Recent measurements of Higgs to bosons decays at the LHC

Tülay Çuhadar Dönszelmann
University of Sheffield
(On behalf of the ATLAS and CMS collaborations)

DIS2019: XVII International Workshop on Deep Inelastic Scattering
Torino (Italy), 8-12 April 2019

Outline

$H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^*$

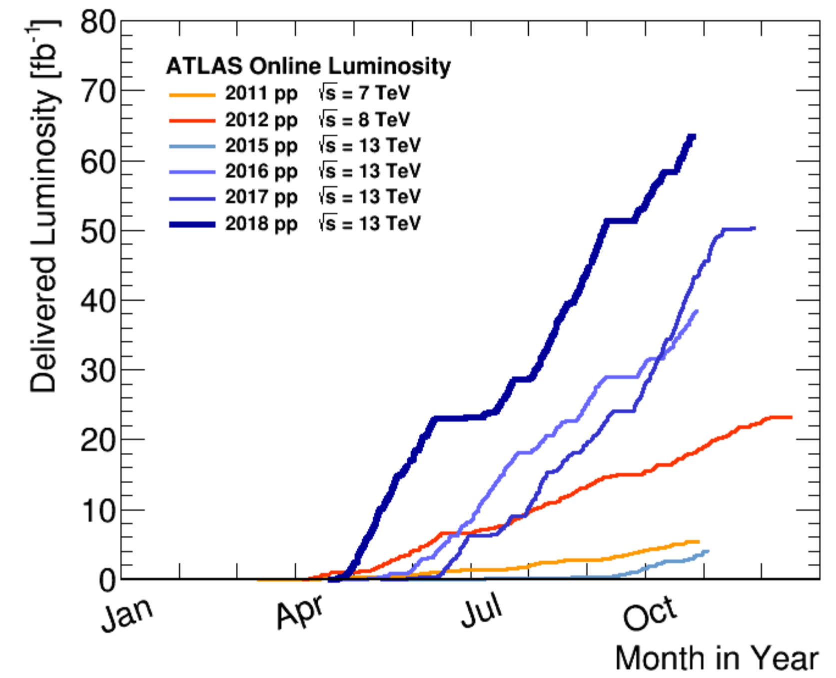
- Higgs mass / width
- Production mode cross sections in Simplified Template Cross Section (STXS)
- Differential fiducial cross section
- Higgs self coupling and anomalous coupling

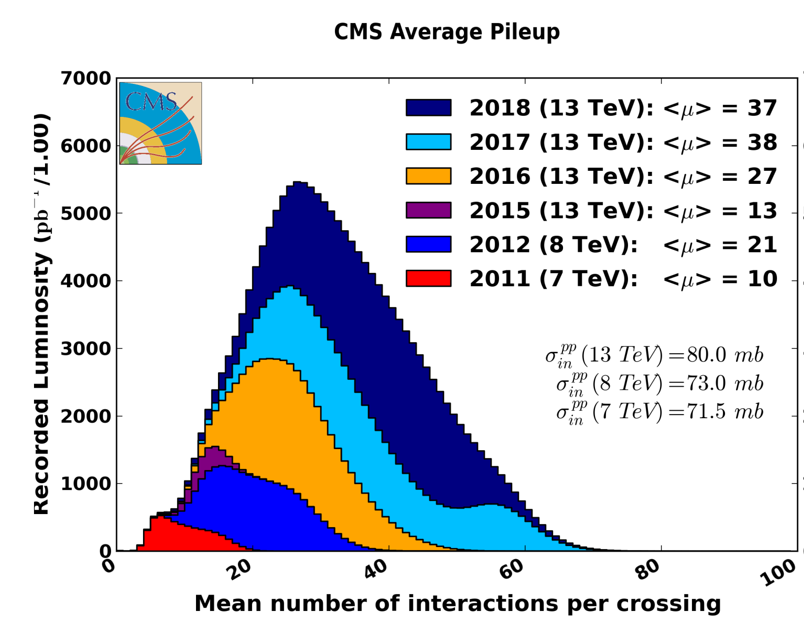
Also discuss:

- Higgs to invisible decays
- Rare decays

Run 1: 25 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV

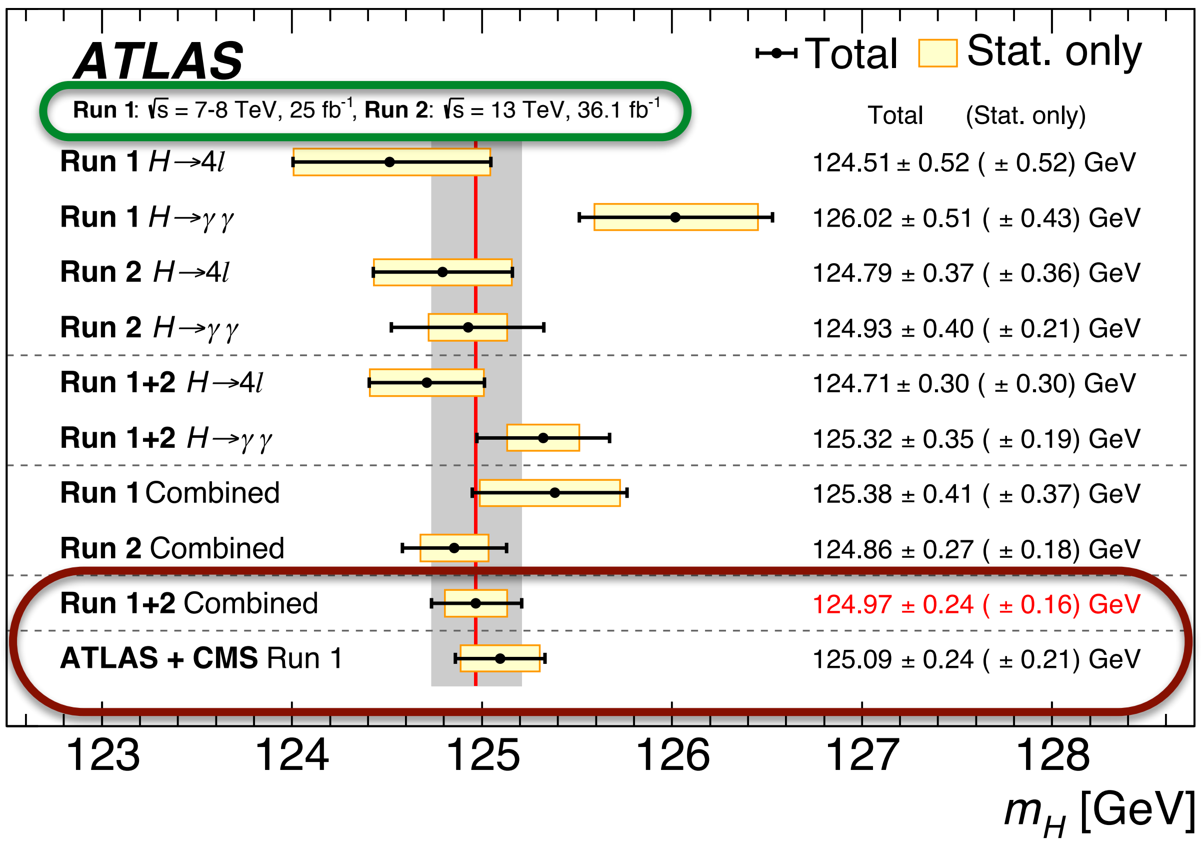
Run 2 : 140 fb^{-1} at $\sqrt{s}$ = 13 TeV

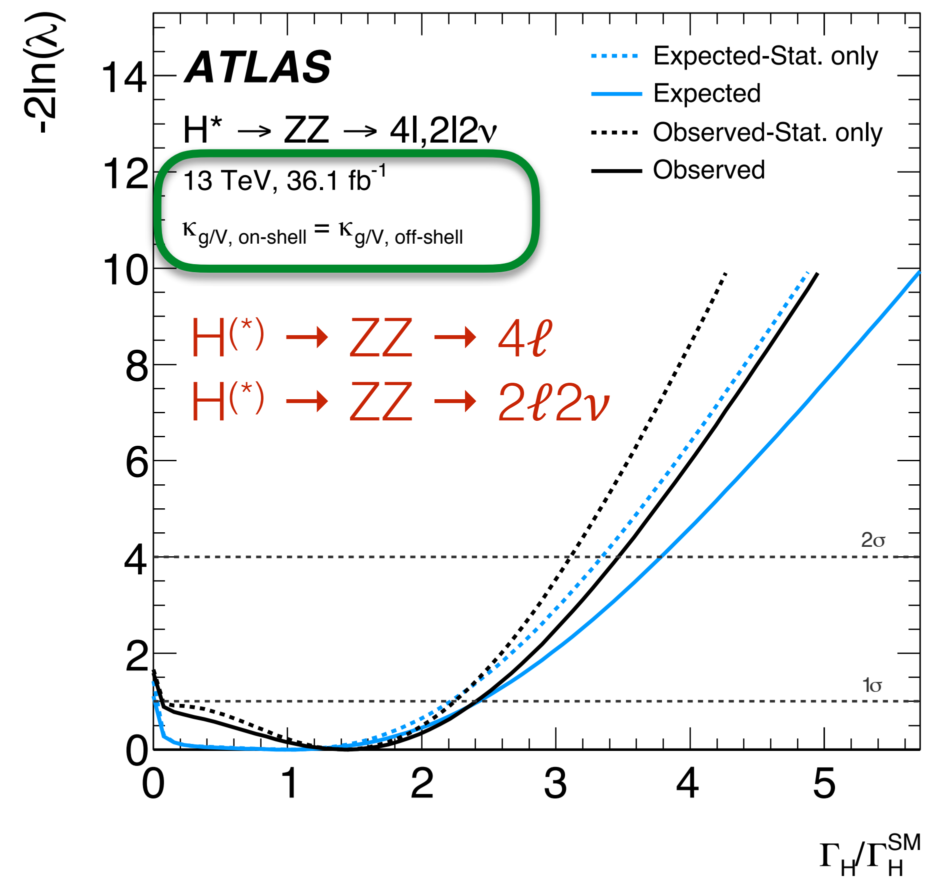




ATLAS: Higgs mass and width

PLB 784 (2018) 345





Run 2 mass measurement:

$H \to \gamma\gamma$ systematic dominated - main source photon energy scale

$H \to 4\ell$ (H→ 4e, 4μ, $2e2\mu$ and $2\mu 2e$) statistics dominated

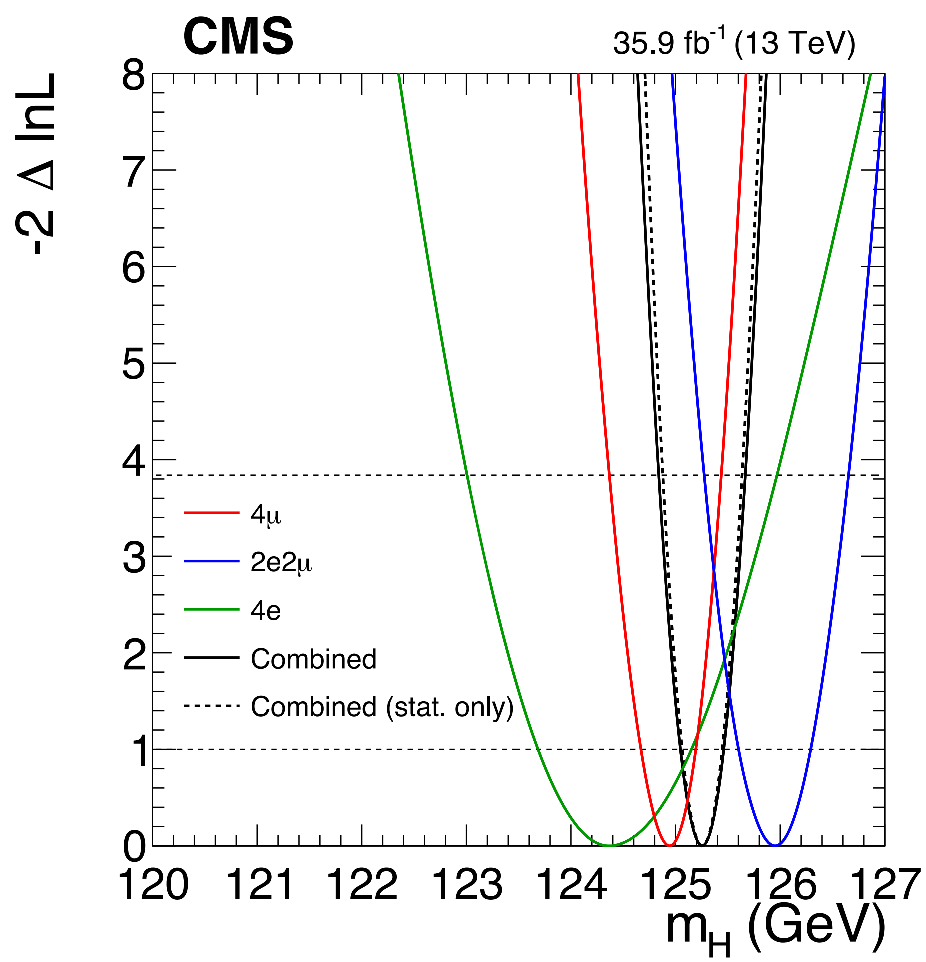
Direct measurement of Higgs width Γ_H : Run 1 $H \to 4\ell$ ($H \to \gamma\gamma$) (PRD 90, 052004):

Γ_H < 2.6 (5.0) GeV at 95% C.L

Indirect measurement of Γ_H: Compare on-shell and off-shell rates, and assuming the couplings of on-shell and off-shell are the same: $\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{SM}$

Γ_H < 14.4 MeV (PLB 786 (2018) 223)

CMS: Higgs mass and width

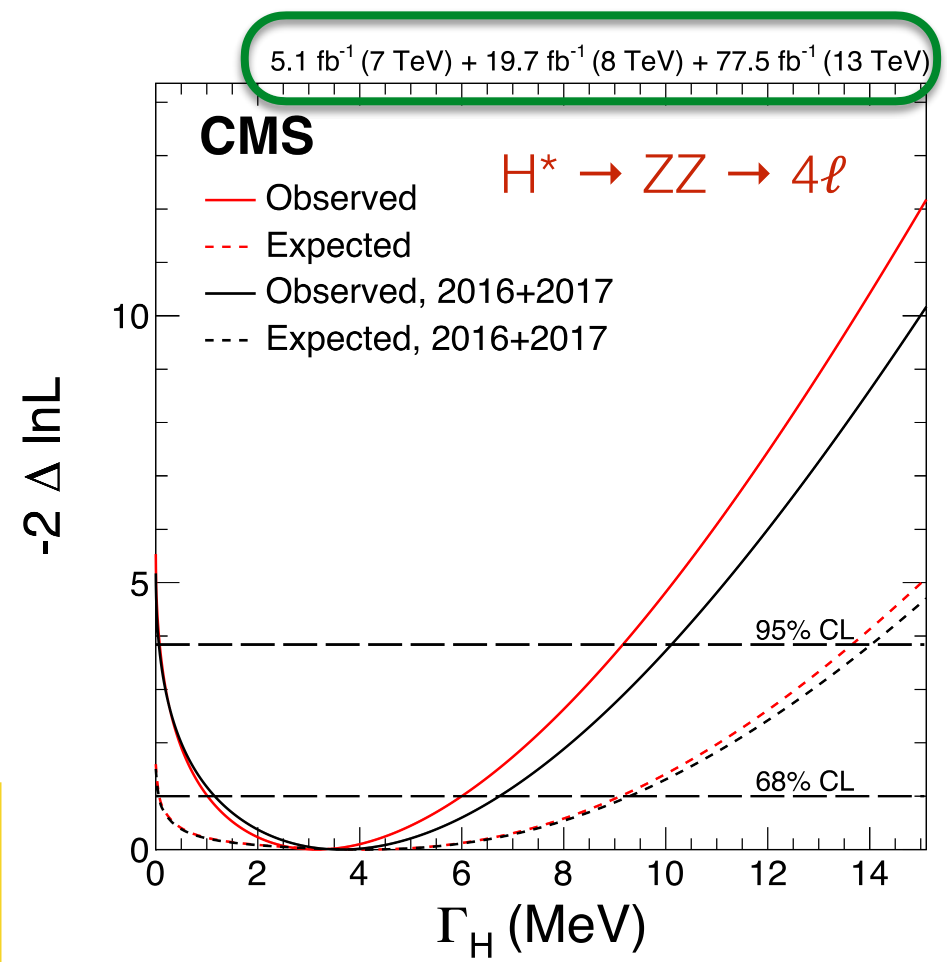


JHEP 11 (2017) 047

Run 2, 36 fb^{-1} : combining $H \to 4e$, 4μ and $2e2\mu$

m_H = 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV

(main systematic: uncertainty in the lepton momentum scale)



Model independent Γ_H measurement using on-shell production in 105 < $m_{4\ell}$ < 140 GeV:

Γ_H < 1.1 GeV at 95% C.L.

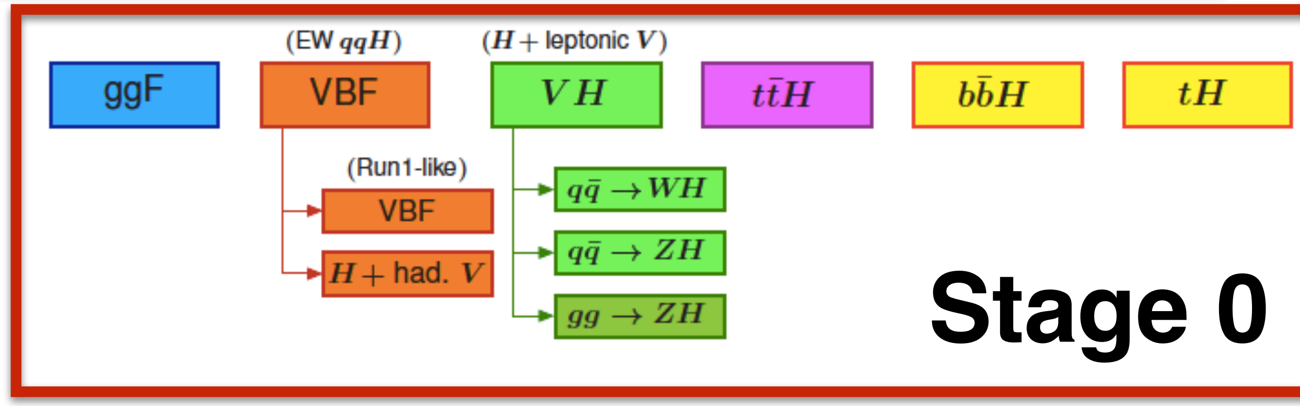
Best limit on Γ_H (arXiv:1901.00174) from indirect measurement: Γ_H < 9.16 MeV at 95% C.L.

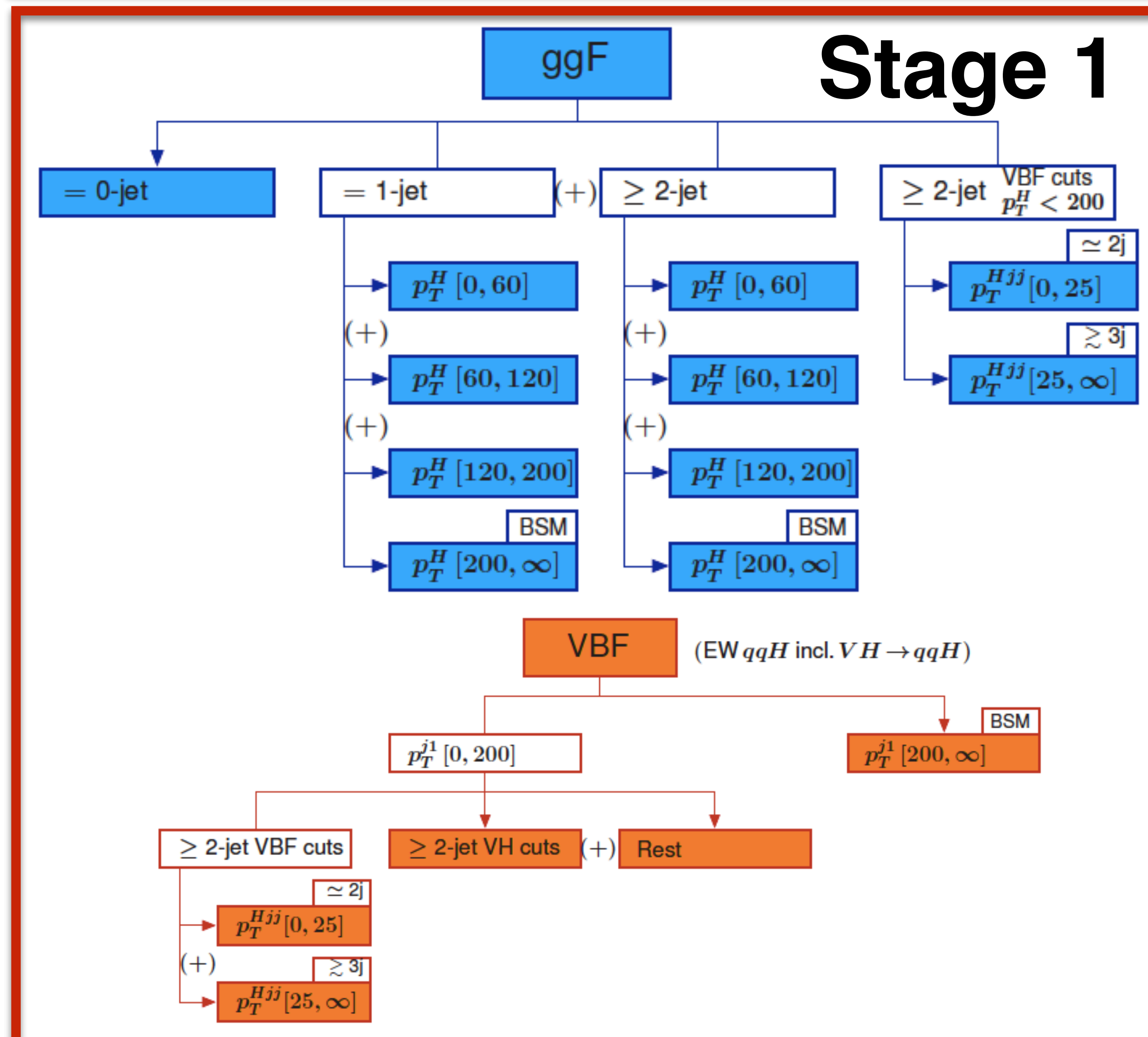
Simplified Template Cross Section (STXS)

arXiv:1610.07922 arXiv:1605.04692

- The goal with STXS method:
  - Maximise sensitivity of measurements
  - Minimise their dependence on the theory
- Categorise events in exclusive phase space regions (signal templates) in different production modes (ggF, VBF, VH, ttH)
- STXS allows to combine different decay channels from LHC experiments

Higgs boson properties are measured with 36 fb^{-1} - 137 fb^{-1} ($\sqrt{s}$ = 13 TeV) for Higgs boson rapidity $|y_H| < 2.5$

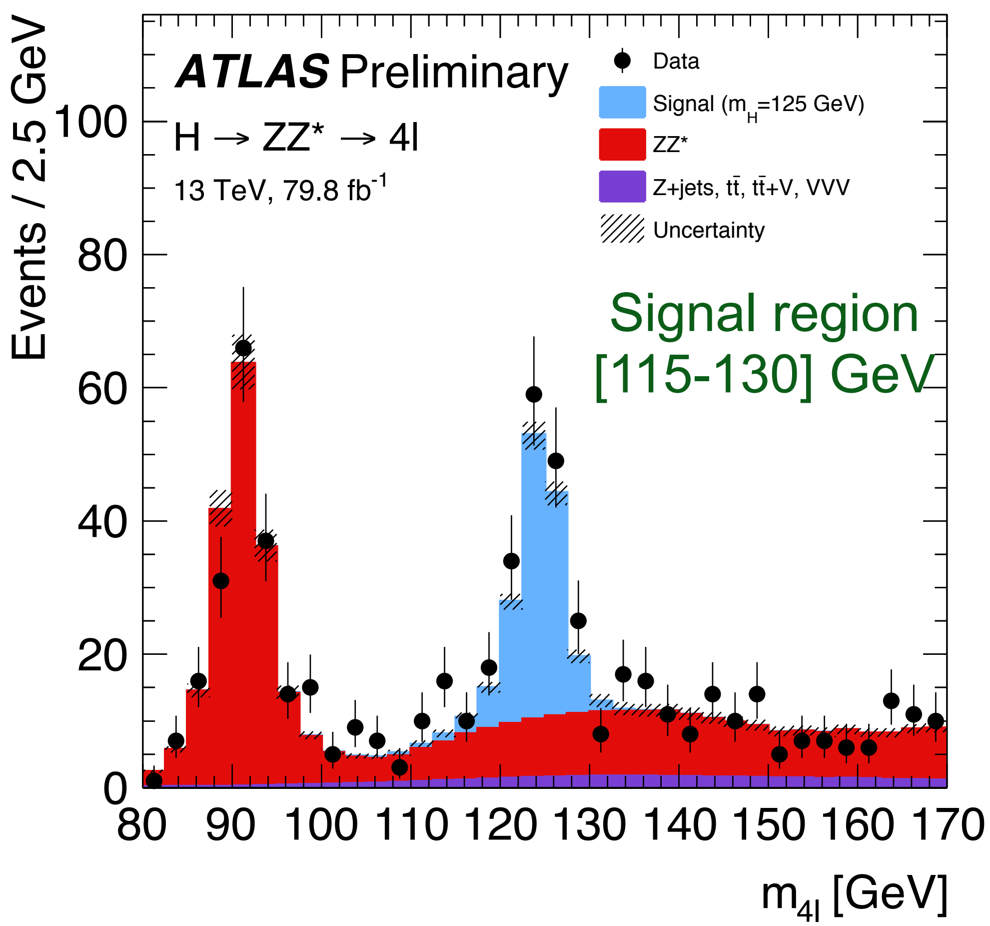




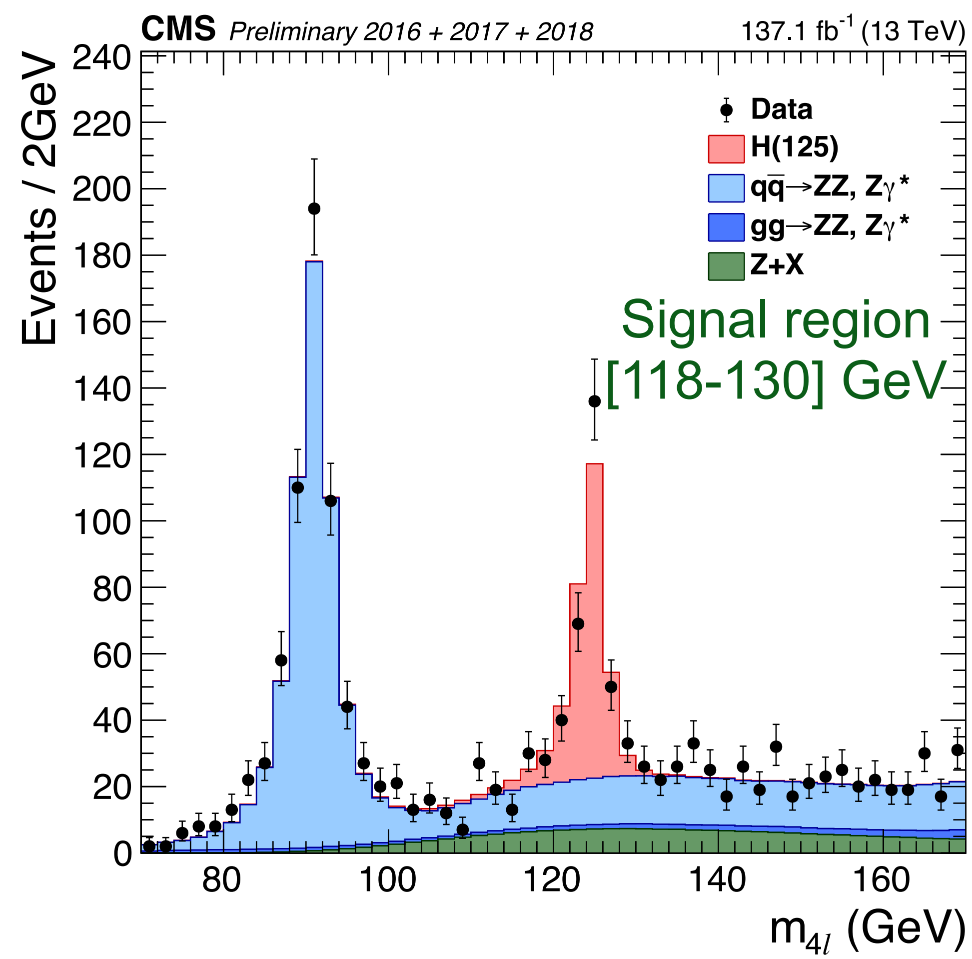
H →4ℓ: Four-lepton Invariant mass distribution

- Small branching fraction (0.0124% at m_H = 125 GeV), final states are fully reconstructable, S/B better than 2
- Backgrounds: (irreducible estimated from simulation) production of ZZ via qq annihilation or gluon fusion, (reducible estimated from data) Z+jets, tt+jets, Zγ+jets, WW+jets, and WZ+jets

ATLAS-CONF-2018-018



CMS-PAS-HIG-19-001

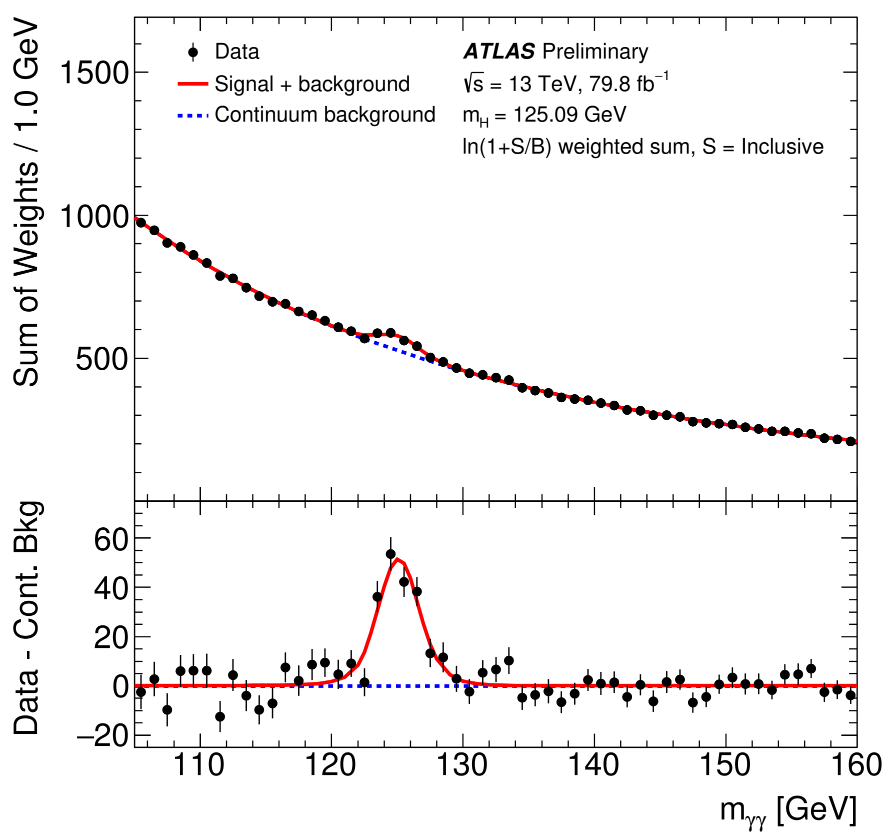


- Cross sections are extracted by minimising twice the negative logarithm of the profile likelihood ratio (-2 ln Λ)
- BDT is trained to separate the production mode from the others

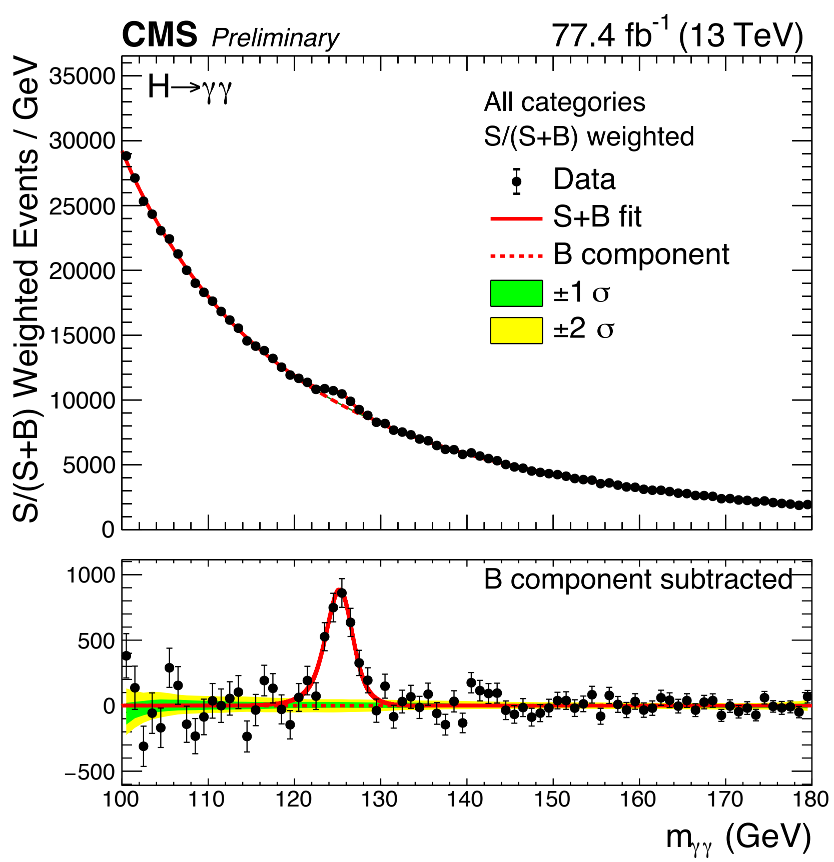
$H \rightarrow \gamma\gamma$: Diphoton invariant mass distribution

- Small branching fraction (0.23% at m_H = 125.09 GeV), final states are fully reconstructable, look for a narrow peak on a smooth background
- Backgrounds: SM diphoton production or γ+jets, jet+jets (estimated from data)

ATLAS-CONF-2018-028



CMS-PAS-HIG-18-029

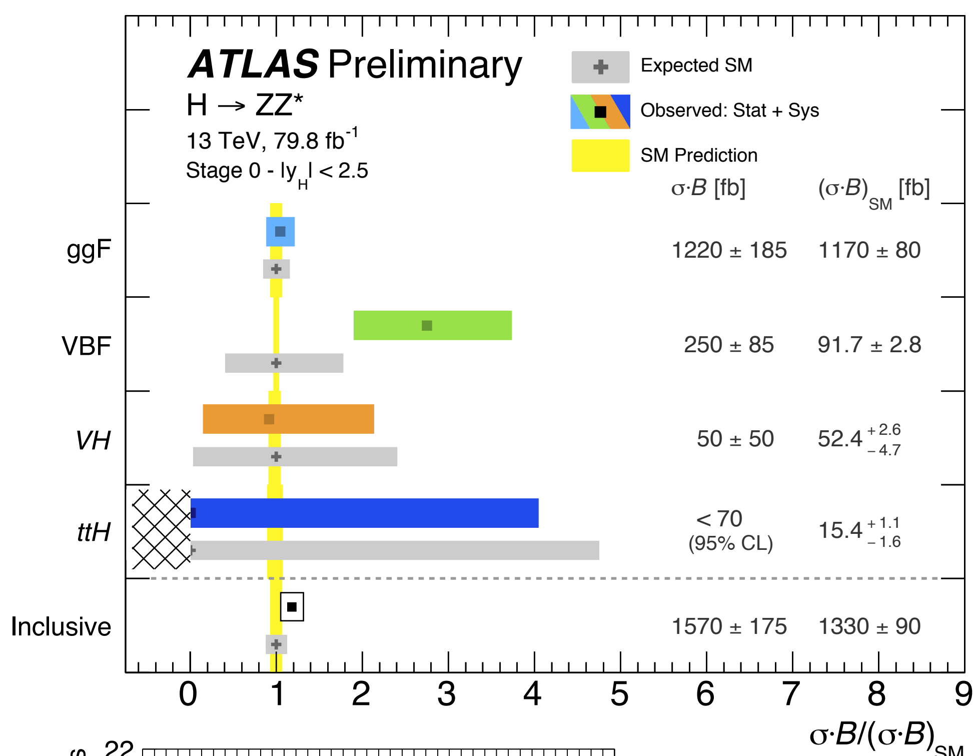


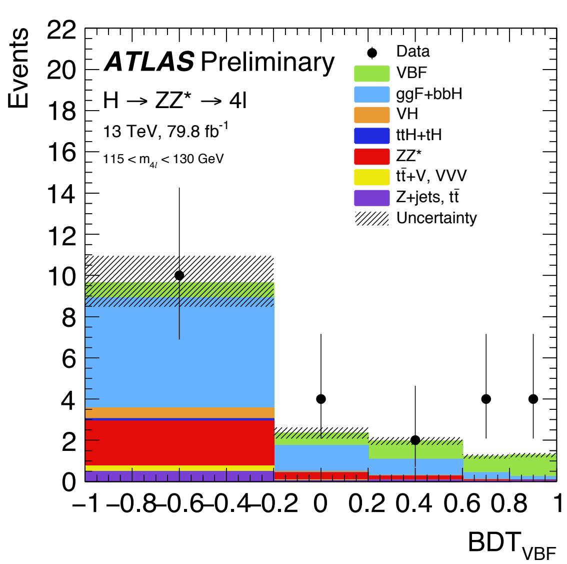
Signal plus background model fit for the sum of all categories, and the residual plot after subtracting the background

ATLAS: Production mode cross sections from $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ (Stage 0)

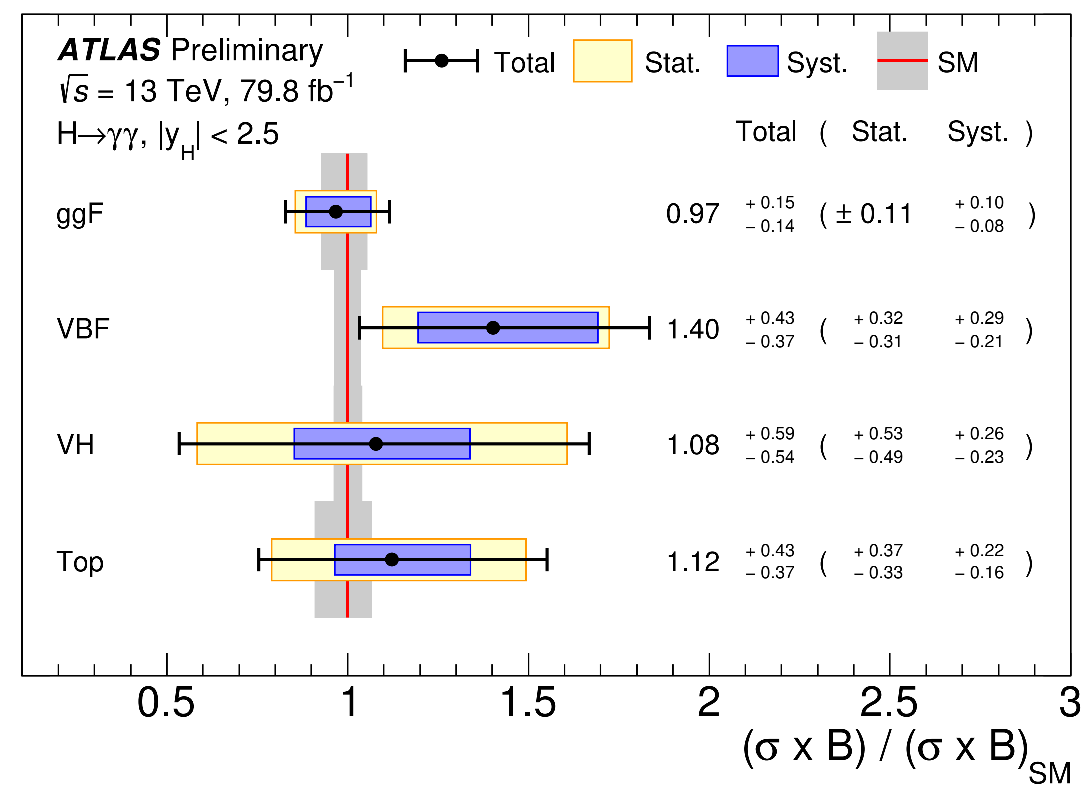
- Measured σ × B in different productions mode
  - Events split in 11 (4ℓ) and 29 ($\gamma\gamma$) categories
- Good agreement with ggF and VH and σ_{VBF} × B is 1.8σ higher than SM prediction (in 4ℓ), evidence of ttH($H \rightarrow \gamma\gamma$) with 4.9$\sigma$ observed significance

ATLAS-CONF-2018-018





ATLAS-CONF-2018-028



Global signal strength for $|y_H| < 2.5$

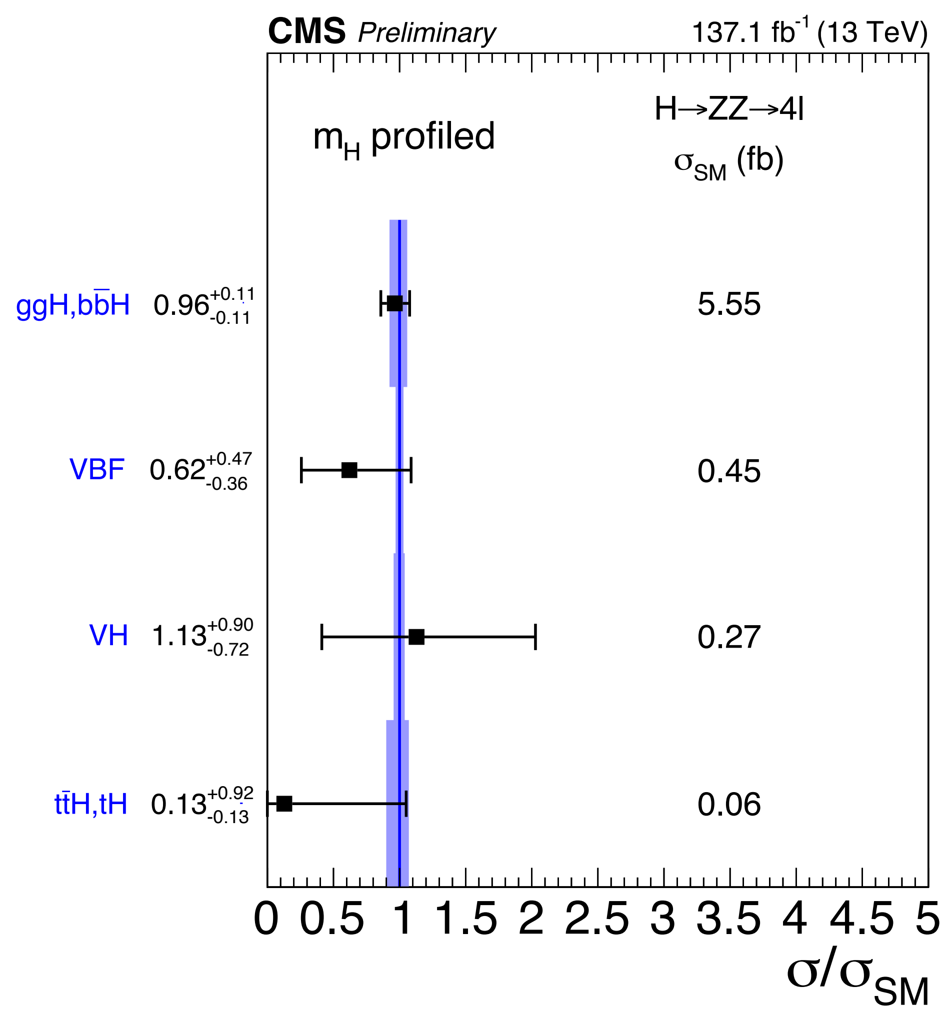
$$\mu_{4l} = 1.19 \pm 0.12(\text{stat.}) \pm 0.06(\text{exp.})^{+0.08}_{-0.07}(\text{th.})$$

$$\mu_{\gamma\gamma} = 1.06 \pm 0.08(\text{stat.})^{+0.08}_{-0.07}(\text{exp.})^{+0.07}_{-0.06}(\text{th.})$$

CMS: Production mode cross sections from $H \to 4\ell$ and $H \to \gamma\gamma$ (Stage 0)

- Measured cross sections in different productions mode
  - Events splitted in 22 (4ℓ) and 14 ($\gamma\gamma$) categories

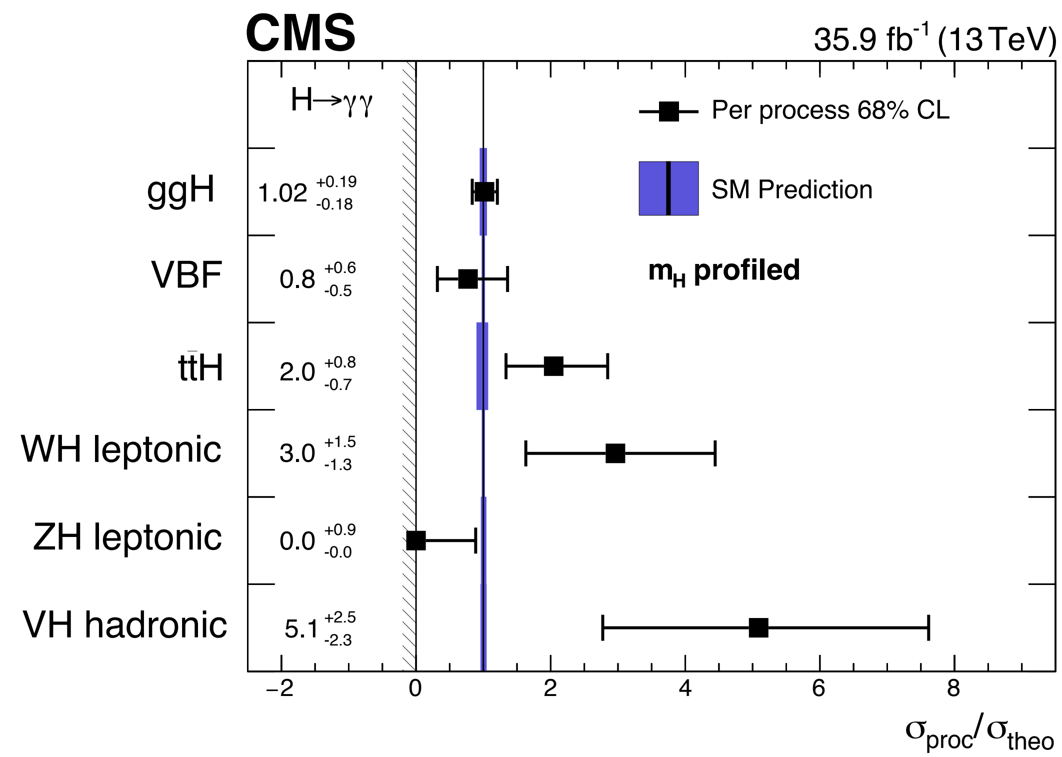
CMS-PAS-HIG-19-001



$$\mu_{4l} = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

(Dominant syst.: lepton ID efficiency & luminosity measurement)

JHEP 11 (2018) 185



$$\mu_{\gamma\gamma} = 1.18^{+0.12}_{-0.11}(\text{stat.})^{+0.09}_{-0.07}(\text{exp.})^{+0.07}_{-0.06}(\text{th.})$$

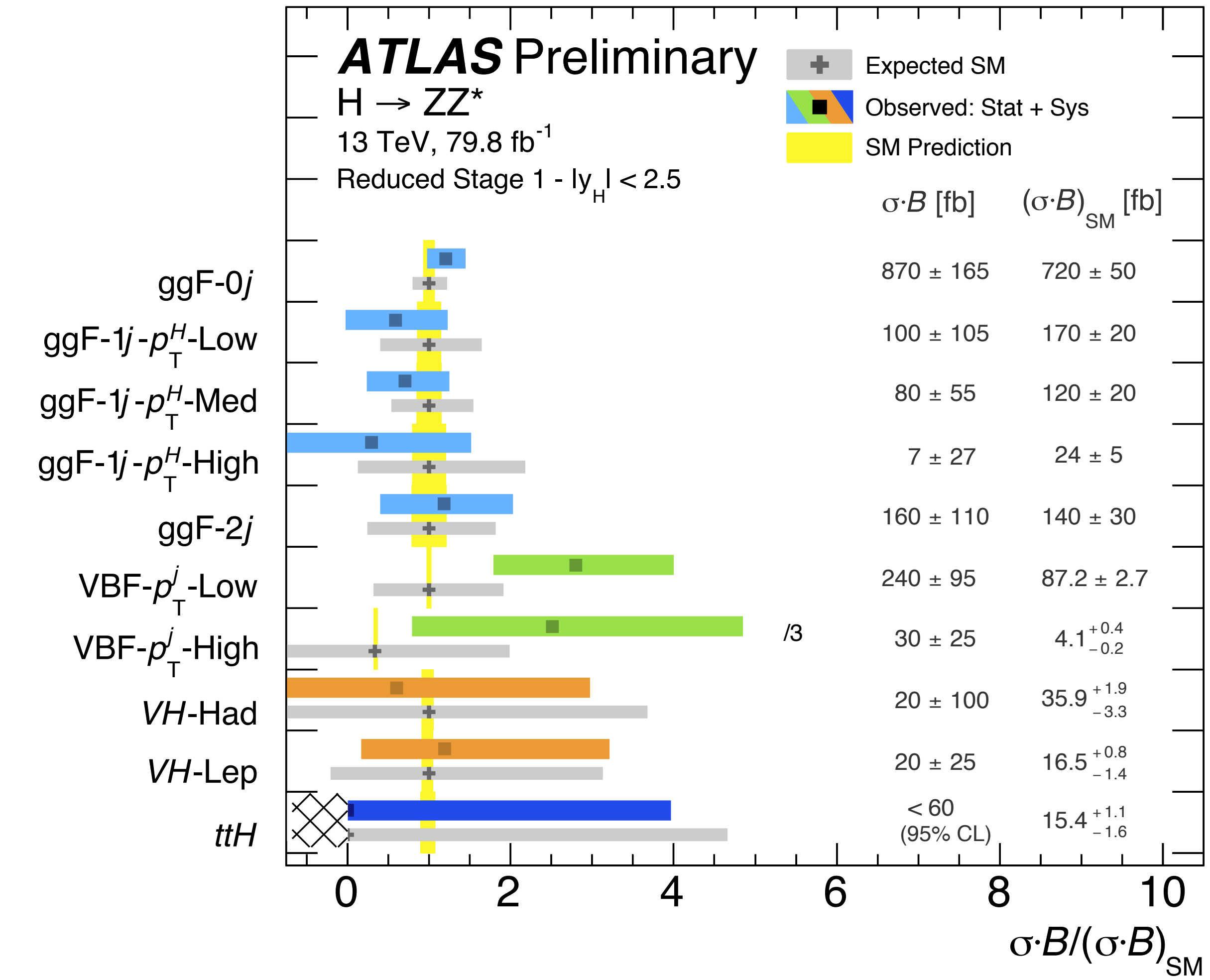
(Dominant syst.: photon shower shape modelling, energy scale/resolution, jet energy scale and luminosity measurement)

With 80 fb-1 CMS-PAS-HIG-18-029

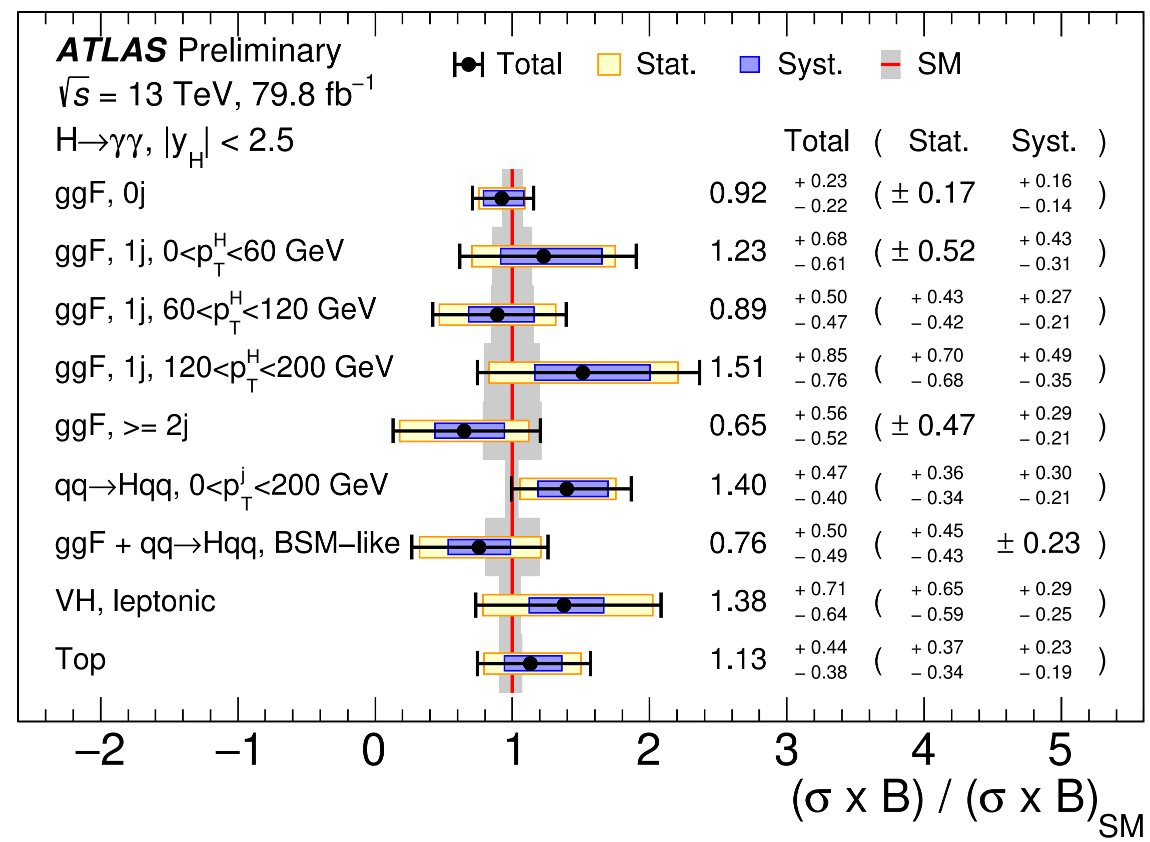
$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = 1.15^{+0.15}_{-0.15} \qquad \frac{\sigma_{qqH}}{\sigma_{qqH}^{SM}} = 0.8^{+0.4}_{-0.3}$$

ATLAS: Production mode cross sections from $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ (Stage 1)

ATLAS-CONF-2018-018



ATLAS-CONF-2018-028



- In all regions, measurements are consistent with SM predictions
- Due to finer categorisation, measurements in stage 1 are statistics limited
- Stage 1 theoretical uncertainties are smaller than Stage 0

See talk by S. Tsuno for the details of ATLAS combination

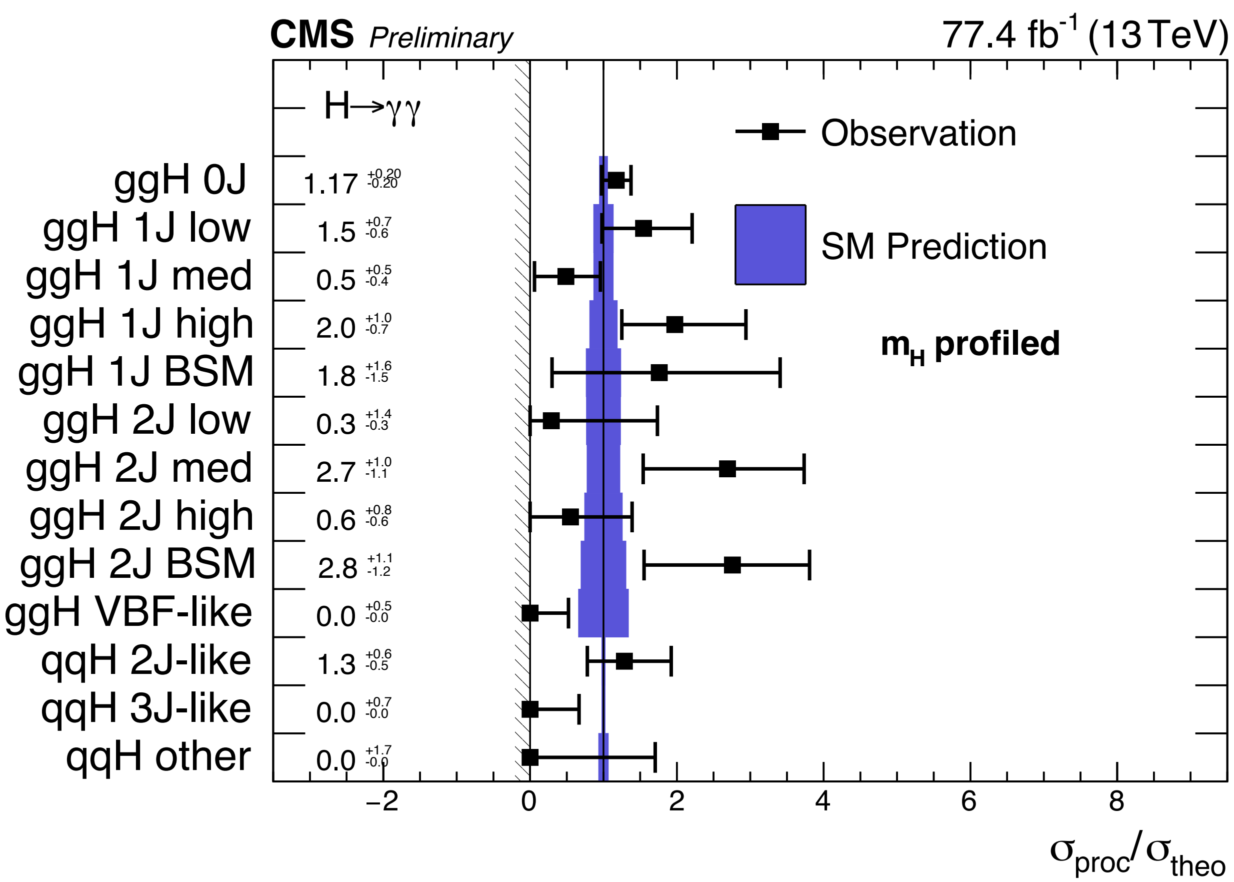
CMS: Production mode cross sections from $H \to 4\ell$ (Stage 1.1) and $H \to \gamma\gamma$ (Stage 1)

- Production mode ⇒ Split to STXS stage 1.1 (stage 1) bins

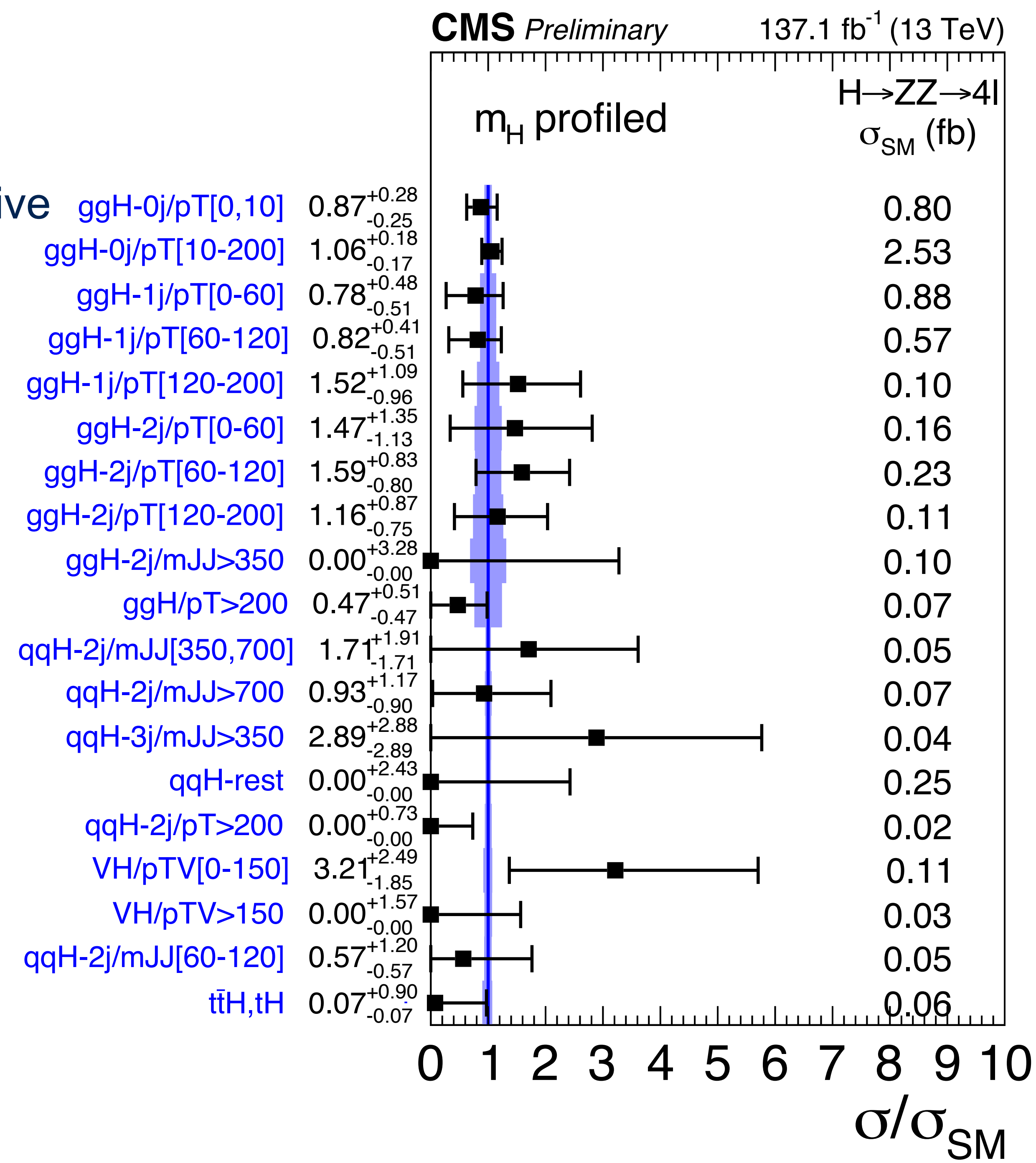
  for 4ℓ ($\gamma\gamma$) ⇒ split to improve sensitivity

  - $\gamma\gamma$ (77.4 fb^{-1}) with 24 event categories
  - Bins are merged due to limited statistics
- Cross section ratios are constrained to be positive

CMS-PAS-HIG-18-029



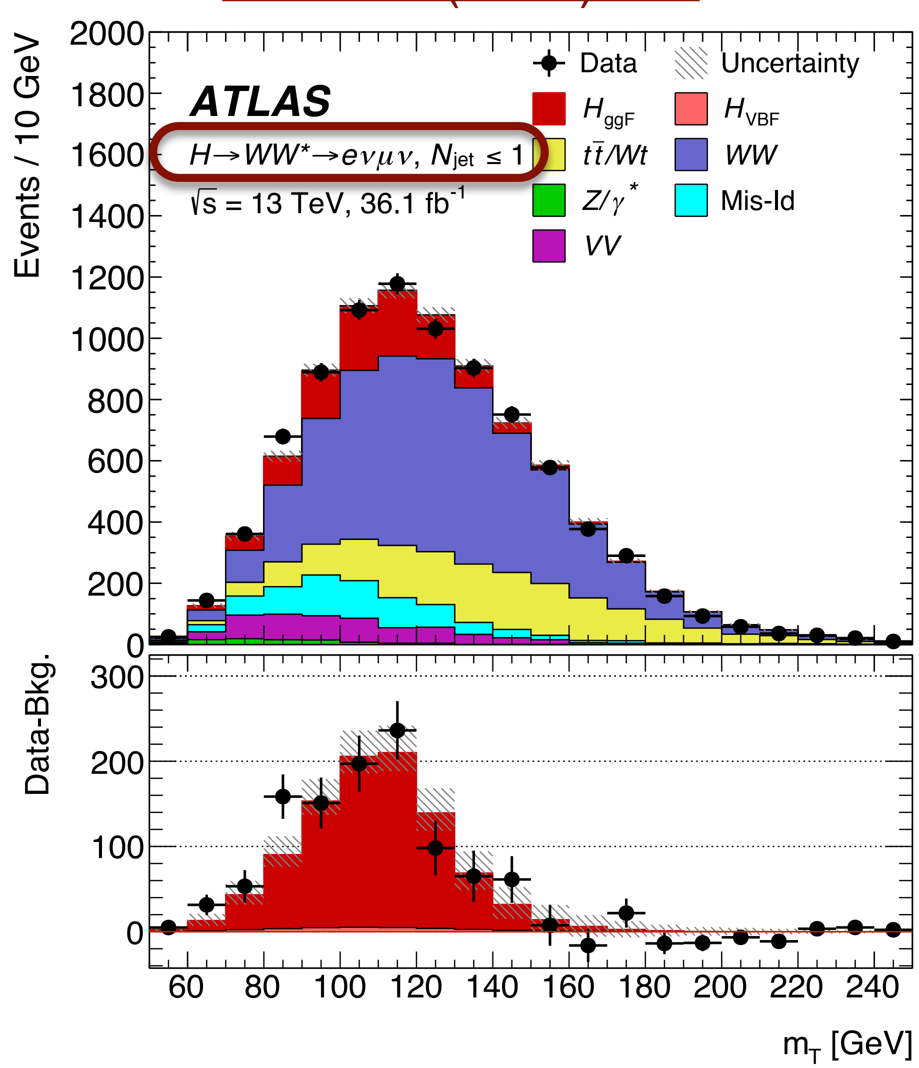
CMS-PAS-HIG-19-001



ATLAS H → WW*: Production mode cross sections

- Inclusive cross section measurements of σ × B(H → WW*) → $e\nu\mu\nu$ at 36 fb^{-1} via ggH and VBF
- Three main categories: 0jet and 1jet (ggF) and 2jet (VBF). Finer categorisation of 0jet & 1jet based on $m_{\ell\ell}$ and sub-leading lepton p_T

PLB 789 (2019) 508



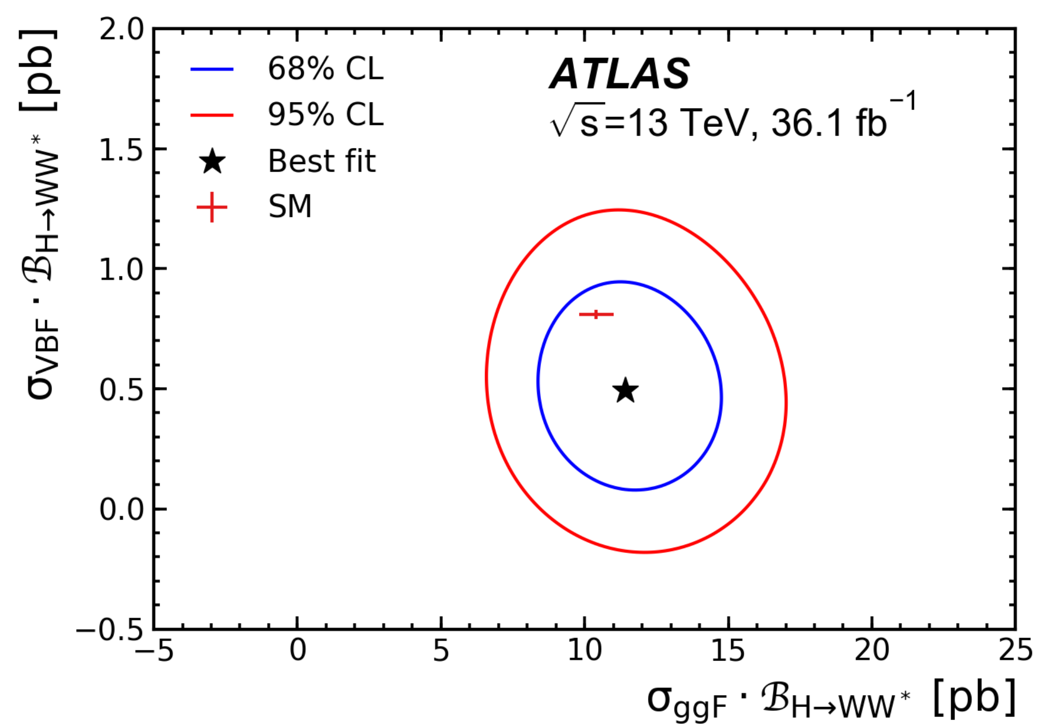
$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \boldsymbol{E}_T^{\text{miss}}\right|^2}$$

$$\sigma_{ggF} \times B = 11.4^{+1.2}_{-1.1}(\text{stat})^{+1.2}_{-1.1}(\text{th.})^{+1.4}_{-1.3}(\text{syst})\ \text{pb}$$

$$\sigma_{ggF} \times B = 10.4 \pm 0.6\ \text{pb (SM prediction)}$$

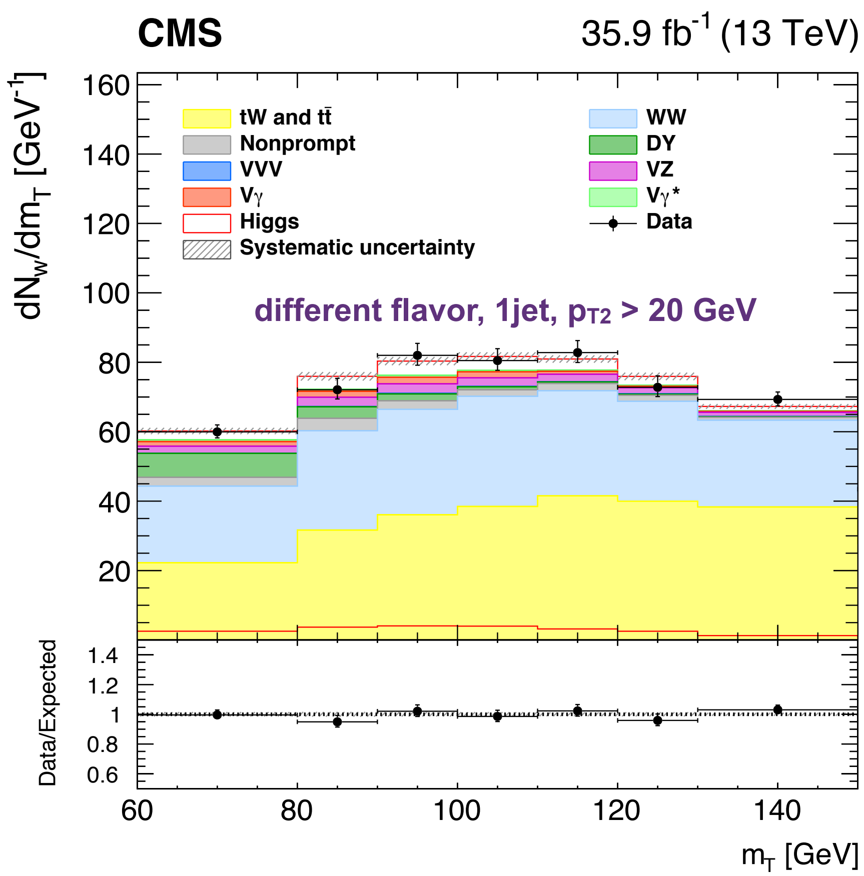
$$\sigma_{VBF} \times B = 0.50^{+0.24}_{-0.22}(\text{stat}) \pm 0.10(\text{th.})^{+0.12}_{-0.13}(\text{syst})\ \text{pb}$$

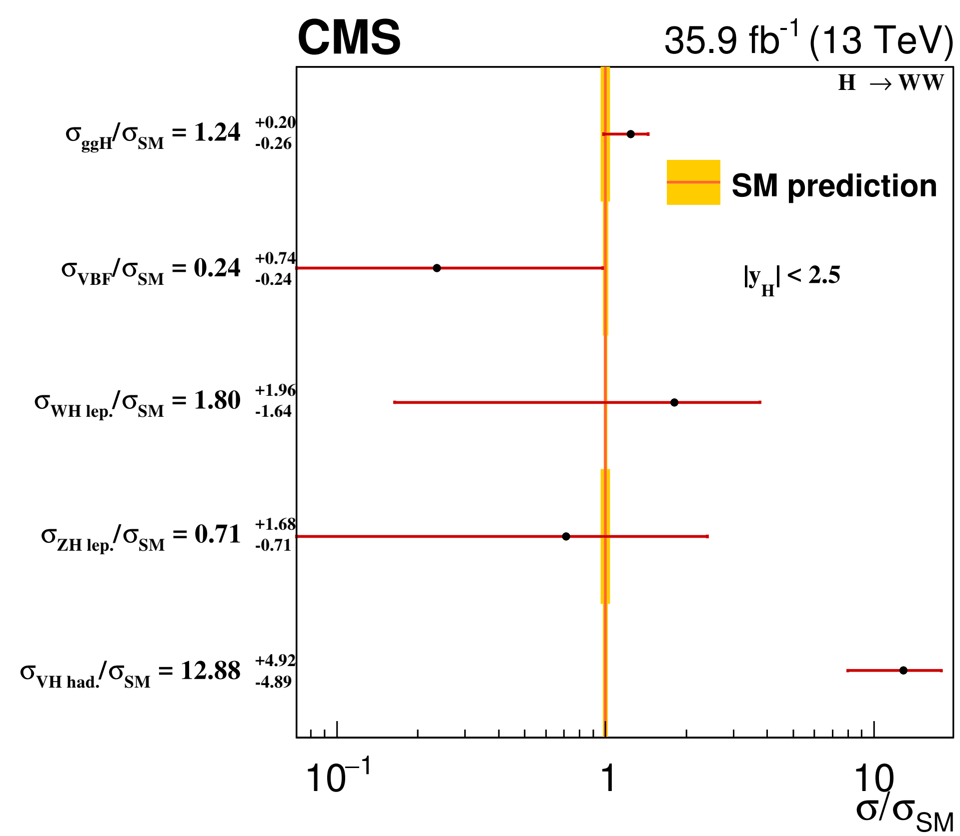
$$\sigma_{VBF} \times B = 0.81 \pm 0.02\ \text{pb (SM prediction)}$$



CMS: H → WW*

- Higgs properties $H \to WW^* \to 2\ell 2\nu$ at 36 fb^{-1} (different and same lepton flavours are considered) PLB 791 (2019) 96





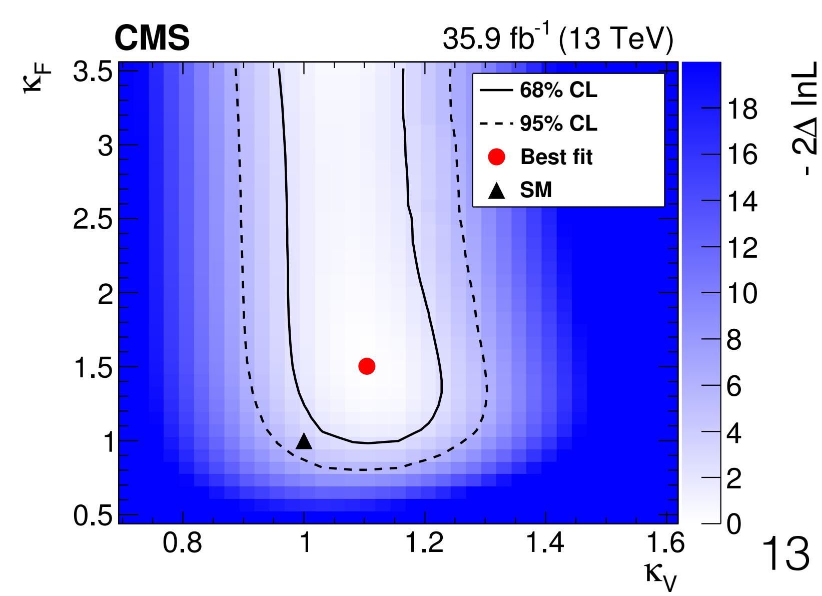
Simultaneous fit to measure the cross sections in the STXS stage 0 for $|y_H| < 2.5$

$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.28 \pm 0.10(\text{stat.}) \pm 0.11(\text{syst.})^{+0.10}_{-0.07}(\text{th.})$$

The best fit values for the two coupling modifiers are used in:

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

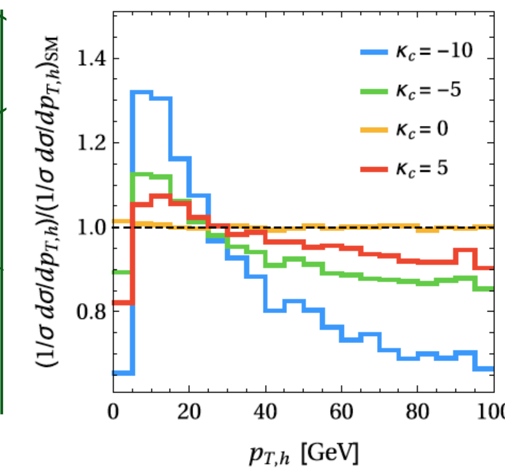
$$\kappa_F = 1.52^{+0.48}_{-0.41} \qquad \kappa_V = 1.10^{+0.08}_{-0.08}$$



ATLAS: Differential fiducial cross section

- Differential cross section as a function of Higgs p_T, N_{jet}, (for $\gamma\gamma$ mode also $|y_{\gamma\gamma}|$ and Jet P_T) are measured
  - High Higgs p_T region is sensitive to pQCD and new physics
  - N_{jet} is sensitive to QCD and composition of the production modes

PRL 118, 121801 (2017)



Normalisation to the N³LO listed in K-factor

$$\frac{d\sigma_i}{dx} = \frac{N_i^{sig}}{c_i\, \Delta x_i\, \mathcal{L}_{int}},$$

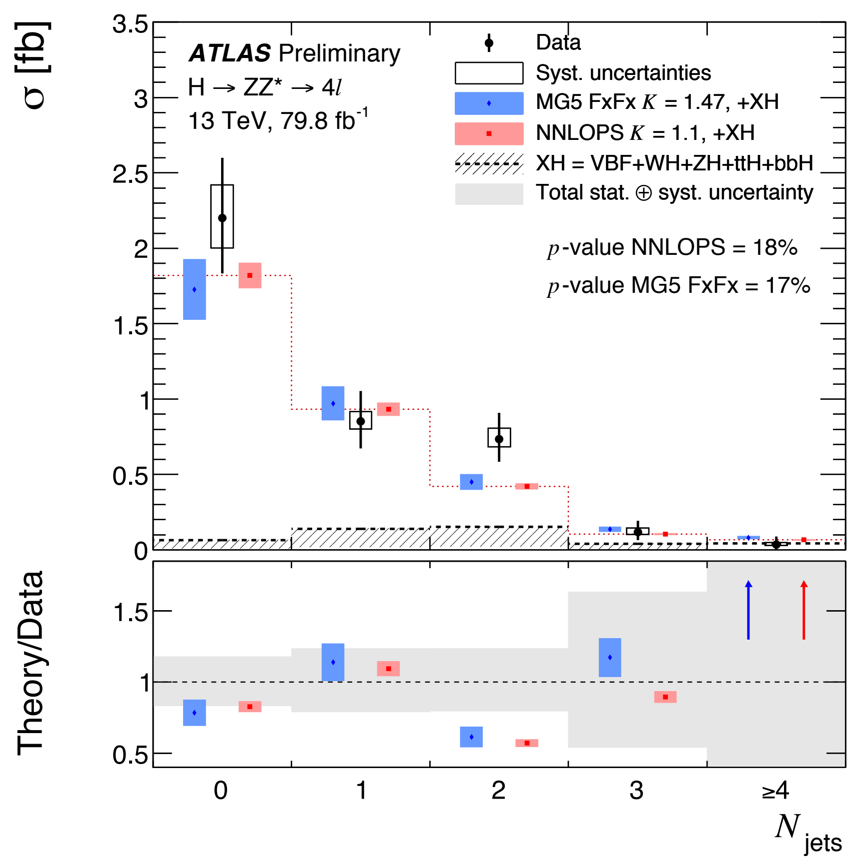
N_i : signal yield from data

c_i: correction factor for detector efficiency and resolution effect

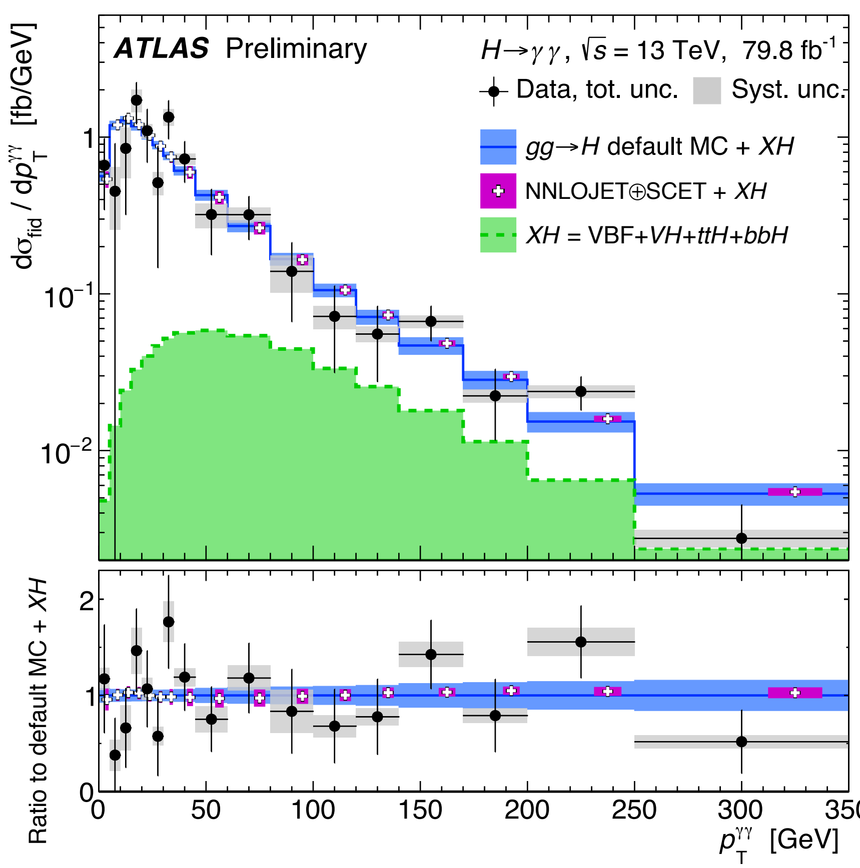
Δx_i: bin width

L : integrated luminosity

ATLAS-CONF-2018-018



ATLAS-CONF-2018-028



$\sigma_{fid,4\ell}$ = 4.04 ± 0.41(stat.) ± 0.22(syst.) fb

$\sigma_{SM,4\ell}$ = 3.35 ± 0.15 fb

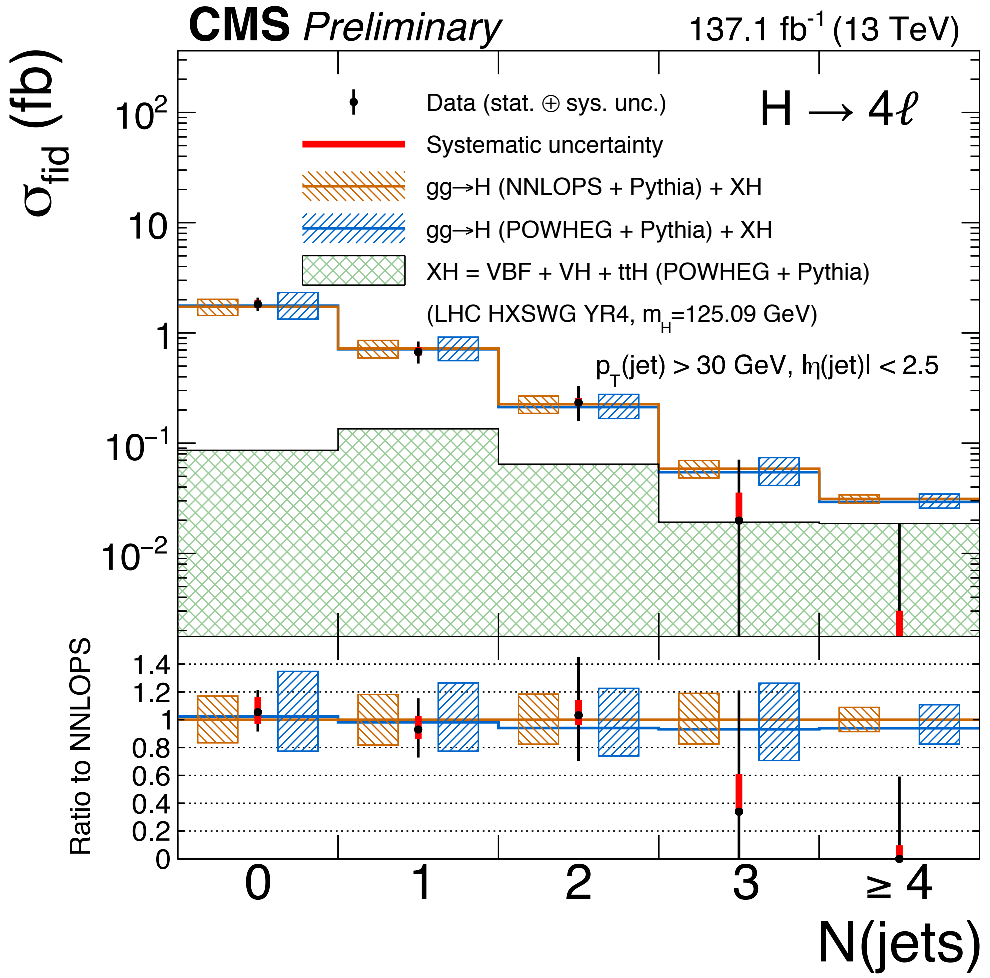
$\sigma_{fid,\gamma\gamma}$ = 60.4 ± 6.1(stat.) ± 6.0(exp.) ± 0.3(th.) fb

$\sigma_{SM,\gamma\gamma}$ = 63.5 ± 3.3 fb

CMS: Differential fiducial cross section

- Differential cross section as a function of Higgs p_T, N_{jet}, $|y_H|$ and Jet P_T are measured (for $\gamma\gamma$, measurement is done for jet kinematics)

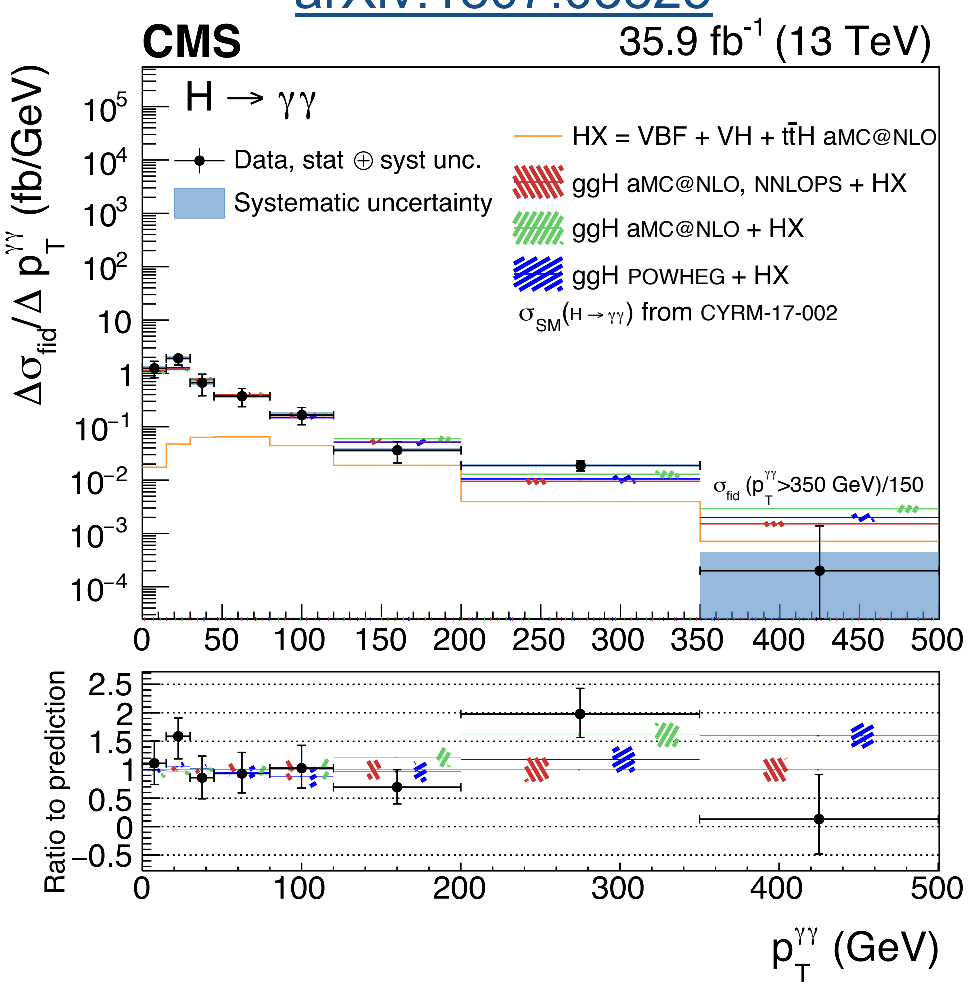
CMS-PAS-HIG-19-001



$$\sigma_{fid,4l} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{SM},4\text{l}} = 2.76 \pm 0.14\ \text{fb}$$

arXiv:1807.03825

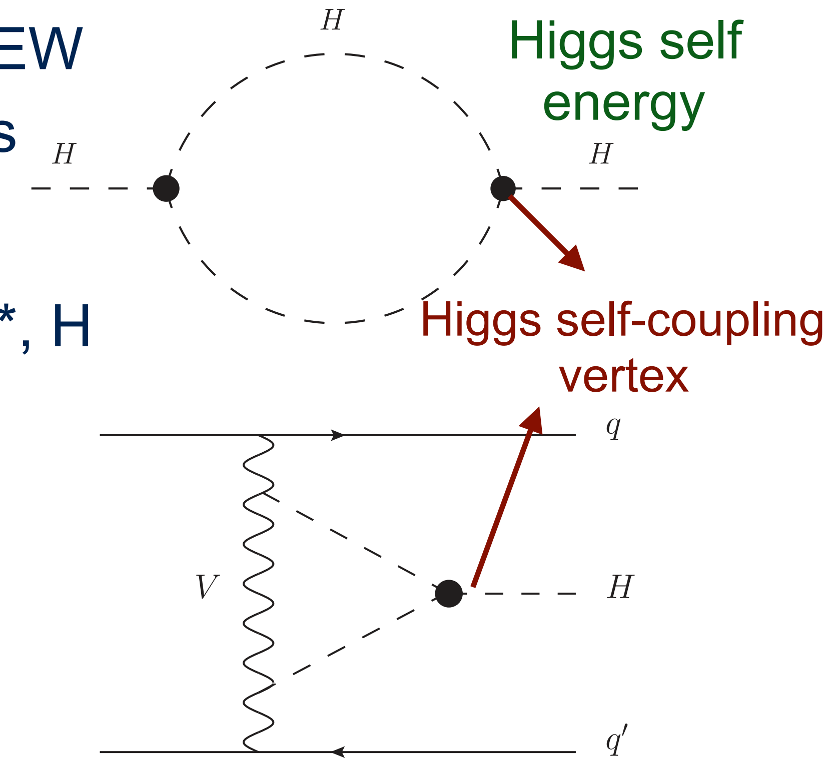


$$\sigma_{fid,\gamma\gamma} = 84 \pm 11(\text{stat.}) \pm 7(\text{syst.})\ \text{fb}$$

$$\sigma_{SM,\gamma\gamma} = 73 \pm 4\ \text{fb}$$

ATLAS: Higgs self coupling

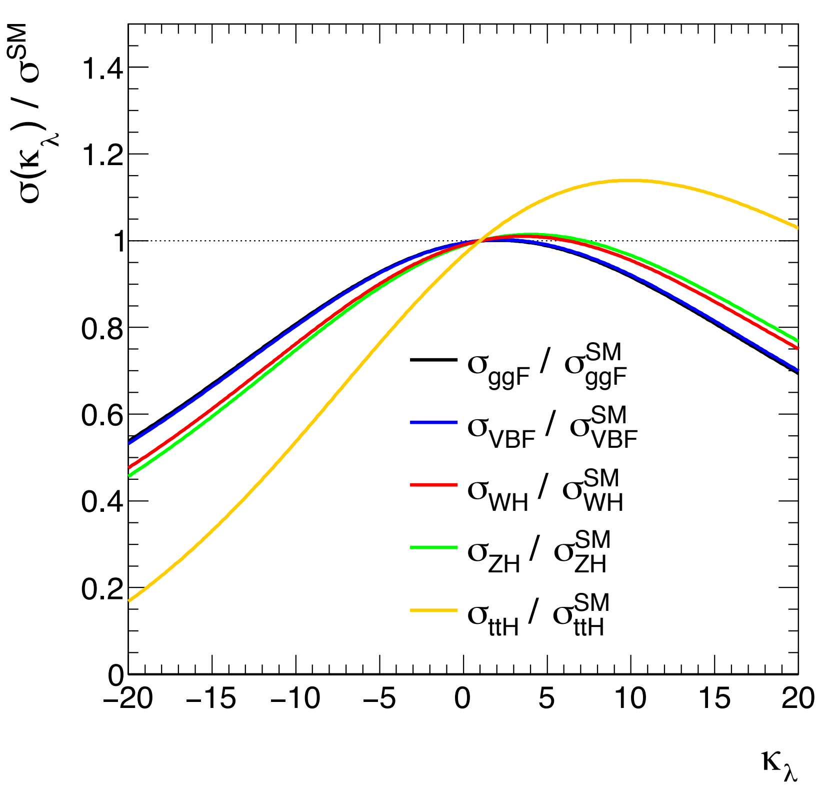
- Higgs boson trilinear self coupling (λ_{HHH}) contributes at NLO EW via Higgs self energy loop corrections and additional diagrams
  - Indirect constraint is set to λ_{HHH} from single Higgs
  - Global fit to single H decays: H → $\gamma\gamma$, H → ZZ*, H → WW*, H →$\tau\tau$ and VH (H →bb) to extract κ_λ
    - Luminosity ranging from 36.1 fb^{-1} to 79.1 fb^{-1}



single Higgs production in VBF

$$\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda) \equiv \frac{\sigma_i(\kappa_\lambda)}{\sigma_{SM,i}} \times \frac{BR_f(\kappa_\lambda)}{BR_{SM,f}} \qquad \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

ATL-PHYS-PUB-2019-009



POIs	Granularity	$\kappa_F{}^{+1\sigma}_{-1\sigma}$	$\kappa_V{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% C.L.]
κ_λ	STXS	1	1	$4.0^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
				$1.0^{+8.8}_{-4.4}$	$[-6.2, 14.4]$
κ_λ	inclusive	1	1	$4.6^{+4.3}_{-4.2}$	$[-2.9, 12.5]$
				$1.0^{+9.5}_{-4.3}$	$[-6.1, 15.0]$
κ_λ, κ_V	STXS	1	$1.04^{+0.05}_{-0.04}$	$4.8^{+7.4}_{-6.7}$	$[-6.7, 18.4]$
			$1.00^{+0.05}_{-0.04}$	$1.0^{+9.9}_{-6.1}$	$[-9.4, 18.9]$
κ_λ, κ_F	STXS	$0.99^{+0.08}_{-0.08}$	1	$4.1^{+4.3}_{-4.1}$	$[-3.2, 11.9]$
		$1.00^{+0.08}_{-0.08}$		$1.0^{+8.8}_{-4.4}$	$[-6.3, 14.4]$

CMS: Higgs anomalous coupling

- Search for anomalous Higgs boson couplings to electroweak vector bosons with the $H\to4\ell$ (ϕ) and $H\to\tau\tau$ (CMS-HIG-17-034) decay channels in VBF and VH using data from Run 1 (25 fb^{-1}) and Run 2 (80 fb^{-1})
- HVV amplitude:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

a_2: CP-even interaction

a_3: CP-odd interaction (pure pseudo-scalar)

Λ_1: leading momentum expansion

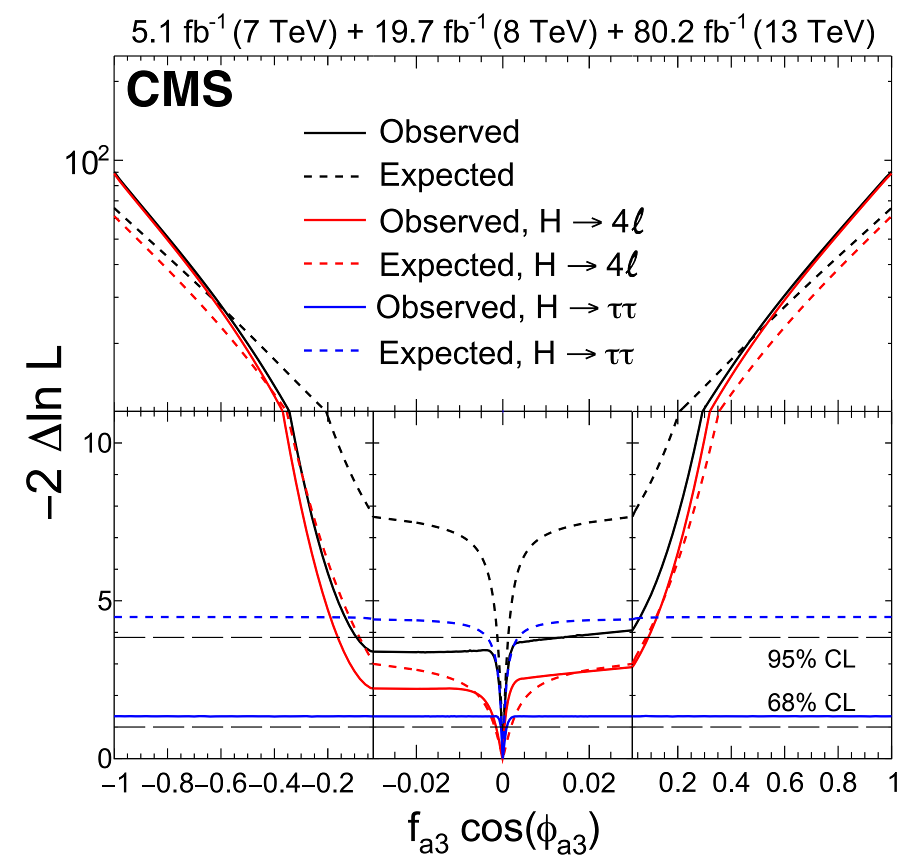
HVV amplitude parameterised as a function of f_{ai}:

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\Sigma_j |a_j|^2 \sigma_j}$$

HVV couplings expressed as effective cross-section fractions and phases ($\phi_{ai} = \arg(a_i/a_1)$):

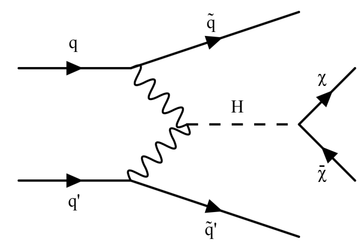
CMS-HIG-17-034

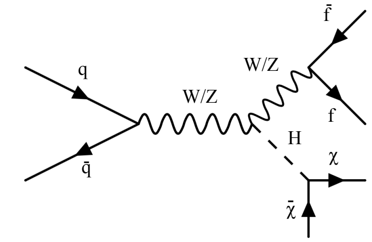
Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$

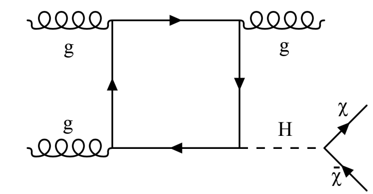


Higgs decay to invisible

- Search for H → invisible (select events with large missing transverse momentum)
  - ATLAS: V(had)H, Z(ℓℓ)H, and VBF
  - CMS: ggF, VH and VBF



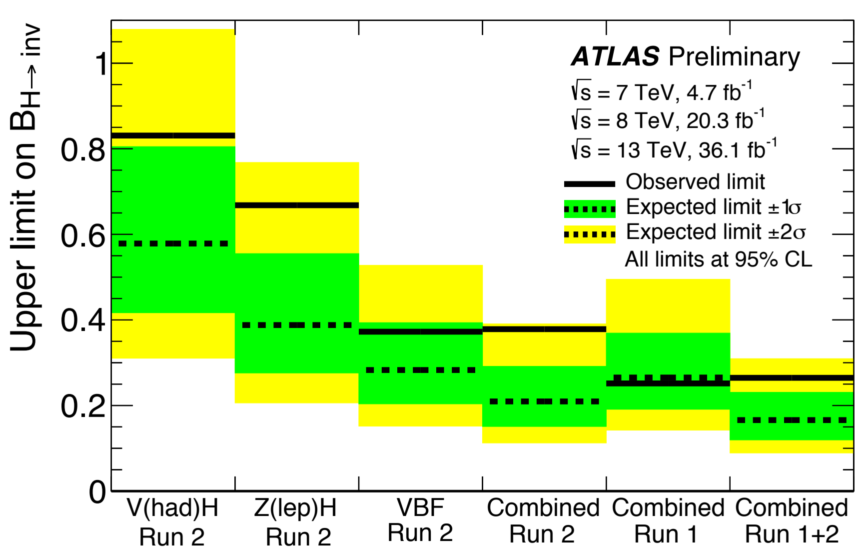


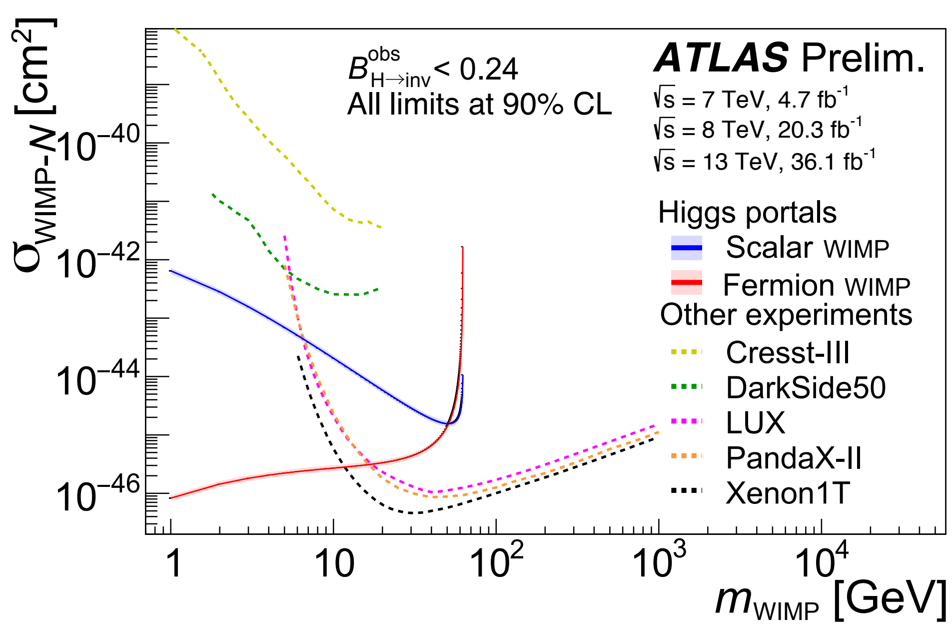


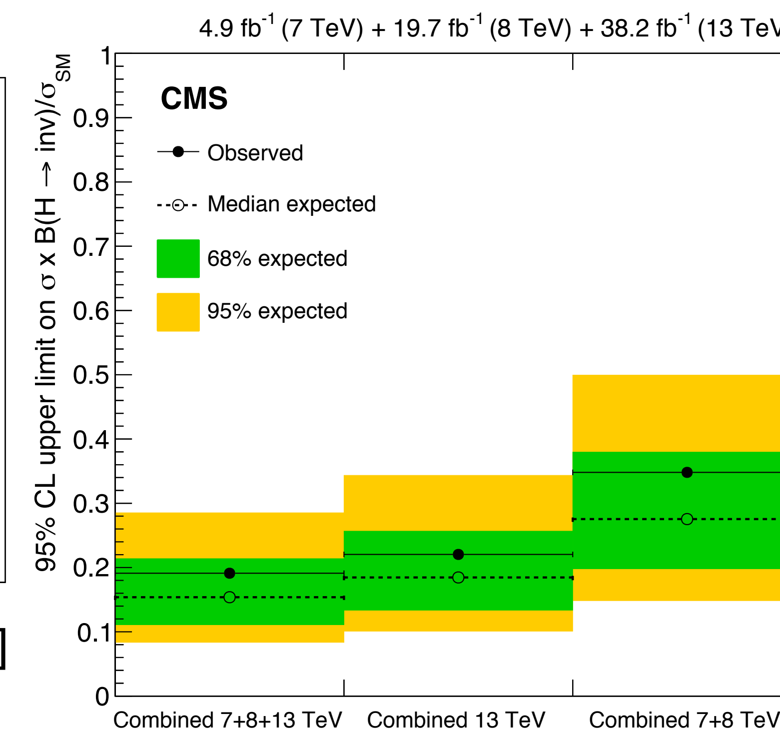
- Indirect limits on the spin-independent DM-nucleon scattering cross section in Higgs-portal models
  - In EFT, assume WIMP is either fermion or boson and use f_N = 0.308±0.018

arXiv:1809.05937

ATLAS-CONF-2018-054







Upper limits at 95 % CL obs(exp)

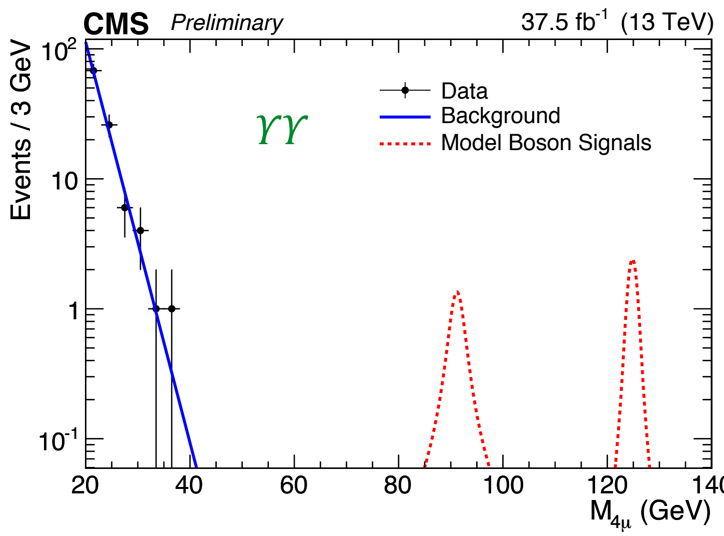
ATLAS (Run1 + Run2)
BR(H → invisible) < 0.26 (0.17)

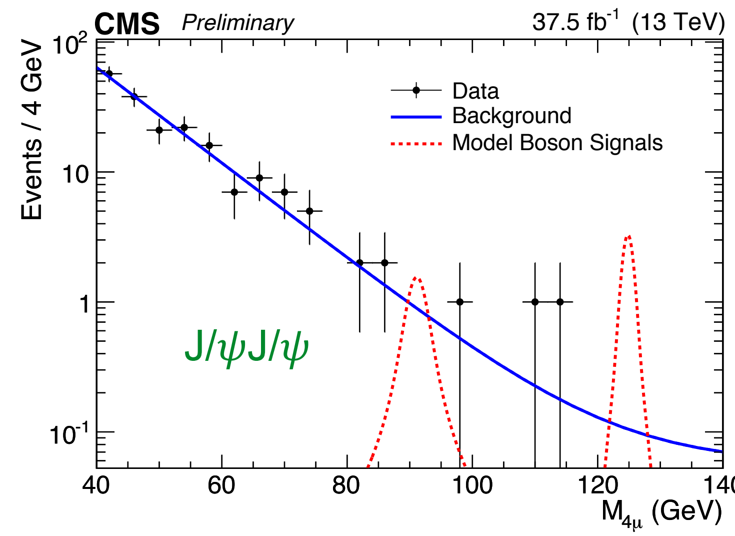
CMS (Run1 + Run2)
(σ/σ_{SM})BR(H → invisible) < 0.19 (0.15)

Rare decays

- Probe Higgs-charm couplings via Higgs rare decays
- CMS: Upper limits @95 C.L. set on the branching fractions of $H \to J/\psi J/\psi$ and $H \to \Upsilon(nS)\Upsilon(nS)$ n=1,2,3 and $J/\psi \to \mu\mu$, $\Upsilon(nS) \to \mu\mu$ with 36 fb^{-1}

CMS-PAS-HIG-18-025





SM prediction

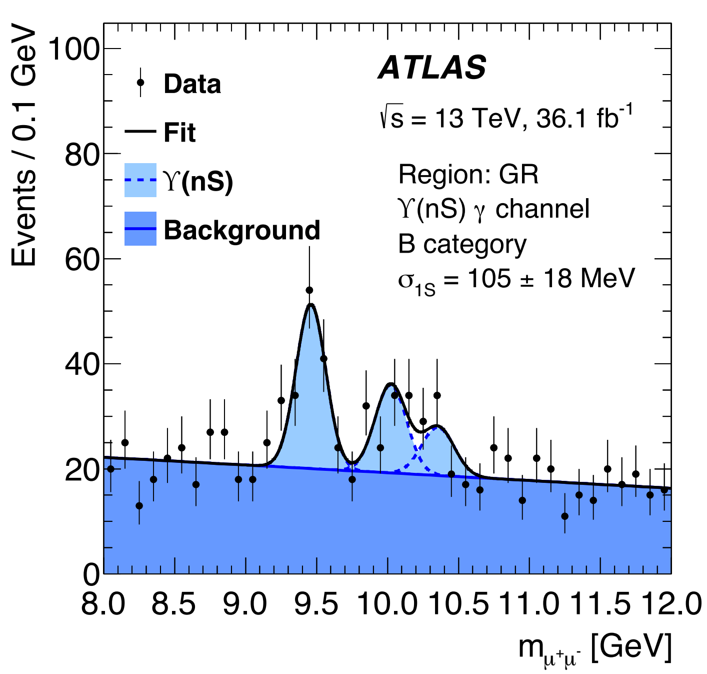
$B(H \to J/\psi J/\psi) = 1.5\times10^{-10}$

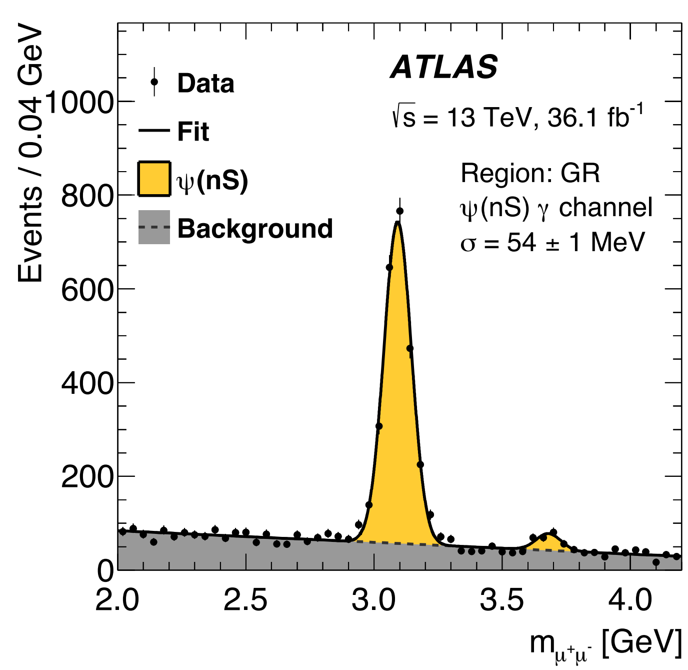
$B(H \to \Upsilon\Upsilon) = 2\times10^{-9}$

	observed	expected
$\mathcal{B}(H \to J/\psi J/\psi) \times 10^3$	1.8	$1.8^{+0.2}_{-0.1}$
$\mathcal{B}(H \to YY) \times 10^3$	1.4	1.4 ± 0.1
$\mathcal{B}(Z \to J/\psi J/\psi) \times 10^6$	2.2	$2.8^{+1.2}_{-0.7}$
$\mathcal{B}(Z \to YY) \times 10^6$	1.5	1.5 ± 0.1

- ATLAS: Upper limits @95 C.L. set on the branching fractions of $H \to J/\psi(\psi(2S))\gamma$ and $H \to \Upsilon(nS)\gamma$ n=1,2,3 and $J/\psi \to \mu\mu$, $\Upsilon(nS) \to \mu\mu$ with 36 fb^{-1}

PLB 786 (2018) 134





Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[10^{-4}]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[10^{-4}]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[10^{-6}]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[10^{-6}]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[10^{-4}]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[10^{-4}]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[10^{-4}]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[10^{-6}]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[10^{-6}]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[10^{-6}]$	$3.0^{+1.3}_{-0.8}$	4.8

SM prediction: $B(H \to J/\psi\gamma) = 2.99\times10^{-6}$

$B(H \to \psi(2S)\gamma) = 1.03\times10^{-6}$

$B(H \to \Upsilon(nS)\gamma) = (5{,}22,\ 1.42,\ 0.91)\times10^{-9}$ (n=1,2,3)

Summary

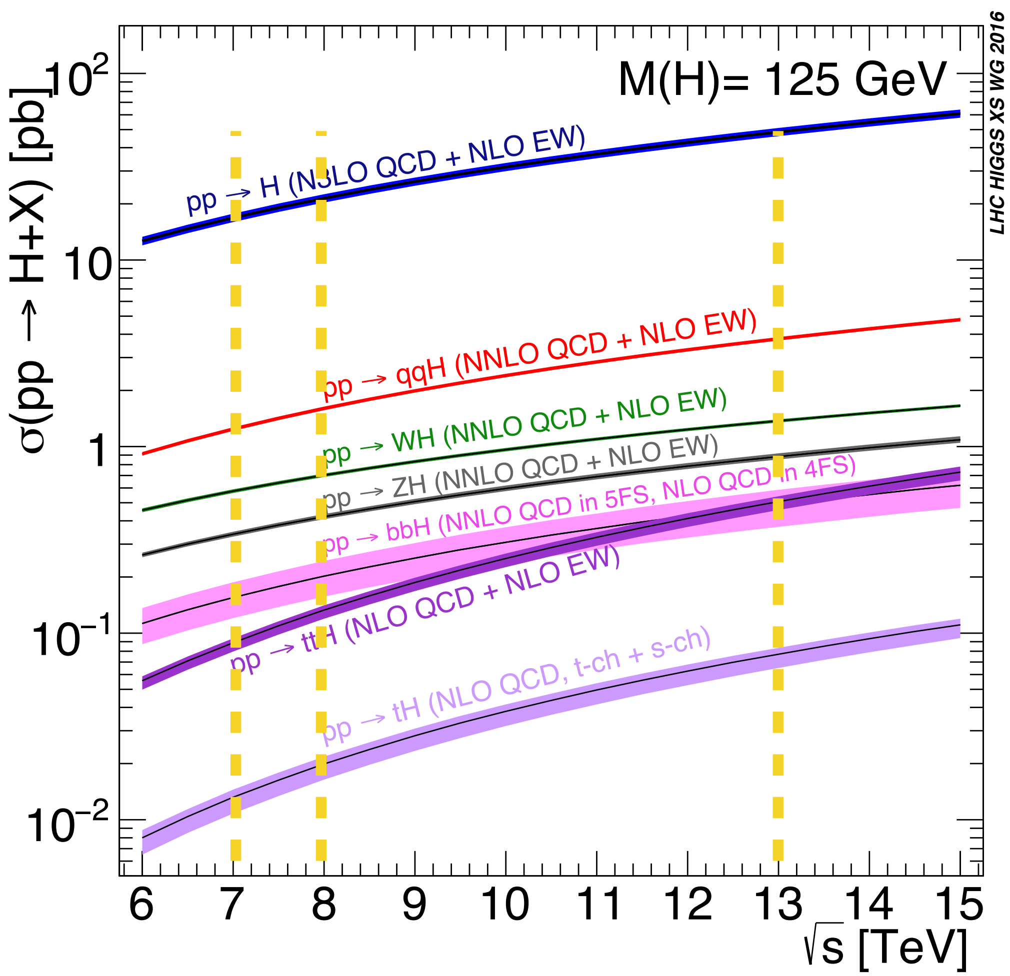
- Higgs discovery channels are investigated using pp collision data with integrated luminosity between 36 fb^{-1} and 137 fb^{-1} at $\sqrt{s}$ = 13 TeV (LHC Run 2)
  - Four main production mechanisms are observed
  - Differential cross sections are measured
  - Possible BSM contributions are explored

- So far, all the results are in agreement with the SM predictions

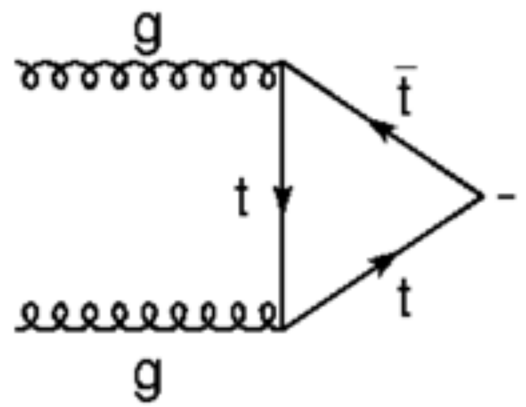
- ATLAS and CMS continue to improve the results and search for deviations from SM with the full LHC Run 2 data (~140 fb^{-1})

BACKUP

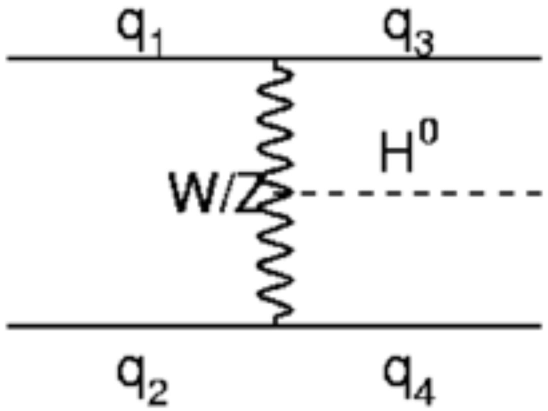
Higgs Production at LHC



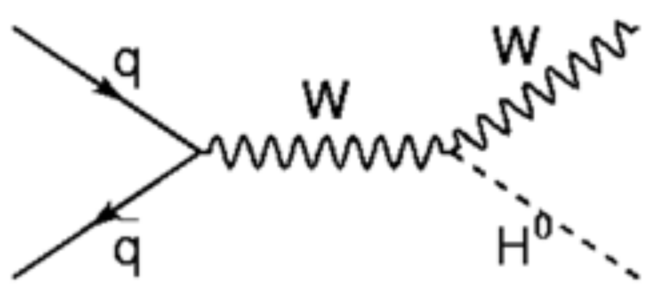
Gluon fusion process (87%)



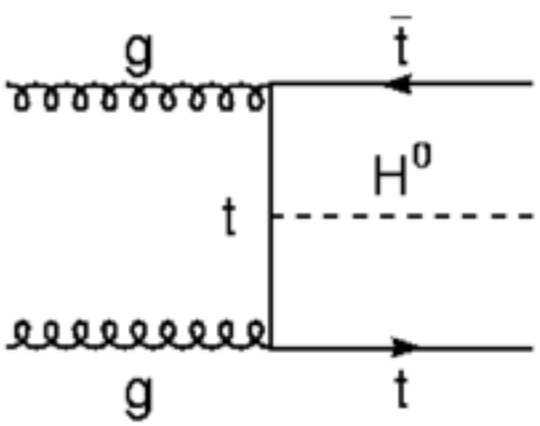
Vector Boson fusion (7%)



Vector Boson fusion (7%)



Vector Boson fusion (7%)

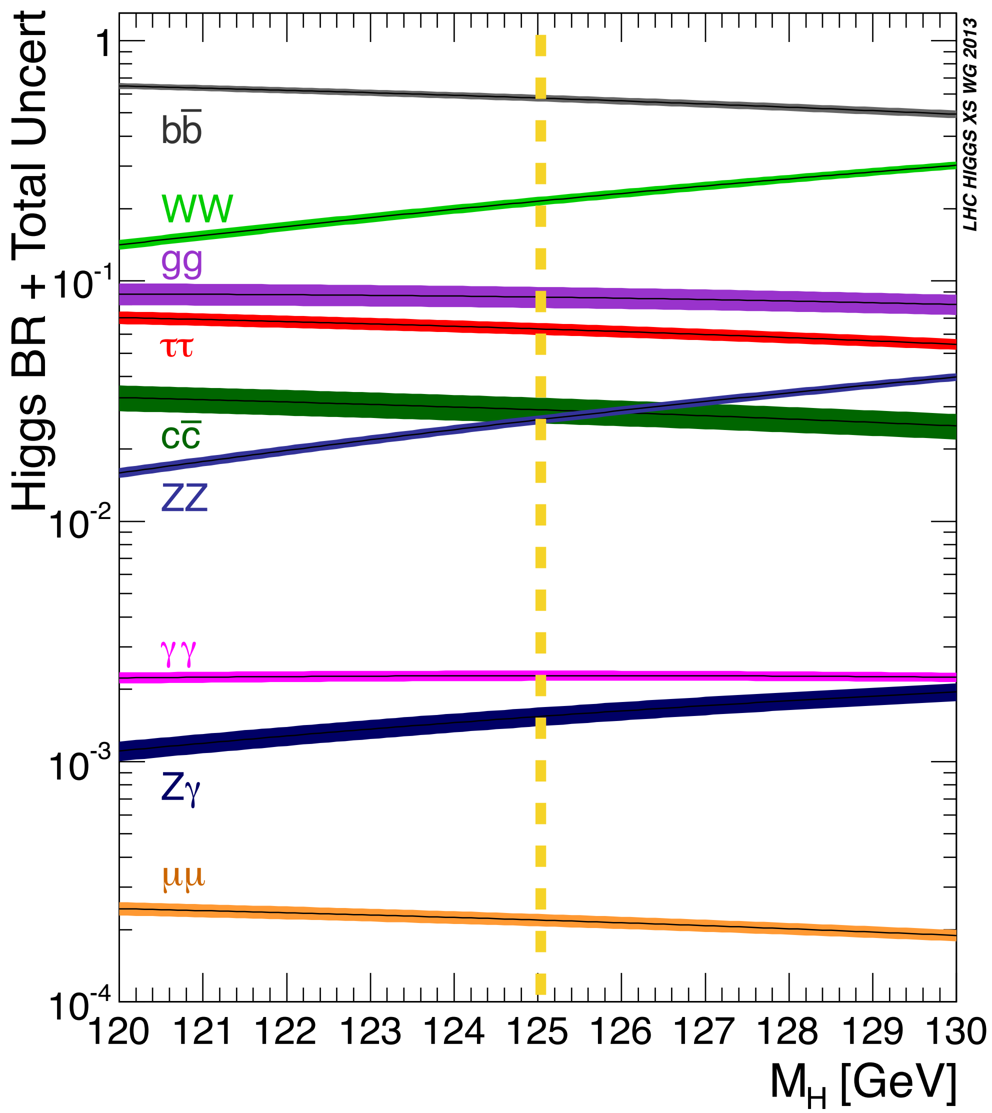


√8 TeV (Run 1) ⇒ √13 TeV (Run 2)

σ(pp→H) increased by ~2.5
σ(pp→ttH) increased by ~4

Cross section [pb] at √s = 13 TeV & m_H = 125.09 GeV			
ggH	VBF	(W/Z)H	(tt/bb)H
49	3.8	1.4/0.9	0.5/0.5

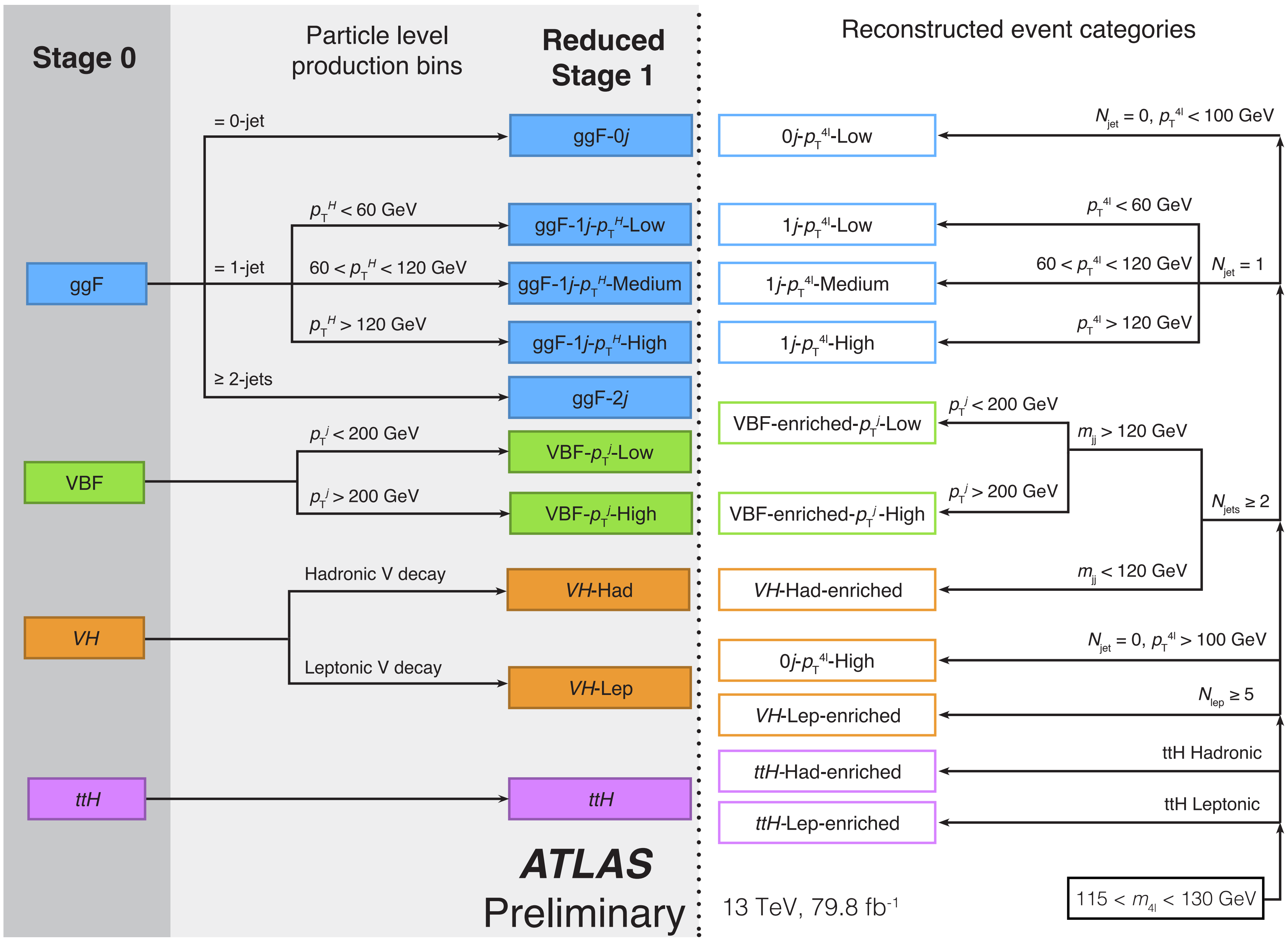
Higgs Production at LHC



Branching fraction at m_H = 125.09 GeV:
WW: 21%, ZZ: 2.64%
$Z\gamma$: 0.2% $\gamma\gamma$: 0.2%

- H→ WW*
  - High branching fraction
  - Poor mass resolution and large background
- H→ ZZ*→4ℓ and H → $(Z/\gamma)\gamma$ decays
  - Small branching fraction
  - Final states are fully reconstructable
  - S/B better than 2
  - Look for a narrow peak on a smooth background

ATLAS: 11 H →ZZ* →4ℓ categorise

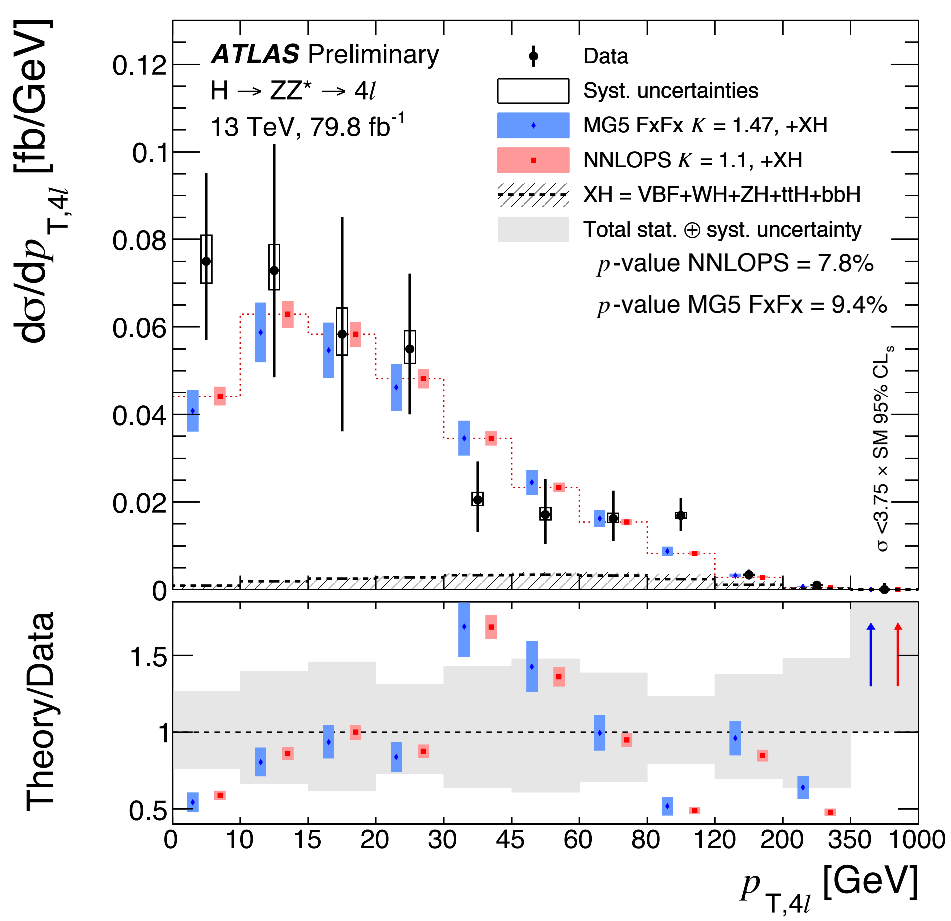


ATLAS: H $\rightarrow \gamma\gamma$ 29 categories

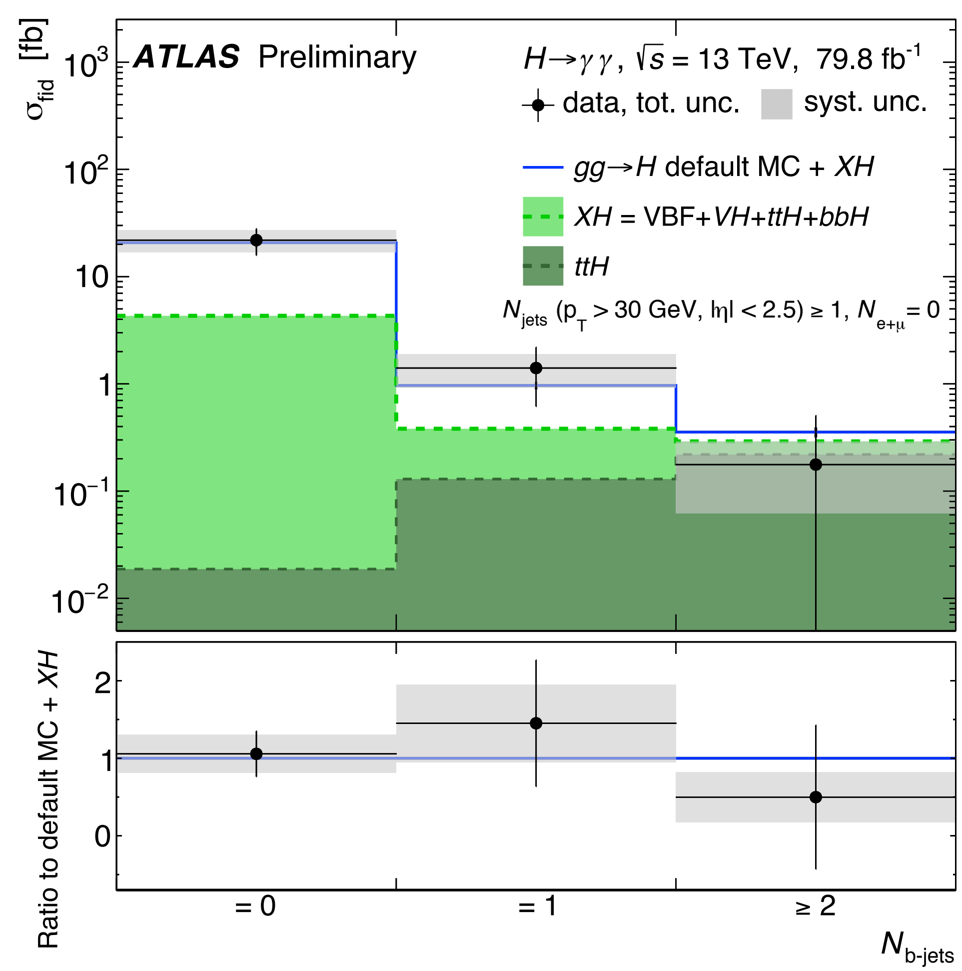
Category label	Selection
ttH lep BDT1	$N_{\rm lep} \geq 1,\ N_{b-\rm jet} \geq 1,\ {\rm BDT}_{\rm ttHlep} > 0.987$
ttH lep BDT2	$N_{\rm lep} \geq 1,\ N_{b-\rm jet} \geq 1,\ 0.942 < {\rm BDT}_{\rm ttHlep} < 0.987$
ttH lep BDT3	$N_{\rm lep} \geq 1,\ N_{b-\rm jet} \geq 1,\ 0.705 < {\rm BDT}_{\rm ttHlep} < 0.942$
ttH had BDT1	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ {\rm BDT}_{\rm ttHhad} > 0.996$
ttH had BDT2	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ 0.991 < {\rm BDT}_{\rm ttHhad} < 0.996$
ttH had BDT3	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ 0.971 < {\rm BDT}_{\rm ttHhad} < 0.991$
ttH had BDT4	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ 0.911 < {\rm BDT}_{\rm ttHhad} < 0.971$
VH dilep	$N_{\rm lep} \geq 2,\ 70\,{\rm GeV} \leq m_{\ell\ell} \leq 110\,{\rm GeV}$
VH lep High	$N_{\rm lep} = 1,\ \lvert m_{e\gamma} - 89\,{\rm GeV}\rvert > 5\,{\rm GeV},\ p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}} > 150\,{\rm GeV}$
VH lep Low	$N_{\rm lep} = 1,\ \lvert m_{e\gamma} - 89\,{\rm GeV}\rvert > 5\,{\rm GeV},\ p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}} < 150\,{\rm GeV},\ E_{\rm T}^{\rm miss}$ significance > 1
VH MET High	$150\,{\rm GeV} < E_{\rm T}^{\rm miss} < 250\,{\rm GeV},\ E_{\rm T}^{\rm miss}$ significance > 9 or $E_{\rm T}^{\rm miss} > 250\,{\rm GeV}$
VH MET Low	$80\,{\rm GeV} < E_{\rm T}^{\rm miss} < 150\,{\rm GeV},\ E_{\rm T}^{\rm miss}$ significance > 8
qqH BSM	$N_{\rm jets} \geq 2,\ p_{\rm T,j1} > 200\,{\rm GeV}$
VH had BDT tight	$60\,{\rm GeV} < m_{\rm jj} < 120\,{\rm GeV},\ {\rm BDT}_{\rm VH} > 0.78$
VH had BDT loose	$60\,{\rm GeV} < m_{\rm jj} < 120\,{\rm GeV},\ 0.35 < {\rm BDT}_{\rm VH} < 0.78$
VBF high-$p_{\rm T}^{Hjj}$ BDT tight	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1} + \eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} > 25\,{\rm GeV},\ {\rm BDT}_{\rm VBF}^{\rm high} > 0.47$
VBF high-$p_{\rm T}^{Hjj}$ BDT loose	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1} + \eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} > 25\,{\rm GeV},\ -0.32 < {\rm BDT}_{\rm VBF}^{\rm high} < 0.47$
VBF low-$p_{\rm T}^{Hjj}$ BDT tight	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1} + \eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} < 25\,{\rm GeV},\ {\rm BDT}_{\rm VBF}^{\rm low} > 0.87$
VBF low-$p_{\rm T}^{Hjj}$ BDT loose	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1} + \eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} < 25\,{\rm GeV},\ 0.26 < {\rm BDT}_{\rm VBF}^{\rm low} < 0.87$
ggF 2J BSM	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \geq 200\,{\rm GeV}$
ggF 2J High	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \in [120, 200]$ GeV
ggF 2J Med	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \in [60, 120]$ GeV
ggF 2J Low	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \in [0, 60]$ GeV
ggF 1J BSM	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \geq 200\,{\rm GeV}$
ggF 1J High	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \in [120, 200]$ GeV
ggF 1J Med	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \in [60, 120]$ GeV
ggF 1J Low	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \in [0, 60]$ GeV
ggF 0J Fwd	$N_{\rm jets} = 0$, one photon with $\lvert\eta\rvert > 0.95$
ggF 0J Cen	$N_{\rm jets} = 0$, two photons with $\lvert\eta\rvert \leq 0.95$

Differential fiducial cross section

ATLAS-CONF-2018-018



ATLAS-CONF-2018-028



CMS: Combination of Production Cross Section

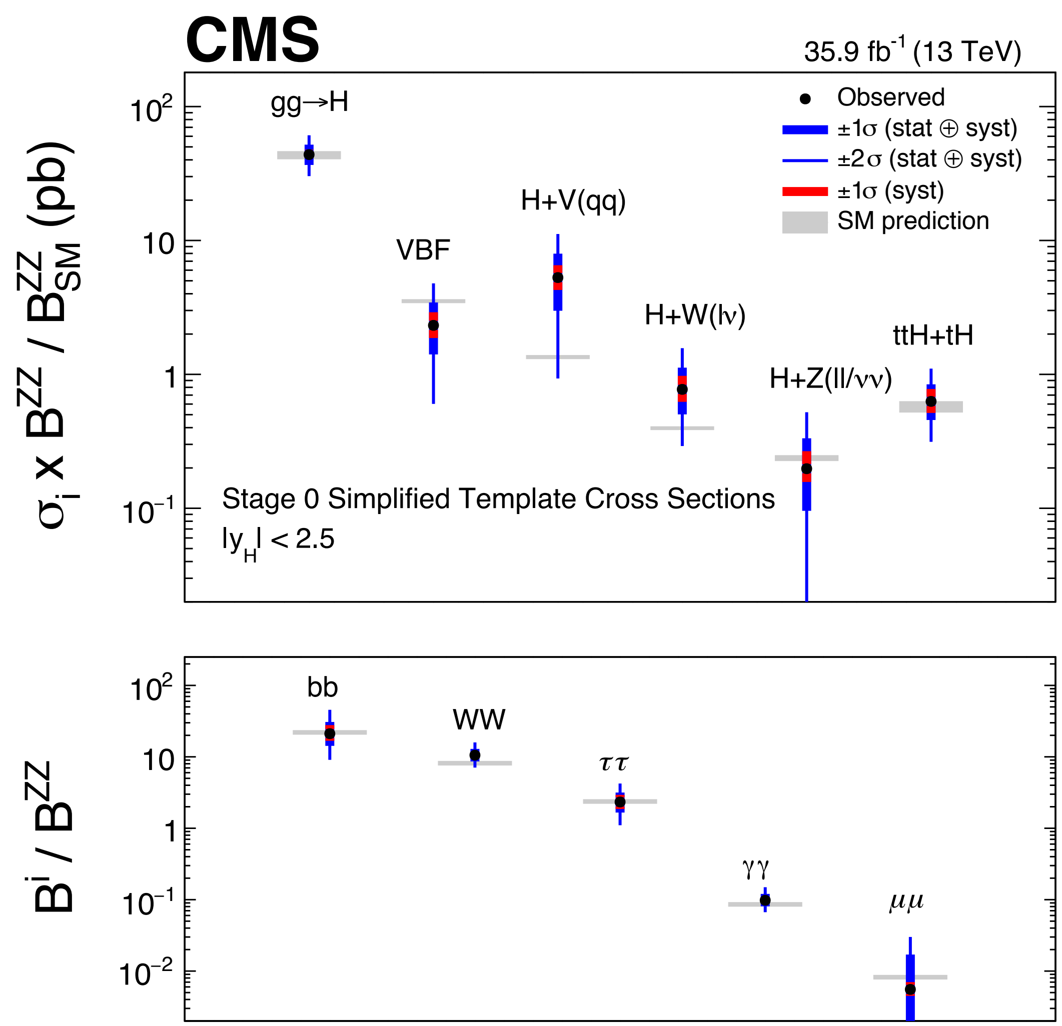
- Combine H → ZZ, WW, $\gamma\gamma$, tt, bb, and $\mu\mu$ at 13 TeV with 36 fb^{-1}
- Compared to the Run 1 results - improvement in the precision of the measurements
  - ggH by 50%, up to 20% for the VBF and VH

CMS *Supplementary* 35.9 fb^{-1} (13 TeV)

	$\sigma_{ggH}B^{ZZ}$	$\sigma_{VBF}B^{ZZ}$	$\sigma_{H+V(qq)}B^{ZZ}$	$\sigma_{H+W(l\nu)}B^{ZZ}$	$\sigma_{H+Z(ll/\nu\nu)}B^{ZZ}$	$\sigma_{ttH}B^{ZZ}$	B^{bb}/B^{ZZ}	$B^{\tau\tau}/B^{ZZ}$	B^{WW}/B^{ZZ}	$B^{\gamma\gamma}/B^{ZZ}$	$B^{\mu\mu}/B^{ZZ}$
$\sigma_{ggH}B^{ZZ}$	1.00	0.13	-0.05	0.28	0.18	0.38	-0.28	-0.27	-0.73	-0.67	-0.04
$\sigma_{VBF}B^{ZZ}$	0.13	1.00	0.13	0.12	0.08	0.17	-0.13	-0.27	-0.26	-0.30	0.00
$\sigma_{H+V(qq)}B^{ZZ}$	-0.05	0.13	1.00	0.09	0.06	0.11	-0.09	-0.36	-0.07	-0.32	0.00
$\sigma_{H+W(l\nu)}B^{ZZ}$	0.28	0.12	0.09	1.00	0.24	0.37	-0.63	-0.18	-0.31	-0.31	0.00
$\sigma_{H+Z(ll/\nu\nu)}B^{ZZ}$	0.18	0.08	0.06	0.24	1.00	0.24	-0.42	-0.13	-0.20	-0.20	0.00
$\sigma_{ttH}B^{ZZ}$	0.38	0.17	0.11	0.37	0.24	1.00	-0.52	-0.32	-0.45	-0.38	-0.02
B^{bb}/B^{ZZ}	-0.28	-0.13	-0.09	-0.63	-0.42	-0.52	1.00	0.21	0.33	0.31	0.02
$B^{\tau\tau}/B^{ZZ}$	-0.27	-0.27	-0.36	-0.18	-0.13	-0.32	0.21	1.00	0.28	0.40	0.00
B^{WW}/B^{ZZ}	-0.73	-0.26	-0.07	-0.31	-0.20	-0.45	0.33	0.28	1.00	0.58	0.03
$B^{\gamma\gamma}/B^{ZZ}$	-0.67	-0.30	-0.32	-0.31	-0.20	-0.38	0.31	0.40	0.58	1.00	0.03
$B^{\mu\mu}/B^{ZZ}$	-0.04	0.00	0.00	0.00	0.00	-0.02	0.02	0.00	0.03	0.03	1.00

ρ (colour scale from −1 to 1)

arXiv:1809.10733



Global strength for $|y_H|<2.5$

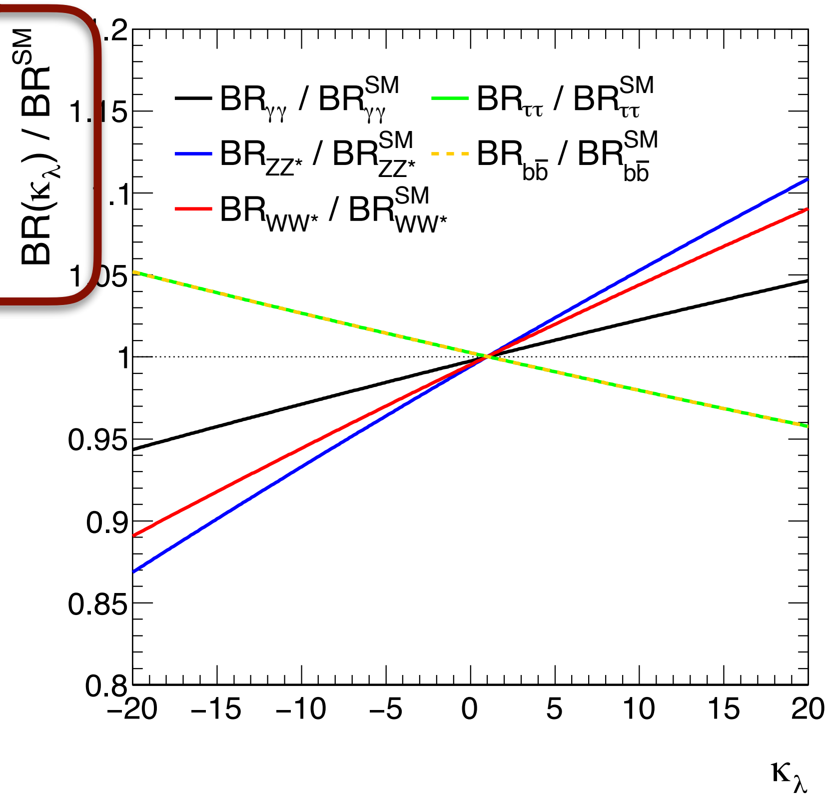
$$\mu = 1.17 \pm 0.06(\text{stat})^{+0.06}_{-0.05}(\text{sig th.}) \pm 0.06(\text{other syst})$$

ATLAS: Rare decays

- ATLAS: Branchings fraction of H $\rightarrow$ J/ψ(ψ(2S)) γ and H $\rightarrow$ Υ(nS)γ n=1,2,3 and J/ψ $\rightarrow$ $\mu\mu$, Υ(nS) $\rightarrow$ $\mu\mu$ with 36 fb^{-1}

$m_{\mu^+\mu^-}$ mass range [GeV]		Observed (expected) background $m_{\mu^+\mu^-\gamma}$ mass range [GeV] 81–101		120–130		Z signal for $\mathcal{B} = 10^{-6}$	H signal for $\mathcal{B} = 10^{-3}$
$J/\psi\,\gamma$	2.9–3.3	92	(89 ± 6)	20	(23.6 ± 1.3)	13.7 ± 1.1	22.2 ± 1.9
$\psi(2S)\,\gamma$	3.5–3.9	43	(42 ± 5)	8	(10.0 ± 0.8)	1.82 ± 0.14	2.96 ± 0.25
$\Upsilon(1S)\,\gamma$	9.0–10.0	115	(126 ± 8)	9	(13.6 ± 1.2)	7.8 ± 0.6	10.7 ± 0.9
$\Upsilon(2S)\,\gamma$	9.5–10.5	106	(121 ± 8)	8	(12.6 ± 1.4)	5.9 ± 0.5	8.1 ± 0.7
$\Upsilon(3S)\,\gamma$	10.0–11.0	112	(113 ± 8)	7	(10.6 ± 1.2)	7.1 ± 0.6	9.2 ± 0.8

ATLAS - Higgs self-coupling



$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
$C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52
K_{EW}^i	1.049	0.932	0.947	0.93	1.014
κ_i^2	κ_F^2	κ_V^2	κ_V^2	κ_V^2	κ_F^2

decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right]$$

- K_{EW} - accounts for the complete NLO EW correction of the production cross section for the process *i* in the SM hypothesis
- C_1 is a process and kinematics-dependent linear coefficient that provides the sensitivity of the measurement to κ_λ

$$Z_H^{\mathrm{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536 \times 10^{-3}$$