CMS H(125) boson decays results

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on behalf of the CMS Collaboration

HH2021, Orsay (France)
20-22/09/2021

Overview

Higgs boson discovery was announced on the 4th of July 2012.

Since then, much effort has been put into determining its properties

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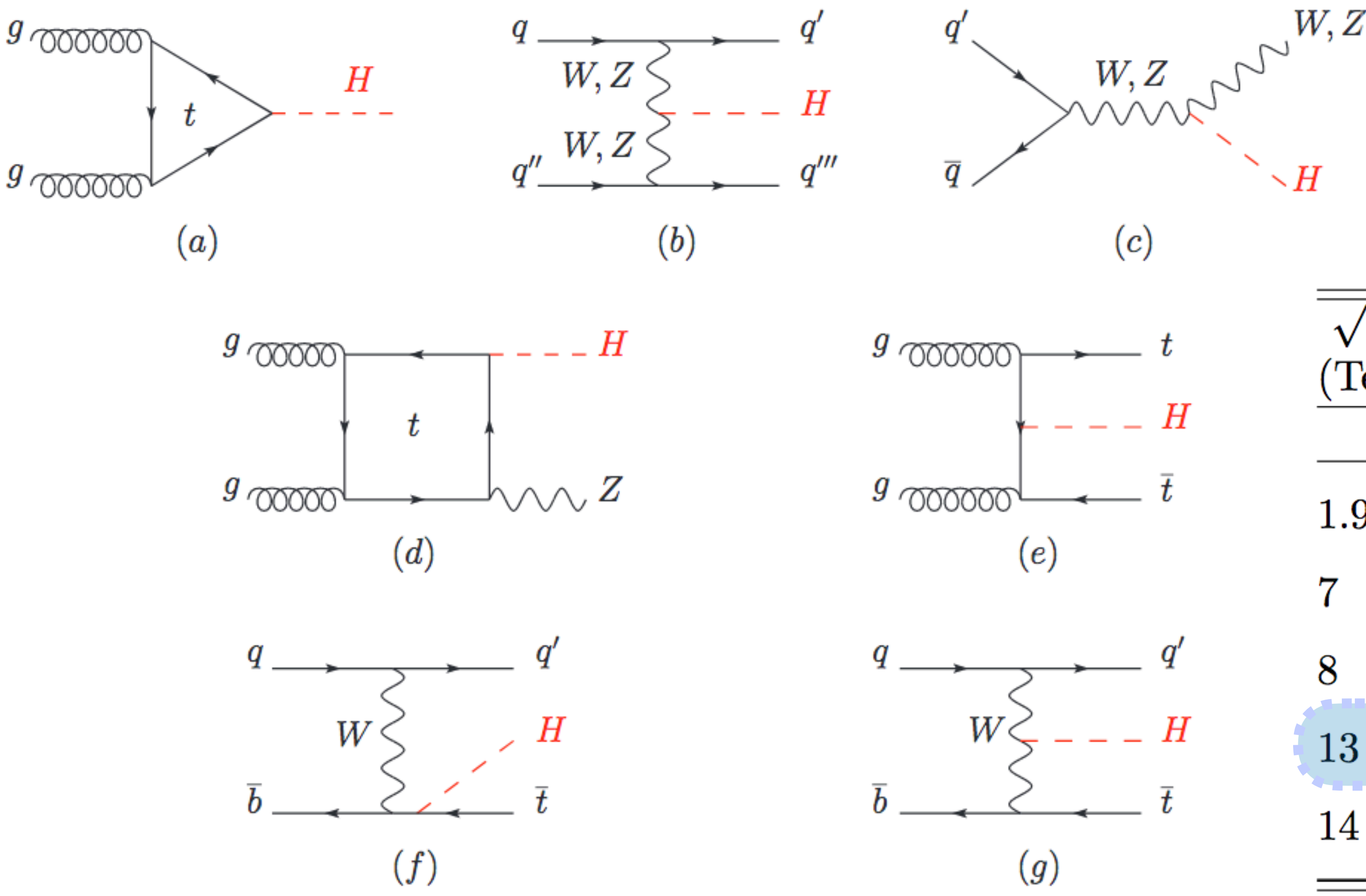

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125$ GeV					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+4.4\%}_{-7.0\%}$	$1.24^{+2.1\%}_{-2.1\%}$	$0.58^{+2.2\%}_{-2.3\%}$	$0.34^{+3.1\%}_{-3.0\%}$	$0.09^{+5.6\%}_{-10.2\%}$	19.1
8	$21.4^{+4.4\%}_{-6.9\%}$	$1.60^{+2.3\%}_{-2.1\%}$	$0.70^{+2.1\%}_{-2.2\%}$	$0.42^{+3.4\%}_{-2.9\%}$	$0.13^{+5.9\%}_{-10.1\%}$	24.2
13	$48.6^{+4.6\%}_{-6.7\%}$	$3.78^{+2.2\%}_{-2.2\%}$	$1.37^{+2.6\%}_{-2.6\%}$	$0.88^{+4.1\%}_{-3.5\%}$	$0.50^{+6.8\%}_{-9.9\%}$	55.1
14	$54.7^{+4.6\%}_{-6.7\%}$	$4.28^{+2.2\%}_{-2.2\%}$	$1.51^{+1.9\%}_{-2.0\%}$	$0.99^{+4.1\%}_{-3.7\%}$	$0.60^{+6.9\%}_{-9.8\%}$	62.1

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H_{BR} @ m_H = 125.09 GeV

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	$\pm 1.5\%$
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Discussed in the next slides

Istituto Nazionale di Fisica Nucleare

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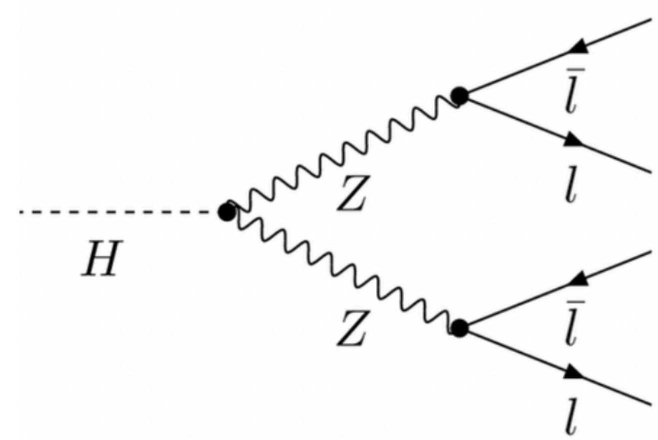
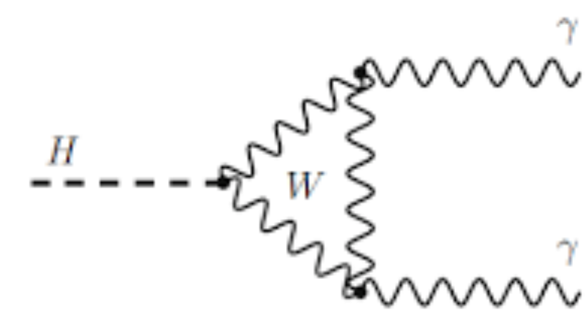
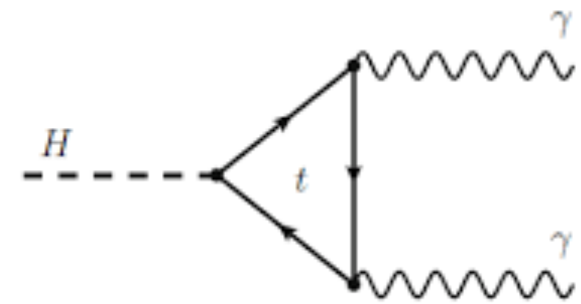
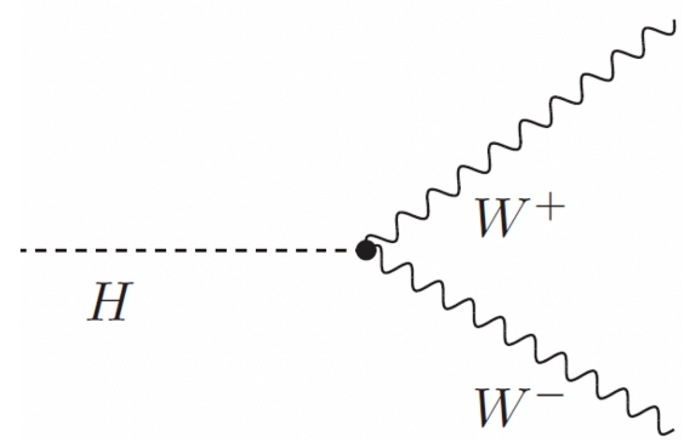


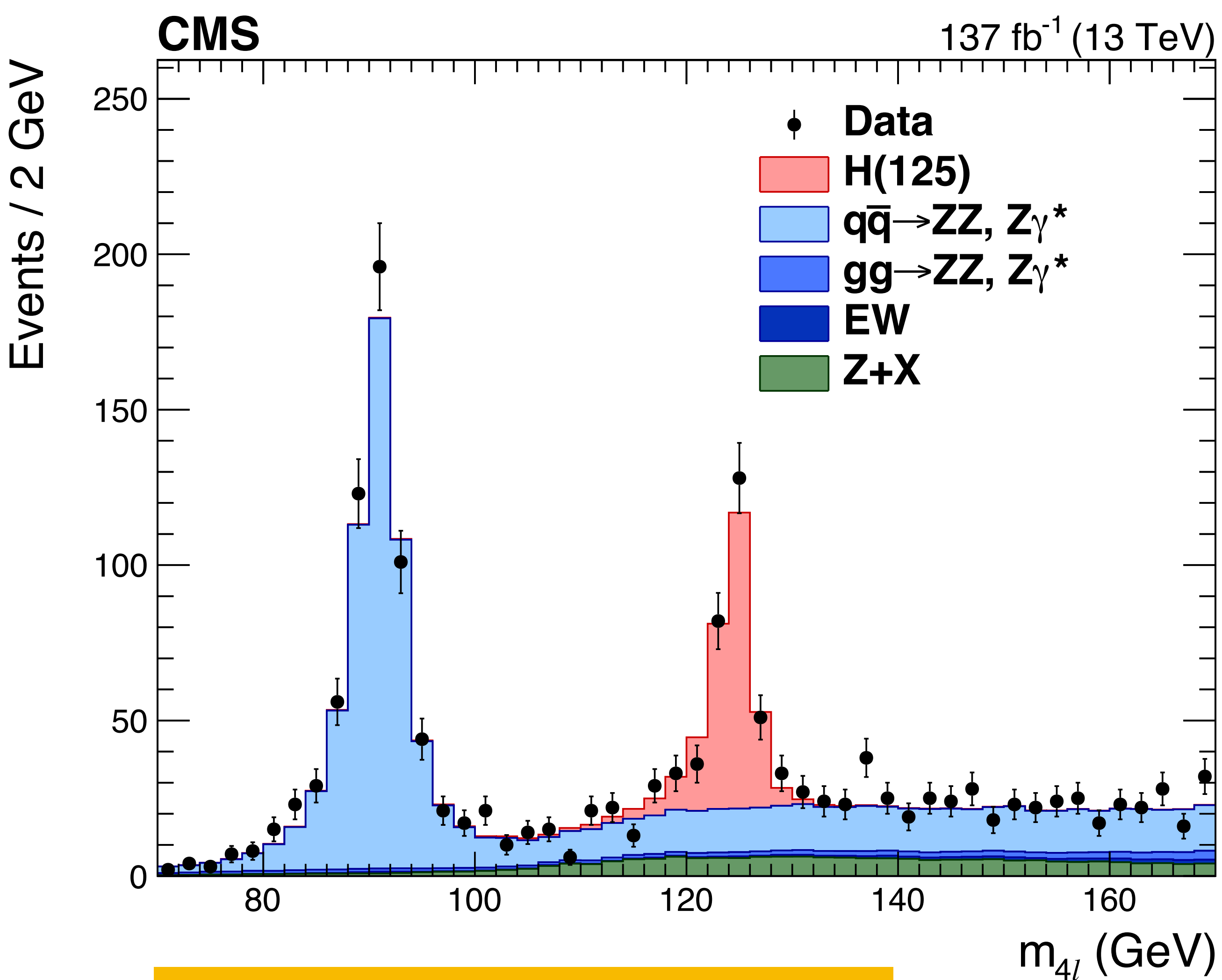






Higgs boson to ZZ→4ℓ

- clear signature
- large signal-to-background ratio due to the complete reconstruction of the final state decay products
- small branching fraction



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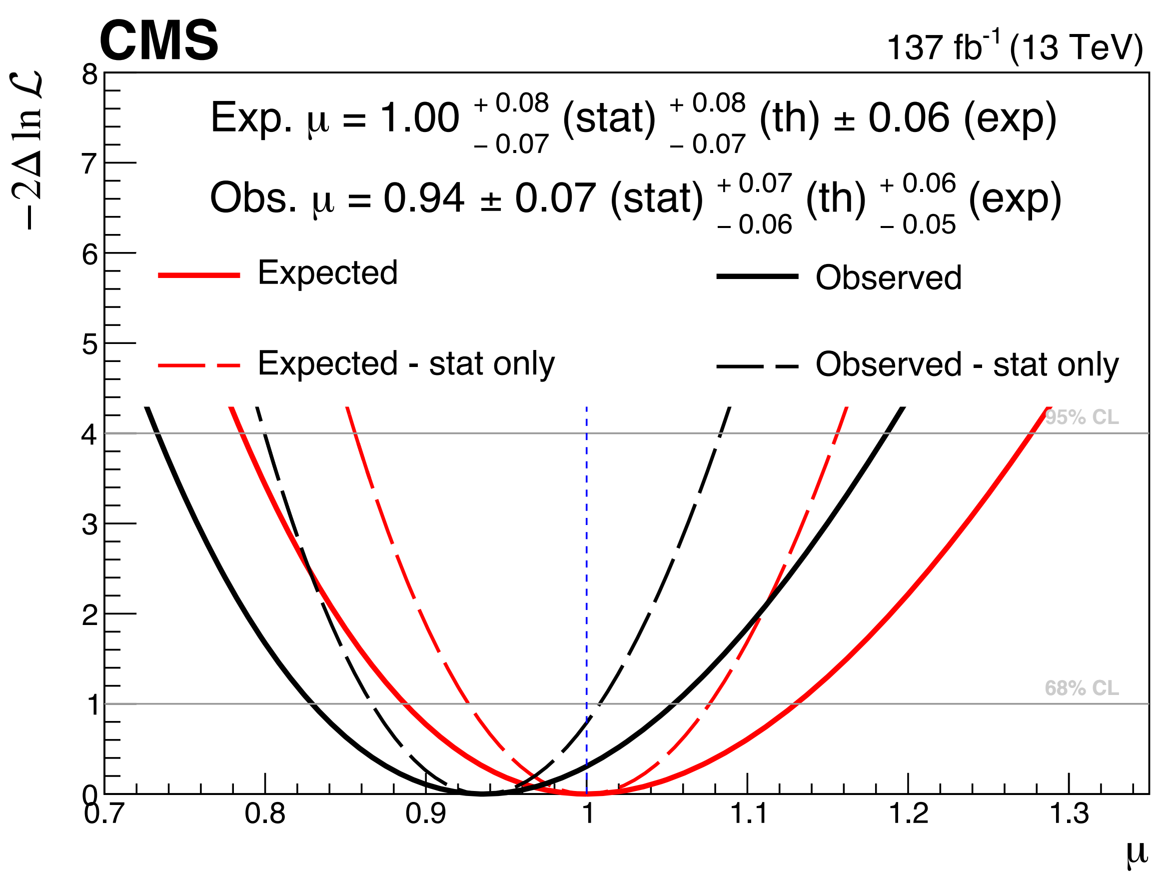
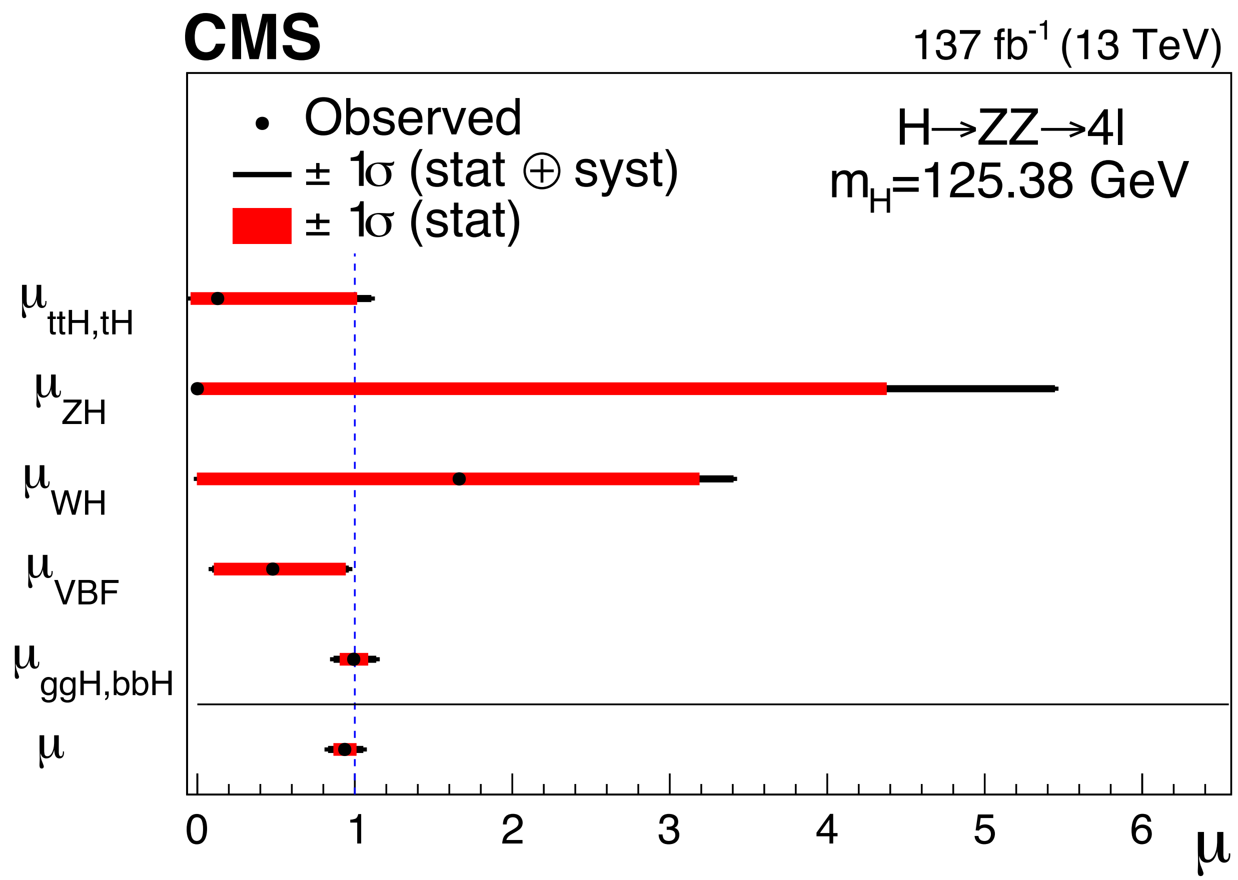
H_{BR} @ m_H = 125.09 GeV

- **Signal line shape**: double-sided Crystal Ball
- **ZZ* backgrounds**: estimated from MC simulation
- **Z+X contribution**: estimated from data

Higgs boson to ZZ→4ℓ





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Signal strength modifier (μ) is defined as the ratio between the measured signal cross section and the SM expectation.

Higgs boson to ZZ→4ℓ

STXS tries to maximise the sensitivity of the measurement, minimising the dependence on the theory predictions, defining several kinematic regions using generator level information.

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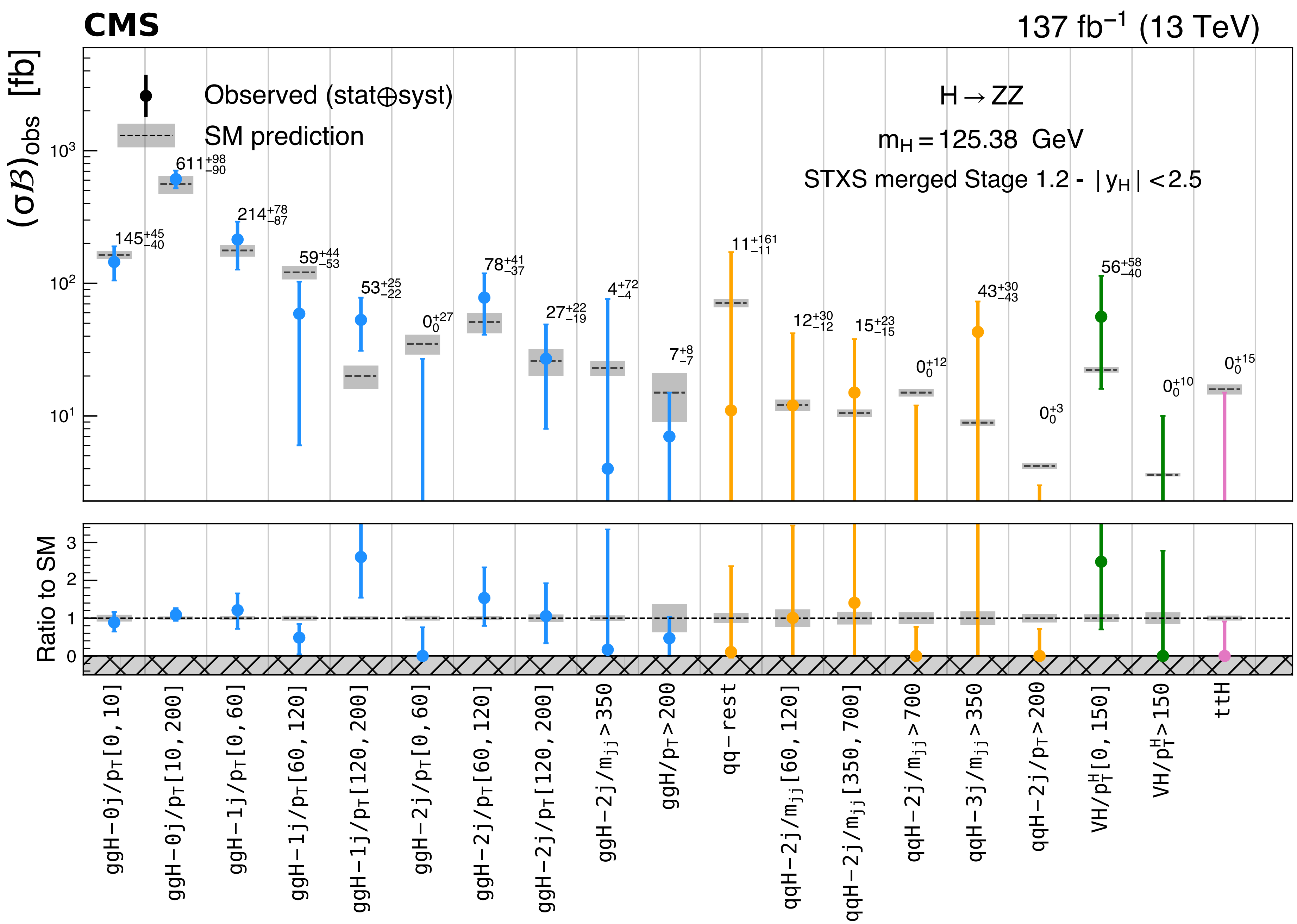

Cross section (σB)
H→ZZ decay
[stage 1.2]

Due to large stat. uncertainties, some bins are merged trying to keep the most possible granularity.

Higgs boson to ZZ→4ℓ

Fiducial cross section: cross section defined in a **fiducial phase space**. The idea is to **minimise the dependence on theoretical uncertainties**. The fiducial volume is defined imposing lepton kinematic cuts and isolation requirements.

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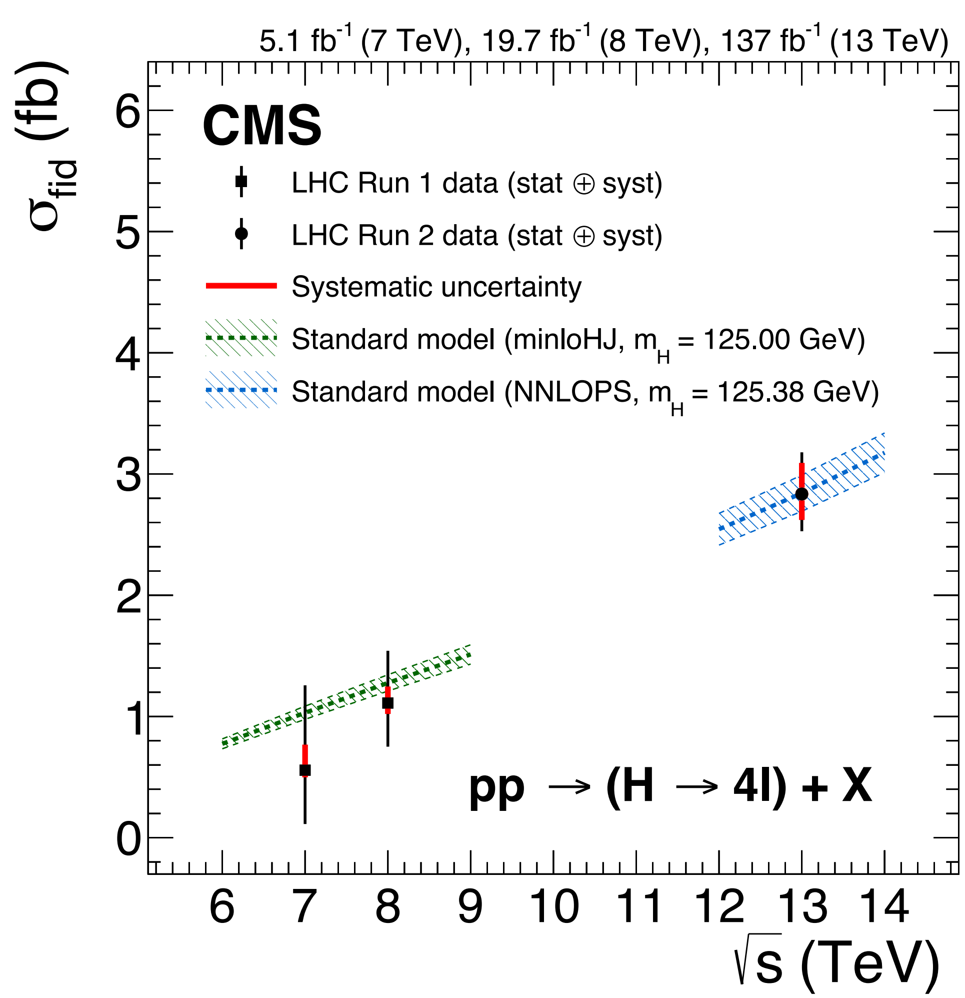
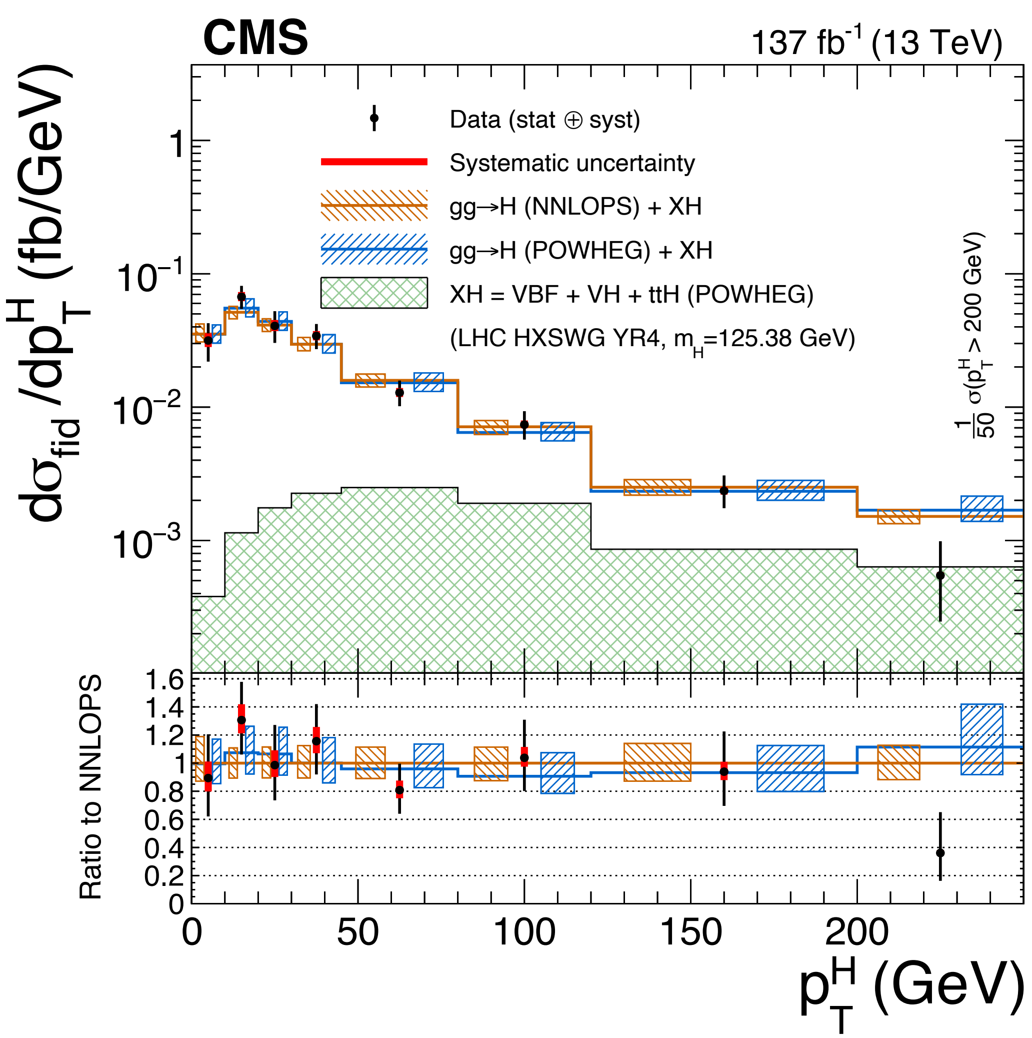
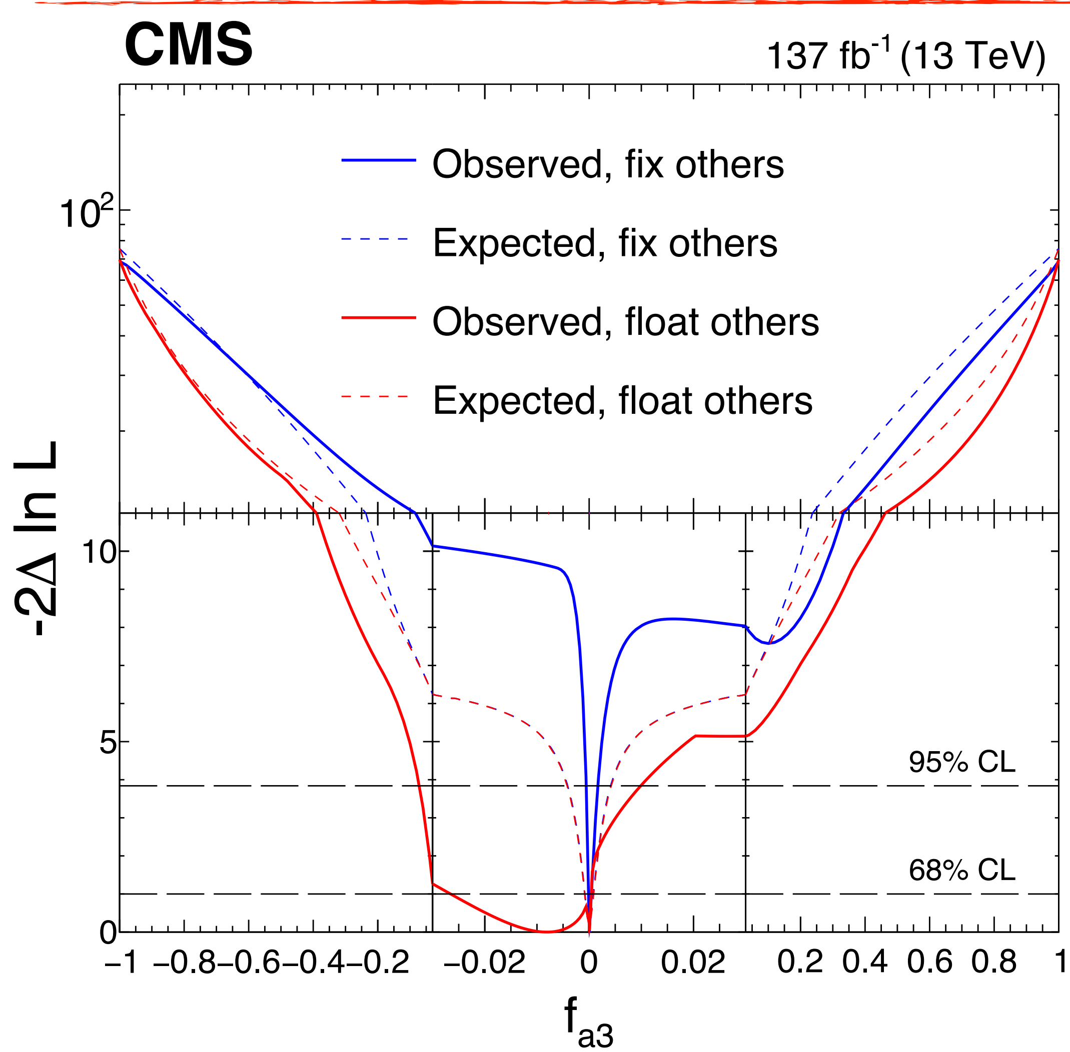


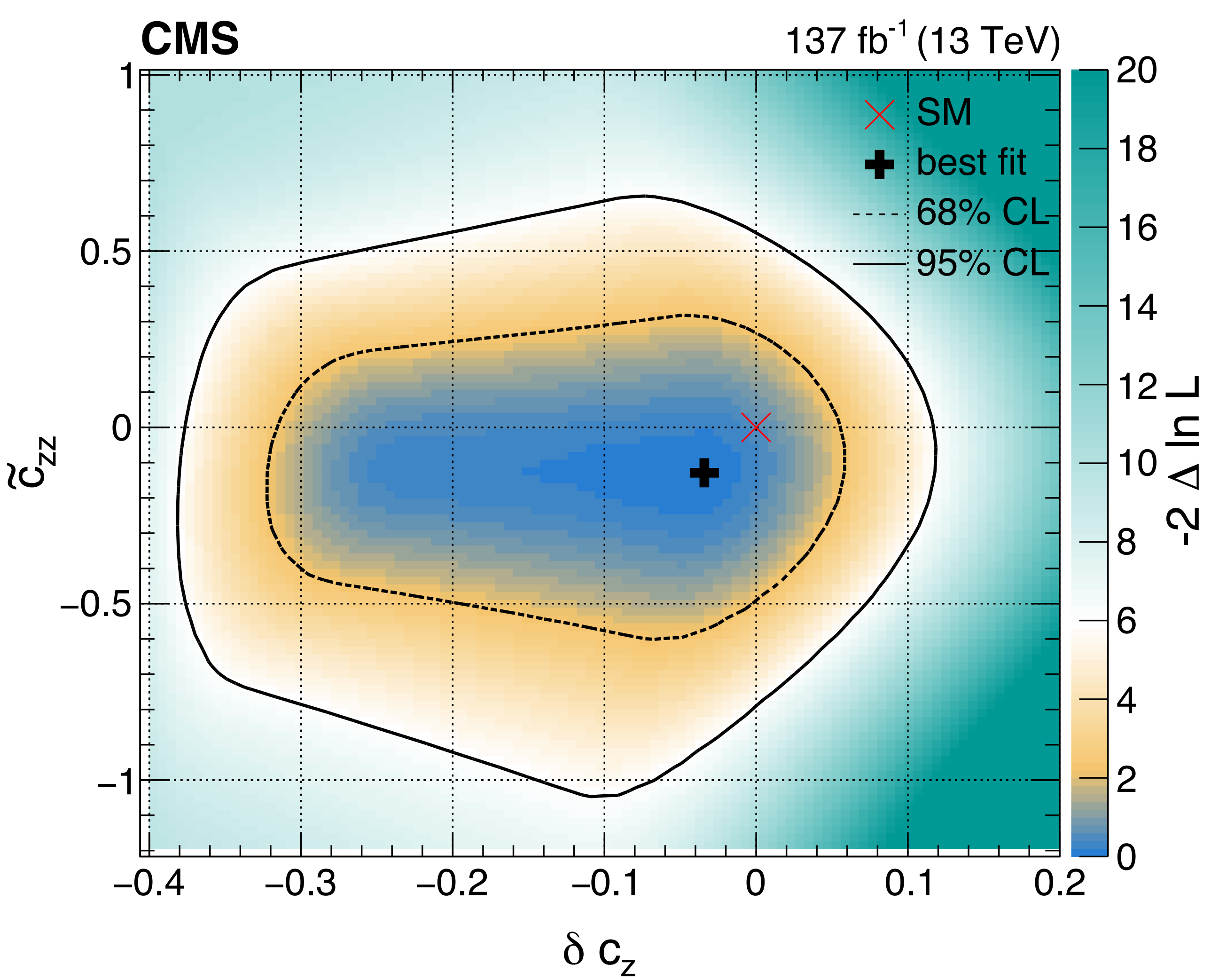


Higgs boson to ZZ→4ℓ

Not only SM measurements, but also search for CP violation and anomalous couplings

arXiv:2104.12152





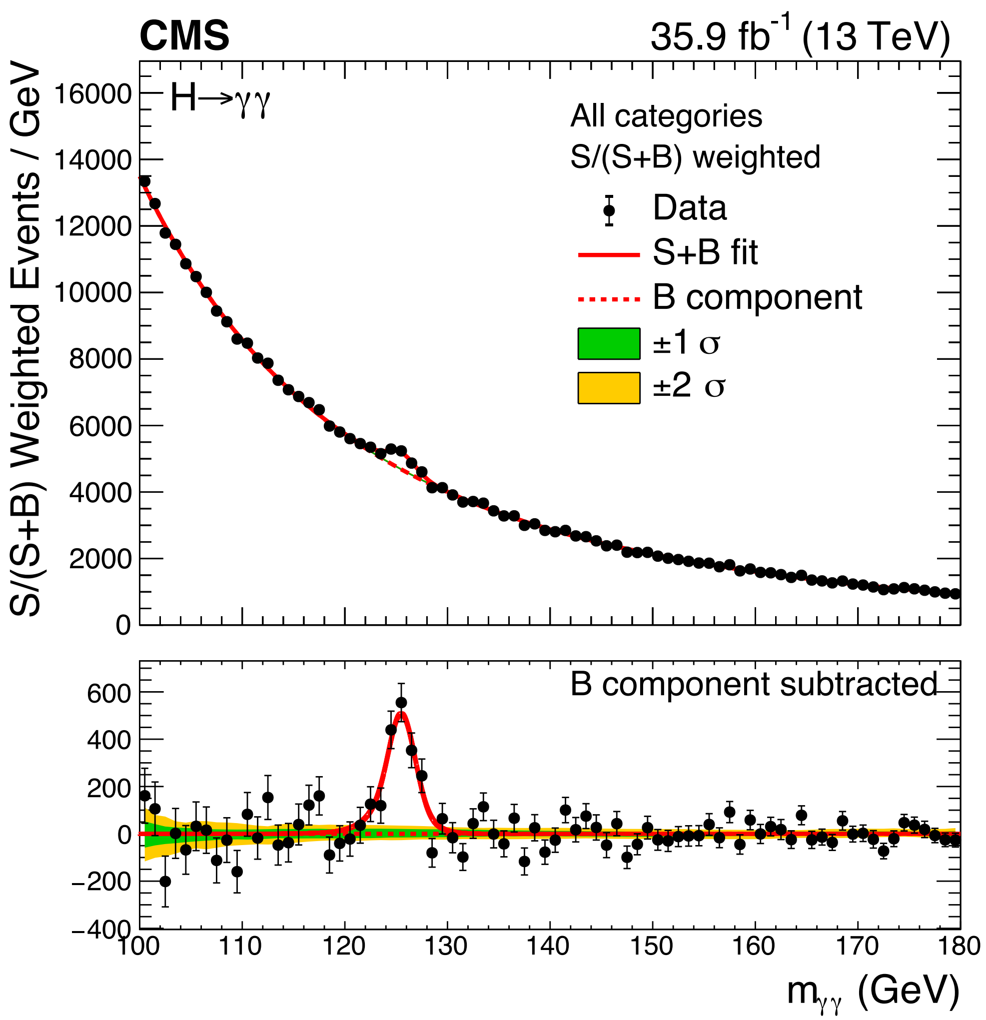
anomalous coupling framework

SMEFT formulation

Higgs boson to γγ

- clear signature
- high precision in reconstructing diphoton invariant mass
- small branching fraction (0.2% @ 125 GeV)

Phys. Lett. B 805 (2020) 135425



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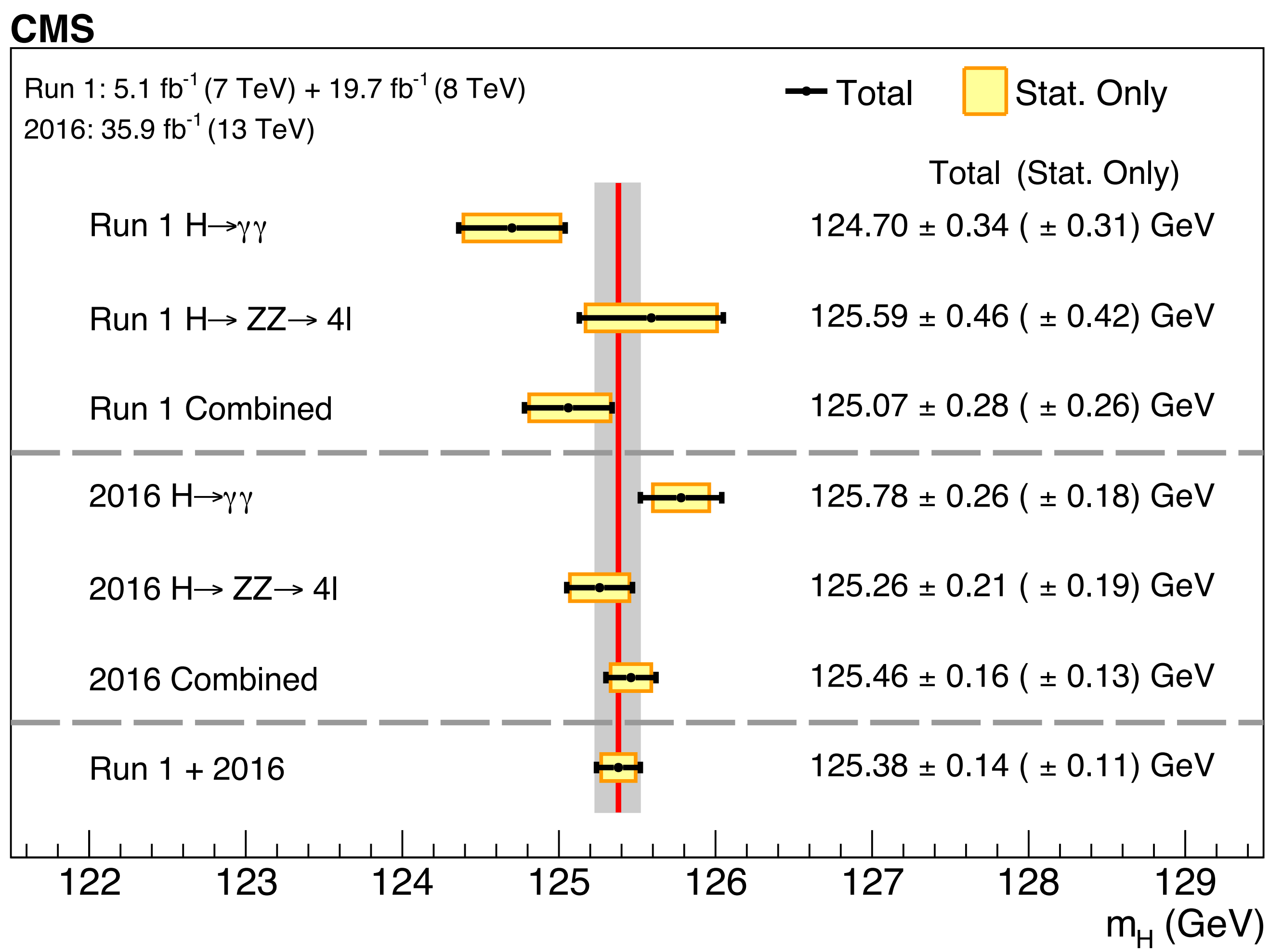


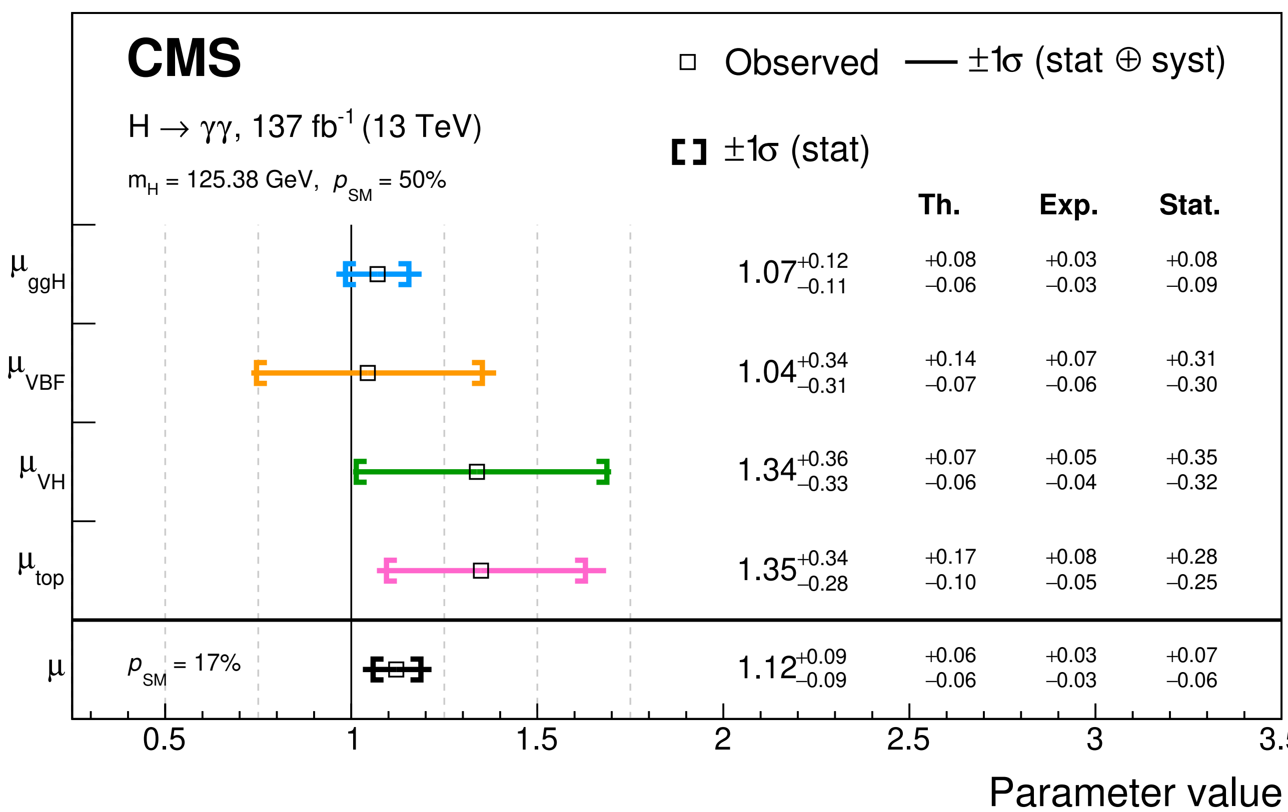
Best Higgs boson mass result up to now:

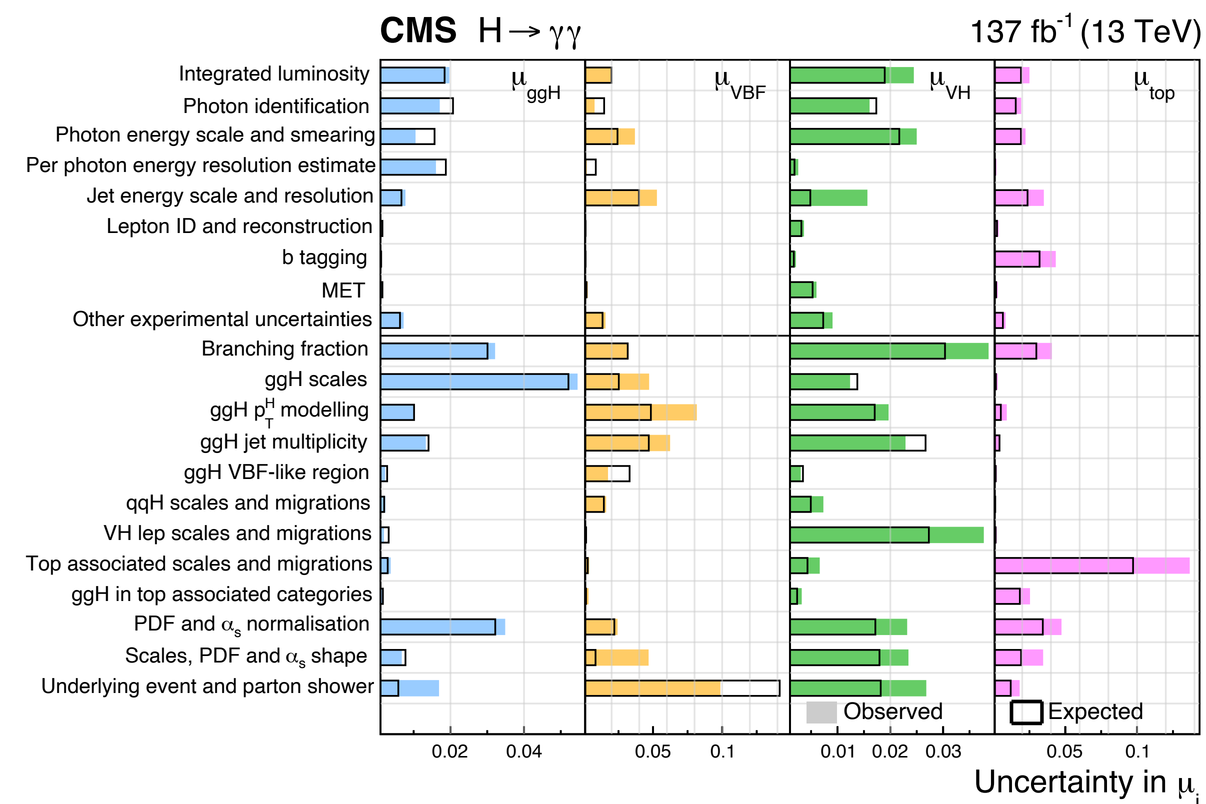
$$125.38 \pm 0.14\ GeV$$

Higgs boson to γγ

Inclusive signal strength modifier (μ)

$$\mu = 1.12^{+0.09}_{-0.09} = 1.12^{+0.06}_{-0.06}(theo)^{+0.03}_{-0.03}(syst)^{+0.07}_{-0.06}(stat)$$



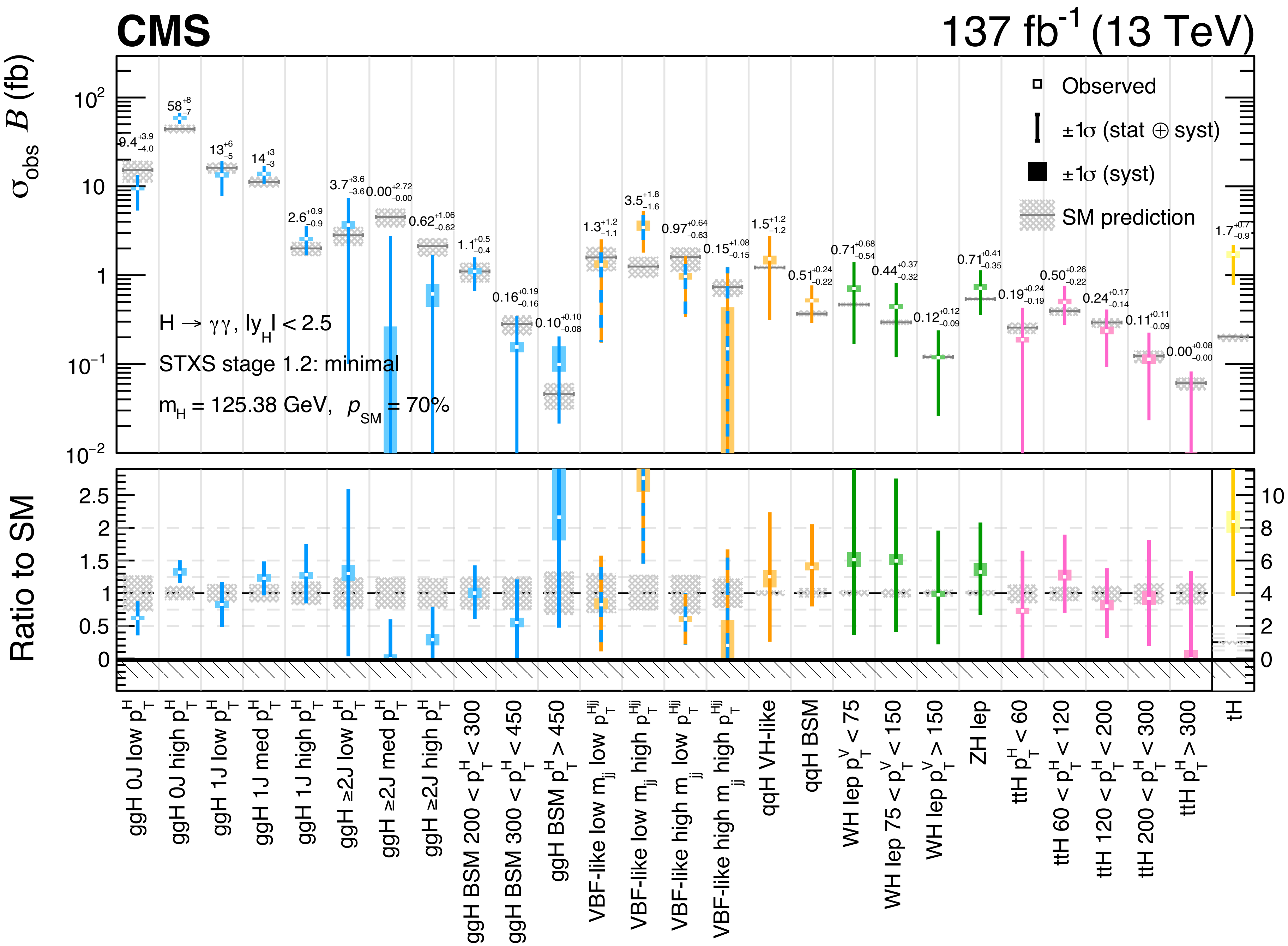


JHEP 07 (2021) 027

Higgs boson to γγ

Several different machine learning algorithms are used for rejection and classification purposes

JHEP 07 (2021) 027



Cross section for H→γγ [stage 1.2 STXS]

Higgs boson to WW→2ℓ 2ν

- second dominating branching ratio (21.4% @ 125 GeV)
- The neutrino in the leptonic decay prevents the full reconstruction of the Higgs boson mass.

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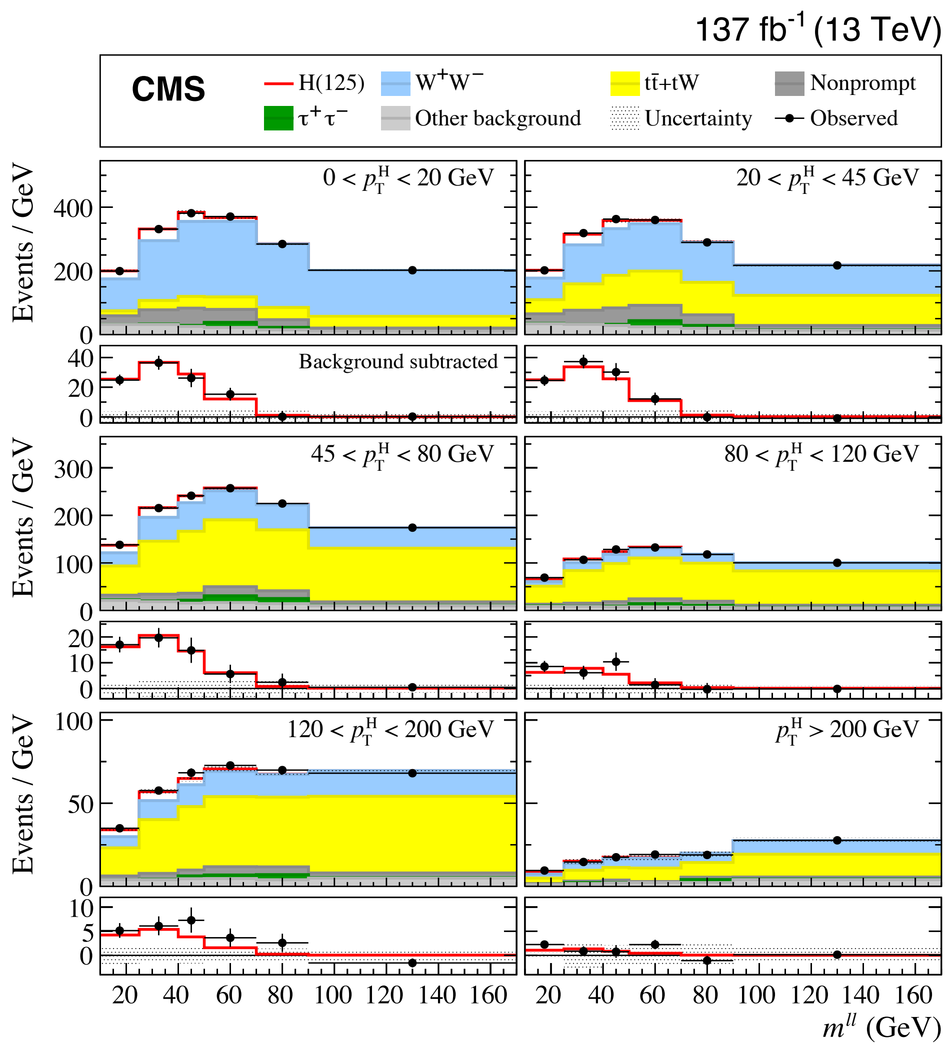
H_{BR} @ m_H = 125.09 GeV

JHEP 03 (2021) 003

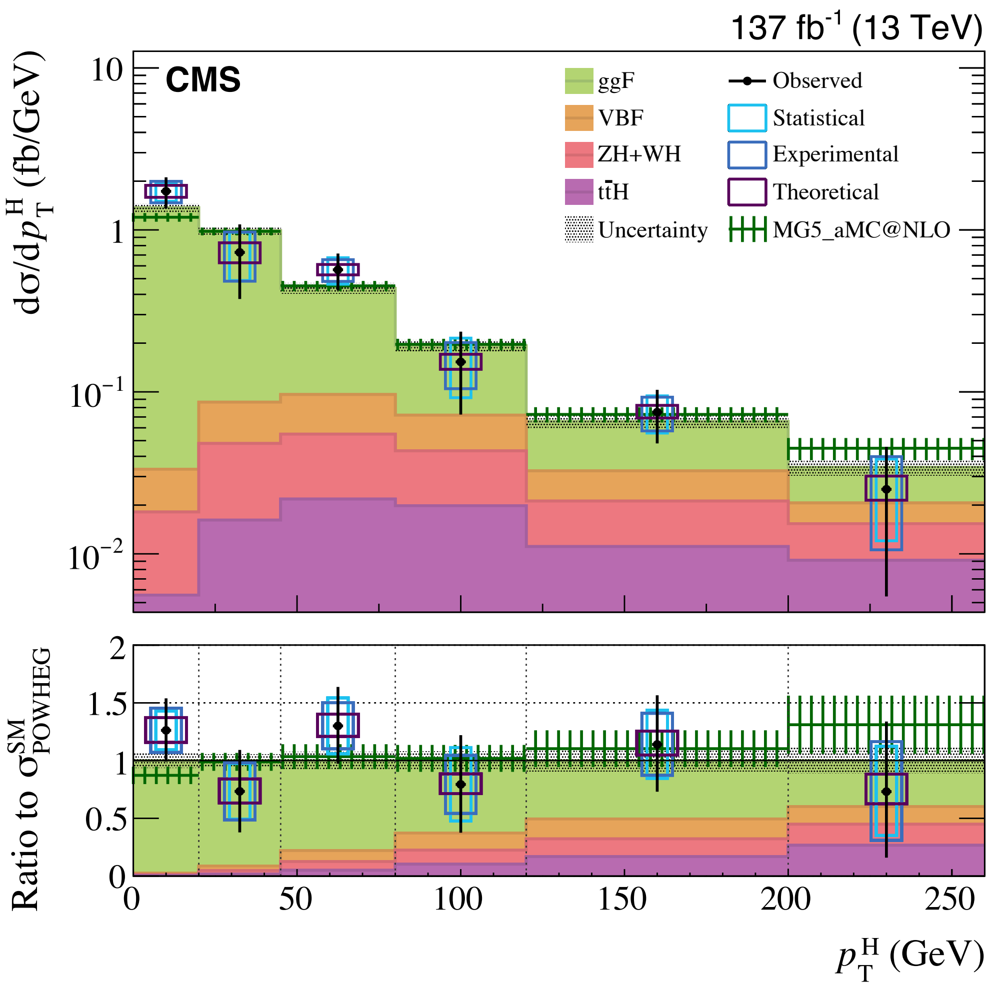


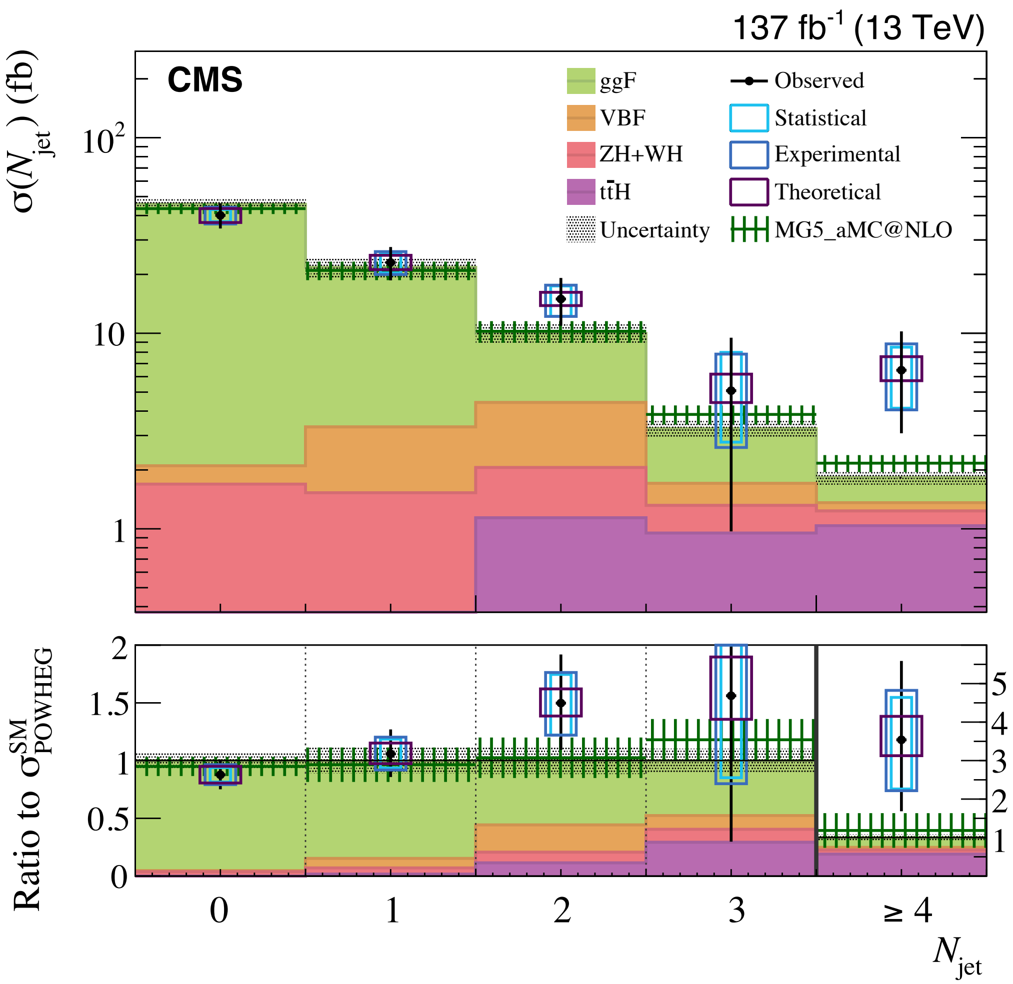
- **Bkg from prompt leptons**: estimated from MC simulation
- **Bkg from nonprompt**: estimated from data

Higgs boson to WW→2ℓ 2ν

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

Fiducial volume definition





JHEP 03 (2021) 003

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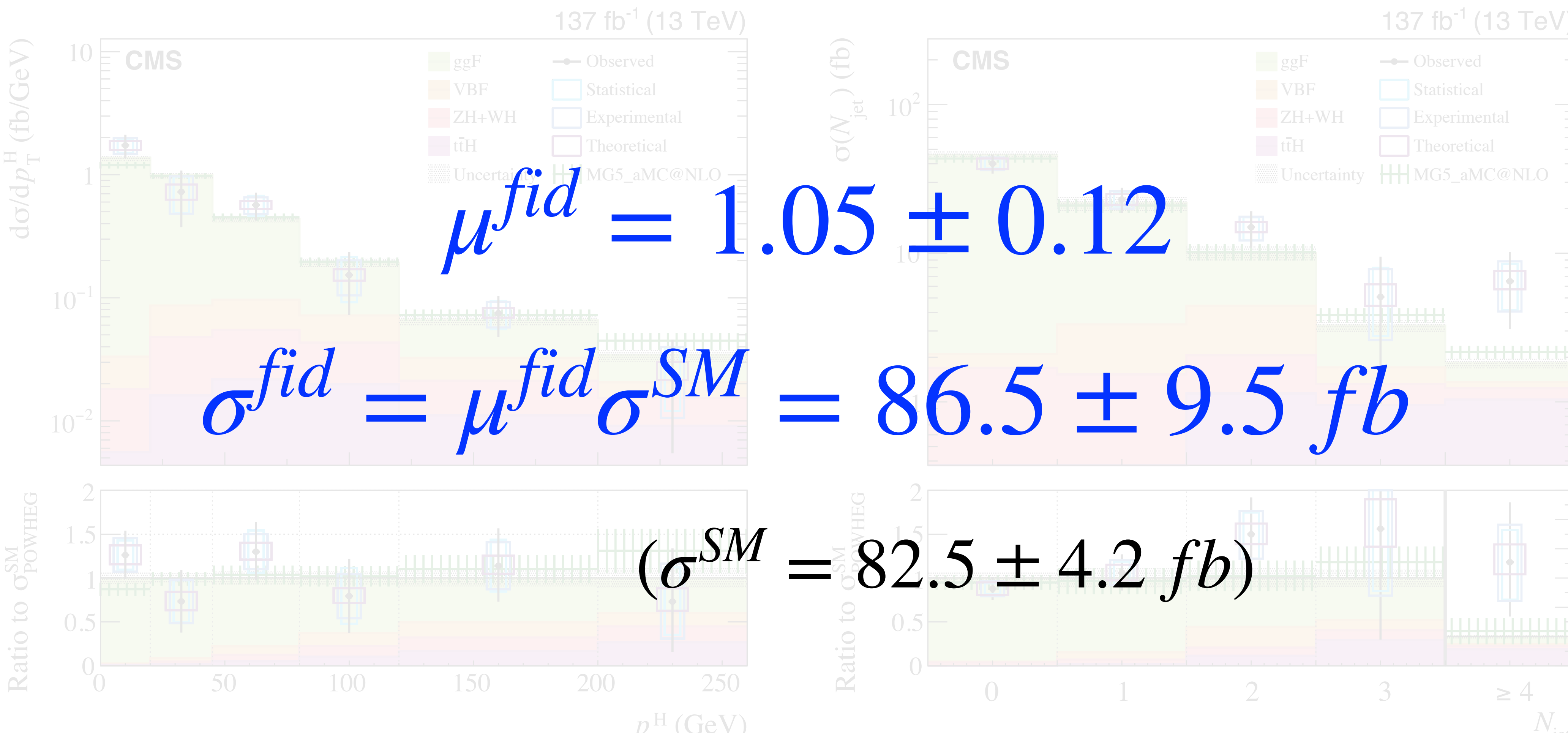


$$\mu^{fid} = 1.05 \pm 0.12$$

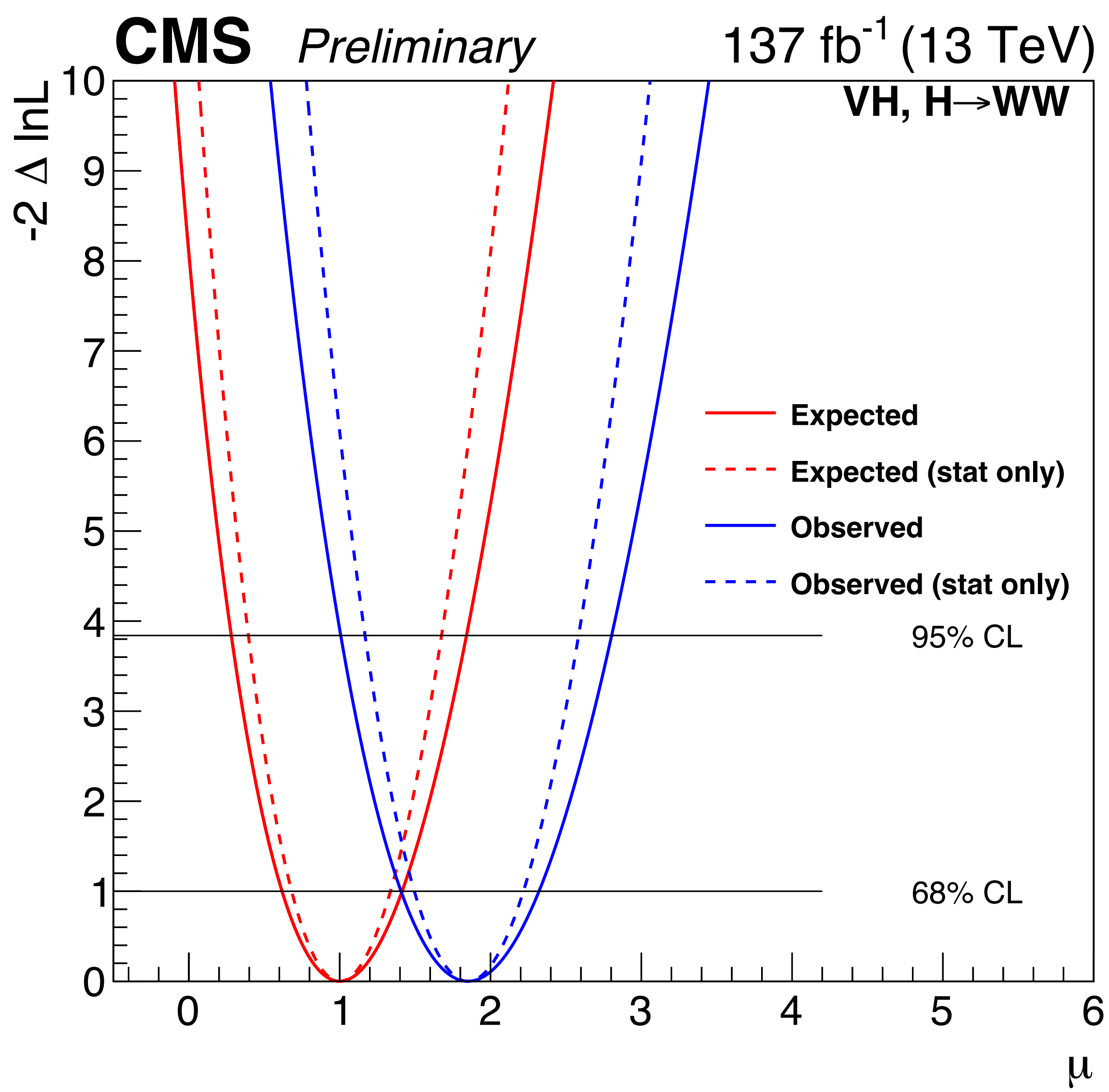
$$\sigma^{fid} = \mu^{fid}\sigma^{SM} = 86.5 \pm 9.5\ fb$$

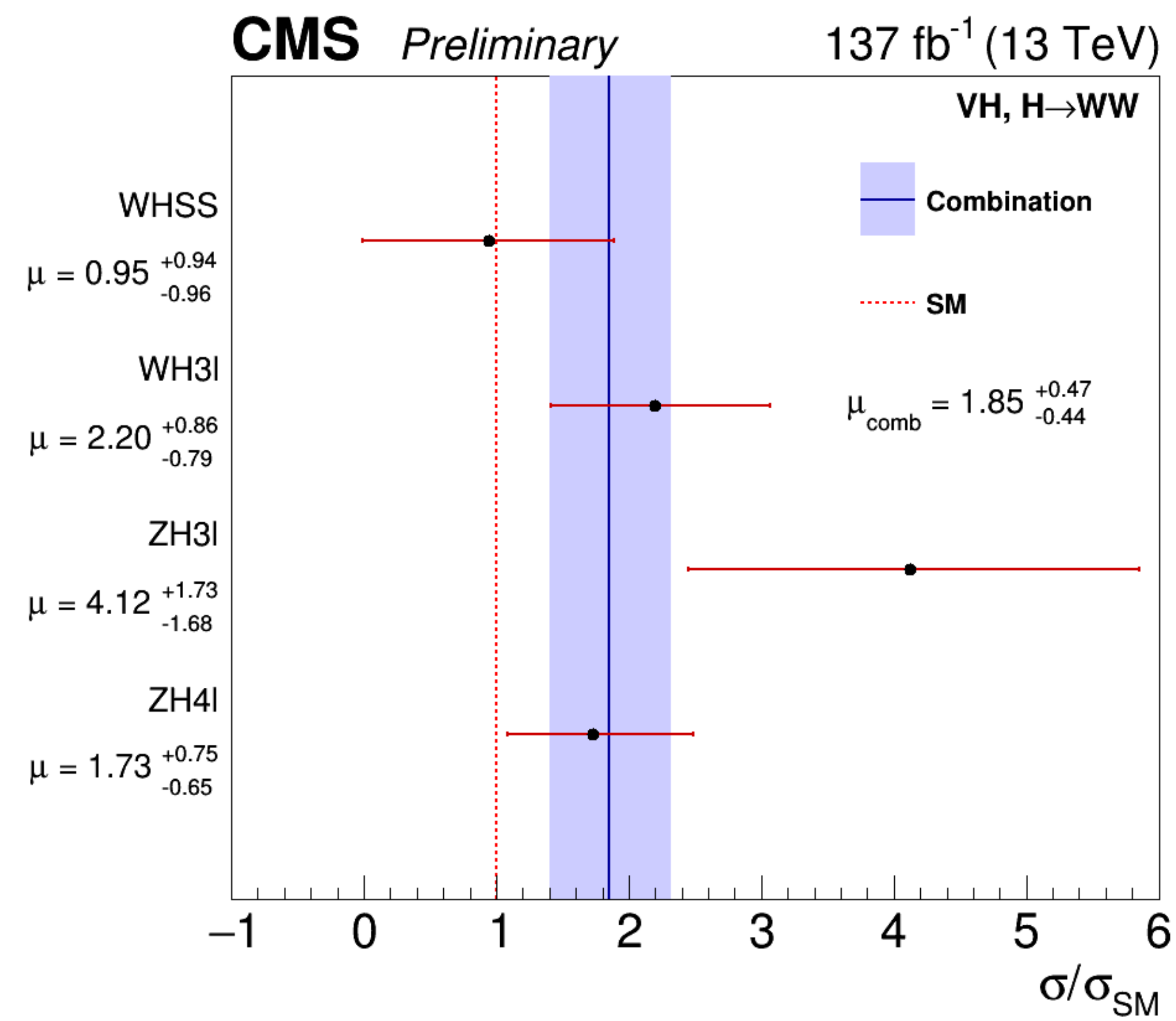
$$(\sigma^{SM} = 82.5 \pm 4.2\ fb)$$

Higgs boson to WW→2ℓ 2ν

Built a dedicated analysis targeting VH production mode

CMS-PAS-HIG-19-017





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

Summary

Boson decays results of the Higgs boson have been presented.

- VV (V = W or Z) and γγ decay channels have been considered.
- CMS sets best result up to now in Higgs boson mass measurement: mass $m_H = 125.38 \pm 0.14$ GeV
- Latest CMS results:
  - ✤ STXS using full Run II data in HZZ and in Hγγ
  - ✤ fiducial (differential) cross section using full Run II data in HZZ and in HWW
  - ✤ anomalous coupling and EFT searches using HZZ
  - ✤ signal strength for HZZ, Hγγ and in HWW (VH targeted analysis) channels
- No deviations from SM expectations have been observed.

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STAY TUNED… RUN 3 IS COMING!

Thanks for the attention

To further discuss about the content of this presentation, please contact me at **filippo.errico@cern.ch**

Backup

Higgs boson to ZZ→4ℓ

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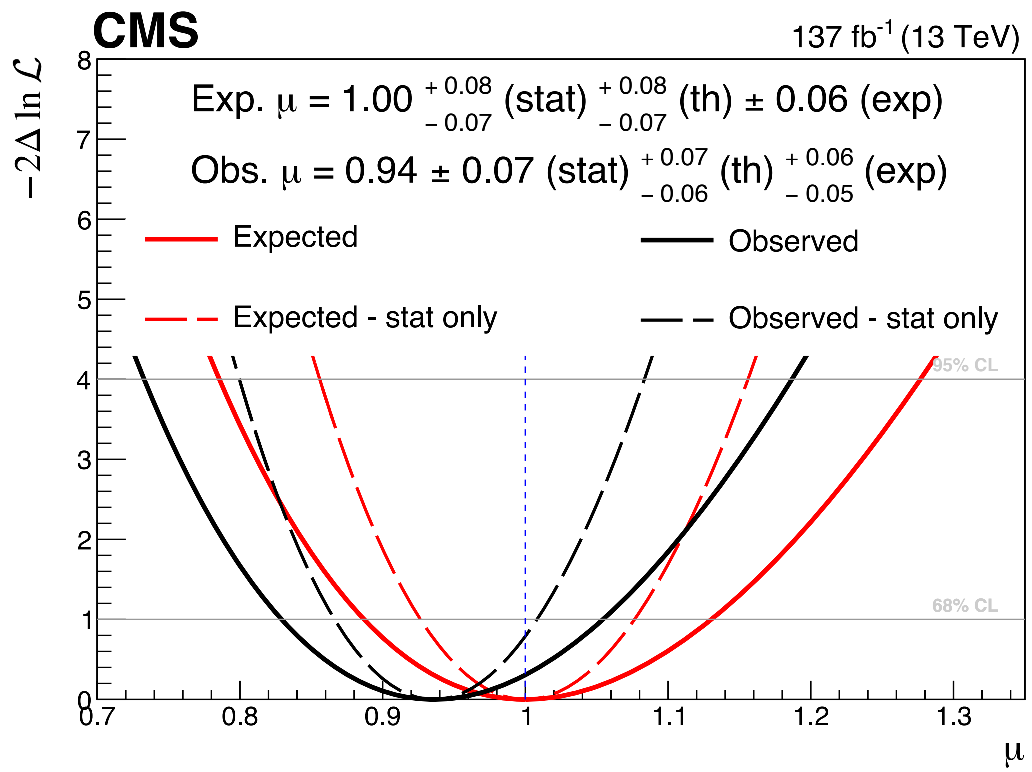
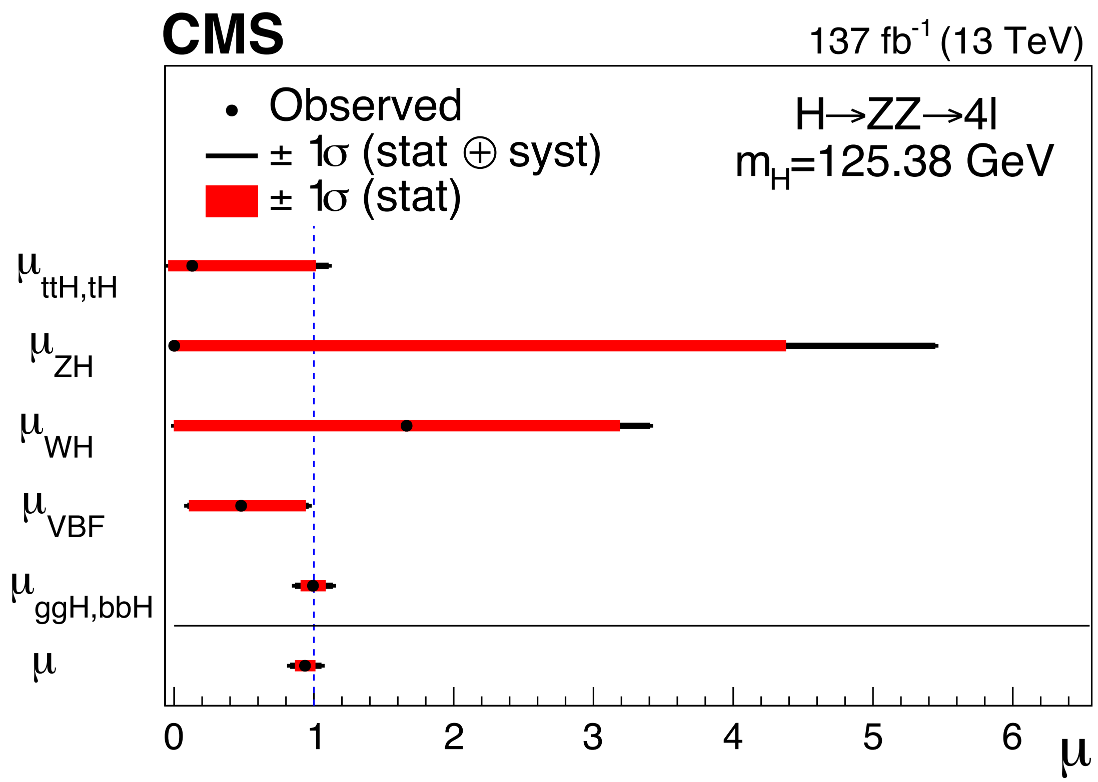




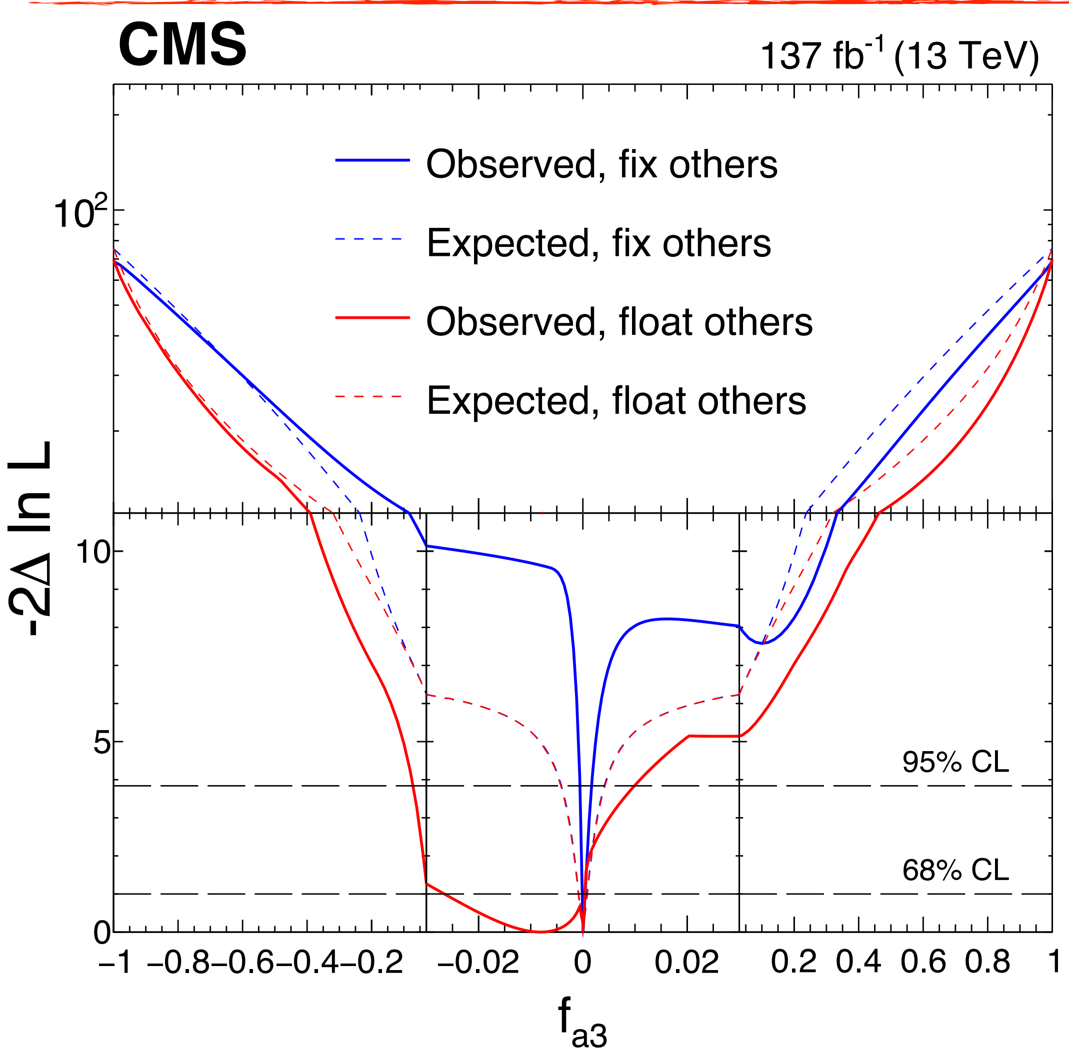
	Expected	Observed
$\mu_{t\bar{t}H,tH}$	$1.00^{+1.23}_{-0.77}$ (stat)$^{+0.51}_{-0.06}$ (syst)	$0.17^{+0.88}_{-0.17}$ (stat)$^{+0.42}_{-0.00}$ (syst)
μ_{WH}	$1.00^{+1.83}_{-1.00}$ (stat)$^{+0.75}_{-0.00}$ (syst)	$1.66^{+1.52}_{-1.66}$ (stat)$^{+0.85}_{-0.00}$ (syst)
μ_{ZH}	$1.00^{+4.79}_{-1.00}$ (stat)$^{+6.76}_{-0.00}$ (syst)	$0.00^{+4.38}_{-0.00}$ (stat)$^{+3.24}_{-0.00}$ (syst)
μ_{VBF}	$1.00^{+0.53}_{-0.44}$ (stat)$^{+0.18}_{-0.12}$ (syst)	$0.48^{+0.46}_{-0.37}$ (stat)$^{+0.14}_{-0.10}$ (syst)
$\mu_{ggH,b\bar{b}H}$	1.00 ± 0.10 (stat)$^{+0.12}_{-0.10}$ (syst)	0.99 ± 0.09 (stat)$^{+0.11}_{-0.09}$ (syst)
μ	$1.00^{+0.08}_{-0.07}$ (stat)$^{+0.10}_{-0.08}$ (syst)	0.94 ± 0.07 (stat)$^{+0.09}_{-0.08}$ (syst)

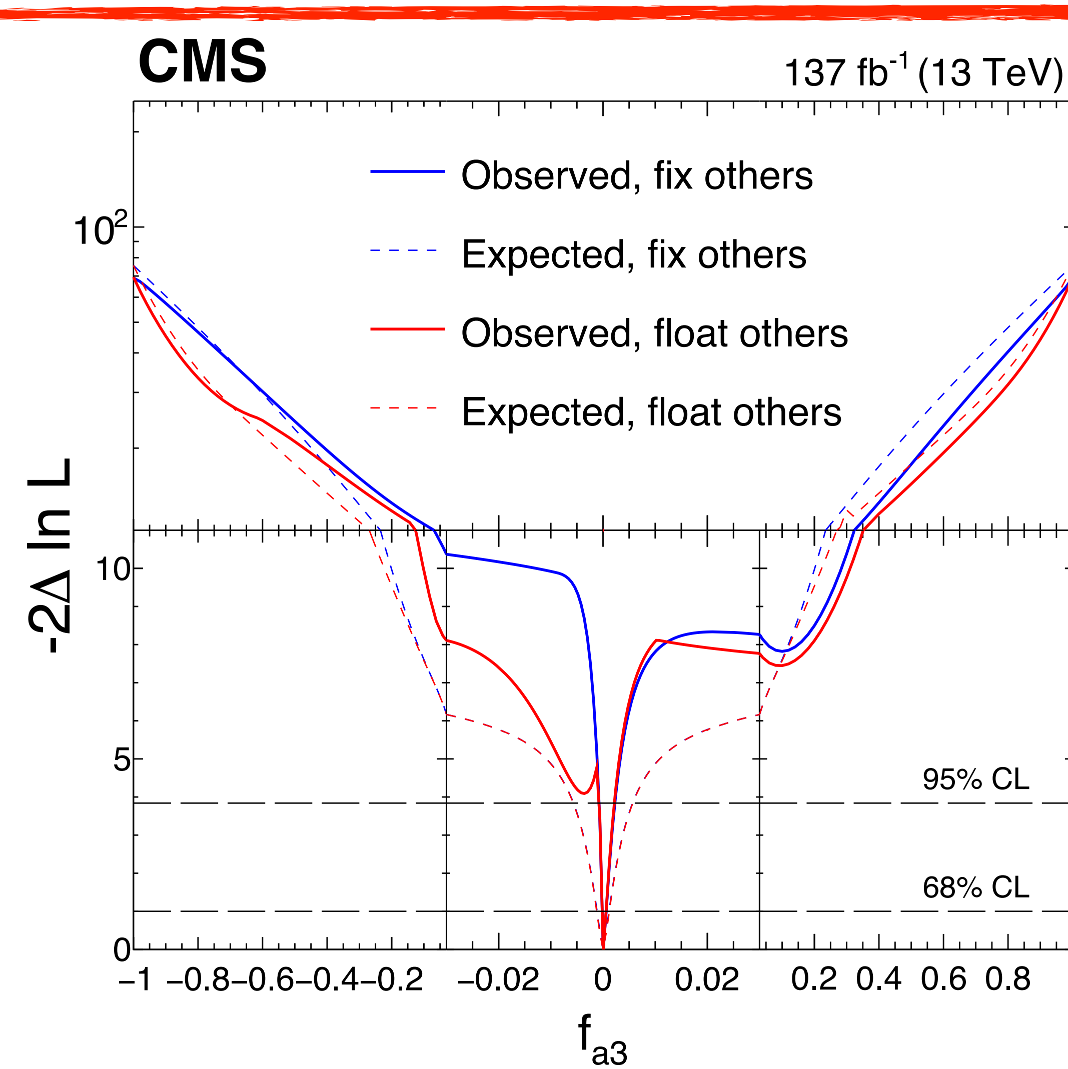
Signal strength modifier (μ) is defined as the ratio between the measured signal cross section and the SM expectation.

Higgs boson to ZZ→4ℓ

Not only SM measurements, but also search for CP violation and anomalous couplings

arXiv:2104.12152





CP-sensitive parameter in the:

anomalous coupling framework

SMEFT formulation

Higgs boson to ZZ→4ℓ

arXiv:2104.12152

Not only SM measurements, but also search for CP violation and anomalous couplings

$$a_1^{WW} = a_1^{ZZ} + \frac{\Delta m_W}{m_W},$$

$$a_2^{WW} = c_w^2 a_2^{ZZ} + s_w^2 a_2^{\gamma\gamma} + 2 s_w c_w a_2^{Z\gamma},$$

$$a_3^{WW} = c_w^2 a_3^{ZZ} + s_w^2 a_3^{\gamma\gamma} + 2 s_w c_w a_3^{Z\gamma},$$

$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) = \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{a_2^{\gamma\gamma} - a_2^{ZZ}}{m_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{a_2^{Z\gamma}}{m_Z^2},$$

$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) = 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{a_2^{\gamma\gamma} - a_2^{ZZ}}{m_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{a_2^{Z\gamma}}{m_Z^2},$$

anomalous coupling framework

SMEFT formulation

$$\delta c_z = \frac{1}{2} a_1 - 1,$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{4\pi\alpha} \frac{\kappa_1}{(\Lambda_1)^2},$$

$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2,$$

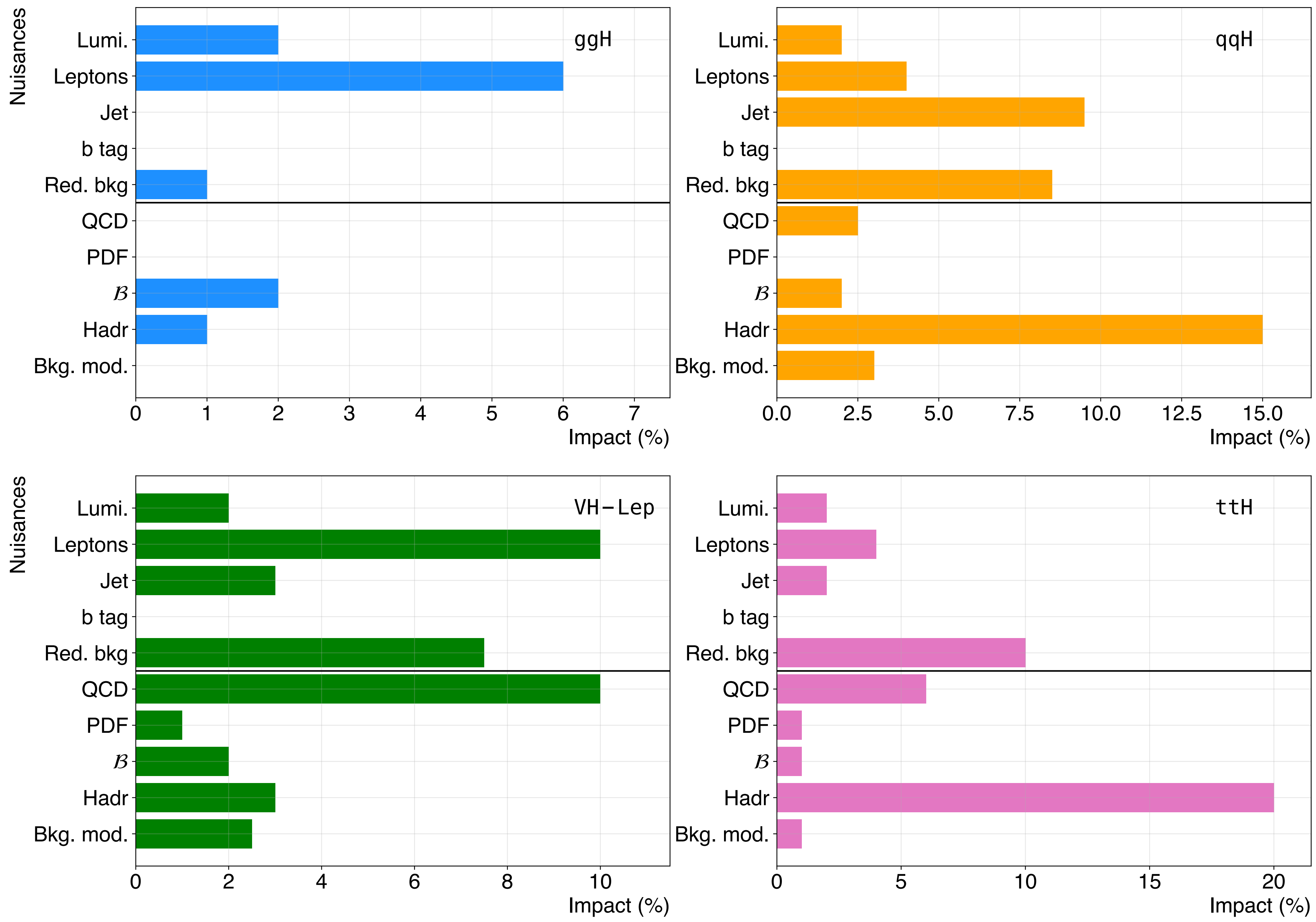
$$\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3.$$

$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg},$$

$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$

Higgs boson to ZZ→4ℓ

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



Higgs boson to ZZ→4ℓ

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

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Next-to-leading lepton p_T	$p_T > 10\,\text{GeV}$
Additional electrons (muons) p_T	$p_T > 7(5)\,\text{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\text{GeV}$

Higgs boson to γγ

Phys. Lett. B 805 (2020) 135425

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Higgs boson to WW→2ℓ

Built a dedicated analysis targeting VH production mode

	WHSS	WH3l	ZH3l	ZH4l
Number of leptons with $p_T > 10$ GeV	2	3	3	4
Number of jets with $p_T > 30$ GeV	≥ 1	0	≥ 1	—

Type	Source	Impact (%)
Theoretical	Renormalization and factorization scale	3
	Parton distribution function	2
	Parton shower, underlying event	2
Experimental	Nonprompt	9
	Sample size of simulation data	8
	Electron	3
	b tag	3
	Jet	2
	Luminosity	2
	WZ normalization	2
	$Z\gamma$ normalization	2
	ZZ normalization	1
	Muon	1

CMS-PAS-HIG-19-017

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

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

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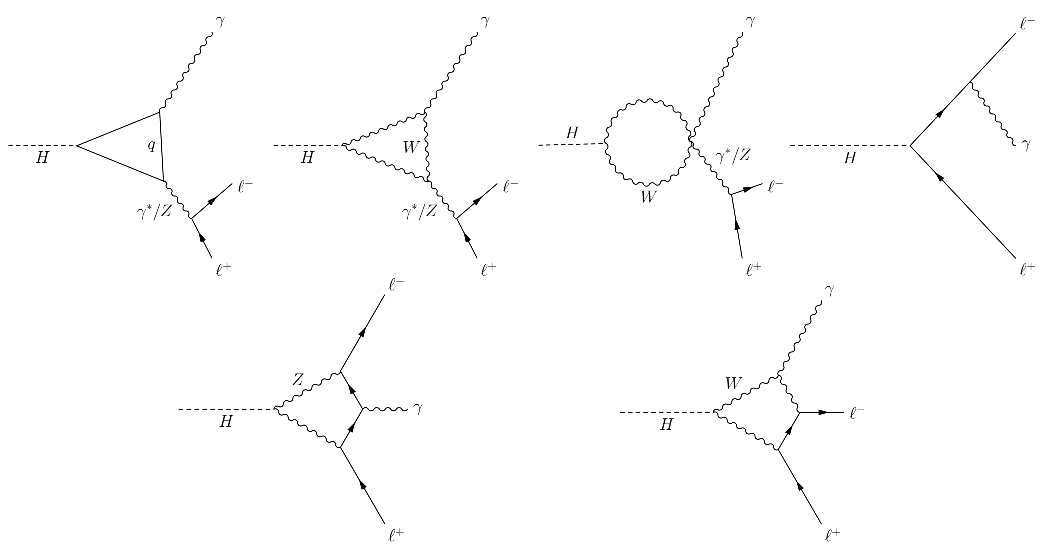
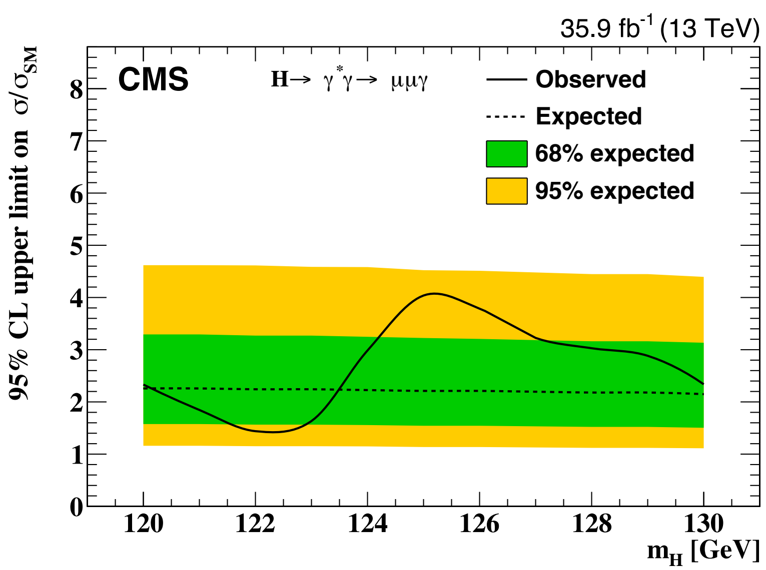
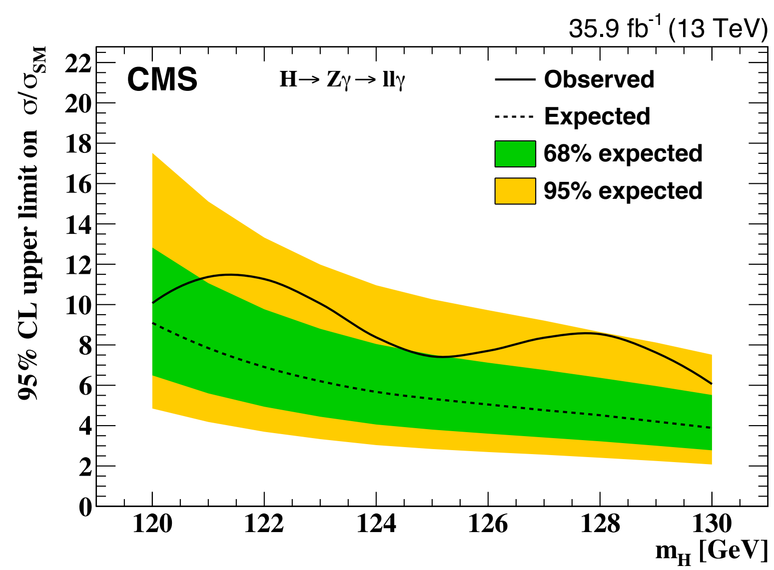
H —> Zγ

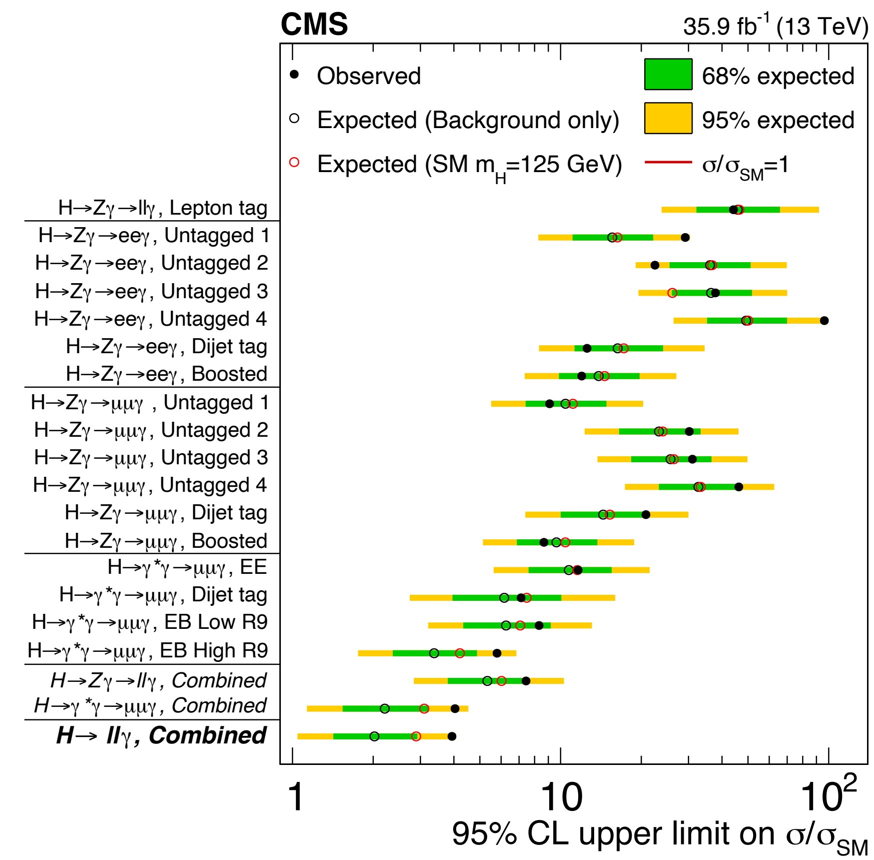
2016



Dominant Feynman diagrams contributing to the H—> ℓℓγ process







Combination:
Exp (obs) limits: 2.0 (3.9) times the SM XS at 125 GeV @ 95% C.L.

pValue Exp(obs) = 0.02 (0.16) corresponding to ~2σ (~1σ)

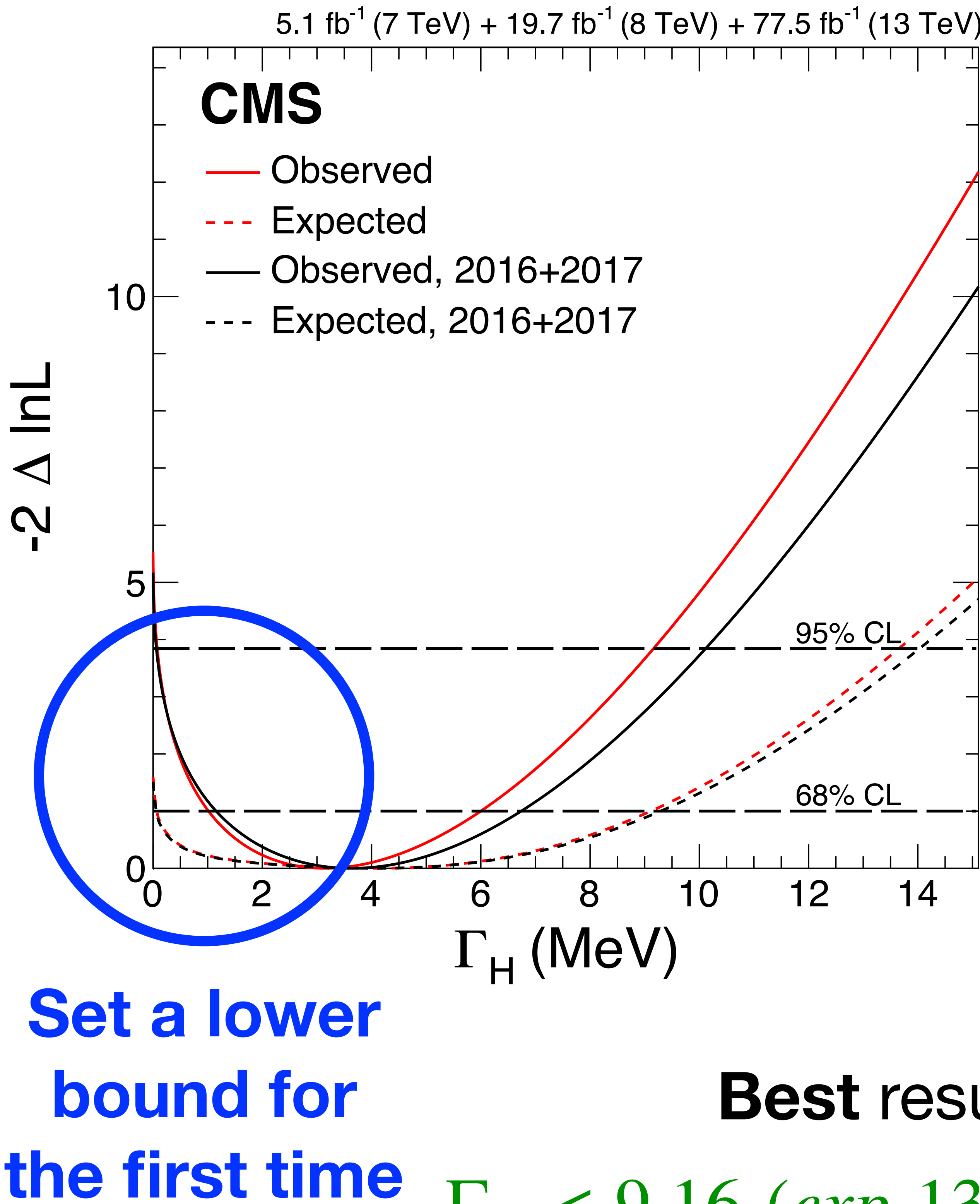
H—>γ*γ—> μμγ

Exp (obs) limits: 2.1 - 2.3 (1.4 - 4.0) times the SM XS

H—>Zγ—> ℓℓγ

Exp (obs) limits: 3.9 - 9.1 (6.1 - 11.4) times the SM XS

Higgs boson decay to ZZ



Phys. Rev. D 99, 112003 (2019)

Difficulties in directly measuring the width (4.07 MeV) due to detector resolution.

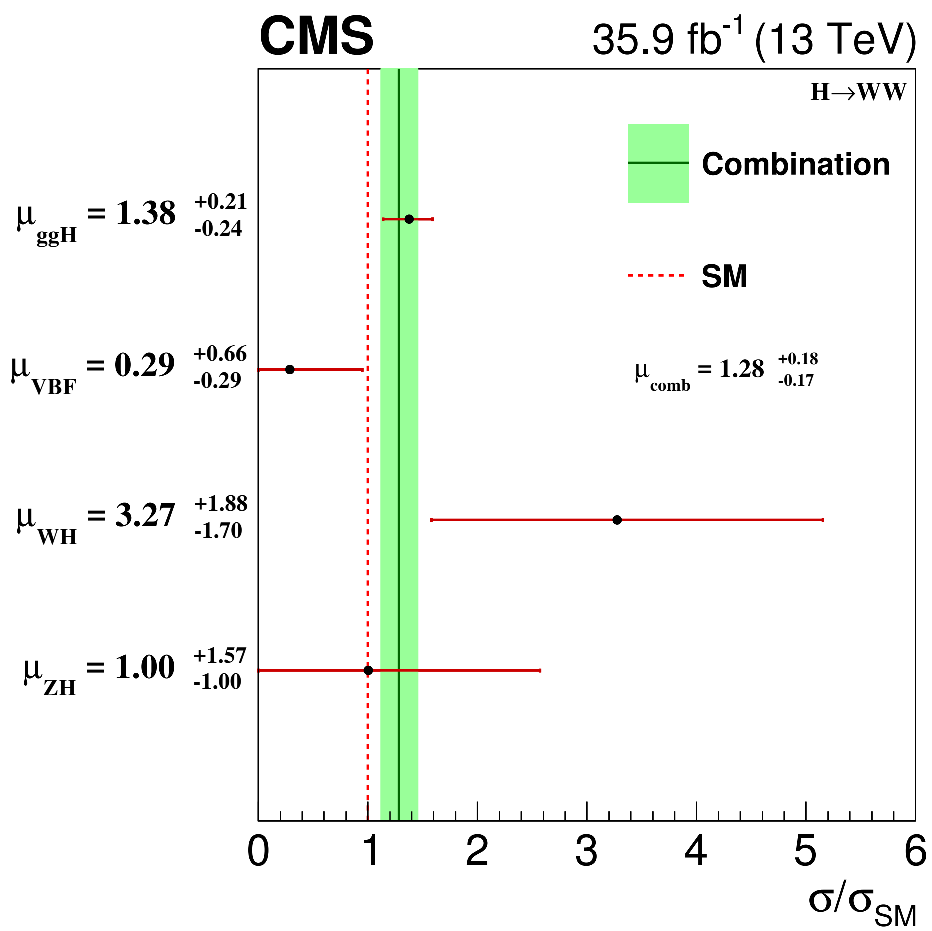
Measured in the H to 4ℓ channel, combining 2016-2017 data with RunI, comparing on-shell and off-shell production:

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

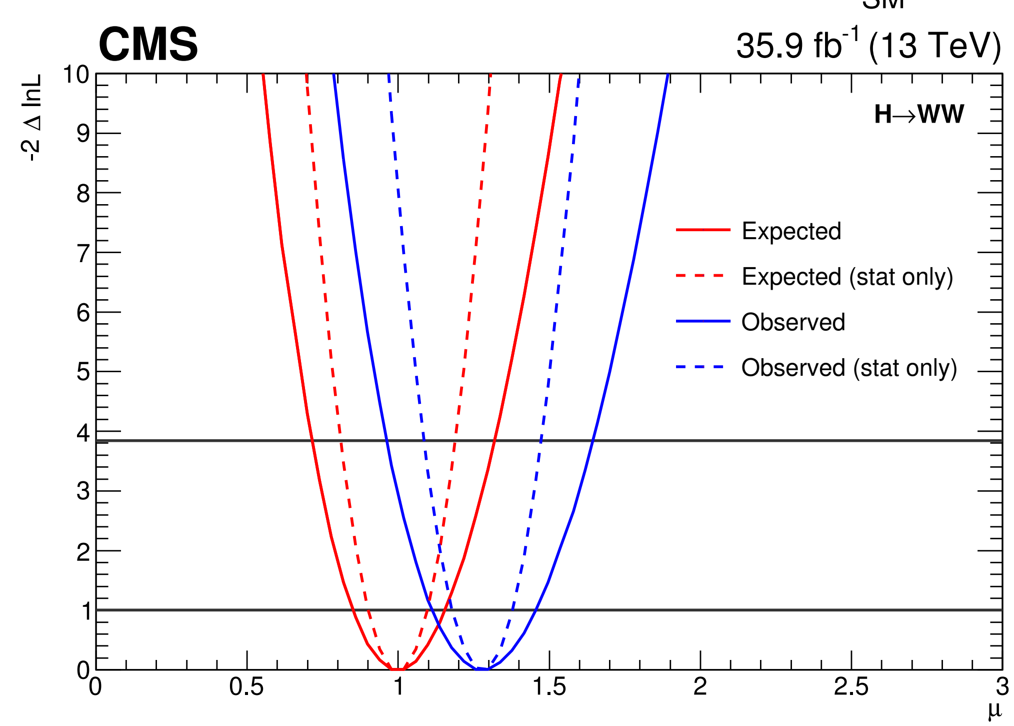
Best result up to now:

$$\Gamma_H < 9.16\ (exp\ 13.7)\ MeV\ @95\%\,C.L.$$

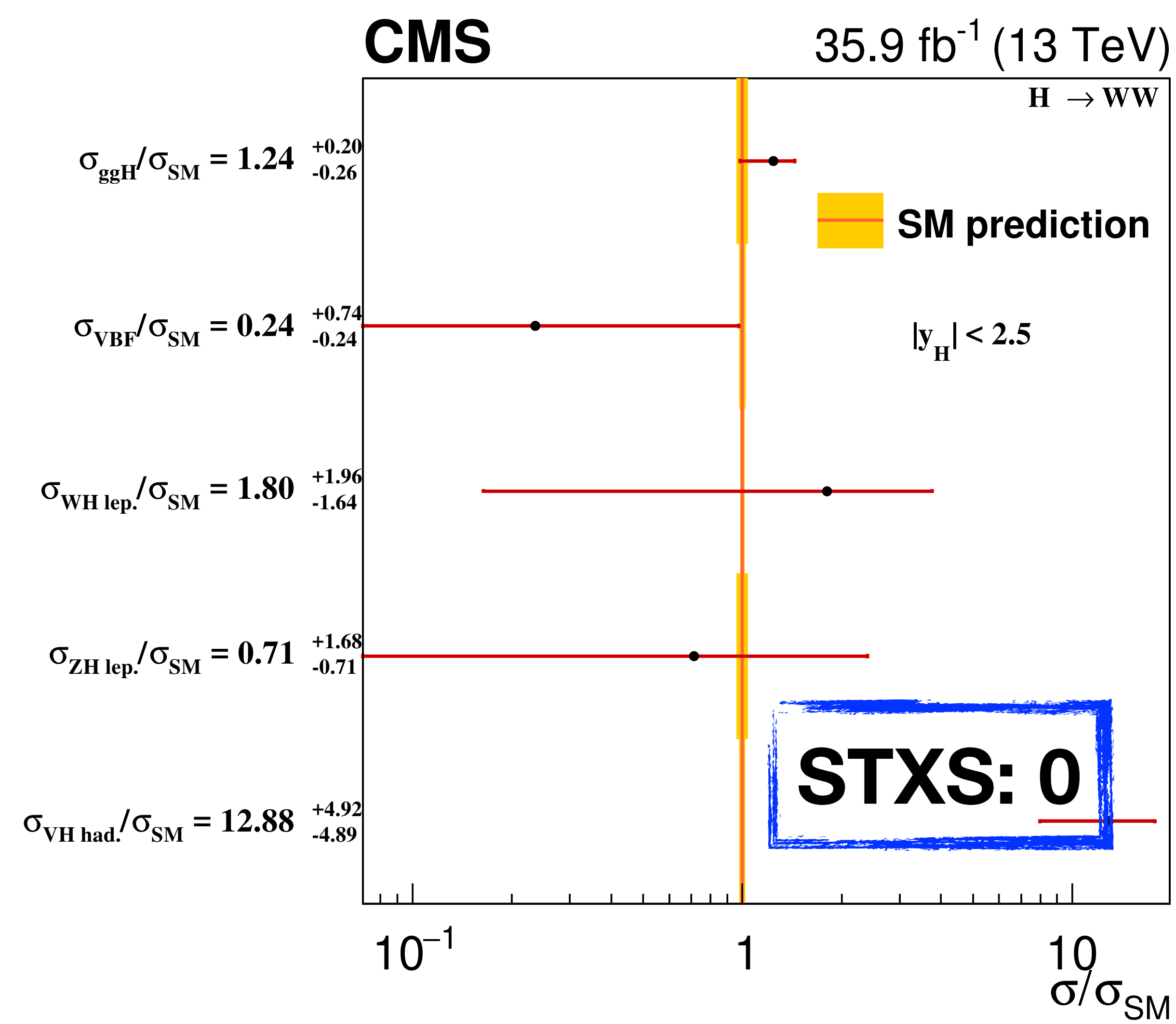
Higgs boson decay to WW



Phys. Lett. B 791 (2019) 96



Phys. Lett. B 791 (2019) 96



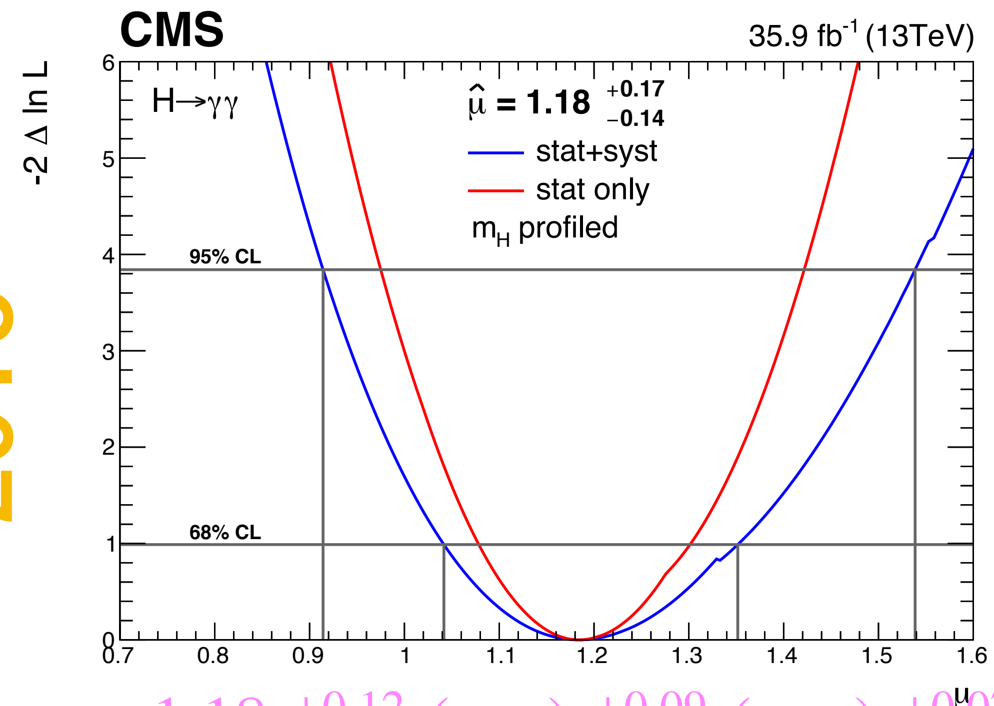
Phys. Lett. B 791 (2019) 96

2016

$$\mu_{HWW} = 1.28 \pm 0.10\ (stat) \pm 0.11\ (syst)\ ^{+0.10}_{-0.07}\ (theo)$$

Higgs boson decay to γγ

2016



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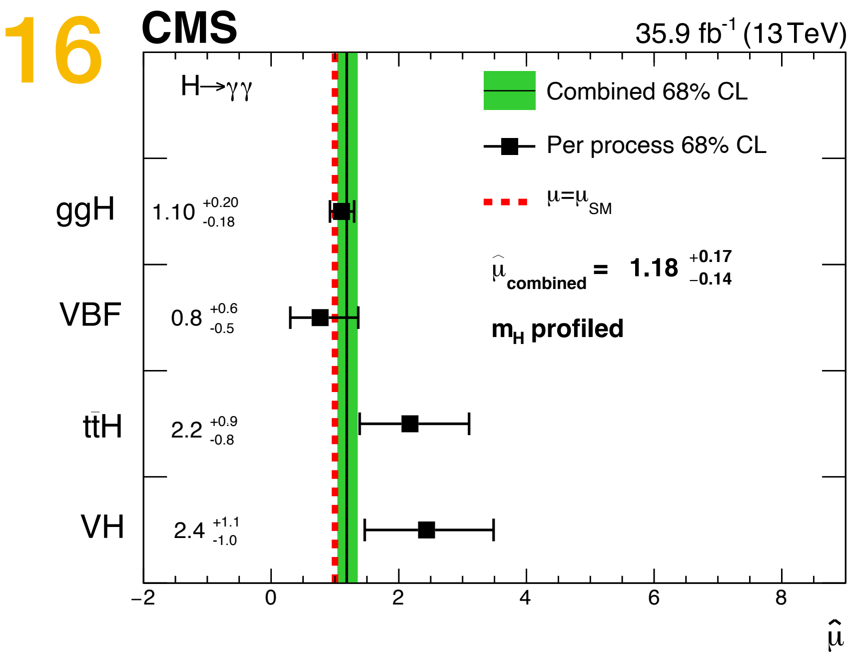
2016



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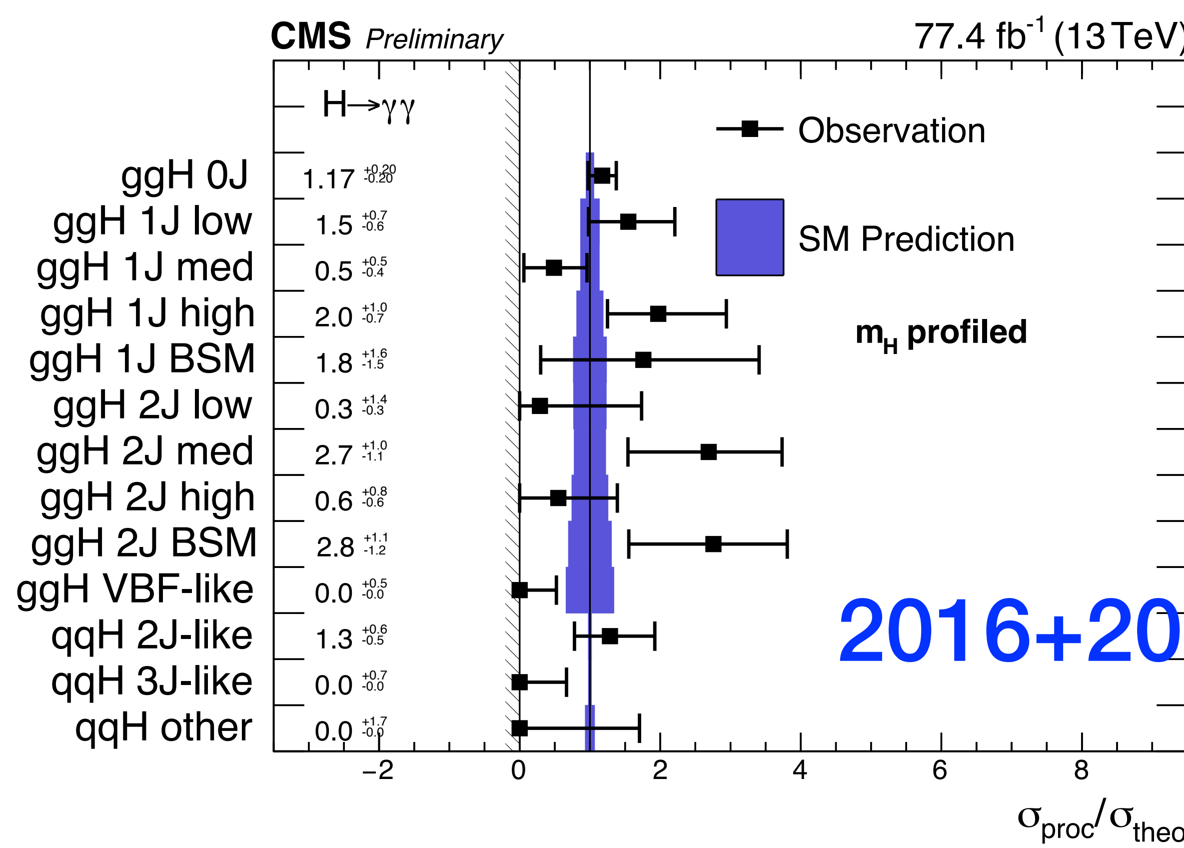
$$\mu_{H\gamma\gamma} = 1.18\,^{+0.12}_{-0.11}\,(stat)\,^{+0.09}_{-0.07}\,(syst)\,^{+0.07}_{-0.06}\,(theo)$$

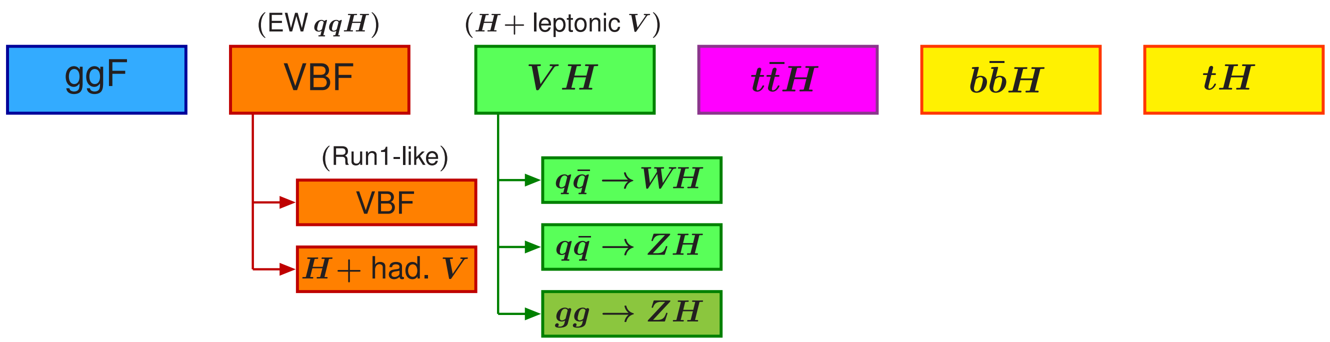
STXS: 1.1



CMS-PAS-HIG-18-029

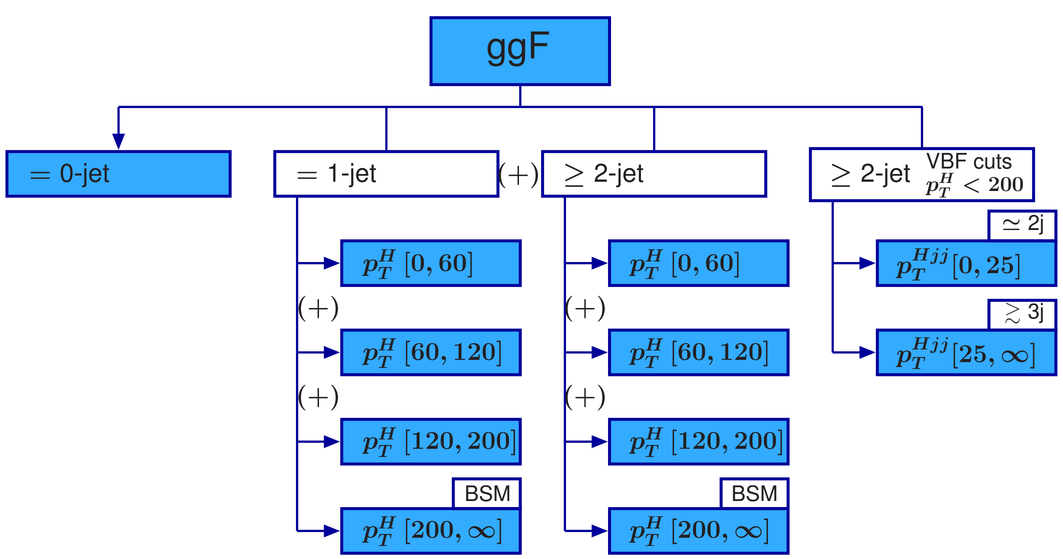
2016+2017

STXS

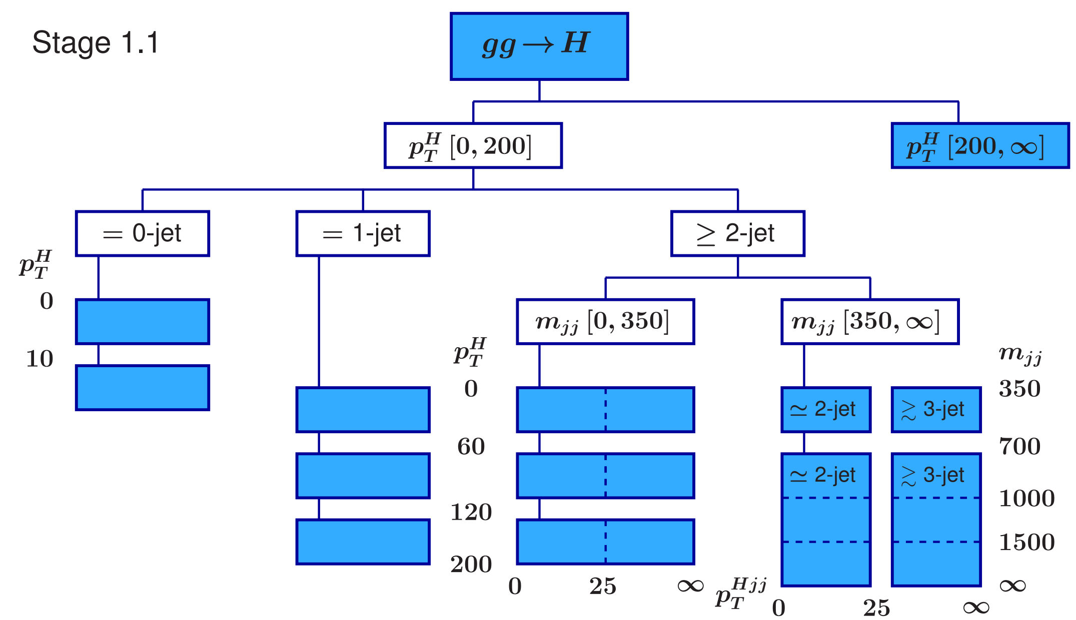


Stage 0

ggF: Stage 1

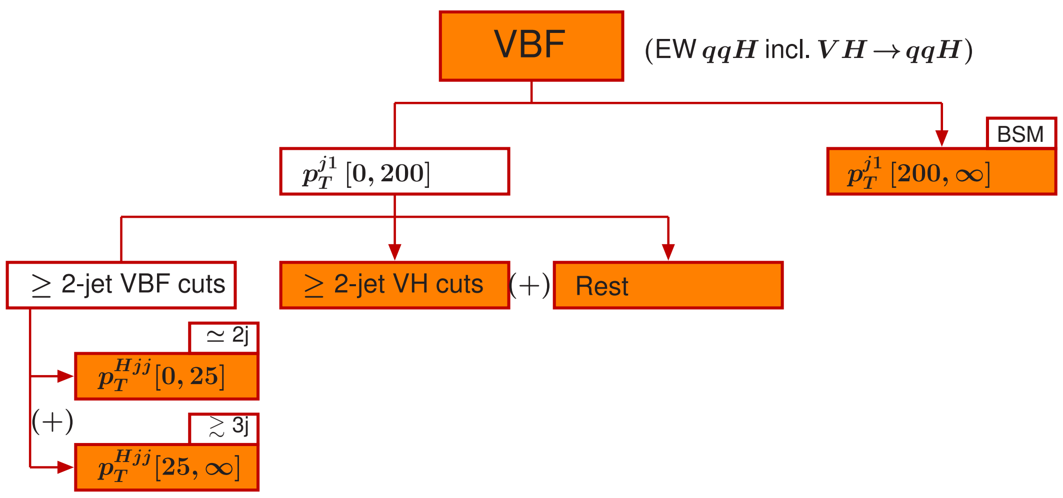


ggF: Stage 1.1

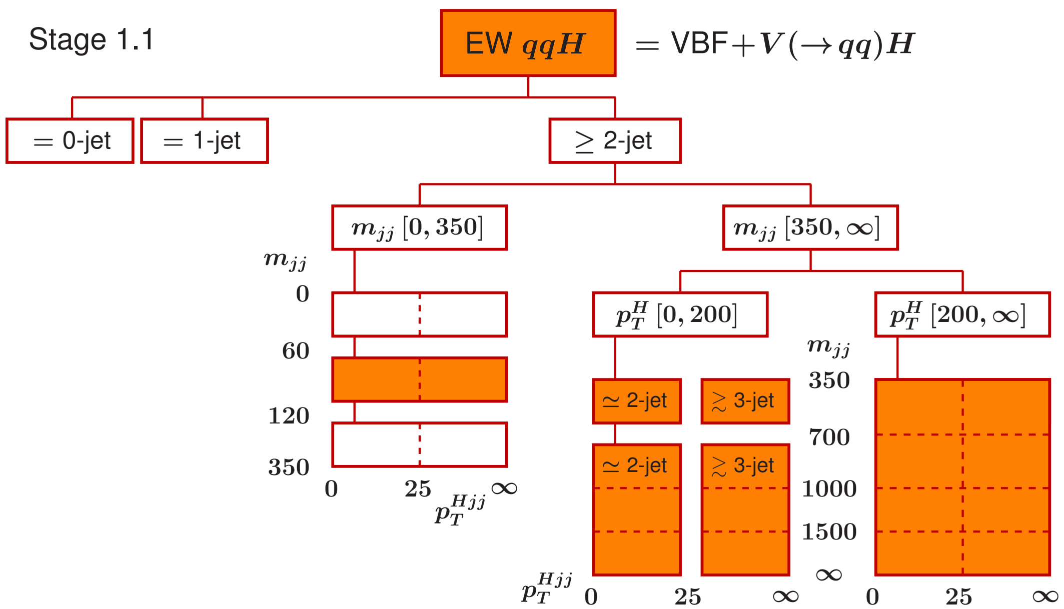


STXS

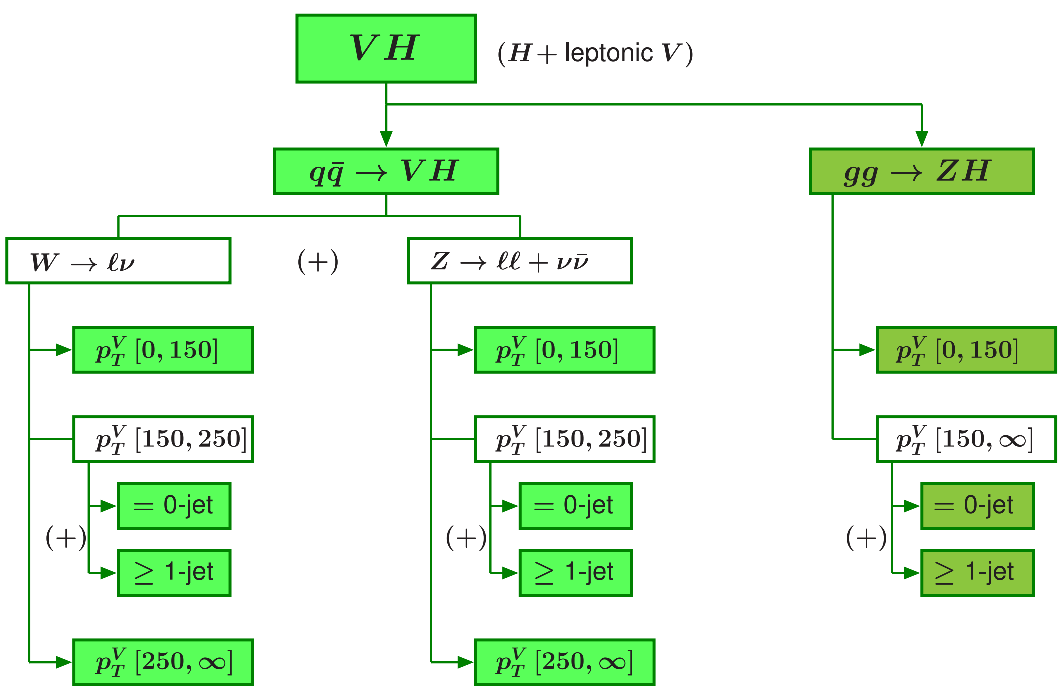
VBF: Stage 1



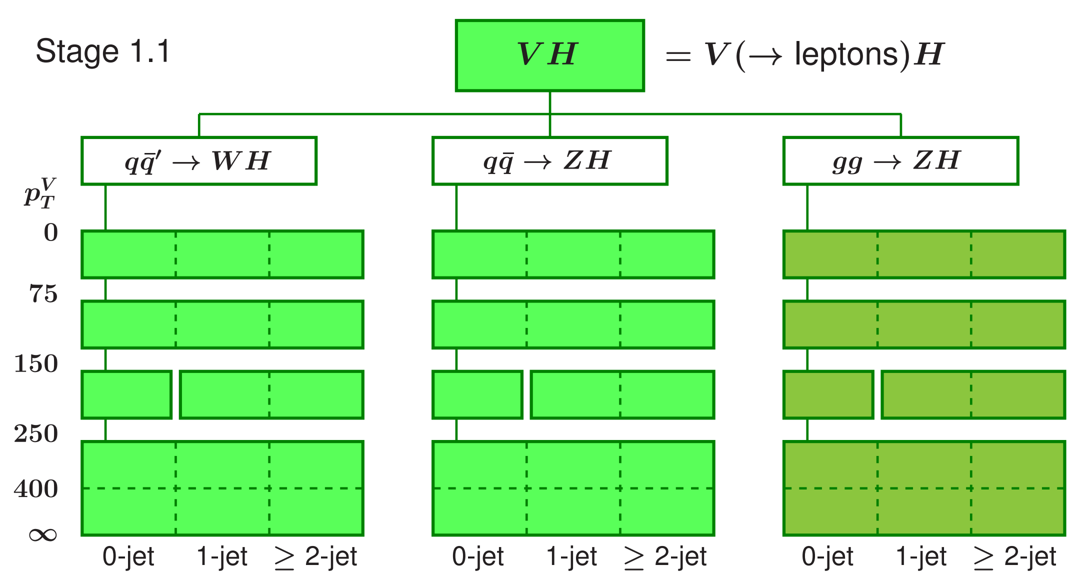
VBF: Stage 1.1



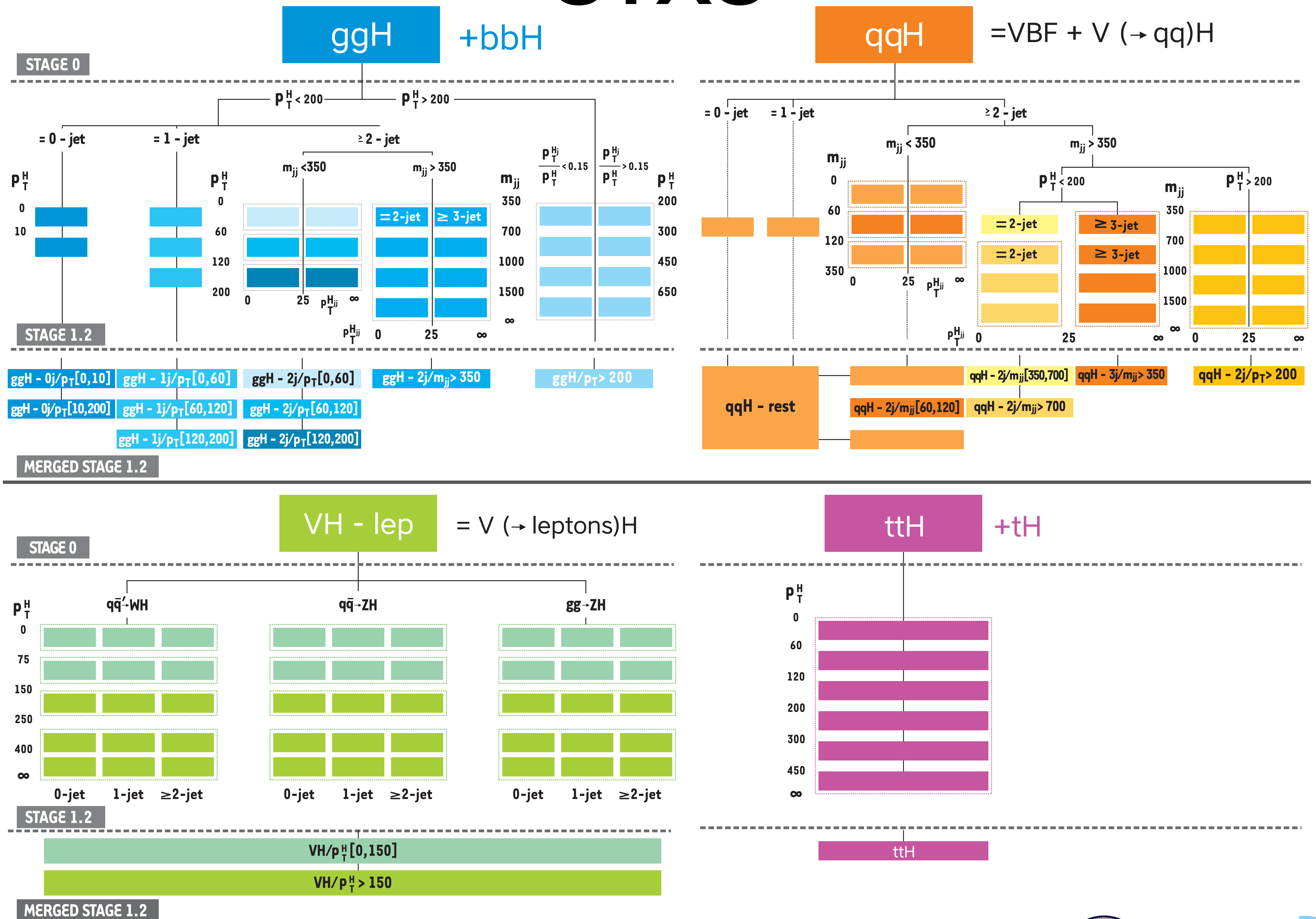
VH: Stage 1



VH: Stage 1.1



STXS



F. Errico, HH2021 Orsay, 20th Sept 2021