Physics Potential at the ILC

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arXiv: 1310.0763 (Higgs)
arXiv: 1307.5248 (BSM)
arXiv: 1307.8265 (Top)
arXiv: 1307.3962 (EW)

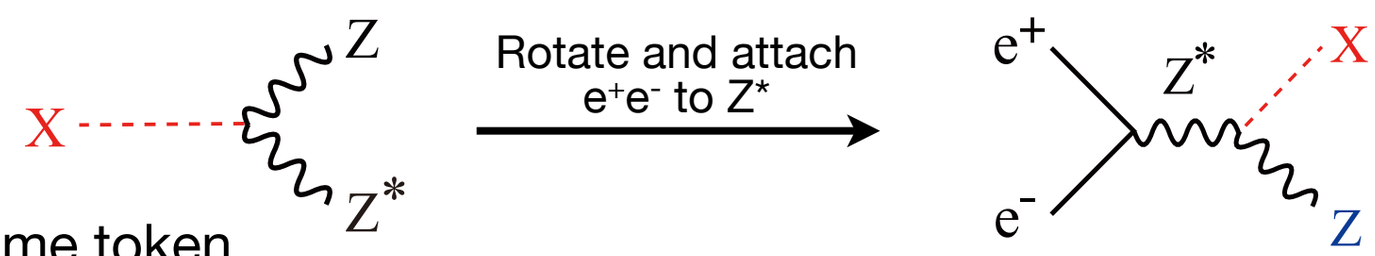
Electroweak Symmetry Breaking
Mystery of something in the vacuum

- 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 don't know why and how it condensed in the vacuum.
- We knew it's there in the vacuum with a vev of 246 GeV and a custodial SU(2) (ρ=1). But other than that we didn't know almost anything about the "something" until July 4, 2012.

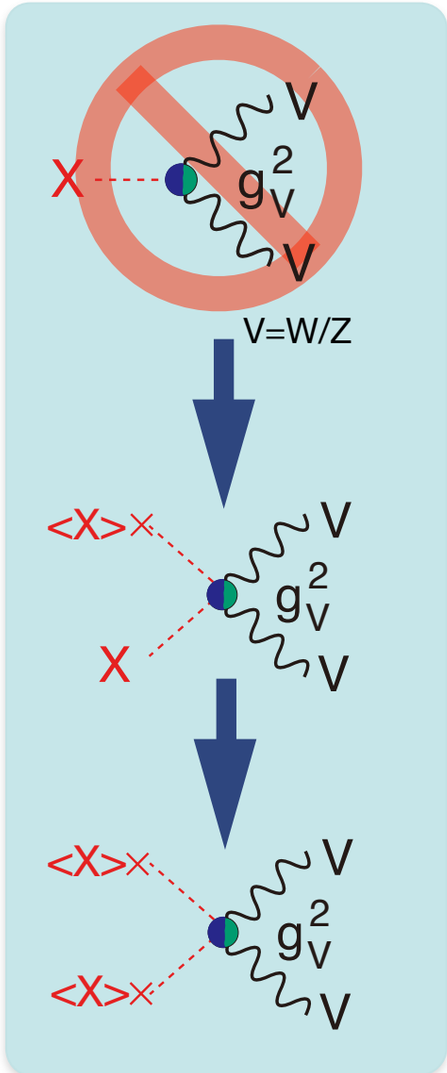
Since the July 4th, the world has changed!

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

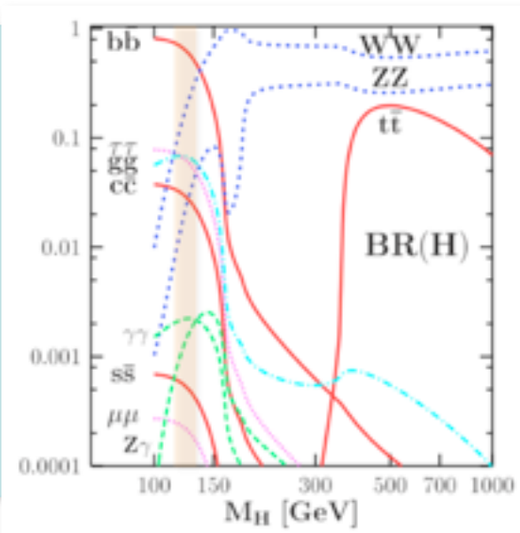
- X(125) → γγ means X is a neutral boson and J ≠ 1 (Landau-Yang theorem).
  Recent LHC results strongly suggest $J^P=0^+$.
- X(125) → ZZ*, WW* ⇒ ∃ XVV couplings: (V=W/Z: gauge bosons)
- There is, however, no gauge coupling like XVV, only XXVV or XXV
  ⇒ XVV probably from XXVV with one X replaced by <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. We need to know WHY X condensed in the vacuum.
- 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^- → *ννX*.

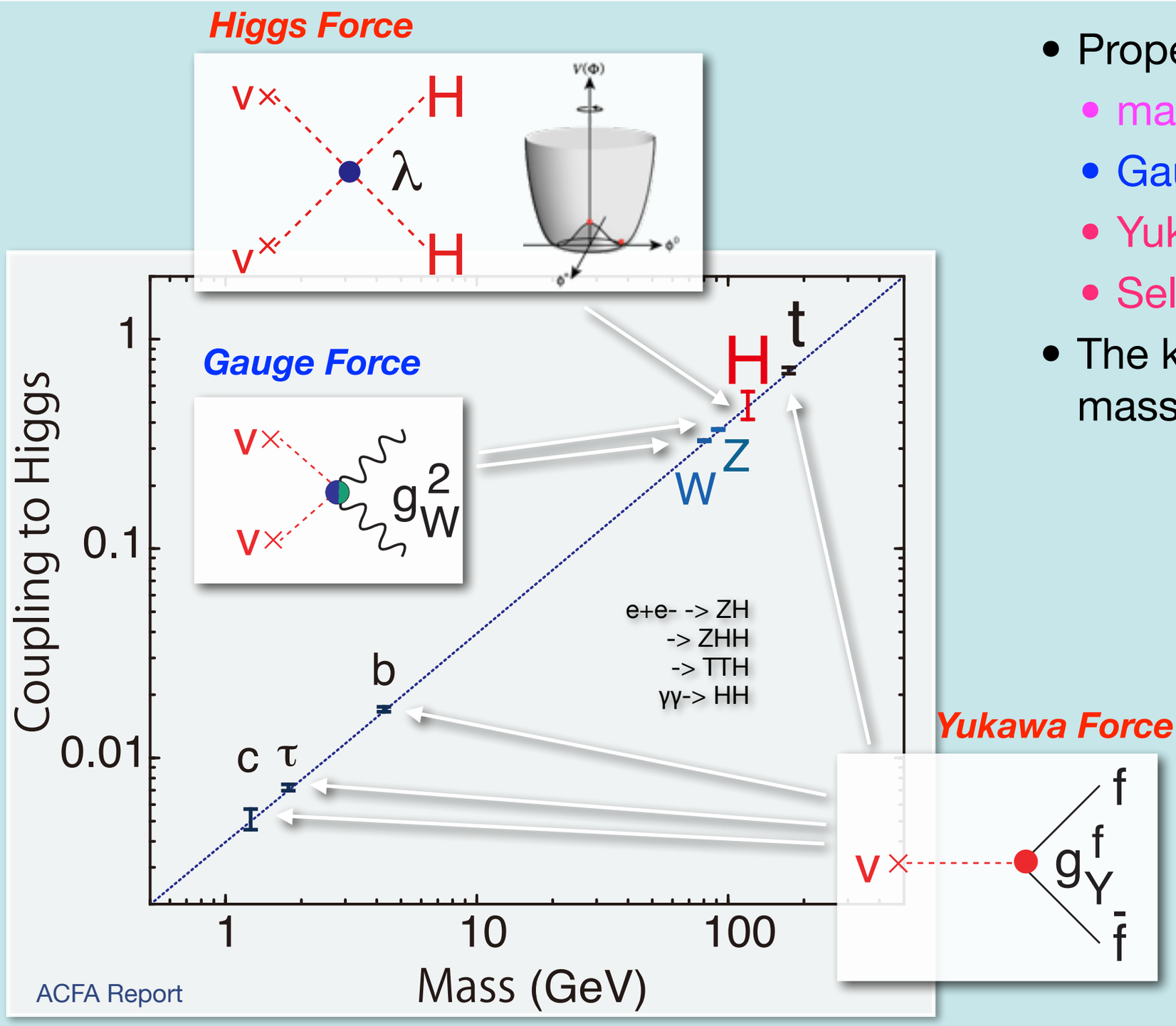


- So we now know that the major Higgs production mechanisms in e^+e^- collisions are indeed available at the ILC ⇒ No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, where variety of decay modes are accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed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

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

Any deviation from the straight line signals BSM!

The Higgs is a window to BSM physics!

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

through Precision Higgs Measurements

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

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

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

Mixing with singlet

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

Composite Higgs

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

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

SUSY

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

Expected deviations are small --> Precision!

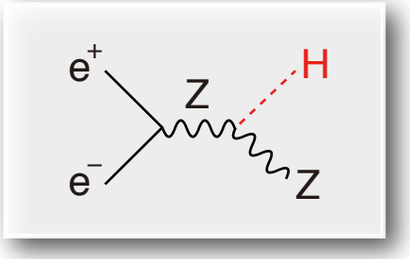
For the precision we need a 500GeV LC

Why 250-500 GeV?

Three well known thresholds

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

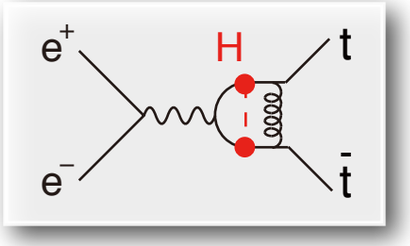
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)



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

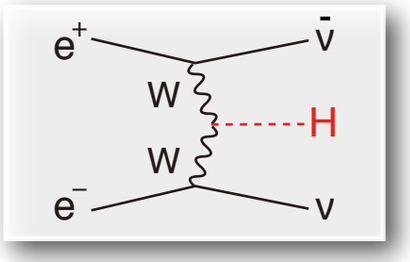
- Threshold scan --> theoretically clean mt measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



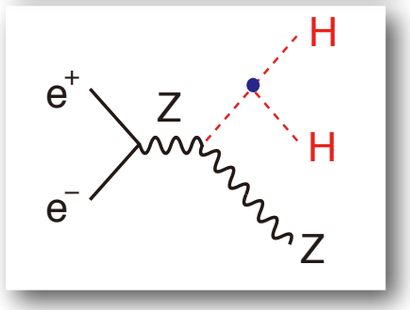
vvH @ 350 - 500GeV :

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



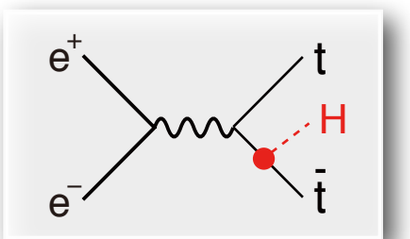
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- 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



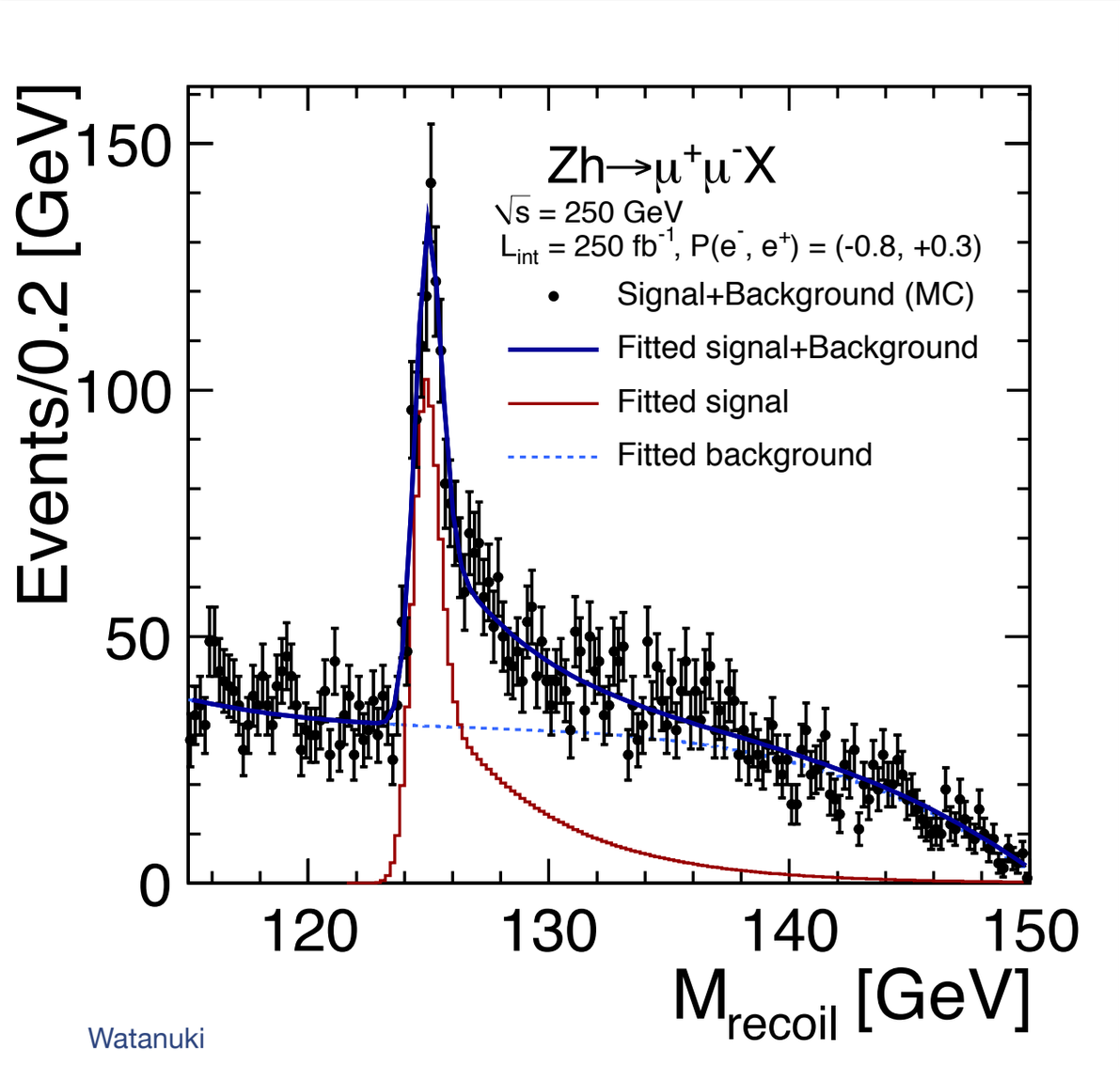
We can complete the mass-coupling plot at ~500GeV!

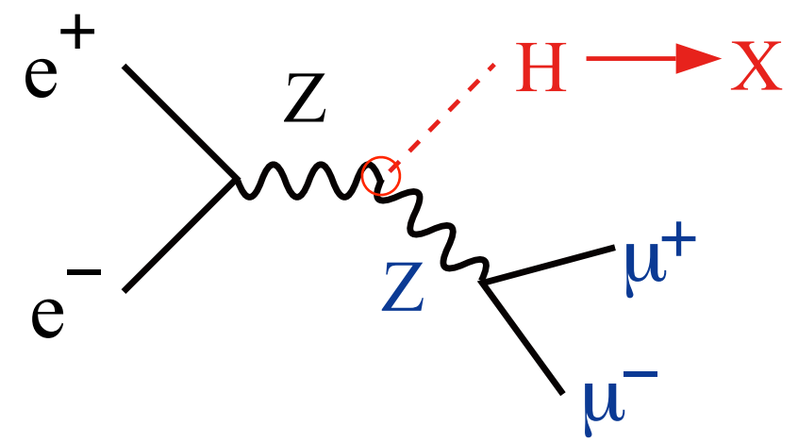
ILC 250

Recoil Mass Measurement

The flagship measurement of ILC 250

Recoil Mass





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

Invisible decay detectable!

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

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

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

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

scaled from mH=120 GeV

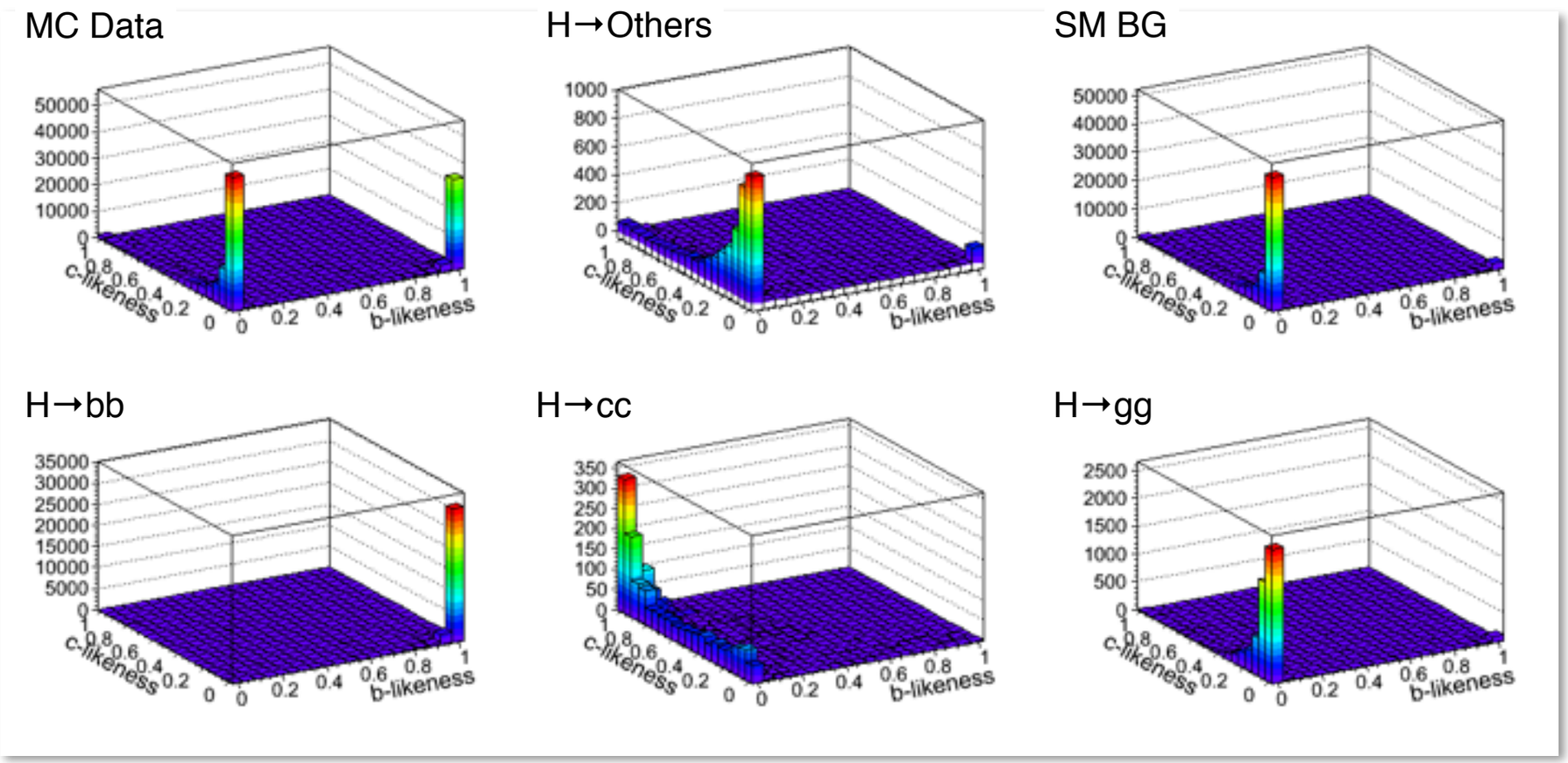
Key Point:

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

σ x BR Measurements

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

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



DBD Physics Chap.

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

scaled from mH=120 GeV

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

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

--> Δσ/σ=2.6% eventually limits the BR measurements.

--> luminosity upgrade (we will come back to this later).

From BRs to Couplings

One of the major advantages of the LC

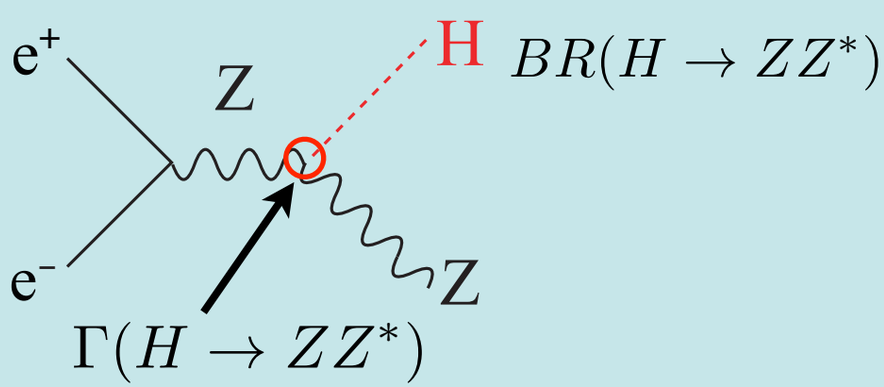
To extract couplings from BRs, we need the total width in general:

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

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

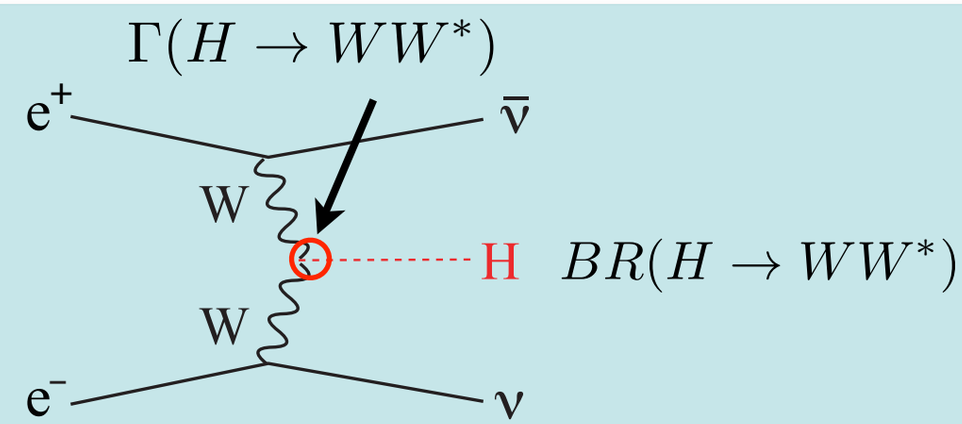
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

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

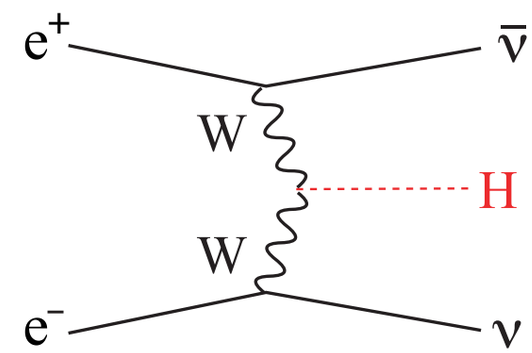
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

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

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

ILD DBD Full Simulation Study



comes in as a powerful tool!

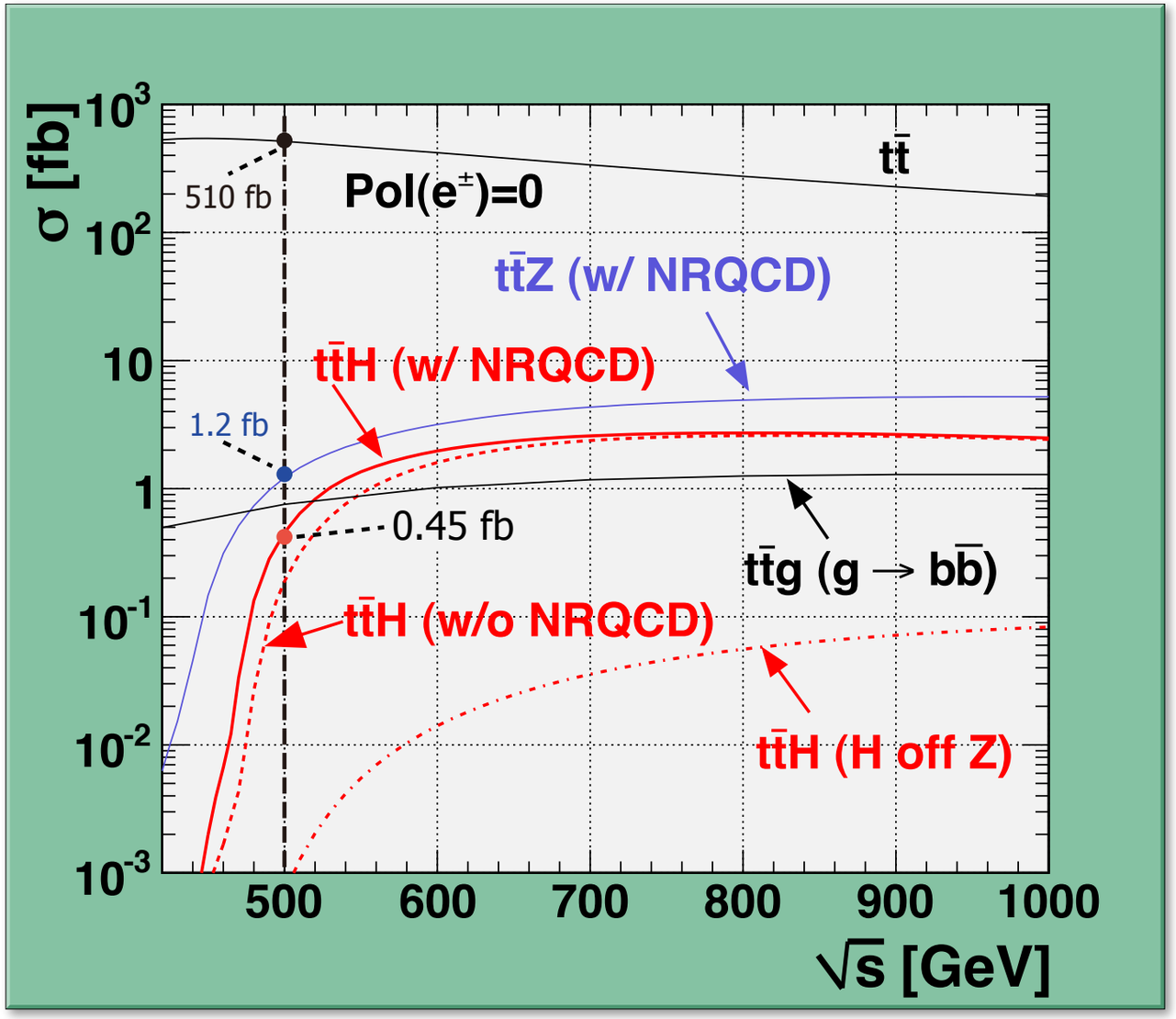
$$\Delta\Gamma_H/\Gamma_H \simeq 5\%$$

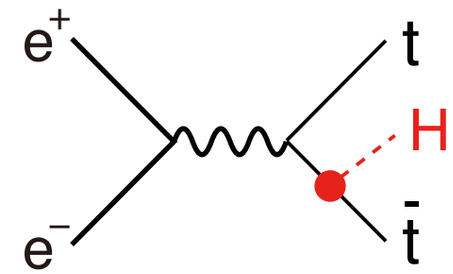
Mode	ΔBR/BR
bb	2.2 (2.9)%
cc	5.1 (8.7)%
gg	4.0 (7.5)%
WW*	3.1 (6.9)%
τ τ	3.7 (4.9)%

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

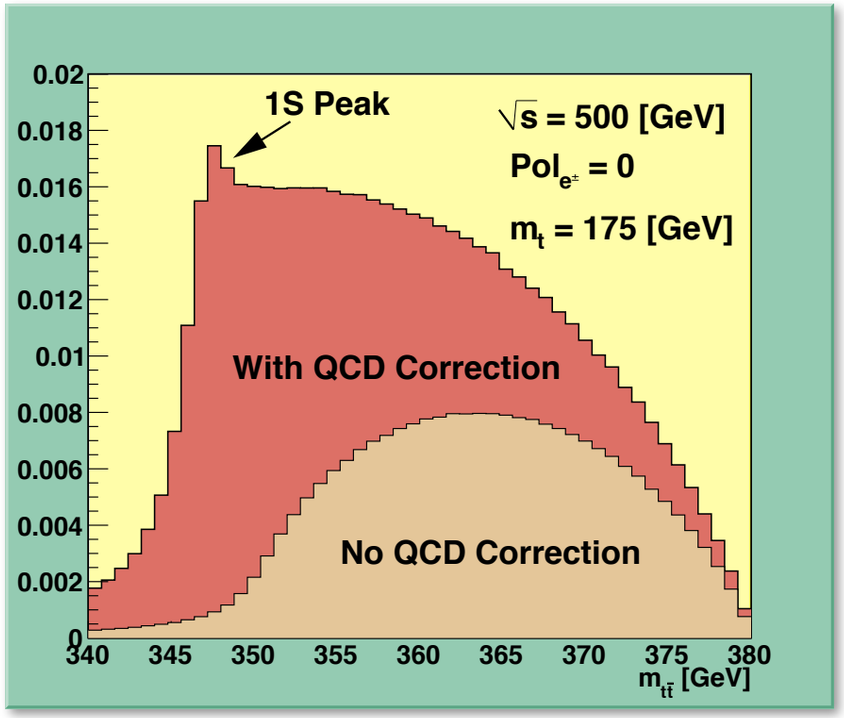
Top Yukawa Coupling

At 500 GeV we can directly access the top Yukawa coupling!





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

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

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

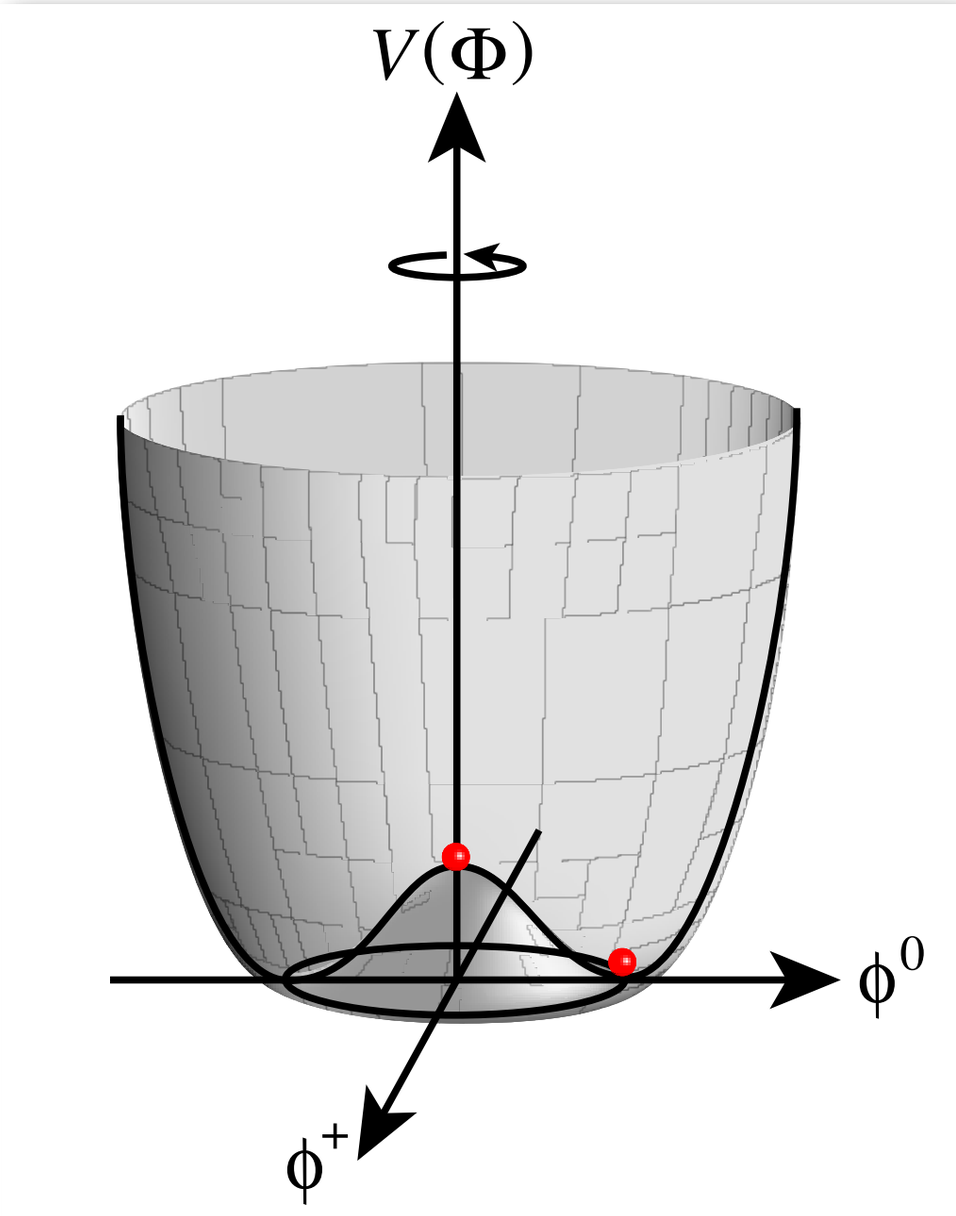
Tony Price, LCWS12 scaled from mH=120 GeV

Notice σ(500+20GeV)/σ(500GeV) ~ 2

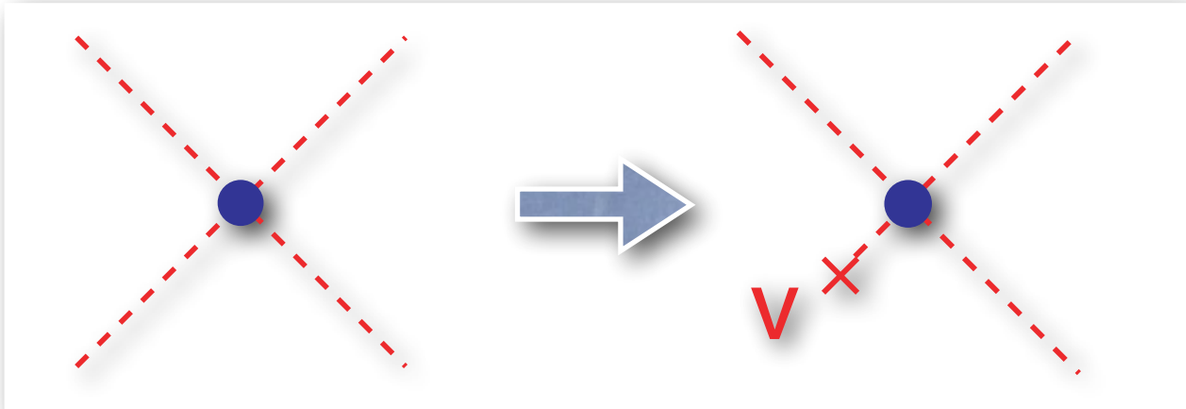
Moving up a little bit helps significantly!

And then Higgs Self-coupling

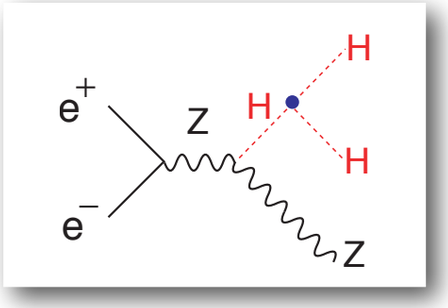
the force that made the Higgs condense in the vacuum

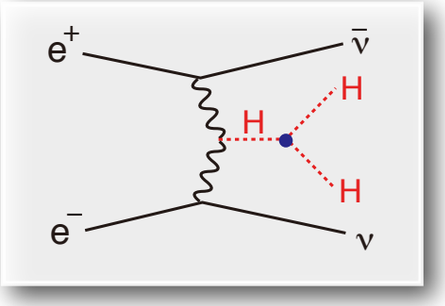


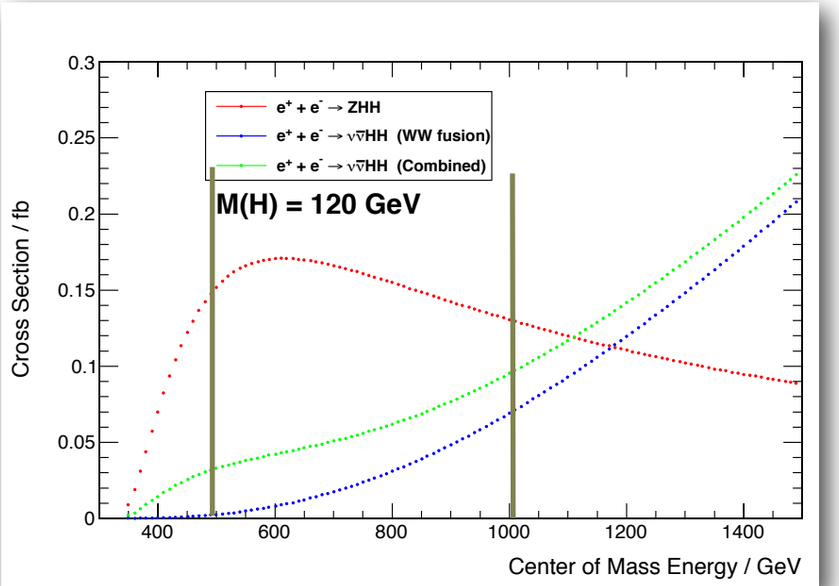
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential

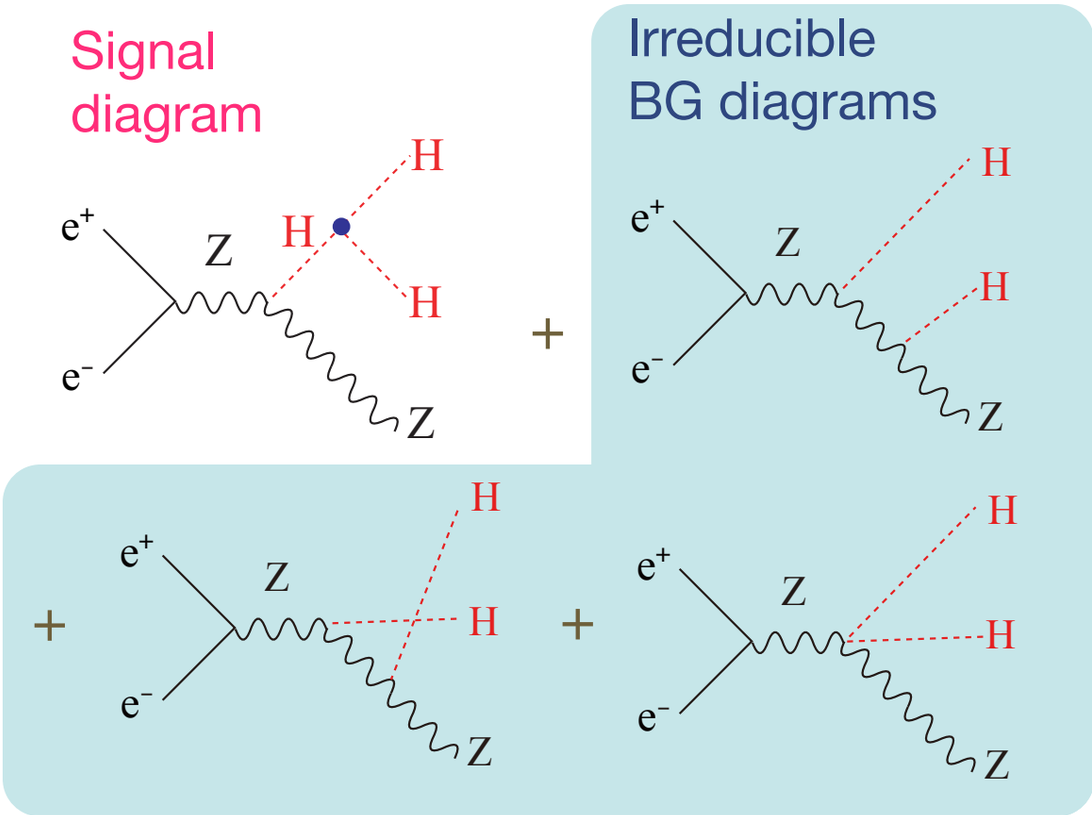






The measurement is very difficult even at ILC.

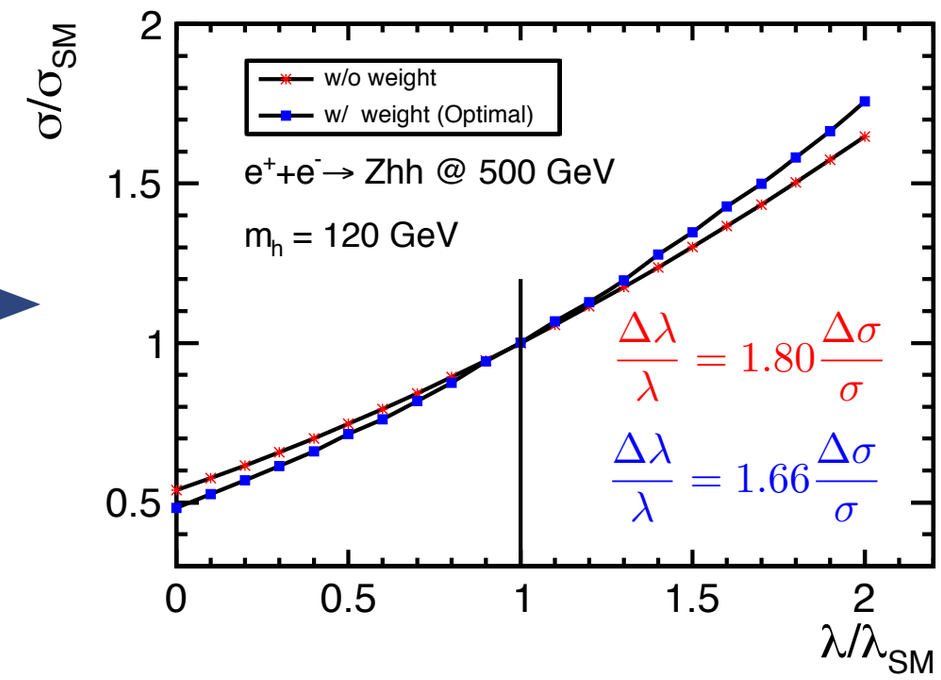
The Problem : BG diagrams dilute self-coupling contribution

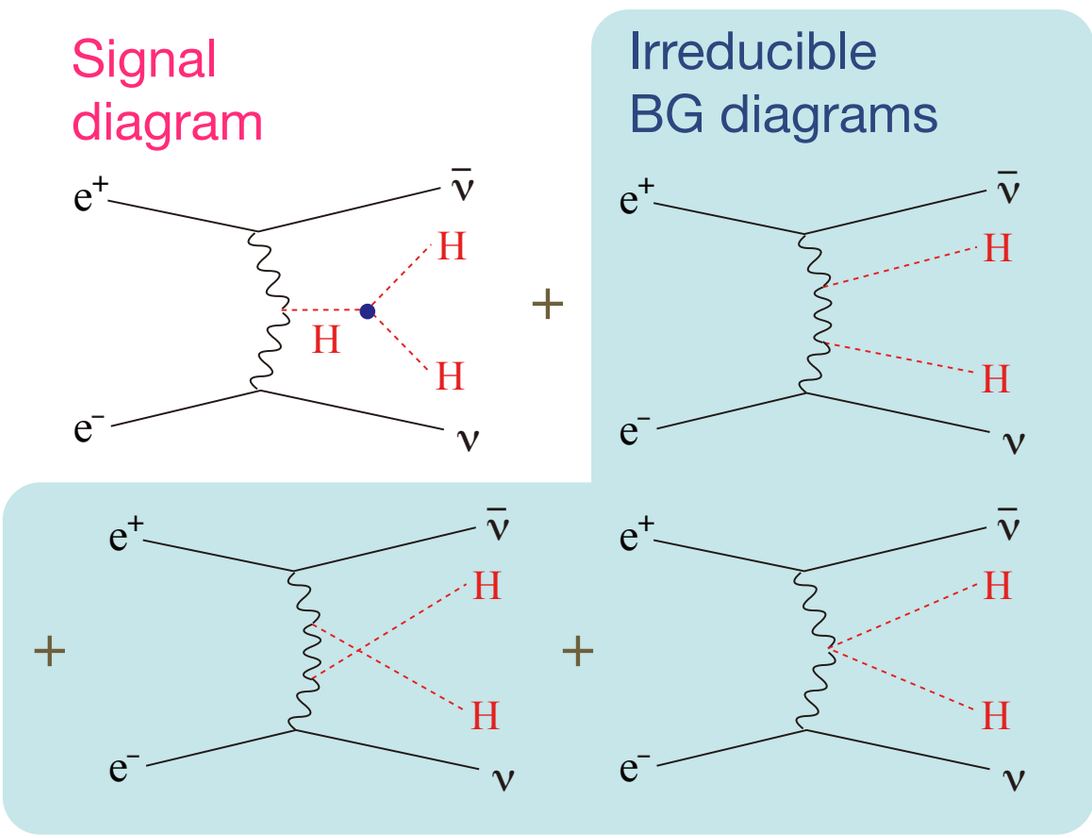


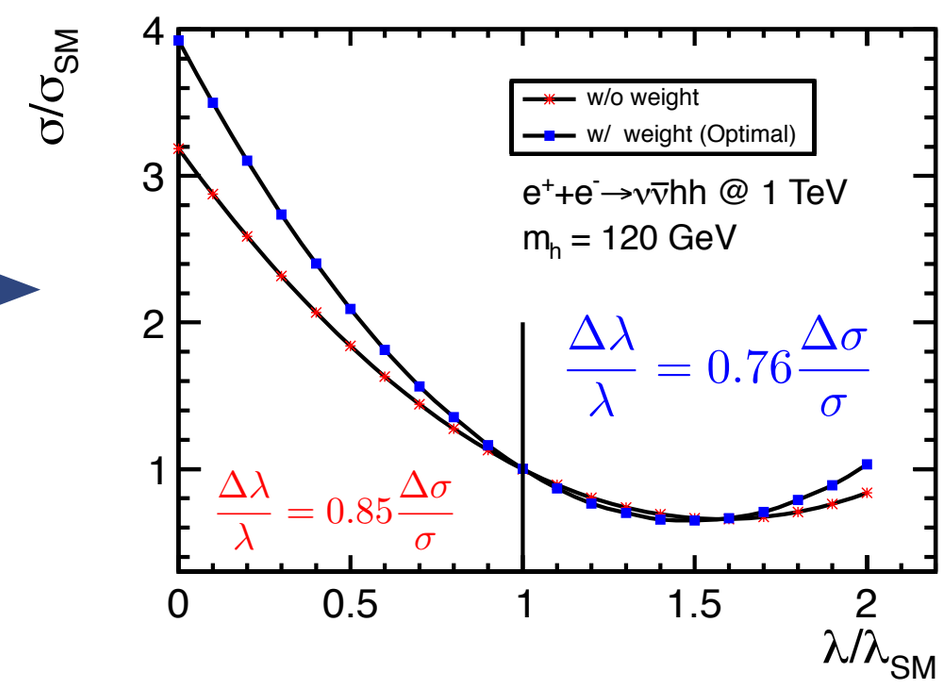
$$\sigma = \lambda^2 S + \lambda I + B$$

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

F=0.5 if no BG diagrams



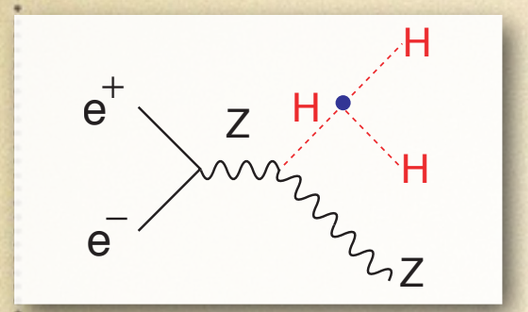




Junping Tian LC-REP-2013-003

DBD full simulation

Higgs self-coupling @ 500 GeV

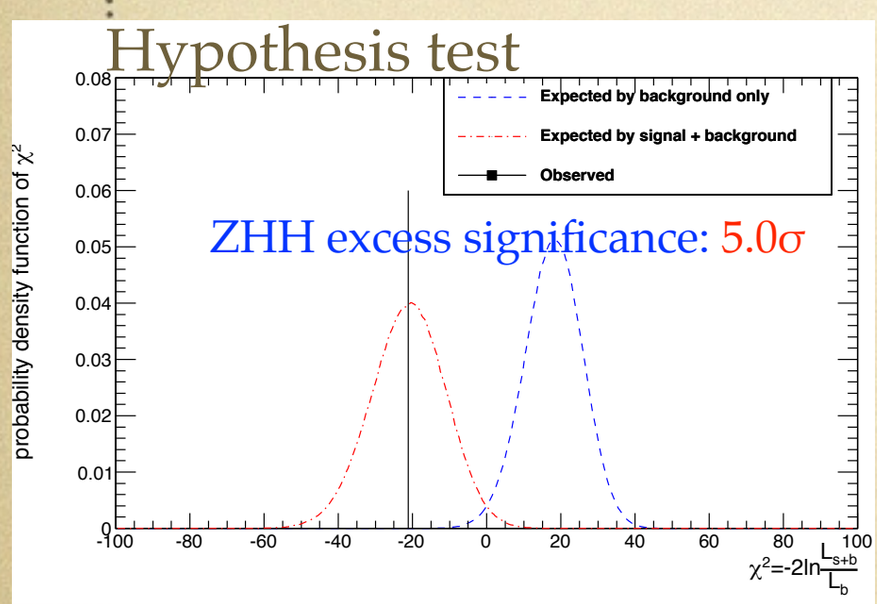


$$e^+ + e^- \to ZHH$$

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

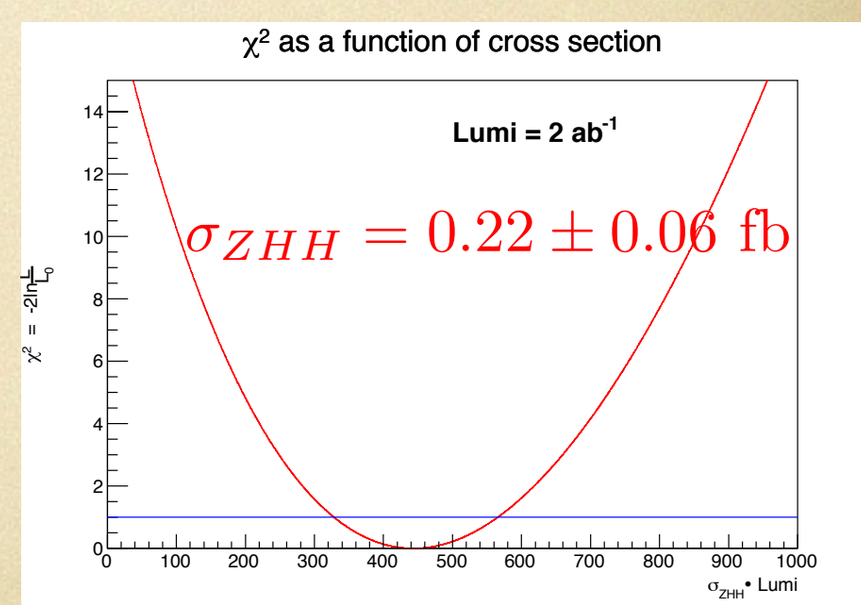
P(e-,e+)=(-0.8,+0.3)

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	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



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

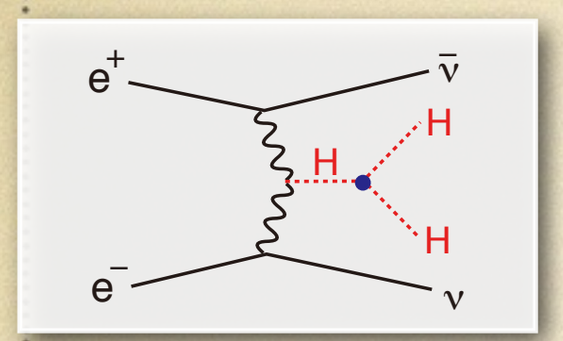
$$\frac{\delta\lambda}{\lambda} = 44\%$$



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

ILC 1000

DBD full simulation



Higgs self-coupling @ 1 TeV

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

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

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

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

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

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

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

Double Higgs excess significance: $> 7\sigma$

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

ILD DBD Study (Junping Tian)

HHH Prospects

Scaled to M(H)=125GeV

Scenario A: HH-->bbbb, full simulation done

Scenario B: by adding HH-->bbWW*, full simulation ongoing,
expect ~20% relative improvement

Scenario C: color-singlet clustering, future improvement,
expected ~20% relative improvement (conservative)

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

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

Baseline

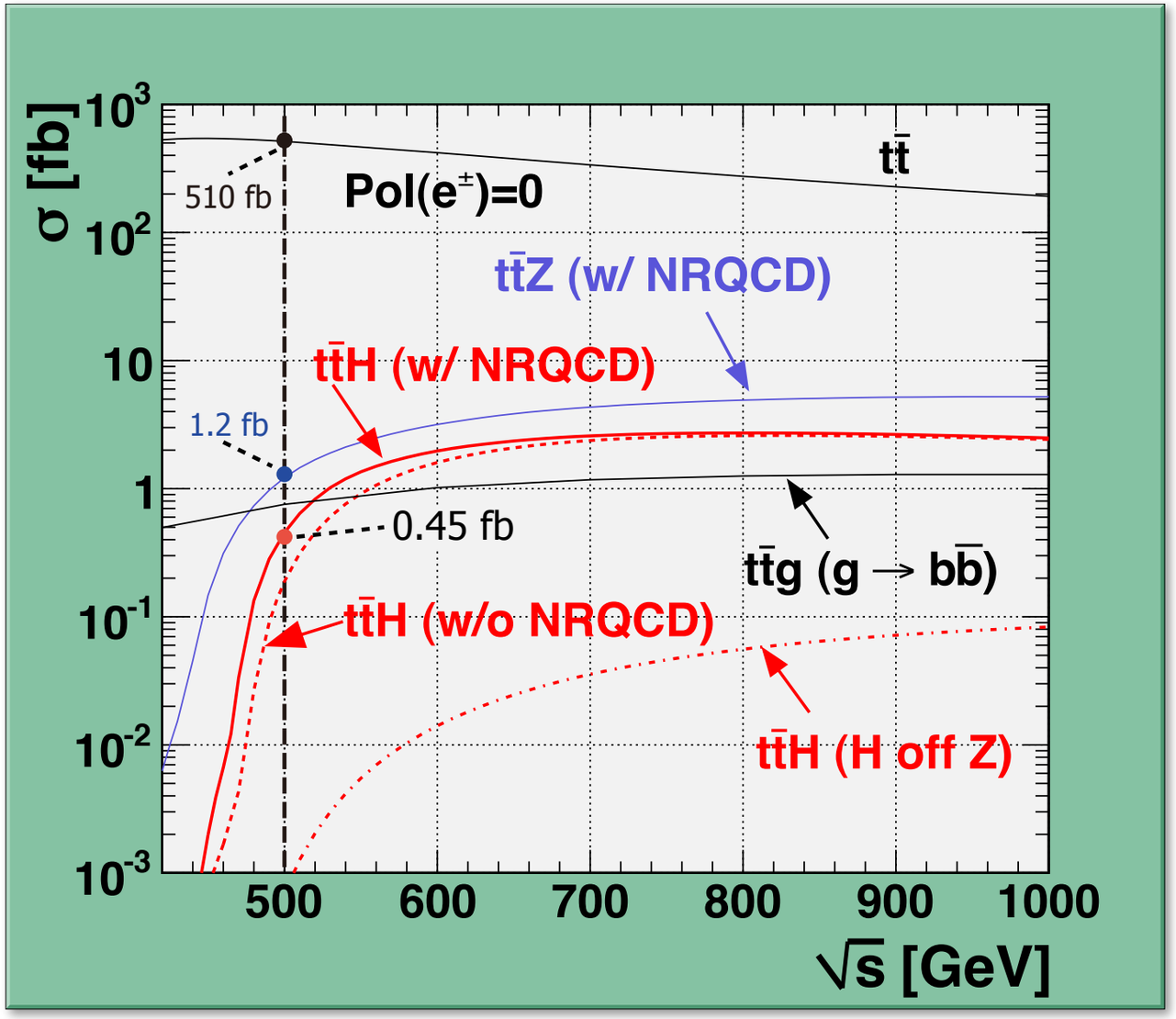
250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

LumiUP

ILD DBD Study
(Junping Tian, Masakazu Kurata)

Top Yukawa Coupling at 1TeV

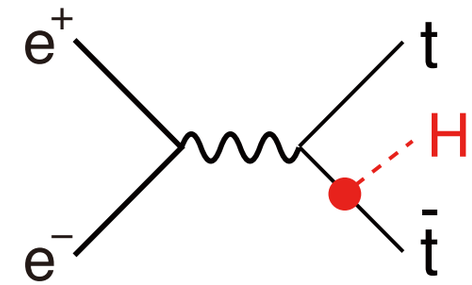
Now it is fully open!



Cross section maximum at around Ecm = 800GeV

Tony Price & Tomohiko Tanabe: ILD DBD Study
Philipp Roloff & Jan Strube: SiD DBD Dtudy

DBD Full Simulation



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

Independent Higgs Measurements at ILC

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

ILC 250+500+1000

Model-independent Global Fit for Couplings

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

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

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t) \qquad (B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

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

$$F_i = S_i \, G_i$$

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

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

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

We are confident that the total theory errors for S_i and G_i will be at the 0.1% level at the time of ILC running.

Systematic Errors

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

arXiv: 1310.0763

Model-independent Global Fit for Couplings

Baseline ILC program

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

(M_H = 125 GeV)

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

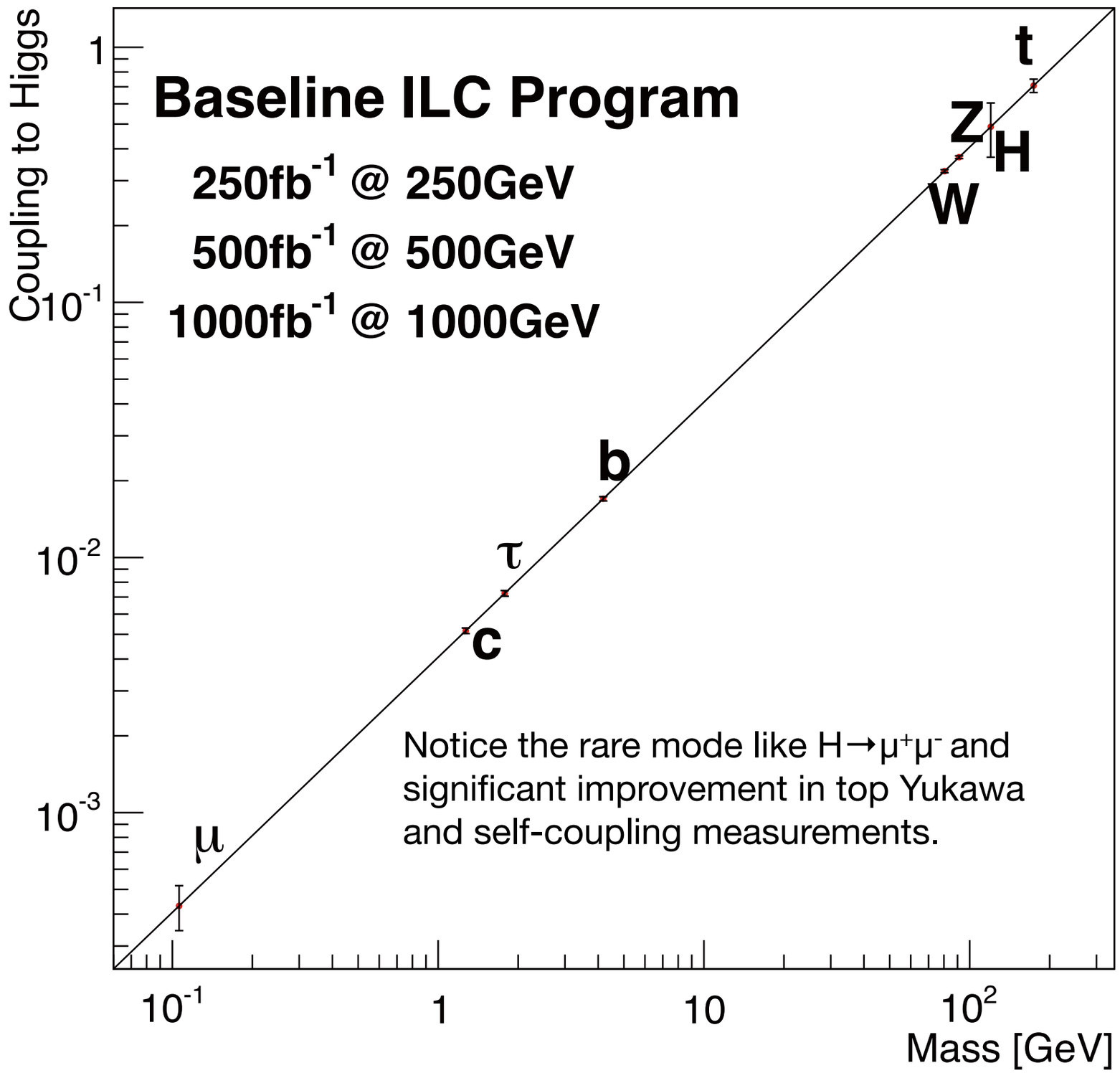
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

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

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

Mass Coupling Relation

After Baseline ILC Program



Model-independent Global Fit for Couplings

Luminosity Upgraded ILC

(M_H = 125 GeV)

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}

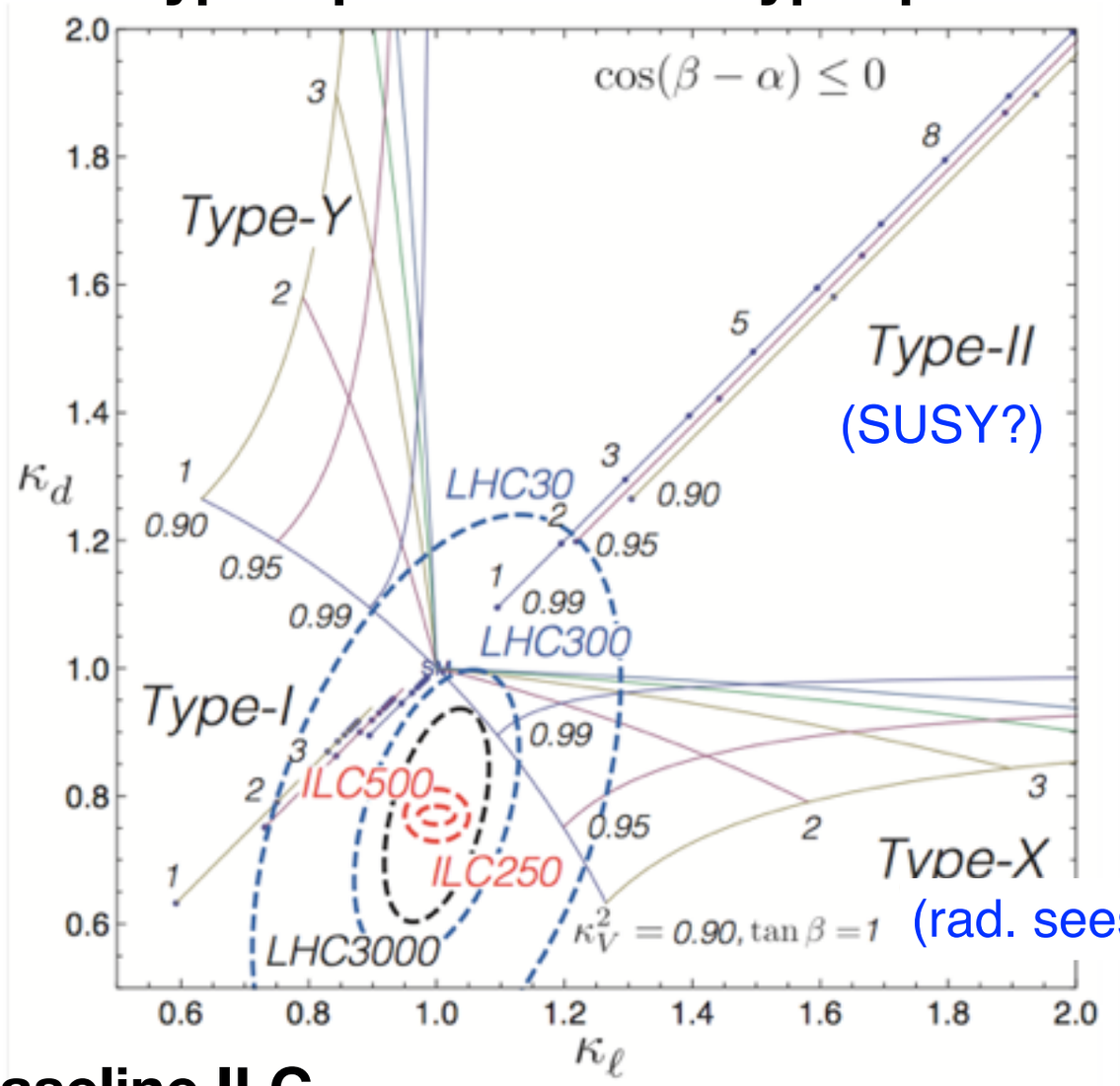
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV P(e-,e+)=(-0.8,+0.2) @ 1 TeV

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

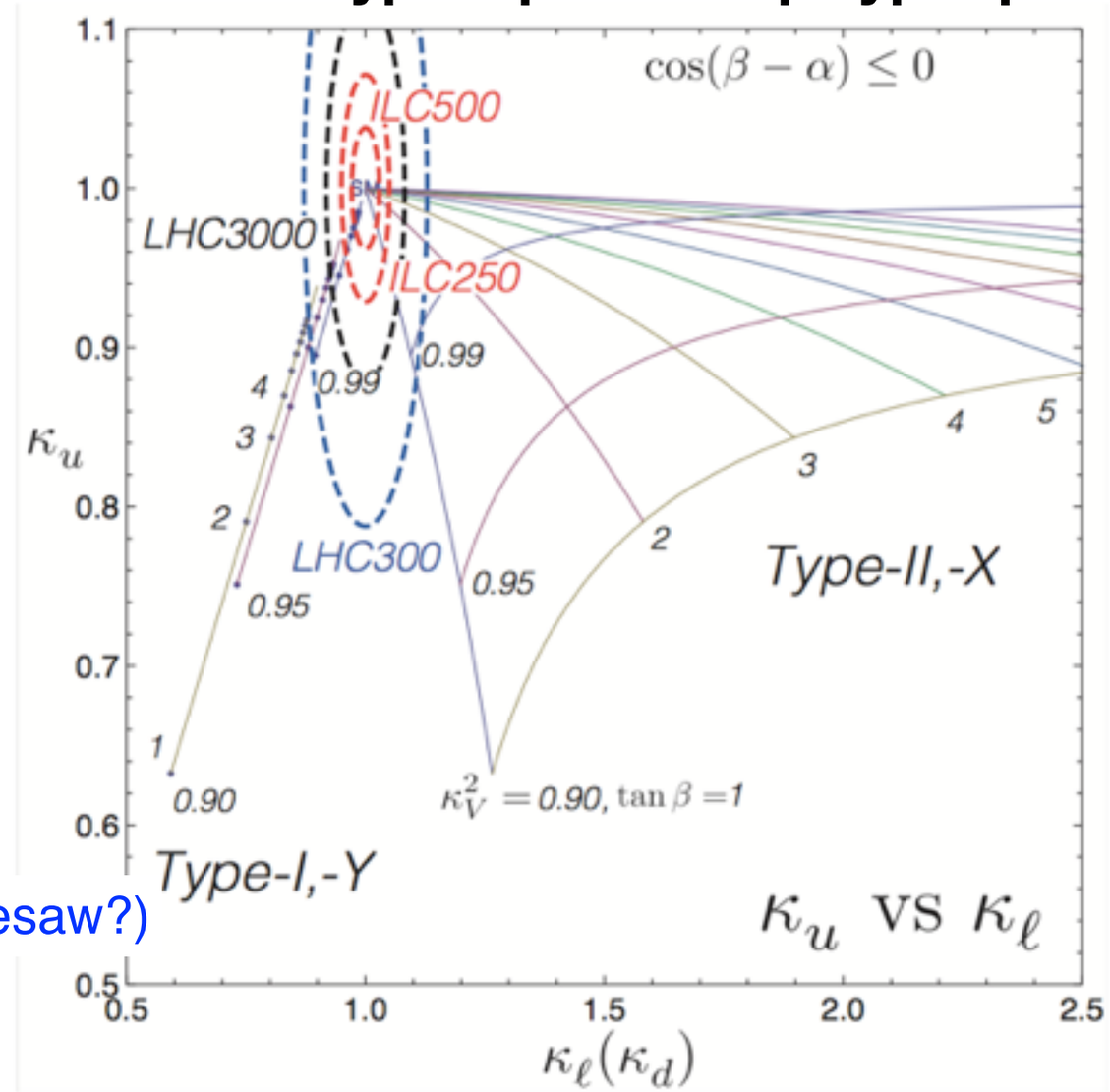
) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

Finger Printing 2HDM

Down-type lepton vs down-type quark



Down-type lepton vs up-type quark



Baseline ILC

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)

Self-Coupling

How did EW phase transition happen?

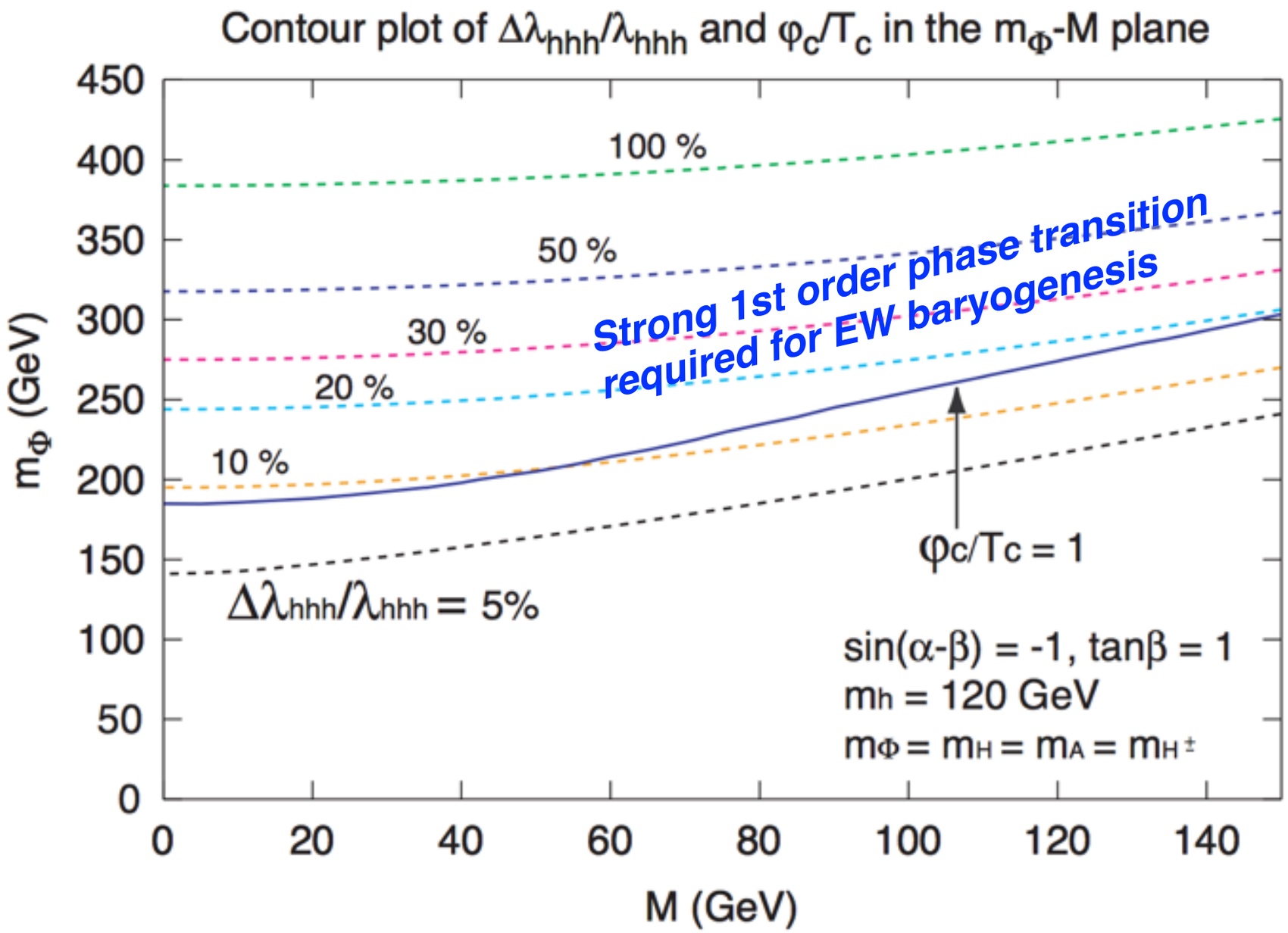


Figure 1.21. The region of strong first order phase transition ($\varphi_c/T_c > 1$) required for successful electroweak baryogenesis and the contour plot of the deviation in the triple Higgs boson coupling from the SM prediction [11], where m_Φ represents degenerated mass of H, A and $H^\pm$ and M is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

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

EWSB Summary

- The primary goal for the next decades is to uncover the secret of the EW symmetry breaking. This will open up a window to BSM and set the energy scale for the E-frontier machine that will follow LHC and ILC.
- Probably LHC will hit systematic limits at O(2-5%) for most of σ×BR measurements, being not enough to see the BSM effects if we are in the decoupling regime.
  Moreover, we need some model assumption to extract couplings from the LHC data.
- The recoil mass measurement at 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 $e^+e^- \rightarrow ZH$ 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 ***completely model-independently*** with staging starting from 250GeV. We may need more data depending on the size of the deviation. The ILC has a luminosity upgrade potential.
- 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

- So far, 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

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

→ light chargino/neutralinos will be higgsino-dominant and nearly degenerate

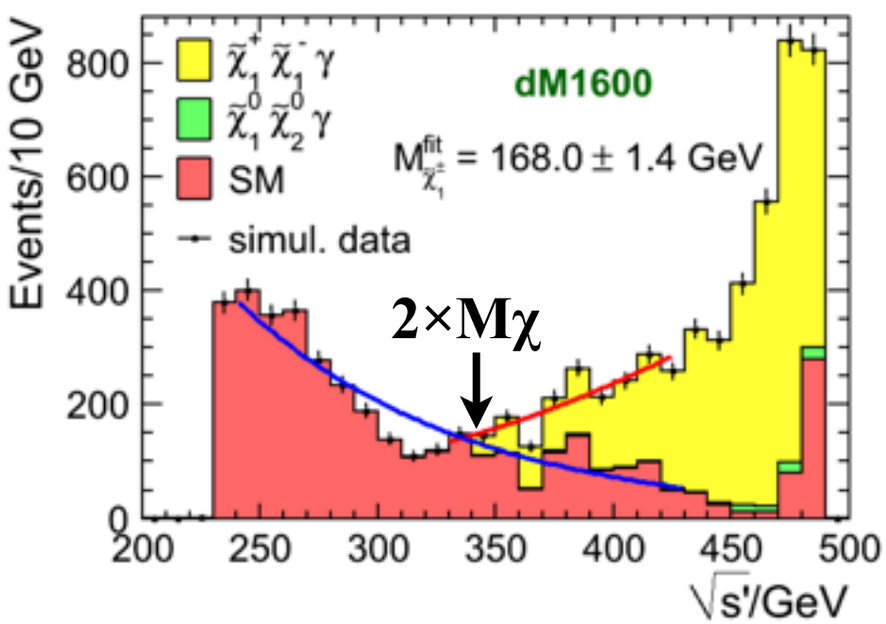
→ typically Δm of 10 GeV or less → ***very difficult for LHC!***

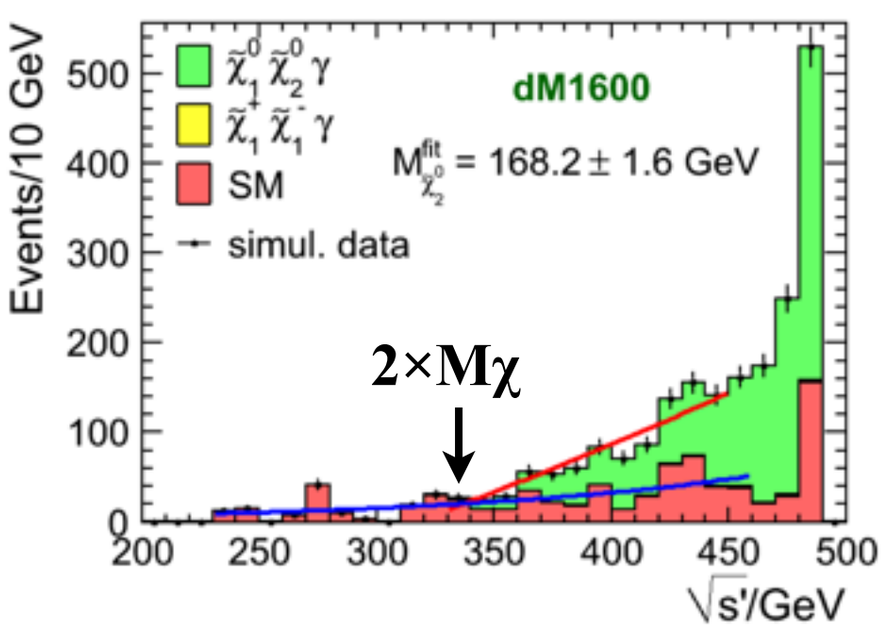
Higgsinos in Natural SUSY (ΔM<a few GeV)

ILC as a Higgsino Factory

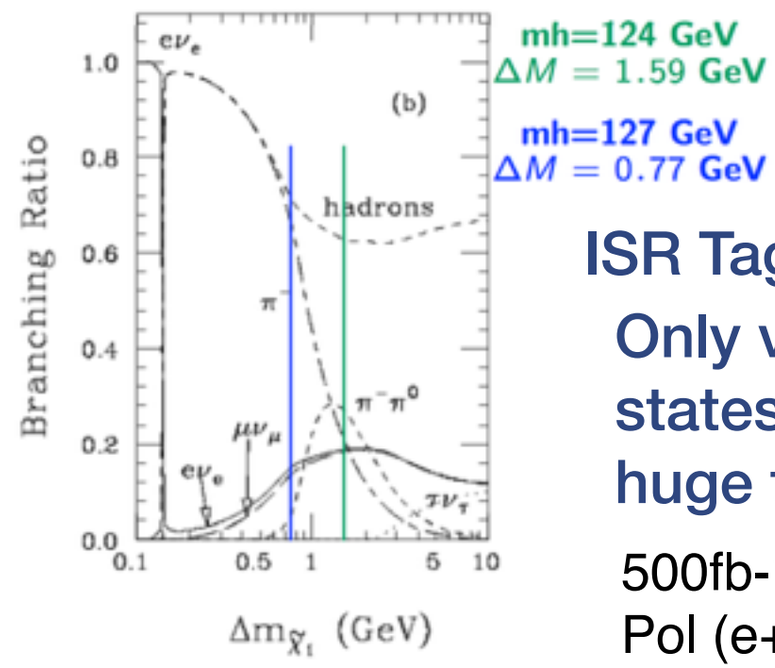
ISR Tagging

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





Ref: C.-H. Chen et al. hep-ph:9512230



Hale Sert
ECFA LCWS 2013, DESY
EPJC (2013) 73:2660

ISR Tagging

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

500fb-1 @ Ecm=500GeV
Pol (e+,e-) = (+0.3,-0.8) and (-0.3,+0.8)

dm1600

Mass Spectrum	
Particle	Mass (GeV)
h	124
$\tilde{\chi}_1^0$	164.17
$\tilde{\chi}_1^\pm$	165.77
$\tilde{\chi}_2^0$	166.87
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3\times 10^3$

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.59$ GeV

$$\delta(\sigma \times BR) \simeq 3\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 2.1(3.7)\,\mathrm{GeV}$$
$$\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 70\,\mathrm{MeV}$$

dm770

Mass Spectrum	
Particle	Mass (GeV)
h	127
$\tilde{\chi}_1^0$	166.59
$\tilde{\chi}_1^\pm$	167.36
$\tilde{\chi}_2^0$	167.63
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3\times 10^3$

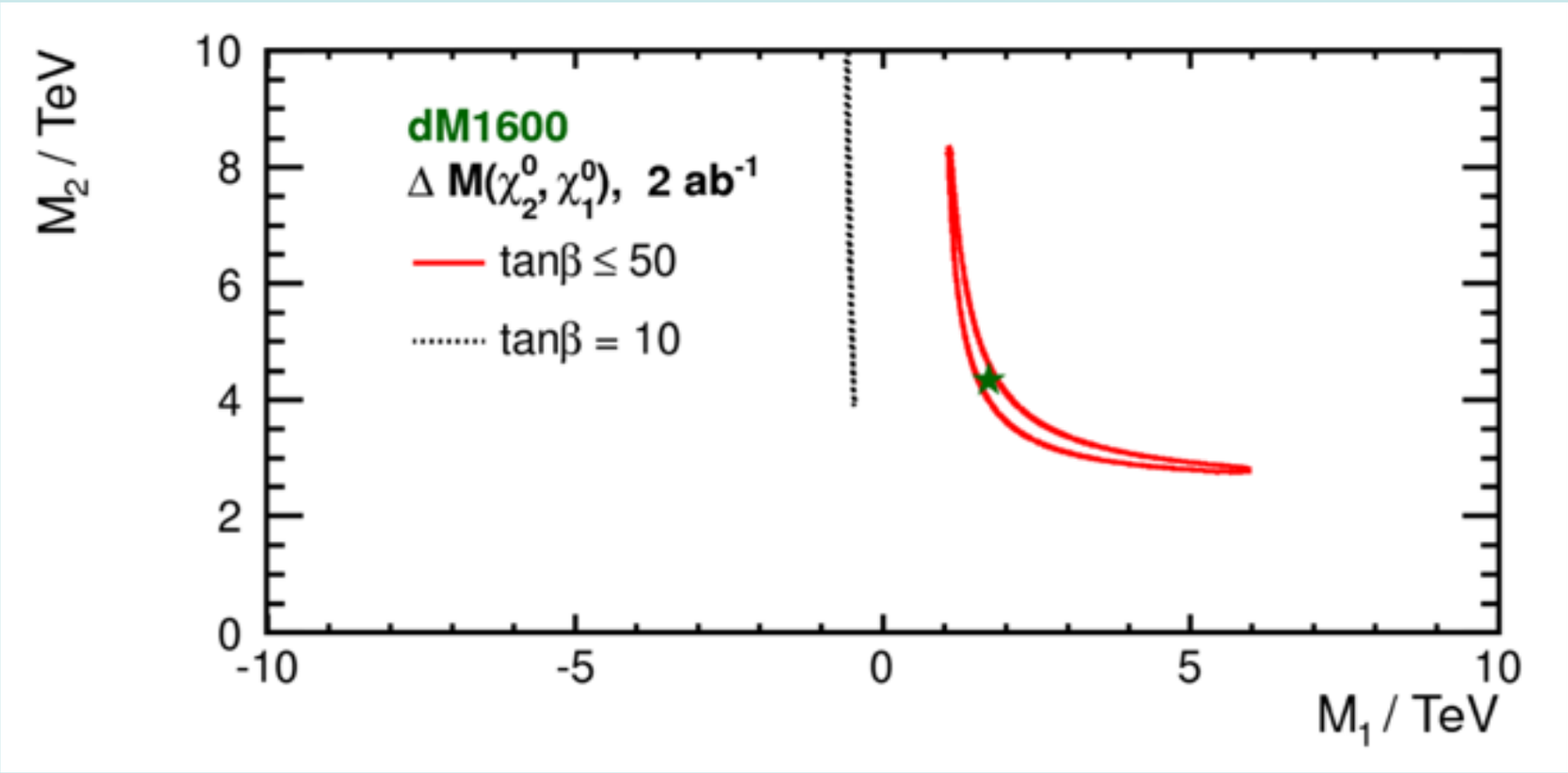
$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.77$ GeV

$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\mathrm{GeV}$$
$$\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\mathrm{MeV}$$

Extracting M1 and M2

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

Hale Sert
ECFA LCWS 2013, DESY
Berggren et al. EPJC (2013) 73:2660

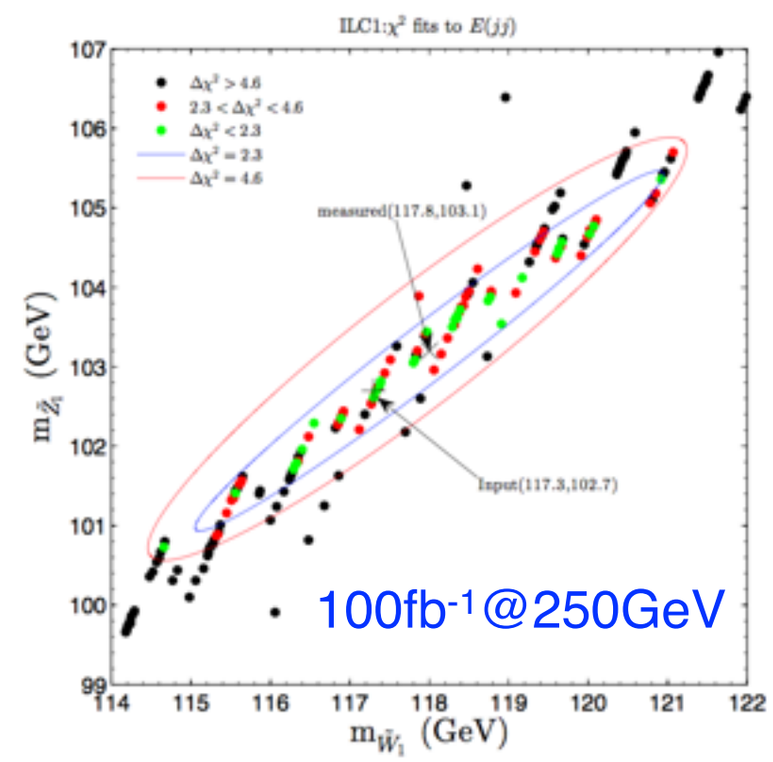


@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	$\sim$ 1.0 (-0.4)	$\sim$ 6.0
M_2 [TeV]	4.4	$\sim$ 2.5 (3.5)	$\sim$ 8.5
μ [GeV]	165.7	166.2	170.1

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

RNS: Baer et al.
arXiv: 1404.7510

ΔM=15GeV



In the radiatively driven natural SUSY (RNS) scenario as in arXiv: 1404.7510, ΔM~10GeV, we can determine M1 and M2 to a few % or better, allowing us to test GUT relation!

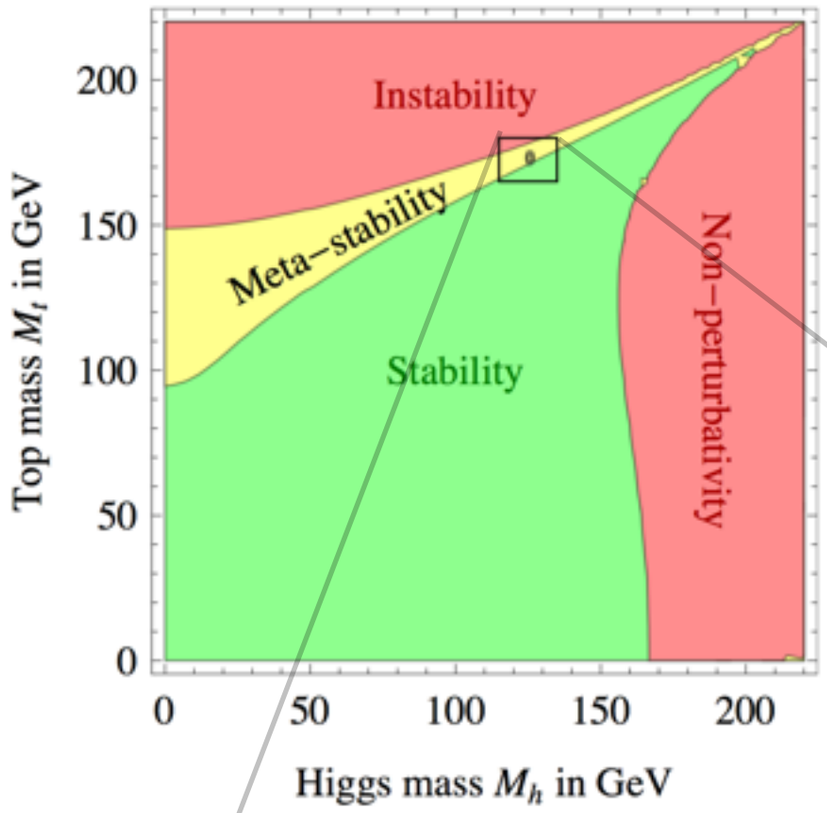
SM up to $\Lambda_{\mathrm{Planck}}$?

What if the Higgs properties would turn out to be just like those of the SM Higgs boson to the ILC precision and no BSM signal found?

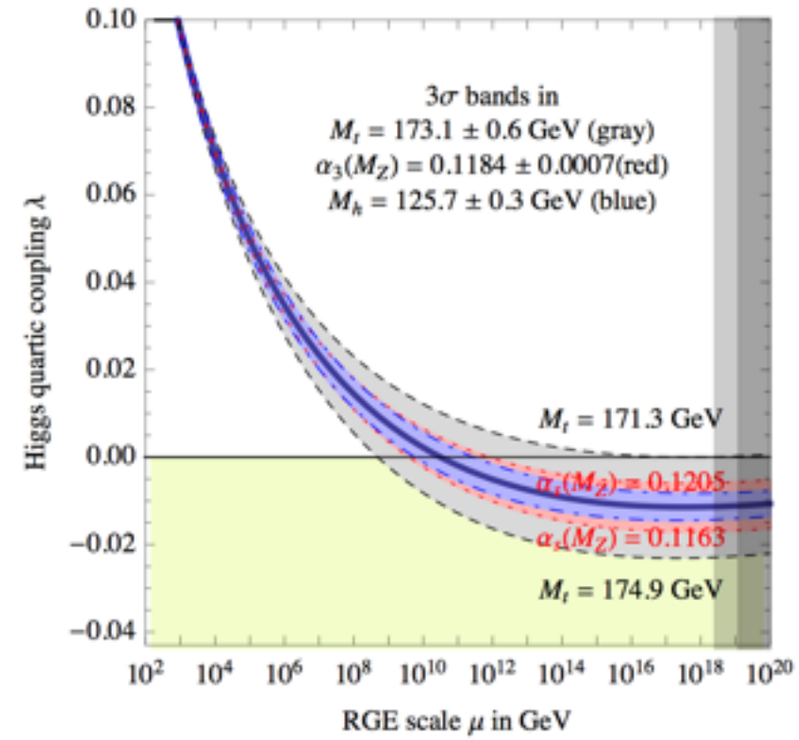
We need to question then the range of validity of the SM.

How far can the SM go?

Stability of SM Vacuum



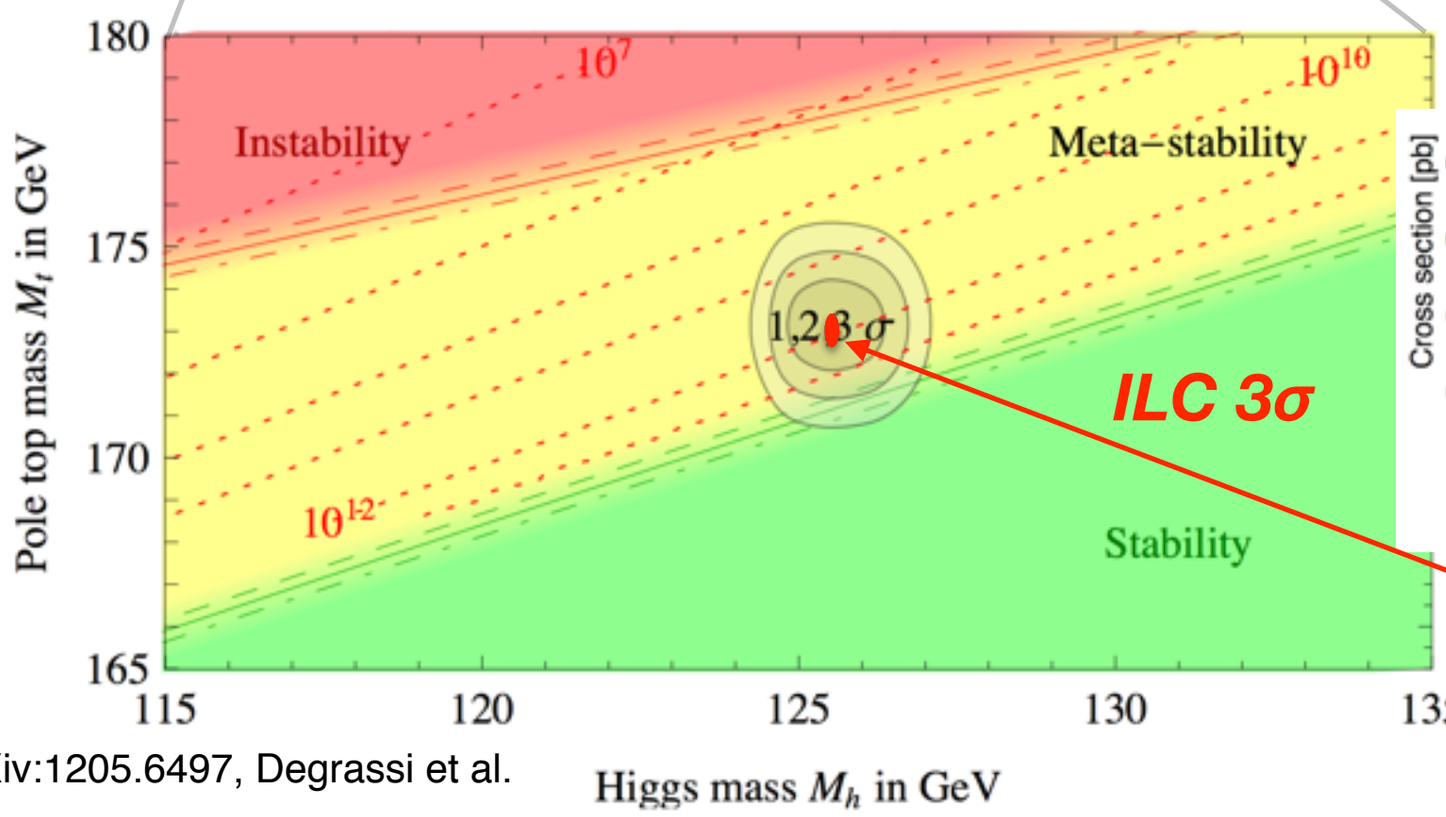
With the 125GeV Higgs boson, the SM vacuum seems to be at a subtle point of meta-stability!



Does λ really become negative below Λ_{Pl}?

or $\lambda(\Lambda_{Pl}) = 0$?

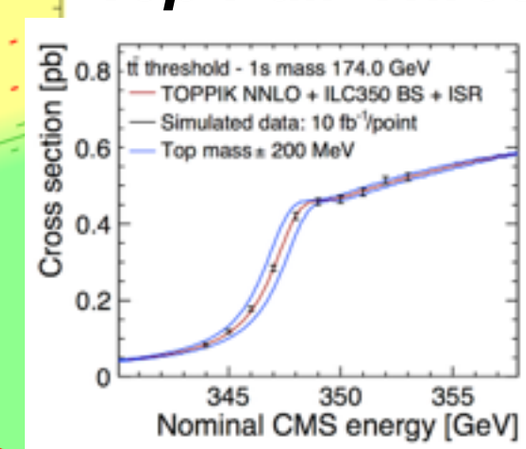
To answer this we need a precision m_t measurement!

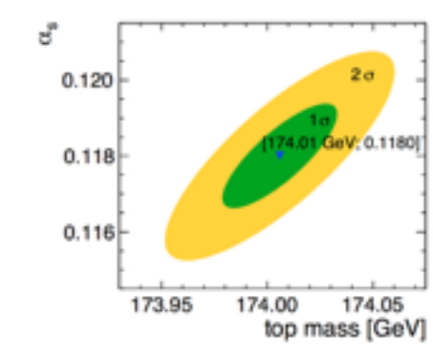


arXiv:1205.6497, Degrassi et al.

Top Pair Threshold

Theoretically very clean measurement of m_t





$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$
$$\Delta m_H = 30\,\mathrm{MeV}$$

ILC pins down the location !

Conclusions

Whatever new physics is awaiting for us, clean environment, polarized beams, and excellent detectors 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 and open up the way to high scale physics!

ILC Situation

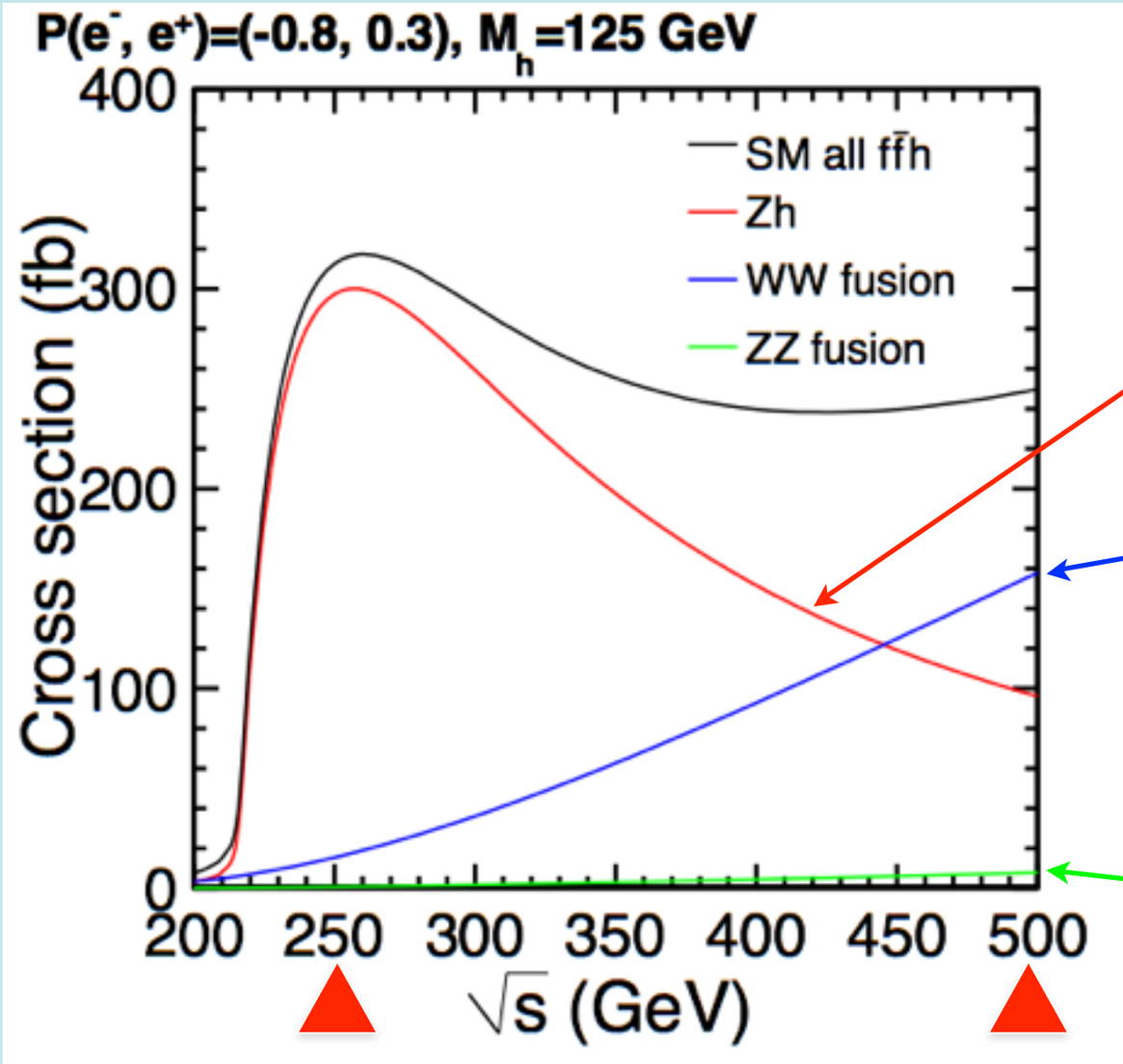
- ILC TDR completed = Technology is ready
- A preferred candidate site in Japan chosen and site specific design started.
- ILC is now a project officially recognized by the Japanese government, a TF has been formed in MEXT (funding agency), and an official review process in MEXT is about to start.
- However, ILC is NOT a Japanese project, BUT an INTERNATIONAL project!
- The Japanese government has just started contacting potential partners in the world.
- **International support** at all levels, **including the grass root level**, is **absolutely necessary** to make ILC happen! We need to convince the government that the world HEP community is eager to realize ILC in the earliest possible timescale!

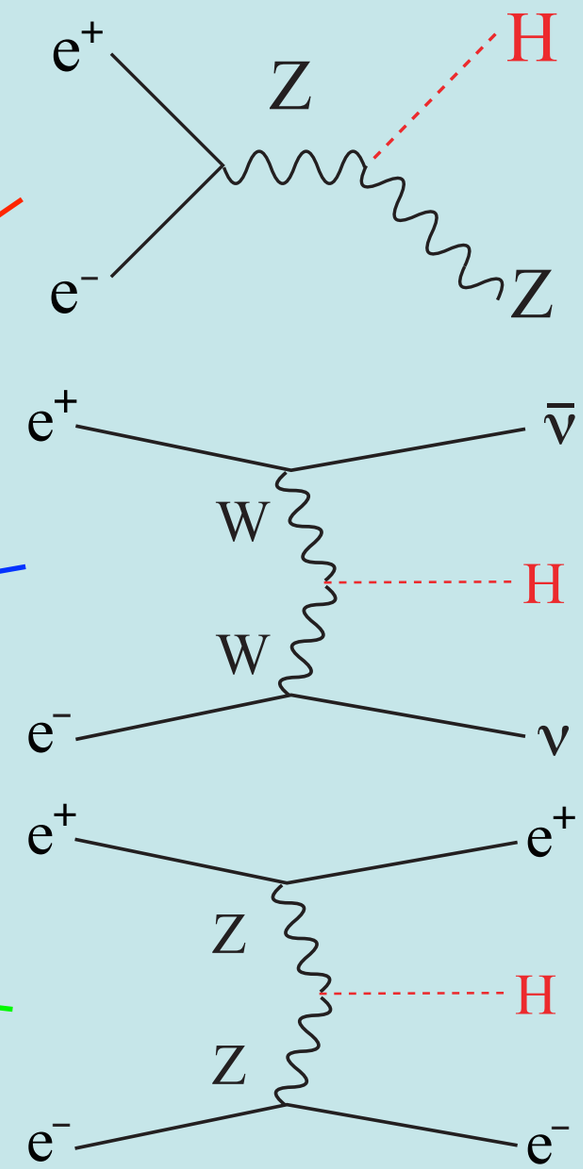
Backup

Main Production Processes

Single Higgs Production

Production cross section





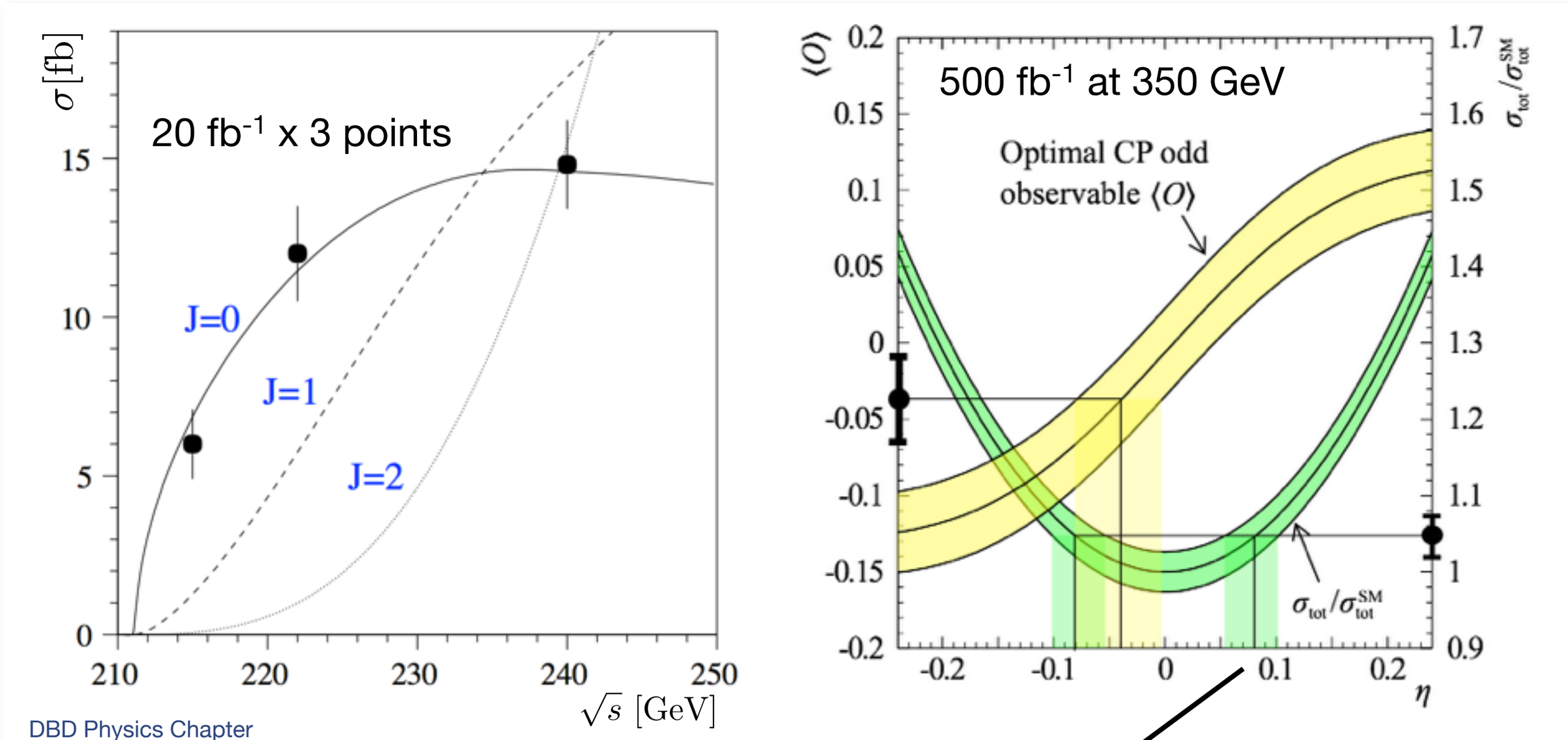
ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

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

Possible to rediscover the Higgs in one day!

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.

Model-dependent Global Fit for Couplings

7-parameter fit

Model Assumptions

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

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

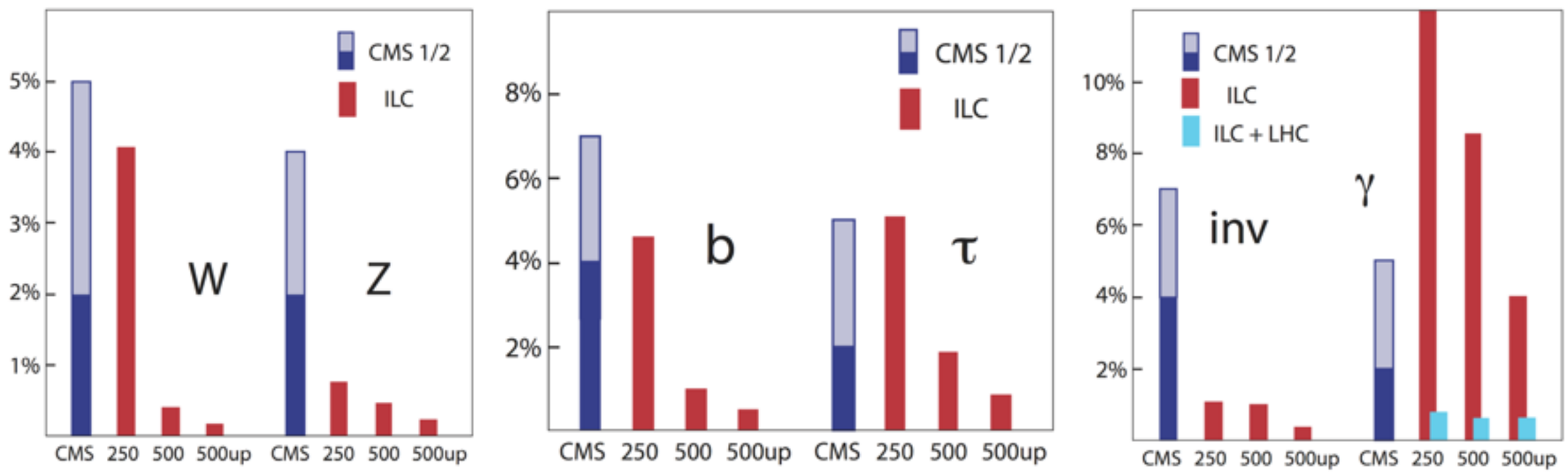
Results

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

Snowmass Higgs WG Report (Draft)

LHC + ILC

M. Peskin, LCWS 2013
arXiv: 1312.4974



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

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

Hunting Ground for Extra Higgs Bosons

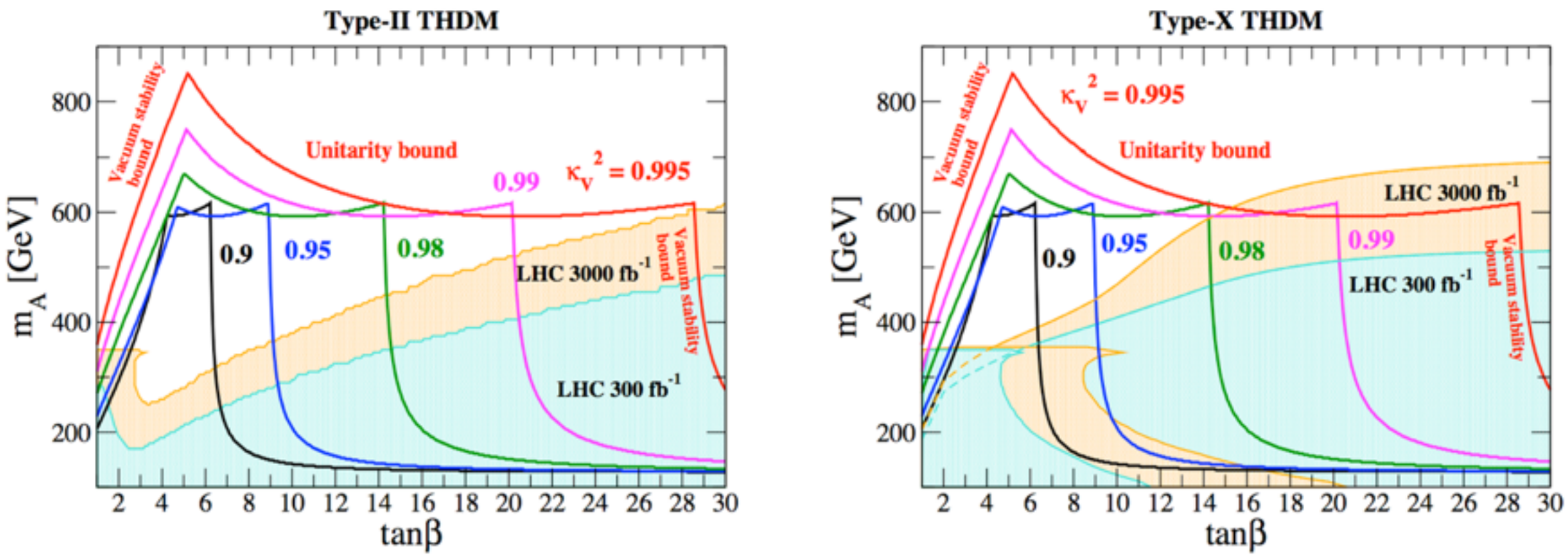


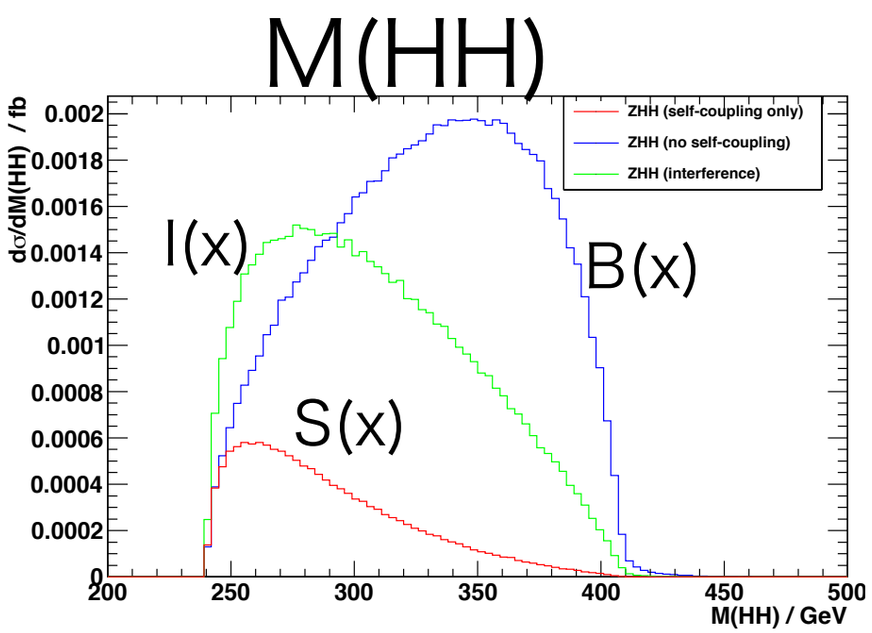
Figure 1.20. Regions below the curves are allowed by the constraints from unitarity and vacuum stability on the $\tan\beta$-m_A plane for each fixed value of κ_V^2 for $M = m_A = m_H = m_{H^+}$ in the Type II and Type X 2HDMs. Expected excluded parameter spaces are also shown by blue (orange) shaded 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)

Self-coupling

Self-coupling Measurement

Weighting Method to Enhance the Sensitivity to λ

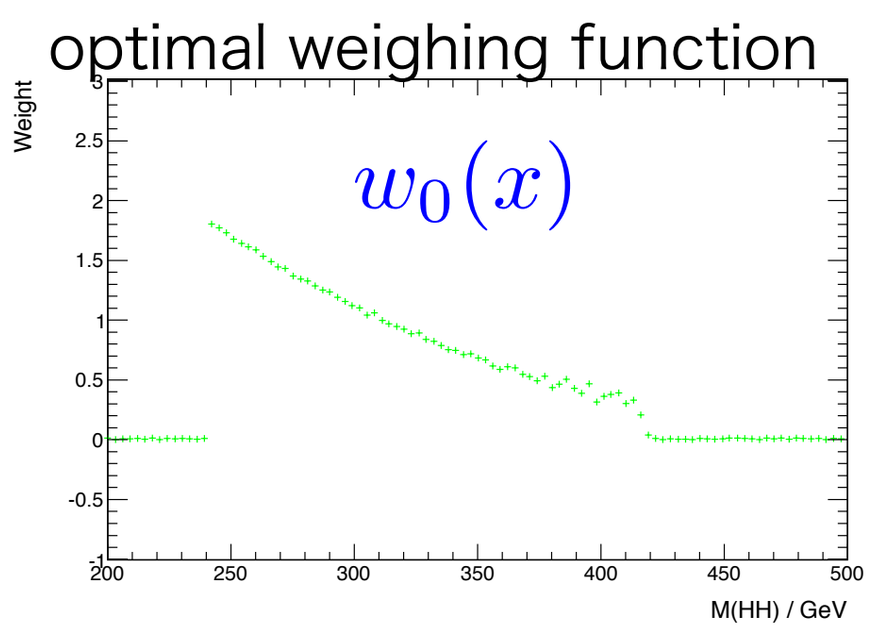


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible interference self-coupling

Observable: weighted cross-section

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



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

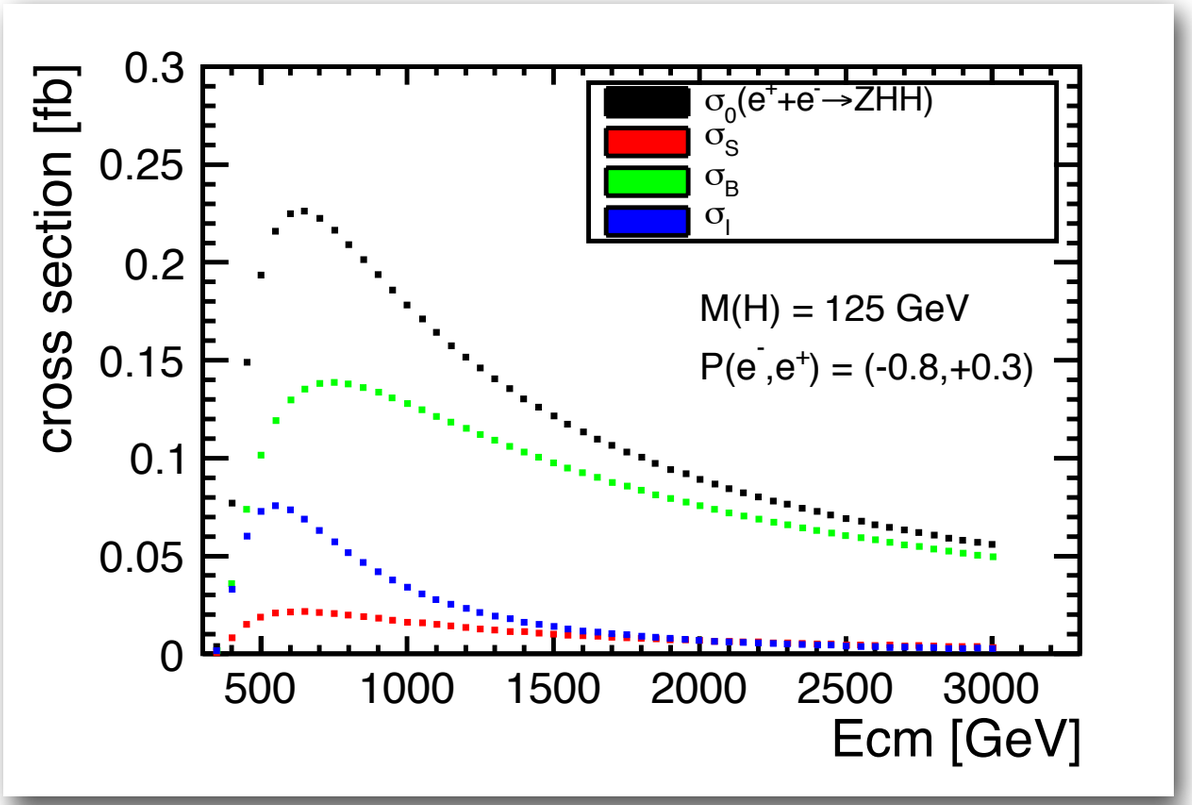
$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

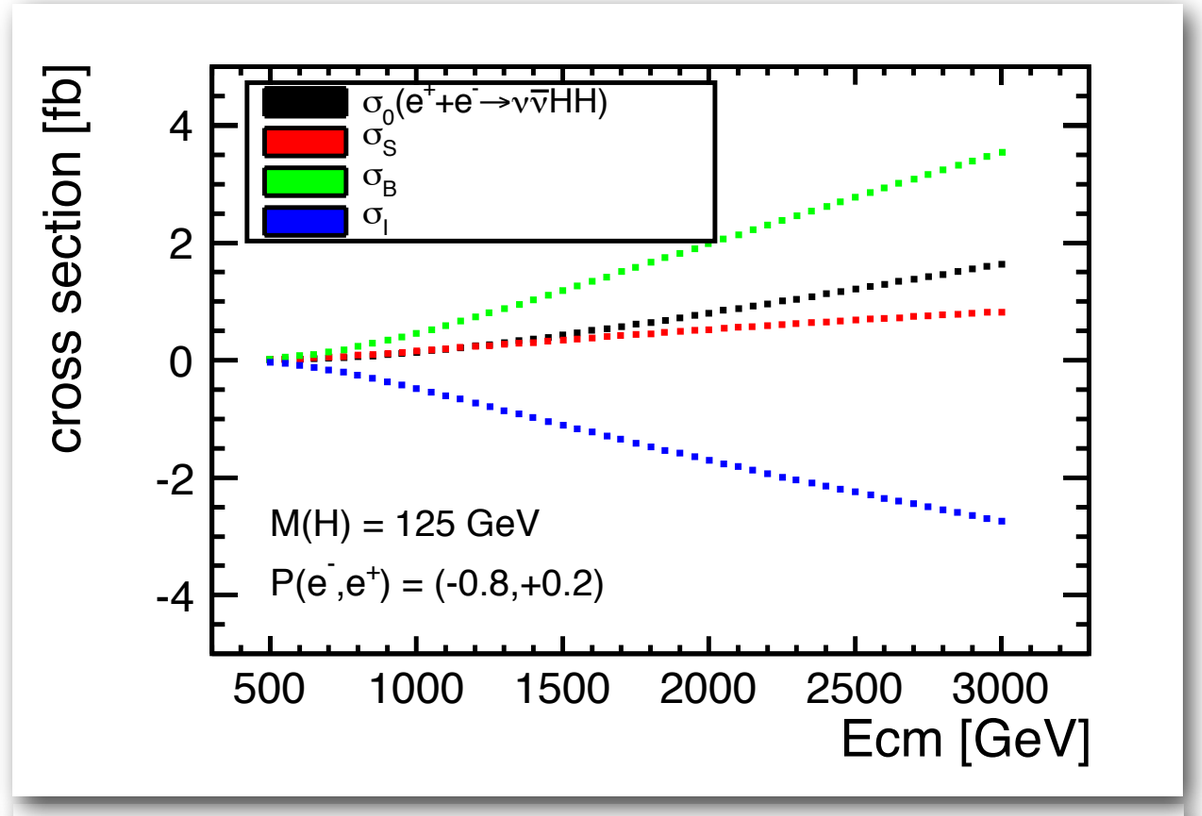
General solution:

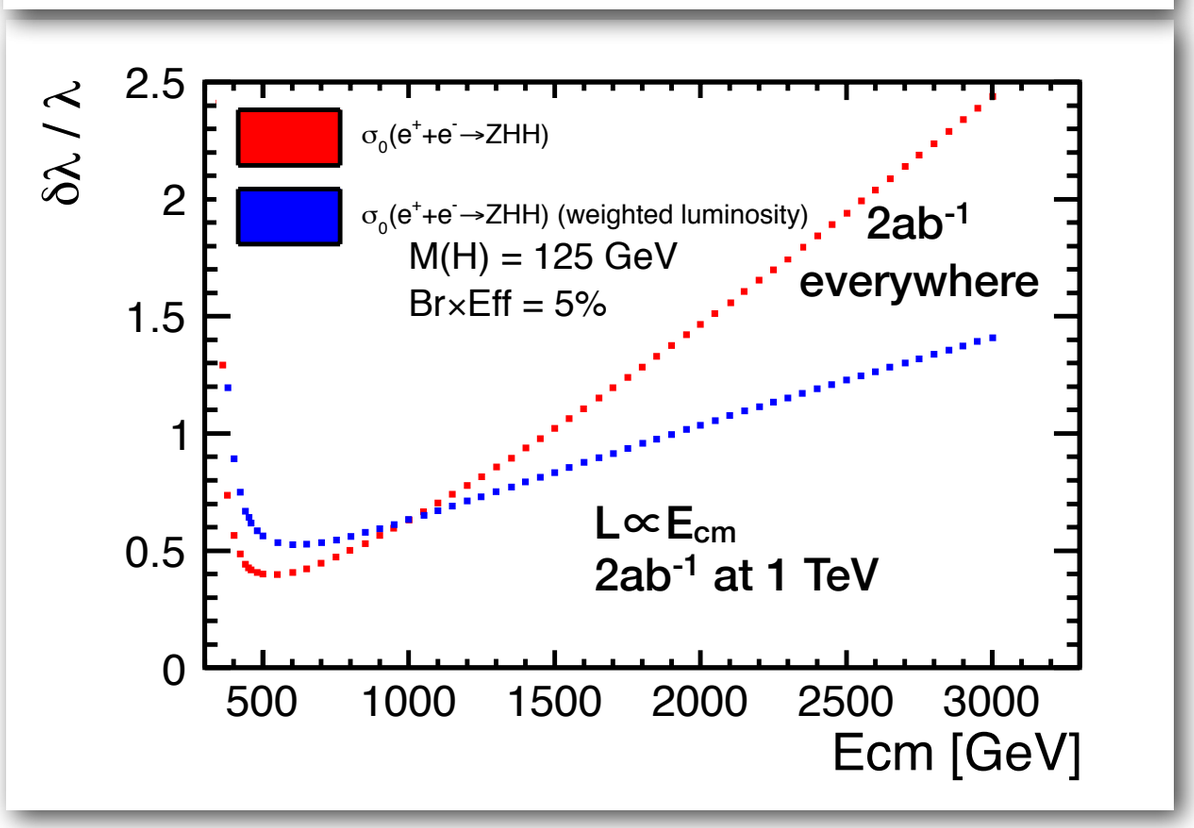
$$w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)}$$

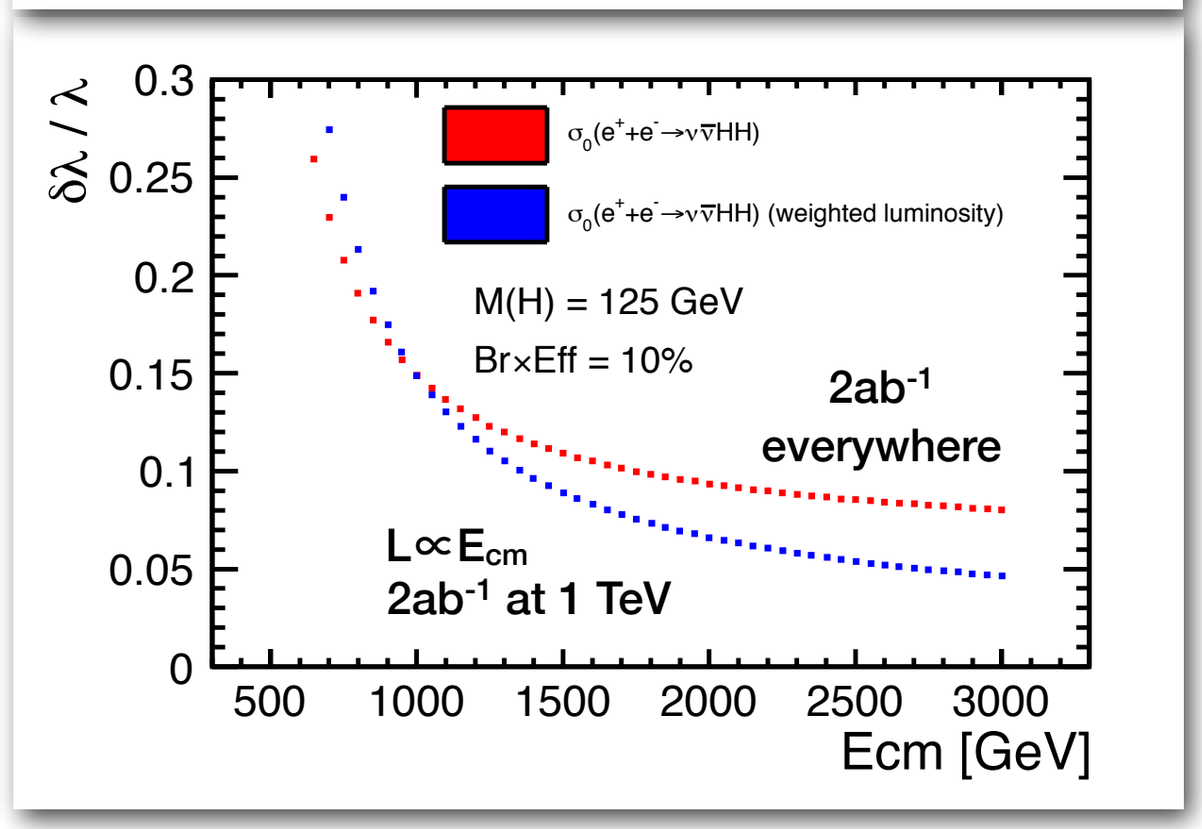
c: arbitrary normalization factor

Expected Coupling Precision as a Function of Ecm



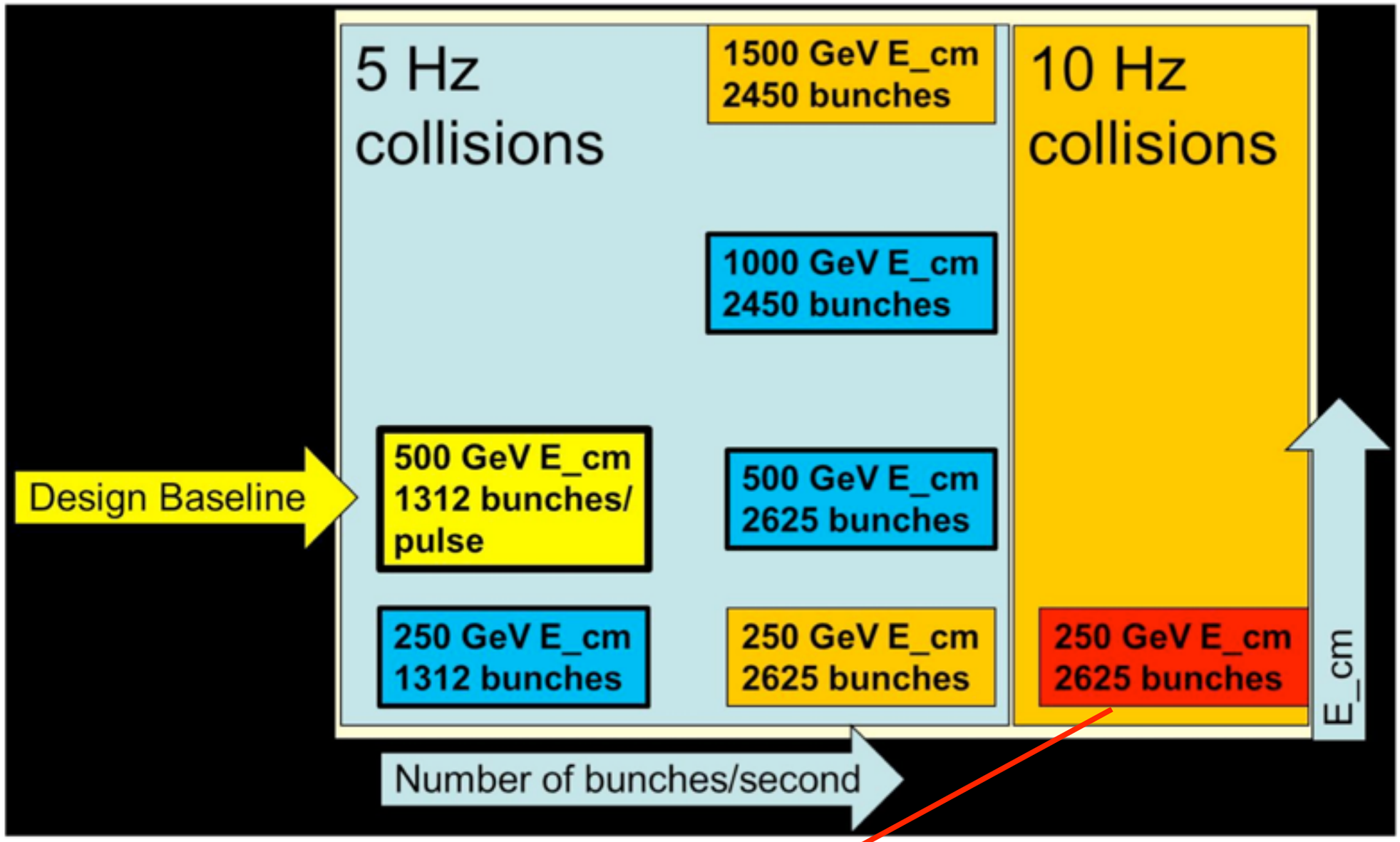






HL-ILC ?

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!

HL-ILC

			1st Stage Higgs Factory	Baseline ILC, after Lumi Upgrade	High Rep Rate Operation
Center-of-mass energy	E_{CM}	GeV	250	250	250
Collision rate	f_{rep}	Hz	5	5	10
Electron linac rate	f_{linac}	Hz	10	10	10
Number of bunches	n_{b}		1312	2625	2625
Pulse current	I_{beam}	mA	5.8	8.75	8.75
Average total beam power	P_{beam}	MW	5.9	10.5	21
Estimated AC power	P_{AC}	MW	129	160	200
Luminosity	L	$\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.5	3.0

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})	Runtime (yr)	Wall Plug E (MW-yr)
ILC(250)	250	250							1.1	130
ILC(500)	250	250		500	500				2.0	270
ILC(1000)	250	250		500	500		1000	1000	2.9	540
ILC(LumUp)	250	1150		500	1600		1000	2500	5.8	1220

Independent Higgs Measurements

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}

Luminosity Upgraded ILC

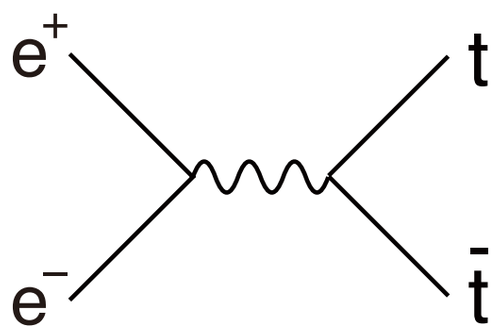
($M_H = 125$ GeV)

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%	0.37%	0.3%
H-->cc	3.9%		7.2%	3.5%	2%
H-->gg	3.3%		6%	2.3%	1.4%
H-->WW*	3%		5.1%	1.3%	1%
H-->ττ	2%		3%	5%	2%
H-->ZZ*	8.4%		14%	4.6%	2.6%
H-->γγ	16%		19%	13%	5.4%
H-->μμ	46.6%	-	-	-	20%

Indirect BSM Searches

Top Quark

Anomalous Couplings in Open Top Production at 500 GeV



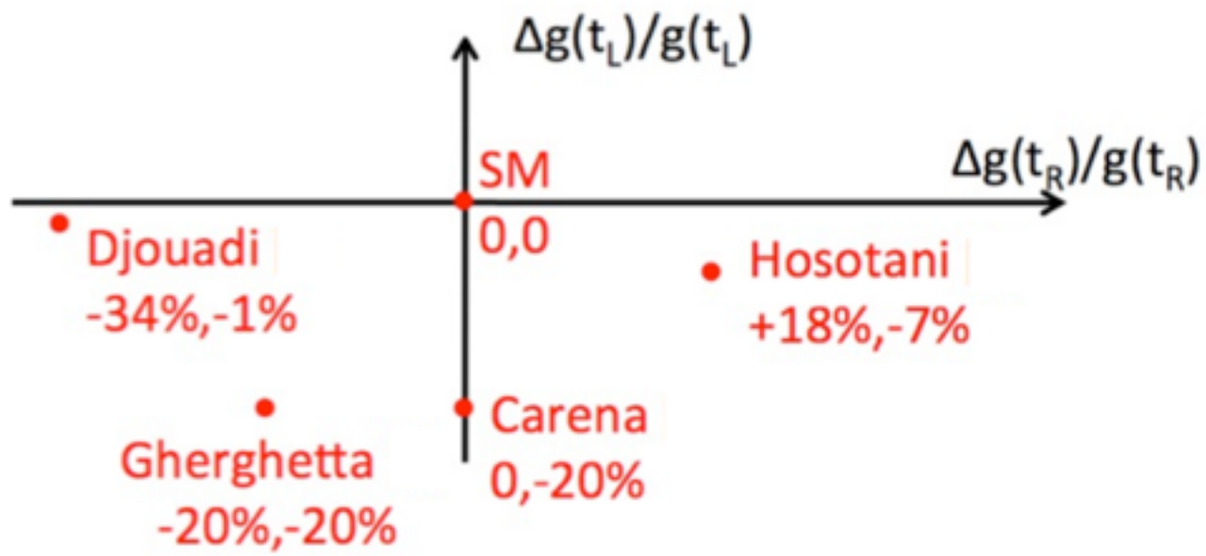


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Figure 34: *Predictions of various groups [40,42–44] on deviations from Standard Model couplings of the t quark within Randall-Sundrum Models. The cartoon is taken from [47].*

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

Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

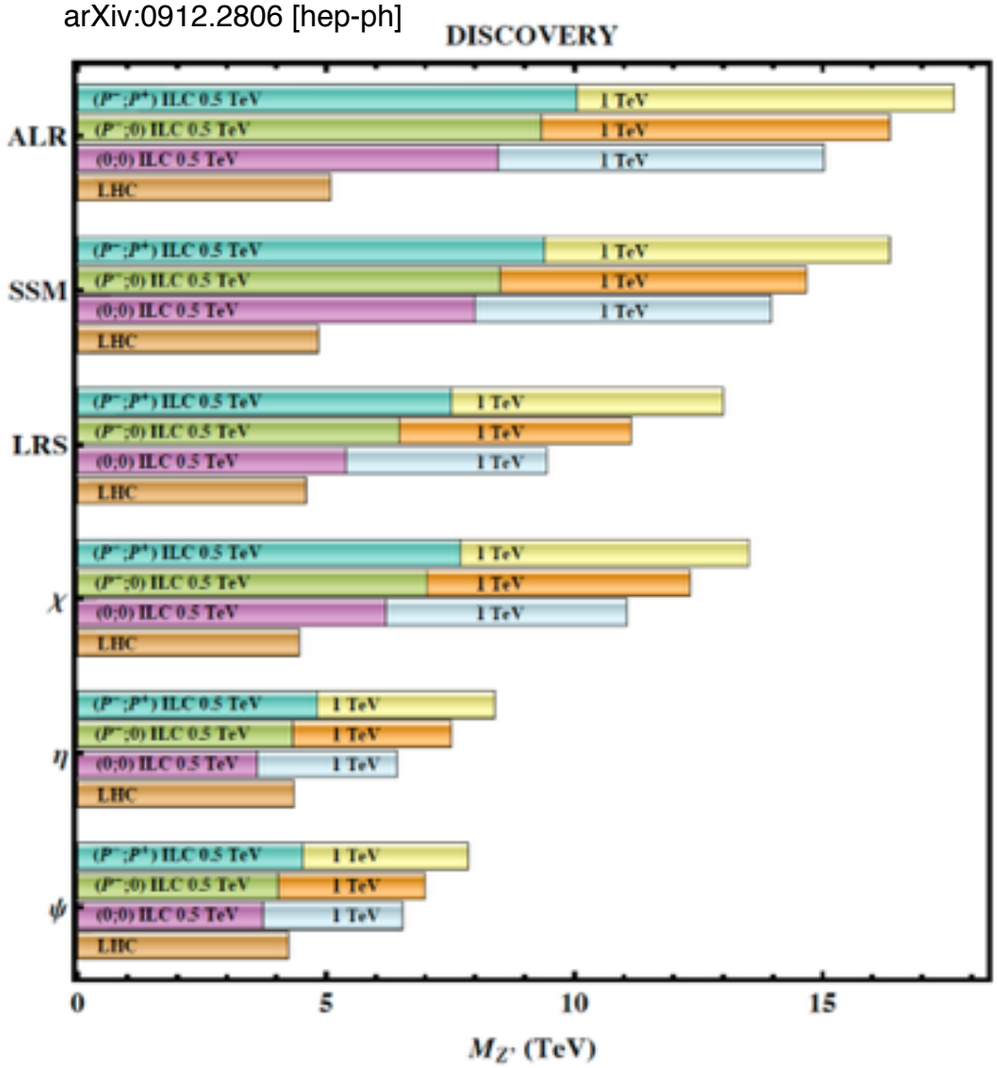
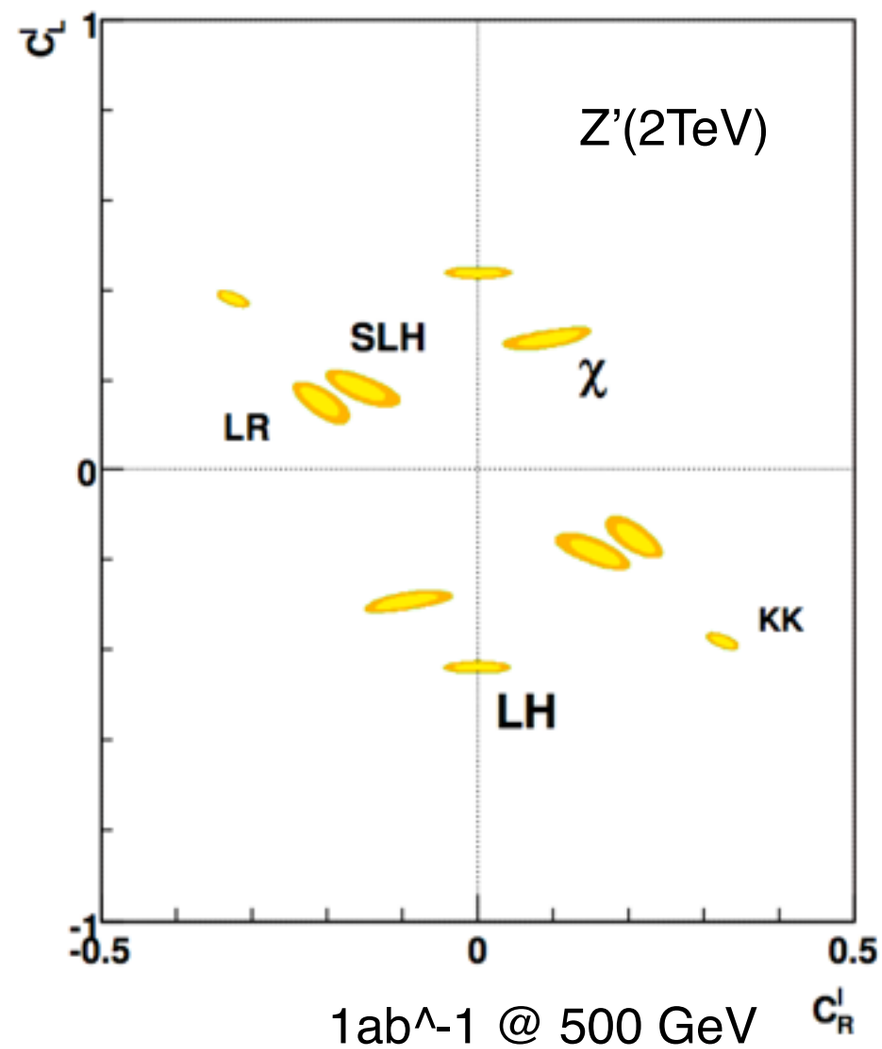


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For details, see [14].

hep-ph/0511335



1ab^-1 @ 500 GeV

ILC's Model ID capability is expected to exceed that of LHC even if we cannot hit the Z' pole.

Beam polarization is essential to sort out various possibilities.

Two-Fermion Processes

Compositeness

S. Riemann, LC-TH-2001-007

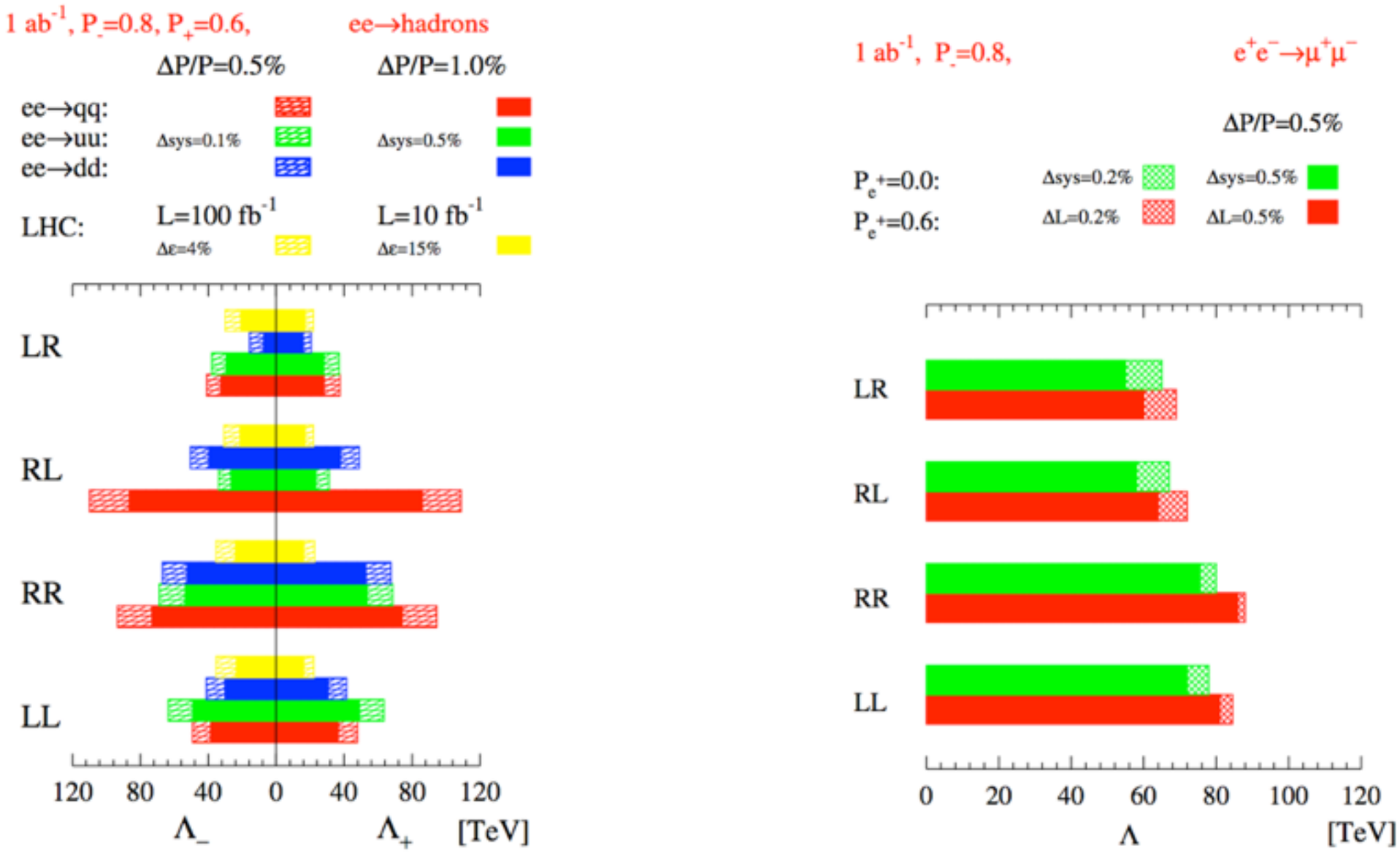


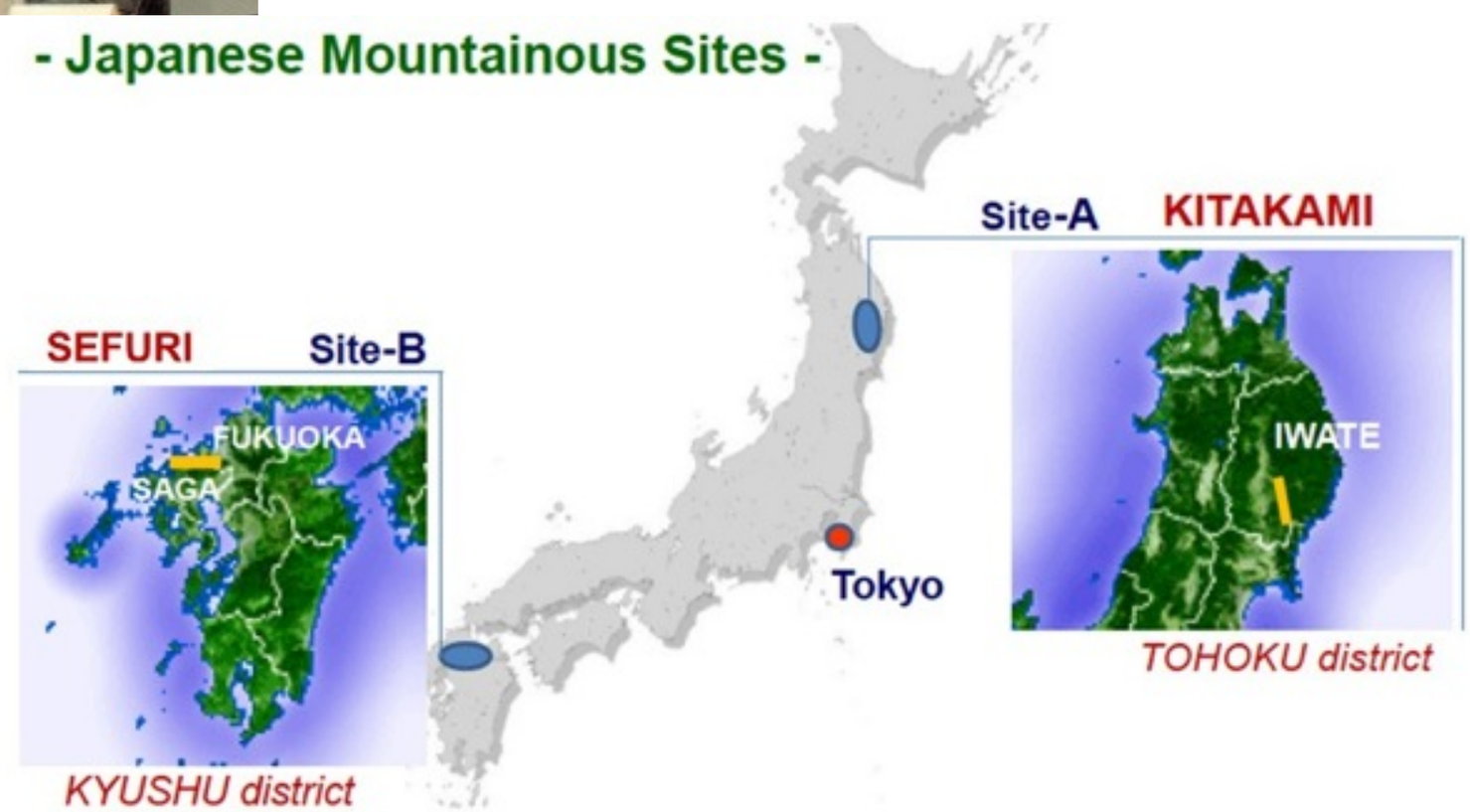
Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.

ILC Situation in Japan

Japan – Preferred Site selection

"Issues that could lead to particularly serious difficulties for the Sefuri site are that the route passes under or near a dam lake, and that the route passes under a city zone. Also, the lengths of access tunnels are longer for the Sefuri site than for the Kitakami site leading to a large merit for the latter in terms of cost, schedule, and drainage"



Preferred Site selected