Combined Higgs boson measurements at ATLAS

Interpretation in EFT and BSM

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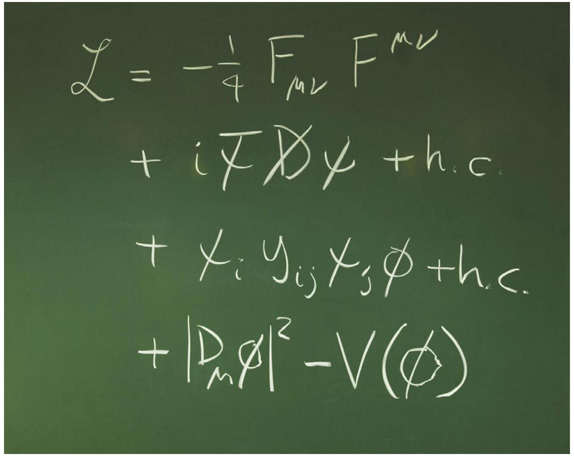
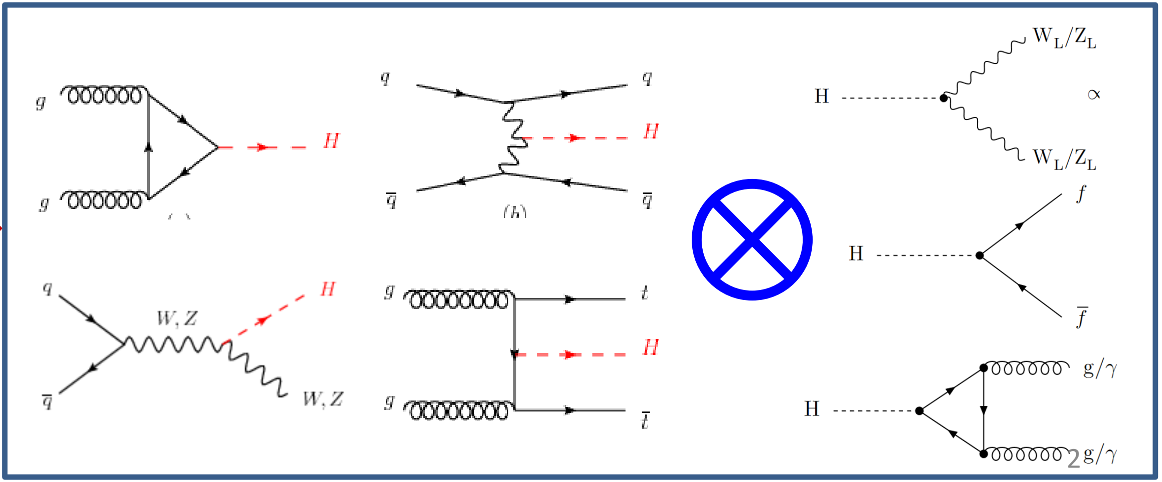
on behalf of ATLAS

SUSY 2021 at Beijing (virtually)

Higgs sector in Standard Model

- SM, a consistent theory, universally predicts the Higgs coupling
- Experiments probes into different final states from several production and decay modes
- Combinations of all channels lead best precision





Content

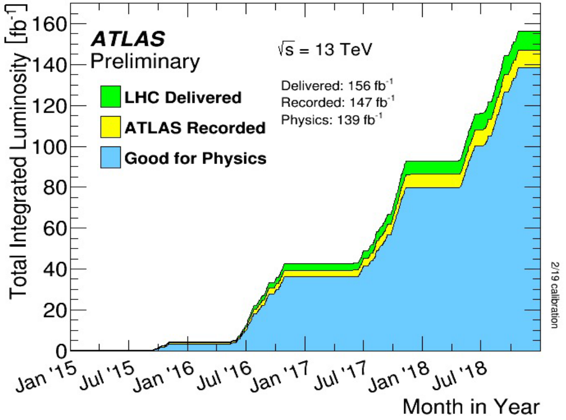
- Signal strength measurements
- κ framework interpretation
- Simplified Template Cross-Section (STXS) measurements
- Effective Field Theory interpretation
- MSSM interpretation

ATLAS-CONF-2020-027

ATLAS-CONF-2020-053

Inputs for combination

- 2015 - 16 : 36 fb^{-1}
- Full Run 2: 139 fb^{-1}



		STXS 1.2		$(\sigma \times \mathrm{BR})$			κ and MSSM	
Exp	PMode	$H \to \gamma\gamma$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to WW^*$	$H \to \tau\tau$	$H \to \mu\mu$	$H \to inv$
ATLAS	ggF	Full Run2	Full Run2	-	2015-16	2015-16	Full Run2	-
	VBF	Full Run2	Full Run2	2015-16	2015-16	2015-16	Full Run2	Full Run2
	WH	Full Run2	Full Run2	Full Run2	-	-	Full Run2	-
	ZH	Full Run2	Full Run2	Full Run2	-	-		-
	$t\bar{t}H$	Full Run2	Full Run2	2015-16	2015-16	2015-16	Full Run2	-
	tH	Full Run2	-	-	-	-	-	

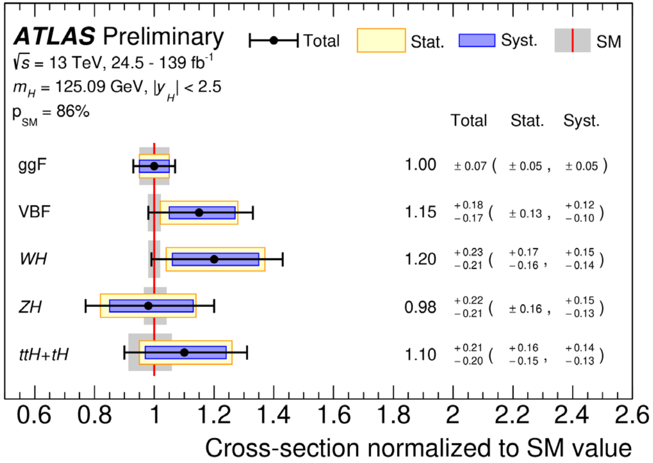
From D. Mungo

Signal strengths

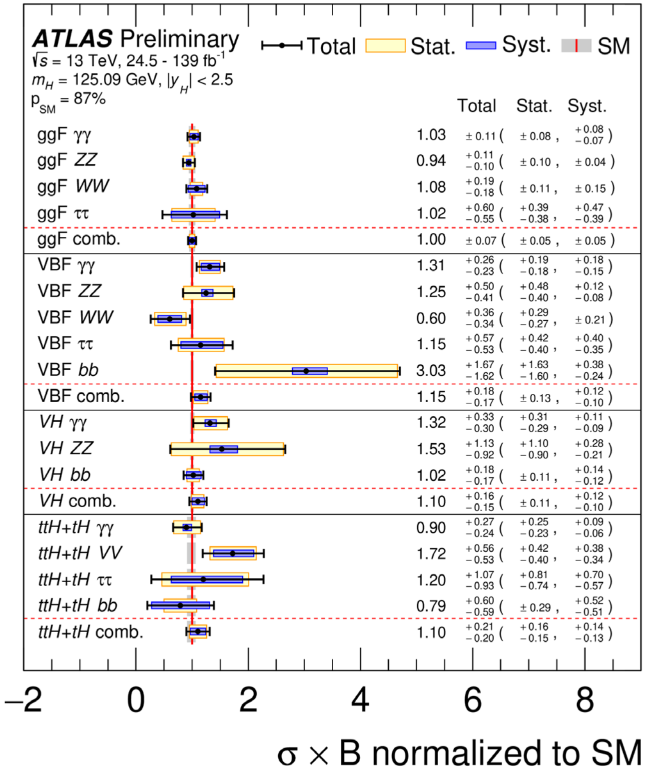
- Signal strength definition: $\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$
- Inclusive: $\mu = 1.06 \pm 0.07$

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

- Production modes
  - Systematics and statistical uncertainties on same level
  - Theoretical uncertainty close to experimental uncertainty in ggF



Measurements in prod. and decay modes



- WW and ττ full Run 2 results just available recently, not included
  - Improvement on VBF expected soon
- Several still limited by statistics
  - Improvement in Run 3 expected

Interpretation: κ framework

- Parameterize Higgs couplings
  - Narrow width approximation → decoupling of prod. and decay
  - Consistent between prod. and decay

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \qquad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

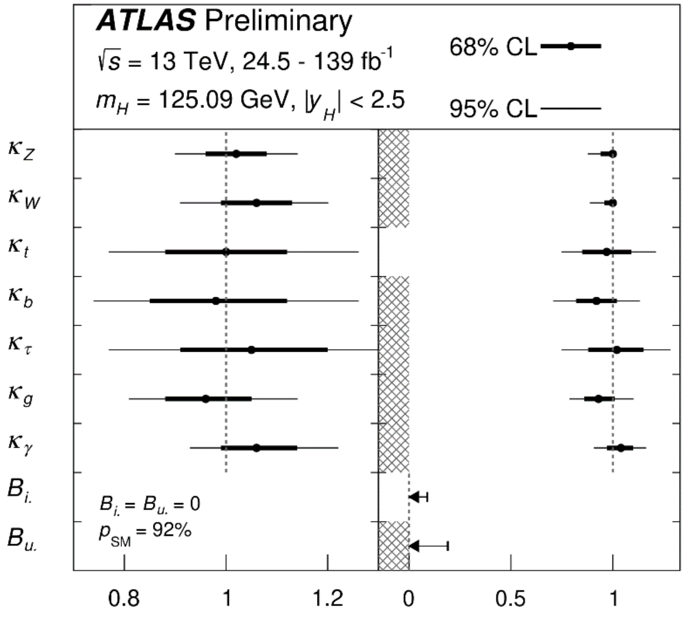
- Note
  - $\mathrm{BR_{inv}}$(invisible) and $\mathrm{BR_{und}}$(undetected) set to 0 at some cases
  - Effective κ_g and κ_γ represented by other couplings

Example of parameterization

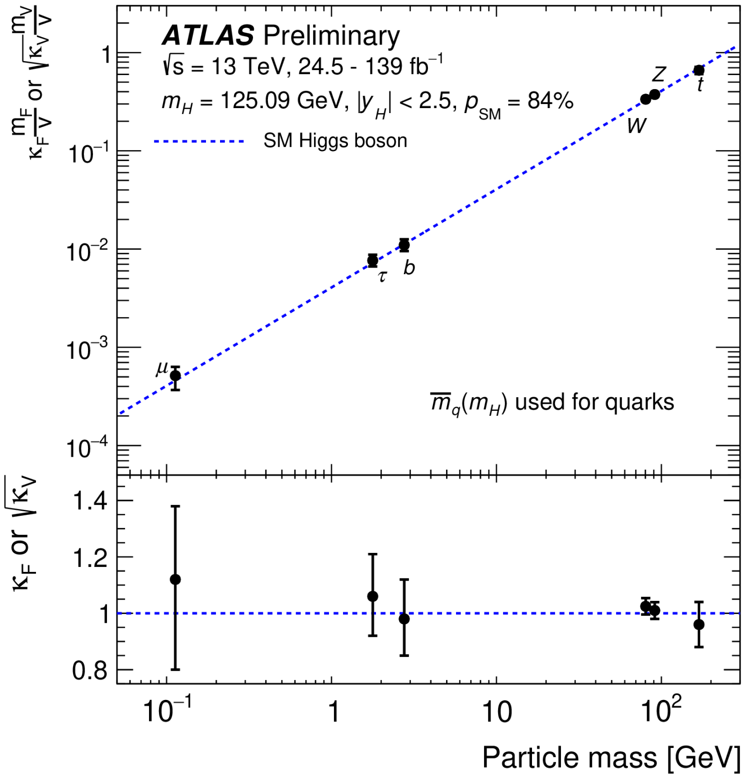
Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(VBF)$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	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 ($B_{\mathrm{i.}} = B_{\mathrm{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2 + 0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2 + 0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2 + 0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

Interpretation: κ framework

Effective vertices all floating
(different treatment on Br_{inv} and Br_{und})

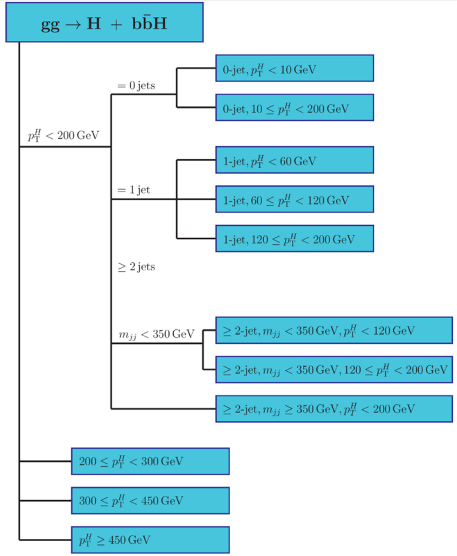


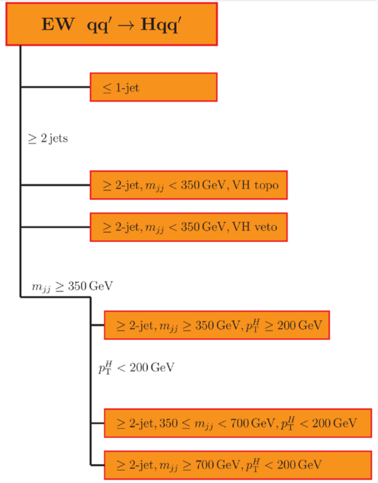
SM loops structure and no BSM contribution

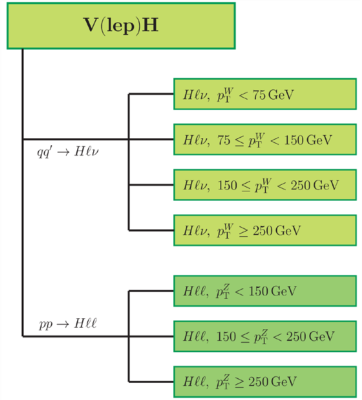


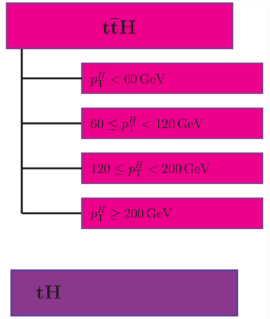
STXS measurement

- Less model-dependent measurement of Higgs production processes
- Partition major processes into different kinematic regions
  - Base fiducial volume: $|y_H| < 2.5$ and $p_T^{jets} > 30$ GeV
  - Binning on p_T^H, N_j, m_{jj}, p_T^V based on STXS-1.2







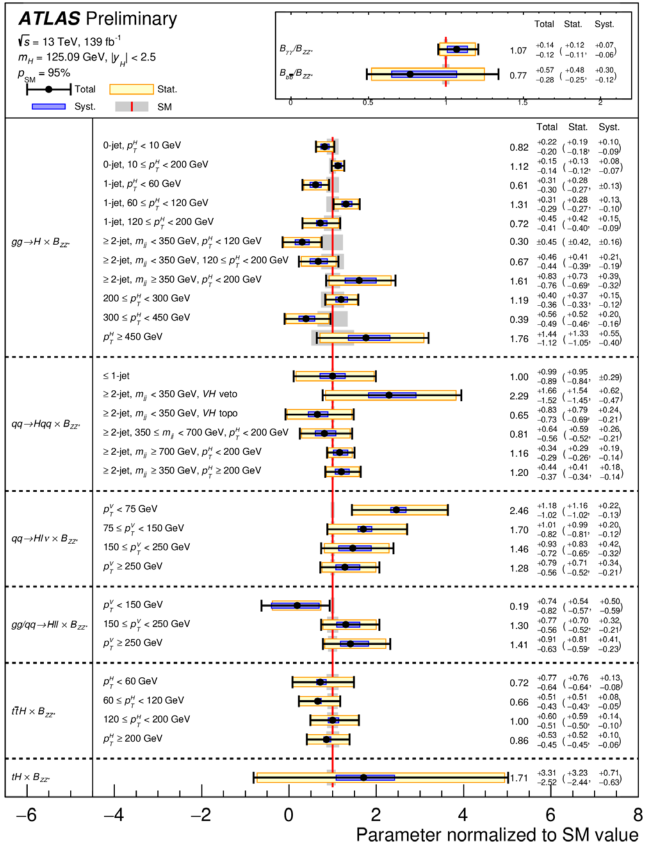


STXS measurement

- $\sigma_i \times BR_f$ reparametrized with BR_{ZZ}
  - Partially cancel common uncertainties

$$\sigma_i \times \mathrm{BR}^f = (\sigma_i \times \mathrm{BR}_{ZZ}) \cdot \left(\frac{\mathrm{BR}^f}{\mathrm{BR}_{ZZ}}\right)$$

- Uncertainties between 10 and 100% (large majority stat limited)
- Good agreement with SM in a wide range of kinematic regions, p_{SM} = 95%

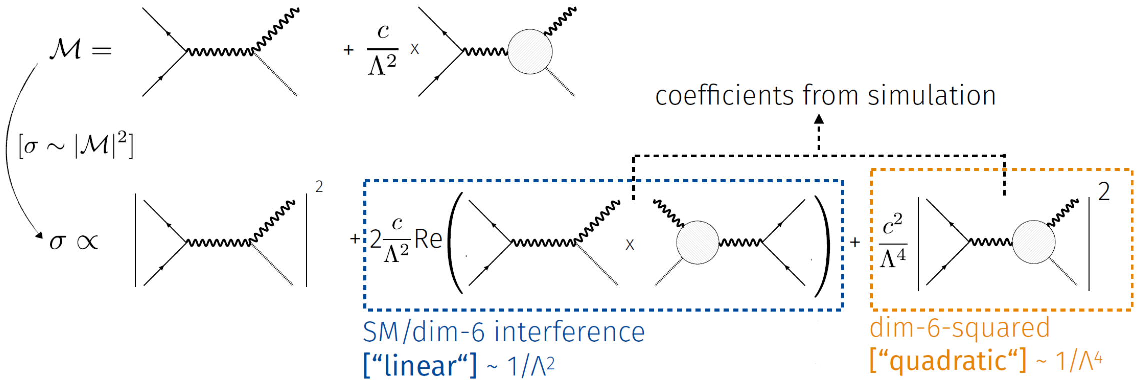


EFT interpretation

- Expand up to dim. 6 operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)}$$

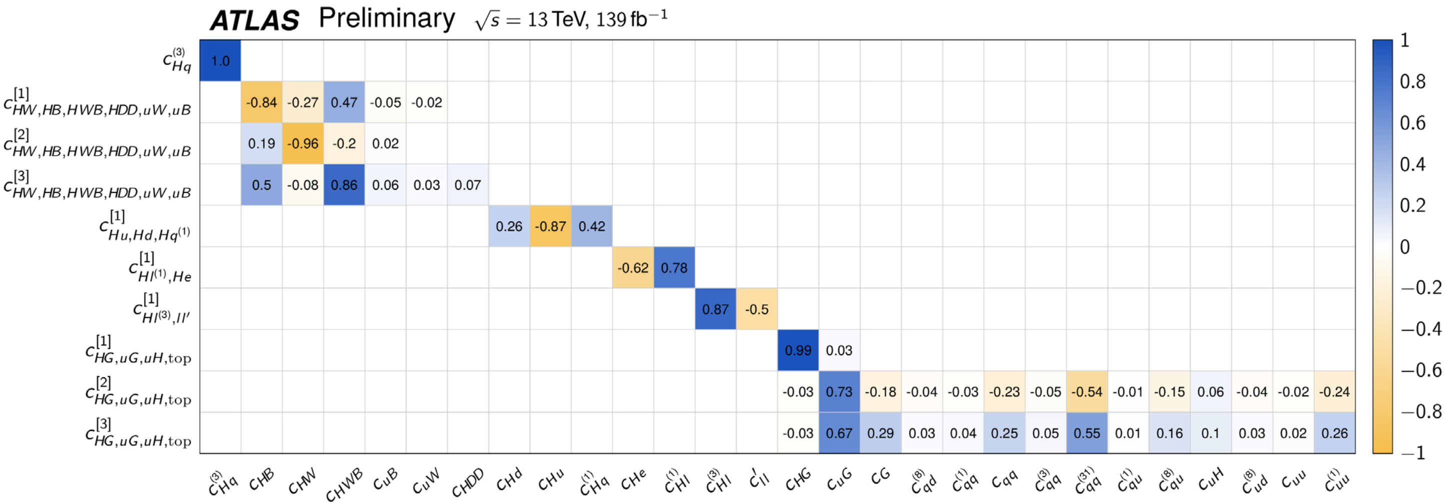
  - Interference term: $1/\Lambda^2$ suppression, linear
  - Dim-6 squared term $1/\Lambda^4$ suppression, quadratic



- More than 30 operators
  - With CP even assumption and >0.1% contribution @ Λ = 1 TeV

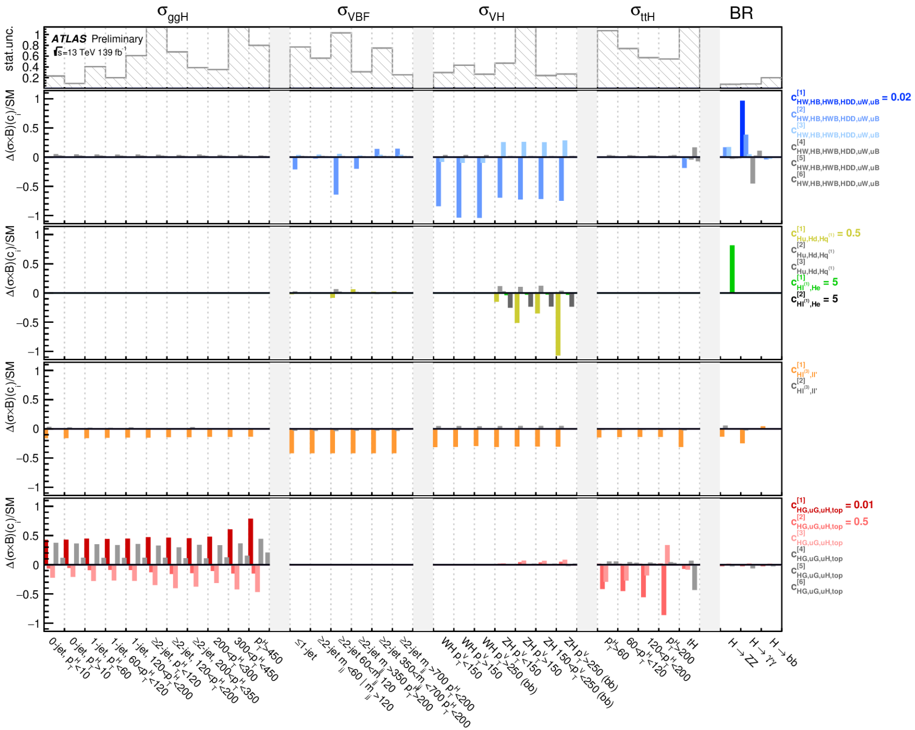
Select operators

- Too many operators, strongly correlated
- Selection procedure:
  - Grouped into subsets of operators with similar effects, according to Asimov covariance matrix PCA and underlying physics
  - Eigen vector decomposition in subspace and select the most sensitive ones

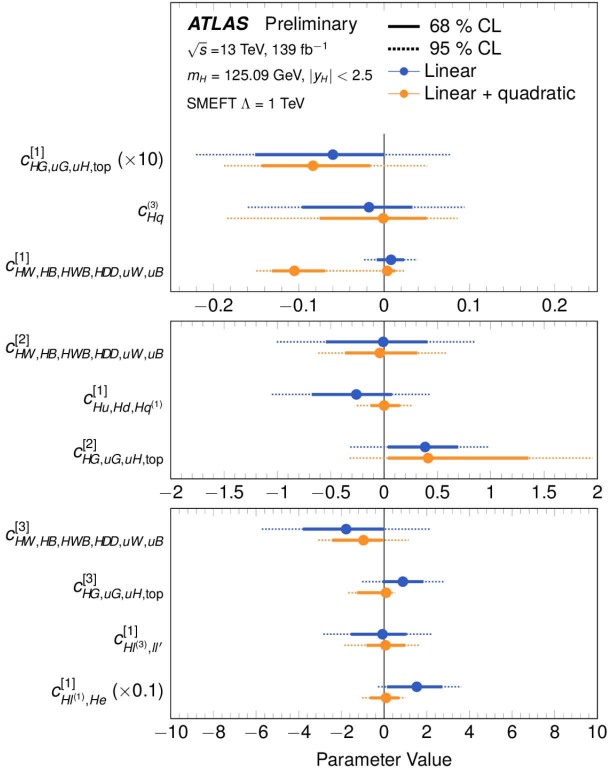


Measurement of rotated operators

Contributions of the rotated operators



Fit the leading 10 rotated operators



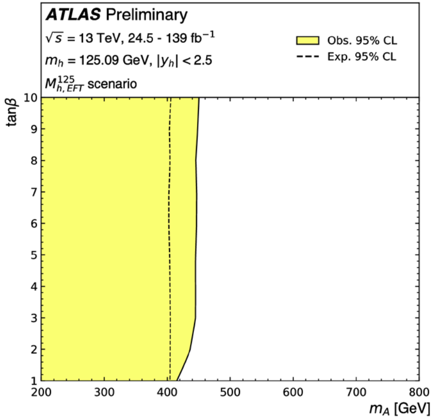
Constraints on new phenomena

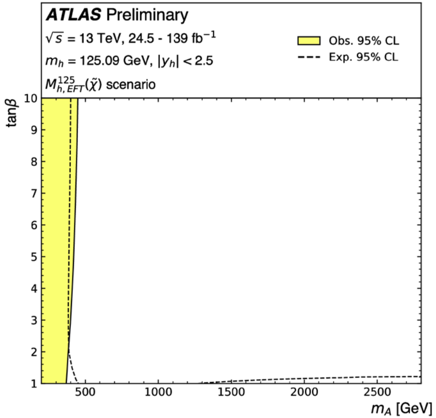
- MSSM: naturalness, DM, unification
  - Two Higgs doublets, five Higgs bosons, one is the SM one (h_0)
- Test the MSSM in six benchmark scenarios
  - scan over m_A (CP odd Higgs mass) and tanβ (ratio of VEVs of Higgs doublets)

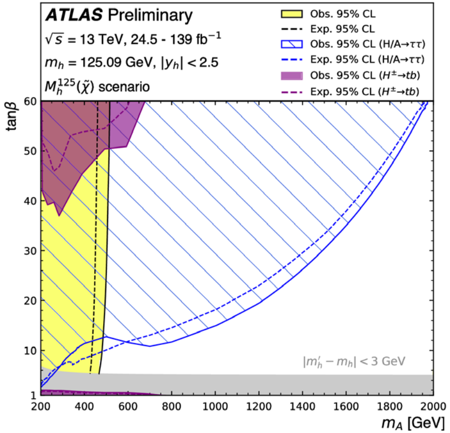
Scenario	Description	Phenomenology
M_h^{125}	SUSY particles very heavy	no in-loop contributions, h/H decay only to SM
$M_h^{125}(\tilde{\chi})$	light $\chi^{\pm}$ and χ^{0}	affect $h^0 \to \gamma\gamma$, new Higgs can decay via $\chi^{\pm}$ and χ^{0}
$M_h^{125}(\tilde{\tau})$	light $\chi^{\pm}$, χ^{0} and $\tilde{\tau}$	as above, but decay via $\chi^{\pm}$ and χ^{0} relevant at high m_A
$M_h^{125}(alignment)$	for each $\tan\beta$, h or H has SM-like coupling	small mixing between the lighter gauginos and heavier higgsinos
$M_{h,EFT}^{125}$	M_{SUSY} scale flexible to ensure a 125 GeV Higgs	similar to M_h^{125}, SUSY contribution via EFT
$M_{h,EFT}^{125}(\tilde{\chi})$	M_{SUSY} scale flexible with light $\chi^{\pm}$ and χ^{0}	similar to $M_h^{125}(\tilde{\chi})$, SUSY contribution via EFT

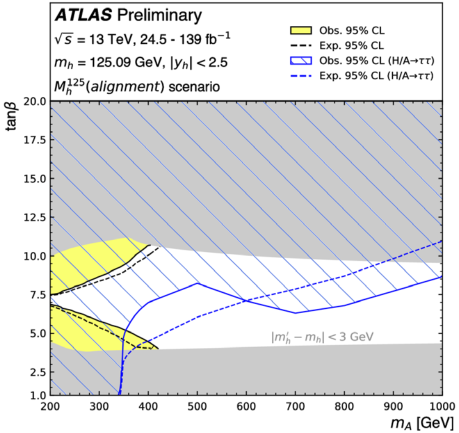
ATLAS MSSM interpretation: results

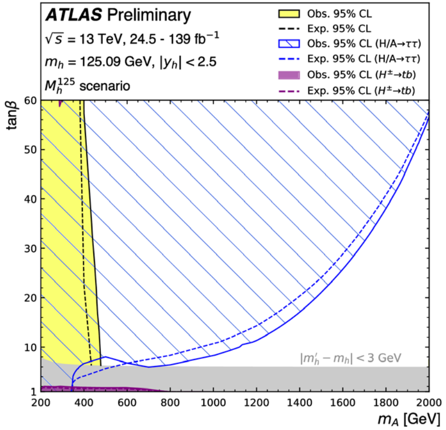
- Compared with direct searches
  - H/A $\rightarrow\tau\tau$ and H$\rightarrow$tb
- Grey areas ruled out
  - predicted m_h^{MSSM} is > 3 GeV away from 125.09 GeV

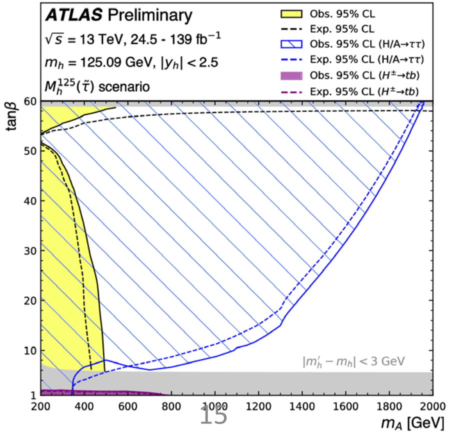












Summary

- Plenty of results produced by ATLAS with full Run2 dataset, improved our understanding of Higgs sector
  - Global signal strength with 7% uncertainty
  - General κ modifiers with < 20% uncertainties
  - STXS results already most bins with < 100% uncertainty
- Interpretation on MSSM and SMEFT
  - First SMEFT interpretations of STXS results (10 independent operators in fit)
  - Constraint on MSSM parameter space for various scenarios
- Limitation for future analyses
  - Signal theo. unc. for global/prod. signal strengths
  - Stat. unc. for STXS measurement

Thank You!

Statistics model

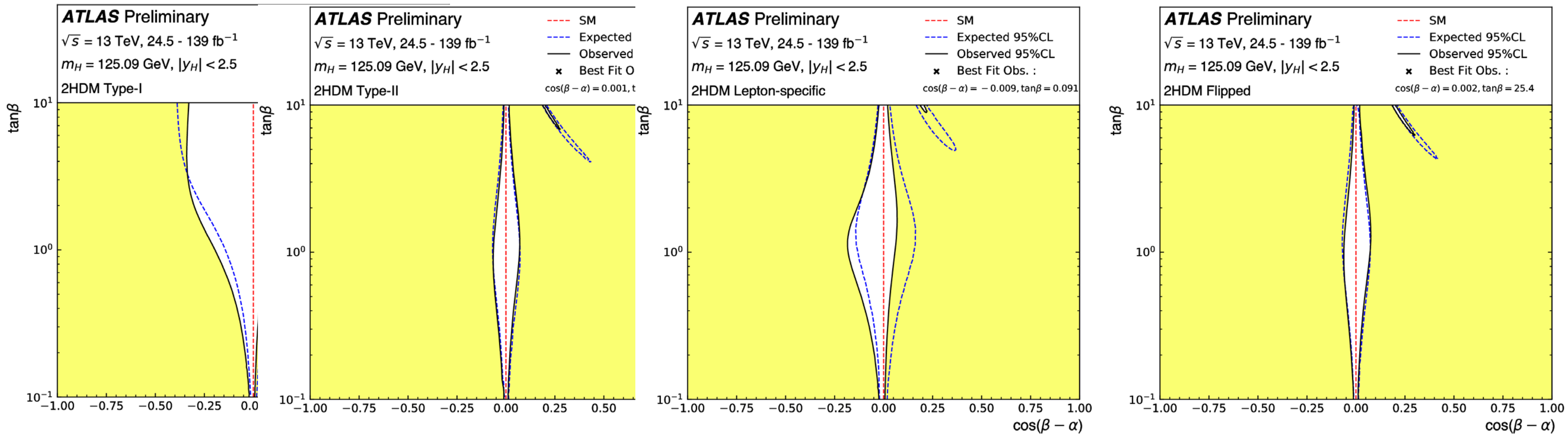
$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma \times B)_{if} \, (A \times \epsilon)_{if,k}$$

- i: production modes or STXS bins, f: decay final states
- L_k: integrated luminosity used in category k
- (A x epsilon)$_{if,k}$: acceptance times efficiency factor
- (sigma x B)$_{if}$: cross section times branching fraction

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

- Asymptotic approximation
- Likelihood is Gaussian, 2lnΛ follows a chi^2 distribution with a number of degrees of freedom n equal to the dimensionality of the vector alpha

- Figure 17 shows the regions of the ¹cos¹V ⍰ Uº. tan Vº plane that are excluded at a confidence level of
- 95% or higher, for each of the four types of 2HDMs. The expected exclusion limits in the SM hypothesis
- are also overlaid. The data are consistent with the alignment limit [134] at cos¹V ⍰ Uº = 0, in which the
- couplings of match those of the SM Higgs boson, within one standard deviation or better in each of
- the tested models. The allowed regions also include narrow, curved petal regions at positive cos¹V ⍰ Uº
- and moderate tan V in the Type II, Lepton-specific, and Flipped models. These correspond to regions
- with cos¹V ¸ Uº 0, for which some fermion couplings have the same magnitude as in the SM, but the
- opposite sign.


ATLAS Preliminary
√s = 13 TeV, 24.5 - 139 fb−1
mH = 125.09 GeV, |yH| < 2.5
2HDM Type-I
ATLAS Preliminary
√s = 13 TeV, 24.5 - 139 fb−1
mH = 125.09 GeV, |yH| < 2.5
2HDM Type-II
SM
Expected
Observed
Best Fit O
cos(β − α) = 0.001, t
ATLAS Preliminary
√s = 13 TeV, 24.5 - 139 fb−1
mH = 125.09 GeV, |yH| < 2.5
2HDM Lepton-specific
SM
Expected 95%CL
Observed 95%CL
Best Fit Obs. :
cos(β − α) = − 0.009, tanβ = 0.091
ATLAS Preliminary
√s = 13 TeV, 24.5 - 139 fb−1
mH = 125.09 GeV, |yH| < 2.5
2HDM Flipped
SM
Expected 95%CL
Observed 95%CL
Best Fit Obs. :
cos(β − α) = 0.002, tanβ = 25.4
tanβ
cos(β − α)

- This scenario is characterized by a flexible mass scale MSUSY of the superpartners. In all the original benchmark scenarios presented above, the supersymmetric partners of the SM fermions (sfermions) are tied to the TeV scale. In this case, the parameter region tan < 5 is ruled out because the mass Mh of the SM-like Higgs boson is predicted to be lower than the measured value.
- To re-open the parameter region of low tan values, the sfermion mass scale, MSUSY is adjusted dynamically from 6 TeV to 1016 TeV to achieve a 125 GeV Higgs. As in this scenario all superparticles are chosen to be so heavy that production and decays of the MSSM Higgs bosons are only mildly affected by their presence, the SUSY contribution to the Higgs properties is calculated with an effective field theory (EFT).

- Figure 14 shows the observed and expected 95% CL exclusion limits of the MSSM in the two-dimensional plane of mA and tan for the M^{125}_{h} , M^{125}_{h} (chi˜), M^{125}_{h} (tau˜), M^{125}_{h} (alignment) benchmark scenarios. For all
- four scenarios, the regions excluded by the Higgs mass requirement (jm0h
- ? 125.09 GeVj < 3 GeV) are
- separately indicated with gray shaded areas.

- M125 h scenario, low mA region is disfavored due to the suppression of h->bb in that region.
- M125 h (tau) scenario, the region at low mA and tan < 55 is excluded due to a predicted significant enhancement of the Higgs width in combination with a suppression of the branching fraction h->gamgam. In the region tan > 55, the tau˜ loop has a significant impact on the hbb coupling, resulting in an enhanced prediction of BR(h->gamgam), and is therefore excluded. The observed exclusion range starts at a larger value of tan than the expected exclusion range because the observed value of kappa_gam is larger than one (kappa_gam= 1.06+-0.08 +-0.07).
- M125 h (chi) scenario, low values of mA are excluded due to the suppression of BR(h->gamgam). In the region with tan < 10, the enhancement of electroweakino effects and the absence of a tau˜ loop will enhance BR(h->gamgam) but the resulting exclusion is less stringent than that of the m0h mass requirement.
- M125 h (alignment) scenario, the limit of alignment without decoupling is only realized for tan ~7 and mA > 170 GeV. For larger values of mA MSSM couplings are more similar to SM couplings causing the allowed region to open up.
- For both the M125 h,EFT and M125 h,EFT(chi˜) scenarios, the limit at low mA is driven by a predicted enhancement in H->bb decays.
- M125 h,EFT(chi) scenario, H->gamgam decay is enhanced in the tan <1.5 region due to presence of light charginos. As the observed coupling of the Higgs boson to photons slightly exceeds the expected value, the constraint from H->gamgam is less strong than expected

Interpretation: κ framework

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	0.98 ± 0.05
λ_{tg}	κ_t / κ_g	1.04 ± 0.12
λ_{Zg}	κ_Z / κ_g	$1.06\ ^{+\,0.12}_{-\,0.11}$
λ_{WZ}	κ_W / κ_Z	$1.04\ ^{+\,0.08}_{-\,0.07}$
$\lambda_{\gamma Z}$	κ_γ / κ_Z	$1.04\ ^{+\,0.07}_{-\,0.06}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	1.04 ± 0.13
λ_{bZ}	κ_b / κ_Z	$0.96\ ^{+\,0.12}_{-\,0.11}$

- Expressed as ratios w.r.t. gg→H→ZZ
  - global scale factor κ_{gZ}
  - ratios with respect to κ_g or κ_Z
  - No assumptions on Higgs total width
- λ_{WZ} tests SU(2) custodial symmetry
- $\lambda_{\gamma Z}$ sensitive to charged particles in Hγγ loop w.r.t. HZZ
- λ_{tg} sensitive to coloured particles in ggH w.r.t. ttH

New phenomena parameterization

$$\mu^{i,X}(m_A, \tan\beta) = \frac{\sigma^i(m_A, \tan\beta)}{\sigma^i_{\mathrm{SM}}} \cdot \frac{B^X(m_A, \tan\beta)}{B^X_{\mathrm{SM}}} \equiv r^i(m_A, \tan\beta) \cdot r^X(m_A, \tan\beta)$$

$$r^X = \frac{\Gamma^{h\to X}_{\mathrm{MSSM}}(m'_h)}{\Gamma^{h\to X}_{\mathrm{SM}}(m'_h)} \cdot \frac{\Gamma^h_{\mathrm{SM}}(m'_h)}{\Gamma^h_{\mathrm{MSSM}}(m'_h)}$$

STXS-0 Process	Expression for cross-section scale factor r^i
ggH	$\sigma^{\mathrm{MSSM}}_{\mathrm{ggH}}(m'_h)/\sigma^{\mathrm{SM}}_{\mathrm{ggH}}(m'_h)$
$b\bar{b}H$	$\sigma^{\mathrm{MSSM}}_{\mathrm{bbH}}(m'_h)/\sigma^{\mathrm{SM}}_{\mathrm{bbH}}(m'_h)$
VBF	$0.73\kappa'^2_W + 0.27\kappa'^2_Z$
$qq/qg\to VH$	κ'^2_V
$t\bar{t}H$	κ'^2_t
$gg\to ZH$	$2.456\kappa'^2_Z + 0.456\kappa'^2_t - 1.903\kappa'_Z\kappa'_t - 0.011\kappa'_Z\kappa'_b + 0.003\kappa'_t\kappa'_b$
tHW	$2.909\kappa'^2_t + 2.310\kappa'^2_W - 4.220\kappa'_t\kappa'_W$
tHq	$2.633\kappa'^2_t + 3.578\kappa'^2_W - 5.211\kappa'_t\kappa'_W$

From the Lagrangian to observables

- Many operators affect Higgs production and/or decay
- This talk: SMEFT interpretations of $H\to ZZ^*\to 4l$, (VH) $H\to bb$ and $H\to\gamma\gamma$
- Generator-level simulation of EFT samples (STXS unfold the detector-level effects)

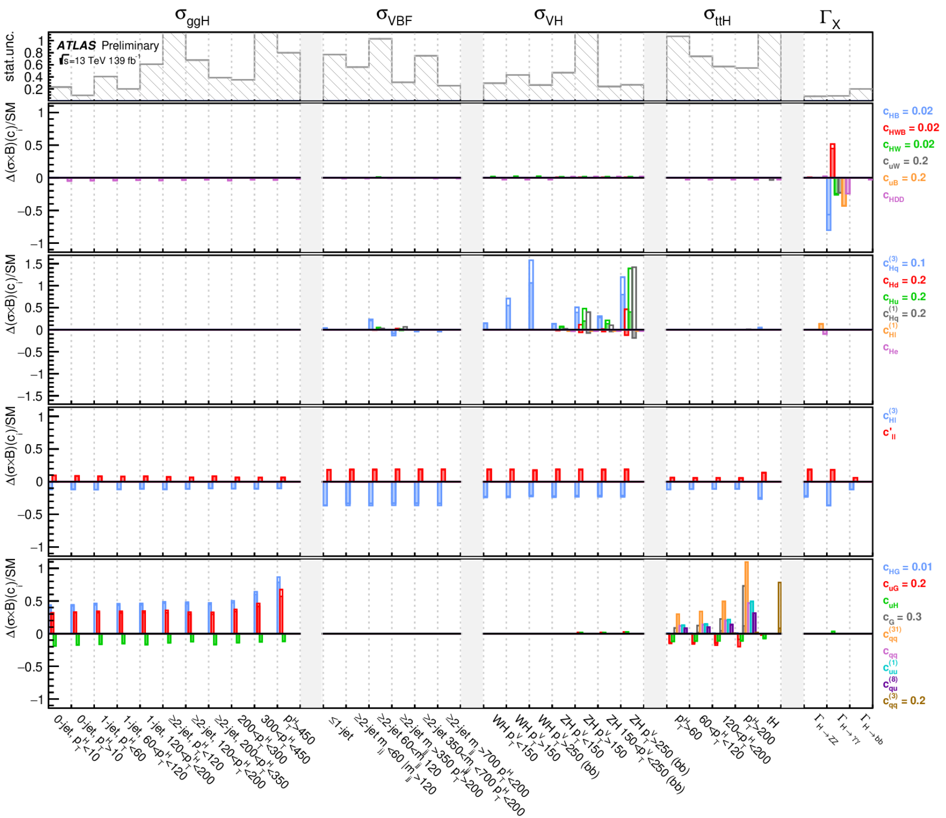
$$\mathcal{L}(\mathrm{data}|\mu,\theta) \to \mathcal{L}(\mathrm{data}|c_i,\theta)$$

Assuming $U(3)^5$ flavor symmetry

Coefficient	Operator	Example process
c_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$	
c_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$	
c_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$	
$c_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_t)(\bar q_r\gamma^\mu q_s)$	
$c_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	
c_{qq}	$(\bar q_p\gamma_\mu q_t)(\bar q_r\gamma^\mu q_s)$	
$c_{qq}^{(31)}$	$(\bar q_p\gamma_\mu\tau^I q_t)(\bar q_r\gamma^\mu\tau^I q_s)$	
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	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	

Coefficient	Operator	Example process
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	
c_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar l_p e_r H)$	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$	
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$	
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$	
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$	
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$	

Each operator's impact on STXS bins



- Many operator effects correlated
- Some operators show p_T^H dependency, some are rather flat across STXS bins
- Further reduction needed