Measuring Higgs Couplings at Future Lepton Colliders

Keisuke Fujii

HC 2014, Oct. 2, 2014

arXiv: 1306.6352 (TDR Phys.)

arXiv: 1310.0763 (Higgs)

Disclaimer

This talk is NOT on lepton collider comparison

BUT on target Higgs physics
at proposed future e^+e^- facilities

I have been working for ILC for long time, so
I am not in the position to make a neutral comparison.

Roughly speaking, Higgs physics at an e^+e^- collider is more or less the same for given $\boldsymbol{E_{cm}}$ and ***effective luminosity*** that takes into account ***beam polarizations***.

➡ You can scale the results for one machine by the effective luminosity of the other.

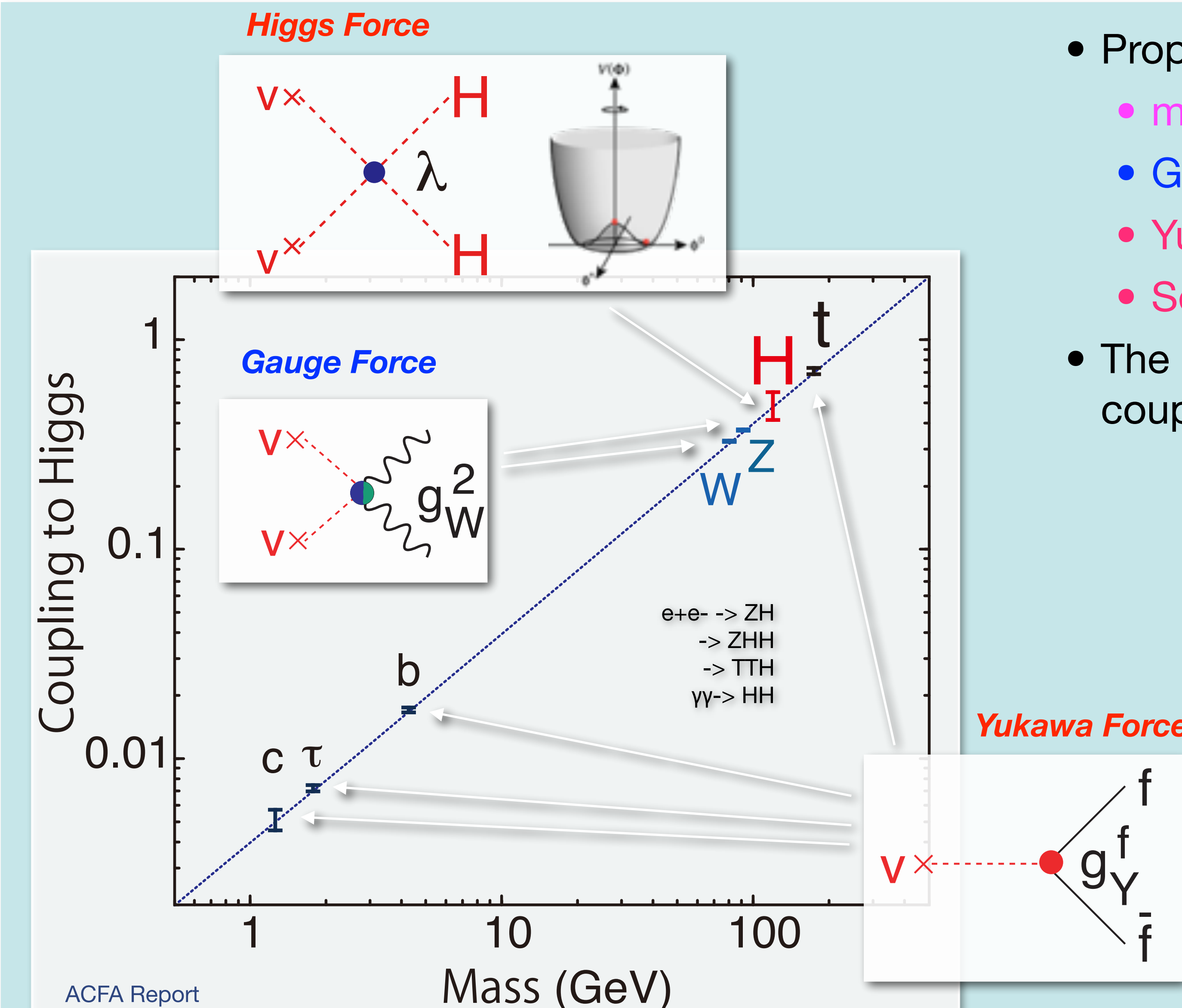
➡ I will take ILC as an example in what follows to illustrate a precision Higgs study scenario at e^+e^- colliders.

Measuring Higgs Couplings at ILC

Keisuke Fujii (KEK)

What Properties to Measure?

The Key is the Mass-Coupling Relation



- Properties to measure are
  - mass, width, J^{PC}
  - Gauge couplings
  - Yukawa couplings
  - Self-coupling
- The key is to measure the mass-coupling relation

If the 125GeV boson is the one to give masses to all the SM particles, coupling should be proportional to mass.

Any deviation from the straight line signals BSM!

The Higgs is a window to BSM physics!

Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

- **Multiplet structure :**
  - Additional singlet? $(\phi + S) + \dots?$
  - Additional doublet? $(\phi + \phi') + \dots?$
  - Additional triplet? $(\phi + \Delta) + \dots?$
- **Underlying dynamics :**
  - ***Why did the Higgs condense in the vacuum?***
  - Weakly interacting or strongly interacting?
    = ***elementary or composite ?***
- **Relations to other questions of HEP :**
  - $\phi + S$ → (B-L) gauge, DM, …
  - $\phi + \phi'$ → Type I : m_ν from small vev, …
    → Type II: SUSY, DM, …
    → Type X: m_ν (rad.seesaw), …
  - $\phi + \Delta$ → m_ν (Type II seesaw), …
  - $\lambda > \lambda_{SM}$ → EW baryogenesis ?
  - $\lambda \downarrow 0$ → inflation ?

→ There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}) \end{cases}$$

SUSY

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Expected deviations are small, typically a few % → ***We need a % level precision!***

We need a LC to cover E_{cm}= 250 to 500 GeV!

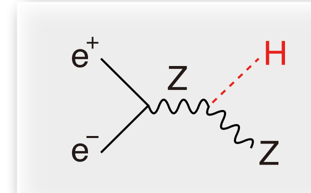
LC 250-500

Higgs-related Physics at Ecm ≲ 500 GeV

Three well know thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

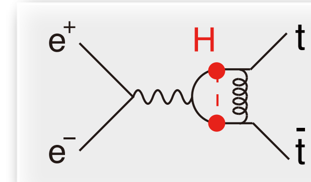
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (***recoil mass***)→***Higgs couplings (other than top)***
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)



ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

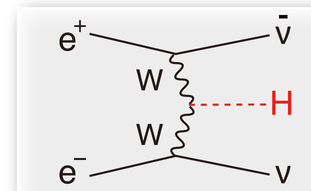
- Threshold scan --> theoretically clean m_t measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of ***top Yukawa*** coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



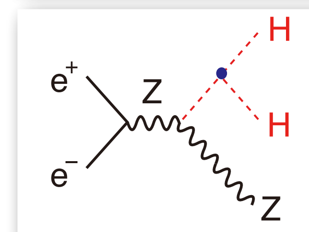
vvH @ 350 - 500GeV :

- ***HWW coupling*** -> ***total width*** --> absolute normalization of Higgs couplings



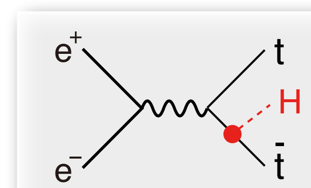
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> ***Higgs self-coupling***



ttbarH @ 500GeV (~2mt+M_H+30GeV) :

- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> ***top Yukawa*** measurable at 500GeV concurrently with the self-coupling



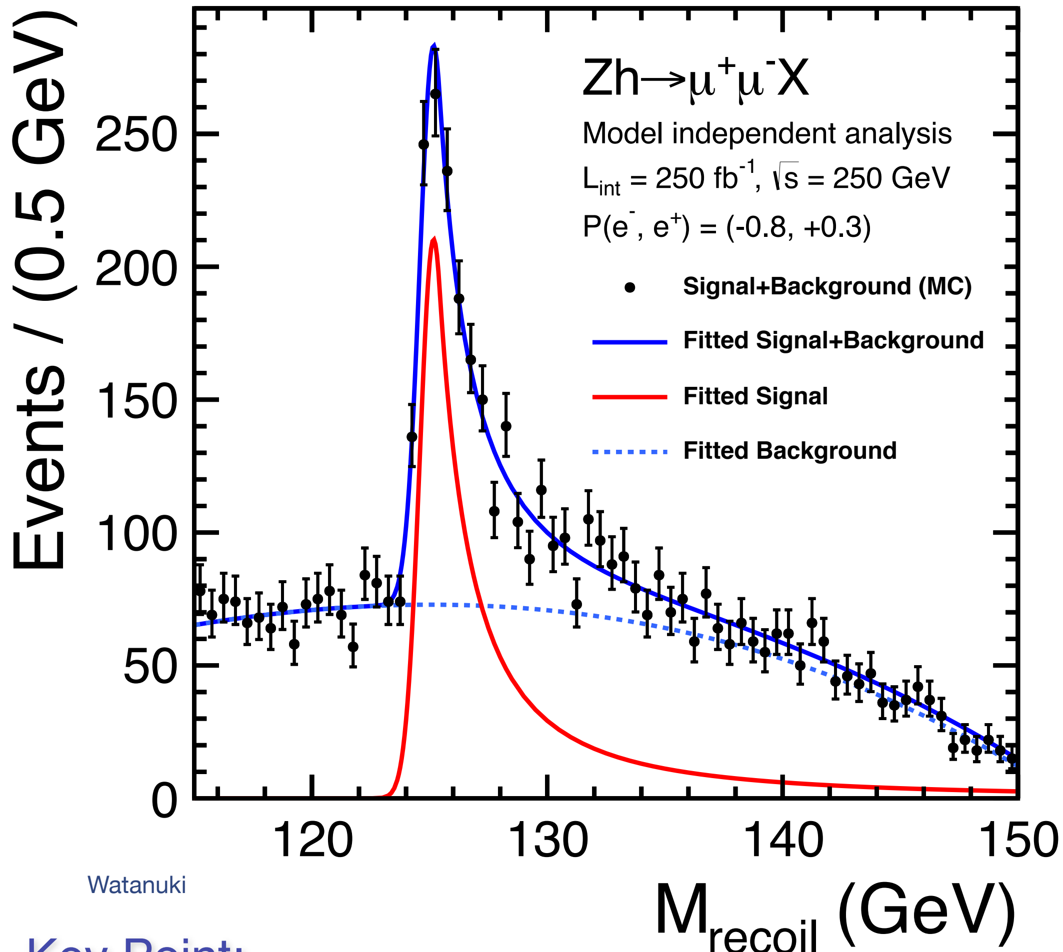
We can access all the relevant Higgs couplings at ~500GeV for the mass-coupling plot!

LC 250

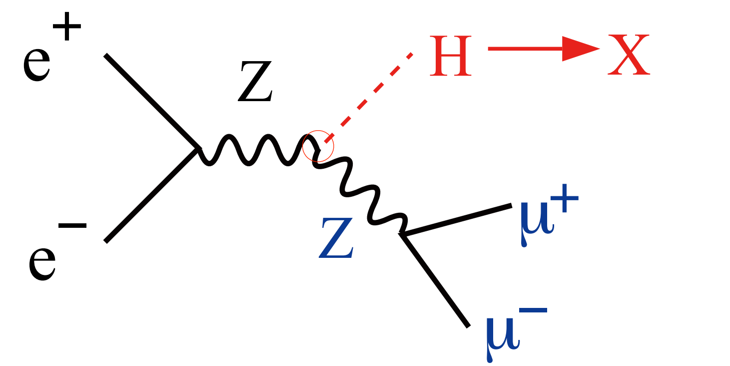
Recoil Mass Measurement: The Key

to unlock the door to fully model-independent determinations of various BRs, Higgs couplings, and total widths

Recoil Mass



Watanuki



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

Invisible decay detectable!

$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$ $\quad m_H = 125\,\mathrm{GeV}$

$$\Delta\sigma_H/\sigma_H = 2.6\%$$

$$\Delta m_H = 30\,\mathrm{MeV}$$

$$BR(\mathrm{invisible}) < 1\%\,@\,95\%\,\mathrm{C.L.}$$

scaled from mH=120 GeV

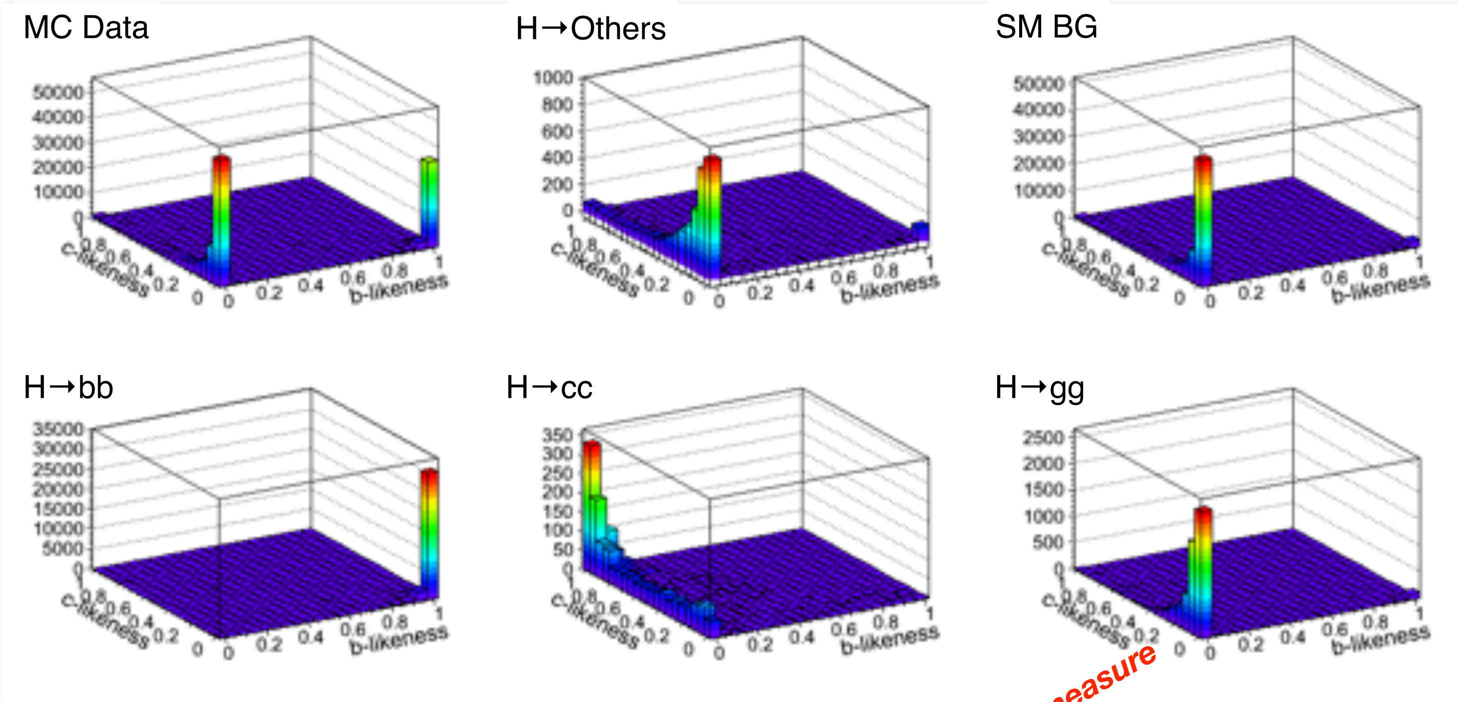
Key Point:

σ_{ZH} is the key to extract BR(h→AA) from σ×BR(h→AA) and g_{hAA} from BR(h→AA) through determination of the total width Γ_h! (great advantage of LC)

High Performance Flavor Tagging : The Key

*to directly access all the major couplings: bb, cc, ττ, gg, WW**

By template fitting, we can separate H →bb, cc, gg, others!



$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$
$m_H = 125\,\mathrm{GeV}$
scaled from mH=120 GeV

	@250GeV
process	ZH
Int. Lumi.	250
Δσ/σ	2.6%
decay mode	ΔσBr/σBr
H → bb	1.2%
H → cc	8.3%
H → gg	7%
H → WW*	6.4%
H → ττ	4.2%

DBD Physics Chap.

What we measure here is not BR itself but σxBR.

What we measure

$$BR = (\sigma \times BR)/\sigma$$

--> Δσ/σ=2.6% eventually limits the BR measurements.
--> luminosity upgrade and/or longer running in a later stage.

Clean environment and a high performance vertex detector are the two powerful weapons of the LC to directly access all of the major couplings (great advantage of the LC)

Total Width and Coupling Extraction

One of the major advantages of the LC

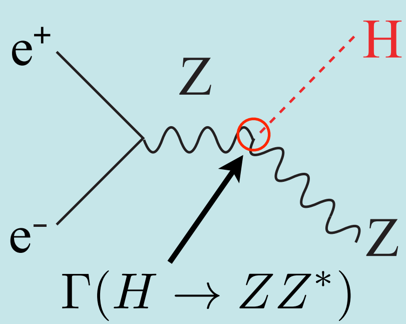
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

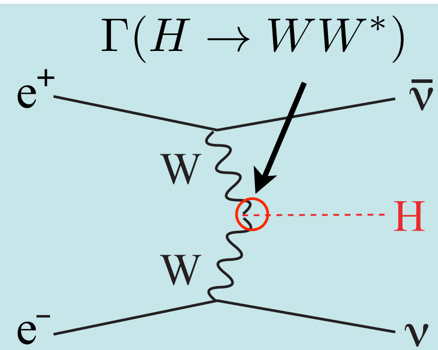
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 20\%$



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 11\%$

C.F.Durig, Helmholtz Alliance 6th WS, Dec. 2012

LC 500

Width and BR Measurements at 500 GeV

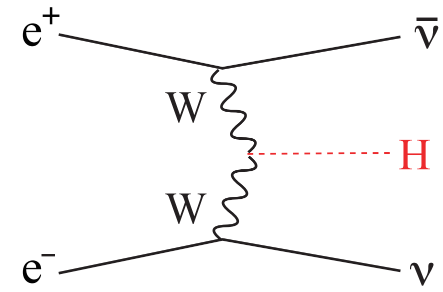
Addition of 500GeV data to 250GeV data

E	independent measurements	relative error
250	σ_{ZH}	2.6%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.2%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	8.3%
	$\sigma_{ZH} \cdot Br(H \to gg)$	7%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	6.4%
	$\sigma_{ZH} \cdot Br(H \to \tau^+\tau^-)$	4.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	10.5%
500	σ_{ZH}	3% (*)
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.8%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	13%
	$\sigma_{ZH} \cdot Br(H \to gg)$	11%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	9.2%
	$\sigma_{ZH} \cdot Br(H \to \tau^+\tau^-)$	5.4%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	0.66%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to c\bar{c})$	6.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to gg)$	4.1%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to WW^*)$	2.4%

$$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$$
$$+500\,\mathrm{fb}^{-1}@500\,\mathrm{GeV}$$
$$m_H = 125\,\mathrm{GeV}$$

ILD DBD Full Simulation Study

*) from hadronic recoil mass measurement (preliminary)



comes in as a powerful tool!

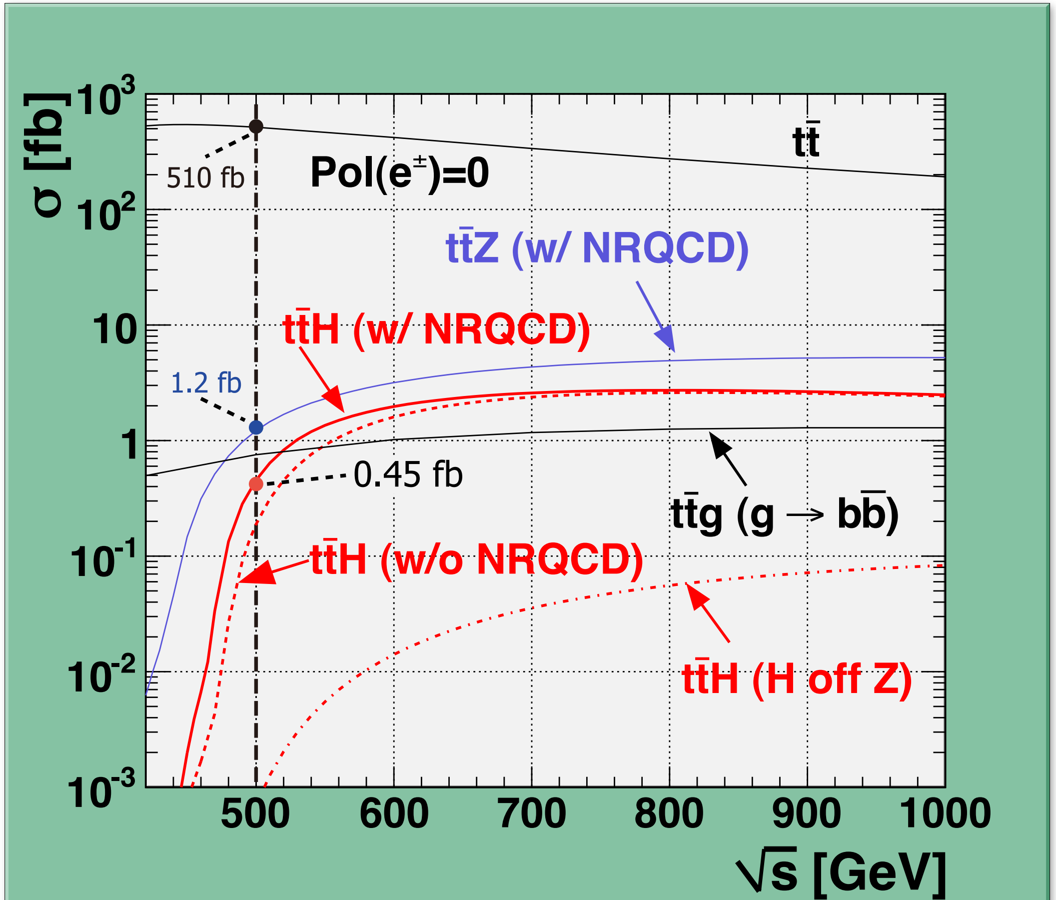
$$\Delta\Gamma_H/\Gamma_H \simeq 5\%$$

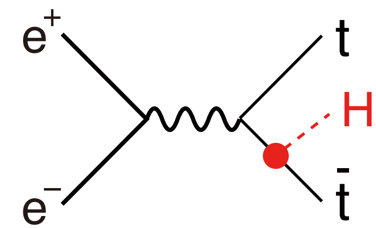
Mode	ΔBR/BR
bb	2.2 (2.9)%
cc	5.1 (8.7)%
gg	4.0 (7.5)%
WW*	3.1 (6.9)%
ττ	3.7 (4.9)%

The numbers in the parentheses are as of $250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$

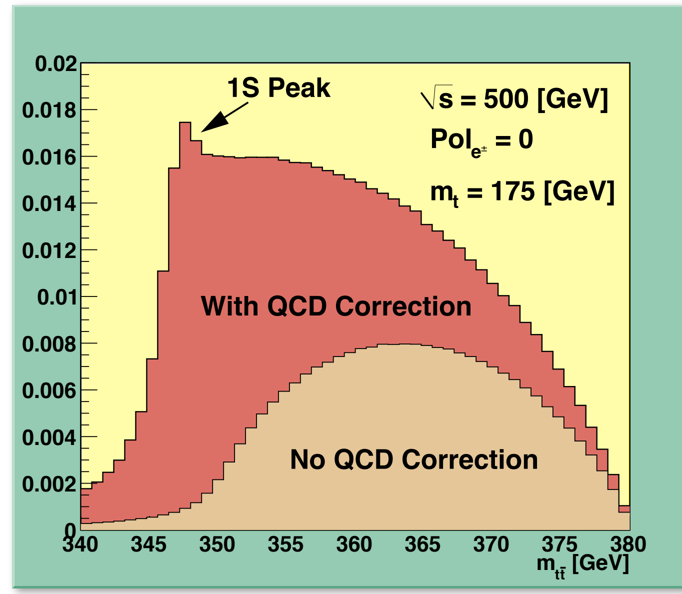
Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed





H-> bb



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff, LCWS12

Tony Price, LCWS12

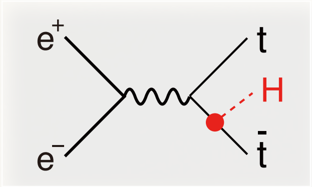
DBD Full Simulation

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$

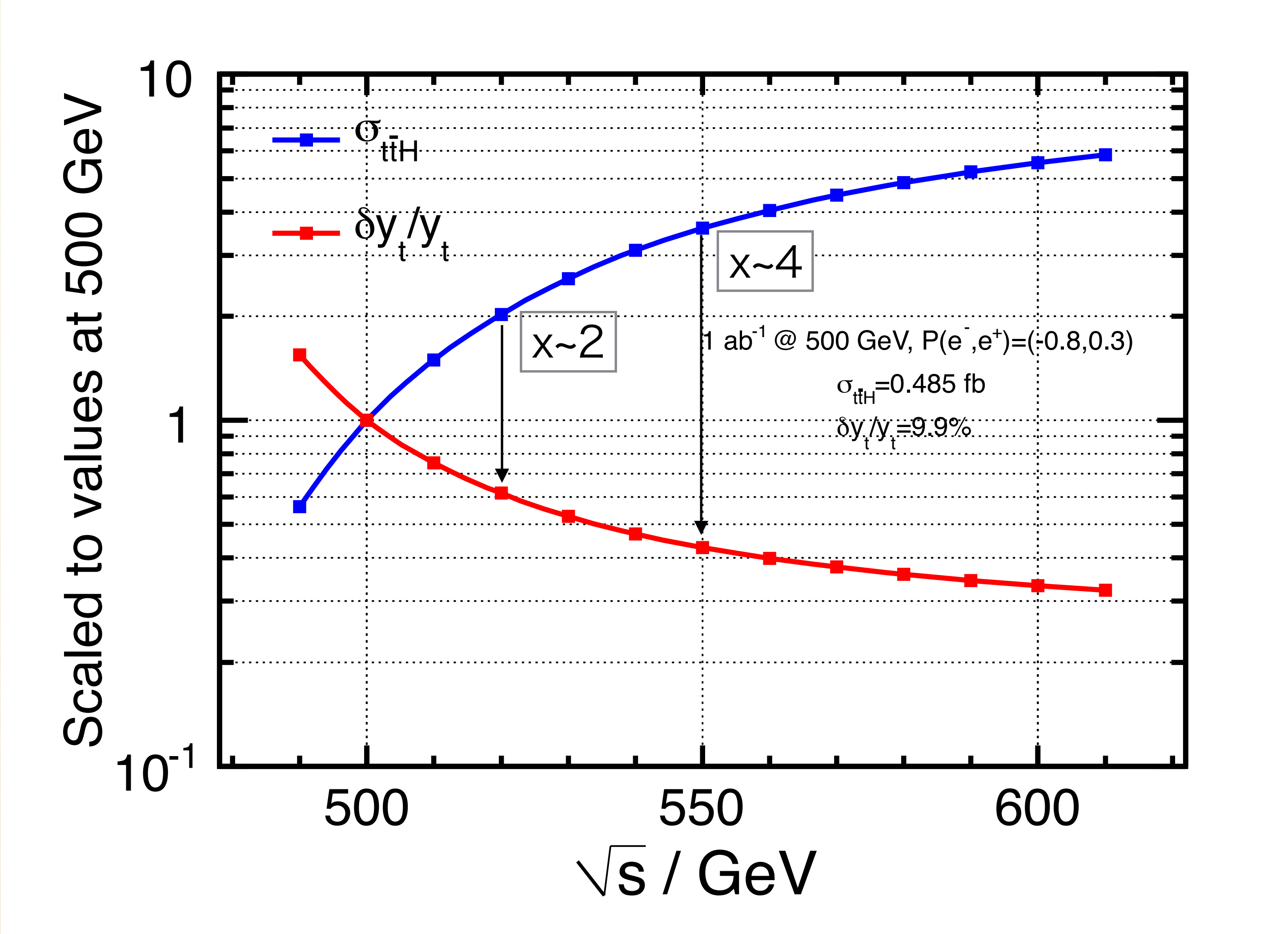
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 — scaled from mH=120 GeV

500 GeV is very close to the threshold.
Moving up a little bit helps significantly!



Top Yukawa coupling

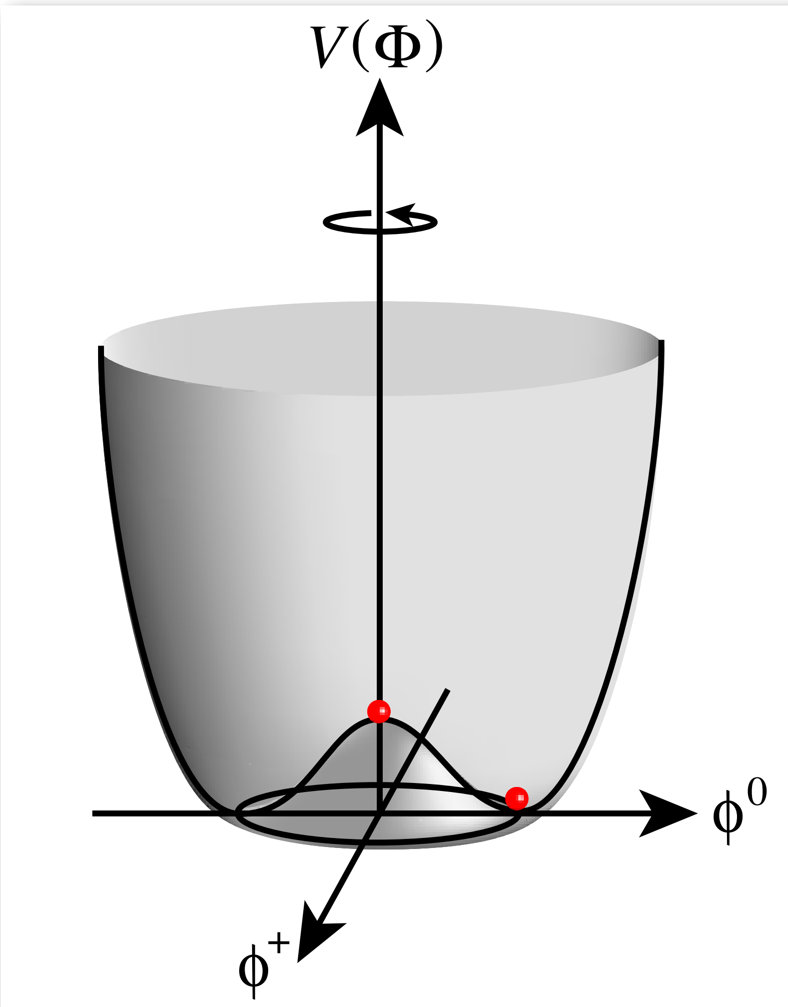


Y. Sudo

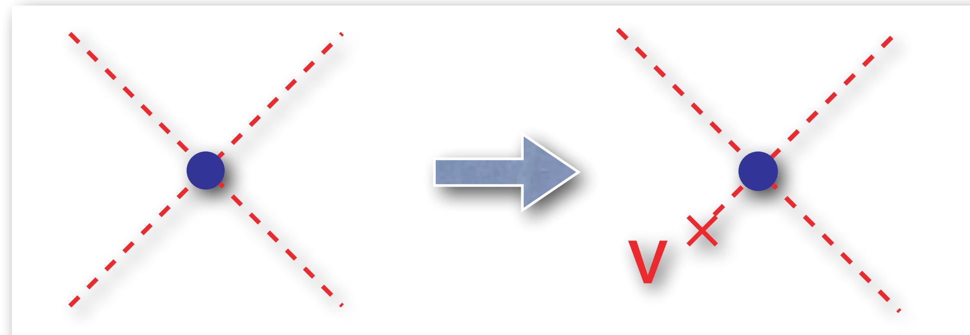
Slight increase of E_{max} is very beneficial!

And then Higgs Self-coupling

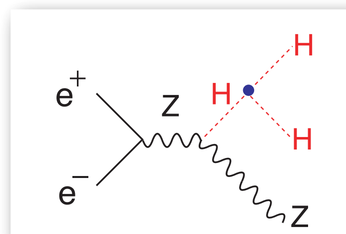
the force that made the Higgs condense in the vacuum

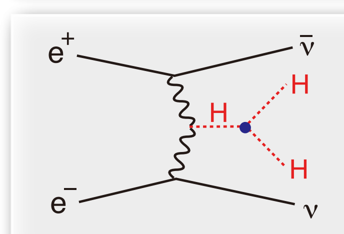


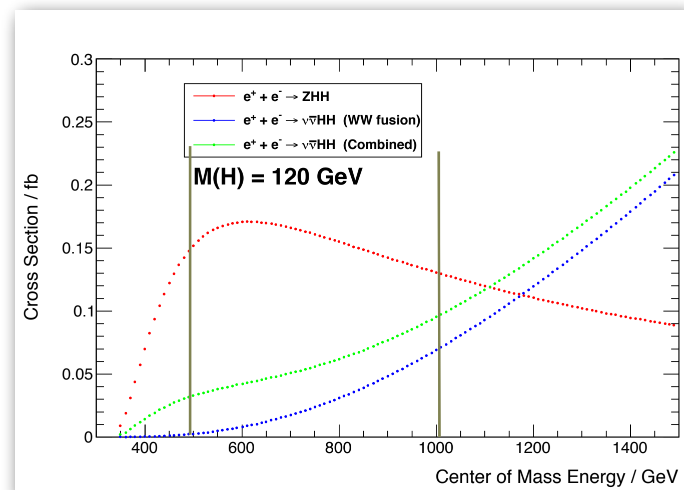
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential

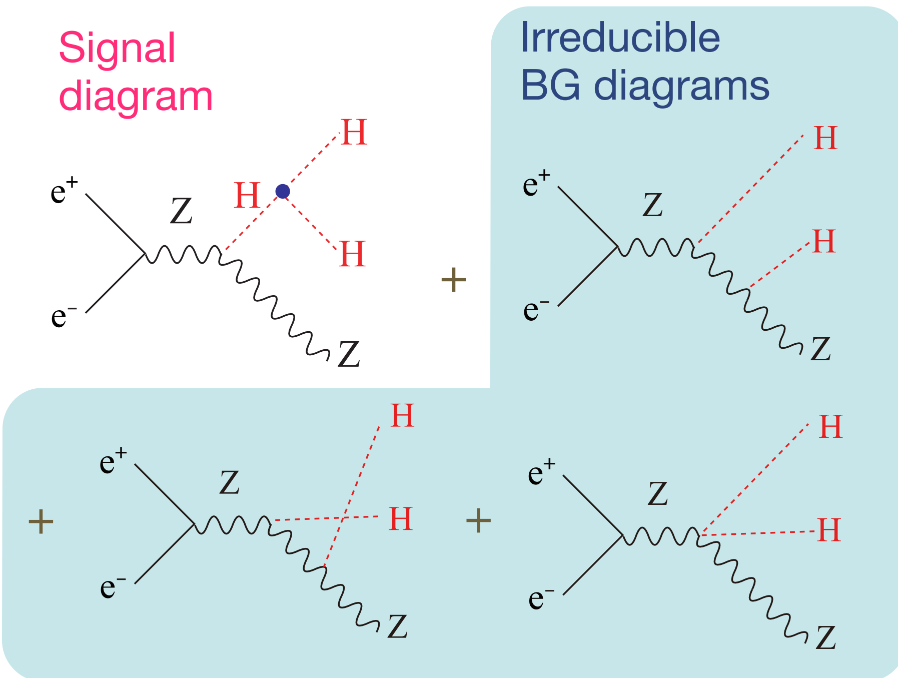






The measurement is very difficult even at LC.

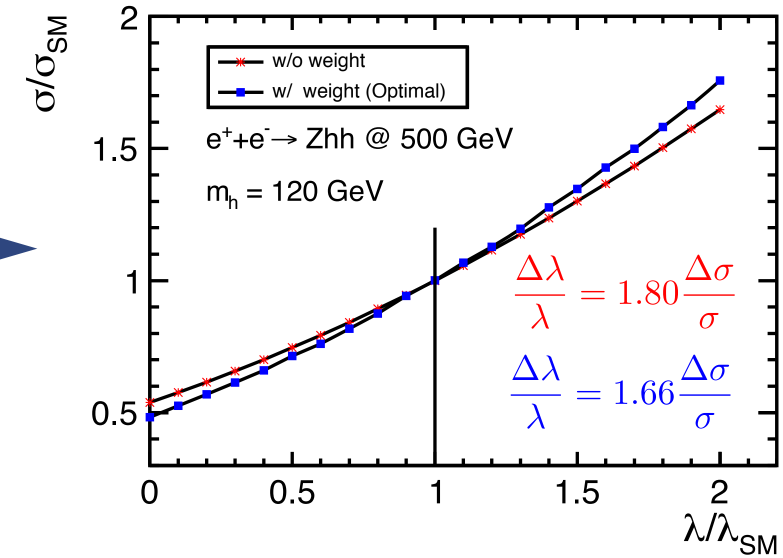
The Problem : BG diagrams dilute self-coupling contribution

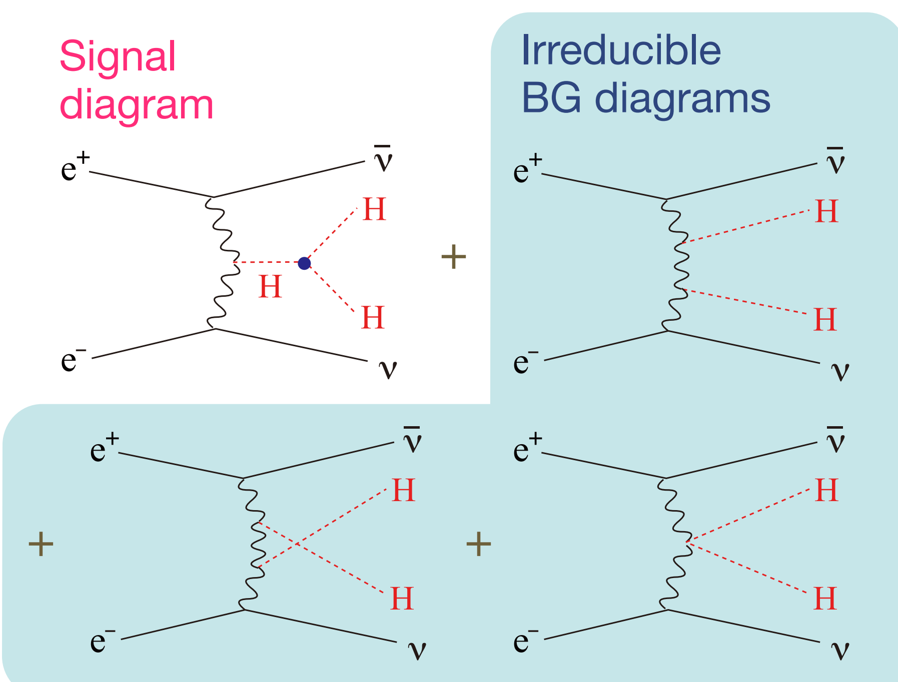


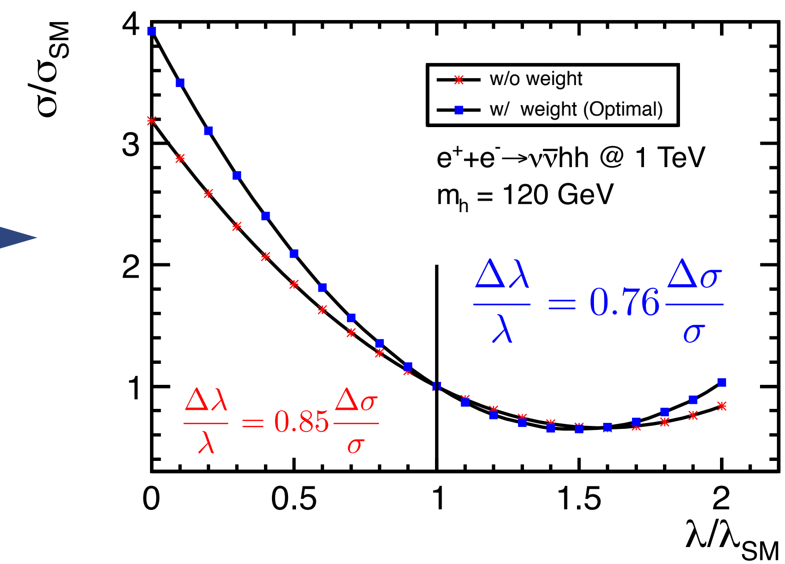
$$\sigma = \lambda^2 S + \lambda I + B$$

$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams



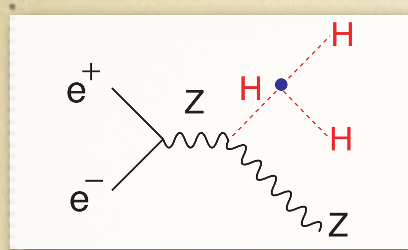




Junping Tian LC-REP-2013-003

DBD full simulation

Higgs self-coupling @ 500 GeV



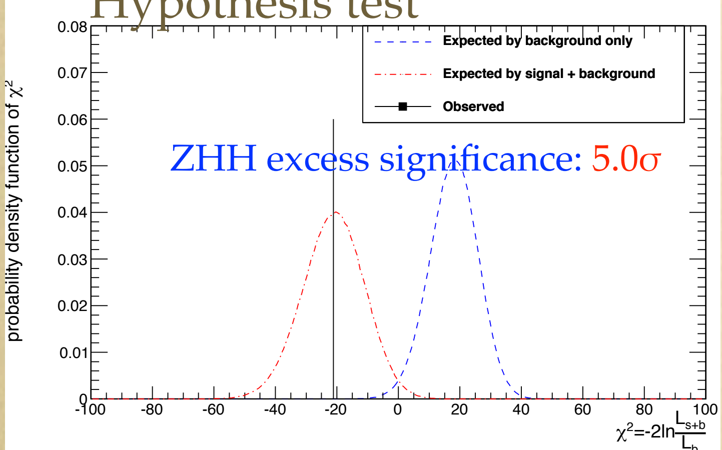
$$e^+ + e^- \rightarrow ZHH$$

$M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

P(e-,e+)=(-0.8,+0.3)

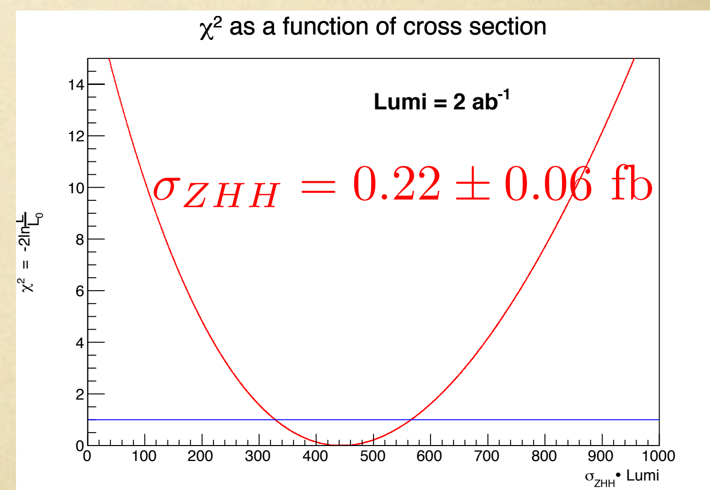
Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6	1.5σ	1.2σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

Hypothesis test



$$\frac{\delta\sigma}{\sigma} = 27\%$$

$$\frac{\delta\lambda}{\lambda} = 44\%$$

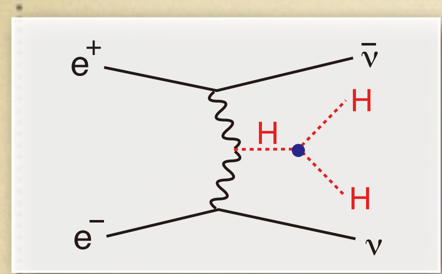


(cf. 80% for qqbbbb at the LoI time)

LC 1000

DBD full simulation

Higgs self-coupling @ 1 TeV



$$e^+ + e^- \to \nu\bar{\nu}HH$$

$M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

P(e-,e+)=(-0.8,+0.2)

	Expected	After Cut
νvhh (WW-F)	272	35.7
νvhh (ZHH)	74	3.88
BG (tt/ννZH)	7.86×10	33.7
significance	0.3	4.29

- better sensitivity factor
- benefit more from beam polarization
- BG tt x-section smaller
- more boosted b-jets

$$\frac{\Delta\sigma}{\sigma} \approx 23\%$$

$$\frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: $> 7\sigma$

Higgs self-coupling significance: $> 5\sigma$

ILD DBD Study (Junping Tian)

Extrapolation to M(H)=125GeV

HHH Prospects

Preliminary full simulation results at 500GeV confirmed the validity of extrapolation. (C.Duerig @ AWLC14)

Scenario A: HH-->bbbb, full simulation done
Scenario B: by adding HH-->bbWW*, full simulation ongoing, expect ~20% relative improvement
Scenario C: color-singlet clustering, future improvement, expected ~20% relative improvement (conservative)

HHH	500 GeV			500 GeV + 1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

Baseline:
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

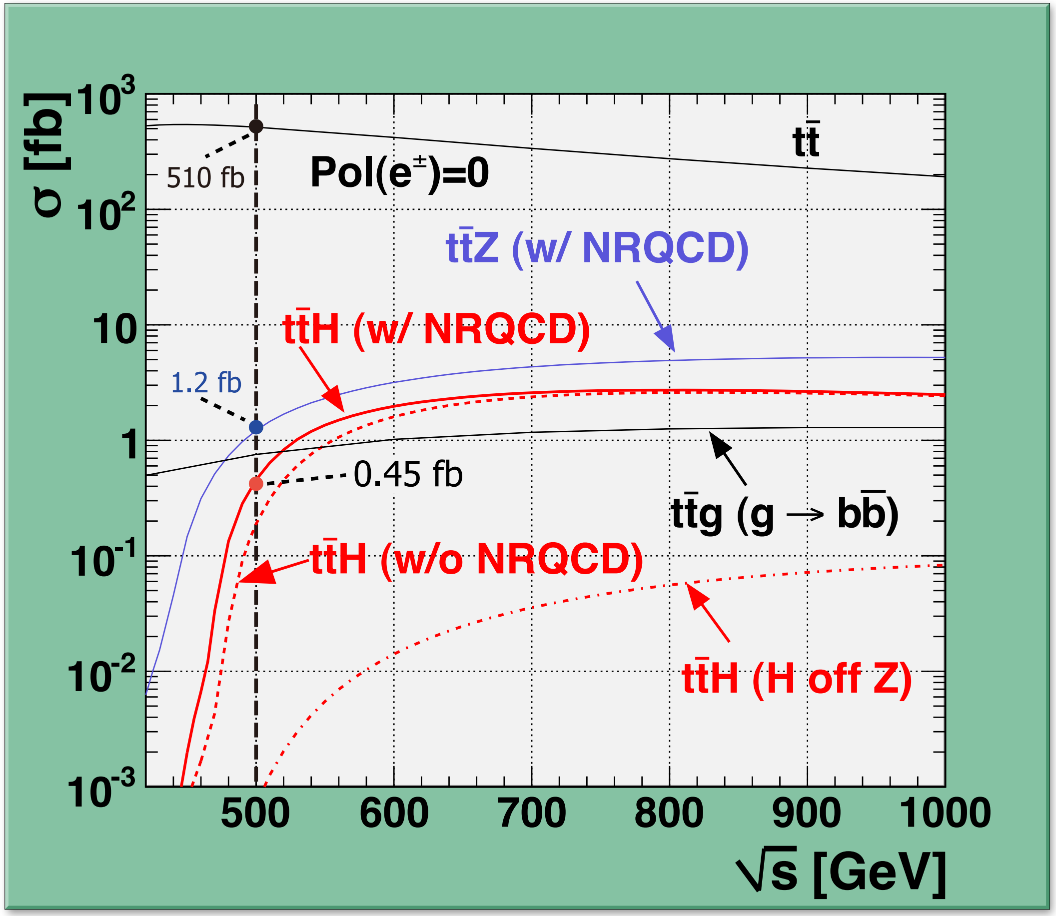
→

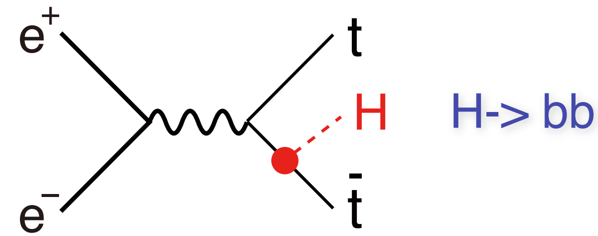
LumiUP:
250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

ILD DBD Study
(Junping Tian, Masakazu Kurata)

Top Yukawa Coupling at 1TeV

Now it is fully open!





Similar significance in both modes

8-jet mode: 7.9σ (TMVA)

L+6-jet mode: 8.4σ (TMVA)

Tony Price & Tomohiko Tanabe: ILD DBD Study

$1\,\text{ab}^{-1}$@500 GeV $\quad m_H = 125$ GeV

$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 — scaled from mH=120 GeV

↓

$1\,\text{ab}^{-1}$@1 TeV $\quad m_H = 125$ GeV

$$\Delta g_Y(t)/g_Y(t) = 3.1\%$$

ILD / SiD DBD Studies

Cross section maximum at around Ecm = 800GeV

Tony Price & Tomohiko Tanabe: ILD DBD Study

Philipp Roloff & Jan Strube: SiD DBD Dtudy

DBD Full Simulation

Independent Higgs Measurements at ILC

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

Baseline (=TDR) LC program

(M_H = 125 GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb	250		500		1000
polarization (e	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	vvH(fusion)	ZH	vvH(fusion)	vvH(fusion)
cross section	2.6%	-	3%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H→bb	1.2%	10.5%	1.8%	0.66%	0.32%
H→cc	8.3%		13%	6.2%	3.1%
H→gg	7%		11%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.4%	1.6%
H→ττ	4.2%		5.4%	9%	3.1%
H→ZZ*	18%		25%	8.2%	4.1%
H→γγ	34%		34%	19%	7.4%
H→μμ	100%	-	-	-	31%

LC 250+500+1000

Model-independent Global Fit for Couplings

33 σxBR measurements (Y_i) and σ_{ZH} ($Y_{34,35}$)

$$\chi^2 = \sum_{i=1}^{35} \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2$$

$$Y_i' = F_i \cdot \frac{g_{HA_iA_i}^2 \cdot g_{HB_iB_i}^2}{\Gamma_0} \qquad (A_i = Z, W, t)$$

$$(B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

$(i = 1, \cdots, 33)$

$$F_i = S_i\, G_i$$

$$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

$$S_i = \left(\frac{\sigma_{ZH}}{g_{HZZ}^2} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_{HWW}^2} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g_{Htt}^2} \right)$$

10 free parameters:

$$g_{HZZ},\ g_{HWW},\ g_{Hbb},\ g_{Hcc},\ g_{Hgg},\ g_{H\tau\tau},\ g_{H\gamma\gamma},\ g_{H\mu\mu},\ g_{Htt},\ \Gamma_0$$

- It is the recoil mass measurement that is the key to unlock the door to this completely model-independent analysis!
- Cross section calculations (S_i) do not involve QCD ISR.
- Partial width calculations (G_i) do not need quark mass 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 LC running.

Systematic Errors

	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

arXiv: 1310.0763

Model-independent Global Fit for Couplings

Baseline ILC program

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

(M_H = 125 GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV

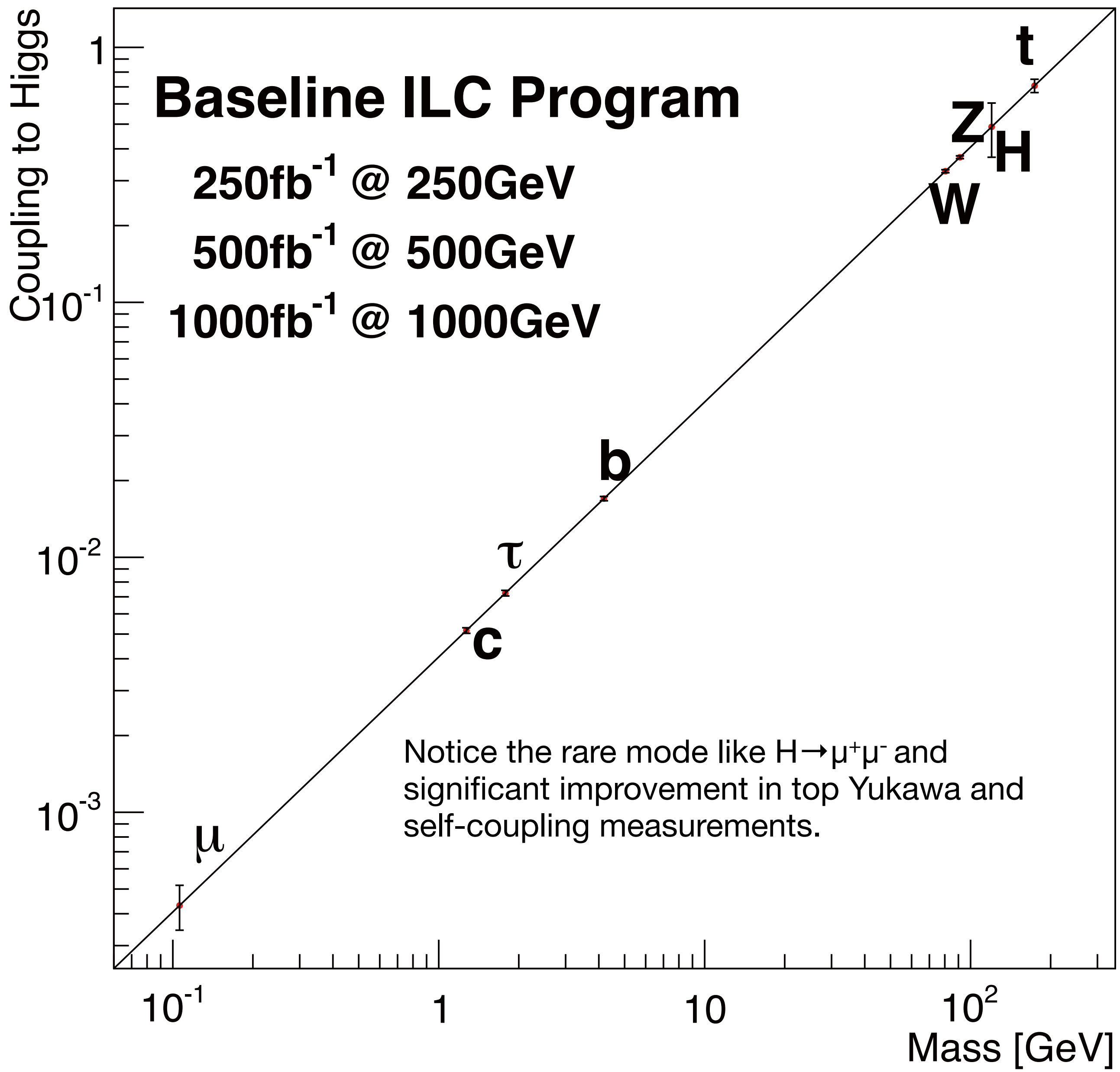
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	1.3%	1%	1%
HWW	4.8%	1.1%	1.1%
Hbb	5.3%	1.6%	1.3%
Hcc	6.8%	2.8%	1.8%
Hgg	6.4%	2.3%	1.6%
Hττ	5.7%	2.3%	1.6%
Hγγ	18%	8.4%	4%
Hμμ	91%	91%	16%
Γ	12%	4.9%	4.5%
Htt	-	14%	3.1%
HHH	-	83%(*)	21%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering it would become 17%!

Mass Coupling Relation

After Baseline LC Program



Notice the rare mode like $H \to \mu^+\mu^-$ and significant improvement in top Yukawa and self-coupling measurements.

Model-independent Global Fit for Couplings

Luminosity Upgraded ILC

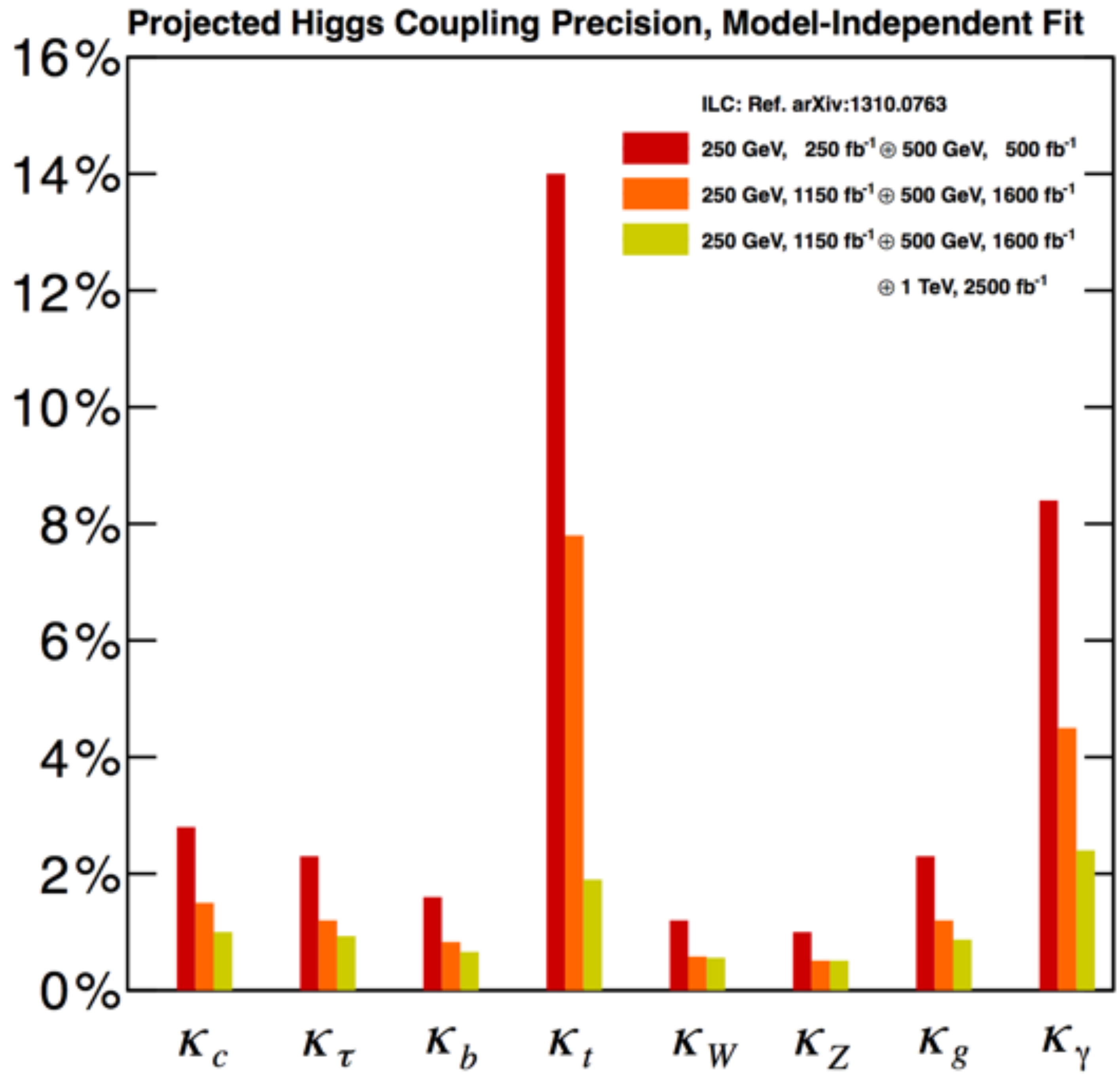
250 GeV: 250 fb^{-1}	250 GeV: 1150 fb^{-1}
500 GeV: 500 fb^{-1}	500 GeV: 1600 fb^{-1}
1 TeV: 1000 fb^{-1}	1 TeV: 2500 fb^{-1}

(M_H = 125 GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
Hττ	2.7%	1.2%	0.9%
Hγγ	8.2%	4.5%	2.4%
Hμμ	42%	42%	10%
Γ	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%
HHH	-	46%(*)	13%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

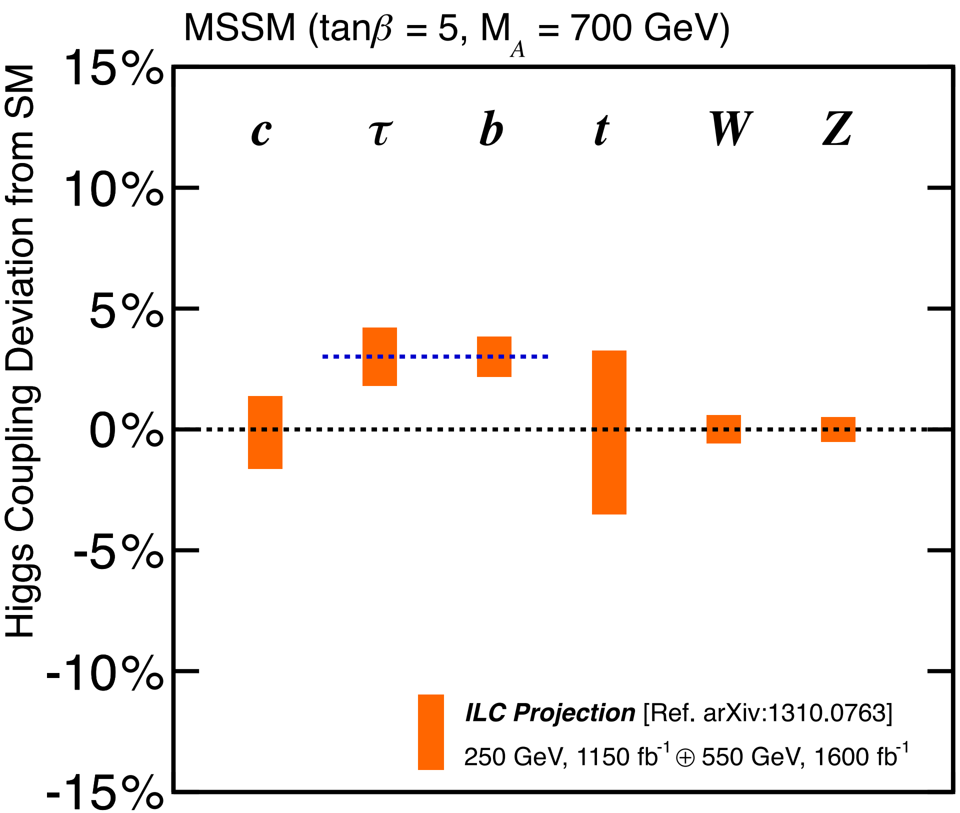


Fully model-independent fit, only possible at LC!

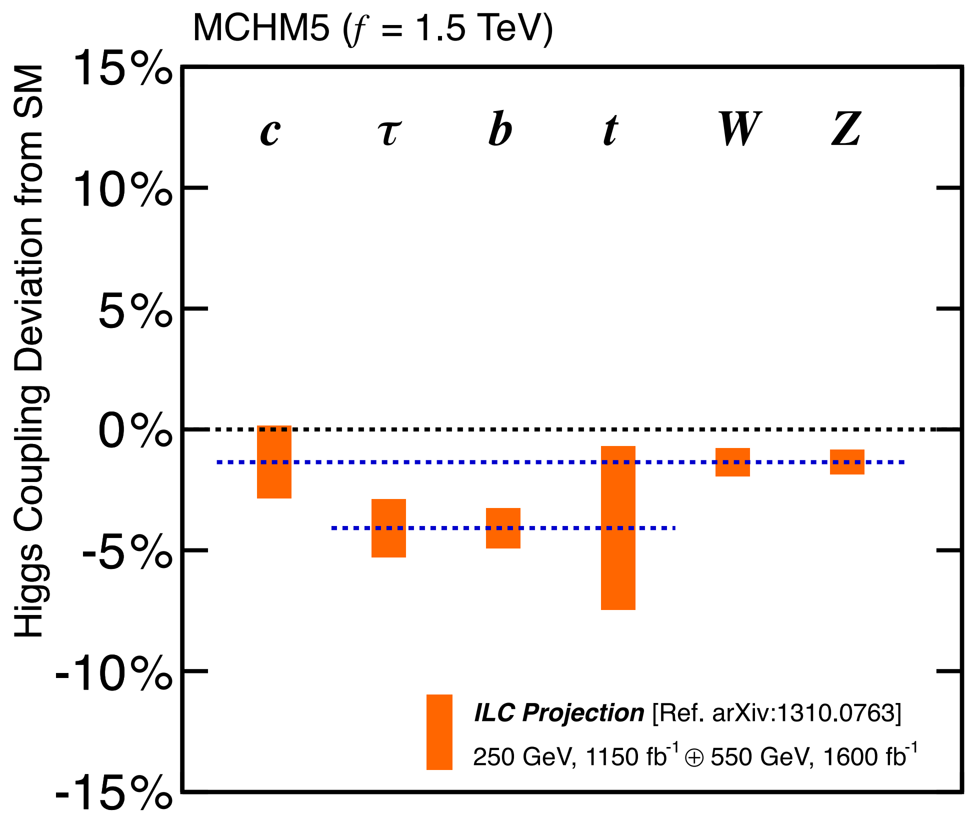
Finger Printing

Elementary v.s. Composite

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



ILC 250+550 LumiUP

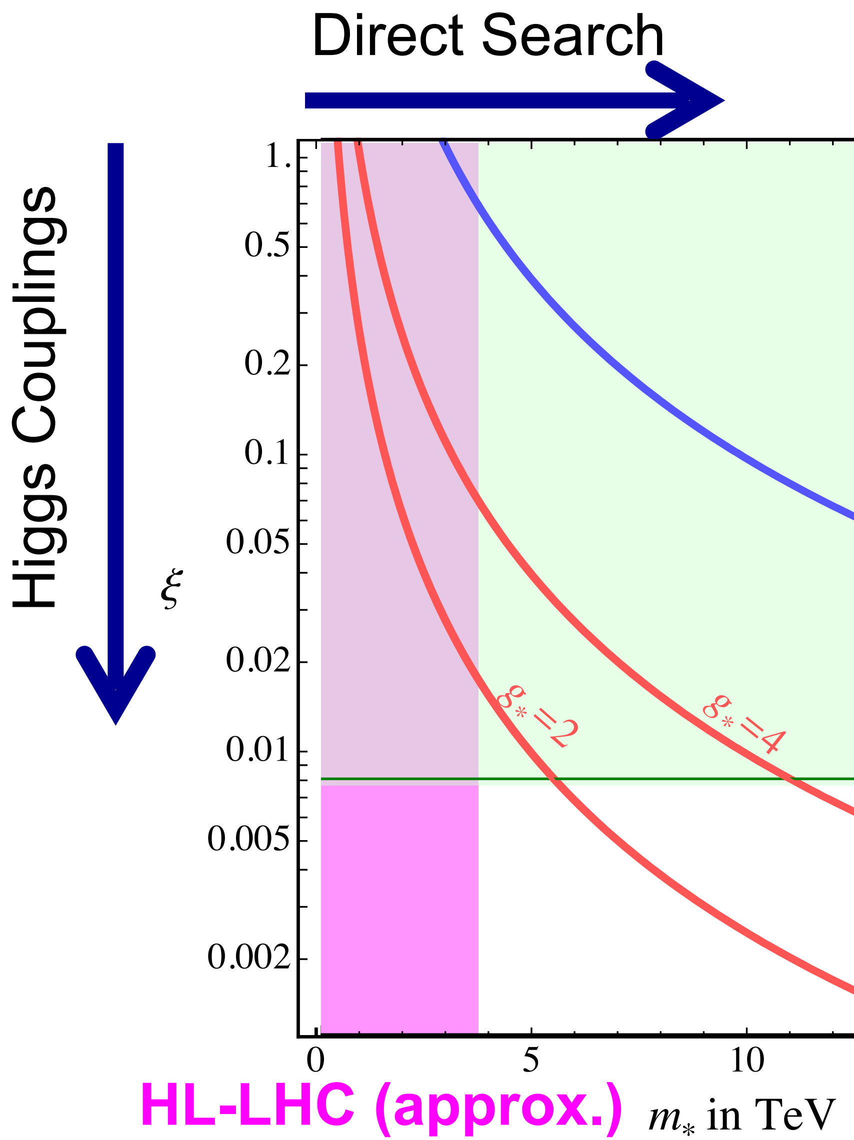
Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the LC

Comparison depends on the coupling strength (g_*)

Based on Contino, et al, JHEP 1402 (2014) 006



$$\xi = \frac{g_*^2}{m_*^2} v^2 = \frac{v^2}{f^2}$$

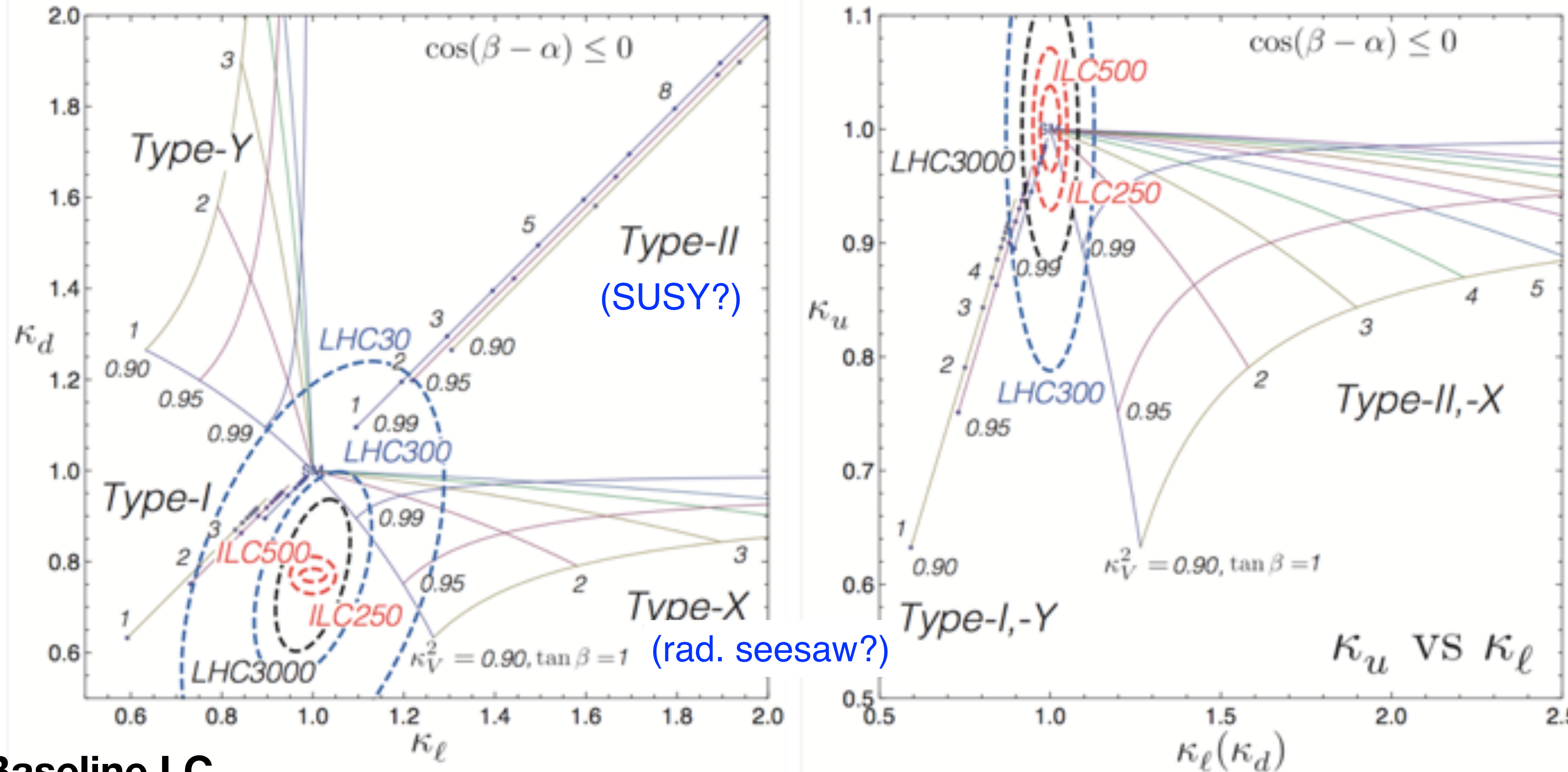
$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \sqrt{1-\xi}$$

ILC (250+500 LumiUP)

$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

Finger Printing **2HDM**

Down-type lepton vs down-type quark **Down-type lepton vs up-type quark**

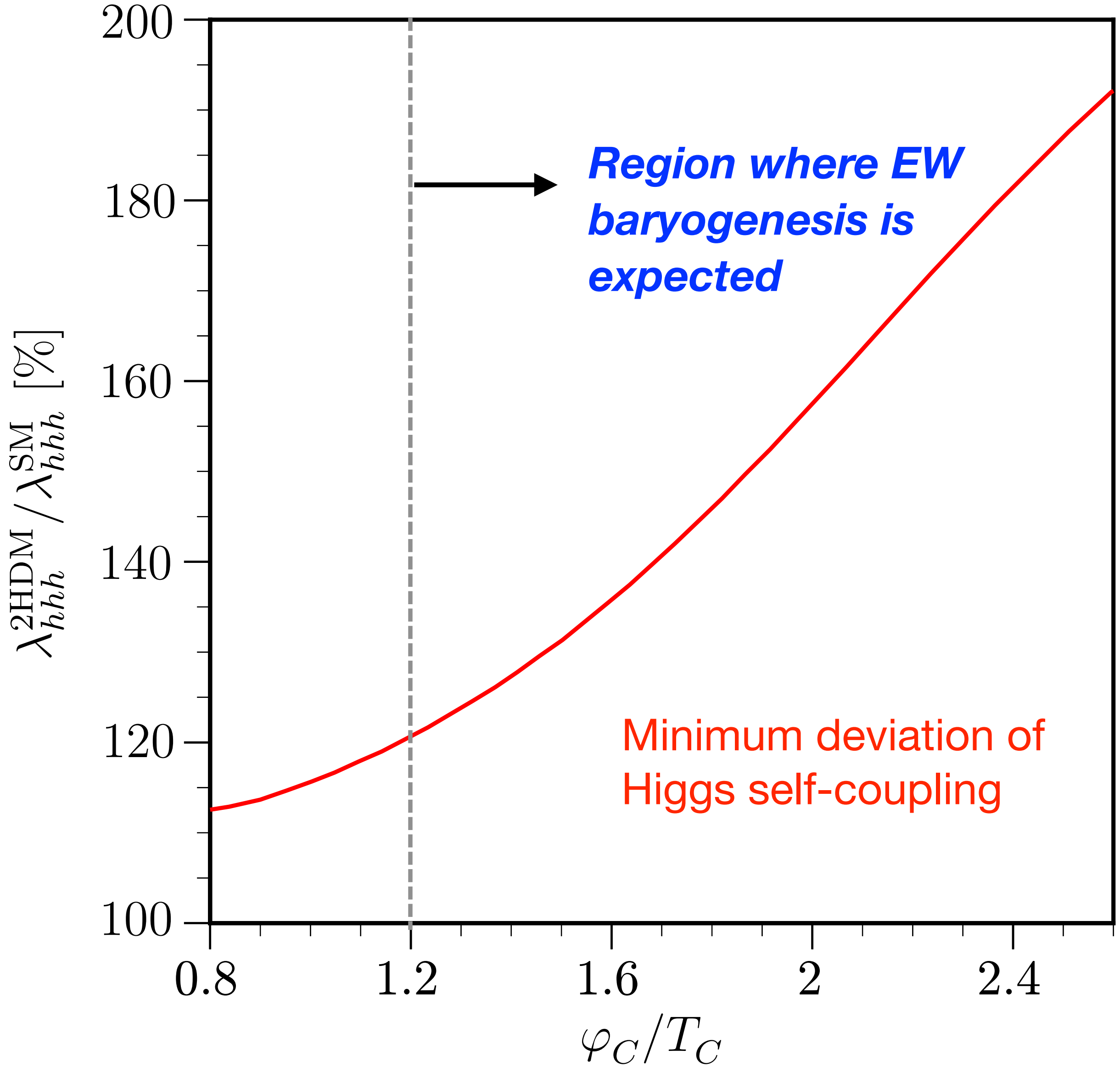


Baseline LC

Figure 1.17. The deviation in $\kappa_f = \xi_h^f$ in the 2HDM with Type I, II, X and Y Yukawa interactions are plotted as a function of $\tan\beta = v_2/v_1$ and $\kappa_V = \sin(\beta - \alpha)$ with $\cos(\beta - \alpha) \leq 0$. For the illustration purpose only, we slightly shift lines along with $\kappa_x = \kappa_y$. The points and the dashed curves denote changes of $\tan\beta$ by one steps. The scaling factor for the Higgs-gauge-gauge coupling constants is taken to be $\kappa_V^2 = 0.99, 0.95$ and 0.90. For $\kappa_V = 1$, all the scaling factors with SM particles become unity. The current LHC constraints, expected LHC and ILC sensitivities on (left) κ_d and κ_ℓ and (right) κ_u and κ_ℓ are added.

Snowmass LC Higgs White Paper (arXiv: 1310.0763)
Kanemura, et al (arXiv: 1406.3294)

Electroweak Baryogenesis



Senaha, Kanemura

<u>Example:</u>

Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling are generally predicted in EW baryogenesis scenarios.

LC can test the idea of baryogenesis occurring at the electroweak scale.

The end-point precisions at ILC will be improved

- ***By improving analysis methods:***
  - **fully use hadronic Z decays for recoil mass (issue: dependence on Higgs decay mode)**
  - **identify exotic Higgs decays (incl. invisible one separately) and use Σ BR = 1 constraint. (cf. Michael Peskin's analysis)**

- ***By optimizing running scenarios:***
  - **How much luminosities at what energies and in which order?**
  - **When do we do energy/luminosity upgrades?**
    → Now being intensively studied.
    → Stay tuned!

Hadronic Recoil Mass

M. Thomson's CLIC analysis, AWLC 2014

Final(?) Results

Process	σ/fb	ϵ_{presel}	$\epsilon_{\mathcal{L}>0.70}$	$N_{\mathcal{L}>0.70}$
$q\bar{q}$	25180	0.5 %	<0.1 %	6211
$q\bar{q}l\nu$	5914	6.4 %	0.1 %	3895
$q\bar{q}q\bar{q}$	5847	4.2 %	0.4 %	10818
$q\bar{q}ll$	1704	1.2 %	0.1 %	1218
$q\bar{q}\nu\bar{\nu}$	325	0.6 %	<0.1 %	35
$H\nu_e\bar{\nu}_e$		- %		
HZ	93.4	44.0 %	20.3 %	9493
$H\to$ invis.		0.6 %	<0.1 %	–
$H\to q\bar{q}/gg$		43.5 %	20.6 %	6211
$H\to WW^*$		44.7 %	19.5 %	2240
$H\to ZZ^*$		40.0 %	18.1 %	254
$H\to\tau^+\tau^-$		47.6 %	21.4 %	738
$H\to\gamma\gamma$		42.8 %	22.1 %	32
$H\to Z\gamma$		41.8 %	17.6 %	17
$H\to\mu^+\mu^-$		39.5 %	20.6 %	3

- For optimal cut
  - signal ~9.5k events
  - background ~ 19k events

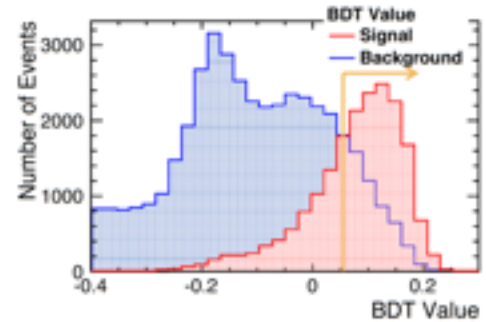
15 % improvement c.f. LCWS analysis

Efficiencies same to ~10 % !!!

almost model independent

BDT Selection

- Preliminary results (7 variable BDT selection)



Signal

Channel	Efficiency
Z H → qq invis.	20.7 %

Backgrounds

Channel	Efficiency	Events
qqlv	<0.1 %	900
qqll	<0.1 %	4
qqvv	1.5 %	2414

- Assuming no invisible decays (1 sigma stat. error):

$$\Delta\sigma_{\text{invis}} = \pm 0.57\ \%$$

(CLIC beam spectrum, 500 fb^{-1} @ 350 GeV, no polarisation)

Model Indepedence

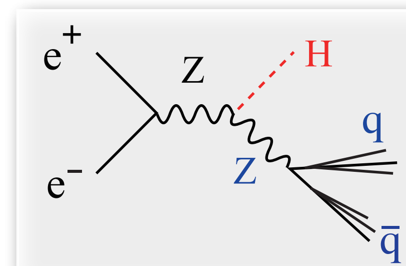
- Combining visible + invisible analysis: wanted M.I.
  - i.e. efficiency independent of Higgs decay mode

Decay mode	$\epsilon^{vis}_{\mathcal{L}>0.70}$	$\epsilon^{invis}_{BDT>0.08}$	$\epsilon^{vis}+\epsilon^{invis}$
$H\to$ invis.	<0.1 %	20.7 %	20.7 %
$H\to q\bar{q}/gg$	20.6 %	<0.1 %	20.6 %
$H\to WW^*$	19.5 %	<0.1 %	19.8 %
$H\to ZZ^*$	18.1 %	0.9 %	19.0 %
$H\to\tau^+\tau^-$	21.4 %	0.1 %	21.5 %
$H\to\gamma\gamma$	22.1 %	<0.1 %	22.1 %
$H\to Z\gamma$	17.6 %	<0.1 %	17.1 %
$H\to\mu^+\mu^-$	20.6 %	<0.1 %	20.6 %
$H\to WW^*\to q\bar{q}q\bar{q}$	19.3 %	<0.1 %	19.3 %
$H\to WW^*\to q\bar{q}l\nu$	19.6 %	<0.1 %	19.6 %
$H\to WW^*\to q\bar{q}\tau\nu$	19.9 %	<0.1 %	19.9 %
$H\to WW^*\to l\nu l\nu$	22.0 %	0.3 %	22.3 %
$H\to WW^*\to l\nu\tau\nu$	16.7 %	0.3 %	17.0 %
$H\to WW^*\to \tau\nu\tau\nu$	12.2 %	1.3 %	13.6 %

Very similar efficiencies

Look at wide range of WW topologies

$$\sigma_{Zh} = \sigma_{Zh}\cdot BR(visible) + \sigma_{Zh}\cdot BR(invisible)$$



Very similar efficiencies ~ model-independent!

$$\Delta\sigma_{Zh} = \pm 1.8\%$$

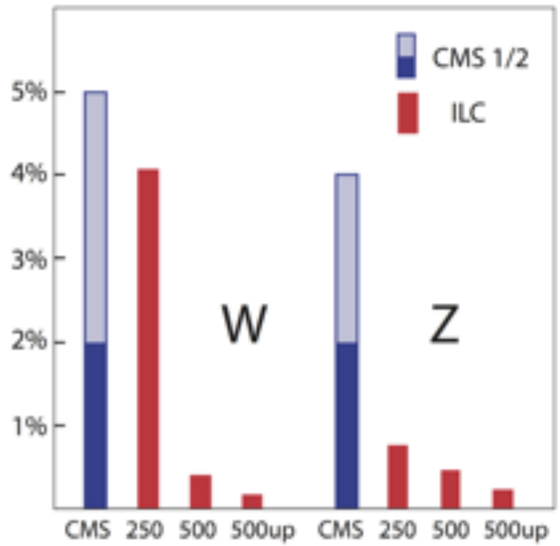
500fb^{-1} @ 350GeV (no beam pol.)

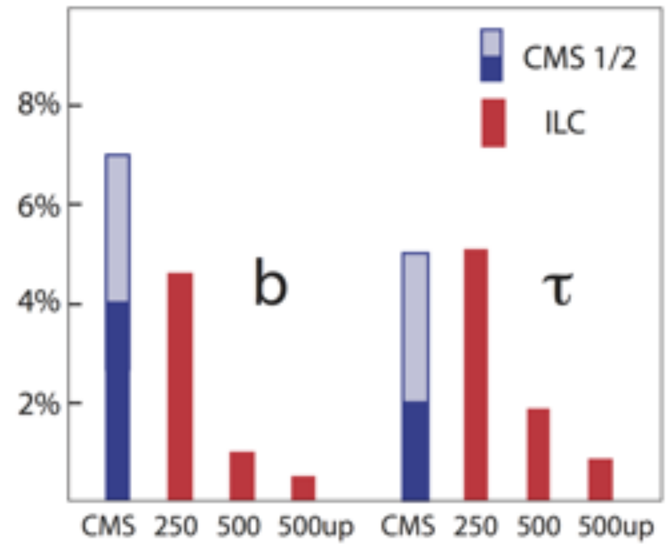
M. Peskin, LCWS 2013
arXiv: 1312.4974

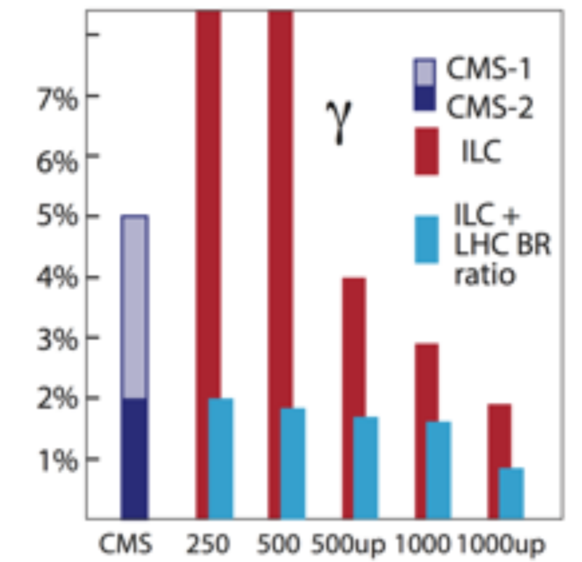
Σ BR = 1

BR(BSM:vis.), BR(inv.) in stead of Γ_h

ILC expectation assumes that BR(BSM:vis.) can be measured as precisely as BR(inv.).







LC greatly improves the LHC precisions and provides the necessary precision for the fingerprinting

For rare decays such as H → γγ, there is powerful synergy of LHC and LC!

Summary

- The primary goal for the next decades is to uncover the secret of the EW symmetry breaking. This will open up a window to BSM and set the energy scale for the E-frontier machine that will follow LHC and LC.
- Probably LHC will hit systematic limits at O(2-5%) for most of σ×BR measurements, being not enough to see the BSM effects if we are in the decoupling regime.
Moreover, we need some model assumption to extract couplings from the LHC data.
- The recoil mass measurement at LC unlocks the door to a fully model-independent analysis.
To achieve the primary goal we hence need a 500 GeV LC for self-contained precision Higgs studies to complete the mass-coupling plot
    - starting from $e^+e^- \to ZH$ at Ecm = 250GeV,
    - then ttbar at around 350GeV,
    - and then ZHH and ttbarH at 500GeV.
- The LC to cover up to 500 GeV is an ideal machine to carry out this mission (regardless of BSM scenarios) and we can do this ***completely model-independently*** with staging starting from 250GeV. We may need more data depending on the size of the deviation. The LC has a luminosity upgrade potential.
- If we are lucky, some extra Higgs boson or some other new particle might be within reach already at LC 500. Let's hope that the upgraded LHC will make another great discovery in the next run.
- If not, we will most probably need the energy scale information from the precision Higgs studies. Guided by the energy scale information, we will go hunt direct BSM signals with a new machine, if necessary.

Backup

LHC vs LC
or
LHC + LC

Model-dependent Global Fit for Couplings

7-parameter fit

Model Assumptions

$$\kappa_c = \kappa_t \quad \text{and} \quad \Gamma_{\text{tot}} = \sum_{i \in \text{SM decays}} \Gamma_i^{\text{SM}} \kappa_i^2$$

$$\kappa_i := g_i / g_i(\text{SM})$$

Results

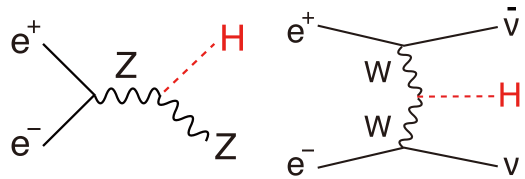
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500
κ_γ	5 − 7%	2 − 5%	8.3%	4.4%	3.8%	2.3%
κ_g	6 − 8%	3 − 5%	2.0%	1.1%	1.1%	0.67%
κ_W	4 − 6%	2 − 5%	0.39%	0.21%	0.21%	0.2%
κ_Z	4 − 6%	2 − 4%	0.49%	0.24%	0.50%	0.3%
κ_ℓ	6 − 8%	2 − 5%	1.9%	0.98%	1.3%	0.72%
$\kappa_d = \kappa_b$	10 − 13%	4 − 7%	0.93%	0.60%	0.51%	0.4%
$\kappa_u = \kappa_t$	14 − 15%	7 − 10%	2.5%	1.3%	1.3%	0.9%

Snowmass Higgs WG Report (arXiv: 1310.8361)

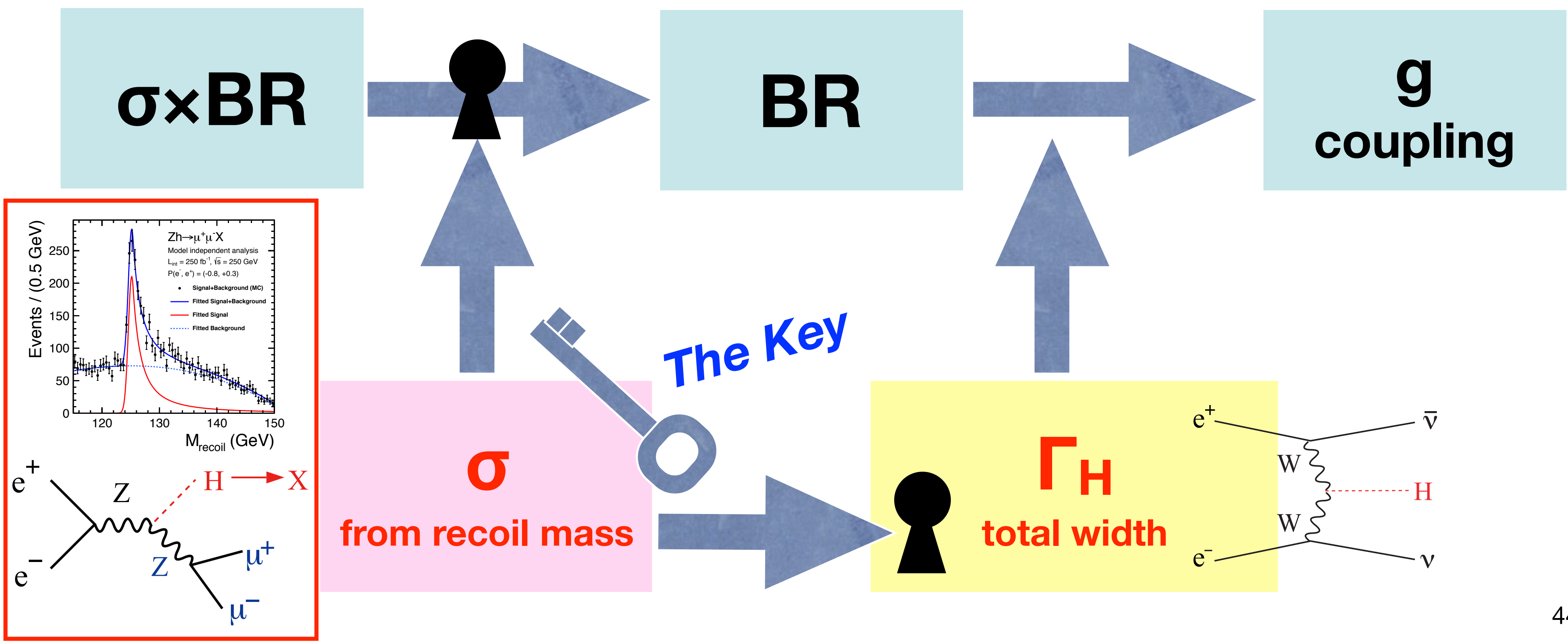
Key Point

At LHC all the measurements are σ×BR measurements.

At ILC all but the σ measurement using recoil mass technique is σ×BR measurements.



$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$



What observables limit the coupling precisions?

The 4 most important ones

- *Y_1: recoil mass*
- *Y_2: WW-fusion h→bb*
- *Y_3: higgsstrahlung h→bb*
- *Y_4: WW-fusion h→WW**

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

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HZZ} g^2_{Hbb}}{\Gamma_H}$$

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

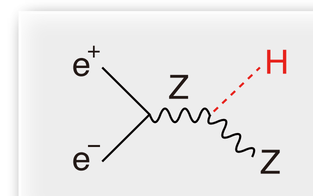
$$\Delta g_{HZZ} \sim \frac{1}{2}\Delta Y_1$$

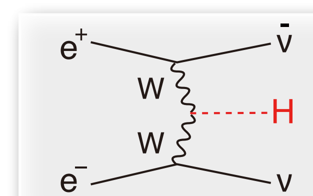
$$\Delta g_{HWW} \sim \frac{1}{2}\Delta Y_1 \oplus \frac{1}{2}\Delta Y_2 \oplus \frac{1}{2}\Delta Y_3$$

$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

$$\Delta\Gamma_H \sim 2\Delta Y_1 \oplus 2\Delta Y_2 \oplus 2\Delta Y_3 \oplus \Delta Y_4$$

Both ZH and ννH productions matter!

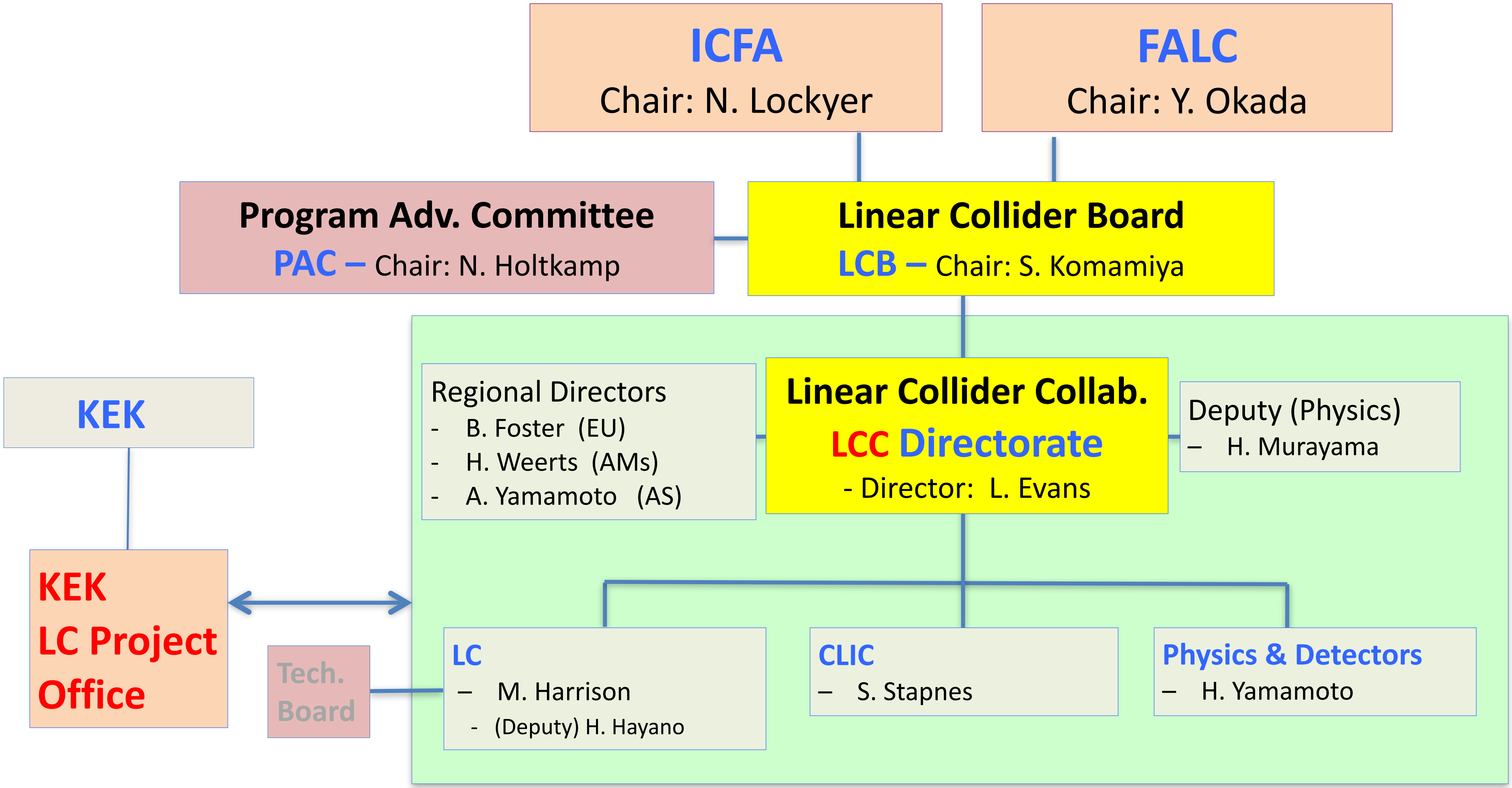




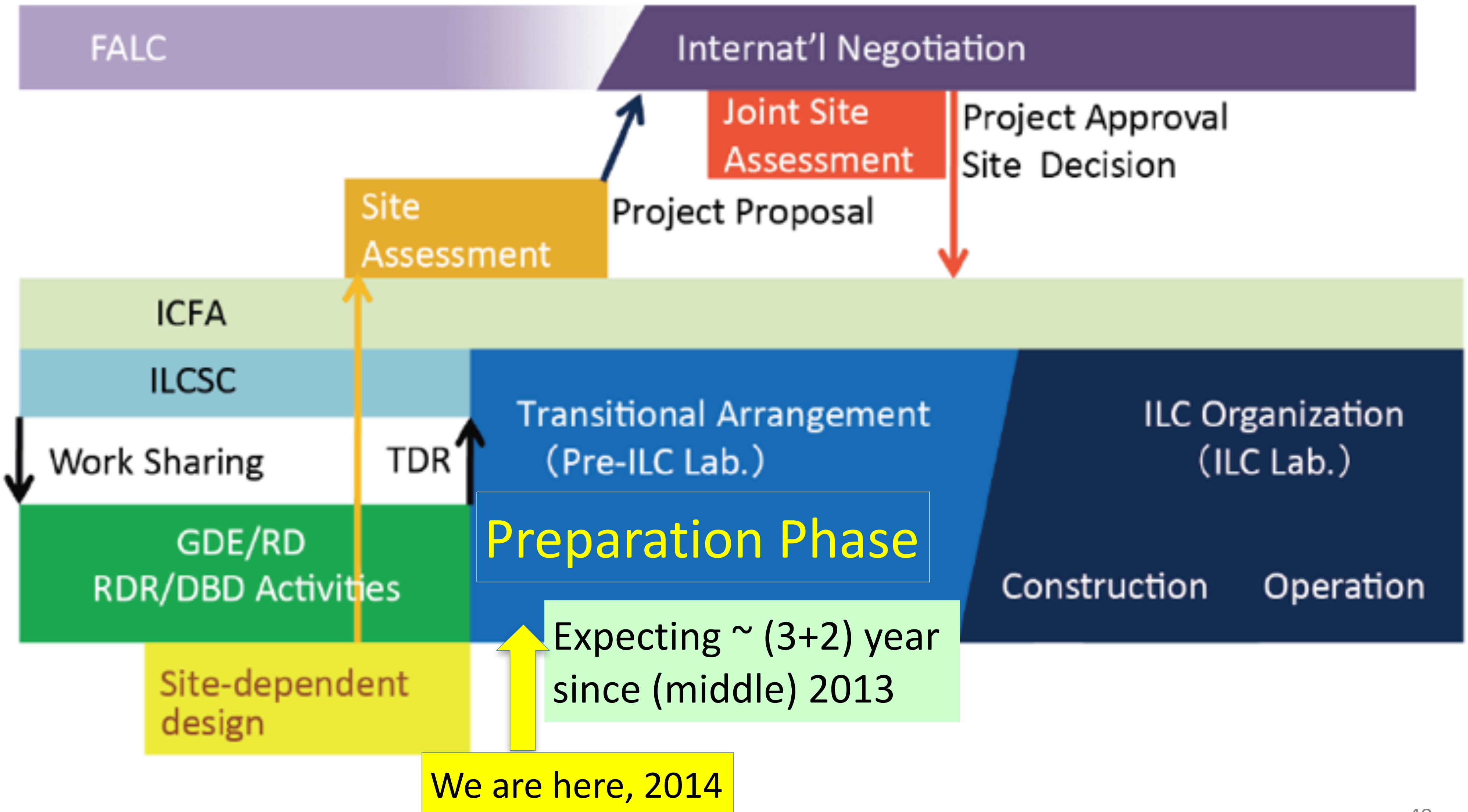
For more details, see J.Tian @ Tokusui Workshop 2013

Project Development

LC in Linear Collider Collaboration

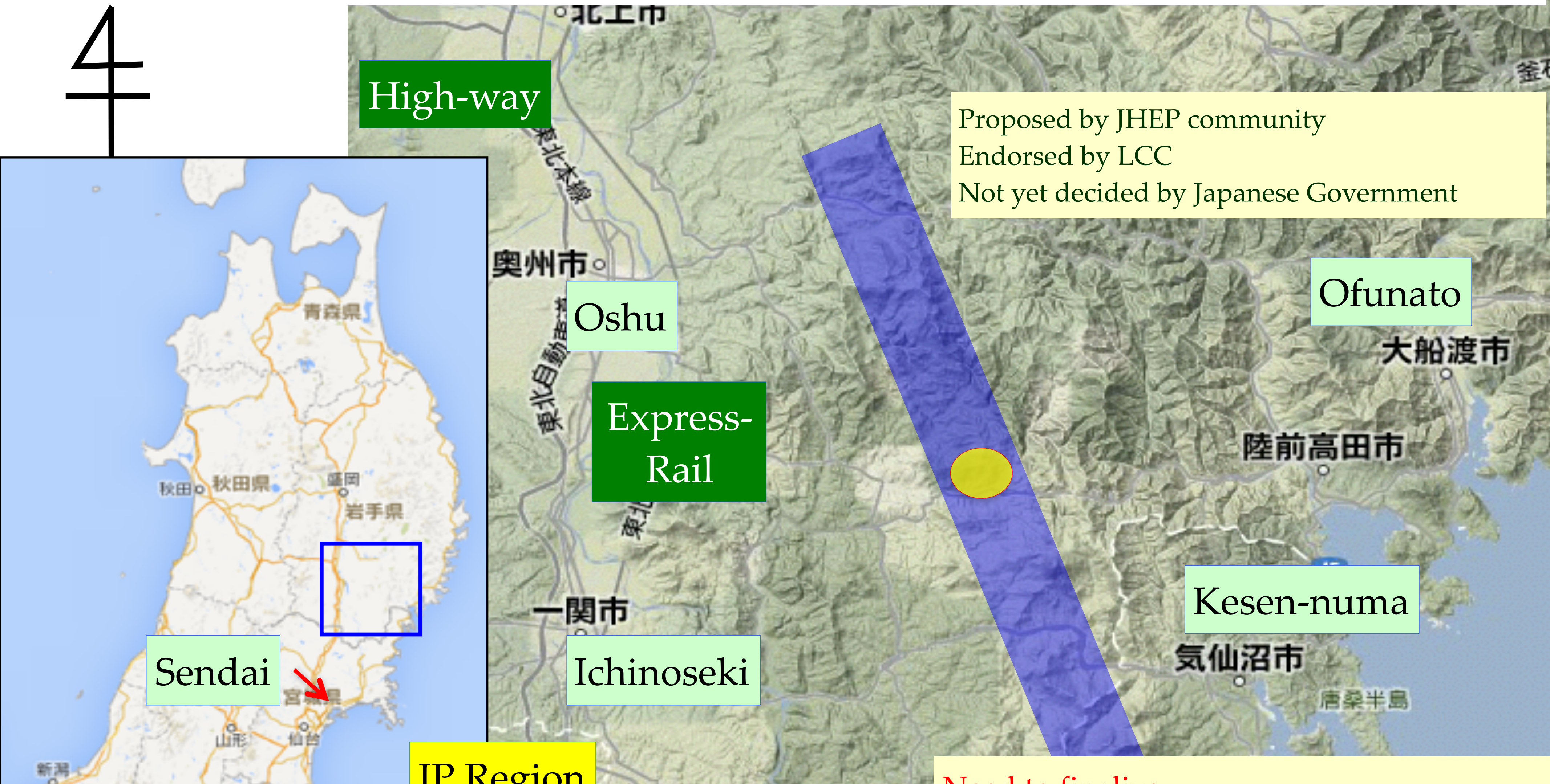


LC Time Line: Progress and Prospect

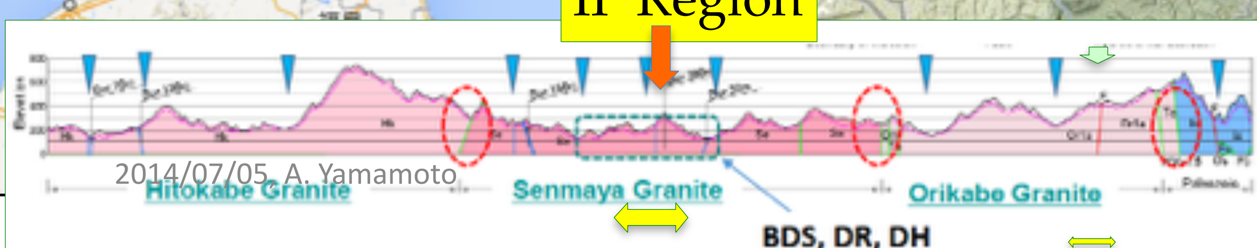


LC Site Candidate Location in Japan: Kitakami Area

Establish a site-specific Civil Engineering Design - map the (site independent) TDR baseline onto the preferred site - assuming "Kitakami" as a primary candidate



Proposed by JHEP community
Endorsed by LCC
Not yet decided by Japanese Government



Need to finalize:

- IP / Linac orientation and length
- Access points and IR infrastructure
- Conventional Facilities and Siting (CFS)
- …

Global Status

Year	Global Status	Status in Japan
2012	- ***TDR "Draft" completed, and technically reviewed, and the cost estimate internally reviewed, in GDE***	
2013	- ***TDR Cost internationally and externally reviewed,*** - ***TDR published*** - ***"GDE" to "LCC"*** - ***European Strategy published***	- ***Candidate site by JHEP, unified,*** - ***Further study for a few year, recommended by SCJ (Science Council J.)***
2014	- - ***US-P5 recommendation published*** - - *Global supports well recognized*	- ***MEXT established LC Task Force*** - ***LC preparatory office started at KEK*** - ***An official budget for the LC investigation/preparation allocated, first time, in MEXT.*** - ***MEXT's ILC review process started in May***

- LC accelerator **technologie**s have been sufficiently developed and matured for the project to move"from Design to Reality" in coming several years.
- **Global cooperation** needs to be further established,
- **LCC** is leading the project under supervision of ICFA and LCB
- Strong supports from EU and US, well recognized and acknowledged,

Based on 2014/07/05, A. Yamamoto