Higgs Physics at the LC and Requirements

Keisuke Fujii (KEK)

The slides have been updated according to Rohini's comment on the importance of the top mass measurement at the ttbar threshold (Ecm~350GeV) and of the tth measurement at around Ecm=1TeV to study a mixed CP Higgs, which had slipped my mind. Thanks, Rohini.

Electroweak Symmetry Breaking

Mystery of something in the vacuum

- The success of the SM is a success of gauge principle. We know that the transverse components of W and Z are gauge fields of the EW gauge symmetry.
- Since the gauge symmetry forbids explicit mass terms for W and Z, it must be broken by something condensed in the vacuum which carries EW charges:

$$\langle 0 \,|\, I_3, Y \,|\, 0 \rangle \neq 0$$

- This “something” supplies 3 longitudinal modes of W and Z:

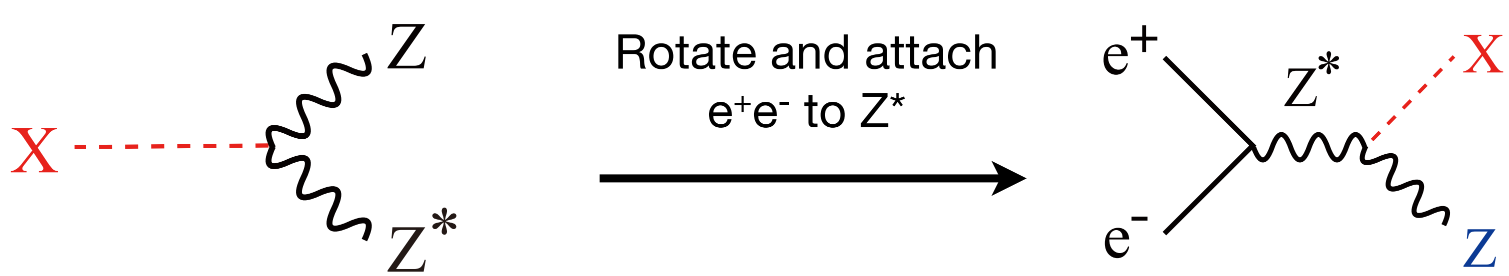
$$W_L^+, W_L^-, Z_L \longleftarrow \chi^+, \chi^-, \chi_3 \quad \text{: Goldstone modes}$$

- Since Left- and right-handed matter fermions carry different EW charges, explicit matter fermion mass terms are also forbidden by the EW gauge symmetry. Their masses have to be generated through their Yukawa interactions with some weak-charged vacuum.
- In the SM, the same “something” mixes the left- and right-handed matter fermions, consequently generating masses and inducing flavor-mixings among generations.
- In order to form the Yukawa interaction terms, we need a complex doublet scalar field. The SM identifies three real component of the doublet with the Goldstone modes that supply the longitudinal modes of W and Z.
- We need one more to form a complex doublet, which is the physical Higgs boson.
- This SM symmetry breaking sector is the simplest and the most economical, but there is no reason for it. The symmetry breaking sector (hereafter called the Higgs sector) might be more complex.
- We don’t know whether the “something” is elementary or composite.
- We knew it’s there in the vacuum with a vev of 246GeV. But other than that we did not know almost anything about the “something” until July 4, 2012.

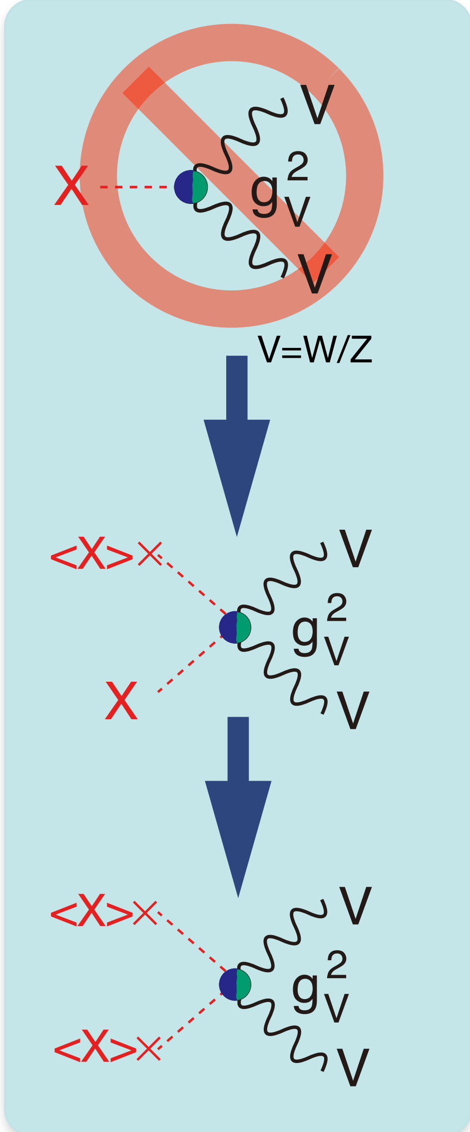
Since the July 4th, the world has changed!

The discovery of the ~125 GeV boson at LHC could be called a quantum jump.

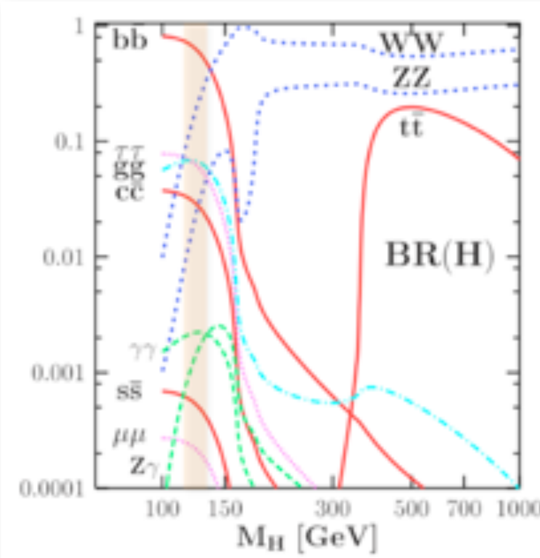
- X -> γγ means X is a boson and J ≠ 1 (Landau-Yang theorem).
- We know that the 125GeV boson decays to ZZ* and WW*, indicating the existence of XVV couplings: (V=W/Z: gauge bosons). There is no gauge coupling like XVV. There are only XXVV or XXV, hence XVV is most probably from XXVV with one X replaced by its vacuum expectation value <X> ≠ 0, namely <X>XVV.
  Then there must be <X><X>VV, a mass term for V, meaning that X is at least part of the origin of the masses of V=W/Z.
  --> This is a great step forward but we need to know whether <X> saturates the SM vev = 246GeV.
- X -> ZZ* means, X can be produced via e^+e^- -> Z* -> ZX



- By the same token, X -> WW* means, X can be produced via W fusion process: e^+e^- -> *ννX*

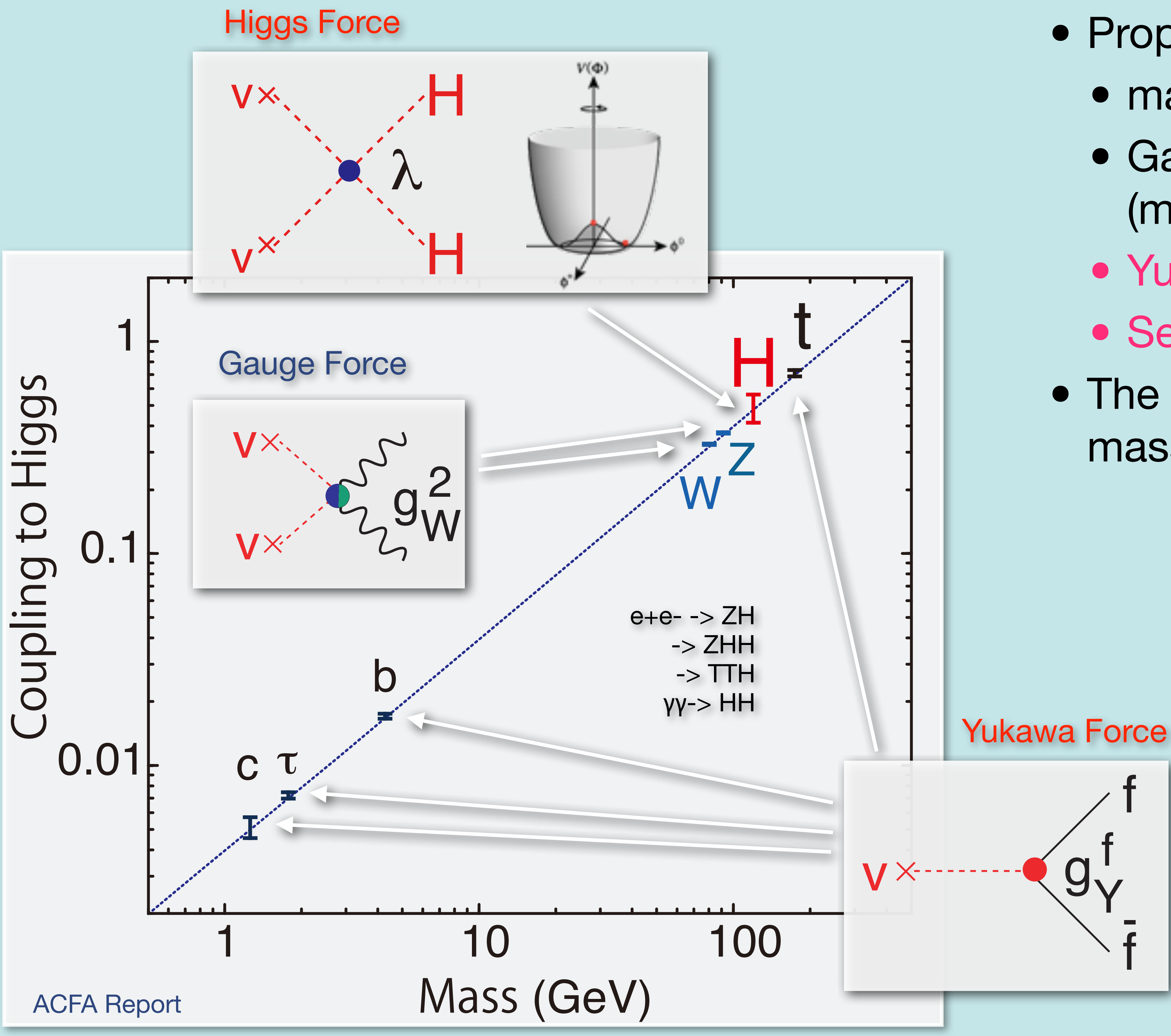


- We knew almost nothing about this "something" until July 4.
- We now know there is indeed "something" which seems to be condensed in the vacuum. --> No lose theorem for a LC.
- ~125GeV is the best place for the LC, where variety of decay modes are accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed all the required properties of the something in the vacuum.



The Mass Coupling Relation

Uncover the secret of the Electroweak Symmetry Breaking



- Properties to measure are
  - mass, width, J^{PC}
  - Gauge quantum numbers (multiplet structure)
  - 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 as a window to BSM physics!

Precision Higgs Studies

The Mission = Bottom-up reconstruction of the EWSB sector

- Through the coupling measurements, determine the Electroweak Symmetry Breaking sector (bottom-up model-independent reconstruction of the Lagrangian for the Higgs and Yukawa sectors):
  - Multiplet structure:
    - Additional singlet?
    - Additional doublet?
    - Additional triplet?
  - Underlying dynamics :
    - Weakly interacting or strongly interacting? = elementary or composite ?
- Relations to other problems :
    - DM
    - EW baryogenesis
    - neutrino mass
    - inflation?

→ Many models discussed in the Higgs Session

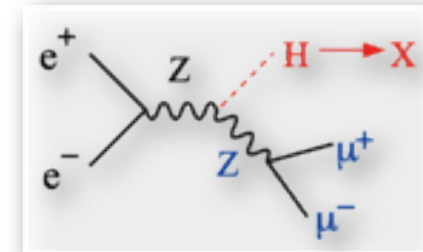
- The July 4 was the opening of a new era which will last probably 20 years or more, where a 500 GeV LC will / must play the central role.

Why 500 GeV?

Three well known thresholds

ZH @ 250 GeV (~mZ+mH+20GeV) :

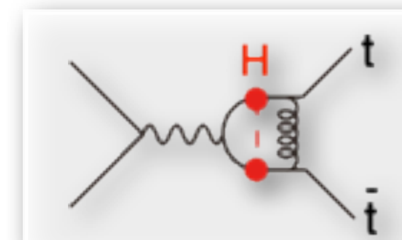
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

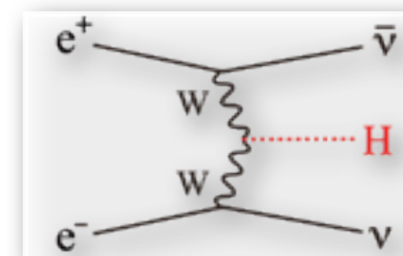


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- Threshold scan --> theoretically clean mt measurement
  --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

$\gamma\gamma \rightarrow$ HH @ 350GeV possibility



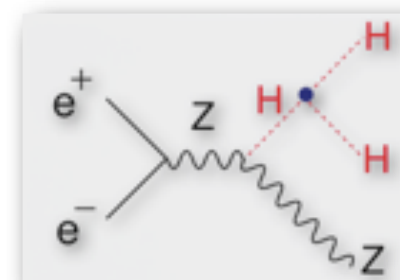


vvH @ 350 - 500GeV :

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

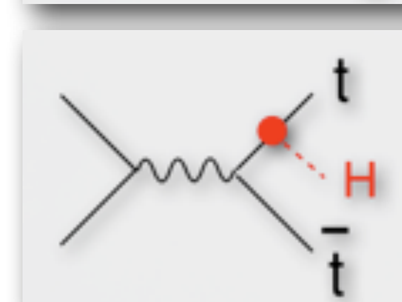
ZHH @ 500GeV (~mZ+2mH+170GeV) :

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



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

- Prod. cross section becomes maximum at around 700GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable at 500GeV concurrently with the self-coupling

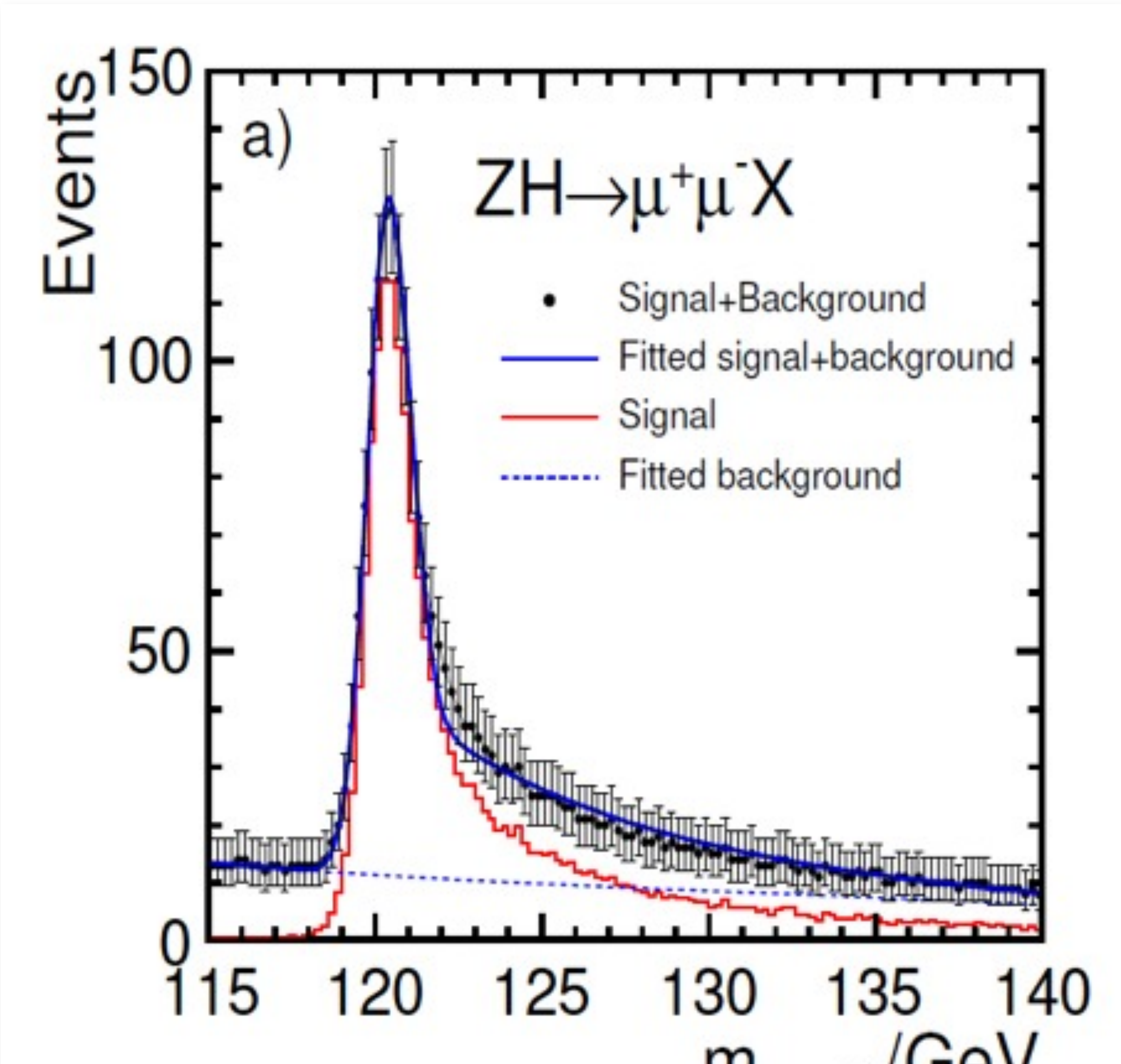


We can complete the mass-coupling plot at ~500GeV!

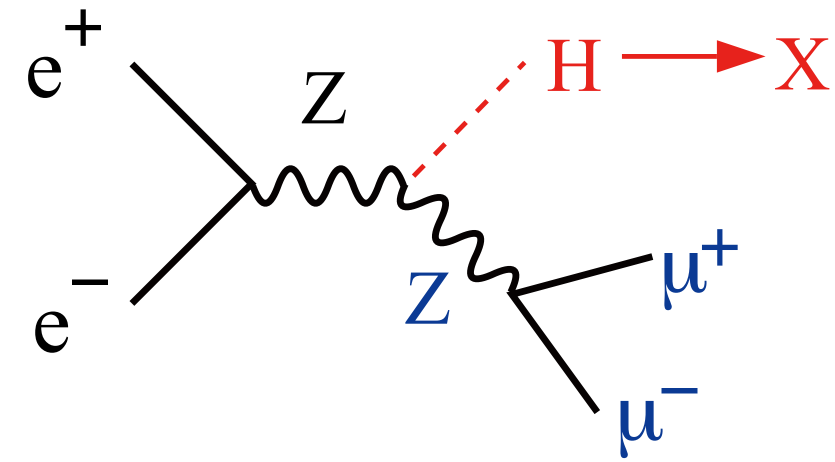
Recoil Mass Measurements

The flagship measurement

Recoil Mass



ILD LoI



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

Invisible decay detectable!

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$

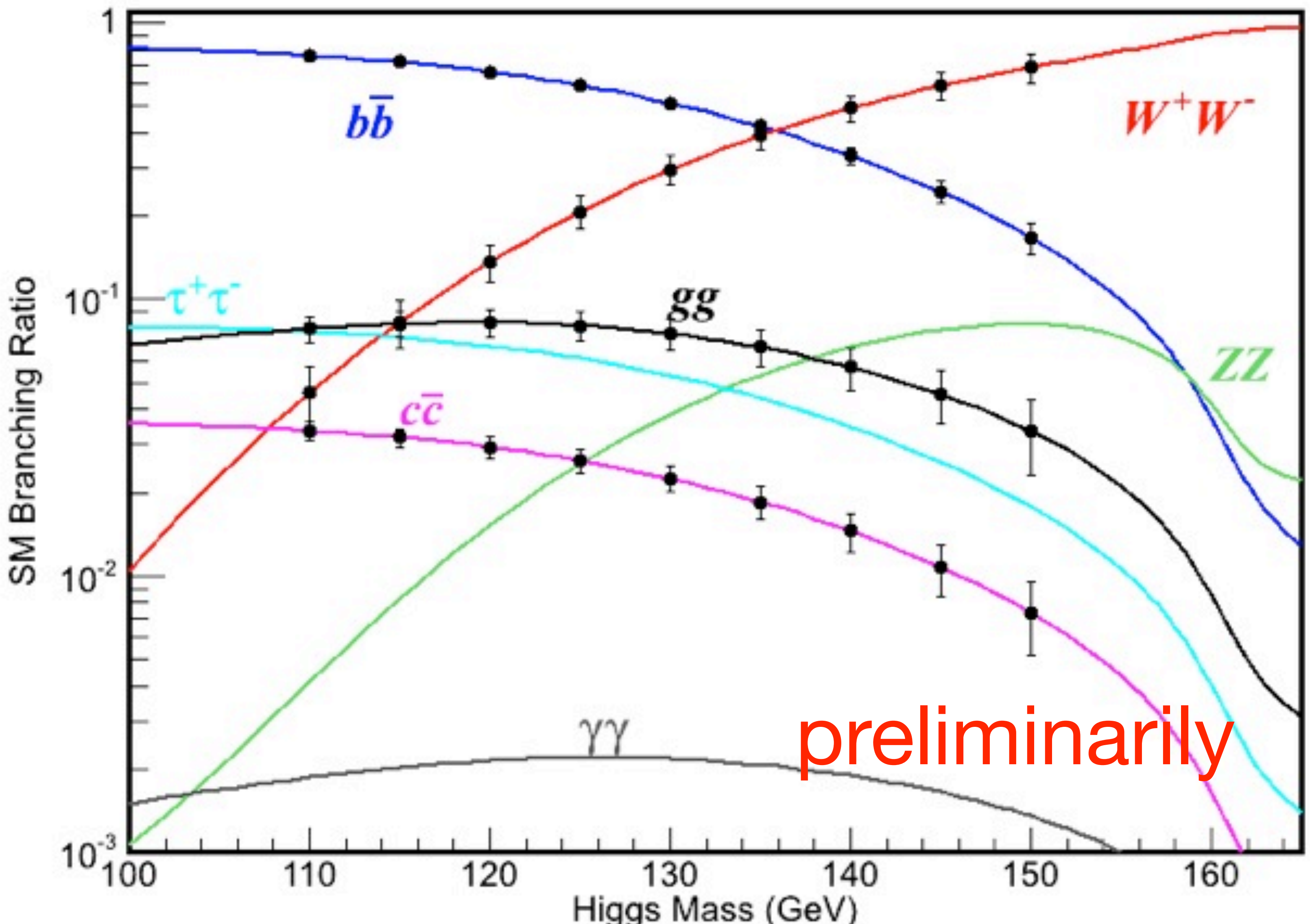
$$\Delta\sigma_H/\sigma_H = 2.5\%$$

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

Model-independent absolute measurement of the HZZ coupling

Branching Ratio Measurements

for b, c, g, tau, WW*



ILD DBD Study (Ono)

$$250\,\text{fb}^{-1} @ 250\,\text{GeV}$$
$$m_H = 120\,\text{GeV}$$

	@ 250 GeV
process	ZH
luminosity · fb	250
cross section	2.5%
	σ·Br
H-->bb	1.0%
H-->cc	6.9%
H-->gg	8.5%
H-->WW*	8.2%
H-->ττ	4-6%
H-->ZZ*	28%
H-->γγ	23-30%

Measurement accuracies extrapolated from Mh=120 GeV results (Final).

To extract BR from σxBR, however, we need σ from the recoil mass measurement.
--> Δσ/σ=2.5% eventually limits the BR measurement.
--> If we want to improve this, we need more data at 250GeV.

H. Ono's talk

Total Width and Coupling Extraction

One of the major advantages of the LC

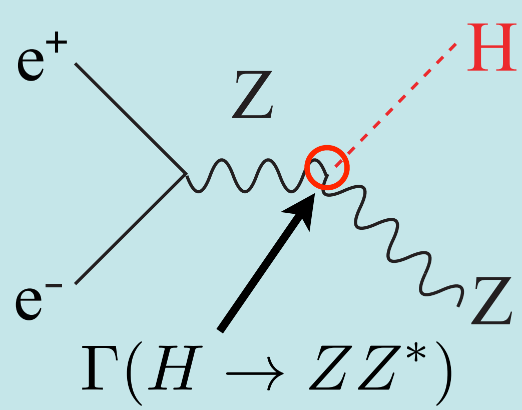
To extract couplings from BRs, we need the total width:

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

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

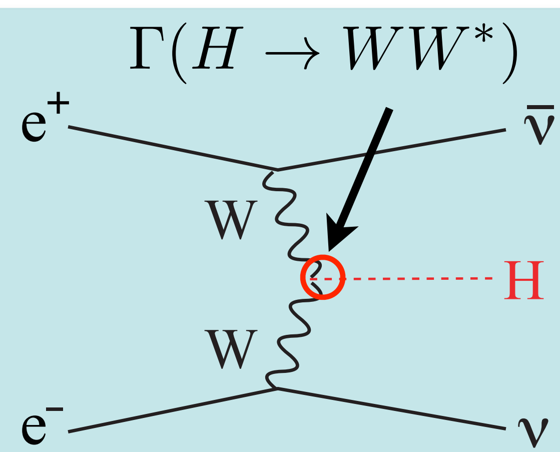
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

In principle, we can use the 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



$BR(H \to WW^*)$

More advantageous but not easy at low E

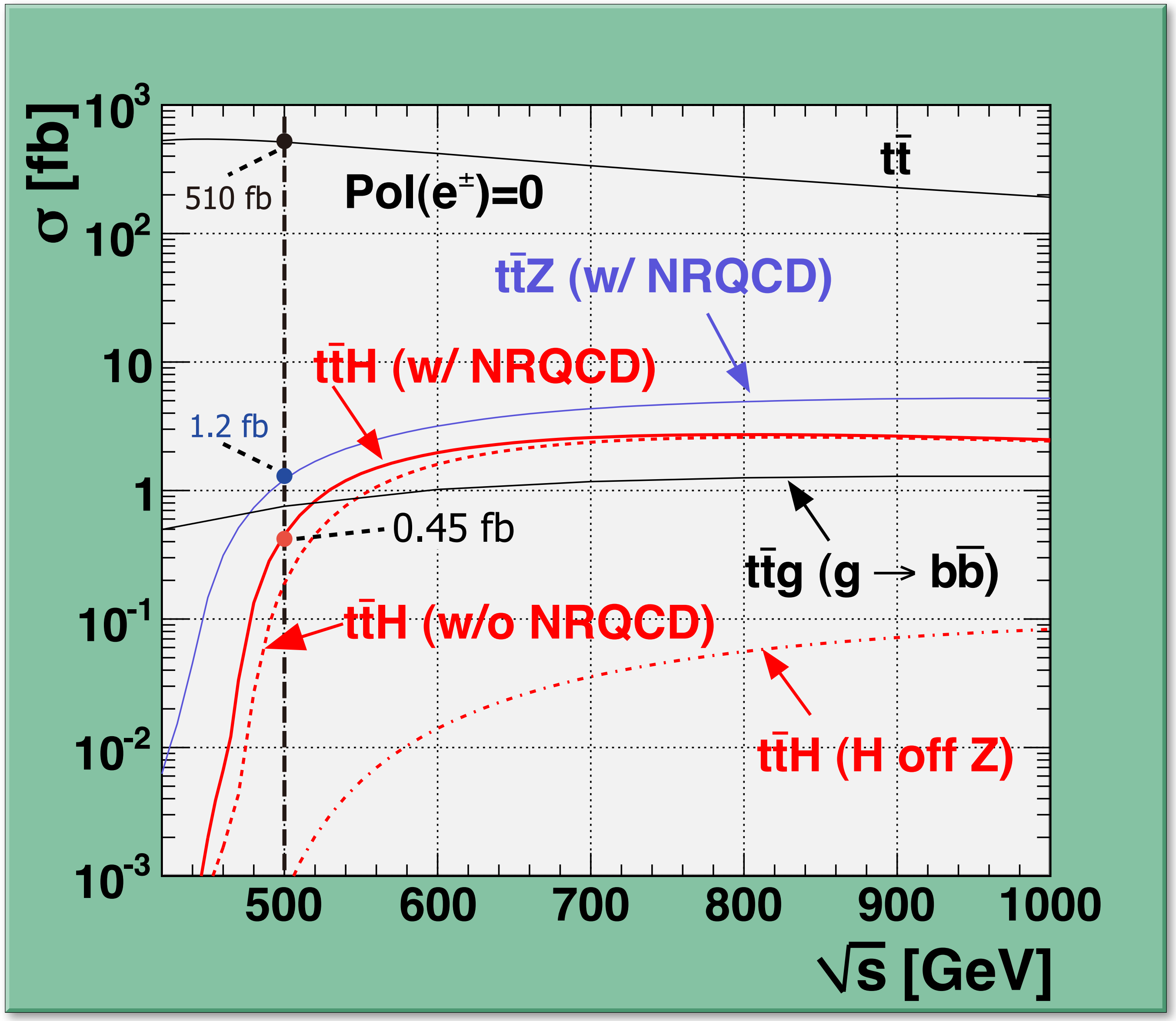
$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$

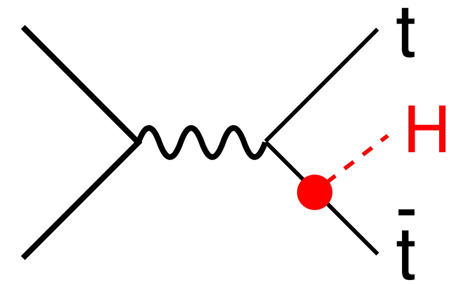
$\Delta\Gamma_H/\Gamma_H \simeq 10\%$

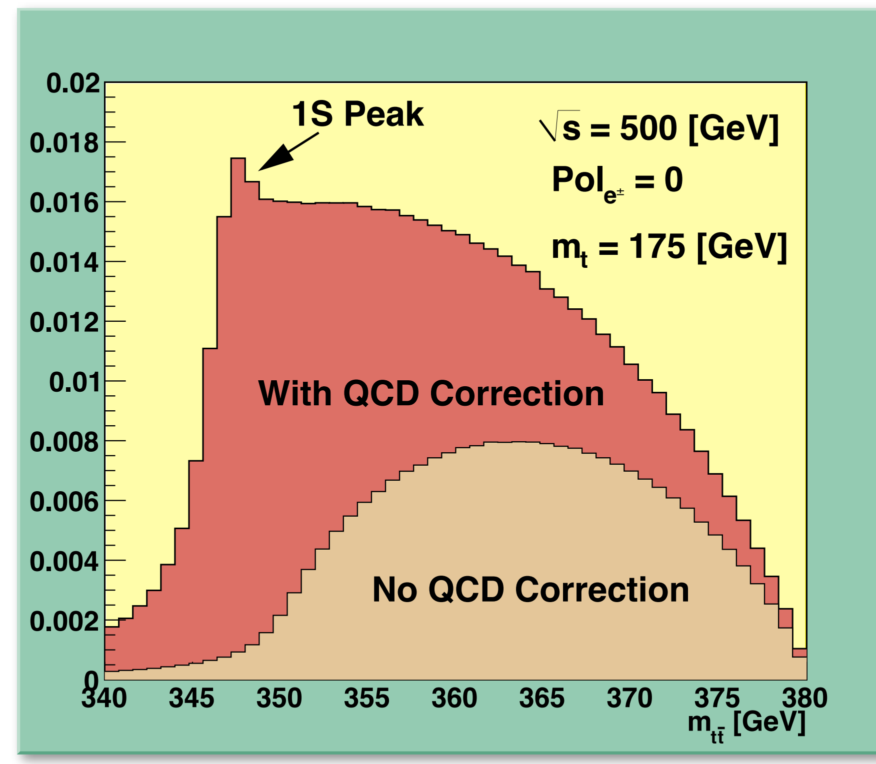
Jenny List's talk

Top Yukawa Coupling

The largest among matter fermions, but not yet observed







A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff

Tony Price's talk

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV}$$

$$\Delta g_Y(t)/g_Y(t) = 10\,\%$$

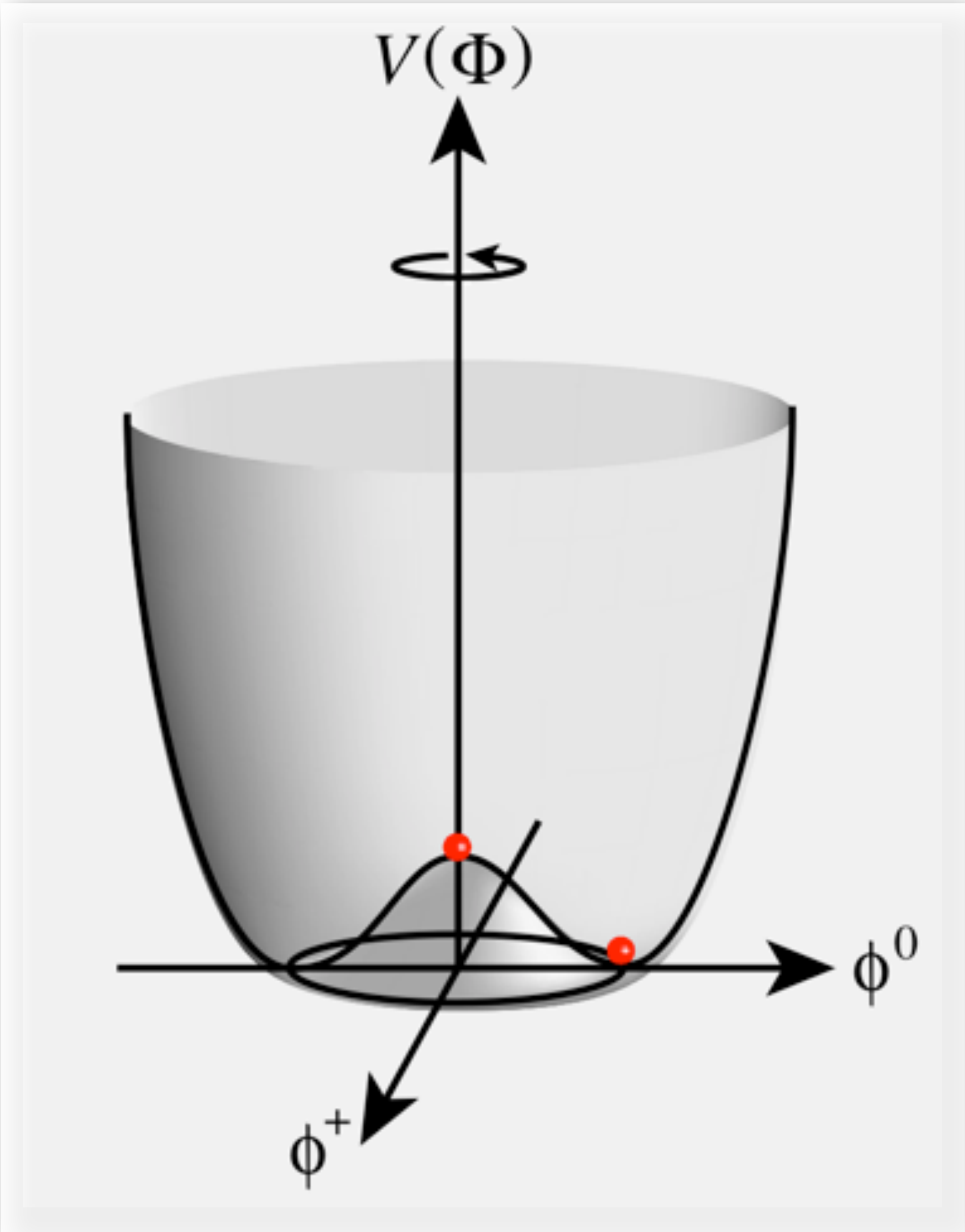
Tony Price's talk

Notice σ(500+20GeV)/σ(500GeV) ~ 2

Moving up a little bit helps significantly!

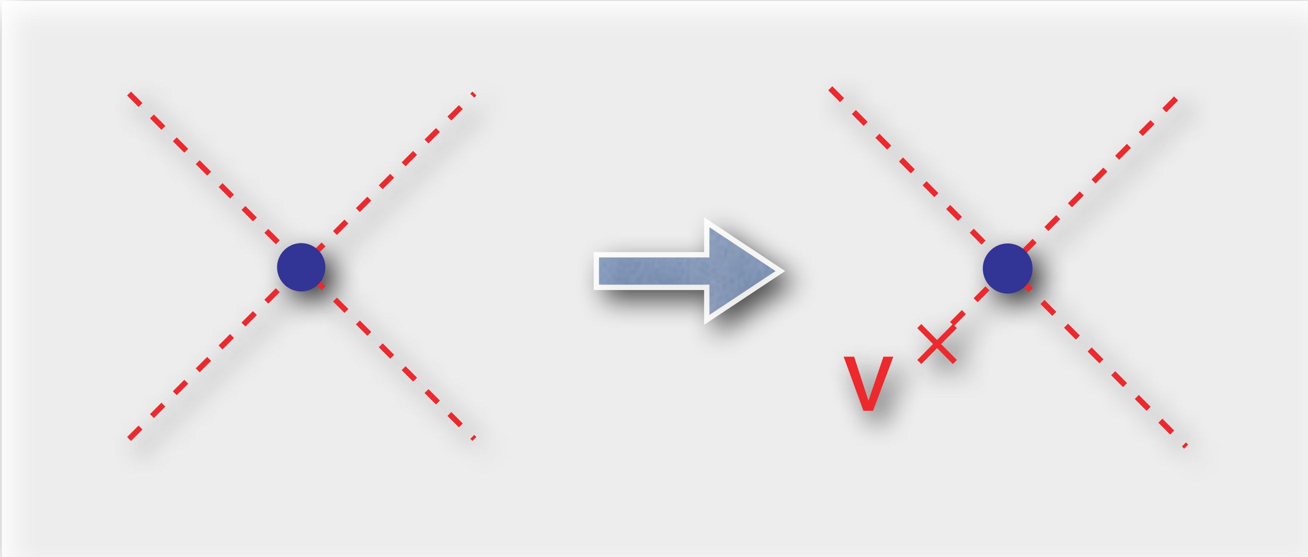
Higgs Self-coupling

What force makes the Higgs condense in the vacuum?



In order to uncover the secret of electroweak symmetry breaking, we need to observe the force that makes the Higgs condense in the vacuum!

We need to measure the Higgs self-coupling



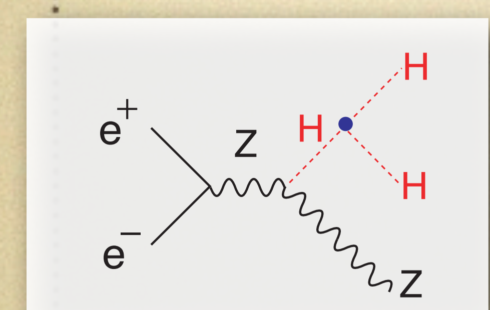
= We need to measure the shape of the Higgs potential

ILD (ACFA Higgs WG: J. Tian et al)

preliminary result (with LCFIPlus)

Pol.: (e+,e-)=(+0.3,-0.8) (red ones are new results) mH=120GeV, 2ab^-1

Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	6.4(7.0)	6.7(8.0)	2.1σ(2.1)	1.7σ(1.8)
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	5.2(7.2)	7.0(9.9)	1.7σ(2.0)	1.4σ(1.7)
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	8.5(9.2)	11.7(11.0)	2.2σ(2.4)	1.9σ(2.1)
		16.6(20.9)	129(140)	1.4σ(1.7)	1.3σ(1.6)



combined significance of ZHH excess: **4.3σ** (3.9)

$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

(0.07)

$$\frac{\delta\sigma}{\sigma} = 29\%$$ (32%)

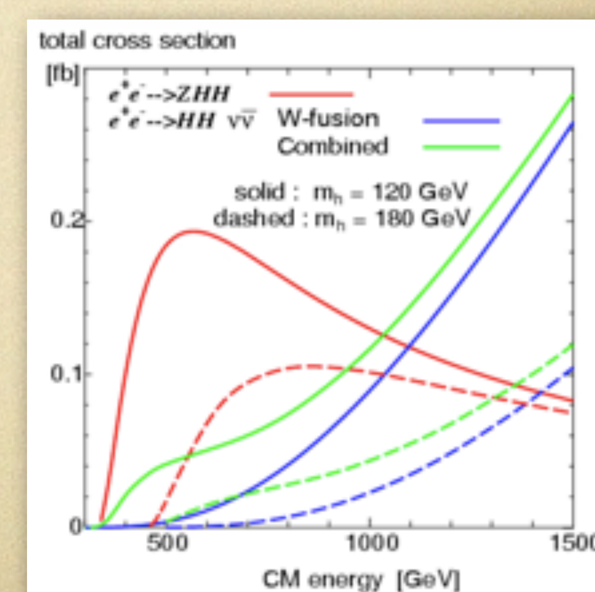
$$\frac{\delta\lambda}{\lambda} = 52\%$$ (57%)

Expected Precision with DBD tools and DBD samples

$$\delta\sigma/\sigma = 22\%$$

$$\delta\lambda/\lambda = 40\%$$

Junping Tian's talk in ILD session



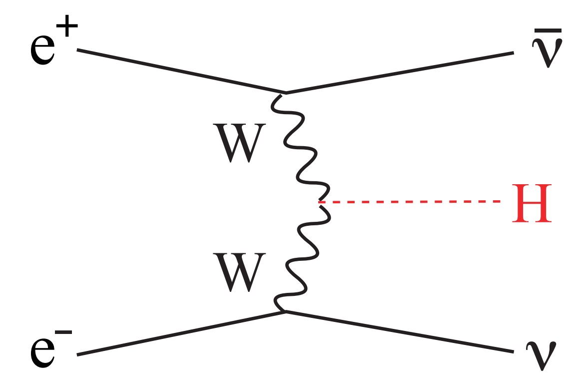
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

measurements (independent)	precision
$X_1 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$ @ 250 GeV	1.0%
$X_2 = \sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$ @ 250 GeV	6.9%
$X_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to gg)$ @ 250 GeV	8.5%
$X_4 = \sigma_{ZH} \cdot \mathrm{Br}(H \to WW^*)$ @ 250 GeV	8.2%
$X_5 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$ @ 500 GeV	1.6%
$X_6 = \sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$ @ 500 GeV	11%
$X_7 = \sigma_{ZH} \cdot \mathrm{Br}(H \to gg)$ @ 500 GeV	13%
$X_8 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b})$ @ 500 GeV	0.60%
$X_9 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to c\bar{c})$ @ 500 GeV	4.0%
$X_{10} = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to gg)$ @ 500 GeV	4.9%
$X_{11} = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*)$ @ 500 GeV	3.0%
$X_{12} = \sigma_{ZH}$	2.5%

ILD DBD Study (Junping Tian)

$$250\ \mathrm{fb}^{-1}@250\ \mathrm{GeV}$$
$$+500\ \mathrm{fb}^{-1}@500\ \mathrm{GeV}$$
$$m_H = 120\ \mathrm{GeV}$$



comes in as a powerful tool!

preliminarily

Mode	ΔBR/BR
bb	2.0 (2.7)%
cc	3.8 (7.3)%
gg	4.4 (8.9)%
WW*	3.5 (8.6)%

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

Why Precision?

Expected precision and deviation

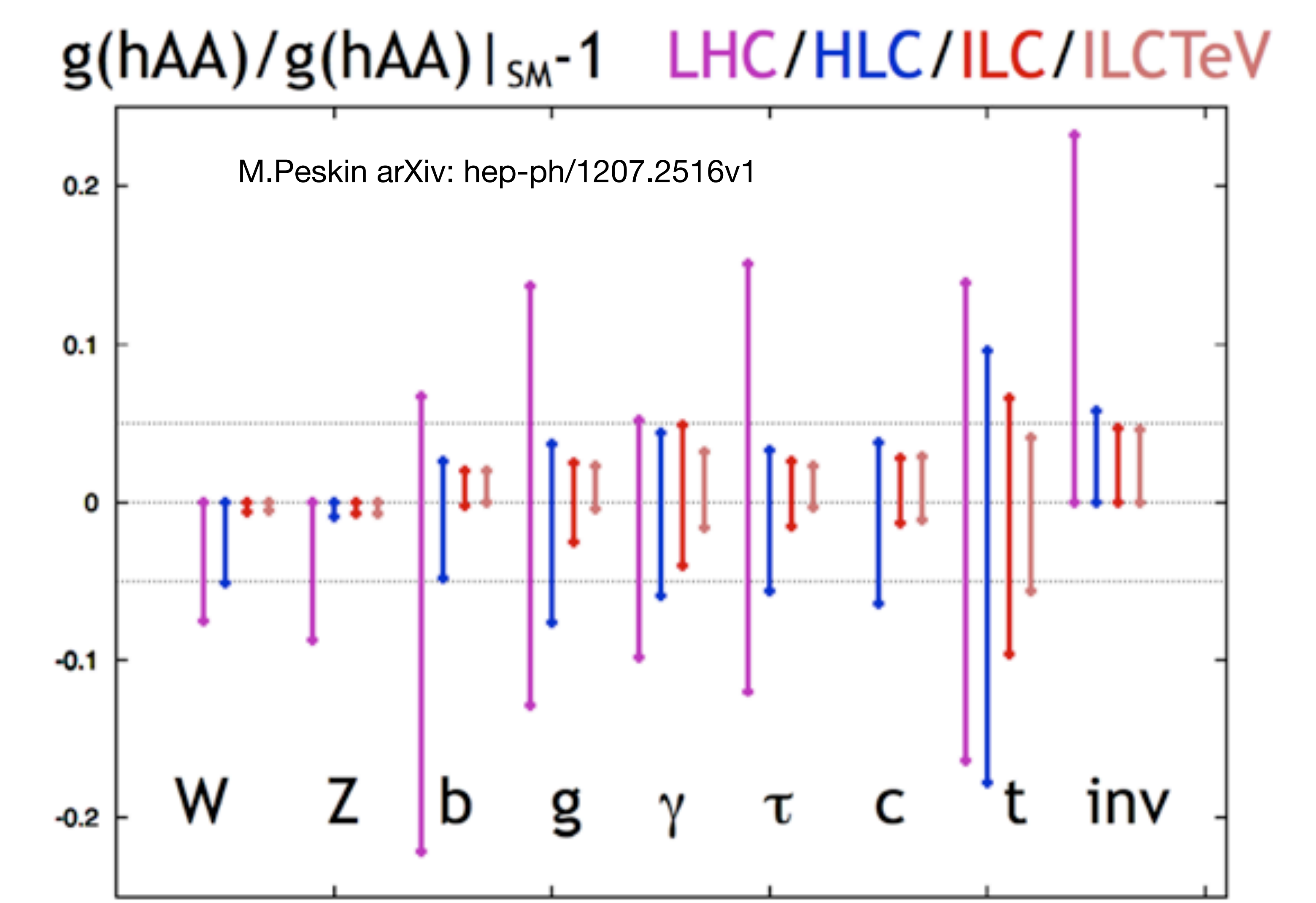


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('HLC'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

LC's precision provides important information on the energy scale for BSM physics.

Assumed Luminosities

LHC = LHC14TeV: 300fb^{-1}

HLC = ILC250: 250fb^{-1}

ILC = ILC500: 500fb^{-1}

ILCTeV = ILC1000: 1000fb^{-1}

Maximum deviation when nothing but the 125 GeV object would be found at LHC

	ΔhVV	$\Delta h\bar{t}t$	$\Delta hb\bar{b}$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

R.S.Gupta, H.Rzehak, J.D.Wells arXiv: 1206.3560v1

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

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

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

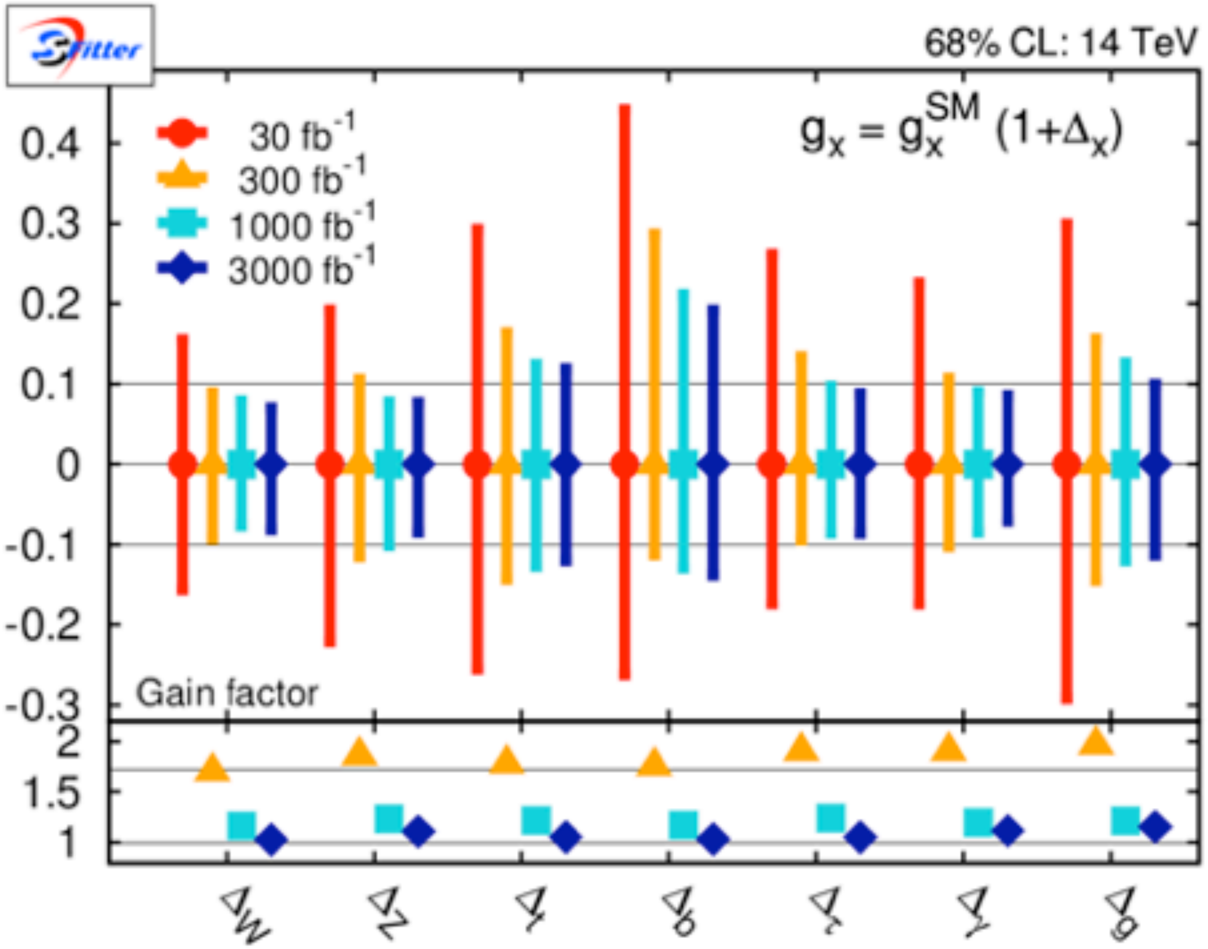
SUSY

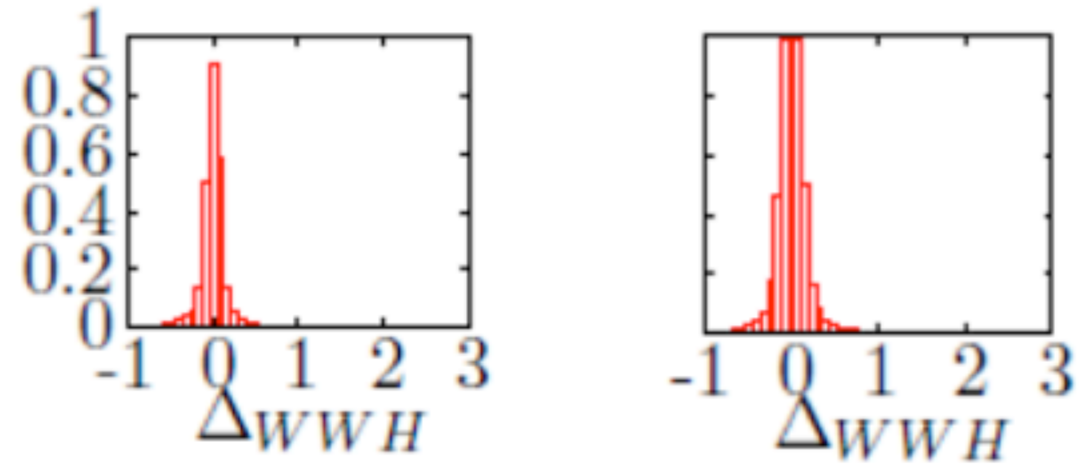
$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Different models predict different deviation patterns
--> Fingerprinting!

ZFitter

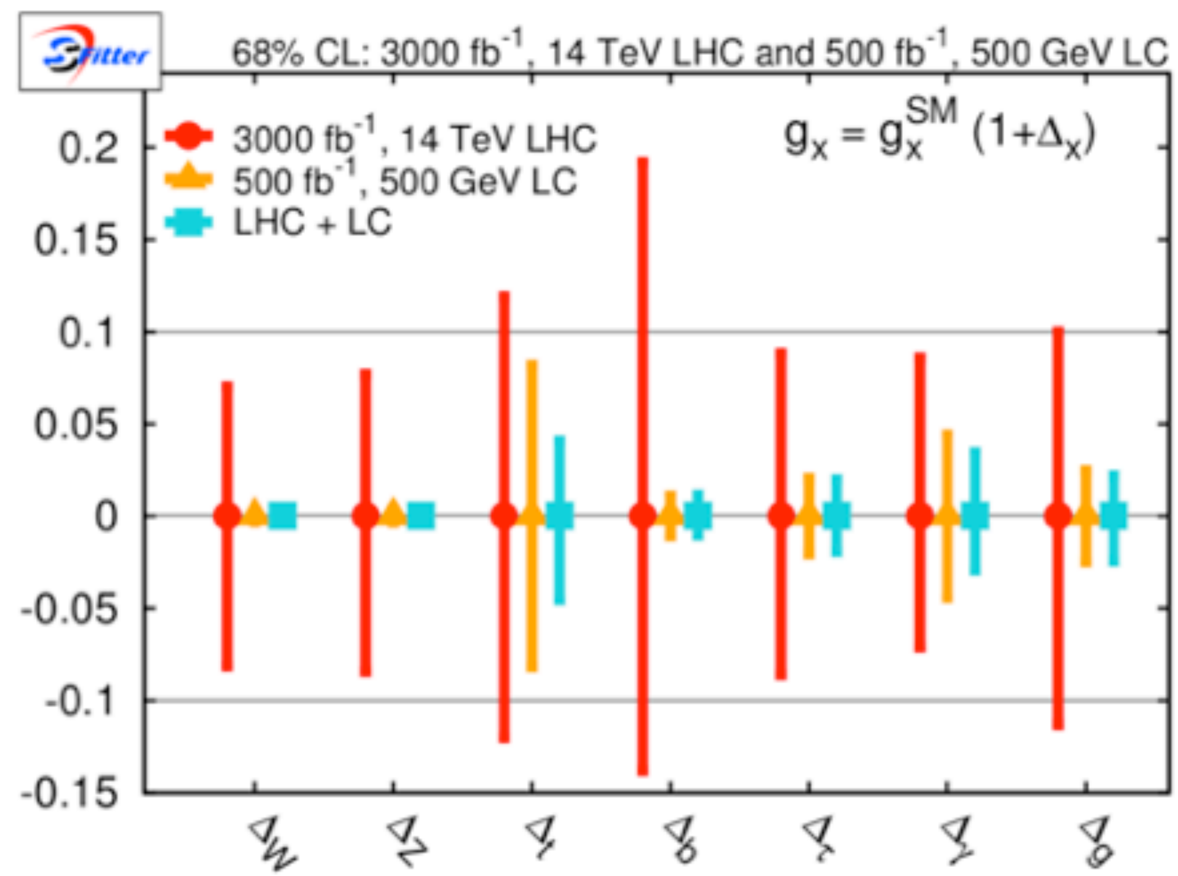
The Higgs sector precision





3000fb^{-1}:

- extrapolate blindly
- full set including effective couplings
- flat top starting at order 100fb-1
- all errors on couplings <20%
- best order 10%
- gain factor less than sqrt(3), naïve sqrt(L) scaling



LHC+ILC combined analysis:

- ILC only Gauss errors (Keisuke Fujii/M. Peskin)
- clear improvement on Δt
- some improvement on D5 couplings $\Delta\gamma, \Delta g$
- LHC⊕ILC better than each machine alone

similar effect to SUSY param determination (closes the circle)

Dirk Zerwas's talk

Fingerprinting Extended Higgs Sector

Higgs as a window to BSM physics

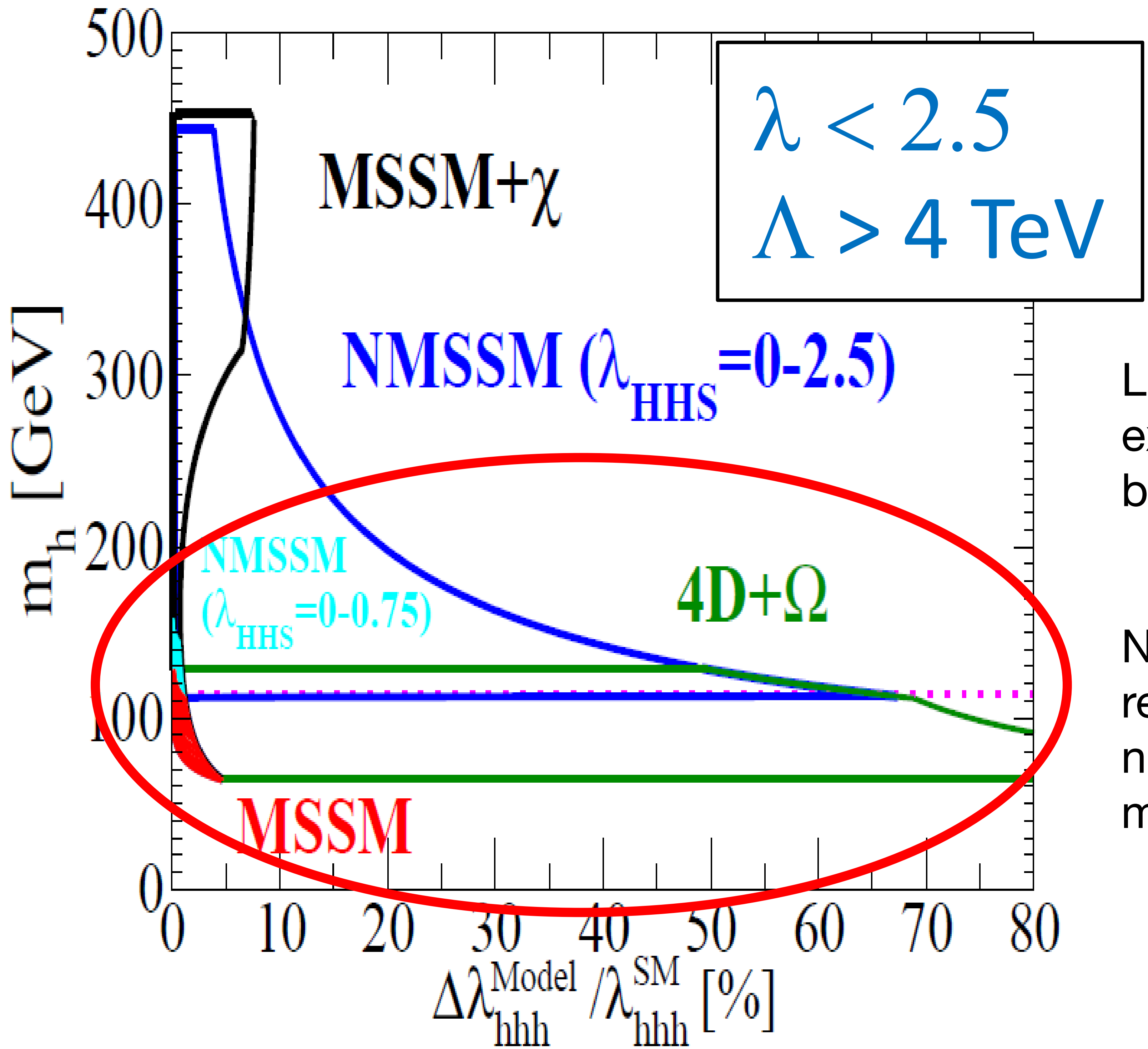
Expected deviation pattern

Different models predict different deviation patterns --> Fingerprinting!

Model	μ	τ	b	c	t	g_V
Singlet mixing	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-I	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-II (SUSY)	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-X (Lepton-specific)	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-Y (Flipped)	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$

Singlet mixing reduces all the coupling uniformly, but 2HDM-I does not.

What if only the slef-coupling deviates from the SM?



Large deviation can be expected in models motivated by EW-baryogenesis scenarios.

Nevertheless, 20% or better relative precision seems necessary for the self-coupling measurement.

Kanemura, Shindou, Yagyu (2010)

Summary

Our primary goal is to uncover the secret of EWSB

ZH @ 250 GeV (~mZ+mH+20GeV) : 250fb^-1 to 500fb^-1

- Higgs mass, width, J^{PC}
- Gauge quantum number -> coupling to H (other than top)
- Absolute meas. of HZZ coupling (recoil mass) --> limiting factor for BR precision (more data?)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g,A(loop)

ttbar @ 340-350GeV (~2mt) : 100-200fb^-1 : ZH meas. Is also possible

- Threshold scan --> theoretically clean mt
- --> indirect meas. of top Yukawa coupling?
- AFB, Top momentum measurements
- Form factor measurements

Self-coupling with γγ → HH @ 350GeV possibility?

vvH @ 350 - 500GeV : 500fb^-1

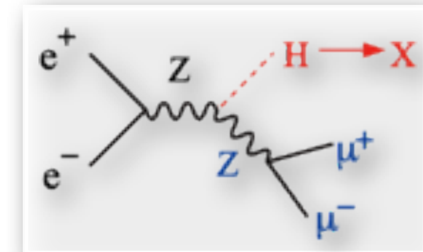
- HWW coupling -> total width to 6% --> absolute normalization of couplings

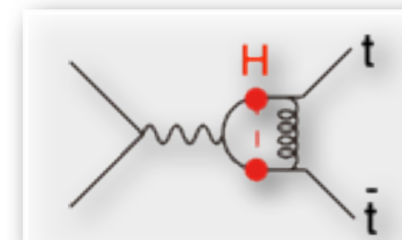
ZHH @ 500GeV (~mZ+2mH+170GeV) : 2ab^-1

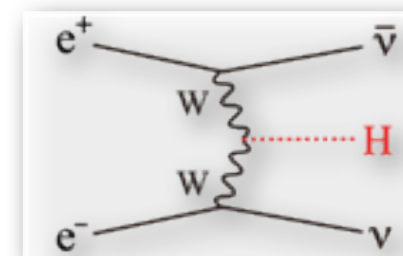
- Prod. cross section attains its maximum at around 500GeV -> Higgs self-coupling to 40% (more data)

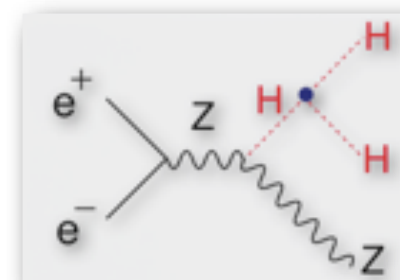
ttbarH @ 500GeV (~2mt+mH+30GeV) : 1ab^-1

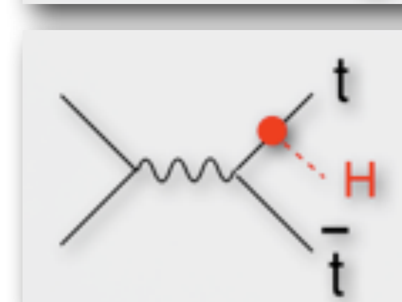
- Prod. cross section becomes maximum at around 700~800 GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable to 10% at 500GeV concurrently with the self-coupling. Slight increase of Ecm significantly increases the cross section near the threshold.









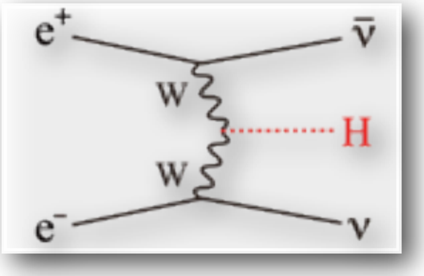


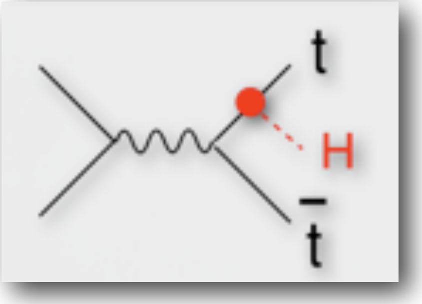
We can complete the mass-coupling plot at ~500GeV!

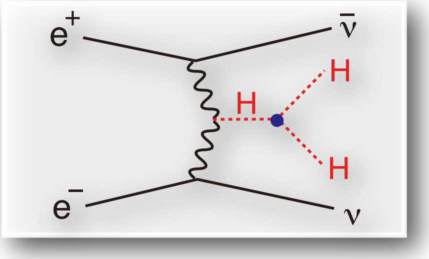
Higgs Physics at Higher Energy

Self-coupling with WBF, top Yukawa at xsection max., other higgses, ...

- vvH @ at >1TeV : 2ab^-1 (pol e+, e-)=(+0.2,-0.8)
  - allows us to measure rare decays such as H -> mu+ mu-, ...
- vvHH @ 1TeV or higher : 2ab^-1 (pol e+, e-)=(+0.2,-0.8)
  - cross section increases with Ecm but the sensitivity might not, because of background diagrams.
  - Nevertheless, $\Delta\lambda/\lambda \simeq 20\%$ (Ref. CLIC, ILD DBD studies) or better is expected.
  - If possible, we want to see the running of the self-coupling (very very challenging).
- ttbarH @ 1TeV : 1ab^-1
  - Prod. cross section becomes maximum at around 700GeV.
  - CP mixing of Higgs can be unambiguously studied.





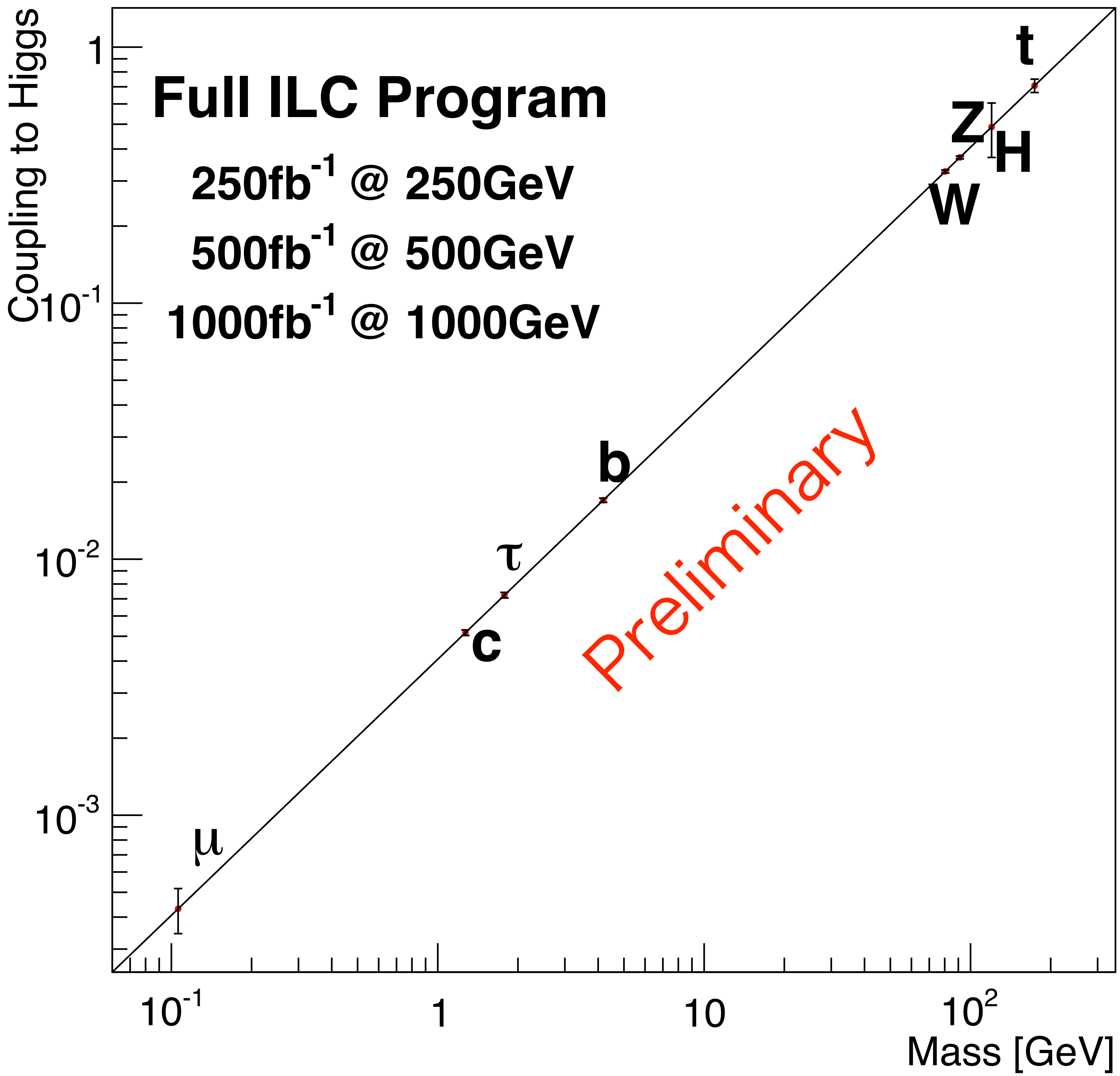


Obvious but most important advantage of higher energies in terms of Higgs physics is its higher mass reach to other Higgses expected in an extended Higgs sector and higher sensitivity to WLWL scattering to decide whether the higgs sector is strongly interacting or not.

In any case we can improve the mass-coupling plot by including the data at 1TeV!

Mass Coupling Relation

After Nominal Full ILC Program



Conclusions

- The primary goal of the ILC 500 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 follows LHC and ILC 500.
- To achieve the primary goal we need self-contained precision Higgs studies to complete the mass-coupling plot
  - starting from e+e- -> ZH at Ecm = mZ+mH+20GeV,
  - then ttbar at around 350GeV,
  - and then ZHH and ttbarH at 500GeV.
- The ILC to cover up to Ecm=500 GeV is absolutely necessary to carry out this mission (regardless of BSM scenarios) and we can do this with staging starting from Ecm at around 250GeV. We may need more data depending on the size of the deviation. Lumi-upgrade possibility should be always kept in our scope.
- If we are lucky, some extra Higgs might be within our reach already at ILC 500. If not, we will need the energy scale information from the precision Higgs studies. Guided by the energy scale information, we will go hunt direct BSM signals, if necessary, with a new machine. Eventually we will need to measure WLWL scattering to decide the Higgs sector is strongly interacting or not.