$t\bar{t}$ at future lepton colliders: an optimal EFT analysis

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Based on 1807.02121 with G. Durieux, M. Perello, M. Vos,
and (partially) on slides by G. Durieux at the CLICdp August meeting.

Outline

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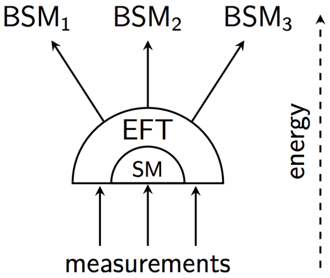
Standard Model Effective Field Theory

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]



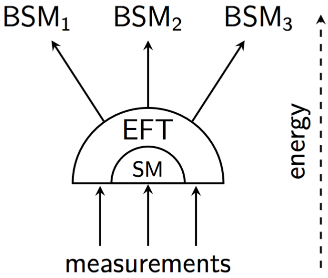
Standard Model Effective Field Theory

systematically parametrizes the theory space in direct vicinity of the SM

- based on SM fields and symmetries
- in a low energy limit

Identify New Physics through precise measurements

(...) 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]



LHC TOP WG EFT standards

Interpreting top-quark LHC measurements in the standard-model effective field theory

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Abstract

This note proposes common standards and prescriptions for the effective-field-theory interpretation of top-quark measurements at the LHC.

[J. Aguilar Saavedra et al.,'18]

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Statically Optimal Observables

[Atwood,Soni, '92] [Diehl,Nachtmann, '94]

minimize the one-sigma ellipsoid in EFT parameter space

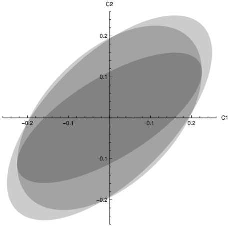
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

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 $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.

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

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



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

1. asymmetries: $O_i \sim \mathrm{sign}\{\sin(i\phi)\}$
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

Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:

[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

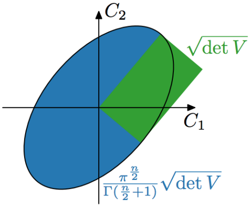
Global Determinant Parameter

[Durieux, Grojean, Gu, Wang, '17]

In a n-dimensional Gaussian fit, with covariance matrix V,

$$\text{GDP} \equiv \sqrt[2n]{\det V}$$

provides a geometric average of the constraints strengths.



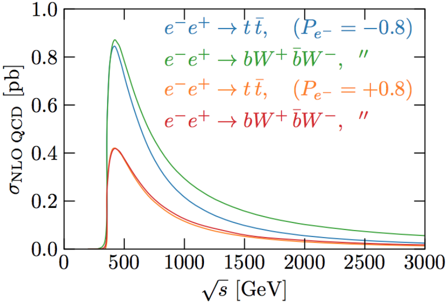
Interestingly, GDP ratios are operator-basis independent!

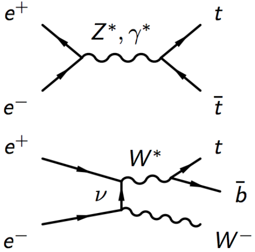
- as the volume scales linearly with coefficient normalization
- as the volume is invariant under rotations

$\Longrightarrow$ conveniently assess constraint strengthening.

Outline

$e^+e^- \to bW^+\bar{b}W^-$





$+\ W^+W^- \to t\,\bar{t}$
catching up at multi-TeV
w/ unitarity breaking effects
[Grojean, Wulzer, You, Zhang]

- σ peaked at about 380 GeV
- enhanced for a left-handed beam
- fall-off as $1/s$
- single-top contribution increasingly important

Operators in the top sector

Two-quark operators: $\mathcal{L}_{\text{EFT}} = \sum_i \frac{C_i}{\Lambda^2} O_i$

Scalar: $O_{u\varphi} \equiv \bar{q}u\,\tilde{\varphi}\quad \varphi^\dagger\varphi,$

Vector:
$$O^1_{\varphi q} \equiv \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \quad \equiv O^+_{\varphi q} + O^V_{\varphi q} - O^A_{\varphi q},$$
$$O^3_{\varphi q} \equiv \bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \quad \equiv O^+_{\varphi q} - O^V_{\varphi q} + O^A_{\varphi q} \qquad \text{(CC also)}$$
$$O_{\varphi u} \equiv \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \quad \equiv O^V_{\varphi q} + O^A_{\varphi q}$$
$$O_{\varphi ud} \equiv \bar{u}\gamma^\mu d \quad \tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu \varphi, \qquad \text{(CC only, } m_b \text{ int.)}$$

Tensor:
$$O_{uB} \equiv \bar{q}\sigma^{\mu\nu} u\,\tilde{\varphi}\, g_Y B_{\mu\nu}, \quad \equiv O_{uA} - \tan\theta_W O_{uZ}$$
$$O_{uW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I u\,\tilde{\varphi}\, g_W W^I_{\mu\nu}, \quad \equiv O_{uA} + \text{cotan}\,\theta_W O_{uZ} \qquad \text{(CC also)}$$
$$O_{dW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I d\,\tilde{\varphi}\, g_W W^I_{\mu\nu}, \qquad \text{(CC only, } m_b \text{ int.)}$$
$$O_{uG} \equiv \bar{q}\sigma^{\mu\nu} T^A u\,\tilde{\varphi}\, g_s G^A_{\mu\nu}. \qquad \text{(NLO only)}$$

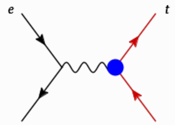
Two-quark–two-lepton operators:

Scalar:
$$O^S_{lequ} \equiv \bar{l}e\ \varepsilon\ \bar{q}u, \qquad \text{(CC also, } m_e \text{ int.)}$$
$$O_{ledq} \equiv \bar{l}e\ \ \bar{d}q, \qquad \text{(CC only, } m_e \text{ int.)}$$

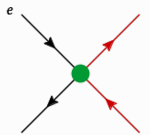
Vector:
$$O^1_{lq} \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q \quad \equiv O^+_{lq} + O^V_{lq} - O^A_{lq},$$
$$O^3_{lq} \equiv \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q \quad \equiv O^+_{lq} - O^V_{lq} + O^A_{lq}, \qquad \text{(CC also)}$$
$$O_{lu} \equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u \quad \equiv O^V_{lq} + O^A_{lq},$$
$$O_{eq} \equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q \quad \equiv O^V_{eq} - O^A_{eq},$$
$$O_{eu} \equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u \quad \equiv O^V_{eq} + O^A_{eq},$$

Tensor: $O^T_{lequ} \equiv \bar{l}\sigma_{\mu\nu} e\ \ \varepsilon\ \ \bar{q}\sigma^{\mu\nu} u.$ (CC also, m_e int.)

Two-fermion (vertex) Op



Four-fermion Op



(Axial-)Vector like $O^V_{\varphi q}$, $O^A_{\varphi q}$

- Sensitivity independent of energy.

Dipole (CP-even) $\mathrm{Re}O_{uA}$, $\mathrm{Re}O_{uZ}$

- $\sim E$ in amplitude, but suppressed by interference at tt level (cross section and A^{FB})
- $\sim E^2$ sensitivity can be obtained with OO

Dipole (CP-odd) $\mathrm{Im}O_{uA}$, $\mathrm{Im}O_{uZ}$

Left-handed *ee* O^V_{lq}, O^A_{lq}

Right-handed *ee* O^V_{eq}, O^A_{eq}

- E^2 dependence in general observables.
- Similar to the V-A vertex operators. Need at least two different CoM energies to distinguish.

Outline

Top-quark EFT

Optimal Observables

$t\bar{t}$ at Lepton Colliders

Prospects

Exploration

Conclusion

Scenarios

- FCC-ee
  - 200 fb^{-1} at 350 GeV;
  - 1.5 ab^{-1} at 365 GeV;
  - no polarization.
- ILC
  - 500 fb^{-1} at 500 GeV;
  - 1.0 ab^{-1} at 1 TeV (i.e. no luminosity upgrade);
  - (-0.3,+0.8) and (+0.3,-0.8), equally shared.
- CLIC
  - 500 fb^{-1} at 380 GeV;
  - 1.5 ab^{-1} at 1.4 TeV;
  - 3.0 ab^{-1} at 3.0 TeV;
  - (0,+0.8) and (0,-0.8), equally shared.

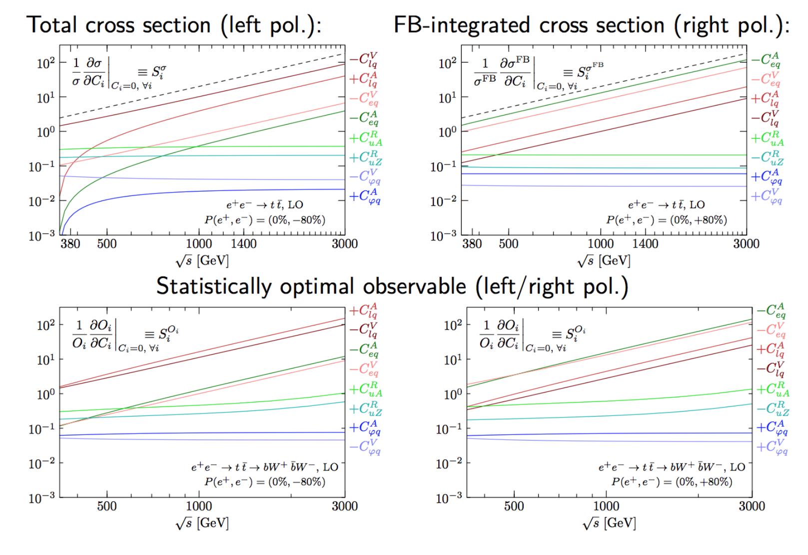
Uncertainties

$\sqrt{s}$ [GeV]	350	365	380	500	1000	1400	3000
acceptance times efficiency [%]	-	-	64-67[8]	$\sim$ 50	-	37-39	33-37
equivalent $t\bar{t}$ event fraction [%]	10	10	10	10	6	6	5

Table 5. Summary of the efficiencies obtained in Refs. [1, 21] (first row) and effective rate fractions available for analysis used in this study (second row). When multiplied by the $e^+e^- \to t\,\bar{t}$ cross section for the nominal centre-of-mass energy and the integrated luminosity, these yield the number of events available for analysis.

- Full-detector simulation performed by ILC and CLIC collaborations.
- Good reconstruction can be obtained with moderate quality cuts.
- Systematics expected to be controlled to the level of statistics.

Sensitivities



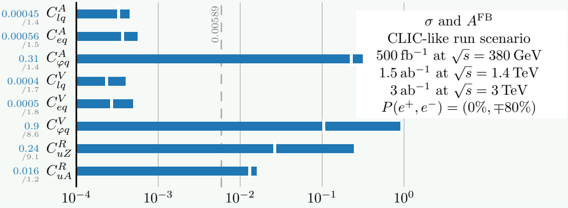
xsec+A^{FB} vs. Optimal Observable (CLIC)

Global (marginalized) sensitivities at CLIC:

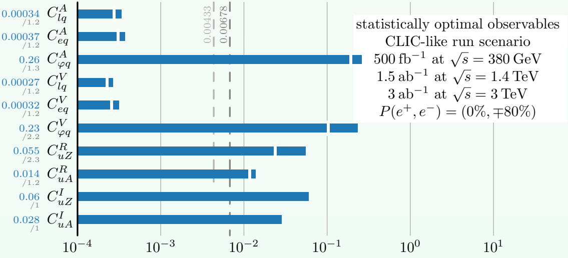
- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- dashed vertical lines: GDP
- gray numbers: global/individual ratios

GDP improvement: a factor of 1.6

$\sigma + A^{FB}$:

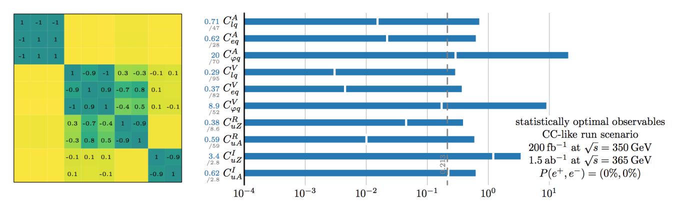


Statistically optimal observables:

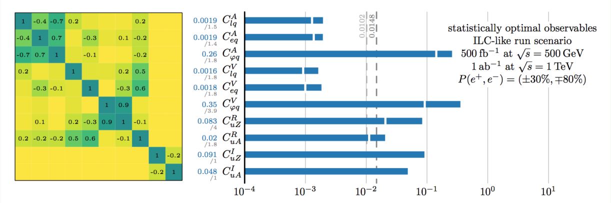


Prospects

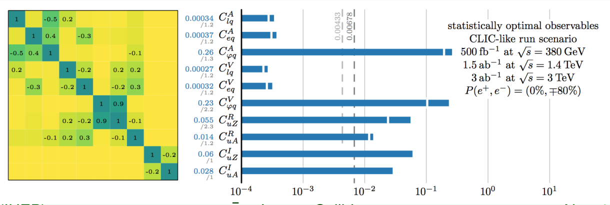
CC:



ILC:



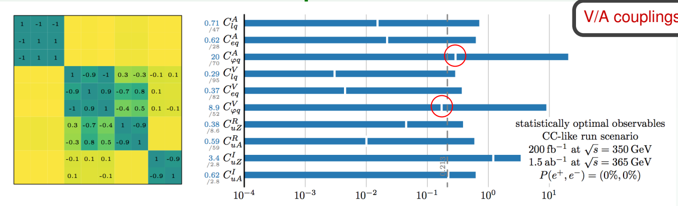
CLIC:



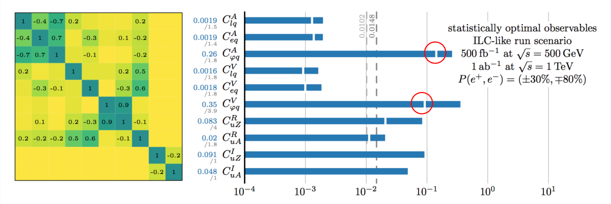
Prospects

V/A couplings

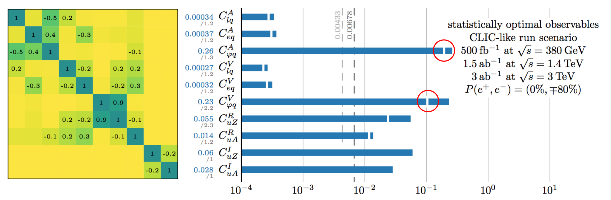
CC:



ILC:



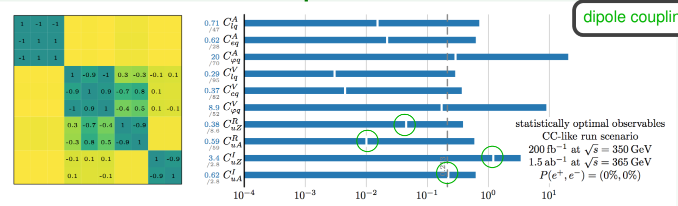
CLIC:



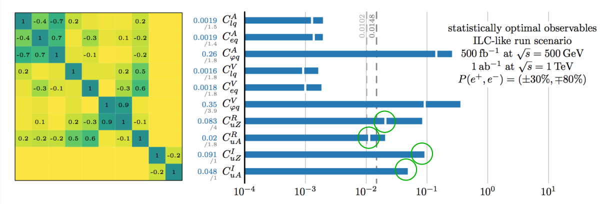
Prospects

dipole couplings

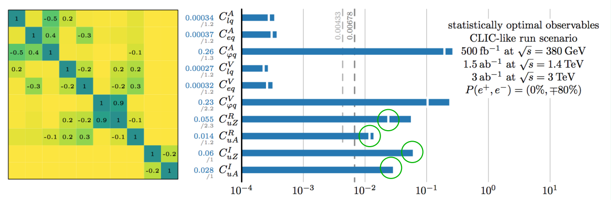
CC:



ILC:



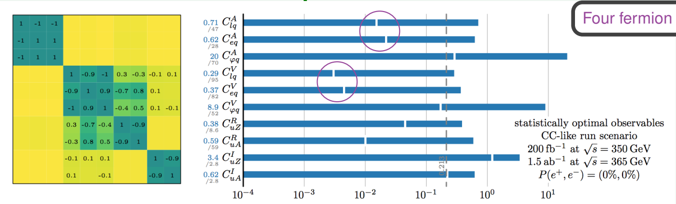
CLIC:



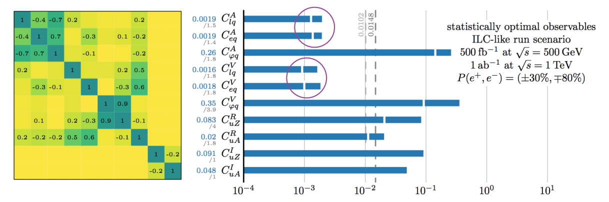
Prospects

Four fermion

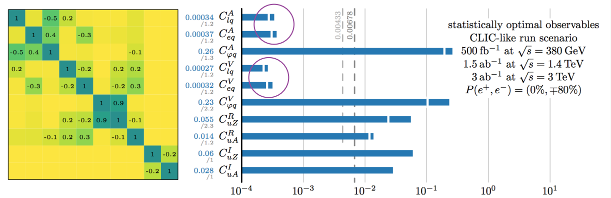
CC:



ILC:



CLIC:



Prospects

Higher energy runs are useful:

- Individual limits on 2-fermion (axial-)vector operators are not improved, but degeneracies with 4-fermion operators are resolved with energy lever arm.
  - At least a factor of three better than the most optimistic HL-LHC prospects.
- Dipole operators can be slightly better.
  - 2 orders of magnitude better than HL-LHC prospects.
- 4-fermion operators are significantly improved.
  - CC-like scenario would probes four-fermion operator couplings a factor of a few smaller, and a ILC- or CLIC-like scenarios two to four orders of magnitude smaller (comparing *qqtt* at LHC with *eett* at e^+e^-)
- Flat directions are reduced.

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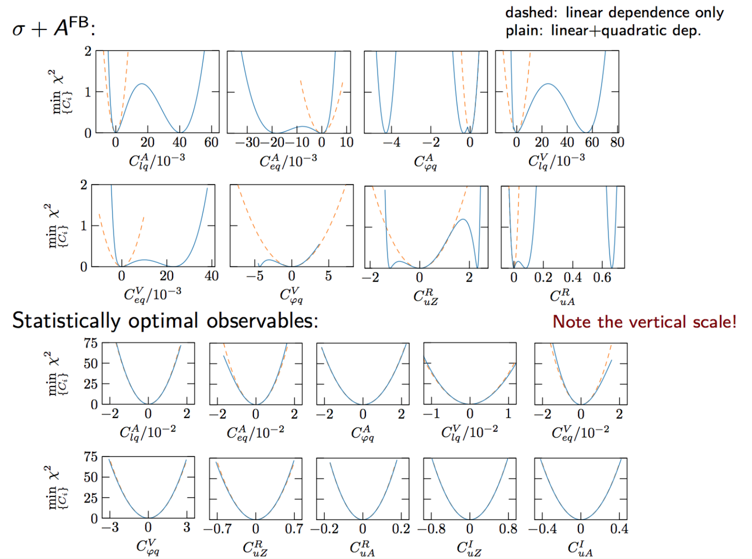
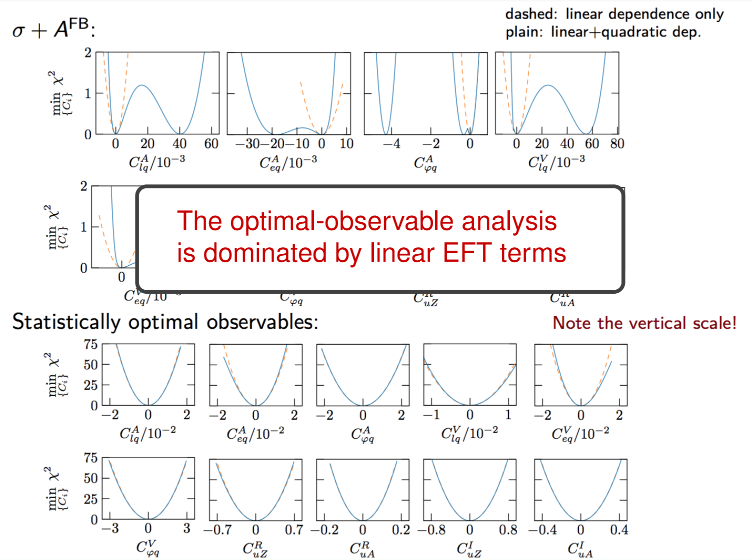
Quadratic vs. Linear (CLIC)



Quadratic vs. Linear (CLIC)



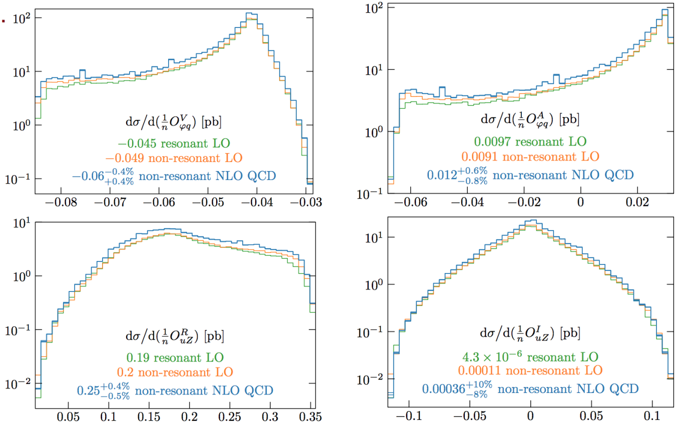
The optimal-observable analysis is dominated by linear EFT terms

TH robustness

Non-resonant and NLO QCD effects can be studied

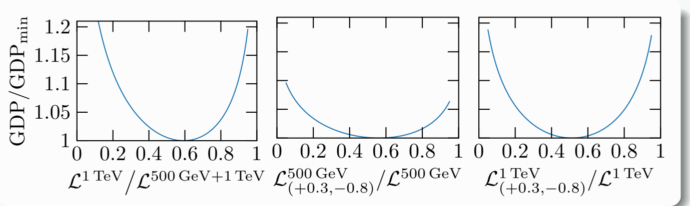
- mostly flat k factor (24% at $\sqrt{s} = 500$ GeV)
- couple-of-percent shape effects, excepted on axial operators ($O(10)\%$)

e.g.



$\sqrt{s} = 500$ GeV, $P(e^+, e^-) = (+30\%, -80\%)$,
quoted average values of distribution are $\bar{O}_i/\mathcal{L}$ in pb,
QCD scale variation from $m_t/2$ to $2m_t$

Optimization



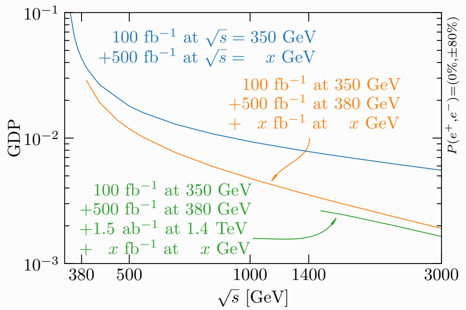
- ILC: the optimal repartition of 1.5 ab^{-1} in total is the following:

$\sqrt{s} = 500\,\text{GeV}$	610 fb^{-1}	57% with $P(e^+, e^-) = (+30\%, -80\%)$
$1\,\text{TeV}$	890 fb^{-1}	51% 〃

- It requires about 4.6 ab^{-1} shared between $\sqrt{s} = 380$ and $500\,\text{GeV}$ runs to achieve the same performance:

$\sqrt{s} = 380\,\text{GeV}$	1.5 ab^{-1}	57%	with $P(e^+, e^-) = (+30\%, -80\%)$
$500\,\text{GeV}$	3.1 ab^{-1}	51%	〃

Energy lever arm



- Runs at two separate centre-of-mass energies are indispensable to distinguish two- and four-fermion operators.
- Average constraint strength improves significantly with the separation between available centre-of-mass energies.
- Four-fermion operators are the mostly affected.

Outline

Conclusion

- Clean and global EFT analyses for $t\bar{t}$ are feasible at future lepton colliders, leading to direct constraints with limited model dependence.
- Statistically optimal observables are theoretically well-motivated and experimentally amenable.
- Lepton colliders would cover orders of magnitude of unexplored top-quark EFT parameter space. The individual limits on the coefficients of the operators modifying top-quark electroweak couplings are one to three orders of magnitude better than present constraints. Improvements by factors of three to two hundred are also expected compared to the most optimistic prospect for the individual reach of the HL-LHC.

Thank you

	existing		expected at high luminosity					expected at e^+e^-		
	TopFitter	Ref. [74]	Ref. [74]	$t\bar{t}V$ [14, 75]	$t\bar{t}V$ 10%	$t\bar{t}V$ 3%	tZj [76]	CC	ILC	CLIC
$C^1_{\varphi q}$	$[-12, 13]$			$[-1.3, 1.0]$	$[-2.0, 2.0]$	$[-0.6, 0.6]$	$[-17, 17]$	0.14	0.076	0.098
$C^3_{\varphi q}$	$[-5.3, 3.1]$			$[-1.0, 1.3]$	$[-2.0, 2.0]$	$[-0.6, 0.6]$	$[-2.8, 1.5]$	0.14	0.076	0.089
$C_{\varphi u}$	$[-20, 17]$			$[-1.3, 3.0]$	$[-3.4, 2.8]$	$[-0.8, 1.0]$	$[-26, 20]$	0.29	0.15	0.18
$C_{\varphi ud}$		$[-11, 14]$	$[-8.4, 11]$				$[-8.4, 8.4]$			
C_{uB}	$[-20, 14]$			$[-4.8, 4.8]$	$[-12, 12]$	$[-6.6, 4.0]$	$[-12, 11]$	0.022	0.022	0.024
C_{uW}	$[-2.0, 2.8]$	$[-2.7, 1.6]$	$[-1.3, 1.3]$	$[-1.4, 1.4]$	$[-3.6, 3.8]$	$[-2.2, 2.2]$	$[-1.3, 1.3]$	0.015	0.014	0.016
C_{dW}		$[-3.4, 3.6]$	$[-2.9, 3.1]$							

Table 6. Individual 95% C.L. limits on two-quark operator coefficients deriving from measurements at hadron colliders. The first two columns show the existing limits derived by the TopFitter group [59] and in Ref. [74]. The next four columns are expected limits with $3\,\text{ab}^{-1}$ of integrated luminosity at the LHC, derived from single top and top decay measurements [74], from differential distributions in $t\bar{t}V$ production [14, 75], and from the total $t\bar{t}V$ cross sections measured with 10% and 3% precision. The tZj columns show limits expected with $300\,\text{fb}^{-1}$ using a $p_T(t) > 250\,\text{GeV}$ selection cut. The last three columns are the individual limits obtained in this work for CC-, ILC- and CLIC-like run scenarios. As discussed in Sec. 6.4 individual constraints are similar in those three cases although global ones are less so.

Anomalous couplings

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

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

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

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 EFT standards

- Reduce the number of OPs to start with (avoid 500+ 4-fermion OPs):

  Baseline $U(2)_q \times U(2)_u \times U(2)_d$:
  Forces the first two generation to appear as $\bar{q}q$, $\bar{u}u$, $\bar{d}d$.

  Extended $U(2)_{q+d+u}$:
  Allows right-handed $\bar{u}d$ and light chirality flipping ones $\bar{q}u$, $\bar{q}d$.

  Restricted Top-philic:
  All operators with SM bosons and (just) top. (and reduced to Warsaw basis)

- Define the relevant degrees of freedom natural for top physics, and fix notations.

- Provide simulation tools and benchmarks: DIM6TOP

  https://feynrules.irmp.ucl.ac.be/wiki/dim6top

- Strategy: validity, linear vs. quadratic approximation, useful outputs, ...