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U.S. DEPARTMENT OF ENERGY

Higgs boson properties: updated combined results from Run-2 ATLAS data

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on behalf of the ATLAS Collaboration

LHC seminar

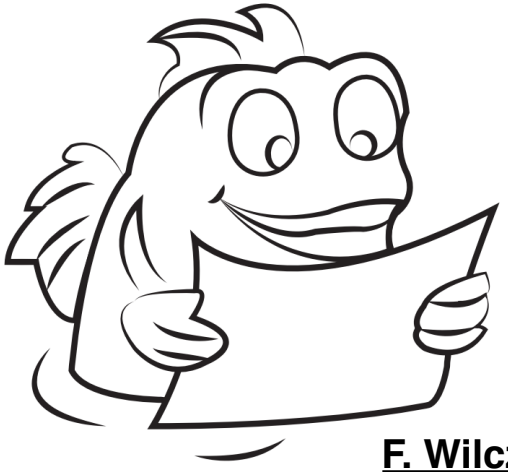
April 23, 2019

ATLAS EXPERIMENT

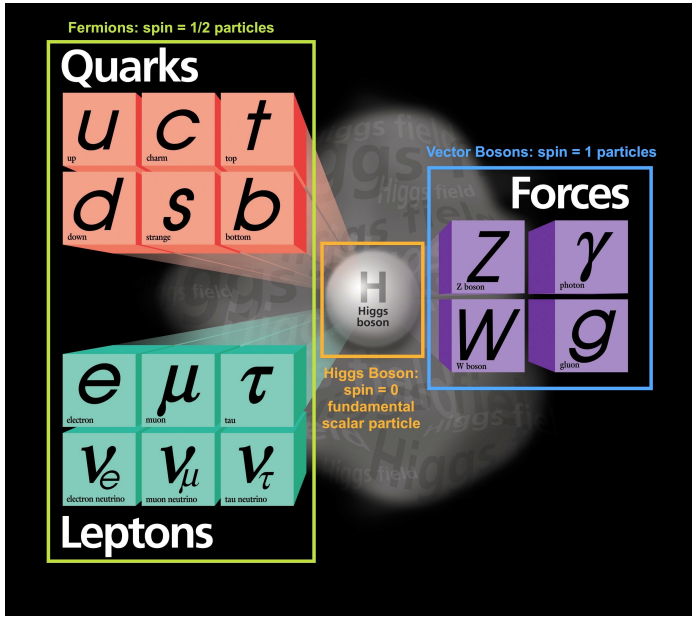
Introduction

- Higgs boson plays a fundamental role in the Standard Model (SM)
- According to the SM, weak bosons, quarks and charged leptons acquire their masses through interaction with the Higgs field
  - The SM predicts Higgs boson couplings to fermions/weak bosons proportional to particle mass/mass^2, due to their different roles in the Higgs mechanism
- Comparison between experimental measurements and the SM predictions serves as an important test bench, and a possible portal to new physics

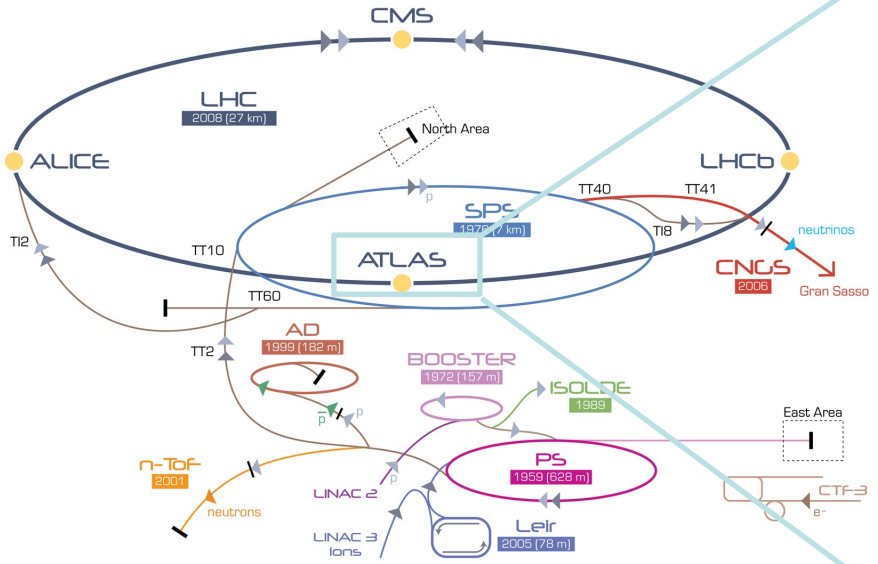
Fish discovered water

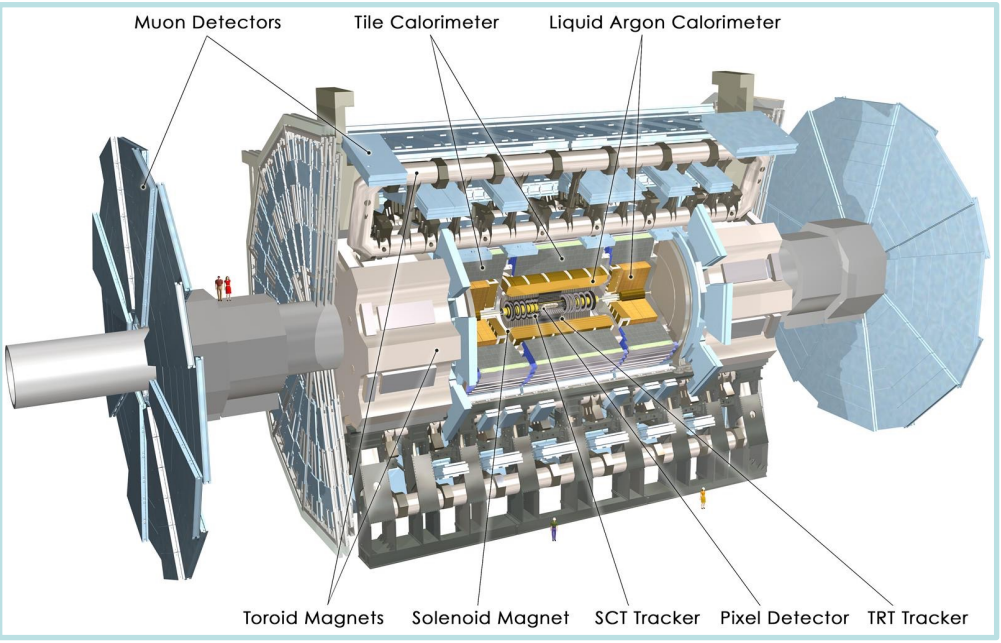


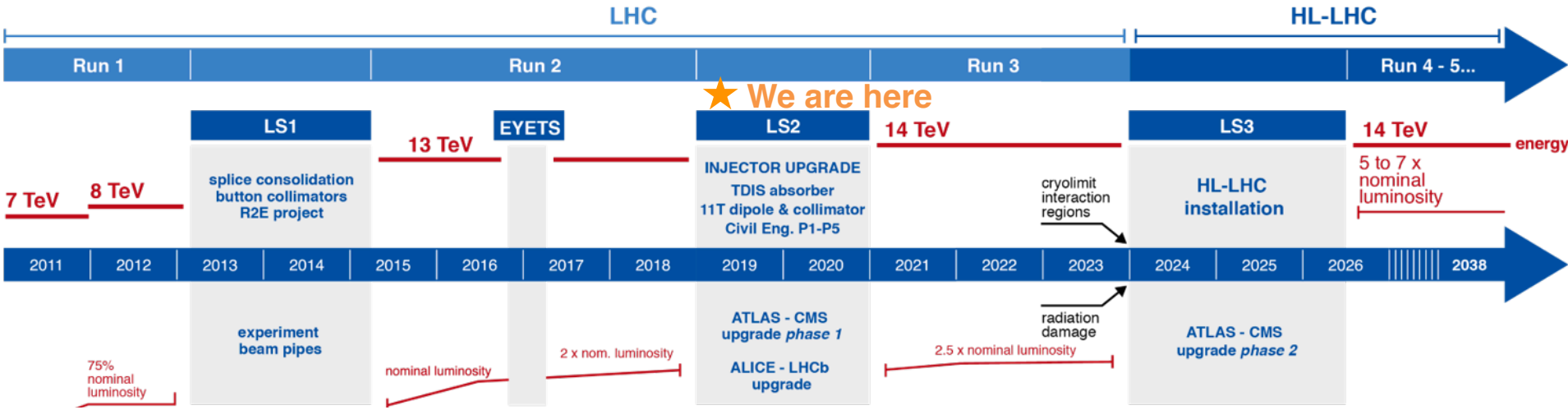
F. Wilczek



LHC and ATLAS detector

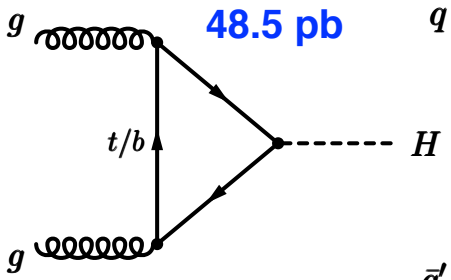






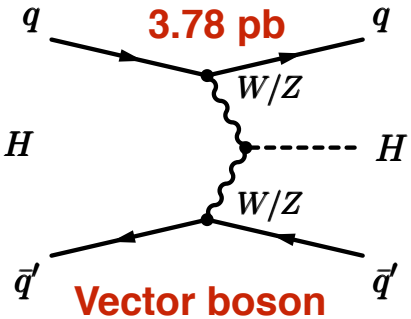
SM Higgs boson production at LHC

Main



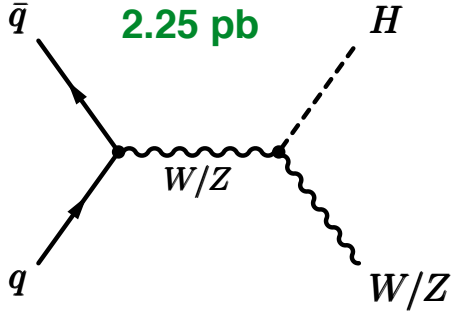
48.5 pb

Gluon-fusion ggF (~87%)



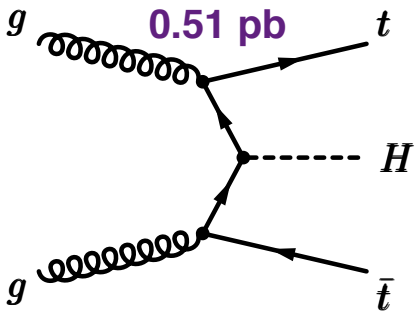
3.78 pb

Vector boson fusion (VBF) (~7%)



2.25 pb

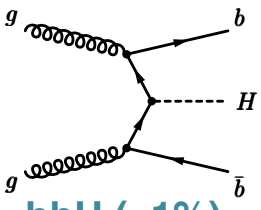
VH (~4%)



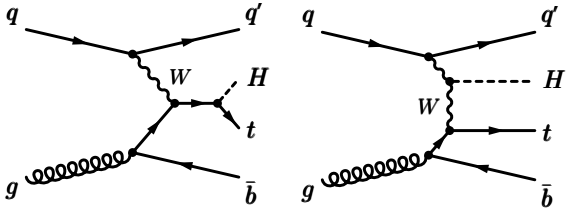
0.51 pb

ttH (~1%)

Rare

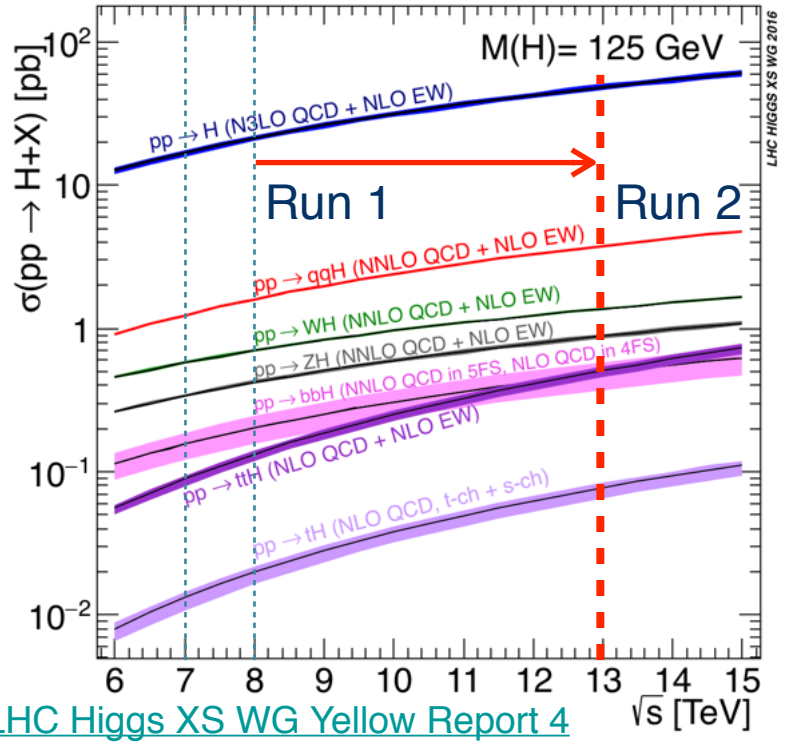


bbH (~1%) 0.49 pb



tH (~0.1%) 0.09 pb

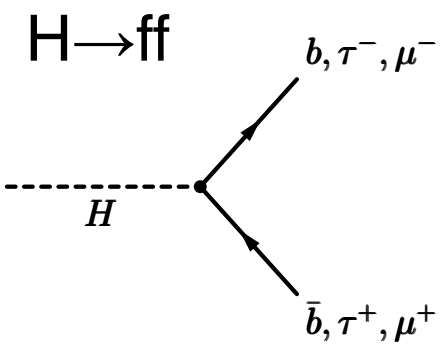
- Distinct topology from each production mode
- Rare production modes difficult to probe, but important for beyond the SM (BSM) scenarios
- Improved accuracy from theory calculations: inclusive σ(ggF) now calculated at N³LO in QCD and NLO in EW, with 5% uncertainty

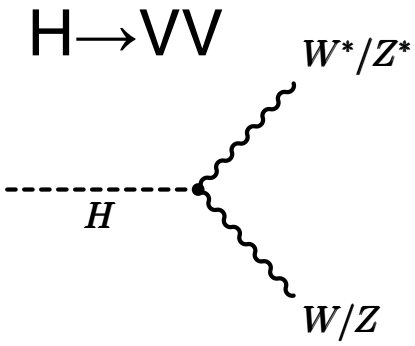


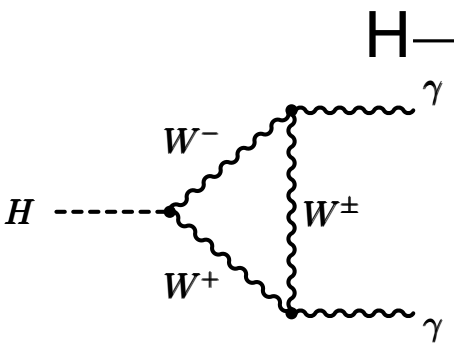
LHC Higgs XS WG Yellow Report 4

Higgs boson decay

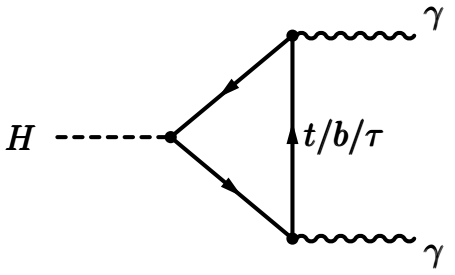
- **"Big five" (most sensitive decay modes): γγ, ZZ, WW, ττ, bb**
  - γγ and ZZ→4l can reconstruct Higgs boson candidate with high resolution
- More "difficult" channels: μμ, Zγ, cc, …
- The SM predicts **4 MeV** total width: far below detector resolution!







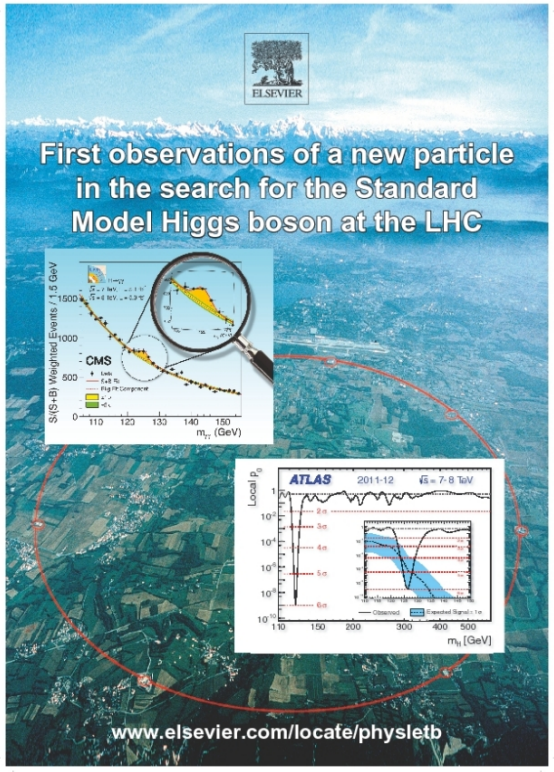
Yellow Report 4



Decay channel	SM BR [%] with m_H=125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23
H→μμ	0.022
H→Zγ	0.154
H→cc	2.88
H→gg	8.18

Discovery of SM-like Higgs boson

Nobel Prize 2013

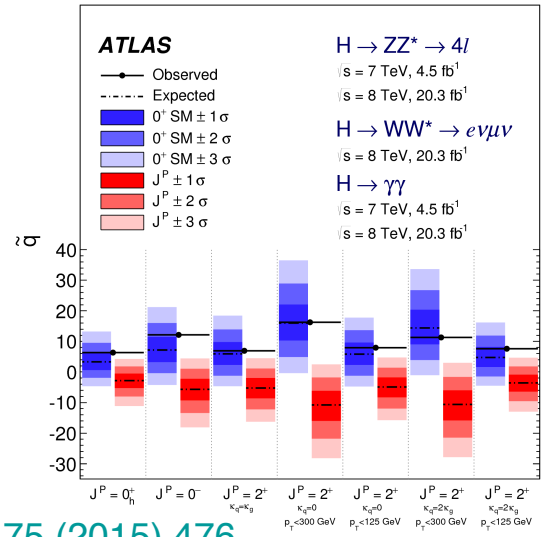


- Discovery opened a new era of particle physics: detailed measurements of the Higgs sector at the LHC

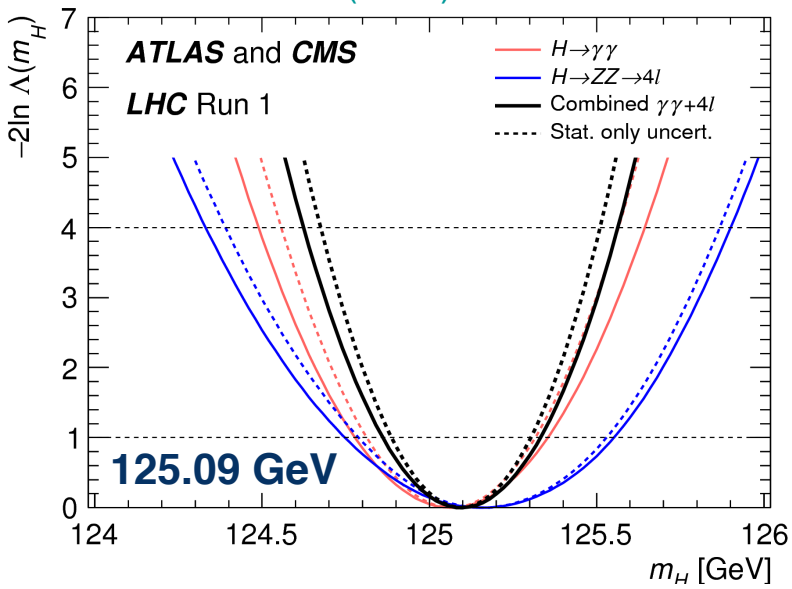
What we learned from Run 1 (incomplete)

Spin-0 nature established, compatible with CP even

Admixture of CP even/odd still possible

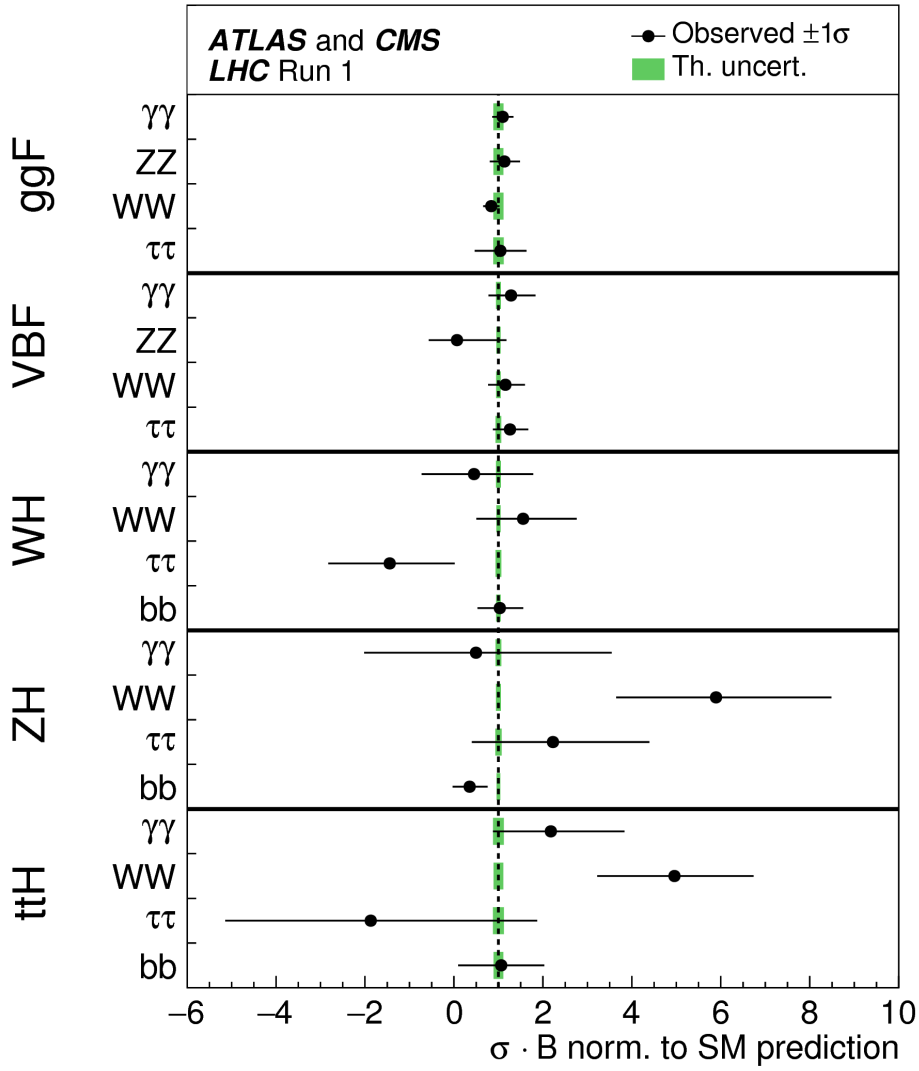


EPJC 75 (2015) 476



Mass known at 0.2% level PRL 114 (2015) 191803

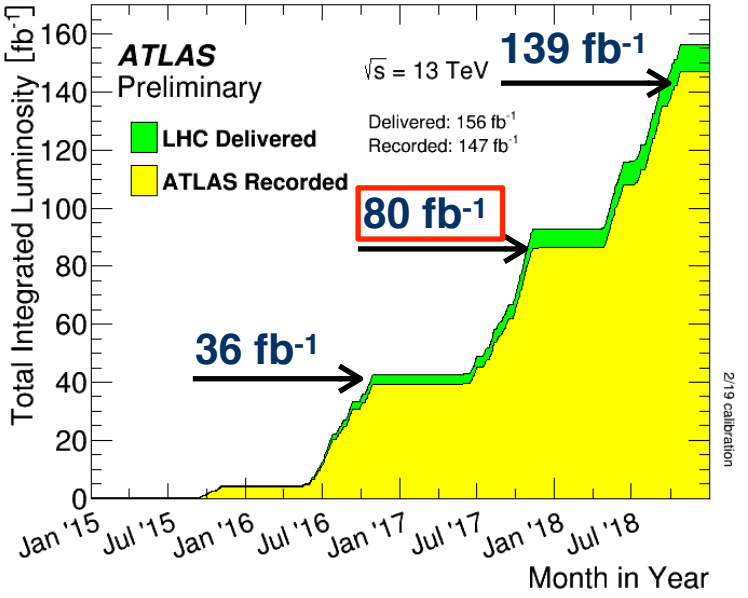
JHEP 08 (2016) 045

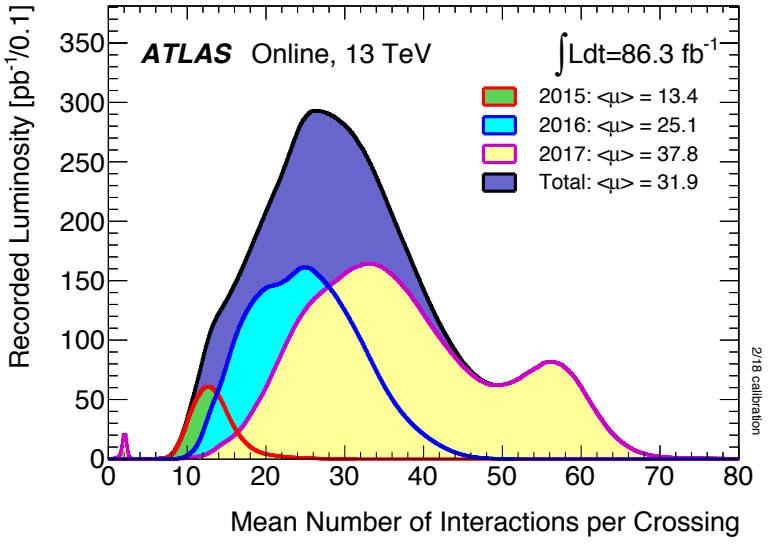


Couplings consistent with the SM

Run 2 data taking

- **Run 2 data-taking successfully finished!**
  - **139 fb^{-1}** of 13 TeV proton-proton collision data collected by ATLAS in total after data quality (DQ) requirements
  - **Great thanks to the CERN accelerator and technical teams for the excellent LHC performance!**
- In this presentation, we will focus on data taken **from 2015 to 2017**, with integrated luminosity up to **80 fb^{-1}** after DQ





ATLAS pp 25ns run: June 5-November 10 2017

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	99.3	99.5	99.4	99.9	97.8	99.9	100	100	99.2

Good for physics: 93.6% (43.8 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb^{-1} and a recorded integrated luminosity of 46.8 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.5 fb^{-1}. Analyses that don't require the toroid magnet can use these data.

How many Higgs bosons do we have?

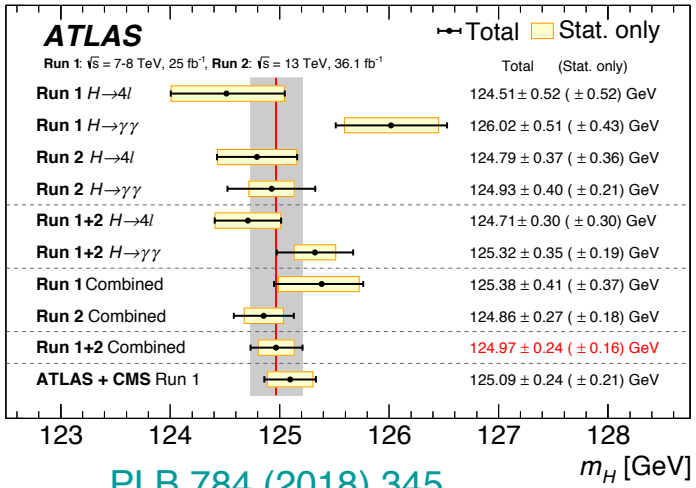
Every fb^{-1} of pp collision at 13 TeV	H→γγ	H→ZZ	H→WW	H→ττ	H→bb
Produced	130	1,500 (7)	12,000 (280)	3,500	32,000 (310)
Selected	46	1.5	42	17	66

Assuming m_H = 125.09 GeV from Run 1 ATLAS-CMS combined measurement

Number in brackets: for H→ZZ it indicates H→4l (l=e, μ). For H→WW it is H→evμv. For H→bb, it is VH where vector boson decays to electrons, muons, and/or neutrinos

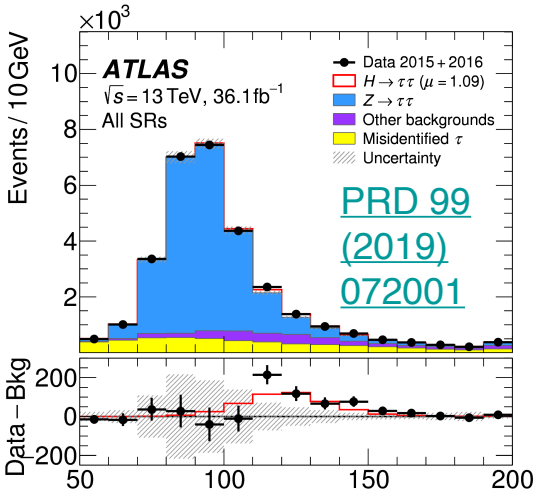
- With every fb^{-1} of 13 TeV pp collision data, the SM predicts about **56,000** Higgs bosons produced
- Analyses discussed today will select about **170 in every fb^{-1}**
  - Large bkg. at LHC introduces difficulty in trigger and analyses: need to stick to relatively clean signatures (leptonic decay; associated production e.g. VH with V→leptons; high-p_T phase-space regions)

ATLAS Run 2 Higgs boson property studies

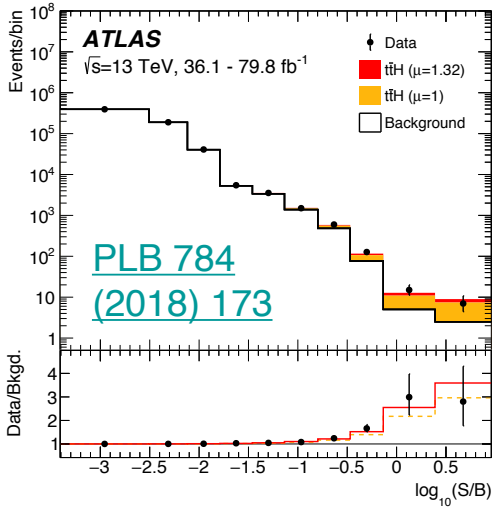


PLB 784 (2018) 345

Updated m_H measurements

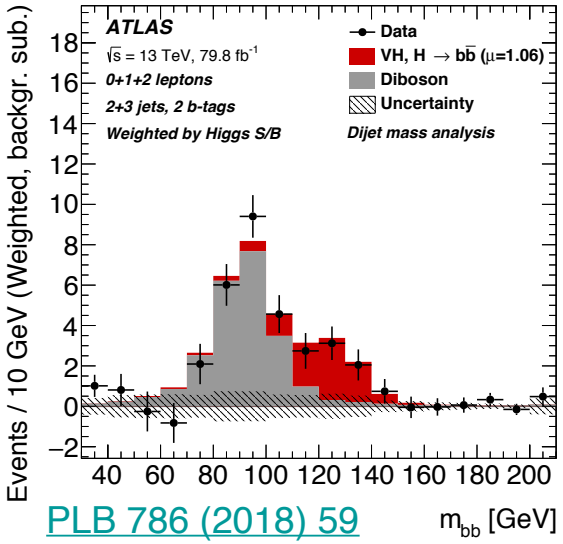


Single experiment observation of H→ττ



Observation of ttH

- Run-2 ATLAS physics program in full swing, with many new results produced to date
- **Today our focus will be on the combined measurement of production cross-sections and decay rates of the Higgs boson, and various interpretations of the results**

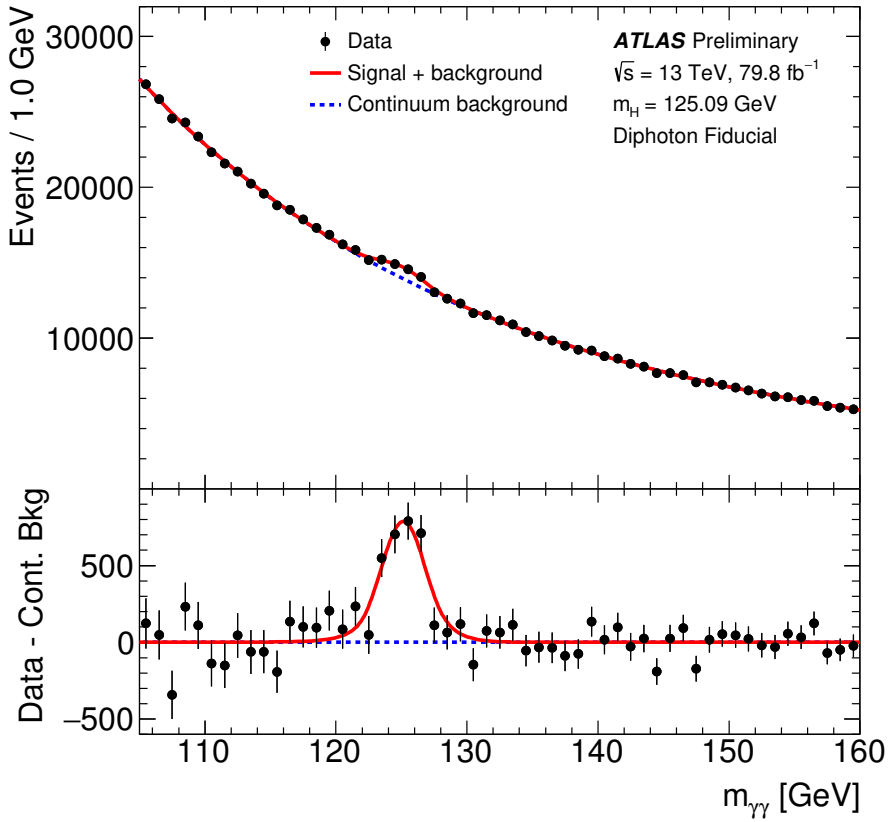


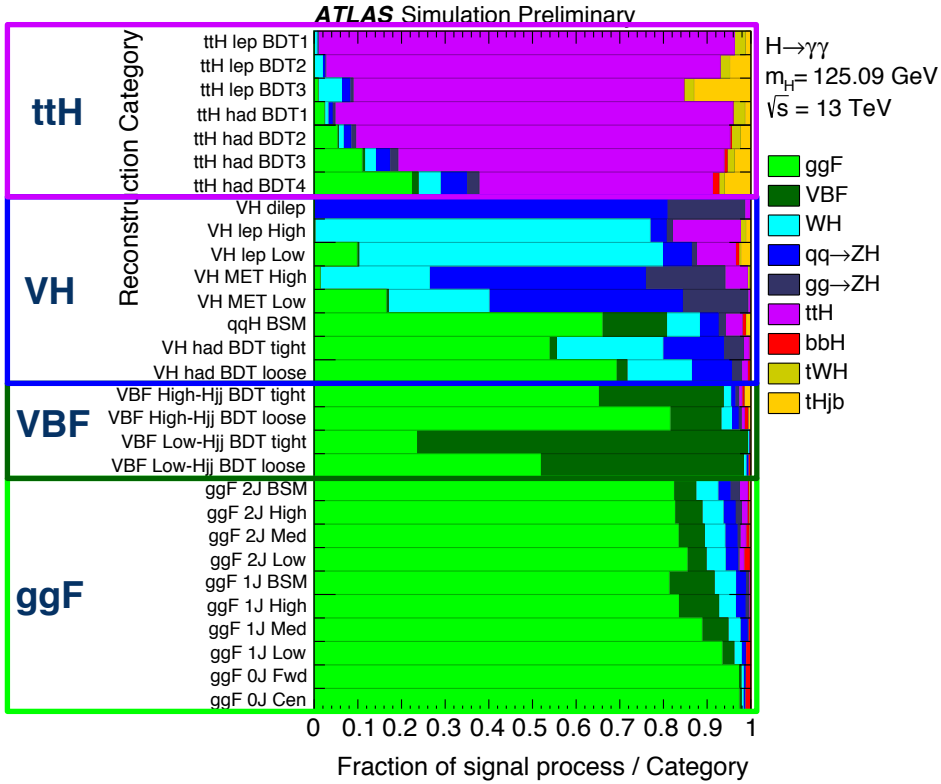
PLB 786 (2018) 59

Observation of H→bb+VH

Individual channels

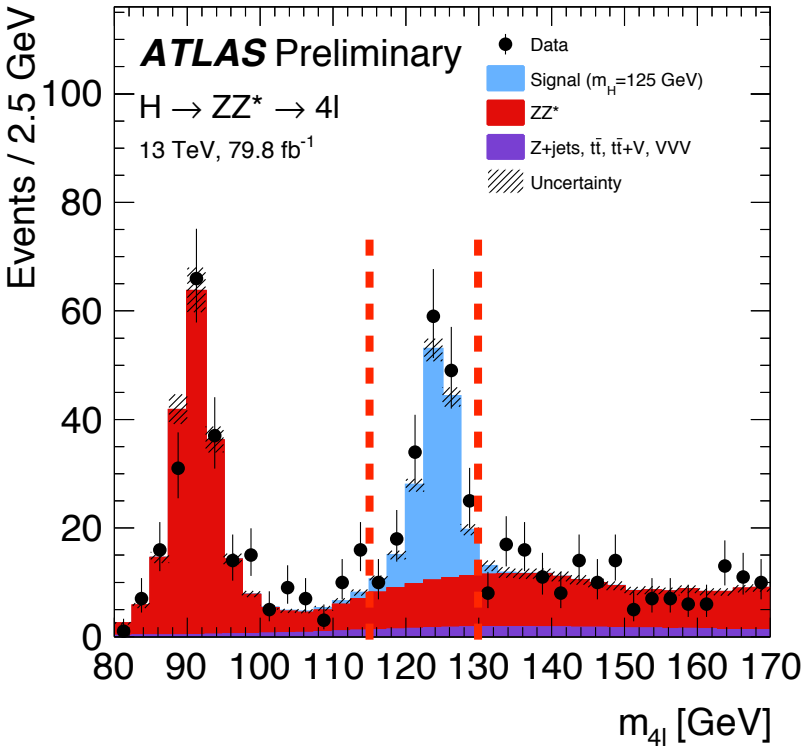
H→γγ (79.8 fb^{-1})

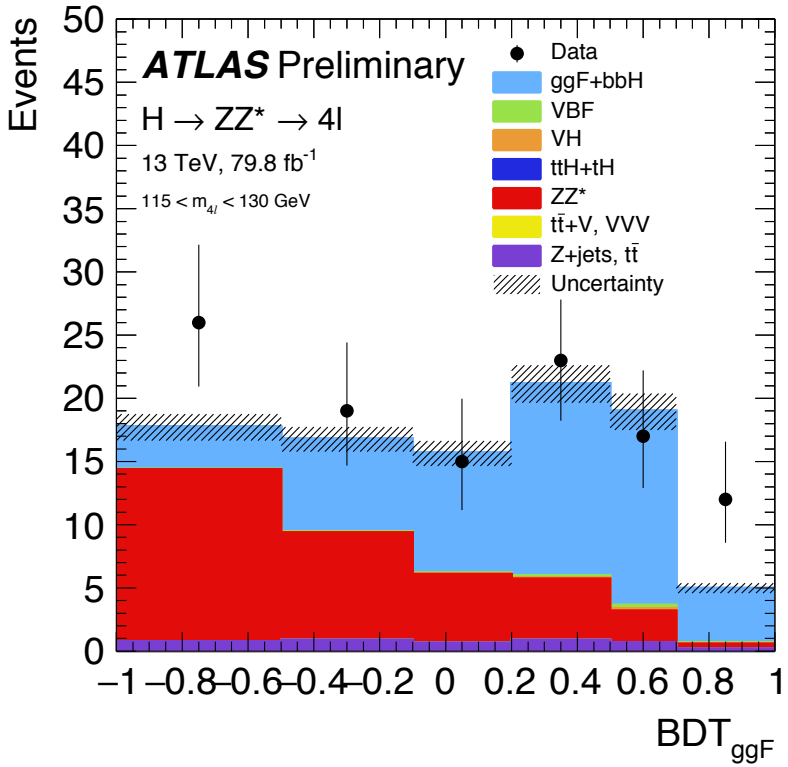




- Large background, but excellent sensitivity ensured by very good photon efficiency and resolution
- Analysis categories designed to isolate out events from different production modes. Also explores different regions within production modes

H→ZZ→4l (l=e, μ, 79.8 fb^{-1})

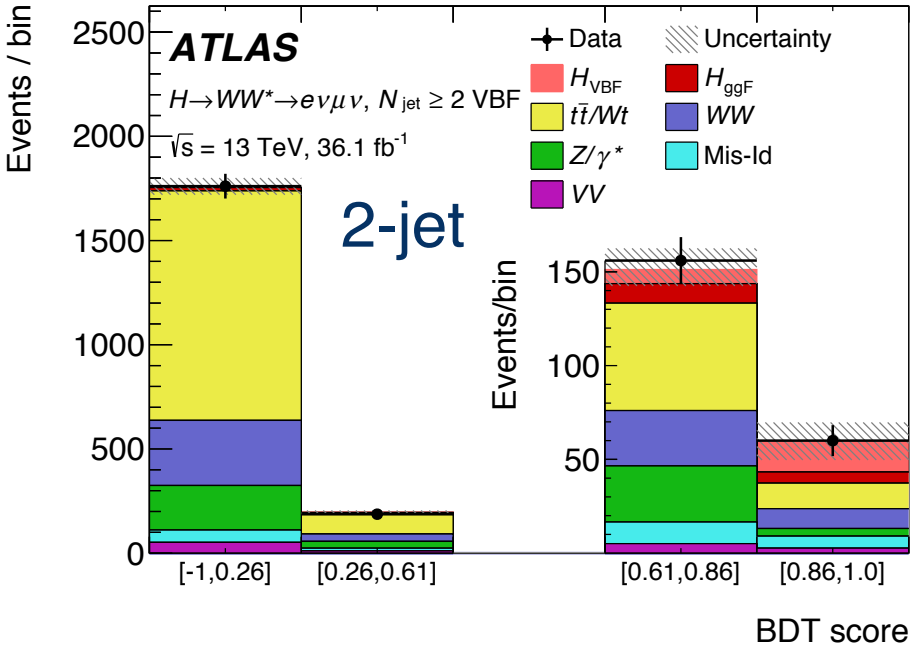


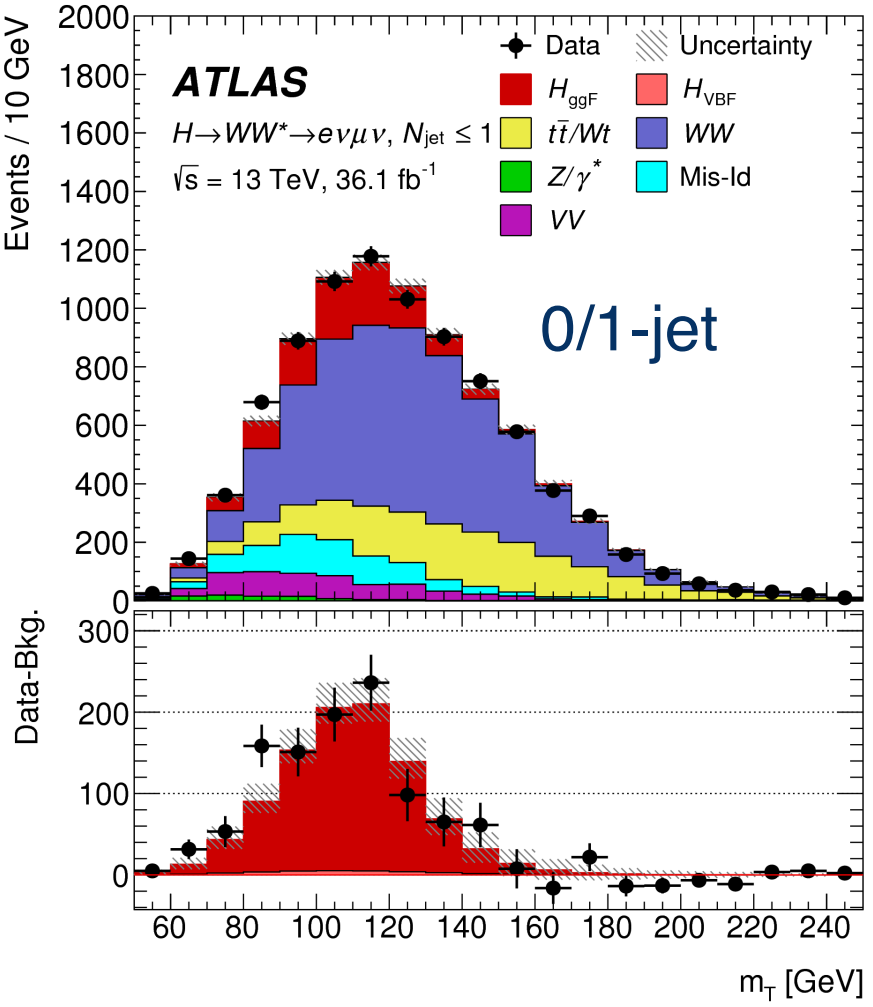


- Very clean channel with high S/B
- Signal region defined by mass window. Boosted Decision Tree (BDT) used to further suppress bkg. inside and increase sensitivity to different production modes

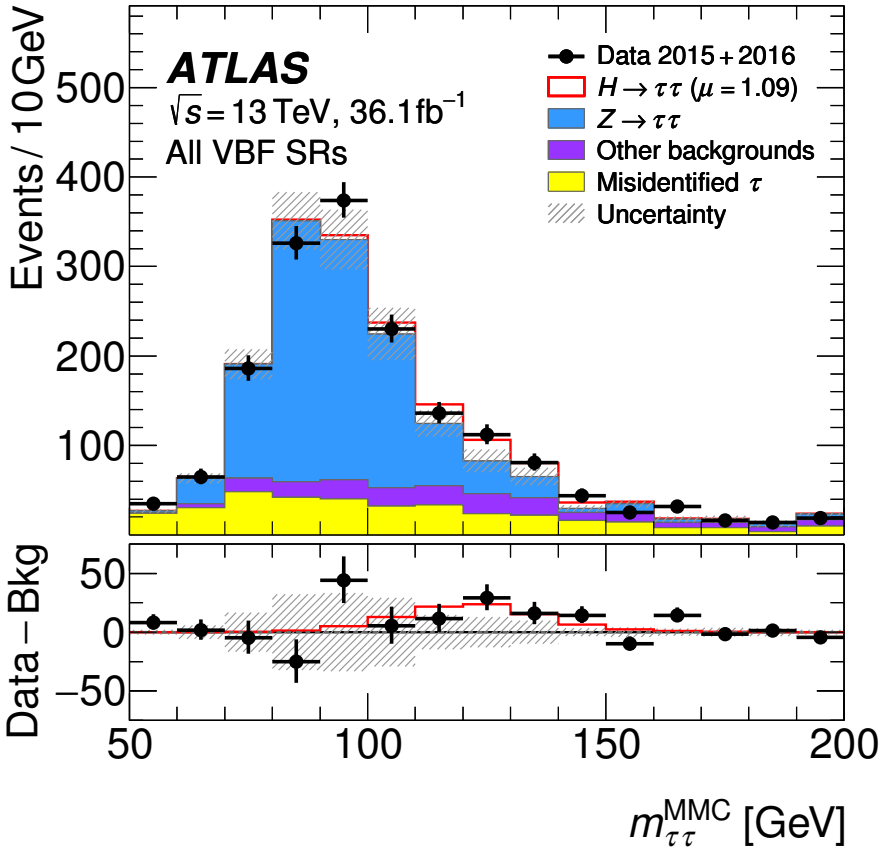
H→WW→eνμν (36.1 fb^{-1})

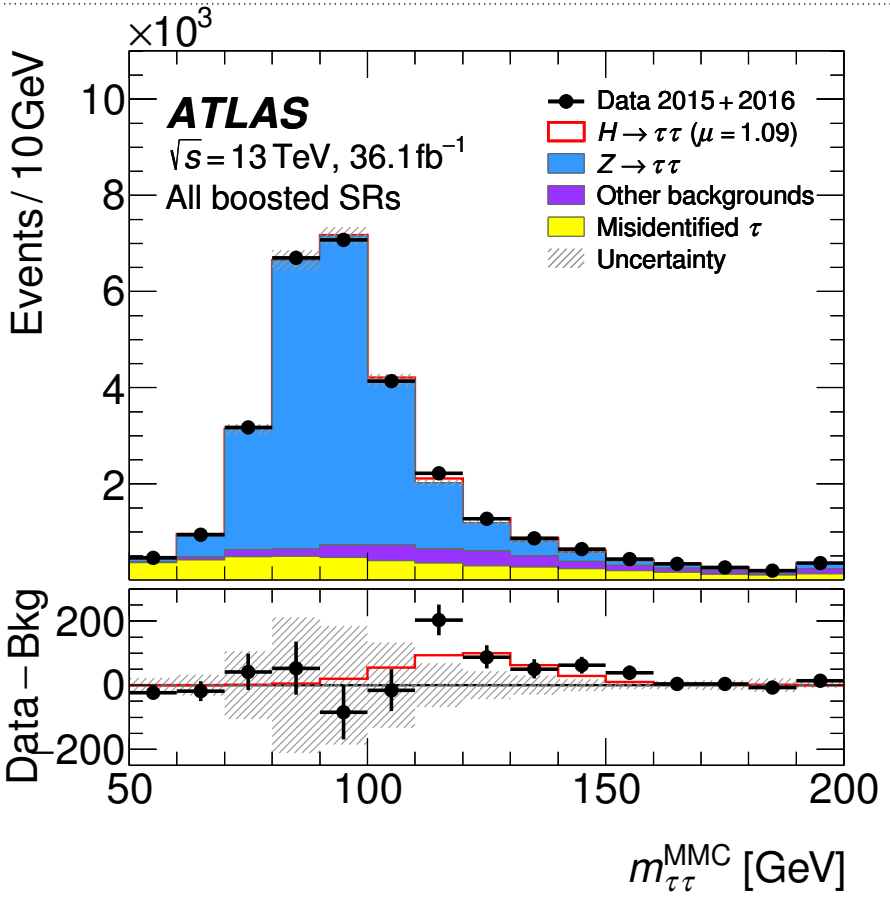
- Vetoing events with jets tagged as from b-quark in signal region (suppress ttbar bkg.)
- Classify events into 0/1/≥2-jet regions
  - 0/1-jet enriched by ggF, using transverse mass (m_T) as discriminant
  - ≥2-jet sensitive to VBF: train BDT to separate VBF from ggF and other bkg.





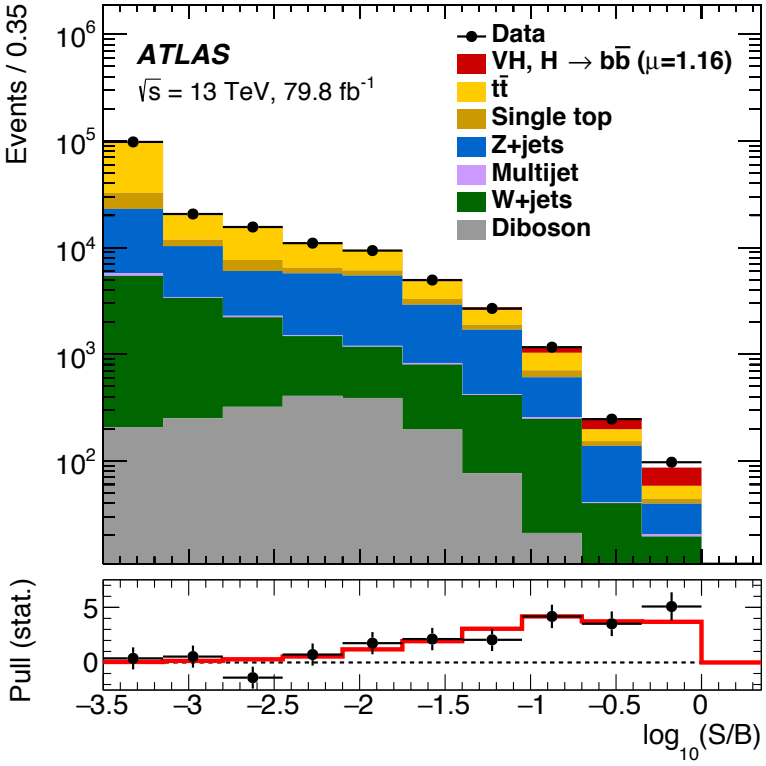
H→ττ (36.1 fb-1)

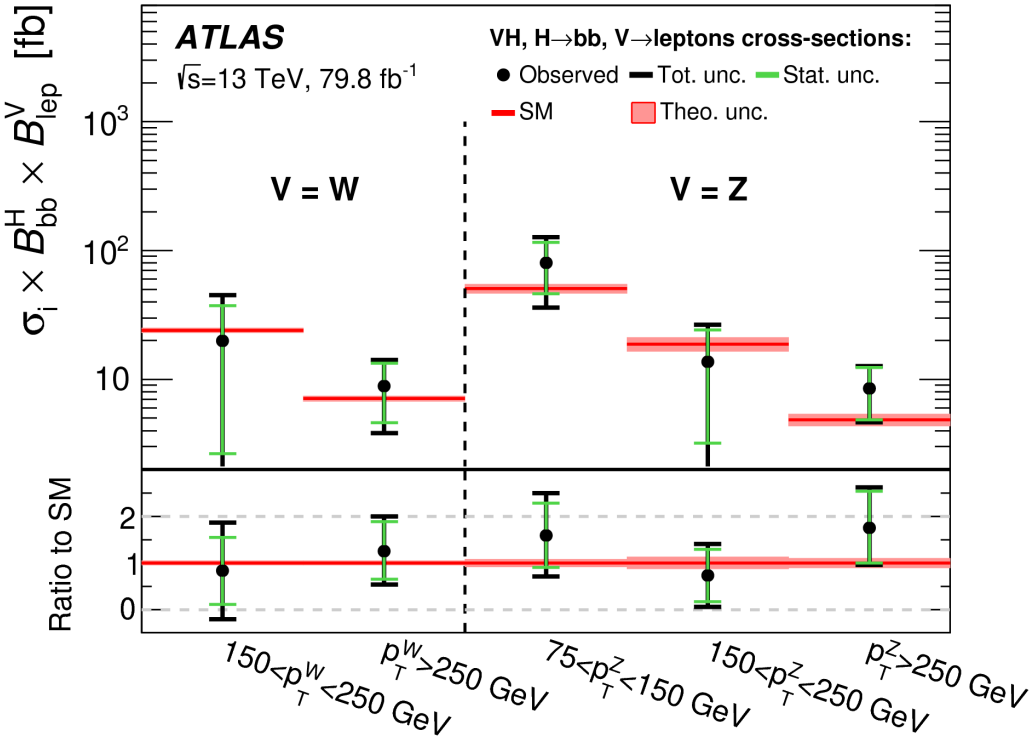




- Exploit all combinations of hadronic and leptonic tau decays
- Analysis targeting VBF and boosted ggF signal events. Exploit more boosted $p_T(\tau\tau)$ spectrum from signal to suppress Z→ττ bkg.

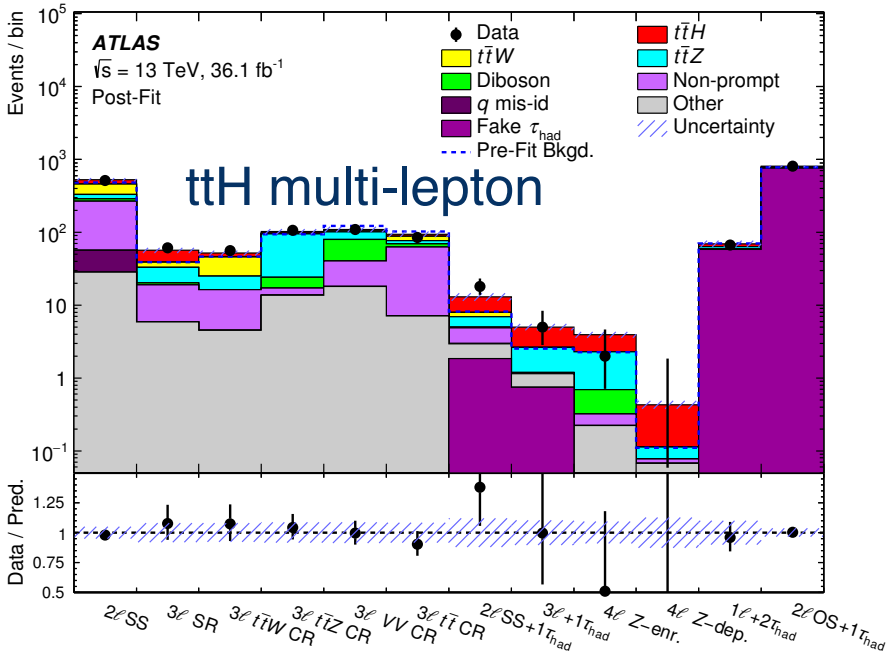
VH, H→bb (79.8 fb^{-1})

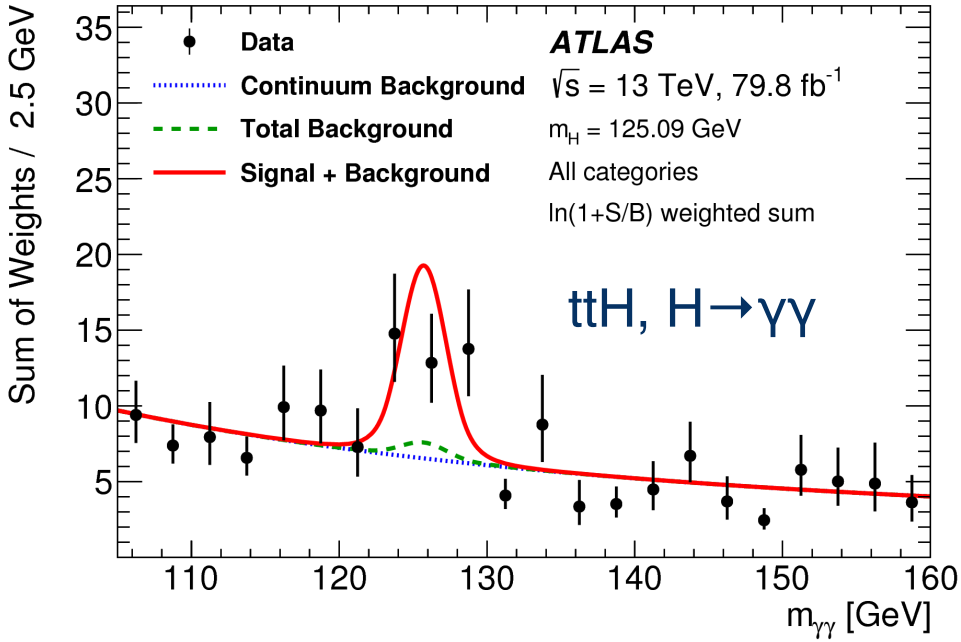




- **Leading analysis for observation of H→bb and VH at LHC**
- Targeting leptonic decay products of vector boson (e, μ, ν) to trigger events
- Divide into 0 charged lepton (e.g. Z→νν), 1 charged lepton (e.g W→lν), or 2 charged leptons (e.g. Z→ll)
- BDT and high $p_T(V)$ selection deployed to suppress the large backgrounds

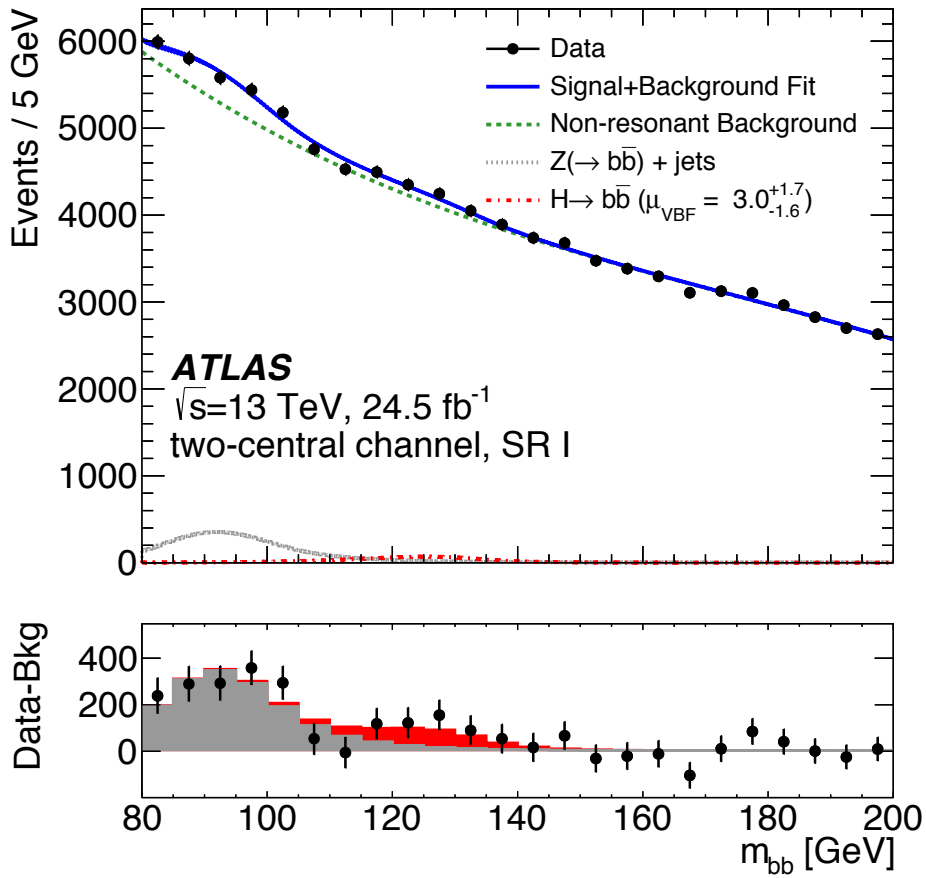
ttH channels (36.1—79.8 fb^{-1})

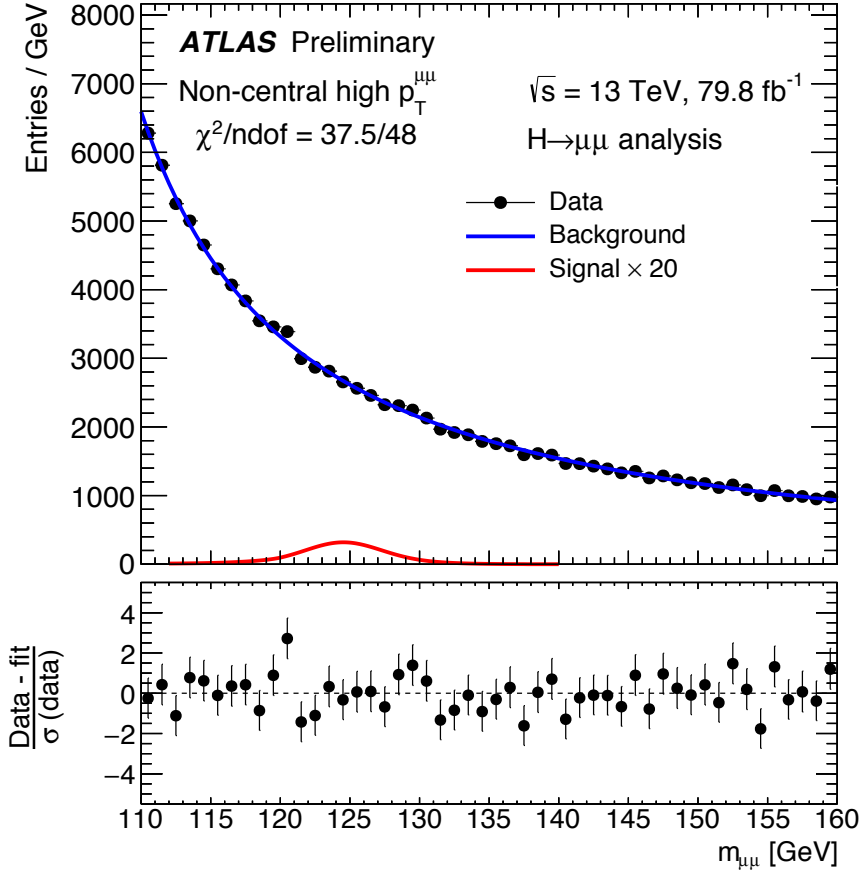




- **ttH multi-lepton (36 fb^{-1})**: targeting WW, ττ, and ZZ decay modes + ttbar with ≥1 leptonic W decay
- **ttH, H→bb (36 fb^{-1})**: targeting ttbar with ≥1 leptonic W decay. Divide into single lepton and dilepton regions
- ttH, H→γγ and ttH, H→ZZ→4l analyses included as part of full H→γγ and H→ZZ→4l analyses introduced before

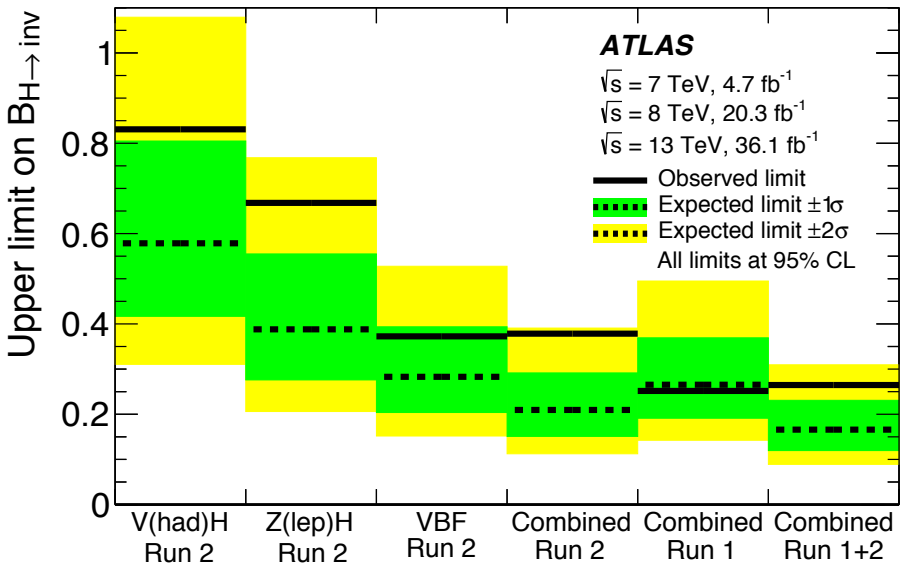
VBF, H→bb (24.5—30.6 fb^{-1}) and H→μμ (79.8 fb^{-1})

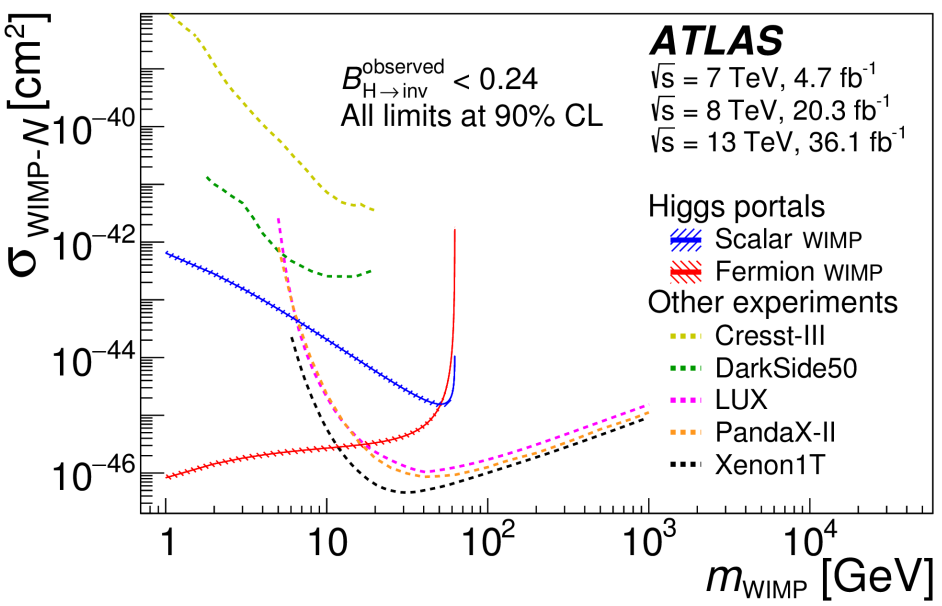




- VBF, H→bb: exploit associated γ or VBF topology for trigger
- H→μμ: bump hunting on the large tail of Drell-Yan bkg. Current 95% CL limit is 2.1×SM expectation

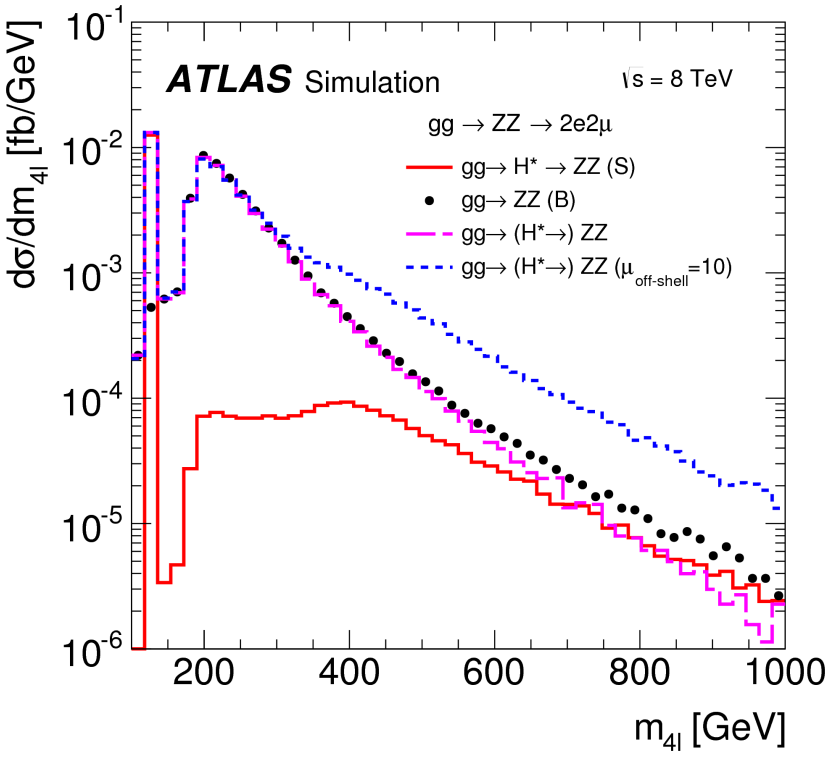
H→invisible searches (36.1 fb^{-1})

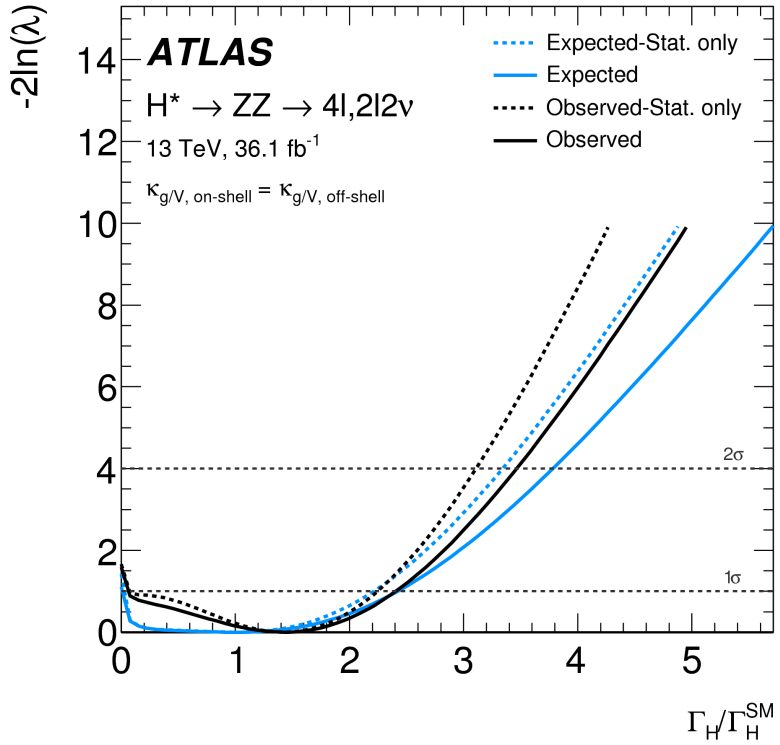




- The SM expectation for H→inv. BR is tiny (0.1% from H→ZZ→4ν), but the BR can be enhanced with BSM physics (e.g. H→dark matter)
- Search for missing transverse momentum signature in VBF and V(had/lep)H topology

Off-shell analysis (36.1 fb^{-1})





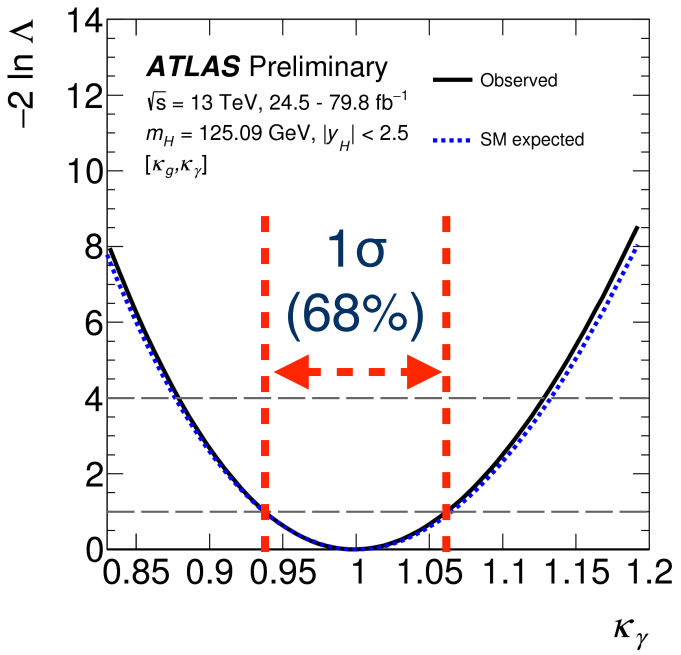
- Study off-shell production of Higgs boson at high mass in ZZ→4l and ZZ→llνν channels
- Assume same couplings in on-shell/off-shell regions to indirectly constrain Higgs boson total width

Statistical methodology

- Construct combined likelihood model as multiplication of individual channel likelihoods
  - Common parameters, e.g. signal cross-sections and nuisance parameters for the same systematic uncertainties, are shared between likelihood of individual channels
- Use profile likelihood ratio Λ as test statistic:

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

- 1-D 68% confidence interval defined by -2lnΛ increasing by 1 (asymptotic limit)
  - Assumption validated with pseudo-experiments in low statistics case

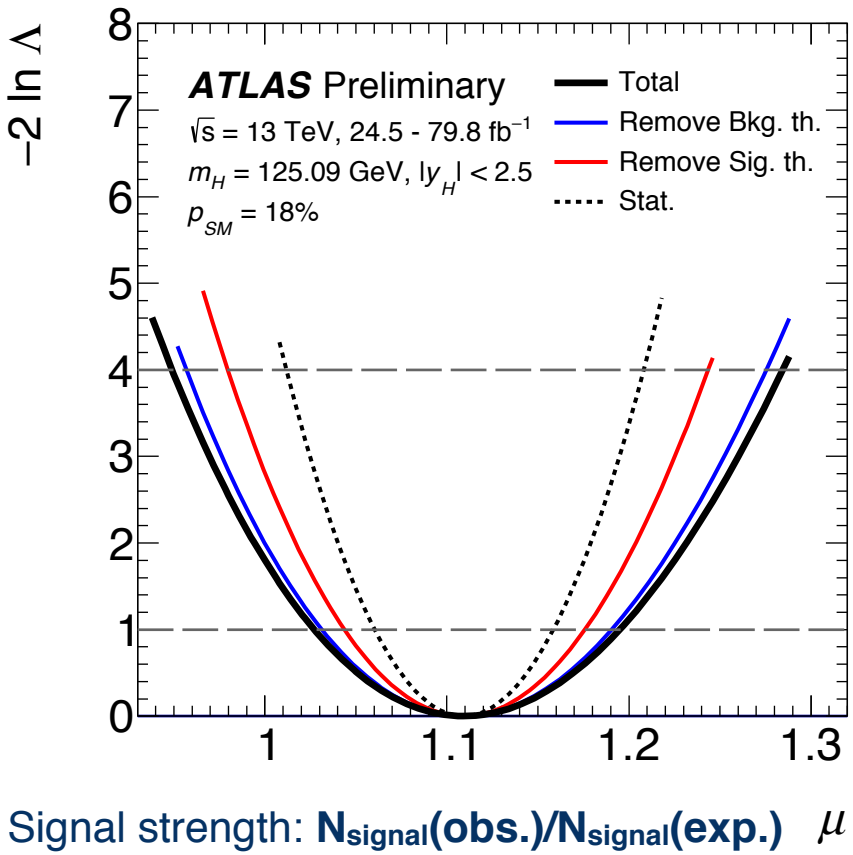


Signal strength & production cross-section measurements

	ggF	VBF	VH	ttH+tH
H→γγ	✔	✔	✔	✔
H→ZZ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔		✔
H→bb	✔	✔	✔	✔

✔: channel included in the combination
✔: channel available but not included in combination

Inclusive signal strength



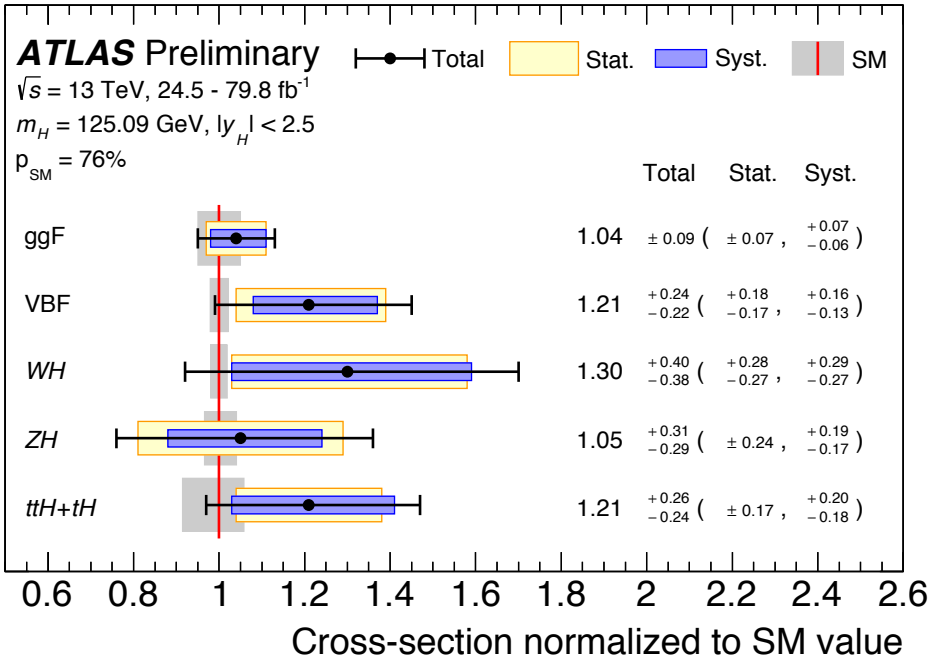
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

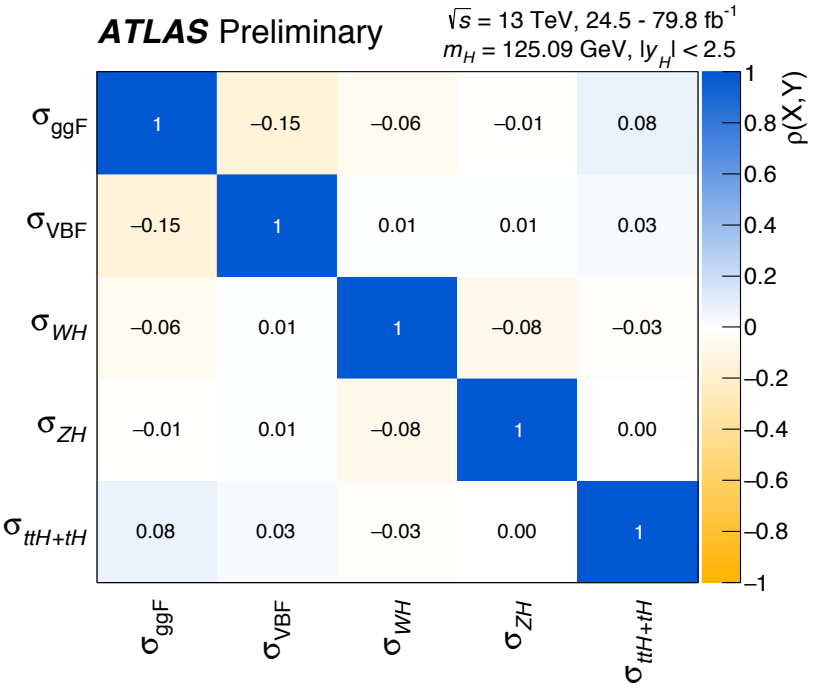
Overall cross-section uncertainty

$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat.})^{+0.05}_{-0.04}(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.03(\text{bkg. th.})$$

- Comparable contribution from statistical, experimental, and signal/bkg. theory uncertainty components

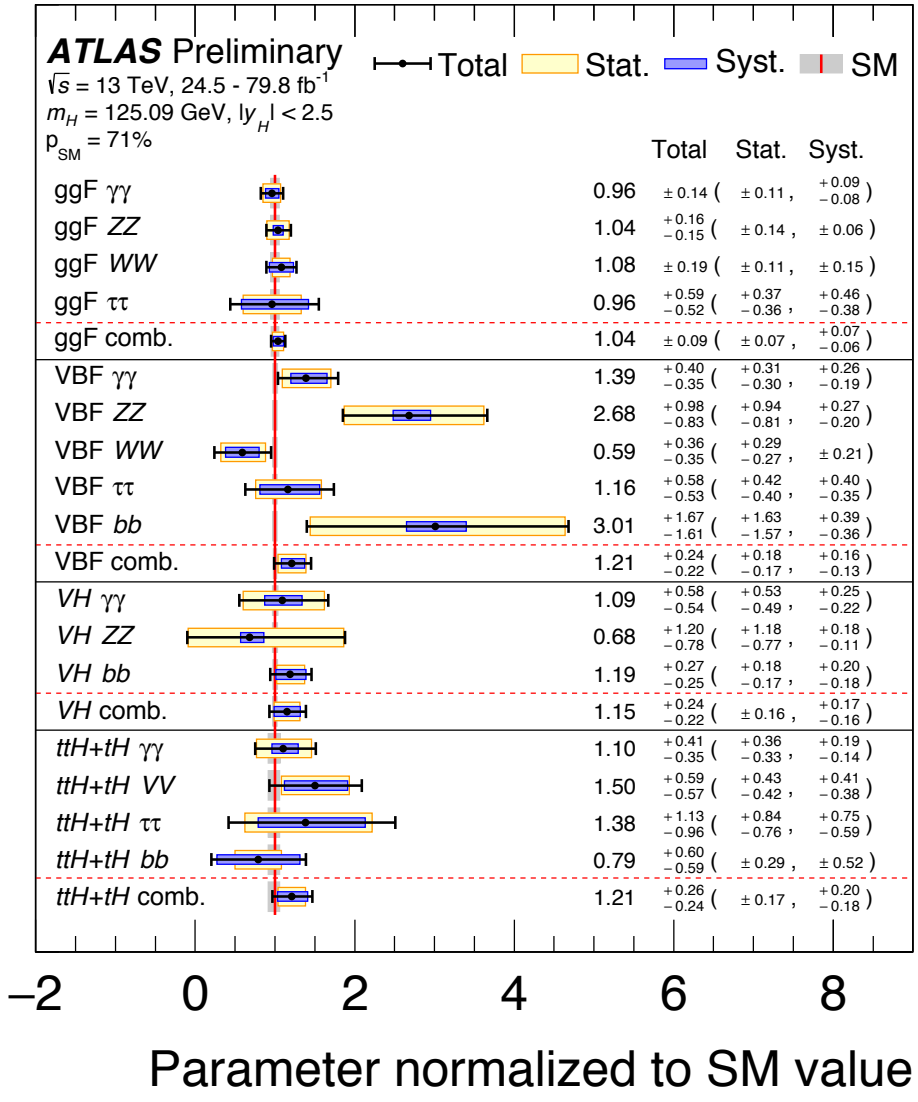
Production mode cross-sections (assuming the SM BRs)

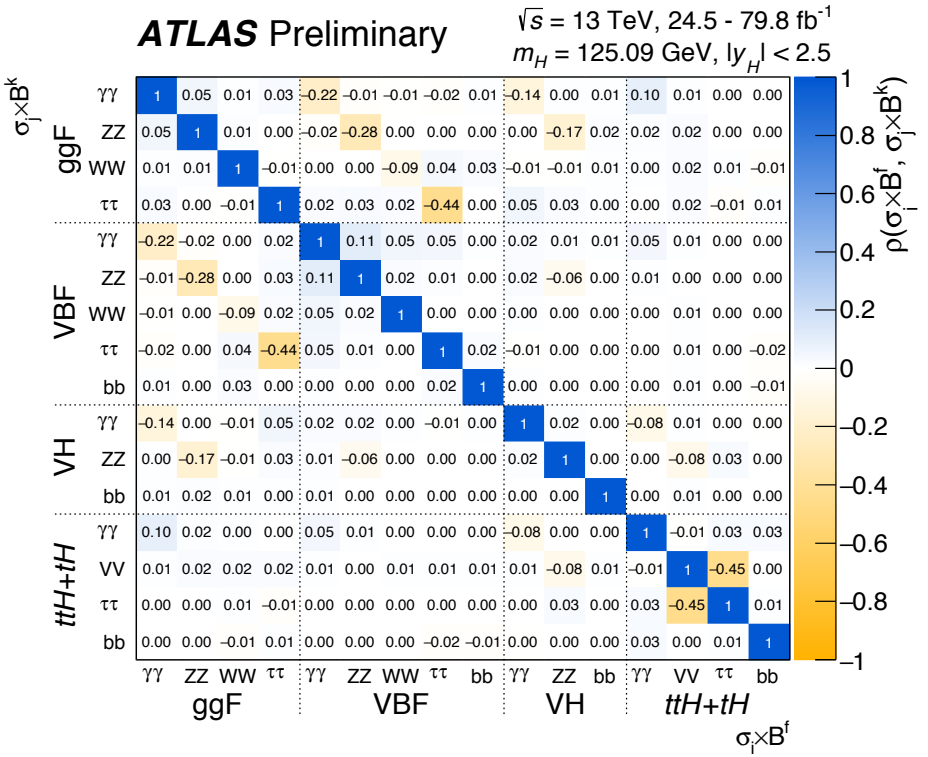




- **ggF cross-section now measured with precision of 9%, close to 5% uncertainty on the N³LO cross section prediction**
- **All major production modes (also all major decay channels) observed!**
  - Single experiment observation of VBF (6.5σ obs., 5.3σ exp.), following Run 1 ATLAS+CMS observation
- Small correlation between measurements of different production modes

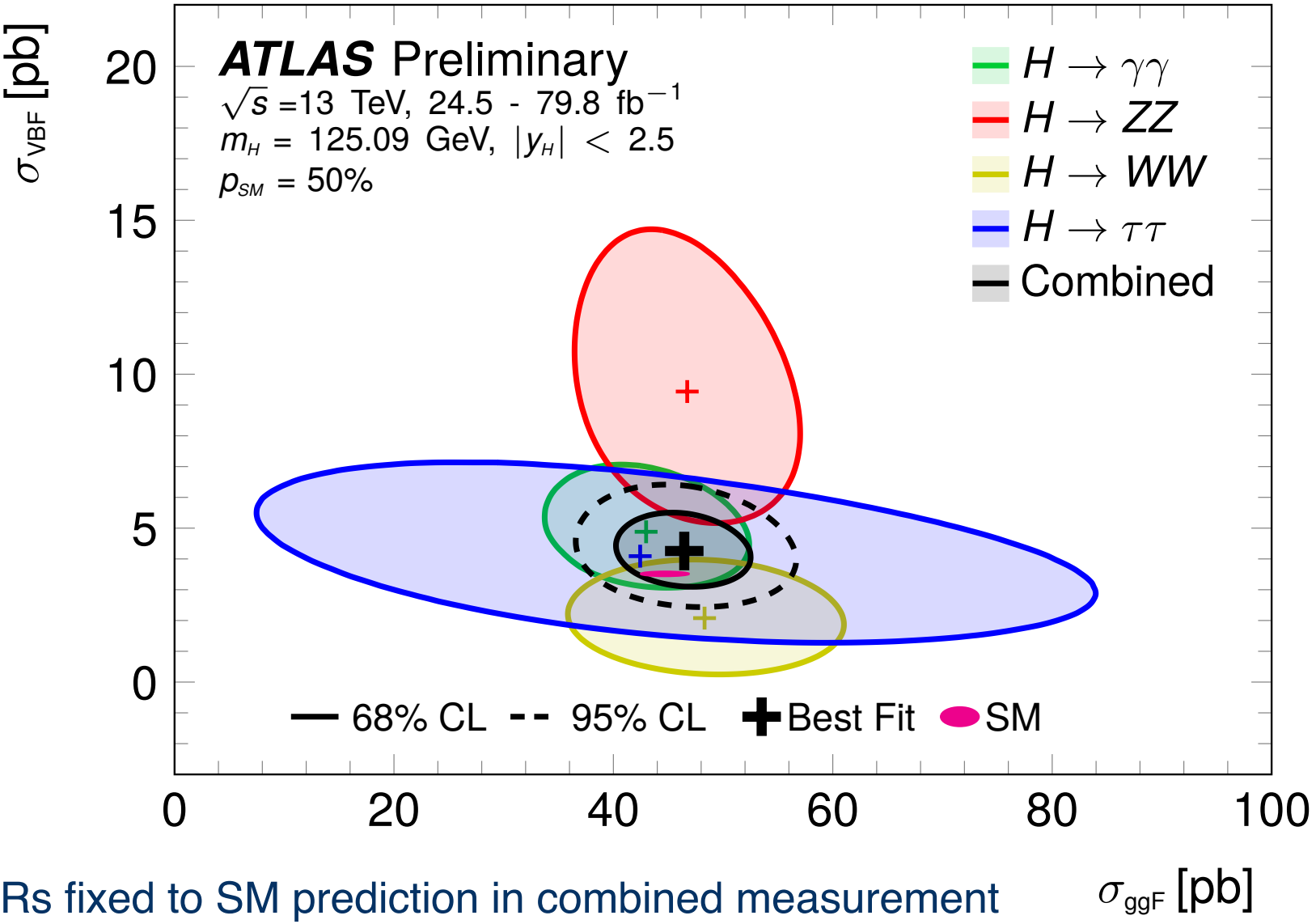
Production cross-section in each decay channel





- Good compatibility among decay channels and also with the SM
- Anti-correlation most notable for ggF vs. VBF, and VV vs. ττ in ttH multi-lepton analysis

ggF vs. VBF contour



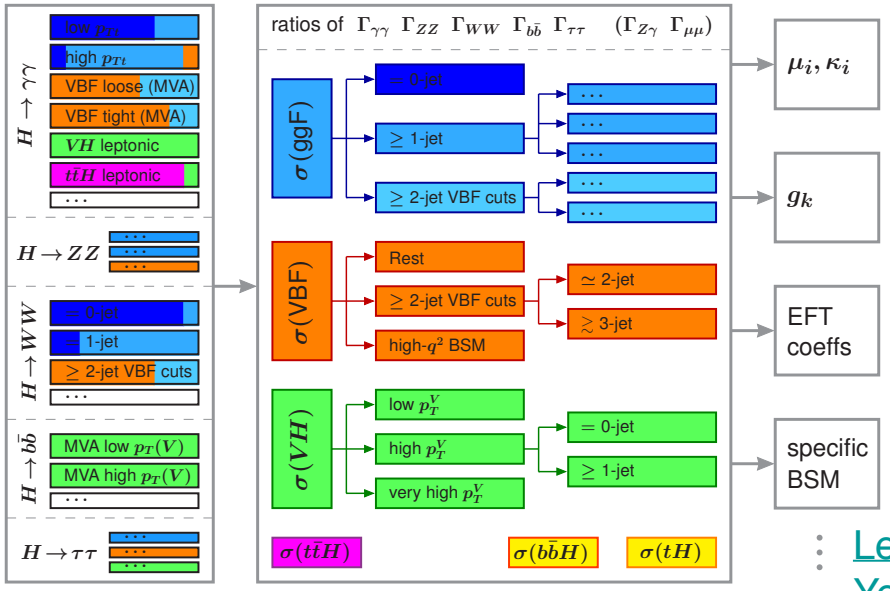
BRs fixed to SM prediction in combined measurement

Simplified Template Cross-Section (STXS) results

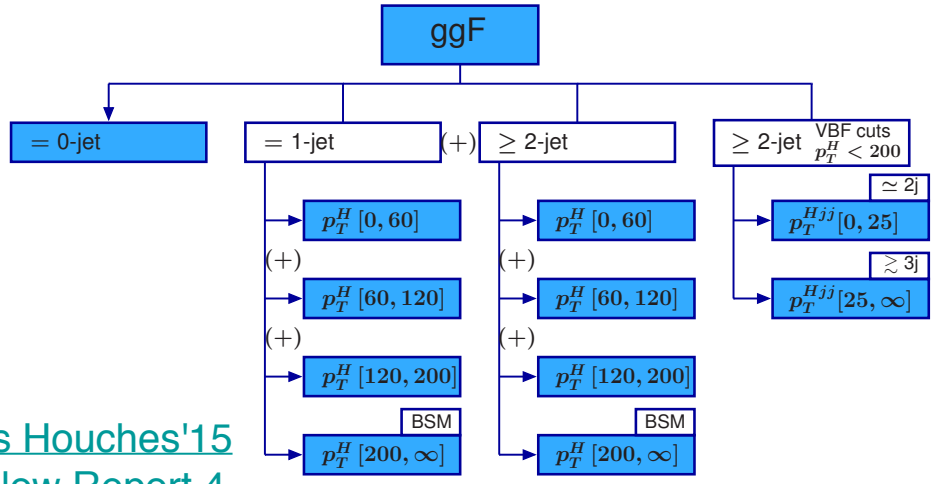
	ggF	VBF	VH	ttH+tH
H→γγ	✔	✔	✔	✔
H→ZZ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔		✔
H→bb	✔	✔	✔	✔

✔: channel included in the combination
✔: channel available but not included in combination

STXS: extension of inclusive-style measurements



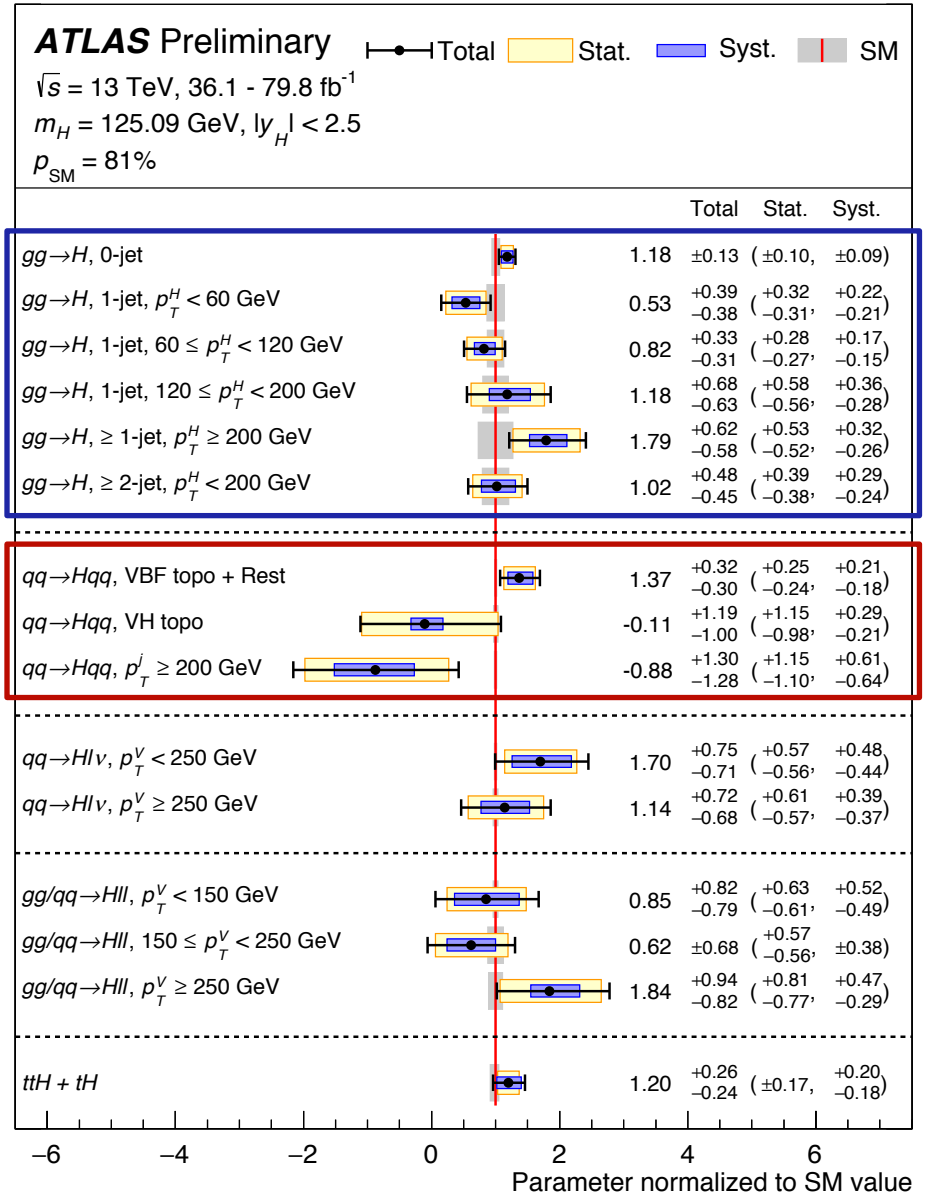
Original proposal of splitting for ggF signal in "Stage 1" STXS framework

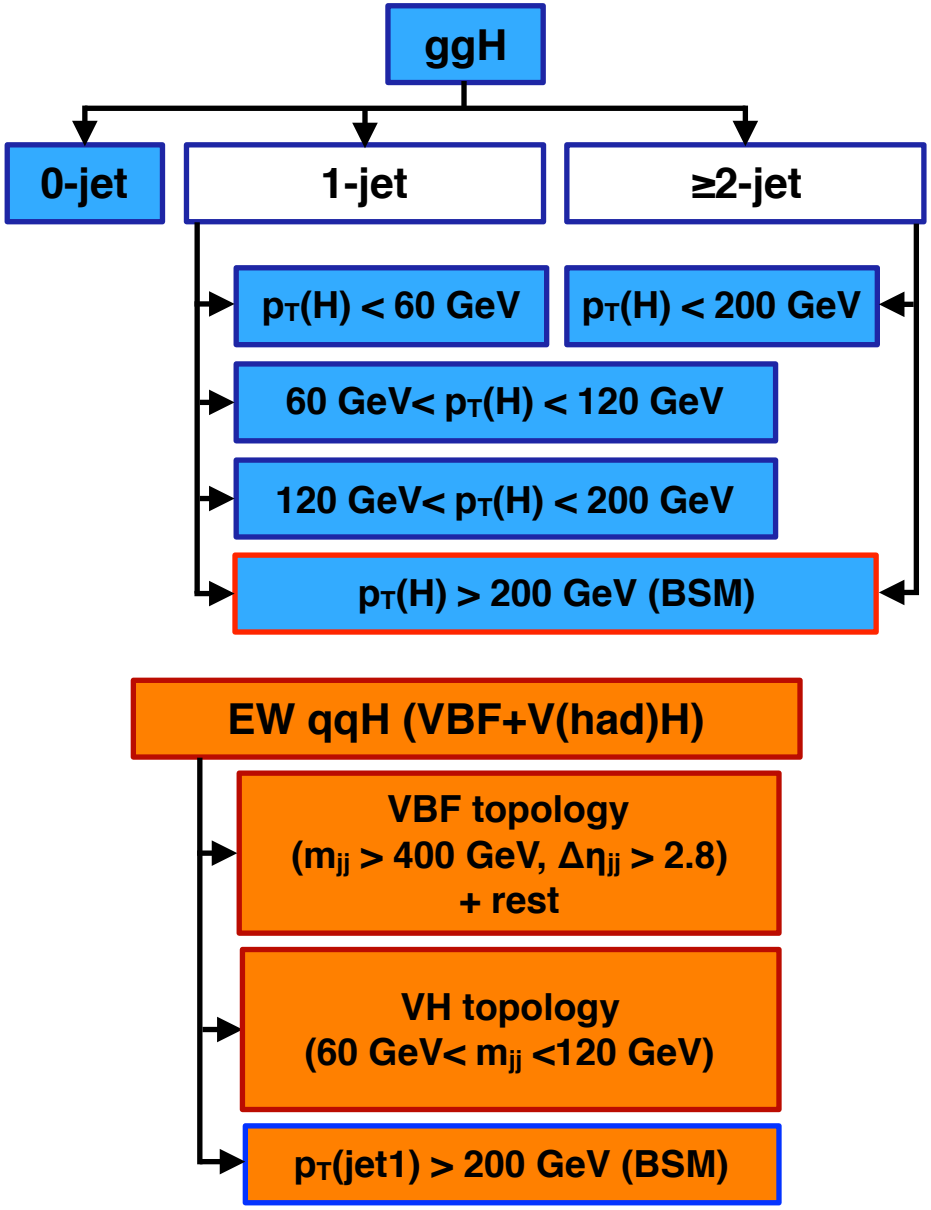


Les Houches'15 Yellow Report 4

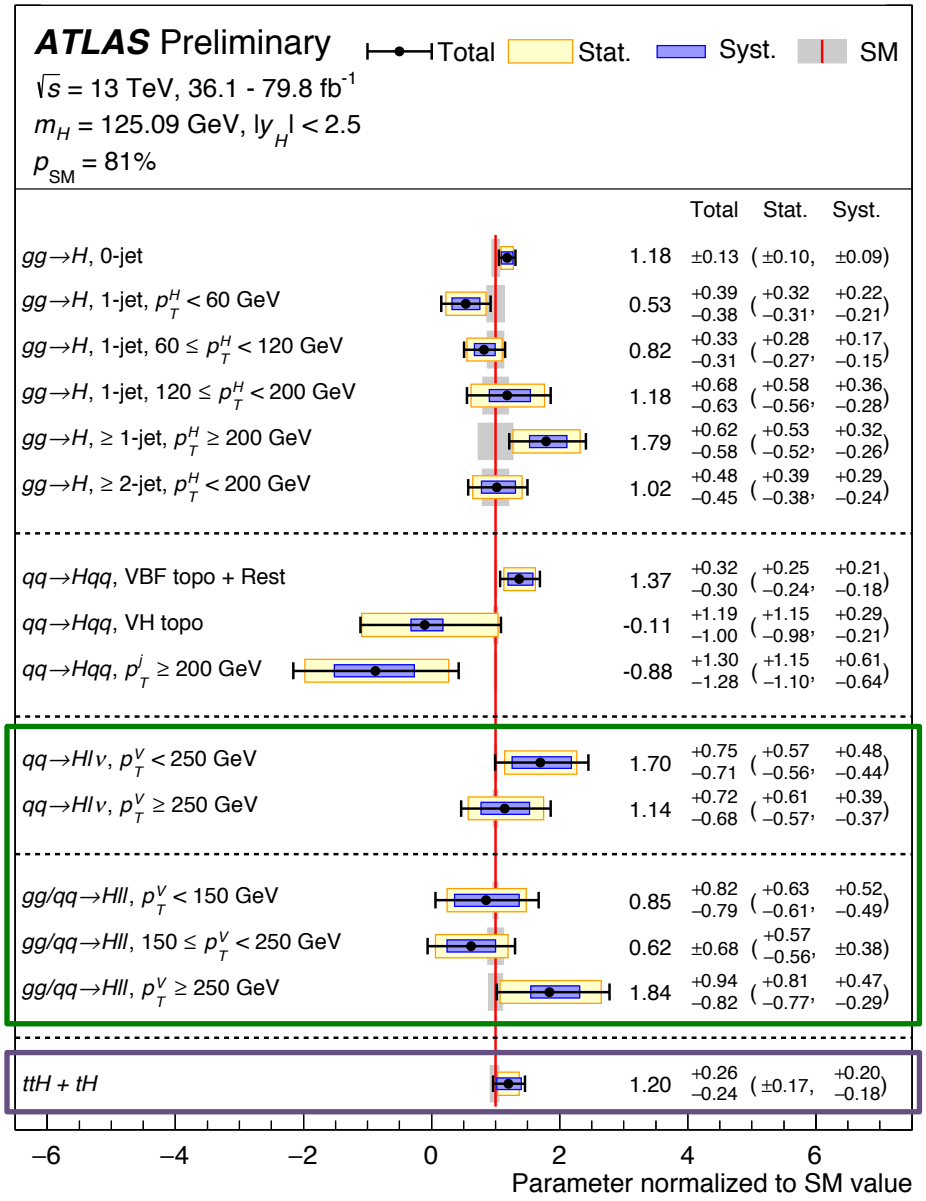
- **Measure cross-section per production mode in different phase-space regions**
  - Reduce model dependence and maximize sensitivity to BSM effects
  - Support kinematic-dependent interpretations (EFT etc.)
- Within each region, use the SM predicted signal templates to fit data
  - Can still exploit powerful analysis techniques (e.g. MVA)

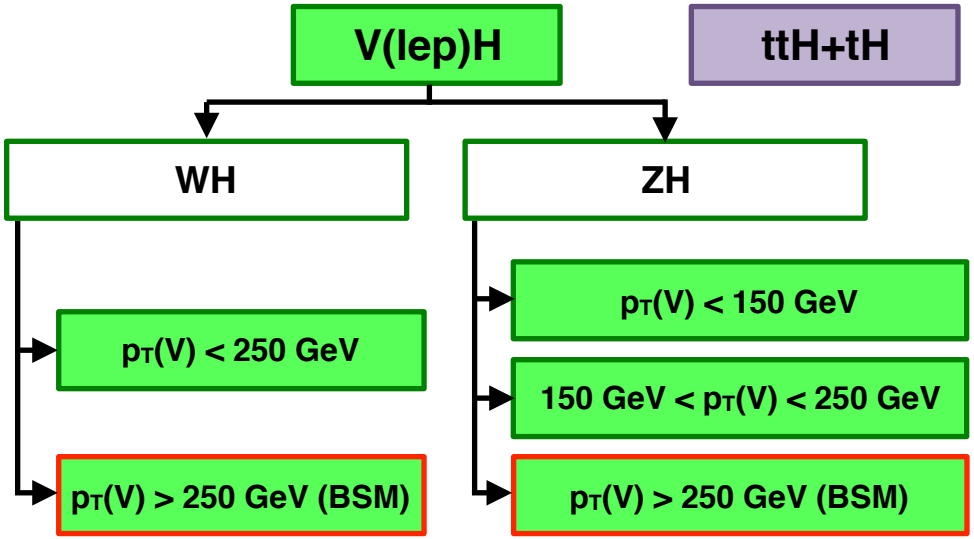
STXS results assuming the SM BRs





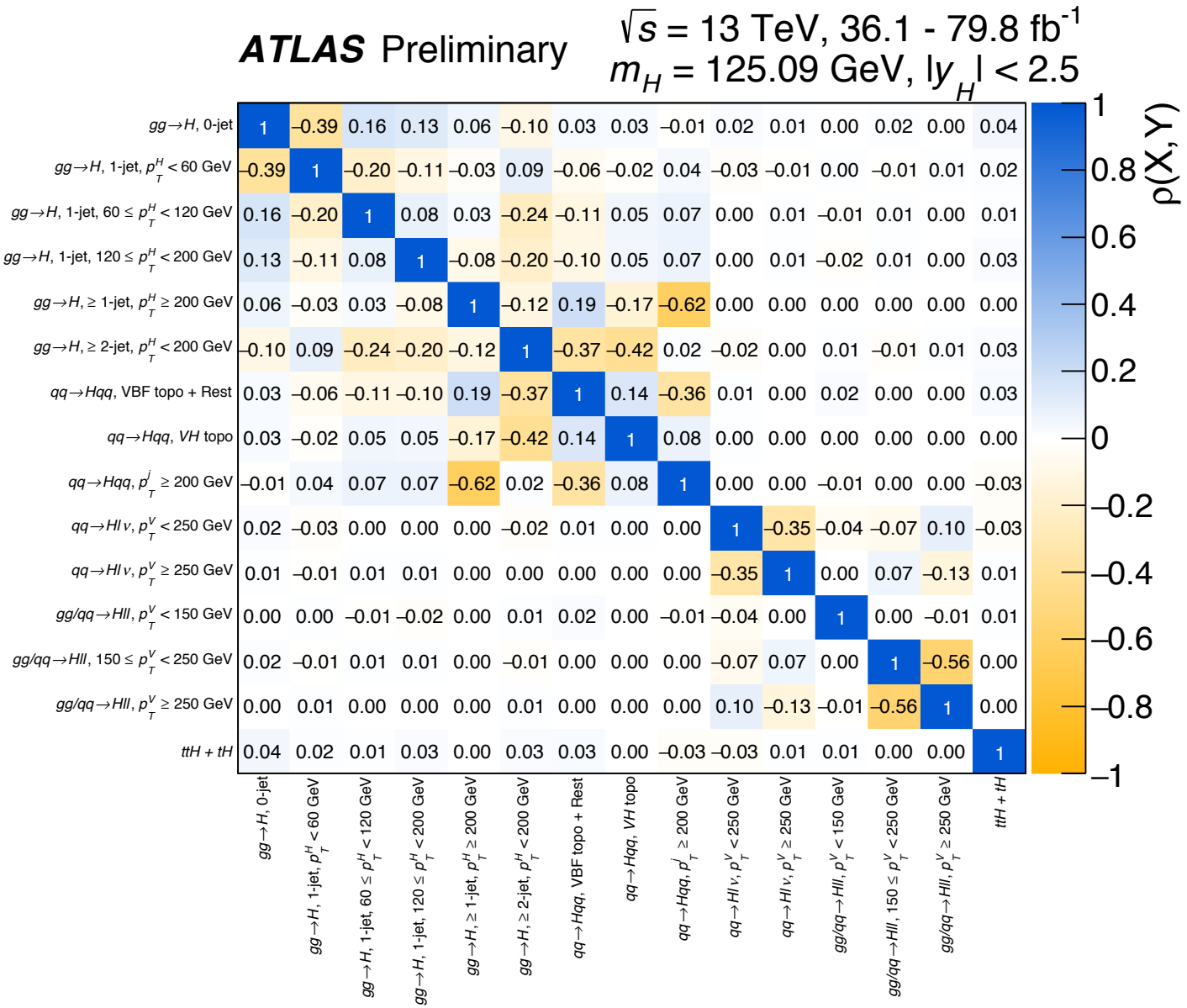
STXS results assuming the SM BRs





- Overall good compatibility with SM (p-value 81%)
- Statistical precision, in particular in most BSM-sensitive regions is still limited: more data will help!

STXS correlation matrix

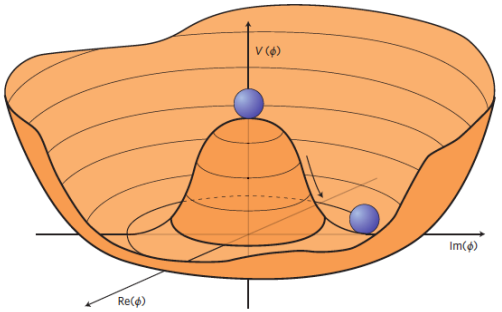


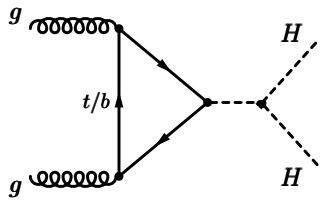
Probe Higgs boson self-coupling using single-Higgs production and STXS framework

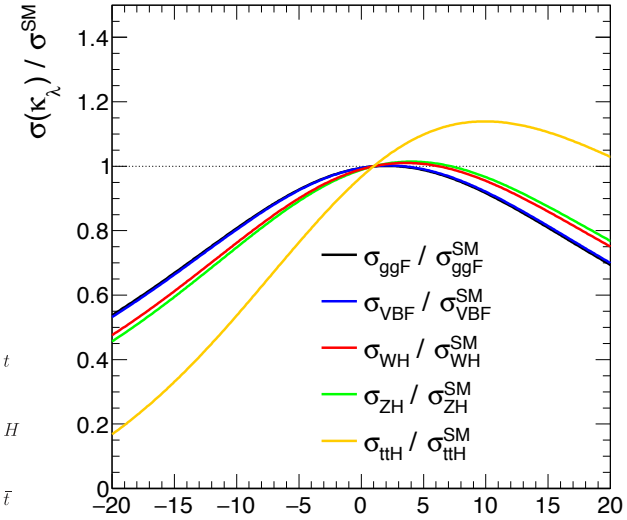
Theoretical framework

- Higgs boson self-coupling is an important parameter of the SM
  - Determined once m_H is fixed in the SM
  - Potential new physics can modify the coupling
- Traditionally studied by searching for Higgs boson pair production
- However, single Higgs boson production & decay rates, as well as kinematics, are also sensitive to the self-coupling through EW corrections: can be exploited to indirectly constrain Higgs boson self-coupling

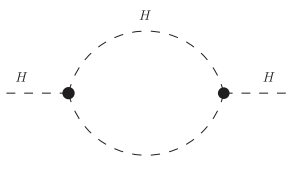
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + O(H^5)$$



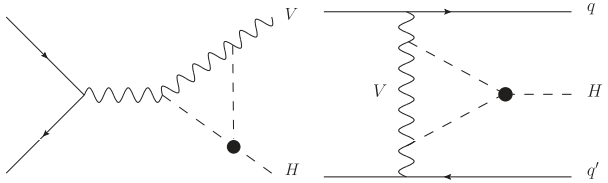




G. Degrassi et. al., JHEP 12 (2016) 080,
F. Maltoni et. al., EPJC 77 (2017) 887

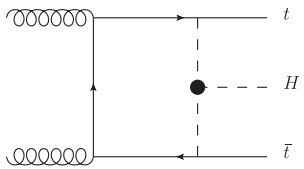


Propagator



VH

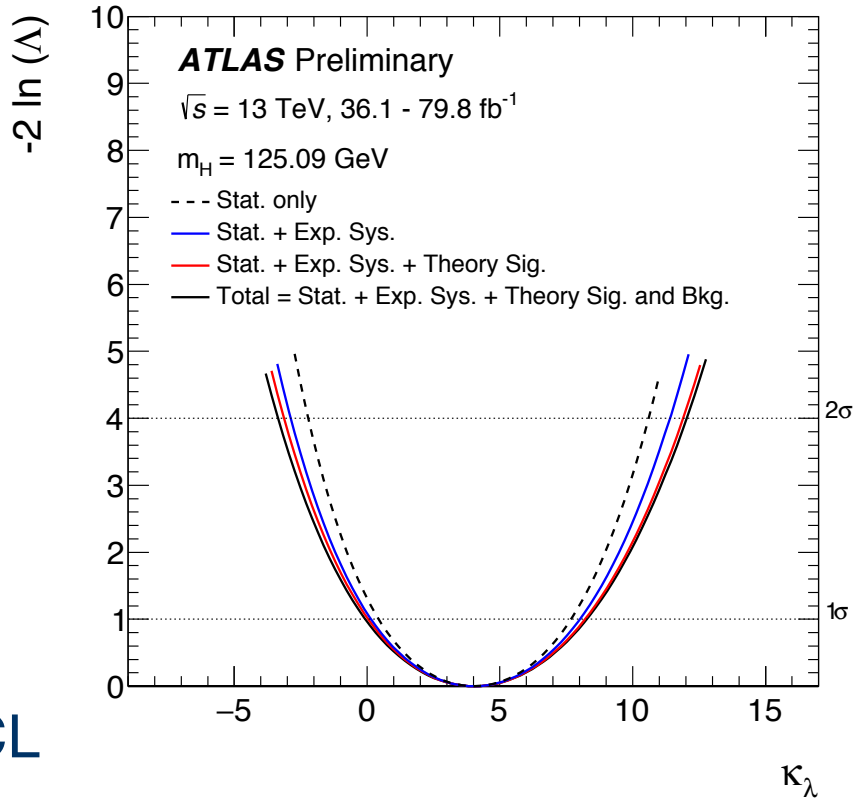
VBF



ttH

Results

- Use inclusive rate for ggF and ttH, and parameterize VBF and VH cross-section in Stage 1 STXS bins as function of self-coupling scale factor $\kappa_\lambda = \lambda_3/\lambda^{SM}_3$
  - Dependence on kinematics in ggF and ttH checked to have small impact on results



- Excluding κ_λ = **[-3.2, 11.9]** @ 95% CL
  - Comparable to limits from 36.1 fb^{-1} di-Higgs boson search: [-5.0, 12.1]
- Assume all single Higgs couplings to be SM-like with current statistics. Without this assumption, the sensitivity to the self-coupling will be marginal

Coupling modifier ("kappa") interpretation

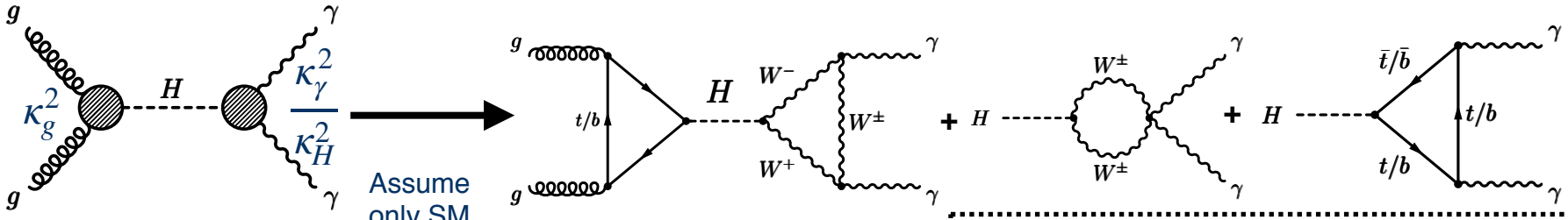
	ggF	VBF	VH	ttH+tH
H→γγ	✔	✔	✔	✔
H→ZZ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔		✔
H→bb	✔	✔	✔	✔

✔: channel included in the combination
✔: channel available but not included in combination

H→μμ (constrains Hμμ coupling), H→inv. (constrains invisible BR), and off-shell (constrains total width) also included in relevant studies

Basic idea

- Leading order motivated framework: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_Z, κ_t…)
- Total width of Higgs boson can be parameterized with the SM contributions, or be considered as one effective scale factor



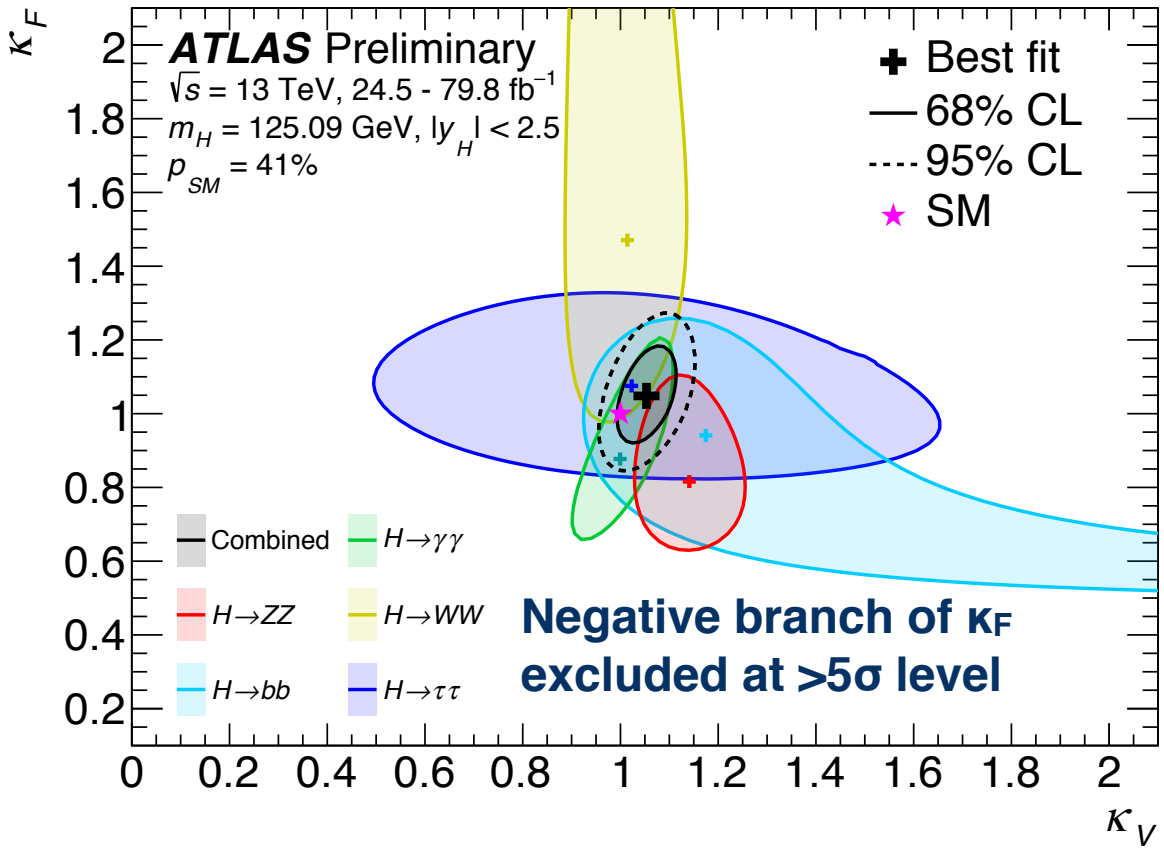
$$\sigma \times BR(gg \to H \to \gamma\gamma) \propto \kappa_g^2 \frac{\kappa_\gamma^2}{\kappa_H^2} \to \frac{(1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b)}{\kappa_g^2} \frac{1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_\tau, \dots)}$$

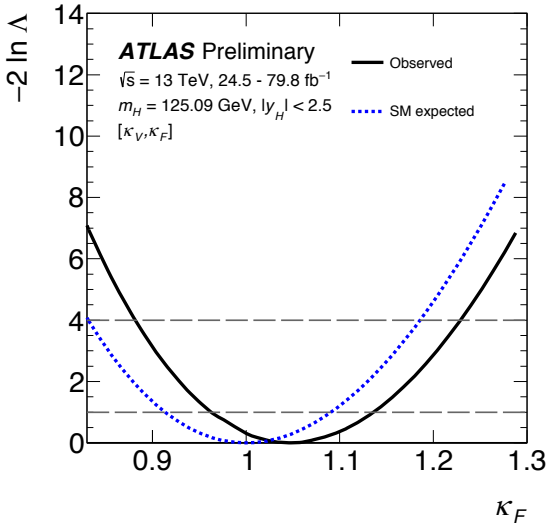
κ_H is the scale factor for total width

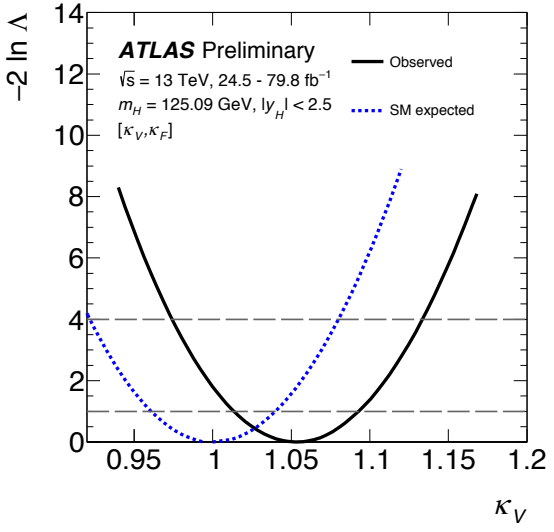
- Invisible BR (B_{inv}) and BSM contribution to undetected BR (B_{undet}) can be considered as:

$$\Gamma_H(\kappa_i, B_{inv}, B_{undet}) = \frac{\kappa_H^2(\kappa_i)}{1 - B_{inv} - B_{undet}} \Gamma_H^{SM}$$

κ_V vs. κ_F

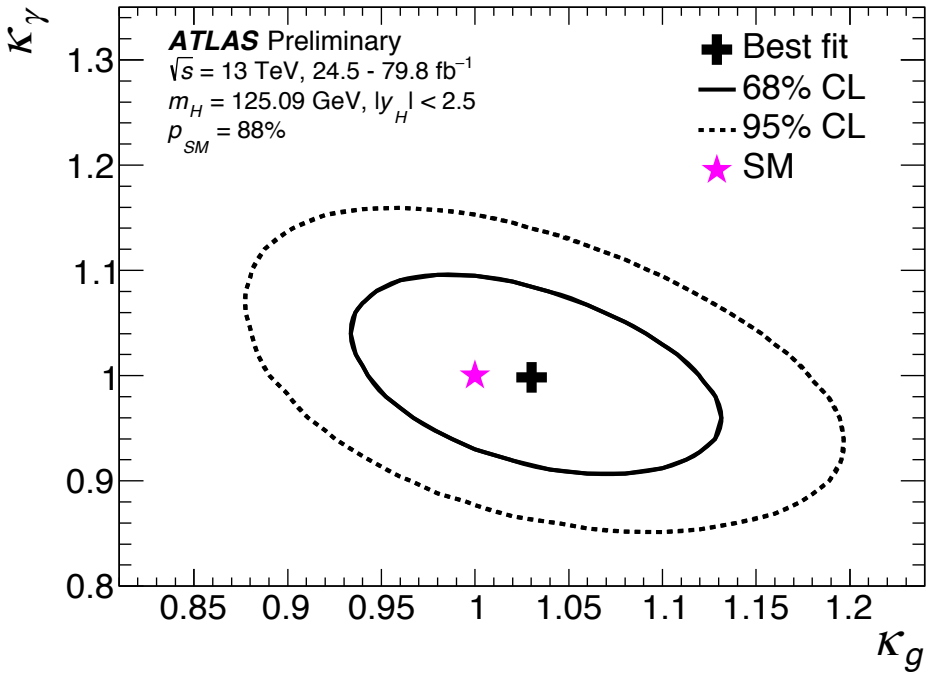


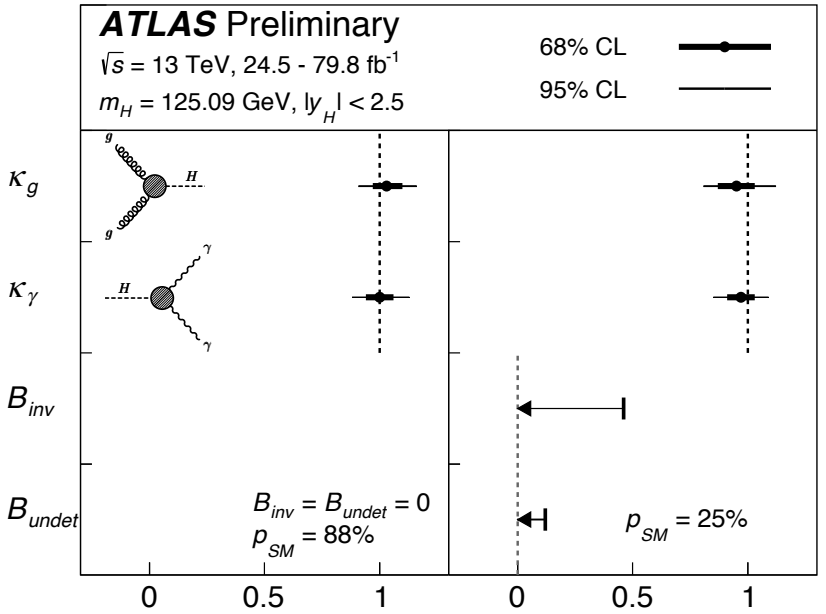




- Uniform coupling for all the fermions and vector-bosons. Assume no BSM physics in loop-induced processes or total width

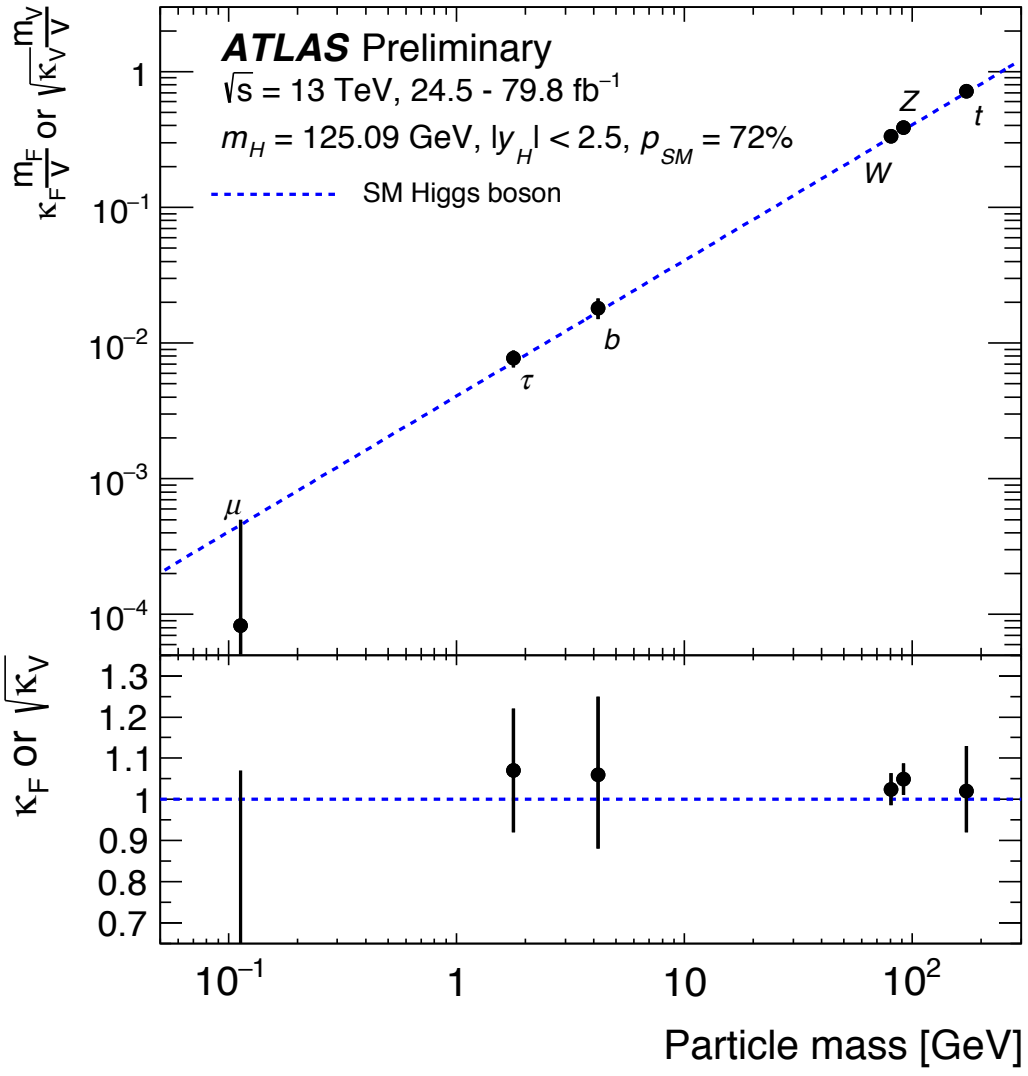
κ_g VS. κ_γ





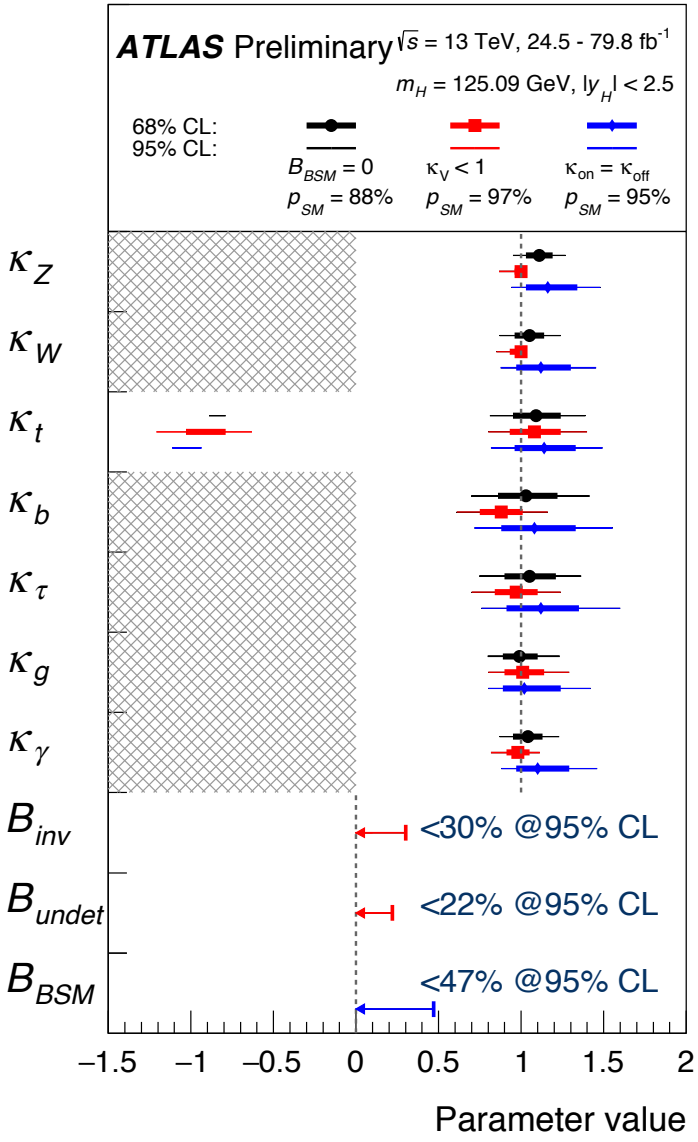
- Focus on ggH and Hγγ interactions, with other coupling strengths fixed to the SM
  - Loop-induced in the SM, sensitive to new physics
- Can also determine B_{inv} and B_{undet} contributions at the same time by including H→inv. searches

Coupling modifier vs. particle mass



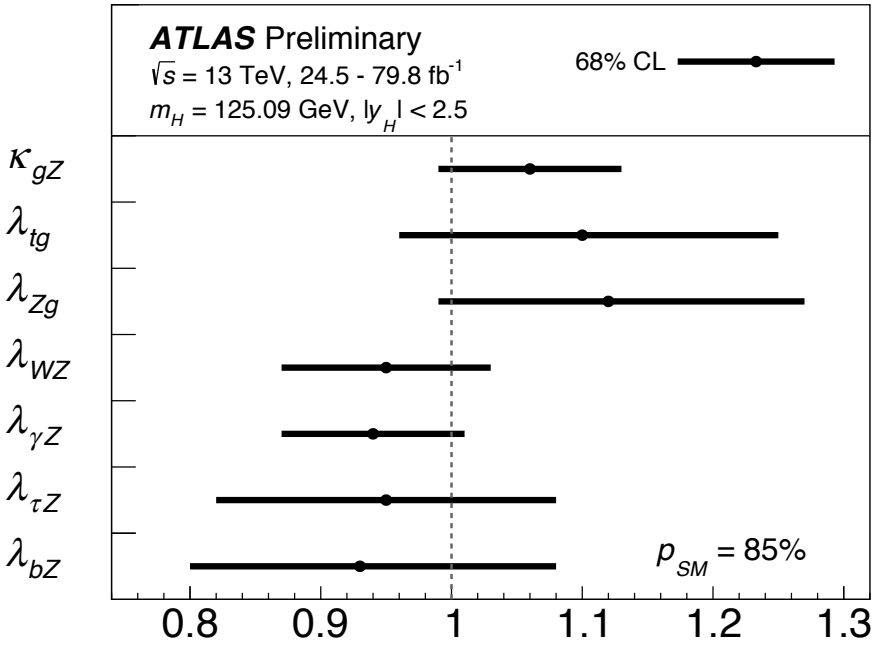
- Assume no BSM contribution in loop-induced processes (ggF, H→γγ etc.) or total width
- Probe all the coupling strengths for which there is sensitivity
- **Good agreement with the SM within uncertainties across 3 orders of magnitude in particle mass!**
  - Hμμ coupling constrained with limited precision

Generic parameterization



- Introduce coupling scale factors for the SM particles where there is sensitivity. Not resolving ggH and Hγγ effective vertices
  - Using tH and gg→ZH process to constrain relative sign of t-H coupling κ_t w.r.t. other couplings (assumed to be positive)
  - Same coupling scale factor for fermions across generations: will be improved once there is sensitivity to 2nd generation fermion couplings
- **Black**: assume $B_{inv}=B_{undet}=0$
- **Red**: constrain B_{inv} and B_{undet} using H→inv.
  - ✳ Since total width is not constrained in this case, need to assume **$\kappa_V \leq 1$** to remove redundant degree of freedom (valid in many BSM models)
- **Blue**: constrain $B_{BSM} = B_{inv} + B_{undet}$ using off-shell analysis (indirect constraint on total width)

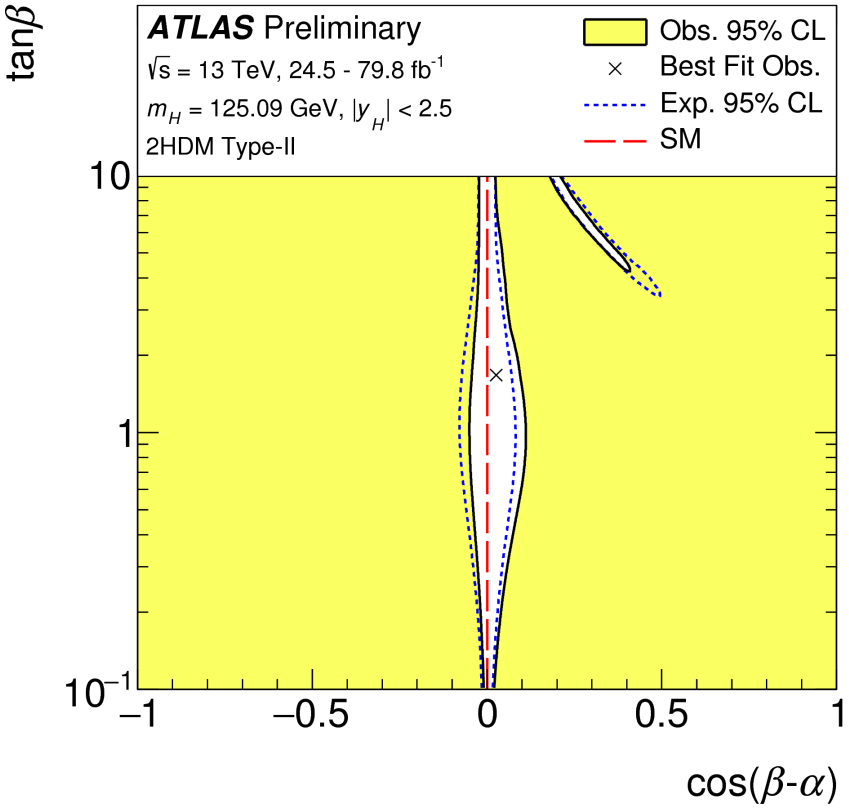
No assumption on total width

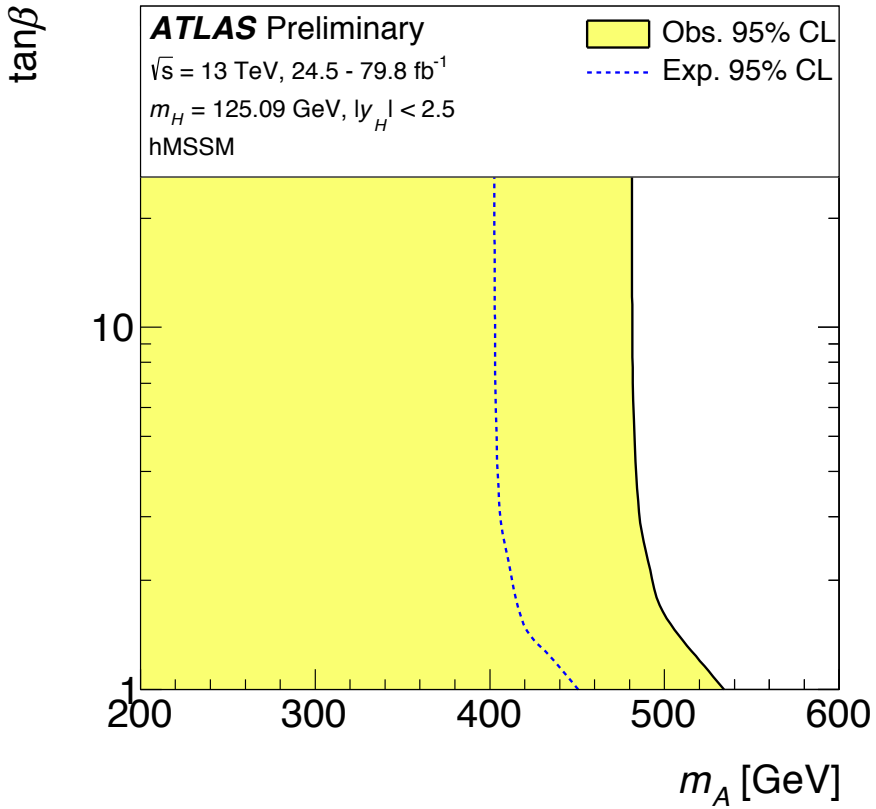


Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t/κ_g	$1.10^{+0.15}_{-0.14}$
λ_{Zg}	κ_Z/κ_g	$1.12^{+0.15}_{-0.13}$
λ_{WZ}	κ_W/κ_Z	0.95 ± 0.08
$\lambda_{\gamma Z}$	κ_γ/κ_Z	0.94 ± 0.07
$\lambda_{\tau Z}$	κ_τ/κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b/κ_Z	$0.93^{+0.15}_{-0.13}$

- Remove assumption on total width by absorbing κ_H into ratios with other parameters
  - **$\lambda_{tg}=\kappa_t/\kappa_g$**: effectively compare the direct determination of the top coupling through ttH production (κ_t) to the indirect determination in the ggF loop (κ_g). Probe new physics in ggH process
  - **$\lambda_{\gamma Z}=\kappa_\gamma/\kappa_Z$**: probe new physics in H→γγ process

BSM interpretations

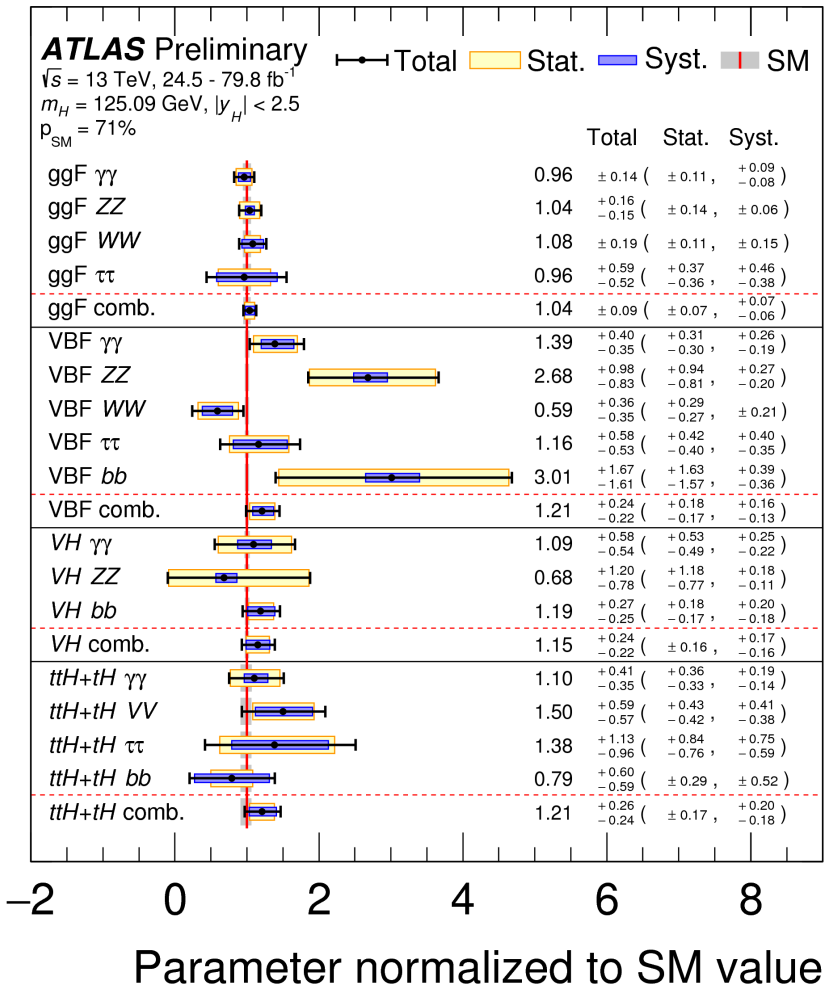




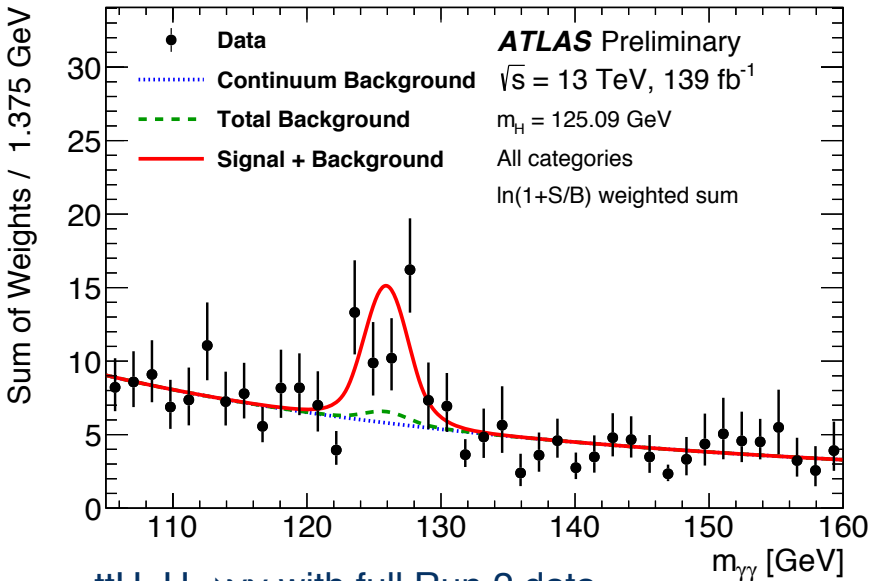
- Two Higgs doublet model (2HDM): assuming the observed Higgs boson is the light neutral scalar. Set limit on mixing angle with the heavy one (**α**) and the ratio of vacuum expectation values of the Higgs doublets (**tanβ**)
- Simplified Minimal Supersymmetric Standard Model: realization of 2HDM. Set limit on **tanβ** and on the mass of the CP-odd scalar ($\mathbf{m_A}$)

Conclusions

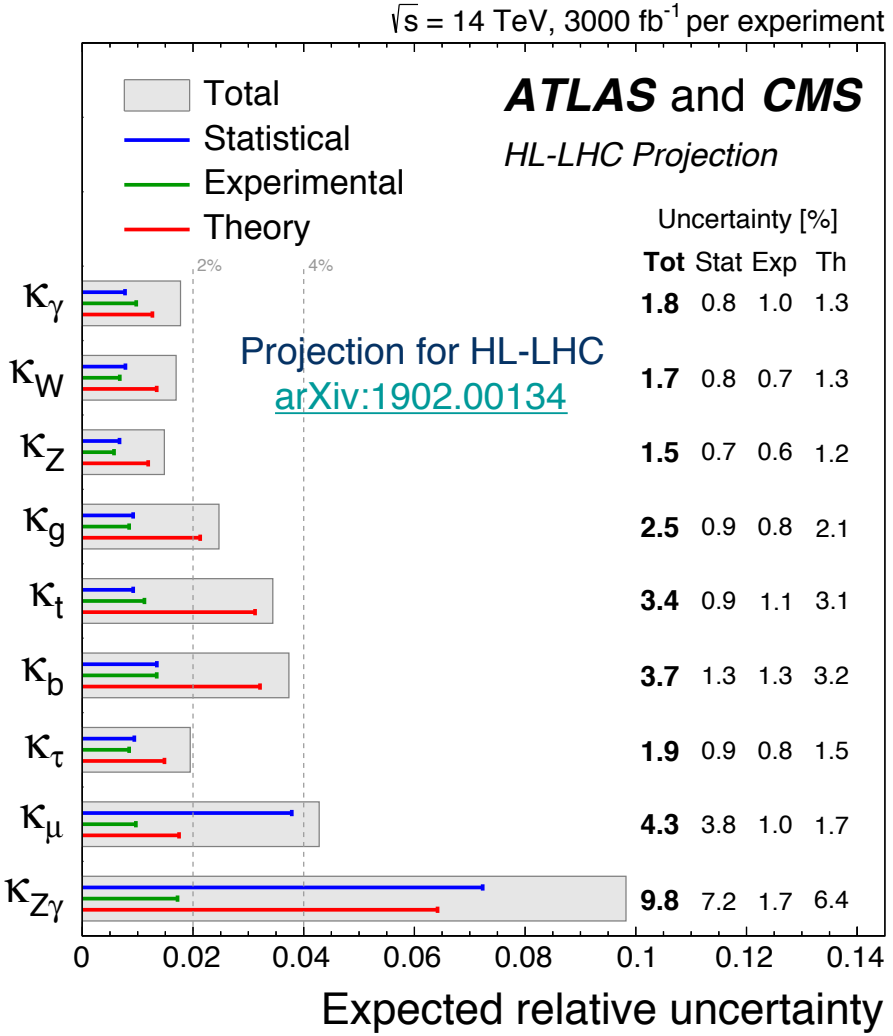
- Combination of analyses based on up to 80 fb^{-1} of Run 2 data improves precision
  - **8%** for inclusive signal strength
  - **10%** level on inclusive production mode cross-section measurements
  - **7~15%** for ratios of coupling modifiers
- Simplified Template Cross-Section framework implemented in major analyses. Many combined results based on granular STXS measurements produced
- All measurements in good agreement with the SM within current uncertainty



Conclusions (cont'd)



ttH, H→γγ with full Run 2 data
ATLAS-CONF-2019-004



- A significantly larger full Run 2 dataset still to analyze
  - x2 stats from combining ATLAS and CMS measurements
- Only **5%** data taken w.r.t. integrated luminosity expected by the end of high luminosity LHC (HL-LHC)

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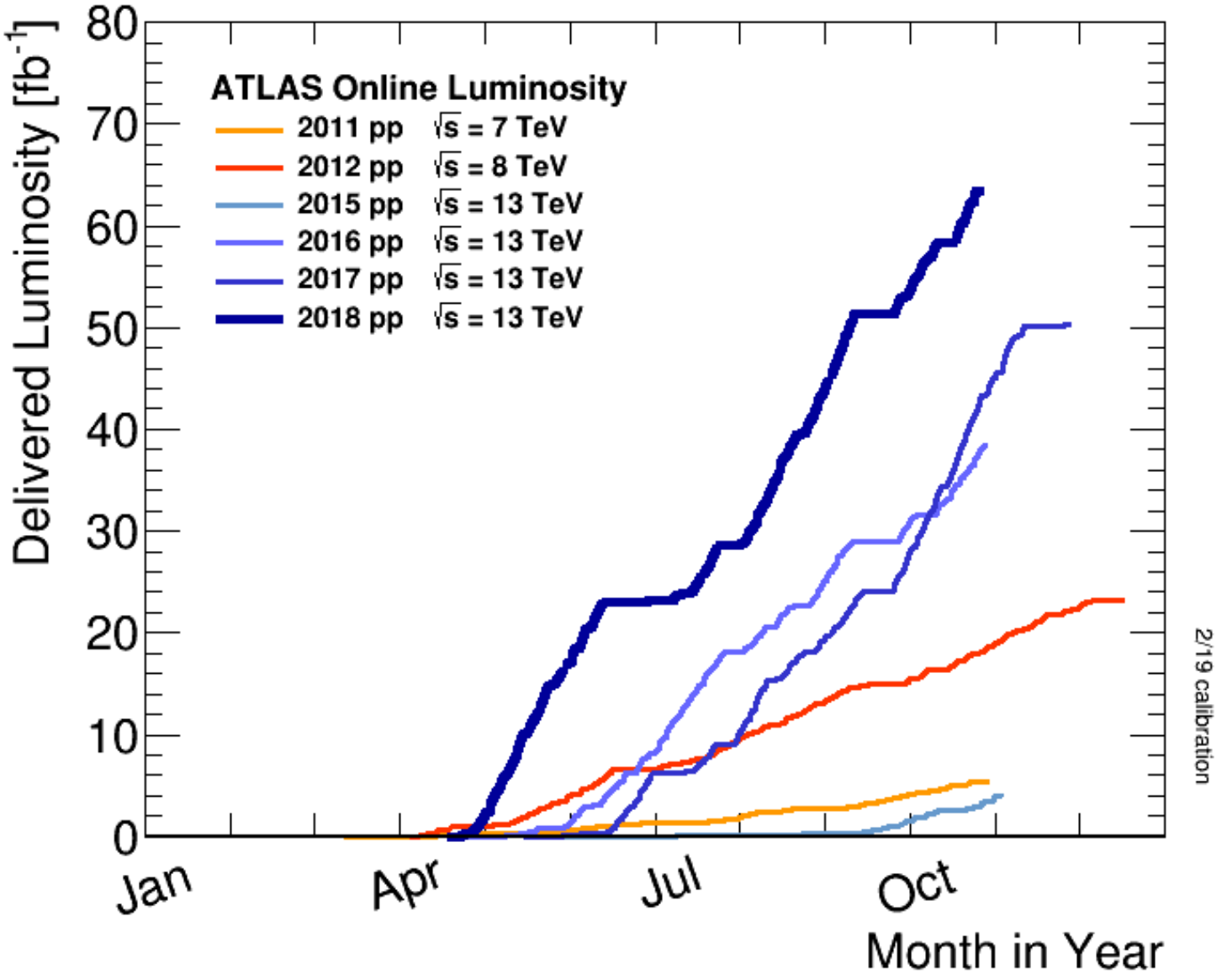
Backup

Delivered luminosity versus time for 2011-2018



Typical MC generators used for Higgs boson signal

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s} = 13$ TeV	Order of σ calculation
ggF	Powheg NNLOPS	Pythia 8	PDF4LHC15	48.52	N^{3}LO(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)

Analysis selection: H→WW

Category	$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\ \text{GeV})} \geq 2$ VBF
Preselection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge $p_T^{\text{lead}} > 22\ GeV$, $p_T^{\text{sublead}} > 15\ GeV$ $m_{\ell\ell} > 10\ GeV$ $p_T^{\text{miss}} > 20\ GeV$		
Background rejection	$\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $p_T^{\ell\ell} > 30\ GeV$	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$ $\max\left(m_T^{\ell}\right) > 50\ GeV$ $m_{\tau\tau} < m_Z - 25\ GeV$	
$H \to WW^* \to e\nu\mu\nu$	$m_{\ell\ell} < 55\ GeV$ $\Delta\phi_{\ell\ell} < 1.8$		central jet veto outside lepton veto
Discriminant variable BDT input variables	m_T		BDT m_{jj}, Δy_{jj}, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T, $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell j}$, p_T^{tot}

CR	$N_{\text{jet},(p_T>30\ \text{GeV})} = 0$ ggF	$N_{\text{jet},(p_T>30\ \text{GeV})} = 1$ ggF	$N_{\text{jet},(p_T>30\ \text{GeV})} \geq 2$ VBF
WW	$55 < m_{\ell\ell} < 110\ GeV$ $\Delta\phi_{\ell\ell} < 2.6$	$m_{\ell\ell} > 80\ GeV$ $\lvert m_{\tau\tau} - m_Z \rvert > 25\ GeV$	
	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$	$\max\left(m_T^{\ell}\right) > 50\ GeV$	
$t\bar{t}/Wt$	$N_{b\text{-jet},(20\ \text{GeV}<p_T<30\ \text{GeV})} > 0$ $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$ $> 30\ GeV$ $\Delta\phi_{\ell\ell} < 2.8$	$N_{b\text{-jet},(p_T>30\ \text{GeV})} = 1$ $N_{b\text{-jet},(20\ \text{GeV}<p_T<30\ \text{GeV})} = 0$ $\max\left(m_T^{\ell}\right) > 50\ GeV$ $m_{\tau\tau} < m_Z - 25\ GeV$	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 1$ central jet veto outside lepton veto
Z/γ^*	$N_{b\text{-jet},(p_T>20\ \text{GeV})} = 0$ $m_{\ell\ell} < 80\ GeV$ no p_T^{miss} requirement $\Delta\phi_{\ell\ell} > 2.8$	$\max\left(m_T^{\ell}\right) > 50\ GeV$ $m_{\tau\tau} > m_Z - 25\ GeV$	central jet veto outside lepton veto $\lvert m_{\tau\tau} - m_Z \rvert \leq 25\ GeV$

Analysis selection: H→ττ

	$\tau_{\text{lep}}\tau_{\text{lep}}$		$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
	$ee/\mu\mu$	$e\mu$		
	$N_{e/\mu}^{\text{loose}} = 2$, $N_{\tau_{\text{had-vis}}}^{\text{loose}} = 0$		$N_{e/\mu}^{\text{loose}} = 1$, $N_{\tau_{\text{had-vis}}}^{\text{loose}} = 1$	$N_{e/\mu}^{\text{loose}} = 0$, $N_{\tau_{\text{had-vis}}}^{\text{loose}} = 2$
	e/μ : Medium, gradient iso.		e/μ : Medium, gradient iso.	
			$\tau_{\text{had-vis}}$: Medium	$\tau_{\text{had-vis}}$: Tight
	Opposite charge		Opposite charge	Opposite charge
	$m_{\tau\tau}^{\text{coll}} > m_Z - 25\,\text{GeV}$		$m_{\text{T}} < 70\,\text{GeV}$	
	$30 < m_{\ell\ell} < 75\,\text{GeV}$	$30 < m_{\ell\ell} < 100\,\text{GeV}$		
	$E_{\text{T}}^{\text{miss}} > 55\,\text{GeV}$	$E_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$	$E_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$	$E_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$
	$E_{\text{T}}^{\text{miss, hard}} > 55\,\text{GeV}$			
	$\Delta R_{\tau\tau} < 2.0$		$\Delta R_{\tau\tau} < 2.5$	$0.8 < \Delta R_{\tau\tau} < 2.5$
	$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$		$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$	$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$
	$0.1 < x_1 < 1.0$		$0.1 < x_1 < 1.4$	$0.1 < x_1 < 1.4$
	$0.1 < x_2 < 1.0$		$0.1 < x_2 < 1.2$	$0.1 < x_2 < 1.4$
	$p_{\text{T}}^{j_1} > 40\,\text{GeV}$		$p_{\text{T}}^{j_1} > 40\,\text{GeV}$	$p_{\text{T}}^{j_1} > 70\,\text{GeV}, \lvert\eta_{j_1}\rvert < 3.2$
	$N_{b\text{-jets}} = 0$		$N_{b\text{-jets}} = 0$	

Signal Region		Inclusive	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
VBF	High-$p_{\text{T}}^{\tau\tau}$	+9pt$p_{\text{T}}^{j_2} > 30\,\text{GeV}$ $\lvert\Delta\eta_{jj}\rvert > 3$ $m_{jj} > 400\,\text{GeV}$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central leptons	—		$p_{\text{T}}^{\tau\tau} > 140\,\text{GeV}$ $\Delta R_{\tau\tau} < 1.5$
	Tight		$m_{jj} > 800\,\text{GeV}$	$m_{jj} > 500\,\text{GeV}$ $p_{\text{T}}^{\tau\tau} > 100\,\text{GeV}$	Not VBF high-$p_{\text{T}}^{\tau\tau}$ $m_{jj} > (1550 - 250 \cdot \lvert\Delta\eta_{jj}\rvert)\,GeV$
	Loose		Not VBF tight		Not VBF high-$p_{\text{T}}^{\tau\tau}$ and not VBF tight
Boosted	High-$p_{\text{T}}^{\tau\tau}$	+1ptNot VBF $p_{\text{T}}^{\tau\tau} > 100\,\text{GeV}$	$p_{\text{T}}^{\tau\tau} > 140\,\text{GeV}$ $\Delta R_{\tau\tau} < 1.5$		
	Low-$p_{\text{T}}^{\tau\tau}$		Not boosted high-$p_{\text{T}}^{\tau\tau}$		

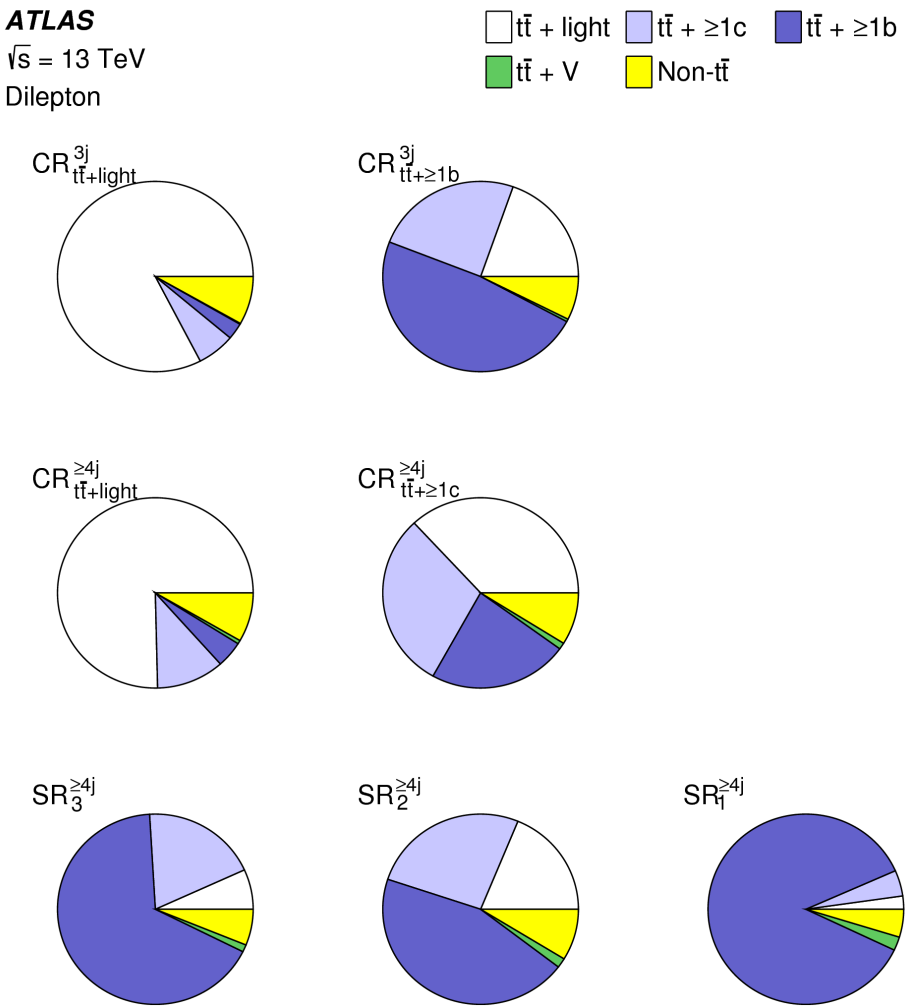
Analysis selection: VH, H→bb

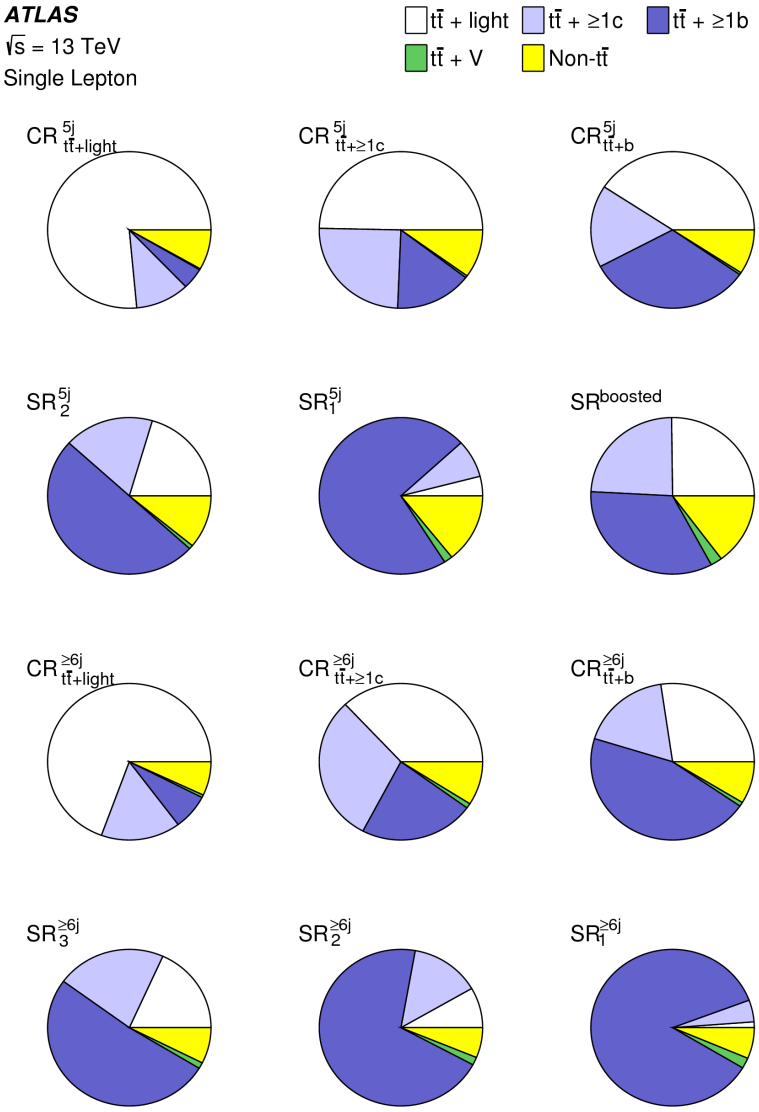
Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b_1}, \vec{b_2})$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–		–
p_{T}^{V} regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Analysis selection: ttH multi-lepton

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(4\ell) - 125\text{ GeV}\rvert > 5$ GeV Split 2 categories: Z-depleted (0 SFOC pairs) and Z-enriched (2 or 4 SFOC pairs)
$1\ell{+}2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
2ℓSS$+1\tau_{\text{had}}$	Two very tight light leptons with $p_{\text{T}} > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV for ee events
2ℓOS$+1\tau_{\text{had}}$	Two loose and isolated light leptons with $p_{\text{T}} > 25, 15$ GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
$3\ell{+}1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_{\text{T}} > 10$ GeV The opposite-charge light lepton must be loose and isolated

Analysis selection: ttH, H→bb





Number of Higgs boson selected in each fb^{-1}

Decay	Total	ggF	VBF	WH	ZH	$t\bar{t}H$+tH
$H \to \gamma\gamma$	46.4	41.1	3.19	0.998	0.676	0.505
$H \to ZZ^*$	1.50	1.24	0.109	0.0316	0.0222	0.104
$H \to WW^*$	42.2	29.8	3.05	0.758	0.209	8.36
$H \to \tau\tau$	17.1	9.31	3.82	0.715	0.419	2.85
$H \to b\bar{b}$	66.0	9.68	9.68	4.81	6.30	35.5
$H \to \mu\mu$	6.67	5.96	0.474	0.143	0.0765	0.0112

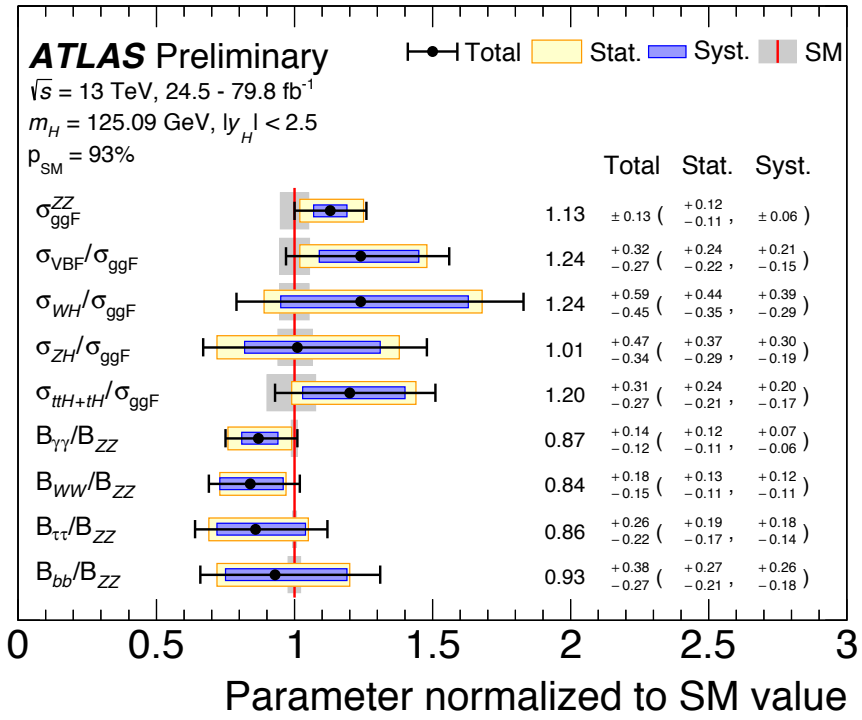
Summary of analyses categories

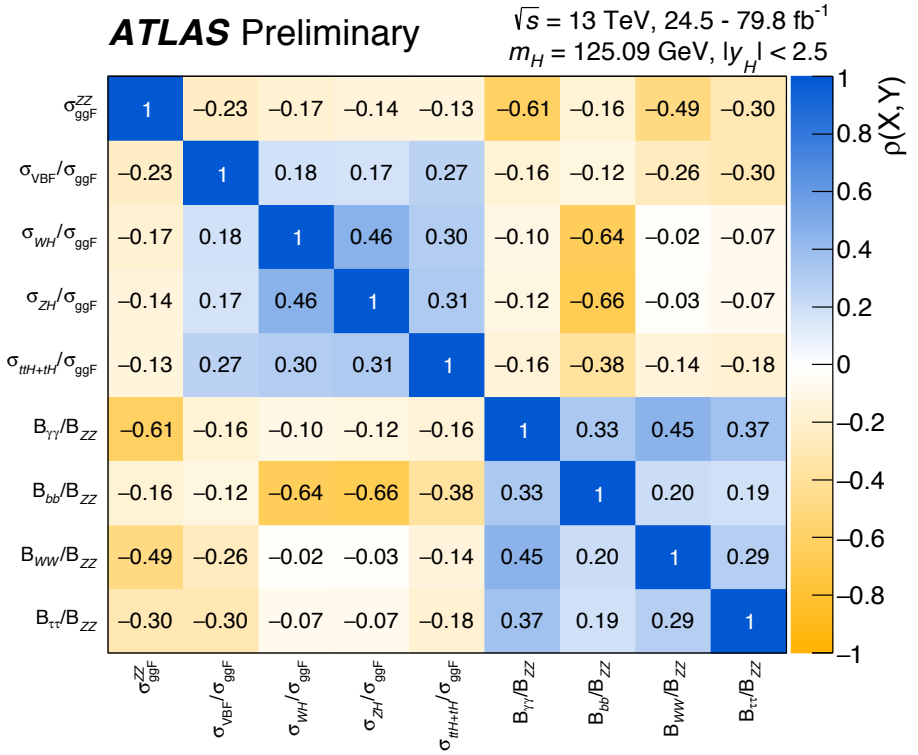
	$H\to\gamma\gamma$	$H\to ZZ^*$	$H\to WW^*$	$H\to\tau\tau$	$H\to b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 ℓ + 2 $\tau_{\rm had}$ $t\bar{t}H$ multilepton 2 opposite-sign ℓ + 1 $\tau_{\rm had}$ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 $\tau_{\rm had}$) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 $\tau_{\rm had}$) $t\bar{t}H$ multilepton 4 ℓ (except $H\to ZZ^*\to 4\ell$) $t\bar{t}H$ leptonic, $H\to ZZ^*\to 4\ell$ $t\bar{t}H$ hadronic, $H\to ZZ^*\to 4\ell$			$t\bar{t}H$ 1 ℓ, boosted $t\bar{t}H$ 1 ℓ, resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ, $p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}}\geq 150$ GeV VH 1 ℓ, $p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}}<150$ GeV VH $E_{\rm T}^{\rm miss}$, $E_{\rm T}^{\rm miss}\geq 150$ GeV VH $E_{\rm T}^{\rm miss}$, $E_{\rm T}^{\rm miss}<150$ GeV VH+VBF $p_{\rm T}^{j1}\geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_{\rm T}^{4\ell}\geq 100$ GeV 2-jet, $m_{jj}<120$ GeV			2 ℓ, $75\leq p_{\rm T}^{V}<150$ GeV, $N_{\rm jets}=2$ 2 ℓ, $75\leq p_{\rm T}^{V}<150$ GeV, $N_{\rm jets}\geq 3$ 2 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=2$ 2 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}\geq 3$ 1 ℓ $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=2$ 1 ℓ $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=3$ 0 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=2$ 0 ℓ, $p_{\rm T}^{V}\geq 150$ GeV, $N_{\rm jets}=3$
VBF	VBF, $p_{\rm T}^{\gamma\gamma jj}\geq 25$ GeV (2 categories) VBF, $p_{\rm T}^{\gamma\gamma jj}<25$ GeV (2 categories)	2-jet VBF, $p_{\rm T}^{j1}\geq 200$ GeV 2-jet VBF, $p_{\rm T}^{j1}<200$ GeV	2-jet VBF	VBF $p_{\rm T}^{\tau\tau}>140$ GeV ($\tau_{\rm had}\tau_{\rm had}$ only) VBF high-m_{jj} VBF low-m_{jj}	VBF, two central jets VBF, four central jets VBF $+\gamma$
ggF	2-jet, $p_{\rm T}^{\gamma\gamma}\geq 200$ GeV 2-jet, 120 GeV $\leq p_{\rm T}^{\gamma\gamma}$ ¡200 GeV 2-jet, 60 GeV $\leq p_{\rm T}^{\gamma\gamma}$ ¡120 GeV 2-jet, $p_{\rm T}^{\gamma\gamma}<60$ GeV 1-jet, $p_{\rm T}^{\gamma\gamma}\geq 200$ GeV 1-jet, 120 GeV $\leq p_{\rm T}^{\gamma\gamma}$ ¡200 GeV 1-jet, 60 GeV $\leq p_{\rm T}^{\gamma\gamma}$ ¡120 GeV 1-jet, $p_{\rm T}^{\gamma\gamma}<60$ GeV 0-jet (2 categories)	1-jet, $p_{\rm T}^{4\ell}\geq 120$ GeV 1-jet, 60 GeV$\leq p_{\rm T}^{4\ell}$ ¡120 GeV 1-jet, $p_{\rm T}^{4\ell}<60$ GeV 0-jet, $p_{\rm T}^{4\ell}<100$ GeV	1-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 1-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV 1-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 1-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV 0-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 0-jet, $m_{\ell\ell}<30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV 0-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}<20$ GeV 0-jet, $m_{\ell\ell}\geq 30$ GeV, $p_{\rm T}^{\ell_2}\geq 20$ GeV	Boosted, $p_{\rm T}^{\tau\tau}>140$ GeV Boosted, $p_{\rm T}^{\tau\tau}\leq 140$ GeV	

Breakdown of uncertainty contributions for inclusive production cross-section measurements

Uncertainty source	$\frac{\Delta\sigma_{\text{ggF}}}{\sigma_{\text{ggF}}}$ [%]	$\frac{\Delta\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}}$ [%]	$\frac{\Delta\sigma_{WH}}{\sigma_{WH}}$ [%]	$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}}$ [%]	$\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}}$ [%]
Statistical uncertainties	6.4	15	21	23	14
Systematic uncertainties	6.2	12	22	17	15
Theory uncertainties	3.4	9.2	14	14	12
Signal	2.0	8.7	5.8	6.7	6.3
Background	2.7	3.0	13	12	10
Experimental uncertainties (excl. MC stat.)	5.0	6.5	9.9	9.6	9.2
Luminosity	2.1	1.8	1.8	1.8	3.1
Background modeling	2.5	2.2	4.7	2.9	5.7
Jets, $E_{\text{T}}^{\text{miss}}$	0.9	5.4	3.0	3.3	4.0
Flavour tagging	0.9	1.3	7.9	8.0	1.8
Electrons, photons	2.5	1.7	1.8	1.5	3.8
Muons	0.4	0.3	0.1	0.2	0.5
τ-lepton	0.2	1.3	0.3	0.1	2.4
Other	2.5	1.2	0.3	1.1	0.8
MC statistical uncertainties	1.6	4.8	8.8	7.9	4.4
Total uncertainties	8.9	19	30	29	21

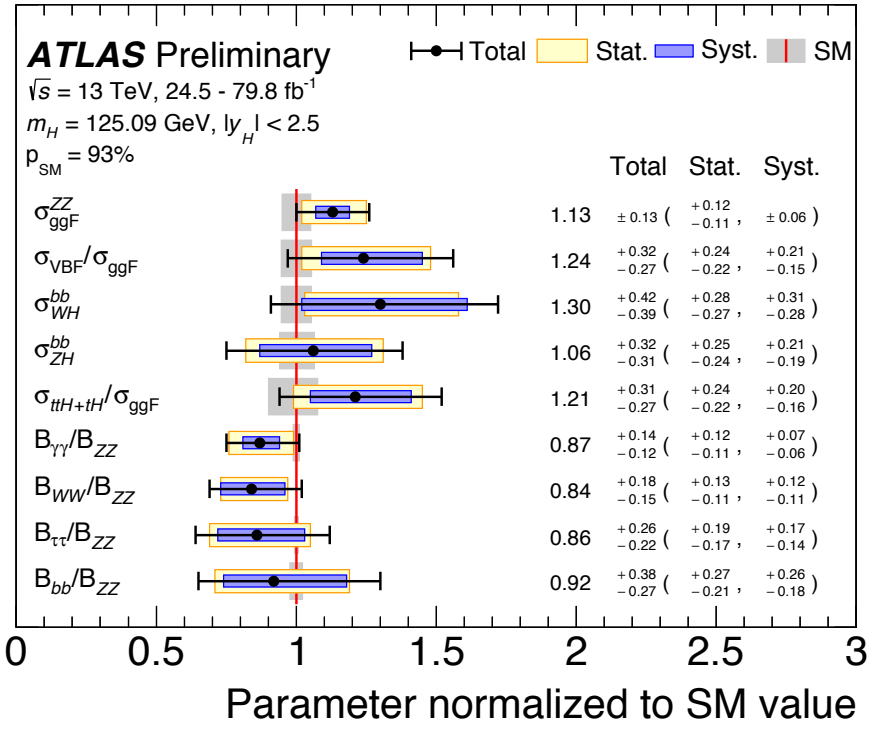
Ratios of cross-sections and BRs

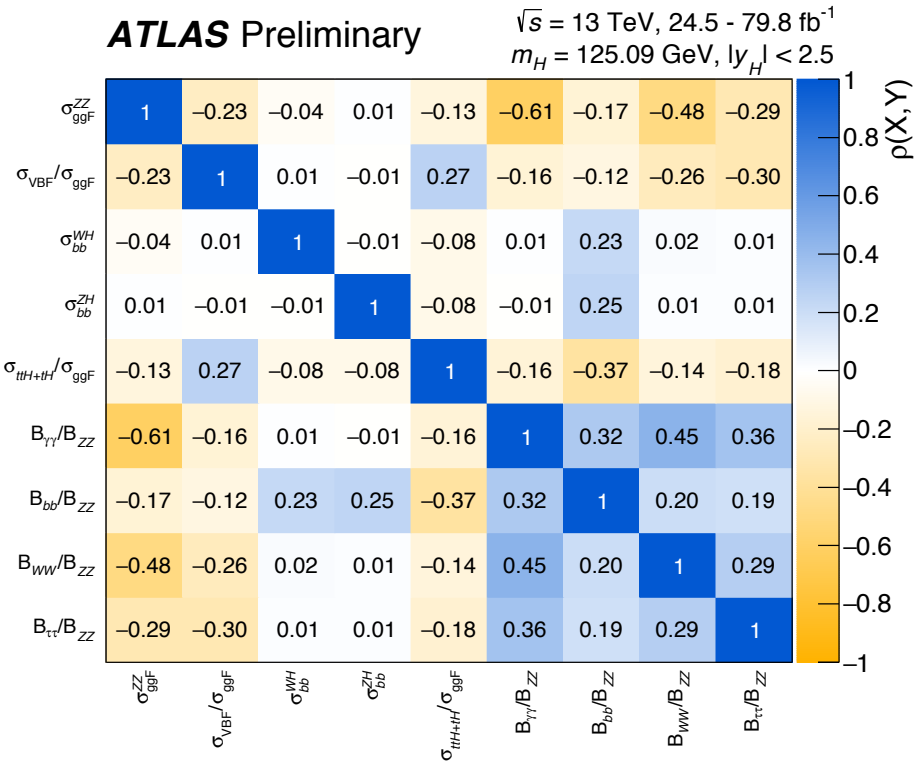




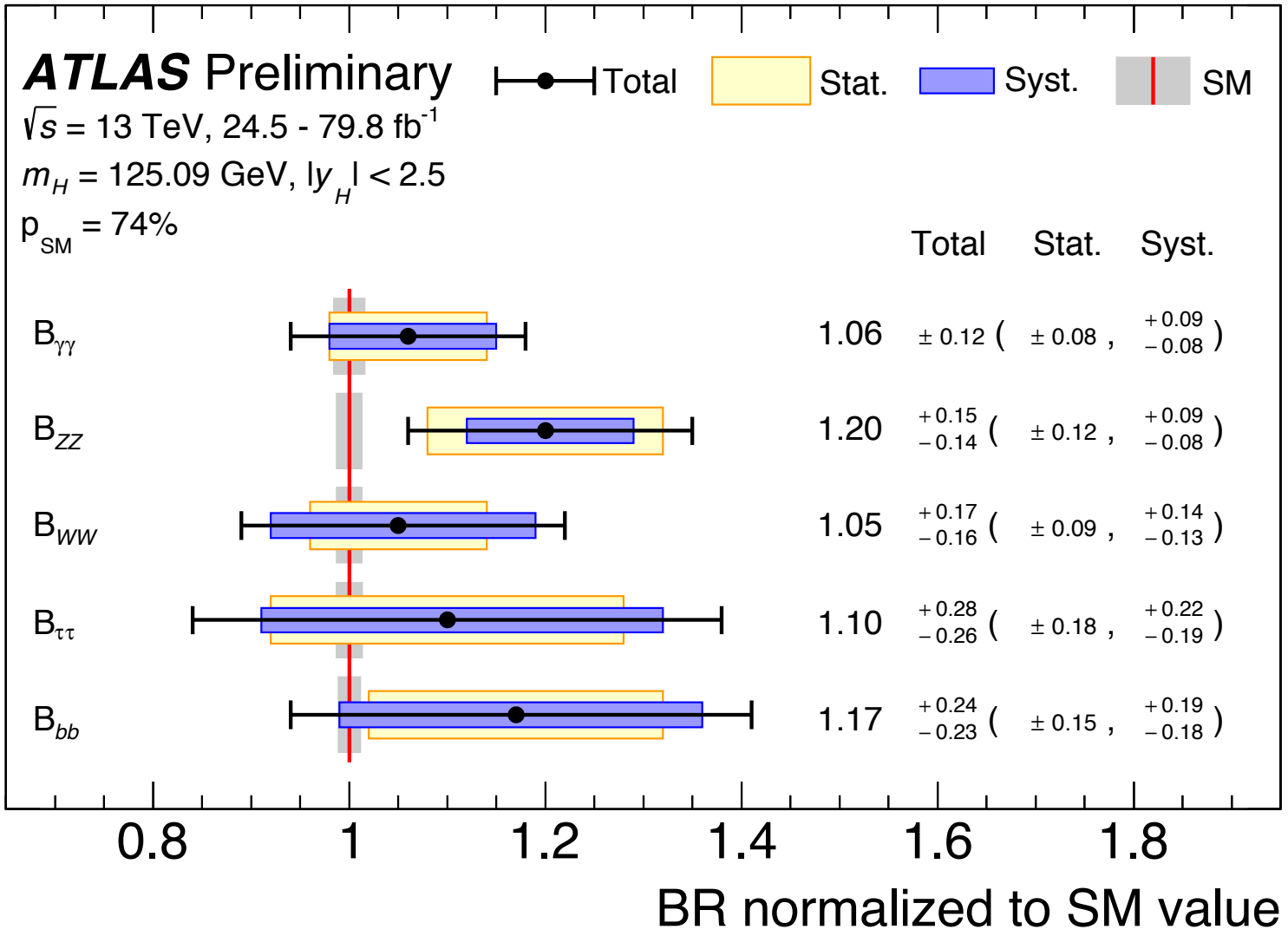
- Use ratios to reduce model dependence, and cancel out common syst.
- ggF cross-section in ZZ channel chosen as normalization basis: ZZ→4l is the cleanest channel, and will dominate the sensitivity with enough stats.
  - However, not necessarily the best choice for current luminosity: e.g. using H→bb to normalize VH could reduce correlations (next slide)

Alternative parameterization for ratios of cross-sections and BRs

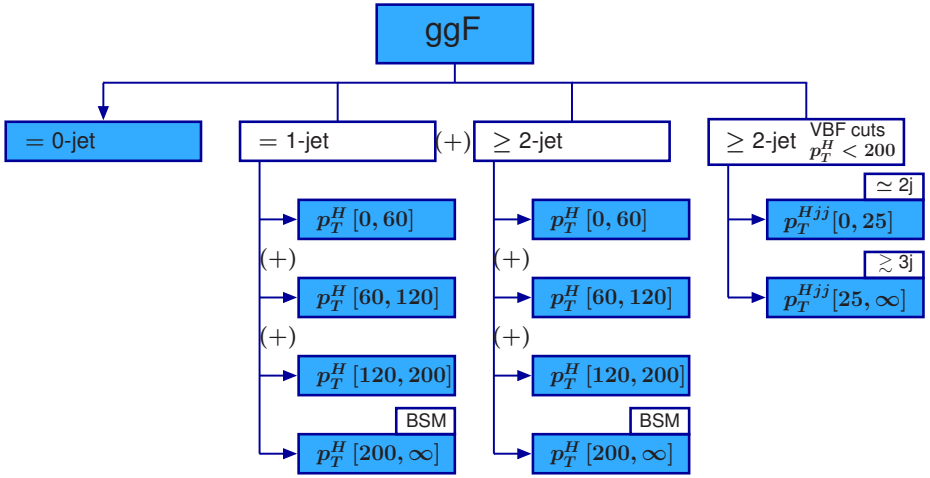


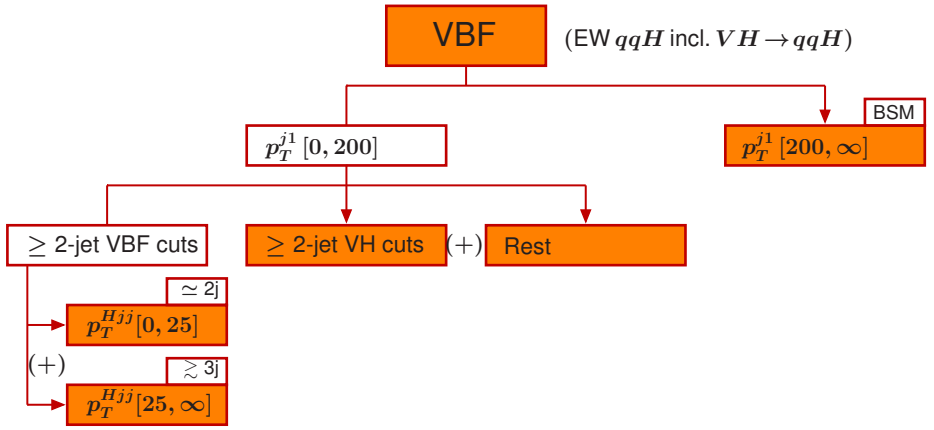


BRs normalized to SM (assuming SM production rate)

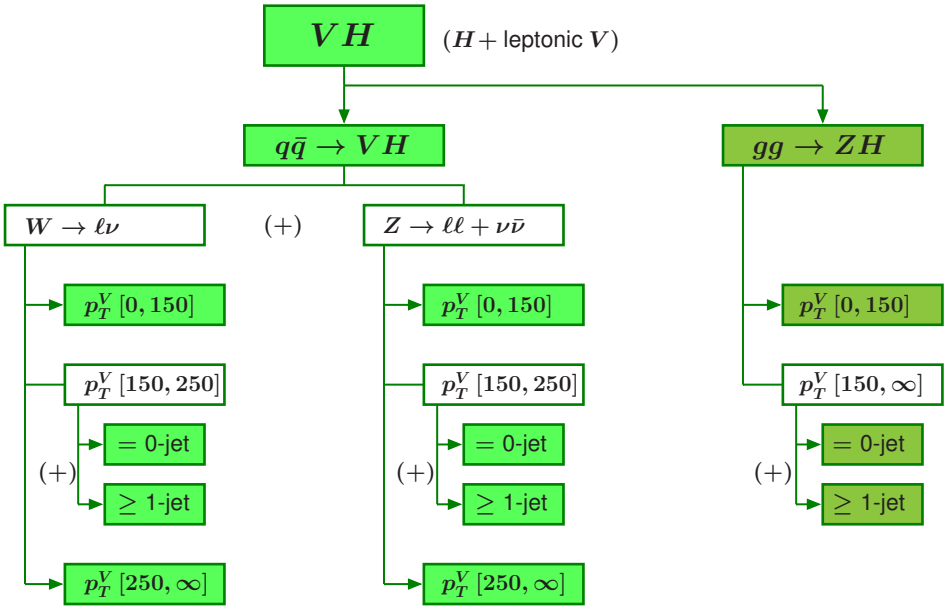


Stage 1 STXS framework

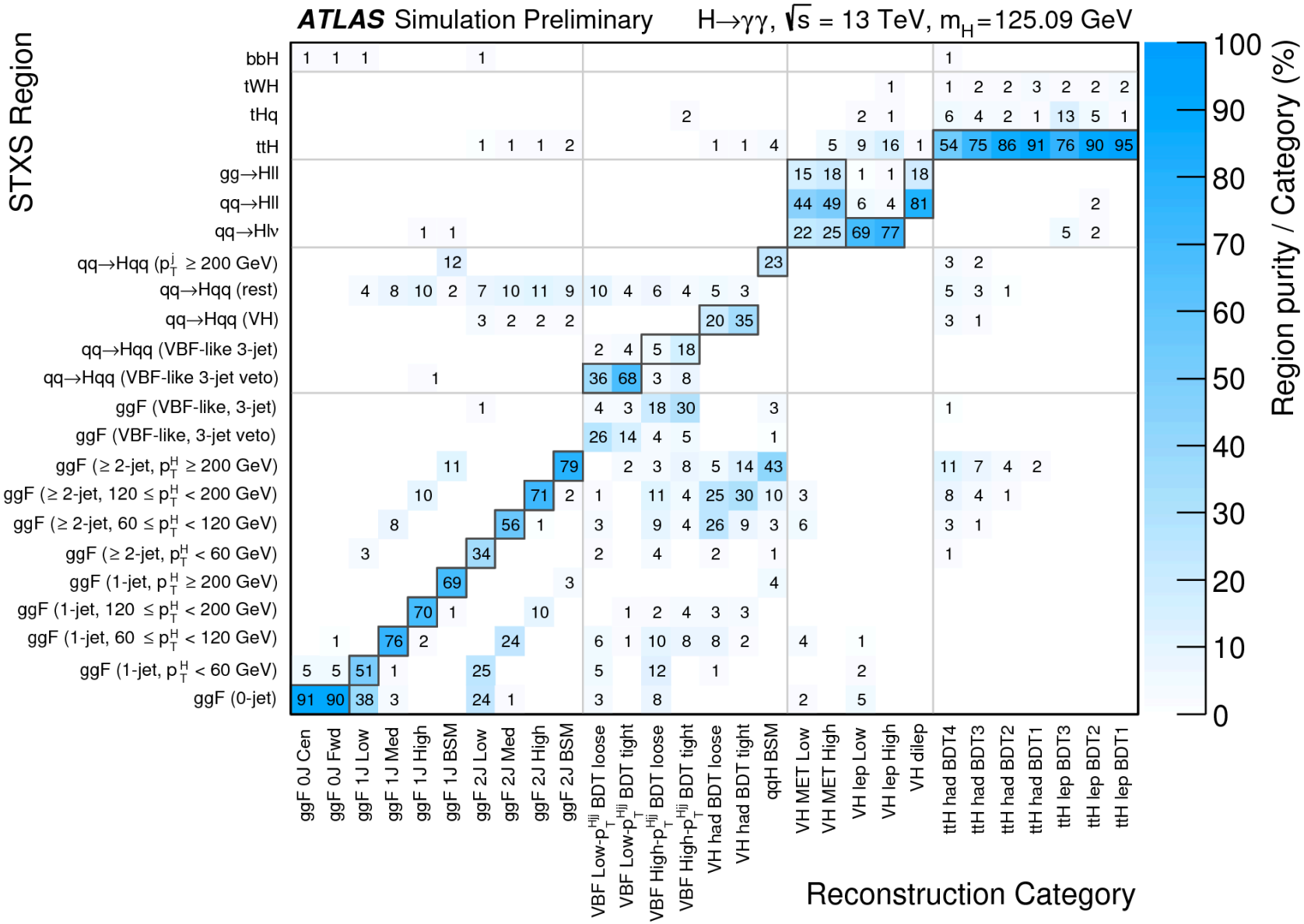




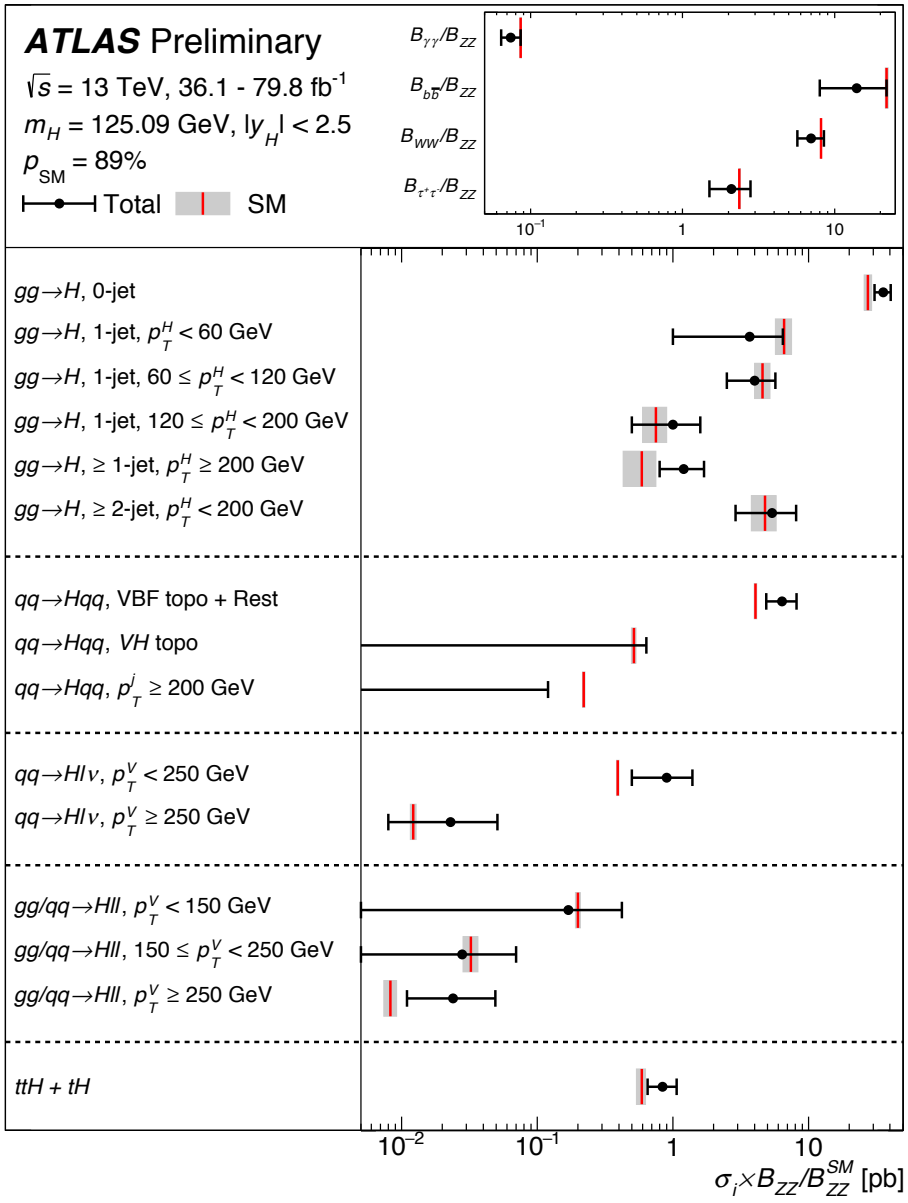
- Only 1 bin for ttH+tH

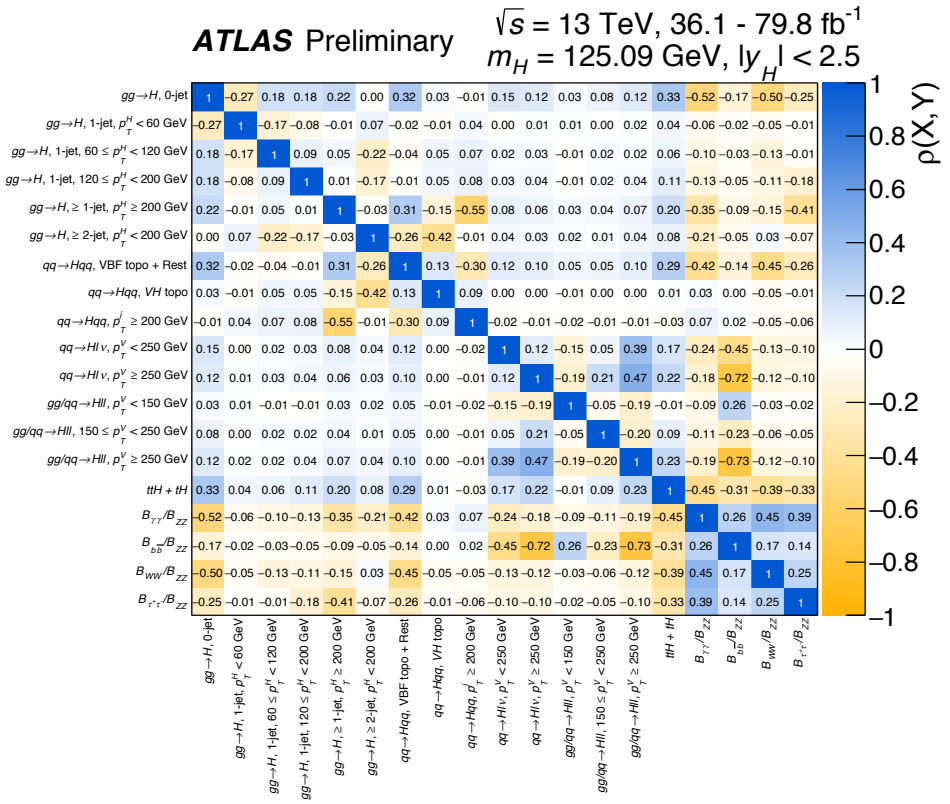


Signal purity split in STXS regions in H→γγ analysis



STXS: floating ratios of BRs





- Normalize all the BRs using B_{ZZ} and measure the ratios
  - Report σxB_{ZZ} instead of σ
- Less model dependence (but more correlations)

Self-coupling interpretation: parameterization

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

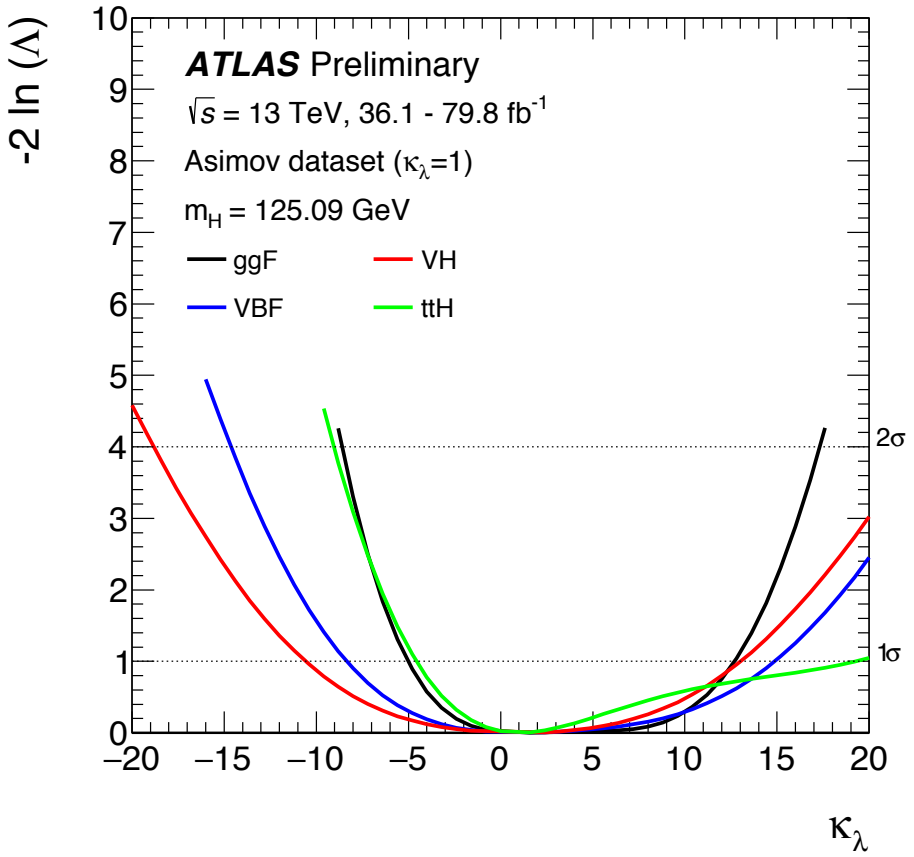
Prod.:

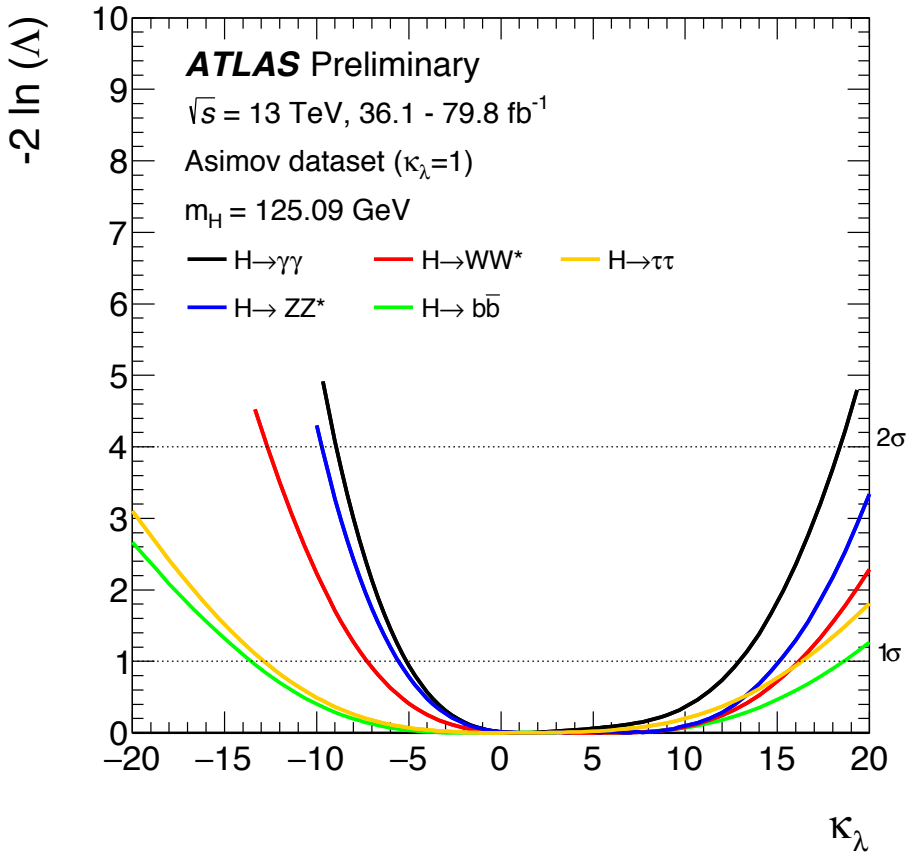
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right] \quad Z_H^{\mathrm{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536 \times 10^{-3}$$

Decay:

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

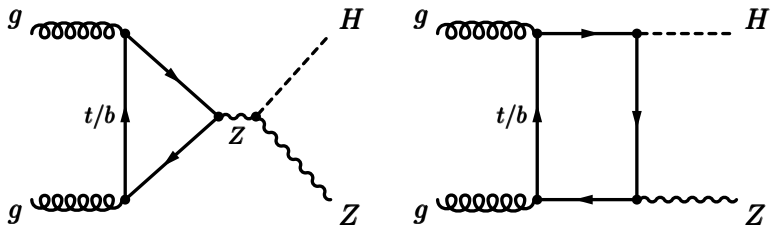
Self-coupling interpretation: dependence on production/decay



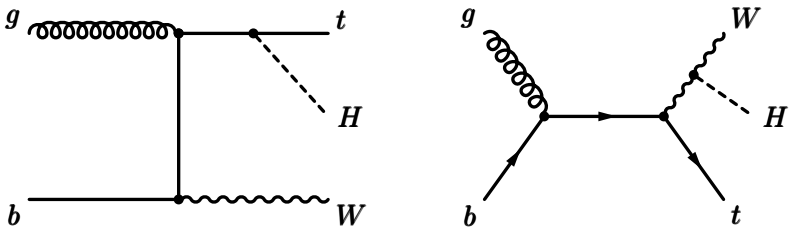


Kappa parameterization

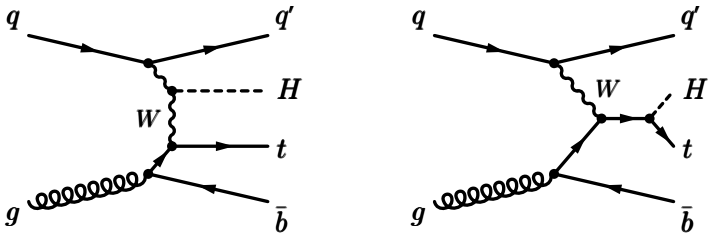
Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	$t-b$	κ_g^2	$1.04\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.04\,\kappa_t\kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73\,\kappa_W^2 + 0.27\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	$t-Z$	$\kappa_{(ggZH)}$	$2.46\,\kappa_Z^2 + 0.46\,\kappa_t^2 - 1.90\,\kappa_Z\kappa_t$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	$t-W$	-	$2.91\,\kappa_t^2 + 2.31\,\kappa_W^2 - 4.22\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	$t-W$	-	$2.63\,\kappa_t^2 + 3.58\,\kappa_W^2 - 5.21\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	$t-b$	κ_g^2	$1.11\,\kappa_t^2 + 0.01\,\kappa_b^2 - 0.12\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (=\kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	$t-W$	κ_γ^2	$1.59\,\kappa_W^2 + 0.07\,\kappa_t^2 - 0.67\,\kappa_W\kappa_t$
$\Gamma^{Z\gamma}$	✓	$t-W$	$\kappa_{(Z\gamma)}^2$	$1.12\,\kappa_W^2 - 0.12\,\kappa_W\kappa_t$
Γ^{ss}	-	-	-	$\kappa_s^2\ (=\kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{inv} = B_{undet} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58\,\kappa_b^2 + 0.22\,\kappa_W^2$ $+0.08\,\kappa_g^2 + 0.06\,\kappa_\tau^2$ $+0.03\,\kappa_Z^2 + 0.03\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$



gg→ZH



tHW

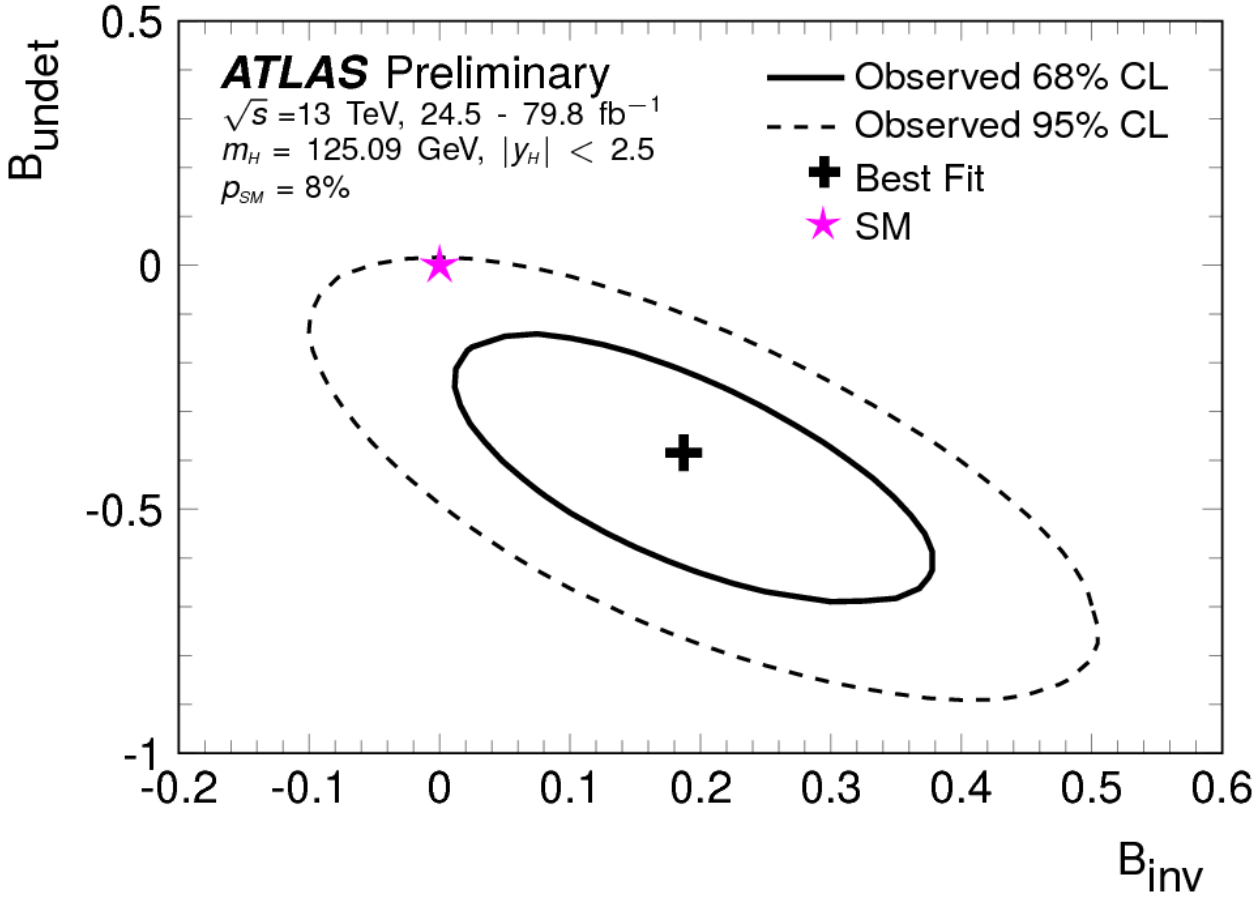


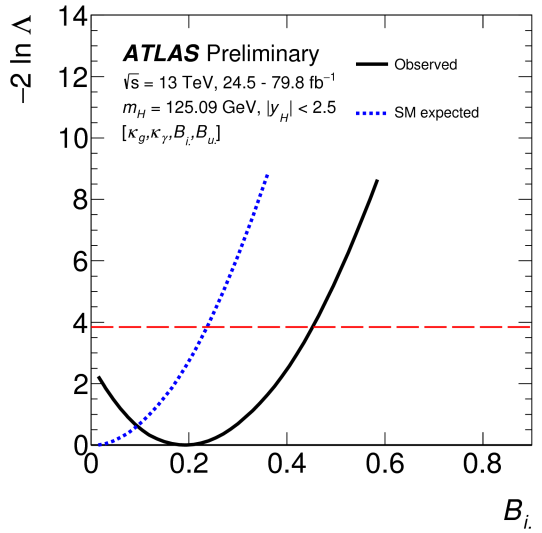
tHq

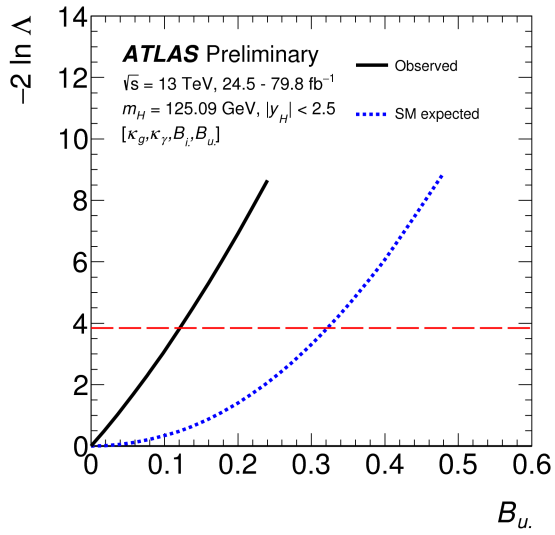
Summary of kappa results from generic model

Parameter	(a) $B_{inv} = B_{undet} = 0$	(b) B_{inv} free, $B_{undet} \geq 0$, $\kappa_{W,Z} \leq 1$	(c) $B_{BSM} \geq 0$, $\kappa_{off} = \kappa_{on}$
κ_Z	1.11 ± 0.08	> 0.87 at 95% CL	$1.16^{+0.18}_{-0.13}$
κ_W	1.05 ± 0.09	> 0.85 at 95% CL	$1.12^{+0.18}_{-0.15}$
κ_b	$1.03^{+0.19}_{-0.17}$	0.88 ± 0.13	$1.08^{+0.25}_{-0.20}$
κ_t	$1.09^{+0.15}_{-0.14}$	$[-1.03, -0.79] \cup [0.93, 1.24]$ at 68% CL	$1.14^{+0.19}_{-0.18}$
κ_τ	$1.05^{+0.16}_{-0.15}$	0.97 ± 0.13	$1.12^{+0.23}_{-0.21}$
κ_γ	1.05 ± 0.09	0.98 ± 0.07	$1.10^{+0.19}_{-0.13}$
κ_g	$0.99^{+0.11}_{-0.10}$	$1.01^{+0.13}_{-0.11}$	$1.02^{+0.22}_{-0.13}$
B_{inv}	-	< 0.30 at 95% CL	-
B_{undet}	-	< 0.22 at 95% CL	-
B_{BSM}	-	-	< 0.47 at 95% CL

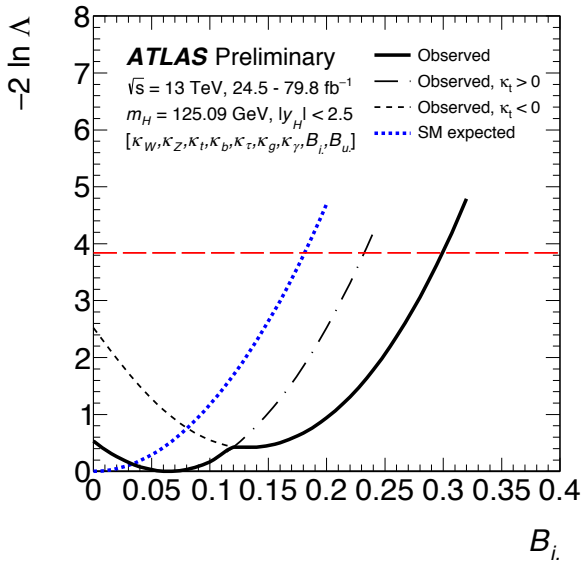
Likelihood scans for inv./undet. BRs

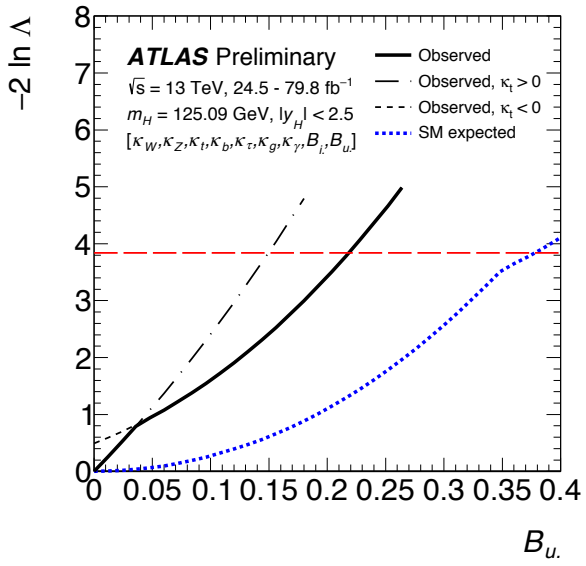


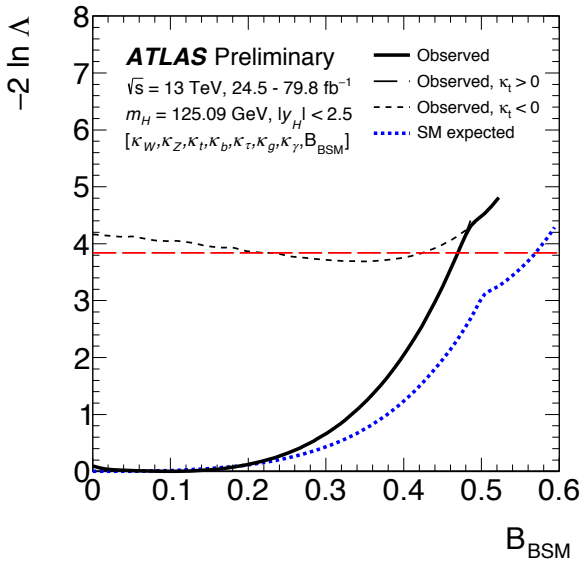




Likelihood scans for inv./undet. BRs (cont'd)

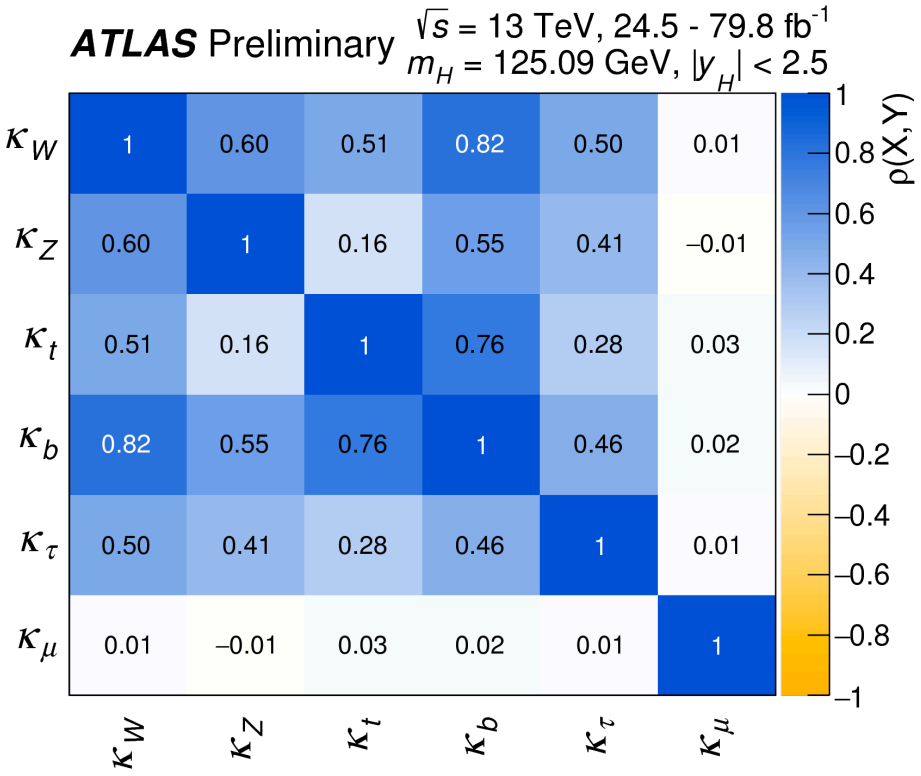


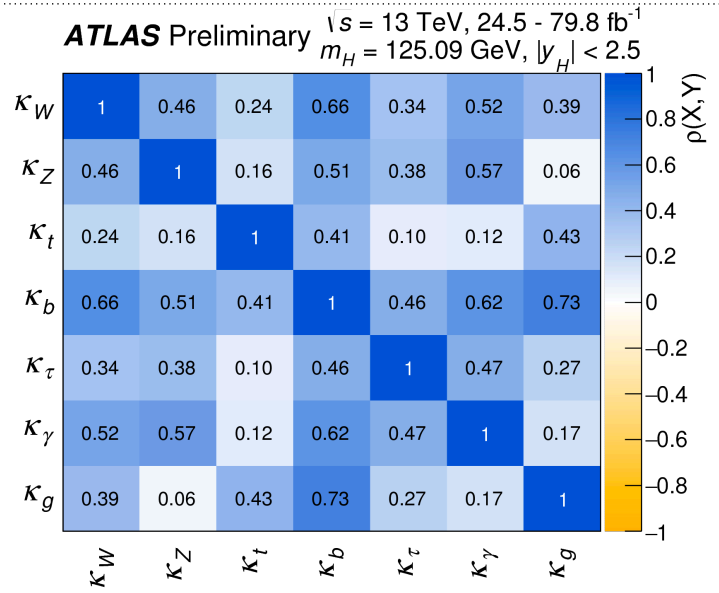


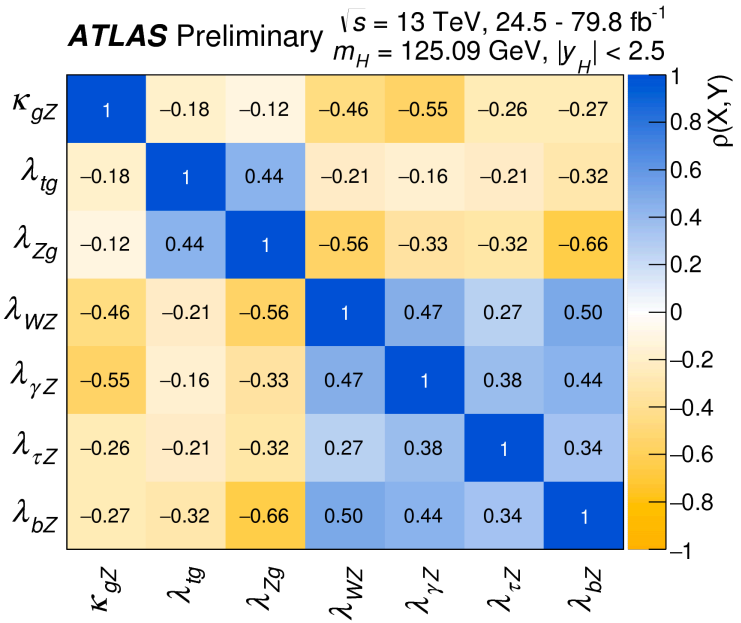


- Need to consider both $\kappa_t>0$ and $\kappa_t<0$ branches in the generic parameterization

Correlation matrices for kappa results

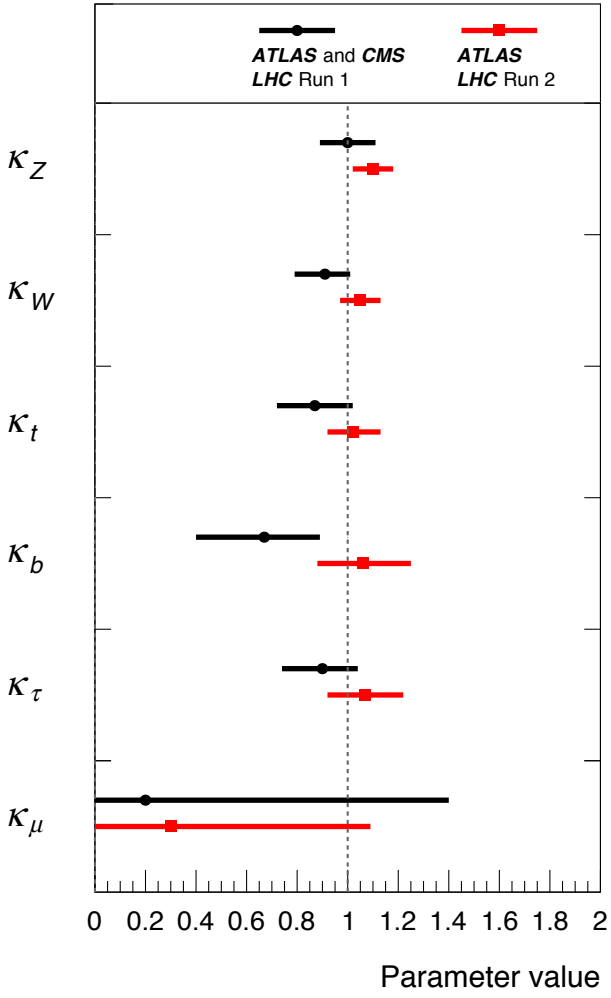


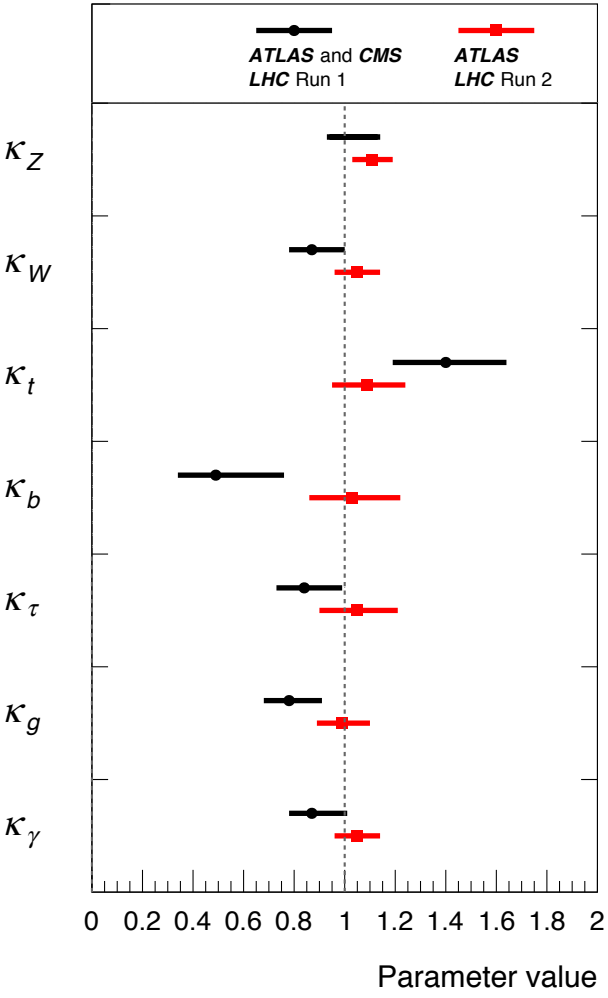


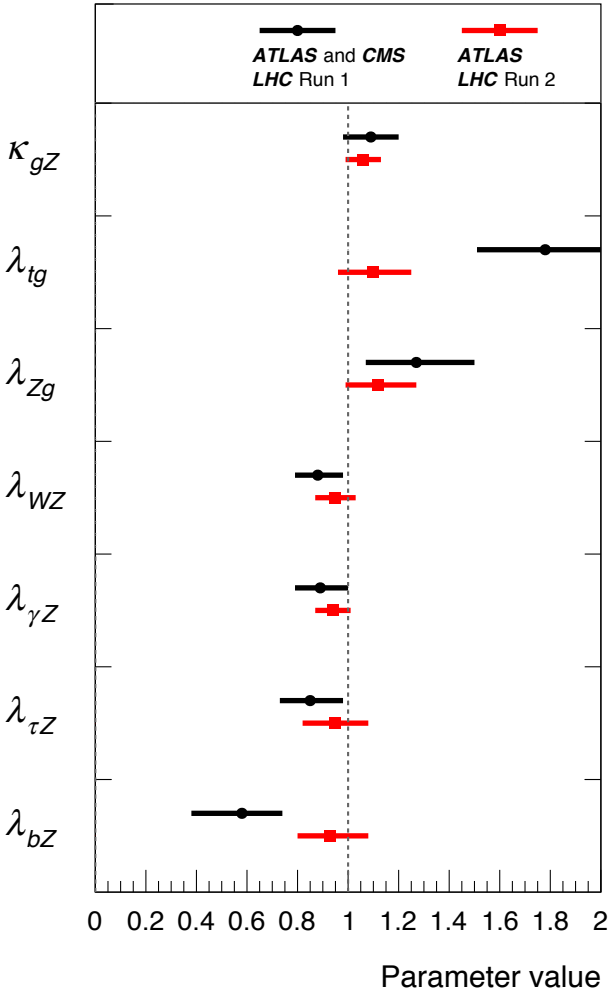


- Strong correlations between parameters

Kappa results comparison with Run 1



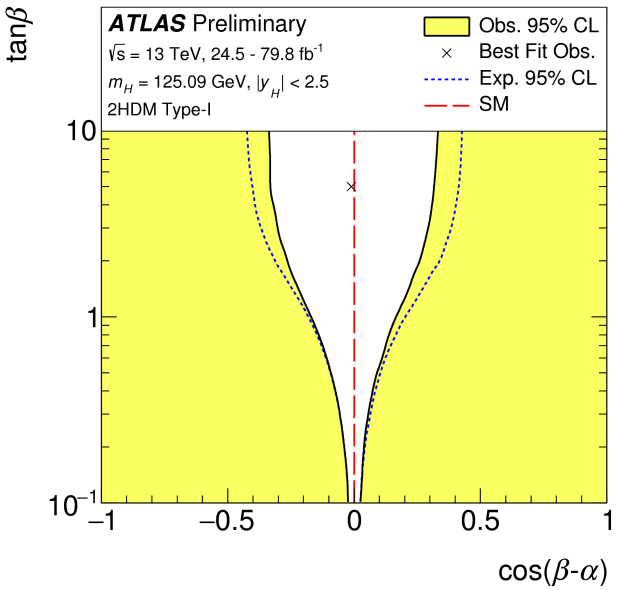


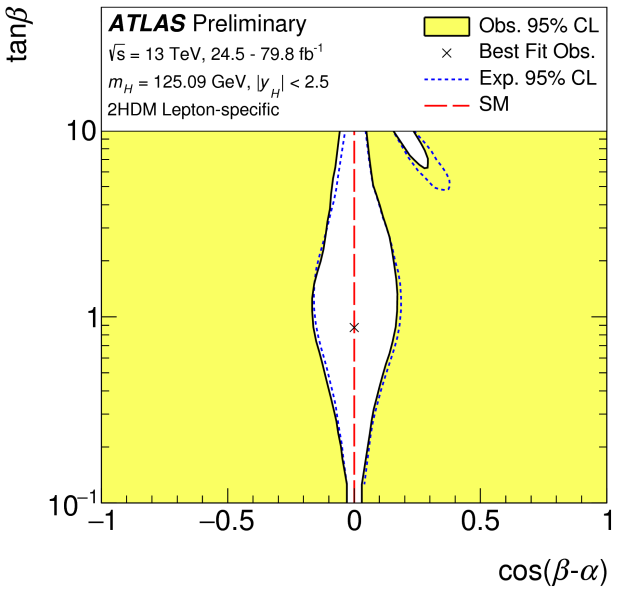


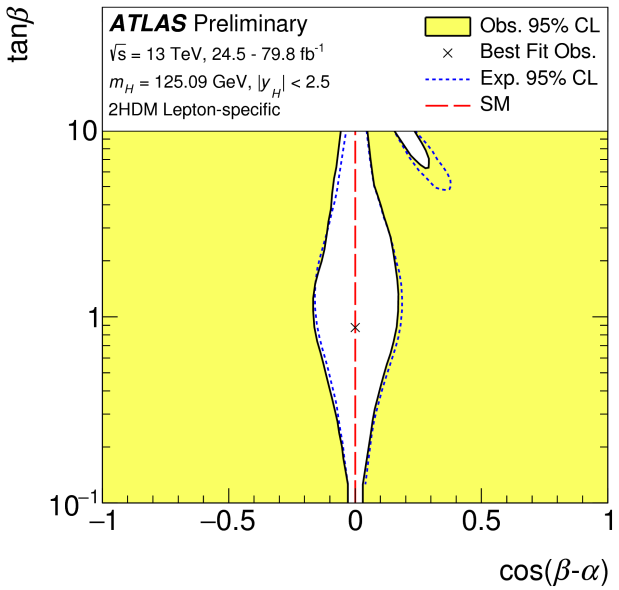
- Significant improvement of precision compared with Run 1 legacy results

✳ $\sigma(ggF)_{SM}$ used in Run 1 is 10% lower compared with updated value used in Run 2

Alternative 2HDM interpretations







Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$