# Higgs Physics at Linear Colliders

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# Outline

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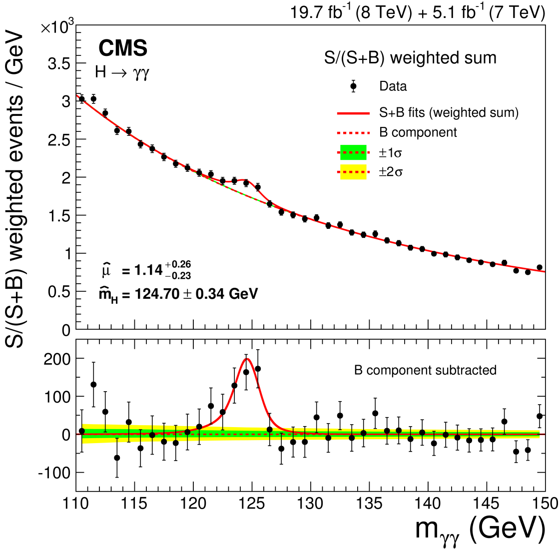
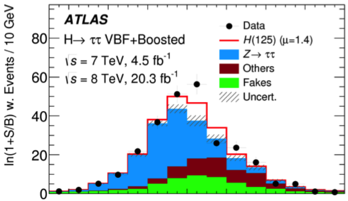
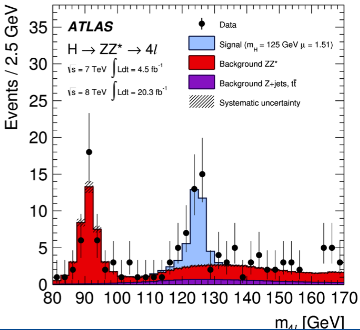
# New Boson Discovered by ATLAS and CMS



# 2013 Nobel Prize in Physics

Peter Higgs

Francois Englert

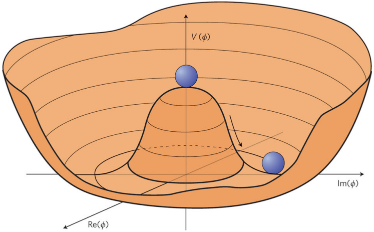
# Electroweak Symmetry Breaking

**Problem:**

- Massive gauge bosons violate gauge invariance in non-abelian gauge theories
- But: W and Z bosons are massive!

**Solution:**

- Electroweak symmetry has to be broken (hidden symmetry)
- Postulate existence of additional isospin doublet of complex scalar field $\phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$
- Adds $\mathcal{L}_H = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi)$
- Choose gauge transformation such that $\phi^+ = 0$ to keep electromagnetic symmetry unbroken (photon is massless)




$$V(\phi) = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{4} \left(\phi^\dagger \phi\right)^2$$

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# Electroweak Symmetry Breaking

- Minimum reached for $\phi^\dagger\phi = \frac{2\mu^2}{\lambda}$

$$< \phi_0 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

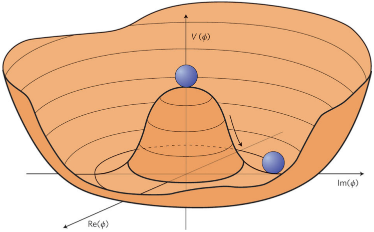
- Vacuum expectation value $\upsilon = \frac{2\mu}{\sqrt{\lambda}}$
- Expand field around minimum

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \upsilon + H(x) \end{pmatrix}$$

- Higgs potential

$$V = \mu^2 H^2 + \frac{\mu^2}{\upsilon} H^3 + \frac{\mu^2}{4\upsilon^2} H^4$$

- Higgs mass: $m_{\mathrm{H}} = \sqrt{2}\mu$
- Triple and quartic Higgs couplings proportional to $m_{\mathrm{H}}\sqrt{\lambda}$ and $\lambda$, respectively




$$V(\phi) = -\mu^2\phi^\dagger\phi + \frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2$$

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# W and Z Boson Masses

- Fundamental vector bosons $W^{1,2,3}$ and $B$ are massless
- Covariant derivative:

$$D_\mu = \partial_\mu - ig_2 \frac{\sigma_a}{2} W^a_\mu + i\frac{g_1}{2} B_\mu$$

- Mass terms appear in Langrangian:

$$\mathcal{L}_\Delta = \frac{1}{2}\left(\frac{g_2 \upsilon}{2}\right)^2 \left((W_1)^2 + (W_2)^2\right) + \frac{1}{2}\left(\frac{\upsilon}{2}\right)^2 (W^3_\mu, B_\mu) \begin{pmatrix} g_2^2 & g_1 g_2 \\ g_1 g_2 & g_1^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Change basis into physical fields:

$$\mathcal{L}_\Delta = \frac{1}{2}\left(\frac{g_2 \upsilon}{2}\right)^2 \mathrm{W}^+_\mu \mathrm{W}^{-\,\mu} + \frac{1}{2}\left(\frac{\upsilon}{2}\right)^2 \left(A_\mu, \mathrm{Z}_\mu\right) \begin{pmatrix} 0 & 0 \\ 0 & 2\left(g_1^2 + g_2^2\right) \end{pmatrix} \begin{pmatrix} A^\mu \\ \mathrm{Z}^\mu \end{pmatrix}$$

- $m_\mathrm{W} = \dfrac{\upsilon}{2} g_2$ and $m_\mathrm{Z} = \dfrac{\upsilon}{2}\sqrt{g_1^2 + g_2^2}$ with $m_\mathrm{W} = m_\mathrm{Z} \cos\theta_w$
- Photon stays massless

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# Yukawa Coupling to Fermions

- In the SM the weak force acts only on left(right)-handed (anti)particles
- Fermion mass term mixes different representations (doublet, singlet) and violate gauge invariance

$$\mathcal{L}_\Delta = m_f(\overline{\psi}_\mathrm{L}\psi_\mathrm{R} + \overline{\psi}_\mathrm{R}\psi_\mathrm{L}), \text{ with } \psi_\mathrm{L} = \begin{pmatrix} \nu_{\mathrm{e}f} \\ \mathrm{e}_\mathrm{L} \end{pmatrix}, \ \psi_\mathrm{R} = \mathrm{e}_\mathrm{R}$$

- Postulate Yukawa coupling of Higgs field to fermions

$$\mathcal{L}_Y^f = -g_f \ \overline{\psi}_\mathrm{L} \ \phi \ \psi_\mathrm{R} - g_f \ \psi_\mathrm{L} \ \phi \ \overline{\psi}_\mathrm{R} \text{ with } \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \upsilon + H \end{pmatrix}$$

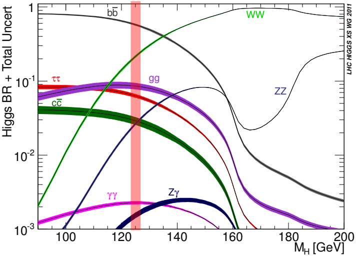
$$\Rightarrow \mathcal{L}_Y^\mathrm{e} = -g_\mathrm{e}\frac{\upsilon}{\sqrt{2}}(\bar{\mathrm{e}}_\mathrm{L} \ \mathrm{e}_\mathrm{R} + \bar{\mathrm{e}}_\mathrm{L} \ \mathrm{e}_\mathrm{R}) - g_\mathrm{e}\frac{1}{\sqrt{2}}(\bar{\mathrm{e}}_\mathrm{L} \ \mathrm{e}_\mathrm{L} H + \bar{\mathrm{e}}_\mathrm{R} \ \mathrm{e}_\mathrm{R} H)$$

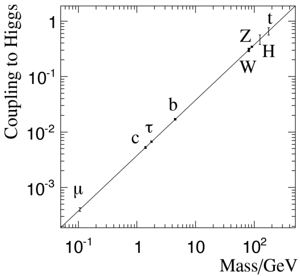
- No neutrino masses
- Fermion mass given by $m_f = g_f \frac{\upsilon}{\sqrt{2}}$
- Coupling to Higgs field proportional to $\frac{m_f}{\upsilon}$

*Higgs couplings to fermions and gauge bosons are independent phenomena*

# SM Higgs Decays

- In the SM Higgs branching ratios depend only on the Higgs mass
- 125 GeV Higgs has sizable branching ratios to large number of final states
  - $H \to b\bar{b}$: 58%
  - $H \to WW^*$: 22%
  - $H \to gg$: 8.5%
  - $H \to \tau^+\tau^-$: 6.4%
  - $H \to ZZ^*$: 2.7%
  - $H \to c\bar{c}$: 2.7%
  - $H \to \gamma\gamma$: 0.23%
  - $H \to Z\gamma$: 0.15%
  - $H \to \mu^+\mu^-$: 0.022%
- Measuring all these decay channels is excellent test of Standard Model

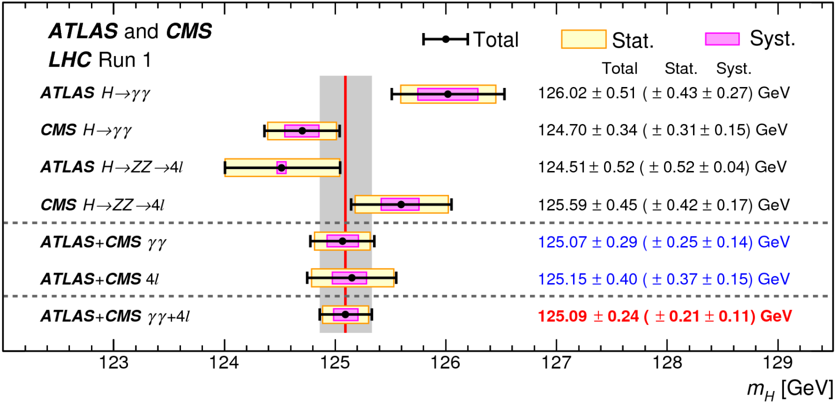


# July 4th, 2012

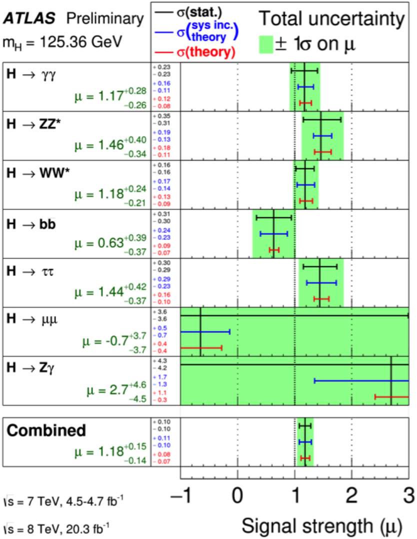

Rolf Heuer: “As a layman, I would say weve found the Higgs boson. As a scientist, I have to ask **what** have we found?”

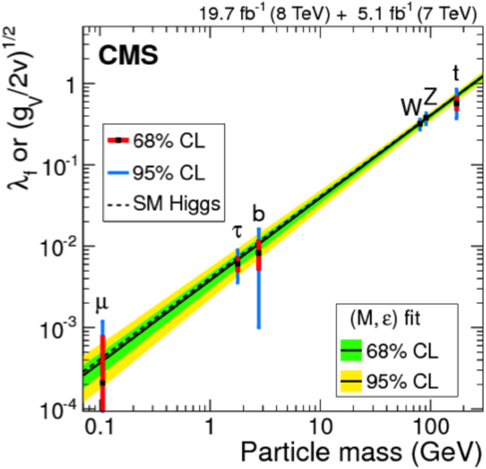
# What do we know about the Higgs?




- New boson with a mass of about 125 GeV
- Consistently measured by ATLAS and CMS in various decay modes

# What do we know about the Higgs?



# What do we know about the Higgs?

**So far all expected decay modes observed consistent with SM within uncertainties!**

- Spin and CP nature look like SM - Need confirmation
- Improve uncertainties on coupling measurements
- Discover expected rare Higgs decay

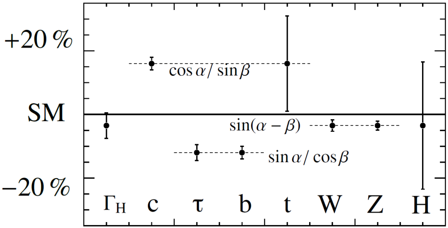
**Probably not within reach of LHC program**

- Decay to c quarks
- Discovery/measurement of Higgs self-coupling

# How well do we need to know the Higgs?

**Without the discovery of new particles the Higgs is the most important probe for new physics**

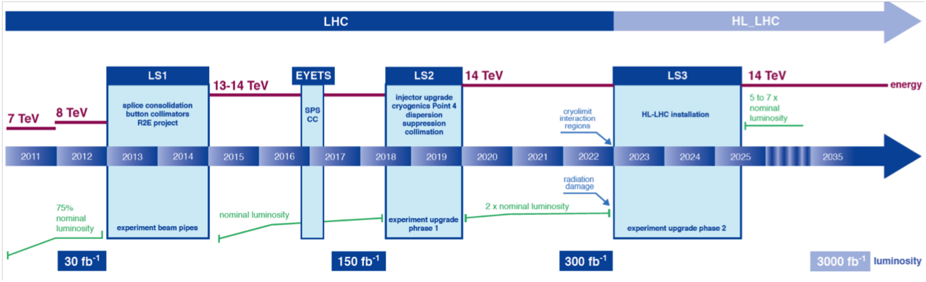
- Heavy particles contribute to loop corrections if they couple to the Higgs
- Deviations from SM couplings typically per cent level for vector bosons, 10% level for 3rd generation fermions
- The pattern of deviations will indicate underlying theory




## Alternatives in the Higgs sector

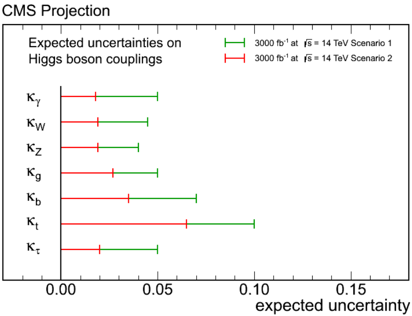
- Extended Higgs sector with additional Higgs doublets and Higgs bosons
- Composite Higgs Models: Higgs boson is composite of fermions of a new strong interaction

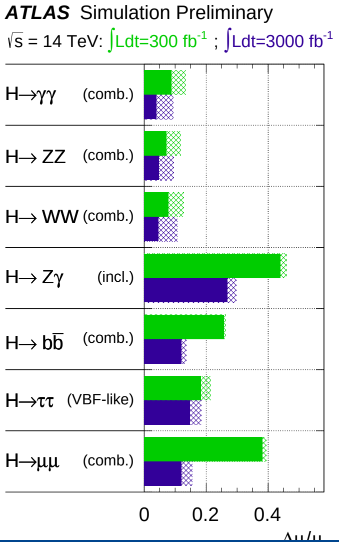
# Future LHC Program




- Until 2022 finish LHC program with 300 $\mathrm{fb}^{-1}$ (10 times more data)
- Upgrade to HL-LHC which increases the instantaneous luminosity by 10
- Full program until 2035 with another 3000 $\mathrm{fb}^{-1}$

# Projections for LHC Reach




- Extrapolations from current analyses
- Taking into account various expected improvements
- %-level uncertainties seem feasible

# Outline

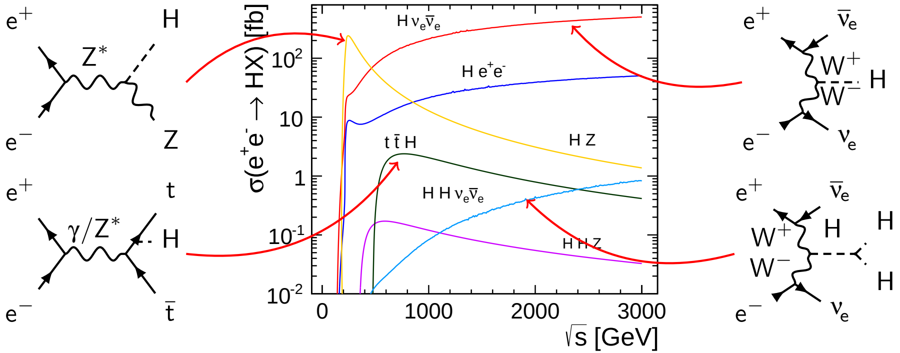


# Why $e^+e^-$ Collisions?

- Collision of fundamental particles: precise knowledge of $E_{\mathrm{cm}}$
- Low rate of high energy interactions
- No trigger required to select data online
- Radiation hardness requirements very relaxed
- No underlying events from proton remnants
- Pile-up from beamstrahlung processes – soft compared to LHC pile-up (mostly forward)

**Very clean experimental environment**
**– especially for detecting hadronic final states**

# Higgs Production at $e^+e^-$ Colliders




- ZH-production (Higgsstrahlung) dominating at threshold around 250 GeV
- WW-fusion rises with $\sqrt{s}$, taking over for $\sqrt{s} > 500\,\text{GeV}$

# Typical LC Higgs Production

- Typical ILC and CLIC beam parameters lead to similar instantaneous luminosity at the same $E_{cm}$
- Assume $\sim$ 5 year running
- Unpolarized beams
- Higher $E_{cm}$ benefits from higher instantaneous luminosity and rising $H\nu_e\bar{\nu}_e$ cross section

| $E_{cm}$ | 250 GeV | 350 GeV | 500 GeV | 1 TeV | 1.5 TeV | 3 TeV |
|---|---|---|---|---|---|---|
| $\sigma(e^+e^- \to ZH)$ | 240 fb | 129 fb | 57 fb | 13 fb | 6 fb | 1 fb |
| $\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$ | 8 fb | 30 fb | 75 fb | 210 fb | 309 fb | 484 fb |
| Integrated $\mathcal{L}$ | $250\,\mathrm{fb}^{-1}$ | $350\,\mathrm{fb}^{-1}$ | $500\,\mathrm{fb}^{-1}$ | $1000\,\mathrm{fb}^{-1}$ | $1500\,\mathrm{fb}^{-1}$ | $2000\,\mathrm{fb}^{-1}$ |
| # ZH events | 60 k | 45.5 k | 28.5 k | 13 k | 7.5 k | 2 k |
| # $H\nu_e\bar{\nu}_e$ events | 2 k | 10.5 k | 37.5 k | 210 k | 460 k | 970 k |

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# Beam Polarization

- In the SM weak interaction only affects left(right)-handed (anti)particles
- Beam polarization directly affects cross sections for WW/ZZ-fusion as well as Higgsstrahlung processes
- 100% electron polarization increases effective signal cross section by $\sim 2$
- This affects signal and most background processes

$$\text{significance} \approx \frac{\sqrt{N_\mathrm{S} + N_\mathrm{B}}}{N_\mathrm{S}}$$

- 80% electron polarization (and 30% positron polarization) would improve the significance by at least $\sqrt{1.8}$ ($\sqrt{2.3}$)

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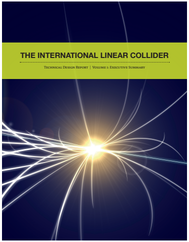
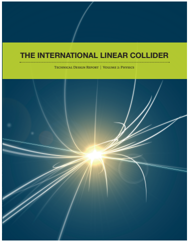
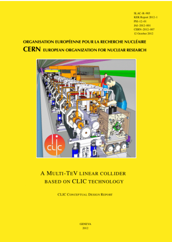
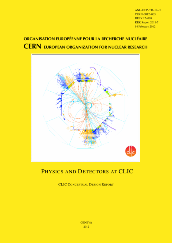
# More than 15 years of Linear Collider Studies

- LC physics potential described in many comprehensive documents
- Physics performance benchmarked in fast and full detector simulations with increasing realism
  - 2001 - TESLA Technical Design Report
  - 2004 - Physics at the CLIC Multi-TeV Linear Collider
  - 2007 - ILC Reference Design Report
  - 2009 - ILD & SiD Letters of Intent
  - 2012 - Physics and Detectors at CLIC: CLIC Conceptual Design Report
  - 2013 - ILC Technical Design Report

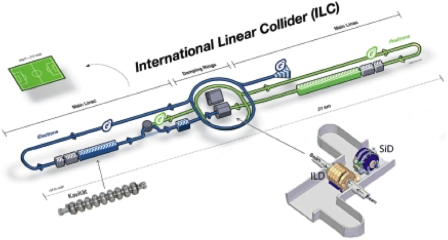



# The International Linear Collider (ILC)

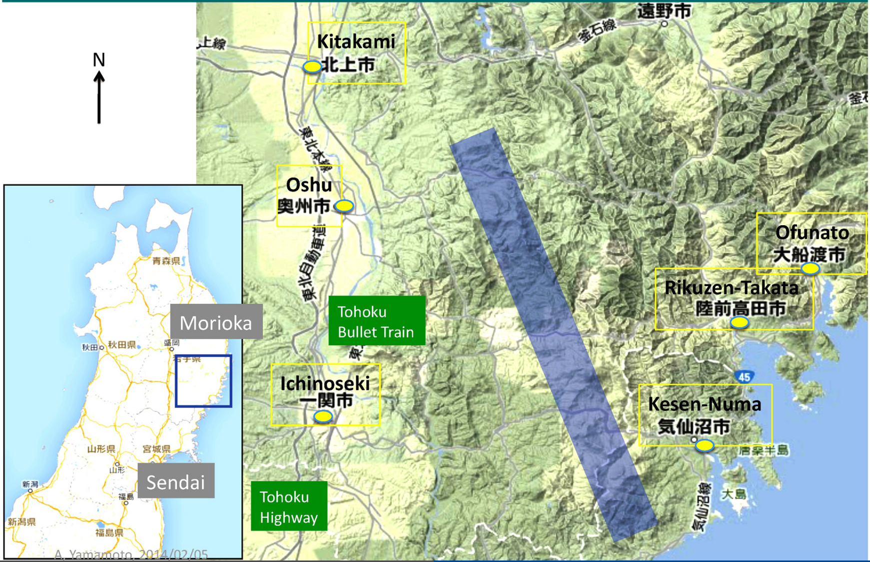



- Energy loss through synchrotron radiation becomes prohibitive for high $\sqrt{s}$

$$\Delta E_{\text{synchrotron}} \propto \frac{E_{\text{beam}}^4}{m^4 \times \text{radius}}$$

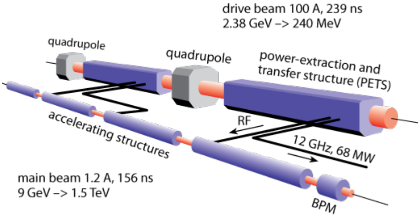
- $e^+e^-$ linear collider with up to $\sqrt{s} = 1\,\mathrm{TeV}$ and $\mathcal{L} \approx 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Using superconducting cavities with a gradient of $35\,\mathrm{MV/m}$ (XFEL design)
- Candidate site selected in Japan
- Project realization by 2025–2030

# ILC Candidate site in Kitakami, Tohoku



# The Compact Linear Collider (CLIC)

- $e^+e^-$ linear collider with up to $\sqrt{s} = 3\,\mathrm{TeV}$ and $\mathcal{L} \approx 6 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- High field gradient to keep accelerator compact: $100\,\mathrm{MV/m}$
- Two-beam acceleration scheme
    - RF power extracted from drive beam
        - low-energy ($2.38\,\mathrm{GeV}$)
        - high-intensity ($100\,\mathrm{A}$)
    - Transfered to main beam acceleration cavities
- Project realization by after 2035

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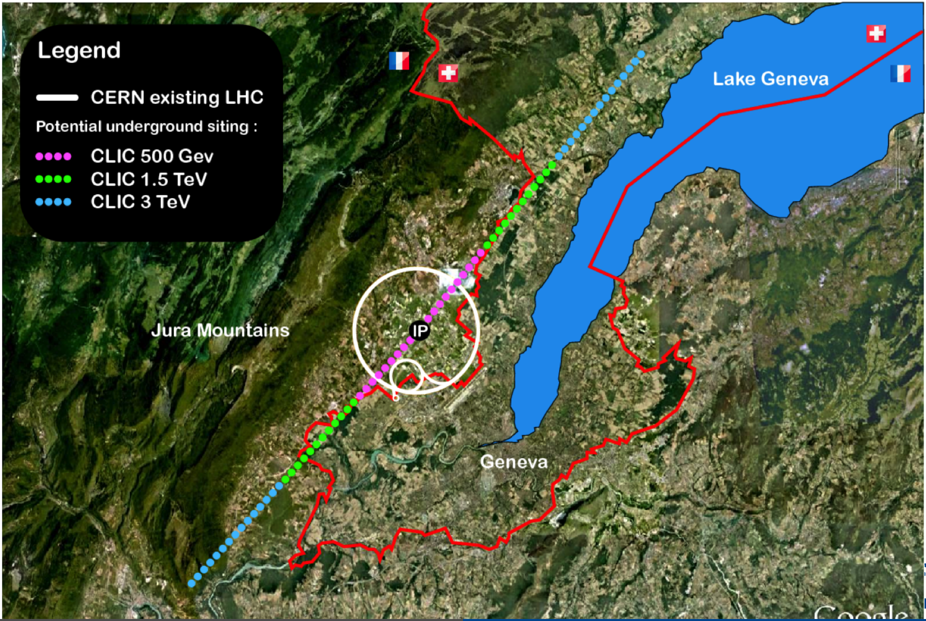

Legend
CERN existing LHC
Potential underground siting :
CLIC 500 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva

# Circular $e^+e^-$ Colliders

**With the Higgs mass being relatively low, circular $e^+e^-$-colliders have become a viable option as Higgs factories**

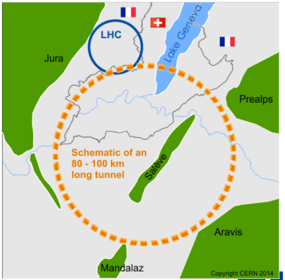
- Allow for extremely high luminosities especially at lower $\sqrt{s}$
- pp-option to justify the scale of the project

## CEPC

- 50–70 km tunnel in China
- Up to 250 GeV $e^+e^-$
- $\mathcal{L} \approx 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per experiment
- Up to 70 TeV pp
- Project realization 2025–2030

## FCC

- 80–100 km tunnel near CERN
- Up to 350 GeV $e^+e^-$
- $\mathcal{L} \approx 1.2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per experiment
- Up to 100 TeV pp
- Project realization by after 2035

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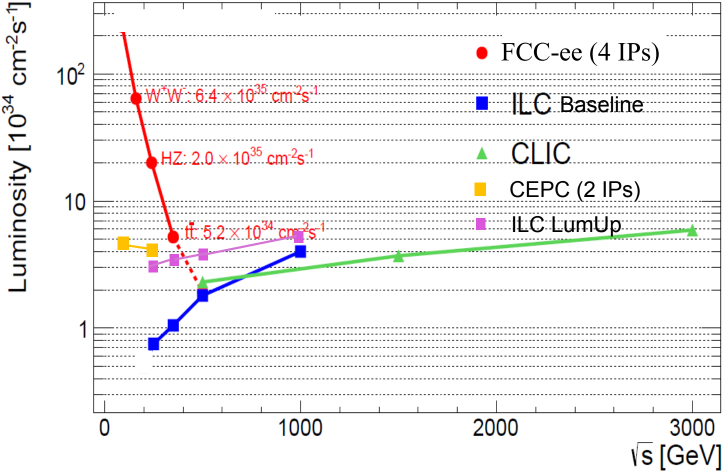
# Comparison of $e^+e^-$ Projects

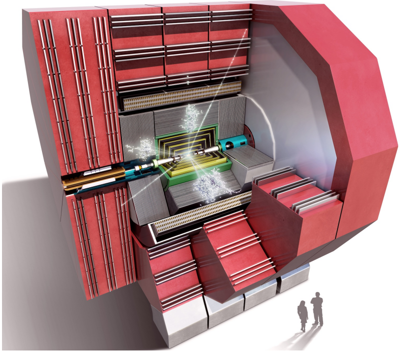



- Note that Higgs production cross section is rising with $\sqrt{s}$
- Linear and circular $e^+e^-$ colliders have complementary physics reach

# $e^+e^-$ Detector Concepts

**Huge progress in detector R&D since design of LHC experiments**

- Excellent momentum resolution to precisely measure leptonic final states:
  $\sigma(p_\mathrm{T})/p_\mathrm{T}^2 \approx 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$
- Excellent jet-energy resolution to distinguish hadronic W, Z and H decays:
  $\sigma(E)/E \approx 3.5\%\text{-}5\%$
- Precise secondary vertex reconstruction for efficient heavy flavor tagging:
  $\sigma(d_0) \approx 5\,\mu\mathrm{m} \oplus 15\,\mu\mathrm{m}/(p\ \sin^{2/3}\theta)$
- Hermetic detector with maximal coverage in the forward region
- Designed for particle flow reconstruction

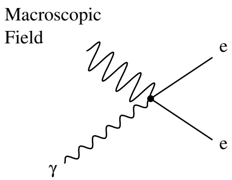


# Beamstrahlung and Beam-Related Backgrounds

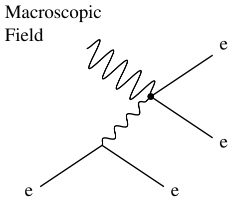
- High luminosity requires small beam sizes and high bunch charge
- Beam-beam interaction leads to Beamstrahlung
- Large number of Beamstrahlung photons lead to important background processes

# Beamstrahlung and Beam-Related Backgrounds

- High luminosity requires small beam sizes and high bunch charge
- Beam-beam interaction leads to Beamstrahlung
- Large number of Beamstrahlung photons lead to important background processes
- Photon conversion in strong fields within bunches



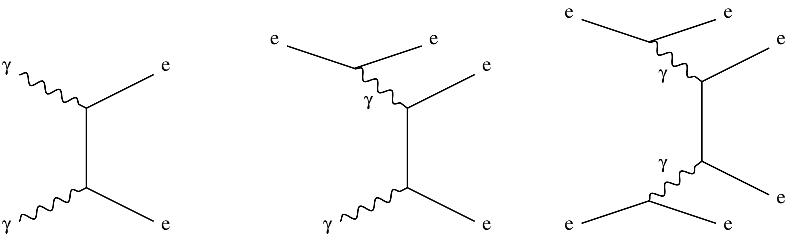

(a) Coherent Pair Production




(b) Trident Pair Production

# Beamstrahlung and Beam-Related Backgrounds

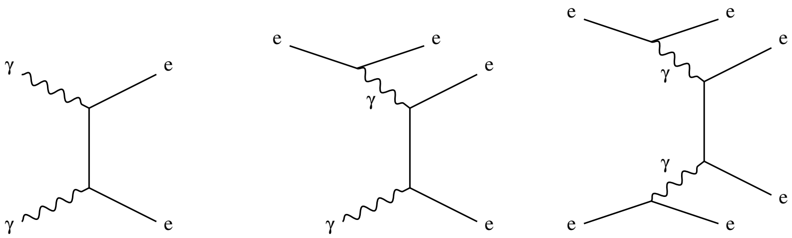
- High luminosity requires small beam sizes and high bunch charge
- Beam-beam interaction leads to Beamstrahlung
- Large number of Beamstrahlung photons lead to important background processes
- Two-photon processes




(a) Breit-Wheeler (b) Bethe-Heitler (c) Landau-Lifshitz

# Beamstrahlung and Beam-Related Backgrounds

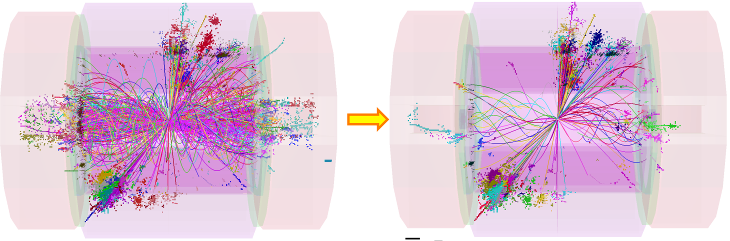
- High luminosity requires small beam sizes and high bunch charge
- Beam-beam interaction leads to Beamstrahlung
- Large number of Beamstrahlung photons lead to important background processes
- Similar (and other) diagrams with hadronic final states ($\gamma\gamma \rightarrow$ hadrons)




(a) Breit-Wheeler (b) Bethe-Heitler (c) Landau-Lifshitz

# CLIC Pile-Up due to Timing

1.2 TeV | 100 GeV



$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8 \text{ jets}$$

1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

- Beamstrahlung and bunch spacing of 0.5 ns result in large out-of-time pile-up
- Require high spatial and timing resolution in calorimeters (ns precision)
- Remove reconstructed out of time particles depending on $p_T$ and $\theta$
- Realistic amount of $\gamma\gamma \to$ hadrons background included in simulation studies

# Outline

# Disclaimer

**Projected results depend strongly on running scenario, i.e. center-of-mass energy and integrated luminosity. I give rough estimates for a full LC program.**

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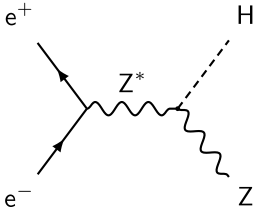
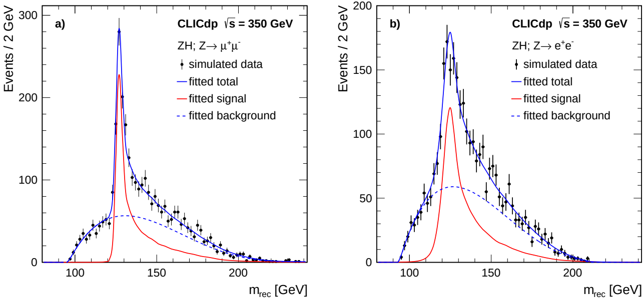
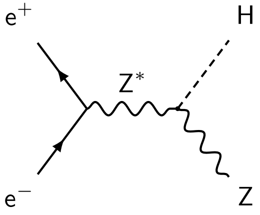
# Higgs Recoil Measurement

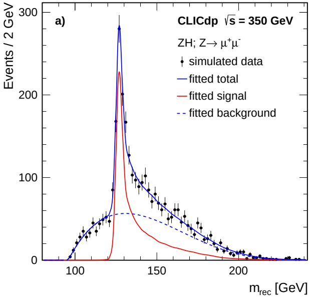


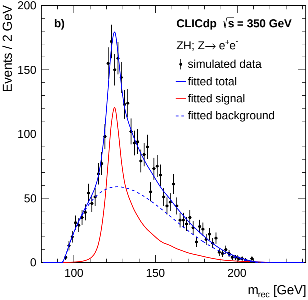




- Measure the recoiling Z independent of H
- Reconstruct Higgs through knowledge of $\sqrt{s}$: $m_{\mathrm{H}}^2 = s - 2\sqrt{s}E_{\mathrm{Z}} + m_{\mathrm{Z}}^2$
- Reconstruction of $\mathrm{Z} \to \mu^+\mu^-$ or $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ is (almost) independent to the Higgs decay mode
- Truely model independent measurement of $g_{\mathrm{HZZ}}$
- **This would work even if the Higgs decayed only to invisible!**
- Drives requirements on momentum resolution in detector design

# Higgs Recoil Measurement

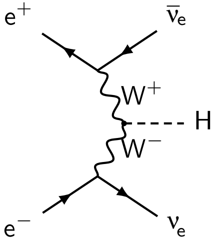


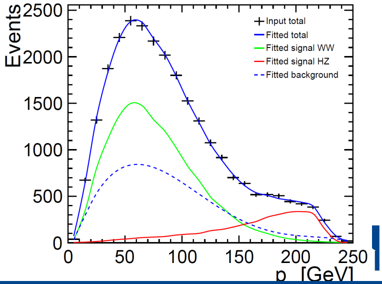




- Can be extended to include $Z \to q\bar{q}$ to improve statistics – if the jet reconstruction is carefully chosen not to be biased by the Higgs decay mode still model independent
- Single most important measurement for model independent fit of the Higgs sector
- Typically $\Delta g_{HZZ}/g_{HZZ} < 1\%$
- Sensitivity to invisible Higgs decays $<< 1\%$

# Relative Coupling of W and Z

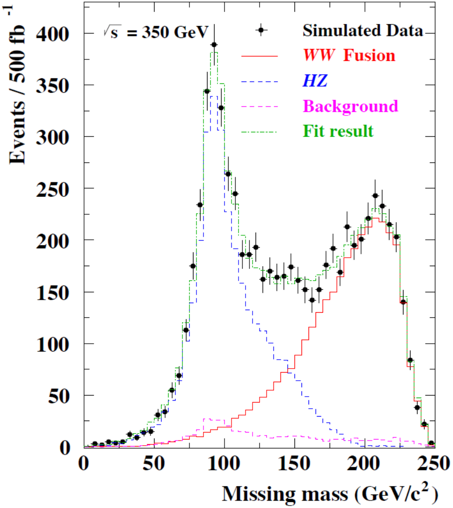



- At $\sqrt{s} = 500\,\mathrm{GeV}$ cross sections for $e^+e^- \to HZ$ and $e^+e^- \to H\nu_e\bar{\nu}_e$ are of similar magnitude
- Allows precise test of the relative coupling $g_{HZZ}/g_{HWW}$
  - $e^+e^- \to HZ \to q\bar{q}\nu\bar{\nu}$
  - $e^+e^- \to H\nu_e\bar{\nu}_e \to q\bar{q}\nu_e\bar{\nu}_e$
  - Determine relative normalization in fit
  - Translate to coupling uncertainty: $\Delta(g_{HZZ}/g_{HWW})/(g_{HZZ}/g_{HWW}) < 2\%$



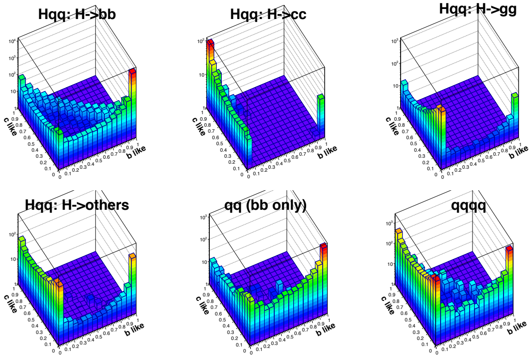
# Model Independent Measurement of Total Width

- Higgs total width very narrow for 125 GeV: $\sim 4\,\mathrm{MeV}$
- Impossible to measure line shape
- Measure WW-fusion cross section in $e^+e^- \to H\nu_e\bar{\nu}_e \to b\bar{b}\nu_e\bar{\nu}_e$
- Measure $H \to WW^*$ in Higgsstrahlung processes (known coupling $g_{HZZ}$)
- $\Delta\Gamma_H^{tot}/\Gamma_H^{tot} = \sigma(e^+e^- \to H\nu_e\bar{\nu}_e)/BR(H \to WW^*)$
- $\Delta\Gamma_H^{tot}/\Gamma_H^{tot} < 5\%$



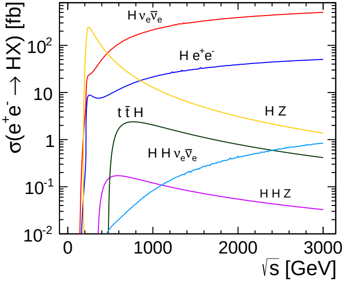
# Hadronic decays to $b\bar{b}$, $c\bar{c}$ and gg

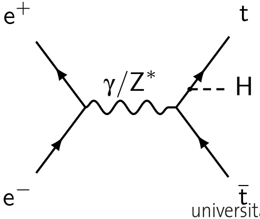
- While the decay to $b\bar{b}$ will be measured at the LHC, $c\bar{c}$ will be extremely difficult
- Combined extraction of all hadronic decays using template fits, allows to use correlations in a combined fit later
- $\Delta g_{\mathrm{Hb\bar{b}}}/g_{\mathrm{Hb\bar{b}}} < 1\%$, $\Delta g_{\mathrm{Hc\bar{c}}}/g_{\mathrm{Hc\bar{c}}} < 3\%$, $\Delta g_{\mathrm{Hgg}}/g_{\mathrm{Hgg}} < 3\%$
- Drives flavor-tagging requirements in the detector design



# Top Yukawa Coupling ($g_{\mathrm{Ht\bar{t}}}$)

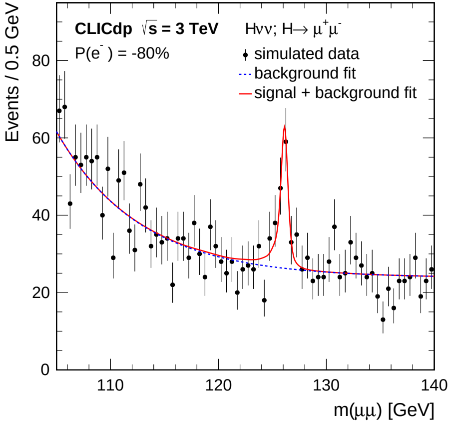
- Only direct measurement of $g_{\mathrm{Ht\bar{t}}}$ in
  $$\mathrm{e^+e^-} \rightarrow \mathrm{t\bar{t}H} \rightarrow \mathrm{bW^+\bar{b}W^-b\bar{b}}$$
- 6 or 8 jet final states
- Requires excellent b-tagging efficiency
- Only possible for $\sqrt{s} \geq 500\,\mathrm{GeV}$
- Combined result for $1\,\mathrm{ab}^{-1}$ @ 1 TeV (preliminary)
  - $\Delta(\sigma \times \mathrm{BR})/(\sigma \times \mathrm{BR}) = 9.0\%$
  - $\Delta(g_{\mathrm{Ht\bar{t}}})/(g_{\mathrm{Ht\bar{t}}}) = 4.5\%$



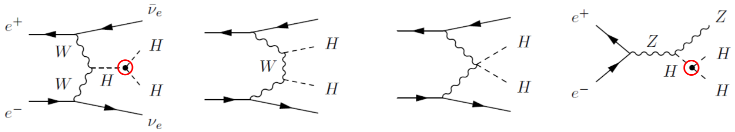



# Rare Processes ($H \to \mu^+\mu^-$)

- Small BR requires large statistics: BR $\approx$ 0.0002
- $2\,\mathrm{ab}^{-1}$ at 3 TeV result in $\sim$ 120 signal events
- Requires excellent momentum resolution
- Requires efficient forward electron tagging to reject $e^+e^- \to e^+e^-\mu^+\mu^-$ background
- $\Delta g_{H\mu\mu}/g_{H\mu\mu} < 8\%$
- Statistics limited unlike at the LHC



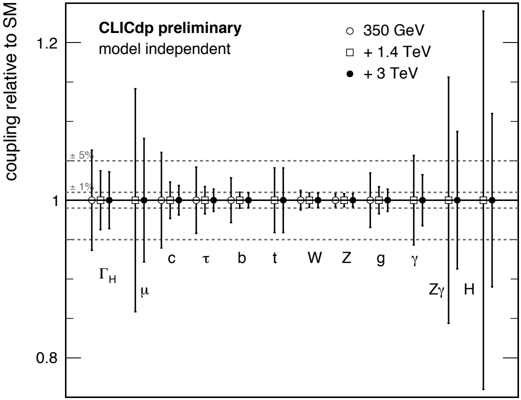
# Measurement of Higgs Self Coupling




$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4 \qquad \lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$$

- Holy grail of Higgs measurements: access to tri-linear Higgs coupling
- Most sensitivity from HH $\rightarrow$ b$\bar{\text{b}}$b$\bar{\text{b}}$ and HH $\rightarrow$ b$\bar{\text{b}}$WW
- Very complex topologies, strongly dependent on b-tagging capabilities
- Also at $e^+e^-$ colliders will be very hard to go beyond 30% uncertainty
- Benefits most from going to high $\sqrt{s}$, CLIC might get to $\Delta\lambda/\lambda < 15\%$
- Simultaneous measurement of quartic coupling at 3 TeV: $\Delta g_{\text{HHWW}}/g_{\text{HHWW}} < 3\%$

# Model-Independent Fit of the Higgs Sector

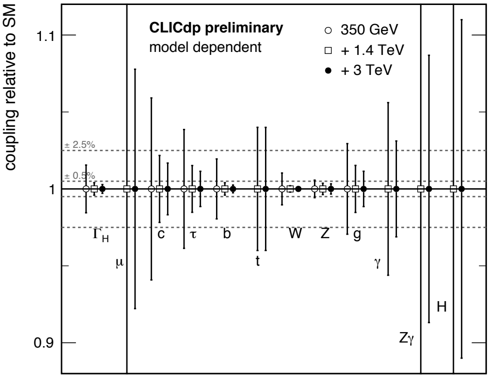



Preliminary

| Parameter | Relative precision 500fb$^{-1}$ 350GeV | +1.5ab$^{-1}$ +1.4TeV | +2ab$^{-1}$ +3TeV |
|---|---|---|---|
| $g_{HZZ}$ | 0.8% | 0.8% | 0.8% |
| $g_{HWW}$ | 1.2% | 0.9% | 0.9% |
| $g_{Hbb}$ | 2.8% | 1.0% | 0.9% |
| $g_{Hcc}$ | 6.1% | 2.3% | 1.9% |
| $g_{H\tau\tau}$ | 4.2% | 1.7% | 1.4% |
| $g_{H\mu\mu}$ | – | 14.1% | 7.8% |
| $g_{Htt}$ | – | 4.1% | <4.1% |
| $g_{Hgg}$ | 3.4% | 1.7% | 1.4% |
| $g_{H\gamma\gamma}$ | – | 5.7% | 3.2% |
| $\Gamma_H$ | 6.3% | 3.7% | 3.6% |

- Combined uncertainty on any coupling limited by measurement of $g_{HZZ}$

# Model-Dependent Fit (á la LHC)




Preliminary

| Parameter | Relative precision 500fb$^{-1}$ 350GeV | +1.5ab$^{-1}$ +1.4TeV | +2ab$^{-1}$ +3TeV |
|---|---|---|---|
| $\kappa_{HZZ}$ | 0.6% | 0.4% | 0.3% |
| $\kappa_{HWW}$ | 1.0% | 0.2% | 0.1% |
| $\kappa_{Hbb}$ | 1.9% | 0.4% | 0.3% |
| $\kappa_{Hcc}$ | 5.9% | 2.2% | 1.7% |
| $\kappa_{H\tau\tau}$ | 3.9% | 1.5% | 1.1% |
| $\kappa_{H\mu\mu}$ | – | 14.1% | 7.8% |
| $\kappa_{Htt}$ | – | 4.0% | <4.1% |
| $\kappa_{Hgg}$ | 2.9% | 1.5% | 1.1% |
| $\kappa_{H\gamma\gamma}$ | – | 5.6% | 3.1% |
| $\Gamma_{H md.derived}$ | 1.6% | 0.4% | 0.3% |

- Describe deviation from SM coupling $\kappa_i^2 = \frac{\Gamma_i}{\Gamma_{i,SM}}$
- Assume no invisible Higgs decay $\Gamma_H = \sum_i \kappa_i^2 \, BR_i$
- **Achievable precision depends largely on assumptions!**

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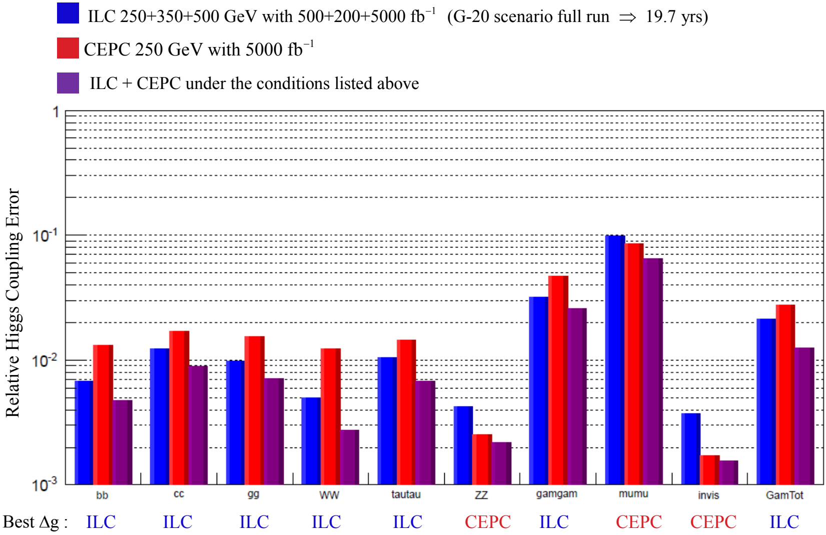
# Snowmass 2013 Comparison

| | ILC 250/500/1000 GeV | | ILC LumiUp‡ 250/500/1000 GeV | | CLIC 1.4/3.0 TeV | | TLEP 240 & 350 GeV |
|---|---|---|---|---|---|---|---|
| | $ZH$ | $\nu\bar{\nu}H$ | $ZH$ | $\nu\bar{\nu}H$ | $ZH^{\dagger}$ | $\nu\bar{\nu}H$ | $ZH(\nu\bar{\nu}H)$ |
| Inclusive | 2.6/3.0/−% | – | 1.2/1.7/−% | – | 4.2% | – | 0.4% |
| $H \to \gamma\gamma$ | 29-38% | −/20-26/7-10% | 16/19/−% | −/13/5.4% | – | 11%/< 11% | 3.0% |
| $H \to gg$ | 7/11/−% | −/4.1/2.3% | 3.3/6.0/−% | −/2.3/1.4% | 6% | 1.4/1.4% | 1.4% |
| $H \to ZZ^*$ | 19/25/−% | −/8.2/4.1% | 8.8/14/−% | −/4.6/2.6% | | 2.3/1.5% | 3.1% |
| $H \to WW^*$ | 6.4/9.2/−% | −/2.4/1.6% | 3.0/5.1/−% | −/1.3/1.0% | 2% | 0.75/0.5% | 0.9% |
| $H \to \tau\tau$ | 4.2/5.4/−% | −/9.0/3.1% | 2.0/3.0/−% | −/5.0/2.0% | 5.7% | 2.8%/< 2.8% | 0.7% |
| $H \to b\bar{b}$ | 1.2/1.8/−% | 11/0.66/0.30% | 0.56/1.0/−% | 4.9/0.37/0.30% | 1% | 0.23/0.15% | 0.2% (0.6%) |
| $H \to c\bar{c}$ | 8.3/13/−% | −/6.2/3.1% | 3.9/7.2/−% | −/3.5/2.0% | 5% | 2.2/2.0% | 1.2% |
| $H \to \mu\mu$ | – | −/−/31% | – | −/−/20% | – | 21/12% | 13% |
| | $t\bar{t}H$ | | $t\bar{t}H$ | | $t\bar{t}H$ | | $t\bar{t}H$ |
| $H \to b\bar{b}$ | −/28/6.0% | | −/16/3.8% | | 8%/< 8% | | – |

- Comparison tables between projects are very political
- At Snowmass 2013 attempt to compare different projects on same footing
- Extremely difficult due to varying assumptions on running scenarios
- Take these kind of tables with a grain of salt

# Combining Results from Different Projects



# Outline



# Summary(1)

- $e^+e^-$-colliders are absolutely necessary to complete our picture of the Higgs
- Linear colliders, especially the ILC are technologically mature projects
- Huge amount of detailed physics simulation studies over the past years
- Low Higgs mass allows to consider circular $e^+e^-$-colliders as Higgs factories
- Recent Publications:
  - ILC Operating Scenarios
    `http://arxiv.org/abs/1506.07830`
  - Physics Case for the International Linear Collider
    `http://arxiv.org/abs/1506.05992`
  - CEPC pre-conceptual design report
    `cepc.ihep.ac.cn/preCDR/Pre-CDR_final_20150317.pdf`
- Upcoming (submission to journal imminent):
  - Higgs Physics at the CLIC Electron-Positron Linear Collider

# Summary(2)

- Projected numbers depend strongly on running scenarios and should thus be used carefully
- Different projects are complementary!
- LHC and HLLHC
  - Best precision for rare non-hadronic decays: $H \to \gamma\gamma$, $H \to \mu^+\mu^-$
  - Best precision for $g_{Htt}$ in associated production with $H \to \gamma\gamma$
- Circular colliders
  - Huge integrated luminosity allows best measurement of $g_{HZZ}$ at $\sqrt{s} = 250\,\mathrm{GeV}$
  - Also allows to improve electroweak measurements significantly at $\sqrt{s} = 91\,\mathrm{GeV}$
- Linear colliders
  - Best for hadronic decay modes
  - Best for Higgs self-coupling, especially when going to high $\sqrt{s}$
  - Discovery potential for new physics in electroweak states more difficulat at the LHC (charginos, neutralinos, sleptons)