Higgs/EWSB Working Group Summary

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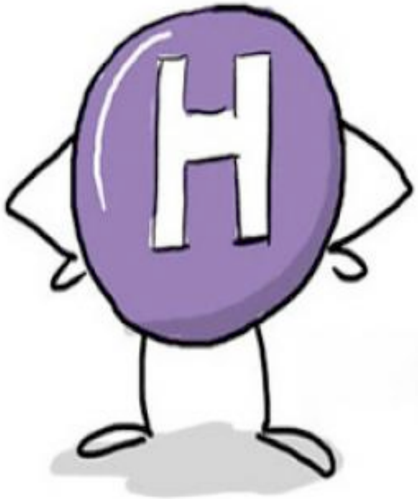
Tokyo, Japan
15 November 2013



Representing the conveners of the Higgs/EWSB Working Group:

Timothy Barklow, Christophe Grojean, Howard Haber, Shinya Kanemura, Philipp Roloff, Jungping Tian

Contributions to the Higgs/EWSB Working group sessions

➢LHC	1	Ganjour
➢ILC	13	Ono, Watanuki, Suehara, Tian, Calancha Paredes, Kawada, Kaneta, Duerig, Kurata, Zheng, Yagyu, Yokoyama, Yokoya
➢CLIC	7	Roloff, Sicking, Thomson, Robson, Vogel, Bozovic-Jelisavcic, Lastovicka
➢TLEP	1	Blondel
➢Theory	6	Tsumura, Reuter, Kikuchi, Khoze, Kakizaki, Shindou
➢Global fits	2	Peskin, Wiebusch
➢Tools	2	Heinemeyer, Kilian

32 talks in total; many new analyses were presented!

Three examples of recent analyses:

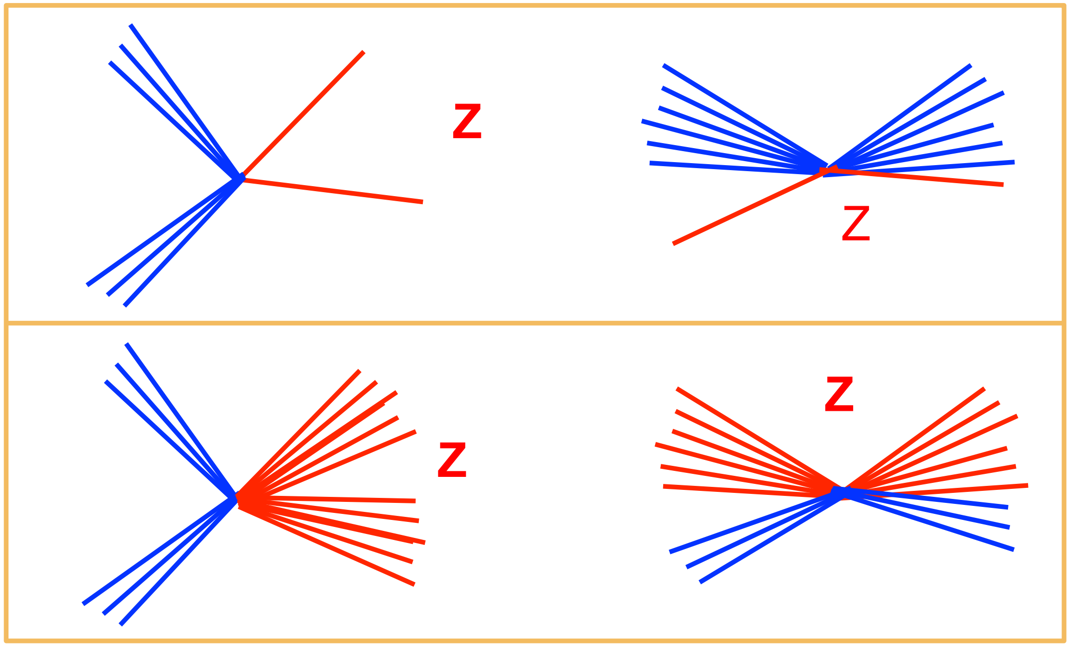
- Increasing the accuracy of the measurement of $\sigma(e^+e^- \to HZ)$ using the $Z \to q\bar{q}$ hadronic decays.
  (ILC: Suehara; CLIC: Thomson)
  See A. Miyamoto, arXiv:1311.2248

- At CLIC: updated Higgs self-coupling analysis (Lastovicka)

- Improving the theoretical precision of M_H in the MSSM via resummation of large logs (Heinemeyer)

Recoil Mass

- ★ To date, most studies only use $Z\to\mu\mu$ and $Z\to ee$
- ★ Statistical precision limited by leptonic BRs of 3.5 %
- ★ Here: extend to $Z\to qq$ ~ 70 % of Z decays
- ★ Strategy – identify $Z\to qq$ decays and look at recoil mass
- ★ Can never be truly model independent:
  - ▪ unlike for $Z\to\mu\mu$ can't cleanly separate H and Z decays



Muons "always" obvious

Here jet finding blurs separation between H and Z

⇨ **Different efficiencies for different Higgs decays**

Summary

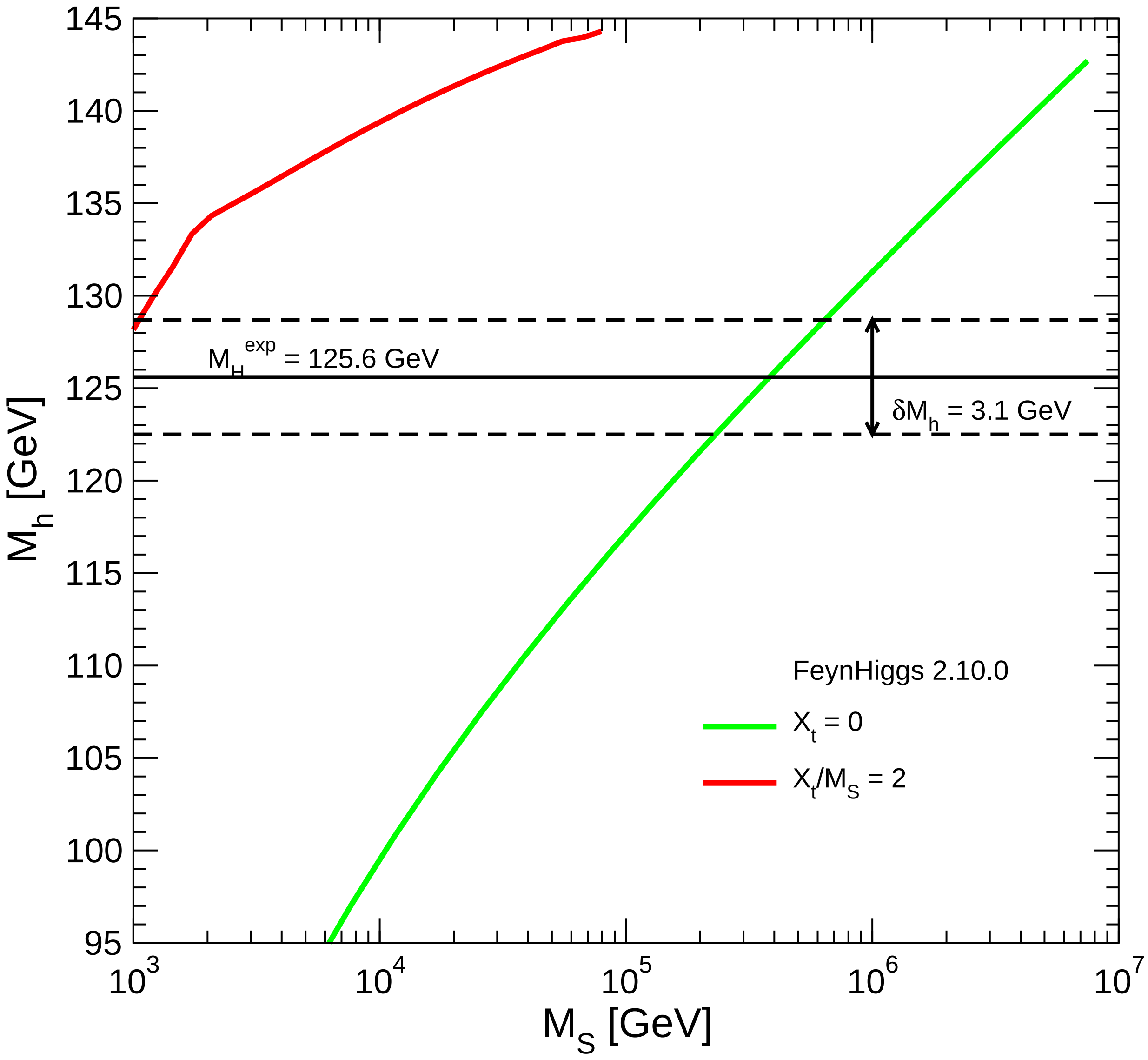
- llh 250 GeV – 3.0/2.5% with 250 fb^{-1} $e^-_L e^+_R$
- Various channels for σ_{ZH}
  - llH 500 GeV – 4.8% with 500 fb^{-1} $e^-_L e^+_R$
  - qqH 350 GeV – 3.6% with 150 + 150 fb^{-1}
  - qqH 500 GeV – 3.9% with 500 fb^{-1} $e^-_L e^+_R$
  - qqH 250 GeV (VERY PRELIMINARY)
    - 2.6% with 250 fb^{-1} $e^-_L e^+_R$
    - 1.4% with 250 fb^{-1} $e^-_R e^+_L$
    - Study ongoing
- Systematic effects should be investigated

SUMMARY

- Results were presented of the Higgs self-coupling measurement with 3 TeV CLIC machine and m_H = 126 GeV
  - Full simulation and reconstruction in CLIC_SiD; realistic beam spectrum, ISR, …
  - Unpolarised beams – beam polarization impact discussed
  - Accounted for realistic γγ→hadrons event pile-up/overlay and for γγ, $e^+γ$, $e^-γ$ backgrounds
  - Event selection based on a poll of neural networks, overtraining checked
  - Two methods: cut-and-count, template fitting
- We observe **15-18 % λ_{HHH}** uncertainty @ 3 TeV
  - Estimated **10%** and **12%** for (-80,30) and (-80,0) beam polarization, resp.
  - Updated numbers for 1.4 TeV are not available yet
    - EPS HEP 2013: 28% unpolarized beams
- Similar approach applied to quartic coupling **g_{HHWW}** leading to **3%** uncertainty @ 3 TeV.

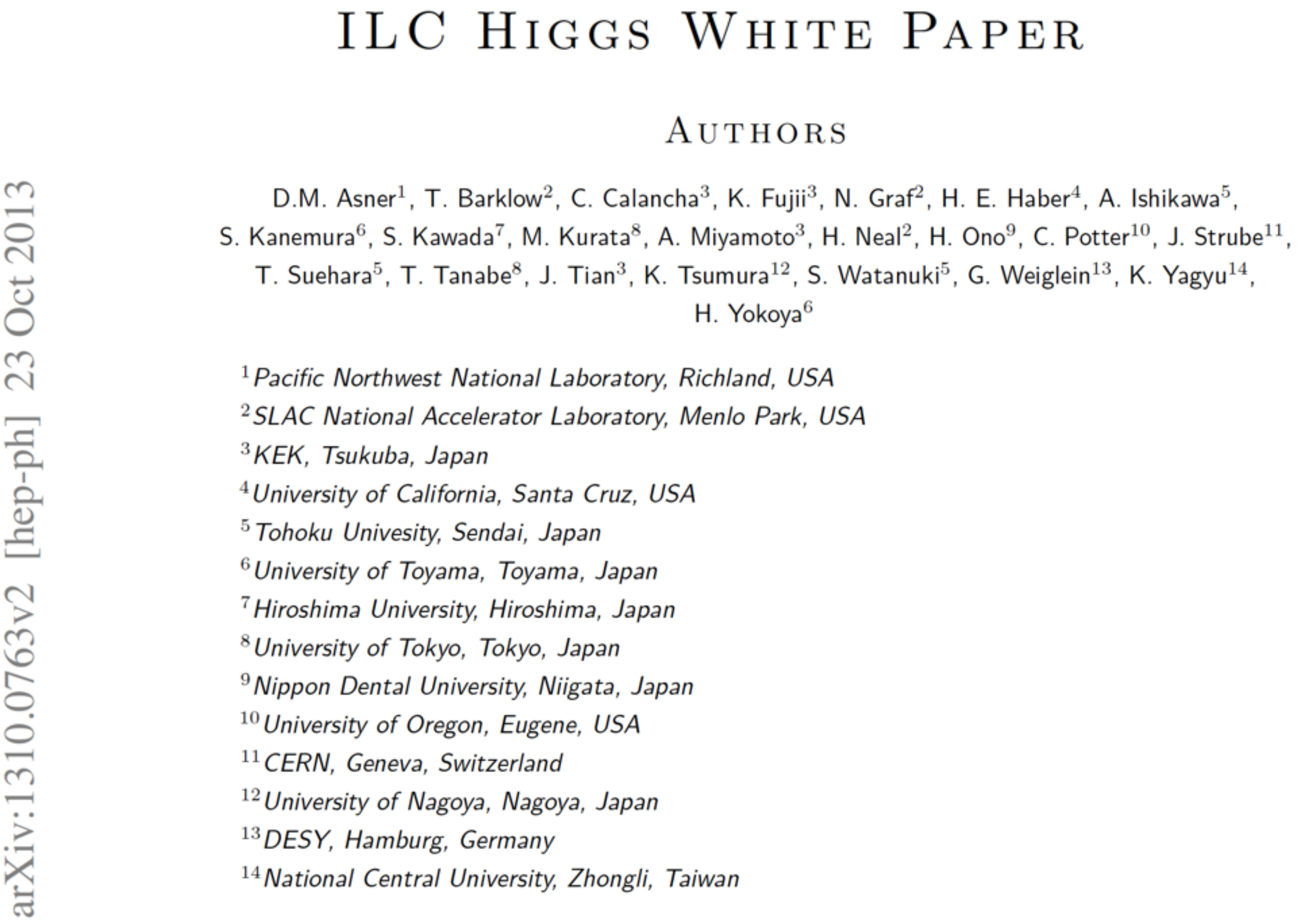
$M_h(M_S)$ for $\tan\beta = 1\,(X_t = 0)$ or $\tan\beta = 40\,(X_t/M_S = 2)$:

[FeynHiggs 2.10.0 - PRELIMINARY]



$\Rightarrow$ "upper bound": $M_S \lesssim 650$ TeV $\Rightarrow$ needs refinement!

Many of the ILC results presented at LCWS 13 were employed in the ILC Higgs White paper, which was submitted to the 2013 Snowmass Study



arXiv:1310.0763v2 [hep-ph] 23 Oct 2013

ILC HIGGS WHITE PAPER

AUTHORS

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ILC Energy/Luminosity scenarios

Stage #	nickname	$E_{cm}(1)$ (GeV)	Lumi (1) (fb^{-1})	$E_{cm}(2)$ (GeV)	Lumi (2) (fb^{-1})	$E_{cm}(3)$ (GeV)	Lumi (3) (fb^{-1})	Runtime (years)
1	ILC (250)	250	250					1.1
2	ILC (500)	250	250	500	500			2.0
3	ILC (1000)	250	250	500	500	1000	1000	2.9
4,5,6	ILC(LumUp)	250	1150	500	1600	1000	2500	5.8

- At each stage, the *accumulated* luminosity of a given energy is listed. The runtimes listed consist of actual elapsed *cumulative* running time at the end of each stage. Assuming that the ILC runs for 1/3 of the time, then the actual time elapsed is equal to the runtime times 3.

- Assume that the ILC is run at its baseline luminosity at 250 GeV (stage 1), then at 500 GeV (stage 2), and finally at 1000 GeV (stage 3)

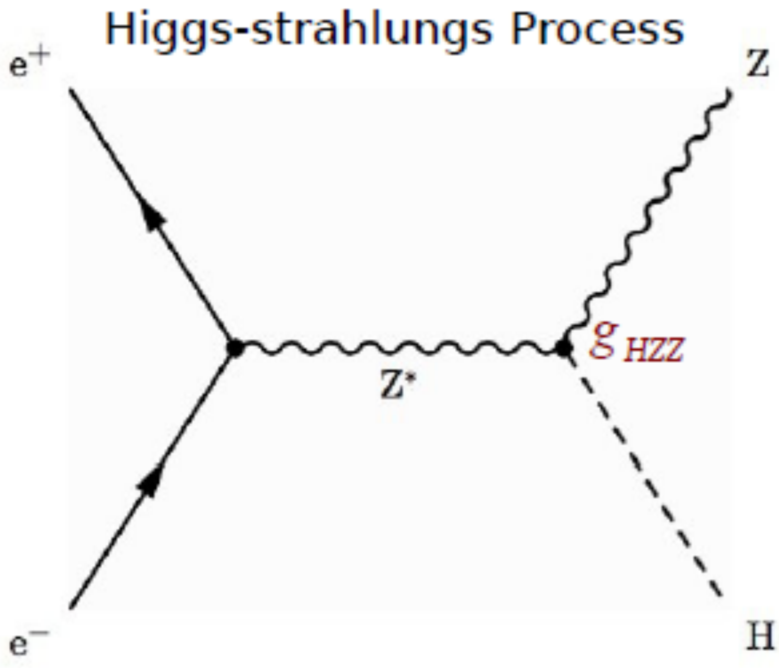
- Then, stages 4,5,6 repeat the successive stages 1, 2 and 3 at the upgraded luminosity.

In real time, this entire program would require 5.8 x 3 = 17.4 years.

What does the ILC actually experimentally measure?

1. $\sigma(e^+e^- \to ZH)$ at $\sqrt{s} = 250$ GeV.

- The *Z* can be reconstructed in charged lepton and quark channels.
- The *H* can be “seen” in the mass spectrum recoiling against the *Z* (including the invisible Higgs decays).
- The *H* can be reconstructed in all of its (main) decay channels.



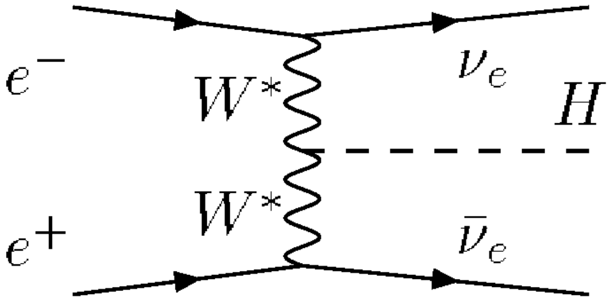
2. By explicitly reconstructing H, one obtains

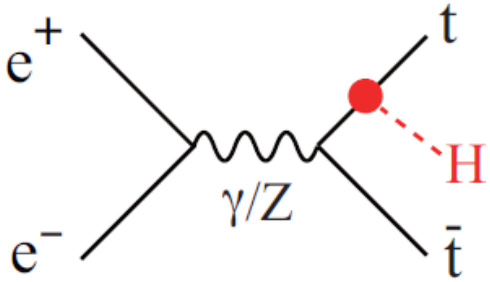
$$\sigma_{ZH} \times \mathrm{Br}(H \to XX)$$

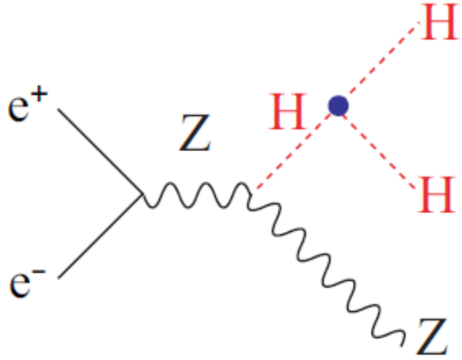
for $XX = b\bar{b}$, $c\bar{c}$, gg, WW^*, $\tau^+\tau^-$, ZZ^*, $\gamma\gamma$ and $\mu^+\mu^-$. Strictly speaking g stands for a hadron jet not identified as a b or c quark. For a SM-like Higgs boson, the Higgs decay into gg dominates over the decays into $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$. (Likewise, Higgs decay into e^+e^- is assumed to be negligible.)

3. Since the ZH production cross section dominates the cross section for $e^+e^- \to \nu\bar{\nu}W^+W^- \to \nu\bar{\nu}H$ at $\sqrt{s} = 250$ GeV, one can only measure $\sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b})$.

4. $e^+e^- \to \nu\bar{\nu}H$, $t\bar{t}H$ and ZHH at $\sqrt{s} = 500$ GeV







- The WW fusion cross section is now competitive with the ZH cross section. Thus, one can now measure

$$\sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to XX)\,,$$

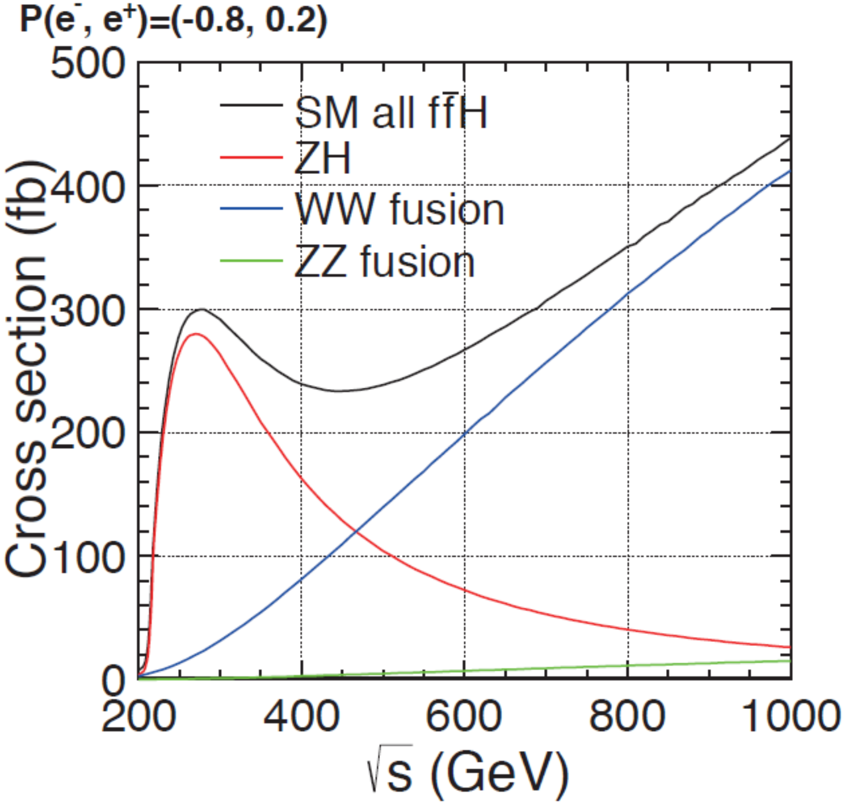
for all the relevant Higgs channels.

- The cross section for $e^+e^- \to t\bar{t}H$ is enhanced near threshold, and yields a measurement of $\sigma_{t\bar{t}H} \times \mathrm{Br}(H \to b\bar{b})$. From this, one can determine the top quark–Higgs Yukawa coupling.

- The process $e^+e^- \to ZHH$ is sensitive to the HHH coupling, although there are other diagrams contributing to ZHH production that do not depend on the triple Higgs vertex.

5. $e^+e^- \to \nu\bar{\nu}H$, $t\bar{t}H$ and $\nu\bar{\nu}HH$ at $\sqrt{s} = 1$ TeV

At $\sqrt{s} = 1$ TeV, the ILC provides better measurements of the top quark Yukawa coupling and the triple Higgs coupling. Moreover, the Higgs production rate has increased significantly from its rate at $\sqrt{s} = 500$ GeV due to the increasing WW fusion cross section.



Model-independent determinations of Higgs couplings

Example--consider the following four independent measurements:

$$Y_1 = \sigma_{ZH} = F_1 \cdot g^2_{HZZ}$$

$$Y_2 = \sigma_{ZH} \times \mathrm{Br}(H \to b\bar{b}) = F_2 \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_T}$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b}) = F_3 \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_T}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to WW^*) = F_4 \cdot \frac{g^4_{HWW}}{\Gamma_T}$$

Γ_T is the Higgs total width, g_{HZZ}, g_{HWW}, and $g_{Hb\bar{b}}$ are the Higgs couplings to ZZ, WW, and $b\bar{b}$, respectively, and F_1, F_2, F_3, F_4 are calculable quantities. For example,

$$F_2 = \left(\frac{\sigma_{ZH}}{g^2_{HZZ}}\right)\left(\frac{\Gamma_{H\to b\bar{b}}}{g^2_{Hb\bar{b}}}\right) .$$

The couplings are obtained as follows:

1. From $Y_1 \quad \Longleftrightarrow \quad g_{HZZ}$
2. From $Y_1Y_3/Y_2 \quad \Longleftrightarrow \quad g_{HWW}$
3. From g_{HWW} and $Y_4 \quad \Longleftrightarrow \quad \Gamma_T$
4. From g_{HZZ}, g_{HWW}, Γ_T and Y_2 or $Y_3 \quad \Longleftrightarrow \quad g_{Hb\bar{b}}$

Summary of expected accuracies $\Delta g_i/g_i$ and Γ_T for model independent determinations of the Higgs boson couplings

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
Γ_T	12 %	5.0 %	4.6 %	2.5 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

The theory errors are $\Delta F_i/F_i$=0.5%. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits.

Summary of expected accuracies for the three cross sections and eight branching ratios obtained from an eleven parameter global fit of all available data.

	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
process	$\Delta\sigma/\sigma$			
$e^+e^- \to ZH$	2.6 %	2.0 %	2.0 %	1.0 %
$e^+e^- \to \nu\bar{\nu}H$	11 %	2.3 %	2.2 %	1.1 %
$e^+e^- \to t\bar{t}H$	-	28 %	6.3 %	3.8 %
mode	$\Delta\mathrm{Br}/\mathrm{Br}$			
$H \to ZZ$	19 %	7.5 %	4.2 %	2.4 %
$H \to WW$	6.9 %	3.1 %	2.5 %	1.3 %
$H \to b\bar{b}$	2.9 %	2.2 %	2.2 %	1.1 %
$H \to c\bar{c}$	8.7 %	5.1 %	3.4 %	1.9 %
$H \to gg$	7.5 %	4.0 %	2.9 %	1.6 %
$H \to \tau^+\tau^-$	4.9 %	3.7 %	3.0 %	1.6 %
$H \to \gamma\gamma$	34 %	17 %	7.9 %	4.7 %
$H \to \mu^+\mu^-$	100 %	100 %	31 %	20 %

Further improvement beyond the ILC Higgs White paper (due to Peskin)

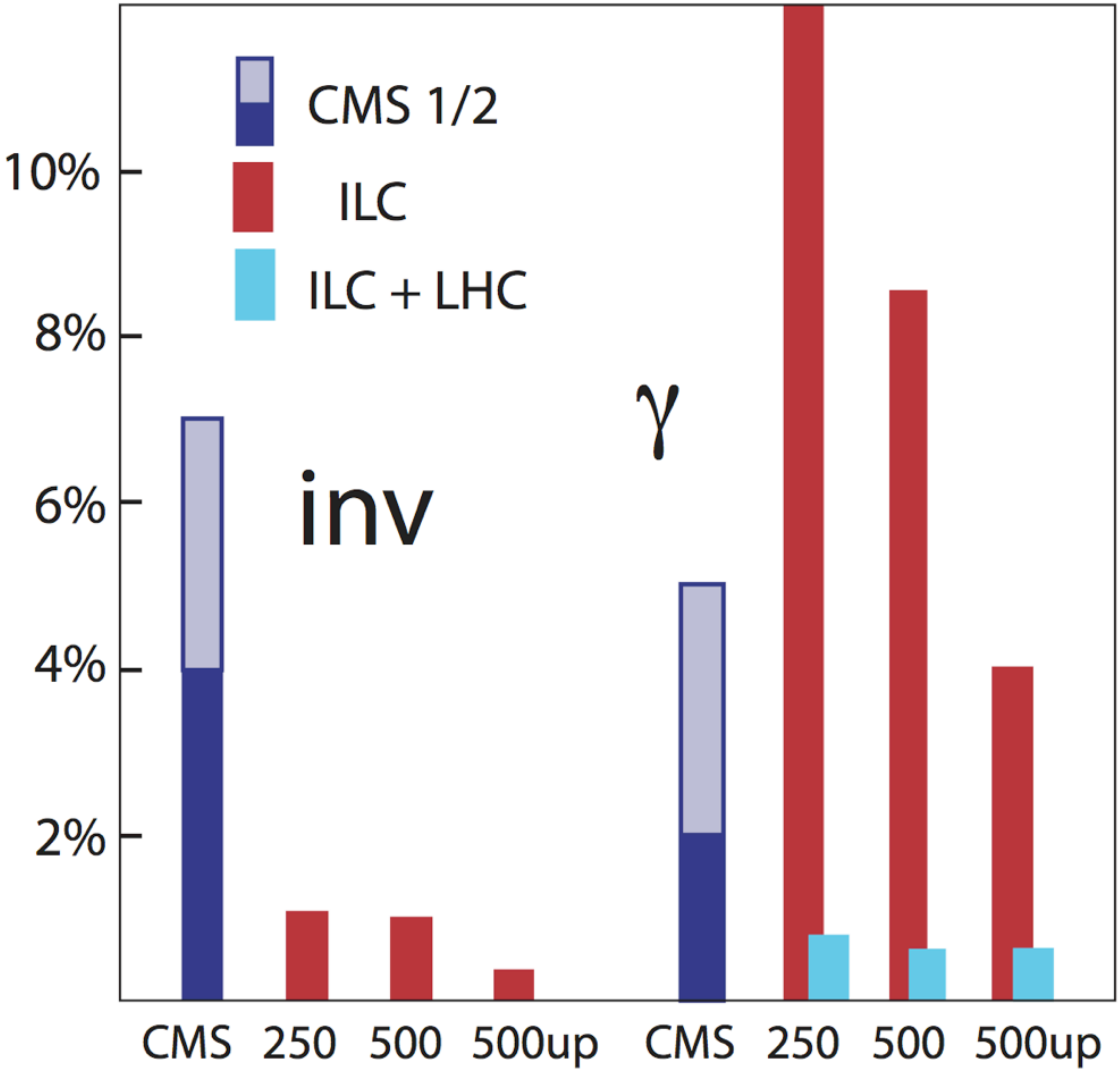
- Use ATLAS projected result of the HL-LHC Higgs analysis

$$\Delta\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^*)}=2.9\%$$

along with the ILC precision measurement of the *HZZ* coupling to obtain a very precise determination of the $H\gamma\gamma$ coupling.

- Improve precision determinations of Higgs couplings by imposing the constraint that

$$\sum_i \mathrm{BR}_i = 1$$


CMS 1/2
ILC
ILC + LHC
10%
8%
6%
4%
2%
inv
γ
CMS
250
500
500up
CMS
250
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500up

The reason for this is that I used a 9-parameter fit constrained to the relation $\sum_i BR_i = 1$.

This constraint is very powerful because determinations of Higgs couplings require constraining the Higgs total width.

$$\sigma(A\overline{A} \to h) \cdot BR(h \to B\overline{B}) \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_T}$$

The constraint has a large effect here:

error in Γ_T	unconstrained	$\sum BR = 1$
ILC 500	5.0%	1.6%
ILC 500 up	2.8%	0.75%
ILC 1000	4.6%	1.2%

Conclusions

- Precision Higgs studies are essential for probing the dynamics of electroweak symmetry breaking (EWSB).
- Future e^+e^- colliders (ILC/CLIC/TLEP) have the capability of significantly reducing the uncertainties in many of the observed Higgs properties that will be measured at LHC, with less reliance on specific model assumptions.
- Beyond coupling measurements, one can also make precision measurements of the Higgs mass and total width, check the CP-properties (including potential CP-violating effects) and the Lorentz structure of Higgs interactions, etc.
- The Higgs boson can serve as a portal to physics beyond the Standard Model (BSM). Thus, precision Higgs studies could provide critical clues to the nature of BSM physics.