Physics at ILC

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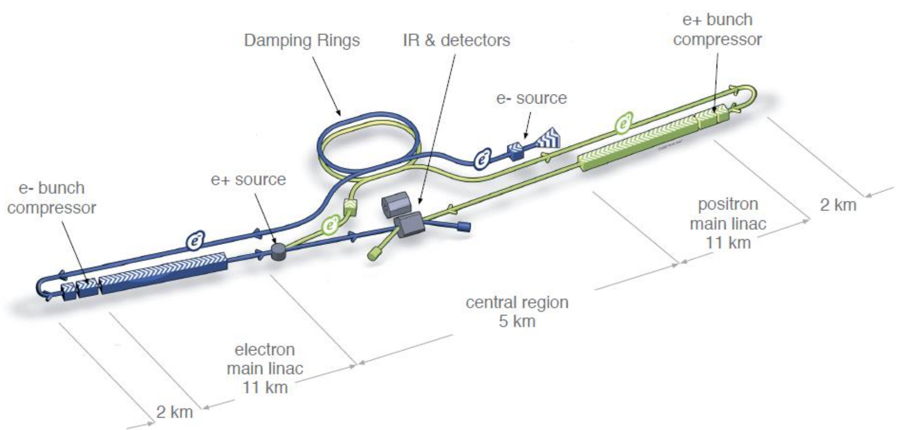
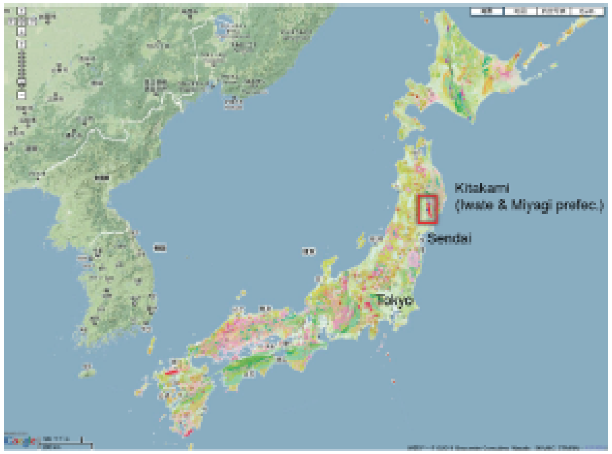
The International Linear Collider

- e^+e^- collider with $\sqrt{s}$ = 250 – 500 GeV, upgradable to $\sqrt{s}$ = 1 TeV
- L ~2×10^{34} cm^{-2} s^{-1}
- 31 km long, SCRF technology
- global collaboration (~130 institutes)

Beam size (IP): 6 nm • 500 nm • 300 mm
Polarization: e^- >80% ; e^+ 30-40%

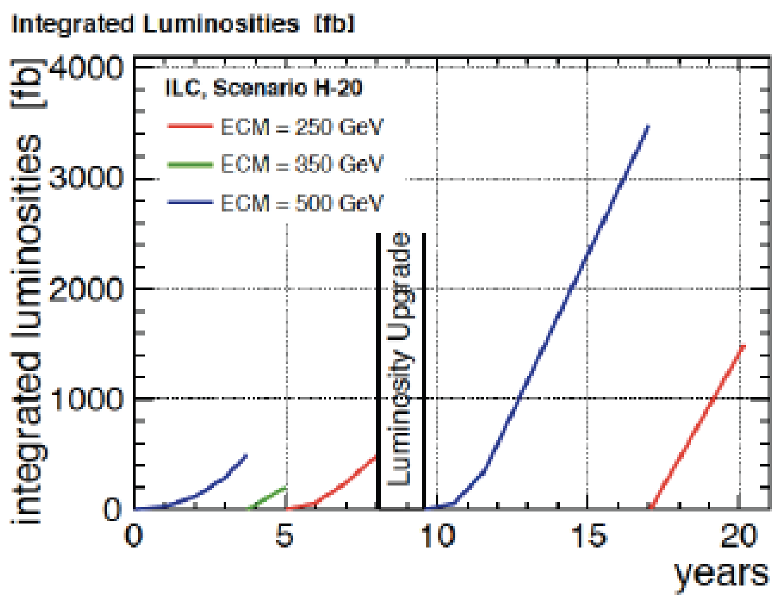




- since August 2013: Kitakami in northern Japan is candidate site
- following the recommendation by the Science Council of Japan, MEXT currently investigates hosting the ILC

Running scenarios at start of data taking

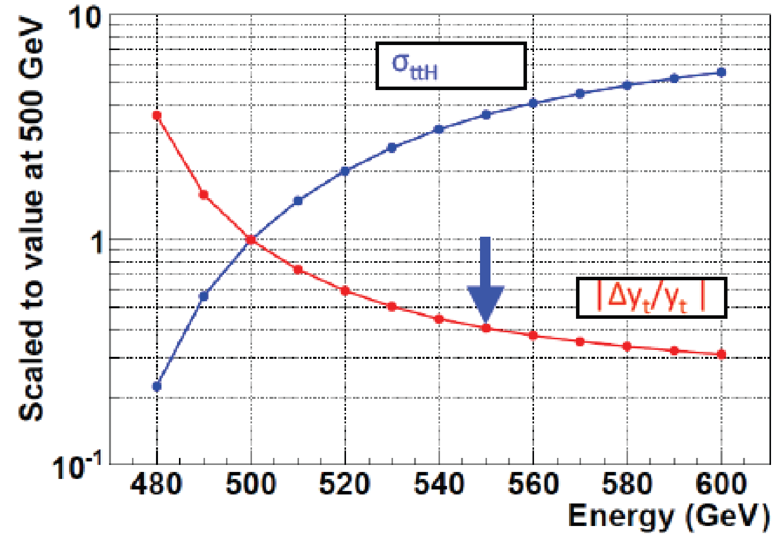
Scenario	Stage	500			500 LumiUP		
	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathscr{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1



T. Barklow et al., arXiv:1506.07830

Recommended scenario (~20 years program):

- Starting at 500 GeV (500 fb^{-1}), then 350 (200 fb-1) and 250 GeV (500 fb^{-1}).

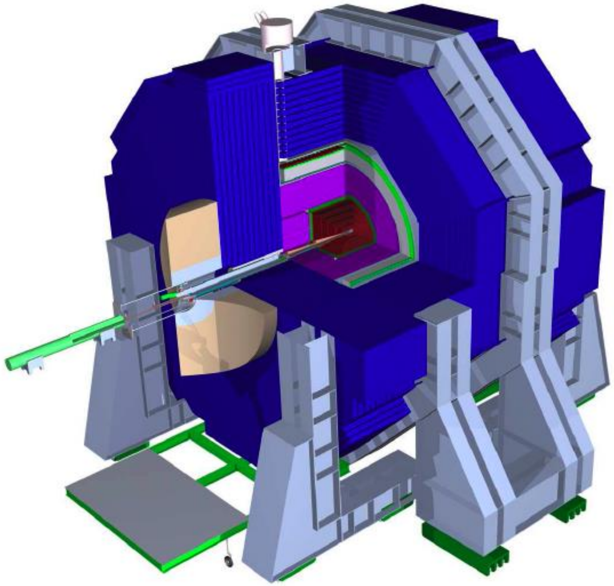


Running scenario will depend on LHC and early ILC results

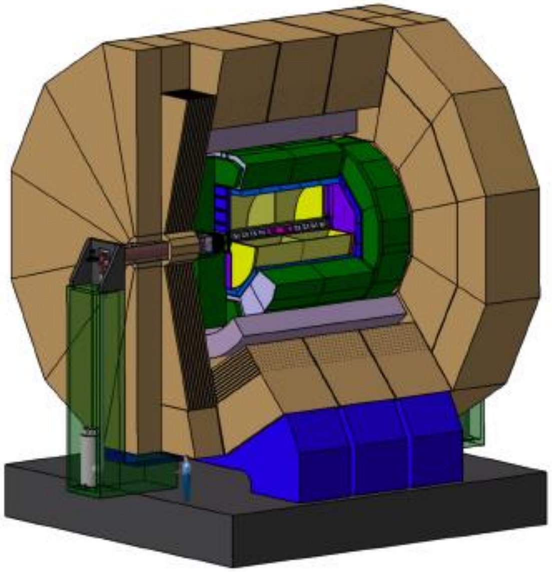
550 GeV is ~2.4 better precision over 500 GeV for ttH coupling measurement

Detectors design strategies

- **SiD**
  - High B field (5 Tesla)
  - Small ECAL ID
  - Small calorimeter volume
    - Finer ECAL granularity
  - Silicon main tracker



- **ILD**
  - Medium B field (3.5 Tesla)
  - Large ECAL ID
    - Particle separation for PFA
  - Redundancy in tracking
  - TPC for main tracker

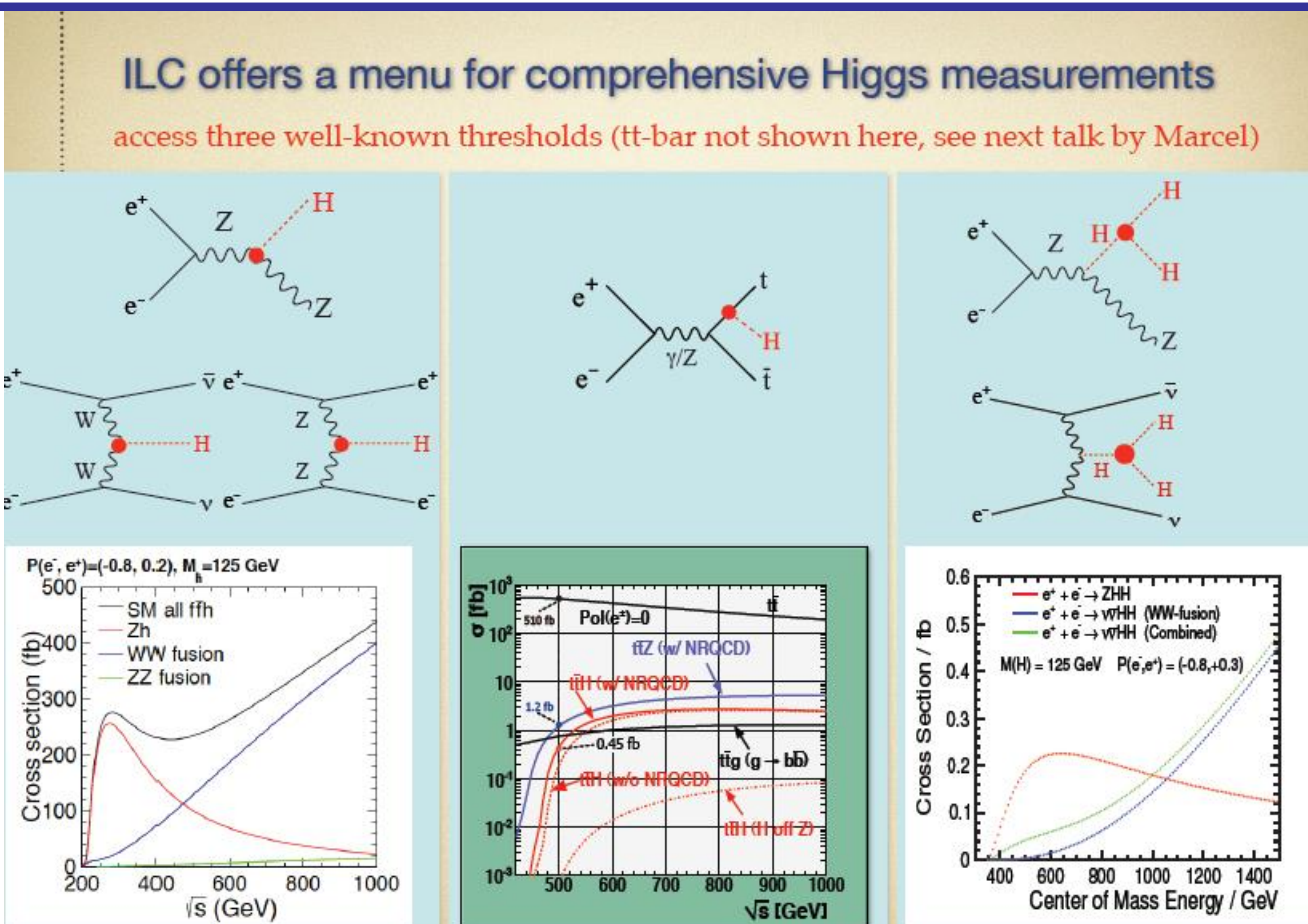


$$\sigma_E/E \sim 3-4\% \sim 30\%/\sqrt{E} \text{ @100GeV}$$

$$\sigma_{1/p_T} \sim 2 \times 10^{-5}\ \text{GeV}^{-1}$$

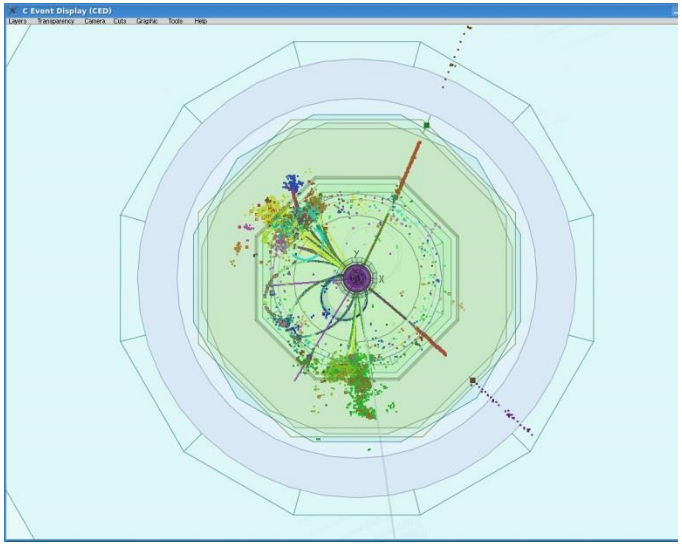
$$\sigma_{r\phi} = 5\ \mu\text{m} \oplus \frac{10}{p(\text{GeV} \sin^{3/2}\theta)}\ \mu\text{m}$$

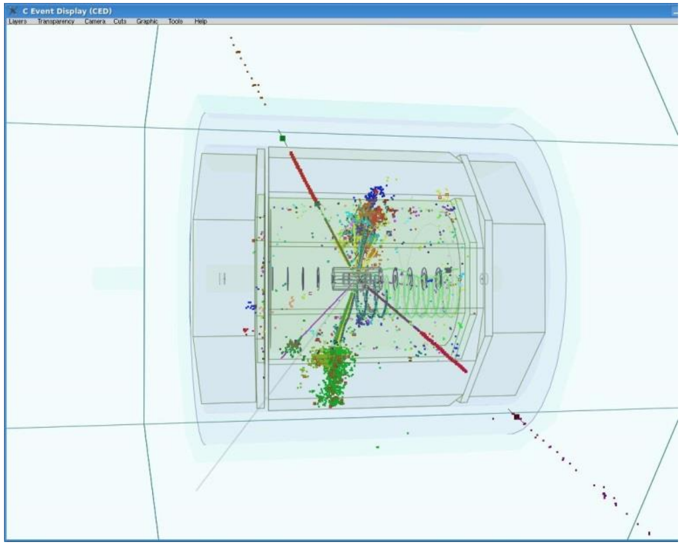
Higgs production at ILC



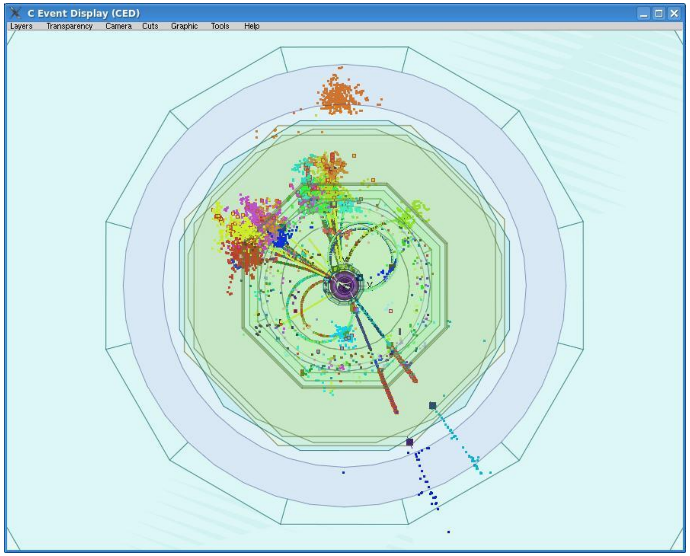
Decay $e^+e^- \rightarrow Z(\mu\mu)\,H(b\bar{b})$

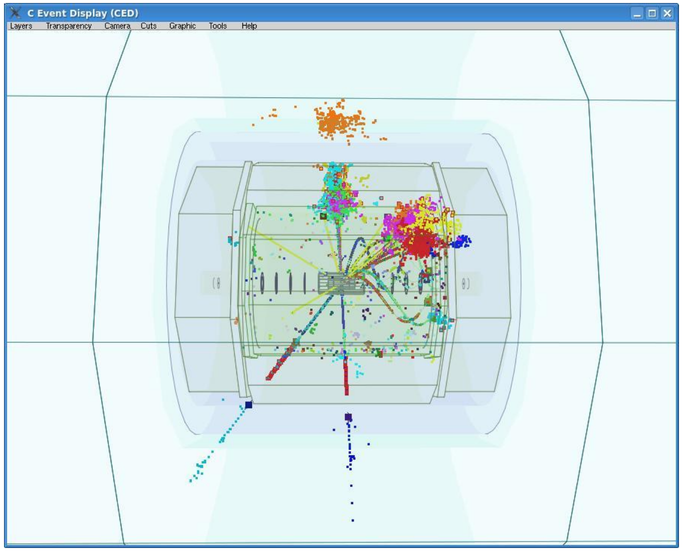
$\sqrt{s}$ = 250 GeV



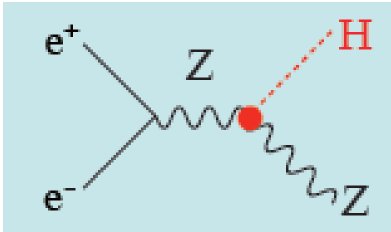


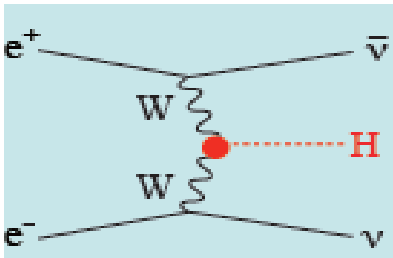
$\sqrt{s}$ = 500 GeV





Higgs boson coupling constant measurements at ILC





$\boxed{Z \rightarrow \mu^+\mu^-}$

$H \rightarrow all$

$H \rightarrow b\bar{b}$

$H \rightarrow WW^*$

$$Y_1 = \sigma_{ZH} = F_1 \cdot g_Z^2$$

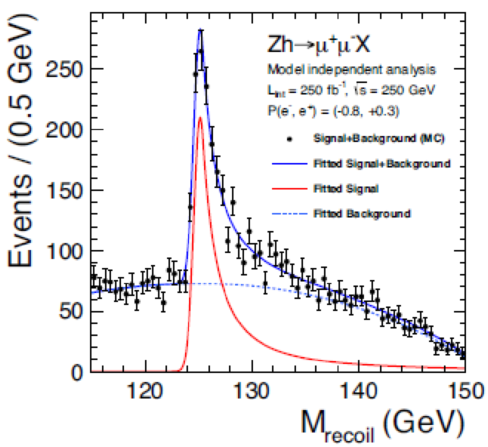
$$Y_2 = \sigma_{ZH} \times \mathrm{Br}(H \rightarrow b\bar{b}) = F_2 \cdot \frac{g_Z^2 g_b^2}{\Gamma_H}$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \rightarrow b\bar{b}) = F_3 \cdot \frac{g_W^2 g_b^2}{\Gamma_H}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \rightarrow WW^*) = F_4 \cdot \frac{g_W^4}{\Gamma_H}$$

$$Y_5 = \sigma_{ZH} \times \mathrm{Br}(H \rightarrow WW^*) = F_5 \cdot \frac{g_Z^2 g_W^2}{\Gamma_H}$$

Constants F_1, F_2, F_3, F_4, F_5 can be calculated with a high accuracy and small theoretical uncertainties



1. Obtain g_Z from first measurement of x-section
2. Obtain ratio g_Z/g_W from the second and third measurements
3. Using obtained g_Z and g_W, we can get Γ_H from four of fifth measurements

Parameters measurable at ILC

Observables to measure at ILC

- σ_{ZH} ← the key!
- $\sigma_{ZH}\times Br(H \to bb)$, $\sigma_{\nu\nu H}\times Br(H \to bb)$
- $\sigma_{ZH}\times Br(H \to cc)$, $\sigma_{\nu\nu H}\times Br(H \to cc)$ ← unique at LC
- $\sigma_{ZH}\times Br(H \to gg)$, $\sigma_{\nu\nu H}\times Br(H \to gg)$
- $\sigma_{ZH}\times Br(H \to WW^*)$, $\sigma_{\nu\nu H}\times Br(H \to WW^*)$
- $\sigma_{ZH}\times Br(H \to ZZ^*)$, $\sigma_{\nu\nu H}\times Br(H \to ZZ^*)$
- $\sigma_{ZH}\times Br(H \to \tau\tau)$, $\sigma_{\nu\nu H}\times Br(H \to \tau\tau)$
- $\sigma_{ZH}\times Br(H \to \gamma\gamma)$, $\sigma_{\nu\nu H}\times Br(H \to \gamma\gamma)$
- $\sigma_{ZH}\times Br(H \to \mu\mu)$, $\sigma_{\nu\nu H}\times Br(H \to \mu\mu)$
- $\sigma_{ZH}\times Br(H \to \mathrm{Invisible})$ ← high sensitivity
- $\sigma_{ttH}\times Br(H \to bb)$ ← direct top-Yukawa
- $\sigma_{ZHH}\times Br^2(H \to bb)$, $\sigma_{\nu\nu HH}\times Br^2(H \to bb)$ ← direct λ_{HHH}

each running stage offers an independent set of observables

Expected accuracy of coupling measurements

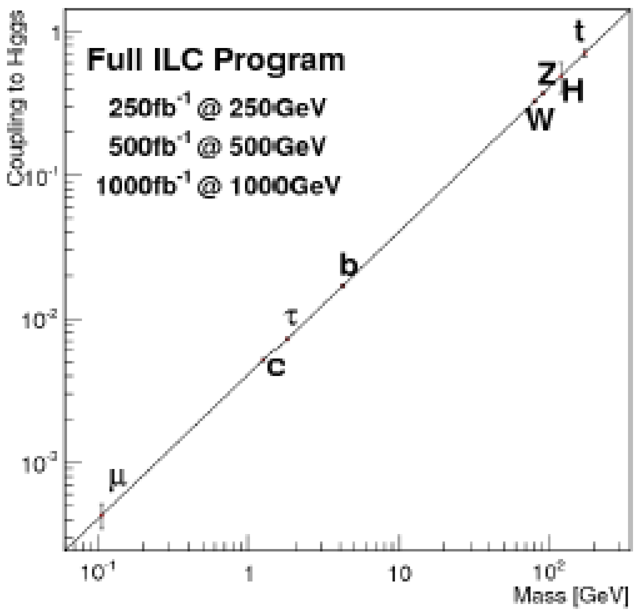
Future measurement of Higgs Couplings

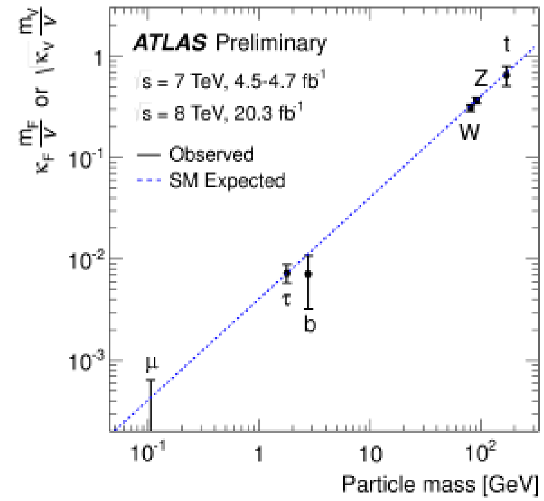
Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

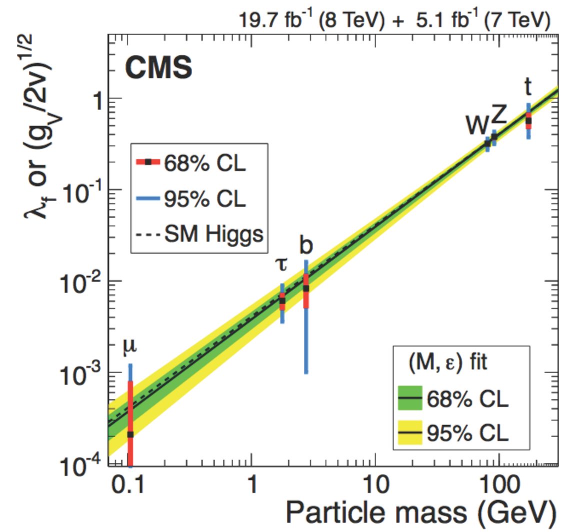
Snowmass Report
1310.8361

Coupling constants can be typically
Measured with better than 1 % at ILC

Expected accuracy of coupling measurements







Coupling	LHC	HL-LHC	LC	HL-LHC + LC
HWW	4-6%	2-5%	0.3%	0.1%
HZZ	4-6%	2-4%	0.5%	0.3%
Htt	14-15%	7-10%	1.3%	1.3%
Hbb	10-13%	4-7%	0.6%	0.6%
$H\tau\tau$	6-8%	2-5%	1.3%	1.2%
$H\gamma\gamma$	5-7%	2-5%	3.8%	3.0%
Hgg	6-8%	3-5%	1.2%	1.1%
Hinvis	—	—	0.9%	0.9%

Fingerprints of BSM models

The study of the deviations from these predictions is guided by the idea that each Higgs coupling has its own personality and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

M. Peskin @ HPNP2015

fermion couplings - multiple Higgs doublets

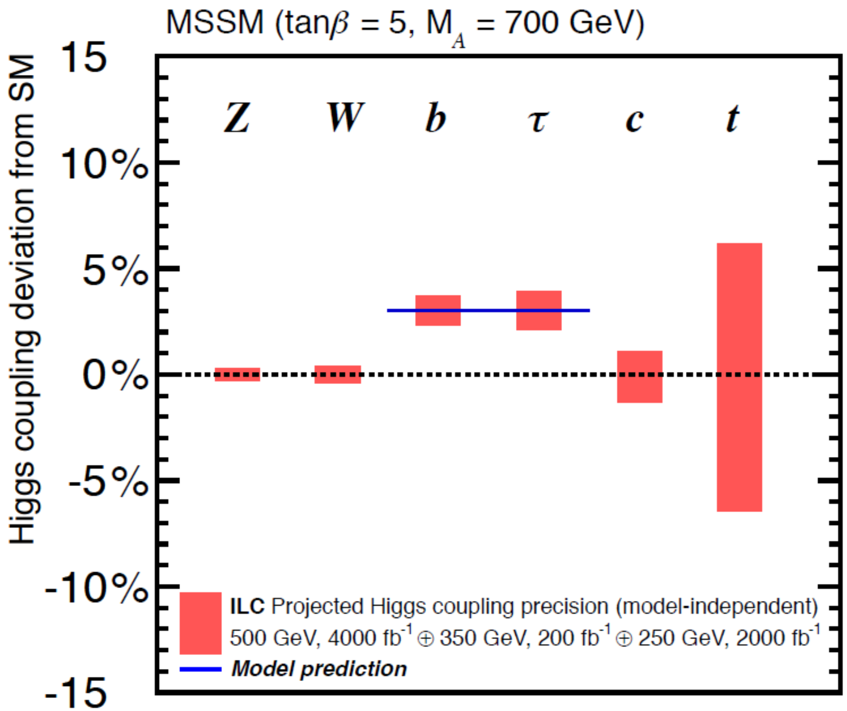
gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy vectorlike particles

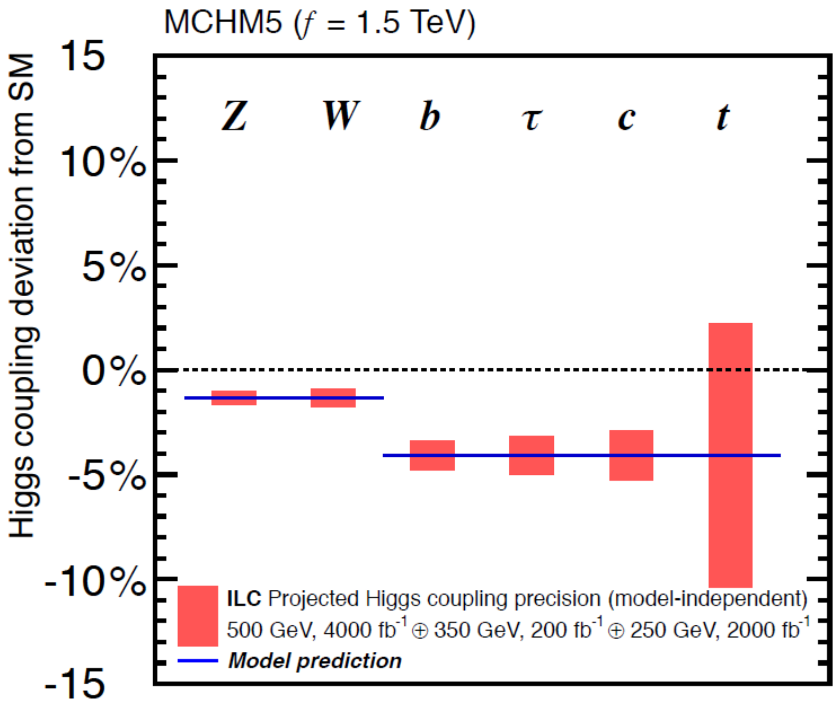
tt coupling - top compositeness

hhh coupling (large deviations) - baryogenesis

Fingerprints of BSM models



A supersymmetric model



A Higgs compositeness model

Error bars indicate the 1σ uncertainties expected from the model-independent fit to the expected full ILC data set.

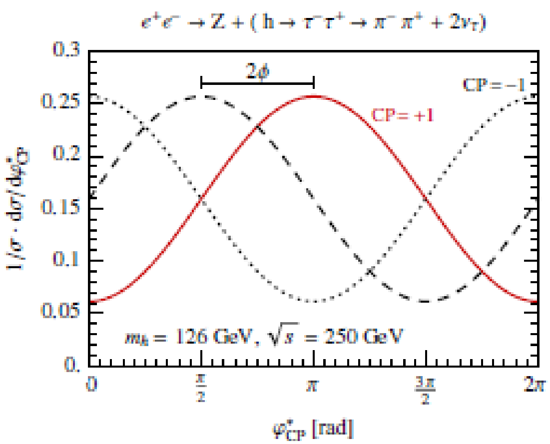
CPV in Higgs decay $h \rightarrow \tau^+\tau^-$

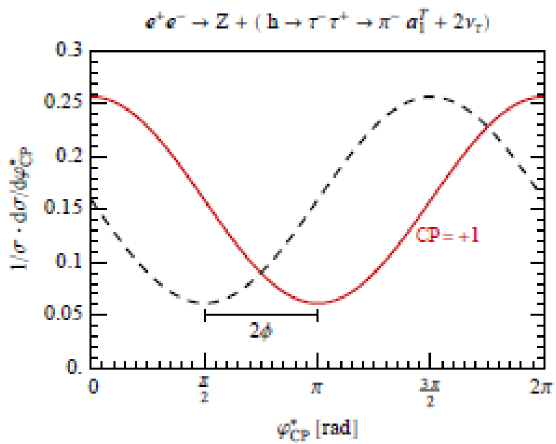
CPV appears in many extensions of Higgs Sector.

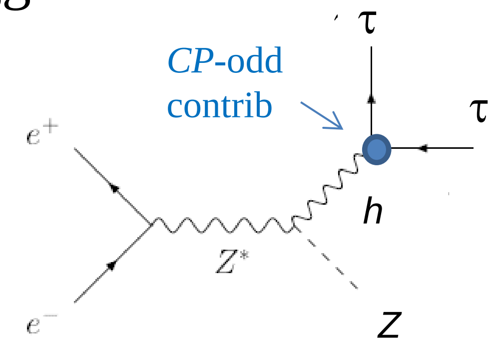
2HDM : two doublets of scalar fields with identical quantum numbers.
Three neutral fields : h, H, A ; two first are *CP*-even, last one is *CP*-odd.
These states are mixed to physical mass states in Higgs basis.

If *h(125)* has small *CP*-odd admixture:

$e^+ e^- \rightarrow Z\, h\,,\quad h \rightarrow \tau^+\tau^-,\quad \tau \rightarrow \pi\,, \rho\,, a_1\,, \ell$





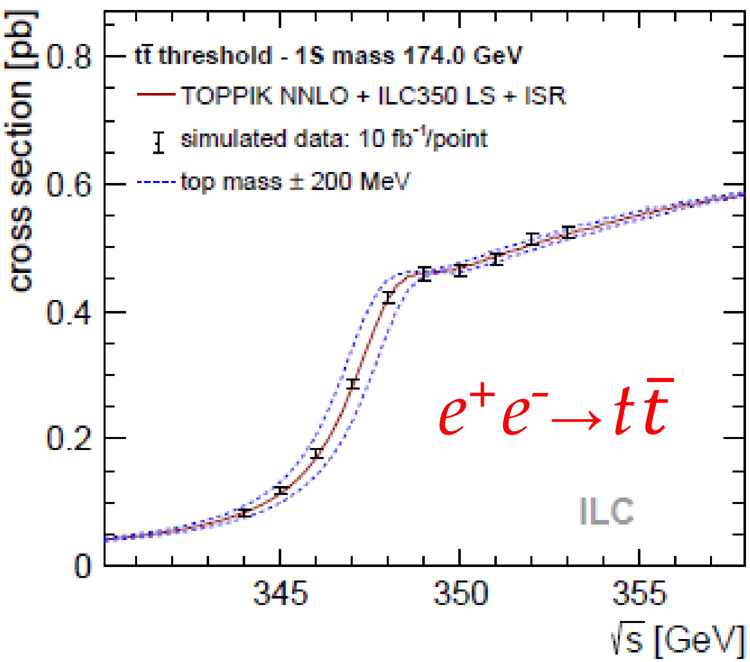


Uncertainties of about (5-10)° in mixing phase at ILC with a few hundreds fb^{-1}.

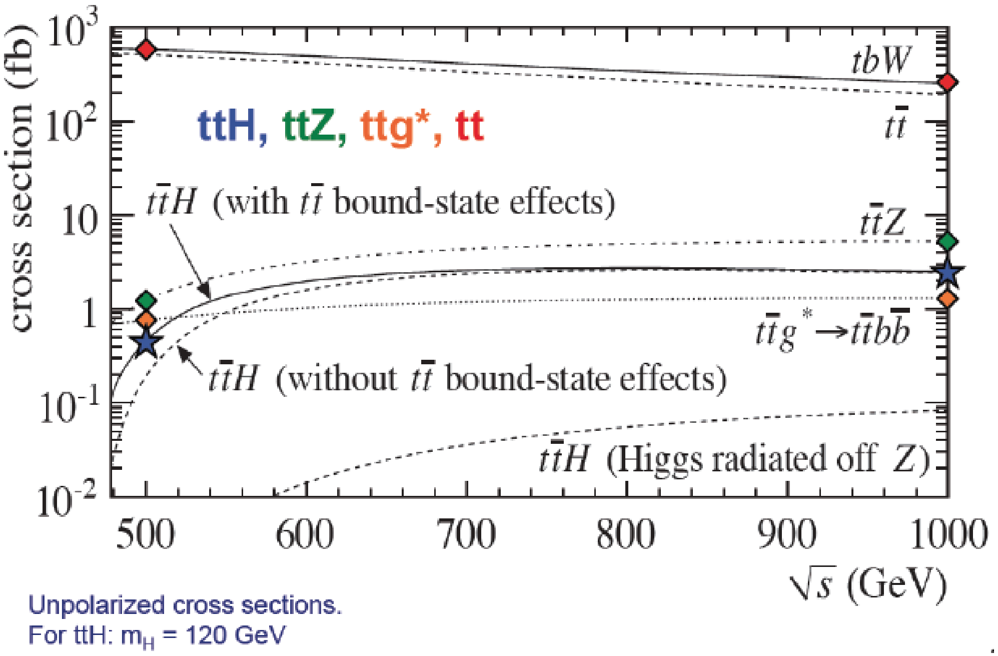
$$\varphi^* = \mathrm{acos}(\,\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp}\,) \qquad (\text{also}\ \ \psi^*_{CP} = \mathrm{acos}(\,\hat{q}^*_{\pi^-} \cdot (\hat{n}^*_{-\perp} \times \hat{n}^*_{+\perp})\,)\,)$$

Here decay products (π, ρ, a_1, ℓ) and their impact parameters have to be measured.

Top quark physics



Top quark production near threshold



Top quark production at different channels

Measurement near threshold: mass with accuracy ~17 MeV, width ~26 MeV.
Measurement of Yukawa coupling with accuracy ~4.2 %.
Measurement of forward-backward asymmetry.
Measurement of exotic top quark couplings at larger energies.

Other topics

$e^+ e^- \to f \bar{f}$

contribution from Z′ and other BSM (in particular Extra Dimensions) can be tested in these processes

$e^+ e^- \to W^+W^- \;/\; ZZ \;/\; Z\,W^+W^- \;/\; ZZZ$

Precision QCD test, measurement of *W* mass

Extensions of Higgs sector

SUSY particles (very weak couplings)

New exotic states

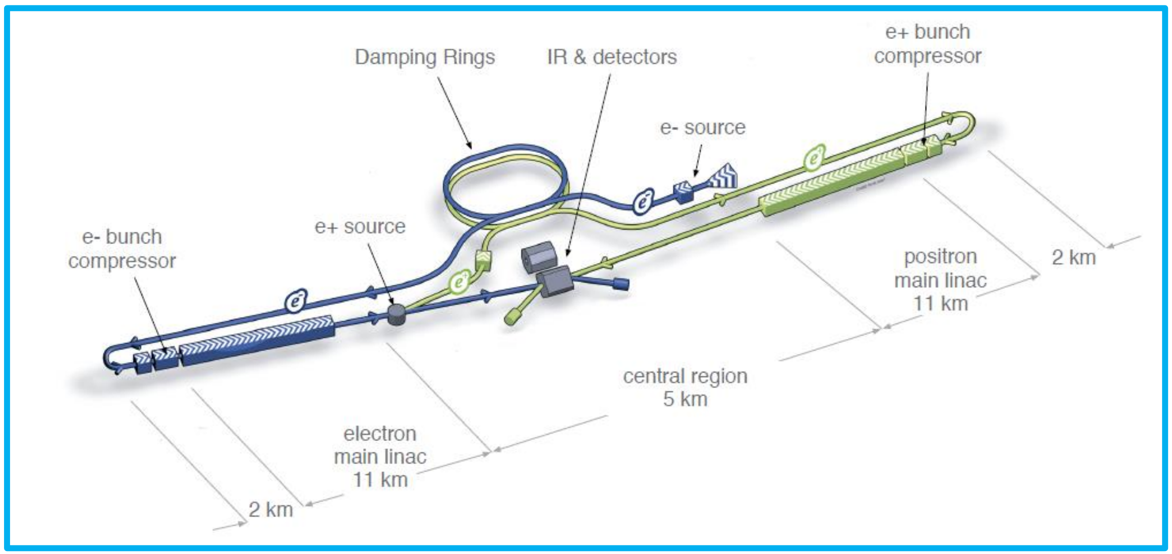
Conclusion

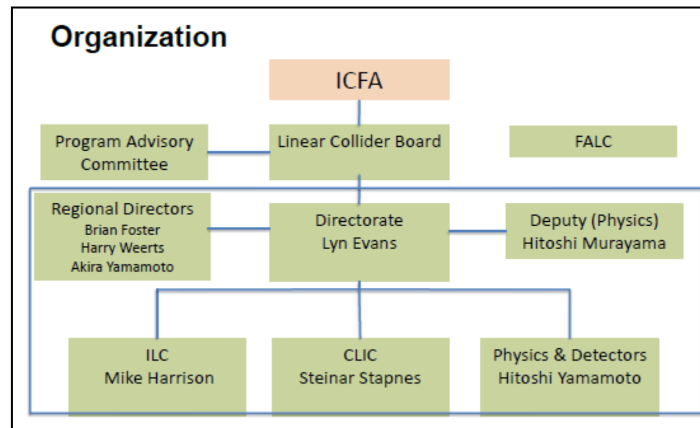
- Wide physics program is proposed for ILC
- Most important topics are precision Higgs boson and top quark measurements
- ILC well suited for BSM physics searches

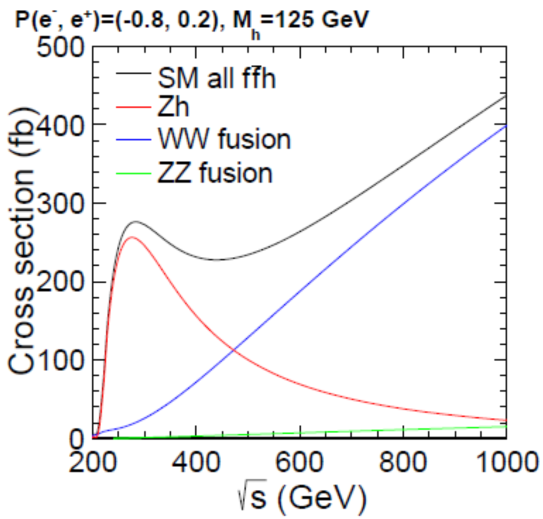
Background information

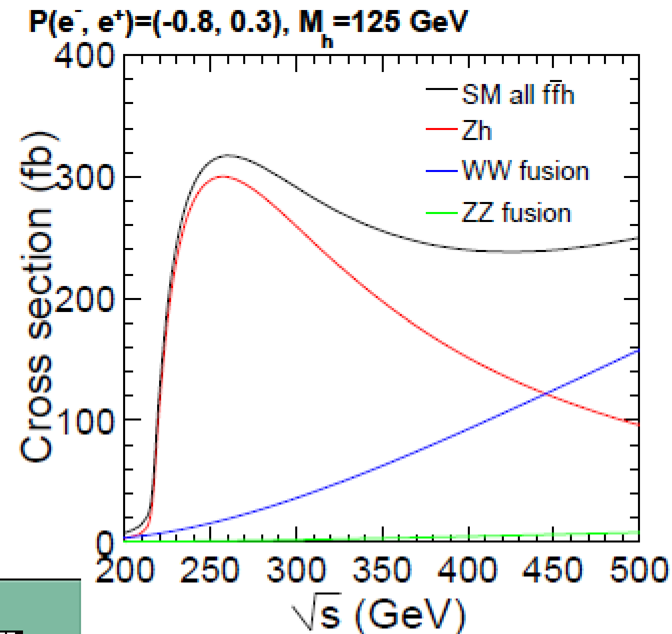
International Linear Collider (ILC)

- The next generation e+e- collider (500GeV, upgradable to 1TeV)
- Design work and accelerator R&D have been carried out in a global framework.
  The ILC TDR was completed by Global Design Effort (GDE) in 2013 and the next phase of design and R&D works has started under the leadership of Linear Collider Collaboration (LCC).
- Discovery of a Higgs particle at LHC in July 2012 set a clear physics target of the initial stage of ILC.






P(e⁻, e⁺)=(-0.8, 0.2), M_h=125 GeV
SM all ff̄h
Zh
WW fusion
ZZ fusion
Cross section (fb)
√s (GeV)


P(e⁻, e⁺)=(-0.8, 0.3), M_h=125 GeV
SM all ff̄h
Zh
WW fusion
ZZ fusion
Cross section (fb)
√s (GeV)

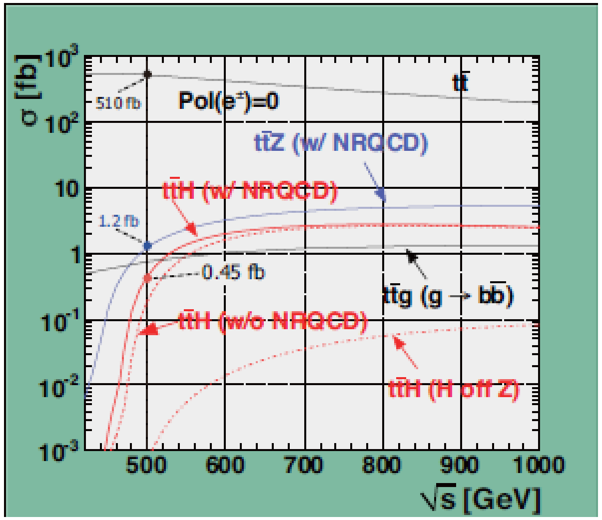

σ [fb]
510 fb
Pol(e⁺)=0
tt̄
tt̄Z (w/ NRQCD)
tt̄H (w/ NRQCD)
1.2 fb
0.45 fb
tt̄g (g → bb̄)
tt̄H (w/o NRQCD)
tt̄H (H off Z)
√s [GeV]

Table 2.3. Expected accuracies for the h boson branching ratios for $m_h = 120$ GeV when the 250 GeV measurements assuming $\mathcal{L} = 250\,\text{fb}^{-1}$ in Table 2.2 are combined with those at $\sqrt{s} = 500$ GeV assuming $\mathcal{L} = 500\,\text{fb}^{-1}$ and $(e^-, e^+) = (-0.8, +0.3)$ beam polarization. The errors on BRs include the error on σ of 2.5% from the recoil mass measurement at $\sqrt{s} = 250$ GeV.

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$			$\Delta BR/BR$
mode	Zh @ 250 GeV	Zh @ 500 GeV	$\nu\bar{\nu}h$ @ 500 GeV	combined
$h \to b\bar{b}$	1.0%	1.6%	0.60%	2.6%
$h \to c\bar{c}$	6.9%	11%	5.2%	4.6%
$h \to gg$	8.5%	13%	5.0%	4.8%
$h \to WW^*$	8.1%	12.5%	3.0%	3.8%
$h \to \tau^+\tau^-$	3.6%	4.6%	11%	3.6%
$h \to ZZ^*$	26%	34%	10%	9.3%
$h \to \gamma\gamma$	23-30%	29-38%	19-25%	13-17%

Expected accuracies for cross section times branching ratio measurements for the 125 GeV h boson.

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ 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)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

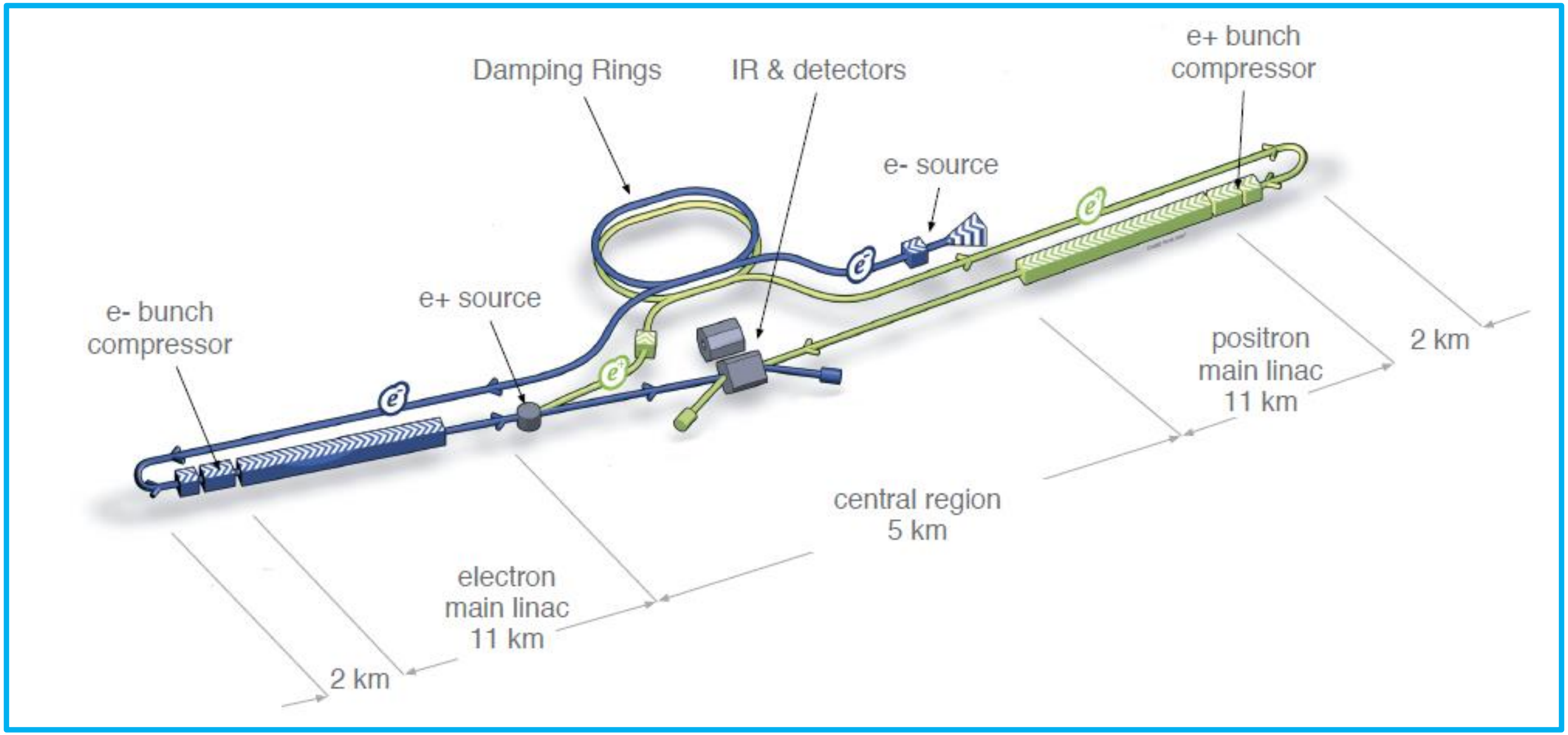
Table 2.5. Expected accuracies for top Yukawa and self-coupling measurements of the $125\,\text{GeV}$ h boson, with the specified energies and luminosity samples. The current analyses use the $h \to b\bar{b}$ mode only.

process	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]	(P_{e^-}, P_{e^+})	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$	$\Delta g/g$
$t\bar{t}h$	500	500	(-0.8,+0.3)	35%	18%
Zhh	500	500	(-0.8,+0.3)	64%	104%
$t\bar{t}h$	1000	1000	(-0.8,+0.2)	8.7%	4.0%
$\nu\bar{\nu}hh$	1000	1000	(-0.8,+0.2)	38%	28%

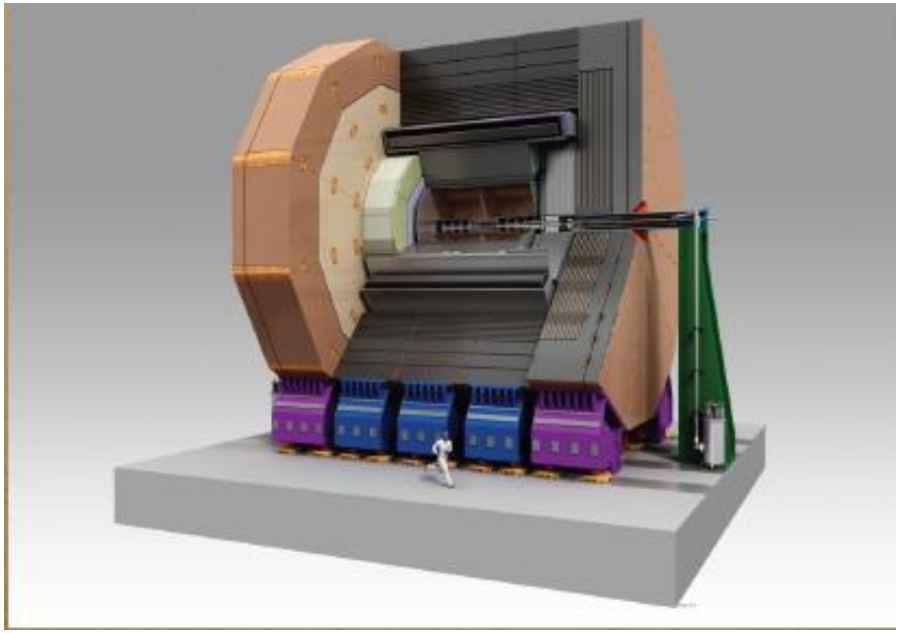
Table 2.6. Expected accuracies for Higgs boson couplings derived from the accuracy estimates for measured rates given in Tables 2.4 and 2.5. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits. The four columns refer to: LHC, 300 fb^{-1}, 1 detector; ILC at 250 GeV, with 250 fb^{-1}; ILC at 500 GeV, with 500 fb^{-1}; ILC at 1000 GeV, with 1000 fb^{-1}. Each column includes the stated data set and all previous ones [65].

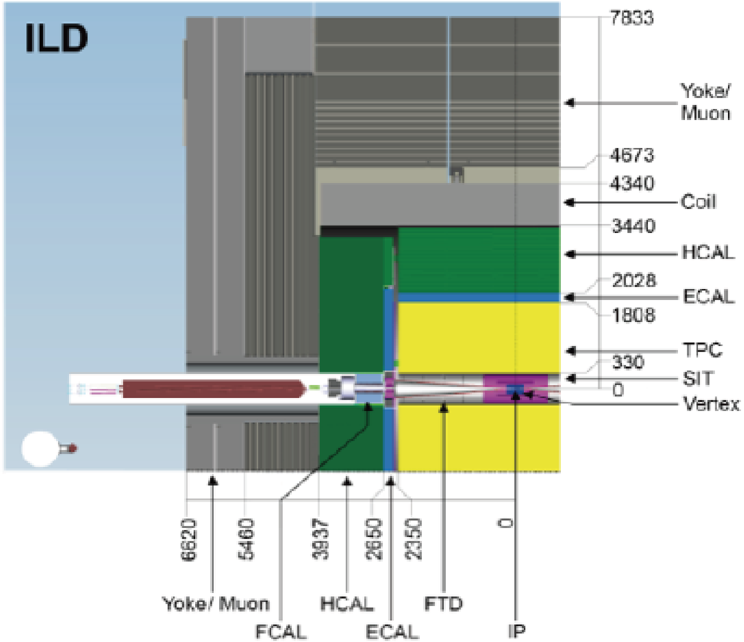
Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7 %
$\mu^+\mu^-$	–	–	–	16 %
self	–	–	104%	26 %
BR(invis.)	$< 9\%$	< 0.44 %	< 0.30 %	< 0.26 %
$\Gamma_T(h)$	20.3%	4.8 %	1.6 %	1.2 %

ILC collider



Baseline ILD detector design



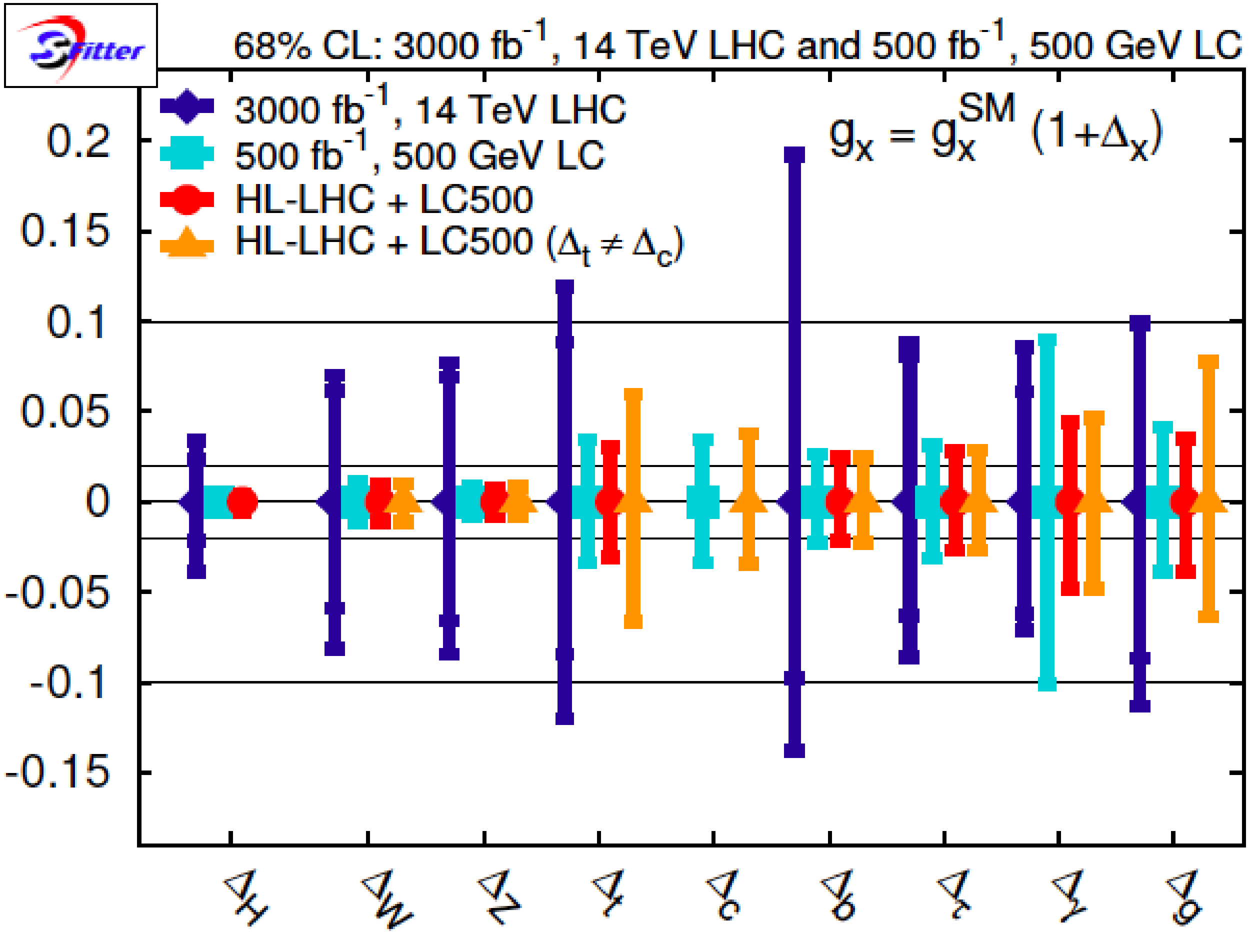


$$\sigma_E/E \sim 3-4\% \sim 30\%/\sqrt{E} \text{ @100GeV}$$

$$\sigma_{1/p_T} \sim 2\times 10^{-5}\ \mathrm{GeV}^{-1}$$

$$\sigma_{r\phi} = 5\ \mu\mathrm{m} \oplus \frac{10}{p(\mathrm{GeV}\sin^{3/2}\theta)}\ \mu\mathrm{m}$$

- separate charged & neutral particles
  - high granular ECAL & HCAL
  - large TPC & High B field
- identify b/c/q-jet
  - high performance VTX
- separate events by time stamping
  - high resolution SIT, SET···
- hermetic
  - endcaps, FTD···
- muon, BCAL, LCAL···

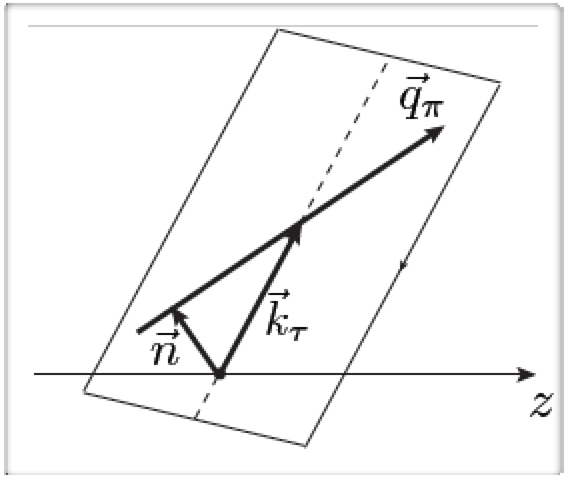


SFitter
68% CL: 3000 fb-1, 14 TeV LHC and 500 fb-1, 500 GeV LC
3000 fb-1, 14 TeV LHC
500 fb-1, 500 GeV LC
HL-LHC + LC500
HL-LHC + LC500 (Δt ≠ Δc)
gx = gx SM (1+Δx)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
ΔH
ΔW
ΔZ
Δt
Δc
Δb
Δτ
Δγ
Δg

CPV in decays $h \to \tau^+\tau^-$

Talk S. Berge at ECFA 2013, Hamburg

- No reconstruction of τ rest frames
- Use impact parameter vectors $\hat{n}_-$, $\hat{n}_+$
  $\varphi \sim acos(\hat{n}_- \cdot \hat{n}_+)$
- Boost $\hat{n}_\pm$ into $\pi^-\pi^+$-ZMF (denoted by *)
  $(n^\mu n_\mu = -1)$:
- $\varphi^* = \mathrm{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp})$
- Measurement of PV necessary
  (from $Z \to e^+e^-$)



$$\varphi^* = \mathrm{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp}) \qquad \psi^*_{CP} = \mathrm{acos}(\hat{q}^*_{\pi^-} \cdot (\hat{n}^*_{-\perp} \times \hat{n}^*_{+\perp}))$$