Total Width Measurement at the ILC

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Based on Work with Tao Han and Zhen Liu
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Table of contents

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Or an unreasonable facsimile thereof...

The LHC will continue to search for new physics in the form of SUSY, Extra Dimensions, Dark Matter, Additional Higgs, Z', W', 4^{th} Generation, etc., etc.

If nothing else it will continue to refine our knowledge of the Higgs via coupling strengths, mass and width.

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If nothing else it will continue to refine our knowledge of the Higgs via coupling strengths, mass and width.

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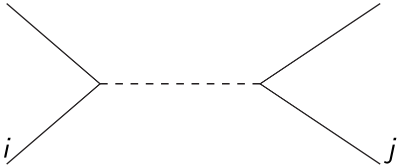
But there is a problem.

The Problem

We don't really measure g_i and Γ at the LHC. We measure processes of the form



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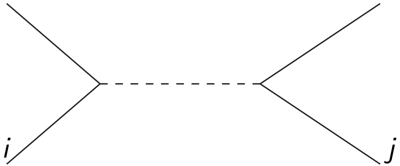


$$\sigma_{ij} \propto \frac{g_i^2 g_j^2}{\Gamma}$$

$$\forall i : g_i \to x g_i \qquad \Gamma \to x^4 \Gamma$$

Regardless of how many σ_{ij}s we measure.

Constraints are model dependent.

The Solution

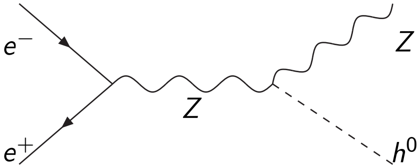
Measure $ii \to h \propto g_i^2$!

Break the degeneracy by measuring inclusive rates.

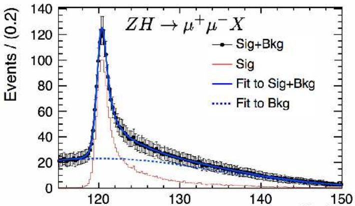
- But, virtually no way to do this at the LHC without assumptions.
- Can't rely on decay products.
- Instead use other particles in interaction to reconstruct a typical signature.
- Recoil mass to the rescue: $ii \to h + X$ then $M(ii - X) = M_h$
- Don't know initial states completely in a hadron collider, but we do at a lepton collider.

Recoil Mass at the ILC

At 250 GeV, we maximize Higgs production via "Higgstrahlung".



This allows a sharp mass peak (especially with $Z \to \mu\mu$) from which we can determine the cross-section $\delta\sigma_{Zh} \sim 2.5\%$. [Hengne Li, 2009]



Higgs Width Determination in General

By measuring the inclusive cross-section $\sigma_{Zh} \equiv \sigma(e^+e^- \to Zh)$ we can extract the coupling constant g_{hZZ} (to $\sim 1\%$).

We can use this to get the total width, and with that we can normalize all other couplings correctly and model independently. **All model independent width determinations depend on this measurement.**

The most straightforward way to calculate the total width:

$$\Gamma = \frac{\sigma_{ZH}^2}{\sigma_{ZZ}}$$

where $\sigma_{ZZ} \equiv \sigma(e^+e^- \to Zh \to ZZZ)$.

Unfortunately this is a rather hard measurement due to small cross-section.

For 250fb^{-1} at 250 GeV, $\delta_{ZZ} \equiv \frac{\Delta\sigma_{ZZ}}{\sigma_{ZZ}} \sim 20\%$. I.e. $\delta_\Gamma \sim 20+\%$.

Generalizing

g_Z is our only independently measure coupling, so we need something proportional to $\frac{g_Z^n}{\Gamma}$. In practice $n = 4$ is our only choice. But, rather than:

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Or even a step further

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{ki}\sigma_{jl}}{\sigma_{Zi}\sigma_{Zj}\sigma_{kl}}$$

Combinations of Measurements

We can also benefit from averaging over equivalent combinations of measurements

$$\Gamma = \sigma_{ZH}^2\left(\frac{1}{\sigma_{ZZ}} \oplus \sum_{i,j\neq Z} \frac{\sigma_{ij}}{\sigma_{Zi}\sigma_{Zj}}\right)$$

$$\Gamma = \sigma_{ZH}^2 \frac{\left(\frac{1}{\sigma_{ZZ}}\frac{1}{\delta_{ZZ}^2} + \sum_{i,j\neq Z} \frac{\sigma_{ij}}{\sigma_{Zi}\sigma_{Zj}} \frac{1}{(\delta_i z^2 + \delta_j z^2 + \delta_{ij}^2)}\right)}{\frac{1}{\delta_{ZZ}^2} + \sum_{i,j\neq Z} \frac{1}{\delta_{iZ}^2 + \delta_{jZ}^2 + \delta_{ij}^2}}$$

(But be careful when propagating errors.)
Also note that for some i, j, multiple processes can give us σ_{ij}.

$$\sigma_{WZ} = \sigma(Zh \to ZWW) \oplus \sigma(WW \to \nu\nu h \to \nu\nu ZZ)$$

In principle, we have many handles, although only some will be useful in terms of significance.

Expected Precisions

Energy	250 GeV	250 GeV	500 GeV	500 GeV
Process	$e^+e^- \to Zh$	$e^+e^- \to Z\nu\nu$	$e^+e^- \to e^+e^-h$	$e^+e^- \to Z\nu\nu$
δ_{Zb}	1.1%		1.8%	0.6%
δ_{ZW}	6.4%		6%	
δ_{Zc}	7.4%		12%	6.2%
$\delta_{Z\tau}$	4.2%		5.4%	14%
$\delta_{Z\gamma}$	$29-38\%$		$29-38\%$	$20-26\%$
δ_{Zg}	9.1%		14%	4.1%
δ_{Wb}		10.5%		0.6%
δ_{WW}				2.6%
δ_{Wc}				6.2%
$\delta_{W\tau}$				14.%
δ_{Wg}				4.1%

Numbers taken from DBD. Thanks to the work of many authors!

Optimum Channels

Clearly, b and W modes are dominant when accessible (for SM-like Higgs). But, at 250 GeV only some channels are available. We want to make maximum use of the data in hand.

- σ_{ZZ} measurable but with poor precision expected. $\delta\Gamma \sim 20\%$.
- Need $\sigma_{ij} : i, j \neq Z$ for other routes. Durig et al. report σ_{Wb} measurable at 10% level. This is the only visible W-fusion channel at this energy, but it makes possible

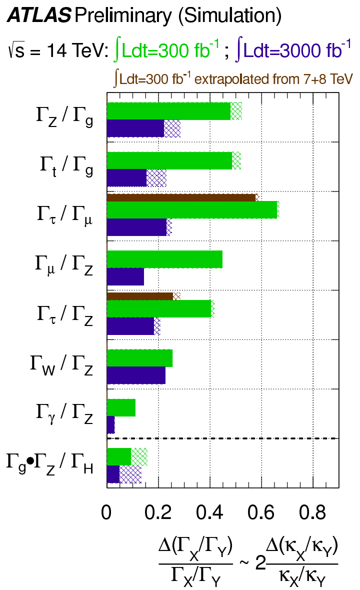
$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{Wb}}{\sigma_{Zb}\sigma_{ZW}}$$

$$\delta\Gamma \simeq 13.4\%.$$

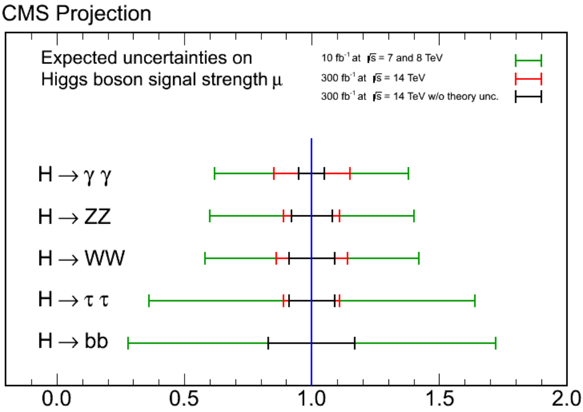
- This exhausts pure ILC options. However, we can turn to LHC data as well.

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{Pi}}{\sigma_{PZ}\sigma_{Zi}}$$

LHC Branching Ratios, Atlas



LHC Higgs Couplings, CMS



250 GeV cont.

Useful LHC channels:

LHC Meas.	LHC Error (300/3000)	$\delta\Gamma$
$\frac{\Gamma_\gamma}{\Gamma_Z}$	12%/3%	32%/30%
$\frac{\Gamma_W}{\Gamma_Z}$	26%/22%	27%/23.5%
$\frac{\Gamma_\tau}{\Gamma_Z}$	40(26)%/18%	40(27)%/19%
$\frac{\Gamma_b}{\Gamma_Z}$	20%/?	21%/ ?

Multiple constraints contribute to best Γ at this energy.

$$\frac{\Gamma}{\sigma_{Zh}^2} = \sigma_{ZZ} \oplus \frac{\sigma_{WZ}\sigma_{bZ}}{\sigma_{Wb}} \oplus \frac{\sigma_{WZ}\sigma_{PZ}}{\sigma_{PW}} \oplus \frac{\sigma_{\gamma Z}\sigma_{PZ}}{\sigma_{P\gamma}} \oplus \frac{\sigma_{\tau Z}\sigma_{PZ}}{\sigma_{P\tau}} \oplus \frac{\sigma_{bZ}\sigma_{PZ}}{\sigma_{Pb}}$$

Options at 500 GeV

With full information from 500 GeV runs, the single best combination is likely to be

$$\Gamma = \sigma_{Zh}^2 \frac{\sigma_{Wb}^2}{\sigma_{Zb}^2 \sigma_{WW}}$$

- With 500fb^{-1} at 500 GeV, expected relative error $\delta\Gamma \simeq 11\%$.
- Assuming full information from 250 and 500 GeV runs $\delta\Gamma \simeq 6\%$.
- However, the more direct route

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{Wb}}{\sigma_{Zb} \sigma_{ZW}}$$

is potentially competitive. The key is optimizing σ_{ZW}.

Analysis of σ_{ZW}

We have carried out a fast simulation of $e^+e^- \to e^+e^-h \to e^+e^-WW$ and backgrounds.

Events generated using the ILC-Whizard setup provided by Mikael Berggren. Beam profiles generated by GuineaPig, Whizard 1.95 matrix elements, Pythia showering and hadronization, SGV3.0 detector simulation.

Test results compare well for $Zh \to \nu\nu bb$ done in full detector simulation by H. Ono.

Make use of $WW \to 4j$ and $WW \to jjl\nu$. Fully reconstructible final states.

Features many kinematic features to discriminate against background.

Limiting factor is total initial size. $N = 473$. Cuts must be **efficient**.

Results

Using all-hadronic and semi-leptonic decays, also considering $Z \to \mu\mu$.

$$\delta\sigma_{ZW} = 6\%$$

Adding in $e^+e^- \to Zh \to ZWW$ at 250 and $e^+e^- \to \nu\nu h \to \nu\nu ZZ$ at 500 GeV

$$\delta\sigma_{ZW} = 4.6\%$$
$$\delta\Gamma_h = 6.8\%$$

Competitive with 'best' channel using σ_{WW}.

Limiting factor is error on the inclusive measurement.

Further improvements would require longer running at 250 GeV, more sophisticated analysis at 500.

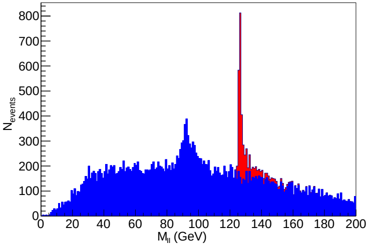
Invisible Decays

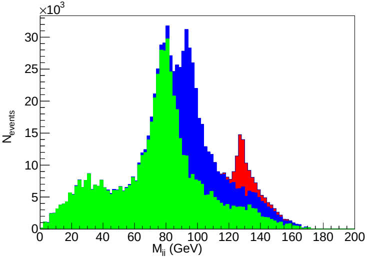
We can also naturally search for invisible decays at the ILC.

Analysis is straightforward: search for recoiling Z at 250 GeV and missing momentum.

We find one can establish

$$BR_{inv} < 0.9\% \text{ at } 95\% \text{ confidence}$$





Model Independent Sensitivities

Relative Error	ILC250			
		+LHC	+ILC500	
				+LHC
δ_Γ	12%	8.7%	5.7%	5.7%
δ_Z	1.3%	1.3%	1.3%	1.3%
δ_W	4.8%	3.6%	1.4%	1.4%
δ_γ	20%	4.2%	9.5%	4.2%
δ_g	7.0%	3.6%	2.5%	2.2%
δ_b	5.3%	3.8%	1.8%	1.7%
δ_c	6.5%	5.3%	2.8%	2.8%
δ_τ	5.7%	4.0%	2.5%	2.4%
$\delta_{\mathrm{Br}_{\mathrm{inv}}}$	0.54(0.52)%	0.54(0.52)%	0.54(0.52)%	0.54(0.52)%

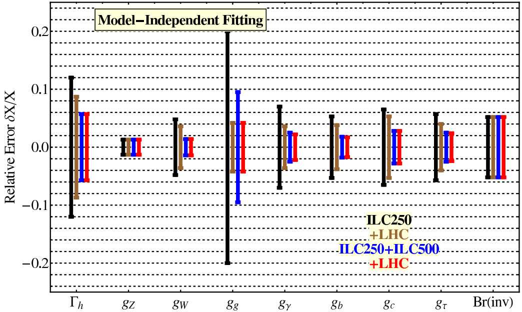
(Mildly) Model Dependent Sensitivities

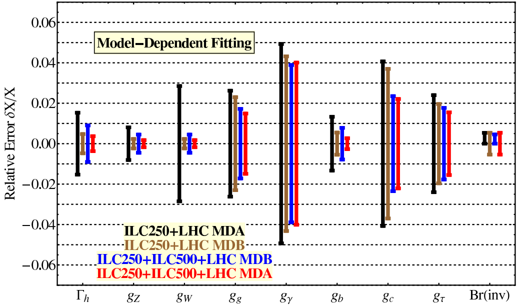
	SM Theo. Error (%)	250 GeV		500 GeV + 250 GeV	
		MDA($\pm$%)	MDB($\pm$%)	MDA($\pm$%)	MDB($\pm$%)
δ_Γ	$\pm$2.0	0.48	1.5	0.37	0.9
δ_Z	+2.2,-2.1	0.23	0.8	0.18	0.5
δ_W	+2.2,-2.1	0.23	2.9	0.18	0.5
δ_γ	$\pm$2.5	4.3	4.9	4.0	3.9
δ_g	+5.1,-5.0	2.3	2.6	1.5	1.7
δ_b	+1.6,-1.7	0.55	1.3	0.27	0.8
δ_c	$\pm$3.0	3.7	4.1	2.2	2.4
δ_τ	$\pm$2.9	2.0	2.4	1.6	1.8
BR_{inv}	—	0.54	< 0.5	0.54	< 0.5

MDA: Assume all significant decay modes are included above.

MDB: Assume $g^2_{hWW}/g^2_{hZZ} = \cos^2\theta_{\rm w}$.

Summary Plots





Conclusions

- ILC provides an ideal environment to assess Higgs width in model-independent way with high precision.
- 250 GeV run suggests multiple avenues to achieve best overall value. Invisible decays can be measured to the 1% level.
- 500 GeV run can be dominated by a few well-studied modes. However, σ_{ZW} channels offer a competitive determination, and can be combined for best sensitivity.
- Further studies may improve some channels, especially at 250 GeV. Limiting factor at 500 is inclusive measurement.
- Mild theoretical assumptions can significantly improve the expected limits.
- All estimates based on SM-like branching fractions!

Summary of Results

Merge down to 4 hadron jets.
Primary cuts

1. Opposite sign ee
2. $70(110) < M_{ee} < 110(150)$
3. $110 < M_{rec} < 250$
4. $M_{4j} < 150$
5. $W_{off} < 70, 55 < W_{on} < 100$
6. $p_W^{hrest} < 45$
7. $L(\theta_j..., Y_{34}, Y_{45})$

	Before Cuts		After Cuts	
	Zh	eeZ	$Z+X$	$ee+X$
Signal	158	315	85	183
$eeqq$	931500		65	100
$eeWW(4j)$	8750		2	9
$eeWW(2jl\nu)$	8390		1	9
$eeZZ/\gamma\gamma$	21235		37	76

$\delta\sigma(ee->eeh, h->WW->4j) = 8.8\%$

Adding in $Z \to \mu\mu$ conservatively

$\delta\sigma_{ZW} = 7.2\%$