

Combined Higgs measurements with ATLAS

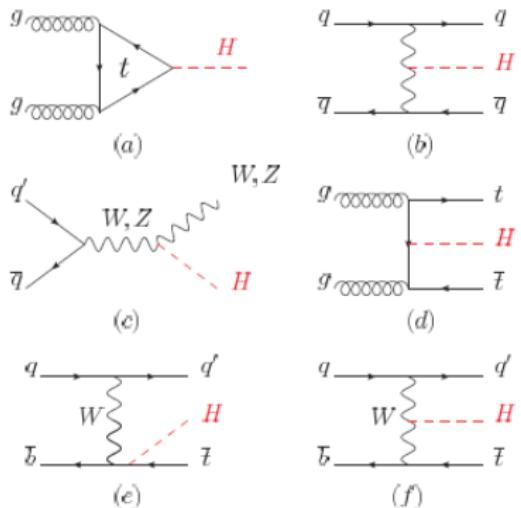
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(IPHC Strasbourg since 01/11/21)

IRN Terrascale workshop
Clermont-Ferrand – November 2021



Introduction

- Many Higgs measurements since discovery in 2012: cross sections, coupling parameters, CP properties, etc.
- So far, all confirming SM predictions

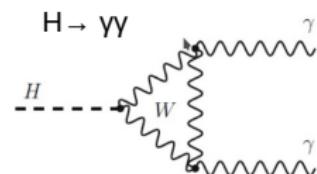
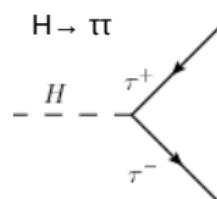
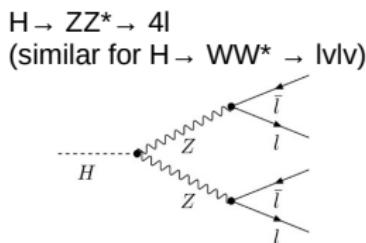
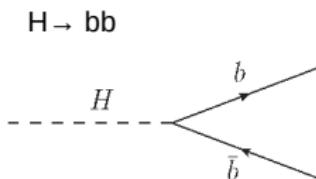


- For given Higgs mass, all couplings / cross sections predicted in SM
- Excellent predictions at high orders that can be compared to measurements
- More information from kinematic dependence of cross sections

Introduction

- Differential cross sections allow to probe kinematic dependence of Higgs production
 - Fully inclusive differential measurements possible only in very few channels ($H\gamma\gamma$, $H4l$) and not easy to combine
 - Production mode measurements have good sensitivity but are model dependent
 - Interpretations can target specific models or be done in a generic way (EFT)
- Large gain from combination of different decay channels: sensitivity in different production modes and kinematic regimes (balancing statistical and systematic uncertainties)
- Latest ATLAS Higgs combination published as conference note for Higgs2021 [ATLAS-CONF-2021-053](#)

Input channels



$H \rightarrow \gamma\gamma$ (0.22%):

- clean, good resolution, smooth bkg.

$H \rightarrow ZZ^* \rightarrow 4\ell$ (0.01%):

- great significance & resolution

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$:

- MET in leptonic W decays

$t\bar{t}H(ML)$:

- channels with many leptons
- based on 36 fb^{-1} analysis

$H \rightarrow b\bar{b}$ (58%):

- difficult selection & modelling
- profit from associated particles

$H \rightarrow \tau\tau$ (6%):

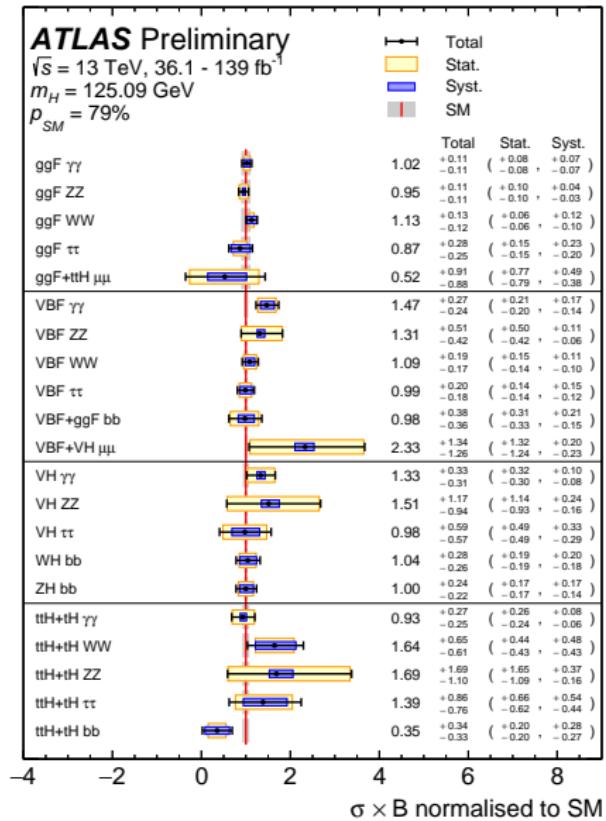
- τ 's reconstructed in many decay modes

$H \rightarrow \mu\mu$ (0.02%):

- only constraint on Higgs to 2nd generation lepton coupling

$H \rightarrow Z\gamma$ (0.015%):

Input channels



- Decay channels most sensitive for different production modes
- Balance between statistics in each channels and experimental / theory constraints

What do we measure

Production modes:

- Identified from associated particles
- Different sensitivity from decays
- Slight model dependence in definition of production modes

STXS:

- Measurements in production modes
- Adding kinematic information in BSM sensitive observable
- Refine bins with larger data stats

Couplings / Interpretations:

- Direct probing if coupling modifiers of Higgs to SM particles
- Can set constraints on BSM models (either concrete or generic in terms of EFT)

Signal strengths:

- Cross section measured relative to SM expectation
- Easy interpretation at the price of maximal model dependence

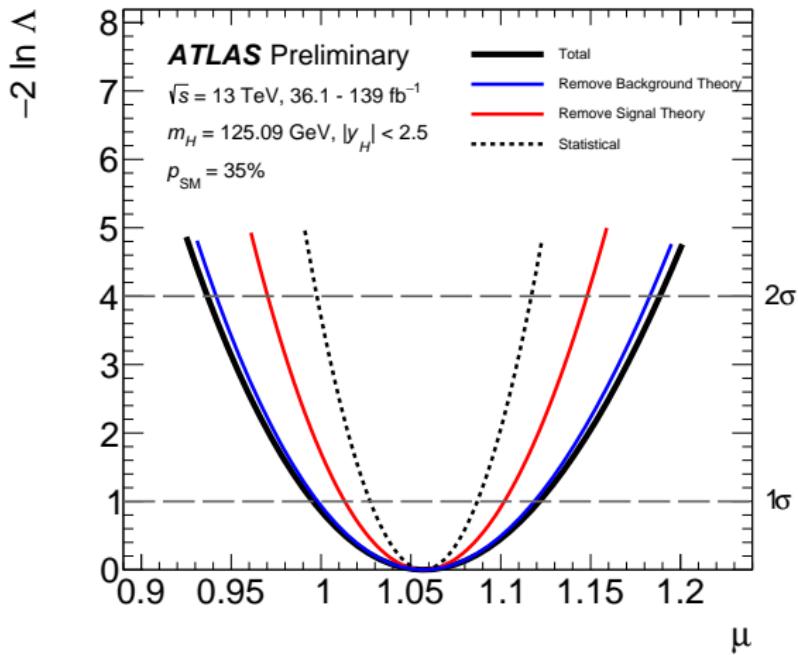
Cross sections:

- More generic results with theory uncertainties only impacting acceptance estimation
- Results can be interpreted in any model

Combination strategy & systematic uncertainties

- POIs mainly targeting production side, common to all decay channels
- In general, analyses sensitive to $\sigma \cdot BR_X$
 - fit $\sigma \cdot BR_{ZZ^*}$ and $\frac{BR_X}{BR_{ZZ^*}}$
caveat: this leads to non-Gaussian correlation
- Systematic uncertainties split as much as possible into physical sources
 - correlate same sources across channels

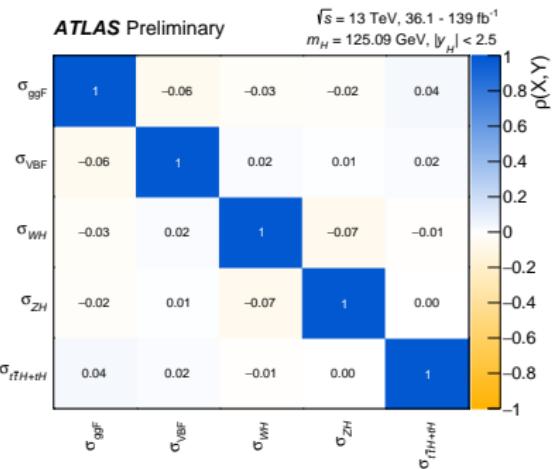
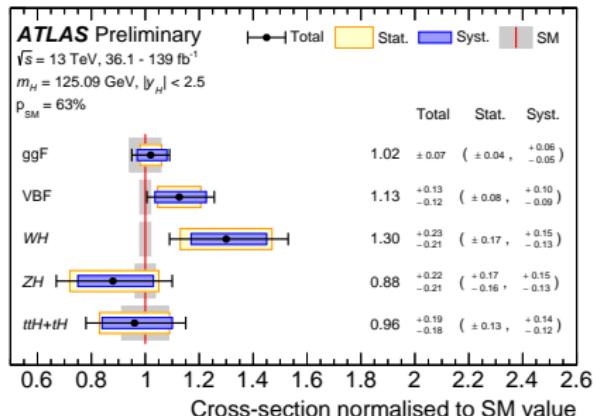
Global signal strength



$$\mu = 1.06 \pm 0.06$$

$$= 1.06 \pm 0.03 \text{ (stat.)} \pm 0.03 \text{ (exp.)} \pm 0.04 \text{ (sig. th.)} \pm 0.02 \text{ (bkg. th.)}$$

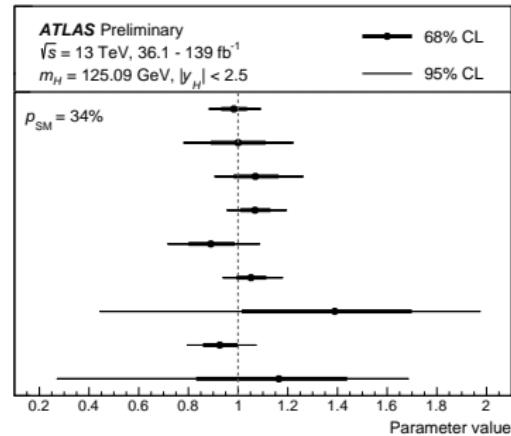
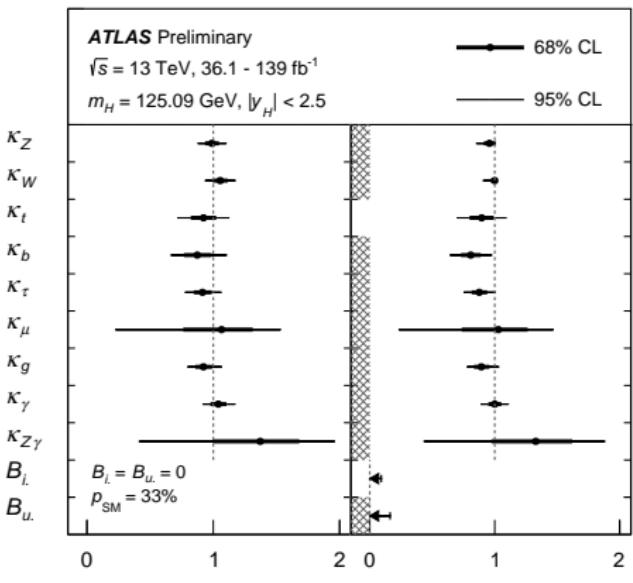
Production mode measurements



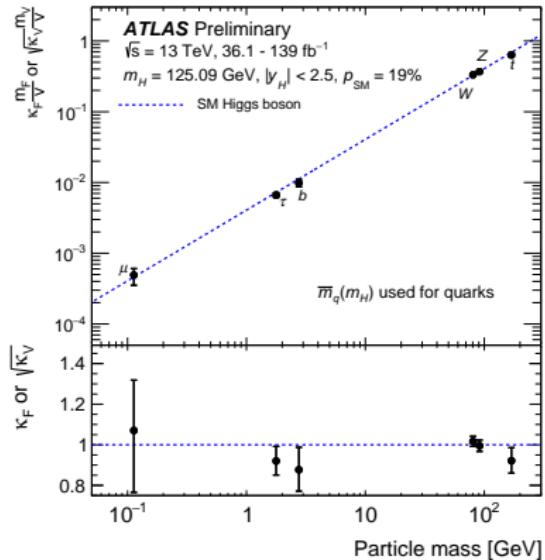
- Main production modes measured with great precision
- Insertion of many decay channels allows to reduce correlations dramatically
- Many of them start to be systematics dominated
- More information obtained from kinematic binning

Coupling parameter measurements

- κ -framework used since Run 1: modifiers to SM Higgs couplings
- Direct interpretation at price of strong model dependence
- Some assumptions needed to include couplings in loops, e.g. in ggF
- Measurements assuming additional BSM couplings



Coupling parameter measurements



- Good visualisation of SM Higgs couplings prediction
- Couplings to 3rd generation fermions all smaller than prediction due to experimental coincidences:
 - downward fluctuation in $t\bar{t}H(b\bar{b})$
 - upward fluctuations in VBF and VH leading to low κ_b and κ_τ

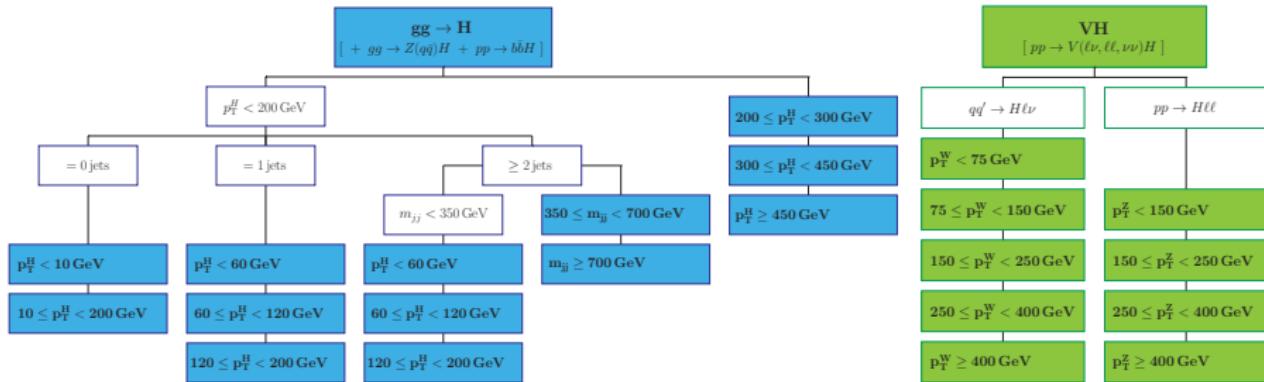
Simplified Template Cross Sections

Differential cross section measurement in each production mode

- probe kin. dependence of SM prediction
 - exploit different sensitivity to production modes in each decay channel in combination

Bins defined dynamically & adapted with growing data statistics:

- fine binning (esp. in high-pT tails) gives sensitivity to BSM
 - acceptance in each bin should be considered flat compared to stat. uncertainty



Simplified Template Cross Sections

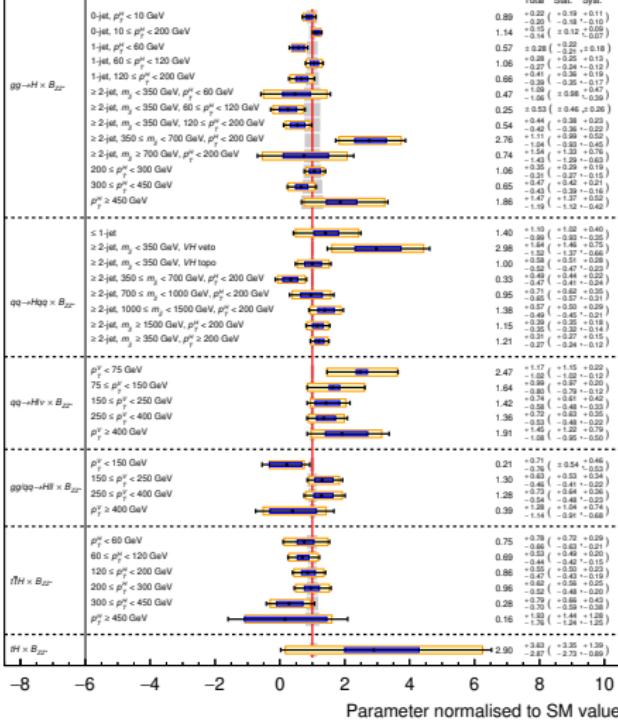
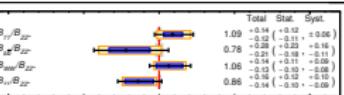
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$

$m_H = 125.09 \text{ GeV}, |\gamma_j| < 2.5$

$P_{\text{SM}} = 92\%$

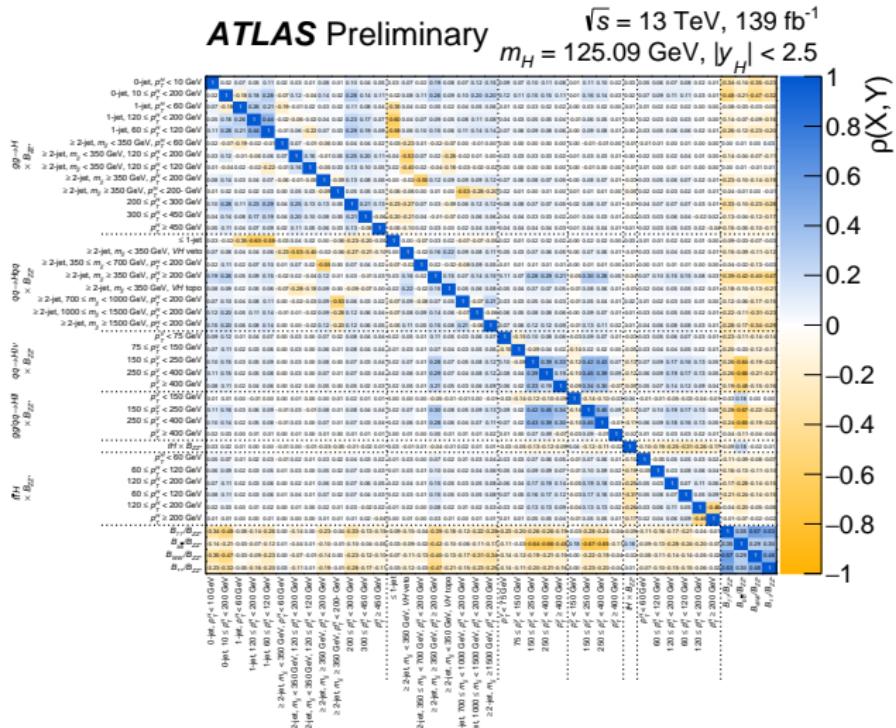
Total Stat. Syst. SM



- Including analyses with stage 1.2 STXS binning available
- Maximal sensitivity from all available input channels
- Measuring more and more bins with great precision; in particular reaching high-pT regime
- Starting to be sensitive to tH production

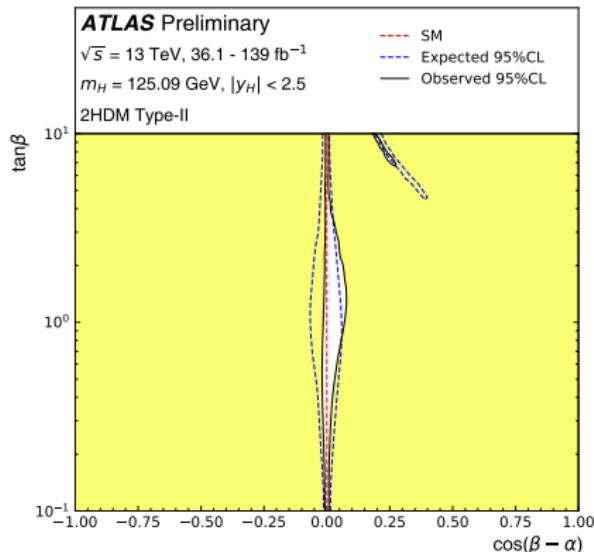
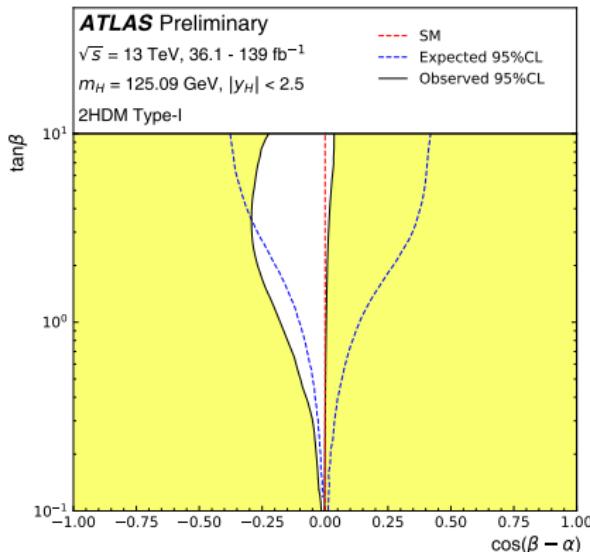
STXS correlations

- Decorrelating production and decay modes when adding channels
- Correlation between BR's from ratio to BR_{ZZ^*}



2HDM interpretation

- Interpretation within concrete models recommended by LHCXS-WG: exclusion limits
- Two-Higgs-Doublet-Models (2HDM): limits from direct searches as well as from Higgs cross sections
- Several benchmark scenarios with different assumptions



- BSM scale Λ not directly accessible by LHC; decoupling from SM:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \dots$$

- linear combination of dimension d operators; Wilson coefficients c_i :

$$\mathcal{L}_n = \sum_i c_i^d \mathcal{O}_i^{d=n}$$

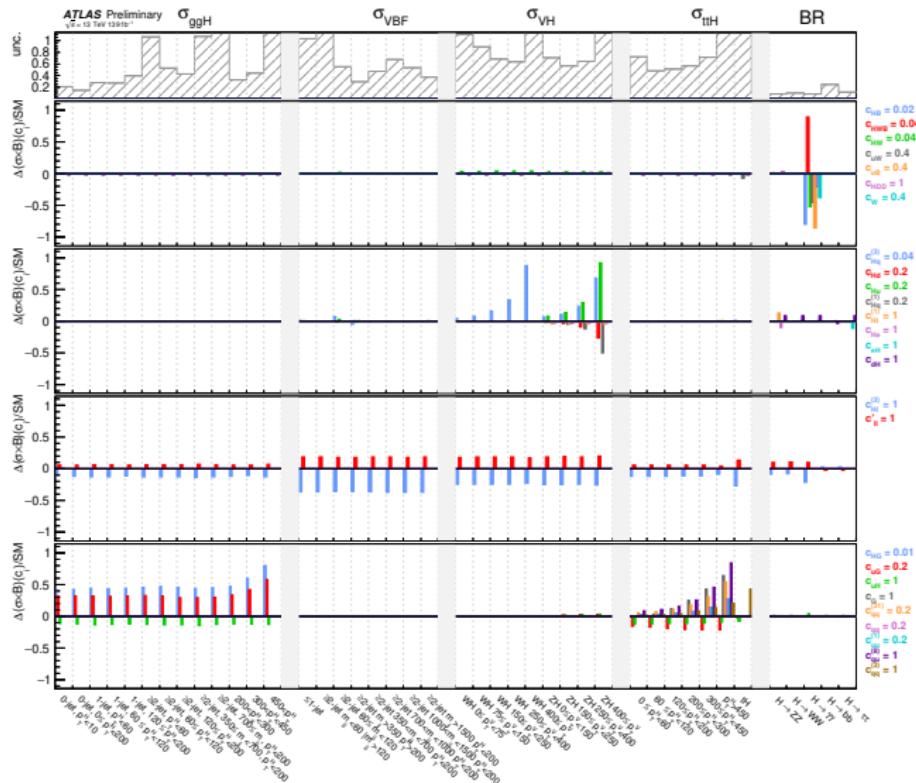
- Constrain $d = 6$ operators in SMEFT with Warsaw basis
- Compute EFT impact relative to SM cross section (or width) and multiply to best SM prediction

$$\frac{\sigma_{EFT}}{\sigma_{SM}} = 1 + \sum_i A_i c_i + \sum_{i,j} B_{ij} c_i c_j$$

- MG_aMC@NLO simulations at NLO (ggF , $ggZH$, $H \rightarrow \gamma\gamma$, $H \rightarrow gg$) or LO (rest)

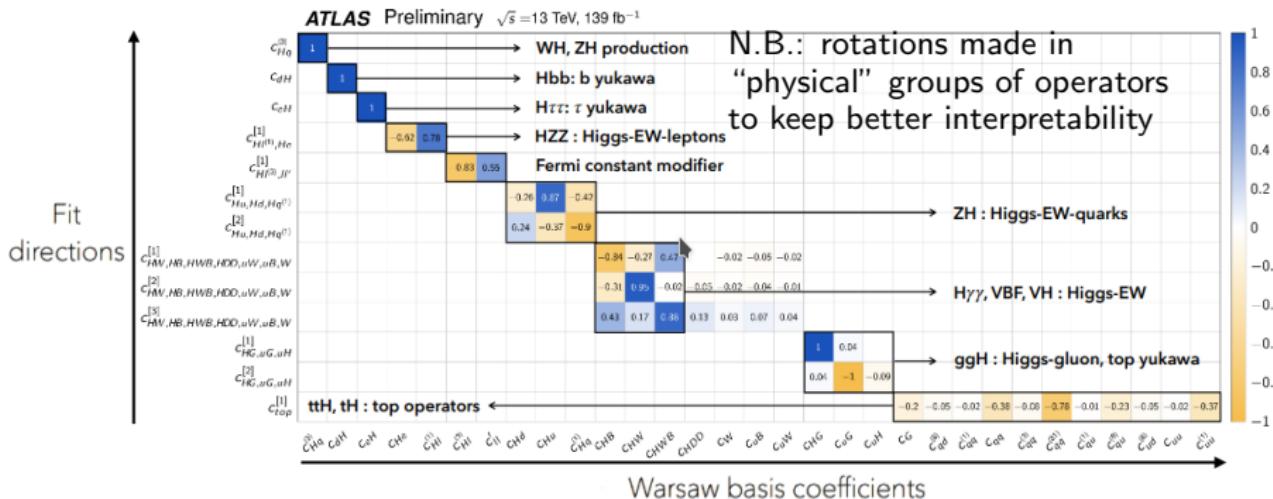
EFT interpretation

Fully linearise impact on $\sigma_{STX,i} \cdot BR_X$; quadratic terms will be added later



Sensitive directions

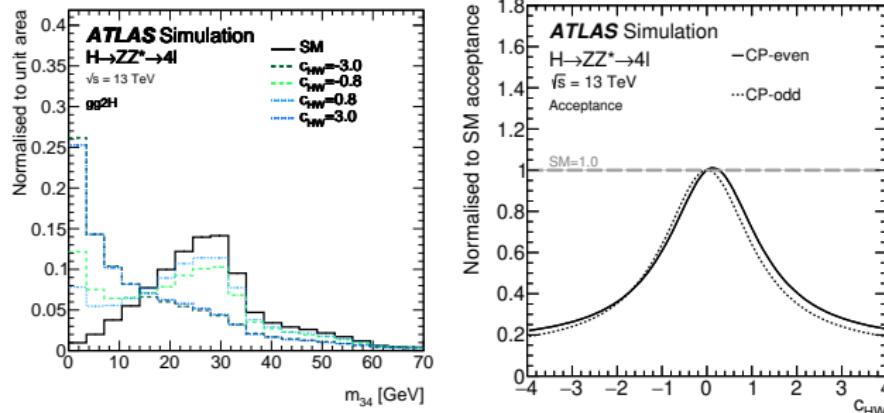
- As inclusive as possible: simultaneous fit of all sensitive directions
- PCA on full EFT info. matrix obtained from linear propagation of EFT parametrisation to STXSxBR cov. matrix
- Retain directions with large eigenvalues ($\sim \frac{1}{\sqrt{\sigma}}$)
- Check that neglected directions have no impact on fitted ones



A note on acceptances

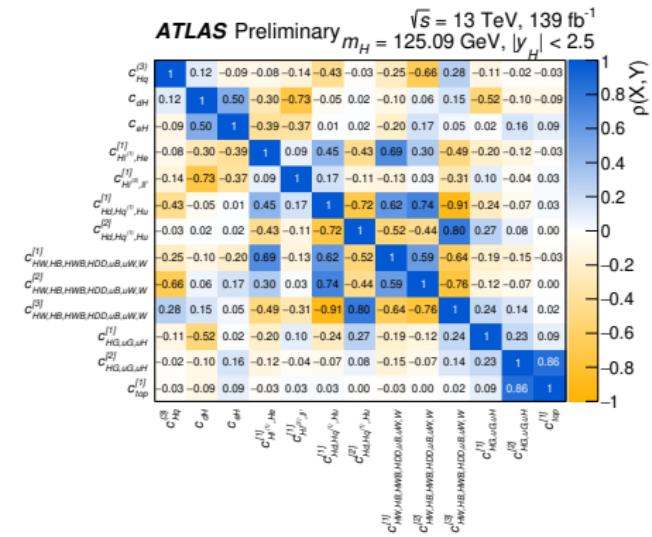
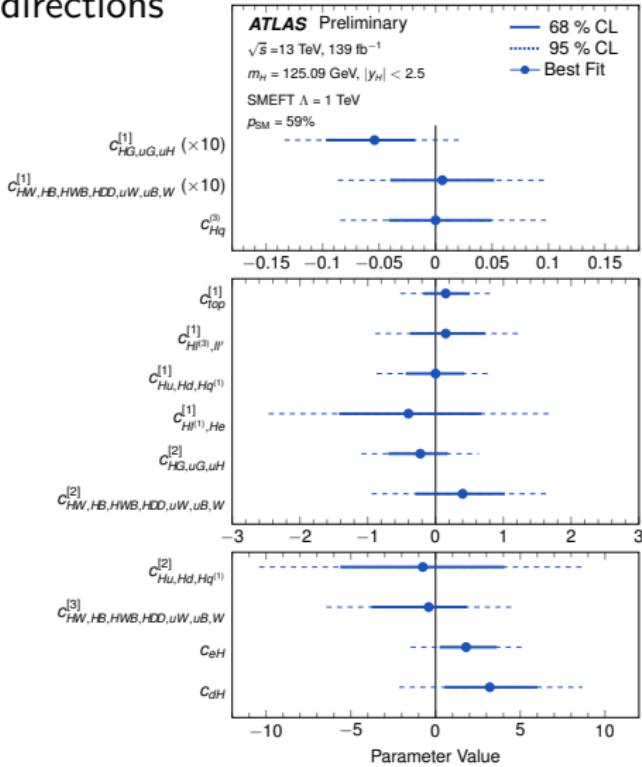
- In general, assuming SM acceptances:
 - STXS bins designed in a way to have relatively flat acceptances
 - studies in $H \rightarrow \gamma\gamma$ and $VH \rightarrow b\bar{b}$ showed max 10% difference due to reco effects
 - Exceptions: $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ selection based on dilepton invariant masses
- using explicit parametrisation of acceptance as a function of Wilson coefficients

[Eur.Phys.J C 80 \(2020\) 957](#)



EFT results

Good sensitivity to around 13 directions



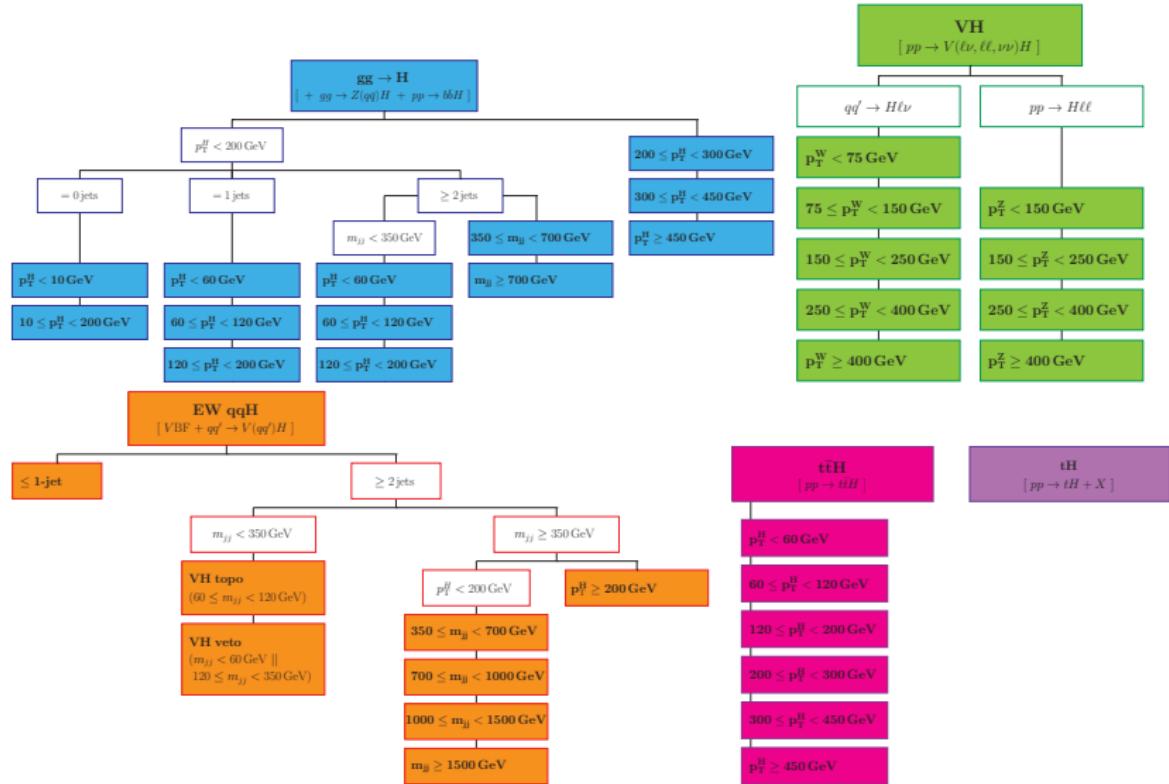
Correlations from experimental constraints between directions expected due to rotation in subgroups

Conclusion

- Combination including all analyses in main decay channels measured with ATLAS (mostly full Run 2)
- So far observed most main production modes; starting to be sensitive to tH
- Kinematic information from STXS stage 1.2; increasing sensitivity in high-pT tails
- Different interpretations in concrete models (2HDM); pushing exclusion limits, complementary to direct searches
- EFT interpretations in maximally general way; future plan for global ATLAS combination and ATLAS + CMS (+LHCb) combination

Backup

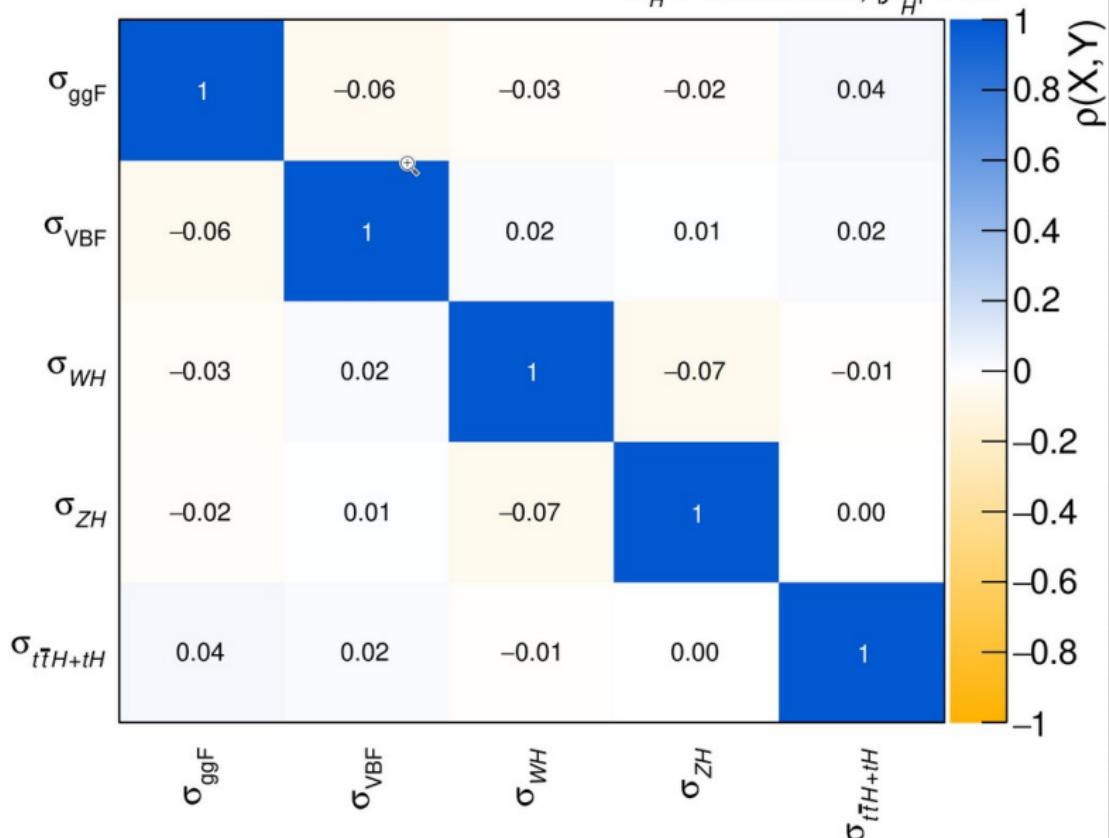
Simplified Template Cross Sections

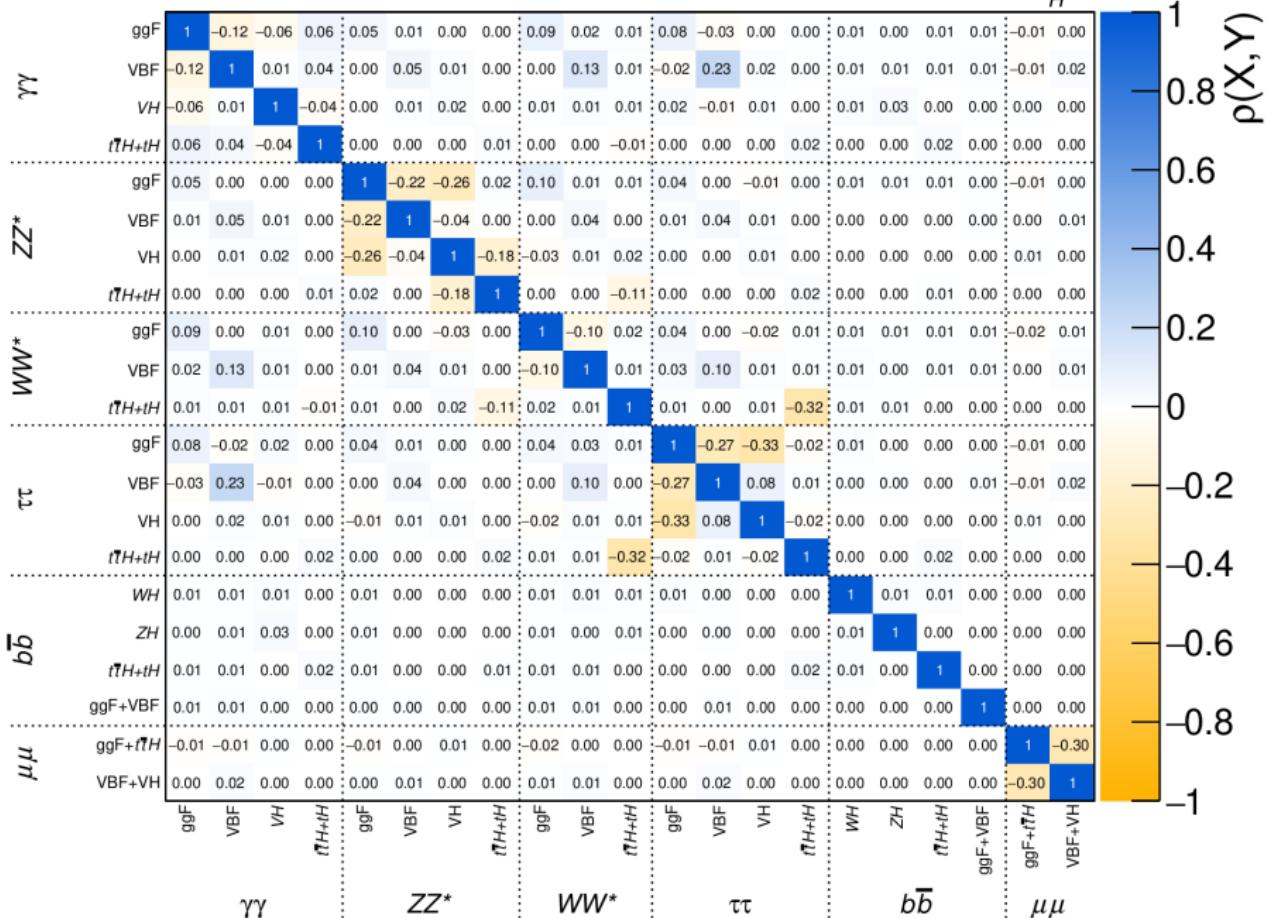


ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}, 36.1 - 139 \text{ fb}^{-1}$

$m_H = 125.09 \text{ GeV}, |\gamma_H| < 2.5$



$m_H = 125.09 \text{ GeV}, |y_H| < 2.5$ 

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}, 36.1 - 139 \text{ fb}^{-1}$

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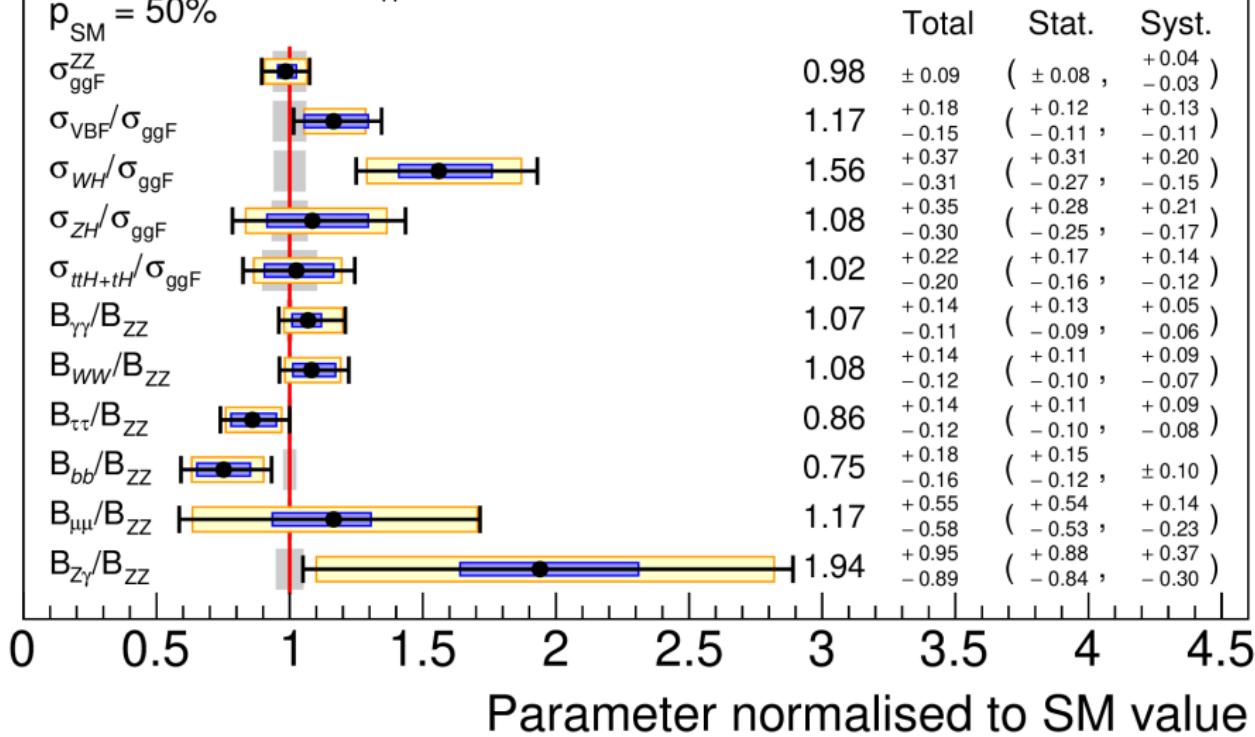
$p_{\text{SM}} = 50\%$

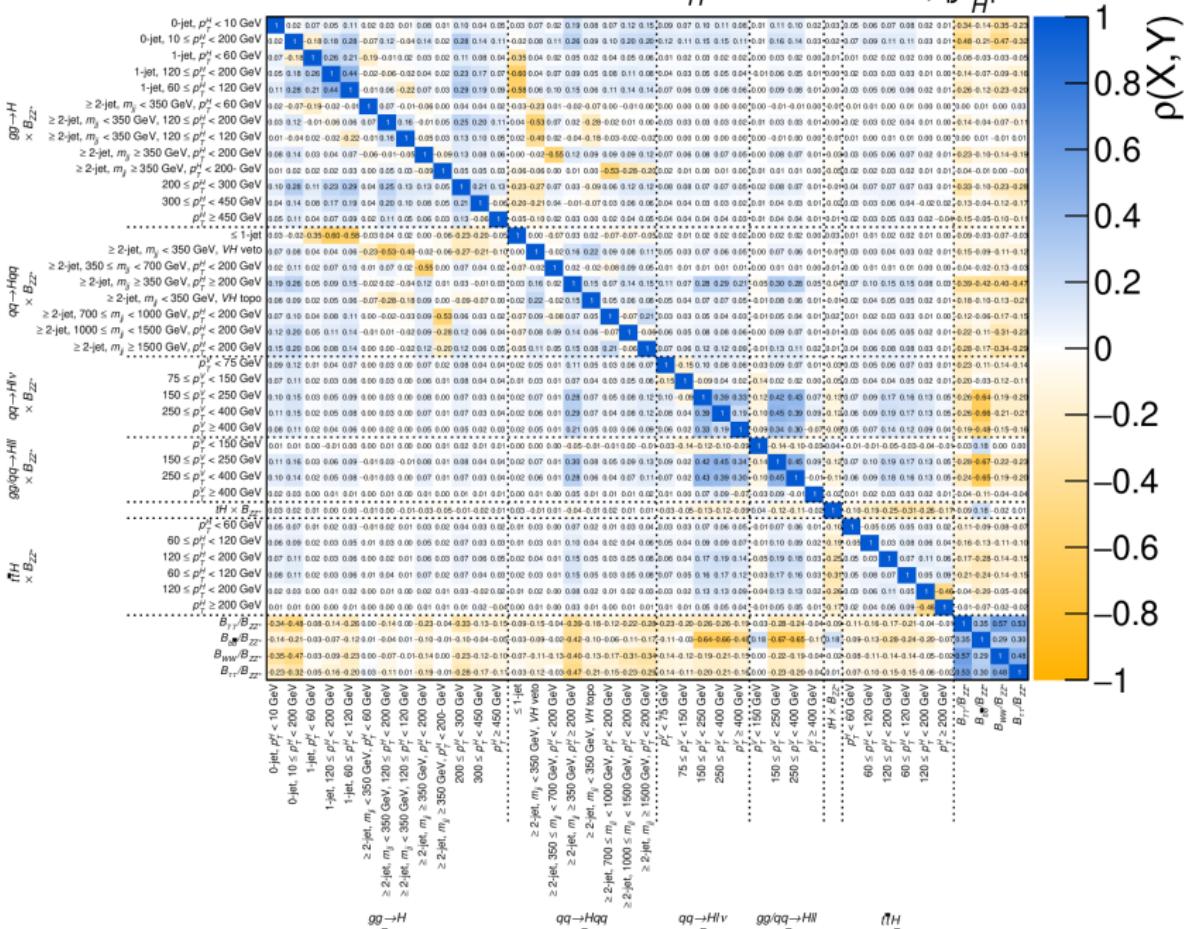
Total

Stat.

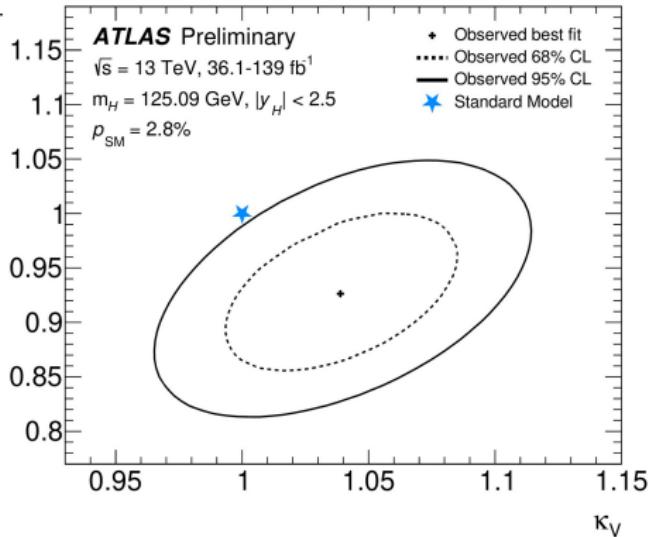
Syst.

SM

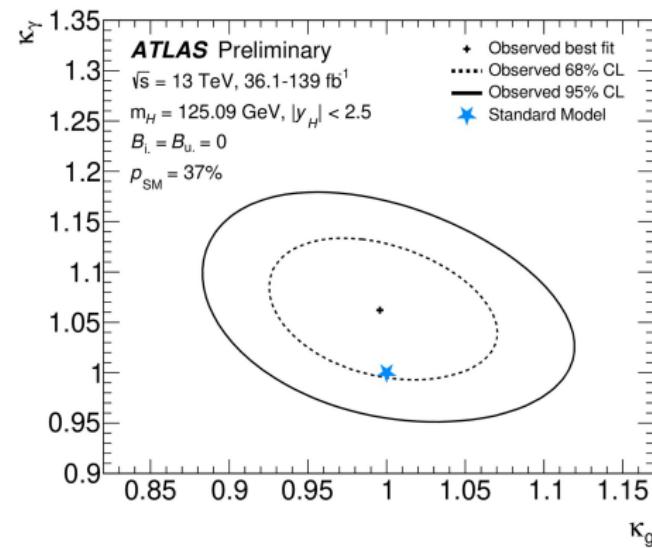




K_F



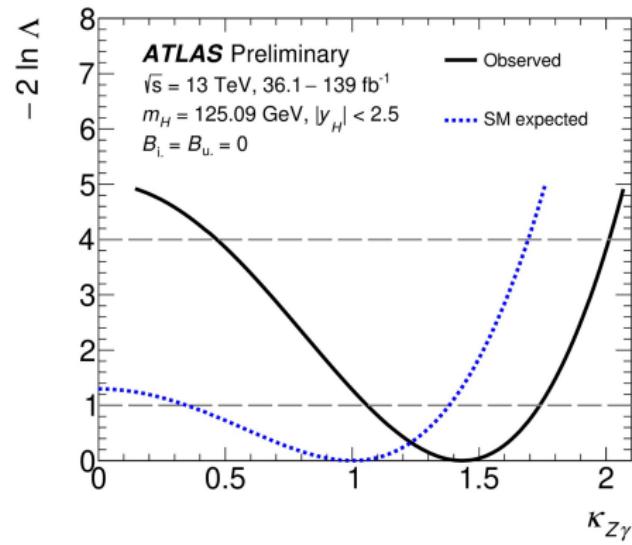
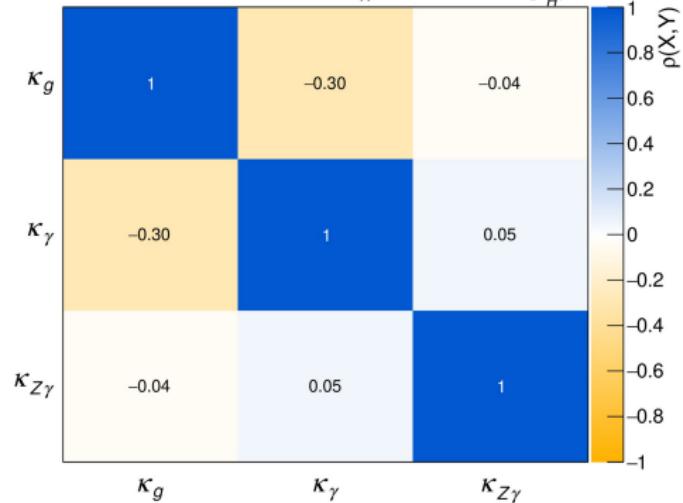
K_V



K_g

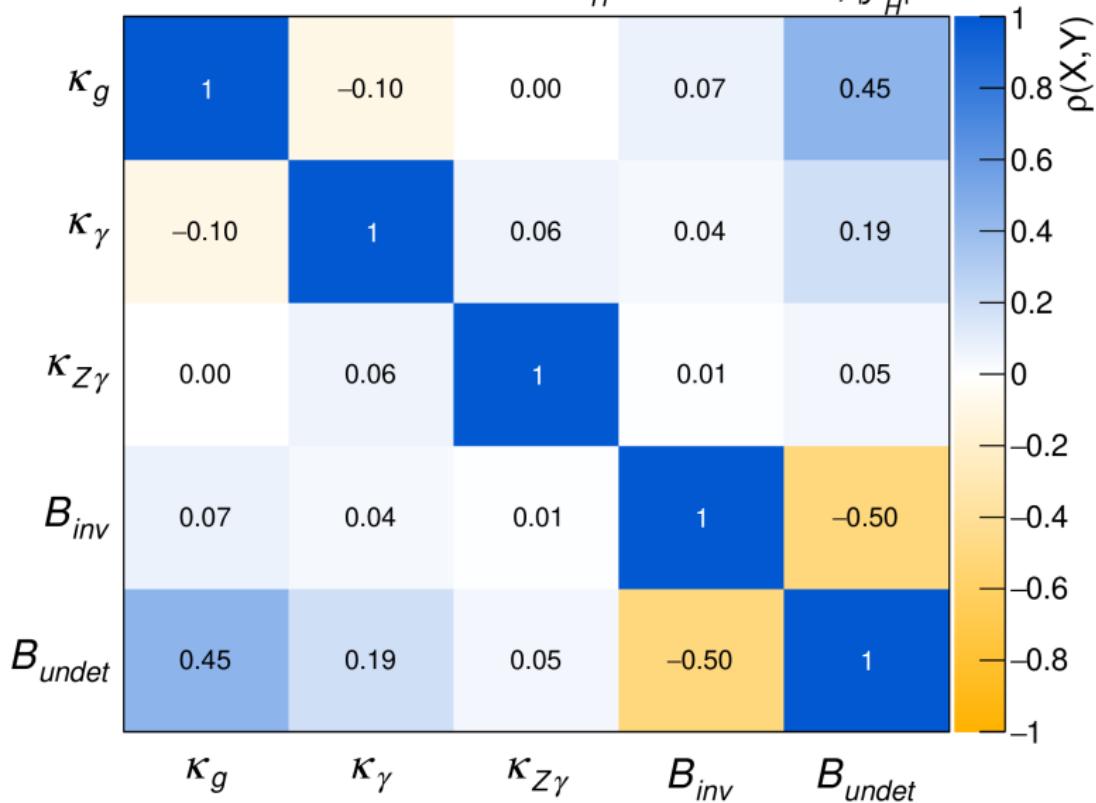
ATLAS Preliminary

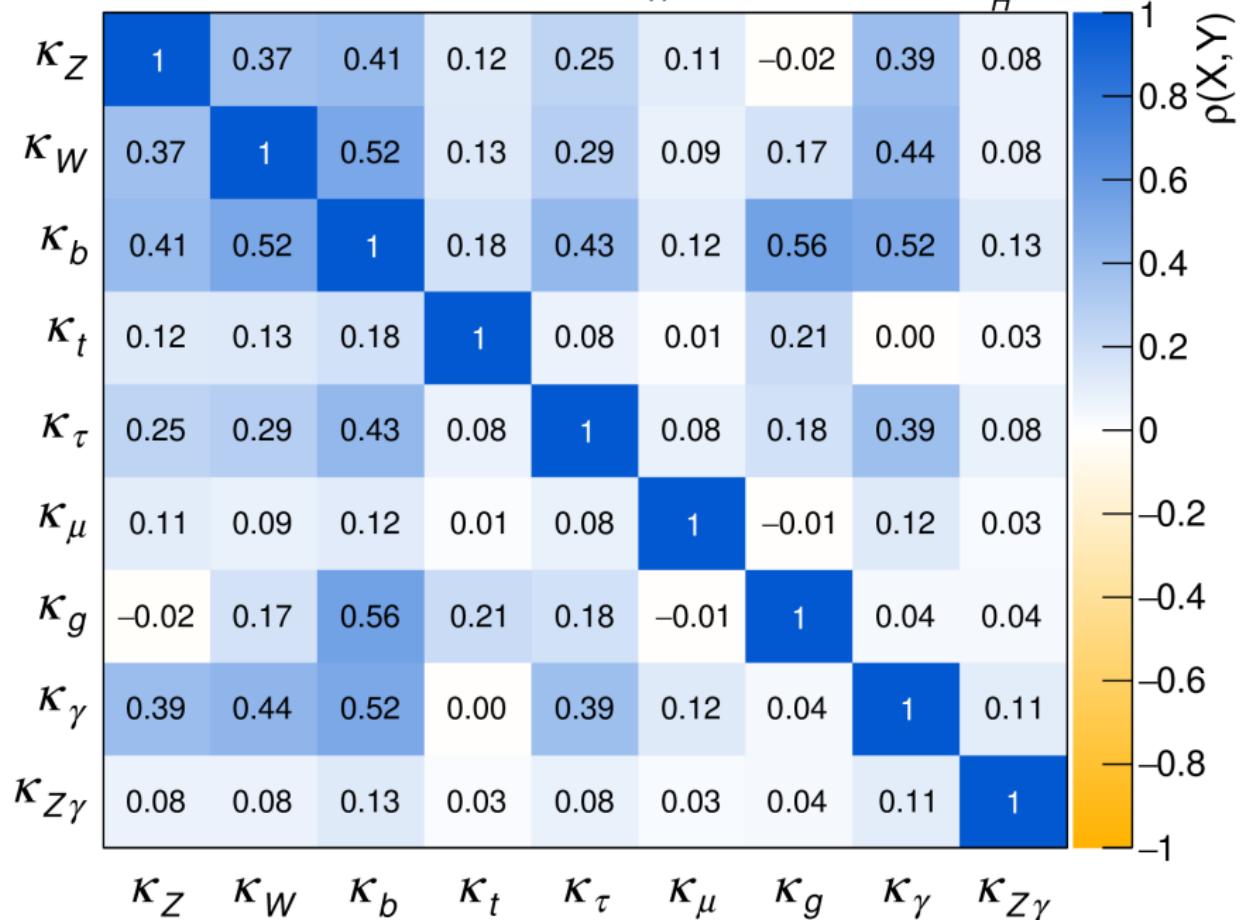
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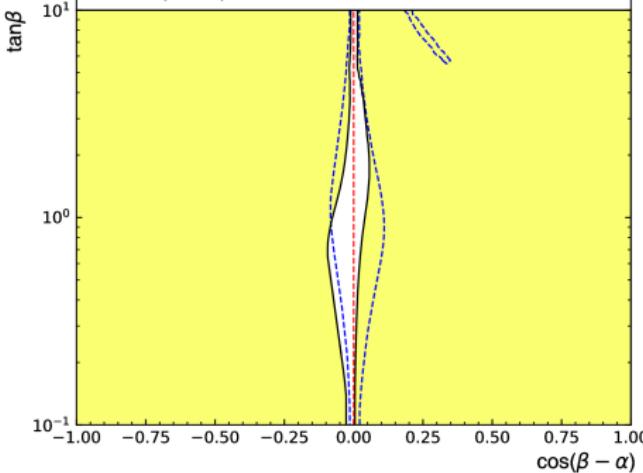
ATLAS Preliminary

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$m_H = 125.09 \text{ GeV}, |y_H| < 2.5$

2HDM Lepton-Specific

SM
Expected 95%CL
Observed 95%CL



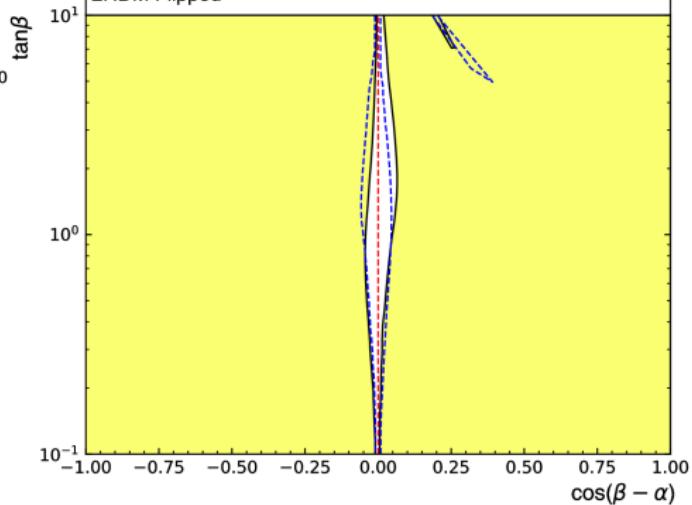
ATLAS Preliminary

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2HDM Flipped

SM
Observed 95%CL
Expected 95%CL

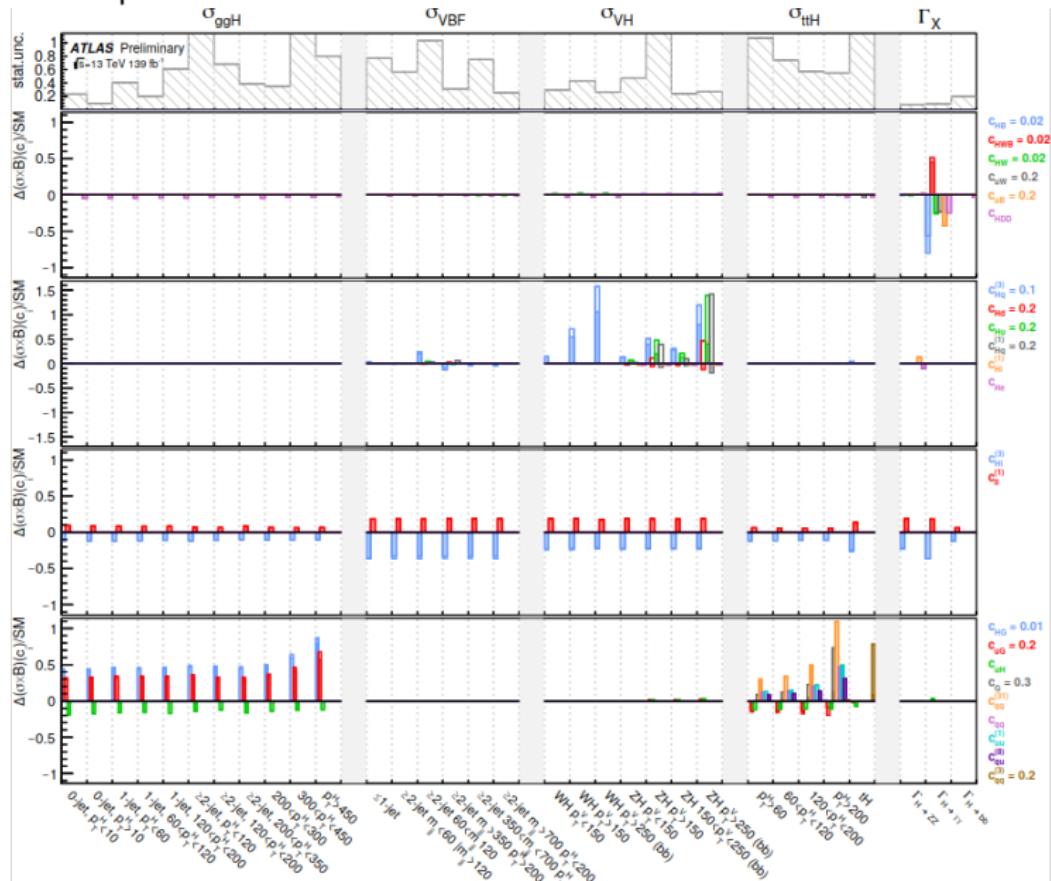


1 : X^3		2 : H^6		3 : $H^4 D^2$		5 : $\psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\square}$	$(H^\dagger H) \square (H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D^\mu H)^*$ $(H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \tilde{H})$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						
4 : $X^2 H^2$		6 : $\psi^2 X H + \text{h.c.}$		7 : $\psi^2 H^2 D$			
Q_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$		
$Q_{H\tilde{G}}$	$H^\dagger H \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$		
Q_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{H} G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$		
$Q_{H\widetilde{W}}$	$H^\dagger H \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{H} W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$		
Q_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H} B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$		
$Q_{H\tilde{B}}$	$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$		
Q_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$		
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$	$Q_{Hud} + \text{h.c.}$	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$		

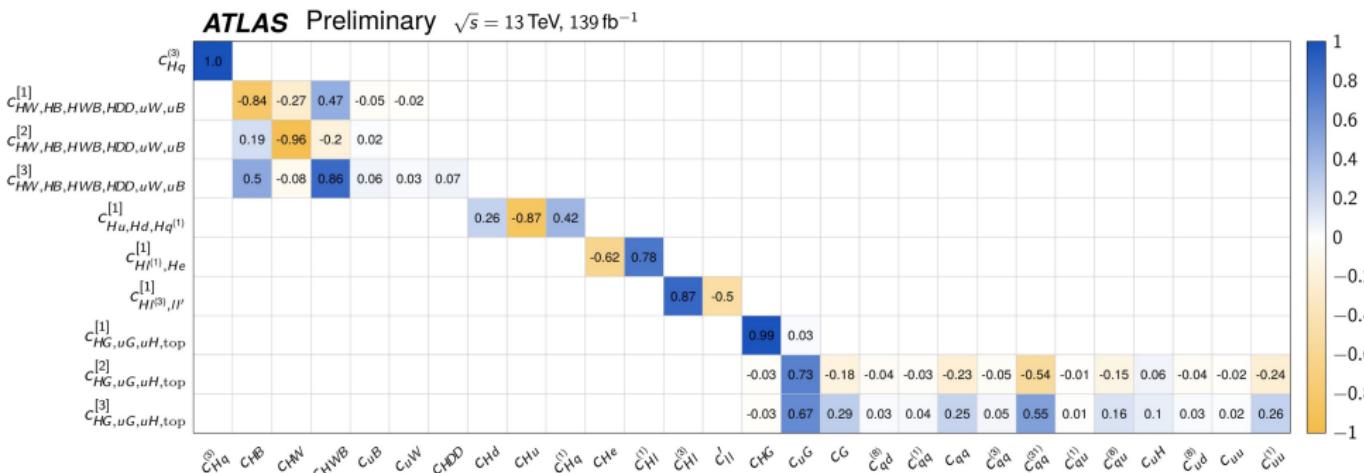
8 : $(\bar{L}L)(\bar{L}L)$		8 : $(\bar{R}R)(\bar{R}R)$		8 : $(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

8 : $(\bar{L}R)(\bar{L}L) + \text{h.c.}$		8 : $(\bar{L}R)(\bar{L}R) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$
			$H^\dagger i \overleftrightarrow{D}_\mu H \equiv H^\dagger i D_\mu H - (i D_\mu H^\dagger) H$
			$H^\dagger i \overleftrightarrow{D}_\mu^I H \equiv H^\dagger i \tau^I D_\mu H - (i D_\mu \tau^I H^\dagger) H$

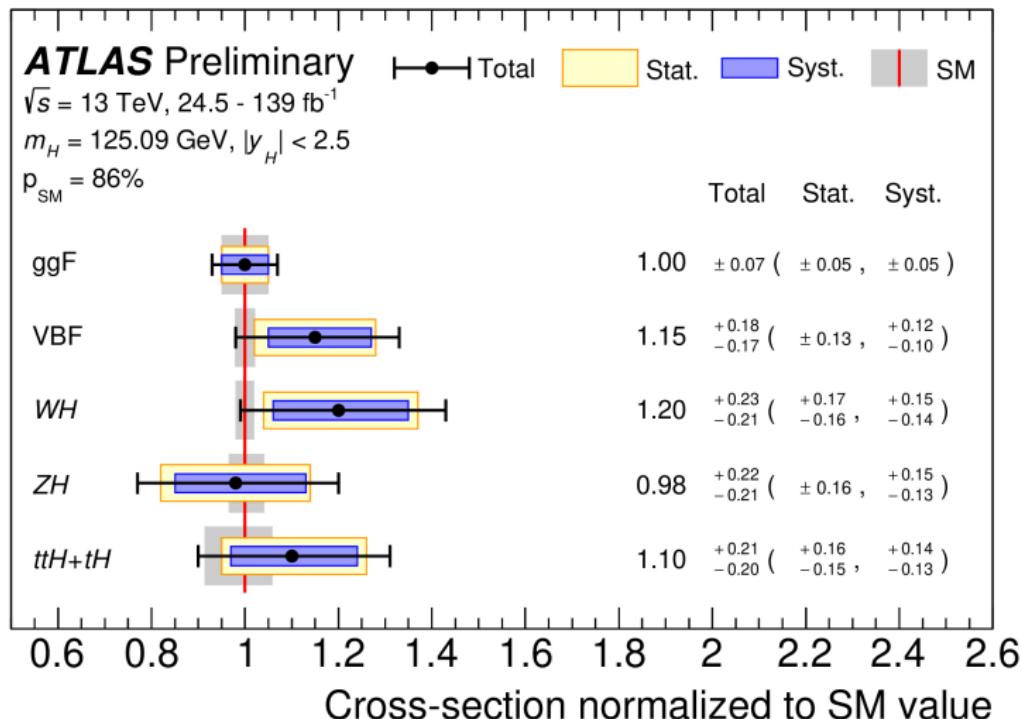
Linear + quadratic parametrisation



Last round (Hyy, H4I, Vhbb – 139 ifb)

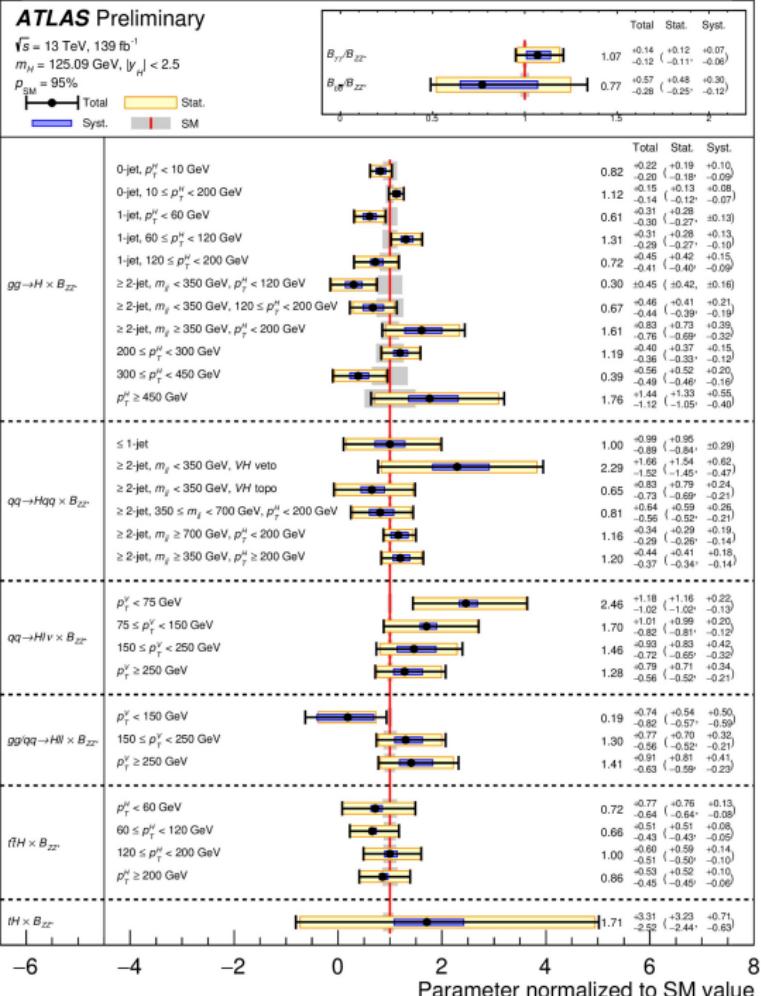


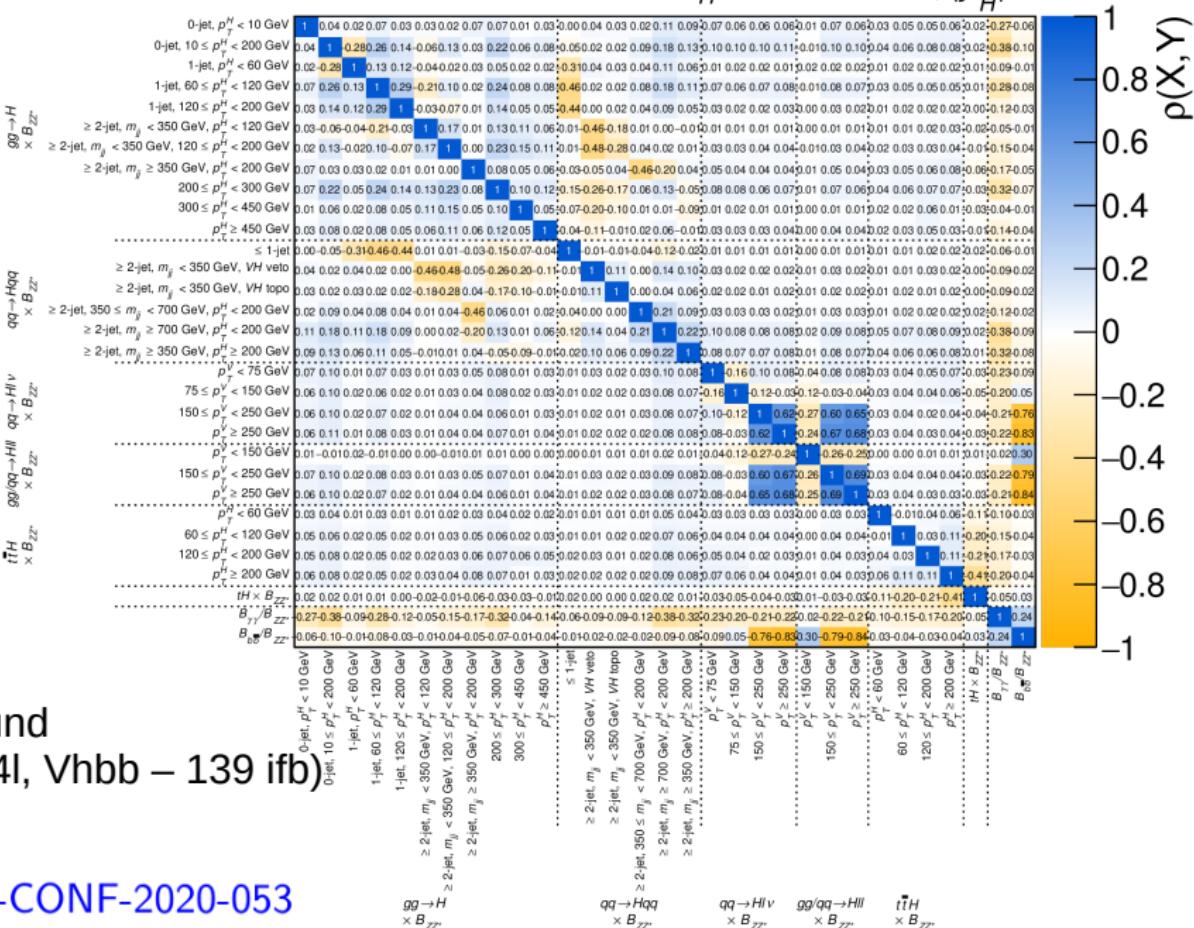
Last round (Hyy, H4l, Vhbb – 139 ifb)



Last round (Hy, H4I, Vhbb – 139 ifb)

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Last round
(Hyy, H4l, Vhbb – 139 ifb)

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ATLAS – combined measurement

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Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c_{Hl}^{(2)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c_{Hq}^{(2)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{H} G_{\mu\nu}^A$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{H} W_{\mu\nu}^I$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H} B_{\mu\nu}$	
$c_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c_{qq}^{(2)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
$c_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c_{qq}^{(4)}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$	
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	
$c_{uu}^{(1)}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$	
$c_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$	
$c_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
$c_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	
$c_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
c_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	

