

Characterizing CLIC's Sensitivity to Decoupled New Physics

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-Dimension-6 operator analysis of the CLIC sensitivity to new physics

John Ellis, Philipp Roloff, Veronica Sanz and TY

[arXiv:1701.04804]

-Sensitivities of Prospective Future $e+e-$ Colliders to Decoupled New Physics,

John Ellis and TY

JHEP 03 (2016) 089 [arXiv:1510.04561]

-Comparing EFT and Exact One-Loop Analyses of Non-Degenerate Stops,

Aleksandra Drozd, John Ellis, Jeremie Quevillon and TY

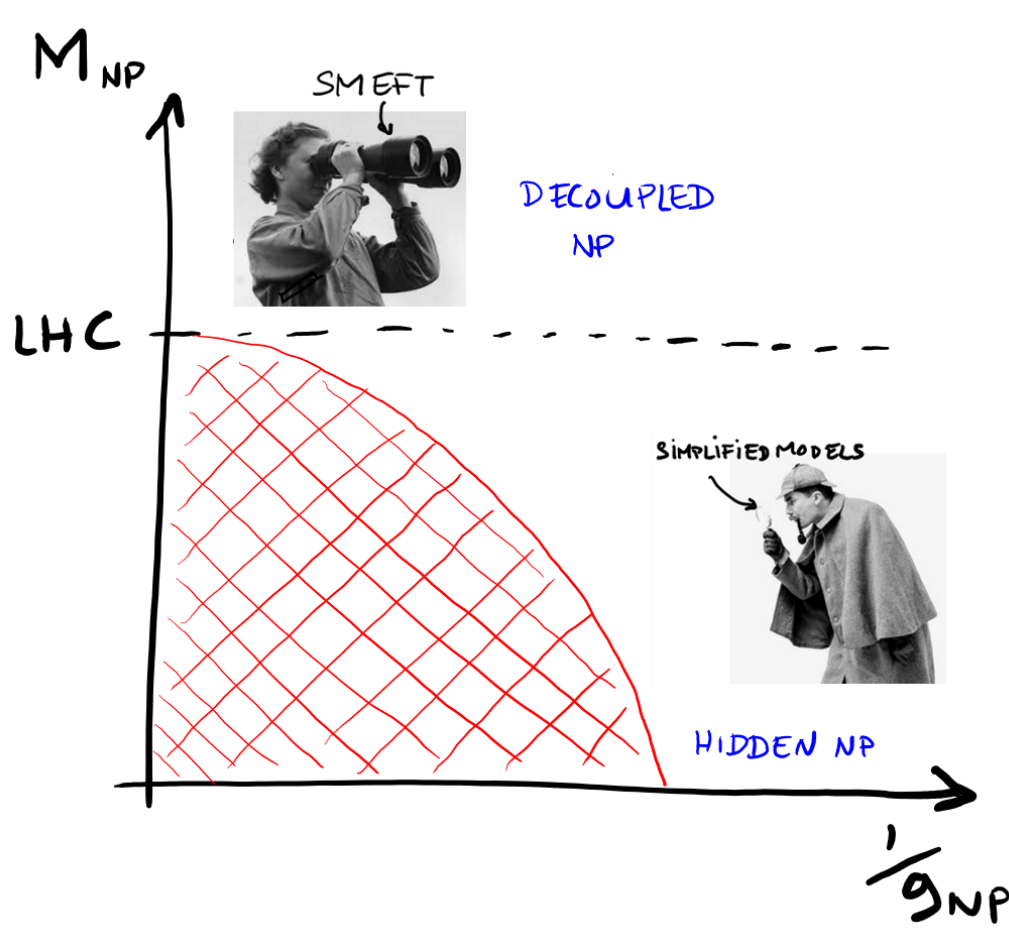
JHEP 06 (2015) 028 [arXiv:1504.02409]

-The Effective Standard Model after LHC Run I,

John Ellis, Veronica Sanz and TY

JHEP 29 (2015) 007 [arXiv:1410.7703]

What do we mean by decoupled new physics?



- Standard Model Effective Field Theory (SM EFT) is a systematic approach to classifying phenomenology of decoupled new physics


Why SM EFT framework?

Markus Luty PASCOS 2015 slide

The TeV Scale

What effective theory captures everything we know experimentally about weak interactions?

1933–1982 4-fermion interactions



$$\sim G_F E^2 \quad \Rightarrow \Lambda \sim \text{TeV}$$

1982–2011 SM without Higgs



$$\sim \frac{g^2 E^2}{m_W^2} \quad \Rightarrow \Lambda \sim \text{TeV}$$

2012-now SM + higher-dimension operators?

$$\Rightarrow \Lambda \lesssim M_P?$$

Assuming a SM Higgs and decoupled new physics at higher energies, the **SM EFT** is *the Fermi theory of the 21st century*

What is the SM EFT?

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
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	$\frac{1}{2}$



$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad +$$

$$\mathcal{L}_{SM}^{\text{dim-6}} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

$$\mathcal{L}_m = \bar{Q}_L i \gamma^\mu D_\mu^L Q_L + \bar{q}_R i \gamma^\mu D_\mu^R q_R + \bar{L}_L i \gamma^\mu D_\mu^L L_L + \bar{l}_R i \gamma^\mu D_\mu^R l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu}$$

$$\mathcal{L}_H = (D_\mu^L \phi)^\dagger (D^{L\mu} \phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R + \text{h.c.} \quad ,$$

- ▶ 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 no flavor structure (Gradkowski et al [arXiv:1008.4884])(2499 in general, Alonso et al [arXiv:1312.2014])

EWPTs	Higgs Physics	TGCs
	$\mathcal{O}_W = \frac{ig}{2} \left(H^\dagger \overset{\leftrightarrow}{D}^\mu H \right) D^\nu W_{\mu\nu}^a$	
	$\mathcal{O}_B = \frac{ig'}{2} \left(H^\dagger \overset{\leftrightarrow}{D}^\mu H \right) \partial^\nu B_{\mu\nu}$	$\mathcal{O}_{3W} = g \frac{\epsilon_{abc}}{3!} W_\mu^{a\nu} W_\nu^b W^{c\rho\mu}$
$\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overset{\leftrightarrow}{D}^\mu H \right)^2$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$	
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \sigma^a \gamma^\mu L_L) (\bar{L}_L \sigma^a \gamma_\mu L_L)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	
$\mathcal{O}_R^e = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H) (\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}_g = g_s^2 H ^2 G_{\mu\nu}^A G^{A\mu\nu}$	
$\mathcal{O}_R^u = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H) (\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}_\gamma = g'^2 H ^2 B_{\mu\nu} B^{\mu\nu}$	
$\mathcal{O}_R^d = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H) (\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_H = \frac{1}{2} (\partial^\mu H ^2)^2$	
$\mathcal{O}_L^{(3)q} = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H) (\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_f = y_f H ^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	
$\mathcal{O}_L^q = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H) (\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_6 = \lambda H ^6$	

Basis adopted from Pomarol and Riva 1308.1426

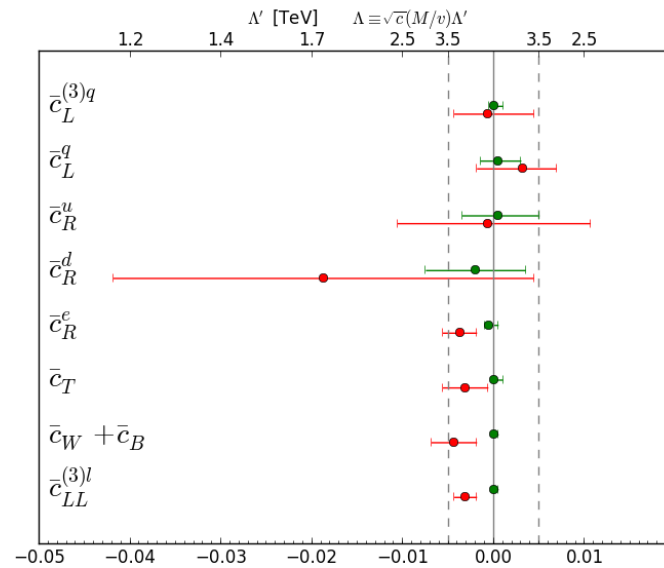
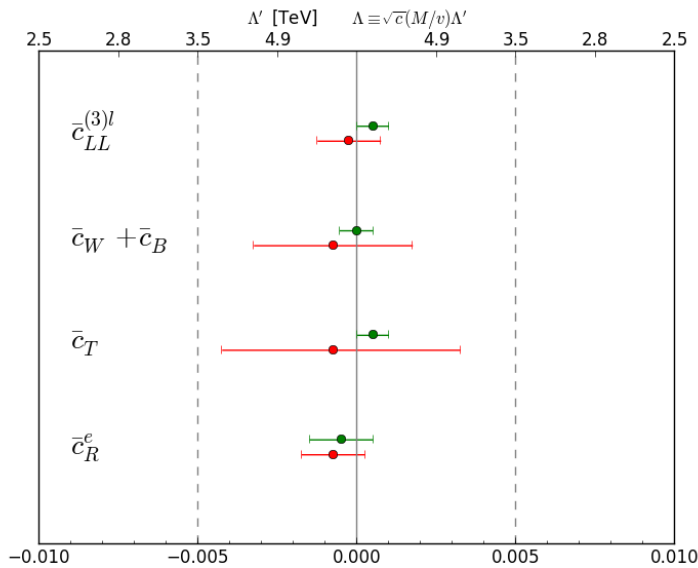
(SILH basis Giudice et al. hep-ph/0703164)

$$\bar{c}_i = c_i \frac{M^2}{\Lambda^2}$$

SM EFT Present Constraints: LEP

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

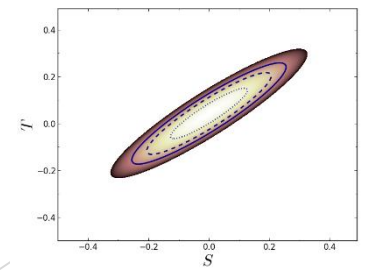
Ellis, Sanz and T.Y. 1410.7703



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

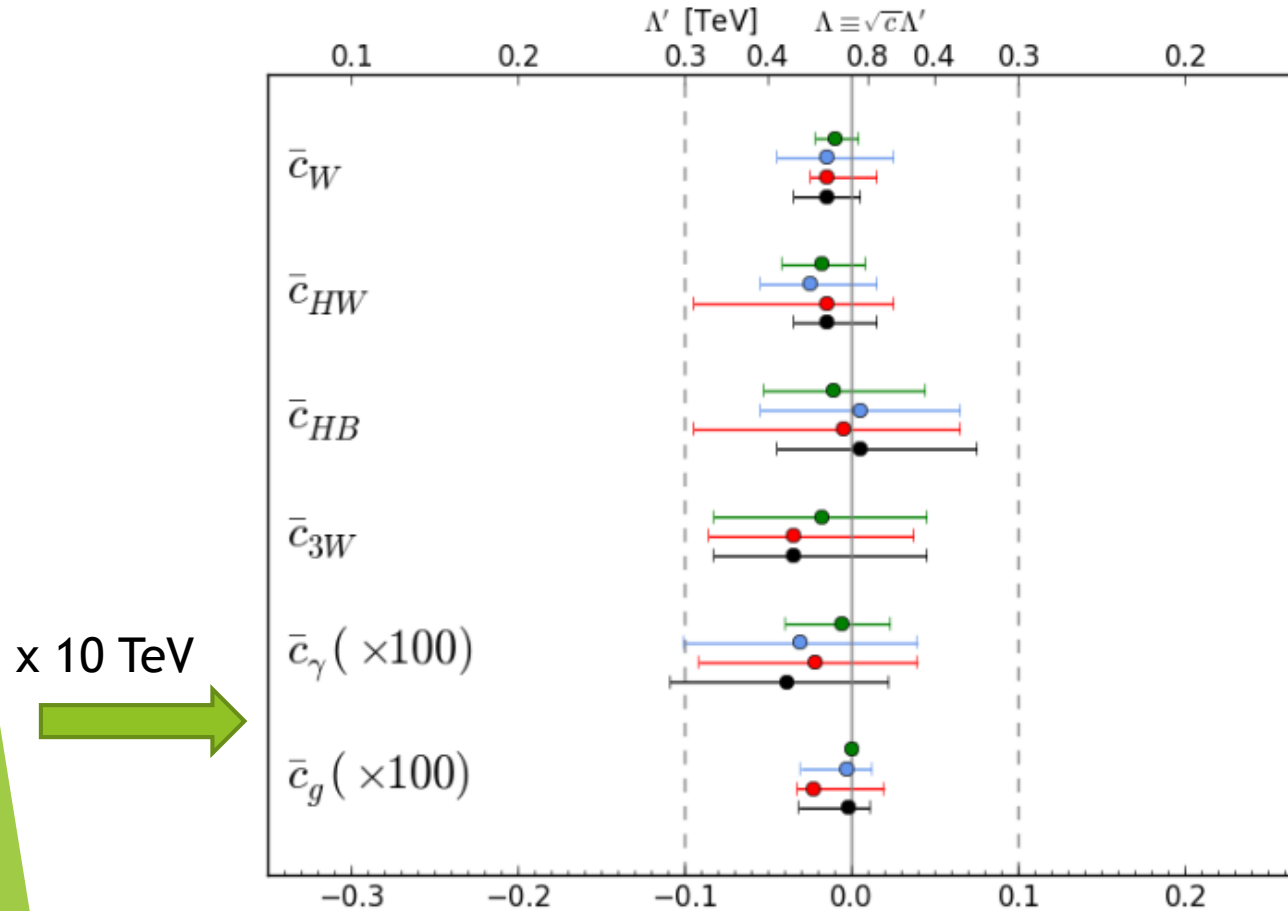
$$S = \frac{4 \sin^2 \theta_W}{\alpha(m_Z)} (\bar{c}_W + \bar{c}_B) \approx 119(\bar{c}_W + \bar{c}_B)$$

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



SM EFT Present Constraints: LHC

- Constraints from LHC triple-gauge coupling measurements and Higgs physics



SM EFT Future Constraints: CLIC

- ▶ Higgs associated production at 350 GeV (for H to gaga, ZZ, Zga, using 34%, 18%, 100% respectively)
- ▶ Higgs VBF production at 1.4 and 3 TeV

1608.0753 Higgs physics at the CLIC e+e- collider

CLIC at 350 GeV		CLIC at 1.4 TeV		CLIC at 3 TeV	
$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow b\bar{b}}$	1.9%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow b\bar{b}}$	0.4%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow b\bar{b}}$	0.3%
$\sigma_{HZ} BR_{H\rightarrow c\bar{c}}$	10.3%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow c\bar{c}}$	6.1%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow c\bar{c}}$	6.9%
$\sigma_{HZ} BR_{H\rightarrow gg}$	4.5%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow gg}$	5.0%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow gg}$	4.3%
$\sigma_{HZ} BR_{H\rightarrow W^+W^-}$	5.1%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow W^+W^-}$	1.0%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow W^+W^-}$	0.7%
$\sigma_{HZ} BR_{H\rightarrow \tau\bar{\tau}}$	6.2%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow \tau\bar{\tau}}$	4.3%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow \tau\bar{\tau}}$	4.4%
$\sigma_{HZ} BR_{H\rightarrow b\bar{b}}$	0.84%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow \gamma\gamma}$	15.0%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow \gamma\gamma}$	10.0%
		$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow Z\gamma}$	42.0%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow Z\gamma}$	30.0%
		$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow ZZ}$	5.6%	$\sigma_{H\nu_e\bar{\nu}_e} BR_{H\rightarrow ZZ}$	3.9%

- ▶ Associated production also important for 1.4 and 3 TeV
- ▶ Triple-gauge coupling measurements also relevant

$$\frac{\Delta[\sigma(HZ) \cdot BR(H \rightarrow b\bar{b})]}{[\sigma(HZ) \cdot BR(H \rightarrow b\bar{b})]} = 3.3\% \text{ at } 1.4 \text{ TeV,}$$

$$\frac{\Delta[\sigma(HZ) \cdot BR(H \rightarrow b\bar{b})]}{[\sigma(HZ) \cdot BR(H \rightarrow b\bar{b})]} = 6.8\% \text{ at } 3 \text{ TeV.}$$

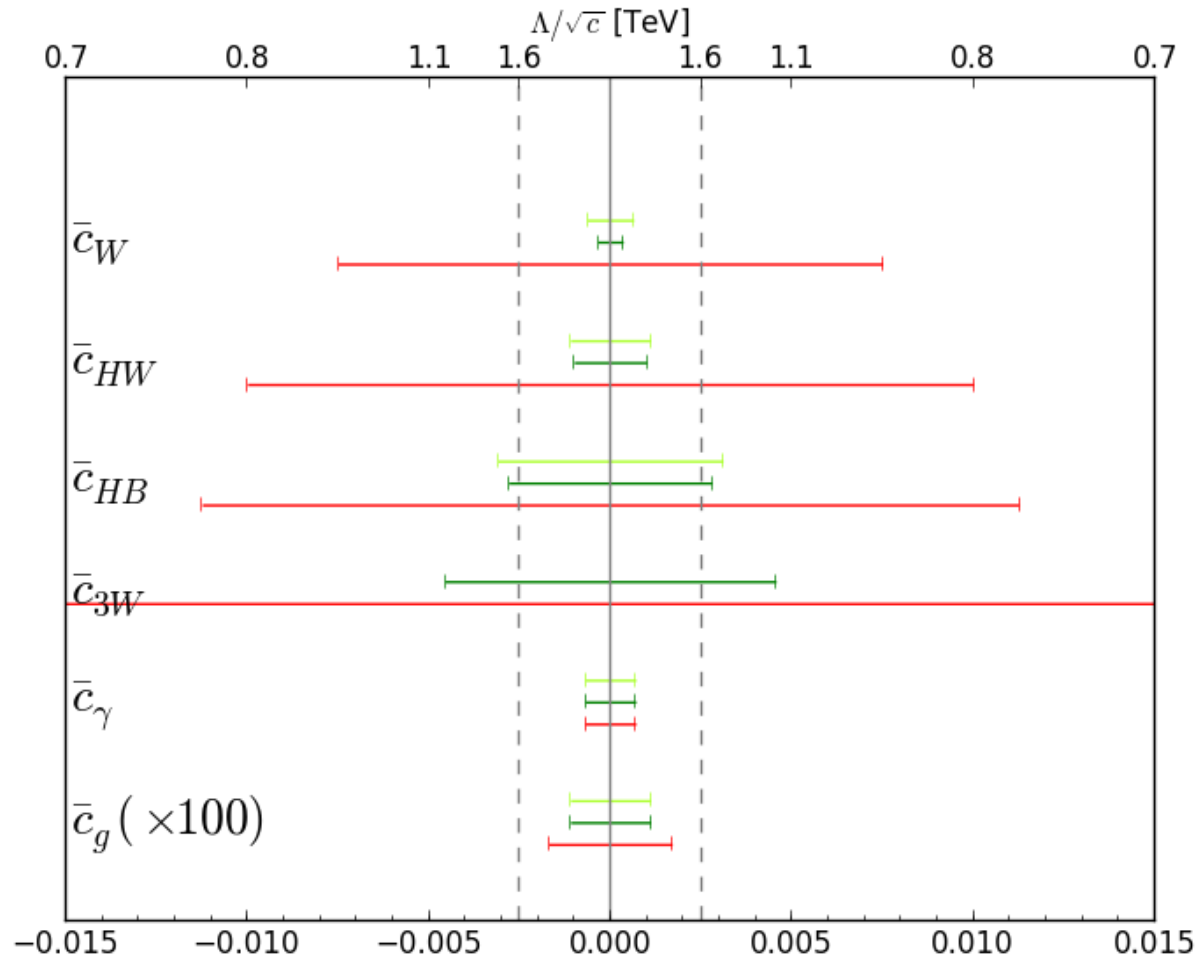
$$\frac{\Delta\sigma(W^+W^-)}{\sigma(W^+W^-)} = 0.1\% \text{ at } 350 \text{ GeV,}$$

$$\frac{\Delta\sigma(W^+W^-)}{\sigma(W^+W^-)} = 0.2\% \text{ at } 1.4 \text{ TeV,}$$

$$\frac{\Delta\sigma(W^+W^-)}{\sigma(W^+W^-)} = 0.3\% \text{ at } 3 \text{ TeV.}$$

SM EFT Future Constraints: CLIC

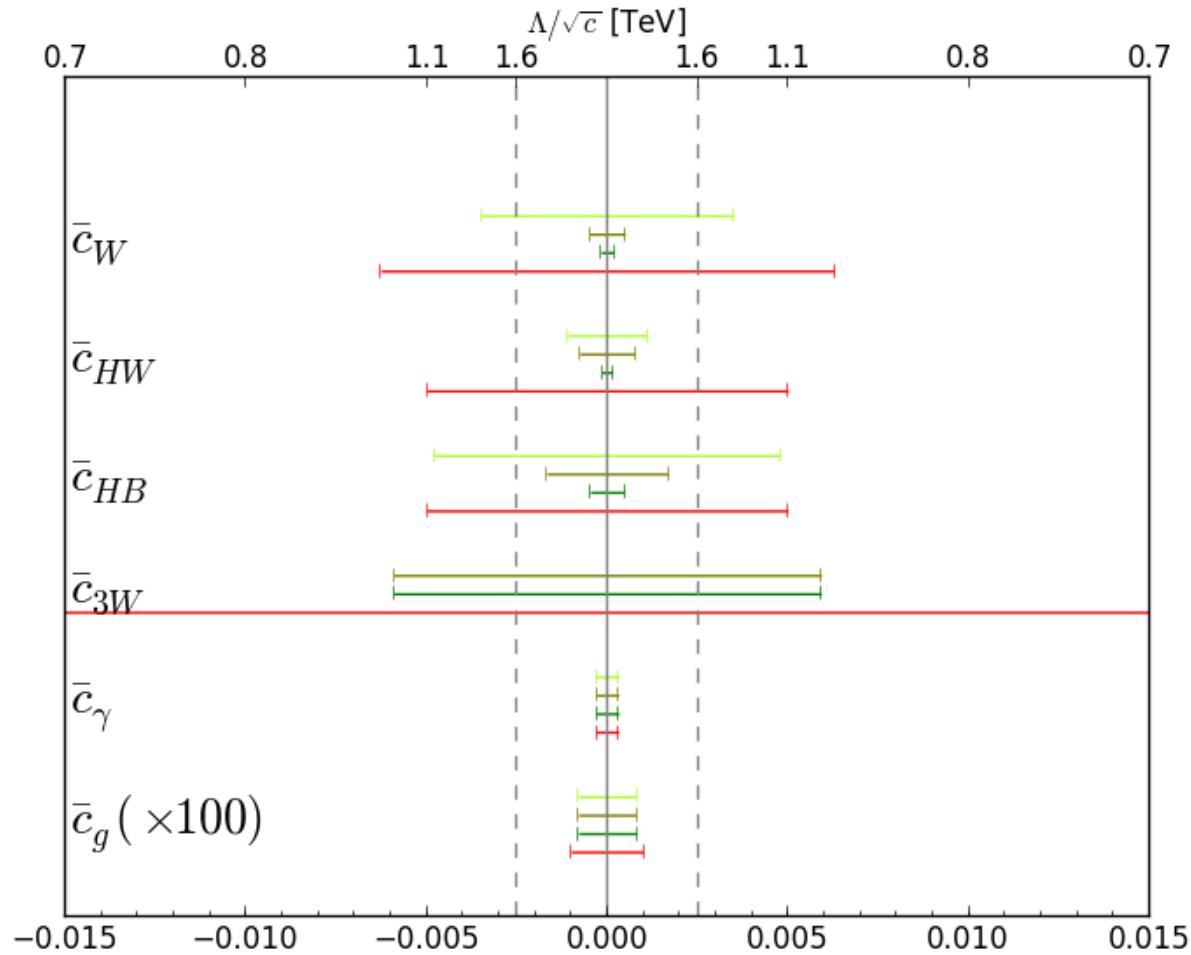
► CLIC 350 GeV



-Light green: Individual, no TGC
 -Dark Green: Individual, including TGC
 -Red: Marginalised

SM EFT Future Constraints: CLIC

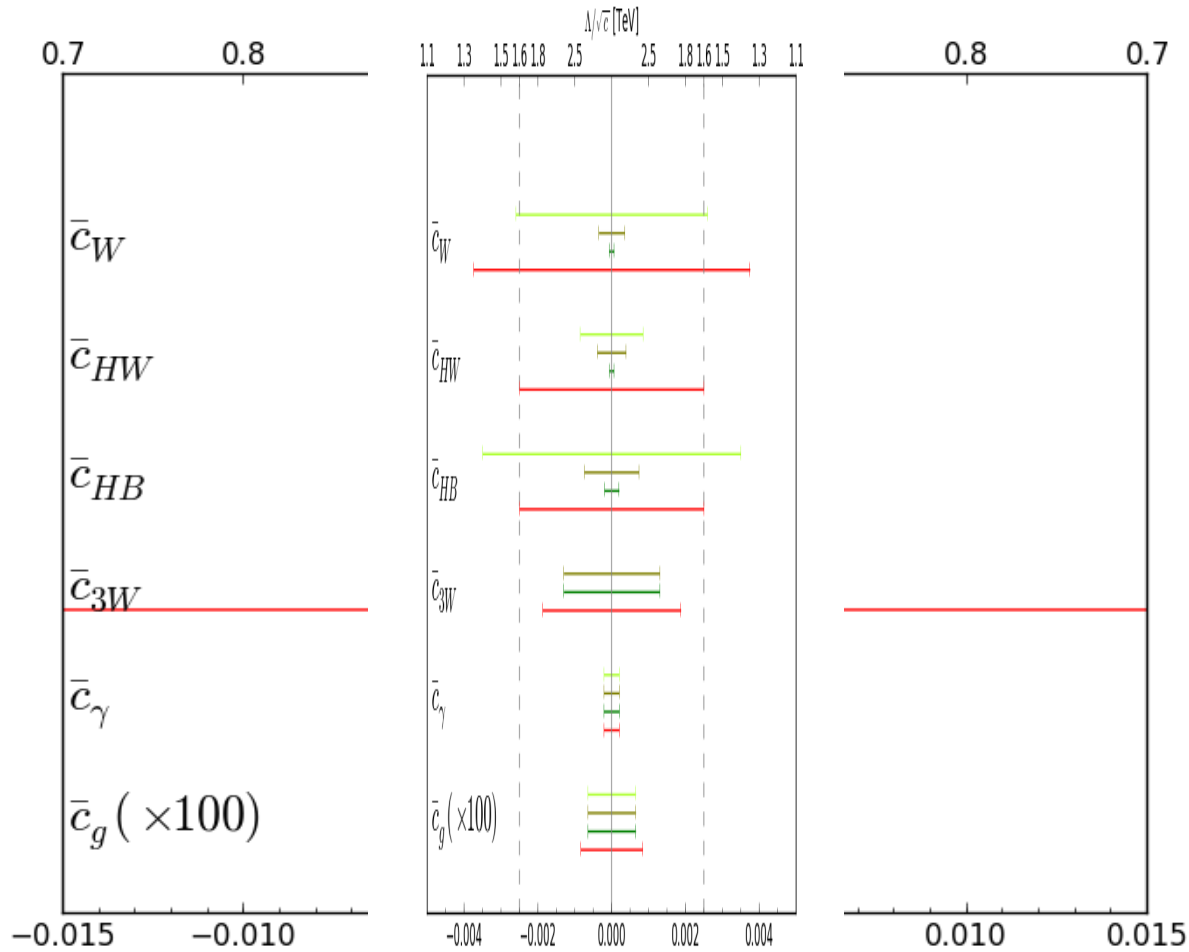
► CLIC 1.4 TeV



- Light green: Individual, no TGC or ZH
- Olive green: Individual, with TGC
- Dark Green: Individual, with TGC+ZH
- Red: Marginalised

SM EFT Future Constraints: CLIC

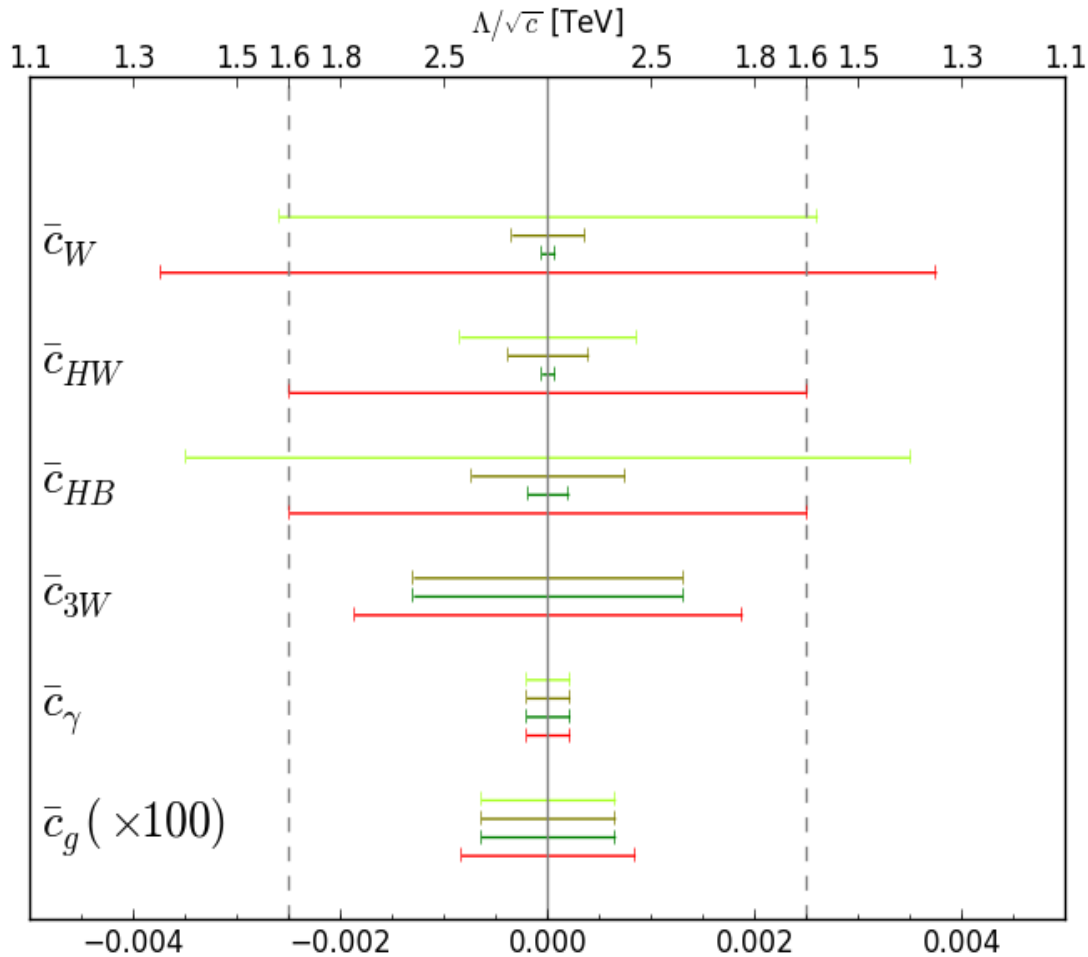
► CLIC 3 TeV



- Light green: Individual, no TGC or ZH
- Olive green: Individual, with TGC
- Dark Green: Individual, with TGC+ZH
- Red: Marginalised

SM EFT Future Constraints: CLIC

► CLIC 3 TeV

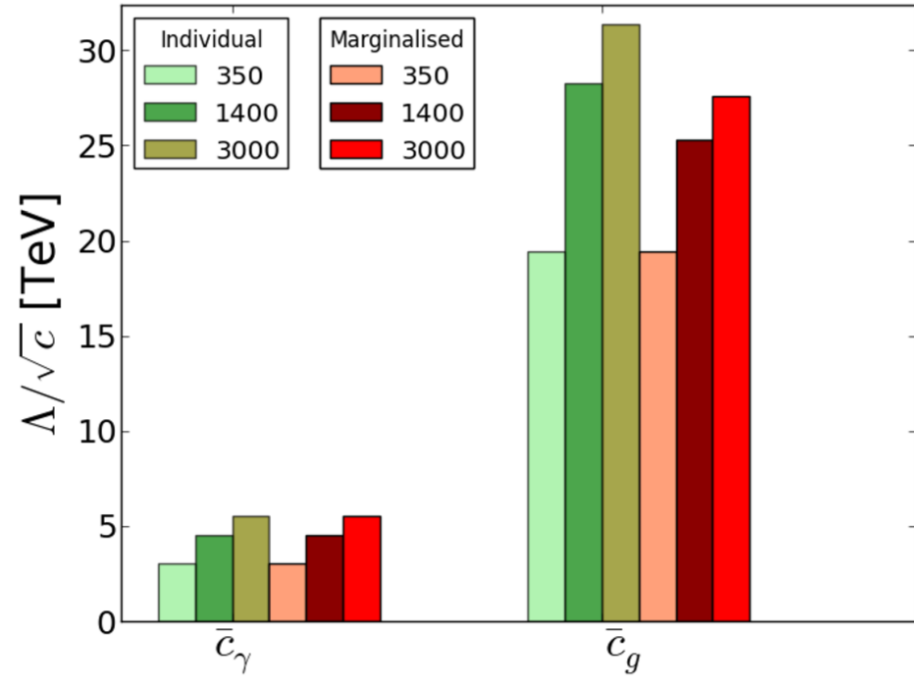
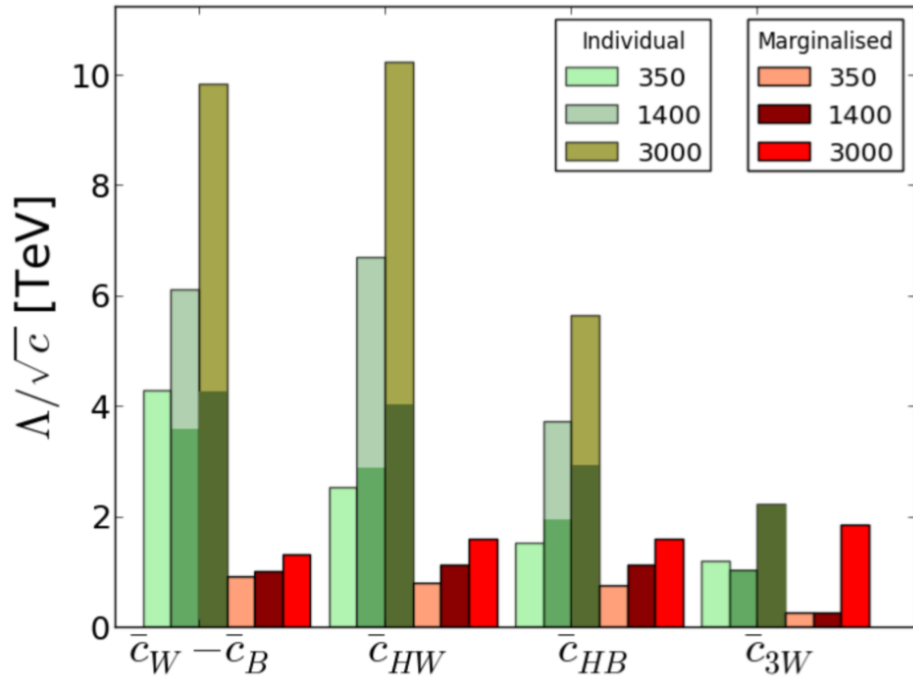


- Light green: Individual, no TGC or ZH
- Olive green: Individual, with TGC
- Dark Green: Individual, with TGC+ZH
- Red: Marginalised

SM EFT Future Constraints: CLIC

► CLIC comparison

1701.04804 Ellis, Roloff, Sanz, TY

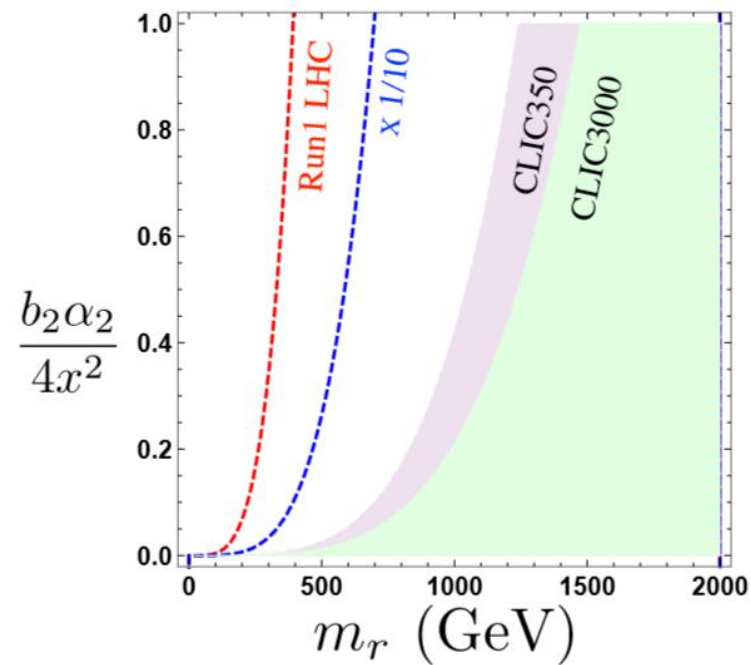
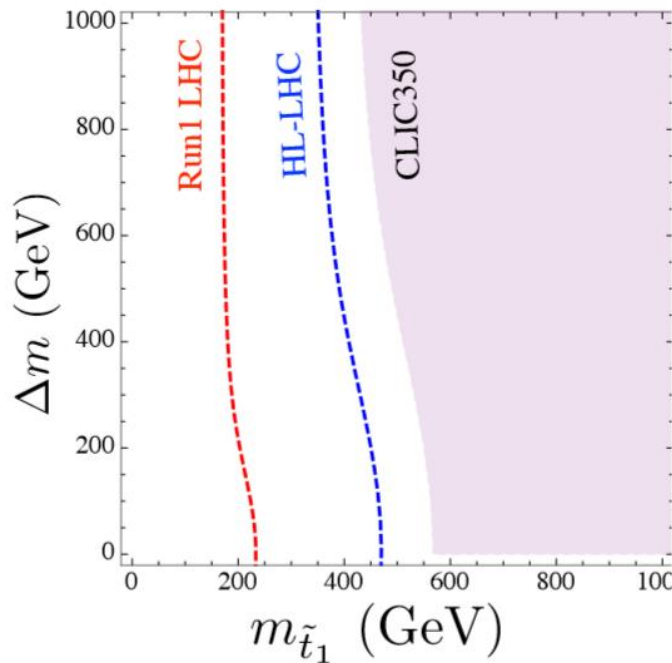


Lighter (darker) shades include (omit) ZH

SM EFT Future Constraints: CLIC

- Translate to indirect constraints on stops and radions

1701.04804 Ellis, Roloff, Sanz, TY



- Note validity of EFT may limit interpretation to strongly-coupled models only

See e.g.

-Contino, Falkowski, Goertz, Grojean, Riva 1604.06444

-Da Liu, Pomarol, Rattazzi, Riva 1603.03064

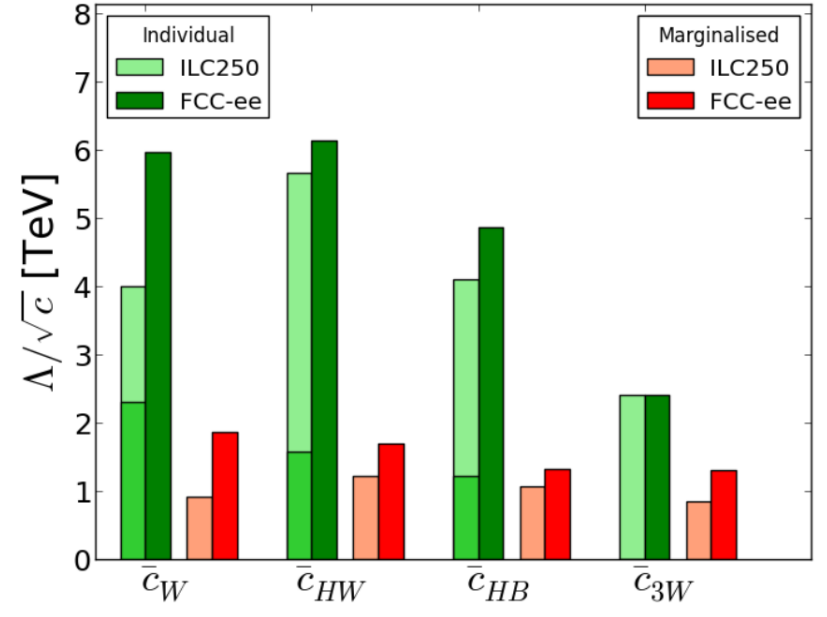
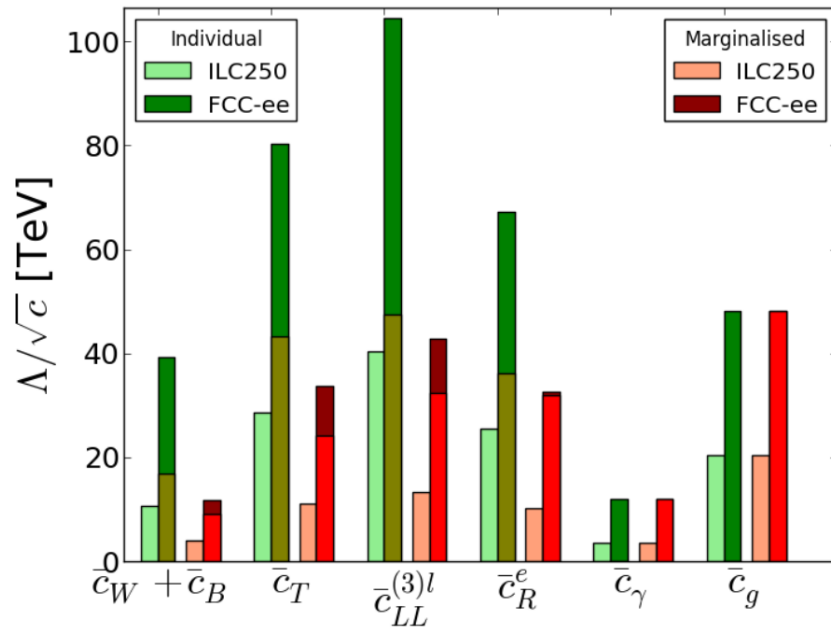
-Falkowski, Gonzales-Alonso, Greljo, Marzocca, Son 1609.06312

Conclusion

- ▶ CLIC may probe new physics both directly and indirectly
- ▶ Future Higgs measurements will be precision probes similar to current LEP observables
- ▶ Indirect sensitivity best characterised in SM EFT framework
- ▶ Certain dimension-6 operators contributing to ZH associated production grow with energy
- ▶ These may constrain specific strongly-coupled models inaccessible to direct searches
- ▶ Complementarity between measurements at different energies

Future e+e- Constraints

J. Ellis and T.Y. [arXiv:1510:04561]



- ▶ Future precision sensitive to TeV scale, even for loop-induced operators