Future lepton colliders theory
indirect probes with global EFTs in the top and Higgs sectors

Gauthier Durieux
(DESY)

1704.02333, GD, C.Grojean, J.Gu, K.Wang

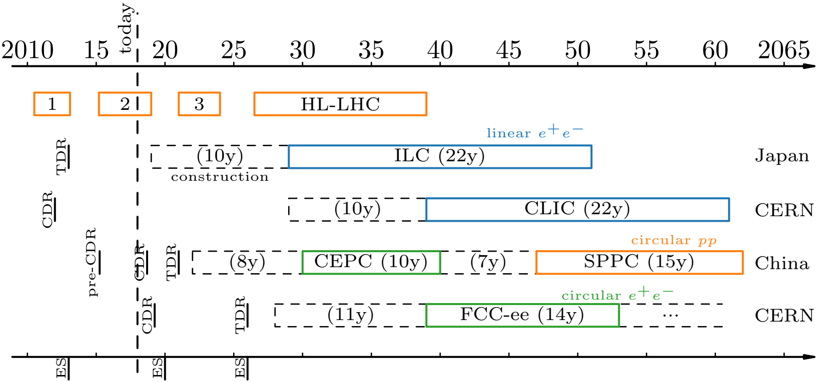
1711.03978, S.Di Vita, GD, C.Grojean, J.Gu, Z.Liu, G.Panico, M.Riembau, T.Vantalon

GD, M.Perelló, M.Vos, C.Zhang, to appear
(see proceedings 1708.09849)

GD, O.Matsedonskyi, to appear

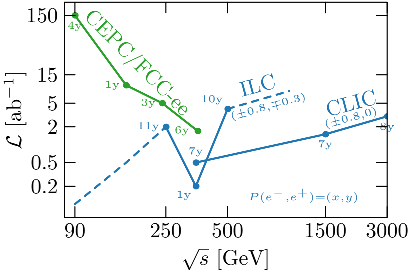
LHCP 2018
Bologna, 8 June

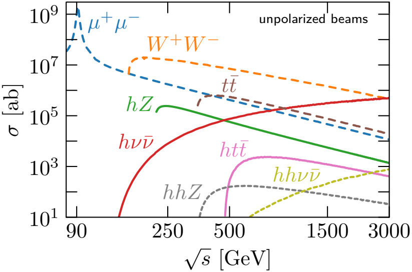
Hypothetical timeline



A new lepton collider could run by 2030 in Asia, by 2040 at CERN.

Physics





- systematics-limited Z-pole meas. (up to 10^{12} Z's vs. 10^7 at LEP)
- up to 10^8 W pairs (mass, triple gauge coup., EW param.)
- millions of clean h's (up to permil coupling meas.)
- millions of tops (clean mass meas., EW couplings)
- thousands of tth
- hundreds of Higgs pairs

→ precision measurements

→ indirect probes of heavy NP

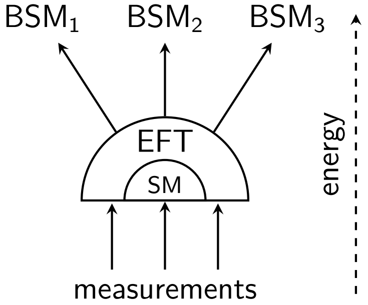
→ weakly coupled NP

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

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

Identify new physics through correlated deviations
in precisely measured observables.

(...) ... *most general*
possi... *including* all *terms*
consis... *assumed symmetry*
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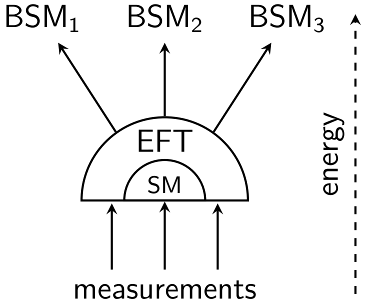
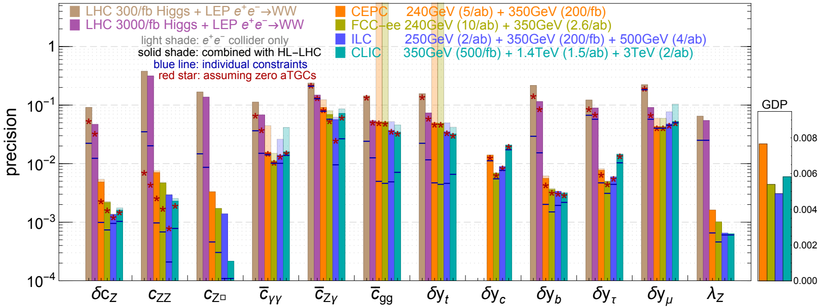


Global Higgs analysis

[1704.02333]

- Higgs-related processes
  $e^+e^- \to hZ,\ W^+W^-$ (incl. distr.), $h\nu\bar{\nu},\ ht\bar{t},$
  $h \to ZZ^*,\ WW^*,\ \gamma\gamma,\ \gamma Z,\ gg,\ b\bar{b},\ c\bar{c},\ \tau^+\tau^-,\ \mu^+\mu^-$
- 13 parameters in the Higgs basis of dim-6 operators [LHCHXSWG-INT-2015-001]
- one-sigma sensitivities:



$\rightarrow$ order of magnitude improvement wrt LHC + y_c measurement

$\rightarrow$ LHC helps for $\bar{c}_{\gamma\gamma}$, δy_μ, and δy_t (below 500 GeV!)

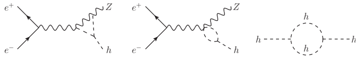
$\rightarrow$ importance of complementary measurements (energies, pol., distr.)

Higgs self-coupling at low energies

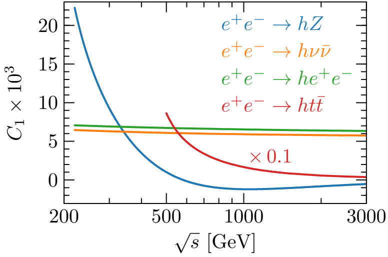
[1711.03978]

- NLO sensitivity (finite and gauge-invariant subset)
- dominated by $e^+e^- \to hZ$ threshold

[McCullough '13]

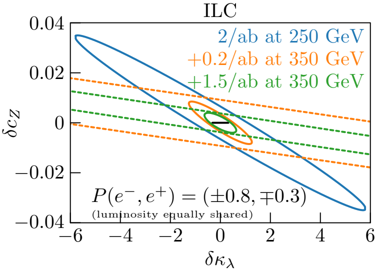


$$\Sigma_{\text{NLO}}/\Sigma_{\text{NLO}}^{\text{SM}} - 1 \simeq (C_1 - 0.0031)\,\delta\kappa_\lambda + \dots$$

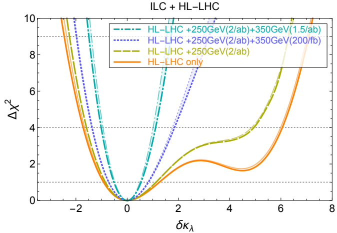


$\to$ few permil hZ measurement naively implies a few 10% constraint

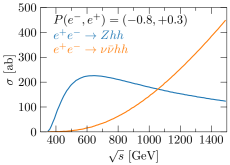
- Marginalizing over 12 other params, 350 GeV run necessary without LHC



- second LHC minimum already resolved by a 250 GeV run



Higgs self-coupling at high energies

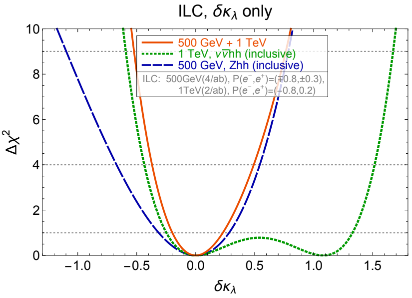


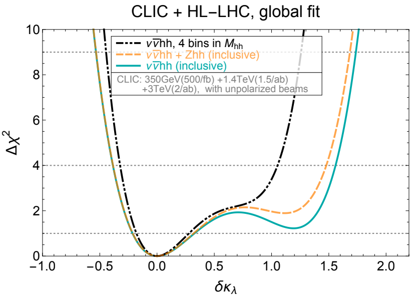
ILC

- perfect complementarity between 500 GeV and 1 TeV runs
- both individual and global $\Delta\chi^2$=1 limits $\sim$ 20%

CLIC

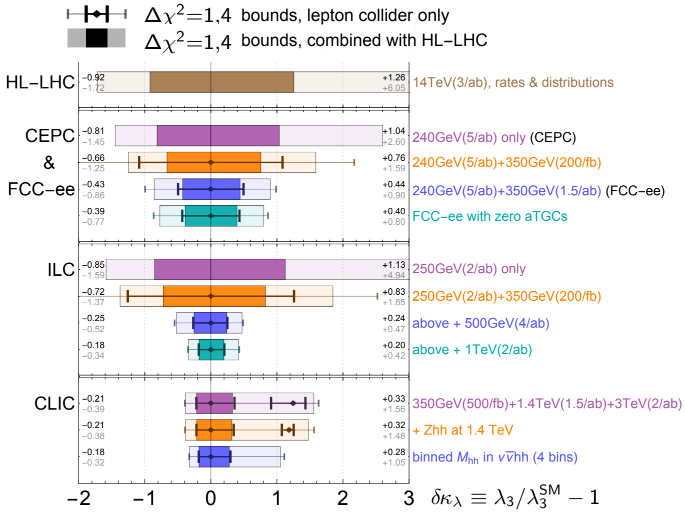
- missing $e^+e^- \to Zhh$ to constrain positive $\delta\kappa_\lambda$
- exploiting m_{hh} instead [Contino et al]
- both individual and global $\Delta\chi^2$=1 limits $\sim -20, +30\%$





Higgs self coupling summary

[1711.03978]



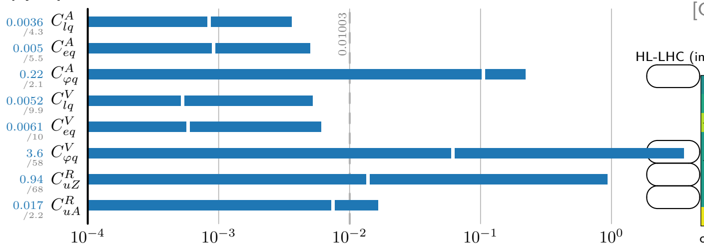
- robust indirect constraints at low energy require a global analysis
  - $\rightarrow \sim 75\%$ precision with $0.2\,\text{ab}^{-1}$ at 350 GeV, $\sim 40\%$ with $1.5\,\text{ab}^{-1}$
- single-Higgs measurements could affect direct high-energy determinations
  - $\rightarrow \sim 20\%$ precision with 500 GeV + 1 TeV runs

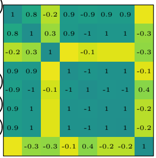
Global top-quark constraints

- linearised EFT
- one-sigma sensitivities, in TeV^{-2}
- white marks: individual constraints

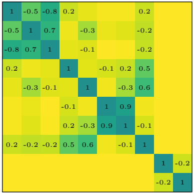
[GD,Perello,Vos,Zhang]

$\sigma + A^{FB}$:

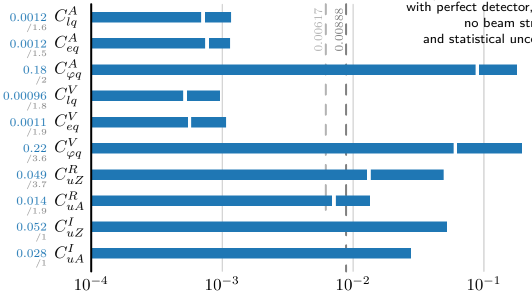




correlation matrices



Statistically optimal observables:



resonant $e^+e^- \to t\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$, analytically at LO
with perfect detector, $\text{Br} \times \epsilon = 20\%$,
no beam structure
and statistical uncertainties only

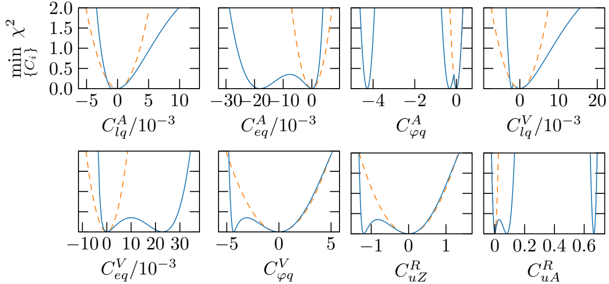
ILC-like scenario

500 fb^{-1} at 500 GeV
1 ab^{-1} at 1 TeV
$P(e^+e^-) = (\mp 0.3, \pm 0.8)$

Linear EFT robustness

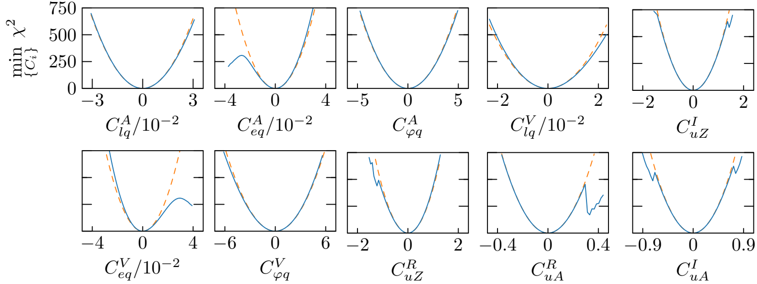
$\sigma + A^{\mathrm{FB}}$:

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



Statistically optimal observables:

Note the vertical scale!



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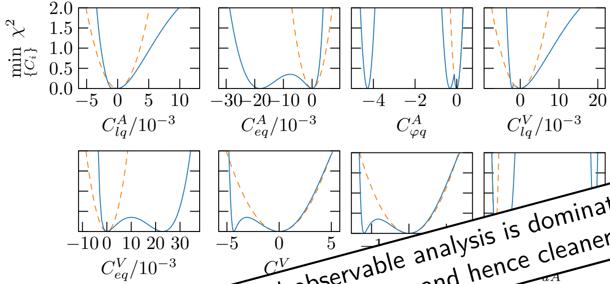
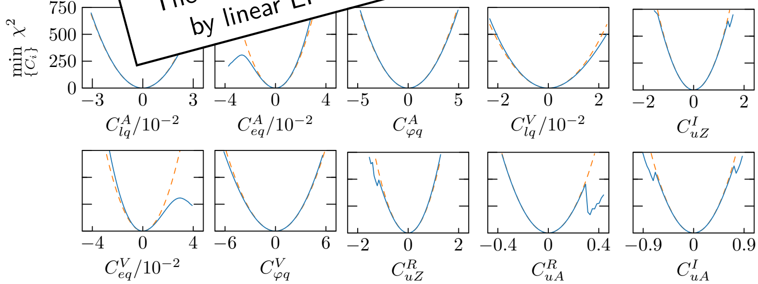


Statistically optim

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

Note the vertical scale!

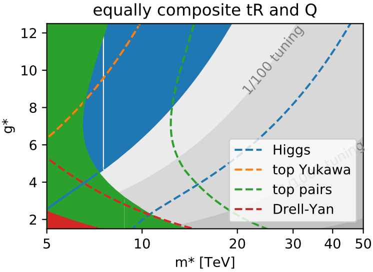


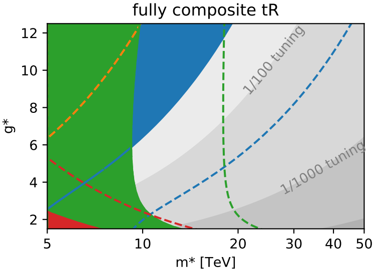
Interpretation in composite Higgs models

[GD,Matsedonskyi]

The Higgs is a *pion* of a new strongly coupled sector, naturally lighter than other resonances.

- typical composite coupling and mass: $g_\star$, $m_\star$
- top mixings with composite resonances: ϵ_t, ϵ_Q $\quad (y_t \simeq \epsilon_t \epsilon_Q g_\star)$
  - ⋆ equally composite t_R & Q $\quad (\epsilon_t = \epsilon_Q \simeq \sqrt{\frac{y_t}{g_\star}})$
  - ⋆ fully composite t_R $\quad (\epsilon_t = 1,\, \epsilon_Q \simeq \frac{y_t}{g_\star})$





five-sigma discovery reach
filled: pessimistic
dashed: optimistic

CLIC-like scenario

500 fb^{-1} at 380 GeV
1.5 ab^{-1} at 1.4 TeV
3 ab^{-1} at 3 TeV
$P(e^+e^-) = (0, \pm 0.8)$

Future lepton colliders theory

Future lepton collider are ideal machines for

- precision measurements,
- indirect probes of heavy NP,
- direct probes of weakly coupled NP.

Global EFT analyses can spot correlated deviations in precisely measured observables

Global constraints on Higgs and top operator coefficients would be improved by an order of magnitude.

Discovery reach would extend to NP scales of order 10 TeV.

Backup

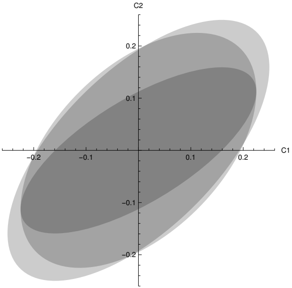
Statistically optimal observables

[Atwood,Soni '92]
[Davier et al '93]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space

(*joint efficient* set of estimators,
saturating the Rao-Cramér-Fréchet bound: $V^{-1} = I$,
just 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 $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



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]

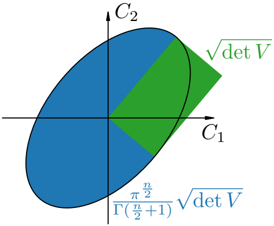
Global determinant parameter

[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.

Up-sector SMEFT

[Grzadkowski et al '10]

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:

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

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

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

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

Tensor:

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

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

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

$O^3_{lq} \equiv \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q \equiv O^+_{lq} - O^V_{lq} + O^A_{lq},$ (CC also)

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

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

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

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.)