Top-quark physics and EFT
Theory overview

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Outline

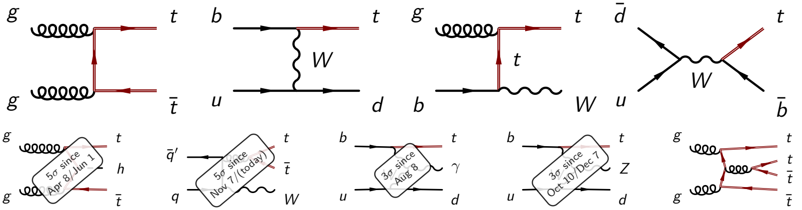
The top and the SM EFT

LHC TOP WG standards

Progresses on global analyses

The SM top quark

- is 23 years old and remains a prime target
- has $y_t \simeq 1$, $V_{tb} \simeq 1$, $\Gamma_t \simeq 1.4$ GeV $> \Lambda_{QCD}$
- has only been produced at hadron colliders

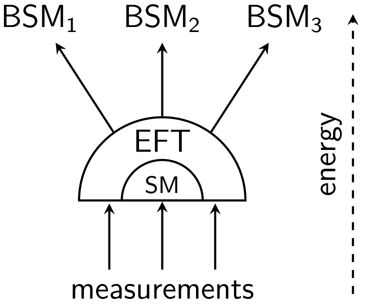


The SM effective field theory

systematically parametrizes the theory space
in direct vicinity of the SM

- based on SM fields and symmetries
- in a low-energy limit
- systematic and renormalizable when global

(...) if one writes down the most general possible Lagrangian, including all *terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry.* [*Phenomenological Lagrangians*, Weinberg '79]



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provides a means to probe new physics
through correlated deviations
in precisely measured observables

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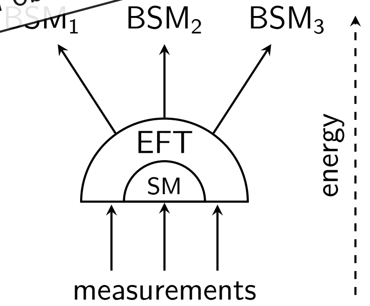


Up-type sector at dim-6

In the *Warsaw* basis: [Grzadkowski et al '10]

Four-quark operators (11)

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$\mathcal{O}_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$\mathcal{O}_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

Two-quark operators (9)

$$\mathcal{O}_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$\mathcal{O}_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$\mathcal{O}_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}\,W^I_{\mu\nu},$$
$$\mathcal{O}_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi\,W^I_{\mu\nu},$$
$$\mathcal{O}_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad\tilde{\varphi}\,B_{\mu\nu},$$
$$\mathcal{O}_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}\,G^A_{\mu\nu},$$

Two-quark-two-lepton operators (8)

$$O_{lq}^{1(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_j\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$\mathcal{O}_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$\mathcal{O}_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$\mathcal{O}_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

$\not{B}$ and $\not{L}$ operators (5)

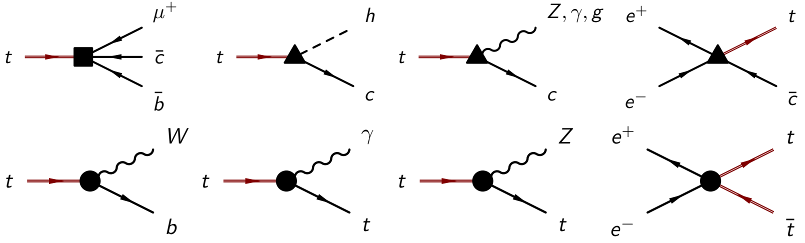
$$\mathcal{O}_{duq}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_{qqu}^{(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_{qqq}^{3(ijkl)} = (\overline{q^c}_{i\alpha}\tau^I\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\tau^I\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma}.$$

+ generation index assignments

The dim-6 SM top quark

[1107.3805]
[1310.1618]

- could violate B at the quark level
- could have sizeable FCNCs
- could have four-point interactions
- could have modified vector and dipole couplings



Anomalous vertices

$$t\bar{t}\gamma: \quad \gamma_\mu \overbrace{\left(F_{1V}^\gamma + \gamma_5 F_{1A}^\gamma\right)}^{\sim\emptyset} + \frac{\sigma_{\mu\nu} i q^\nu}{2m_t} \overbrace{\left(F_{2V}^\gamma + i\gamma_5 F_{2A}^\gamma\right)}^{\sim \mathrm{Re},\mathrm{Im}\{c_W C_{uB}^{(33)} + s_W C_{uW}^{(33)}\}}$$

$$t\bar{t}Z: \quad \gamma_\mu \overbrace{\left(F_{1V}^Z + \gamma_5 F_{1A}^Z\right)}^{\sim C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}, C_{\varphi u}^{(33)}} + \frac{\sigma_{\mu\nu} i q^\nu}{2m_t} \overbrace{\left(F_{2V}^Z + i\gamma_5 F_{2A}^Z\right)}^{\sim \mathrm{Re},\mathrm{Im}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}}$$

$$t\bar{b}W: \quad \gamma_\mu \overbrace{\left(F_{1V}^W + \gamma_5 F_{1A}^W\right)}^{\sim -C_{\varphi ud}^{(33)} \pm C_{\varphi q}^{3(33)}} + \frac{\sigma_{\mu\nu} i q^\nu}{2m_t} \overbrace{\left(F_{2V}^W + i\gamma_5 F_{2A}^W\right)}^{\sim -C_{dW}^{(33)*} \pm C_{uW}^{(33)}}$$

Insufficiencies:

- miss four-fermion operators,
- conflict with gauge invariance,
  do not allow for radiative corrections to be computed,
- complex couplings where the tree-level EFT prescribes real ones,
- hide correlations induced by gauge invariance,
  preclude the combination of measurements in various sectors

LHC TOP WG standards

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by the TH community, with extensive feedback from EXP [1802.07237]

- General guiding principle for EFT use,
  and conventional assumptions about BSM flavour
- Definition of convenient linear combinations,
  and dedicated implementation for MC simulation [here]
- Specific example of global analysis strategy,
  with useful EXP output identified
- Indicative direct & indirect constraints

Conventional BSM flavour assumptions (FCNCs treated separately)

To prioritize the study of flavour structures

Lepton sector (not critical)

- rather loose $[U(1)_{l+e}]^3$ aka flavour diagonality
- could easily be restricted to $U(3)_{l+e}$, $U(3)_l \times U(3)_e$, or ...

Quark sector (baseline and variants)

mostly restrict the large number of four-quark operators

Baseline: $U(2)_q \times U(2)_u \times U(2)_d$ among first two generations

$\equiv$ SM flavour symmetry in the limit $y_{u,d,s,c} \to 0$, $V_{\text{CKM}} \to \mathbb{I}$
forces the first two generations to appear as $\sum_{i=1,2} \bar{q}_i q_i$, $\bar{u}_i u_i$, $\bar{d}_i d_i$

Extended: $U(2)_{q+u+d}$ [sugg. by J.A.Aguilar-Saavedra]

- allows light right-handed charged currents $\sum_{i=1,2} \bar{u}_i d_i$
- allows light chirality flipping currents $\sum_{i=1,2} \bar{q}_i u_i$, $\bar{q}_i d_i$

Restricted: *top-philic* scenario [sugg. by A.Wulzer]

- assumes NP generates all operators with tops and bosons
- then project that over-complete set on the Warsaw basis with EOM, etc.

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Baseline: $U(2)_q \times U(2)_u \times U(2)_d$ among first two generations

d.o.f. counting

	baseline	extended	restricted
four heavy quarks	$11 + 2$ CPV		5
two light and two heavy quarks	14	$+10 + 10$ CPV	} 5
two heavy quarks and two leptons	$(8 + 3$ CPV$)\times 3$		
two heavy quarks and bosons	$9 + 6$ CPV		$9 + 6$ CPV

- assumes NP generates all operators with tops and bosons
- then project that over-complete set on the Warsaw basis with EOM, etc.

Collection of indicative constraints

To set a measure in EFT parameter space

- Direct measurements at Tevatron and LHC [coll. by E.Vryonidou]
- Indirect high-p_T constraints
  - $b\bar{b} \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ [coll. by D.Marzocca]
  - EW precision observables [coll. by C.Zhang]
- Meson decays and mixings [coll. by D.Marzocca]
  - $B \to D^{(*)}\ell\nu$, $B \to K^{(*)}\ell\ell$, $B_c \to \tau^+\tau^-$
  - $D - \bar{D}$, $B_s - \bar{B}_s$
- CPV [coll. by W.Dekens, J.de Vries, V.Cirigliano, E.Mereghetti]
  - n and e EDMs
  - $A_{CP}(B \to X_s\gamma)$

Progresses on global analyses

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Necessity

- to preserve the systematic coverage of BSM scenarios
- to ensure renormalizability, order by order
- to probe correlated deviation in precisely measured observables

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Top operators in top processes (loosely defined)

- most comprehensive attempt by TopFitter [1512.03360]
    - global constraints on 9 op. (12 considered)
    - 195 observables ($t\bar{t}$, single t, associated prod., decay)
    - SM (N)NLO k-factors in each bin

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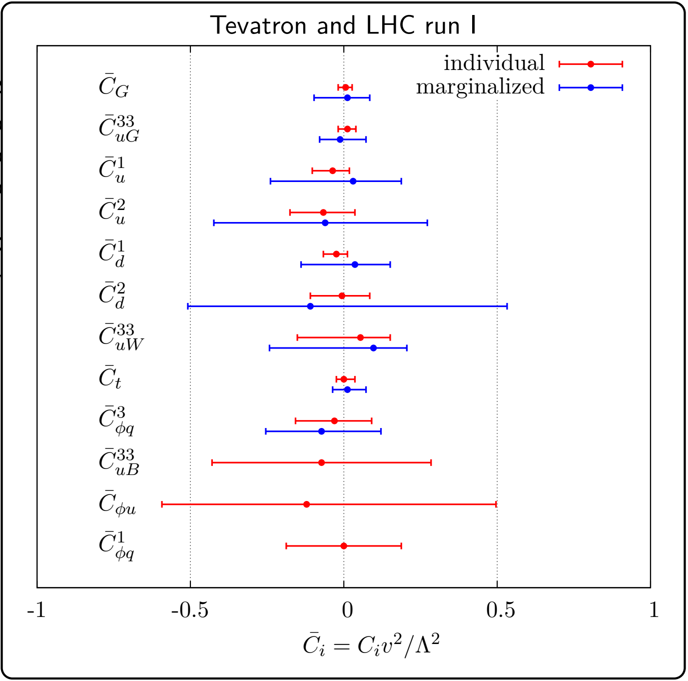

[1512.03360]

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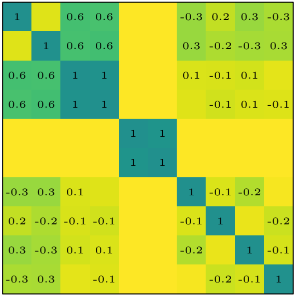
  - 195 observables ($t\bar{t}$, single t, associated prod., decay)
  - SM (N)NLO k-factors in each bin
- prospects from HL-LHC
  - factor $\mathcal{O}$(1-10) improvement on individual sensitivities
  - electroweak couplings (beside tbW) difficult to access
- prospects from lepton colliders
  - global analysis of $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ with 10 op. [1807.02121]
  - factor $\mathcal{O}$(10-1000) improvement on individual sensitivities

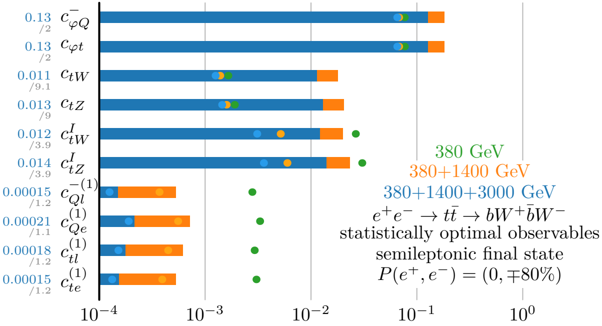
Progresses on global analyses

Necessity

- to preserve the systematic coverage of BSM scenarios

CLIC scenario (1, 2.5, and 5 ab^{-1}), 1σ, in TeV^{-2}, bars: global, blobs: individual





→ stat. opt. obs. are powerful and EXP amenable

→ two centre of mass are needed

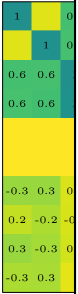
→ high-energy helps four-fermion operators

Progresses on global analyses

Necessity

CLIC

vidual

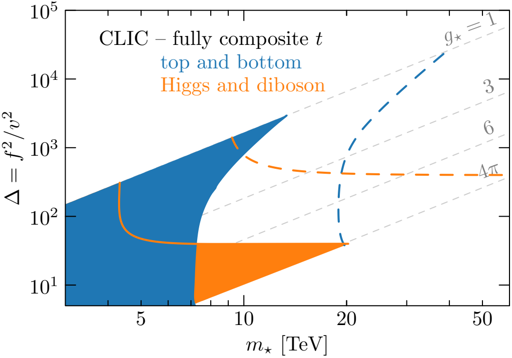


eV
W^-
servables
tate
0%)

... and four-fermion operators drive top limits on compositeness

5σ reach, filled: conservative, dashed: optimistic

[1807.10273]



→ Higgs probes fine tuning

→ top pushes higher mass scale

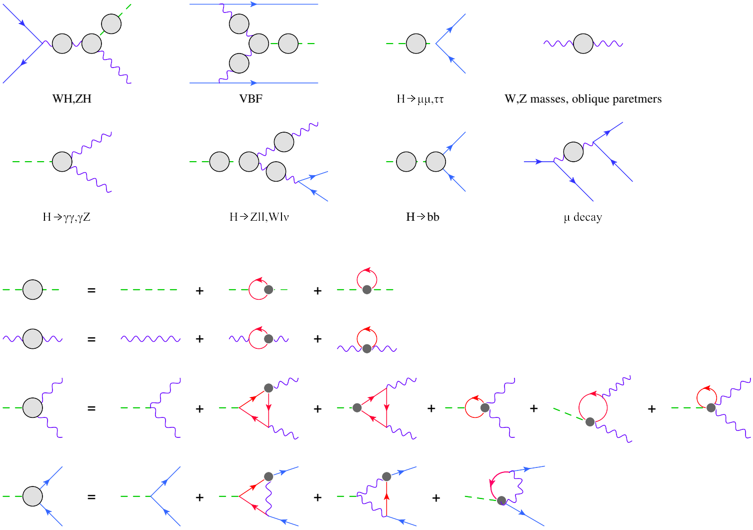
Progresses on global analyses

Top operators in Higgs and diboson processes

- comprehensive loop calculations in MadGraph [1804.09766]

Progresses on global analyses

fully differential reweighting for had. and lep. collisions



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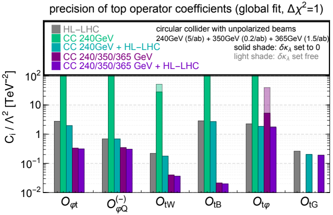
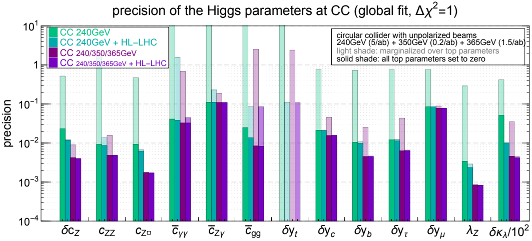
global analysis of Higgs, diboson and top at circular colliders





$\rightarrow$ imprecision on the top affects the Higgs (possibly a lot)

$\rightarrow$ high individual sensitivity to the top from Higgs measurements

$\rightarrow$ largely diluted in a global analysis, though more differential distr. could help

Progresses on global analyses

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Top FCNCs

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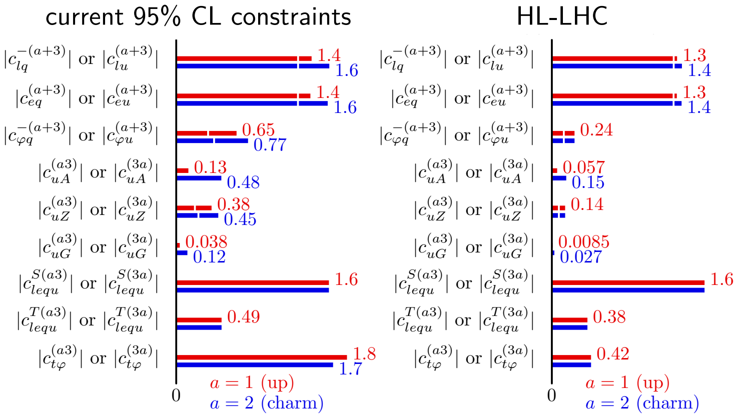
- update and HL-LHC prospects [HL-LHC Yellow Rep.]

Progresses on global analyses



– limited improvement on *eetq* (dominated by LEP2)

– factors of 2-4 on tqZ,γ,g,h

PRELIMINARY

Progresses on global analyses

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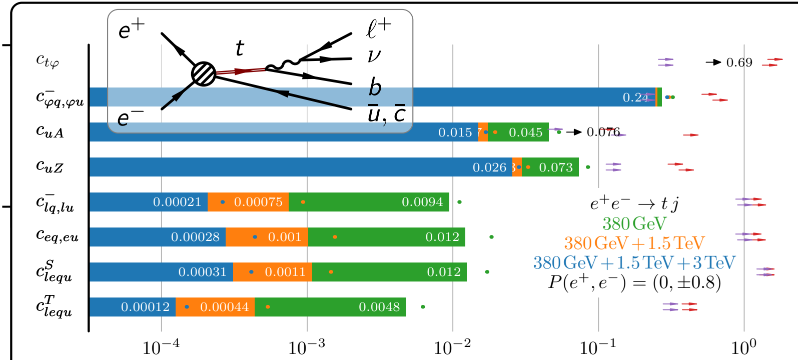

global 95% CL limits, in TeV^{-2}, CLIC scenario (0.5, 1.5, 3 ab^{-1})

arrows: **decay**, current, $\text{HL-LHC}^{\text{up}}_{\text{charm}}$

→ more sensitive than FCNC decay

→ available below $t\bar{t}$ threshold and benefits from high energies

PRELIMINARY

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Top operators in the B processes

- in FCNCs (not global) [0704.1482] [1105.0364] [1105.0364]
- ...

Summary

The top quark has been in the spotlight for 20^+ years.

Still, it retains shadows to be lit
by the (HL-)LHC and future colliders.

The standard-model EFT is our prime exploration framework.

Common standards by the LHC TOP WG set firmer grounds.

More global and detailed analyses now challenge
theorists and experimentalists.

Let's explore what's out there!