Search for Light Scalars Produced in Association with a Z boson at the 250 GeV stage of the ILC

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Motivation

The scalar found in 2012: the SM Higgs?

Many BSMs predict one or more extra scalars:

- 2HDM, NMSSM, Randall Sundrum model
- a scalar S^0 lighter than 125 GeV is well motivated.

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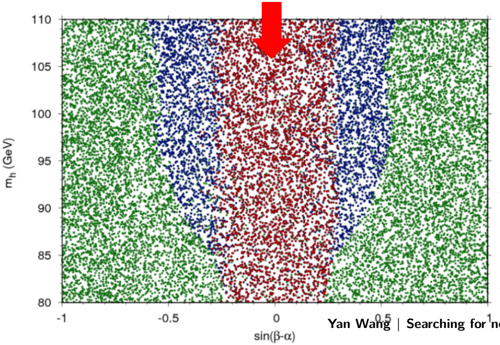
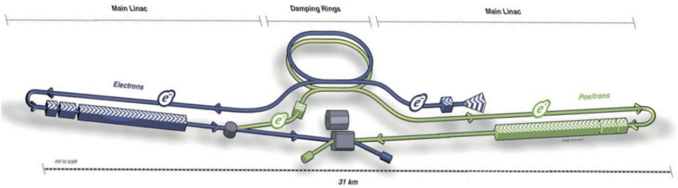
survived after indirect + LEP + LHC constrains



- LEP/LHC constrains rely on the model details: CP, mass hierarchy, couplings, etc.
- want a better result?

ILC — The International Linear Collider



- ILC properties:
  - e^+e^- collider, with polarized beams (e^-: $\pm$ 0.8, e^+: $\mp$0.3).
- ILC running scenario for totally 22 years:
  - $\sqrt{s} = 250$ GeV and $\int Ldt = 2/ab$ for the first stage $\rightarrow$ "ILC@250"
  - Energy-upgradable
    - $\sqrt{s} = 350$ GeV and $\int Ldt = 0.2/ab$
    - $\sqrt{s} = 500$ GeV and $\int Ldt = 4/ab$
    - upgradable to 1 TeV.
- 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	
m_h region (GeV)	<115	<160	
luminosity	totally ~2.5 fb^{-1}	2000 fb^{-1}	recoil mass
polorization	×	√	angle correlation
detector	ALEPH,DELPHI,OPAL,L3	ILD, SiD	resolution
search channels	2b2q,$2b2\nu$,2b2l, $\tau\tau qq$	model independent	

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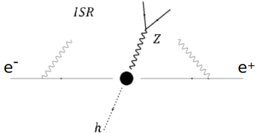
- comparing with LHC
  - LHC, complex initial states and backgrounds, $S^0 \rightarrow \gamma\gamma/ZZ$... channel, large uncertanties.
  - ILC, e^+e^- well known initial states, **clean environment**, **model-independent**.

The Recoil Method on SM Higgs at ILC

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

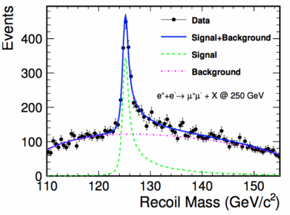
Higgsstrahlung process $e^+e^- \rightarrow Z + H/h$



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

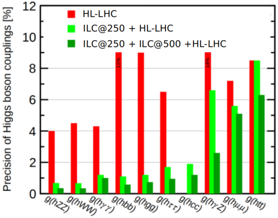
SM Higgs recoil mass distribution (ILD)

Phys. Rev. D 94, 113002 (2016)



SM Higgs coupling for ILC and HL-LHC

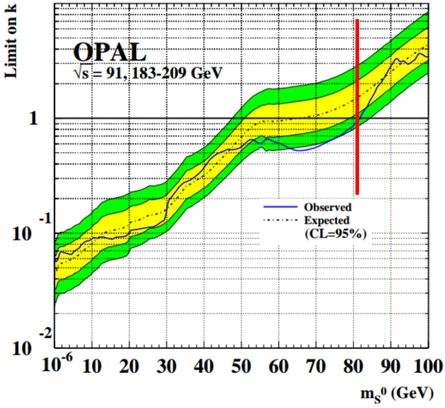
arXiv:1710.07621



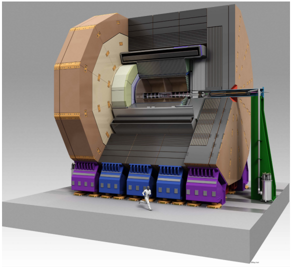
the same method on light scalar searching, **SM** $H \rightarrow$ **a lighter** S^0.

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

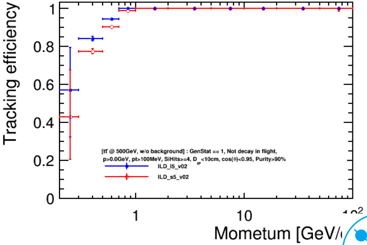
- the OPAL detector
- Decay-mode independent searches for new scalar bosons
- energy & luminosity:
  - 91.2 GeV and 115.4 pb^{-1} at LEP1
  - 161 to 202 GeV and **662.4 pb^{-1}** at LEP2.
- light higgs mass: 10 keV - 100 GeV
- $k = \frac{\sigma_{S^0 Z}}{\sigma_{H_{\text{SM}} Z}(m_{H_{SM}} = m_{S^0})}$



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



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



The signal MC samples

- $M_{S^0} = 10, 15, 20, ..., 120$ GeV, every 5 GeV step.
- decay branch ratios are the same as the 125 GeV SM Higgs boson.

Full SM backgrounds, including 125 GeV Higgs.

analysis flow

Principle: using the smallest amount of information of S_0 decay.

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

01 a muon pair

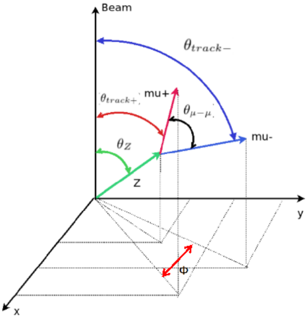
02 $M_Z \in [73, 120]$ GeV

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

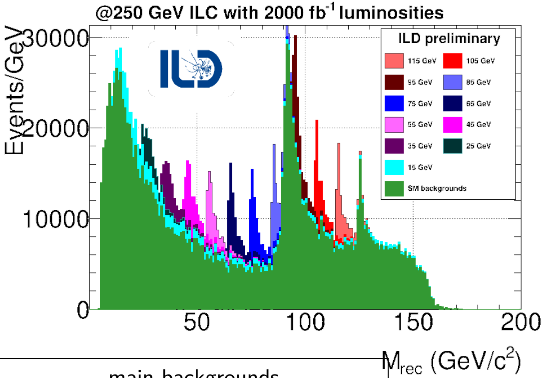
05 Multi-Variate Analysis : angles

06 photon veto : veto ISR photon



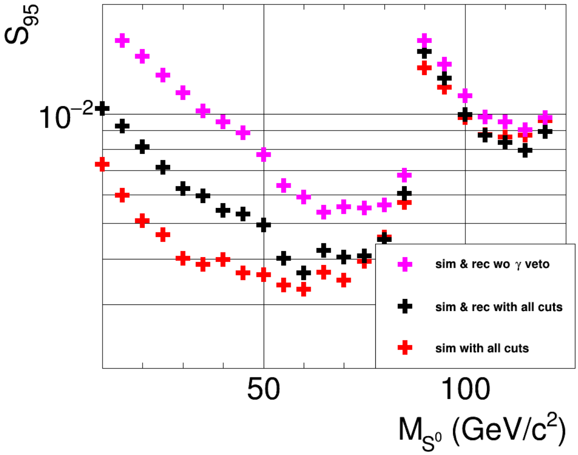
recoil mass distribution

- recoil mass distribution for different M_{S^0}.
- 2000 fb^{-1}, ILC@250. $P(e^-, e^+) = (\pm 80\%, \pm 30\%)$.
- $f(-+, +-, --, ++) = (45\%, 45\%, 5\%, 5\%)$.



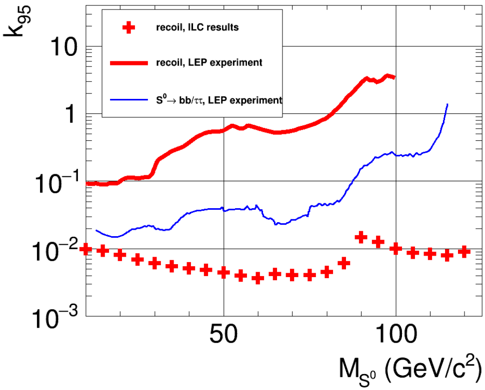
mass region	main backgrounds
$125 > M_{S^0} > M_Z$	$e^+e^- \to \mu^+\mu^- f\bar{f},\ H(125) \to \mu^+\mu^-$
$M_{S^0} \sim M_Z$	$e^+e^- \to \mu^+\mu^-,\ H(125) \to \mu^+\mu^-$
$M_Z > M_{S^0} > 40$	$e^+e^- \to \mu^+\mu^-, \quad e^+e^- \to \mu^+\mu^-$
$40 > M_{S^0}$	$e^+e^- \to \mu^+\mu^-$

Comparing with MC results



- 95% CL upper bounds on scale factor of cross section with likelihood methods
- MC results with the same cuts.
- slightly different in the low mass region → ISR photons.

Comparing with LEP results



- $k = \frac{\sigma_{S^0 Z}}{\sigma_{H_{\mathrm{SM}} Z}(m_{H_{SM}} = m_{S^0})}$
- LEP recoil: LEP2 data from 161 GeV to 202 GeV, combined LEP1 data.
- LEP traditional: exclusive reconstruction of Z and h decay, mainly $h \to bb$, $h \to \tau\tau$.
- 1-2 orders of magnitude improvement over LEP's recoil results $\to$ discovery opportunity!
- when $100 \geq M_h \geq 50$ GeV, trend are similar with LEP.

Conclusion

- A lighter higgs is favored in many BSM models
  - 2HDM, NMSSM, RS ...
- A model-independent analysis has been performed.
  - mass range [10, 120) GeV
  - 2000 fb^{-1}, when $\sqrt{s} = 250$ GeV.
  - $(-+, +-, --, ++) = (45\%, 45\%, 5\%, 5\%)$ polarization scenario
- Exclusion limits for k^{95} (cross section scale factor)
  - $k^{95} \in$ (0.003-0.02).
  - 1-2 orders of magnitude more sensitive than LEP covering substancial new phase space

backup

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 → 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 constrain rely on the model details: CP, mass hierarchy, couplings, etc.

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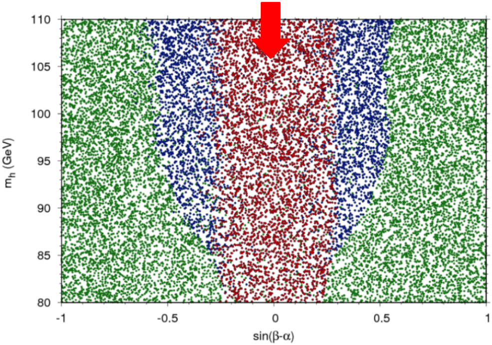


2HDM, Type I:

$tan\beta > 1.2$,

$m_A > 60$ GeV,

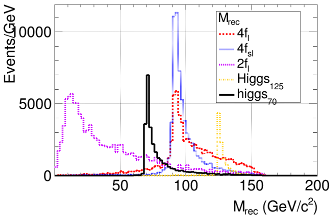
$m_{H^\pm} > 80$ GeV ..

cut effi

Four regions.

mass region	main backgrounds
$125 > M_{S^0} > M_Z$	$4f^{sl}_{zz}$, $4f_{zz/ww}$, SM Higgs
$M_{S^0} \sim M_Z$	$4f^{l}_{zz}$, $4f^{sl}_{zz}$, $4f_{zz/ww}$, SM Higgs
$M_Z > M_{S^0} > 40$	$2f_l$, $4f_{zz}$, $4f_{zz/ww}$
$40 > M_{S^0}$	$2f_l$

signal & bkgs



Cut efficiencies for different masses:

$\int Ldt = 2000 fb^{-1}$	new higgs	$4f_l$	$4f_{sl}$	$2f_l$	$total\ bk$	cut efficiency	significance
m_h = 115 GeV	17419.6	61033.9	53869.4	13877.7	128781	0.67	45.56
m_h = 90 GeV	22198.2	63210.7	74563	18514.2	156288	0.59	52.54
m_h = 70 GeV	26841.3	51671.6	60357.7	37166.6	149196	0.57	63.97
m_h = 50 GeV	30493.5	46128.1	54372.8	80074.4	180575	0.54	66.37
m_h = 30 GeV	33843.7	51206.6	55743.3	213184	320134	0.49	56.88

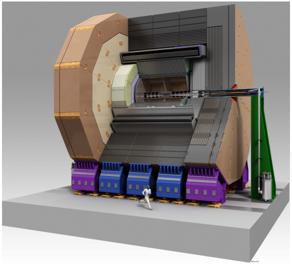
$$\text{significance} = \frac{S}{\sqrt{S+B}}, \quad \text{and } S = \kappa^2_{gZZ} \times \sigma^{m_h}_{h\mu\mu} \times \mathfrak{L}, \quad \text{where } \kappa_{gZZ} = 1$$

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.

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 signal MC samples

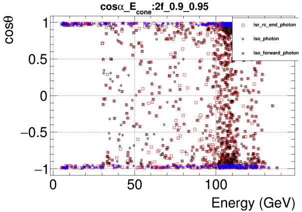
- $M_{S^0} = 10, 15, 20, ..., 120$ GeV, every 5 GeV step.
- decay branch ratios are the same as the 125 GeV SM Higgs boson.

The background MC samples:

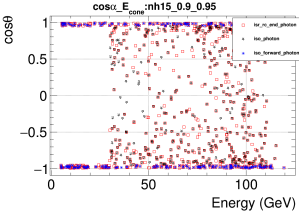
- 2-fermion $(2f^l, 2f^h)$ leptonic/bhabha/hadronic
- 4-fermion $(4f^l,\ 4f^{sl},\ 4f^h)$ leptonic/semi-lepton/hadronic
- SM Higgs, $Higgs_{125}$
- $\gamma\gamma$ backgrounds

ISR photon veto

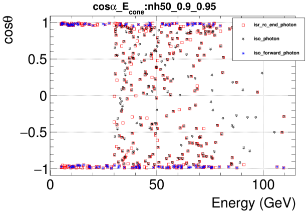
$2f_l$ process



$M_{S^0} = 15$ 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