Complementary M_{H} Measurements at ILC

(i) Threshold cross-section, ii) Direct reconstruction

Graham W. Wilson

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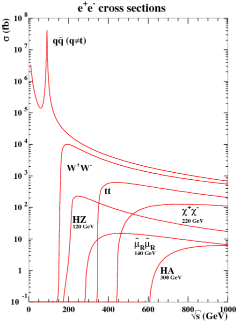
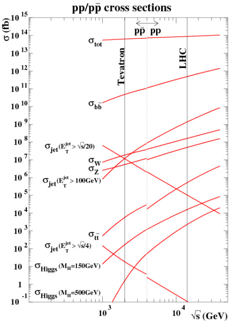




Introduction

Higgs Mass Measurements

- LHC is measuring, and will continue to measure M_{H} using direct mass reconstruction in the $\gamma\gamma$ and 4-lepton channels. Current PDG average has an error of 240 MeV based on RunI data.
- ILC can measure the Higgs mass cleanly using the recoil mass in the dilepton channels. H20 precision estimate is 14 MeV. Sensitivity per fb^{-1} depends on beam spectrum. Higher $\sqrt{s}$ of limited utility.

Today: Alternative and Complementary ILC Higgs Mass Measurements

- M_{H} from the Threshold Cross-Section
- Direct reconstruction of M_{H} at ILC. Assume 1M produced Higgs particles over the course of the program. Focus for now on 4l and $\mu\mu$.

For direct reconstruction, the issue for each channel, is can one compete statistically and systematically in terms of M_{H} precision with LHC.

$$\Delta M = \sigma_M/\sqrt{N}$$

Typically with a factor of 100 more events at LHC, one needs ILC detector mass resolution to be 10 times better than LHC. LHC systematic wall? 0.01–0.1 σ_M ?

Motivation for Precise Higgs Mass Measurement

Why measure M_{H} as precisely as possible?

- Why not?
- It is naively not as important as a test of the SM as the top mass and the W mass, but it is something that is directly accessible in a relatively optimized way at the initial-stage of an ILC starting at $\sqrt{s} = 250$ GeV.
- Parametric uncertainties from M_{H} enter coupling determinations due to the strong phase-space related dependence in the ZZ* and WW* decays. See eg. Almeida, Lee, Pokorski, Wells, PRD89, 033006 (2014).

$$\left(\frac{\Delta\Gamma_{\mathrm{ZZ}}}{\Gamma_{\mathrm{ZZ}}}\right) = 15.3 \left(\frac{\Delta M_{\mathrm{H}}}{M_{\mathrm{H}}}\right) \quad (1)$$

$$\left(\frac{\Delta\Gamma_{\mathrm{WW}}}{\Gamma_{\mathrm{WW}}}\right) = 13.7 \left(\frac{\Delta M_{\mathrm{H}}}{M_{\mathrm{H}}}\right) \quad (2)$$

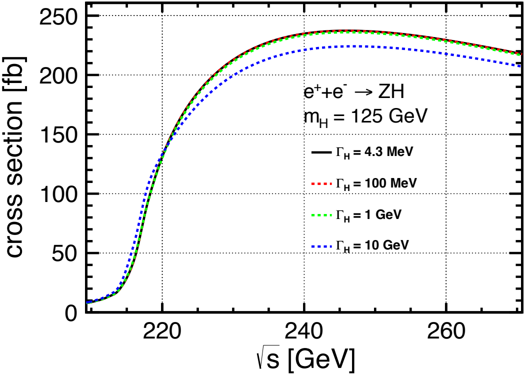
So for 0.1% parametric uncertainty from M_{H} on these partial widths, need error on M_{H} of 8 MeV.

Nominal threshold for ZH production is $M_\mathrm{H} + M_\mathrm{Z} \approx 216.2$ GeV

Measurement of the ZH cross-section can be used to determine M_H.

M_H will likely be known to at least 100 MeV. So no need to scan if sole model-dependence is M_H

Modest statistics - so statistics dominated measurement. Less need and less advantage (than WW threshold) for a (polarized) scan.



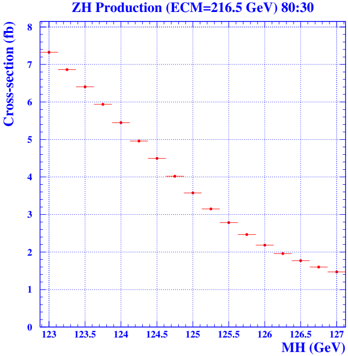
Optimal $\sqrt{s} \approx 216.5$ GeV. How accurate? How much lumi?

- Calculate $\mathrm{e}^{+}\mathrm{e}^{-} \rightarrow \nu_{\mu}\overline{\nu}_{\mu}\mathrm{H}$ (ZH-like) cross-sections with Whizard 2.5
- $B(Z \rightarrow \nu_{\mu}\overline{\nu}_{\mu}) = 0.067$
- Include ISR. For now have neglected beam-spread and beam-strahlung
- Study various beam polarization scenarios
- Statistical sensitivity from signal statistics depends on the statistical error on the cross-section measurement and the slope of the cross-section dependence on M_{H}

$$\Delta M_{\mathrm{H}} = \sqrt{\sigma}\left|\frac{d\sigma}{dM_{\mathrm{H}}}\right|^{-1}\frac{1}{\sqrt{\varepsilon\mathcal{L}}}$$

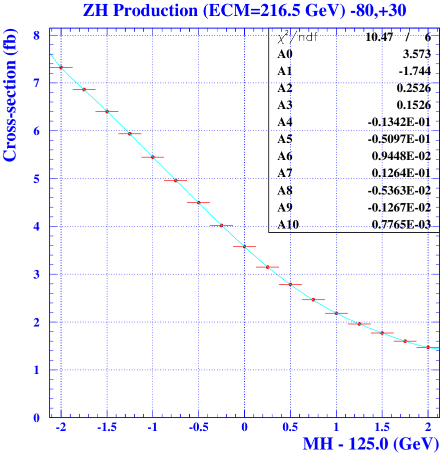
- Similar considerations for M_{W} at LEP161 (unpolarized beams) led to

$$\Delta M_{\mathrm{W}} = 29\ \mathrm{MeV}\ /\ \sqrt{\varepsilon\mathcal{L}(\mathrm{fb}^{-1})}$$



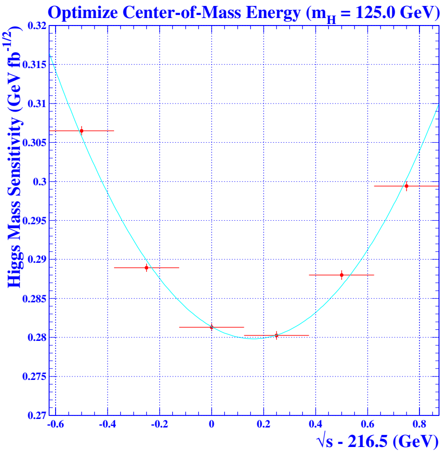
Threshold Cross-section Study Method

- Polynomial fits to $e^+e^- \to \nu_\mu \overline{\nu}_\mu H$ cross-section vs $M_H - 125.0$ GeV for each $\sqrt{s}$
- Errors are Whizard integration errors
- Increase polynomial degree if resulting χ^2 lowered by more than 1
- Statistical sensitivity coefficient, at $M_H = 125.0$ GeV, $\alpha \equiv \sqrt{\sigma} \left| \frac{d\sigma}{dM_H} \right|^{-1}$, is given by $\sqrt{A0}/|A1|$.
- Example for (-80% e^-, +30% e^+) at $\sqrt{s} = 216.5$ GeV:
- $\alpha = 1.08$ GeV$/\sqrt{\text{fb}}$
- $\alpha_{ZH} \approx \alpha \sqrt{B(Z \to \nu_\mu \overline{\nu}_\mu)} =$ 280 MeV$/\sqrt{\text{fb}}$



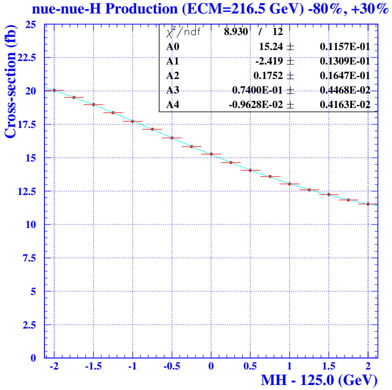
$\sigma = 3.6$ fb. $\sigma_{ZH} = 53.3$ fb

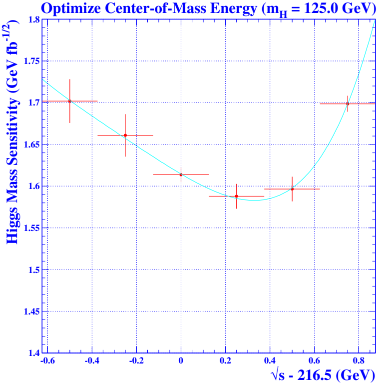
- Check $\sqrt{s}$ dependence of Higgs mass sensitivity for ZH
- Optimal $\sqrt{s} \approx 216.65$ GeV
- Roughly nominal + 0.5 GeV (same as WW)
- Statistical sensitivity factor, 280 MeV/$\sqrt{\mathrm{fb}}$, is ten times less precise (cf 29 MeV/$\sqrt{\mathrm{fb}}$).
- Substantial integrated luminosity needed to target 25 MeV and below.



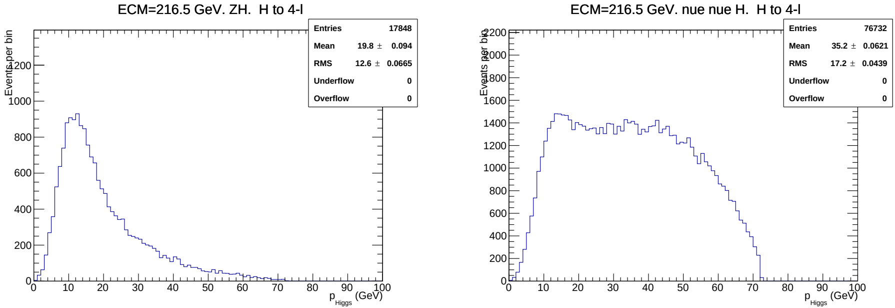
For -80%(L) e^-, +30%(R) e^+

Process has contributions from ZH and WW-fusion. WW-fusion contribution dilutes M_H sensitivity significantly. (1.58 GeV/$\sqrt{\text{fb}}$ cf 1.08 GeV/$\sqrt{\text{fb}}$ for $e^+e^- \to \nu_\mu\overline{\nu}_\mu H$)





[Initial indication: $e^+e^- \to e^+e^-H$ is ZH-like with no significant dilution from ZZ fusion]



- Scope for kinematic cuts to reduce WW-fusion contribution and/or categorize events as more or less ZH-like recuperating some of the lost sensitivity
- It may be feasible by kinematic cuts/criteria to increase the slope of σ vs M_{H} in some channels (suppressing ISR, mass cuts on the Z etc.)
- NB So far no considerations at all about background contributions NOR on event selection efficiency. Study naively assumes 100% efficiency for all channels, and no background

Higgs Sensitivity Numbers from Threshold Cross-section

For various beam polarization configurations. For ZH, beam polarization is of some use.

Mass Sensitivities ($\sqrt{s} = 216.5$ GeV, $M_{\mathrm{H}} = 125.0$ GeV)

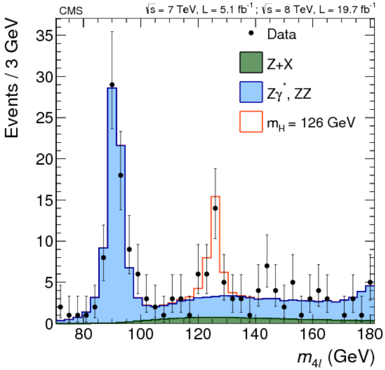
Setting	α_{HZ}[MeV/$\sqrt{\mathrm{fb}}$]	ΔM_{H} [MeV] (50 fb^{-1})	ΔM_{H} [MeV] (0.5 ab^{-1})
−80, +30	279	39.5	12.5
−90, +60	250	35.3	11.2
−80, +60	255	36.1	11.4
−90, +30	268	37.9	12.0
+80, −30	342	48.4	15.3
−80, −30	366	51.7	16.4
+80, +30	422	59.7	18.9
−80, 0	310	43.9	13.9
+80, 0	376	53.2	16.8
0, 0	341	48.2	15.2
−100, +100	218	30.8	9.8
+100, −100	272	38.5	12.2

NB. Signal statistical error only. 100% efficiency, no background.

To do

If you agree that this is of some interest, need some estimate of backgrounds, to clarify feasibility. Clearly need more channel-by-channel event selection procedure to keep backgrounds under control.

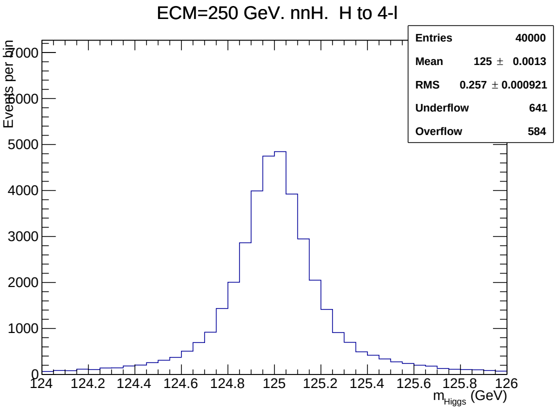
Note that running at threshold is likely not so attractive for other measurements ....



What can we do at ILC?

Can we use other channels?

$\sigma_M \approx 2.0$ GeV



$\sigma_M \approx 0.19$ GeV

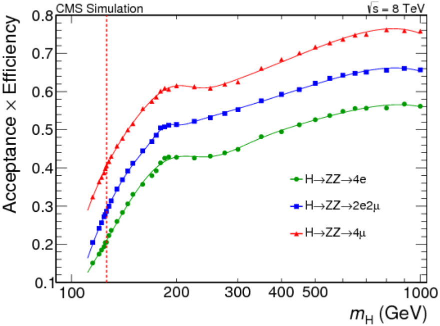
Yes indeed. An ILC detector gives mass resolution about 10 times better than LHC !

Estimated using PYTHIA8 events including FSR. Assumes tracking-like momentum resolution for electrons and muons. ECAL-like resolution for photons. Possibly OK for $\mu\mu\mu\mu$, likely underestimate for $ee\mu\mu$ and $eeee$.

Numerology

LHC cross-sections are substantial.

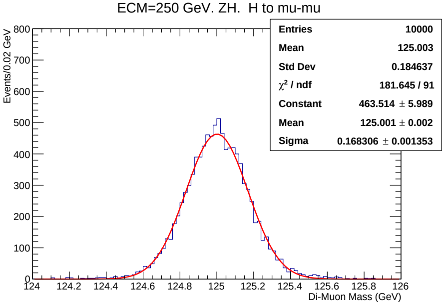
- ggFusion (8 TeV) $= 21$ pb
- ggFusion (13 TeV) $= 49$ pb
- ggFusion (14 TeV) $= 55$ pb.



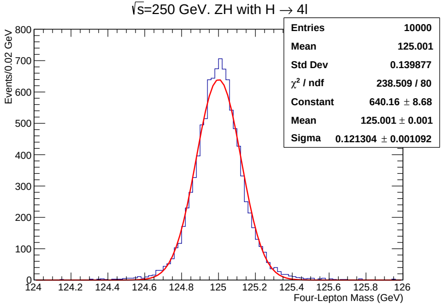
acceptance*efficiency modest - more so (I think) at 13 TeV. Backgrounds often substantial (especially $\gamma\gamma$)

Simulations

Generated Higgs events both with Whizard and Pythia8. 4-vector smearing based on ILD type tracker, ECAL, HCAL and PFA resolutions. Pythia8 samples include FSR (final-state radiation).
Most promising channels appear to be Higgs decays to $\mu^+\mu^-$ and Higgs to 4 leptons (assume for now the same p resolution for e and μ ...).
The 2-body decay has higher momenta (worse resolution). Four-leptons have lower momenta (better resolution). Here Whizard ZH samples with NO FSR.



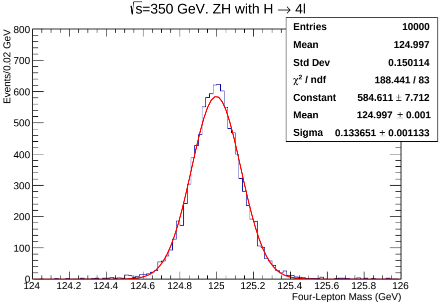
$\sigma_M = 0.168$ GeV

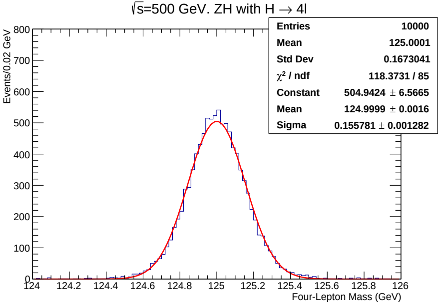


$\sigma_M = 0.121$ GeV

$\sqrt{s}$ dependence?

Whizard ZH samples (No FSR) with $H \to \mu\mu\mu\mu$.
At $\sqrt{s} = 250$ GeV, $\sigma_M = 0.121$ GeV.
Now $\sqrt{s} = 350$ GeV and $\sqrt{s} = 500$ GeV.





$\sigma_M = 0.134$ GeV $\qquad\qquad$ $\sigma_M = 0.156$ GeV

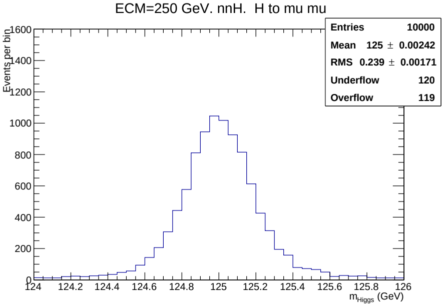
This is in contrast to the recoil mass. And additionally the WW-fusion production can be utilized at high $\sqrt{s}$ (lower p_{H} compared to ZH at high $\sqrt{s}$)

Simulations with FSR

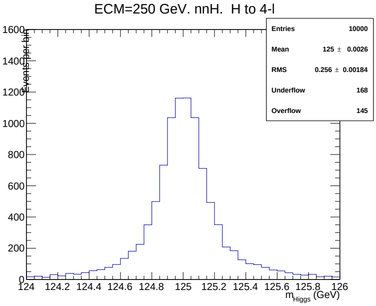
WW-fusion events with Pythia8. These include FSR (final-state radiation). ISR photons are flagged at "truth level" and not included in the mass estimation. Most promising channels appear to be Higgs decays to $\mu^+\mu^-$ and Higgs to 4 leptons.

The 2-body decay has higher momenta (worse resolution). Four-leptons have lower momenta (better resolution). But more leptons so more FSR. Following are $\mu^+\mu^-$ and 4l based on tracker + FSR photons (4e, 2e2μ and 4μ). Better ECAL resolution would help ...

Estimate σ_M from Voigtian fit (BW convolved with Gaussian).



$\sigma_M = 0.21$ GeV



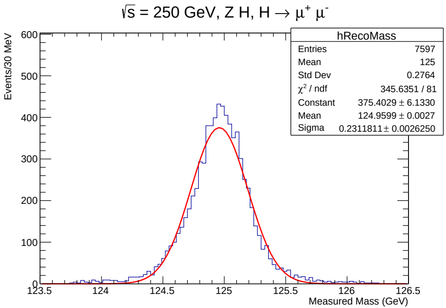
$\sigma_M = 0.19$ GeV

Full simulations with FSR: Work in progress

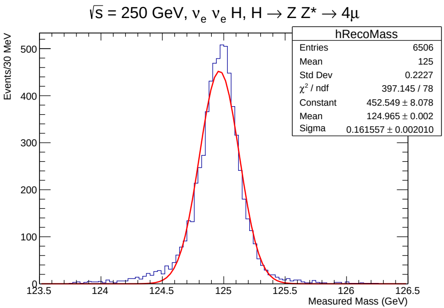
Use ILD full simulation and reconstruction. Detector ILD_l4_v02. ilcsoft v01-19-04.

Two samples at $\sqrt{s} = 250\ GeV$ with Pythia8 including FSR. ZH for decay to $\mu^+\mu^-$ and WW-fusion for decay to 4μ.

First look. Use mass estimate using just the muonic system ignoring any FSR photons. Mass resolutions estimated for events where the muon tracks alone satisfy a Higgs mass constraint,($p_{\rm fit} > 0.5\%$). Most of rejected events will have significant FSR and will need different treatment.



$\sigma_M = 0.23$ GeV



$\sigma_M = 0.16$ GeV

BRs, mass resolution estimates, ΔM guesstimates

Assume 1M produced (and detected) Higgs particles for ILC. Neglect background. LHC mass resolution estimate based on CMS.

Mass Uncertainty Prospects

Decay Mode	BR (SM)	LHC σ_M [GeV]	σ_M [GeV]	ΔM_{H} [MeV]
bb	0.5824	X	3.1	(4.1)
cc	0.0289	X	3.1	(18.2)
gg	0.0819	X	3.1	(10.8)
$\gamma\gamma$	22.70×10^{-4}	1.6	2.2	46.2
$\mu^+\mu^-$	2.176×10^{-4}	X	0.21	14.2
$\mu^+\mu^-\mu^+\mu^-$	3.249×10^{-5}	1.7	0.17	29.8
$e^+e^-\mu^+\mu^-$	5.897×10^{-5}	2.3	(0.19)	24.7
$e^+e^-e^+e^-$	3.254×10^{-5}	2.8	(0.22)	38.6
Others		X		

Averaging the four leptonic channels one gets an overall statistical uncertainty of 10.9 MeV.

Caveats

Other $M_{\rm H}$ Measurement Methods at ILC

- Full reconstruction of 4-jet events was studied for TESLA.
- Potential for direct reconstruction with $H \rightarrow bb$ but this is a systematically challenging approach.

Event Selection

- 4l channel. Common wisdom - should be straightforward. I agree.
- $\mu^+\mu^-$ channel. To date, ILC studies have not demonstrated efficient isolation of this signal from significant residual backgrounds. It has yet to be shown that this channel can be isolated cleanly. Studies have emphasized $\nu_{\rm e}\overline{\nu_{\rm e}}H$ at $\sqrt{s} >= 500$ GeV.
- My take: I believe that ZH production at $\sqrt{s} = 250$ GeV should be more tractable and deserves in-depth study for this $\mu^+\mu^-$ channel

Summary and Conclusions

Threshold

- Threshold Cross-Section Statistical Sensitivity Factor is 280 MeV/$\sqrt{\mathrm{fb}^{-1}}$
- M_{H} uncertainty from threshold below 50 MeV will likely need at least 50 fb^{-1}
- Significant dedicated luminosity needed to be competitive with recoil mass
- Firmer conclusions would need more detailed study with event selection and background estimates
- Would be good to understand if threshold shape is sensitive to EFT parameters.

Direct Reconstruction

- Direct reconstruction of the Higgs mass in "golden channels" looks to be very competitive with LHC and other ILC methods. One single event can give a mass resolution better than the current world average.
- This deserves more study with full simulation - started.
- Electron reconstruction (tracking) needs more attention.
- ECAL energy resolution is an issue for FSR reconstruction.
- Even better momentum resolution very valuable.

Backup Slides