ATLAS Higgs Combination

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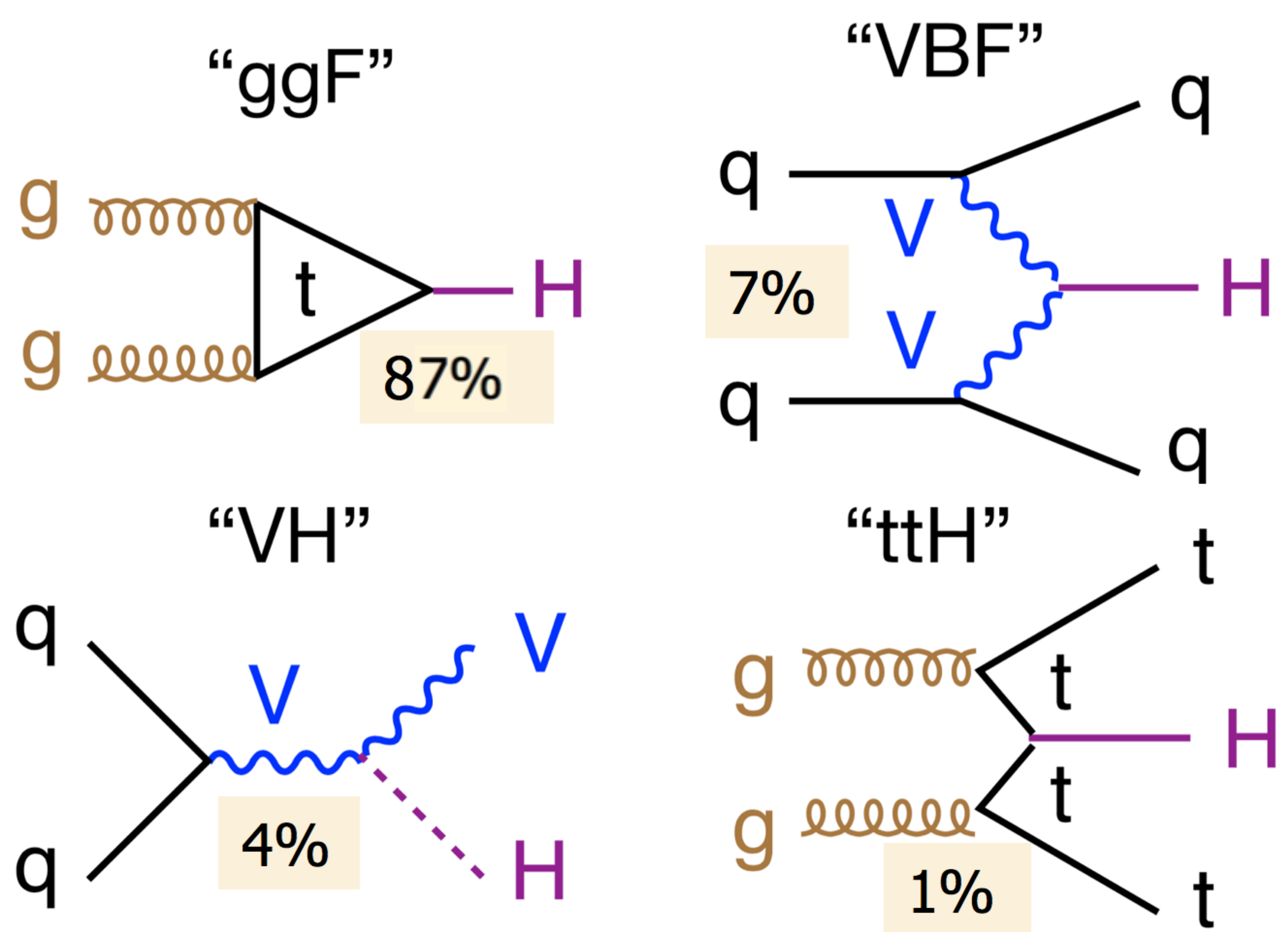
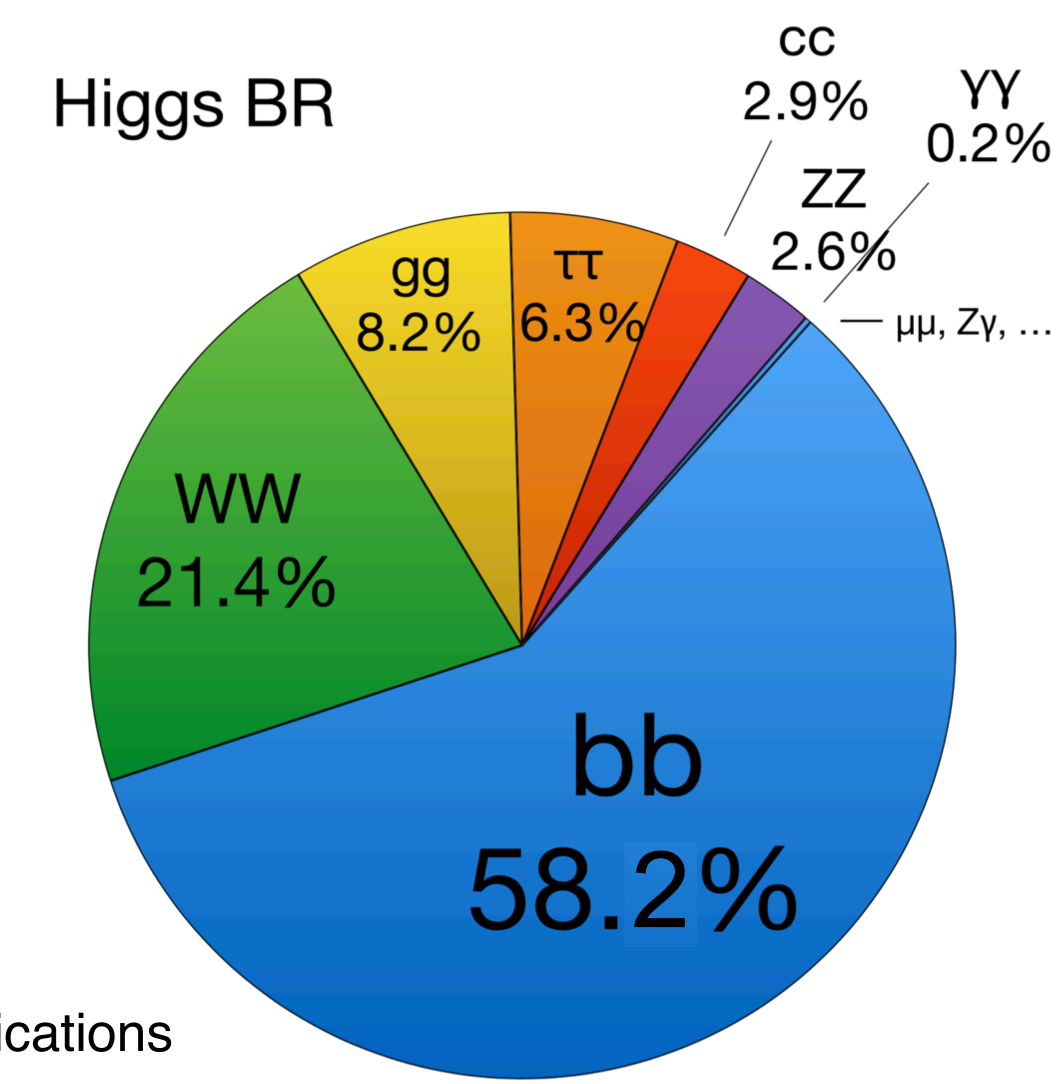
on behalf of the ATLAS Collaboration

September 20-22, 2021 - Orsay-Paris
Higgs Hunting Workshop

Introduction

- Since the Higgs discovery by ATLAS and CMS in 2012, many **Higgs property studies** (mass, spin, parity, couplings, cross sections, etc.) have been performed
- Today: combined measurements of Higgs boson using **13 TeV data** collected with the ATLAS detector (ATLAS-CONF-2020-027, ATLAS-CONF-2020-053, ATLAS-CONF-2019-032)





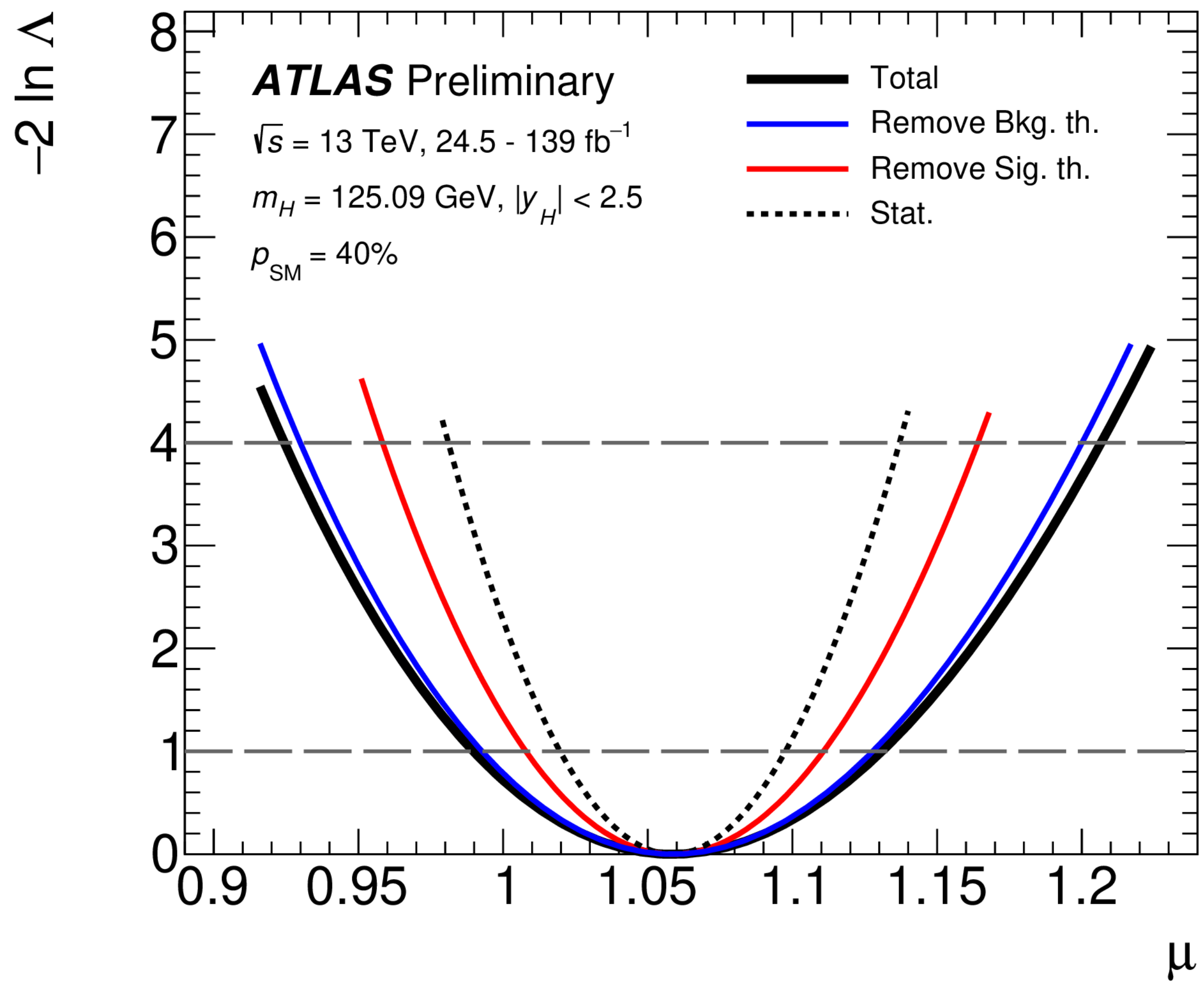
Figures from https://msneubauer.github.io with modifications for Higgs Mass = 125 GeV

Signal strength & production cross-section measurements

	ggF	VBF	VH	ttH+tH
$H\to\gamma\gamma$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\to ZZ$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (36-139 fb^{-1})
$H\to WW$	✔ (36 fb^{-1})	✔ (36 fb^{-1})		
$H\to\tau\tau$	✔ (36 fb^{-1})	✔ (36 fb^{-1})		
$H\to bb$		✔ (25-31 fb^{-1})	✔ (139 fb^{-1})	✔ (36 fb^{-1})

✔: channel included in the combination

Inclusive signal strength



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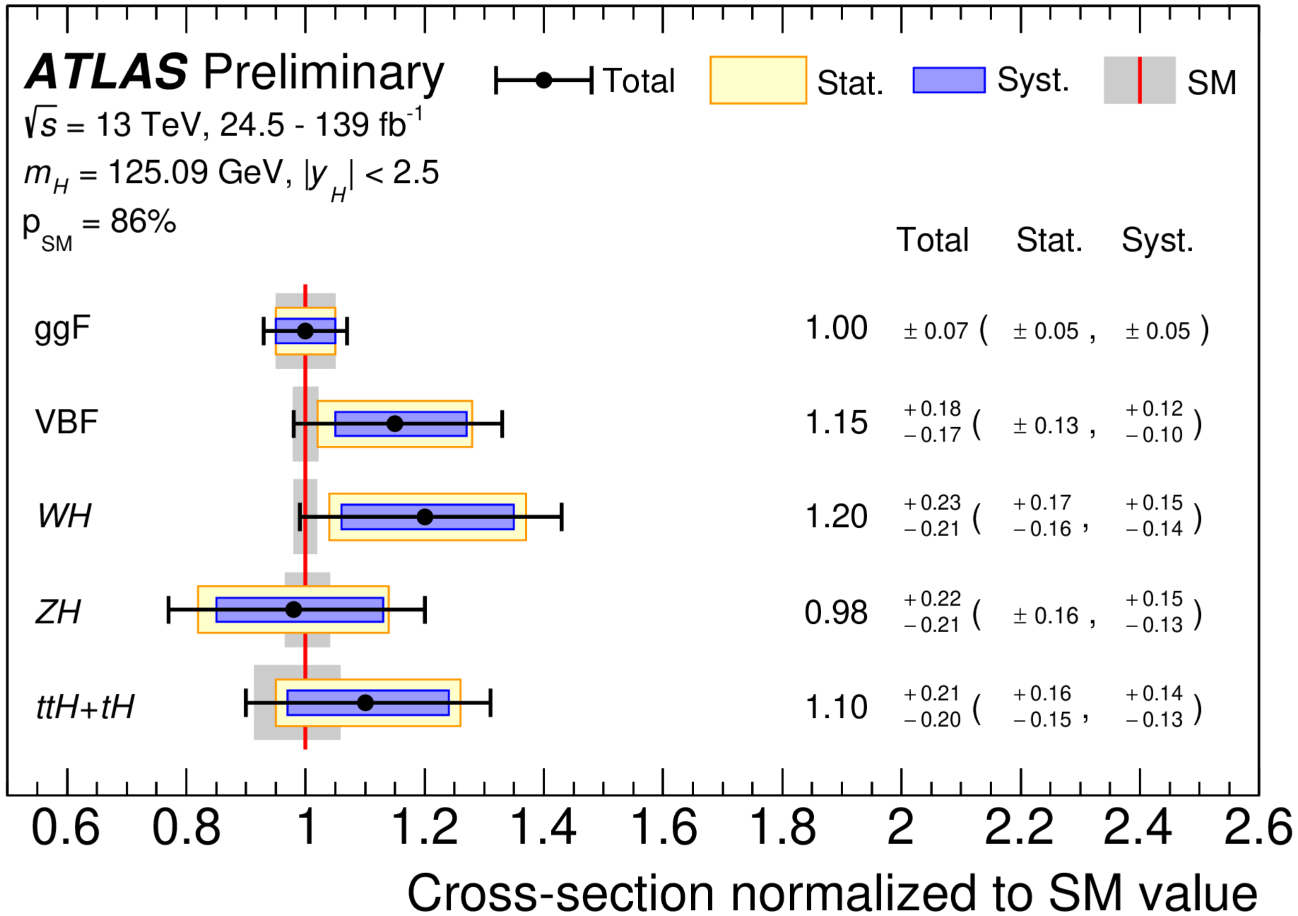
- Inclusive signal strength, defined as the measured Higgs boson signal yield normalized to its SM prediction, is determined to be

$$\mu = 1.06 \pm 0.07 = 1.06 \pm 0.04(\text{stat.}) \pm 0.03(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$$

- This measurement is systematically limited

Production mode cross sections (assuming the SM decays)



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- ggF cross section is now measured with 7% precision
  - Precision of N3LO cross section prediction: 5%
- All major production modes (ggF, VBF, WH, ZH, ttH) are observed!
  - WH: 6.3σ, ZH: 5.0σ

Simplified template cross section (STXS) measurements

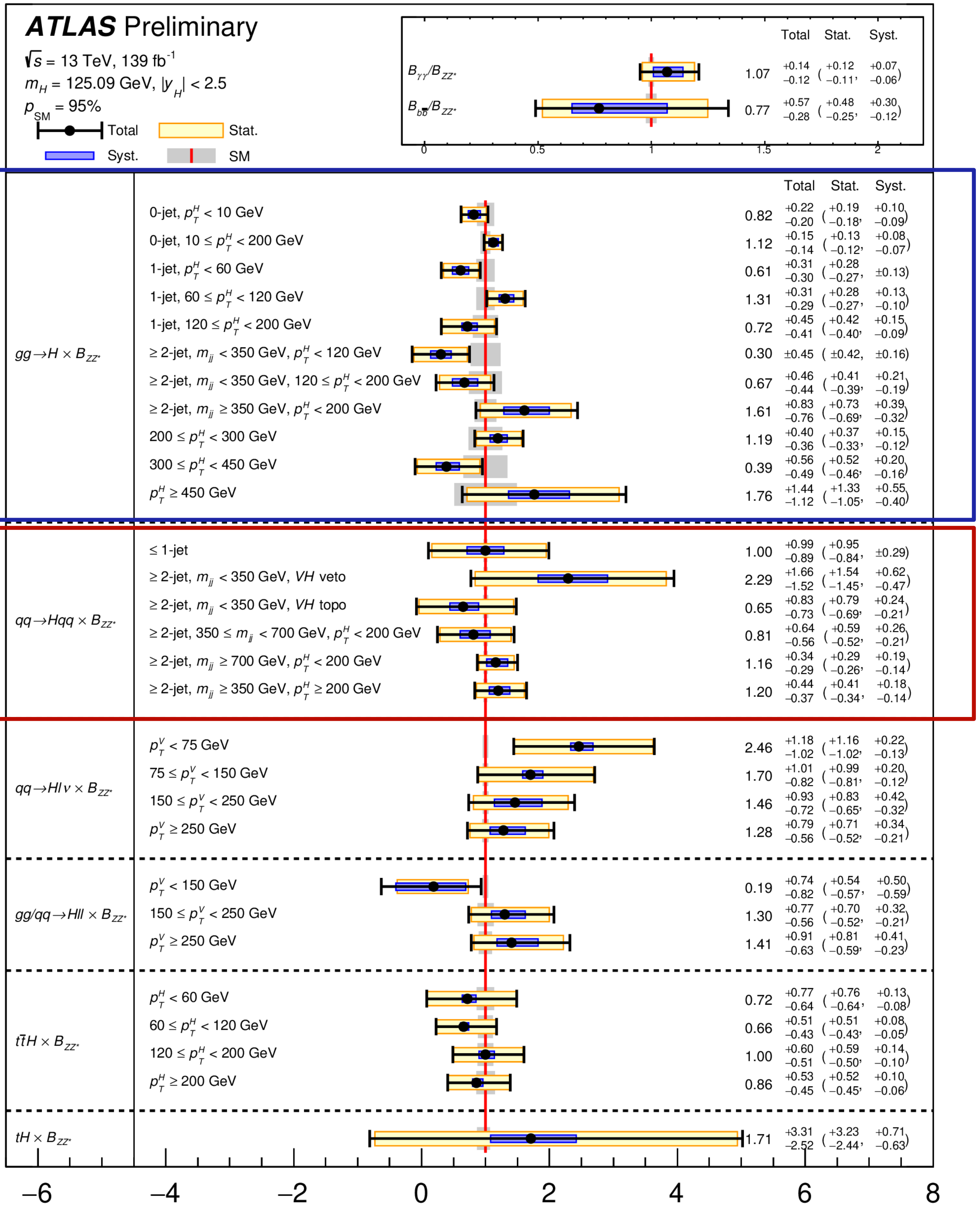
	ggF	VBF	VH	ttH+tH
$H\rightarrow\gamma\gamma$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\rightarrow ZZ$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\rightarrow bb$			✔ (139 fb^{-1})	

✔: channel included in the combination

Simplified template cross sections

- Measure production mode cross-sections in various phase-space regions, which are chosen according to
  - sensitivity to BSM effects
  - avoidance of large theory uncertainties
  - matching to experimental selections
- Within each region, use the SM predicted signal templates to fit data
  - Can still exploit powerful analysis techniques (e.g. MVA)
- STXS are measured granularly in this combination
  - without assuming the SM decays of Higgs boson

STXS results



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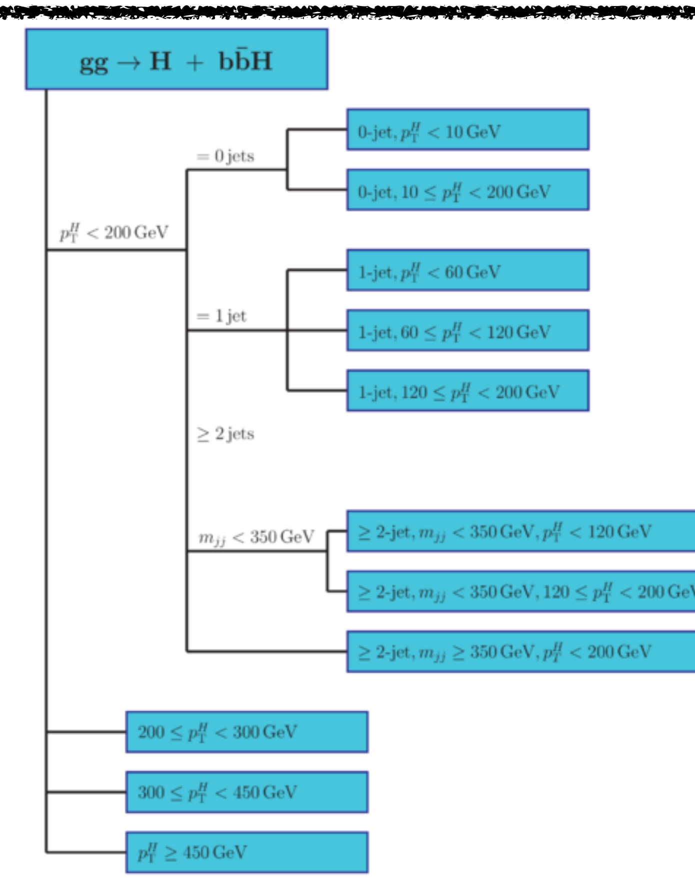
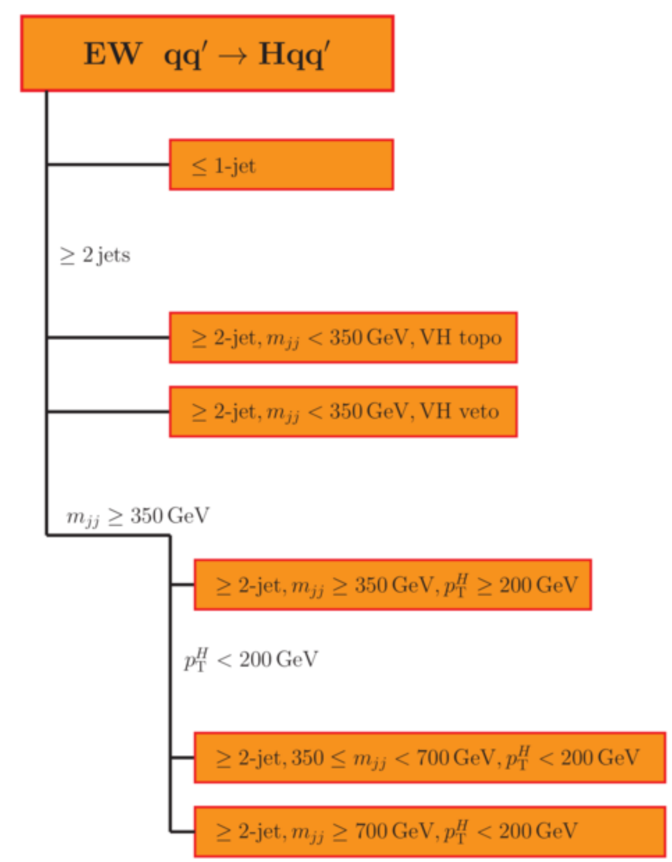
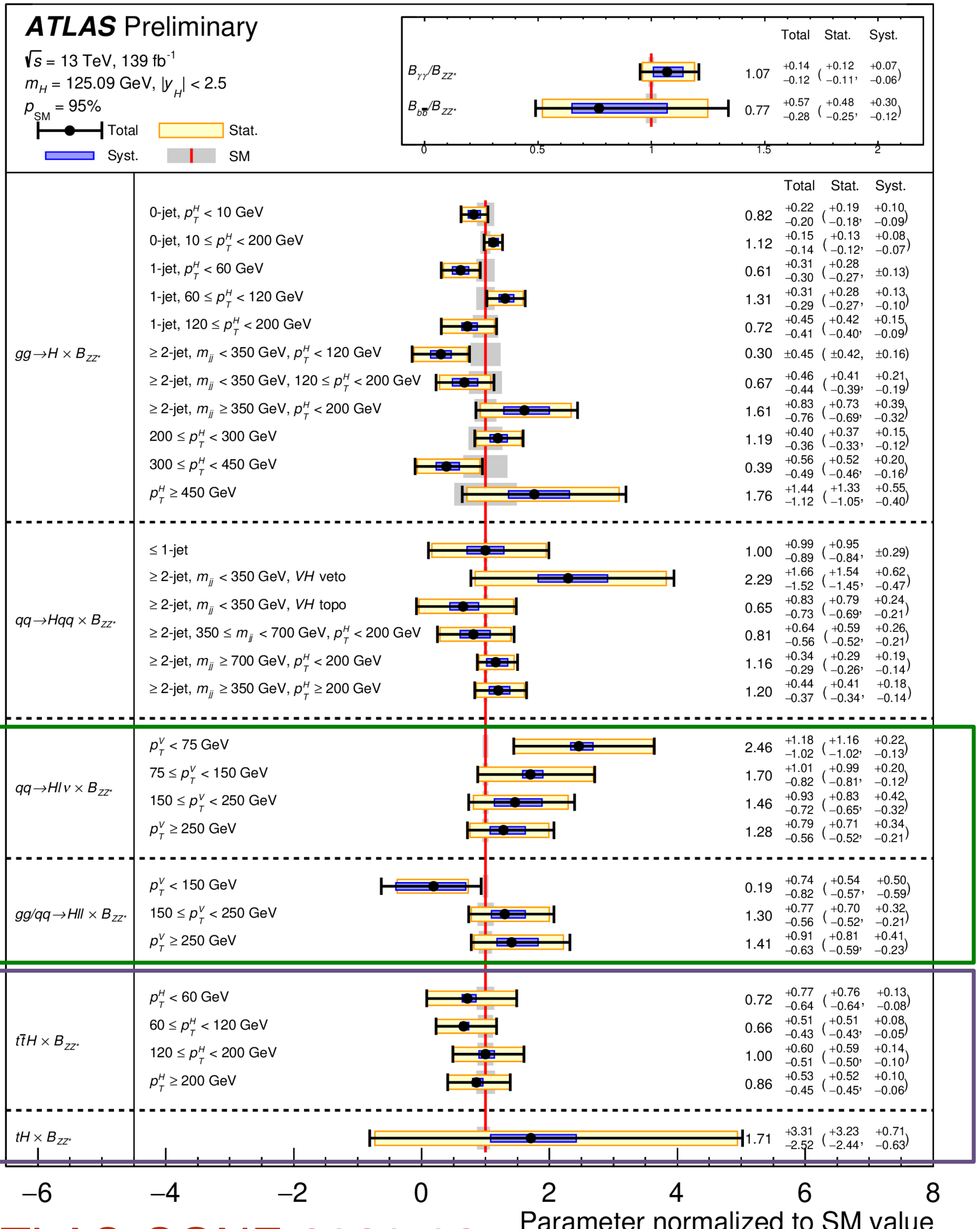




STXS results



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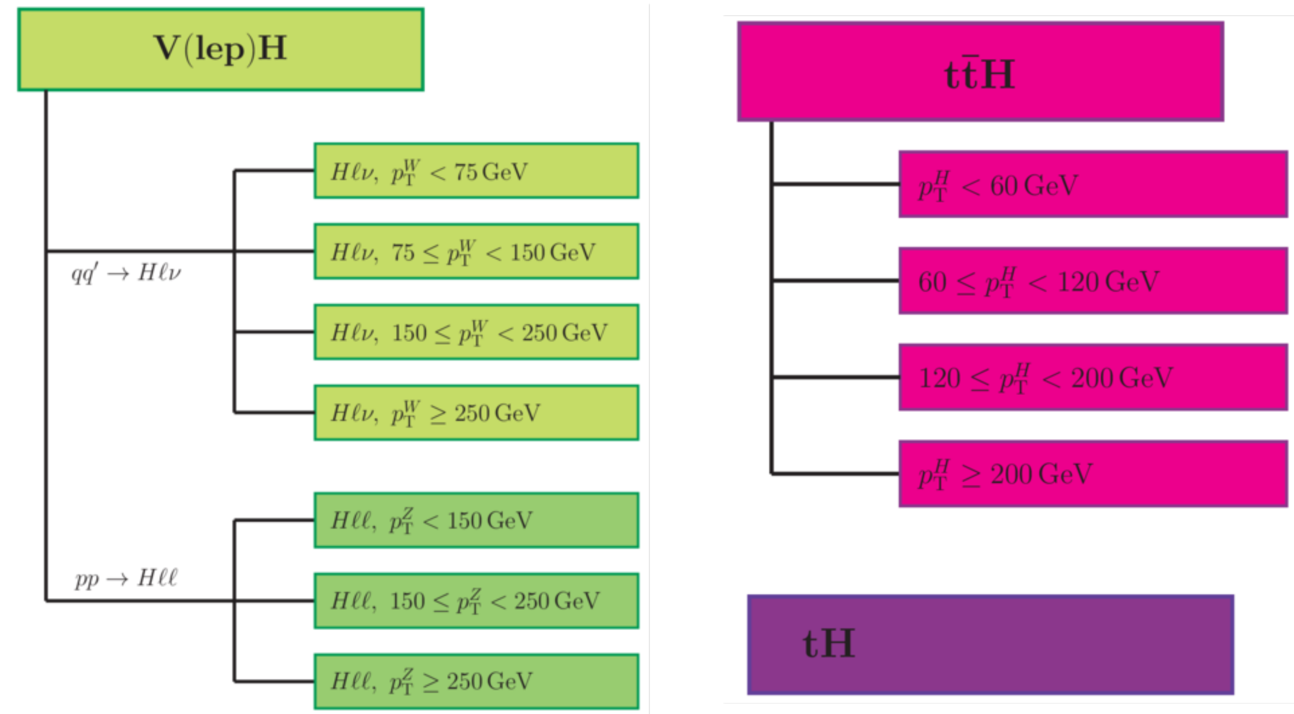

- 29 regions are probed, good compatibility with the SM prediction
- All regions are statistically limited; in some regions (e.g. ggF 0-jet) systematics are not negligible
- The upper limit on the tH cross section is 8.4 times the SM prediction

Coupling modifier ("kappa") interpretation

<table>
<tr><th></th><th>ggF</th><th>VBF</th><th>VH</th><th>ttH+tH</th></tr>
<tr><td>$H \to \gamma\gamma$</td><td>✔ (139 fb^{-1})</td><td>✔ (139 fb^{-1})</td><td>✔ (139 fb^{-1})</td><td>✔ (139 fb^{-1})</td></tr>
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</table>

✔: channel included in the combination

Analyses of $H \to \mu\mu$ (139 fb^{-1}) and $H \to$invisible (139 fb^{-1}) are also included in relevant studies

Coupling modifier ("kappa")

- Leading order motivated framework: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_t…)
- In this framework, production cross section times decay branch fraction of i→H→f can be parameterized as

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H},$$

  - (this allows for a consistent treatment of production and decay)
- Total width of Higgs boson can be expressed as

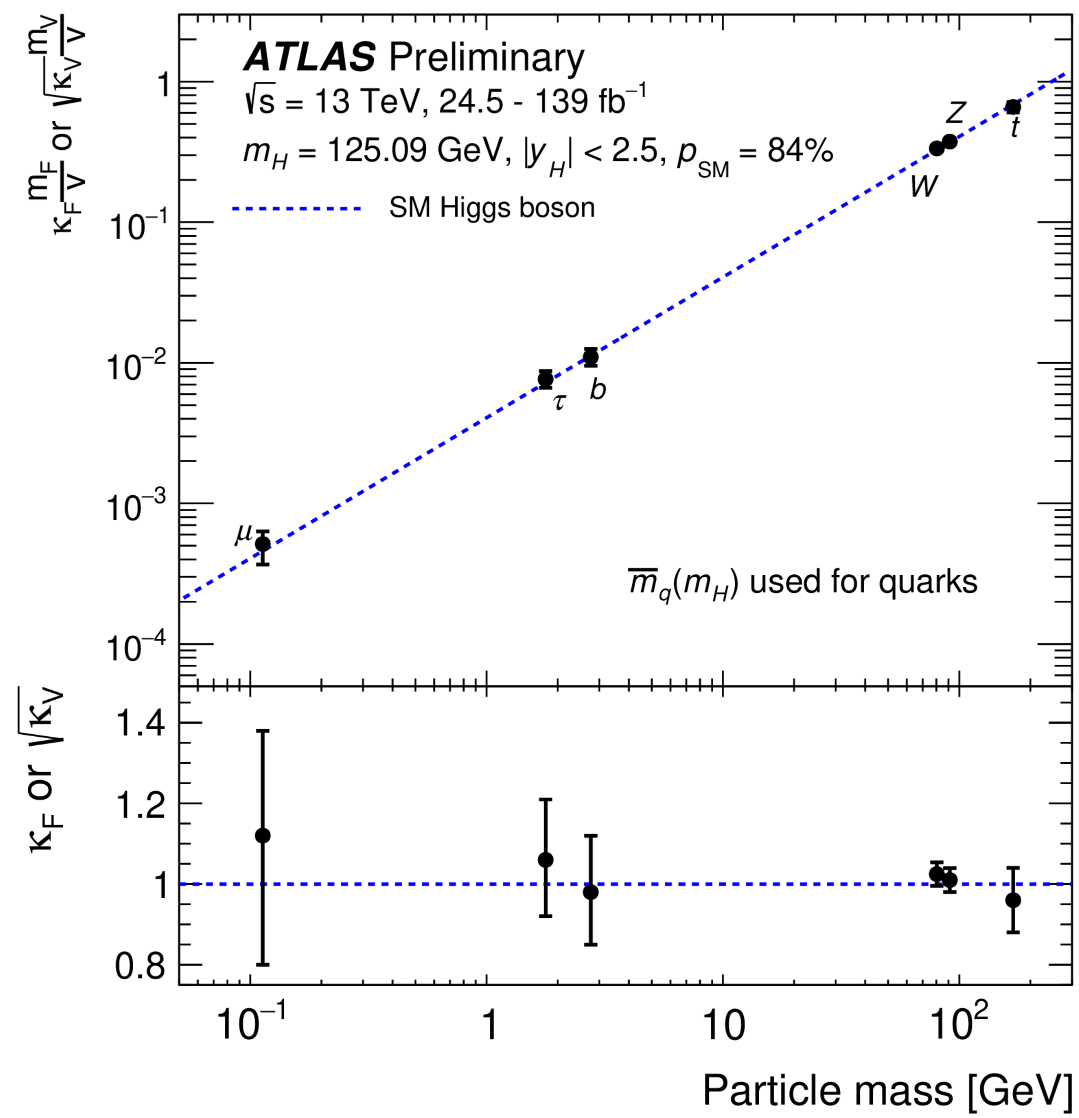
$$\Gamma_H(\boldsymbol{\kappa}, B_{\text{i.}}, B_{\text{u.}}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\text{i.}}, B_{\text{u.}})\,\Gamma_H^{\text{SM}}$$

$B_{i.}$= BSM contribution to BR of invisible decays which are identified through a missing transverse momentum signature

$B_{u.}$= BSM contribution to BR of undetected decays to which none of the analyses in the combination are sensitive

Coupling modifier vs. particle mass

- Assume no BSM contribution in loop-induced processes (ggF, H→γγ etc.) or total width. Resolve ggF and Hγγ effective vertices
- Good agreement with the SM across 3 orders of magnitude of particle mass!



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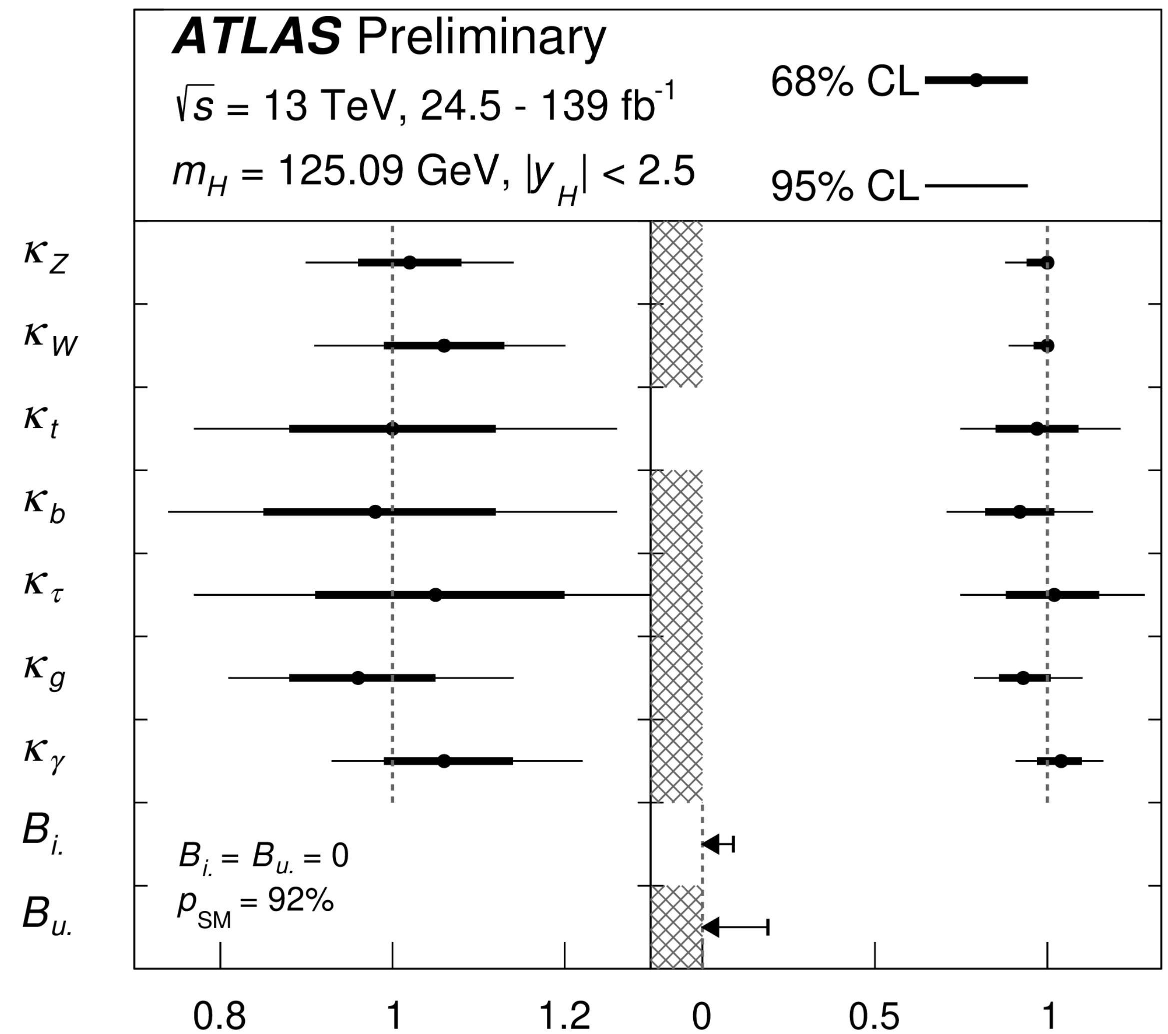
Coupling modifier: different scenarios

- Not resolving ggF and Hγγ effective vertices (and introducing corresponding coupling modifiers κ_g, κ_γ), explore two different scenarios for total width:
  - **Left**: assume $B_{i.}=B_{u.}=0$
  - **Right**: constrain $B_{i.}$ and $B_{u.}$ using H→invisible analysis and $\kappa_V < 1$



$B_{i.}<0.09$ at 95% CL
$B_{u.}<0.19$ at 95% CL

- All coupling modifiers are measured to be compatible with the SM

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Interpretation of STXS measurements with Effective Field Theory (EFT)

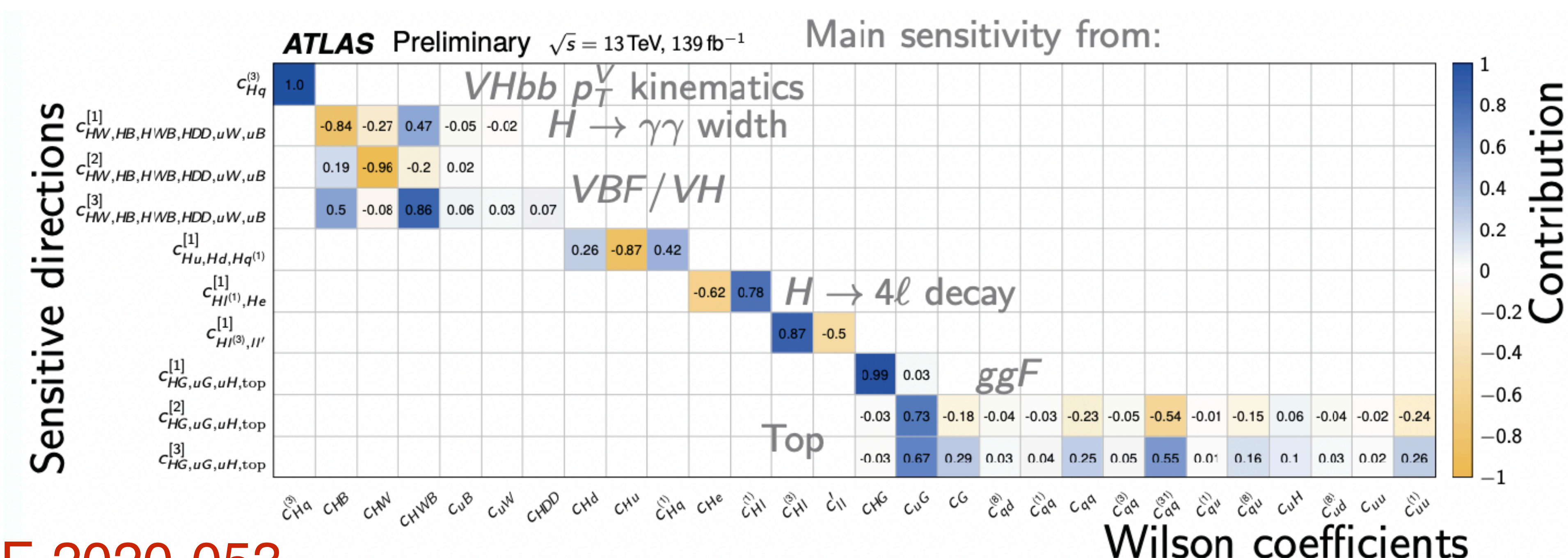
	ggF	VBF	VH	ttH+tH
$H\rightarrow\gamma\gamma$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\rightarrow ZZ$	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
$H\rightarrow bb$			✔ (139 fb^{-1})	

✔: channel included in the combination

Interpretation of STXS with EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots$$

- Parameterize the signal strengths, $(XS*BR)_{meas}/(XS*BR)_{SM}$, directly with Wilson coefficients of d=6 SMEFT operators
- Rotate the SMEFT basis cj to eigenvector cj' and fit 10 sensitive eigenvectors simultaneously
  - these eigenvectors are obtained from identifying groups of operators with similar impact and performing eigenvector decomposition for the covariance matrix of the measurement



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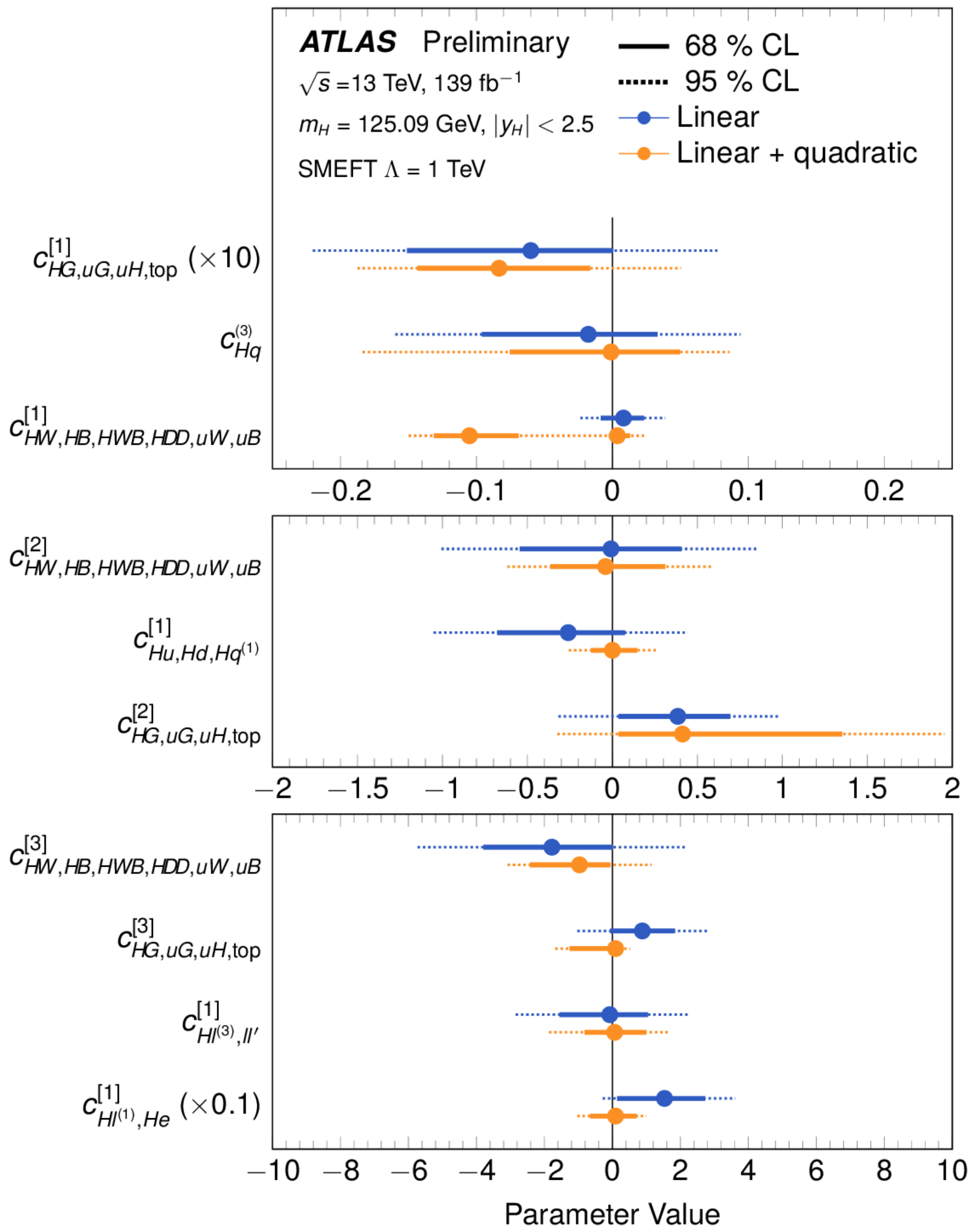
Interpretation of STXS with EFT

From a simultaneous fit

- All measured parameters are consistent with the SM expectation within their uncertainties

- Comparison of the linear model and the linear+quadratic model shows sizeable sensitivity to operators suppressed by Λ^4



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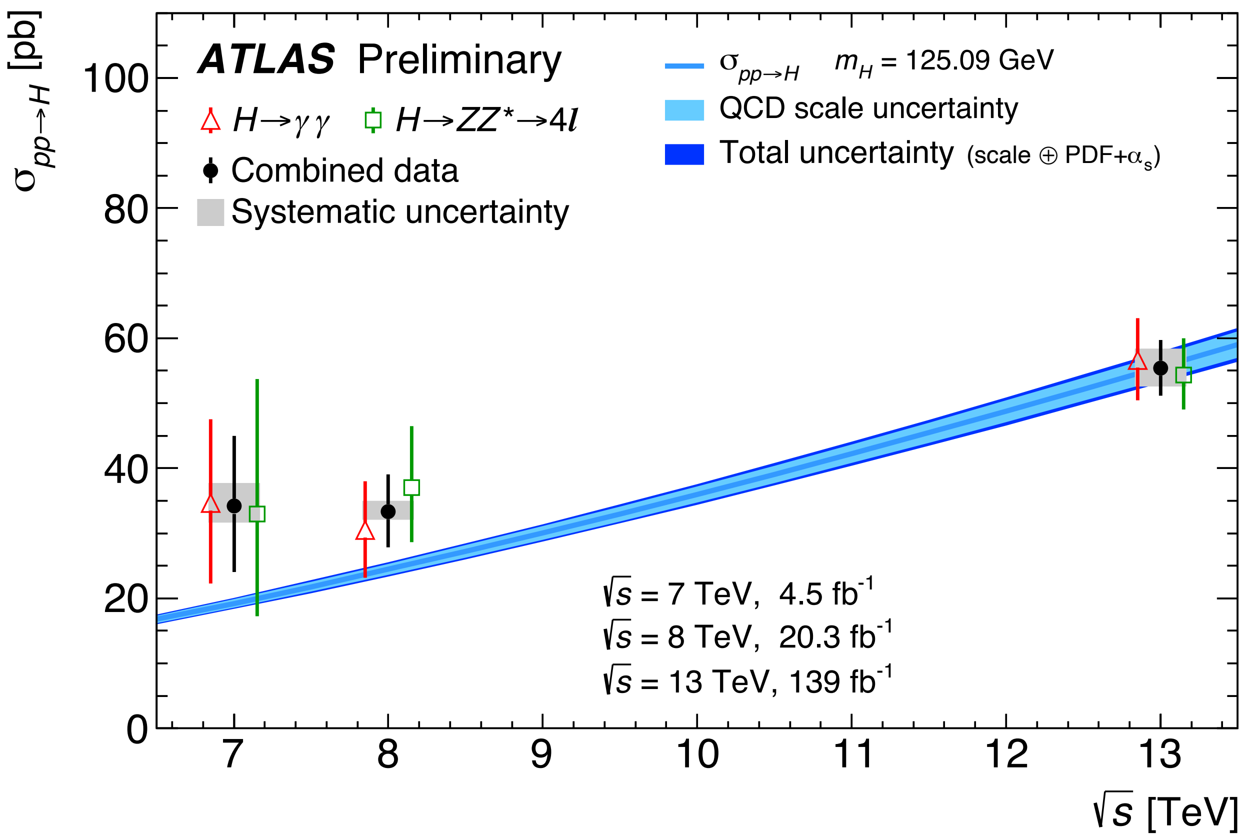
Combined measurements of the total and differential cross sections of Higgs boson production

Including the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4$-lepton decay channels
Using the full Run-2 dataset recorded by ATLAS, corresponding to *139* fb^{-1}

Total and differential cross sections

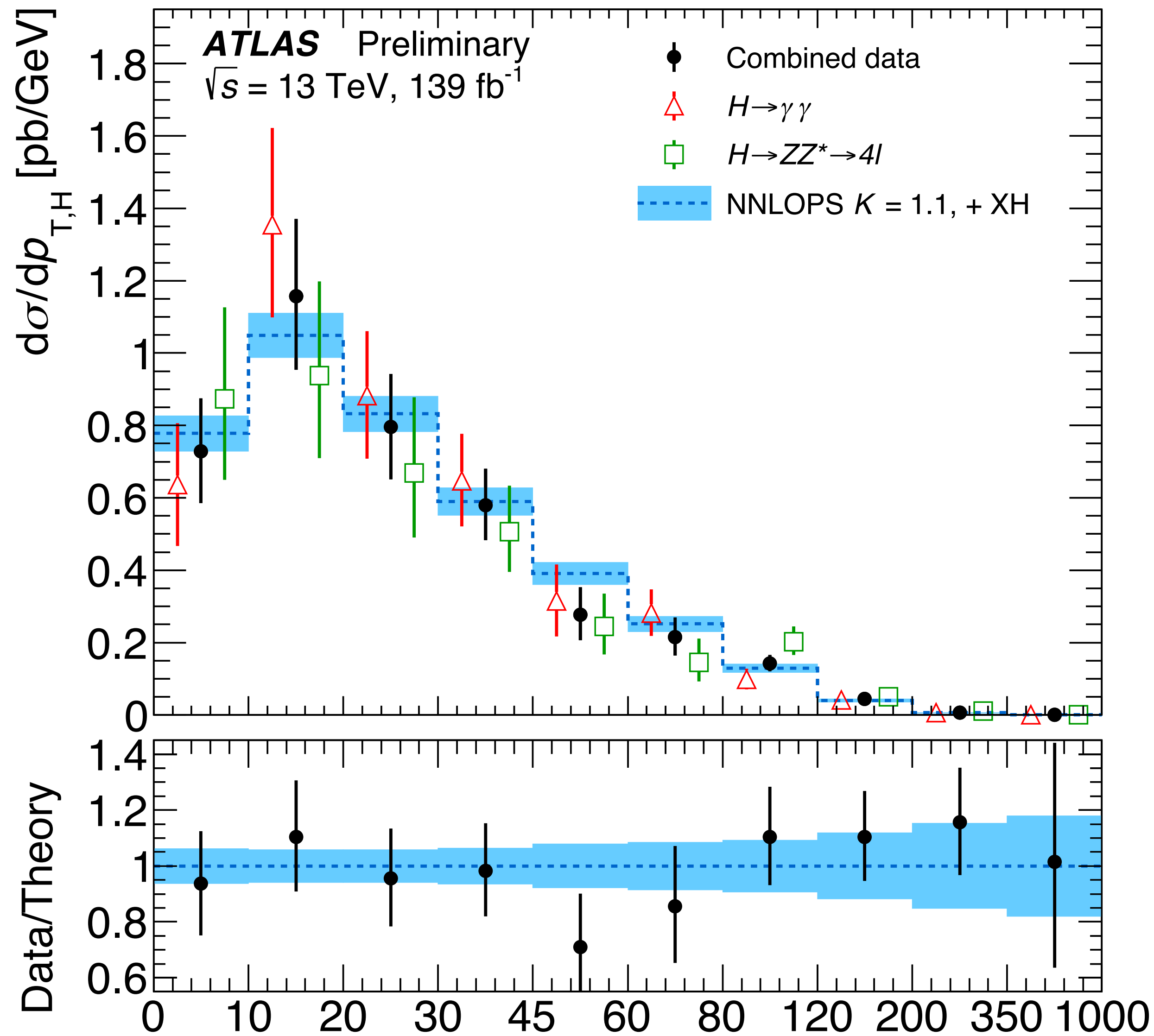


For total cross section at 13 TeV,

$$combined\ measurement : 55.4^{+4.3}_{-4.2} pb$$

(~8% precision)

$$SM\ prediction : 55.6 \pm 2.5 pb$$



Higgs transverse momentum

(~20% precision in 9 bins)

ATLAS-CONF-2019-032

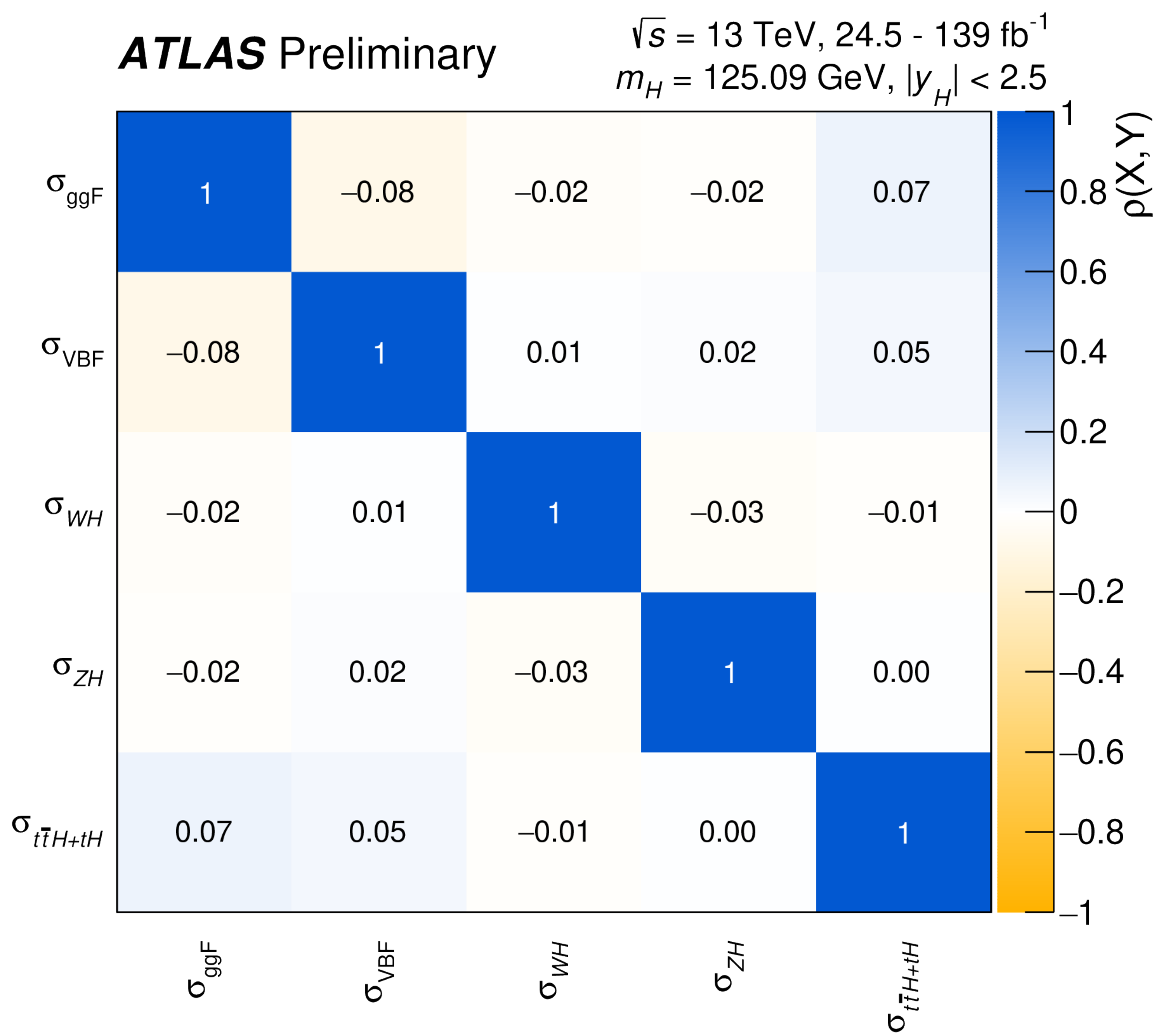
- The results from the two decay channels are found to be compatible with each other, and their combination agrees with the Standard Model prediction

Summary

- Based on up to **139 fb^{-1}** of Run 2 data, ATLAS performed combined measurements of Higgs boson production and decays:
  - inclusive signal strength
  - production cross sections
  - simplified template cross sections
- Based on **139 fb^{-1}** of full Run 2 data, ATLAS performed combined measurements of total and differential Higgs boson cross sections
- All major production modes (ggF, VBF, WH, ZH, ttH) are observed
- All measurements are in agreement with the SM within the improved uncertainties
- Results can be interpreted using “kappa”, EFT and BSM models

Backup slides

Production mode cross sections (assuming the SM decays)



	σ_{ggF}	σ_{VBF}	σ_{WH}	σ_{ZH}	$\sigma_{t\bar{t}H+tH}$
σ_{ggF}	1	−0.08	−0.02	−0.02	0.07
σ_{VBF}	−0.08	1	0.01	0.02	0.05
σ_{WH}	−0.02	0.01	1	−0.03	−0.01
σ_{ZH}	−0.02	0.02	−0.03	1	0.00
$\sigma_{t\bar{t}H+tH}$	0.07	0.05	−0.01	0.00	1

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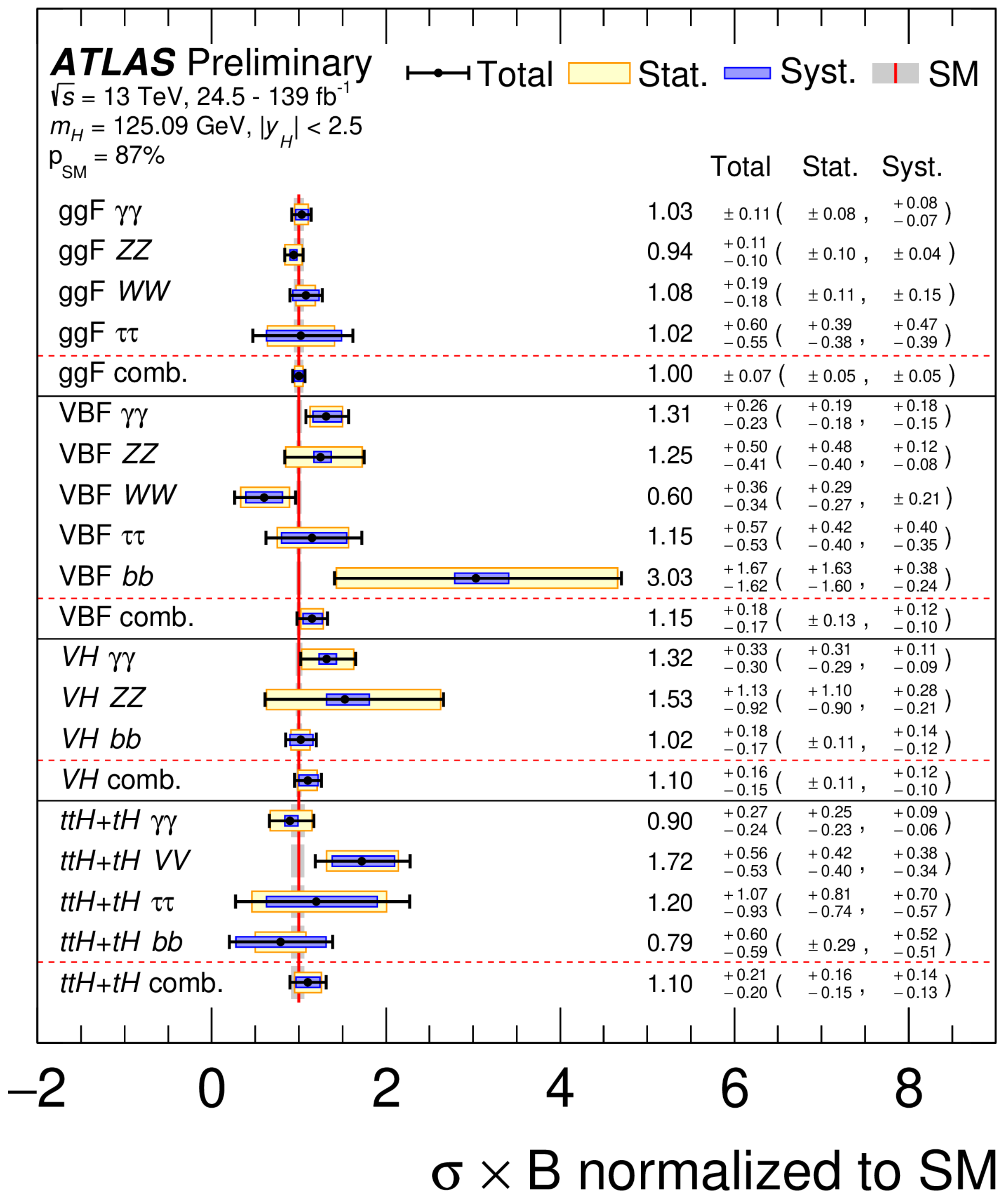
Production mode cross sections in each decay channel



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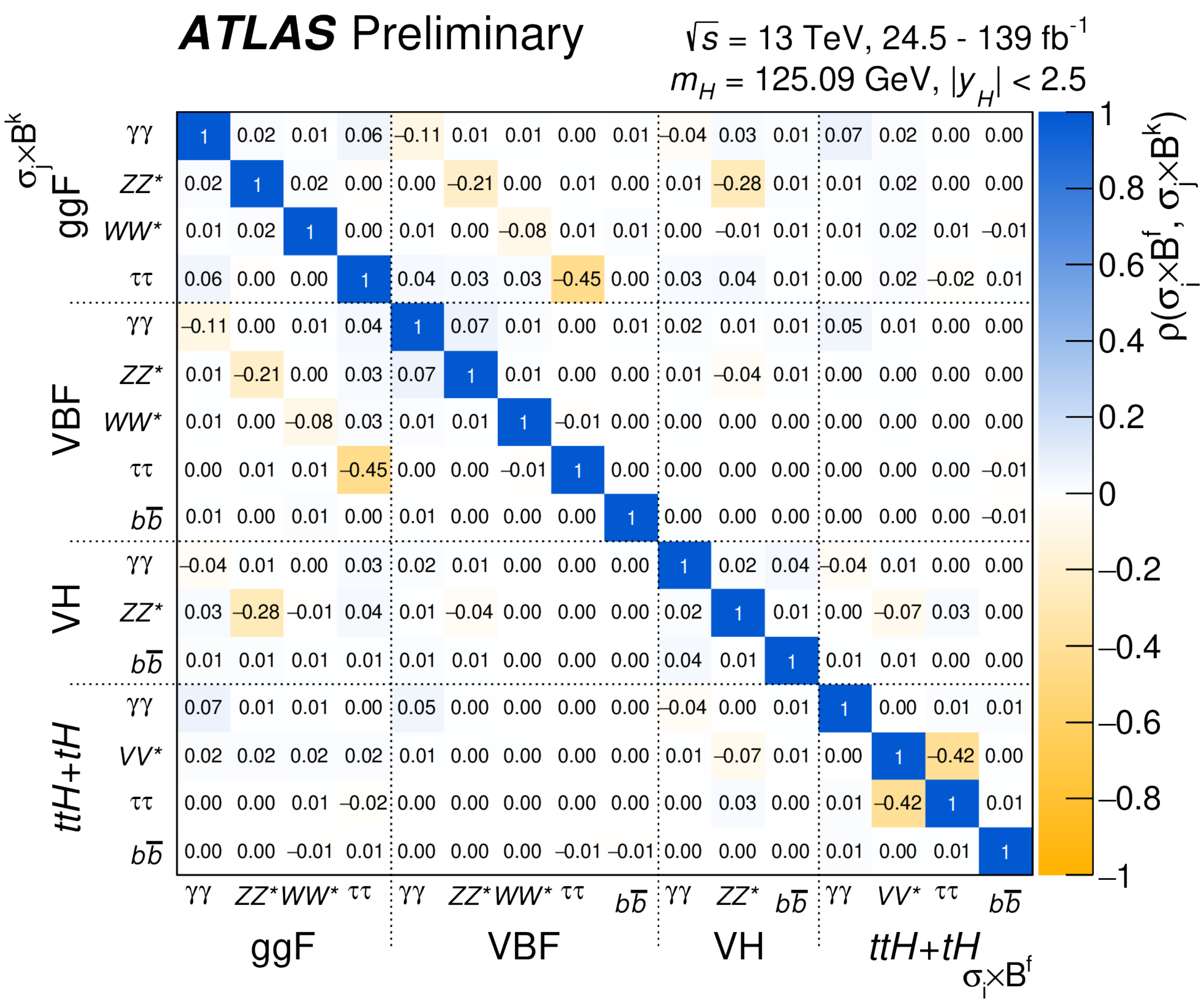
Production mode cross sections in each decay channel



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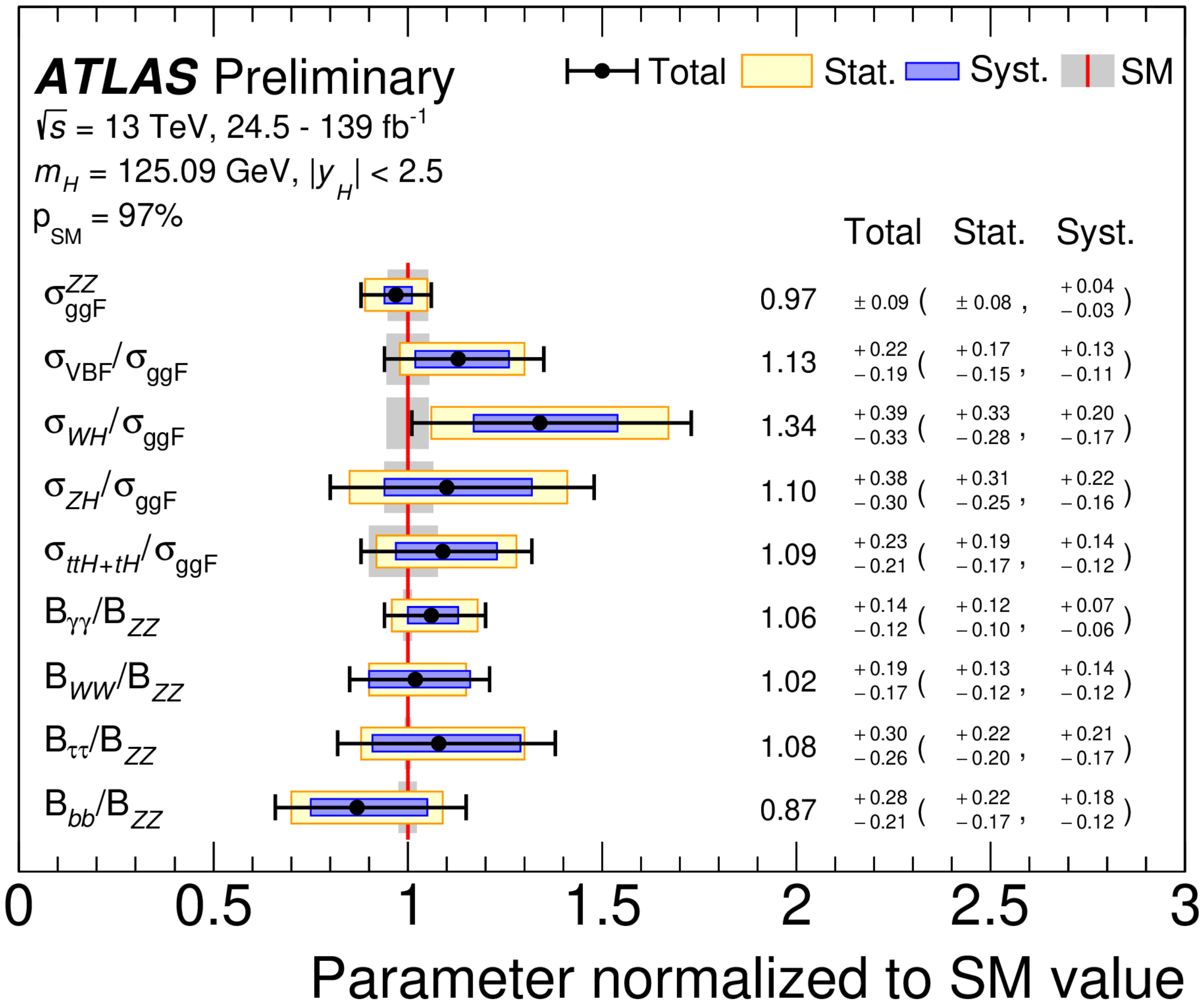
Production mode cross sections and decay branch ratios



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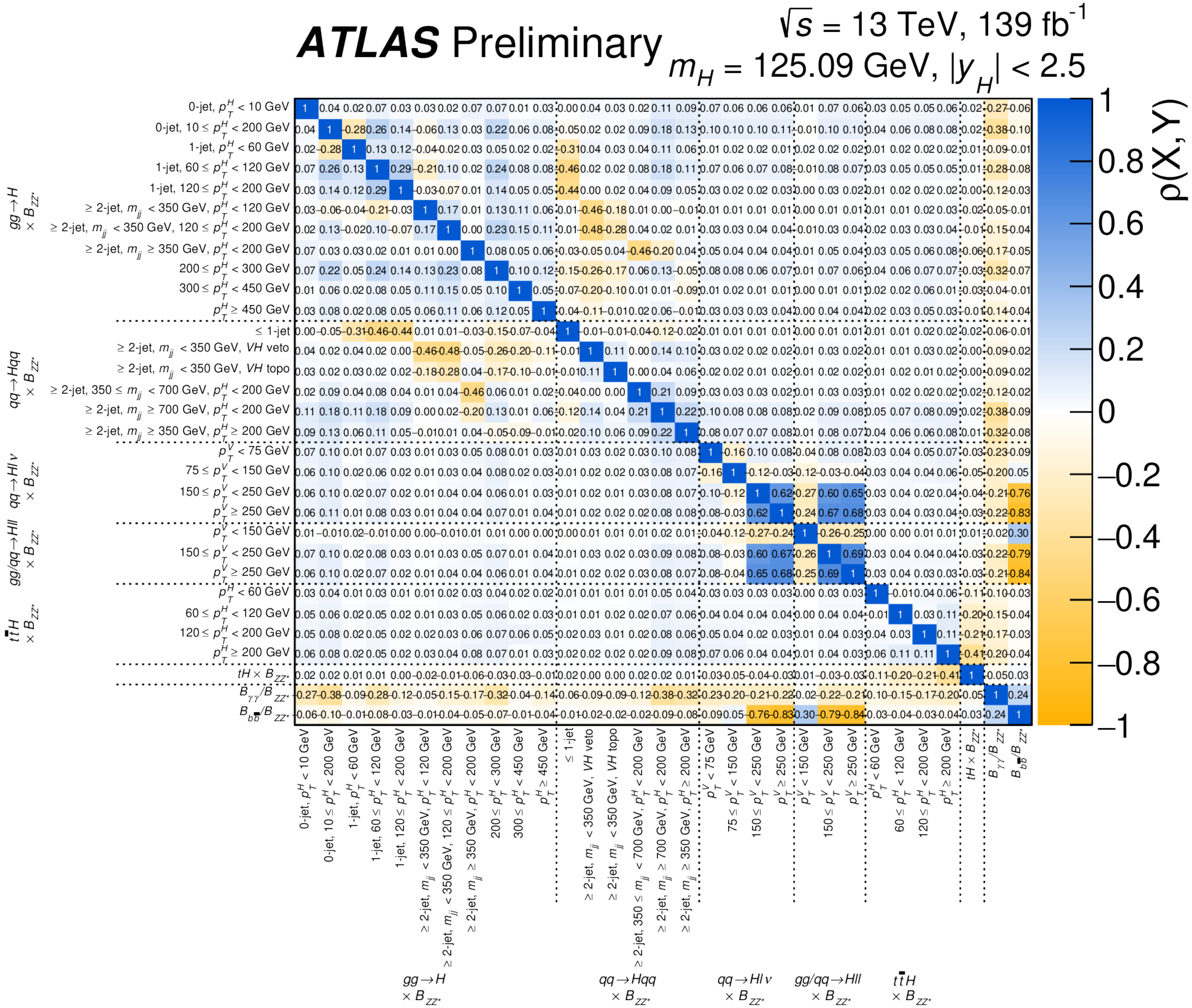
STXS results



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Parametrizations using coupling modifier ("kappa")

Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

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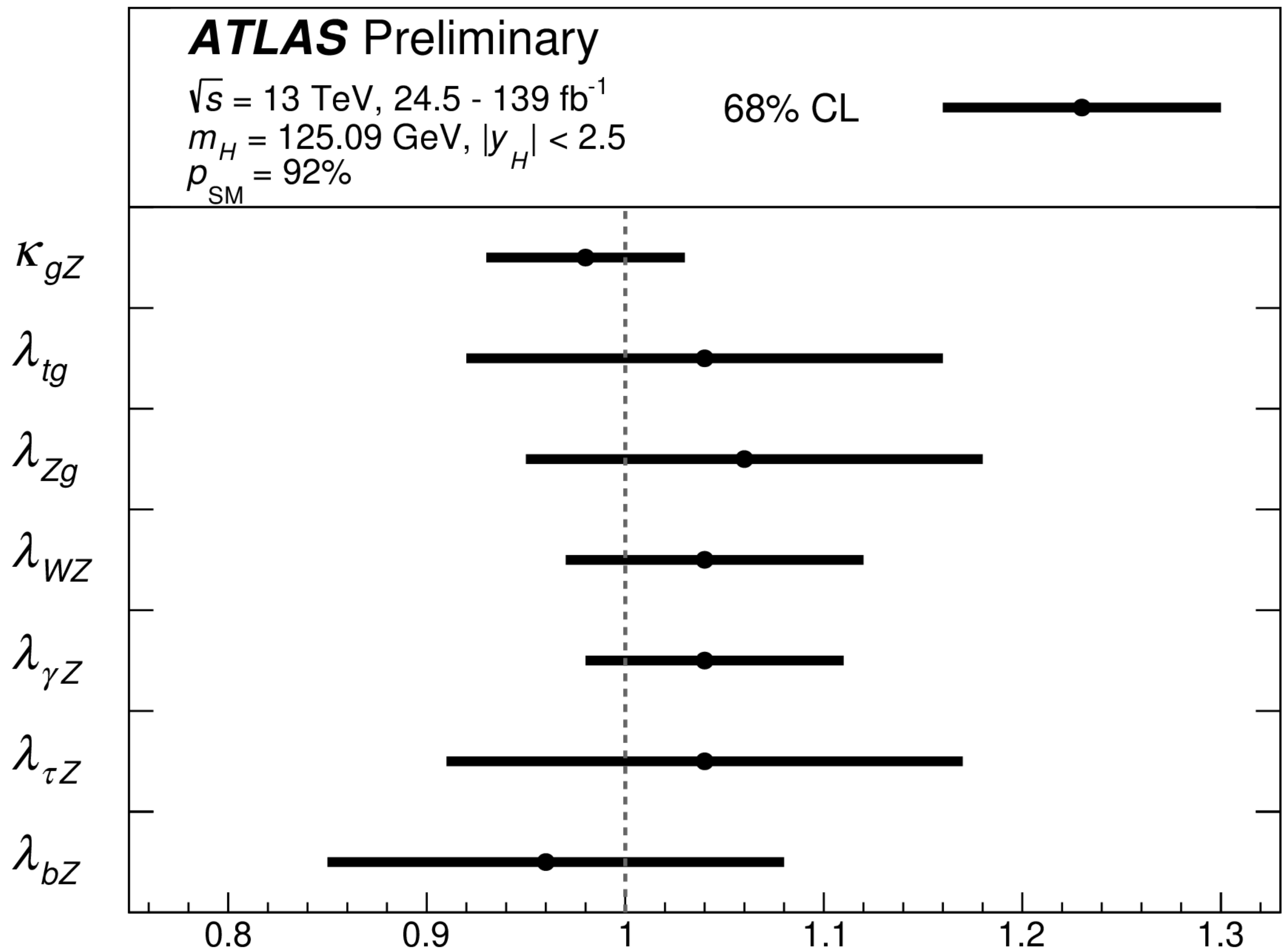
Coupling modifier interpretation: no assumption on total width



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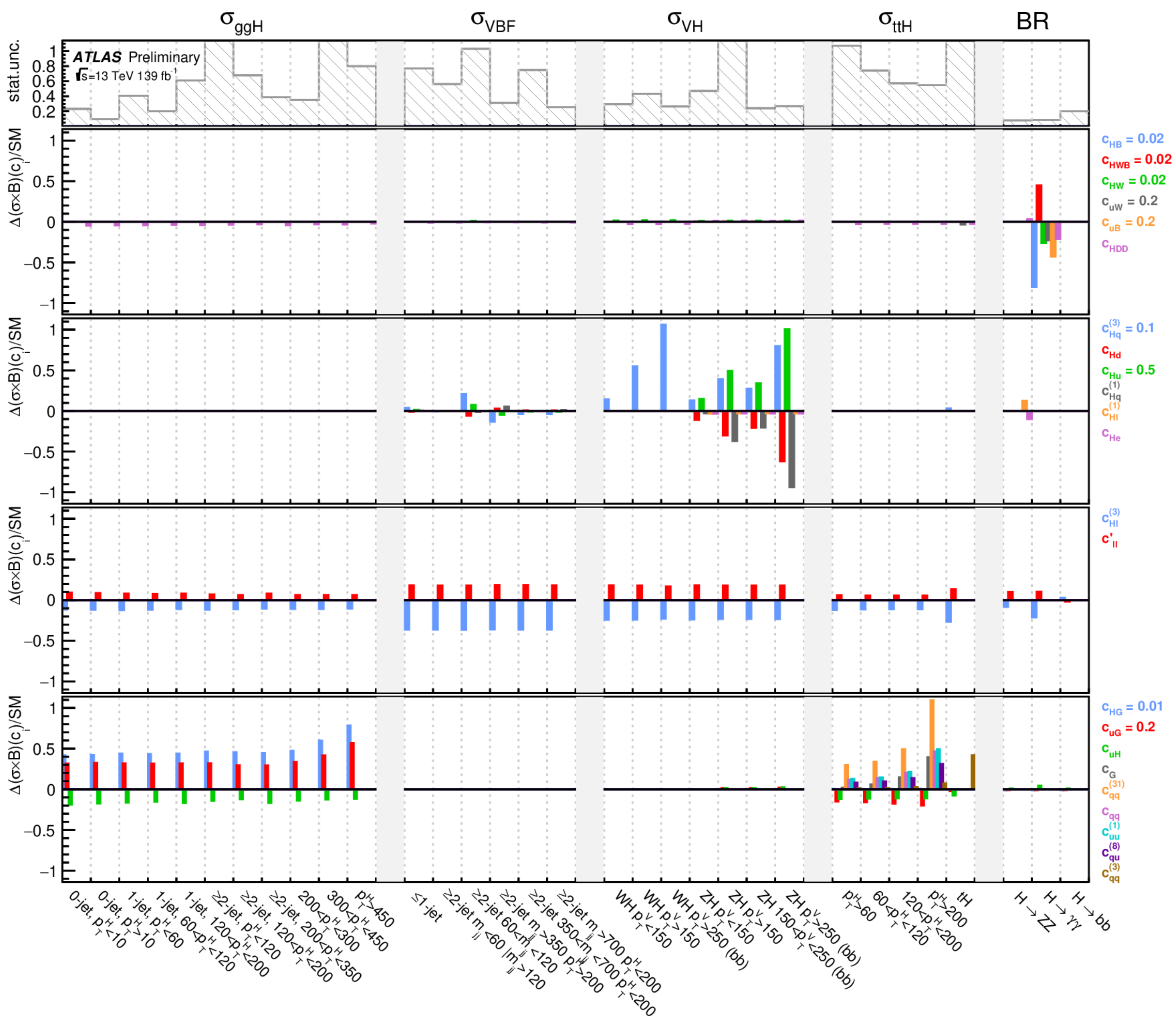
Wilson coefficients

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$(H^\dagger D^\mu H)^*\,(H^\dagger D_\mu H)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

ATL-PHYS-CONF-2020-053

Interpretation of STXS with EFT



ATL-PHYS-CONF-2020-053

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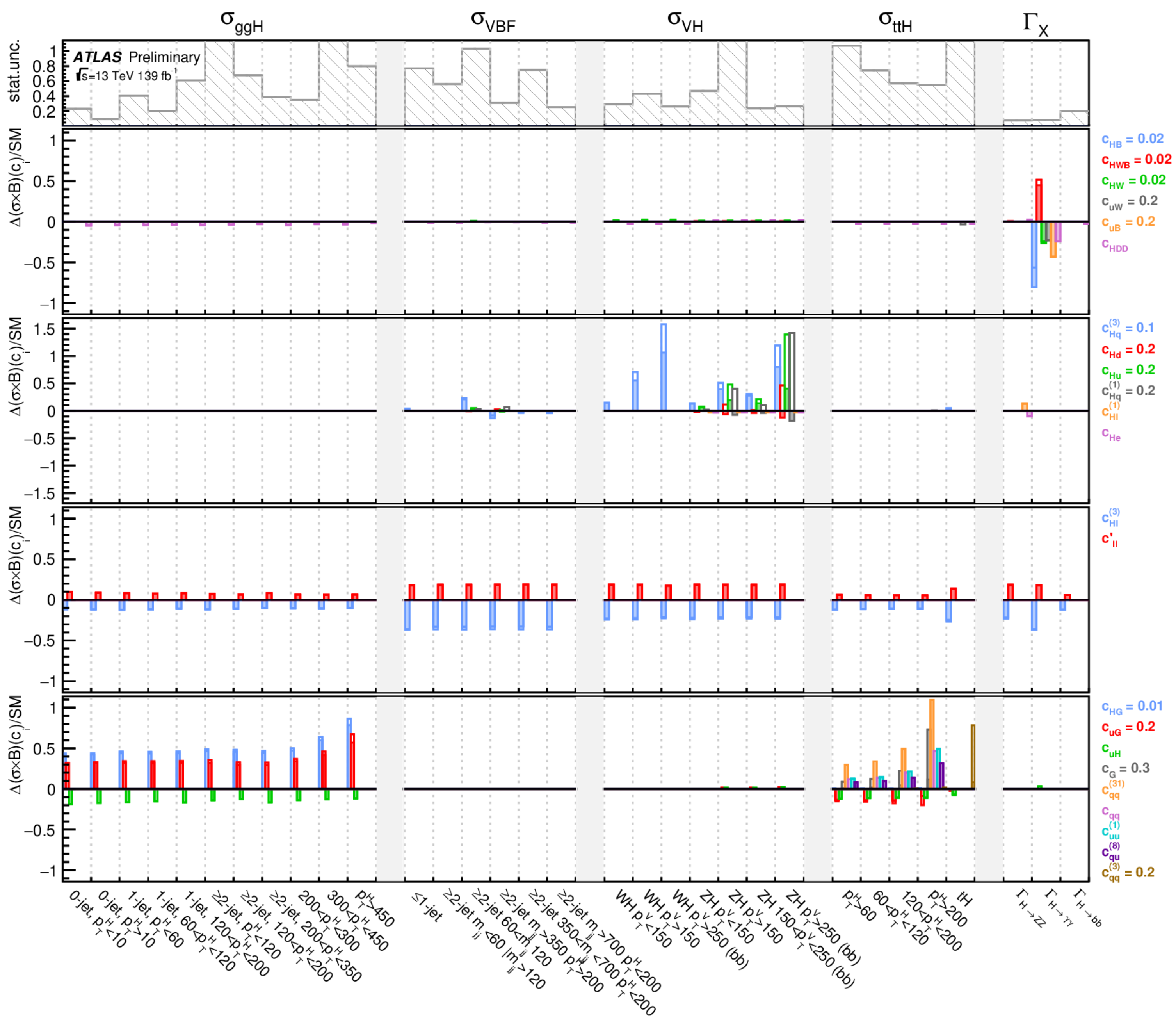

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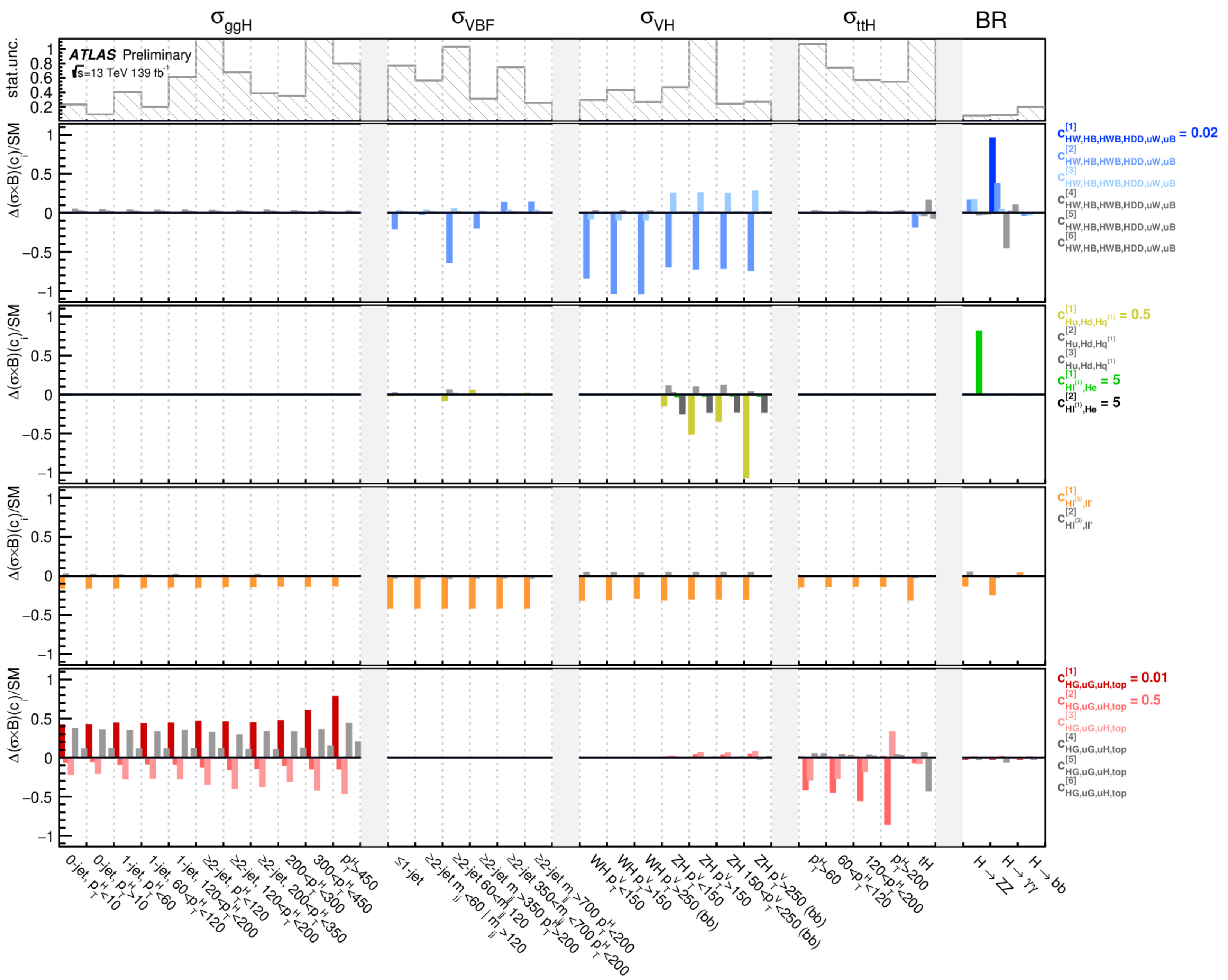

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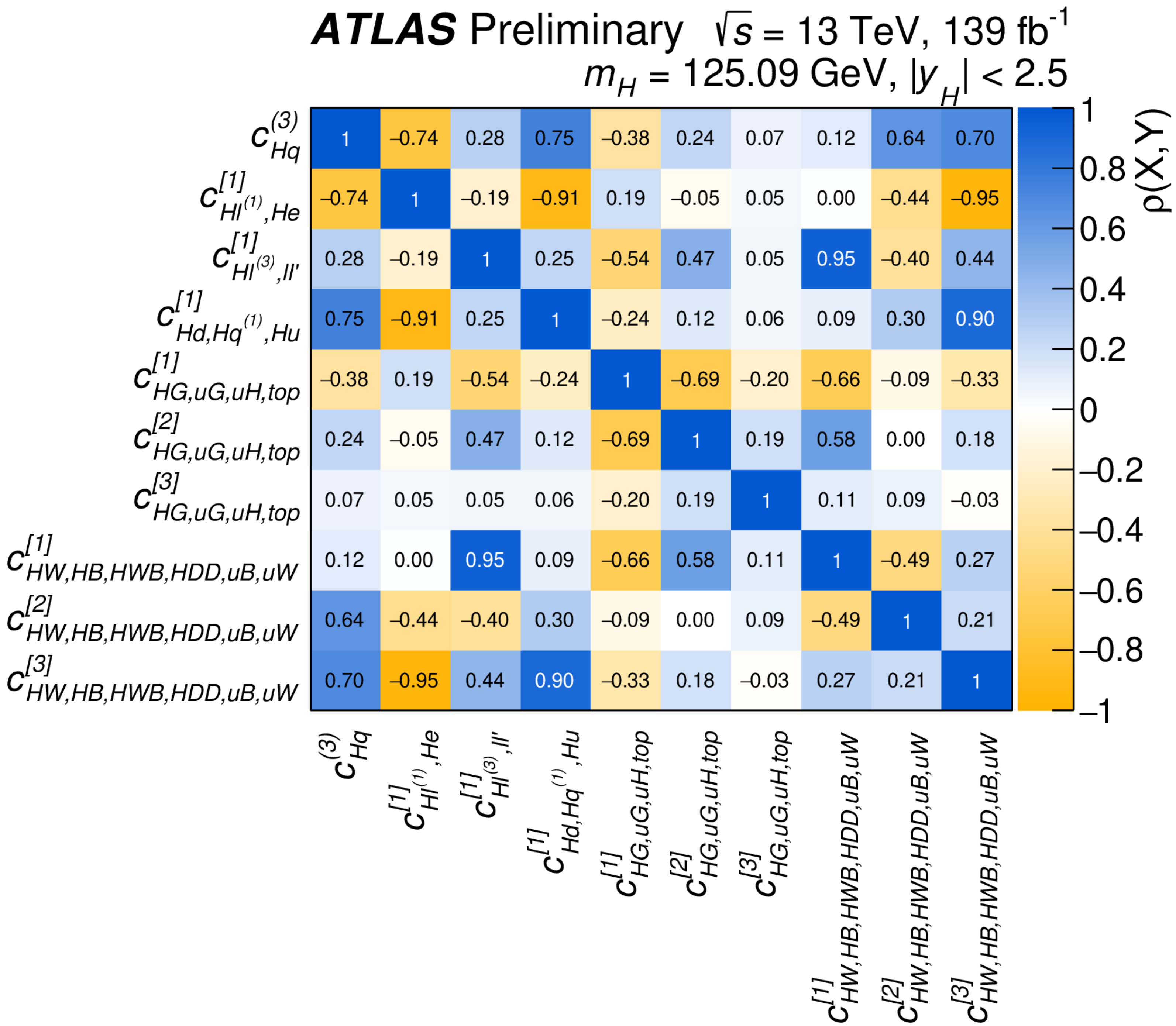

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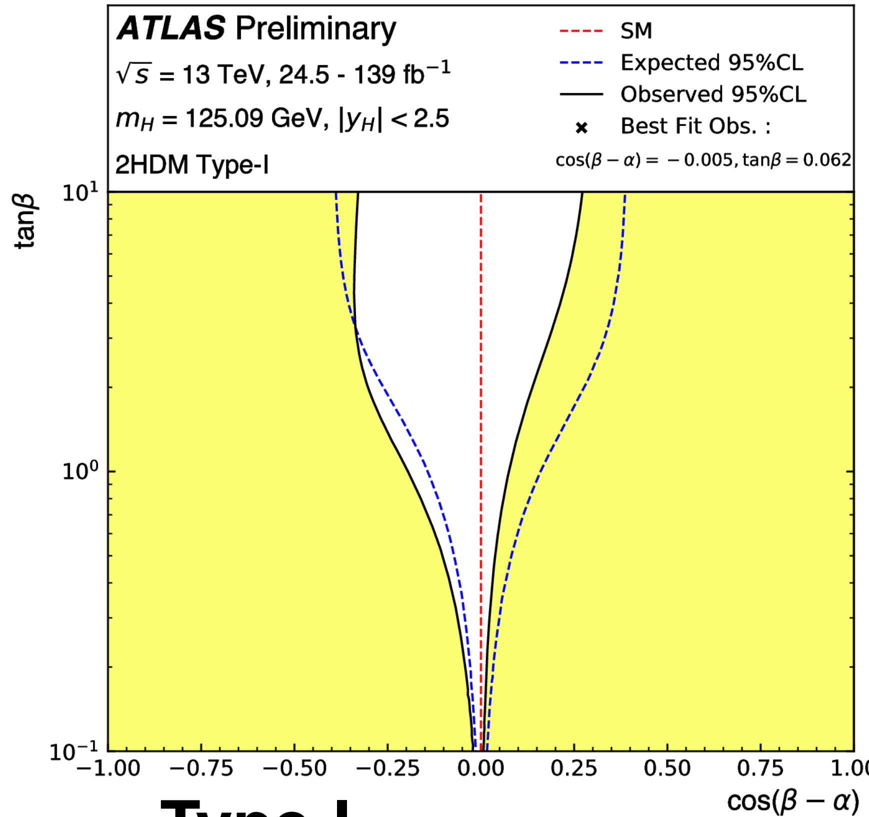
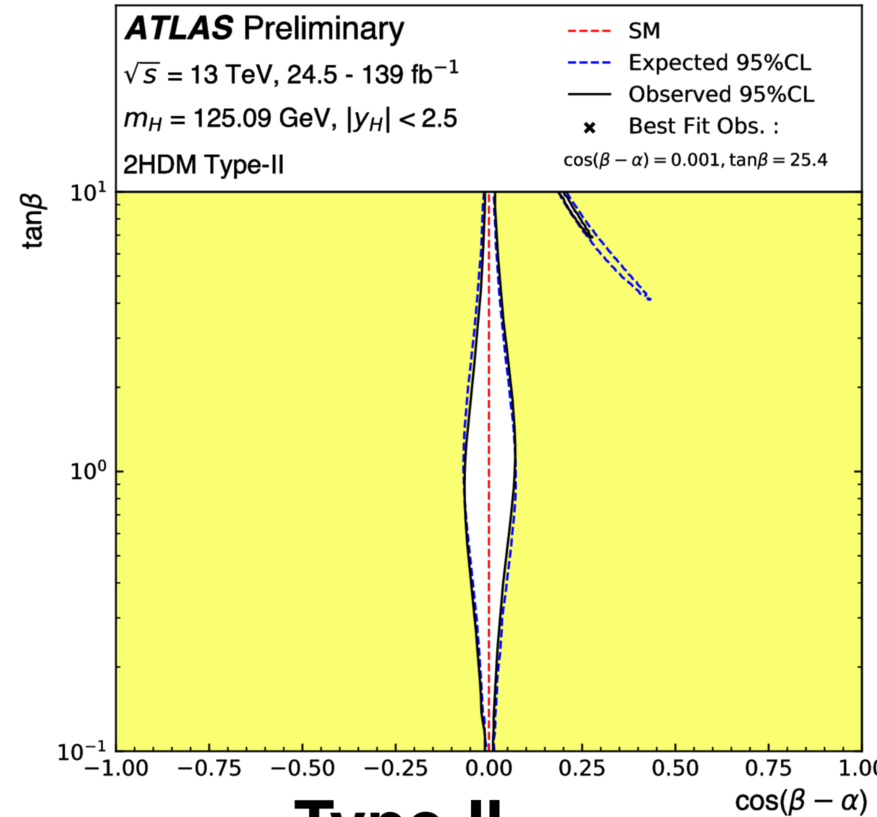
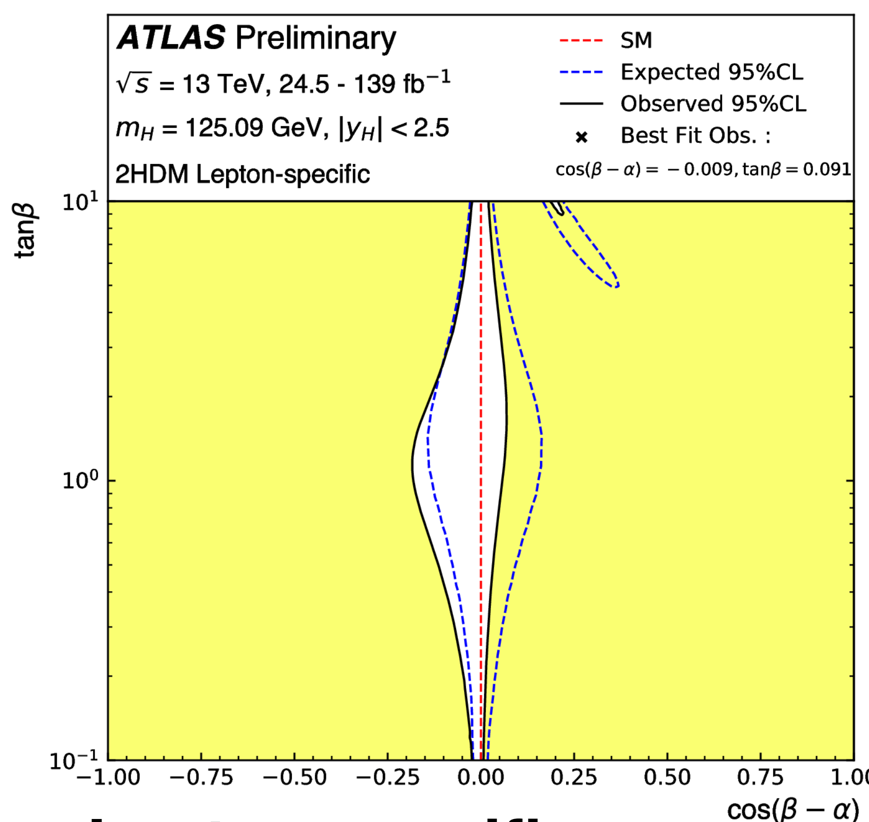
Constraints on Two Higgs Doublet Model (2HDM)



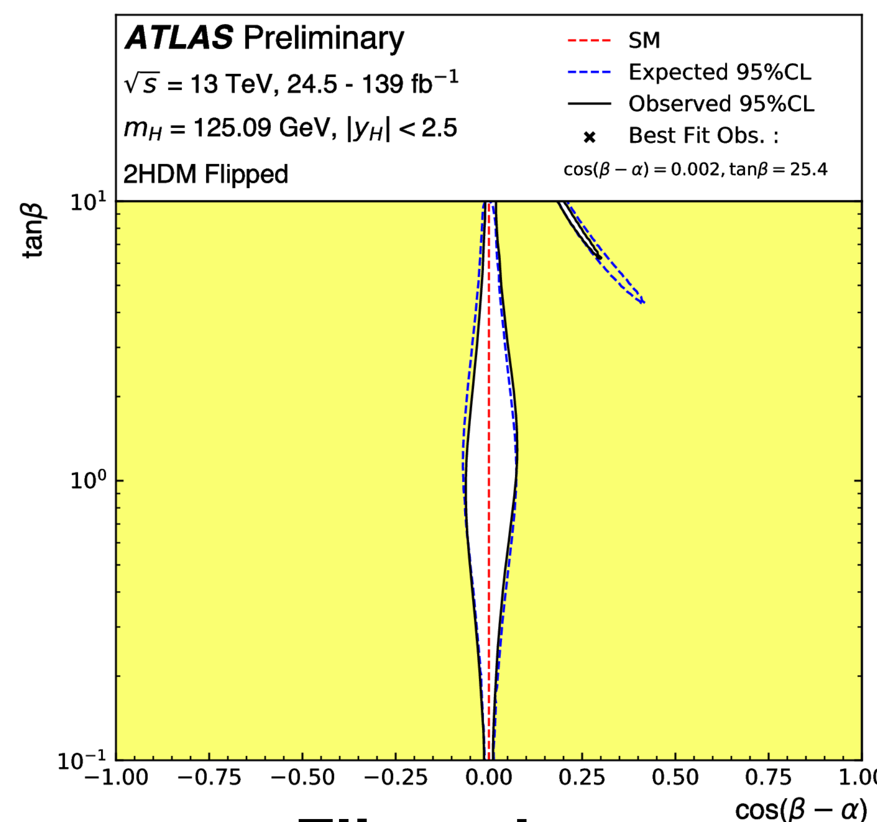
Type-I



Type-II



Lepton-specific



Flipped

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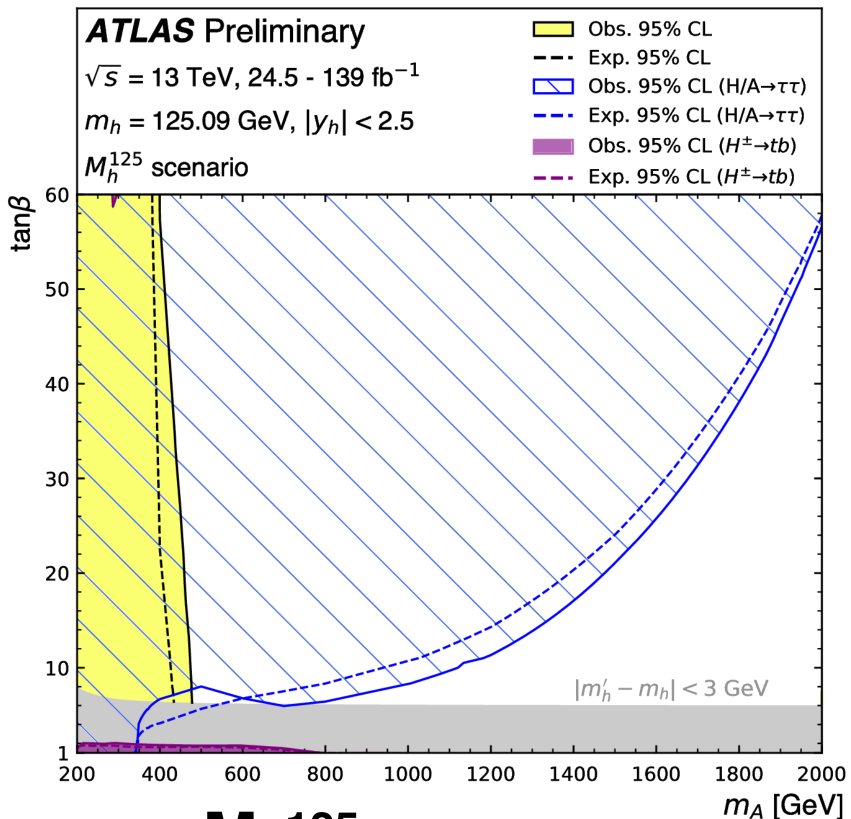
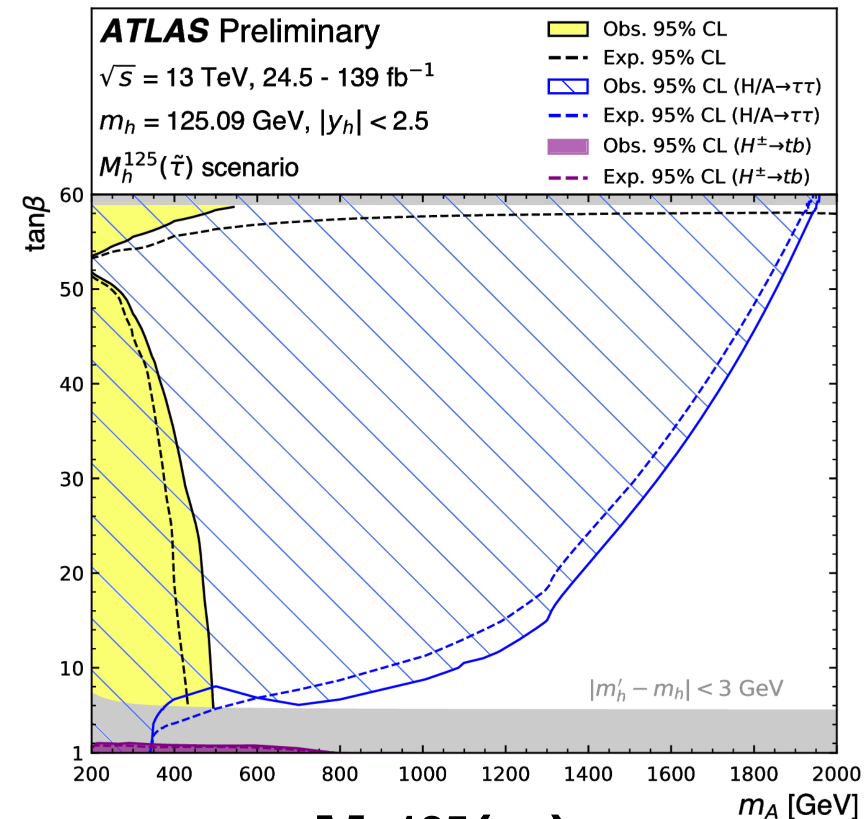
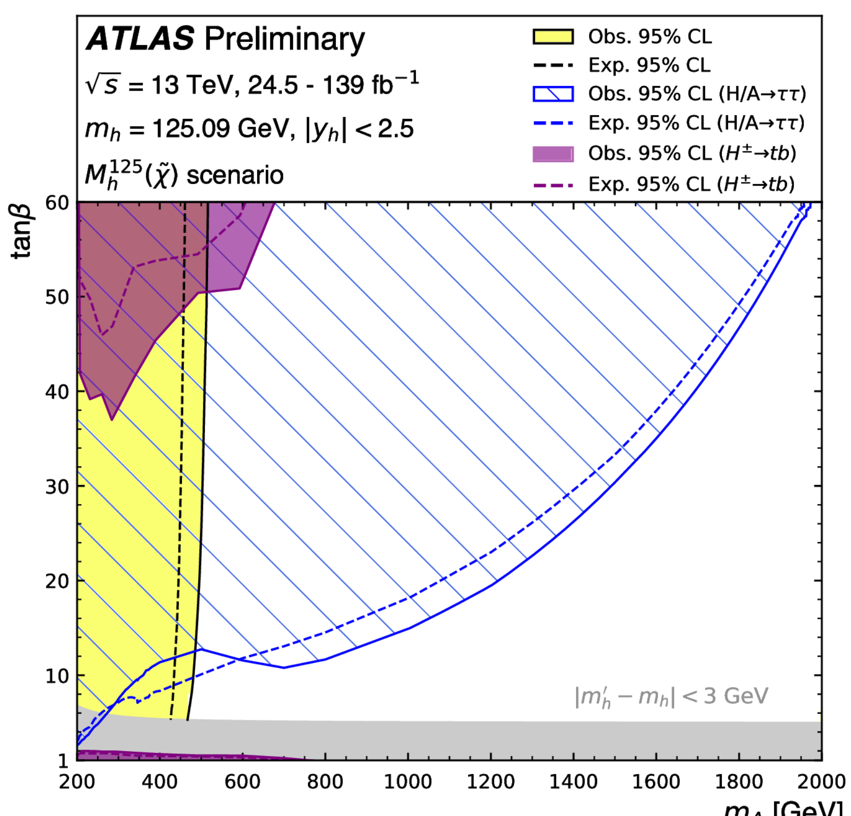
Constraints on Minimal Supersymmetric Standard Model (MSSM)



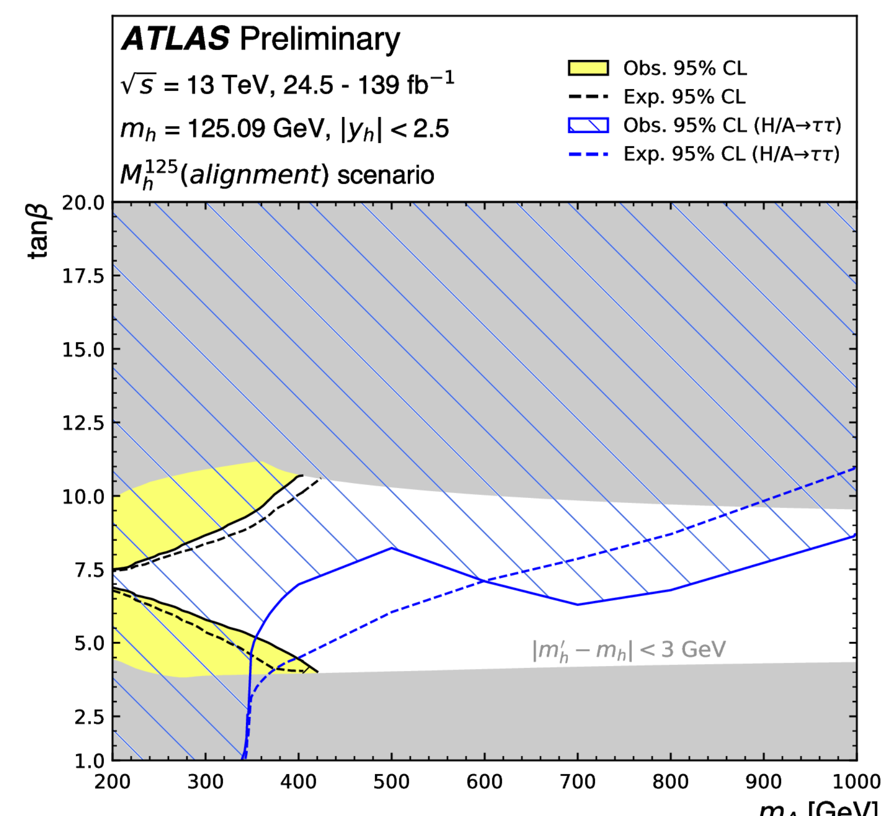
M_h^{125}



$M_h^{125}(\tau\sim)$



$M_h^{125}(\chi\sim)$



M_h^{125}(alignment)

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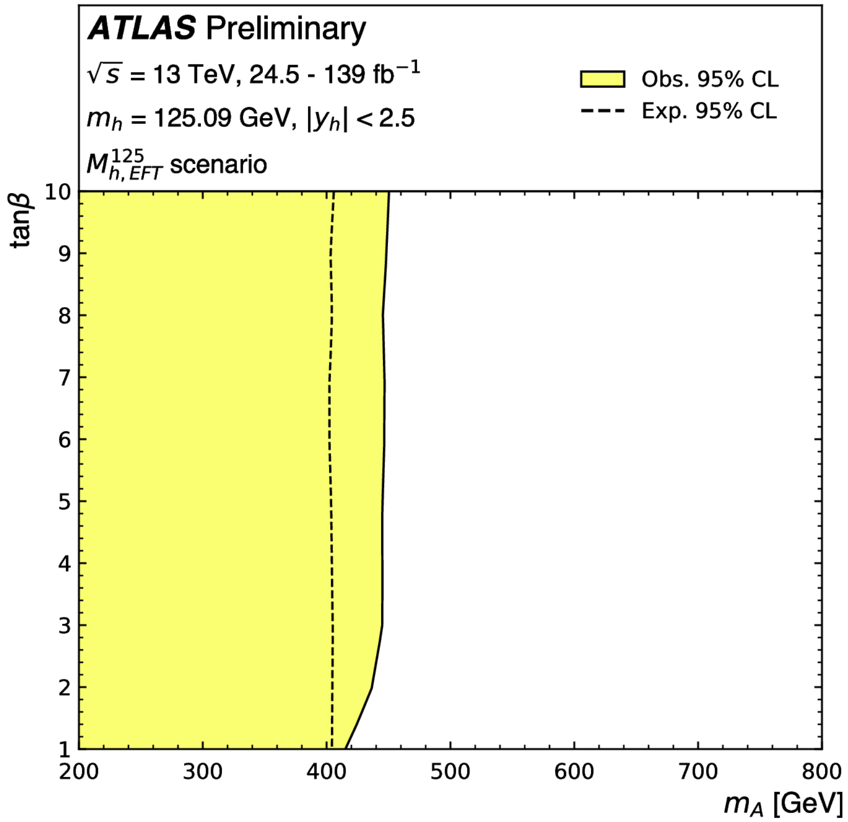
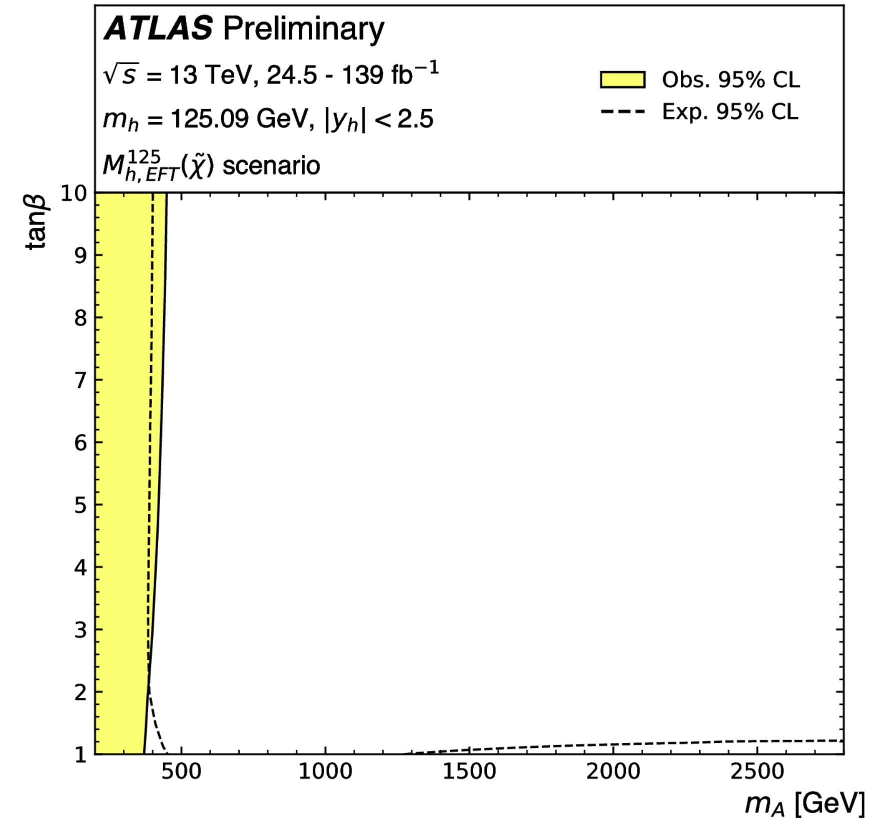
Constraints on Minimal Supersymmetric Standard Model (MSSM)



$M_{h,EFT}^{125}$



$M_{h,EFT}^{125}(\chi^{\sim})$

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