BSM Searches at CLIC

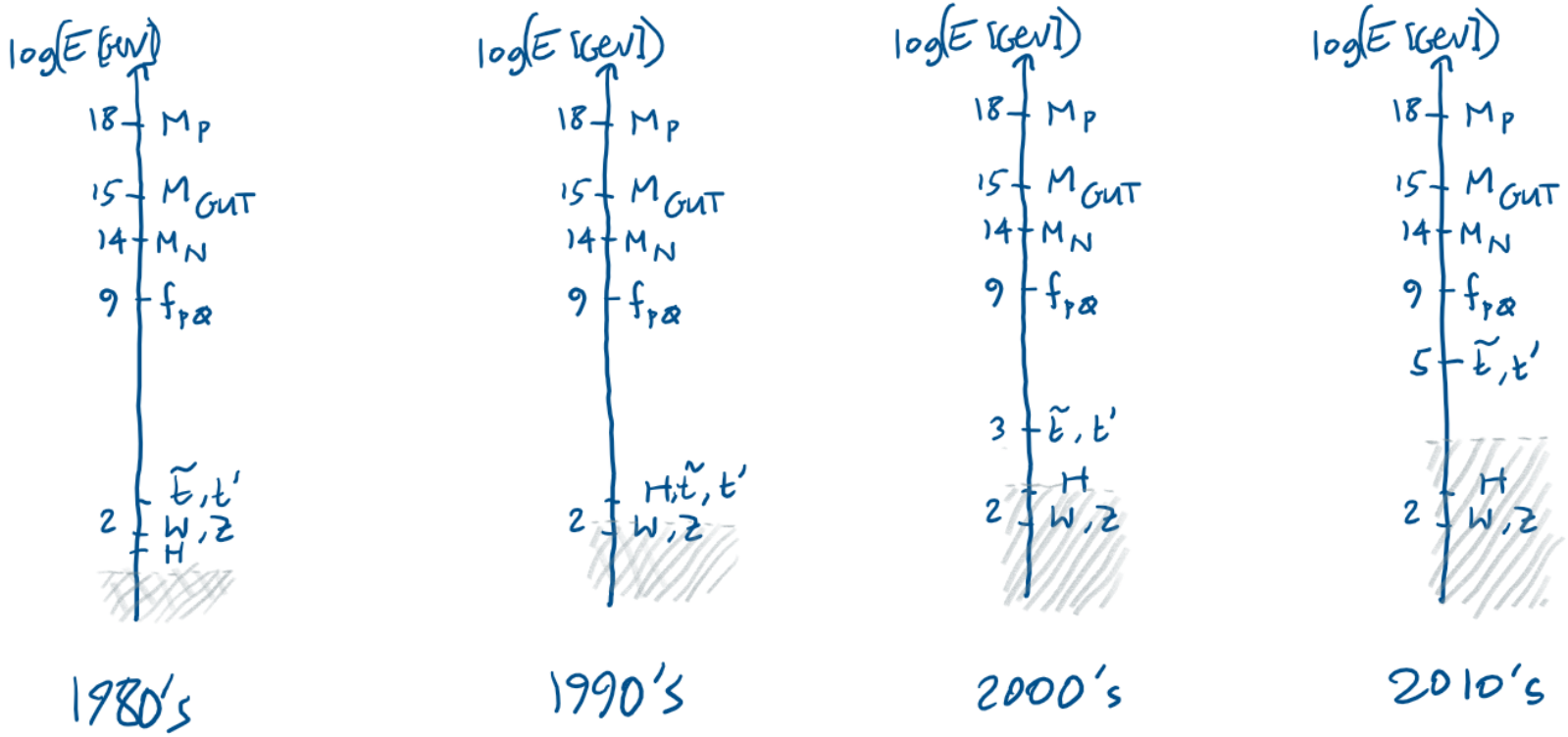
Tevong You

Introduction

- Motivation for the SMEFT framework
- Projected sensitivity to BSM at CLIC
- VBF top pair production at CLIC
- CLIC light-by-light scattering

Motivation for the SMEFT framework

- Evolving picture of BSM thanks to experiment



- The Standard Model *is* an **effective field theory**

Motivation for the SMEFT framework

- New physics appear to be decoupled at higher energies
- Given particle content, write down *all* terms allowed by symmetries…

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

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

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

- …Including **higher-dimensional** operators!

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

- Generated by new physics at scale $\Lambda \gg v$

SMEFT framework

- Unique dim-5 Weinberg operator, violates lepton number, predicts neutrino masses
- Modulo flavour structure, there are **59** dim-6 (CP-even) operators in a **non-redundant** basis

Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
Gradkowski et al [arXiv:1008.4884]

- **~19** operators relevant for EWPT, TGC, and Higgs physics

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

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

SMEFT framework

- Unique dim-5 Weinberg operator, violates lepton number, predicts neutrino masses
- Modulo flavour structure, there are **59** dim-6 (CP-even) operators in a **non-redundant** basis

Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
Gradkowski et al [arXiv:1008.4884]

- **~19** operators relevant for EWPT, TGC, and Higgs physics

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

Operators benefit from precision at ILC/CEPC/FCC-ee

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

SMEFT framework

- Unique dim-5 Weinberg operator, violates lepton number, predicts neutrino masses
- Modulo flavour structure, there are **59** dim-6 (CP-even) operators in a **non-redundant** basis

Buchmuller and Wyler (Nucl. Phys. B 268 (1986) 621)
Gradkowski et al [arXiv:1008.4884]

- **~19** operators relevant for EWPT, TGC, and Higgs physics

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

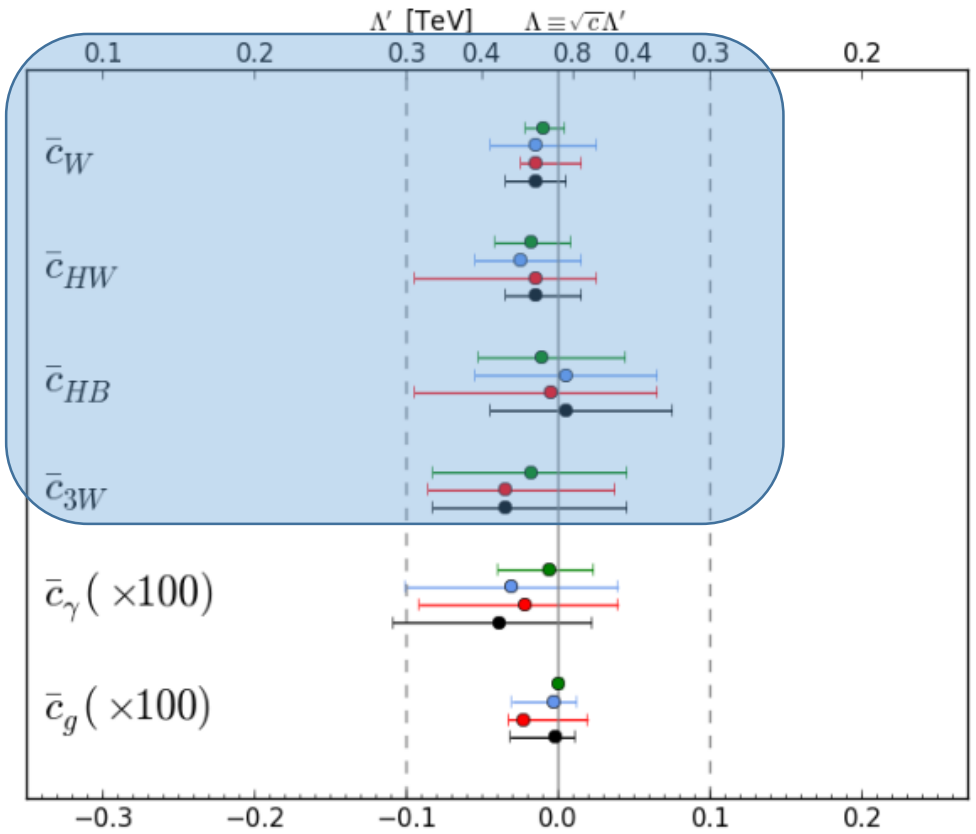
Operators benefit from energy-growing effects at CLIC

In SILH basis (Giudice et al. hep-ph/0703164), adopted from Pomarol and Riva (1308.1426)

Present state of Higgs SMEFT limits

- Higgs and TGC sensitivity **< 1 TeV** at LHC

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

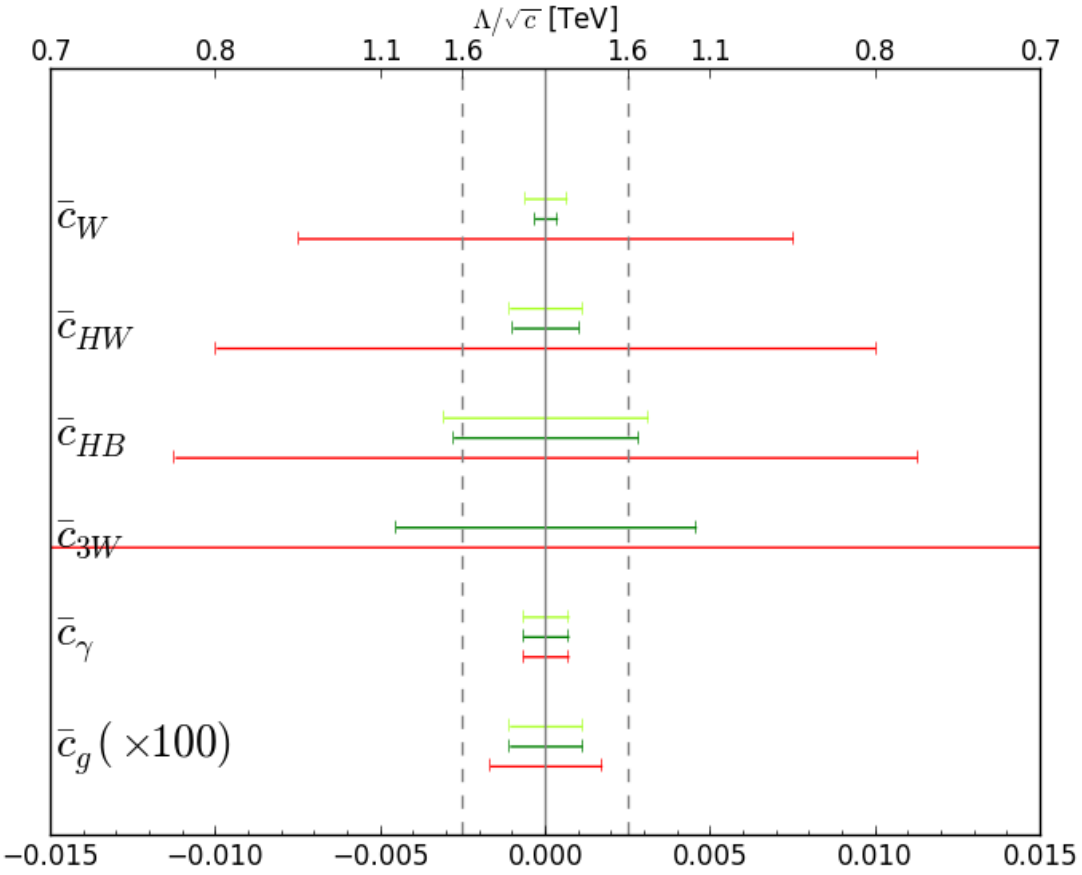


Ellis, Sanz and T.Y. 1410.7703

- Not *precision observables* yet

Higgs and TGC at CLIC

- CLIC 350 GeV



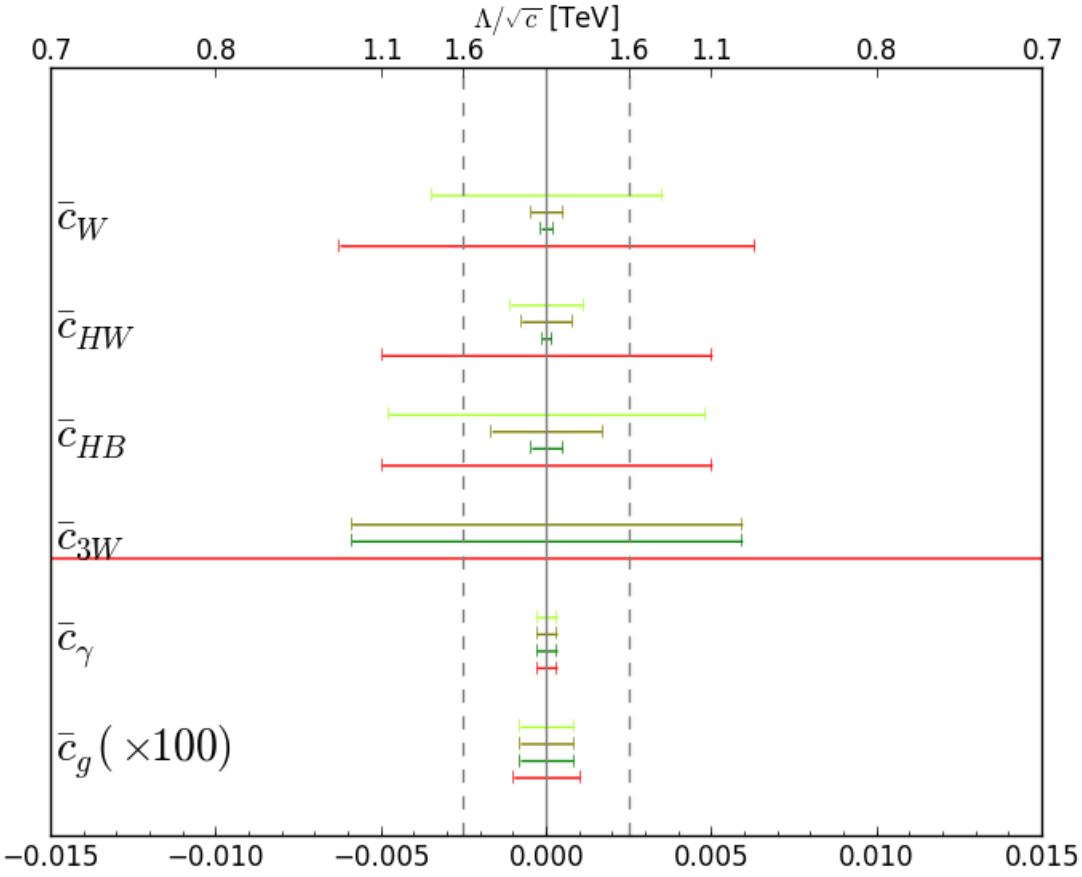
$$\bar{c}_i = c_i \frac{M^2}{\Lambda^2}$$

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

1701.04804 Ellis, Roloff, Sanz, TY

Higgs and TGC at CLIC

- CLIC 1.4 TeV



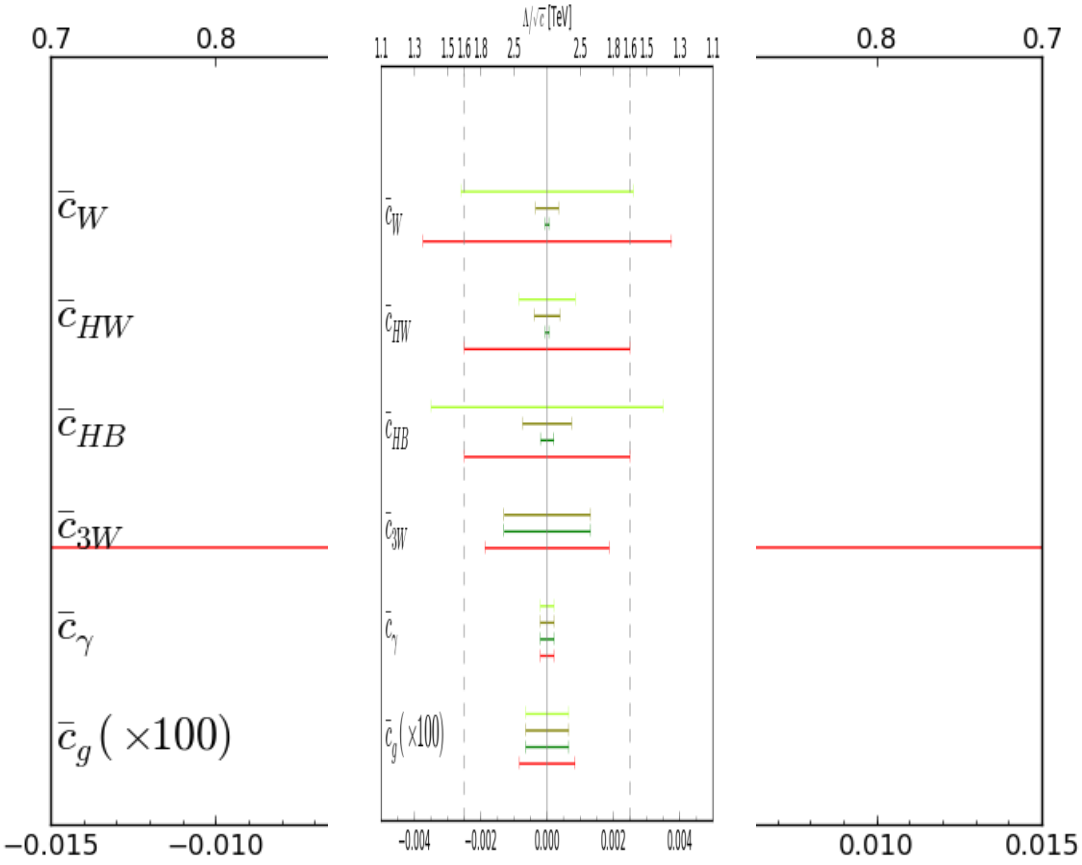
$$\bar{c}_i = c_i \frac{M^2}{\Lambda^2}$$

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

1701.04804 Ellis, Roloff, Sanz, TY

Higgs and TGC at CLIC

- CLIC 3 TeV



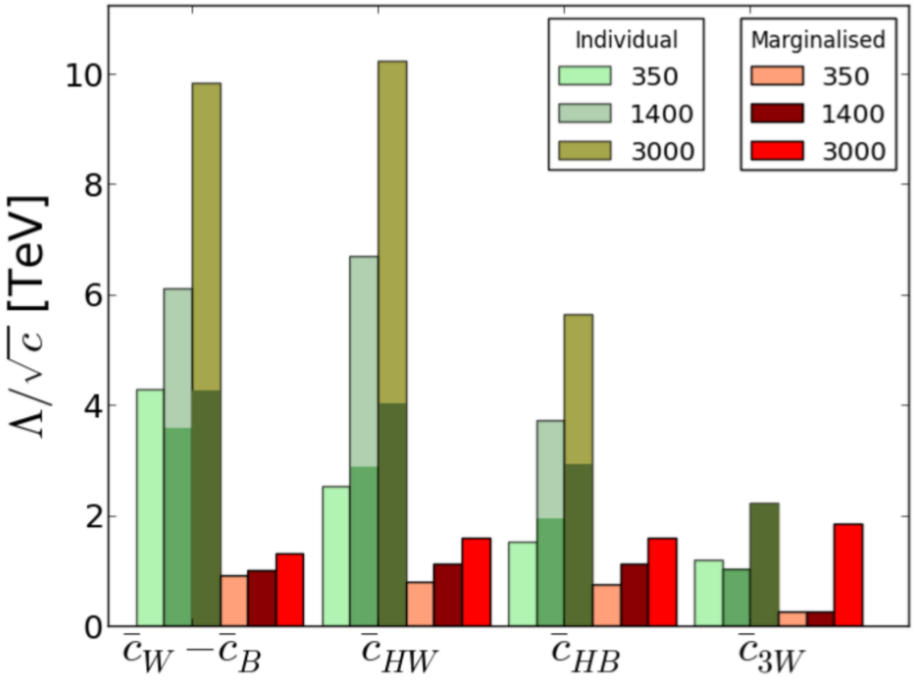
$$\bar{c}_i = c_i \frac{M^2}{\Lambda^2}$$

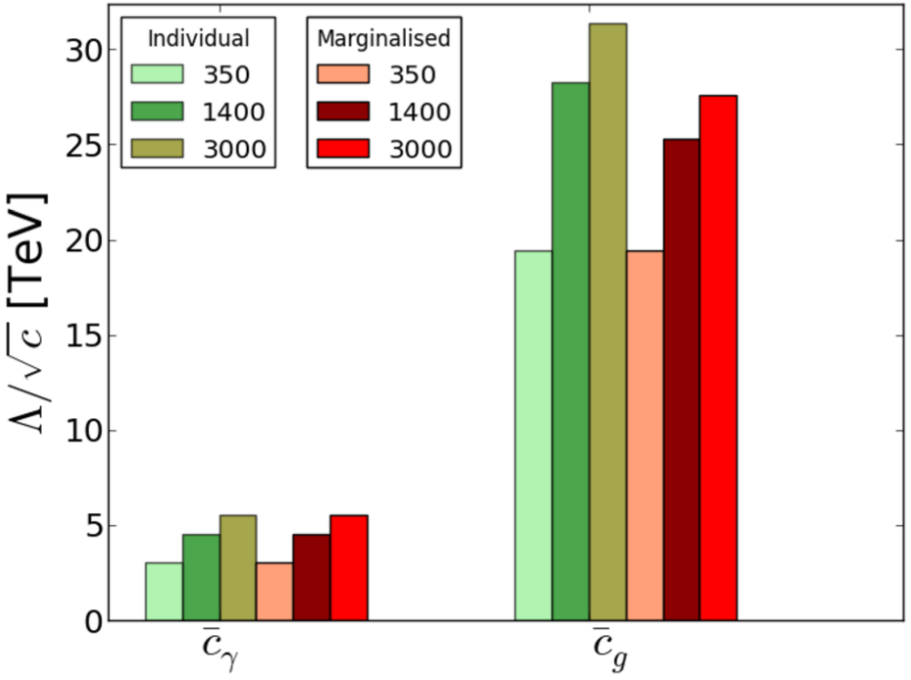
-Light green: Individual, no TGC or ZH
-Olive green: Individual, with TGC
-Dark Green: Individual, with TGC+ZH
-Red: Marginalised

1701.04804 Ellis, Roloff, Sanz, TY

Higgs and TGC at CLIC

- Summary of TeV reach



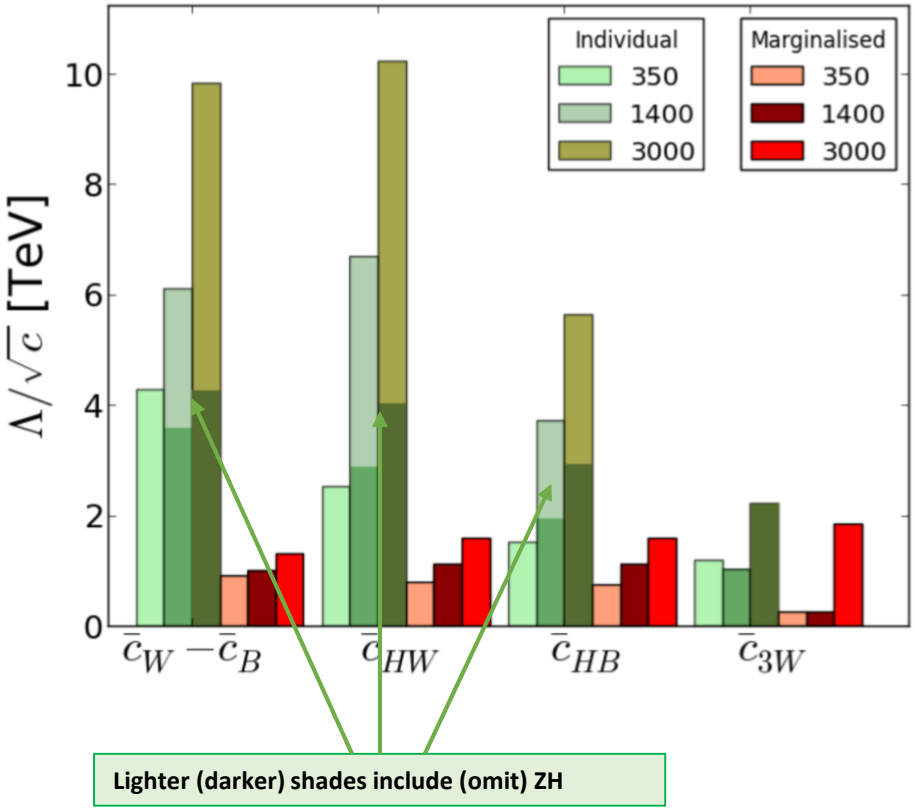


Lighter (darker) shades include (omit) ZH

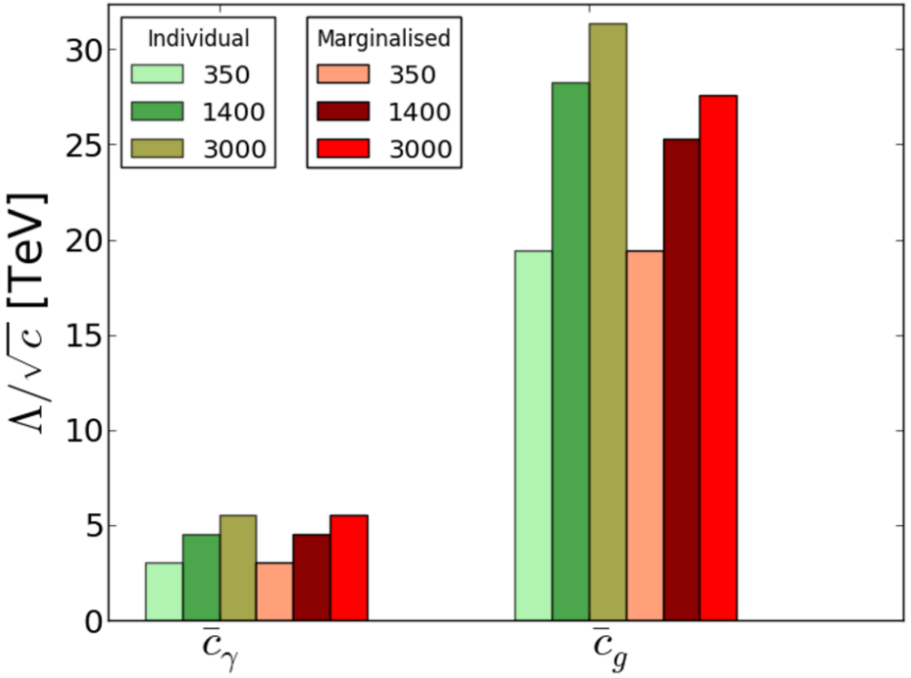
1701.04804 Ellis, Roloff, Sanz, TY

Higgs and TGC at CLIC

- Summary of TeV reach



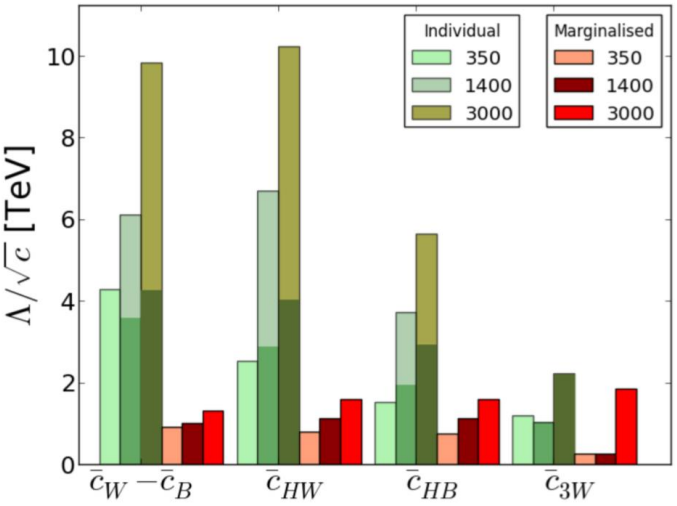
Lighter (darker) shades include (omit) ZH



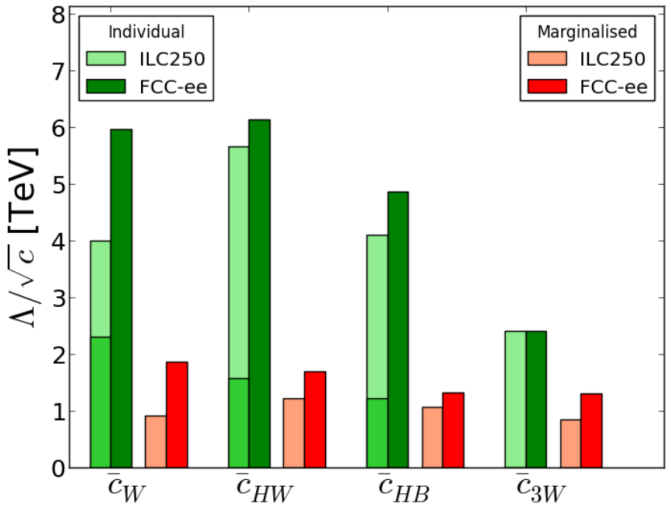
1701.04804 Ellis, Roloff, Sanz, TY

Higgs and TGC at CLIC

- Summary of TeV reach



- c.f. ILC250 and FCC-ee precision reach on these operators

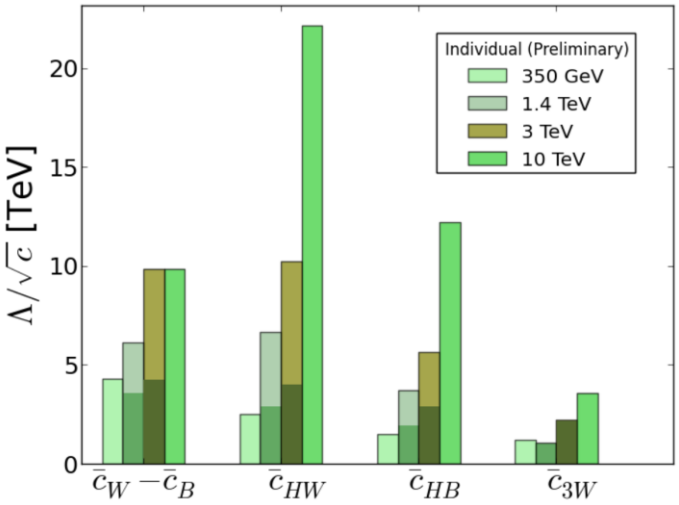


1510.04561 Ellis, TY

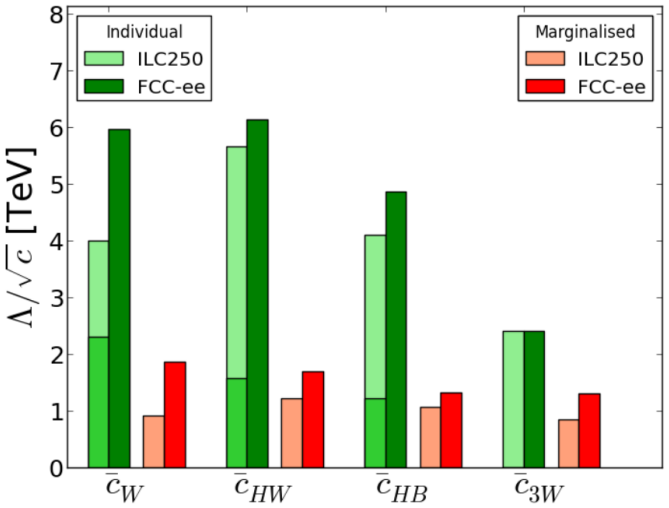
Lighter (darker) shades include (omit) TGCs

Higgs and TGC at CLIC

- Preliminary 10 TeV reach



- c.f. ILC250 and FCC-ee precision reach on these operators

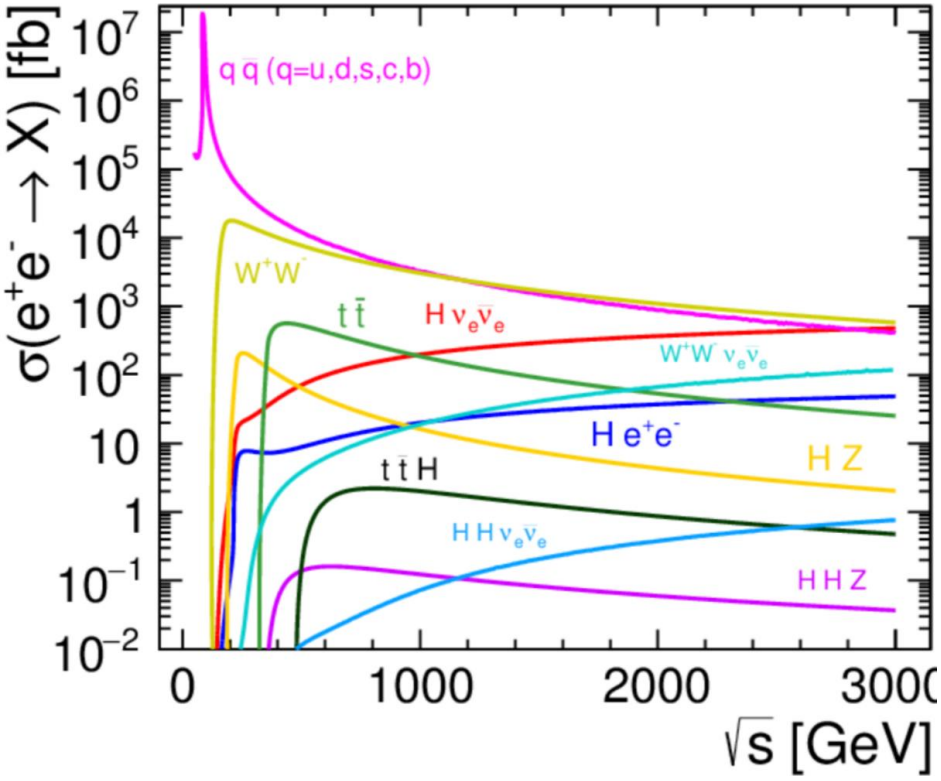


1510.04561 Ellis, TY

Lighter (darker) shades include (omit) TGCs

VBF top pair production

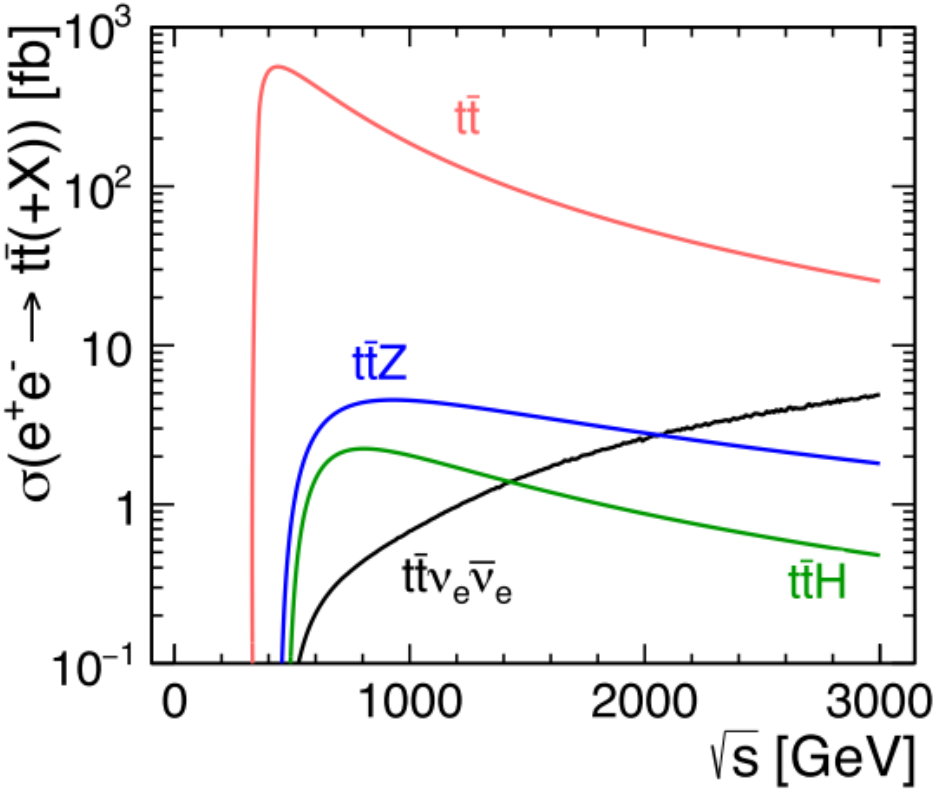
- Top pair production peaks close to threshold



- Studied $e^+e^- \rightarrow \nu\bar{\nu}t\bar{t}$, enhanced with energy

VBF top pair production

- Top pair production peaks close to threshold



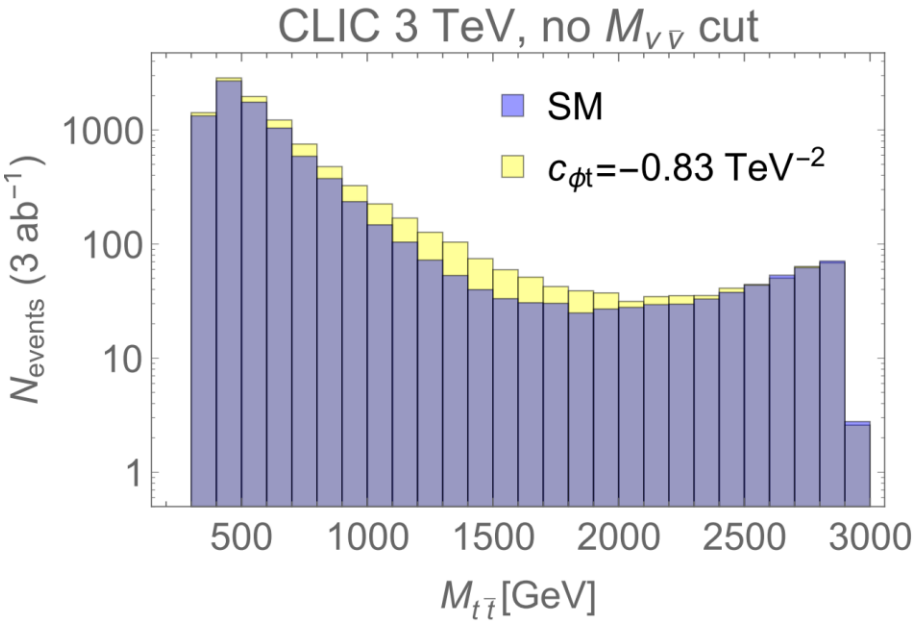
CLICdp top report

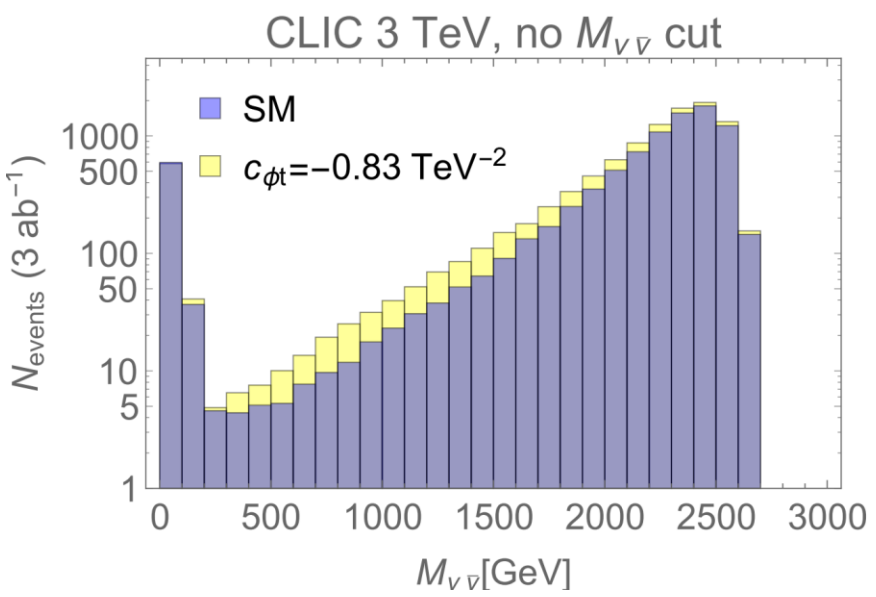
- Studied $e^+e^- \to \nu\bar{\nu}t\bar{t}$, enhanced with energy

VBF top pair production

- Dim-6 energy growth in $e^+e^- \to \nu\bar{\nu}t\bar{t}$ differential distributions

C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]



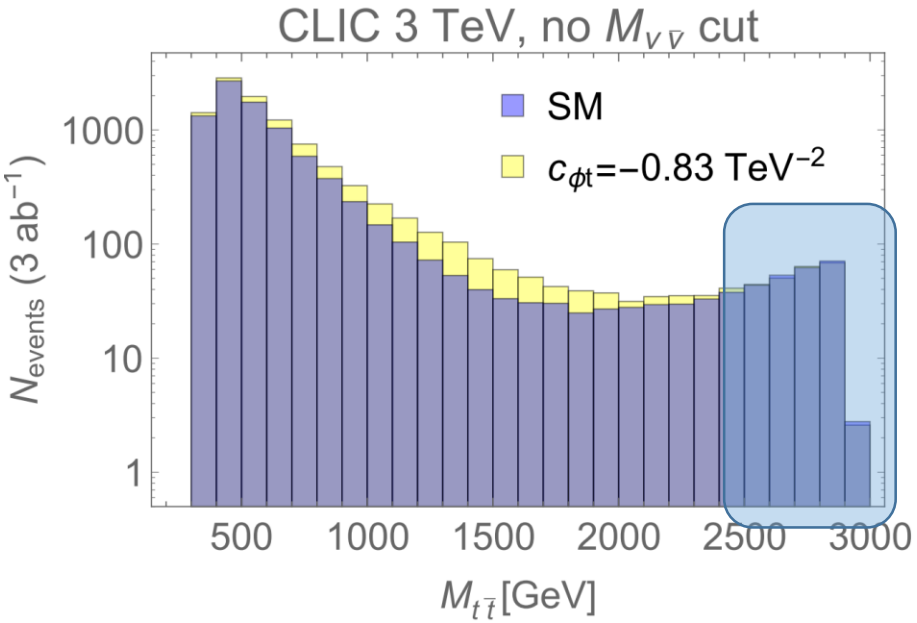


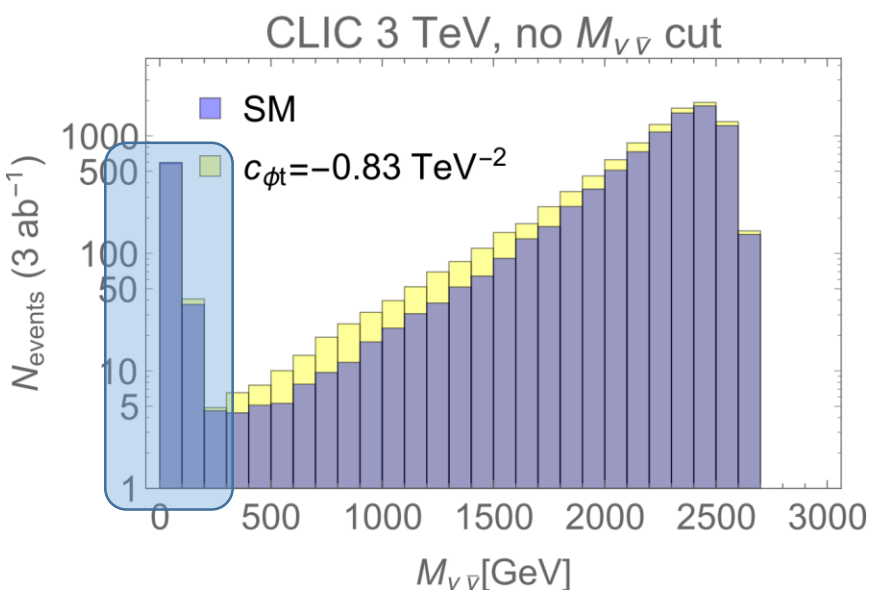
- Recover energy-growing behaviour in tail by cutting on $M_{\nu\bar{\nu}}$ to remove Z-pole contribution

VBF top pair production

- Dim-6 energy growth in $e^+e^- \to \nu\bar{\nu}t\bar{t}$ differential distributions

C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]



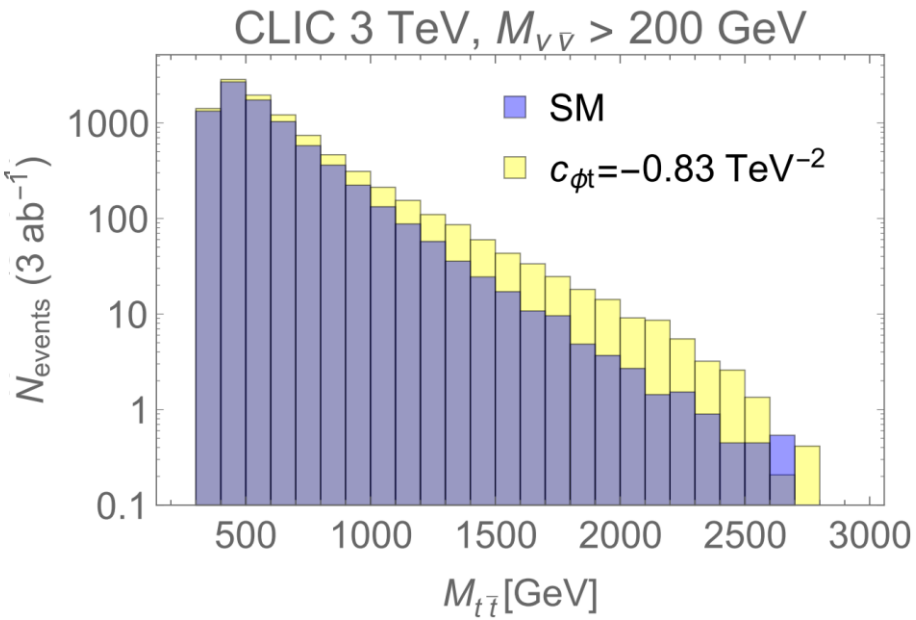


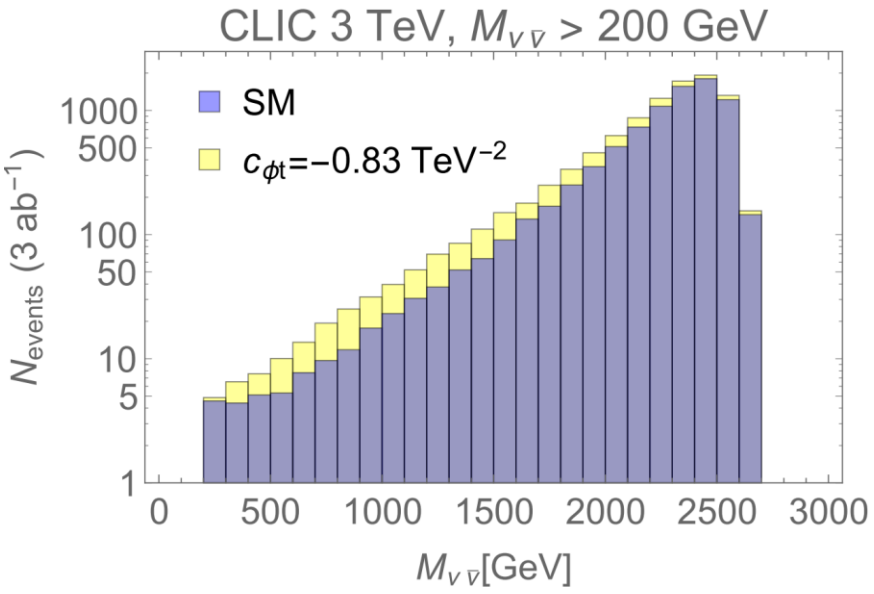
- Recover energy-growing behaviour in tail by cutting on $M_{\nu\bar{\nu}}$ to remove Z-pole contribution

VBF top pair production

- Dim-6 energy growth in $e^+e^- \to \nu\bar{\nu}t\bar{t}$ differential distributions

C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]

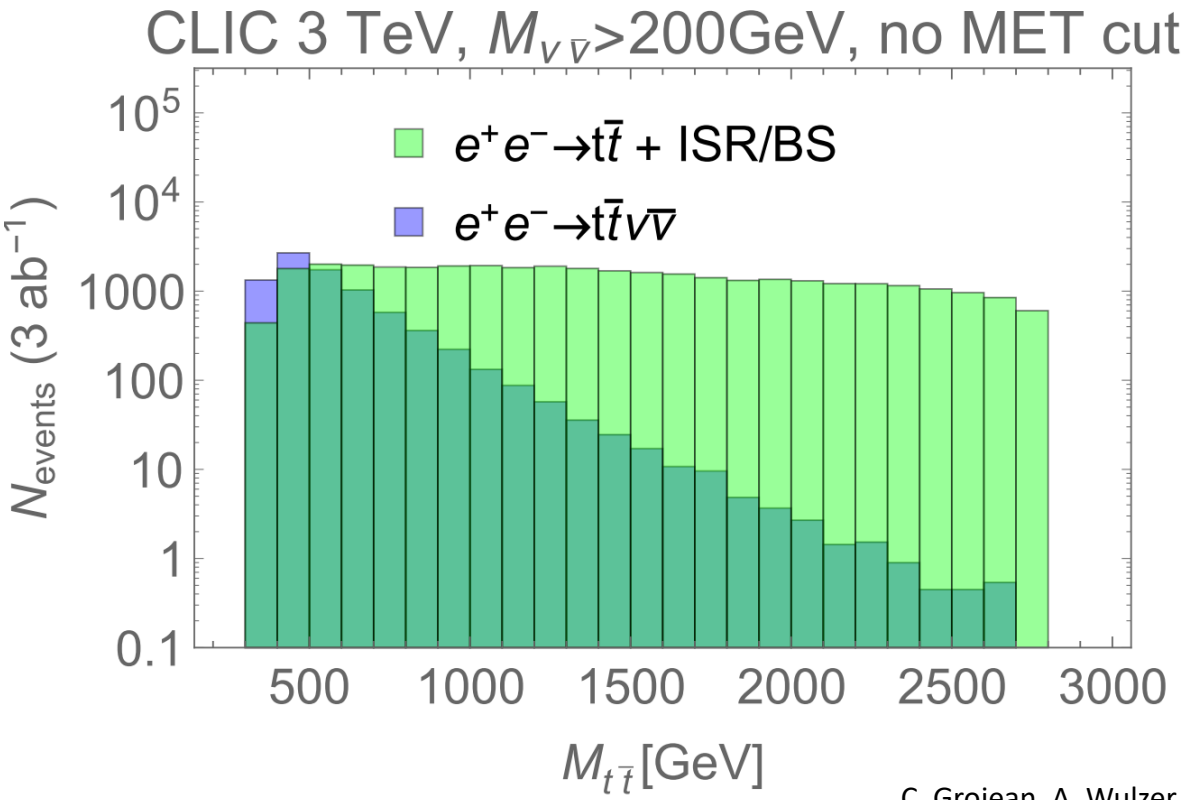




- Recover energy-growing behaviour in tail by cutting on $M_{\nu\bar{\nu}}$ to remove Z-pole contribution

VBF top pair production

- ISR/Beamstrahlung background from SM $e^+e^- \to t\bar{t}$

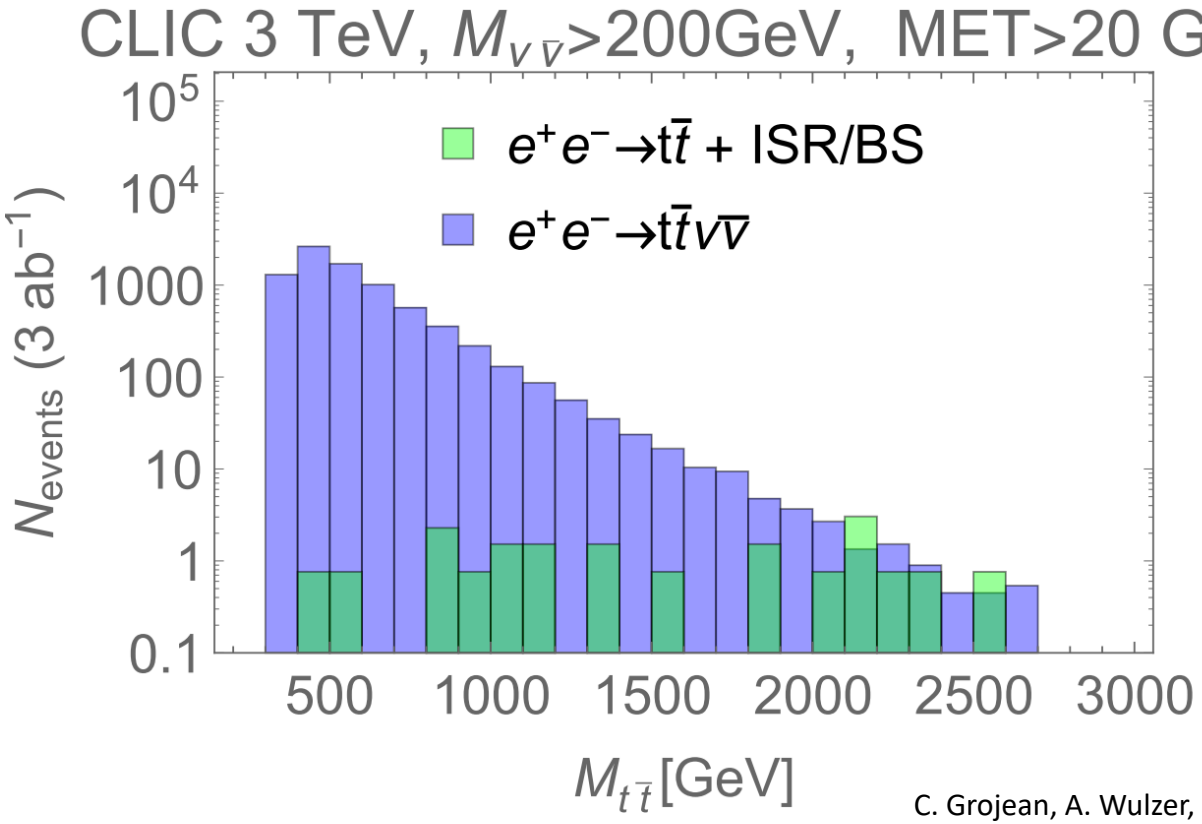


C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]

- Efficiently removed by MET cut

VBF top pair production

- ISR/Beamstrahlung background from SM $e^+e^- \to t\bar{t}$

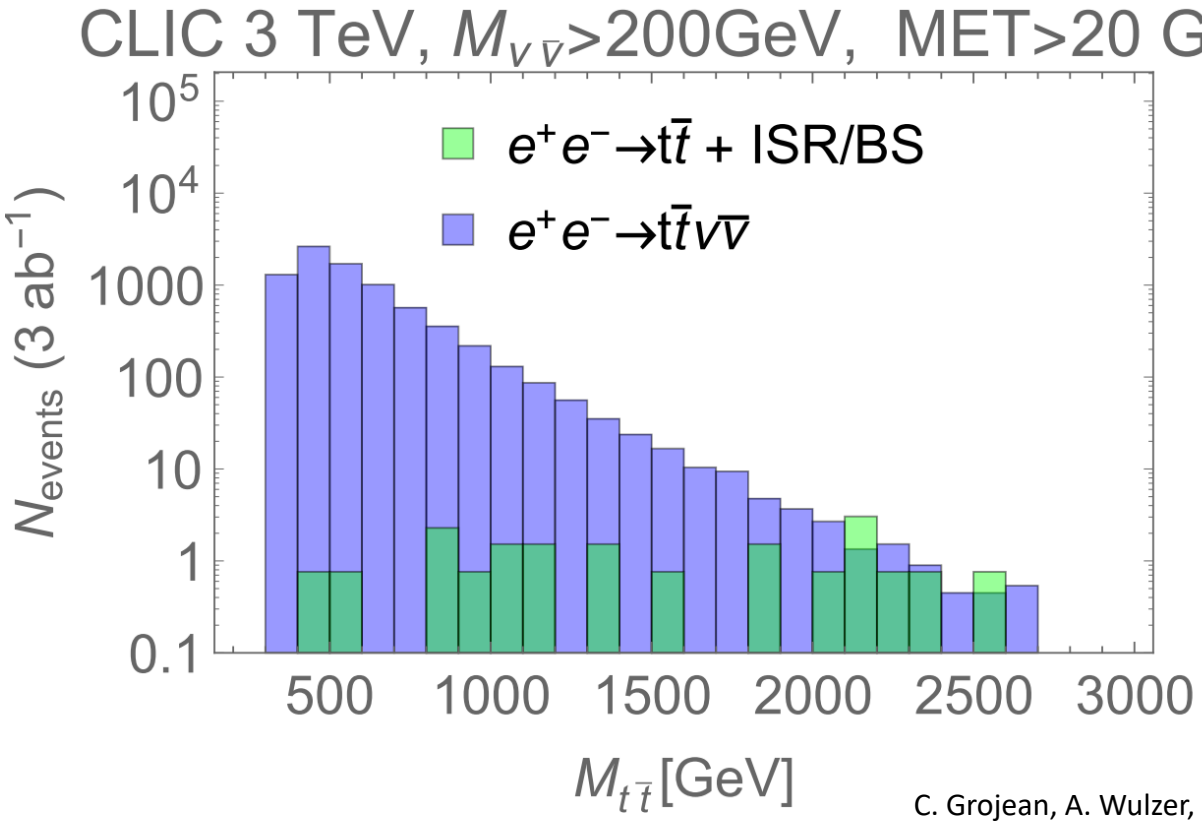


C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]

- Efficiently removed by MET cut

VBF top pair production

- ISR/Beamstrahlung background from SM $e^+e^- \to t\bar{t}$

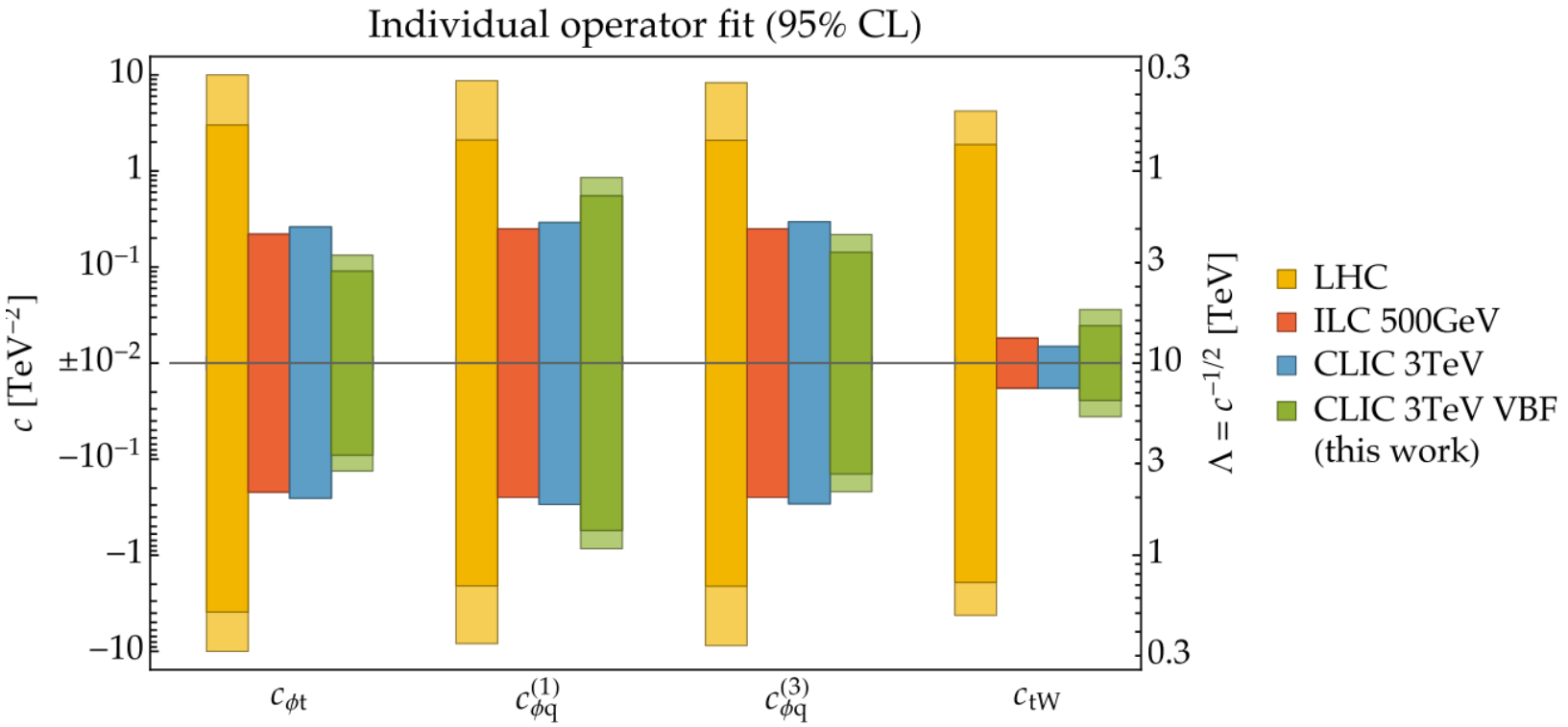


C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]

- Efficiently removed by MET cut

VBF top pair production

- Summary of projected top operators sensitivity



C. Grojean, A. Wulzer, Z. Zhang, TY [CLICdp top report]

- Comparable and complementary to other channels

CLIC light-by-light scattering

- Also benefits from higher energies

J. Ellis, N. Mavromatos, P. Roloff, TY [in progress]

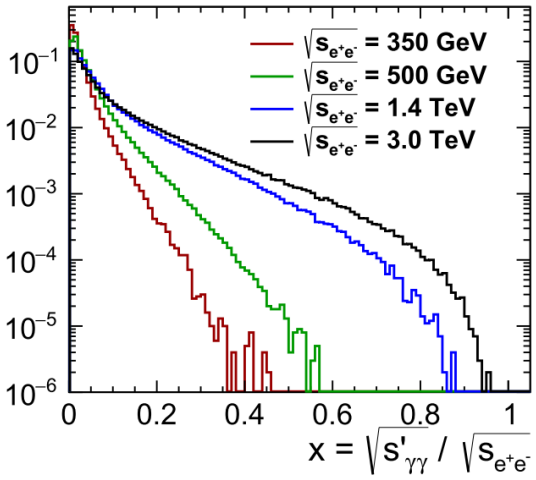


Figure 4: *The distributions of the $\gamma\gamma$ scattering centre-of-mass energy $\sqrt{s'_{\gamma\gamma}}$ at four CLIC energies: $\sqrt{s_{e^+e^-}} = 350$ GeV, 500 GeV, 1.4 TeV and 3 TeV (red, green, blue and black histograms, respectively.*

- Constrains Born-Infeld theory and vector EFTs

$$\mathcal{L}_{\rm BI} = \beta^2\left(1 - \sqrt{1 + \frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu} - \frac{1}{16\beta^4}(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2}\right)$$

$$\mathcal{L}_{\rm EFT} \supset c_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + c_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

CLIC light-by-light scattering

- Also benefits from higher energies

J. Ellis, N. Mavromatos, P. Roloff, TY [in progress]

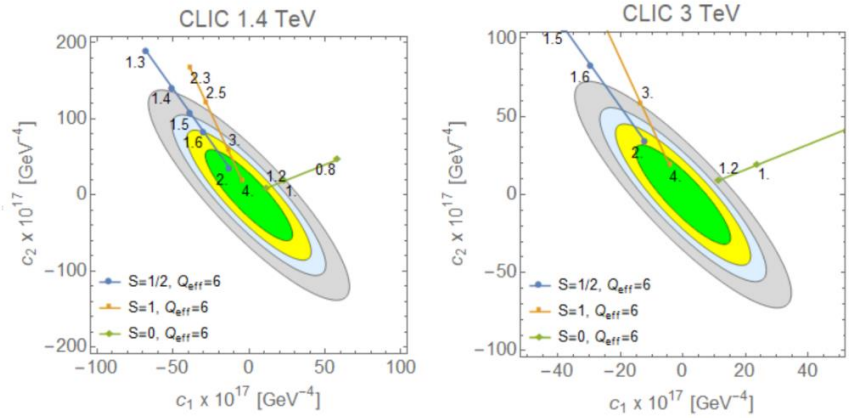


Figure 6: *Contours in the (c_1, c_2) plane of 1-, 2-, 3-, and 5-σ significance sensitivities of possible CLIC measurements at centre-of-mass energies of 1.4 TeV (left panel) and 3 TeV (right panel). The potential 5-σ discovery region is shaded grey, and the potential 95% exclusion reach in yellow. Also shown are the lines corresponding to the Heisenberg-Euler contributions of heavy beyond-the Standard-Model spin 0, 1/2 and 1 particles in blue, orange, and green, respectively, with effective charge $Q_{eff} = 6$. The dots are labelled with the masses of the particles in units of TeV.*

- Constrains Born-Infeld theory and vector EFTs

$$\mathcal{L}_{\rm BI} = \beta^2\left(1 - \sqrt{1 + \frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu} - \frac{1}{16\beta^4}(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2}\right)$$

$$\mathcal{L}_{\rm EFT} \supset c_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + c_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

Conclusion

- SMEFT is a relatively model-independent and systematic framework for mapping the path to BSM
- A high energy lepton collider can take advantage of energy-growing indirect effects of new physics
- Beyond CLIC: what can be learnt about the tens of TeV scale?