Top quark FCNCs at the LHC and e^+e^- colliders

Gauthier Durieux
(CERN)

Global approach to top-quark flavor-changing interactions,
GD, F. Maltoni, C. Zhang, Phys.Rev. D91 (2015) 074017, [1412.7166]

Section 8.1 in *Opportunities in flavour physics at the HL-LHC and HE-LHC*,
GD, T. Kitahara, C. Zhang, [1812.07638]

Section 3.1.2 in *The CLIC potential for new physics*, GD, [1812.02093]

Section 10.1.4 in *ILC report to Snowmass*, GD, M. Vos, [2203.07622]

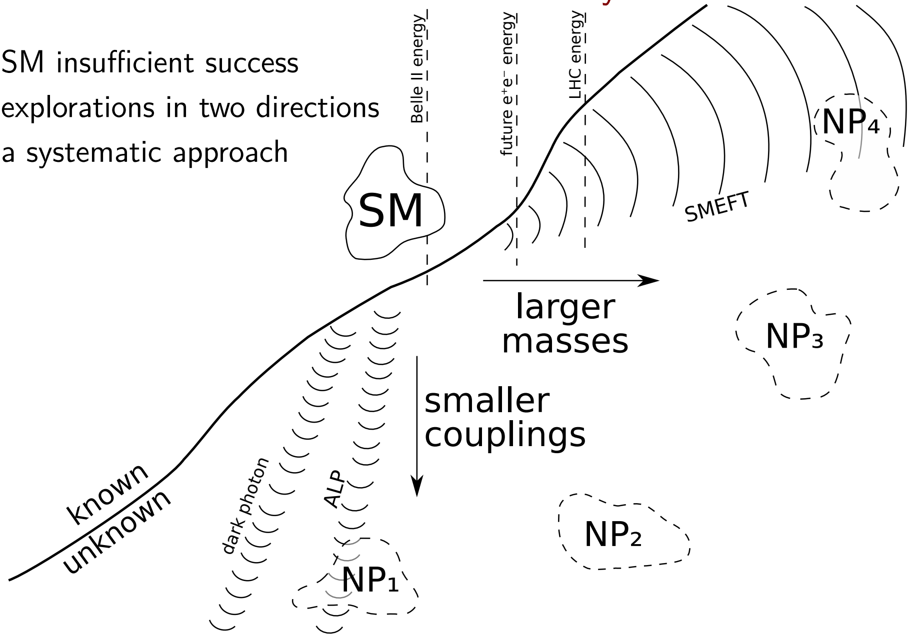
ECFA Workshop – DESY – 6 Oct 2022

The standard model effective field theory

SM insufficient success

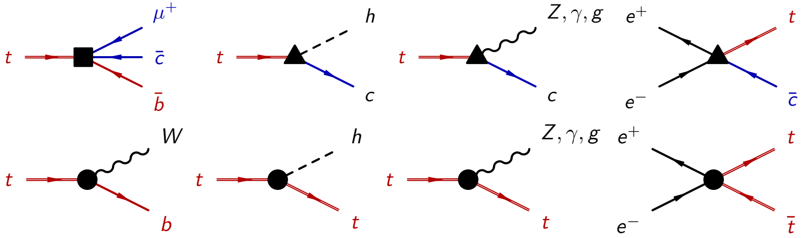
explorations in two directions

a systematic approach



The dim>4 top quark

- violates B at the quark level [Dong, GD, Gérard, Han, Maltoni '11] [CMS '13]
- has tree-level flavour-changing neutral currents
- has four-point interactions
- has modified vector and dipole couplings



Top-quark FCNCs at dim≤4

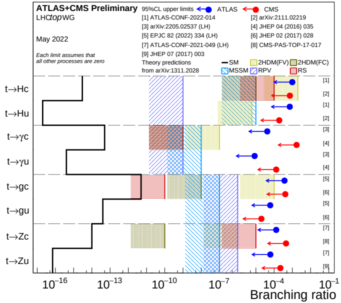
vanishingly small...

[Eilam et al, 91]
[Mele et al, 98]

e.g.:

	$\mathrm{Br}^{\mathrm{SM}}$	$\mathrm{Br}^{\mathrm{exp}}$
$t \to cg$	$\sim 10^{-11}$	$\lesssim 10^{-4*}$
$t \to c\gamma$	$\sim 10^{-12}$	$\lesssim 10^{-3*}$
$t \to cZ$	$\sim 10^{-13}$	$\lesssim 10^{-4}$
$t \to ch$	$\sim 10^{-14}$	$\lesssim 10^{-3}$

vs. about $2 \cdot 10^{9}$ tops/ab^{-1} at 13 TeV
$6 \cdot 10^{10}$ tops/ab^{-1} at 100 TeV



Anomalous coupling shortcomings

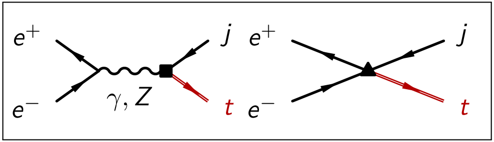
Scalar: $\bar{t}q \quad h$

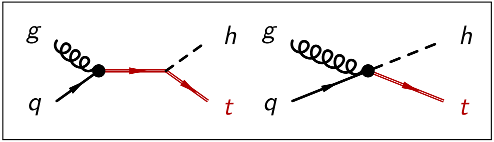
Vector: $\bar{t}\gamma^\mu q \quad Z_\mu$

Tensor: $\bar{t}\sigma^{\mu\nu} q \quad A_{\mu\nu}$

$\bar{t}\sigma^{\mu\nu} q \quad Z_{\mu\nu}$

$\bar{t}\sigma^{\mu\nu} T^A q \quad G^A_{\mu\nu}$





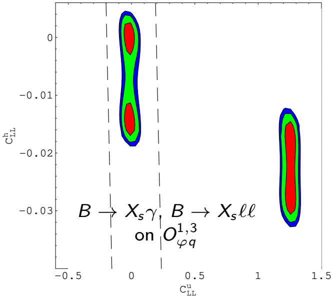
- Missing four-point interactions:
  - four-fermion operators
  - a *tqgh* vertex arising from $\bar{q}\sigma^{\mu\nu} T^A u \; \tilde{\varphi} \quad G^A_{\mu\nu}$
- Missing correlations:
  of '$v + h$' type
  of '$W + Z + \gamma$' type
  of '$(t_L \quad [V_{\text{CKM}} d_L]^3)^T$' type

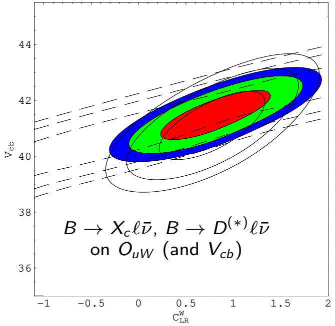
B physics probes

tqV impact at tree and loop levels:

[Han, Whisnant, Young, Zhang '96, '96]
[Fox, Ligeti, Papucci, Perez, Schwartz '07]
[Gong, Hao, Li, Yang, Yuan '10, '11, '11, '13]

- $B^0\overline{B}^0, B^0_s\overline{B}^0_s, K^0\overline{K}^0$ oscillations
- $B \to D^{(*)}\ell\nu$, $B \to X_c\ell\nu$, $B \to \pi\ell\nu$, $B \to X_u\ell\nu$
- $B \to X_s\gamma$, $B \to \rho\gamma$
- $B \to X_s\ell\ell$, $B \to K^{(*)}\ell\ell$, $B_{d,s} \to \mu^+\mu^-$
- $B \to X_s\nu\bar{\nu}$, $B \to K^{(*)}\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$





Direct searches with on-shell tops

			tqg, T	$tqgh$ T	$tq\gamma$ T	tqZ V,T	$tq\ell\ell$ S,V,T	$tqqq$ S,V,T	tqh S
The broken-phase effective Lagrangian:			✓	✗	✓	✓,✓	✗	✗	✓
production	• $e^+e^- \to t\, j$	OPAL, DELPHI, ALEPH, L3			✓	✓,✗	✗		
production	$e^- p \to e^- t$	**H1**, ZEUS			✓	✗	✗		
production	• $p\overset{(-)}{p} \to t$	CDF, **ATLAS**	✓						
production	$p\overset{(-)}{p} \to t\, j$	D0, **CMS**	✓		✗	✗		✗	
production	• $p\, p \to t\, \gamma$	CMS	✗		✓				
production	$p\, p \to t\, \ell^+\ell^-$	CMS	✓		✗	✗,✓	✗		
production	$p\, p \to t\, \gamma\gamma$	—	✗	✗	✗				✗
decay	$t \to j\gamma$	**CDF**, D0, ATLAS, CMS			✓				
decay	• $t \to j\ell^+\ell^-$	CDF, D0, ATLAS, **CMS**			✗	✓,✗	✗		
decay	• $t \to j\gamma\gamma$	**CMS**, ATLAS			✗				✓

One single contribution is often assumed.

Predictions

Interferences:

e.g. $\Gamma^{m_{\ell\ell}\in[78,102]\text{ GeV}}_{t\to j\,\ell^+\ell^-} = 10^{-5}\text{ GeV} \times \left(\frac{1\text{ TeV}}{\Lambda}\right)^4 \times$

$$\text{Re}\begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34}i & \underset{-}{+0.014} - \underset{-}{0.013}i \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18}i & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09}i & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3}\,i & \underset{-}{-0.007} + \underset{-}{0.017}i \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095}i & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095}i & \underset{-}{+0.27} + \underset{-}{0.2}i \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029}i & \underset{-}{+0.16} + \underset{-}{0.14}i \\ & & & & \underset{-9\%}{+6.6} & \underset{-}{-0.53} - \underset{-}{0.47}i \\ & & & & & \underset{-}{+0.002} \end{pmatrix} \begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}$$

$$+\text{Re}\begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34}i & \underset{-}{-0.002} + \underset{-}{0.013}i \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18}i & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09}i & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3}\,i & \underset{-}{+0.0067} - \underset{-}{0.006}i \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095}i & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095}i & \underset{-}{-0.17} - \underset{-}{0.09}i \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029}i & \underset{-}{-0.098} - \underset{-}{0.068}i \\ & & & & \underset{-9\%}{+6.6} & \underset{-}{+0.31} + \underset{-}{0.21}i \\ & & & & & \underset{-}{+0.00066} \end{pmatrix} \begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}$$

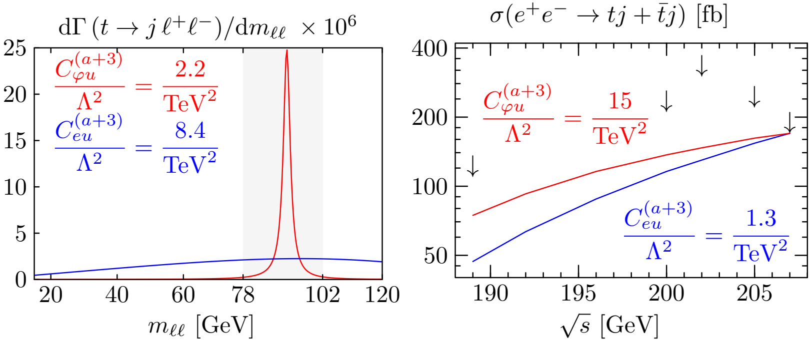
$$+\underset{0\%}{0.02}\left(|C_{lequ}^{1(13)}|^2 + |C_{lequ}^{1(31)}|^2\right) + \underset{-9\%}{0.81}\left(|C_{lequ}^{3(13)}|^2 + |C_{lequ}^{3(31)}|^2\right)$$

NLO QCD:

- two-quark op.: implemented in UFO model [Degrande et al. 14']
- two-quark–two-lepton op.: computed analytically [GD, Maltoni, Zhang 14']
- four-quarks op.: not computed

Four-fermion operators

[1412.7166]



More sensitivity in off-Z-peak region of $t \to j\ell\ell$ (smaller Drell-Yan bkg).
High-energy lepton colliders are powerful probes for *eetq*.

Four-fermion operators

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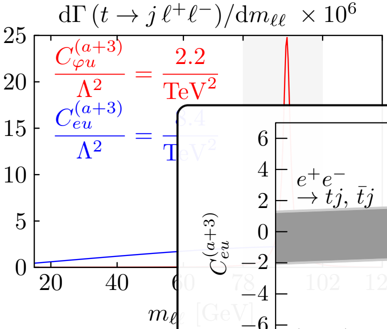

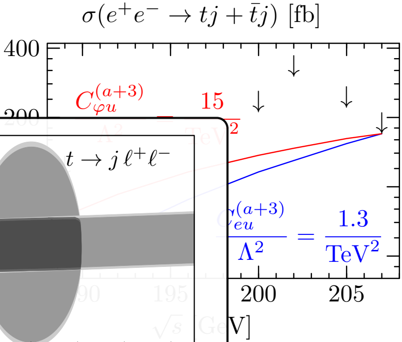

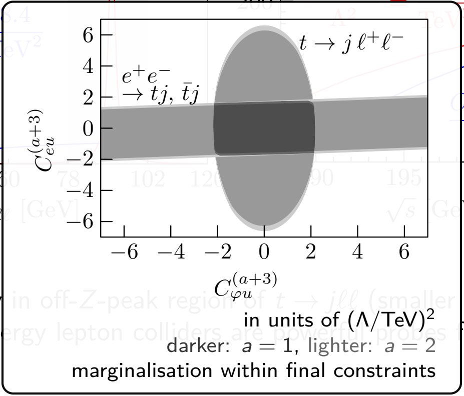

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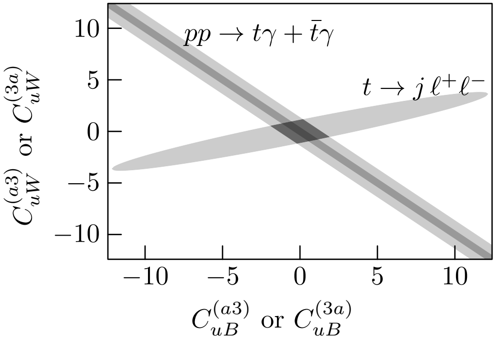
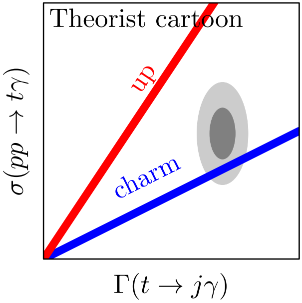
Production vs. decay

Discriminate the *tc* and *tu* interactions through proton PDF.



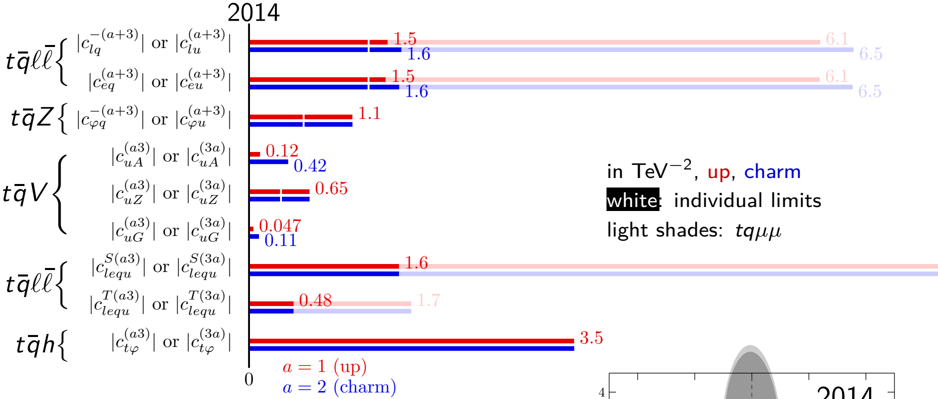


$C_{uA} \equiv C_{uW} + C_{uB}$
$C_{uZ} \equiv C_{uW} \cot\theta_W - C_{uB} \tan\theta_W$

in units of $(\Lambda/\text{TeV})^2$
darker: $a = 1$ (up), lighter: $a = 2$ (charm)
marginalising within C_{uG} constraints

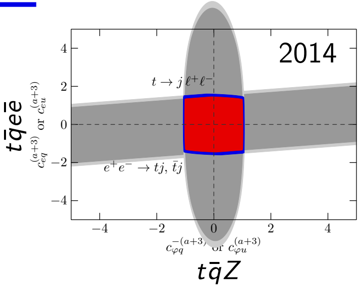
Global prospects until 2040

[GD, Maltoni, Zhang '14]
[*Flavour at HL-LHC* '18]



in TeV^{-2}, up, charm
white: individual limits
light shades: $tq\mu\mu$

- 52 complex dim-6 operator coefficients
- NLO QCD predictions (10–30% effects)
- measurements from LEP, Tevatron, LHC



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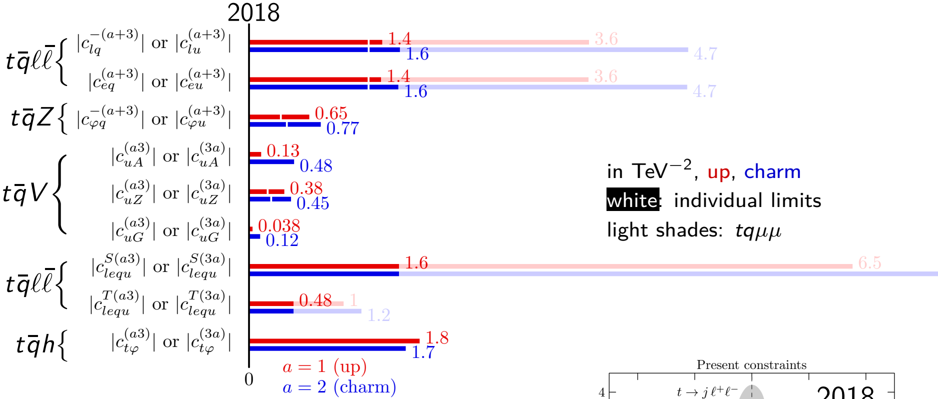

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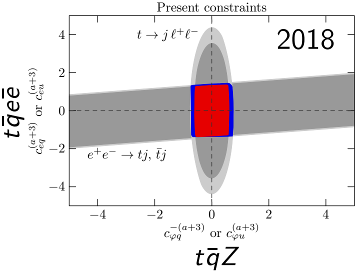

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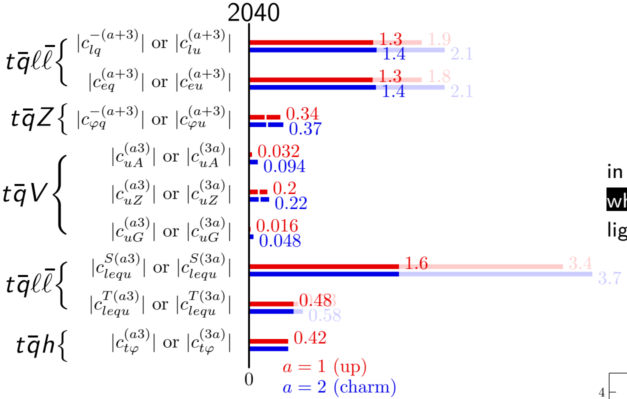

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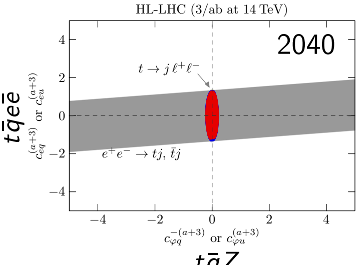
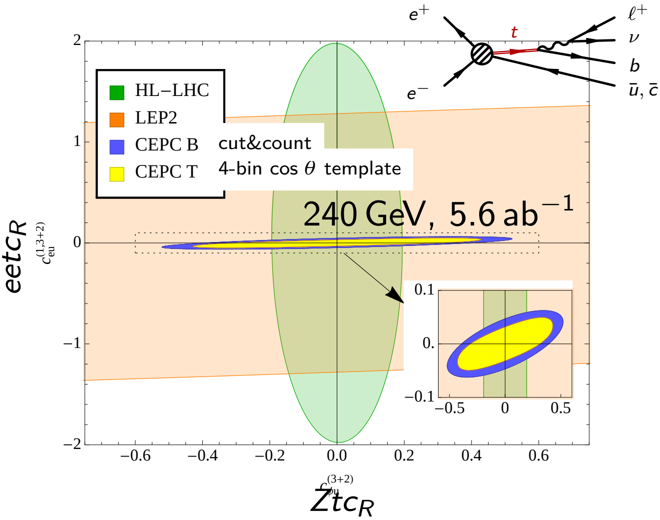


$e^+e^- \to tq$ at future colliders

[Tesla: Aguilar-Saavedra, Riemann '01]
[FCC-ee: Khanpour, Khatibi, Khatiri, Mohammadi '14]
[CLIC: GD '18]
[CEPC: Shi, Zhang '19]
[ILC: GD '22]

accessible below the $t\bar{t}$ threshold



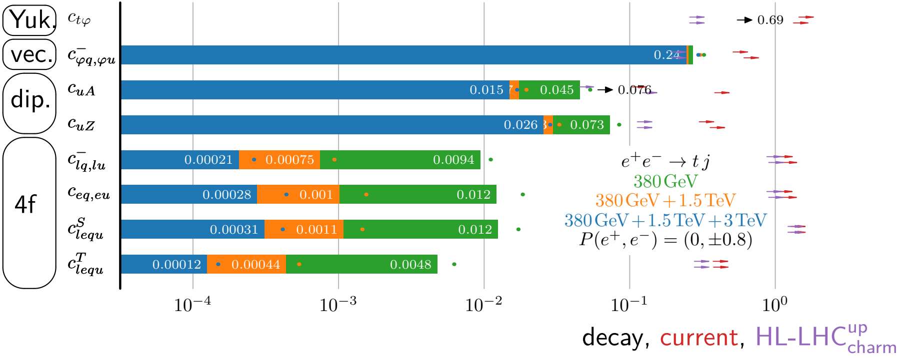
Linear colliders

[CLIC '18] [ILC '22]

Use *statistically optimal observables*, against $e^+e^- \to W^+W^-$ bkg
Extrapolate efficiencies from previous studies ($\epsilon \propto 1/\sqrt{s}^{1.9}$)

[TESLA '01]
[FCC-ee '14]

global 95% CL limits, in TeV^{-2}, CLIC scenario (0.5, 1.5, 3 ab^{-1})



Four-fermion sensitivity benefits from high energies.

Linear colliders

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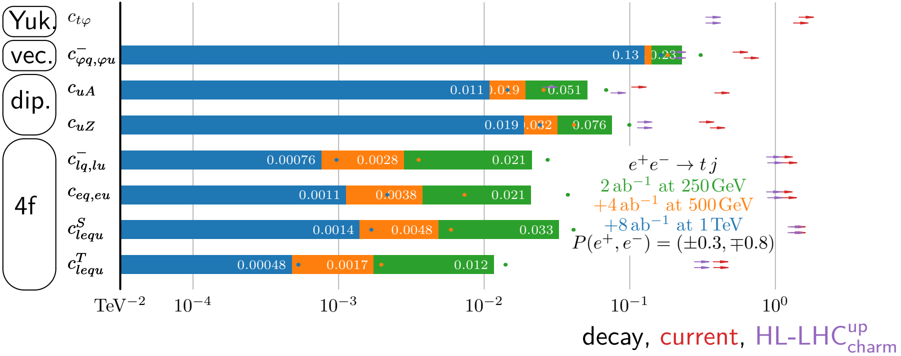
Use *statistically optimal observables*, against $e^+e^- \to W^+W^-$ bkg
Extrapolate efficiencies from previous studies ($\epsilon \propto 1/\sqrt{s}^{1.9}$) [TESLA '01] [FCC-ee '14]

global 95% CL limits, in TeV^{-2}, ILC scenario (2, 4, 8 ab^{-1})



Four-fermion sensitivity benefits from high energies.

Top-quark FCNCs

Global EFT interpretations are manageable (at NLO in QCD).

Relevant four-fermion operators are often ignored.
Off-Z-peak $m_{\ell\ell}$ regions have enhanced sensitivities.

Production and decay processes are complementary
but anomalous-coupling combinations cannot be reinterpreted.

The HL-LHC would bring 2-4 improvements on tqZ, γ, g, h
and $\mu\mu tq$ operator coefficient limits.

Future lepton colliders would dramatically improve $eetq$,
starting from below the $t\bar{t}$ threshold.

Extras

Statistically optimal observables

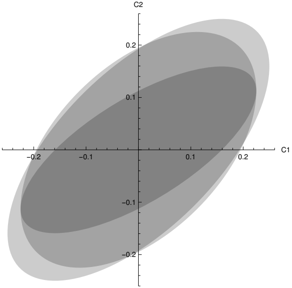
minimize the one-sigma ellipsoid in EFT parameter space

(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,
the stat. opt. obs. are the average values of $O_i(\Phi) = n\, \sigma_i(\Phi)/\sigma_0(\Phi)$.

The associated covariance at $C_i = 0$, $\forall i$ is

$$\text{cov}(C_i, C_j)^{-1} = \epsilon\mathcal{L} \int \text{d}\Phi\ \frac{\sigma_i(\Phi)\sigma_j(\Phi)}{\sigma_0(\Phi)}.$$



e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1