Higgs Synergies/Complementarities

Berlin, May 30, 2017
“FCC week”

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*many thanks to Jiayin Gu for his help in producing several plots
The Higgs in the (B)SM landscape

The fundamental principles governing the structure of Higgs sector are yet unknown (many arbitrary parameters taking seemingly un-natural values)

The Higgs plays a vital role in our life (masses, stability of vacuum, DM?, inflation?)

It has an intimate link with the high energy completion of the SM
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The Higgs discovery has been an important milestone for HEP
but it hasn’t taught us much about BSM yet

typical Higgs coupling deformation: \[ \frac{\delta g_h}{g_h} \sim \frac{g^2 v^2}{\Lambda_{BSM}^2} \]

current (and future) LHC sensitivity \( O(10-20)\% \leftrightarrow \Lambda_{BSM} > 500-700 \text{ GeV} \)

not doing better than direct searches
(except maybe for flavor violating processes, e.g. \( h \rightarrow \mu \tau \))
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Higgs precision programme is very much wanted complementary and synergetic measurements are essential to achieve this goal
The Higgs is the only particle in the SM that interacts with itself. In view of the signals obtained through various production and decay modes, we will use them as reference inputs to precisely correlate the strength of the Higgs boson, allowing the top-Higgs interaction to be measured with a statistical precision at the 1% level – a factor 10 improvement over what is hoped for from the LHC. Similar precision can be reached for particles like the FCC will be needed to explore, more than 10 times more than will be available by the end of LHC operations. During its planned 25 years of data-taking, more than 10^7 top quarks or Higgs bosons, almost 10^9 charged leptons, and 10^12 light sterile neutrinos will be produced for each TeV proton–proton collision, almost 10^11 times the number of data points collected during LHC operations.

At 100 TeV, almost 10^12 produced top quarks will radiate a jet that would be indistinguishable from a hard Higgs boson produced by the top quark decay. The top-Higgs interaction will therefore be experimentally discovered by measuring the single mass peak of the Higgs boson and its strong decay to a top quark pair. The search for Higgs bosons at very large transverse momentum, or by testing the Higgs boson production and decay rates, would be achieved by comparing with previous and existing experimental results. However, experimentalists have been using an oversimplified PR plot to estimate the ultimate precision on the Higgs properties, which we will now summarise. The table shows the sensitivity of the Higgs boson mass measurement after the HL-LHC, FCC-ee, FCC-hh, and FCC-eh to EFT parameters. The FCC-ee can provide the most detail of the Higgs potential by measuring the invisible decay rate. The FCC-eh can provide the most detail of the invisible decay rate. The FCC-eh can provide the sensitivity of the Higgs boson mass measurement after the HL-LHC, FCC-ee, FCC-hh, and FCC-eh to EFT parameters. The FCC-eh can provide the sensitivity of the Higgs boson mass measurement after the HL-LHC, FCC-ee, FCC-hh, and FCC-eh to EFT parameters.
\[
\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{SM}}
\]

\[
\mu_f = \frac{\text{BR}[h \to f]}{\text{BR}[h \to f]_{SM}}
\]
Higgs precision: from $\kappa$ to EFT

$$\mu_i = \frac{\sigma[i \rightarrow h]}{(\sigma[i \rightarrow h])_{\text{SM}}}$$

$$\mu_f = \frac{\text{BR}[h \rightarrow f]}{(\text{BR}[h \rightarrow f])_{\text{SM}}}$$

$$(\sigma \cdot \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\text{SM}}(gg \rightarrow H) \cdot \text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma) \cdot \frac{K_g^2 \cdot K_{\gamma}^2}{K_H^2}$$

individual coupling rescaling factors
Higgs precision: from $\kappa$ to EFT

$$\mu_i = \frac{\sigma[i \rightarrow h]}{(\sigma[i \rightarrow h])_{SM}}$$

$$\mu_f = \frac{\text{BR}[h \rightarrow f]}{(\text{BR}[h \rightarrow f])_{SM}}$$

$$\left(\sigma \cdot \text{BR}\right)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot \text{BR}_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Well suited parametrization for inclusive measurements
But doesn’t do justice to wealth of information available (in particular at e+e- colliders)
Higgs precision: from $\kappa$ to EFT

$$\mu_i = \frac{\sigma[i \rightarrow h]}{(\sigma[i \rightarrow h])_{SM}}$$

$$\mu_f = \frac{\text{BR}[h \rightarrow f]}{(\text{BR}[h \rightarrow f])_{SM}}$$

**Pros of EFT**

- correlations between different channels/observables
- combination of measurements at different energies e.g. EW precision data and Higgs measurements
- test of self-consistency

Well suited parametrization for inclusive measurements

But doesn’t do justice to wealth of information available (in particular at $e^+e^-$ colliders)
Higgs synergy/complementarity

“(A∪B) > A+B”

1. (SM input parameter determination to control parametric uncertainties)
   - obvious examples: $m_Z$, $m_W$, $\alpha_{em}$, $\alpha_s$, $m_t$ ...
   - but also
     \[
     \frac{\Delta \Gamma_{H \rightarrow bb}}{\Gamma_{H \rightarrow bb}} \approx \frac{\Delta m_b(m_b)}{10 \text{ MeV}} \times 0.56\%
     \]
     sub-\% precision requires reducing current uncertainties by a factor 3-5.

2. (Higgs ratios @ hh + absolute normalization @ ee)

3. EW + Higgs synergy

4. Diboson + Higgs synergy

5. LHC and FCC-ee synergy for top Yukawa measurement

6. Inclusive rate + distributions complementarity

7. 240GeV + 350GeV complementarity

8. ee/ep/pp (…PDF measurements to control PDF uncertainties in Higgs data)
EW + Higgs

Reducing numbers of parameters

\[ Z \overset{h}{\otimes} f = \frac{1}{2v} \times Z \overset{f}{\otimes} f \]

Modifications in \( h \to Z f f \) related to \( Z \to f f \)
EW + Higgs

1. Reducing numbers of parameters

2. Exploring different regions of parameter space (in specific models)

Assuming composite Higgs, elementary gauge bosons:

\[ \mathcal{L}_{BSM}^{d=6} = \frac{1}{m_*^2} \frac{1}{g_*^2} \hat{\mathcal{L}}[g_*, H, g_W V_\mu, \partial_\mu] \]
1. Reducing numbers of parameters

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Assuming composite Higgs, elementary gauge bosons:

$$\mathcal{L}^d_{BSM} = \frac{1}{m^*_+ \, g^*_+} \hat{\mathcal{L}}[g_+ H, g_w V_\mu, \partial_\mu]$$

**S-parameter @ee:** [De Blas et. al.] (LEP: 10^{-3})

$$\frac{g_w g'_w}{m^*_+} H^\dagger \sigma_a H W_{\mu \nu}^a B^{\mu \nu} \quad \hat{S} = \frac{m^2_w}{m^*_+} < 10^{-4}$$

Grojean-Wulzer @ FCC physics week '17
EW + Higgs

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- S-parameter @ee: [De Blas et. al.] (LEP: \(10^{-3}\))
  \[
  \frac{g_m g'}{m_*^2} H^\dagger \sigma_{\alpha} H W_{\mu\nu}^{\alpha} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}
  \]

- Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)
  \[
  \frac{g^2}{m_*^2} \partial_{\mu}|H|^2 \partial^{\mu}|H|^2 \Rightarrow \delta_{K_{V,F}} = \frac{g^2 v^2}{m_*^2} < 3 \times 10^{-3}
  \]

Grojean-Wulzer @ FCC physics week '17
Reducing numbers of parameters

Exploring different regions of parameter space (in specific models)

Assuming composite Higgs, elementary gauge bosons:

\[
\mathcal{L}^{d=6}_{\text{BSM}} = \frac{1}{m^2_*} \left( \frac{1}{g^2_*} \right) \mathcal{L}[g_*, H, g_w V_\mu, \partial_\mu]
\]

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

\[
\frac{g_w g'}{m_*^2} H^\dagger \sigma_\alpha H W^a_{\mu\nu} B^{\mu\nu} \quad \Rightarrow \quad \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}
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\frac{g^2}{m_*^2} \partial_\mu |H|^2 \partial^\mu |H|^2 \quad \Rightarrow \quad \delta_{KV,F} = \frac{g^2 v^2}{m_*^2} < 3 \times 10^{-3}
\]

W @hh: (energy + accuracy) (HL-LHC < 10^{-4})

\[
\frac{g_w^2}{g_*^2 m_*^2} (D_\mu W_{\nu\rho})^2 \quad \Rightarrow \quad W = \frac{g_w^2 m_*^2}{g_*^2 m_*^2} < 4 \times 10^{-6}
\]
Gauge bosons + Higgs

In EFT$_{\text{dim-6}}$

- 8 deformations affecting Higgs physics alone
- 2 deformations affecting Higgs and diboson data

TGC (1%) are a priori more constraining than
  Higgs (10%)

Is there any value in doing a global fit?
In EFT\textsuperscript{(dim-6)}

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\[(\text{TGC} \cup \text{Higgs}) > (\text{TGC}) + (\text{Higgs})\]

Strong correlations between 2 data sets

\[
\begin{align*}
\delta m_γ & \sim \delta m_\ell,
\delta g_1 & \sim \delta g_2.
\end{align*}
\]
In EFT\textsubscript{(dim-6)}

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Impact of LHC WW data?
Impact of FCC-ee\textsubscript{350GeV} WW data?
Impact of FCC-hh WW data?

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Impact of LHC WW data?
Impact of FCC-ee 350GeV WW data?
Impact of FCC-hh WW data?

![Graph showing precision reach at FCC-ee 240GeV (10/ab) assuming different systematics for e⁺e⁻ → WW](image)

FCC-ee 240GeV (10/ab), all measurements included, assuming the following systematics in each bin of the differential distributions of e⁺e⁻ → WW:

- Green: 0% (∞ precision in WW data: significant improvements in Higgs coupling determination)
- Yellow: 0.5%
- Orange: 1%
- Red: 2%
- Grey: Higgs measurements only

No WW data: some Higgs couplings badly pinned down

Durieux, Grojean, Gu, Wang '17

Precision reach at FCC-ee 240GeV (10/ab), all measurements included, assuming the following systematics in each bin of the differential distributions of e⁺e⁻ → WW:
1) HL-LHC compensates for the absence of tth measurement at FCC-ee
2) In principle tt near threshold could also help assessing $\gamma_t$ individually (not yet included in this plot)
Top + Higgs

1. Low energy ee collider doesn’t have access to top Yukawa

2. Exploring different regions of parameter space (in specific models)

   Composite tR, comp. Higgs, elementary tL and gauge

   \[ \mathcal{L}^d_{\text{BSM}} = \frac{1}{m^2} \frac{1}{g^2} \hat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu] \]
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   - Composite tR, comp. Higgs, elementary tL and gauge
   - $\mathcal{L}_{\text{BSM}}^{d=6} = \frac{1}{m_*^2} \frac{1}{g_*^2} \hat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$

   **ttH coupling @hh/ee:** [Reports] (HL-LHC:10%)
   - $\frac{y_t g_*^2}{m_*^2} |H|^2 q_L H t_R$
   - $\frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2 \times 10^{-2}$
   - Diff. oper.s comb. in ee and hh!!

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Exploring different regions of parameter space (in specific models)

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$$\mathcal{L}_{BSM}^{d=6} = \frac{1}{m_*^2} \frac{1}{g_*^2} \mathcal{L}[g_* t_R, y_t q_L, g_* H, g_W V_{\mu}, \partial_{\mu}]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2} H^2 q_L H t_R \rightarrow \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2 \times 10^{-2}$$

Diff. oper.s comb. in ee and hh!!

ttV coupling @ee/hh: [Janot / Farina et.al.]

$$\frac{g_*^2}{m_*^2} H^l \tilde{D}_\mu H \tilde{T}_{R^\mu} t_R \rightarrow \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?
1. low energy ee collider doesn’t have access to top Yukawa

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**Composite tR,** comp. Higgs, **elementary tL** and gauge

\[
\mathcal{L}_{BSM}^{d=6} = \frac{1}{m_*^2} \frac{1}{g_*^2} \hat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]
\]

**ttH coupling @hh/ee:** [Reports] (HL-LHC:10%)

\[
\frac{y_t g_*^2}{m_*^2} H^i \bar{D}_\mu H^j \partial_\mu t_R \quad \Rightarrow \quad \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2 \times 10^{-2}
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Diff. oper.s comb. in ee and hh!!

**ttV coupling @ee/hh:** [Janot / Farina et.al.]

\[
\frac{g_*^2 H^i \bar{D}_\mu H^j \partial_\mu t_R}{m_*^2} \quad \Rightarrow \quad \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}
\]

Same hh reach from en. + acc.?

**Zbb coupling @ee:** [ee Report] (LEP:10^{-3})

\[
\frac{y_t^2}{m_*^2} H^i \bar{D}_\mu H^j \partial_\mu q_L + \ldots \quad \Rightarrow \quad \frac{\delta g_{bl}}{g_b} = \frac{m_*^2}{m_*^2} < 2 \times 10^{-4}
\]

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Christophe Grojean

Berlin, May 30, 2017
Top + Higgs

1. low energy ee collider doesn’t have access to top Yukawa

2. Exploring different regions of parameter space (in specific models)

   Composite tR, comp. Higgs, elementary tL and gauge

   \[ \mathcal{L}_{BSM}^{d=6} = \frac{1}{m_0^2} \frac{1}{g_*^2} \hat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu] \]

   **ttH coupling @hh/ee:** [Reports] (HL-LHC:10%)
   
   \[ \frac{y_t g_2^2}{m_*^2} \hat{H}^2 q_L H t_R \rightarrow \frac{\delta y_t}{y_t} = \frac{g_2^2 v^2}{m_*^2} < 2 \times 10^{-2} \]

   Diff. oper.s comb. in ee and hh!!

   **4-top contact interactions @hh:**
   
   \[ \frac{g_2^2}{m_*^2} (\bar{t}_R \gamma_\mu t_R)^2 \rightarrow \frac{g_2^2}{m_*^2} < \frac{1}{\Lambda_4^2} \]

   \[ \frac{y_t^2}{m_*^2} (\bar{q}_L \gamma_\mu q_L)(\bar{t}_R \gamma_\mu t_R) \rightarrow \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_4^2} \]

   \[ \frac{y_t^4}{g_*^2 m_*^2} (\bar{q}_L \gamma_\mu q_L)^2 \rightarrow \frac{y_t^4}{g_*^2 m_*^2} < \frac{1}{\Lambda_4^2} \]

   No study available (?)

   Grojean-Wulzer @ FCC physics week ’17
Inclusive rates + distributions

1) with a run at 240 GeV alone, crucial to have access to angular distributions to break degeneracies
2) with a second run at higher energy makes it less important to look at distributions
Runs at different energies break degeneracies plaguing coupling fits at 240GeV alone

240GeV + 350GeV

share the luminosity between different energies
(run at two different energies compensates for the lack of beam polarization)
Runs at different energies break degeneracies plaguing coupling fits at 240GeV alone

240GeV + 350GeV

GDP quantifies the overall precision measurement (the smaller - the better)
Sharing the luminosity between the energies reduces the GDP faster than accumulating luminosity at low energy

FCC–ee 240GeV and 350GeV, assuming a fixed total 12.6/ab luminosity
L(240GeV) = 12.6, 10, 8, 6, 4, 2, 0 ab⁻¹, L(350GeV) = 12.6/ab – L(240GeV)
dark shade: individual fit assuming all other 10 parameters are zero
Higgs self-coupling(s)

M. McCullough '14

At 240 GeV:

\[ \sigma_{Zh} = \left( \frac{e}{e} \right) + \left( \frac{Z}{h} \right)^2 \]

\[ \delta_{\sigma}^{240} = 100 \left( 2\delta_Z + 0.014\delta_h \right) \% \]

can we disentangle NLO effects from \( h^3 \) from LO effects from other Higgs couplings?
Higgs self-coupling(s)

M. McCullough '14

At 240 GeV:

\[ \sigma_{Zh} = \begin{pmatrix} 2 \Re \end{pmatrix} \]

\[ \delta_{240}^{\sigma} = 100(2\delta_Z + 0.014\delta_h) \% \]

can we disentangle NLO effects from \( h^3 \) from LO effects from other Higgs couplings?

**not at the LHC**

10 parameters for 9 observables
one flat direction!

Incl. single Higgs data

\[ \Delta \chi^2 \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

\[ -4 \quad -2 \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

- 3 ab^{-1}

- \( \kappa_4 \) exclusive fit
- \( \kappa_4 \) exclusive CMS II
- global fit (Higgs + TGC) \( \times 20 \)
Higgs self-coupling(s)

1) if you run at 240 GeV, bound starts to become meaningful only if perfect control of di-boson
2) combining 240+350 improves significantly the bounds on $h^3$

not at the LHC
10 parameters for 9 observables
one flat direction!
better hope at ee
10 parameters for more than 10 observables

1 main production mode: ZH & 1
subdominant production: VBF
+ access to full angular distributions (4) and/or beam polarizations (2)
7 (+2) accessible decay modes: ZZ, WW, $\gamma\gamma$, $Z\tau\tau$, $bb$, $gg$, (cc, $\mu\mu$)

\[ \sigma_{Zh} = \]
1) if you run at 240 GeV, bound starts to become meaningful only if perfect control of di-boson
2) combining 240+350 improves significantly the bounds on $h^3$
3) combination FCC-ee and HL-LHC is very powerful (especially if you cannot afford FCC-ee @ 350GeV)

not at the LHC
10 parameters for 9 observables
one flat direction!

better hope at ee
10 parameters for more than 10 observables

1 main production mode: ZH & I
subdominant production: VBF
+ access to full angular distributions (4) and/or beam polarizations (2)
7 (+2) accessible decay modes: ZZ, WW, $\gamma\gamma$, $Z\tau\tau$, $bb$, $gg$, (cc, $\mu\mu$)
Conclusions

Higgs discovery = profound change in paradigm:
missing SM particle $\rightarrow$ tool to explore SM and venture into physics landscape beyond

we should exploit the full power of this new tool
rich opportunities for synergy/complementarity
the case is growing with several new examples beyond trivial ones
it is up to us to make the best use of them

it takes two to "synergy"
FCC-ee has a lot to offer to partners and a lot to gain too
it is time to join forces
Christophe Grojean

**e^+e^- Colliders**

### CepC
- **5/ab @ 240GeV**
- **10/ab @ 240GeV**
- **200/fb @ 350GeV**
- **2.6/ab @ 350GeV**

### FCC-ee
- **10/ab @ 240GeV**
- **0.5/ab @ 350GeV**
- **200/fb @ 350GeV**
- **4/ab @ 500GeV**

### ILC
- **2/ab @ 250GeV**
- **P(e^+,e^-)=(±80%,±30%)**
- **(200/fb @ 350GeV)**
- **(1.5/ab @ 1.4TeV)**
- **(3/ab @ 3TeV)**

### CLIC
- **0.5/ab @ 350GeV**
- **(250 GeV, 5 ab)**
- **(500 GeV, 2 ab)**
- **(1.4 TeV, 1 ab)**
- **(1.4 TeV, 2 ab)**

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<td><strong>5 ab @ 240 GeV</strong></td>
<td><strong>350 TeV, 10 ab</strong></td>
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<tr>
<td><strong>Z#h</strong></td>
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**Table 2: The estimated precision of CEPC and FCC-ee Higgs measurements. We gather here the constraints obtained from scaling with luminosity. See Table 9.**

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**Table 13: Additional figures for the measurements of the diboson process (C Additional figures 8).**

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**Figure 17**

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**Higgs synergies**
Future measurements used in the fit

- Higgsstrahlung production: $e^+e^- \rightarrow hZ$ (rates and distributions), followed by Higgs decays in various channels,
- Higgs production through weak-boson-fusion: $e^+e^- \rightarrow \nu\bar{\nu}h$,
- Higgs production in association with top quarks: $e^+e^- \rightarrow t\bar{t}h$,
- weak boson pair production: $e^+e^- \rightarrow WW$ (rate and distributions).

\[\text{Future measurements used in the fit}\]

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Higgs Basis

\[ \mathcal{L} \supset \frac{h}{v} \left[ \delta c_w \frac{g^2 v^2}{2} W_\mu^+ W_-^\mu + \delta c_z \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z^\mu \right. \]
\[ + c_{ww} \frac{g^2}{2} W_{\mu\nu}^+ W_-^{\mu\nu} + c_{wq} g^2 \left( W_\mu^- \partial_\nu W_\nu^{+\mu} + \text{h.c.} \right) + \hat{\gamma}_\gamma \frac{e^2}{4\pi^2} A_{\mu\nu} A^{\mu\nu} \]
\[ + c_{zz} \frac{g^2 + g'^2}{4} Z_{\mu\nu} Z^{\mu\nu} + \hat{\gamma}_\gamma \frac{e \sqrt{g^2 + g'^2}}{2\pi^2} Z_{\mu\nu} A^{\mu\nu} + c_{gq} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{gg} g' Z_\mu \partial_\nu A^{\mu\nu} \]
\[ + \frac{g^2}{48\pi^2} \left( \hat{\gamma}_{gg} \frac{h}{v} + \hat{\gamma}_{gg}^{(2)} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu} - \sum_f \left[ m_f \left( \delta y_f \frac{h}{v} + \delta y_f^{(2)} \frac{h^2}{2v^2} \right) \bar{f} \gamma \gamma \gamma f + \text{h.c.} \right] \]
\[ - (\kappa_\lambda - 1) \lambda_3^{SM} v h^3, \]

with

\[ \delta c_w = \delta c_z, \]
\[ c_{ww} = c_{zz} + \frac{g^2}{\pi^2 (g^2 + g'^2)} \hat{c}_{\gamma\gamma} + \frac{g'^2}{\pi^2 (g^2 + g'^2)} \hat{c}_{\gamma\gamma}, \]
\[ c_{wq} = \frac{1}{g^2 - g'^2} \left[ \frac{g^2 c_{\gamma\gamma} + g'^2 c_{zz} - g'^2}{\pi^2 (g^2 + g'^2)} \hat{c}_{\gamma\gamma} - \left( g^2 - g'^2 \right) \frac{g'^2}{\pi^2 (g^2 + g'^2)} \hat{c}_{\gamma\gamma} \right], \]
\[ c_{gq} = \frac{1}{g^2 - g'^2} \left[ 2 g^2 c_{\gamma\gamma} + (g^2 + g'^2) c_{zz} - \frac{g^2}{\pi^2} \hat{c}_{\gamma\gamma} - \frac{g'^2}{\pi^2} \hat{c}_{\gamma\gamma} \right] \]
\[ \hat{c}_{gg}^{(2)} = \hat{c}_{gg}, \]
\[ \delta y_f = 3 \delta y_f - \delta c_z. \]

10 parameters

- 6 deformations of Higgs couplings to gauge bosons
  \[ \delta c_z, \ c_{zz}, \ \hat{c}_{\gamma\gamma}, \ \hat{c}_{\gamma\gamma}, \ \hat{c}_{gg}. \]
- 3 deformations of Higgs couplings to fermions
  \[ \delta y_t, \ \delta y_b, \ \delta y_{\tau}. \]
- 1 deformation of Higgs self-couplings
  \[ \kappa_\lambda. \]
with
\[
\delta c_w = \delta c_z , \\
\delta_{ww} = \delta_{zz} + \frac{g^2}{2\pi} \left[ \frac{g^2}{g^2 - g^2} \right] \hat{c}_{m\gamma} + \frac{g^4}{2\pi(g^2 + g^2)} \hat{c}_{\gamma\gamma} , \\
\delta_{wz} = \frac{1}{g^2 - g^2} \left[ g^2 \hat{c}_{z\gamma} + g^2 \hat{c}_{wz} - \epsilon^2 \frac{g^2}{2\pi(g^2 + g^2)} \hat{c}_{\gamma\gamma} - (g^2 - g^2) \frac{g^2}{2\pi(g^2 + g^2)} \hat{c}_{\gamma\gamma} \right] , \\
\delta_{zz} = \delta_{zz} + \frac{1}{g^2 - g^2} \left[ 2g^2 \hat{c}_{z\gamma} + (g^2 + g^2) \hat{c}_{zz} - \epsilon^2 \frac{g^2}{2\pi} \hat{c}_{\gamma\gamma} - \frac{g^2 - g^2}{2\pi} \hat{c}_{\gamma\gamma} \right] , \\
\hat{c}_{(2)}^{(2)} = \hat{c}_{gg} , \\
\delta y_f^{(3)} = \delta y_f - \delta c_z .
\]
Running at different energies

\[
\frac{\sigma_{hZ}}{\sigma_{hZ}^{SM}} \approx 1 + 2 \delta_{Z} + c_{ZZ} + c_{Z\Box} + c_{\gamma\gamma} + c_{Z\gamma}
\]

interferences between s-channel Z and \( \gamma \) amplitudes are accidentally suppressed in the unpolarized total cross section

large interference for polarized beam

\[
\frac{\sigma_{WW\rightarrow h}}{\sigma_{WW\rightarrow h}^{SM}} \approx 1 + 2 \delta_{Z} + c_{ZZ} + c_{Z\Box} + c_{\gamma\gamma} + c_{Z\gamma}
\]
Introducing the Global Determinant Parameter

Figure 6: In a two-dimensional parameter space, the area of the Gaussian one-sigma ellipse is proportional to the square root of the determinant of the covariance matrix, $\sqrt{\det \sigma^2}$. In $n$ dimensions, the $n$th root of this quantity or *global determinant parameter* (GDP) provides an average of constraints strengths. GDP $\equiv \sqrt[n]{\det \sigma^2}$ ratios measure improvement in global constraint strengths independently of effective-field-theory operator basis.

ratios of GDP are independent of parameters normalization
ratios of GDP are independent of EFT operator basis

smaller GDP = better precision