LC capabilities for a Higgs at 125 GeV

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

LHC@TSP
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We are living in the post-discovery area of the Higgs

Congratulations LHC

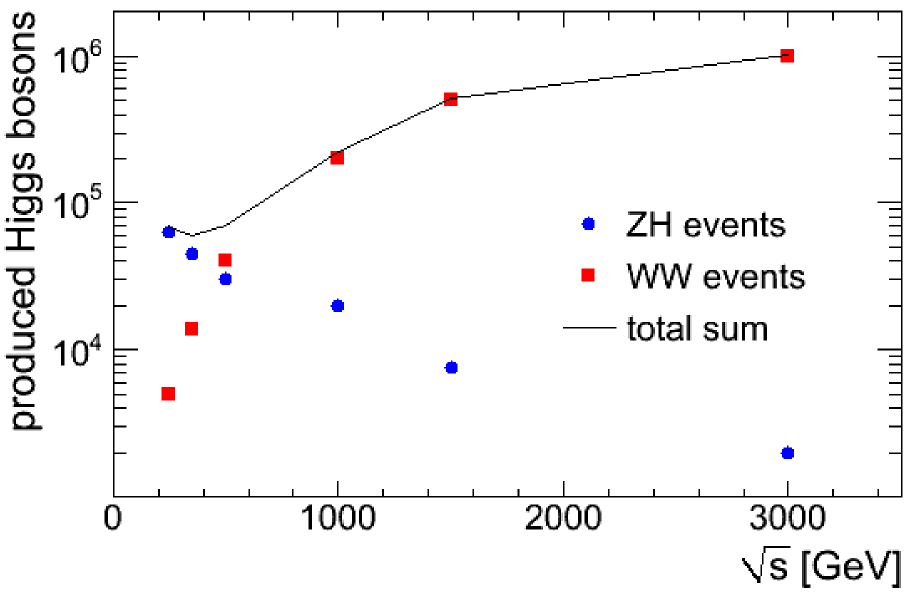
A giant on the shoulder of giants

Linear Colliders - Full Exploration of the Higgs Sector

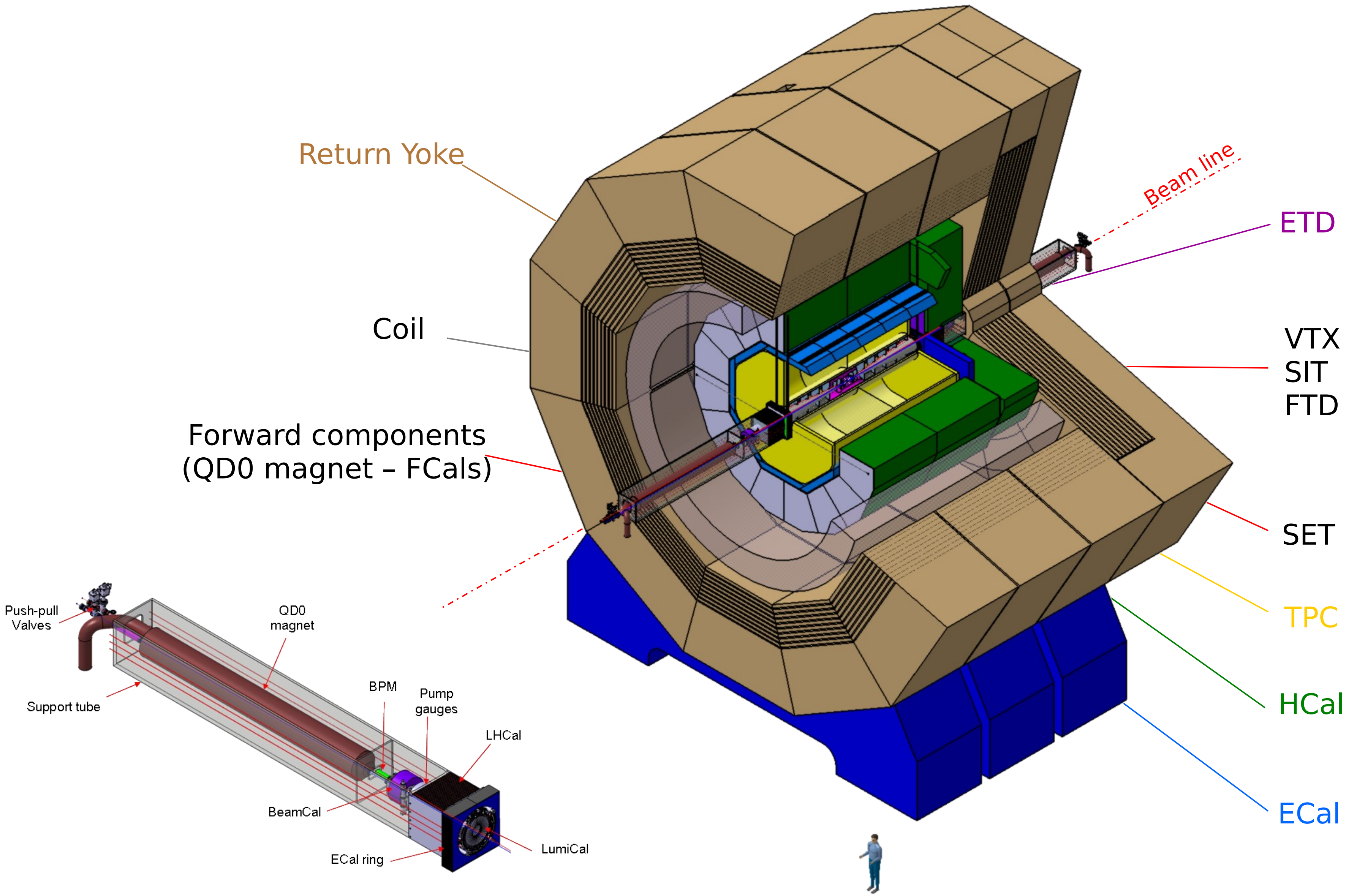
- Two accelerator concepts: ILC and CLIC
  - ILC: Proven superconducting RF structures, 500 GeV with upgrade to 1 TeV Physics currently studied in the range from 250 GeV to 1 TeV
  - CLIC: Two-beam acceleration concept, still in development, energy stages from 500 GeV to 3 TeV, Physics currently studied in the range from 350 GeV to 3 TeV

- High number of Higgs bosons at all energies: Exploit precise reconstruction at lower energies, high statistics and access to sub-leading channels at higher energies

For a mass of 126 GeV, a wide range of decays and couplings are accessible at a LC



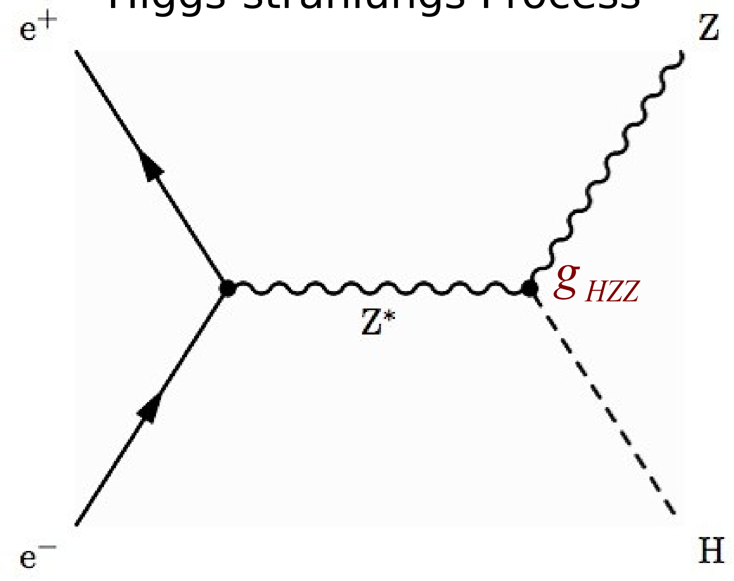
LC Detector proposal – e.g. ILD



Efficient software environment
→ A lot of studies based on full detector simulation
Validated by intensive detector R&D effort

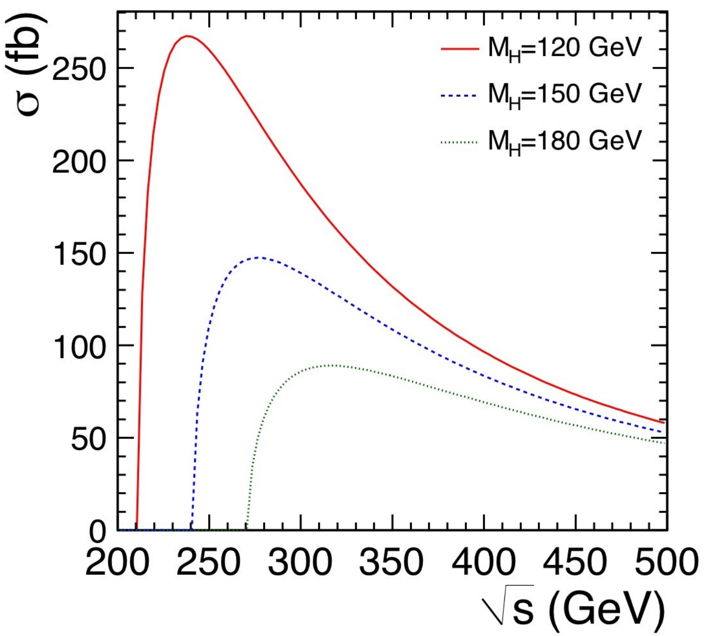
Higgs-strahlung Cross Section and Higgs Mass at LC

Higgs-strahlungs Process



Golden Plated Channel at e^+e^- Colliders

Sensitive to coupling at HZZ Vertex



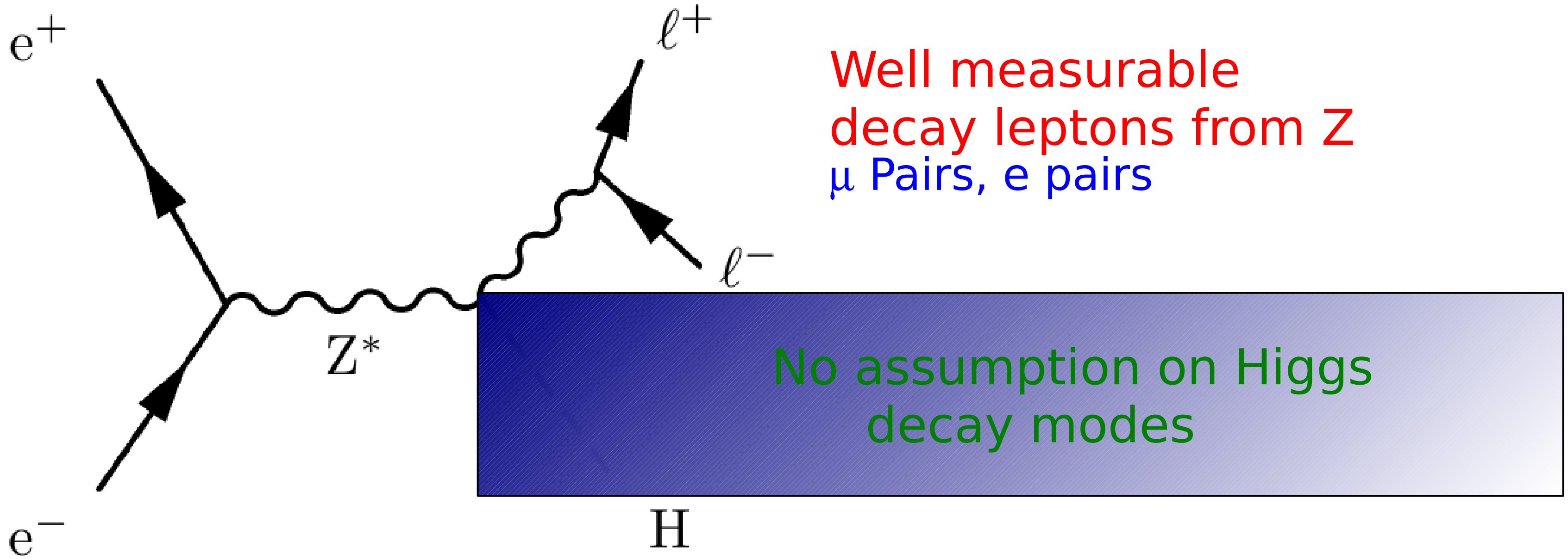
Production Cross Section of SM Higgs Boson

Maximal at HZ production threshold

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

Why golden plated Channel?

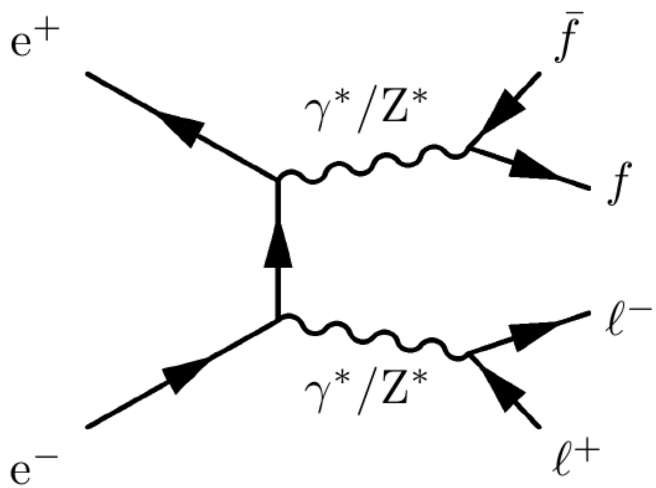
Higgs Mass and ZZH coupling by
Model Independent
measurement

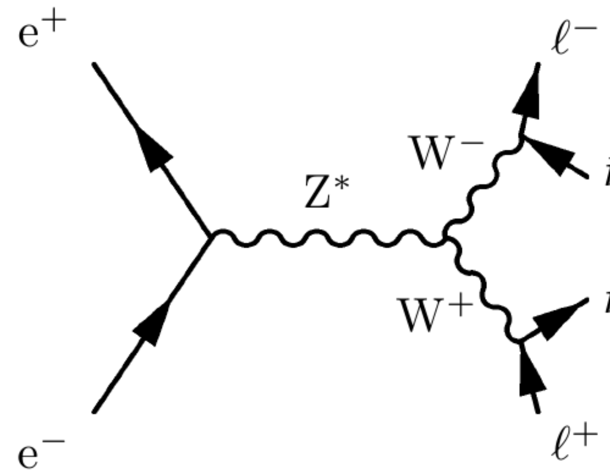


Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

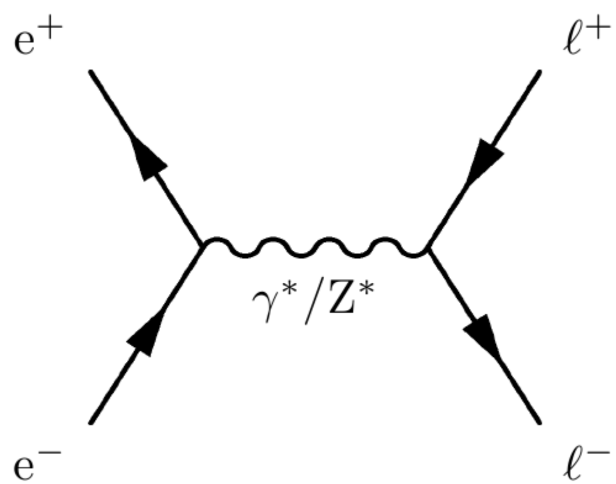
(Main) Background Processes

Boson Pair Production

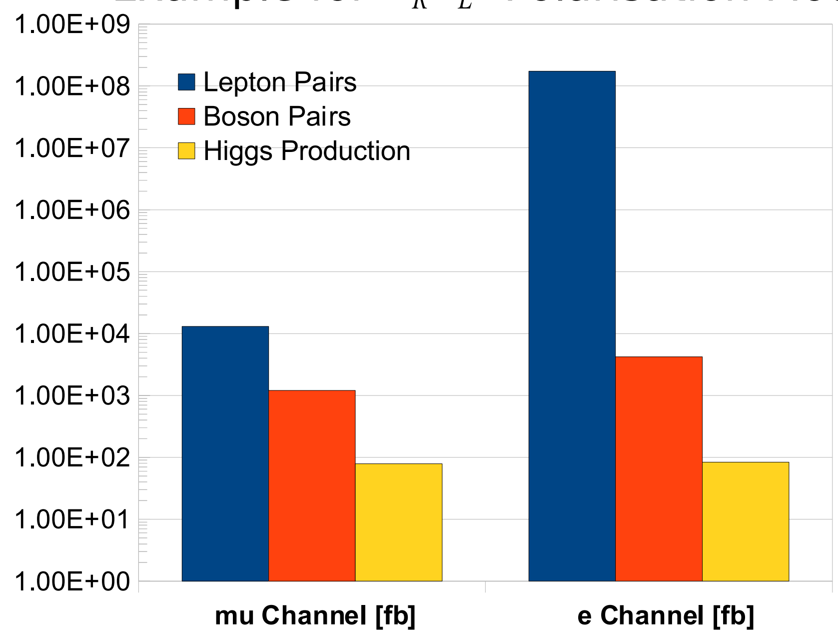




Lepton Pair Production



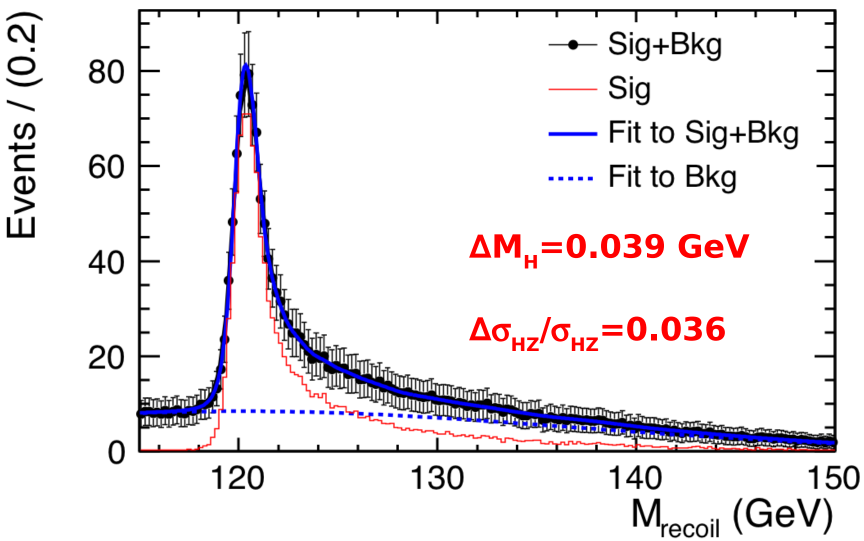
Example for $e^-_R e^+_L$ Polarisation Mode



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

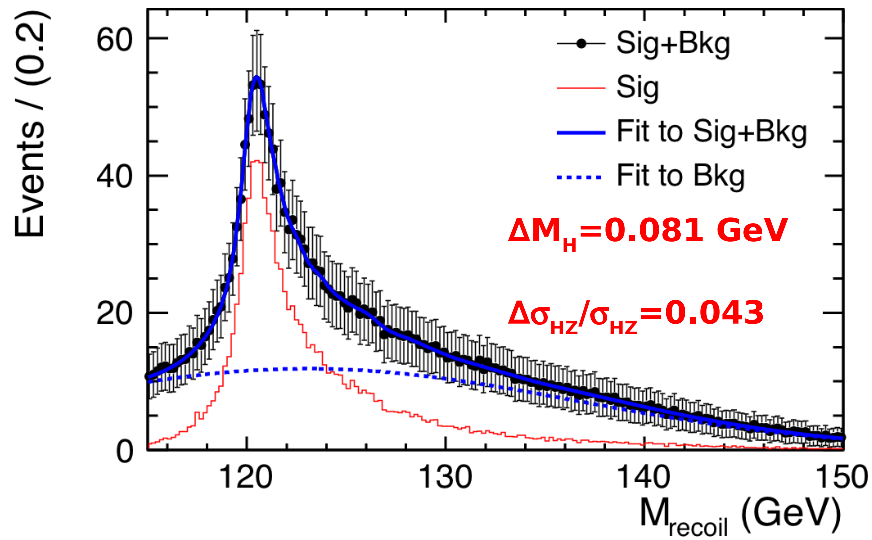
Results (see also arXiv:1202.1439)

Muon Channel



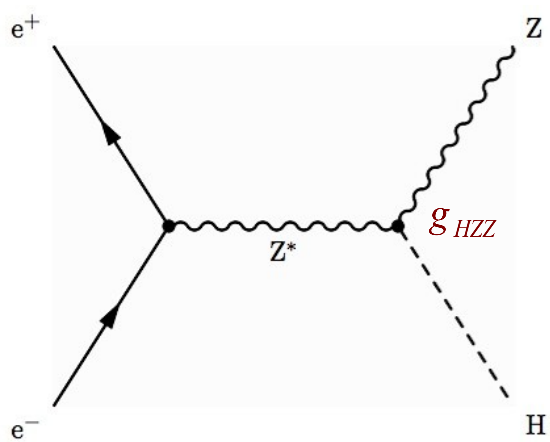
Very Precise Measurement
S/B = 8 in Peak Region

Electron Channel



Less Precise
Bremsstrahlung in detector material

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



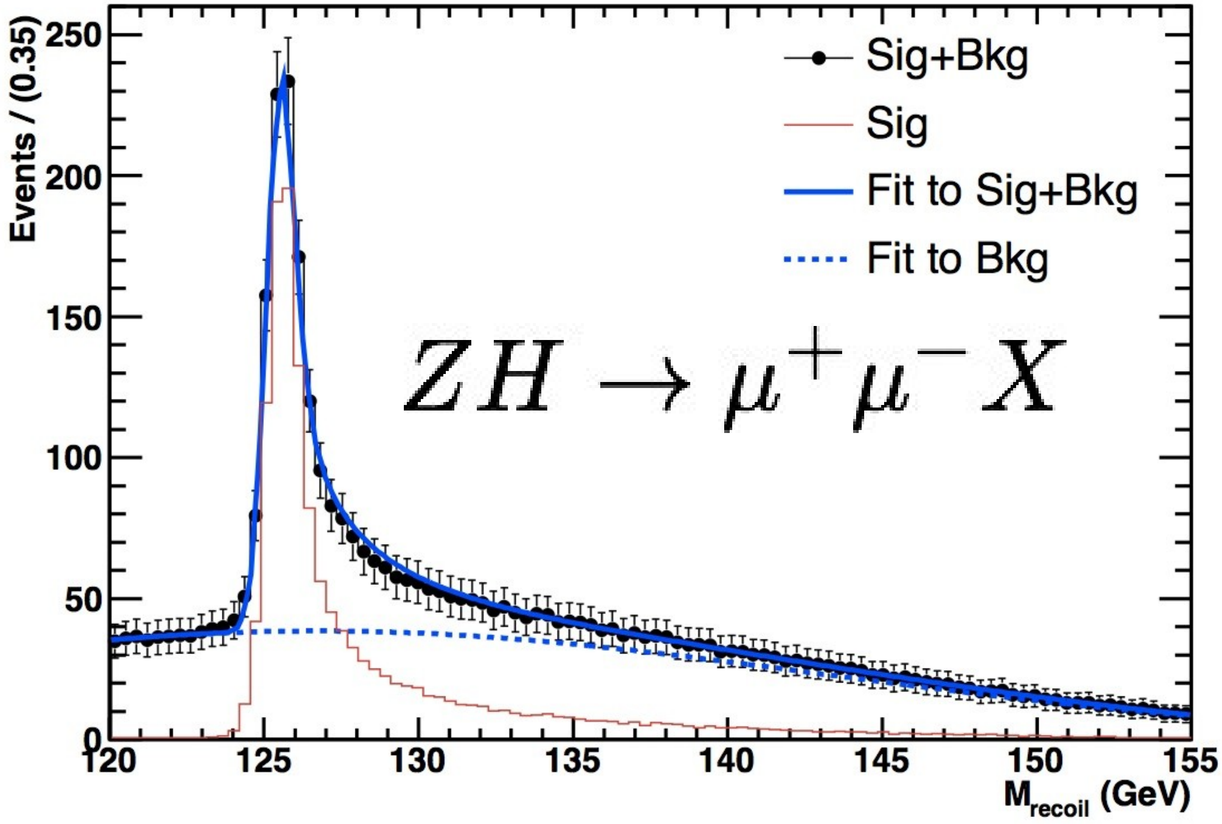
$$\sigma_{HZ} \sim g^2_{HZZ}$$

⇒ Precision in g_{HZZ} coupling 1-2%

Sensitivity to 15% deviations
SM prediction of cross section

Study for Mh = 125.3 GeV – SM Higgs

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



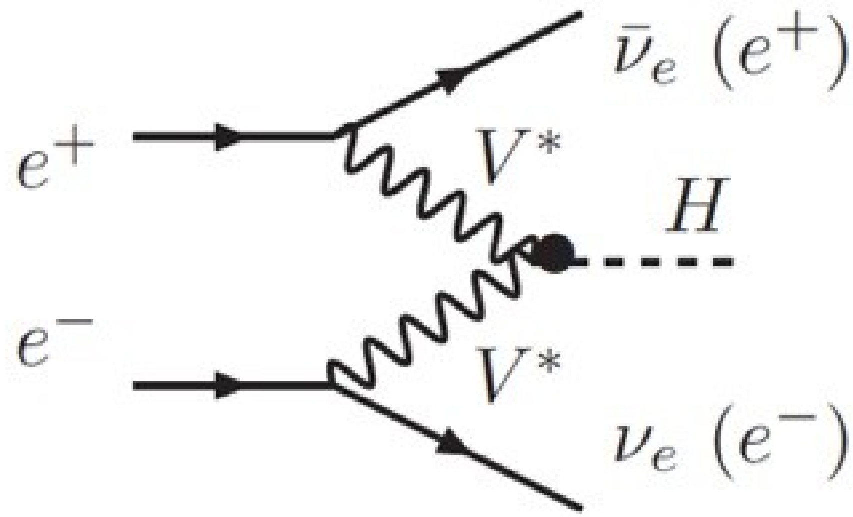
$$M_h = 125.3 \pm 0.03\,\mathrm{GeV}$$

$$\sigma_{ZH} = 10.32 \pm 0.37\,\mathrm{fb},\ 3.6\%$$

Higgs at 125.3 GeV “permits” the same precision as Higgs at 120 GeV

Coupling to the W

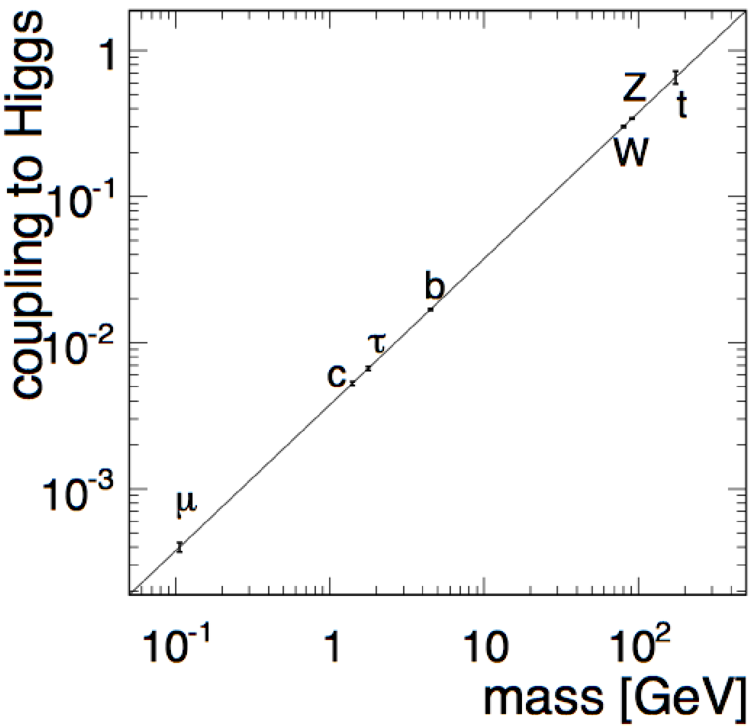
- Directly accessible in WW fusion:

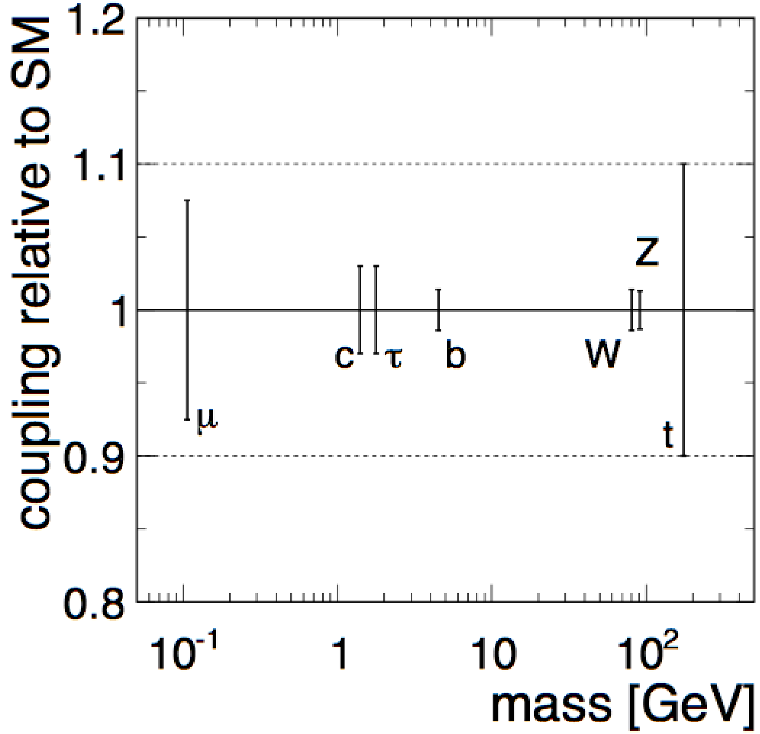


Measurement of the production cross section in one visible decay also measured model-independently in the ZH - process allows to extract the coupling
1.4% at 500 GeV (500 fb^{-1}), comparable at higher energy

- 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 $\Gamma_H = \Gamma(\mathrm{H} \to \mathrm{WW}^*)/Br(\mathrm{H} \to \mathrm{WW}^*)$ measurable to the 5% level

Higgs Couplings - Introduction

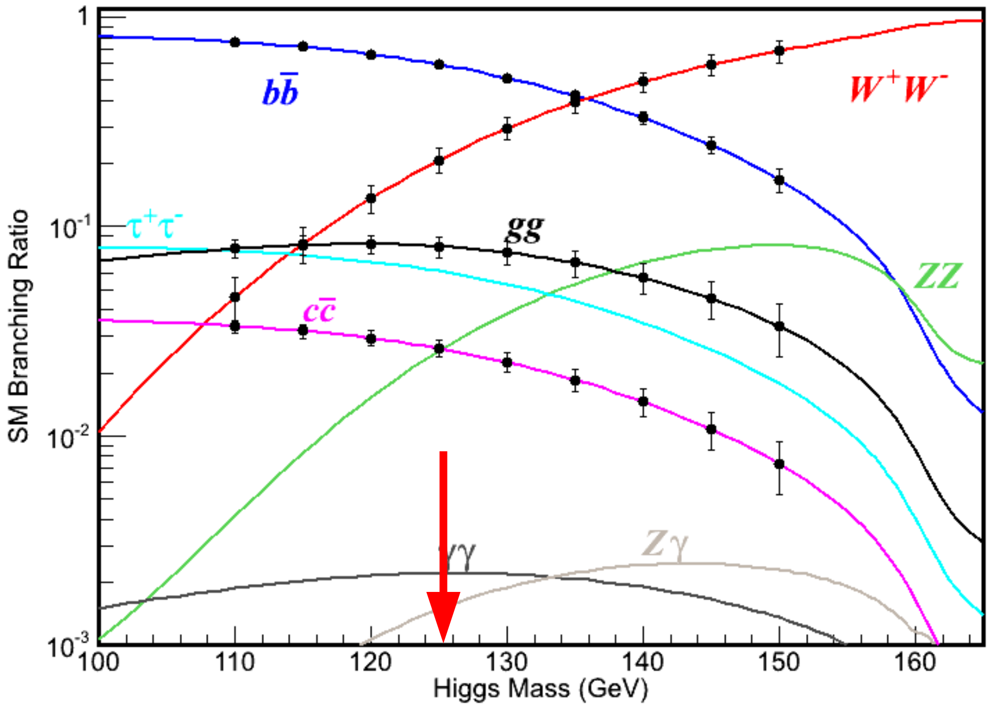




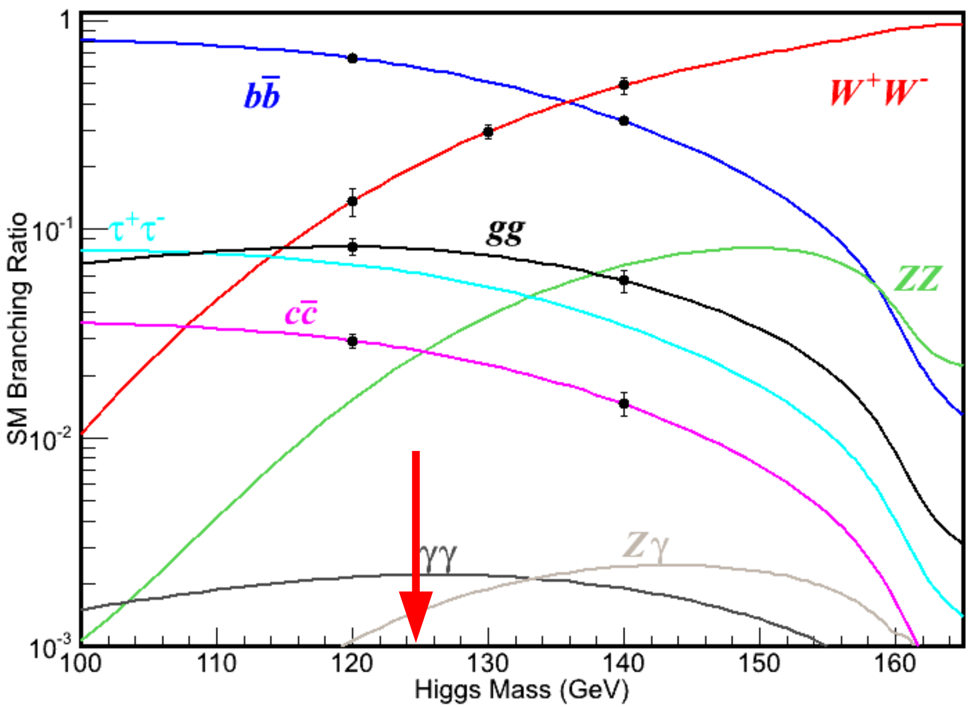
- A Linear Collider running at several energies will provide precise measurements of relevant Higgs couplings: Possibility to confirm the Higgs mechanism of the SM
- Precision matters: Detect deviations, for example due to extended Higgs sectors (SUSY,composite, ...):Expected on the 10% - 15% level in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

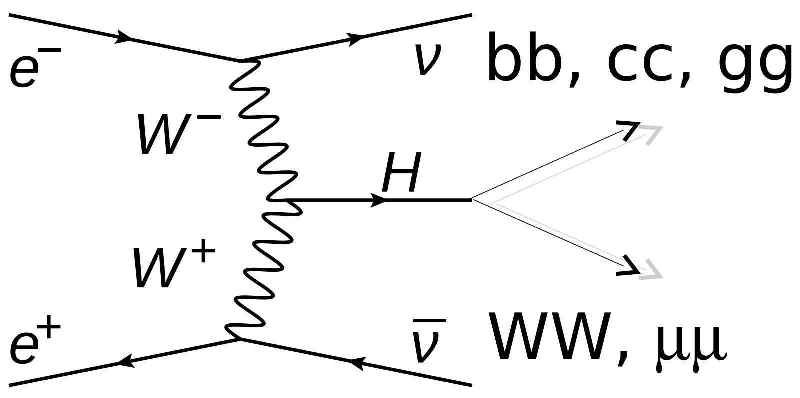
Expected to improve including lv+2j

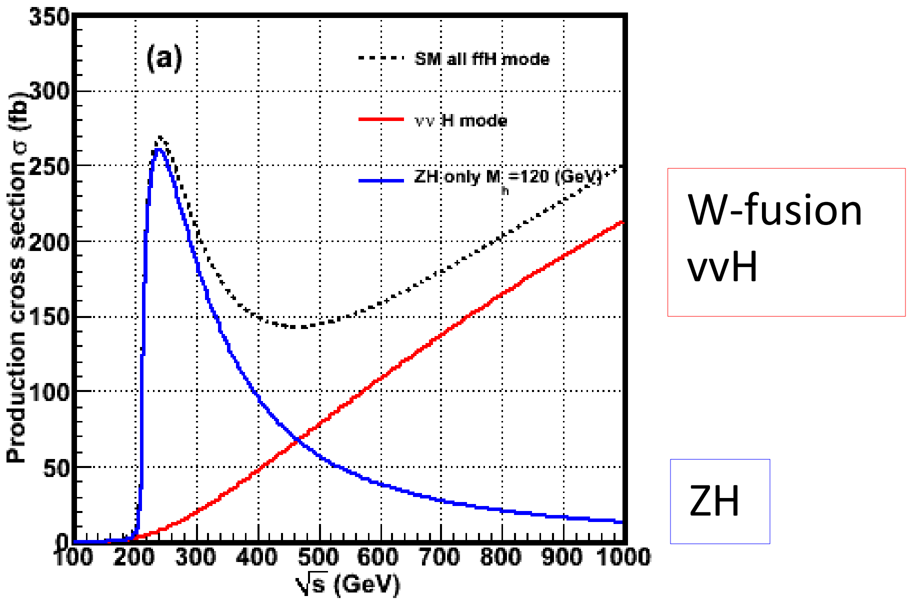
σZH=2.5% uncertainty is also included

νvH @ 1 TeV

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

Main produced through W-fusion



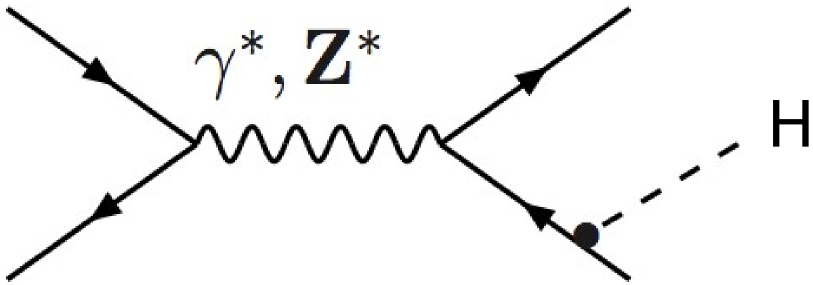


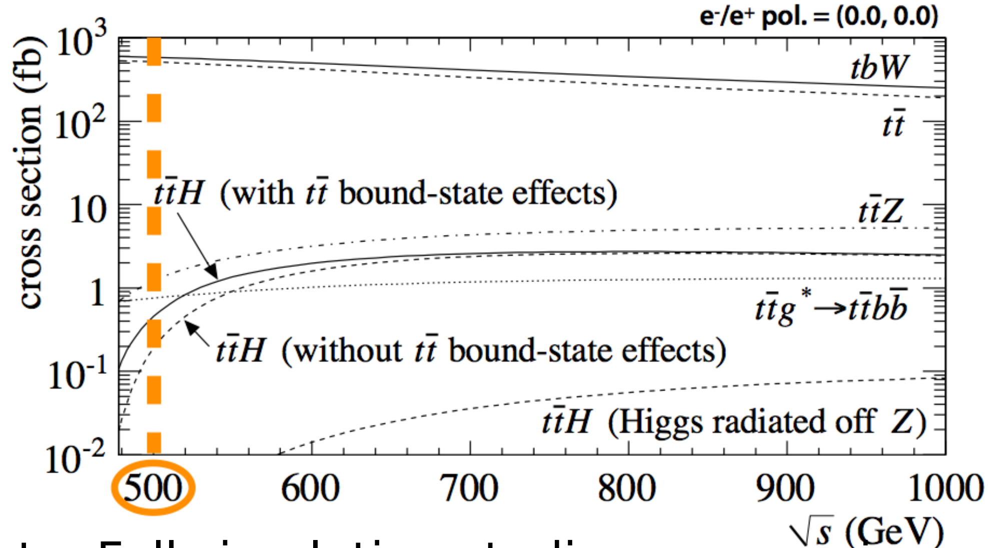
H→bb, cc, gg (Hadronic decay)
Di-jet reconstruction

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

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

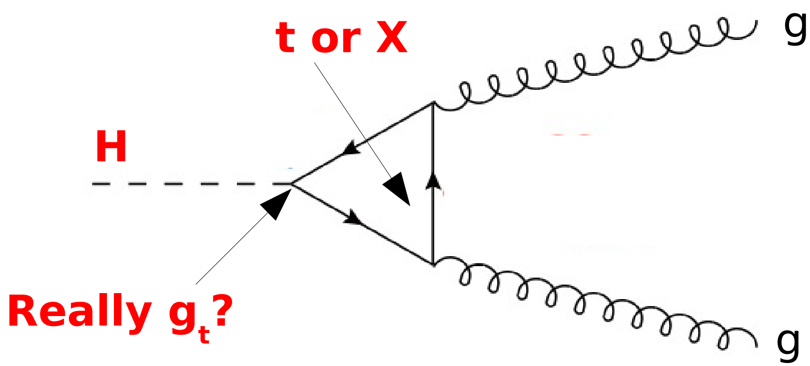
Top Yukawa coupling





- 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!!!

A compilation of expected precisions on couplings

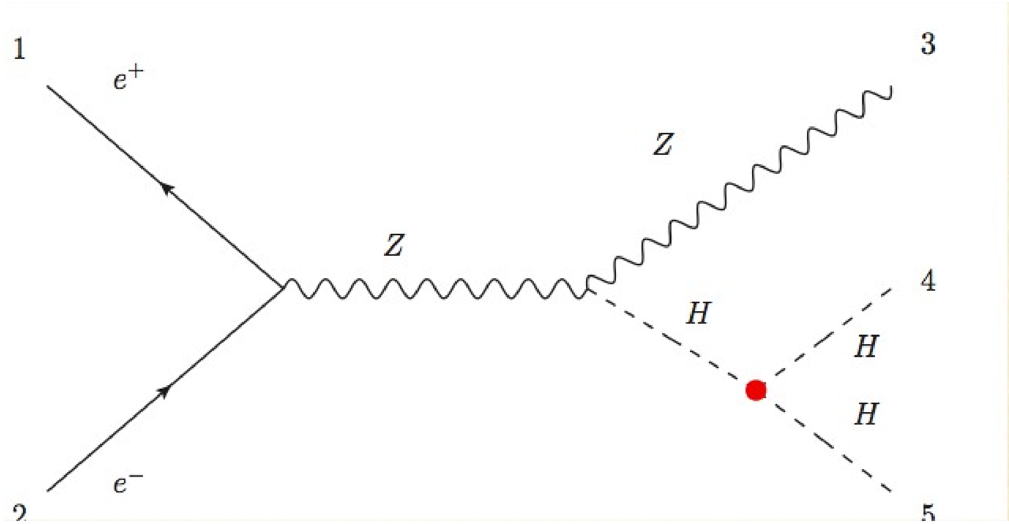
From M. Peskin: arxiv:1207.2516v1 based on studies of Japanese ILD group

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

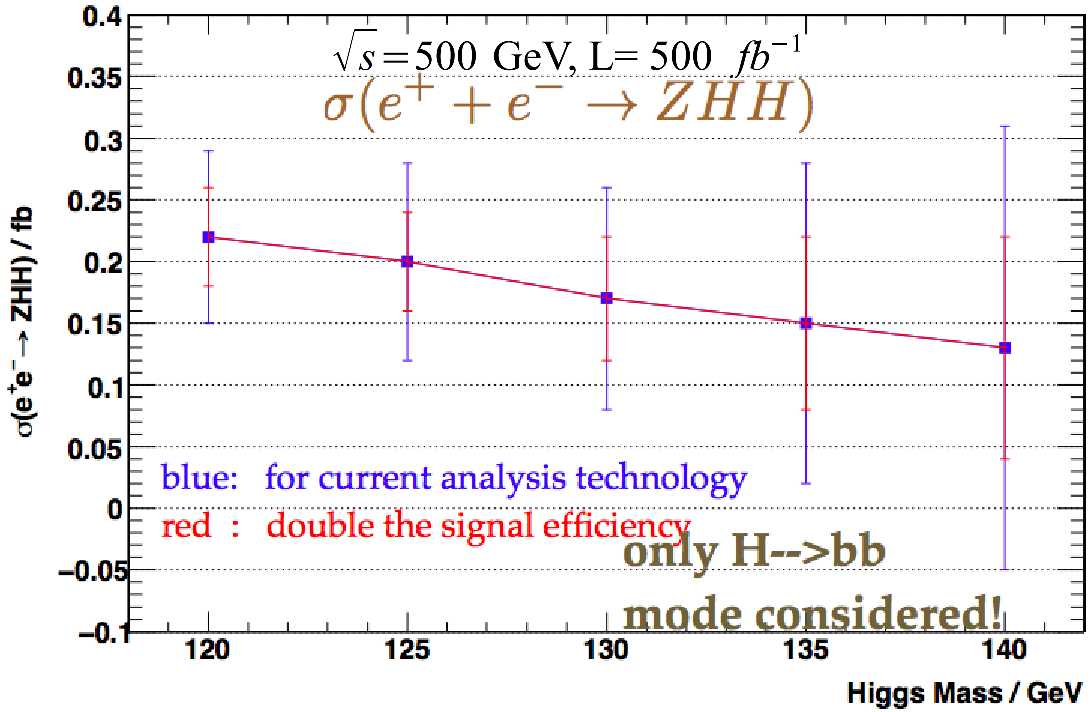
Higgs self coupling



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:

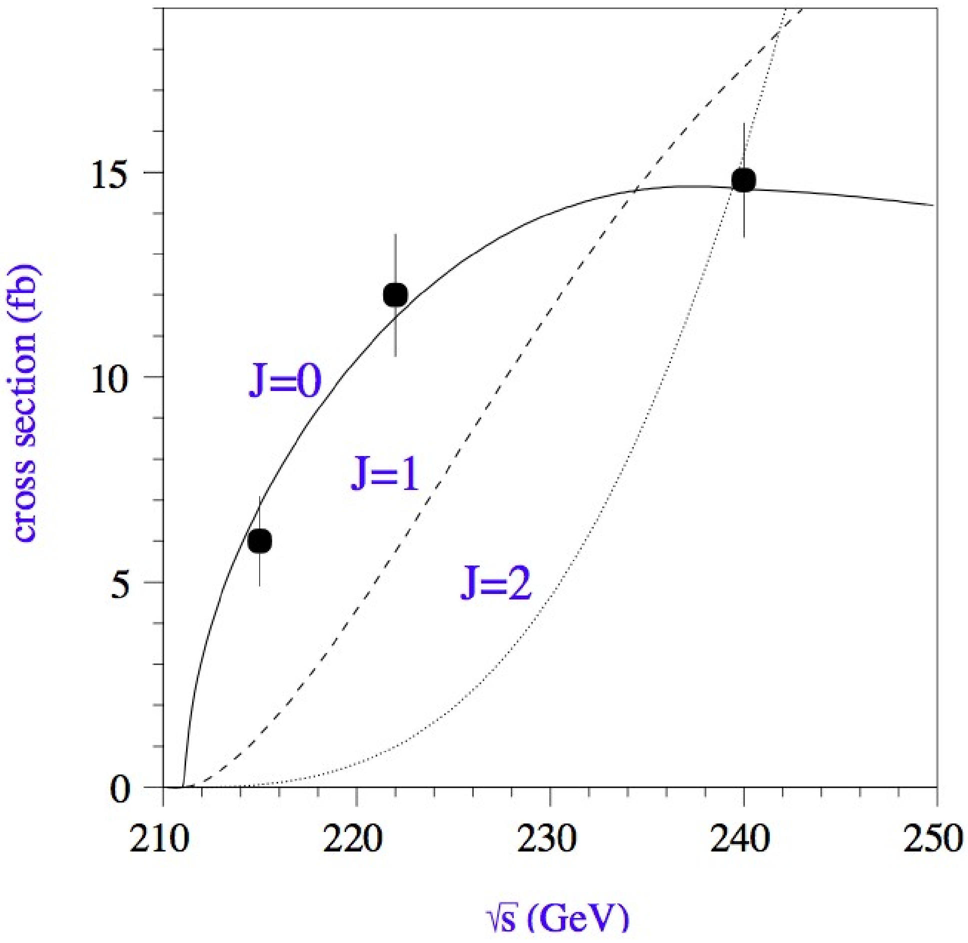
About 40% uncertainty
For m_H = 125 GeV
(Full simulation!!!!)

Study aims at 20%

Extremely difficult analysis

RN

Spin of the Higgs boson



"Almost trivial at LC'

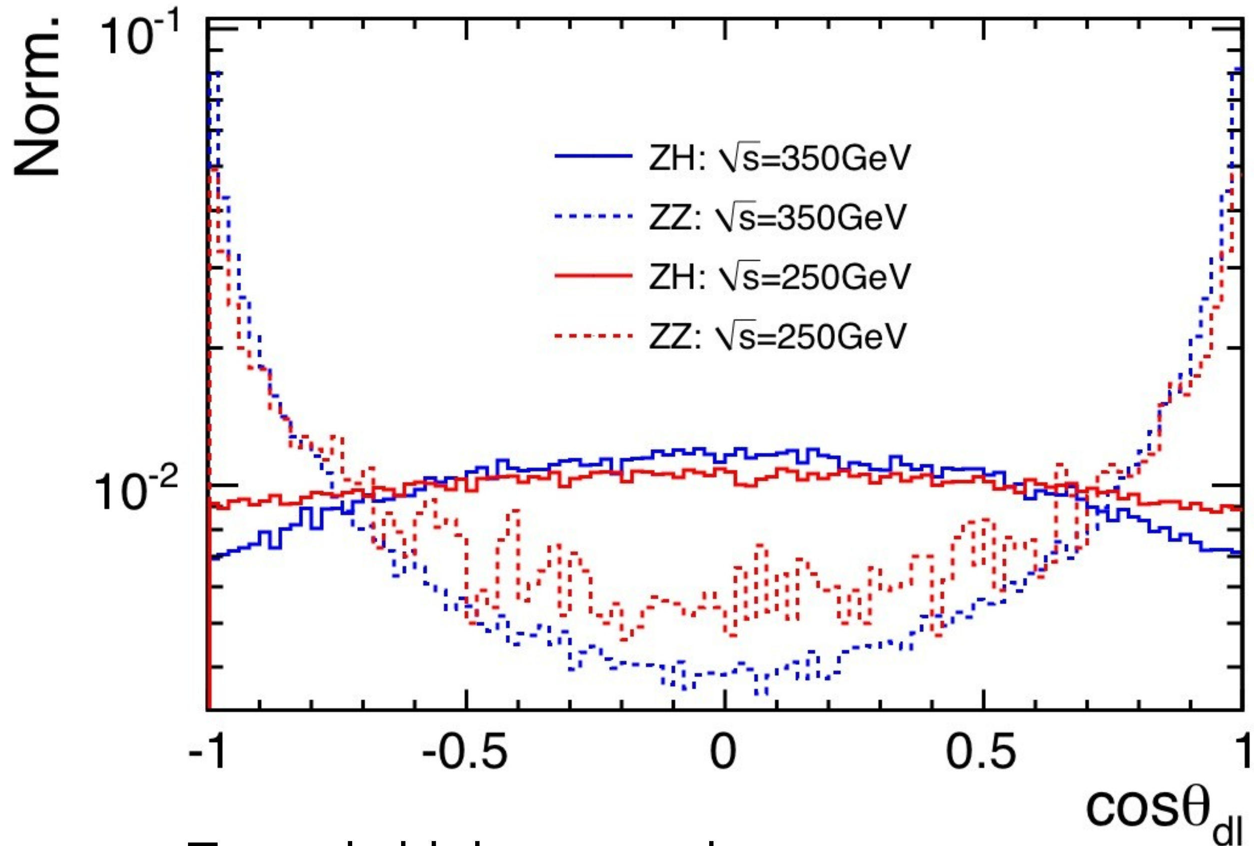
- Quick threshold scan
  ~20 fb^{-1}/point
  <=> Few months of running

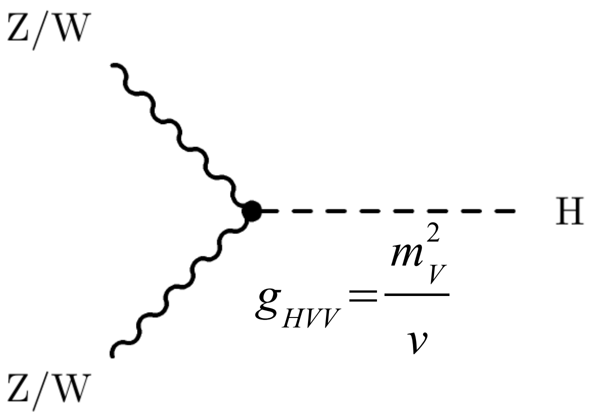
- Clear distinction different
  Spins

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

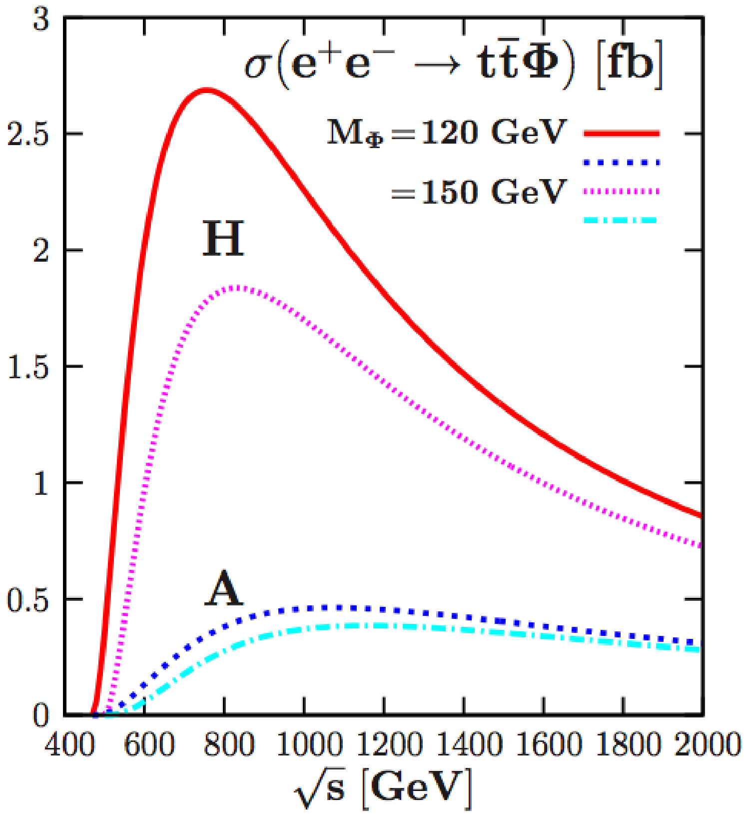
Towards higher energies:
ZH: Signal: Z retrieves its **Goldstone** nature
ZZ: Z retrieves its photonic nature

- 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

Higgs quantum numbers – CP via ttH

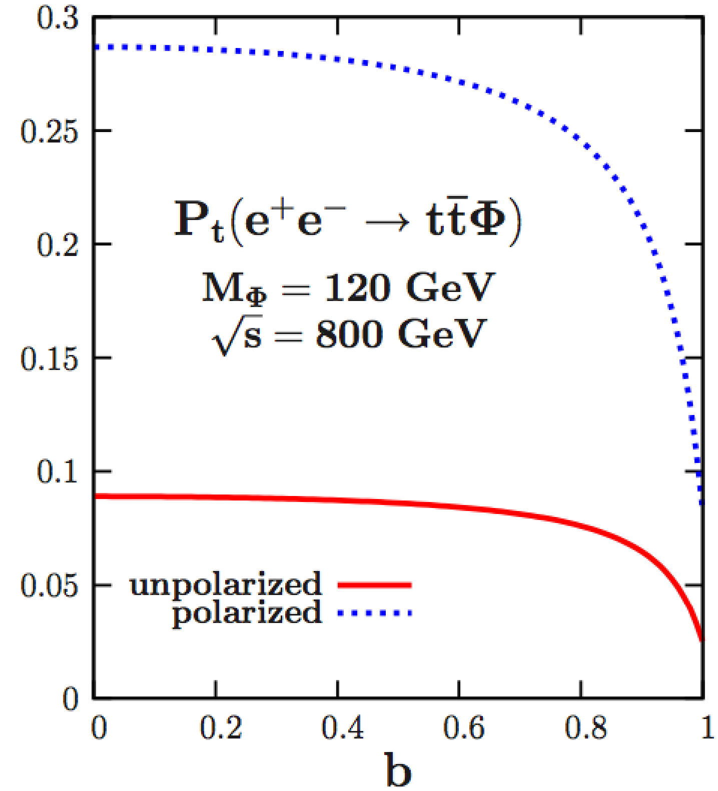
(A priori) Democratic coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation



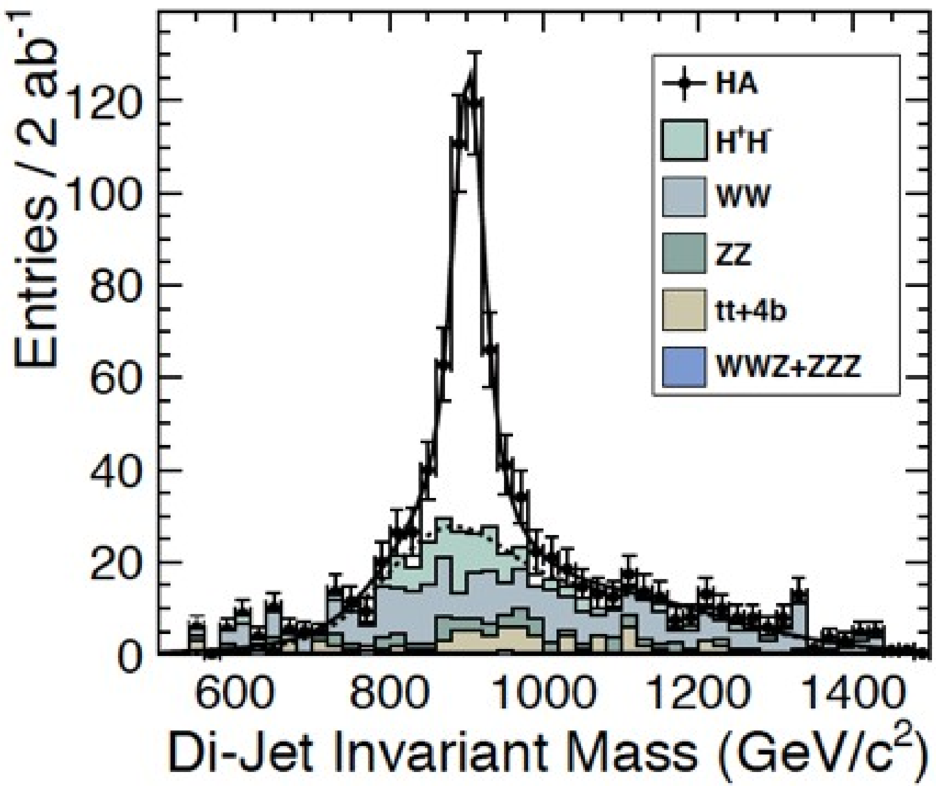
Sensitivity to CP odd admixture
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

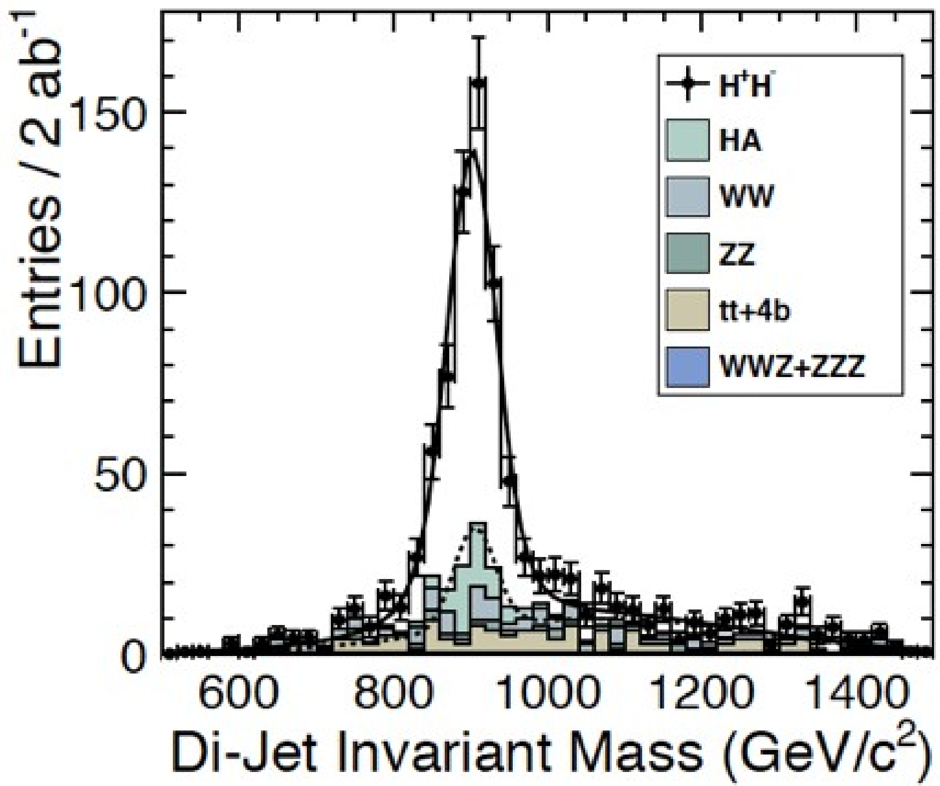
More new bosons ...

- At a multi-TeV LC, also heavy Higgses, for example in SUSY (H^0, A^0, $H^{\pm}$), are easily accessible:

CLIC CDR



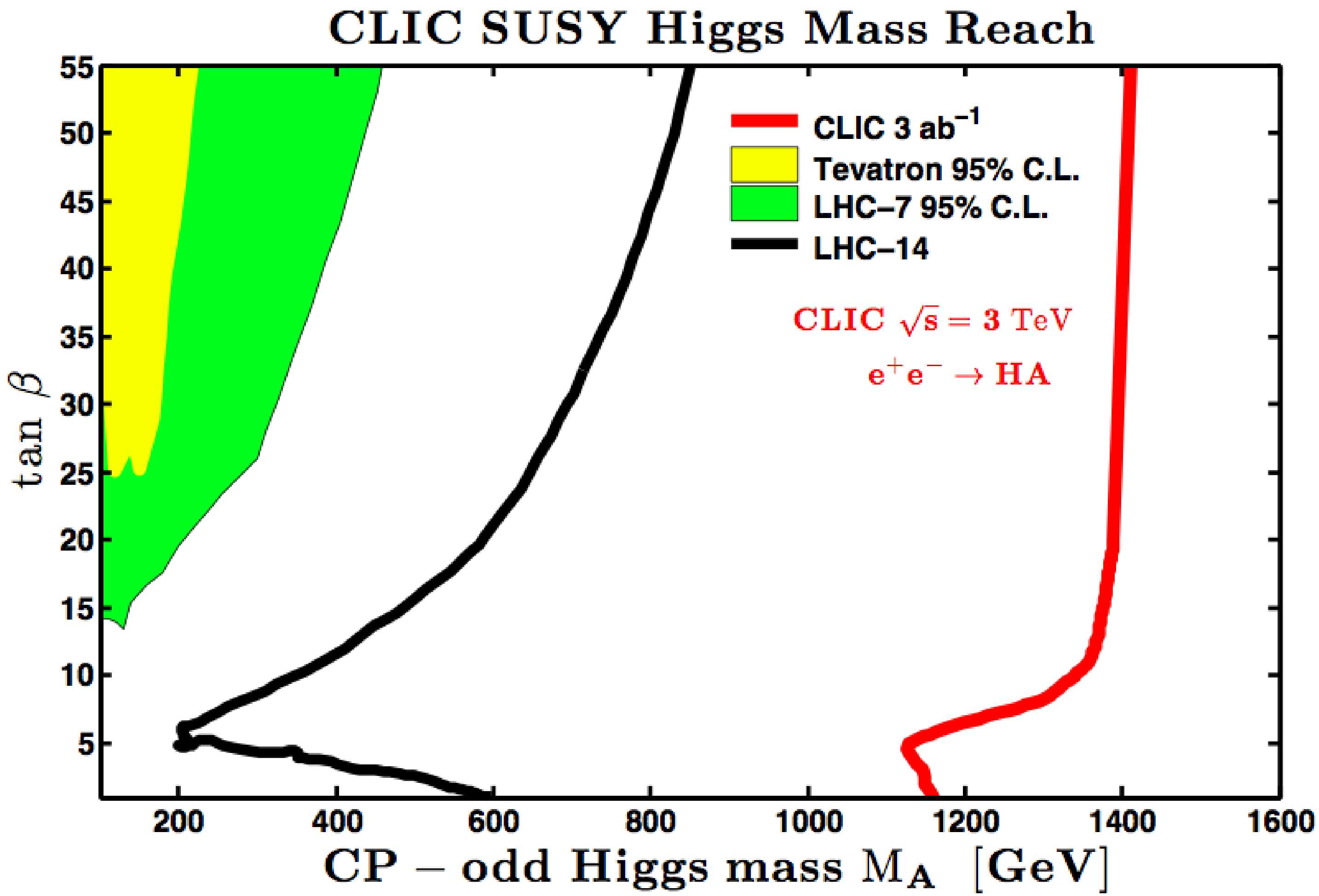
(a) $e^+e^- \rightarrow b\bar{b}b\bar{b}$



(b) $e^+e^- \rightarrow t\bar{b}b\bar{t}$

0.3% precision for TeV-scale masses at a 3 TeV LC

Search reach for Heavy Higgs at LC

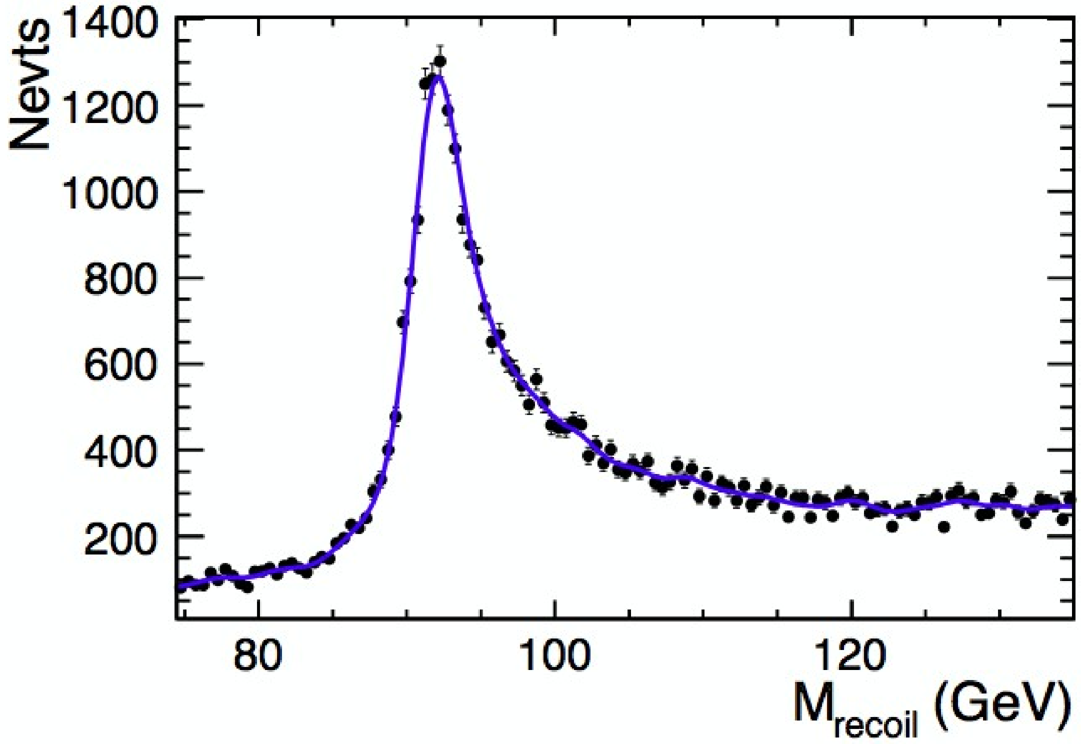


- Impressive coverage!
- Higgs decay may be source of Dark Matter

Light Higgs states in MSSM

Extended Higgs sector may include a Higgs lighter than the SM like one
What is the potential of an LC to detect such a state?

'Recoil' peak in ee->ZZ



–Δm ~ 30 MeV for 250fb^{-1}
=> Light Higgs may have a chance to “survive” in ZZ background

- What are typical Production cross sections?

Remarks:
- A particle with a mass of ~80 GeV would be preferrable
- Would require running at corresponding production threshold
- May need appropriate choice of beam polarisation
- A particle with $J^{CP} = 0^{++}$ would facilitate the detection
- Definite statement would need careful revision of cuts

Summary and Outlook

- The discovery of the new boson is starting time of exciting times !!!

- 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
  Potential to 'see' additional Higgs Bosons

- Excellent S/N noise ratio in Higgs-strahlung

  Higgs mass at an accuracy of ~ 50 MeV, too good today (?)

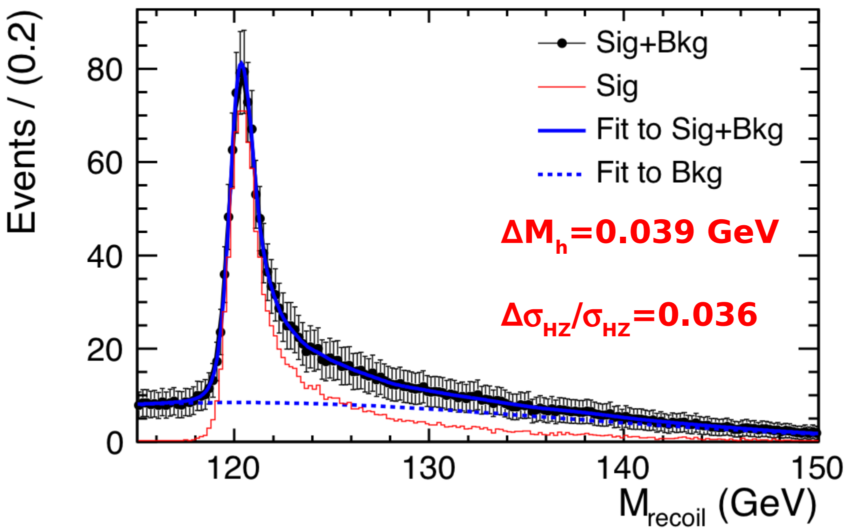
- The mass of the new boson implies a fantastic physics program already below 1 TeV

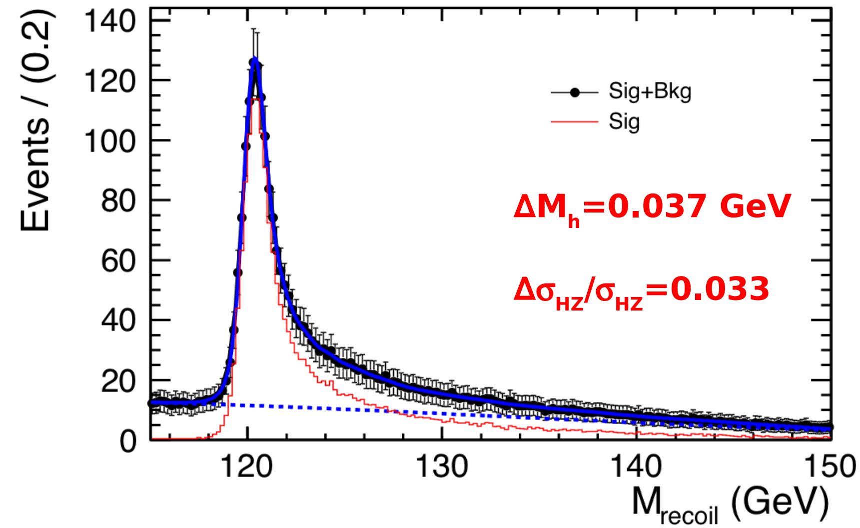
Backup Slides

Model Independent ↔ Model Dependant Analysis

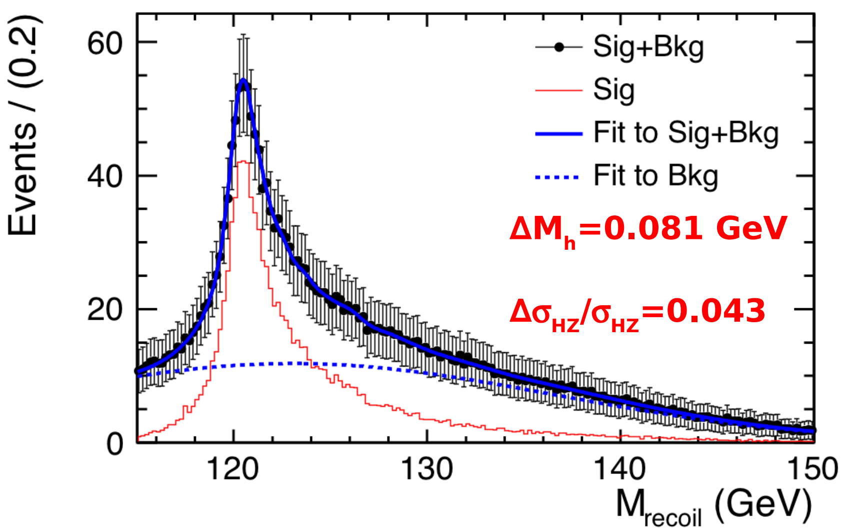
Model dependency by exploiting track activity from SM Higgs decays

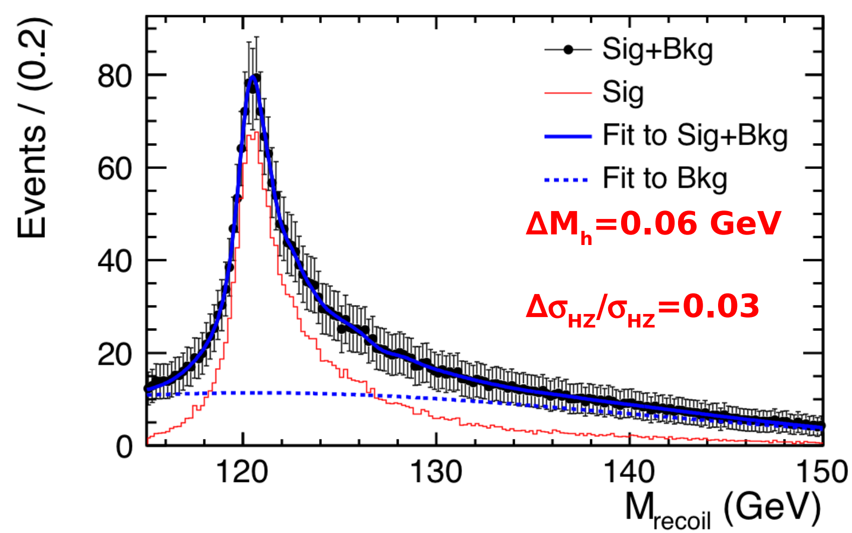
Muon Channel





Electron Channel





Only little further improvements by introducing Model Dependency

Background Rejection

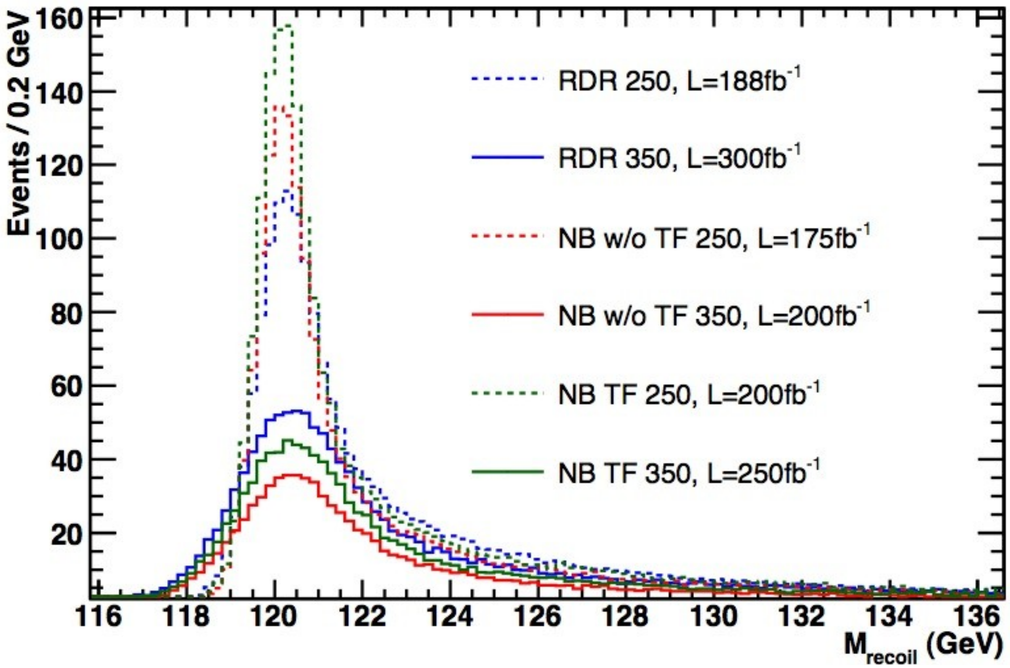
ILD

$P_{T,dl} > 20$ 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



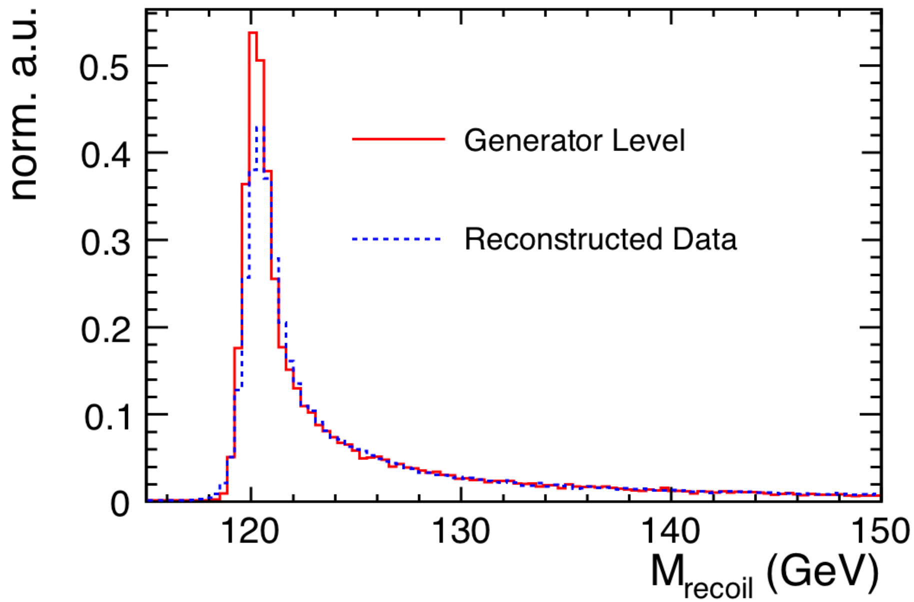
Beam Par	$\mathcal{L}_{\rm int}$ (fb^{-1})	ϵ	S/B	M_H (GeV)	σ (fb) ($\delta\sigma/\sigma$)
RDR 250	188	55%	62%	120.001 ± 0.043	11.63 ± 0.45 (3.9%)
RDR 350	300	51%	92%	120.010 ± 0.087	7.13 ± 0.28 (4.0%)
NB w/o TF 250	175	61%	62%	120.002 ± 0.032	11.67 ± 0.42 (3.6%)
NB w/o TF 350	200	52%	84%	120.003 ± 0.106	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

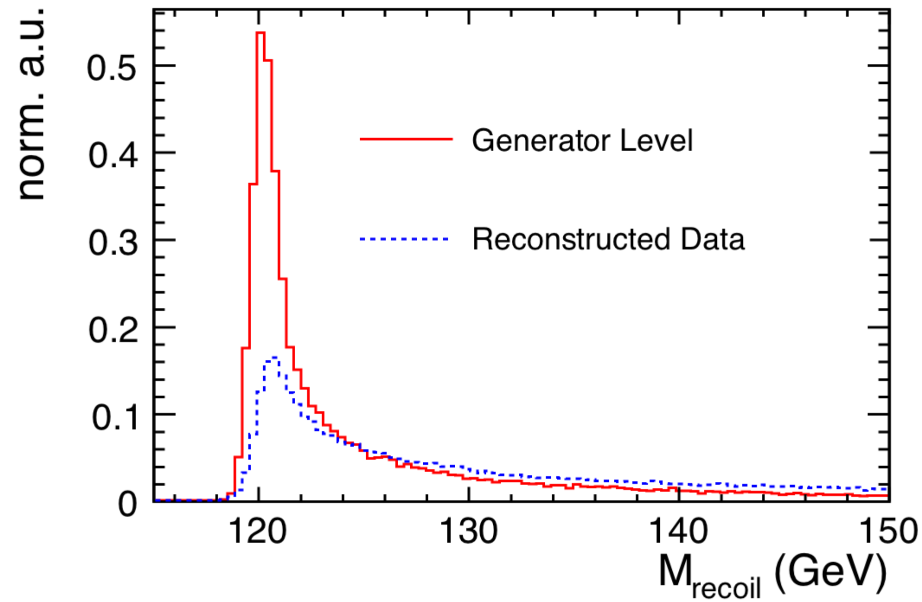
Muon Channel



$\Delta M_{tot} = 650$ MeV

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

Electron Channel



$\Delta M_{tot} = 750$ MeV

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

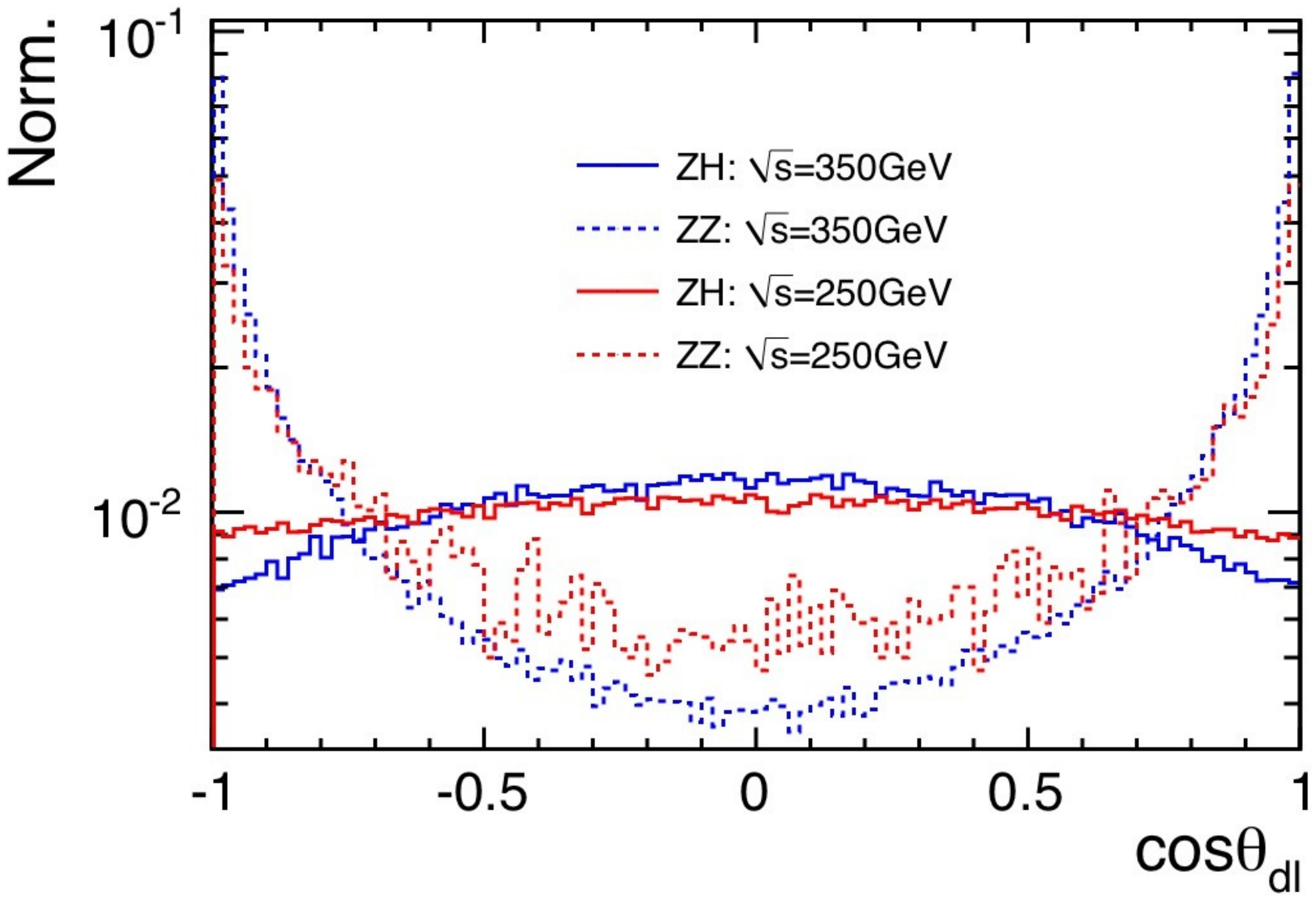
Uncertainties of incoming beams are dominant source of Statistical Error

(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

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

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

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