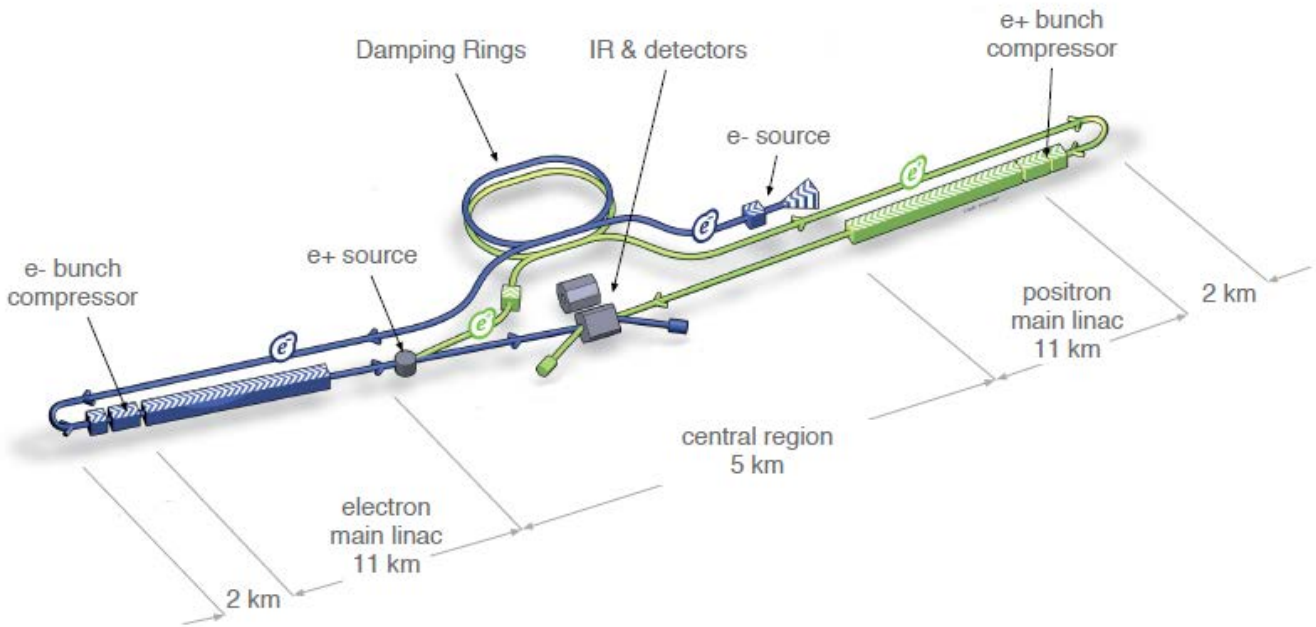
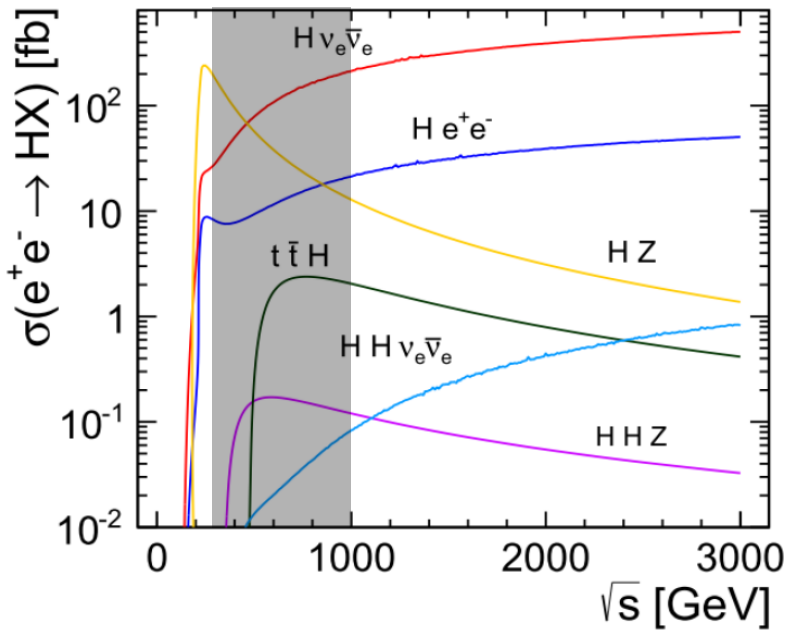
EF5. The message from the LHC seems to be that with data in hand, we consistently outperform expectations for extraction of Higgs properties. In that case, what would an ILC contribute? What key assumptions are we making now that we could relax with ILC inputs?

| Mode | LHC 300 $\mathrm{fb}^{-1}$ | LHC 3000 $\mathrm{fb}^{-1}$ |
|---|---|---|
| $\gamma\gamma$ | $(5-7)\%$ | $(2-5)\%$ |
| $gg$ | $(6-8)\%$ | $(3-5)\%$ |
| $WW$ | $(4-5)\%$ | $(2-3)\%$ |
| $ZZ$ | $(4-5)\%$ | $(2-3)\%$ |
| $t\bar{t}$ | $(14-15)\%$ | $(7-10)\%$ |
| $b\bar{b}$ | $(10-13)\%$ | $(4-7)\%$ |
| $\tau^+\tau^-$ | $(6-8)\%$ | $(2-5)\%$ |

| Mode | LHC 300 $\mathrm{fb}^{-1}$ | LHC 3000 $\mathrm{fb}^{-1}$ |
|---|---|---|
| $\mu^+\mu^-$ | 30% | 10% |
| $hhh$ | - | 50% |
| BR(invis.) | < (17 – 28)% | < (6-17)% |
| $c\bar{c}$ | - | - |
| $\Gamma_T(h)$ | - | - |

# *ILC* : $e^+e^-$ Linear Collider at 250 GeV < $\sqrt{s}$ < 1000 GeV



# Energy/Lumi Scenarios

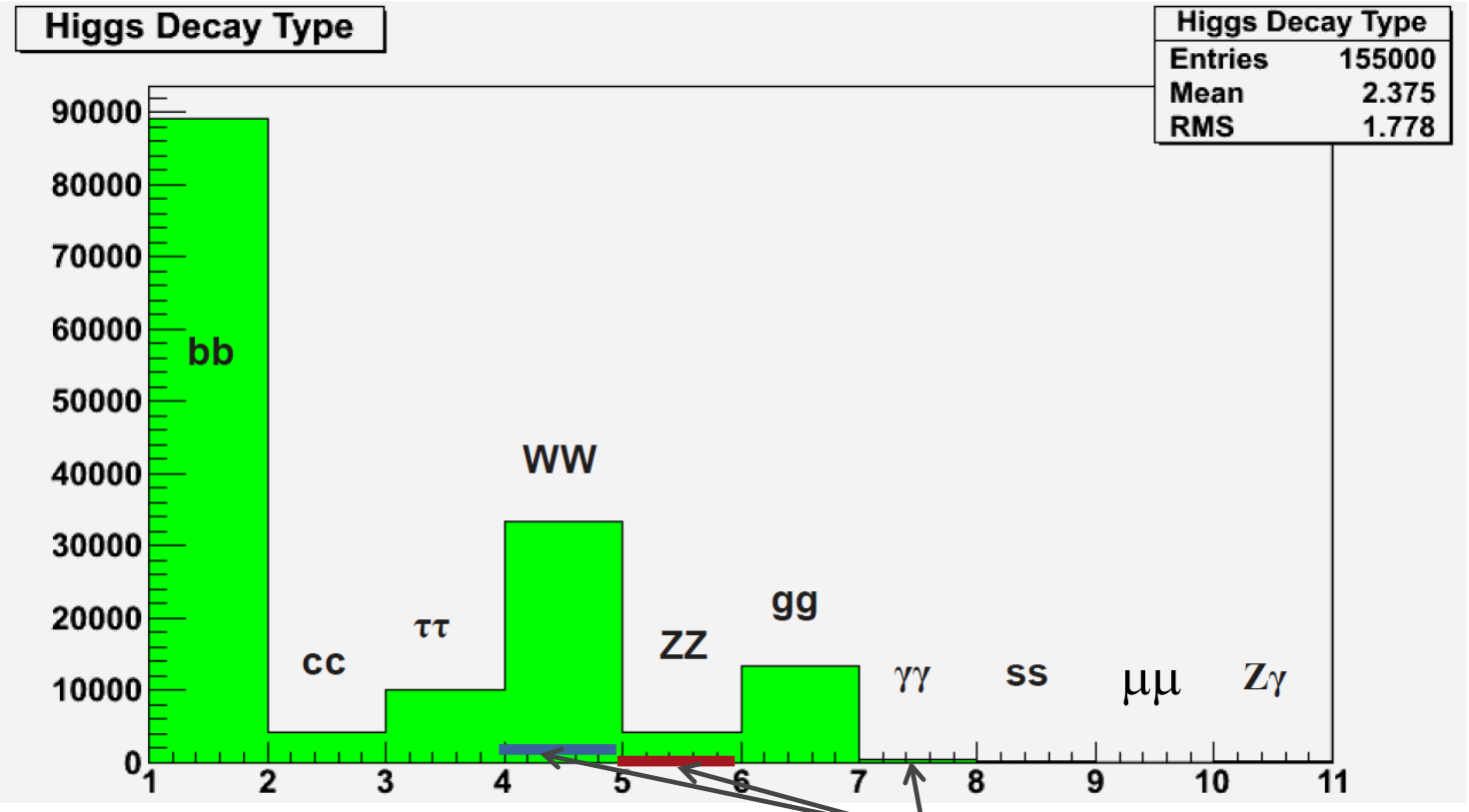
- Each scenario corresponds to accumulated luminosity at a certain point in time.
- Assumption: run for $3X10^7$ s at baseline lumi at each of Ecm=250,500,1000 GeV, in that order. Then go back and run for $3X10^7$ s at upgrade lumi at each of Ecm=250,500,1000 GeV.

| Scenario # | Nickname | Ecm(1) (GeV) | Lumi(1) ($fb^{-1}$) | + | Ecm(2) (GeV) | Lumi(2) ($fb^{-1}$) | + | Ecm(3) (GeV) | Lumi(3) ($fb^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | ILC(250) | 250 | 250 | | | | | | |
| 2 | ILC(500) | 250 | 250 | | 500 | 500 | | | |
| 3 | ILC(1000) | 250 | 250 | | 500 | 500 | | 1000 | 1000 |
| 4 | ILC(LumUp) | 250 | 1150 | | 500 | 1600 | | 1000 | 2500 |

# QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

- All beam crossings are triggered at the ILC
- All background is electroweak.
- Roughly, the detection efficiency is independent of decay mode $\Rightarrow \Delta(\sigma \bullet BR) / \sigma \bullet BR \propto 1/\sqrt{BR}$

- LHC Higgs detection efficiency is uneven across decay modes.
- Higgs was discovered in decays modes with $\gamma, e, \mu$, which have relatively small BR's
- Qualitatively, there is complementarity between the ILC and LHC with respect to decay modes.




$WW \rightarrow l\nu l\nu \quad l = e, \mu$

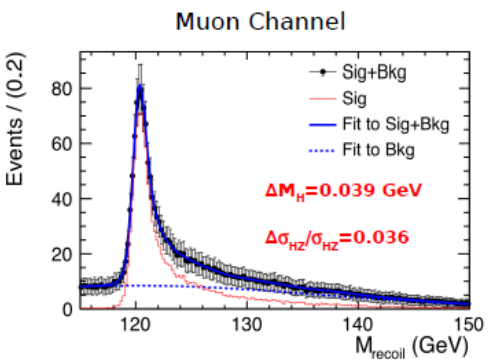
$ZZ \rightarrow l^+ l^- l^+ l^- \quad l = e, \mu$

Discovery decay modes at LHC

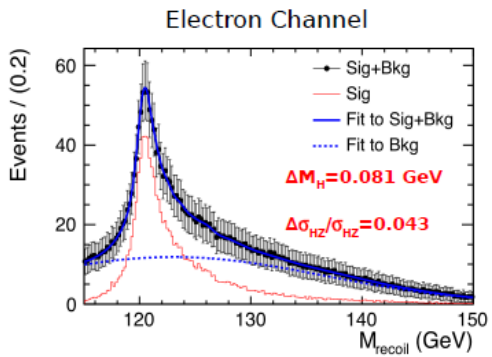
# QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

- Almost all ILC Higgs measurements are measurements of $\sigma \bullet BR$ .
- One crucial measurement is different: the Higgs recoil measurement of $\sigma(e^+e^- \to ZH)$.
- $\sigma_{ZH}$ is the key that unlocks the door to model independent measurements of the Higgs BR's and $\Gamma_{tot}$ at the ILC.

- All LHC Higgs measurements are measurements of $\sigma \bullet BR$



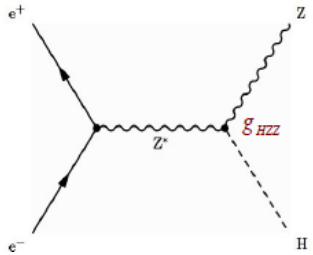

**Very Precise Measurement**
**S/B = 8 in Peak Region**




**Less Precise**
**Bremsstrahlung in detector material**

Combined: $\Delta M_H = .032$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=2.5% for L= 250 fb$^{-1}$

$\Delta M_H = .015$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=1.2% for L=1150 fb$^{-1}$




$\sigma_{HZ} \sim g^2_{HZZ}$

$\Rightarrow \Delta g_{HZZ} / g_{HZZ} = 1.3\%$ (0.6%) for L=250 (1150) fb$^{-1}$

## ILC model independent global coupling fit using 32 $\sigma \bullet BR$ measurements $Y_i$ and $\sigma_{ZH}$ measurement $Y_{33}$

$$\chi^2 = \sum_{i=1}^{i=33} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2 ,$$

$$Y_i' = F_i \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{Htt} g^2_{Hb\bar{b}}}{\Gamma_0}$$

$$F_i = S_i G_i \quad \text{where } S_i = \left(\frac{\sigma_{ZH}}{g_Z^2}\right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_W^2}\right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g_t^2}\right), \text{ and } G_i = \left(\frac{\Gamma_i}{g_i^2}\right).$$

The cross section calculations $S_i$ do not involve QCD ISR.

The partial width calculations $G_i$ do not require quark masses as input.

We are confident that the total theory errors for $S_i$ and $G_i$ will be at the 0.1% level at the time of ILC running.

THESE AND OTHER QUALITATIVE DIFFERENCES BETWEEN ILC & LHC LEAD TO QUANTITATIVE IMPROVEMENTS OVER LHC

7 Parameter HXSWG Benchmark *

| Mode | LHC | | ILC(1000) | ILC(LumUp) |
|---|---|---|---|---|
| | $300\ \mathrm{fb}^{-1}$ | $3000\ \mathrm{fb}^{-1}$ | | |
| $\gamma\gamma$ | $(5-7)\%$ | $(2-5)\%$ | 3.8 % | 2.3 % |
| $gg$ | $(6-8)\%$ | $(3-5)\%$ | 1.1 % | 0.67 % |
| $WW$ | $(4-5)\%$ | $(2-3)\%$ | 0.21 % | 0.13 % |
| $ZZ$ | $(4-5)\%$ | $(2-3)\%$ | 0.44 % | 0.22 % |
| $t\bar{t}$ | $(14-15)\%$ | $(7-10)\%$ | 1.3 % | 0.76 % |
| $b\bar{b}$ | $(10-13)\%$ | $(4-7)\%$ | 0.51 % | 0.31 % |
| $\tau^+\tau^-$ | $(6-8)\%$ | $(2-5)\%$ | 1.3 % | 0.72 % |

* Assume $\kappa_c = \kappa_t$ & $\Gamma_{tot} = \sum_{\text{SM decays i}} \Gamma_i^{SM} \kappa_i^2$

Other Higgs Couplings

| Mode | LHC 300 $\mathrm{fb}^{-1}$ | LHC 3000 $\mathrm{fb}^{-1}$ | ILC(1000) | ILC(LumUp) |
|---|---|---|---|---|
| $\mu^+\mu^-$ | 30% | 10% | 16 % | 10 % |
| $hhh$ | - | 50% | 21 % | 13 % * |
| BR(invis.) | $<$ (17 – 28)% | $<$ (6-17)% | $<$ 0.69 % | $<$ 0.32 % |
| $c\bar{c}$ | - | - | 2.0 % | 1.1 % |
| $\Gamma_T(h)$ | - | - | 5.6 % | 2.7 % |

* Current full simulation result using $H \to b\bar{b}$ , $WW^*$ only. Results will improve as more Higgs decay modes are added, and as jet combinatoric problems are solved.

# Backup Slides


9

# ILC Accelerator Parameters from TDR

Baseline Luminosity

Upgrade Luminosity

| | | | Baseline 500 GeV Machine | | | 1st Stage | L Upgrade | $E_{CM}$ Upgrade | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | A | B |
| Centre-of-mass energy | $E_{CM}$ | GeV | 250 | 350 | 500 | 250 | 500 | 1000 | 1000 |
| Collision rate | $f_{rep}$ | Hz | 5 | 5 | 5 | 5 | 5 | 4 | 4 |
| Electron linac rate | $f_{linac}$ | Hz | 10 | 5 | 5 | 10 | 5 | 4 | 4 |
| Number of bunches | $n_b$ | | 1312 | 1312 | 1312 | 1312 | 2625 | 2450 | 2450 |
| Bunch population | $N$ | $\times 10^{10}$ | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.74 | 1.74 |
| Bunch separation | $\Delta t_b$ | ns | 554 | 554 | 554 | 554 | 366 | 366 | 366 |
| Pulse current | $I_{beam}$ | mA | 5.8 | 5.8 | 5.8 | 5.8 | 8.8 | 7.6 | 7.6 |
| Main linac average gradient | $G_a$ | MV m$^{-1}$ | 14.7 | 21.4 | 31.5 | 31.5 | 31.5 | 38.2 | 39.2 |
| Average total beam power | $P_{beam}$ | MW | 5.9 | 7.3 | 10.5 | 5.9 | 21.0 | 27.2 | 27.2 |
| Estimated AC power | $P_{AC}$ | MW | 122 | 121 | 163 | 129 | 204 | 300 | 300 |
| RMS bunch length | $\sigma_z$ | mm | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.250 | 0.225 |
| Electron RMS energy spread | $\Delta p/p$ | % | 0.190 | 0.158 | 0.124 | 0.190 | 0.124 | 0.083 | 0.085 |
| Positron RMS energy spread | $\Delta p/p$ | % | 0.152 | 0.100 | 0.070 | 0.152 | 0.070 | 0.043 | 0.047 |
| Electron polarisation | $P_-$ | % | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Positron polarisation | $P_+$ | % | 30 | 30 | 30 | 30 | 30 | 20 | 20 |
| Horizontal emittance | $\gamma\epsilon_x$ | μm | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Vertical emittance | $\gamma\epsilon_y$ | nm | 35 | 35 | 35 | 35 | 35 | 30 | 30 |
| IP horizontal beta function | $\beta_x^*$ | mm | 13.0 | 16.0 | 11.0 | 13.0 | 11.0 | 22.6 | 11.0 |
| IP vertical beta function | $\beta_y^*$ | mm | 0.41 | 0.34 | 0.48 | 0.41 | 0.48 | 0.25 | 0.23 |
| IP RMS horizontal beam size | $\sigma_x^*$ | nm | 729.0 | 683.5 | 474 | 729 | 474 | 481 | 335 |
| IP RMS veritcal beam size | $\sigma_y^*$ | nm | 7.7 | 5.9 | 5.9 | 7.7 | 5.9 | 2.8 | 2.7 |
| Luminosity | $L$ | $\times 10^{34}$ cm$^{-2}$s$^{-1}$ | 0.75 | 1.0 | 1.8 | 0.75 | 3.6 | 3.6 | 4.9 |
| Fraction of luminosity in top 1% | $L_{0.01}/L$ | | 87.1% | 77.4% | 58.3% | 87.1% | 58.3% | 59.2% | 44.5% |
| Average energy loss | $\delta_{BS}$ | | 0.97% | 1.9% | 4.5% | 0.97% | 4.5% | 5.6% | 10.5% |
| Number of pairs per bunch crossing | $N_{pairs}$ | $\times 10^3$ | 62.4 | 93.6 | 139.0 | 62.4 | 139.0 | 200.5 | 382.6 |
| Total pair energy per bunch crossing | $E_{pairs}$ | TeV | 46.5 | 115.0 | 344.1 | 46.5 | 344.1 | 1338.0 | 3441.0 |

# Lumi Upgrade at Ecm=250 GeV*

* not in TDR – private communication from Marc Ross and Nick Walker

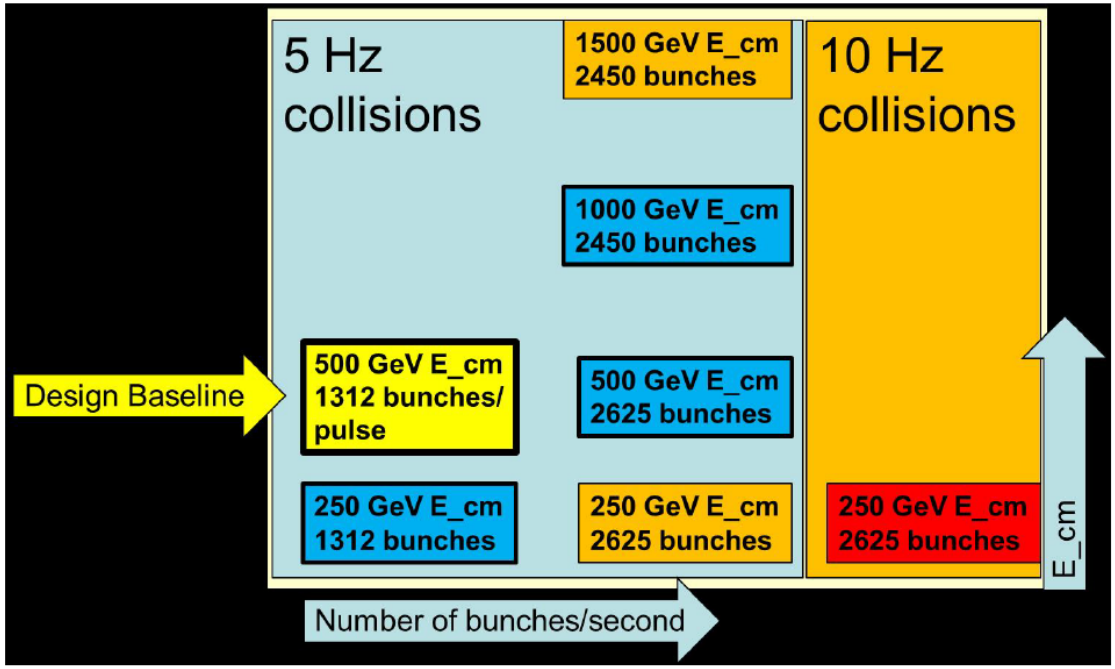



**Table 1.2.** ILC Higgs factory operational modes

Baseline Luminosity

Upgrade Luminosity

| | | | 1st Stage Higgs Factory | Baseline ILC, after Lumi Upgrade | High Rep Rate Operation |
|---|---|---|---|---|---|
| Centre-of-mass energy | $E_{CM}$ | GeV | 250 | 250 | 250 |
| Collision rate | $f_{rep}$ | Hz | 5 | 5 | 10 |
| Electron linac rate | $f_{linac}$ | Hz | 10 | 10 | 10 |
| Number of bunches | $n_b$ | | 1312 | 2625 | 2625 |
| Pulse current | $I_{beam}$ | mA | 5.8 | 8.75 | 8.75 |
| Average total beam power | $P_{beam}$ | MW | 5.9 | 10.5 | 21 |
| Estimated AC power | $P_{AC}$ | MW | 129 | 160 | 200 |
| Luminosity | $L$ | $\times 10^{34}$ cm$^{-2}$s$^{-1}$ | 0.75 | 1.5 | 3.0 |

**Table 5.1.** Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV $h$ boson assuming you run $3 \times 10^7$ s at the baseline differential luminosity for each center of mass energy. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

| $\sqrt{s}$ and $\mathcal{L}$ $(P_{e^-}, P_{e^+})$ | 250 fb$^{-1}$ at 250 GeV (-0.8,+0.3) | | 500 fb$^{-1}$ at 500 GeV (-0.8,+0.3) | | | | 1 ab$^{-1}$ at 1 TeV (-0.8,+0.2) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $Zh$ | $\nu\bar{\nu}h$ | $Zh$ | $\nu\bar{\nu}h$ | $t\bar{t}h$ | $Zhh$ | $\nu\bar{\nu}h$ | $t\bar{t}h$ | $\nu\bar{\nu}hh$ |
| $\Delta\sigma/\sigma$ | 2.5% | - | - | - | | 42.7% | | | 26.3% |
| BR(invis.) | $<$ 0.80 % | - | - | - | - | | | | |
| mode | $\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$ | | | | | | | | |
| $h \to b\bar{b}$ | 1.2% | 10.5% | 1.8% | 0.66% | 28% | | 0.32% | 6.0% | |
| $h \to c\bar{c}$ | 8.3% | - | 13% | 6.2% | | | 3.1% | | |
| $h \to gg$ | 7.0% | - | 11% | 4.1% | | | 2.3% | | |
| $h \to WW^*$ | 6.4% | - | 9.2% | 2.4% | | | 1.6% | | |
| $h \to \tau^+\tau^-$ | 4.2% | - | 5.4% | 9.0% | | | 3.1% | | |
| $h \to ZZ^*$ | 19% | - | 25% | 8.2% | | | 4.1% | | |
| $h \to \gamma\gamma$ | 29-38% | - | 29-38% | 20-26% | | | 7-10% | | |
| $h \to \mu^+\mu^-$ | 100% | - | - | - | | | 31% | | |

**Table 5.2.** Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV $h$ boson assuming you run $3 \times 10^7$ s at the sum of the baseline and upgrade differential luminosities for each center of mass energy. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

| $\sqrt{s}$ and $\mathcal{L}$ $(P_{e^-}, P_{e^+})$ | 1150 fb$^{-1}$ at 250 GeV (-0.8,+0.3) | | 1600 fb$^{-1}$ at 500 GeV (-0.8,+0.3) | | | | 2.5 ab$^{-1}$ at 1 TeV (-0.8,+0.2) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $Zh$ | $\nu\bar{\nu}h$ | $Zh$ | $\nu\bar{\nu}h$ | $t\bar{t}h$ | $Zhh$ | $\nu\bar{\nu}h$ | $t\bar{t}h$ | $\nu\bar{\nu}hh$ |
| $\Delta\sigma/\sigma$ | 1.2% | - | - | - | | 23.7% | | | 16.7% |
| BR(invis.) | $<$ 0.37 % | - | - | - | | | - | | |
| mode | $\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$ | | | | | | | | |
| $h \to b\bar{b}$ | 0.56% | 4.9% | 1.0% | 0.37% | 16% | | 0.20% | 3.8% | |
| $h \to c\bar{c}$ | 3.9% | - | 7.2% | 3.5% | | | 2.0% | | |
| $h \to gg$ | 3.3% | - | 6.0% | 2.3% | | | 1.4% | | |
| $h \to WW^*$ | 3.0% | - | 5.1% | 1.3% | | | 1.0% | | |
| $h \to \tau^+\tau^-$ | 2.0% | - | 3.0% | 5.0% | | | 2.0% | | |
| $h \to ZZ^*$ | 8.8% | - | 14% | 4.6% | | | 2.6% | | |
| $h \to \gamma\gamma$ | 16% | - | 19% | 13% | | | 5.4% | | |
| $h \to \mu^+\mu^-$ | - | - | - | - | | | 20% | | |