Challenges in Global Interpretation of Data from Future e⁺e⁻ Colliders and Interplay with HL-LHC

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Introduction

- **Particle Physics at the end of the HL-LHC?** The discovery of the 125 GeV Higgs boson may be the “only” discovery of the LHC
  - So we have all the ingredients required to confirm the validity of the SM at low energies…
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✓ So we have all the ingredients required to confirm the validity of the SM at low energies…

✓ …but the Higgs also reminds us of the limitations of the Standard Model…
  - How do we understand the mechanism of EWSB?
  - Hierarchy problem: Why $M_h \ll M_P$?
Introduction

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✓ …but the Higgs also reminds us of the limitations of the Standard Model…
  - How do we understand the mechanism of EWSB?
  - Hierarchy problem: Why $M_h \ll M_P$?

⇒ **BSM:** $\Delta M_h^2 = $ SM + New Physics $\sim 0$
Introduction

- **Going beyond:** Until now, we had the Standard Mode (e.g. via EWPT) to guide our searches for the Top and Higgs ...

... W, Z bosons \rightarrow Top quark \rightarrow Higgs boson \rightarrow ?

... from here on, however, we are exploring the unknown with the only guidance of our (apparently unsuccessful) model-building experience

We know that this:

$$\Delta M_h^2 = \text{SM} + \text{New} \sim 0$$

would naturally come with sizeable modifications of the Higgs couplings

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m^2_h} \equiv \epsilon_T \equiv \text{fine tuning} \quad \left( \frac{\delta g_h}{g_h} \bigg|_{LHC} \sim O(10 - 20)\% \right)$$

⇒ Precision Higgs physics is a key tool to learn from BSM indirectly

⇒ Future e+e- Higgs factories
Introduction

- Future $e^+e^-$ Higgs factories:

  ![Lepton Colliders Diagram]

  - Different approaches for an EW/Higgs/Top factory, e.g.
    - LC: Polarization can help disentangling NP effects & control systematics
    - CC: High luminosity (plus several IP). Z-pole run → Tera Z
    - High-E runs → Access to $t\bar{t}$ (LC & CC), $ttH$ and $HH$ (LC) thresholds

- In this talk I will focus mostly on the Higgs factory option

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**Linear $e^+e^-$ Colliders**

- $\sqrt{s}$ [GeV]: 250 (350/500/1000?)
- $(P_{e^-}, P_{e^+})$: $\pm 80%$/$\pm 30%$
- $L[ab^{-1}]$: 2 (0.2/4/8?)

**Circular $e^+e^-$ Colliders**

- $\sqrt{s}$ [GeV]: 91/161/240
- $(P_{e^-}, P_{e^+})$: -
- $L[ab^{-1}]$: 16/2.6/5.6

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Kick-off meeting of ECFA workshops on $e^+e^-$ Higgs/EW/Top factory
June 18, 2021
Introduction

- Future $e^+e^-$ Higgs factories:

Lepton Colliders

LEP/SLC → ?

Linear $e^+e^-$ Colliders

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<tr>
<td>$(P_{e-}, P_{e+})$</td>
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<td>±80%/0%</td>
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<td>1/2.5/5</td>
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Circular $e^+e^-$ Colliders

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<td>150/10/5/1.5</td>
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- Different approaches for an EW/Higgs/Top factory, e.g.
  - LC: Polarization can help disentangling NP effects & control systematics
  - CC: High luminosity (plus several IP). Z-pole run → Tera Z
  - High-E runs → Access to $t\bar{t}$ (LC & CC), $ttH$ and $HH$ (LC) thresholds

How do we frame/guide BSM searches using the measurements that will be possible in these facilities?

⇒ We need a general (B)SM interpretation “framework”

- In this talk I will focus mostly on the Higgs factory option
Interpretation Framework
Effective Field Theories
Effective Field Theories

• We are interested in exploring BSM deformations of Higgs properties without being “attached” to any particular model (no reason to do so)

• What is reasonable to assume?
  ✓ QFT
  ✓ At low-energies the particle content seem to match the SM one
    ‣ No new particles with masses $\sim v_{EW}$ showing up in direct searches
      (Though this possibility cannot be completely excluded and much lighter particles also possible)
  ✓ Similarly, SM gauge invariance seems to work well…
    (With respect to current precision… )

• This is actually enough to build a robust theory framework to interpret experimental indirect tests of new physics

⇒ Effective Field Theories

We don't need to know this to describe the physics here
Effective Field Theories

- EFT provide a phenomenological tool to parameterise BSM deformations in a model-independent way (consistent with some general assumptions)

- Two EFTs consistent with the SM particles and symmetries at low energies, differing in the treatment of the scalar sector:
  - ✓ The non-linear/Higgs EFT (HEFT): EW symmetry non-linearly realised
  - ✓ The (dimension-6) SMEFT: EW symmetry linearly realised

  \[ \text{SM} \subset \text{SMEFT} \subset \text{HEFT} \]

- In short:
  - ✓ **HEFT**: when there are light BSM states (compared to EW scale) or BSM sources of symmetry breaking
  - ✓ **SMEFT**: when heavy new states (compared to EW scale)

for a geometrical interpretation of the differences between HEFT and SMEFT
Effective Field Theories

- EFT as a phenomenological tool for indirect BSM searches

![Diagram showing the relationship between High Energy UV theory/BSM and Low Energy SM ⊂ EFT through Matching and Phenomenology Constraints]

- Limits on NP?
- Correlations

LaTeX materials for the talks at the ECFA kick-off meeting, June 18, 2021
Effective Field Theories

- EFT as a phenomenological tool for indirect BSM searches

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**Diagram:**
- **High Energy**
  - UV theory/BSM
  - Matching
  - RGE

- **Low Energy**
  - SM ⊂ EFT

- **Top-Down**
  - Higgs
  - EW
  - Flavor
  - ... 
  - \( \mathcal{L}_{EFT} \)

**Phenomenology Constraints**

- Signal of NP?
- Limits on NP?
- Correlations
**Effective Field Theories**

- EFT as a phenomenological tool for indirect BSM searches

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High Energy

UV theory/BSM

Matching \( \Lambda \)

RGE

Low Energy

SM \( \subset \) EFT

---

What can we learn about BSM?

\( \Rightarrow \) Inverse problem

(See M. Peskin’s talk)

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Bottom-up

Assumptions

SMEFT/HEFT

Dim 6, 8, ...

Flavor Struct.

LO, NLO

... 

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Phenomenology Constraints

- Top
- EW
- Higgs
- Flavor
- ...

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\( \mathcal{L}_{\text{EFT}} \)

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Signal of NP?

Limits on NP?

Correlations

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June 18, 2021
**Effective Field Theories: SMEFT**

- **SMEFT**: SM particles and symmetries at low energies, with the Higgs scalar in an SU(2)\(_L\) doublet + mass gap with new physics (entering at scale \(\Lambda\))

\[
\mathcal{L}_{UV}(?) \rightarrow \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots
\]

\[
\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad \quad [\mathcal{O}_i] = d \rightarrow \left( \frac{q}{\Lambda} \right)^{d-4}
\]

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

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<table>
<thead>
<tr>
<th>Operator</th>
<th>Notation</th>
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<tr>
<td>((\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L))</td>
<td>(O_i^{(1)})</td>
<td>((\bar{Q}<em>L \gamma^\mu T</em>{AQL})(\bar{Q}<em>L \gamma^\mu T</em>{AQL}))</td>
<td>(O_i^{(8)})</td>
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<tr>
<td>((\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L))</td>
<td>(O_{iQ})</td>
<td>((\bar{Q}<em>L \gamma^\mu D</em>{AQL})(\bar{Q}<em>L \gamma^\mu D</em>{AQL}))</td>
<td>(O_{iD})</td>
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<td>((\bar{Q}<em>L \gamma^\mu T</em>{AUR})(\bar{Q}<em>L \gamma^\mu T</em>{AUR}))</td>
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<td>\phi^+\phi\rangle)</td>
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<td>((\phi^+D_{\mu}\phi)(\bar{L}_L \gamma^\mu L_L))</td>
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**Warsaw basis operators (Neglecting flavour)**

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**Effective Field Theories: SMEFT**

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- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

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### Only a relatively small subset is relevant for a (low-\(E\)) \(e^+e^-\) Higgs factory at LO

\(~O(20-30)\) operators depending on flavour assumptions
**Effective Field Theories: SMEFT**

- **SMEFT** in the mass eigenstate basis (unitary gauge). LO EW/Higgs interactions:

\[
\Delta \mathcal{L}_{6}^{hVV} = \frac{h}{v} \left[ 2 \delta c_{w} m_{W}^{2} + W_{\mu}^{+} W_{\mu}^{-} + \delta c_{z} m_{Z}^{2} Z_{\mu} Z_{\mu} + c_{w} g^{2} (W_{-}^{\mu} W_{\mu}^{+ \nu} + \text{h.c.}) + c_{\gamma} g^{2} Z_{\mu} Z_{\nu} + c_{\gamma} g' Z_{\mu} \partial_{\mu} A_{\mu} \right] \\
+ \frac{g^{2}}{2} W_{\mu}^{+} W_{\mu}^{-} + c_{g_{w}} \frac{g^{2}}{4} C_{\mu} C_{\mu} + c_{\gamma} \frac{g^{2}}{4} A_{\mu} A_{\mu} + c_{\gamma} \frac{g^{2} + g'^{2}}{2} Z_{\mu} A_{\mu} + c_{\gamma} \frac{g^{2} + g'^{2}}{4} Z_{\mu} Z_{\mu} \\
\delta c_{w} = \delta c_{z} + 4 \delta m, \\
c_{w} = c_{w} + 2 \sin^{2} \theta_{w} c_{\gamma} + \sin^{4} \theta_{w} c_{\gamma}, \\
c_{w} = \frac{1}{g^{2} - g'^{2}} \left[ g^{2} c_{\gamma} + g'^{2} c_{\gamma} - e^{2} \sin^{2} \theta_{w} c_{\gamma} - (g^{2} - g'^{2}) \sin^{2} \theta_{w} c_{\gamma} \right] \\
c_{\gamma} = \frac{1}{g^{2} - g'^{2}} \left[ 2 g^{2} c_{\gamma} + (g^{2} + g'^{2}) c_{\gamma} - e^{2} c_{\gamma} - (g^{2} - g'^{2}) c_{\gamma} \right], \\
\]

\[
\Delta \mathcal{L}_{6}^{aTGC} = i e \delta \kappa_{\gamma} A^{\mu} W_{\mu}^{+} W_{\mu}^{-} + i g \cos \theta_{w} \left[ \delta g_{12} (W_{\mu}^{+} W_{\mu}^{-} - W_{\mu}^{+} W_{\mu}^{-}) Z_{\nu} + \delta g_{12} - \frac{g^{2} \delta \kappa_{\gamma} Z_{\mu} W_{\mu}^{+} W_{\nu}^{-} \right] \\
+ i \frac{g \lambda_{\gamma}}{m_{W}^{2}} \left[ \sin \theta_{w} W_{\mu}^{+} W_{\nu}^{-} \right], \\
\]

\[
\Delta \mathcal{L}_{6}^{hff} = - \frac{h}{v} \sum_{f = u, d, e} \delta y_{f} m_{f} \tilde{f} \tilde{f} + \text{h.c.} \\
\]

\[
\Delta \mathcal{L}_{6}^{hff, hff} = \frac{g}{\sqrt{2}} \left( 1 + 2 \frac{h}{v} \right) W_{\mu}^{+} \left[ \delta g_{L}^{W_{\mu}^{+}} Z_{\mu} e + \delta g_{R}^{W_{\mu}^{+}} Z_{\mu} d + \delta g_{R}^{Z_{\mu}} \tilde{f} \tilde{f} + \text{h.c.} \right] \\
+ \sqrt{g^{2} + g'^{2}} \left( 1 + 2 \frac{h}{v} \right) Z_{\mu} \left[ \sum_{f = u, d, e} \delta g_{L}^{Z_{\mu} f} \tilde{f} \tilde{f} + \sum_{f = u, d, e} \delta g_{R}^{Z_{\mu} f} \tilde{f} \tilde{f} \right] \\
\]

Higgs parameterisation: LHCHXSWG-INT-2015-001

Kick-off meeting of ECFA workshops on $e^+e^-$ Higgs/EW/Top factory
June 18, 2021
Effective Field Theories: SMEFT

- **SMEFT** in the mass eigenstate basis (unitary gauge). LO EW/Higgs interactions:

\[
\Delta \mathcal{L}^\text{HV} = \frac{\hbar}{v} \left[ 2 \delta \frac{m_w^2}{2} W_{\mu}^+ W_{\mu}^- + \delta c_V n_2^2 Z\mu Z\mu + c_{\gamma} g^2 \left( W_{\mu}^- \partial_{\nu} W_{\mu}^+ + \text{h.c.} \right) + c_{\gamma} n_2^2 Z\mu Z\mu + c_{\gamma} g' Z\mu \partial_{\mu} A_{\nu} \right] \\
+ \frac{c_{\gamma}}{2} g^2 W_{\mu}^+ W_{\mu}^- - c_{\gamma} g^2 n_2^2 C_{\mu\nu} C_{\mu\nu} + c_{\gamma} n_2^2 A_{\mu\nu} A_{\mu\nu} + c_{\gamma} \frac{g^2 + g'^2}{2} Z_{\mu\nu} A_{\mu\nu} + c_{\gamma} \frac{g^2 + g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} \\
\delta c_V = \delta c_\gamma + 4 m_t \\
c_{\gamma} = c_{\gamma} + 2 \sin^2 \theta_w c_{\gamma\gamma} + \sin^4 \theta_w c_{\gamma} \\
c_{\gamma} = 1 + \frac{1}{g^2 - g'^2} \left[ g^2 c_{\gamma} + g'^2 c_{\gamma} - e^2 \sin^2 \theta_w \right] \\
c_{\gamma} = 1 + \frac{1}{g^2 - g'^2} \left[ 2 g^2 c_{\gamma} + (g^2 + g'^2) c_{\gamma} \right]
\]

- **Richer structure than SM:**
  - 15 independent structures (not counting flavor)
  - Connected to other par via SMEFT corr.

- **aTGC**

\[
\Delta \mathcal{L}^\text{aTGC} = \frac{\imath e}{\sqrt{2}} \bar{\nu} \gamma^\mu \nu W_{\mu}^+ W_{\nu}^- + \imath g \cos \theta_w \left[ \delta \frac{1}{2} (W_{\nu}^+ W_{\nu}^- - W_{\nu}^+ W_{\nu}^+) Z^\nu + \left( 1 - \frac{g^2}{g^2} \right) Z^\nu W_{\mu}^+ W_{\nu}^- \right] \\
+ \frac{g}{m_W} \left( \sin \theta_w W_{\mu}^+ W_{\nu}^- \nu^\rho A_{\rho} + \cos \theta_w W_{\mu}^+ W_{\nu}^- W_{\nu}^+ \nu^\rho Z_{\nu} \right)
\]

- Only \( \lambda_2 \) is independent
- \( \delta g_{12} \) and \( \delta k_\gamma \) related to HVV couplings

- **Hff**

\[
\Delta \mathcal{L}^\text{Hff} = - \frac{\hbar}{v} \sum_{f=u,d,e} \delta \gamma_f m_f \bar{f} f + \text{h.c.}
\]

- **Vf & Hff**

\[
\Delta \mathcal{L}^\text{Vf,Hff} = \frac{g}{\sqrt{2}} \left( 1 + \frac{\hbar}{v} \right) W_{\mu}^+ \left( \delta g_L \nu \gamma_{\mu} e + \delta g_R \nu \gamma_{\mu} d + \delta g_{V}\nu \gamma_{\mu} d + \text{h.c.} \right) \\
+ \sqrt{g^2 + g'^2} \left( 1 + \frac{\hbar}{v} \right) Z_{\mu} \left[ \sum_{f=u,d,e,v} \delta g_L \bar{f} \gamma_{\mu} f + \sum_{f=u,d,e} \delta g_R \bar{f} \gamma_{\mu} f \right]
\]
**Effective Field Theories: SMEFT**

- **SMEFT**: Keeps tracks of correlations imposed by gauge invariance and linearly realised EWSB

\[
\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 
0 \\
\nu + h 
\end{pmatrix}
\]

**Linear EWSB**

**SM gauge invariance**

\[
D_\mu = \partial_\mu + igA_\mu
\]

\[
\Phi^\dagger D_\mu \phi (\bar{e}R^\gamma \mu e_R^j)
\]

\[
Ze^+e^- \quad \text{Vff}
\]

\[
iD_\mu \phi^\dagger D_\nu \phi B_{\mu\nu}
\]

\[
Z_{\mu\nu}W_{\mu}^+W_{\nu}^- \quad \text{aTGC}
\]

\[
(Wv)(Wv) \leftrightarrow (\partial h)(Zv) \quad \text{HVV}
\]
**Effective Field Theories: SMEFT**

- **SMEFT**: Keeps tracks of correlations imposed by gauge invariance and linearly realised EWSB

### Linear EWSB

\[
\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix}
0 \\
v + h
\end{pmatrix}
\]

### SM gauge invariance

\[
D_\mu = \partial_\mu + ig A_\mu
\]

Use EWPO (Z-pole) to constrain \(hZee\) interactions (Higgs)

Use di-Boson (aTGC) to constrain \(hVV\) interactions (Higgs) (or viceversa)

A. Falkowski et al., PRL 116 (2016) 011801
Challenges at future e⁺e⁻ colliders
Higgs factories and interplay with EW/Top
Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

Future colliders combined with HL-LHC

SMEFT_{ND} fit

Higgs couplings

Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

What goes into this figure?

Assumptions/Simplifications
- CP-even. \(Hff\) and \(Vff\) (\(HVff\))
  diagonal in the physical basis
- No 4-fermion, dipole ops.
- \(Vff\) (\(HVff\)) flavour universality
  respected by first 2 quark families
- Dim-6 + truncation at linear level.
  TH unc.: SM only.

Warsaw basis

SM +
\[O^{(n)}_{\phi f}, O_{f \phi}, O_{\phi V} \]
\[O_{\phi D}, O_{lt} \]
...  
5 SM pars
+ 30 NP pars

Dim 6 mass eigenstate Lag.

Fit to
Higgs
EWPO
WW (aTGC)
Top

\[g_{H X}^{\text{eff}} 2 \equiv \frac{\Gamma_{H \rightarrow X}}{\Gamma_{H \rightarrow X}^{\text{SM}}} \]

Posterior predictions for PO

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June 18, 2021
Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

The general conclusion of the study is that all proposed future $e^+e^-$ Higgs factories have similar physics capabilities

ECFA study should focus on exploring the physics potential beyond these ESU studies, to strengthen the case for building at least one of these future facilities

Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

**Largest improvement wrt HL-LHC and most precise couplings**

\( hVV \): near per mile level precision

But optimal* extraction requires combination of other processes

\[ \Rightarrow \text{Interplay Higgs/EW} \]

* with max. experimental accuracy

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* [Higgs@FC WG September 2019](https://arxiv.org/abs/1910.11775)

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Kick-off meeting of ECFA workshops on e+e- Higgs/EW/Top factory

June 18, 2021
• Precision of **Higgs measurements** expected to be close to per mille level in several cases

• **Is the knowledge of the EW interactions** from LEP/SLD enough to neglect EW uncertainties in the extraction of **Higgs properties**?

Interplay Higgs/EW factories

- What is the relevance of the EW factory for the Higgs runs:

  precision reach on effective couplings from full EFT global fit

![Diagram showing Higgs couplings and ratios, real EW / perfect EW](image)

**Ratios, real EW / perfect EW**

**Higgs couplings**

**aTGCs**

**δg_{ZZ}, δg_{WW}, δg_{gg}, δg_{tt}, δg_{cc}, δg_{bb}, δg_{μμ}, δg_{1,Z}, δk_{Y}, λ_{Z}**

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**Notes:**

- HL-LHC S2 + LEP/SLD
- CEPC Z/WW/240GeV
- FCC-ee Z/WW/240GeV
- FCC-ee Z/WW/240GeV/365GeV
- ILC 250GeV + Z @250GeV
- ILC 250GeV/350GeV
- ILC 250GeV/350GeV/500GeV
- CLIC 380GeV+ Z @380GeV
- CLIC 380GeV/1.5TeV
- CLIC 380GeV/1.5TeV/3TeV

**Light shade:** CEPC/FCC-ee without Z-pole

**Perfect EW & TGC**

lepton colliders are combined with HL-LHC & LEP/SLD
imposed U(2) in 1&2 gen quarks

---

**References:**

Interplay Higgs/EW factories

- What is the relevance of the EW factory for the Higgs runs:
  precision reach on effective couplings from full EFT global fit

---

Ratios, real EW / perfect EW

Are LEP/SLD EW precision measurements enough?

**Interplay Higgs/EW factories**

- What is the relevance of the EW factory for the Higgs runs:
  
  precision reach on effective couplings from full EFT global fit

  **“Perfect EW” measurements**

  Assume Z-pole precision is such that it can constrain any contributing dim-6 effect beyond the sensitivity of other processes (Higgs), e.g.

  \[
  \begin{align*}
  & Z \quad v \quad e^- \\
  & \quad v \quad e^+ \\
  & Z \quad h \quad v \quad e^- \\
  & \quad v \quad e^+ \\
  \end{align*}
  \]

  \[\approx 0\]

  Are LEP/SLD EW precision measurements enough?

---

**Interplay Higgs/EW factories**

- What is the relevance of the EW factory for the Higgs runs:

  - The precision reached for each Higgs for the four future lepton colliders considered: CEPC, FCC-ee, ILC and CLIC.
  - Numerical results are sensitive to different combinations of parameters and can help resolving approximate TGC dominance assumption.
  - At the ILC, the measurement of Higgsstrahlung production are however reduced to factors of about 1.5.
  - Modifications of electroweak parameters (shown in figure 2) do not seem to be significant EW uncertainties.
  - Numerical results are also reported in this talk.

**Note:**
- Polarization partially compensates the absence of Z-pole at linear colliders…
- …plus use rad. return to measure EWPO

---

**Figure 2: Global one-sigma reach of future lepton colliders on Higgs and triple-gauge couplings.**

Ratios, real EW / perfect EW

- CEPC 240 GeV, FCCee 250 GeV, ILC 250 GeV, CLIC 380 GeV

---

**Interplay Higgs/EW factories**

- Impact of di-Boson measurements in Higgs couplings
- Optimal Observable Analysis of EFT effects in \( e^+e^- \to W^+W^- \to jj\ell\nu, \quad \ell = e, \mu \)

**Full EFT parameterisation**

Maximal differential information

Stat. Uncertainty only (idealised)

Compensate absence of sys. via efficiency

Jorge de Blas
University of Granada


Kick-off meeting of ECFA workshops on e+e- Higgs/EW/Top factory
June 18, 2021

---

**Figure 6** Impact of diboson measurement precision on Higgs and triple-gauge couplings.
**Interplay Higgs/EW factories**

- Impact of di-Boson measurements in Higgs couplings
- Optimal Observable Analysis of EFT effects in $e^+e^- \rightarrow W^+W^- \rightarrow jj\ell\nu$, $\ell = e, \mu$

**Similar Optimal Observable analysis could be applied to other processes**

⇒ Use all possible differential information

⇒ Optimize sensitivity to BSM deformations
More on BSM precision: Impact of SM precision calculations and uncertainties

Need dedicated theory effort to reduce SM TH errors to O(0.1%)
Higgs couplings at future Higgs factories

- More on BSM precision: Impact of SM precision calculations and uncertainties

<table>
<thead>
<tr>
<th>Decay</th>
<th>Partial width [keV]</th>
<th>Projected future unc. $\Delta \Gamma / \Gamma$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>2379</td>
<td>$0.2$ $0.6^b$ $&lt; 0.1^d$ $-$</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>256</td>
<td>$&lt; 0.1$ $-$ $-$ $-$</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>118</td>
<td>$0.2$ $1.0^b$ $&lt; 0.1^d$ $-$</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>0.89</td>
<td>$&lt; 0.1$ $-$ $-$ $-$</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>883</td>
<td>$\lesssim 0.4$ $-$ $-$ $0.1^d$</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>335</td>
<td>$1.0$ $-$ $0.5^d$ $-$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>108</td>
<td>$\lesssim 0.3^d$ $-$ $-$ $0.1^d$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$-$</td>
<td>$&lt; 1.0$ $-$ $-$ $-$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>2.1</td>
<td>$1.0$ $-$ $-$ $0.1^d$</td>
</tr>
</tbody>
</table>

Intrinsic TH unc in production
e.g. $e^+ e^- \rightarrow ZH$

- LO to NLO: 5-10%  
- Missing 2-loop: O(1%)  
- Full 2-loop should reduce uncertainty to O(0.1%)  
- Z width effects relevant at this level of precision?

Assessment of TH uncertainty may require full 2->3 NNLO

In any case, reducible with necessary effort from theory side

From $e^+ e^- \rightarrow ZH$.

$^1$For $\delta M_H = 10$ MeV. Adjusted for Higgs mass precision at CLIC.

$^b$For $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV. (Lattice projection).

$^d$For $\delta \alpha_s = 0.0002$. (Lattice projection).

Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

EFT results projected into effective Higgs couplings

\[ g_{H_X}^{\text{eff}} = \frac{\Gamma_{H_X}^{\text{eff}}}{\Gamma_{H + X}} \]

Future colliders combined with HL-LHC
- HL-LHC
- HL+HELHC
- HL+LHeC
- HL+CEPC

SMEFT\textsubscript{ND} fit

Higgs couplings

Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

Top Yukawa not directly accessible at “low-E” Higgs factory

Sensitivity comes mainly from \( h \to gg \)

\[
\Gamma_{h \to gg} \sim \left| g_{hgg,\text{eff}}^{\text{SM}} (1 + \delta y_t) + C \phi G \frac{v}{\Lambda^2} \right|^2
\]

\[
\delta y_t \sim - \sqrt{\frac{v}{2m_t}} C_{u\phi,33} \frac{v^2}{\Lambda^2} + \ldots
\]

Resolved via \( t\bar{t}H \) from HL-LHC/High-E \( e^+e^- \) factory

(More on this later)

The effects of \( C_{u\phi} \)

(and other EFT top operators)

could also be tested via NLO effects

\[ g_{HAX}^{\text{eff}} \frac{2}{\Gamma_{H+X}} = \frac{\Gamma_{H+X}}{\Gamma_{H+X}} \]

**Higgs couplings at future Higgs factories**

- Indirect effects of Top interaction in observables via loop effects

**H production and decay**

**EW production**

Does not require specific Top measurements: effects in **precision** EW/Higgs observables → Accessible at low-E circular/linear colliders

---

**Figure 1**

To answer these two questions, in this work we compute the EW loop-induced contributions. Diagrams that can be obtained by crossing legs or decay of the Higgs boson, the oblique parameters, and the SM input parameters which we will take into account.

**Key words:**
- Effective field theory
- Top quark
- Lepton collider
- Precision electroweak operators

---

**Figure 2**

**ILC 250 Stage**

- HL-LHC Run 2
- HL-LHC S2

**ILC 240GeV**

- w/ top
- w/ top + LHC Run 2
- w/ top + HL-LHC S2

- e+e- Higgs/EW/Top factory

**Figure 3**

The precision of top operator coefficients (global fit, $\Delta \chi^2 = 1$) is shown with the light shades. The results shown with the solid shade: $c_V$ set to 0. The fourth and fifth columns display the predictions from the corresponding global fits.

---

**Figure 4**

The rational $R^2$ counterterms are computed following the conventions of Ref. [20].
**Interplay Higgs/Top factories**

- Some Tops operators not strongly constrained → extra uncertainties in H pars…

  precision of the Higgs parameters at CC (global fit, $\Delta\chi^2=1$)

  ![Graph showing precision of top operator coefficients](image)

- … plus studies **restricted to EW top operators**. Large number of ops. in a global study (including also 4-fermion operators) would not permit to close the fit…

  ⇒ Need to combine with direct $tt$ measurements from $ee$ Top factory runs

  Also needed to disentangle Top Yukawa in global EFT $ee \to tth$ analysis!

  ![Diagram showing $ee \to tth$](image)

  **No global EW+Higgs+Top projection available yet**

  ⇒ Is it possible to close all directions in $tt$?
Dedicated **Global EFT** analysis of $e^+e^- \rightarrow tt$ using statistical optimal observables

**✓ Covariance matrix available for FCCee (350-365 GeV), ILC (500-1000 GeV) and CLIC (380-3000 GeV)**

![Diagram of observables](image)

**Idealized framework:** Only stat. error. What is the effect of Top systematics?
Interplay Higgs/Top factories

- Dedicated **Global EFT** analysis of $e^+e^- \rightarrow tt$ using statistical optimal observables
- Covariance matrix available for FCCee (350-365 GeV), ILC (500-1000 GeV) and CLIC (380-3000 GeV)

Flat directions

$\rightarrow 2$ separate energies needed to separate $t\bar{t}Z$ and $e\bar{e}t$ operators ($\Delta E$ ?)

**Idealized framework:** Only stat. error. What is the effect of Top systematics?
Challenges at future $e^+e^-$ colliders

Interplay with HL-LHC
Interplay with the HL-LHC

- HL-LHC potential explored in detail mostly from the point of view of Higgs physics:

  - Based only on inclusive measurements. HL-LHC can do more → high energy
    ✓ Boosted: Higgs + high-pT, WH/ZH at large invariant masses, Off-shell …
    ✓ Projections for STXS?
### Interplay with the HL-LHC

- Constraints on rare Higgs decays will be still dominated by HL-LHC

<table>
<thead>
<tr>
<th>kappa-0</th>
<th>HL-LHC</th>
<th>LHeC</th>
<th>HE-LHC</th>
<th>ILC</th>
<th>CLIC</th>
<th>CEPC</th>
<th>FCC-ee</th>
<th>FCC-ee/ch/hh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S2</td>
<td>S2'</td>
<td>250</td>
<td>500</td>
<td>1000</td>
<td>380</td>
<td>15000</td>
<td>3000</td>
</tr>
<tr>
<td>(\kappa_W) [%]</td>
<td>1.7</td>
<td>0.75</td>
<td>1.4</td>
<td>0.98</td>
<td>1.8</td>
<td>0.29</td>
<td>0.24</td>
<td>0.86</td>
</tr>
<tr>
<td>(\kappa_Z) [%]</td>
<td>1.5</td>
<td>1.2</td>
<td>1.3</td>
<td>0.9</td>
<td>0.29</td>
<td>0.23</td>
<td>0.22</td>
<td>0.5</td>
</tr>
<tr>
<td>(\kappa_t) [%]</td>
<td>2.3</td>
<td>3.6</td>
<td>1.9</td>
<td>1.2</td>
<td>2.3</td>
<td>0.97</td>
<td>0.66</td>
<td>2.5</td>
</tr>
<tr>
<td>(\kappa_b) [%]</td>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>0.7</td>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td>(\kappa_\gamma) [%]</td>
<td>1.9</td>
<td>7.6</td>
<td>1.6</td>
<td>1.2</td>
<td>6.7</td>
<td>3.4</td>
<td>1.9</td>
<td>98*</td>
</tr>
<tr>
<td>(\kappa_{Z\gamma}) [%]</td>
<td>10.0</td>
<td>5.7</td>
<td>3.8</td>
<td>99*</td>
<td>86*</td>
<td>85*</td>
<td>120*</td>
<td>15</td>
</tr>
</tbody>
</table>

In this case there is also no strong correlation between the untagged branching fraction and \(\kappa\). As discussed before, for these hadron colliders a constraint on \(\kappa\) is not necessary, and therefore it is not used as a constraint.

**Figure 2**

The results of the kappa-3 benchmark scenario are also presented graphically in figure 2. Expected relative precision (%) of the \(\kappa\) are shown in the appendix.

**Higgs@FC WG**

Kappa-3, 2019

Future colliders combined with HL-LHC

Uncertainty values on \(\Delta \kappa\) in %.

Limits on Br (%) at 95% CL.
Interplay with the HL-LHC

... and so it would seem for the Top Yukawa coupling...

<table>
<thead>
<tr>
<th>kappa-0</th>
<th>HL-LHC</th>
<th>LHeC</th>
<th>HE-LHC</th>
<th>ILC</th>
<th>CLIC</th>
<th>CEPC</th>
<th>FCC-ee</th>
<th>FCC-ee/eh/hh</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>κ_1 [%]</td>
<td>1.7</td>
<td>0.75</td>
<td>1.4</td>
<td>0.98</td>
<td>1.8</td>
<td>0.29</td>
<td>0.24</td>
<td>0.86</td>
</tr>
<tr>
<td>κ_2 [%]</td>
<td>1.5</td>
<td>1.2</td>
<td>1.3</td>
<td>0.9</td>
<td>0.29</td>
<td>0.23</td>
<td>0.22</td>
<td>0.5</td>
</tr>
<tr>
<td>κ_3 [%]</td>
<td>2.3</td>
<td>3.6</td>
<td>1.9</td>
<td>1.2</td>
<td>2.3</td>
<td>0.97</td>
<td>0.66</td>
<td>2.5</td>
</tr>
<tr>
<td>κ_4 [%]</td>
<td>1.9</td>
<td>7.6</td>
<td>1.6</td>
<td>1.2</td>
<td>6.7</td>
<td>3.4</td>
<td>1.9</td>
<td>9.8*</td>
</tr>
<tr>
<td>κ_5 [%]</td>
<td>10.3</td>
<td>-</td>
<td>5.7</td>
<td>3.8</td>
<td>99*</td>
<td>86*</td>
<td>85*</td>
<td>120*</td>
</tr>
<tr>
<td>κ_6 [%]</td>
<td>4.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>4.3</td>
</tr>
<tr>
<td>κ_7 [%]</td>
<td>3.3</td>
<td>-</td>
<td>2.8</td>
<td>1.7</td>
<td>-</td>
<td>6.9</td>
<td>1.6</td>
<td>-</td>
</tr>
<tr>
<td>κ_8 [%]</td>
<td>1.9</td>
<td>3.3</td>
<td>1.5</td>
<td>1.1</td>
<td>1.9</td>
<td>0.70</td>
<td>0.57</td>
<td>3.0</td>
</tr>
</tbody>
</table>

ILC/CLIC at the highest E

Higgs@FC WG
Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on Δκ in %
Limits on BR (%) at 95% CL.

Standalone Fut. Colliders

HL-LHC + Fut. Colliders

Jorge de Blas
University of Granada

Kick-off meeting of ECFA workshops on e-e Higgs/EW/Top factory
June 18, 2021
Interplay with the HL-LHC

- …but $ttH$ at the HL-LHC is even more complicated than at $e^+e^-$

\[ O_{t\phi} = y_t^3 \left( Q^t \right) (Q_t) \tilde{\phi} \]
\[ O_{\phi G} = y_t^2 \left( \phi^\dagger \phi \right) G^A_{\mu
u} G^{A\mu\nu} \]
\[ O_{tG} = y_t g_s (Q_\mu \sigma_{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu} \]

4-fermion operators

Constrained from multijets
Krauss et al arXiv:1611.00767

What is the ultimate precision of the Top Yukawa at the HL-LHC?
Interplay with the HL-LHC

- No projections of global Top fit available for HL-LHC but LHC fits combining Top & Higgs already available in literature

- A similar global study needed for HL-LHC projections, to understand what is the ultimate expected precision for $y_t$ at the HL-LHC and a proper combination with future $e^+e^-$ Higgs factories

Figure 4.3. The best-fit values and 95% CL intervals for a global fit based on linear EFT calculations, comparing the outcome of the NS and MCfit methods. We display the results corresponding to the 50 coefficients listed in Table 2.5 (except for $c_{\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\·

Concluding remarks
Summary and Conclusions

• In this talk I focused mostly on some challenges regarding the interpretation of measurements at a future Higgs factory
  ✓ Main focus of future $e^+e^-$ projects and justified from theory point of view:
    Naturalness: solutions to hierarchy problem $\rightarrow$ Deviations in Higgs couplings

• A general model-independent interpretation of measurements can be done within the consistent theory framework of Effective Field Theories

• SMEFT interpretation benefits from the interplay of different types of measurements at $e^+e^-$ Higgs/EW/Top factories
  ✓ Global studies combining EW/Higgs/diBoson available in the literature…
  ✓ …separate studies including Top effects also there…
  ✓ …but no truly global EW/Higgs/diBoson/Top fit yet…
    Needed to precisely establish the indirect physics potential

• Combination with HL-LHC Higgs projections:
  ✓ Helps in dealing with low-stat processes (Higgs rare decays)
  ✓ Determination of the Top interactions for low-E colliders: no fully global study available yet…
    What is the ultimate precision of the Top Yukawa at fut. colliders?
With its limitations, the ESU study was enough to constraint a reasonably large set of EFT interactions relevant for “Higgs” BSM scenarios.
Summary and Conclusions

But there were several issues not covered in the ESU studies

• EW precision observables:
  ✓ Detailed assessment of impact of SM uncertainties for EWPO in SMEFT fits.
  ✓ Clarify systematics for heavy flavor observables \((A_q, R_q)\).
  ✓ Exploit EW obs. outside the Z-pole (low and high energy) ⇒ add 4-fermion ops.
  ✓ Flavor (and CP violation): not explored in the ESU SMEFT fits.

• Higgs and Multi-boson processes:
  ✓ Boosted Higgs, Higgs off-shell measurements, …
  ✓ Full EFT studies of \(e^+e^- \rightarrow W^+W^-\): Use of “optimal” observables.
  ✓ High-\(E\) probes of EFT effects that grow with the energy.
  ✓ Vector boson scattering: not included in ESU studies.

• Interplay EW/Higgs/Top: Top sector only explored superficially:
  ✓ Consider effects from 4-fermion operators or top dipole operators.
  ✓ Exploit NLO effects of Top couplings in H/EW.

• SMEFT assumptions:
  ✓ Impact of SMEFT uncertainties: NLO, \((\text{dim-6})^2\) vs. \text{dim 8}, …
  ✓ Non-universality: combine with flavor data to explore more flavor BSM scenarios
  ✓ HEFT?
Summary and Conclusions

But there were several issues not covered in the ESU studies

- EW precision observables:
  ✓ Detailed assessment of impact of SM uncertainties for EWPO in SMEFT fits.
  ✓ Clarify systematics for heavy flavor observables \((A_q, R_q)\).
  ✓ Exploit EW obs. outside the Z-pole (low and high energy) ⇒ add 4-fermion ops.
  ✓ Flavor (and CP violation): not explored in the ESU SMEFT fits.

- Higgs and Multi-boson processes:
  ✓ Boosted Higgs, Higgs off-shell measurements, …
  ✓ Full EFT studies of \(e^+e^- \rightarrow W^+W^-\). Use of “optimal” observables.
  ✓ High-\(E\) probes of EFT effects that grow with the energy.
  ✓ Vector boson scattering: not included in ESU studies.

- Interplay EW/Higgs/Top: Top sector only explored superficially:
  ✓ Consider effects from 4-fermion operators or top dipole operators.
  ✓ Exploit NLO effects of Top couplings in H/EW.

- SMEFT assumptions:
  ✓ Impact of SMEFT uncertainties: NLO, \((\text{dim-6})^2\) vs. \text{dim 8}, …
  ✓ Non-universality: combine with flavor data to explore more flavor BSM scenarios
  ✓ HEFT?

How far can we go in exploring the full dimensionality of the EFT parameter space using all info available at future colliders?
The Higgs width

- **Hadron colliders:**
  - ✓ Diphoton interference studies ~8-22 × SM
  - ✓ κ-fit requires extra constraints (e.g. |κ_V|<1)
  - ✓ HZZ on-shell vs off-shell: ~20% precision but model-dependent

- **Lepton colliders:** absolute measurement of $\sigma_{ZH}$ (→ couplings) increases model independence

**Example: κ-framework**

From recoil mass method

$$\frac{\sigma(e^+e^- \to ZH)}{\text{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \approx \left[ \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)} \right]_{\text{SM}} \times \Gamma_H$$

**Enough data to extract Higgs width in EFT formalism too (see, e.g. ILC studies)**

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\delta \Gamma_H$ [%] from Ref.</th>
<th>Extraction technique standalone result</th>
<th>$\delta \Gamma_H$ [%] kappa-3 fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC_{250}</td>
<td>2.3 EFT fit [3, 4]</td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td>ILC_{500}</td>
<td>1.6 EFT fit [3, 4, 14]</td>
<td></td>
<td>1.1</td>
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<tr>
<td>ILC_{1000}</td>
<td>1.4 EFT fit [4]</td>
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<td>1.0</td>
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<tr>
<td>CLIC_{380}</td>
<td>4.7 κ-framework [98]</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>CLIC_{1500}</td>
<td>2.6 κ-framework [98]</td>
<td></td>
<td>1.7</td>
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<tr>
<td>CLIC_{3000}</td>
<td>2.5 κ-framework [98]</td>
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<td>1.6</td>
</tr>
<tr>
<td>CEPC</td>
<td>2.8 κ-framework [103,104]</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>FCC-ee_{240}</td>
<td>2.7 κ-framework [1]</td>
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<tr>
<td>FCC-ee_{365}</td>
<td>1.3 κ-framework [1]</td>
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<td>1.1</td>
</tr>
</tbody>
</table>

Indirect determination of H width with O(1-2%) precision
The Higgs self-coupling

- Comparison of capabilities to measure the $h^3$ coupling

<table>
<thead>
<tr>
<th>Higgs-pair production</th>
<th>Via loop effect in single Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron Colliders</td>
<td></td>
</tr>
<tr>
<td></td>
<td><img src="Image" alt="Feynman diagram" /></td>
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<tr>
<td>Lepton Colliders</td>
<td></td>
</tr>
<tr>
<td></td>
<td><img src="Image" alt="Feynman diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>di-Higgs</th>
<th>single-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>exclusive</td>
<td></td>
</tr>
<tr>
<td>1. di-H, excl.</td>
<td>3. single-H, excl.</td>
</tr>
<tr>
<td>• Use of $\sigma(\text{HH})$</td>
<td>• single Higgs processes at higher order</td>
</tr>
<tr>
<td>• only deformation of $\kappa \lambda$</td>
<td>• only deformation of $\kappa \lambda$</td>
</tr>
<tr>
<td>global</td>
<td></td>
</tr>
<tr>
<td>2. di-H, glob.</td>
<td>4. single-H, glob.</td>
</tr>
<tr>
<td>• Use of $\sigma(\text{HH})$</td>
<td>• single Higgs processes at higher order</td>
</tr>
<tr>
<td>• deformation of $\kappa \lambda$ + of the single-H couplings</td>
<td>• deformation of $\kappa \lambda$ + of the single Higgs couplings</td>
</tr>
<tr>
<td>(a) do not consider the effects at higher order of $\kappa \lambda$ to single H production and decays</td>
<td>(b) these higher order effects are included</td>
</tr>
</tbody>
</table>
The Higgs self-coupling

- Comparison of capabilities to measure the $h^3$ coupling

<table>
<thead>
<tr>
<th>Collider</th>
<th>Single-Higgs</th>
<th>Di-Higgs</th>
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</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>50%</td>
<td>~50%</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>10%</td>
<td>~15%</td>
</tr>
<tr>
<td>FCC-ee/ee</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>FCC-ee/eh/hh</td>
<td>20%</td>
<td>34%</td>
</tr>
<tr>
<td>CEPC</td>
<td>27%</td>
<td>34% (10%)</td>
</tr>
<tr>
<td>CLIC</td>
<td>36%</td>
<td>27% (10%)</td>
</tr>
</tbody>
</table>

Little sensitivity via single-Higgs w/o 365 GeV run

Assuming upgrade to 500 GeV (1000 GeV)

**Interplay with the HL-LHC**

**Rare Higgs decays - Light quark Yukawa couplings**

**Limits extracted from the bound on BR<sub>unt</sub> in a Kappa fit**

- **WARNING**: Hadron collider results assume |k<sub>v</sub>|<1

No assumption needed when including a lepton collider