Fitting simplified template cross sections for EFT parameters

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Overview

STXS introduction

STXS fit strategy

External constraints

Equations relating STXS to EFT

Issues

STXS introduction

LHC Higgs working group has defined standard binning for cross section measurements using unfolding ('diffXS') or SM template distributions ('STXS')

The standards allow for public 'tools' mapping the measurements to EFT parameters

Hope to extend to EW measurements (joint LHC Higgs + EW meeting)

STXS vs diffXS:

- STXS implemented in workspaces as an intermediate translation of data: effectively a direct fit to data
- STXS can better fit low-statistics regions (no unfolding)
- STXS relies on SM distributions for extrapolations within bins and migrations across bins
    - Leads to theory uncertainties and potential model-dependence

STXS fit strategy

General strategy is to start with simplest fit and add detail based on expected impact

First attempt:

- Use LO HEL implementation of SILH basis in Madgraph
    - Update to more complete Warsaw basis or NLO when available

- Reduce parameter set using external constraints
    - Take tightly constrained parameters to be zero
    - Can relax to Gaussian constraints to check impact
        - Also can include running and theory uncertainties when available

- Use equations relating STXS to EFT parameters to fit the data

Documenting tools and procedures in a Higgs WG note with V. Sanz

External constraints

Operator	Coefficient	Constraint
$\mathcal{O}_g = \frac{g_s^2}{m_W^2}\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$c'_g = \frac{m_W^2}{\Lambda^2}16\pi^2\,\texttt{cG}$	$(-0.050, 0.017)$
$\tilde{\mathcal{O}}_g = \frac{g_s^2}{m_W^2}\lvert H\rvert^2 G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$	$\tilde{c}'_g = \frac{m_W^2}{\Lambda^2}16\pi^2\,\texttt{tcG}$	$(-0.019, 0.019)$
$\mathcal{O}_\gamma = \frac{g'^2}{m_W^2}\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$c'_\gamma = \frac{m_W^2}{\Lambda^2}16\pi^2\,\texttt{cA}$	$(-0.17, 0.035)$
$\tilde{\mathcal{O}}_\gamma = \frac{g'^2}{m_W^2}\lvert H\rvert^2 B_{\mu\nu}\tilde{B}^{\mu\nu}$	$\tilde{c}'_\gamma = \frac{m_W^2}{\Lambda^2}16\pi^2\,\texttt{tcA}$	$(-0.19, 0.19)$
$\mathcal{O}_u = \frac{y_u}{v^2}\lvert H\rvert^2 u_L H u_R + \text{h.c.}$	$c_u = \frac{v^2}{\Lambda^2}\texttt{cu}$	
$\mathcal{O}_d = \frac{y_d}{v^2}\lvert H\rvert^2 d_L H d_R + \text{h.c.}$	$c_d = \frac{v^2}{\Lambda^2}\texttt{cd}$	
$\mathcal{O}_\ell = \frac{y_\ell}{v^2}\lvert H\rvert^2 \ell_L H \ell_R + \text{h.c.}$	$c_\ell = \frac{v^2}{\Lambda^2}\texttt{cl}$	
$\mathcal{O}_H = \frac{1}{2v^2}\left(\partial^\mu\lvert H\rvert^2\right)^2$	$c_H = \frac{v^2}{\Lambda^2}\texttt{cH}$	
$\mathcal{O}_6 = \frac{\lambda}{v^2}\left(H^\dagger H\right)^3$	$c_6 = \frac{v^2}{\Lambda^2}\texttt{c6}$	
$\mathcal{O}_{HW} = \frac{ig}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$c_{HW} = \frac{m_W^2}{\Lambda^2}\texttt{cHW}$	$(-0.035, 0.015)$
$\tilde{\mathcal{O}}_{HW} = \frac{ig}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$	$\tilde{c}_{HW} = \frac{m_W^2}{\Lambda^2}\texttt{tcHW}$	$(-0.06, 0.06)$
$\mathcal{O}_{HB} = \frac{ig'}{m_W^2}\left(D^\mu H\right)^\dagger (D^\nu H) B_{\mu\nu}$	$c_{HB} = \frac{m_W^2}{\Lambda^2}\texttt{cHB}$	$(-0.045, 0.075)$
$\tilde{\mathcal{O}}_{HB} = \frac{ig'}{m_W^2}\left(D^\mu H\right)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$	$\tilde{c}_{HB} = \frac{m_W^2}{\Lambda^2}\texttt{tcHB}$	$(-0.23, 0.23)$
$\mathcal{O}_W \pm \mathcal{O}_B = \frac{ig}{2m_W^2}\left(H^\dagger\sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$c_{W-B} = \frac{m_W^2}{\Lambda^2}(\texttt{cWW} - \texttt{cB})$	$(-0.035, 0.005)$
$\pm\frac{ig'}{2m_W^2}\left(H^\dagger D^\mu H\right)\partial^\nu B_{\mu\nu}$	$c_{W+B} = \frac{m_W^2}{\Lambda^2}(\texttt{cWW} + \texttt{cB})$	$(-0.0033, 0.0018)$
$\mathcal{O}_{3W} = \frac{g^3}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}_\rho W^{\rho\mu k}$	$c_{3W} = \frac{m_W^2}{\Lambda^2}\texttt{c3W}$	$(-0.083, 0.045)$
$\tilde{\mathcal{O}}_{3W} = \frac{g^3}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}_\rho \tilde{W}^{\rho\mu k}$	$\tilde{c}_{3W} = \frac{m_W^2}{\Lambda^2}\texttt{tc3W}$	$(-0.18, 0.18)$

Operators constrained by Higgs & EW data
Constraints taken from global Run 1 fit by Ellis, Sanz, and You
CP-violating operators constrained from individual fits

External constraints

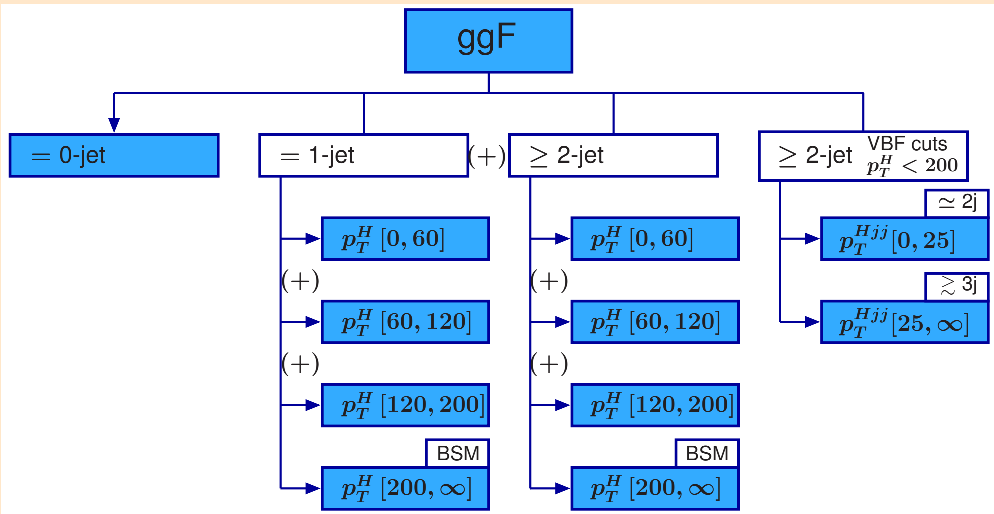
Operator	Coefficient	Constraint
$\mathcal{O}_T = \frac{1}{2v^2}\left(H^\dagger D^\mu H\right)^2$	$c_T = \frac{v^2}{\Lambda^2}\texttt{cT}$	$(-0.0043, 0.0033)$
$\mathcal{O}_{2W} = \frac{g^2}{m_W^2} D^\mu W^k_{\mu\nu} D_\rho W_k^{\rho\nu}$	$c_{2W} = \frac{m_W^2}{\Lambda^2}\texttt{c2W}$	
$\mathcal{O}_{2B} = \frac{g^2}{m_W^2} \partial^\mu B_{\mu\nu} \partial_\rho B^{\rho\nu}$	$c_{2B} = \frac{m_W^2}{\Lambda^2}\texttt{c2B}$	
$\mathcal{O}_R^u = \frac{1}{v^2}\left(iH^\dagger D_\mu H\right)(\bar{u}_R\gamma^\mu u_R)$	$c_R^u = \frac{v^2}{\Lambda^2}\texttt{cHu}$	$(-0.011, 0.011)$
$\mathcal{O}_R^d = \frac{1}{v^2}\left(iH^\dagger D_\mu H\right)(\bar{d}_R\gamma^\mu d_R)$	$c_R^d = \frac{v^2}{\Lambda^2}\texttt{cHd}$	$(-0.042, 0.0044)$
$\mathcal{O}_R^e = \frac{1}{v^2}\left(iH^\dagger D_\mu H\right)(\bar{e}_R\gamma^\mu e_R)$	$c_R^e = \frac{v^2}{\Lambda^2}\texttt{cHe}$	$(-0.0018, 0.00025)$
$\mathcal{O}_L^q = \frac{1}{v^2}\left(iH^\dagger D_\mu H\right)(\bar{Q}_L\gamma^\mu Q_L)$	$c_L^q = \frac{v^2}{\Lambda^2}\texttt{cHQ}$	$(-0.0019, 0.0069)$
$\mathcal{O}_L^{(3)q} = \frac{1}{v^2}\left(iH^\dagger \sigma^a D_\mu H\right)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	$c_L^{(3)q} = \frac{v^2}{\Lambda^2}\texttt{cpHQ}$	$(-0.0044, 0.0044)$
$\mathcal{O}_{LL}^{(3)L} = \frac{1}{v^2}(\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma^\mu L_L)$	$c_{LL}^{(3)l}$	$(-0.0013, 0.00075)$
$\mathcal{O}_{3G} = \frac{g_s^3}{m_W^2} f_{abc} G^a_{\mu\nu} G^{\nu b}_\rho G^{\rho\mu c}$	$c_{3G} = \frac{m_W^2}{\Lambda^2}\texttt{c3G}$	$(-0.00026, 0.00026)$
$\tilde{\mathcal{O}}_{3G} = \frac{g_s^3}{m_W^2} f_{abc} G^a_{\mu\nu} G^{\nu b}_\rho \tilde{G}^{\rho\mu c}$	$\tilde{c}_{3G} = \frac{m_W^2}{\Lambda^2}\texttt{tc3G}$	
$\mathcal{O}_{2G} = \frac{g_s^2}{m_W^2} D^\mu G^a_{\mu\nu} D_\rho G_a^{\rho\nu}$	$c_{2G} = \frac{m_W^2}{\Lambda^2}\texttt{c2G}$	

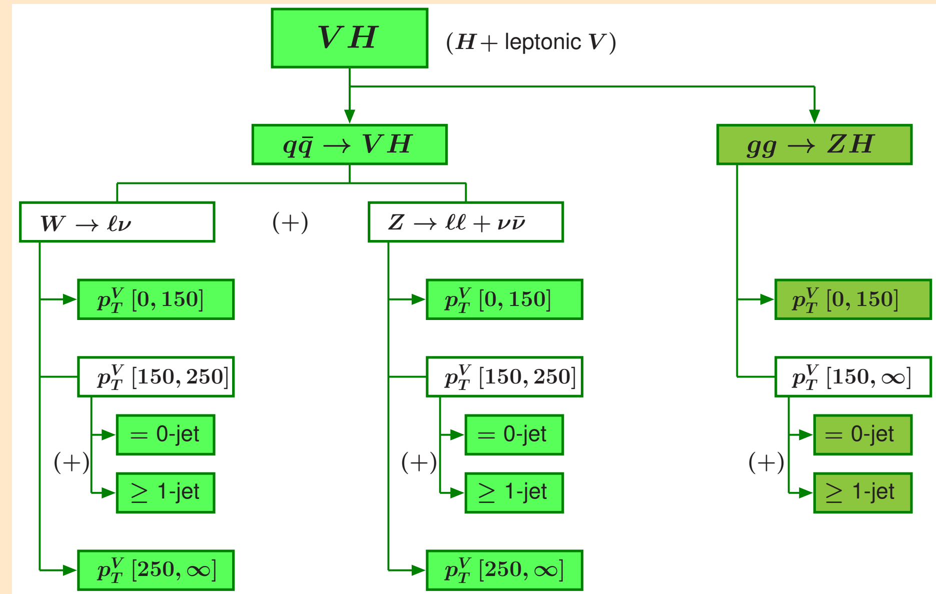
Operators constrained by EW & QCD data
EW constraints taken from global fit by Ellis, Sanz, and You
QCD constraint taken from individual fit by Krauss, Kuttimalai, and Plehn

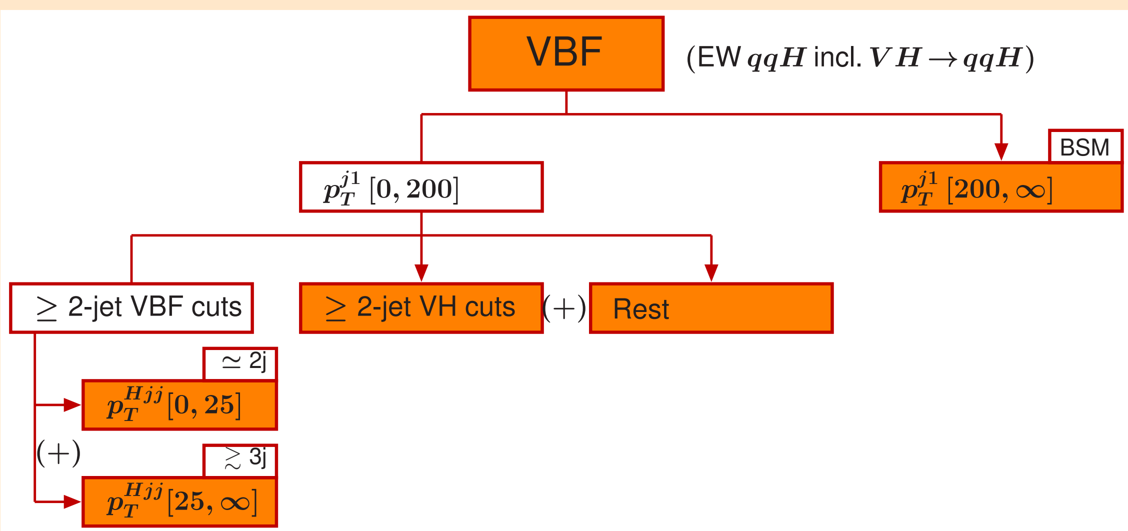
12 additional HEL operators not constrained
Four-fermion operators not implemented in HEL

Mapping STXS to EFT

Use "Stage 1" STXS: $\sigma_i \times \mathcal{B}_{4\ell}$







Can update to Stage 1.5 or Stage 2 when available / appropriate

Mapping STXS to EFT

Take cross sections and decay widths to be quadratic functions of EFT

Have validated approximation to substantially higher accuracy than data

$$\sigma_{EFT} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

$$\frac{\sigma_{int}}{\sigma_{SM}} = \sum_i A_i c_i,$$

$$\frac{\sigma_{BSM}}{\sigma_{SM}} = \sum_{ij} B_{ij} c_i c_j$$

$$\mathcal{B}_{4\ell} = \frac{\Gamma_{4\ell}}{\sum_f \Gamma_f} \approx \frac{\Gamma_{4\ell}^{SM}}{\sum_f \Gamma_f^{SM}} \left[1 + \sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j - \sum_f \left(\sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j \right)\right],$$

$$\frac{\Gamma_f}{\Gamma_{4\ell}} \approx \frac{\Gamma_f^{SM}}{\Gamma_{4\ell}^{SM}} \left[1 + \sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j - \left(\sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j \right)\right]. \quad (3)$$

Madgraph options available to directly evaluate A_i and B_{ij} for $i = j$
(Not yet available for NLO?)

Need to subtract two calculations to get B_{ij} for $i \neq j$

Initial fit: Keep B_{ij} in fit in case interference is suppressed
Should not be too model-dependent since B_{ij} is leading SM-independent term
Can also fit with $B_{ij} = 0$ to test impact

Equations relating STXS to EFT

Do not include terms where coefficient is less than 0.1% of leading term (expect NLO to become relevant)

Cross-section region	$\sum_i A_i c_i$	$\sum_{ij} B_{ij} c_i c_j$
$gg \to H$ (0-jet)		
$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	$56c'_g$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)		
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 18c_{3G} + 12c_{2G}$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ (1-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 55c_{3G} + 36c_{2G}$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ ($\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ ($\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 22c_{3G} + 17c_{2G}$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 89c_{3G} + 69c_{2G}$	$790(c'^2_g + c'^2_{\tilde{g}}) + 63000c^2_{2G}$ $+34000(c^2_{3G} + c^2_{3\tilde{G}})$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j3} < 25$ GeV)	$56c'_g$	$790(c'^2_g + c'^2_{\tilde{g}})$
$gg \to H$ ($\geq$ 2-jet VBF-like, $p_T^{j3} \geq 25$ GeV)	$56c'_g + 9c_{3G}$	$790(c'^2_g + c'^2_{\tilde{g}})$
$qq \to Hqq$ VBF-like, $p_T^{j3} < 25$ GeV)	$56c'_g$	$790(c'^2_g + c'^2_{\tilde{g}})$
$qq \to Hqq$ VBF-like, $p_T^{j3} \geq 25$ GeV)	$56c'_g + 9c_{3G}$	$790(c'^2_g + c'^2_{\tilde{g}})$
$qq \to Hqq$ ($p_T^j \geq 200$ GeV)	$-1.1c_H - 1.2c_T + 17c_{2W}$ $+0.6c_B - 26c_{HW} - 1.8c_{HB}$ $+0.3c_{HQ} - 16c_{\tilde{HQ}} - c_{Hu}$ $+0.3c_{Hd}$	$1.4c^2_T + 560c^2_{2W} + 12c^2_B$ $+660c^2_{HW} + 13c^2_{HB} + 220c^2_{HQ}$
$gg/qq \to Hll/Hl\nu$		
$gg/qq \to ttH$	$-c_H + 3c_u + c_G$ $+314c_{uG} + 28c_{3G} - 13c_{2G}$	$124000c^2_{uG} + 142000(c^2_{3G} + c^2_{3}$ $-112000c_{uG}c_{3G} + 50400c_{uG}c_{2}$

At LO could use gg→H jet binning to constrain c_{2G} and c_{3G} *in situ*

Equations relating STXS to EFT

Partial width	$\sum_i A_i c_i$	$\sum_{ij} B_{ij} c_i c_j$
$H \to b\bar{b}$ $H \to WW^*$		
$H \to ZZ^*$	$52c_{2W} + 14c_B + 15c_{HW}$ $-4.4c_{HB} + 10(c_{Hl} + c_{\tilde{H}l})$	$230c_{2W}c_{HW} + 220c_{2W}(c_{Hl} + c_{\tilde{H}l})$ $+210c_{2W}c_B$
$H \to \gamma\gamma$ $H \to \tau\tau$ $H \to gg$ $H \to cc$	$-5.9c'_\gamma$	$8.4(c'^2_\gamma + c'^2_{\tilde{\gamma}})$

Example: fit to two channels (ZZ and $\gamma\gamma$) could constrain c_g', c_γ', c_{HW}, c_{HB}, c_{W-B}, c_u (also c_{2G}, c_{3G} at expense of c_u?)

Ideally incorporate top data to constrain c_{uG}, jet data to constrain c_{2G} and c_{3G}

Issues

EW scheme not clear in HEL

Appears to have m_W, $\boldsymbol{\alpha}_{EM}$ and G_F as inputs

m_Z given by the equation:

$$mZ^2 = mZ^2_{SM}\left[1 - cT + \frac{8cA\sin^4(\theta_W) + 2cWW\cos^2(\theta_W) + cB\sin^2(\theta_W)}{\cos^2(\theta_W)}\right]$$

Since m_Z includes fit parameters we should constrain it to SM prediction

What is SM prediction of m_Z in this EW scheme?

Based on usual m_W prediction, expect ~91.19 GeV with ~15 MeV uncertainty

No clear EFT uncertainty prescription

- would also help motivate truncation cutoff

Need to define fit ranges

- what upper bound on c_i to use?
- what minimum scale for validity?