ATLAS Results on H(125) Bosons Decays

Toni Baroncelli
INFN Sezione Roma TRE
On the behalf of the ATLAS Collaboration

Outline of the talk

Higgs physics in di-boson final states: Overview of the (so far) ATLAS Run-2 measurements in WW*/ZZ*/γγ decay channels (36 fb^{-1},80 fb^{-1}) production inclusive & ttH –enhanced 80 fb^{-1} New!

Higgs boson cross-sections, which?

- *Fiducial inclusive and Differential, Total, Production, Simplified Template Cross Sections (STXS)*

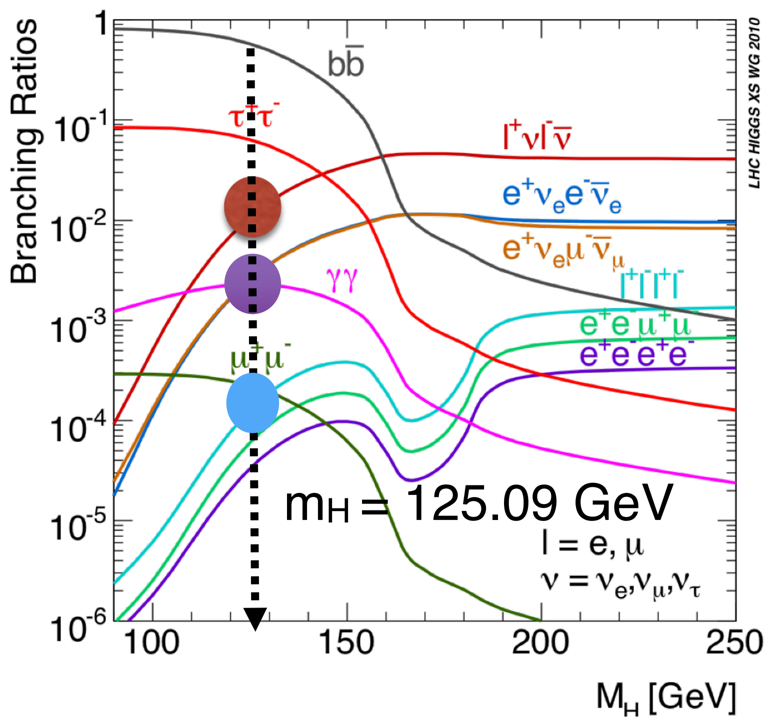
Decay Process	H→γγ	H→ZZ*→4l	H→WW*→eνμν	ttH→ZZ*/γγ	ttH→Multileptons
∫Ldt(fb-1) , cms energy	79.8, √s=13TeV	79.8, √s=13TeV	36.1, √s=13TeV	up to 79.8, √s=7,8,13TeV	36.1, √s=13TeV
Document	ATLAS-CONF-2018-028	ATLAS-CONF-2018-018	ATLAS-CONF-2018-004	arXiv:1806.00425	Phys. Review Letters D 97, 072003 (2018)
Fiducial integrated cross-sections	✅	✅			
Fiducial differential cross-sections	✅	✅			
STXS	✅	✅			
Total			✅	✅	✅

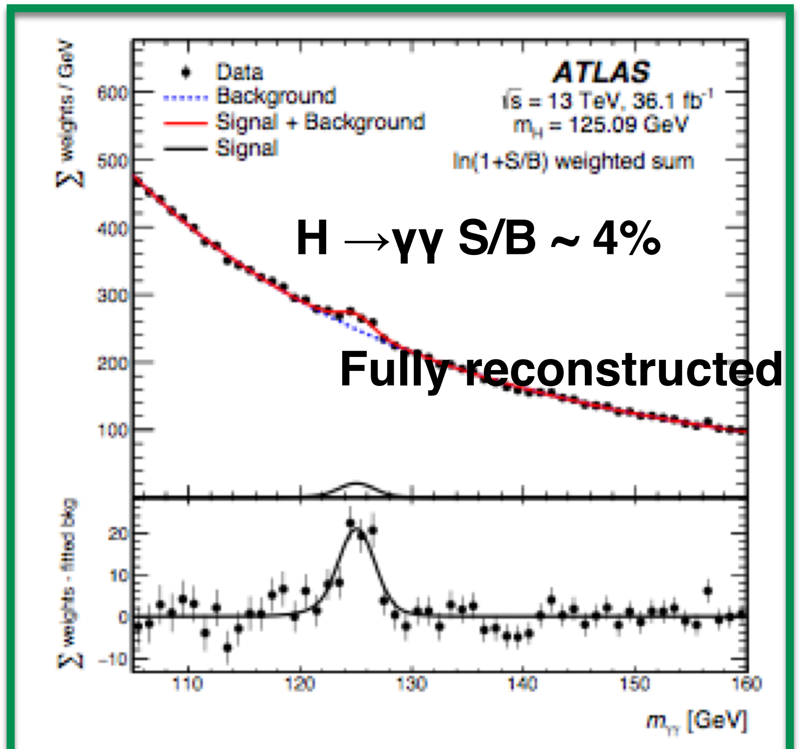
- *Remarks and Conclusions*

Combination: talk by Daniela Rebuzzi

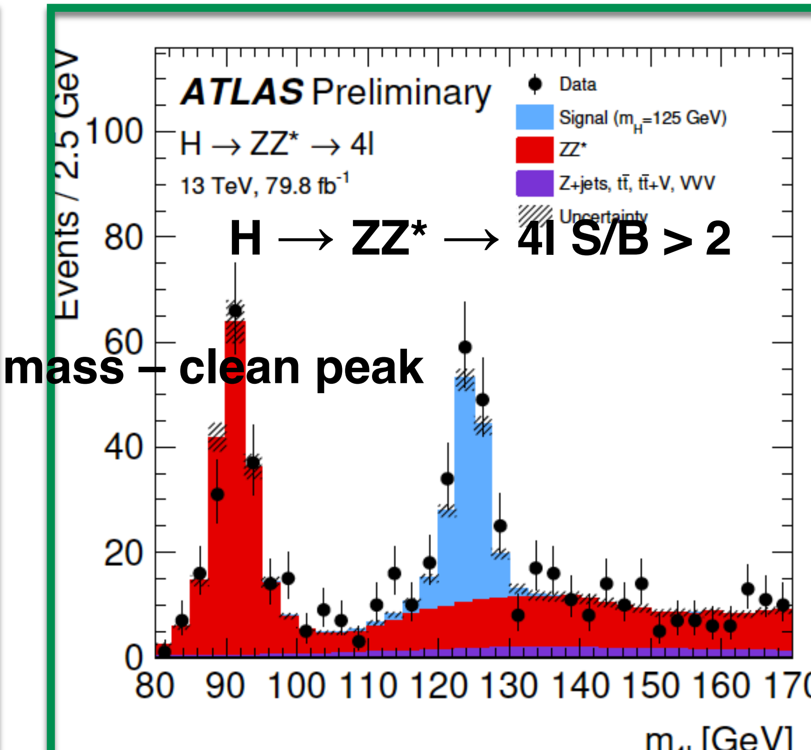
Higgs boson measurements in diboson final states

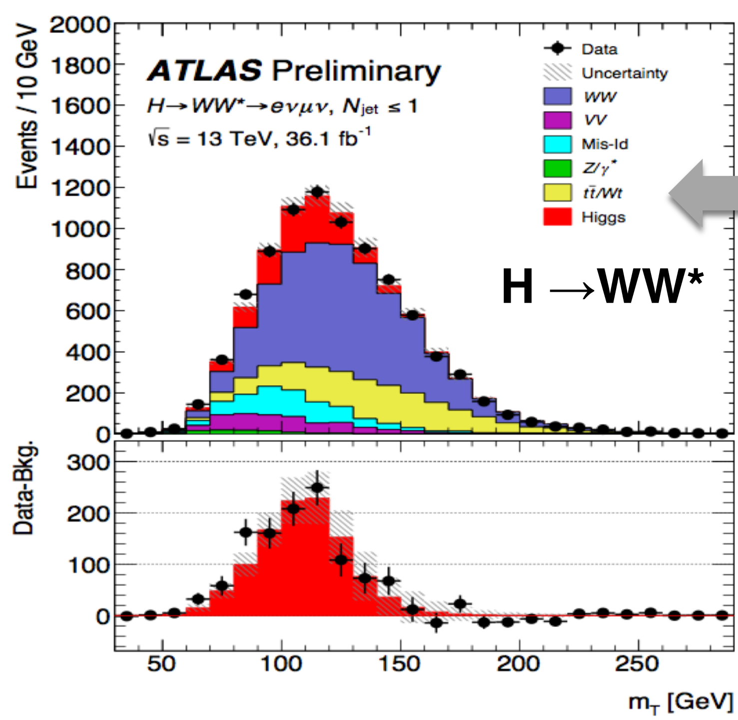
Despite the low branching fraction of H → WW*(→lνlν)/ZZ*(4l)/γγ, these decays channels have a clean signature and constitute a powerful tool for many Higgs boson properties measurements. Use good isolated leptons and photons, invariant & transverse mass & jets





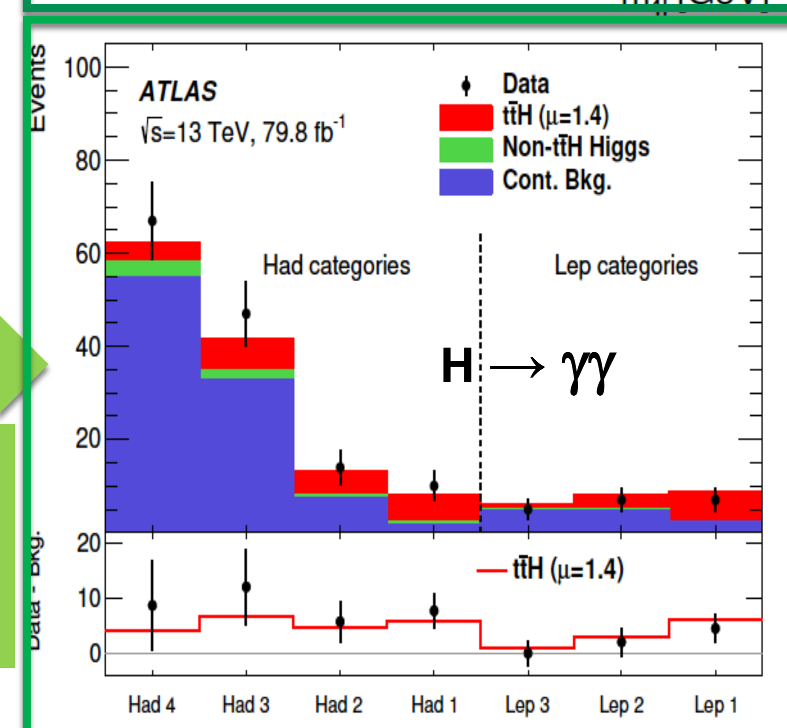
Fully reconstructed mass – clean peak





WW*: Larger BR ~ 1.5% Clean signature
Low S/B ratio

New result ttH enhanced: ZZ & WW & γγ …decays using 80 fb⁻¹
Analysis strategy uses BDT's



H→WW*→eνμν - Analysis

Analysis strategy in brief

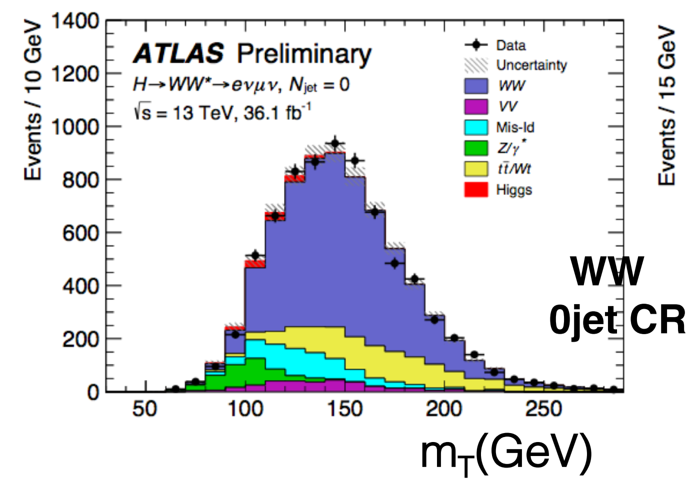
ATLAS-CONF-2018-004

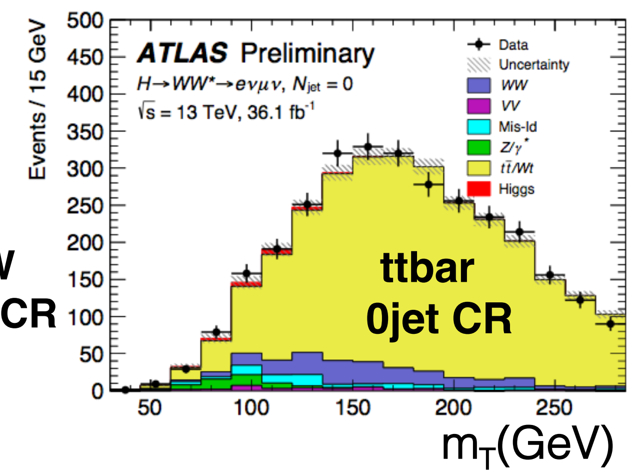
Recent result!

- **Signature**: two prompt isolated leptons (close-by leptons) and (loose) missing momentum
- **Events split in 3 major Signal Regions** on Njets(*):
  - **Njet = 0 and Njet = 1 (ggF dominated)**
    - m_T used as discriminant
  - **Njet ≥ 2 (VBF dominated)**
    - BDT used as discriminant

b-jet veto in all categories to reduce ttbar

- Irreducible backgrounds data-normalized via CRs
- Mis-identified leptons fully data-driven





(*) complete event selection table in backup

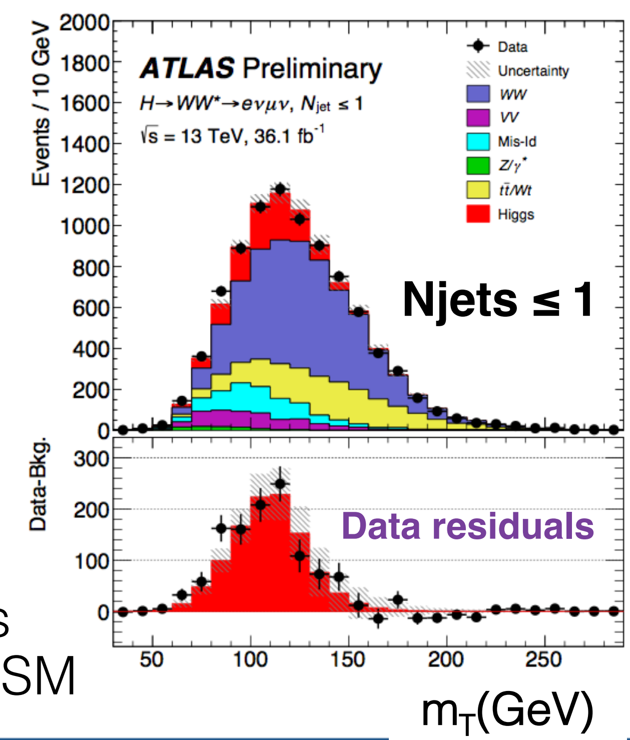
- Simultaneous SRs and CR max likelihood fit
  - **8 SR regions defined for Njet = 0 & 1:**
    - Different bkg composition
    - Enhance sensitivity
    - mT shape fit with 8(6) for Njet=0(1)

$$[2\times m_{ll}]\cdot[2\times p_T^{sub-leading}]\cdot[e\mu/\mu e]$$

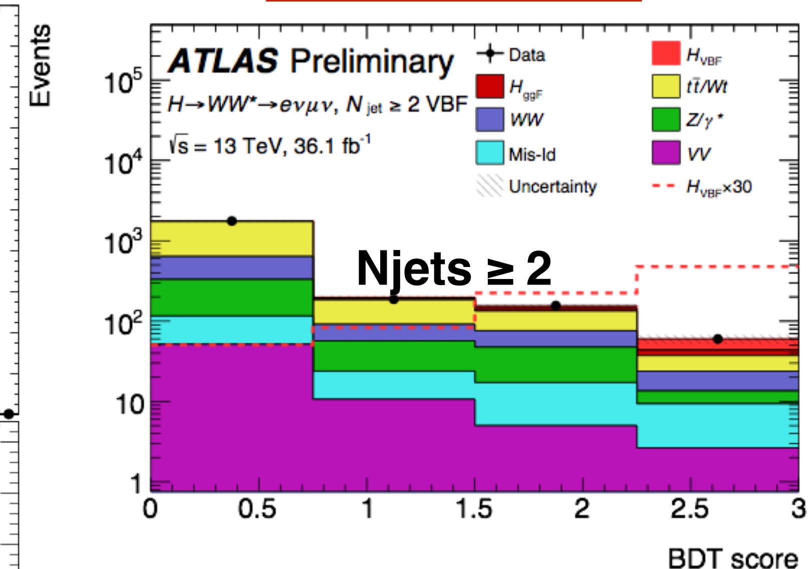
- **4 BDT bins for VBF enriched category**
  - S(VBF)/B ~0.6 in the last bin

⇒ extract both ggF and VBF cross-sections
- Other production/decays modes fixed to SM

ggF: 6.3σ (exp. 5.2σ)



VBF: 1.9σ (exp. 2.7σ)



Signal fraction at best 14%

H→WW*→eνμν - Results

Signal strength and cross-section results:

Run-2

$$\mu_{ggF} = 1.21^{+0.12}_{-0.11}(\text{stat.})^{+0.18}_{-0.17}(\text{sys.}) = 1.21^{+0.22}_{-0.21}$$
$$\mu_{VBF} = 0.62^{+0.30}_{-0.28}(\text{stat.}) \pm 0.22(\text{sys.}) = 0.62^{+0.37}_{-0.36}$$

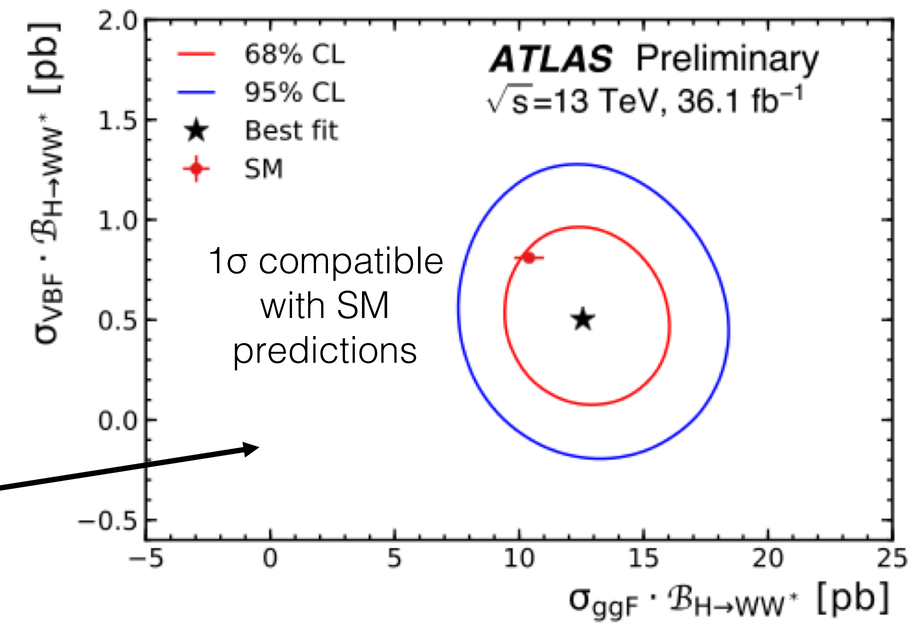
Run-1

$$\mu_{ggF} = 1.02^{+0.29}_{-0.26}$$
$$\mu_{VBF} = 1.27^{+0.53}_{-0.45}$$

$$\sigma_{ggF} \cdot \mathcal{B}_{H\to WW^*} = 12.6^{+1.3}_{-1.2}(\text{stat.})^{+1.9}_{-1.8}(\text{sys.})\ \text{pb} = 12.6^{+2.3}_{-2.1}\ \text{pb}$$
$$\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.23}(\text{stat.}) \pm 0.18(\text{sys.})\ \text{pb} = 0.50^{+0.30}_{-0.29}\ \text{pb.}$$

Predicted cross-sections:
ggF 10.4±0.6 pb VBF 0.81±0.02

68% and 95% CL contours



Uncertainties on the cross-sections measurement:

Significant uncertainties from Theory:
- ~5% on σ(ggF) due to WW background modelling
- 15% on σ(VBF) due to QCD scale on ggF in VBF phase space

Limited MC statistics important especially **in VBF**

σ(ggF) dominated by systematics (exp~theo)

precision of the measurements →

Source	$\frac{\Delta\sigma_{ggF}}{\sigma_{ggF}}$ [%]	$\frac{\Delta\sigma_{VBF}}{\sigma_{VBF}}$ [%]
Data statistics	±8	±46
CR statistics	±8	±9
MC statistics	±5	±23
Theoretical uncertainties	±8	±21
ggF signal	±5	±15
VBF signal	<1	±15
WW	±5	±12
Top-quark	±4	±4
Experimental uncertainties	±9	±8
b-tagging	±5	±6
Pile-up	±5	±2
Jet	±3	±4
Electron	±3	<1
Misidentified leptons	±5	±9
Luminosity	±2	±3
TOTAL	±17	±59

Higgs boson cross-section measurements: Nomenclature

In Run-2 different Higgs boson cross-section measurements considered:

- fiducial cross-sections(inclusive & differential): Measured in fiducial volume to avoid model-dependent extrapolations → only correct for inefficiencies & reconstruction effects

$$\sigma_{i,\mathrm{fid}} = \sigma_i \times A_i \times \mathcal{B} = \frac{N_{i,\mathrm{fit}}}{\mathcal{L} \times C_i}, \quad C_i = \frac{N_{i,\mathrm{reco}}}{N_{i,\mathrm{part}}};$$

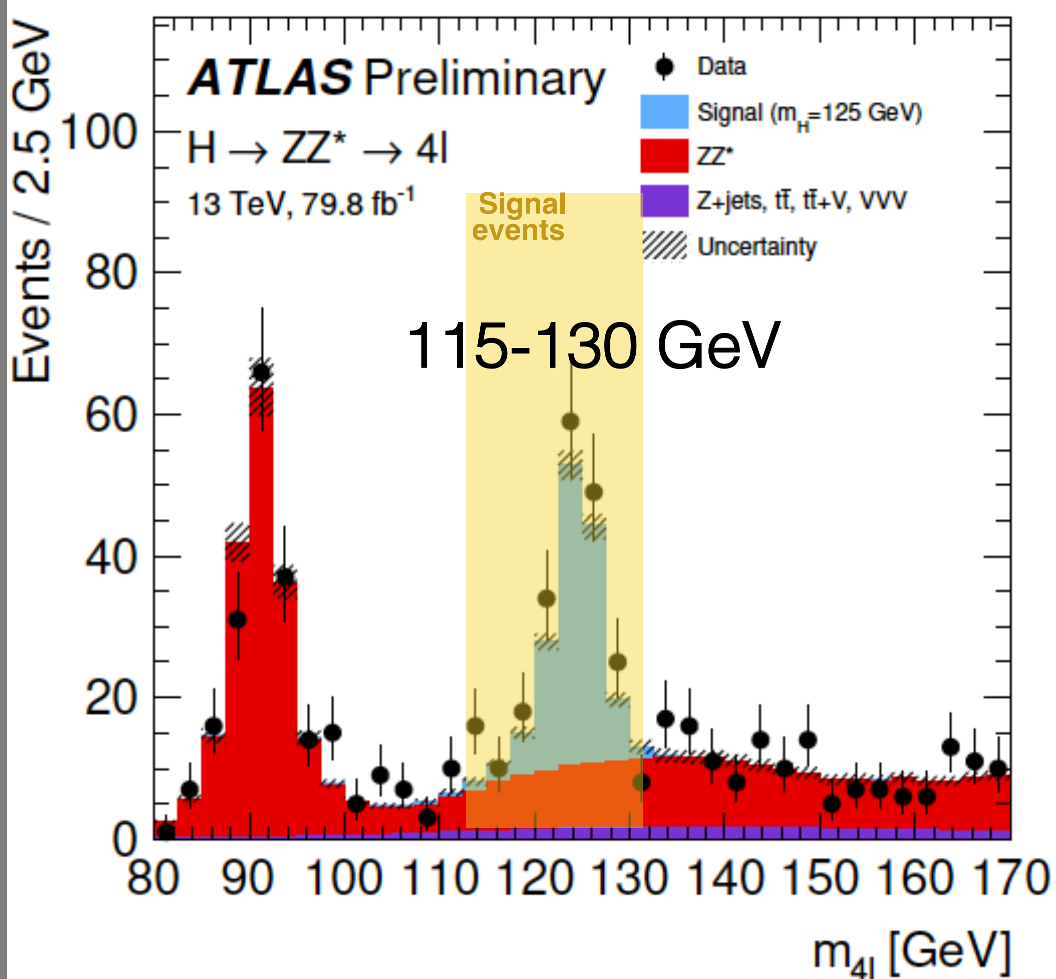
i = bin of differential distribution
[C_i = 50%(75%) for H4l(Hγγ)]

- Simplified Template Cross Section framework* (STXS)): simple fiducial region definitions matching specific experimental categories (ggF 0jets, etc..), allows to reduce theoretical uncertainties (*)
- Total cross-section: extrapolate to full phase space and combine channels

(*) LHC Higgs X-Sec WG: : 4 [arXiv:1610.07922]

H→ZZ*→4l inclusive and differential cross-section

ATLAS-CONF-2018-018



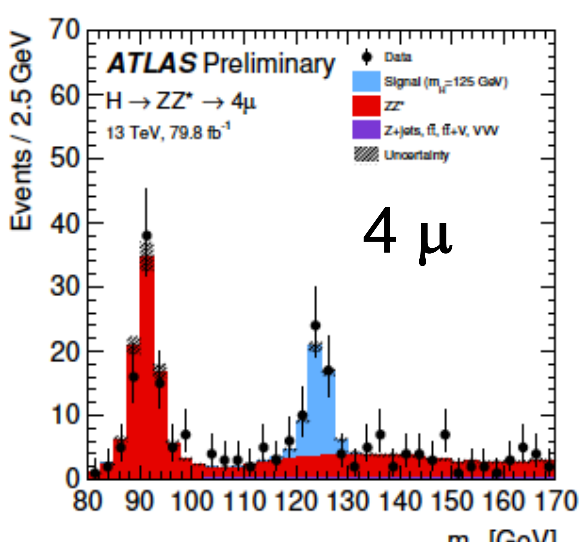
Use template mass distributions for signal & background to fit m4l for each decay channel or differential distributions to extract N_{Signal}

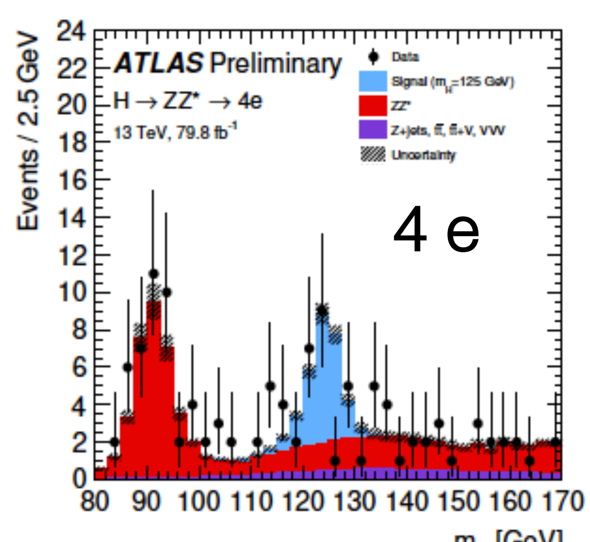
Background mostly by non resonant ZZ* production. Normalization of background shape checked using special control region

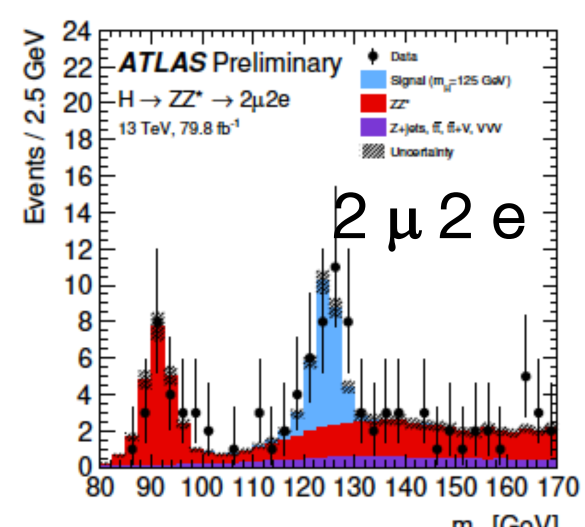
Expected and observed events in the mass window 115 < m4l < 130 GeV

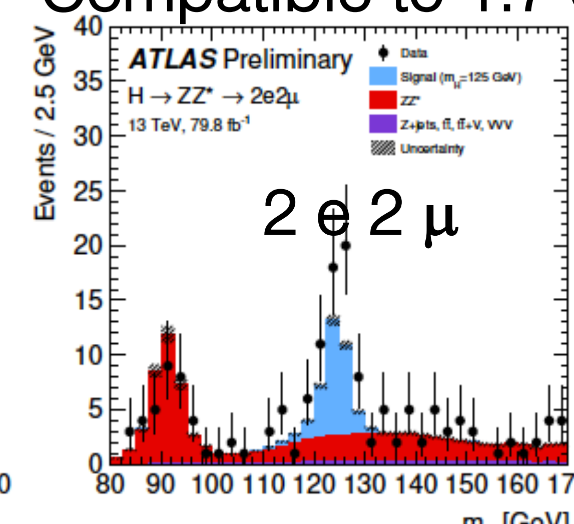
Final state	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
4μ	40.5 ± 1.7	19.0 ± 1.1	1.71 ± 0.10	61.2 ± 2.0	64
$2e2\mu$	28.2 ± 1.2	13.3 ± 0.8	1.38 ± 0.10	42.8 ± 1.4	64
$2\mu 2e$	22.1 ± 1.4	9.2 ± 0.9	2.99 ± 0.09	34.3 ± 1.7	39
$4e$	21.1 ± 1.4	8.6 ± 0.8	2.90 ± 0.09	32.5 ± 1.6	28
Total	112 ± 5	50 ± 4	8.96 ± 0.12	171 ± 6	195

Compatible to 1.7 σ





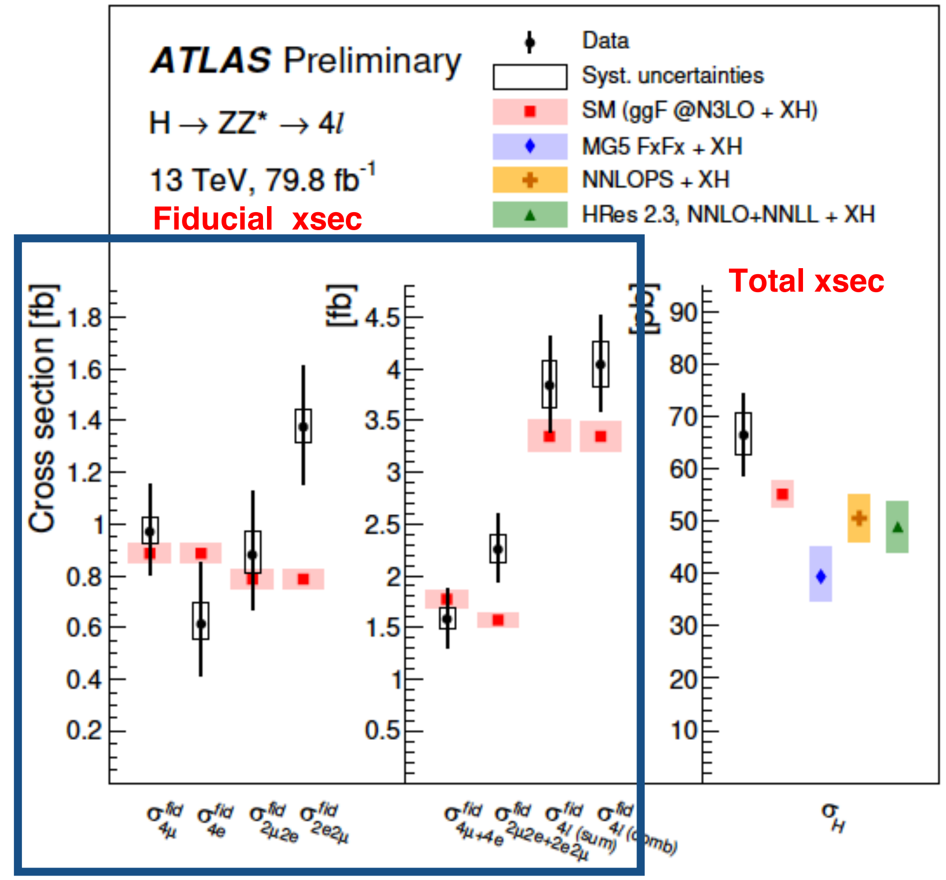




H→ZZ*→4l inclusive and differential cross-section

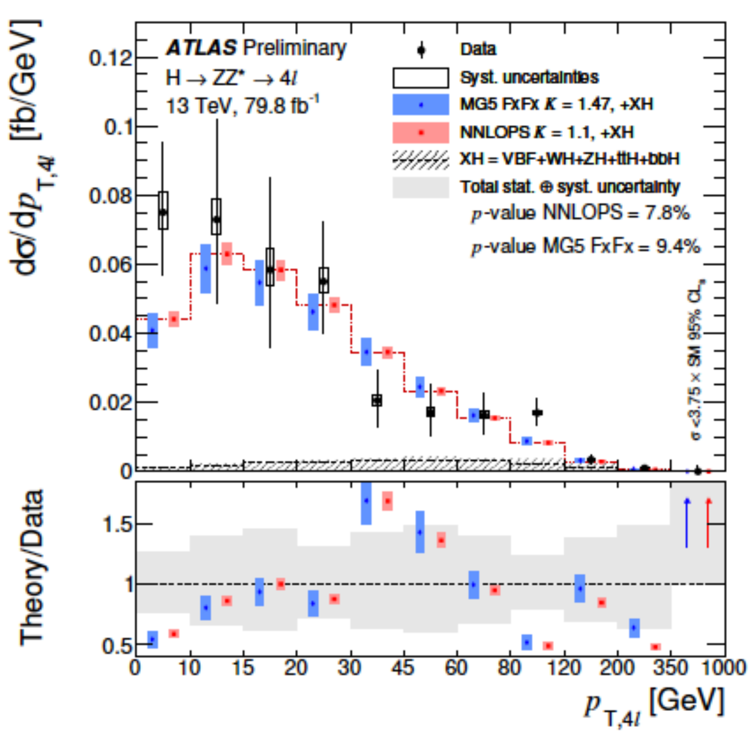
ATLAS-CONF-2018-018

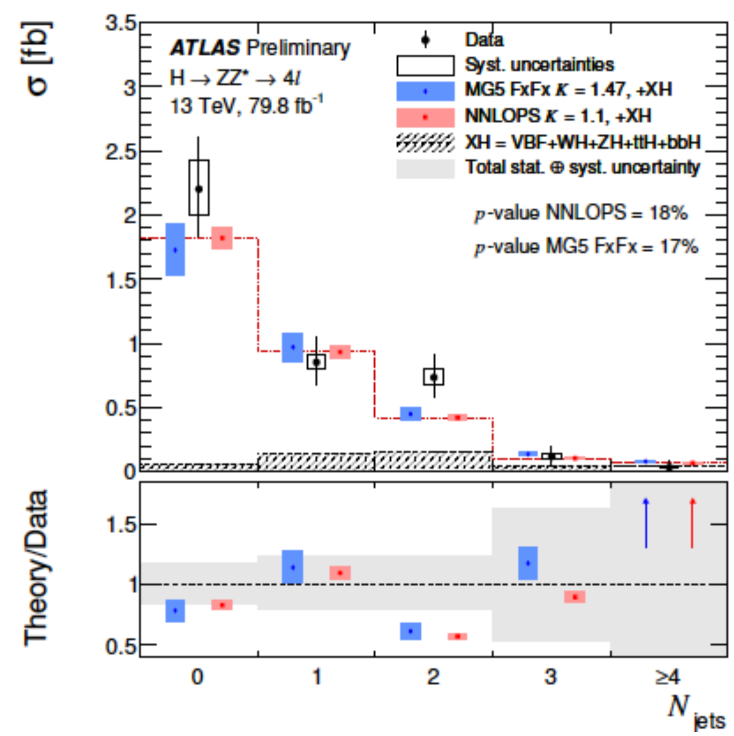
Cross section [fb]	Data (± (stat.) ± (syst.))			Standard Model prediction	p-value [%]
$\sigma_{4\mu}$	0.97	±0.17	±0.05	0.886 ± 0.039	62
σ_{4e}	0.61	±0.21	±0.07	0.886 ± 0.039	25
$\sigma_{2\mu 2e}$	0.88	±0.21	±0.08	0.786 ± 0.035	66
$\sigma_{2e2\mu}$	1.37	±0.22	±0.07	0.786 ± 0.035	0.3
$\sigma_{4\mu+4e}$	1.58	±0.27	±0.10	1.77 ± 0.07	51
$\sigma_{2\mu 2e+2e2\mu}$	2.26	±0.31	±0.13	1.57 ± 0.06	2.4
σ_{sum}	3.84	±0.41	±0.23	3.35 ± 0.15	27
σ_{comb}	4.04	±0.41	±0.22	3.35 ± 0.15	12
σ_{tot} [pb]	67.2	±6.8	±4.1	55.7 ± 2.5	13



Njets —> test modelling of radiations at high p_T, sensitive to prod modes

p_{TH} —> test perturbative QCD





Overall good theoretical description of data. Precision statistically limited

Combined inclusive fiducial xsec:

$$\sigma_{fid,comb} = 4.04 \pm 0.41(stat) \pm 0.22(syst) fb$$

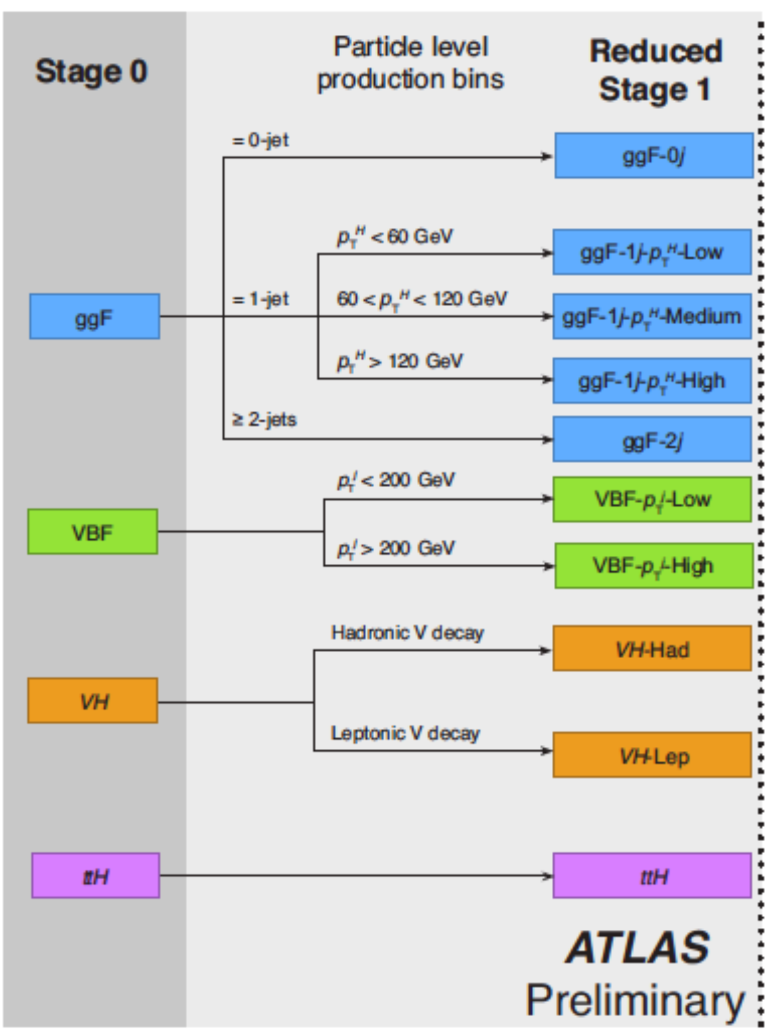
$$\sigma_{fid,SM} = 3.35 \pm 0.15 fb$$

Categorization of ZZ events & Simplified Template Cross Sections

Categories based on particle-level events by dedicated generators

Reconstruction categories in data

Higgs production mode

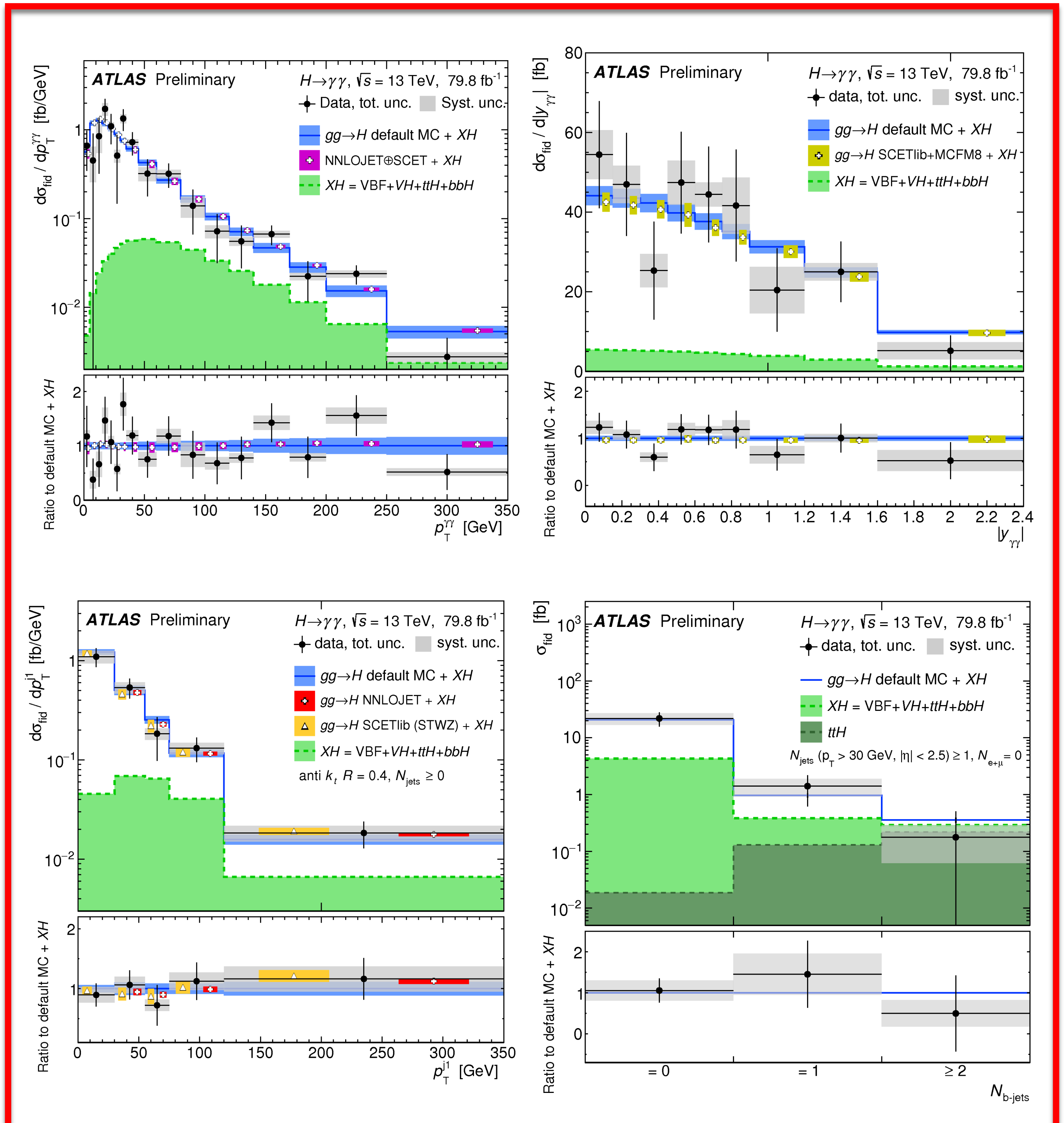


Production bin	Cross section $(\sigma \cdot \mathcal{B})$ [pb] SM expected	Cross section $(\sigma \cdot \mathcal{B})$ [pb] Observed	$(\sigma \cdot \mathcal{B})/(\sigma \cdot \mathcal{B})_{SM}$ Observed
Reduced Stage-1 production bins, $\|y_H\| < 2.5$			
ggF-$0j$	0.72 ± 0.05	$0.85 \pm 0.14 \pm 0.08$	$1.19 \pm 0.20 \pm 0.10$
ggF-$1j$-p_T^H-Low	0.170 ± 0.020	$0.09 \pm 0.09 \pm 0.04$	$0.5 \pm 0.5 \pm 0.3$
ggF-$1j$-p_T^H-Med	0.120 ± 0.020	$0.11 \pm 0.06 \pm 0.02$	$0.95 \pm 0.51 \pm 0.13$
ggF-$1j$-p_T^H-High	0.024 ± 0.005	$0.007 \pm 0.026 \pm 0.006$	$0.3 \pm 1.1 \pm 0.3$
ggF-$2j$	0.140 ± 0.030	$0.16 \pm 0.10 \pm 0.03$	$1.15 \pm 0.76 \pm 0.26$
VBF-p_T^j-Low	0.0872 ± 0.0027	$0.22 \pm 0.09 \pm 0.02$	$2.6 \pm 1.0 \pm 0.2$
VBF-p_T^j-High	$0.0041^{+0.0004}_{-0.0002}$	$0.03 \pm 0.02 \pm 0.01$	$7.4 \pm 6.0 \pm 0.7$
VH-Had	$0.0359^{+0.0019}_{-0.0033}$	$0.02 \pm 0.10 \pm 0.01$	$0.6 \pm 2.9 \pm 0.3$
VH-Lep	$0.0165^{+0.0008}_{-0.0014}$	$0.04 \pm 0.03 \pm 0.01$	$2.5 \pm 2.1 \pm 0.1$
ttH	$0.0154^{+0.0011}_{-0.0016}$	< 0.06	< 4.02

Exclusive bins in Higgs production

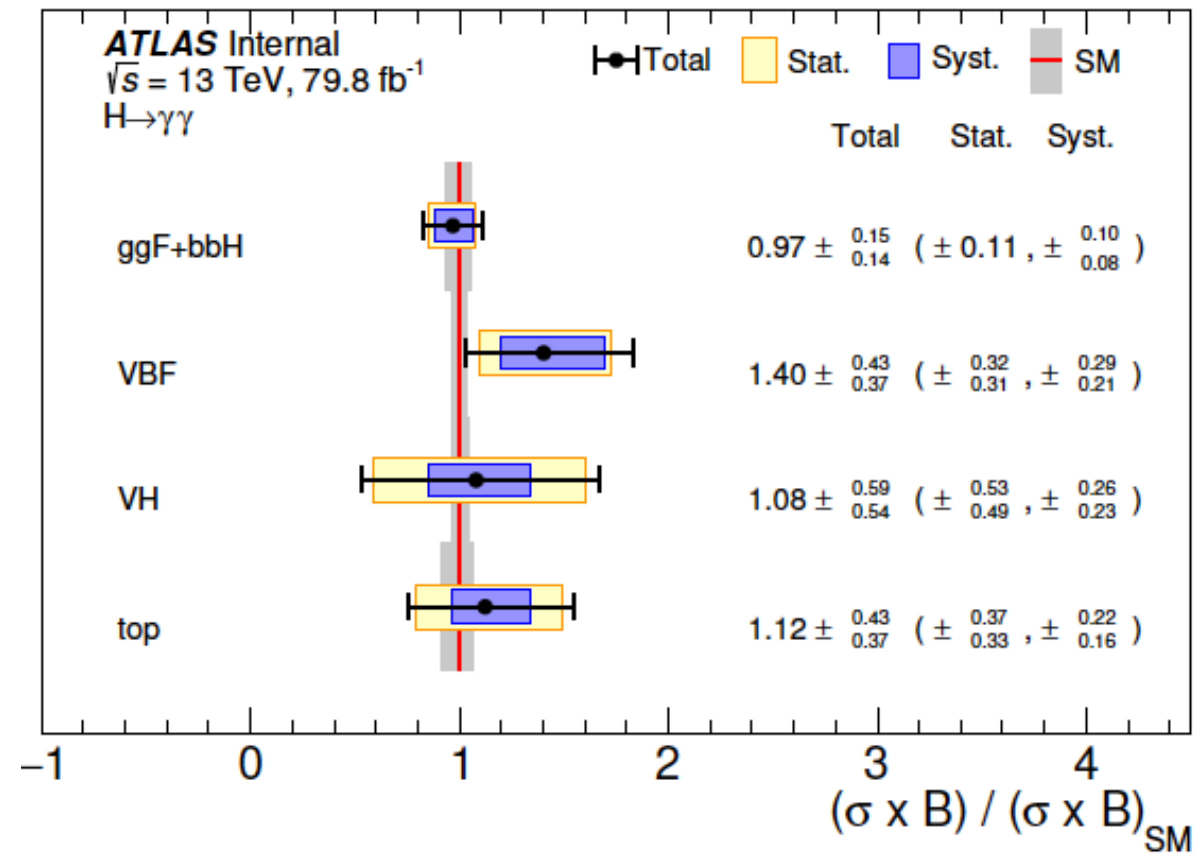
H→γγ fiducial inclusive and differential cross-section

Fit $m_{\gamma\gamma}$ distribution as superposition of signal + background



Inclusive fiducial xsec:

$$\sigma_{fid} = 60.4 \pm 6.1(stat) \pm 0.3(theo) fb$$
$$\sigma_{SM} = 63.5 \pm 3.3 fb$$



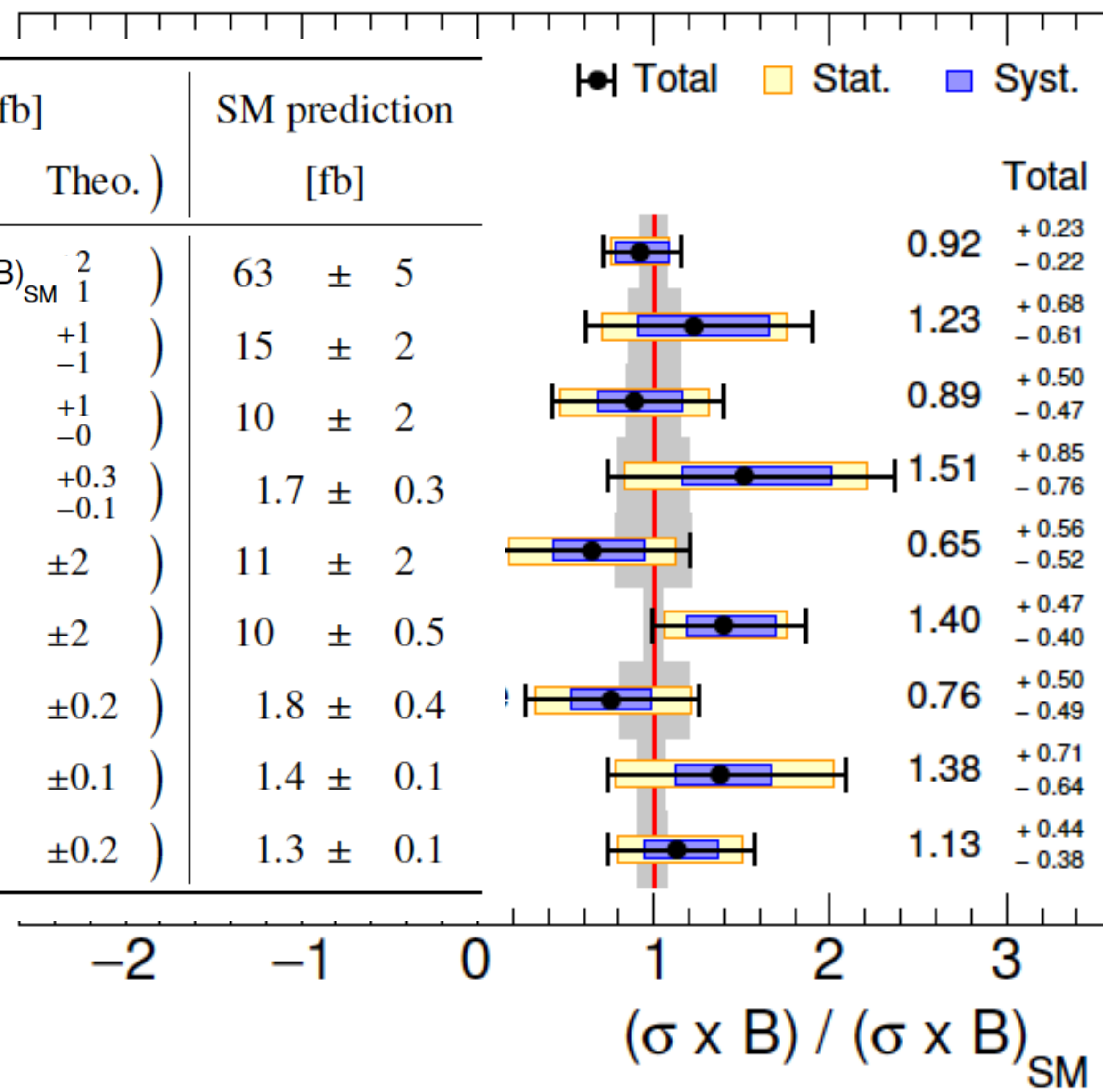
Overall good theoretical description of data.
Precision statistically limited

H→γγ, Simplified Template Cross Sections STXS

ATLAS-CONF-2018-028

Due to the limitation of the data sample only the 9 most sensitive categories are introduced.
Good agreement between data and SM prediction is observed

Measurement region ($\lvert y_H \rvert < 2.5$)	Result [fb]	Uncertainty [fb] Total	(Stat.	Exp.	Theo.)	SM prediction [fb]
ggF, 0 jet	58	$^{+15}_{-14}$	(σ x B) / (σ x B)$_{SM}$		$^{2}_{1}$	63 ± 5
ggF, 1 jet, $p_T^H < 60$ GeV	18	$^{+10}_{-9}$	±8	$^{+6}_{-5}$	$^{+1}_{-1}$	15 ± 2
ggF, 1 jet, $60 \le p_T^H < 120$ GeV	9	±5	±4	$^{+3}_{-2}$	$^{+1}_{-0}$	10 ± 2
ggF, 1 jet, $120 \le p_T^H < 200$ GeV	2.6	$^{+1.5}_{-1.3}$	±1.2	$^{+0.8}_{-0.6}$	$^{+0.3}_{-0.1}$	1.7 ± 0.3
ggF, ≥ 2 jet	7	±6	±5	$^{+3}_{-2}$	±2	11 ± 2
$qq \to Hqq$, $p_T^j < 200$ GeV	15	$^{+5}_{-4}$	±4	±2	±2	10 ± 0.5
ggF + $qq \to Hqq$, BSM-like	1.4	±0.9	±0.8	±0.4	±0.2	1.8 ± 0.4
VH, leptonic	2.0	$^{+1.1}_{-1.0}$	$^{+1.0}_{-0.9}$	±0.4	±0.1	1.4 ± 0.1
Top	1.5	$^{+0.6}_{-0.5}$	±0.5	±0.2	±0.2	1.3 ± 0.1



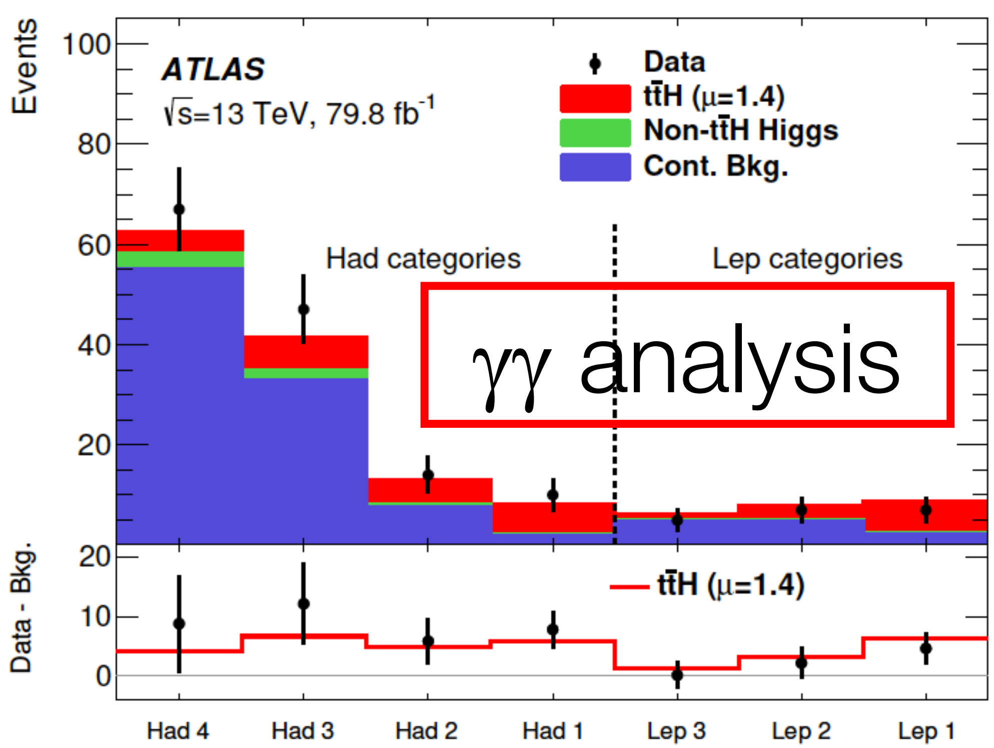
Total Higgs boson cross-section: tt (H → ZZ* & γγ)

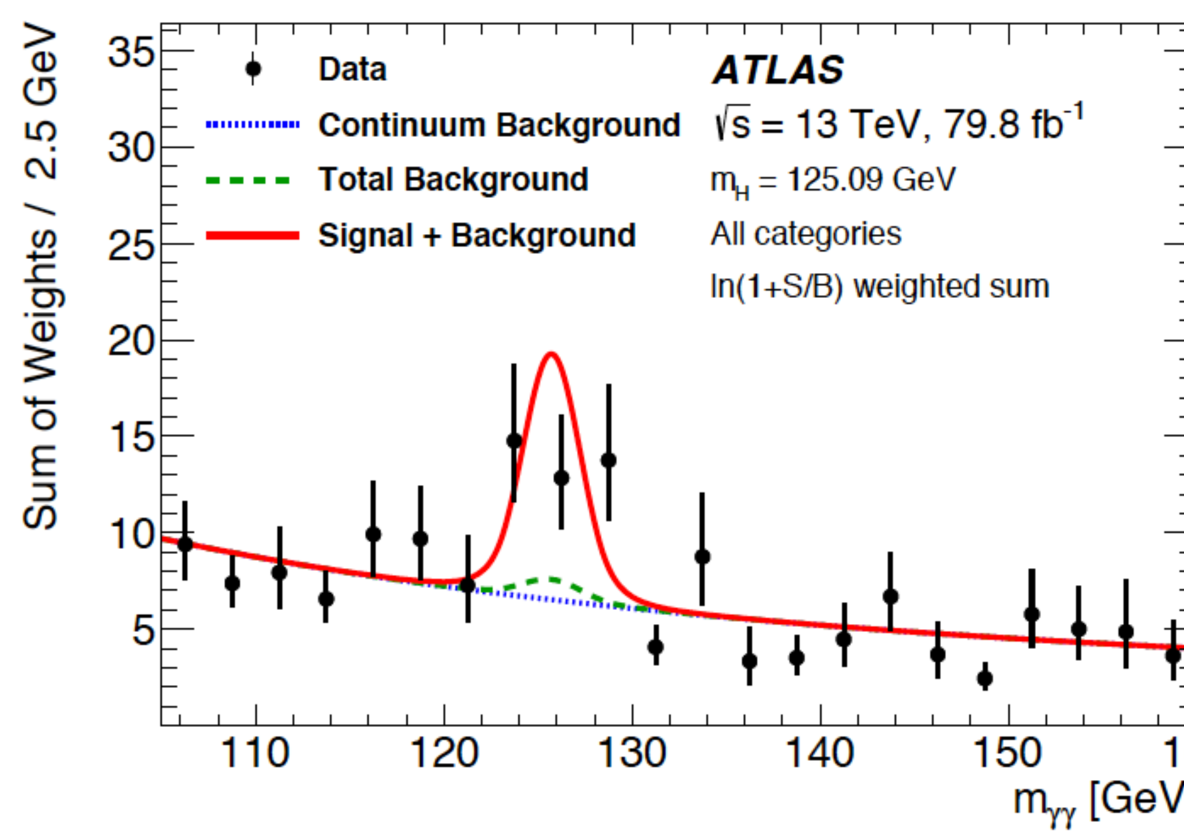
arXiv:1806.00425v1

γγ analysis and ZZ* analysis: separate hadronic and leptonic decays using BDT-based categories

Small S/B: Had 1–Had 4
Large S/B: Lep 1–Lep 3

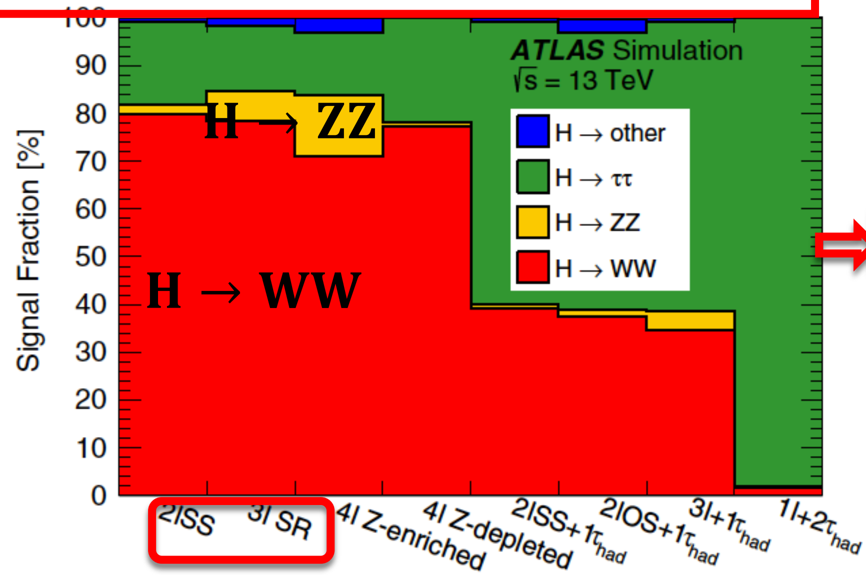
Bin	$t\bar{t}H$ (signal)		Non-$t\bar{t}H$ Higgs		Non-Higgs		Total (Expected)		Observed Total
$H \to \gamma\gamma$									
Had 1	4.2	± 1.1	0.49	± 0.33	1.8	± 0.5	6.4	± 1.3	10
Had 2	3.4	± 0.7	0.7	± 0.6	7.5	± 1.1	11.6	± 1.5	14
Had 3	4.7	± 0.9	2.0	± 1.7	32.9	± 2.2	39.6	± 3.2	47
Had 4	3.0	± 0.5	3.2	± 3.1	55.0	± 2.8	61	± 5	67
Lep 1	4.5	± 1.0	0.24	± 0.09	2.2	± 0.6	6.9	± 1.2	7
Lep 2	2.2	± 0.4	0.27	± 0.10	4.6	± 0.9	7.1	± 1.0	7
Lep 3	0.82	± 0.18	0.30	± 0.13	4.6	± 0.9	5.7	± 0.9	5
$H \to ZZ^* \to 4\ell$									
Had 1	0.169	± 0.031	0.021	± 0.007	0.008	± 0.008	0.198	± 0.033	0
Had 2	0.216	± 0.032	0.20	± 0.09	0.22	± 0.12	0.63	± 0.16	0
Lep	0.212	± 0.031	0.0256	± 0.0023	0.015	± 0.013	0.253	± 0.034	0



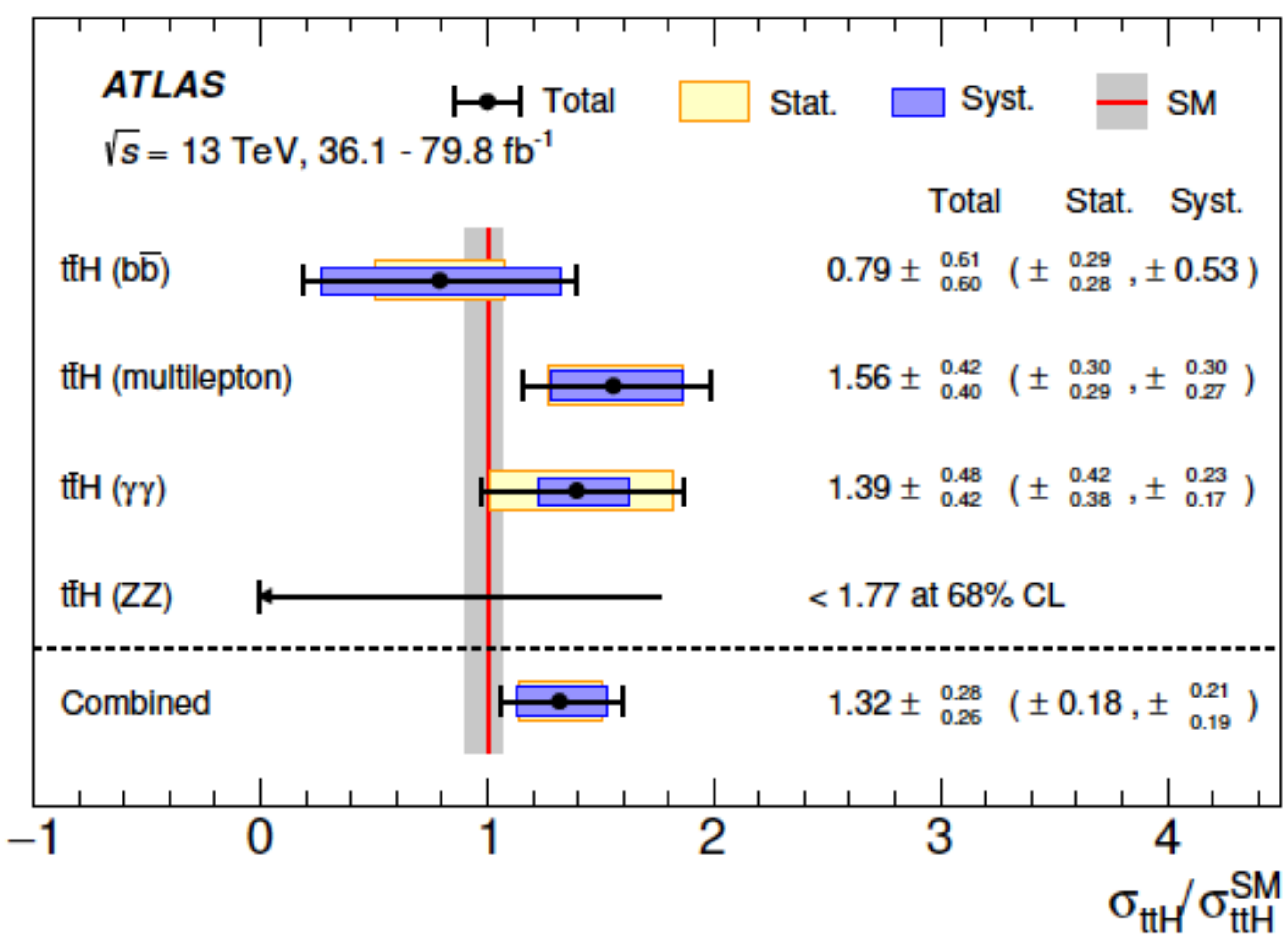


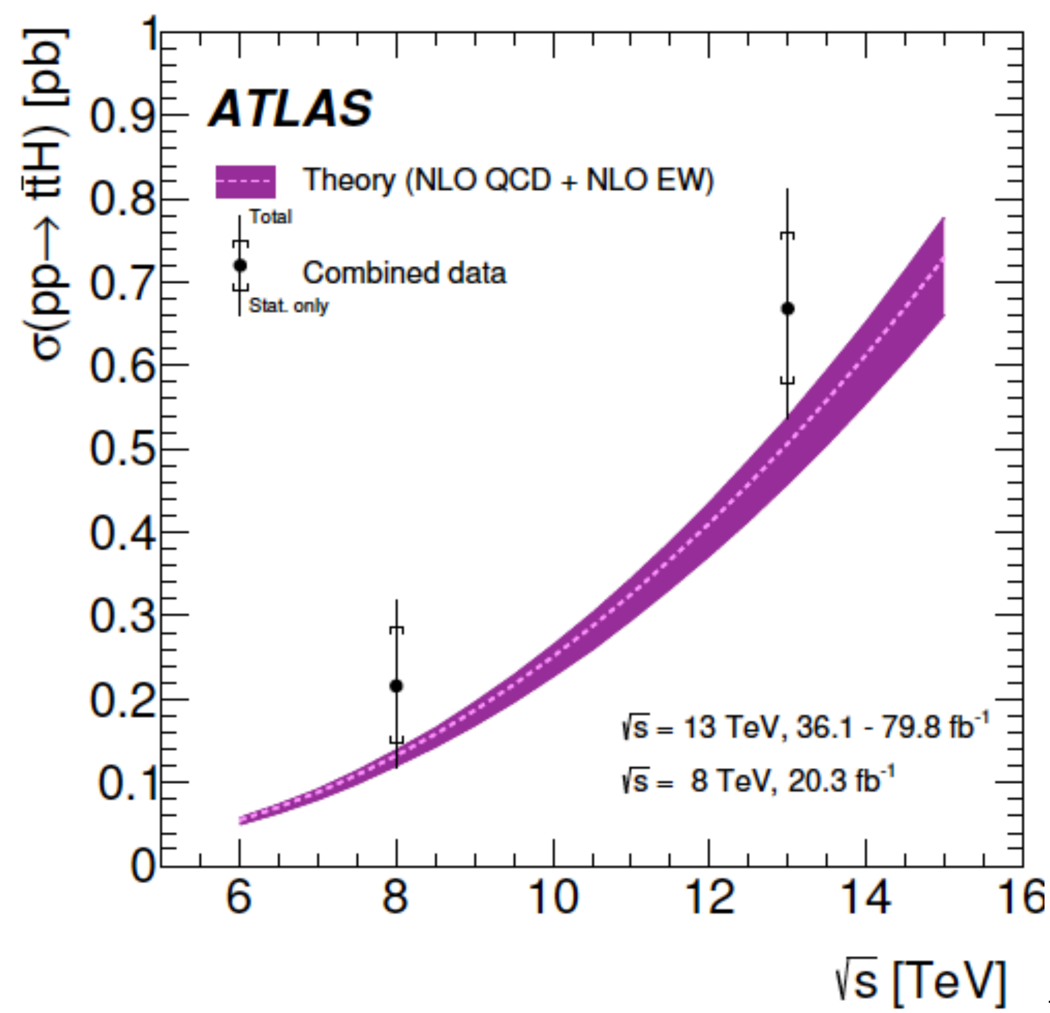
Total Higgs ttH boson cross-section Combination

Largest samples: 2lSS + 3lSR



Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \to bb$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ



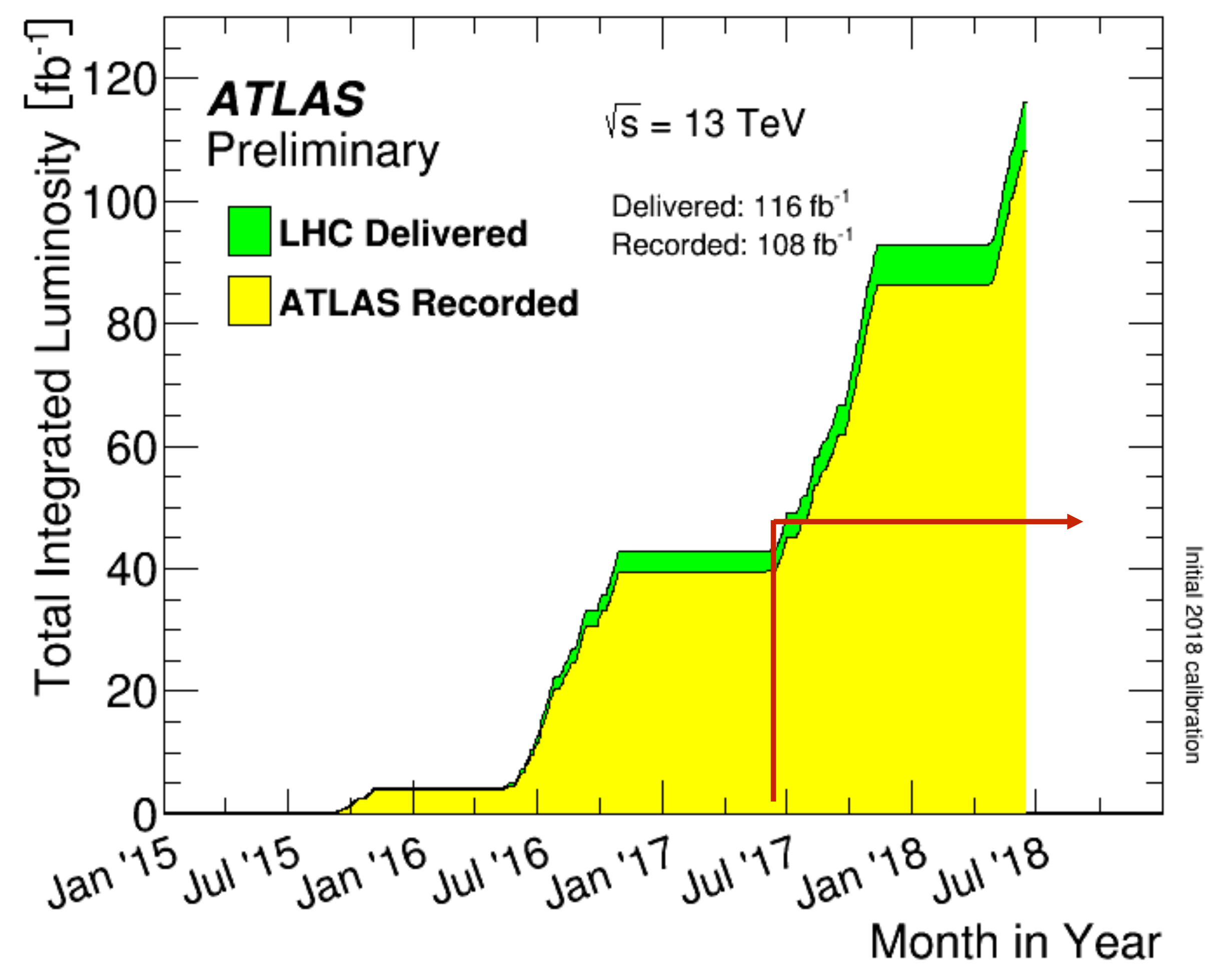


Remarks and Conclusions

- A summary of the first set of ATLAS Run-II Higgs boson properties measurements has been presented
  - Precision of cross-section measurements ~2 times better than with Run-I dataset
  - Overall, a remarkable good agreement with SM predictions observed

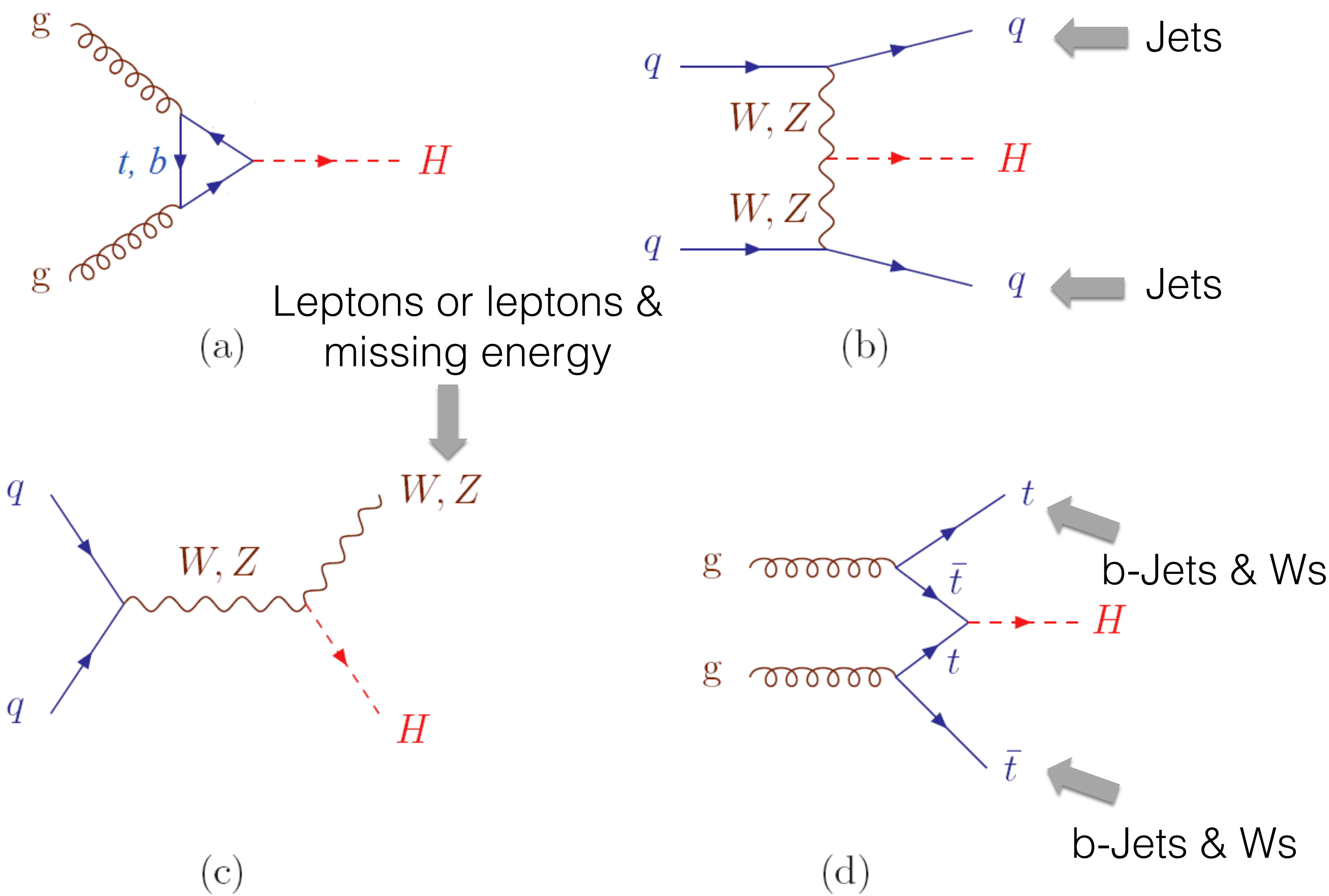
- Most of the measurements limited by statistics:
  - So far most results are based on ~80 fb^{-1}
  - And more data expected in this last year of LHC Run-2 data-taking

Stay tuned for the sequel of the Higgs characterisation saga!



Backup

Production modes & topologies



Selection in a nutshell

Large number of different topologies & reconstruction techniques.

Commonly used objects are:

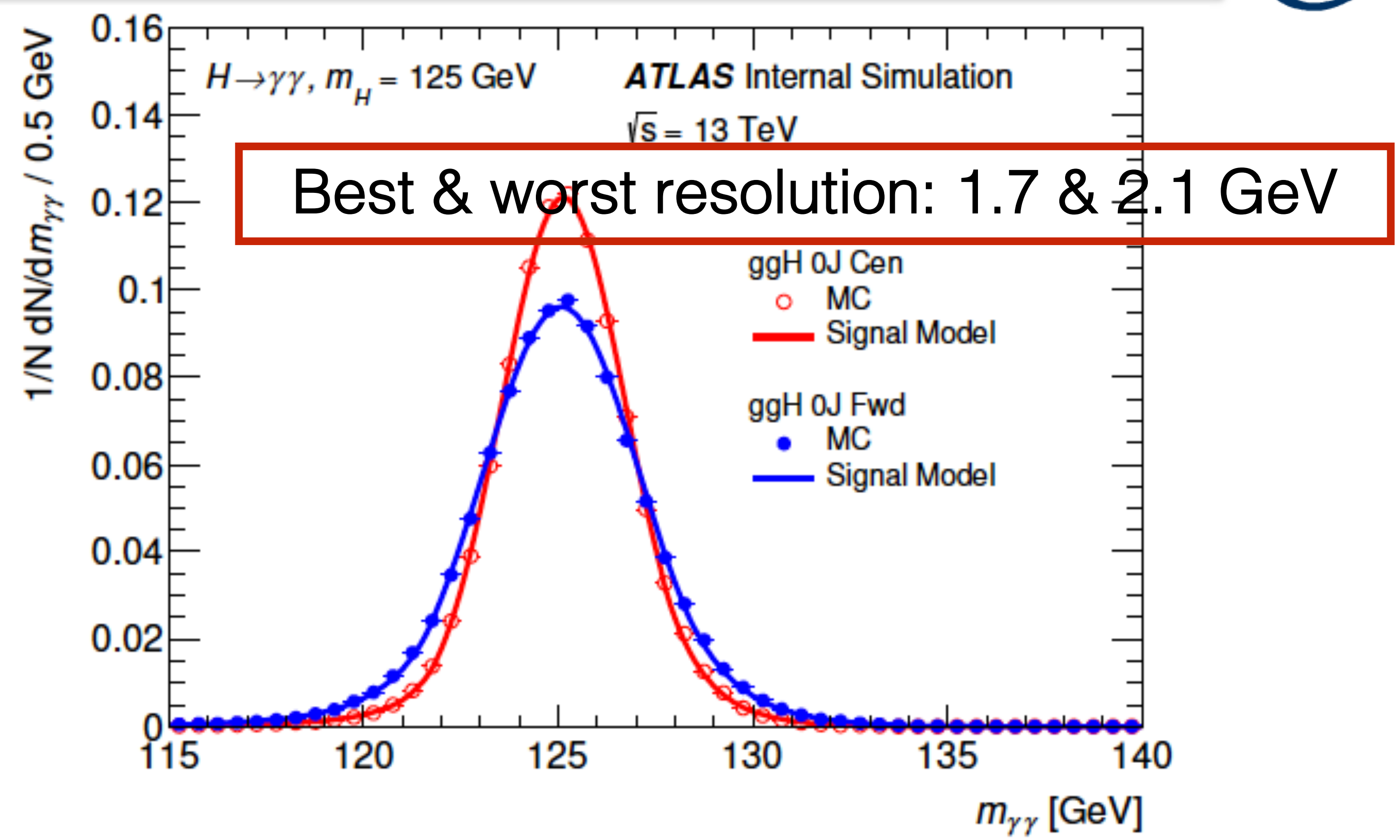
- Isolated & good quality leptons; charge & flavour in leptonic decays of bosons
- Isolated & good quality photons
- Invariant (transverse) masses Z (W)
- Jets (hadronic decays of bosons)
- B-tagged jets (for ttH topologies)

	H→γγ	H→ZZ*→4l	H→WW*→eνμν	ttH, H→γγ,WW*,ZZ*
∫Ldt(fb-1); |η| interval	36.1, $\sqrt{s}$=13TeV <2.37 && excluding 1.37-1.52	79.8, $\sqrt{s}$=13TeV <2.47	36.1, $\sqrt{s}$=13TeV <2.37 && excluding 1.37 1.52	79.8 (36.1), $\sqrt{s}$=13TeV <2.47
Objects	**Photons: Reconstruction quality, isolation, E_T>25GeV, $E_T/m_{\gamma\gamma}$>0.25,0.35**	**Leptons: 2 SF,OC pairs; p_T>20,15,10,5 GeV 50<m12(GeV)<106; 12-50<m34(GeV)<115 115<m_{4l}(GeV)<130**	**Leptons: Isolated $e^\pm \mu^\mp$ pairs p_T>22,15 GeV**	**isolated photons & b-jet & [(had decays) or (lep decays)] isolated leptons & b-jet & [(had decays) or (lep decays)]**
Method	**Fit distribution of $m_{\gamma\gamma}$ as signal + background.** Categorisation	**Fit distribution of m_{4l} as signal + background.** Categorisation	**Transverse mass of di - lepton+E_T^{miss} discriminating variable** Categorisation	**Multi-variate analysis (MVA)** Categorisation

H→γγ inclusive and differential cross-section

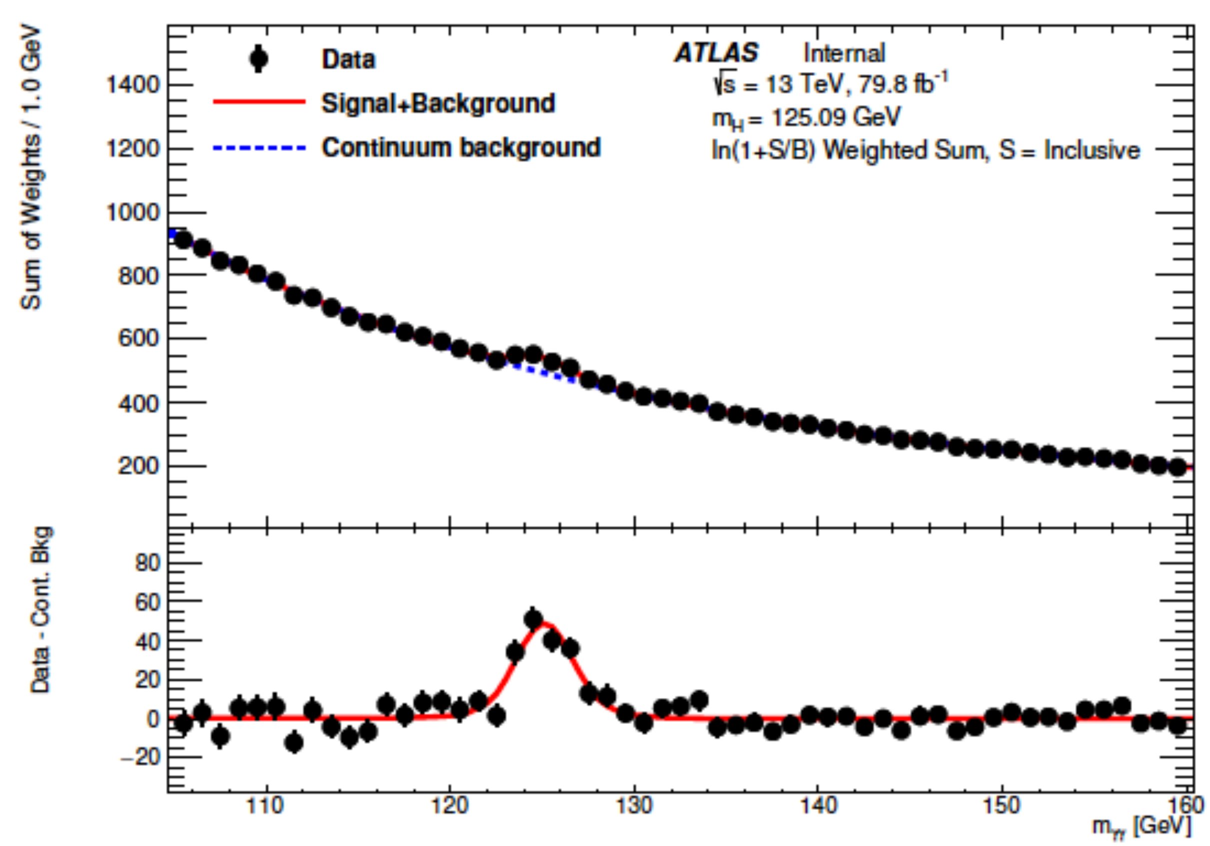
CONF-HIGG-2018-02

Fit mγγ distribution as superposition of signal + background



Signal is modelled as a double-sided Crystal Ball.

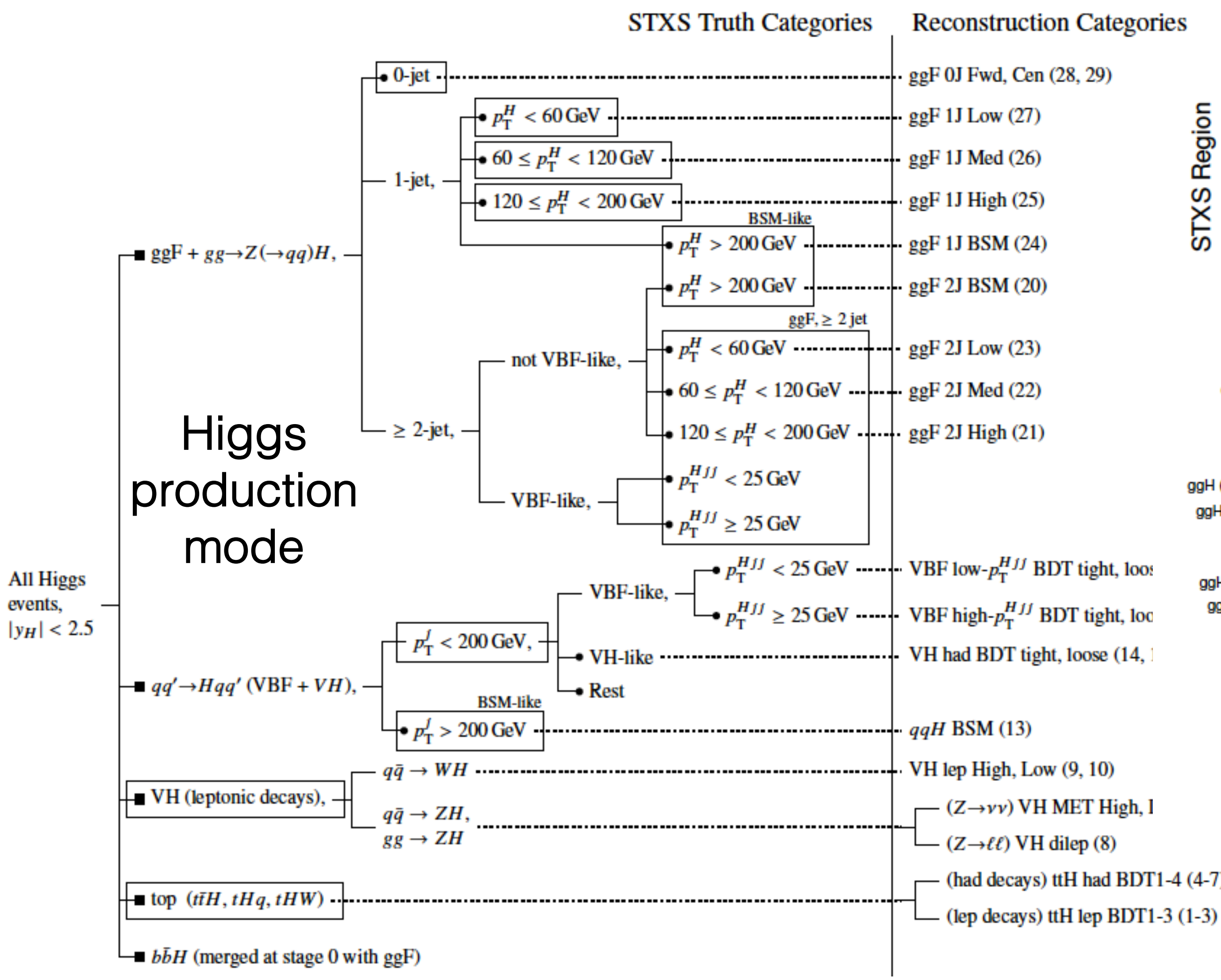
Background parametrisation chosen as best trade-off between small bias in signal determination & small number of function parameters.

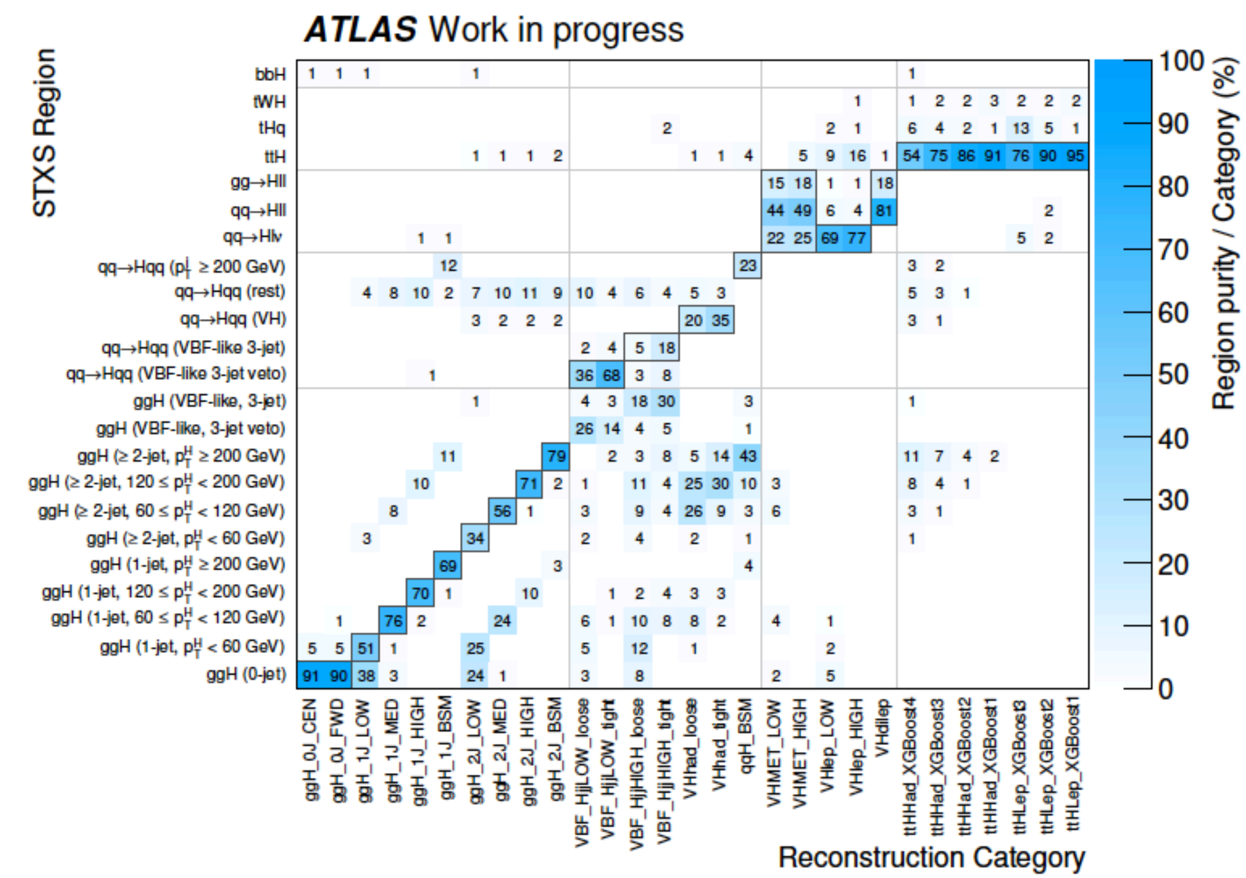


Categorization of γγ events

Exclusive bins in Higgs production

Reconstruction categories in data





9 STXS categories
(2 'BSM categories combined)

Good match between STXS & reconstruction categories

ATLAS EXPERIMENT

Cross sections & generators

INFN ROMA Tre

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s}$ = 13 TeV	Order of σ calculation
ggF	Powheg NNLOPS	Pythia 8	PDF4LHC15	48.52	$N^3LO(QCD)+NLO(EW)$
VBF	Powheg-Box	Pythia 8	PDF4LHC15	3.78	approximate-NNLO(QCD)+NLO(EW)
WH	Powheg-Box	Pythia 8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}'\to ZH$	Powheg-Box	Pythia 8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg\to ZH$	Powheg-Box	Pythia 8	PDF4LHC15	0.12	NNLO(QCD)+NLO(EW)
$t\bar{t}H$	Powheg-Box	Pythia 8	PDF4LHC15	0.51	NNLO(QCD)+NLO(EW)
$b\bar{b}H$	Powheg-Box	Pythia 8	PDF4LHC15	0.49	NNLO(QCD)+NLO(EW)
tHq	MG5_aMC@NLO	Pythia 8	CT10	0.07	4FS(LO)
tHW	MG5_aMC@NLO	Herwig++	CT10	0.02	5FS(NLO)
$\gamma\gamma$	Sherpa	Sherpa	CT10		
$V\gamma\gamma$	Sherpa	Sherpa	CT10		
$t\bar{t}\gamma\gamma$	MG5_aMC@NLO	Pythia 8	PDF4LHC15		

Process	Matrix Element (Alternative)	PDF	PS (Alternative)	Precision σ
ggF	POWHEG-BOX v2 NNLOPS [4–6] (MG5_aMC@NLO [22, 23])	PDF4LHC15 NNLO [7]	PYTHIA 8 [8] (HERWIG 7 [24])	N^3LO QCD + NLO EW [10–14]
VBF	POWHEG-BOX v2 (MG5_aMC@NLO)	PDF4LHC15 NLO	PYTHIA 8 (HERWIG 7)	NNLO QCD + NLO EW [10, 15–17]
VH	POWHEG-BOX v2 [25]	PDF4LHC15 NLO	PYTHIA 8	NNLO QCD + NLO EW[26–28]
$qq\to WW$	SHERPA 2.2.2 [29, 30] (POWHEG-BOX v2, MG5_aMC@NLO)	NNPDF3.0NNLO [31]	SHERPA 2.2.2 [32, 33] (HERWIG++ [24])	NLO [34]
$gg\to WW$	SHERPA 2.1.1 [34]	CT10 [35]	SHERPA 2.1	NLO [36]
$WZ/V\gamma^*/ZZ$	SHERPA 2.1	CT10	SHERPA 2.1	NLO [34]
$V\gamma$	SHERPA 2.2.2 (MG5_aMC@NLO)	NNPDF3.0NNLO	SHERPA 2.2.2 (CSS variation [32, 37])	NLO [34]
$t\bar{t}$	POWHEG-BOX v2 [38] SHERPA 2.2.1	NNPDF3.0NLO	PYTHIA 8 [39] (HERWIG 7)	NNLO+NNLL [40]
Wt	POWHEG-BOX v1 [41] (MG5_aMC@NLO)	CT10 [35]	PYTHIA 6.428 [42] (HERWIG++)	NLO [41]
Z+jets	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	NLO [43]

ATLAS EXPERIMENT

Cross sections & generators

INFN ROMA Tre

Production process		σ [pb]
ggF	$(gg \to H)$	48.6 ± 2.4
VBF	$(qq' \to Hqq')$	3.78 ± 0.08
WH	$(q\bar{q}' \to WH)$	1.373 ± 0.028
ZH	$(q\bar{q}/gg \to ZH)$	0.88 ± 0.04
ttH	$(q\bar{q}/gg \to t\bar{t}H)$	0.51 ± 0.05
bbH	$(q\bar{q}/gg \to b\bar{b}H)$	0.49 ± 0.12
tH	$(q\bar{q}/gg \to tH)$	0.09 ± 0.01
Decay process		$\mathcal{B}$ $[\cdot\ 10^{-4}]$
$H \to ZZ^*$		262 ± 6
$H \to ZZ^* \to 4\ell$		1.240 ± 0.027

$\sqrt{s}$ (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	$15.3^{+10\%}_{-10\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	17.5
8	$19.5^{+10\%}_{-11\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	22.3
13	$44.1^{+11\%}_{-11\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.51^{+9\%}_{-13\%}$	50.6
14	$49.7^{+11\%}_{-11\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.61^{+9\%}_{-13\%}$	57.1

ATLAS EXPERIMENT

Asymptotic formulae for likelihood-based tests of new physics

Glen Cowan[1], Kyle Cranmer[2], Eilam Gross[3], Ofer Vitells[3,a]

INFN ROMA Tre

Suppose for each event in the signal sample one measures a variable x and uses these values to construct a histogram $\mathbf{n} = (n_1, \ldots, n_N)$. The expectation value of n_i can be written

$$E[n_i] = \mu s_i + b_i, \tag{2}$$

where the mean number of entries in the ith bin from signal and background are

$$s_i = s_{\mathrm{tot}} \int_{\mathrm{bin}\, i} f_s(x; \boldsymbol{\theta}_s)\, dx, \tag{3}$$

$$b_i = b_{\mathrm{tot}} \int_{\mathrm{bin}\, i} f_b(x; \boldsymbol{\theta}_b)\, dx. \tag{4}$$

Here the parameter μ determines the strength of the signal process, with $\mu = 0$ corresponding to the background-only hypothesis and $\mu = 1$ being the nominal signal hypothesis. The functions $f_s(x; \boldsymbol{\theta}_s)$ and $f_b(x; \boldsymbol{\theta}_b)$ are the probability density functions (pdfs) of the variable x for signal and background events, and $\boldsymbol{\theta}_s$ and $\boldsymbol{\theta}_b$ represent parameters that characterize the shapes of pdfs. The quantities s_{tot} and b_{tot} are the total mean numbers of signal and background events, and the integrals in (3) and (4) represent the probabilities for an event to be found in bin i. Below we use $\boldsymbol{\theta} = (\boldsymbol{\theta}_s, \boldsymbol{\theta}_b, b_{\mathrm{tot}})$ to denote all of the nuisance parameters. The signal normalization s_{tot} is not, however, an adjustable parameter but rather is fixed to the value predicted by the nominal signal model.

In addition to the measured histogram $\mathbf{n}$ one often makes further subsidiary measurements that help constrain the nuisance parameters. For example, one may select a control sample where one expects mainly background events and from them construct a histogram of some chosen kinematic variable. This then gives a set of values $\mathbf{m} = (m_1, \ldots, m_M)$ for the number of entries in each of the M bins. The expectation value of m_i can be written

$$E[m_i] = u_i(\boldsymbol{\theta}), \tag{5}$$

where the u_i are calculable quantities depending on the parameters $\boldsymbol{\theta}$. One often constructs this measurement so as to provide information on the background normalization parameter b_{tot} and also possibly on the signal and background shape parameters.

The likelihood function is the product of Poisson probabilities for all bins:

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k}. \tag{6}$$

To test a hypothesized value of μ we consider the *profile likelihood* ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}. \tag{7}$$

Systematic uncertainties on WW*→eνμν result

Source	$\frac{\Delta\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}}$ [%]	$\frac{\Delta\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}}$ [%]
Data statistics	±8	±46
CR statistics	±8	±9
MC statistics	±5	±23
Theoretical uncertainties	±8	±21
ggF signal	±5	±15
VBF signal	<1	±15
WW	±5	±12
Top-quark	±4	±4
Experimental uncertainties	±9	±8
b-tagging	±5	±6
Pile-up	±5	±2
Jet	±3	±4
Electron	±3	<1
Misidentified leptons	±5	±9
Luminosity	±2	±3
TOTAL	±17	±59

Run1/Run2 comparison for WW*→eνμν result

	μ_{ggF}	stat.	syst.
ATLAS, 13 TeV, 36.1 fb^{-1}	$1.21^{+0.22}_{-0.21}$	10%	15%
ATLAS, 7+8 TeV, 24.8 fb^{-1}	$1.02^{+0.29}_{-0.26}$	19%	20%
CMS, 13 TeV, 35.9 fb^{-1}	$1.38^{+0.21}_{-0.24}$	-	-

	μ_{VBF}	total
ATLAS, 13 TeV, 36.1 fb^{-1}	$0.62^{+0.37}_{-0.36}$	59%
ATLAS, 7+8 TeV, 24.8 fb^{-1}	$1.27^{+0.53}_{-0.45}$	$^{+41\%}_{-35\%}$
CMS, 13 TeV, 35.9 fb^{-1}	$0.29^{+0.66}_{-0.29}$	$^{+228\%}_{-100\%}$

CMS also gives results for VH.

Theory ggF cross section prediction improved in Run 2 w.r.t. Run 1.
μ of Run 2 uses different cross section prediction than in Run 1.

- Good compatibility between Run 1 and Run 2, as well as ATLAS and CMS
- ggF: Precision improved by 36% with respect to Run 1.
  - Systematic uncertainties reduced by 25%.
- VBF signal strength low in Run 2
  - Expected significance is 2.7σ for the Run 1 and the Run 2 measurements

→ New measurements in *H→WW** will contribute to combined Higgs results

H→ZZ*→4l inclusive and differential cross-section

- Experimental and particle level selection as similar as possible to minimise theory uncertainties

Fiducial phase space definition

Leptons and jets	
Muons:	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
Jets:	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
Jet-lepton overlap removal:	$\Delta R(\text{jet}, \ell) > 0.1$ (0.2) for muons (electrons)
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per channel)	
Mass requirements:	$50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115\ GeV < m_{4\ell} < 130$ GeV

Fiducial xsections
are defined at the particle level
==> correct the number of reconstructed events by
the difference in acceptance between detector-level and particle level

ATLAS EXPERIMENT

$H \to ZZ^* \to 4l$ inclusive and differential cross-section

INFN ROMA Tre

SR event yields

Final state	SM Higgs	ZZ^*	$Z+$jets, $t\bar{t}$ WZ, ttV, VVV	Expected	Observed
4μ	20.1 ± 2.1	9.8 ± 0.5	1.3 ± 0.3	31.2 ± 2.2	33
$4e$	10.6 ± 1.2	4.4 ± 0.4	1.3 ± 0.2	16.3 ± 1.3	16
$2e2\mu$	14.2 ± 1.4	7.1 ± 0.4	1.0 ± 0.2	22.3 ± 1.5	32
$2\mu 2e$	10.8 ± 1.2	4.6 ± 0.4	1.4 ± 0.2	16.8 ± 1.3	21
Total	56 ± 6	25.9 ± 1.5	5.0 ± 0.6	87 ± 6	102

Exclusive, Inclusive and Total cross-section

Cross section	Data ($\pm$ (stat) $\pm$ (sys))	LHCXSWG prediction	p-value [%]
$\sigma_{4\mu}$ [fb]	$0.92\ ^{+0.25}_{-0.23}\ ^{+0.07}_{-0.05}$	0.880 ± 0.039	88
σ_{4e} [fb]	$0.67\ ^{+0.28}_{-0.23}\ ^{+0.08}_{-0.06}$	0.688 ± 0.031	96
$\sigma_{2\mu 2e}$ [fb]	$0.84\ ^{+0.28}_{-0.24}\ ^{+0.09}_{-0.06}$	0.625 ± 0.028	39
$\sigma_{2e2\mu}$ [fb]	$1.18\ ^{+0.30}_{-0.26}\ ^{+0.07}_{-0.05}$	0.717 ± 0.032	7
$\sigma_{4\mu+4e}$ [fb]	$1.59\ ^{+0.37}_{-0.33}\ ^{+0.12}_{-0.10}$	1.57 ± 0.07	65
$\sigma_{2\mu 2e+2e2\mu}$ [fb]	$2.02\ ^{+0.40}_{-0.36}\ ^{+0.14}_{-0.11}$	1.34 ± 0.06	6
σ_{sum} [fb]	$3.61\ ^{+0.54}_{-0.50}\ ^{+0.26}_{-0.21}$	2.91 ± 0.13	19
σ_{comb} [fb]	$3.62\ ^{+0.53}_{-0.50}\ ^{+0.25}_{-0.20}$	2.91 ± 0.13	18
σ_{tot} [pb]	$69\ ^{+10}_{-9}\ \pm 5$	55.6 ± 2.5	19

Higgs boson signal xsections normalised to LHCXS WG predictions:

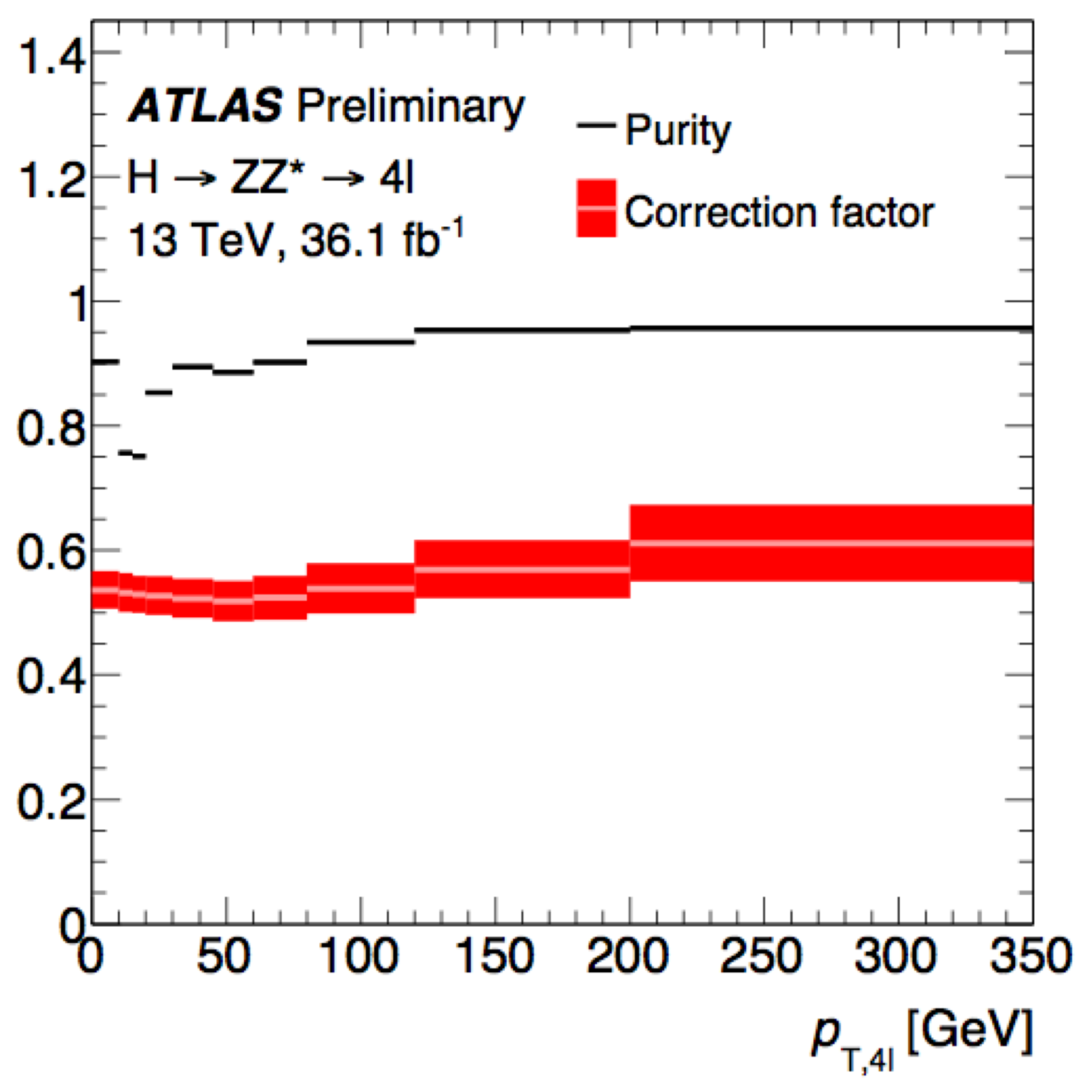
- for ggF, N3LO in QCD and NLO EW corrections applied
- VBF is fully NLO (approximate NNLO QCD corrections applied)

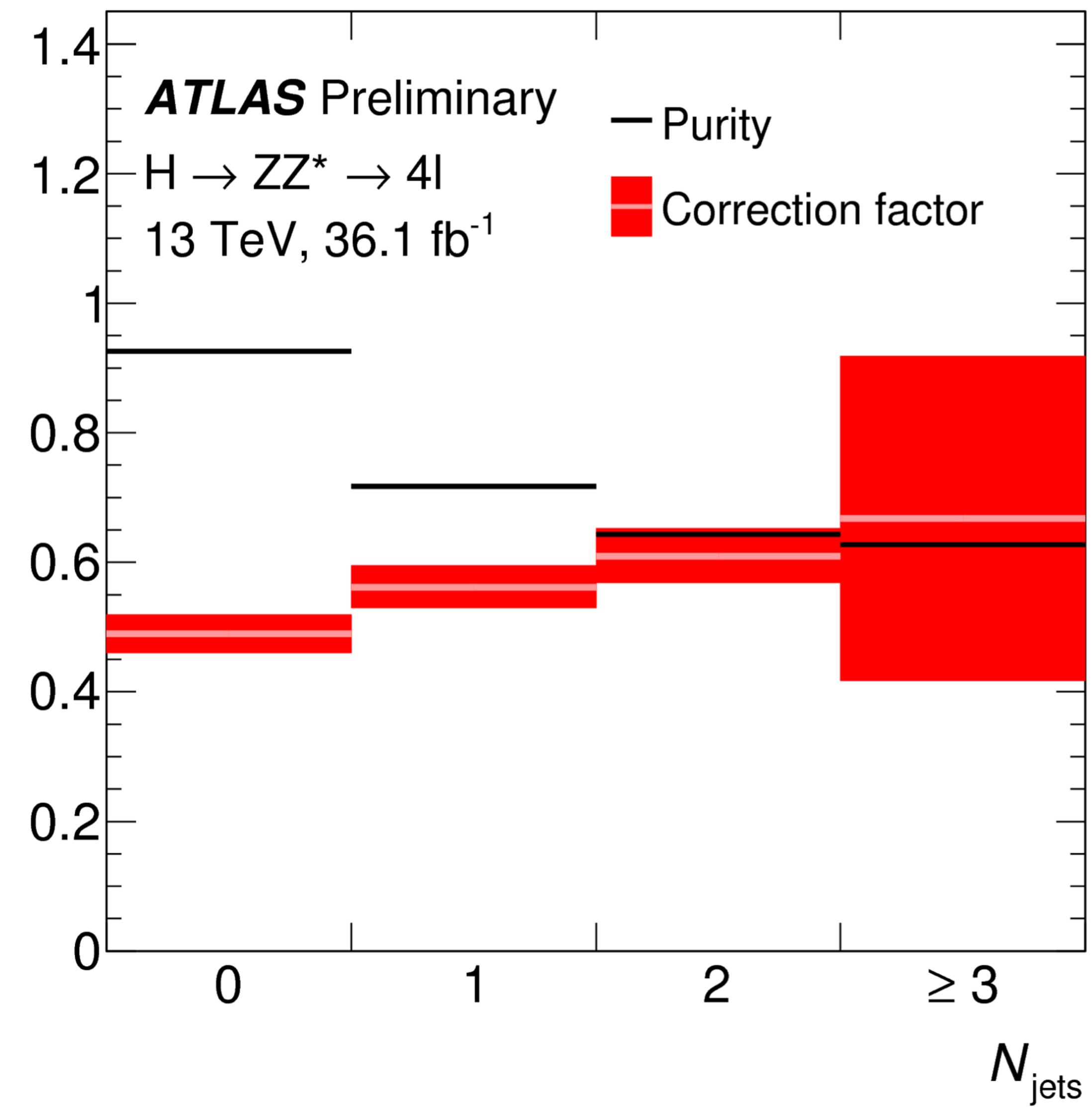
Uncertainties breakdown

Observable	Stat unc. [%]	Systematic unc. [%]	Dominant systematic components [%] e	jets	μ	ZZ^* theo	Model	$Z+$jets $+ t\bar{t}$	Lumi
σ_{comb}	14	7	3	< 0.5	3	2	0.8	0.8	4
$d\sigma/dp_{T,4\ell}$	30 − 150	3 − 11	1 − 4	< 0.5	1 − 3	0 − 7	0 − 6	1 − 6	3 − 5
$\partial\sigma/\partial p_{T,4\ell}$ (0j)	31 − 52	10− 18	2 − 5	3 − 16	1 − 4	3 − 8	1	2 − 3	3 − 5
$\partial\sigma/\partial p_{T,4\ell}$ (1j)	35 − 15	6 − 30	1 − 4	2 − 29	1 − 3	1 − 4	1 − 11	1 − 2	3 − 5
$\partial\sigma/\partial p_{T,4\ell}$ (2j)	30 − 41	5 − 21	1 − 3	2 − 19	1 − 3	1 − 5	1 − 7	1 − 2	3 − 5
$d\sigma/d\|y_{4\ell}\|$	29 − 120	5 − 8	2 − 4	< 0.5	2 − 3	1 − 2	0 − 1	1 − 1	3 − 5
$d\sigma/d\|\cos\theta^*\|$	31 − 100	5 − 8	2 − 4	< 0.5	2 − 3	1 − 2	0 − 2	1 − 4	3 − 5
$d\sigma/dm_{34}$	26 − 53	4 − 13	2 − 5	< 0.5	1 − 5	1 − 6	0 − 1	1 − 3	3 − 5
$\partial^2\sigma/\partial m_{12}\,\partial m_{34}$	21 − 40	4 − 12	2 − 4	< 0.5	1 − 4	1 − 6	0 − 1	1 − 4	3 − 5
$d\sigma/dN_{jets}$	22 − 44	6 − 31	1 − 4	4 − 22	1 − 3	2 − 4	1 − 22	1 − 2	3 − 5
$d\sigma/dp_T^{lead.jet}$	30 − 53	5 − 18	1 − 4	3 − 16	1 − 3	2 − 3	1 − 8	1 − 2	3 − 5
$d\sigma/d\Delta\phi_{jj}$	29 − 43	9 − 17	1 − 3	8 − 14	1 − 3	3 − 4	1 − 7	1 − 1	3 − 5
$d\sigma/dm_{jj}$	23 − 100	9 − 27	1 − 4	8 − 24	1 − 4	3 − 8	1 − 7	0 − 3	3 − 5

H→ZZ*→4l inclusive and differential cross-section

Bin-by-bin correction factors for detector inefficiencies and reconstruction



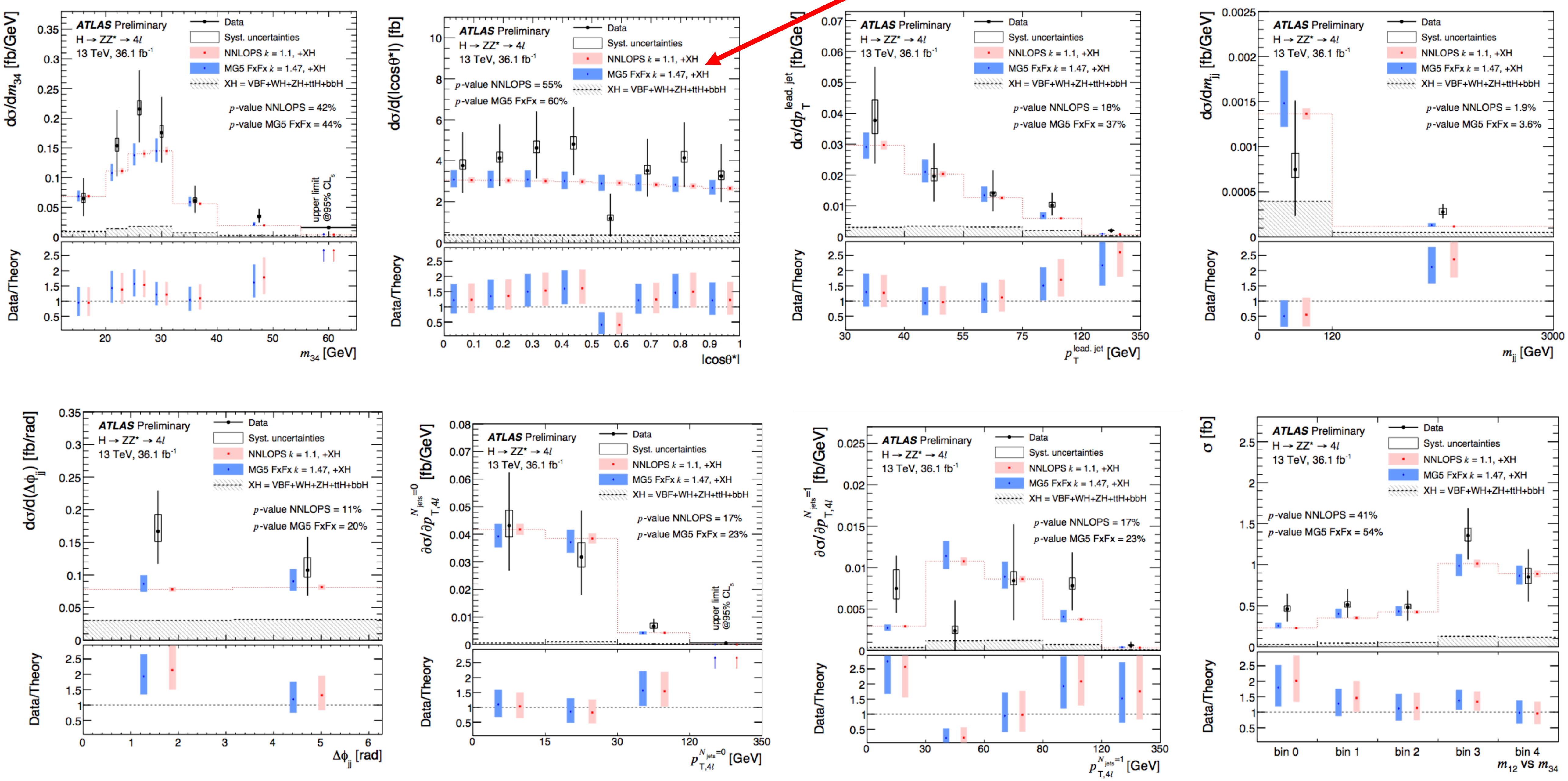


- For ggF, NNLOPS sample used to derived the correction factor
- correction factors agree within 15% for all production modes except for ttH, due to the missing isolation requirement needed to identify leptons from hadronic jets at particle level
- Large uncertainty on the last bin of Njets due to exp jet reconstruction uncertainty mainly

H→ZZ*→4l inclusive and differential cross-section

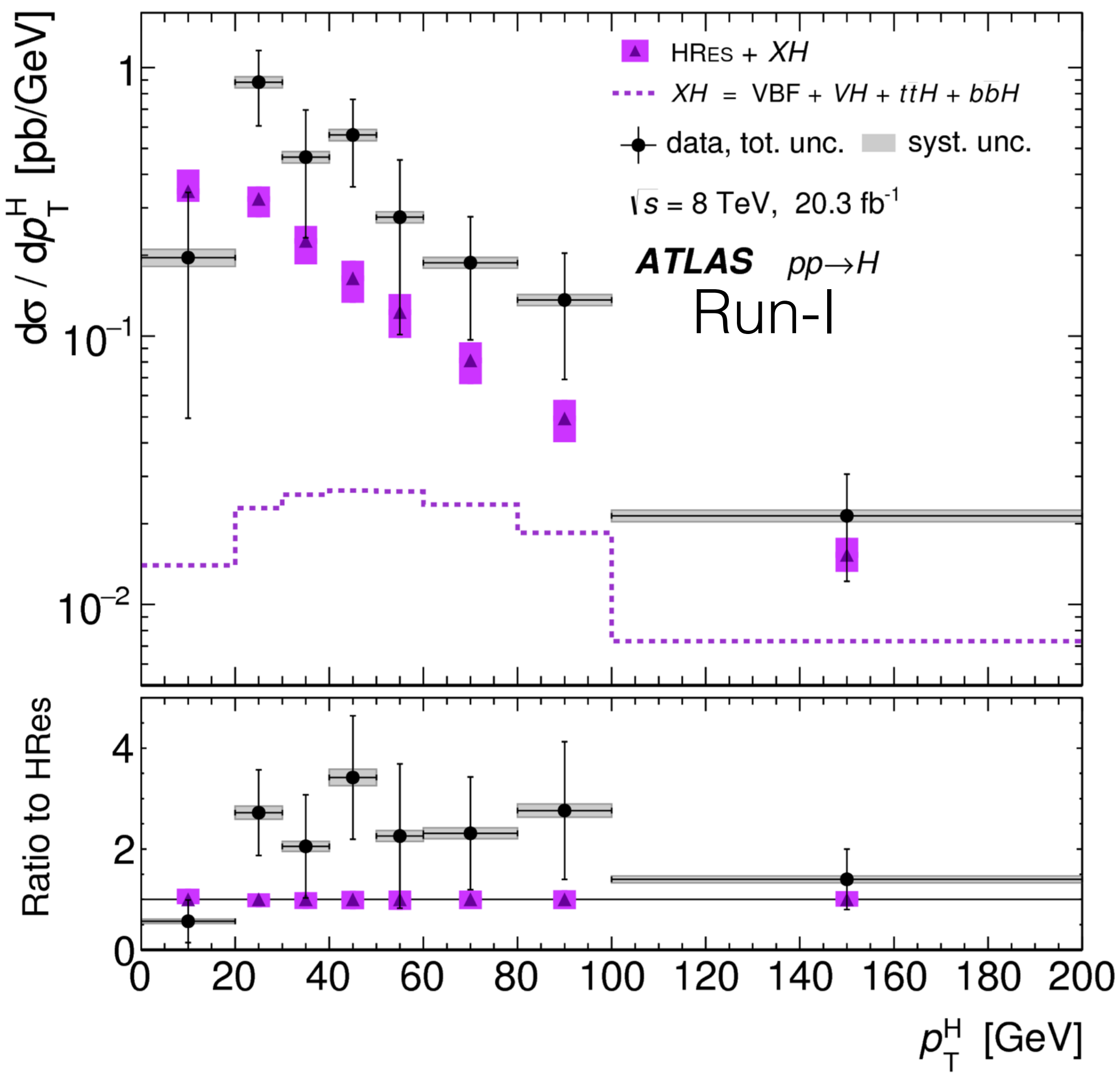
More differential distributions…

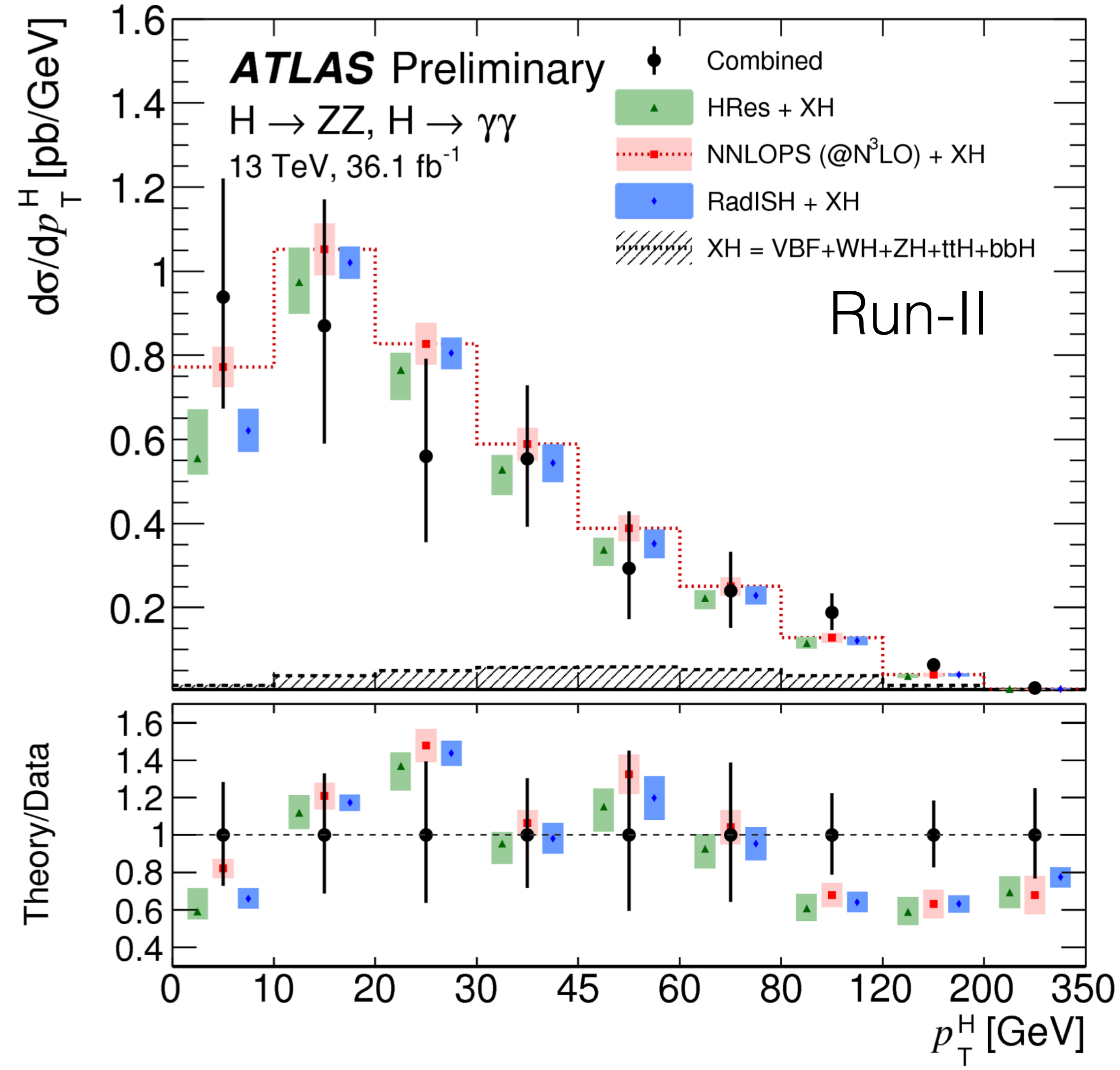
different ggF predictions normalized to N3LO with the corresponding k-factors XH processes have been added



H→ZZ*→4l inclusive and differential cross-section

Run-I/Run-II comparison





More bins at high-pt and gain in statistical precision.
Not enough sensitivity to different generators (yet)

Production cross-sections in 4l channel

σ×B measured in several dedicated mutually exclusive regions of the phase space based on the production process. Production bins are chosen in such a way that the measurement precision is maximised and at the same time possible BSM contributions can be isolated.

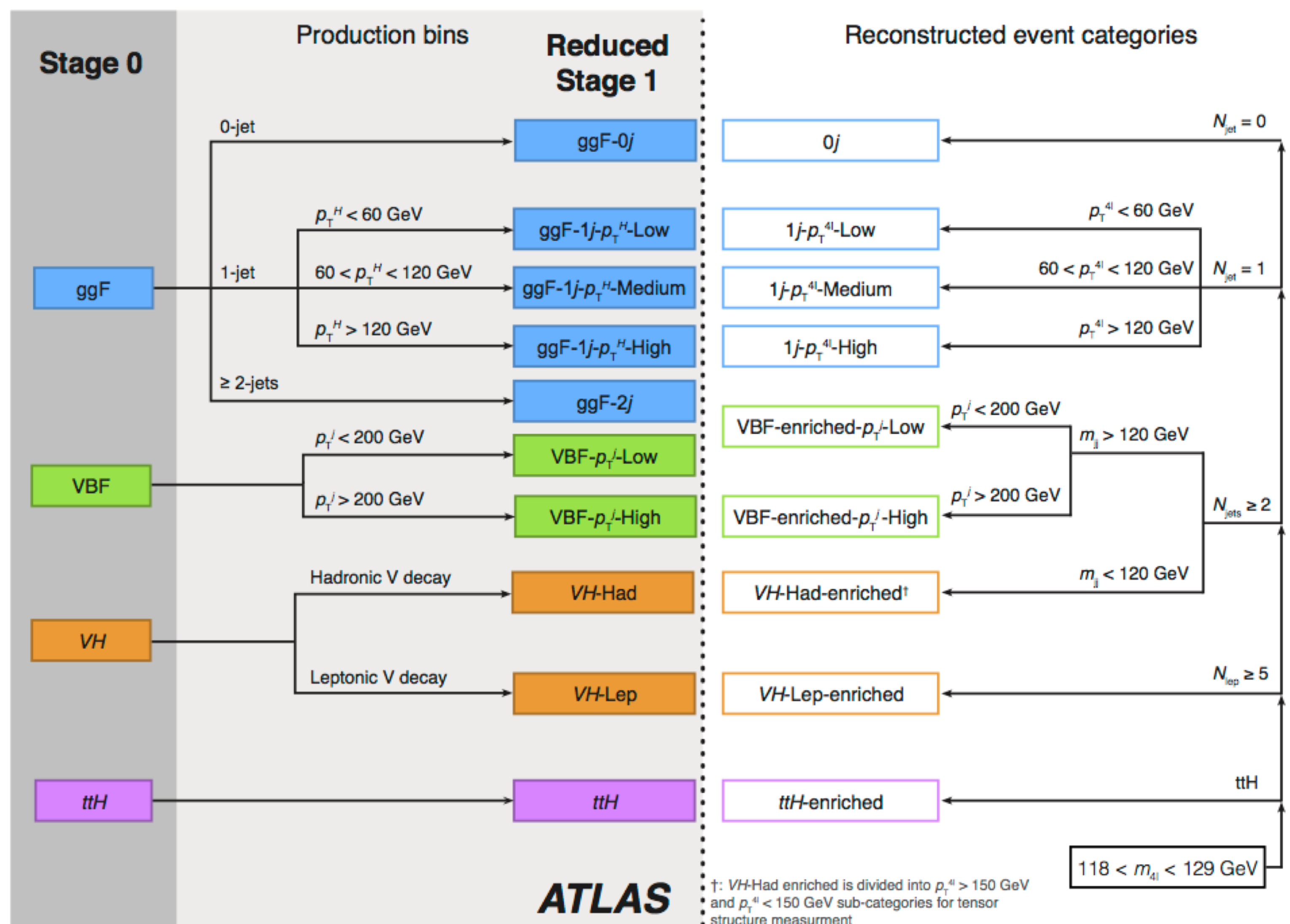
- *simple fiducial region definitions for each Higgs production mode* based on Higgs kinematics and associated particles → match experimental categories

Advantage: cross-sections can be interpreted in terms of Higgs boson couplings, and theory uncertainties enter only at that stage

Two sets of production bins considered: Stage 0 (more inclusive ==> smaller statistical uncertainty) and Reduced Stage 1(*) (smaller theoretical uncertainties)

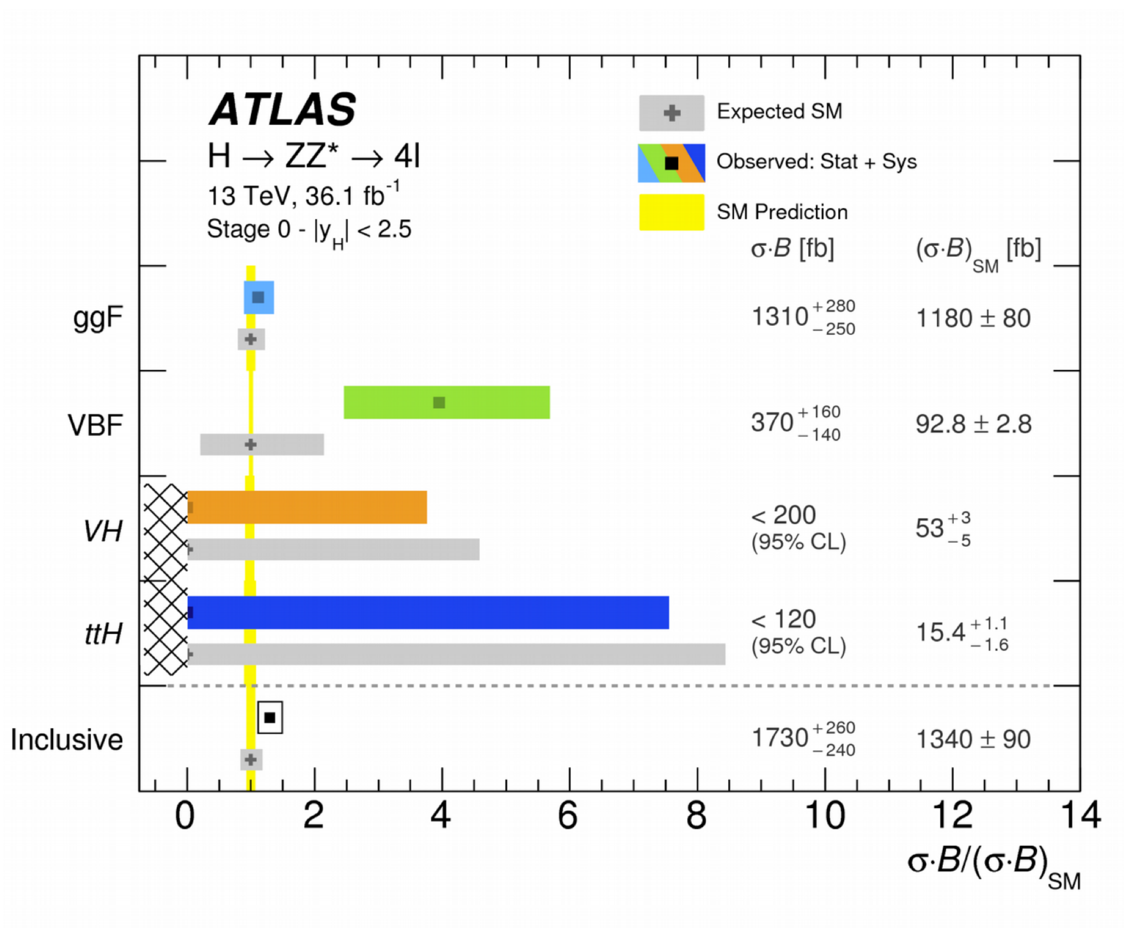
e.g. exclusive jet bins and $p_T H$

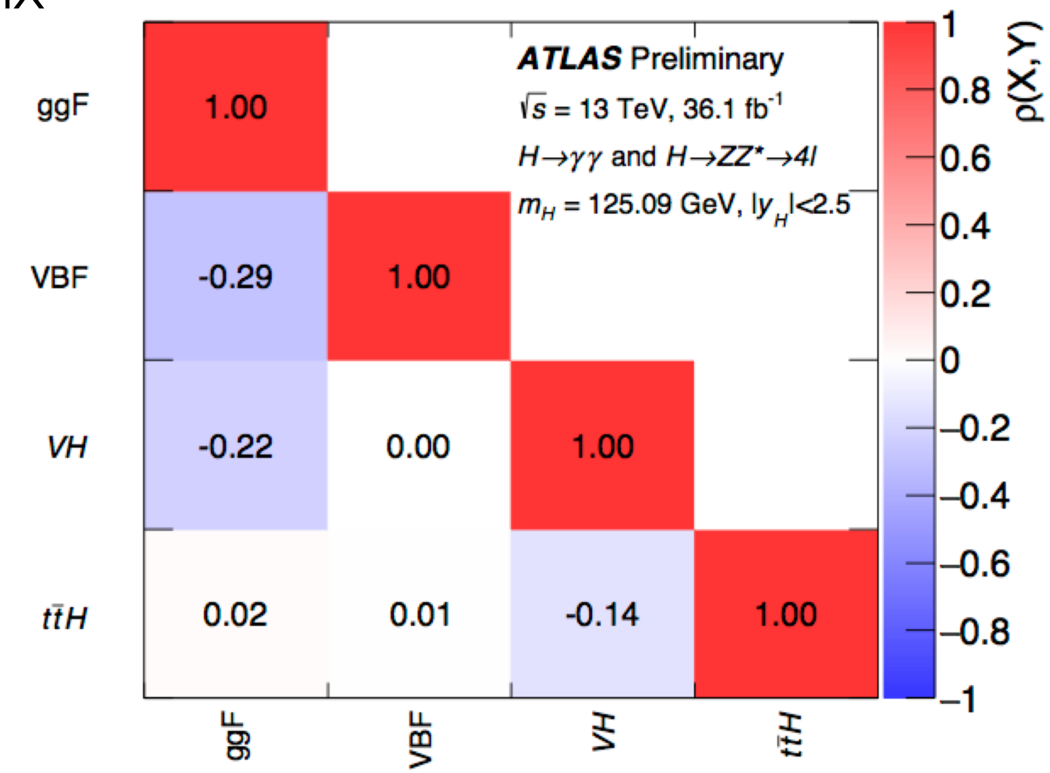
(*) too fine granularity for precise measurements in all STXS Stage-1 bins => merge some categories



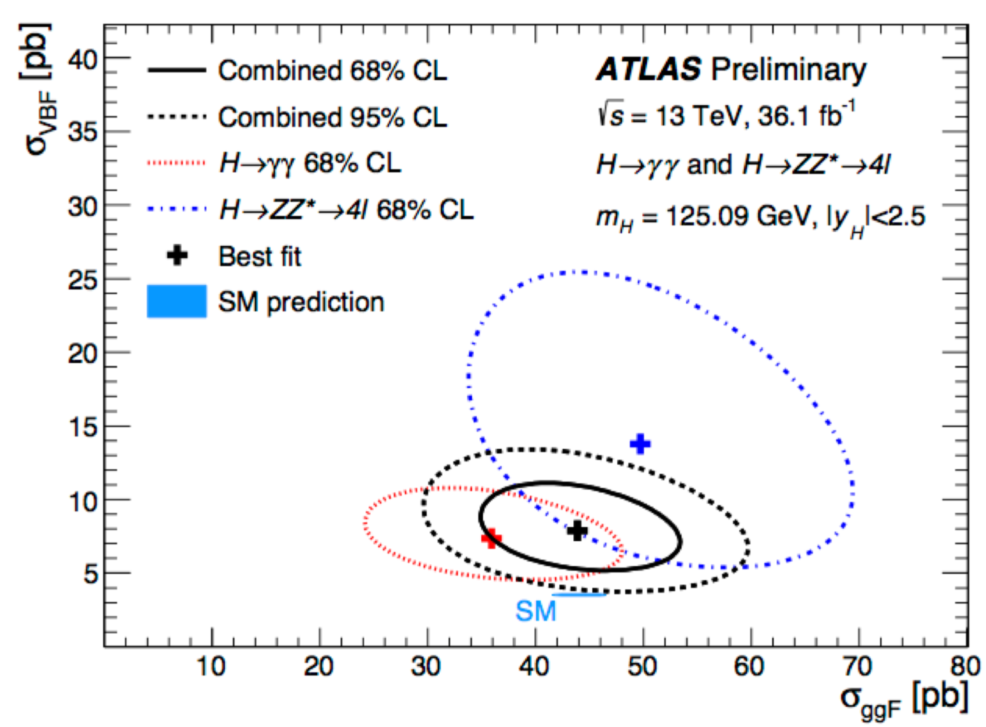
H→4l Stage-0 production cross-section measurements

Combination of Stage-0 production cross-section measurements: Correlation matrix

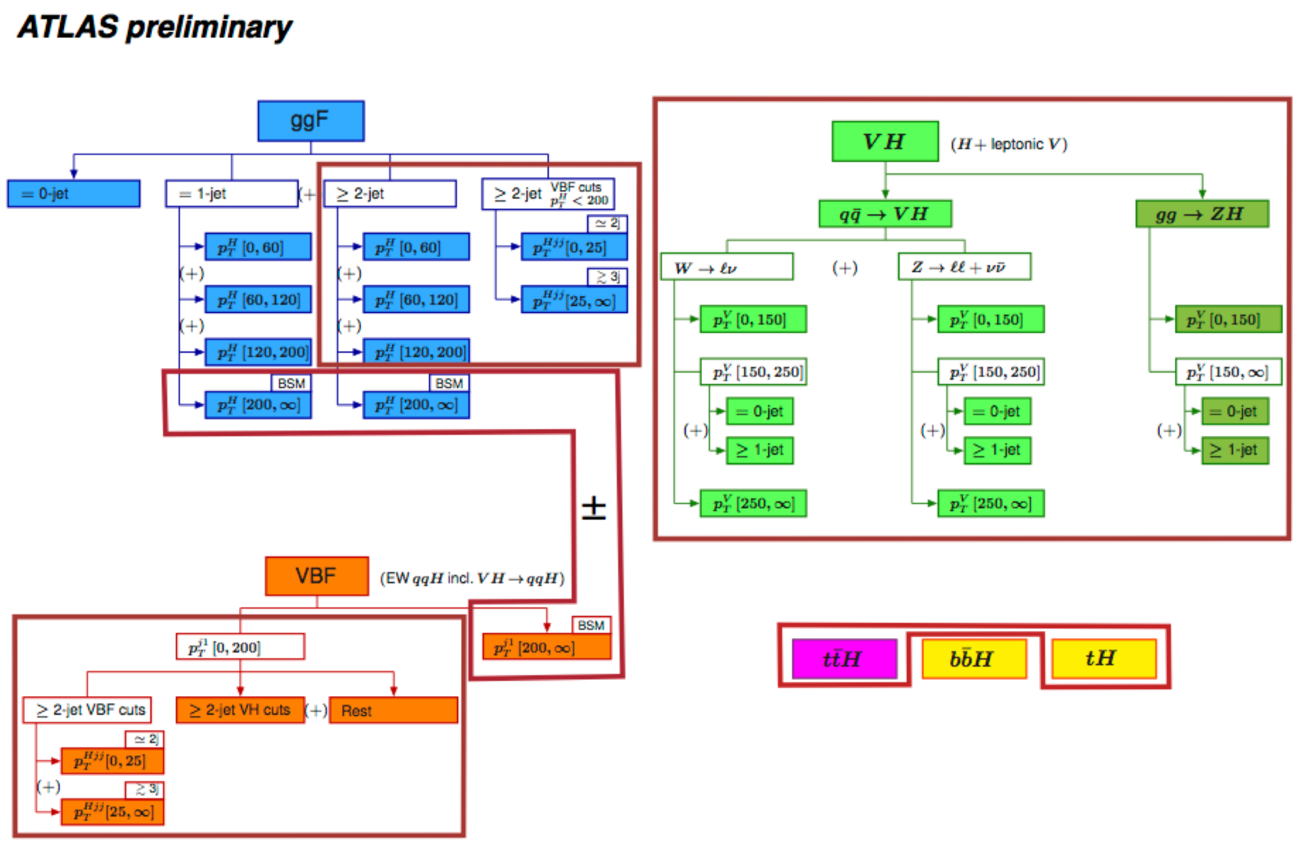




ggF and VBF anti-correlated since VBF category has large contribution from ggF production

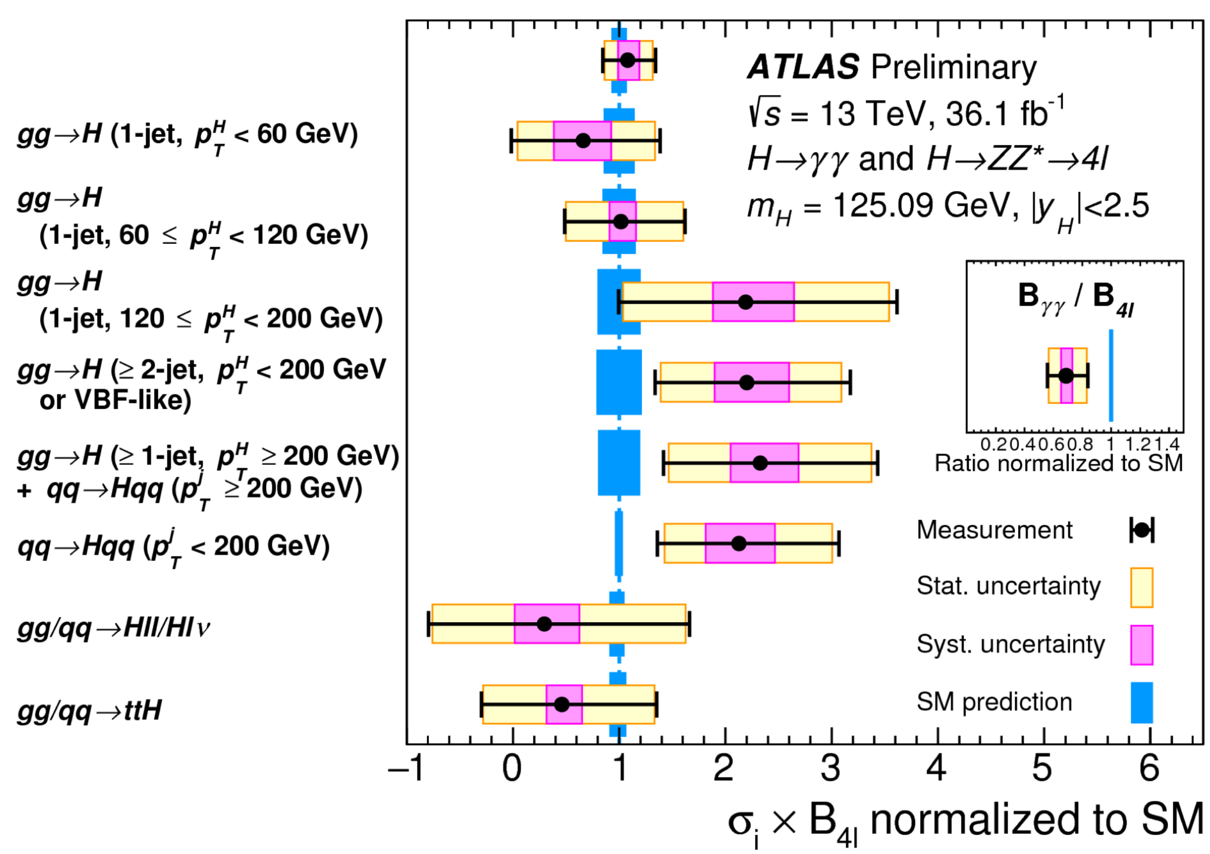


H→4l Stage-0 production cross-section measurements



Stage-1 and bins merging for intermediate Stage-1 ATLAS measurements

Towards Stage-1 Template XS measurement:
9 categories



Additional details H →4l

Table 2: List of event selection requirements which define the fiducial phase space for the cross section measurement. SFOS lepton pairs are same-flavour opposite-sign lepton pairs.

Leptons and jets	
Leptons:	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets:	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
remove jets with:	$\Delta R(\text{jet}, \ell) < 0.1$
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements:	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	115 GeV$< m_{4\ell} <$ 130 GeV
If extra leptons with $p_T > 12$ GeV:	Quadruplet with the largest ME

Table 2: Event selection criteria used to define the signal regions in the $H \to WW^* \to e\nu\mu\nu$ analysis.

<table>
<tr><th>Category</th><th>$N_{\text{jet}} = 0$</th><th>$N_{\text{jet}} = 1$</th><th>$N_{\text{jet}} \geq 2$, VBF</th></tr>
<tr><td rowspan="2">Preselection</td><td colspan="3">Two isolated, different-flavour, leptons ($\ell = e, \mu$) with opposite charge
$p_T^{\text{lead}} > 22$ GeV , $p_T^{\text{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="2">$E_T^{\text{miss, track}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="3">$N_{b\text{-jet},(p_T > 20\text{ GeV})} = 0$</td></tr>
<tr><td rowspan="2">$\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$
$p_T^{\ell\ell} > 30$ GeV</td><td>max $\left(m_T^{\ell}\right) > 50$ GeV</td><td></td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$H \to WW^* \to e\nu\mu\nu$
topology</td><td colspan="2">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td>Central Jet Veto
Outside Lepton Veto</td></tr>
<tr><td>Discriminant Variable
BDT input variables</td><td colspan="2">m_T</td><td>BDT
$m_{jj}, \Delta y_{jj}, m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_T, \sum C_\ell, \sum_{\ell,j} m_{\ell j}, p_T^{\text{tot}}$</td></tr>
</table>

H→γγ inclusive and differential cross-section

Table 14: Summary of the particle-level definitions of the five fiducial integrated regions described in the text. The photon isolation $p_{\mathrm{T}}^{\mathrm{iso},0.2}$ is defined analogously to the reconstructed-level track isolation as the transverse momentum of the system of charged particles within $\Delta R < 0.2$ of the photon.

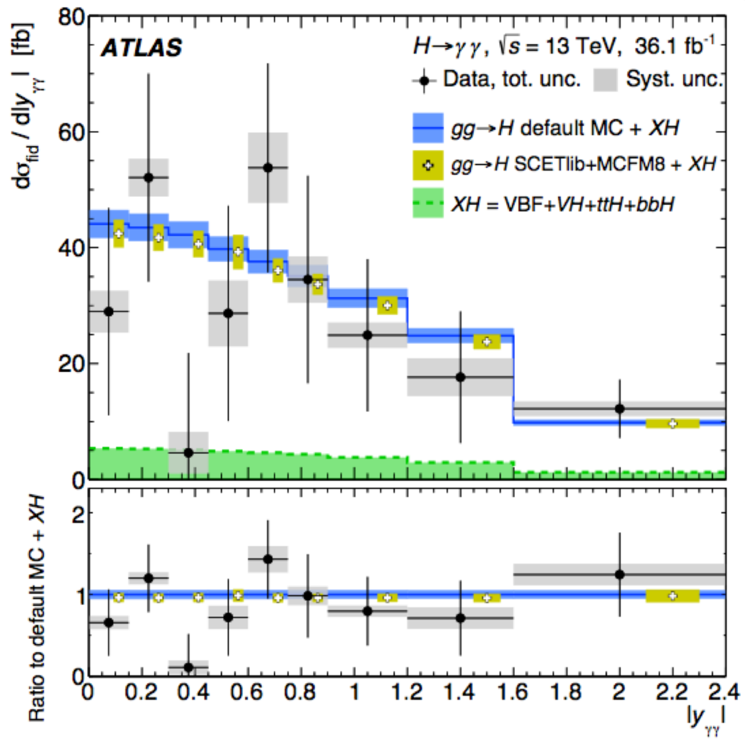
Objects	Definition
Photons	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$, $p_{\mathrm{T}}^{\mathrm{iso},0.2}/p_{\mathrm{T}}^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_{\mathrm{T}} > 30$ GeV, $\lvert y\rvert < 4.4$
Leptons, ℓ	e or μ, $p_{\mathrm{T}} > 15$ GeV, $\lvert\eta\rvert < 2.47$ for e (excluding $1.37 < \lvert\eta\rvert < 1.52$) and $\lvert\eta\rvert < 2.7$ for μ
Fiducial region	**Definition**
Diphoton fiducial	$N_\gamma \geq 2$, $p_{\mathrm{T}}^{\gamma_1} > 0.35\, m_{\gamma\gamma} = 43.8$ GeV, $p_{\mathrm{T}}^{\gamma_2} > 0.25\, m_{\gamma\gamma} = 31.3$ GeV
VBF-enhanced	Diphoton fiducial, $N_j \geq 2$ with $p_{\mathrm{T}}^{\mathrm{jet}} > 25$ GeV, $m_{jj} > 400$ GeV, $\lvert\Delta y_{jj}\rvert > 2.8$, $\lvert\Delta\phi_{\gamma\gamma,jj}\rvert > 2.6$
$N_{\mathrm{lepton}} \geq 1$	Diphoton fiducial, $N_\ell \geq 1$
High $E_{\mathrm{T}}^{\mathrm{miss}}$	Diphoton fiducial, $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV, $p_{\mathrm{T}}^{\gamma\gamma} > 80$ GeV
$t\bar{t}H$-enhanced	Diphoton fiducial, $(N_j \geq 4,\ N_{b\text{-jets}} \geq 1)$ or $(N_j \geq 3,\ N_{b\text{-jets}} \geq 1,\ N_\ell \geq 1)$

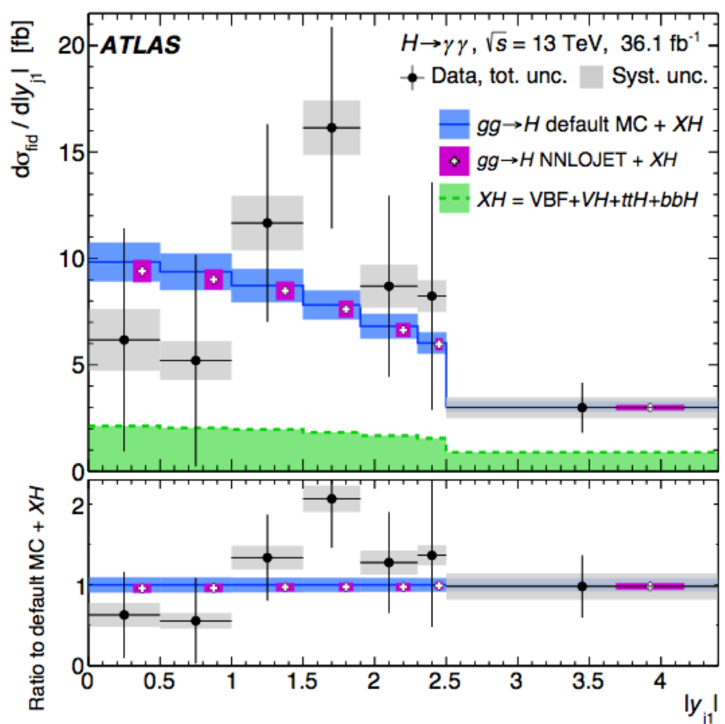
Measured fiducial cross-sections

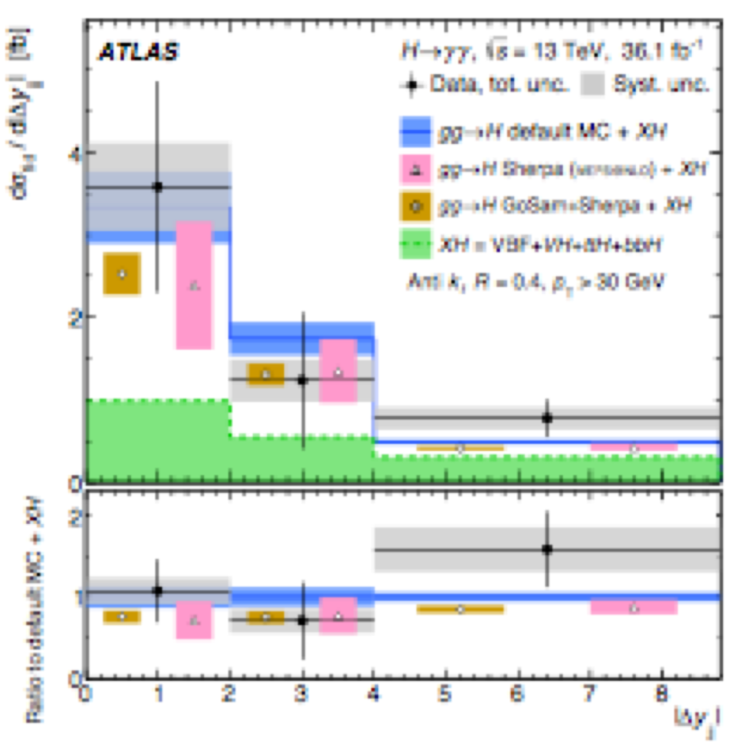
Fiducial region	Measured cross section	SM prediction	
Diphoton fiducial	55 ± 9 (stat.) ± 4 (exp.) ± 0.1 (theo.) fb	64 ± 2 fb	[N^3LO + XH]
VBF-enhanced	3.7 ± 0.8 (stat.) ± 0.5 (exp.) ± 0.2 (theo.) fb	2.3 ± 0.1 fb	[default MC + XH]
$N_{\mathrm{lepton}} \geq 1$	≤ 1.39 fb 95% CL	0.57 ± 0.03 fb	[default MC + XH]
High $E_{\mathrm{T}}^{\mathrm{miss}}$	≤ 1.00 fb 95% CL	0.30 ± 0.02 fb	[default MC + XH]
$t\bar{t}H$-enhanced	≤ 1.27 fb 95% CL	0.55 ± 0.06 fb	[default MC + XH]

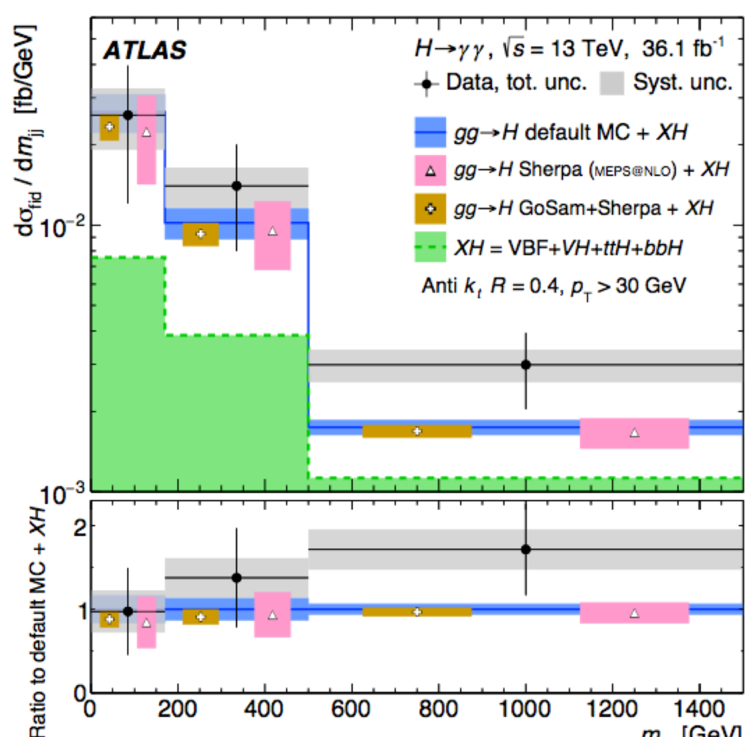
H→γγ inclusive and differential cross-section

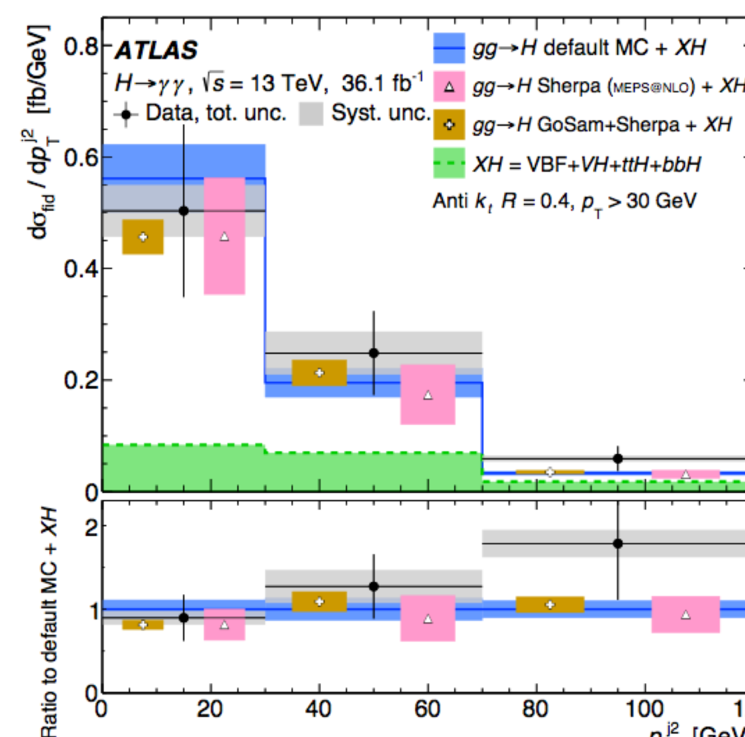
More differential distributions…







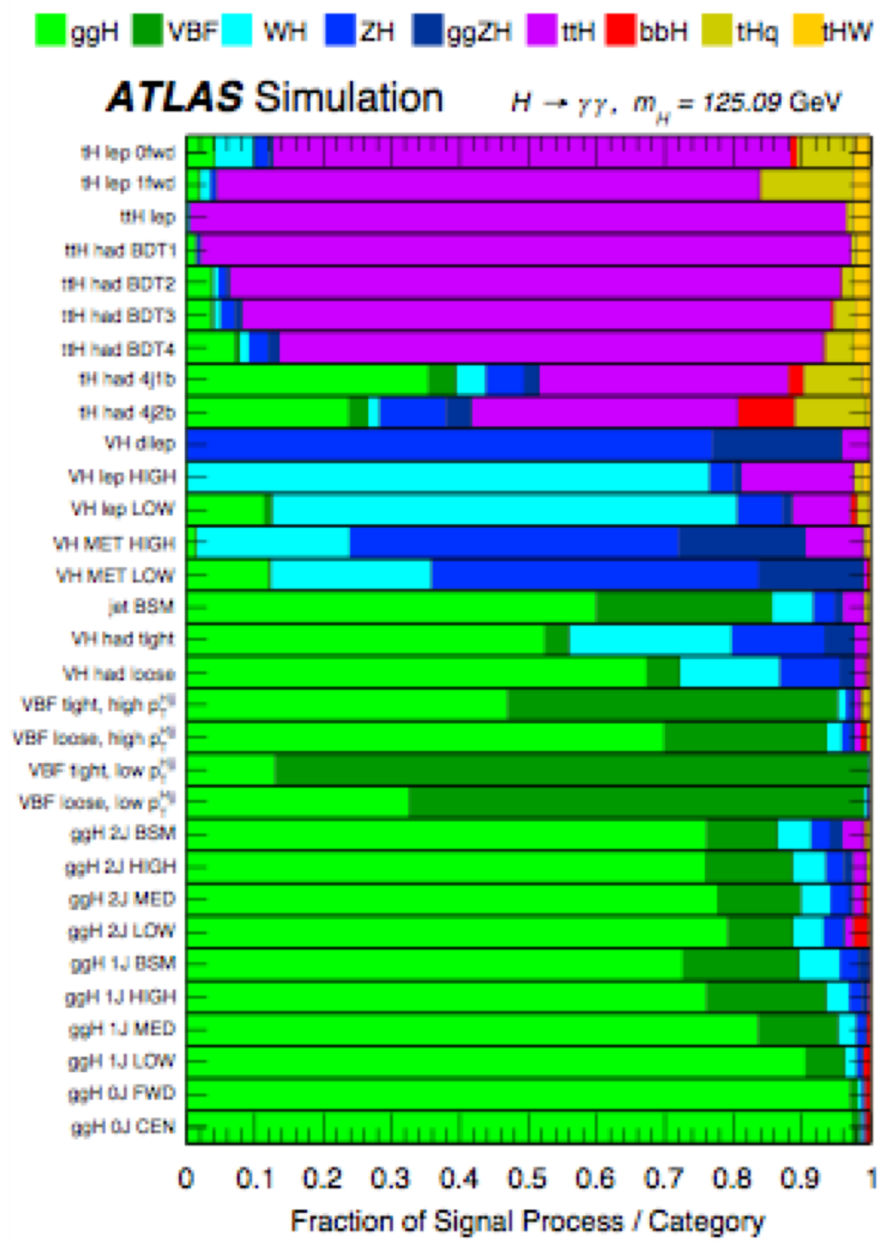


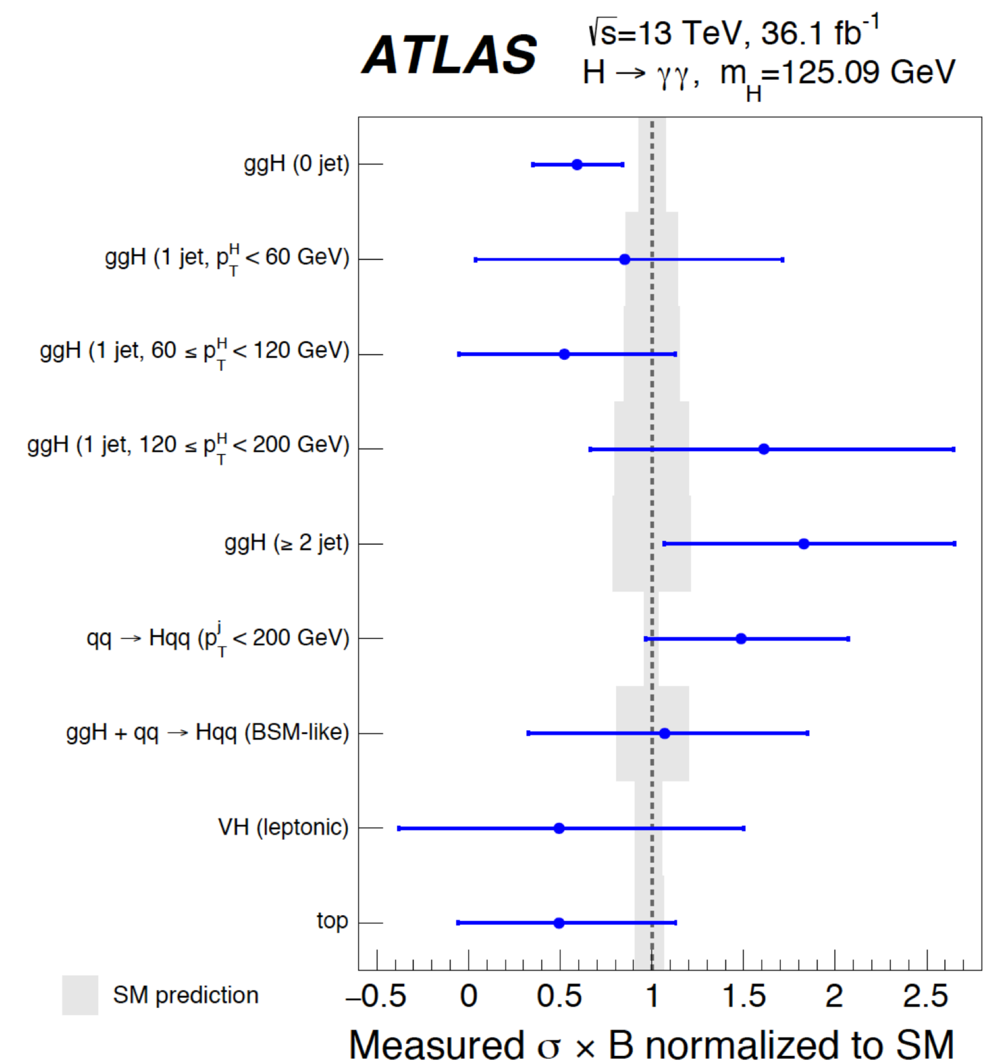


Production cross-sections in γγ channel

The events satisfying the diphoton selection classified into 31 exclusive categories that are optimized for the best separation of the Higgs boson production processes and for the maximum sensitivity to the phase space regions defined by the stage 1 of the simplified template cross-section framework. A combined fit to the event reconstruction categories is then performed to determine nine simplified template cross sections (with |yH|< 2.5).

No sensitivity to all the 31 categories ==> merge categories and fit in only 10/31 final categories

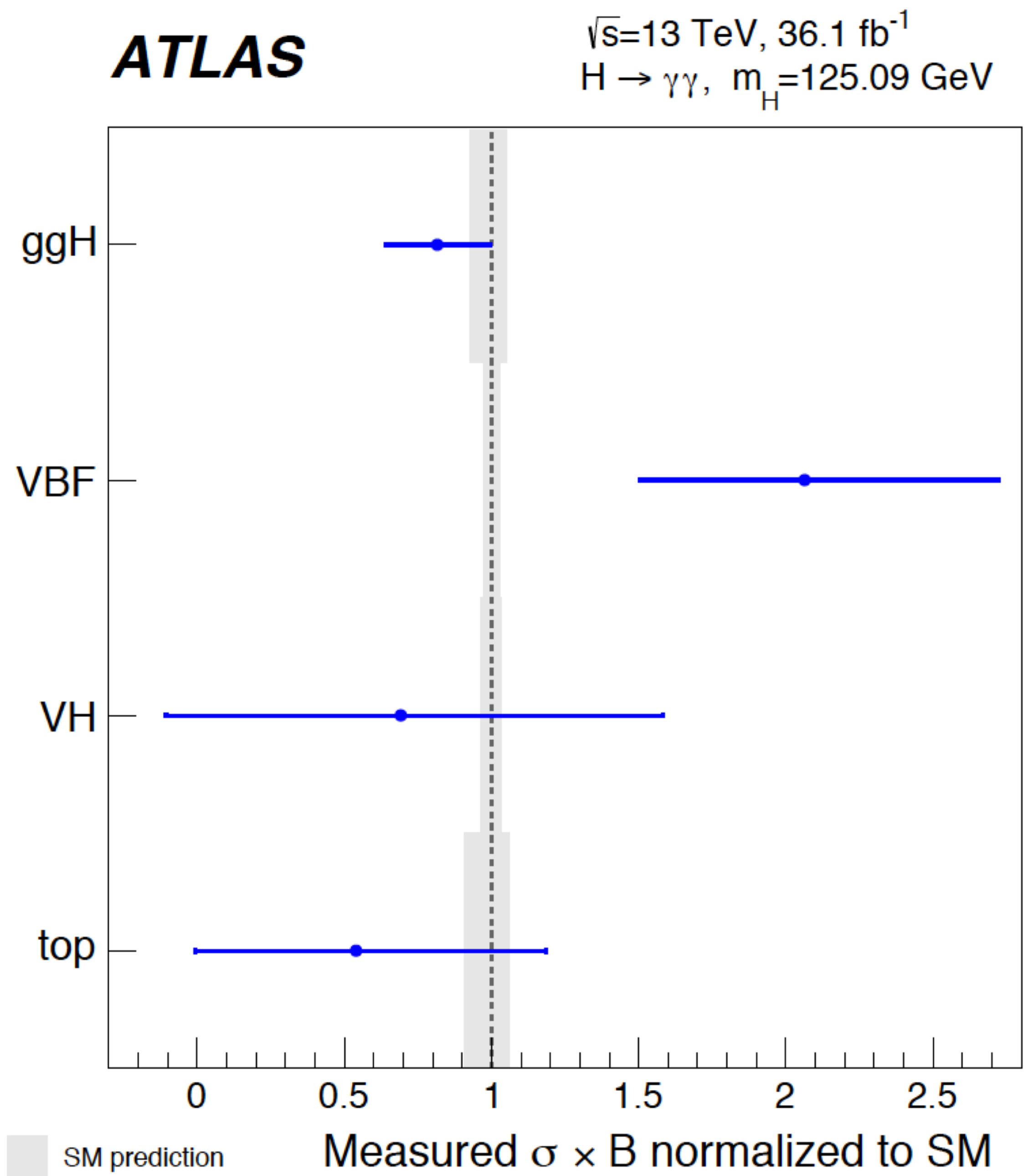




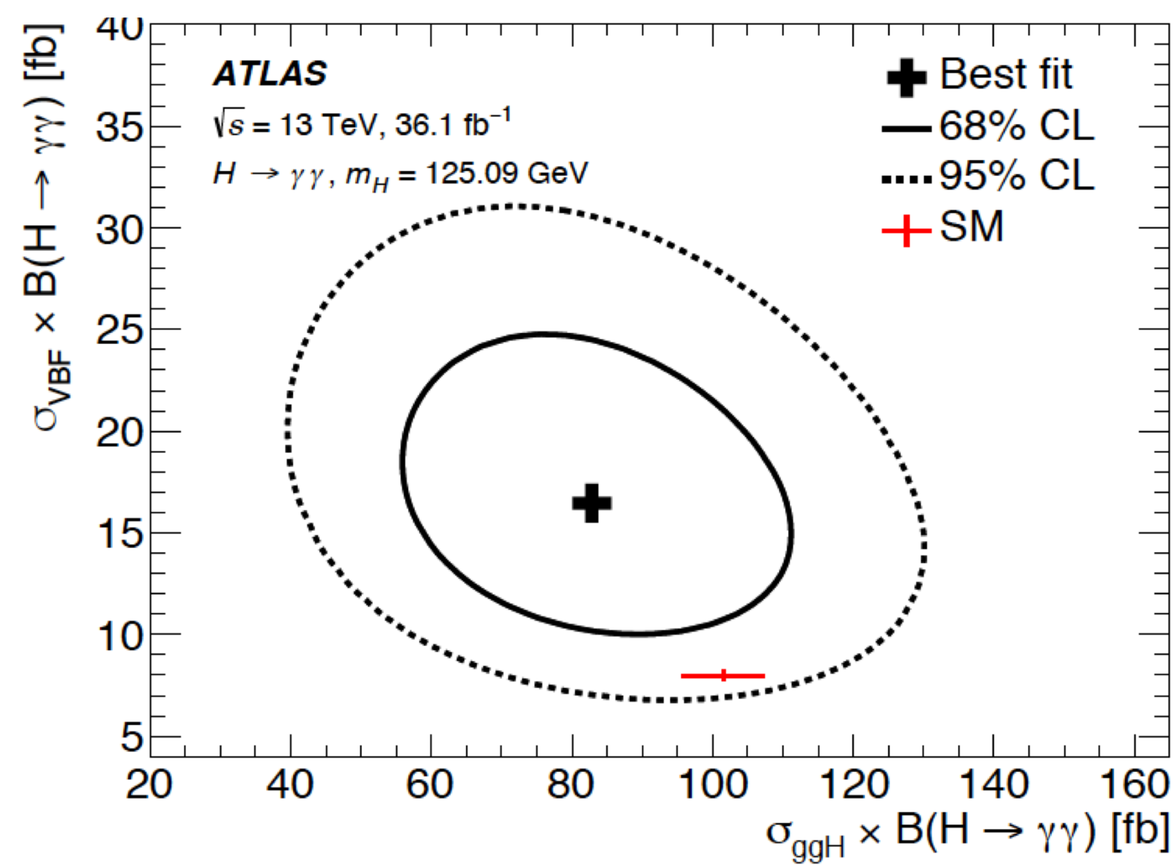
Production cross-sections in γγ channel

bbH merged to ggH

In general, all main production modes can be probed in diboson decays



68% and 95% CL 2D counters VBF vs ggF top and VH profiled in the fit

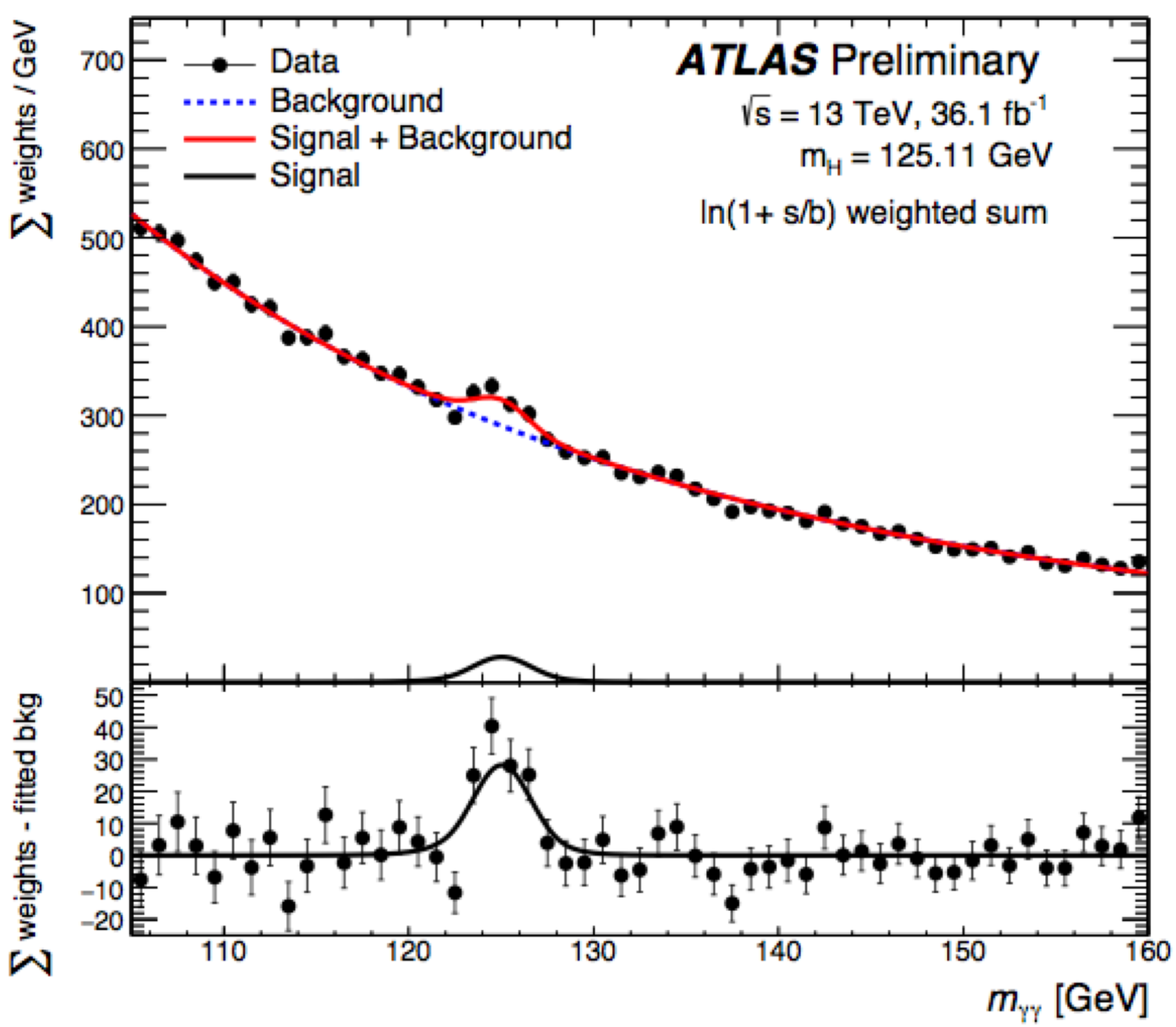


Measurements agree with SM predictions within 2σ

Higgs boson mass - γγ channel

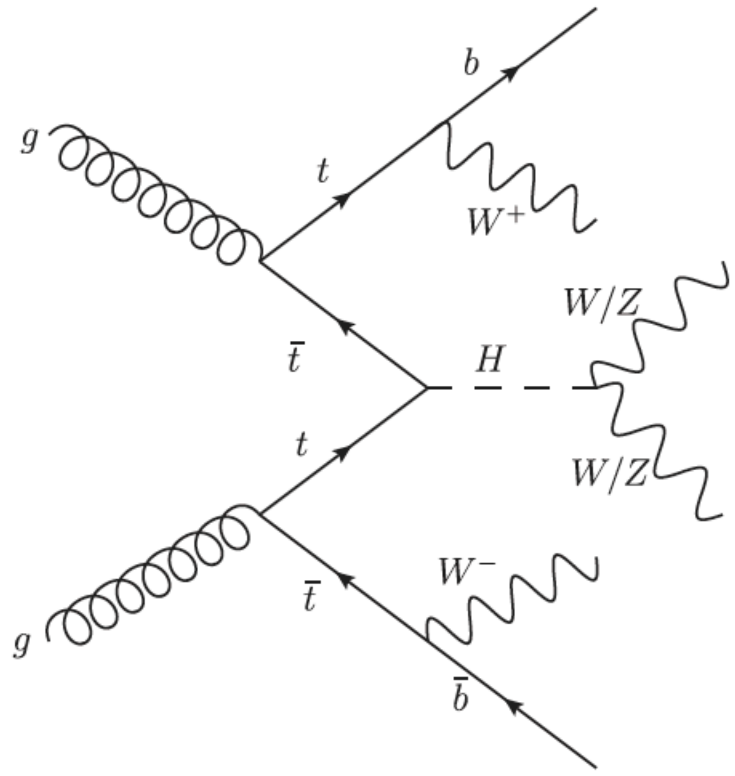
Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
LAr cell non-linearity	±200
LAr layer calibration	±190
Non-ID material	±120
Lateral shower shape	±110
ID material	±110
Conversion reconstruction	±50
$Z \to ee$ calibration	±50
Background model	±50
Primary vertex effect on mass scale	±40
Resolution	$^{+20}_{-30}$
Signal model	±20

Systematic uncertainties breakdown



Higgs boson measurements in diboson final states - ttH

80 fb^{-1} taken at a center-of-mass energy of 13 TeV have been used to search for the ttH in the H → ZZ*/γγ decay channel (and combined with previous measurements using 36 fb^{-1})



BDT analysis used in both cases to discriminate between signal and backgrounds

BDT distributions in ttH analysis