The golden couple of the SM: 
**top and Higgs at present and future colliders**

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CLIC week, CERN, 24 January 2019

Based on old work with Pöschl, Richard and I. García, more recent results with CLICdp and G. Durieux & C. Zhang, and ongoing work with S. Jung & J. Tian and others
The Higgs boson

In 2012, the LHC discovers a new, fundamental scalar
→ interactions tested so far compatible with a Higgs boson

With the discovery of the Higgs boson the SM is complete
→ focus shifting from searches to tests of SM internal consistency

The Higgs boson is a probe to physics beyond the SM
→ focus of HEP and this workshop
The top quark

The other SM particle to escape scrutiny at LEP
  → precise constraints on top (EW) couplings are missing

The SM particle with the closest connection to the Higgs
  → top Yukawa coupling is a key target of HEP
    (see talks by Yandong Liu and Kaori Fuyuto at this workshop)

The top quark has a special role in SM extensions
  → light stop in SUSY, composite top in composite Higgs models
    (see talks by Stefania de Curtis and Rikard Enberg later at this workshop)
Top and Higgs

The message of this talk:

A precise knowledge of the top quark is important for Higgs physics…
Top and Higgs

The message of this talk:

Even if you think the top quark is boring you may be forced to understand it…
A well-known example: the EW fit

The Electroweak fit forms a stringent test of the internal consistency of the Standard Model

M. Baak et al., arXiv:1407.3792

Top mass may drive the Higgs potential at high scale negative

(But universe not likely to decay any time soon)

Buttazzo et al arXiv:1307.3536v4
V. Branchina at this workshop
Top mass at hadron colliders

Tev.+LHC top mass combination (2014): \( m_t = 173.3 \pm 0.7 \text{ GeV} \) (arXiv:1403.4427)

*Baak et al. add 500 MeV theory uncertainty*

Electroweak fit yields indirect
\( m_W = 80.354 \pm 8 \text{ MeV} \)

Error budget dominated by \( m_t \)
- \( m_t \): 5 MeV
- \( m_Z \): 2.5 MeV
- \( m_H \): 1 MeV
- \( \alpha_s \): 2 MeV

Balance is important: must match the precision of several measurements to achieve the ultimate closure test of the Standard Model
Top mass at hadron colliders

Direct mass

LHC 3 ab\(^{-1}\) prospects:

\[ \Delta m_t = \pm 0.2 \text{ (exp.)} \pm ? \text{ GeV} \]

(Pole mass)

Higgs as a probe for New Physics, Osaka, Feb. 2019

(arXiv:1902.04070)
Top mass at $e^+e^-$ colliders

A multi-parameter fit can extract a threshold mass with excellent precision

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Statistical uncertainty:</td>
<td>~20 MeV</td>
<td>$200 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>Scale uncertainty:</td>
<td>~40 MeV</td>
<td>$N^3\text{LO QCD, arXiv:1506.06864}$</td>
</tr>
<tr>
<td>Parametric uncertainty:</td>
<td>~30 MeV</td>
<td>$\alpha_s \text{ world average, arXiv:1604.08122}$</td>
</tr>
<tr>
<td>Experimental syst:</td>
<td>25-50 MeV</td>
<td>$\text{including LS, arXiv:1309.0372}$</td>
</tr>
</tbody>
</table>

This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030
Top quark EW couplings

Large BSM family predicts sizeable deviations from SM

- 5D models by several authors (A. Wulzer)
  *Richard, arXiv:1403.2893*

- 4D Composite Higgs Model
  *Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)*
Top EW couplings at the LHC

**Neutral current:** $ttZ$, $tty$ associated production ($tZ$, $ty$)
→ processes “discovered”, cross section measurements 10-20%

**Charged current:** single top production, top decay observables
→ precision top physics at the LHC

Current status:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Prospect studies:
Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911
FCChh SM study, arXiv:1607.01831
Top quark production at $e^+e^-$ colliders

$\sqrt{s} > 2m_t$, s-channel x-sec maximum $\sim 420$ GeV
VBF and $t\bar{t}H$ production accessible above 500 GeV

The best laboratory to test $\gamma t\bar{t}$ and $Zt\bar{t}$ vertices

Measurements of cross-section, $A_{FB}$ and CP-odd observables

Double the number of observables with LR and RL polarizations
Perform a simple fit of the form factors describing $ttZ/\gamma$ vertex
Top EW couplings at lepton colliders

\[ \Gamma_{\mu}^{\ell\ell\ell} (k^2, q, \bar{q}) = i e \left\{ \gamma_\mu \left( F_{1V}^X (k^2) + \gamma_5 F_{1A}^X (k^2) \right) - \frac{\sigma^{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( i F_{2V}^X (k^2) + \gamma_5 F_{2A}^X (k^2) \right) \right\} \]

Prospects for HL-LHC: PRD71, 054013, PRD73, 034016


Higgs as a probe for New Physics, Osaka, feb. 2019
Quantify BSM sensitivity in a model-agnostic way with limits on anomalous D6 operator coefficients in Effective Field Theory

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}(\Lambda^{-4}) \]

*EFT analyses “by sector” are becoming the standard interpretation for LHC analyses.*

*Very powerful benchmarking tool for future projects.*
EFT constraints on top quark operators from the LHC

Order (1) constraints on the QCD operators (ttg, ttqq)

First, weak limits on operators that affect top EW interactions

Differential cross section measurements
Englert et al., arXiv:1607.04304

Rare associated production processes yield limits on top quark EW couplings

Further progress to come from the exploration of regions with enhanced sensitivity and new SM processes (ttH, ttZ, ttW, ttγ, tZ, tγ,...)
New: global fit to the top sector


SMEFiT analysis of LHC top quark data

34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)
Top QCD : very good individual limits ~0.1, global limits O(1)
New: global fit to the top sector


34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)
Top QCD : very good individual limits ∼0.1-1, global limits O(1-10)
Top EW   : poorer individual limits, typically O(several), first global results!
top EFT fit at future colliders

Sensitivity to four-fermion operators increases strongly with energy

Ultimate precision in global EFT fit requires a collider with two energy stages and polarization

Higgs as a probe for New Physics, Osaka, feb. 2019

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Top EFT fit at the LC

Two-fermion operators:
- LC prospects exceed LHC run 2 by two orders of magnitude

Four-fermion operators:
- LC limits on eett operators can compete with hadron collider limits on qqtt

CLICdp top paper, arXiv:1807.02441
Durieux, Perello, Zhang, Vos, arXiv:1807.02121

Two-fermion operators:
- $C^V_{\phi q}$
- $C^A_{\phi q}$
- $C^R_{uA}$
- $C^R_{uZ}$

LC: 500 GeV, 0.5 ab$^{-1} \otimes 1$ TeV, 1 ab$^{-1}$
CLIC: 380 GeV, 0.5 ab$^{-1} \otimes 1.5$ TeV, 1.5 ab$^{-1} \otimes 3$ TeV, 3 ab$^{-1}$

68% C.L. limits [TeV$^{-2}$] vs. new physics scale [TeV]

Higgs as a probe for New Physics, Osaka, Feb. 2019
A simpler fit

Identify an “isolated system” of top EW operators

\[ C_{t\phi} = \text{modifies top Yukawa} \]
\[ C^1_{\phi Q} = \text{modifies left-handed coupling of top quark} \]
\[ C^3_{\phi Q} = \text{idem.} \]
\[ C_{\phi t} = \text{modifies right-handed coupling of top quark} \]
\[ C_{tW} = \text{top dipole moment} \]
\[ C_{tB} = \text{idem.} \]
\[ C_{\phi b} = \text{bottom quark} \]
\[ C_{dW} = \text{bottom quark dipole} \]

Shared with bottom quark
\[ \rightarrow \text{LEP constraints} \]

Bottom quark operators: the prize to pay for including \( e^+e^- \rightarrow b\bar{b} \) constraints

Does not include QCD operators, which are tightly constrained
Does not include l\( l\ell \) four-fermion operators, like (most) other analyses
Does not include CP-violating interactions, which can be constrained very well
EFT: combined bottom-top fit

Bottom production provides an exactly complementary constraint

Other possibilities (top width, W polarization, $b\bar{b}Z$ production at LHC) provide complementary information, but of relatively poor precision.
Dedicated fit to top EW operators: prospects

Dedicated fit using only top EW operators [M. Perelló, M. Vos, preliminary]

Current LEP+LHC limits improve in future scenarios
- HL-LHC S1: reduce stat. uncertainty, today’s systematics → little or no progress
- HL-LHC S2: exp. systematics/sqrt(L), theory/2 → factor 2-5 for top operators
- ILC250: nominal Higgs run, 2 ab⁻¹ → strong impact bottom operators
- ILC500: as per H20 scenario, 4 ab⁻¹ → top operators improve dramatically
The Higgs fit and the top Yukawa coupling
LHC establishes $t\bar{t}H$ production!

$t\bar{t}H$ production observed in both ATLAS and CMS [see T. Masubuchi]

Measurement of the top Yukawa coupling is competitive with indirect result

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**ATLAS, PLB 784, 173-191 (2018)**

**CMS, PRL 120, 231801 (2018)**

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**indirect 8 TeV**

Run I: $k_t = 1.43 \pm 0.23$

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**direct 13 TeV**

CMS: $\mu_{t\bar{t}H} = 1.26 \pm 0.3$

ATLAS: $\mu_{t\bar{t}H} = 1.32 \pm 0.3$

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Higgs as a probe for New Physics, Osaka, Feb. 2019
Example: Indirect Yukawa coupling at the LHC

The **indirect constraint on the top Yukawa coupling** from top loops in $gg \to H$ (and $H \to \gamma\gamma$) is quite powerful.

In a global EFT analysis it is very hard to distinguish the effect of a direct $Hgg$ coupling ($c_g$) from that of the operator that modifies the top Yukawa coupling ($c_y$).

**Direct measurement in $t\bar{t}H$** is necessary in a global analysis.

Azatov et al., arXiv:1608.00977
New: global fit to the top sector


Marginalized limit $\gg$ individual for operator that shifts top Yukawa

SMEFiT analysis of LHC top quark data

34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)
Top QCD: very good individual limits $\sim$0.1, global limits $\mathcal{O}(1)$
A combined Higgs-top-EW EFT fit?

The Higgs rates depend on top Yukawa coupling AND other top EW couplings

NLO relation between Higgs observables and top EFT operator coefficient known

*Vryonidou & Zhang, arXiv:1804.09766*

<table>
<thead>
<tr>
<th>channel</th>
<th>(\mu_{EFT} ) [GeV]</th>
<th>(O_{q'b})</th>
<th>(O_{q'Q}^{(+)})</th>
<th>(O_{q'Q}^{(-)})</th>
<th>(O_{tW})</th>
<th>(O_{tB})</th>
<th>(O_{t\gamma})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow bb)</td>
<td>125</td>
<td>-0.15</td>
<td>-0.06</td>
<td>0.24</td>
<td>-1.13</td>
<td>-0.28</td>
<td>0</td>
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<tr>
<td>(H \rightarrow bb)</td>
<td>1000</td>
<td>0.79</td>
<td>0.54</td>
<td>-1.25</td>
<td>-8.16</td>
<td>0.34</td>
<td>0</td>
</tr>
<tr>
<td>(H \rightarrow \mu\mu, \tau\tau)</td>
<td>125</td>
<td>-0.15</td>
<td>0.001</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(H \rightarrow \mu\mu, \tau\tau)</td>
<td>1000</td>
<td>0.79</td>
<td>0.002</td>
<td>-0.79</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>125</td>
<td>-3.37</td>
<td>5.86</td>
<td>2.64</td>
<td>0</td>
<td>-56.4</td>
<td>-117.9</td>
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<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>1000</td>
<td>6.95</td>
<td>16.2</td>
<td>-2.52</td>
<td>0</td>
<td>14.0</td>
<td>101.3</td>
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<tr>
<td>(H \rightarrow Z\gamma)</td>
<td>125</td>
<td>0.51</td>
<td>2.20</td>
<td>2.74</td>
<td>0</td>
<td>-39.5</td>
<td>14.0</td>
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<tr>
<td>(H \rightarrow Z\gamma)</td>
<td>1000</td>
<td>4.35</td>
<td>6.04</td>
<td>0.83</td>
<td>0</td>
<td>33.9</td>
<td>-51.6</td>
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<tr>
<td>(H \rightarrow Zll)</td>
<td>125</td>
<td>-0.54</td>
<td>-0.10</td>
<td>0.56</td>
<td>-0.00</td>
<td>0.19</td>
<td>-0.06</td>
</tr>
<tr>
<td>(H \rightarrow Zll)</td>
<td>1000</td>
<td>0.33</td>
<td>0.74</td>
<td>-1.25</td>
<td>-0.06</td>
<td>0.05</td>
<td>0.33</td>
</tr>
<tr>
<td>(H \rightarrow Wl\nu)</td>
<td>125</td>
<td>-0.15</td>
<td>-0.24</td>
<td>0.38</td>
<td>0.00</td>
<td>-0.13</td>
<td>0</td>
</tr>
<tr>
<td>(H \rightarrow Wl\nu)</td>
<td>1000</td>
<td>0.79</td>
<td>0.63</td>
<td>-1.42</td>
<td>-0.05</td>
<td>0.33</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 1. Percentage deviation \(\mu_{ij}\) for decay channel \(i\) and operator \(j\).*

Coefficients are large and existing constraints are poor: cannot ignore the top EW operators in a global EFT analysis.

Crucial for on top Yukawa and Higgs self-coupling at a 250 GeV collider.

*Durieux et al., arXiv:1809.03520*
Indirect top Yukawa coupling at the ILC

\[
\mu_{h \to gg} = \frac{\Gamma_{h \to gg}}{\Gamma_{SM}} = 1 + 2 \Delta y_t ,
\]

\[
\mu_{h \to \gamma\gamma} = \frac{\Gamma_{h \to \gamma\gamma}}{\Gamma_{SM}} = 1 - 0.56 \Delta y_t .
\]

H → gg rate at 250 GeV yields a 1% precision on top Yukawa coupling in a one-parameter fit

S. Jung, J. Tian, M. Perelló:

H → γγ as powerful as H → gg

But… result for top Yukawa coupling is not robust in a global analysis.

Durieux et al., arXiv:1809.03520

Design reports quote 2.8% uncertainty from t̄tH analysis at 550 GeV
Towards a global analysis

Linear collider fit of the Higgs sector
arXiv:1708.08912
[see J. Tian]

20 operator coefficients
EWPO + TGC + Higgs data

Adding top EW operators
(based on Vryonidou & Zhang, additional work by S. Jung)

<table>
<thead>
<tr>
<th>Operator</th>
<th>2 ab$^{-1}$ w. pol.</th>
<th>2 ab$^{-1}$ 350 GeV</th>
<th>5 ab$^{-1}$ no pol.</th>
<th>+ 1.5 ab$^{-1}$ at 350 GeV</th>
<th>full ILC 250+500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g(hbb)$</td>
<td>1.04</td>
<td>1.08</td>
<td>0.98</td>
<td>0.66</td>
<td>0.55</td>
</tr>
<tr>
<td>$g(hcc)$</td>
<td>1.79</td>
<td>2.27</td>
<td>1.42</td>
<td>1.15</td>
<td>1.09</td>
</tr>
<tr>
<td>$g(hgg)$</td>
<td>1.60</td>
<td>1.65</td>
<td>1.31</td>
<td>0.99</td>
<td>0.89</td>
</tr>
<tr>
<td>$g(hWW)$</td>
<td>0.65</td>
<td>0.56</td>
<td>0.80</td>
<td>0.42</td>
<td>0.34</td>
</tr>
<tr>
<td>$g(h\tau\tau)$</td>
<td>1.16</td>
<td>1.35</td>
<td>1.06</td>
<td>0.75</td>
<td>0.71</td>
</tr>
<tr>
<td>$g(hZZ)$</td>
<td>0.66</td>
<td>0.57</td>
<td>0.80</td>
<td>0.42</td>
<td>0.34</td>
</tr>
<tr>
<td>$g(h\gamma\gamma)$</td>
<td>1.20</td>
<td>1.15</td>
<td>1.26</td>
<td>1.04</td>
<td>1.01</td>
</tr>
<tr>
<td>$g(h\mu\mu)$</td>
<td>5.53</td>
<td>5.71</td>
<td>5.10</td>
<td>4.87</td>
<td>4.95</td>
</tr>
<tr>
<td>$g(hbb)/g(hWW)$</td>
<td>0.82</td>
<td>0.90</td>
<td>0.58</td>
<td>0.51</td>
<td>0.43</td>
</tr>
<tr>
<td>$g(hWW)/g(hZZ)$</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>$\Gamma_h$</td>
<td>2.38</td>
<td>2.50</td>
<td>2.11</td>
<td>1.49</td>
<td>1.50</td>
</tr>
<tr>
<td>$\alpha(e^+e^- \to Zh)$</td>
<td>0.70</td>
<td>0.77</td>
<td>0.50</td>
<td>0.22</td>
<td>0.61</td>
</tr>
<tr>
<td>$BR(h \to inv)$</td>
<td>0.30</td>
<td>0.56</td>
<td>0.30</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>$BR(h \to other)$</td>
<td>1.50</td>
<td>1.63</td>
<td>1.09</td>
<td>0.94</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 3: Projected relative errors for Higgs boson couplings and other Higgs observables, in %, comparing the full EFT fit described in Section 4 to other possible $e^+e^-$ collider scenarios. The second column shows a fit with 2 ab$^{-1}$, with 80% electron and zero positron polarization, and with a higher energy of 350 GeV. The third and fourth columns show scenarios with no polarization but higher integrated luminosity, 5 ab$^{-1}$ at 250 GeV in the third column and 5 ab$^{-1}$ at 250 GeV plus 1.5 ab$^{-1}$ at 350 GeV in the fourth column. The fifth column gives the result of the fit described in Section 6 including data from 250 and 500 GeV. The notation is as in Table 1.
Towards a global analysis: ILC250 + LEP + HL-LHC

Higgs fit extended with relevant top operators, register change of bounds with respect to the nominal fit of arXiv:1710.07621

The top operators (esp. $C_{ft}$, $C_{tB}$) prove to be a real nuisance for the Higgs fit:

- with current top operator bounds: 4 Higgs parameter degrade O(100%)
- with HL-LHC S2 bounds: $g(hZ\gamma)$, $g(hWW)$, $g(hZZ)$ affected >30%
- with HL-LHC S2 bounds: other Higgs parameters within 10%
- with ILC500 data: fit returns to nominal results

Effect on indirect extraction of top Yukawa and Higgs self-coupling to be assessed
Summary

Top quark properties/interactions are important for the Higgs program;

Three examples:
- Top quark mass:
  - test internal consistency of SM; important for accurate predictions
  - 500 MeV today, possibly 200 MeV at HL-LHC, 50 MeV in $e^+e^-$ threshold scan
- Top quark EW couplings:
  - sensitive probe of composite Higgs models; important in global fits
  - 1-10 TeV$^2$ today, up to two orders improvement at LC with energy above 350 GeV
- Top quark Yukawa coupling:
  - one of the key targets in HEP; complex interplay direct and indirect results
  - large uncertainty today, (few) %-level sensitivity is possible at LC above 550 GeV

Global fit in Effective Field Theory is important to:
- avoid reliance on ad-hoc models
- compare sensitivity across processes
- understand complex relations of Higgs-top-EW sectors