Higgs Physics at Future Lepton Colliders

- with a slight emphasis on ILC -

Frank Simon
Max-Planck-Institute for Physics

Higgs Couplings 2018
Tokyo, Japan, November 2018
Outline

• Higgs Production at Lepton Colliders
• Collider Options: Linear, Circular
• Higgs Measurements at e⁺e⁻ Colliders: A Few Examples
• Interpretations: Fits, model discrimination & discovery

Will only discuss e⁺e⁻ colliders
[μ colliders provide the possibility for s-channel production (+ the same processes as e⁺e⁻), but are still (very) far off the real axis]
Outline

- Higgs Production at Lepton Colliders
- Collider Options: Linear, Circular
- Higgs Measurements at e+e- Colliders: A Few Examples
- Interpretations: Fits, model discrimination & discovery

Will only discuss e+e- colliders
[μ colliders provide the possibility for s-channel production (+ the same processes as e+e-), but are still (very) far off the real axis]

A word on numbers:
Projected precisions in flux at present, with ongoing work towards the Update of the European Strategy for Particle Physics. Comparisons between different projects are highly non-trivial, and are not attempted here. In general:

Linear Colliders: ILC & CLIC based on full simulations with realistic detector models, complete background and signal samples, uncheated reconstruction, event selection and analysis

Circular Colliders: FCCee using fast simulations and parametrized studies, CEPC full detector simulations with partial samples
Motivation: Pushing the SM beyond its Breaking Point

Finding New Physics in the Higgs Sector

- The Standard Model makes unambiguous predictions about the couplings of the Higgs Boson, which are modified in many BSM models

Examples from PRD 97, 053003 (2018)

% -level precision provides substantial discovery potential - how can this be achieved?

Higgs Physics at Lepton Colliders - Higgs Couplings 2018, November 2018

Frank Simon (fsimon@mpp.mpg.de)
Lepton vs Hadron Colliders

A Question of Backgrounds

- Higher cross section for Higgs production in pp (by ~ 2 orders of magnitude), but: very high background $10^9$ x higher cross section
- In $e^+e^-$: background processes ~ 100 (or less) x higher cross section: high signal purity and efficiency possible
Higgs Production in $e^+e^-$ Collisions

Evolution of Cross Sections with Energy
Higgs Production in $e^+e^-$ Collisions

Evolution of Cross Sections with Energy

![Graph showing the evolution of cross sections with energy.](Image)

- $\sigma(e^+e^- ) \rightarrow H e^+e^-$
- $t\bar{t}H$
- $H H \nu_e\bar{\nu}_e$
- $H H Z$
- $H Z$
- $H\nu_e\bar{\nu}_e$

250 GeV:
Maximum of $ZH$ production
Higgs Production in e⁺e⁻ Collisions

Evolution of Cross Sections with Energy

- 250 GeV:
  - Maximum of ZH production
- 350 GeV:
  - WW fusion kicks in (and top pair production)
Higgs Production in $e^+e^-$ Collisions

Evolution of Cross Sections with Energy

$$\sigma(e^+e^- \rightarrow HX) \quad [fb]$$

![Graph showing the evolution of cross sections with energy](image)

- **250 GeV**: Maximum of ZH production
- **350 GeV**: WW fusion kicks in (and top pair production)
- **500 - 1000+ GeV**: ttH: direct access to top Yukawa coupling

Maximum of ZH production

WW fusion kicks in (and top pair production)

ttH: direct access to top Yukawa coupling
Higgs Production in $e^+e^-$ Collisions

Evolution of Cross Sections with Energy

$\sigma(e^+e^- \rightarrow HX) \ [fb]$ vs. $\sqrt{s} \ [GeV]$

- $250 \ GeV$: Maximum of $ZH$ production
- $350 \ GeV$: $WW$ fusion kicks in (and top pair production)
- $500 - 1000+ \ GeV$: $ttH$: direct access to top Yukawa coupling
- $500 \ GeV$; $1+ \ TeV$: Higgs self-coupling
Higgs Production in $e^+e^-$ Collisions

Evolution of Cross Sections with Energy

- Polarisation plays a role as well:
  - Boosting of signal, reduction of background (or vice versa)
  - Adds key additional input for global fits & increases sensitivity to new phenomena

250 GeV:
Maximum of ZH production

350 GeV:
WW fusion kicks in
(and top pair production)

500 - 1000+ GeV:
ttH: direct access to top
Yukawa coupling

500 GeV; 1+ TeV:
Higgs self-coupling
**e^+e^- Colliders at the Energy Frontier**

*Constraints imposed by Physics*

- Very simple cost model for storage rings: 
  \[ a \frac{E^4}{R} + b R \]
  (a and b taken from LEP - band using optimistic and pessimistic ways of calculating LEP costs)
  NB: Luminosity steeply drops with E in this scenario!

- Likewise for Linear Colliders: 
  \[ c + d E \]
  NB: Relative large offset due to complex infrastructure needed irrespective of final energy - this makes storage rings more efficient up to ~ 300 GeV
**Constraints imposed by Physics**

- Very simple cost model for storage rings:
  
  \[ a \frac{E^4}{R} + b R \]

  *(a and b taken from LEP - band using optimistic and pessimistic ways of calculating LEP costs)*

  **NB:** Luminosity steeply drops with \( E \) in this scenario!

- Likewise for Linear Colliders:
  
  \[ c + d E \]

  **NB:** Relative large offset due to complex infrastructure needed irrespective of final energy - this makes storage rings more efficient up to ~ 300 GeV

Rings are impossible to beat at low energy,
Linear Colliders are high-energy machines!
e^+e^- Colliders at the Energy Frontier

Constraints imposed by Physics

- Very simple cost model for storage rings: 
  \[ a \frac{E^4}{R} + b R \]
  (a and b taken from LEP - band using optimistic and pessimistic ways of calculating LEP costs)
  NB: Luminosity steeply drops with E in this scenario!

- Likewise for Linear Colliders:
  \[ c + d E \]
  NB: Relative large offset due to complex infrastructure needed irrespective of final energy - this makes storage rings more efficient up to ~ 300 GeV

- Rings are impossible to beat at low energy, Linear Colliders are high-energy machines!

- And it is not just about construction costs and energy: 
  Power consumption, capability for polarisation,…

\[ \Rightarrow \] Not a straight-forward optimisation!
The Facilities: Rings
FCCee, CEPC

- “Low tech”, large circumference accelerators - as a first stage of the scientific exploitation of a circular tunnel - later followed by a high-energy hadron collider
- Add state-of-the-art ingredients: Nano-beams, high-gradient SCRF, ...

100 km circumference
booster synchrotron required to achieve high luminosities

synchrotron radiation power:
FCCee: 50 MW/beam
CEPC: up to 30 MW/beam

136 GeV - 365 GeV
91 GeV - 240 GeV

Higgs Physics at Lepton Colliders - Higgs Couplings 2018, November 2018
Frank Simon (fSimon@mpp.mpg.de)
The Facilities: Linear Colliders

ILC, CLIC

• High gradient linear accelerators - intrinsically upgradeable in energy (increase in length, higher-gradient acceleration technologies)

ILC (International Linear Collider)

~ 20 km for 250 GeV
~ 30 km for 500 GeV

superconducting RF
baseline 250 GeV, full TDR energy 500 GeV, potential to 1+ TeV
The Facilities: Linear Colliders

**ILC, CLIC**

- High gradient linear accelerators - intrinsically upgradeable in energy (increase in length, higher-gradient acceleration technologies)

**ILC** (International Linear Collider)

- ~ 20 km for 250 GeV
- ~ 30 km for 500 GeV

superconducting RF

baseline 250 GeV, full TDR energy 500 GeV, potential to 1+ TeV

**CLIC** (Compact Linear Collider)

- 2-beam acceleration
- three stages from 380 GeV (11 km) to 3 TeV (50 km)
Linear Collider Detectors

… similar for FCCee, CEPC

- Realistic detector concepts for Linear Colliders established over the last ~ 15 years
- Capitalize on (and drive) technological advances
- Exploit LC conditions: benign background levels, low event rates, collider time structure, …
Linear Collider Detectors

… similar for FCCee, CEPC

- Realistic detector concepts for Linear Colliders established over the last ~ 15 years
- Capitalize on (and drive) technological advances
- Exploit LC conditions: benign background levels, low event rates, collider time structure, …

highly granular calorimeters & PFA reconstruction

low-mass tracking (all-silicon or TPC)

precision vertex detectors
Linear Collider Detectors

… similar for FCCee, CEPC

- Realistic detector concepts for Linear Colliders established over the last ~ 15 years
- Capitalize on (and drive) technological advances
- Exploit LC conditions: benign background levels, low event rates, collider time structure, …

- Highly granular calorimeters & PFA reconstruction
- Low-mass tracking (all-silicon or TPC)
- Precision vertex detectors

- Key technologies demonstrated in beam tests - performance results used to validate full detector simulations
In Relation to the Higgs Program

Cross-over of luminosity curves in the focus region of Higgs physics

- NB: Circular colliders can have more than one IP (default: 2), while for linear colliders several detectors do not result in an increase in statistics

- Choice of collider energy reflects luminosity evolution with energy: For circular colliders, 240 GeV provides highest ZH statistics, for linear colliders 250 GeV is better
Model Independence: The Pillar of Higgs Physics in $e^+e^-$

The ZH Higgsstrahlung Process

- What model independence means: Measure the coupling of the Higgs Bosons to elementary particles free from model assumptions (e.g. how it decays)
- Requires: The “tagging” of Higgs production without observing the particle directly
  - Not possible at hadron colliders

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-b\bar{b}$

ILD, 250 GeV
Model Independence: The Pillar of Higgs Physics in e⁺e⁻

The ZH Higgsstrahlung Process

- What model independence means: Measure the coupling of the Higgs Bosons to elementary particles free from model assumptions (e.g. how it decays)
- Requires: The “tagging” of Higgs production without observing the particle directly
- Not possible at hadron colliders

\[ m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s} \]

ILD, 250 GeV

\[ e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b} \]
Model Independence: The Pillar of Higgs Physics in $e^+e^-$

The ZH Higgsstrahlung Process

- What model independence means: Measure the coupling of the Higgs Bosons to elementary particles free from model assumptions (e.g. how it decays)
- Requires: The “tagging” of Higgs production without observing the particle directly
- Not possible at hadron colliders

\[ m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s} \]

ILD, 250 GeV

$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$
• Significantly extending the HZ sample:
  Using hadronic Higgs decays - adds
  x4 in statistical sensitivity
• requires careful analysis setup to
  ensure model independence
Hadronic Recoils & Invisible Decays

Fully exploiting Higgsstrahlung

- Significantly extending the HZ sample: Using hadronic Higgs decays - adds x4 in statistical sensitivity
- requires careful analysis setup to ensure model independence

HZ events can be used to constrain invisible Higgs decays:
Limits on the few per mille level

example from CLIC
Precision Measurements of Couplings

Exploring the Higgs Sector

- The main measurements to make:

\[ \sigma \text{ for } Z \text{ recoil measurements} \]

\[ \sigma_{\text{recoil}} \propto g_{HZZ}^2 \]

directly constrain the coupling of Higgs to Z in a model-independent way
Precision Measurements of Couplings
Exploring the Higgs Sector

• The main measurements to make:
  - \( \sigma \) for Z recoil measurements
    \[
    \sigma_{\text{recoil}} \propto g_{HZZ}^2
    \]
    directly constrain the coupling of Higgs to Z in a model-independent way
  
  - \( \sigma \times \text{BR} \) for specific Higgs decays
    \[
    \sigma \times \text{BR}(H \to ff) \propto \frac{g_{Hii}^2 g_{Hff}^2}{\Gamma_{\text{tot}}}
    \]
The main measurements to make:

- $\sigma$ for Z recoil measurements

\[ \sigma_{\text{recoil}} \propto g_{HZZ}^2 \]

directly constrain the coupling of Higgs to Z in a model-independent way

- $\sigma \times \text{BR}$ for specific Higgs decays

\[ \sigma \times \text{BR}(H \rightarrow ff) \propto \frac{g_{Hii}^2 g_{Hff}^2}{\Gamma_{\text{tot}}} \]

measure couplings to fermions and bosons using production and decay

\[ \Rightarrow \] can be made model-independent in combination with the measurement of the HZ coupling in recoil
Unique Measurements at Lepton Colliders

Enabled by the clean environment

- H→bb: A difficult channel at LHC, a “simple” measurement in e⁺e⁻

at LHC

- Low backgrounds, and highly capable detectors enable observations of final states that are hard or impossible at LHC

at e⁺e⁻

# of Higgs produced: ~4,000,000
significance: 5.4σ

~400
5.2σ

J. Tiang, LCWS 2018
Unique Measurements at Lepton Colliders

**Enabled by the clean environment**

- Higgs decays to jets: difficult (or impossible) at hadron colliders

Measurement of $H \rightarrow bb$, $cc$, $gg$

- Profits from excellent flavor tagging enabled by low-mass high-resolution vertex trackers in moderate background environment

Example from CLIC
Unique Measurements at Lepton Colliders
Enabled by the clean environment

- Higgs decays to jets: difficult (or impossible) at hadron colliders

Measurement of $H \rightarrow \text{bb, cc, gg}$
- Profits from excellent flavor tagging enabled by low-mass high-resolution vertex trackers in moderate background environment

![Diagram showing Higgs decays to jets](example from CLIC)
Accessing the Couplings to First Generation Leptons

**A long shot - Requires extreme Luminosities**

- The only chance to access couplings to first generation: Study of s-channel Higgs production in e+e- collisions
- Requires high luminosities and very small energy spread at 125.1 GeV

With special monochromatization setups for FCCee:

Energy spreads of 10 MeV / 6 MeV may be achievable, at significantly reduced luminosity (7 ab⁻¹/year / 2 ab⁻¹/year)

NB: signal sits on very large backgrounds

For both options of the energy spread: Expected signal significance ~ 0.4 σ / \sqrt{t/[\text{years}]}

⇒ Upper limit of 2.5 x SM at 95% CL reachable in ~ 5 years (one IP) of dedicated running
Directly measuring the Coupling to the Top Quark

Requires higher Energies

- Direct access to the top Yukawa coupling provided by ttH final state: requires energy ≥ 500 GeV (ideal ~ 550 GeV - 1.5 TeV)

![Diagram of ttH decay](image)

**Figure 20:** Relative cross section and top Yukawa coupling precision versus centre-of-mass energy, extrapolated based on scaling of signal and main background cross-sections.

---

**6 Modifications of Running Scenarios in Case of New Physics**

The above running scenarios have been derived based on the particles we know today. However, there are many good reasons to expect discoveries of new phenomena at the LHC or the ILC itself. Obviously, such a discovery would lead to modifications of the proposed running scenarios. Since the possibilities are manifold, we outline here the basic techniques which exploit the tunability of centre-of-mass energy and beam helicities at the ILC in order to characterize new particles. In practice, the initial run at $p_s = 500$ GeV would serve as a scouting run. Careful analysis of these data will then give some first information, which would guide the optimisation of the running program for the following years.

**Threshold Scans**

As in the case of the top quark or the $W$ boson, threshold scans are also important tools for a precise determination of the masses of new particles. This has been studied in the literature.
Directly measuring the Coupling to the Top Quark

Requires higher Energies

- Direct access to the top Yukawa coupling provided by $t\bar{t}H$ final state: requires energy $\geq 500$ GeV (ideal $\sim 550$ GeV - $1.5$ TeV)

**ILC:** $\Delta g_{ttH}/g_{ttH} \sim 6.3\%$ with $4$ ab$^{-1}$ @ $500$ GeV
would be $\sim 3\%$ @ $550$ GeV
(and $\sim 13\%$ @ $485$ GeV: achieving design energy critical!)

**CLIC:** $\Delta g_{ttH}/g_{ttH} \sim 2.9\%$ with $2.5$ ab$^{-1}$ @ $1.4$ TeV

**Figure 20:** Relative cross section and top Yukawa coupling precision versus centre-of-mass energy, extrapolated based on scaling of signal and main background cross-sections.

6 Modifications of Running Scenarios in Case of New Physics

The above running scenarios have been derived based on the particles we know today. However, there are many good reasons to expect discoveries of new phenomena at the LHC or the ILC itself. Obviously, such a discovery would lead to modifications of the proposed running scenarios. Since the possibilities are manifold, we outline here the basic techniques which exploit the tunability of centre-of-mass energy and beam helicities at the ILC in order to characterize new particles. In practice, the initial run at $p_s = 500$ GeV would serve as a scouting run. Careful analysis of these data will then give some first information, which would guide the optimisation of the running program for the following years.

Threshold Scans

As in the case of the top quark or the $W$ boson, threshold scans are also important tools for a precise determination of the masses of new particles. This has been studied in the literature.

\[ \Delta g_{ttH} \]
Measuring the Higgs Self-Coupling

Requires higher Energies - may be the ultimate Challenge in Higgs Physics

- Two processes with double Higgs final states provide access to the self-coupling $\lambda$:

the final state also receives contributions from the quartic coupling
Measuring the Higgs Self-Coupling

Requires higher Energies - may be the ultimate Challenge in Higgs Physics

- Two processes with double Higgs final states provide access to the self-coupling $\lambda$:

  - the final state also receives contributions from the quartic coupling

  - cross section depends non-linearly on $\lambda$, measurements at different energies / of different processes lift degeneracies
Measuring the Higgs Self-Coupling

Requires higher Energies - may be the ultimate Challenge in Higgs Physics

- Two processes with double Higgs final states provide access to the self-coupling $\lambda$:

  \[ \text{CLIC: A combination of ZHH (1.4 TeV) and } \nu\nu\text{HH (1.4 TeV + 3 TeV), combining cross section and } M_{\text{HH}} \text{ differential} \]

  \[ \Delta \lambda/\lambda \sim [-7\%, +11\%] \text{ with} \]

  \[ 2.5 \text{ ab}^{-1} \text{ @ 1.4 TeV, } 5 \text{ ab}^{-1} \text{ @ 3 TeV} \]

  \[ \sim \sim 10\% \text{ measurement feasible - but only at multi - TeV collider} \]

- Cross section depends non-linearly on $\lambda$, measurements at different energies / of different processes lift degeneracies

  \[ \text{ILC: Using the ZHH process} \]

  \[ \Delta \lambda/\lambda \sim 27\% \text{ with } 4 \text{ ab}^{-1} \text{ @ 500 GeV} \]
Interpreting Higgs Measurements

A Word on Fits

- The Higgs coupling measurements at any present and future collider unfold their full potential in global fits of all observables - possibly beyond Higgs measurements alone
- The evaluation of the potential of future colliders is based on such fits using projected precisions on various Higgs (and other) measurements as input
Interpreting Higgs Measurements

A Word on Fits

• The Higgs coupling measurements at any present and future collider unfold their full potential in global fits of all observables - possibly beyond Higgs measurements alone
• The evaluation of the potential of future colliders is based on such fits using projected precisions on various Higgs (and other) measurements as input

Typical fits used in this context:

• “Model-independent” fit

  minimize a $\chi^2$ with all measurements:

  $\chi^2 = \sum_i \frac{(C_i - 1)^2}{\Delta F_i^2}$

  $C_{Z\ell} = g_{HZZ}^2$

  $C_{Z\ell, H \to b\bar{b}} = \frac{g_{HZZ}^2 g_{Hbb}^2}{\Gamma_H}$

  $C_{H\ell\ell, \ell\ell \to b\bar{b}} = \frac{g_{HWW}^2 g_{Hbb}^2}{\Gamma_H}$

  $\ldots$

  $\Delta F_i$: uncertainty of measurement ($\sigma$ or $\sigma x \text{BR}$)

  total width as a free parameter: no constraints imposed on BSM decays

  N.B.: Not fully model independent, does not account for certain possible BSM features of HV couplings
Interpreting Higgs Measurements

A Word on Fits

• The Higgs coupling measurements at any present and future collider unfold their full potential in global fits of all observables - possibly beyond Higgs measurements alone
• The evaluation of the potential of future colliders is based on such fits using projected precisions on various Higgs (and other) measurements as input

Typical fits used in this context:

• "Model-independent" fit
  minimize a $\chi^2$ with all measurements:
  $\chi^2 = \sum_i \frac{(C_i - 1)^2}{\Delta F_i^2}$
  $C_{ZH} = g_{HZZ}^2$
  $C_{ZH,H \rightarrow bb} = \frac{g_{HZZ}^2 g_{Hbb}^2}{\Gamma_H}$
  $C_{H_{WW},H \rightarrow bb} = \frac{g_{HWW}^2 g_{Hbb}^2}{\Gamma_H}$
  $\Delta F_i$: uncertainty of measurement ($\sigma$ or $\alpha x BR$)

• "Model-dependent $\kappa$" fit
  the same as the MI fit, with the total width constrained to the sum of the SM decays
  $\kappa_i^2 = \frac{\Gamma_i}{\Gamma_{i|SM}}$
  $\Gamma_{H,md} = \sum_i \kappa_i^2 BR_i$
  total width as a free parameter: no constraints imposed on BSM decays
  N.B.: Not fully model independent, does not account for certain possible BSM features of HV couplings
Interpreting Higgs Measurements

A Word on Fits

- The Higgs coupling measurements at any present and future collider unfold their full potential in global fits of all observables - possibly beyond Higgs measurements alone
- The evaluation of the potential of future colliders is based on such fits using projected precisions on various Higgs (and other) measurements as input

Typical fits used in this context:

- **“Model-independent” fit**
  minimize a $\chi^2$ with all measurements:
  \[
  \chi^2 = \sum_i \frac{(C_i - 1)^2}{\Delta F_i^2}
  \]

- **“Model-dependent $\kappa$” fit**
  the same as the MI fit, with the total width constrained to the sum of the SM decays

- **“Model-independent EFT” fit**
  A global fit of Higgs and other EW observables parametrizing deviations from the SM by various operators - allows for couplings not included in $\kappa$ fit, includes connections between W and Z couplings

N.B.: Not fully model independent, does not account for certain possible BSM features of HV couplings

$$
\begin{align*}
C_{ZH} &= g_{HZZ}^2 \\
C_{ZH, H \to bb} &= \frac{g_{HZZ}^2 g_{Hbb}^2}{\Gamma_H} \\
C_{H_{\nu\nu}, H \to bb} &= \frac{g_{HWW}^2 g_{Hbb}^2}{\Gamma_H} \\
\cdots
\end{align*}
$$

$\Delta F_i$: uncertainty of measurement ($\sigma$ or $\sigma x BR$)

$$
\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}} \quad \Gamma_{H, md} = \sum_i \kappa_i^2 BR_i
$$

total width as a free parameter: no constraints imposed on BSM decays
Extracting the Total Width

*Model independent measurement at high precision*

- $e^+e^-$ colliders provide the possibility for a model-independent measurement of the total width at the level of a few %:
Extracting the Total Width

*Model independent measurement at high precision*

- $e^+e^-$ colliders provide the possibility for a model-independent measurement of the total width at the level of a few %:

- In the “model-independent fit” framework the total width is obtained from production and decay of the Higgs:

\[
\sigma(ZH) \times BR(H \rightarrow ZZ) \propto \frac{g_{HZZ}^4}{\Gamma_{tot}} \quad \text{and} \quad \sigma(ZH) \propto g_{HZZ}^2
\]

⇒ The low BR of H->ZZ and correspondingly large uncertainties make this determination relatively imprecise
Extracting the Total Width

Model independent measurement at high precision

- \( e^+e^- \) colliders provide the possibility for a model-independent measurement of the total width at the level of a few %:

- In the “model-independent fit” framework the total width is obtained from production and decay of the Higgs:

  \[
  \sigma(ZH) \times BR(H \rightarrow ZZ) \propto \frac{g_{HZZ}^4}{\Gamma_{tot}} \quad \text{and} \quad \sigma(ZH) \propto g_{HZZ}^2
  \]

  - The low BR of H\(\rightarrow\)ZZ and correspondingly large uncertainties make this determination relatively imprecise

  - Profits substantially from higher energy, where WW fusion becomes relevant:

    \[
    \sigma(H\nu_e\nu_e) \times BR(H \rightarrow WW^*) \propto \frac{g_{HWW}^4}{\Gamma_{tot}}
    \]

    \[
    \frac{\sigma(e^+e^- \rightarrow ZH) \times BR(H \rightarrow b\bar{b})}{\sigma(e^+e^- \rightarrow H\nu_e\nu_e) \times BR(H \rightarrow b\bar{b})} \propto \frac{g_{HZZ}^2}{g_{HWW}^2}
    \]

    need the “model-independent anchor” of the ZH measurement
Extracting the Total Width

\[ \text{Model independent measurement at high precision} \]

- $e^+e^-$ colliders provide the possibility for a model-independent measurement of the total width at the level of a few %:

- In the “model-independent fit” framework the total width is obtained from production and decay of the Higgs:

\[
\sigma(ZH) \times BR(H \to ZZ) \propto \frac{g_{HZZ}^4}{\Gamma_{tot}} \quad \text{and} \quad \sigma(ZH) \propto g_{HZZ}^2
\]

- The low BR of H->ZZ and correspondingly large uncertainties make this determination relatively imprecise.

- Profits substantially from higher energy, where WW fusion becomes relevant:

\[
\sigma(H\nu_e\nu_e) \times BR(H \to WW^*) \propto \frac{g_{HWW}^4}{\Gamma_{tot}}
\]

\[
\frac{\sigma(e^+e^- \to ZH) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to H\nu_e\nu_e) \times BR(H \to b\bar{b})} \propto \frac{g_{HZZ}^2}{g_{HWW}^2}
\]

- Higher energies important for width measurements

- In EFT fits W and Z are connected, there the width can be well constrained also without WW fusion.

Need the “model-independent anchor” of the ZH measurement.
Perspectives on Precision
Still in flux - Meant as a rough Guide

• Comparisons of the potential of different colliders are non-straightforward: The projections are based on different levels of realism / pessimism / optimism in detector modeling, analysis techniques, systematic uncertainties and machine parameters / running scenarios,…

Here: Taking the “model independent” fit results - combine the projected uncertainties on $\sigma_{xBR}$

<table>
<thead>
<tr>
<th></th>
<th>ILC 250</th>
<th>ILC 500</th>
<th>CLIC 380</th>
<th>CLIC 3 TeV</th>
<th>CEPC</th>
<th>FCCee 240</th>
<th>FCCee 365</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{HZZ}/g_{HZZ}$</td>
<td>0.38</td>
<td>0.30</td>
<td>0.6</td>
<td>0.6</td>
<td>0.25</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>$\delta g_{HWW}/g_{HWW}$</td>
<td>1.8</td>
<td>0.40</td>
<td>1.0</td>
<td>0.6</td>
<td>1.4</td>
<td>1.3</td>
<td>0.47</td>
</tr>
<tr>
<td>$\delta g_{Hbb}/g_{Hbb}$</td>
<td>1.8</td>
<td>0.60</td>
<td>2.1</td>
<td>0.7</td>
<td>1.3</td>
<td>1.4</td>
<td>0.68</td>
</tr>
<tr>
<td>$\delta g_{Hcc}/g_{Hcc}$</td>
<td>2.4</td>
<td>1.2</td>
<td>4.4</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
<td>1.23</td>
</tr>
<tr>
<td>$\delta g_{Hgg}/g_{Hgg}$</td>
<td>2.2</td>
<td>0.97</td>
<td>2.6</td>
<td>1.0</td>
<td>1.5</td>
<td>1.7</td>
<td>1.03</td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>1.9</td>
<td>0.80</td>
<td>3.1</td>
<td>1.0</td>
<td>1.5</td>
<td>1.4</td>
<td>0.80</td>
</tr>
<tr>
<td>$\delta g_{Hqq}/g_{Hqq}$</td>
<td>5.6</td>
<td>5.1</td>
<td>5.7</td>
<td>8.7</td>
<td>9.6</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>$\delta g_{HYY}/g_{HYY}$</td>
<td>1.1</td>
<td>1.0</td>
<td>2.3</td>
<td>3.7</td>
<td>4.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>-</td>
<td>6.7</td>
<td>-</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\delta \Gamma_{H}/\Gamma_{H}$</td>
<td>3.9</td>
<td>1.7</td>
<td>4.7</td>
<td>2.5</td>
<td>2.8</td>
<td>2.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

ILC 250: 2 ab⁻¹ @ 250 GeV
ILC 500: +0.2 ab⁻¹ @ 350 GeV
+ 4 ab⁻¹ @ 500 GeV
CLIC 380: 1 ab⁻¹ @ 380 GeV
CLIC 3 TeV: + 2.5 ab⁻¹ @ 1.5 TeV
+ 5 ab⁻¹ @ 3 TeV
CEPC: 5.6 ab⁻¹ @ 240 GeV
FCCee 240: 5 ab⁻¹ @ 240 GeV
FCCee 365: + 1.5 ab⁻¹ @ 365 GeV
Perspectives on Precision

Still in flux - Meant as a rough Guide

- Comparisons of the potential of different colliders are non-straightforward: The projections are based on different levels of realism / pessimism / optimism in detector modeling, analysis techniques, systematic uncertainties and machine parameters / running scenarios,…

Here: Taking the “model independent” fit results - combine the projected uncertainties on σxBR

<table>
<thead>
<tr>
<th></th>
<th>ILC 250</th>
<th>ILC 500</th>
<th>CLIC 380</th>
<th>CLIC 3 TeV</th>
<th>CEPC</th>
<th>FCCee 240</th>
<th>FCCee 365</th>
</tr>
</thead>
<tbody>
<tr>
<td>δg_{HZZ}/g_{HZZ}</td>
<td>0.38</td>
<td>0.30</td>
<td>0.6</td>
<td>0.6</td>
<td>0.25</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>δg_{HWW}/g_{HWW}</td>
<td>1.8</td>
<td>0.40</td>
<td>1.0</td>
<td>0.6</td>
<td>1.4</td>
<td>1.3</td>
<td>0.47</td>
</tr>
<tr>
<td>δg_{Hbb}/g_{Hbb}</td>
<td>1.8</td>
<td>0.60</td>
<td>2.1</td>
<td>0.7</td>
<td>1.3</td>
<td>1.4</td>
<td>0.68</td>
</tr>
<tr>
<td>δg_{Hcc}/g_{Hcc}</td>
<td>2.4</td>
<td>1.2</td>
<td>4.4</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
<td>1.23</td>
</tr>
<tr>
<td>δg_{Hgg}/g_{Hgg}</td>
<td>2.2</td>
<td>0.97</td>
<td>2.6</td>
<td>1.0</td>
<td>1.5</td>
<td>1.7</td>
<td>1.03</td>
</tr>
<tr>
<td>δg_{Htt}/g_{Htt}</td>
<td>1.9</td>
<td>0.80</td>
<td>3.1</td>
<td>1.0</td>
<td>1.5</td>
<td>1.4</td>
<td>0.80</td>
</tr>
<tr>
<td>δg_{HH}\gamma/g_{HH}\gamma</td>
<td>5.6</td>
<td>5.1</td>
<td>5.7</td>
<td>8.7</td>
<td>9.6</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>δg_{H\mu\mu}/g_{H\mu\mu}</td>
<td>1.1</td>
<td>1.0</td>
<td>2.3</td>
<td>3.7</td>
<td>4.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>δg_{H\gamma\gamma}/g_{H\gamma\gamma}</td>
<td>-</td>
<td>6.7</td>
<td>-</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>δΓ_{H}/Γ_{H}</td>
<td>3.9</td>
<td>1.7</td>
<td>4.7</td>
<td>2.5</td>
<td>2.8</td>
<td>2.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

ILC 250: 2 ab⁻¹ @ 250 GeV
ILC 500: +0.2 ab⁻¹ @ 350 GeV
   + 4 ab⁻¹ @ 500 GeV
CLIC 380: 1 ab⁻¹ @ 380 GeV
CLIC 3 TeV: + 2.5 ab⁻¹ @ 1.5 TeV
   + 5 ab⁻¹ @ 3 TeV
CEPC: 5.6 ab⁻¹ @ 240 GeV
FCCee 240: 5 ab⁻¹ @ 240 GeV
FCCee 365: + 1.5 ab⁻¹ @ 365 GeV
Perspectives on Precision

Still in flux - Meant as a rough Guide

• Comparisons of the potential of different colliders are non-straightforward: The projections are based on different levels of realism / pessimism / optimism in detector modeling, analysis techniques, systematic uncertainties and machine parameters / running scenarios,…

Here: Taking the “model independent” fit results - combine the projected uncertainties on $\sigma_{xBR}$

<table>
<thead>
<tr>
<th></th>
<th>ILC 250</th>
<th>ILC 500</th>
<th>CLIC 380</th>
<th>CLIC 3 TeV</th>
<th>CEPC</th>
<th>FCCee 240</th>
<th>FCCee 365</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{HZZ}/g_{HZZ}$</td>
<td>0.38</td>
<td>0.30</td>
<td>0.6</td>
<td>0.6</td>
<td>0.25</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>$\delta g_{HWW}/g_{HWW}$</td>
<td>1.8</td>
<td>0.40</td>
<td>1.0</td>
<td>0.6</td>
<td>1.4</td>
<td>1.3</td>
<td>0.47</td>
</tr>
<tr>
<td>$\delta g_{Hbb}/g_{Hbb}$</td>
<td>1.8</td>
<td>0.60</td>
<td>2.1</td>
<td>0.7</td>
<td>1.3</td>
<td>1.4</td>
<td>0.68</td>
</tr>
<tr>
<td>$\delta g_{Hcc}/g_{Hcc}$</td>
<td>2.4</td>
<td>1.2</td>
<td>4.4</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
<td>1.23</td>
</tr>
<tr>
<td>$\delta g_{Hgg}/g_{Hgg}$</td>
<td>2.2</td>
<td>0.97</td>
<td>2.6</td>
<td>1.0</td>
<td>1.5</td>
<td>1.7</td>
<td>1.03</td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>1.9</td>
<td>0.80</td>
<td>3.1</td>
<td>1.0</td>
<td>1.5</td>
<td>1.4</td>
<td>0.80</td>
</tr>
<tr>
<td>$\delta g_{HWW}/g_{HWW}$</td>
<td>1.1</td>
<td>1.0</td>
<td>2.3</td>
<td>3.7</td>
<td>4.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>-</td>
<td>6.7</td>
<td>-</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\delta \Gamma_{H}/\Gamma_{H}$</td>
<td>3.9</td>
<td>1.7</td>
<td>4.7</td>
<td>2.5</td>
<td>2.8</td>
<td>2.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

ILC 250: 2 ab$^{-1}$ @ 250 GeV
ILC 500: +0.2 ab$^{-1}$ @ 350 GeV
   + 4 ab$^{-1}$ @ 500 GeV
CLIC 380: 1 ab$^{-1}$ @ 380 GeV
CLIC 3 TeV: + 2.5 ab$^{-1}$ @ 1.5 TeV
   + 5 ab$^{-1}$ @ 3 TeV
CEPC: 5.6 ab$^{-1}$ @ 240 GeV
FCCee 240: 5 ab$^{-1}$ @ 240 GeV
FCCee 365: + 1.5 ab$^{-1}$ @ 365 GeV
Perspectives on Precision
Still in flux - Meant as a rough Guide

- Comparisons of the potential of different colliders are non-straightforward: The projections are based on different levels of realism / pessimism / optimism in detector modeling, analysis techniques, systematic uncertainties and machine parameters / running scenarios,…

Here: Taking the “model independent” fit results - combine the projected uncertainties on $\sigma_x BR$

<table>
<thead>
<tr>
<th></th>
<th>ILC 250</th>
<th>ILC 500</th>
<th>CLIC 380</th>
<th>CLIC 3 TeV</th>
<th>CEPC</th>
<th>FCCee 240</th>
<th>FCCee 365</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{HZZ}/g_{HZZ}$</td>
<td>0.38</td>
<td>0.30</td>
<td>0.6</td>
<td>0.6</td>
<td>0.25</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>$\delta g_{HWW}/g_{HWW}$</td>
<td>1.8</td>
<td>0.40</td>
<td>1.0</td>
<td>0.6</td>
<td>1.4</td>
<td>1.3</td>
<td>0.47</td>
</tr>
<tr>
<td>$\delta g_{Hbb}/g_{Hbb}$</td>
<td>1.8</td>
<td>0.60</td>
<td>2.1</td>
<td>0.7</td>
<td>1.3</td>
<td>1.4</td>
<td>0.68</td>
</tr>
<tr>
<td>$\delta g_{Hcc}/g_{Hcc}$</td>
<td>2.4</td>
<td>1.2</td>
<td>4.4</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
<td>1.23</td>
</tr>
<tr>
<td>$\delta g_{Hgg}/g_{Hgg}$</td>
<td>2.2</td>
<td>0.97</td>
<td>2.6</td>
<td>1.0</td>
<td>1.5</td>
<td>1.7</td>
<td>1.03</td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>1.9</td>
<td>0.80</td>
<td>3.1</td>
<td>1.0</td>
<td>1.5</td>
<td>1.4</td>
<td>0.80</td>
</tr>
<tr>
<td>$\delta g_{Hmm}/g_{Hmm}$</td>
<td>5.6</td>
<td>5.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta g_{Hlv}/g_{Hlv}$</td>
<td>1.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td>2.3</td>
<td>3.7</td>
<td>4.7</td>
</tr>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>-</td>
<td>6.7</td>
<td>-</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\delta \Gamma_H/\Gamma_H$</td>
<td>3.9</td>
<td>1.7</td>
<td>4.7</td>
<td>2.5</td>
<td>2.8</td>
<td>2.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

ILC 250: 2 ab$^{-1}$ @ 250 GeV
ILC 500: +0.2 ab$^{-1}$ @ 350 GeV
   + 4 ab$^{-1}$ @ 500 GeV
CLIC 380: 1 ab$^{-1}$ @ 380 GeV
CLIC 3 TeV: + 2.5 ab$^{-1}$ @ 1.5 TeV
   + 5 ab$^{-1}$ @ 3 TeV
CEPC: 5.6 ab$^{-1}$ @ 240 GeV
FCCee 240: 5 ab$^{-1}$ @ 240 GeV
FCCee 365: + 1.5 ab$^{-1}$ @ 365 GeV
A Closer Look at ILC - in relation to LHC

Based on preliminary numbers in preparation for the ESU

• ILC (and other e^+e^- colliders) provide model-independent measurements of couplings - can be used to extend model independence to LHC measurements

![Bar chart showing precision of Higgs boson couplings in percentage]
A Closer Look at ILC - in relation to LHC

Based on preliminary numbers in preparation for the ESU

**Model Independent Fit**

- ILC (and other e^+e^- colliders) provide model-independent measurements of couplings - can be used to extend model independence to LHC measurements

**Model Dependent Fit**

- ILC (and other e^+e^- colliders) go substantially beyond HL-LHC precision for a model-dependent analysis of Higgs results - 1 order of magnitude improvement in key channels

---

- **Higgs Physics at Lepton Colliders** - Higgs Couplings 2018, November 2018

Frank Simon (fSimon@mpp.mpg.de)
Precision measurements of couplings may show deviations from the Standard Model.

“Fingerprinting” of deviation pattern reveals underlying mechanisms.
• Precision measurements of couplings may show deviations from the Standard Model
• “Fingerprinting” of deviation pattern reveals underlying mechanisms
• Discrimination power between models illustrated with EFT fit of ILC projections

Integrated Luminosities [fb^{-1}]

ILC, Scenario H20-staged-dBS
- ECM = 250 GeV
- ECM = 350 GeV
- ECM = 500 GeV

years

ILC 250 GeV 2 ab^{-1} Higgs and cTGCs EFT interpretation

model discrimination in \sigma

SM
pMSSM
2HDM-II
2HDM-X
2HDM-Y
Composite
LHT-6
LHT-7
Radion
Singlet

LUMINOUS UPGRADE
ENERGY UPGRADE

Higgs Physics at Lepton Colliders - Higgs Couplings 2018, November 2018

Frank Simon (fSimon@mpp.mpg.de)
• Precision measurements of couplings may show deviations from the Standard Model
• “Fingerprinting” of deviation pattern reveals underlying mechanisms

• Discrimination power between models illustrated with EFT fit of ILC projections
• higher energy may be decisive
The Path towards the Real Axis

Waiting for Green Light… and for Strategies

• Decisions on next generation of facilities expected in the coming year(s):
  • Statement from Japan on ILC expected in coming weeks - possible site in Kitakami, north of Sendai
  • Update of European Strategy for Particle Physics: Towards the next project at CERN, but also with global consequences
The Path towards the Real Axis
Waiting for Green Light… and for Strategies

- Decisions on next generation of facilities expected in the coming year(s):
  - Statement from Japan on ILC expected in coming weeks - possible site in Kitakami, north of Sendai
  - Update of European Strategy for Particle Physics: Towards the next project at CERN, but also with global consequences

ILC Time Line: Progress and Prospect
The Path towards the Real Axis

Waiting for Green Light… and for Strategies

- Decisions on next generation of facilities expected in the coming year(s):
  - Statement from Japan on ILC expected in coming weeks - possible site in Kitakami, north of Sendai
  - Update of European Strategy for Particle Physics: Towards the next project at CERN, but also with global consequences

ILC Time Line: Progress and Prospect

- ILC technology ready:
  European XFEL at DESY in operation, a 10% prototype of ILC main LINAC
Conclusions

• $e^+e^-$ colliders provide the natural next step beyond HL-LHC for a thorough exploration of the Higgs sector:
  • Model-independent measurements of couplings and total width
  • Improvement of precision by up to an order of magnitude in many channels
  • Access to couplings difficult or impossible to measure at LHC

• Two classes of colliders under discussion:
  • Circular colliders FCCee, CEPC, with high luminosity for the ZH process and a maximum reach of 365 GeV
  • Linear colliders ILC and CLIC, with polarized beams and intrinsic energy upgradeability, currently up to 3 TeV
    • Uniquely capable of measuring the self-coupling - requires TeV+ energies for precision measurements

• It is decision time:
  • Concrete statement from Japan expected before the end of the year
  • Update of European Strategy for Particle Physics to set future directions at CERN (and elsewhere) in 2020
  • Progress in China towards CEPC / SppC
Extras
Linear Colliders
Key Elements & Performance Drivers

- Future $e^+e^-$ colliders need:
  - High energy to explore the energy frontier
  - High luminosity to cope with falling cross sections, and to make precision measurements

For *linear colliders*, this means:
- High acceleration gradient
- Extreme focusing of beams

Considerable complexity: “offset” in the costs in the “zero energy limit”
Linear Colliders

Key Elements & Performance Drivers

- Future e⁺e⁻ colliders need:
  - High energy to explore the energy frontier
  - High luminosity to cope with falling cross sections, and to make precision measurements

For linear colliders, this means:
- High acceleration gradient
- Extreme focusing of beams

Considerable complexity: “offset” in the costs in the “zero energy limit”
Linear Colliders
Key Elements & Performance Drivers

- Future $e^+e^-$ colliders need:
  - High energy to explore the energy frontier
  - High luminosity to cope with falling cross sections, and to make precision measurements

For **linear colliders**, this means:
- High acceleration gradient
- Extreme focusing of beams

Considerable complexity:
“offset” in the costs in the “zero energy limit”
Linear Colliders
Key Elements & Performance Drivers

- Future e⁺e⁻ colliders need:
  - High energy to explore the energy frontier
  - High luminosity to cope with falling cross sections, and to make precision measurements

For linear colliders, this means:
- High acceleration gradient
- Extreme focusing of beams

Considerable complexity: “offset” in the costs in the “zero energy limit”

Need for focusing results in beamstrahlung: Effect on physics through
- Luminosity spectrum
- Background
Linear Colliders

Key Elements & Performance Drivers

- Future e⁺e⁻ colliders need:
  - High energy to explore the energy frontier
  - High luminosity to cope with falling cross sections, and to make precision measurements

For **linear colliders**, this means:
- High acceleration gradient
- Extreme focusing of beams

Considerable complexity: “offset” in the costs in the “zero energy limit”

Need for focusing results in beamstrahlung: Effect on physics through
- Luminosity spectrum
- Background

⇒ The linear layout provides a straight-forward energy upgrade path!
Linear Colliders

Main Technological Options

- Two collider concepts - based on different main linac technologies:

  The International Linear Collider

  - Superconducting RF structures, ~ 35 MV/m
Linear Colliders

Main Technological Options

- Two collider concepts - based on different main linac technologies:

  The International Linear Collider

  - Superconducting RF structures, ~ 35 MV/m

  - Fully established technology, used in European XFEL recently constructed at DESY (a ~ 10% prototype of the ILC main linac)
Linear Colliders

Main Technological Options

- Two collider concepts - based on different main linac technologies:

  **The International Linear Collider**
  - Superconducting RF structures, ~ 35 MV/m
  - Fully established technology, used in European XFEL recently constructed at DESY (a ~ 10% prototype of the ILC main linac)

  **The Compact Linear Collider**
  - Warm structures, 2 beam acceleration, ~ 100 MV/m
Linear Colliders

*Main Technological Options*

- Two collider concepts - based on different main linac technologies:
  
  **The International Linear Collider**
  - Superconducting RF structures, ~ 35 MV/m
  - Fully established technology, used in European XFEL recently constructed at DESY (a ~ 10% prototype of the ILC main linac)

  **The Compact Linear Collider**
  - Warm structures, 2 beam acceleration, ~ 100 MV/m
  - All key steps successfully demonstrated: high-current drive beam, power transfer & acceleration, 100 MV/m gradient
  - In progress: Industrialization, application in smaller facilities
Linear Colliders
 Plans for Facilities

- Concrete worked-out designs for both facilities
- CLIC: Conceptual Design Report in 2012

- Now proposed as a 250 GeV machine, upgradeable to 500 GeV, with ultimate potential to 1 - 1.5 TeV
- A staged machine, with an initial energy of 380 GeV and ultimate energy of 3 TeV
Schedule: CLIC

The Road to Physics

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion