Higgs at a Linear Collider

Tim Barklow (SLAC)
August 3, 2012

Outline

- Higgs Factory Options Under Discussion in Summer 2012
- The International Linear Collider (ILC) Machine
- Experimental Environment at the ILC
- Higgs Physics with the ILC:
- Summary

Main reference for Higgs Physics at the ILC:

H. Baer, et al., Physics at the International Linear Collider,

to appear in the ILC Detailed Baseline Design Report (2012).

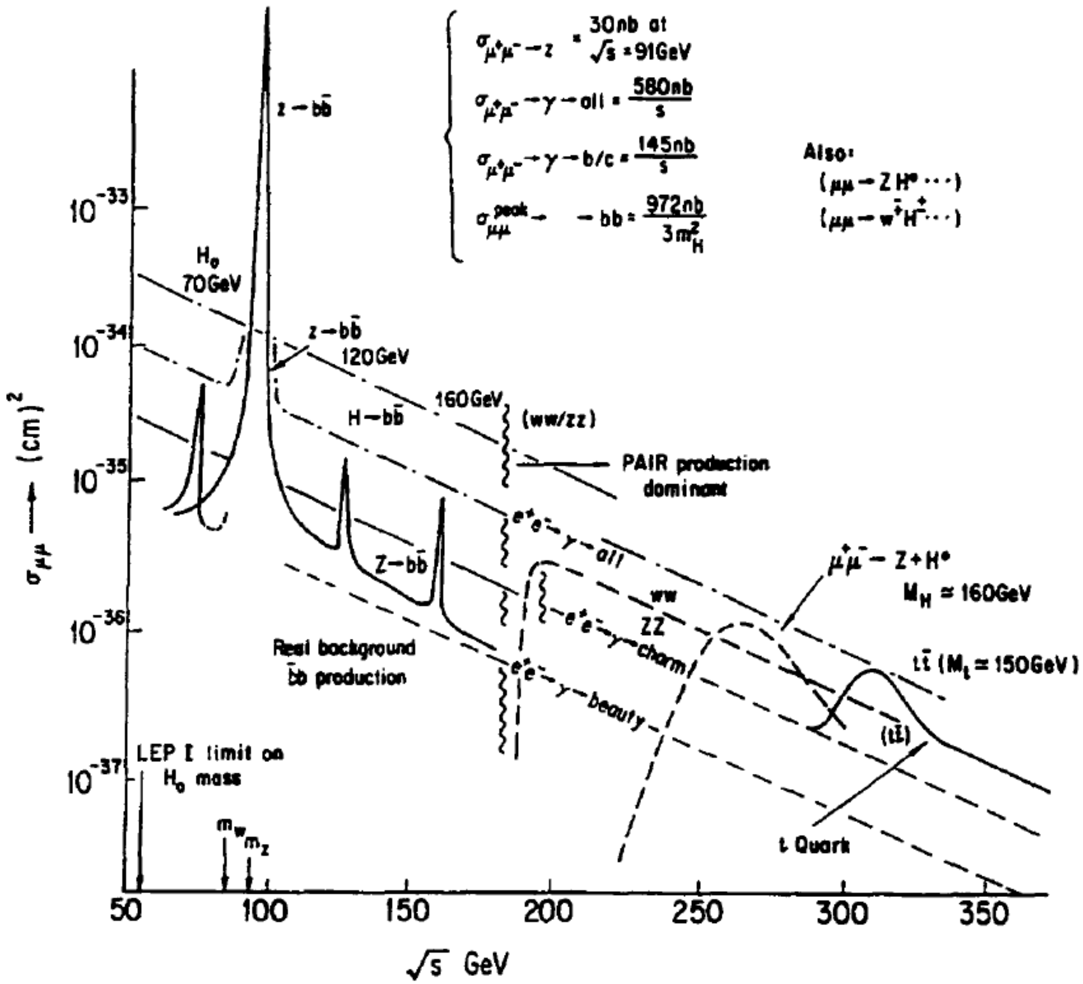
A preliminary version is available at :

http://lcsim.org/papers/DBDPhysics.pdf

Higgs Factory Options Under Discussion in Summer 2012

- $\mu^+\mu^-$ Collider at $\sqrt{s} = 126$ GeV
- $\gamma\gamma$ Collider at $\sqrt{s} = 126$ GeV
- e^+e^- Storage Ring at $\sqrt{s} = 240$ GeV
- e^+e^- Linear Collider with 250 GeV $\leq \sqrt{s} \leq$ 1000 GeV (ILC or CLIC)

$\mu^+\mu^- \rightarrow H$ ($\sqrt{s}$=M$_H$ Muon Collider Higgs Factory)



Using $\sigma_{peak} = \dfrac{972\text{ nb}}{3M_H^2}\dfrac{1}{BR(H\rightarrow bb)}$

$\sigma_{peak}(\mu^+\mu^- \rightarrow H, M_H = 126\text{ GeV})$=35.3 pb

But must include muon beam energy spread

$\Delta E_{beam} / E_{beam}$	$\sigma_{eff}(\mu^+\mu^- \rightarrow H, M_H = 126\text{ GeV})$
0	35.3 pb
.01%	10.1 pb
0.1%	1.0 pb
0.4%	250 fb

$\sigma(\mu^+\mu^- \rightarrow b\overline{b}) = 9.1\text{ pb @ }\sqrt{s} = 126\text{ GeV}$

Luminosity requirements tied strongly to achievable $\Delta E_{beam} / E_{beam}$.

As an aside, simply scaling by mass

$\sigma_{peak}(e^+e^- \rightarrow H, M_H = 126\text{ GeV})\text{=35.3 pb}\times\dfrac{M_e^2}{M_\mu^2}$

$= 0.8\text{ fb}$

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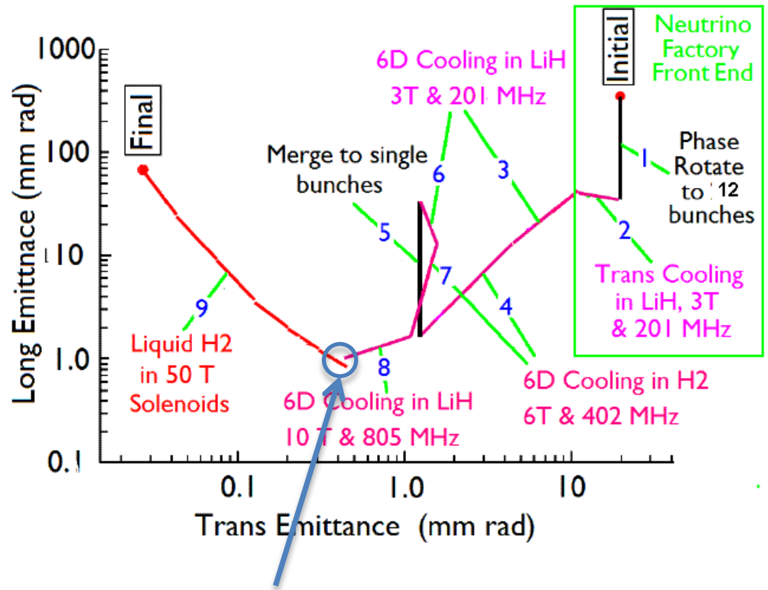
125 GeV $\mu^+\mu^-$ Higgs Factory (D.Neuffer)



Stop cooling here:
$\varepsilon_{\perp N}$ =0.3π·mm·rad, $\varepsilon_{||N}$ =1π·mm·rad

There were a couple of early designs which can be taken as the starting point, e.g.:

- C.Johnstone, W.Wan, A.Garren, PAC 99, p.3066

Parameter	Unit	Value
Beam energy	GeV	62.5
Circumference, C	m	300
Number of IPs	-	1
β*	cm	5
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.5
Momentum spread	%	0.005
Bunch length, σ_s	cm	5
Long. emittance, $\varepsilon_{||N}$	π·mm·rad	1.5
Number of muons / bunch	10^{12}	2
Number of bunches / beam	-	1
Beam-beam parameter, ξ	-	0.0043
Repetition rate	Hz	30*
Average luminosity	10^{31}/cm^2/s	1.5
p-driver power	MW	4

*) only 2, not 4 p-bunches are required on the target → twice the reprate at the same p-driver power

$e^-e^- \to e^-e^-H$ (Photon-Photon Collider Higgs Factories)

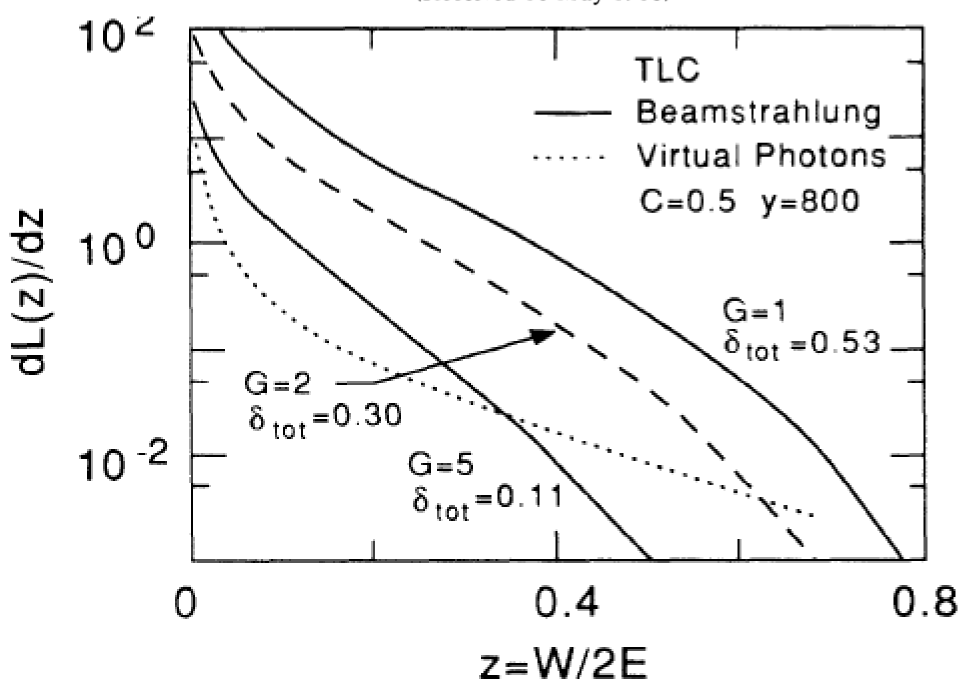
Whether one is trying to produce high energy photons by cranking up the beamstrahlung photon energies in e^-e^- collisions, or by colliding the electron beams with laser beams near the IP, one needs an e^-e^- $\sqrt{s} \approx 1.25 \times M_H \approx 158$ GeV to produce Higgs bosons via $\gamma\gamma \to$ H at an appreciable rate.

Quantum Beamstrahlung: Prospects for a Photon-Photon Collider

Richard Blankenbecler and Sidney D. Drell

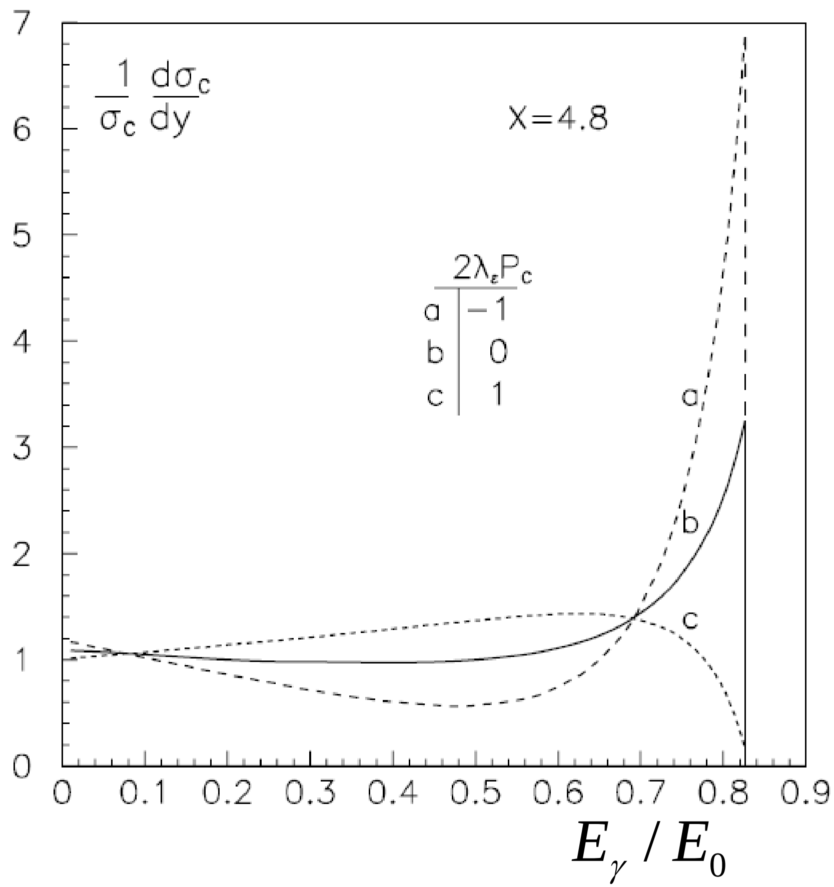
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

(Received 16 May 1988)

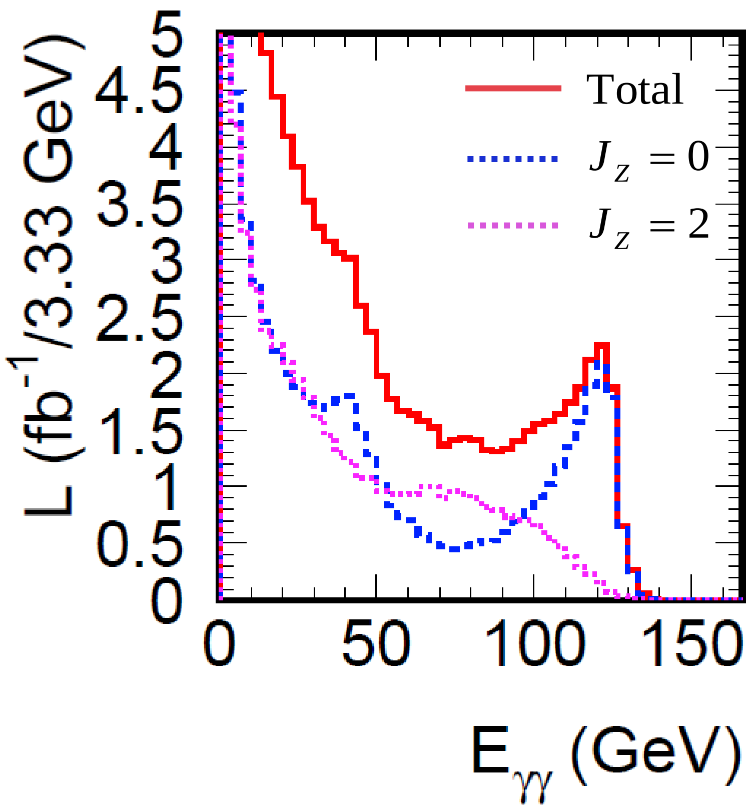


$e^- e^- \to e^- e^- H$ (Photon-Photon Collider Higgs Factories)

Collide the electron beams with laser beams near the IP



$x = 4.3 \;\; P_\gamma = +1.0 \;\; P_e = -0.8$



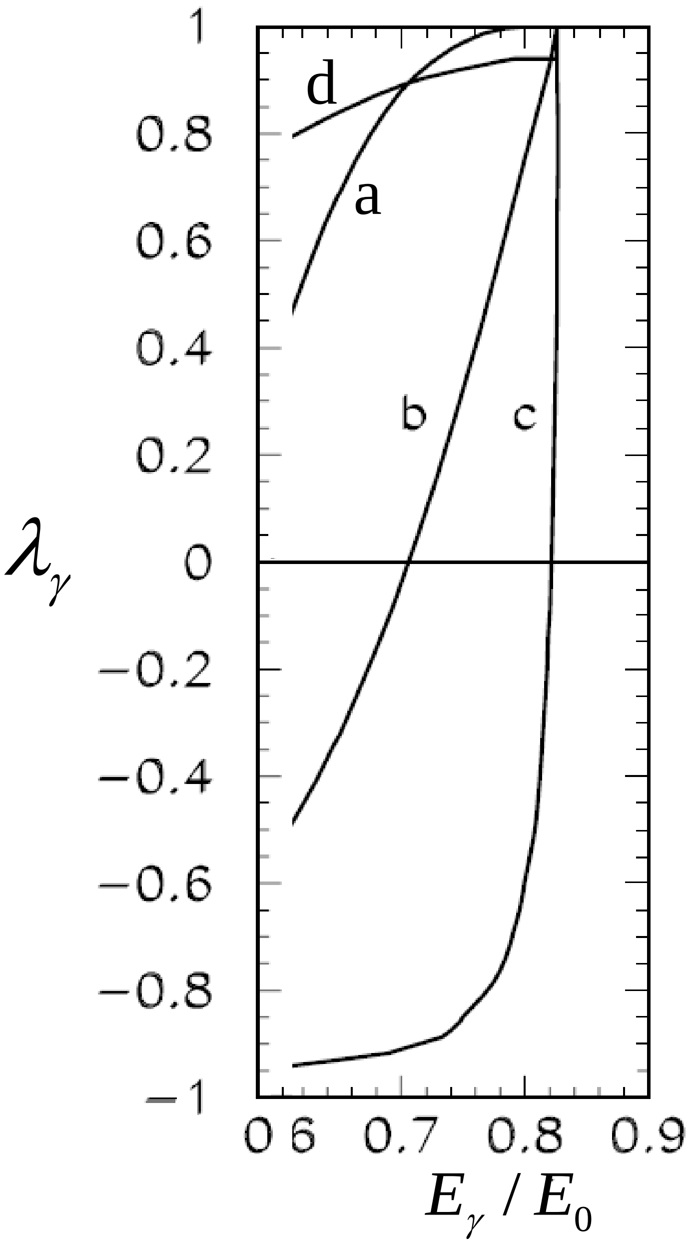
High electron polarization enhances the luminosity at high $E_{\gamma\gamma}$

$e^-e^- \to e^-e^-H$ (Photon-Photon Collider Higgs Factories)

High electron polarization provides another benefit.

At the high end of the photon energy spectrum ($E_\gamma / E_0 > 0.6$) the helicity λ_γ of the backscattered photons follows the helicity λ_e of the incoming electrons.

Without high electron polarization the enhancement of the J=0 Higgs signal and suppression of the J=2 $b\bar{b}$ background would collapse.

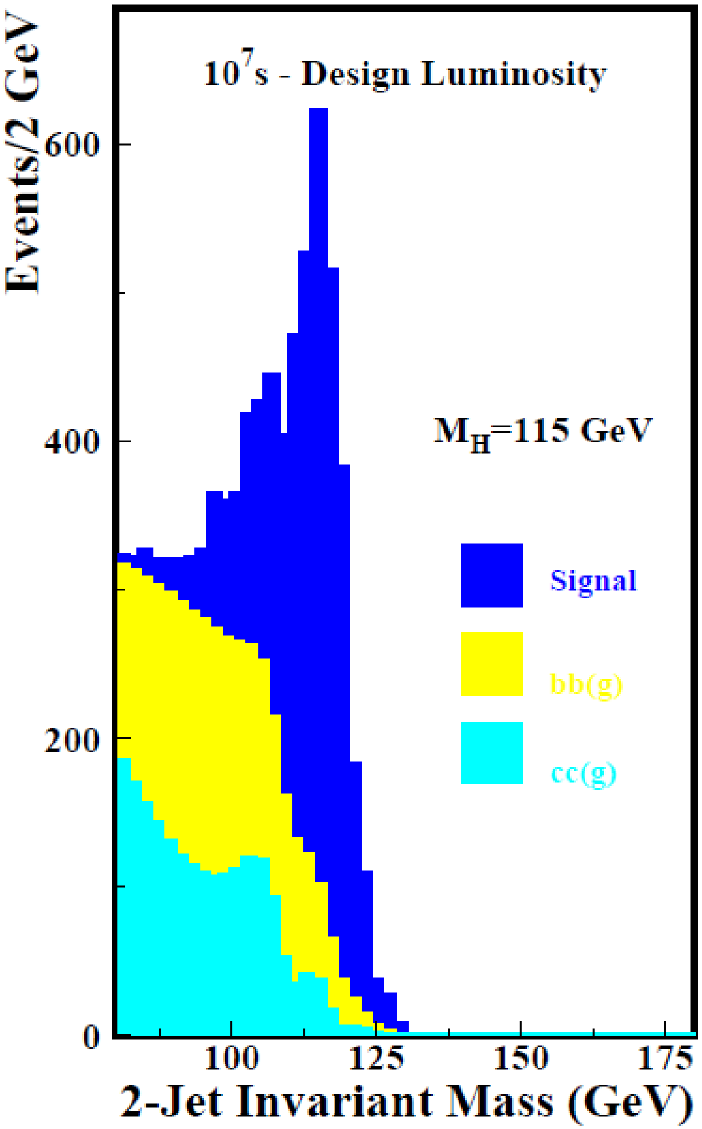


	P_c	$2\lambda_e$
a	-1	1
b	-1	0
c	-1	-1
d	0	1

$e^-e^- \to e^-e^-H$ (Photon-Photon Collider Higgs Factories)

PLC Measurement of $H \to b\bar{b}$

This plot is from the CLICHE study assuming M_H =115 GeV and 200 fb^{-1}. There are many other examples like this.

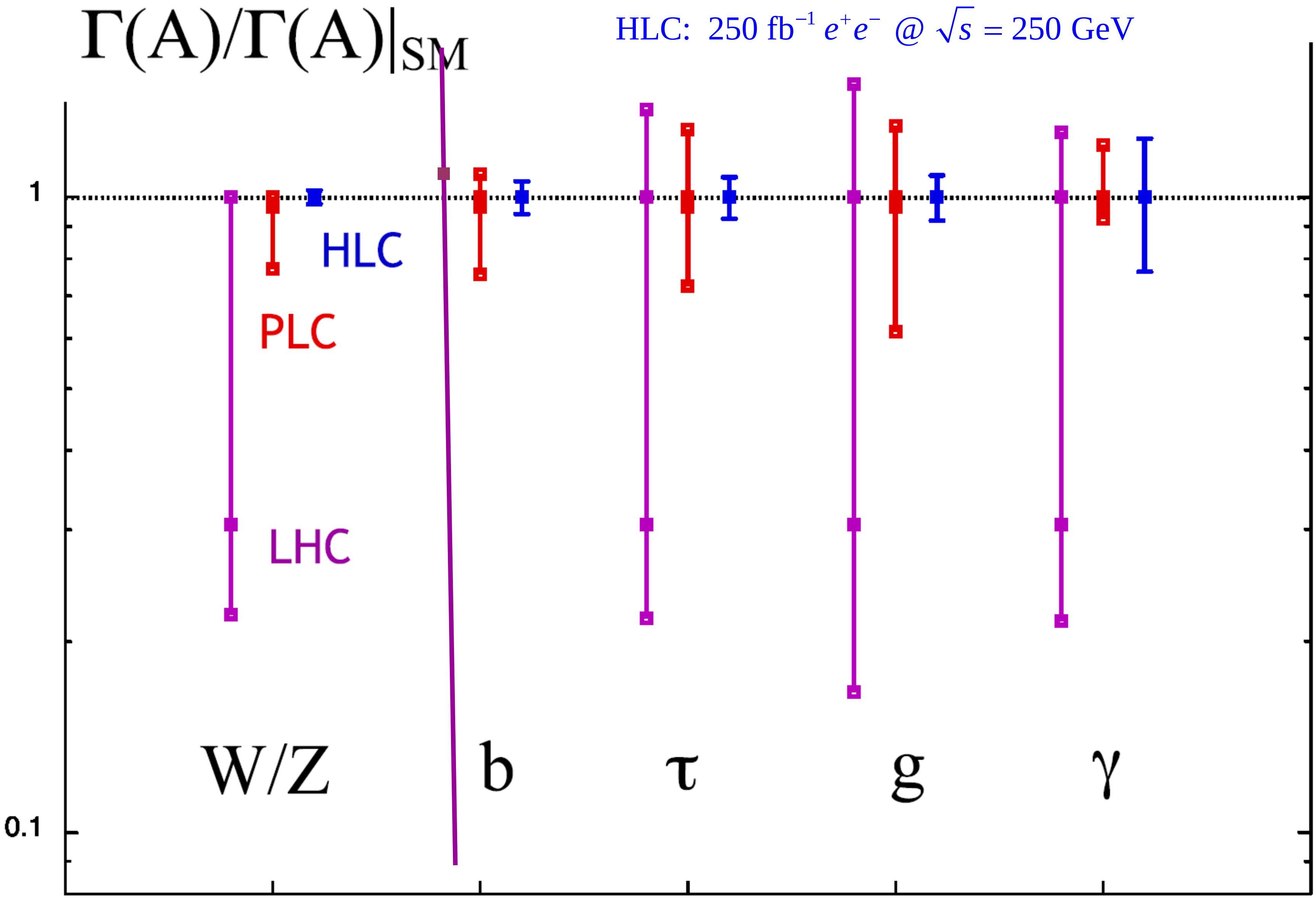


2009 Study

LHC: 100 fb^{-1} per experiment @ $\sqrt{s} = 14$ TeV

PLC: 60 fb^{-1} $\gamma\gamma$ @ $\sqrt{s} \approx 126$ GeV

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

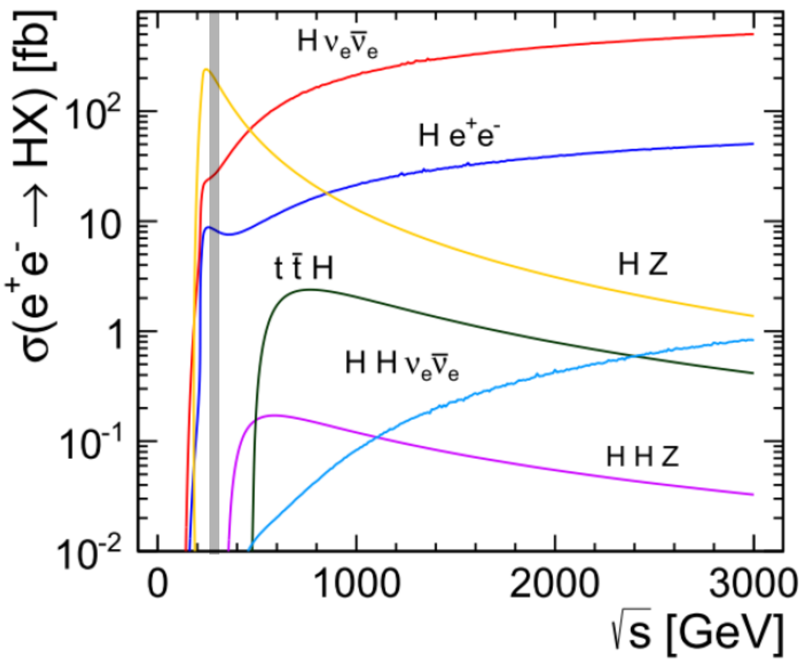


e^+e^- Storage Ring at $\sqrt{s} = 240$ GeV

LEP3: A HIGH LUMINOSITY e^+e^- COLLIDER IN THE LHC TUNNEL TO STUDY THE HIGGS BOSON *

A.P. Blondel, U. Geneva, Switzerland; F. Zimmermann, CERN, Geneva, Switzerland;
M. Koratzinos, Geneva, Switzerland; M. Zanetti, MIT, Cambridge, Massachusetts, USA

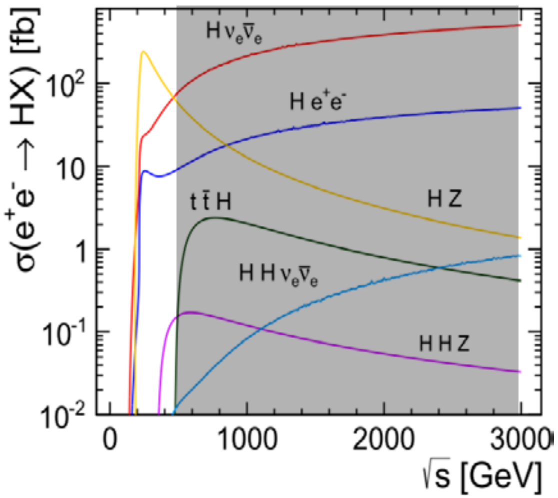
$\sigma(e^+e^- \to ZH) \approx 200$ fb $M_H = 125$ GeV $\sqrt{s} \approx 240$ GeV

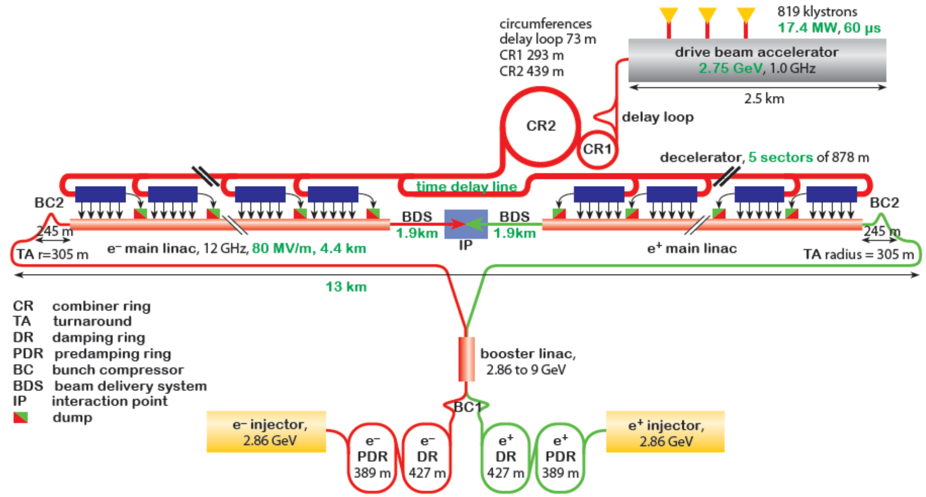


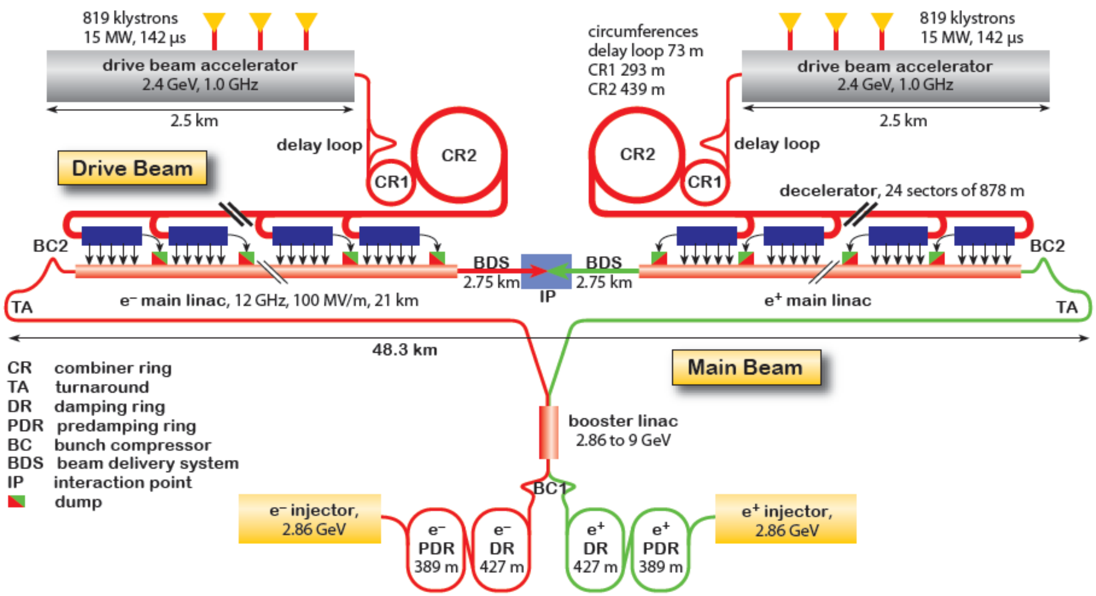
	LEP2	LHeC	LEP3	DLEP
b. energy E_b [GeV]	104.5	60	120	120
circumf. [km]	26.7	26.7	26.7	53.4
beam current [mA]	4	100	7.2	14.4
#bunches/beam	4	2808	4	60
#e−/beam [10^{12}]	2.3	56	4.0	16.0
horiz. emit. [nm]	48	5	25	10
vert. emit. [nm]	0.25	2.5	0.10	0.05
bending rad. [km]	3.1	2.6	2.6	5.2
part. number J_ε	1.1	1.5	1.5	1.5
mom. c. α_c [10^{-5}]	18.5	8.1	8.1	2.0
SR p./beam [MW]	11	44	50	50
β^*_x [m]	1.5	0.18	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1
σ^*_x [μm]	270	30	71	45
σ^*_y [μm]	3.5	16	0.32	0.22
hourglass F_{hg}	0.98	0.99	0.67	0.75
E^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	3.5
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	4.6
$\delta_{max,RF}$ [%]	0.77	0.66	4.2	5.0
ξ_x/IP	0.025	N/A	0.09	0.05
ξ_y/IP	0.065	N/A	0.08	0.05
f_s [kHz]	1.6	0.65	3.91	0.91
E_{acc} [MV/m]	7.5	11.9	20	418
eff. RF length [m]	485	42	606	376
f_{RF} [MHz]	352	721	1300	1300
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.16
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23	0.17
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107	142
number of IPs	4	1	2	2
beam lifetime [min]	360	N/A	16	22
Υ_{BS} [10^{-4}]	0.2	0.05	10	8
n_γ/collision	0.08	0.16	0.60	0.25
ΔE^{BS}/col. [MeV]	0.1	0.02	33	12
ΔE^{BS}_{rms}/col. [MeV]	0.3	0.07	48	26

* Also K.Oide, ‘SuperTRISTAN - A possibility of ring collider for Higgs factory,’ KEK Seminar, 13February 2012

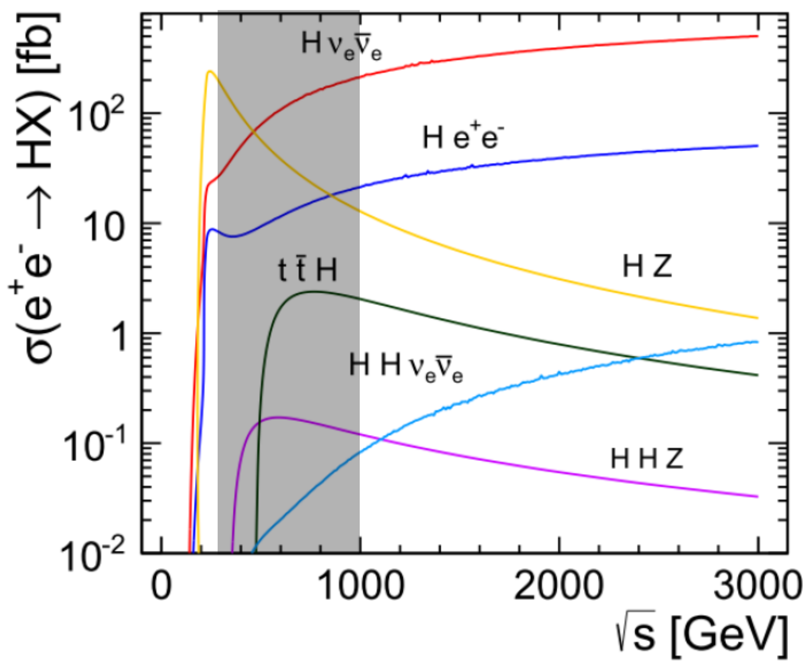
e^+e^- Linear Collider at 500 GeV < $\sqrt{s}$ < 3000 GeV (CLIC)

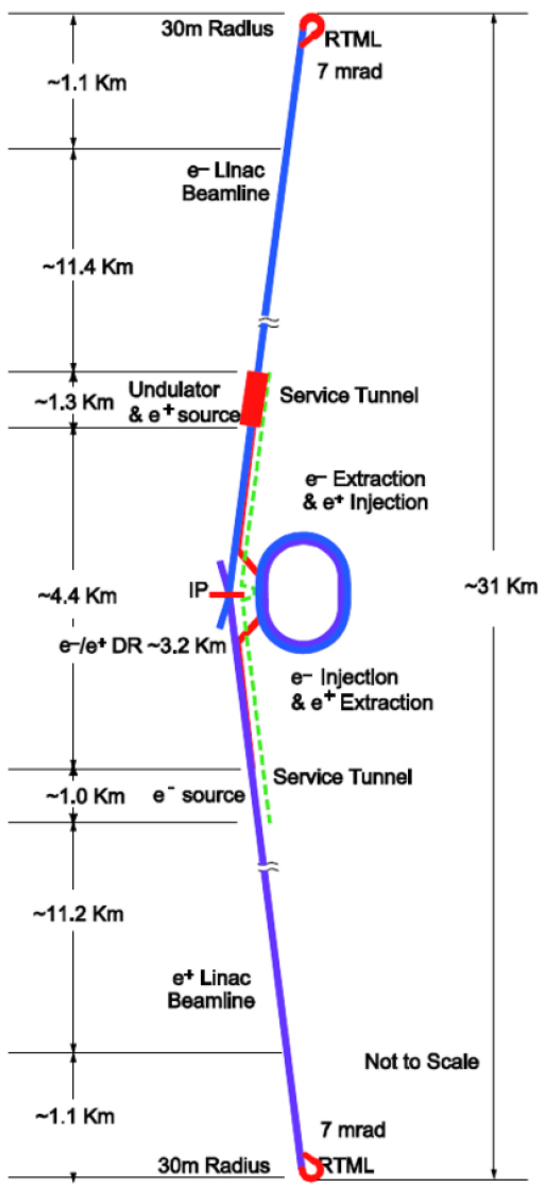






e^+e^- Linear Collider at 240 GeV < $\sqrt{s}$ < 1000 GeV (ILC)





*

e^+e^- Linear Collider at 240 GeV < $\sqrt{s}$ < 1000 GeV (ILC)

IP and General Parameters			TF = Traveling Focus					L Upgrade	E_{cm} Upgrade	
Centre-of-mass energy	E_{cm}	**GeV**	**200**	**230**	**250**	**350**	**500**	**500**	**1000**	**1000**
									A1	B1b
Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
Electron bunch population	N_-	$\times10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Positron bunch population	N_+	$\times10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Bunch separation	t_b	ns	554	554	554	554	554	366	366	366
Electron RMS energy spread	p/p	%	0,206	0,194	0,190	0,158	0,124	0,124	0,083	0,085
Positron RMS energy spread	p/p	%	0,190	0,165	0,152	0,100	0,070	0,070	0,043	0,047
Electron polarisation	P_-	%	80	80	80	80	80	80	80	80
Positron polarisation	P_+	%	31	31	30	30	30	30	20	20
simulation: Luminosity	L	$\times10^{34}$ cm^{-2}s^{-1}	0,498	0,607	0,681	0,878	1,50	3,00	3,23	4,31
Coherent waist shift	W_y	m	250	250	250	250	250	250	190	190
Luminosity (inc. waist shift)	**L**	**$\times10^{34}$ cm^{-2}s^{-1}**	**0,56**	**0,67**	**0,75**	**1,0**	**1,8**	**3,6**	**3,6**	**4,9**
Fraction of luminosity in top 1%	$L_{0.01}$/L		91,3%	88,6%	87,1%	77,4%	58,3%	58,3%	59,2%	44,5%
Average energy loss	E_{BS}		0,65%	0,83%	0,97%	1,9%	4,5%	4,5%	5,6%	10,5%
Number of pairs per bunch crossing	N_{pairs}	$\times10^3$	44,7	55,6	62,4	93,6	139,0	139,0	200,5	382,6

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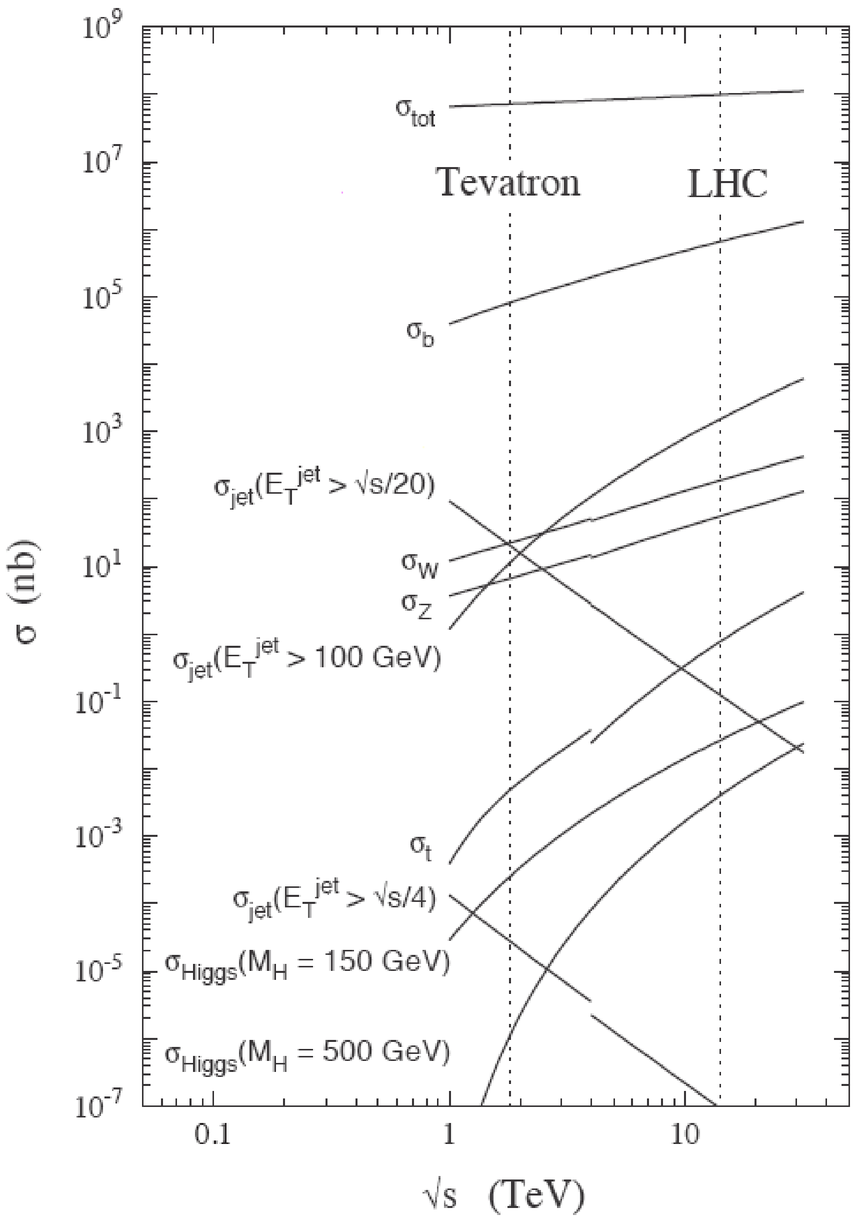
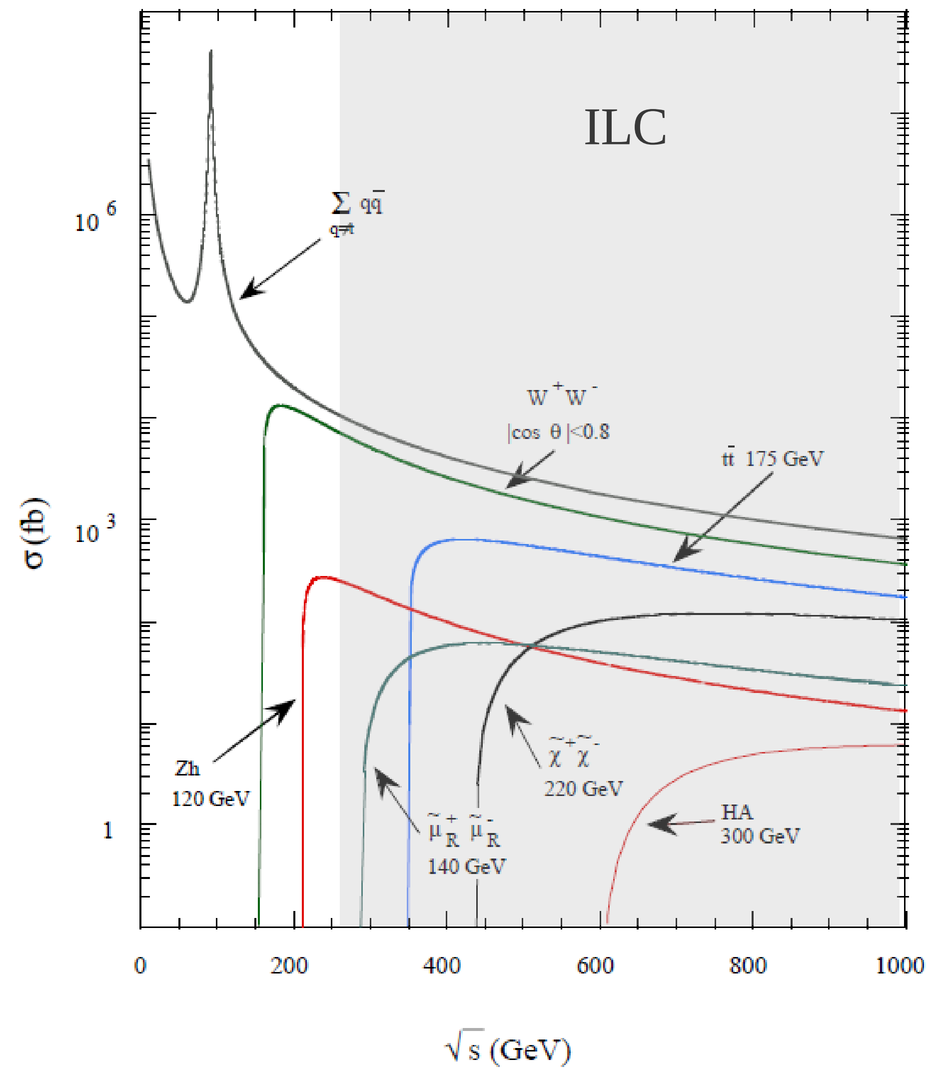
Signal and Background Cross Sections at LHC and ILC

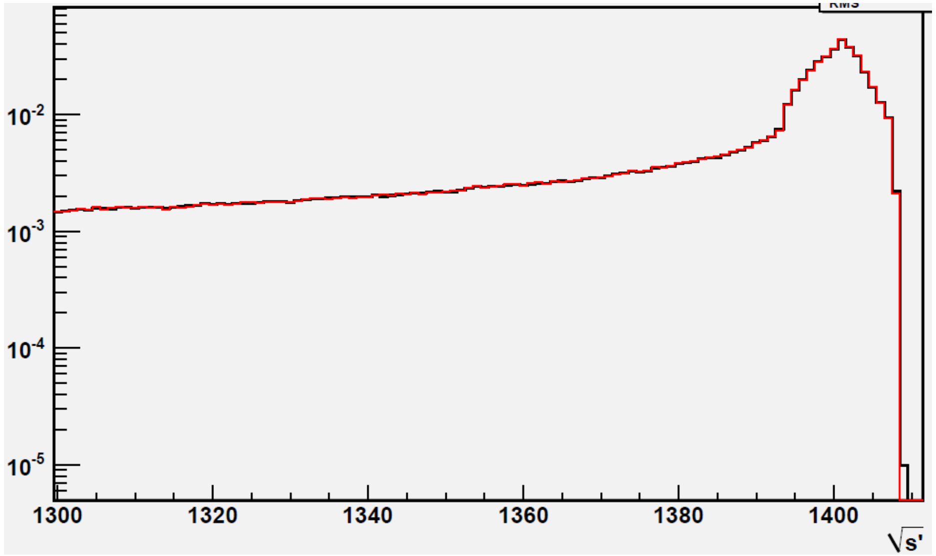


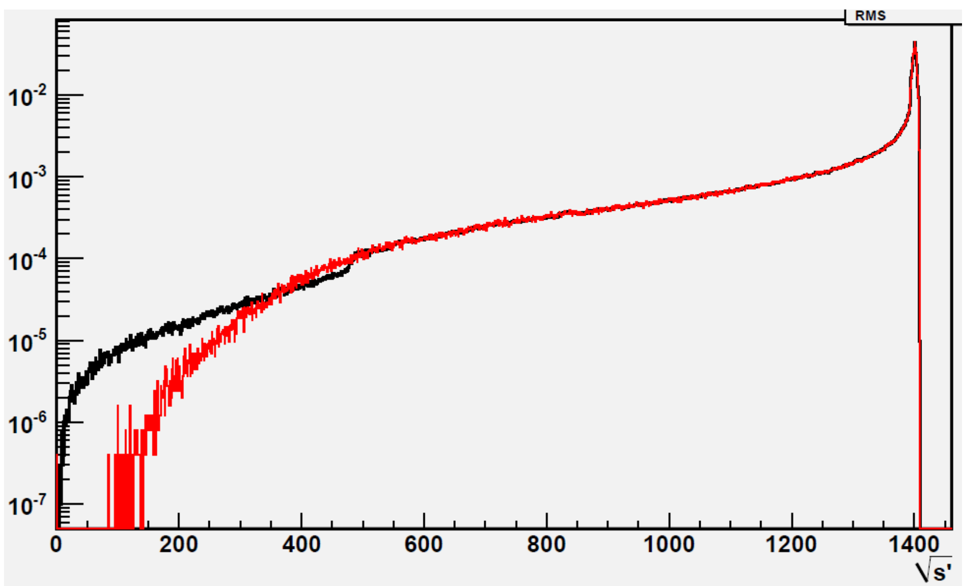
Note: No trigger at ILC - read out detector every bunch crossing



e^+e^- Linear Collider at 240 GeV < $\sqrt{s}$ < 1000 GeV (ILC)

Beamstrahlung





Guinea-Pig

VEGAS MC Integration

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e^+e^- Linear Collider at 240 GeV < $\sqrt{s}$ < 1000 GeV (ILC)

$\gamma\gamma \to$ *hadrons*

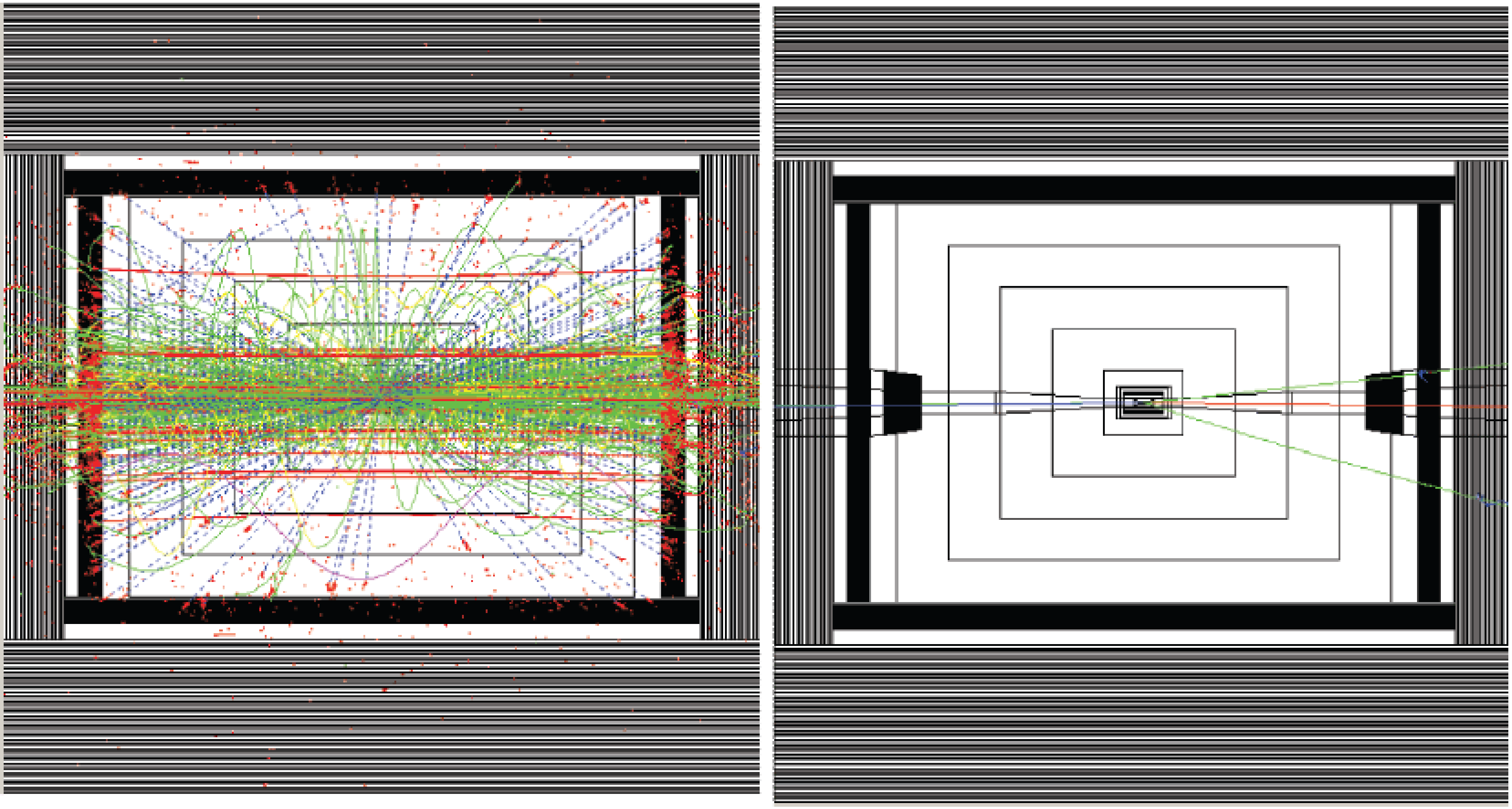


Figure 1.5: Physics backgrounds from $\gamma\gamma$ produced e^+e^- pairs, muon pairs, and hadronic events integrated over 150 bunch crossings (left) and a single bunch crossing (right).

e^+e^- Linear Collider at 240 GeV < $\sqrt{s}$ < 1000 GeV (ILC)

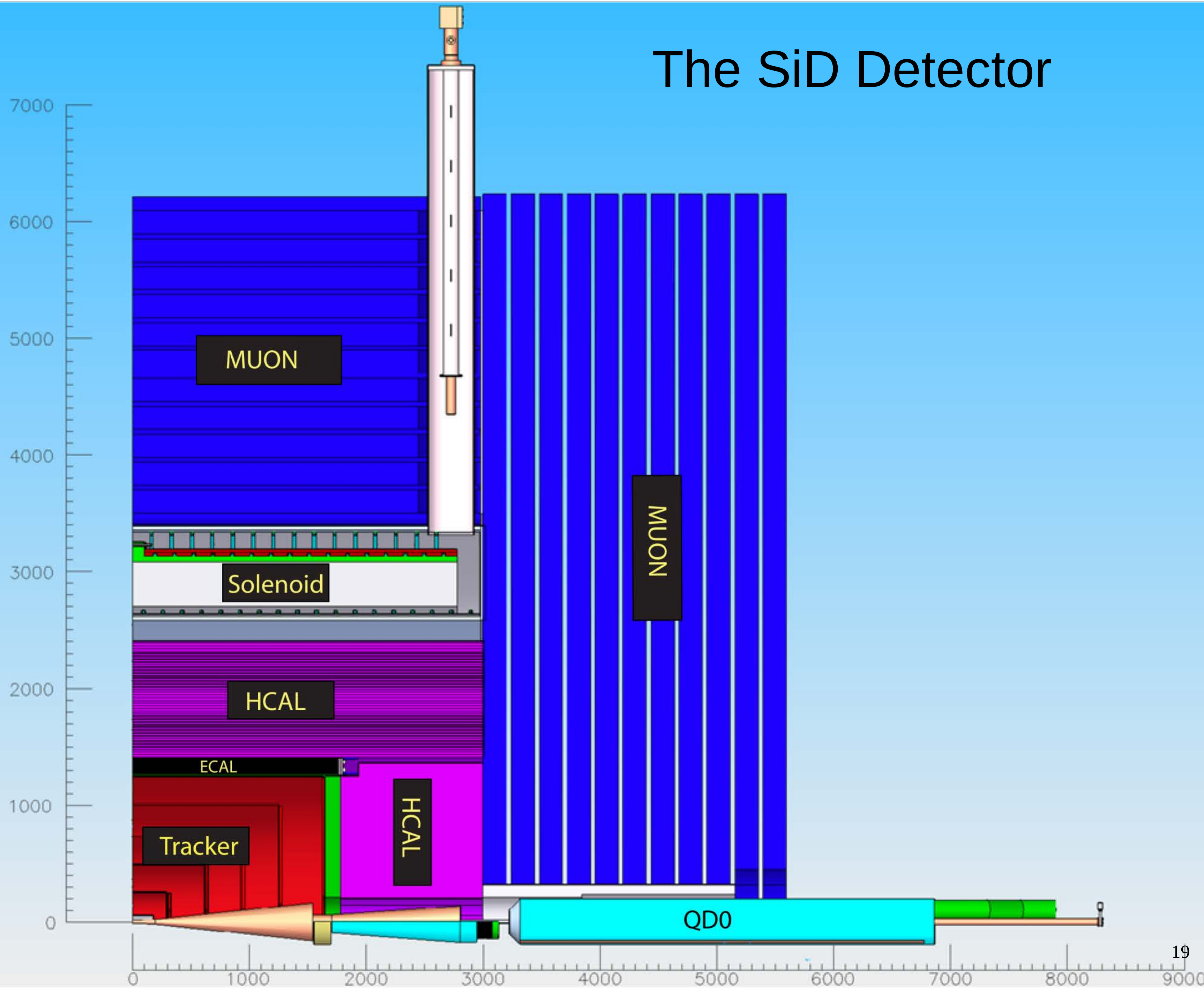
e^+e^- Polarization

IP and General Parameters			TF = Traveling Focus							
								L Upgrade	E_{cm} Upgrade	
Centre-of-mass energy	E_{cm}	**GeV**	**200**	**230**	**250**	**350**	**500**	**500**	**1000**	**1000**
									A1	B1b
Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
Electron bunch population	N_-	$\times 10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Positron bunch population	N_+	$\times 10^{10}$	2,0	2,0	2,0	2,0	2,0	2,0	1,74	1,74
Bunch separation	t_b	ns	554	554	554	554	554	366	366	366
Electron RMS energy spread	p/p	%	0,206	0,194	0,190	0,158	0,124	0,124	0,083	0,085
Positron RMS energy spread	p/p	%	0,190	0,165	0,152	0,100	0,070	0,070	0,043	0,047
Electron polarisation	P_-	%	80	80	80	80	80	80	80	80
Positron polarisation	P_+	%	31	31	30	30	30	30	20	20

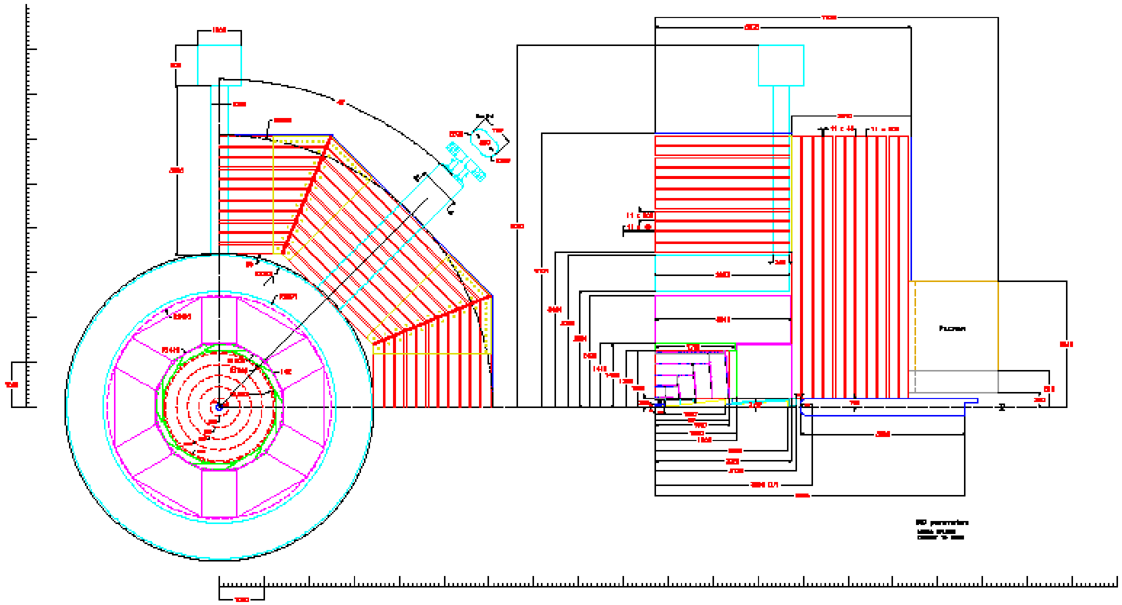
Polarized e^+e^- beams:

- Approximate collision of the fundamental $e_L^- e_R^+$ / $e_R^- e_L^+$ fields before EWSB
- Enhance/suppress processes to improve S/B; in particular $e_L^- e_R^+$ ($e_R^- e_L^+$) combination is used to enhance (suppress) W boson radiation.
- Disentangle amplitudes with γ^* and Z propagators

The 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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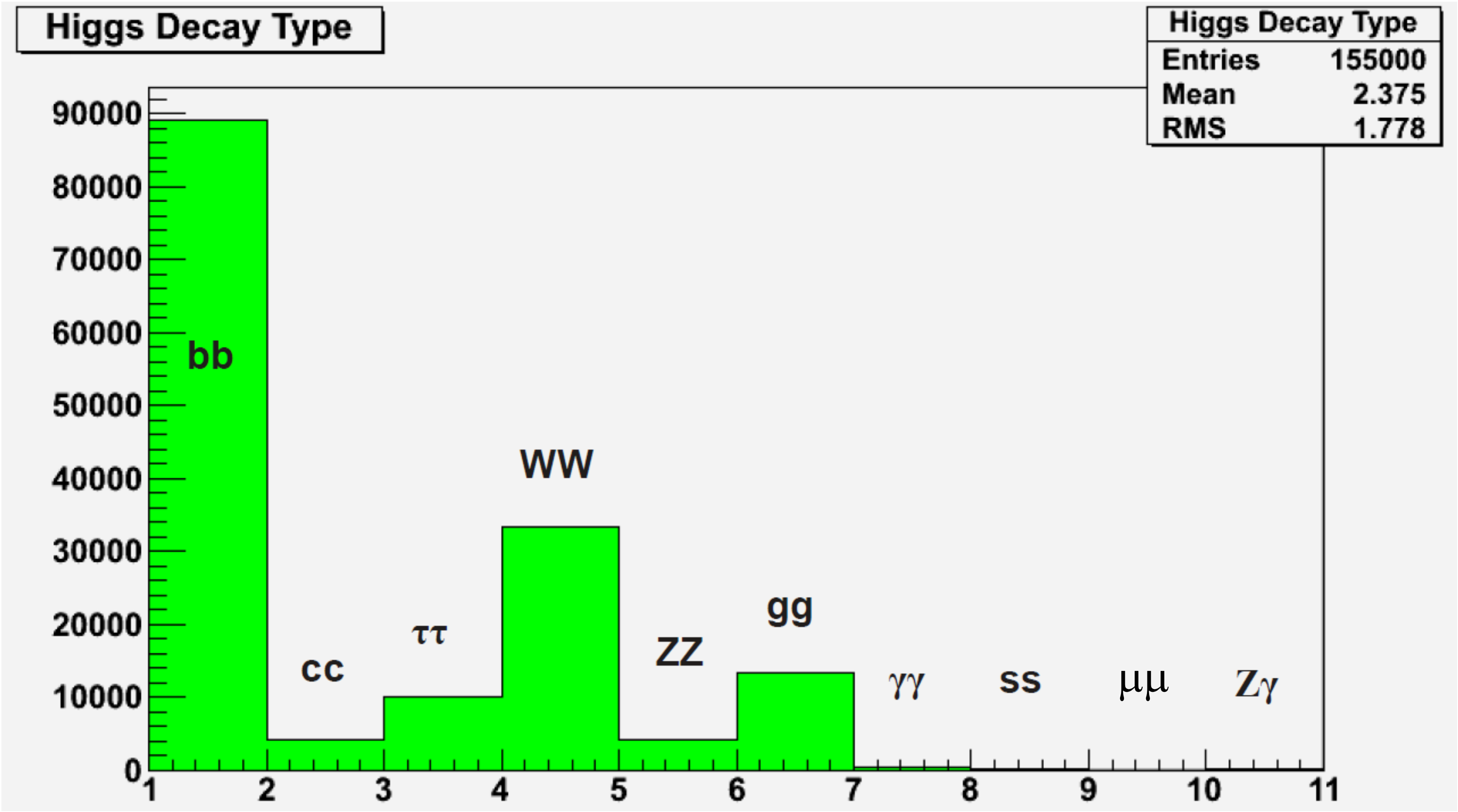
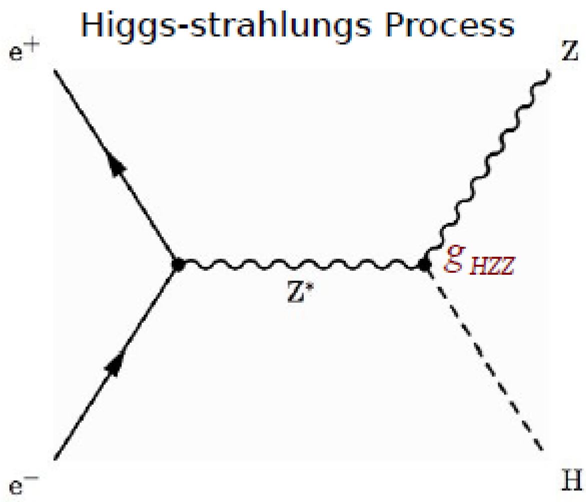
SM Higgs decay mode histogram M_H=125 GeV

Because all background is electroweak at the ILC, all Higgs decays, including fully hadronic decays, are accessible without any special conditions.



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

Higgs-strahlung Cross Section and Higgs Mass at the ILC



Golden Plated Channel at e^+e^- Colliders

Sensitive to coupling at HZZ Vertex

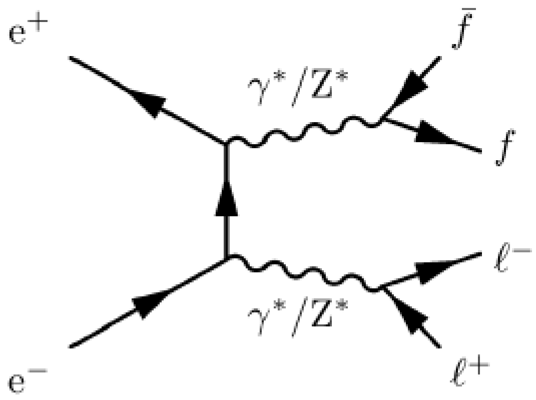
$Z \to e^+e^-$, $\mu^+\mu^-$

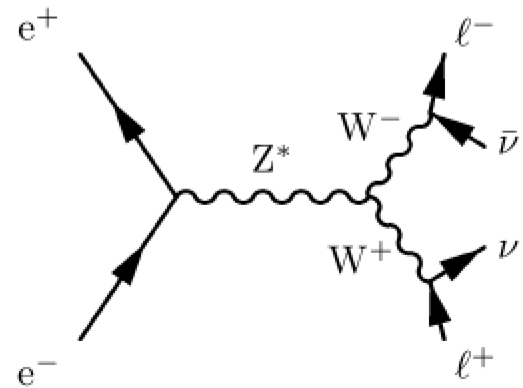
H $\to$ anything, incl invisible

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

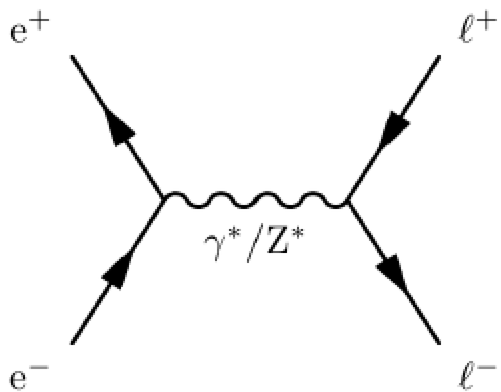
(Main) Background Processes

Boson Pair Production

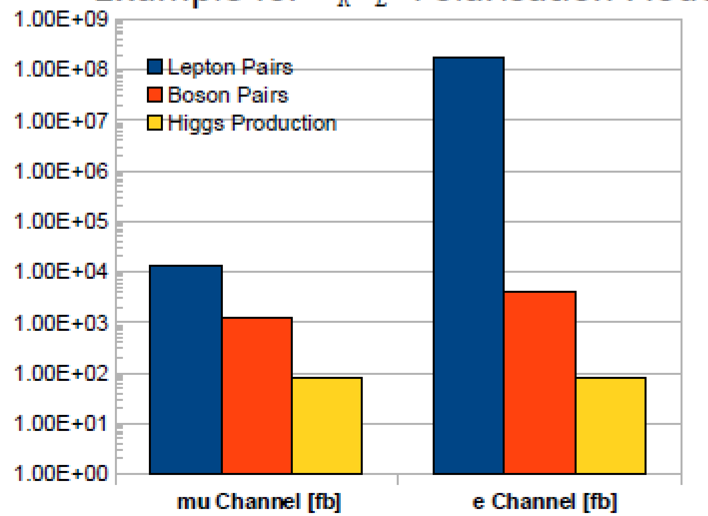




Lepton Pair Production



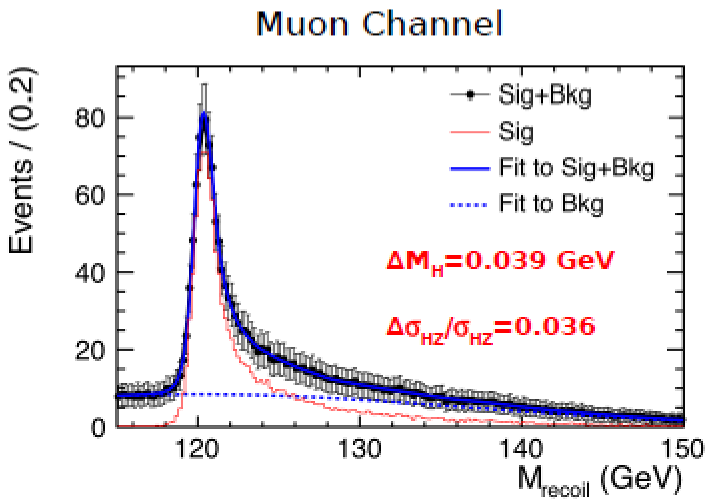
Example for $e_R^- e_L^+$ Polarisation Mode



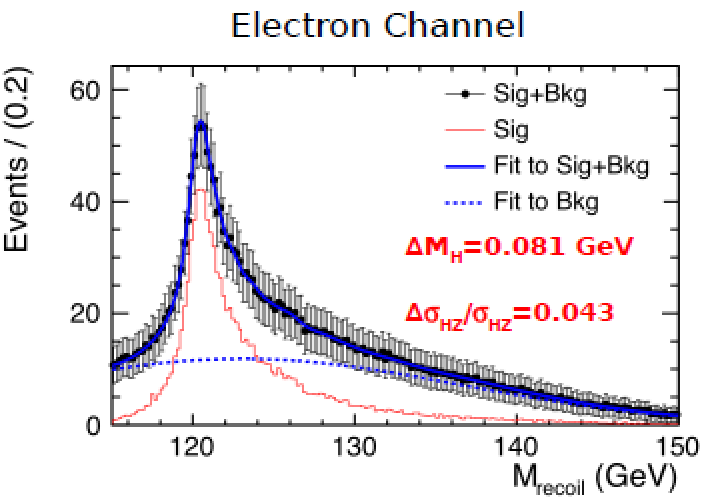
Background Rejection

$P_{T,dl} > 20$ 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

Results

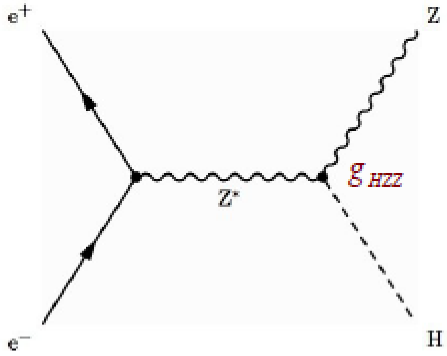


Very Precise Measurement
S/B = 8 in Peak Region



Less Precise
Bremsstrahlung in detector material

Combined: ΔM_H=0.035 GeV, $\Delta\sigma_{HZ}/\sigma_{HZ}$=0.027



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

⇒ Precision in g_{HZZ} coupling 1-2%

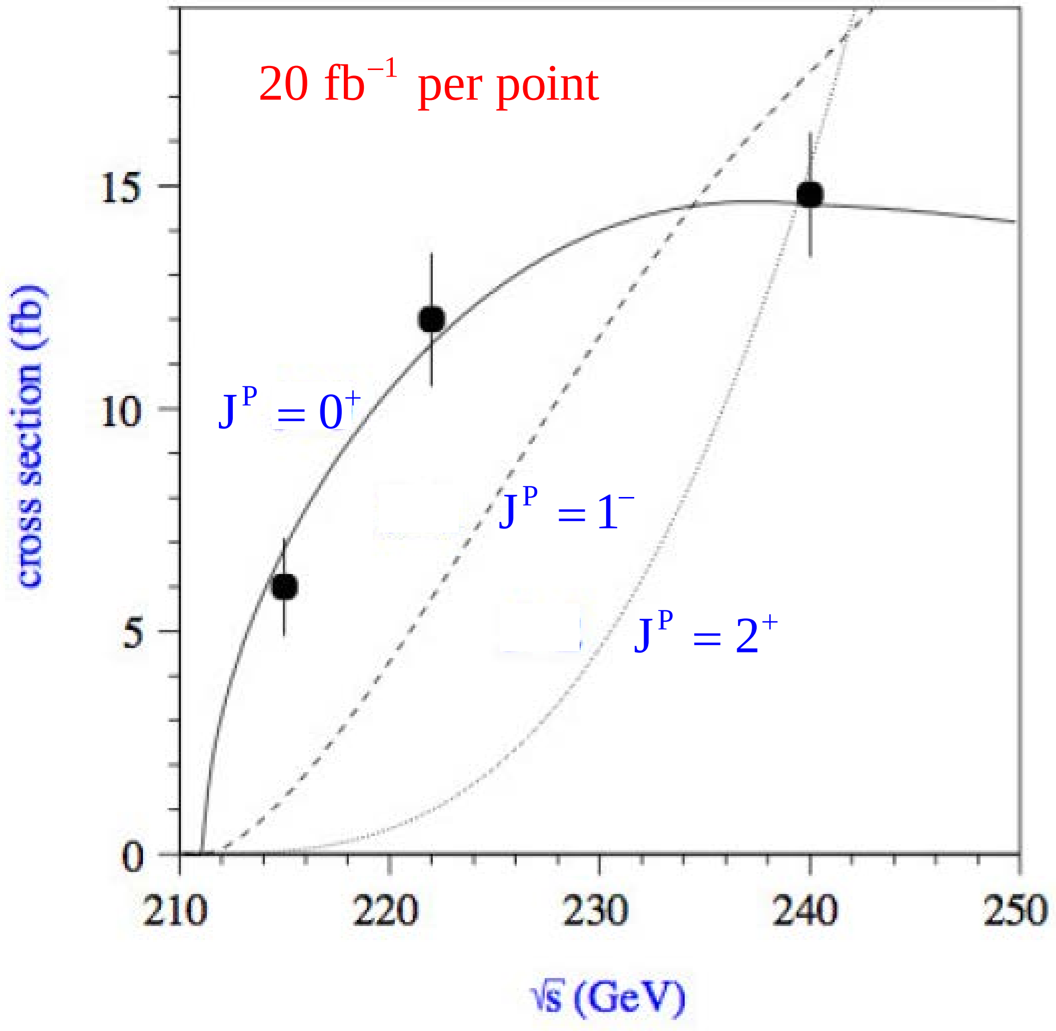
Sensitivity to 15% deviations
SM prediction of cross section

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

g_{HZZ} measurement also gives you sensitivity to Γ_{tot}

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

Higgs Spin



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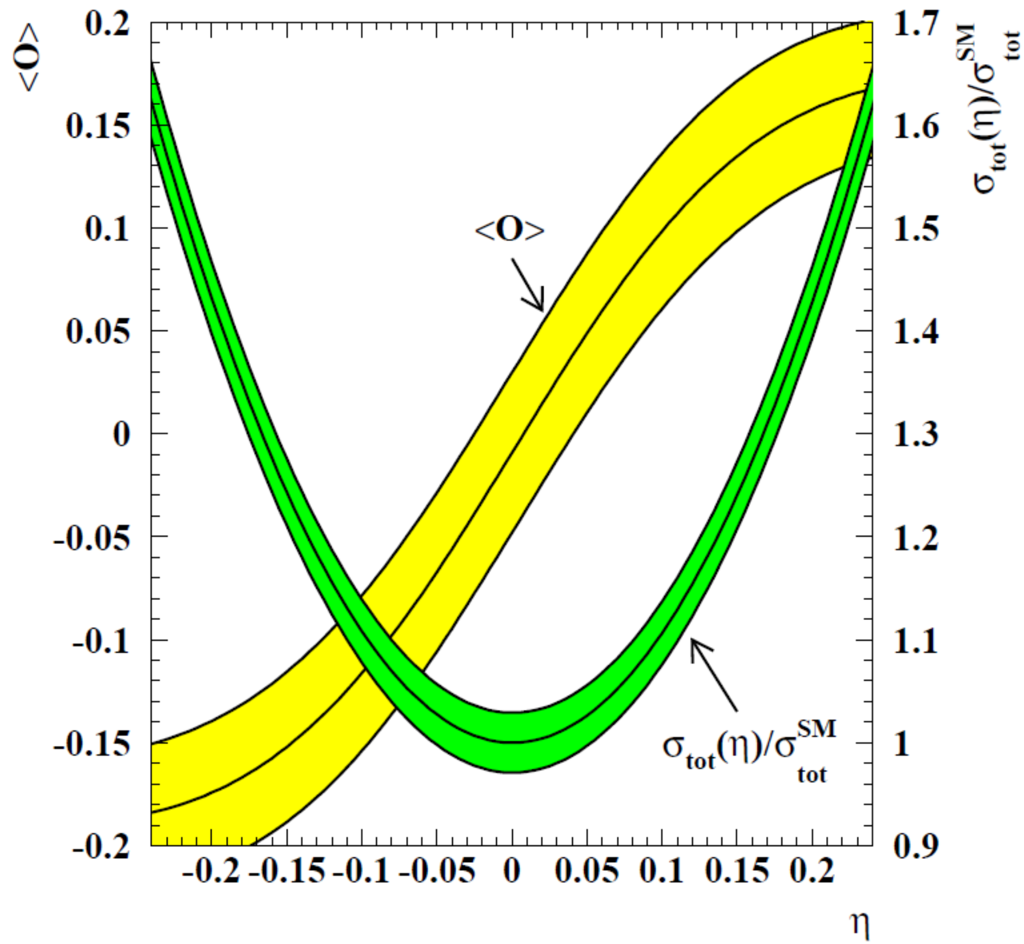
$$e^+e^- \to ZH \qquad \sqrt{s} = 350\ \text{GeV}$$

Higgs CP

$$\mathcal{M}_{\phi Z} = \mathcal{M}_{HZ} + \eta \cdot \mathcal{M}_{AZ}$$

Optimal observable O built from angles of $\mu^+\mu^-$ from decay of the Z

$< O >$ most sensitive for small η
For larger η $\sigma_{tot}(\eta)$ is better

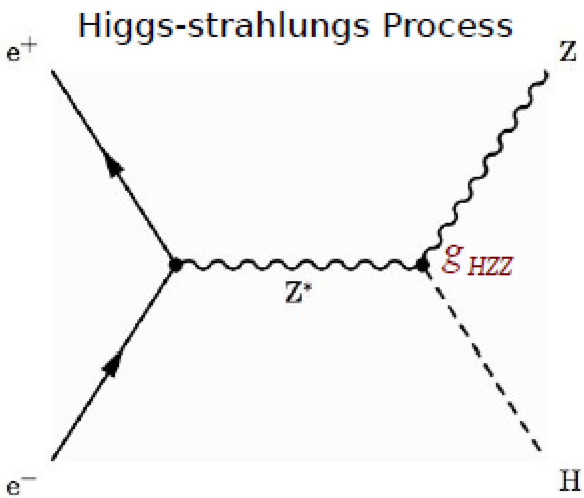


$L = 500\ \text{fb}^{-1}$

method	w/o σ_{tot}	with σ_{tot}
	$\Delta\eta$	
$\cos\theta$	0.046	0.033
$opt.obs.\mathcal{O}$	0.032	0.026
$< \mathcal{O} >$	0.032	0.026

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

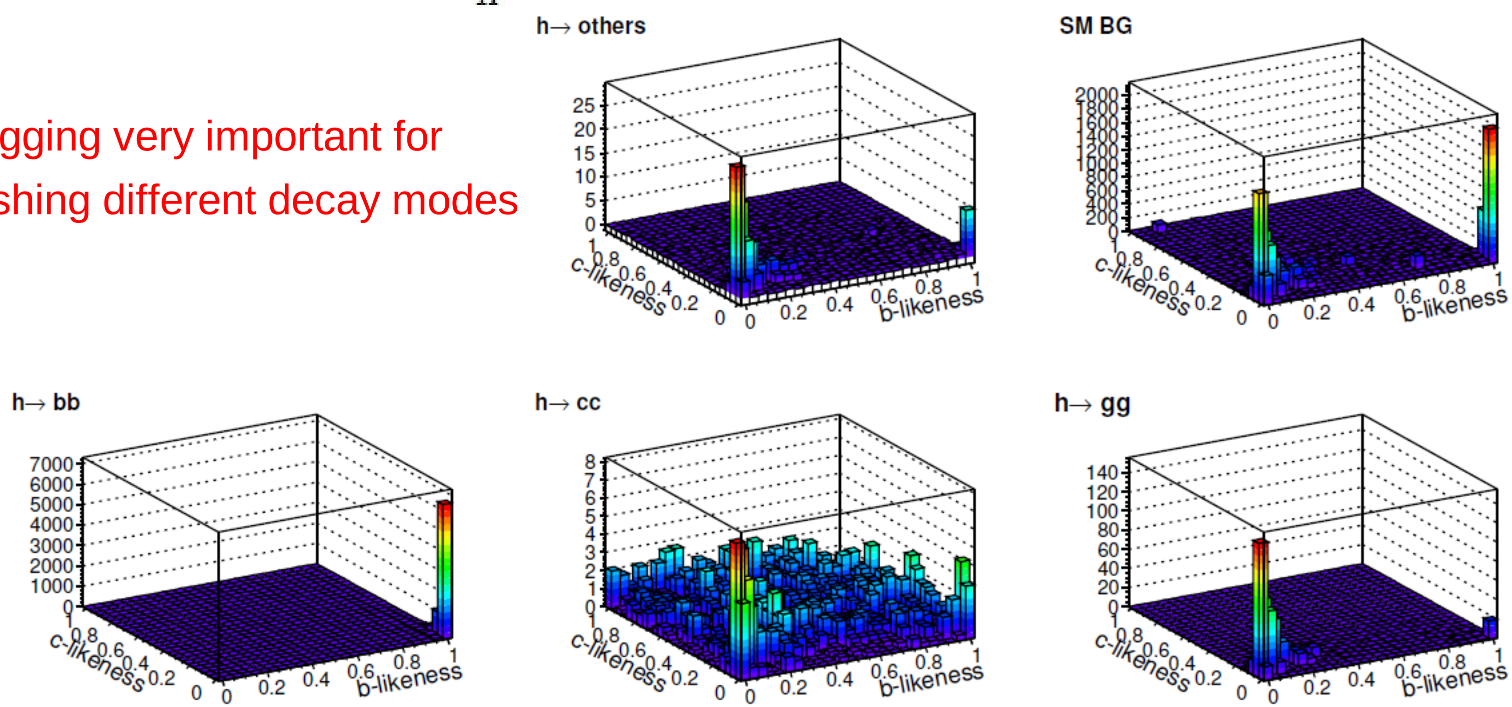
$\sigma \times$ BR measurements



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

Divide by $\sigma(e^+e^- \to ZH)$ measurement to get BR's

Flavor tagging very important for distinguishing different decay modes



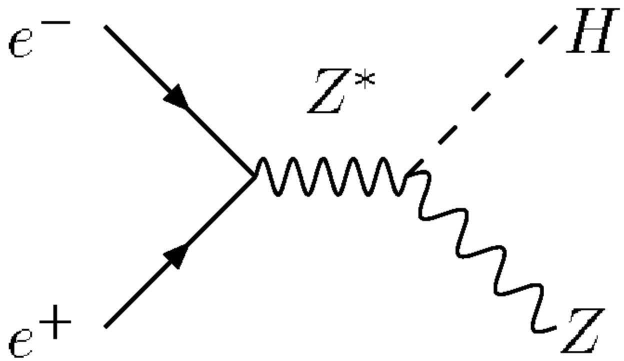
$e^+e^- \to ZH \qquad \sqrt{s} \approx 250$ GeV

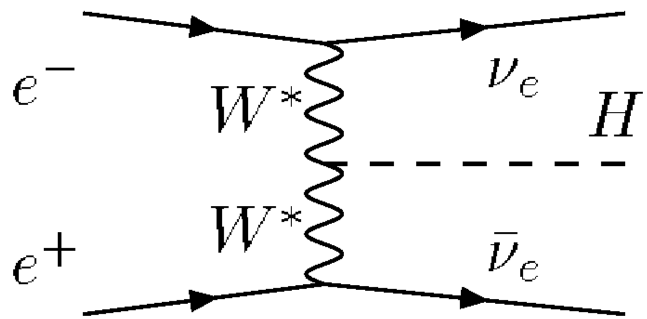
$\sigma \times$BR measurements

Results L=250 fb^{-1}

Observable	Expected Error
ILC at 250 GeV with 250 fb^{-1}	
$\sigma(Zh)$	0.025
$\sigma(Zh) \cdot BR(b\bar{b})$	0.010
$\sigma(Zh) \cdot BR(c\bar{c})$	0.069
$\sigma(Zh) \cdot BR(gg)$	0.085
$\sigma(Zh) \cdot BR(WW)$	0.08
$\sigma(Zh) \cdot BR(ZZ)$	0.28
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.05
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.27
$\sigma(Zh) \cdot BR(\text{invisible})$	0.005

$e^+e^- \to ZH,\ \nu\nu\mathrm{H}\ \ \sqrt{s} = 350$ GeV

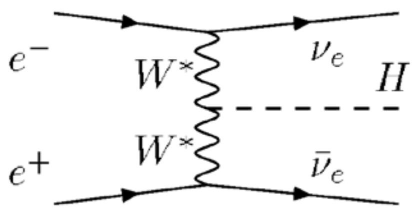


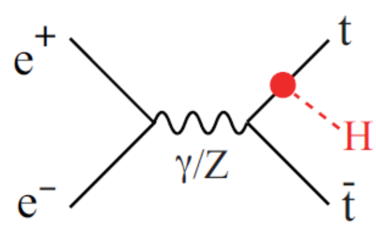


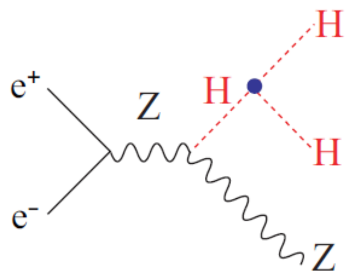
At $\sqrt{s} \approx 350$ GeV the ZH cross section has fallen off, but the cross section for $e^+e^- \to \nu\nu H$ comes into play so the total Higg cross section remains $\sigma(e^+e^- \to ZH\ \&\ \nu\nu H\ ) \approx 250$ fb.

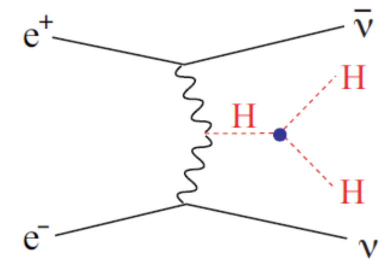
$\sqrt{s} \approx 350$ GeV is expected to give better branching fraction measurements than $\sqrt{s} \approx 250$ GeV due to improved S/B. The quantitative comparison is still under study. Also one gets a more complete Higgs profile using the WW fusion channel. The g_{HWW} coupling can be measured by 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 $\Delta\mathrm{BR(H} \to \mathrm{WW^*)} \ll \Delta\mathrm{BR(H} \to ZZ^*)$.
A relative error of 6% on Γ_{tot} is expected at $\sqrt{s} \approx 350$ GeV with 500 fb^{-1}

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

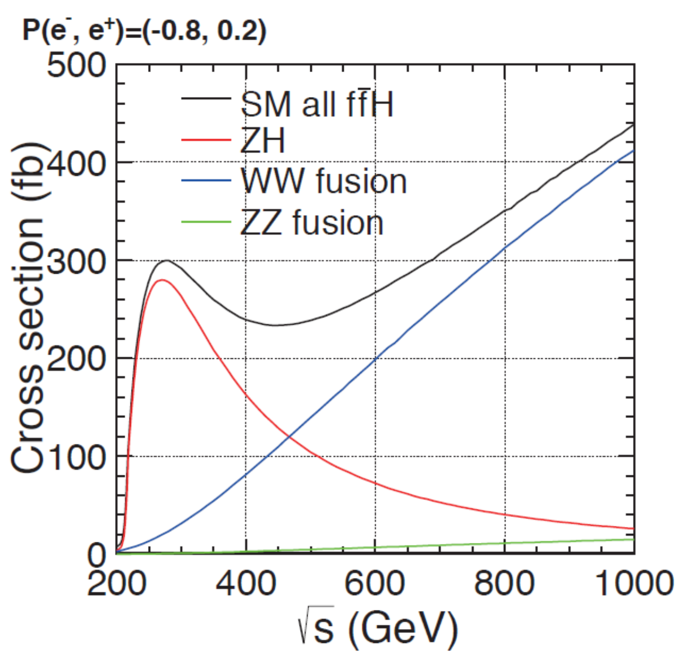


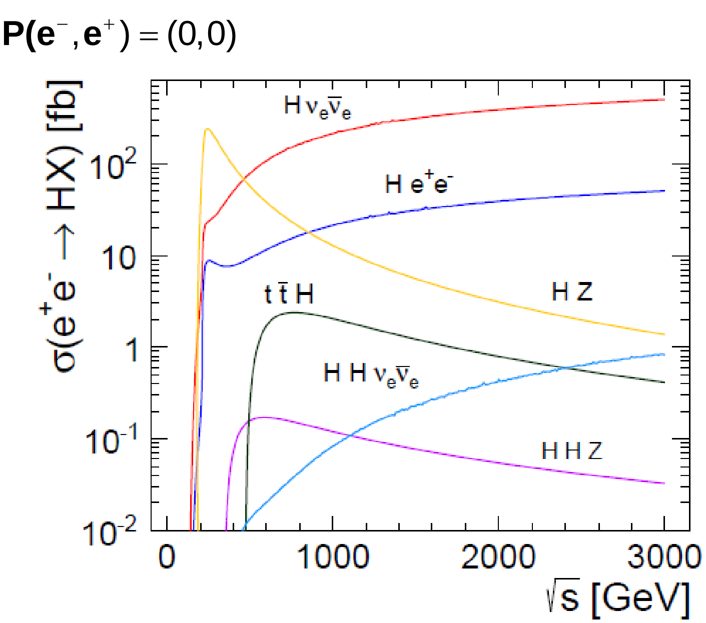




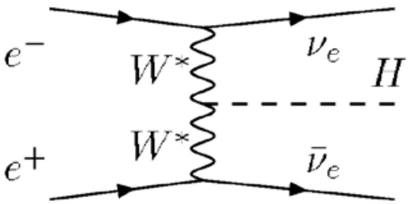


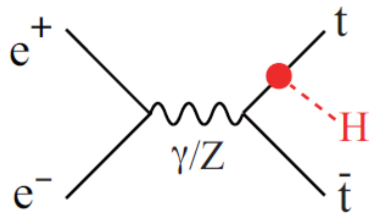
At a $\sqrt{s} \approx 1$ TeV e^+e^- collider additional Higgs production modes are available such as $e^+e^- \to tth$ and $e^+e^- \to ZHH$, which provide measurements of the top Yukawa coupling and Higgs self coupling, respectively. In addition an e^+e^- collider continues as a Higgs factory at $\sqrt{s} \approx 1$ TeV since the total Higgs cross section is larger than the total cross sections at 250 and 350 GeV, especially if polarized beams are used:

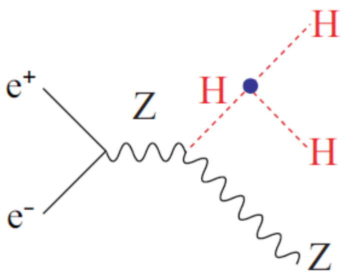


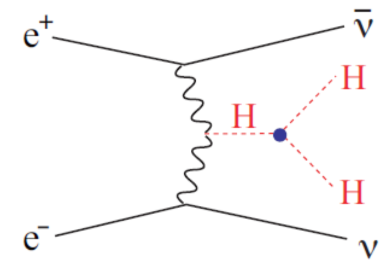


$e^{+}e^{-} \to \nu\nu\mathrm{H}$, ttH , ZHH , $\nu\nu HH$ $\sqrt{s} =$ 1 TeV









Results

ILC at 1 TeV with 1000 fb^{-1}	
$\sigma(WW) \cdot BR(WW)$	0.01
$\sigma(WW) \cdot BR(gg)$	0.018
$\sigma(WW) \cdot BR(\tau + \tau -)$	0.02
$\sigma(WW) \cdot BR(\gamma\gamma)$	0.05
$\sigma(WW) \cdot BR(\mu^+\mu^-)$	0.24
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	0.12
λ_{hhh}	0.20

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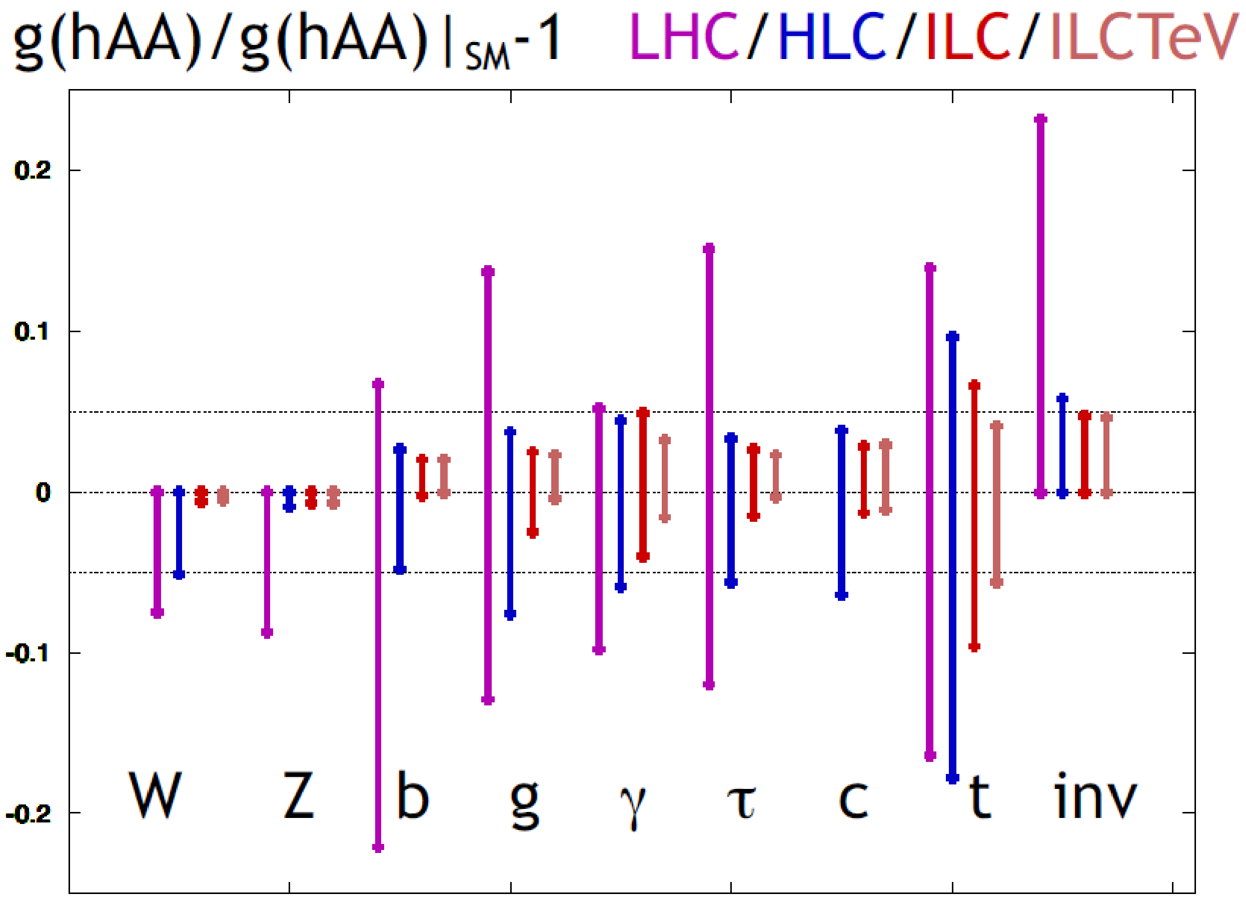
Comparison of LHC and ILC Coupling Measurements

LHC: 150 fb^{-1} per experiment @ $\sqrt{s} = 14$ TeV

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

ILC: 500 fb^{-1} e^+e^- @ $\sqrt{s} \approx 350 - 500$ GeV

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



M.Peskin arXiv:1207.2516 [hep-ph]

Summary

- Several ideas for Higgs factories are under currently under discussion. However the most mature, realistic design at this time is the ILC, which can start at Ecm=250 GeV and can then be reasonably upgraded to higher energies to continue Higgs physics and hopefully other physics.
- The ILC can significantly improve the Higgs coupling measurements over what the LHC will ultimately achieve. It is a more natural environment in which to study the Higgs. The ability to probe couplings to the several percent level is crucial to distinguishing different Higgs models.

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