ILC Higgs physics case

(and report from LCWS14)

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Outline

- ILC Higgs physics case, short review
  - ILC Higgs physics
  - Requirements on precision for NP scenarios

- ILC prospected precision + some LCWS14 updates
  - Total σ and total Γ
  - Higgs couplings
  - Higgs self-coupling
  - Fingerprinting BSM scenarios with Higgs

- Summary and comments

N.B. 1: this talk is not a comprehensive report of all the tremendous amount of work going on to make the ILC physics case even stronger. Selection of topics based on personal choice.

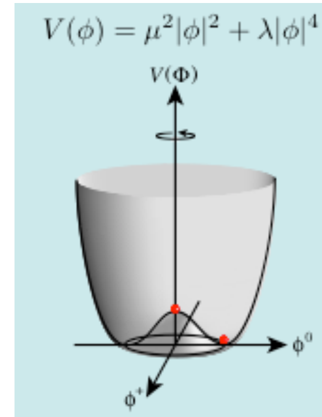
N.B. 2: results collected from ILC TDR, Snowmass report, HiggsHunting, HiggsCoupling and LCWS 2013 & 2014.

EWSB is a BSM physics case…

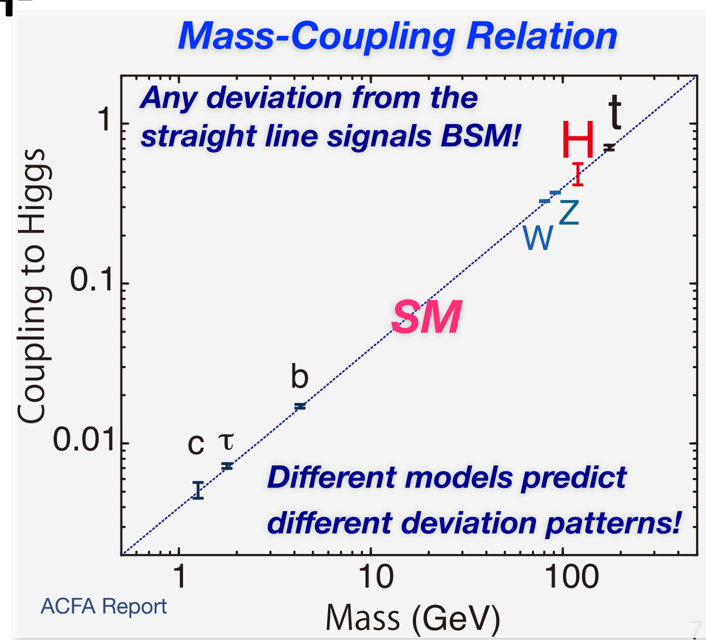
- Most important question to be addressed :
  - **Is the Higgs elementary or composite ?**
  - (weakly or strongly interacting ?)
- In the case od SUSY:
  - elementary Higgs in an extended multiplet structure XHDM with X≥2.

  → search for SuSy part and **extra higgses H, A, H$^{\pm}$**

  → **look for deviations in Higgs couplings**
- In case of compositeness (new QCD-like interaction):
  - H(125) is composite
  - → **look for deviations in Higgs and Top (ttZ) couplings**
- → ***need a precision facility : ILC***

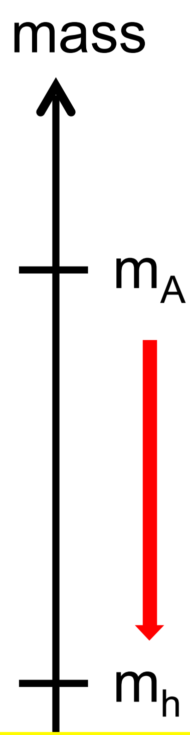


Why $\mu^2 < 0$?



BSM deviations in Higgs couplings

Size of deviation depends on NP scale :



Example 1: MSSM (tanβ=5, radiative corrections ≈ 1)

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

ex.: theory error on hbb estimated down to 0.4% when ILC run (Peskin)

heavy Higgs mass

Example 2: Minimal Composite Higgs Model

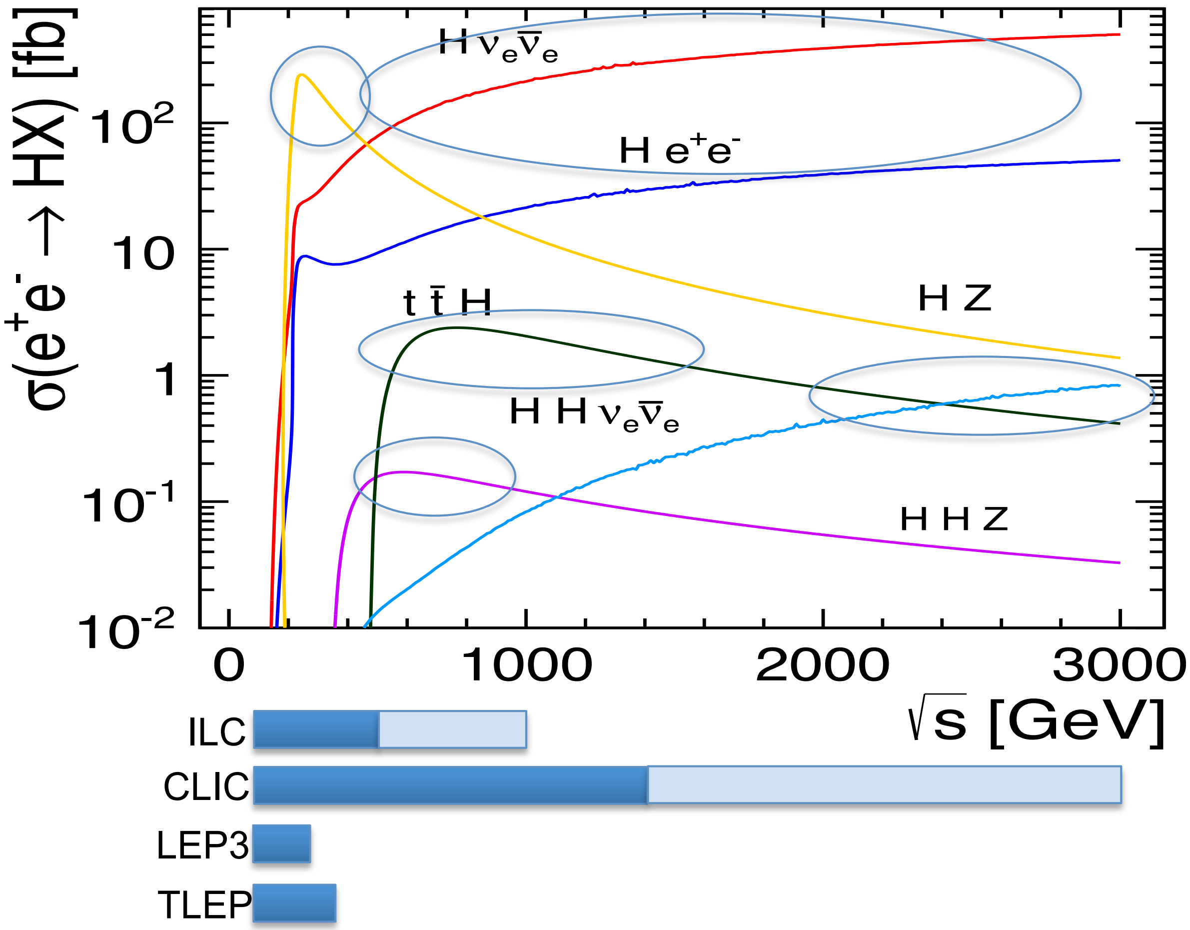
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

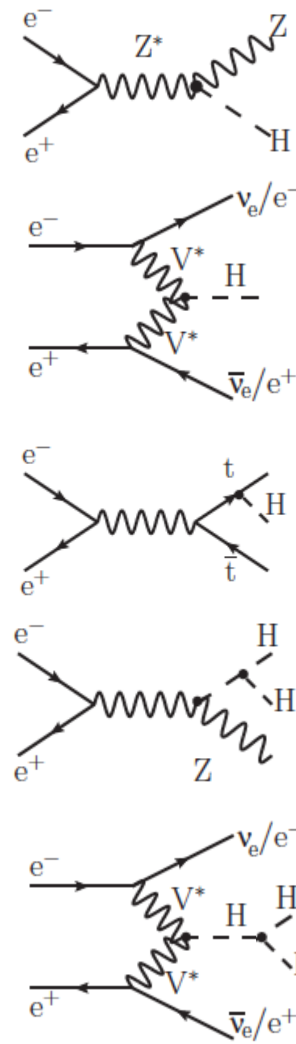
composite scale

Recent work:
P.Giardino, et al.arXiv:1303.3570 [hep-ph];
A.Djouadi, J.Quevillon,arXiv:1304.1787 [hep-ph];
NMSSM model:
G.~Belanger et al., JHEP **1301**(2013) 069;
R.Barbieri, et al., arXiv:1304.3670 [hep-ph];
Two Higgs Doublets:
B.Grinstein,P.Uttayarat,arXiv:1304.0028 [hep-ph];
O.~Eberhardt et al., arXiv:1305.1649 [hep-ph].

NP at 1 TeV gives few percent deviation
→ *need for sub-percent precision*

Higgs production at e^+e^-





Mass
g_Z (m.i.)
BR´s
(LHC)-invisible

Γ_{tot}

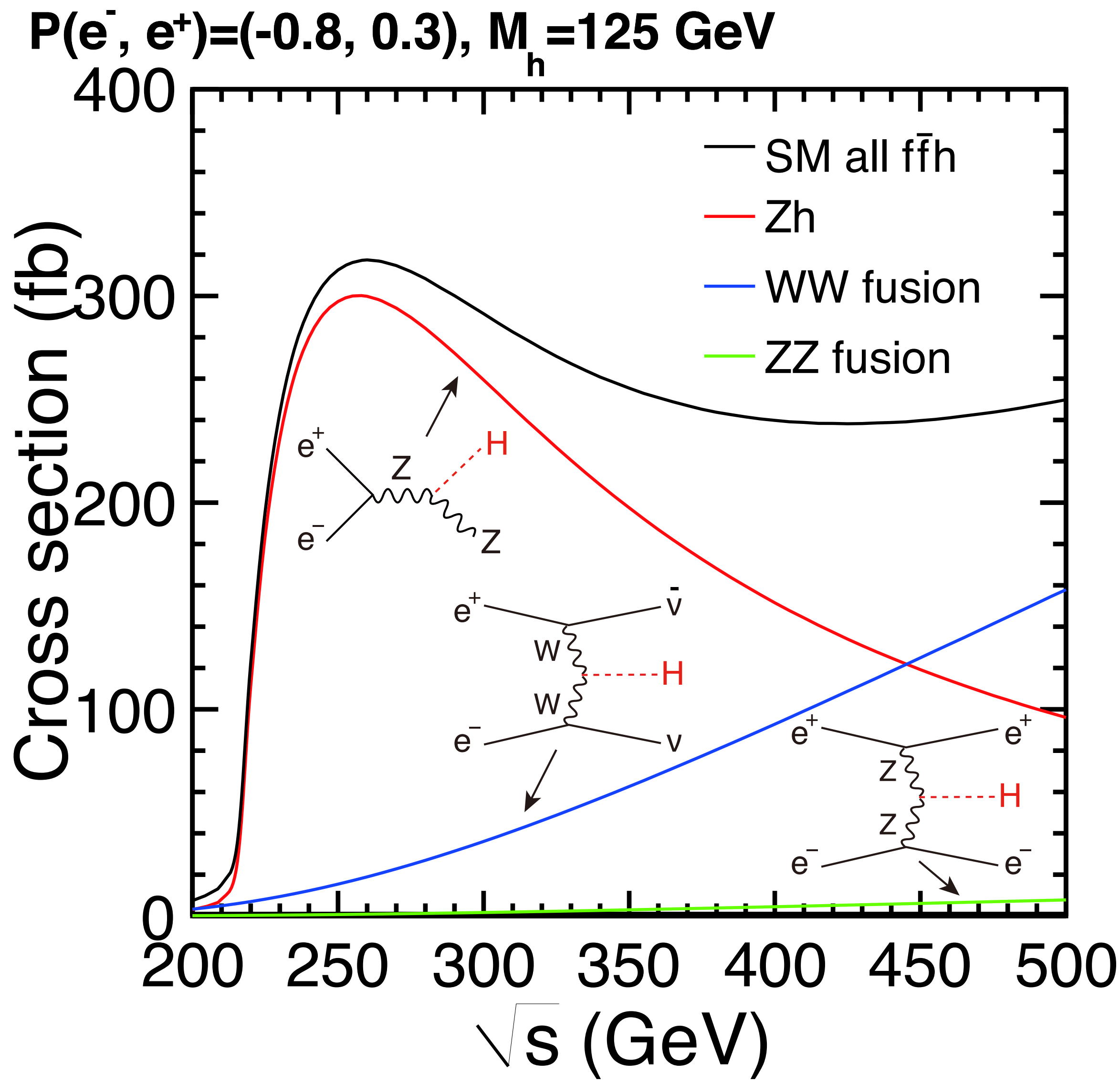
g_t (ILC,CLIC)

g_{HHH} (ILC500)

g_{HHH} (ILC1000, CLIC)

Advantage of wide range in √s to probe for different processes

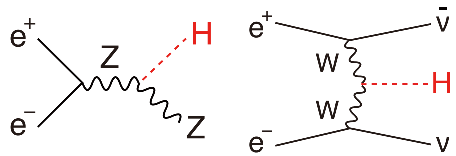
Higgs production at e^+e^- at E_{CM}<500 GeV



The Key to ILC Higgs physics

At LHC all the measurements are σ×BR measurements.

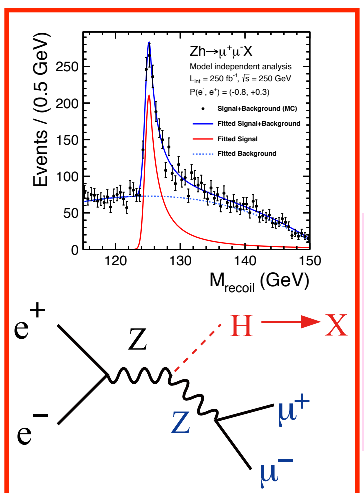
At ILC all but the σ measurement using recoil mass technique is σ×BR measurements.



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

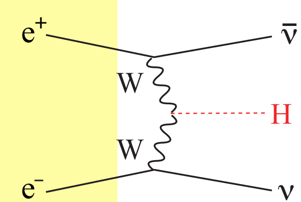
σ×BR → **BR** → **g coupling**

The Key



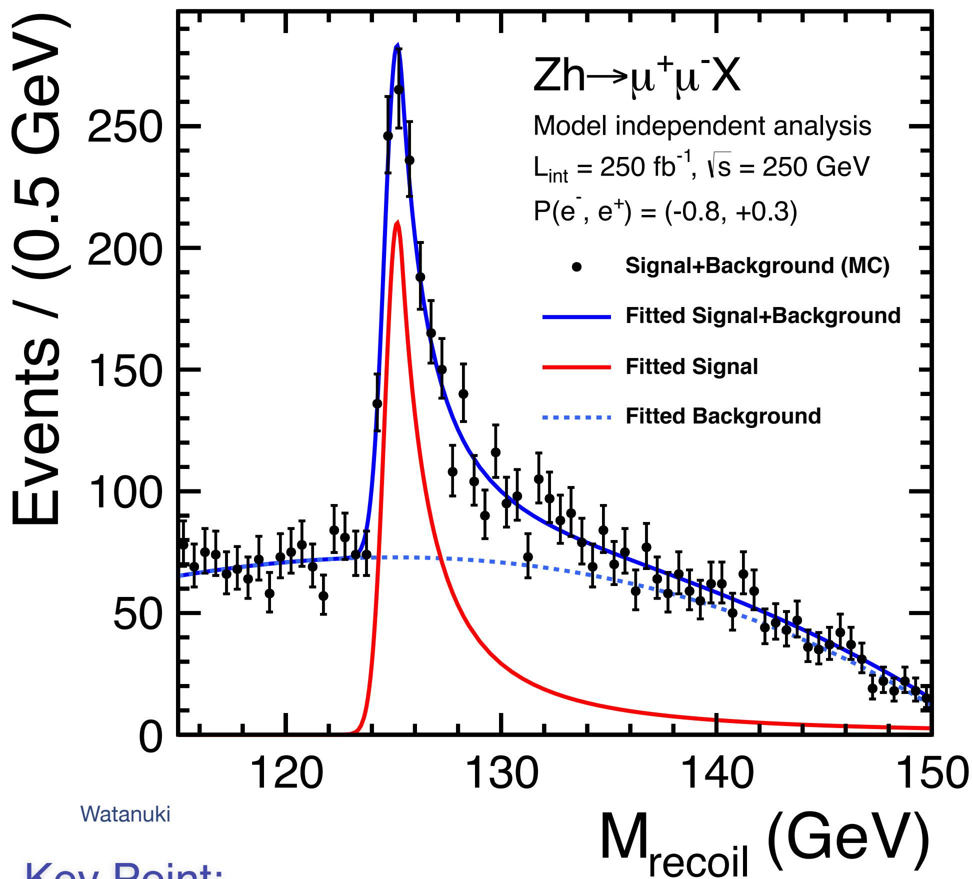
σ
from recoil mass

Γ_H
total width

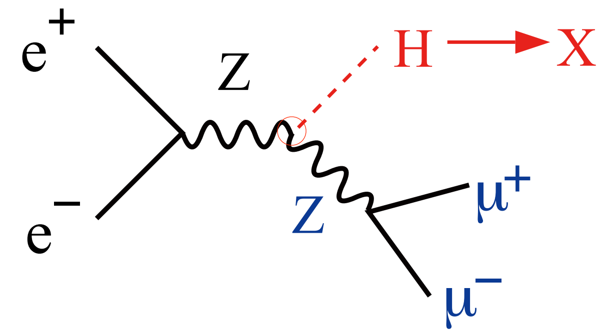


Higgs recoil mass

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

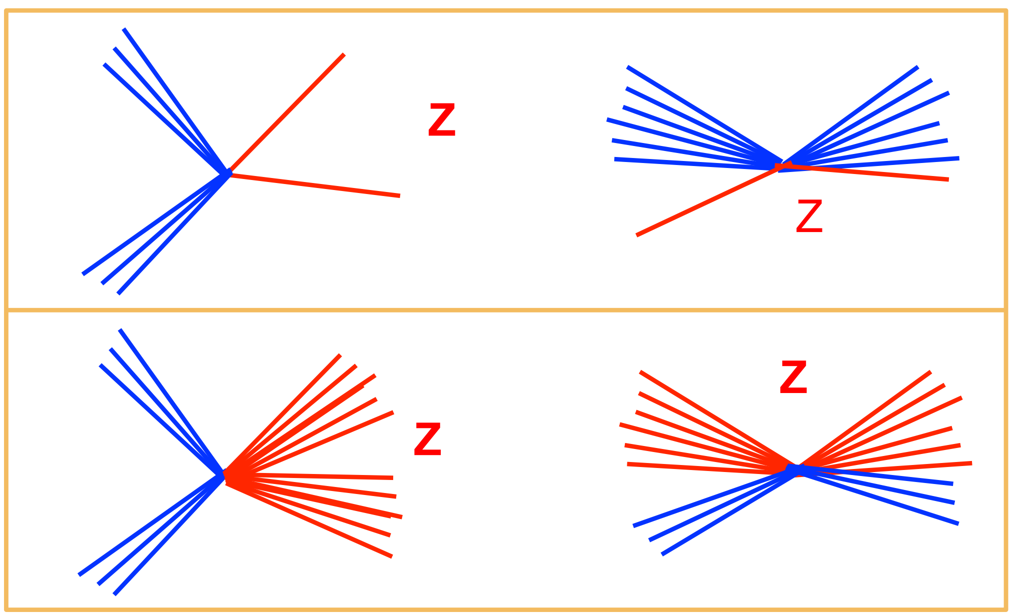
Key Point:

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 LC)

Keisuke Fujii @ Higgs Couplings 2014, Trino

Higgs recoil mass

- To date, most studies only use $Z \to \mu\mu$ and $Z \to ee$
- Statistical precision limited by leptonic BRs of 3.5 %
- Here: extend to $Z \to qq$ ~ 70 % of Z decays
- Strategy – identify $Z \to qq$ decays and look at recoil mass
- Can never be truly model independent:
  - unlike for $Z \to \mu\mu$ can't cleanly separate H and Z decays



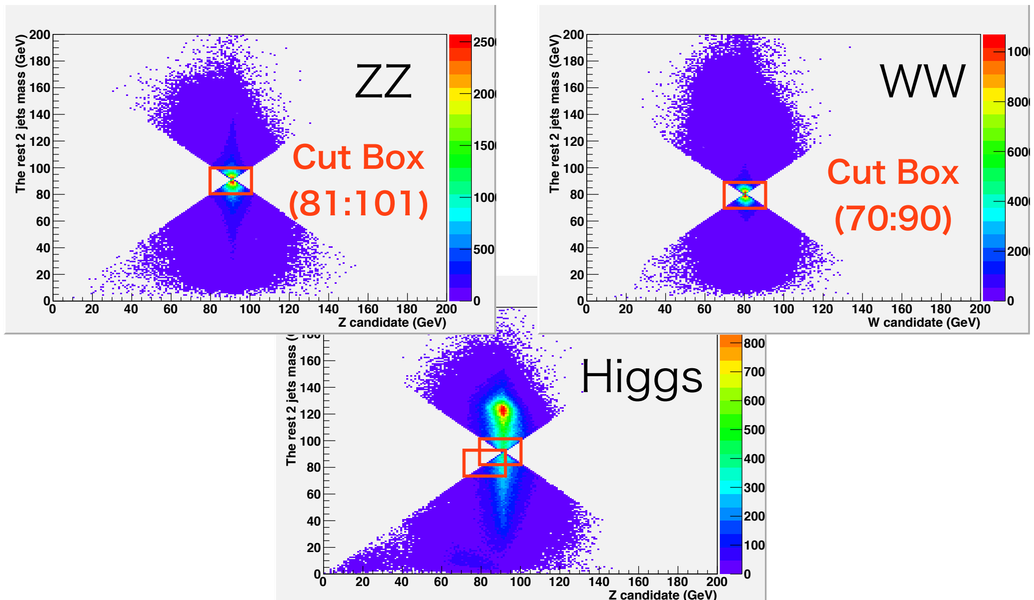
Muons "always" obvious

Here jet finding blurs separation between H and Z

Different efficiencies for different Higgs decays

Higgs recoil study wit ZH→qqH

Separating ZZ and WW → 4jets from HZ :



Linear Collider WorkShop 2014 @ Belgrade : Tatsuhiko Tomita : 09/10/2014

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- The precision of total cross section left 5.6% -> 4.7%, right 4.0% -> 3.3% from AWLC. (but still not satisfactory.)
- Categorization can reduce difference of efficiency especially tautau, WW->leptonic.
- Current cut has bias for gg and WW.

Tatsuhiko Tomita/ Taikan Suehara

Using categorization

- Categorization is a powerful tool to reduce difference of efficiency among Higgs decay modes.
  - Categorize events using number of jets, leptons, taus, etc.
  - Minimize the difference of efficiency in each category (decay modes with too small fraction in the category is negligible.)
  - Calculate partial cross section from each category
  - Combine all cross section from categories to get the total cross section of ZH production.

prospects

- Use likelihood to improve statistical precision.
- Equalize the cut efficiency of each Higgs decay mode.
- Improve tau separation by optimizing tau finder.
- Estimate systematic errors.

Model independent coupling extraction

ILC: need to measure Γ_{tot} in addition to absolute BR´s to extract couplings in a model-independent way

$$\sigma_{vis} = \sigma_{prod} \times BR(H \to f)$$

$$\sigma_{prod} \sim g_{Hi}^2 \quad and \quad BR(H \to f) = \frac{\Gamma_f}{\Gamma_{tot}} \sim \frac{g_{Hf}^2}{\Gamma_{tot}}$$

$$\sigma_{vis} \sim \frac{g_{Hi}^2 g_{Hf}^2}{\Gamma_{tot}(g_{Hj}, j=1\ldots n)}$$

Γ_T is the Higgs total width, g_{HZZ}, g_{HWW}, and $g_{Hb\bar{b}}$ are the Higgs couplings to ZZ, WW, and $b\bar{b}$, respectively, and F_1, F_2, F_3, F_4 are calculable quantities. For example,

$$F_2 = \left(\frac{\sigma_{ZH}}{g_{HZZ}^2}\right)\left(\frac{\Gamma_{H\to b\bar{b}}}{g_{Hb\bar{b}}^2}\right).$$

The couplings are obtained as follows:

1. From $Y_1 \iff g_{HZZ}$
2. From $Y_1Y_3/Y_2 \iff g_{HWW}$
3. From g_{HWW} and $Y_4 \iff \Gamma_T$
4. From g_{HZZ}, g_{HWW}, Γ_T and Y_2 or $Y_3 \iff g_{Hb\bar{b}}$

Model-independent determinations of Higgs couplings

Example--consider the following four independent measurements:

$$Y_1 = \sigma_{ZH} = F_1 \cdot g_{HZZ}^2$$

$$Y_2 = \sigma_{ZH} \times \mathrm{Br}(H \to b\bar{b}) = F_2 \cdot \frac{g_{HZZ}^2 g_{Hb\bar{b}}^2}{\Gamma_T}$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b}) = F_3 \cdot \frac{g_{HWW}^2 g_{Hb\bar{b}}^2}{\Gamma_T}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to WW^*) = F_4 \cdot \frac{g_{HWW}^4}{\Gamma_T}$$

1

In reality :

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

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

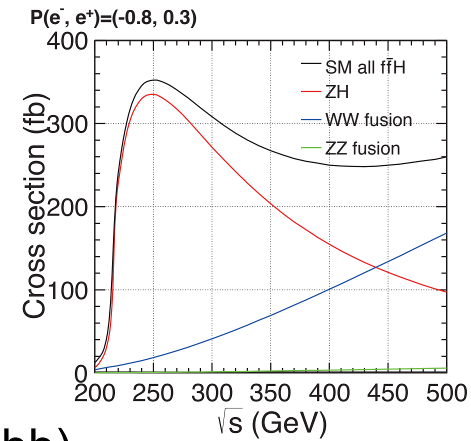
10 free parameters:

g_{HZZ}, g_{HWW}, g_{Hbb}, g_{Hcc}, g_{Hgg}, $g_{H\tau\tau}$, $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, g_{Htt}, Γ_0

Total Higgs Width

Need to measure WW-fusion cross section (e.g. $e^+e^- \rightarrow H\nu\nu \rightarrow bb\nu\nu$)

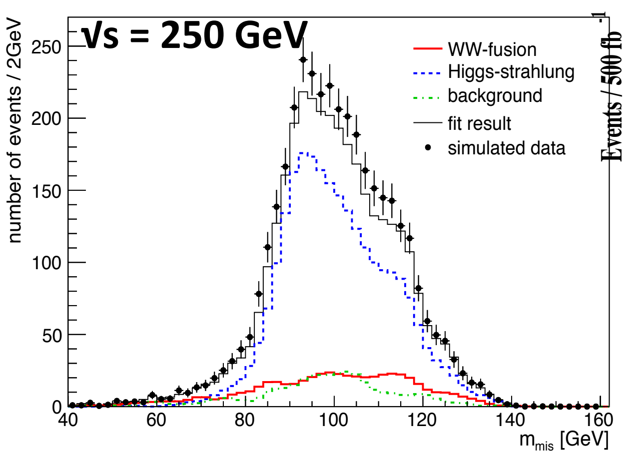
- need to separate from $HZ \rightarrow bb\nu\nu$ (+ handle interference)
- WW-fusion small at HZ threshold! → need higher $\sqrt{s}$

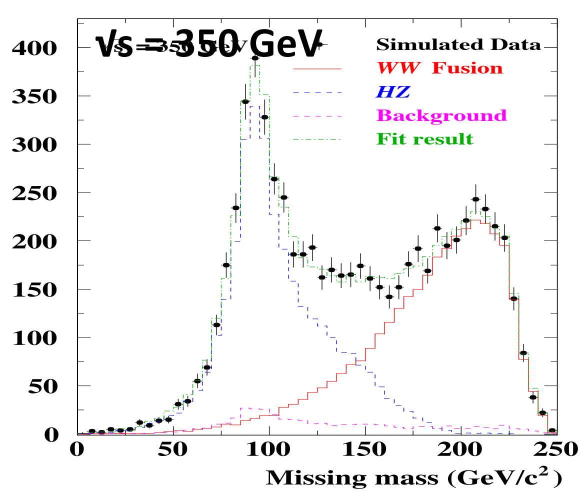


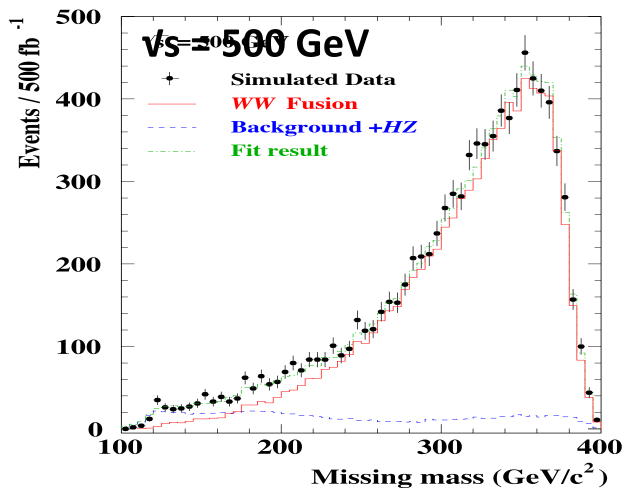
precision on $\sigma_{WW\text{-fusion}}$:

250 GeV	11.0 %
350 GeV	3.6 %
500 GeV	3.2 %

} dominated by error on $BR(H \rightarrow bb)$



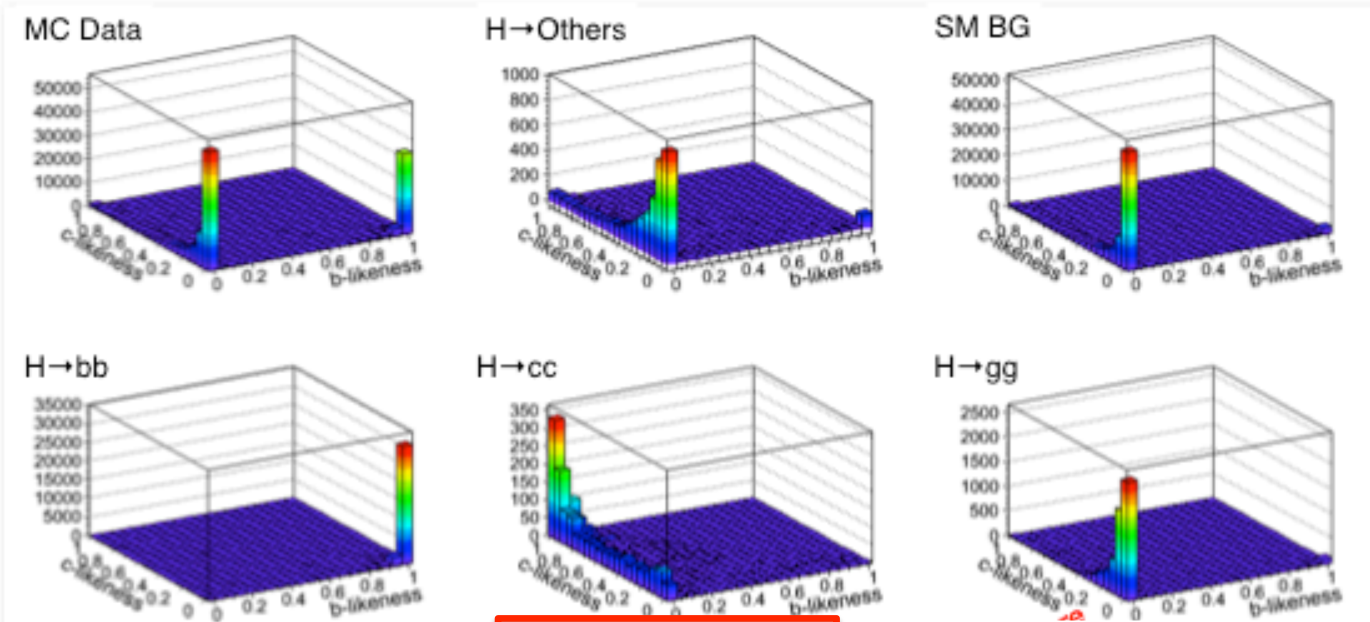




[Dürig; Meyer,KD]

High performance flavor tagging

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

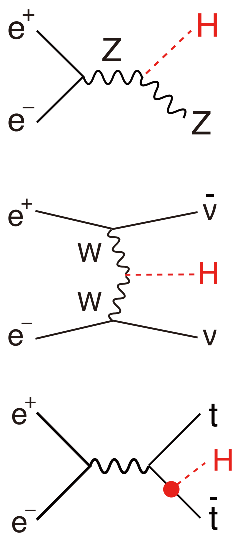


Updated from LOI,
now m_H=125
+ tagging improvement
from LCFIVertex -> LCFIPlus
but will revisit flavour-tagging
performance for cc

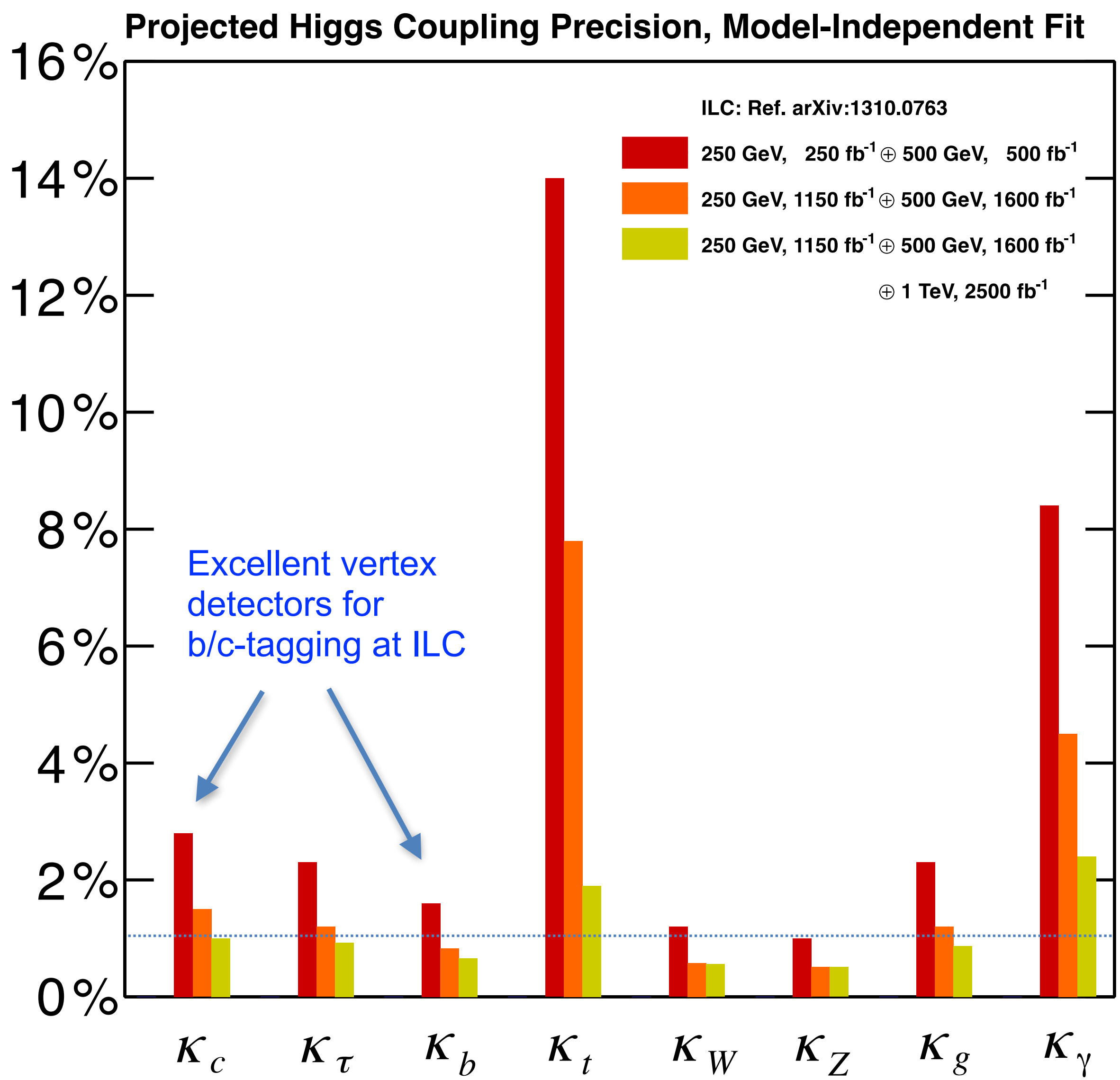
work on-going still optimizing

Updated results	250 GeV			350 GeV		
L(fb^{-1})	250 fb^{-1} P(-0.8,+0.3)			330 fb^{-1} P(-0.8,+0.3)		
ΔσBR/σBR	bb	cc	gg	bb	cc	gg
ννh (WW and ZH)	1.6%	14.8%	9.7%	1.1%	14.6%	4.6%
ggh (ZH)	1.6%	24.0%	18.4%	1.5%	15.0%	13.2%
eeh (ZH)	4.4%	57.4%	36.3%	6.5%	>100%	>100%
μμh (ZH)	3.4%	34.0%	22.3%	4.6%	65.7%	30.9%
Combined	1.0%	11.6%	7.8%	0.9%	10.3%	4.3%
Extrapolated	1.1%	8.0%	6.8%	0.9%	6.5%	5.2%

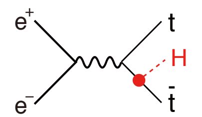
Higgs coupling precision



All of major Higgs decay modes accessible at ILC!

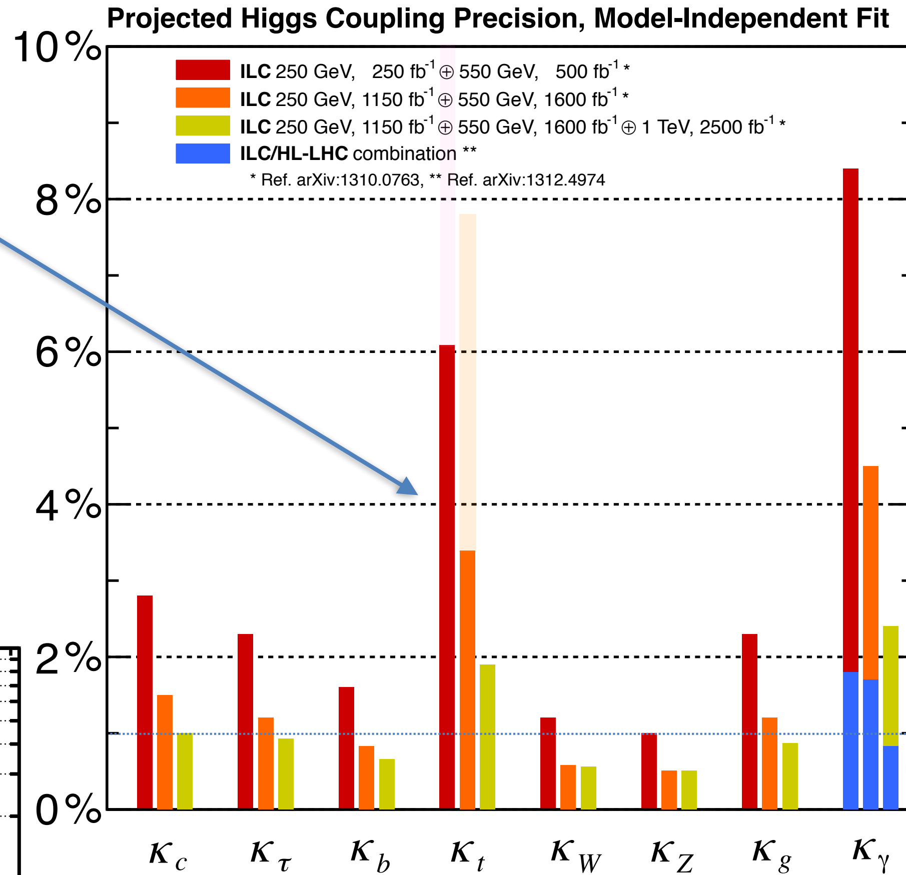


Improved Higgs coupling precision



Top Yukawa improves by going to 550 GeV

Near threshold → a factor of 4 enhancement of σ_{tth} by going from 500GeV to 550 GeV

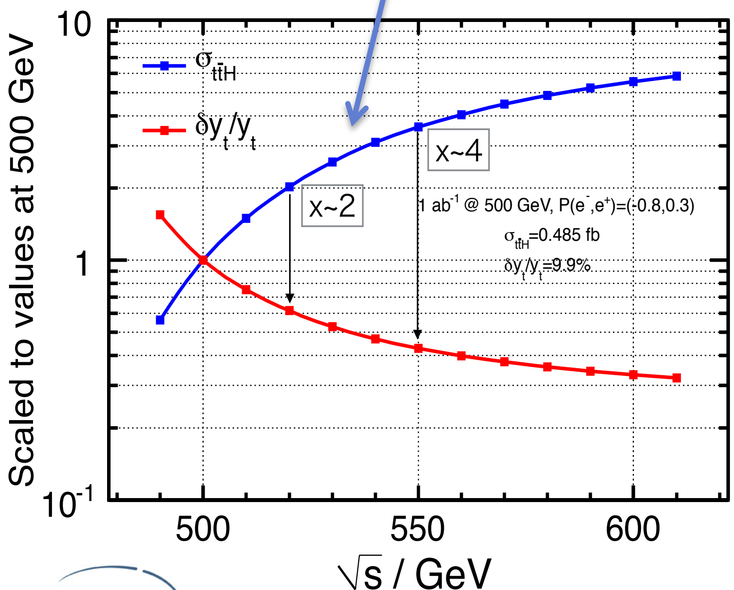


LHC can precisely measure

BR(h→γγ) / BR(h→ZZ*) = $(\kappa_\gamma / \kappa_Z)^2$

ILC can precisely measure κ_Z

Better hγγ with LHC/ILC synergy



- Use ATLAS projected result of the HL-LHC Higgs analysis

$$\Delta\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^*)} = 2.9\%$$

along with the ILC precision measurement of the *HZZ* coupling to obtain a very precise determination of the $H\gamma\gamma$ coupling.

- Improve precision determinations of Higgs couplings by imposing the constraint that

$$\sum_i \mathrm{BR}_i = 1$$

Model Independent global coupling fit

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

(Baseline ILC program)

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%	1%
HWW	2.3%	0.6%	0.6%	1.1%
Hbb	2.5%	0.8%	0.7%	1.3%
Hcc	3.2%	1.5%	1%	1.8%
Hgg	3%	1.2%	0.93%	1.6%
Hττ	2.7%	1.2%	0.9%	1.6%
Hγγ	8.2%	4.5%	2.4%	4%
Hμμ	42%	42%	10%	16%
Γ	5.4%	2.5%	2.3%	4.5%
Htt	-	7.8%	1.9%	3.1%
HHH	-	46%(*)	13%(*)	21%(*)

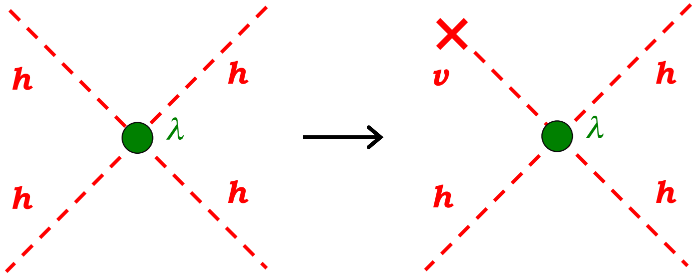
) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

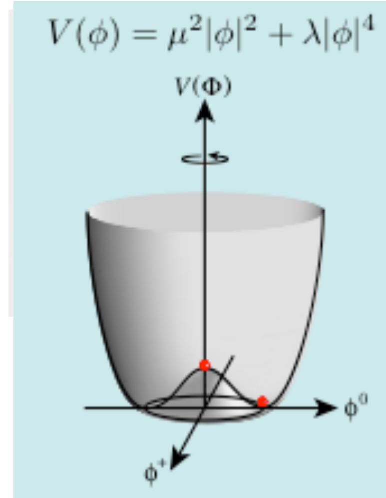
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

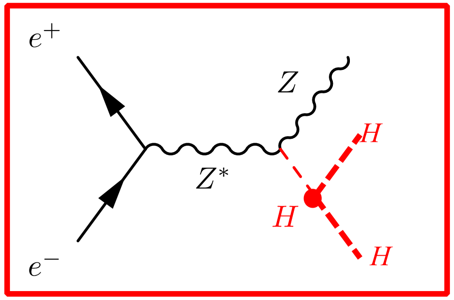
LPNHE PARIS

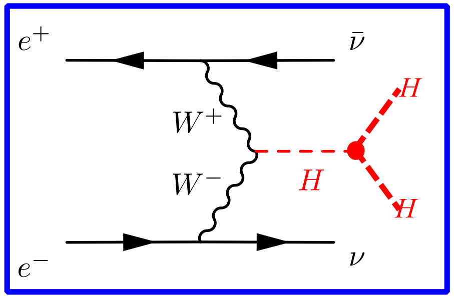
Higgs self coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation





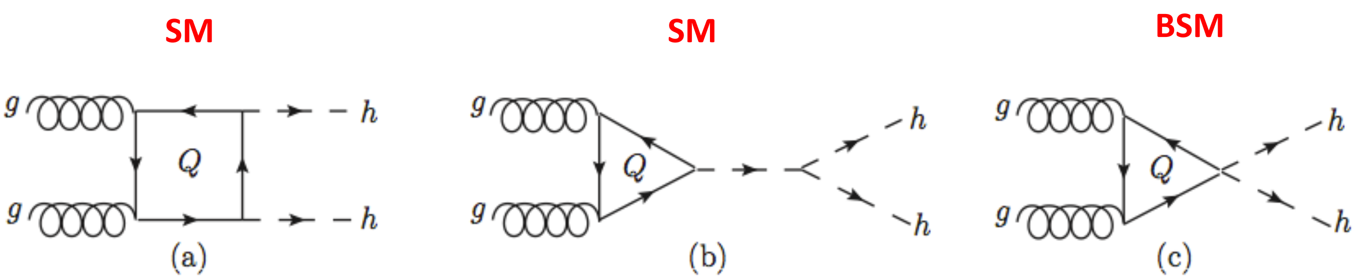




Anomalous couplings could show up everywhere!

- Self-coupling measurements offers the most direct way to test the paradigm of spontaneous symmetry breaking.

  One of the most important Higgs measurements at a future machine!

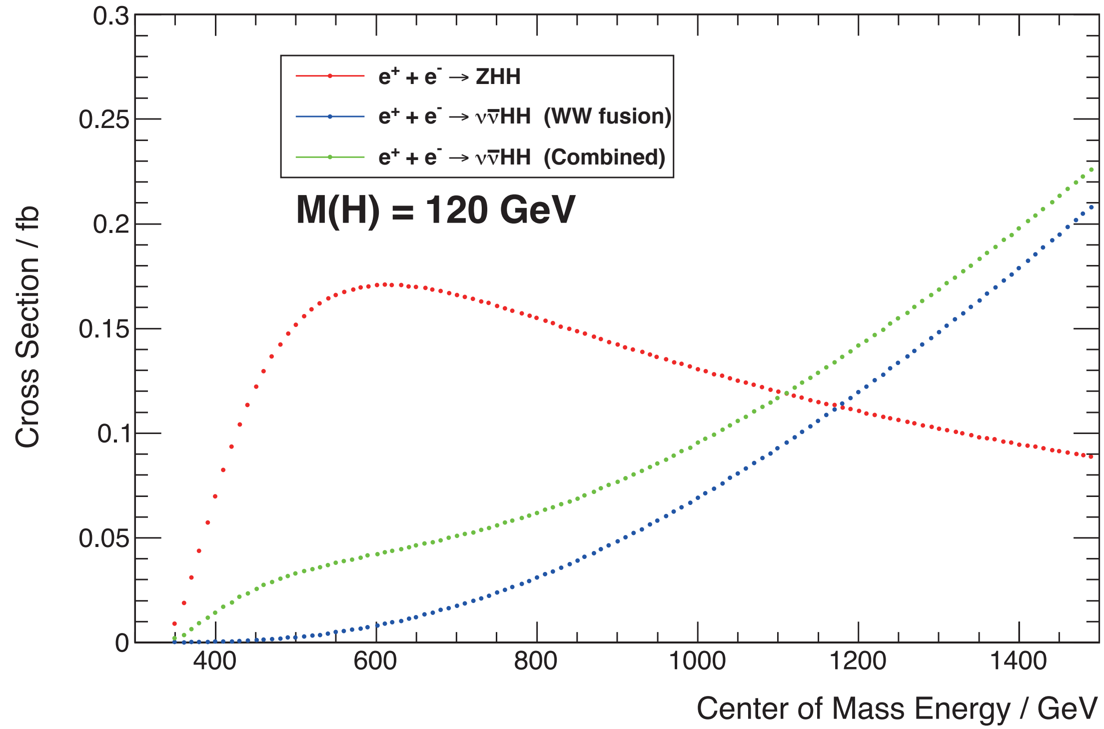


Higgs self coupling at ILC

LC:
two choices:

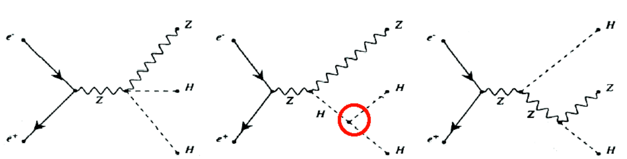
$e^+e^- \rightarrow ZHH$
(maximum of σ around $\sqrt{s} \approx 600$ GeV)
→ ILC500 (~100 events in 500 fb^{-1})

$e^+e^- \rightarrow HH\nu\nu$
(σ rising with $\sqrt{s}$)
→ ILC1000 (~140 events in1 ab^{-1})
→ CLIC1400 (~250 events in 1.5 ab^{-1})
→ CLIC3000 (~1250 events in 2 ab^{-1})



challenges:
- huge number of different final states (huge effort needed)
- „dilution“ due to interference with non-HHH diagrams (not sensitive to λ_{HHH})

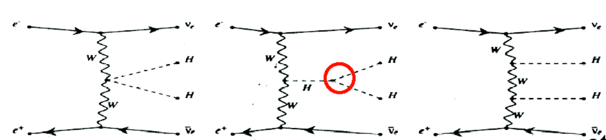
$\star\ e^+e^- \rightarrow ZHH$



etc..

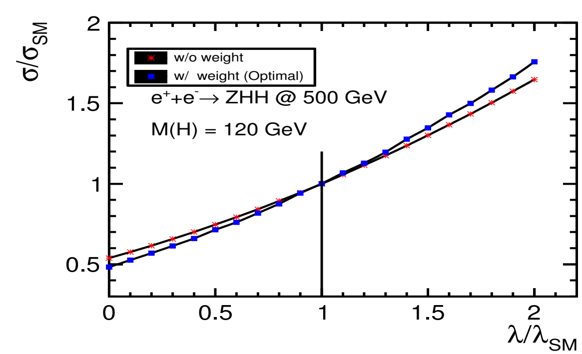
$d\lambda/\lambda = 1.8\ d\sigma/\sigma$
→1.66 with weighting

$\star\ e^+e^- \rightarrow (W^+W^-)\nu\bar{\nu} \rightarrow HH\nu\bar{\nu}$



etc.

$d\lambda/\lambda = 0.85\ d\sigma/\sigma$
→0.76 with weighting



HHH prospects at 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
νvhh (WW-F)	272	35.7
νvhh (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: $> 5\sigma$

(with HH→bbbb)

→ extrapolation for M_H = 125 GeV

+

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

Masakazu Kurata

HIGGS SELF COUPLING ANALYSIS USING THE EVENTS CONTAINING H→WW* DECAY

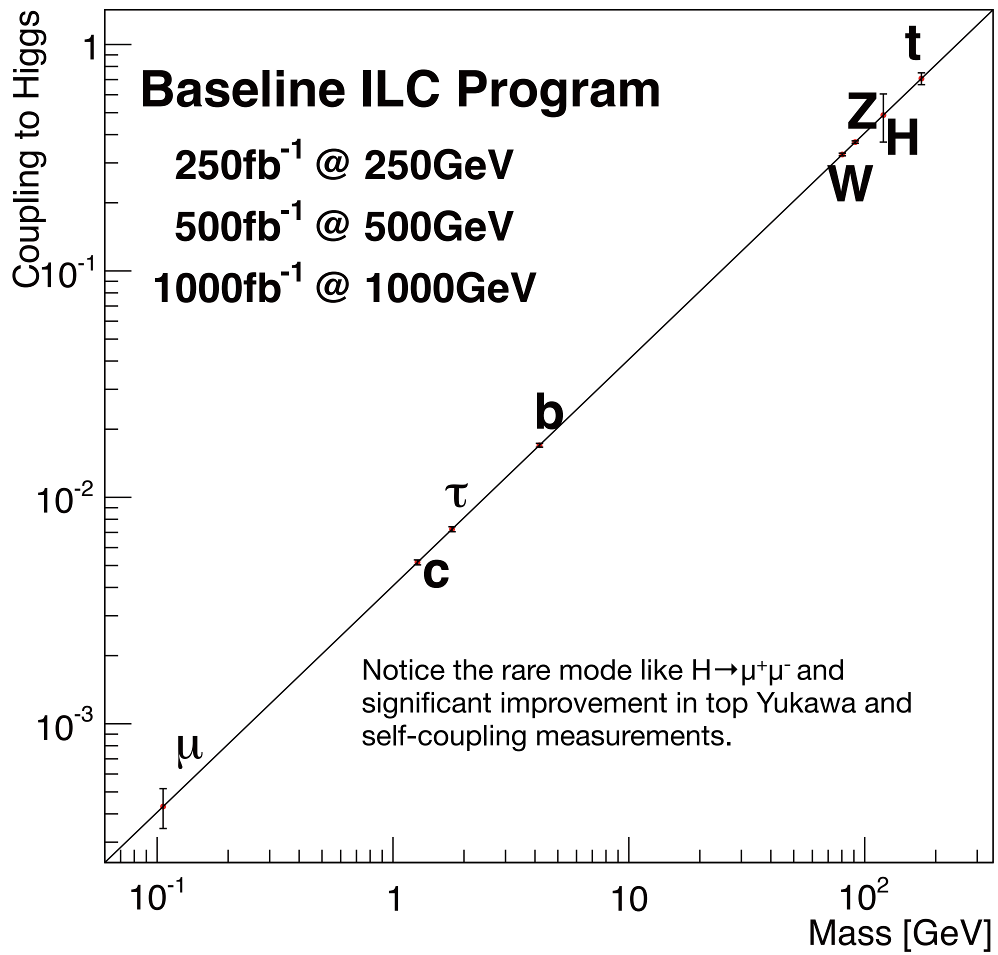
- Effect of track energy correction using particle ID is small, but going to good direction
- Kinematic fitting will be a good tool for mass resolution improvement

arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	(−0.8, 0.3)	(−0.8, 0.3)	(−0.8, 0.3/0.2)	(−0.8, 0.3/0.2)
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

Ongoing analysis improvements ***towards O(10)% measurement***

Mass *vs* Higgs coupling relation

After Baseline LC Program

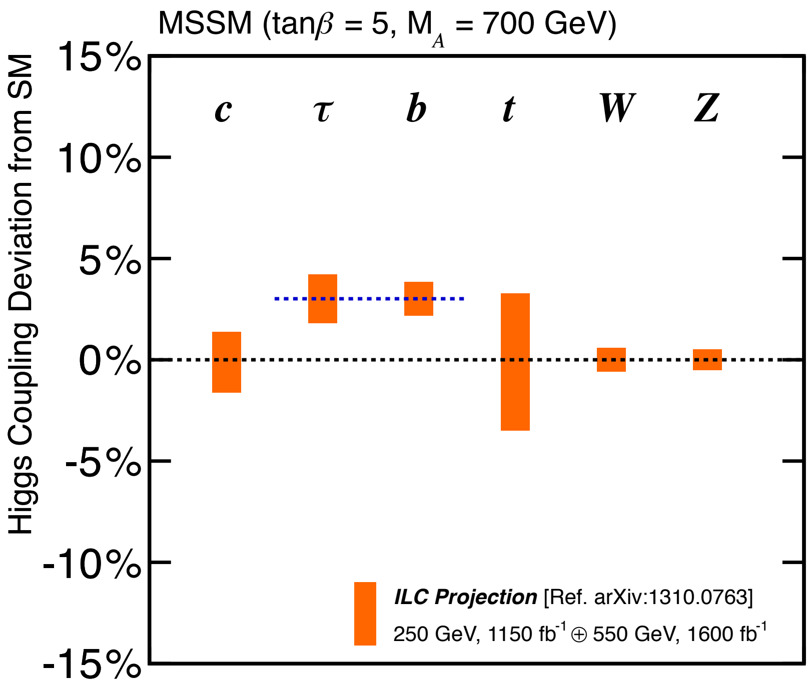


→ would like to see this within my lifetime ☺ … not on the SM straight line though !

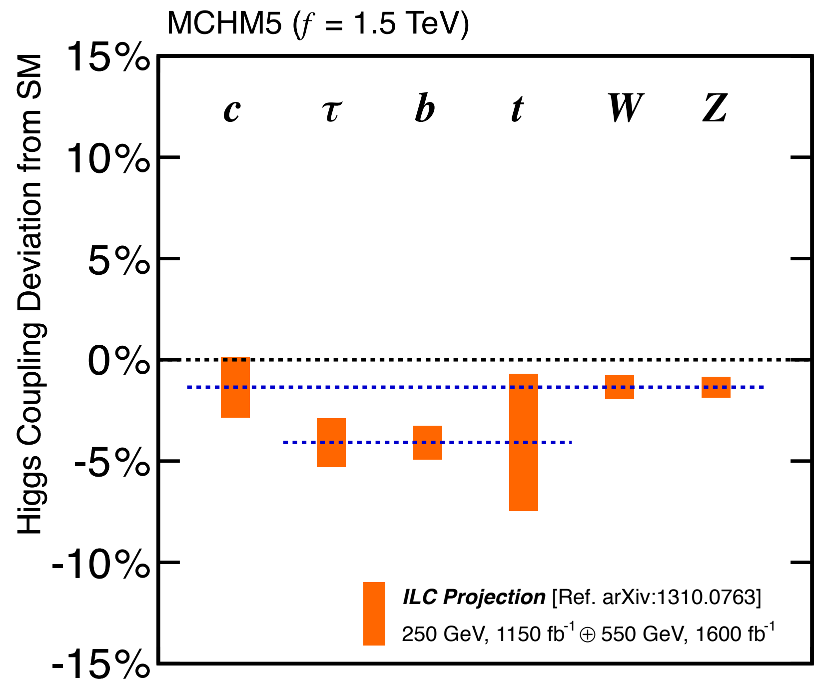
Higgs coupling deviation scenarios

Elementary *vs* *Composite*

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



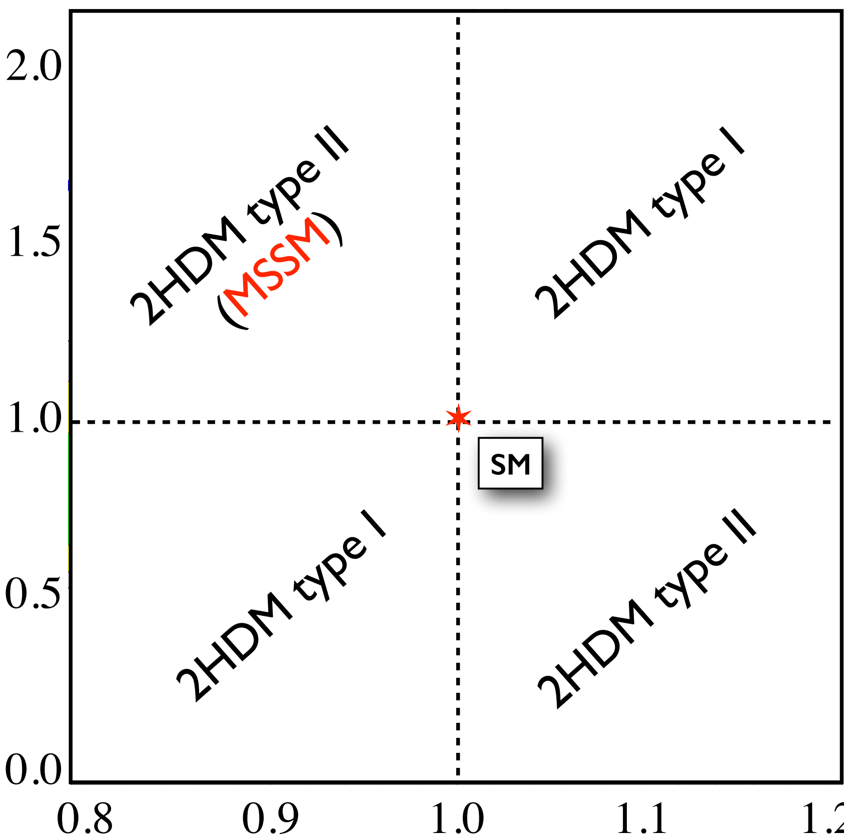
ILC 250+550 LumiUP

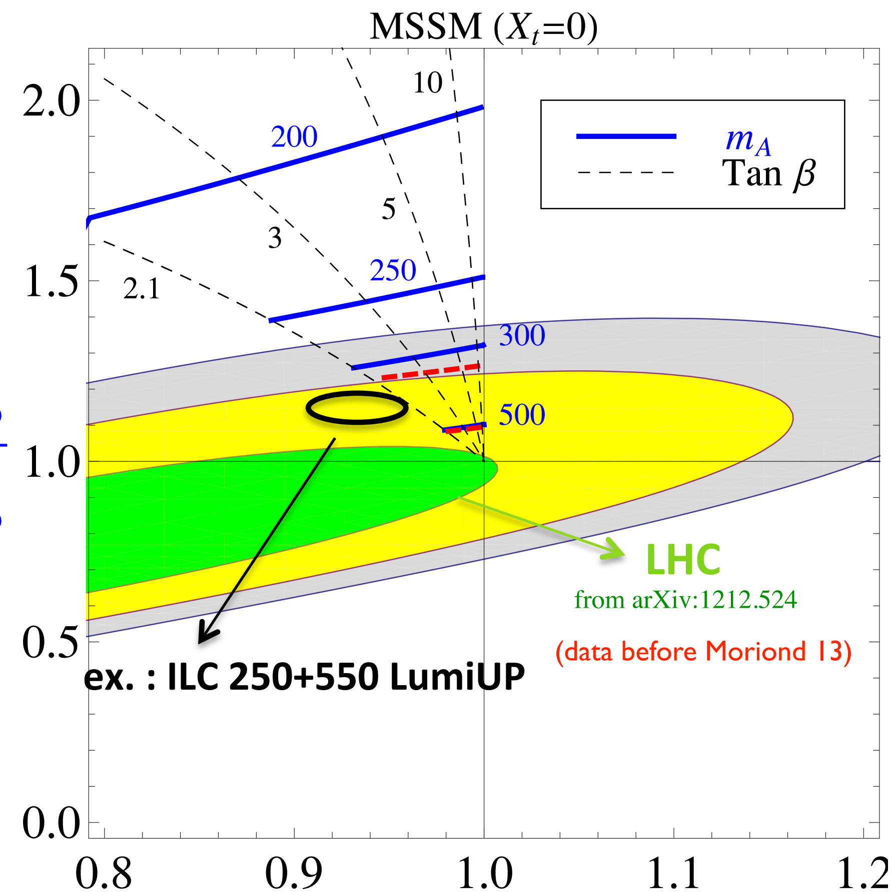
Multiplet structure – 2HDM

Table 1.8. Four possible $\mathbb{Z}_2$ charge assignments that forbid tree-level Higgs-mediated FCNC effects in the 2HDM. [82].

	Φ_1	Φ_2	U_R	D_R	E_R	U_L, D_L, N_L, E_L
Type I	+	−	−	−	−	+
Type II (MSSM like)	+	−	−	+	+	+
Type X (lepton specific)	+	−	−	−	+	+
Type Y (flipped)	+	−	−	+	−	+

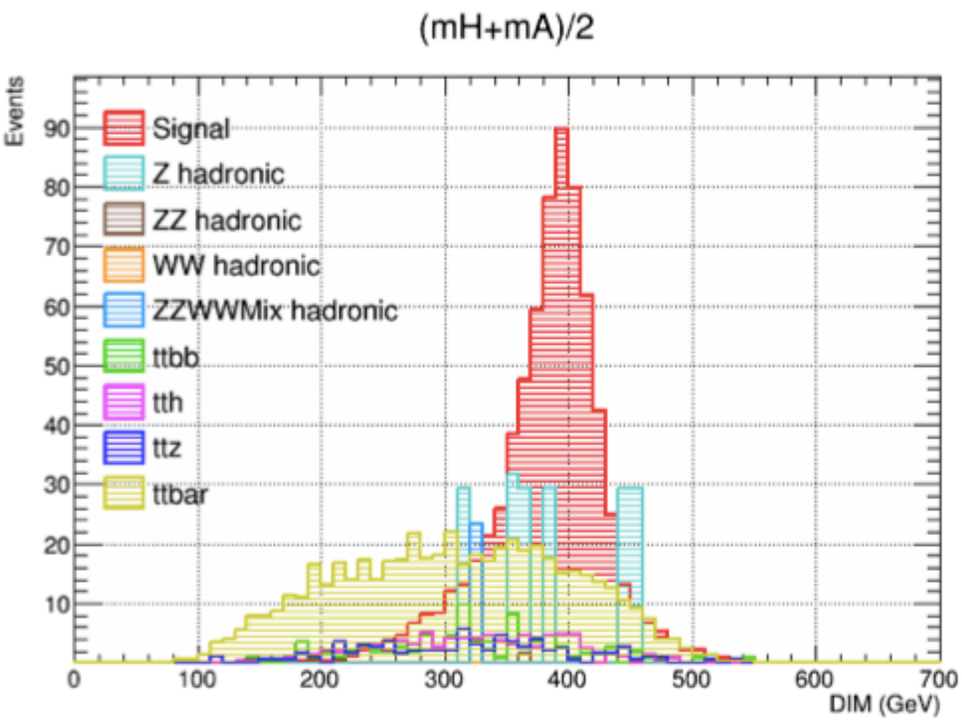
g_{hbb}/g^{SM}_{hbb} *vs* g_{htt}/g^{SM}_{htt} plane
appropriate to tackle 2HDM scenario





$e^+e^- \rightarrow HA \rightarrow bbbb$ @ 1 TeV ILC

The ILC with $\sqrt{s} = 1$ TeV can directly study extra Higgs bosons with masses less than 500 GeV in relatively low tanβ regions, which can't be detected easily in LHC.



same mass for both particles, 400 GeV
$tan\beta = 10$
x-section: $\sqrt{s} = 1$ TeV 2.38 fb
prominent decay into bb(bar)
Branching fraction for $H \rightarrow bb$ 77%
$A \rightarrow bb$ 65%

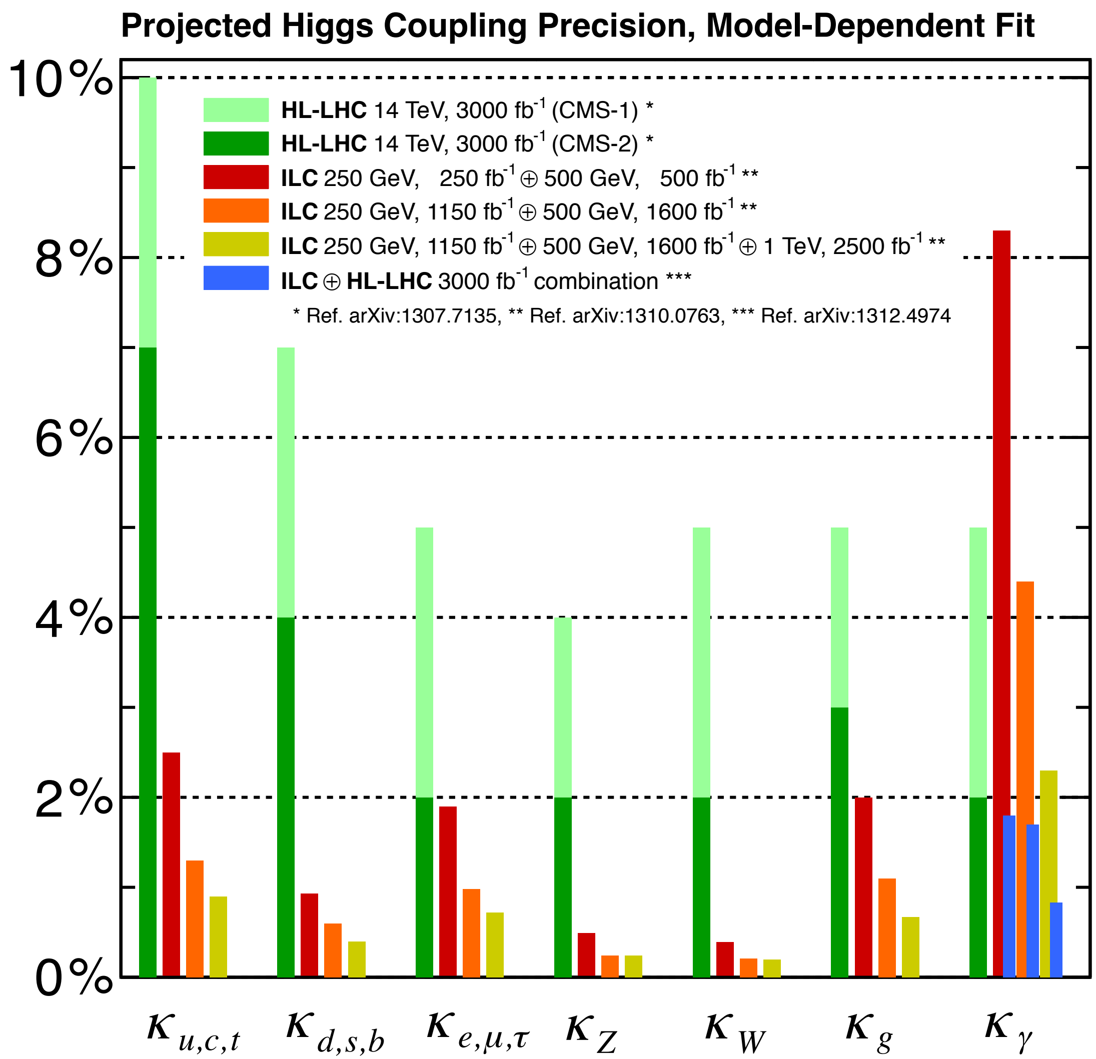
Clear separation of signal

Will set limits as function of mass / tanβ

Abhinav Dubey/ Jan Strube

Comparison with HL-LHC

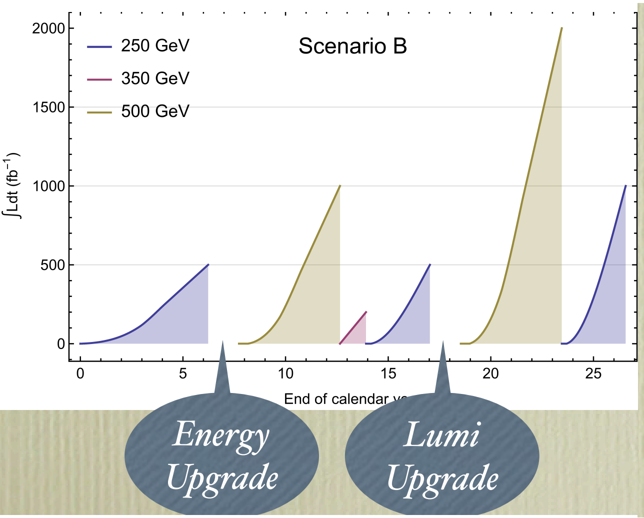
- Compared to the HL-LHC, ILC will provide factors of 2 - 10 improvement on couplings in model-dependent studies
- High degree of synergies for H->γγ, where LHC will provide the highest precision



Summary and comments

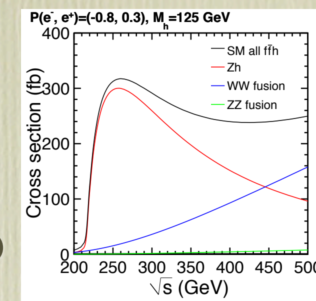
- ILC has already a very exciting physics case and the Higgs sector is one of the main players.
- No need for day by day comparison with circular, better go ahead steady and push for improvements.
- The BSM physics reach, in a complete MI Higgs sector study, will increase with ongoing work toward precision improvements, especially on :
  - full use of **hadronic Z decays** for recoil mass (and hence x-sec) to improve absolute coupling extraction.
  - **Higgs self coupling** is crucial but very difficult. Effort needed to go beyond current 10% level determination at 1 TeV.
  - **detector performance and design** optimization on hadronic jets (reconstruction, PF algos, tagging, Energy and m_{jj} resolution …) in **multi-jet events** (qqH, ttH, W/ZHH, …)
  - switch to MI **EFT** approach on Higgs coupling analysis
- And very important : *optimization of machine parameters E_{CM}, Luminosity and …* **project timeline →**

ILC staging scenarios : 250 … 500 GeV

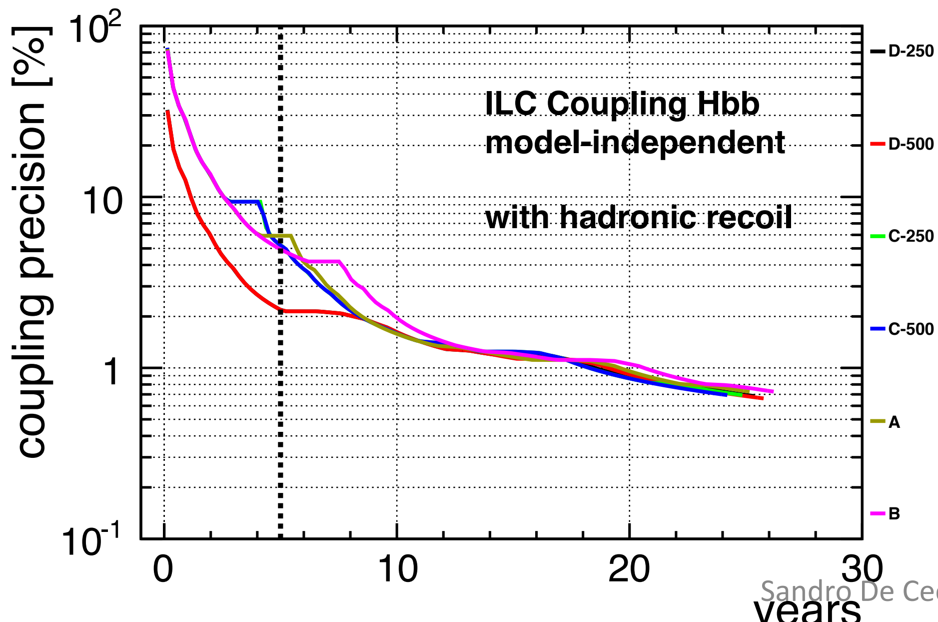


Start at 350 GeV?

- If staging is necessary, starting at 350 GeV presents scientific advantages over 250 GeV. Therefore, we discuss this possibility.
- At 350 GeV, Higgs production comes largely from the Higgsstrahlung process, but the important WW-fusion process is rising, increasing three-fold from 250 GeV to 350 GeV.
- This increase enables precise measurements of both the Z-Higgs coupling (g_{HZZ}) and the W-Higgs coupling (g_{HWW}) at 350 GeV.



Accuracies in the first 5 years :



	HL-LHC	ILC Scenario B	ILC Scenario D-500
$\sqrt{s}$ (GeV)	1400	250	350
L (fb^{-1})	3000	360	470
$\gamma\gamma$	2-5 %	14.8 %	10.9 %
gg	3-5 %	4.8 %	2.9 %
WW	2-5 %	3.9 %	0.63 %
ZZ	2-4 %	0.63 %	0.49 %
$t\bar{t}$ ($c\bar{c}$)	7-10 %	5.3 %	3.7 %
$b\bar{b}$	4-7 %	3.8 %	1.3 %
$\tau^+\tau^-$	2-5 %	4.3 %	2.4 %
$\Gamma_T(h)$	5-8 %	7.3 %	2.1 %

BACKUP

Higgs x-sections and BR's

Summary of expected accuracies for the three cross sections and eight branching ratios obtained from an eleven parameter global fit of all available data.

	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
process	$\Delta\sigma/\sigma$			
$e^+e^- \to ZH$	2.6 %	2.0 %	2.0 %	1.0 %
$e^+e^- \to \nu\bar{\nu}H$	11 %	2.3 %	2.2 %	1.1 %
$e^+e^- \to t\bar{t}H$	-	28 %	6.3 %	3.8 %
mode	$\Delta \mathrm{Br}/\mathrm{Br}$			
$H \to ZZ$	19 %	7.5 %	4.2 %	2.4 %
$H \to WW$	6.9 %	3.1 %	2.5 %	1.3 %
$H \to b\bar{b}$	2.9 %	2.2 %	2.2 %	1.1 %
$H \to c\bar{c}$	8.7 %	5.1 %	3.4 %	1.9 %
$H \to gg$	7.5 %	4.0 %	2.9 %	1.6 %
$H \to \tau^+\tau^-$	4.9 %	3.7 %	3.0 %	1.6 %
$H \to \gamma\gamma$	34 %	17 %	7.9 %	4.7 %
$H \to \mu^+\mu^-$	100 %	100 %	31 %	20 %

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Higgs Γ_T and couplings

Summary of expected accuracies $\Delta g_i/g_i$ and Γ_T for model independent determinations of the Higgs boson couplings

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
Γ_T	12 %	5.0 %	4.6 %	2.5 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

The theory errors are $\Delta F_i/F_i$=0.5%. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits.

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Higgs recoil with ZH→qqH - categorization

Categories (example 0lep,0tau)

category	0lep,0tau	before	after	difference		w/o categories
H->all	81.6%	448,212	185,999 (41.5%)	----		-----
H->bb	96.8%	300,853	119,211 (39.6%)	-4.5%		-5.1%
H->WW(l)	8.3%	1,048	429 (40.9%)	+1.4%		-73.4%
H->WW(sl)	29.7%	15,921	5,618 (35.3%)	-14.9%		+10.4%
H->WW(h)	91.9%	51,524	23,773 (46.1%)	+11.1%		+36.4%
H->gg	96.6%	46,773	23,636 (50.5%)	+21.7%		+31.9%
H->$\tau\tau$	12.2%	4,368	1,362 (31.2%)	-24.8%		-52.6%
H->ZZ	78.2%	11,811	4,766 (40.4%)	-2.7%		+8.1%
H->cc	96.3%	13,895	6,284 (45.2%)	+8.9%		+8.7%
H->$\gamma\gamma$	91.3%	1,873	793 (42.3%)	-1.9%		+2.8%

Linear Collider WorkShop 2014 @ Belgrade : Tatsuhiko Tomita : 09/10/2014 21

Model Independent global coupling fit

Baseline ILC program

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

(M_H = 125 GeV)

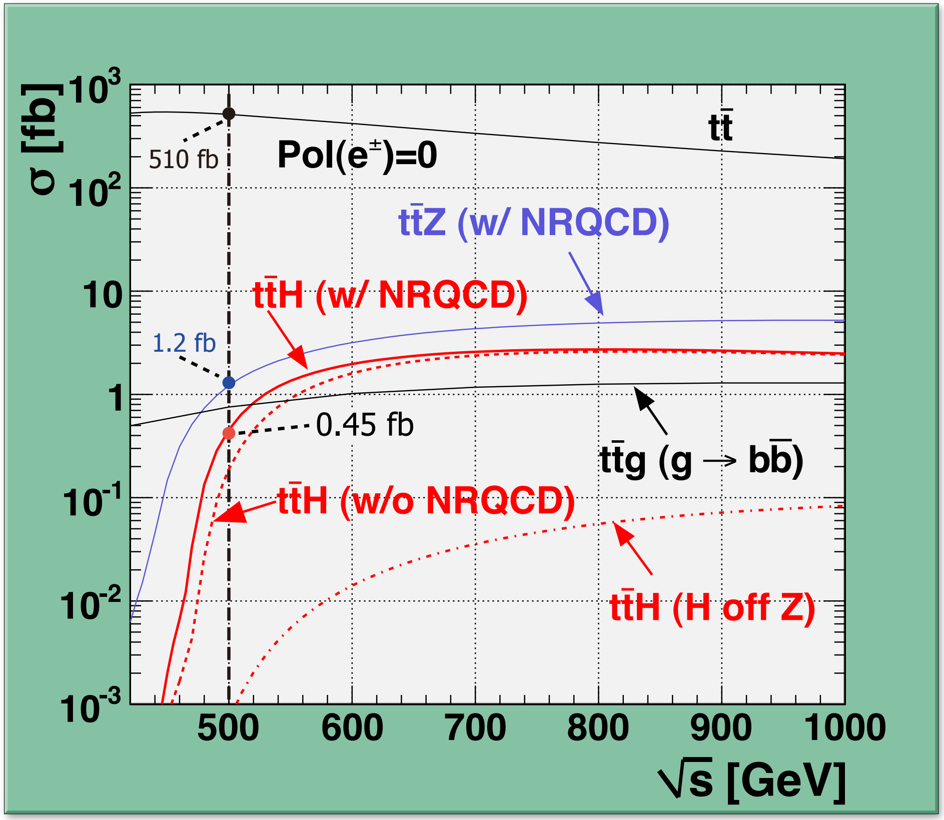
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV

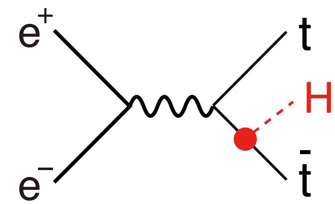
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

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%
$H\tau\tau$	5.7%	2.3%	1.6%
$H\gamma\gamma$	18%	8.4%	4%
$H\mu\mu$	91%	91%	16%
Γ	12%	4.9%	4.5%
Htt	-	14%	3.1%
HHH	-	83%(*)	21%(*)

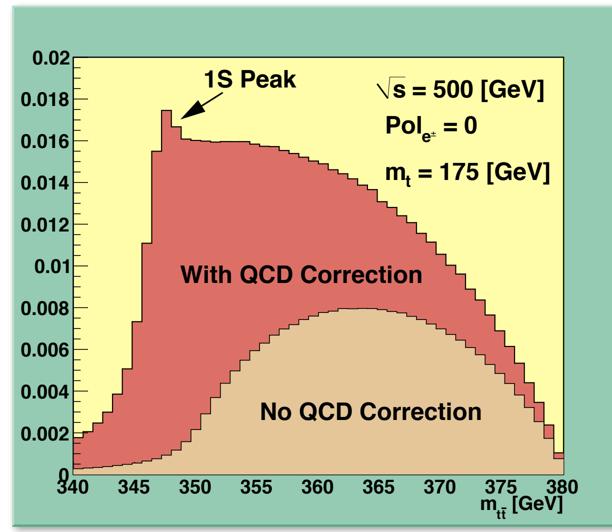
) With H->WW (preliminary), if we include expected improvements in jet clustering it would become 17%!

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

500 GeV is very close to the threshold. Moving up a little bit helps significantly!

Further improvements (Peskin)

- Improve precision determinations of Higgs couplings by imposing the constraint that

$$\sum_i \mathrm{BR}_i = 1$$

The reason for this is that I used a 9-parameter fit constrained to the relation $\sum_i BR_i = 1$.

This constraint is very powerful because determinations of Higgs couplings require constraining the Higgs total width.

$$\sigma(A\overline{A} \to h) \cdot BR(h \to B\overline{B}) \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_T}$$

The constraint has a large effect here:

error in Γ_T	unconstrained	$\sum BR = 1$
ILC 500	5.0%	1.6%
ILC 500 up	2.8%	0.75%
ILC 1000	4.6%	1.2%

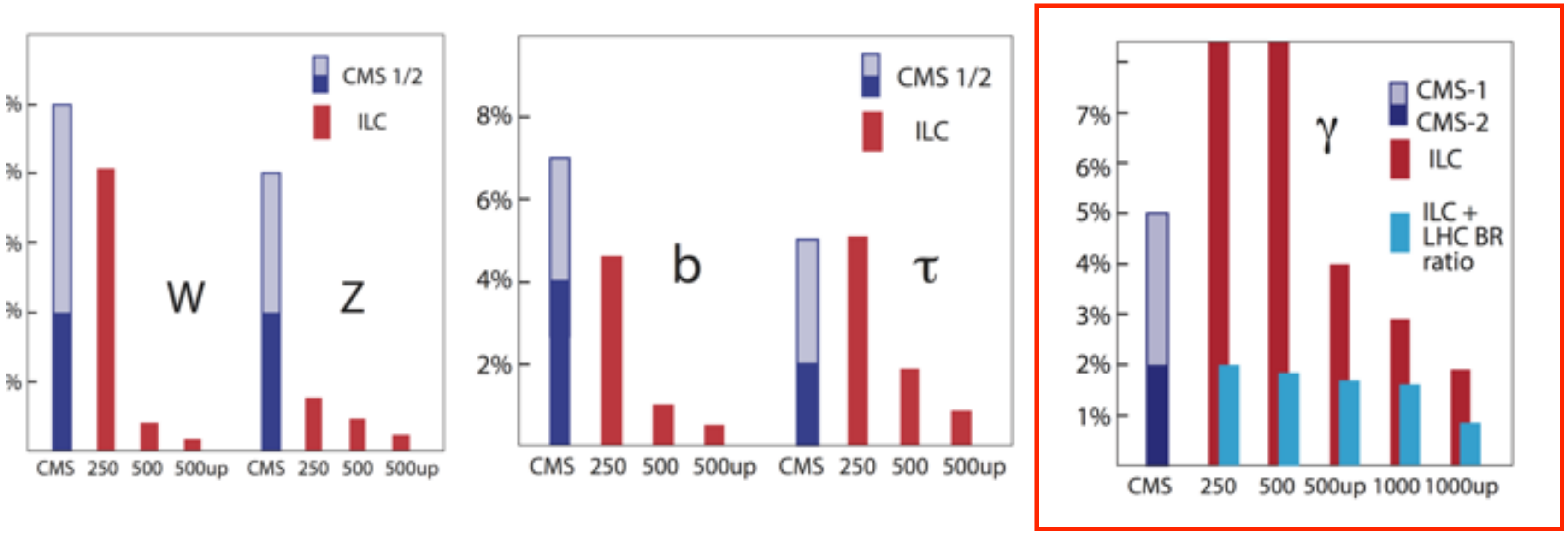
Improved expectations

M. Peskin, LCWS 2013
arXiv: 1312.4974

Σ BR = 1

BR(BSM:vis.), BR(inv.) in stead of Γ_h

ILC expectation assumes that BR(BSM:vis.) can be measured as precisely as BR(inv.).



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

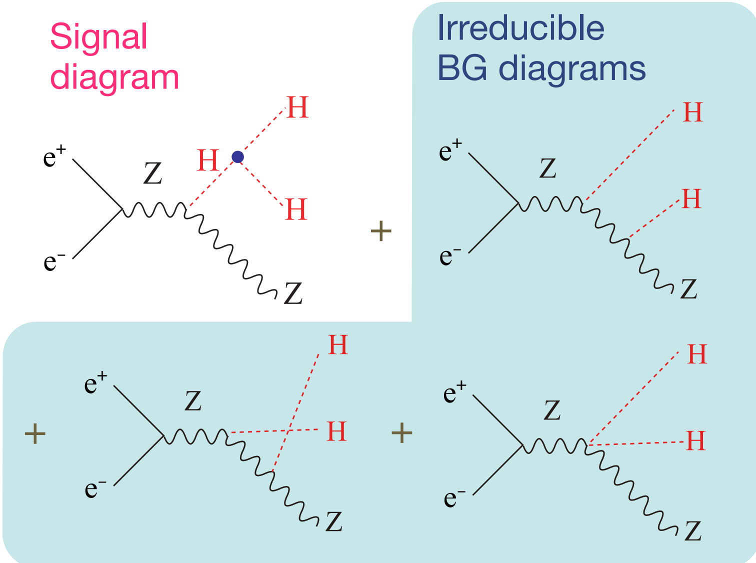
For rare decays such as H → γγ, there is powerful synergy of LHC and LC!

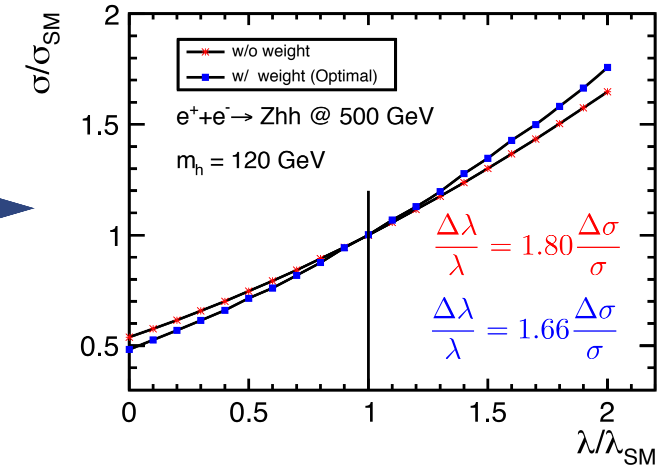
Higgs self coupling BG dilution

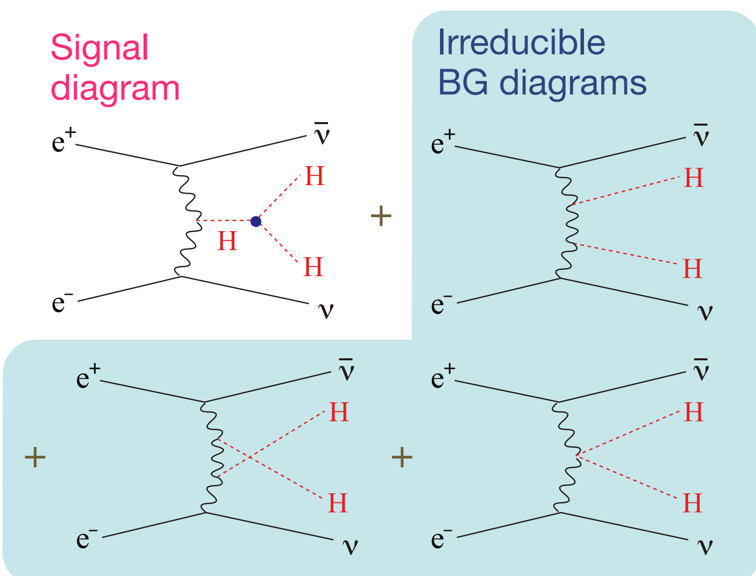
$$\sigma = \lambda^2 S + \lambda I + B$$

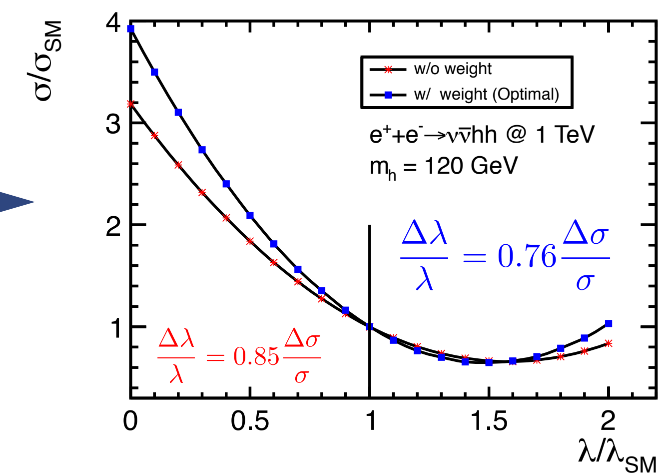
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams



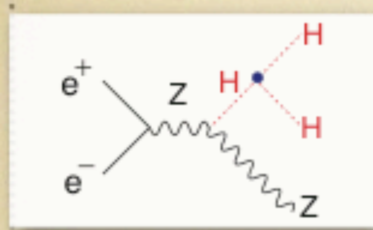






Junping Tian LC-REP-2013-003

Higgs self-coupling @ 500 GeV



$$e^+ + e^- \rightarrow ZHH$$

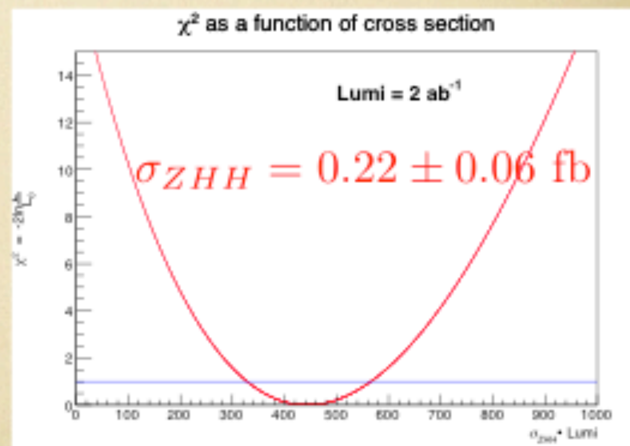
$M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

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

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6	1.5σ	1.2σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

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

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



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

Extrapolation to M(H)=125GeV

HHH Prospects

Preliminary full simulation results at 500GeV confirmed the validity of extrapolation. (C.Duerig @ AWLC14)

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		LumiUP
250 GeV: 250 fb^{-1}	→	250 GeV: 1150 fb^{-1}
500 GeV: 500 fb^{-1}	→	500 GeV: 1600 fb^{-1}
1 TeV: 1000 fb^{-1}	→	1 TeV: 2500 fb^{-1}

ILD DBD Study
(Junping Tian, Masakazu Kurata)

Deviations in extended Higgs sectors

Survey according to Haber's decoupling theorem with $M = 1$ TeV:

Model	Δg_{HVV}	$\Delta g_{Hb\bar{b}}$	$\Delta g_{H\gamma\gamma}$
Singlet Mixing	$\approx 6\%$	$\approx 6\%$	$\approx 6\%$
2HDM	$\approx 1\%$	$\approx 10\%$	$\approx 1\%$
Decoupled MSSM	$\approx -0.0013\%$	$\approx 1.6\%$	$< 1.5\%$
Composite	$\approx -3\%$	$\approx -(3-9)\%$	$\approx -9\%$
Top Partner	$\approx -2\%$	$\approx -2\%$	$\approx 1\%$

[ILC TDR, Michael Peskin]

(see e.g. plenary talks by Keisuke Fujii and Philipp Roloff)

$\Longrightarrow$ Need for high precision to discover differences from SM Higgs!
$\Longrightarrow$ High order contributions in theoretical calculations required at a LC, although by far smaller than at LHC!

Some predictions are very sensitive to numerical input values:
Variation of m_H by ± 200 MeV $\leftrightarrow$ BR$(H \to ZZ^{(*)}/WW^{(*)}) \sim \pm 2.5\%$!

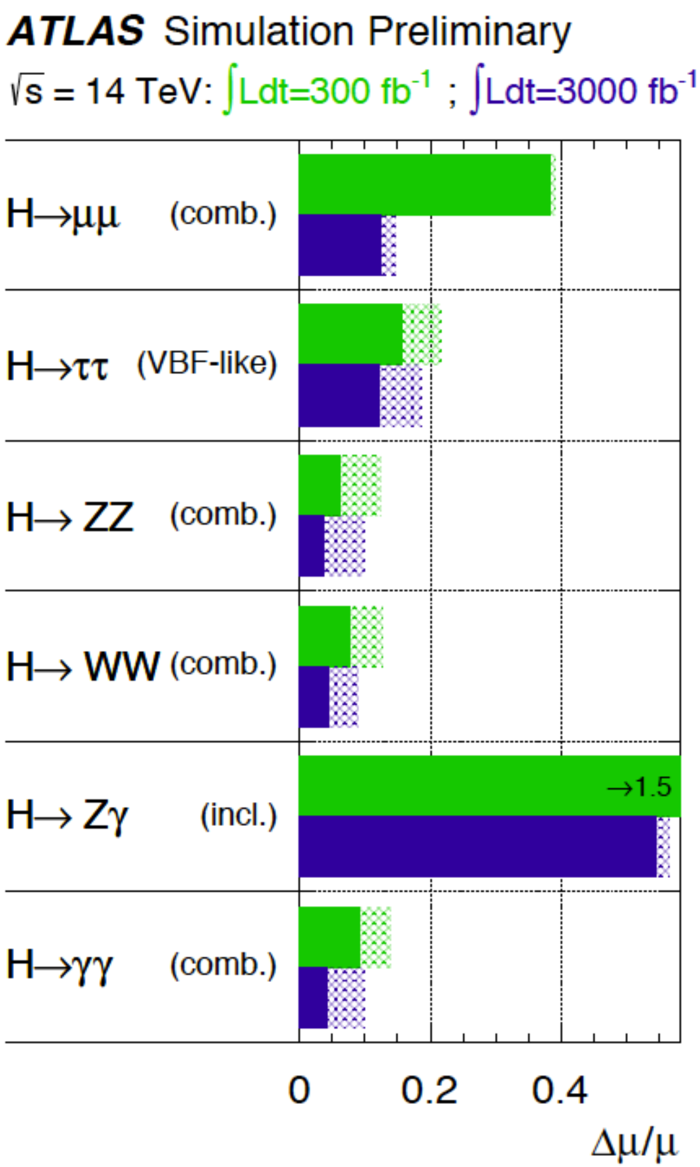
Future measurements of Higgs couplings

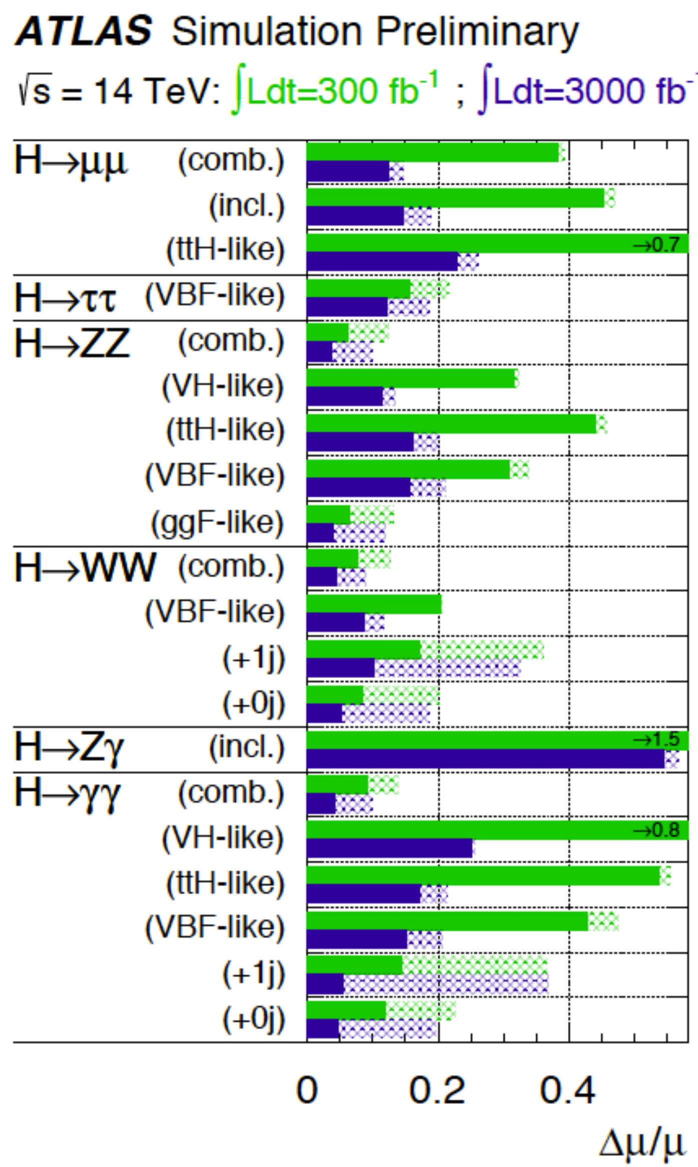
Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%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

Snowmass Report 1310.8361

Coupling constants can be typically Measured with better than 1 % at ILC

HL-LHC measurements of σxBR





CLIC sensitivity (snowmass report)

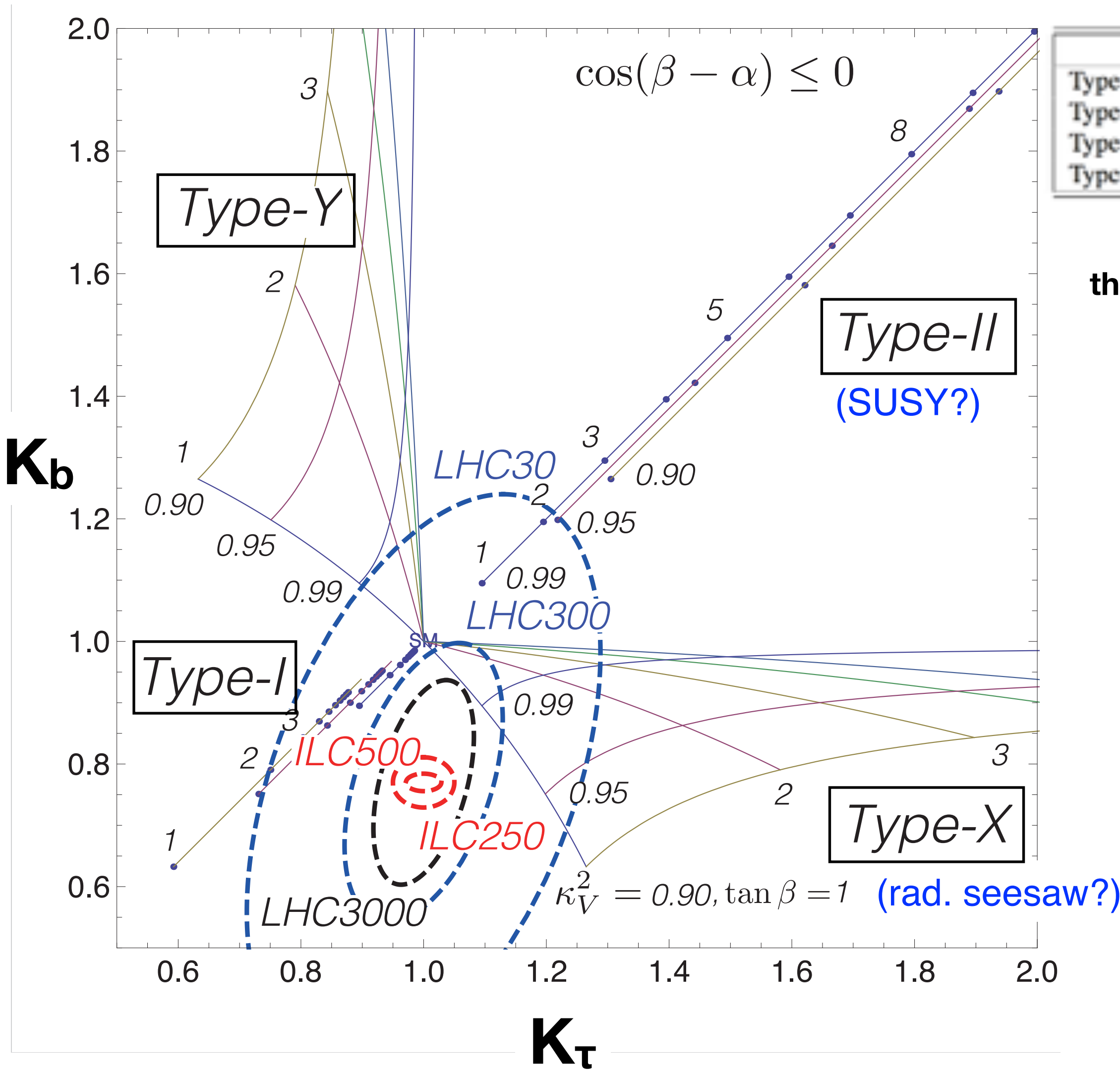
Channel	Measurement	Observable	Statistical precision		
			350 GeV $500\ \mathrm{fb}^{-1}$	1.4 TeV $1.5\ \mathrm{ab}^{-1}$	3.0 TeV $2.0\ \mathrm{ab}^{-1}$
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \text{invisible})$	Γ_inv	tbd	–	–
ZH	$\mathrm{H} \to \mathrm{b\bar{b}}$ mass distribution	m_H	tbd	–	–
$\mathrm{H\nu_e\bar{\nu}_e}$	$\mathrm{H} \to \mathrm{b\bar{b}}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{Z} \to \ell^+\ell^-)$	g^2_HZZ	4.2%	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_\mathrm{HZZ}g^2_\mathrm{Hbb}/\Gamma_\mathrm{H}$	1%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_\mathrm{HZZ}g^2_\mathrm{Hcc}/\Gamma_\mathrm{H}$	5%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{gg})$		6%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \tau^+\tau^-)$	$g^2_\mathrm{HZZ}g^2_\mathrm{H\tau\tau}/\Gamma_\mathrm{H}$	5.7%	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{WW}^*)$	$g^2_\mathrm{HZZ}g^2_\mathrm{HWW}/\Gamma_\mathrm{H}$	2%†	–	–
ZH	$\sigma(\mathrm{HZ}) \times BR(\mathrm{H} \to \mathrm{ZZ}^*)$	$g^2_\mathrm{HZZ}g^2_\mathrm{HZZ}/\Gamma_\mathrm{H}$	tbd	–	–
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_\mathrm{HWW}g^2_\mathrm{Hbb}/\Gamma_\mathrm{H}$	3%†	0.3%	0.2%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{c\bar{c}})$	$g^2_\mathrm{HWW}g^2_\mathrm{Hcc}/\Gamma_\mathrm{H}$	–	2.9%	2.7%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{gg})$		–	1.8%	1.8%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \tau^+\tau^-)$	$g^2_\mathrm{HWW}g^2_\mathrm{H\tau\tau}/\Gamma_\mathrm{H}$	–	3.7%	tbd
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mu^+\mu^-)$	$g^2_\mathrm{HWW}g^2_\mathrm{H\mu\mu}/\Gamma_\mathrm{H}$	–	29%*	16%
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \gamma\gamma)$		–	15%*	tbd
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{Z}\gamma)$		–	tbd	tbd
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{WW}^*)$	$g^4_\mathrm{HWW}/\Gamma_\mathrm{H}$	tbd	1.1%*	0.8%*
$\mathrm{H\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{H\nu_e\bar{\nu}_e}) \times BR(\mathrm{H} \to \mathrm{ZZ}^*)$	$g^2_\mathrm{HWW}g^2_\mathrm{HZZ}/\Gamma_\mathrm{H}$	–	3%†	2%†
$\mathrm{He^+e^-}$	$\sigma(\mathrm{He^+e^-}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_\mathrm{HZZ}g^2_\mathrm{Hbb}/\Gamma_\mathrm{H}$	–	1%†	0.7%†
$\mathrm{t\bar{t}H}$	$\sigma(\mathrm{t\bar{t}H}) \times BR(\mathrm{H} \to \mathrm{b\bar{b}})$	$g^2_\mathrm{Htt}g^2_\mathrm{Hbb}/\Gamma_\mathrm{H}$	–	8%	tbd
$\mathrm{HH\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{HH\nu_e\bar{\nu}_e})$	g_HHWW	–	7%*	3%*
$\mathrm{HH\nu_e\bar{\nu}_e}$	$\sigma(\mathrm{HH\nu_e\bar{\nu}_e})$	λ	–	28%	16%
$\mathrm{HH\nu_e\bar{\nu}_e}$	with −80% e^- polarization	λ	–	21%	12%

TLEP estimates

	TLEP 240 (10 ab^{-1})	ILC 250 (0.25 ab^{-1})
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**	100%

Table 4: Statistical precision for Higgs measurements obtained from the proposed TLEP programme at $\sqrt{s} = 240$ GeV only (shown in Table 3). For illustration, the baseline ILC figures at $\sqrt{s} = 250$ GeV, taken from Ref. [6], are also given. The order-of-magnitude smaller accuracy expected at TLEP in the $H \to \gamma\gamma$ channel is the threefold consequence of the larger luminosity, the superior resolution of the CMS electromagnetic calorimeter, and the absence of background from Beamstrahlung photons.

Multiplet structure – 2HDM



	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)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

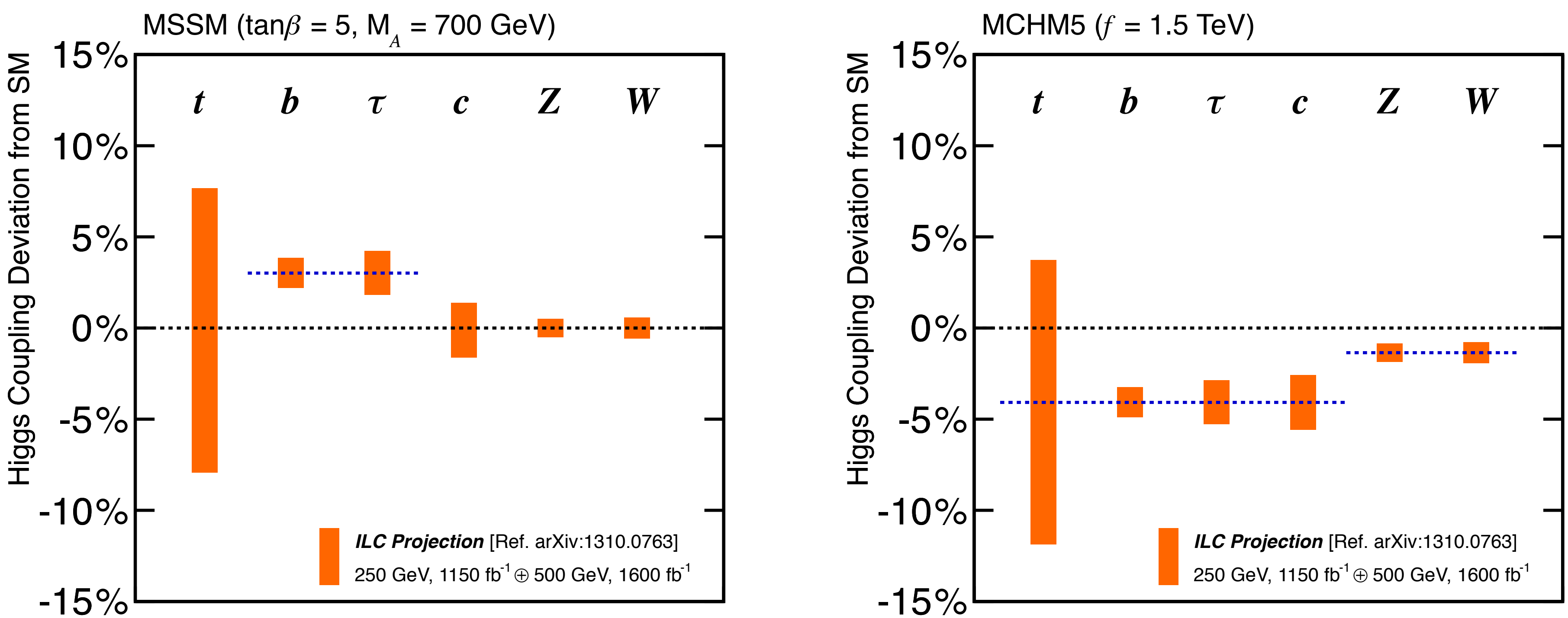
$K_V^2 = \sin(\beta-\alpha)^2 = 1 \Leftrightarrow$ SM

*Given a deviation of the Higgs to Z coupling: **$\Delta K_v^2 = 1-K_v^2 = 0.01$** we will be able to **discriminate the 4 models!***

TDR ILC

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Higgs coupling deviation scenarios



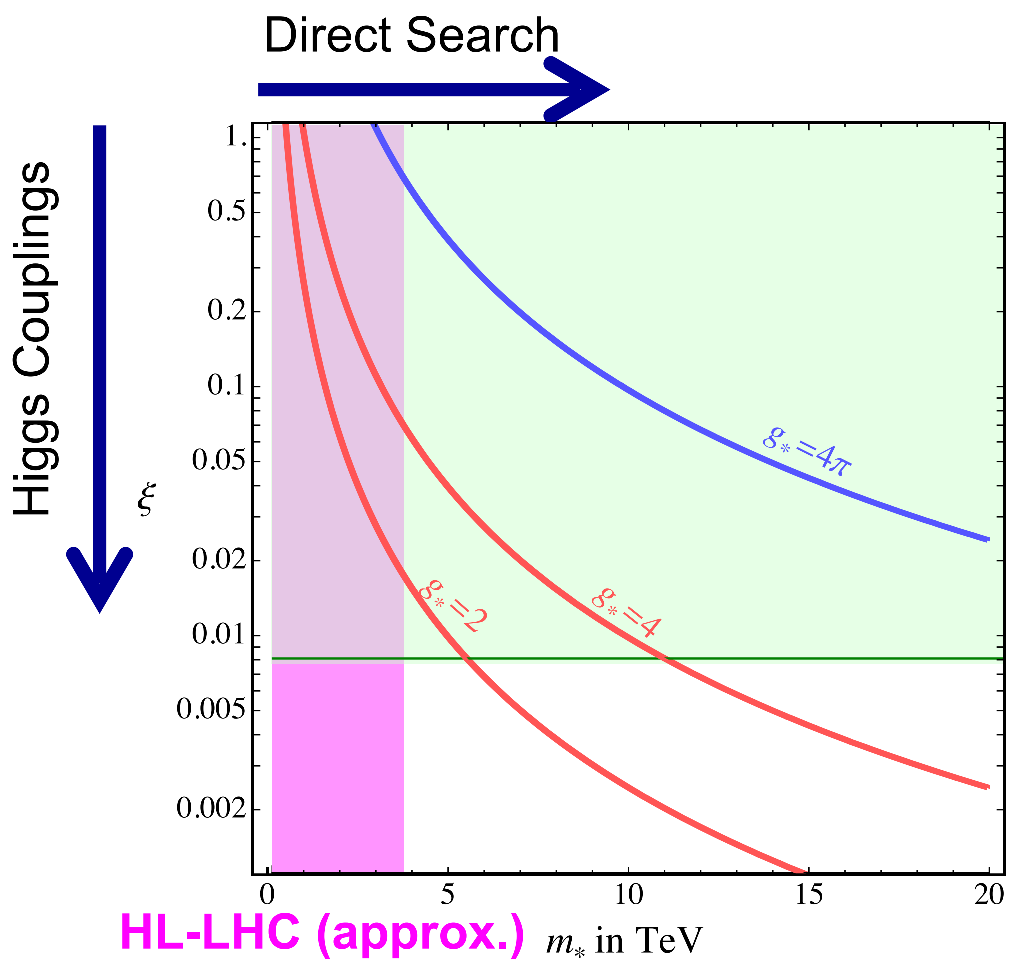
- ILC precision matters - ILC will be capable to distinguish between different models of more complex Higgs sectors
  - SUSY - multiple Higgs bosons
  - Composite Higgs boson

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 LC

Comparison depends on the coupling strength (g_*)



Based on Contino, et al, JHEP 1402 (2014) 006

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

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

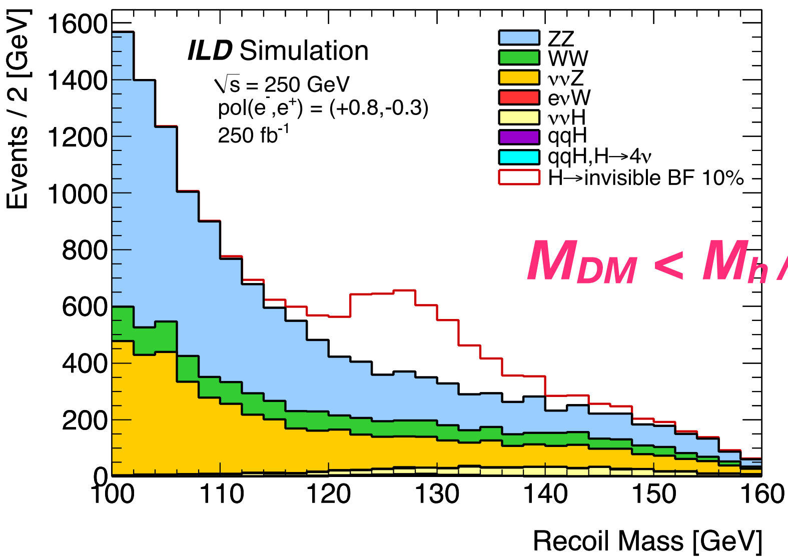
ILC (250+500 LumiUP)

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

WIMP Dark Matter at ILC

WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

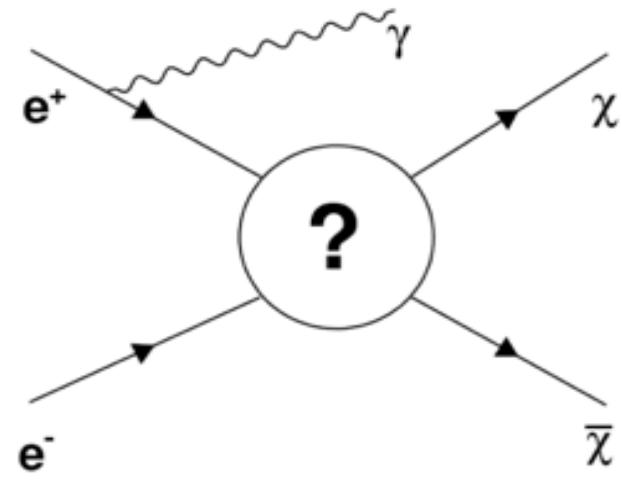
Higgs Invisible Decay



$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%
at 250 GeV, 1150 fb^{-1}

Monophoton Search



→ ***M_{DM} reach ~ Ecm/2***

In many models, DM has a charged partner as in higgsino DM case of SUSY.

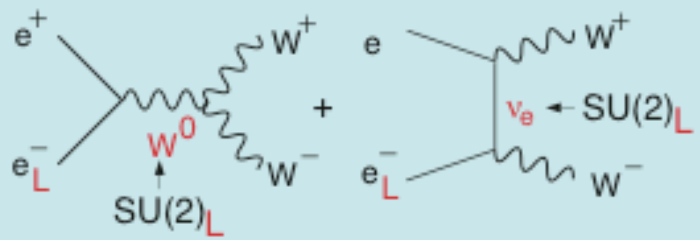
SUSY-specific signatures (decays to DM)

- light Higgsino, light stau, etc.

Effect of beam polarization

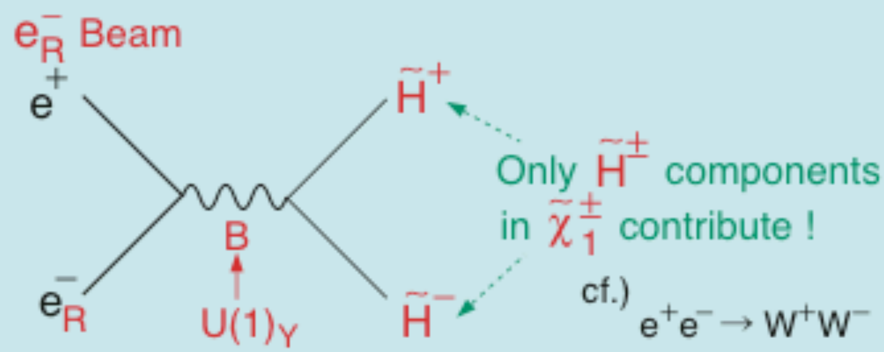
W^+W^- *(Largest SM BG in SUSY searches)*

BG Suppression



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

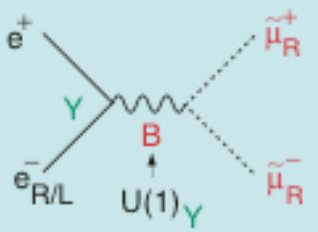
Chargino Pair



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

Decomposition

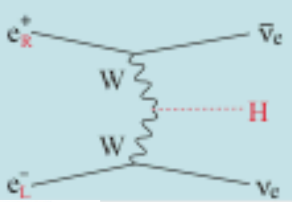
Slepton Pair



$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

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

WW-fusion Higgs Prod.



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

Signal Enhancement