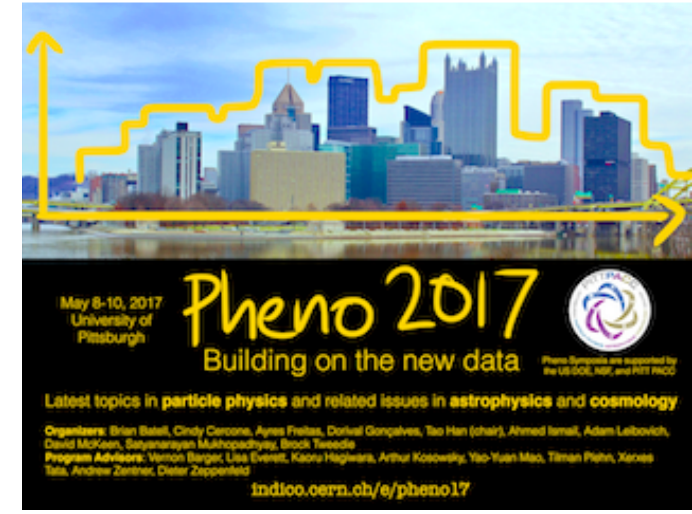


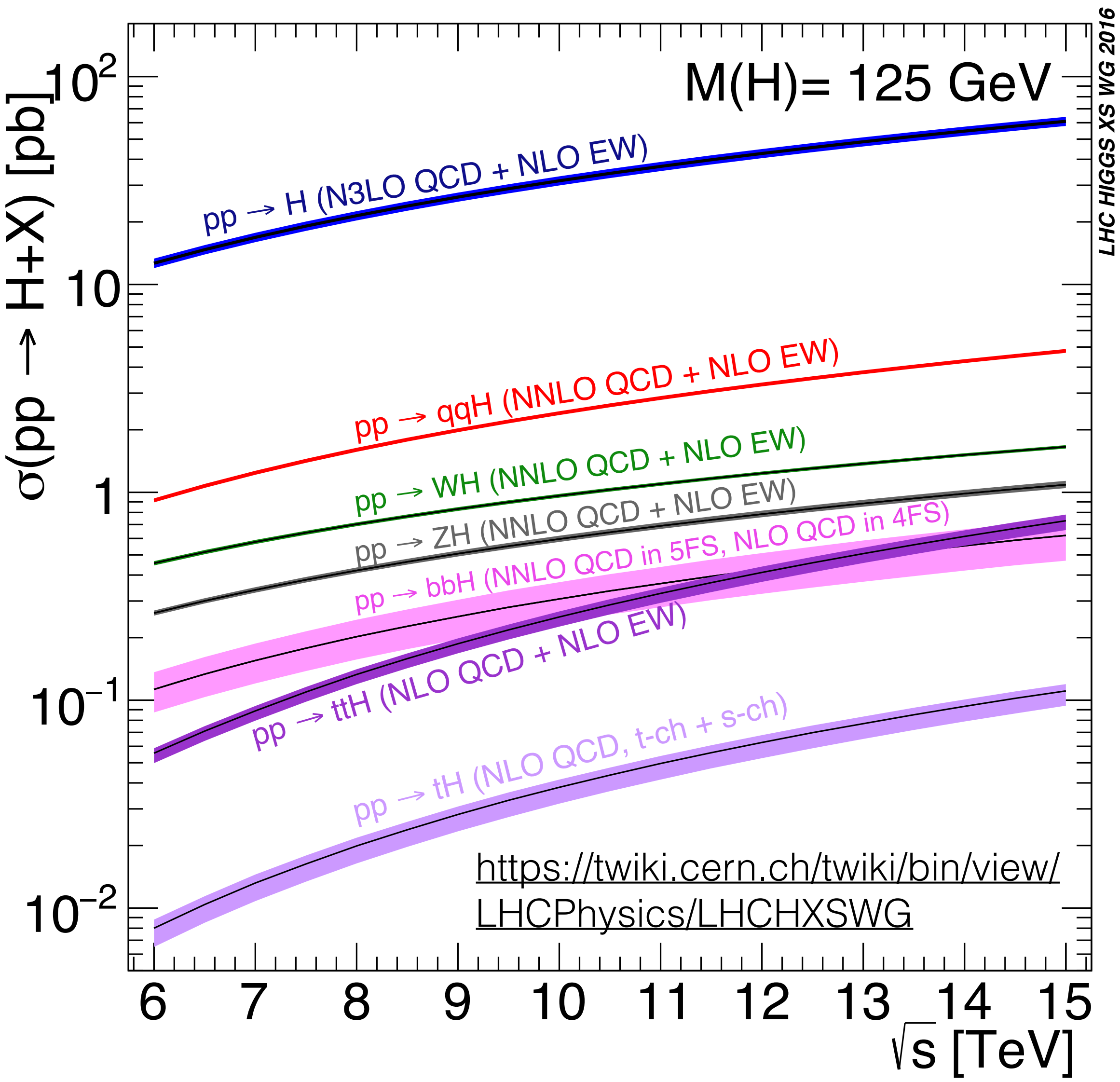
Measurement of cross sections and couplings of the Higgs Boson in boson decay channels with the ATLAS detector

Valerio Bortolotto
on Behalf of the ATLAS Collaboration

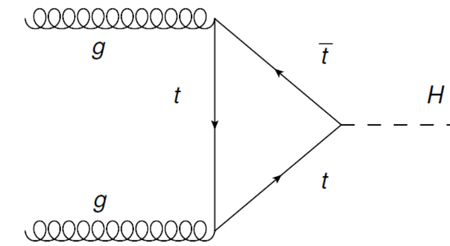
Overview

- The Standard Model Higgs Boson at LHC
    - Production Cross Section
    - Higgs Branching Ratio
- Analyses Overview
    - $H \rightarrow ZZ$
    - $H \rightarrow \gamma\gamma$
    - $H \rightarrow WW$
- Conclusions

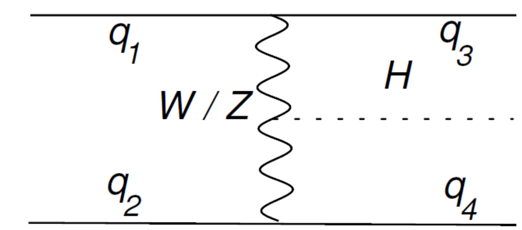
The SM Higgs Boson at LHC



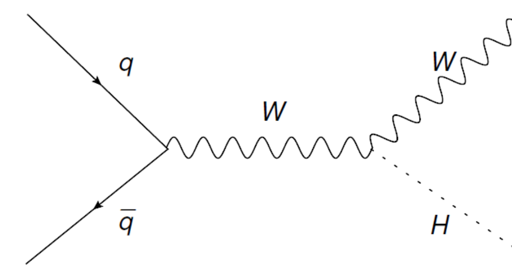
Gluon Gluon Fusion (ggF)



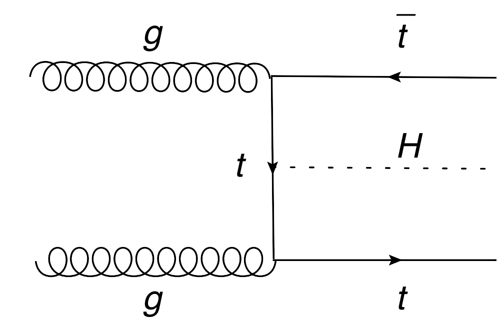
Vector Boson Fusion (VBF)



Associated Production with a vector boson (VH)



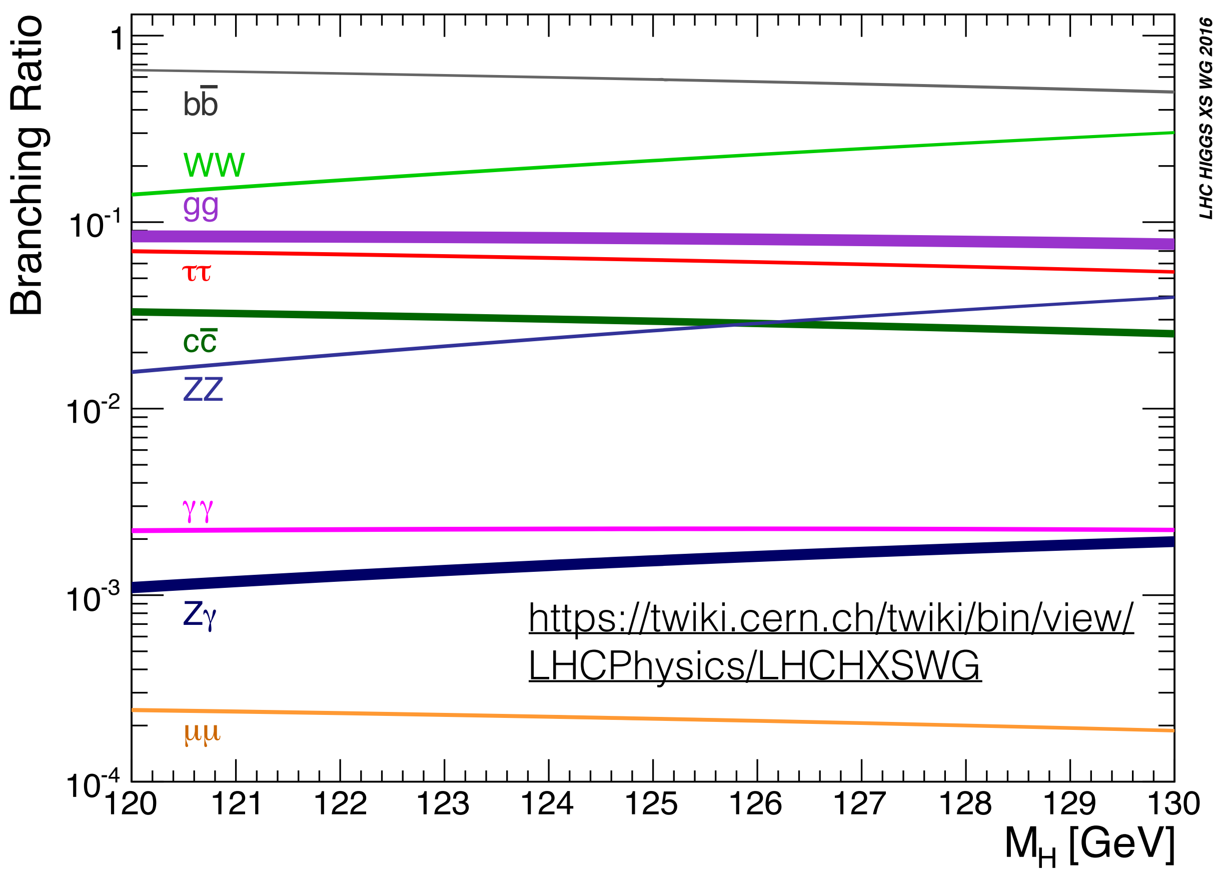
Associated Production with top quarks (ttH)



Higgs boson production Cross Section (pb) at LHC m(H) = 125.09 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG	ggF	VBF	WH	ZH	ttH
7 TeV	16,82	1,24	0,58	0,34	1,23 10^{-2}
8 TeV	21,39	1,60	0,70	0,42	1,87 10^{-2}
13 TeV	48,52	3,78	1,37	0,88	8,20 10^{-2}

The SM Higgs Boson at LHC



H→ WW

Easy identification in lvlv final state but poor mass resolution

H→ ZZ

Easy identification in 4l final state and good mass resolution (low statistics)

H→ γγ

Easy identification and good mass resolution

- Possible to measure cross sections for specific production modes in specific bin (Simplified Template Cross Section) → maximize the sensitivity of the measurements and minimize their theory dependence

- H → WW and H → ZZ really powerful in the VH and VBF to study Higgs boson coupling with vector boson

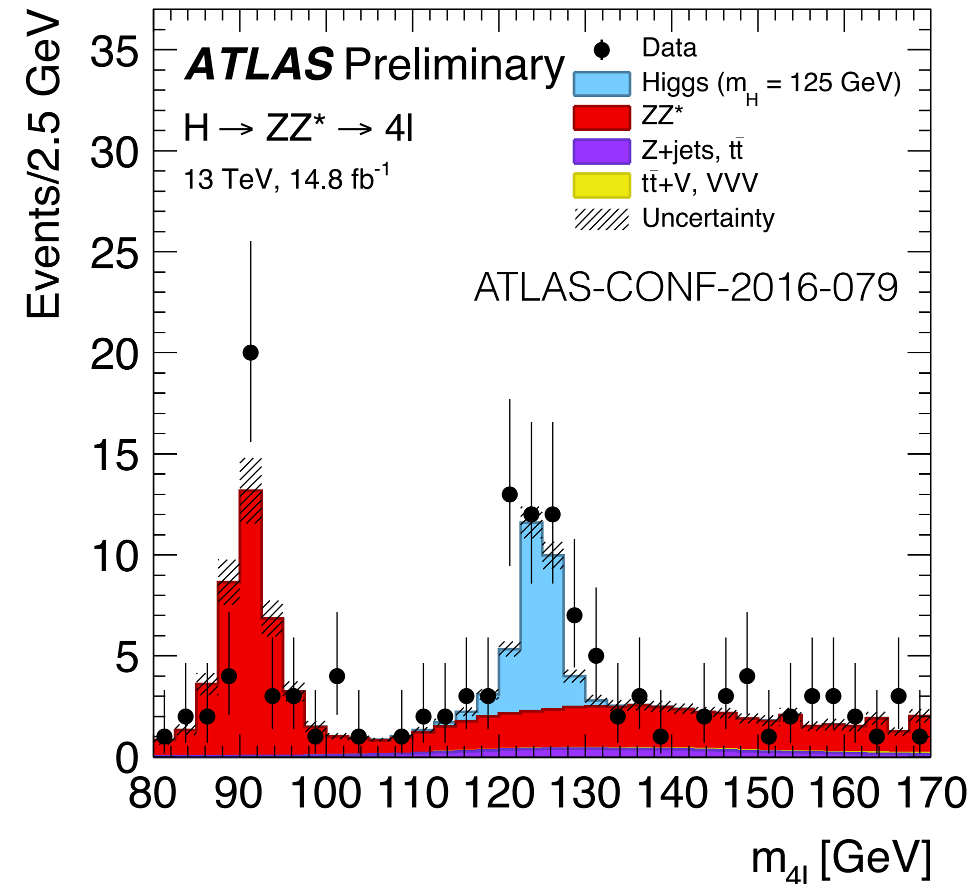
Higgs boson Branching Ratio (BR) m(H) = 125.09 GeV

H→ WW	H→ ZZ	H→ γγ
21,52%	2,64%	0,227%

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

H → ZZ in 4 leptons final state

- Main selections:
  - Jet P_T
  - Leptons isolation and P_T
    (5 GeV for Muons and 7 GeV for Electrons)
  - Two pairs of same flavours leptons
    opposite-charge
  - P_T thresholds on leptons
    (20, 15 and 10 GeV)
  - Leading di-lepton inv mass m_{12}
    50 GeV < m_{12} < 106 GeV
  - Sub leading di-lepton inv mass m_{34}
    12 GeV < m_{34} < 115 GeV
  - Selecting a smaller range for
    4-leptons invariant mass



- For 14.8 fb^{-1} at $\sqrt{s}$ = 13 TeV and 118 < m_{4l} < 129 GeV

Final State	Signal full mass range	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$ ttV, VVV, WZ	S/B	Expected	Observed
4μ	8.8 ± 0.6	8.2 ± 0.6	3.11 ± 0.30	0.31 ± 0.04	2.4	11.6 ± 0.7	16
$2e2\mu$	6.1 ± 0.4	5.5 ± 0.4	2.19 ± 0.21	0.30 ± 0.04	2.2	8.0 ± 0.4	12
$2\mu 2e$	4.8 ± 0.4	4.4 ± 0.4	1.39 ± 0.16	0.47 ± 0.05	2.3	6.2 ± 0.4	10
$4e$	4.8 ± 0.5	4.2 ± 0.4	1.46 ± 0.18	0.46 ± 0.05	2.2	6.1 ± 0.4	6
Total	24.5 ± 1.8	22.3 ± 1.6	8.2 ± 0.8	1.54 ± 0.18	2.3	32.0 ± 1.8	44

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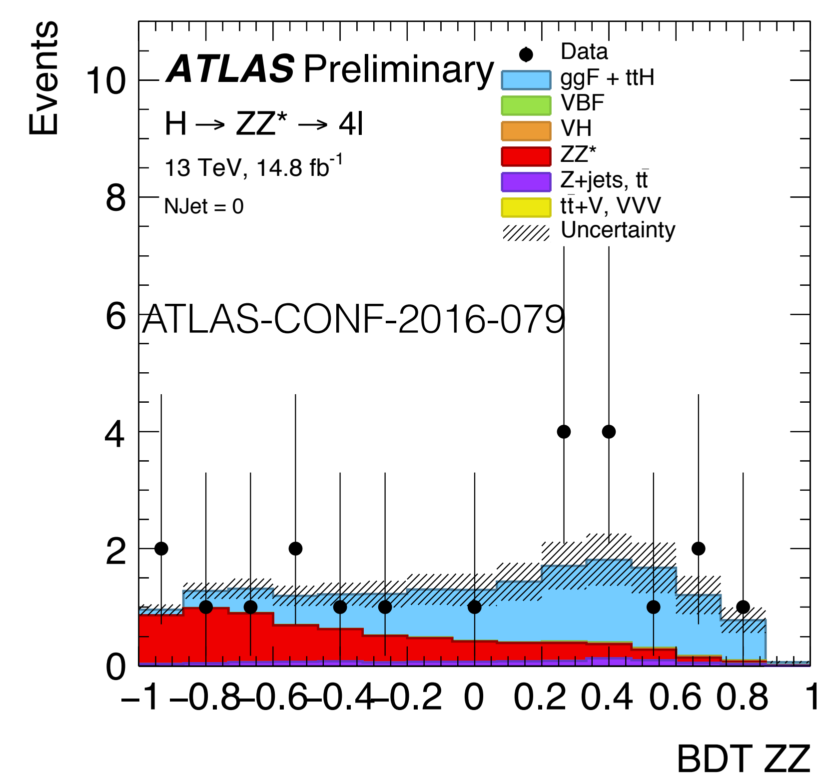

N_{jet} = 0 and 118 < m_{4l} < 129 GeV

H → ZZ → 4l Fiducial Cross Sections

- Fiducial Volume:

↓

Truth selections →

Lepton definition	
Muons: $p_{\mathrm{T}} > 5$ GeV, $\|\eta\| < 2.7$	Electrons: $p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	Leading leptons $p_{\mathrm{T}} > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV

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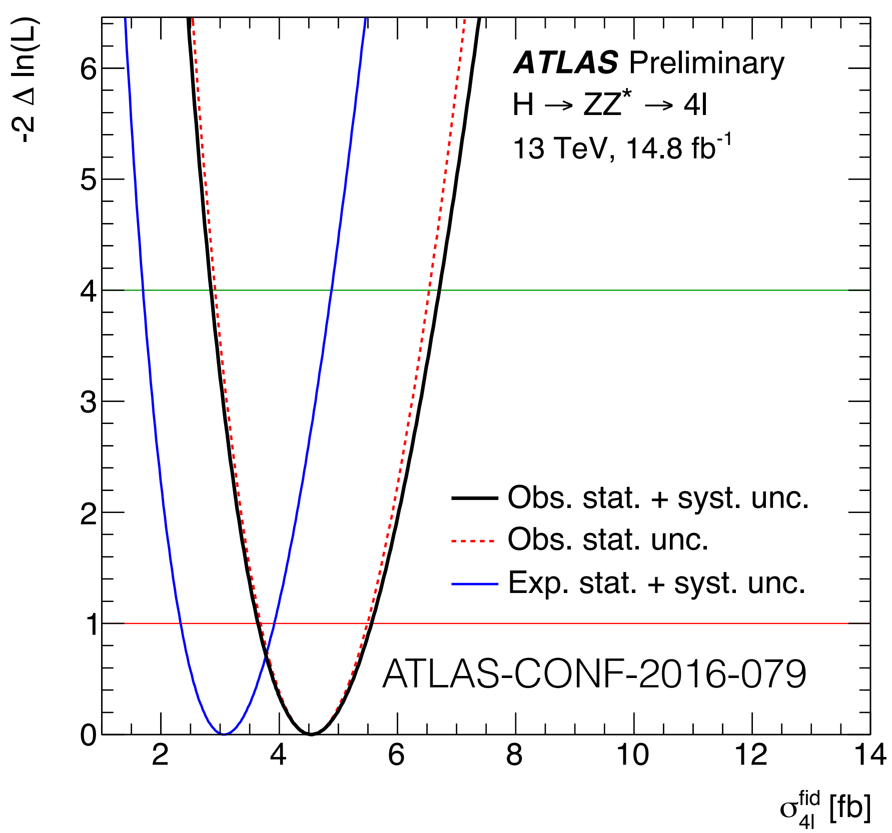
- Using the m_{4l} distribution as observable:



Final state	measured σ_{fid} [fb]	$\sigma_{\mathrm{fid,SM}}$ [fb]
4μ	$1.28\,^{+0.48}_{-0.40}$	$0.93\,^{+0.06}_{-0.08}$
$4e$	$0.81\,^{+0.51}_{-0.38}$	$0.73\,^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\,^{+0.58}_{-0.46}$	$0.67\,^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\,^{+0.49}_{-0.40}$	$0.76\,^{+0.05}_{-0.06}$

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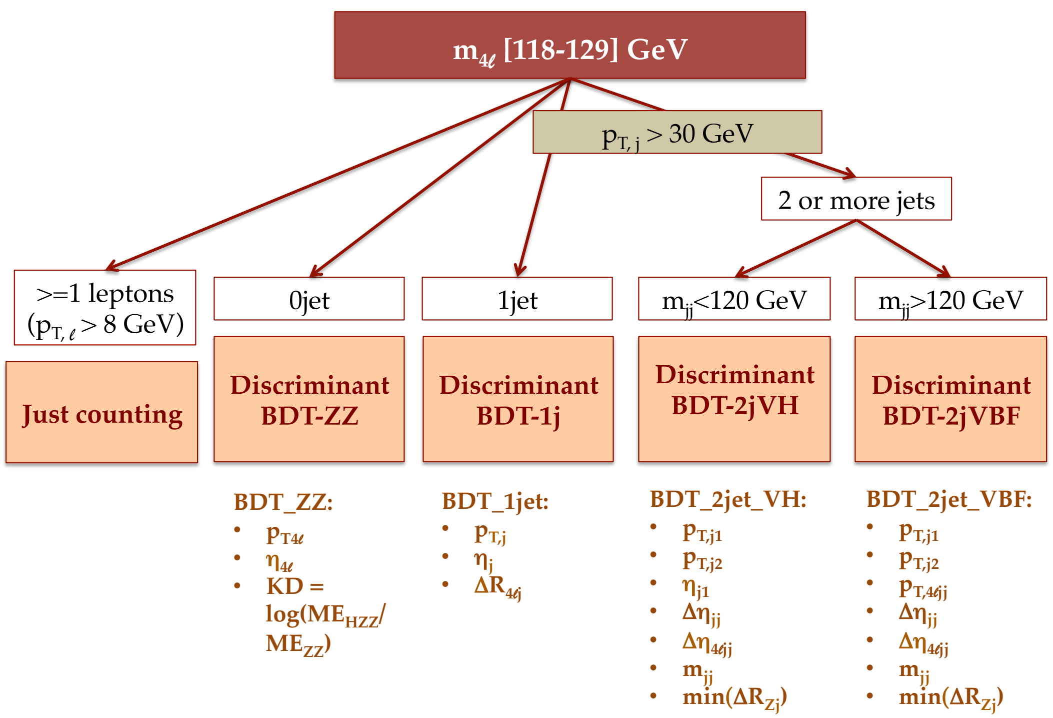
$$\sigma^{4\ell}_{\mathrm{fid,sum}} = 4.48^{+1.01}_{-0.89}\ \mathrm{fb}$$
$$\sigma^{4\ell}_{\mathrm{fid,comb}} = 4.54^{+1.02}_{-0.90}\ \mathrm{fb}$$

$$\sigma^{4\ell}_{\mathrm{fid,SM}} = 3.07^{+0.21}_{-0.25}\ \mathrm{fb}$$

$$\sigma_{\mathrm{tot,SM}} = 55.5^{+3.8}_{-4.4}\ \mathrm{pb}$$
$$\sigma_{\mathrm{tot}} = 81^{+18}_{-16}\ \mathrm{pb}$$

total cross section contains extrapolation factors to the full phase space (e.g. $|y_H| > 2.5$)

H → ZZ → 4l Production modes and couplings



Analysis category	Signal ggF + $b\bar{b}H$ + $t\bar{t}H$	Signal VBF	Signal WH	Signal ZH	Background ZZ^*	Background Z + jets, $t\bar{t}$	Total expected	Observed
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008	1.62 ± 0.21	0.44 ± 0.07	8.5 ± 2.4	12
2-jet VBF enriched	1.9 ± 0.9	0.92 ± 0.07	0.074 ± 0.007	0.052 ± 0.005	0.22 ± 0.05	0.24 ± 0.11	3.4 ± 0.9	9
2-jet VH enriched	1.1 ± 0.5	0.084 ± 0.009	0.143 ± 0.012	0.101 ± 0.009	0.166 ± 0.035	0.088 ± 0.011	1.6 ± 0.5	2
VH-leptonic	0.055 ± 0.004	< 0.01	0.067 ± 0.004	0.011 ± 0.001	0.016 ± 0.002	0.012 ± 0.010	0.16 ± 0.01	0
Total	20 ± 4	1.71 ± 0.14	0.47 ± 0.04	0.315 ± 0.027	8.2 ± 0.9	1.62 ± 0.07	32 ± 4	44

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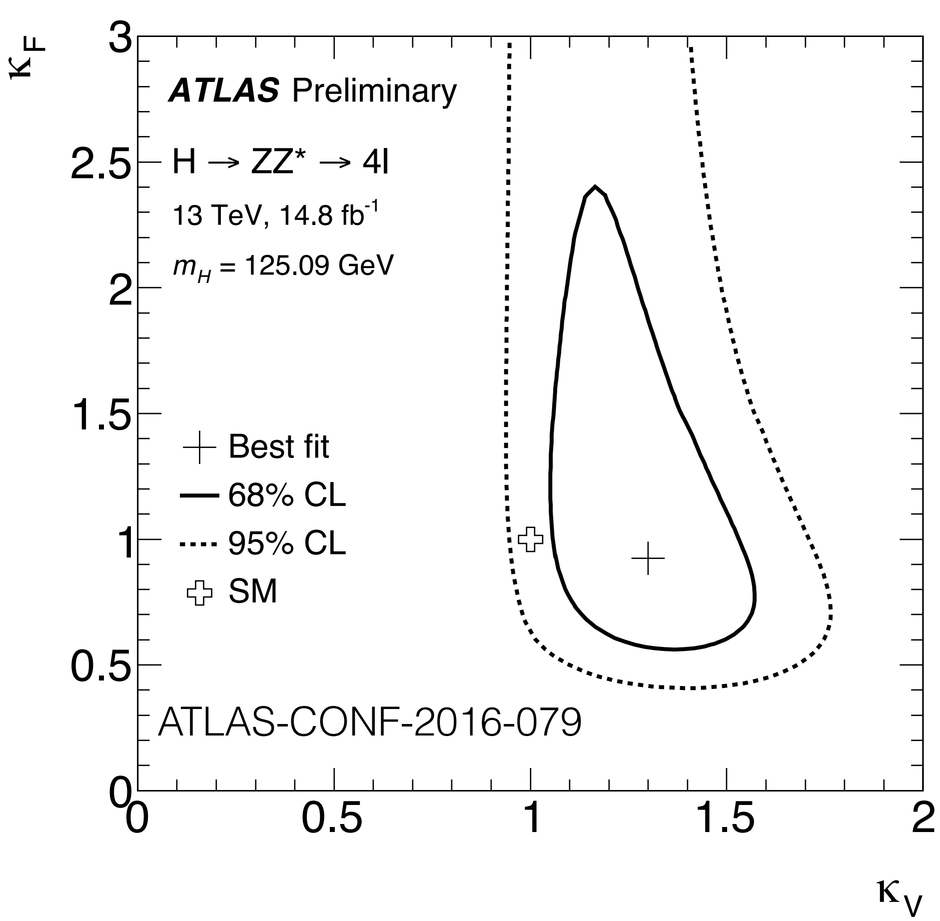
$$\sigma_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \mathrm{pb}$$
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb}$$
$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb}$$

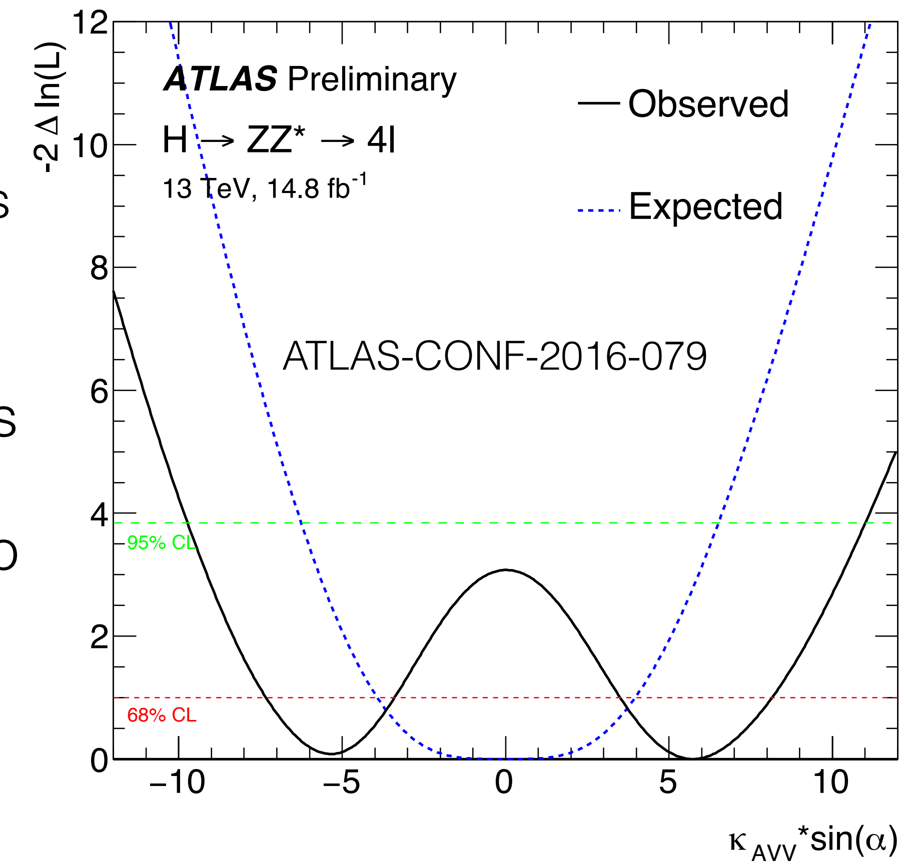
$$\sigma_{\mathrm{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \mathrm{pb}$$
$$\sigma_{\mathrm{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \mathrm{pb}$$
$$\sigma_{\mathrm{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \mathrm{pb}$$

- Interpretation can be done in SM or BSM scenario:



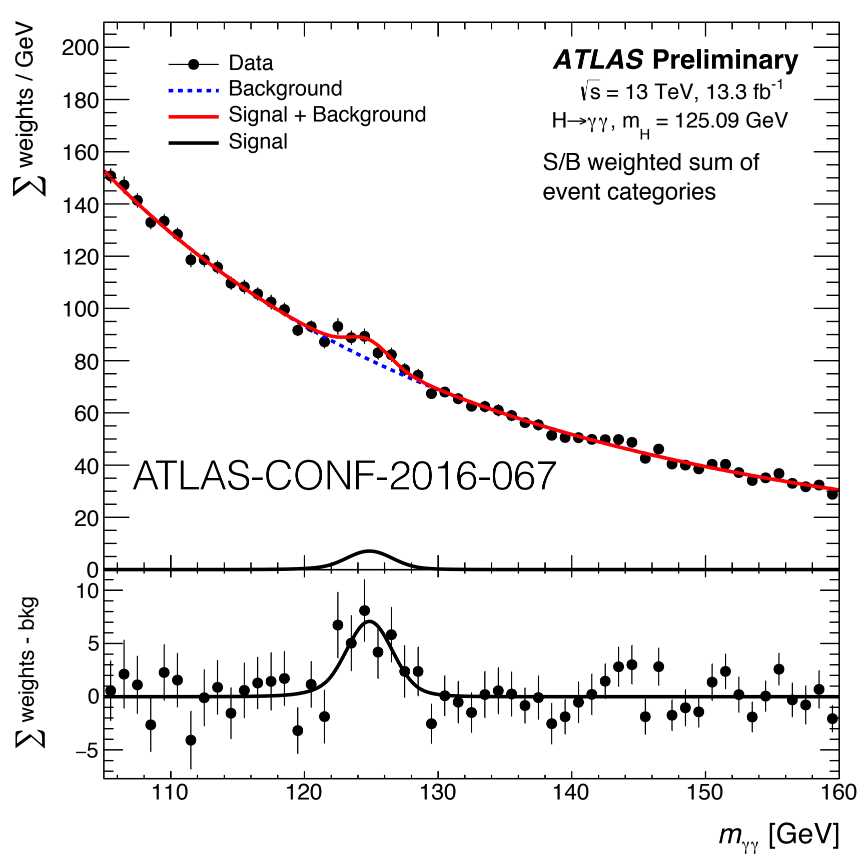
K_F = coupling with fermions
K_V = coupling with vector bosons

Interpretation within the Higgs Characterization Model fixing all the other BSM couplings to 0 and SM coupling fixed to 1



$H \to \gamma\gamma$

- Main selections:
  - Photons identification and isolation
  - Photons E_T > 25 GeV and $|\eta|$ < 2.37 (excluded 1.37 < $|\eta|$ < 1.52)
  - Di-Photon invariant mass ($m_{\gamma\gamma}$)
  - $E_T/m_{\gamma\gamma}$ > 0.35 (0.25) for leading (subleading) photon



13.3 fb^{-1} at $\sqrt{s}$ = 13 TeV

- Fiducial volume: ATLAS-CONF-2016-067

	diphoton baseline	VBF enhanced	single lepton
Photons	$|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30\,\text{GeV}$, $|y| < 4.4$ $m_{jj} > 400\,\text{GeV}$, $|\Delta y_{jj}| > 2.8$ $|\Delta\phi_{\gamma\gamma,jj}| > 2.6$	- - -
Leptons	-	-	$p_T > 15\,\text{GeV}$ $|\eta| < 2.47$

Fiducial volume contains a truth-level isolation selection for photons

- Categorization for productions mode analysis:

Category	Events	B_{90}	S_{90}	f_{90}	Z_{90}	S_{90}^{fit}
Central low-p_{Tt}	31907	3500	180	0.05	3.04	120
Central high-p_{Tt}	1319	140	20	0.13	1.66	15
Forward low-p_{Tt}	85129	13000	310	0.02	2.73	200
Forward high-p_{Tt}	3977	540	33	0.06	1.38	25
VBF loose	604	76	15	0.16	1.62	21
VBF tight	76	8.8	7.3	0.45	2.19	13
VH hadronic loose	937	120	8.9	0.07	0.81	4.7
VH hadronic tight	66	6.7	2.3	0.26	0.86	1.0
VH E_T^{miss}	20	2.4	0.81	0.26	0.50	0.18
VH one-lepton	8	1.0	0.57	0.37	0.53	0.12
VH dilepton	3	0.4	0.30	0.43	0.43	0.07
$t\bar{t}H$ hadronic	72	8.1	1.8	0.18	0.60	-0.23
$t\bar{t}H$ leptonic	19	2.3	1.3	0.36	0.78	-0.18

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H → γγ Cross Sections

- Fiducial Results:

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Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8\,^{+3.4}_{-4.4}$	$[\text{N}^3\text{LO} + \text{XH}]$
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	[NNLOPS + XH]

- Production cross section and signal strengths (μ):

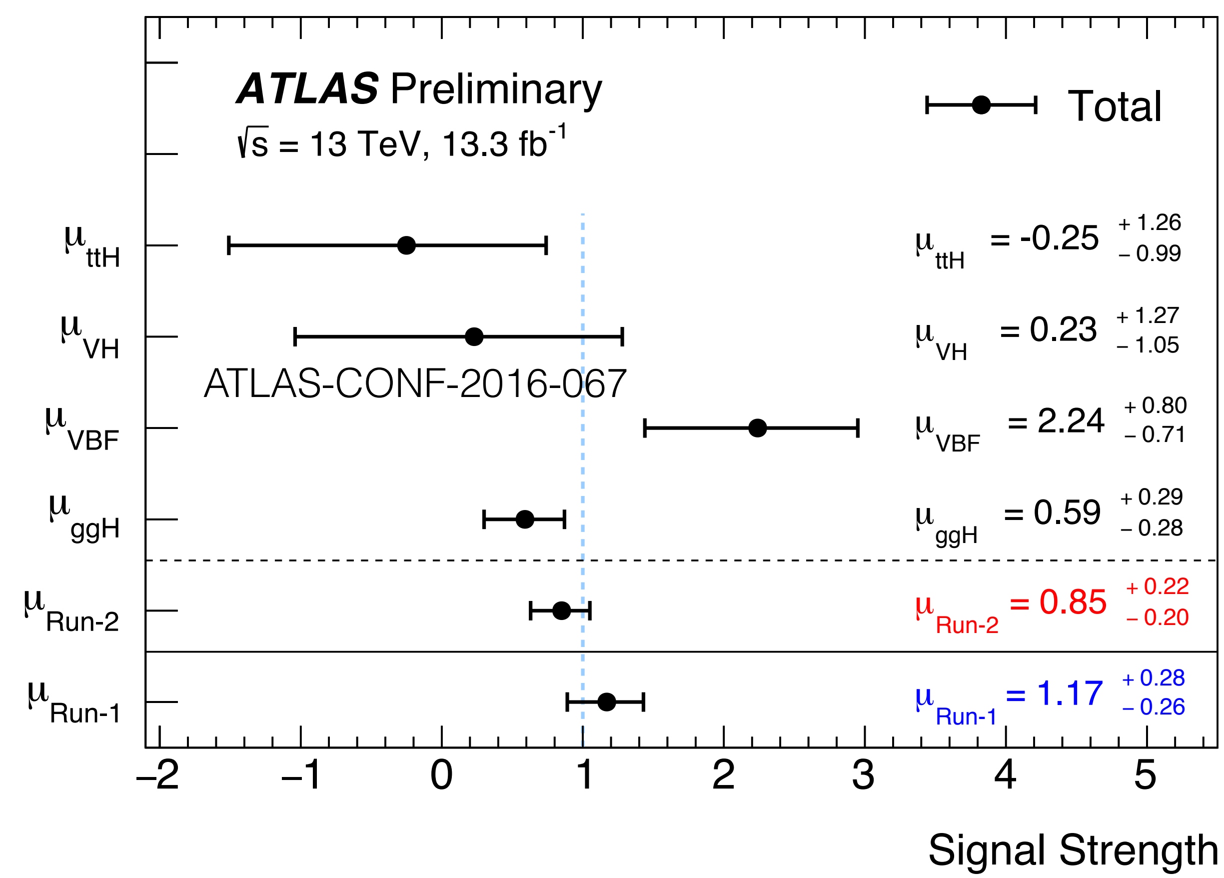
$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 65\,^{+32}_{-31}\ \text{fb}$$

$$\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 19.2\,^{+6.8}_{-6.1}\ \text{fb}$$

$$\sigma_{VH} \times \mathcal{B}(H \to \gamma\gamma) = 1.2\,^{+6.5}_{-5.4}\ \text{fb}$$

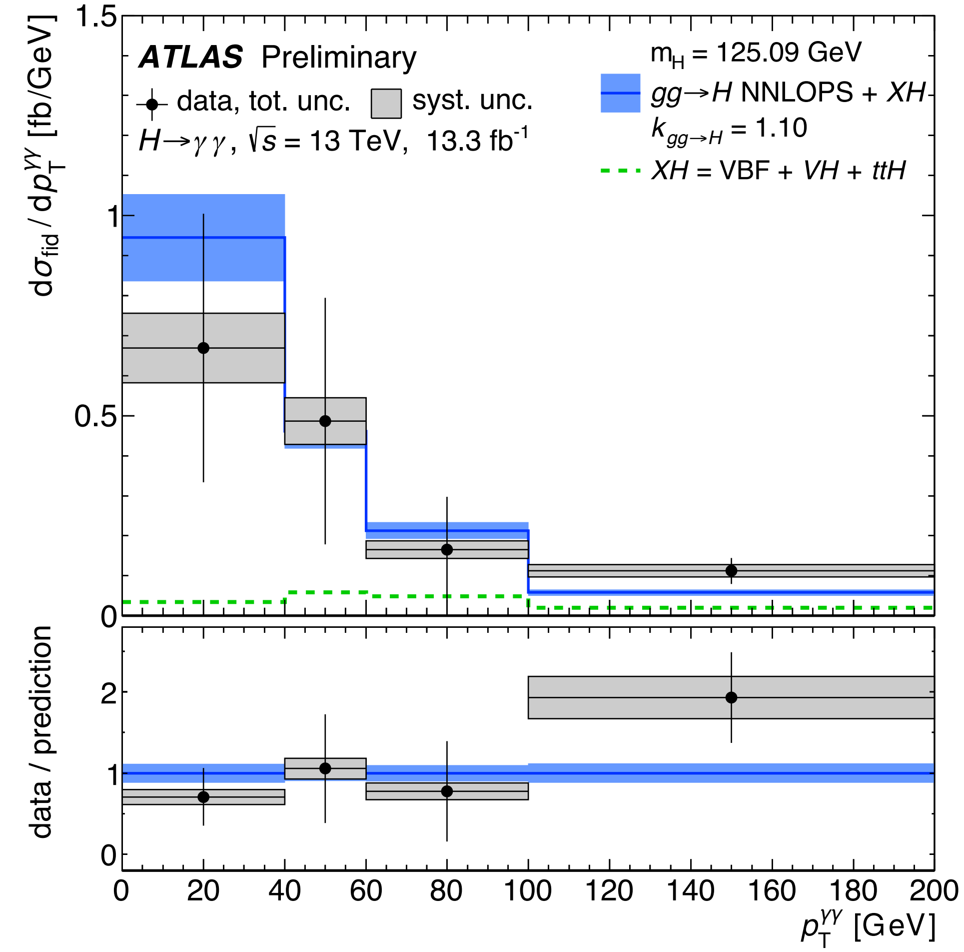
$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = -0.3\,^{+1.4}_{-1.1}\ \text{fb}$$

The μ is the ratio between the observation and the expectation (σ*BR)



H → γγ Differential Cross Sections

- Differential results obtained for:
  - $P_{T\gamma\gamma}$ and $|y_{\gamma\gamma}|$
  - N_{jets} and P_T leading jet
  - M_{jj} and $\Delta\phi_{jj}$
  - cosθ*



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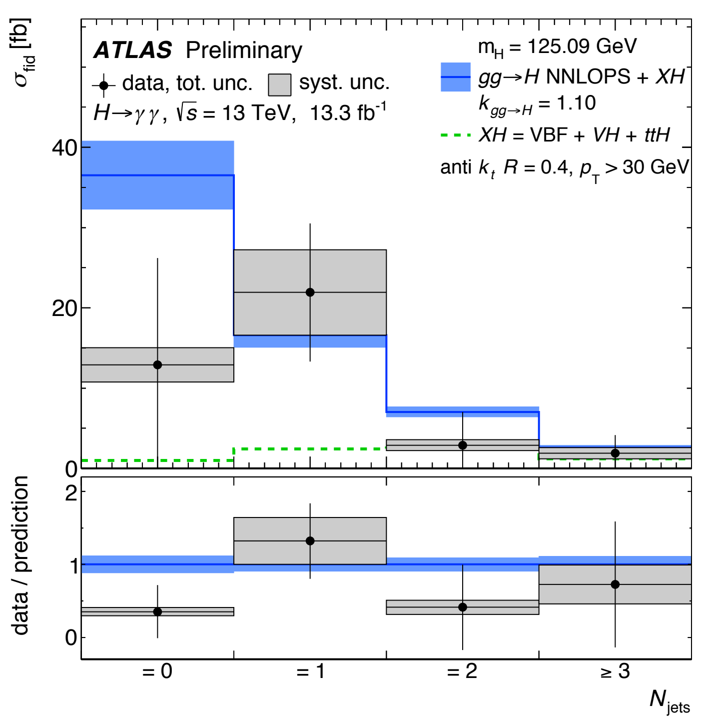

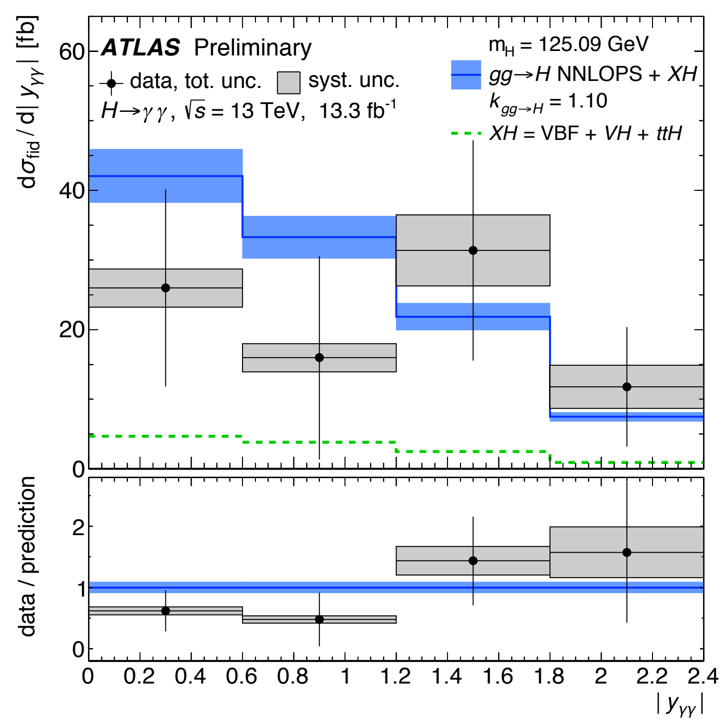

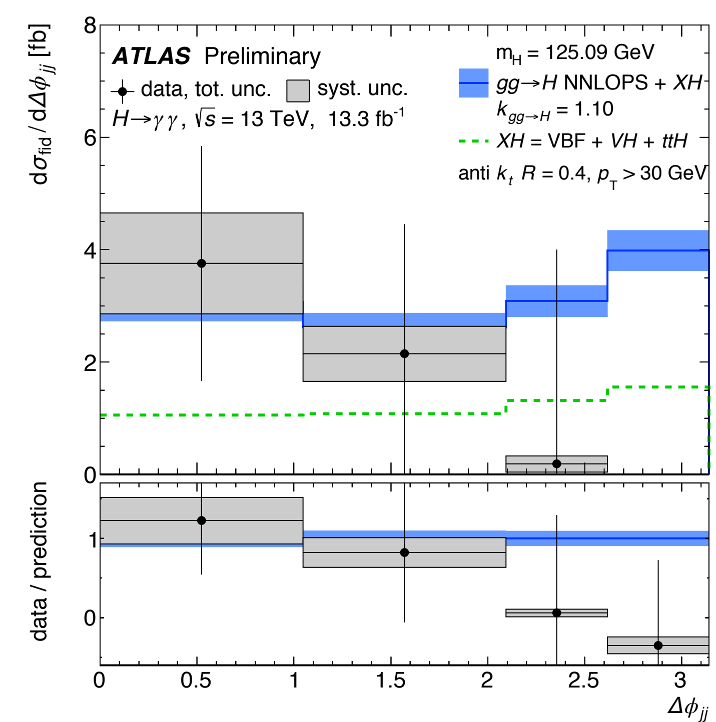

H → ZZ and H → γγ combination

- Combination of cross sections studies of $H\to\gamma\gamma$ (13.3 fb^{-1}) and $H\to ZZ$ (14.8 fb^{-1}) at $\sqrt{s}$ = 13 TeV
- ATLAS studied several possible models:

- For production cross section and BR the use $|Y_H| < 2.5$
- For global signal strength and total cross section and extrapolation to the full phase space (including $|Y_H| > 2.5$ is done)

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Fit model	Number of parameters of interest
Independent $\sigma_{\mathtt{i}} \cdot B^f$	7
Independent $\sigma_{\mathtt{i}}$ assuming SM B^f	5
$(\sigma \cdot B)^{ZZ}_{\mathtt{ggF}}$, $\sigma_{\mathtt{VBF}}/\sigma_{\mathtt{ggF}}$ and $B^{\gamma\gamma}/B^{ZZ}$	3
Global signal strength μ	$1 \longrightarrow \mu = 1.13^{+0.18}_{-0.17}$

- Categorizations described in the previous slides are used:

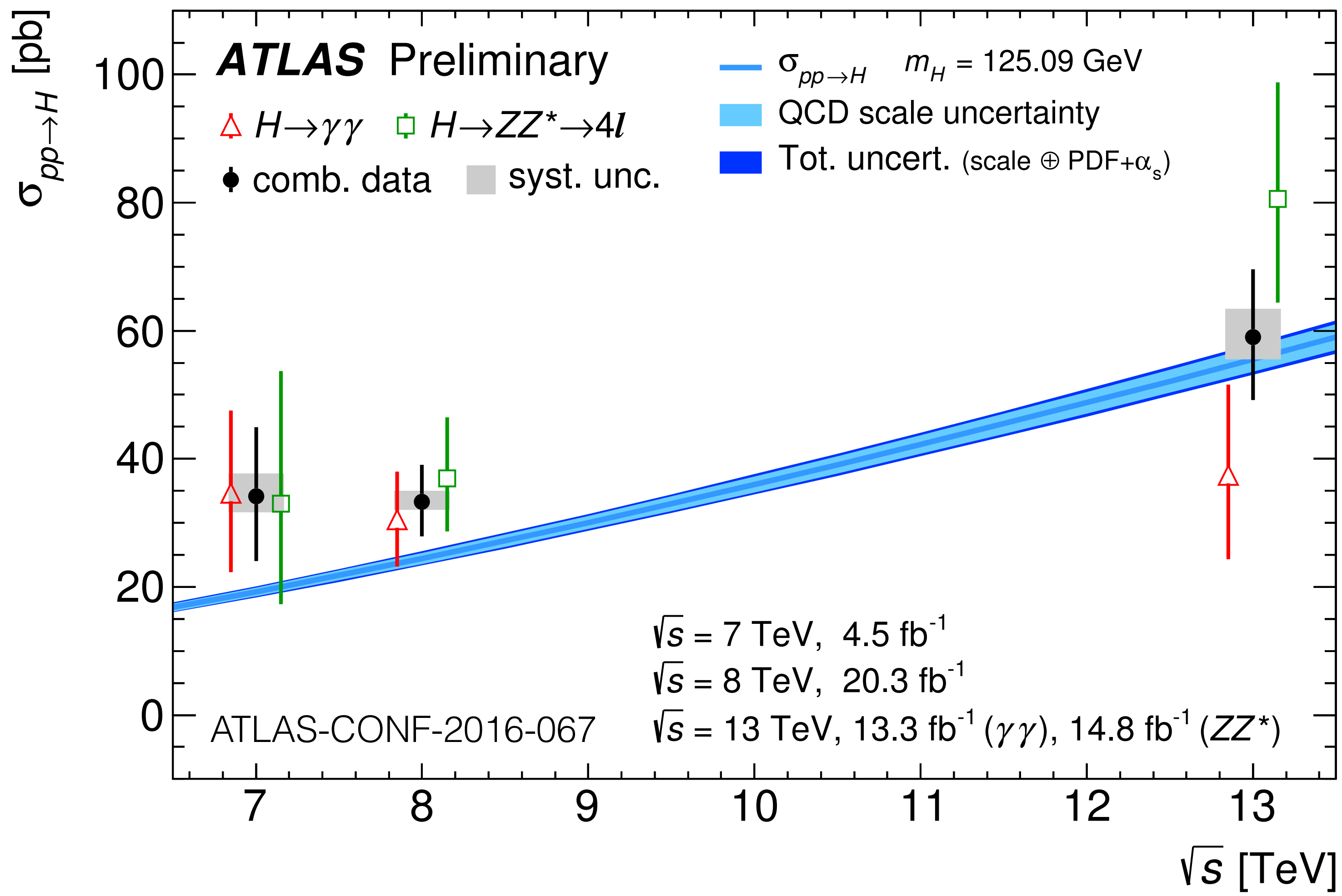
		$H\to ZZ^*$	$H\to\gamma\gamma$
ggF	Best fit value (pb)	$1.58^{+0.46}_{-0.39}$	$0.063^{+0.030}_{-0.029}$
	SM prediction (pb)	1.18 ± 0.07	0.101 ± 0.006
VBF	Best fit value (fb)	350^{+260}_{-200}	18^{+6}_{-6}
	SM prediction (fb)	93.0 ± 2.8	8.00 ± 0.29
VHhad	Best fit value (fb)	fixed to SM	$-2.5^{+6.8}_{-5.8}$
	SM prediction (fb)	36.0 ± 1.2	3.09 ± 0.12
VHlep	Best fit value (fb)	fixed to SM	$1.0^{+2.5}_{-1.9}$
	SM prediction (fb)	17.0 ± 0.5	1.46 ± 0.05
top	Best fit value (fb)	fixed to SM	$-0.3^{+1.6}_{-1.2}$
	SM prediction (fb)	15.9 ± 1.5	1.36 ± 0.13

	Best fit value (pb)	SM prediction (pb)
$\sigma_{\mathtt{ggF}}$	$47.8^{+9.8}_{-9.4}$	44.5 ± 2.3
$\sigma_{\mathtt{VBF}}$	$7.9^{+2.8}_{-2.4}$	3.52 ± 0.07
$\sigma_{\mathtt{VHhad}}$	$-2.5^{+2.9}_{-2.6}$	1.36 ± 0.03
$\sigma_{\mathtt{VHlep}}$	$0.32^{+1.07}_{-0.79}$	0.64 ± 0.02
$\sigma_{\mathtt{top}}$	$-0.11^{+0.67}_{-0.54}$	0.60 ± 0.06

ATLAS-CONF-2016-081

H → ZZ and H → γγ combination

- Study on the total cross section pp → H + X using the inclusive signal yields (no split in categories for the production modes)



Decay channel	Total cross section ($pp \to H + X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

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H → WW

- Analysis in Run II focused on VBF and WH (using 5.8 fb^{-1} from 2015-2016 all at $\sqrt{s}$ = 13 TeV)
- VBF selections:

	Signal region	$Z \to \tau\tau$ CR	Top-quark CR
Preselection	Two isolated leptons ($\ell = e, \mu$) with opposite charge $p_T^{lead} > 25GeV$ ($p_T^{lead} > 22GeV$ for muons in 2015), $p_T^{sublead} > 15GeV$ $m_{\ell\ell} > 10GeV$, $N_{jet} \geq 2$		
	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$
A BDT is trained at this level. Eight discriminant variables are used: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_T, Δy_{jj}, m_{jj}, p_T^{tot}, $\sum_{\ell,j} m_{\ell j}$, and $\eta_\ell^{centrality}$			
Selection	$m_{\tau\tau} < 66.2GeV$	$\lvert m_{\tau\tau} - m_Z\rvert < 25GeV$	–
	–	$m_{\ell\ell} < 80GeV$	–
	OLV applied, CJV applied, BDT > −0.8		
	SR1: $-0.8 < \text{BDT} \leq 0.7$	–	–
	SR2: $0.7 < \text{BDT} \leq 1$	–	–

- WH selections:

Category	Z-dominated SR ≥ 1 SFOS pair	Z-depleted SR no SFOS pair
Preselection	Three isolated leptons (p_T >15 GeV) total charge = ±1 ≥ 1 lepton matches to the trigger	
Background Rejection	$N_{jet} \leq 1$, $N_{b\text{-jet}} = 0$	
	$E_T^{miss} > 50$ GeV	–
	$\lvert m_{\ell^+\ell^-} - m_Z\rvert > 25$ GeV	$Z/\gamma^* \to ee$ veto
	$m_{\ell^+\ell^-}^{max} < 200$ GeV	
	$m_{\ell^+\ell^-}^{min} > 12$ GeV	$m_{\ell^+\ell^-}^{min} > 6$ GeV
$H \to WW^* \to \ell\nu\ell\nu$ topology	$\Delta R_{\ell_0\ell_1} < 2.0$	

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- Results:

$$\sigma_{\text{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 1.4^{+0.8}_{-0.6}(\text{stat})^{+0.5}_{-0.4}(\text{sys})\ \text{pb} \quad \mu_{\text{VBF}} = 1.7^{+1.0}_{-0.8}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$$

$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.9^{+1.1}_{-0.9}(\text{stat})^{+0.7}_{-0.8}(\text{sys})\ \text{pb} \quad \mu_{WH} = 3.2^{+3.7}_{-3.2}(\text{stat})^{+2.3}_{-2.7}(\text{sys})$$

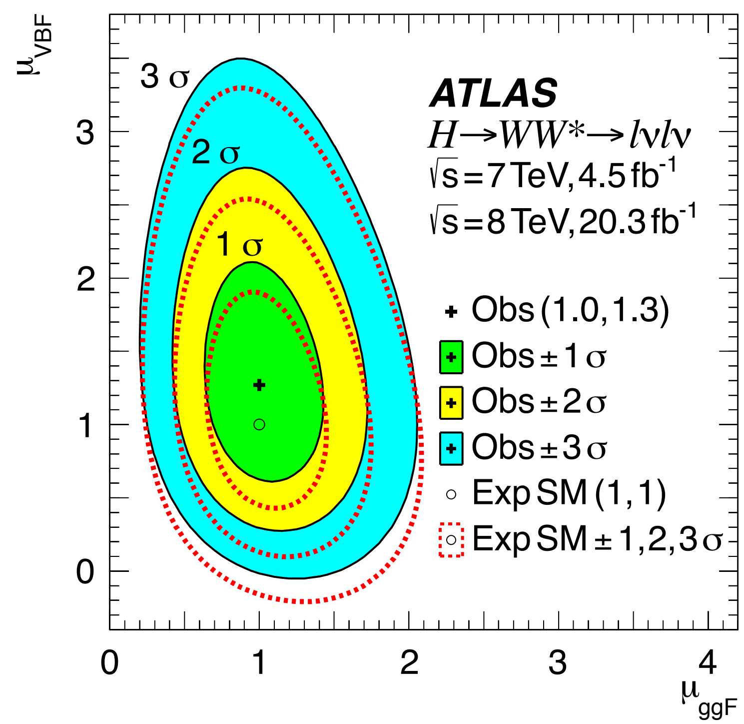
H → WW

- Run I studies on H → WW:
- Signal Strengths and coupling (25 fb^{-1})

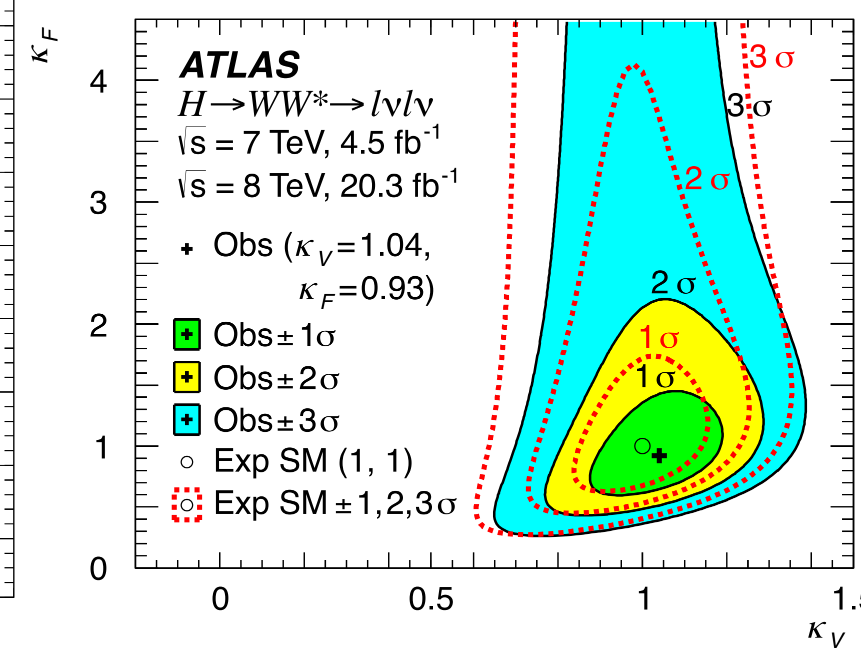
$$\mu = 1.09\,^{+0.23}_{-0.21},$$
$$\mu_{\rm ggF} = 1.02\,^{+0.29}_{-0.26},$$
$$\mu_{\rm VBF} = 1.27\,^{+0.53}_{-0.45}.$$

$$\kappa_F = 0.93\ \begin{matrix}+0.24\\-0.18\end{matrix}\ \begin{matrix}+0.21\\-0.14\end{matrix} = 0.93\ \begin{matrix}+0.32\\-0.23\end{matrix}$$
$$\kappa_V = 1.04\ \begin{matrix}+0.07\\-0.08\end{matrix}\ \begin{matrix}+0.07\\-0.08\end{matrix} = 1.04\ \pm 0.11.$$
$$\quad\quad\quad\quad (\text{stat})\quad (\text{syst})$$

arXiv:1412.2641



arXiv:1412.2641



- ggf differential and fiducial cross section (20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV)

$$\sigma^{\rm fid}_{\rm ggF} = 36.0 \pm 7.2(\text{stat}) \pm 6.4(\text{sys}) \pm 1.0(\text{lumi})\ \text{fb}$$
$$\sigma^{\rm fid}_{\rm ggF} = 25.1^{+1.8}_{-2.0}(\text{QCDscales})^{+1.9}_{-1.7}(\text{PDF})\ \text{fb} = 25.1 \pm 2.6\ \text{fb}.$$

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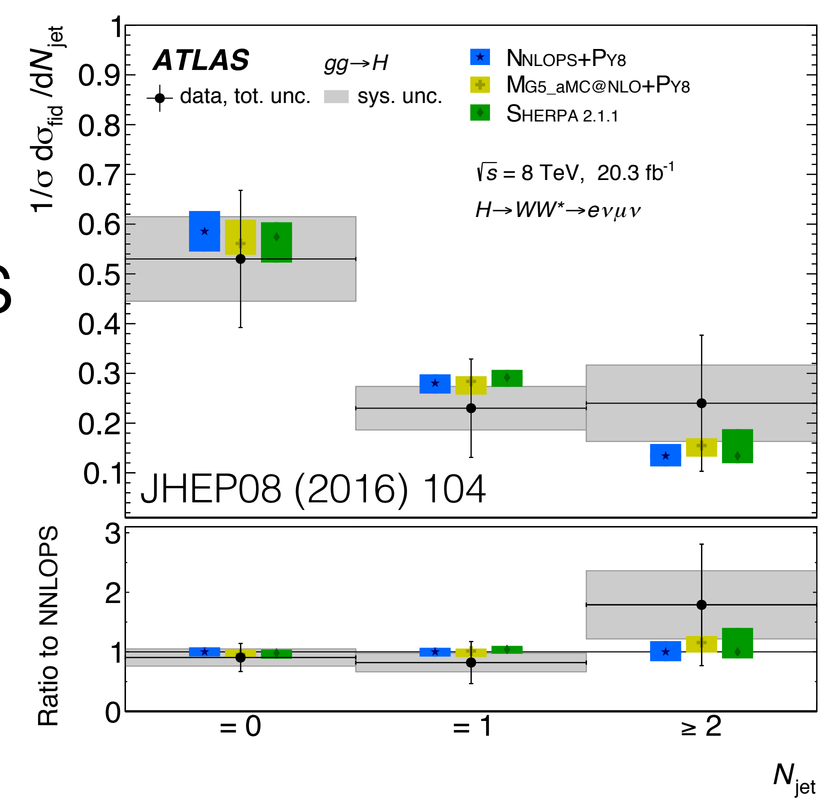
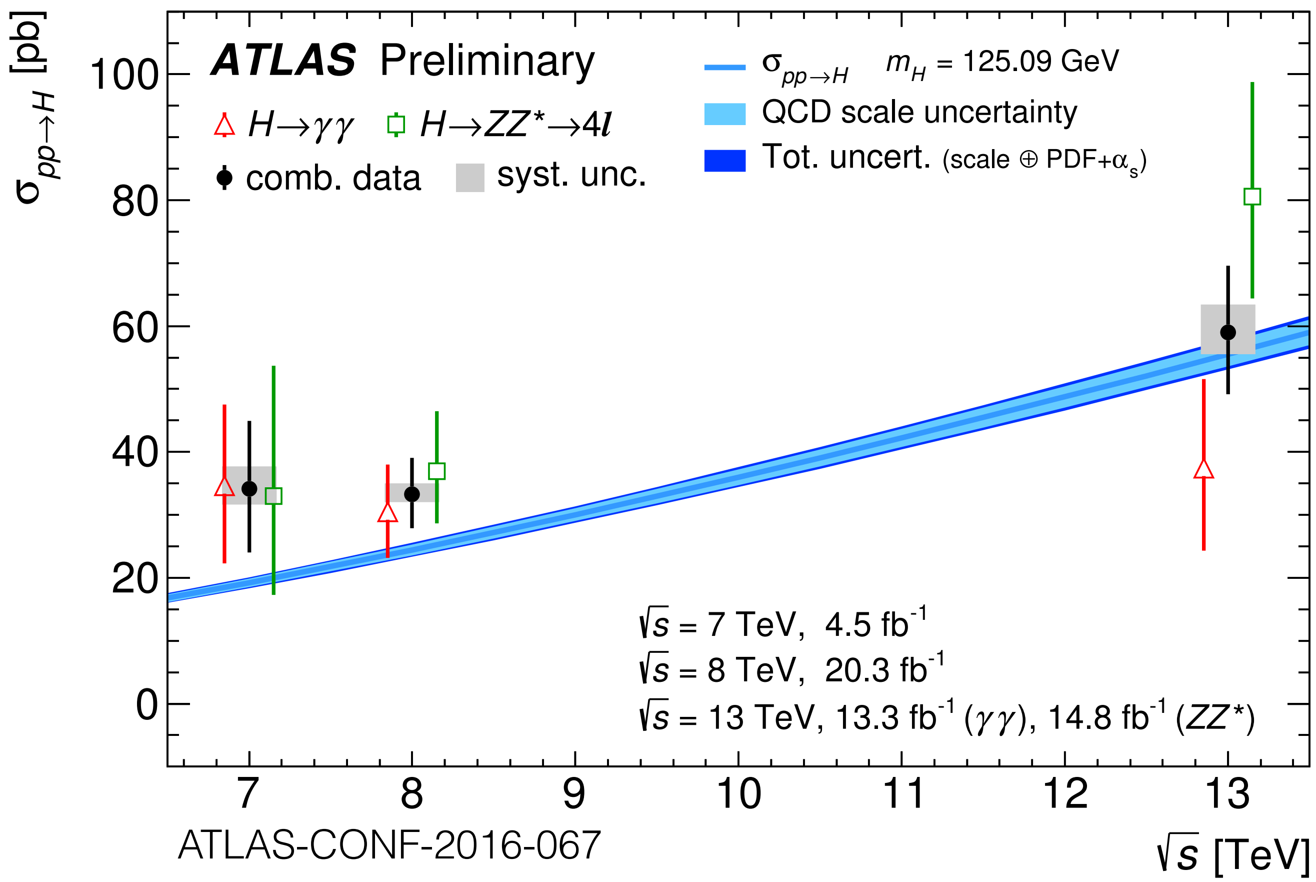


Public:
- -N_{jets}
- -P_{TH}
- -$|y_{ll}|$
- -$P_{T,jet1}$

Conclusions

- Overview of the ATLAS analyses on the Higgs boson decaying into bosons were presented



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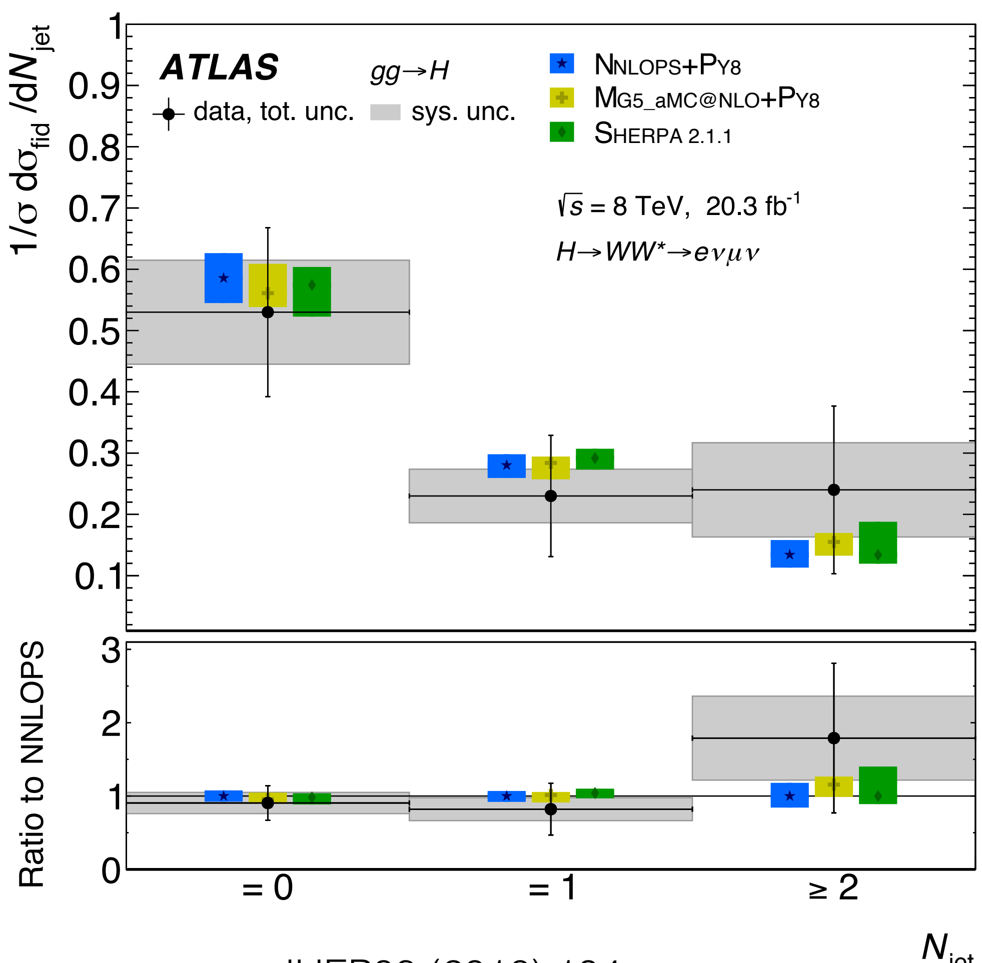
- H → ZZ and H → γγ and their combination

- H → WW



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- Update results for single channel with more statistic (full 2016 ≈ 36 fb^{-1})

- Combination for differential cross section and couplings (SM and BSM)

Thanks

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Bibliography

- Cross section and branching ration:
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

- $H \rightarrow ZZ$
  ATLAS-CONF-2016-079

- $H \rightarrow \gamma\gamma$
  ATLAS-CONF-2016-067

- Combination $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
  ATLAS-CONF-2016-081

- $H \rightarrow WW$
  ATLAS-CONF-2016-112
  arXiv:1412.2641
  JHEP08 (2016) 104