Search for Extra Scalars Produced in Association with a Z boson at the ILC

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on behalf of the ILD concept group

LCWS 2018, Arlington

October 25, 2018

Motivation

The SM-like scalar H^{125} was found in 2012:
$\Rightarrow$ the real SM Higgs?

Theoretical:

- Many BSMs predict one or more extra scalars.
  - 2HDM, NMSSM, Randall Sundrum model ...

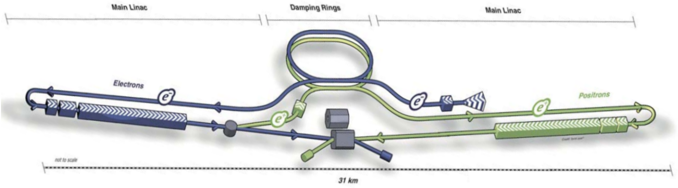
* many models.
* many parameters.
* very weak couplings

Experimental:

- LHC/LEP(*) constraints rely on the model details:
  - CP, mass hierarchy, couplings, etc.
- precise constraints are necessary.

We want a better result!

ILC — The International Linear Collider



- ILC properties:
  - e^+e^- collider, with polarized beams (e^-: $\pm$ 0.8, e^+: $\pm$0.3).
- ILC running scenario for about 20 years:
  - The first stage ILC@250 $\rightarrow \sqrt{s} =$ 250 GeV and $\int Ldt = 2000\,\text{fb}^{-1}$
  - Energy-upgradable: ILC@500 $\rightarrow \sqrt{s} =$ 500 GeV and $\int Ldt = 4000\,\text{fb}^{-1}$
- Construction under political consideration in Japan.

Comparing LEP/LHC and ILC

- comparing with LEP: ILC is sensitive to lighter scalars with smaller S^0ZZ coupling.

	LEP	ILC	improvement
max $\sqrt{s}$ (GeV)	189-209	250 and 500	
m_h region (GeV)	<115	<160 and $<$ 410	
luminosity	totally $\sim$2.5 fb^{-1}	2000 fb^{-1} and 4000 fb^{-1}	recoil mass
polarization	$\times$	$\surd$	angle correlation
detector e.g.σ_{1/p_T}	6×10^{-4} GeV^{-1}	2×10^{-5} GeV^{-1}	resolution
search channels	$2b2q$,$2b2\nu$,$2b2l$, $\tau\tau qq$	model independent	

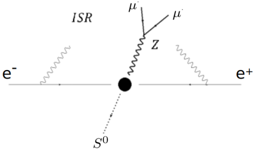
Phys.: Conf. Ser. 110 042030

- comparing with LHC
  - LHC, complex initial states and backgrounds, $S^0 \rightarrow \gamma\gamma/ZZ$... channel, large uncertanties.
  - ILC, e^+e^- well known initial states, **clean environment**, **model-independent**.

The Recoil Method on SM Higgs at ILC

e^+e^- collider $\rightarrow$ know the initial states behaviour $\rightarrow$ recoil technique $\rightarrow$ model independence

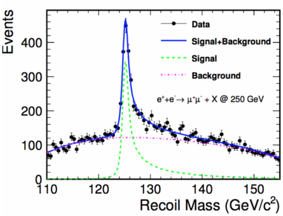
Higgsstrahlung process $e^+e^- \rightarrow Z + H^{125}/S^0$



- $M_{rec}^2 = (\sqrt{s} - E_{\mu\mu})^2 - |\vec{p}_{\mu\mu}|^2$
- $M_{\mu\mu} \sim M_Z$, $M_{rec} \sim M_{H^{125}/S^0}$

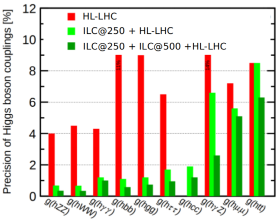
SM H^{125} recoil mass distribution (ILD)

Phys. Rev. D 94, 113002 (2016)



SM H^{125} coupling for ILC and HL-LHC

arXiv:1710.07621

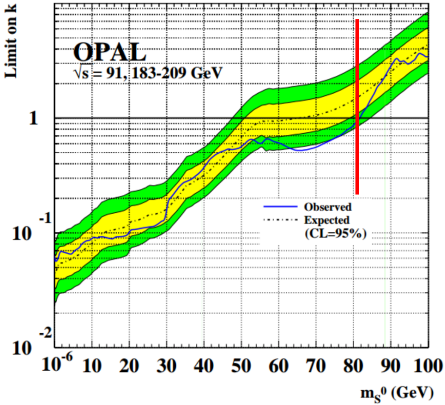


the same method on light scalar searching, **SM $H \rightarrow$ a lighter S^0**.

The Recoil Results at LEP

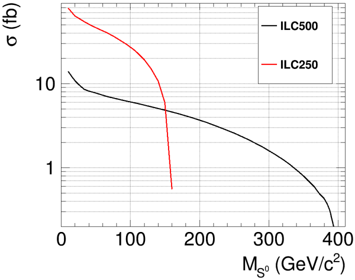
LEP results (CERN-EP-2002-032) :

- the OPAL detector
- Decay-mode independent searches for new scalar bosons
- energy & luminosity:
  - 91.2 GeV and 0.115 fb^{-1} at LEP1
  - 161 to 202 GeV and **0.662 fb^{-1}** at LEP2.
- light higgs mass: 10 keV - 100 GeV
- $k = \frac{\sigma_{S^0 Z}}{\sigma_{H_{\text{SM}} Z}(m_{H_{SM}} = m_{S^0})}$



Signal and backgrounds

The signal production:



The signal decay ⇒ same as SM H^{125}.

The signal MC samples

- The signal MC samples @ ILC@250
  - $M_{S^0} = 10, 15, 20, ..., 160$ GeV,
  - polarization ratio: $(45\%, 45\%, 5\%, 5\%)$.
- The signal MC samples @ ILC@500
  - $M_{S^0} = 10, 20, ..., 410$ GeV,
  - polarization ratio: $(40\%, 40\%, 10\%, 10\%)$.

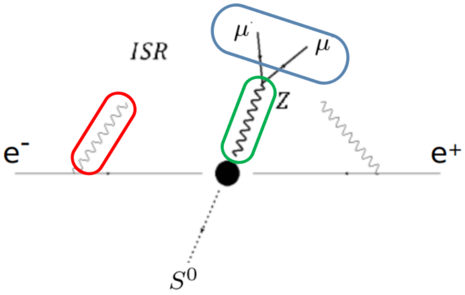
The background MC samples:

1. 2-fermion leptonic/bhabha/hadronic
2. 4-fermion leptonic/semi-lepton/hadronic
3. 6-fermion $t\bar{t}$, $llWW$, $qqWW$...
4. SM Higgs, $Higgs_{125}$
5. $\gamma\gamma$ backgrounds

Analysis Strategy

Principle: using the smallest amount of information of S^0 decay.

- a pair of isolated muon, with opposite charges.
- ISR photons may undermine S^0 recoil distribution.

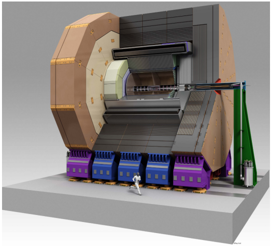


ILD (International Large Detector)

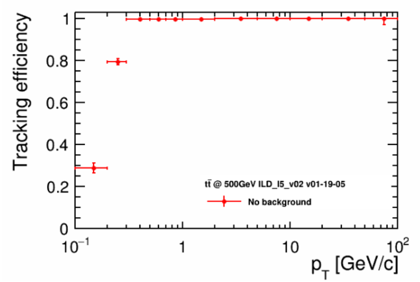
c.f. Mon 16:30 pm, J.List

- optimized for particle flow
- Momentum resolution: $\sigma_{1/p_T} < 2 * 10^{-5}$ GeV^{-1}
- excellent tracking and calorimeter performance

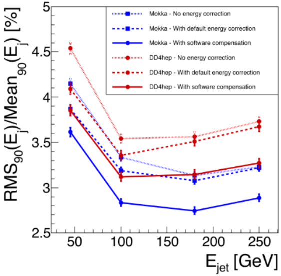
(arXiv:1306.6327, ILC TDR)



tracking performance



calorimeter performance



Analysis flow

01 a muon pair

02 $M_Z \in [73, 120]$ GeV

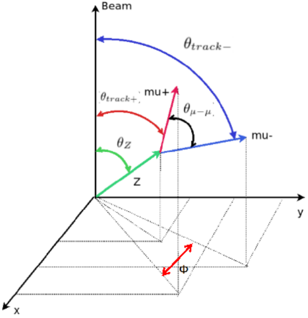
03 $P_T^Z \in [10, 128 - 4 \times \frac{M_h}{10}]$ GeV

04 $\cos\theta_{mis} < 0.98$ when $E_{mis} > 10$ GeV

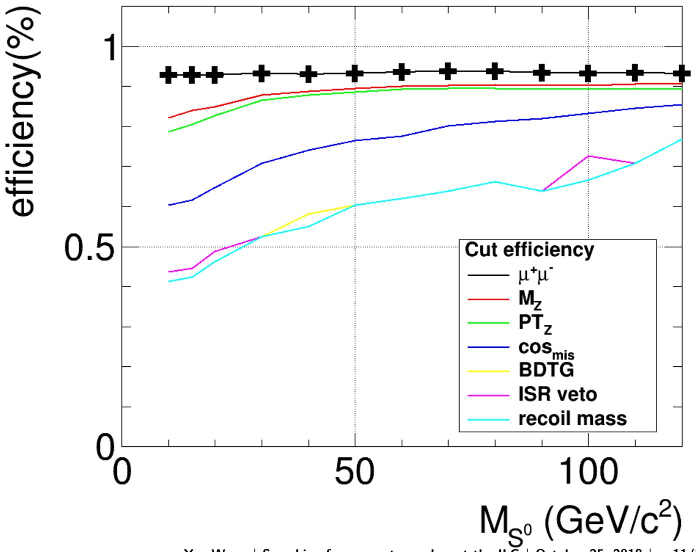
05 Multi-Variate Analysis : angles

06 photon veto : veto ISR photon

$$\chi^2(M_{\mu^+\mu^-}, M_{\rm rec}) = \frac{(M_{\mu^+\mu^-} - M_Z)^2}{\sigma^2_{M_{\mu^+\mu^-}}} + \frac{(M_{\rm rec} - M_h)^2}{\sigma^2_{M_{\rm rec}}}.$$

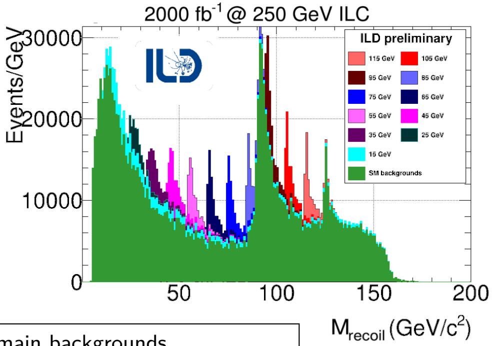


Cut efficiency for the signal



Recoil Mass Distribution at 250 GeV

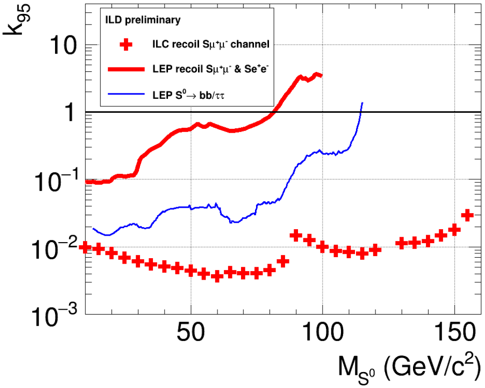
- recoil mass distribution for different M_{S^0}.
- 2000 fb^{-1}, ILC@250.



mass region	main backgrounds
$125 > M_{S^0} > M_Z$	$e^+e^- \to \mu^+\mu^- f\bar{f}$, $ZH^{125} \to \mu^+\mu^- H^{125}$
$M_{S^0} \sim M_Z$	$e^+e^- \to \mu^+\mu^- f\bar{f}$
$M_Z > M_{S^0} > 40$	$e^+e^- \to \mu^+\mu^-, \quad e^+e^- \to \mu^+\mu^-$
$40 > M_{S^0}$	$e^+e^- \to \mu^+\mu^-$

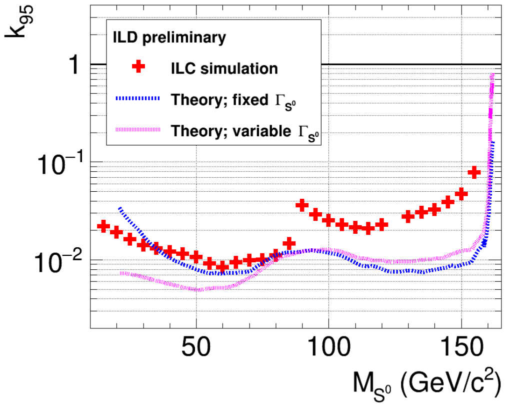
Comparing with LEP

same definition k_{95} with OPAL, exclusion limits with the likelihood method for $\frac{\sigma_{S^0 Z}}{\sigma_{H_{SM} Z}(m_{H_{SM}}=m_{S^0})}$



- ILC recoil: only $S\mu^+\mu^-$.
- LEP recoil: combine $S\mu^+\mu^-$ and Se^+e^- channels.
- LEP $S^0 \to bb/\tau\tau$: exclusive reconstruction of Z and h decay.
- 1-2 orders better than LEP.

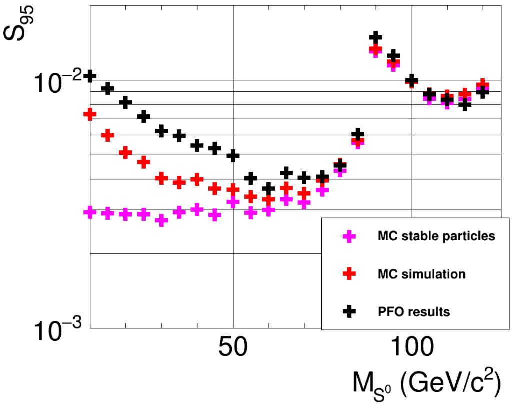
Comparing with Theoretical LEP Extroplation Results



The ILC theoretical prediction, extrapolated from the LEP measurements. P.Drechsel etc. arXiv:1801.09662

- 500 fb^{-1}, $P(e^-, e^+) = (-80\%, +30\%)$, fixed/variable scalar widths.
- theoretical prediction combines $S\mu^+\mu^-$ and Se^+e^- channels.
- theoretical prediction doesn't include SM Higgs background.

Impact of Detector Resolution and Photon Veto

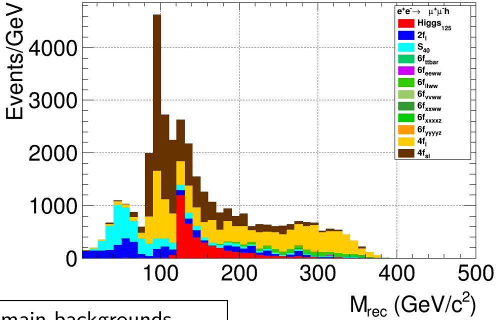


Two reasons for differences from LEP in the low mass region

- fixed width/variable width
- ISR photons

Extra scalars at 500 ILC → Recoil Mass Distribution

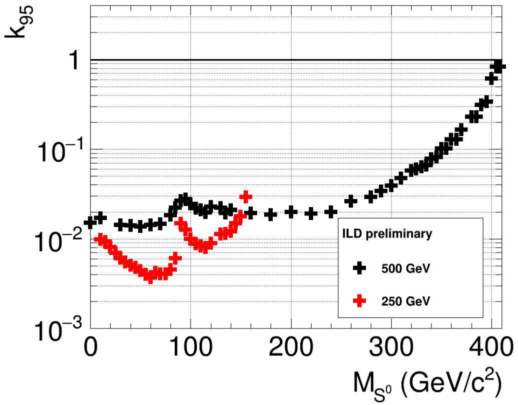
- recoil mass distribution for different M_{S^0}.
- 4000 fb^{-1}, ILC@500.



mass region	main backgrounds
$M_{S^0} > 125$	$\mu^+\mu^- f\bar{f}$, $\mu^+\mu^- H^{125}$, $6f$
$125 > M_{S^0} > M_Z$	$\mu^+\mu^- f\bar{f}$, $\mu^+\mu^- H^{125}$
$M_{S^0} \sim M_Z$	$\mu^+\mu^- f\bar{f}$,
$M_Z > M_{S^0} > 40$	$\mu^+\mu^-$, $\mu^+\mu^-$
$40 > M_{S^0}$	$\mu^+\mu^-$

Extra scalars at 500 ILC → Exclusion Limits

Prelimiary results for 500 GeV.



Conclusion

- An extra scalar is favored in many BSM models
  - 2HDM, NMSSM, RS ...
- A model-independent analysis has been performed for $\mu\mu S^0$ channel.
  - mass range [10, 160) GeV, 2000 fb^{-1}, when $\sqrt{s} = 250$ GeV.
  - mass range [10, 410) GeV, 4000 fb^{-1}, when $\sqrt{s} = 500$ GeV.
- Sensitivities for k_{95} (cross section scale factor) are given
  - 1-2 orders of magnitude more sensitive than LEP
  - covering new phase spaces

Backup Slides

Theoretical Motivation

The higgs boson found at 2012: the SM Higgs?

Many BSMs predict one or more extra scalars:

- General Two Higgs Doublet Model (2HDM...)
  - with 2 scalars: h, H, 1 pheudoscalar A, 2 charged particles
- Next-to-Minimal Supersymmetric Standard Model (NMSSM)
  - with 3 scalars: h1, h2, h3, 2 pheudoscalars A1, A2, 2 charged particles
- Randall Sundrum model
  - a radion

In these models, a scalar lighter than 125 GeV is well motivated.

LHC Higgs boson rather SM-like $\rightarrow$ new higgs coupling to Z boson strongly suppressed.
Could we find it at the ILC?

Past Experiment Results parameters

LEP SM Higgs searches: constrain other extra scalars, whose properties, especially decay profile, are similar as SM higgs's.

LEP/LHC constraints rely on the model details: CP, mass hierarchy, couplings, etc.

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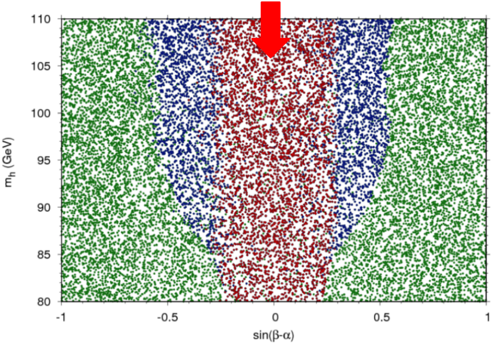
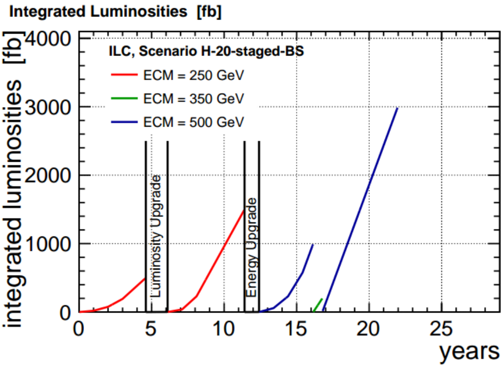
survived after indirect + LEP + LHC constrains



2HDM, Type I:
$tan\beta > 1.2$,
$m_A > 60$ GeV,
$m_{H^\pm} > 80$ GeV ..

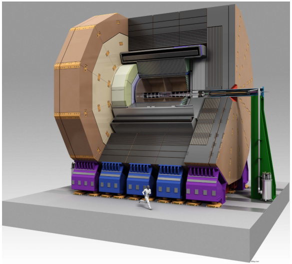
ILC run plan

- totally 22 years
- $(-+, +-, --, ++) = (45\%, 45\%, 5\%, 5\%)$ polarization scenario



ILD (International Large Detector) and full simulation of Signal and SM Background

- new trackers, calorimeters, 3.5T magnetic field, yoke for muon, forward system
- Requirements:
  - Impact parameter resolution: $\sigma_{r\phi} < 5 \oplus 10/(p\ sin^{3/2}\theta)\mu m$
  - Momentum resolution: $\sigma_{1/p_T} < 2 * 10^{-5}$ GeV^{-1}
  - Energy resolution: $\sigma_E/E = 3 - 4\%$



The generator and simulation software

- WHIZARD 1.95 + Pythia 6
- ILCSoft-01-17-09 (Mokka) + ILD detector concept
- ILCSoft-02-00-01 (DD4Hep) + ILD detector concept

The background MC samples:

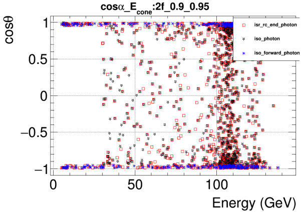
- 2-fermion ($2f^l$,$2f^h$) leptonic/bhabha/hadronic
- 4-fermion ($4f^l$, $4f^{sl}$, $4f^h$) leptonic/semi-lepton/hadronic
- SM Higgs, $Higgs_{125}$
- 6-fermion
- $\gamma\gamma$ backgrounds

likelihood method

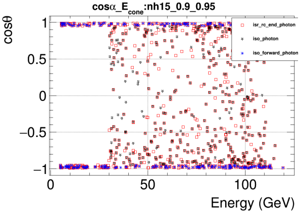
- 2 σ exclusion limits with a bin-by-bin comparison between the signal and backgrounds recoil mass histograms.
- the background-only hypothesis — no new higgs in the investigated mass range.
- the signal-plus-background hypothesis — the new higgs is assumed to be produced.
- a global test-statistic $X(m_h) = \mathcal{L}(s(m_h))/\mathcal{L}(0)$ is constructed to discriminate signal and background.
- the distributions of $X(m_h)$ are normalised to become probability density functions $\rightarrow$ integrated to be the confidence levels $CL_b(m_h)$ and $CL_{s+b}(m_h)$.
- the ratio $CL_s(m_h) = CL_{s+b}(m_h)/CL_b(m_h)$ is used to described that the signal confidence one might have obtained in the absence of background.

ISR photon veto

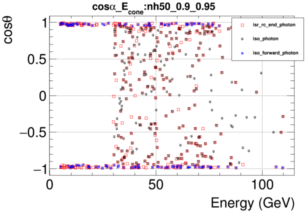
$2f_l$ process



$M_{S^0} = 15$ GeV process



$M_{S^0} = 50$ GeV process



- There is photon return effects in $2f$ process.
- identify ISR photon by
  - ISR photon in the central region (cos$\theta < 0.95$): $E_{\text{central}} > 100$ GeV
  - ISR photon in the forward region ($0.95 <$ cos$\theta < 0.99$): $E_{\text{forward}} > 60$ GeV
  - ISR cone around photon axis: cos$\alpha = 0.90$
  - Energy ratio inside the ISR photon cone: $\frac{E}{E_{\text{cone}}} = 0.95$

comparing LEP2 and my strategy for searching light scalars

OPAL's strategy

- at least two opposite charged leptons
- isolation of lepton tracks, $\alpha^1_{iso} > 15°$, $\alpha^2_{iso} > 10°$
- find two best leptons $m_{ll} \sim m_Z$
- invariant mass of the lepton pair, $M_{\mu\mu} \in [81.2, 101.2]$ GeV
- $p^Z_{ll} > 50$ GeV
- polar angle of missing momentum, $|\theta_{mis}|$<0.95 for $p_{mis} > 5$ GeV
- acoplanarity
- ISR photon veto

my strategy

- at least two isolated muon, with IsolatedLeptonTagging Processor
- find two best leptons, $m_{ll} \sim m_Z$ and $m_{rec} \sim m_h$
- Recovery of bremsstrahlung and FSR photons
- Reconstruct Z boson mass $M_{\mu\mu} \in [73, 120]$ GeV.
- 70 GeV $> P^Z_T >$ 10 GeV
- the polar angle of the missing momentum, $|\theta_{mis}| < 0.98$, when $E_{mis} > 10$ GeV
- MVA:$M_{\mu^+\mu^-}$, $cos(\theta_Z)$, $cos(\theta_{\mu^+\mu^-})$, $cos(\theta_{\mu+})$, $cos(\theta_{\mu-})$,acoplanarity
- ISR photon veto