“Ultimate” Higgs Measurements at ILC, LEP3, and TLEP

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2012 was the year of the Higgs.

The discovery of the new boson at 125 GeV was front-page news around the world. It brought wide attention to the vitality and interest of the global program in high-energy physics.

At the July 4 seminar, Rolf Heuer emphasized that the discovery of the 125 GeV boson was the beginning of a new line of research.

Indeed, the discovery gives a new, direct window into the mystery of electroweak symmetry breaking.

In the year after the Higgs discovery, there should be a proposal for a new collider dedicated to precision Higgs measurements.

This collider should be able to produce an "ultimate" Higgs program:

measurements of
- as many couplings of the Higgs boson as possible
- with model-independent interpretation
- to the percent level

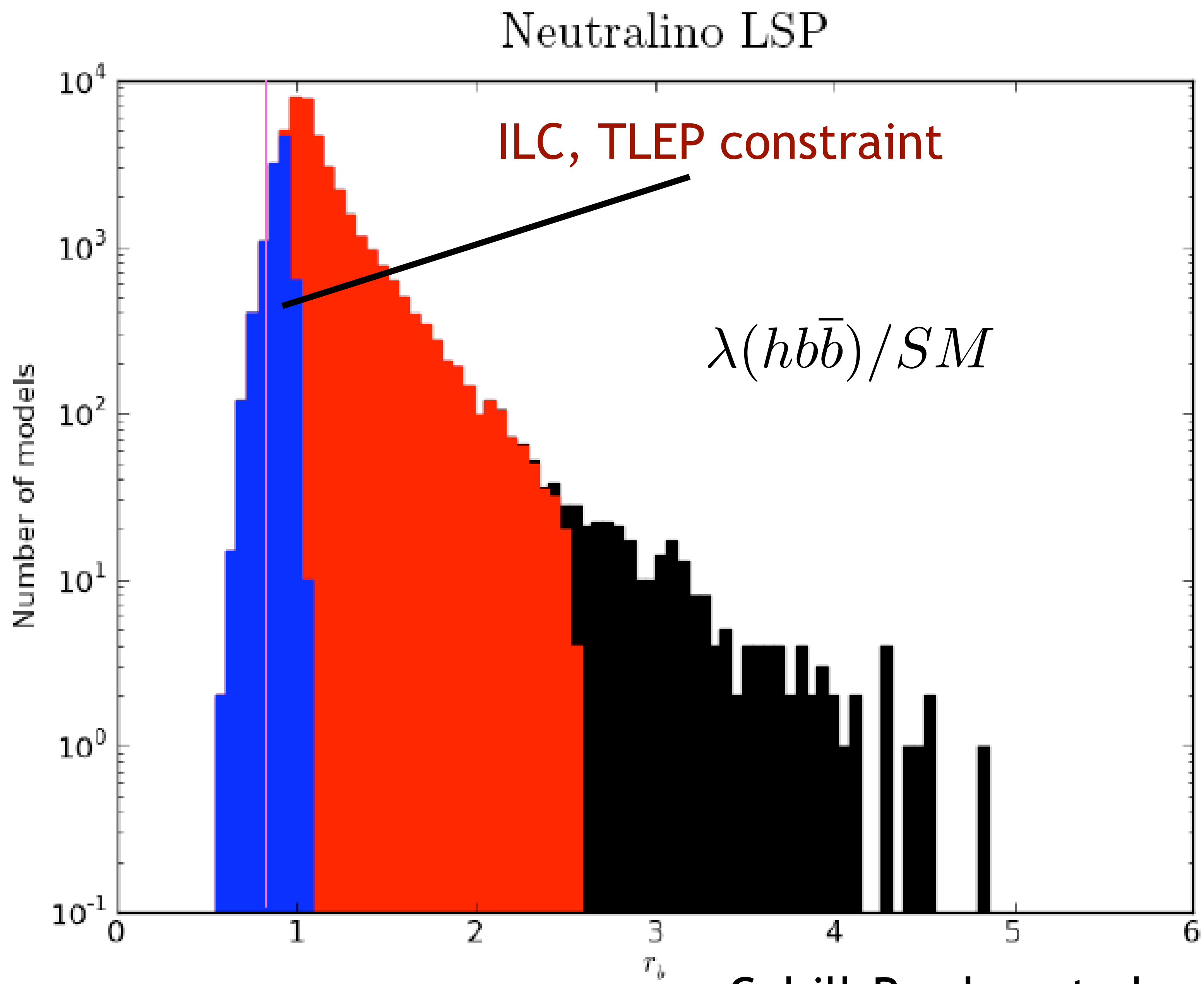
From here on, I will assume that the 125 GeV boson is the/a Higgs boson.

If this is not true, the situation is even more interesting: The Higgs boson must exist, and LHC measurements suggest that it cannot be heavy.

I will assume, conservatively, that the properties of this particle are close to those of the Standard Model Higgs Boson.

This need not be true. At this moment, our understanding of the electroweak symmetry breaking sector is close to complete ignorance.

for example, from a survey of currently allowed SUSY models:



Cahill-Rowley et al. pMSSM

In this talk, I will discuss some aspects of an "ultimate" Higgs program and compare the capabilities of proposed colliders.

However, I should first making some comments about the three leading proposals -- ILC, LEP3, and TLEP.

ILC is a proposal for now.   The TDR has been completed. The project has acquired considerable political interest in Japan (more about this later).   Geological studies of two sites have been performed. The time is right for a construction proposal.

LEP3 is an interesting and economical proposal. However, to take data in the 2020's, it is in conflict with the High-Luminosity LHC. HL-LHC is a highly motivated project that builds on the large investment made in the LHC. The energy of LEP3 is strictly limited to 250 GeV.

The costs of these two projects to Europe are comparable.

TLEP is requires a major construction project. In Europe, it must begin after HL-LHC. It might be constructed in the 2030's and take data in the 2040's. Thus, it is in a different time frame from the previous two projects.

The 80 km tunnel envisioned for TLEP can also host a hadron collider (TLHC). This might well be the future of particle physics in Europe.

I will now discuss the estimates of Higgs measurement capabilities of these machines and the conversion of those estimates to measurement errors on the Higgs couplings.

It will be obvious that - weighting all claims equally - TLEP has the best capabilities. It has the highest luminosity, can plausibly support multiple detectors, and can reach energies well above the Higgs threshold. In the following, I will omit the comparison with TLEP in the figures. The final errors would in any event be tiny on the graphs that I will show. These are given in a table at the end of the lecture.

Comparison of ILC and LEP3 is more interesting. It contains some conceptual issues that are important to understand. My talk will concentrate on this.

The information in the Higgs couplings to Standard Model particles is codified by the quantities:

$$\kappa_A = g(hA\overline{A})/SM$$

The couplings to gg , $\gamma\gamma$, and γZ should be treated as distinct additional couplings. These could involve the tree-level $ht\bar{t}$ and hWW couplings and also contributions from new heavy species.

If we can measure a total cross section, we have

$$\sigma(A\overline{A} \to h)/SM = \kappa_A^2$$

A ratio of branching ratios gives

$$BR(h \to A\overline{A})/BR(h \to B\overline{B}) = \kappa_A^2/\kappa_B^2$$

The interpretation of these quantities is fairly unambiguous.

However, more typically, what we measure is

$$\mu_{AB} = \sigma(A\overline{A} \to h) BR(h \to B\overline{B})/SM$$

This is proportional to $\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})/\Gamma_T$

or to

$$\frac{\kappa_A^2 \kappa_B^2}{\sum_C \kappa_C^2 \, BR(h \to C\overline{C})|_{SM}}$$

At the LHC, it is not possible to measure total cross sections for Higgs production. In additional to truly invisible decay modes, there are modes not visible in the hadron collider environment (e.g., gg). Also, it is not possible to measure the total Higgs width directly.

At the moment, there are no direct measurements of ratios of branching ratios. Different event selection strategies are used for each final state.

At the LHC, it is not possible to extract the κ_A in a model-independent way. It is possible that an unobserved decay mode might increase the total width of the Higgs uncontrollably.

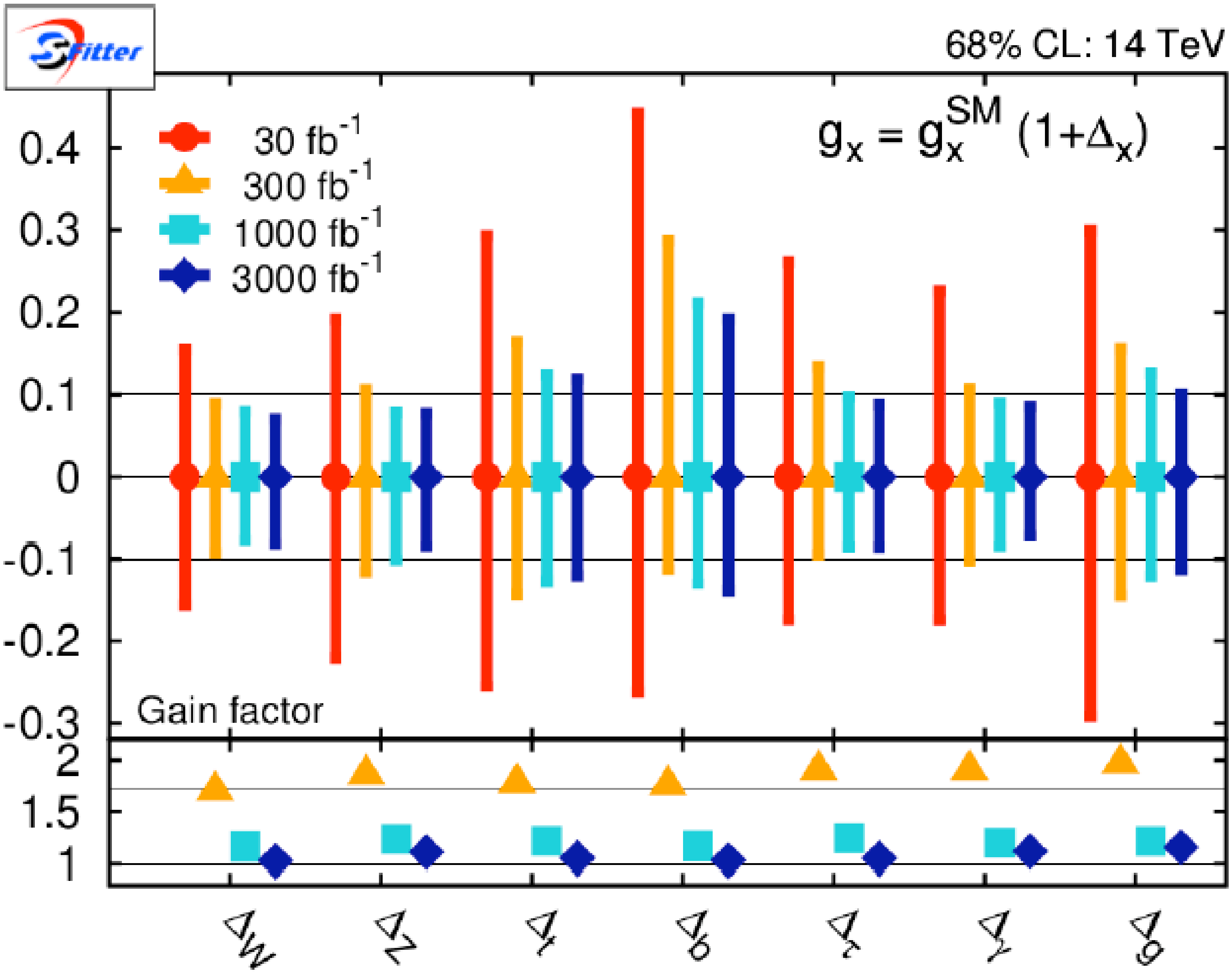
A relatively mild theoretical assumption that resolves this issue is

$$\kappa_W \leq 1 \quad \kappa_Z \leq 1$$

This is roughly equivalent to the statement that the various Higgs bosons in the theory contribute additively to the W and Z masses. It is correct in models with no doubly charged Higgs and no Higgs CP violation.

Using this assumption, several groups, starting with Duhrssen et al., have estimated the ultimate accuracy of the LHC measurements for "model-independent" Higgs couplings.

A "model-independent" determination should involve a global fit with at least 9 free parameters. Fits to (C_F, C_V) are interesting for today but will be irrelevant or misleading in the precision era.



Sfitter, D. Zerwas at LCWS 2012

The expectations for LHC are excellent, but, for an "ultimate" Higgs program, we need to do still better.

I will first discuss the determination of Higgs coupling from measurements at 250 GeV.

On the next slide, I present the measurement accuracies on the relevant observables predicted by the various groups of proponents. For this talk, I will take these at face value.

The heading of each column gives the facility, the integrated luminosity in fb-1, and the number of detectors assumed.

The ILC numbers are estimates from the Asian ILD group. The "official" ILC numbers are being compiled later this month.

I thank Keisuke Fujii and Patrick Janot for help with this table.

Estimated Fractional Errors on Measurements at 250 GeV e^+e^- Colliders

Observable	ILC (250)	ILC (500)	LEP3 (2/500)	LEP3 (4/500)	TLEP (4/2500)
$\sigma(Zh)$	0.025	0.018	0.019	0.013	0.004
$\sigma(Zh) \cdot BR(b\bar{b})$	0.010	0.007	0.008	0.005	0.002
$\sigma(Zh) \cdot BR(c\bar{c})$	0.069	0.049	0.053	0.038	0.013
$\sigma(Zh) \cdot BR(gg)$	0.085	0.060	0.061	0.043	0.014
$\sigma(Zh) \cdot BR(WW)$	0.08	0.057	0.036	0.025	0.009
$\sigma(Zh) \cdot BR(ZZ)$	0.28	0.20	0.099	0.070	0.031
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.05	0.035	0.033	0.022	0.008
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.27	0.19	0.095	0.066	0.030
$\sigma(Zh) \cdot BR(\text{invis})$	0.005	0.0035	0.006	0.004	0.002
$\sigma(WW) \cdot BR(b\bar{b})$	0.07	0.05	0.07	0.05	0.022
$m(h)$ (in MeV)	32	23	37	26	8

ILC and LEP3 have similar quoted instantaneous luminosity at 250 GeV

$$0.75 \times 10^{34} \quad vs. \quad 10^{34}$$

ie. equal to within the errors. I find the comparison of ILC(500) to LEP3 (2/500) most direct. I have assumed that ATLAS and CMS will be used, and will be fitted out with ILC-type pixel vertex detectors for LEP3 running.

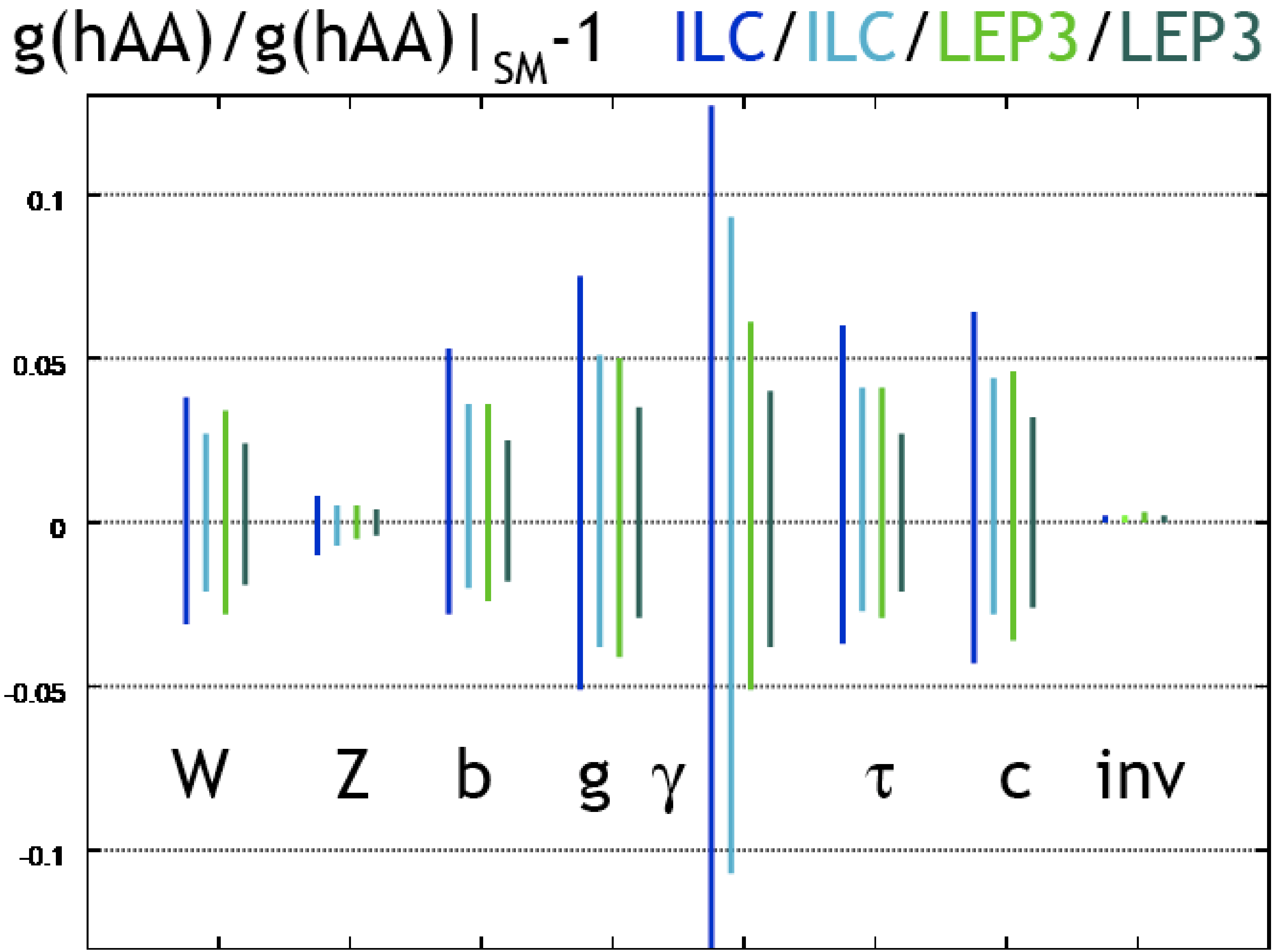
Janot has argued that this is overly optimistic, because circular machines have intrinsically higher availability than linear colliders. Availability depends on some machine properties, and also on factors like organizational discipline and electric power contracts that theorists do not understand. I will leave this question to the experts. I hope that it will be discussed in a balanced way in the Snowmass 2013 reports.

In any event, passing the two ILC and two LEP3 columns through the machinery of a 9-parameter fit with central values equal to the Standard Model and errors as given, I find the picture on the next slide.

The first 4 scenarios in the Table above are displayed left to right for each Higgs coupling.

The invisible couplings are plotted as the 1 sigma limit on the BR. This is of order 0.2% in all cases.

No assumed LHC data is included in this analysis.



g(hAA) / g(hAA) |$_{SM}$-1 ILC / ILC / LEP3 / LEP3
0.1
0.05
0
-0.05
-0.1
W
Z
b
g
γ
τ
c
inv

There are some things to note about this figure:

The advantage of high luminosity is apparent, but it is not as strong as one might have expected.

Some coupling errors are much larger than those quoted in the CMS report arXiv:1208.1662v2. For example, for the two LEP3 scenarios:

	here	CMS eprint
g(hbb)	3.0%/1.7%	1.0%/0.7%
g(hWW)	3.1%/2.2%	2.2%/1.5%

What is the issue ?

The problem is that the coupling deviations are given by

$$\kappa_A^2 = \Gamma_A/(SM) = BR(h \to A\overline{A}) \cdot \Gamma_T/(SM)$$

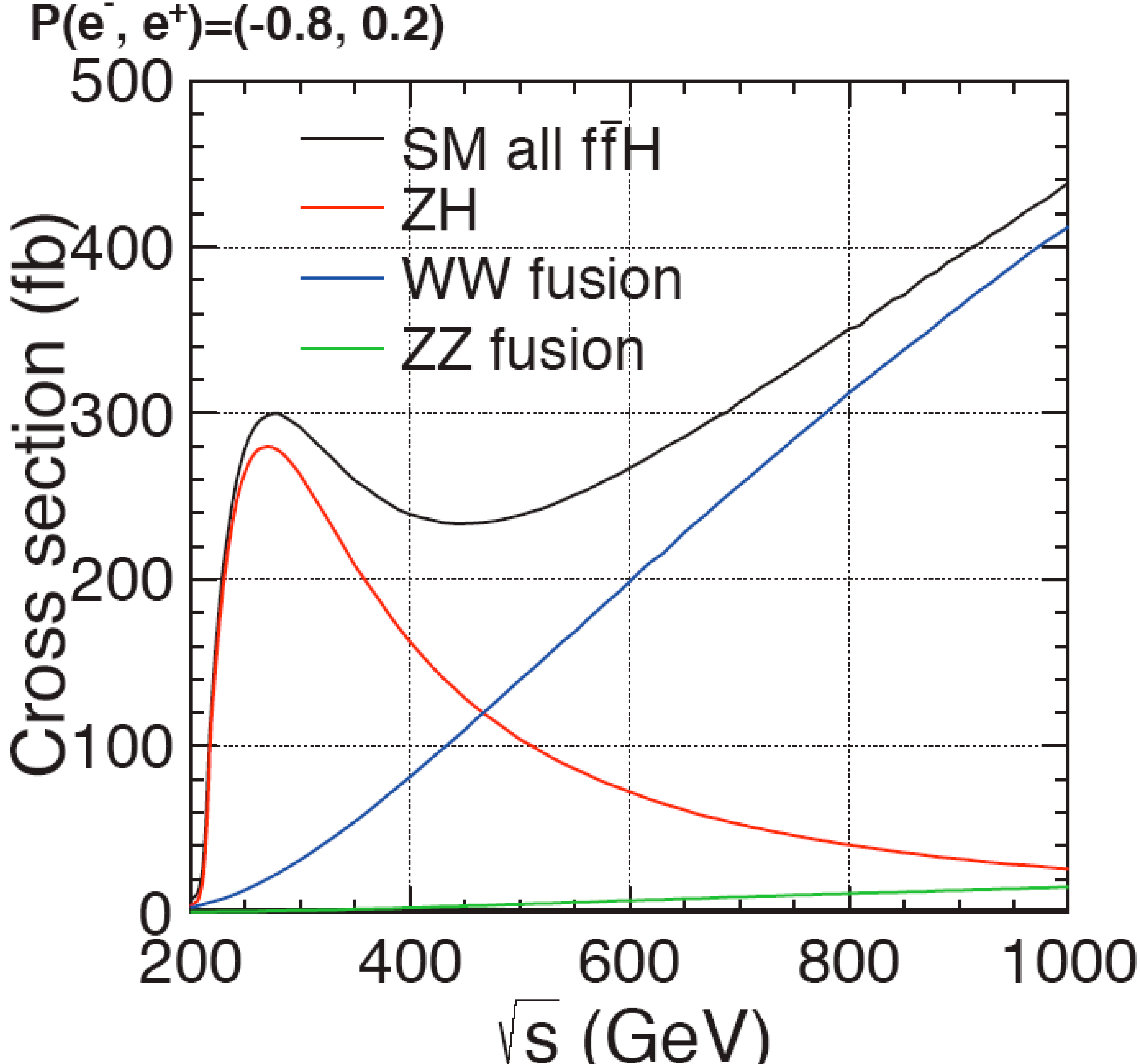
It is not possible to measure the Higgs boson width directly at an e+e- collider if it is as small as predicted in the Standard Model (4 MeV).

The Higgs width can be determined in a model-independent way using

$$\Gamma_T = \Gamma(h \to ZZ)/BR(h \to ZZ)$$

Because the ZZ mode is relatively rare, the BR is not well measured. This method is then statistics limited. This effect dominates the errors in couplings and ruins the perfection of the global fit.

The solution to this problem is running at higher energy.



P(e⁻, e⁺)=(-0.8, 0.2)
SM all ff̄H
ZH
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
√s (GeV)

Above about 400 GeV, the WW fusion production of the Higgs boson turns on: $e^+e^- \to \nu\overline{\nu}h$

Then one can use the equation

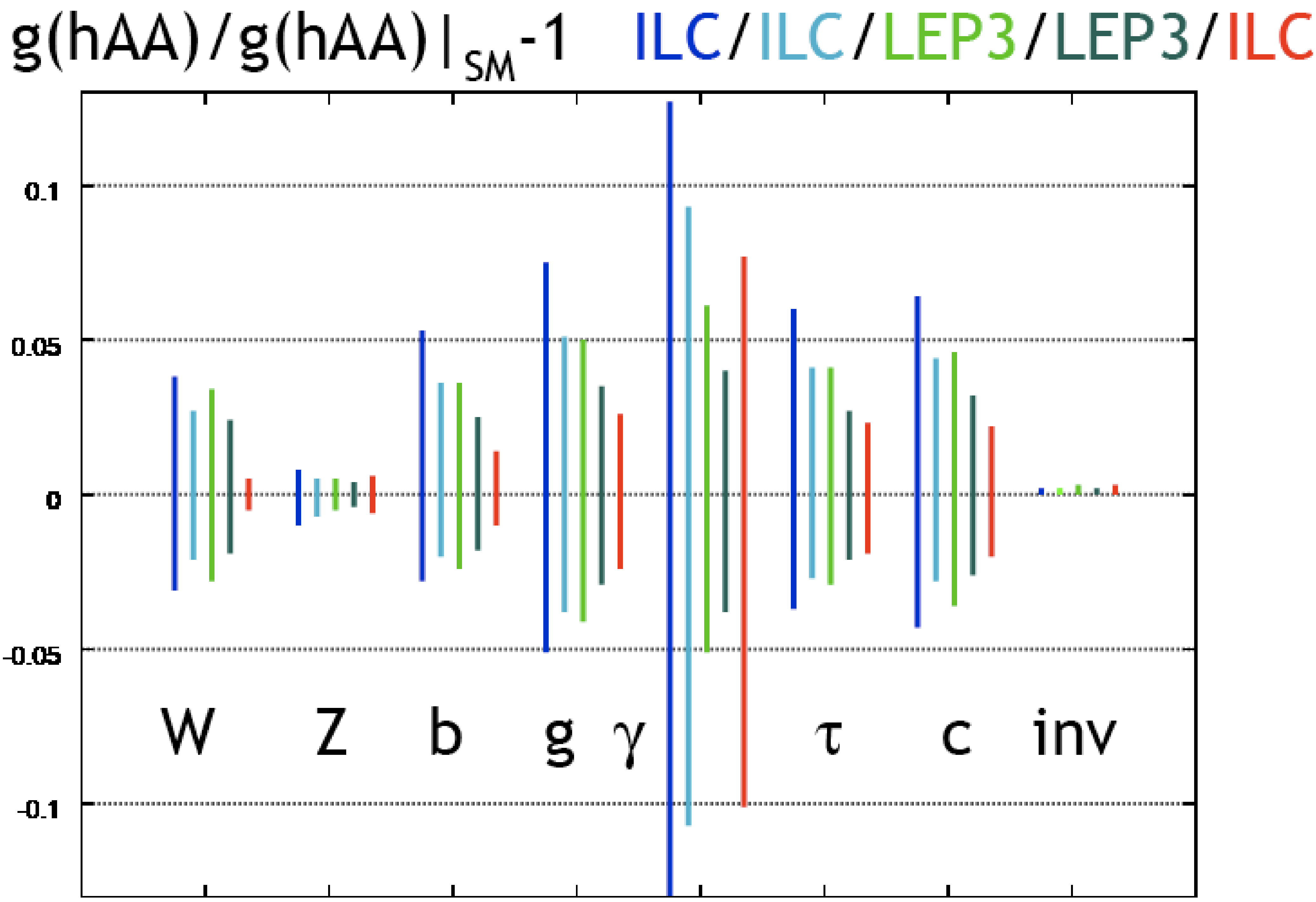
$$\Gamma_T = \Gamma(h \to WW)/BR(h \to WW)$$

to assist in normalizing the fit.

To illustrate this, I add to the previous slide the results for the full ILC program:

250 fb-1 at 250 GeV,   500 fb-1 at 500 GeV

ILC at 500 GeV with 500 fb^{-1}	
$\sigma(Zh) \cdot BR(b\bar{b})$	0.016
$\sigma(Zh) \cdot BR(c\bar{c})$	0.11
$\sigma(Zh) \cdot BR(gg)$	0.13
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.07
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.36
$\sigma(WW) \cdot BR(b\bar{b})$	0.006
$\sigma(WW) \cdot BR(c\bar{c})$	0.04
$\sigma(WW) \cdot BR(gg)$	0.049
$\sigma(WW) \cdot BR(WW)$	0.03
$\sigma(WW) \cdot BR(\tau^+\tau^-)$	0.05
$\sigma(WW) \cdot BR(\gamma\gamma)$	0.28
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	0.2



g(hAA) / g(hAA) |SM-1
ILC / ILC / LEP3 / LEP3 / ILC
0.1
0.05
0
-0.05
-0.1
W
Z
b
g
γ
τ
c
inv

The W and b couplings are now determined with high precision.

The statistics on the gamma coupling is disappointingly low. However, there is no reason to worry. The ratio of branching ratios

$$BR(h \to \gamma\gamma)/BR(h \to ZZ)$$

will be measured accurately at the LHC. When this is combined with the rest of the fit, we will know the gamma coupling quite well.

Estimated Fractional Errors on Higgs Couplings

Observable	ILC (250)	ILC (500)	LEP3 (2/500)	LEP3 (4/500)	ILC(500)
$g(hWW)$	0.035	0.025	0.031	0.022	0.005
$g(hZZ)$	0.009	0.006	0.005	0.004	0.006
$g(hb\bar{b})$	0.028	0.049	0.030	0.017	0.012
$g(hgg)$	0.063	0.045	0.045	0.032	0.025
$g(h\gamma\gamma)$	0.100	0.057	0.056	0.039	0.089
$g(h\tau\tau)$	0.049	0.034	0.035	0.025	0.021
$g(hc\bar{c})$	0.054	0.036	0.041	0.029	0.021
$BR(invis.)$	0.002	0.002	0.003	0.002	0.003

ILC(500) includes the full nominal program, 250 fb^{-1} at 250 GeV and then 500 fb^{-1} at 500 GeV.

Including LHC data (1 experiment, 300 fb^{-1}) with the final ILC results does not change those numbers significantly, except that the error on $\gamma\gamma$ improves to 0.043. HL-LHC with ILC would presumably improve this accuracy further.

For completeness, I give the coupling results for TLEP. As I anticipated, the very high luminosity with 4 detectors leads to excellent results for the Higgs couplings. Still, there is a marked improvement when just a few more accurate measurement from the WW fusion process at higher energy are included.

additional TLEP measurements at 350 GeV, with 350 fb-1 and 4 detectors:

Observable	
	TLEP(4/350)
$\sigma(WW) \cdot BR(b\bar{b})$	0.004
$\sigma(WW) \cdot BR(WW)$	0.017

Estimated Fractional Errors on Higgs Couplings

Observable		
	TLEP (4/2500)	TLEP (350)
$g(hWW)$	0.009	0.003
$g(hZZ)$	0.002	0.002
$g(hb\overline{b})$	0.009	0.004
$g(hgg)$	0.012	0.009
$g(h\gamma\gamma)$	0.018	0.016
$g(h\tau\tau)$	0.010	0.006
$g(hc\overline{c})$	0.011	0.008
$BR(invis.)$	0.001	0.001

TLEP(4/350) includes the full nominal program, 2500 fb^{-1} at 250 GeV and then 350 fb^{-1} at 350 GeV, with 4 detectors.

I return to the result that ILC at 250 GeV and then 500 GeV gives an excellent strategy for an "ultimate" Higgs program.

Operation of ILC above 500 GeV will also give accurate values of the Higgs coupling to top and the Higgs self-coupling. Current estimates of the errors on these couplings for the 1000 GeV ILC are

top	4.1%
self-coupling	24 %

The full ILC program also includes topics such as precision top quark studies that are relevant to the picture of electroweak symmetry breaking and complementary to the LHC.

This concludes the physics content of the talk.

However, I have some other news about ILC to convey to this workshop.

The ILC is now receiving much attention by government officials and other influential parties in Japan. Some of these are:

Advanced Accelerator Association Promoting Science and Technology -- a consortium of 91 corporate, 38 university members, including Canon, Hitachi, IBM Japan, Mitsubishi, NEC, Toshiba, ...

Japan Policy Council -- organ of Hiroya Masuda, a university of Tokyo professor involved in the founding of Tsukuba, which calls for a new Tsukuba as a path to regional development

Federation of Diet Members for Promoting ILC -- a bi-partisan organization

Inclusion of ILC in the Tohoku earthquake/tsunami reconstruction proposal from the Iwate provincial government

Most recently, inclusion of ILC in the party platform of the Liberal Democratic Party prepared for the recent election.

32　科学技術政策の強力な推進力となる真の「司令塔」機能の再構築

資源の少ないわが国にとって、今後の社会・経済をさらに発展させるため、企業の研究開発投資が激減する中、新たな成長に向けて国主導で科学技術イノベーションをリードするのが喫緊の課題です。

しかし、年間約 3.6 兆円にも及ぶ科学技術関係予算については、文部科学省を中心に、経済産業省や厚生労働省等、関係省庁に予算が配分され、各省内で同様な研究が行われている事例も見受けられ、縦割りの弊害が顕著です。また、限られた予算にも関わらず、効果的な配分が行われていないのが現状です。

そこで、産業の生命線である科学技術を国家戦略として推進し、「価値の創造拠点」とするべく、総合科学技術会議の「権限」「体制」「予算システム」を抜本的に強化し、真の「司令塔」機能へと再構築します。

具体的には、各省庁の縦割りを排し、強力な予算配分権限を集中させ、適正な評価を行うことができる人材育成とシステムの構築を行います。例えば、素粒子物理分野の大規模プロジェクトである ILC（国際リニアコライダー※研究所建設）計画等を含む国際科学イノベーション拠点作りに日本が主導的な役割を果たせるなど、再生医療※や創エネ・省エネ・蓄エネ等の重点分野を産学の知を結集した国家戦略として強力に推進します。

A very urgent issue for the leaders of the country is to take the lead in science and technology innovation and aim for new growth in order to develop the future society and economy.

... and have Japan play a leading role in the formation of an international scientific innovation base that includes, for example, the plan for the ILC ...

Thus, in Japan, the program of high energy physicists seems to be in step with the broader analysis of the needs of society.

For more details, see the talk of Atsuto Suzuki at the ILC Tokusui Workshop, Dec. 2012:

https://ilcagenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=5907

This is a unique, once-in-a-generation opportunity to launch a true partner for CERN in Asia.

Much of the attraction of ILC for Japan is that it is a global project of top scientific priority. Thus, the project needs the approval and support of Europe and the US. At this moment, the acknowlegement of support by CERN and US DOE is probably more important than money.

Conclusions:

The discovery of the Higgs boson calls for a collider dedicated to precision study of this boson. This is a new route to the mystery of electroweak symmetry breaking, the one route opened so far by the LHC.

Among the proposals for this collider, ILC is on the table now. Its higher energy stages are not superfluous for Higgs. Instead, they are essential parts of an ultimate Higgs program.

ILC is now under serious consideration for constrution in Japan. It would be foolish to ignore this opportunity. We must seize it.