Physics 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.

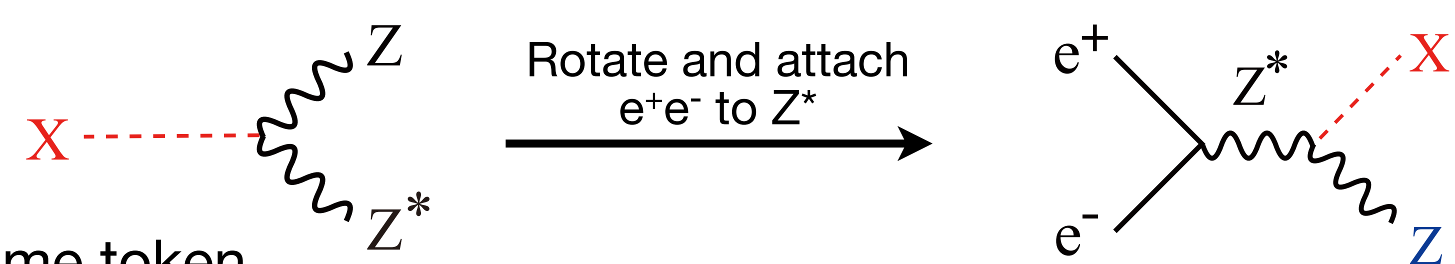
- We don't know whether the "something" is elementary or composite.

- 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.

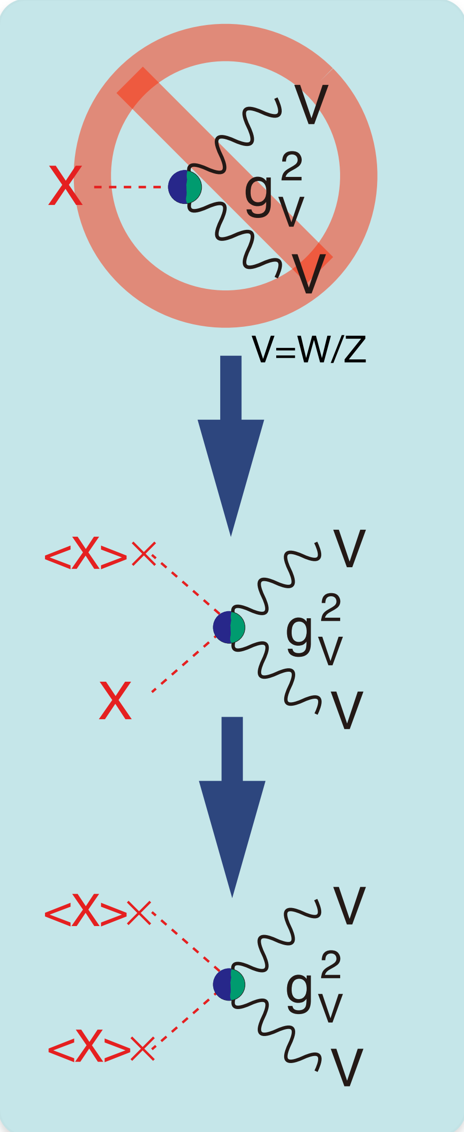
Since the July 4th, the world has changed!

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

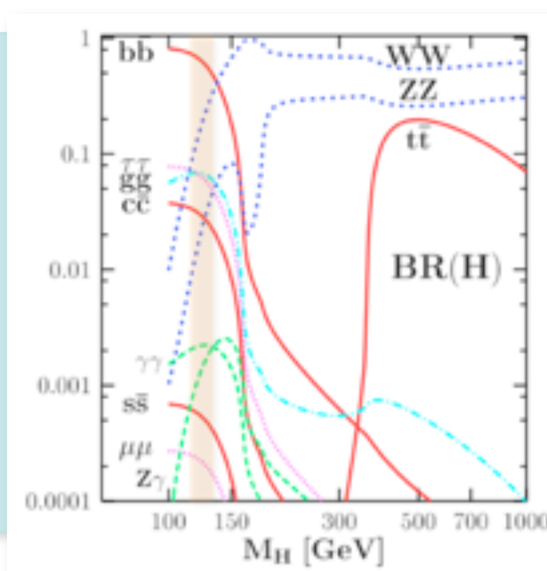
- $X(125) \to \gamma\gamma$ means X is a neutral boson and $J \neq 1$ (Landau-Yang theorem). Recent LHC results prefer $J^P=0^+$.
- $X(125) \to ZZ^*, WW^* \Rightarrow \exists$ XVV couplings: (V=W/Z: gauge bosons)
- There is no gauge coupling like XVV, only XXVV or XXV
  ⇒ XVV probably from XXVV with one X replaced by $\langle X \rangle \neq 0$, namely $\langle X \rangle$XVV
  ⇒ There must be $\langle X \rangle \langle X \rangle$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 $\langle X \rangle$ saturates the SM vev = 246GeV.
- $X \to ZZ^*$ means, X can be produced via $e^+e^- \to Z^* \to ZX$.



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

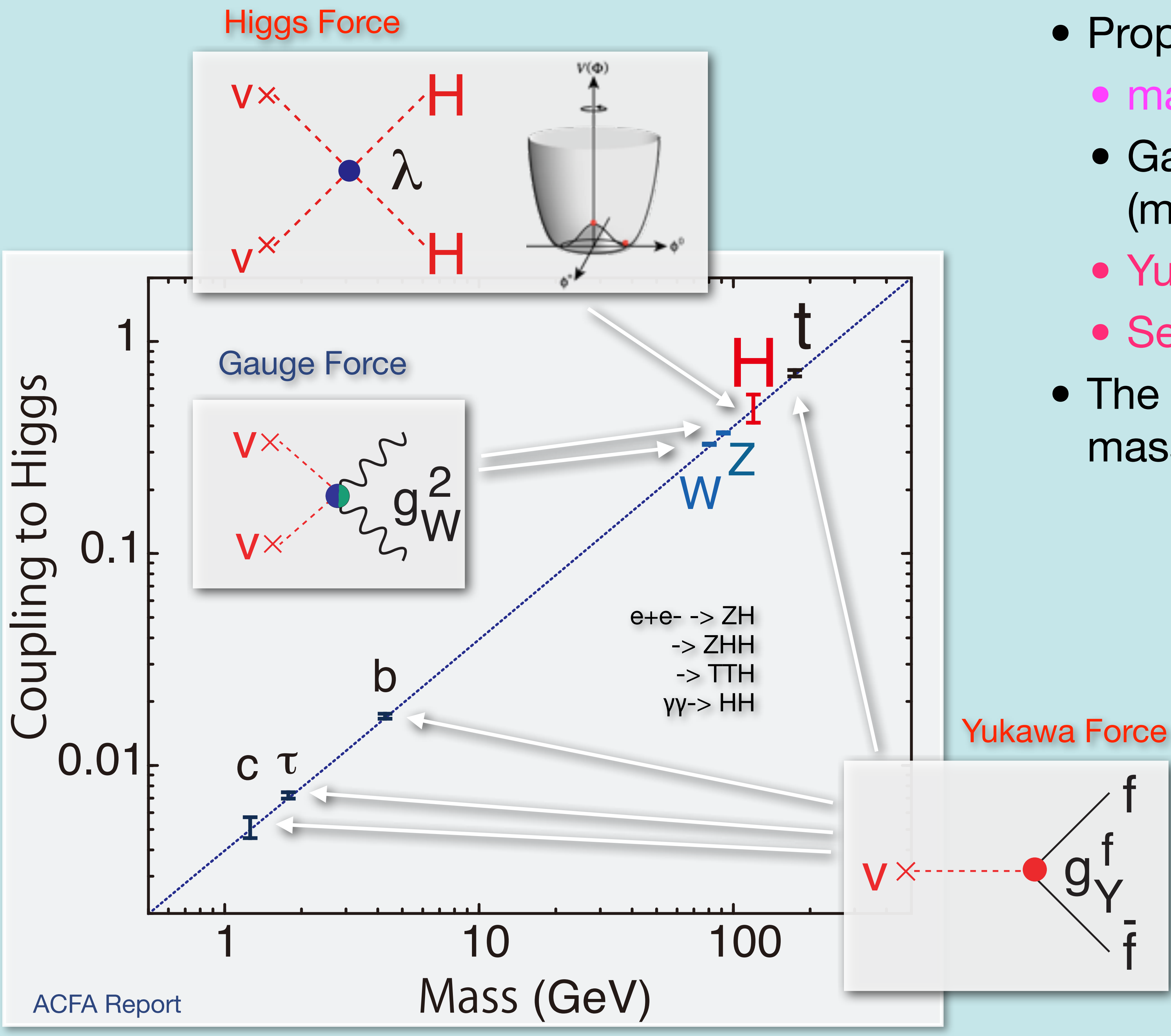


- So we now know that the major Higgs production mechanisms in e^+e^- collisions are indeed available at the ILC ⇒ No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, where variety of decay modes are accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed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

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

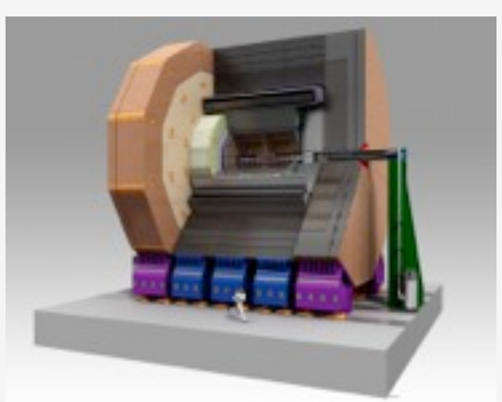
$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}) \end{cases}$$

SUSY

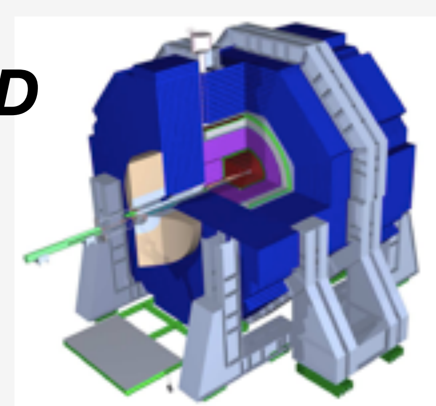
$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Expected deviations are small --> Precision!

ILD



SiD



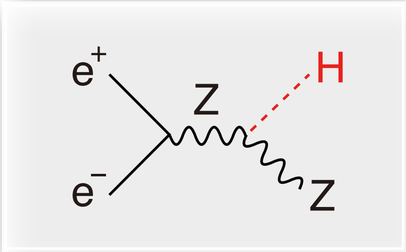
For the precision we need a 500GeV LC and high precision detectors

Why 250-500 GeV?

Three well known thresholds

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

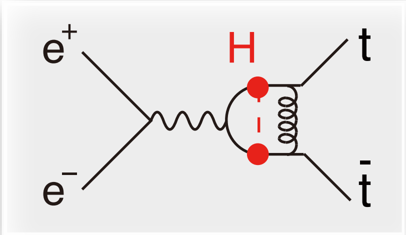
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

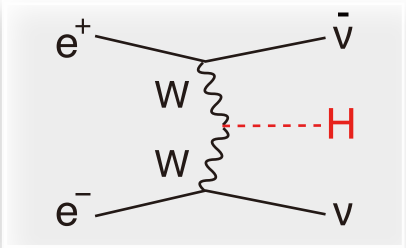


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- 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



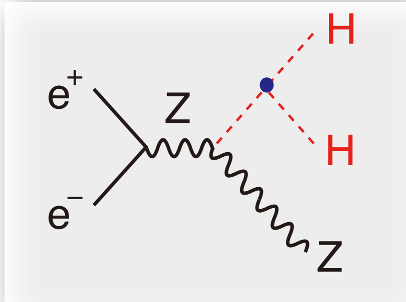


vvH @ 350 - 500GeV :

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

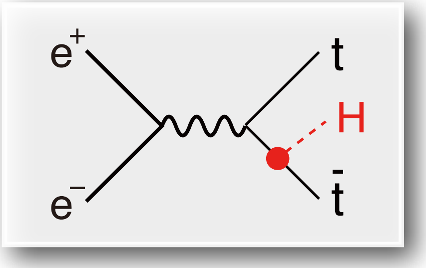
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- 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



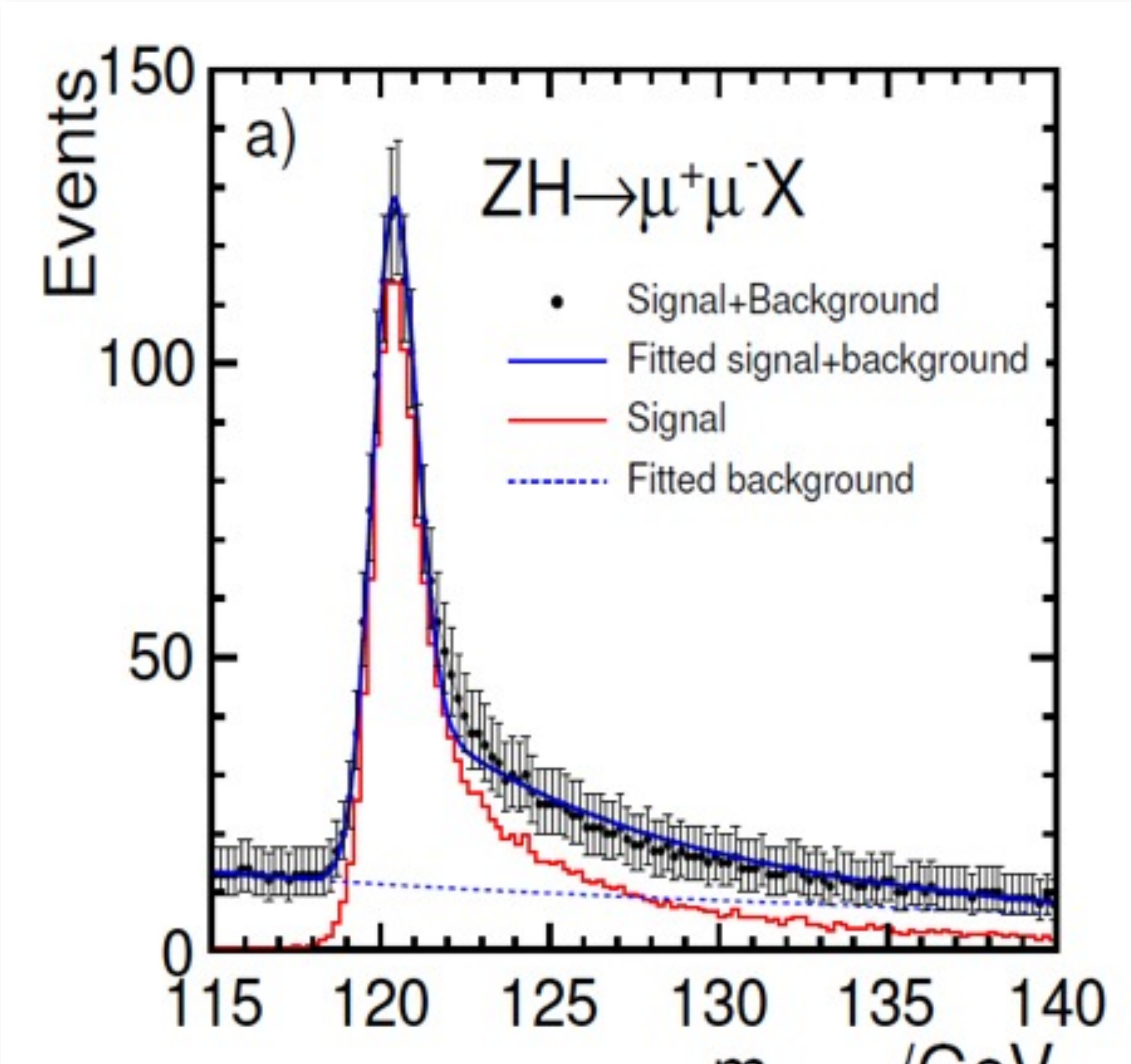
We can complete the mass-coupling plot at ~500GeV!

ILC 250

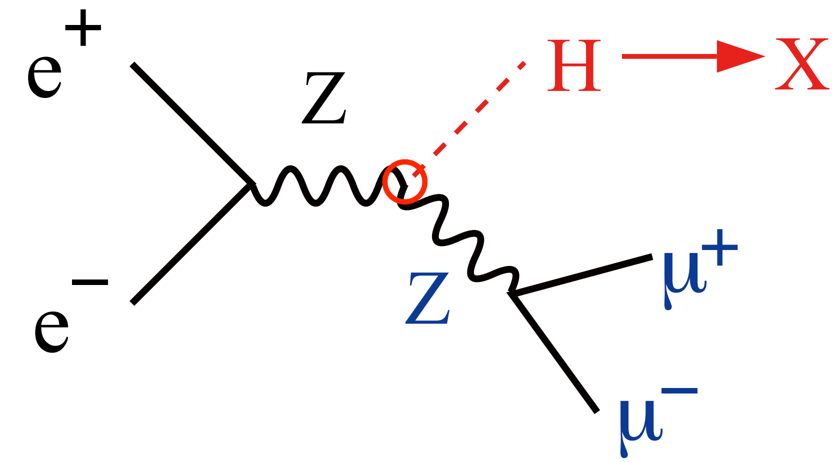
Recoil Mass Measurement

The flagship measurement of ILC 250

Recoil Mass



ILD LoI



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

Invisible decay detectable!

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

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

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

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

scaled from mH=120 GeV

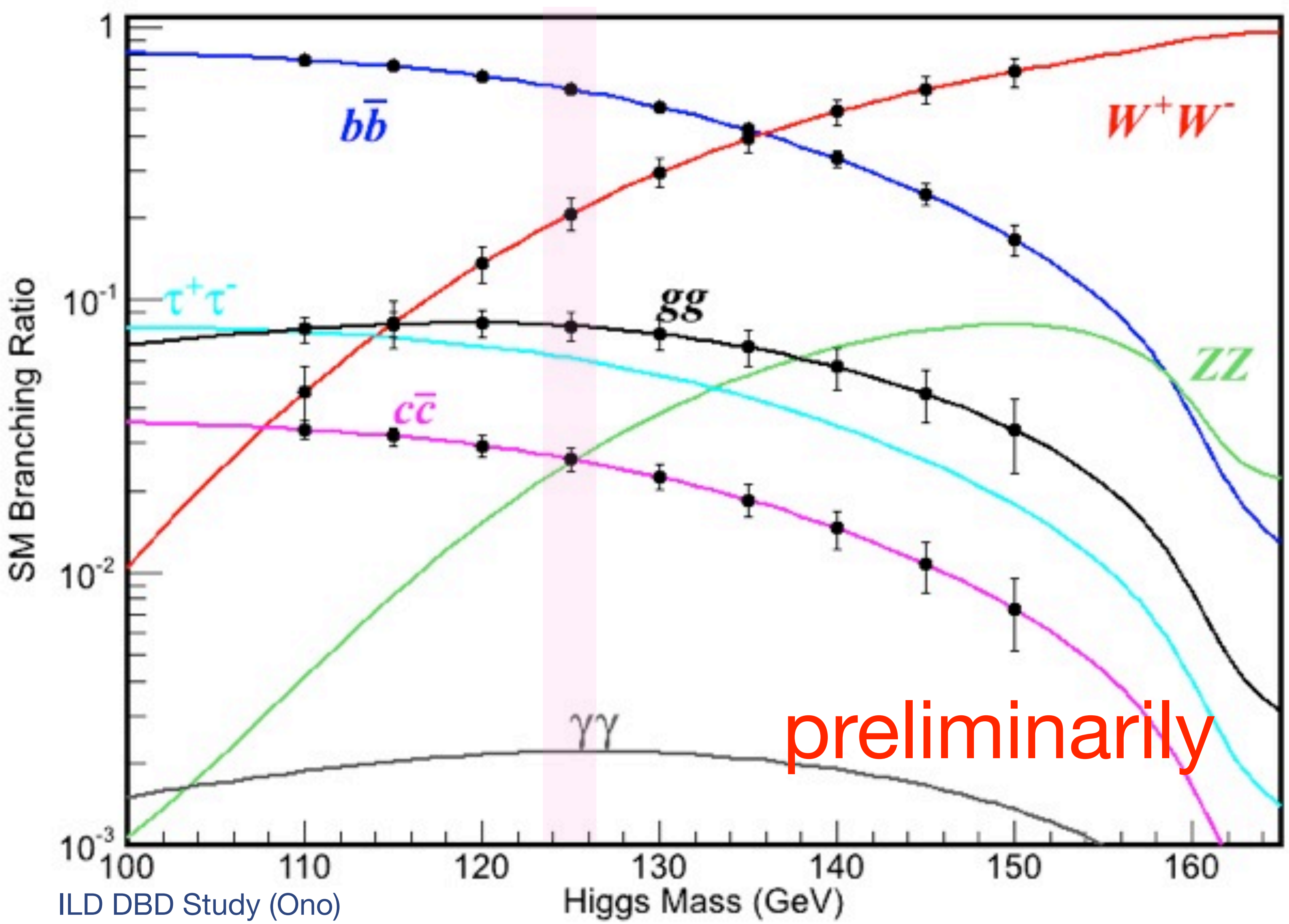
Model-independent absolute measurement of σ_{ZH} (the HZZ coupling)

Branching Ratio Measurements

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

DBD Physics Chap.

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



ILD DBD Study (Ono)

	@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 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

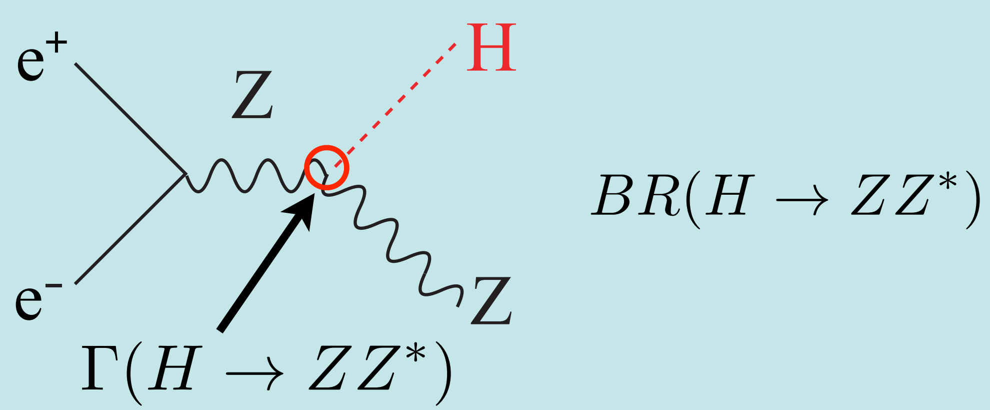
To extract couplings from BRs, we need the total width:

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

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

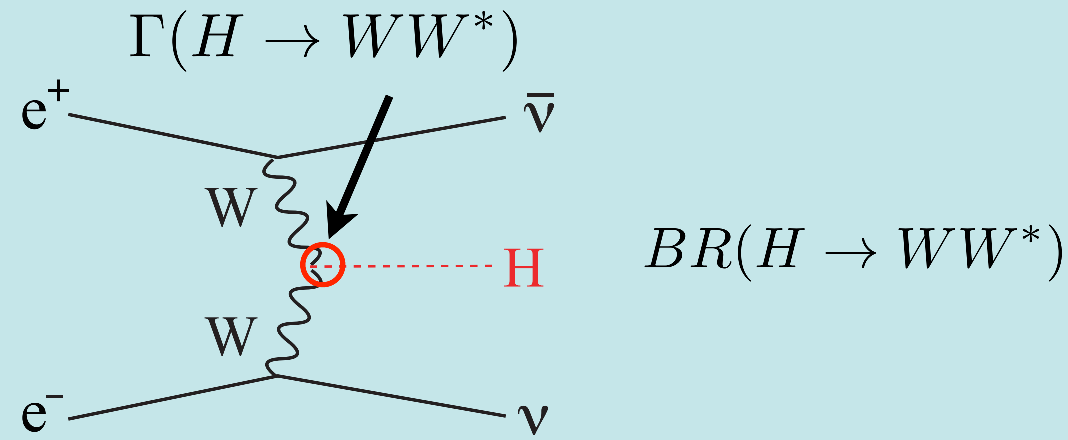
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

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



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

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



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

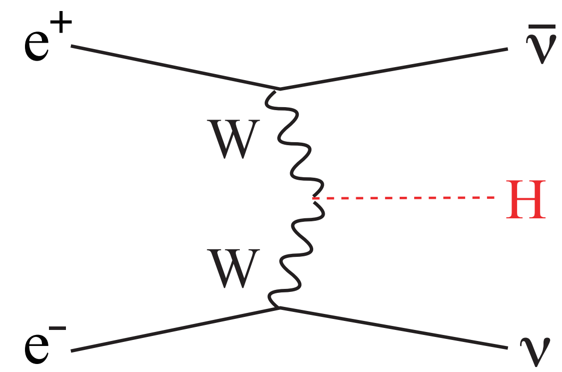
Width and BR Measurements at 500 GeV

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!

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

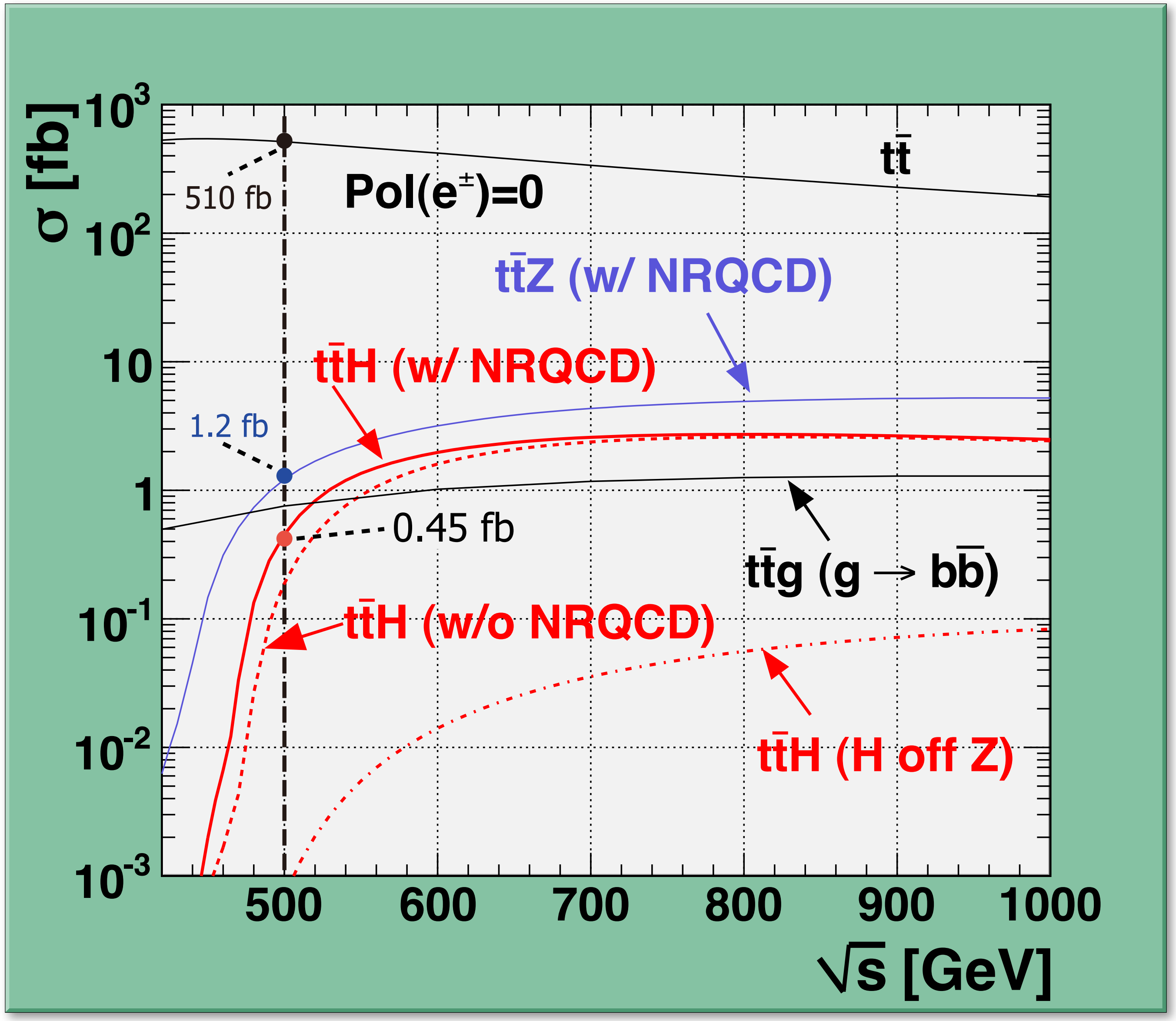
Mode	ΔBR/BR
bb	2.7 (2.7)%
cc	5.2 (7.8)%
gg	4.5 (9.5)%
WW*	3.6 (6.9)%
ττ	4.1 (4.9)%

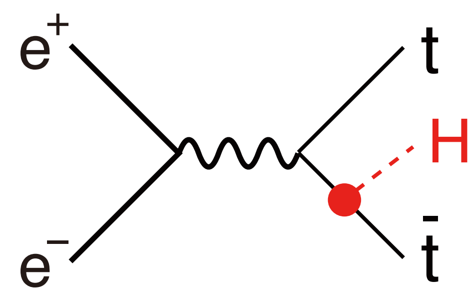
The numbers in the parentheses are as of $250\,\text{fb}^{-1}$@$250\,\text{GeV}$

ILD DBD Study (Junping Tian)

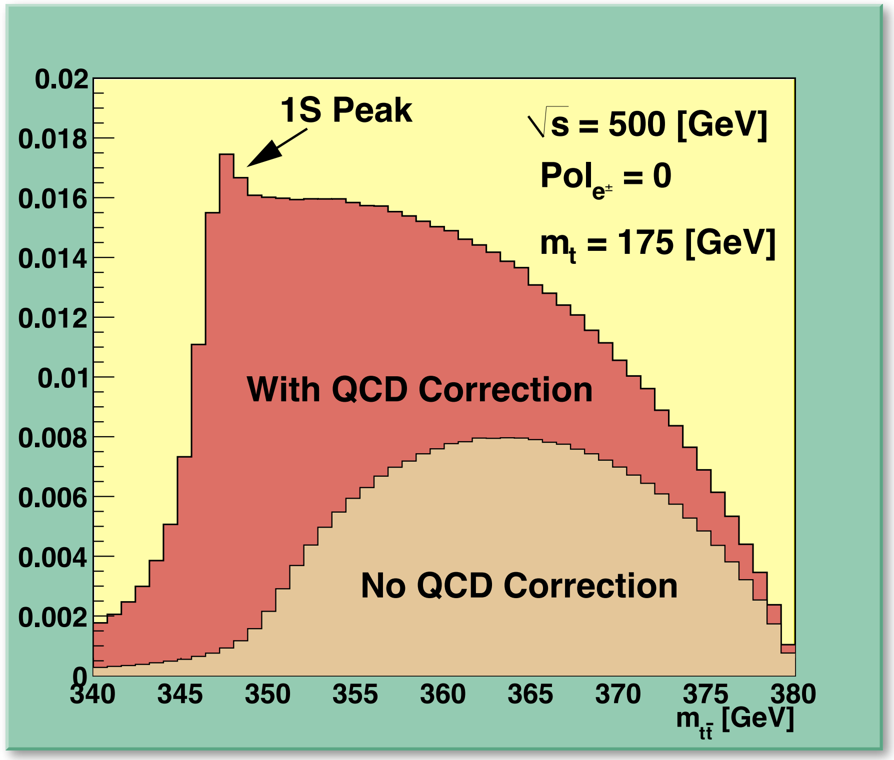
Top Yukawa Coupling

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

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

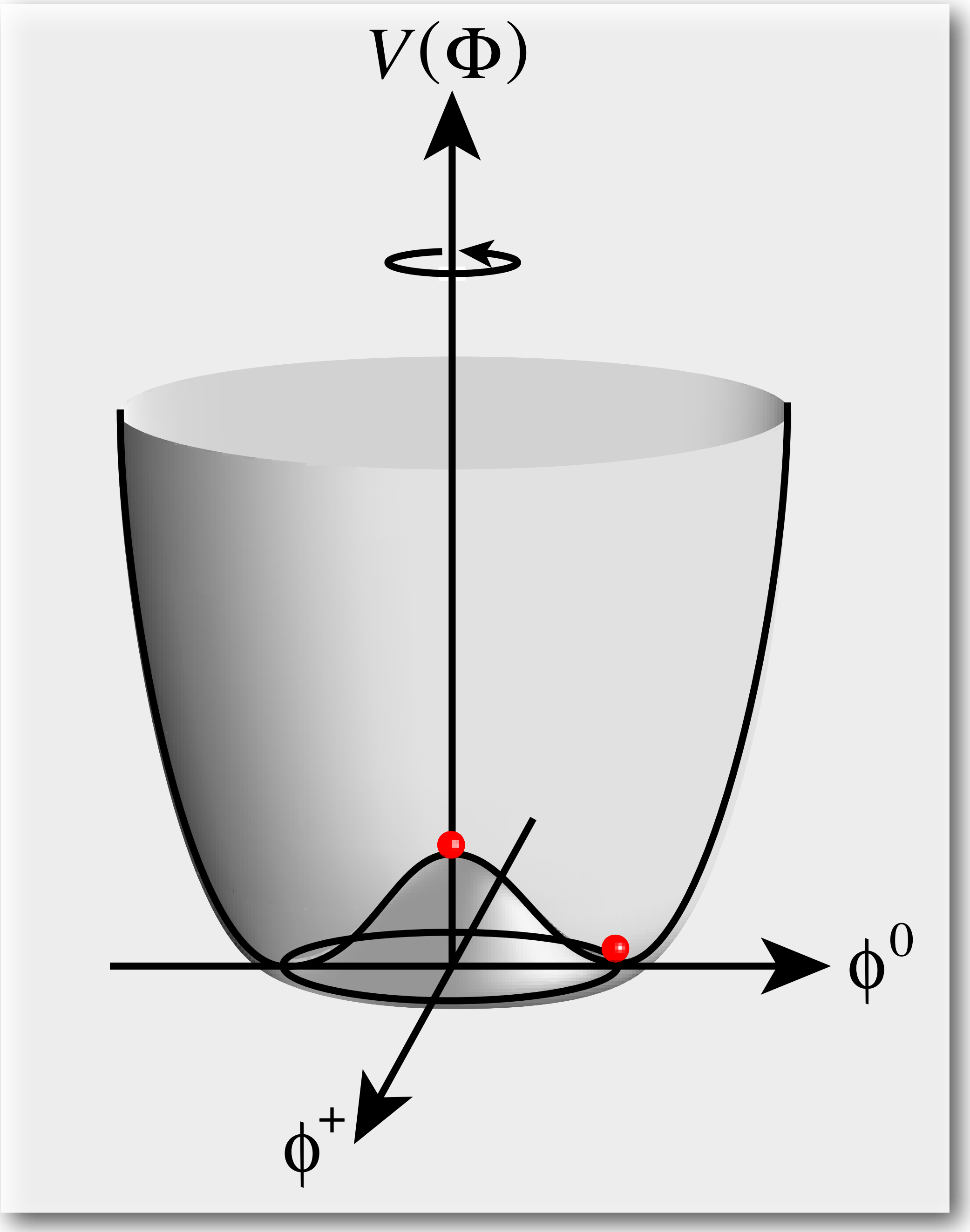
$$\Delta g_Y(t)/g_Y(t) = 13\,\%$$

Tony Price, LCWS12 scaled from mH=120 GeV

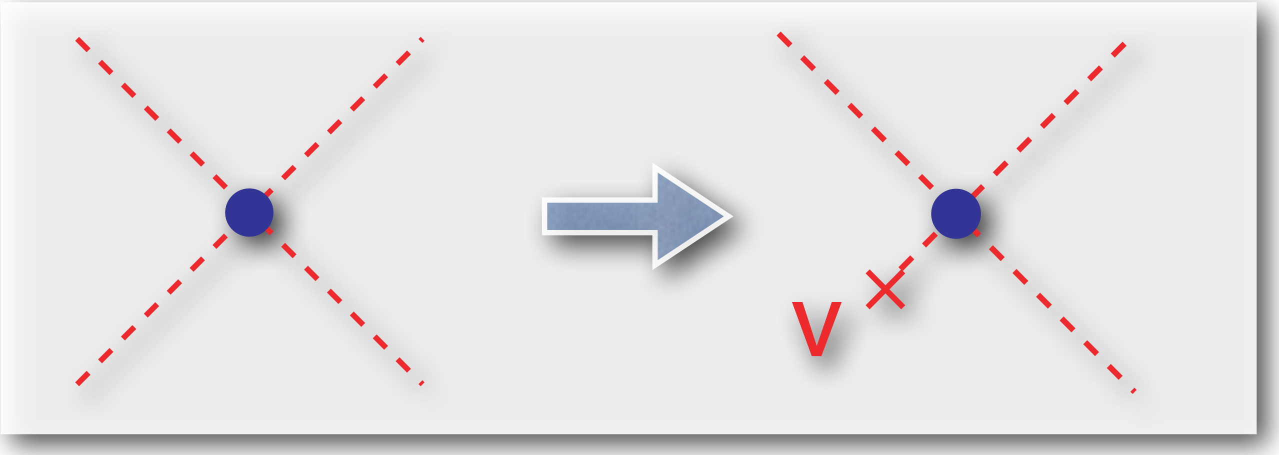
Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

Higgs Self-coupling

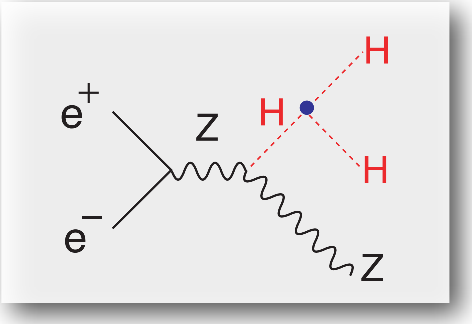
What force makes the Higgs condense in the vacuum?

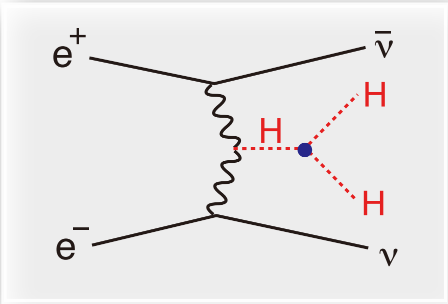


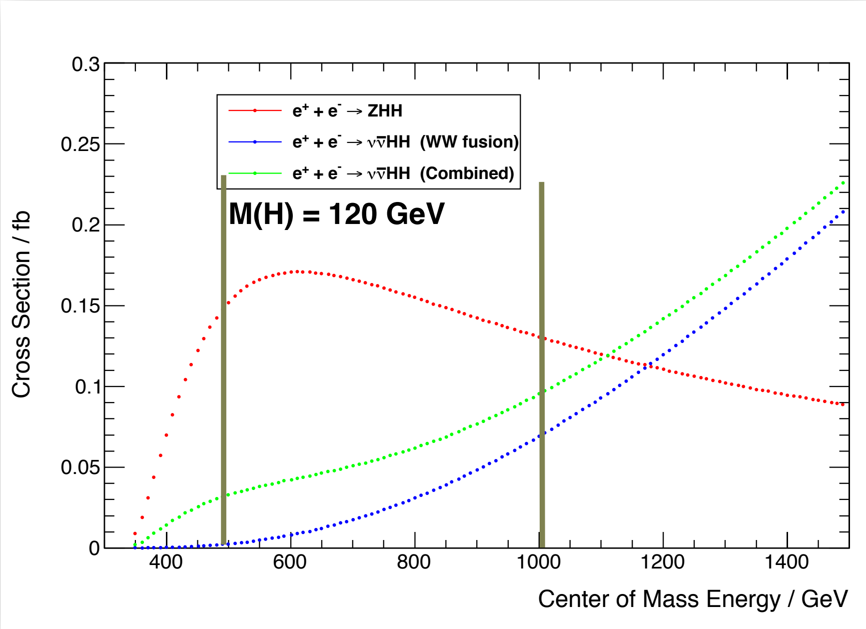
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential

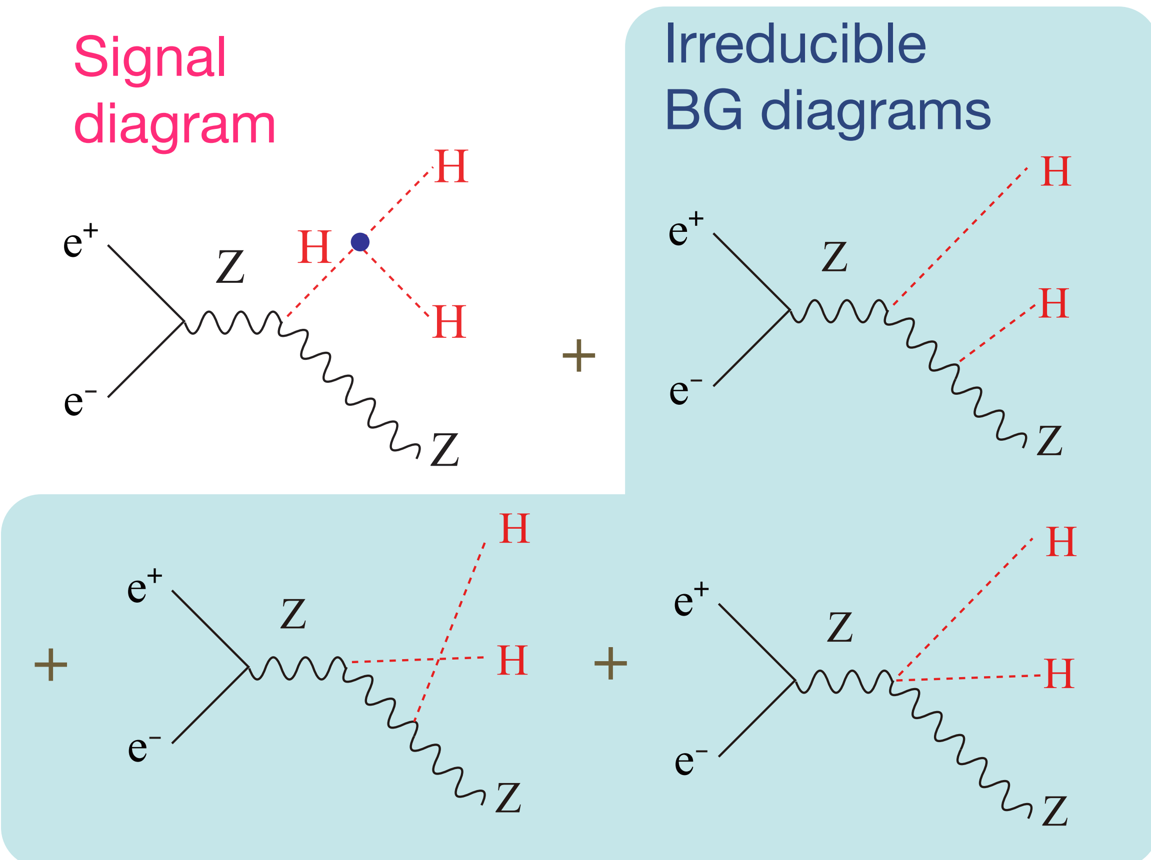






The measurement is very difficult even at ILC.

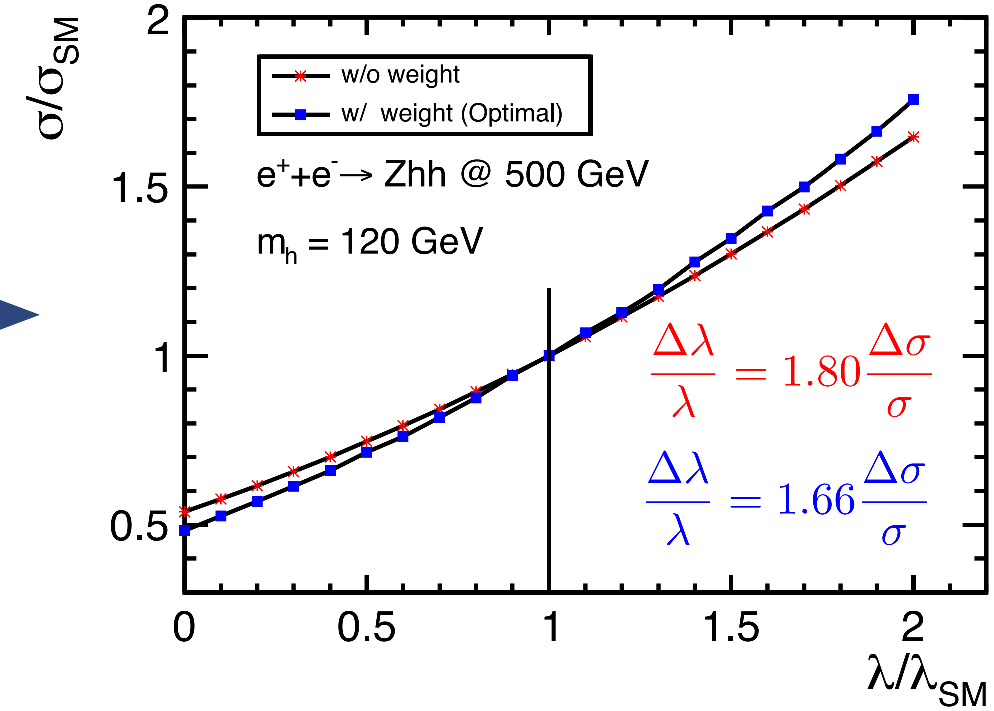
The Problem : BG diagrams dilute self-coupling contribution

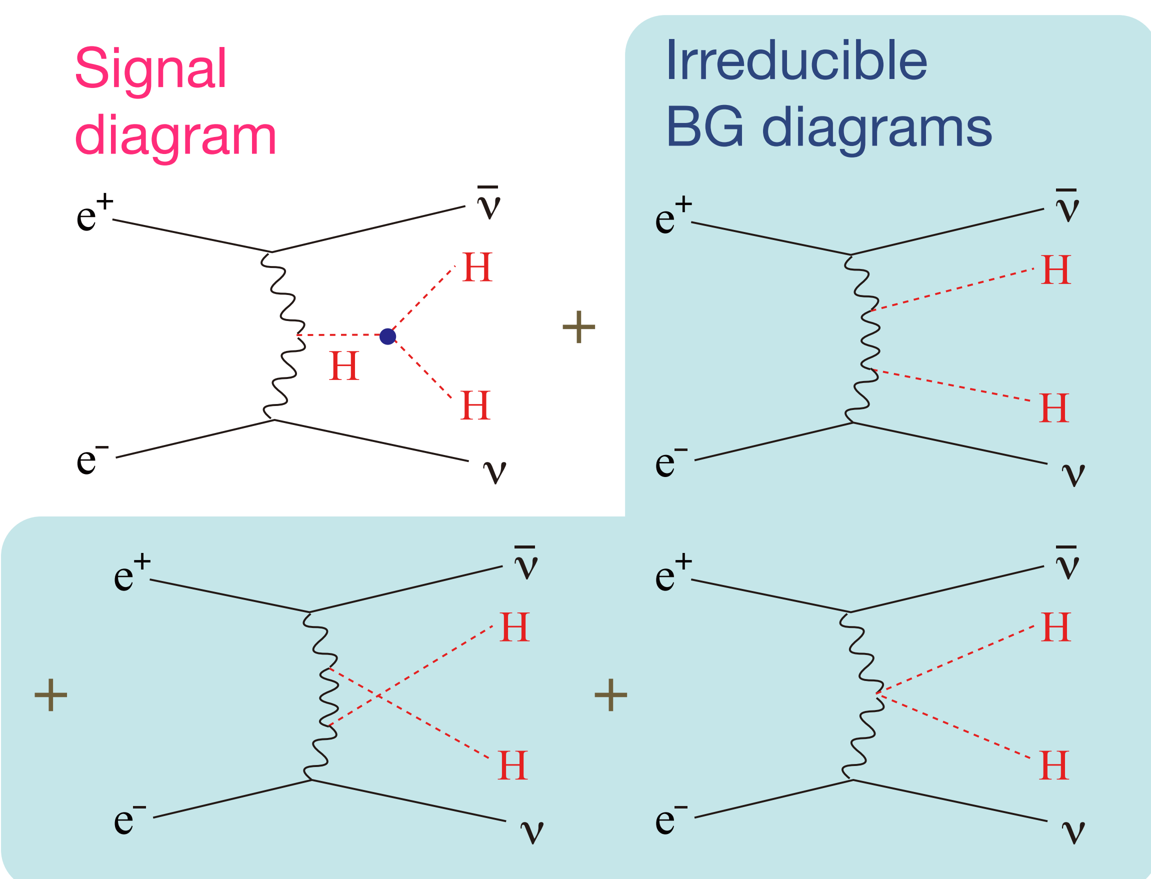


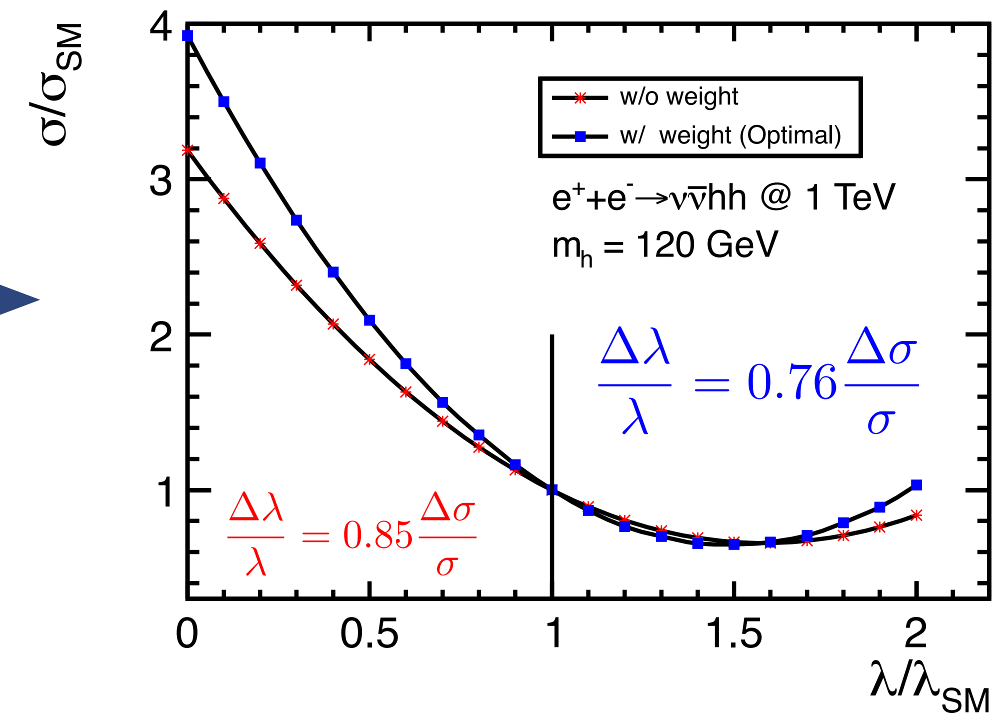
$$\sigma = \lambda^2 S + \lambda I + B$$

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

F=0.5 if no BG diagrams







Junping Tian LC-REP-2013-003

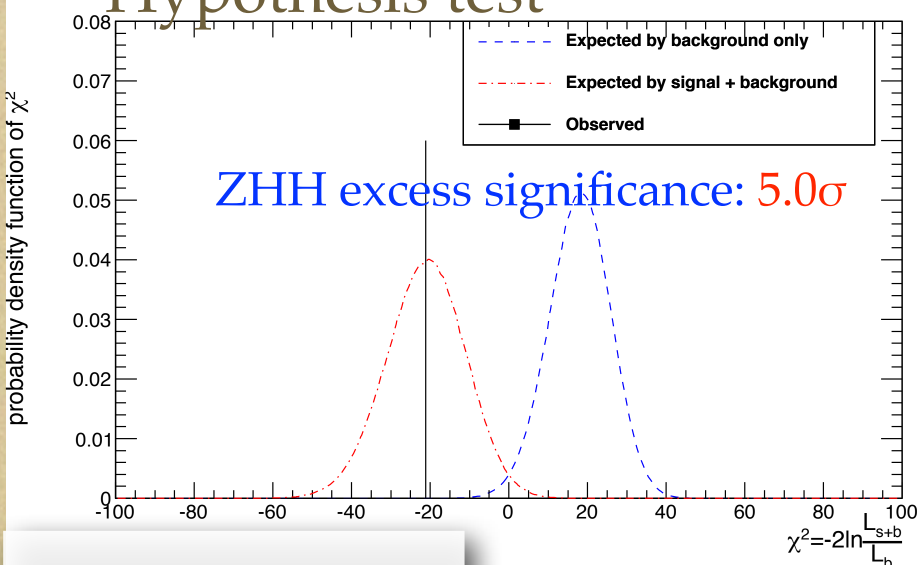
DBD full simulation

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

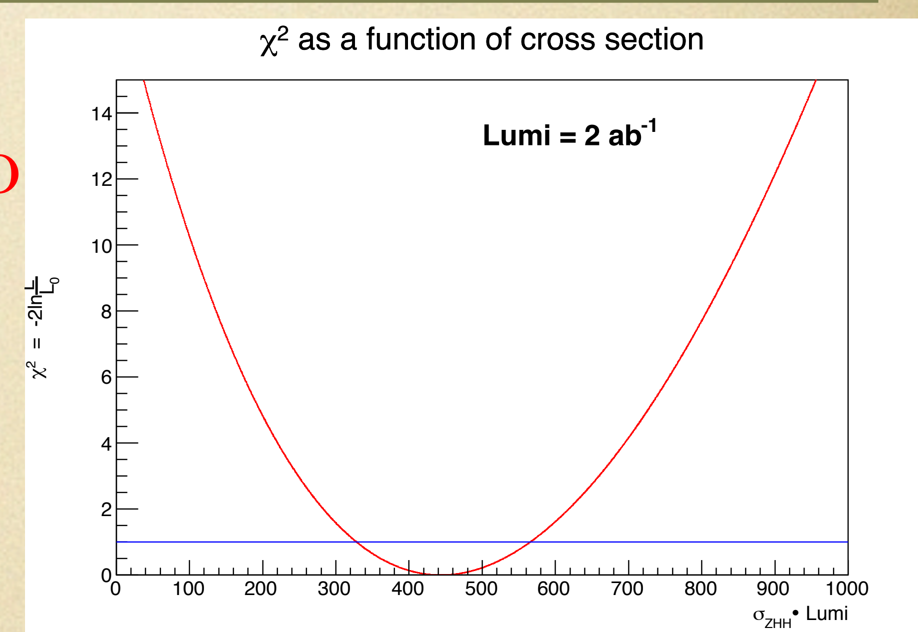
Hypothesis test

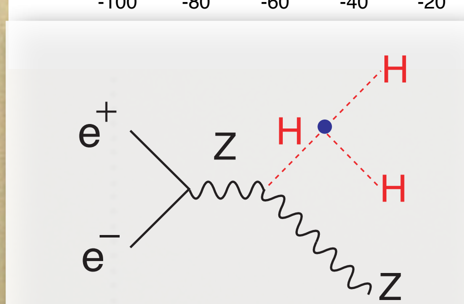


$$\sigma_{ZHH} = 0.22 \pm 0.06 \text{ fb}$$

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

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





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

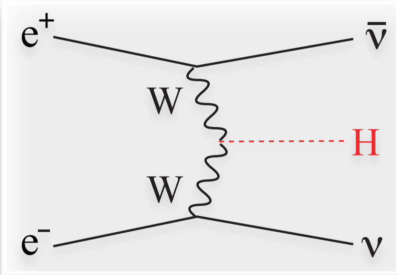
ILC 1000

Higgs Physics at Higher Energy

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

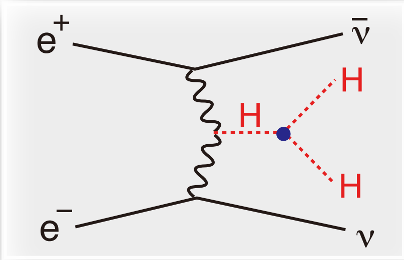
ννH @ at >1TeV : > 1ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

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



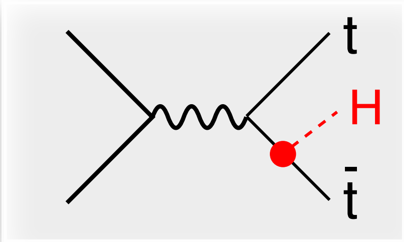
ννHH @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

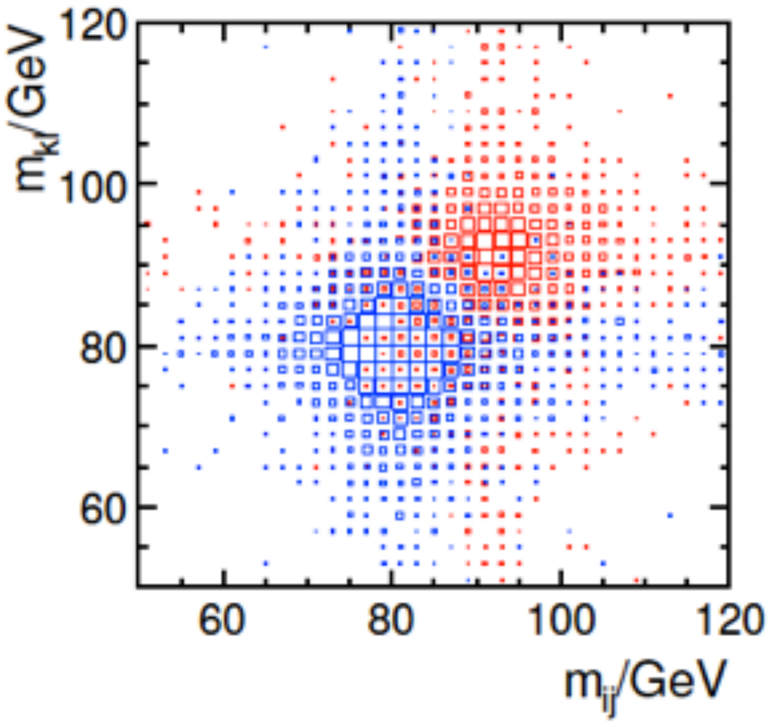
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).



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

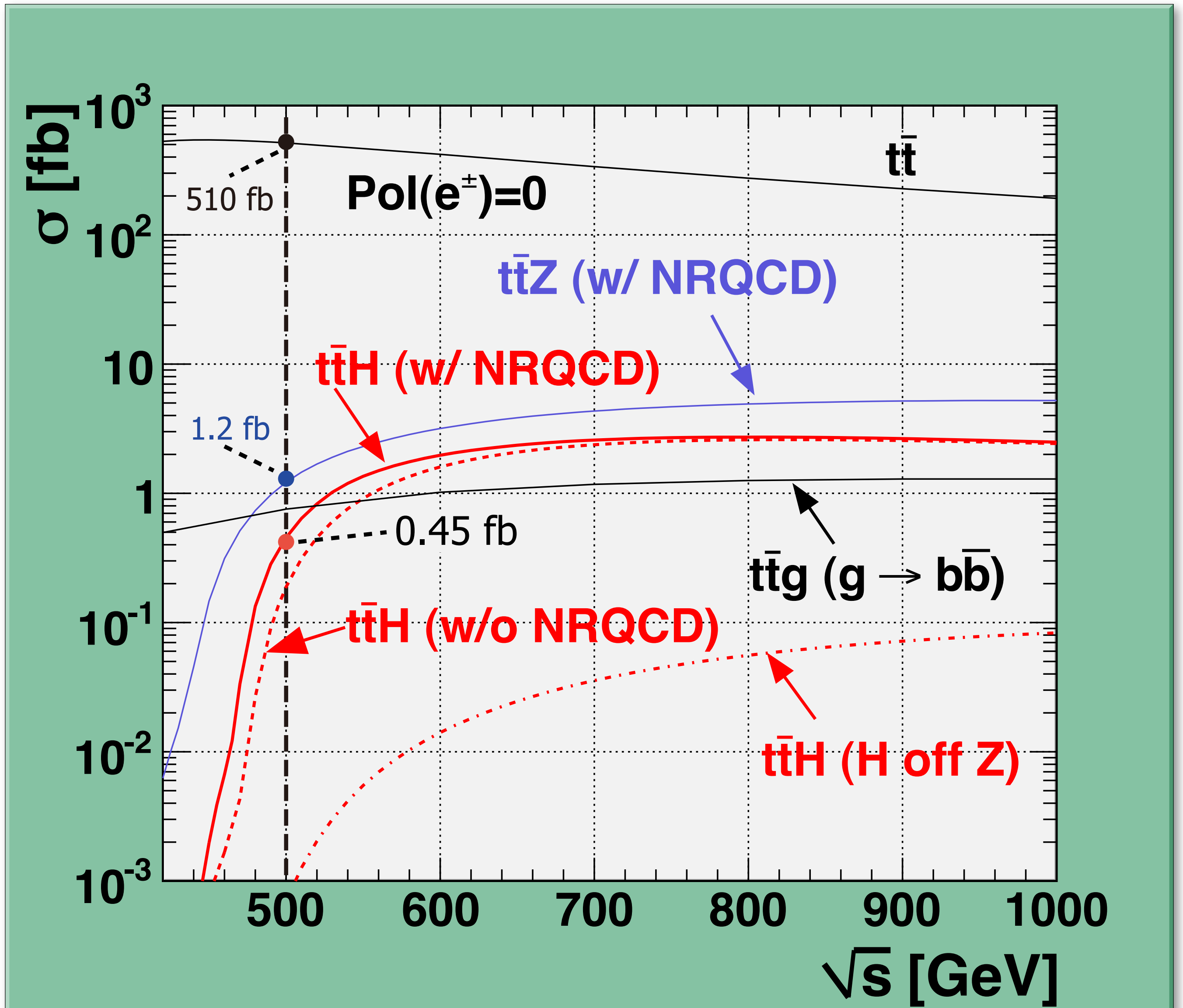
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

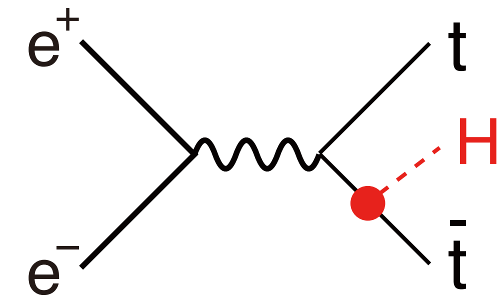
($M_H = 125$ GeV)

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→bb	1.1%	10.5%	1.8%	0.66%	0.32%
H→cc	7.4%		12%	6.2%	3.1%
H→gg	9.1%		14%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.6%	1.6%
H→ττ	4.2%		5.4%	14%	3.5%
H→ZZ*	19%		25%	8.2%	4.1%
H→γγ	48%		48%	33%	11%

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

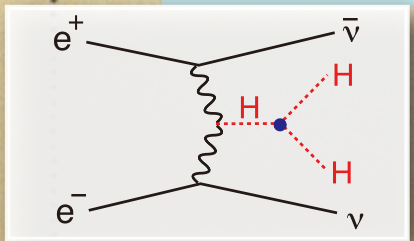
	Expected	After Cut
ννhh (WW F)	272	35.7
ννhh (ZHH)	74.0	3.88
BG (tt/ννZH)	7.86×10^5	33.7
significance	0.30	4.29

- 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)

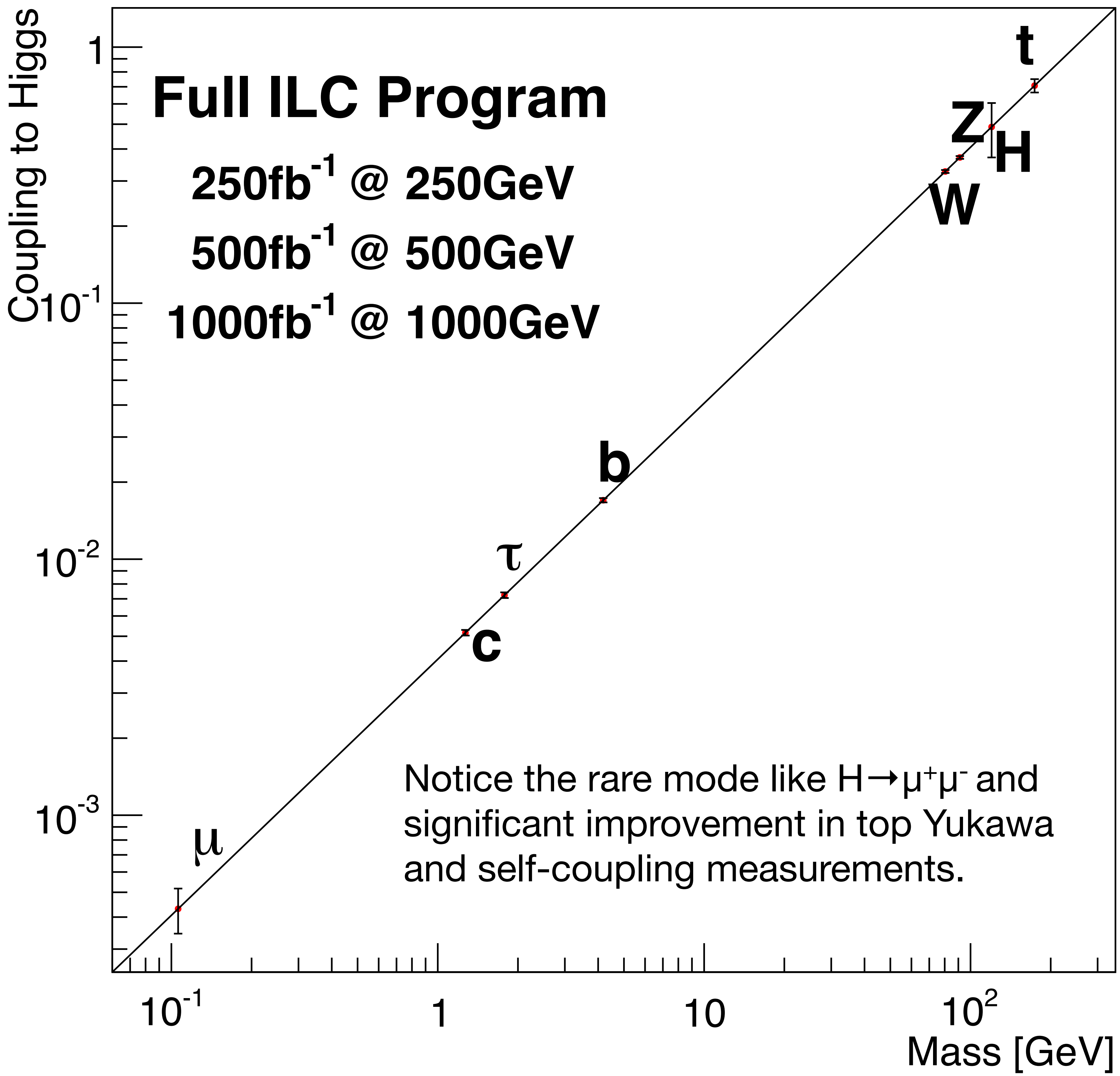
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV

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%
Hττ	5.7%	2.5%	2.0%
Hγγ	25%	12%	5.2%
Hμμ	-	-	16%
Γ_0	11%	5.9%	5.6%
Htt	-	16%	3.8%
HHH	-	104%	26%

Mass Coupling Relation

After Canonical 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

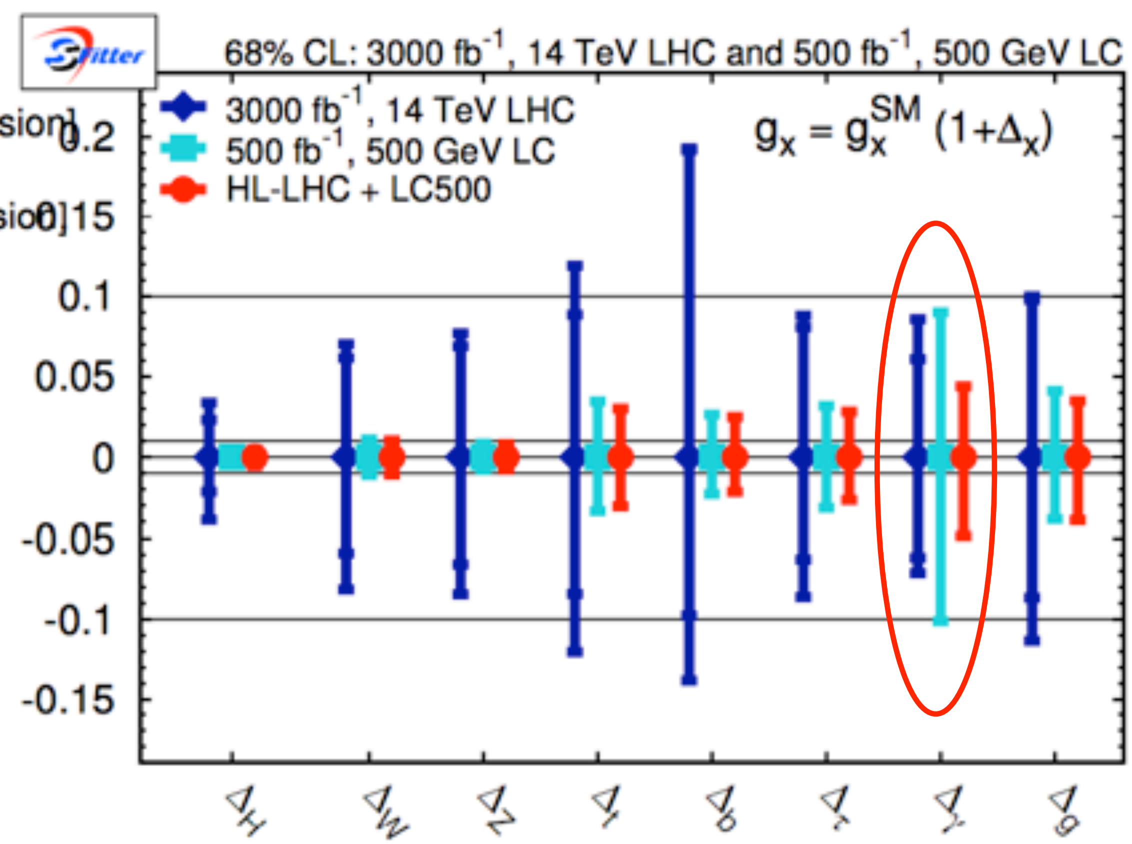
– LHC extrapolations unclear [SFitter version]

– 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

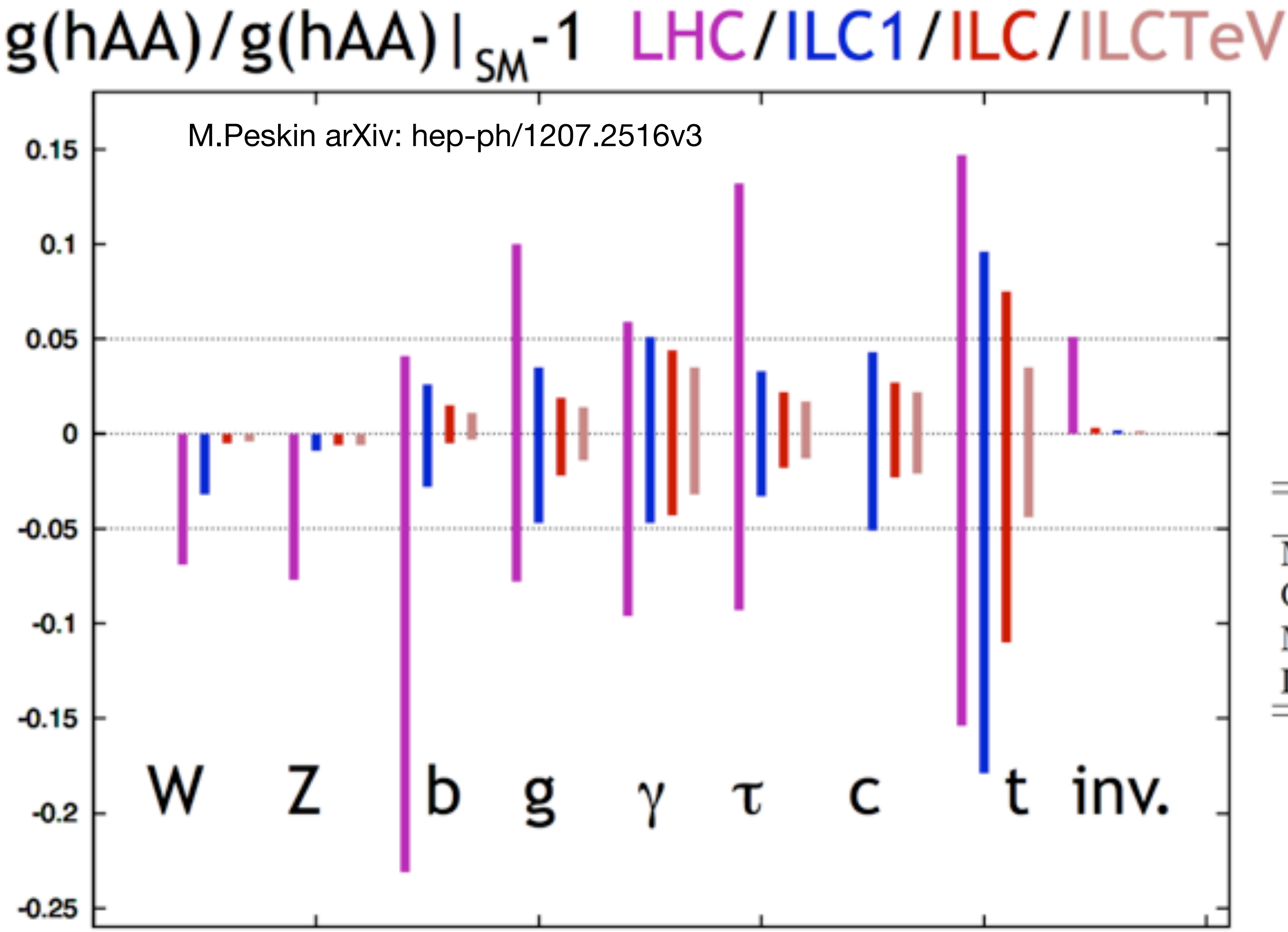


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC 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!

HL-ILC ?

High Luminosity ILC

The current ILC design is rather conservative!

ILC Luminosity Upgrade

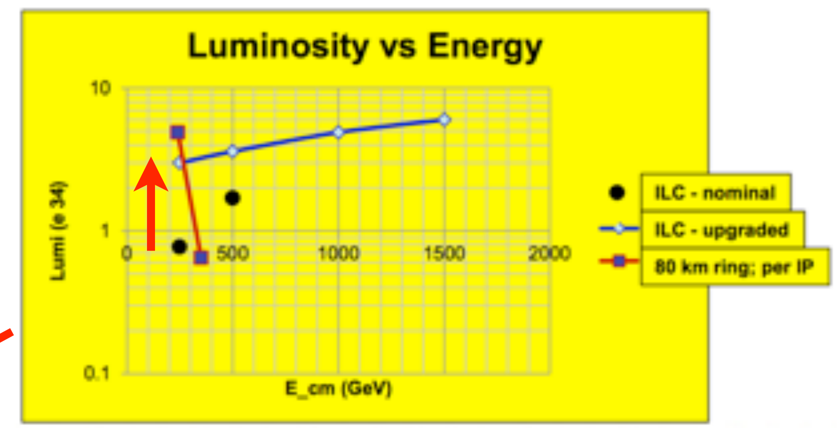
- Concept: increase n_b from 1312 → 2625
  - Reduce linac bunch spacing 554 ns → 336 ns
  - Increase pulse current 5.8 → 8.8 mA
  - Increase number of klystrons by ~50%
- Doubles beam power → ×2 L ($3.6\times10^{34} cm^{-2}s^{-1}$)
- Damping ring:
  - Electron ring doubles current (389mA → 778mA)
  - Positron ring: possible 2^{nd} (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%)

14 March, 2013 Marc Ross, SLAC 11

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

x4 upgrade @250GeV

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%
Hττ	3.0%	1.3%	1.0%
Hγγ	13%	5.9%	2.9%
Hμμ	-	-	9.3%
Γ_0	6.1%	3.1%	3.0%
Htt	-	8.5%	2.6%

HHH	-	50%	15%

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 $\sigma \times Br$ 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.

Last but Not Least

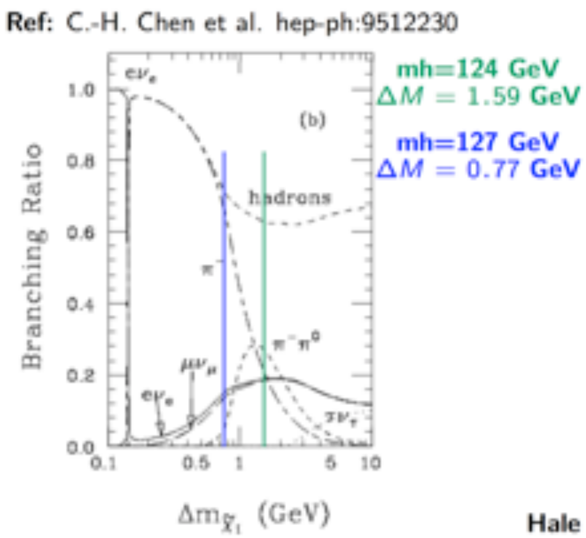
- In this talk I have been focusing on the case where X(125GeV) alone would be the probe for BSM physics, but there is a good chance for the higher energy run of LHC to bring us more.
- It is also very important to stress that ILC, too, is an energy frontier machine. It will access the energy region never explored with any lepton collider. There can be a zoo of new uncolored particles or new phenomena that are difficult to find at LHC but can be discovered and studied in detail at ILC.
- For instance
  - Natural SUSY : naturalness prefers μ not far above 100GeV
    --> light chargino/neutralinos will be higgsino-dominant and nearly degenerate
    --> typically Δm of a few GeV or less (very difficult for LHC)
    --> Δm as small as 50MeV possible with ISR tagging at ILC
    --> If Δm=800MeV --> possible to measure m to 1.5GeV and Δm to 20MeV
    --> ILC will also be a Higgsino factory!
  - Possible anomalies in precision studies of properties of top, W/Z, and two-fermion processes

Higgsinos in Natural SUSY (ΔM<a few GeV)

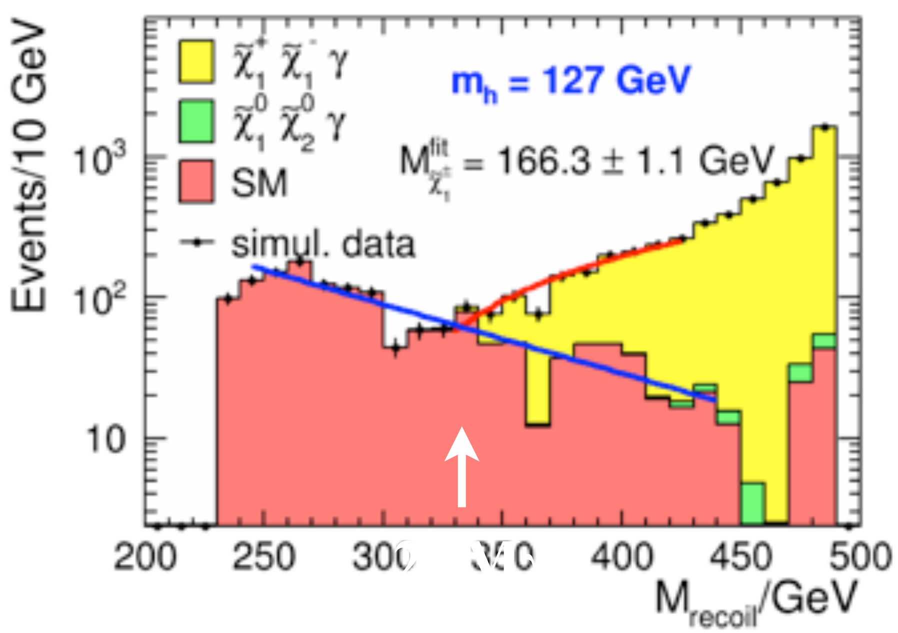
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$

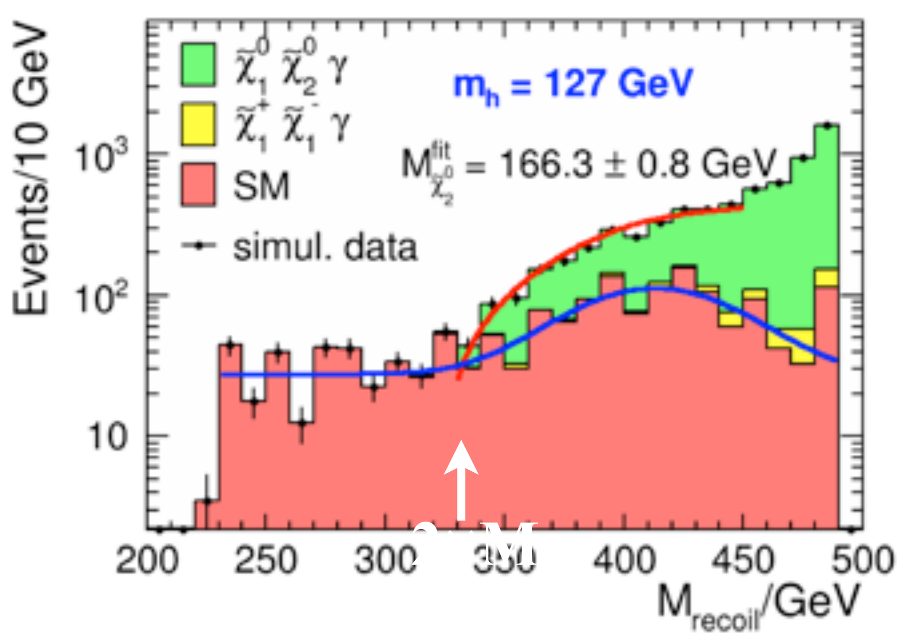
ISR Tagging

Hale Sert
ECFA LCWS 2013, DESY



Only very soft particles in the final states → Require a hard ISR to kill huge two-photon BG!





Conclusion

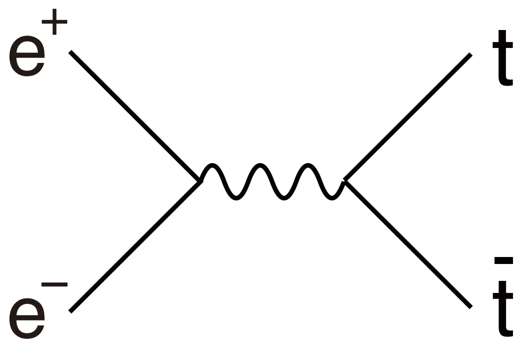
- Light Higgsinos are well motivated by naturalness
- It is a challenging scenario for LHC
- Separation of Higgsinos at the reconstructed level is possible at the ILC
- Assumed
  - $\sqrt{s} = 500$ GeV
  - $\int \mathcal{L}dt = 500\ fb^{-1}$ with $P(e^+,e^-) = (+30\%, -80\%)$ and $P(e^+,e^-) = (-30\%, +80\%)$ each
- Statistical uncertainities for $P(e^+,e^-) = (+30\%, -80\%)$

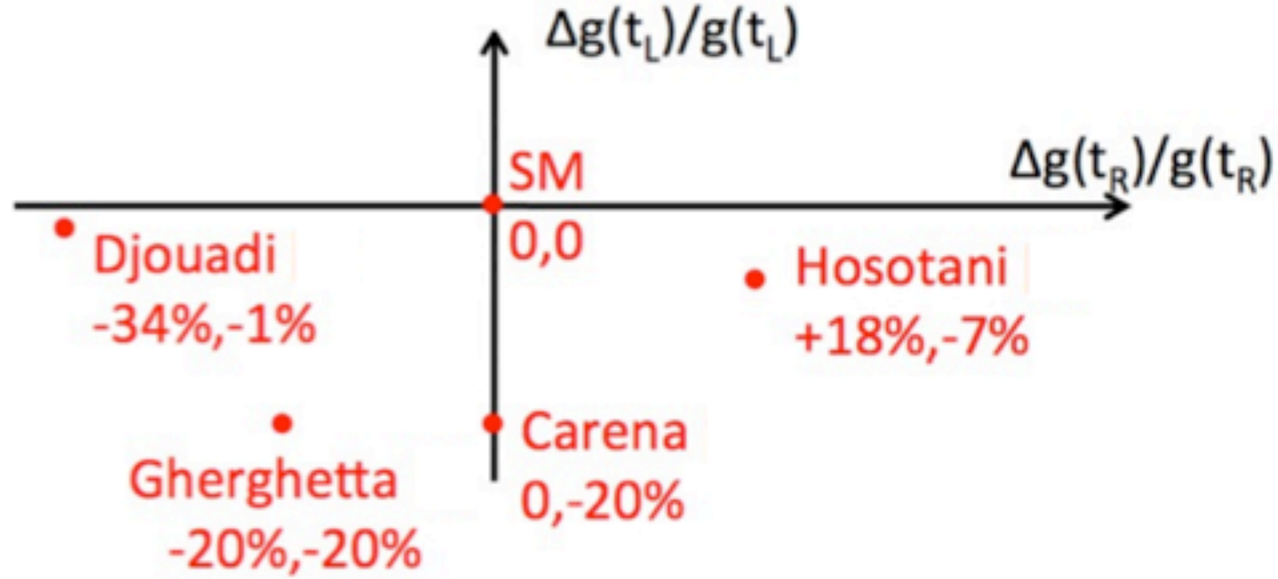
m_h=124 GeV
- $\delta(\sigma \times BR) \approx 3\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 2.1(3.7)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 70$ MeV

m_h=127 GeV
- $\delta(\sigma \times BR) \approx 1.5\ \%$ $\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_2^0}) \approx 1.5(1.6)$ GeV $\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 20$ MeV

Top Quark

Anomalous Couplings in Open Top Production at 500 GeV





LAL 11-222

Figure 34: *Predictions of various groups [40,42–44] on deviations from Standard Model couplings of the t quark within Randall-Sundrum Models. The cartoon is taken from [47].*

coupling	LHC, 300 fb^{-1}	e^+e^- [23]	coupling	LHC, 300 fb^{-1}	e^+e^- [23]
$\Delta\widetilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}	$\Delta\widetilde{F}^{Z}_{1V}$	$^{+0.24}_{-0.62}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{1A}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}	$\Delta\widetilde{F}^{Z}_{1A}$	$^{+0.052}_{-0.060}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}	$\Delta\widetilde{F}^{Z}_{2V}$	$^{+0.27}_{-0.19}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2A}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}	$\Delta\widetilde{F}^{Z}_{2A}$	$^{+0.28}_{-0.27}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

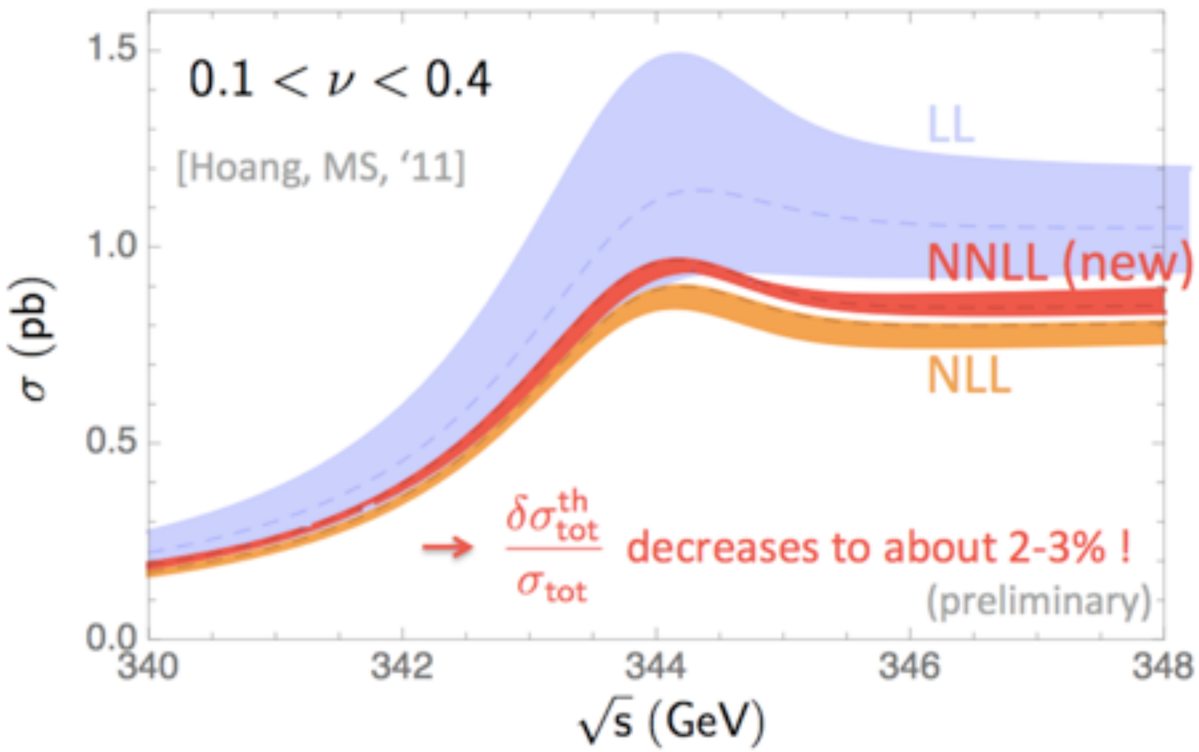
Table 12: *Sensitivities achievable at 68.3% CL for the anomalous ttV ($V=\gamma, Z$) couplings $\widetilde{F}^{V}_{1V,A}$ and $\widetilde{F}^{V}_{2V,A}$ of Eq. (59) at the LHC for integrated luminosities of 300 fb^{-1}, and the ILC with $\sqrt{s}=500$ GeV (taken from Ref. [23]). Only one coupling at a time is allowed to deviate from its SM value. Table and caption have been copied from [16].*

arXiv:hep-ph/0601112v2

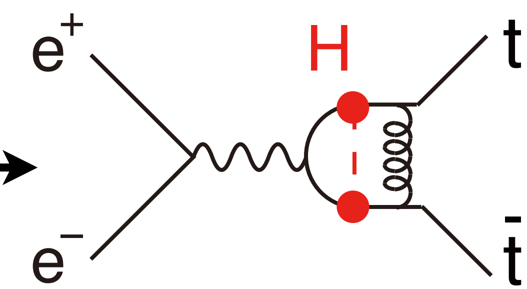
Top Quark

Threshold Region

M.Stahlhofen Top Phys WS 2012



Theory improving! →

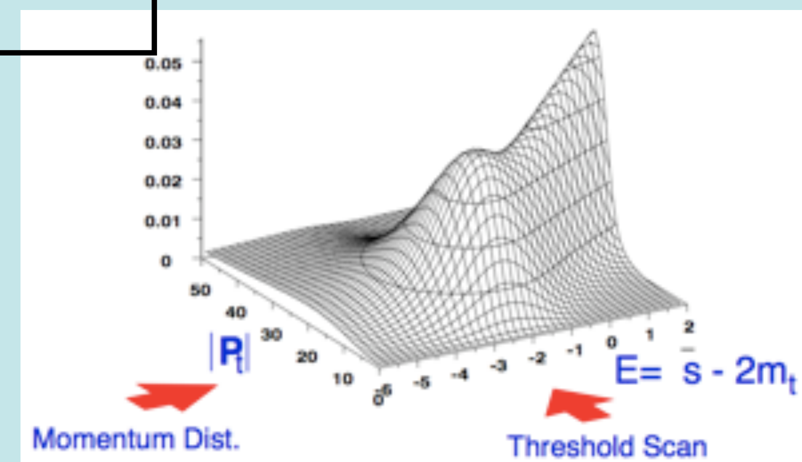


~10% effect

Expected accuracies

$$\Delta m_t = 34\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0023$$
$$\Delta\Gamma_t = 42\,\mathrm{MeV}$$

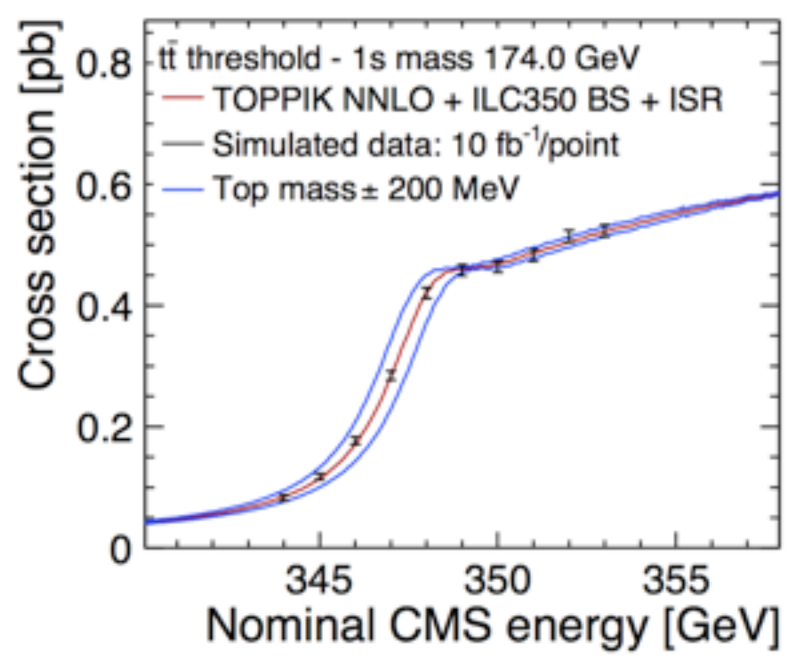
Threshold scan alone



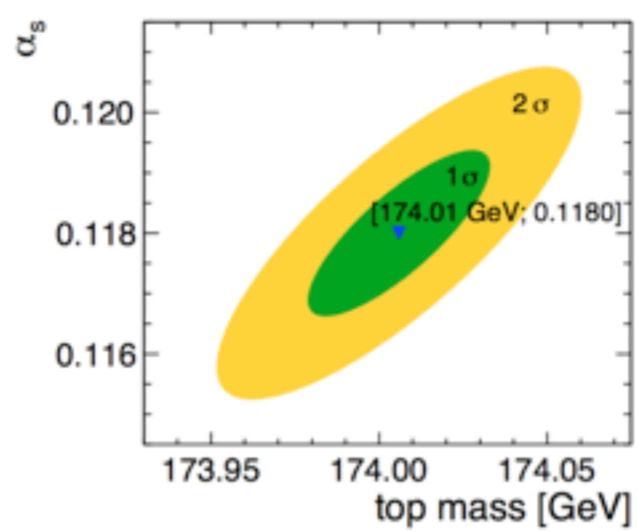
+ A$_{FB}$ & Top Momentum

$$\Delta m_t = 19\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0012$$
$$\Delta\Gamma_t = 32\,\mathrm{MeV}$$

arXiv:hep-ph/0601112v2



F.Simon Top Phys WS 2012



$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$

Shinya Kanemura, this WS

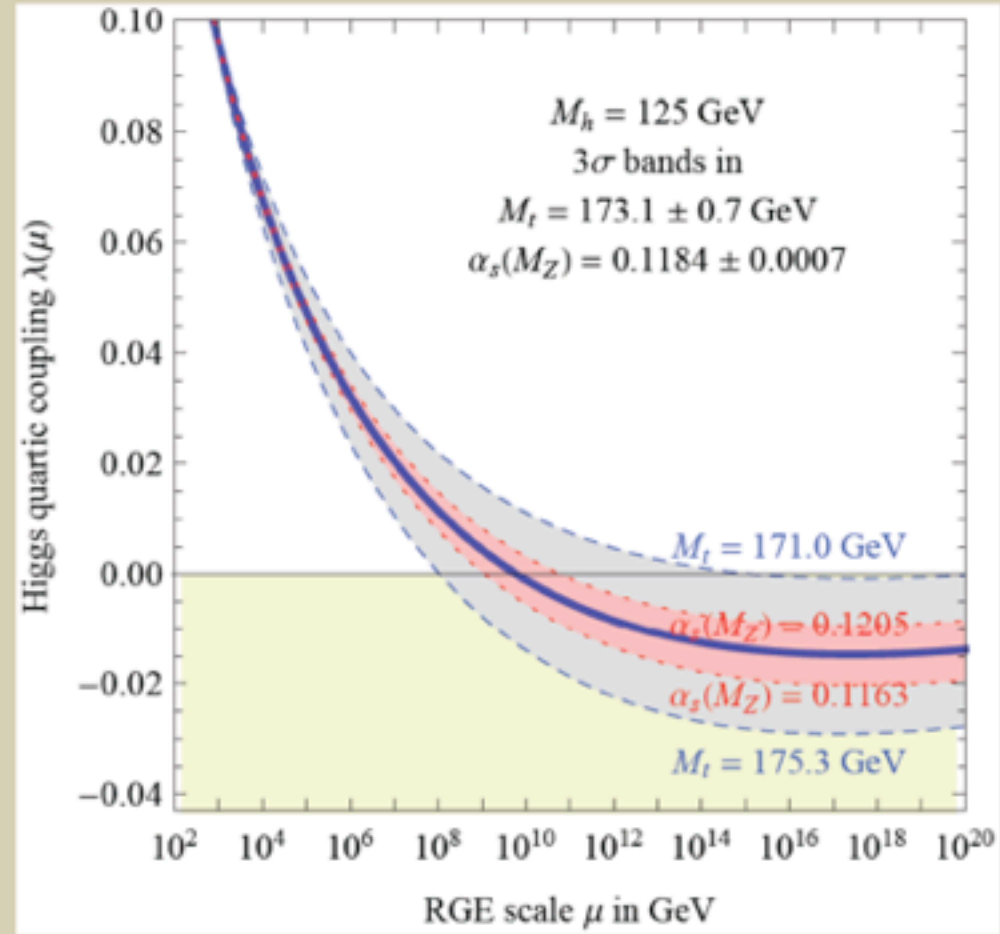
Vacuum Stability of the SM

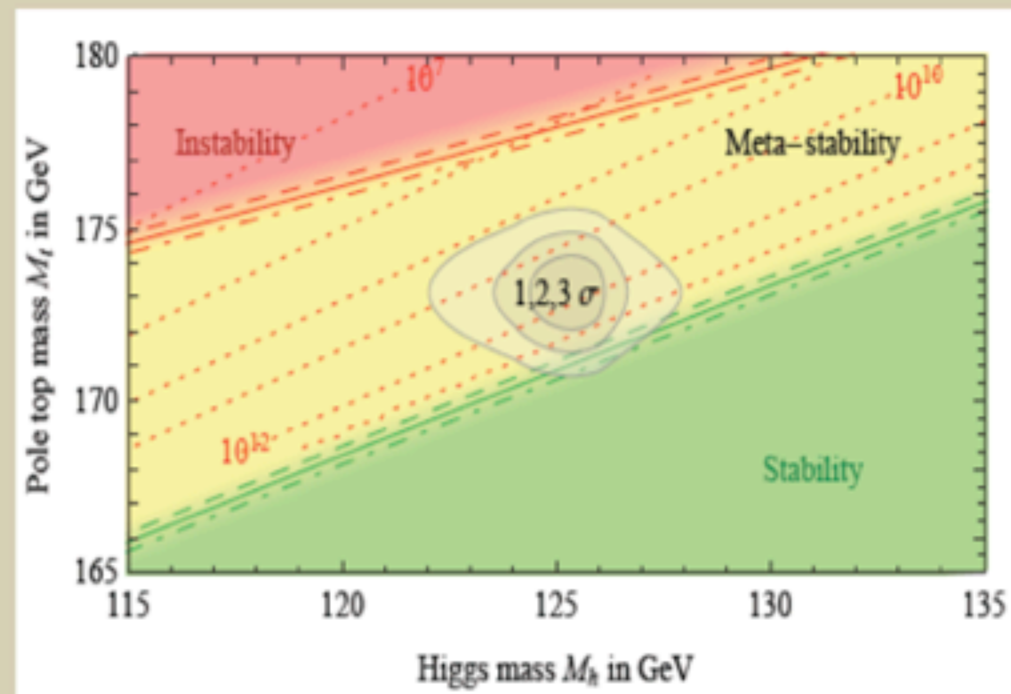
With the discovered 126 GeV Higgs boson, λ becomes negative below Planck Scale

Cut off $\Lambda = 10^7 - 10^{15}$ GeV
large uncertainty comes from large Δm_t

At ILC, $\Delta m_t \approx 30$ MeV is expected
Cutoff Λ can be better determined

At Planck Scale, $\lambda(M_{pl}) < 0$, but the theory satisfies the condition of **the meta-stable vacuum**





arXiv:1205.6497, Degrassi et al

Last but Not Least

- In this talk I have been focusing on the case where X(125GeV) alone would be the probe for BSM physics, but there is a good chance for the higher energy run of LHC to bring us more.
- It is also very important to stress that ILC, too, is an energy frontier machine. It will access the energy region never explored with any lepton collider. There can be a zoo of new uncolored particles or new phenomena that are difficult to find at LHC but can be discovered and studied in detail at ILC.
- Examples
  - Natural SUSY : naturalness prefers μ not far above 100GeV
    --> light chargino/neutralinos will be higgsino-dominant and nearly degenerate
    --> typically Δm of a few GeV or less (very difficult at LHC)
    --> Δm as small as 50MeV possible with ISR tagging at ILC
    --> If Δm=800MeV --> possible to measure m to 1.5GeV and Δm to 20MeV
    --> ILC will also be a Higgsino factory!
  - Possible anomalies in precision studies of properties of top, W/Z, and two-fermion processes
- Whatever new physics is awaiting for us, clean environment, polarized beams, and excellent jet energy resolution to reconstruct W/Z/t/H in their hadronic decays will enable us to uncover the nature of the new physics through model-independent precision measurements.