Higgs Bosons at Future Lepton Colliders
Outline

➤ Introduction
- Case for precision Higgs physics
- Future lepton collider projects in a nutshell

➤ Higgs Production at Lepton Colliders
- Processes
- Energy
- Luminosity

➤ Higgs studies at lepton collider
- Couplings
- Mass
- Total width
- BSM Higgs

➤ Conclusions
Case for precision Higgs physics

How large are potential deviations from BSM physics?
How well do we need to measure Higgs couplings?

- To be sensitive to a deviation $\delta$, the measurement needs a precision of at least $\delta/3$, better $\delta/5$.
- Implications of new physics scale on couplings from heavy states or through mixing.

$$g = g_{SM} [1 + \Delta] : \Delta = \mathcal{O}(v^2/\Lambda^2)$$

Percent-level precision needed to test TeV scale
There is no strict limit to the precision needed!
Why Lepton Colliders?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS+CMS Measured</th>
<th>ATLAS+CMS Expected uncertainty</th>
<th>ATLAS Measured</th>
<th>CMS Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Z$</td>
<td>$1.03_{-0.11}^{+0.11}$</td>
<td>$+0.10$</td>
<td>$1.00_{-0.14}^{+0.14}$</td>
<td>$1.07_{-0.18}^{+0.17}$</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>$0.91_{-0.10}^{+0.10}$</td>
<td>$+0.10$</td>
<td>$0.92_{-0.13}^{+0.13}$</td>
<td>$0.90_{-0.15}^{+0.15}$</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>$1.43_{-0.22}^{+0.23}$</td>
<td>$+0.26$</td>
<td>$1.31_{-0.30}^{+0.30}$</td>
<td>$1.56_{-0.32}^{+0.34}$</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>$0.88_{-0.13}^{+0.13}$</td>
<td>$+0.16$</td>
<td>$0.97_{-0.19}^{+0.19}$</td>
<td>$0.82_{-0.17}^{+0.19}$</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>$0.60_{-0.18}^{+0.18}$</td>
<td>$+0.25$</td>
<td>$0.61_{-0.26}^{+0.26}$</td>
<td>$0.61_{-0.26}^{+0.27}$</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>$0.81_{-0.10}^{+0.11}$</td>
<td>$+0.17$</td>
<td>$0.94_{-0.15}^{+0.18}$</td>
<td>$0.70_{-0.13}^{+0.15}$</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>$0.92_{-0.12}^{+0.11}$</td>
<td>$+0.12$</td>
<td>$0.88_{-0.14}^{+0.14}$</td>
<td>$0.96_{-0.15}^{+0.17}$</td>
</tr>
</tbody>
</table>

CMS Projection

**Percent level (2-10%) precision in reach**

**Fantastic performance already today**

Key question is the evolution systematic uncertainty

---


Future Lepton Collider Projects

- International Linear Collider (ILC)
- Compact Linear Collider (CLIC)
- Circular Electron Positron Collider (CEPC)
- Future Circular Collider (FCC-ee)
- Muon Collider

Superconducting RF Linac

- **ILC**
  - 31 km, 30 V/m
  - 500 GeV
- **ILC-upgrade**
  - 50 km, 45 V/m
  - 1000 GeV

Kitakami site (north of Sendai)

TDR delivered June 2013
Future Lepton Collider Projects

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Baseline - 10y program
Future Lepton Collider Projects

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<table>
<thead>
<tr>
<th></th>
<th>Baseline ILC</th>
<th>Lumi Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision rate [Hz]</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Electron linac rate [Hz]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1312</td>
<td>2625</td>
</tr>
<tr>
<td>Estimated power [MW]</td>
<td>129</td>
<td>200</td>
</tr>
<tr>
<td>Luminosity [x10^{34}cm^{-2}s^{-1}]</td>
<td>0.75</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Integrated Luminosities [fb]

ILC, Scenario H-20
- ECM = 250 GeV
- ECM = 350 GeV
- ECM = 500 GeV

Luminosity Upgrade
Future Lepton Collider Projects

➡ International Linear Collider (ILC)

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➡ Muon Collider

CLIC
50km, 100V/m
3000 GeV

- Normal conducting accelerator structures operated at room temperature
- Two beam acceleration technique provides 100MV/m gradient
- Implementation in energy stages, driven by physics and technical considerations
- Each stage correspond to 4-5 years of data taking

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy</td>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>350</td>
<td>1400</td>
<td>3000</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>$L_{\text{int}}$</td>
<td>ab$^{-1}$</td>
<td>0.5</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

CDR Vol 2: Physics and Detectors - arXiv:1203.5940
Future Lepton Collider Projects

- International Linear Collider (ILC)
- Compact Linear Collider (CLIC)
- Circular Electron Positron Collider (CEPC)
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- Muon Collider

CEPC
50km
250 GeV
Future Lepton Collider Projects

- International Linear Collider (ILC)
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- Future Circular Collider (FCC-ee)
- Muon Collider

CDR in preparation for 2018

FCC-ee
100km, 200MV
350 GeV

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>90</th>
<th>160</th>
<th>240</th>
<th>350</th>
<th>350+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ (ab$^{-1}$/year)</td>
<td>86.0</td>
<td>15.2</td>
<td>3.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Events/year</td>
<td>$3.6 \times 10^{12}$</td>
<td>$6.1 \times 10^{7}$</td>
<td>$7.0 \times 10^{5}$</td>
<td>$4.2 \times 10^{5}$</td>
<td>$2.5 \times 10^{4}$</td>
</tr>
<tr>
<td>Event type</td>
<td>Z</td>
<td>WW</td>
<td>HZ</td>
<td>t\bar{t}</td>
<td>WW $\rightarrow$ H</td>
</tr>
<tr>
<td>Years</td>
<td>0.3 (2.5)</td>
<td>1</td>
<td>3</td>
<td>0.5</td>
<td>3</td>
</tr>
</tbody>
</table>

crab-waist configuration with four interaction points
Future Lepton Collider Projects

- International Linear Collider (ILC)
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- Luminosity and energy are limited by the power budget, i.e. amount of synchrotron radiation (50MW per beam)
- One finds that ideally, all charge should be in a few single bunches at max energy
- Lifetime of beams very limited
- Solution: top-up injection scheme
Future Lepton Collider Projects

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Ph. Lebrun
Future Lepton Collider Projects

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Mark Palmer: MAP program
Physics at Lepton Colliders

- Electroweak production
  - cross sections are predicted with (sub)percent precision
- Lepton here really means electrons and muons
- Relative low rate
  - trigger on every event
- Well defined collision rate
  - missing mass reconstruction
- Clean events, smaller backgrounds
  - comparing to pp machine

Example ILD event display
Higgs Production at Lepton Collider

$e^+e^- \rightarrow ZH$ production maximal at 240-260 GeV
Higgs Production at Lepton Collider

- $e^+e^-\rightarrow ZH$ production maximal at 240-250 GeV
- Beam polarization increases Higgs cross sections

44% increase in cross section
Higgs Production at Lepton Collider

- $e^+e^- \rightarrow ZH$ production maximal at 240-250 GeV
- Multi-TeV collider Higgs production

![Graph showing Higgs production cross-sections at various energies for different processes such as $t\bar{t}H$, $HH\nu_e\bar{\nu}_e$, $HZ$, and $HHZ$.]
Higgs Production at Lepton Colliders

**s-channel production**
- very small cross section
- reduced by ISR and beam spread
- $\sigma^{\text{born}}(\mu^+\mu^-\rightarrow H) \approx 40,000 \, \sigma^{\text{born}}(e^+e^-\rightarrow H)$
- $\sigma(e^+e^-\rightarrow H) = 50\text{ab}$ (nominal $\delta E/E$)
- $\sigma(\mu^+\mu^-\rightarrow H) = 15\text{pb}$ (nominal $\delta E/E$)

**Beam-spread improvements**
- FCC-ee via monochromators
- Muon collider via improved cooling
- Feasibility and impact on luminosity need study

**Polarization**
Energy and Luminosity

- International Linear Collider (ILC)
- Compact Linear Collider (CLIC)
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- Future Circular Collider (FCC-ee)
- Muon Collider
Multi-TeV Lepton Collider Figure of Merit

Lepton Colliders
Wall Plug Power

Lepton Colliders Figure of Merit:
Luminosity per wall plug power

C.M. colliding beam energy (TeV)

ILC  CLIC  PWFA  LPA  DLA  Muon Collider

ILC  CLIC  PWFA  LPA  DLA  Muon Collider
### Higgs Related Physics at Lepton Colliders

<table>
<thead>
<tr>
<th>√s [GeV]</th>
<th>√s</th>
<th>Measurements (incomplete list)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>m_Z</td>
<td>m_Z, Γ_Z, α_s, α_{QED}</td>
</tr>
<tr>
<td>125</td>
<td>m_H</td>
<td>s-channel Higgs production</td>
</tr>
<tr>
<td>160</td>
<td>2m_W</td>
<td>m_W, α_s</td>
</tr>
<tr>
<td>240-250</td>
<td>m_H + m_Z + ...</td>
<td>m_H, Γ_H, J^{PC}, g_{HXX}, BSM decays</td>
</tr>
<tr>
<td>340-355</td>
<td>2*m_{top}</td>
<td>g_{HWW}, Γ_H, indirect g_{Htt}, m_{top}</td>
</tr>
<tr>
<td>500</td>
<td>2*m_{top} + m_H + ...</td>
<td>g_{HHH}, g_{Htt}</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>m_{NP}</td>
<td>g_{Htt}, g_{HHH}, BSM Higgs</td>
</tr>
</tbody>
</table>
Higgs Precision Measurements

- Recoil method unique to lepton collider
- Tag Higgs event independent of decay mode
- Provides precision and model independent measurements of
  - $\sigma(ee \rightarrow ZH) \propto g_{HZZ}^2$
  - $m_H$
- Key input to $\Gamma_H$

$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |p_{\ell\ell}|^2$$
Precision Higgs Couplings

- Measure $\sigma(ee\rightarrow ZH) \times BR(H\rightarrow X)$ by identifying X
- Example: $\sigma(ee\rightarrow ZH) \times BR(H\rightarrow ZZ) \propto g_{HZZ}^4/\Gamma_H$
- Total width from combination of measurements or fit - $\delta\Gamma_H = 0.04$ MeV (FCC-ee)
- Hadronic and invisible Z decays increase precision
- Branching fraction to invisible tested directly to 0.19% @ 95% CL

<table>
<thead>
<tr>
<th>Coupling</th>
<th>FCC-ee -240</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{HZZ}$</td>
<td>0.16%</td>
<td>0.15%  (0.18%)</td>
</tr>
<tr>
<td>$g_{HWW}$</td>
<td>0.85%</td>
<td>0.19%  (0.23%)</td>
</tr>
<tr>
<td>$g_{Hbb}$</td>
<td>0.88%</td>
<td>0.42%  (0.52%)</td>
</tr>
<tr>
<td>$g_{Hcc}$</td>
<td>1.0%</td>
<td>0.71%  (0.87%)</td>
</tr>
<tr>
<td>$g_{Hgg}$</td>
<td>1.1%</td>
<td>0.80%  (0.98%)</td>
</tr>
<tr>
<td>$g_{H\tau\tau}$</td>
<td>0.94%</td>
<td>0.54%  (0.66%)</td>
</tr>
<tr>
<td>$g_{H\mu\mu}$</td>
<td>6.4%</td>
<td>6.2%  (7.6%)</td>
</tr>
<tr>
<td>$g_{H\gamma\gamma}$</td>
<td>1.7%</td>
<td>1.5%  (1.8%)</td>
</tr>
<tr>
<td>BR$_{exo}$</td>
<td>0.48%</td>
<td>0.45%  (0.55%)</td>
</tr>
</tbody>
</table>

stat. uncertainties
Precision Higgs Couplings

Measurements will built on, complement, and supersede LHC results

Projected Higgs coupling precision (7-parameter fit)

- ILC Baseline
- ILC Lumi upgrade

arXiv:1506.07830
arXiv:1506.05992
Precision Higgs couplings
Higgs self-coupling through loop corrections

- Very large datasets at high energy allow extreme precision $g_{ZH}$ measurements
- Indirect and model-dependent probe of Higgs self-coupling
## Expected Precision on Higgs Parameters

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>μ-Collider</th>
<th>CLIC</th>
<th>ILC</th>
<th>CEPC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H$ [MeV]</td>
<td>0.06</td>
<td>30</td>
<td>5.5</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_H$ [MeV]</td>
<td>0.17</td>
<td>8.5</td>
<td>0.16</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>$g_{HZZ}$ [%]</td>
<td>-</td>
<td>2.1</td>
<td>0.6</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>$g_{HWW}$ [%]</td>
<td>2.2</td>
<td>2.1</td>
<td>0.8</td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$g_{Hbb}$ [%]</td>
<td>2.3</td>
<td>2.2</td>
<td>1.5</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>$g_{H\tau\tau}$ [%]</td>
<td>5</td>
<td>2.5</td>
<td>1.9</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>$g_{HYY}$ [%]</td>
<td>10</td>
<td>5.9</td>
<td>7.8</td>
<td>4.7</td>
<td>1.5</td>
</tr>
<tr>
<td>$g_{Hcc}$ [%]</td>
<td>-</td>
<td>2.4</td>
<td>2.7</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>$g_{Hgg}$ [%]</td>
<td>-</td>
<td>2.3</td>
<td>2.3</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>$g_{Htt}$ [%]</td>
<td>-</td>
<td>4.5</td>
<td>18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$g_{H\mu\mu}$ [%]</td>
<td>2.1</td>
<td>11</td>
<td>20</td>
<td>8.6</td>
<td>6.2</td>
</tr>
<tr>
<td>$g_{HHH}$ [%]</td>
<td>-</td>
<td>24</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

for ~10y operation
lots of “!,*,?” in this table
s-channel Higgs production

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; $\sigma(\text{ee} \rightarrow H) = 1.6\text{fb}$; $\sigma(\text{e}^+\text{e}^- \rightarrow H) = 50\text{ab}$ (nominal $\delta E/E$)
- Various Higgs decay channels studied

Work in progress

- Can monochromators yield energy spread of Higgs width or smaller? At what luminosity cost?
- Energy scan $O(10\text{MeV})$ around $m_H$ will be needed to locate exact $\sqrt{s}$
- Polarization increases cross section (e.g. by $x2$ at $P=70\%$). At what luminosity cost?

L = $10\ \text{ab}^{-1}$

$\kappa_e < 1.75$ at 95% CL
Exclusive Higgs boson decays

- First and second generation couplings accessible
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

- Also interesting to FCC-hh program
- Alternative H\rightarrow MV decays should be studied (V= \gamma, W, and Z)

\[
\frac{BR_{h\rightarrow \rho \gamma}}{BR_{h\rightarrow bb}} = \frac{\kappa_\gamma [(1.9 \pm 0.15)\kappa_\gamma - 0.24\kappa_u - 0.12\kappa_d]}{0.57\kappa_b^2} \times 10^{-5}
\]

- H \rightarrow J/\Psi \gamma
- H \rightarrow \phi \gamma
- H \rightarrow \rho \gamma
- H \rightarrow \omega \gamma

\rightarrow \ y_c \ y_s \ y_u, \ y_d
CP violation can be studied by searching for CP-odd contributions; CP-even already established


Higgs to Tau decays of interest

Studies consider intermediated resonances ($\rho, a_1$)

\[ \mathcal{L}_{hff} \propto h\bar{f}(\cos \Delta + i\gamma_5 \sin \Delta)f \]

<table>
<thead>
<tr>
<th>Colliders</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCCee (1 ab(^{-1}))</th>
<th>FCCee (5 ab(^{-1}))</th>
<th>FCCee (10 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (1(\sigma))</td>
<td>25°</td>
<td>8.0°</td>
<td>5.5°</td>
<td>2.5°</td>
<td>1.7°</td>
</tr>
</tbody>
</table>

Largely unexplored!

ZH events allow for detailed studies of rare and exotic decays

- improved with hadronic and invisible Z decays
- set requirements for lepton collider detector

Coupling measurements have sensitivity to BSM decays

Dedicated studies using specific final states improve sensitivity

Example: Higgs to invisible, flavor violating Higgs, and many more

Modes with of limited LHC sensitivity are of particular importance to lepton collider program

- currently under study

A muon collider at $\sqrt{s} = m_H$ is a *charming* Higgs factory

- but not competitive with other $e^+e^-$ collider options
- Higgs width better measured at $e^+e^-$ colliders
- Precision on $g_{H\mu\mu}$ compatible with HL-LHC performance

Case for muon collider

- if $H(125)$ has nearby (a few to a few hundred MeV) peaks
- allows study of heavy H and A (also a case for CLIC), but masses have to be known

Muon collider may be the best way to achieve multi-TeV lepton collider

- substantial R&D remains
### Complementarity to Hadron Collider Program

**setup for Tilman’s talk**

<table>
<thead>
<tr>
<th>gH(x_y)</th>
<th>ZZ</th>
<th>WW</th>
<th>(\gamma\gamma)</th>
<th>Z(\gamma)</th>
<th>tt</th>
<th>bb</th>
<th>(\tau\tau)</th>
<th>cc</th>
<th>ss</th>
<th>(\mu\mu)</th>
<th>uu,dd</th>
<th>ee</th>
<th>(\Gamma_H)</th>
<th>HH</th>
<th>BR_{exo}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FCC-ee</strong></td>
<td>0.15</td>
<td>0.19</td>
<td>1.5</td>
<td>0.42</td>
<td>0.54</td>
<td>0.71</td>
<td>H(\rightarrow)V(\gamma)</td>
<td>6.2</td>
<td>H(\rightarrow)V(\gamma) ee(\rightarrow)H</td>
<td>0.9</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HL-LHC</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>(\sim10)</td>
<td>(\sim5)</td>
<td>4</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>(\sim5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(\sim30)</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

- Almost perfect complementarity between lepton and hadron collider Higgs program
- In some cases the complementarity is obvious, in others more subtle

➡️ **Uncertainty in %**.
Exploration of Higgs Physics at the LHC on its way

- We have seen impressive Run-I results this week
- HL-LHC will set a high bar for Higgs physics

Lepton Colliders offer impressive precision Higgs program

- Complementarity to hadron collider program

FCC-ee promises largest Higgs dataset

- and path to next generation hadron collider (FCC-hh)

Muon collider is not a competitive Higgs factory
Colliders of the 21st Century

- LHC
- HL-LHC
- ILC
- CLIC (μ-collider)
- FCC (ee, hh, eh)
- CEPC
- SppC

Year:
- 2015
- 2025
- 2035
- 2045
- 2055
References / Input from

- s-channel Higgs production: D.d’Enterria, R.Aleksan, G.Wojcik
- CMS: Snowmass report, ECFA report
- Prospective Studies for LEP3 with the CMS detector http://arxiv.org/abs/1208.1662
- CP measurement: http://arxiv.org/abs/1308.1094, Felix Xu's meeting in the meeting
- Luminosity needs for FCC-hh and Higgs @ 100 TeV: M.Mangano, Plehn, et al
- Exclusive Higgs decays: Y. Soreq
- ...
Higgs prospects for the HL-LHC

Coupling precision 2-10 % factor 2-3 improvement from HL-LHC

Key question is the evolution systematic uncertainty

Higgs prospects for the HL-LHC

**Di-Higgs production: exciting prospects of the HL-LHC**
- Gluon fusion cross section is only $40.2\text{fb}$ [NNLO] at 14 TeV
- Vector boson fusion cross section is 2fb

**Most interesting final states**
- $bb\gamma\gamma$ [320 expected events in 3ab-1]
- $bb\tau\tau$ [9000 expected]
- $bbbb$ [40k expected (2k in VBF)]
- $bbWW$ [30000 exp. events]

**Goal is to reach minimum sensitivity of 3σ for SM production and with that to BSM scenarios**

<table>
<thead>
<tr>
<th>Process / Selection Stage</th>
<th>HH</th>
<th>ZH</th>
<th>ttH</th>
<th>bbH</th>
<th>$\gamma\gamma$+jets</th>
<th>$\gamma$+jets</th>
<th>jets</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Selection &amp; Fit Mass Window</td>
<td>22.8</td>
<td>29.6</td>
<td>178</td>
<td>6.3</td>
<td>2891</td>
<td>1616</td>
<td>292</td>
<td>113</td>
</tr>
<tr>
<td>Kinematic Selection Mass Windows</td>
<td>14.6</td>
<td>14.6</td>
<td>3.3</td>
<td>2.0</td>
<td>128</td>
<td>96.9</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>9.9</td>
<td>3.3</td>
<td>1.5</td>
<td>0.8</td>
<td>8.5</td>
<td>6.3</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

CMS - central photon yield
Higgs Physics at the FCC-ee

- Precision Higgs coupling studies and total width
- Higgs self coupling through loop corrections
- 1st and 2nd fermion generation couplings
- Rare and exotic decays (e.g. DM decays)
- Extra Higgs bosons
- Tensor structure

### FCC-ee

<table>
<thead>
<tr>
<th>Total Integrated Luminosity (ab^{-1})</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Higgs bosons from e^+e^- \rightarrow HZ</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Number of Higgs bosons from boson fusion</td>
<td>50,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{HZ}$</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow bb)$</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow cc)$</td>
<td>1.2%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow gg)$</td>
<td>1.4%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow WW)$</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow \tau\tau)$</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow ZZ)$</td>
<td>3.1%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow \gamma\gamma)$</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times BR(H \rightarrow \mu\mu)$</td>
<td>13%</td>
</tr>
</tbody>
</table>

stat. uncertainties
ILC Timeline

Delivered TDR

- Negotiations among governments
- Prepare for international lab
- Accelerator detailed design
- R&D for cost-effective production
- Site studies

International agreement
- “Green-light” for construction
- Preparation for bidding

Construction

- 2013
- 2016
- 2018
- 2027

as proposed by LC Collaboration

Kitakami site (north of Sendai)
CERN (FCC) Timelines

• LHC and HL-LHC operation until ~2035
• Must start now developing FCC concepts to be ready in time
CEPC-SppC Timelines

CEPC

1st Milestone: pre-CDR (by the end of 2014) → R&D funding request to Chinese government in 2015 (China's 13th Five-Year Plan 2016-2020)

SppC