Status and prospects of STXS measurements in ATLAS and CMS

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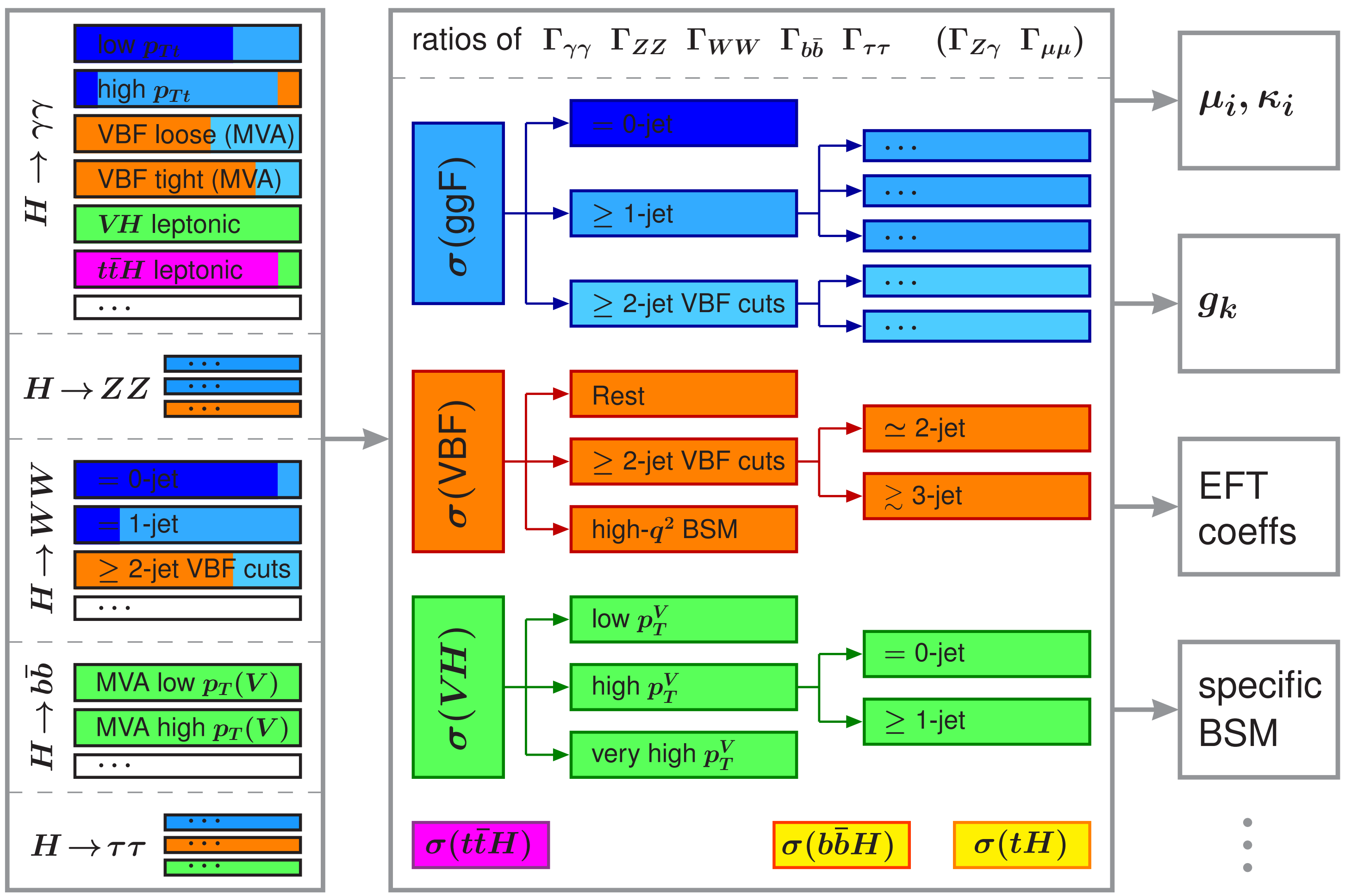
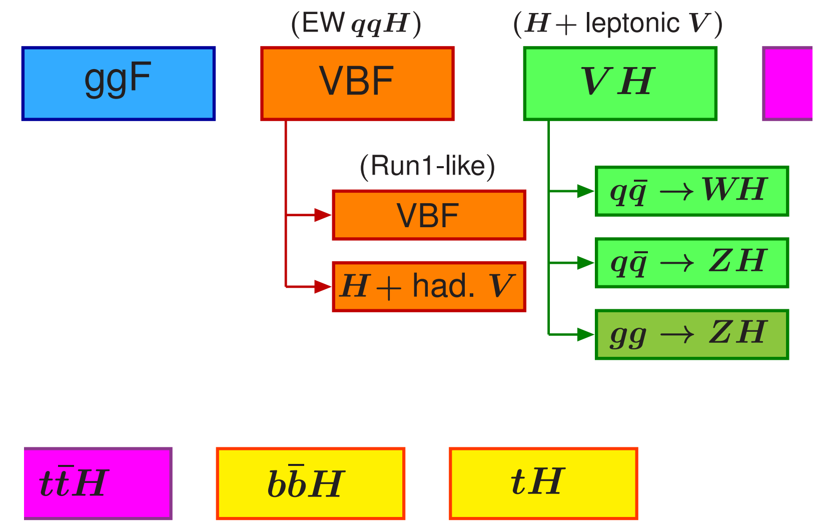
on behalf of the ATLAS and CMS collaborations

May 20, 2019, LHCP, Puebla

Introduction

[1610.07922]



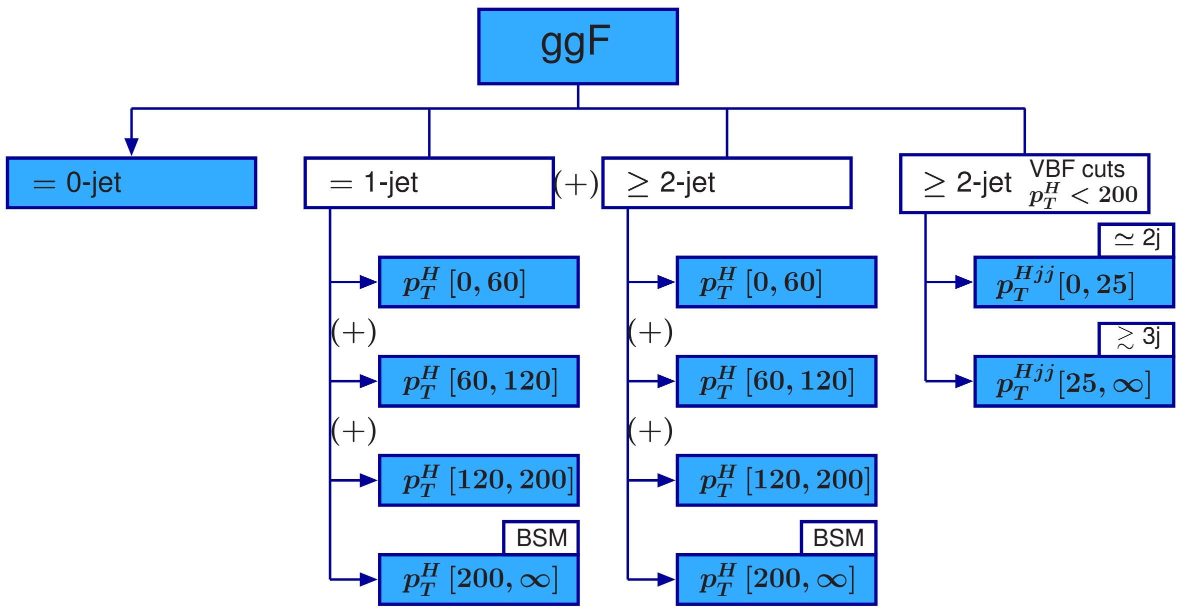


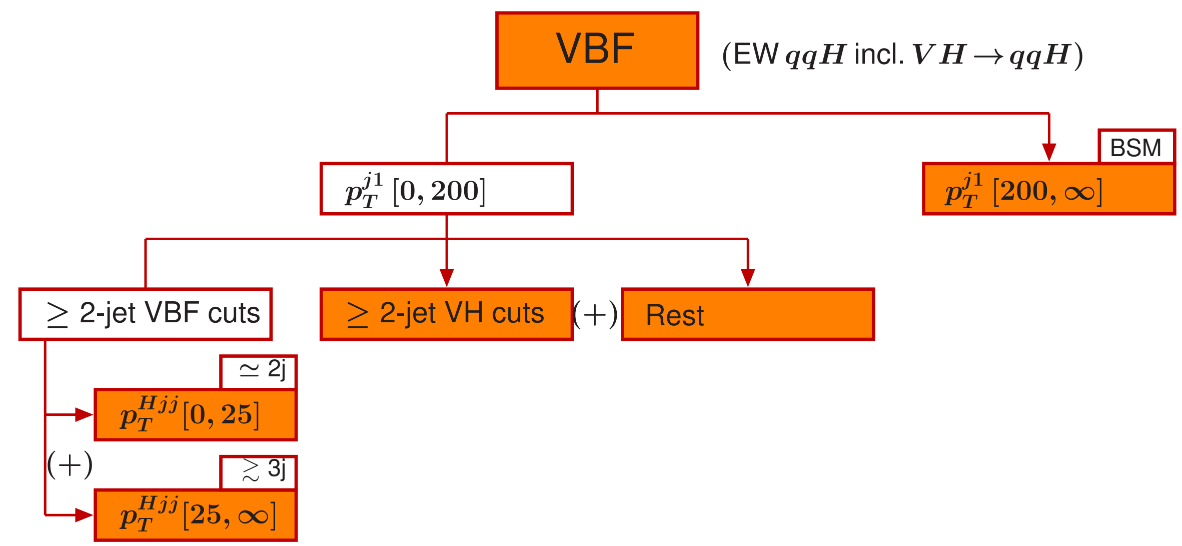
- Bins are split from main production cross sections in $|Y_H| < 2.5$ (Stage 0, Stage 1…)

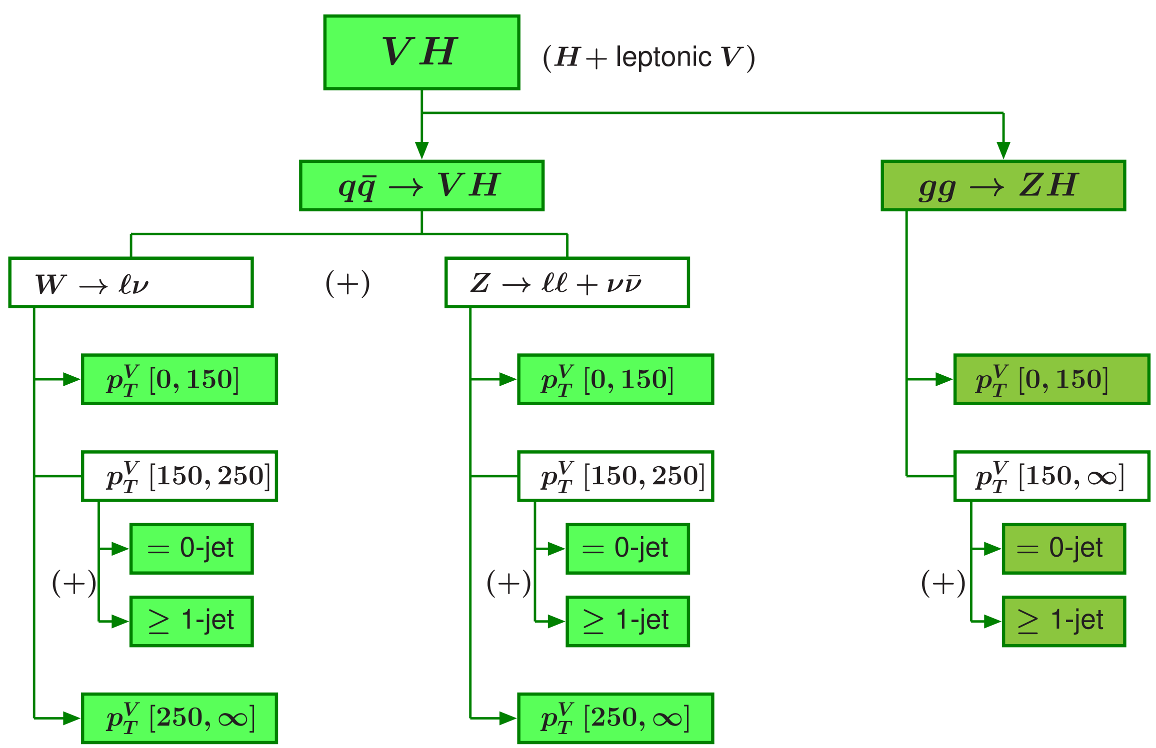
- Simplified template cross sections (STXS) are the Higgs boson production cross sections in exclusive kinematic bins
- Reduce model dependence, maximise sensitivity to new physics, constrain coupling modifiers (κ), EFT coefficients, BSM tests

Stage 1 binning

[1610.07922]







- ggF, VBF, VH bins are split using number of jets and pT
- Possibilities for merging bins are indicated by (+)
- There is revised Stage 1.1 binning to capture more of the VBF kinematic and the low pT gluon fusion [twiki]

In this talk

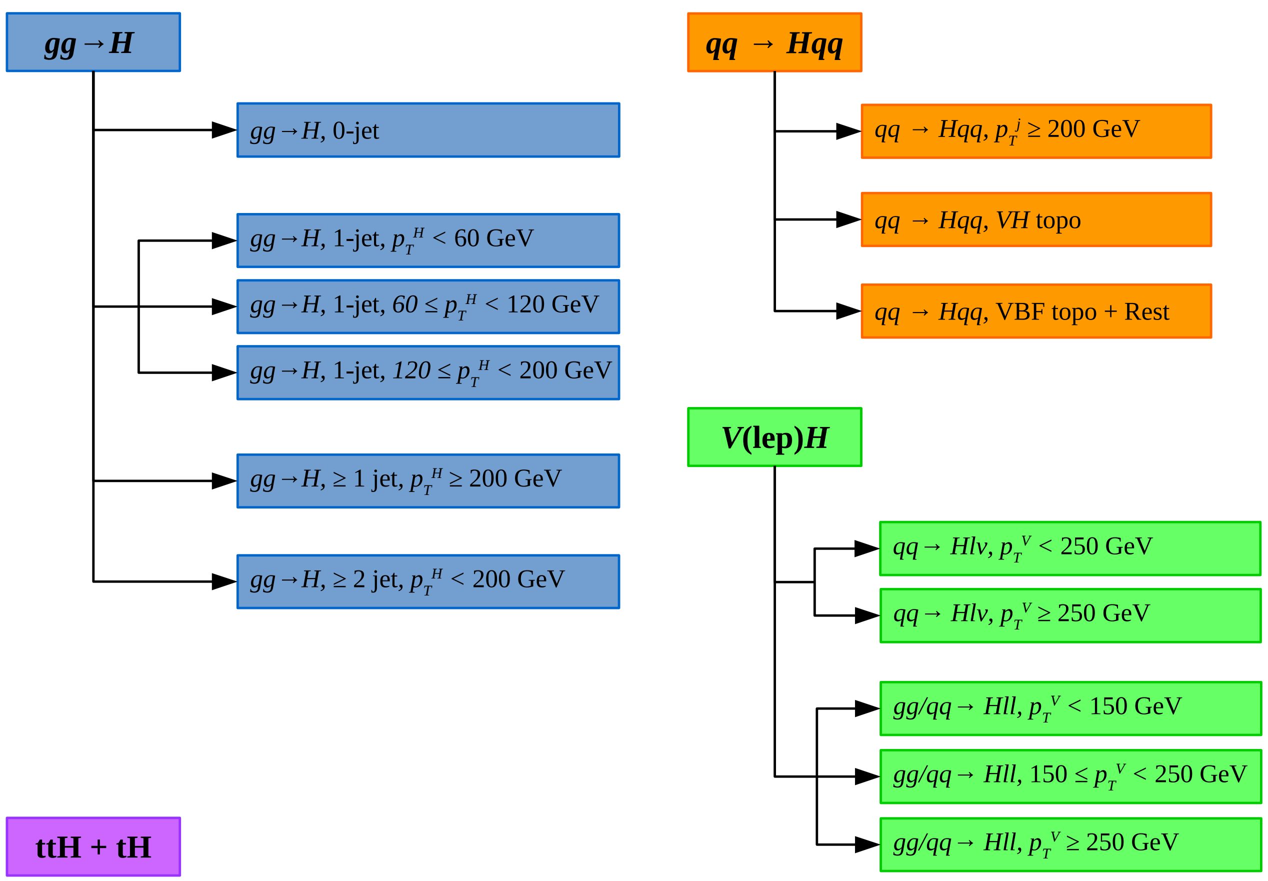
- Following results are covered in this talk:
  - ATLAS combined at 80 fb^{-1} [ATLAS-CONF-2019-005]
  - CMS combined at 36 fb^{-1} [1809.10733]
  - ATLAS self-coupling at 80 fb^{-1} [ATL-PHYS-PUB-2019-009]
  - ATLAS+CMS projections at 3000 fb^{-1} [1902.00134]

- New results in individual channels are covered in Hangtao's talk [link], Markus's talk [link], Luca's talk [link], and John's talk [link]
- List of channels with STXS results:

ATLAS	CMS
ZZ at 80 fb^{-1} [ATLAS-CONF-2018-018]	ZZ at 140 fb^{-1} [CMS-PAS-HIG-19-001]
$\gamma\gamma$ at 80 fb^{-1} [ATLAS-CONF-2018-028]	$\gamma\gamma$ at 80 fb^{-1} [CMS-PAS-HIG-18-029]
bb at 80 fb^{-1} [1903.04618]	$\tau\tau$ at 80 fb^{-1} [CMS-PAS-HIG-18-032]
$\tau\tau$ at 36 fb^{-1} [1811.08856]	WW at 36 fb^{-1} [CMS-PAS-HIG-16-042]

ATLAS combined at 80 fb^{-1}

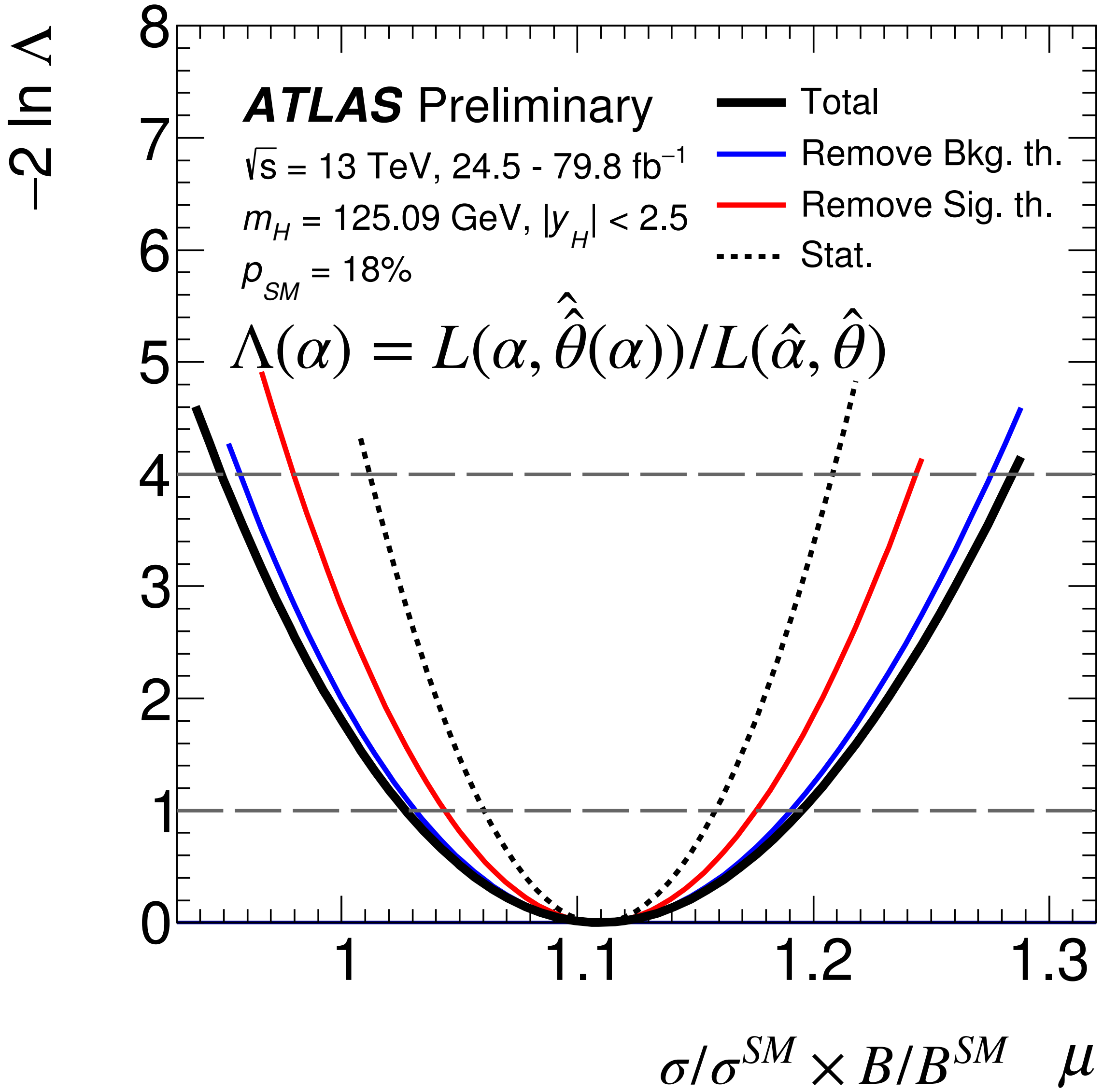
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	79.8
VBF, $H \to b\bar{b}$	24.5 – 30.6
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H \to$ invisible	36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$	36.1



- [ATLAS-CONF-2019-005]
- Reduced Stage 1 inputs except for VBF, H → bb, μμ, invisible and off-shell, which are only used in the κ framework

- ggF signal: Powheg Box NNLOPS, normalised to N³LO QCD with NLO EW corrections
- VBF, VH, (ttH) signal: Powheg Box NLO, normalised to NNLO (NLO) QCD with NLO EW corrections

Global signal strength [ATLAS-CONF-2019-005]

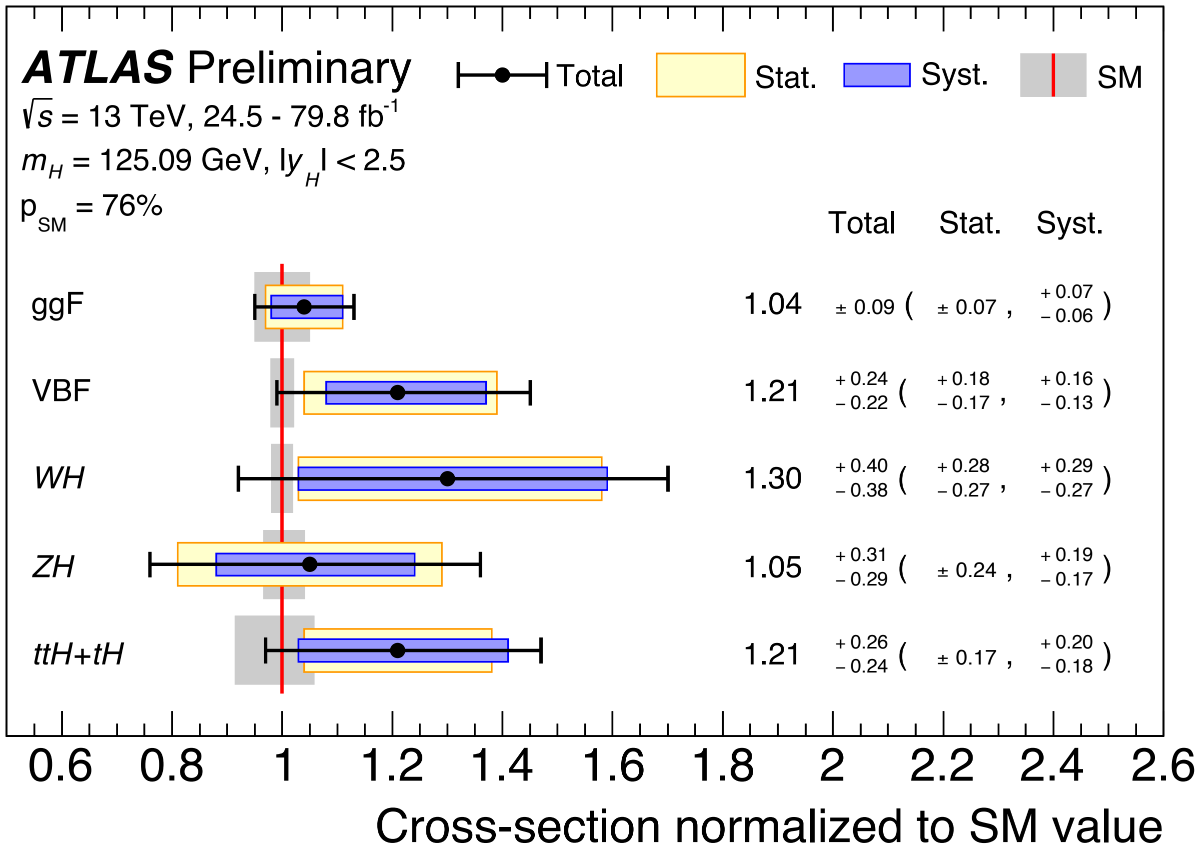


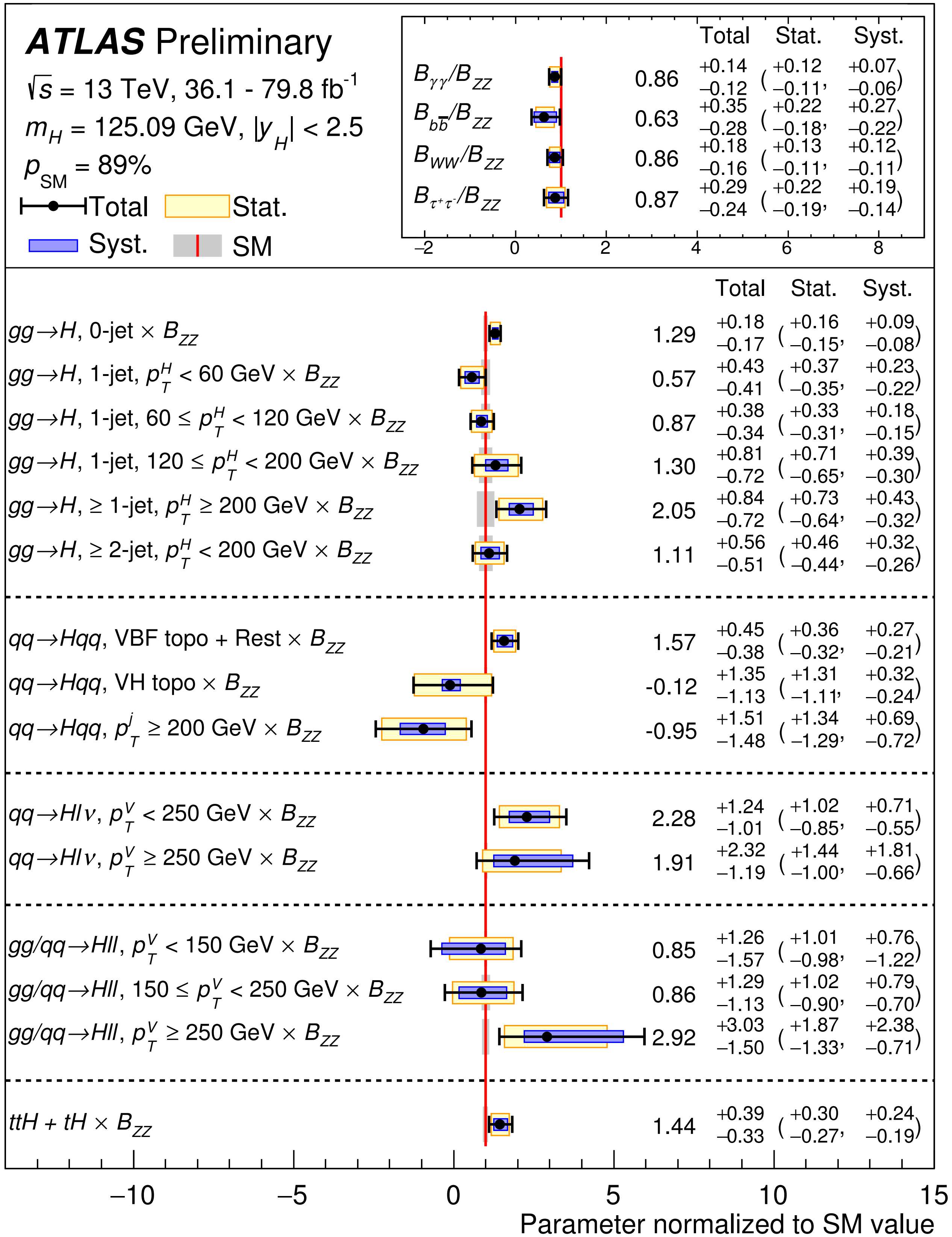
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
→ Signal	4.2
→ Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
→ Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.4
Flavour tagging	1.1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

- $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\ (\mathrm{stat.})\ ^{+0.05}_{-0.04}\ (\mathrm{exp.})\ ^{+0.05}_{-0.04}\ (\mathrm{sig.th.})\ \pm 0.03\ (\mathrm{bkg.th.})$
- Dominant uncertainties: Signal theory (4.2%), background theory (2.6%), photon (2.2%), luminosity (2%)

STXS results

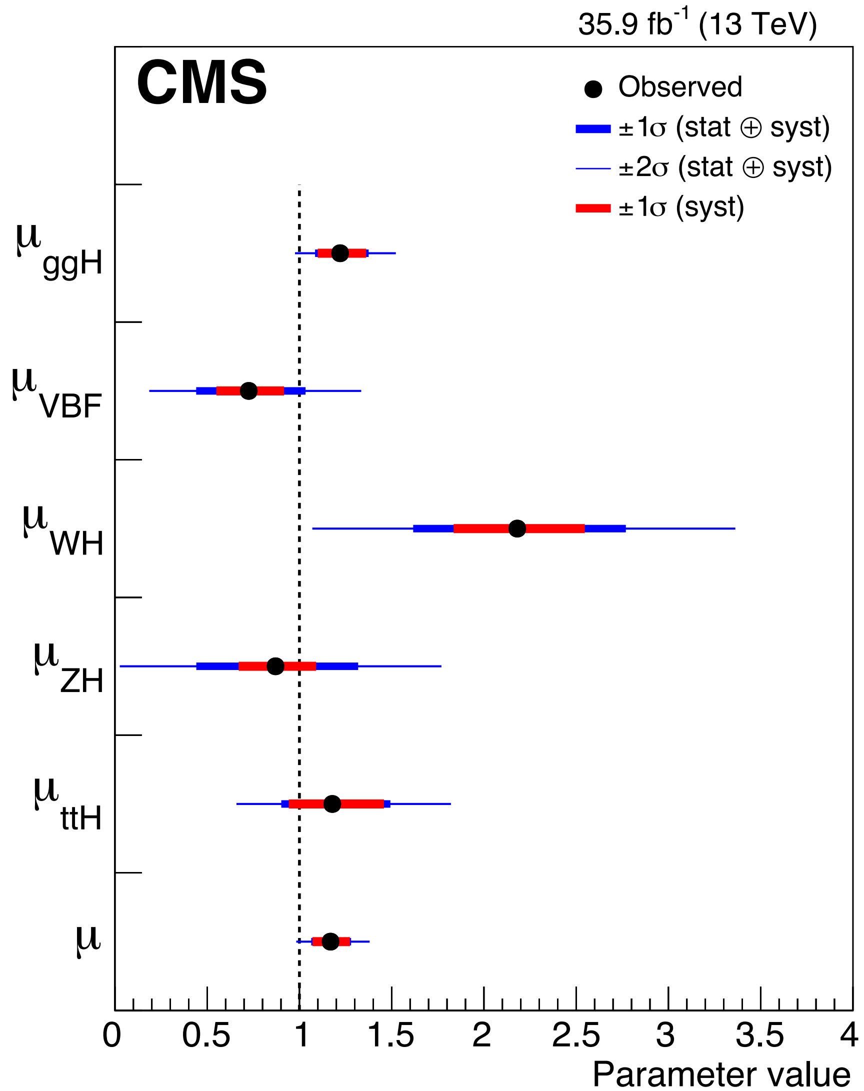
[ATLAS-CONF-2019-005]





- Production cross sections assuming SM branching ratio (left) reduced Stage 1 (right)
- All major production modes are now observed with > 5σ, still limited stat in BSM bins

CMS combined at 36 fb^{-1} [1809.10733]

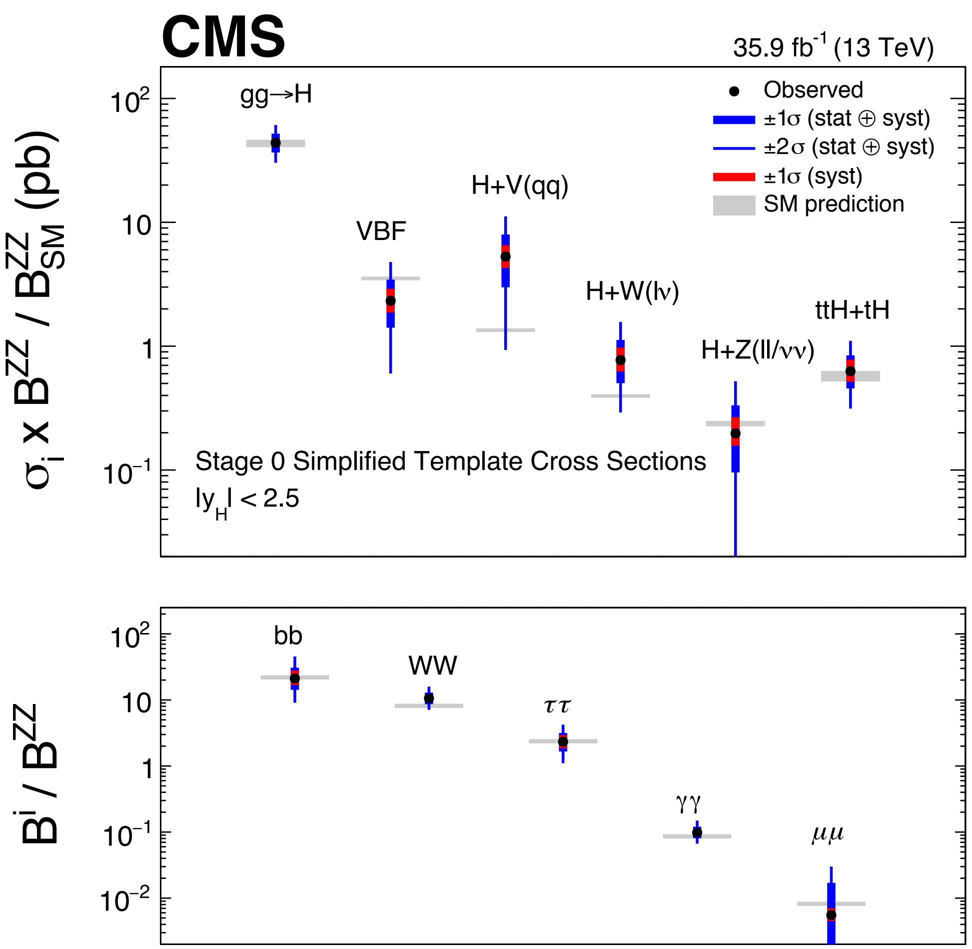


Production process	Best fit value	Uncertainty	stat.	syst.
ggH	1.22	$^{+0.14}_{-0.12}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.12}_{-0.10}$ $\left(^{+0.09}_{-0.08}\right)$
VBF	0.73	$^{+0.30}_{-0.27}$ $\left(^{+0.29}_{-0.27}\right)$	$^{+0.24}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$
WH	2.18	$^{+0.58}_{-0.55}$ $\left(^{+0.53}_{-0.51}\right)$	$^{+0.46}_{-0.45}$ $\left(^{+0.43}_{-0.42}\right)$	$^{+0.34}_{-0.32}$ $\left(^{+0.30}_{-0.29}\right)$
ZH	0.87	$^{+0.44}_{-0.42}$ $\left(^{+0.43}_{-0.41}\right)$	$^{+0.39}_{-0.38}$ $\left(^{+0.38}_{-0.37}\right)$	$^{+0.20}_{-0.18}$ $\left(^{+0.19}_{-0.17}\right)$
ttH	1.18	$^{+0.30}_{-0.27}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.26}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$

- $\mu = 1.17 \pm 0.10 = 1.11 \pm 0.06$ (stat) $^{+0.06}_{-0.05}$ (sig theo) ± 0.06 (other syst)
- Dominant uncertainties: Signal theory (5%), luminosity (2.5%)
- 50% level improvement compared to Run 1 due to increased cross section, improved theory uncertainty, additional event categories

STXS results

[1809.10733]

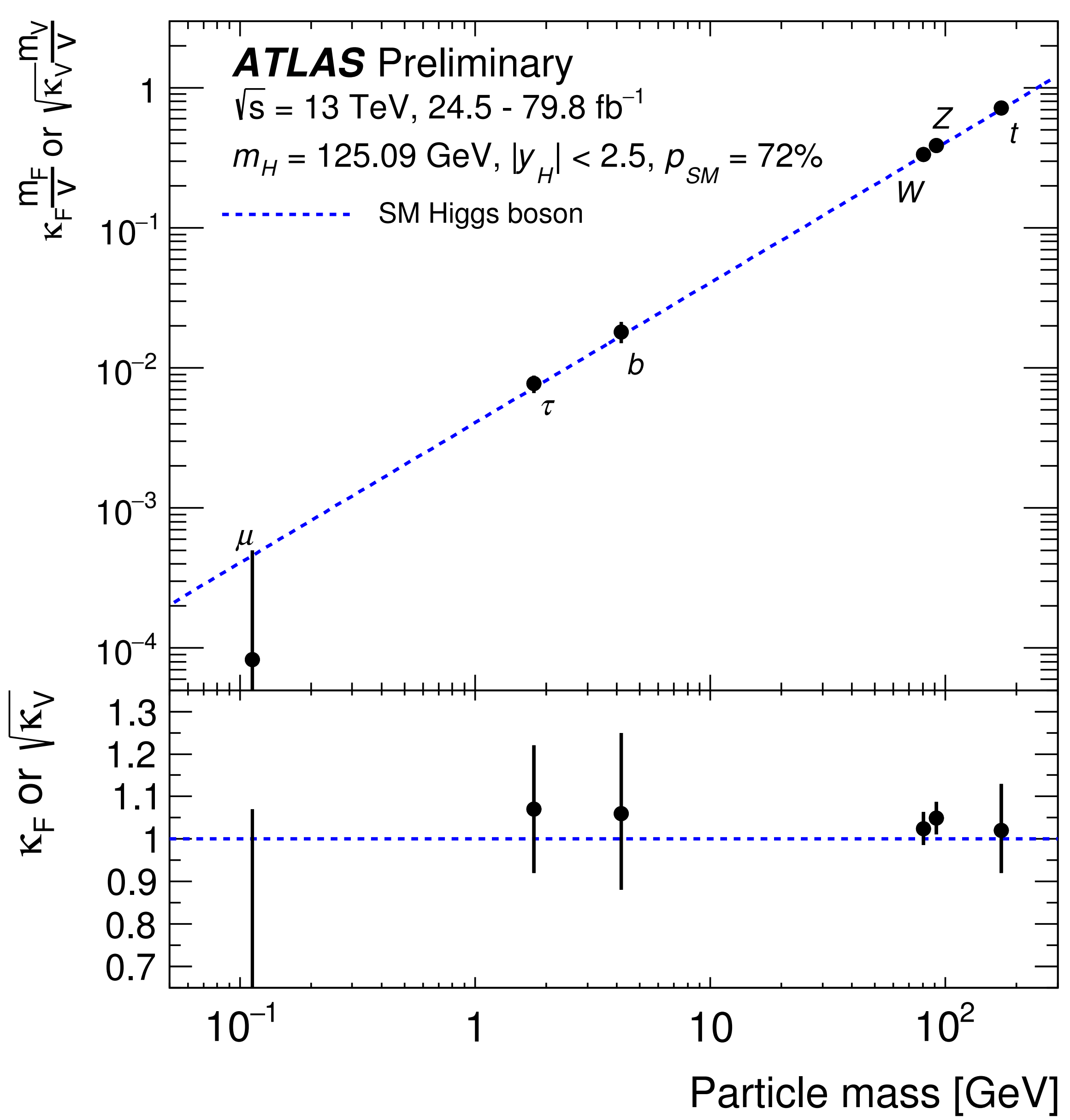


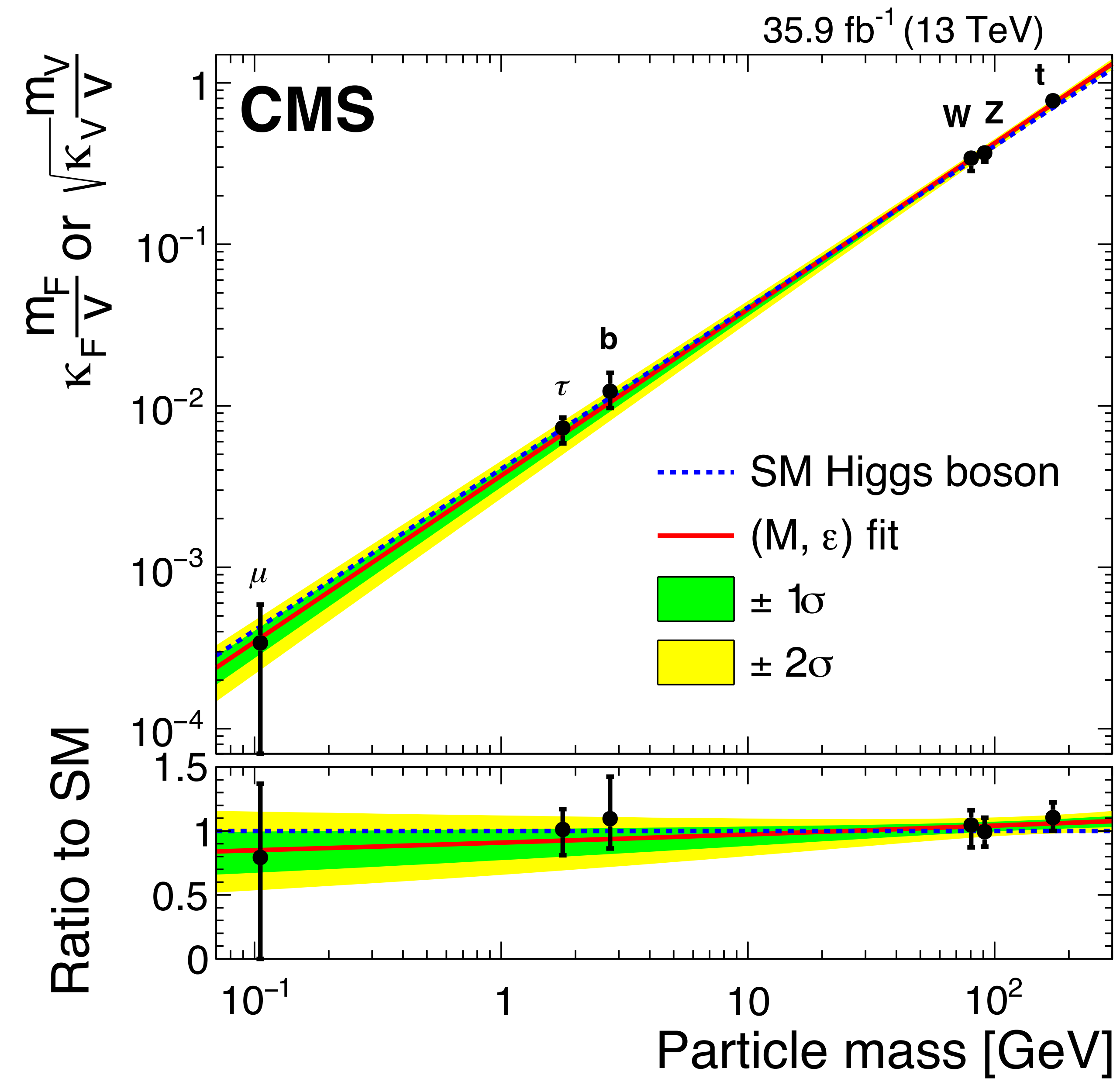
Parameter	Best fit	Uncertainty stat	Uncertainty syst	Parameter	Best fit	Uncertainty stat	Uncertainty syst
$\sigma_{ggH}\mathcal{B}^{ZZ}$	$1.00\,{}^{+0.19}_{-0.16}\,\left({}^{+0.18}_{-0.16}\right)$	${}^{+0.16}_{-0.15}\,\left({}^{+0.16}_{-0.15}\right)$	${}^{+0.09}_{-0.07}\,\left({}^{+0.09}_{-0.07}\right)$	$\mathcal{B}^{bb}/\mathcal{B}^{ZZ}$	$0.96\,{}^{+0.44}_{-0.31}\,\left({}^{+0.57}_{-0.38}\right)$	${}^{+0.32}_{-0.24}\,\left({}^{+0.40}_{-0.29}\right)$	${}^{+0.30}_{-0.20}\,\left({}^{+0.41}_{-0.25}\right)$
$\sigma_{VBF}\mathcal{B}^{ZZ}$	$0.66\,{}^{+0.32}_{-0.26}\,\left({}^{+0.40}_{-0.32}\right)$	${}^{+0.27}_{-0.22}\,\left({}^{+0.33}_{-0.27}\right)$	${}^{+0.17}_{-0.13}\,\left({}^{+0.22}_{-0.16}\right)$	$\mathcal{B}^{\tau\tau}/\mathcal{B}^{ZZ}$	$0.98\,{}^{+0.35}_{-0.28}\,\left({}^{+0.36}_{-0.29}\right)$	${}^{+0.24}_{-0.20}\,\left({}^{+0.26}_{-0.21}\right)$	${}^{+0.25}_{-0.20}\,\left({}^{+0.25}_{-0.19}\right)$
$\sigma_{H+V(qq)}\mathcal{B}^{ZZ}$	$3.93\,{}^{+2.00}_{-1.71}\,\left({}^{+1.66}_{-1.05}\right)$	${}^{+1.77}_{-1.53}\,\left({}^{+1.49}_{-1.05}\right)$	${}^{+0.93}_{-0.75}\,\left({}^{+0.72}_{-0.00}\right)$	$\mathcal{B}^{WW}/\mathcal{B}^{ZZ}$	$1.30\,{}^{+0.29}_{-0.24}\,\left({}^{+0.24}_{-0.20}\right)$	${}^{+0.24}_{-0.20}\,\left({}^{+0.20}_{-0.16}\right)$	${}^{+0.17}_{-0.13}\,\left({}^{+0.14}_{-0.11}\right)$
$\sigma_{H+W(\ell\nu)}\mathcal{B}^{ZZ}$	$1.95\,{}^{+0.88}_{-0.68}\,\left({}^{+0.69}_{-0.52}\right)$	${}^{+0.72}_{-0.57}\,\left({}^{+0.56}_{-0.44}\right)$	${}^{+0.51}_{-0.38}\,\left({}^{+0.40}_{-0.29}\right)$	$\mathcal{B}^{\gamma\gamma}/\mathcal{B}^{ZZ}$	$1.14\,{}^{+0.26}_{-0.20}\,\left({}^{+0.23}_{-0.19}\right)$	${}^{+0.23}_{-0.18}\,\left({}^{+0.21}_{-0.17}\right)$	${}^{+0.13}_{-0.09}\,\left({}^{+0.11}_{-0.08}\right)$
$\sigma_{H+Z(\ell\ell/\nu\nu)}\mathcal{B}^{ZZ}$	$0.84\,{}^{+0.57}_{-0.43}\,\left({}^{+0.71}_{-0.46}\right)$	${}^{+0.49}_{-0.40}\,\left({}^{+0.56}_{-0.41}\right)$	${}^{+0.29}_{-0.17}\,\left({}^{+0.44}_{-0.22}\right)$	$\mathcal{B}^{\mu\mu}/\mathcal{B}^{ZZ}$	$0.67\,{}^{+1.40}_{-1.36}\,\left({}^{+1.35}_{-1.28}\right)$	${}^{+1.39}_{-1.35}\,\left({}^{+1.34}_{-1.28}\right)$	${}^{+0.18}_{-0.13}\,\left({}^{+0.17}_{-0.05}\right)$
$\sigma_{ttH}\mathcal{B}^{ZZ}$	$1.08\,{}^{+0.37}_{-0.30}\,\left({}^{+0.38}_{-0.31}\right)$	${}^{+0.26}_{-0.22}\,\left({}^{+0.28}_{-0.23}\right)$	${}^{+0.26}_{-0.19}\,\left({}^{+0.26}_{-0.20}\right)$				

- Stage 0 STXS and branching ratio with respect to ZZ
- bbH is merged to ggH due to the lack of sensitivity
- qqZH and ggZH are merged because they can not easily be separated
- tH is merged to ttH due to the lack of dedicated analysis

Coupling modifiers

[ATLAS-CONF-2019-005]
[1809.10733]

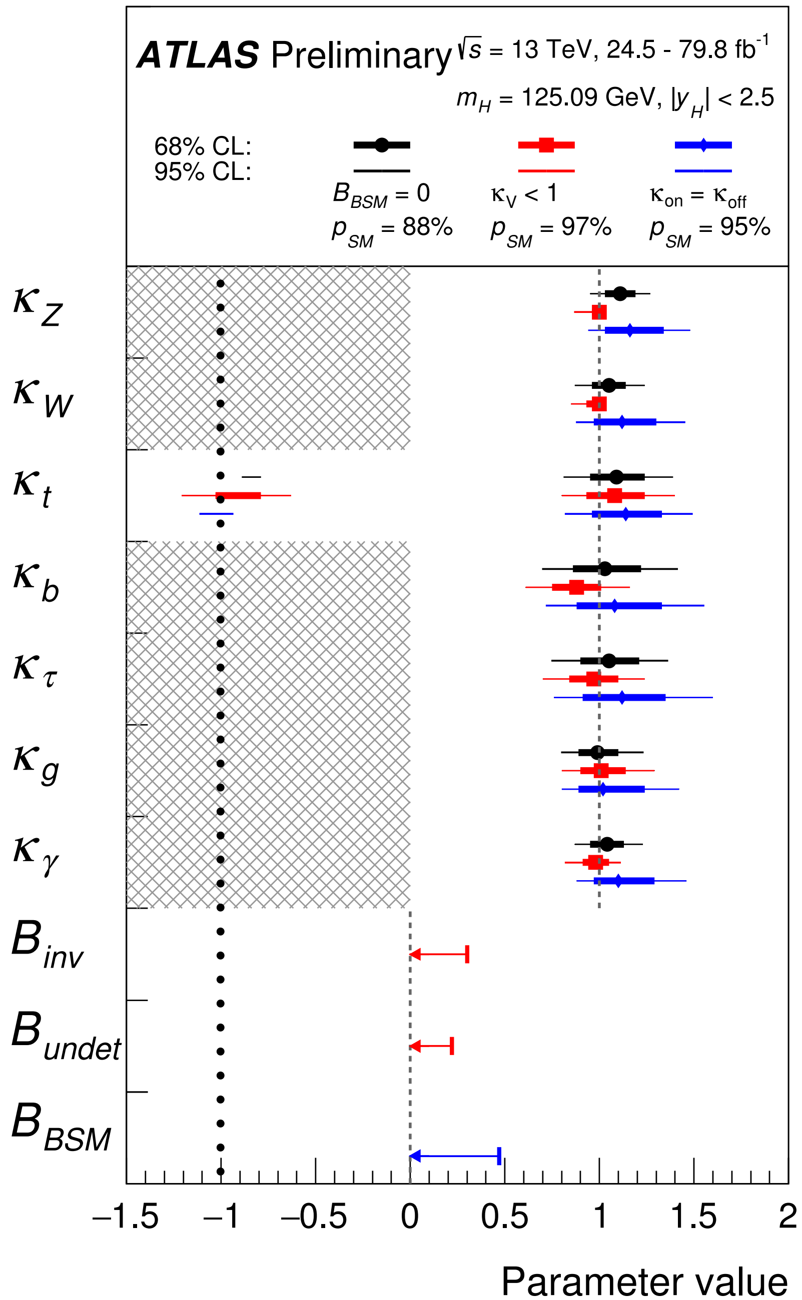


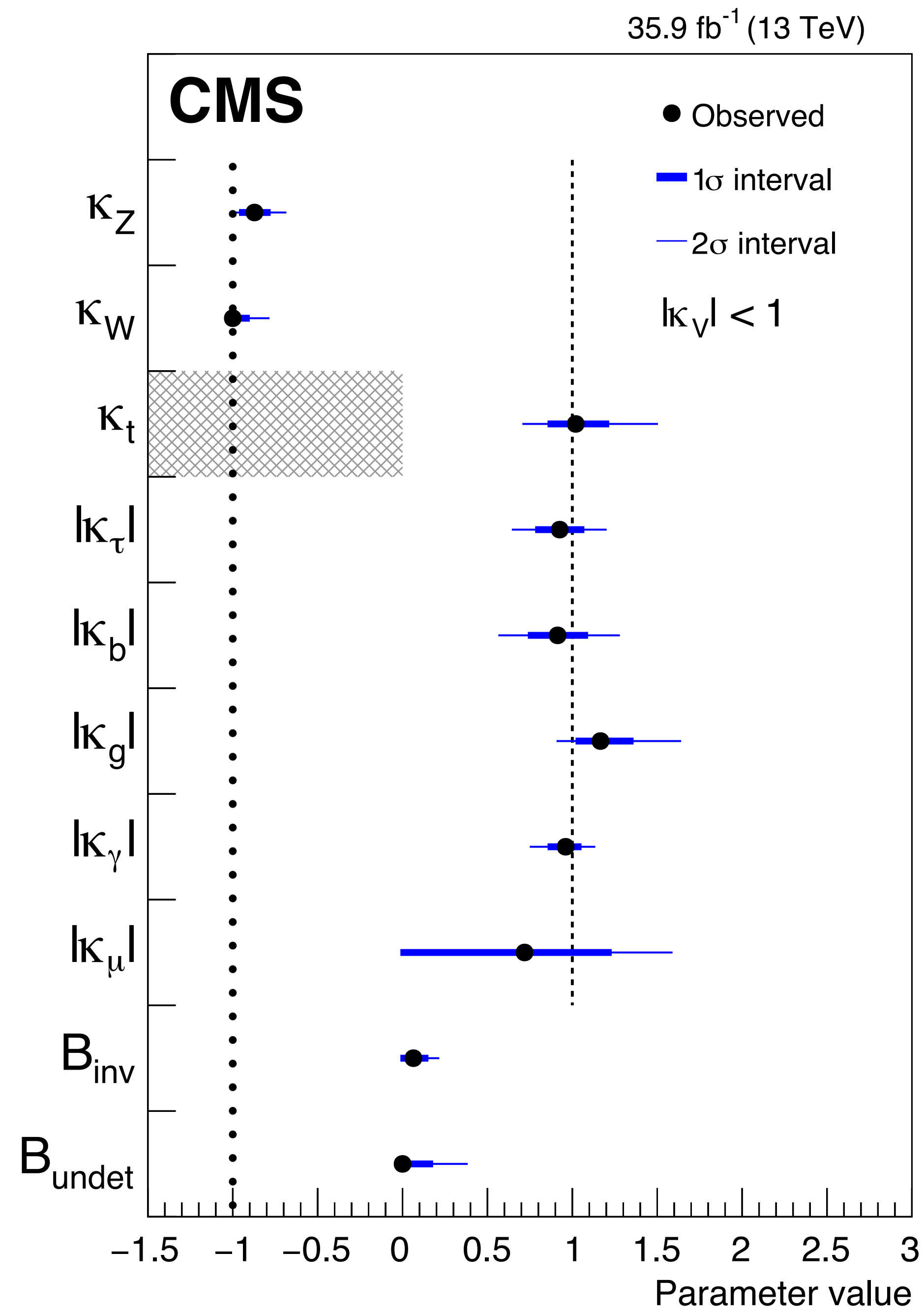


- Generic parametrisation assuming no new particles in loops and decays
- Consistent with SM Yukawa coupling

Coupling modifiers

[ATLAS-CONF-2019-005]
[1809.10733]

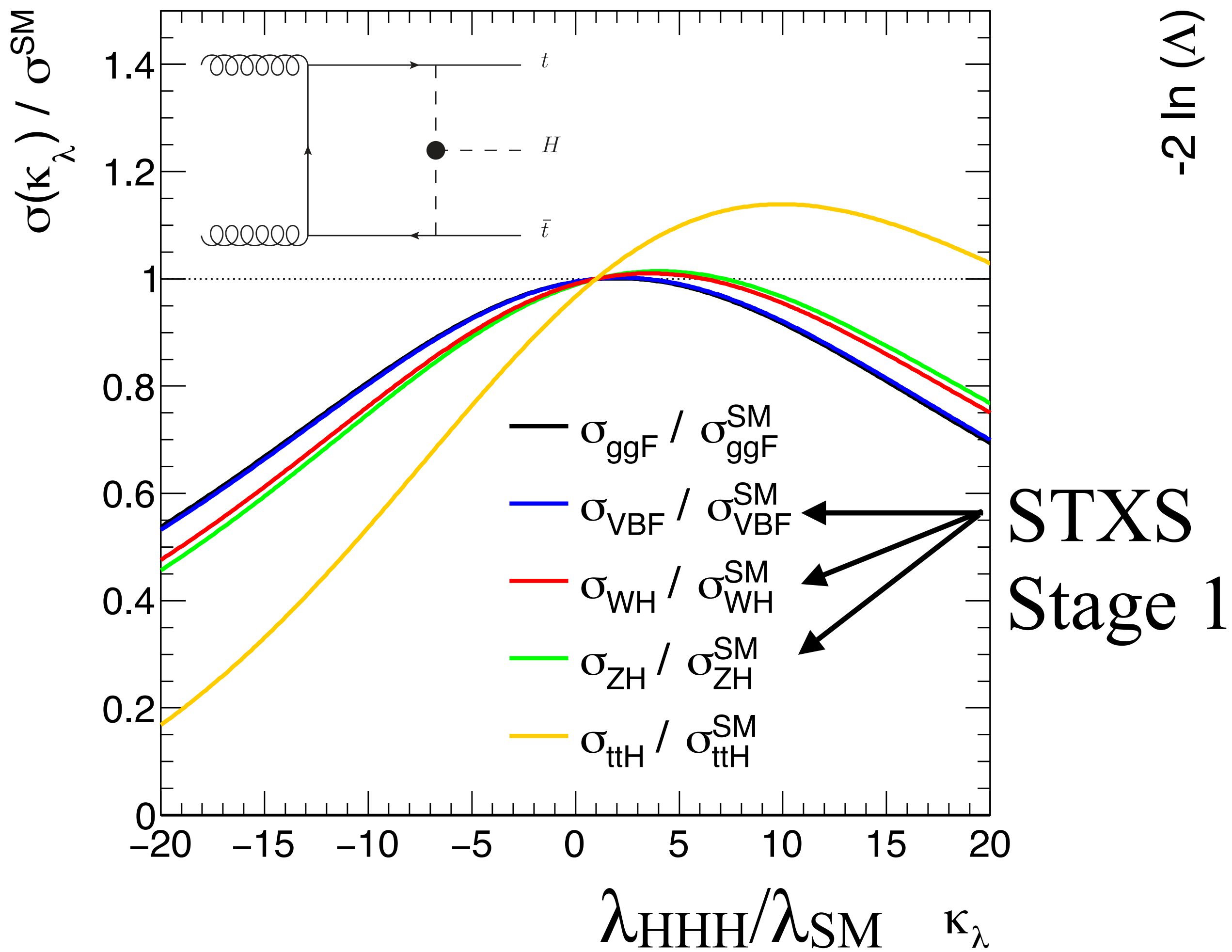


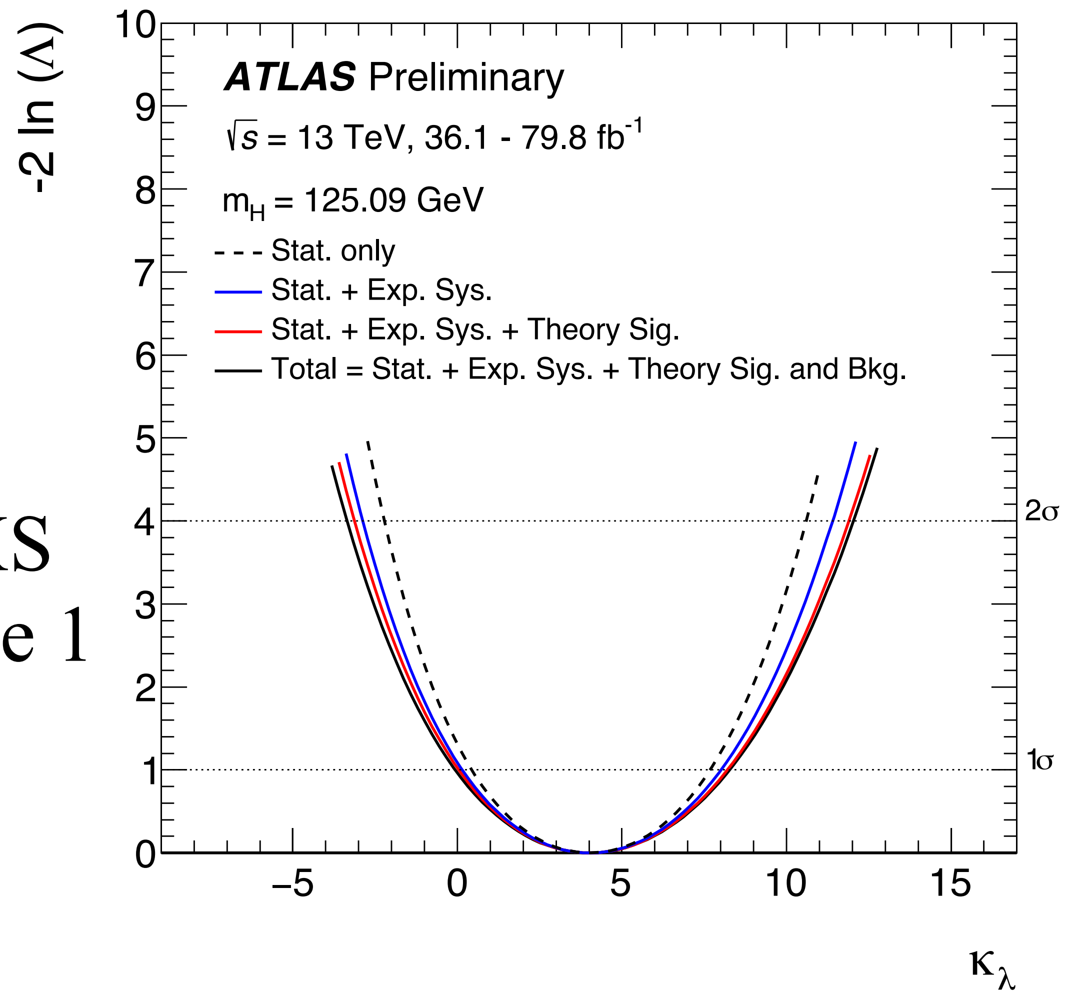


- Generic parametrisation using effective κ_g and κ_γ. In CMS (right), κ_V is allowed to go negative and is close to -1 → $|\kappa_V|$ is still close to 1

ATLAS self-coupling at 80 fb^{-1}

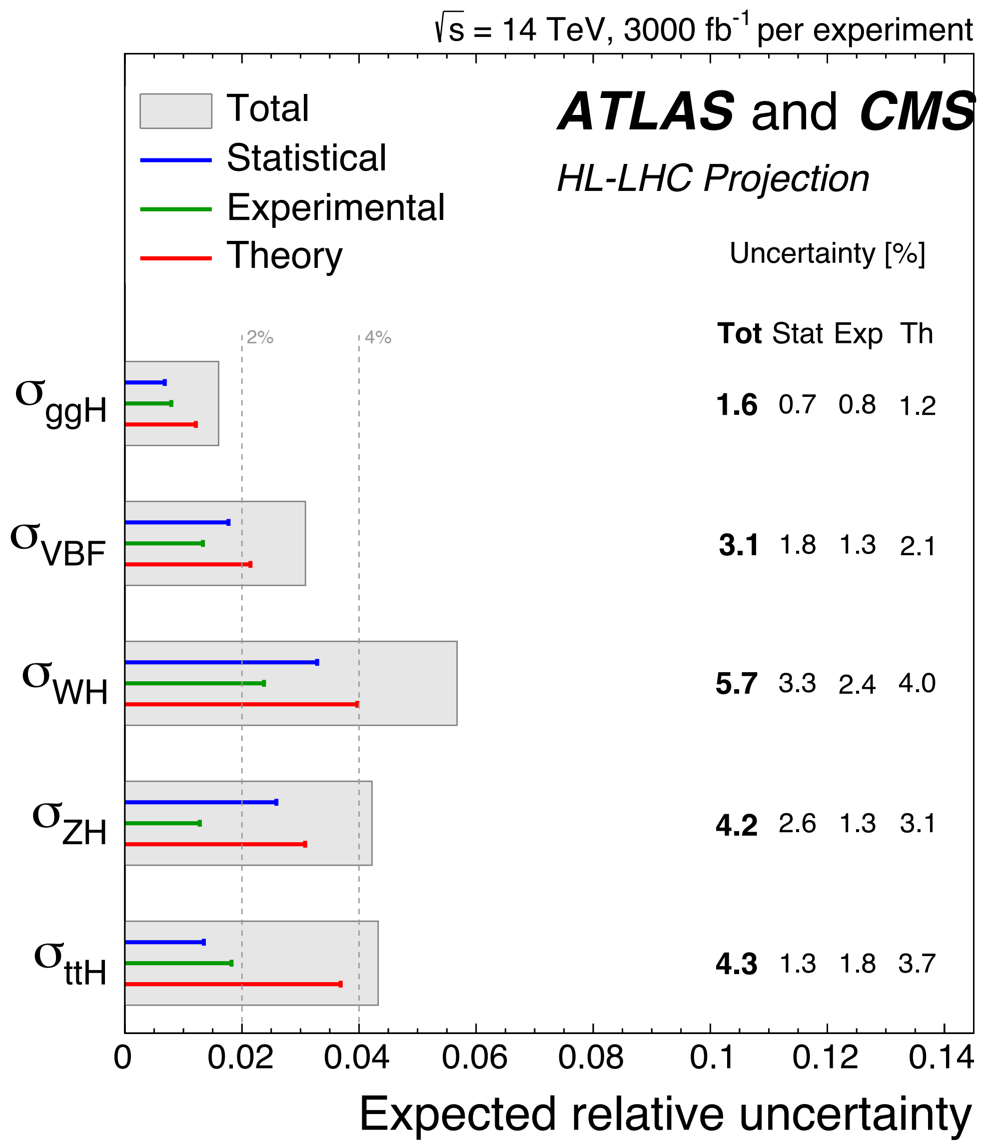
[ATL-PHYS-PUB-2019-009]

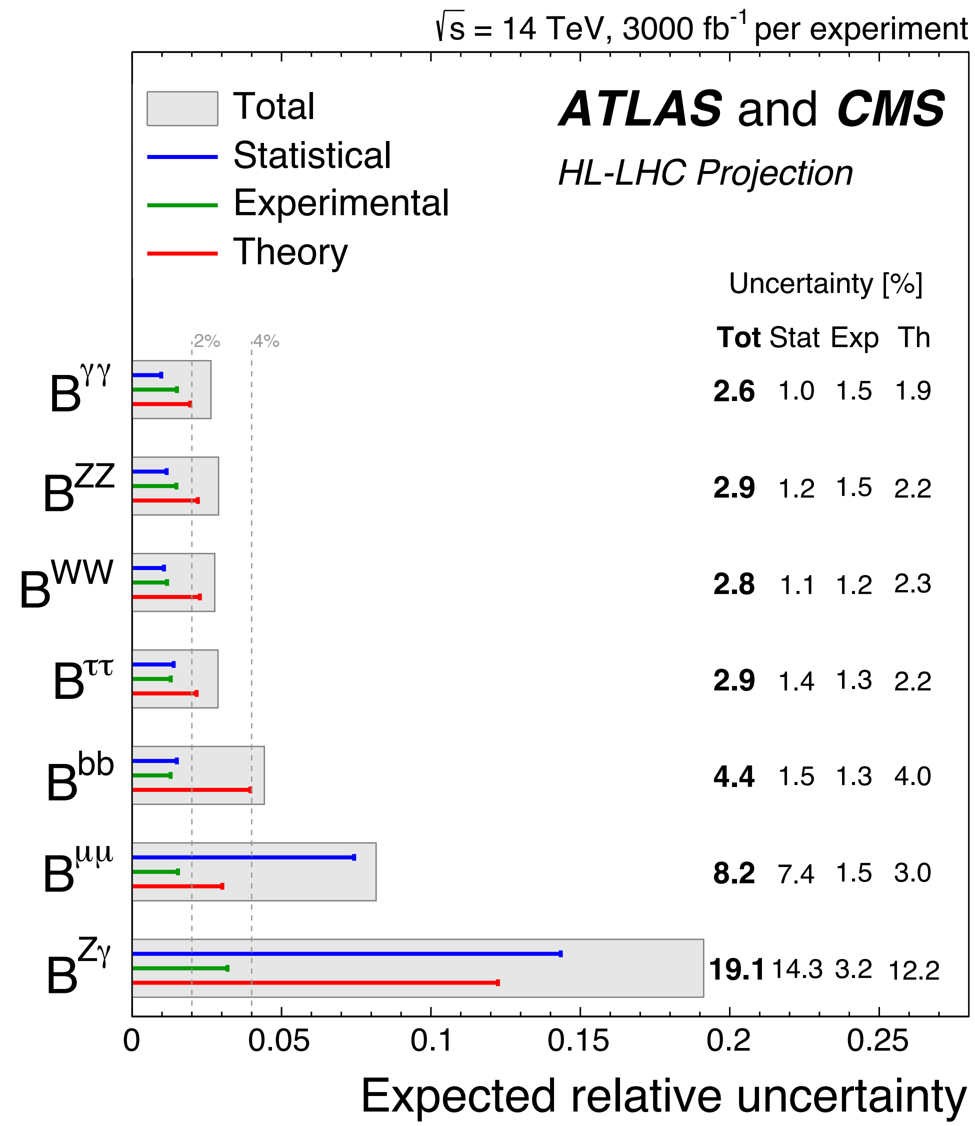




- The self-coupling contributes at NLO EW corrections via the Higgs self energy loop and additional diagrams (left)
- Constraint on the self-coupling using single Higgs production (right): $-3.2 < \kappa_\lambda < 11.9$, sensitivity comparable to HH searches

ATLAS+CMS projections [1902.00134]





- Reduced systematic uncertainties reflecting the situation which is expected at the end of HL-LHC, with negligible mc stat and background function uncertainty, and half theory uncertainty (S2)
- More detail in Jose's talk [link]

Summary

- Combined measurements:
  - Using up to 80 fb^{-1}, reduced Stage 1 STXS are being prepared
  - Dominant uncertainties: Signal theory, background theory, luminosity, photon (Still limited statistics in BSM bins)
- ATLAS self-coupling at 80 fb^{-1}:
  - Sensitivity comparable to HH searches, dedicated kinematic binning including ggH and ttH can improve the sensitivity
- ATLAS+CMS projections:
  - A few% level expected uncertainty on main production cross sections and branching ratios at 3000 fb^{-1}

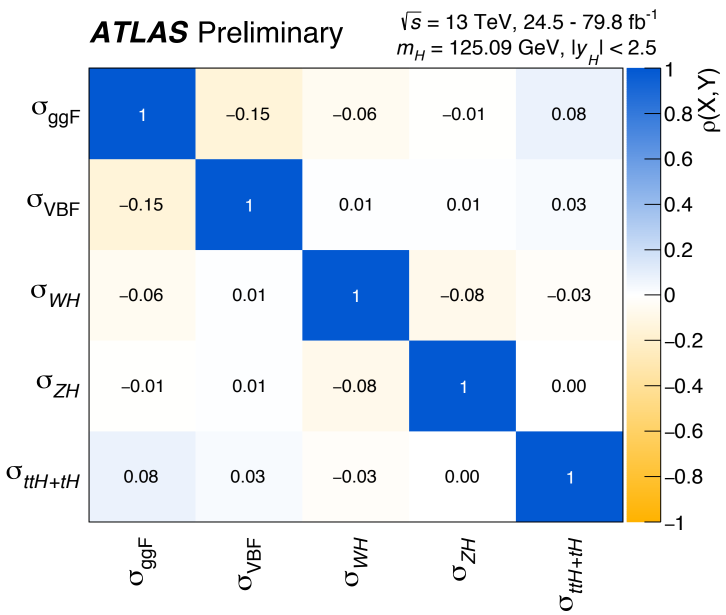
- Let’s get ready for the full Run 2 140 fb^{-1} results

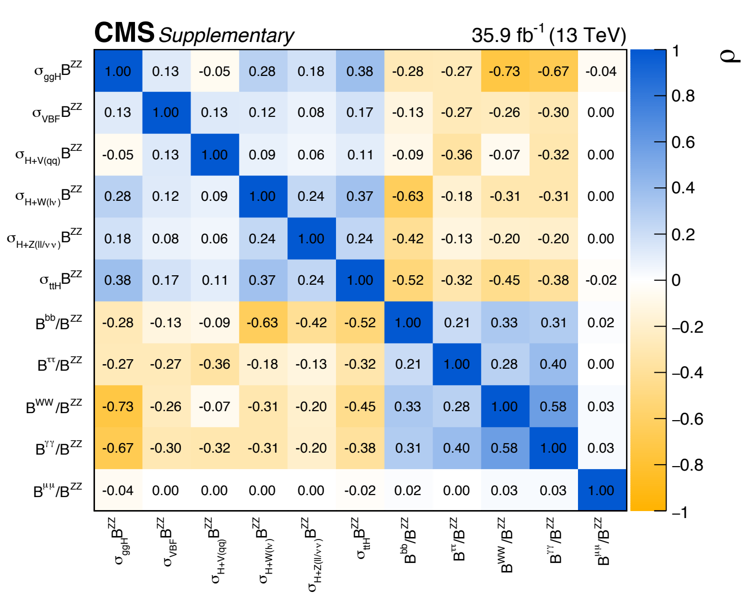
Backup

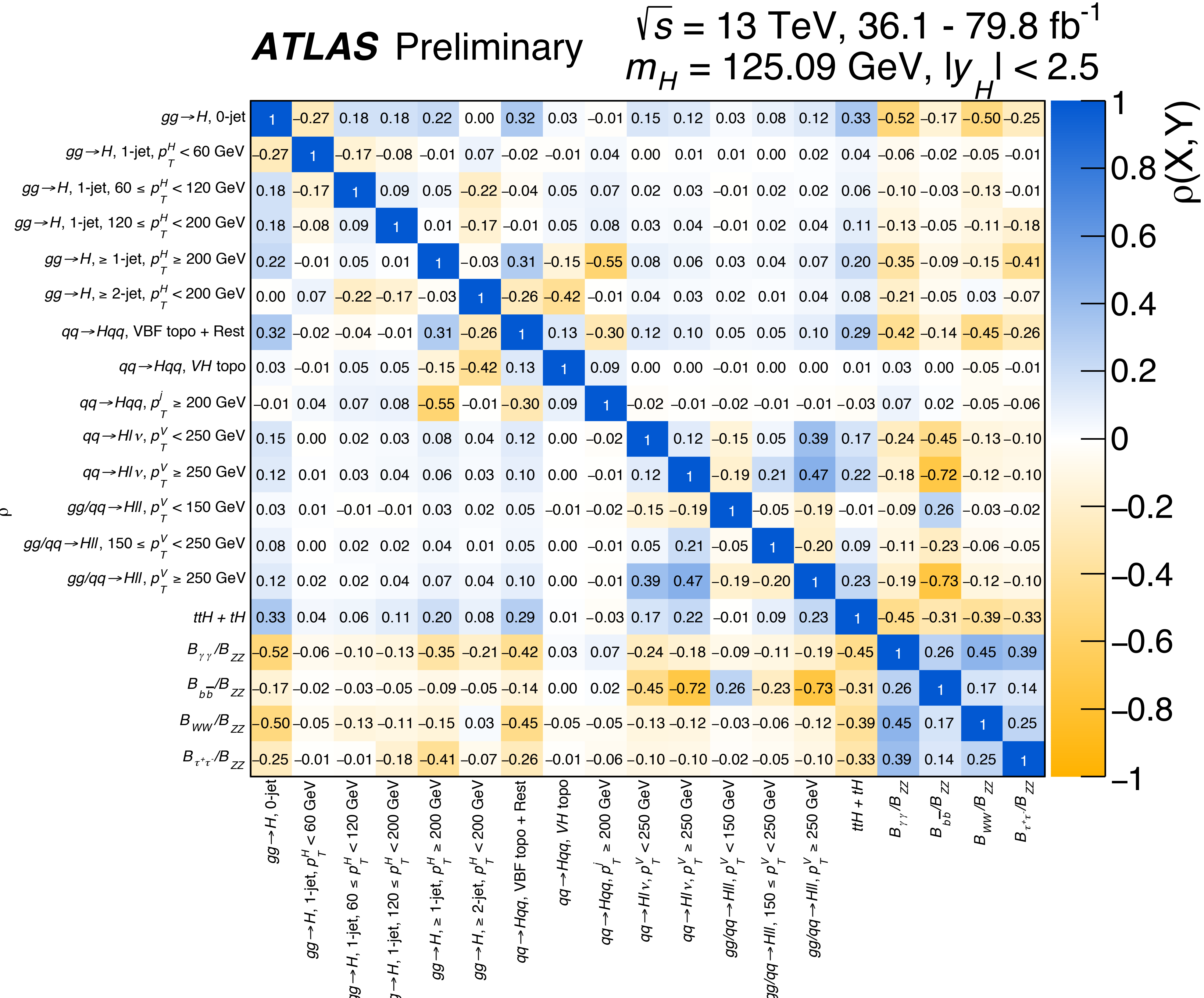
Correlation matrices

[ATLAS-CONF-2019-005]

[1809.10733]







CMS combined at 36 fb^{-1} [1809.10733]

Production and decay tags		Expected signal composition
$H \to \gamma\gamma$, Section 3.1		
$\gamma\gamma$	Untagged	74–91% ggH
	VBF	51–80% VBF
	VH hadronic	25% WH, 15% ZH
	WH leptonic	64–83% WH
	ZH leptonic	98% ZH
	VH p_T^{miss}	59% VH
	ttH	80–89% ttH, ≈8% tH
$H \to ZZ^{(*)} \to 4\ell$, Section 3.2		
4μ, $2e2\mu/2\mu2e$, 4e	Untagged	≈95% ggH
	VBF 1, 2-jet	≈11–47% VBF
	VH hadronic	≈13% WH, ≈10% ZH
	VH leptonic	≈46% WH
	VH p_T^{miss}	≈56% ZH
	ttH	≈71% ttH
$H \to WW^{(*)} \to \ell\nu\ell\nu$, Section 3.3		
$e\mu/\mu e$	ggH 0, 1, 2-jet	≈55–92% ggH, up to ≈15% $H \to \tau\tau$
	VBF 2-jet	≈47% VBF, up to ≈25% $H \to \tau\tau$
ee+$\mu\mu$	ggH 0, 1-jet	≈84–94% ggH
$e\mu$+jj	VH 2-jet	22% VH, 21% $H \to \tau\tau$
3ℓ	WH leptonic	≈80% WH, up to 19% $H \to \tau\tau$
4ℓ	ZH leptonic	85–90% ZH, up to 14% $H \to \tau\tau$
$H \to \tau\tau$, Section 3.4		
$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	0-jet	≈70–98% ggH, 29% $H \to WW$ in $e\mu$
	VBF	≈35–60% VBF, 42% $H \to WW$ in $e\mu$
	Boosted	≈48–83% ggH, 43% $H \to WW$ in $e\mu$

VH production with $H \to bb$, Section 3.5		
$Z(\nu\nu)bb$	ZH leptonic	≈100% VH, 85% ZH
$W(\ell\nu)bb$	WH leptonic	≈100% VH, ≈97% WH
$Z(\ell\ell)bb$	Low-$p_T(V)$ ZH leptonic	≈100% ZH, of which ≈20% ggZH
	High-$p_T(V)$ ZH leptonic	≈100% ZH, of which ≈36% ggZH
Boosted H Production with $H \to bb$, Section 3.6		
$H \to bb$	$p_T(H)$ bins	≈72–79% ggH
ttH production with $H \to$ leptons, Section 3.7.1		
$H \to WW, \tau\tau, ZZ$	2ℓss	$WW/\tau\tau \approx 4.5$, ≈5% tH
	3ℓ	$WW:\tau\tau:ZZ \approx 15:4:1$, ≈5% tH
	4ℓ	$WW:\tau\tau:ZZ \approx 6:1:1$, ≈3% tH
	$1\ell+2\tau_h$	96% ttH with $H \to \tau\tau$, ≈6% tH
	$2\ell ss+1\tau_h$	$\tau\tau:WW \approx 5:4$, ≈5% tH
	$3\ell+1\tau_h$	$\tau\tau:WW:ZZ \approx 11:7:1$, ≈3% tH
ttH production with $H \to bb$, Section 3.7.2		
$H \to bb$	$t\bar{t} \to$ jets	≈83–97% ttH with $H \to bb$
	$t\bar{t} \to 1\ell$+jets	≈65–95% ttH with $H \to bb$, up to 20% H -
	$t\bar{t} \to 2\ell$+jets	≈84–96% ttH with $H \to bb$
Search for $H \to \mu\mu$, Section 3.8		
$\mu\mu$	S/B bins	56–96% ggH, 1–42% VBF
Search for invisible H decays, Section 3.9		
$H \to$ invisible	VBF	52% VBF, 48% ggH
	ggH + ≥ 1 jet	80% ggH, 9% VBF
	VH hadronic	54% VH, 39% ggH
	ZH leptonic	≈100% ZH, of which 21% ggZH

- ggF signal: Powheg NNLOPS, normalised to N^3LO QCD with NLO EW corrections
- VBF, VH, (ttH) signal: Powheg NLO, normalised to NNLO (NLO) QCD with NLO EW corrections