Higgs and top measurements

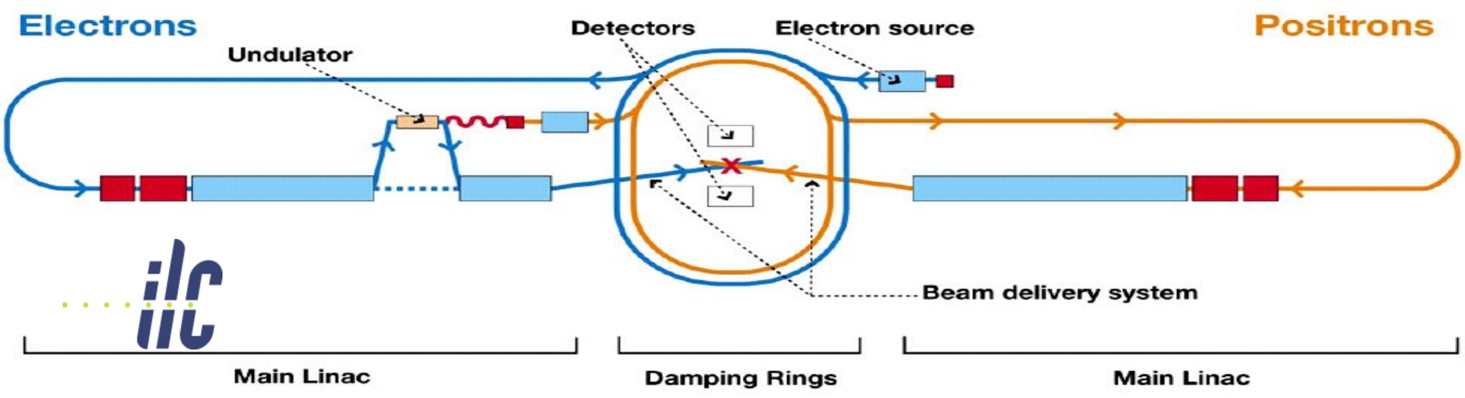
and the role of polarised beams

Roman Pöschl

With the help of H. Li, F. Richard, F. Simon
Material stolen from R. Godbole et al., M. Peskin, H. Ono
T. Price and several others

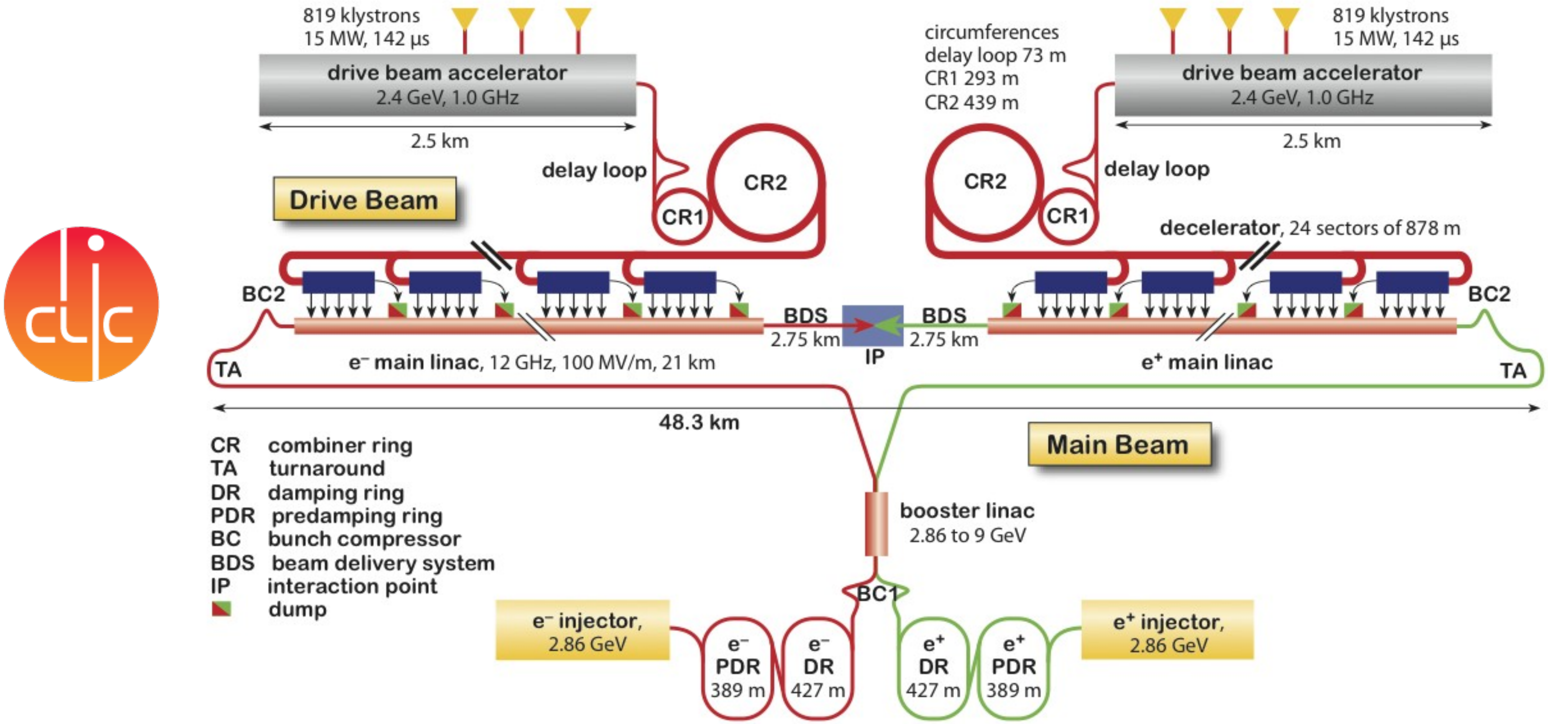
Helmholtz Allianz Workshop
Physics at the Terascale
DESY December 2012

(Future) Linear electron-positron colliders



Energy: 0.1 - 1 TeV

TDR in 2012
+ DBD for detectors



Energy: 0.5 - 3 TeV

CDR in 2012

ILC Parameters

Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years

E_{cm} adjustable from 200 – 500 GeV

Ability to scan between 200 and 500 GeV

Energy stability and precision below 0.1%

Electron polarization of at least 80%

- The machine must be upgradeable to 1 TeV
- Positron Polarisation desireable as an upgrade

Beam polarisation – Useful Formulae

$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL}) + (P-P')(\sigma_{RL}-\sigma_{LR})\right] \qquad (1)$$

$$\sigma_{P,P'} = \frac{1-PP'-(P-P')}{4}\sigma_{LR} + \frac{1-PP'+(P-P')}{4}\sigma_{RL} \qquad (2)$$

$$P_{eff} = \frac{|P|+|P'|}{1+|P||P'|} \qquad (3)$$

Electroweak physics:

- Typically $\sigma_{LR} > \sigma_{RL}$
  but less background for σ_{RL}
- It naively clear that one would like to have
  at least one beam *strongly* polarised
  Would like to approach Peff = 1

For a comprehensive discussion on physics with polarised beams (positrons) at LC
See arXiv:hep-ph/0507011

Linear Colliders - Full Exploration of electroweak sector

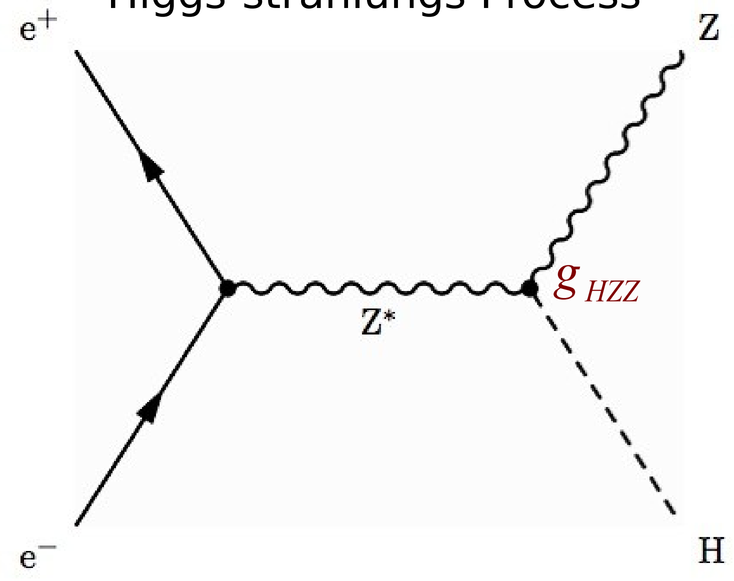
(Table proposed by M. Peskin for ILC DBD)

Energy	Key Reaction	Physics Goal	Polarization
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	A
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	H
	$e^+e^- \to WW$	precision W couplings	H
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	A
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings	L
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'	A
	$e^+e^- \to Zhh$	Higgs self-coupling	H
700–1000 GeV	$e^+e^- \to t\bar{t}h$	Higgs coupling to top	H
	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling	L
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector	L
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top	L

A – Polarisation asymmetry is essential element of study
H – Enhancement or suppression ob background
L - Process goes through $e_L^- e_R^+$ with benefit from fully polarised beams

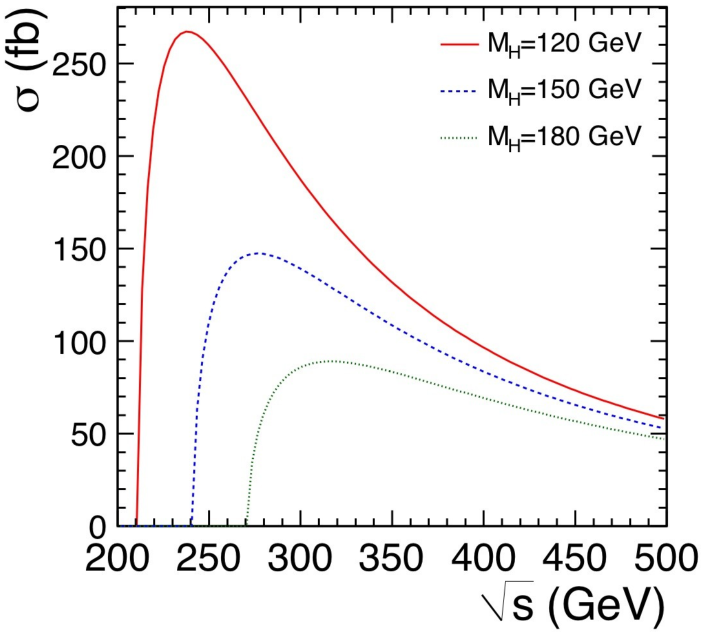
Higgs-strahlung Cross Section and Higgs Mass at LC

Higgs-strahlungs Process



Golden Plated Channel at e^+e^- Colliders

Sensitive to coupling at HZZ Vertex



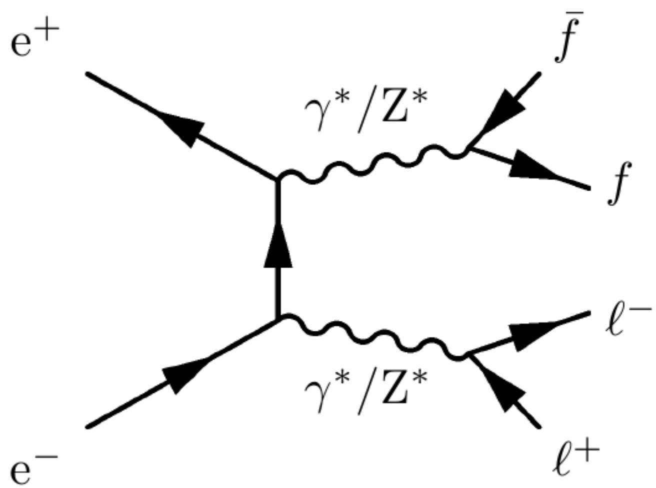
Production Cross Section of SM Higgs Boson

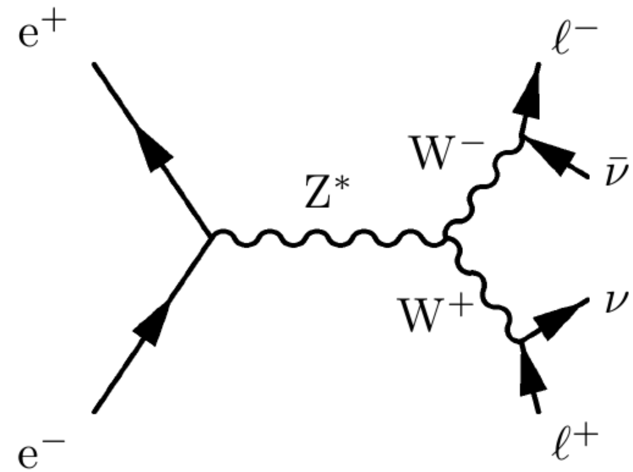
Maximal at HZ production threshold

Higgs Strahlung at $\sqrt{s}$ = 250 GeV for m_H = 120 GeV

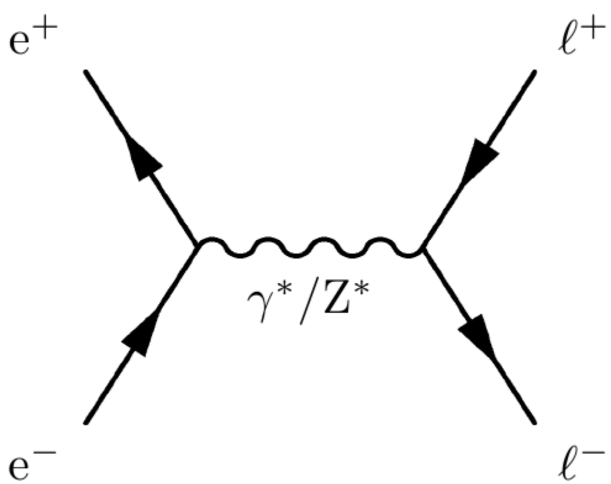
(Main) Background Processes

Boson Pair Production

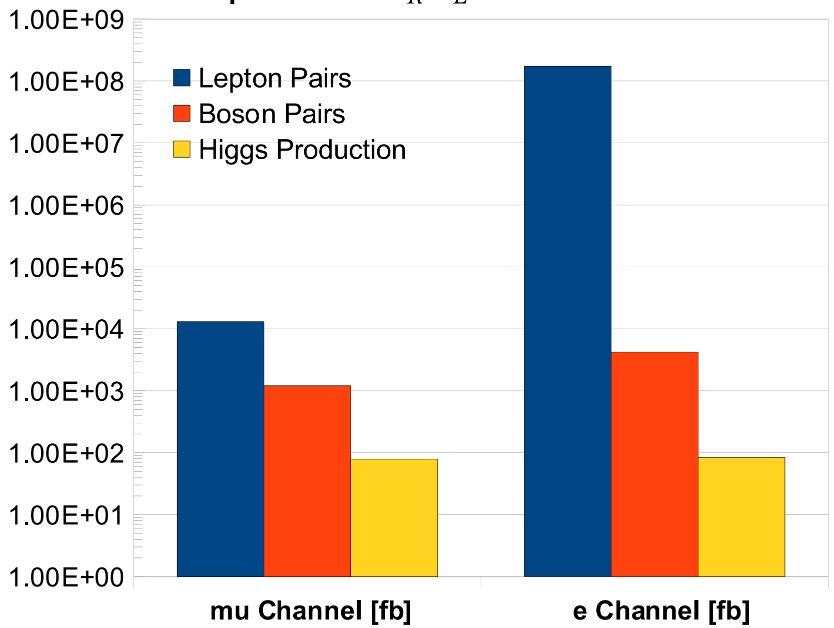




Lepton Pair Production



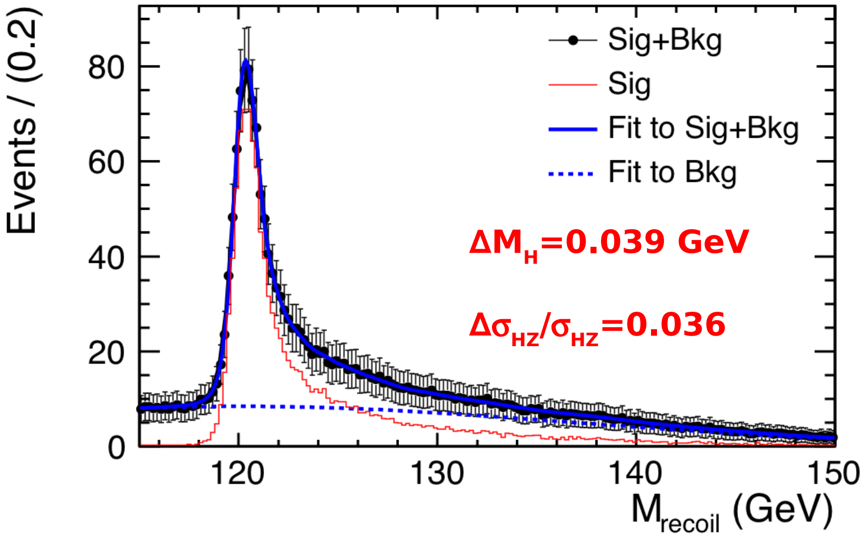
Example for $e_R^- e_L^+$ Polarisation Mode



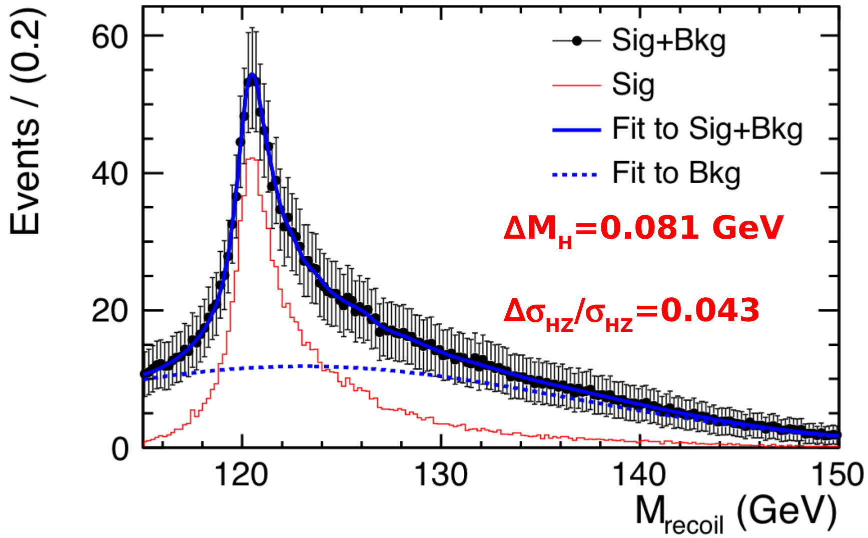
Huge Background mainly due to Bhabhas $\sigma_{signal}/\sigma_{bkgr.}$ ~0

Results (see also arXiv:1202.1439)

Muon channel



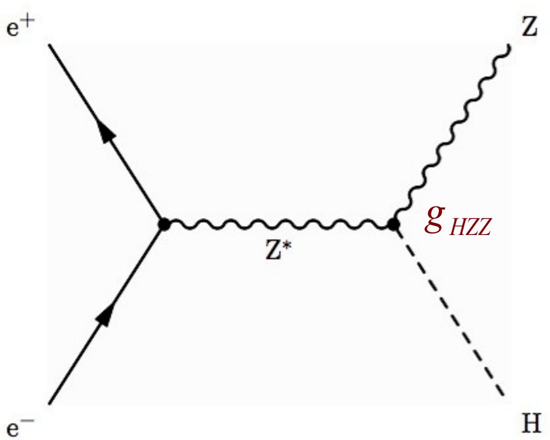
Electron channel



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



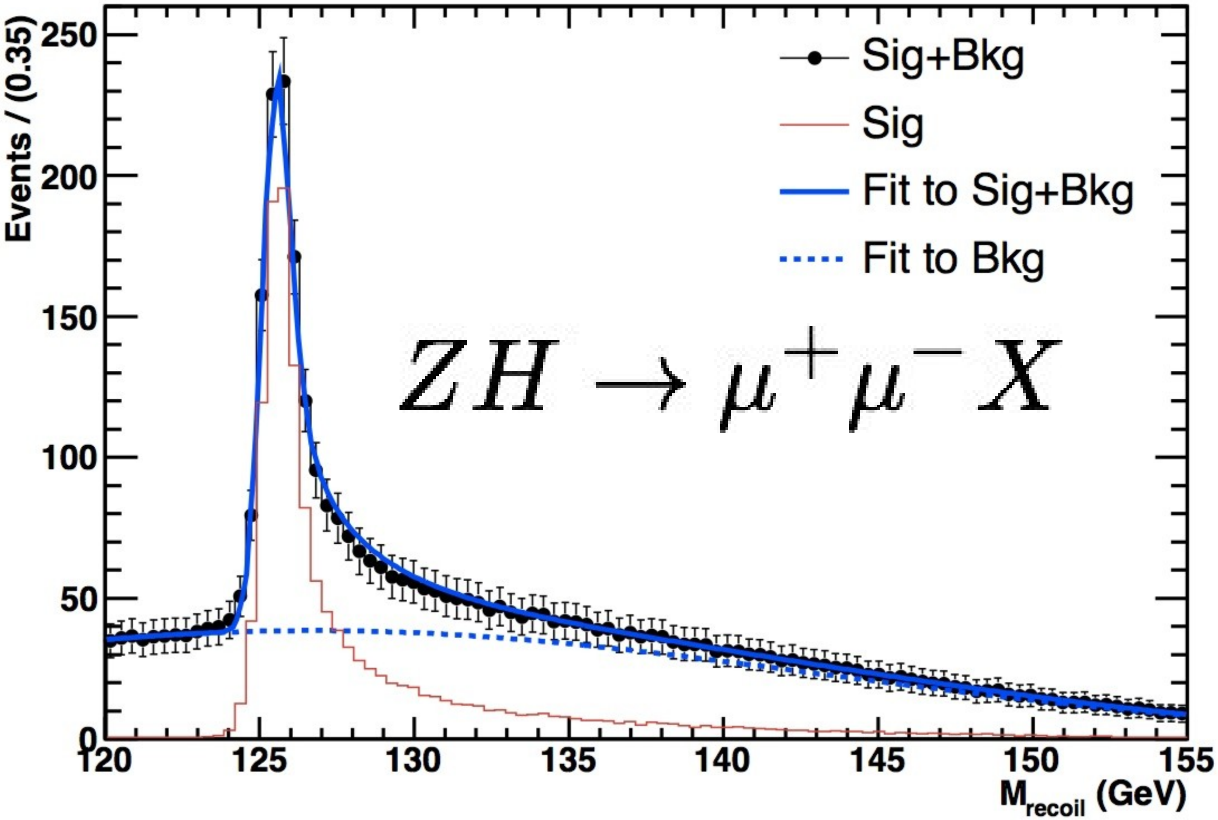
$$\sigma_{HZ} \sim g^2_{HZZ}$$

⇒ Precision in g_{HZZ} coupling 1-2%

Sensitivity to 15% deviations
SM prediction of cross section

Study for M_H = 125.3 GeV – SM Higgs

(H. Li, fast simulation validated with full simulation)

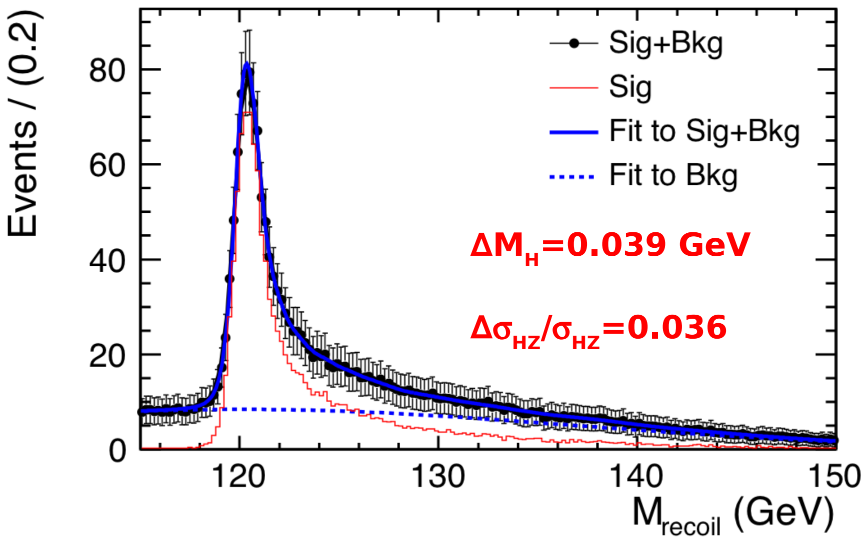


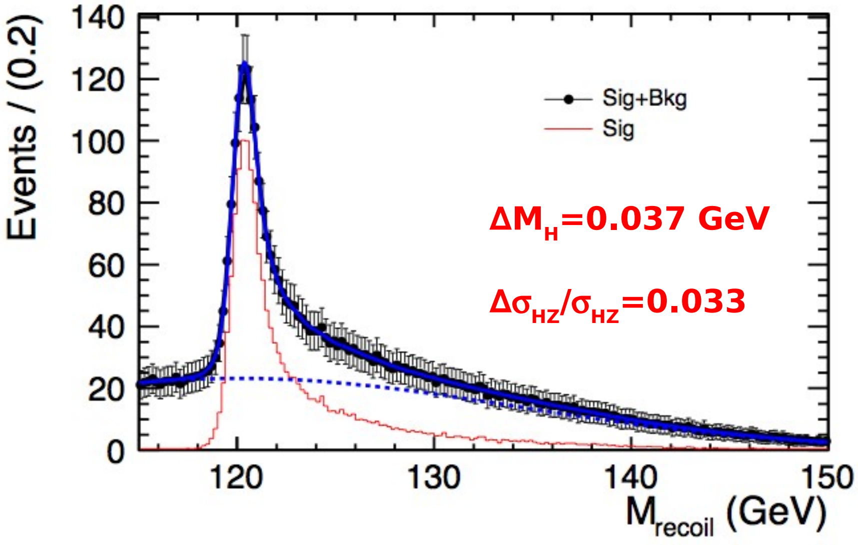
$$M_h = 125.3 \pm 0.03\,\mathrm{GeV}$$
$$\sigma_{ZH} = 10.32 \pm 0.37\,\mathrm{fb},\ 3.6\%$$

Higgs at 125.3 GeV "permits" the same precision as Higgs at 120 GeV

Comparison of two polarisation modes

$e^-_R\, e^+_L$ Muon Channel $e^-_L\, e^+_R$





- Comparable precisions for two polarisation modes

Mode $e^-_L\, e^+_R$
A priori Large WW background $\sigma_{WW} \sim 500 \times \sigma_{HZ}$

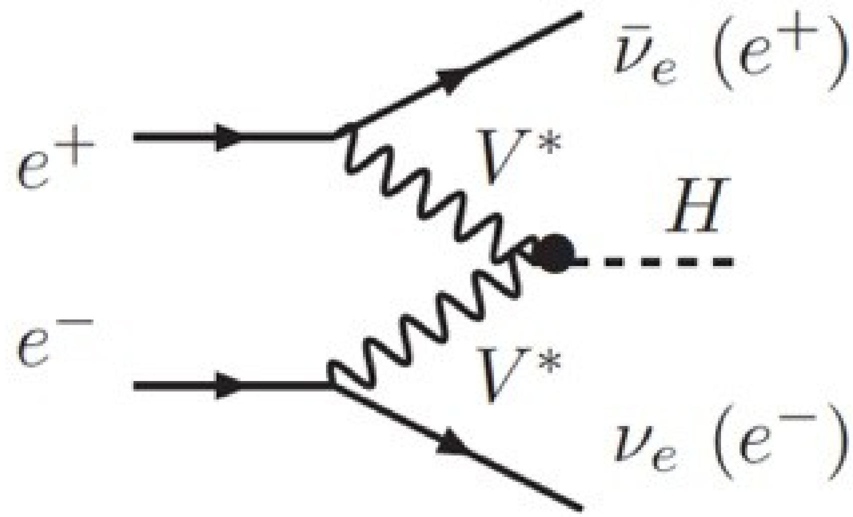
Mode $e^-_R\, e^+_L$
Smaller WW background $\sigma_{WW} \sim 50 \times \sigma_{HZ}$

In both cases dominant ZZ background, more important
For $e^-_L\, e^+_R$ mode

Little influence of beam polarisation due to efficient cuts against background

Coupling to the W

- Directly accessible in WW fusion:



Measurement of the production cross section in one visible decay also measured model-independently in the ZH - process allows to extract the coupling
1.4% at 500 GeV (500 fb^{-1}), comparable at higher energy

- The ZZ fusion process has a cross section on the level of 10% of the WW fusion:
- Towards higher energies possible to measure $\frac{g_{\mathrm{HWW}}}{g_{\mathrm{HZZ}}} = cos^2\theta_W$
- For mH < 140 GeV: Total width $\Gamma_H = \Gamma(\mathrm{H} \rightarrow \mathrm{WW}^*)/Br(\mathrm{H} \rightarrow \mathrm{WW}^*)$
 measurable to the 5% level

Strong influence on polarisation

E_{cms} = 1 TeV

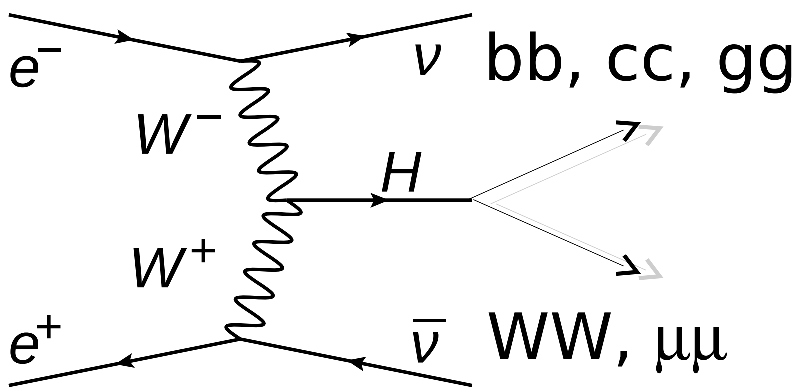
Estimated generated events for both polarization

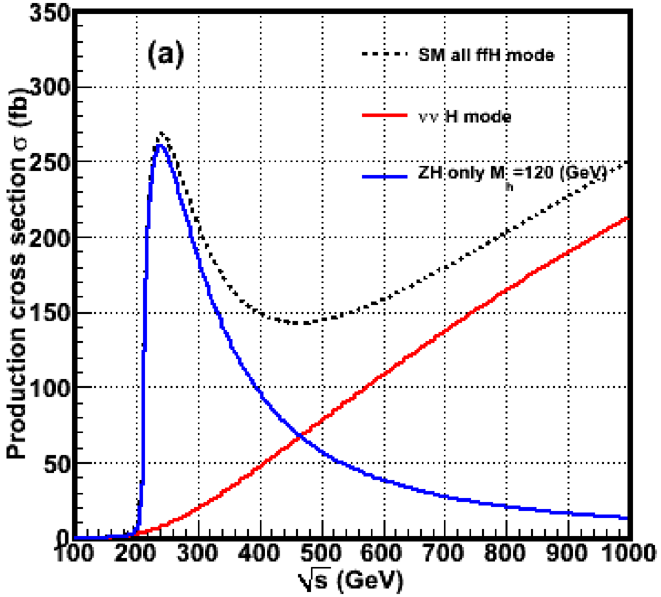
L=500 fb^{-1}	(-0.8, +0.2)	(+0.8, -0.2)	Pol reduction
h→All	223,408	30,697	86%
2f	3,890,180	2,699,560	31%
4f	9,168,850	6,341,460	31%
6f	121,842	34,163	72%
BG sum	13,180,872	9,075,183	31%
S/N	0.0169	0.0034	80%

vvH @ 1 TeV

DBD benchmark process: σ*BR for Hμμ, bb, cc, WW, gg

Main produced through W-fusion





W-fusion vvH

ZH

H→bb, cc, gg (Hadronic decay)
Di-jet reconstruction

H→μμ: Muon ID
H→WW*: (4j, lv+2j, 2l+2v)

Main backgrounds (WW,ZZ)
ee→ll for H→μμ

W fusion - Some numbers for 500 GeV

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

(-0.8, +0.2): σ = 14046 fb

(-0.8, 0): σ = 11707 fb

(-0.8, +0.6): σ = 18723 fb

(-1,0): σ = 13000 fb

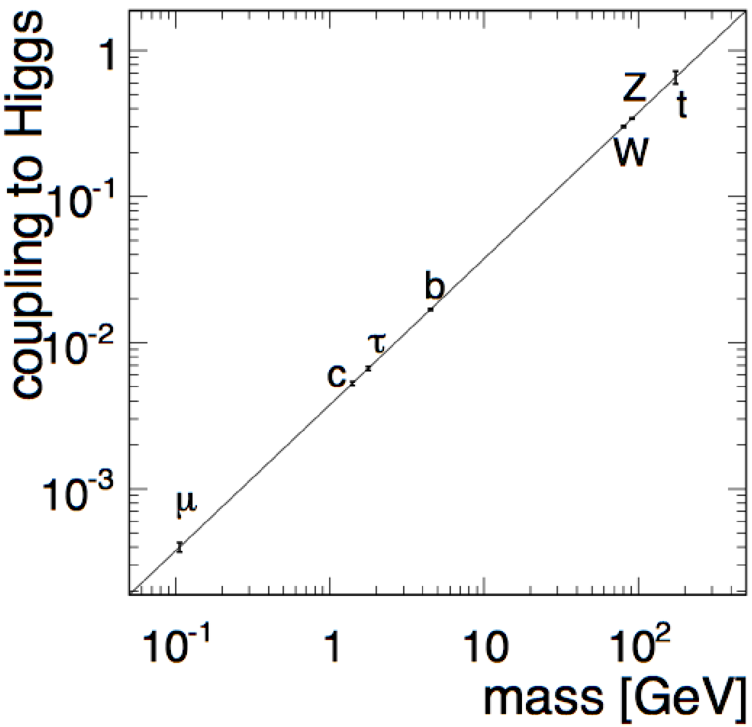
(-1, 1): σ = 26000 fb

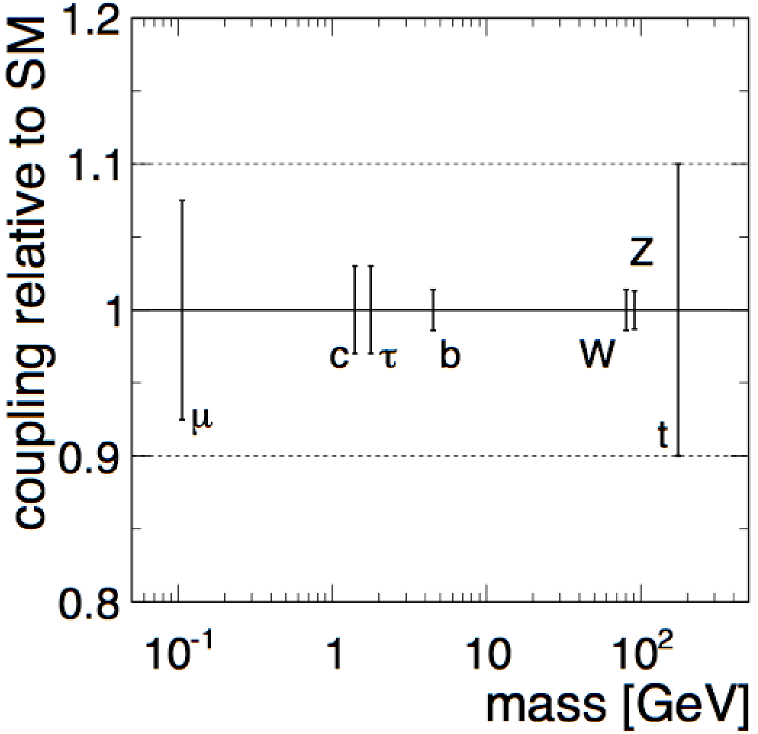
(0,0): σ = 6500 fb

- Clear that one needs polarisation

  - Polarised electrons are 'easy'
  - For polarised positrons one has to ponder economy at construction time vs. cost of running time

Higgs Couplings - Introduction

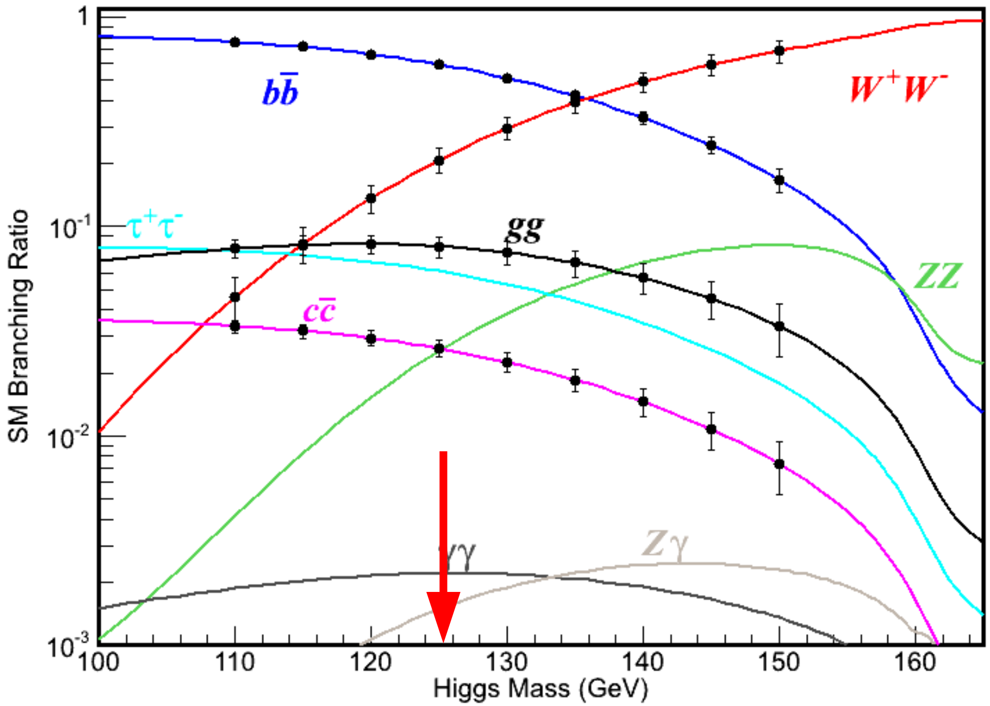




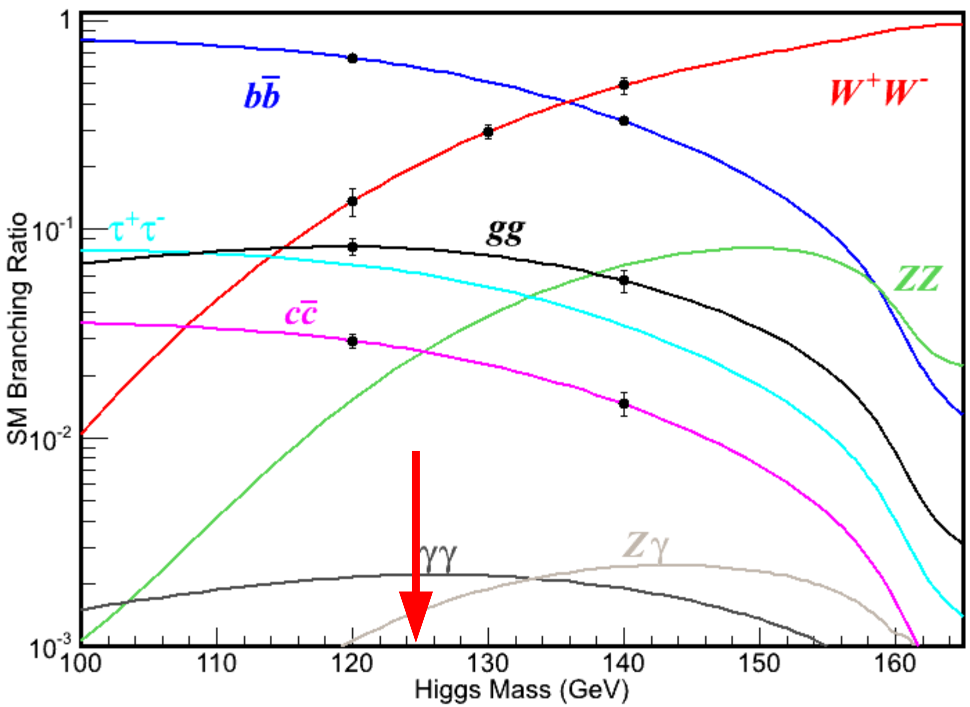
- A Linear Collider running at several energies will provide precise measurements of relevant Higgs couplings: Possibility to confirm the Higgs mechanism of the SM
- Precision matters: Detect deviations, for example due to extended Higgs sectors (SUSY,composite, ...):Expected on the 10% - 15% level in fermions,on the few % level in gauge bosons in typical Two-Higgs-Doublet models

Higgs BR in light Higgs mass region

Ecm=250 GeV, L=250 fb-1, Pol(e+,e-)=(+30%, -80%) or (-30%, +80%)(ww)



Just extrapolate to the other masses from the accuracies at Mh=120 GeV w/o considering efficiency differences (LCWS11)



Add H→WW*→4j full simulation results

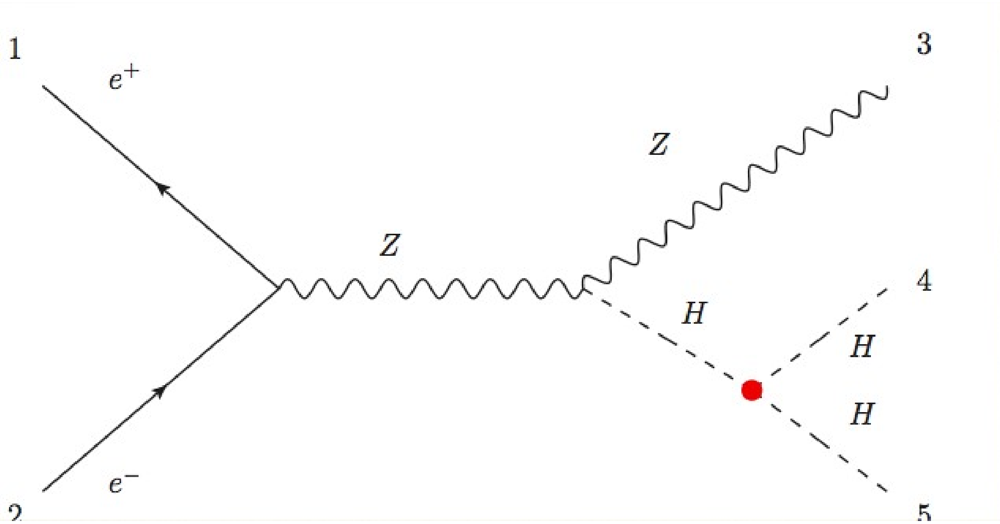
Mh=120 GeV (13.4%)

Mh=130 GeV (6.9%)

Expected to improve including lv+2j

σZH=2.5% uncertainty is also included

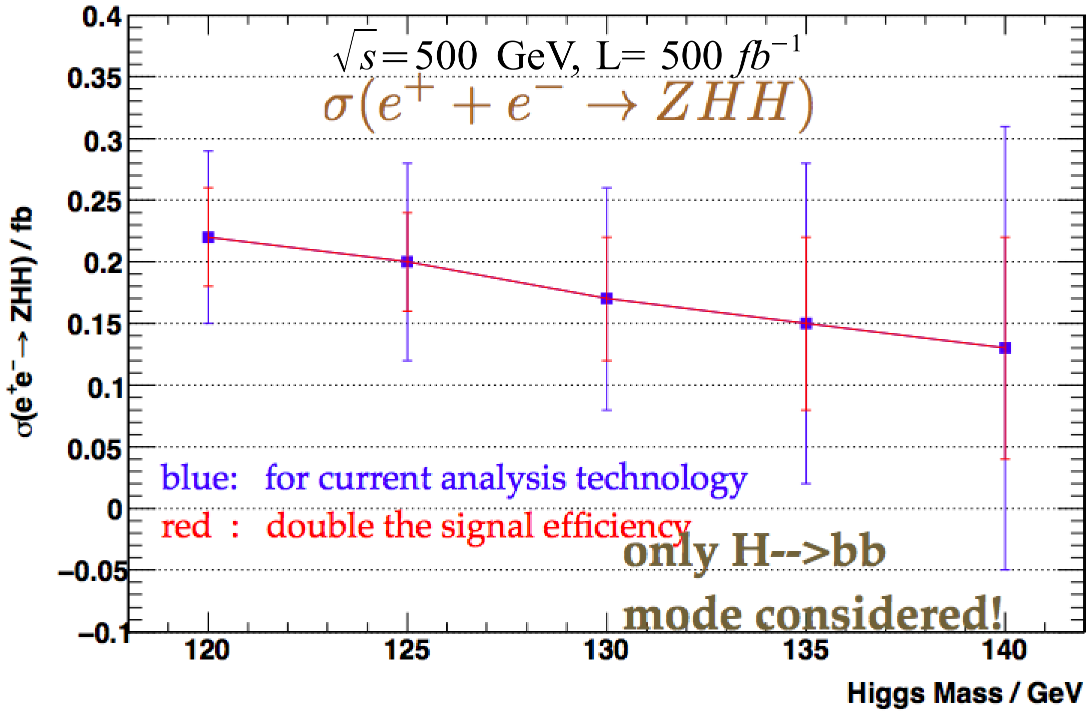
Higgs self coupling



Higgs potential
(after spontaneous symmetry breaking)

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

$$\lambda = \lambda_{SM} = \frac{m_H^2}{v} \text{ where } v = 246 \text{ GeV}$$



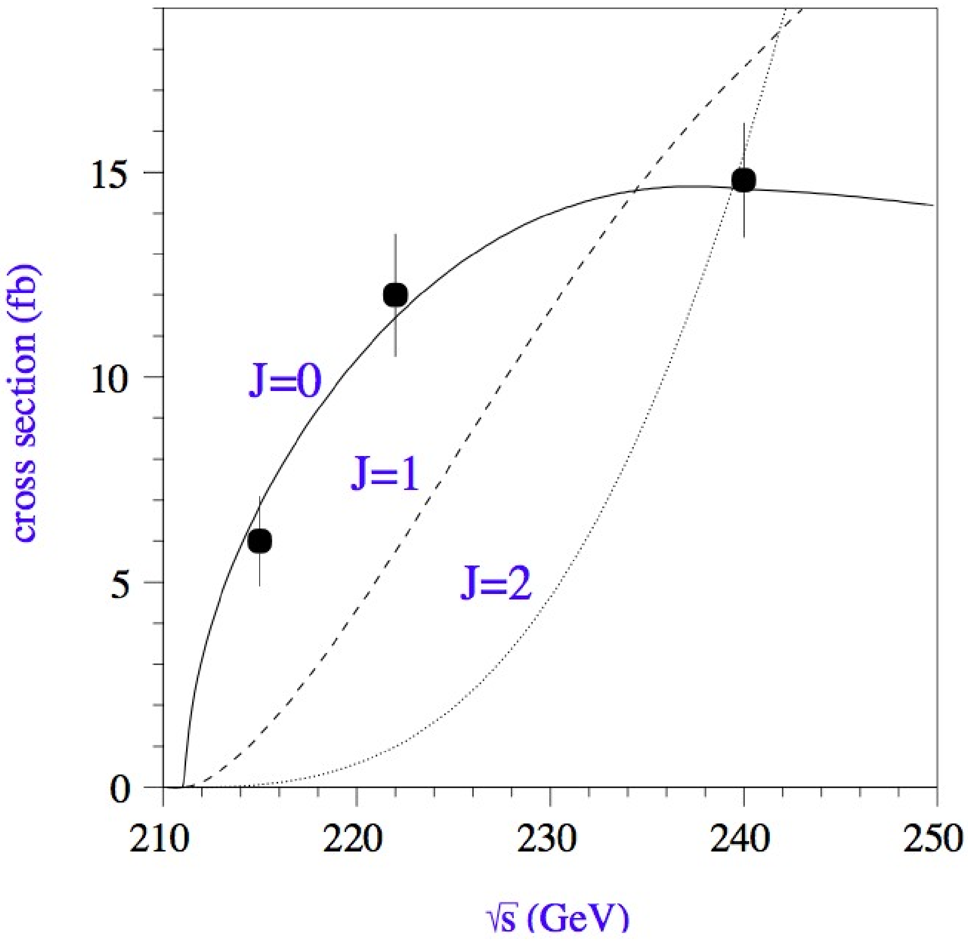
Current status:

About 40% uncertainty
For m_H = 125 GeV
(Full simulation!!!!)

Study aims at 20%

Extremely difficult analysis

Spin of the Higgs boson



“Almost trivial at LC'

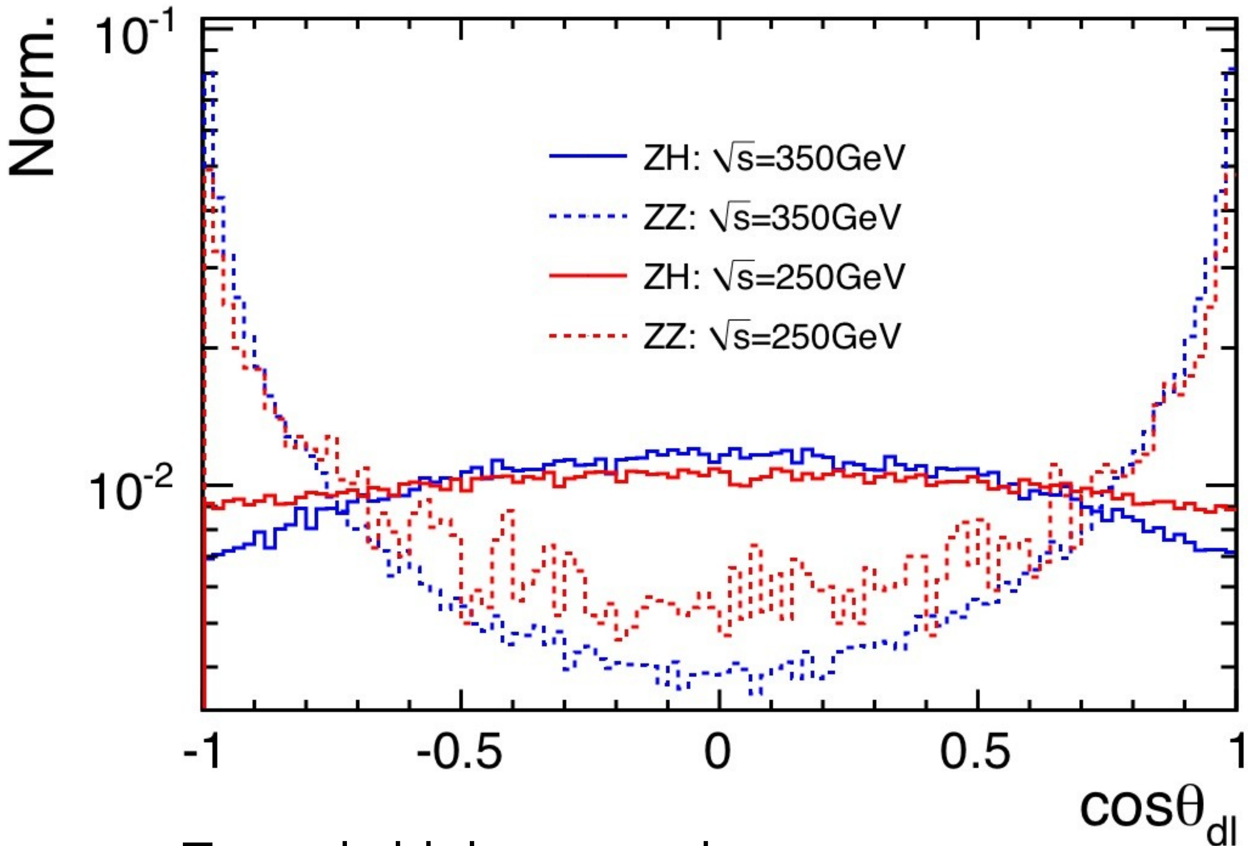
- Quick threshold scan
  ~20 fb^{-1}/point
  <=> Few months of running

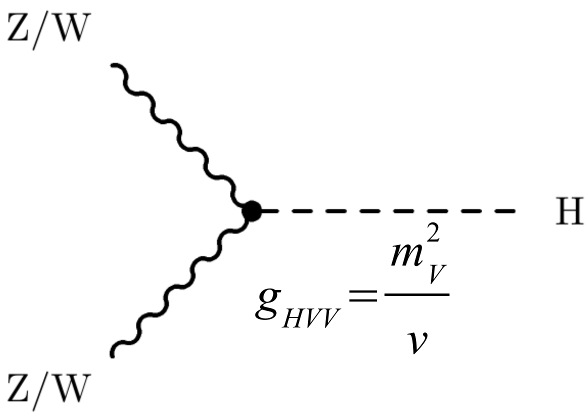
- Clear distinction different
  Spins

Spin determination not a unique to LC but the start of a program of a precise determination of Higgs quantum numbers

Higgs quantum numbers – CP via HVV

HZ and ZZ Production





SM implies:

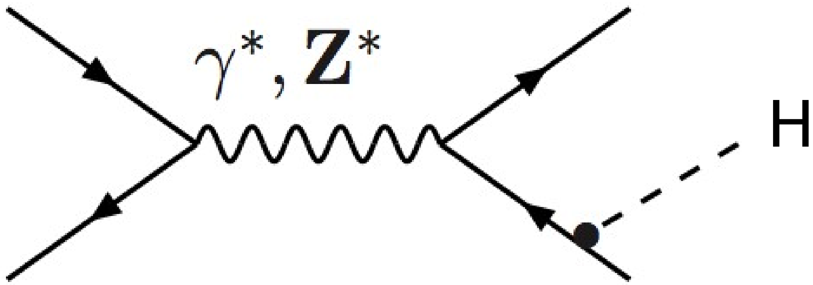
$J^{CP} = 0^{++}$

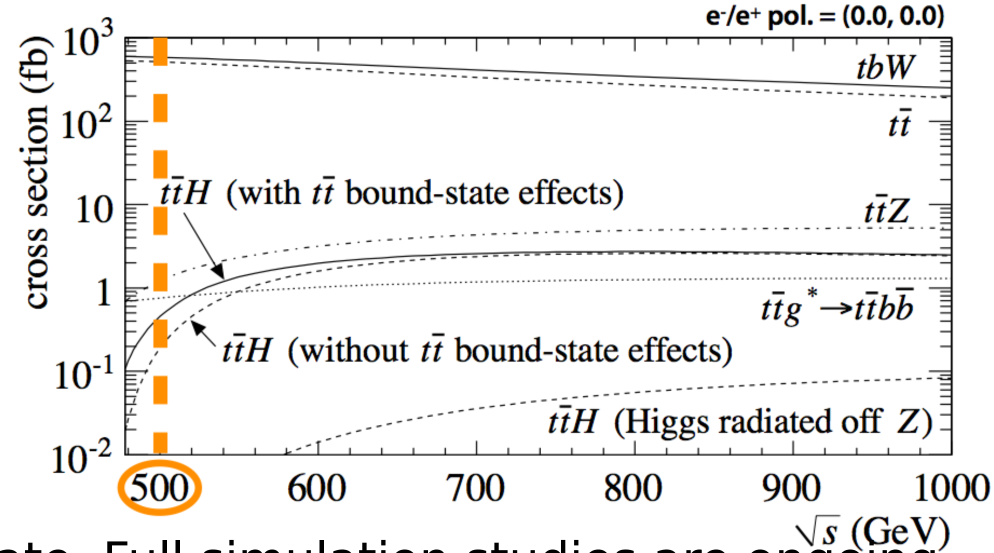
i.e. Projection of CP even state via HVV

Towards higher energies:
ZH: Signal: Z retrieves its **Goldstone** nature
ZZ: Z retrieves its photonic nature

- Coupling to HVV allows for confirmation of specific character of Higgs production within SM -> only test at small cms energies
- Need additional observables (and higher cms) to pin down CP quantum numbers of scalar boson

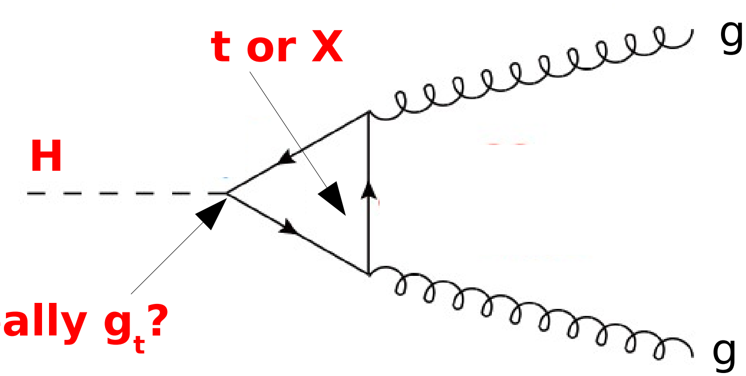
Top Yukawa coupling





- Challenging analysis: Multi jet final state, Full simulation studies are ongoing
  Current estimation on precision ~ 10%
- Off topic: Don't forget compositeness

... to be checked against: H->gg



LC is unique for this kind of test!!!

Good news ...

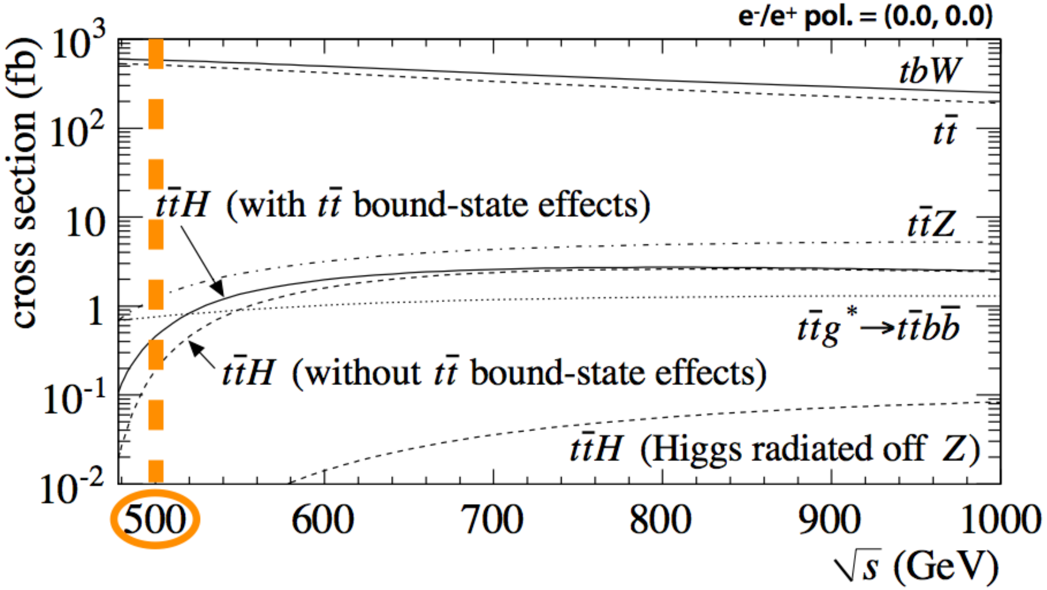
ILD DBD analysis at 1 TeV

$$\left(\frac{\Delta g_{ttH}}{g_{ttH}}\right)_{stat.} \approx 11.2\% \text{ for } P_{e^-} = -0.8, P_{e^+} = +0.2$$

$$\left(\frac{\Delta g_{ttH}}{g_{ttH}}\right)_{stat.} \approx 13.7\% \text{ for } P_{e^-} = +0.8, P_{e^+} = -0.2$$

Combined:

$$\left(\frac{\Delta g_{ttH}}{g_{ttH}}\right)_{stat.} \approx 7.5\%$$



ttH is about to become a measurement

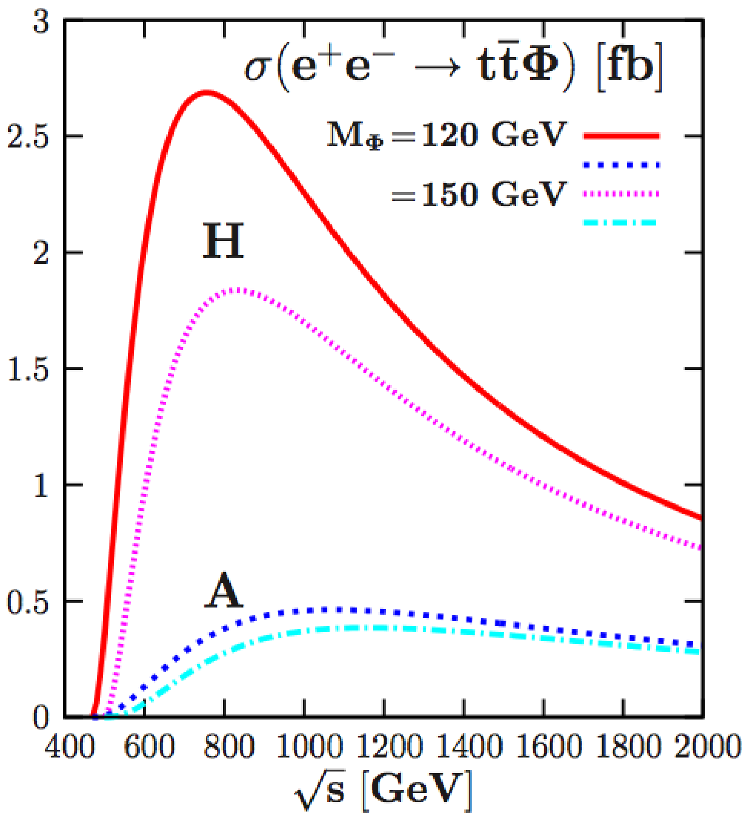
Please note: $\sigma_{1\ \mathrm{TeV}} \sim \sigma_{600\ \mathrm{GeV}}$

Higgs quantum numbers – CP via ttH

Godbole et al. LCWS2007

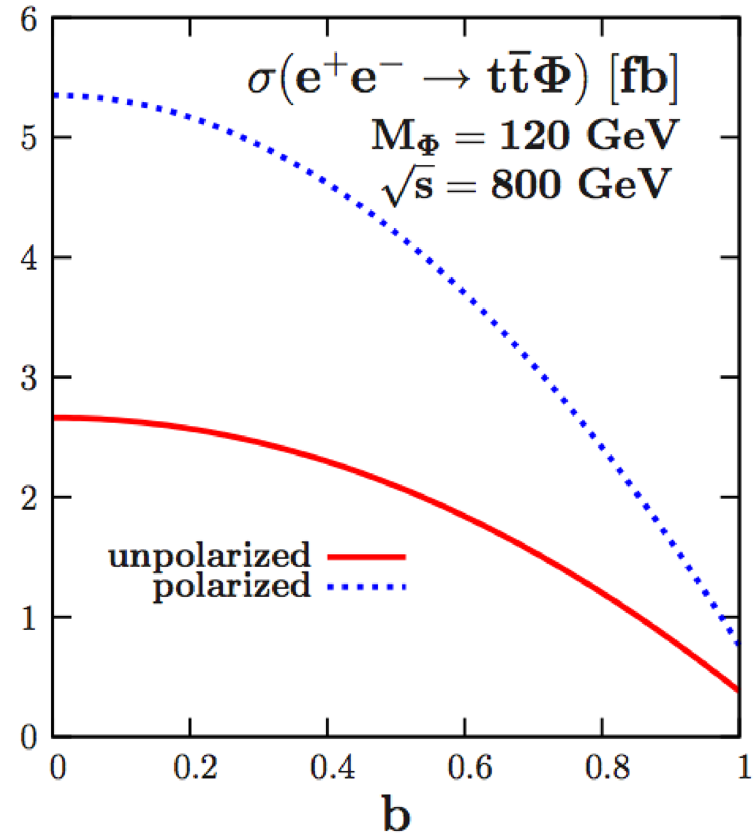
(A priori) Democratic coupling of top quark to CP odd and CP even scalar

Cross section unpolarised



Dramatic differences for
CP odd and CP even scalar

Cross section
with polarised beams (-0.8,0.6)

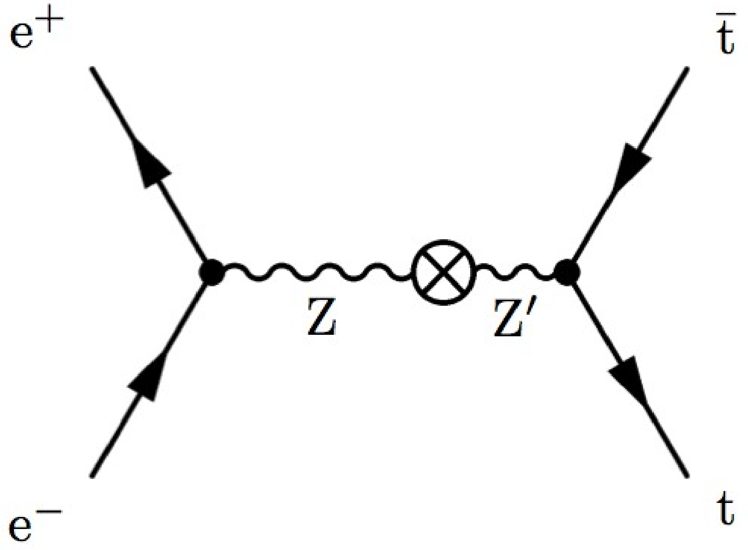


Sensitivity to CP odd admixture
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

Asymmetries in top quark production

The following are results of LAL/IFIC collab.



- Test of chiral structure at ttV vertex

- Need degrees of freedom to disentangle Z and γ

Sensitivity to Z' (?) and $(g\text{-}2)_t$ => scale of compositeness

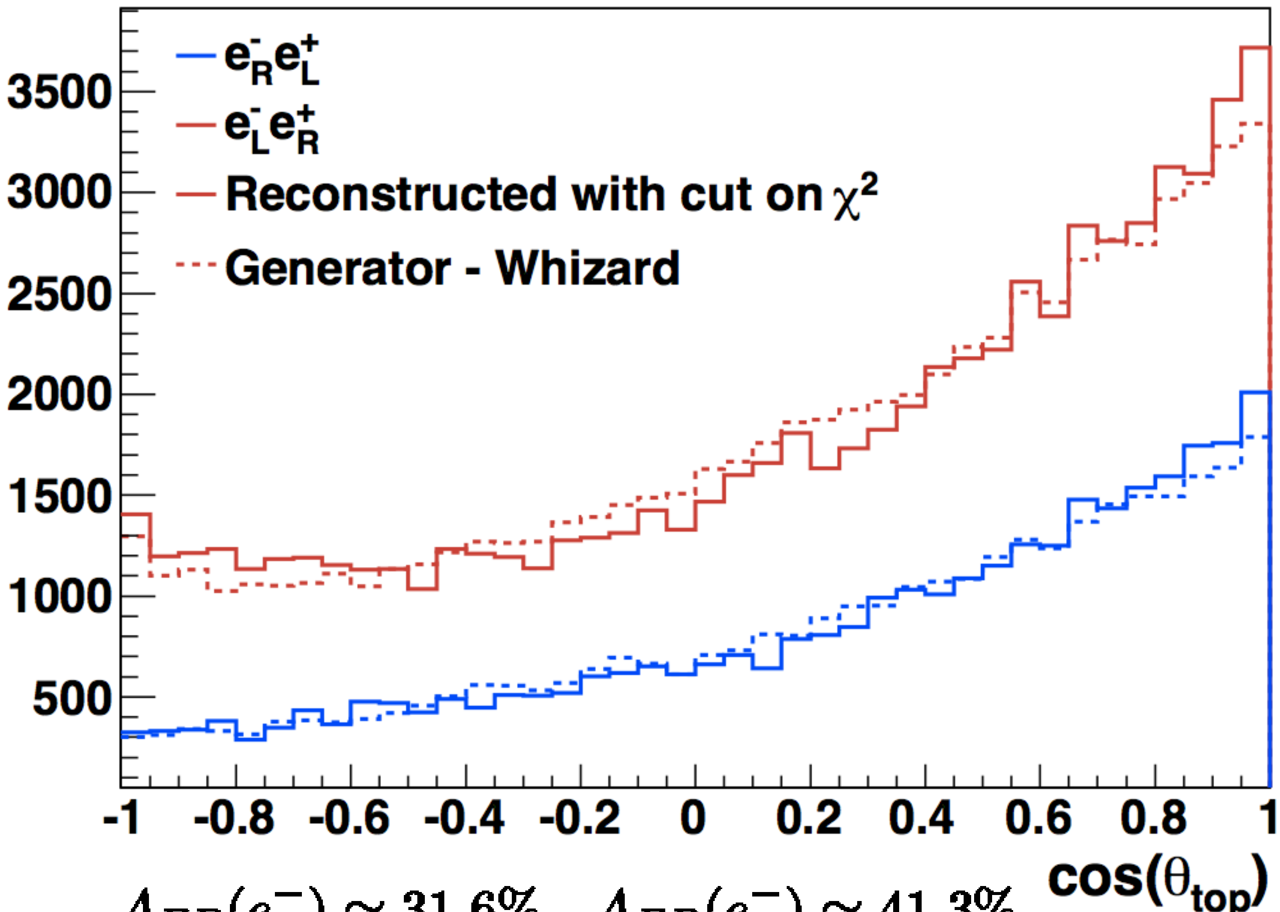
$$\Gamma_{\mu}^{ttV}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^{V}(k^2)+\gamma_5\widetilde{F}_{1A}^{V}(k^2)\right)+\frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^{V}(k^2)+\gamma_5\widetilde{F}_{2A}^{V}(k^2)\right)\right\}$$

$$\Gamma_{\mu}^{ttV}(k^2,q,\bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^{V}(k^2)+\gamma_5 F_{1A}^{V}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^{V}(k^2)+\gamma_5 F_{2A}^{V}(k^2)\right)\right\}$$

Top may be messenger to New Physics
Beam polarisation is essential

'Classical' observable A_{FB}

Not trivial to get clean measurement: Ambiguities in event reconstruction



$$A_{FB}(e^-_L) \approx 31.6\%, \quad A_{FB}(e^-_R) \approx 41.3\%$$

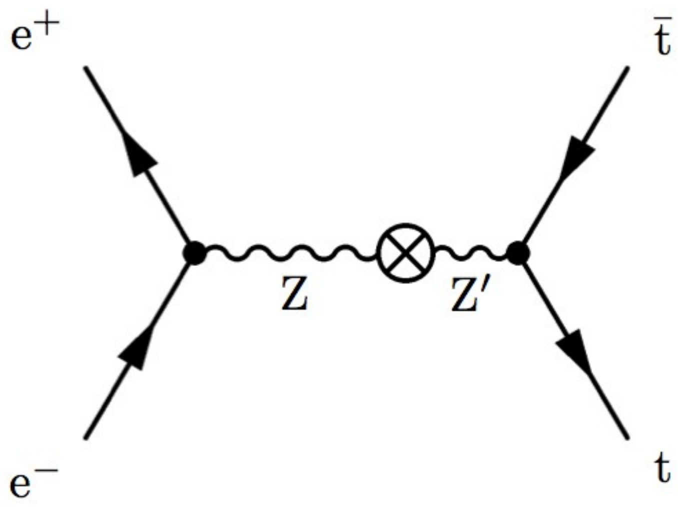
A priori A_{FB} itself relatively insensitive to beam polarisation

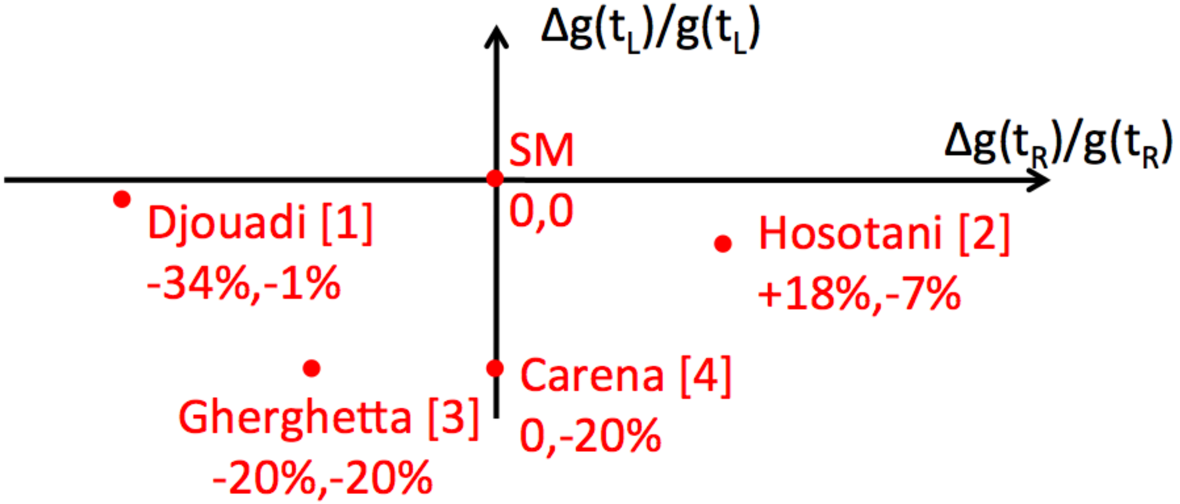
But one can create nearly purely left or right handed samples with at least one strongly polarised beams

=> Sensitivity to New Physics for right handed beams

Top quark and new physics

New physics modify electroweak couplings to Z





Example: RS models with extra dimensions

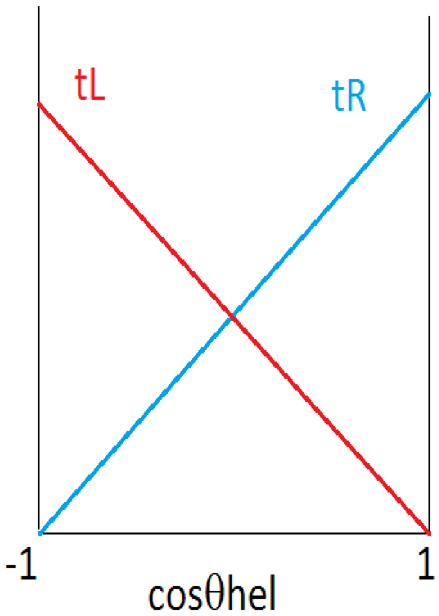
- Asymmetries predicted within Standard Model
  New physics modify these asymmetries
  ILC: 'Usual Forward-Backward Asymmetry AFB
  Left-Right asymmetries through polarised beams

Pe- / Pe+ (80% / 0)	ALR	AFBtR	AFBtL		QZtL	QZtR
stat. error	1.3%	1.2 %	1.4 %		1.0 %	1.9 %

New observable A_{hel}

Differential decay rate in <u>top rest frame:</u>

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_\ell} = \frac{1+\lambda_t cos\theta_\ell}{2} \quad \text{with } \lambda_t = 1 \text{ for } t_R \text{ and } \lambda_t = -1 \text{ for } t_L$$



Forward backward asymmetry **Ahel**

Slope measures fraction of tR,L in sample

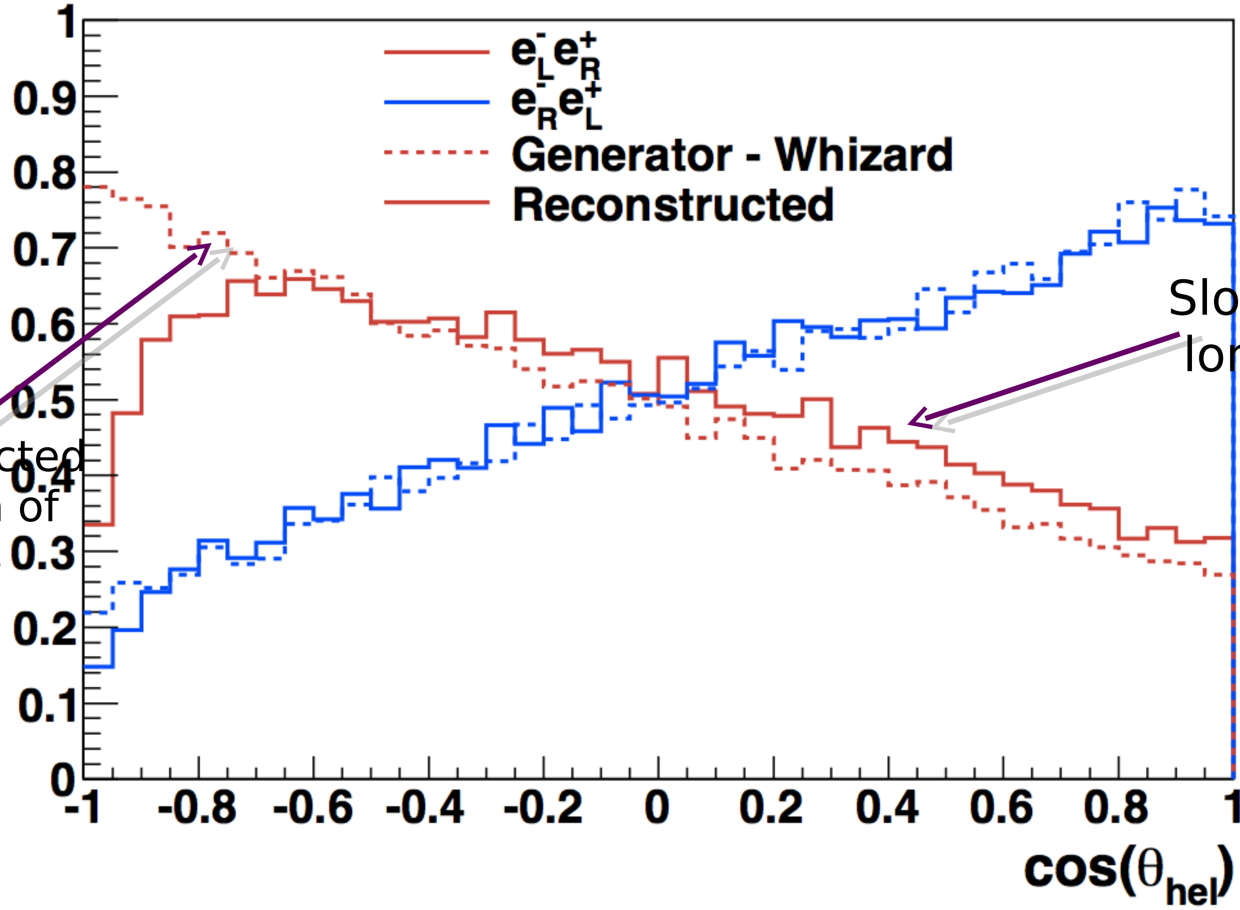
=>Couplings of top quarks to vector bosons

Define: $A_{hel,L}$ for $e^-_L e^+_R$ and $A_{hel,R}$ for $e^-_R e^+_L$

$\Rightarrow$ Set of four observables
σ_L, σ_R instead of A_{LR} $A_{hel,R}$, $A_{hel,L}$
to determine unknowns $g_\gamma(t_L), g_\gamma(t_R), g_Z(t_L), g_Z(t_R)$

Results on A_{hel}

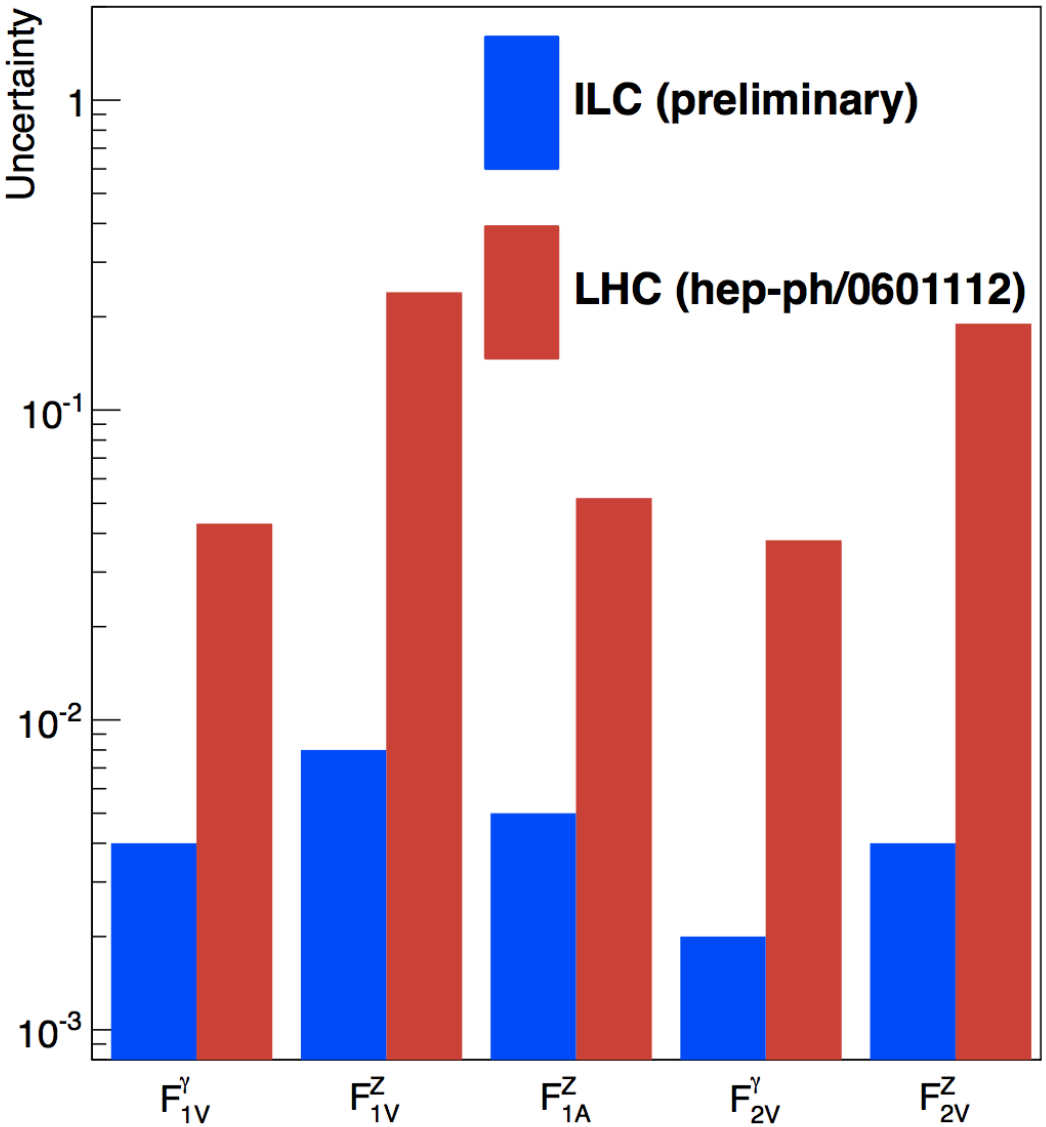
Results with Whizard and full ILD simulation at √s = 500 GeV



Region affected by rejection of soft leptons

Slope stable over long range in cos θ

Form factors: Comparison ILC <-> LHC



- Independent determination of Form Factors
  Use AFB, s and Ahel for two beam polarisations

- Spectacular improvement By ILC (Factor 10-100)

- LHC can measure directly ttγ and ttZ but ILC can disentangle

ILC Beam polarisation is essential

Preliminary interpretation shows that results offer sensitivity versus M_{KK} up to 48 TeV and compositeness scale of top up to 100 TeV

Summary and Outlook

- (I)LC offers possibility to fully explore known electroweak sector and provides
  Great sensitivity for physics BSM

- Precise tomography of the new boson, kind of matter, at a future Linear Collider
  Model independent determination of gHZZ couplings
  Precise determination of couplings to W, c, b, t, tau, (mu)
  H-> gg
  Higgs self coupling
  Spin and CP quantum numbers

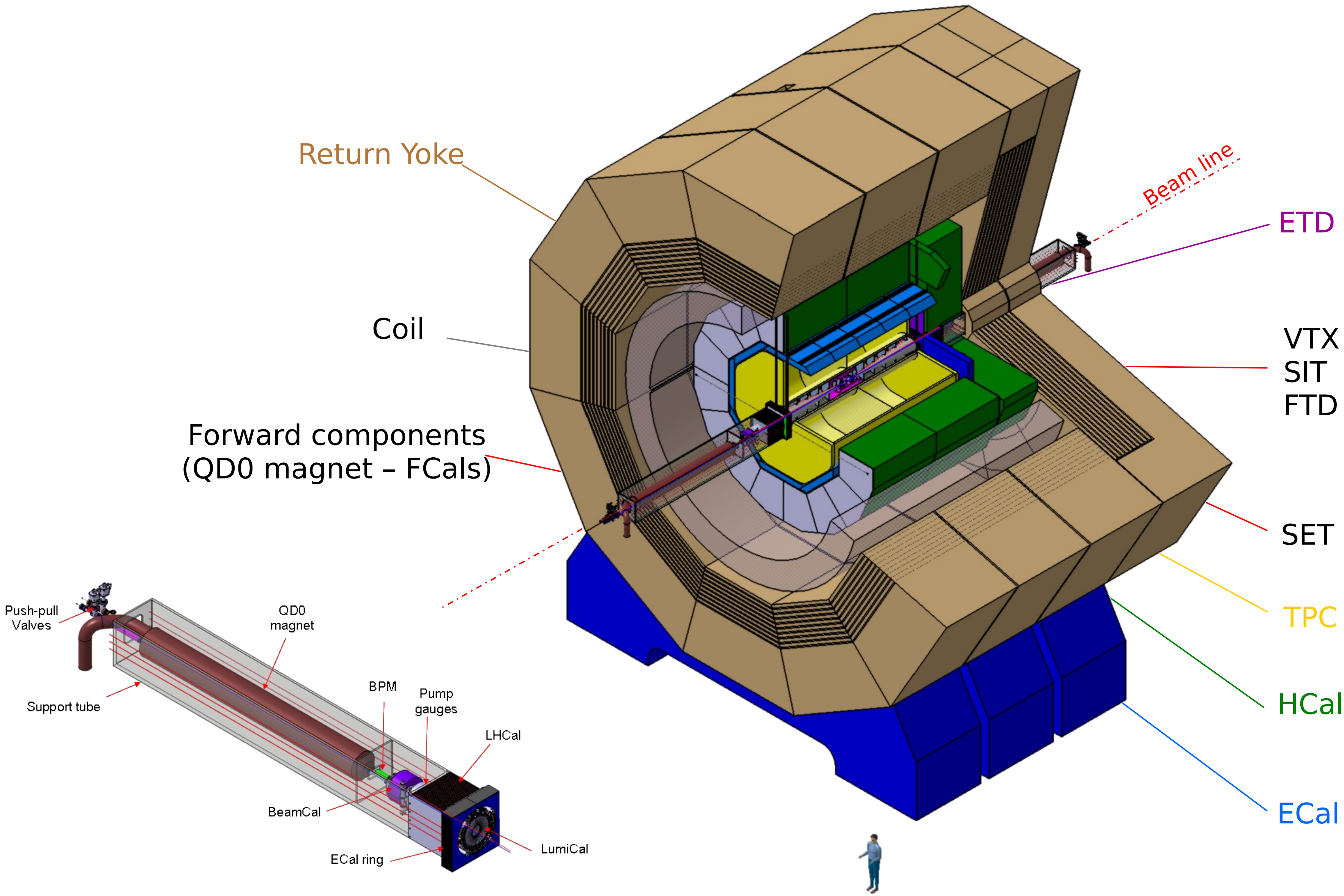
- Very rich program of top quark physics (should be second pillar of ILC program!)
  Disentangling of couplings of t to gamma and Z measurement of
  => Great reach to physics above 1 TeV

- Role of beam polarisation
  Less important for HZ at threshold
  → Dominant background is ZZ
  → Efficient cuts agains WW background
  Situation for ZHH unclear (remarks from audience welcomed) but I am worried
  that it first has other problems to be overcome

  Essential for tt (asymmetries)
  Samples can be enriched with tops of given helicity
  New physics may alter couplings to left and right handed tops
  Essential for ttH to determine quantum numbers of Higgs boson

Backup Slides

LC Detector proposal – e.g. ILD



Efficient software environment

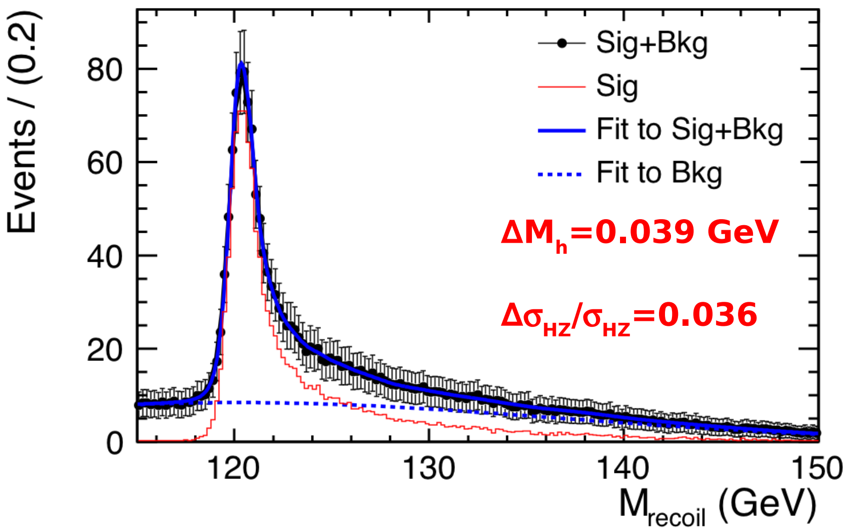
→ A lot of studies based on full detector simulation

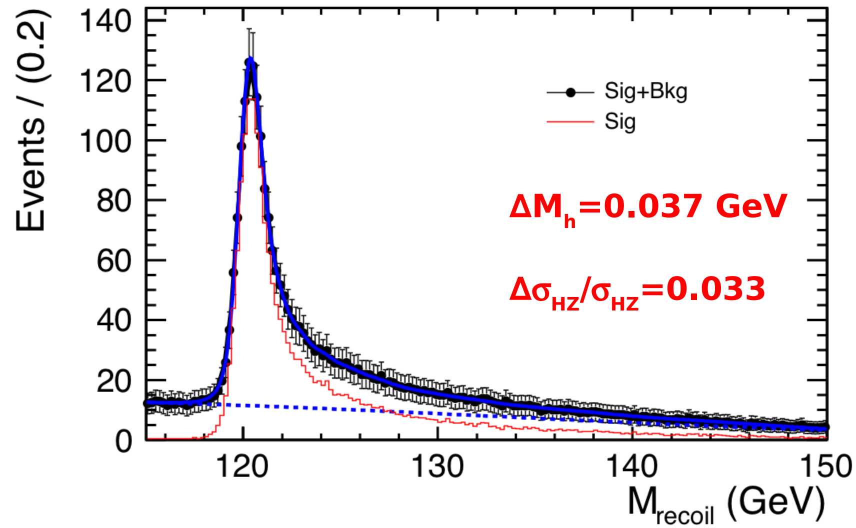
Validated by intensive detector R&D effort

Model Independent ↔ Model Dependant Analysis

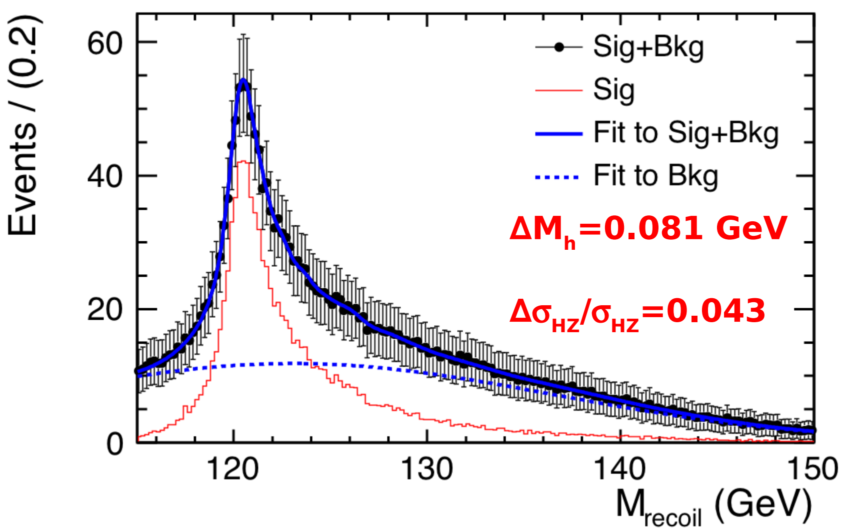
Model dependency by exploiting track activity from SM Higgs decays

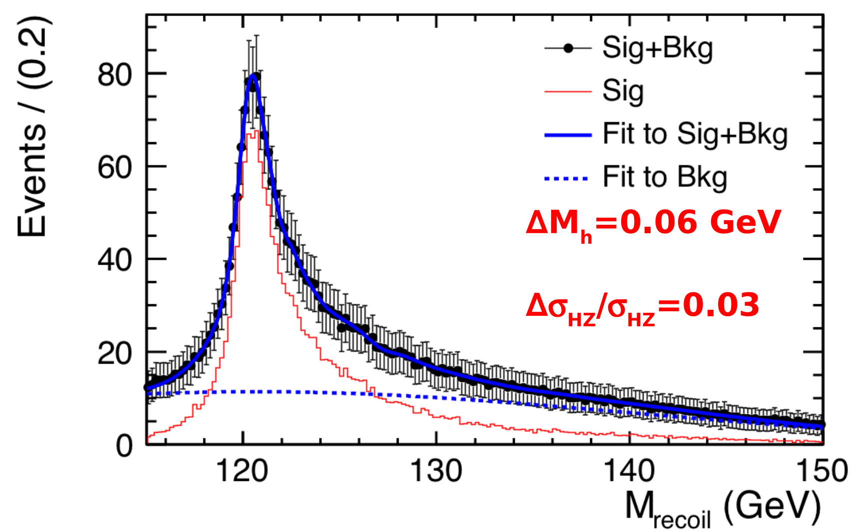
Muon Channel





Electron Channel

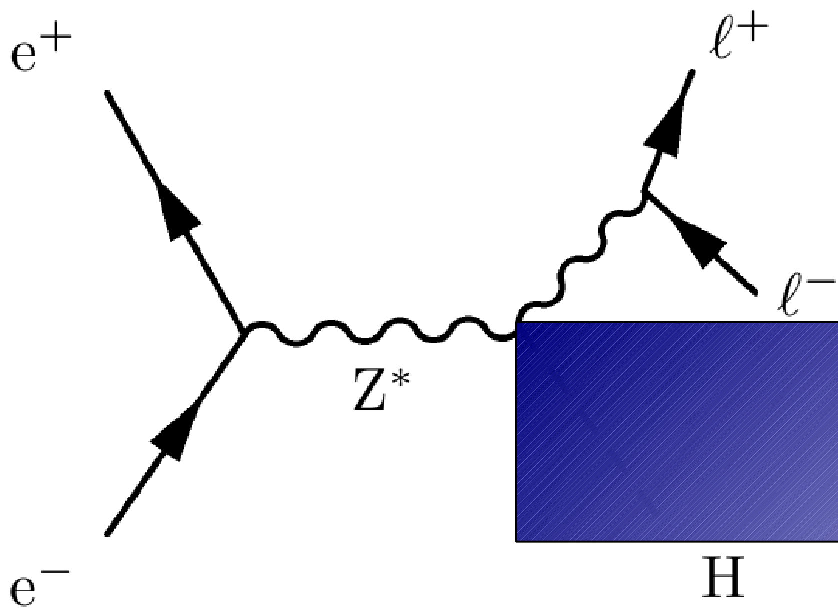




Improvements in S/N by specific analyses

Why golden plated Channel?

Higgs Mass and ZZH coupling by **Model Independent** measurement



Well measurable decay leptons from Z

μ Pairs, e pairs

No assumption on Higgs decay modes

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

A compilation of expected precisions on couplings

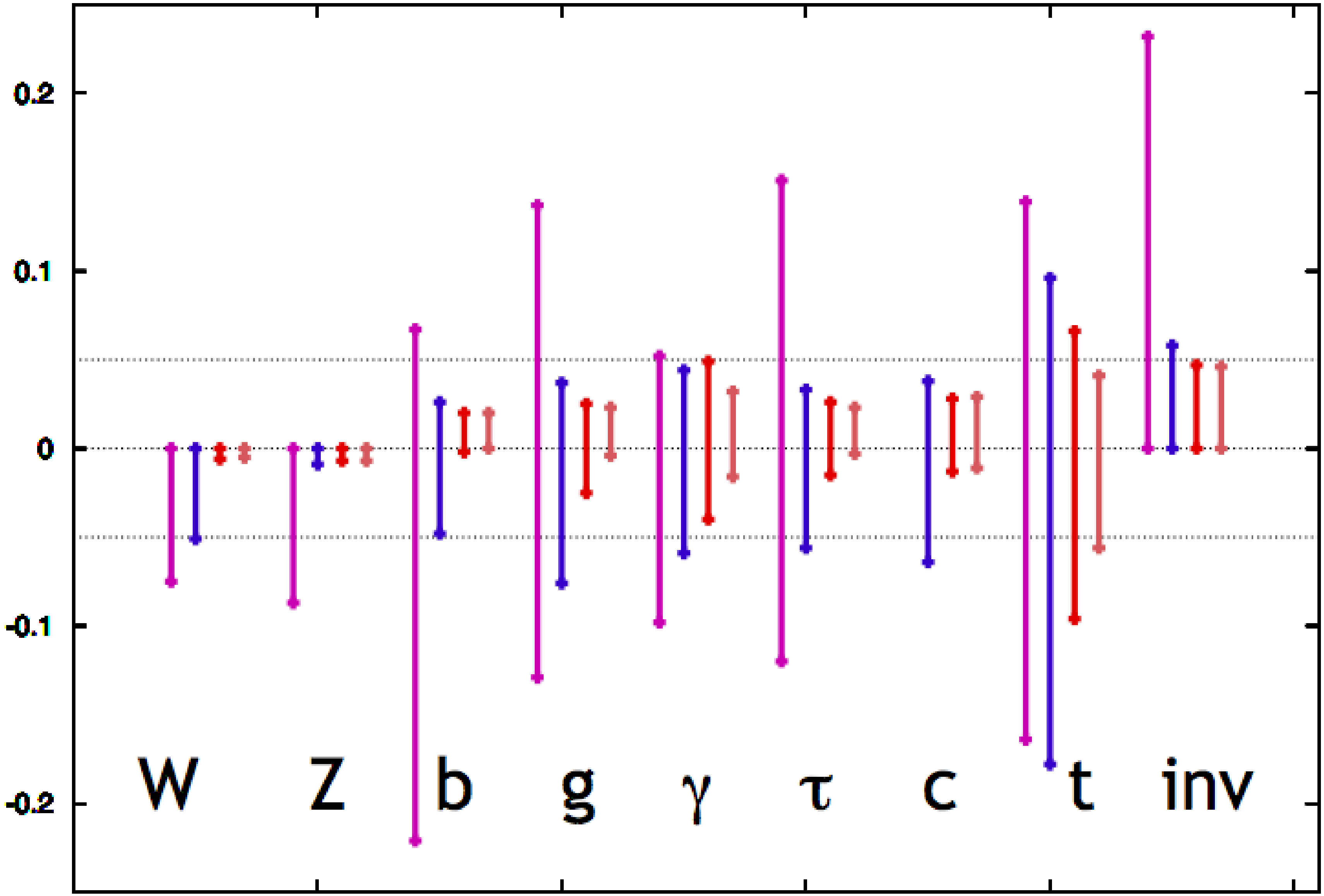
From M. Peskin: arxiv:1207.2516v1 based on studies of Japanese ILD group

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

ILC at 500 GeV with 500 fb^{-1}	
$\sigma(Zh) \cdot BR(b\bar{b})$	0.016
$\sigma(Zh) \cdot BR(c\bar{c})$	0.11
$\sigma(Zh) \cdot BR(gg)$	0.13
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.07
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.36
$\sigma(WW) \cdot BR(b\bar{b})$	0.006
$\sigma(WW) \cdot BR(c\bar{c})$	0.04
$\sigma(WW) \cdot BR(gg)$	0.049
$\sigma(WW) \cdot BR(WW)$	0.03
$\sigma(WW) \cdot BR(\tau^+\tau^-)$	0.05
$\sigma(WW) \cdot BR(\gamma\gamma)$	0.28
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	0.2

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
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	0.12

$g(hAA)/g(hAA)|_{SM}-1$ LHC/HLC/ILC/ILCTeV



Background Rejection

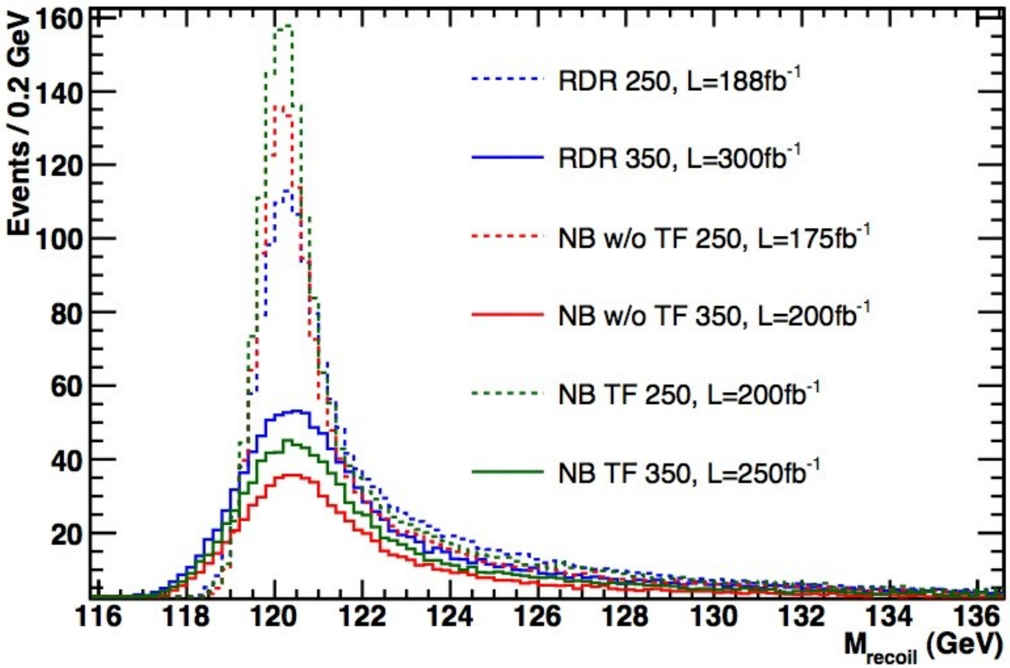
ILD

$P_{T,dl} > 20$ 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

- Relaxed constraint on dilepton Mass
- Cuts more closely 'tailored' to background

Signal/Background > 30%

Fast Simulation Tool for Higgs-strahlung – Fast reaction to changing beam parameters



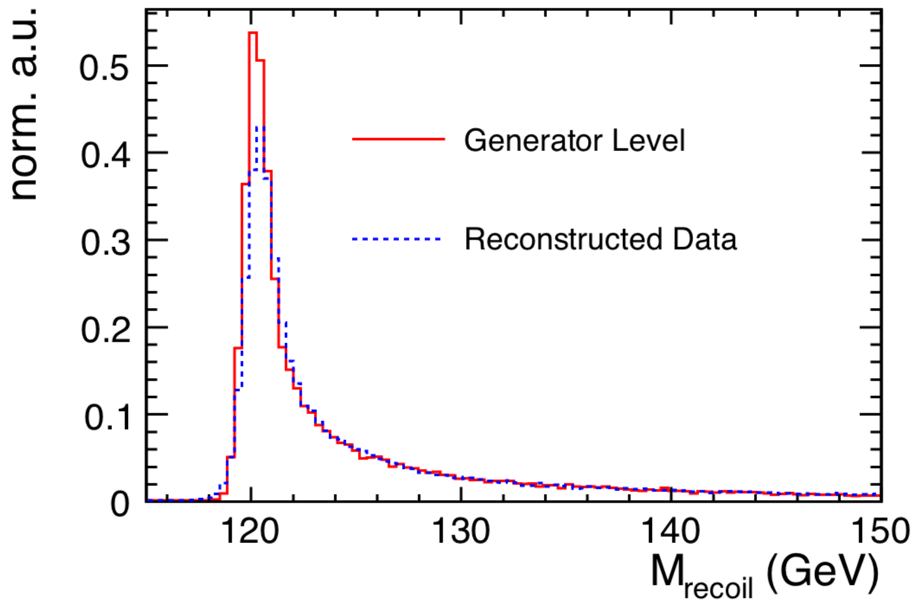
Beam Par	$\mathcal{L}_{\text{int}}$ (fb^{-1})	ϵ	S/B	M_H (GeV)	σ (fb) ($\delta\sigma/\sigma$)
RDR 250	188	55%	62%	120.001 ± 0.043	11.63 ± 0.45 (3.9%)
RDR 350	300	51%	92%	120.010 ± 0.087	7.13 ± 0.28 (4.0%)
NB w/o TF 250	175	61%	62%	120.002 ± 0.032	11.67 ± 0.42 (3.6%)
NB w/o TF 350	200	52%	84%	120.003 ± 0.106	7.09 ± 0.35 (4.9%)
NB w/ TF 250	200	63%	59%	120.002 ± 0.029	11.68 ± 0.40 (3.4%)
NB w/ TF 350	250	51%	89%	120.005 ± 0.093	7.09 ± 0.31 (4.4%)

Table 6: Results based on NB beam parameters, assuming a beam polarization of (e^- : -80%, e^+ : $+30\%$), comparing with those of RDR beam parameters.

Currently best "fast" reaction tool for ILC studies – Extendable?
Replies to "urgently" needed studies (according to benchmark note)

Influence of Accelerator Parameters

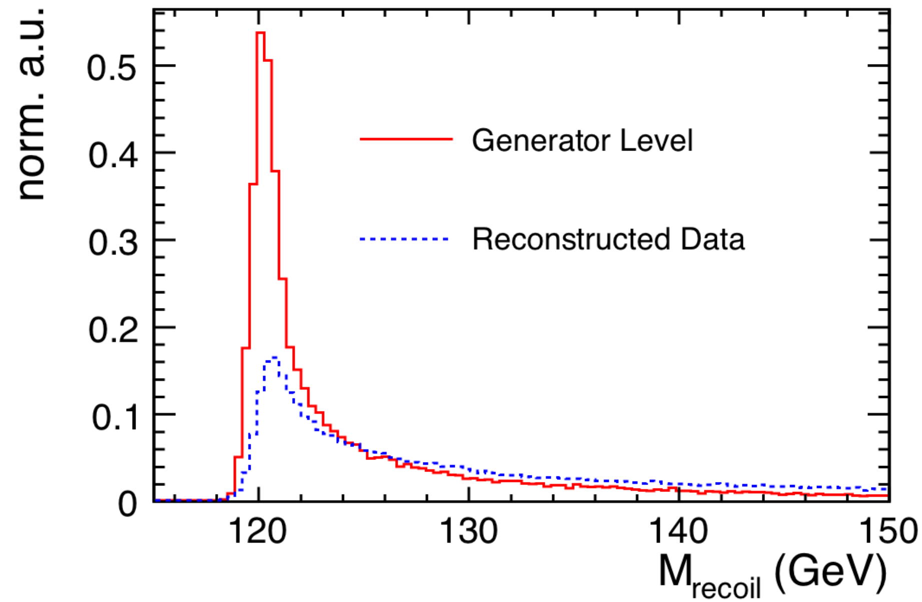
Muon Channel



ΔM_{tot} = 650 MeV

$\Delta M_{mach.}$ = 560 MeV $\Delta M_{det.}$ = 330 MeV

Electron Channel



ΔM_{tot} = 750 MeV

$\Delta M_{mach.}$ = 560 MeV $\Delta M_{det.}$ = 500 MeV

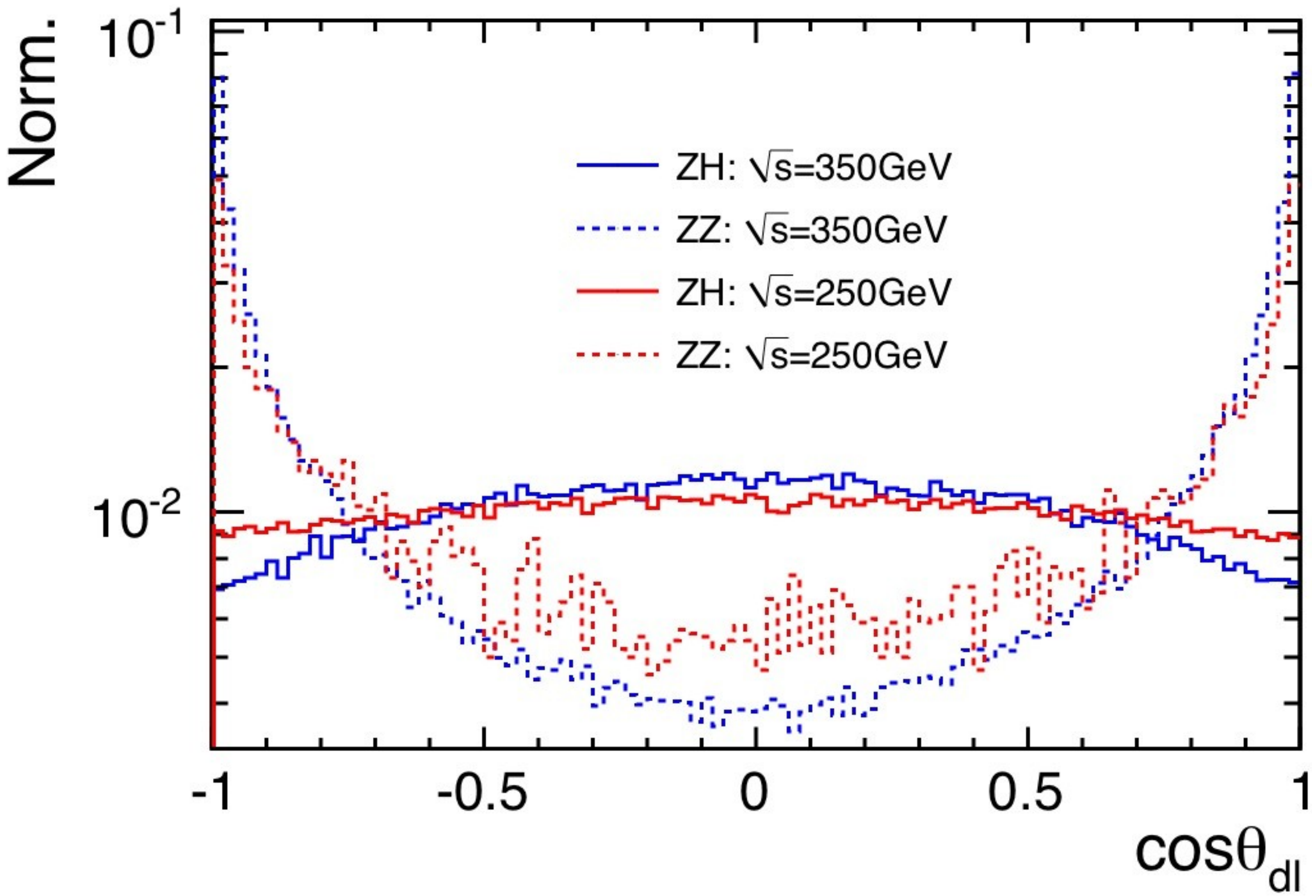
Uncertainties of incoming beams are dominant source of Statistical Error

(even in Electron Channel)

Higgs-strahlung is key process for optimisation of ILC design

Angular Distributions for 250 and 350 GeV

HZ and ZZ Background



Better Signal/Background Separation at higher Energies

ZH Signal: Z retrieves its Goldstone nature
ZZ Background: Z retrieves its photonic nature

H→WW* study

- ννH, H→WW* at 1 TeV as DBD benchmark process

H→WW* →4j at Ecm=250 GeV , L=250 fb-1, (e+, e-)=(-0.3, +0.8)

1. Forced 4 jets clustering
2. Jet paring with M_{jj} as one on-shell W and M_{4j} as H

$$\chi^2 = \left(\frac{M_W^{Rec} - M_W}{\sigma_W}\right)^2 + \left(\frac{M_H^{Rec} - M_H}{\sigma_H}\right)^2$$

Mh=120 and 130 GeV
are studied from LHC results
WW→lν+2j is next target

$e^+e^- \rightarrow \nu_e\overline{\nu_e}H, H \rightarrow WW^*$