Higgs Couplings at the ILC

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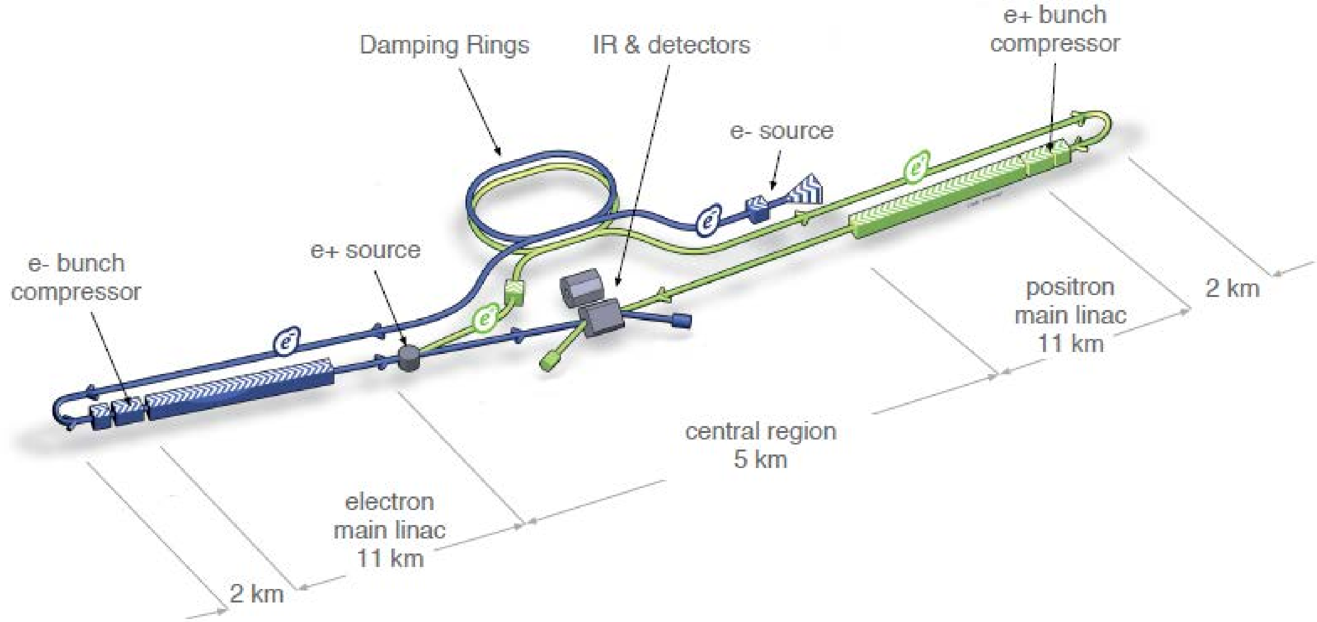
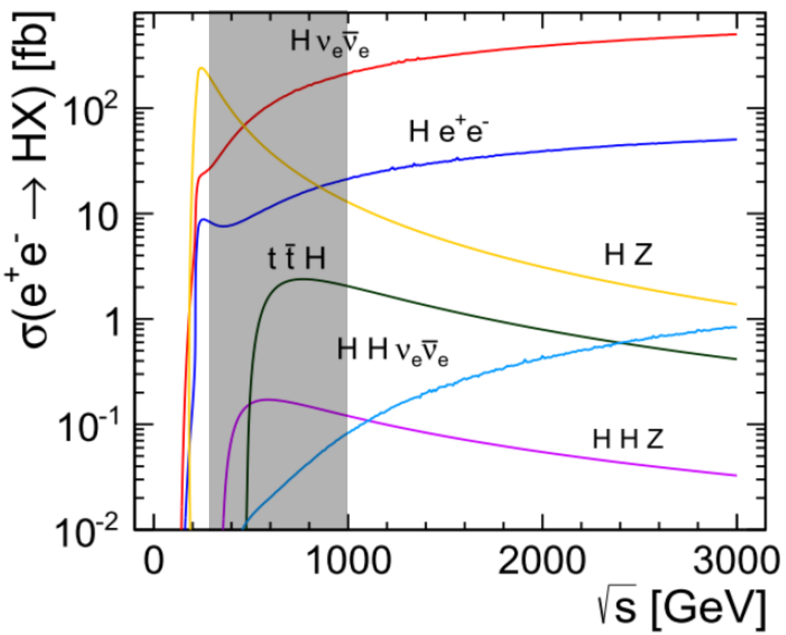
ILC : e^+e^- Linear Collider at 250 GeV < $\sqrt{s}$ < 1000 GeV





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	Δt_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	σ_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	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_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	δ_{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

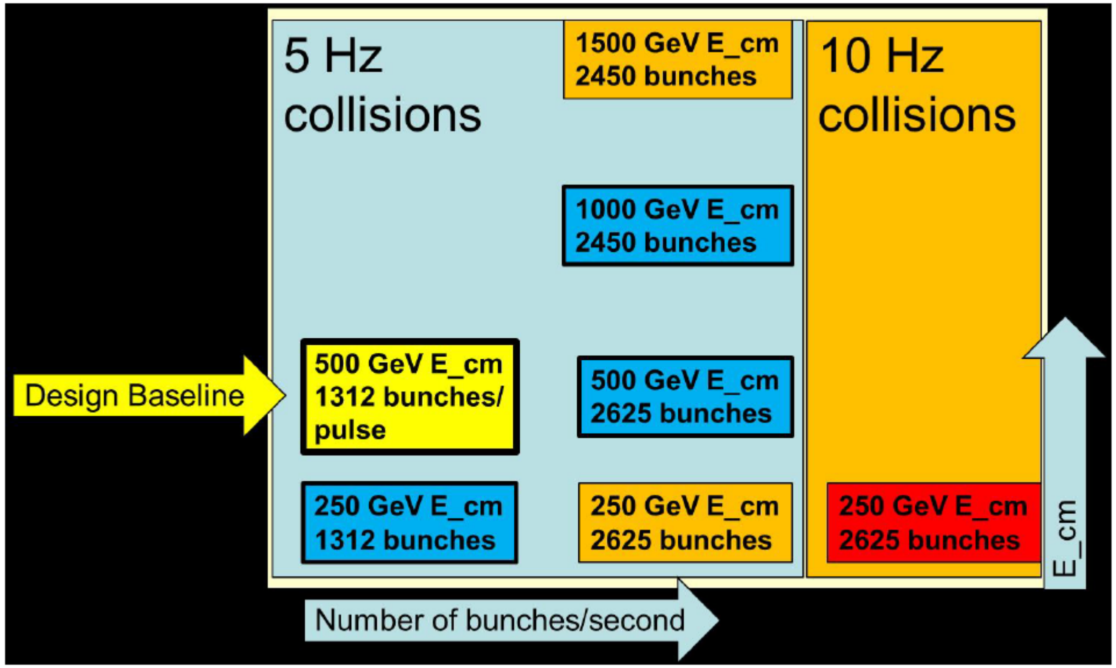


Table 1.2. ILC Higgs factory operational modes

Baseline Luminosity

Upgrade Luminosity

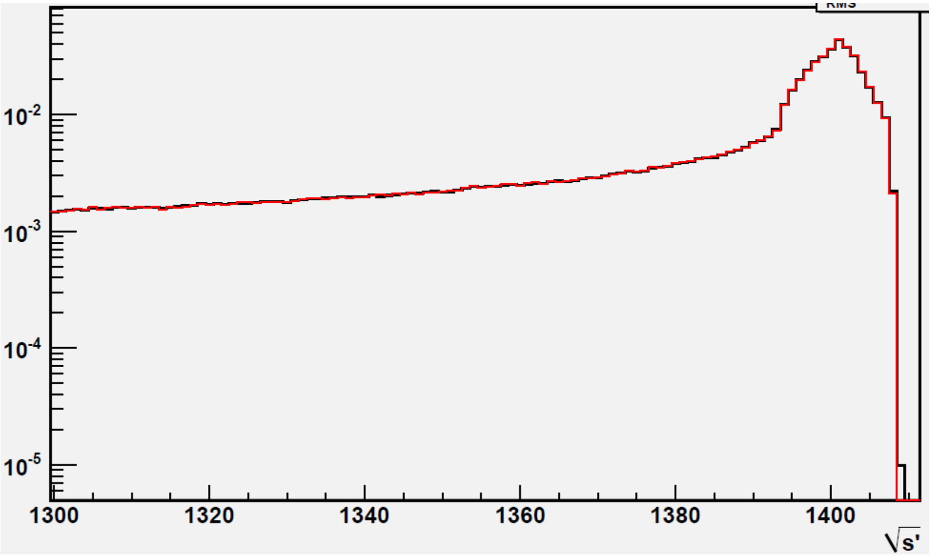
			1st Stage Higgs Factory	Baseline ILC, after Lumi Upgrade	High Rep Rate Operation
Centre-of-mass energy	E_{CM}	GeV	250	250	250
Collision rate	f_{rep}	Hz	5	5	10
Electron linac rate	f_{linac}	Hz	10	10	10
Number of bunches	n_b		1312	2625	2625
Pulse current	I_{beam}	mA	5.8	8.75	8.75
Average total beam power	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

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.

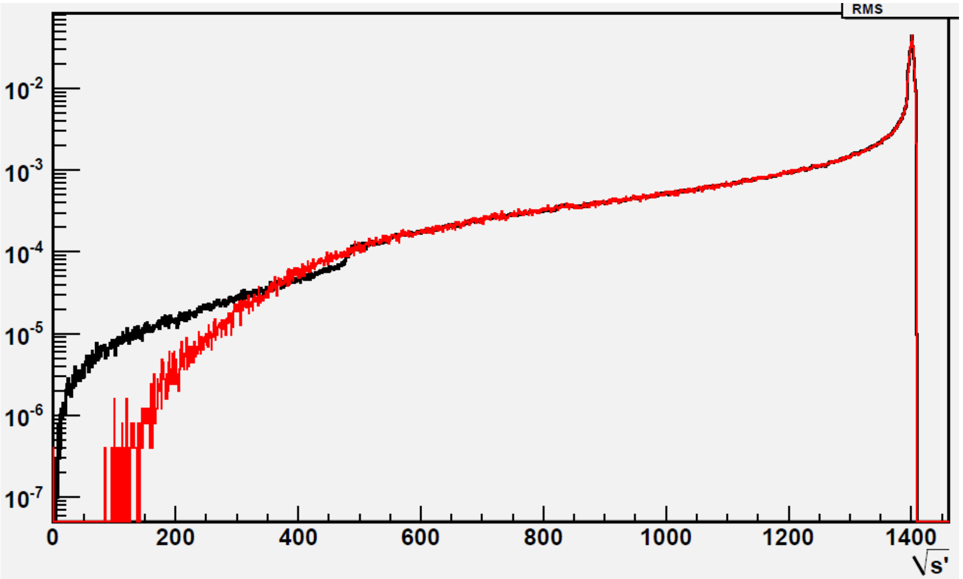
Scenario #	Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})
1	ILC(250)	250	250						
2	ILC(500)	250	250		500	500			
3	ILC(1000)	250	250		500	500		1000	1000
4	ILC(LumUp)	250	1150		500	1600		1000	2500

Beamstrahlung



Guinea-Pig

VEGAS MC Integration



$\gamma\gamma \rightarrow$ *hadrons*

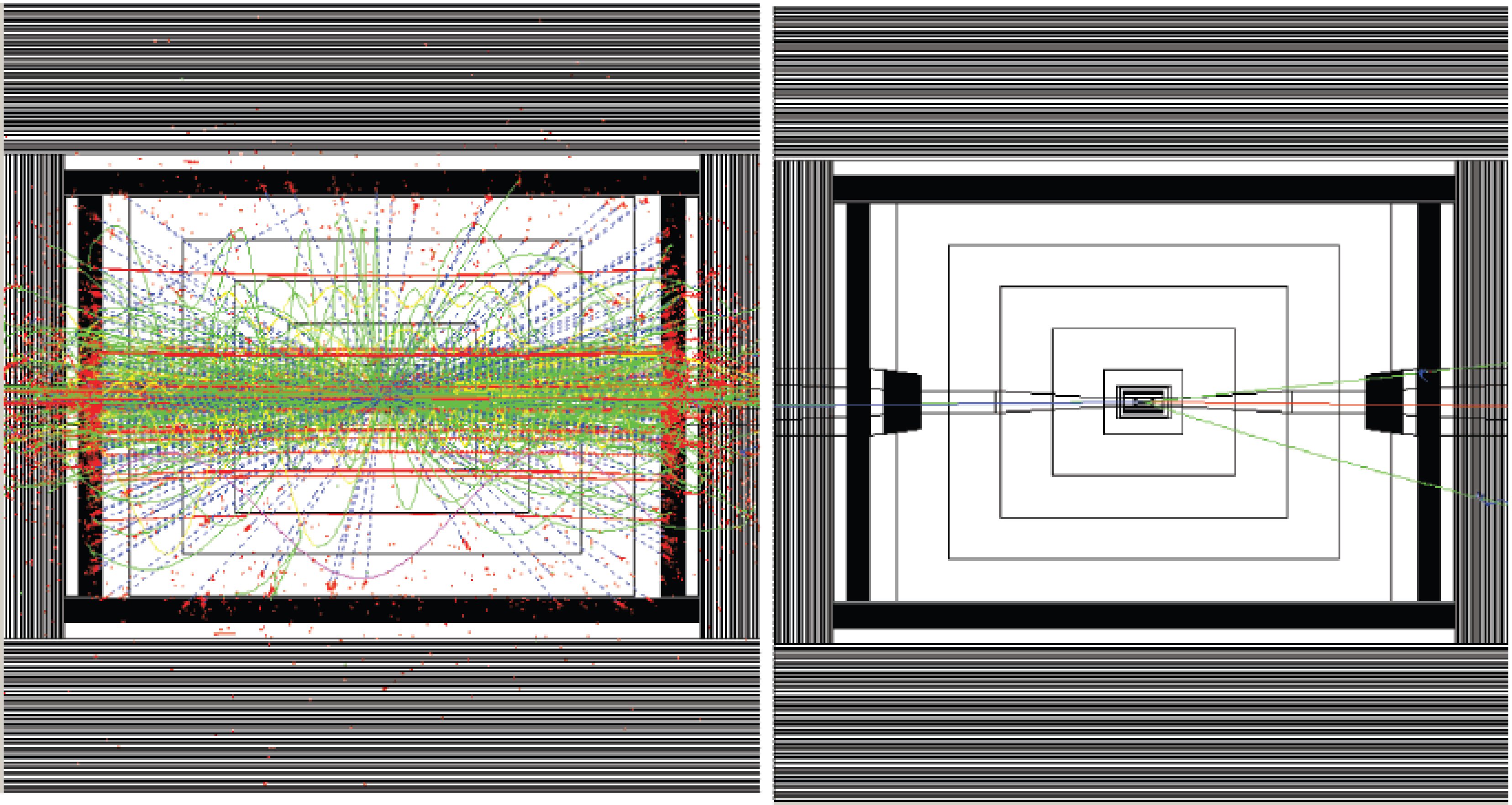
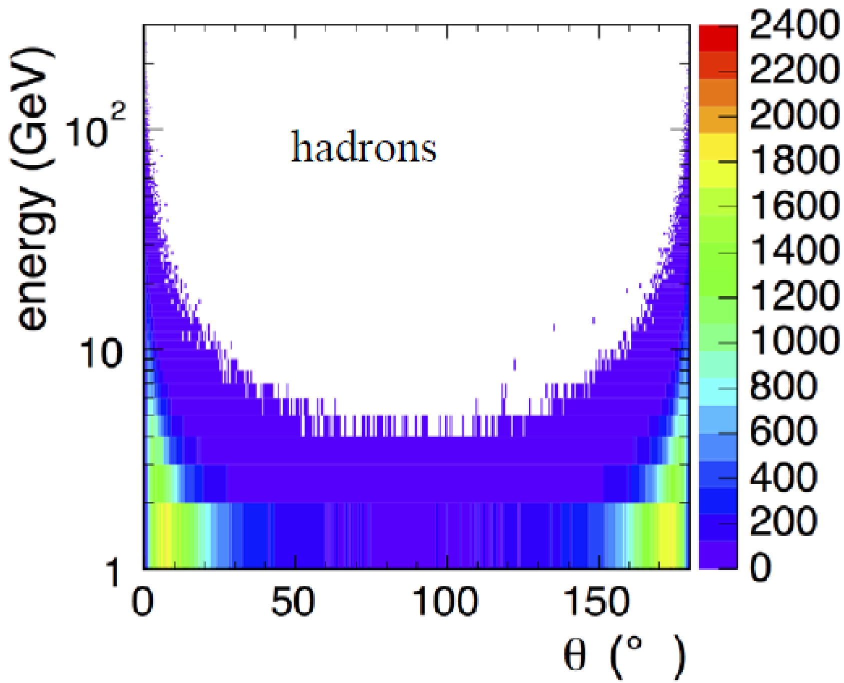
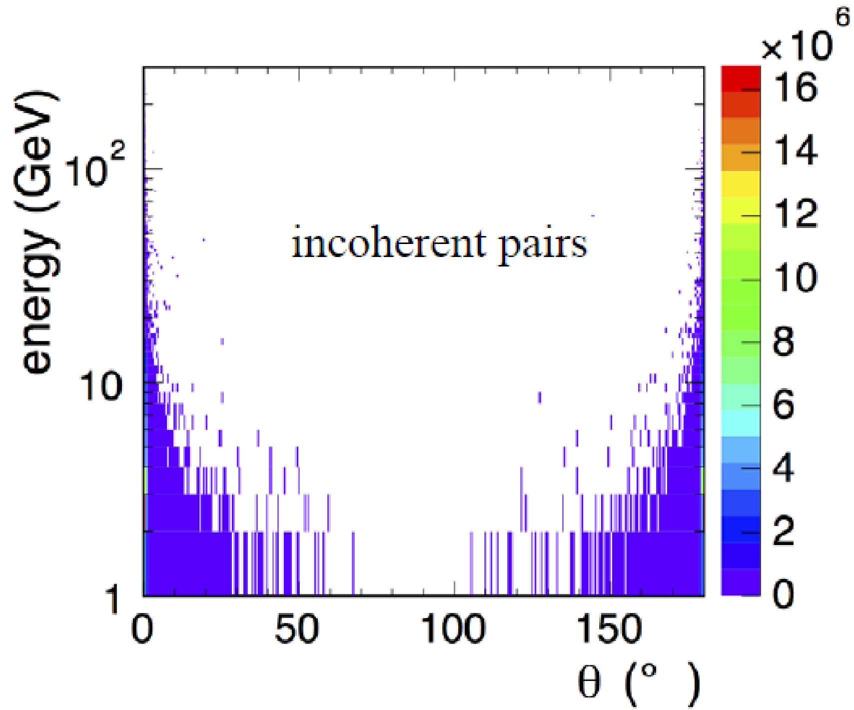


Figure 1.5: Physics backgrounds from $\gamma\gamma$ produced e^+e^- pairs, muon pairs, and hadronic events integrated over 150 bunch crossings (left) and a single bunch crossing (right).

Angular distribution of background

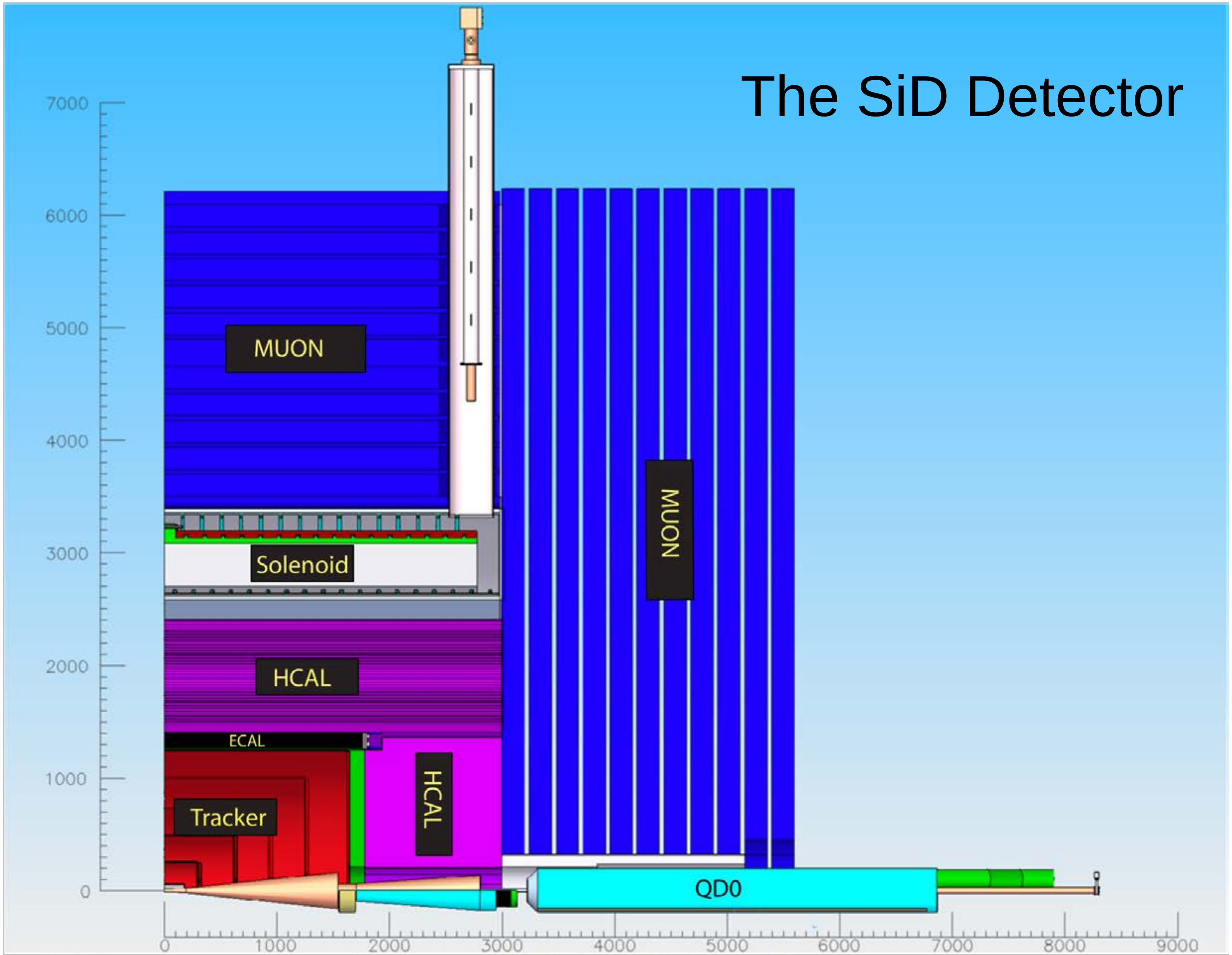




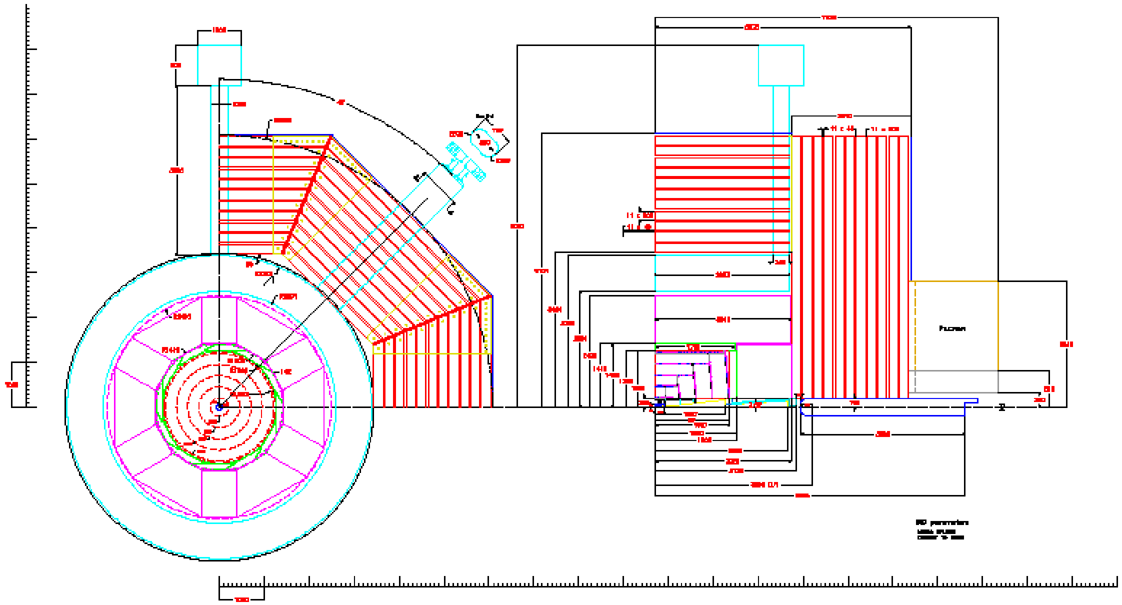
Incoherent pairs affect mostly occupancies and tracking efficiencies

Hadrons have enough energy to reach the calorimeter

Full Simulation Performed with ILD and/or SiD Detector



SiD Global Parameters



Detector	Technology	Radius (m)		Axial (z) (m)	
		Min	*Max*	*Min*	*Max*
Vertex Detector	Pixels	0.014	0.06		0.18
Central Tracking	Strips	0.206	1.25		1.607
Endcap Tracker	Strips	0.207	0.492	0.85	1.637
Barrel Ecal	Silicon-W	1.265	1.409		1.765
Endcap Ecal	Silicon-W	0.206	1.25	1.657	1.8
Barrel Hcal	RPCs	1.419	2.493		3.018
Endcap Hcal	RPCs	0.206	1.404	1.806	3.028
Coil	5 tesla	2.591	3.392		3.028
Barrel Iron	RPCs	3.442	6.082		3.033
Endcap Iron	RPCs	0.206	6.082	3.033	5.673

Combining barrel and endcaps these trackers and calorimeters cover $|\cos\theta| \le 0.99$

LumiCal and BeamCal are used for $|\cos\theta| > 0.99$

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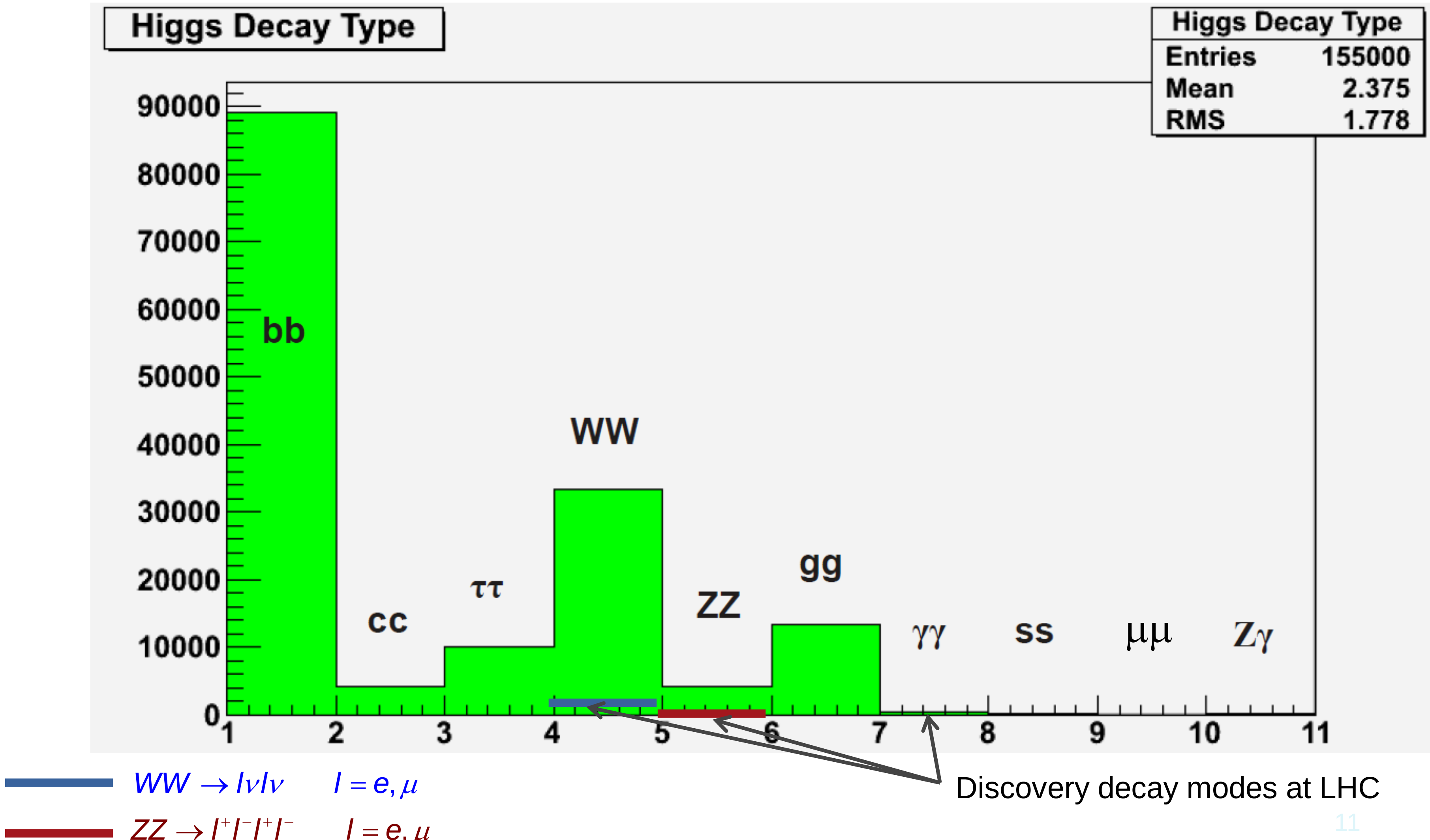
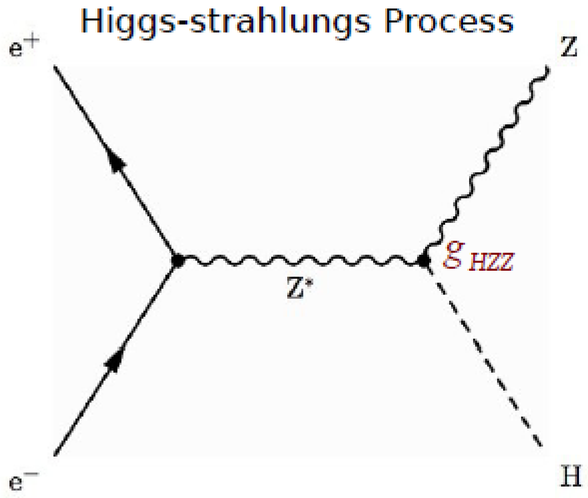
SM Higgs decay mode histogram M_H=125 GeV

Because all background is electroweak at the ILC, all Higgs decays, including fully hadronic decays, are triggered (all crossings are triggered at the ILC) and accessible without hard cuts.



$$\sigma(e^+e^- \rightarrow ZH) \qquad \sqrt{s} = 250 \text{ GeV}$$

Higgs-strahlung Cross Section and Higgs Mass at the ILC



Golden Plated Channel at e⁺e⁻ Colliders

Sensitive to coupling at HZZ Vertex

$Z \rightarrow e^+e^- \; , \mu^+\mu^-$

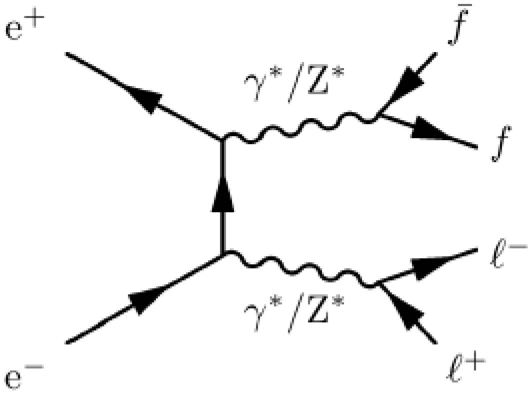
H $\rightarrow$ anything, incl invisible

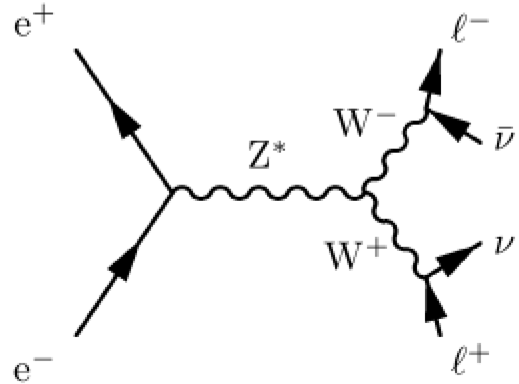
Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2\,E_Z\sqrt{s}$

$$\sigma(e^+e^- \to ZH) \qquad \sqrt{s} = 250 \text{ GeV}$$

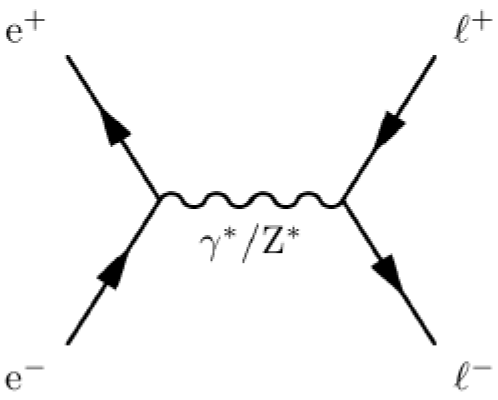
(Main) Background Processes

Boson Pair Production

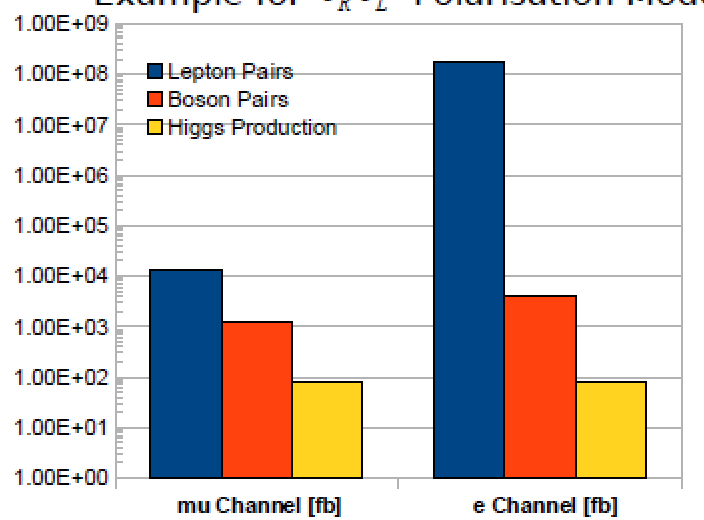




Lepton Pair Production



Example for $e_R^- e_L^+$ Polarisation Mode



$$\sigma(e^+e^- \to ZH) \qquad \sqrt{s} = 250 \text{ GeV}$$

Background Rejection

$P_{T,dl} > 20$ GeV
$80 < M_{dl-} < 100$ GeV
$0.2 <$ acop < 3.0
$\Delta P_{Tbal.} > 10$ GeV
$|\cos\theta_{miss.}| < 0.99$
$115 < M_{recoil} < 150$ GeV
Dedicated cuts for radiative events
Multivariate Analysis

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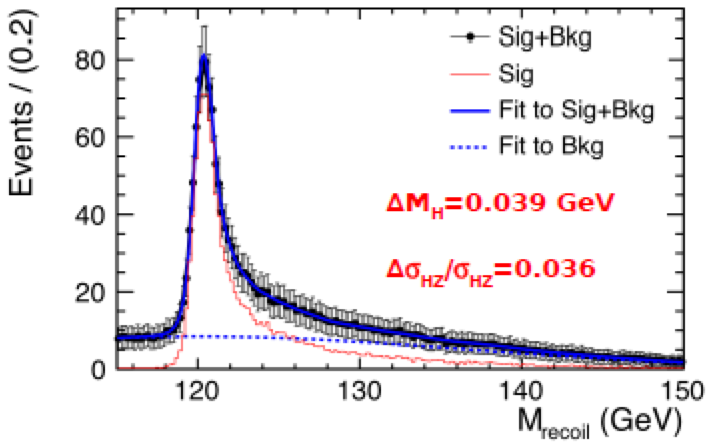
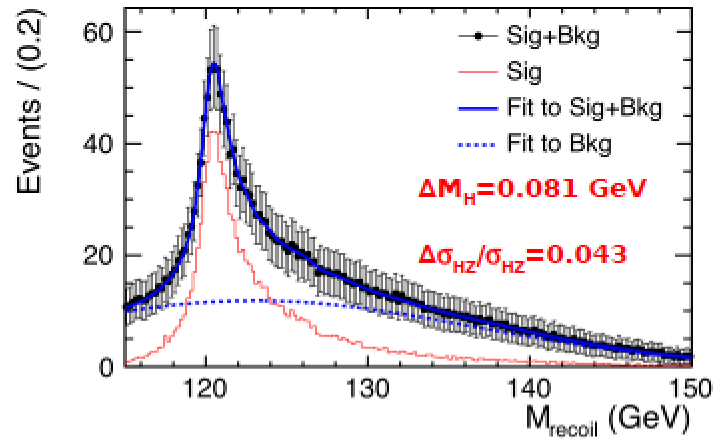
Results $\sigma(e^+e^- \to ZH)$ $\sqrt{s} = 250$ GeV

Muon Channel



Very Precise Measurement
S/B = 8 in Peak Region

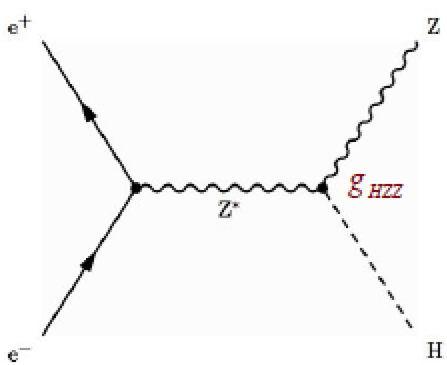
Electron Channel



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}



$\sigma_{HZ} \sim g_{HZZ}^2$

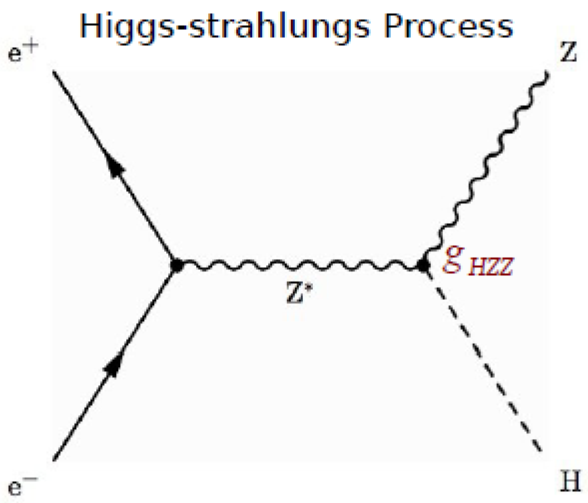
$\Rightarrow \Delta g_{HZZ} / g_{HZZ} = 1.3\%$ (0.6%) for L=250 (1150) fb^{-1}

When combined with a measurement of BR($H \to ZZ^*$)

g_{HZZ} measurement gives $\Delta\Gamma_{tot} = 11\%$ (5.4%) for L=250 (1150) fb^{-1}

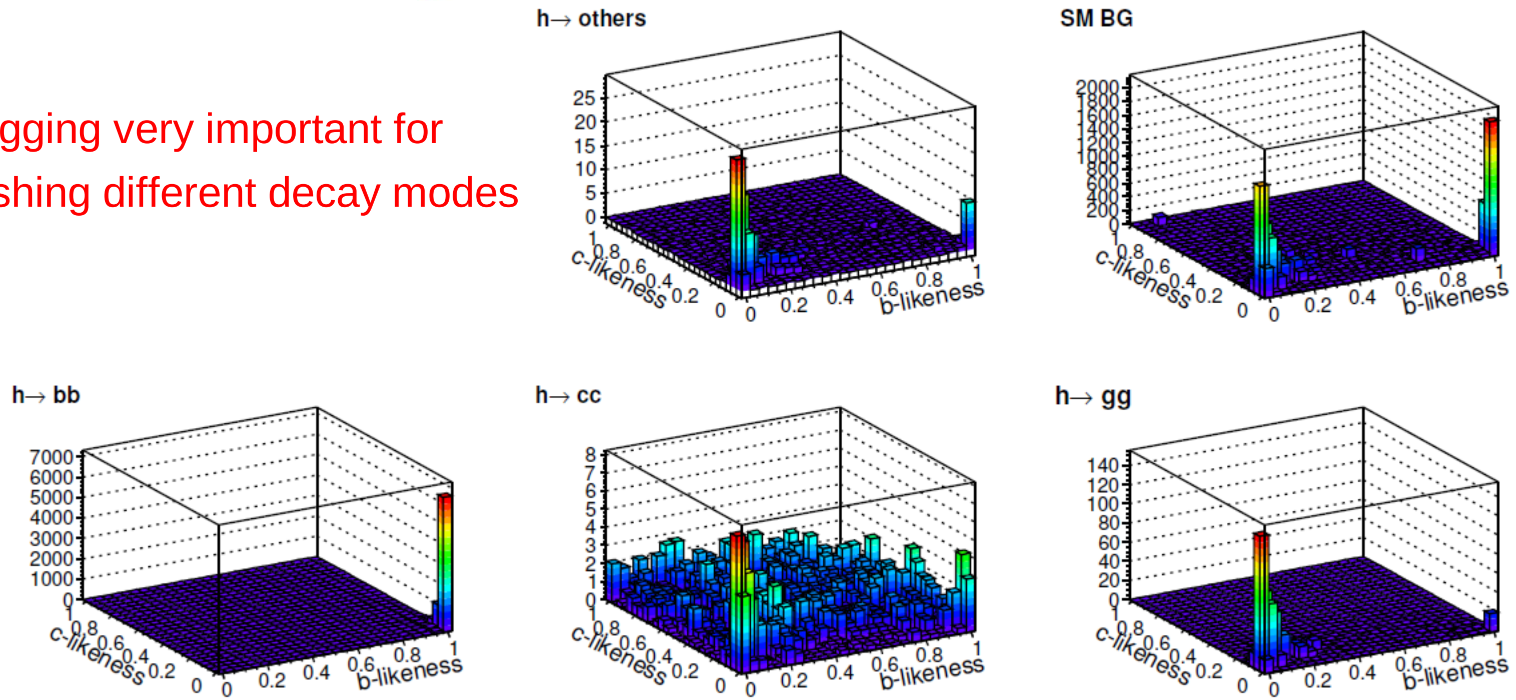
$$e^+e^- \to ZH \qquad \sqrt{s} = 250 \text{ GeV}$$

$\sigma \times$ BR measurements



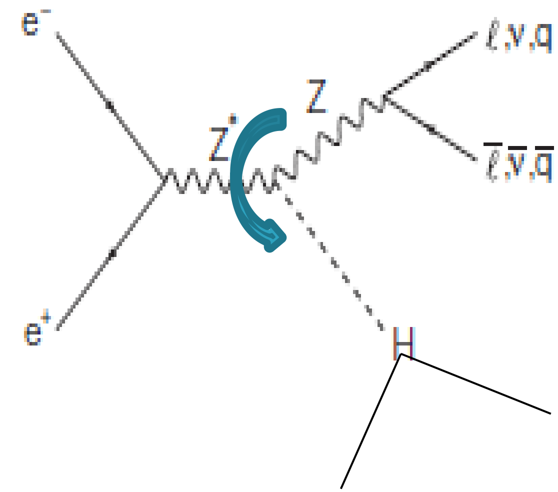
All Z decays are used for measurement of $\sigma \times$ BR. These include $Z \to qq$ and $Z \to \nu\nu$.

Flavor tagging very important for distinguishing different decay modes



Invisible Higgs Decay

- In the SM, an invisible Higgs decay is H → ZZ* →4ν process and its BF is small ~0.1%
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - The decay products are dark matter candidates.



- At the LHC, one can search for invisible Higgs decays by using recoil mass from Z or summing up BFs of observed decay modes with some assumptions.
  - The upper limit is O(10%).
- At the ILC, we can search for invisible Higgs decays using a recoil mass technique with model independent way!
  - e+e- → ZH

$$P_H = P_{e+e-} - P_Z$$

known measured

$e^+e^- \to ZH,\ Z \to qq,\ H \to \text{invis.}\qquad \sqrt{s} = 250\ \text{GeV}$

Signal and Backgrounds

- Signal
  - Pseudo signal : $e^+e^- \to ZH,\ Z \to qq,\ H \to ZZ^* \to 4\nu$
- Backgrounds
  - found qqll, qqlν and qq$\nu\nu$ final states are the dominant backgrounds.
    - other backgrounds also studied

  - ZZ semileptonic : one Z→qq, the other Z→ll, $\nu_\mu\nu_\mu$, $\nu_\tau\nu_\tau$
  - WW semileptonic : one W→qq, the other W→lν
  - $Z\nu_e\nu_e$, Z→qq
  - $We\nu_e$, W→qq
  - $\nu\nu$H, generic H decays
  - qqH, generic H decays

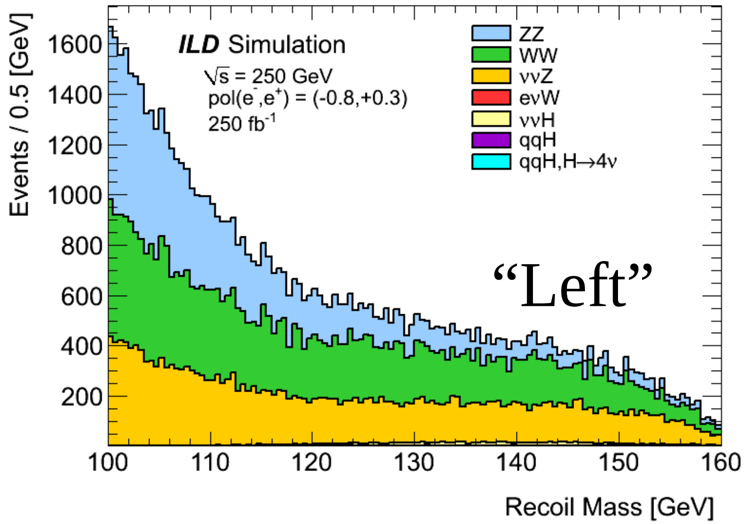
Polarizations of P(e+,e-)=(+30%,-80%), (-30%, +80%)

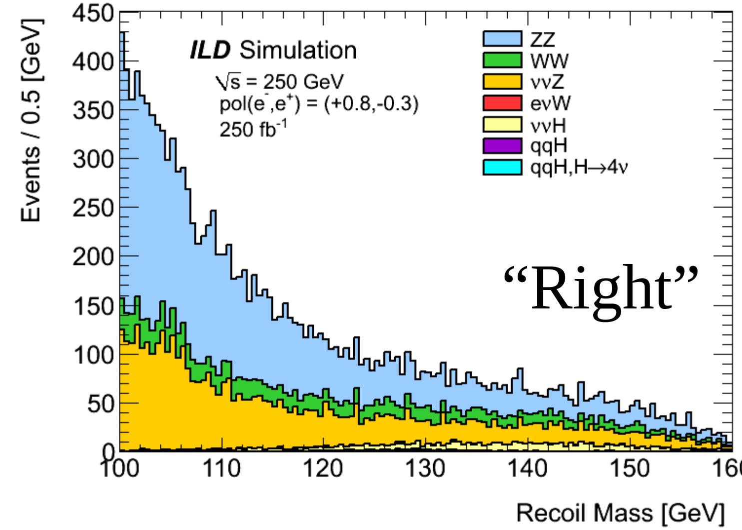
Throughout the slides, denoted as "Left" and "Right" polarizations

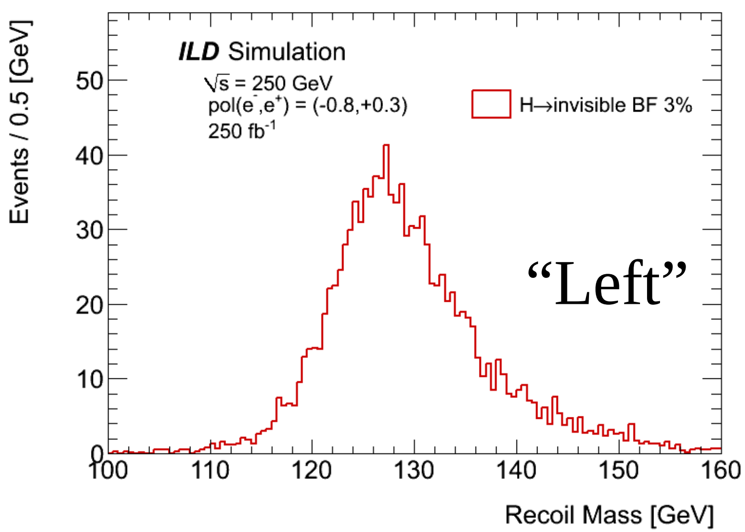
$e^+e^- \to ZH, \;\; \mathrm{Z} \to \mathrm{qq}, \;\; \mathrm{H} \to \mathrm{invis.} \qquad \sqrt{s} = 250 \text{ GeV}$

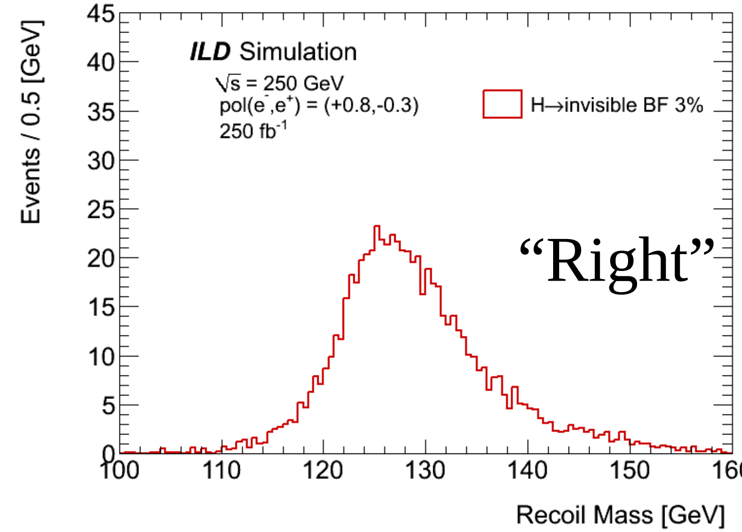
Final Recoil Mass

- Dominant backgrounds are ZZ, WW, ννZ





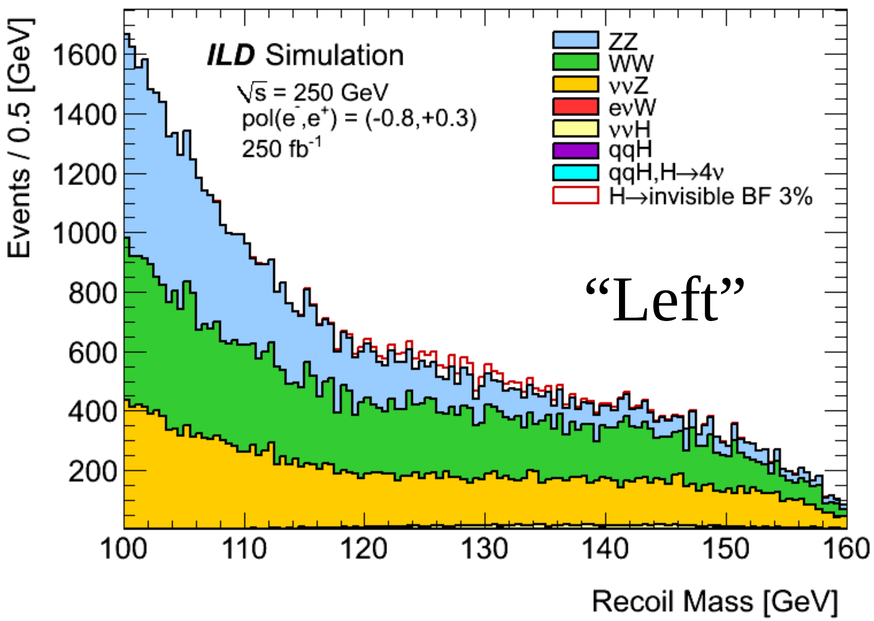


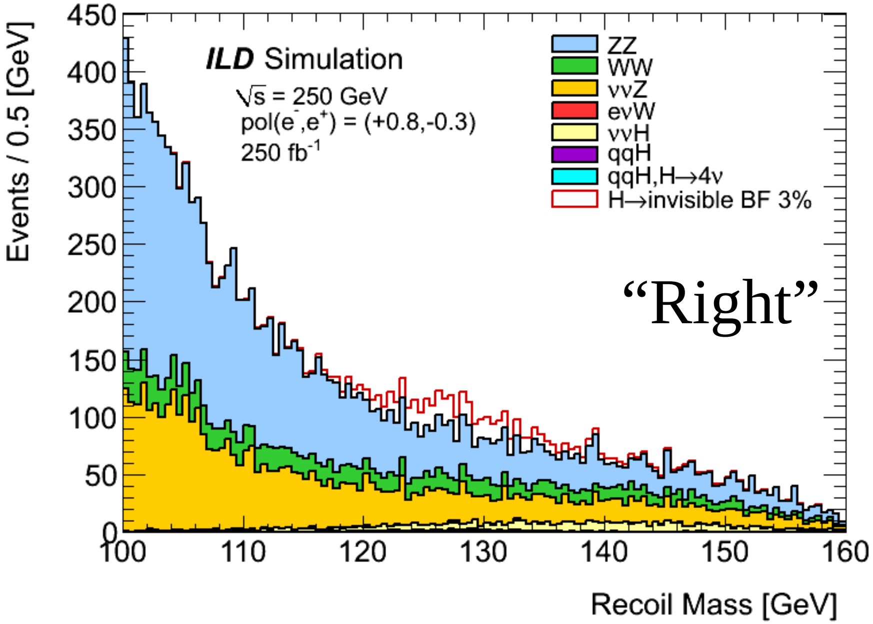


$e^+e^- \to ZH,\ \ Z \to qq,\ \ H \to \text{invis.} \qquad \sqrt{s} = 250\ \text{GeV}$

Signal Overlaid

- If BF(H→invisible) = 3%
  - Signal is clearly seen for “Right” polarization





$$e^+e^- \to ZH,\ \ \mathrm{Z} \to \mathrm{qq},\ \ \mathrm{H} \to \mathrm{invis.} \qquad \sqrt{s} = 250\ \mathrm{GeV}$$

Toy MC

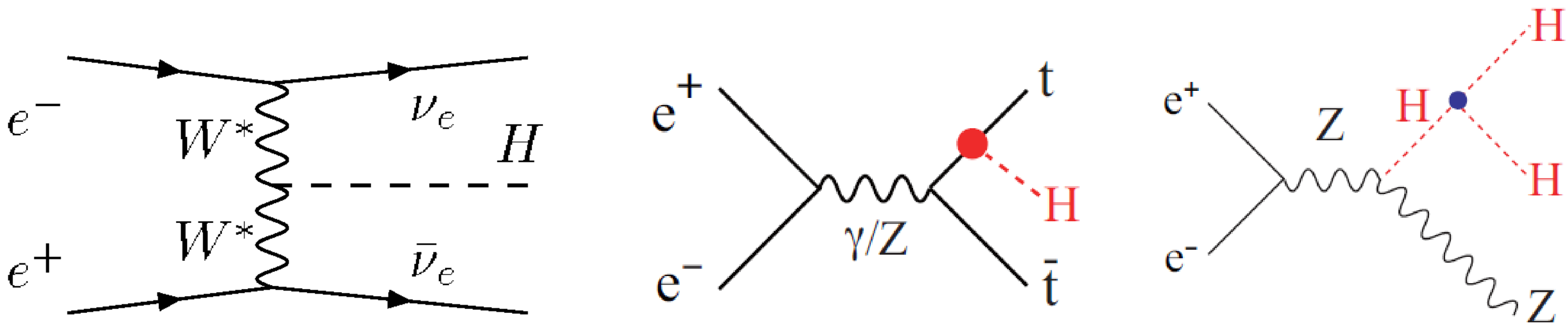
- Toy MC are performed to set upper limits on the BF
  - In the fitting to M_{recoil}, Only yields for signal and backgrounds are floated.
    - The backgrounds include a peaking ZH, H→4ν component
  - 10000 pseudo experiments for each polarization
- The results with 250fb^{-1}
  - "Left" polarization : BF (H→invisible) < 0.95% @ 95% CL
  - "Right" polarization : BF (H→invisible) < 0.69% @ 95% CL
    - The invisible does not include a H→ZZ*→4ν final state.
  - If 1150fb^{-1} data is accumulated, 0.44% and 0.32% for "Left" and "Right"
- The "Right" result is consistent with fast simulator results I presented at ECFA@DESY
  - BF < 0.7% @ 95% CL
- From a crude toy MC scan, 5σ observation down to 2.8% and 2.0% for "Left" and "Right", respectively.
  - Need much more toy MC events.

$e^+e^- \to ZH \qquad \sqrt{s} = 250$ GeV

$\Delta(\sigma \bullet BR) / (\sigma \bullet BR)$

mode	L=250 fb^{-1} Zh	L=250 fb^{-1} $\nu\bar{\nu}h$	L=1150 fb^{-1} Zh	L=1150 fb^{-1} $\nu\bar{\nu}h$
$h \to b\bar{b}$	1.2%	10.5%	0.56%	4.9%
$h \to c\bar{c}$	8.3%	-	3.9%	-
$h \to gg$	7.0%	-	3.3%	-
$h \to WW^*$	6.4%	-	3.0%	-
$h \to \tau^+\tau^-$	4.2%	-	2.0%	-
$h \to ZZ^*$	19%	-	8.8%	-
$h \to \gamma\gamma$	29-38%	-	16%	-
$h \to \mu^+\mu^-$	100%	-	-	-
BR(invis.)	< 0.80 %	-	< 0.37 %	-

$e^+e^- \to \nu\nu H$,ttH,ZHH $\sqrt{s} = 500$ GeV

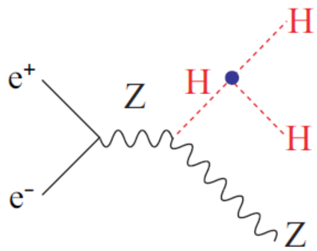


One gets a more complete Higgs profile at $\sqrt{s} \approx 500$ GeV
using the WW fusion channel, ttH production and the ZHH final state.

The g_{HWW} coupling can be measured by combining
a measurement of $\sigma(\nu\nu H) \times BR(H \to bb)$ with $BR(H \to bb)$ obtained at $\sqrt{s} \approx 250$ GeV .
The g_{HWW} measurement gives a better estimate of Γ_{tot} than g_{HZZ} since ΔBR(H $\to$ WW*) $\ll$ ΔBR(H $\to$ ZZ*).
A relative error of 6% on Γ_{tot} is expected at by combining 250 fb^{-1} at $\sqrt{s} = 250$ GeV with 500 fb^{-1} at $\sqrt{s} = 500$ GeV.

Cross section for $e^+e^- \to ttH$ significantly enhanced near threshold due to $t\bar{t}$ bound state effects. This leads to a measurement of the top Yukawa coupling $\Delta y_t / y_t = 14.1\%$ with 500 fb^{-1} at $\sqrt{s} = 500$ GeV.

$e^+e^- \to ZHH \; \sqrt{s} = 500$ GeV



J.Tian, "Study of Higgs Self-Coupling at the ILC Based on Full Detector Simulation at $\sqrt{s}$ = 500 & 1000 GeV" , LC-REP-2013-003

TABLE VI: The numbers of the remaining signal and background events in each search mode of the $e^+e^- \to ZHH$ analysis based on the full detector simulation at 500 GeV, with the beam polarization $P(e^-, e^+) = (-0.8, +0.3)$. The last two columns are ZHH excess significance (i) and cross section measurement significance (ii). The $qqHH$ mode and $llHH$ mode are both separated into two categories: (a) $bbHH$ dominant, (b) light $qqHH$ dominant, (c) electron-type $llHH$, (d) muon-type $llHH$.

Search Mode	Signal	Background	Significance (i)	Significance (ii)
$qqHH$ (a)	13.6	30.7	2.2σ	2.0σ
$qqHH$ (b)	18.8	90.6	1.9σ	1.8σ
$\nu\nu HH$	8.5	7.9	2.5σ	2.1σ
$llHH$ (c)	3.7	4.3	1.5σ	1.1σ
$llHH$ (d)	4.5	6.0	1.5σ	1.2σ

Combining all channels, one gets, for L=500 fb^{-1} at $\sqrt{s} = 500$ GeV,

$\Delta\sigma_{ZHH} / \sigma_{ZHH} = 53\%$ and

$\Delta\lambda / \lambda = 88\%$

for L=1600 fb^{-1} at $\sqrt{s} = 500$ GeV one gets

$\Delta\sigma_{ZHH} / \sigma_{ZHH} = 30\%$ and

$\Delta\lambda / \lambda = 49\%$

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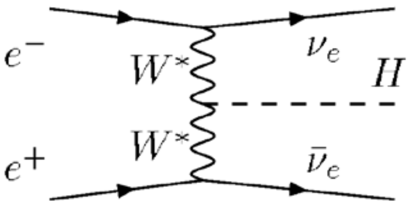
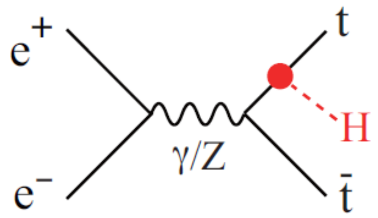
$$e^+e^- \to ZH, \quad \nu\nu H \qquad \sqrt{s} = 500 \text{ GeV} \quad (P_{e^-}, P_{e^+}) = (-0.8, +0.3)$$

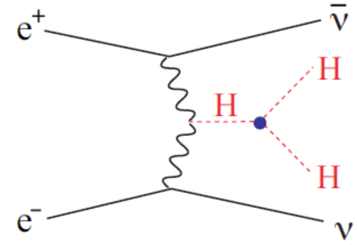
$$\Delta(\sigma \bullet BR) / (\sigma \bullet BR)$$

	L=500 fb^{-1}		L=1600 fb^{-1}	
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.8%	0.66%	1.0%	0.37%
$h \to c\bar{c}$	13%	6.2%	7.2%	3.5%
$h \to gg$	11%	4.1%	6.0%	2.3%
$h \to WW^*$	9.2%	2.6%	5.1%	1.4%
$h \to \tau^+\tau^-$	5.4%	14%	3.0%	7.8%
$h \to ZZ^*$	25%	8.2%	14%	4.6%
$h \to \gamma\gamma$	29-38%	20-26%	19%	13%
$h \to \mu^+\mu^-$	-	-	-	-
BR(invis.)	-	-	-	-

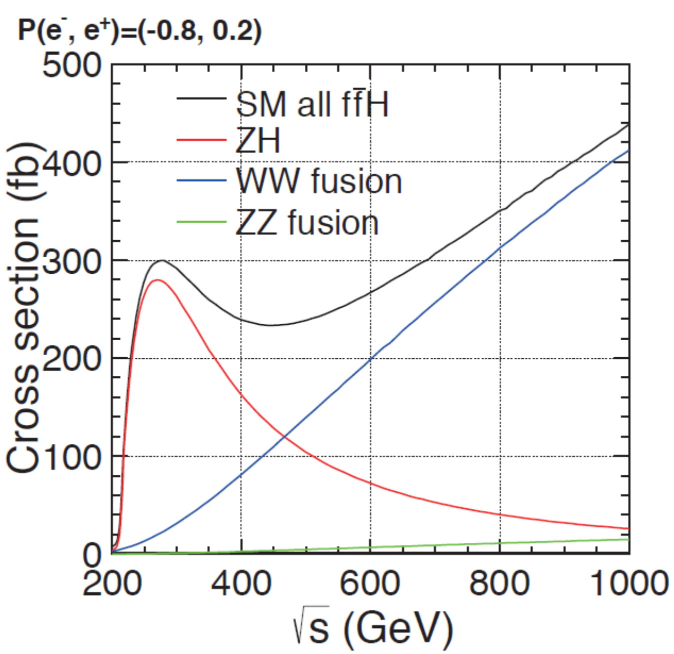
$e^+e^- \to \nu\nu$H , ttH , $\nu\nu HH$ $\sqrt{s}$ = 1 TeV

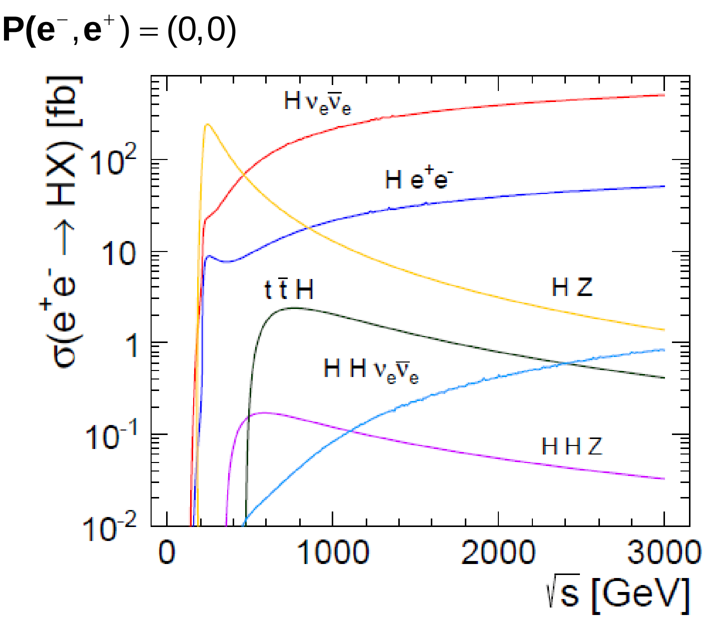




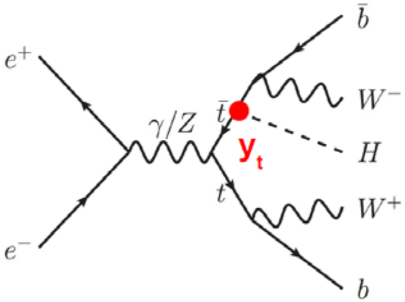


At $\sqrt{s} \approx 1$ TeV an e^+e^- collider provides better measurements of the top Yukawa coupling and Higgs self coupling. In addition an e^+e^- collider becomes a Higgs factory again since the total Higgs cross section is larger than the total cross sections at 250 GeV, especially if polarized beams are used:



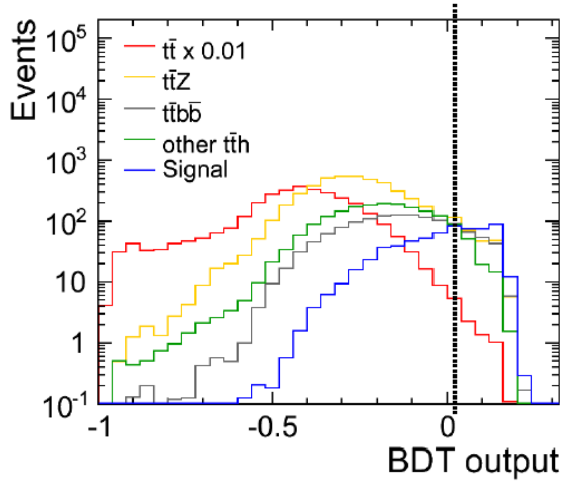


Top Yukawa Coupling at Ecm=1000 GeV

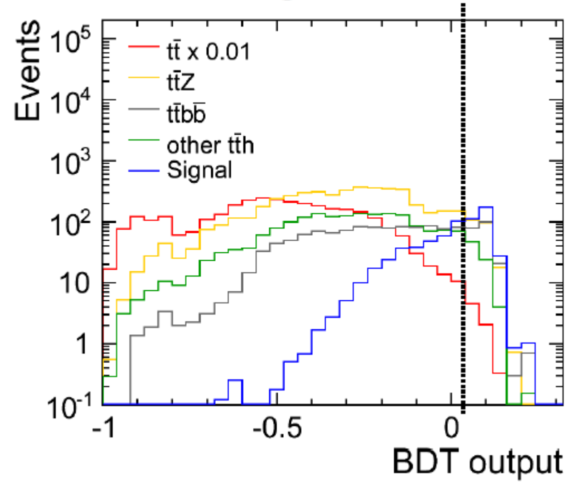


- **Final states:** - "6 jets": $t(\to qqb)\bar{t}(\to l\nu\bar{b})H(\to b\bar{b})$, m_H = 125 GeV
  - "8 jets": $t(\to qqb)\bar{t}(\to qq\bar{b})H(\to b\bar{b})$, m_H = 125 GeV

6 jets: BDT > 0.0266



8 jets: BDT > 0.0363



Combine 6 and 8 jet results: $\Delta y_t \,/\, y_t$ = 4.0% (2.5%) for L=1000 fb^{-1} (2500 fb^{-1})

Note : These are direct percent-level measurements of the top Yukawa coupling.
Statistical errors only, but systematic errors should be much smaller.

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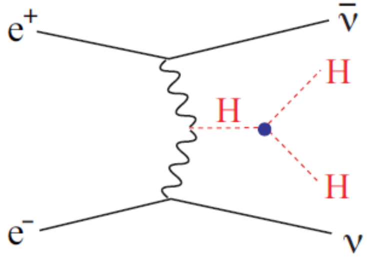
$e^+e^- \to \nu\nu HH \ \sqrt{s} = 1000$ GeV



Cut1: $Evis < 700 + 5MissPt$ GeV.

Cut2: $\mathrm{MLP}_{l\nu bbqq} > 0.84$.

Cut3: $\mathrm{MLP}_{\nu\nu bbbb} > 0.36$.

Cut4: $Bmax3 + Bmax4 > 0.71$.

TABLE VII: The reduction table for the signal and backgrounds after the final selection for $\nu\nu HH$ at 1 TeV mode, together with the number of expected events and generated events. The cuts names are explained in text.

Process	expected	generated	pre-selection	Cut1	Cut2	Cut3	Cut4
$\nu\nu HH$ $(fusion)$	272	1.05×10^5	127	107	77.2	47.6	35.7
$\nu\nu HH$ (ZHH)	74.0	2.85×10^5	32.7	19.7	6.68	4.88	3.88
$yyxye\nu$	1.50×10^5	6.21×10^5	812	424	44.4	11.0	0.73
$yyxyl\nu$	2.57×10^5	1.17×10^6	13457	4975	202	84.5	4.86
$yyxyyx$	3.74×10^5	1.64×10^6	18951	4422	38.5	26.7	1.83
$\nu\nu bbbb$	650	2.87×10^5	553	505	146	6.21	4.62
$\nu\nu ccbb$	1070	1.76×10^5	269	242	63.3	2.69	0.19
$\nu\nu qqh$	3125	7.56×10^4	522	467	257	30.6	17.6
BG	7.86×10^5		34597	11054	758	167	33.7

For L=1000 fb^{-1} at $\sqrt{s} = 1000$ GeV, one gets

$\Delta\sigma_{ZHH} / \sigma_{ZHH} = 33\%$ and

$\Delta\lambda / \lambda = 25\%$

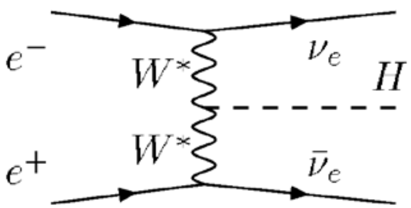
J.Tian, "Study of Higgs Self-Coupling at the ILC Based on Full Detector Simulation at $\sqrt{s} = 500$ & 1000 GeV", LC-REP-2013-003

for L=2500 fb^{-1} at $\sqrt{s} = 1000$ GeV one gets

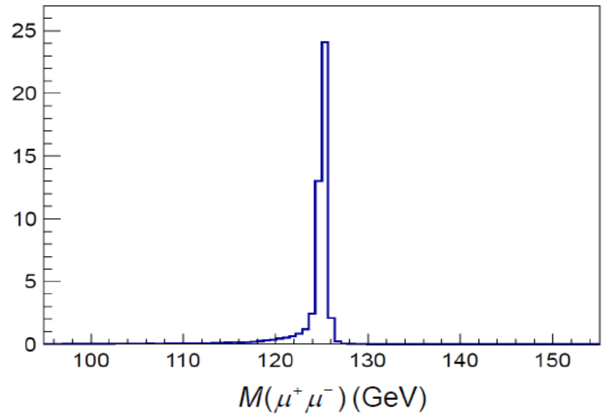
$\Delta\sigma_{ZHH} / \sigma_{ZHH} = 21\%$ and

$\Delta\lambda / \lambda = 16\%$

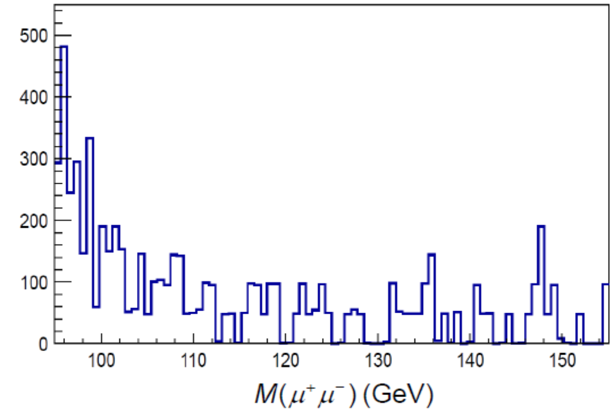
$e^+e^- \to \nu\nu H \quad \sqrt{s} = 1$ TeV



SiD $e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}\mu^+\mu^-$ after cuts



SiD *all bgnd* after cuts



Signal & Bgnd L=500 fb^{-1}

Process	N_{Events}
$e^+e^- \to \nu_e\bar{\nu}_e h \to \nu_e\bar{\nu}_e\mu^+\mu^-$	20.0 ± 0.1
$e^+e^- \to \nu_e\bar{\nu}_e\mu^+\mu^-$	17.4 ± 5.3
$e^+e^- \to \nu_\mu\bar{\nu}_\mu\mu^+\mu^-$	7.9 ± 3.5
$e^+e^- \to \nu_\tau\bar{\nu}_\tau\mu^+\mu^-$	1.6 ± 1.6
$e^+e^- \to t\bar{t} \to b\bar{b}\nu_\mu\bar{\nu}_\mu\mu^+\mu^-$	0.8 ± 0.2
$e^+e^- \to \nu_\tau\bar{\nu}_\mu\tau^+\mu^-$	0.2 ± 0.1
$\gamma\gamma \to \nu_\mu\bar{\nu}_\mu\mu^+\mu^-$	29.3 ± 6.7
$e^-\gamma \to e^-\nu_\mu\bar{\nu}_\mu\mu^+\mu^-$	4.8 ± 2.7
$e^-\gamma \to \nu_e\nu_\mu\bar{\nu}_\mu\mu^-\mu^+\mu^-$	1.6 ± 1.6
$e^-\gamma \to \nu_e\bar{\nu}_\mu\mu^-\mu^+\mu^-$	0.2 ± 0.2
$e^+e^- \to q\bar{q}\nu_\mu\bar{\nu}_\mu\mu^+\mu^-, q \neq b$	0.2 ± 0.1

For L=1000 fb^{-1} at $\sqrt{s} = 1000$ GeV, one gets

$\Delta\sigma \bullet BR / \sigma \bullet BR = 31\%$ and

$\Delta g_{H\mu\mu} / g_{H\mu\mu} = 16\%$

for L=2500 fb^{-1} at $\sqrt{s} = 1000$ GeV one gets

$\Delta\sigma \bullet BR / \sigma \bullet BR = 20\%$ and

$\Delta g_{H\mu\mu} / g_{H\mu\mu} = 10\%$

$$e^+e^- \to \nu\nu H \qquad \sqrt{s} = 1000 \text{ GeV} \quad (P_{e^-}, P_{e^+}) = (-0.8, +0.2)$$

$$\Delta(\sigma \bullet BR) / (\sigma \bullet BR)$$

mode	L=1000 fb^{-1} $\nu\bar{\nu}h$	L=2500 fb^{-1} $\nu\bar{\nu}h$
$h \to b\bar{b}$	0.32%	0.20%
$h \to c\bar{c}$	3.1%	2.0%
$h \to gg$	2.3%	1.4%
$h \to WW^*$	1.6%	1.0%
$h \to \tau^+\tau^-$	3.5%	2.2%
$h \to ZZ^*$	4.1%	2.6%
$h \to \gamma\gamma$	7-10%	5.4%
$h \to \mu^+\mu^-$	31%	20%
BR(invis.)	-	-

Model Independent Coupling Fit

Take N-1 independent $\sigma \times$ BR measurements Y_i and one σ_{ZH} measurement (Y_N)
and fit for 9 couplings $HZZ, HWW, Hbb, Hcc, Hgg, H\tau\tau, H\mu\mu, Htt, H\gamma\gamma, \Gamma_0$
by minimizing

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2 \qquad \text{e.g.} \quad Y_i' = F_i \frac{g_{HZZ}^2 g_{Hcc}^2}{\Gamma_0}$$

$$\Delta g_{Hxx} / g_{Hxx}$$

Mode	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
ZZ	1.3 %	1.3 %	1.3 %	0.61 %
WW	4.8 %	1.4 %	1.4 %	0.65 %
$b\bar{b}$	5.3 %	1.8 %	1.5 %	0.75 %
$c\bar{c}$	6.8 %	3.0 %	2.0 %	1.1 %
gg	6.4 %	2.5 %	1.8 %	0.94 %
$\tau^+\tau^-$	5.7 %	2.5 %	2.0 %	1.0 %
$\gamma\gamma$	18 %	8.4 %	4.1 %	2.4 %
$\mu^+\mu^-$	–	–	16 %	10 %
$\Gamma_T(h)$	11 %	6.0 %	5.6 %	2.7 %

Model Independent Coupling Summary

$$\Delta g_{Hxx} / g_{Hxx}$$

	Mode	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
	ZZ	1.3 %	1.3 %	1.3 %	0.61 %
	WW	4.8 %	1.4 %	1.4 %	0.65 %
	$b\bar{b}$	5.3 %	1.8 %	1.5 %	0.75 %
	$c\bar{c}$	6.8 %	3.0 %	2.0 %	1.1 %
	gg	6.4 %	2.5 %	1.8 %	0.94 %
	$\tau^+\tau^-$	5.7 %	2.5 %	2.0 %	1.0 %
	$\gamma\gamma$	18 %	8.4 %	4.1 %	2.4 %
	$\mu^+\mu^-$	–	–	16 %	10 %
	$\Gamma_T(h)$	11 %	6.0 %	5.6 %	2.7 %
	$t\bar{t}$	– %	18 %	4.0 %	2.5 %
	self	–	88%	25 %	16 %
*	BR(invis.)	< 0.69 %	< 0.69 %	< 0.69 %	< 0.32 %

* 95% C.L. limit

Model Dependent Coupling Fit

It is sometimes useful to extract couplings from ILC data using certain model assumptions in order to compare experimental precisions with facilities that cannot determine Higgs couplings in a model independent manner.

We believe the most straightforward way to compare ILC and LHC Higgs coupling precisions is to have both facilities perform a global coupling fit with only the assumption $g^2_{HWW} < g^2_{HWW}|_{SM}$ and $g^2_{HZZ} < g^2_{HZZ}|_{SM}$

$\Delta g_{Hxx} / g_{Hxx}$ assuming $g^2_{HWW} < g^2_{HWW}|_{SM}$ and $g^2_{HZZ} < g^2_{HZZ}|_{SM}$

Mode	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
WW	1.9 %	0.24 %	0.17 %	x.xx %
ZZ	0.44 %	0.30 %	0.27 %	x.xx %
$b\bar{b}$	2.7 %	0.94 %	0.69 %	x.xx %
gg	4.0 %	2.0 %	1.4 %	x.xx %
$\gamma\gamma$	4.9 %	4.3 %	3.3 %	x.xx %
$\tau^+\tau^-$	3.3 %	1.9 %	1.4 %	x.xx %
$c\bar{c}$	4.7 %	2.5 %	2.1 %	x.xx %
$t\bar{t}$	14.2 %	9.3 %	3.7 %	x.xx %
$\mu^+\mu^-$	–	–	16 %	x.xx %
self	–	88%	25 %	x.xx %
BR(invis.)	$<$ 0.44 %	$<$ 0.30 %	$<$ 0.26 %	x.xx %
$\Gamma_T(h)$	4.8 %	1.6 %	1.2 %	x.xx %

Model Dependent Coupling Fit

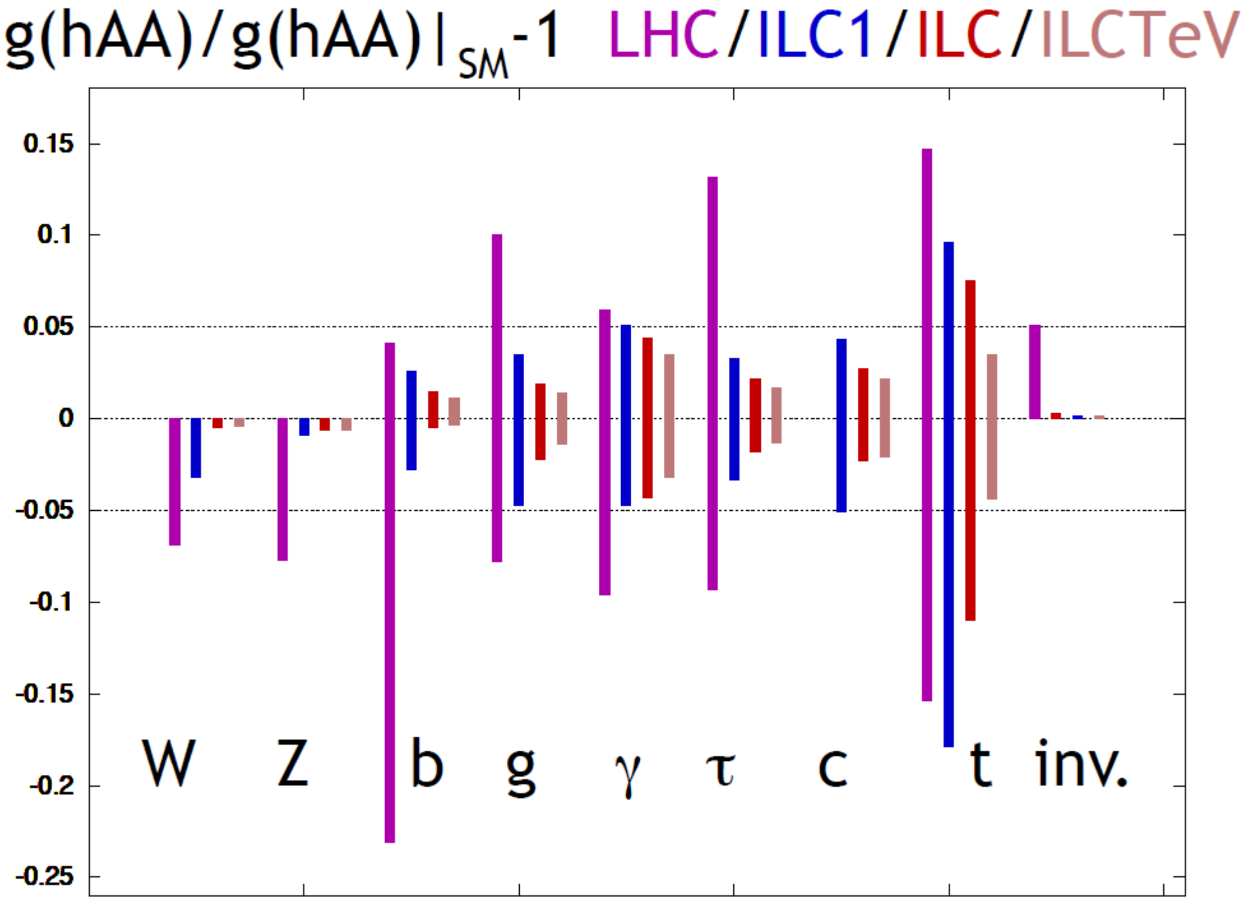
assuming $g^2_{HWW} < g^2_{HWW}|_{SM}$ and $g^2_{HZZ} < g^2_{HZZ}|_{SM}$

LHC: 300 fb^{-1}, 1 detector @ $\sqrt{s} = 14$ TeV

ILC1: LHC+ 250 fb^{-1} e^+e^- @ $\sqrt{s} = 250$ GeV

ILC: ILC1+ 500 fb^{-1} e^+e^- @ $\sqrt{s} = 500$ GeV

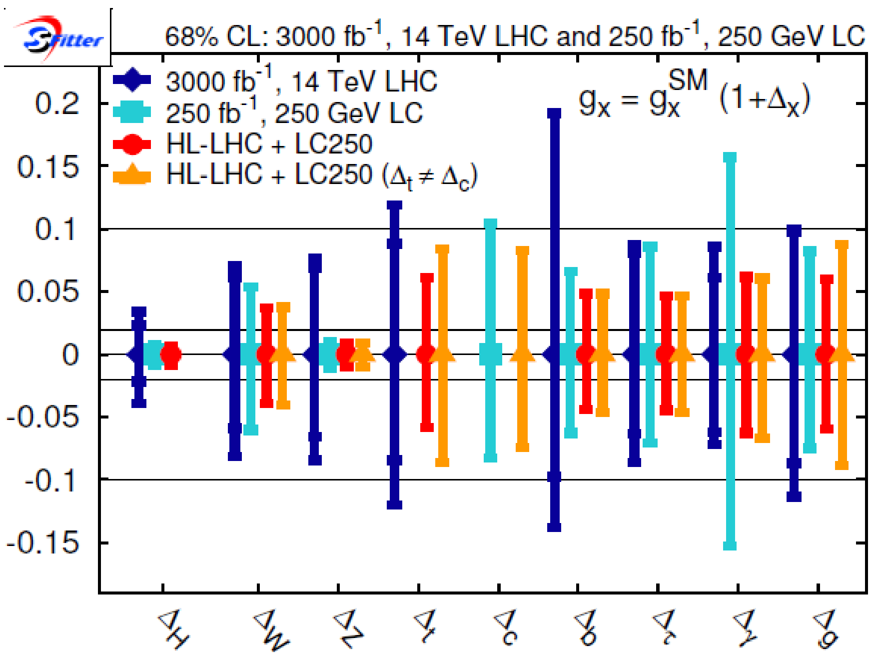
ILCTEV: ILC+ 1000 fb^{-1} e^+e^- @ $\sqrt{s}$=1000 GeV

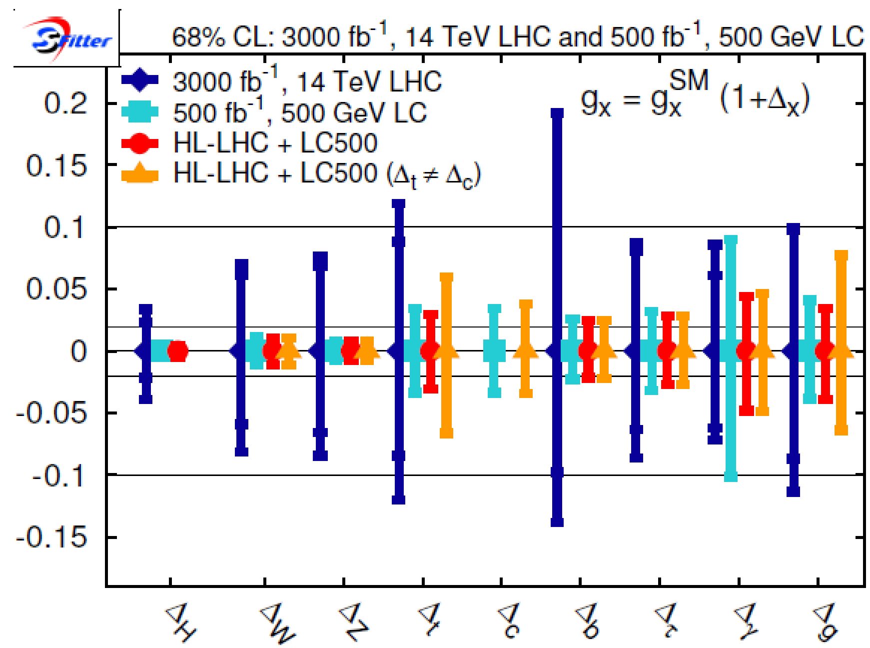


Model Dependent Coupling Fits

Alternatively, ILC can fit for the κ_i coupling scaling factors of arXiv : 1029.0040.
We are in the process of doing that for our Snowmass measurement errors with the help of Dirk Zerwas and Michael Rauch.

To get an idea of what these results might look like, here are some plots of similar fits from earlier this year:





Summary

- The ILC will study the 125 GeV Higgs Boson through the processes $e^+e^- \rightarrow ZH$, $\nu\nu$H, ttH
- The ILC can easily access decay modes that are difficult to access at the LHC, and may have limited precision for rare decays that the LHC will cover well. It is therefore positioned to complement the LHC qualitatively.
- The ILC will make a model independent 2.7% measurement of the total width of the Higgs Boson.
- The Higgs couplings to W,Z,b will be measured to less than 0.75% without model assumptions.
- The Higgs couplings to g,c,τ will be measured to about 1% without model assumptions.
- A 95% C.L. limit of 0.32% can be placed on the Higgs branching fraction to invisible decays.
- The top yukawa coupling can be measured to a 2.5% accuracy.
- The Higgs self coupling can be measured with an accuracy of 16%
- Some thought has to go into how we compare the coupling precisions of ILC and LHC in the Snowmass writeup.