Global probes for the top-quark EFT

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(DESY)

Global and optimal probes for the top-quark EFT at future lepton colliders
GD, Martín Perelló, Marcel Vos (Valencia), Cen Zhang (IHEP), [1807.02121],

Top-quark physics at the CLIC electron-positron linear collider
CLICdp, [1807.02441],

The top-quark window on compositeness at future lepton colliders
GD, Oleksii Matsedonskyi (DESY), [1807.10273],

Top-quark FCNC production,
in *The CLIC physics potential*, [to appear].

CLICdp collaboration meeting
CERN, 28 August 2018

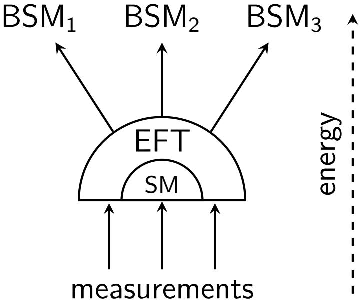
1. The top-quark EFT
2. Top-quark pair production
3. Composite Higgs interpretation
4. Top-quark FCNC production

The 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]



The standard model effective field theory

systematically parametrizes the theory space in direct vicinity of the SM

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Identify new physics through correlated deviations in precisely measured observables.

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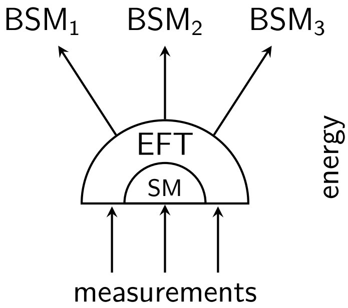

LHC TOP WG EFT standards

[1802.07237]

Make reasonable assumptions

- focus a priori on processes and operators involving top quarks
- determine which contributions are relevant
- prioritize the study of flavour structures

Fix notation

- define d.o.f. natural for top physics at the LHC
- fix notation, normalization, and indicative allowed ranges
- provide simulation tools as TH/EXP interface

Discuss analysis strategies (one example)

- address the challenges of a global EFT
- highlight useful experimental outputs

LHC TOP WG EFT standards

[1802.07237]

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Fix notation

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- pr… ols as TH/EXP interface

Quote your results in these standards
for comparison and combination with others!

Discuss analysis strategies (one example)

- address the challenges of a global EFT
- highlight useful experimental outputs

Statistically optimal observables
&
global determinant parameter

Statistically optimal observables

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

minimize the one-sigma ellipsoid in EFT parameter space

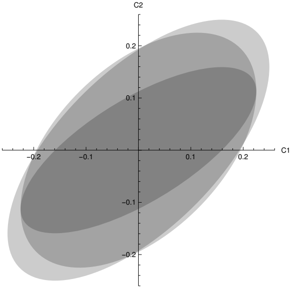
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

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

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



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

Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

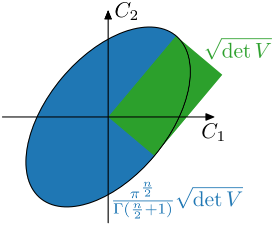
Global determinant parameter

[GD, 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.



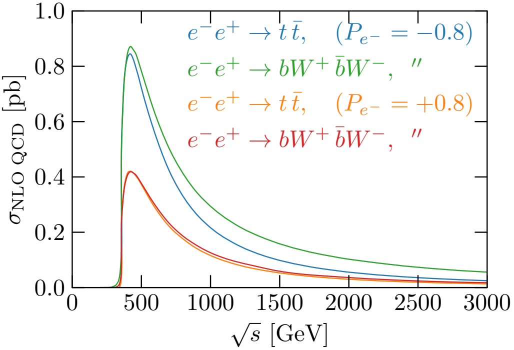
Interestingly, GDP ratios are operator-basis independent!

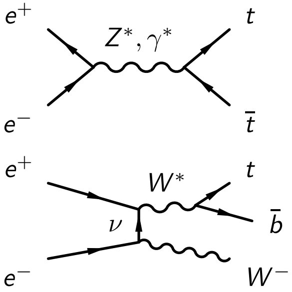
- as the volume scales linearly with coefficient normalization
- as the volume is invariant under rotations

$\Longrightarrow$ conveniently assess constraint strengthening.

2. Top-quark pair production

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





$+\ W^+W^- \to t\,\bar{t}$
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

Up-sector SMEFT

[Grzadkowski et al '10]

Two-quark operators:

$$\mathcal{L}_{\mathrm{EFT}} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

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

Vector:

$$O^1_{\varphi q} \equiv \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \qquad \equiv O^+_{\varphi q} + O^V_{\varphi q} - O^A_{\varphi q},$$

$$O^3_{\varphi q} \equiv \bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \qquad \equiv O^+_{\varphi q} - O^V_{\varphi q} + O^A_{\varphi q}$$ (CC also)

$$O_{\varphi u} \equiv \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \qquad \equiv O^V_{\varphi q} + O^A_{\varphi q}$$

$$O_{\varphi ud} \equiv \bar{u}\gamma^\mu d \quad \tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu \varphi,$$ (CC only, m_b int.)

Tensor:

$$O_{uB} \equiv \bar{q}\sigma^{\mu\nu} u \, \tilde{\varphi} \, g_Y B_{\mu\nu}, \qquad \equiv O_{uA} - \tan\theta_W O_{uZ}$$

$$O_{uW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I u \, \tilde{\varphi} \, g_W W^I_{\mu\nu}, \qquad \equiv O_{uA} + \mathrm{cotan}\,\theta_W O_{uZ}$$ (CC also)

$$O_{dW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I d \, \tilde{\varphi} \, g_W W^I_{\mu\nu},$$ (CC only, m_b int.)

$$O_{uG} \equiv \bar{q}\sigma^{\mu\nu} T^A u \, \tilde{\varphi} \, g_s G^A_{\mu\nu}.$$ (NLO only)

Two-quark–two-lepton operators:

Scalar:

$$O^S_{lequ} \equiv \bar{l} e \quad \varepsilon \quad \bar{q} u,$$ (CC also, m_e int.)

$$O_{ledq} \equiv \bar{l} e \quad \bar{d} q,$$ (CC only, m_e int.)

Vector:

$$O^1_{lq} \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q \qquad \equiv O^+_{lq} + O^V_{lq} - O^A_{lq},$$

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$$O_{lu} \equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u \qquad \equiv O^V_{lq} + O^A_{lq},$$

$$O_{eq} \equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q \qquad \equiv O^V_{eq} - O^A_{eq},$$

$$O_{eu} \equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u \qquad \equiv O^V_{eq} + O^A_{eq},$$

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

Up-sector SMEFT

[Grzadkowski et al '10]

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$O_{uW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I u \, \tilde{\varphi} \, g_W W$ ... (CC also)

$O_{dW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I$ ... (CC only, m_b int.)

$O_{uG} \equiv$ ... (NLO only)

8+2 CPV d.o.f.'s can be probed linearly in $e^+e^- \to t\bar{t} \to bW^+ \bar{b}W^-$ at LO and in the $m_b/m_t \to 0$ limit.

Two-qua...

Scal... (CC also, m_e int.)

... $d q,$ (CC only, m_e int.)

Vector ... $\equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q \quad \equiv O^+_{lq} + O^V_{lq} - O^A_{lq},$

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Anomalous vertices

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

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

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

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

CLIC prospects

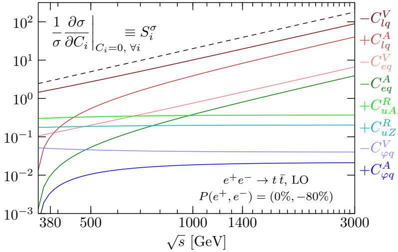
resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$, analytical LO observable def.
effective stat. efficiencies determined with full sim.
in semi-leptonic final state

$500\,\text{fb}^{-1}$ at $\sqrt{s} = 380\,\text{GeV}$
$1.5\,\text{ab}^{-1}$ at $\sqrt{s} = 1.4\,\text{TeV}$
$3\,\text{ab}^{-1}$ at $\sqrt{s} = 3\,\text{TeV}$

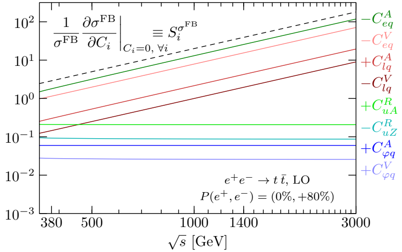
$P(e^+, e^-) = (0\%, \mp 80\%)$

Sensitivities

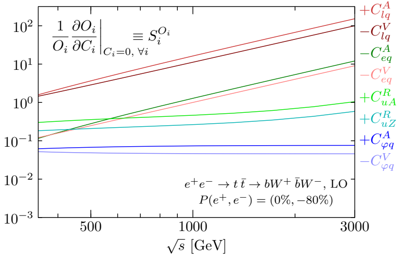
Total cross section (left pol.):

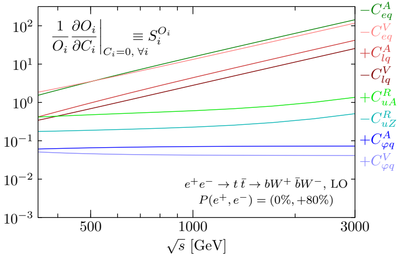


FB-integrated cross section (right pol.):



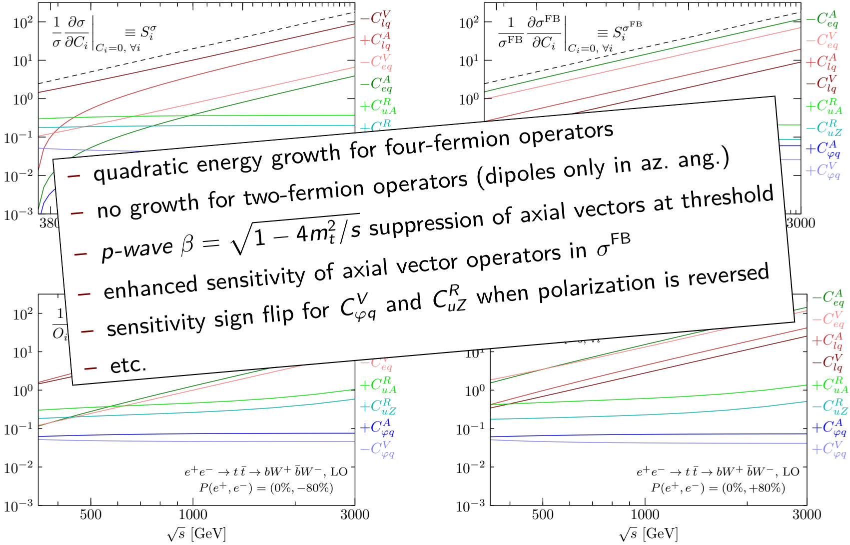
Statistically optimal observable (left/right pol.)





Sensitivities

Total cross section (left pol.): FB-integrated cross section (right pol.):

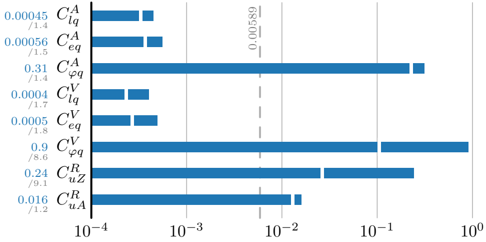


– quadratic energy growth for four-fermion operators
– no growth for two-fermion operators (dipoles only in az. ang.)
– *p*-wave $\beta = \sqrt{1 - 4m_t^2/s}$ suppression of axial vectors at threshold
– enhanced sensitivity of axial vector operators in σ^{FB}
– sensitivity sign flip for $C_{\varphi q}^V$ and C_{uZ}^R when polarization is reversed
– etc.

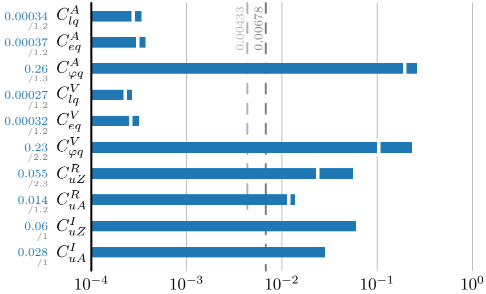
Global sensitivities

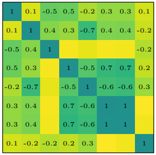
- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- dashed vertical lines: GDPs
- gray numbers: global/individual ratios

$\sigma + A^{\text{FB}}$:

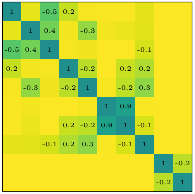


Statistically optimal observables:





correlation matrices



factor of 1.6 improvement of the 8-coefficient GDP

with linear coefficient dependence only

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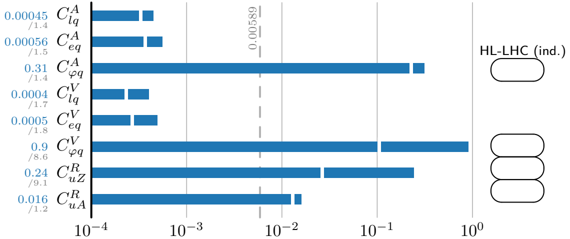

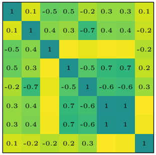

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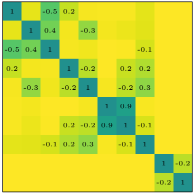
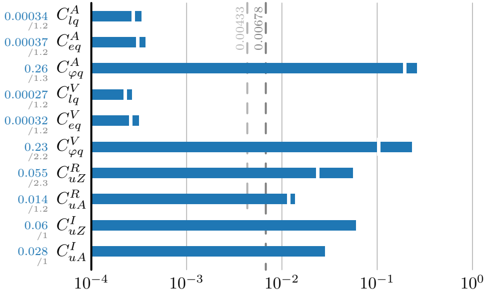


Statistically optimal observables:



$\mathcal{O}(10^{1-3})$ better than HL projections

with linear coefficient dependence only

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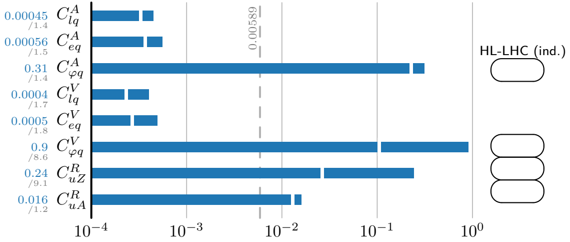
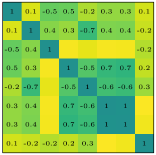
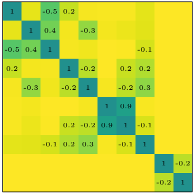




correlation matrices



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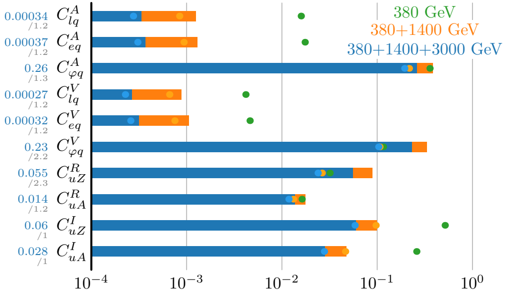

high energy benefits four-fermion op.

with linear coefficient dependence only

Global sensitivities

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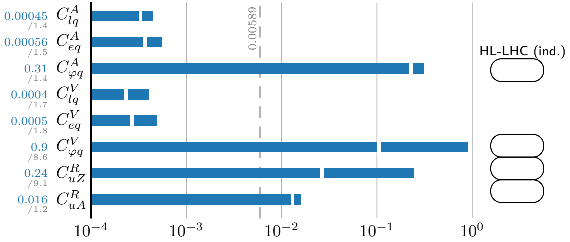

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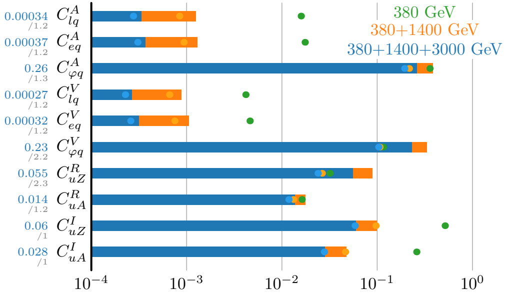

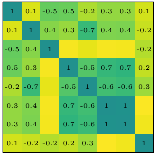

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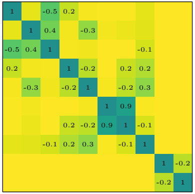

runs at two $\sqrt{s}$ are required

with linear coefficient dependence only

Global sensitivities

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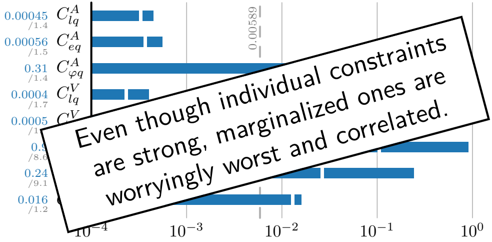
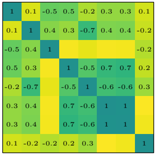


Even though individual constraints are strong, marginalized ones are worryingly worst and correlated.



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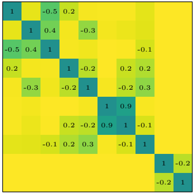

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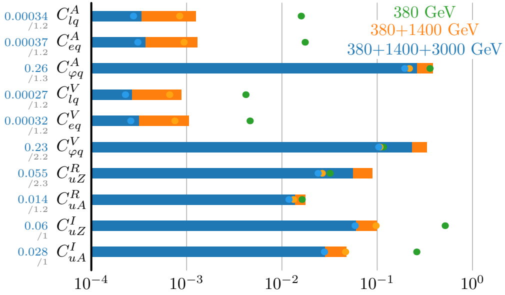


runs at two $\sqrt{s}$ are required

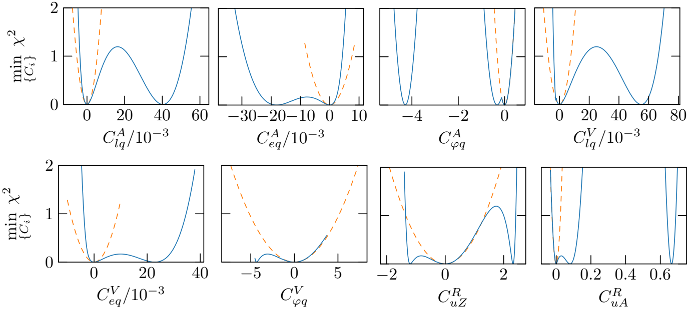
with linear coefficient dependence only

Robustness

Linear EFT truncation

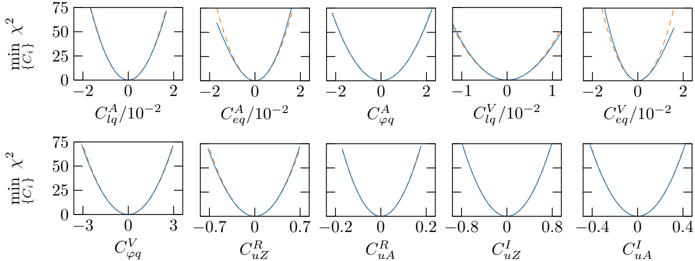
$\sigma + A^{\mathrm{FB}}$:

dashed: linear dependence only
plain: linear+quadratic dep.



Statistically optimal observables:

Note the vertical scale!



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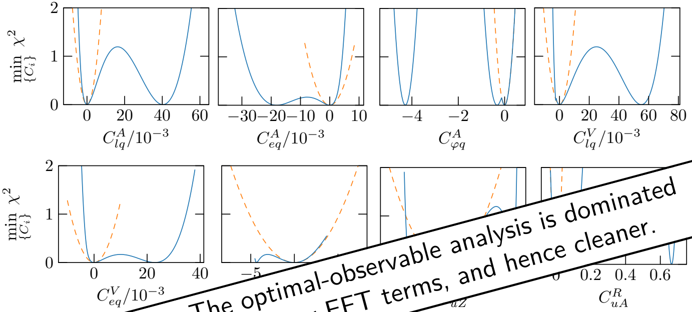
plain: linear+quadratic dep.

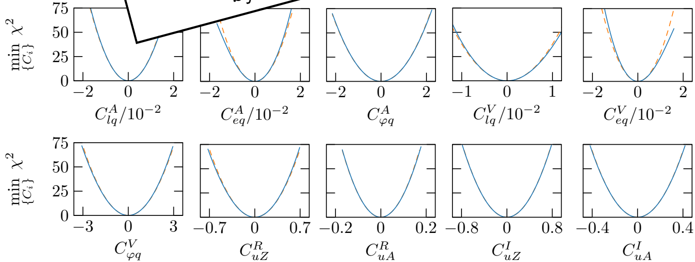
$\sigma + A^{\mathrm{FB}}$:



The optimal-observable analysis is dominated by linear EFT terms, and hence cleaner.

Statistically o

Note the vertical scale!



Experimental reconstruction

Full-detector simulation performed by CLICdp.

Good reconstruction can be obtained with moderate quality cuts.

Effective $t\bar{t}$ reco. efficiency in semileptonic channel ($\text{Br}^{e+\mu} \simeq 29\%$):

$\sqrt{s}$ [GeV]	380		1400		3000	
$P(e^-)$	−80%	+80%	−80%	+80%	−80%	+80%
ϵ	12.9% (σ) 4.7% (A_{FB}) 7.8% (OO)	12.1%	6%	5.8%	4.6%	4.7%

- bW mis-pairing with left-handed beam at low energy
- larger beam energy spectrum tails at high energies
- larger single-top bkg. at high energies

Systematics expected to be controlled to the level of statistics

Experimental reconstruction

[1807.02441]

Full-detector simulation performed by CLICdp.

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Effective $t\bar{t}$ reco. efficiency in semileptonic channel ($\text{Br}^{e+\mu} \simeq 29\%$):

$\sqrt{s}$ [GeV]	380		1400		3000	
$P(e^-)$	−80%	+80%	−80%	+80%	−80%	+80%
ϵ	10% (σ) 10% (A_{FB}) 10% (OO)	10%	6%	6%	5%	5%

- bW mis-pairing with left-handed beam at low energy
- larger beam energy spectrum tails at high energies
- larger single-top bkg. at high energies

Systematics expected to be controlled to the level of statistics

numbers used here, for simplicity

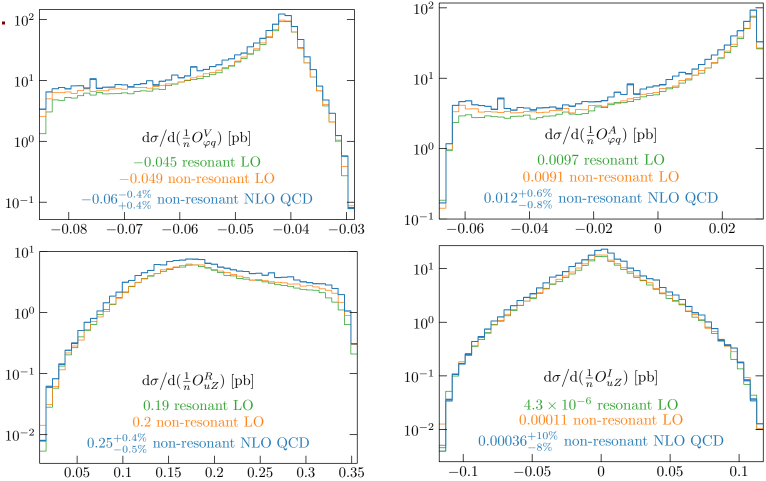
Theoretical prediction

[similar procedure in Gristan et al]

Non-resonant and NLO QCD effects can be studied

- mostly flat k factor (24% at $\sqrt{s} = 500\,\text{GeV}$)
- 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 $2m_t$

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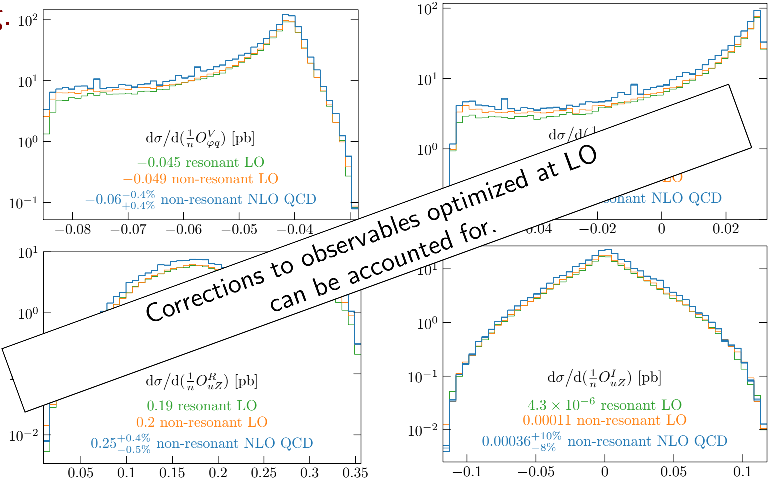


Corrections to observables optimized at LO can be accounted for.

$\sqrt{s} = 500$ 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 $2m_t$

Run parameter optimization

Warning: In specific models, certain EFT directions would have more weight.

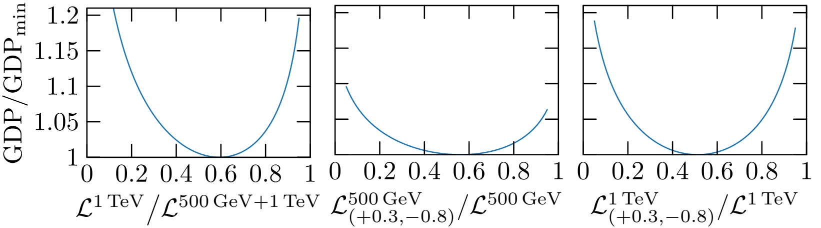
Sharing $1.5\,\text{ab}^{-1}$ between two energies and polarizations

Optimal repartition:

$\sqrt{s} = 500$ GeV	$570\,\text{fb}^{-1}$	61% with $P(e^+, e^-) = (+0.3, -0.8)$
1 TeV	$930\,\text{fb}^{-1}$	52%

$\longrightarrow$ GDP is 1.02 times better than the benchmark one

(for the OO analysis with all 10 coefficients)

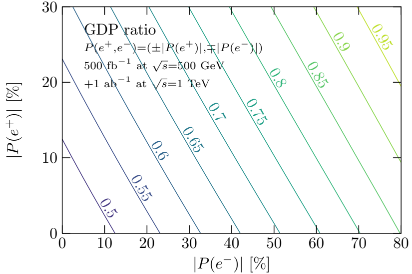


Same performances require $5.6\,\text{ab}^{-1}$ with only $\sqrt{s} = 380 + 500$GeV:

$\sqrt{s} = 380$ GeV	$1.7\,\text{ab}^{-1}$	59%	with $P(e^+, e^-) = (+0.3, -0.8)$.
500 GeV	$3.9\,\text{ab}^{-1}$	53%	

Degrading polarization or energy lever arm

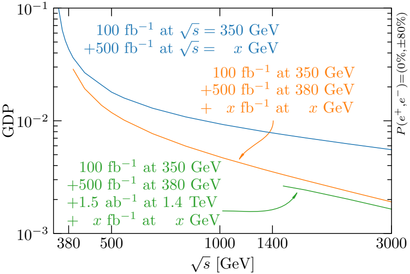
500 GeV + 1 TeV



10% polarization costs ∼ 5% of GDP

w.r.t. $P(e^+, e^-) = (\pm 30\%, \mp 80\%)$:

- $P(e^+)$ compensated by 140% lumi
- $P(e^+, e^-)$ 〃 by 460% lumi



$\sqrt{s}$ lever arm is necessary

3. Interpretation in composite Higgs models

Framework

- The Higgs is composite, pNGB of a new strong sector
- Typical strong sector coupling and mass: $g_\star$, $m_\star$
- Linear mixings between SM states and composite ones: ϵ_u, ϵ_q

$\rightarrow$ dimensional analysis for strong-sector operator coefficients

$$\frac{m_\star^4}{g_\star^2}\, O^{\text{dim-6}}\left(\epsilon_\psi \frac{g_\star}{m_\star^{3/2}}\psi, \frac{g}{m_\star^2}F^{\mu\nu}, \frac{g_\star}{m_\star}\phi\right)$$

up to order-one factors or justified suppressions

in particular $y_t \simeq \epsilon_u \epsilon_q g_\star$

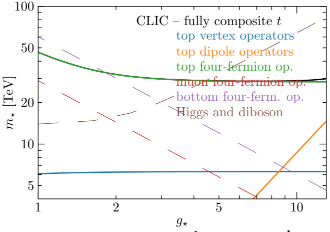
fix either $\epsilon_u = \epsilon_q \simeq \sqrt{\frac{y_t}{g_\star}}$: equally composite top left and right

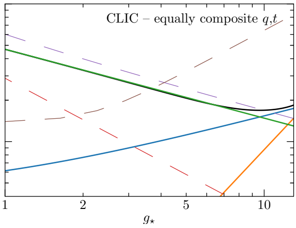
$\epsilon_u = 1,\ \epsilon_q \simeq \frac{y_t}{g_\star}$: fully composite top right

CLIC prospects

[Higgs fit from 1704.02333]

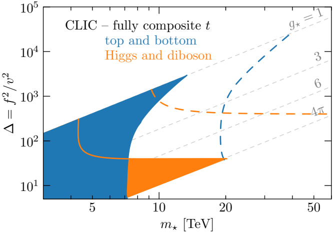
One-sigma sensitivities in (coupling,mass) plane

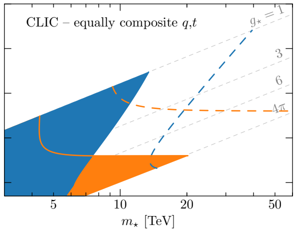




power counting exactly satisfied

Five-sigma discovery reach in (mass,tuning) plane





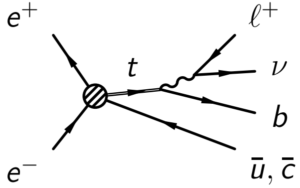
power counting satisfied up to $\pm[1/2, 2]$ $\rightarrow$ filled: pessimistic

$\rightarrow$ dashed: optimistic

4. Top-quark FCNC production

accessible from the lowest energies
still benefiting from the highest

$e^+e^- \to tj$ setup



- Use pseudo OO's (quadratic dependence!) on the semileptonic final state

[TESLA: hep-ph/0102197]
[FCC-ee: 1408.2090]

- Choose ϵ to match existing studies

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]	$P(e^+, e^-)$	Br$(t \to j\gamma)$ before fit	ϵ before fit	ϵ after fit	Br after fit
240	3000	(0, 0)	3.70×10^{-5}	0.30	0.30	3.7×10^{-5}
350	3000	(0, 0)	9.86×10^{-6}	0.19	0.14	1.1×10^{-5}
500	3000	(0, 0)	6.76×10^{-6}	0.057	0.072	6.0×10^{-6}
500	300	(0, 0)	2.2×10^{-5}	0.054	0.072	1.9×10^{-5}
800	500	(0, 0)	7.8×10^{-6}	0.037	0.029	8.7×10^{-6}

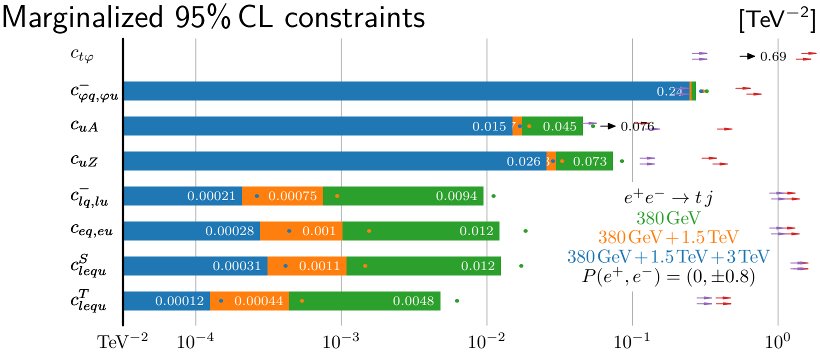
- Extrapolate to CLIC run parameters and go global
  - $\epsilon = \epsilon(\sqrt{s}) = (125\,\text{GeV}/\sqrt{s})^{1.92}$
  - include four-fermion operators

- Use LHC TOP WG standards

[1802.07237]

$e^+e^- \to tj$ prospects

PRELIMINARY



- compared to decay: black arrows
- compared to current limits: red arrows $^{\text{up}}_{\text{charm}}$
- compared to HL-LHC estimates: purple arrows $^{\text{up}}_{\text{charm}}$
- without beam polarization: blobs

[CLIC YR]

Global probes for the top-quark EFT

Clean global EFT analyses are feasible
at future lepton colliders.

Statistically optimal observables are
theoretically well-motivated and experimentally amenable.

CLIC would cover orders of magnitude of unexplored top-quark
EFT parameter space.

High-energy top pair production is particularly relevant to
composite Higgs models.

Single top FCNC production is a powerful probe
that should be further studied experimentally.