25th International Workshop on Weak Interactions and Neutrinos,
Heidelberg, 10th June 2015

The Effective Standard Model

Tevong You

Based on work with **John Ellis** and **Veronica Sanz:**

-*The Effective Standard Model after LHC Run I*,
JHEP 29 (2015) 007 [arXiv:1410.7703]

-*Complete Higgs Sector Constraints on Dimension-6 Operators*,
JHEP 1407 (2014) 036 [arXiv:1404.3667]

And **Aleksandra Drozd**, **John Ellis** and **Jeremie Quevillon:**

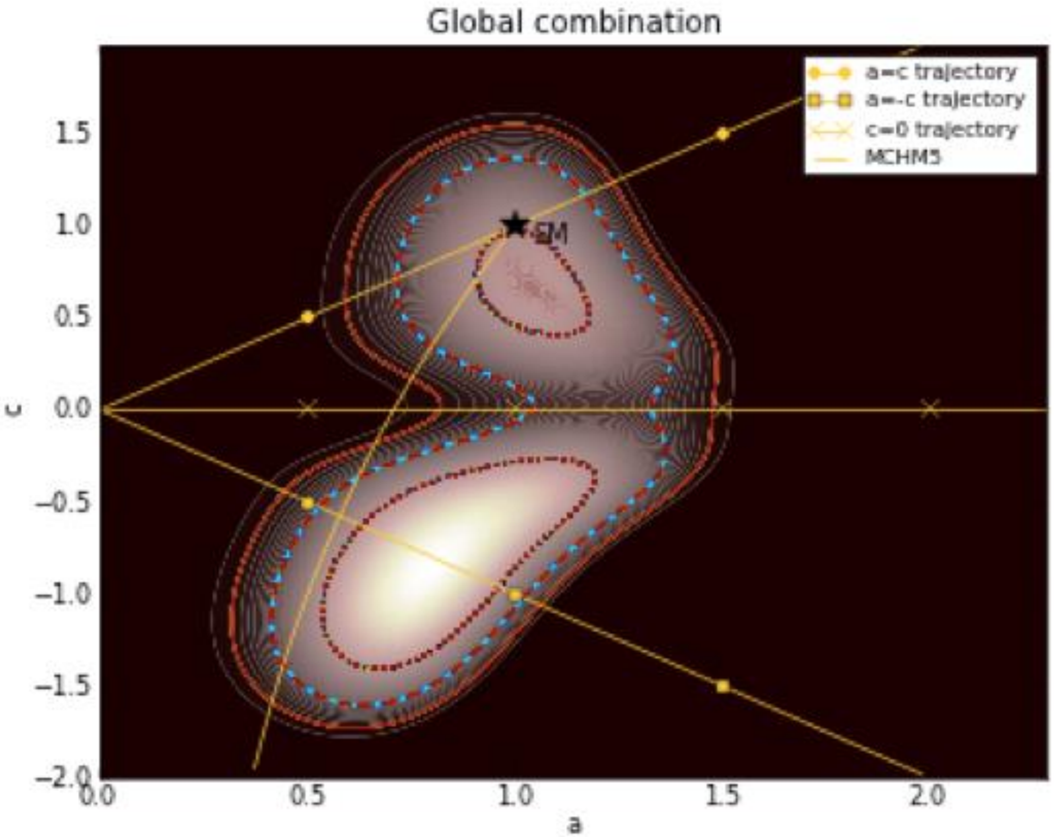
-*Comparing EFT and Exact One-Loop Analyses of Non-Degenerate Stops*,
JHEP 06 (2015) 028 [arXiv:1504.02409]

Content

- A Standard Model Higgs?
- The Standard Model as an effective theory
- EWPT constraints on dim-6 operators
- Higgs constraints on dim-6 operators
- Triple-gauge-couplings constraints on dim-6 operators
- Indirect constraints on a light stop and the universal one-loop effective action
- Conclusion

A Standard Model Higgs?

- Could have had very different coupling patterns than SM!



March 2012 pre-discovery

J. Ellis and T.Y. [arXiv:1204.0464]

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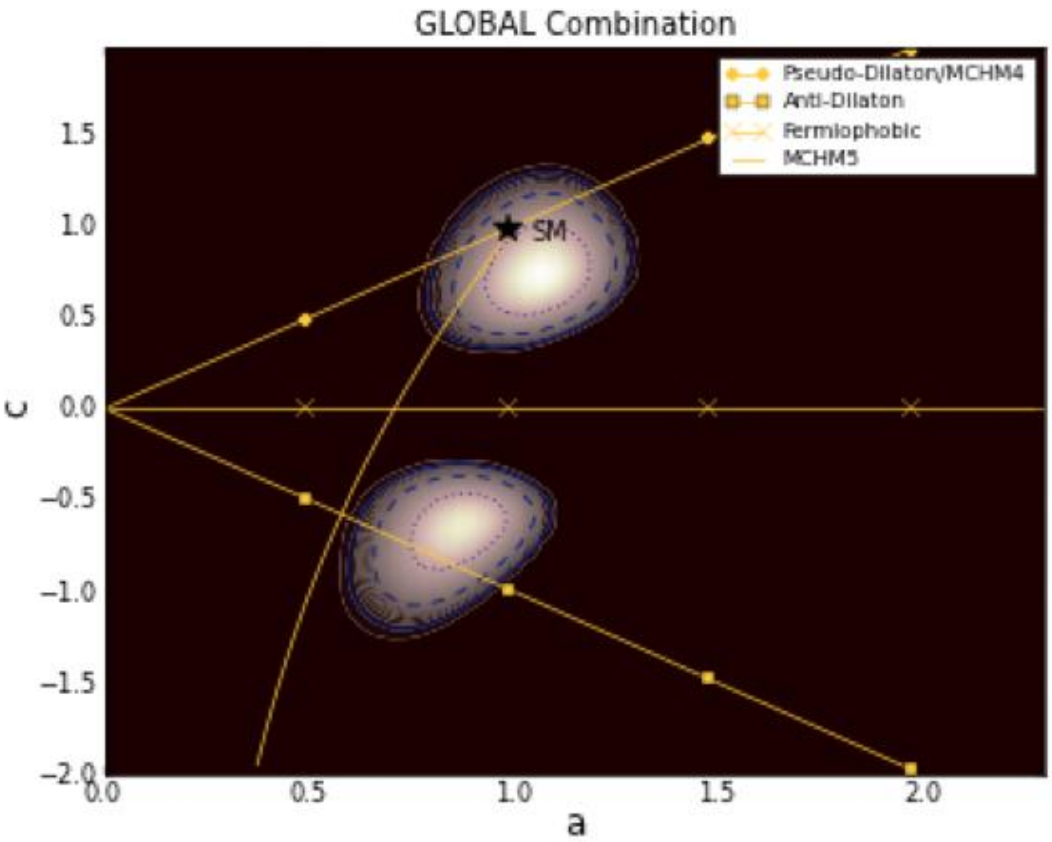

Moriond 2013

J. Ellis and T.Y. [arXiv:1303.1879]

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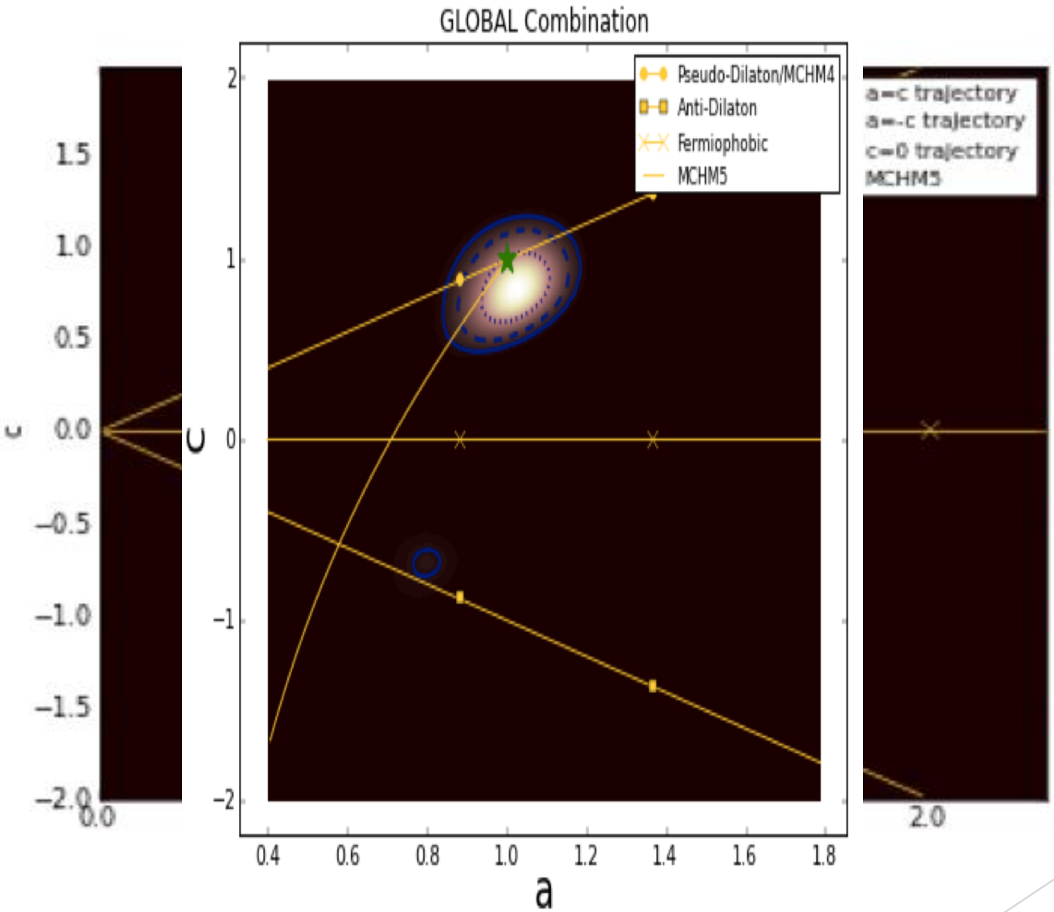


July 2012 post-discovery
J. Ellis and T.Y. [arXiv:1207.1693]

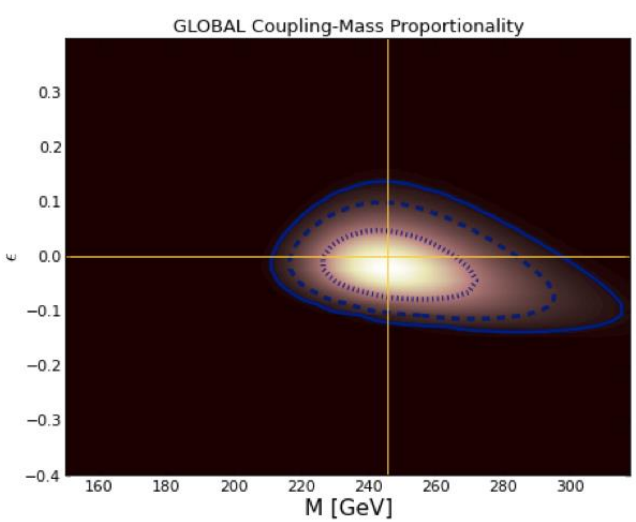
A Standard Model Higgs?

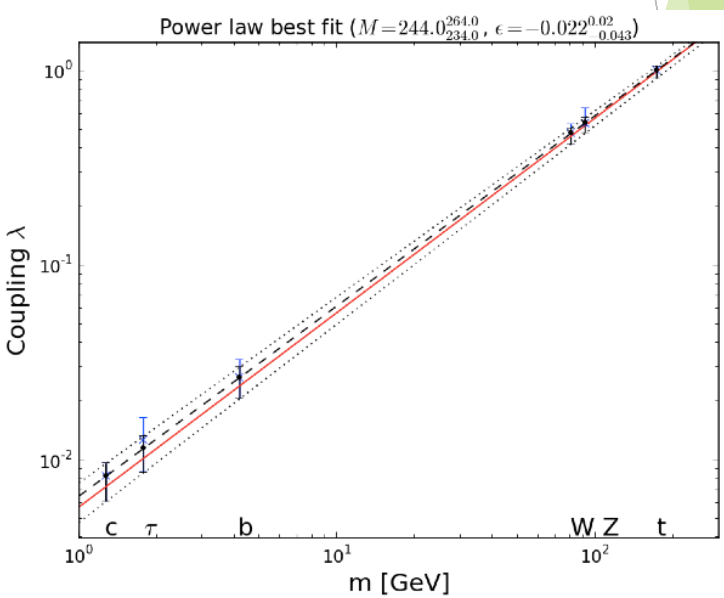
- Responsible for electroweak symmetry breaking and giving mass?
- Rescale couplings by general scale and power to test mass-proportionality

$$c_f = \frac{\lambda'_f}{\lambda_f} = v\left(\frac{m_f^\epsilon}{M^{1+\epsilon}}\right), \quad a_V = \frac{g'_V}{g_V} = v\left(\frac{M_V^{2\epsilon}}{M^{(1+2\epsilon)}}\right)$$

J. Ellis and T.Y. [arXiv:1303.1879]

- General mass-independent scalar has $\epsilon = -1$
- SM corresponds to M = 246 GeV, $\epsilon = 0$



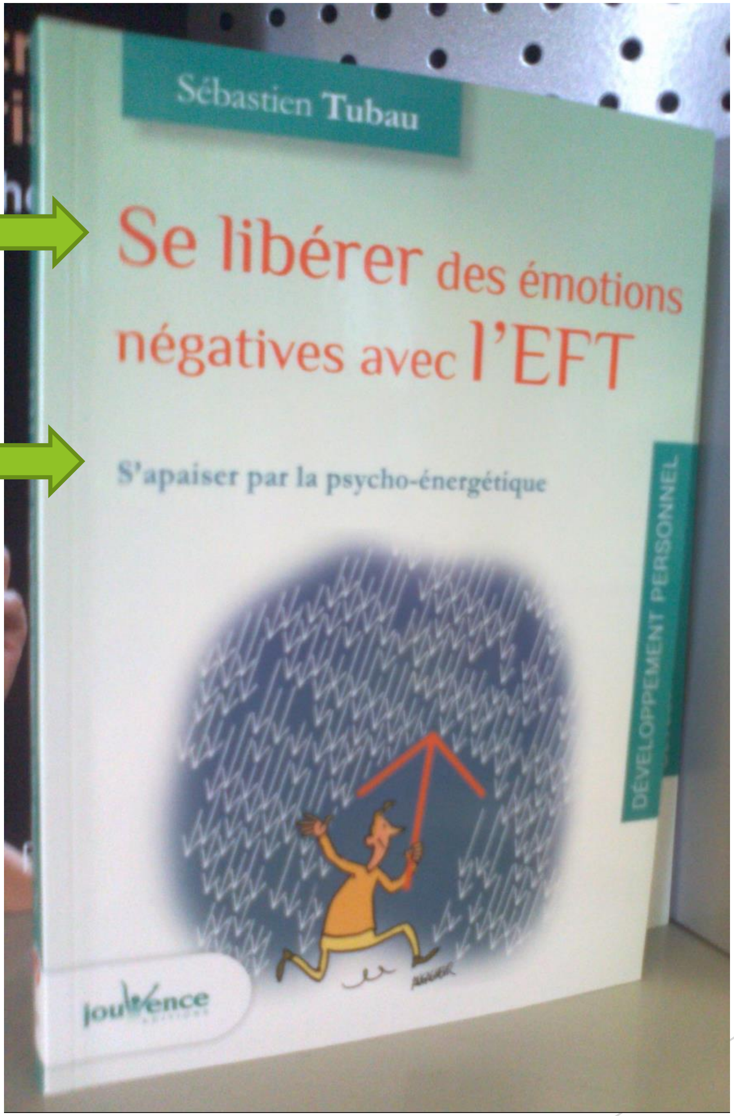


The Standard Model as an Effective Theory

- Motivation

Free yourself from negative emotions with EFT

Find peace with high energies



The Standard Model as an Effective Theory

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The Standard Model as an Effective Theory

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	**3**	**2**	$\frac{1}{6}$
q_R^u	**3**	**1**	$\frac{2}{3}$
q_R^d	**3**	**1**	$-\frac{1}{3}$
L_L	**1**	**2**	$-\frac{1}{2}$
l_R	**1**	**1**	-1
ϕ	**1**	**2**	$\frac{1}{2}$

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad + \quad \mathcal{L}_{\rm SM}^{\rm dim\text{-}6} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

$$\begin{aligned}
\mathcal{L}_m &= \bar{Q}_L i\gamma^\mu D_\mu^L Q_L + \bar{q}_R i\gamma^\mu D_\mu^R q_R + \bar{L}_L i\gamma^\mu D_\mu^L L_L + \bar{l}_R i\gamma^\mu D_\mu^R l_R \\
\mathcal{L}_G &= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} \\
\mathcal{L}_H &= (D_\mu^L\phi)^\dagger(D^{L\mu}\phi) - V(\phi) \\
\mathcal{L}_Y &= y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,
\end{aligned}$$

- Most of these are four-fermion operators, constrained independently from EWPTs, TGCs, Higgs physics
- Linear combinations of operators affect different measurements
- Choice of subset or full complete set of operators
  - Different models predict different subsets of operators
  - Model-independent approach: Avoid redundancies in operator basis, difference choice of bases in literature
- First classified systematically by Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
- 59 dim-6 CP-even operators in a non-redundant basis, assuming MFV (Gradkowski et al [arXiv:1008.4884 [hep-ph]])

Organizing principle(s) of dimension-6 operators

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$
$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

(SILH basis) Pomarol and Riva 1308.1426

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R + \text{h.c.}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R + \text{h.c.}$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L \sigma^a \gamma_\mu Q_L)(\bar{L}_L \sigma^a \gamma^\mu L_L)$		$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

$$H^\alpha \to H^\alpha + a(H^\dagger H) H^\alpha / f^2$$

e.g. Operators involving SM bosons only:

Type I: Can be induced at tree-level

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2 \;,\quad \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2 \;,\quad \mathcal{O}_r = |H|^2 |D_\mu H|^2 \;,\quad \mathcal{O}_6 = \lambda |H|^6 \,.$$
$$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu} \;,\quad \mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu} \,,$$
$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2 \;,\quad \mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2 \;,\quad \mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2 \,.$$

$$D^\nu W^a_{\mu\nu} = igH^\dagger \frac{\sigma^a}{2} \overleftrightarrow{D}_\mu H + g \sum_f \bar{f}_L \frac{\sigma^a}{2} \gamma_\mu f_L \,,$$
$$\partial^\nu B_{\mu\nu} = ig' Y_H H^\dagger \overleftrightarrow{D}_\mu H + g' \sum_f \left[Y^f_L \bar{f}_L \gamma_\mu f_L + Y^f_R \bar{f}_R \gamma_\mu f_R \right] \,,$$
$$D^\nu G^A_{\mu\nu} = g_s \sum_q \bar{q} T^A \gamma_\mu q \,,$$

$$\mathcal{O}_B = \mathcal{O}_{HB} + \frac{1}{4}\mathcal{O}_{BB} + \frac{1}{4}\mathcal{O}_{WB} \,,$$
$$\mathcal{O}_W = \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_{WW} + \frac{1}{4}\mathcal{O}_{WB} \,.$$

Type II: Generated at loop level

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \;,\quad \mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu} \,,$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \;,\quad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \,,$$
$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu} \;,\quad \mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^B_{\nu\rho} G^{C\,\rho\mu} \,,$$
$$\mathcal{O}_{WB} = g' g H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{\mu\nu\,a}$$

EWPTs constraints on dim-6 operators

- Electroweak precision tests: Measurements at the Z-peak and W mass

$e^+e^- \to f\bar{f}$	Γ_Z[GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011
at Z-pole	σ_h^0[nb]	41.541 ± 0.037	41.467 ± 0.009
	R_e^0	20.804 ± 0.050	20.756 ± 0.011
	R_μ^0	20.785 ± 0.033	20.756 ± 0.011
	R_τ^0	20.764 ± 0.045	20.801 ± 0.011
	R_b	0.21629 ± 0.00066	0.21578 ± 0.00010
	R_c	0.1721 ± 0.0030	0.17230 ± 0.00004
	$A_{fb}^{0,e}$	0.0145 ± 0.0025	0.01622 ± 0.00025
	$A_{fb}^{0,\mu}$	0.0169 ± 0.0025	0.01622 ± 0.00025
	$A_{fb}^{0,\tau}$	0.0188 ± 0.0017	0.01622 ± 0.00025
	$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1031 ± 0.0008
	$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0737 ± 0.0006
	$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2319 ± 0.0012	0.23152 ± 0.00014
	A_e	0.1514 ± 0.0019	0.1471 ± 0.0011
	A_μ	0.142 ± 0.015	0.1471 ± 0.0011
	A_τ	0.1433 ± 0.0041	0.1471 ± 0.0011
W mass	M_W[GeV]	80.410 ± 0.032	80.376 ± 0.017

See Wells & Zhang expansion formalism [arXiv:1406.6070 [hep-ph]]

- Dim-6 operators affect observables through Zff coupling, vector boson self-energies, and input parameter modifications

$$\mathcal{L} = \frac{e}{2sc}\bar{f}\gamma^\mu(g_V^f - g_A^f\gamma^5)fZ_\mu.$$

$$\Gamma_{ff} = \frac{e^2 M_Z}{48\pi s^2 c^2}(g_V^{f2} + g_A^{f2}),$$

$$A_f = 2\frac{g_V^f/g_A^f}{1+(g_V^f/g_A^f)}.$$

$$\alpha_{0\mathrm{EM}} = \frac{e^2}{4\pi} \quad , \quad G_{F0} = \frac{1}{\sqrt{2}v^2} \quad , \quad m_{Z0} = \frac{v}{2}\sqrt{g^2+g'^2},$$

EWPTs constraints on dim-6 operators

- χ^2 fit of theory predictions with experimental measurements

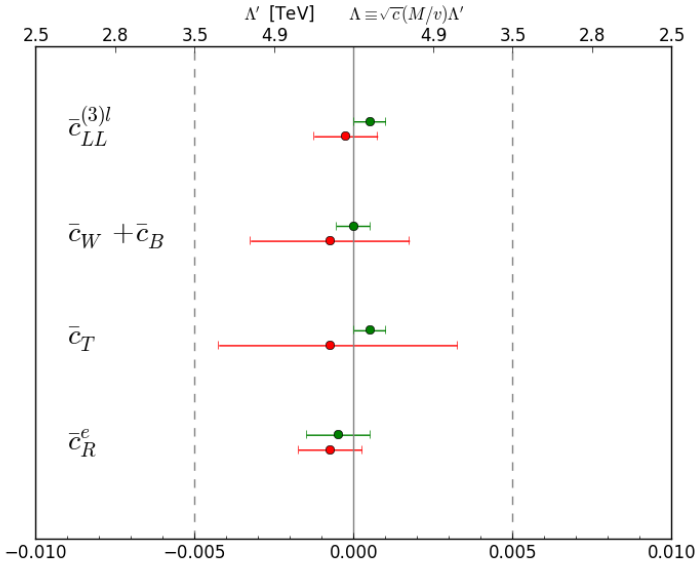
$$\chi^2(p_{\rm SM}, p_\alpha) = \sum_{i,j} (\hat{\mathcal{O}}_i^{\rm th} - \hat{\mathcal{O}}_i^{\rm exp})(\sigma^2)^{-1}_{ij}(\hat{\mathcal{O}}_j^{\rm th} - \hat{\mathcal{O}}_j^{\rm exp}) \quad , \quad (\sigma^2)_{ij} = \Delta\hat{\mathcal{O}}_i^{\rm exp}\rho_{ij}\Delta\hat{\mathcal{O}}_j^{\rm exp}$$

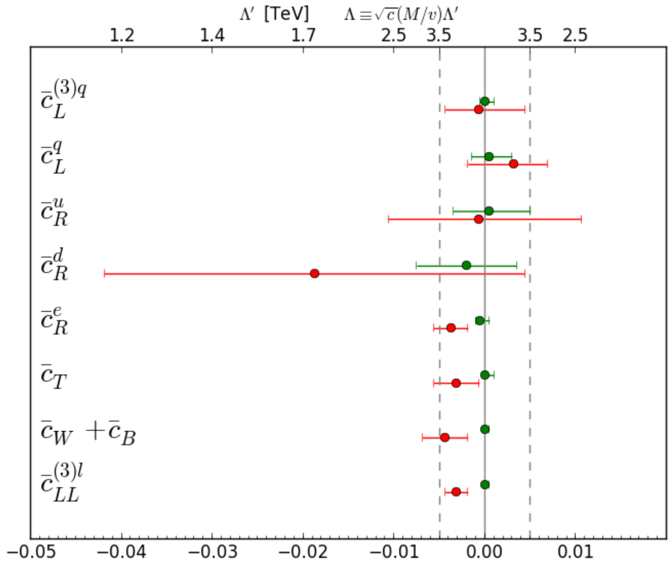
- Marginalized constraints on a complete non-redundant basis of dim-6 operators affecting EWPTs

Operator	Coefficient	LEP Constraints Individual	LEP Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W + c_B)$	$(-0.00055, 0.0005)$	$(-0.0033, 0.0018)$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\frac{v^2}{\Lambda^2}c_T$	$(0, 0.001)$	$(-0.0043, 0.0033)$
$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$	$\frac{v^2}{\Lambda^2}c_{LL}^{(3)l}$	$(0, 0.001)$	$(-0.0013, 0.00075)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	$\frac{v^2}{\Lambda^2}c_R^e$	$(-0.0015, 0.0005)$	$(-0.0018, 0.00025)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\frac{v^2}{\Lambda^2}c_R^u$	$(-0.0035, 0.005)$	$(-0.011, 0.011)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\frac{v^2}{\Lambda^2}c_R^d$	$(-0.0075, 0.0035)$	$(-0.042, 0.0044)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^{(3)q}$	$(-0.0005, 0.001)$	$(-0.0044, 0.0044)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^q$	$(-0.0015, 0.003)$	$(-0.0019, 0.0069)$

EWPTs constraints on dim-6 operators

- Marginalized constraints on a complete non-redundant basis of dim-6 operators affecting EWPTs

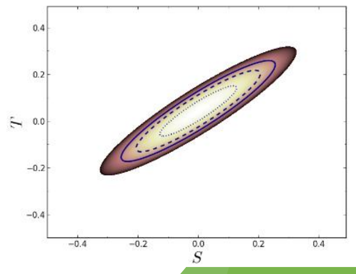




- S,T parameter corresponds to $(c_W + c_B), c_T$ subset

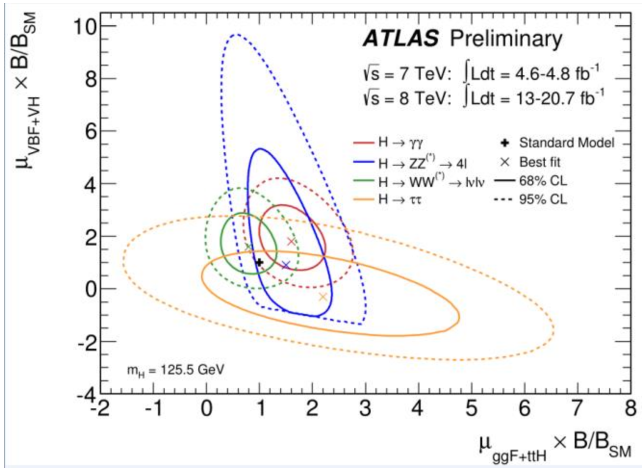
$$S = \frac{4\sin^2\theta_W}{\alpha(m_Z)}(\bar{c}_W + \bar{c}_B) \approx 119(\bar{c}_W + \bar{c}_B)$$

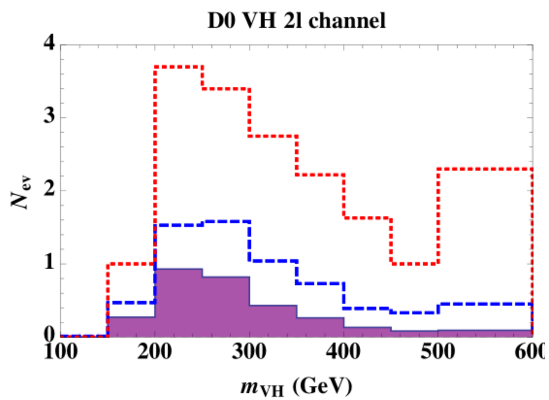
$$T = \frac{1}{\alpha(m_Z)}\bar{c}_T \approx 129\bar{c}_T\,.$$

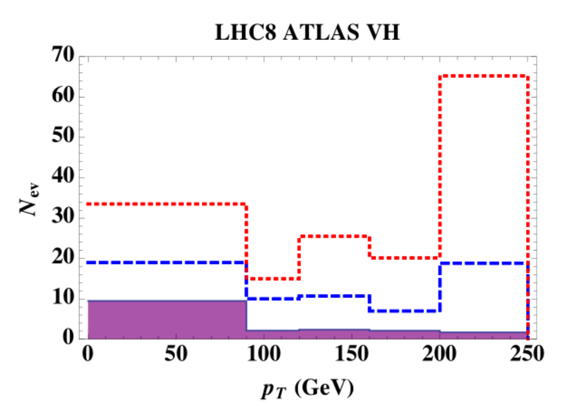


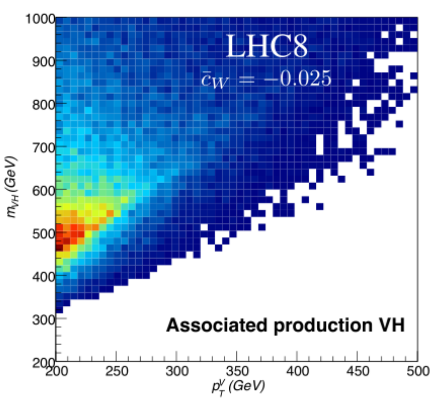
Higgs constraints on dim-6 operators

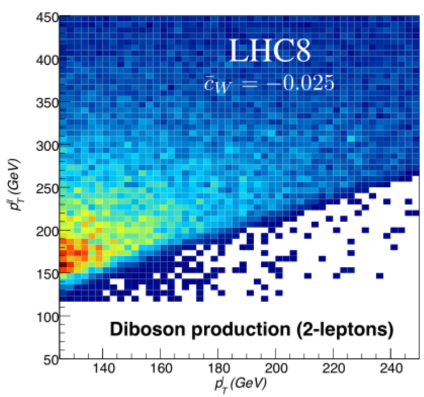
- Operators affect Higgs signal strength measurements, differential distributions

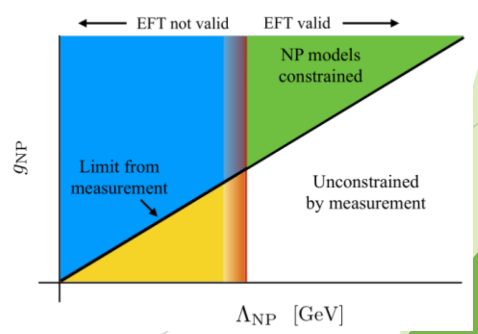








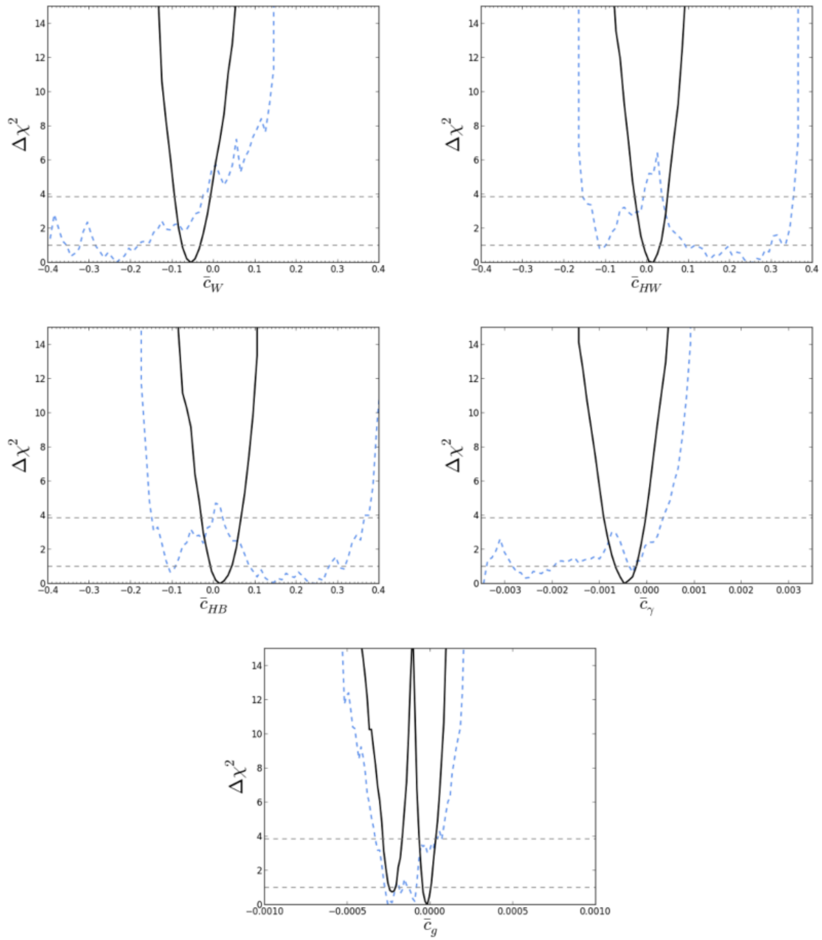




Englert and Spannowsky [arXiv:1408.5147]

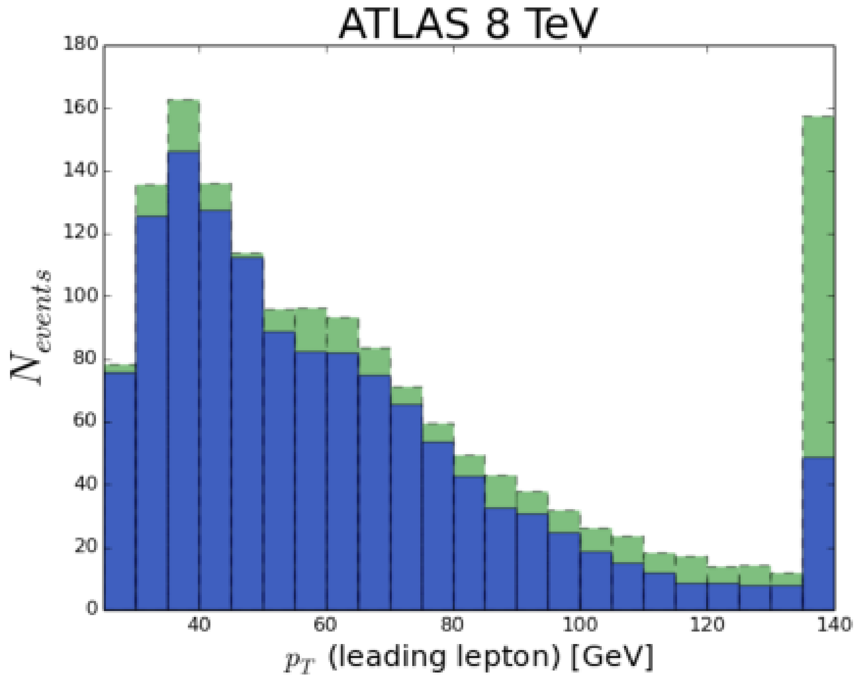
Higgs constraints on dim-6 operators

- Marginalized constraints on these operators, blind direction eliminated by associated production differential distributions



TGC constraints on dim-6 operators

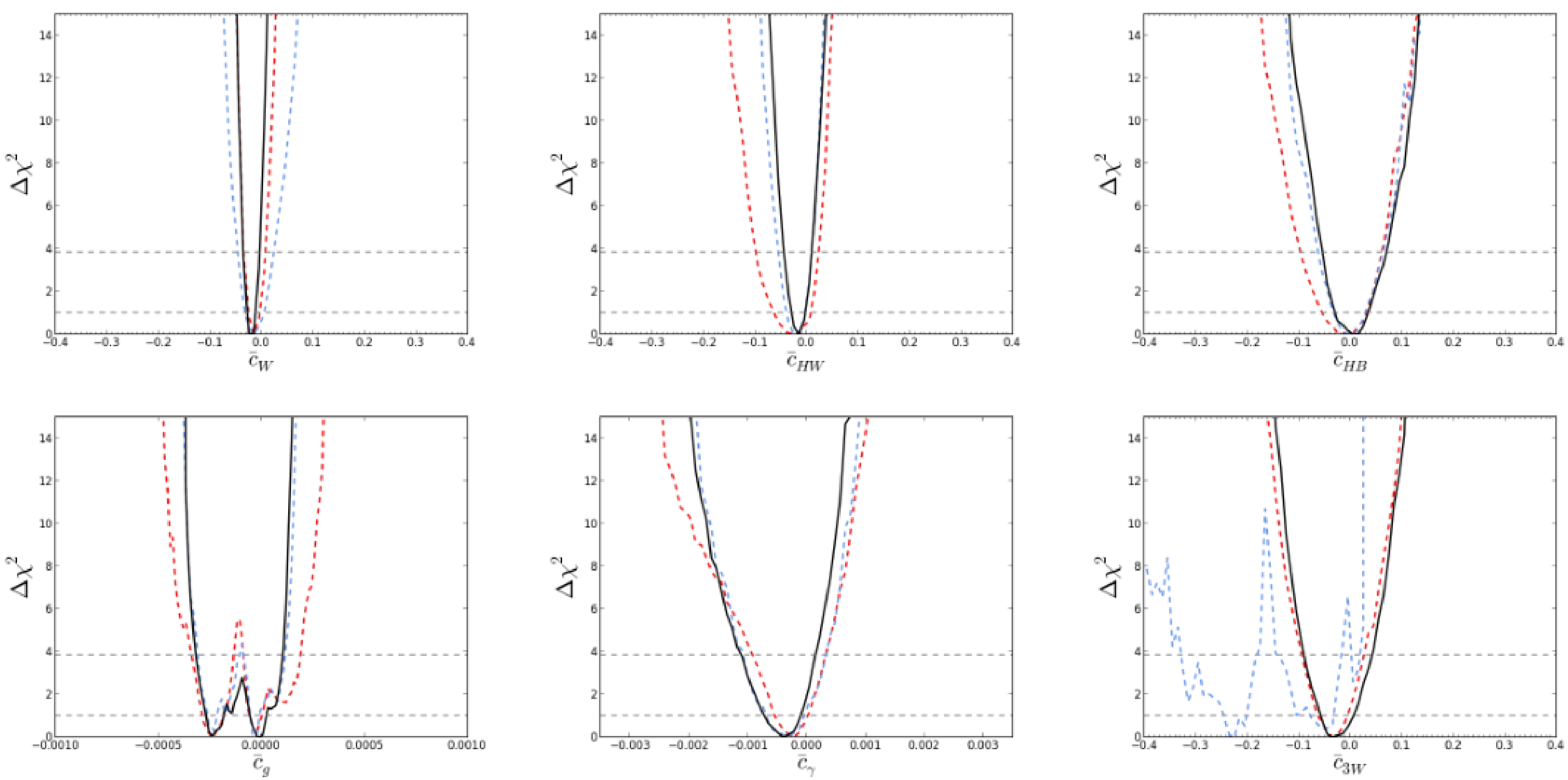
- Triple-gauge-couplings sensitive at high pT to certain dim-6 operators



LEP blind direction: See Falkowski, Fichet, Mohan, Riva and Sanz "TGC Couplings at LEP Revisited" [arXiv:1405.1617]

TGC constraints on dim-6 operators

- Marginalized constraints over all operators affecting TGCs and Higgs physics



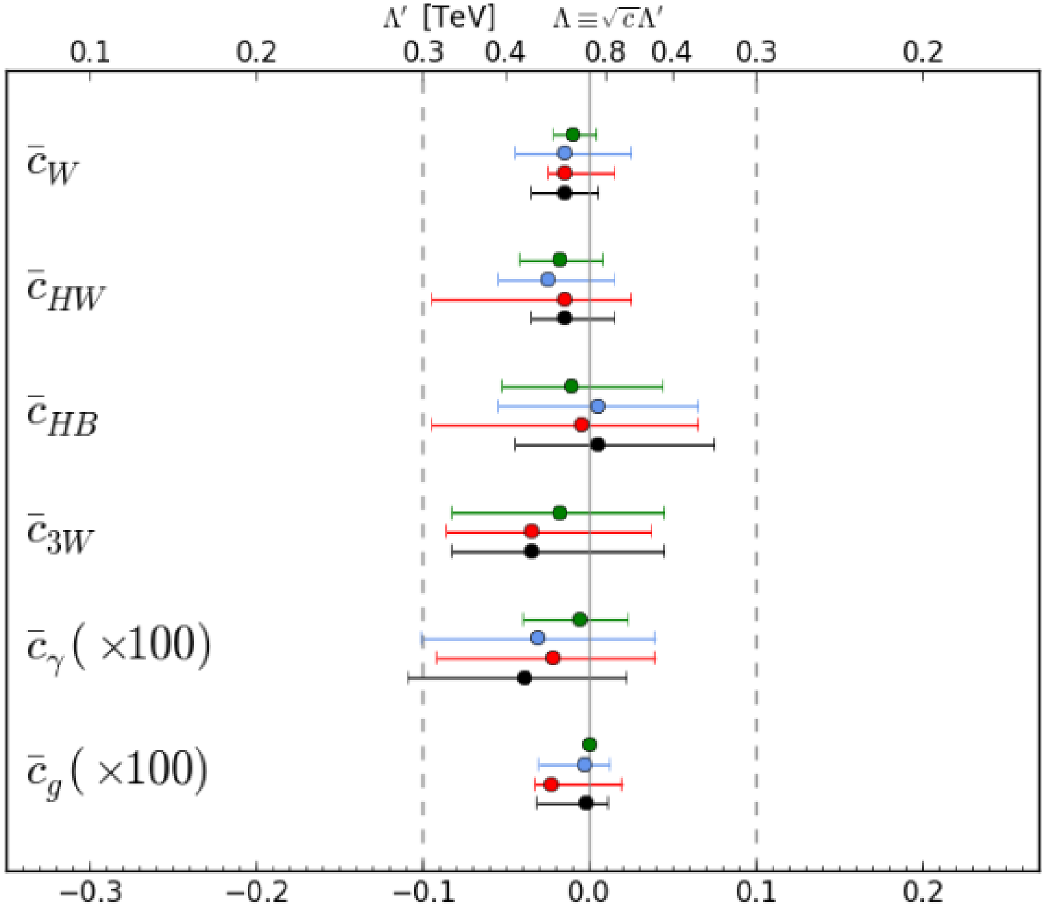
- TGCs complimentary, and essential for c_{3W}

Higgs+TGCs constraints on dim-6 operators

Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$	$\frac{m_W^2}{\Lambda^2} c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_g$	$(0, 3.0) \times 10^{-5}$	$(-3.2, 1.1) \times 10^{-4}$
$\mathcal{O}_\gamma = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_\gamma$	$(-4.0, 2.3) \times 10^{-4}$	$(-11, 2.2) \times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	$\frac{v^2}{\Lambda^2} c_H$	$(-,-)$	$(-,-)$
$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2} c_f$	$(-,-)$	$(-,-)$

Higgs+TGCs constraints on dim-6 operators

x 10 TeV

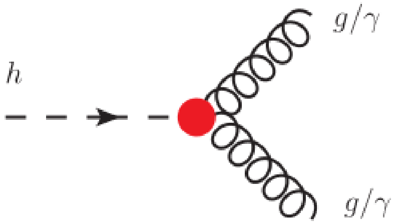


Indirect Constraints on Stops

- Cg, Cgamma loop-induced in MSSM, lowers EFT cut-off
- Determine validity by comparing EFT vs full calculation
- EFT calculation simplified by Covariant Derivative Expansion (CDE) method (Henning, Lu & Murayama [arXiv:1412.1837])
- Systematic way of integrating out UV degrees of freedom in manifestly gauge-invariant way
- Universality: Easier to determine Wilson coefficients for any other model
- Additional motivation for EFT approach

Indirect Constraints on Stops

- Matching with Feynman diagrams
- Calculate observable in EFT



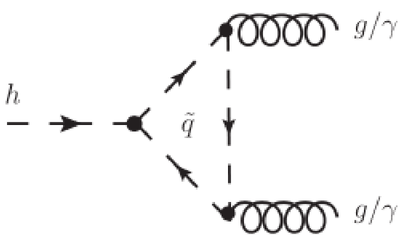
$$iV^{\mu\nu}_{hgg}(p_2,p_3) = -4ig_3^2\sqrt{2}v\frac{\bar{c}_g}{m_W^2}(p_2p_3g^{\mu\nu} - p_2^\nu p_3^\mu)$$

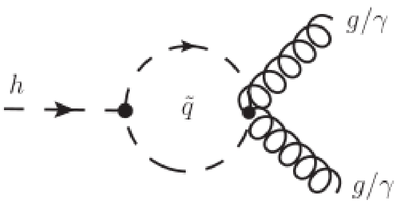
$$iV^{\mu\nu}_{h\gamma\gamma}(p_2,p_3) = -4ie^2\sqrt{2}v\frac{\bar{c}_\gamma}{m_W^2}(p_2p_3g^{\mu\nu} - p_2^\nu p_3^\mu)$$

$$\mathcal{A}^{hgg}_{EFT} = -16g_s^2\sqrt{2}v\frac{\bar{c}_g}{m_W^2}\left(\xi_2^*.\xi_3^*M_h^2 - 2(\xi_2^*.p_1)(\xi_3^*.p_1)\right) ,$$

$$\mathcal{A}^{h\gamma\gamma}_{EFT} = -2g_1^2\cos^2\theta_W\sqrt{2}v\frac{\bar{c}_\gamma}{m_W^2}\left(\xi_2^*.\xi_3^*M_h^2 - 2(\xi_2^*.p_1)(\xi_3^*.p_1)\right)$$

- Calculate observable in MSSM





Indirect Constraints on Stops

- Match the two to obtain Wilson coefficient

$$(\bar{c}_g^{\rm MSSM})^{\tilde{t}} = \frac{m_W^2}{6(4\pi)^2}\frac{N_g^{\tilde{t}}}{D_g^{\tilde{t}}}\,,$$

$$N_g^{\tilde{t}} = \frac{c_{2\beta}g_1^2}{s_W^2}\left[v^2 c_{2\beta}g_1^2\left(2c_{2W}+1\right)+3\left(3v^2h_t^2+2\left(m_{\tilde{t}_R}^2-m_{\tilde{Q}}^2\right)c_{2W}+2m_{\tilde{Q}}^2+m_{\tilde{t}_R}^2\right)\right]$$
$$+36h_t^2\left(v^2h_t^2+m_{\tilde{Q}}^2+m_{\tilde{t}_R}^2-X_t^2\right)\,,$$

$$D_g^{\tilde{t}} = \frac{v^2 c_{2\beta}g_1^2}{s_W^2}\left[v^2 c_{2\beta}g_1^2\left(2c_{2W}+1\right)+3\left(3v^2h_t^2+4\left(m_{\tilde{t}_R}^2-m_{\tilde{Q}}^2\right)c_{2W}+4m_{\tilde{Q}}^2+2m_{\tilde{t}_R}^2\right)\right]$$
$$+36\left(v^2h_t^2+2m_{\tilde{Q}}^2\right)\left(v^2h_t^2+2m_{\tilde{t}_R}^2\right)-72v^2h_t^2X_t^2\,,$$

$$(\bar{c}_g^{\rm MSSM})^{\tilde{b}} = \frac{m_W^2}{6(4\pi)^2}\frac{c_{2\beta}g_1^2\left\{6\left[\left(m_{\tilde{b}_R}^2-m_{\tilde{Q}}^2\right)c_{2W}+m_{\tilde{Q}}^2+2m_{\tilde{b}_R}^2\right]-v^2c_{2\beta}g_1^2\left(c_{2W}+2\right)\right\}}{\left(12m_{\tilde{b}_R}^2-v^2c_{2\beta}g_1^2\right)\left[v^2c_{2\beta}g_1^2\left(c_{2W}+2\right)-24m_{\tilde{Q}}^2s_W^2\right]}$$

Indirect Constraints on Stops

- Integrating out directly from path integral using CDE

$$\mathcal{L}_{\text{UV}} = \mathcal{L}_{\text{SM}} + (\Phi^\dagger F(x) + \text{h.c.}) + \Phi^\dagger(P^2 - M^2 - U(x))\Phi + \mathcal{O}(\Phi^3)\,,$$

$$e^{iS_{\text{eff}}[\phi](\mu)} = \int \mathcal{D}\Phi\, e^{iS[\phi,\Phi](\mu)}. \qquad S_{\text{eff}} \approx S[\Phi_c] + \frac{i}{2}\text{Tr}\log\left(-\left.\frac{\delta^2 S}{\delta\Phi^2}\right|_{\Phi_c}\right)$$

$$\mathcal{L}^{\text{eff}}_{\text{1-loop}} = i\int \frac{d^4q}{(2\pi)^4}\text{Tr}\ln[-(\tilde{G}_{\nu\mu}\partial/\partial q_\mu + q_\mu)^2 + M^2 + \tilde{U}]\,,$$

$$\tilde{G}_{\nu\mu} \equiv \sum_{n=0} \frac{n+1}{(n+2)!}[P_{\alpha_1},[\ldots[P_{\alpha_n},G'_{\nu\mu}]]]\frac{\partial^n}{\partial q_{\alpha_1}\ldots q_{\alpha_n}}\,,$$

$$\tilde{U} = \sum_{n=0}\frac{1}{n!}[P_{\alpha_1},[\ldots[P_{\alpha_n},U]]]\,.$$

$$\mathcal{L}^{\text{eff}}_{\text{1-loop}} \supset i\int\frac{d^4q}{(2\pi)^4}\text{Tr}\left\{B^{-2}\left(-\frac{1}{4}G'_{\nu\mu}G'^{\nu\mu}\right) - \frac{8}{3}q_\alpha q_\nu B^{-3}\left(-\frac{1}{4}G'^{\alpha}{}_{\mu}G'^{\nu\mu}\right)\right\}$$

$$B^{-1} = -\Delta\sum_{n=0}(\Delta U)^n$$

See
-Henning, Lu & Murayama [arXiv:1412.1837]
-Gaillard Nucl. Phys. B 268 (1986) 669
-Cheyette Nucl. Phys. B 297 (1988) 183

Indirect Constraints on Stops

- Universal non-degenerate one-loop effective Lagrangian

$$\mathcal{L}^{\text{eff}}_{\text{1-loop}} \supset \frac{1}{(4\pi)^2}\left\{-\frac{1}{12}\text{Tr}\left(\bar{U}G'_{\mu\nu}G'^{\mu\nu}\right)+\frac{1}{24}\text{Tr}\left(\bar{U}^2G'_{\mu\nu}G'^{\mu\nu}\right)+\frac{1}{240}\text{Tr}\left(\left[\bar{U},G'_{\mu\nu}\right]\left[\bar{U},G'^{\mu\nu}\right]\right)\right\}$$

$$\bar{U}_{ij} \equiv \frac{U_{ij}}{m_i m_j}$$

(Remaining dim-6 operators work in progress. For complete degenerate case see HLM)

$$\mathcal{L}_{\text{UV}} = \mathcal{L}_{\text{SM}} + (\Phi^\dagger F(x) + \text{h.c.}) + \Phi^\dagger(P^2 - M^2 - U(x))\Phi + \mathcal{O}(\Phi^3)\,,$$

- E.g. MSSM stop with gluon field strength tensor

$$\Phi = (\tilde{Q}\,,\tilde{t}^*_R)\,, \qquad M^2 = \begin{pmatrix} m^2_{\tilde{Q}} & 0 \\ 0 & m^2_{\tilde{t}_R}\end{pmatrix}$$

$$U = \begin{pmatrix} (h_t^2+\frac{1}{2}g_2^2c_\beta^2)\tilde{H}\tilde{H}^\dagger+\frac{1}{2}g_2^2s_\beta^2HH^\dagger-\frac{1}{2}(g_1^2Y_{\tilde{Q}}c_{2\beta}+\frac{1}{2}g_2^2)|H|^2 & h_tX_t\tilde{H} \\ h_tX_t\tilde{H}^\dagger & (h_t^2-\frac{1}{2}g_1^2Y_{\tilde{t}_R}c_{2\beta})|H|^2 \end{pmatrix}$$

$$\mathcal{L}^{\text{eff}}_{\text{1-loop}} \supset \frac{1}{(4\pi)^2}\frac{1}{24}\left(\frac{h_t^2-\frac{1}{6}g_1^2c_{2\beta}}{m^2_{\tilde{Q}}}+\frac{h_t^2+\frac{1}{3}g_1^2c_{2\beta}}{m^2_{\tilde{t}_R}}-\frac{h_t^2X_t^2}{m^2_{\tilde{Q}}m^2_{\tilde{t}_R}}\right)g_3^2|H|^2G^a_{\mu\nu}G^{a\mu\nu}$$

Indirect Constraints on Stops

- Easily add sbottoms, electroweak field strength…

$$\Phi = (\tilde{Q}\,, \tilde{t}_R^*\,, \tilde{b}_R^*) \qquad G'_{\mu\nu} = \begin{pmatrix} W'^a_{\mu\nu}\tau^a + Y_{\tilde{Q}} B'_{\mu\nu}\mathbb{1} & 0 \\ 0 & -Y_{\tilde{t}_R} B'_{\mu\nu} \end{pmatrix}$$

$$\mathcal{L}_{\text{dim-6}} \supset \frac{\bar{c}_{BB}}{m_W^2}\mathcal{O}_{BB} + \frac{\bar{c}_{WW}}{m_W^2}\mathcal{O}_{WW} + \frac{\bar{c}_{WB}}{m_W^2}\mathcal{O}_{WB}$$

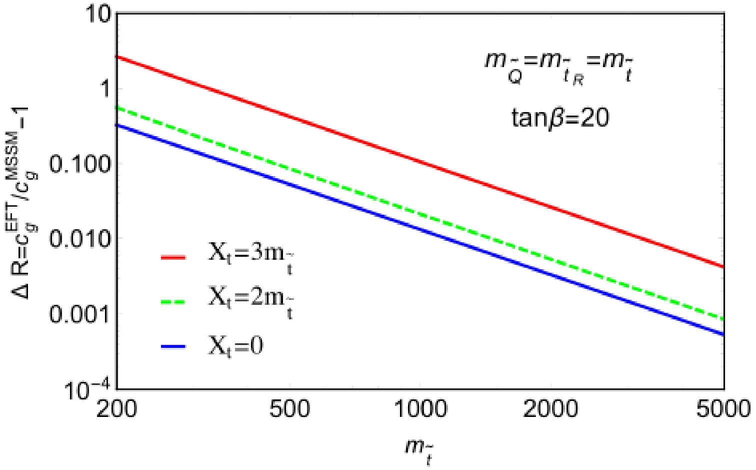
$$\mathcal{O}_{BB} = g_1^2 |H|^2 B_{\mu\nu}B^{\mu\nu} \quad , \quad \mathcal{O}_{WW} = g_2^2 |H|^2 W^a_{\mu\nu}W^{a\mu\nu} \quad , \quad \mathcal{O}_{WB} = 2 g_1 g_2 H^\dagger \tau^a H W^a_{\mu\nu} B^{\mu\nu}\,,$$

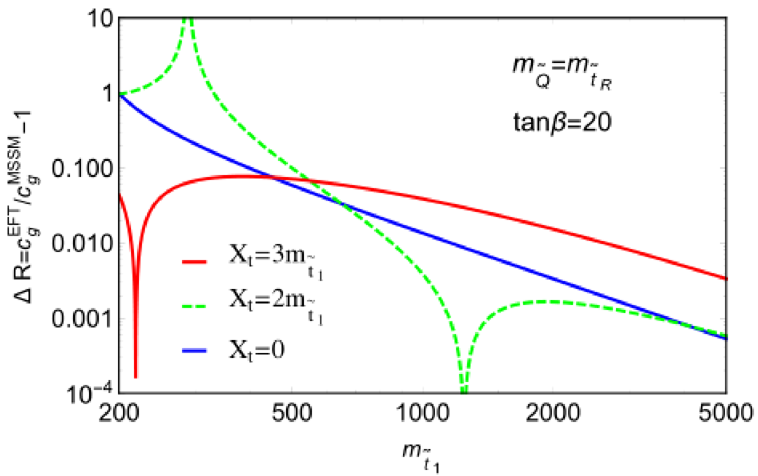
$$\begin{aligned}
\bar{c}_{BB} = \frac{m_W^2}{(4\pi)^2} \Bigg(& \frac{1}{144}\frac{(h_t^2 - \frac{1}{6}g_1^2 c_{2\beta})}{m_{\tilde{Q}}^2} + \frac{1}{9}\frac{(h_t^2 + \frac{1}{3}g_1^2 c_{2\beta})}{m_{\tilde{t}_R}^2} + \frac{1}{36}\frac{(h_t^2 - \frac{1}{6}g_1^2 c_{2\beta})}{m_{\tilde{b}_R}^2} \\
& - \frac{19}{360}\frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2} - \frac{1}{90}\frac{h_b^2 X_b^2}{m_{\tilde{Q}}^2 m_{\tilde{b}_R}^2} \Bigg)\,, \\
\bar{c}_{WW} = \frac{m_W^2}{(4\pi)^2} \Bigg(& \frac{1}{16}\frac{(h_t^2 - \frac{1}{6}g_1^2 c_{2\beta})}{m_{\tilde{Q}}^2} - \frac{1}{40}\frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2} - \frac{1}{40}\frac{h_b^2 X_b^2}{m_{\tilde{Q}}^2 m_{\tilde{b}_R}^2} \Bigg)\,, \\
\bar{c}_{WB} = \frac{m_W^2}{(4\pi)^2} \Bigg(& -\frac{1}{48}\frac{(2h_t^2 + g_2^2 c_{2\beta})}{m_{\tilde{Q}}^2} + \frac{1}{30}\frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2} + \frac{1}{120}\frac{h_b^2 X_b^2}{m_{\tilde{Q}}^2 m_{\tilde{b}_R}^2} \Bigg)\,.
\end{aligned}$$

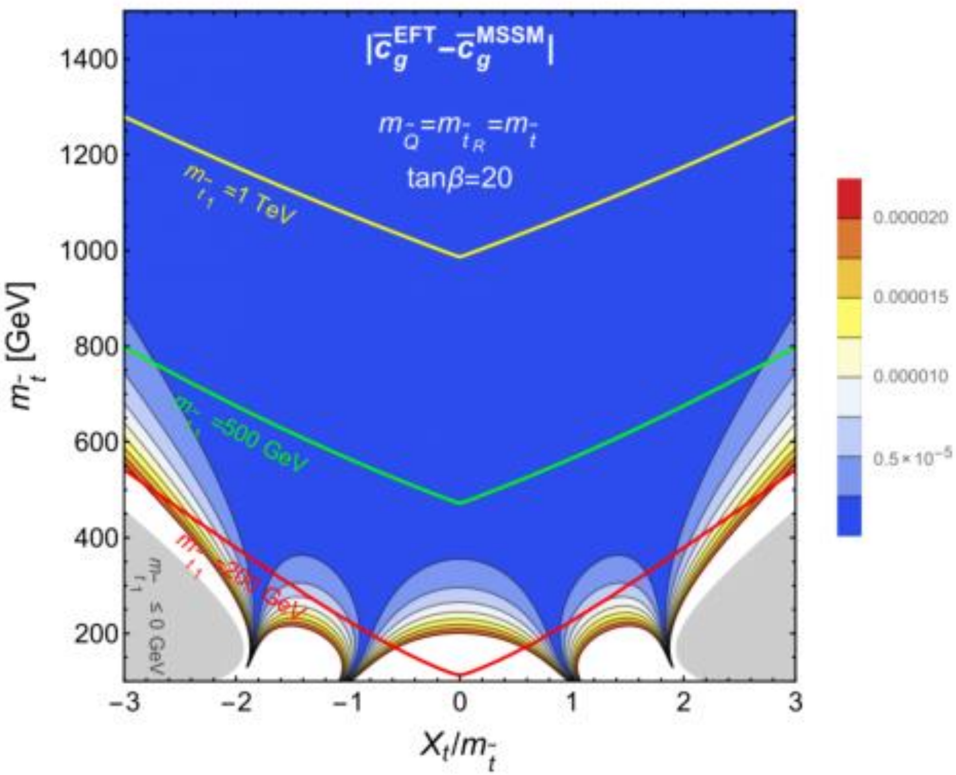
Note: in our basis we eliminate cWB, cWW (see backup slides)

Indirect Constraints on Stops

- Operators > dim-6 become important when EFT cut-off/stop mass is too low
- Compare EFT dim-6 vs full MSSM amplitude

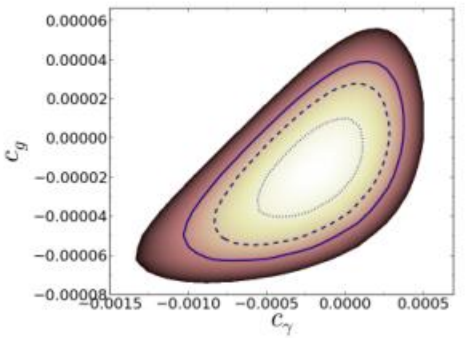


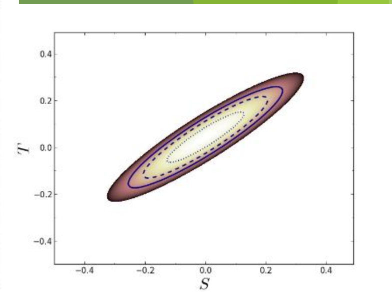


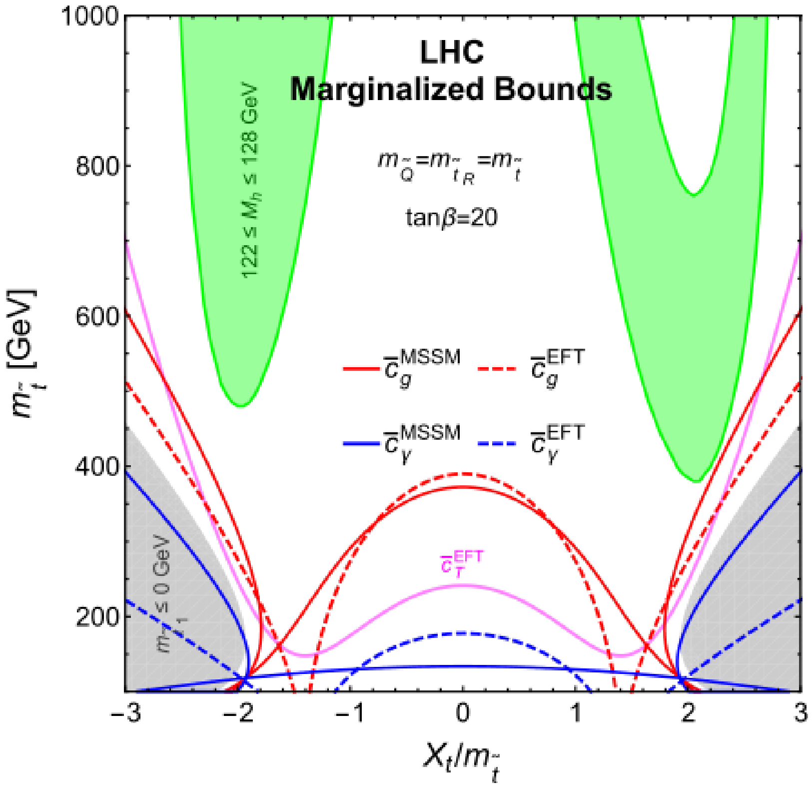


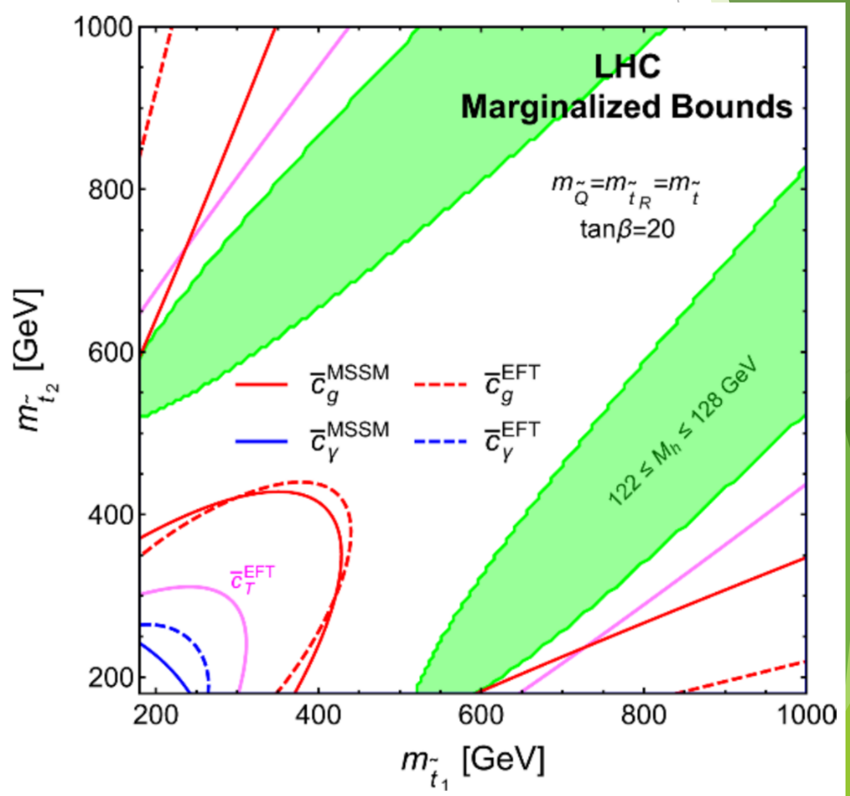
Indirect Constraints on Stops

Coeff.	Experimental constraints		95 % CL limit	deg. $m_{\tilde{t}_1}$, $X_t = 0$
$\bar{c}_g$	LHC	marginalized	$[-4.5, 2.2] \times 10^{-5}$	~ 410 GeV
		individual	$[-3.0, 2.5] \times 10^{-5}$	~ 390 GeV
$\bar{c}_\gamma$	LHC	marginalized	$[-6.5, 2.7] \times 10^{-4}$	~ 215 GeV
		individual	$[-4.0, 2.3] \times 10^{-4}$	~ 230 GeV
$\bar{c}_T$	LEP	marginalized	$[-10, 10] \times 10^{-4}$	~ 290 GeV
		individual	$[-5, 5] \times 10^{-4}$	~ 380 GeV
$\bar{c}_W + \bar{c}_B$	LEP	marginalized	$[-7, 7] \times 10^{-4}$	~ 185 GeV
		individual	$[-5, 5] \times 10^{-4}$	~ 195 GeV



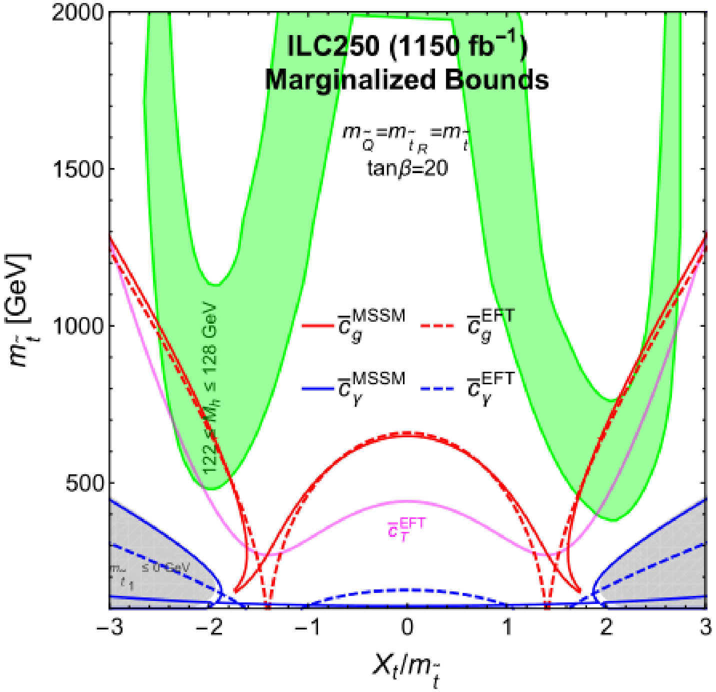


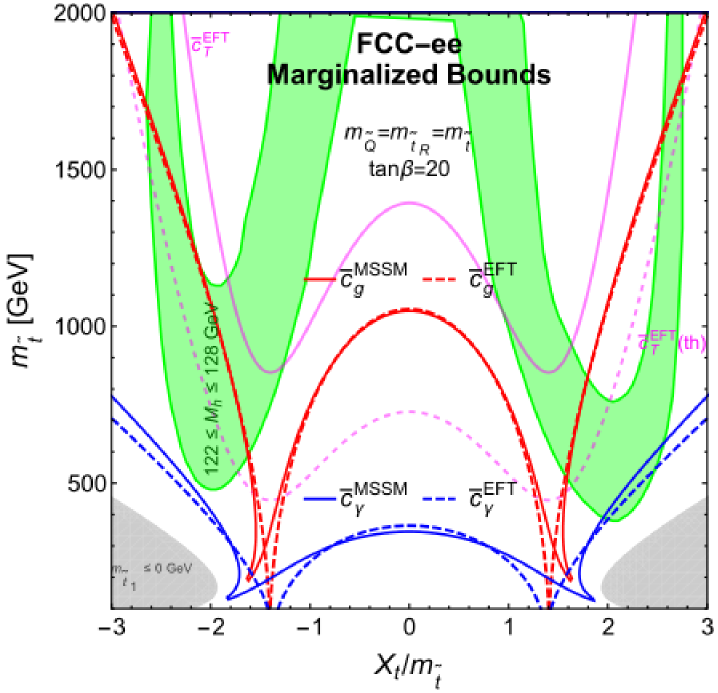




Indirect Constraints on Stops

Coeff.	Experimental constraints		95 % CL limit	deg. $m_{\tilde{t}_1}$ $X_t = 0$	deg. $m_{\tilde{t}_1}$ $X_t = m_{\tilde{t}}/2$
$\bar{c}_g$	$\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$	marginalized	$[-7.7, 7.7] \times 10^{-6}$	~ 675 GeV	~ 520 GeV
		individual	$[-7.5, 7.5] \times 10^{-6}$	~ 680 GeV	~ 545 GeV
	FCC-ee	marginalized	$[-3.0, 3.0] \times 10^{-6}$	~ 1065 GeV	~ 920 GeV
		individual	$[-3.0, 3.0] \times 10^{-6}$	~ 1065 GeV	~ 915 GeV
$\bar{c}_\gamma$	$\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$	marginalized	$[-3.4, 3.4] \times 10^{-4}$	~ 200 GeV	~ 40 GeV
		individual	$[-3.3, 3.3] \times 10^{-4}$	~ 200 GeV	~ 35 GeV
	FCC-ee	marginalized	$[-6.4, 6.4] \times 10^{-5}$	~ 385 GeV	~ 250 GeV
		individual	$[-6.3, 6.3] \times 10^{-5}$	~ 390 GeV	~ 260 GeV
$\bar{c}_T$	$\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$	marginalized	$[-3, 3] \times 10^{-4}$	~ 480 GeV	~ 285 GeV
		individual	$[-7, 7] \times 10^{-5}$	~ 930 GeV	~ 780 GeV
	FCC-ee	marginalized	$[-3, 3] \times 10^{-5}$	~ 1410 GeV	~ 1285 GeV
		individual	$[-0.9, 0.9] \times 10^{-5}$	~ 2555 GeV	~ 2460 GeV
$\bar{c}_W + \bar{c}_B$	$\mathrm{ILC}^{1150\mathrm{fb}^{-1}}_{250\mathrm{GeV}}$	marginalized	$[-2, 2] \times 10^{-4}$	~ 230 GeV	~ 170 GeV
		individual	$[-6, 6] \times 10^{-5}$	~ 340 GeV	~ 470 GeV
	FCC-ee	marginalized	$[-2, 2] \times 10^{-5}$	~ 545 GeV	~ 960 GeV
		individual	$[-0.8, 0.8] \times 10^{-5}$	~ 830 GeV	~ 1590 GeV

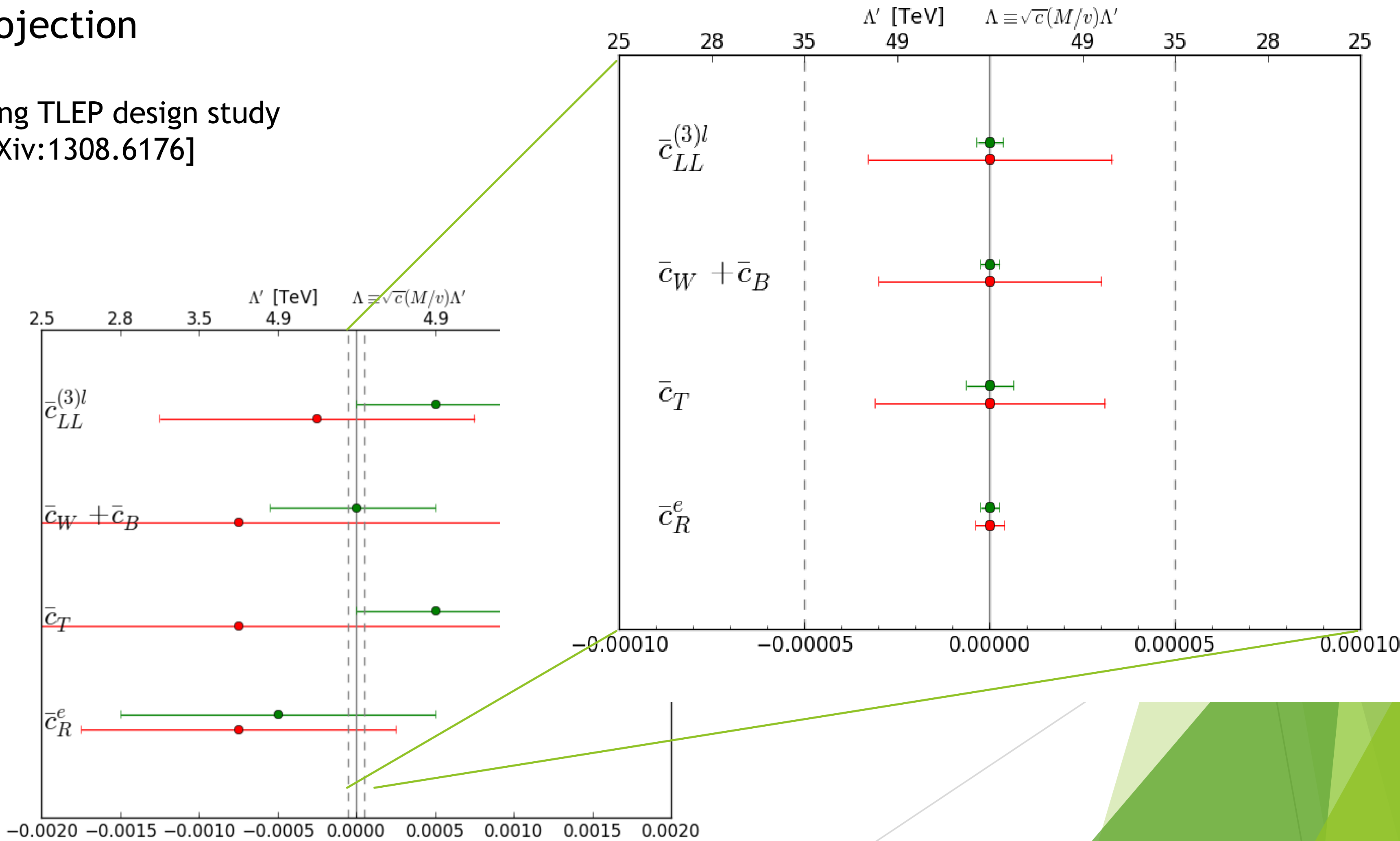




Future colliders: FCC-ee (TLEP)

EWPT constraints projection

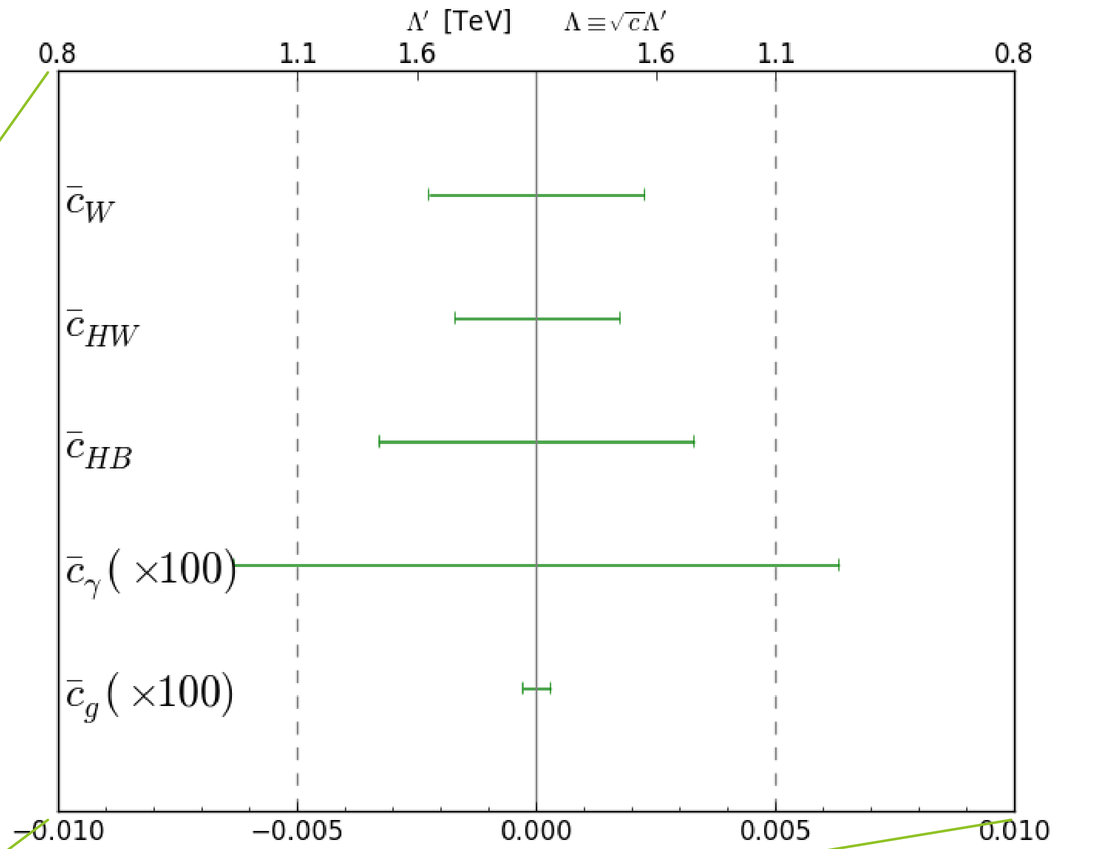
Using TLEP design study [arXiv:1308.6176]

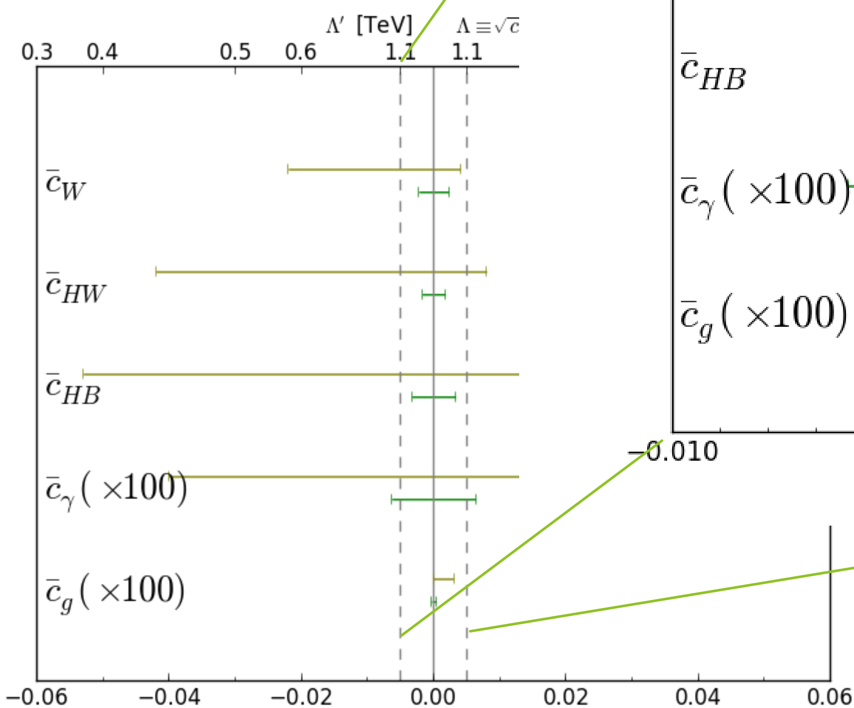


Future colliders: FCC-ee (TLEP)

Higgs one-by-one constraints projection

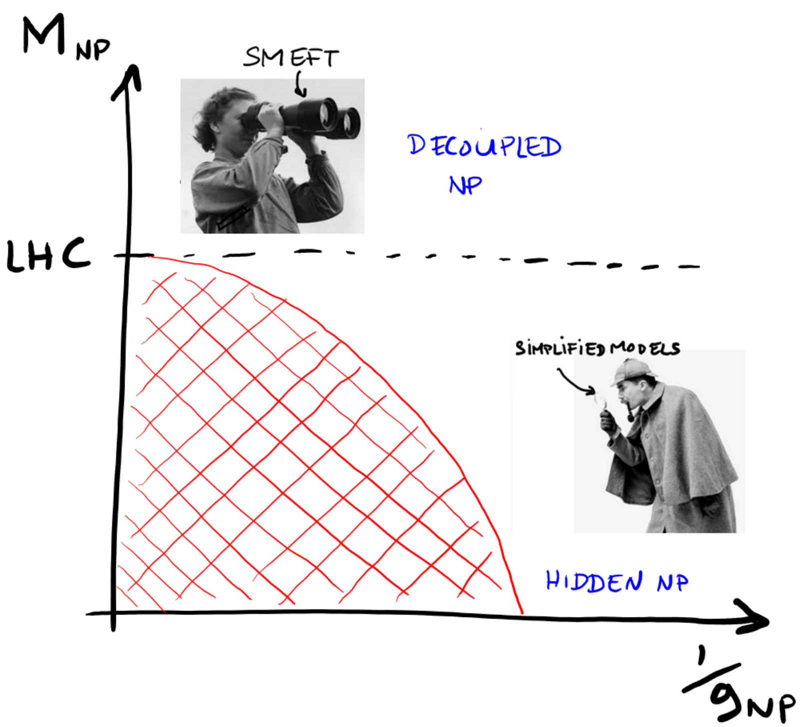
Using TLEP design study [arXiv:1308.6176]





Conclusion

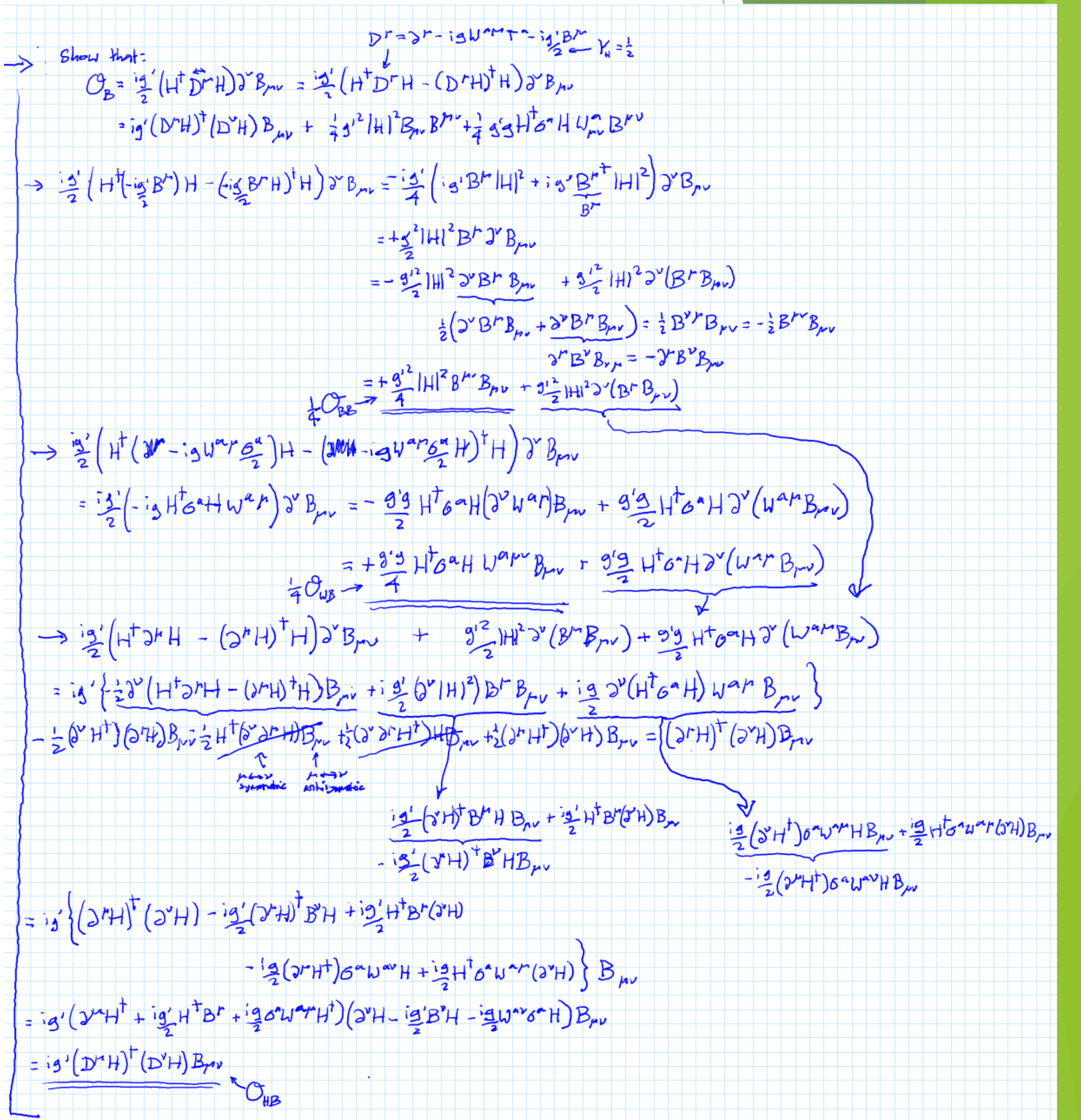
- All decoupled new physics is a non-zero Wilson coefficient!
- Effective SM a natural framework in which to characterise phenomenology
- Simplifies setting constraints on UV models from experimental observables
- Also simplifies calculation of these experimental observables



Changing basis example

- Operators related by integration by parts, e.g.

$$\mathcal{O}_B = \mathcal{O}_{HB} + \frac{1}{4}\mathcal{O}_{BB} + \frac{1}{4}\mathcal{O}_{WB}$$



Changing basis example

- Operators related by integration by parts, e.g.

① $\mathcal{O}_B = \mathcal{O}_{HB} + \frac{1}{4}\mathcal{O}_{BB} + \frac{1}{4}\mathcal{O}_{WB}$

② $\mathcal{O}_W = \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_{WW} + \frac{1}{4}\mathcal{O}_{WB}$

So starting from HLM basis,

$$\mathcal{L} = c_W \mathcal{O}_W + c_B \mathcal{O}_B + c_{WB}\mathcal{O}_{WB} + c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB} + c_{WW}\mathcal{O}_{WW} + c_{BB}\mathcal{O}_{BB}$$

use ② $\mathcal{O}_{WW} \to 4\mathcal{O}_W - 4\mathcal{O}_{HW} - \mathcal{O}_{WB}$

$$\Rightarrow \mathcal{L} = (c_W + 4c_{WW})\mathcal{O}_W + c_B\mathcal{O}_B + (c_{WB} - c_{WW})\mathcal{O}_{WB} + (c_{HW} - 4c_{WW})\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB} + c_{BB}\mathcal{O}_{BB}$$

use ① $\mathcal{O}_{WB} \to 4\mathcal{O}_B - 4\mathcal{O}_{HB} - \mathcal{O}_{BB}$

$$\Rightarrow \mathcal{L} = \underbrace{(c_W + 4c_{WW})}_{c'_W}\mathcal{O}_W + \underbrace{(c_B + 4(c_{WB} - c_{WW}))}_{c'_B}\mathcal{O}_B + \underbrace{(c_{HW} - 4c_{WW})}_{c'_{HW}}\mathcal{O}_{HW} + \underbrace{(c_{HB} - 4(c_{WB} - c_{WW}))}_{c'_{HB}}\mathcal{O}_{HB} + \underbrace{(c_{BB} - (c_{WB} - c_{WW}))}_{c'_{BB}}\mathcal{O}_{BB}$$

$c'_W = c_W + 4c_{WW}$

$c'_B = c_B + 4c_{WB} - 4c_{WW}$

$c'_{HW} = c_{HW} - 4c_{WW}$

$c'_{HB} = c_{HB} - 4c_{WB} + 4c_{WW}$

$c'_{BB} = c_{BB} - c_{WB} + c_{WW}$

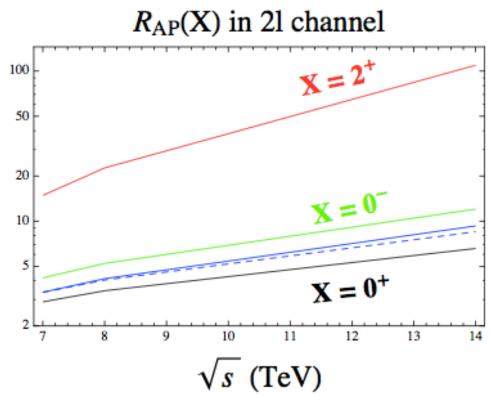
$c'_{WB} = 0 \quad c'_{WW} = 0$

In our basis $S \propto c'_W + c'_B$ and $h\gamma\gamma \propto c'_{BB}$

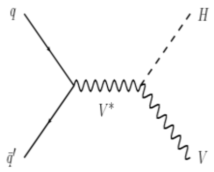
∴ in HLM basis $S \propto c_W + \cancel{4c_{WW}} + c_B + 4c_{WB} - \cancel{4c_{WW}}$ and $h\gamma\gamma \propto c_{BB} + c_{WW} - c_{WB}$ as required

A Standard Model Higgs?

- How do we know it's a scalar i.e. spin zero?
- Indirectly: Signal strength ratios in different channels disfavoured simple spin-2 graviton (arXiv:1211.3068)
- Indirectly: Energy dependence of H->bb channel between Tevatron and LHC

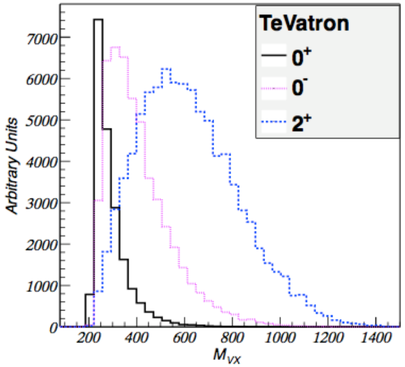


J.Ellis, D.S.Hwang, V.Sanz and T.Y. [arXiv:1208.6002]



- Directly: Higgs associated production

Combination of CDF and D0 excludes spin-2 at 4.9-sigma (FERMILAB-CONF-14-265-E)



J.Ellis, V.Sanz and T.Y. [arXiv:1303.0208]