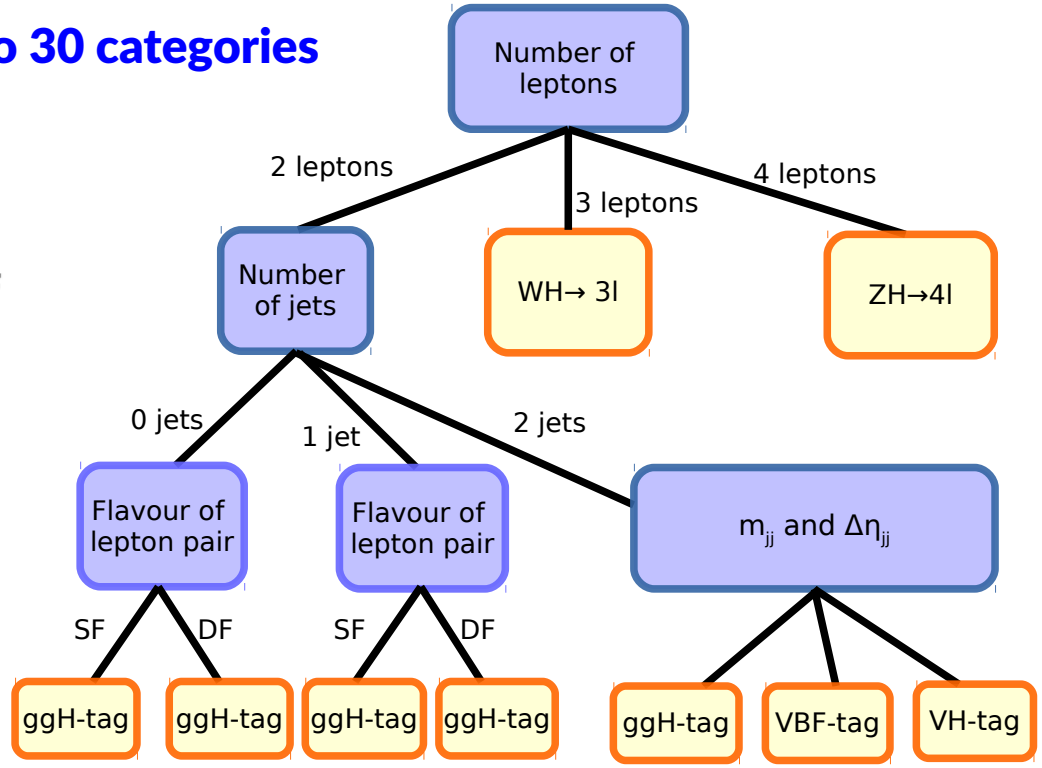
H→WW→2ℓ2υ at 13 TeV

CMS-HIG-16-042
arXiv:1806.05246 – submitted to PLB

- Preselection:
  - 2 opposite charge leptons with p_{T1}>25 GeV and p_{T2}>10(13) GeV for μ(e)
  - MET>20 GeV, $p_{T\ell\ell}$>30 GeV
  - b-tagged jet veto → reduce the top quark background
- **Main systematics**: lepton reconstruction, background data driven estimation and ggH theoretical uncertainties.



Events split into 30 categories



SF: Same Flavour (ee/μμ)
DF: Different Flavour (eμ)

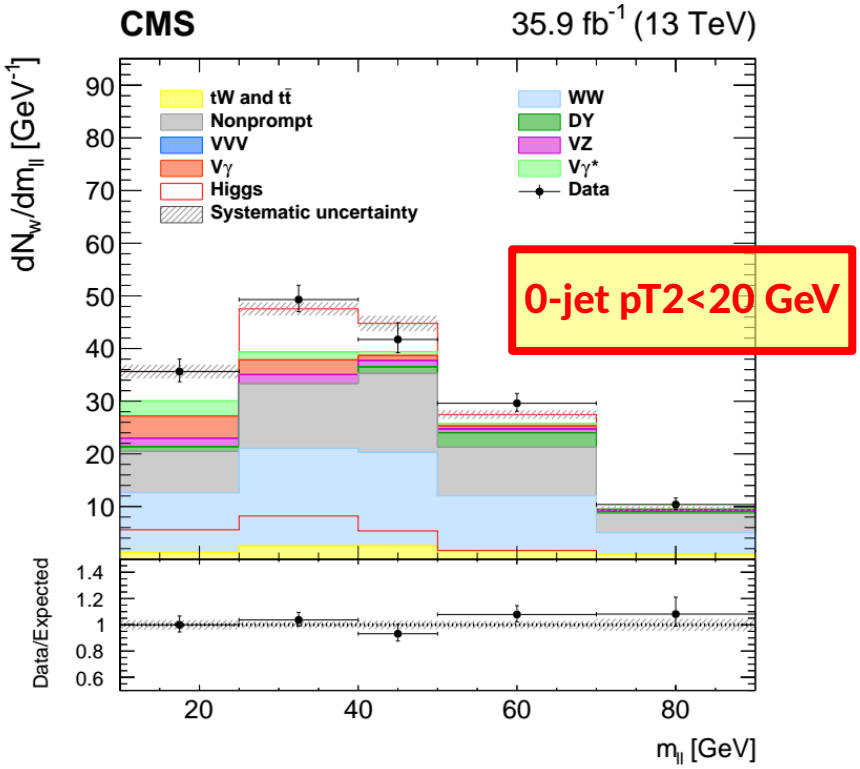
ggH-tagged categories

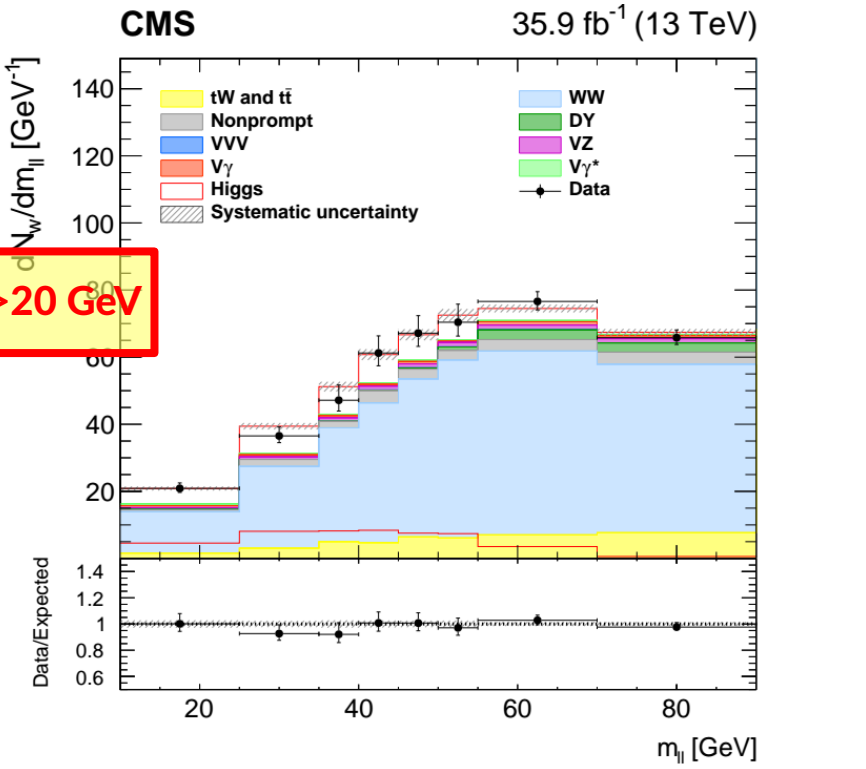
- Main discriminating variables: **m_{ll} and m_T**

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

  - 2D MC template fit in the ggH-tagged DF categories.
  - Event counting in ggH-tagged SF categories (optimized using a BDT).
- **0, 1 and 2 jets categories** to tackle top quark background.
- Events split according to lepton pair flavour and charge
  - $e^+\mu^-$, $e^-\mu^+$, μ^+e^-, μ^-e^+, e^+e^-, $\mu^+\mu^-$
- Events further split according to the subleading lepton p_T (p_{T2}><20 GeV).

} Reduce nonprompt background

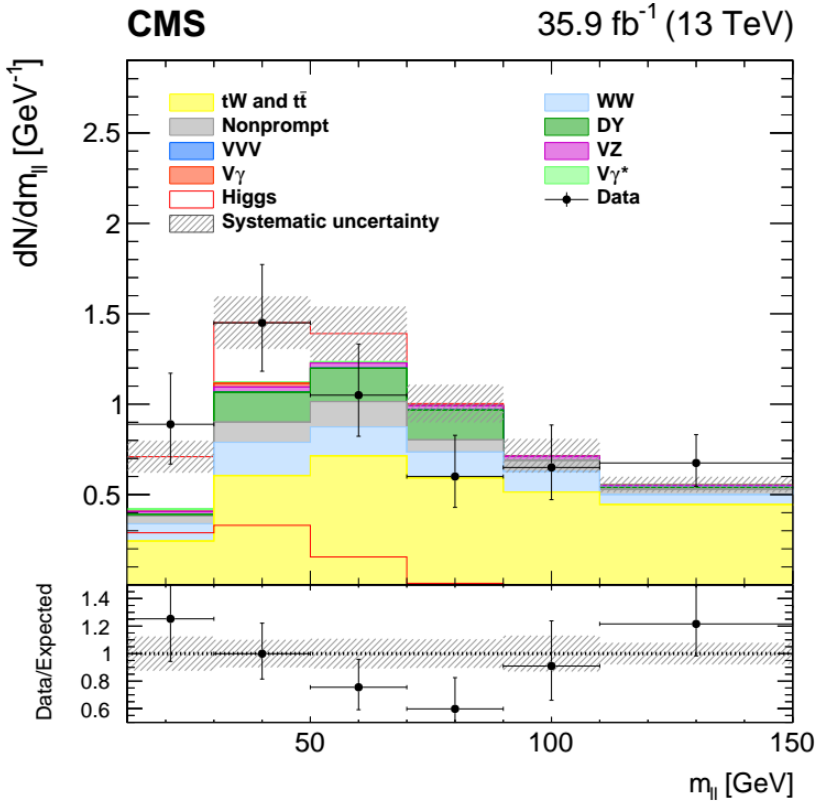




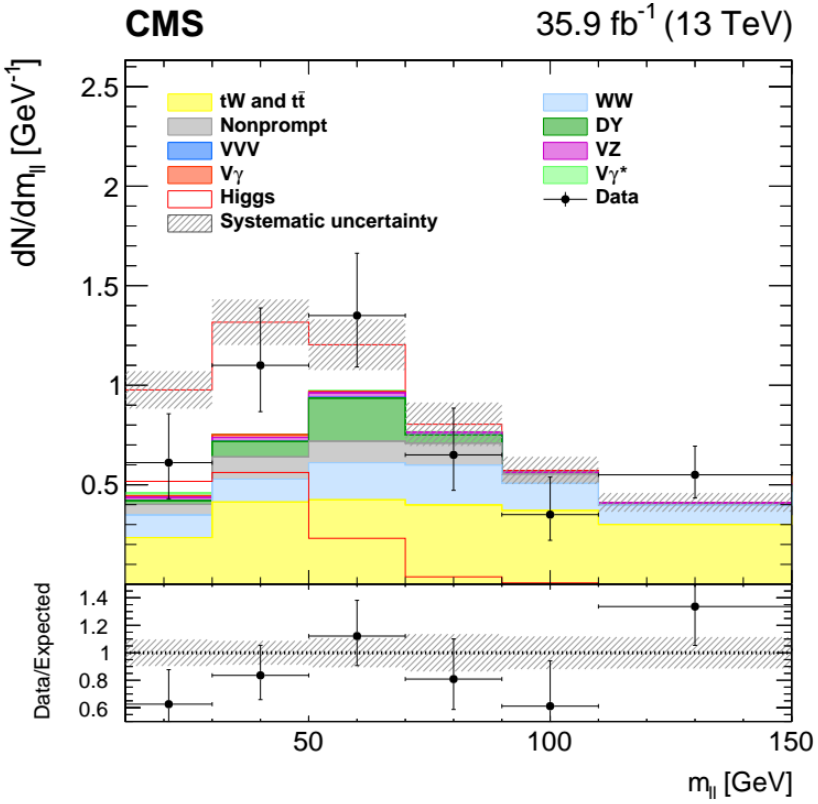
VBF-tagged categories

- S/B enhanced by selecting events with VBF topology
  - m_{jj}>400 GeV and $|\Delta\eta_{jj}|$>3.5
- MC template fit of the m_{ll} distribution in 2 m_{jj} categories.
  - Exploit different signal and background composition to gain sensitivity.

400<m_{jj}<700 GeV



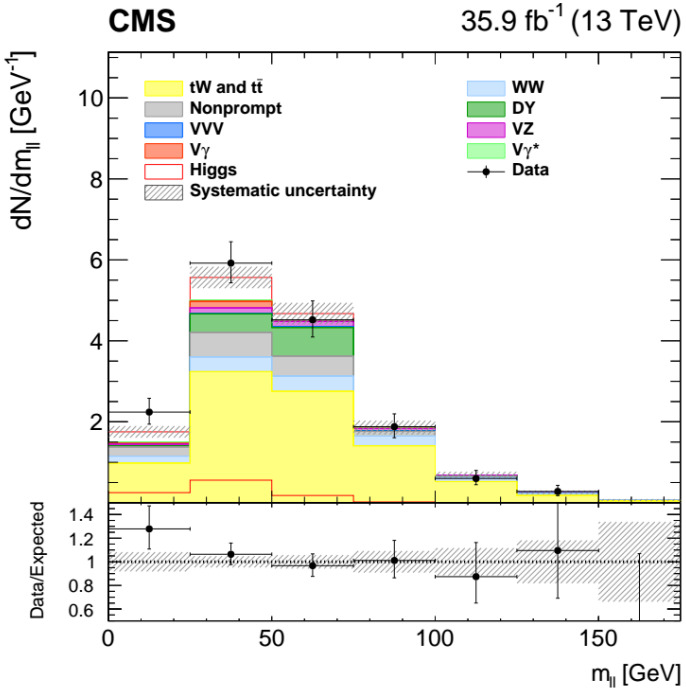
m_{jj}>700 GeV



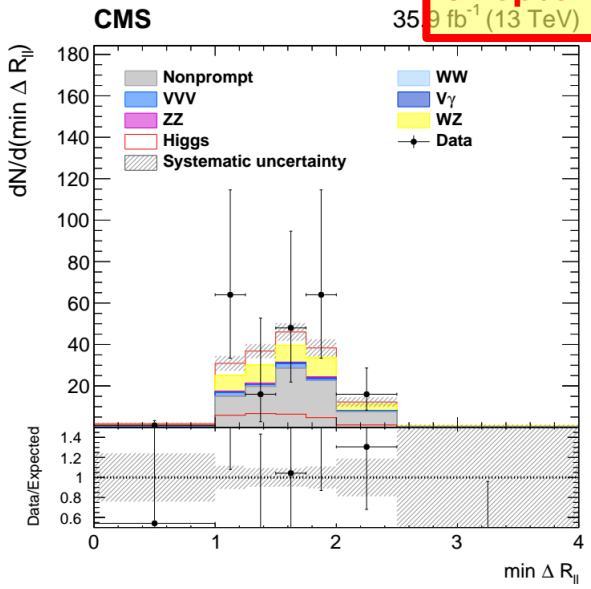
VH-tagged categories

- 3 different categories aiming at 3 different final states:
  - VH-tagged with V→hadrons, H→WW→2l2ν → **Shape analysis based on m_{ll}**
  - 3 lepton WH-tagged with W→lν, H→WW→2l2ν → **Shape analysis based on min(ΔR_{ll})**
  - 4 lepton ZH-tagged with Z→2l, H→WW→2l2ν → **Event counting analysis**

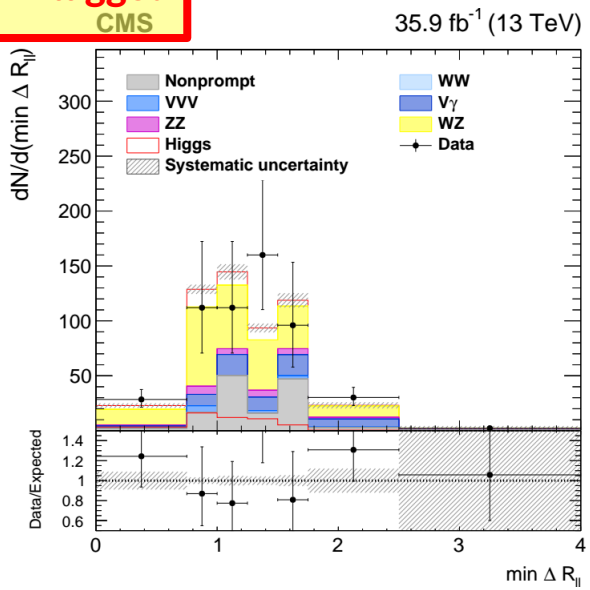
2-jet VH-tagged



3-lepton WH-tagged



$\mu^{\mp}\mu^{\pm}e^{\mp}/e^{\mp}e^{\pm}\mu^{\mp}$

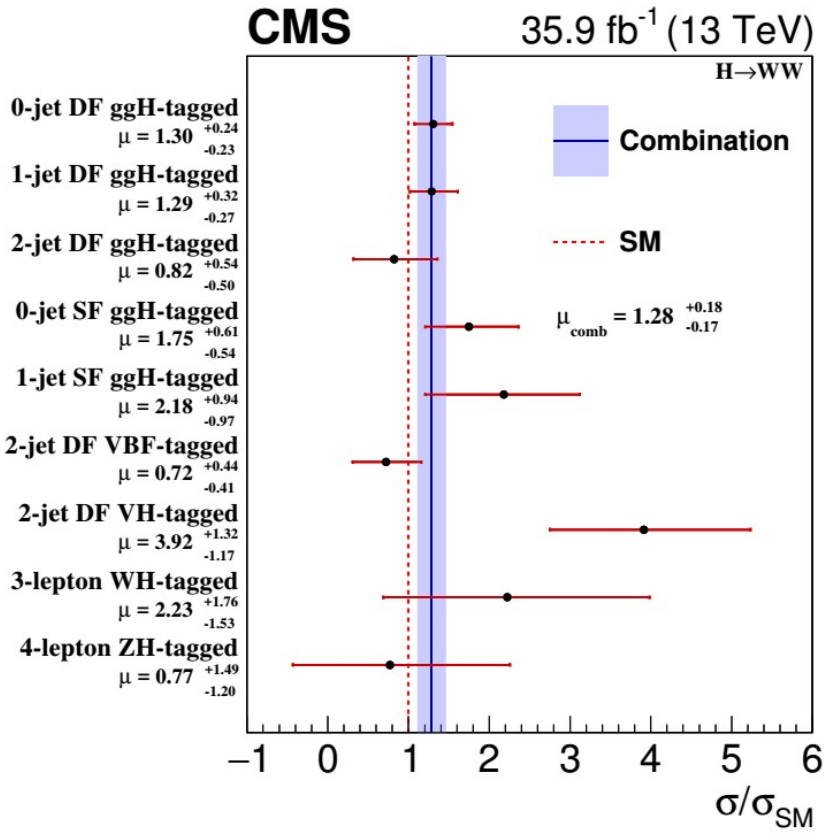


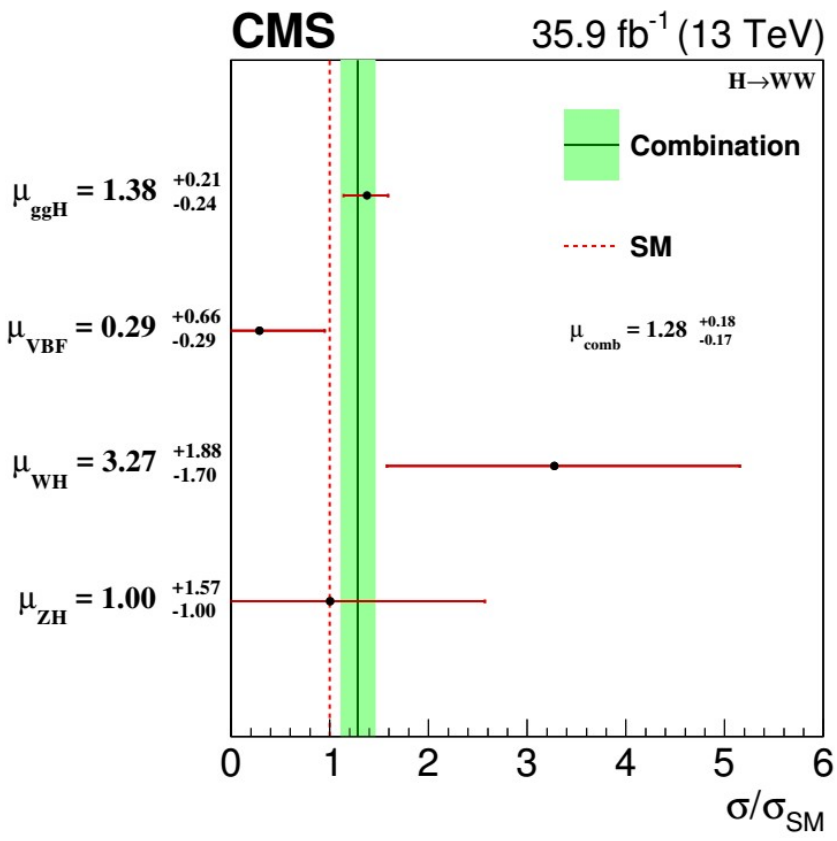
$\mu^{\pm}\mu^{\pm}e^{\mp}/e^{\pm}e^{\pm}\mu^{\mp}$

Additional event splitting in WH- and ZH-tagged categories according to the flavour and charge of the leptons.

Signal strength measurements

- Signal strengths (σ/σ_{SM}) measured from a simultaneous binned likelihood fit of all signal and control regions.
  - Different fits to measure σ/σ_{SM} per-category or per-production mechanism.





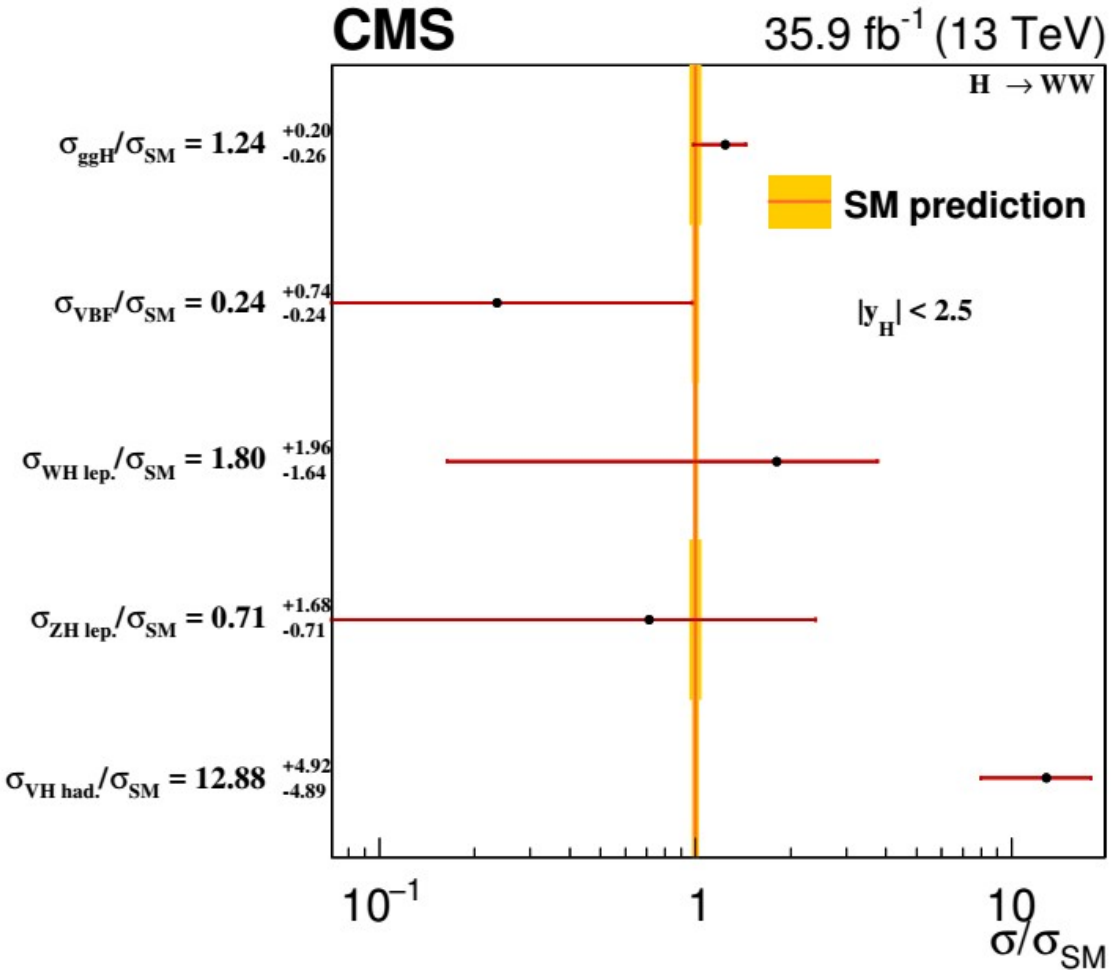
$$\mu = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10(\text{stat}) \pm 0.11(\text{syst})^{+0.10}_{-0.07}(\text{theo})$$
$$\text{Significance} = 9.1\sigma (7.1\sigma \text{ exp})$$

Significance computed in the asymptotic approximation.

First H→WW observation in CMS!

Signal strength measurements

- Measurement of the fiducial cross sections in the “stage-0” simplified template cross section framework.

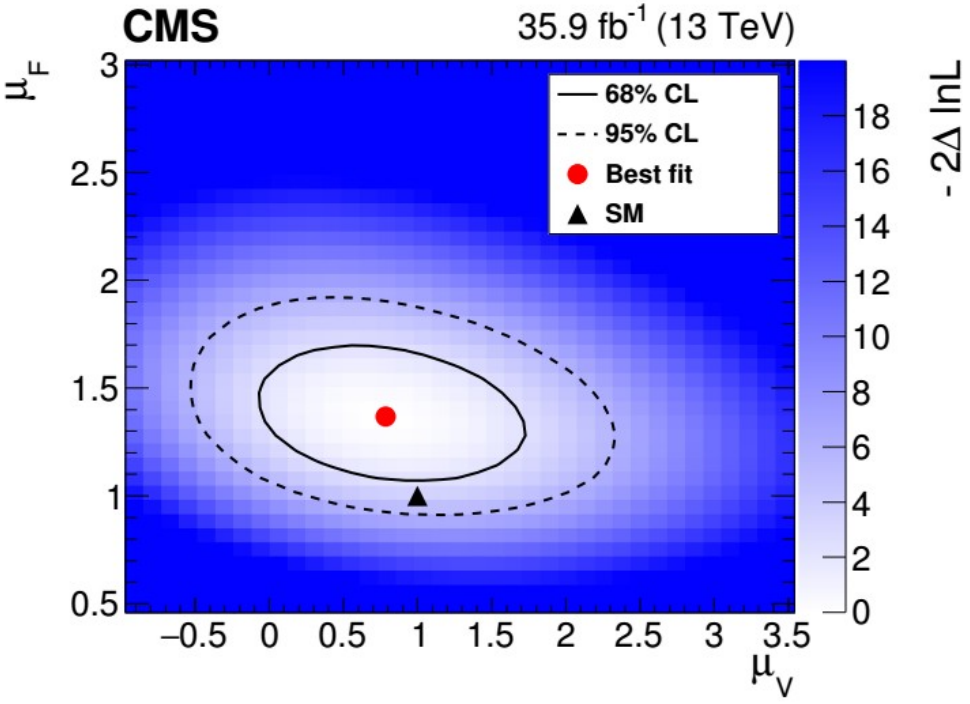


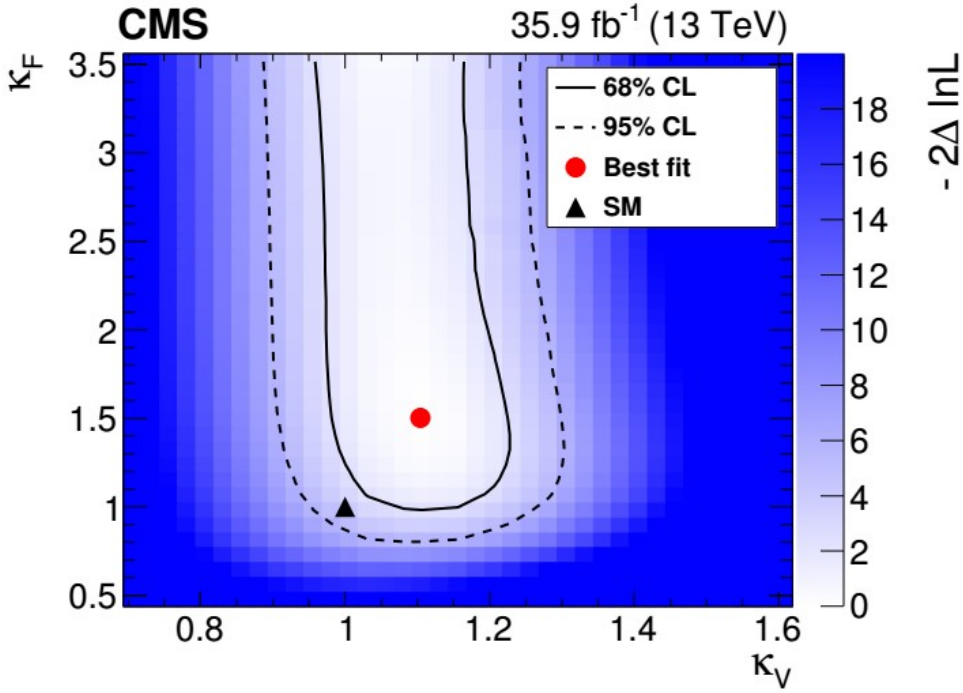
- Fiducial cross sections measured for 5 signal processes:
  - ggH, VBF, W(→lν)H, Z(→ll)H, V(→had)H
- Signal processes defined requiring $|y_H|<2.5$ at generator level.
- SM prediction for signal cross sections taken from LHC Higgs XS WG (YR4).

Measurement of the Higgs couplings

- Measurement of the Higgs boson couplings to fermions and vector bosons:
  - μ_F, μ_V: signal strengths associated to ggH and VBF/VH
  - κ_F, κ_V: coupling constants associated to fermionic and bosonic processes, as defined in the "kappa" framework.

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



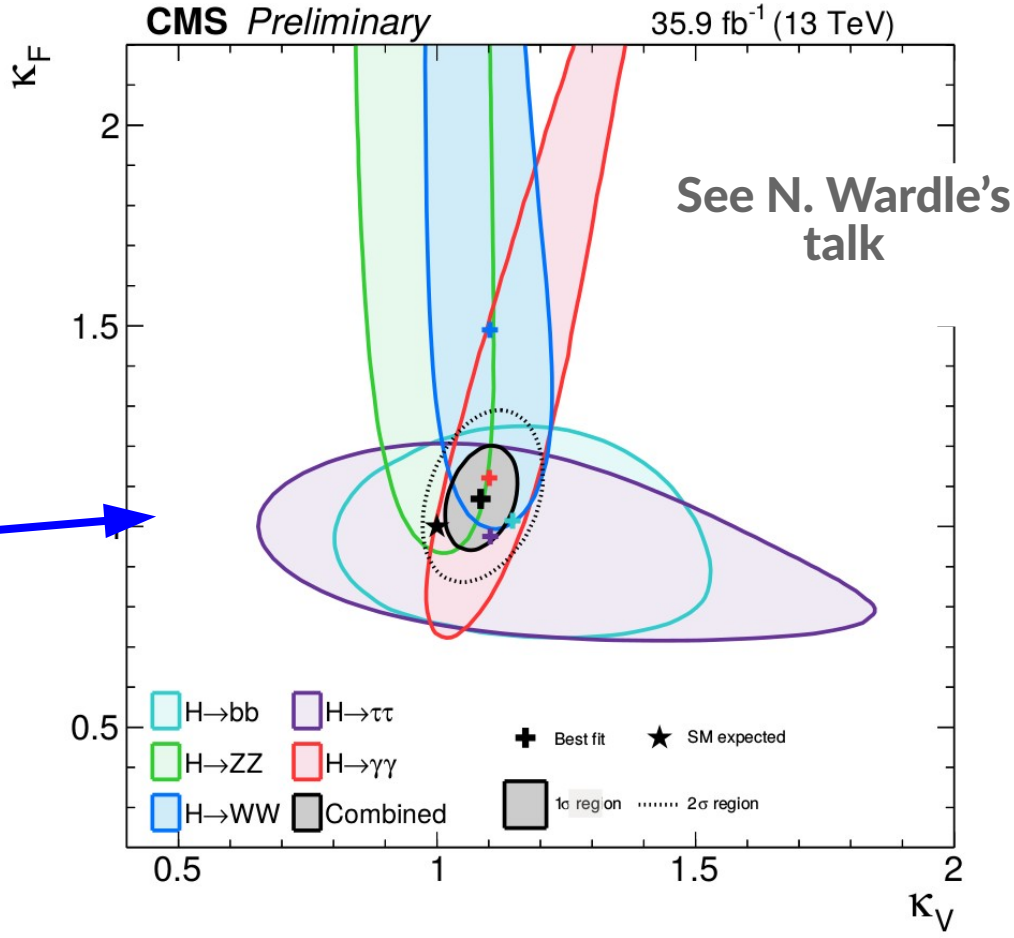


Compatibility with SM within 2σ

Conclusions

- H→WW is one of the most promising channels for the measurement of Higgs production cross section and couplings.

- **First observation in CMS of the H→WW channel** made with Run2 data.
- Various interesting measurements confirm the SM predictions.
- **Key contribution to the CMS Higgs combination measurement.**



- The results showed some tensions that have to be monitored with more data.
  - Many categories still limited by statistical uncertainty.

- More data → full characterization of the Higgs boson properties.
- **Stay tuned for new results!**

BACKUP SLIDES

Event requirements

Category	Subcategory	Requirements
Preselection	—	$m_{\ell\ell} > 12\,\text{GeV}$, $p_{\text{T1}} > 25\,\text{GeV}$, $p_{\text{T2}} > 13\ (10)\,\text{GeV}$ for e (μ), $p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$, $p_{\text{T}}^{\ell\ell} > 30\,\text{GeV}$ no additional leptons with $p_{\text{T}} > 10\,\text{GeV}$ electron and muon with opposite charges
0-jet ggH-tagged	$e^+\mu^-$, $e^-\mu^+$, μ^+e^-, μ^-e^+; $p_{\text{T2}} > 20\,\text{GeV}$	$m_{\text{T}} > 60\,\text{GeV}$, $m_{\text{T}}^{\ell 2, p_{\text{T}}^{\text{miss}}} > 30\,\text{GeV}$ subleading lepton $p_{\text{T}} > 20\,\text{GeV}$ no jets with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with p_{T} between 20 and 30 GeV
	$e^+\mu^-$, $e^-\mu^+$, μ^+e^-, μ^-e^+; $p_{\text{T2}} < 20\,\text{GeV}$	$m_{\text{T}} > 60\,\text{GeV}$, $m_{\text{T}}^{\ell 2, p_{\text{T}}^{\text{miss}}} > 30\,\text{GeV}$ subleading lepton $p_{\text{T}} < 20\,\text{GeV}$ no jets with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with p_{T} between 20 and 30 GeV
1-jet ggH-tagged	$e^+\mu^-$, $e^-\mu^+$, μ^+e^-, μ^-e^+; $p_{\text{T2}} > 20\,\text{GeV}$	$m_{\text{T}} > 60\,\text{GeV}$, $m_{\text{T}}^{\ell 2, p_{\text{T}}^{\text{miss}}} > 30\,\text{GeV}$ subleading lepton $p_{\text{T}} > 20\,\text{GeV}$ exactly one jet with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$
	$e^+\mu^-$, $e^-\mu^+$, μ^+e^-, μ^-e^+; $p_{\text{T2}} < 20\,\text{GeV}$	$m_{\text{T}} > 60\,\text{GeV}$, $m_{\text{T}}^{\ell 2, p_{\text{T}}^{\text{miss}}} > 30\,\text{GeV}$ subleading lepton $p_{\text{T}} < 20\,\text{GeV}$ exactly one jet with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$
2-jet ggH-tagged	eμ	at least two jets with $p_{\text{T}} > 30\,\text{GeV}$ $m_{\text{T}}^{\ell 2, p_{\text{T}}^{\text{miss}}} > 30\,\text{GeV}$ and $m_{\text{T}} > 60\,\text{GeV}$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$ $m_{jj} < 65\,\text{GeV}$ or $105 < m_{jj} < 400\,\text{GeV}$

Event requirements

Category	Subcategory	Requirements
Preselection	—	$m_{\ell\ell} > 12\,\text{GeV}$, $p_{\text{T1}} > 25\,\text{GeV}$, $p_{\text{T2}} > 13\ (10)\,\text{GeV}$ for e(μ), $p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$, $p_{\text{T}}^{\ell\ell} > 30\,\text{GeV}$ no additional leptons with $p_{\text{T}} > 10\,\text{GeV}$ electron and muon with opposite charges
2-jet VBF-tagged	eμ low m_{jj}	exactly two jets with $p_{\text{T}} > 30\,\text{GeV}$ $60 < m_{\text{T}} < 125\,\text{GeV}$ leptons η between the two leading jets $400 < m_{jj} < 700\,\text{GeV}$ and $\lvert\Delta\eta_{jj}\rvert > 3.5$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$
	eμ high m_{jj}	exactly two jets with $p_{\text{T}} > 30\,\text{GeV}$ $60 < m_{\text{T}} < 125\,\text{GeV}$ leptons η between the two leading jets $m_{jj} > 700\,\text{GeV}$ and $\lvert\Delta\eta_{jj}\rvert > 3.5$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$

Category	Subcategory	Requirements
Preselection	—	$m_{\ell\ell} > 12\,\text{GeV}$, $p_{\text{T1}} > 25\,\text{GeV}$, $p_{\text{T2}} > 13\ (10)\,\text{GeV}$ for e (μ) $p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$, $p_{\text{T}}^{\ell\ell} > 30\,\text{GeV}$ no additional leptons with $p_{\text{T}} > 10\,\text{GeV}$ electron and muon with opposite charges
2-jet VH-tagged	eμ	at least two jets with $p_{\text{T}} > 30\,\text{GeV}$ two leading jets with $\lvert\eta\rvert < 2.5$ $60 < m_{\text{T}} < 125\,\text{GeV}$ and $\Delta R_{\ell\ell} < 2$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$ $65 < m_{jj} < 105\,\text{GeV}$ and $\lvert\Delta\eta_{jj}\rvert < 3.5$

Event requirements

Category	Subcategory	Requirements
Preselection	—	$m_{\ell\ell} > 12\,\text{GeV}$, $p_{\text{T1}} > 25\ (20)\,\text{GeV}$ for e (μ), $p_{\text{T2}} > 13\ (10)\,\text{GeV}$ for e (μ), track $p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$, $p_{\text{T}}^{\ell\ell} > 30\,\text{GeV}$ no additional leptons with $p_{\text{T}} > 10\,\text{GeV}$ two electrons or two muons with opposite charges
0-jet ggH-tagged	e^+e^- $p_{\text{T2}} < 20\,\text{GeV}$ $\mu^+\mu^-$ $p_{\text{T2}} < 20\,\text{GeV}$	DYMVA > 0.991, $m_{\ell\ell} < 55\,\text{GeV}$, $m_{\text{T}} > 50\,\text{GeV}$, $p_{\text{T2}} < 20\,\text{GeV}$, $\Delta\phi_{\ell\ell} < 1.7$ no jets with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$
	e^+e^- $p_{\text{T2}} > 20\,\text{GeV}$ $\mu^+\mu^-$ $p_{\text{T2}} > 20\,\text{GeV}$	DYMVA > 0.991, $m_{\ell\ell} < 55\,\text{GeV}$, $m_{\text{T}} > 50\,\text{GeV}$, $20\,\text{GeV} < p_{\text{T2}} < 50\,\text{GeV}$, $\Delta\phi_{\ell\ell} < 1.7$ no jets with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$
1-jet ggH-tagged	e^+e^- $\mu^+\mu^-$	DYMVA > 0.95, $m_{\ell\ell} < 57\,\text{GeV}$, $50 < m_{\text{T}} < 155\,\text{GeV}$, $p_{\text{T1}} < 50\,\text{GeV}$, $\Delta\phi_{\ell\ell} < 1.75$ exactly one jet with $p_{\text{T}} > 30\,\text{GeV}$ no b-tagged jets with $p_{\text{T}} > 20\,\text{GeV}$

Event requirements

Category	Subcategory	Requirements
Preselection	—	$p_{T1} > 25\,\text{GeV}$, $p_{T2} > 20\,\text{GeV}$, $p_{T3} > 15\,\text{GeV}$ no additional leptons with $p_T > 10\,\text{GeV}$ min–$m_{\ell^+\ell^-} > 12\,\text{GeV}$, total lepton charge sum ± 1
3-lepton WH-tagged	OSSF	no jets with $p_T > 30\,\text{GeV}$ no b-tagged jets with $p_T > 20\,\text{GeV}$ $p_T^{\text{miss}} > 50\,\text{GeV}$, min–$m_{\ell^+\ell^-} < 100\,\text{GeV}$ Z boson veto: $\lvert m_{\ell\ell} - m_Z \rvert > 25\,\text{GeV}$ $\Delta\phi(\ell\ell\ell, \vec{p}_T^{\,\text{miss}}) > 2.2$
	SSSF	no jets with $p_T > 30\,\text{GeV}$ no b-tagged jets with $p_T > 20\,\text{GeV}$ $\Delta\phi(\ell\ell\ell, \vec{p}_T^{\,\text{miss}}) > 2.5$

Category	Subcategory	Requirements
Preselection	—	four tight and isolated leptons, with zero total charge $p_T > 25\,\text{GeV}$ for the leading lepton $p_T > 15\,\text{GeV}$ for the second leading lepton $p_T > 10\,\text{GeV}$ for the remaining two leptons no additional leptons with $p_T > 10\,\text{GeV}$ Z dilepton mass $> 4\,\text{GeV}$ X dilepton mass $> 4\,\text{GeV}$
4-lepton ZH-tagged	XSF	$\lvert m_{\ell\ell} - m_Z \rvert < 15\,\text{GeV}$ $10 < m_X < 50\,\text{GeV}$ $35 < p_T^{\text{miss}} < 100\,\text{GeV}$ four-lepton invariant mass $> 140\,\text{GeV}$
	XDF	$\lvert m_{\ell\ell} - m_Z \rvert < 15\,\text{GeV}$ $10 < m_X < 70\,\text{GeV}$ $p_T^{\text{miss}} > 20\,\text{GeV}$ no b-tagged jets with $p_T > 20\,\text{GeV}$

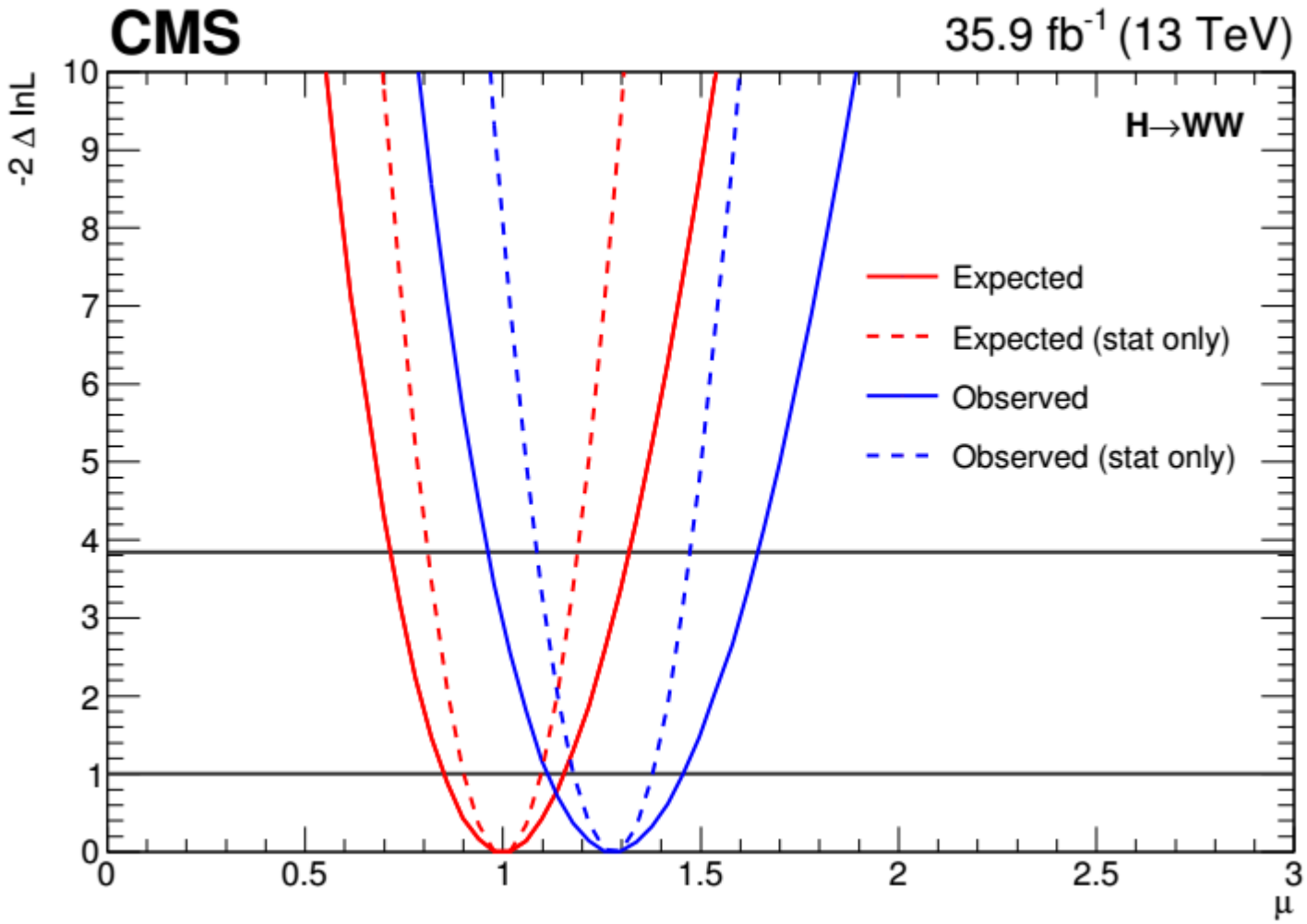
Yields

	Category							
	0-jet DF		1-jet DF		0-jet SF		1-jet SF	
	ggH-tagged		ggH-tagged		ggH-tagged		ggH-tagged	
ggH	483.1	(642.1)	269.1	(339.3)	231.2	(324.6)	82.0	(92.8)
VBF	5.6	(7.4)	22.1	(29.4)	1.5	(2.5)	5.9	(9.3)
WH	12.4	(16.4)	15.8	(20.6)	3.3	(4.3)	2.9	(3.8)
ZH	5.2	(6.9)	5.0	(6.7)	2.6	(3.4)	1.4	(1.8)
$t\bar{t}H$	<0.1	(<0.1)	0.2	(0.2)	<0.1	(<0.1)	<0.1	(<0.1)
$b\bar{b}H$	3.4	(4.4)	1.5	(2.0)	1.7	(2.3)	0.5	(0.7)
Signal	509	(677)	313	(398)	240	(337)	93	(108)
±total unc.		(±31)		(±19)		(±24)		(±13)
WW	7851	(9088)	3553	(3727)	1596	(1805)	373	(365)
Top quark	2505	(2422)	5395	(5224)	334	(339)	452	(443)
Nonprompt	1555	(1006)	781	(482)	301	(260)	111	(97)
DY	154	(154)	283	(302)	437	(459)	178	(216)
$VZ/V\gamma^*$	368	(385)	327	(338)	101	(104)	43	(43)
$V\gamma$	213	(210)	137	(128)	23	(26)	17	(19)
Other diboson	5.1	(5.3)	3.5	(3.7)	9.3	(9.4)	2.0	(2.1)
Triboson	9.3	(9.6)	16	(17)	1.2	(1.2)	1.3	(1.3)
Background	12660	(13280)	10496	(10222)	2803	(3004)	1177	(1186)
±total unc.		(±141)		(±178)		(±97)		(±83)
Data	13964		10591		3364		1308	

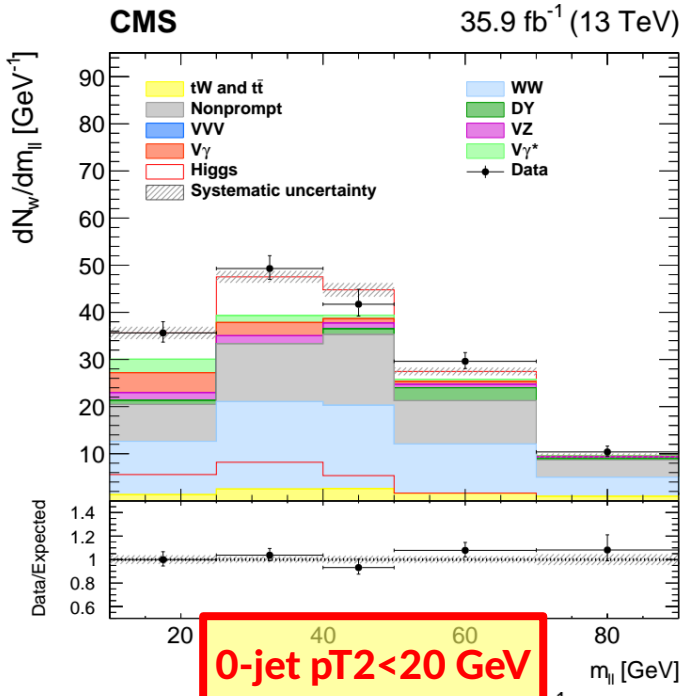
Yields

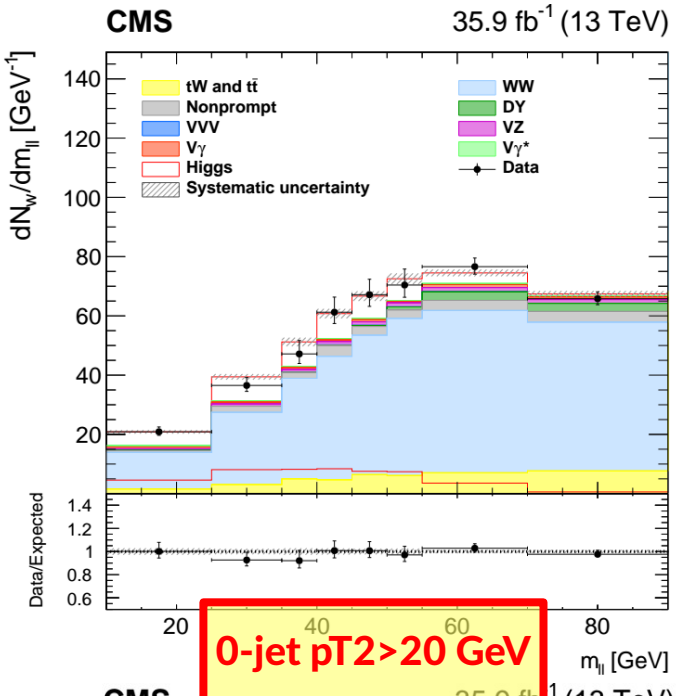
	Category							
	2-jet DF ggH-tagged		2-jet DF VBF-tagged		2-jet DF VH-tagged		3-lepton WH-tagged		4-lepton ZH-tagged	
ggH	80.4	(100.6)	11.6	(14.6)	13.9	(17.4)	<0.1	(<0.1)	<0.1	(<0.1)
VBF	10.3	(13.3)	19.2	(24.5)	0.4	(0.6)	<0.1	(<0.1)	<0.1	(<0.1)
WH	7.2	(9.3)	0.2	(0.2)	3.6	(4.6)	5.4	(7.2)	<0.1	(<0.1)
ZH	3.3	(4.3)	<0.1	(<0.1)	1.5	(2.1)	0.2	(0.2)	2.7	(3.5)
$t\bar{t}H$	1.6	(2.1)	<0.1	(<0.1)	0.1	(0.2)	<0.1	(<0.1)	<0.1	(<0.1)
$b\bar{b}H$	0.6	(0.7)	<0.1	(0.1)	<0.1	(<0.1)	<0.1	(<0.1)	<0.1	(<0.1)
Signal	103	(130)	31	(40)	20	(25)	5.6	(7.4)	2.7	(3.5)
±total unc.		(±16)		(±3)		(±3)		(±0.7)		(±0.3)
WW	1048	(860)	69	(46)	52	(34)	<0.1	(<0.1)	<0.1	(<0.1)
Top quark	5197	(5187)	157	(158)	230	(229)	<0.1	(<0.1)	0.3	(0.3)
Nonprompt	359	(305)	30	(20)	42	(37)	19	(21)	<0.1	(<0.1)
DY	110	(112)	20	(19)	29	(30)	<0.1	(<0.1)	<0.1	(<0.1)
$VZ/V\gamma^*$	136	(137)	7.1	(6.9)	11	(10)	<0.1	(<0.1)	<0.1	(<0.1)
$V\gamma$	59	(53)	2.8	(2.8)	4.2	(4.6)	3.8	(9.6)	<0.1	(<0.1)
Other diboson	2.1	(2.3)	0.3	(0.3)	1.2	(1.3)	32	(37)	13	(13)
Triboson	15	(15)	0.3	(0.3)	2.0	(2.0)	2.1	(2.1)	0.4	(0.4)
Background	6926	(6671)	287	(253)	371	(348)	57	(70)	13.7	(13.7)
±total unc.		(±502)		(±17)		(±37)		(±7)		(±0.6)
Data	6802		285		386		85		15	

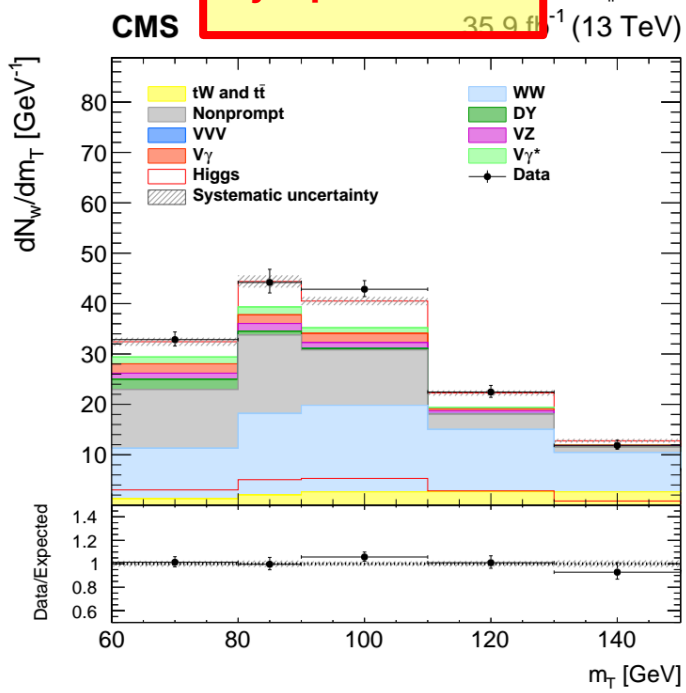
Likelihood scan

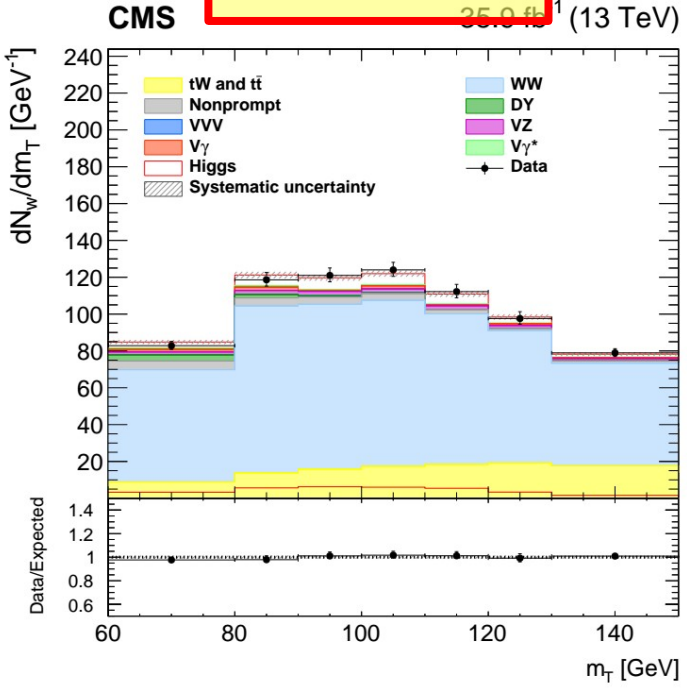


Signal regions

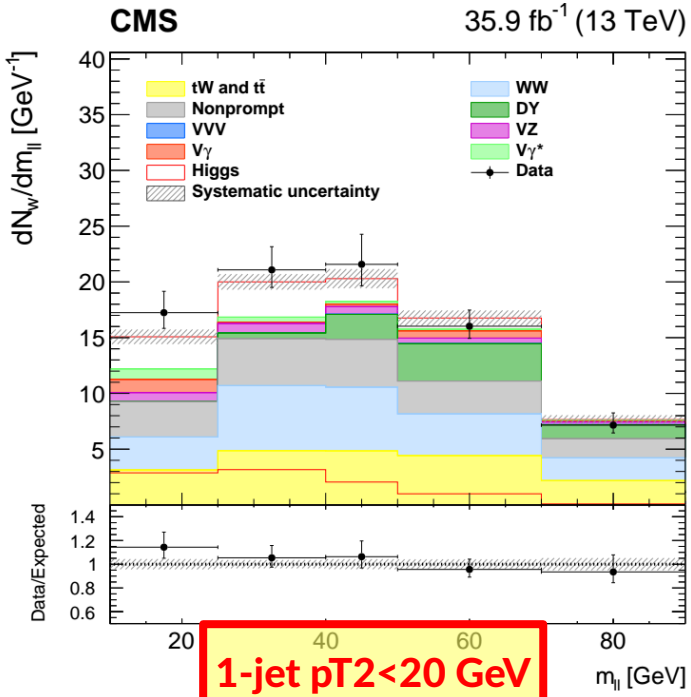


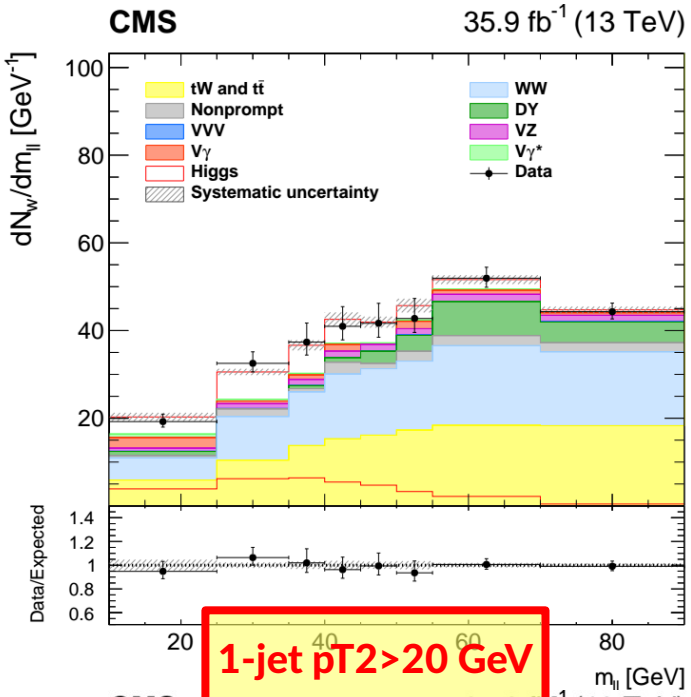


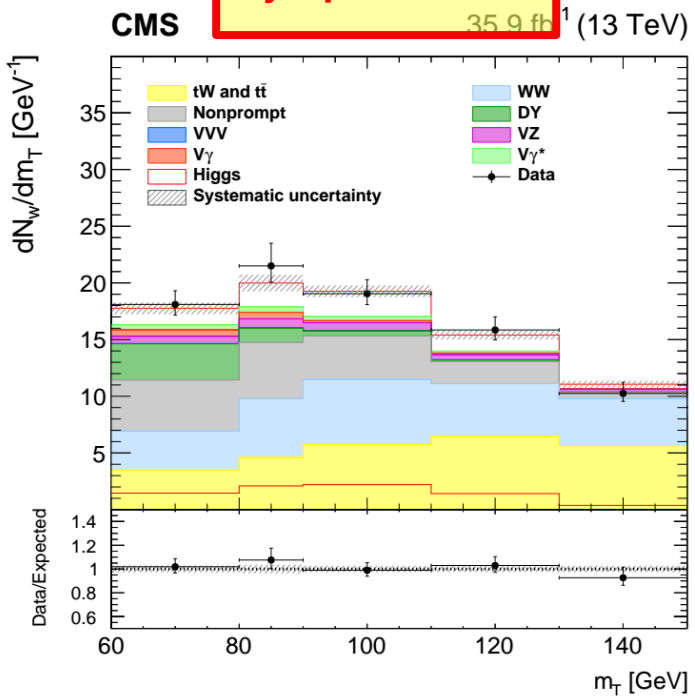


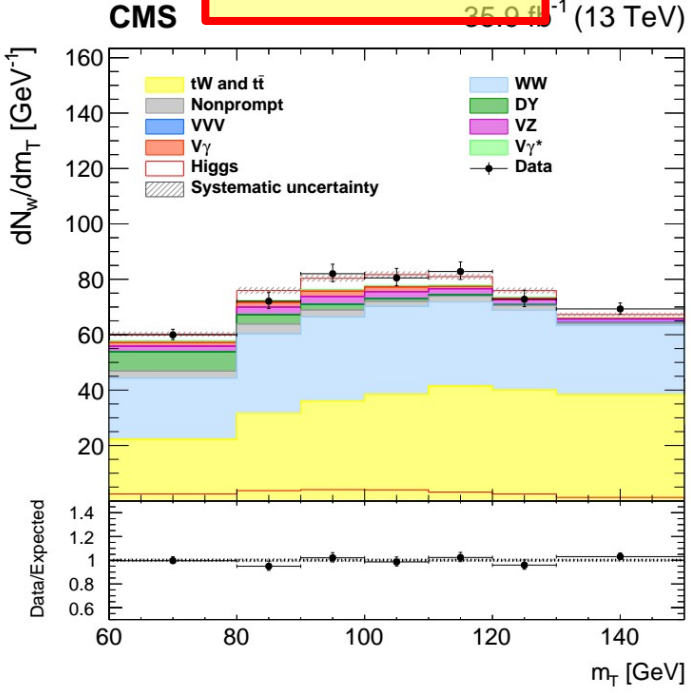


Signal regions

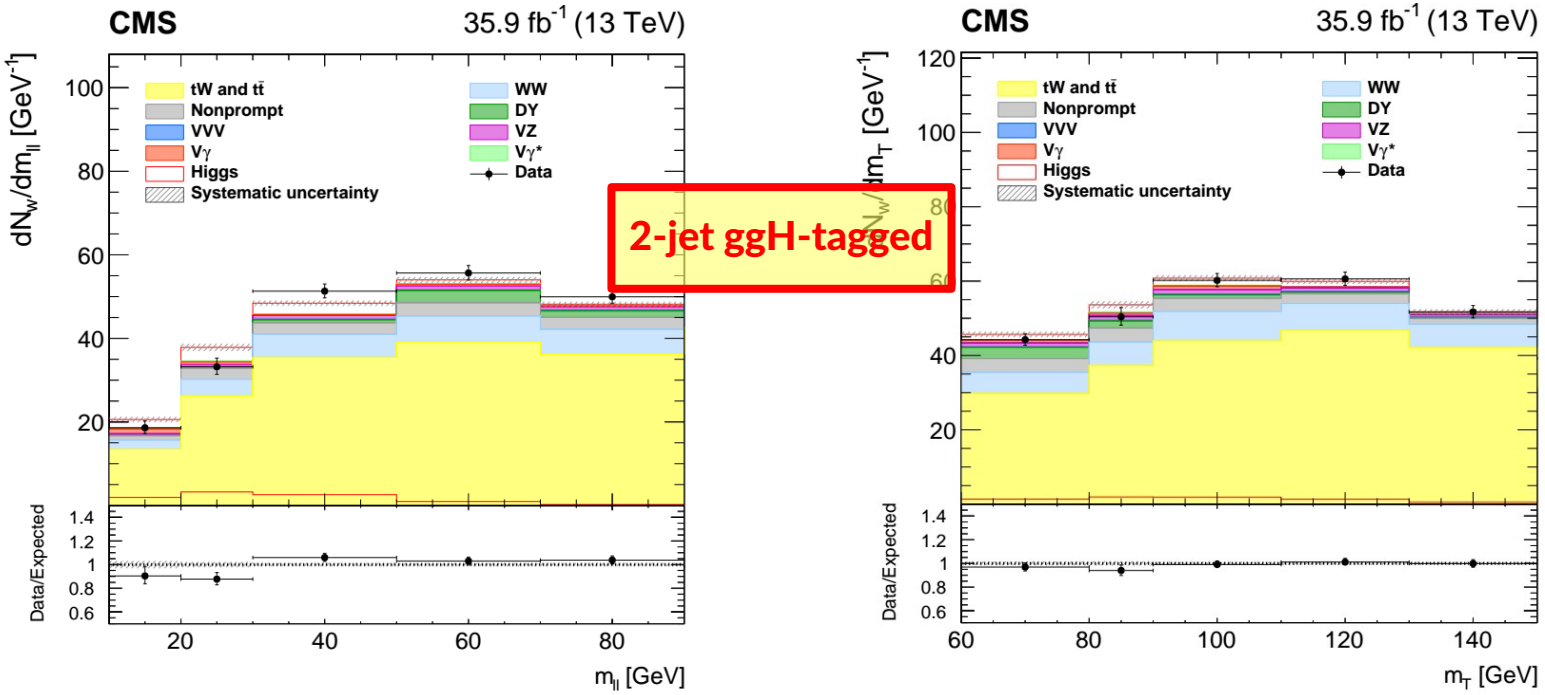


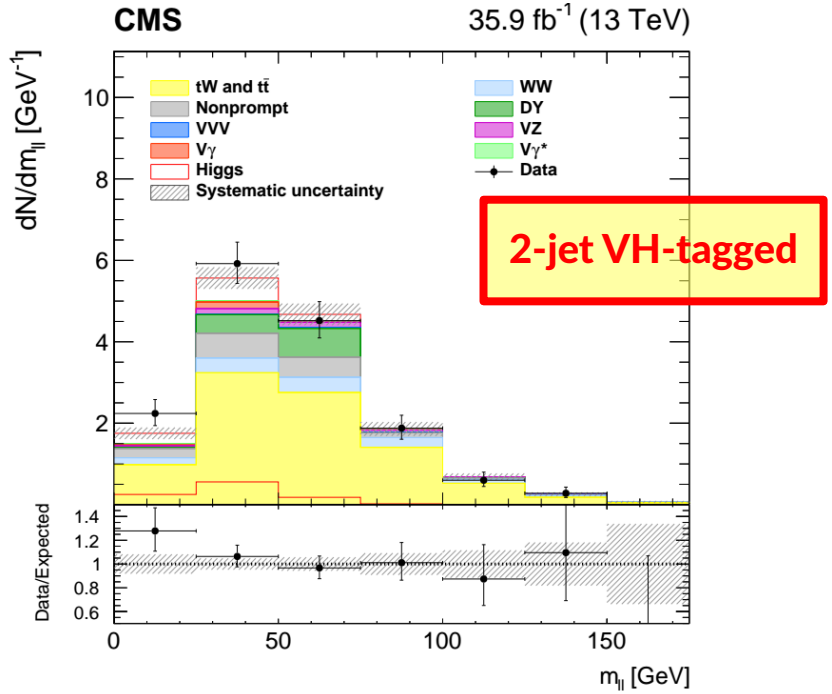




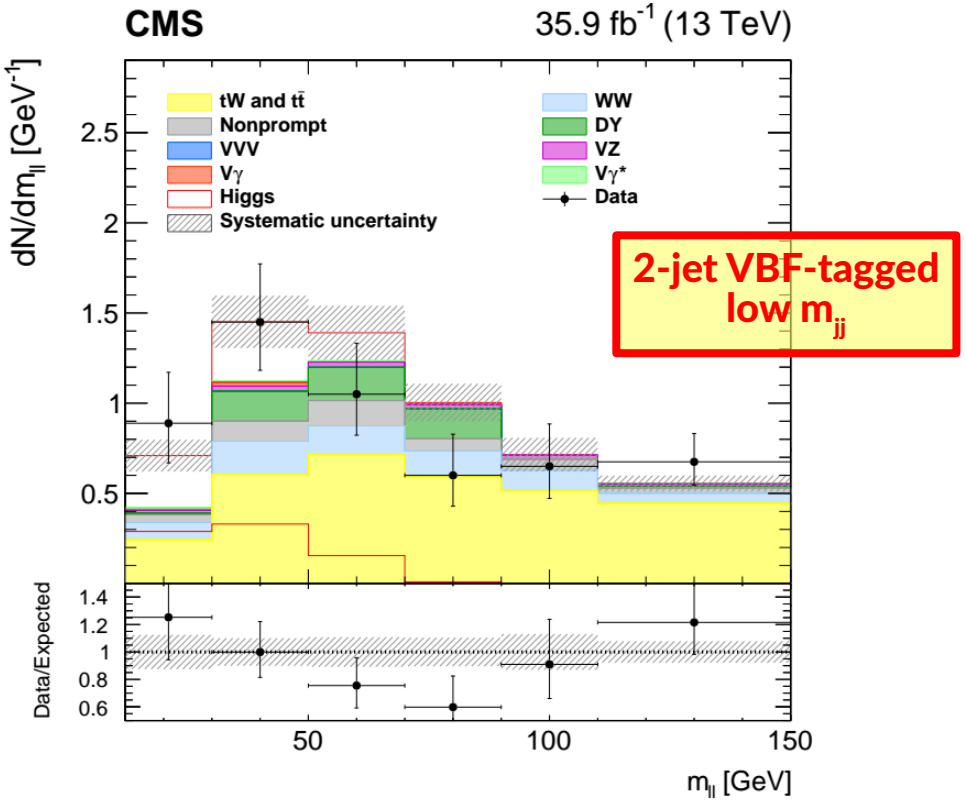


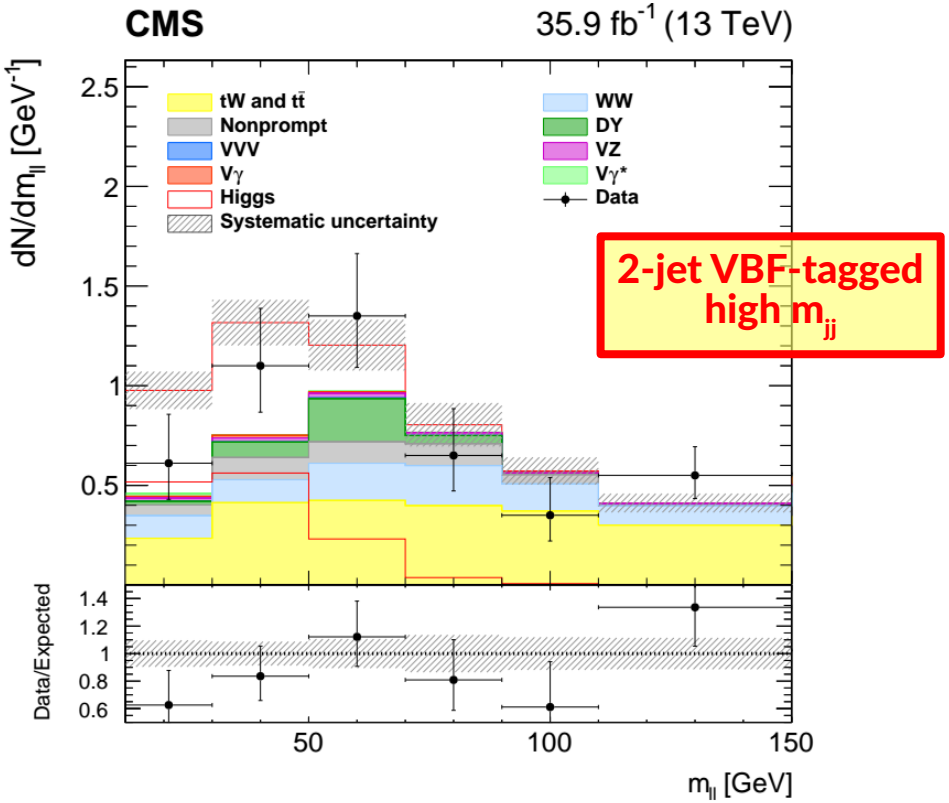
Signal regions



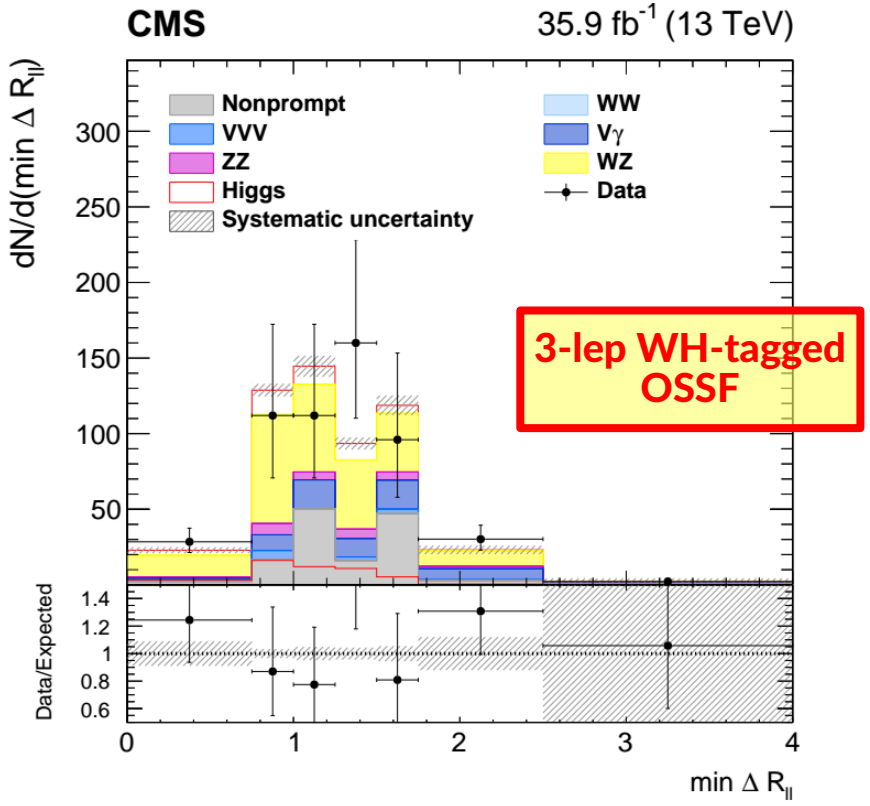


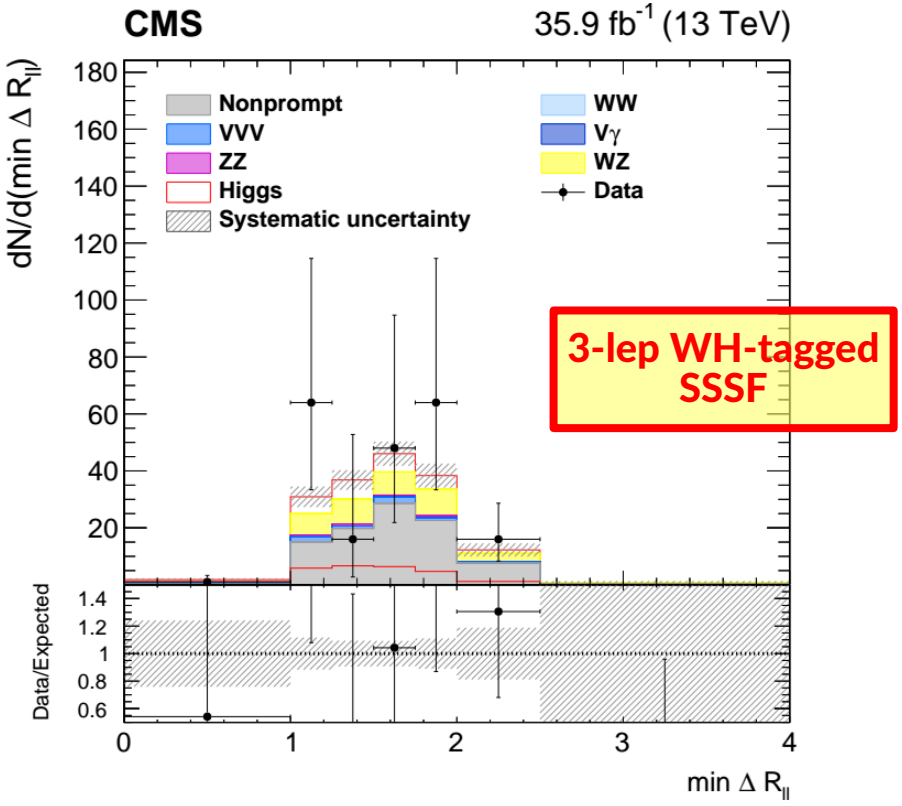
Signal regions





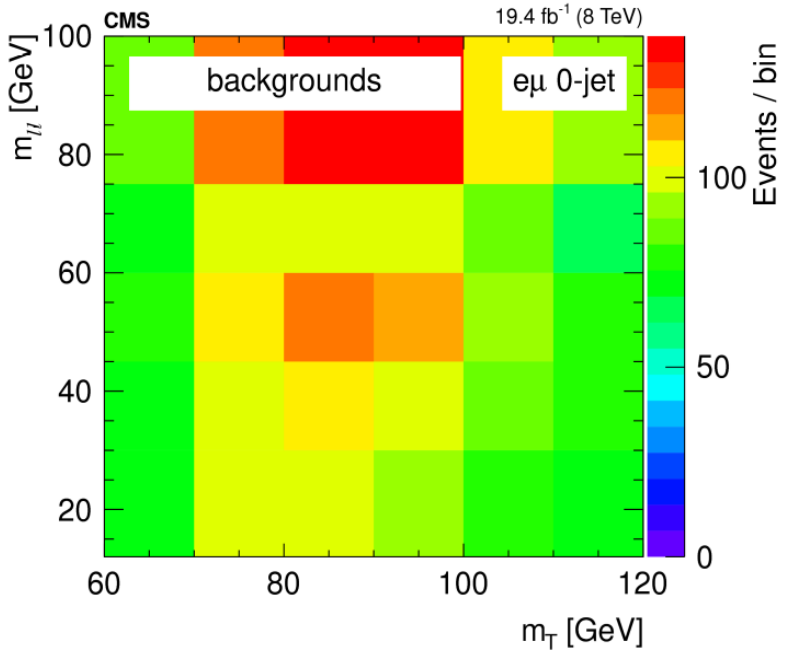
Signal regions



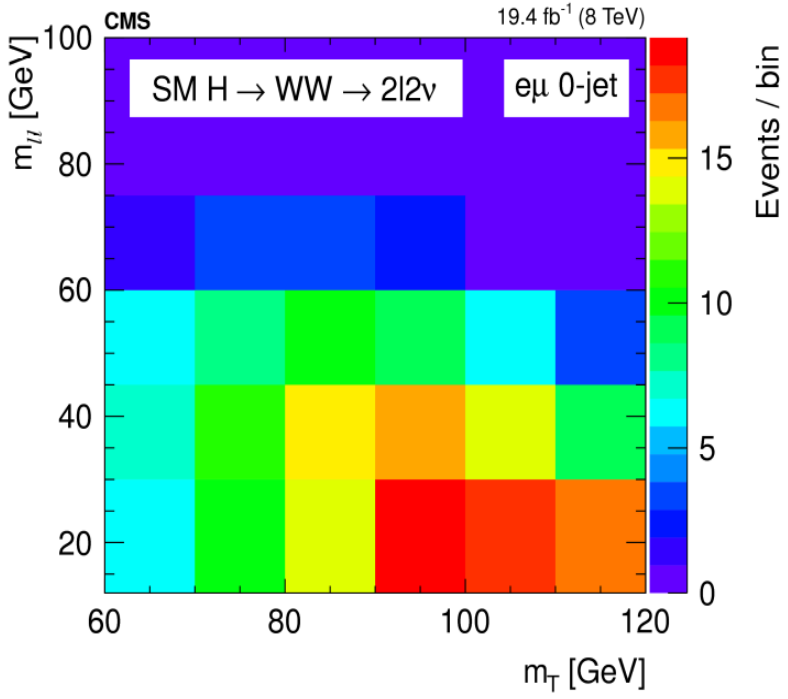


Analysis strategy

- Exploit the signal kinematics to reduce background contamination
  - **Dilepton invariant mass m_{ll}**
  - **Transverse mass m_T**

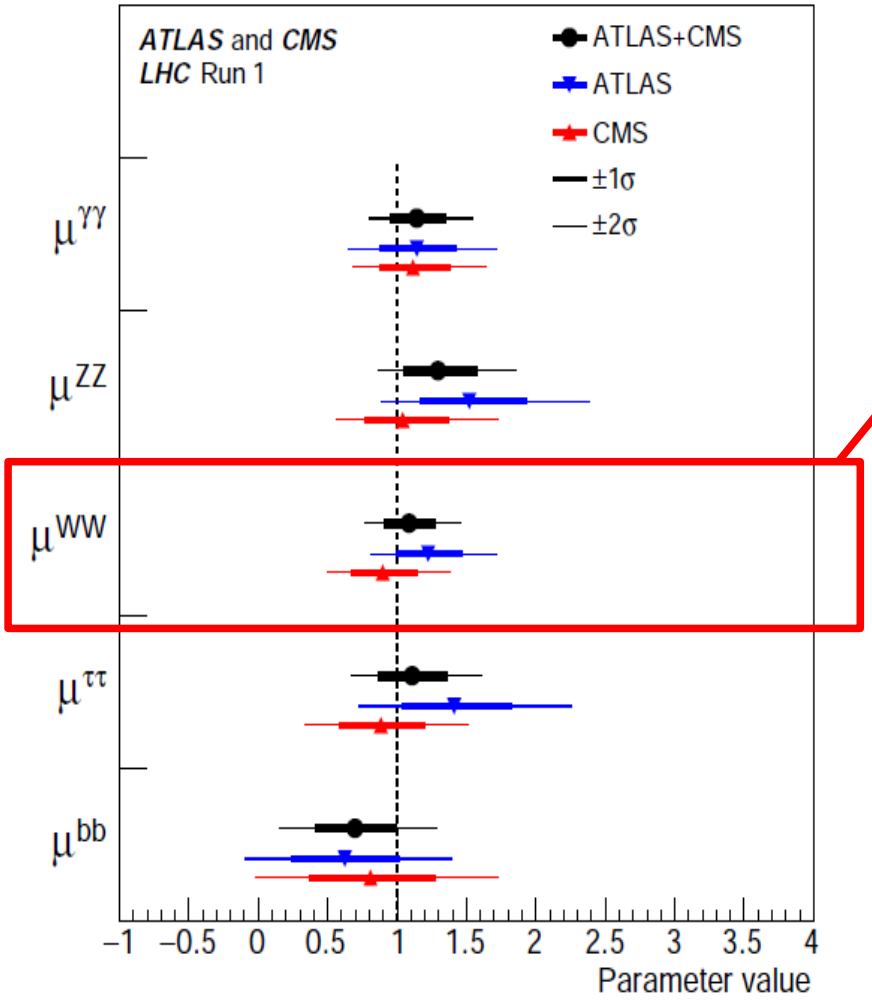


- **Split in categories with different jet multiplicity**
  - 0 jets, 1 jet, >= 2 jets, 2 jets with VBF topology
- Define **control regions** to measure the main **backgrounds directly using data**
  - Top → e.g. invert the b-veto requirement
  - WW → large m_{ll} and small m_T



Run 1 ATLAS and CMS combination

JHEP08(2016)045



ATLAS

$\mu = 1.22^{+0.23}_{-0.21}$

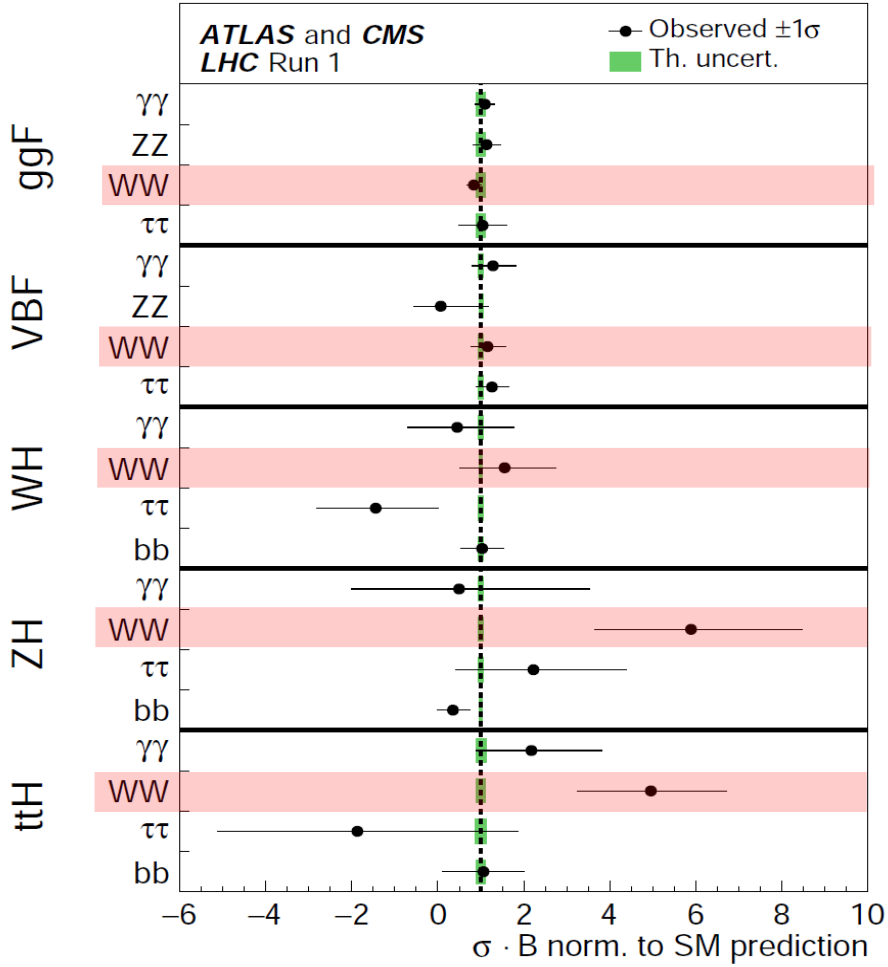
$\sigma = 6.8(5.8)$

CMS

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

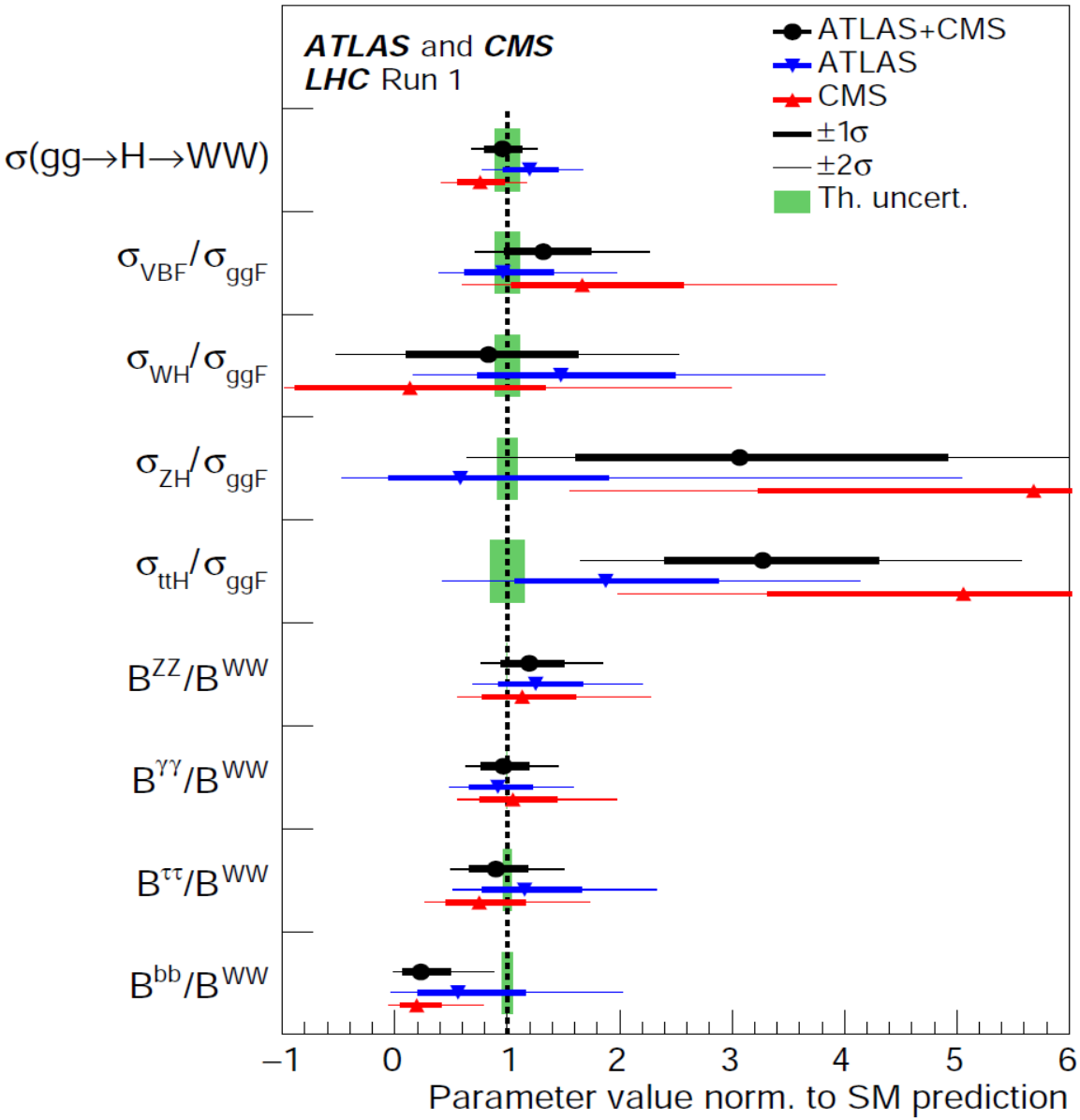
$\sigma = 4.8(5.6)$

$\mu = 1.09^{+0.18}_{-0.16}$



Most precise signal strength measurement comes from H→WW

Run 1 ATLAS and CMS combination



- Ratios of production cross sections and branching fractions.