Physics at ILC

Keisuke Fujii

Hue Univ., July 24, 2014

arXiv: 1306.6352 (TDR Phys.)

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.

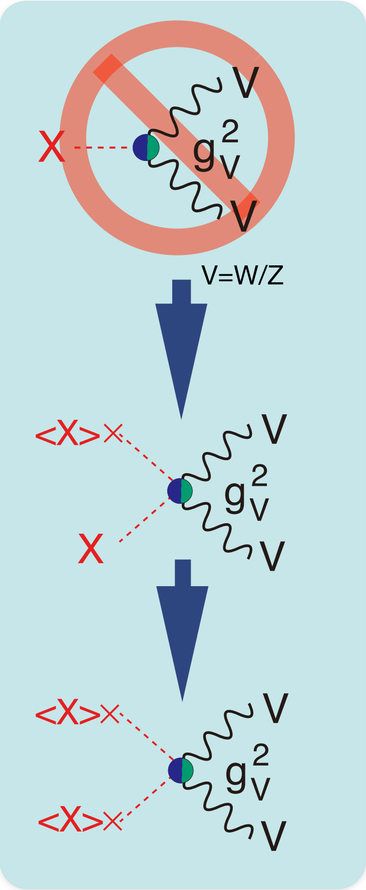
- This SM symmetry breaking sector is the simplest and the most economical, but there is no reason for it. The symmetry breaking sector might be more complex.

- We don’t know whether the “something” is elementary or composite.
- We don’t know why and how it condensed in the vacuum.

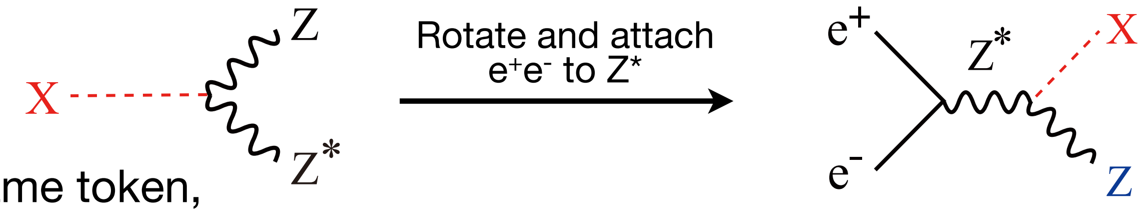
- We knew it’s there in the vacuum with a vev of 246 GeV and a custodial SU(2) (ρ=1). But other than that we didn’t know almost anything about the “something” until July 4, 2012.

Since the July 4th, the world has changed!

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

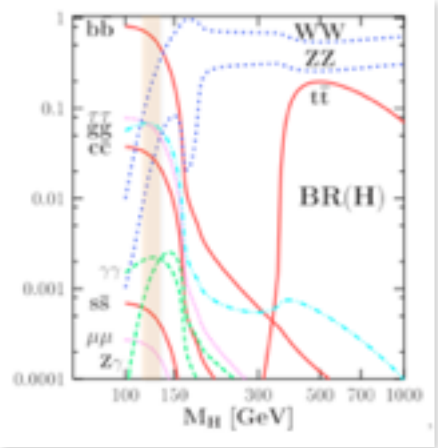


- X(125) → $\gamma\gamma$ means X is a neutral boson and $J \neq 1$ (Landau-Yang theorem).
  Recent LHC results strongly suggest $J^P=0^+$.
- X(125) → ZZ*, WW* ⇒ ∃ XVV couplings: (V=W/Z: gauge bosons)
- There is, however, no gauge coupling like XVV, only XXVV or XXV
  ⇒ XVV probably from XXVV with one X replaced by $\langle X \rangle \neq 0$, 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. → X is a Higgs!
  ⇒ 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 $e^+e^- \to Z^* \to ZX$.



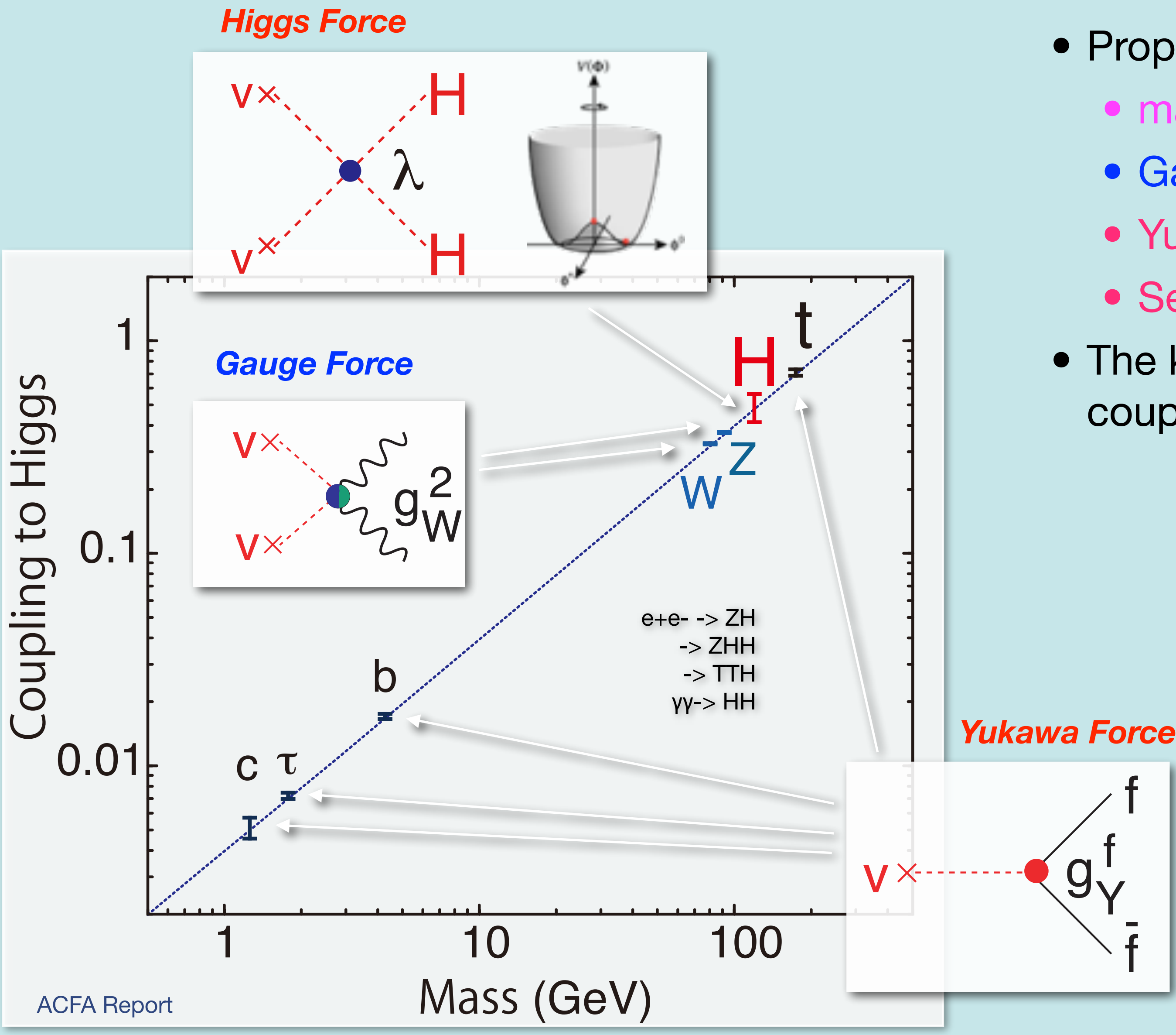
- By the same token,
  X → WW* means, X can be produced via W fusion: $e^+e^- \to \nu\bar{\nu}X$.

- 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 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!

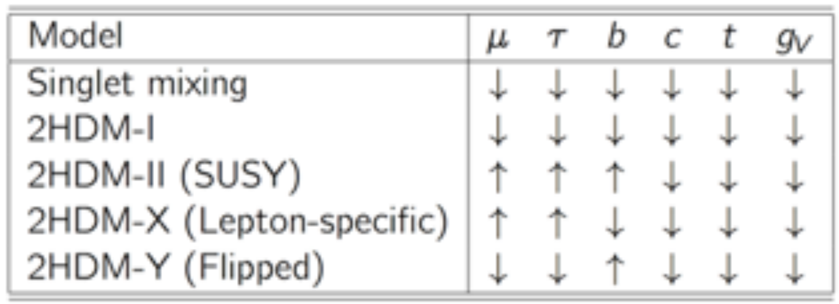
Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

- Multiplet structure :
  - Additional singlet? (ϕ + S)
  - Additional doublet? (ϕ + ϕ’)
  - Additional triplet? (ϕ + Δ)
- Underlying dynamics :
  - Why did the Higgs condense?
  - Weakly interacting or strongly interacting?
    = elementary or composite ?
- Relations to other questions of HEP :
  - ϕ + S → (B-L) gauge, DM, …
  - ϕ + ϕ’ → Type I : m_ν from small vev, …
    → Type II : SUSY, DM, …
    → Type X: m_ν (rad.seesaw), …
  - ϕ + Δ → 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

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

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!

For the precision we need a 500GeV ILC

LC 250-500

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

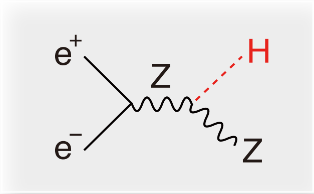
ZHH @ 500GeV (~M_Z+2M_H+170GeV)：

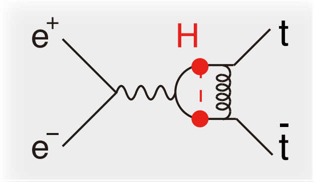
- Prod. cross section attains its maximum at around 500GeV -> Higgs self-coupling

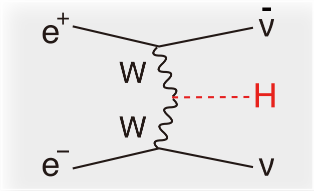
ttbarH @ 500GeV (~2mt+M_H+30GeV)：

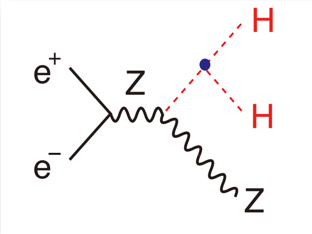
- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable at 500GeV concurrently with the self-coupling

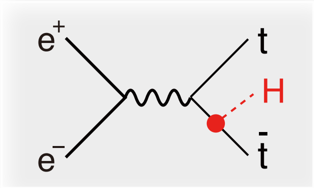
We can complete the mass-coupling plot at ~500GeV!







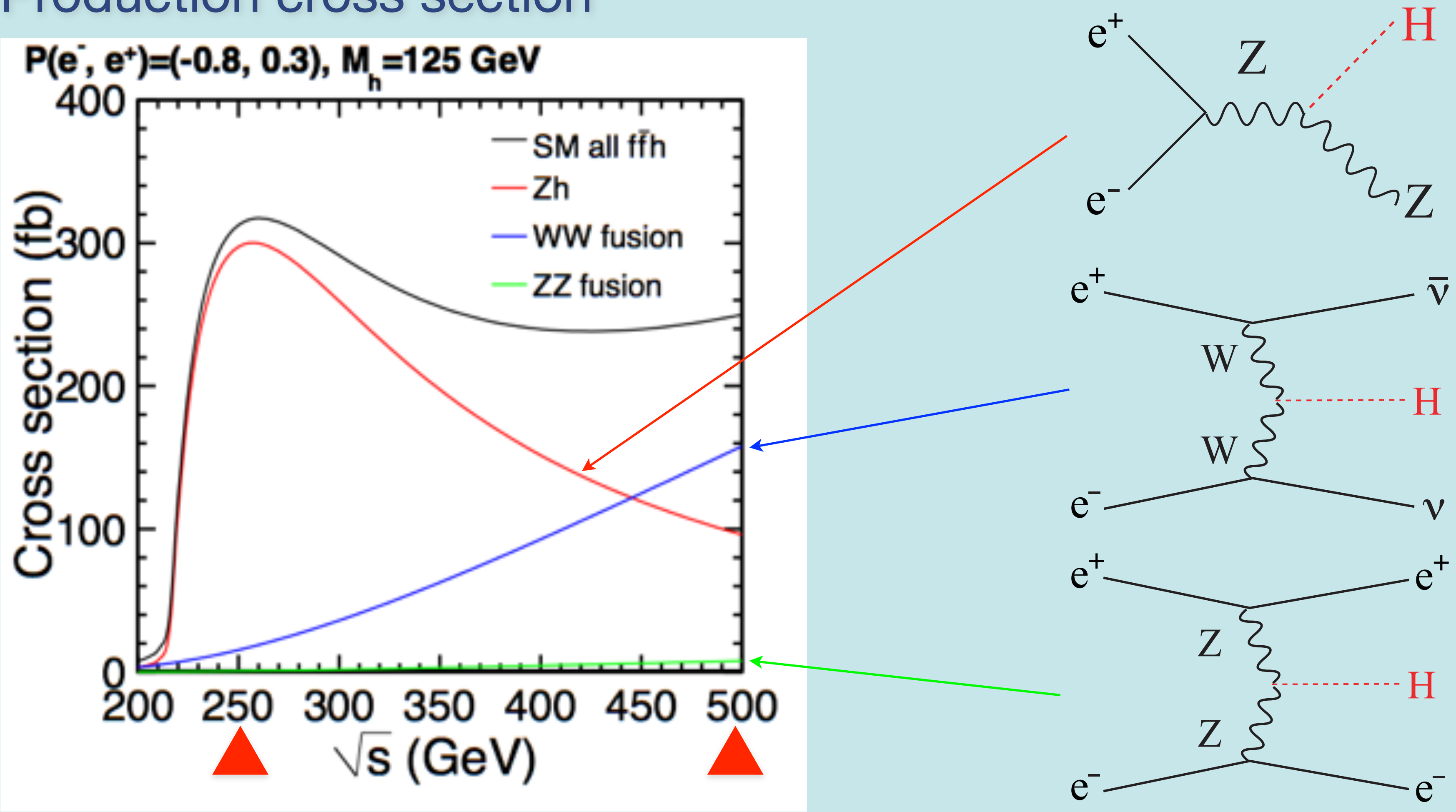




Main Production Processes

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})

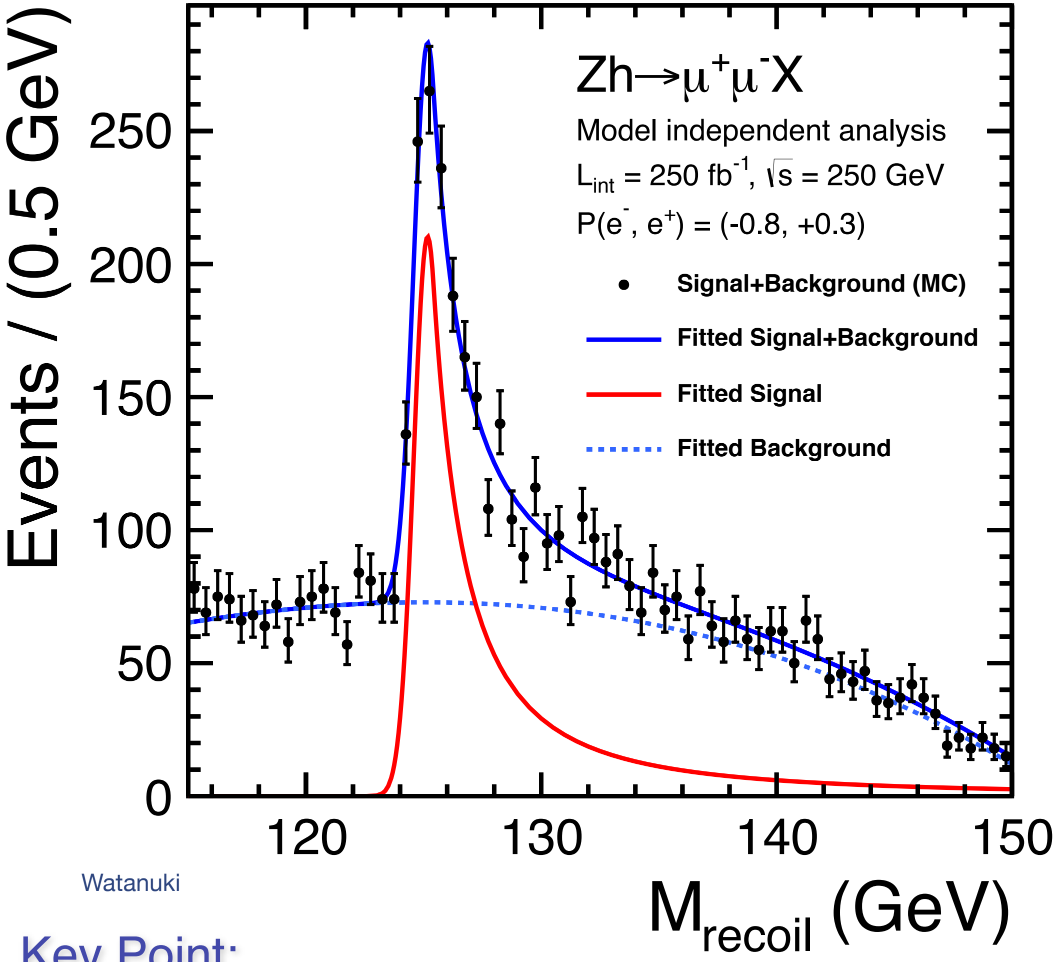
Possible to rediscover the Higgs in one day!

ILC 250

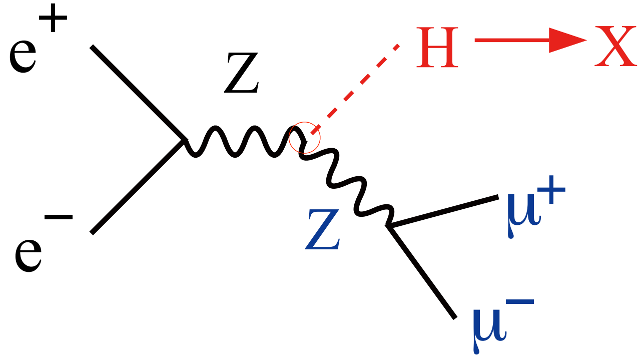
Recoil Mass Measurement: The Key

to unlock the door to fully model-independent determinations of various BRs, Higgs couplings, and total widths

Recoil Mass



Watanuki



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

Invisible decay detectable!

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

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

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

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

scaled from mH=120 GeV

Key Point:

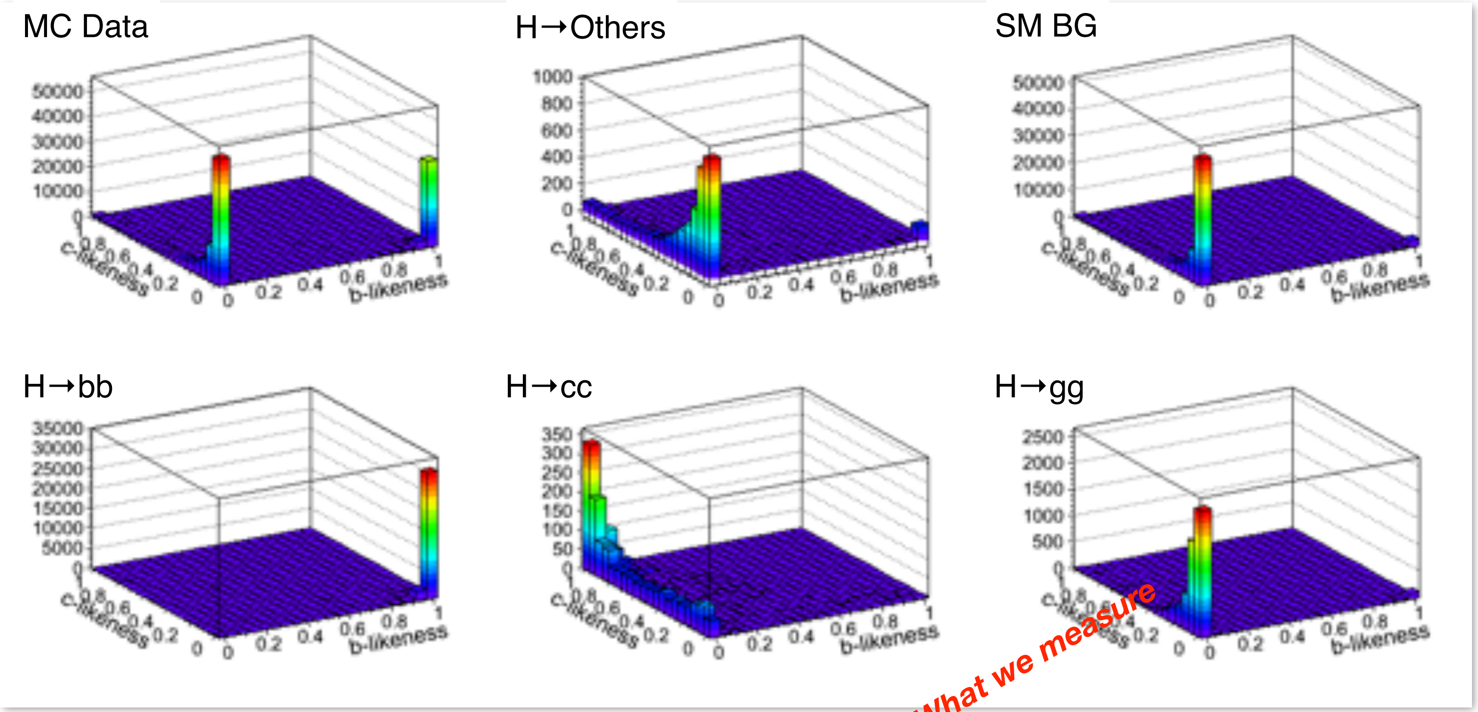
σ_{ZH} is the key to extract BR(h→AA) from σ×BR(h→AA) and g_{hAA} from BR(h→AA) through determination of the total width Γ_h! (great advantage of ILC)

High Performance Flavor Tagging : The Key

*to directly access major couplings: bb, cc, ττ, gg, WW**

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

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



What we measure

What we measure here is not BR itself but σxBR.

$$BR = \boxed{(\sigma \times BR)}/\sigma$$

--> Δσ/σ=2.6% eventually limits the BR measurements.
--> luminosity upgrade and/or longer running in a later stage.

	@250GeV
process	ZH
Int. Lumi.	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%

DBD Physics Chap.

Clean environment and a high performance vertex detector are the two powerful weapons of the ILC to directly access all of the major couplings (great advantage of the ILC)

Total Width and Coupling Extraction

One of the major advantages of the LC

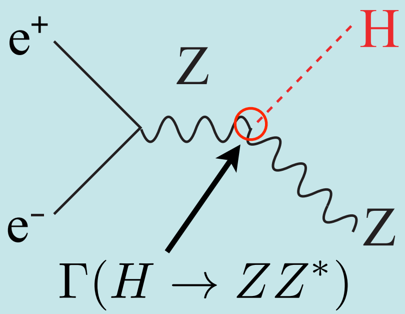
To extract couplings from BRs, we need the total width:

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

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

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

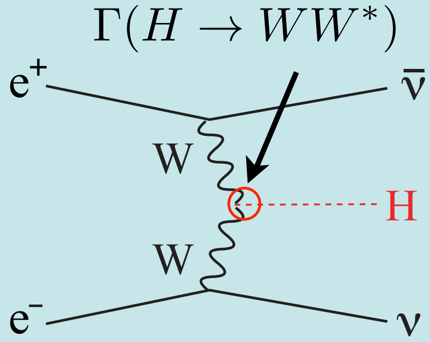
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

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

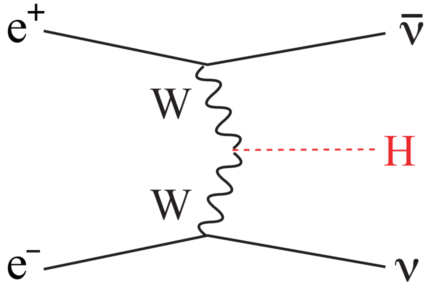
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

E	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%

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

ILD DBD Full Simulation Study



comes in as a powerful tool!

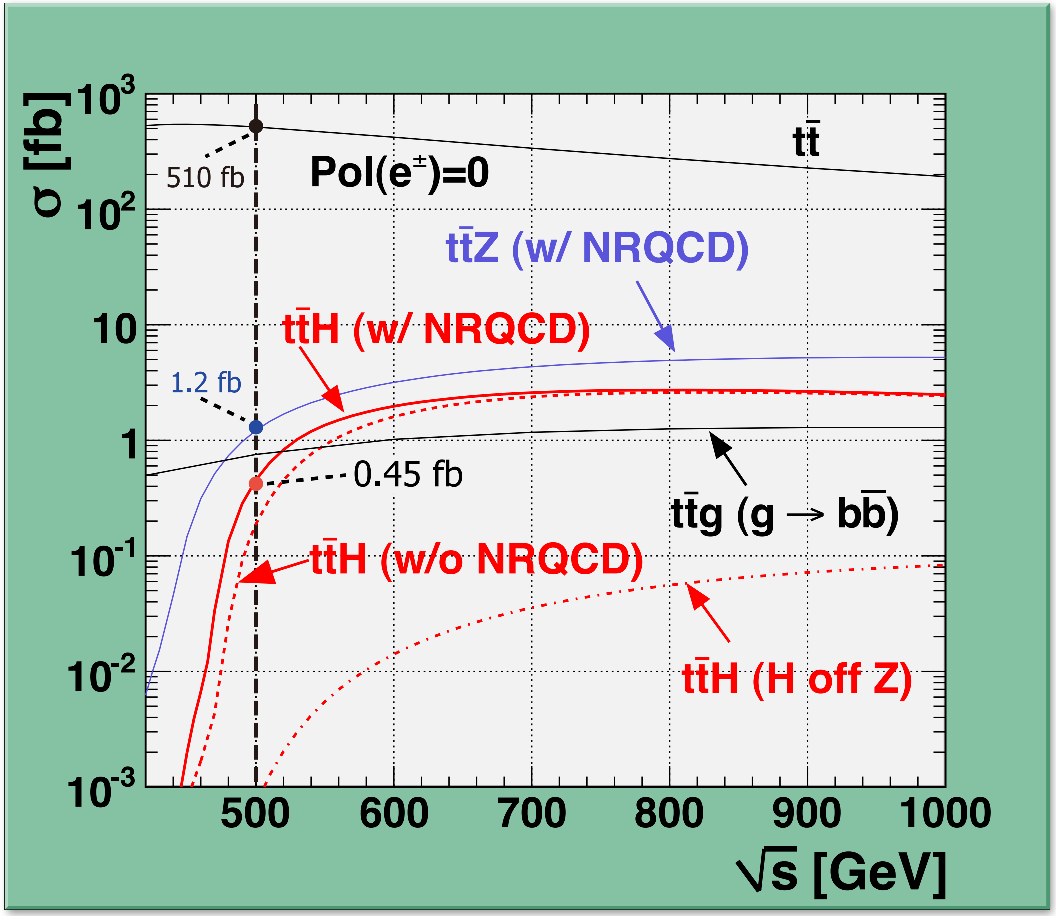
$$\Delta\Gamma_H/\Gamma_H \simeq 5\%$$

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

Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed

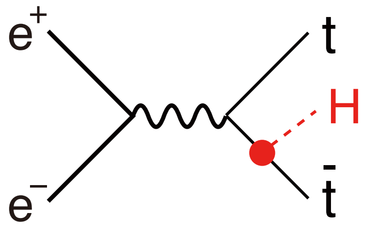


Cross section maximum at around Ecm = 800GeV

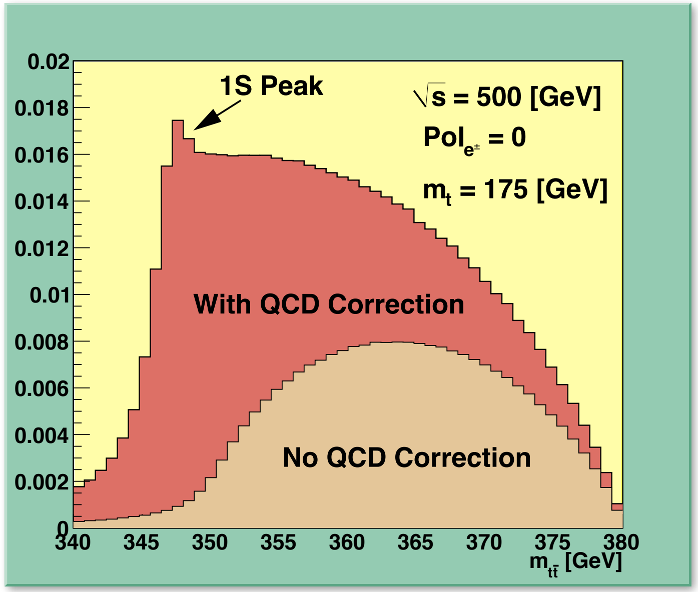
Philipp Roloff, LCWS12

Tony Price, LCWS12

DBD Full Simulation



H-> bb



A factor of 2 enhancement from QCD bound-state effects

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

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

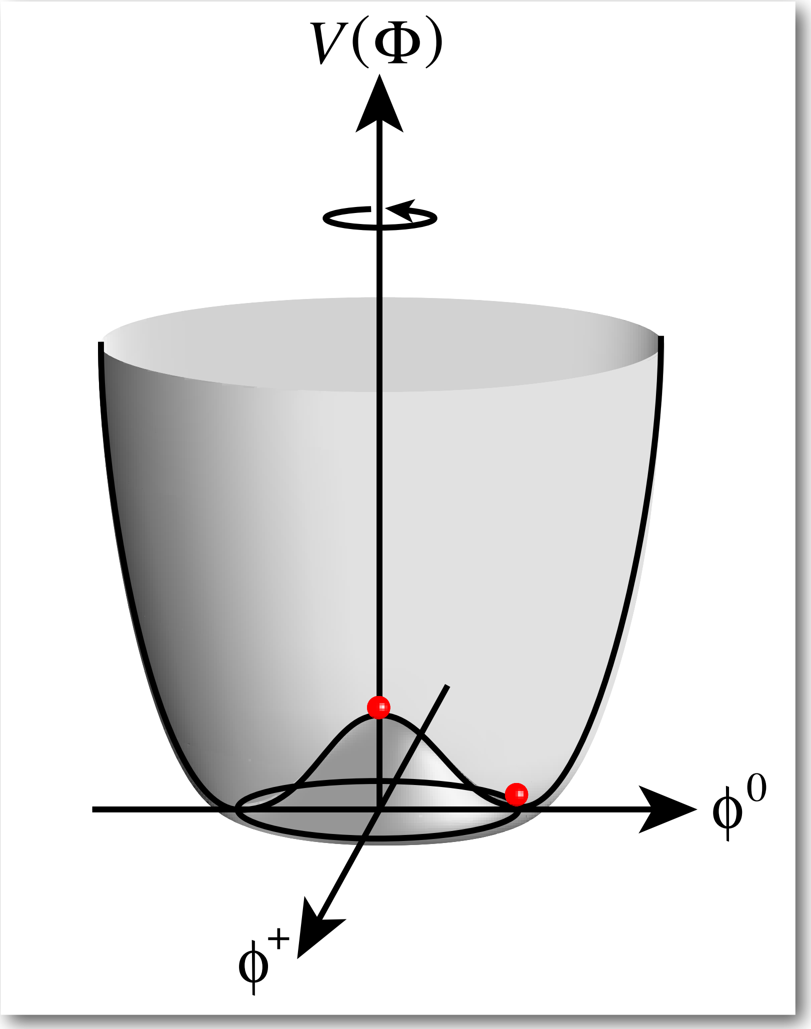
Tony Price, LCWS12

scaled from mH=120 GeV

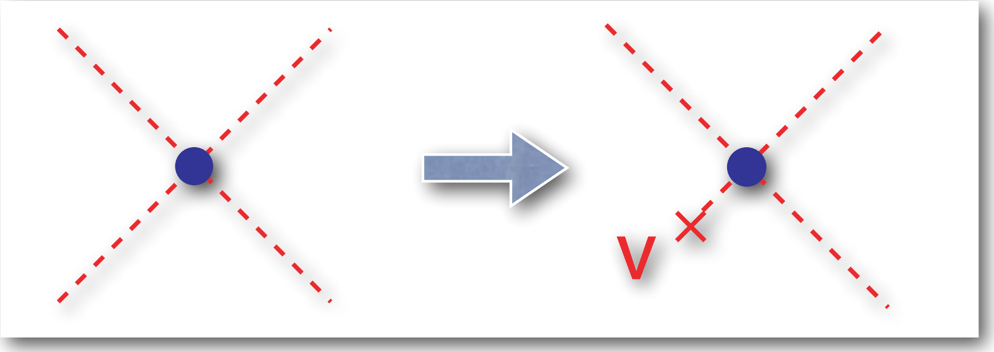
Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

And then Higgs Self-coupling

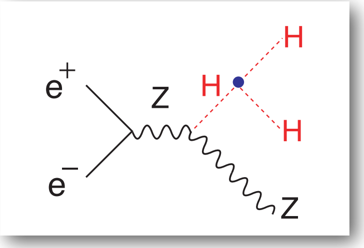
the force that made the Higgs condense in the vacuum

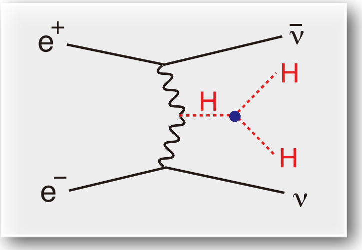


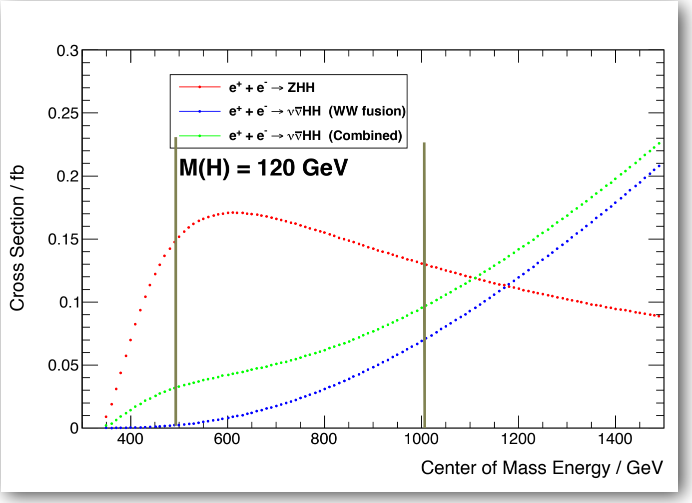
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential







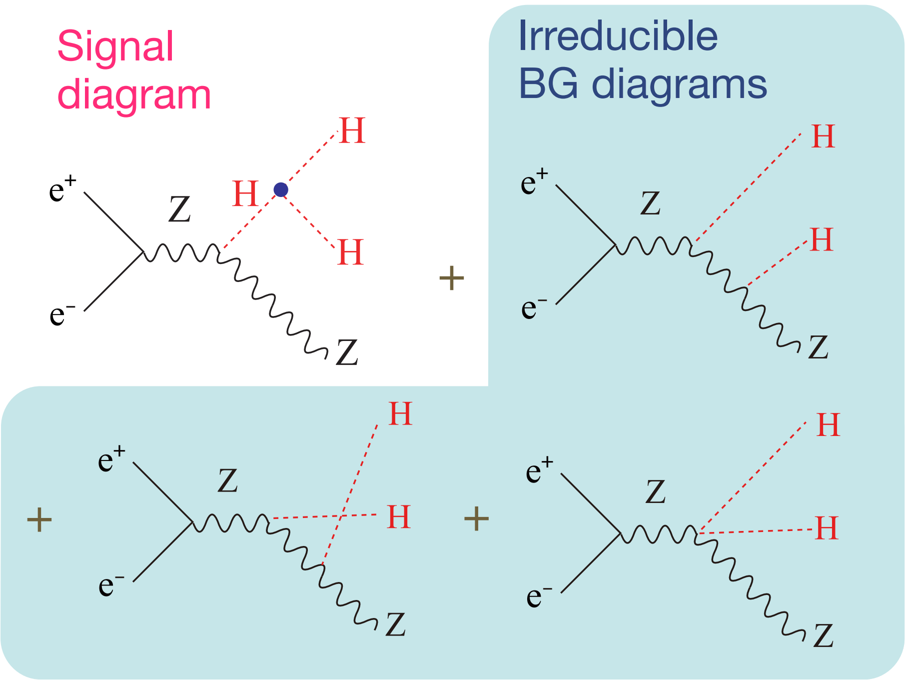
The measurement is very difficult even at ILC.

The Problem : BG diagrams dilute self-coupling contribution

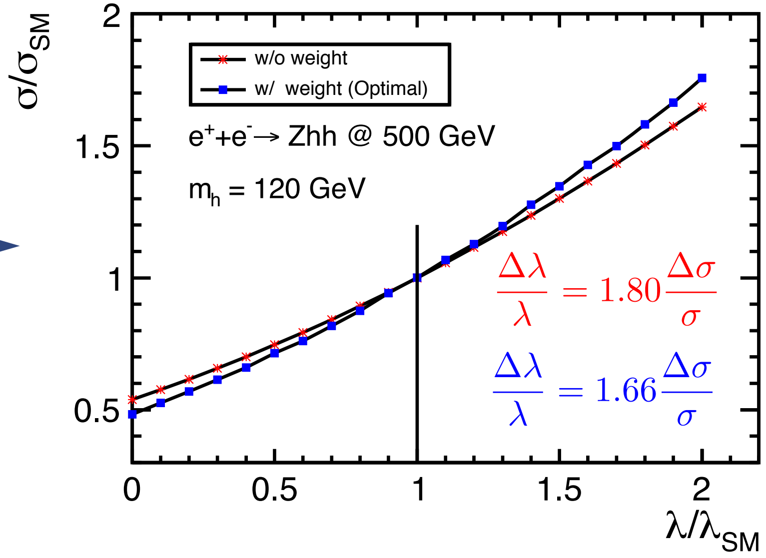
$$\sigma = \lambda^2 S + \lambda I + B$$

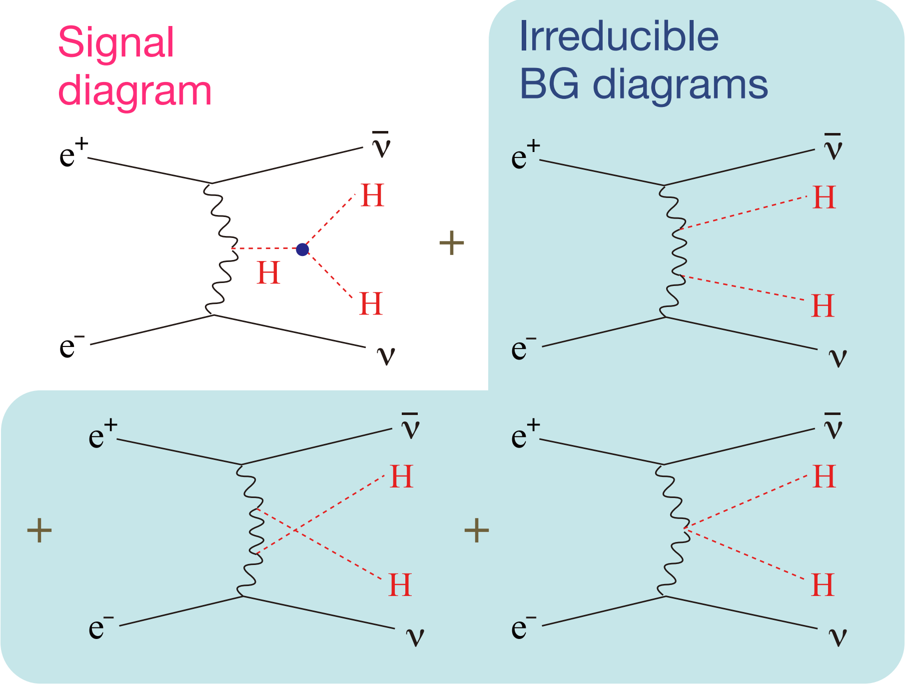
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams

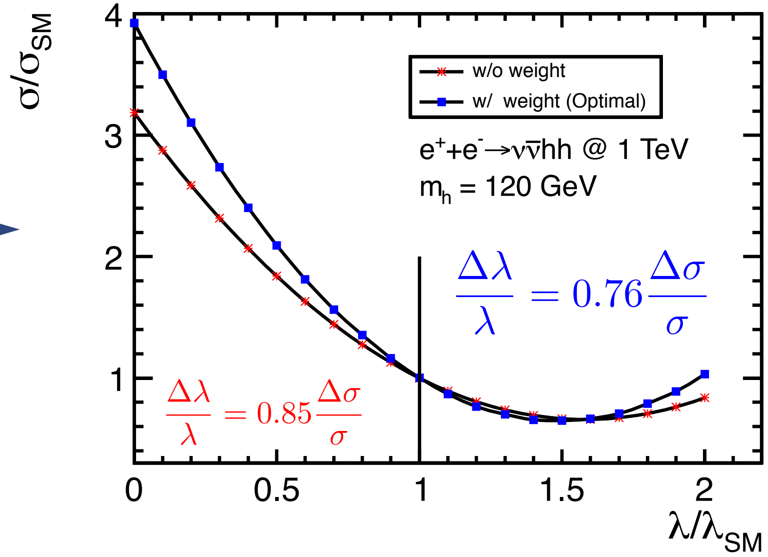

Signal diagram

Irreducible BG diagrams




Signal diagram

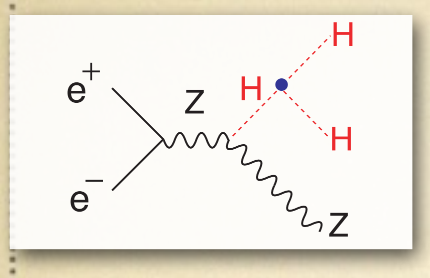
Irreducible BG diagrams



Junping Tian LC-REP-2013-003

DBD full simulation

Higgs self-coupling @ 500 GeV



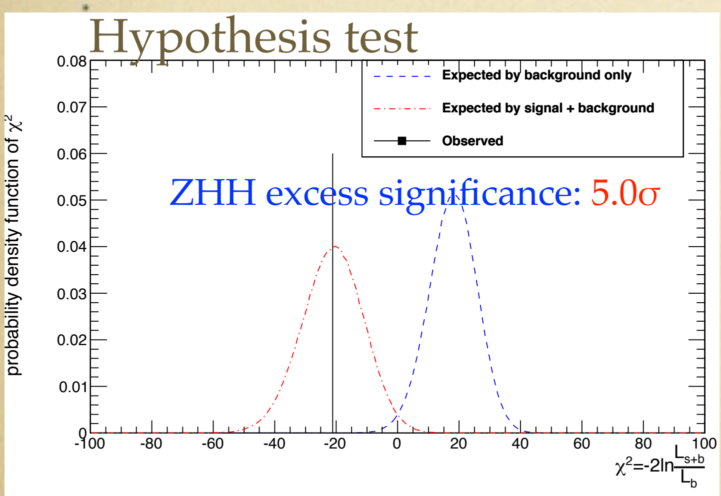
$$e^+ + e^- \to ZHH$$

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

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

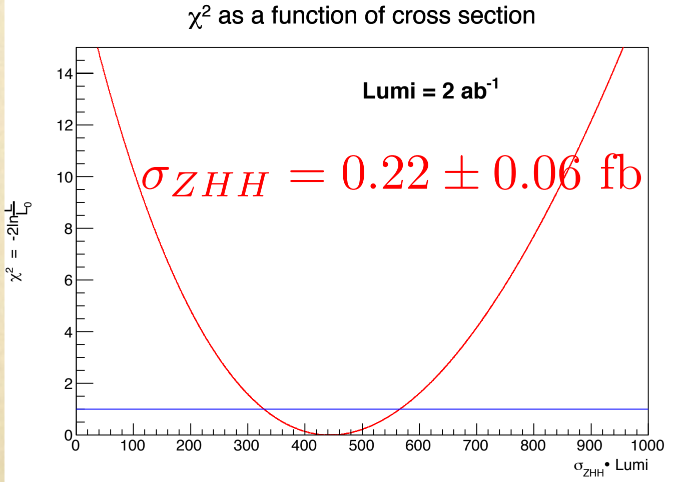
Hypothesis test



ZHH excess significance: 5.0σ

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

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



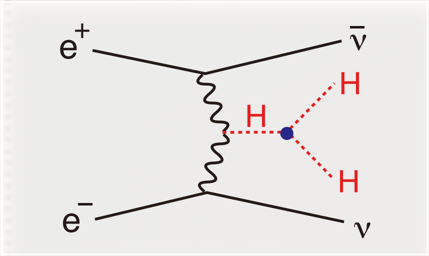
$\sigma_{ZHH} = 0.22 \pm 0.06$ fb

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

ILD DBD Study (Junping Tian)

ILC 1000

DBD full simulation



Higgs self-coupling @ 1 TeV

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

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

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

	Expected	After Cut
vvhh (WW-F)	272	35.7
vvhh (ZHH)	74	3.88
BG (tt/vvZH)	7.86×10^{5}	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: > 7σ

Higgs self-coupling significance: > 5σ

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%

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

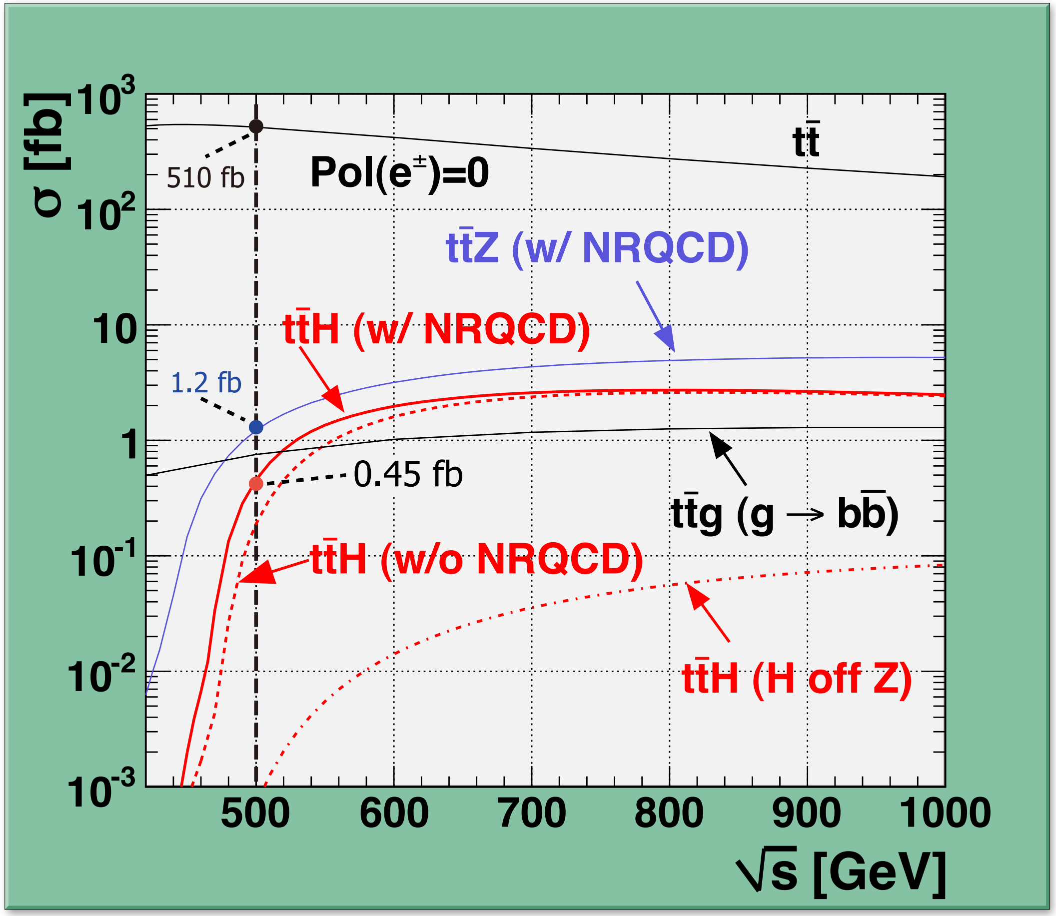
→

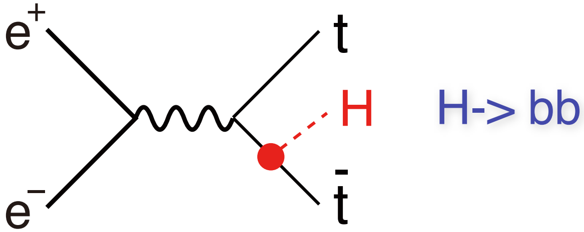
LumiUP:
250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

ILD DBD Study
(Junping Tian, Masakazu Kurata)

Top Yukawa Coupling at 1TeV

Now it is fully open!





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

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} ($Y_{34,35}$)

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

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t)$$

$$(i = 1, \cdots, 33) \qquad (B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

$$F_i = S_i \, G_i$$

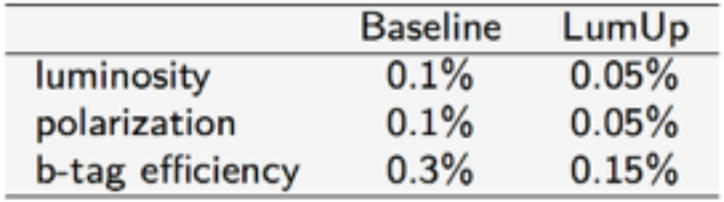
$$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

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

- 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

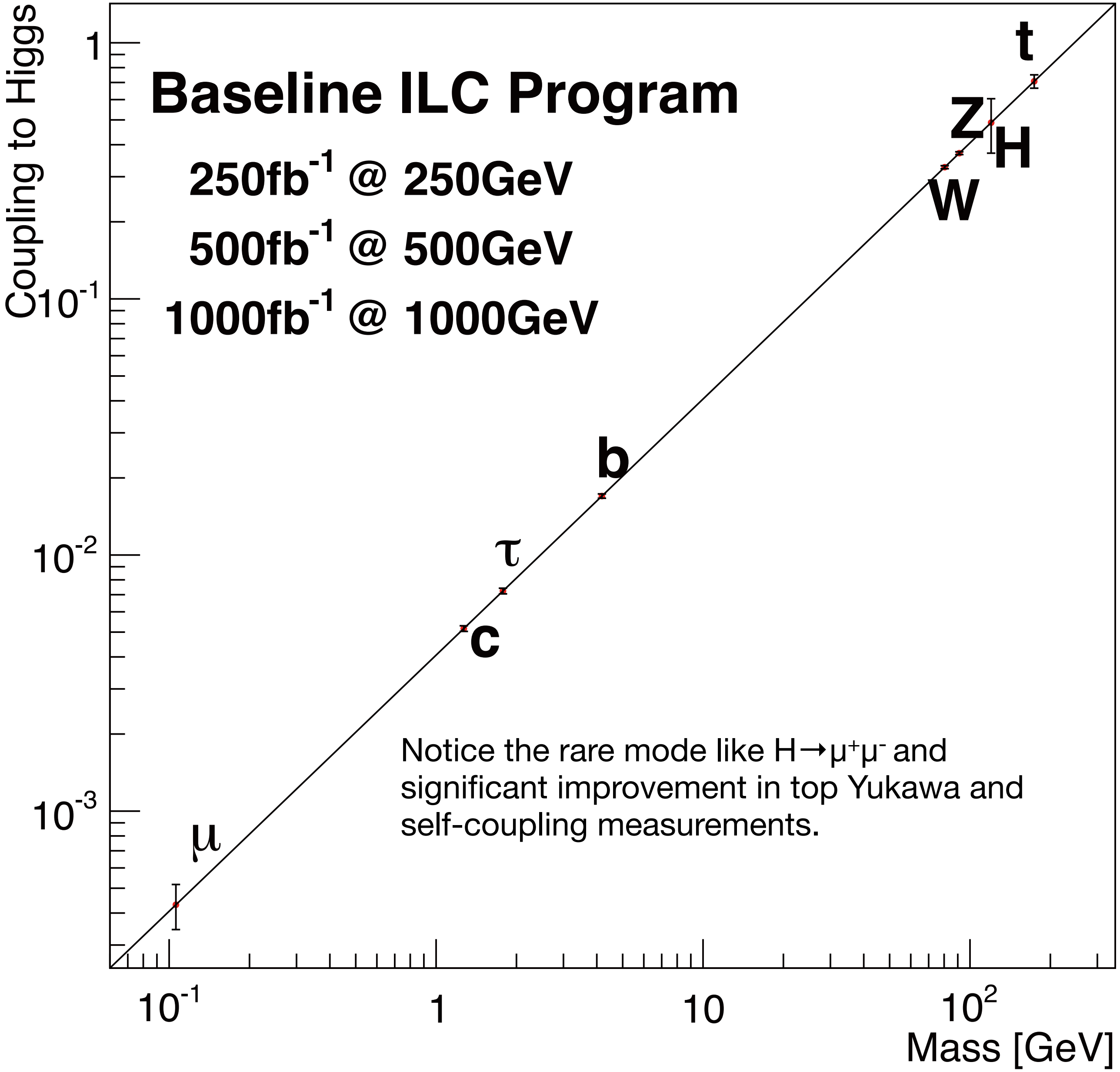
coupling	250 GeV	250 GeV + 500	250 GeV + 500
HZZ	1.3%	1%	1%
HWW	4.8%	1.1%	1.1%
Hbb	5.3%	1.6%	1.3%
Hcc	6.8%	2.8%	1.8%
Hgg	6.4%	2.3%	1.6%
Hττ	5.7%	2.3%	1.6%
Hγγ	18%	8.4%	4%
Hμμ	91%	91%	16%
Γ	12%	4.9%	4.5%
Htt	-	14%	3.1%

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



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

Model-independent Global Fit for Couplings

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)

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

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

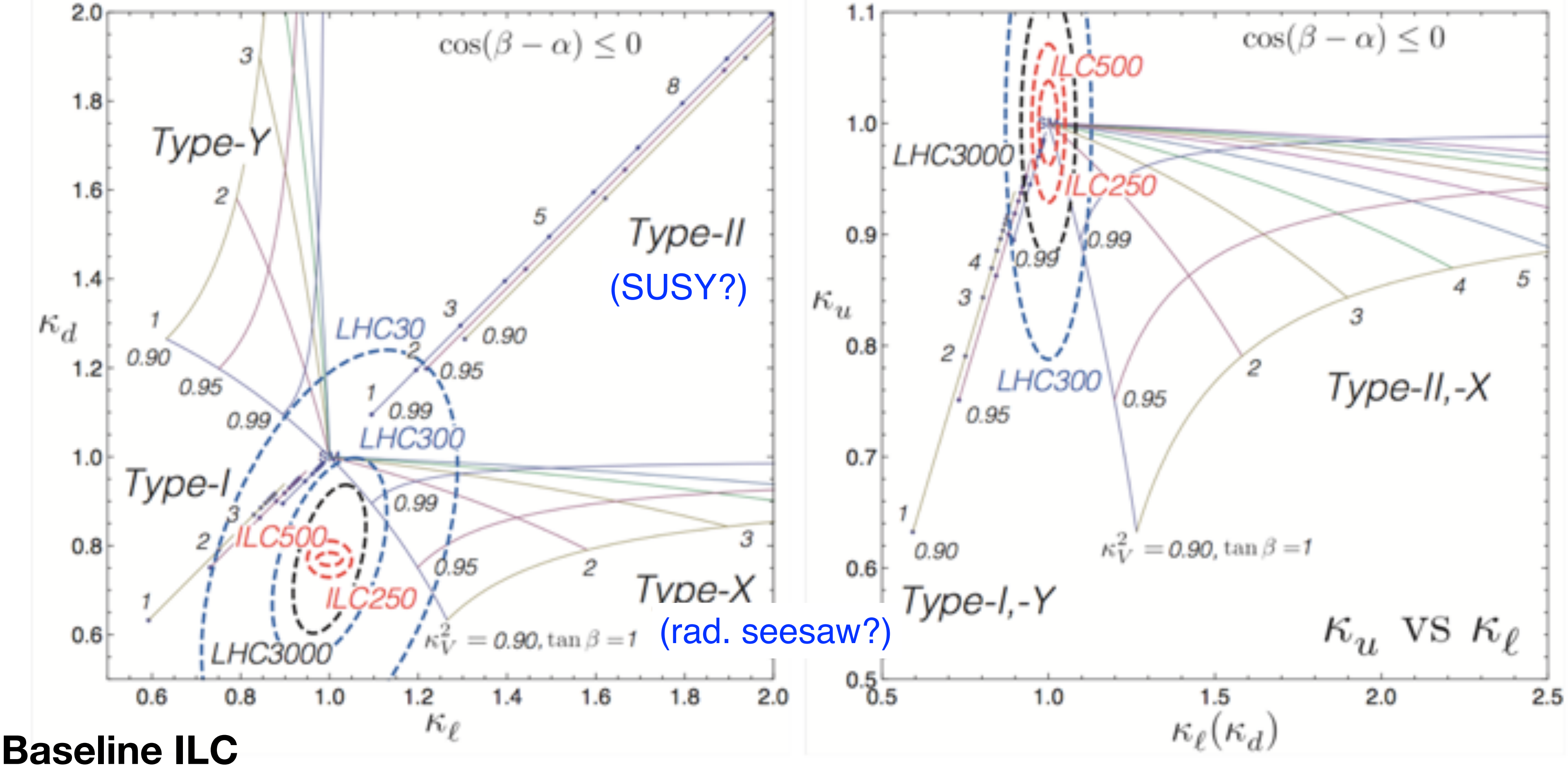
coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
Hττ	2.7%	1.2%	0.9%
Hγγ	8.2%	4.5%	2.4%
Hμμ	42%	42%	10%
Γ	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

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**



(SUSY?)

(rad. seesaw?)

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.

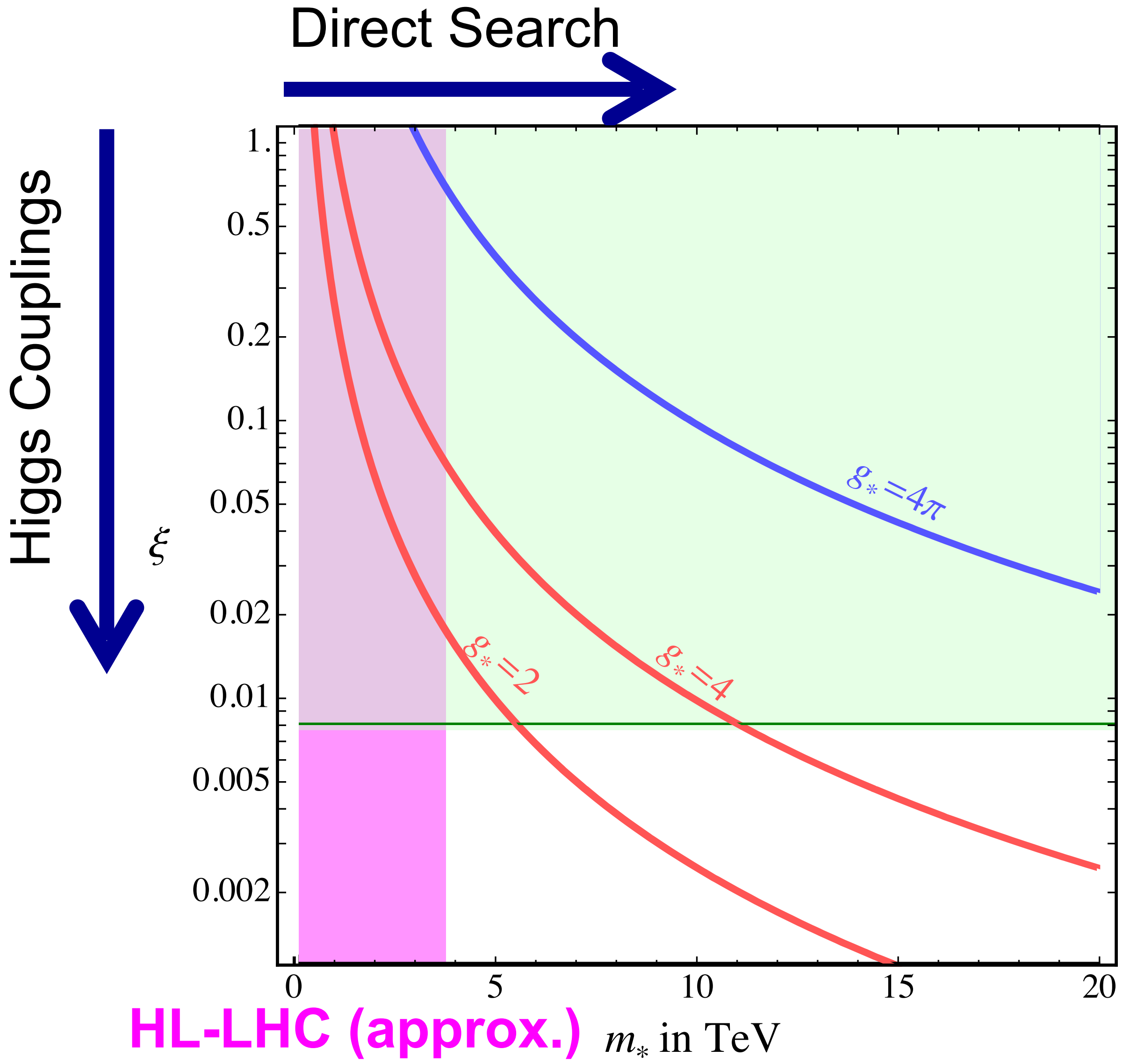
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Composite Higgs: Reach

Complementary approaches to probe composite Higgs models

- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)



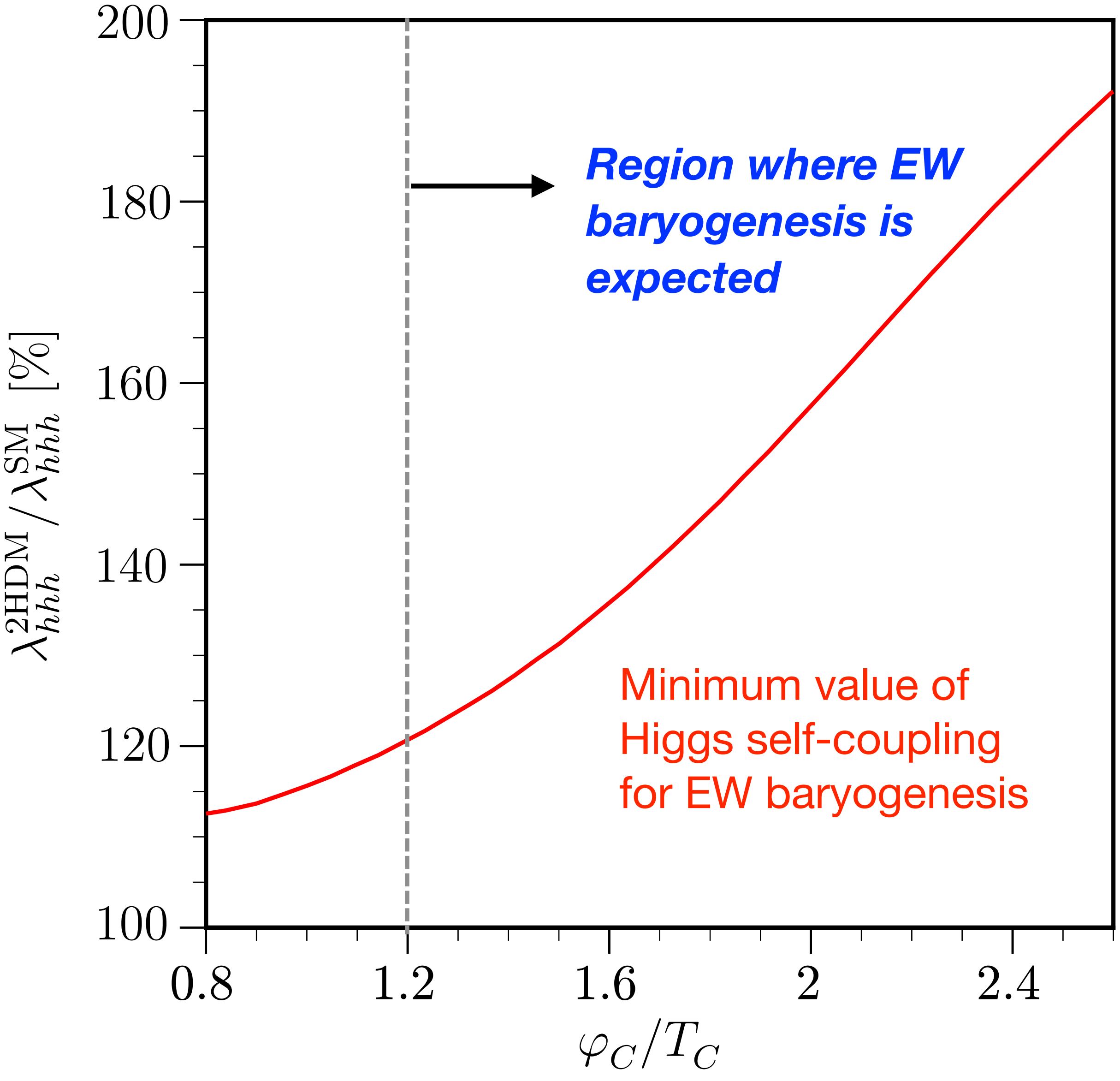
$$\xi = \frac{g_*^2}{m_*^2} v^2$$

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

ILC

$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

Electroweak Baryogenesis



Region where EW baryogenesis is expected

Minimum value of Higgs self-coupling for EW baryogenesis

Senaha, Kanemura

Example:

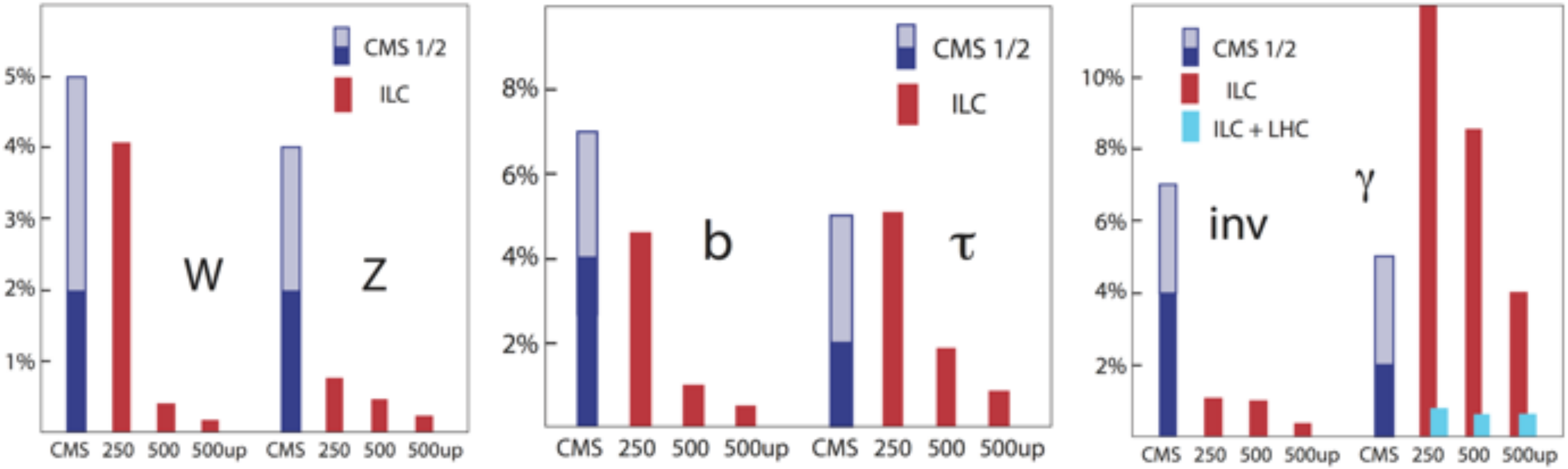
Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling are generally predicted in EW baryogenesis scenarios.

ILC can test the idea of baryogenesis occurring at the electroweak scale.

LHC + ILC

M. Peskin, LCWS 2013
arXiv: 1312.4974

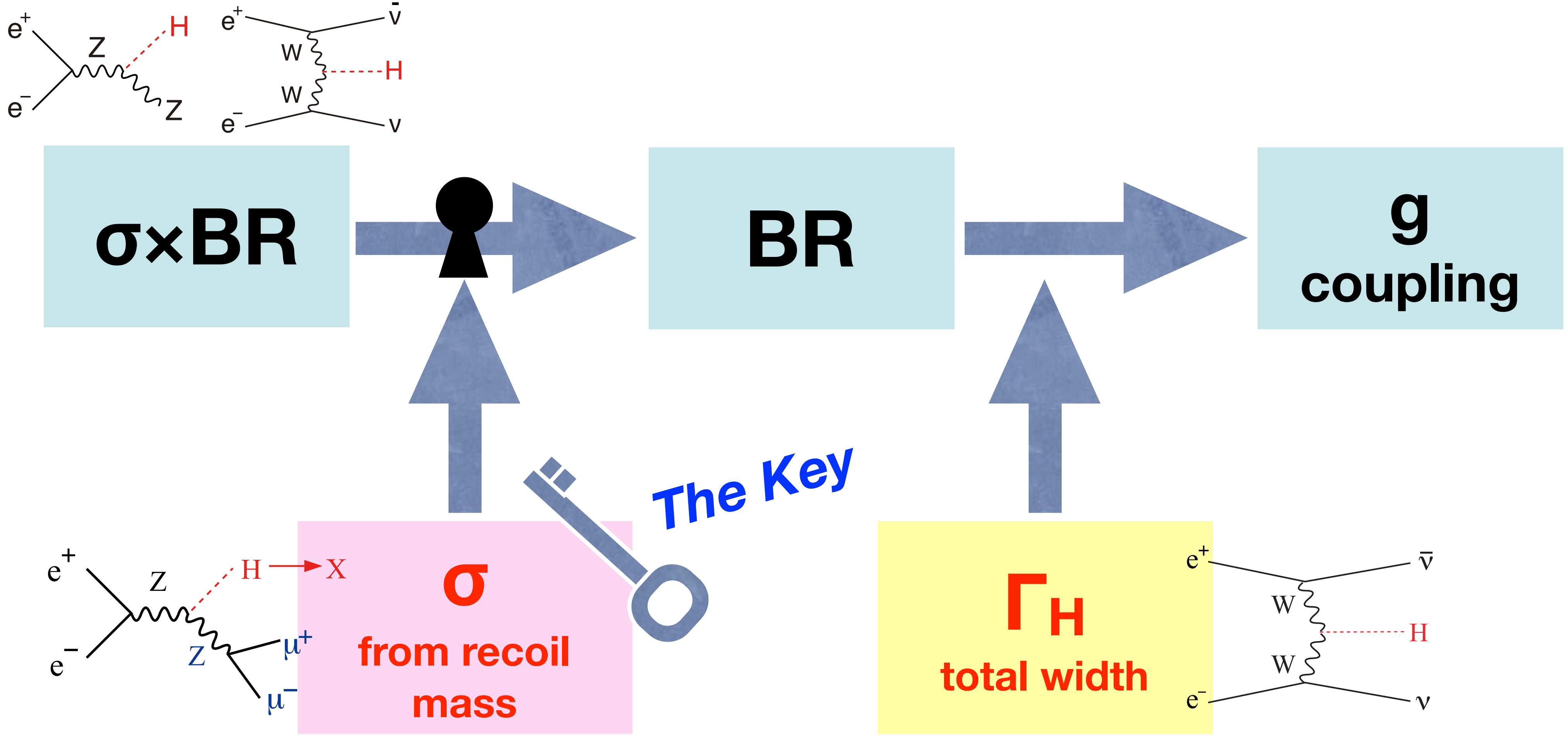


ILC greatly improves the LHC precisions and provides the necessary precision for the fingerprinting

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

At LHC all the measurements are σ×BR measurements.

At ILC all but the σ measurement using recoil mass technique is σ×BR measurements.



σ×BR

BR

g coupling

The Key

σ from recoil mass

Γ_H total width

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*** but colored sparticles can be heavy enough to escape LHC detection

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

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

→ ***typically Δm of 20 GeV or less*** → ***very difficult for LHC!***

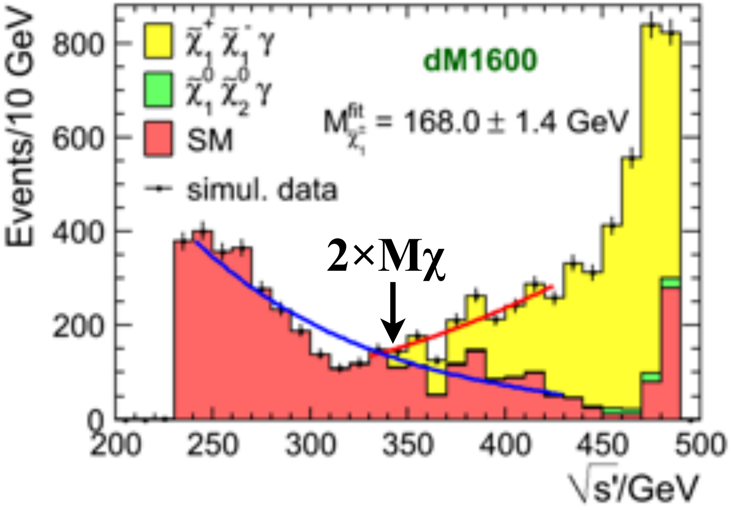
Higgsinos in Natural SUSY (ΔM<a few GeV)

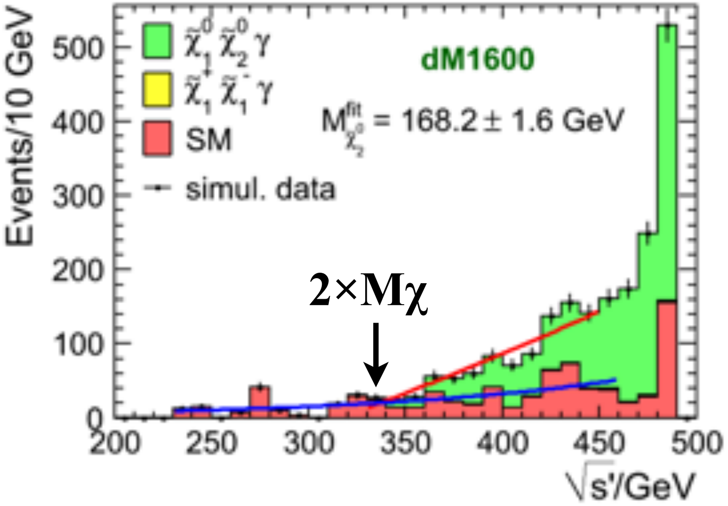
ILC as a Higgsino Factory

ISR Tagging

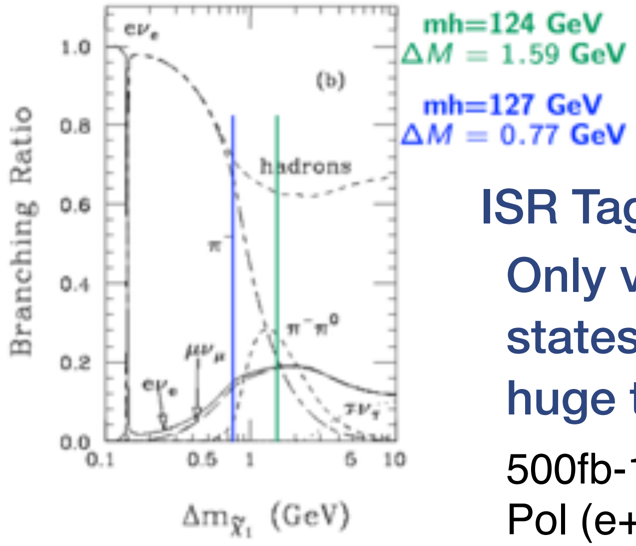
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$

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





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	$\sim 2-3\times10^3$

$\Delta M(\tilde{\chi}_1^\pm,\tilde{\chi}_1^0) = 1.59$ 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	$\sim 2-3\times10^3$

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

$$\delta(\sigma\times BR)\simeq 1.5\%$$

$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0})\simeq 1.5(1.6)\,\mathrm{GeV}$$

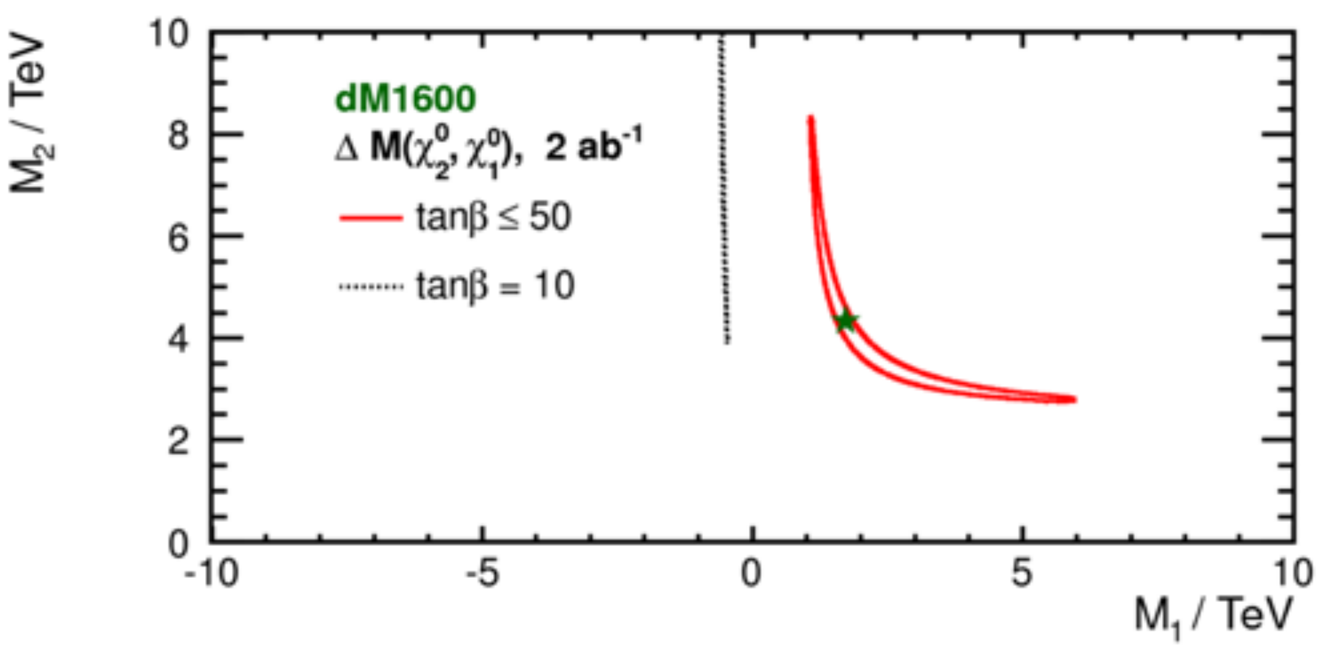
$$\delta\Delta M(\tilde{\chi}_1^\pm,\tilde{\chi}_1^0)\simeq 20\,\mathrm{MeV}$$

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

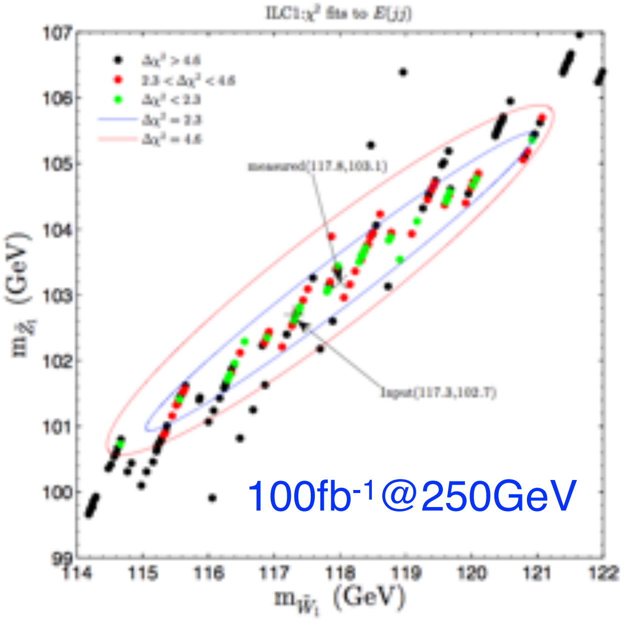


@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	~ 1.0 (-0.4)	~ 6.0
M_2 [TeV]	4.4	~ 2.5 (3.5)	~ 8.5
μ [GeV]	165.7	166.2	170.1

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

RNS: Baer et al.
arXiv: 1404.7510

ΔM=15GeV



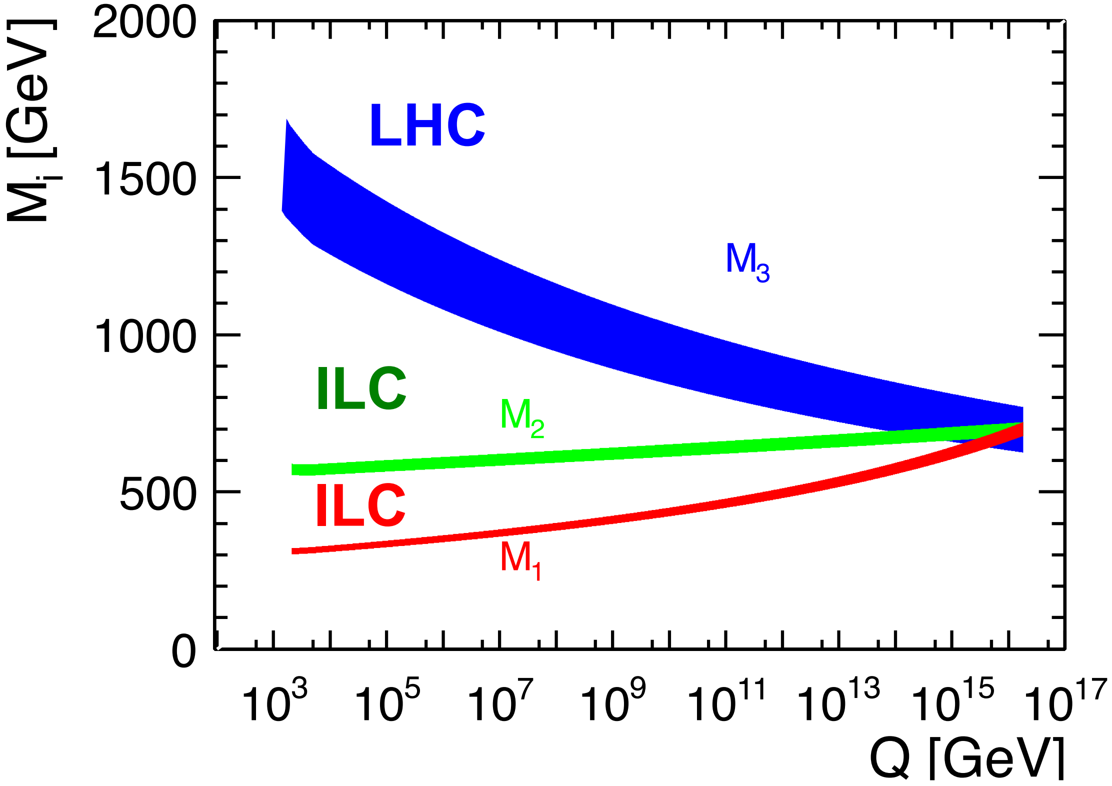
100fb^{-1}@250GeV

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!

Gaugino mass relation

- Chargino/Neutralino @ ILC → probe M_1-M_2 gaugino mass relation
- Gluino @ LHC → test of gaugino mass relation by ILC-LHC complementarity
- Gives a prediction of the gluino mass scale
- Discrimination of SUSY spontaneous symmetry breaking scenarios

Gaugino mass unification:
Higgsino-like LSP scenario
By Baer, List



LHC: gluino discovery
→ mass determination

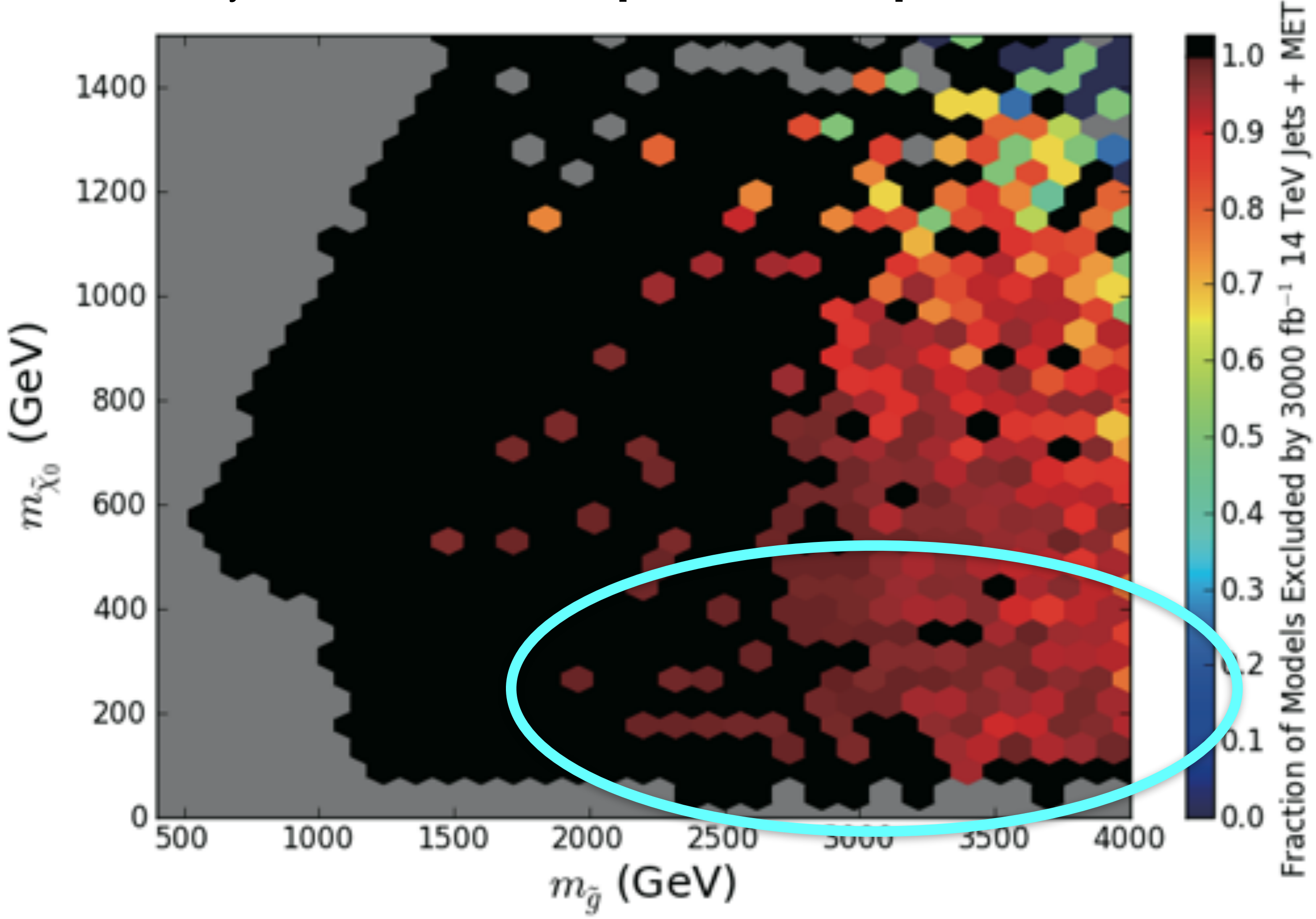
ILC: Higgsino discovery
→ M1, M2 via mixing between
Higgsino and Bino/Wino

Dark Matter Search

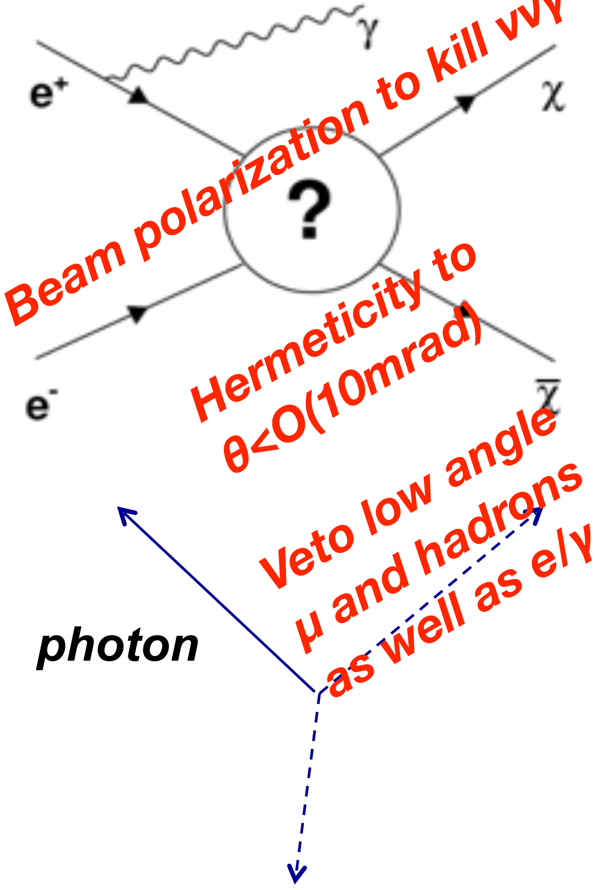
LHC 14 TeV, 3000 fb-1, ***Jets+MET*** analysis only
pMSSM Neutralino DM expected exclusion

may use mono-jet

Cahill-Rowley, Hewett, Ismail, Rizzo [arXiv:1307.8444]



LC:
single photon search



Beam polarization to kill ννγ

Hermeticity to θ<O(10mrad)

Veto low angle μ and hadrons as well as e/γ

Loopholes of HL-LHC → Hunting ground of ILC

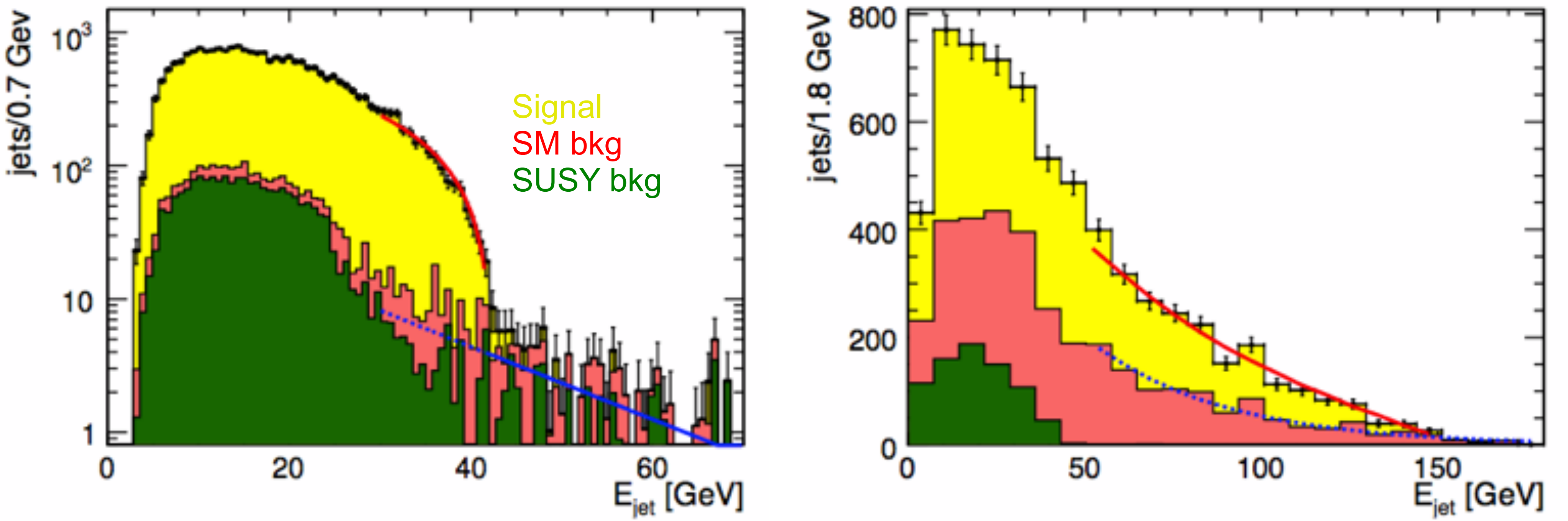
Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

Observation of lighter and heavier stau states with decay to DM + hadronic tau

Benchmark point: m(LSP) = 98 GeV, m(stau1) = 108 GeV, m(stau2) = 195 GeV

Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)



Stau1 mass resolution ~0.1%

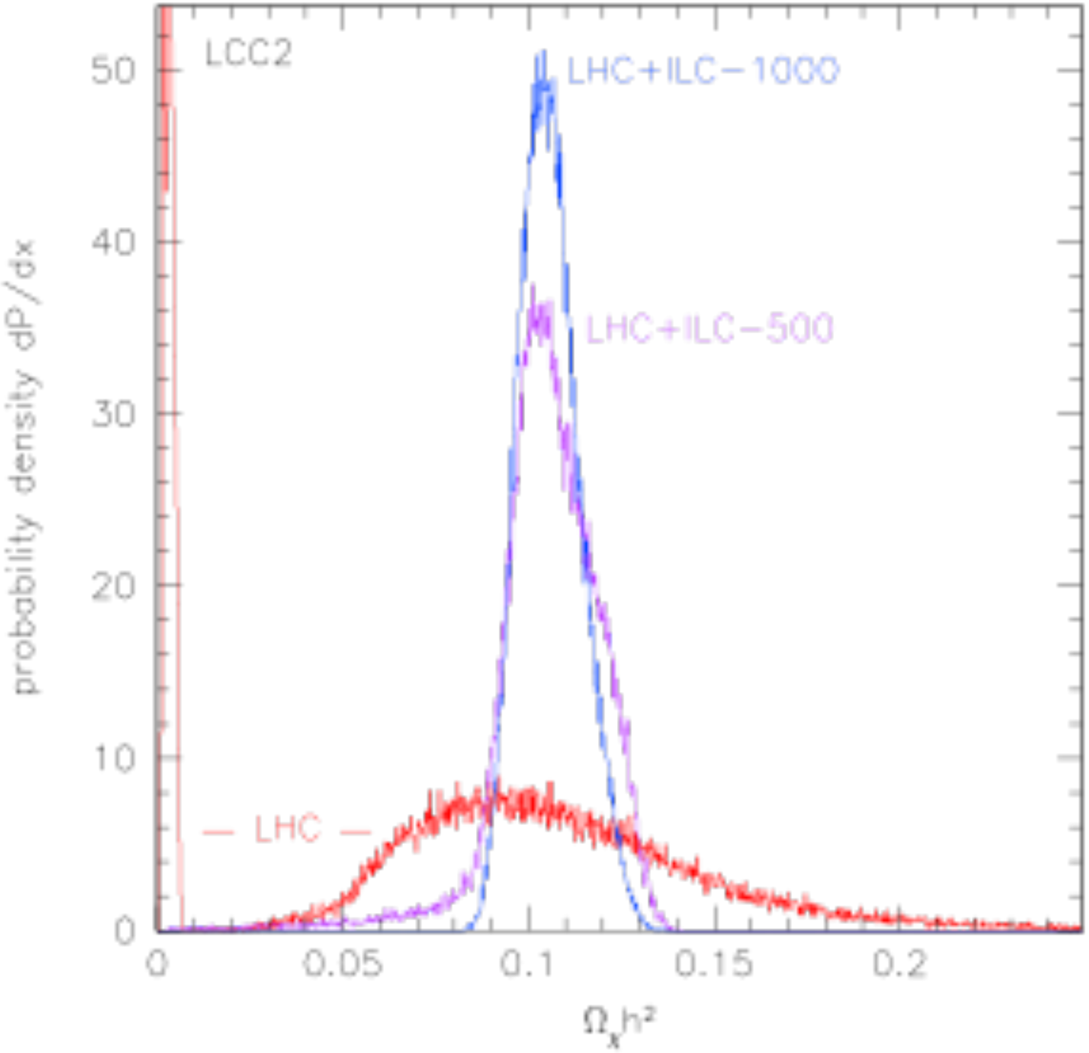
Stau2 mass resolution ~3%

→ LSP mass resolution ~1.7%

DM Relic Abundance

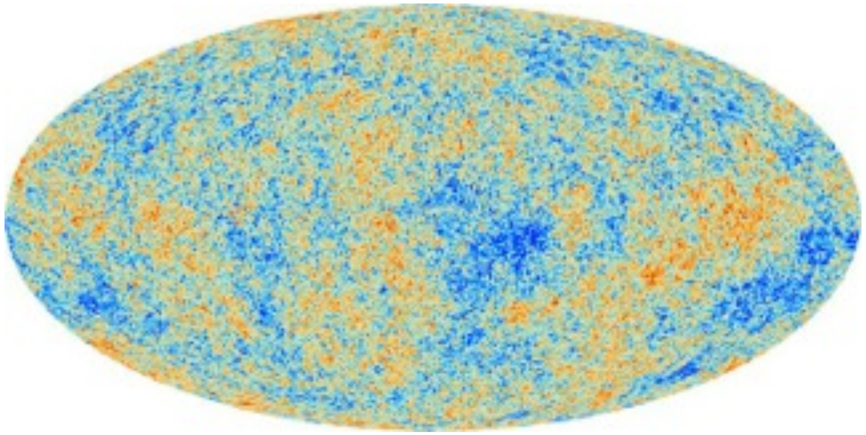
WMAP/Planck

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187

ESA/Planck



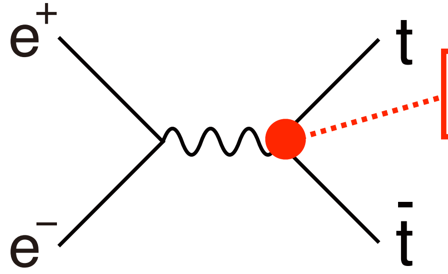
Once a DM candidate is discovered, crucial to test consistency with the measured DM relic abundance.

→ ILC precise measurements of mass and cross sections

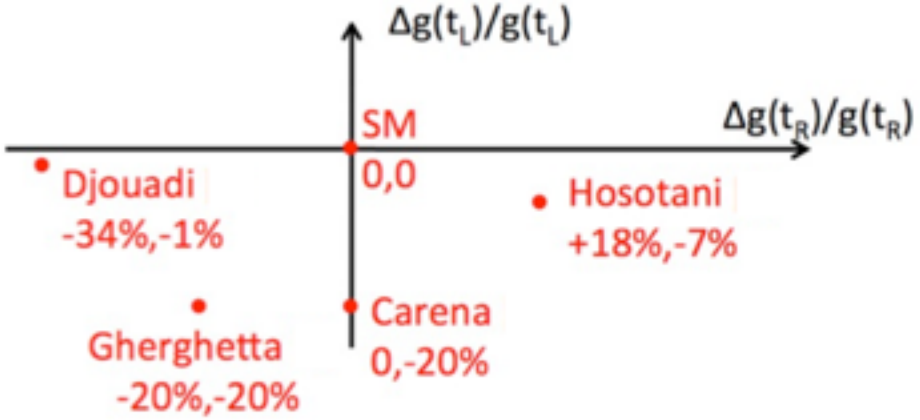
Top

Open Top Production

Anomalous Couplings in Open Top Production at 500 GeV



$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$



LAL 11-222

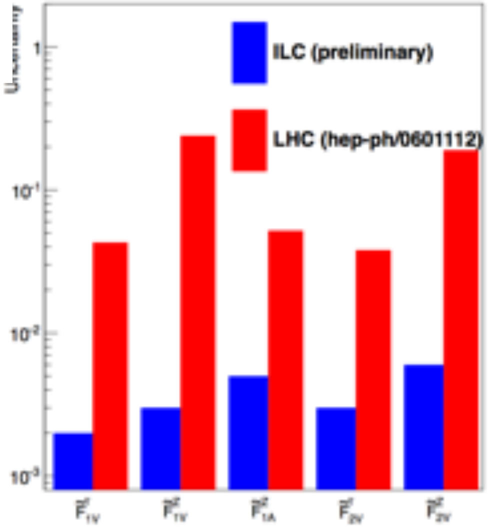


Figure 34: *Predictions of various groups [40,42–44] on deviations from Standard Model couplings of the t quark within Randall-Sundrum Models. The cartoon is taken from [47].*

Coupling	LHC [40] $\mathcal{L} = 300$ fb^{-1}	e^+e^- [52] $P_{e^-} = \pm 0.8$	e^+e^- [45] $\mathcal{L} = 500$ fb^{-1}, $P_{e^-,e^+} = \pm 0.8, \mp 0.3$
$\Delta\widetilde{F}_{1V}^\gamma$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$
$\Delta\widetilde{F}_{1V}^Z$	$^{+0.24}_{-0.62}$	$^{+0.012}_{-0.012}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$
$\Delta\widetilde{F}_{1A}^Z$	$^{+0.052}_{-0.060}$	$^{+0.013}_{-0.013}$, $\mathcal{L} = 100$ fb^{-1}	$^{+0.006}_{-0.006}$
$\Delta\widetilde{F}_{2V}^\gamma$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.001}_{-0.001}$
$\Delta\widetilde{F}_{2V}^Z$	$^{+0.27}_{-0.19}$	$^{+0.009}_{-0.009}$, $\mathcal{L} = 200$ fb^{-1}	$^{+0.002}_{-0.002}$

Table 3: Sensitivities achievable at 68.3% CL for the CP-conserving t quark form factors $\widetilde{F}_{1V,A}^X$ and $\widetilde{F}_{2V}^X$ defined in (1), at LHC and at the ILC. The assumed luminosity samples and, for ILC, beam polarization, are indicated. In the LHC studies and in the study [52], only one form factor at a time is allowed to deviate from its SM value. In study [45] the form factors are allowed to vary independently.

Coupling	LHC [40] $\mathcal{L} = 300$ fb^{-1}	e^+e^- [51] $\mathcal{L} = 300$ fb^{-1}, $P_{e^-e^+} = -0.8$
$\Delta\mathrm{Re}\,\widetilde{F}_{2A}^\gamma$	$^{+0.17}_{-0.17}$	$^{+0.007}_{-0.007}$
$\Delta\mathrm{Re}\,\widetilde{F}_{2A}^Z$	$^{+0.35}_{-0.35}$	$^{+0.008}_{-0.008}$
$\Delta\mathrm{Im}\,\widetilde{F}_{2A}^\gamma$	$^{+0.17}_{-0.17}$	$^{+0.008}_{-0.008}$
$\Delta\mathrm{Im}\,\widetilde{F}_{2A}^Z$	$^{+0.035}_{-0.035}$	$^{+0.015}_{-0.015}$

Table 4: Sensitivities achievable at 68.3% CL for the t quark CP-violating magnetic and electric dipole form factors $\widetilde{F}_{2A}^X$ defined in (1), at the LHC and at linear e^+e^- colliders as published in the TESLA TDR. The assumed luminosity samples and, for TESLA, the beam polarization, are indicated. In the LHC studies and in the TESLA studies, only one form factor at a time is allowed to deviate from its SM value.

arXiv:hep-ph/1307.8265

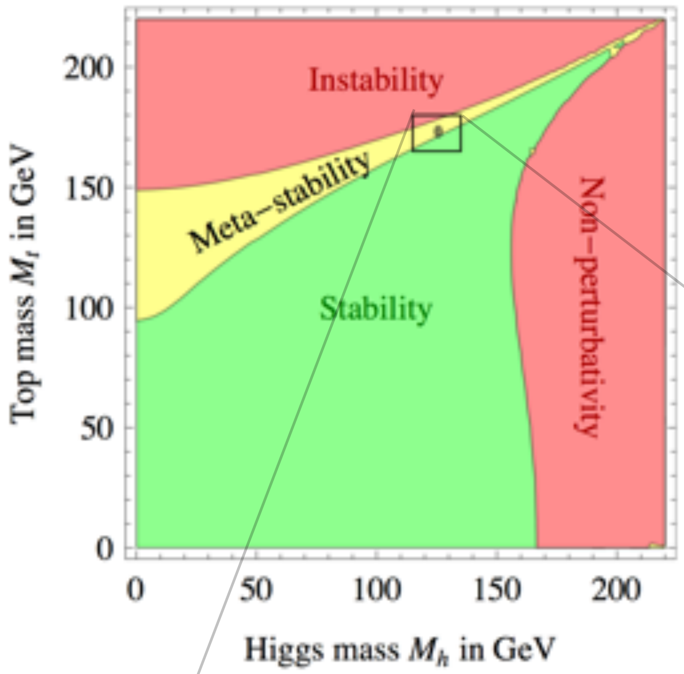
SM up to Λ_{Planck}?

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

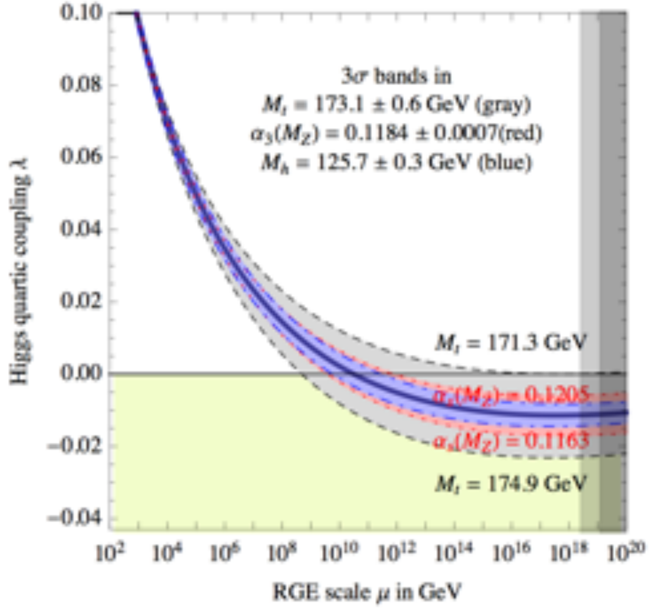
We would need to question then the range of validity of the SM.

How far can the SM go?

Stability of SM Vacuum



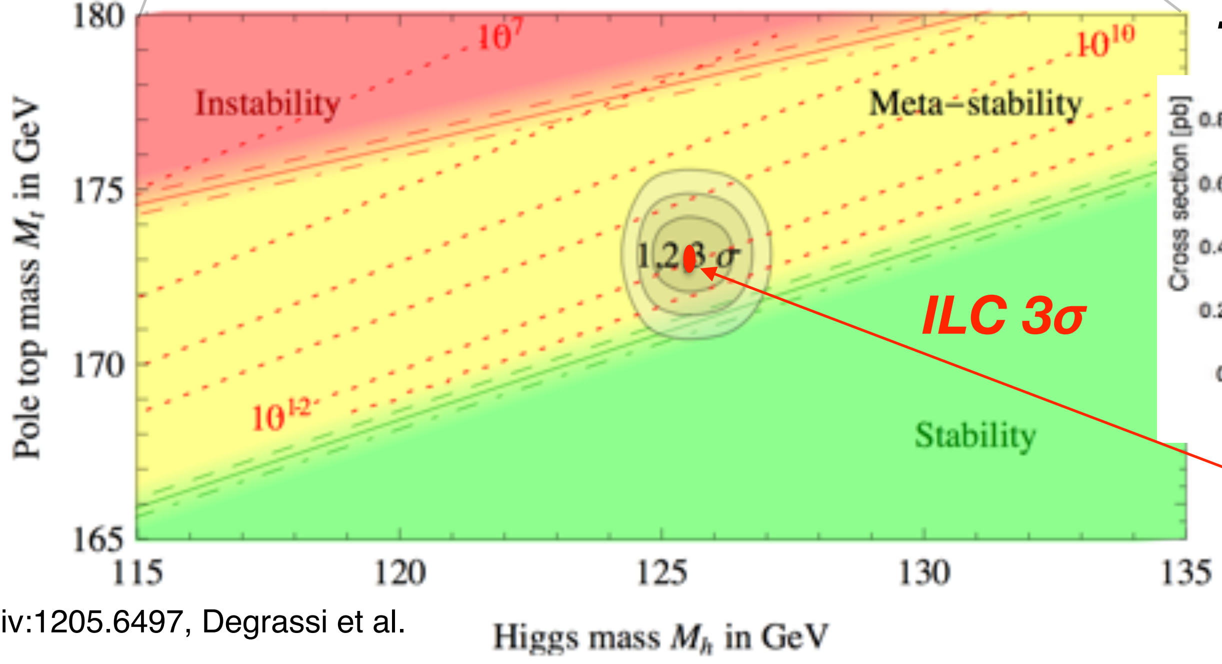
With the 126GeV Higgs boson, the SM vacuum seems to be at a subtle point of meta-stability!



Does λ really become negative below Λ_{Pl}?

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

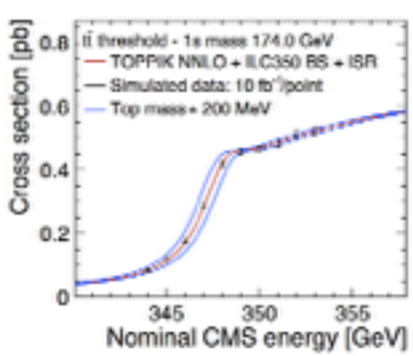
To answer this we need a precision m_t measurement!



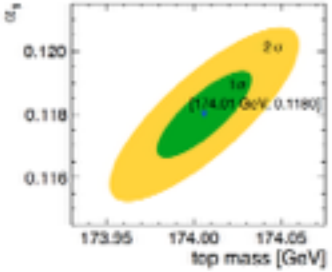
ILC 3σ

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!

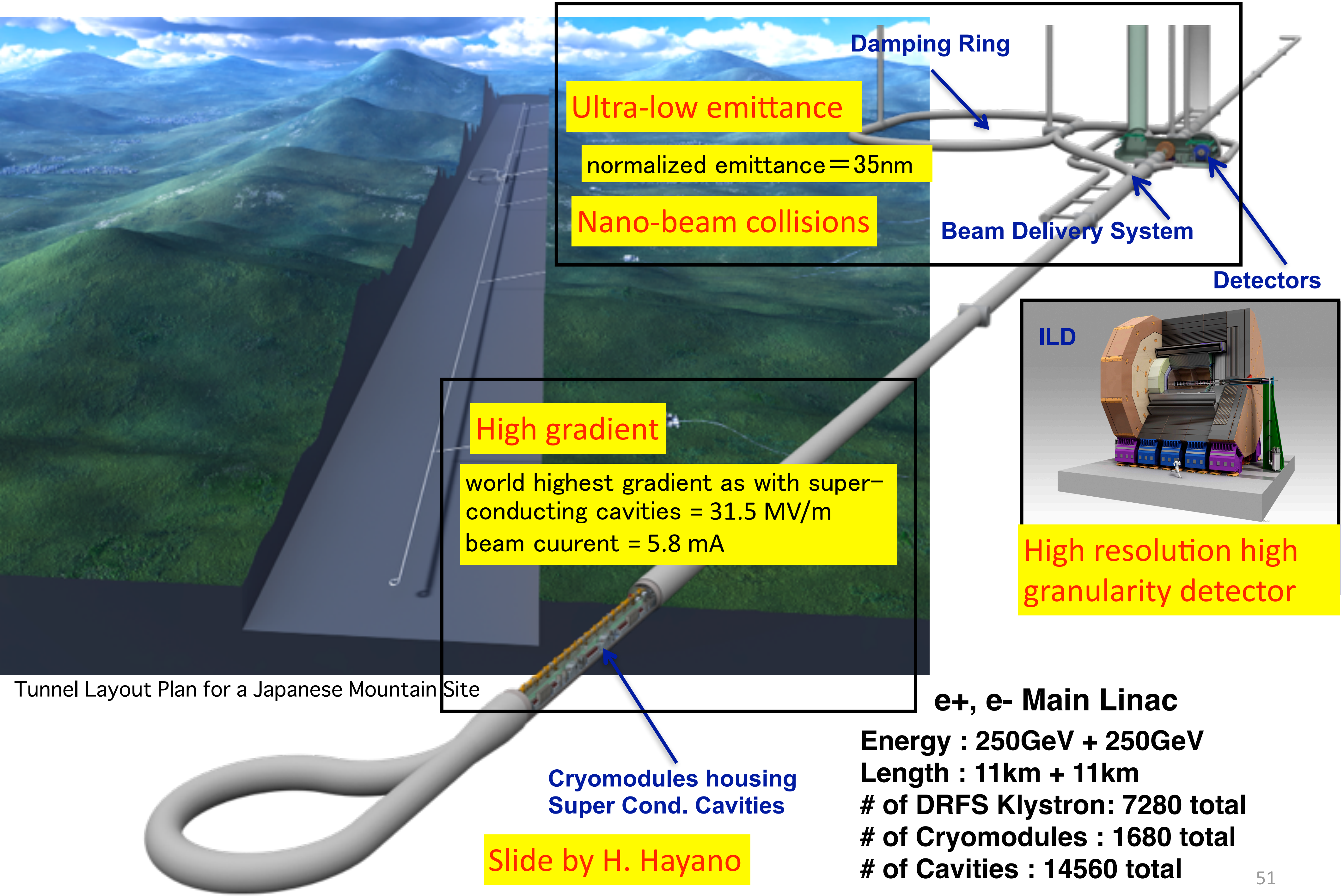
ILC Situation

- 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

Backup

Design to Reality

Bird's Eye View of the ILC Accelerator



Tunnel Layout Plan for a Japanese Mountain Site

Ultra-low emittance

normalized emittance＝35nm

Nano-beam collisions

High gradient

world highest gradient as with super−
conducting cavities = 31.5 MV/m
beam cuurent = 5.8 mA

High resolution high granularity detector

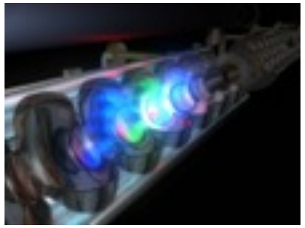
e+, e- Main Linac

Energy : 250GeV + 250GeV
Length : 11km + 11km
# of DRFS Klystron: 7280 total
# of Cryomodules : 1680 total
# of Cavities : 14560 total

Slide by H. Hayano

ILC Accelerator

Advantage of Superconducting RF



- Ultra-high ($Q_0 = 10^{10}$):
  - small surface resistance → almost zero power (heat) in cavity walls
  - use relatively low-power microwave source to 'charge up' cavity
- Long beam pulses (~1 ms)
  - → intra-pulse feedback
- Larger aperture / smaller beam loss
  - → better beam quality w/ larger aperture - lower wake-fields
- Work necessary on engineering for:
  - Cryomodule (thermal insultation)
  - Cryogenics
  - Gradient to be further improved

Luminosity:

RF efficiency

RF power / beam current

$$L \propto \frac{\eta P_{RF}}{E_{CM}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y}}$$

Vertical emittance (tiny beams)

- Luminosity proportional to RF efficiency ILC
  - for given total power (electricity bill !),
  - ~160MW @ 500GeV
- Capable of efficiently accelerating high beam currents
- Low impedance aids preservation of high beam quality (low emittance)

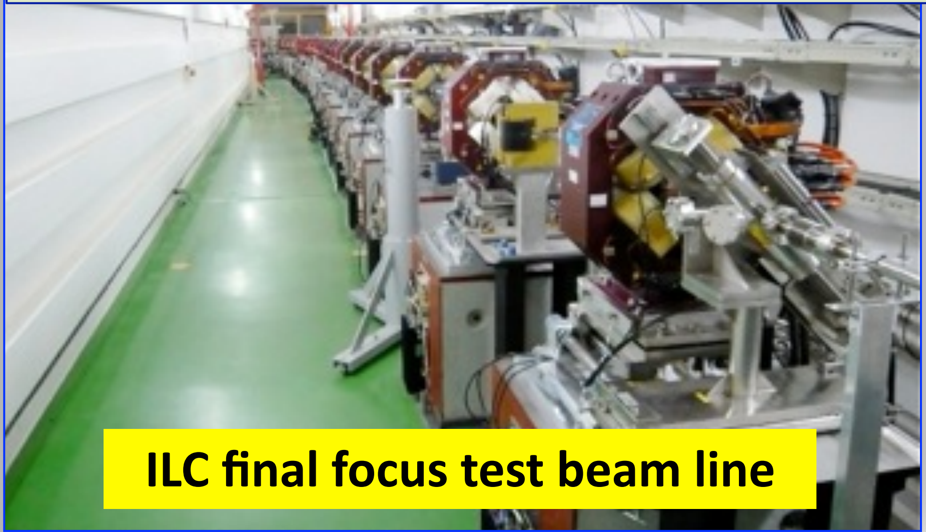
→ Ideal for Linear Collider

ILC Accelerator R&D at KEK

Achieved >90% yield for ILC spec cavities

ILC super conducting RF cavity R&D

ATF2: International effort hosted by KEK from teams from UK, France, US, Korea, China, Japan; beam spot size: ***goal=37nm*** (corresponding to 6nm of ILC), ***44nm achieved!***

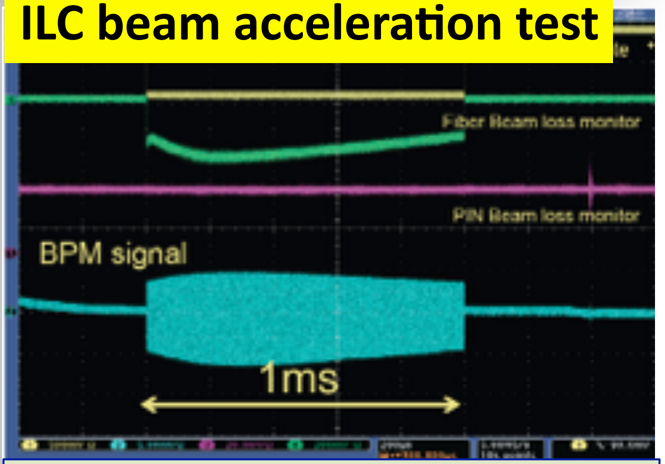


ILC final focus test beam line

ILC cryo-module R&D

S1–Global: international collaboration for cryo–module assembly, connection and high power test by Germany, US, UK, Italy, Japan, hosted by KEK

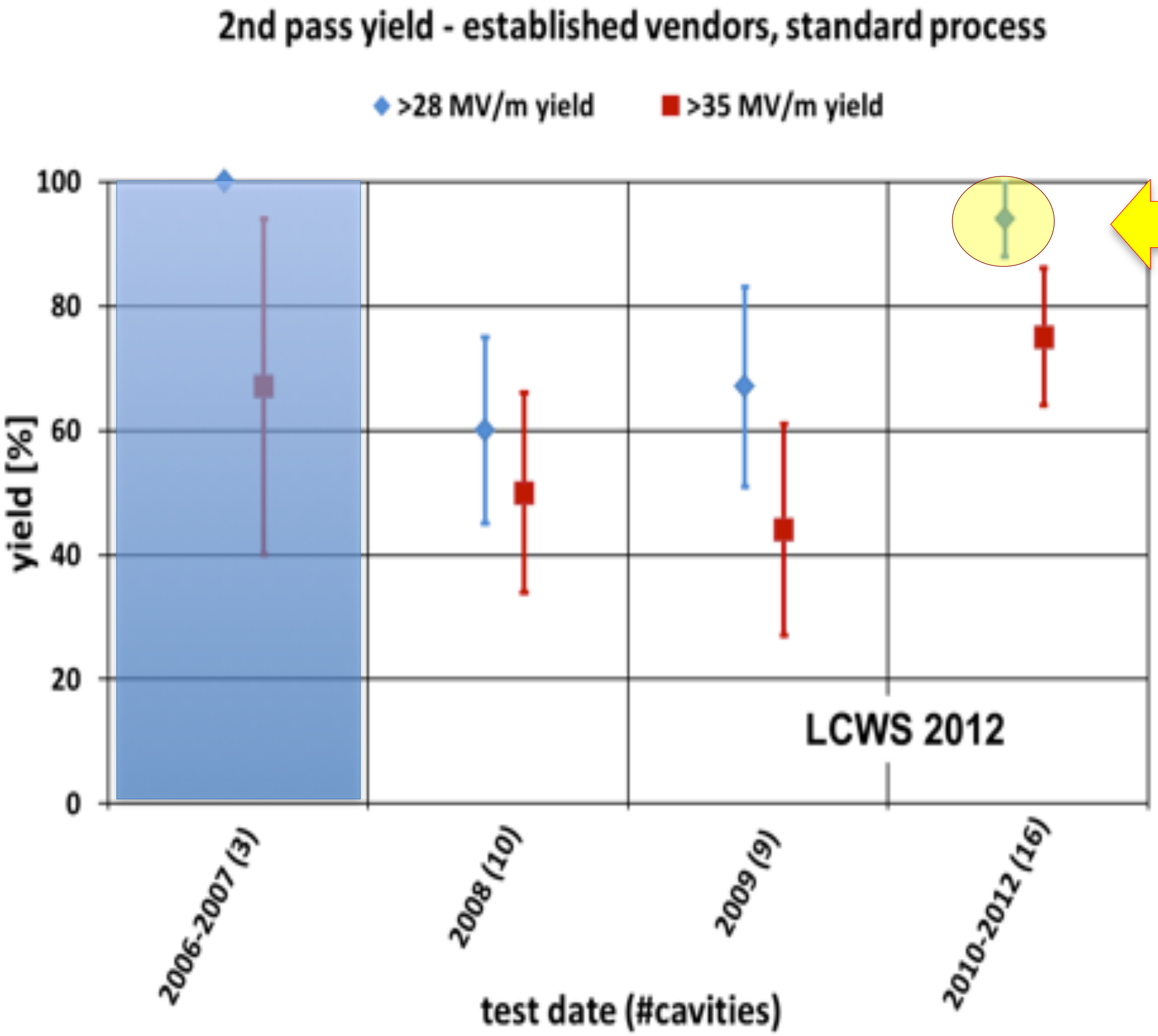
ILC beam acceleration test



Achieved stable operation with the same duration (1 ms) and current (6.6 mA) as ILC

High gradient acceleration with super-conducting RF cavities

Progress in SCRF Cavity Gradient



Production yield:
94 % at > 35+/-20%

Average gradient:
37.1 MV/m

reached (2012)

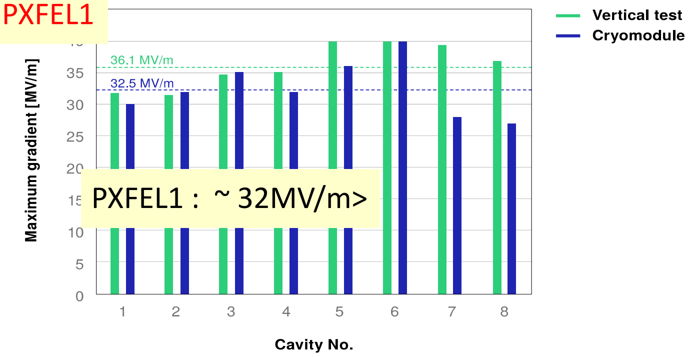
Cryomodule System Test

DESY: FLASH

- ❖ 1.25 GeV linac (TESLA-Like tech.)
- ❖ ILC-like bunch trains:
- ❖ 600 ms, 9 mA beam (2009); 800 ms 4.5 mA (2012)
- ❖ RF-cryomodule string with beam → PXFEL1 operational at FLASH

← Demonstrated

XFEL Prototype at PXFEL1



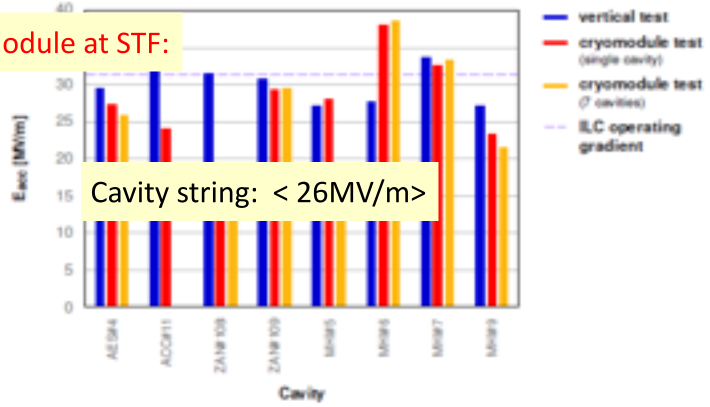
PXFEL1 : ~ 32MV/m>

KEK: STF/STF2

- ❖ S1-Global: completed (2010)
- ❖ Quantum Beam Accelerator (Inverse Llaser Compton): 6.7 mA, **1 ms**
- ❖ CM1 test with beam (2014 ~2015)
- ❖ STF-COI: Facility to demonstrate CM assembly/test in near future

← Demonstrated

S1 Global Cryomodule at STF:



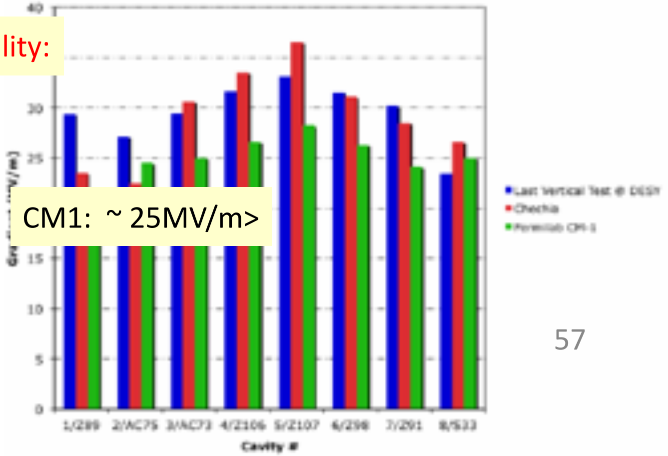
Cavity string: < 26MV/m>

FNAL: ASTA

(Advanced Superconducting Test Accelerator)

- ❖ CM1 test complete
- ❖ CM2 operation (2013)
- ❖ CM2 with beam (soon)

CM1 at NML Facility:



CM1: ~ 25MV/m>

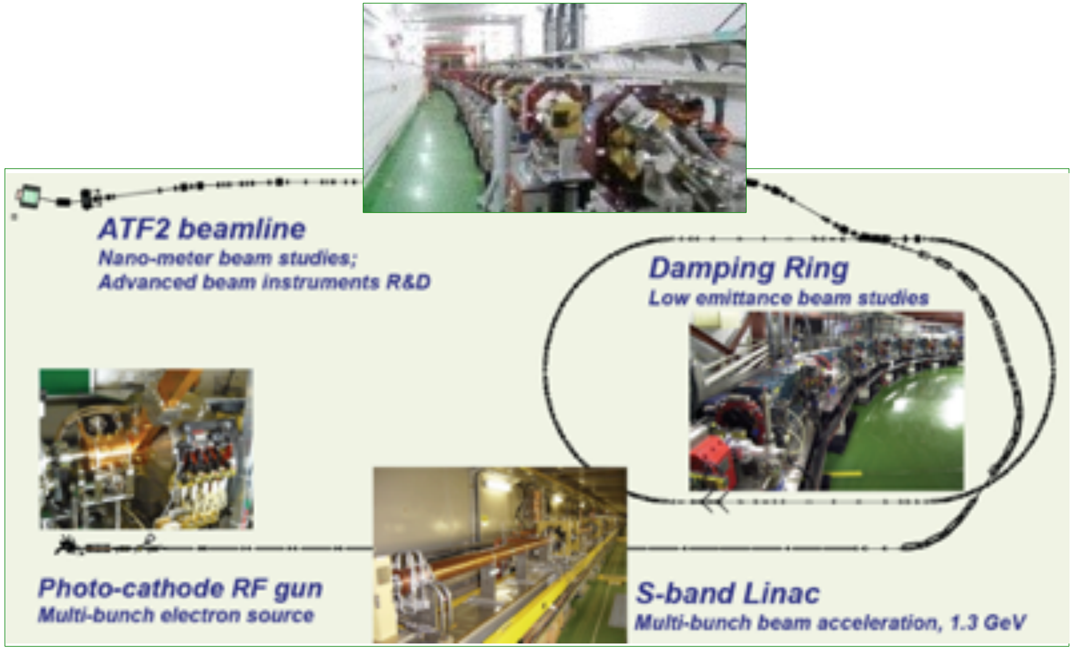
2014/07/05, A. Yamamoto

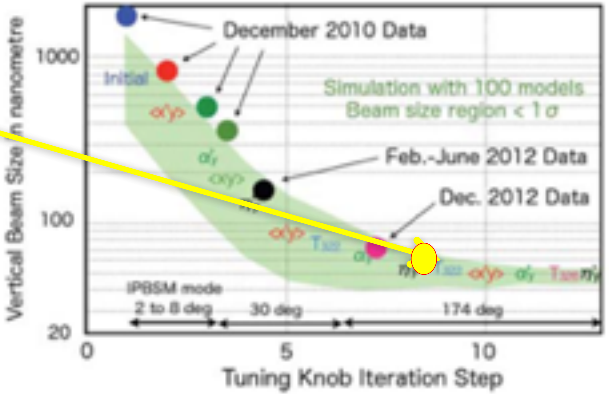
Nano-beam generation / control

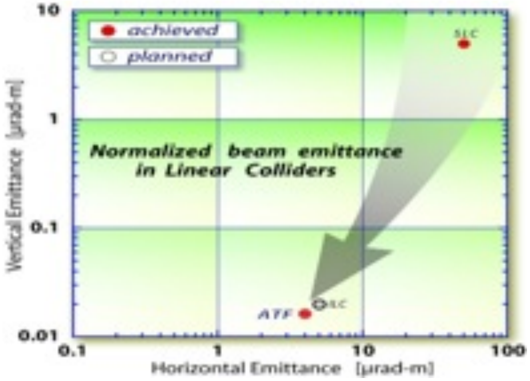
ATF2 Progress by 2013

Ultra-small beam

- Low emittance : KEK-ATF
  - 4 pm achieved
  - (ILC target value, in 2004).
- Small vertical beam size : KEK ATF2
  - Goal = 37 nm,
    - 160 nm (spring, 2012)
    - 65 nm (April, 2013) at low beam current



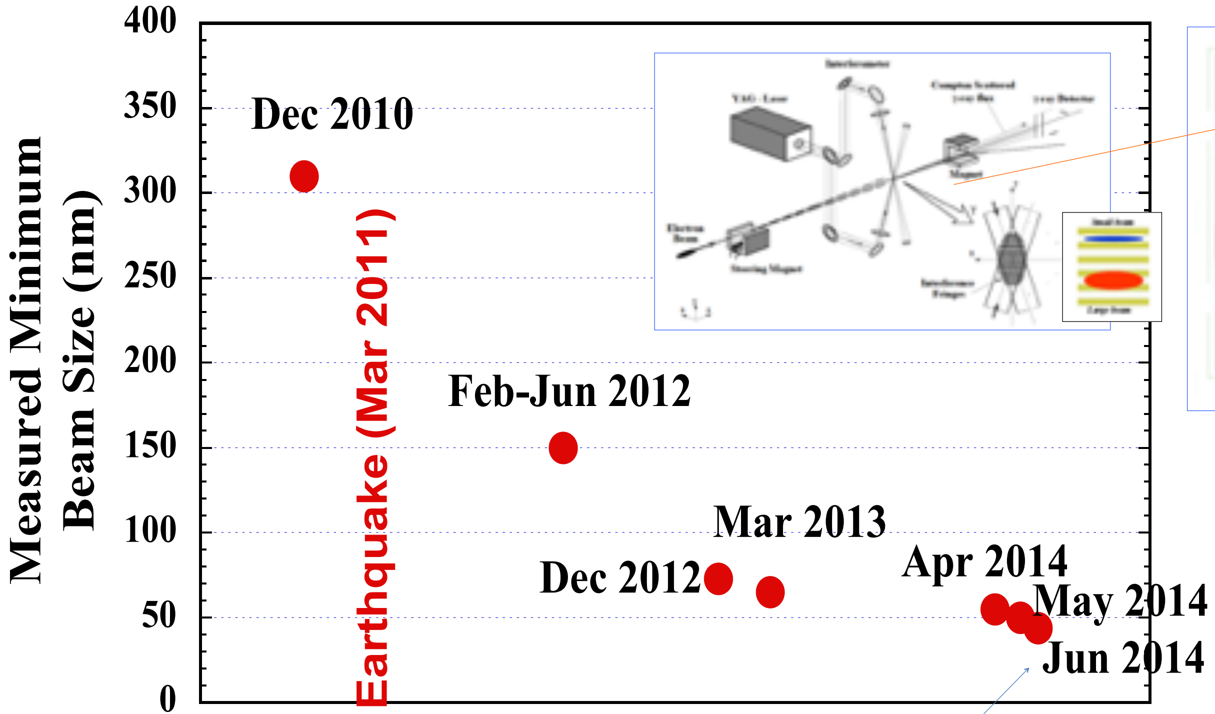


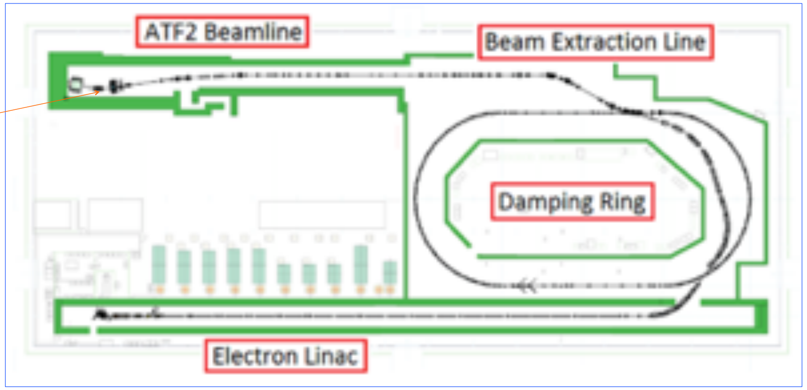


IPAC2014, K. Kubo

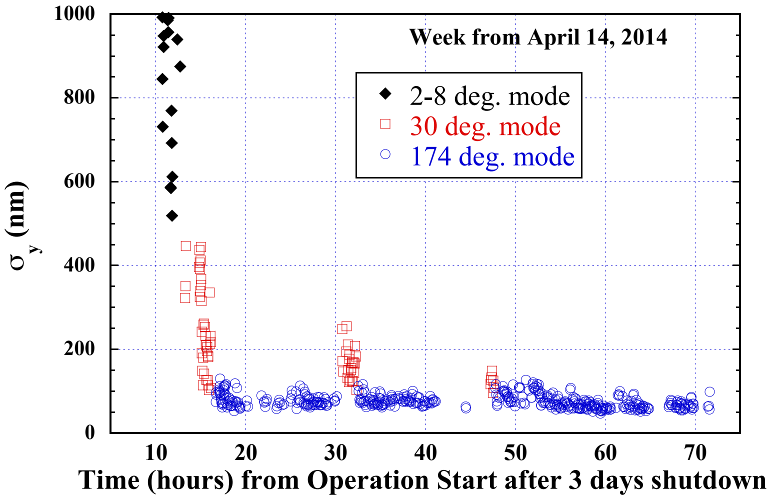
Progress in measured min. beam size at ATF2

Progress in 2014 (We are almost there!)





Beam Size 44 nm observed,
(Goal : 37 nm)



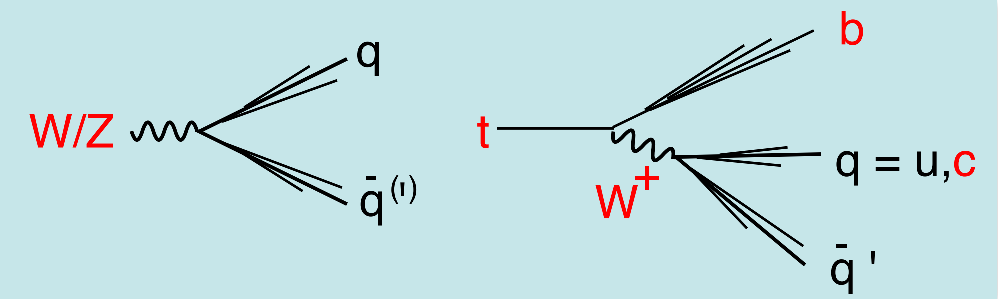
Reproducible in short time!

ILC Detector

ILC 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

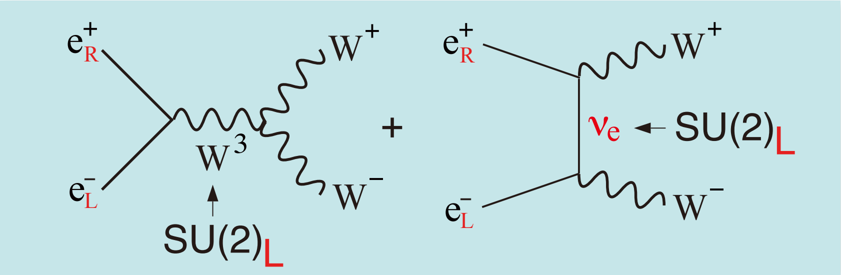
high granularity calorimetry

Hermeticity

down to O(10mrad) or better

both ECAL and HCAL inside the solenoid

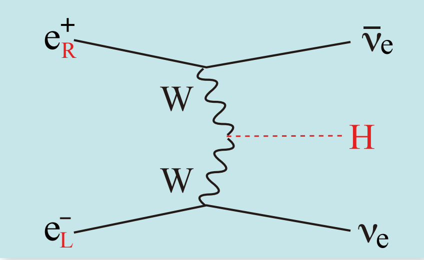
Select Feynman diagrams with polarized beams



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 !

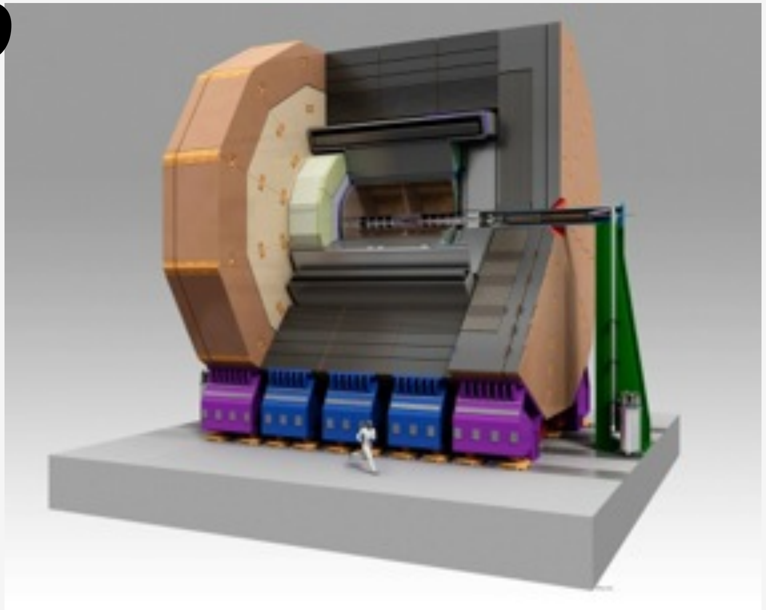


	ILC	CLIC	TLEP
Pol (e	-0.8	-0.8	0
Pol (e	+0.3	0	0
(σ/σ	1.8x1.3=2.34	1.8x1.0=1.8	1

Beam polarization acts as luminosity doubler !

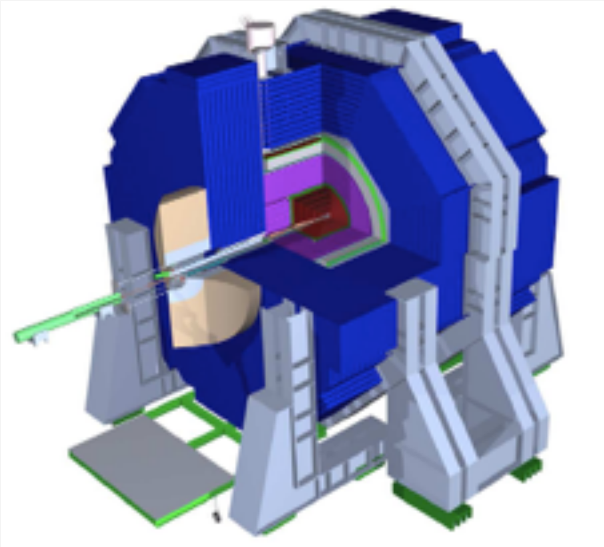
Detailed Baseline Design Document

ILD



- Large R with TPC tracker
- – 32 countries, 151 institutions, ~700 members
- – Most members from Asia and Europe
- – B=3.5T, TPC + Si trackers
- – ECal: R=1.8m

SiD

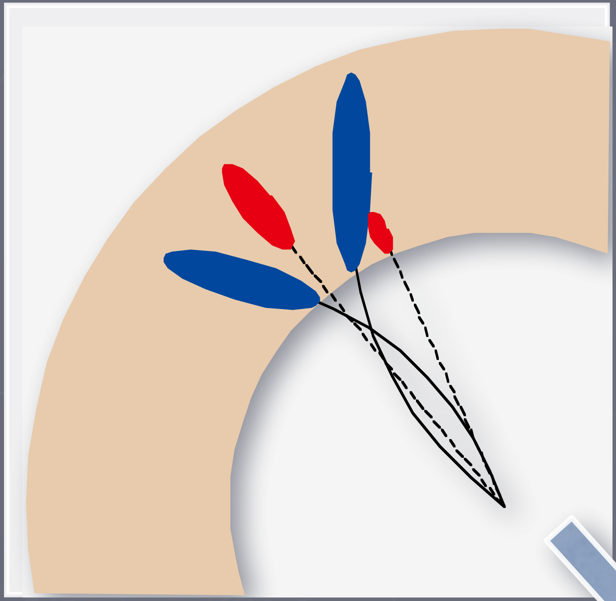


- High B with Si strip tracker
- – 18 countries, 77 institutions, ~240 members
- – Mostly American
- – B=5T, Si only tracker
- – ECal : R=1.27m

Both detector concepts are optimized for Particle Flow Analysis

Particle Flow Analysis

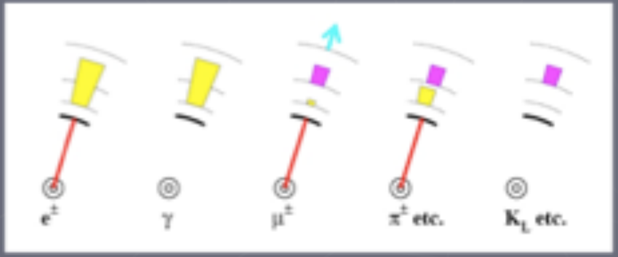
How to measure jet energies precisely?



Charged Particles

Tracker’s resolution is much better than that from calorimetry

Use tracking devices

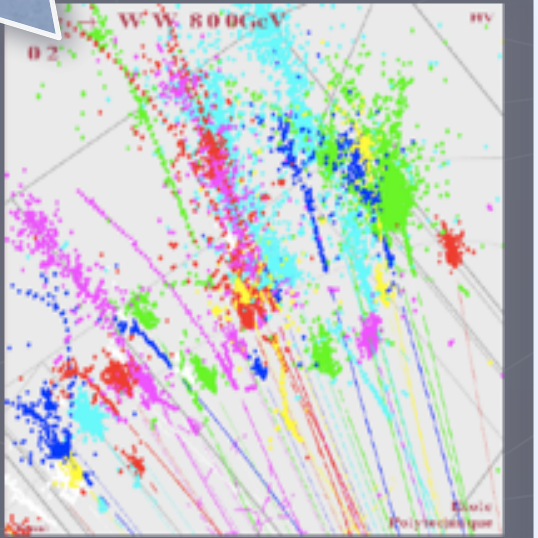


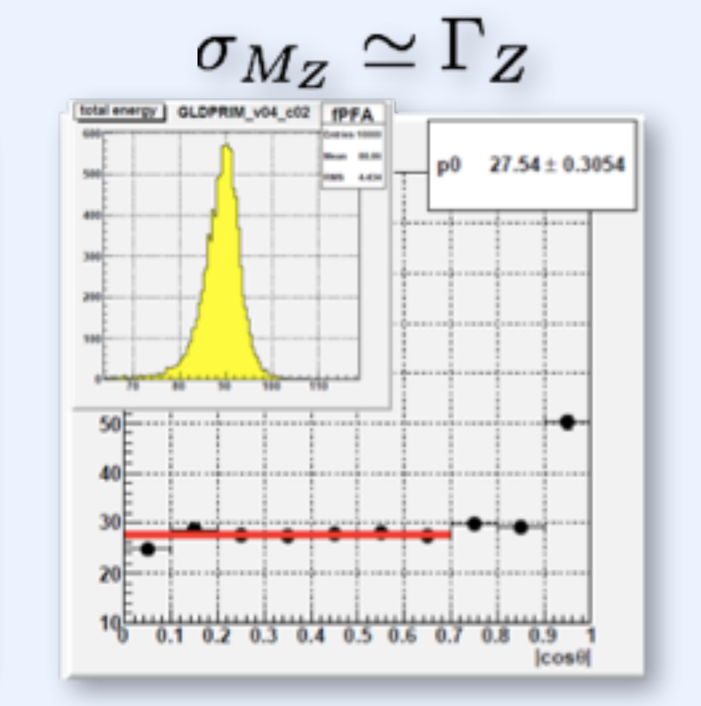
Neutral Particles

Use calorimetry

PFA

- Remove charged particle signals in calorimeters
- Needs 1-to-1 matching of tracks and calorimeter clusters
- Needs ultra-high granularity calorimeter

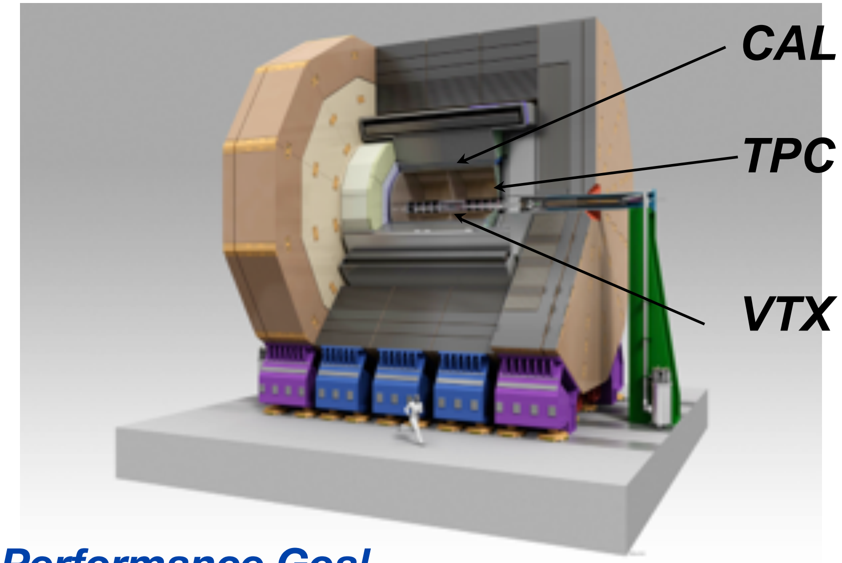




$$\sigma_{M_Z} \simeq \Gamma_Z$$

Detector R&D : ILD

Component R&D



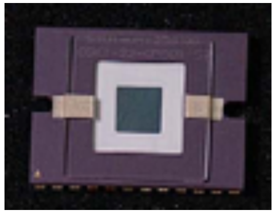
Performance Goal
as compared to LHC detectors

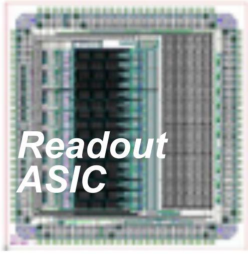
Vertex resolution	2-7 times better
Momentum resolution	10 times better
Jet energy resolution	2 times better

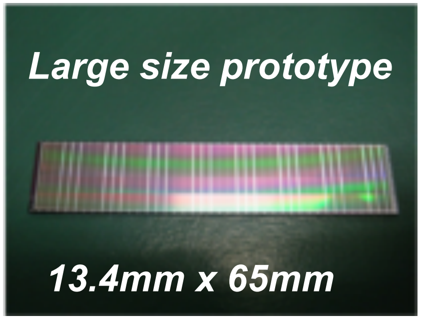
The key is ultra high granularity!

Detector	ILC	ATLAS	Granularity
Vertex Det.	5×5µm	400×50µm	x 800
Tracker	1×6mm	13mm	x 2.2
EM Calorimeter	Silicon: 5×5mm Scintillator : 5×45mm	39×39mm	x 61 x 7

Vertex Detector R&D



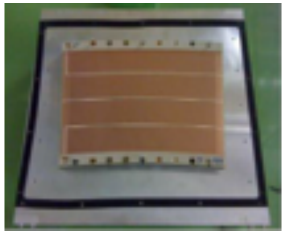




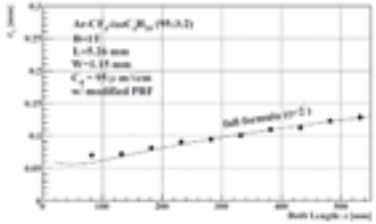
6um pixel now working!

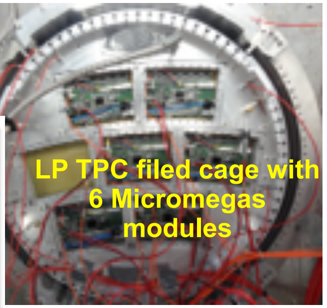
Proof of principle for sensor technology finished!
Now R&D on ladder, support structure, and 2-phase CO2 cooling system.

TPC R&D



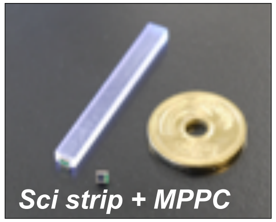
Spatial resolution
Asian GEM module

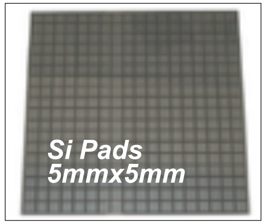


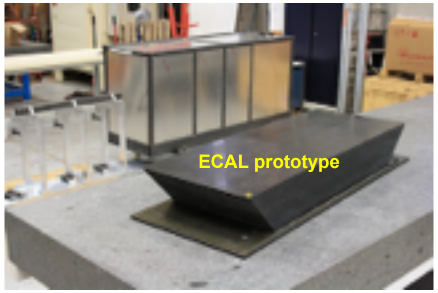


Both GEM and Micromegas modules have achieved the performance goal: point resolution < 100um (3.5T)

Calorimeter R&D



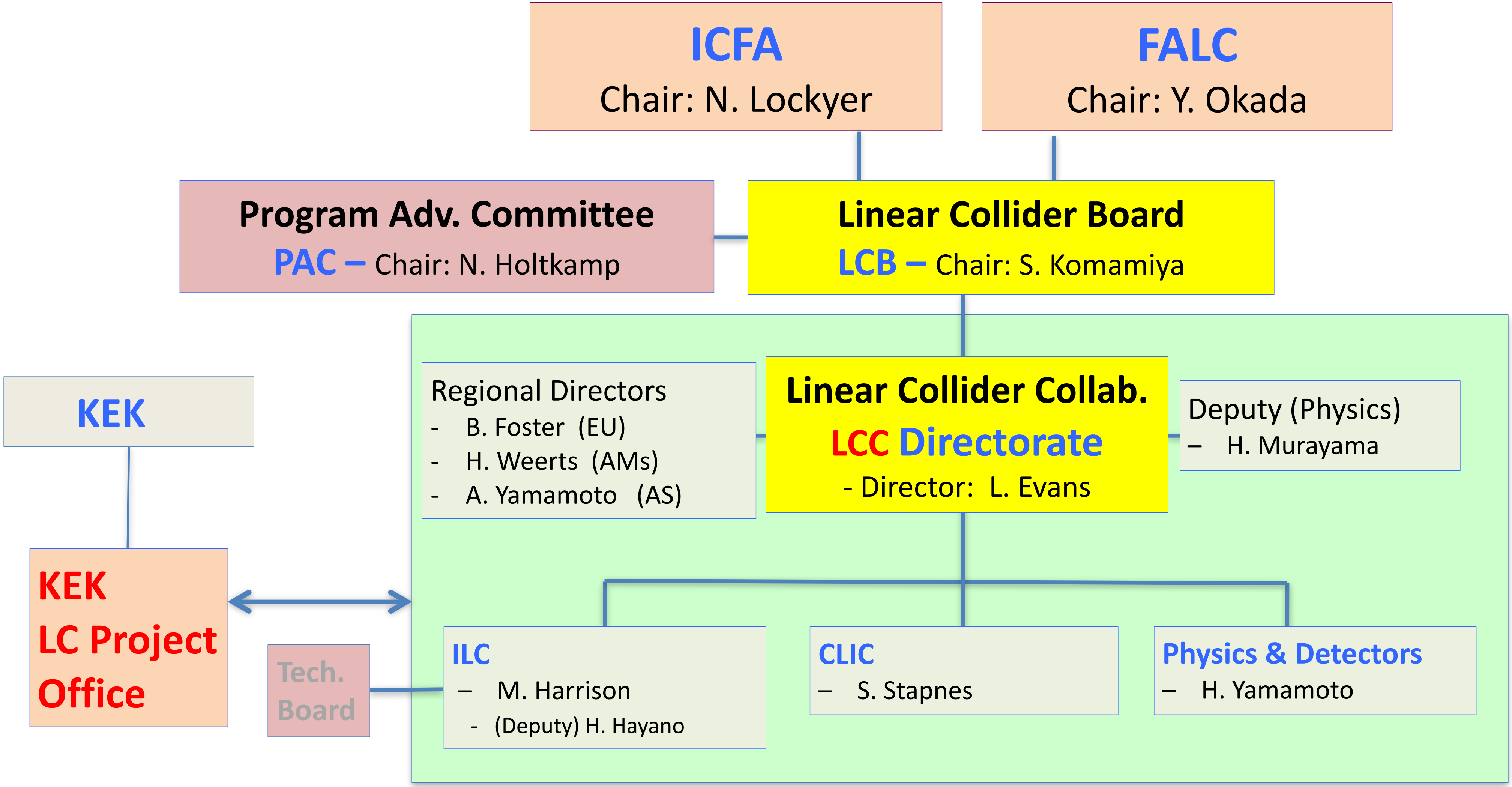




Test beam data well reproduced by MC simulation, one-particle energy resolution has reached performance goal!

Project Development

ILC in Linear Collider Collaboration



ICFA
Chair: N. Lockyer

FALC
Chair: Y. Okada

Program Adv. Committee
PAC – Chair: N. Holtkamp

Linear Collider Board
LCB – Chair: S. Komamiya

KEK

Regional Directors
- B. Foster (EU)
- H. Weerts (AMs)
- A. Yamamoto (AS)

Linear Collider Collab.
LCC Directorate
- Director: L. Evans

Deputy (Physics)
– H. Murayama

KEK
LC Project
Office

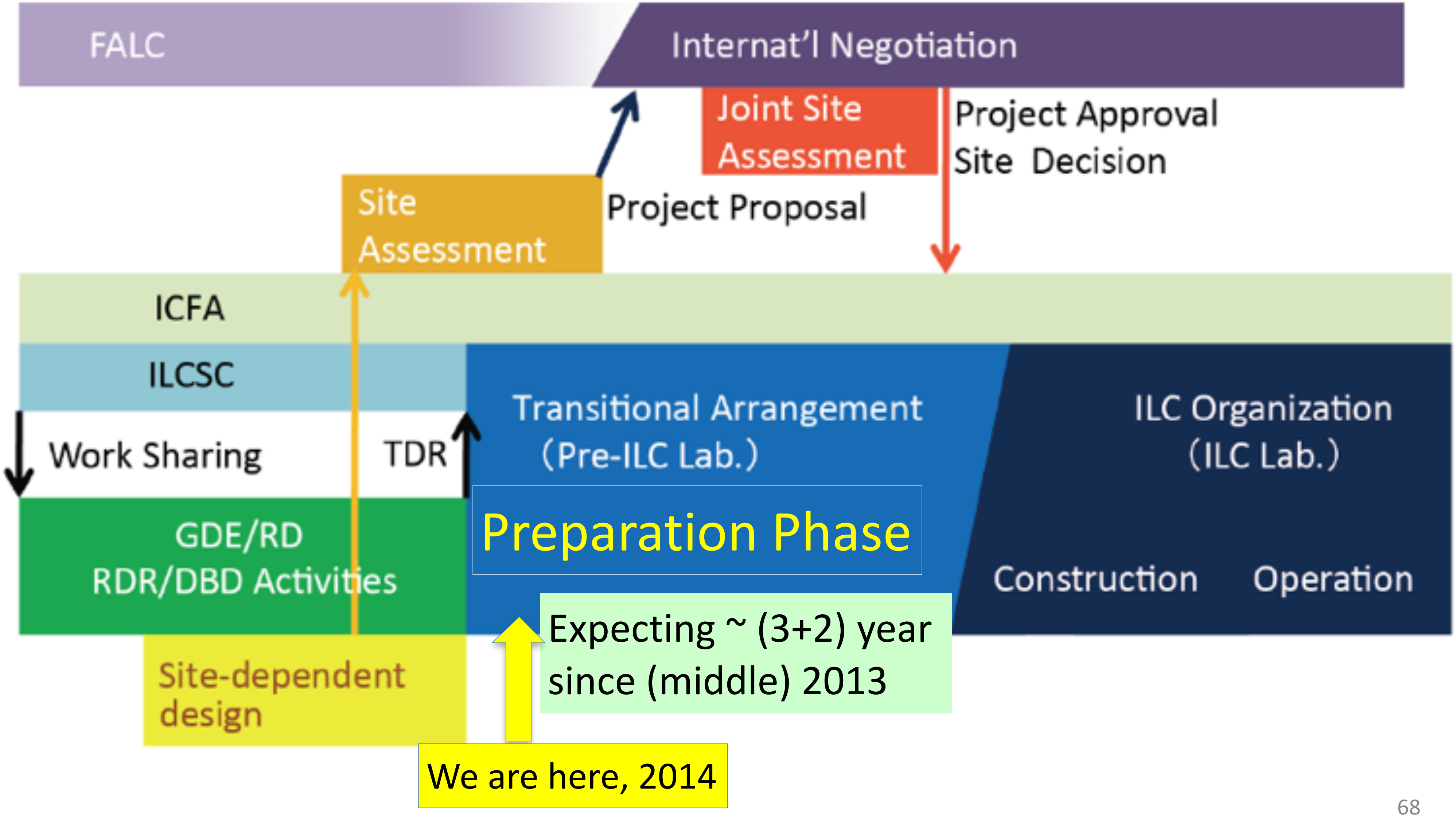
Tech. Board

ILC
– M. Harrison
- (Deputy) H. Hayano

CLIC
– S. Stapnes

Physics & Detectors
– H. Yamamoto

ILC Time Line: Progress and Prospect



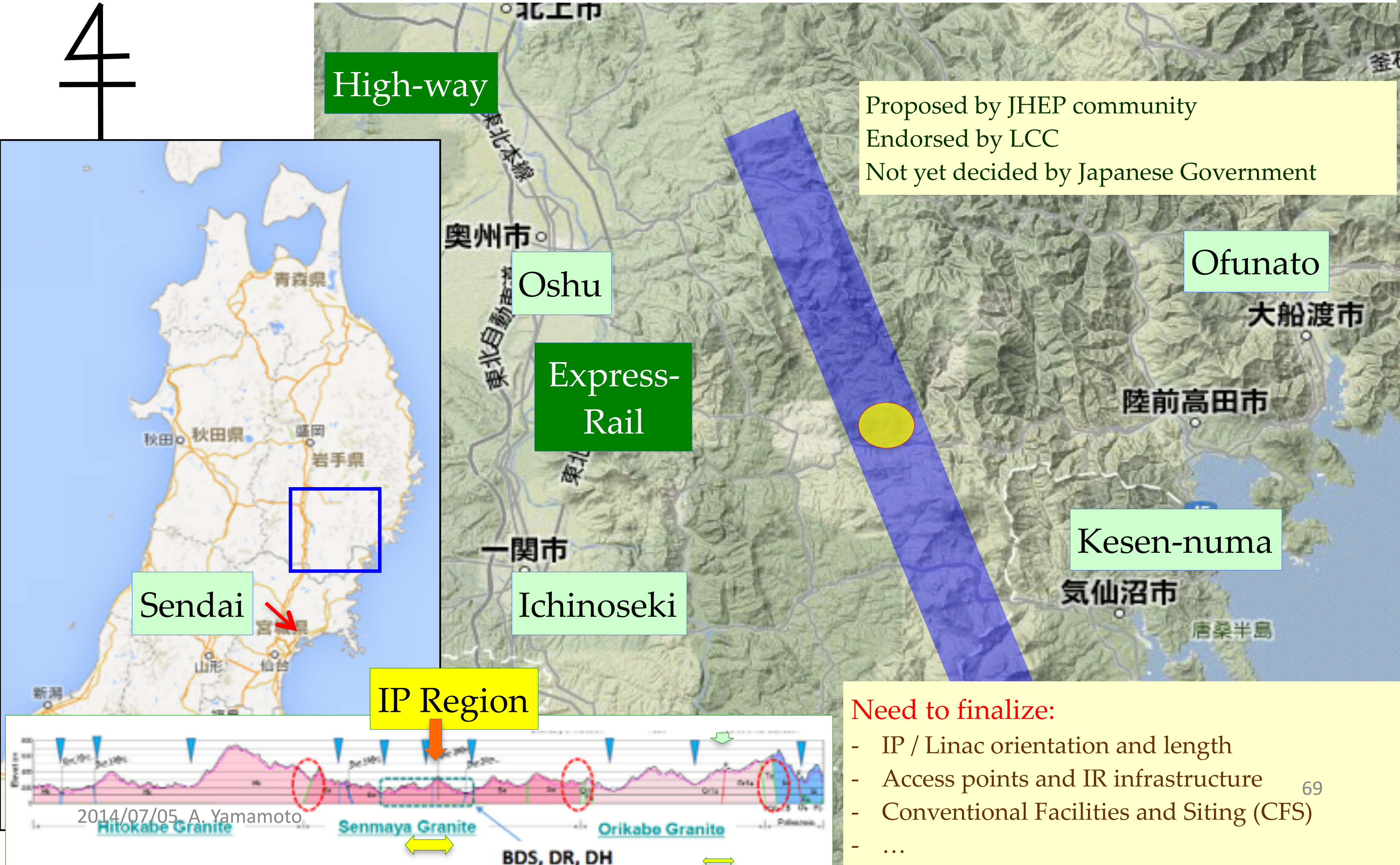
Preparation Phase

Expecting ~ (3+2) year since (middle) 2013

We are here, 2014

ILC Site Candidate Location in Japan: Kitakami Area

Establish a site-specific Civil Engineering Design - map the (site independent) TDR baseline onto the preferred site - assuming “Kitakami” as a primary candidate



Proposed by JHEP community
Endorsed by LCC
Not yet decided by Japanese Government

Need to finalize:

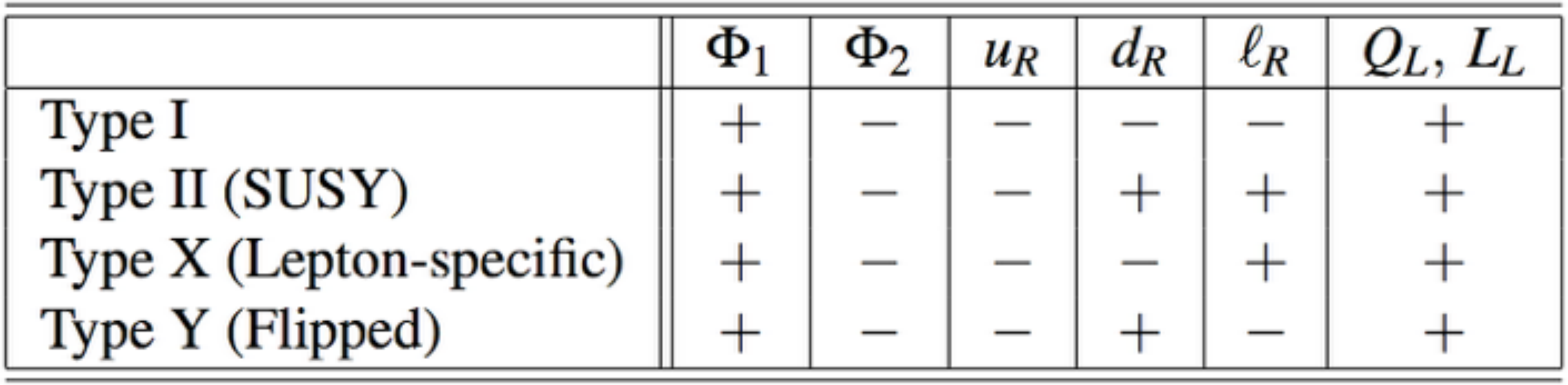
- IP / Linac orientation and length
- Access points and IR infrastructure
- Conventional Facilities and Siting (CFS)
- …

Global Status

Year	Global Status	Status in Japan
2012	- ***TDR "Draft" completed, and technically reviewed, and the cost estimate internally reviewed, in GDE***	
2013	- ***TDR Cost internationally and externally reviewed,*** - ***TDR published*** - ***"GDE" to "LCC"*** - ***European Strategy published***	- ***Candidate site by JHEP, unified,*** - ***Further study for q few year, recommended by SCJ (Science Council J.)***
2014	- - ***US-P5 recommendation published*** - - *Global supports well recognized*	- ***MEXT established ILC Task Force*** - ***ILC preparatory office starts at KEK*** - ***An official budget for the ILC investigation/preparation allocated, first time, in MEXT.***

- ILC accelerator **technologies** have been sufficiently developed and matured for the project to move"from Design to Reality" in coming several years.
- **Global cooperation** needs to be further established,
- **LCC** is leading the project under supervision of ICFA and LCB
- Strong supports from EU and US, well recognized and acknowledged,

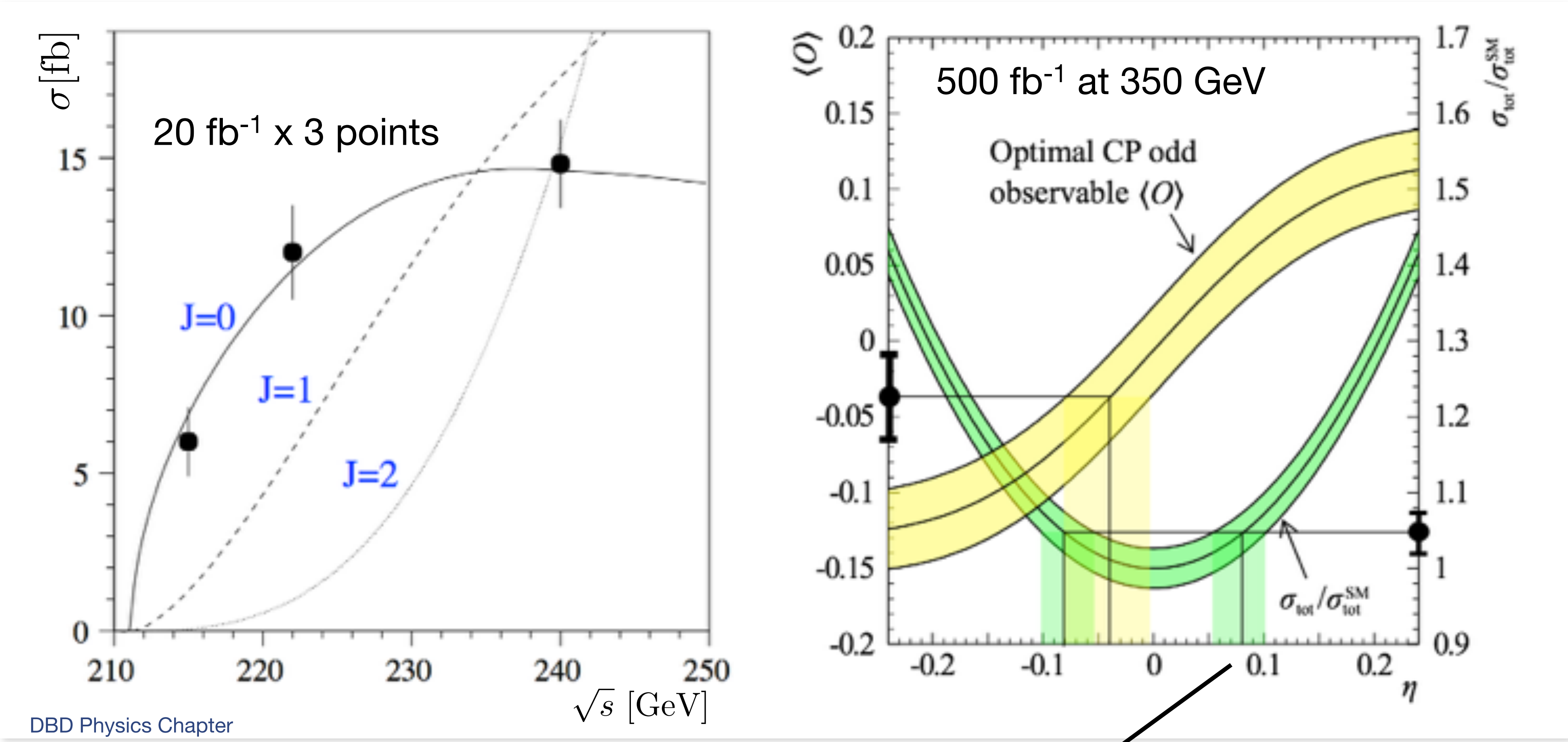
Higgs



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II (SUSY)	$+$	$-$	$-$	$+$	$+$	$+$
Type X (Lepton-specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y (Flipped)	$+$	$-$	$-$	$+$	$-$	$+$

Spin and CP Mixing

Measurements that compliment those at LHC



20 fb^{-1} x 3 points

500 fb^{-1} at 350 GeV

DBD Physics Chapter

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

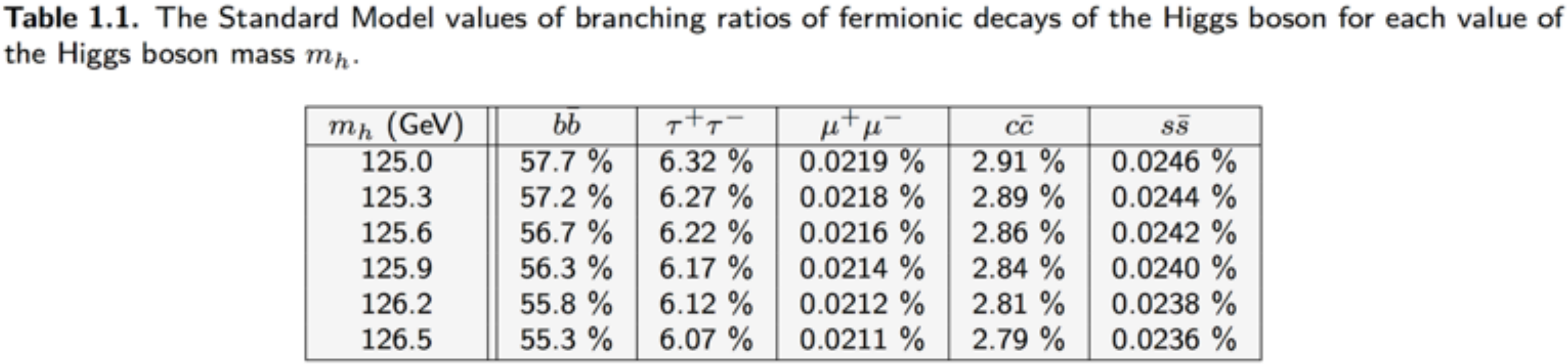


Table 1.1. The Standard Model values of branching ratios of fermionic decays of the Higgs boson for each value of the Higgs boson mass m_h.

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 %

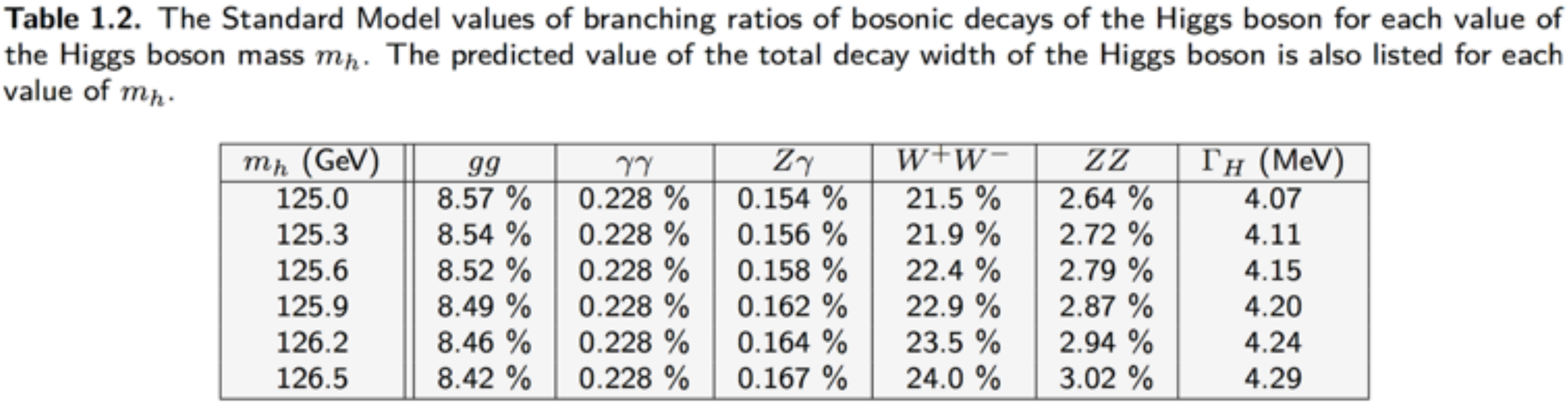
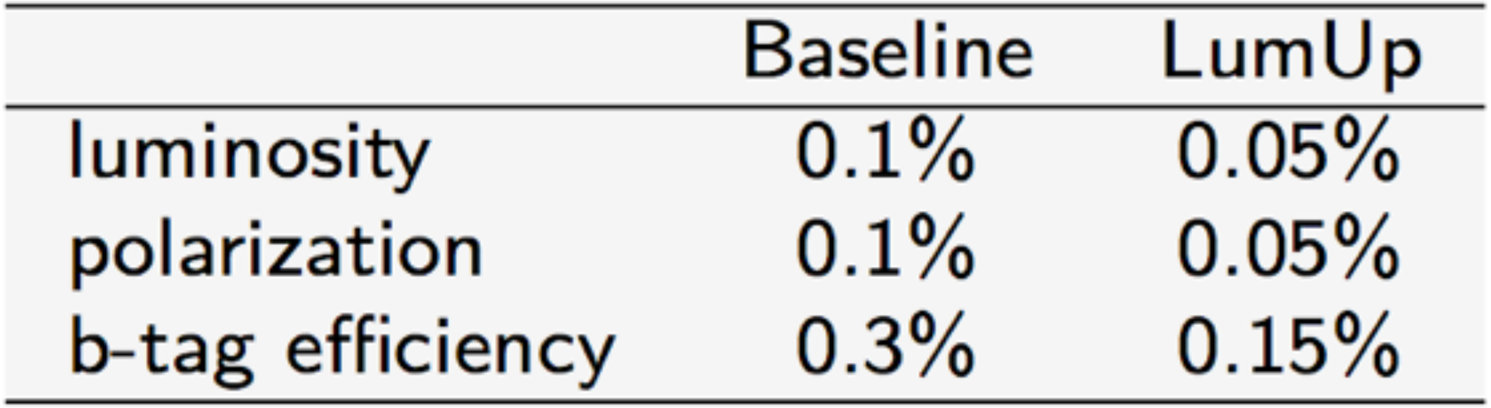


Table 1.2. The Standard Model values of branching ratios of bosonic decays of the Higgs boson for each value of the Higgs boson mass m_h. The predicted value of the total decay width of the Higgs boson is also listed for each value of m_h.

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

Model-dependent Global Fit for Couplings

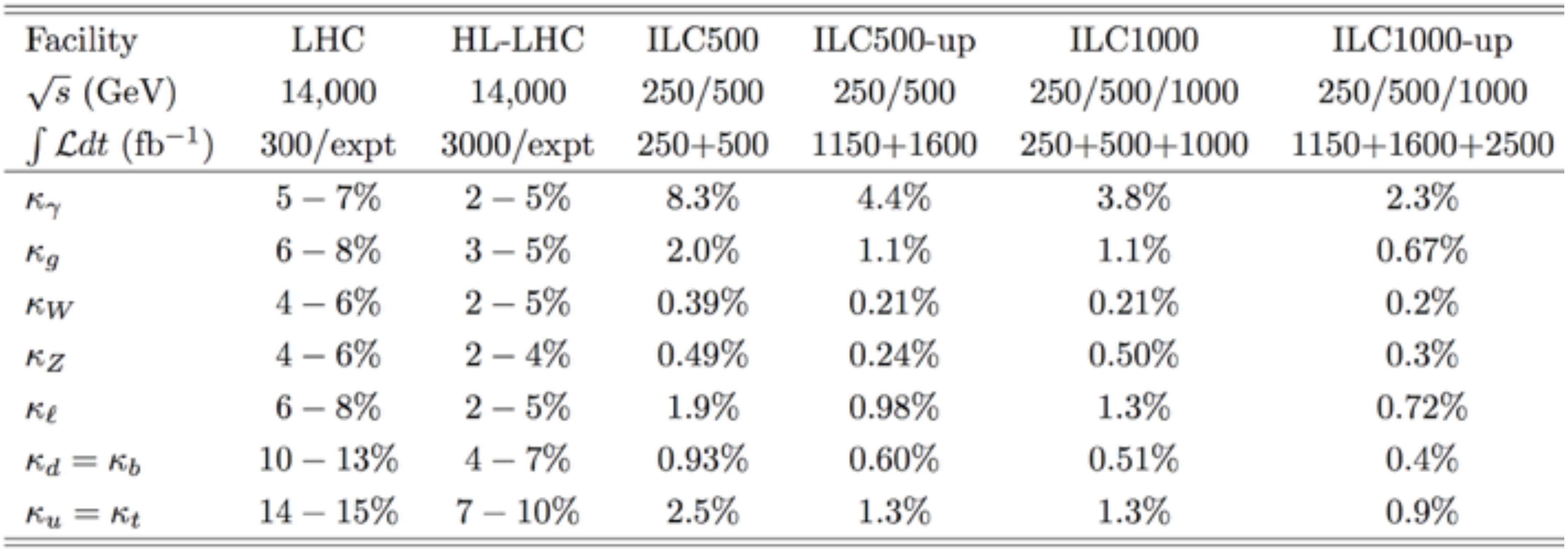
7-parameter fit

Model Assumptions

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

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

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)

What observables limit the coupling precisions?

The 4 most important ones

- *Y_1: recoil mass*
- *Y_2: WW-fusion h→bb*
- *Y_3: higgsstrahlung h→bb*
- *Y_4: WW-fusion h→WW**

$$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$$

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HZZ} g^2_{Hbb}}{\Gamma_H}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

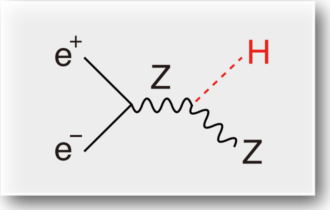
$$\Delta g_{HZZ} \sim \frac{1}{2}\Delta Y_1$$

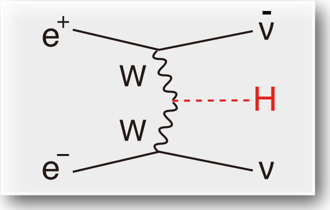
$$\Delta g_{HWW} \sim \frac{1}{2}\Delta Y_1 \oplus \frac{1}{2}\Delta Y_2 \oplus \frac{1}{2}\Delta Y_3$$

$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

$$\Delta\Gamma_H \sim 2\Delta Y_1 \oplus 2\Delta Y_2 \oplus 2\Delta Y_3 \oplus \Delta Y_4$$

Both ZH and ννH productions matter!

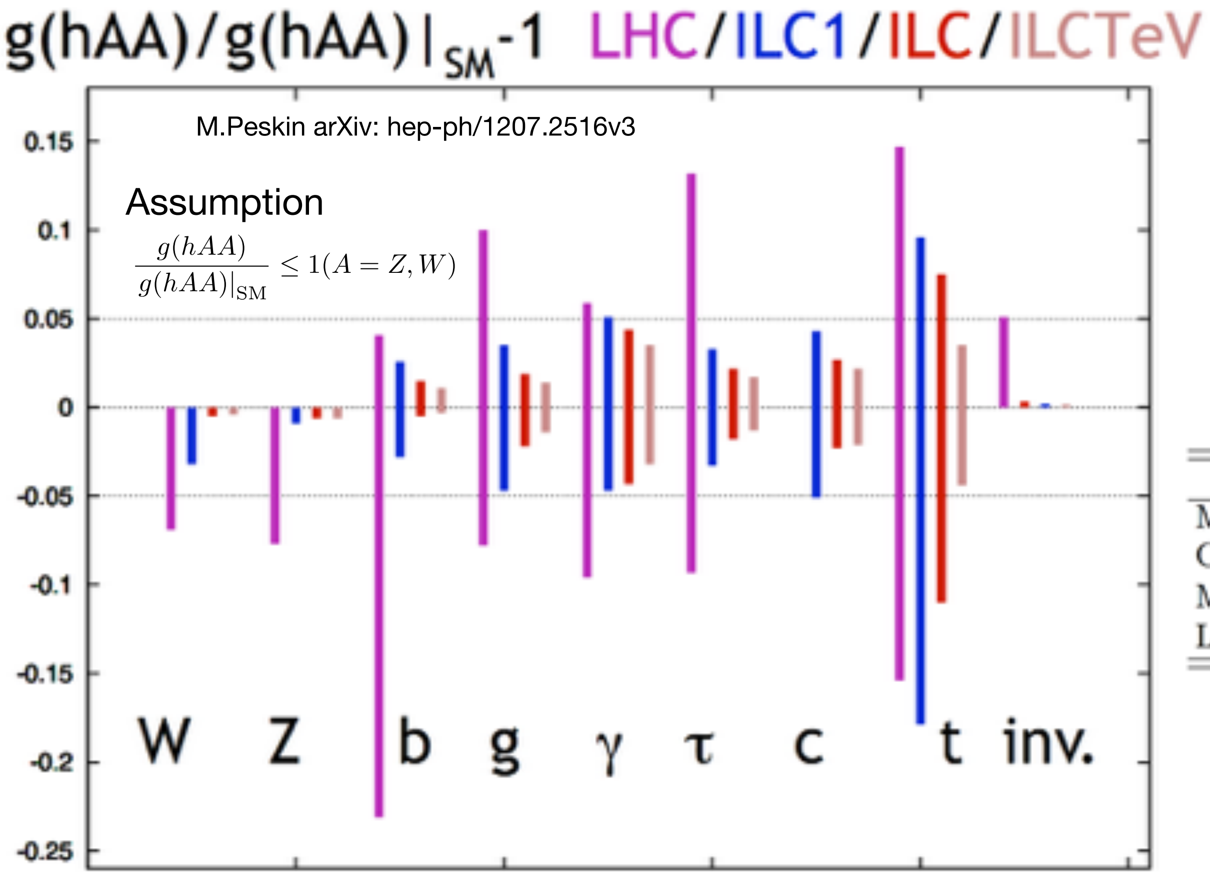




For more details, see J.Tian @ Tokusui Workshop 2013

Expected Precision and Deviation

Combined Fit with LHC data



M.Peskin arXiv: hep-ph/1207.2516v3

Assumption

$$\frac{g(hAA)}{g(hAA)|_{\rm SM}} \leq 1 (A = Z, W)$$

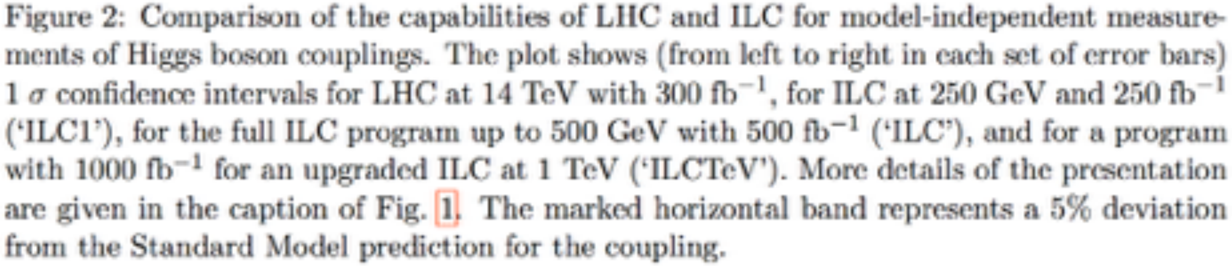


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC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

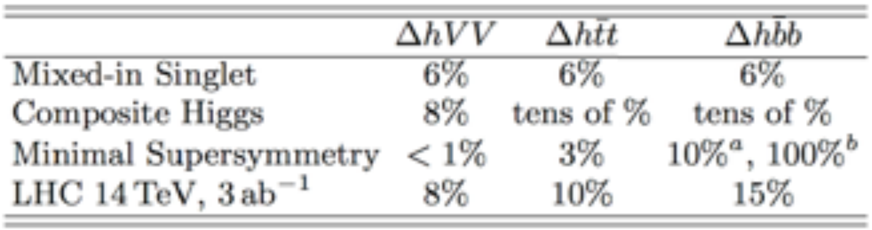
LHC = LHC14TeV: 300fb^{-1}

HLC = ILC250: 250fb^{-1}

ILC = ILC500: 500fb^{-1}

ILCTeV = ILC1000: 1000fb^{-1}

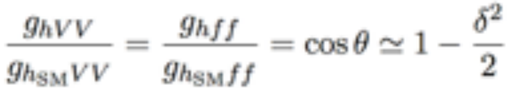
Maximum deviation when nothing but the 125 GeV object would be found at LHC



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

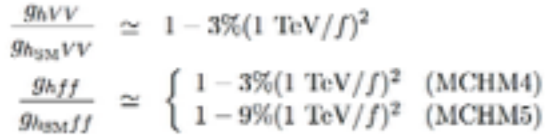
R.S.Gupta, H.Rzehak, J.D.Wells arXiv: 1206.3560v1

Mixing with singlet



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

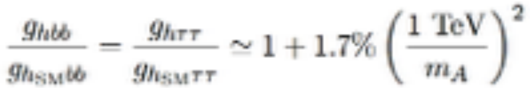
Composite Higgs



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

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

SUSY



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

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

Hunting Ground for Extra Higgs Bosons

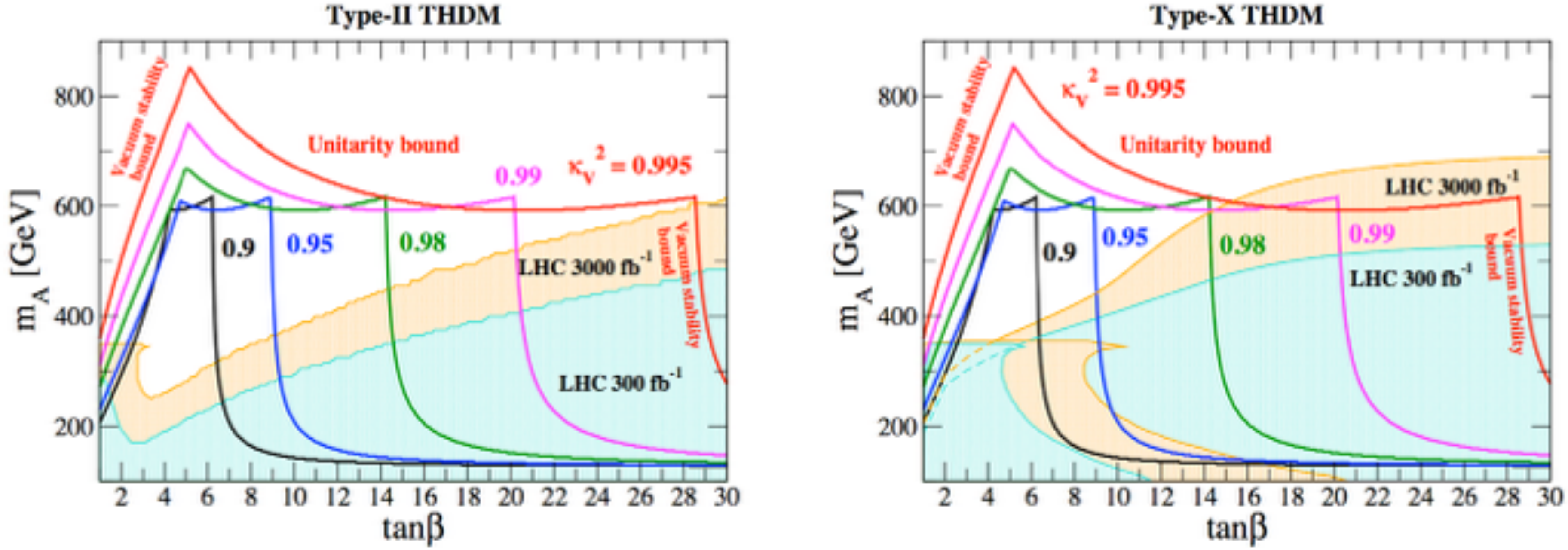
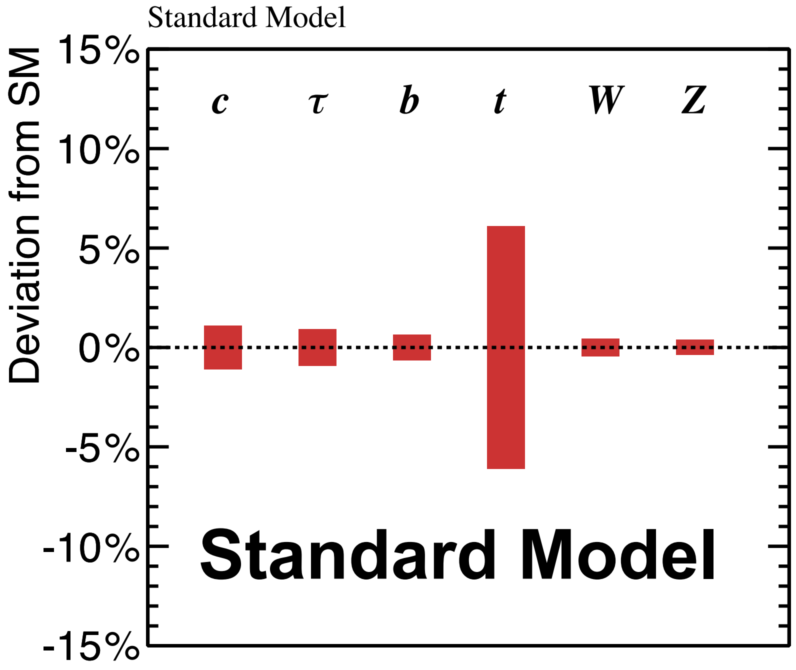


Figure 1.20. Regions below the curves are allowed by the constraints from unitarity and vacuum stability on the $\tan\beta$-m_A plane for each fixed value of κ_V^2 for $M = m_A = m_H = m_{H^+}$ in the Type II and Type X 2HDMs. Expected excluded parameter spaces are also shown by blue (orange) shaded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

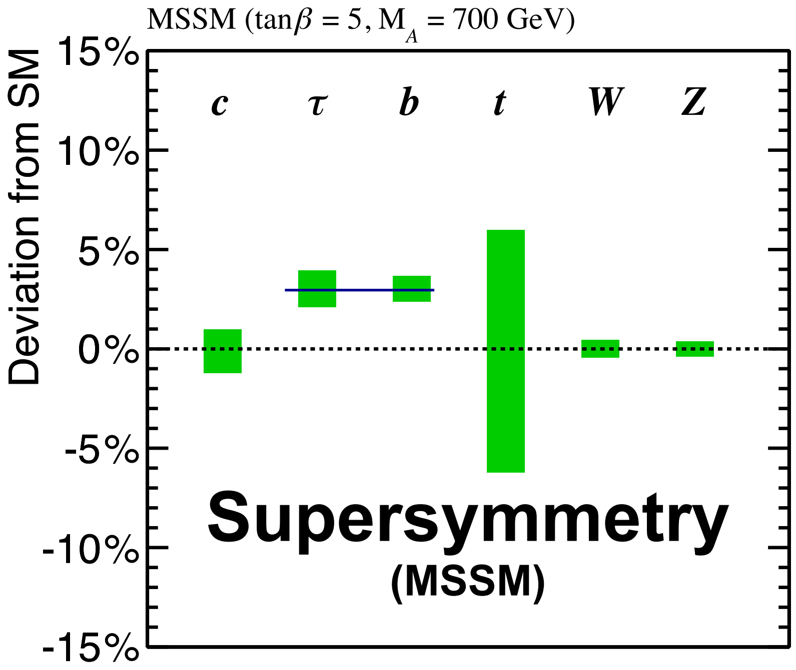
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

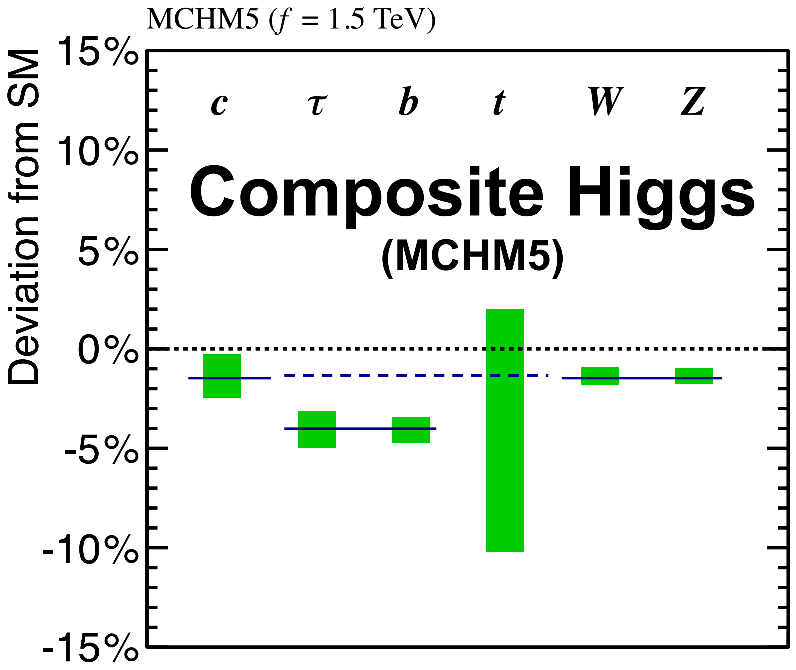
Finger Printing: Elementary v.s. Composite

Deviations in Higgs couplings is a signature of many BSM theories. The pattern of the deviations can be specific to certain models. The precision Higgs coupling measurements at the ILC at the 1% level enable us to fingerprint the different models.



Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

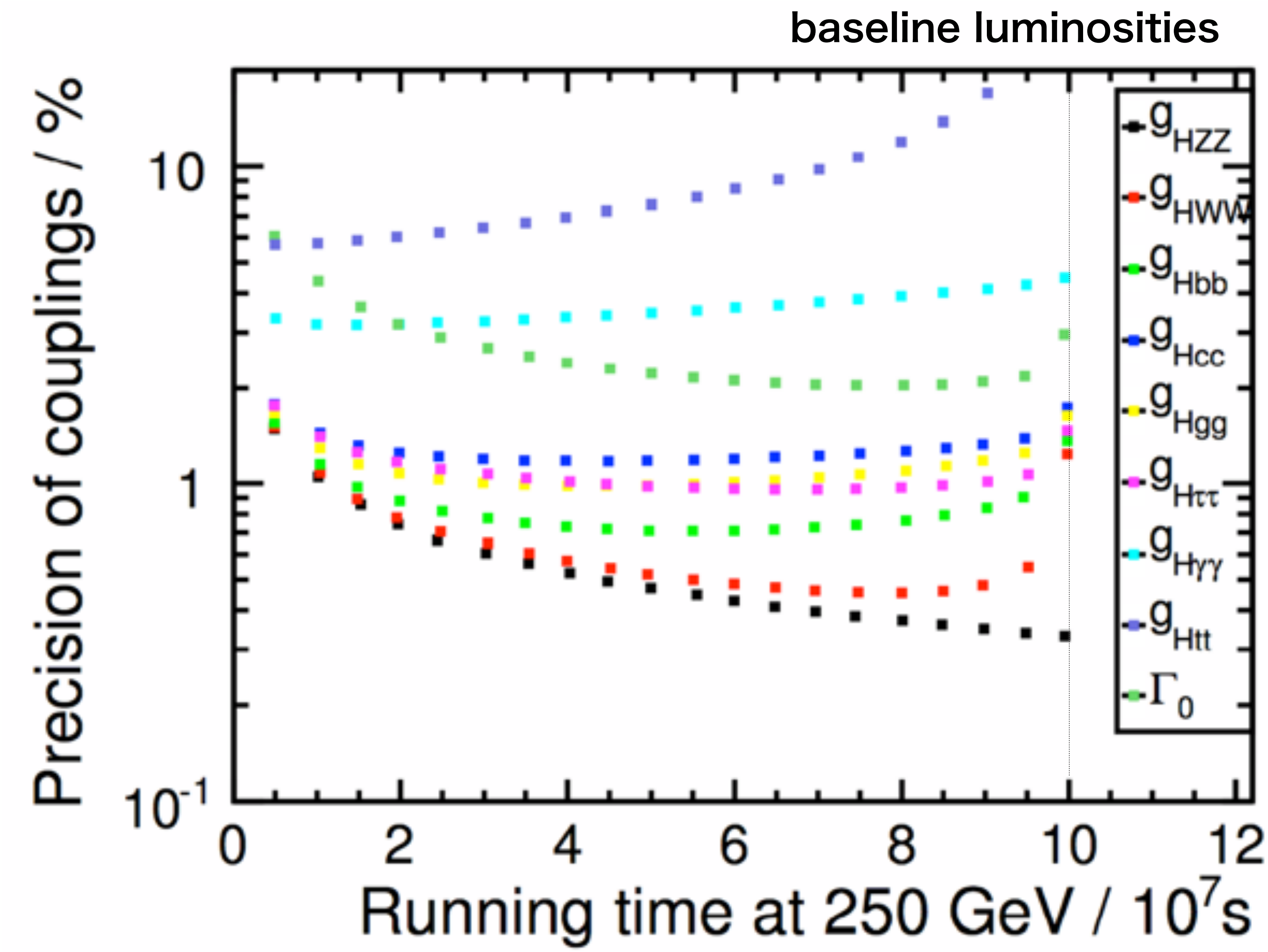




Coupling Precisions

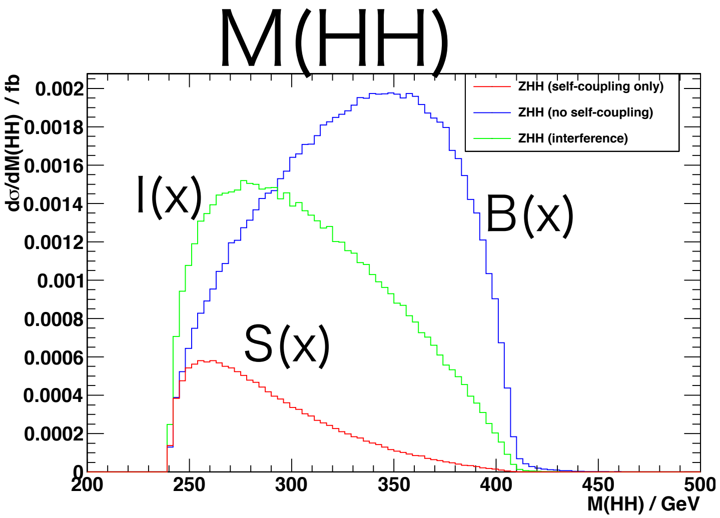
Running Scenarios

baseline luminosities



Self-coupling Measurement

Weighting Method to Enhance the Sensitivity to λ

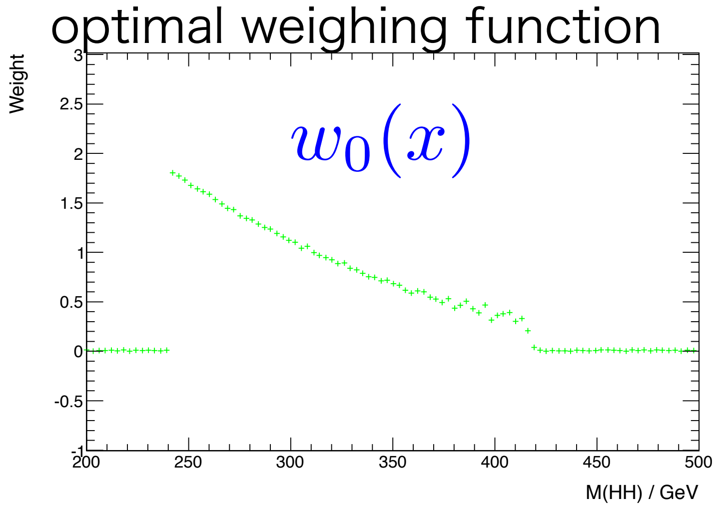


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

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):

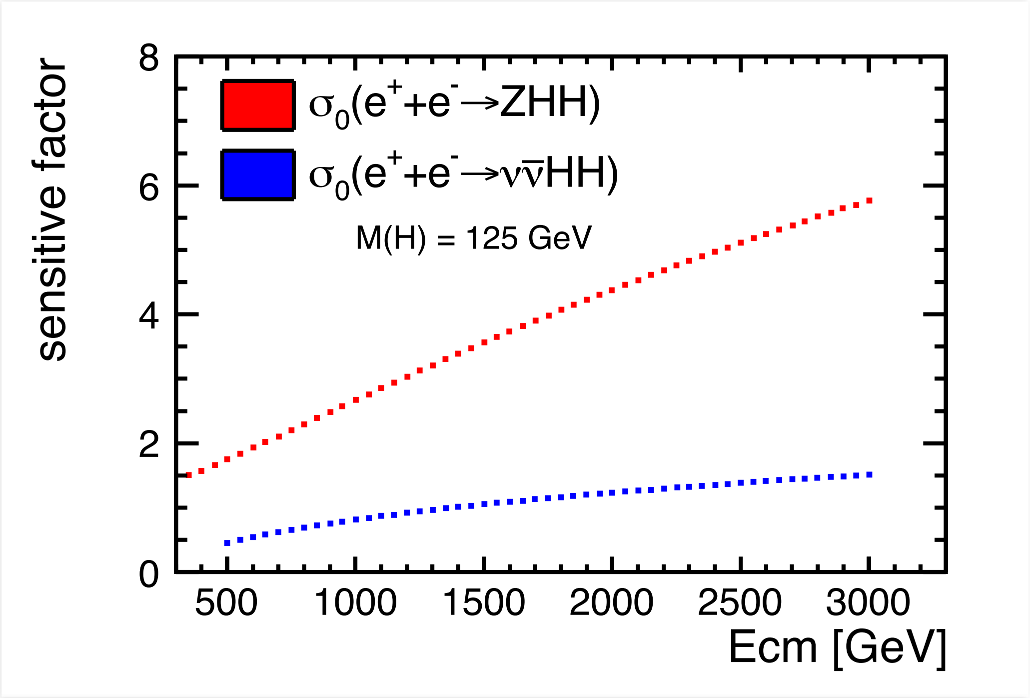
$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

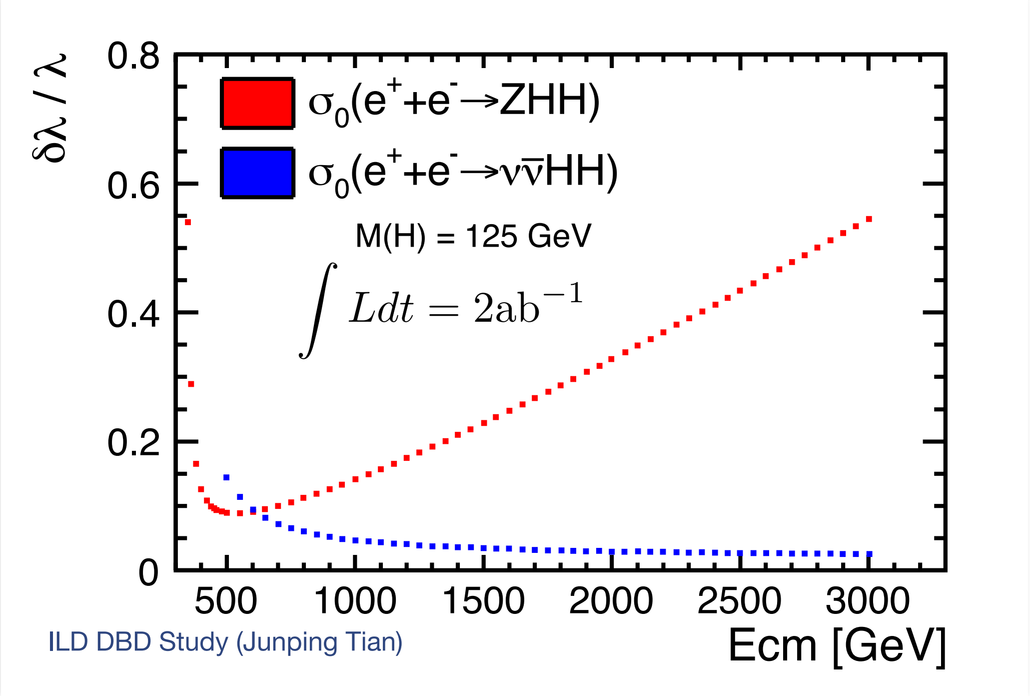
General solution:

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

c: arbitrary normalization factor

Expected Coupling Precision as a Function of Ecm





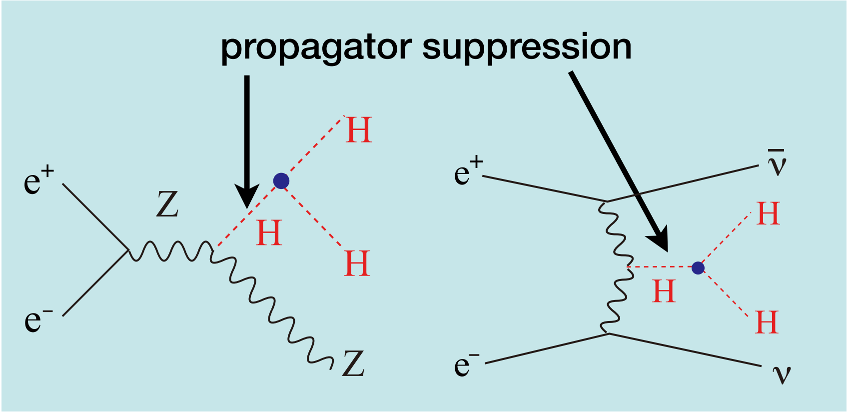
ILD DBD Study (Junping Tian)

Sensitivity Factor

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

F=0.5 if no BG diagrams there

BG diagrams dominate at high E_{cm}



⇒ F grows quickly with Ecm !

Coupling Precision

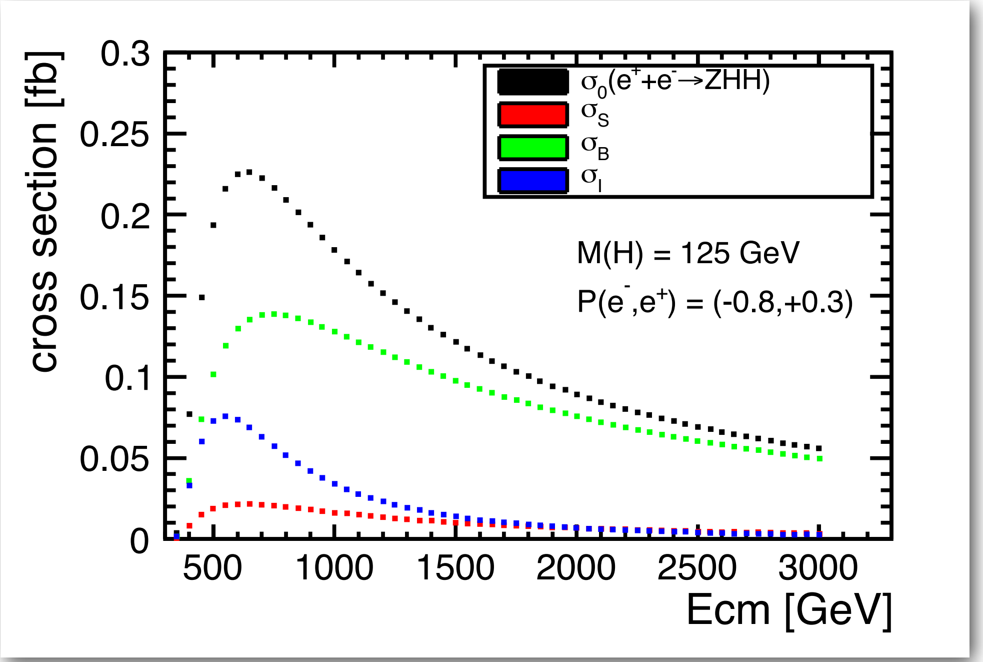
ZHH : **optimal Ecm ~ 500 GeV**

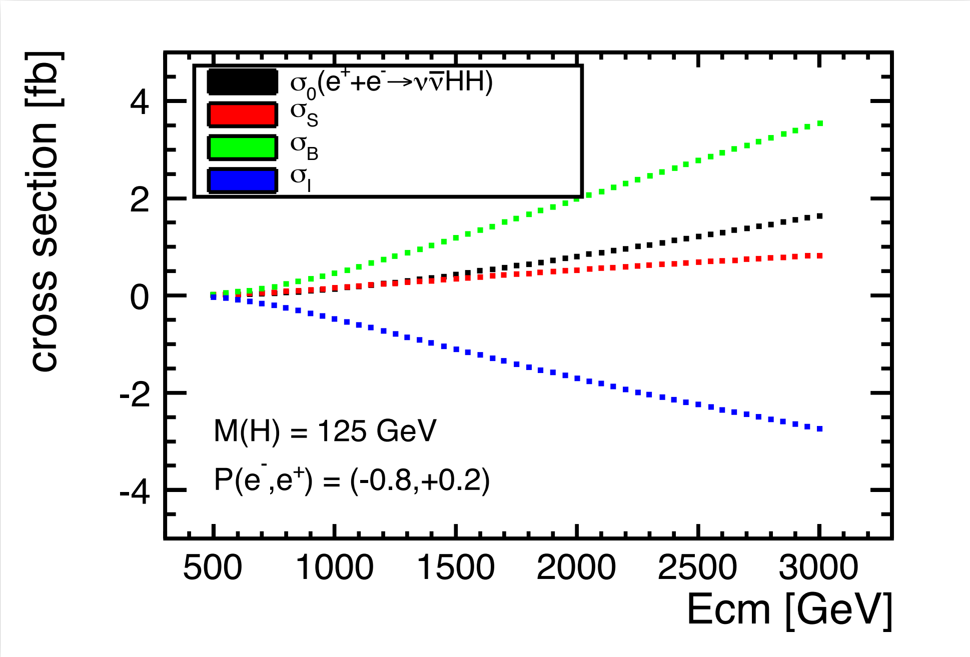
though the cross section maximum is at around Ecm = 600 GeV

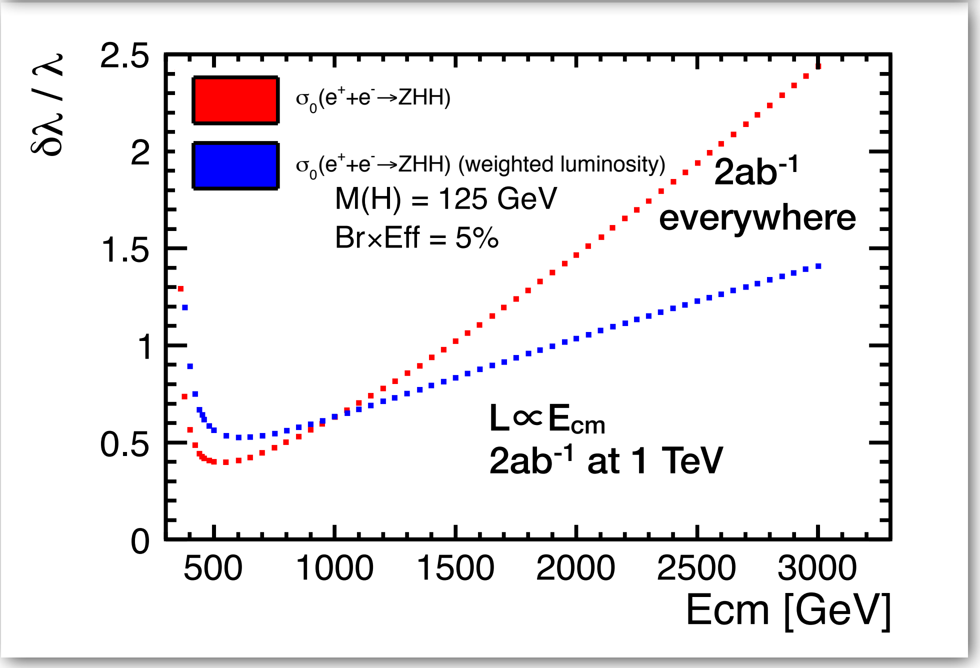
vvHH :

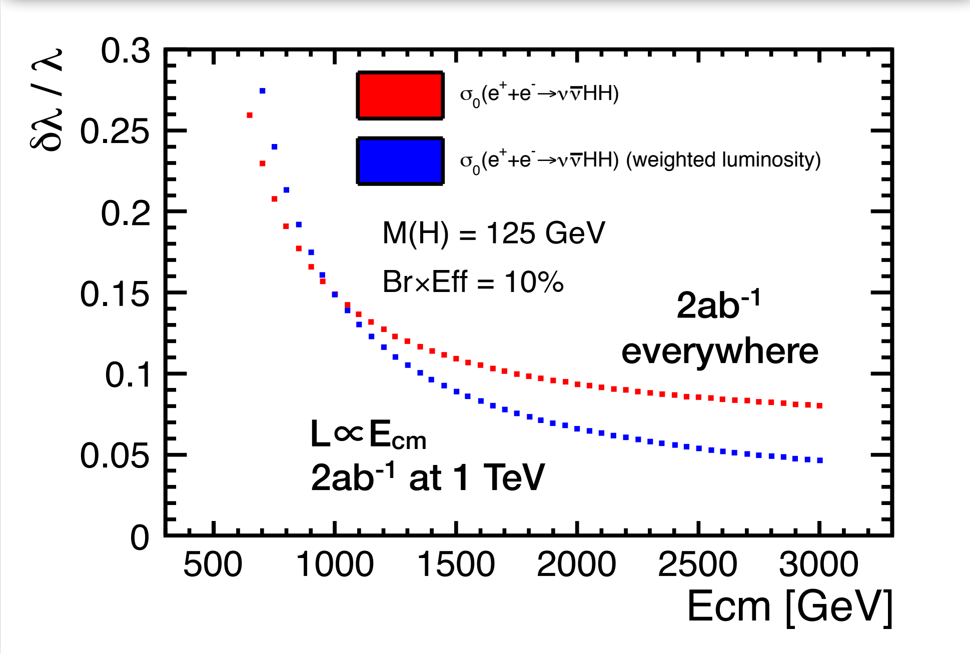
Precision slowly improves with Ecm

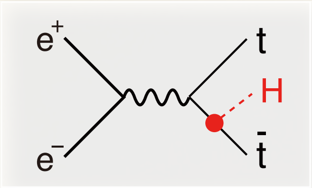
Expected Coupling Precision as a Function of Ecm



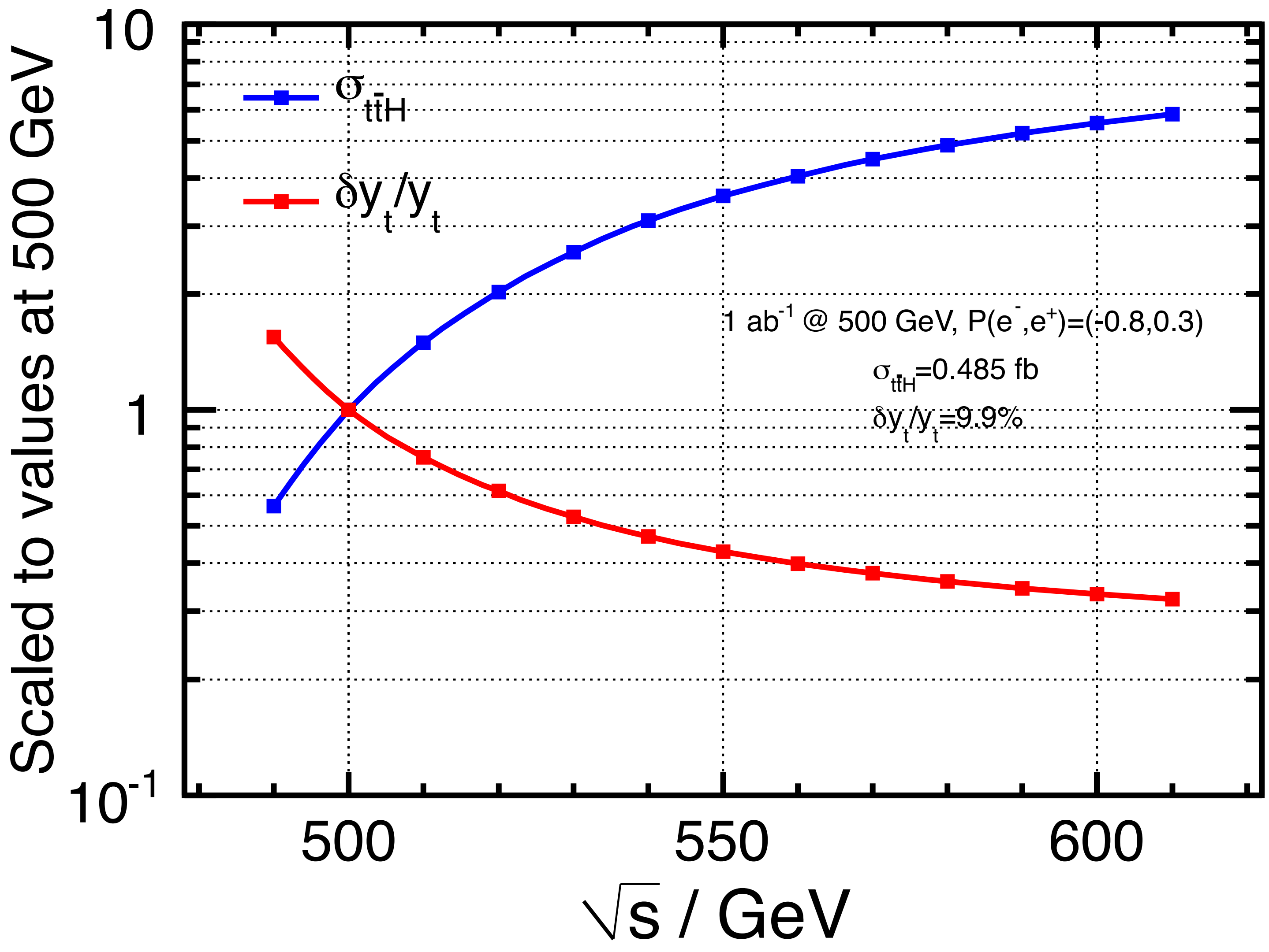








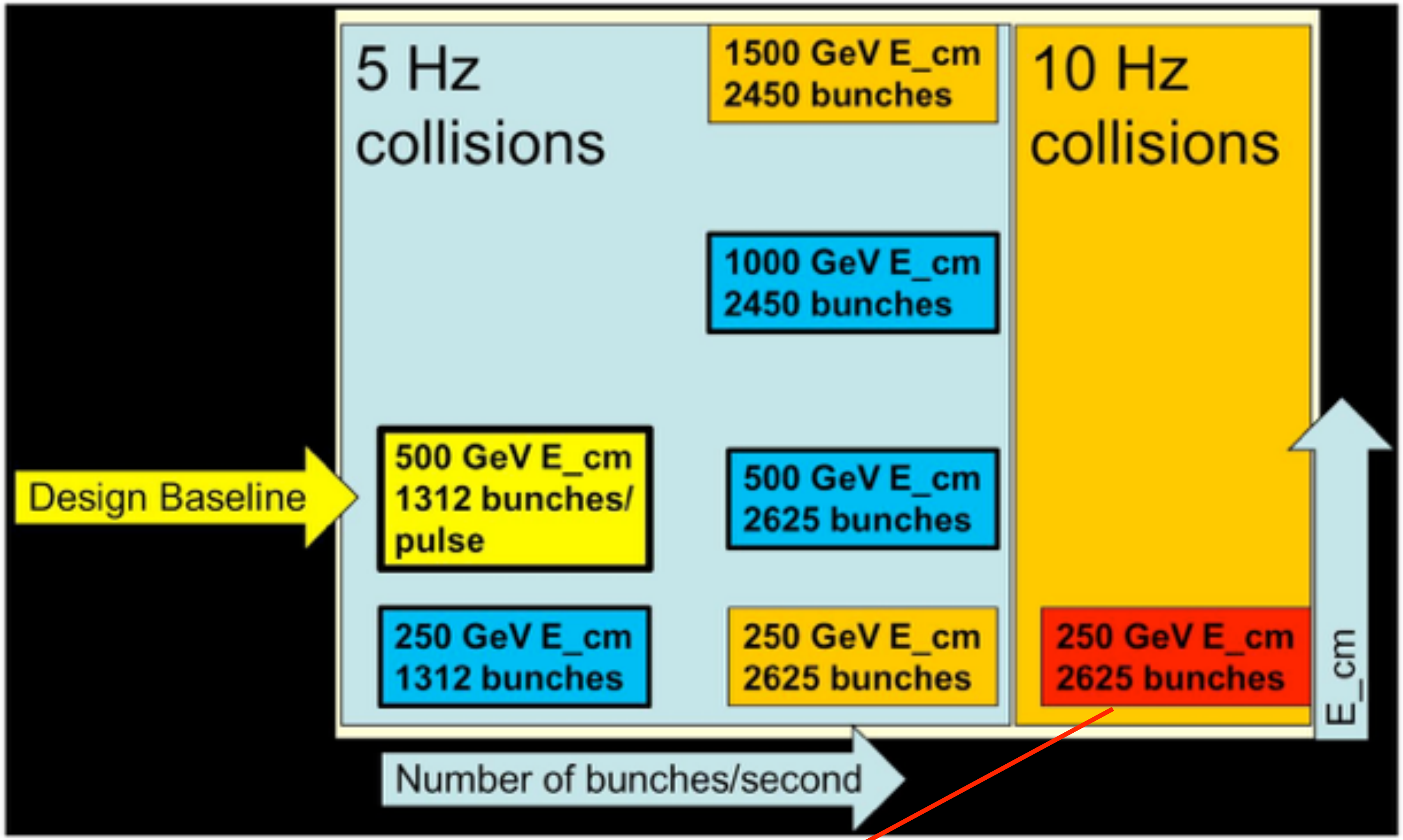
Top Yukawa coupling



Y. Sudo

HL-ILC ?

ILC Stages and Upgrades



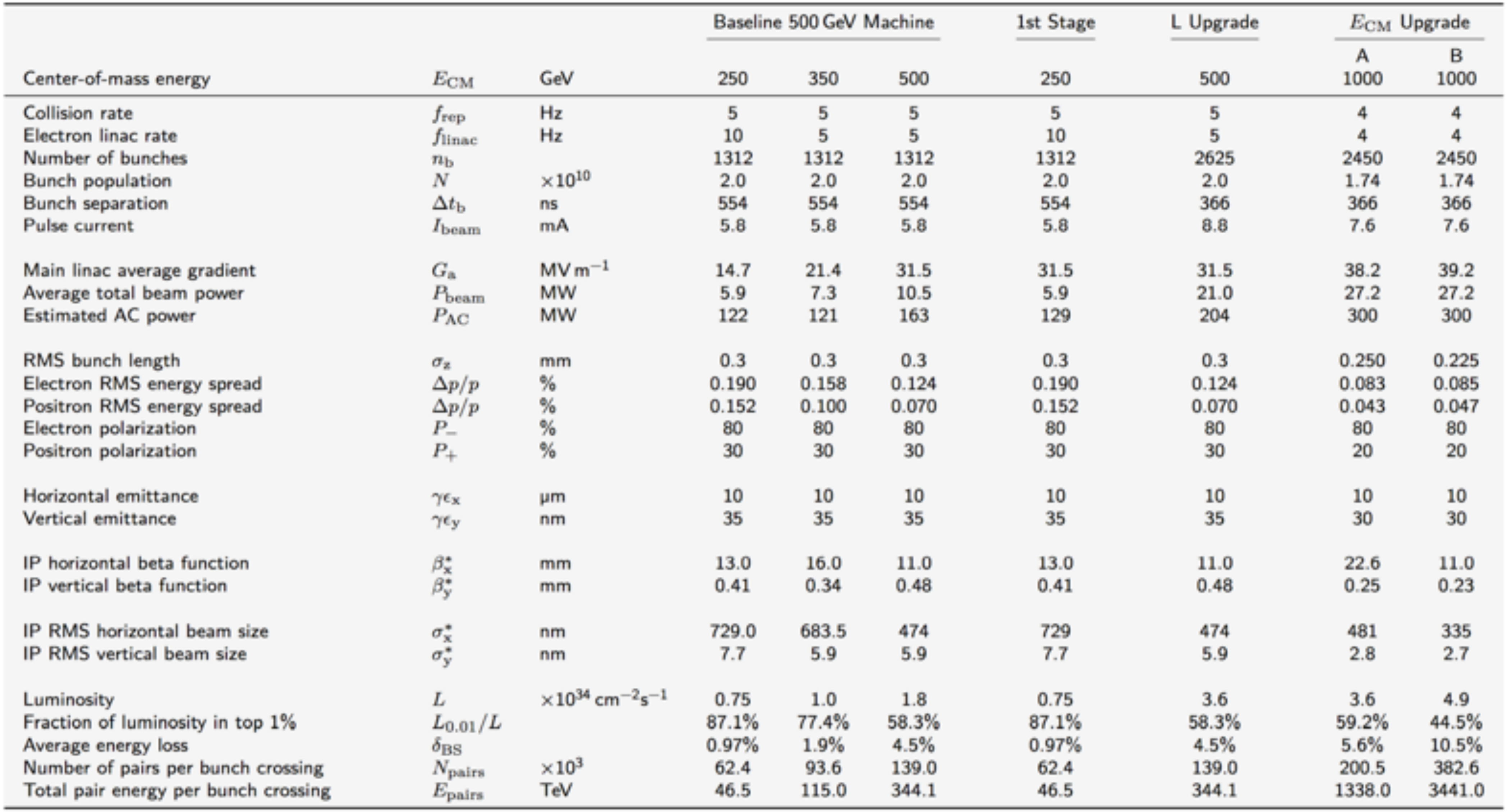
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

x4 upgrade
@250GeV

Blue: upgrade described in TDR

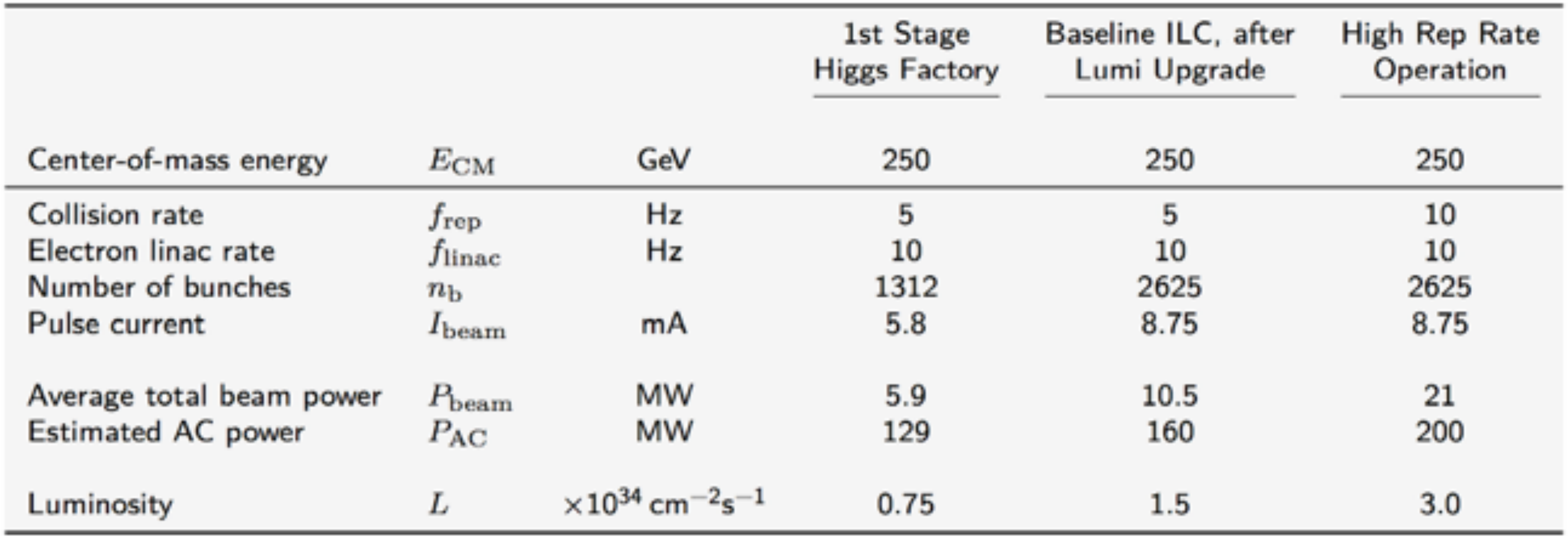
The current ILC design is rather conservative!

TDR

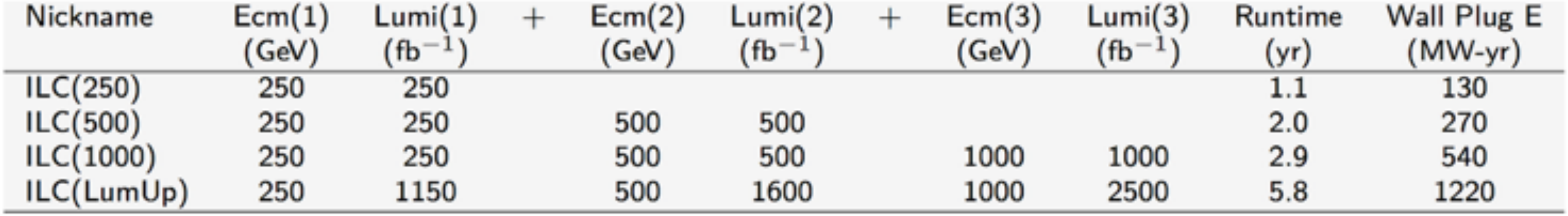


			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Center-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarization	P_-	%	80	80	80	80	80	80	80
Positron polarization	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β^*_x	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β^*_y	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ^*_x	nm	729.0	683.5	474	729	474	481	335
IP RMS vertical beam size	σ^*_y	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

HL-ILC

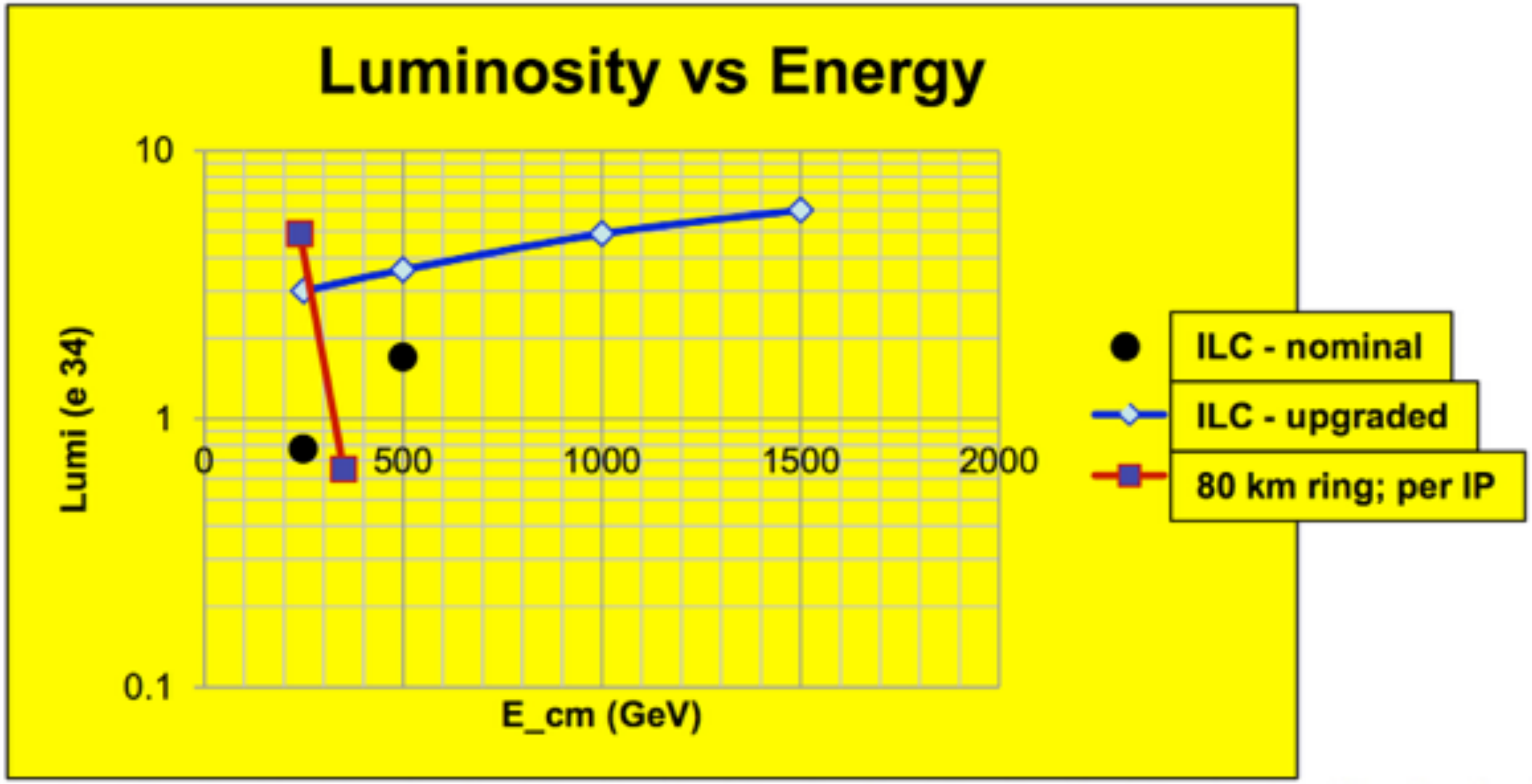


			1st Stage Higgs Factory	Baseline ILC, after Lumi Upgrade	High Rep Rate Operation
Center-of-mass energy	E_{CM}	GeV	250	250	250
Collision rate	f_{rep}	Hz	5	5	10
Electron linac rate	f_{linac}	Hz	10	10	10
Number of bunches	n_{b}		1312	2625	2625
Pulse current	I_{beam}	mA	5.8	8.75	8.75
Average total beam power	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

High Luminosity ILC



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}

Hypothetical HL-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%

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%
Hgg	3%	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	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

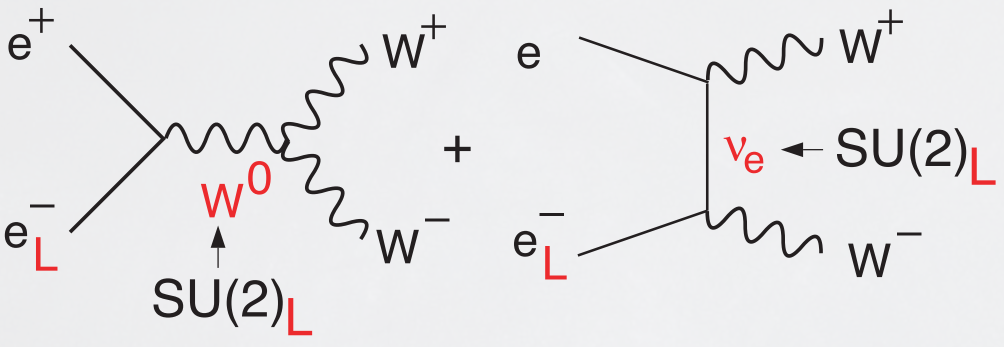
HHH	-	46%(*)	13%(*)

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

SUSY

Power of Beam Polarization

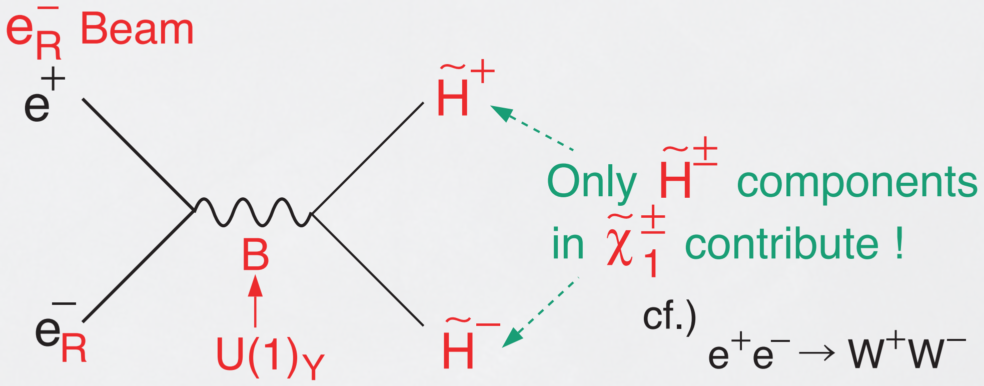
W^+W^- (Largest SM BG)



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

BG Suppression

Chargino Pair



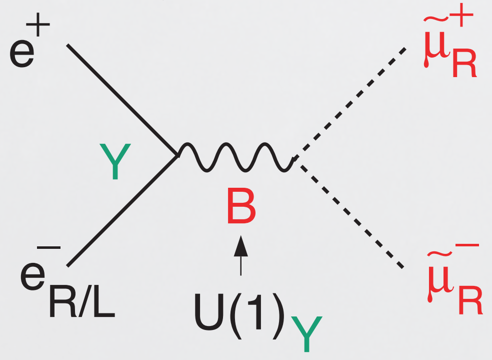
Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \underset{\langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle}{\underset{\parallel}{\bullet}} \cdot \tilde{H}^\pm$$

Decomposition

Slepton Pair



$Y_L = -1/2$: e^-_L

$Y_R = -1$: e^-_R

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

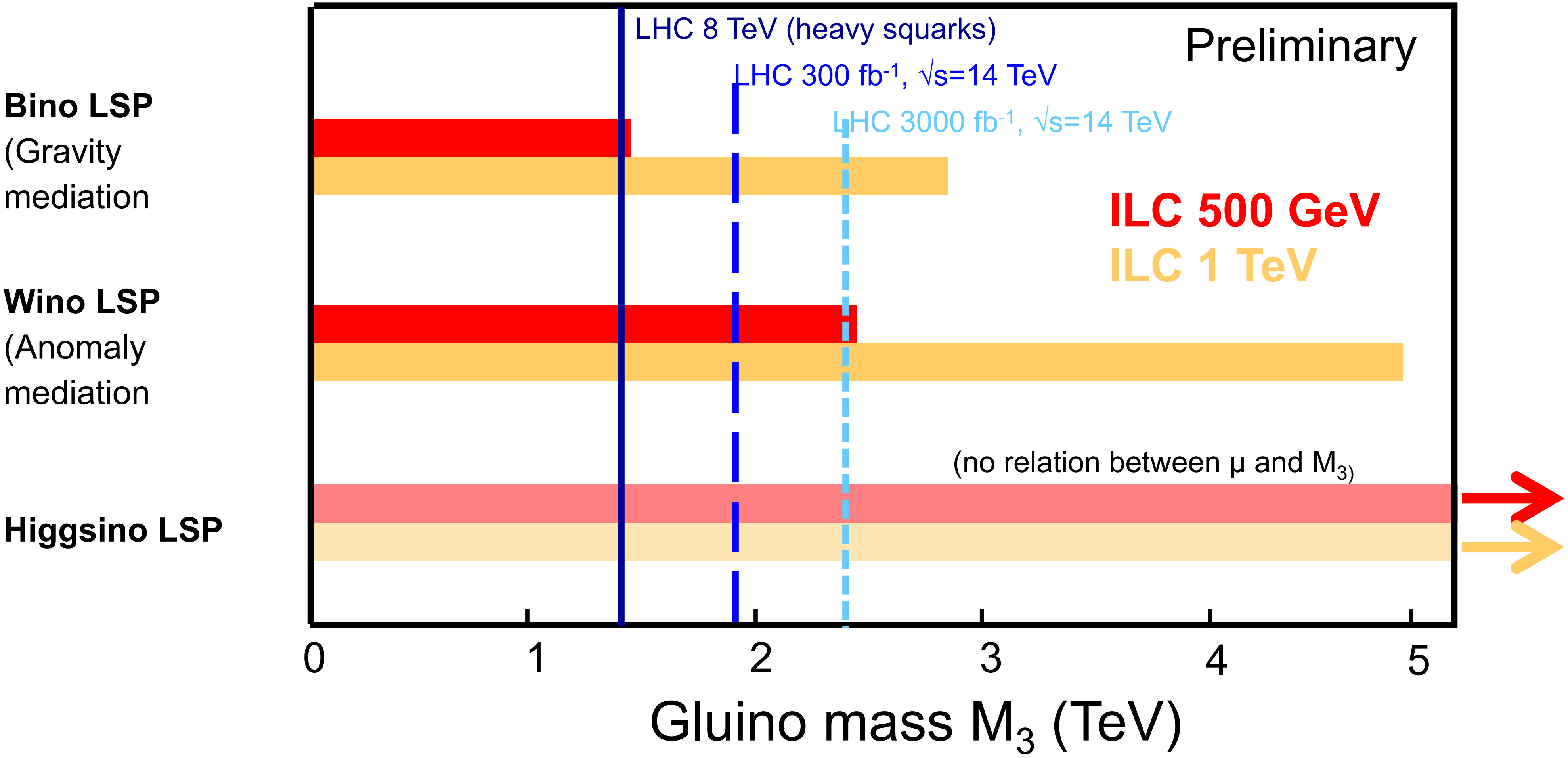
Signal Enhancement

Sensitivity to SUSY

Gluino search at LHC

Chargino/Neutralino search at ILC

→ Comparison assuming gaugino mass relations



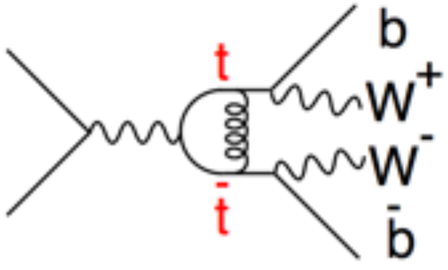
* Assumptions: MSUGRA/GMSB relation $M_1 : M_2 : M_3 = 1 : 2 : 6$; AMSB relation $M_1 : M_2 : M_3 = 3.3 : 1 : 10.5$

Top

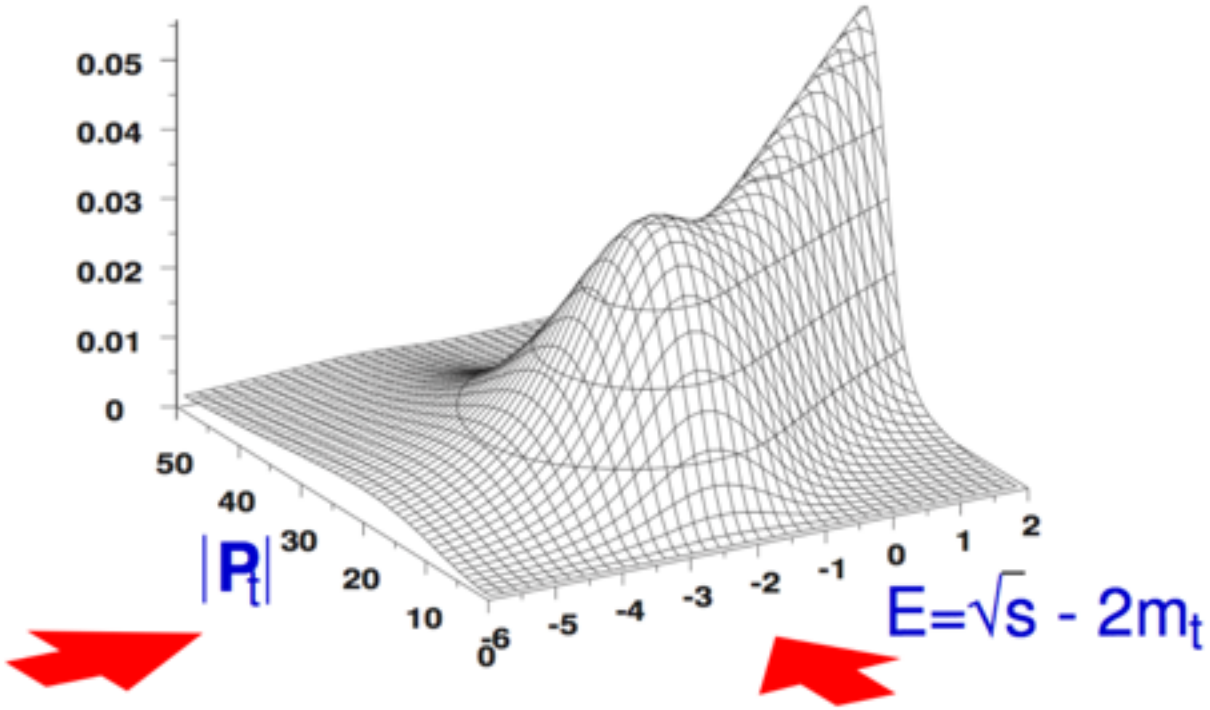
Top Quark

Threshold Region

How to access G experimentally



$p_{top} = p_{bW} = p_{3jets}$



Momentum Dist.

$$\frac{d\sigma_{t\bar{t}}}{d|\mathbf{p}|} \propto |\langle \mathbf{p}\,|\,G\,|\,\mathbf{x}=\mathbf{0}\,\rangle|^2$$

$$\simeq \left|\sum_n \frac{\phi_n(\mathbf{p})\Psi_n^*(\mathbf{0})}{E-E_n+i\Gamma_n/2}\right|^2$$

momentum space wave fun.

Threshold Scan

$$\sigma_{t\bar{t}} \propto Im\,\langle\,\mathbf{x}=\mathbf{0}\,|\,G\,|\,\mathbf{x}=\mathbf{0}\,\rangle$$

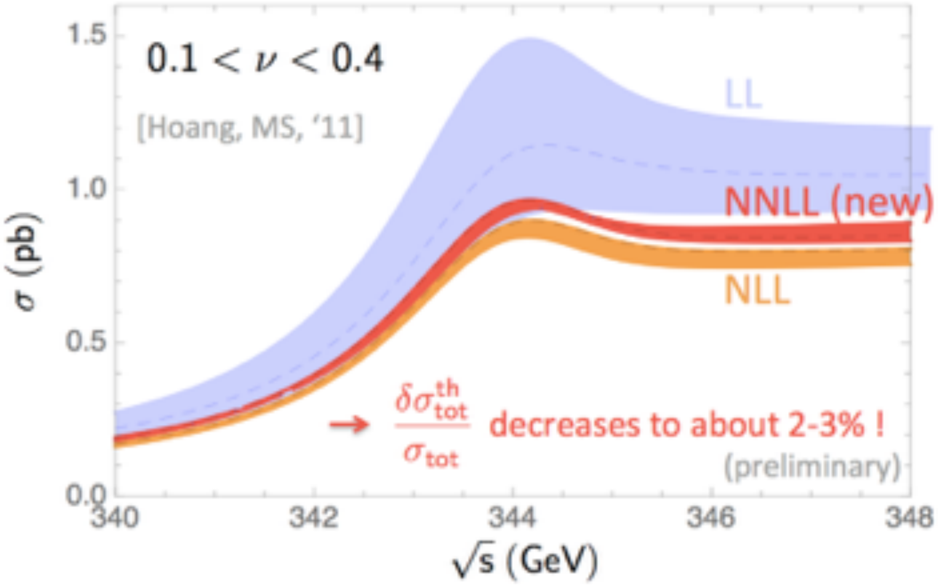
$$\simeq Im\sum_n \frac{|\Psi_n(\mathbf{0})|^2}{E-E_n+i\Gamma_n/2}$$

wave function at origin

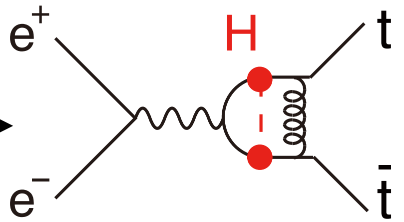
Top at Threshold

Threshold Scan

M.Stahlhofen Top Phys WS 2012



Theory improving! →

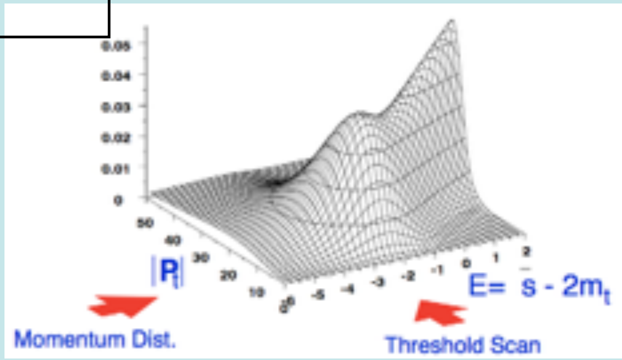


~10% effect

Expected accuracies

$$\boxed{\begin{aligned}\Delta m_t &= 34\,\mathrm{MeV}\\ \Delta\alpha_s(m_Z) &= 0.0023\\ \Delta\Gamma_t &= 42\,\mathrm{MeV}\end{aligned}}$$

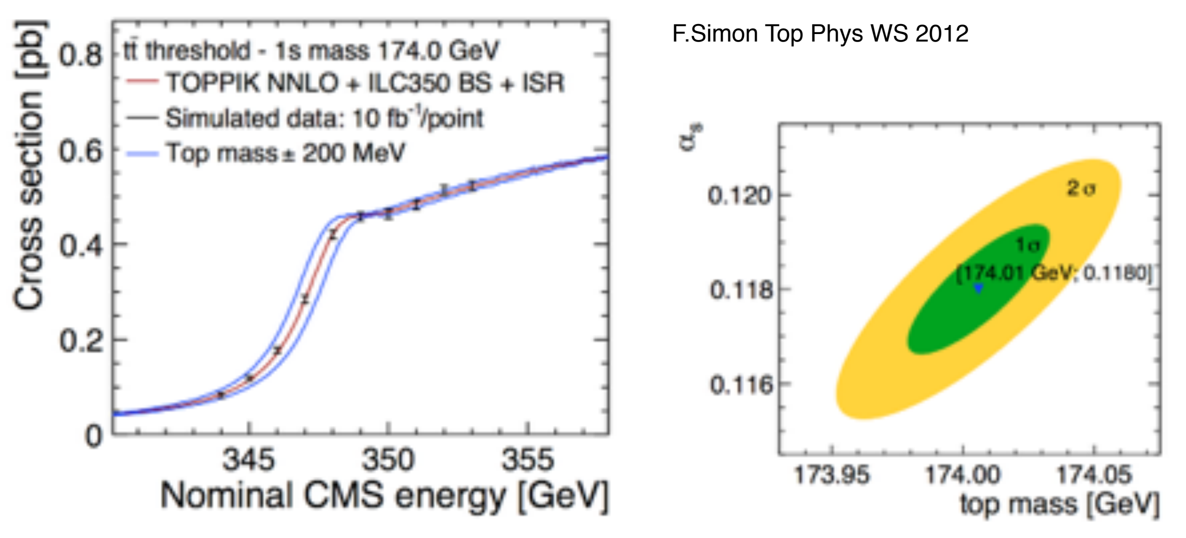
Threshold scan alone



+ A_{FB} & Top Momentum

$$\boxed{\begin{aligned}\Delta m_t &= 19\,\mathrm{MeV}\\ \Delta\alpha_s(m_Z) &= 0.0012\\ \Delta\Gamma_t &= 32\,\mathrm{MeV}\end{aligned}}$$

arXiv:hep-ph/0601112v2



F.Simon Top Phys WS 2012

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

Top Quark

Open Top Region

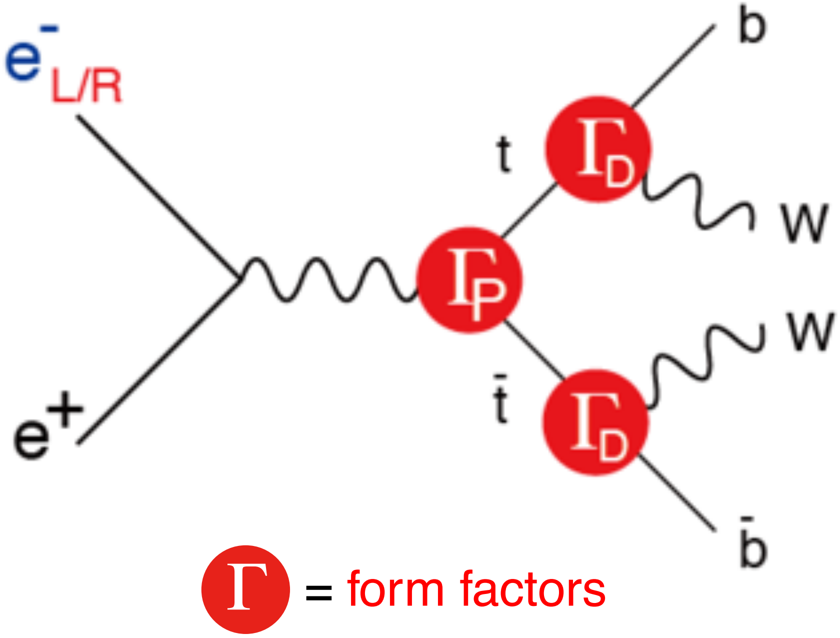
Key points

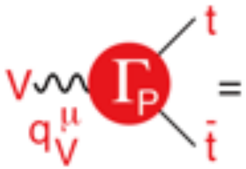
$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

The top decays before forming a top hadron.

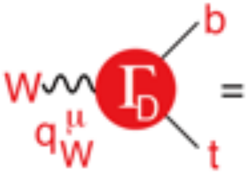
Top spin is measurable by angular analysis of decay products.

+ Polarized beams are available at ILC





$$= \quad \mathcal{L}_{\rm int}^{ttV} = g_W\left[V_\mu \bar{t}\gamma^\mu\left(F_{1L}^V P_L + F_{1R}^V P_R\right)t - \frac{1}{v}(\partial_\nu V_\mu)\bar{t}\sigma^{\mu\nu}\left(F_{2L}^V P_L + F_{2R}^V P_R\right)t\right] + \text{h.c.}$$



$$= \quad \mathcal{L}_{\rm int}^{tbW} = \frac{g_W}{\sqrt{2}}\left[W_\mu^- \bar{b}\gamma^\mu\left(F_{1L}^W P_L + F_{1R}^W P_R\right)t - \frac{1}{v}(\partial_\nu W_\mu^-)\bar{b}\sigma^{\mu\nu}\left(F_{2L}^W P_L + F_{2R}^W P_R\right)t\right] + \text{h.c.}$$

Indirect BSM Searches

Two-Fermion Processes

Z’ Search / Study

arXiv:0912.2806 [hep-ph]

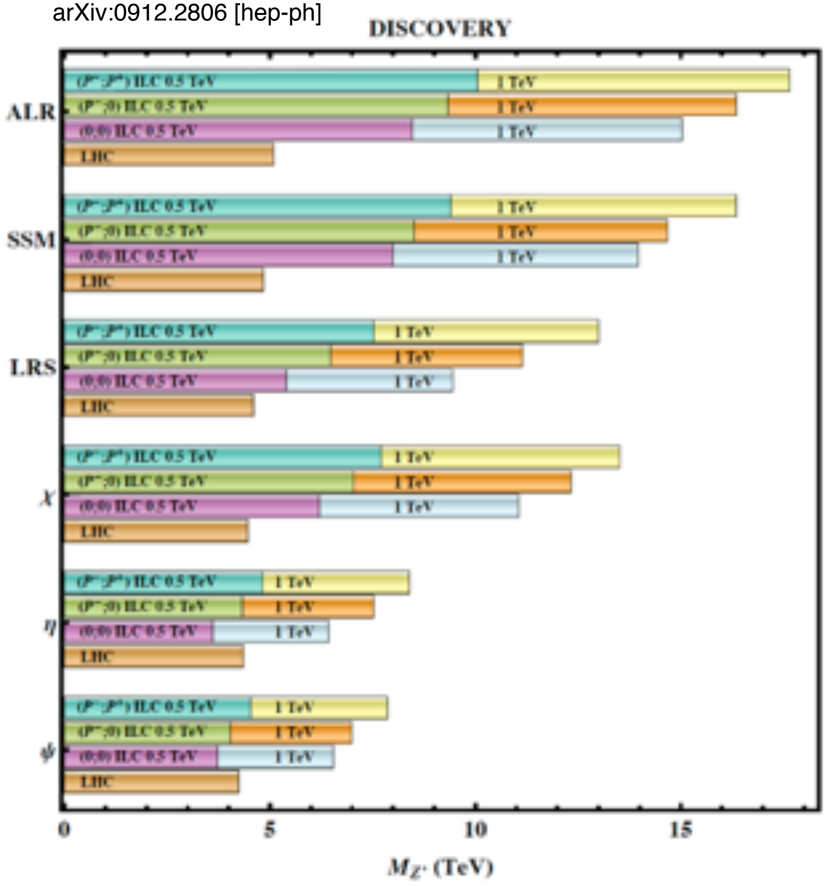
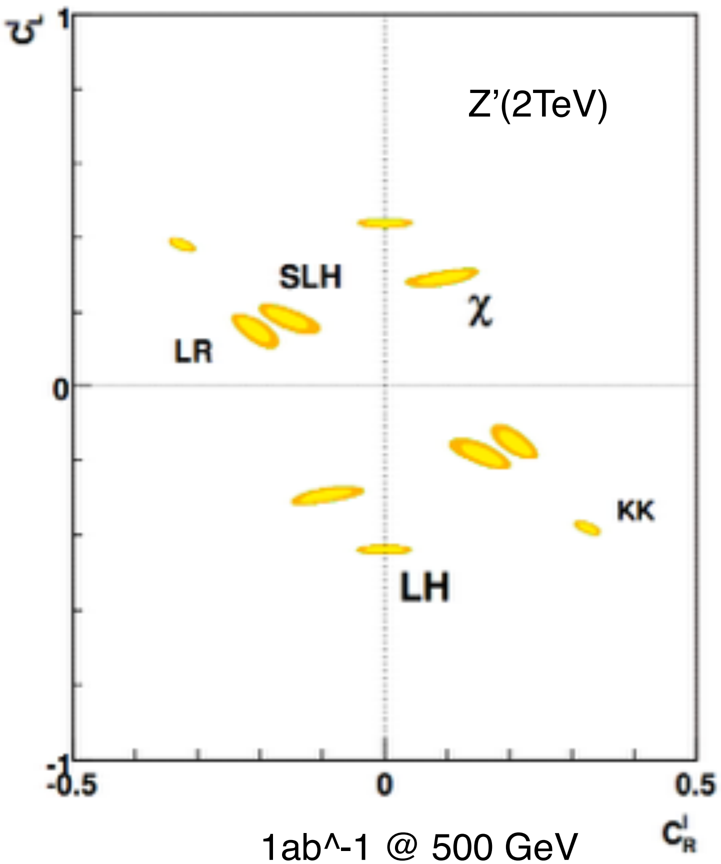


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For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

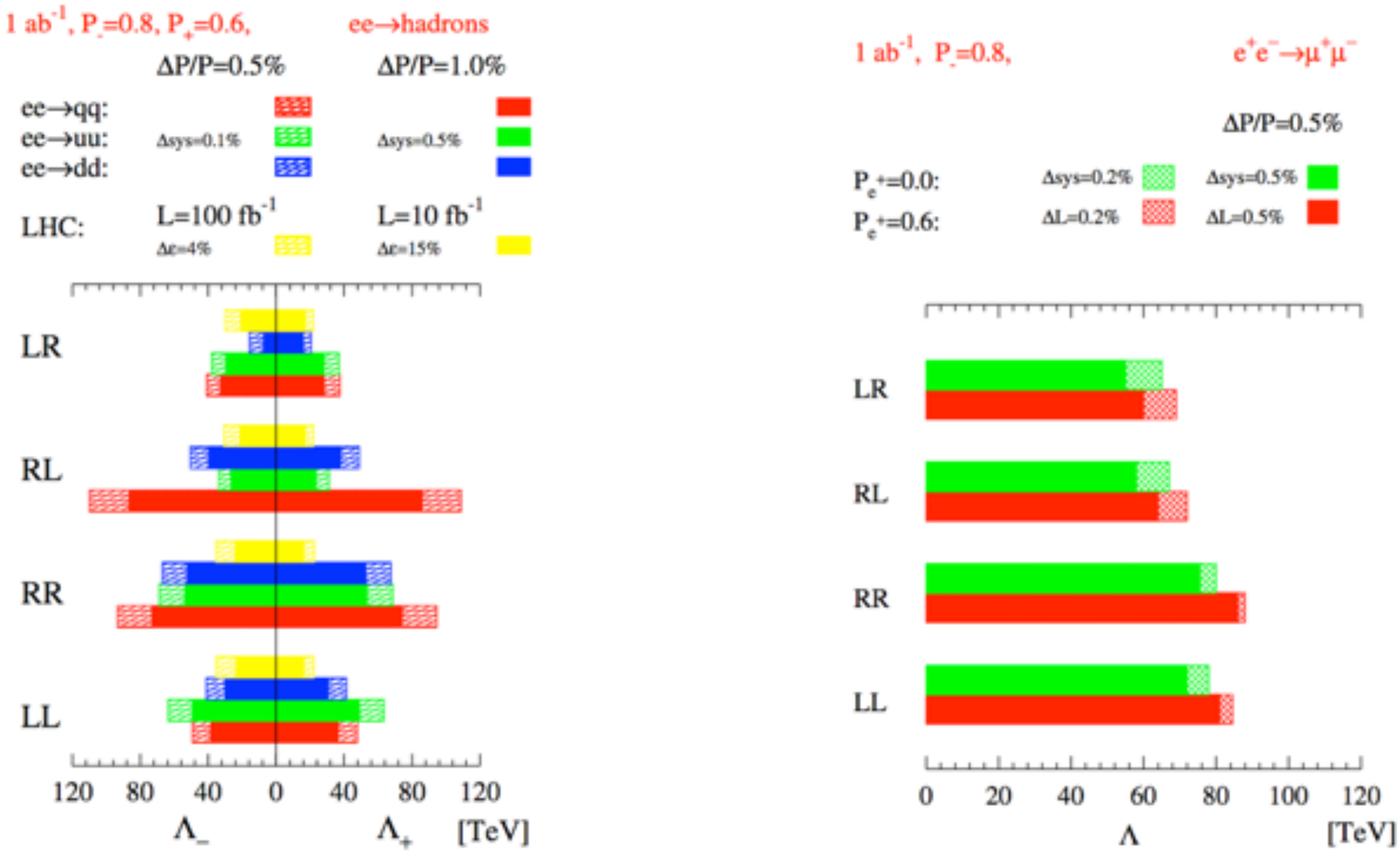


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.