Higgs e^+e^- Future Facilities

Keisuke Fujii (KEK)

Disclaimer

This talk is NOT on machines

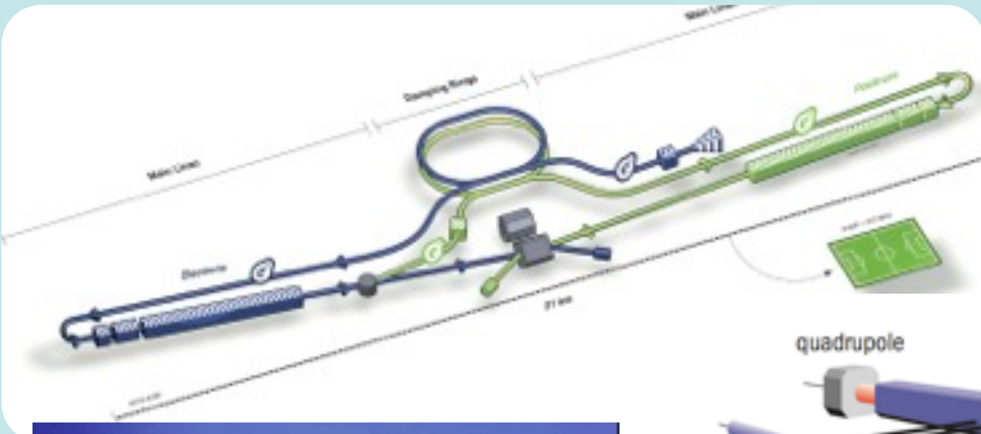
BUT on target Higgs physics
at proposed future e^+e^- facilities

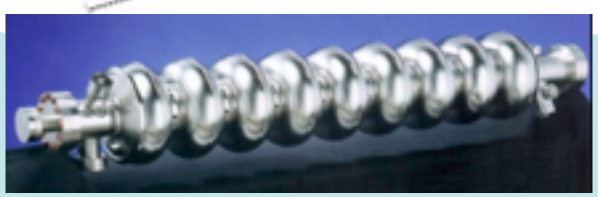
I have been working for ILC for long time, so
I am not in the position to make a neutral comparison.

Machine Options

Linear v.s. Circular, Cold v.s. Warm

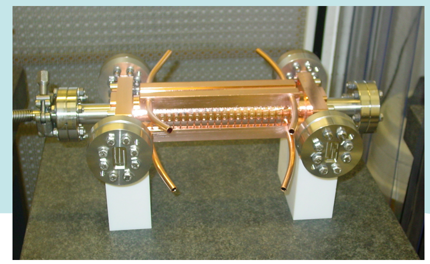
Linear Colliders

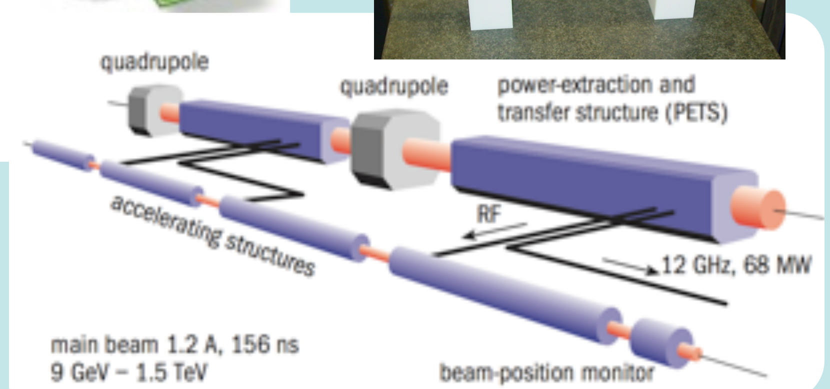




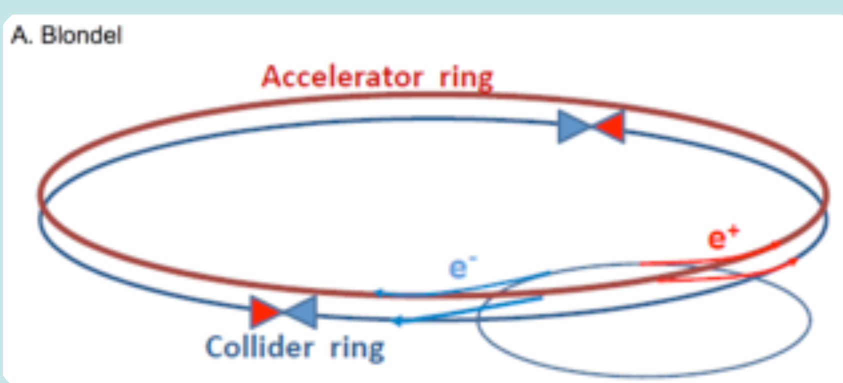
ILC: Cold

CLIC: Warm





Circular Colliders



TLEP: 80km ring

TLEP
SuperTRISTAN
CHF (china)
FNAL site filler
.....

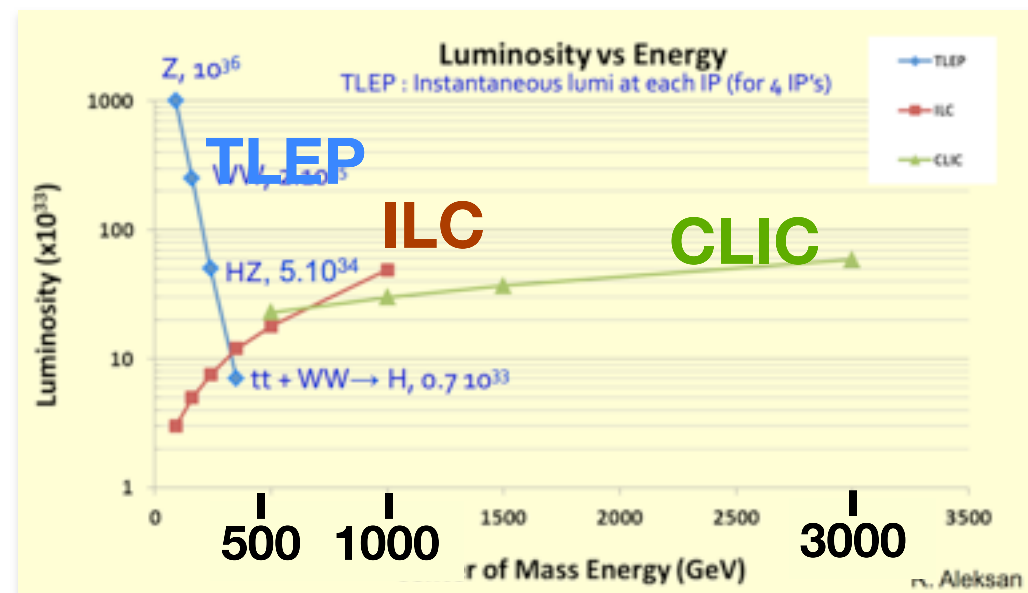
Key Factors for Physics

- E_{cm} range
- Luminosity
- Polarizations (Pe^-,Pe^+)

E_{cm} range

TLEP	: Ecm < 350 GeV (top)
ILC	: Ecm < 1000 (1500?) GeV
CLIC	: Ecm < 3000 GeV

Luminosity



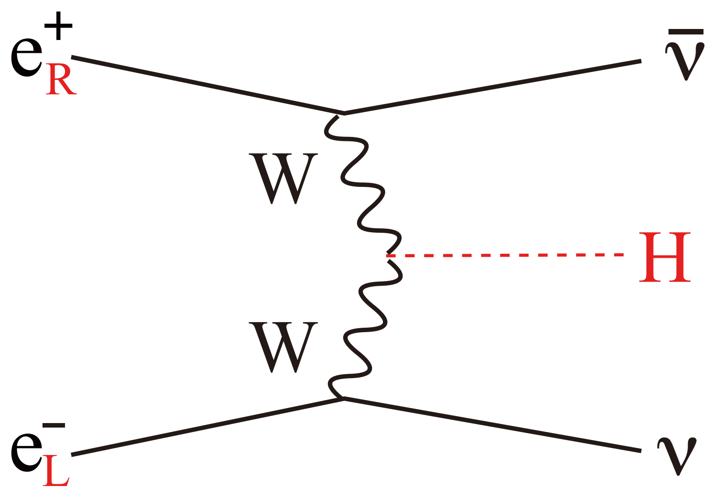
80km CC (TLEP) can give higher luminosities at <240 GeV than LC

But Physics also depends on beam polarizations !

Power of Beam Polarization

Electroweak interaction is Left-Right asymmetric

For instance



$e^+e^- \rightarrow \nu\bar{\nu}H$

To this process, only left-handed electrons and right-handed positrons contribute !

If you have a wrong combination, cross section is zero.

Beam polarization plays an essential role !

	ILC	CLIC	TLEP
Pol (e^-)	-0.8	-0.8	0
Pol (e^+)	+0.3	0	0
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34	1.8x1.0=1.8	1

Polarizations act as a kind of luminosity doubler !

Don't just compare luminosity values !

Wall Plug AC Power

Luminosity is not free, it costs AC power

ilc Collider 'Wall Plug' **AC Power** use:

ILC and 80 km ring:	ILC -H	ILC-nom	Ring - H	Ring - t
E_cm (GeV)	250	500	240	350
SRF Power to Beam (MW)	5.2	10.5	100	100
Eff. RF Length (m)	7,837	15,674	600	1200
RF klystron peak efficiency (%)	65	65	65	65
klystron operating margin, HVPS, Klystron Aux and klystron water cooling (% inefficiency)	→ 30 + 20 Additional inefficiency due cavity fill-time		20*	20
Overall system RF efficiency (%)	10	14	45	45
Cryo (MW)	16	32	20	40
Normal Conducting (exc. Injector complex) (MW)	6	10	120**	120
Injector complex	32	32	16***	16
Conventional (Air, lighting, ..)	6	6****	18	18
Total (exc. detector)	**112**	**153**	**396**	**416**

* 5% for operating margin, 2% for auxiliaries, 3% for HVPS and 10% for water cooling
** assume 1.5 kW / m tunnel inclusive (ILC avg. 3 kW / m)
*** from SSC / Fermilab injector (linac + LEB + MEB); assumes LHC not needed
**** 6 MW for 30 km beam tunnel complex; ~3x more for 80 ring

Assume two separate collider rings – similar to B Factories

14 March, 2013 Marc Ross, SLAC

ILC has a room for luminosity upgrade !

I will return to this point later if time allows.

So much for machine options

Roughly speaking, Higgs physics at an e^+e^- collider is more or less the same for given 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.

Precision Higgs Studies at ILC

Keisuke Fujii (KEK)

Electroweak Symmetry Breaking

Mystery of something in the vacuum

- Success of the SM = success of gauge principle

  W_T and Z_T = gauge fields of the EW gauge symmetry

- Gauge symmetry forbids explicit mass terms for W and Z
  → it must be broken by something condensed in the vacuum: $\langle 0 \,|\, I_3, Y \,|\, 0 \rangle \neq 0 \quad \langle 0 \,|\, I_3 + Y \,|\, 0 \rangle = 0$

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

  $$W_L^+, W_L^-, Z_L \longleftarrow \chi^+, \chi^-, \chi_3$$: Goldstone modes

- Left- (f_L) and right-handed (f_R) matter fermions carry different EW charges.

  Their explicit mass terms also forbidden by the EW gauge symmetry

  They must be generated through their Yukawa interactions with some weak-charged vacuum

- In the SM, the same "something" mixes f_L and f_R → generating masses and inducing flavor-mixings

- In order to form the Yukawa interaction terms, we need a complex doublet scalar field, which has four real components. The SM identifies three of them with the Goldstone modes.

- 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 might be more complex.

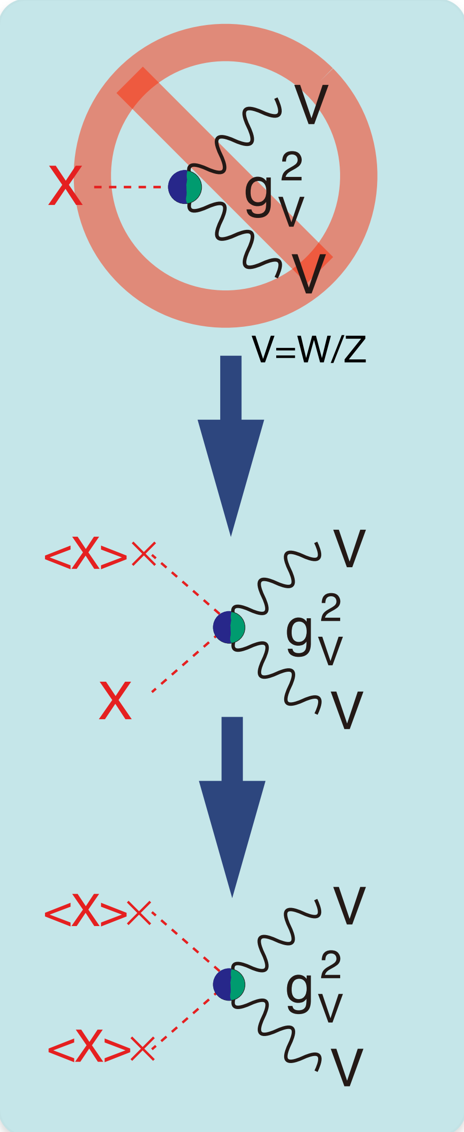
- We don't know whether the "something" is elementary or composite.

- We knew it's there in the vacuum with a vev of 246 GeV. But other than that we didn't know almost anything about the "something" until July 4, 2012.

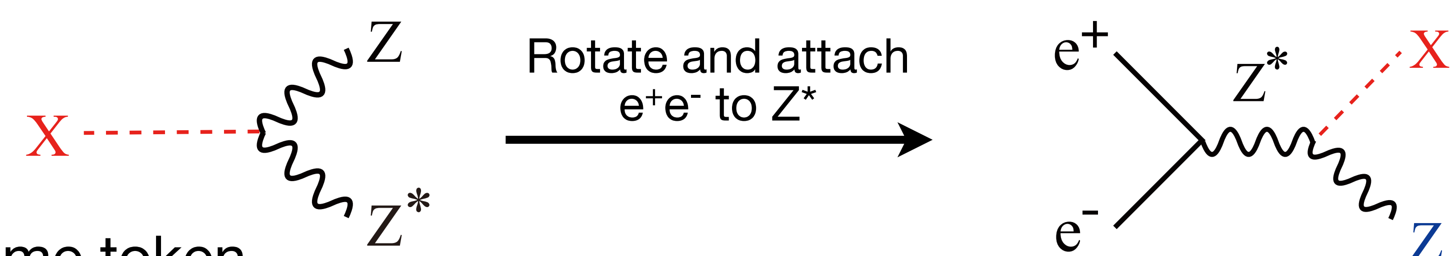
Since the July 4th, the world has changed!

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

- X(125) → γγ means X is a neutral boson and J ≠ 1 (Landau-Yang theorem). Recent LHC results prefer $J^P=0^+$.
- X(125) → ZZ*, WW* ⇒ ∃ XVV couplings: (V=W/Z: gauge bosons)
- There is no gauge coupling like XVV, only XXVV or XXV
  ⇒ XVV probably from XXVV with one X replaced by <X> ≠ 0, namely <X>XVV
  ⇒ There must be <X><X>VV, a mass term for V.
  ⇒ 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.

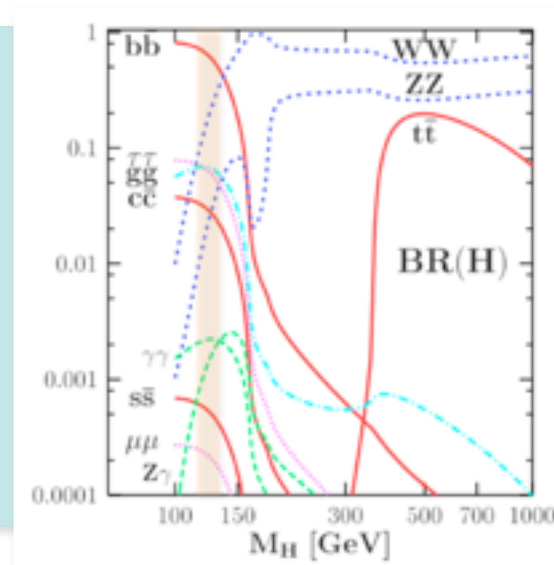


- X -> ZZ* means, X can be produced via e^+e^- → Z* → ZX.



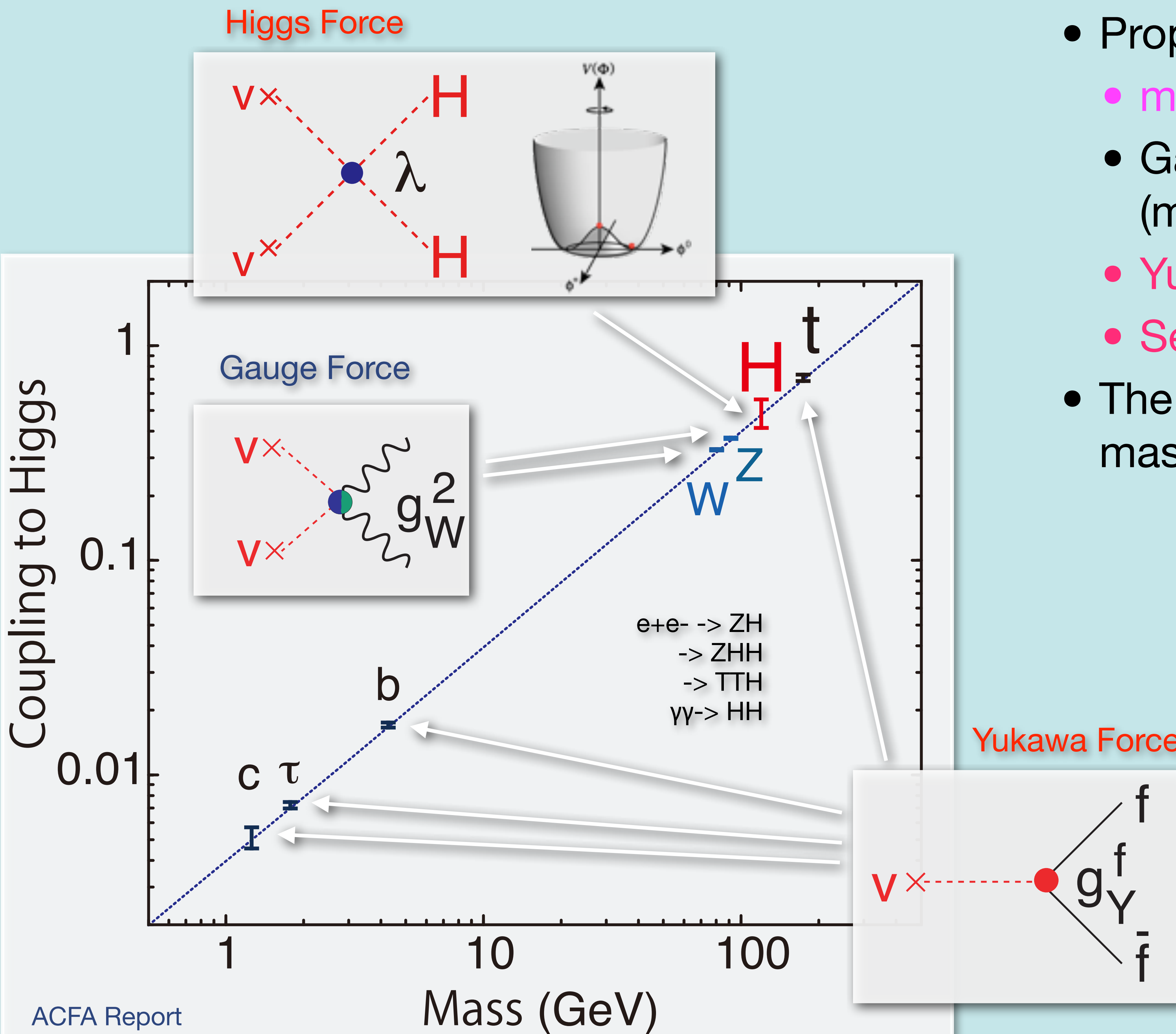
- By the same token,
  X → WW* means, X can be produced via W fusion: e^+e^- → $\nu\nu X$.

- So we now know that the major Higgs production processes in e^+e^- collisions are indeed available at the ILC ⇒ No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, 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.



What Properties to Measure?

The Key is the Mass-Coupling Relation



- 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 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?
  - Additional doublet?
  - Additional triplet?
- Underlying dynamics :
  - Weakly interacting or strongly interacting?
    = elementary or composite ?
- Relations to other problems :
  - DM
  - EW baryogenesis
  - neutrino mass
  - 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

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

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

SUSY

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

Expected deviations are small --> Precision!

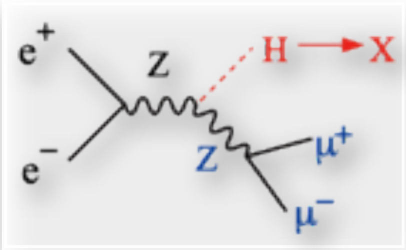
The July 4 was the opening of a new era which will last probably 20 years or more, where a 500 GeV LC such as ILC will / must play the central role.

Why 250-500 GeV?

Three well known thresholds

ZH @ 250 GeV (~MZ+MH+20GeV) :

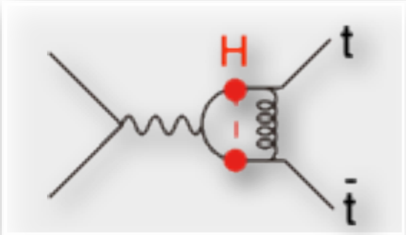
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)



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

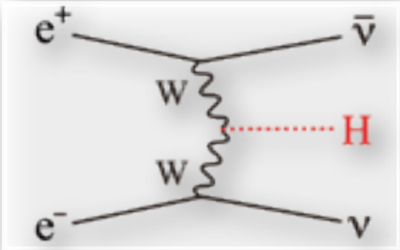
- Threshold scan --> theoretically clean mt measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of top Yukawa coupling
- AFB, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



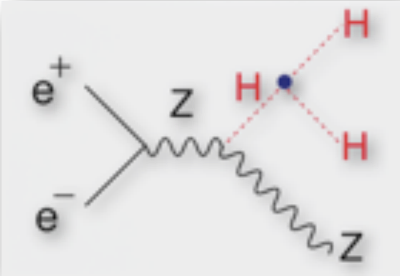
vvH @ 350 - 500GeV :

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



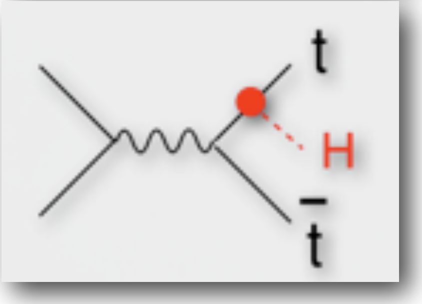
ZHH @ 500GeV (~MZ+2MH+170GeV) :

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



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

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



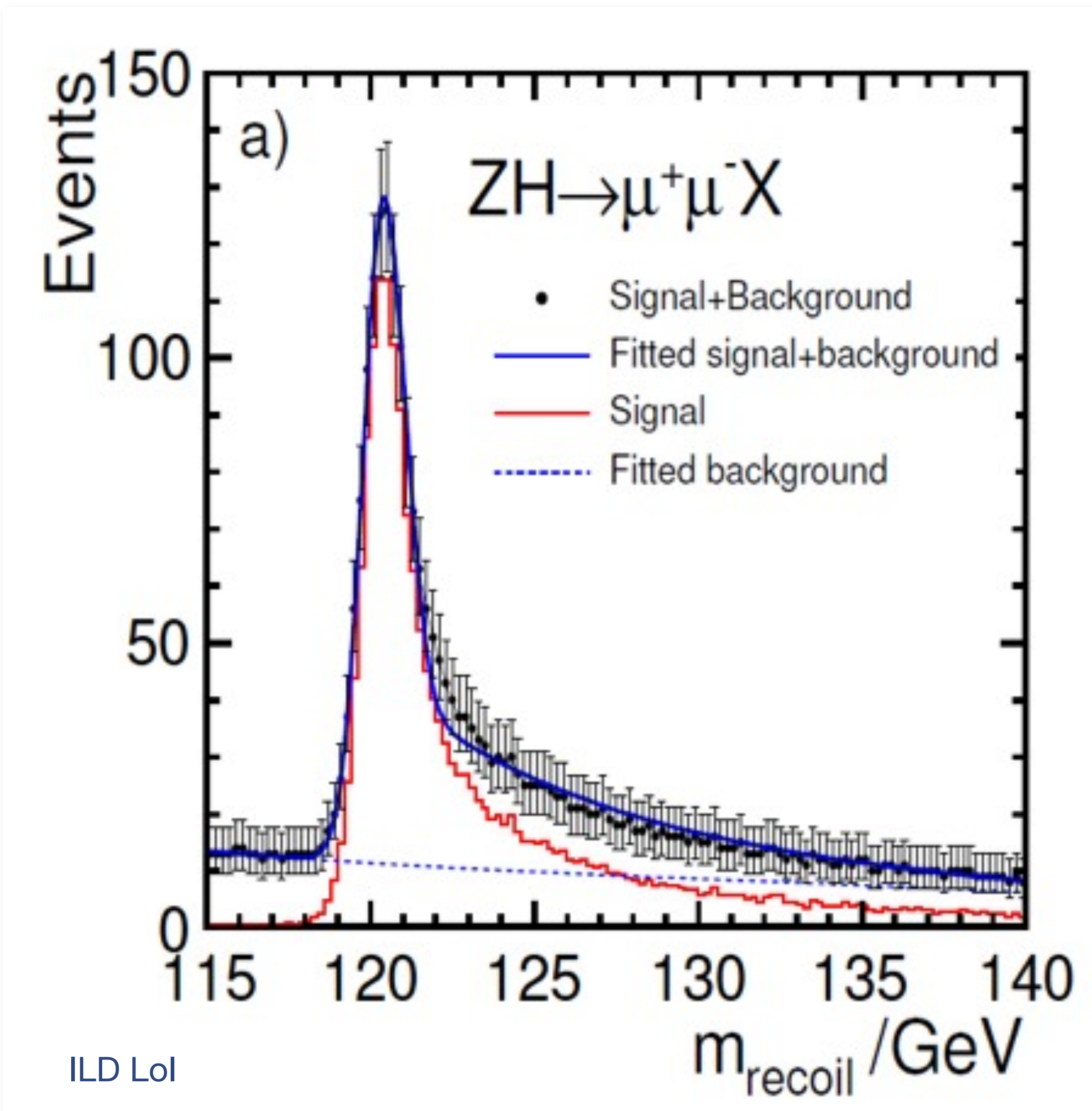
We can complete the mass-coupling plot at ~500GeV!

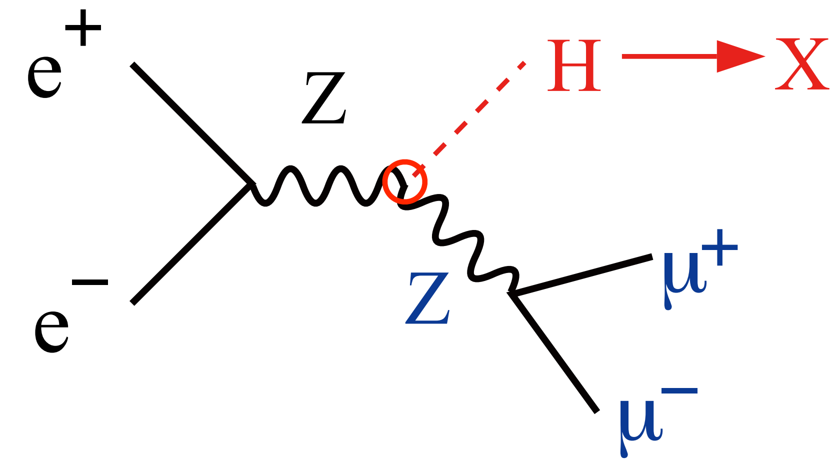
ILC 250

Recoil Mass Measurement

The flagship measurement of ILC 250

Recoil Mass





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

Invisible decay detectable!

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

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

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

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

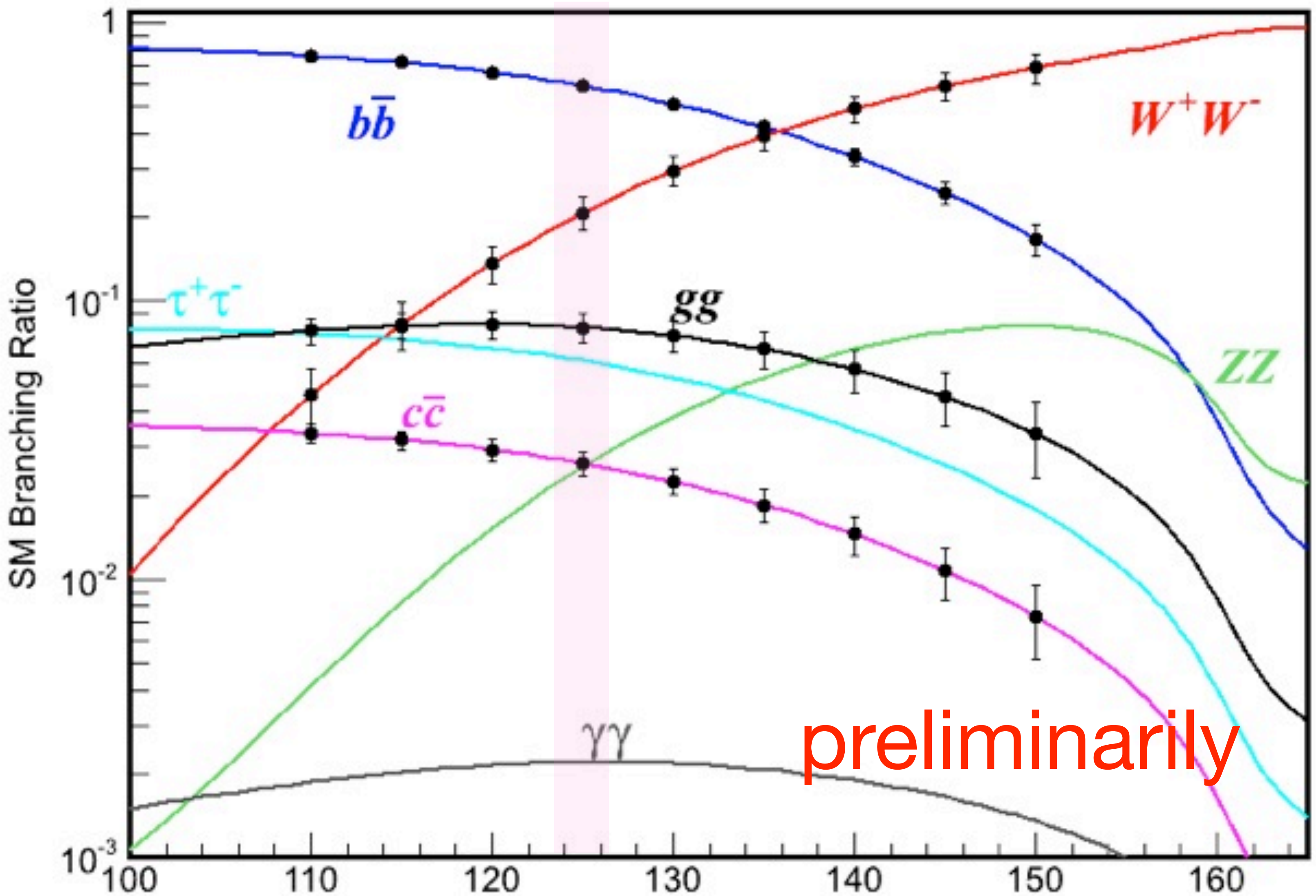
scaled from mH=120 GeV

Model-independent absolute measurement of the HZZ coupling

Branching Ratio Measurements

for b, c, g, tau, WW*, ...

DBD Physics Chap.



ILD DBD Study (Ono)

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

scaled from mH=120 GeV

	@250GeV
process	ZH
Int. Lumi. [fb^{-1}]	250
Δσ/σ	2.6%
decay mode	ΔσBr/σBr
H → bb	1.1%
H → cc	7.4%
H → gg	9.1%
H → WW*	7.4%
H → ττ	4.2%
H → ZZ*	19%
H → γγ	29-38%

preliminarily

What we measure is not BR itself but σxBR.

To extract BR from σxBR, we need σ from the recoil mass measurement.
--> Δσ/σ=2.6% eventually limits the BR measurements.
--> If we want to improve this, we need more data at 250GeV.
Note: x2 lumi. upgrade is possible by increasing #bunches/train back to the RDR value.

Total Width and Coupling Extraction

One of the major advantages of the LC

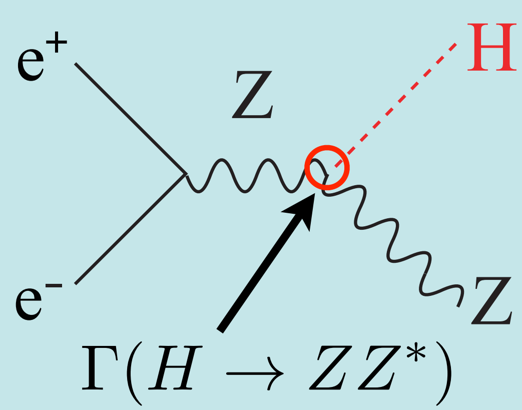
To extract couplings from BRs, we need the total width:

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

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

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

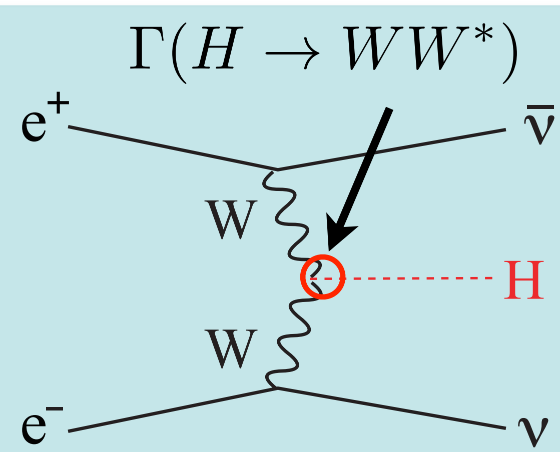
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

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

ILC 500

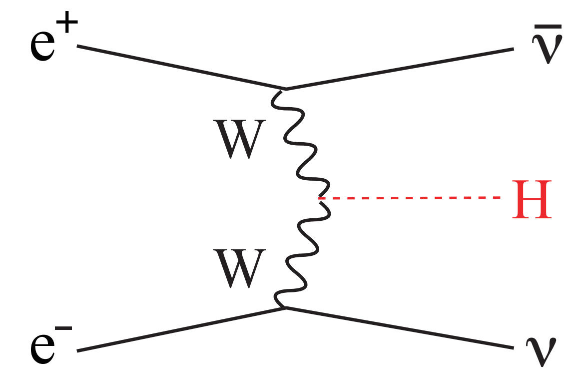
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

E_{cm} [GeV]	independent measurements	relative error
250	σ_{ZH}	2.6%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.1%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	7.4%
	$\sigma_{ZH} \cdot Br(H \to gg)$	9.1%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	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	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.8%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	12%
	$\sigma_{ZH} \cdot Br(H \to gg)$	14%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	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%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to WW^*)$	2.6%

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

ILD DBD Full Simulation Study



comes in as a powerful tool!

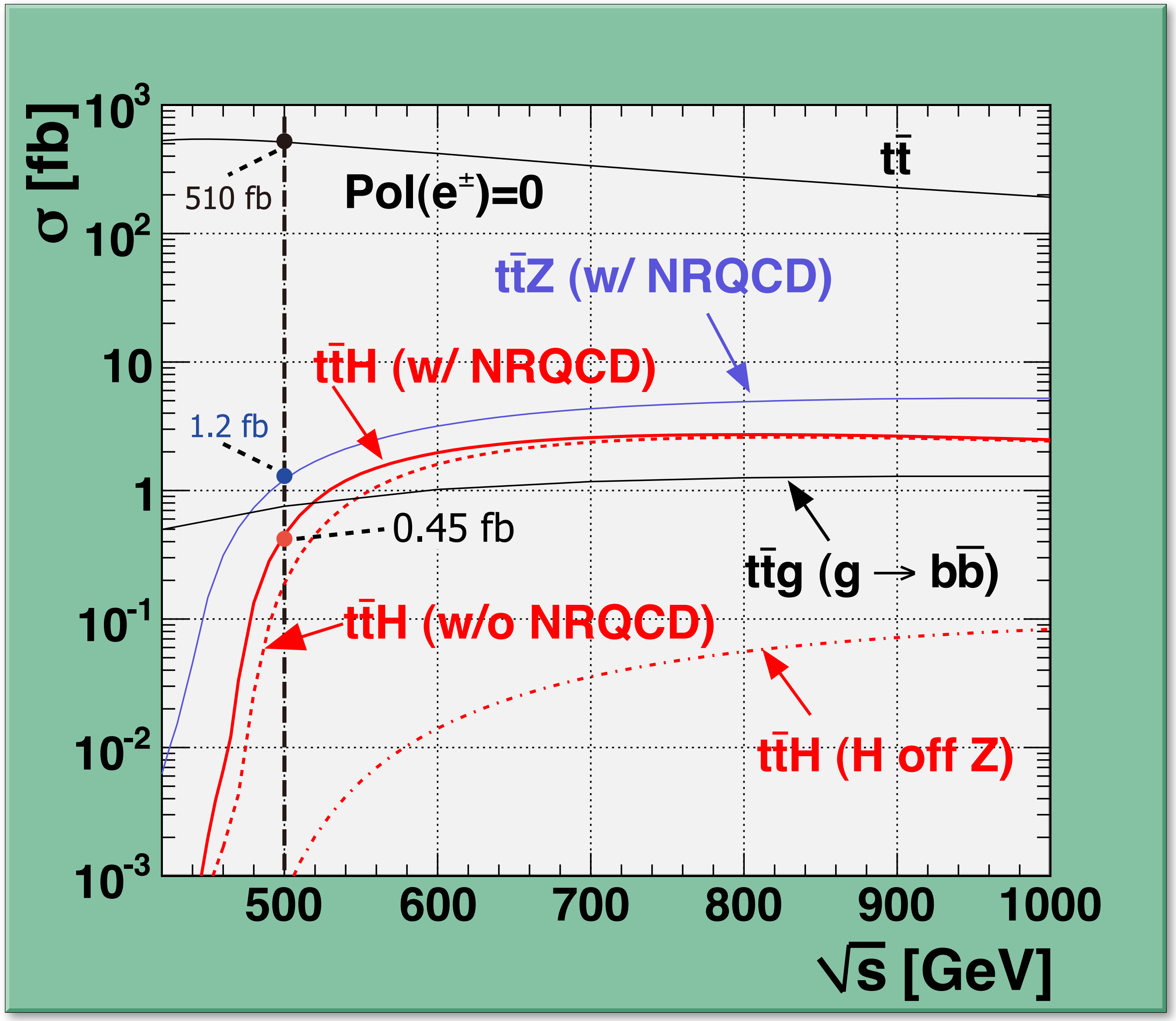
$$\Delta\Gamma_H/\Gamma_H \simeq 6\%$$

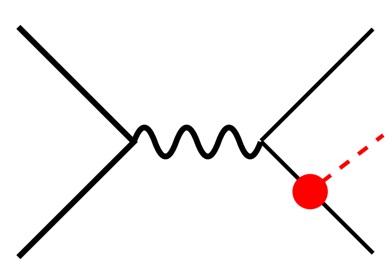
Mode	ΔBR/BR
bb	2.7 (2.7)%
cc	5.2 (7.8)%
gg	4.5 (9.5)%
WW*	3.6 (6.9)%
τ τ	4.1 (4.9)%

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

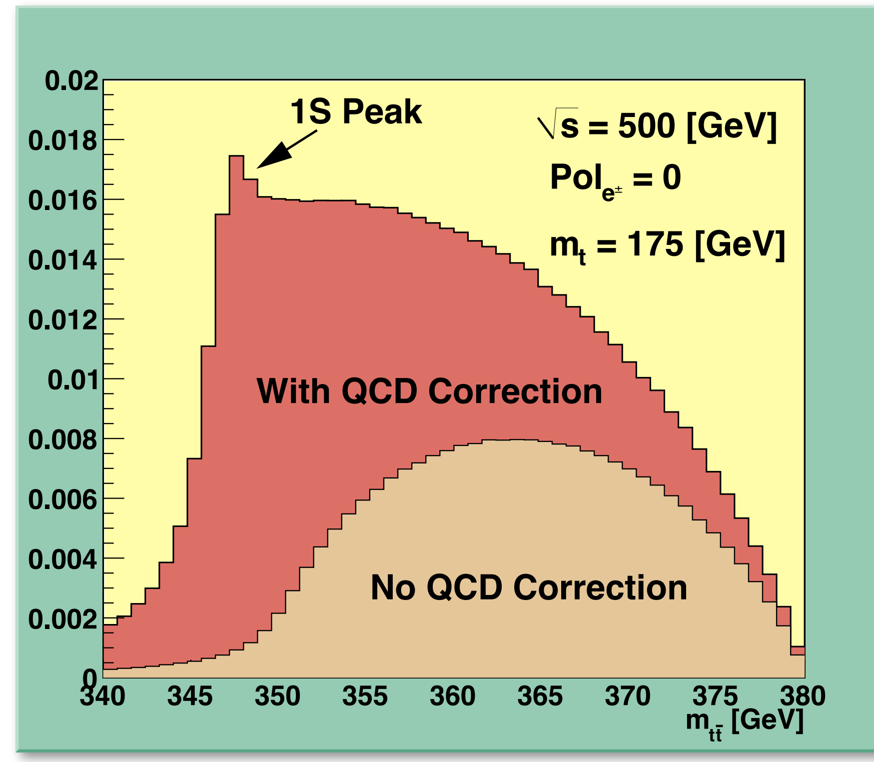
Top Yukawa Coupling

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

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

$$\Delta g_Y(t)/g_Y(t) = 13\,\%$$

Tony Price, LCWS12

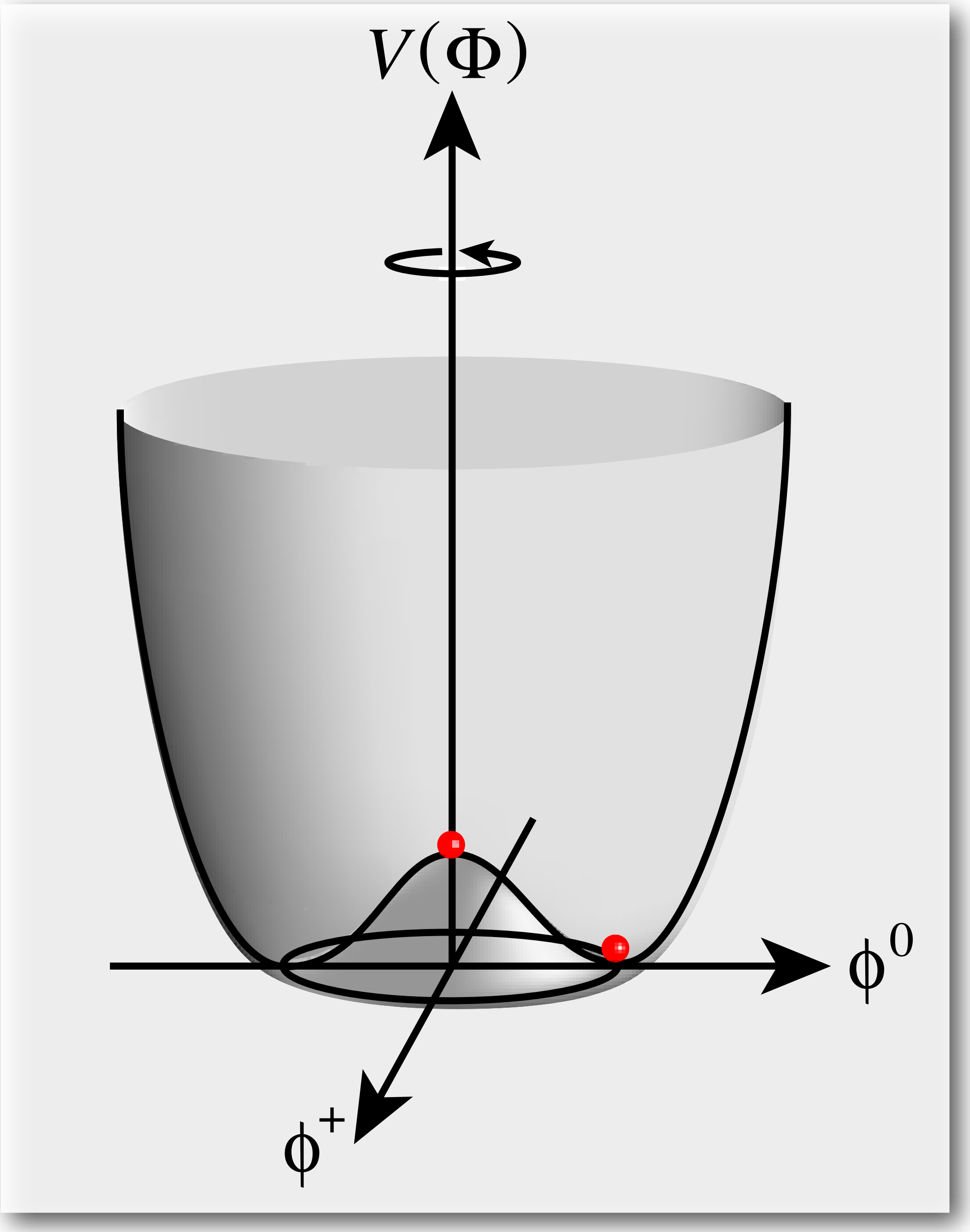
scaled from mH=120 GeV

Notice σ(500+20GeV)/σ(500GeV) ~ 2

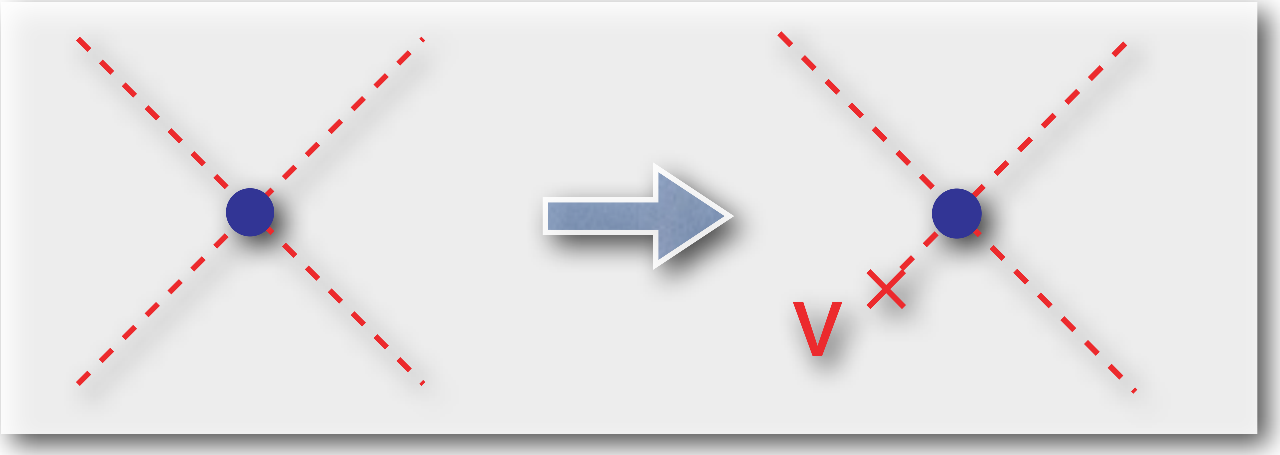
Moving up a little bit helps significantly!

Higgs Self-coupling

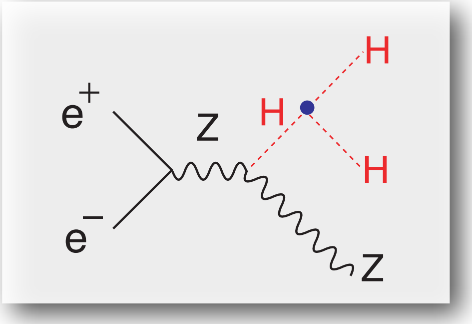
What force makes the Higgs condense in the vacuum?

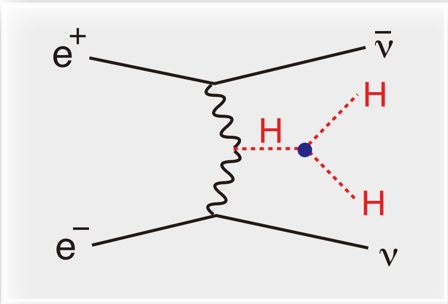


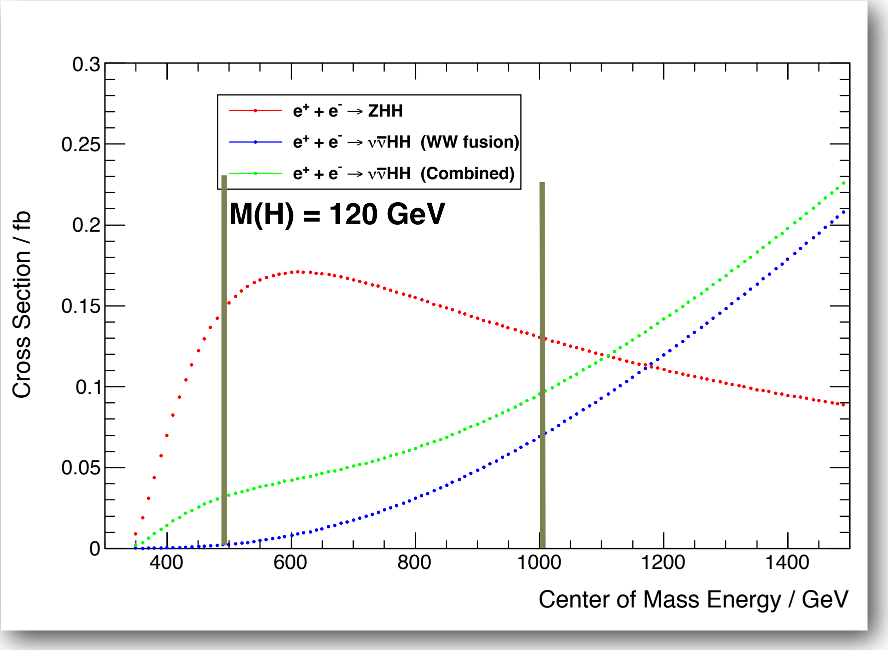
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential







The measurement is very difficult even at ILC.

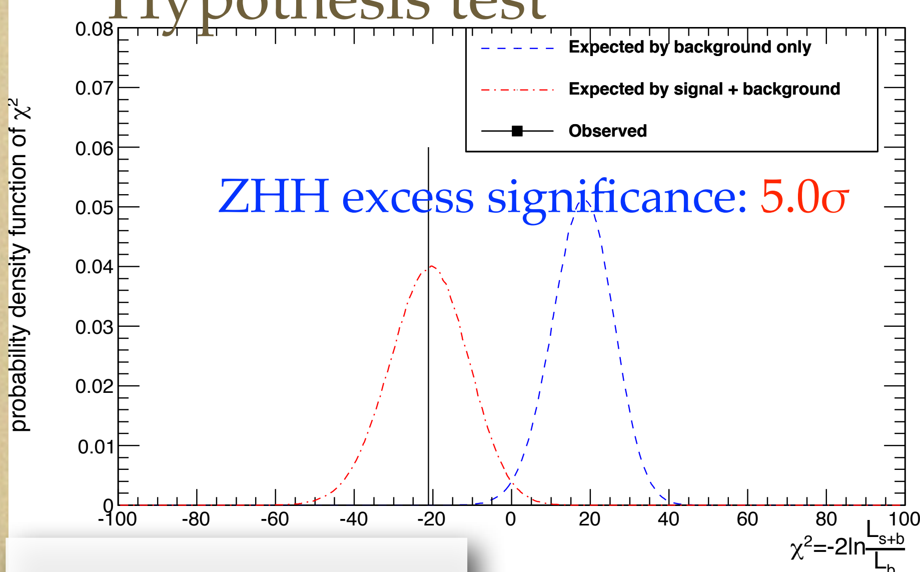
DBD full simulation

Higgs self-coupling @ 500 GeV (combined)

P(e-,e+)=(-0.8,+0.3) $e^+ + e^- \to ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6.0	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

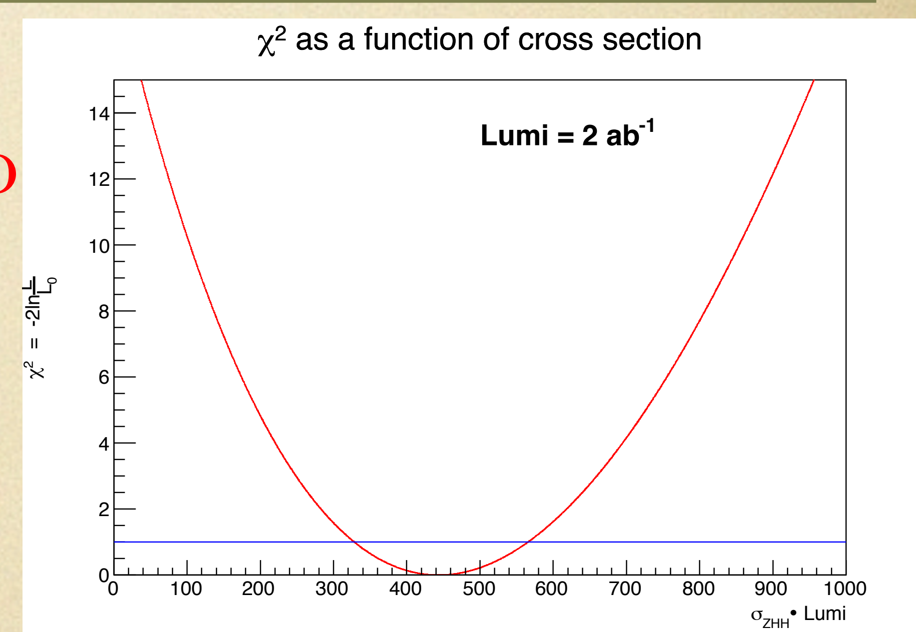
Hypothesis test

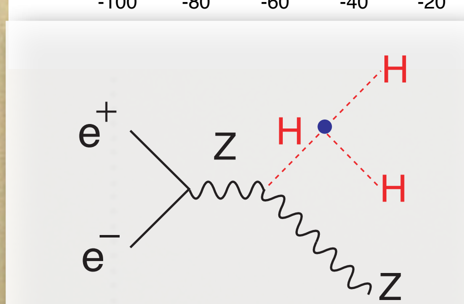


$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

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

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





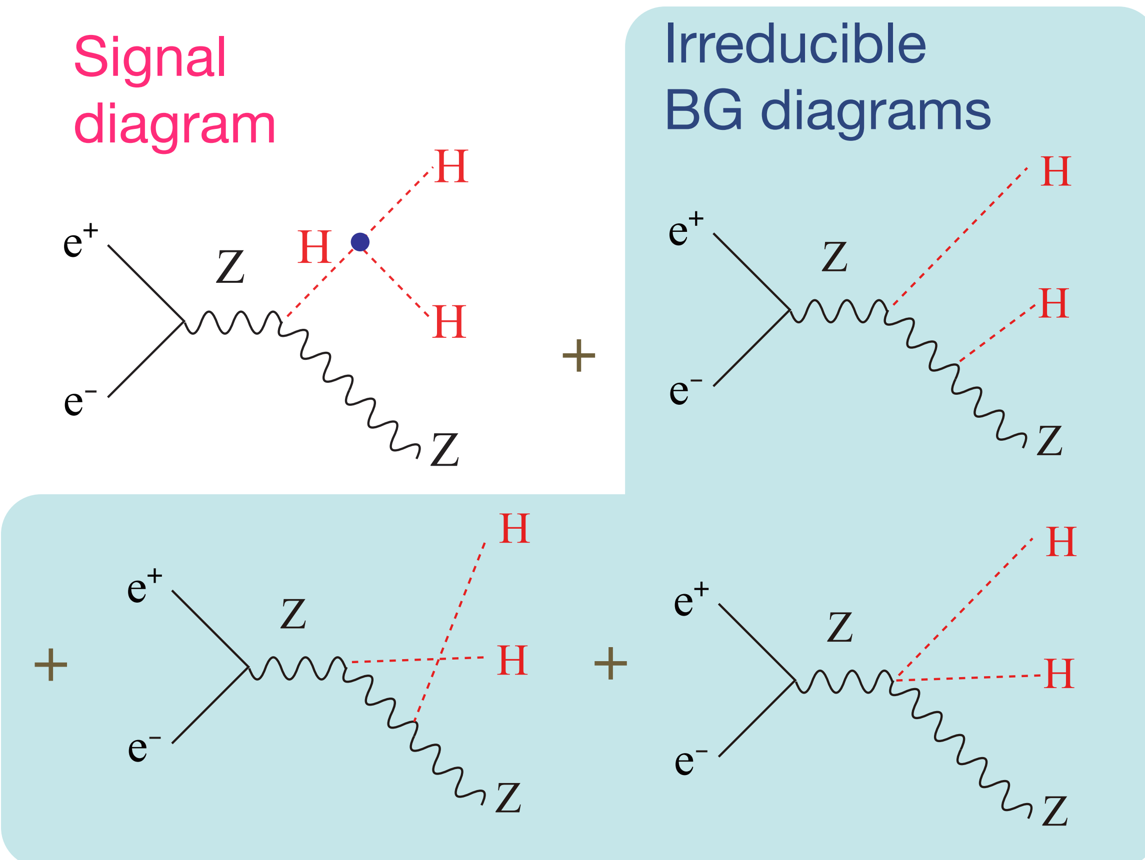
(cf. 80% for qqbbbb at the LoI time)

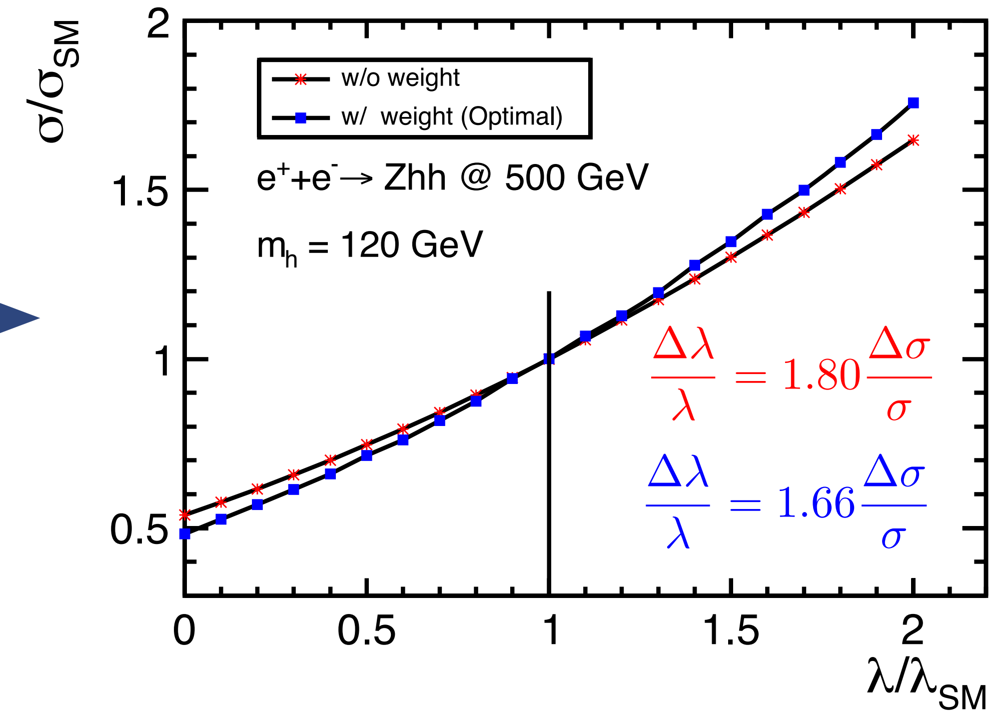
The Problem : BG diagrams dilute self-coupling contribution

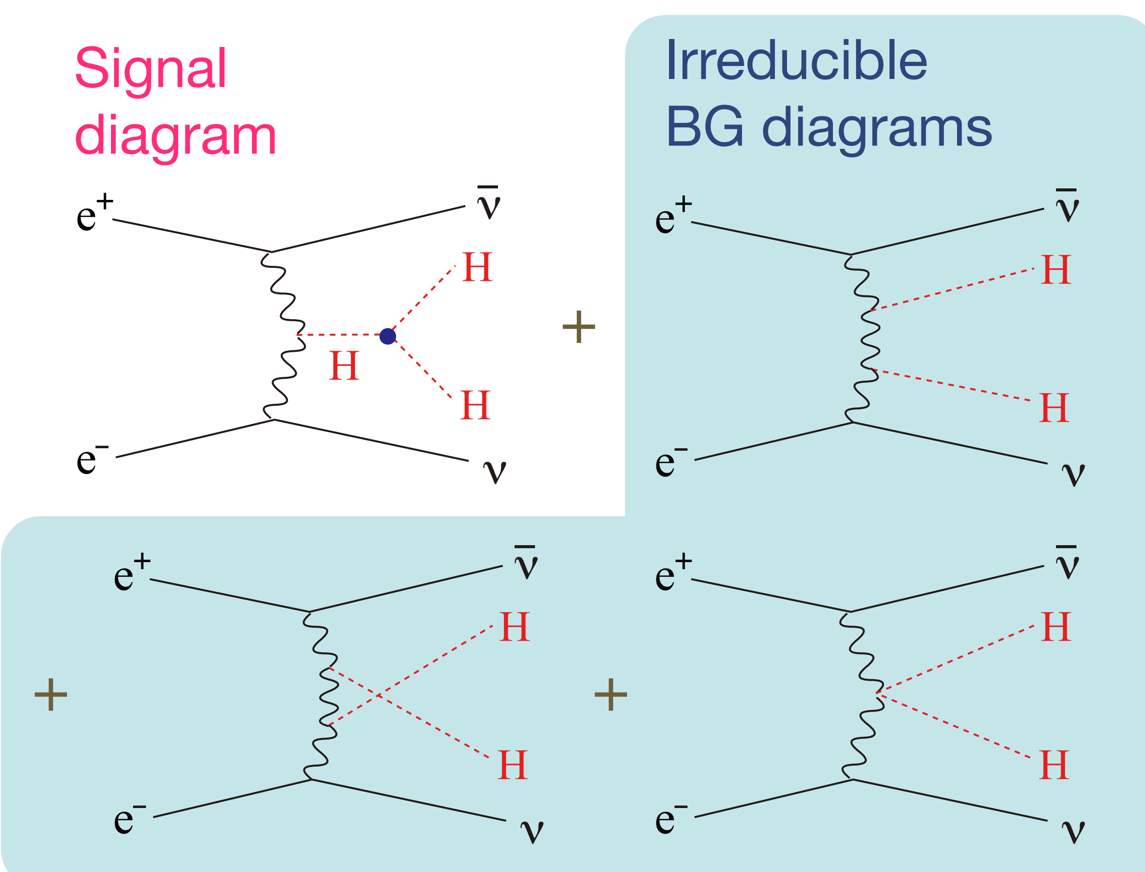
$$\sigma = \lambda^2 S + \lambda I + B$$

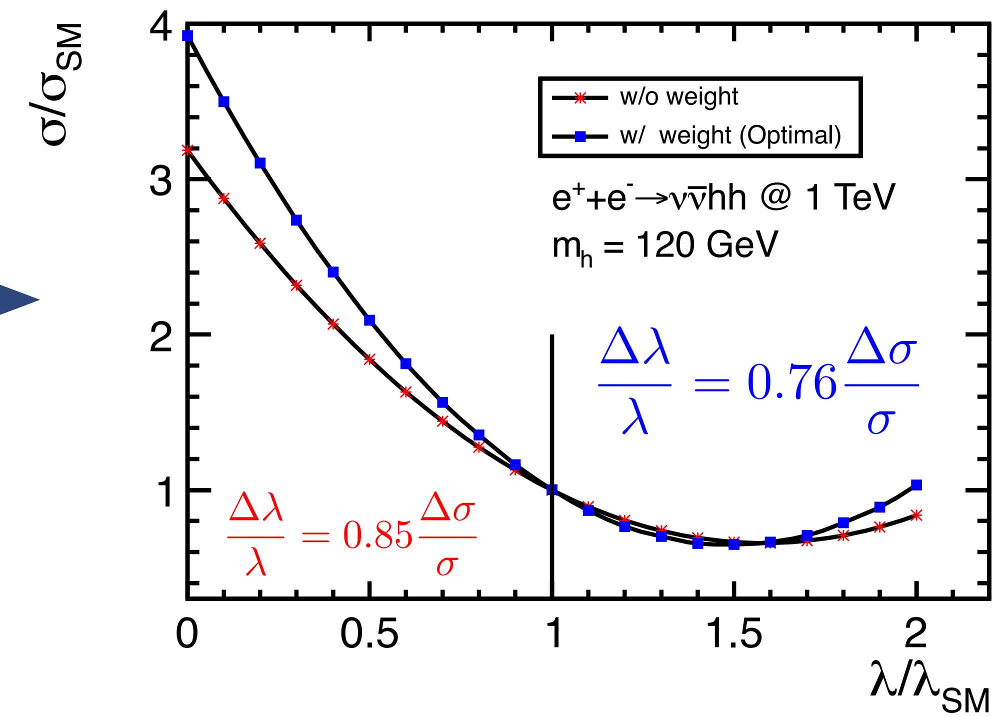
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams









Junping Tian LC-REP-2013-003

ILC 1000

Higgs Physics at Higher Energy

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

vvH @ at >1TeV : > 1ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

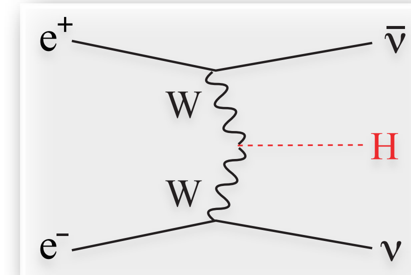
- allows us to measure rare decays such as H -> $\mu^+ \mu^-$, ...
- further improvements of coupling measurements

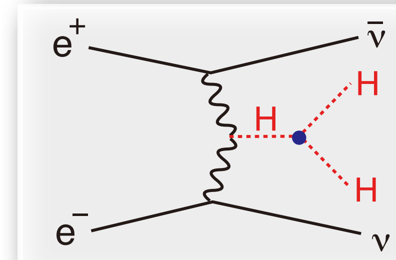
vvHH @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

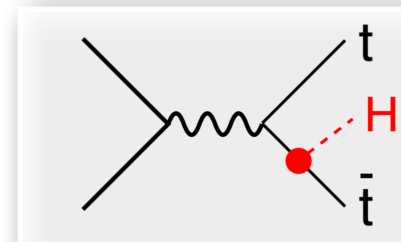
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).

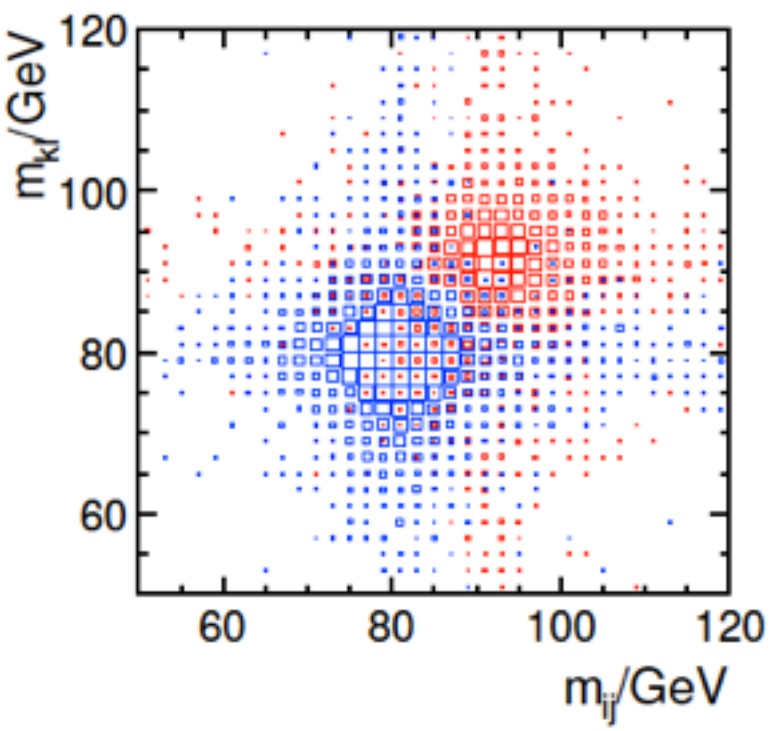
ttbarH @ 1TeV : 1ab^{-1}

- Prod. cross section becomes maximum at around 800GeV.
- CP mixing of Higgs can be unambiguously studied.









Obvious but most important advantage of higher energies in terms of Higgs physics is, however, its higher mass reach to other Higgs bosons expected in extended Higgs sectors and higher sensitivity to $W_L W_L$ 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!

Independent Higgs Measurements at ILC

Canonical ILC program

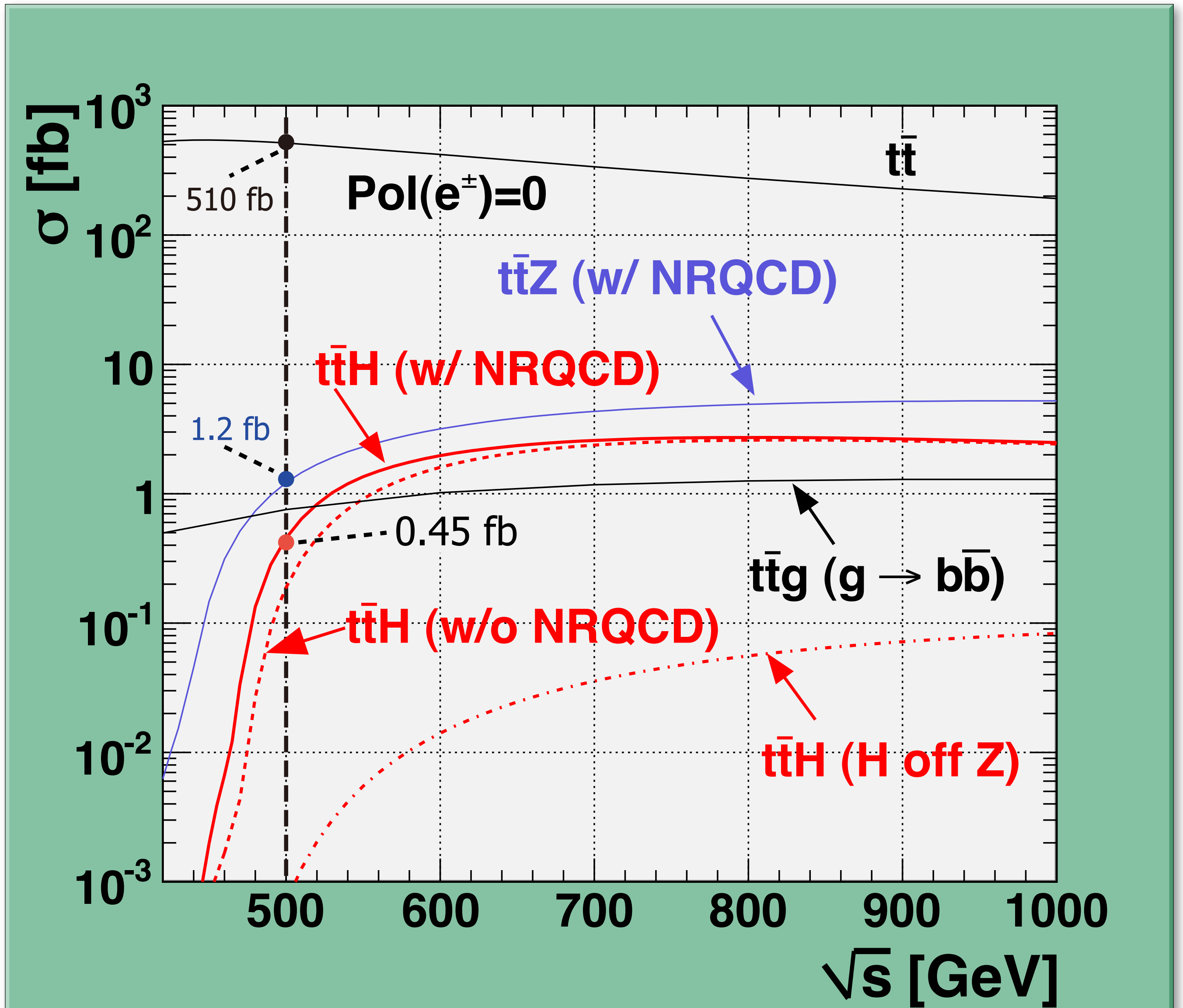
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

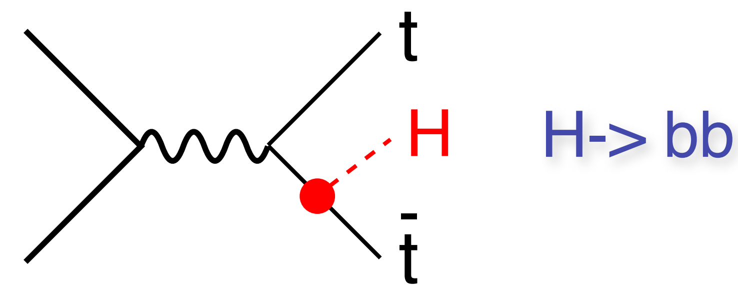
($M_H = 125$ GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb^{-1}]	250		500		1000
polarization (e^-,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%	-	-		
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
$H \to bb$	1.1%	10.5%	1.8%	0.66%	0.32%
$H \to cc$	7.4%		12%	6.2%	3.1%
$H \to gg$	9.1%		14%	4.1%	2.3%
$H \to WW^*$	6.4%		9.2%	2.6%	1.6%
$H \to \tau\tau$	4.2%		5.4%	14%	3.5%
$H \to ZZ^*$	19%		25%	8.2%	4.1%
$H \to \gamma\gamma$	48%		48%	33%	11%

Top Yukawa Coupling at 1TeV

The largest among matter fermions, but not yet observed





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

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

$$\Delta g_Y(t)/g_Y(t) = 13\,\%$$

Tony Price, LCWS12 — scaled from mH=120 GeV

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

$$\Delta g_Y(t)/g_Y(t) = 4.0\,\%$$

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

DBD full simulation

Higgs self-coupling @ 1 TeV

P(e-,e+)=(-0.8,+0.2) $e^+ + e^- \to \nu\bar{\nu}HH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

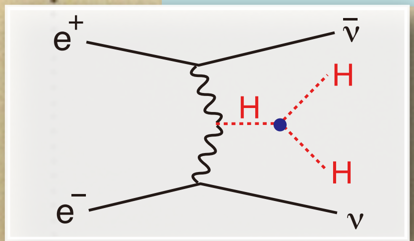
	Expected	After Cut
νvhh (WW F)	272	35.7
νvhh (ZHH)	74.0	3.88
BG (tt/ννZH)	7.86×10^5	33.7
significance	0.30	4.29

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

$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: $> 7\sigma$

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



ILD DBD Study (Junping Tian)

ILC 250+500+1000

Model-independent Global Fit for Couplings

Canonical ILC program

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

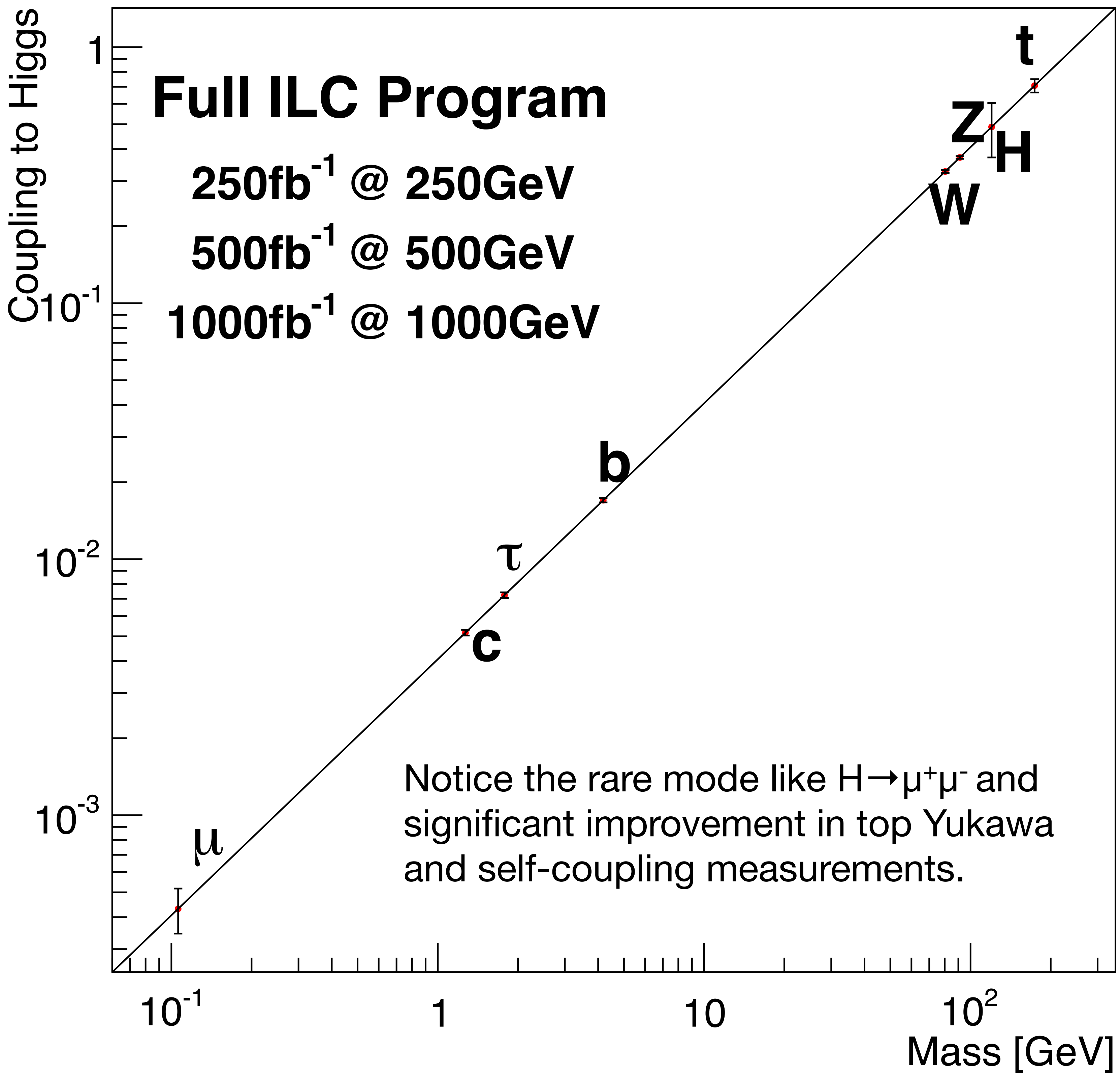
(M_H = 125 GeV)

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%	1.3%	1.3%
HWW	4.8%	1.4%	1.4%
Hbb	5.3%	1.8%	1.5%
Hcc	6.5%	2.9%	2.0%
Hgg	7.0%	2.5%	1.8%
$H\tau\tau$	5.7%	2.5%	2.0%
$H\gamma\gamma$	25%	12%	5.2%
$H\mu\mu$	-	-	16%
Γ_0	11%	5.9%	5.6%
Htt	-	16%	3.8%
HHH	-	104%	26%

Mass Coupling Relation

After Canonical ILC Program



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

LHC + ILC

Expected Precision and Deviation

Combined Fit with LHC data

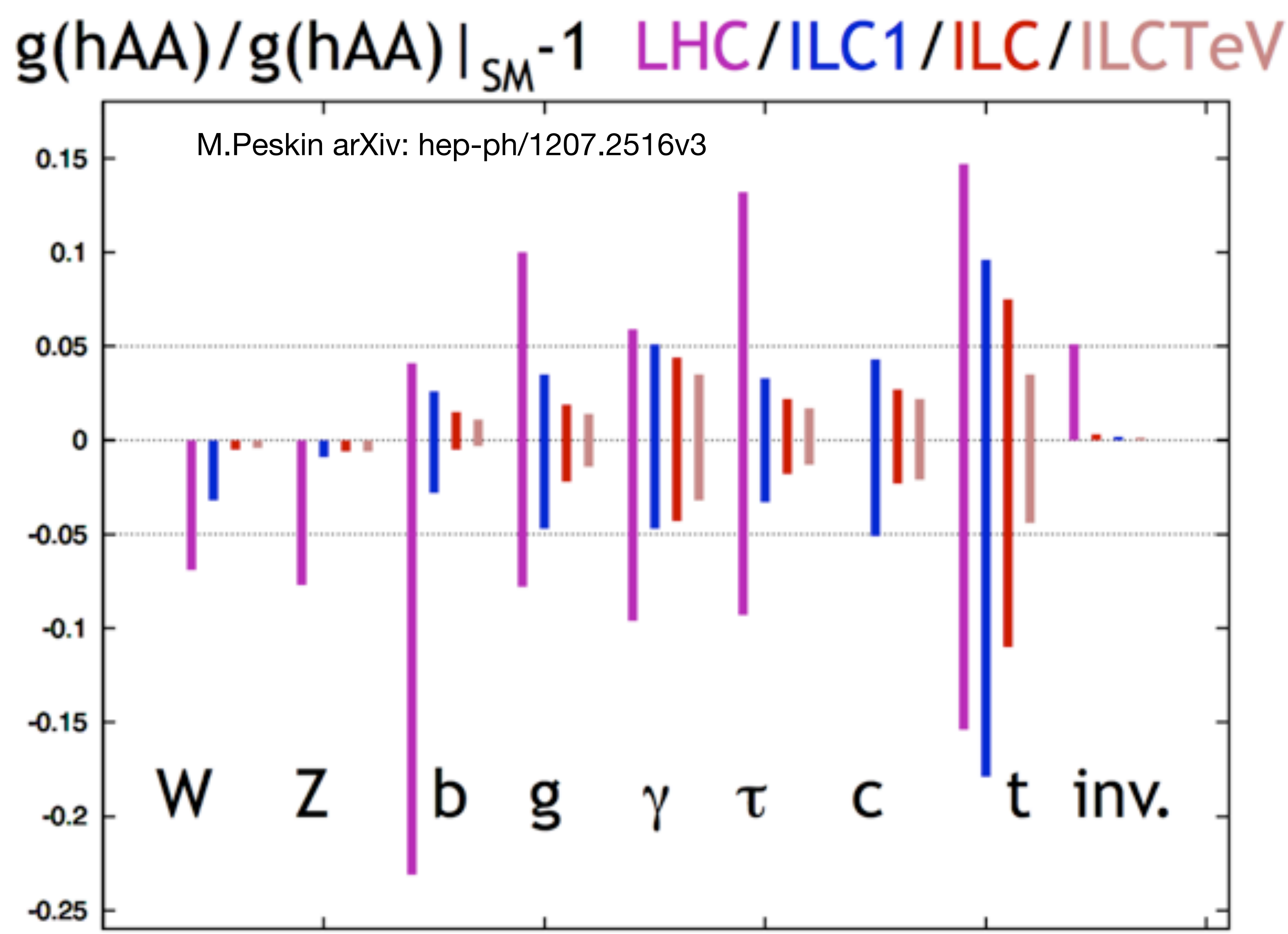


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC 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'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

Assumed Luminosities

LHC = LHC14TeV: $300 fb^{-1}$

HLC = ILC250: $250 fb^{-1}$

ILC = ILC500: $500 fb^{-1}$

ILCTeV = ILC1000: $1000 fb^{-1}$

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

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
xed-in Singlet	6%	6%	6%
mposite Higgs	8%	tens of %	tens of %
nimal Supersymmetry	< 1%	3%	$10\%^a$, $100\%^b$
IC 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

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

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

SUSY

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

Fingerprinting is possible or we will get lower bounds on the BSM scale!

Conclusions

- 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 ILC 500.
- Probably LHC will hit systematic limits at O(5-10%) for most of σ×Br measurements, being not enough to see the BSM effects if we are in the decoupling regime.
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 $e^+e^- \rightarrow ZH$ at Ecm = 250GeV,
    - then ttbar at around 350GeV,
    - and then ZHH and ttbarH at 500GeV.
- The ILC to cover up to 500 GeV is an ideal machine to carry out this mission (regardless of BSM scenarios) and we can do this with staging starting from 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 boson or some other new particle might be within reach already at ILC 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

HL-ILC ?

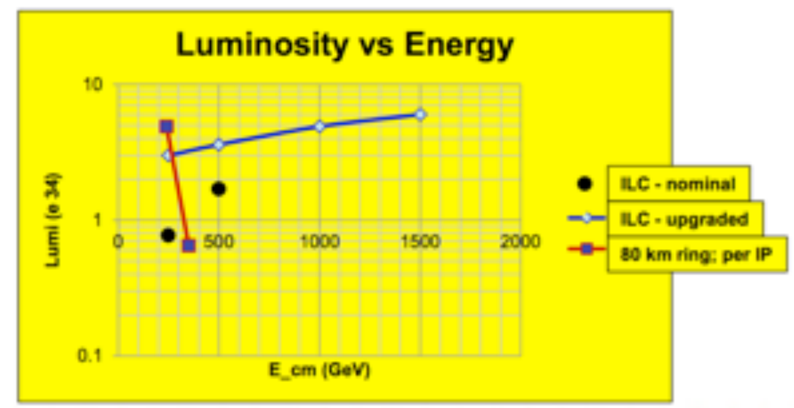
High Luminosity ILC

- TLEP can host 4 detectors → but extra 2 detectors cost ~ \$1G ⇔ x2 Luminosity upgrade of ILC
- Polarizations at LC ⇔ effective luminosity doubler
- Wall plug power: ILC < TLEP
- E_{cm} can be further optimized: e.g. tth

ILC at low/high Ecm

- **Low E_{cm} operation of upgraded ILC:**
  - L_{250} ~ 3e34; Wall plug 200 MW
  - Higgs Factory Option
- **High E_{cm} ~ 1.5 TeV**
  - L_{1500} ~ 6e34; Wall plug 340 MW

Assumes 2x improved efficiency; 2450 bunches



14 March, 2013 Marc Ross, SLAC 13

ILC Luminosity Upgrade

- Concept: increase n_b from 1312 → 2625
  - Reduce linac bunch spacing 554 ns → 336 ns
  - Increase pulse current 5.8 → 8.8 mA
  - Increase number of klystrons by ~50%
- Doubles beam power → ×2 L ($3.6\times10^{34}cm^{-2}s^{-1}$)
- Damping ring:
  - Electron ring doubles current (389mA → 778mA)
  - Positron ring: possible 2nd (stacked) ring (e-cloud limit)
- AC power: 161 MW → 204 MW (est.)
  - AC power increased by ×1.5
  - shorter fill time and longer beam pulse results in higher RF-beam efficiency (44% → 61%)

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Snowmass e^+e^- Collider Luminosity (fb^{-1})
based on 3×10^7 s running time for ILC & LEP3/TLEP

Ecm(GeV)	ILC	ILC Lum Upgrade	LEP3	TLEP
250	250	900	300	1500
350	300	950		200
500	500	1100		
1000	1500	1500		

Independent Higgs Measurements

Hypothetical HL-ILC

250 GeV: 900 fb^{-1}
500 GeV: 2200 fb^{-1}
1 TeV: 3000 fb^{-1}

($M_H = 125$ GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity · fb	250		500		1000
polarization (e-,e+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	vvH(fusion)	ZH	vvH(fusion)	vvH(fusion)
cross section	1.4%	-	-		
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H-->bb	0.58%	5.5%	0.87%	0.32%	0.19%
H-->cc	3.9%		5.8%	3.0%	1.8%
H-->gg	4.8%		6.7%	2.0%	1.3%
H-->WW*	3.4%		4.4%	1.2%	0.93%
H-->ττ	2.2%		2.6%	6.7%	2.0%
H-->ZZ*	10%		12%	3.9%	2.4%
H-->γγ	25%		23%	16%	6.4%

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

→

250 GeV: 900 fb^{-1}
500 GeV: 2200 fb^{-1}
1 TeV: 3000 fb^{-1}

Coupling Measurements

Hypothetical HL-ILC

250 GeV: 900 fb^{-1}
500 GeV: 2200 fb^{-1}
1 TeV: 3000 fb^{-1}

(M_H = 125 GeV)

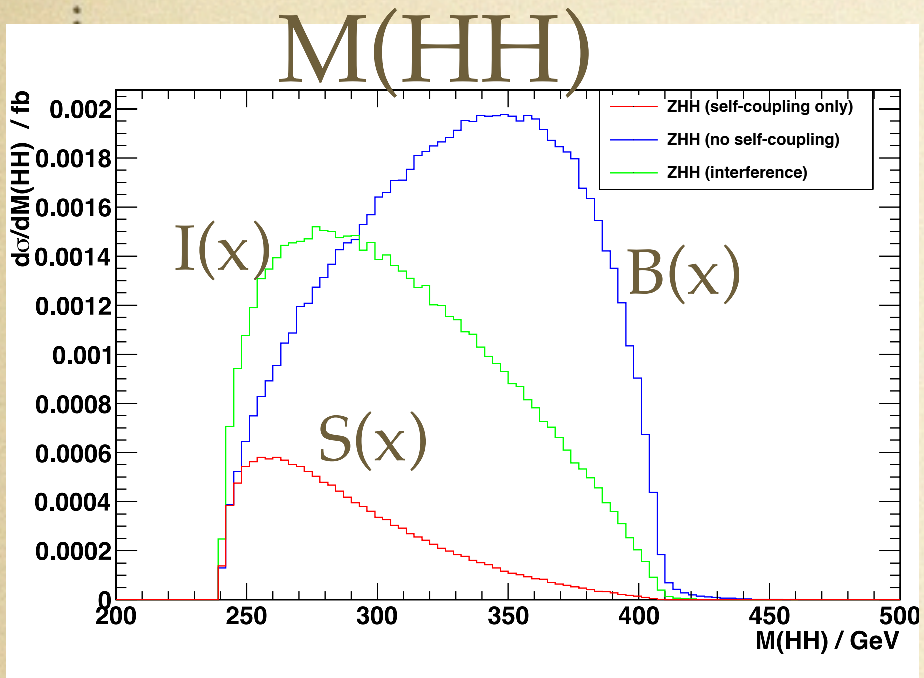
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV   P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.70%	0.70%	0.70%
HWW	2.5%	0.75%	0.74%
Hbb	2.8%	0.93%	0.81%
Hcc	3.4%	1.4%	1.1%
Hgg	3.7%	1.3%	0.96%
$H\tau\tau$	3.0%	1.3%	1.0%
$H\gamma\gamma$	13%	5.9%	2.9%
$H\mu\mu$	-	-	9.3%
Γ_0	6.1%	3.1%	3.0%
Htt	-	8.5%	2.6%

HHH	-	50%	15%

Self-coupling

weighting method to enhance the coupling sensitivity

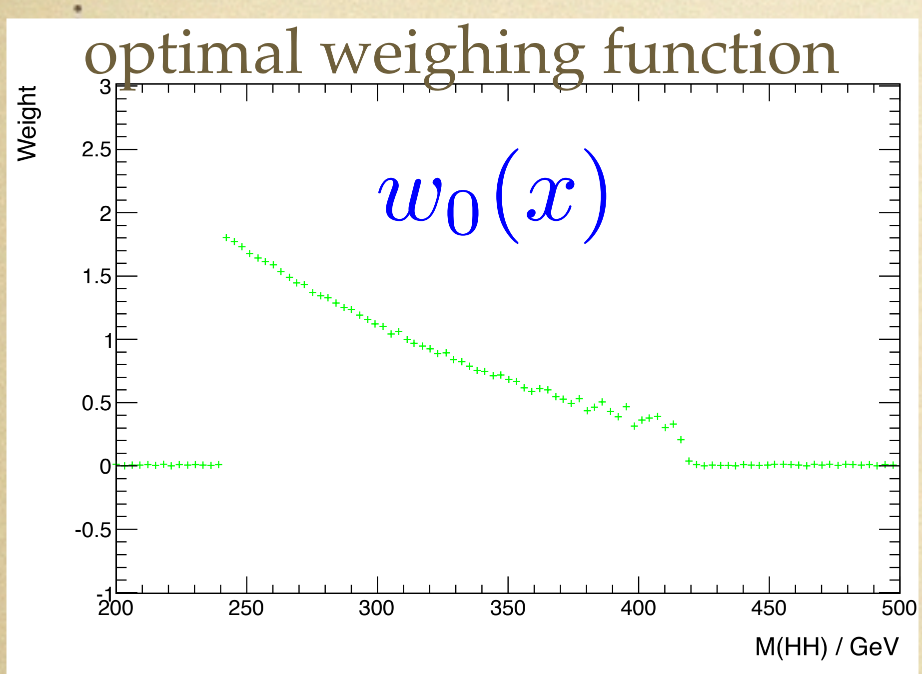


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible　interference　self-coupling

observable: weighted cross-section

$$\sigma_w = \int \frac{\mathrm{d}\sigma}{\mathrm{d}x} w(x) \mathrm{d}x$$



equation of the optimal w(x) (variational principle):

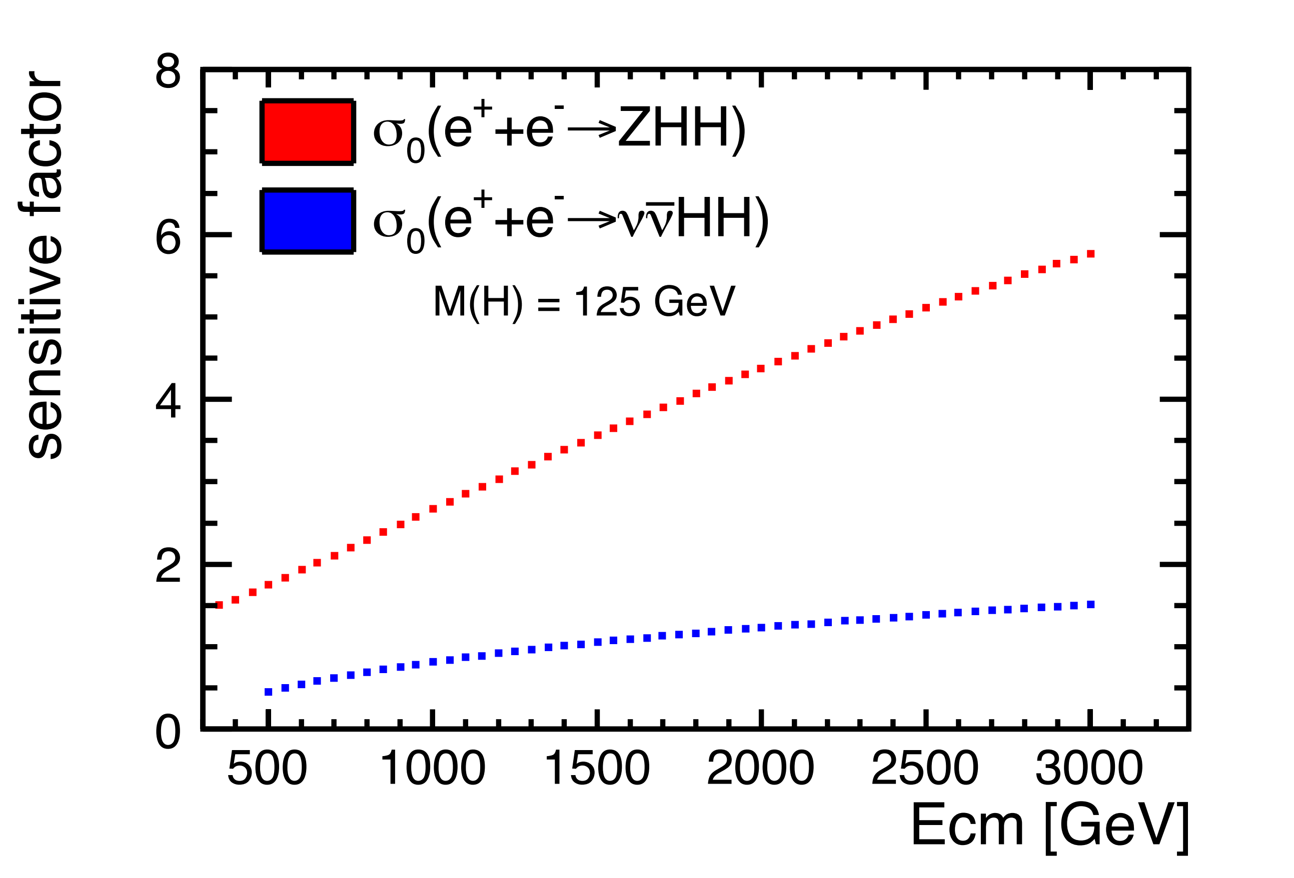
$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

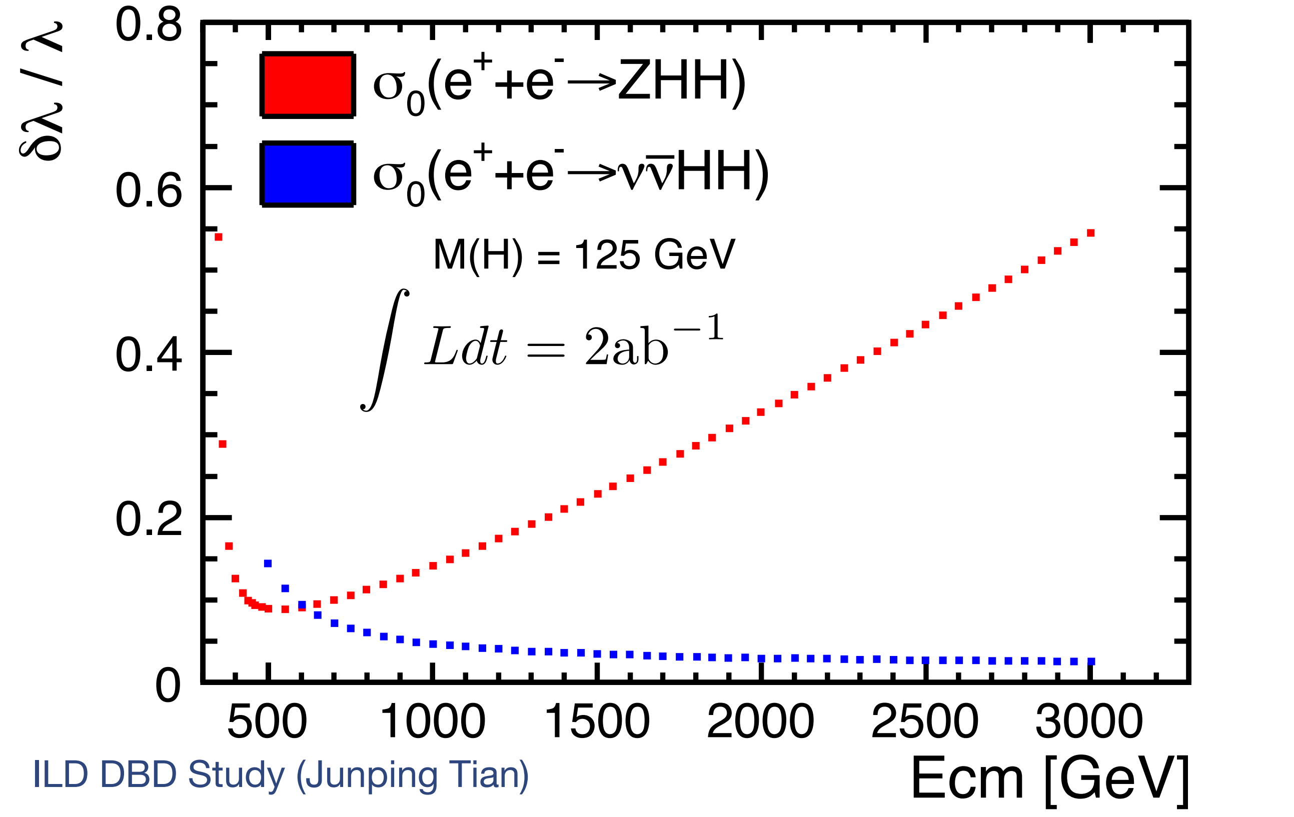
general solution:

$$w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)}$$

c: arbitrary normalization factor

Expected Coupling Precision as a Function of Ecm





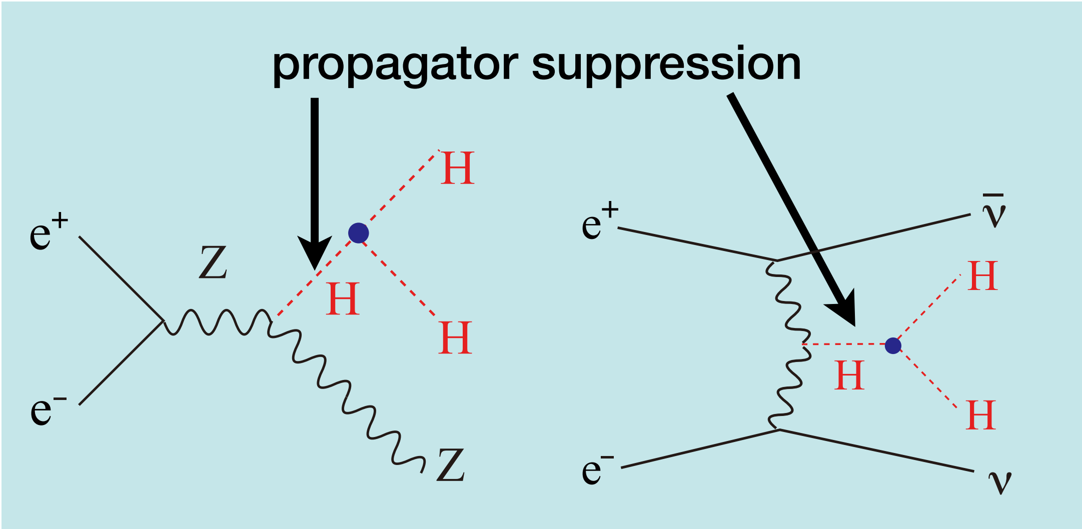
ILD DBD Study (Junping Tian)

Sensitivity Factor

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

F=0.5 if no BG diagrams there

BG diagrams dominate at high E_{cm}



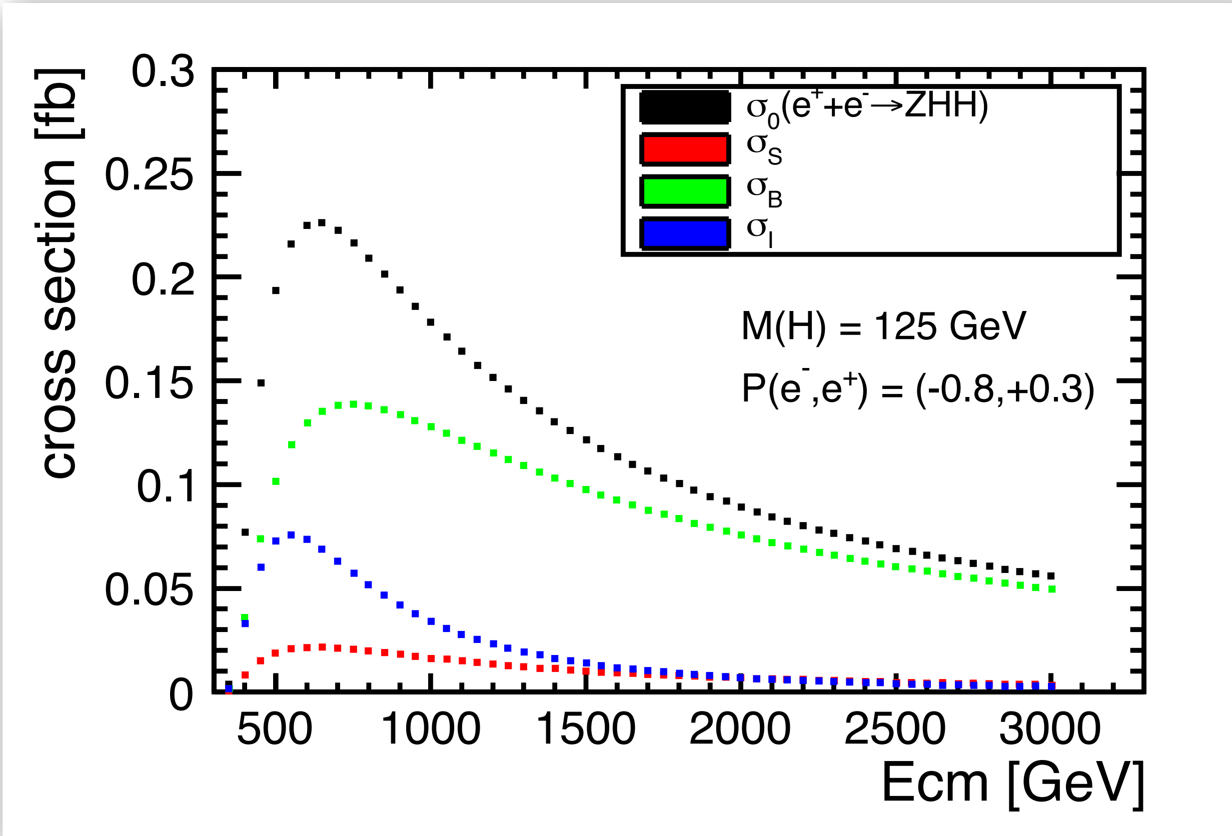
⇒ F grows quickly with Ecm !

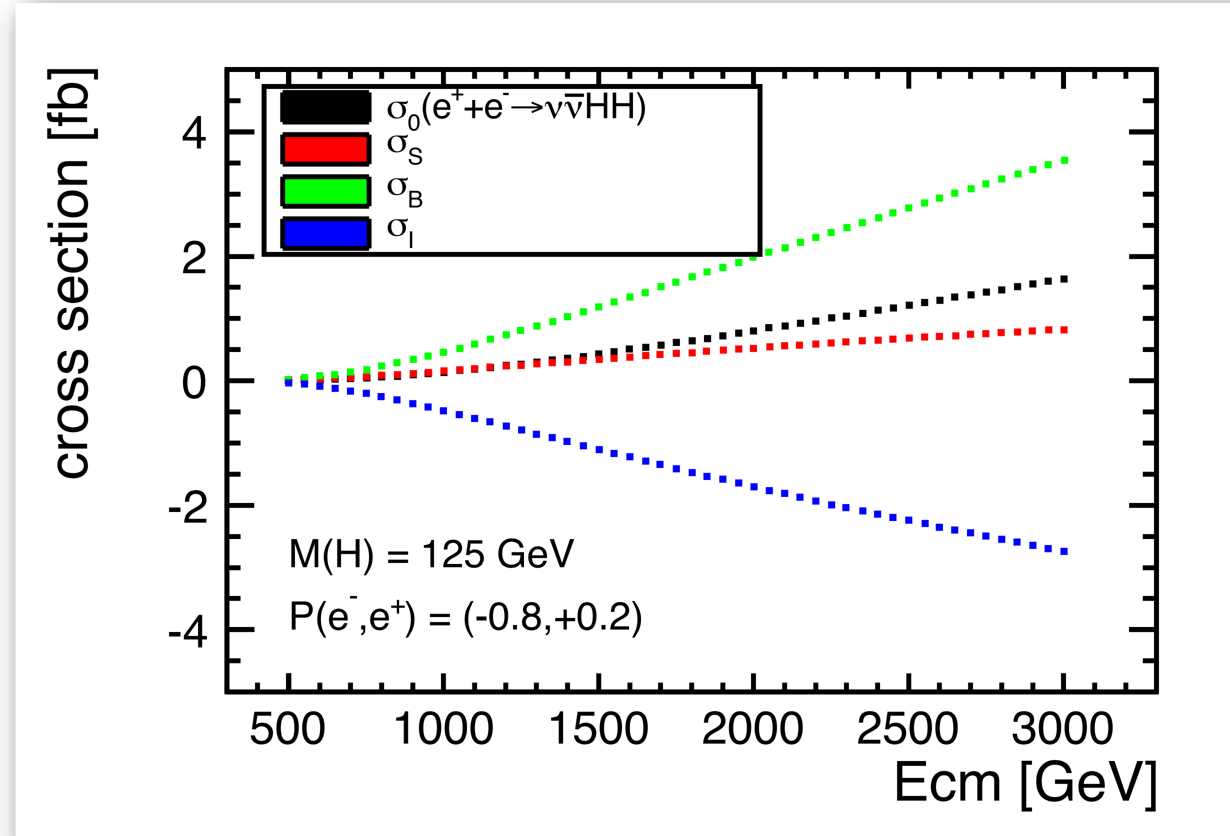
Coupling Precision

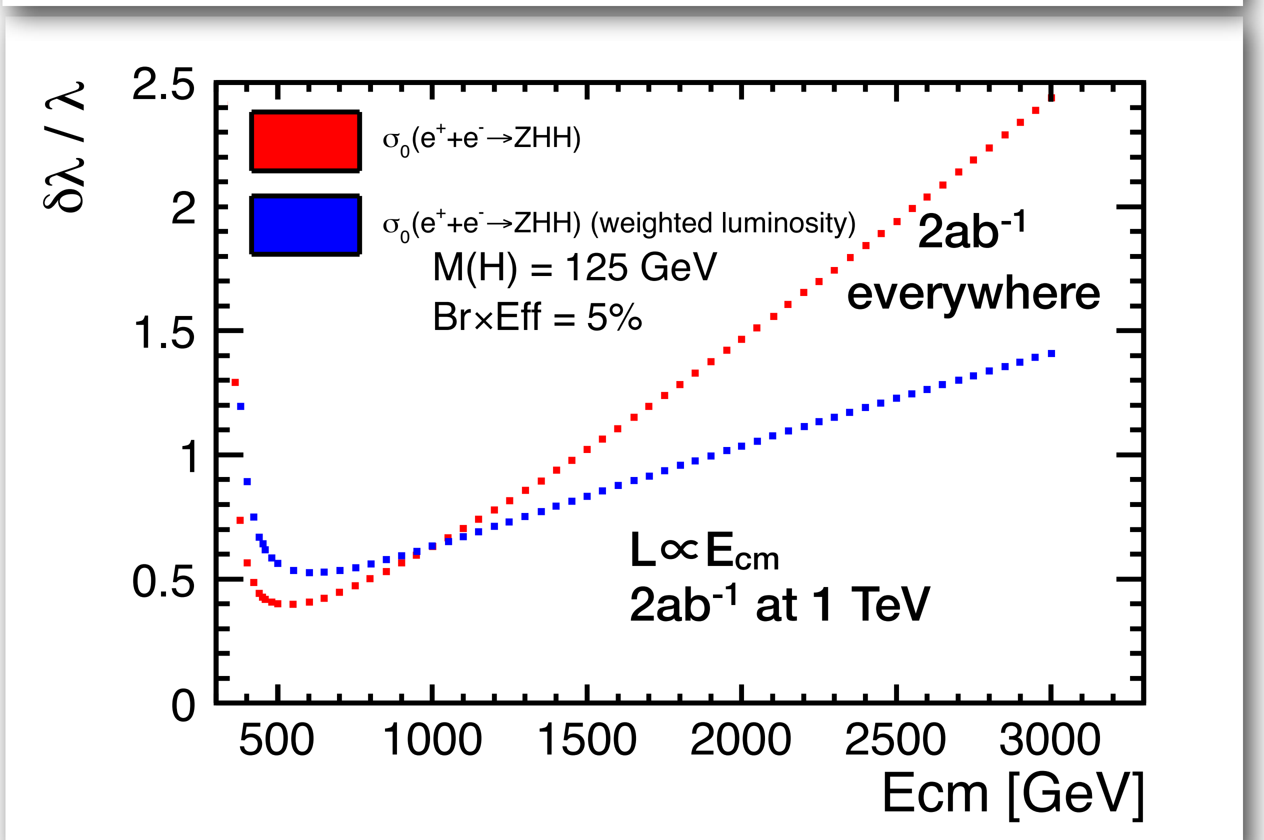
ZHH : **optimal Ecm ~ 500 GeV though the cross section maximum is at around Ecm = 600 GeV**

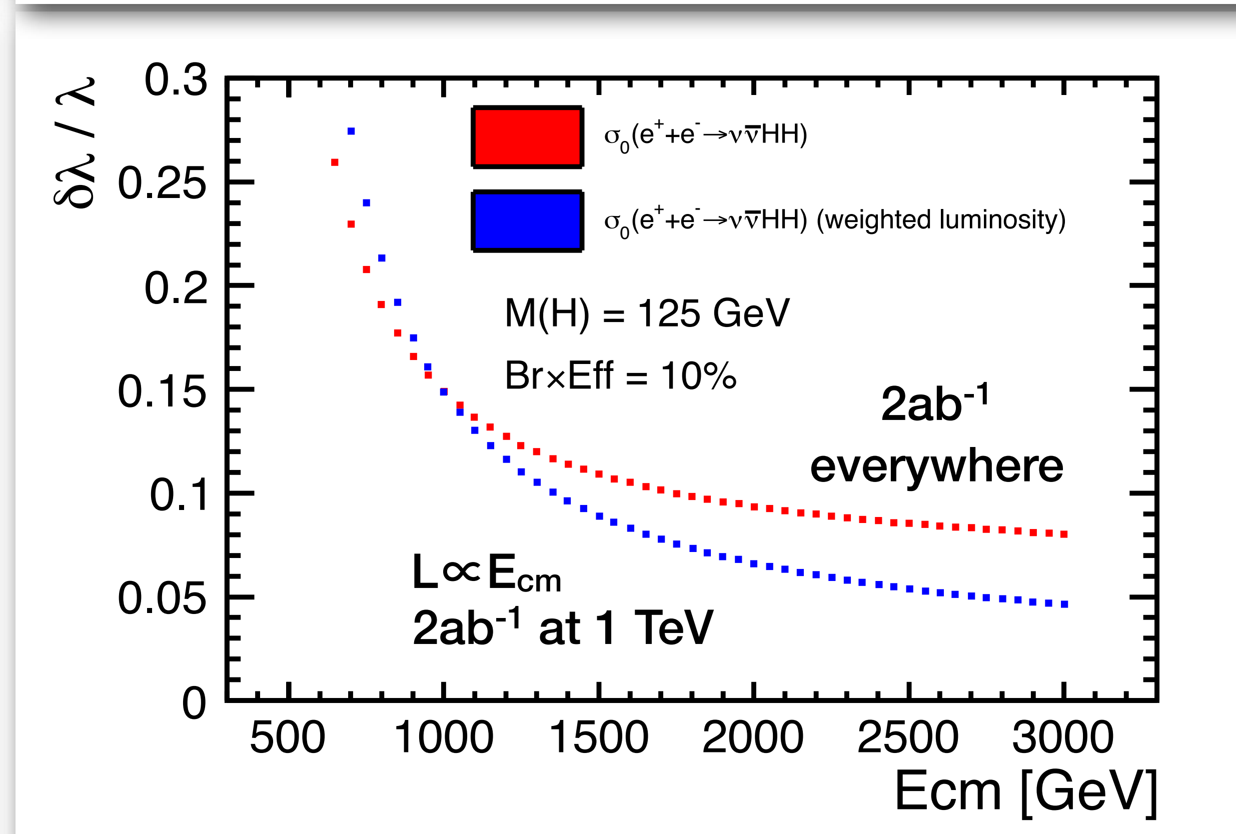
ννHH : **Precision slowly improves with Ecm**

Expected Coupling Precision as a Function of Ecm









ILD DBD Study (Junping Tian)

Higgs Self-coupling
CLIC Summary (120 GeV Higgs, unpolarised beams)

1.4 TeV	1.5 ab^{-1}	$\sigma_{HH\nu\nu}$ uncertainty	λ_{HHH} uncertainty
	Cut-and-count	30.2%	(x1.20 = 36%)
	Template CS fit	24 - 26%	(x1.20 = 29 - 31%)
	Template λ_{HHH} fit		$\Delta\lambda/\lambda \approx 31\%$
	from RMS	-	30 - 31 %
	per experiment	-	31.5 - 33 %
3.0 TeV	2.0 ab^{-1}		
	Cut-and-count	13.8%	(x1.54 = 21.2%)
	Template CS fit	9.7 - 10.8%	(x1.54 = 15 - 16.6%)
	Template λ_{HHH} fit		$\Delta\lambda/\lambda \approx 16\%$
	from RMS	-	16.2 - 18.5%
	per experiment	-	15.4 - 17.2%

preliminary

further approx. 20% (30%) improvement expected for 80-0 (80-30) polarisation

CLIC Higgs self-coupling studies: Tomas Lastovicka & Jan Strube

$\Delta\lambda/\lambda \approx 16\% \rightarrow 13\,(11)\%$ at 3TeV