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

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Introduction

Theory:

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

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

Current Experiments:

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

Previous Results:

250 GeV ILC
The talk on LCWS 2017
The talk on LCWS 2018
The talk on ICHEP 2018

500 GeV ILC
The IDR note

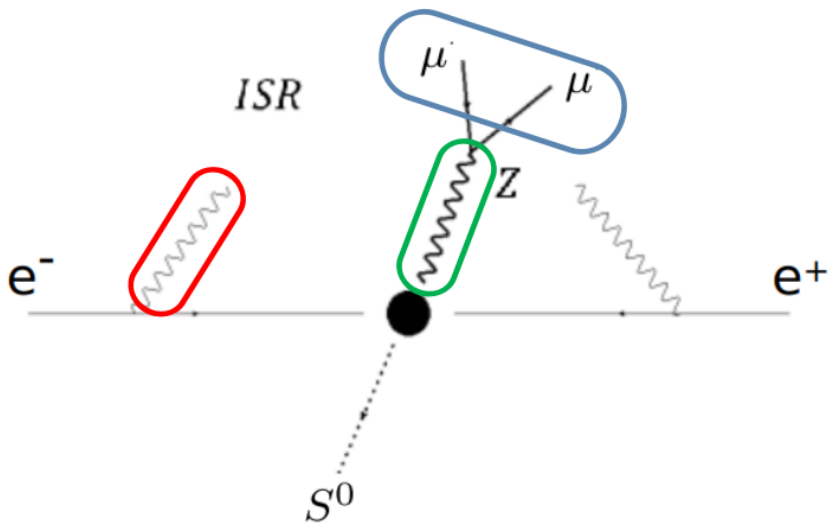
In

this talk, update results at 250 GeV and 500 GeV ILC.

Analysis Strategy

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

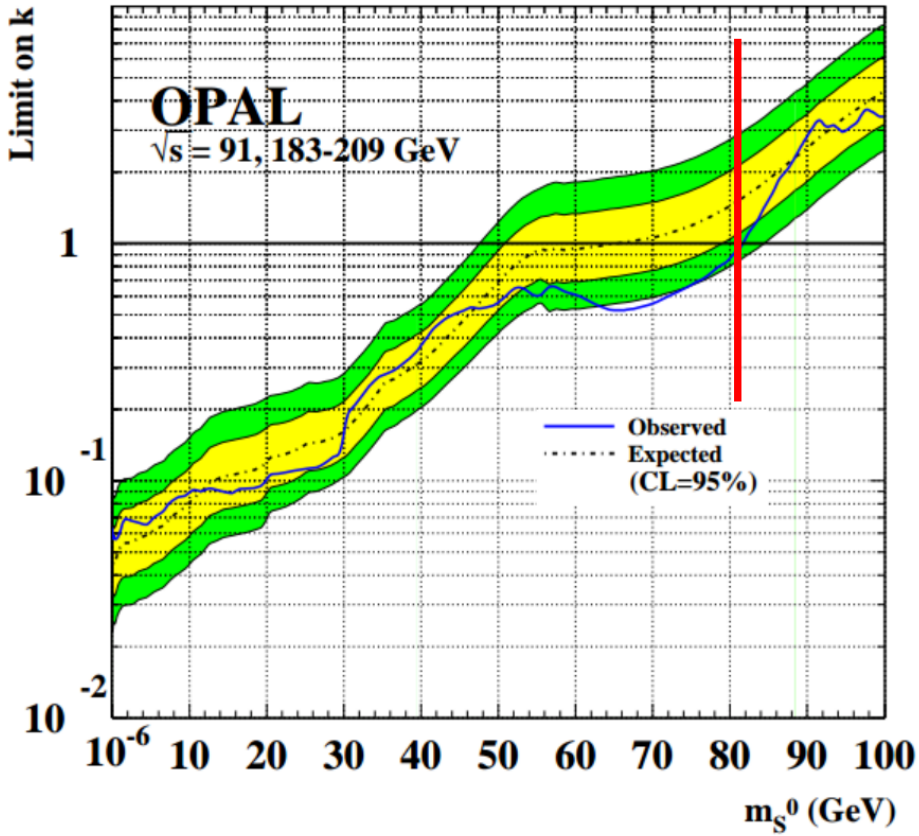
- e^+e^- collider $\rightarrow$ know the initial states behaviour $\rightarrow$ recoil technique $\rightarrow$ model independence.
- a pair of isolated muon, with opposite charges.
- ISR photons may undermine S^0 recoil distribution.
- $M^2_{rec} = (\sqrt{s} - E_{\mu\mu})^2 - |\vec{p}_{\mu\mu}|^2$
- $M_{\mu\mu} \sim M_Z$, $M_{rec} \sim M_{H^{125}/S^0}$



The Recoil Results at LEP

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

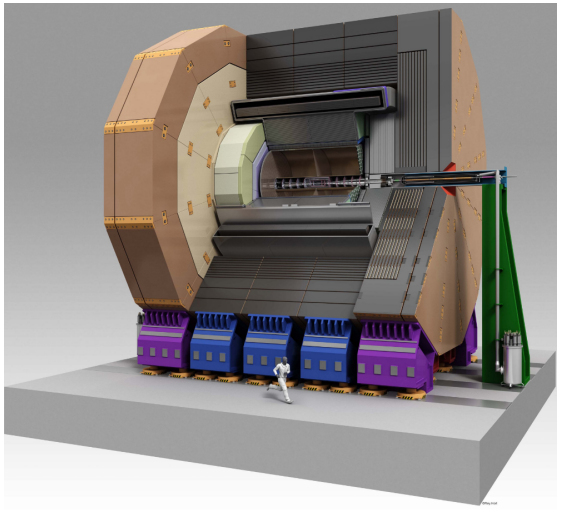
- the OPAL detector
- Decay-mode independent searches for new scalar bosons
- energy & luminosity:
  - 91.2 GeV and 0.115 fb^{-1} at LEP1
  - 161 to 202 GeV and **0.662 fb^{-1}** at LEP2.
- light higgs mass: 10 keV - 100 GeV
- $k = \frac{\sigma_{S^0 Z}}{\sigma_{H_{SM} Z (m_{H_{SM}} = m_{S^0})}}$



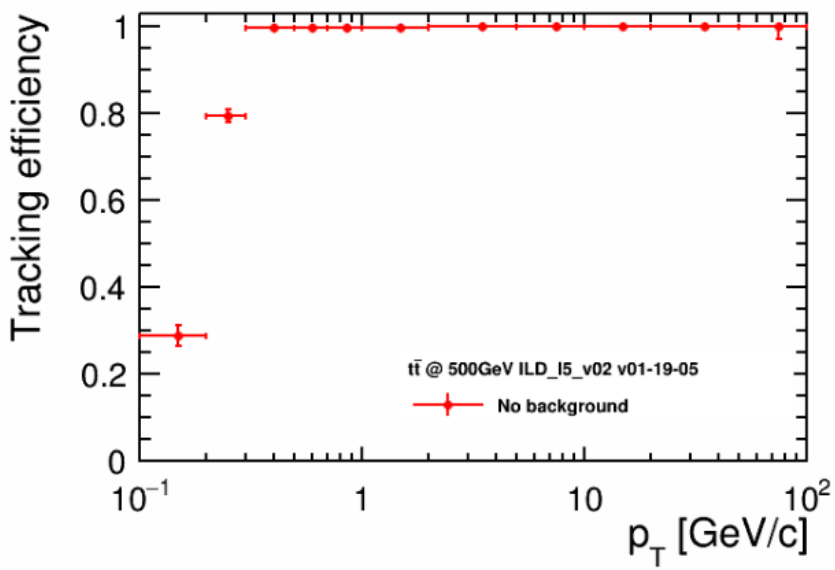
ILD (International Large Detector)

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

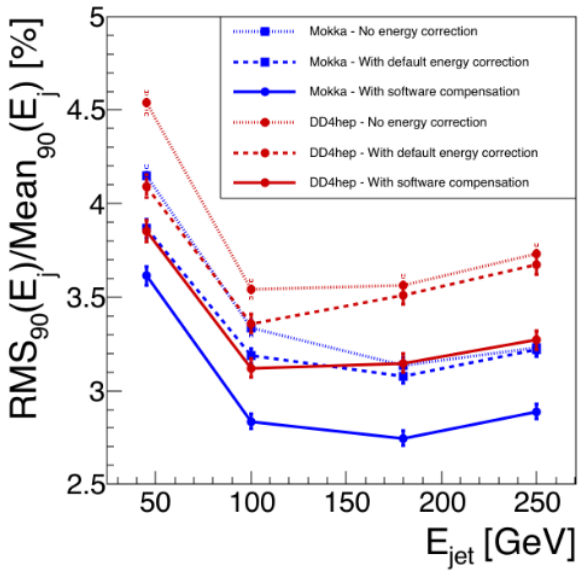
(arXiv:1306.6327, ILC TDR)



tracking performance



calorimeter performance



Comparing LEP/LHC and ILC

- comparing with LEP: ILC is sensitive to extra 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	

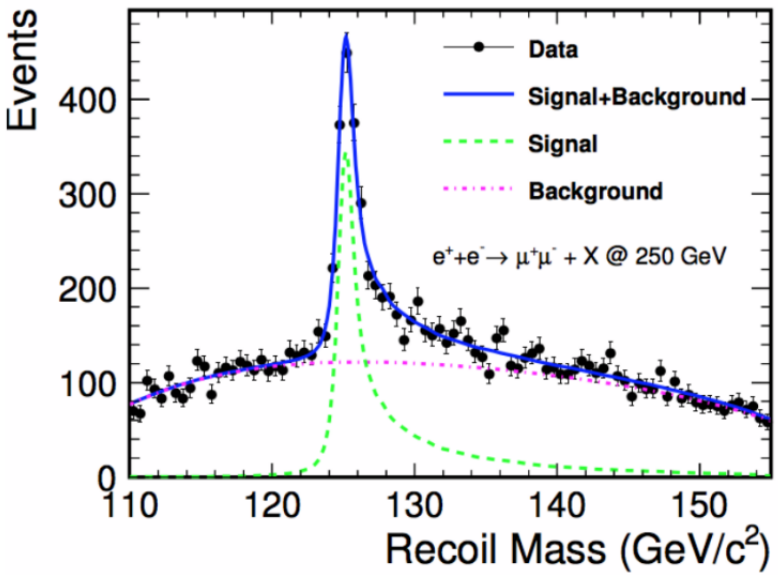
Phys.: Conf. Ser. 110 042030

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

The Recoil Method on SM Higgs at the ILC

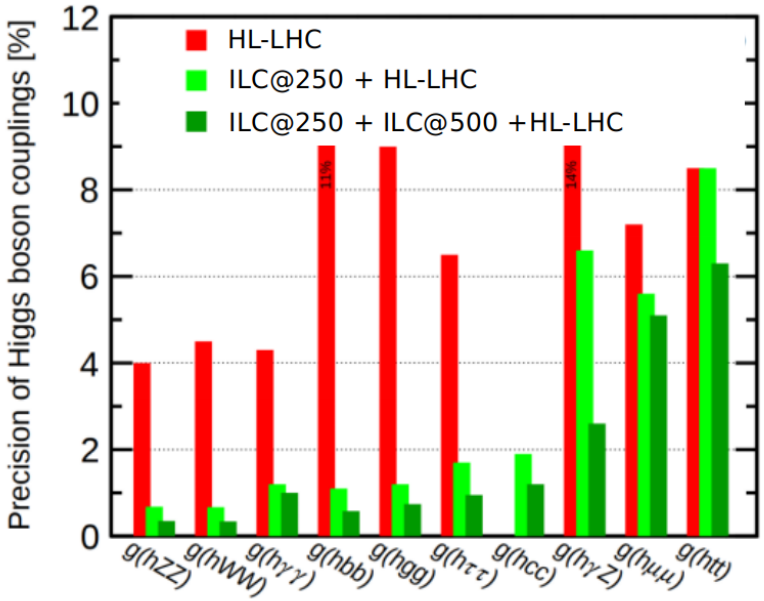
SM H^{125} recoil mass distribution (ILD)

Phys. Rev. D 94, 113002 (2016)



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

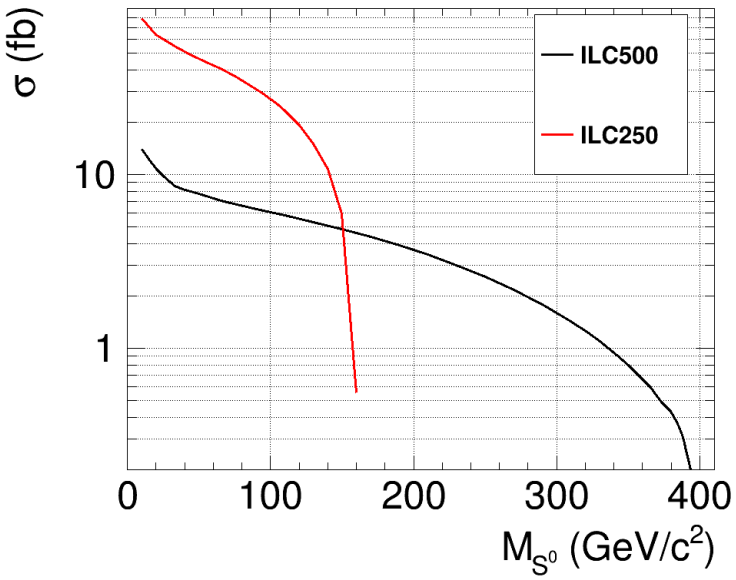
arXiv:1710.07621

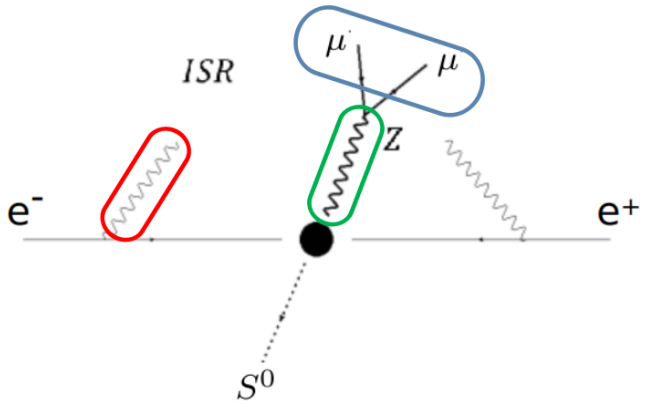


the same method on extra scalar searching, **SM** $H \to S^0$.

The Signal in this talk

The signal production:





- The signal MC samples @ ILC@250
  - $M_h = 10, 15, 20, ..., 160$ GeV,
- The signal MC samples @ ILC@500
  - $M_h = 10, 20, ..., 410$ GeV,

The signal decay $\Rightarrow$ similar as SM H^{125}, only change the scalar's mass.

The backgrounds

Included all relevant SM backgrounds:

1. 2-fermion leptonic/bhabha/hadronic (2f): $e^+e^- \to \mu^+\mu^-$
2. 4-fermion leptonic/semi-lepton/hadronic (4f): $e^+e^- \to WW/ZZ/WZ$
3. 6-fermion $t\bar{t}$, $llWW$, $qqWW$... (6f)
4. SM Higgs, $Higgs_{125}$
5. $\gamma\gamma$ backgrounds

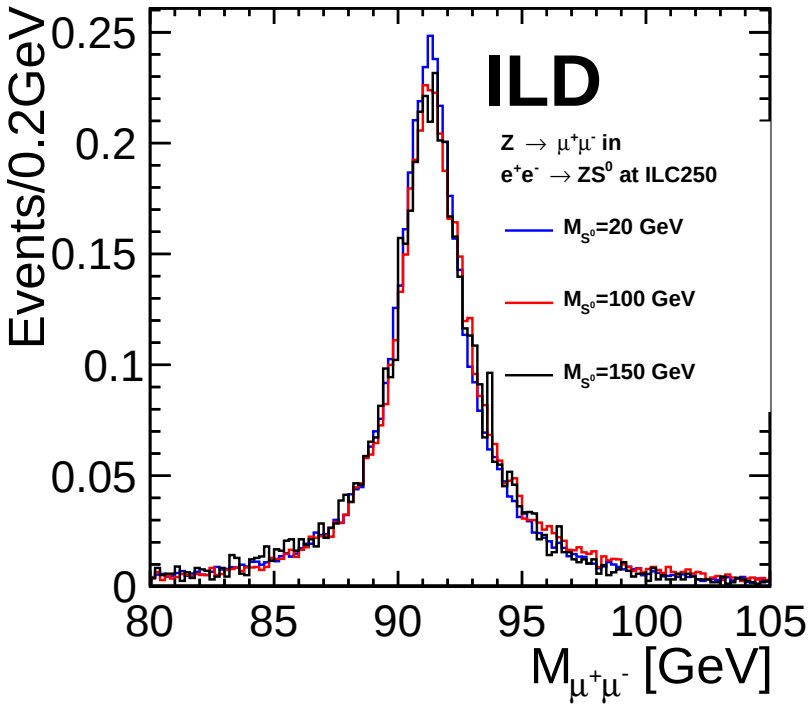
Geant4-based full detector simulation with ILD model
250 GeV : DBD samples
500 GeV : IDR-L/IDR-S samples

Analyze algorithms

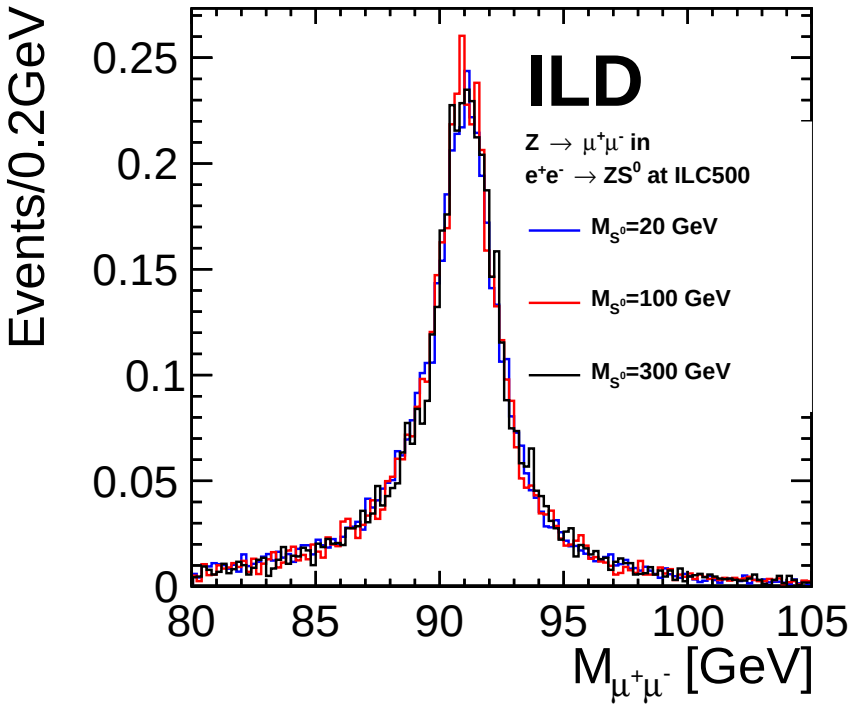
- a pair of muons, $M_{\mu\mu} \sim M_Z$, $M_{rec} \sim M_{S^0}$
- ISR photon tagging, boost leptons to effective C.M. frame
- MVA1 training for 2f background events
- MVA2 training for 4f background events
- recoil mass
- get 2σ exclusion limits k_{95} ($k = \frac{\sigma_{S^0 Z}}{\sigma_{H_{\mathrm{SM}} Z (m_{H_{SM}} = m_{S^0})}}$)

1. muon pair's invariant mass for different M_S signals

250 GeV ILC



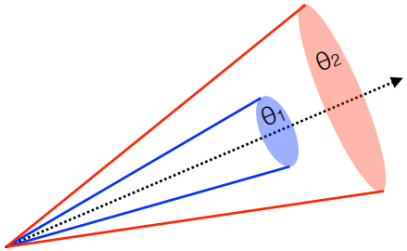
500 GeV ILC



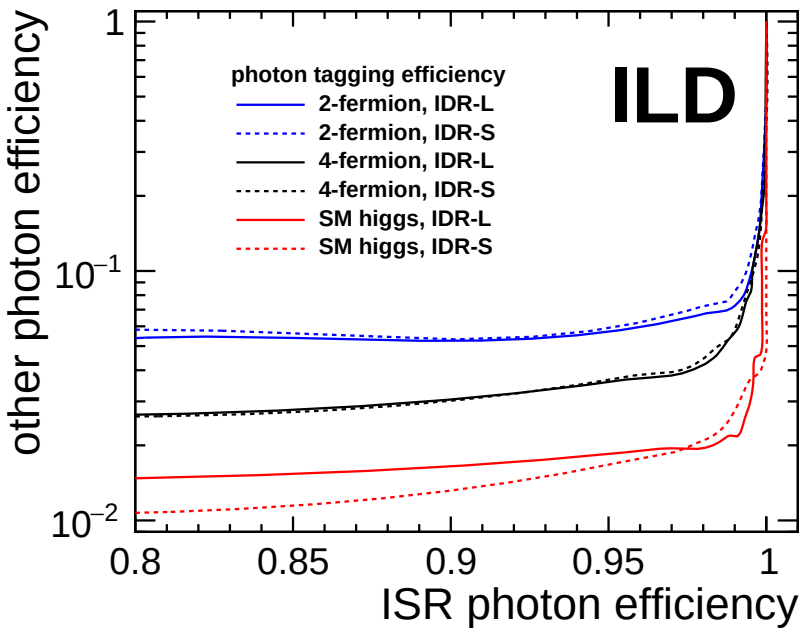
$$\chi^2(M_{\mu^+\mu^-}, M_{\rm rec}) = \frac{(M_{\mu^+\mu^-} - M_Z)^2}{\sigma^2_{M_{\mu^+\mu^-}}} + \frac{(M_{\rm rec} - M_{S^0})^2}{\sigma^2_{M_{\rm rec}}}, \quad (1)$$

2. ISR Photons Tagging

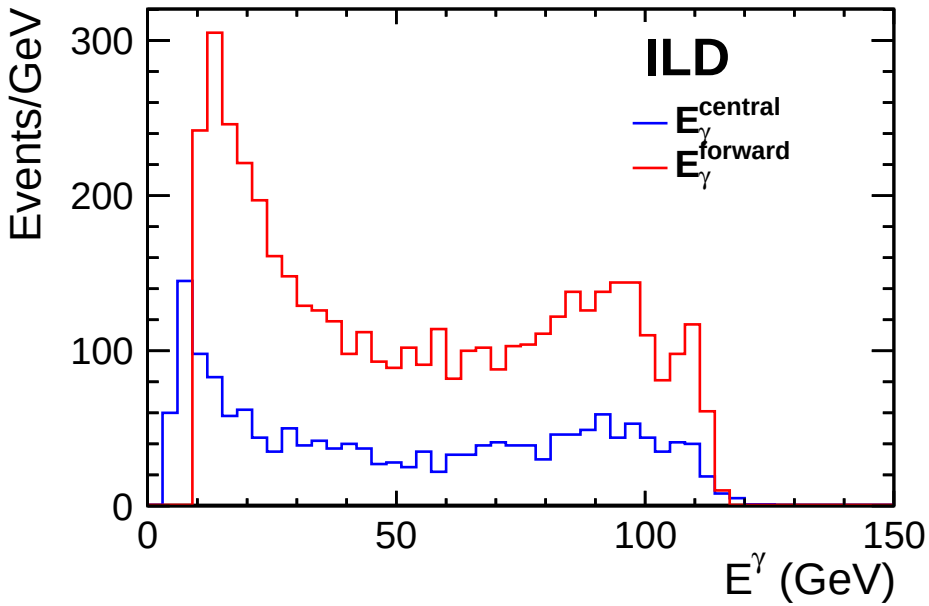
two cone method
BDTG training with 2f, 4f, SM higgs events.



Photons Tagging efficiency

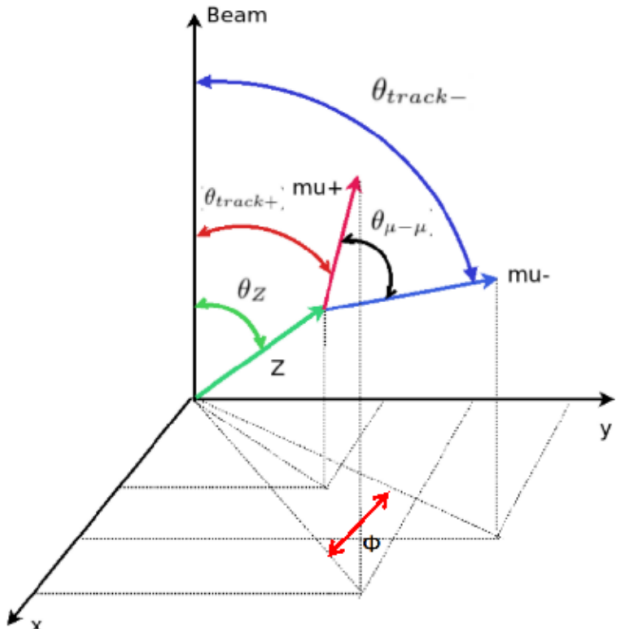


photon energy distribution

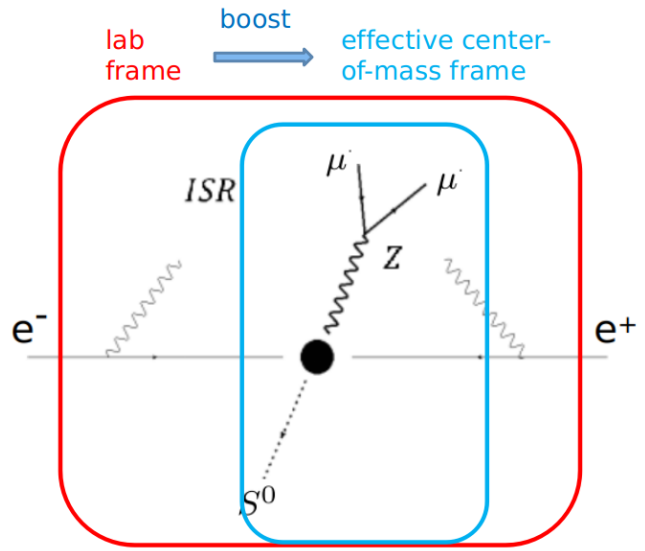


3. BDTG: input observables

input observables:
$M_{\mu\mu}$, $\cos\theta_{\mu+}$, $\cos\theta_{\mu-}$,
$\cos\theta_Z$, $\cos\theta_{\mu+-\mu-}$, acoplanar



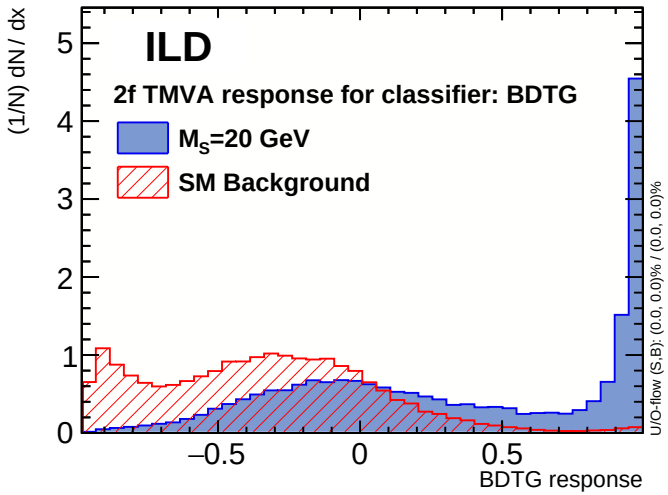
if there is ISR : boost leptons in the effective center-of-mass reference frame

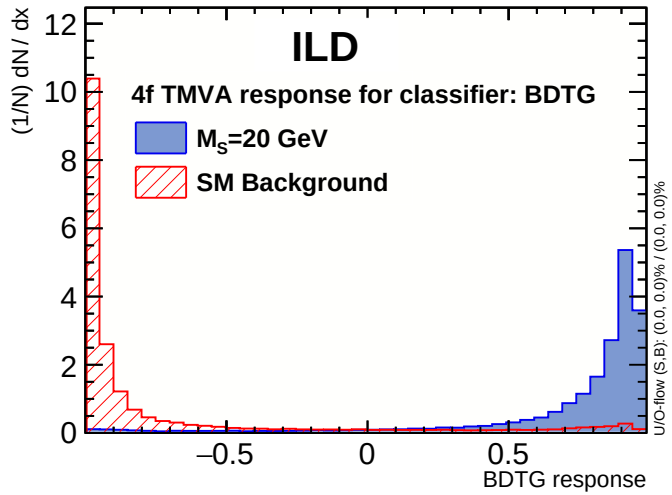


training two BDTG
BDTG1: 2fermion background events like $e^+e^- \to \mu^+\mu^-$
BDTG2: 4 fermion background events, like WW/ZZ/WZ...

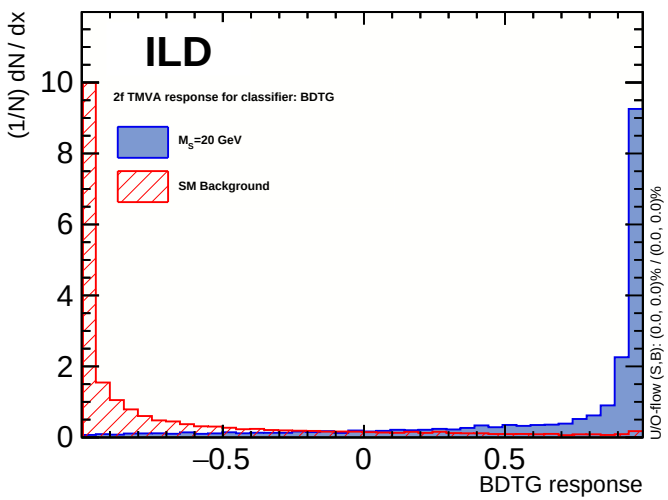
3. BDTG output

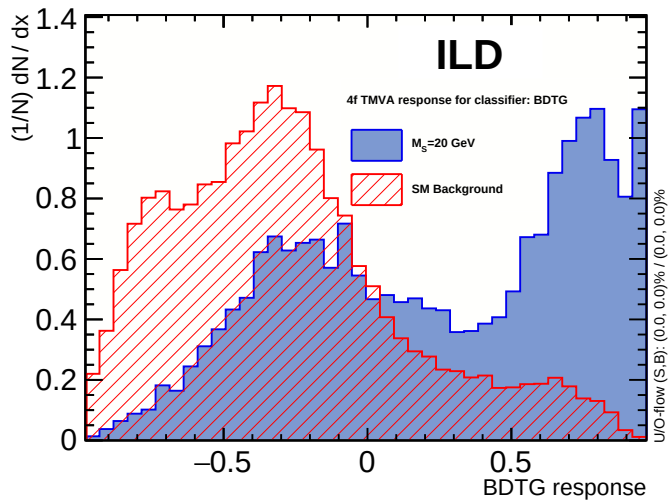
250 GeV ILC, $M_S = 20$ GeV BDTG output, left $\rightarrow$ train 2f events, right $\rightarrow$ train 4f events





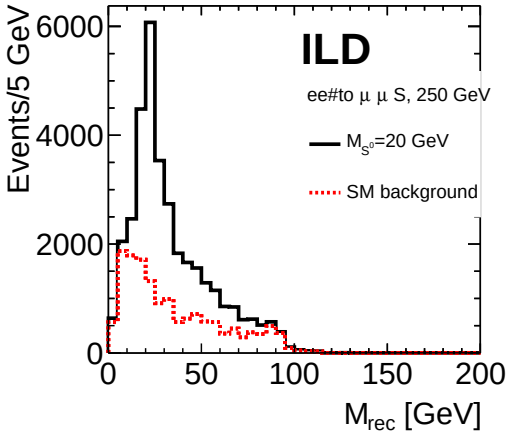
500 GeV ILC, $M_S = 20$ GeV BDTG output, left $\rightarrow$ train 2f events, right $\rightarrow$ train 4f events

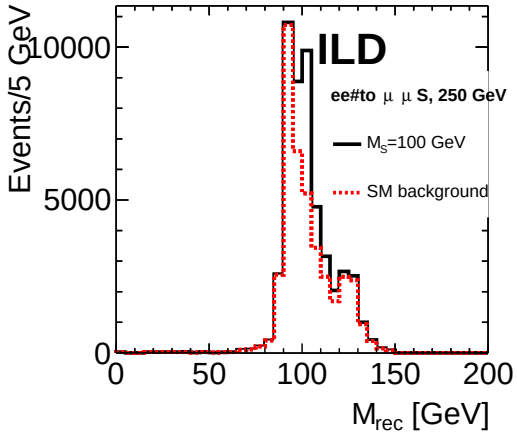


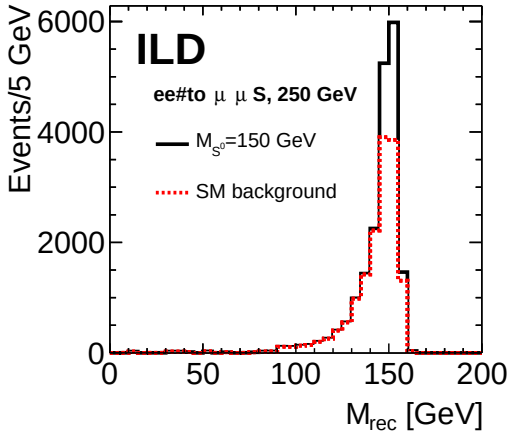


4. recoil mass

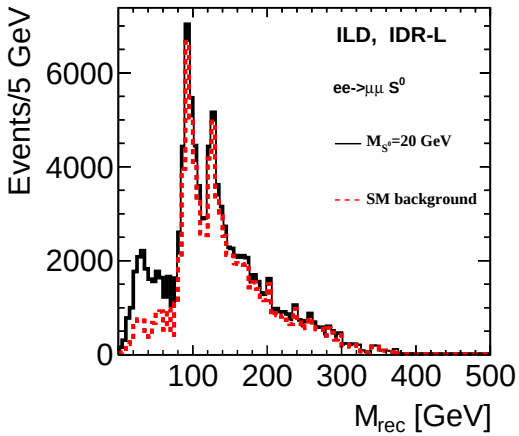
250 GeV ILC, $M_S = 20, 100, 150$ GeV

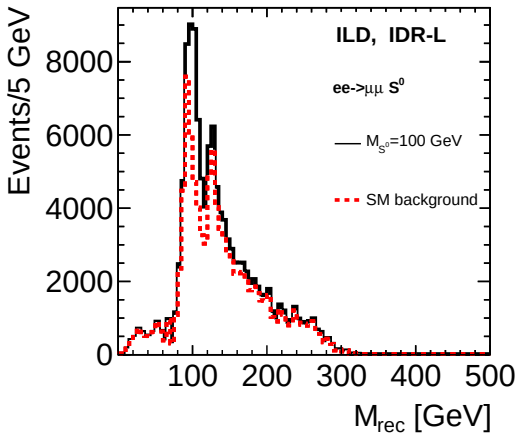


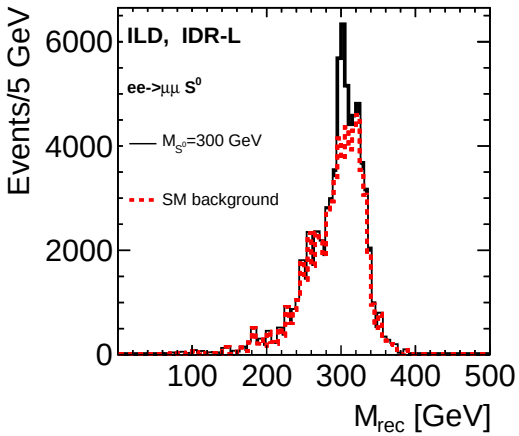




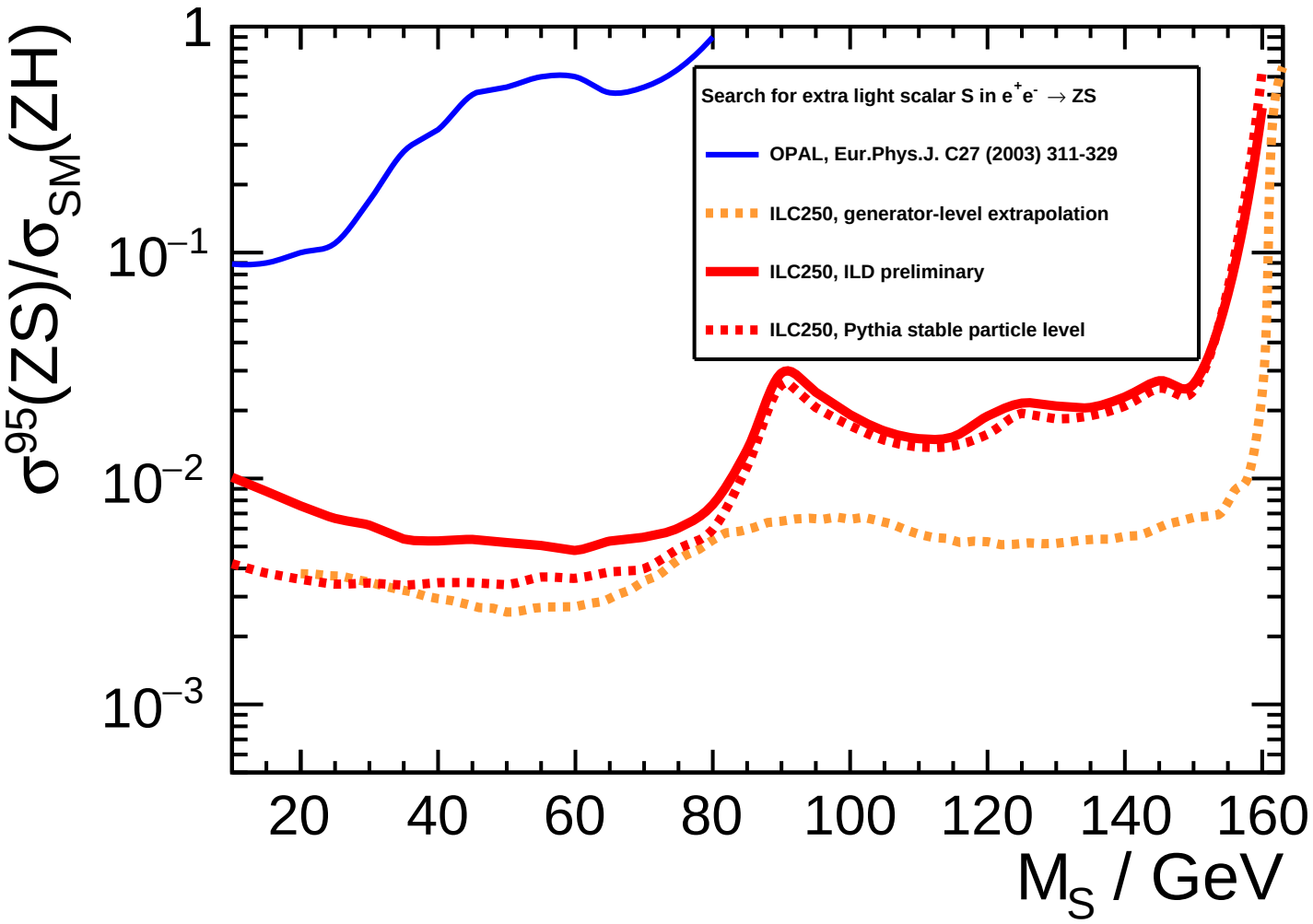
500 GeV ILC, $M_S = 20, 100, 300$ GeV



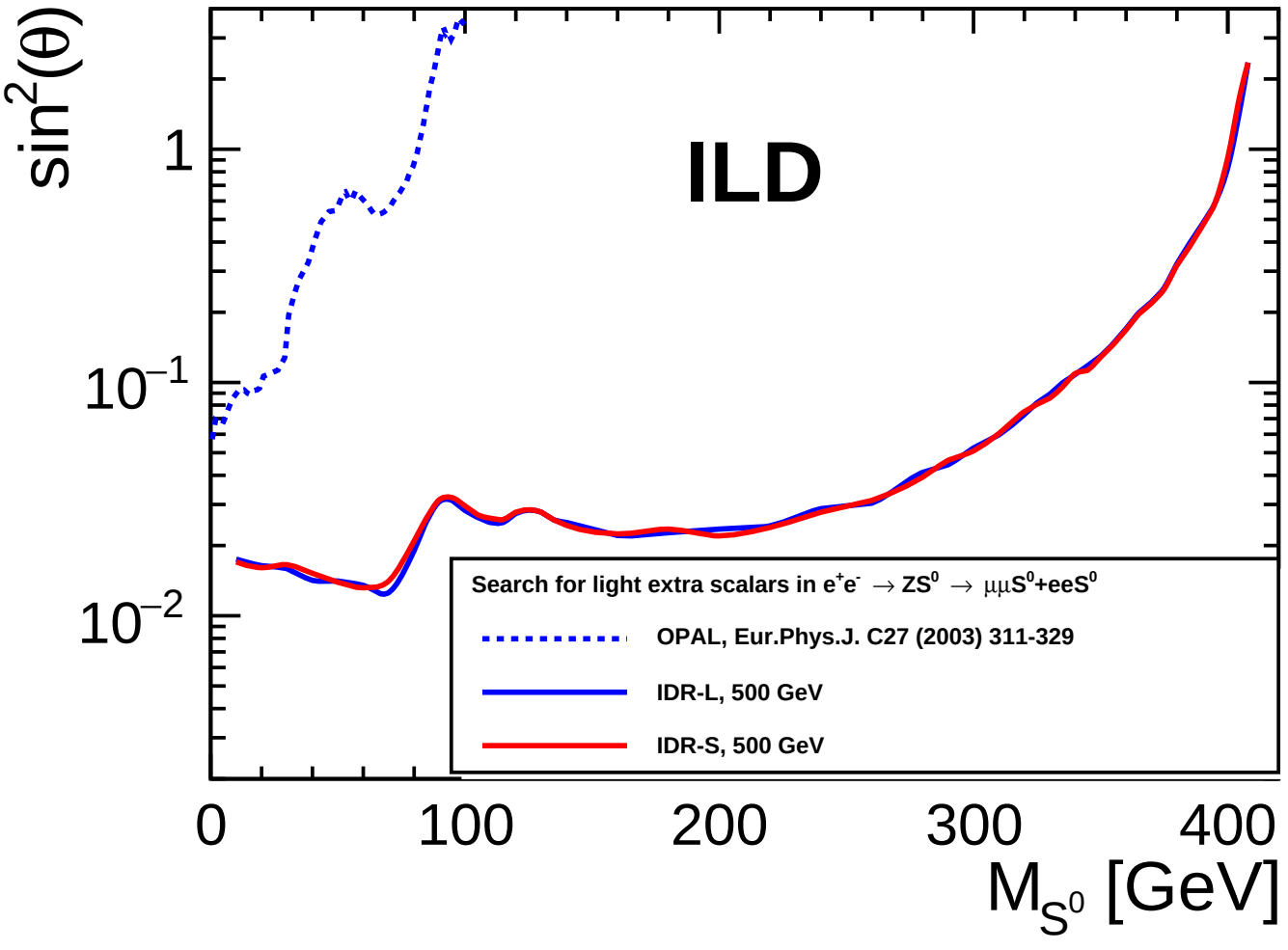




final exclusion limits at 250 GeV ILC



final exclusion limits at 500 GeV ILC



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 at 250 GeV and 500 GeV ILC.
  - 1-2 orders of magnitude more sensitive than LEP
  - covering new phase spaces

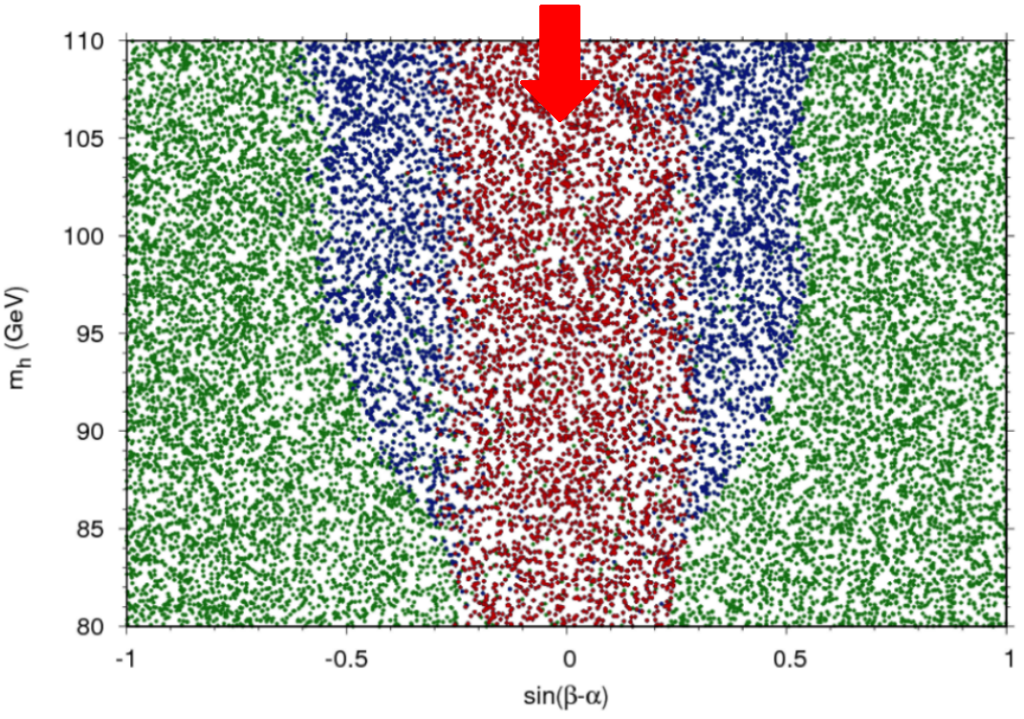
Past Experiment Results parameters

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.

JHEP 12 (2016) 068

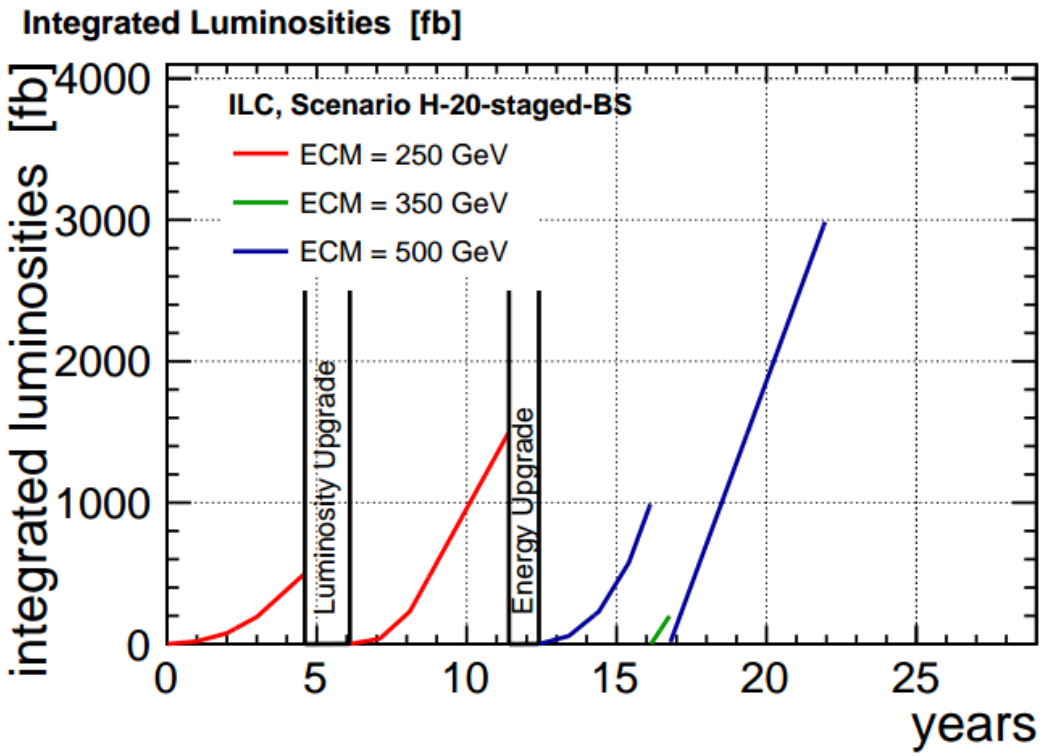
survived after indirect + LEP + LHC constrains



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

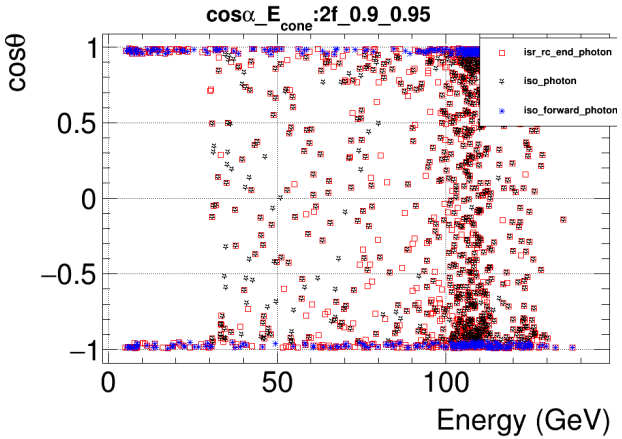
ILC run Scenario

- totally 22 years
- $(-+, +-, --, ++) = (45\%, 45\%, 5\%, 5\%)$ polarization scenario for 250 GeV
- $(-+, +-, --, ++) = (40\%, 40\%, 10\%, 10\%)$ polarization scenario for 500 GeV

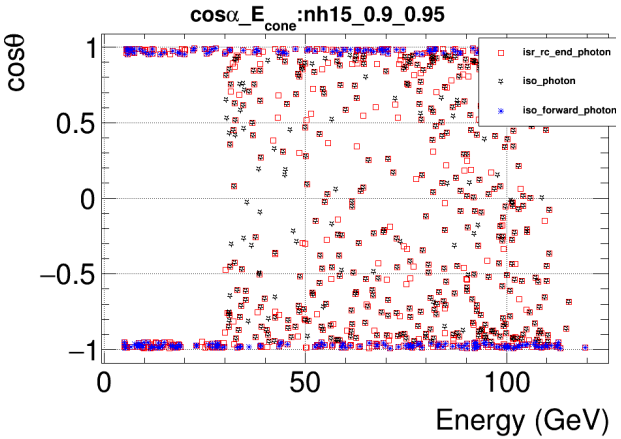


ISR photon veto

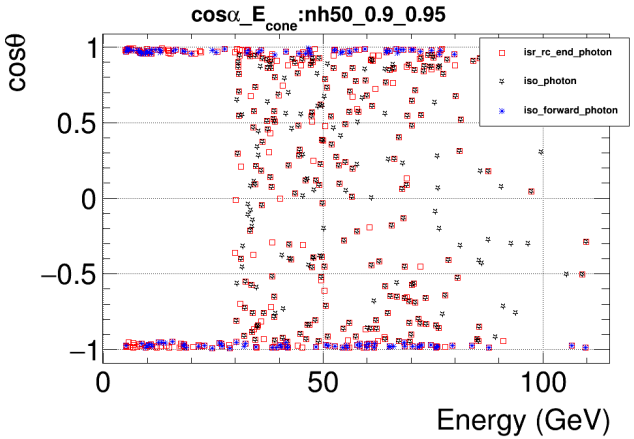
$2f_l$ process



$M_h = 15\,\text{GeV}$ process



$M_h = 50\,\text{GeV}$ process



- There is photon return effects in $2f$ process.
- identify ISR photon by
  - ISR photon in the central region ($\cos\theta < 0.95$): $E_{\text{central}} > 100\,\text{GeV}$
  - ISR photon in the forward region ($0.95 < \cos\theta < 0.99$): $E_{\text{forward}} > 60\,\text{GeV}$
  - 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 extra 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