Higgs at ILC

Experiments

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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.

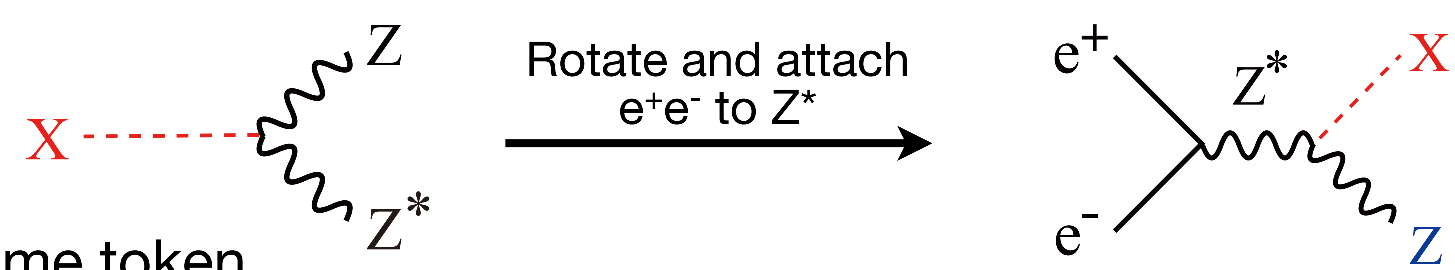
- We don't know whether the "something" is elementary or composite.

- 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.

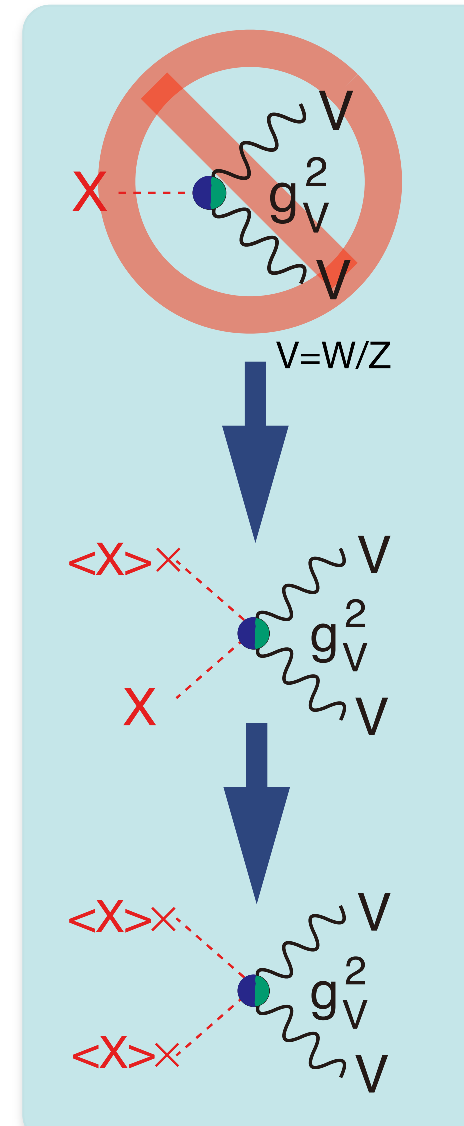
Since the July 4th, the world has changed!

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

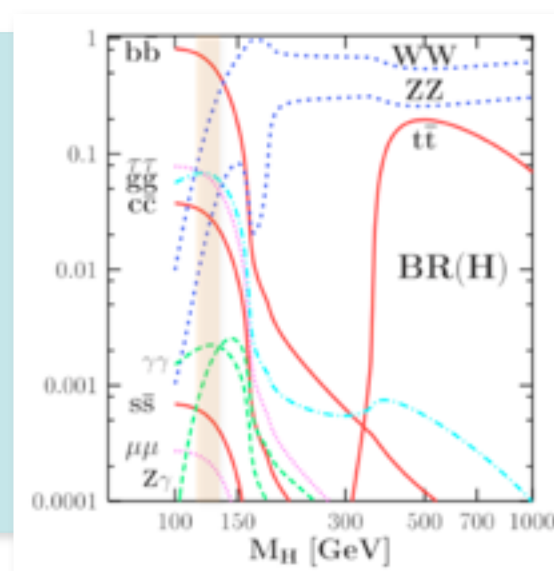
- X(125) → γγ means X is a neutral boson and J ≠ 1 (Landau-Yang theorem). Recent LHC results prefer $J^P=0^+$.
- X(125) → ZZ*, WW* ⇒ ∃ XVV couplings: (V=W/Z: gauge bosons)
- There is no gauge coupling like XVV, only XXVV or XXV
  ⇒ XVV probably from XXVV with one X replaced by <X> ≠ 0, namely <X>XVV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

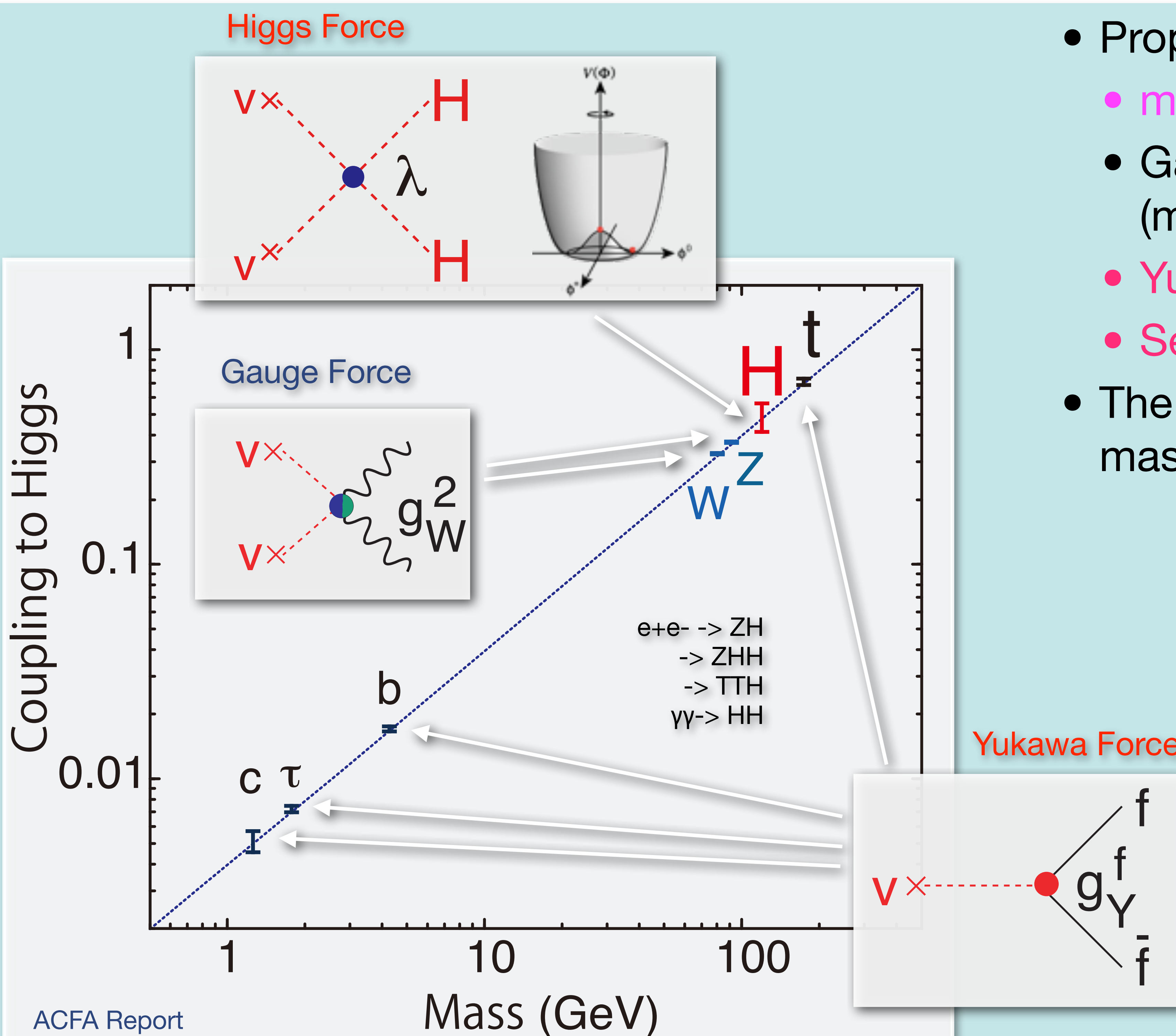


- So we now know that the major Higgs production mechanisms in e^+e^- collisions are indeed available at the ILC ⇒ No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, where variety of decay modes are accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed 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 questions of HEP :
  - 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

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

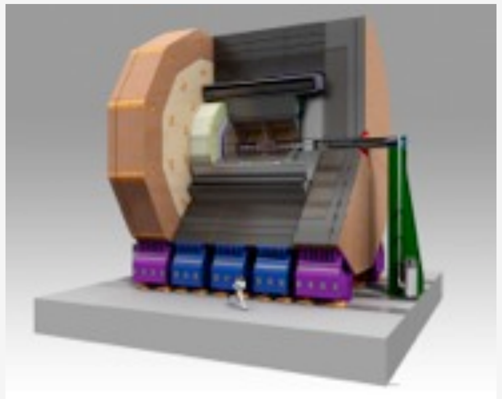
$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}) \end{cases}$$

SUSY

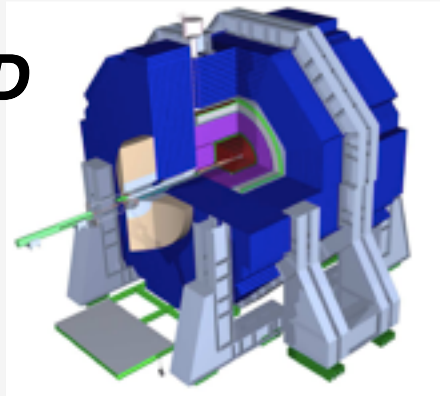
$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Expected deviations are small --> Precision!

ILD



SiD

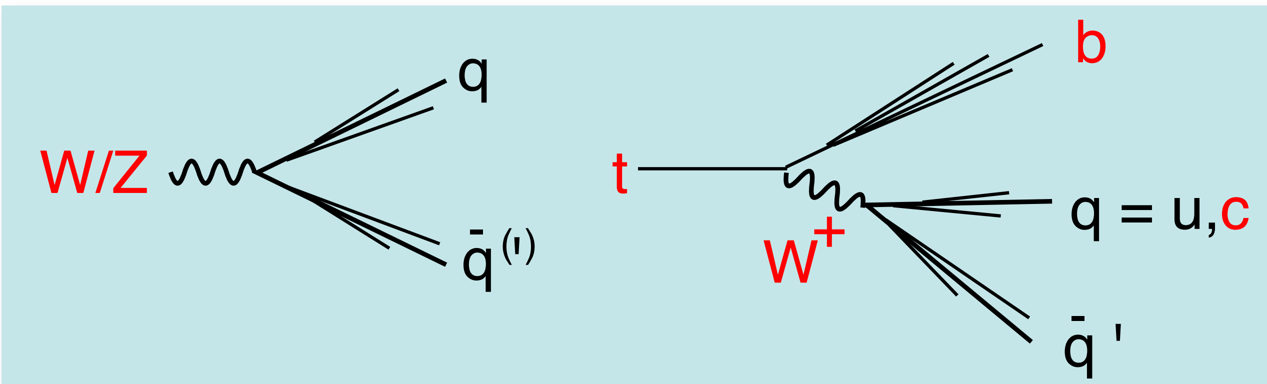


For the precision we need a 500GeV LC and high precision detectors

LC Experiments

View events as viewing Feynman diagrams

Reconstruct events in terms of (q, l, gb, hb)



Jet invariant mass → W/Z/t/h ID → p^μ

→ angular analysis → s^μ

Missing momentum → neutrinos

b/c ID with 2ndary/3tiary vertices

Thin and high resolution vertexing

Particle Flow Analysis

High resolution tracking

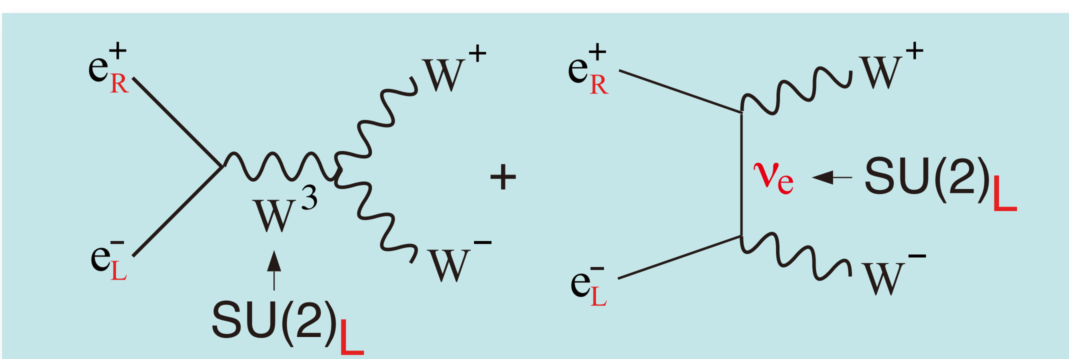
high granularity calorimetry

Hermeticity

down to O(10mrad) or better

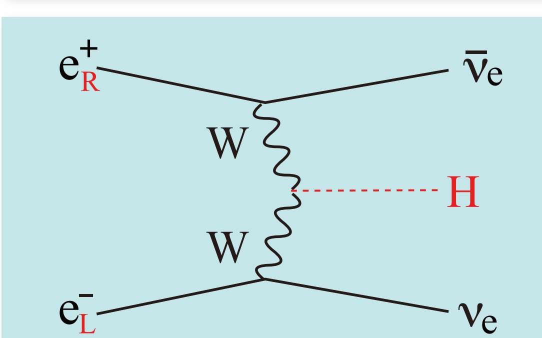
both ECAL and HCAL inside the solenoid

Select Feynman diagrams with polarized beams



To these processes, 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

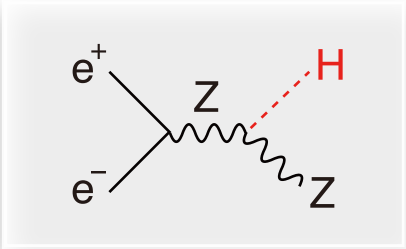
Beam polarization acts as luminosity doubler !

Why 250-500 GeV?

Three well known thresholds

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

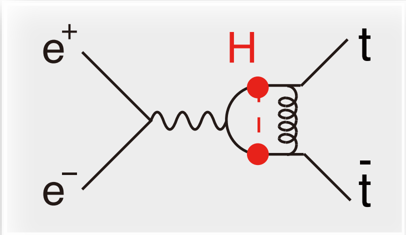
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass)   -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)



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

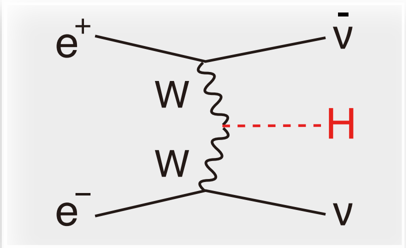
- Threshold scan --> theoretically clean mt measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



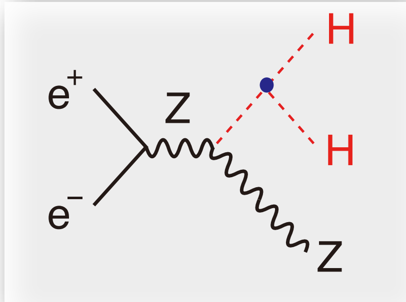
vvH @ 350 - 500GeV :

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



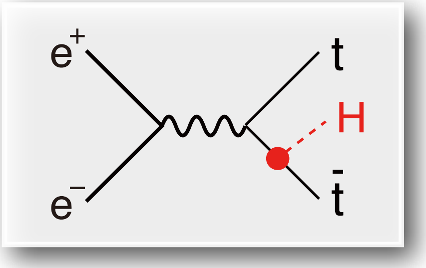
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- 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

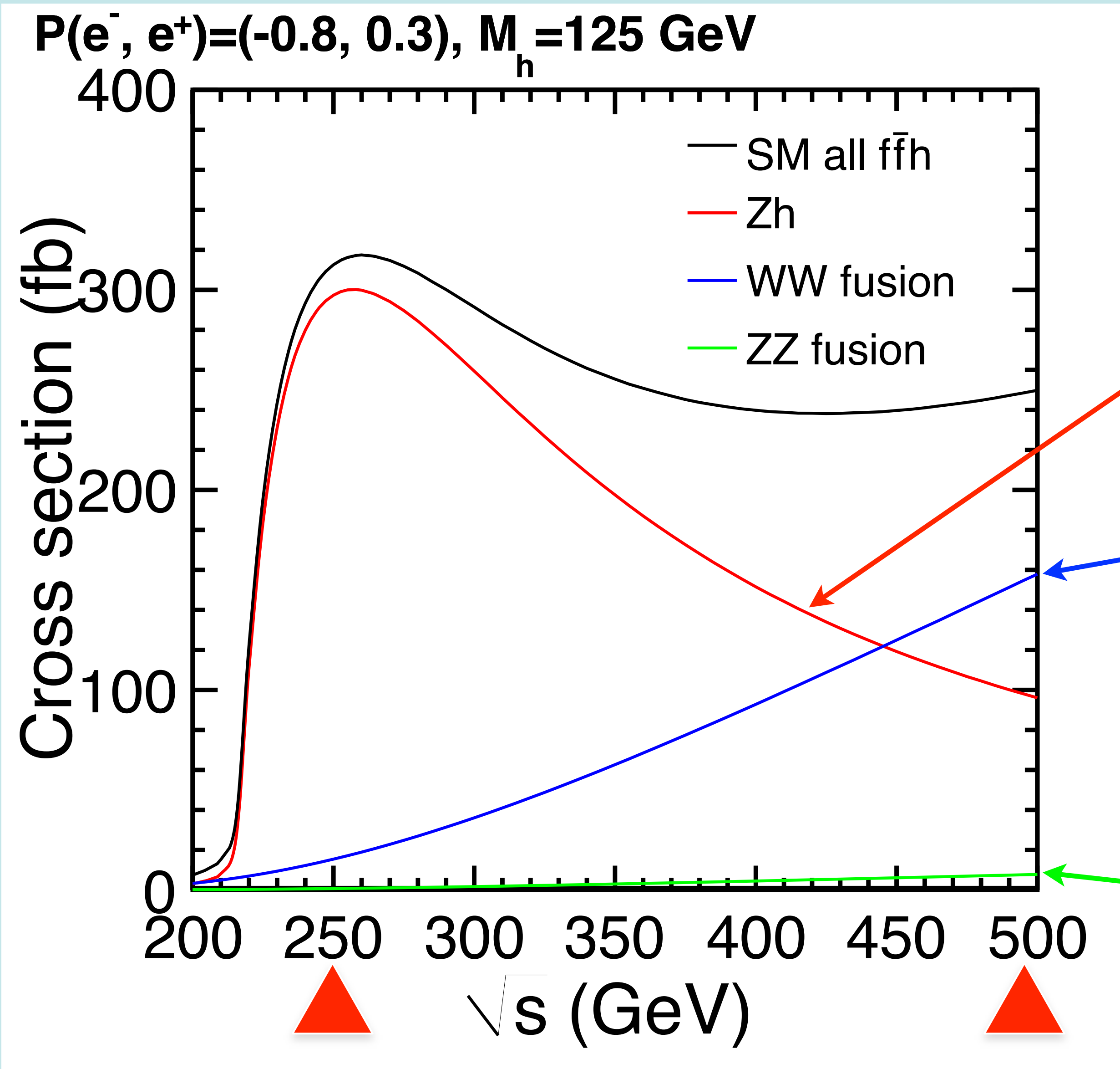


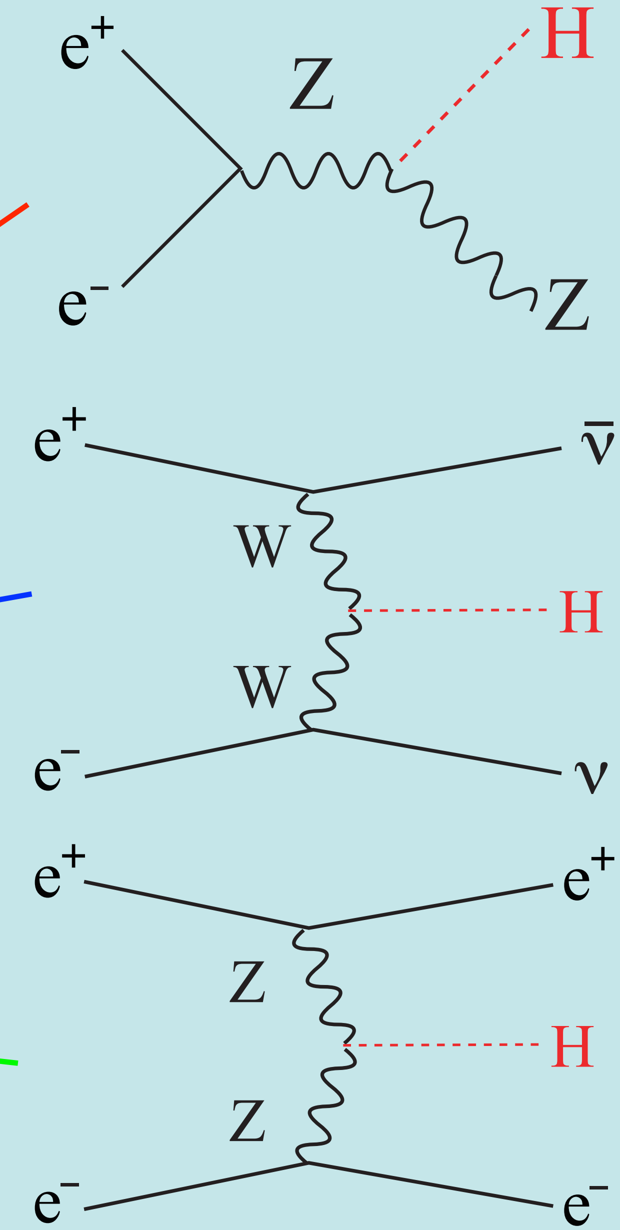
We can complete the mass-coupling plot at ~500GeV!

Main Production Processes

Single Higgs Production

Production cross section





ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

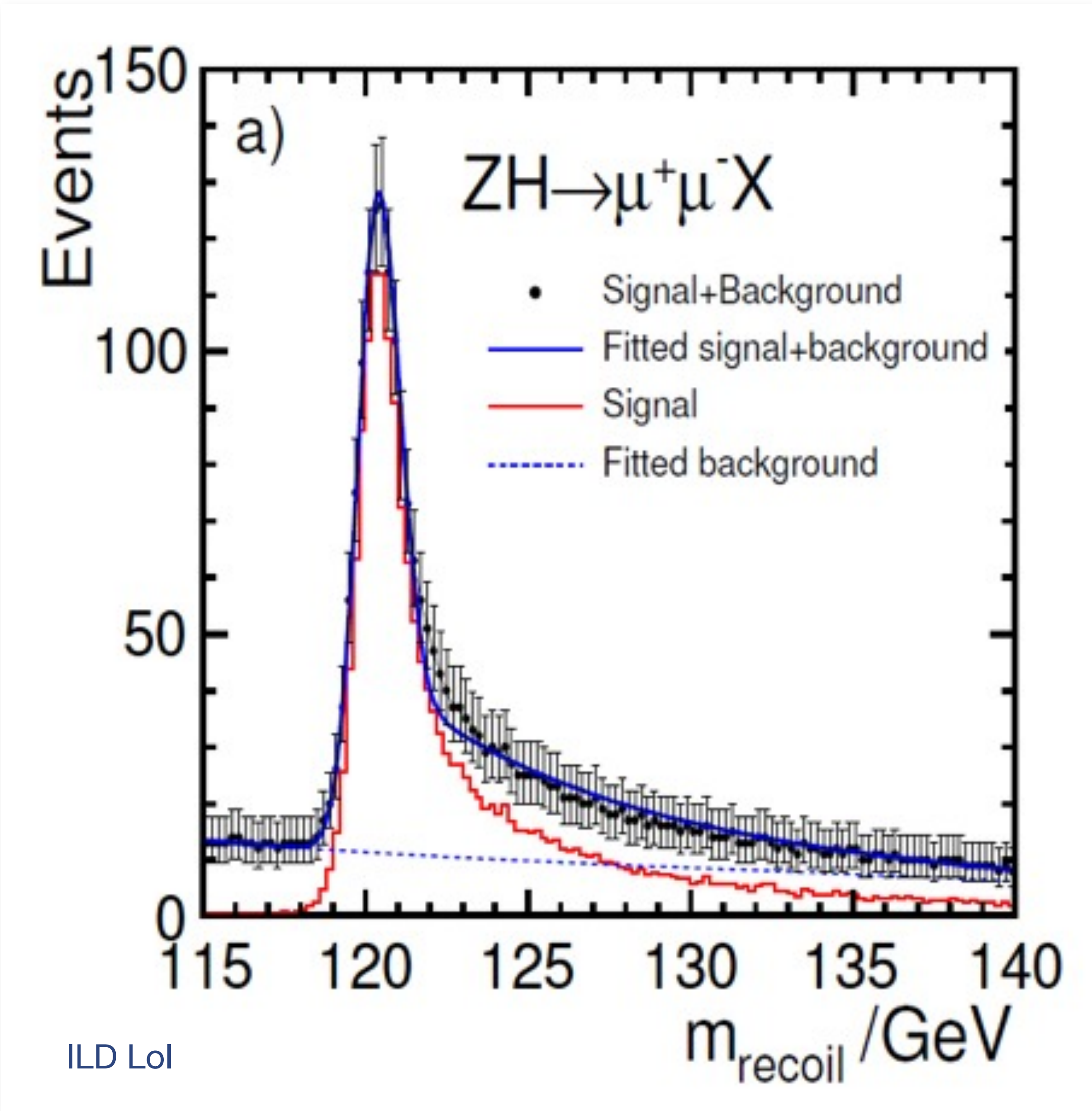
Possible to rediscover the Higgs in one day!

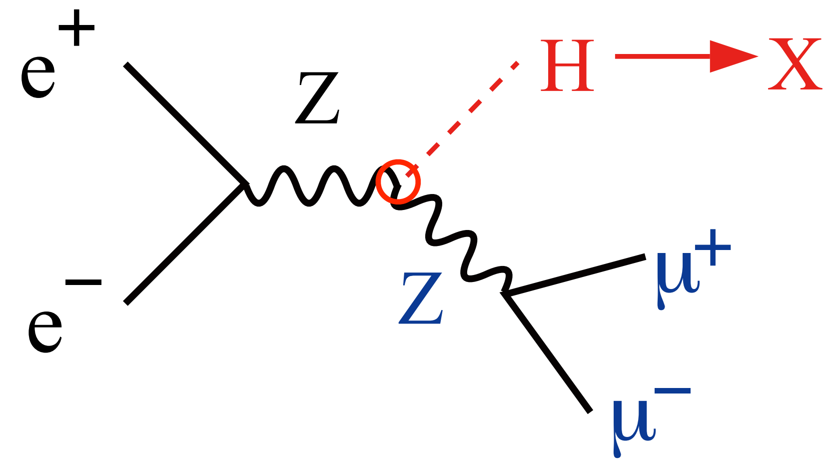
ILC 250

Recoil Mass Measurement

The flagship measurement of ILC 250

Recoil Mass





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

Invisible decay detectable!

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

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

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

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

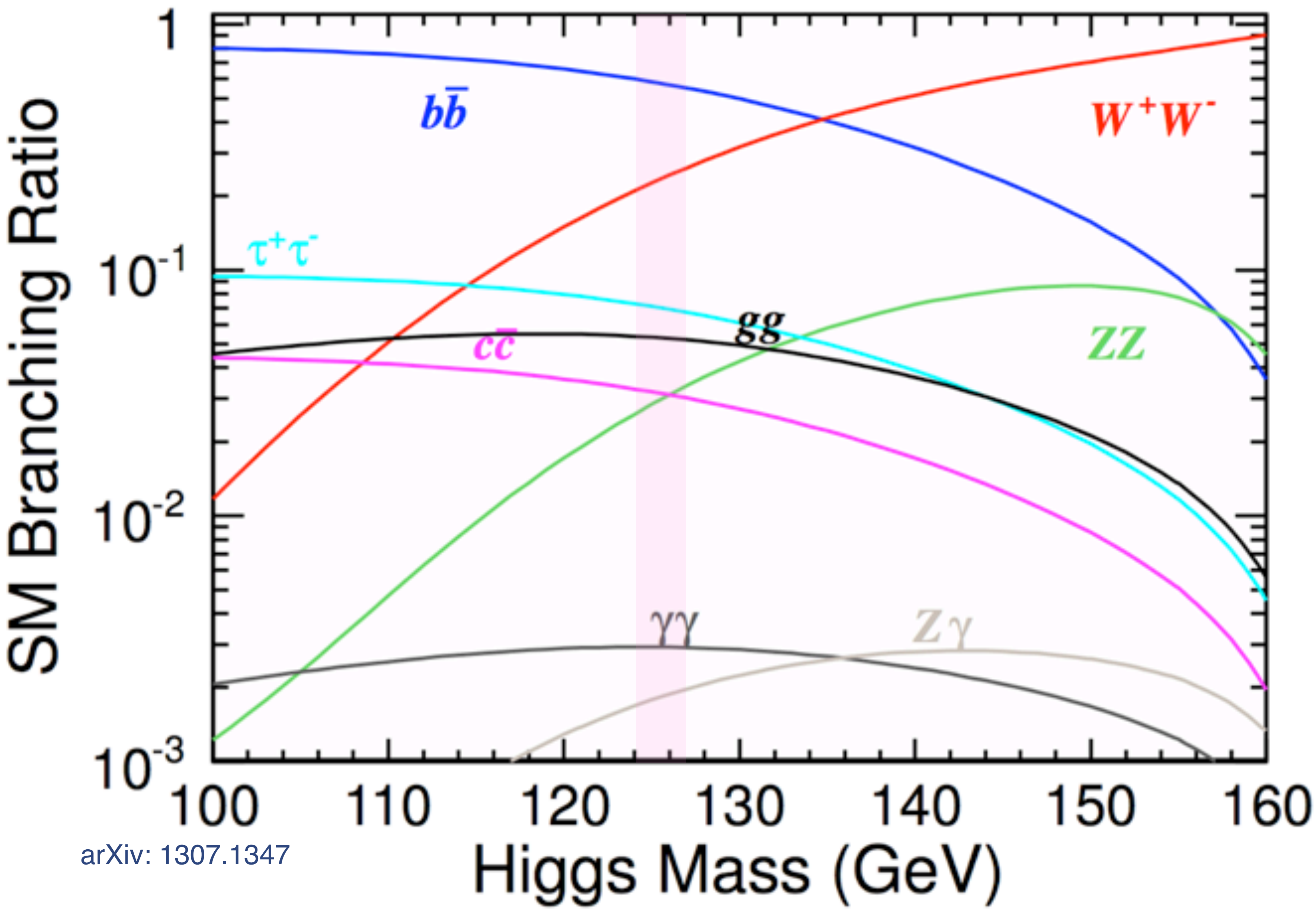
scaled from mH=120 GeV

Model-independent absolute measurement of σ_{ZH} (the HZZ coupling)

σ x BR Measurements

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

DBD Physics Chap.



arXiv: 1307.1347

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

scaled from mH=120 GeV

	@250GeV
process	ZH
Int. Lumi. [fb^{-1}]	250
Δσ/σ	2.6%
decay mode	ΔσBr/σBr
H → bb	1.2%
H → cc	8.3%
H → gg	7.0%
H → WW*	6.4%
H → ττ	4.2%
H → ZZ*	18%
H → γγ	34%

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 situation, we need more data at 250GeV.

We need to seriously think about luminosity upgrade scenario.

Total Width and Coupling Extraction

One of the major advantages of the LC

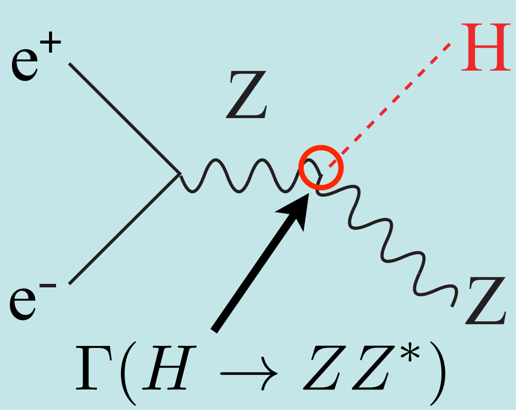
To extract couplings from BRs, we need the total width:

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

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

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

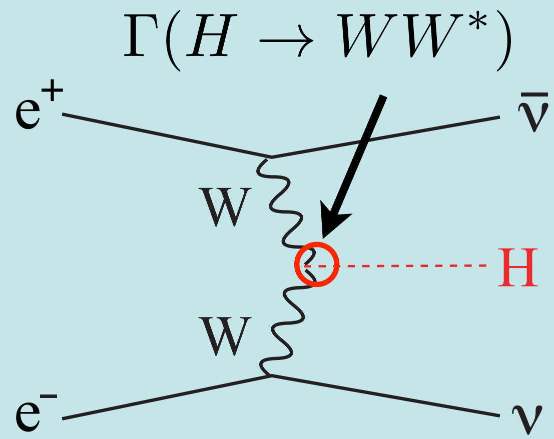
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

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

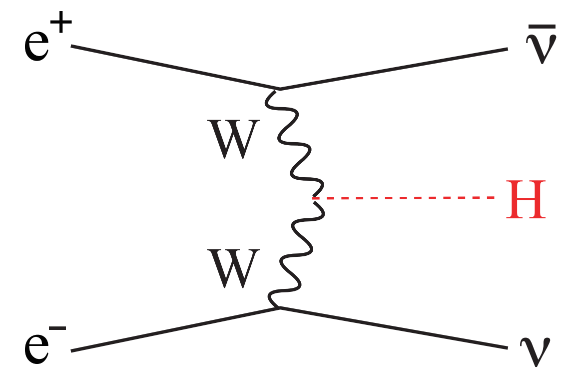
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

E_{cm} [GeV]	independent measurements	relative error
250	σ_{ZH}	2.6%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.2%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	8.3%
	$\sigma_{ZH} \cdot Br(H \to gg)$	7.0%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	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}	3.0%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	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



comes in as a powerful tool!

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

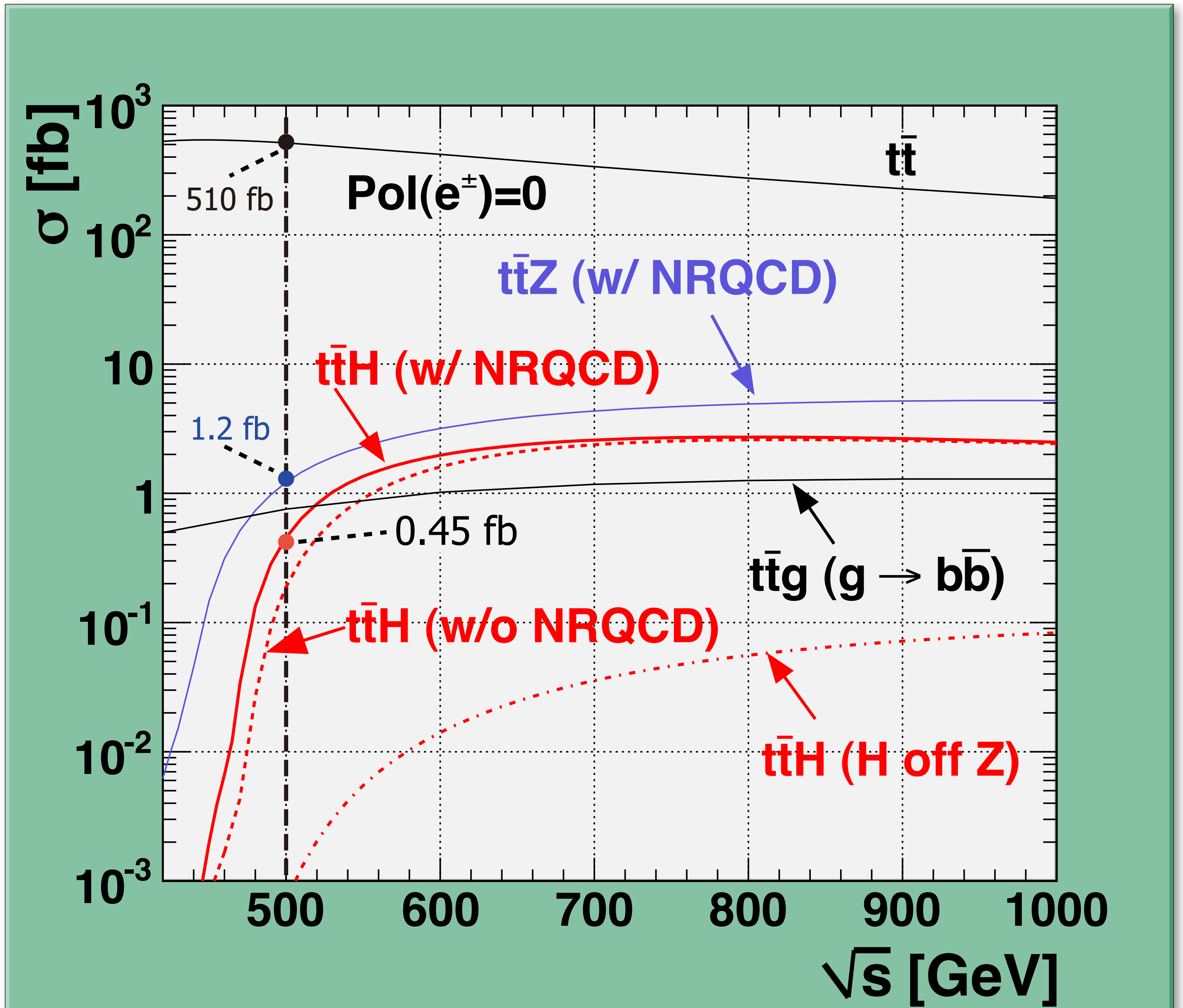
Mode	ΔBR/BR
bb	2.2 (2.9)%
cc	5.1 (8.7)%
gg	4.0 (7.5)%
WW*	3.1 (6.9)%
τ τ	3.7 (4.9)%

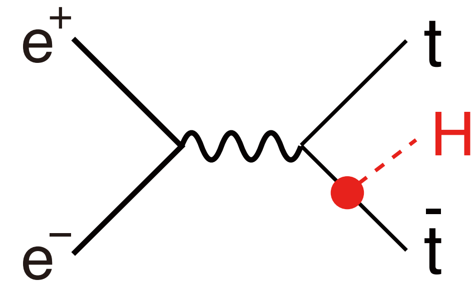
The numbers in the parentheses are as of $250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$

ILD DBD Study (Junping Tian)

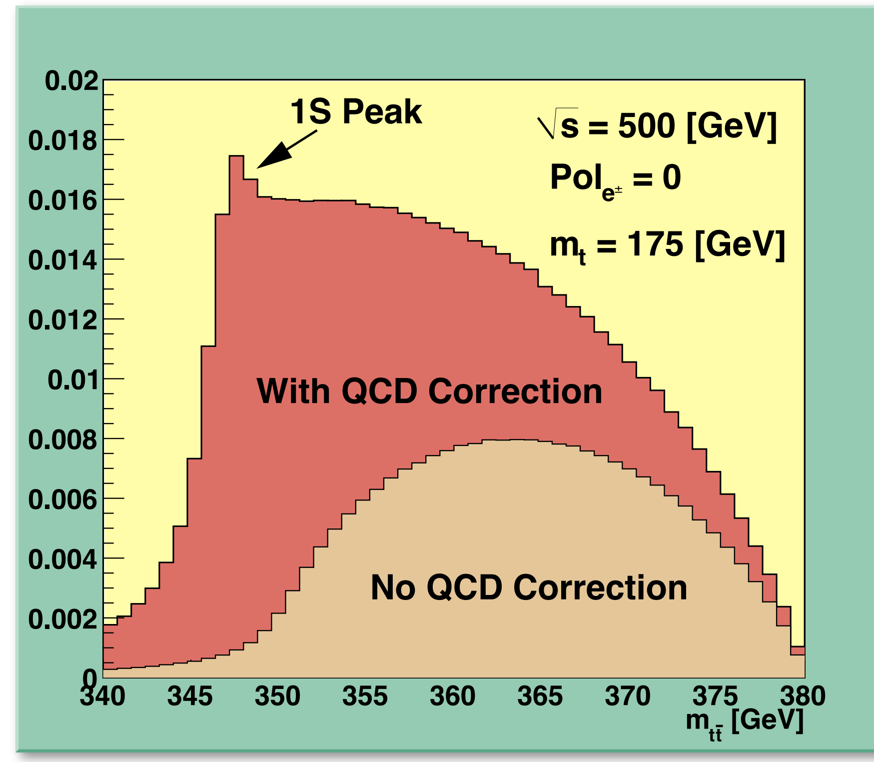
Top Yukawa Coupling

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

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

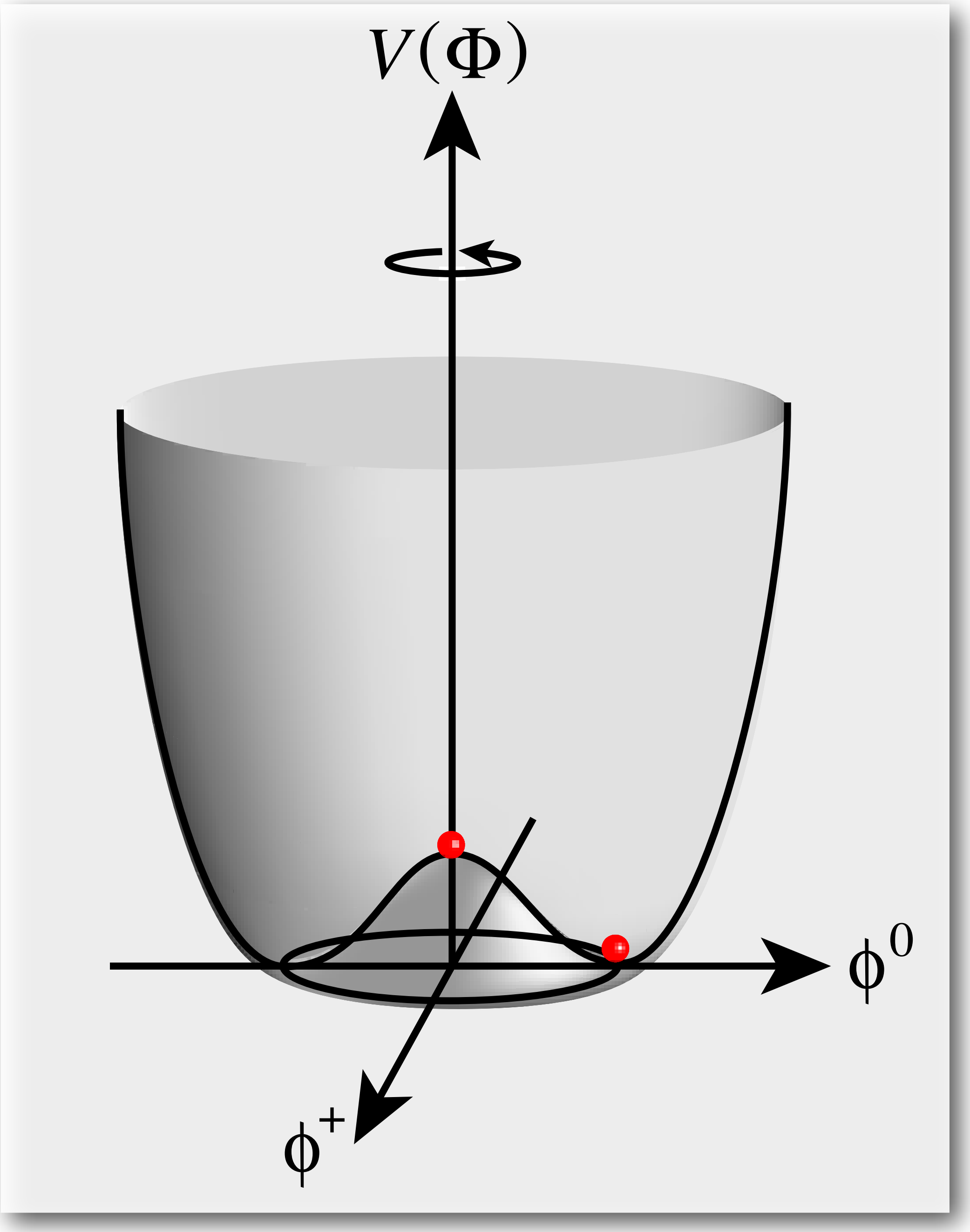
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 scaled from mH=120 GeV

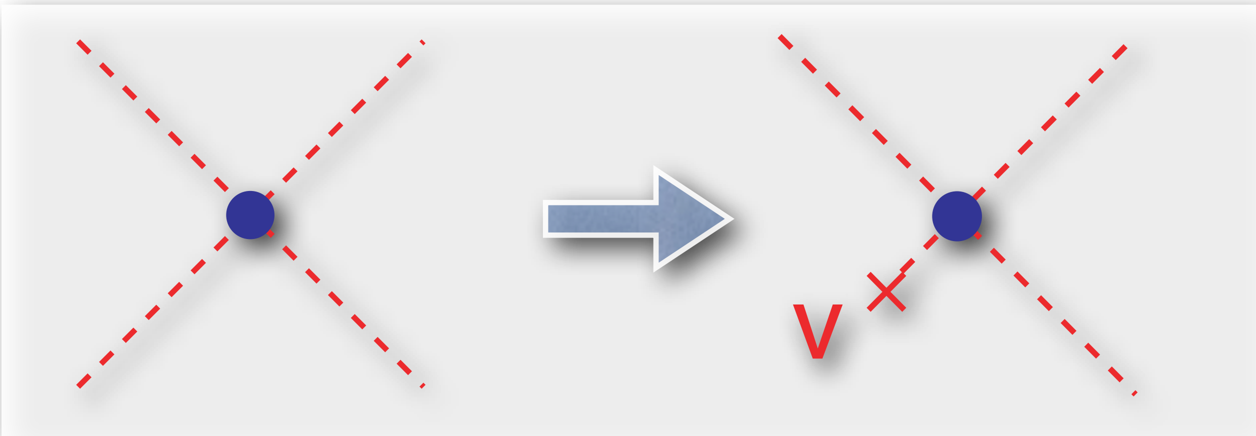
Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

Higgs Self-coupling

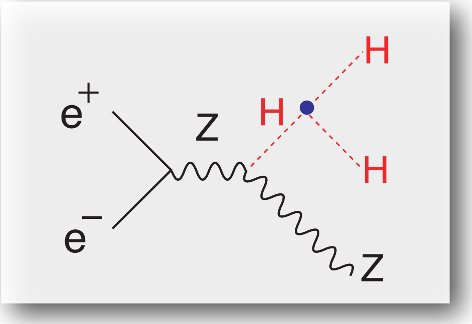
What force makes the Higgs condense in the vacuum?

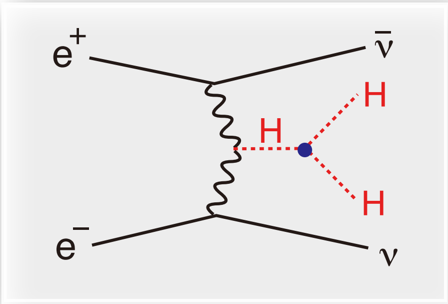


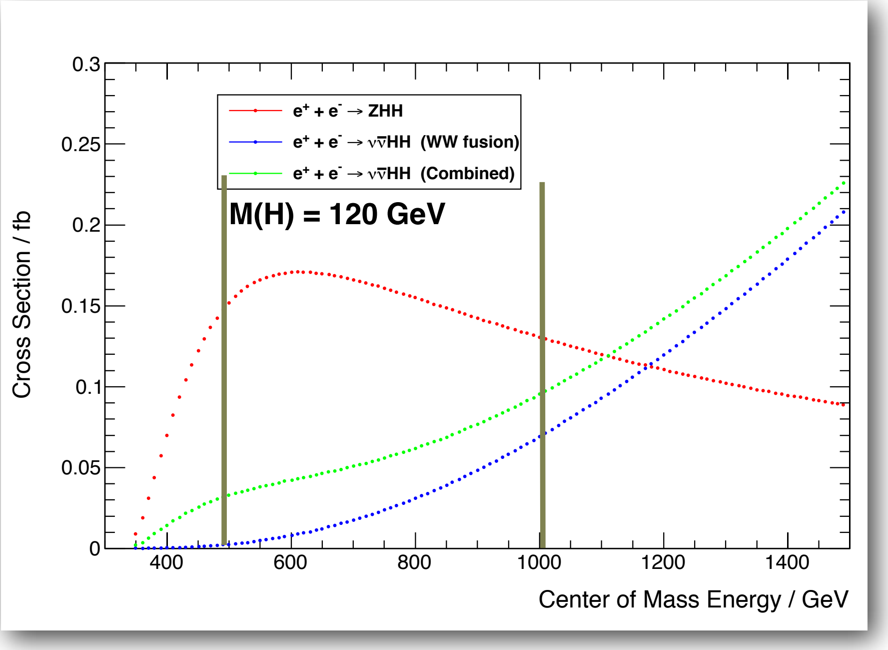
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential

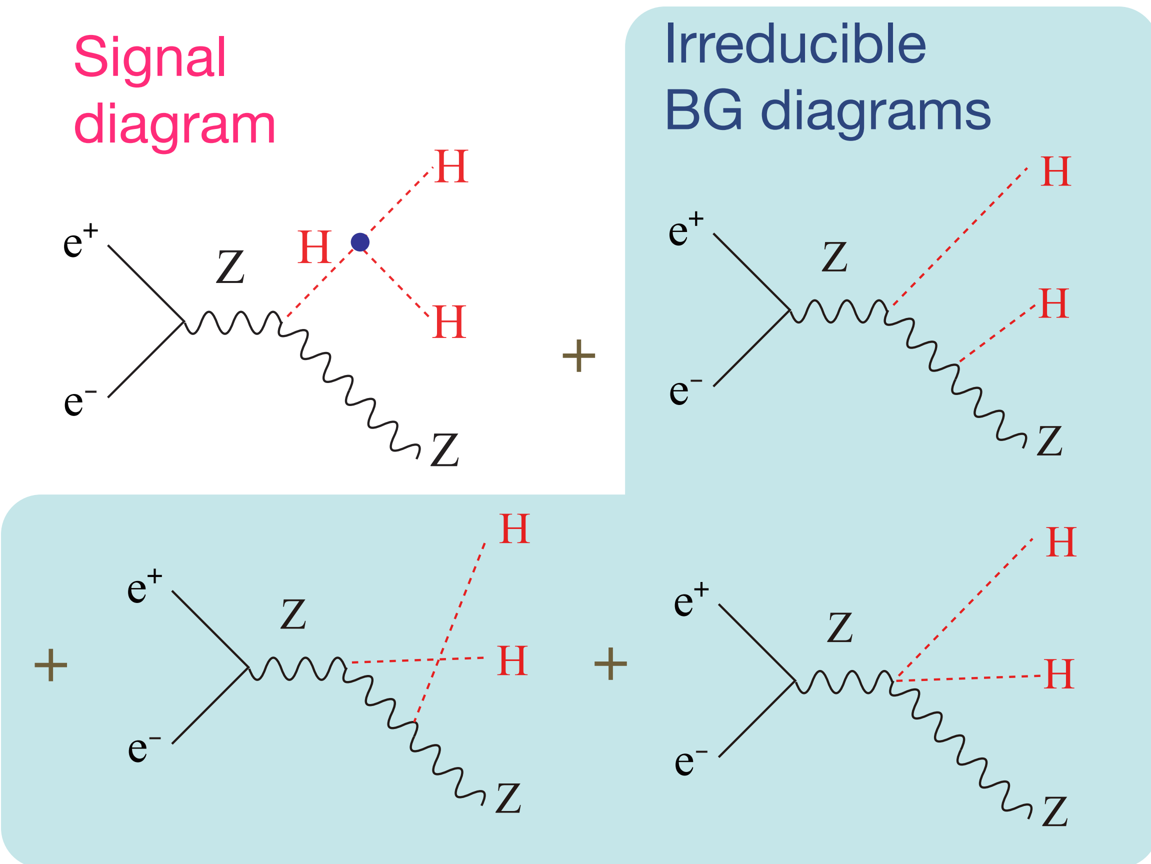






The measurement is very difficult even at ILC.

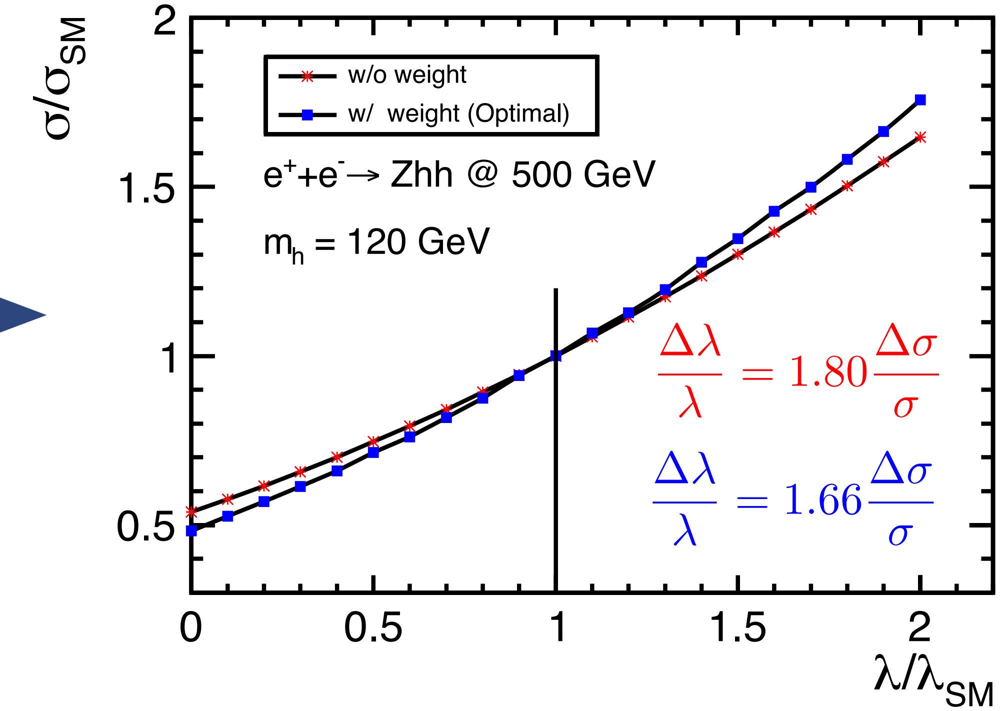
The Problem : BG diagrams dilute self-coupling contribution

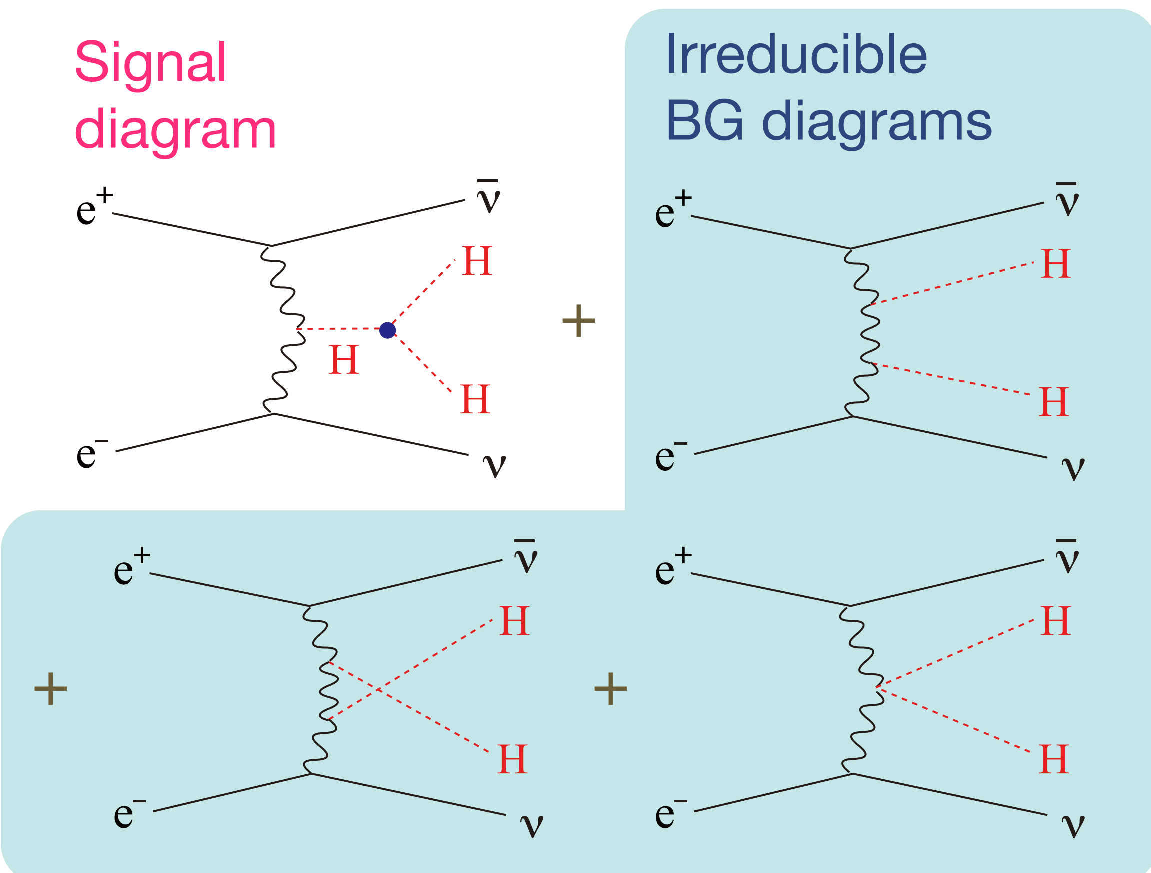


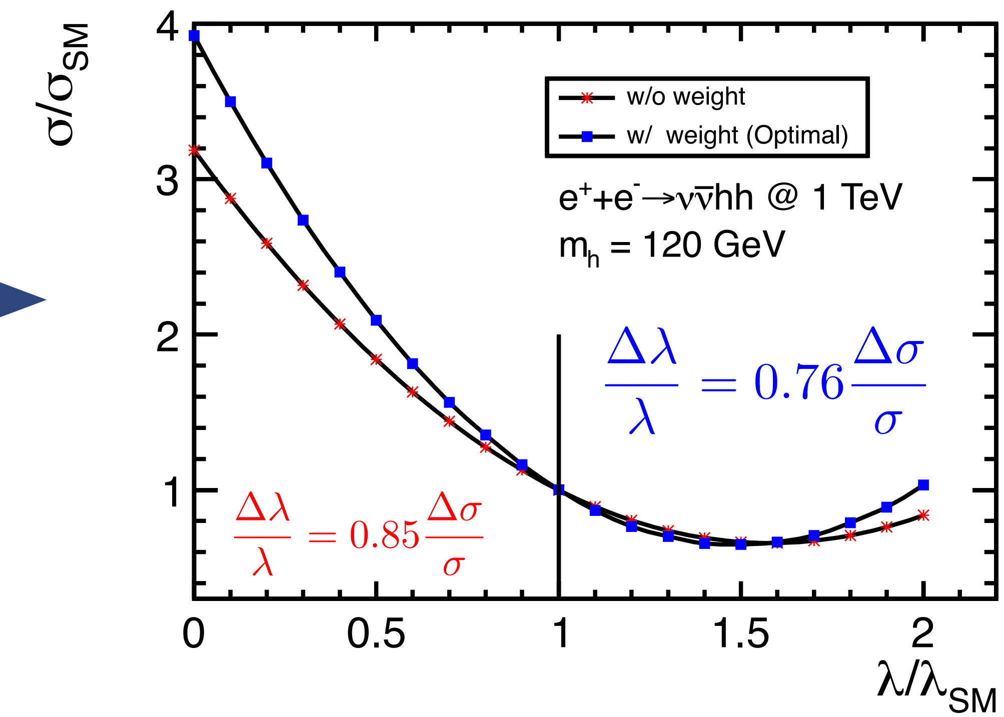
$$\sigma = \lambda^2 S + \lambda I + B$$

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

F=0.5 if no BG diagrams







Junping Tian LC-REP-2013-003

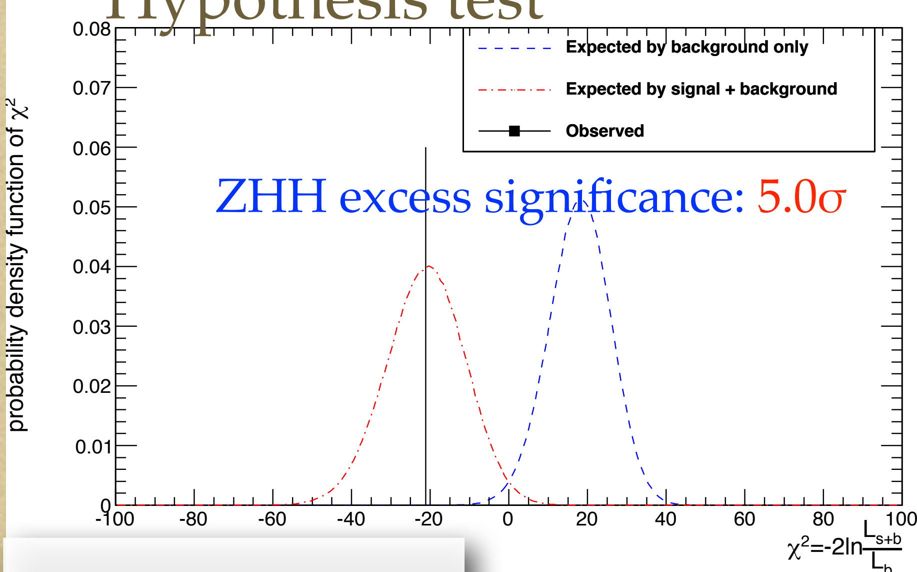
DBD full simulation

Higgs self-coupling @ 500 GeV (combined)

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

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6.0	1.5σ	1.2σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	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

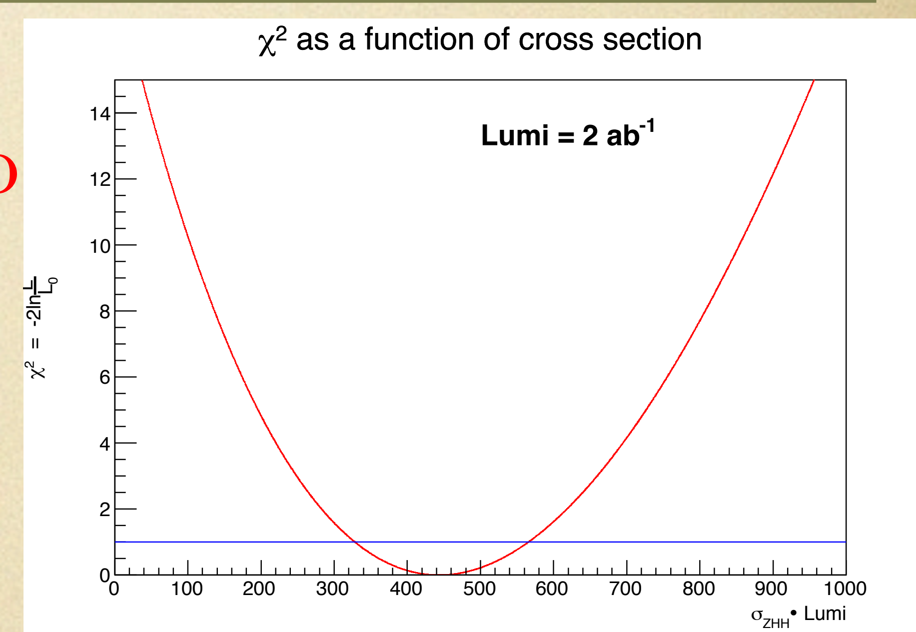
Hypothesis test

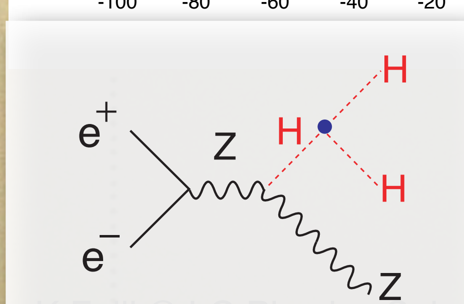


$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

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

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





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

ILC 1000

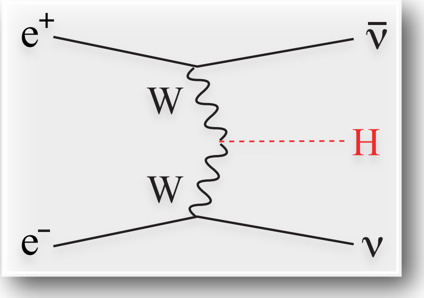
19

Higgs Physics at Higher Energy

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

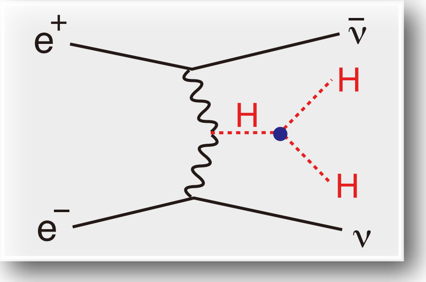
$\nu\nu H$ @ at >1TeV : > 1ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

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



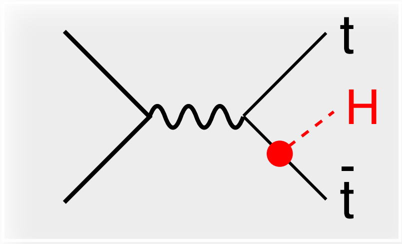
$\nu\nu HH$ @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

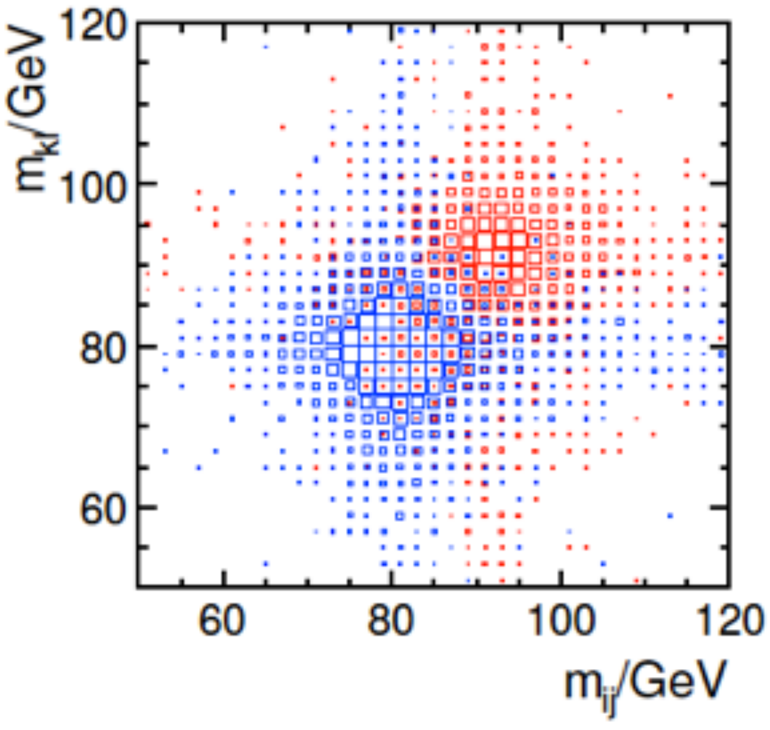
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).



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

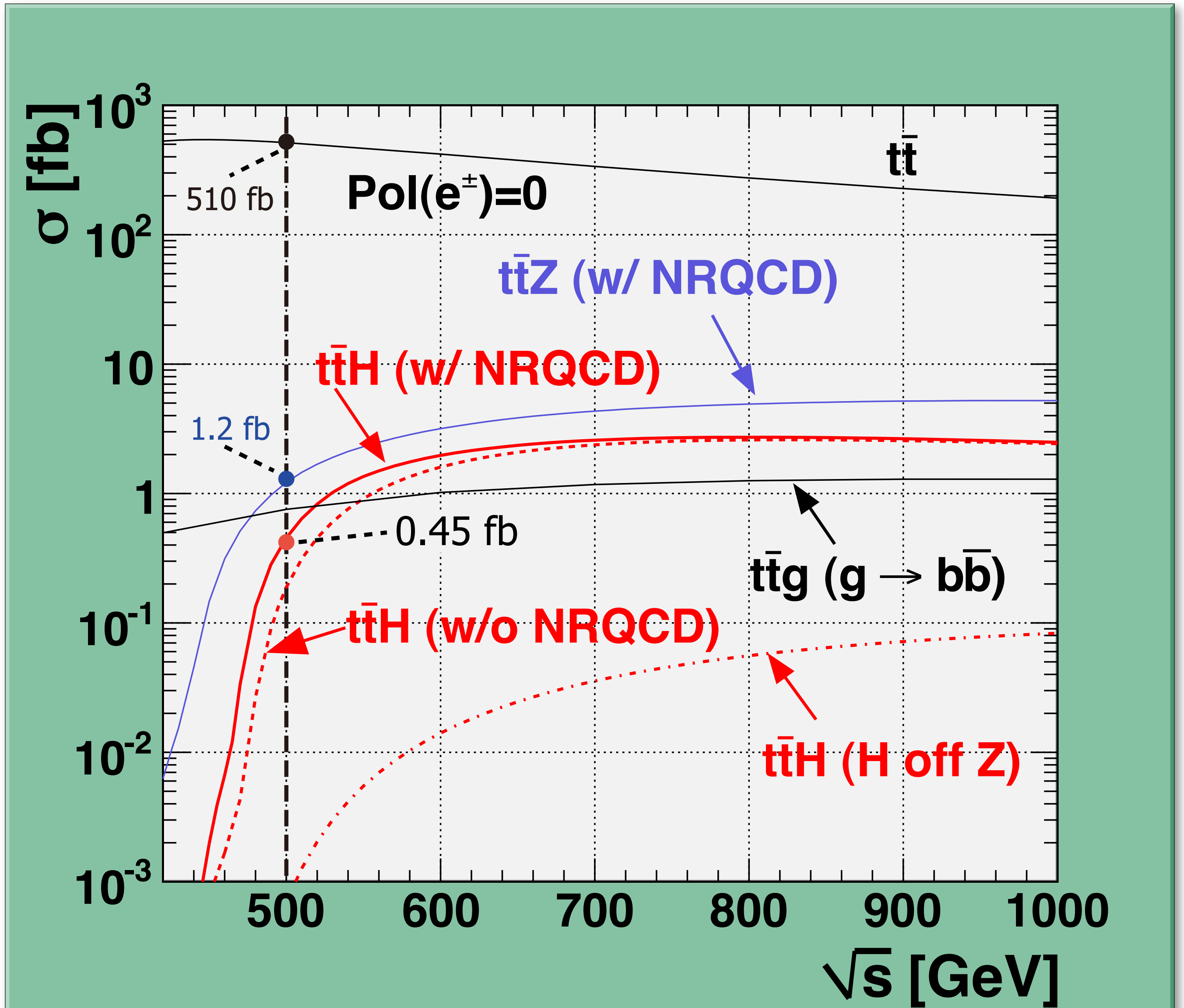
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

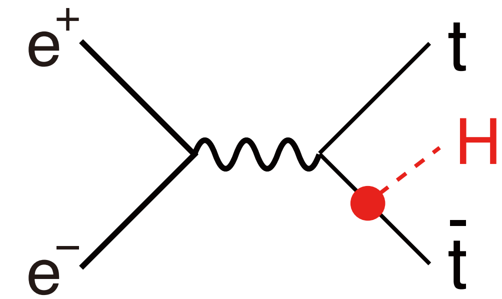
$(M_H = 125\ \text{GeV})$

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%	-	3.0%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H→bb	1.2%	10.5%	1.8%	0.66%	0.5%
H→cc	8.3%		13%	6.2%	3.1%
H→gg	7.0%		11%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.4%	1.6%
H→ττ	4.2%		5.4%	9.0%	3.1%
H→ZZ*	18%		25%	8.2%	4.1%
H→γγ	34%		34%	23%	8.5%
H→μμ	100%	-	-	-	31%

Top Yukawa Coupling at 1TeV

The largest among matter fermions, but not yet observed





H-> bb

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

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

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

Tony Price, LCWS12 — scaled from mH=120 GeV

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

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

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

DBD full simulation

Higgs self-coupling @ 1 TeV

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

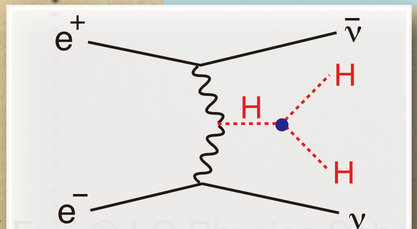
	Expected	After Cut
νvhh (WW F)	272	35.7
νvhh (ZHH)	74.0	3.88
BG (tt/ννZH)	7.86×10^5	33.7
significance	0.30	4.29

- 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)

HHH Prospects

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
Canonical	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

ILC 250+500+1000

Model-independent Global Fit for Couplings

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

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

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \quad (i = 1, \cdots, 33)$$

$$(A_i = Z, W, t)$$

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

$$F_i = S_i \, G_i$$

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

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

- The recoil mass measurement 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 ILC running.

Model-independent Global Fit for Couplings

Baseline ILC program

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

$(M_H = 125\ \mathrm{GeV})$

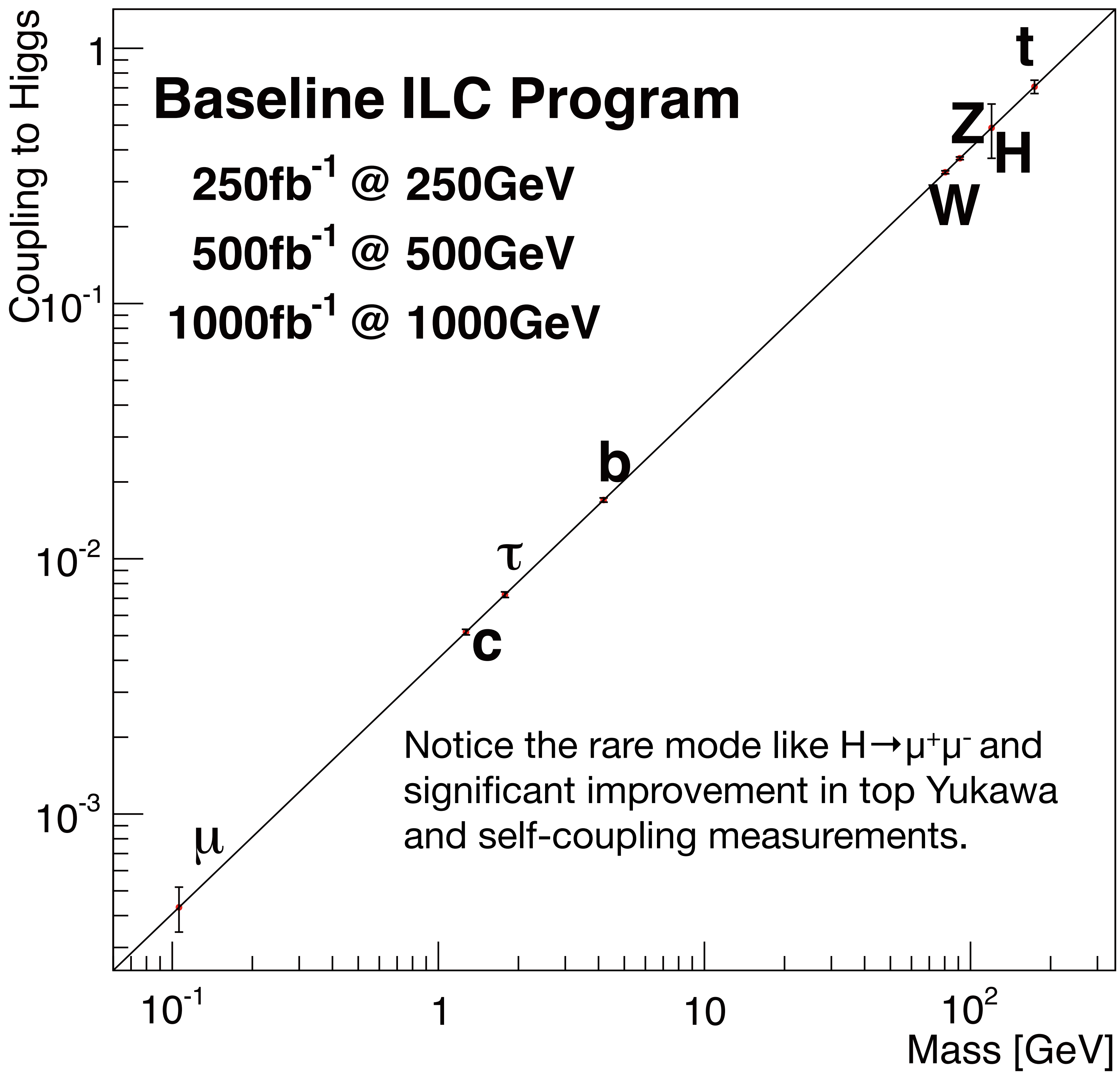
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV   P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	1.3%	1.0%	1.0%
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%
$H\tau\tau$	5.7%	2.3%	1.6%
$H\gamma\gamma$	18%	8.4%	4.0%
$H\mu\mu$	91%	91%	16%
Γ_0	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 ILC Program



LHC + ILC

Higgs couplings

Tilman Plehn
ECFA LCWS 2013, DESY

LHC including Moriond/Aspen data [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

– focus SM-like [secondary solutions possible]

– six couplings and ratios from data

g_b from width

g_g vs g_t not yet possible

[similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]

– poor man's analyses: $\Delta_H, \Delta_V, \Delta_f$

– Tevatron $H \to b\bar{b}$ with little impact

Future dinosaurs

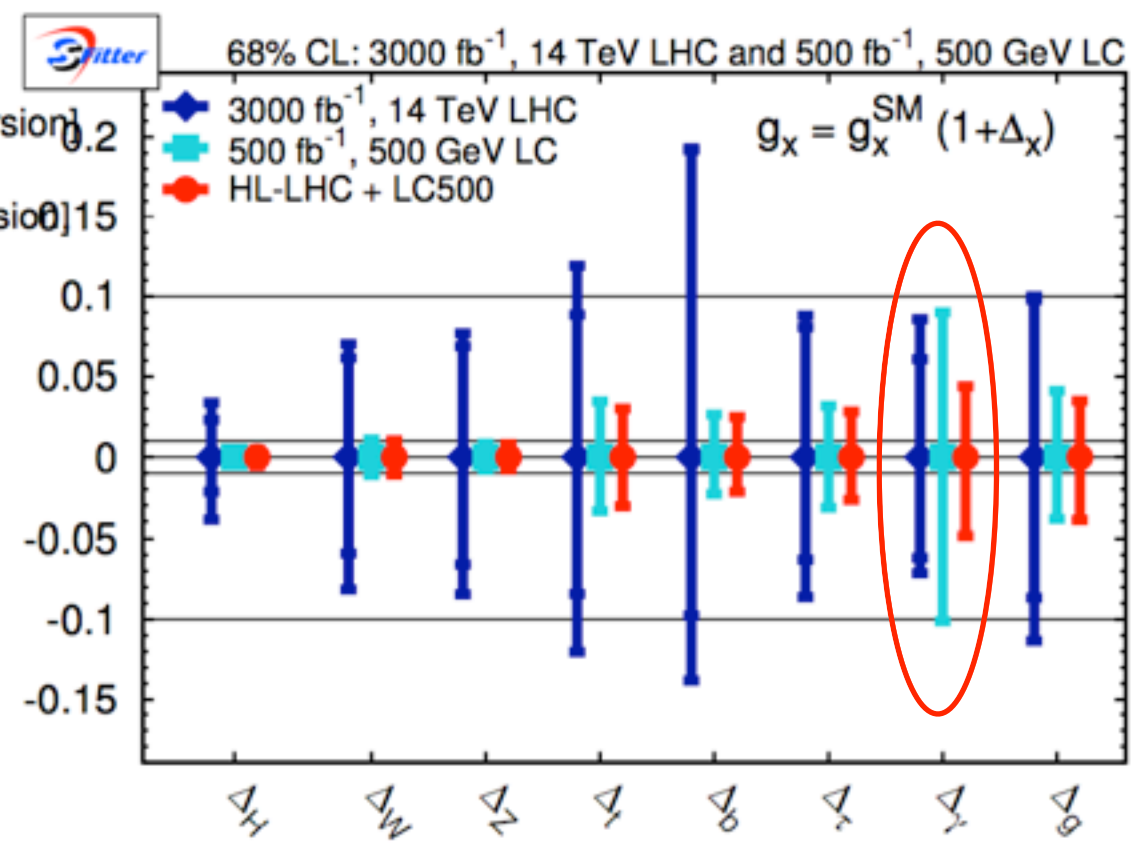
– LHC extrapolations unclear [SFitter version]

– theory extrapolations tricky [SFitter version]

– ILC case obvious [500 GeV for now]

– interplay in loop-induced couplings

– $t\bar{t}H$ important at LHC and ILC



LHC+LC500 Synergy!

Expected Precision and Deviation

Combined Fit with LHC data

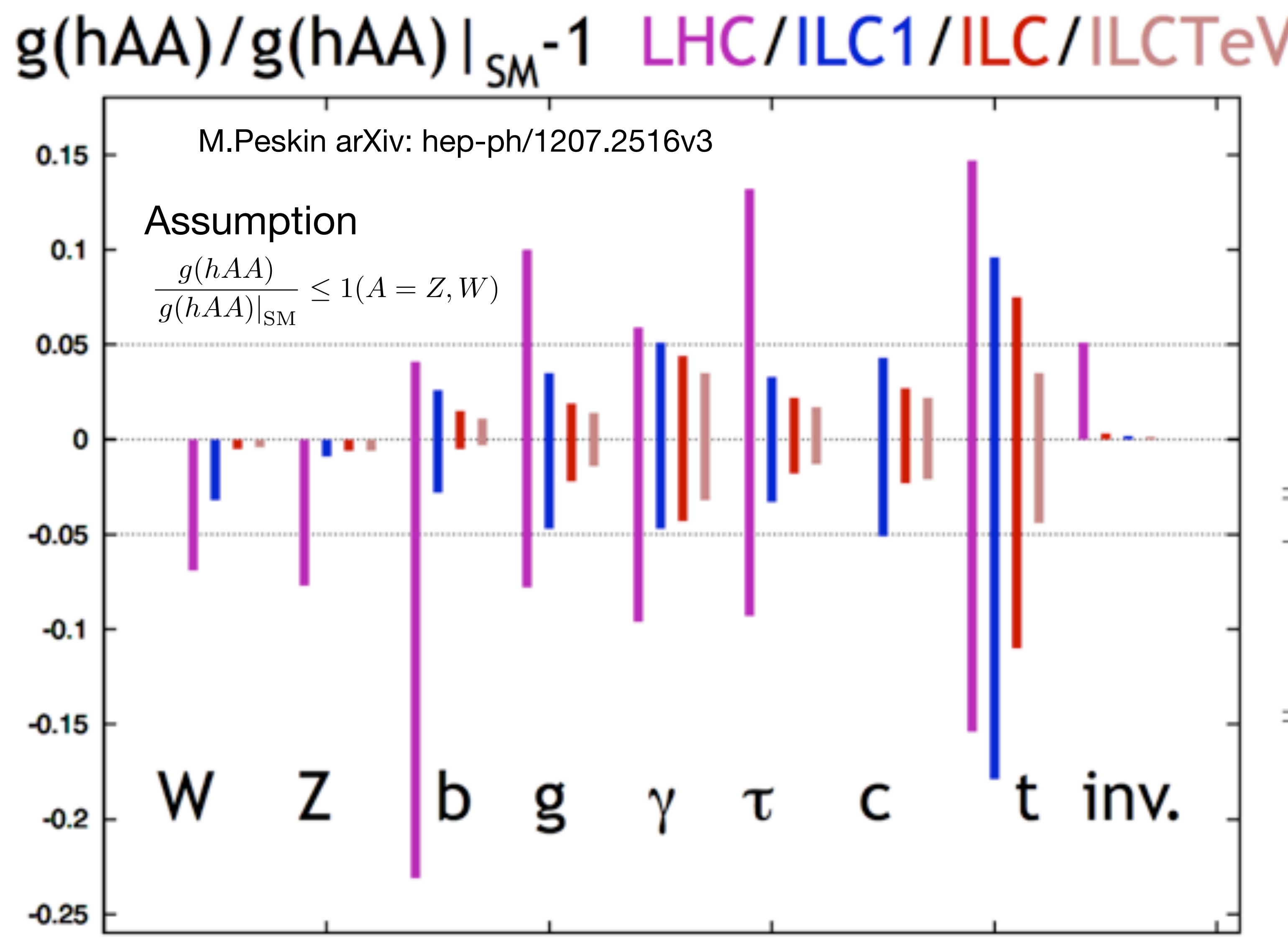


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC 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: 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	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
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

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

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

SUSY

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

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

Model-dependent Global Fit for Couplings

7-parameter fit

Model Assumptions

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

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

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 (Draft)

Finger Printing

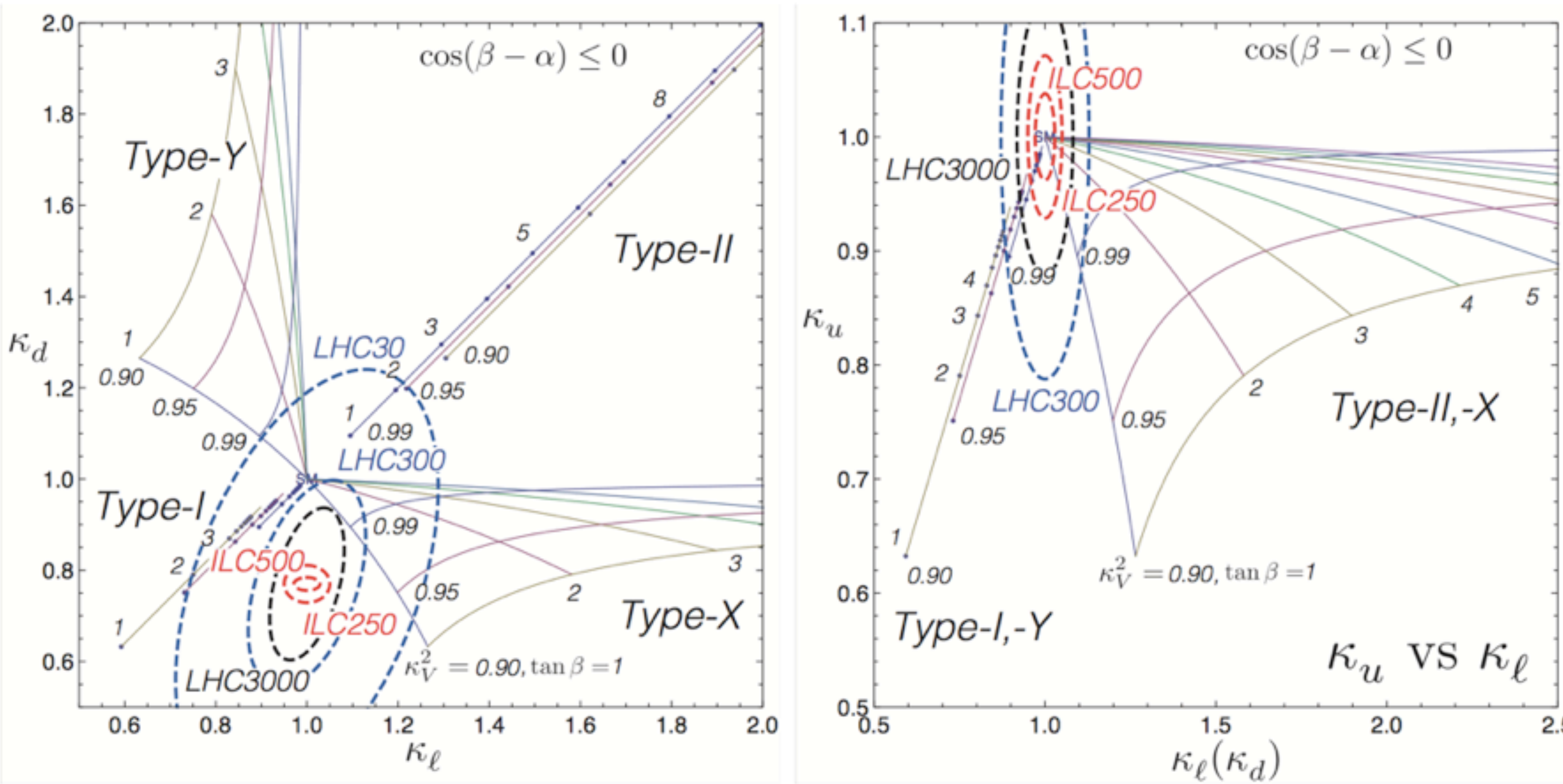


Figure 1.17. The deviation in $\kappa_f = \xi_h^f$ in the 2HDM with Type I, II, X and Y Yukawa interactions are plotted as a function of $\tan\beta = v_2/v_1$ and $\kappa_V = \sin(\beta - \alpha)$ with $\cos(\beta - \alpha) \le 0$. For the illustration purpose only, we slightly shift lines along with $\kappa_x = \kappa_y$. 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 ILC Higgs White Paper (arXiv: 1310.0763)

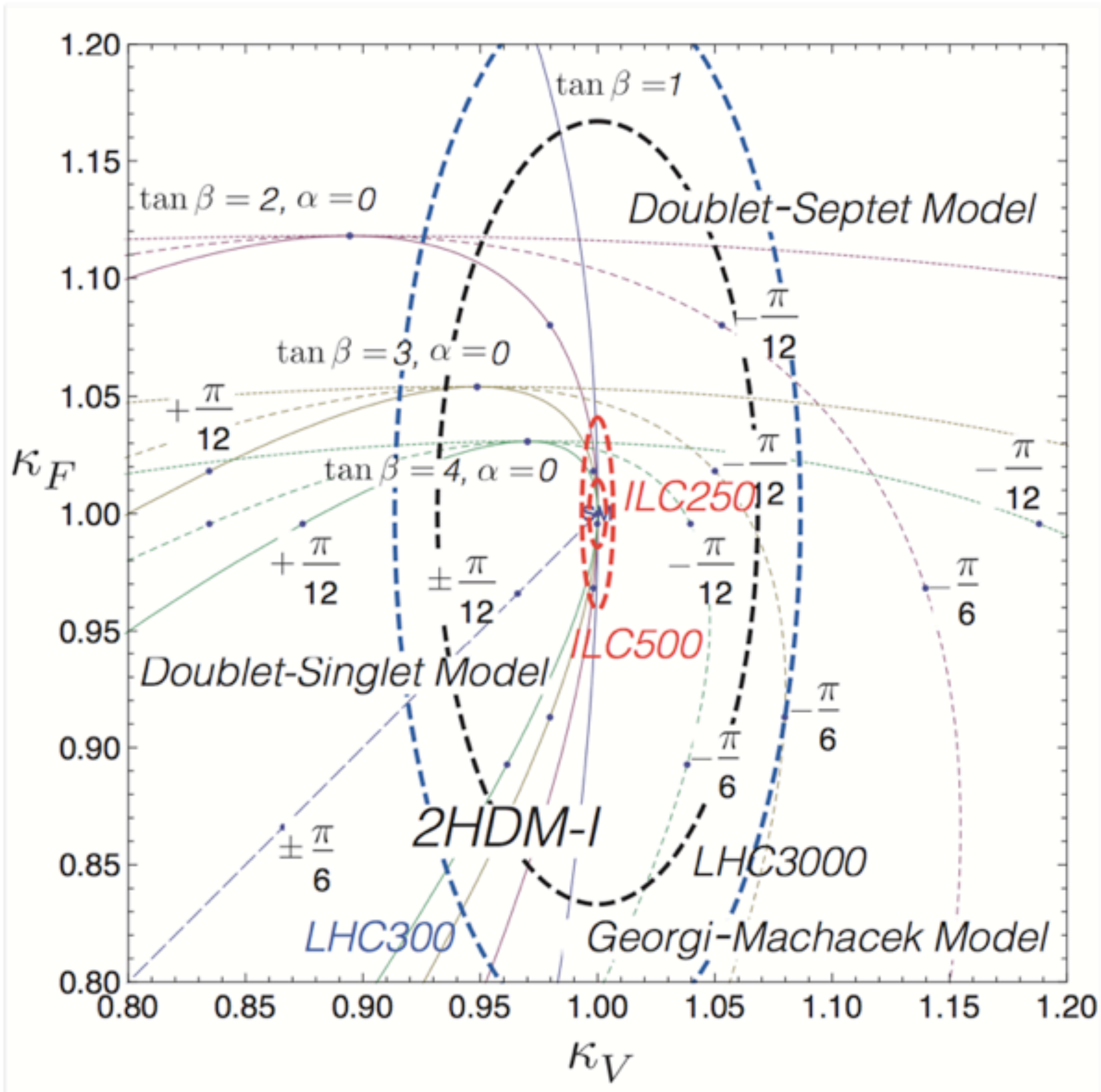


Figure 1.18. The scaling factors in models with universal Yukawa coupling constants.

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Self-Coupling

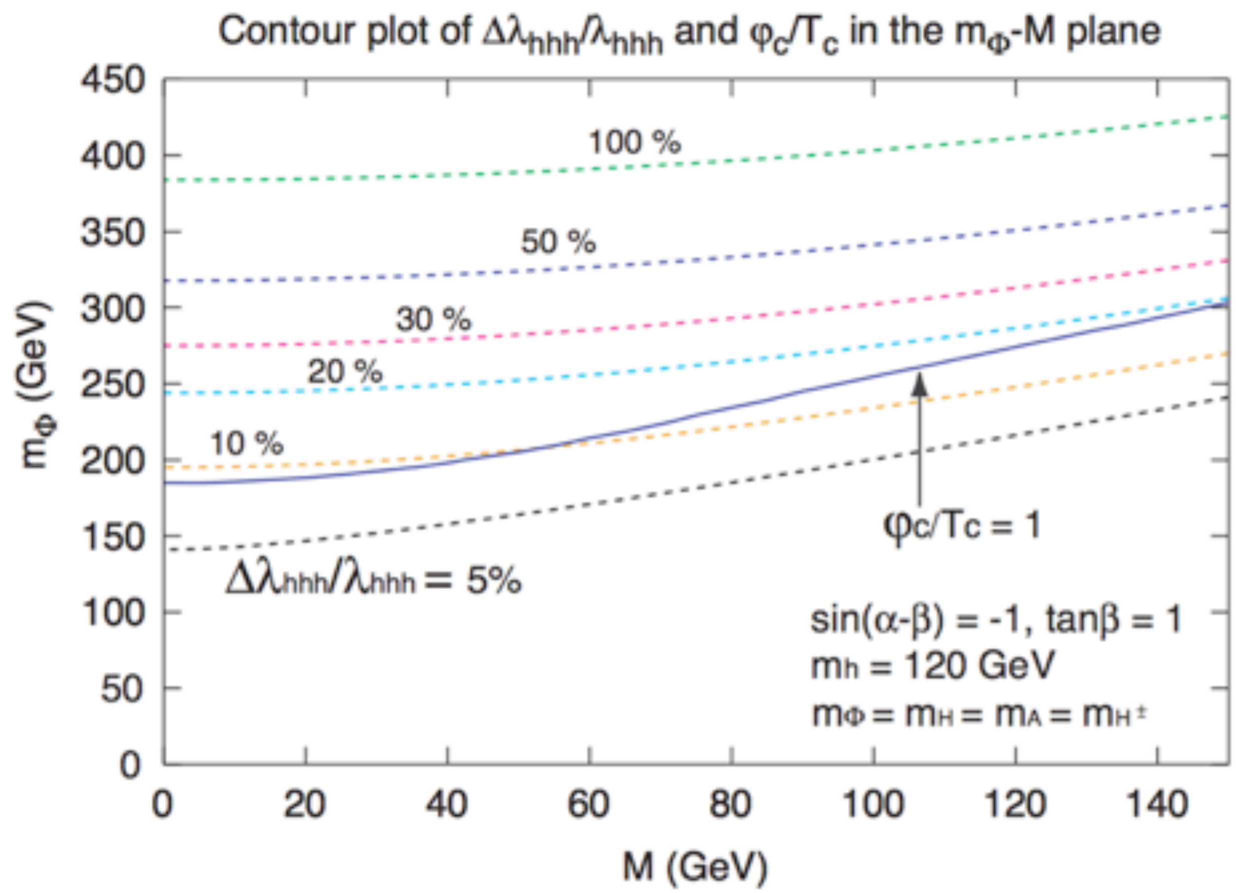
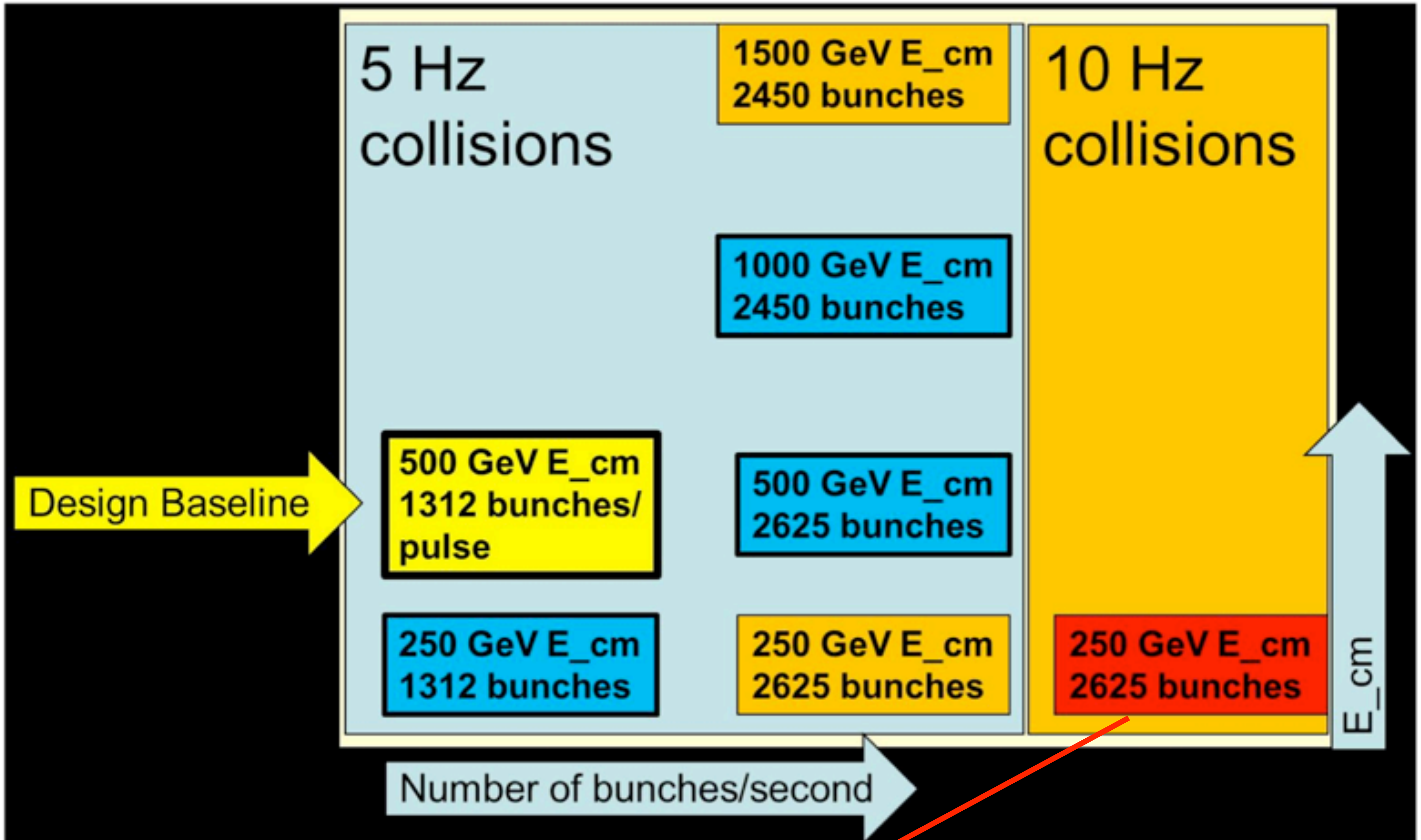


Figure 1.21. The region of strong first order phase transition ($\varphi_c/T_c > 1$) required for successful electroweak baryogenesis and the contour plot of the deviation in the triple Higgs boson coupling from the SM prediction [11], where m_Φ represents degenerated mass of H, A and $H^\pm$ and M is the soft-breaking mass of the discrete symmetry in the Higgs potential.

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

HL-ILC ?

ILC Stages and Upgrades



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

x4 upgrade
@250GeV

Blue: upgrade described in TDR

The current ILC design is rather conservative!

Independent Higgs Measurements

Hypothetical HL-ILC

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

→

250 GeV:	1150 fb^{-1}
500 GeV:	1600 fb^{-1}
1 TeV:	2500 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	1.2%	-	1.7%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H-->bb	0.56%	4.9%	1.0%	0.37%	0.3%
H-->cc	3.9%		7.2%	3.5%	2.0%
H-->gg	3.3%		6.0%	2.3%	1.4%
H-->WW*	3.0%		5.1%	1.3%	1.0%
H-->ττ	2.0%		3.0%	5.0%	2.0%
H-->ZZ*	8.4%		14%	4.6%	2.6%
H-->γγ	16%		19%	13%	5.4%
H-->μμ	46.6%	-	-	-	20%

Coupling Measurements

Hypothetical HL-ILC

250 GeV: 1150 fb^{-1}
500 GeV: 1600 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%	1.0%
Hgg	3.0%	1.2%	0.93%
$H\tau\tau$	2.7%	1.2%	0.9%
$H\gamma\gamma$	8.2%	4.5%	2.4%
$H\mu\mu$	42%	42%	10%
Γ_0	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%!

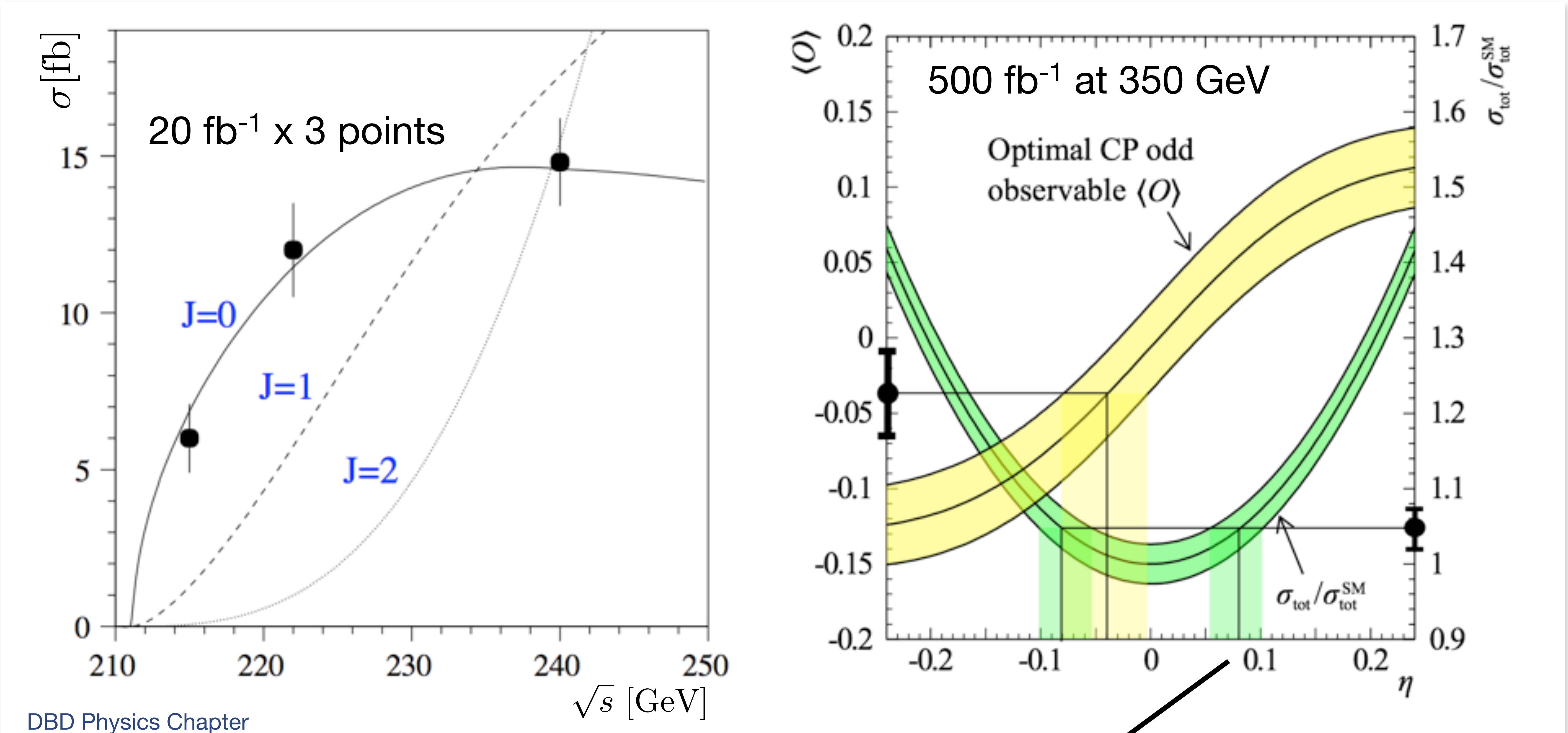
Conclusions

- 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.
- 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.
  Moreover, we need some model assumption to extract couplings from the LHC data.
- The recoil mass measurements at ILC 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 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 ***completely model-independently*** 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

Spin and CP Mixing

Measurements that compliment those at LHC



Search for small CP-odd admixture to a few %

CP-odd ZHH coupling is loop-induced, may not be the best way, though.

SM Higgs BRs

arXiv: 1307.1347

Table 1.1. The Standard Model values of branching ratios of fermionic decays of the Higgs boson for each value of the Higgs boson mass m_h.

m_h (GeV)	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$c\bar{c}$	$s\bar{s}$
125.0	57.7 %	6.32 %	0.0219 %	2.91 %	0.0246 %
125.3	57.2 %	6.27 %	0.0218 %	2.89 %	0.0244 %
125.6	56.7 %	6.22 %	0.0216 %	2.86 %	0.0242 %
125.9	56.3 %	6.17 %	0.0214 %	2.84 %	0.0240 %
126.2	55.8 %	6.12 %	0.0212 %	2.81 %	0.0238 %
126.5	55.3 %	6.07 %	0.0211 %	2.79 %	0.0236 %

Table 1.2. The Standard Model values of branching ratios of bosonic decays of the Higgs boson for each value of the Higgs boson mass m_h. The predicted value of the total decay width of the Higgs boson is also listed for each value of m_h.

m_h (GeV)	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ	Γ_H (MeV)
125.0	8.57 %	0.228 %	0.154 %	21.5 %	2.64 %	4.07
125.3	8.54 %	0.228 %	0.156 %	21.9 %	2.72 %	4.11
125.6	8.52 %	0.228 %	0.158 %	22.4 %	2.79 %	4.15
125.9	8.49 %	0.228 %	0.162 %	22.9 %	2.87 %	4.20
126.2	8.46 %	0.228 %	0.164 %	23.5 %	2.94 %	4.24
126.5	8.42 %	0.228 %	0.167 %	24.0 %	3.02 %	4.29

Systematic Errors

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

arXiv: 1310.0763

Hunting Ground for Extra Higgs Bosons

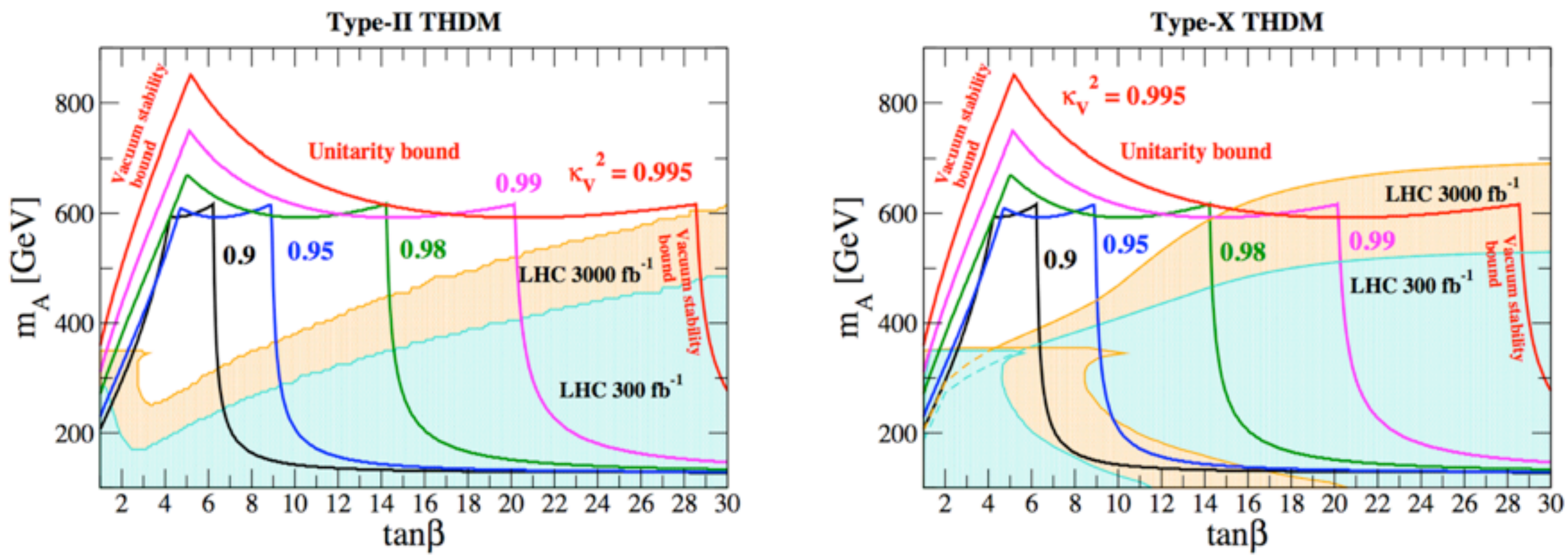
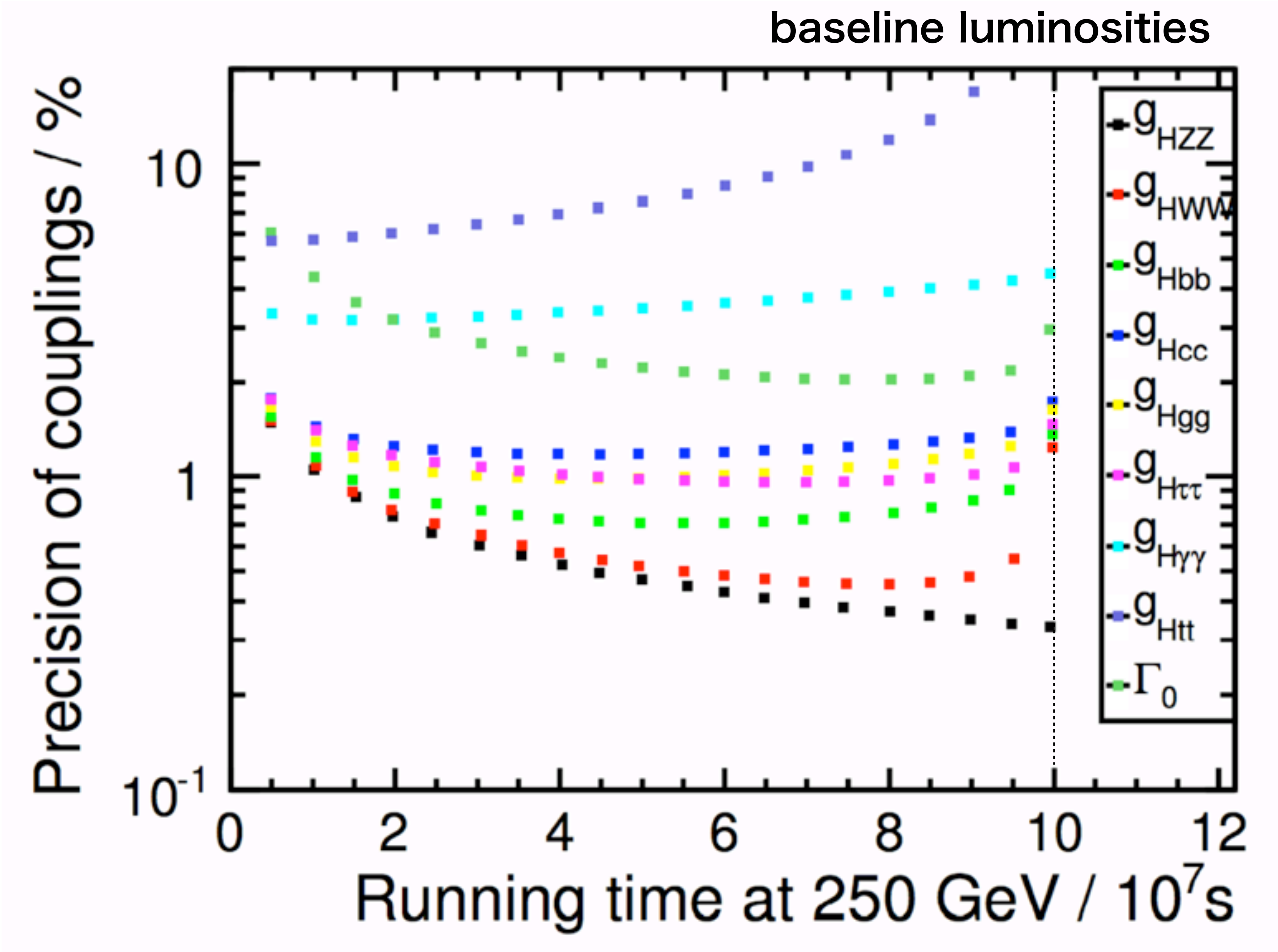


Figure 1.20. Regions below the curves are allowed by the constraints from unitarity and vacuum stability on the $\tan\beta$-m_A plane for each fixed value of κ_V^2 for $M = m_A = m_H = m_{H^+}$ in the Type II and Type X 2HDMs. Expected excluded parameter spaces are also shown by blue (orange) shaded regions from the gluon fusion production and associate production of A and H with bottom quarks and tau leptons at the LHC with the collision energy to be 14 TeV with the integrated luminosity to be 300 fb^{-1} (3000 fb^{-1}).

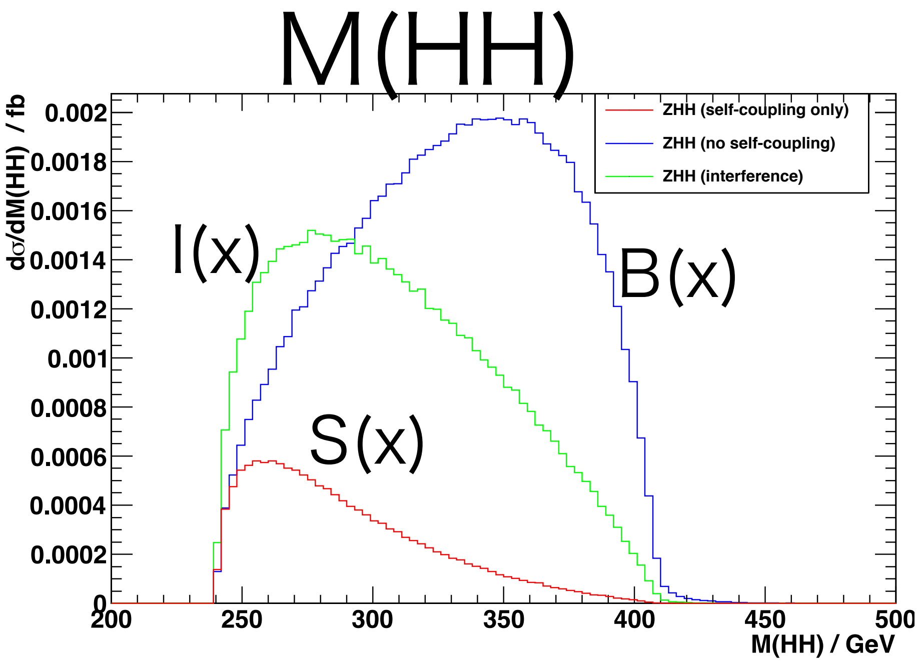
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Coupling Precisions
Running Scenarios



Self-coupling Measurement

Weighting Method to Enhance the Sensitivity to λ



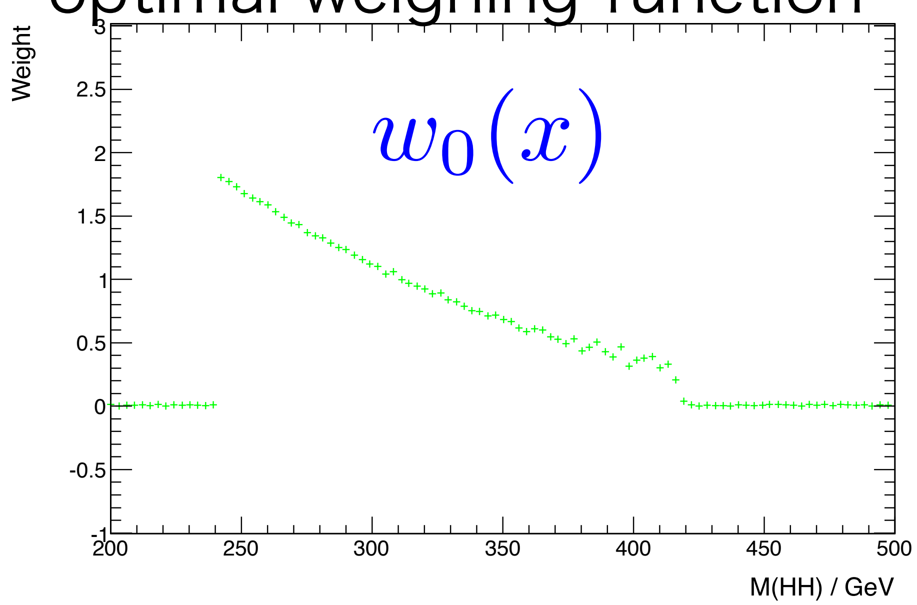
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible interference self-coupling

Observable: weighted cross-section

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

optimal weighing function



Equation for the optimal w(x) (variational principle):

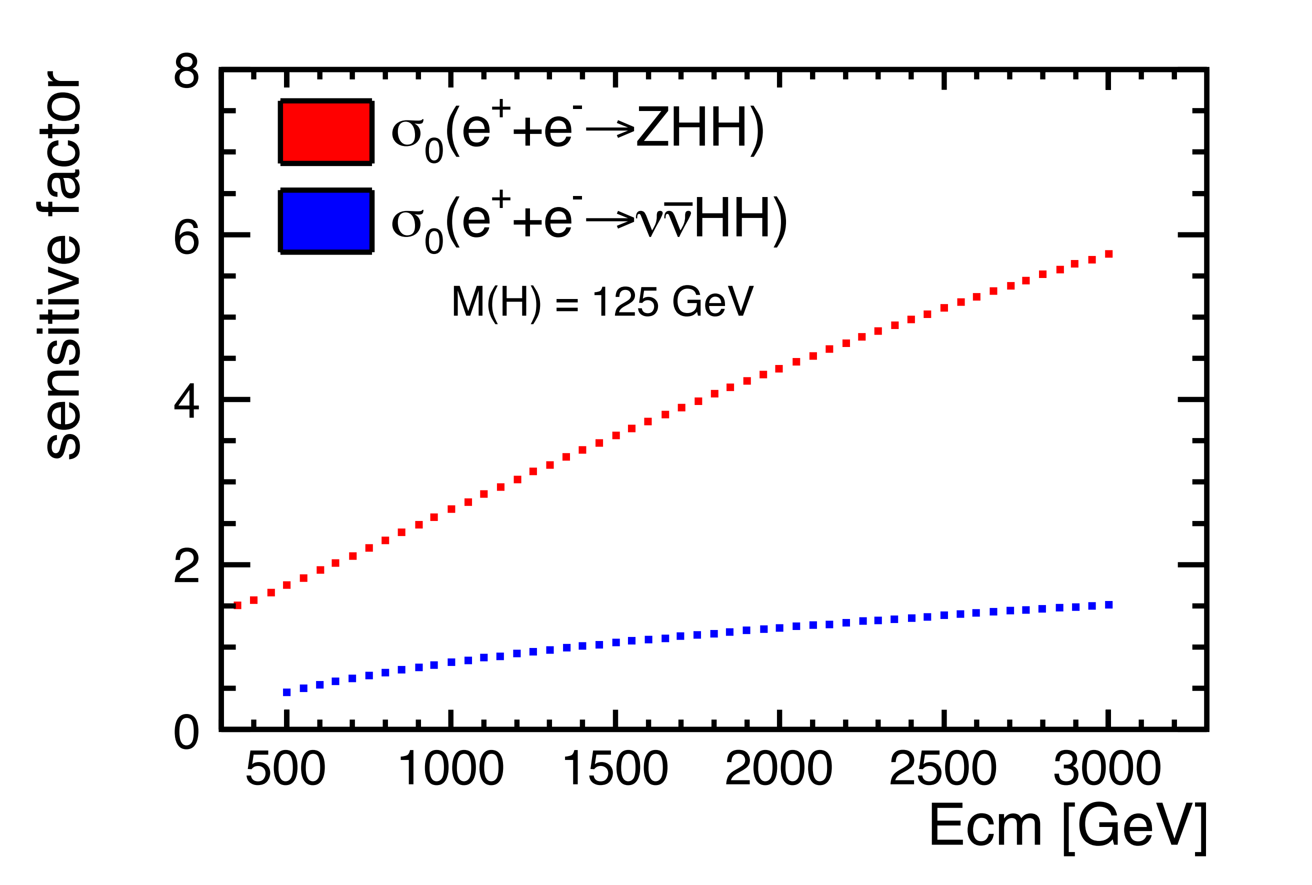
$$\sigma(x)w_0(x)\int (I(x)+2S(x))w_0(x)\mathrm{d}x = (I(x)+2S(x))\int \sigma(x)w_0^2(x)\mathrm{d}x$$

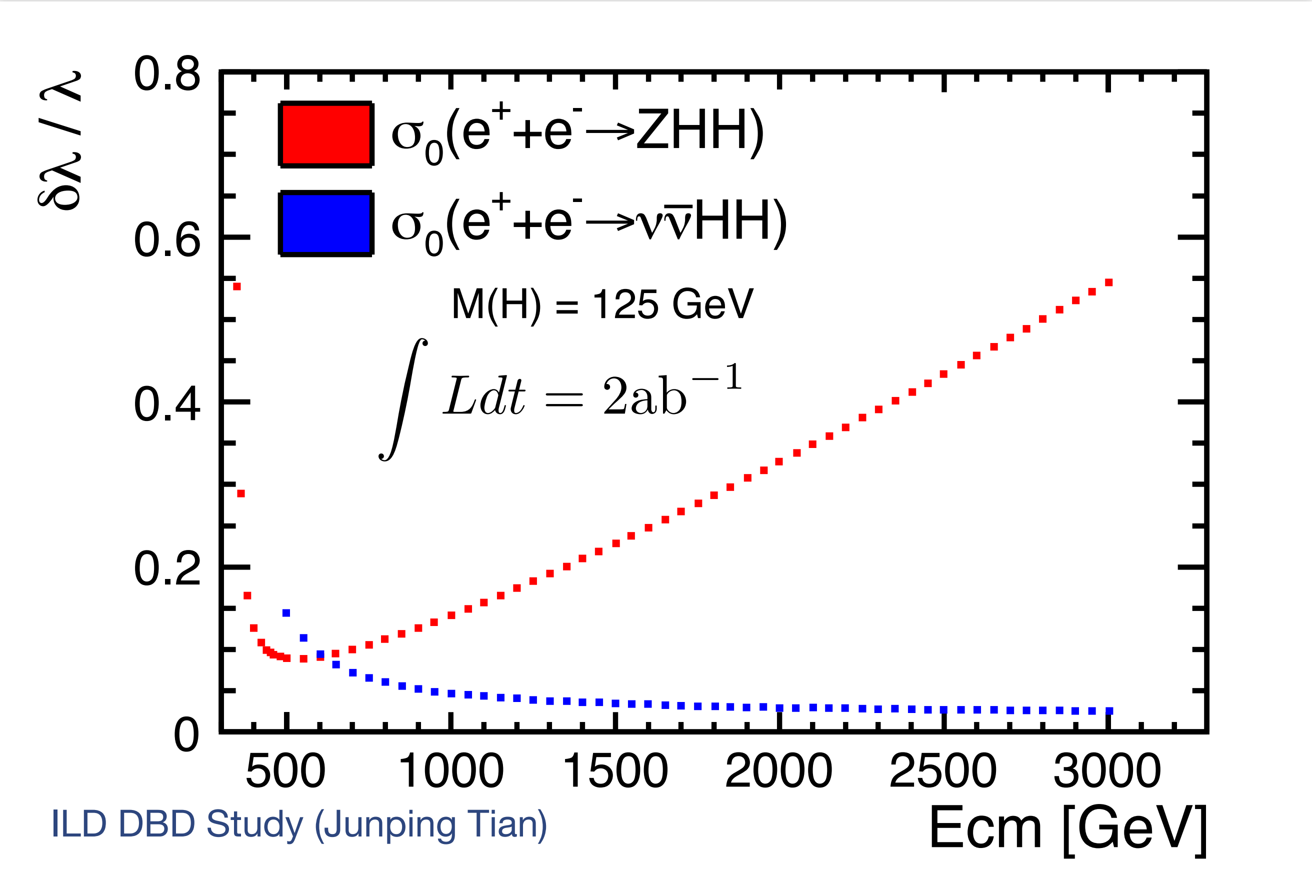
General solution:

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

c: arbitrary normalization factor

Expected Coupling Precision as a Function of Ecm



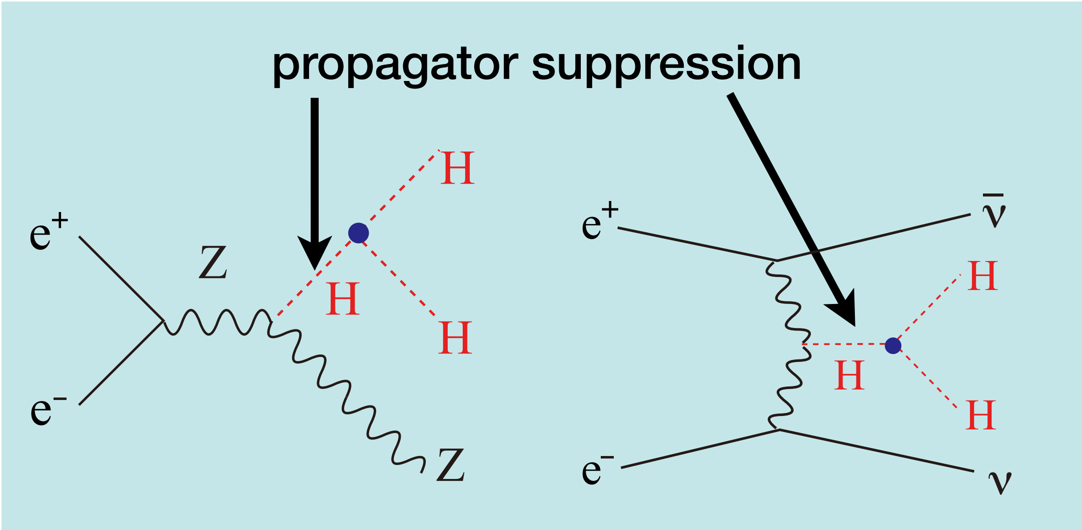


Sensitivity Factor

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

F=0.5 if no BG diagrams there

BG diagrams dominate at high E_{cm}



⇒ F grows quickly with Ecm !

Coupling Precision

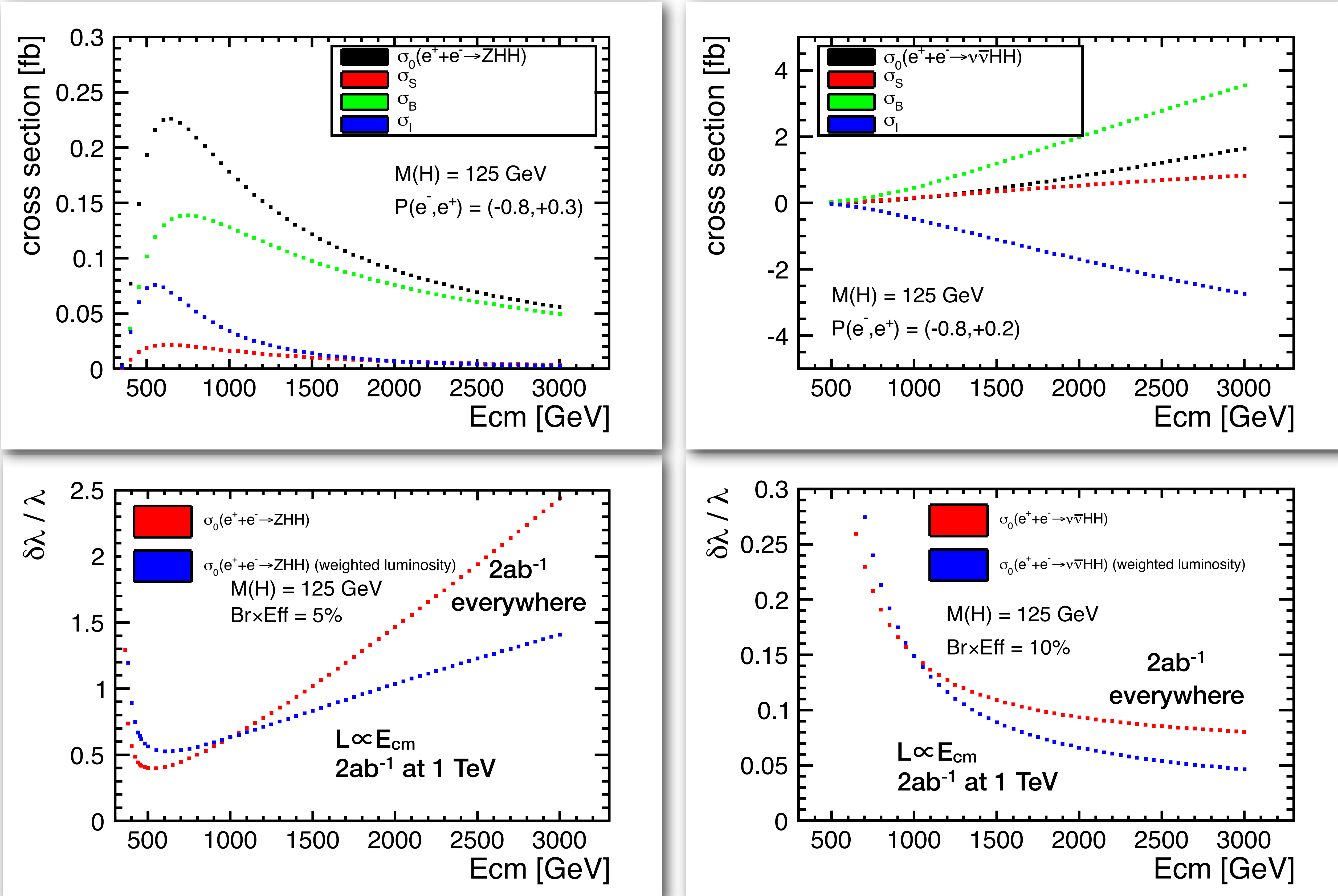
ZHH : optimal Ecm ~ 500 GeV

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)