Snowmass Higgs Report
- Highlights -

2013/09/04

Keisuke Fujii

Claims against ILC

- For all the Higgs couplings other than htt and hhh, TLEP can do much better than ILC owing to its higher luminosity and capability to host 4 detectors.

- TLEP tunnel can house a 100TeV class pp collider that would provide much better precisions for htt and hhh than ILC.

- ILC's precision on various Higgs couplings are only a factor of two or so better than those from HL-LHC, if possible future improvements in analysis techniques and theory errors are taken into account.

- Though TLEP cannot measure the htt and hhh couplings, they can be measured at HL-LHC with similar precisions to those expected at ILC.

Tim Barklow's Presentation at the Higgs Colloquium

EF5. The message from the LHC seems to be that with data in hand, we consistently outperform expectations for extraction of Higgs properties. In that case, what would an ILC contribute? What key assumptions are we making now that we could relax with ILC inputs?

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	LHC	
Mode	300 fb^{-1}	3000 fb^{-1}
$\gamma\gamma$	$(5-7)\%$	$(2-5)\%$
gg	$(6-8)\%$	$(3-5)\%$
WW	$(4-5)\%$	$(2-3)\%$
ZZ	$(4-5)\%$	$(2-3)\%$
$t\bar{t}$	$(14-15)\%$	$(7-10)\%$
$b\bar{b}$	$(10-13)\%$	$(4-7)\%$
$\tau^+\tau^-$	$(6-8)\%$	$(2-5)\%$

	LHC	
Mode	300 fb^{-1}	3000 fb^{-1}
$\mu^+\mu^-$	30%	10%
hhh	-	50%
BR(invis.)	$< (17-28)\%$	$< (6\text{-}17)\%$
$c\bar{c}$	-	-
$\Gamma_T(h)$	-	-

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Energy/Lumi Scenarios

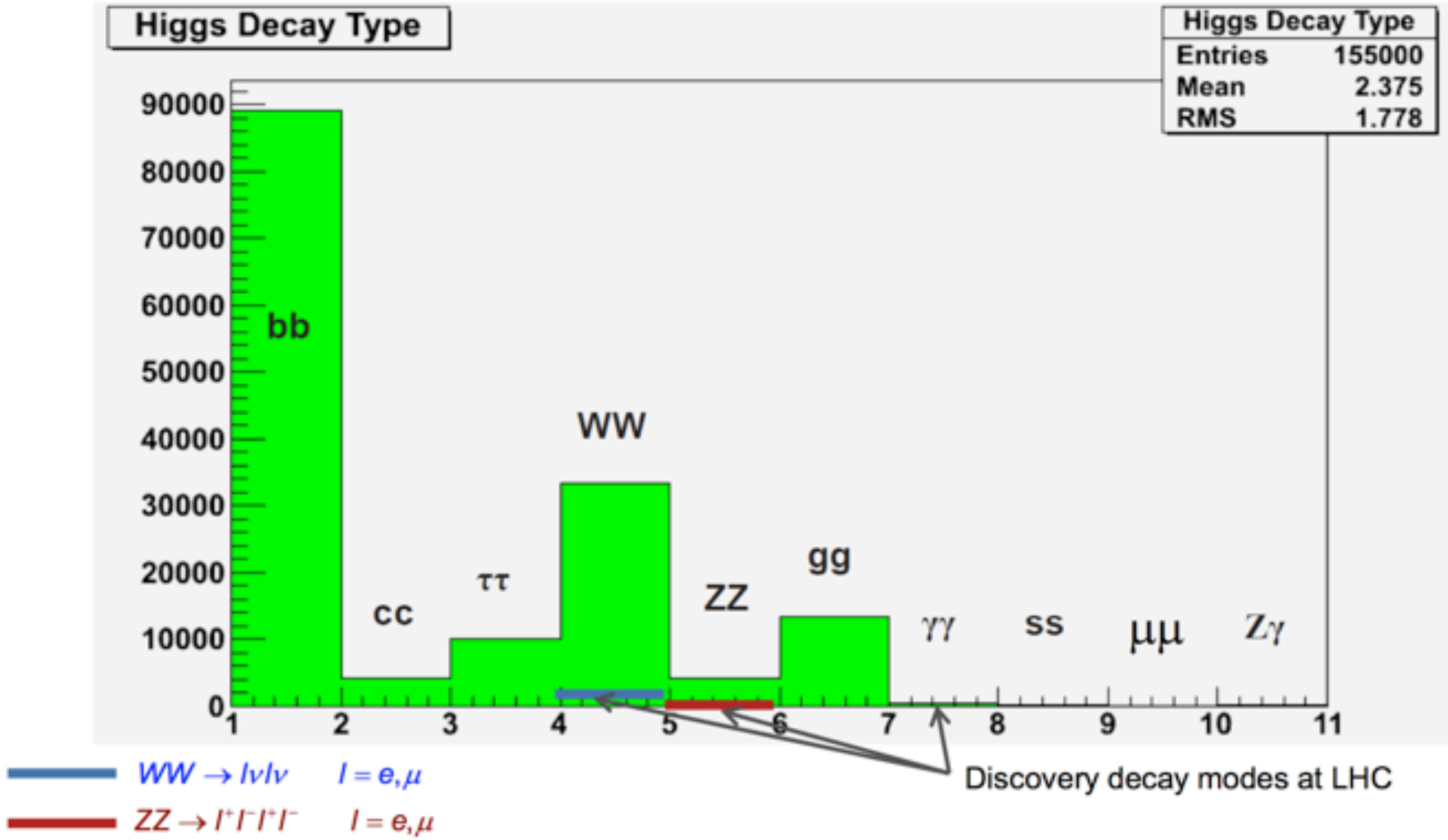
- Each scenario corresponds to accumulated luminosity at a certain point in time.
- Assumption: run for $3X10^7$ s at baseline lumi at each of Ecm=250,500,1000 GeV, in that order. Then go back and run for $3X10^7$ s at upgrade lumi at each of Ecm=250,500,1000 GeV.

Scenario #	Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})
1	ILC(250)	250	250						
2	ILC(500)	250	250		500	500			
3	ILC(1000)	250	250		500	500		1000	1000
4	ILC(LumUp)	250	1150		500	1600		1000	2500

QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

- All beam crossings are triggered at the ILC
- All background is electroweak.
- Roughly, the detection efficiency is independent of decay mode $\Rightarrow \Delta(\sigma \bullet BR) / \sigma \bullet BR \propto 1/\sqrt{BR}$

- LHC Higgs detection efficiency is uneven across decay modes.
- Higgs was discovered in decays modes with γ, e, μ, which have relatively small BR's
- Qualitatively, there is complementarity between the ILC and LHC with respect to decay modes.



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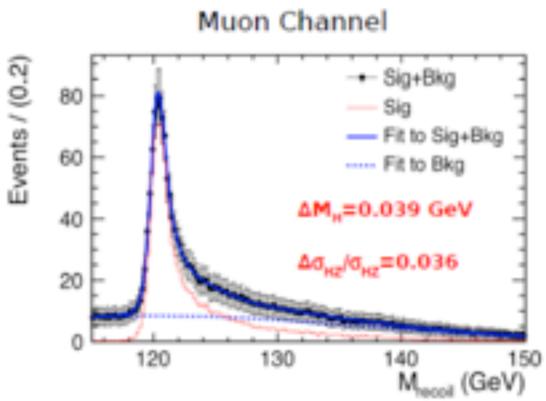
QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

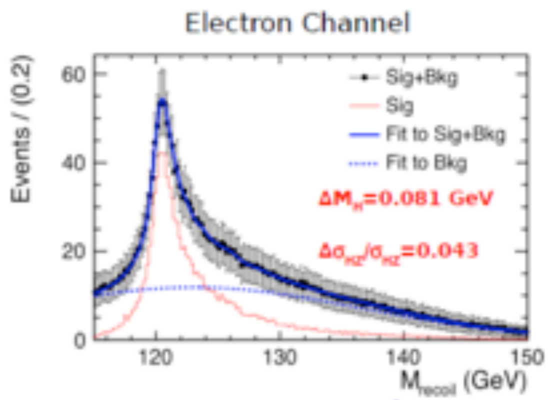
- Almost all ILC Higgs measurements are measurements of $\sigma \bullet BR$.
- One crucial measurement is different: the Higgs recoil measurement of $\sigma(e^+e^- \to ZH)$.
- σ_{ZH} is the key that unlocks the door to model independent measurements of the Higgs BR's and Γ_{tot} at the ILC.

- All LHC Higgs measurements are measurements of $\sigma \bullet BR$

and hence model-dependent!



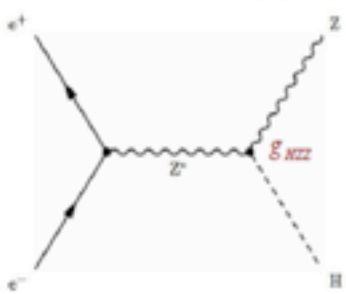
Very Precise Measurement
S/B = 8 in Peak Region



Less Precise
Bremsstrahlung in detector material

Combined: $\Delta M_H = .032$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=2.5% for L= 250 fb^{-1}

$\Delta M_H = .015$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=1.2% for L=1150 fb^{-1}



$\sigma_{HZ} \sim g^2_{HZZ}$

$\Rightarrow \Delta g_{HZZ} / g_{HZZ} = 1.3\%\ (0.6\%)$ for L=250 (1150) fb^{-1}

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QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

ILC model independent global coupling fit using 32 $\sigma \bullet BR$ measurements Y_i and σ_{ZH} measurement Y_{33}

$$\chi^2 = \sum_{i=1}^{i=33} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2,$$

$$Y_i' = F_i \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{Htt} g^2_{Hb\bar{b}}}{\Gamma_0}$$

$$F_i = S_i G_i \quad \text{where } S_i = \left(\frac{\sigma_{ZH}}{g_Z^2}\right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_W^2}\right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g_t^2}\right), \text{ and } G_i = \left(\frac{\Gamma_i}{g_i^2}\right).$$

The cross section calculations S_i do not involve QCD ISR.

The partial width calculations G_i do not require quark masses as input.

We are confident that the total theory errors for S_i and G_i will be at the 0.1% level at the time of ILC running.

THESE AND OTHER QUALITATIVE DIFFERENCES BETWEEN ILC & LHC LEAD TO QUANTITATIVE IMPROVEMENTS OVER LHC

7 Parameter HXSWG Benchmark *

Mode	LHC 300 fb^{-1}	LHC 3000 fb^{-1}	ILC(1000)	ILC(LumUp)
$\gamma\gamma$	$(5-7)\%$	$(2-5)\%$	3.8 %	2.3 %
gg	$(6-8)\%$	$(3-5)\%$	1.1 %	0.67 %
WW	$(4-5)\%$	$(2-3)\%$	0.21 %	0.13 %
ZZ	$(4-5)\%$	$(2-3)\%$	0.44 %	0.22 %
$t\bar{t}$	$(14-15)\%$	$(7-10)\%$	1.3 %	0.76 %
$b\bar{b}$	$(10-13)\%$	$(4-7)\%$	0.51 %	0.31 %
$\tau^+\tau^-$	$(6-8)\%$	$(2-5)\%$	1.3 %	0.72 %

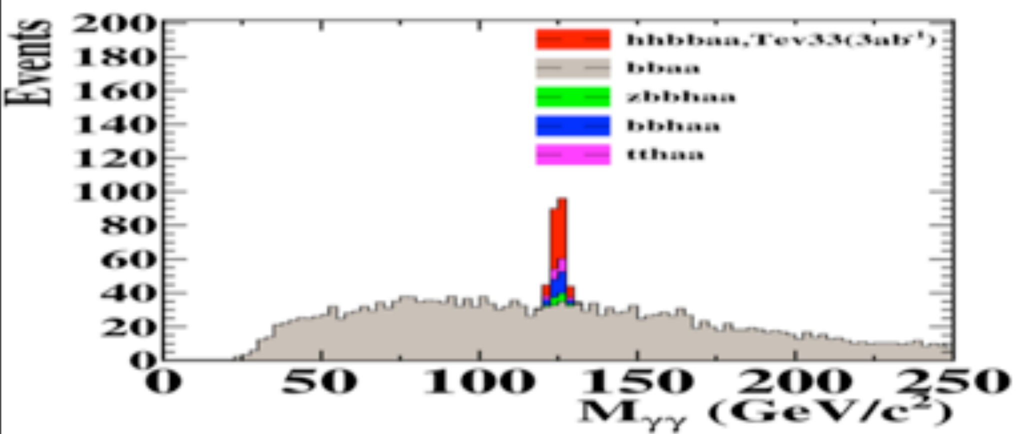
* Assume $\kappa_c = \kappa_t$ & $\Gamma_{tot} = \sum_{\text{SM decays } i} \Gamma_i^{SM} \kappa_i^2$

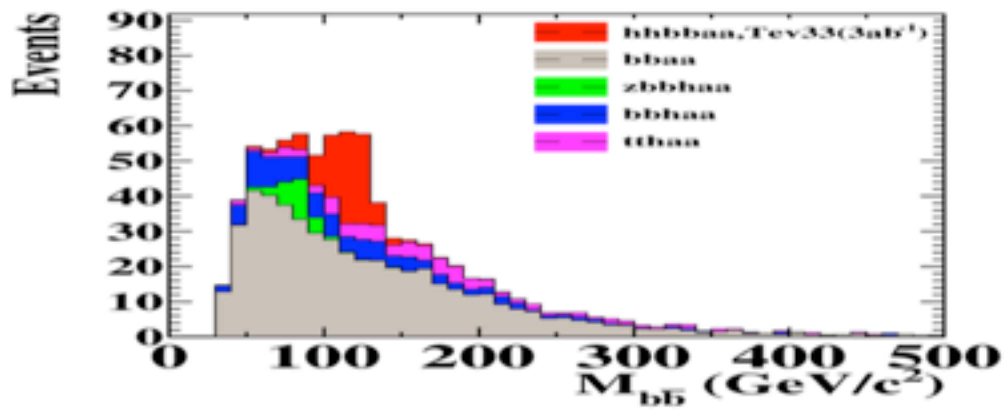
Weiming Yao’s Presentation at a Higgs Parallel Session

Self-coupling at HL-LHC & HE-LHC

• Expected $S/\sqrt{B}$ ~ 2.3, 6.2, 15 for $\sqrt{s}$=14, 33, 100 TeV with 3 ab^{-1}.

	HL-LHC (3 ab^{-1})			TeV33 (3 ab^{-1})			TeV100 (3 ab^{-1})		
Samples	$\sigma \cdot Br$	Acc.	Expect	$\sigma \cdot Br$	Acc.	Expect	$\sigma \cdot Br$	Acc.	Expect
	(fb)	(%)	Evnts	(fb)	(%)	Evnts	(fb)	(%)	Evnts
$HH(b\bar{b}\gamma\gamma)$	0.089	6.2	16.6	0.545	5.04	82.4	3.73	3.61	403.9
$bb\gamma\gamma$	294	0.0045	40.1	1085	0.0039	126.4	5037	0.00275	415.4
$z(b\bar{b})h(\gamma\gamma)$	0.109	1.48	4.86	0.278	1.41	11.8	0.875	1.57	41.2
$b\bar{b}h(\gamma\gamma)$	2.23	0.072	4.82	9.84	0.084	24.8	50.5	0.099	150.5
$t\bar{t}h(\gamma\gamma)$	0.676	0.178	3.62	4.76	0.12	16.5	37.3	0.11	124.2
Total B	-	-	53.4	-	-	179.5	-	-	731.3
$S/\sqrt{B}$	-	-	2.3	-	-	6.2	-	-	15.0





• Results are consistent with European Strategy studies at HL-LHC.

• The bbγγ QCD production seems dominant source of background.

• With 3ab^{-1}, the Higgs self-coupling could be measured to be $^{+35\%}_{-23\%}$ ($^{+15\%}_{-10\%}$) statistic only by observing HH→bbγγ at $\sqrt{s}$=33 (100) TeV collider.

Answers to the Claims

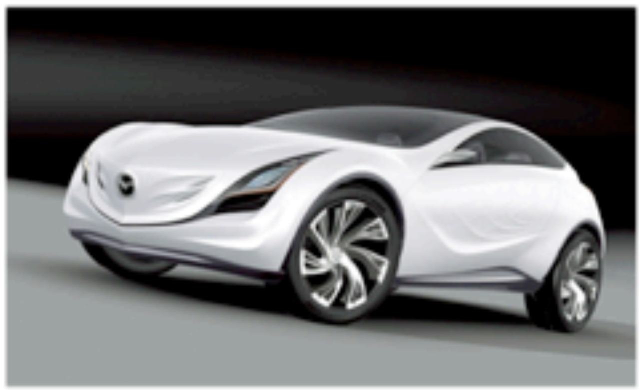
- For all the Higgs couplings other than htt and hhh, TLEP can do much better than ILC owing to its higher luminosity and capability to host 4 detectors.
  - ➡ With HL-ILC including both energy and luminosity upgrades, there is no qualitative difference in precisions.
- TLEP tunnel can house a 100TeV class pp collider that would provide much better precisions for htt and hhh than ILC.
  - ➡ The HL-ILC can model-independently determine htt to 2% and hhh to 13%, wheres the corresponding HC precisions are model-dependent and that turned out to be similar or even worse even at 100TeV VLHC. Much worse at HL-LHC.
- ILC's precision on various Higgs couplings would be only a factor of two or so better than those from HL-LHC, if possible future improvements in analysis techniques and theory errors are taken into account.
  - ➡ LHC needs model assumptions to extract couplings, while ILC can determine them completely model-independently. If the same model assumptions are made, ILC's precisions will be far much better.
- Though TLEP cannot measure the htt and hhh couplings, they can be measured at HL-LHC with similar precisions to those expected at ILC.
  - ➡ See the answer to bullet number 2.

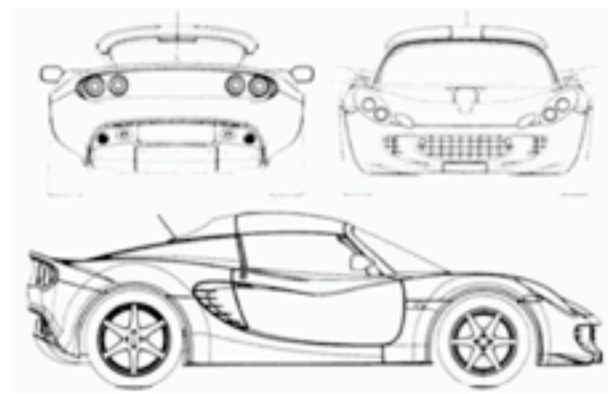
Energy Frontier Summary by Chip Broock

Excerpts from Higgs Part

the Proposal Frontier

LHC 100/fb	LHC 300/fb	LHC 3/ab	ILC 250-500GeV	ILC 1TeV	CLIC >1TeV	MC	TLEP	VLHC
years beyond TDR	TDR	LOI	TDR	TDR	CDR			





couplings by facility

Extrapolating LHC requires a strategy

2 numbers shown:
optimistic*– conservative

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

$$^{*}\ \delta(\text{sys}) \propto \frac{1}{\sqrt{\mathcal{L}}} \quad \& \quad \delta(\text{theory}) \downarrow 1/2$$

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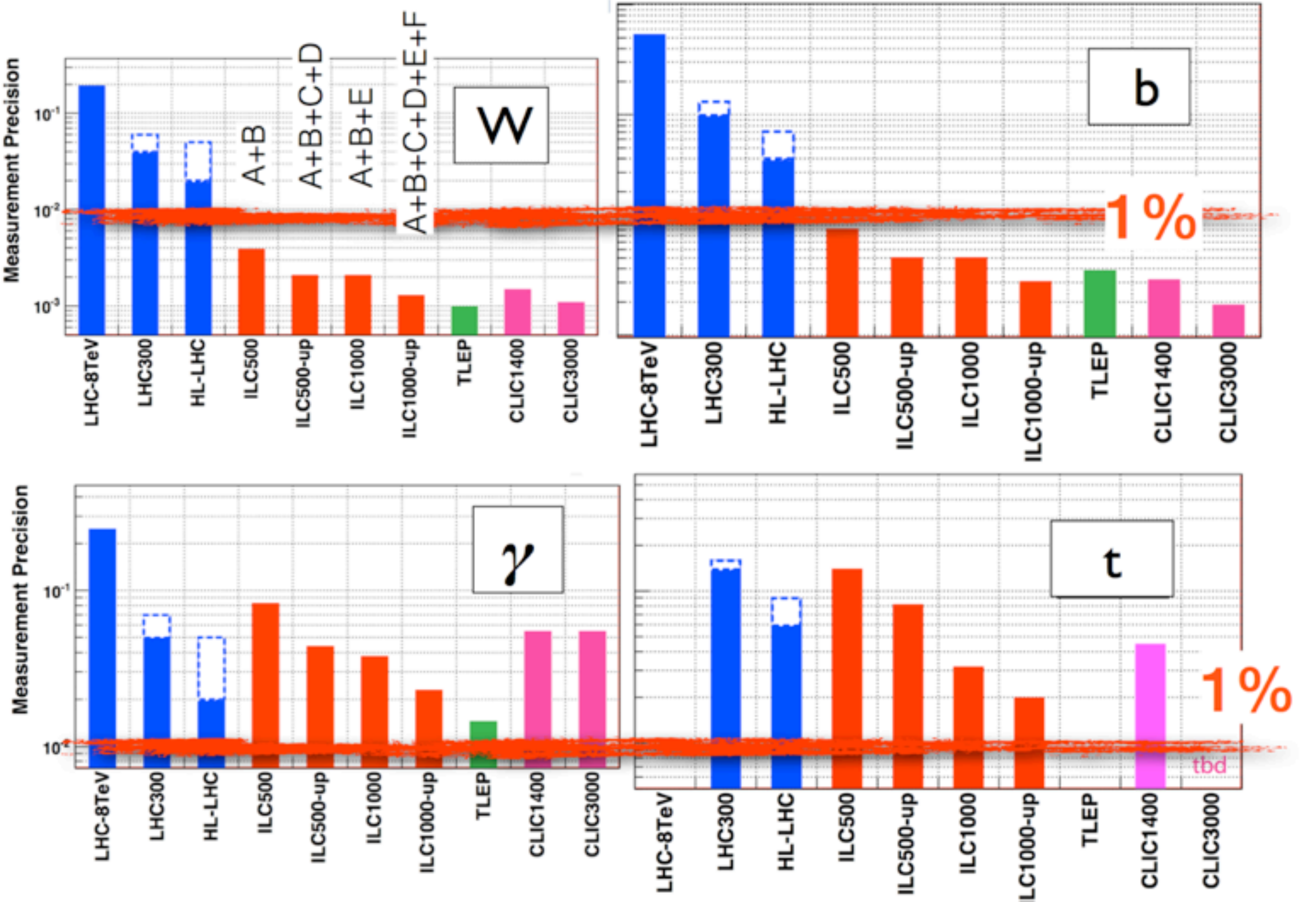
Precision in kappa by facility



The Higgs Boson message

1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

   The light Higgs boson must be explained.

   An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.

2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.

3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.

Origin of EWSB **Origin of matter** **Naturalness** **Unification** **New forces**

Dark matter **Elementary?**

bottom line

This Higgs Boson changes everything.

We're obligated to understand it using all tools.

Snowmass Summary by Ian Shipsey

Excerpts from EF part

LHC: 300 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **Clarification of Higgs couplings, mass, spin, CP to the 10% level.**
2. First direct measurement of top-Higgs couplings
3. Precision W mass below 10 MeV.
4. First measurements of VV scattering.
5. Theoretically and experimentally precise top quark mass to 600 MeV
6. Measurement of top quark couplings to gluons, Zs, Ws, photons with a precision potentially sensitive to new physics, a factor 2-5 better than today
7. **Search for top squarks and top partners and ttbar resonances predicted in models of composite top, Higgs.**
8. New generation of PDFs with improved g and antiquark distributions.
9. Precision study of electroweak cross sections in pp, including gamma PDF.
10. **x2 sensitivity to new particles: supersymmetry, Z', top partners – key ingredients for models of the Higgs potential – and the widest range of possible TeV-mass particles.**
11. Deep ISR-based searches for dark matter particles.

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From the EF summary by Chip Brock

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.**
2. Measurement of rare Higgs decays: mu mu, Z gamma with 100 M Higgs.
3. **First measurement of Higgs self-coupling.**
4. Deep searches for extended Higgs bosons
5. Precision W mass to 5 MeV
6. **Precise measurements of VV scattering; access to Higgs sector resonances**
7. Precision top mass to 500 MeV
8. Deep study of rare, flavor-changing, top couplings with 10 G tops.
9. Search for top squarks & partners in models of composite top, Higgs in the expected range of masses.
10. Further improvement of q, g, gamma PDFs to higher x, Q^2
11. A 20-40% increase in mass reach for generic new particle searches - can be 1 TeV step in mass reach
12. **EW particle reach increase by factor 2 for TeV masses.**
13. Any discovery at LHC–or in dark matter or flavor searches–can be **followed up**

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From the EF summary by Chip Brock

ILC, up to 500 GeV

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays**
2. **Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.**
3. Higgs CP studies in fermionic channels (e.g., tau tau)
4. **Giga-Z program for EW precision, W mass to 4 MeV and beyond.**
5. Improvement of triple VB couplings by a factor 10, to accuracy below expectations for Higgs sector resonances.
6. Theoretically and experimentally precise top quark mass to 100 MeV.
7. **Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs**
8. Search for rare top couplings in e+e- -> t cbar, t ubar.
9. Improvement of α_S from Giga-Z
10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

Higgs EW Top QCD NP/flavor

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From the EF summary by Chip Brock

We welcome the initiative for ILC in Japan

- U.S. accelerator community is capable to contribute
  - Supported by the physics case as part of a balanced program
- ILC design is technically ready to go
  - TDR incorporates leadership U.S. contributions to machine physics & technology
    - SRF, high power targetry (e+ source), beam delivery, damping rings, beam dynamics
- Important that there is an upgrade path of ILC to higher energy & luminosity (> 500 GeV, > 10^{34} $cm^{-2}s^{-1}$)

We are experienced & ready to do it

From the ACF summary by William Barletta

Next Step

What we want

- We have the 125 GeV boson that is a powerful tool to explore the symmetry breaking sector (SBS).
  We need to invent a way to make maximal use of it.
  - Is it possible to map various BSM models in ideally a single and hopefully a small number of generic parameter spaces so as to compare the physics reach of ILC with that of the future upgraded LHC.
  - If yes, explore the possibility of fingerprinting BSM models in the generic parameter space.
- The most important Mission of ILC = bottom-up reconstruction of the SBS and clarification of its relation to other open questions of elementary particle physics.
  - Make a strategy to reconstruct the SBS
    - Shape of SBS: Multiplet Structure (a SM-like 2-let main but what about small admixtures of 1-let?, 3-let? If there, how many?, ...)
    - Dynamics behind SBS: weakly/strongly interacting = elementary/composite
  - Clarify relation to other open questions: DM, Baryogenesis, Neutrino mass, Hierarchy, ...
- ILC is an energy frontier machine. We need to re-examine the possibilities given the existence of the 125GeV boson and their relations to the open questions.

More Exercises Needed

- For theorists:
  - ILC can measure various quantities such as mh, gamma_h, ghxx, mt, etc. far better than LHC. But how accurately do we really need to measure them? → partly done in the snowmass study
  - What will be the ultimate theoretical uncertainties in various predictions for LHC and ILC, respectively?
- For Experimentalists:
  - Update all the old analyses with mh=120 GeV to mh=125GeV → partly done
  - Complete the analyses such as rare Higgs decays: → partly done but not fully yet
  - Improve the analyses such as self-coupling, H->gamma gamma where the results are not yet satisfactory. → being worked on
  - With the projected running scenarios described in DBD, the most measurements are still statistically limited and should improve by a luminosity upgrade or by running longer. Nevertheless, ILC, too, will hit systematics limits, eventually. It is probably the right time to start more serious studies of expected systematic errors.
    - Identify possible sources of systematic errors
    - Estimate to what degree we can control them → partly done but not fully yet