Measurement of Higgs couplings and self-coupling at the ILC

Junping Tian (KEK)

---on behalf of the ILD detector concept group

EPS-HEP 2013, Apr. 18-24, KTH, Stockholm

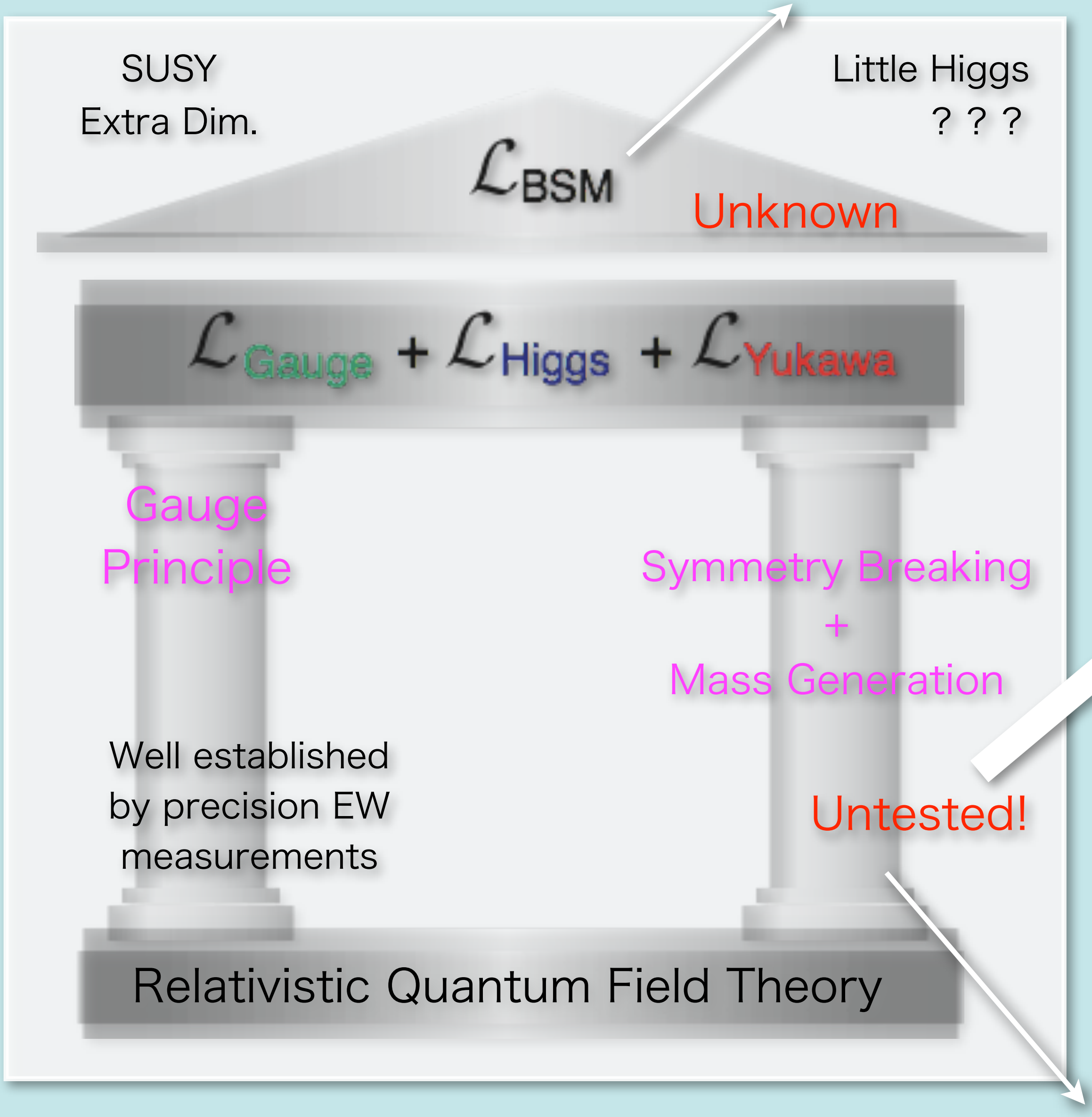
ILC TDR completed, welcome to check the 5 volumes!

Primary Goal

Mystery Test of the 2nd pillar, then BSM

2 Main Pillar of SM

There's a good chance that the dark matter is in the ILC range



SUSY
Extra Dim.

Little Higgs
? ? ?

$\mathcal{L}_{BSM}$

Unknown

$\mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$

Gauge Principle

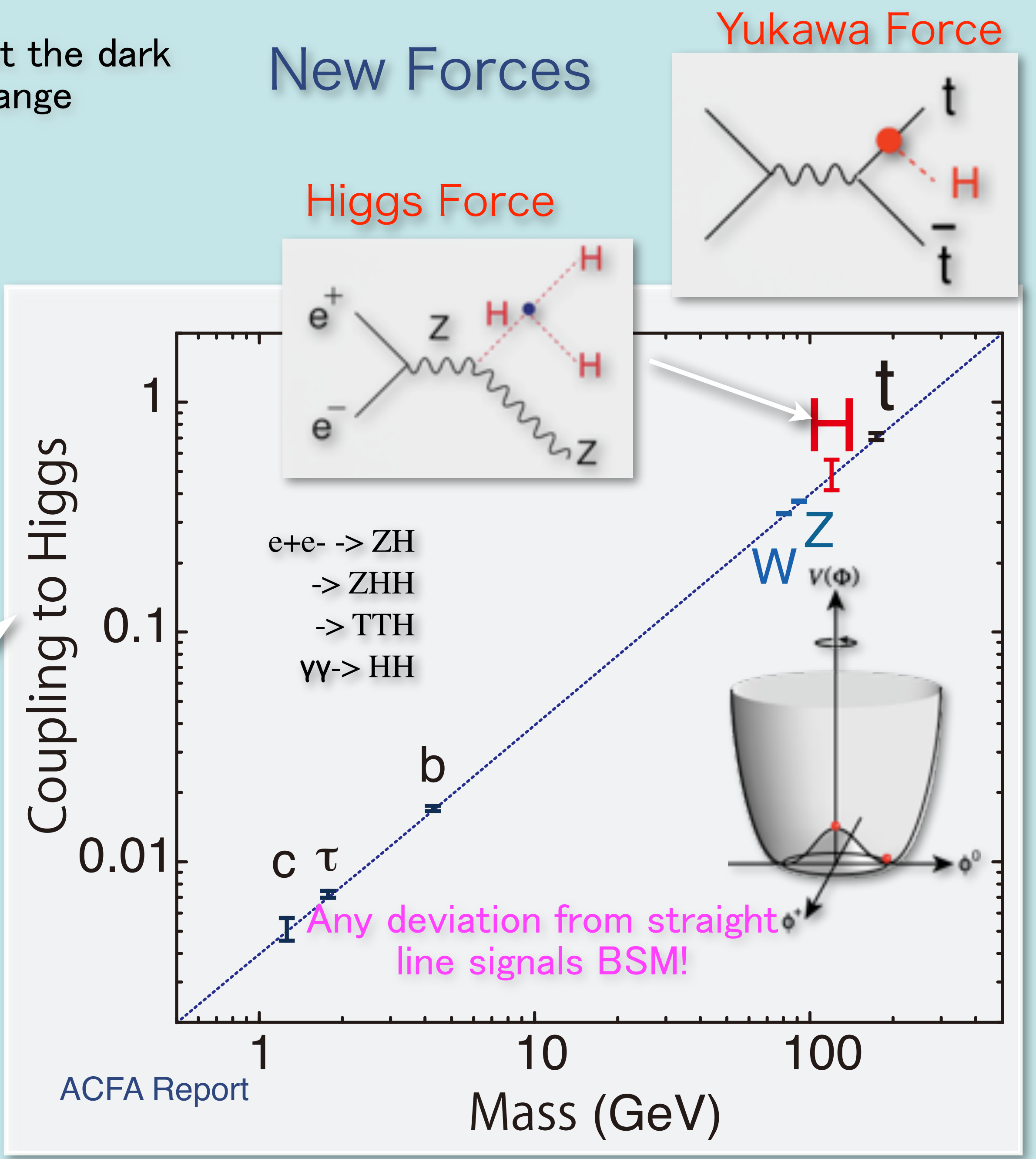
Symmetry Breaking
+
Mass Generation

Well established by precision EW measurements

Untested!

Relativistic Quantum Field Theory

New Forces



Any deviation from straight line signals BSM!

Wd do not know how firm this pillar is. The answer surely lines in the TeV Region

First test the 2nd pillar by precision Higgs study and then put

Beyond the Standard Model roof!

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

through Precision Higgs Measurements

Mass & J$^{\mathrm{CP}}$ $\quad M_h \quad \Gamma_h \quad J^{\mathrm{CP}}$

test CP mixture (Yanyan's talk)

L_{Higgs} $\quad hhh: \quad -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \quad -6i\lambda = -3i\frac{m_h^2}{v^2}$

observe the force to make higgs condense

L_{Gauge}

$$W^+_\mu W^-_\nu h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W^+_\mu W^-_\nu hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$$

$$Z_\mu Z_\nu h: \; i\frac{g^2 + g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2 + g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$$

test the SSB, SU(2), saturation to <vev>

L_{Yukawa} $\quad h\bar{f}f: \quad -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$

crucial to test the mass coupling proportionality

L_{Loop} $\quad h\gamma\gamma \quad hgg \quad h\gamma Z$

sensitive to the new particles in the loop

comprehensively reveal the Higgs nature and with precision

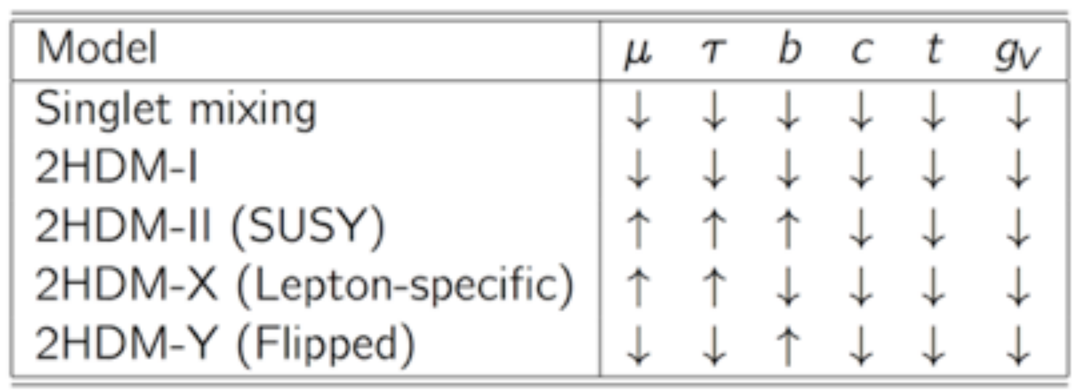
Precision is the light on new physics BSM

ref: TDR Physics Volume

- Multiplet structure :
  - Additional singlet?
  - Additional doublet?
  - Additional triplet?
- Underlying dynamics :
  - Weakly interacting or strongly interacting? = elementary or composite ?
- Relations to other problems :
  - DM
  - EW baryogenesis
  - neutrino mass
  - inflation?

--> There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!



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

Mixing with singlet

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

Composite Higgs

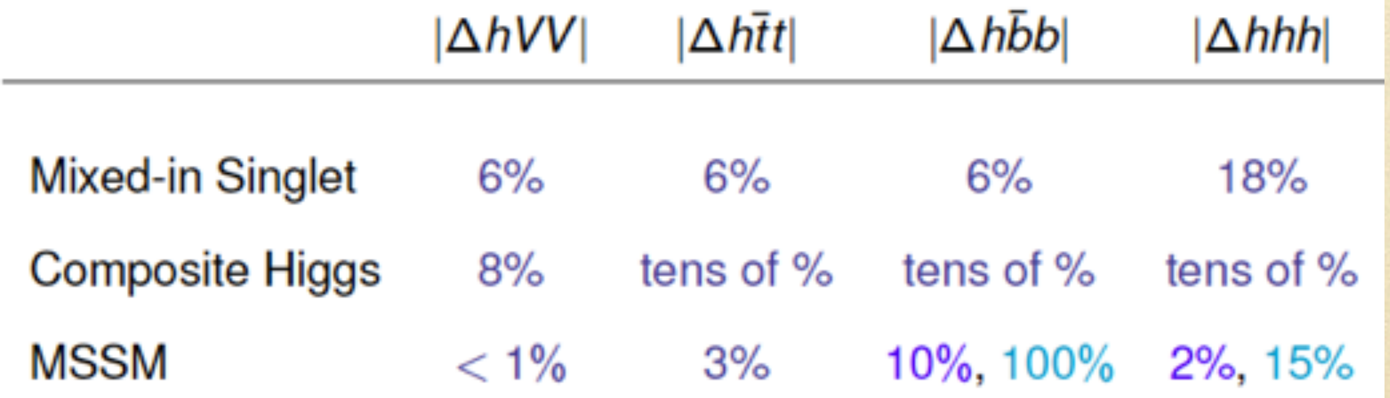
$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\%(1\ {\rm TeV}/f)^2$$

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

SUSY

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

Expected deviations are small --> Precision!



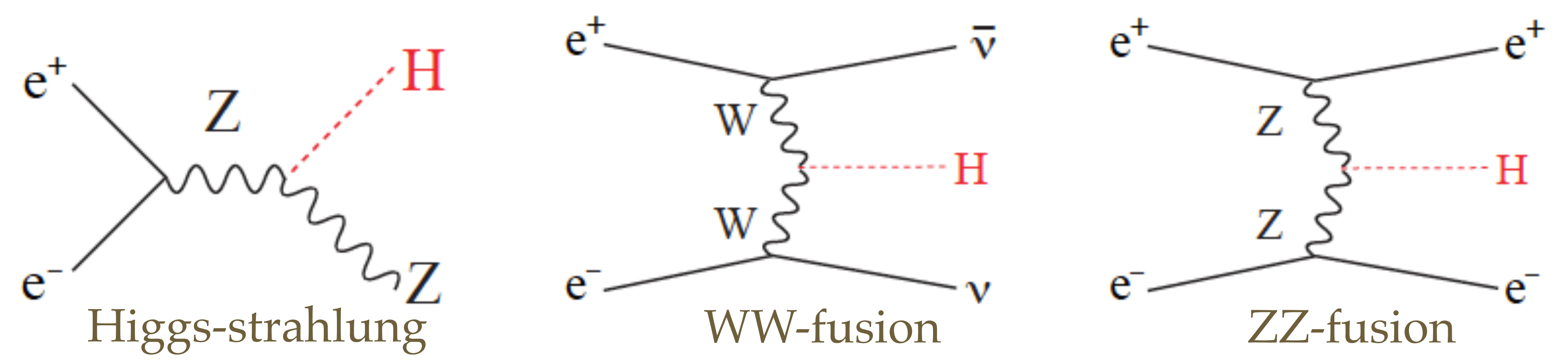
	$\|\Delta hVV\|$	$\|\Delta h\bar{t}t\|$	$\|\Delta h\bar{b}b\|$	$\|\Delta hhh\|$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	< 1%	3%	10%, 100%	2%, 15%

Rzehak @ ECFA2013

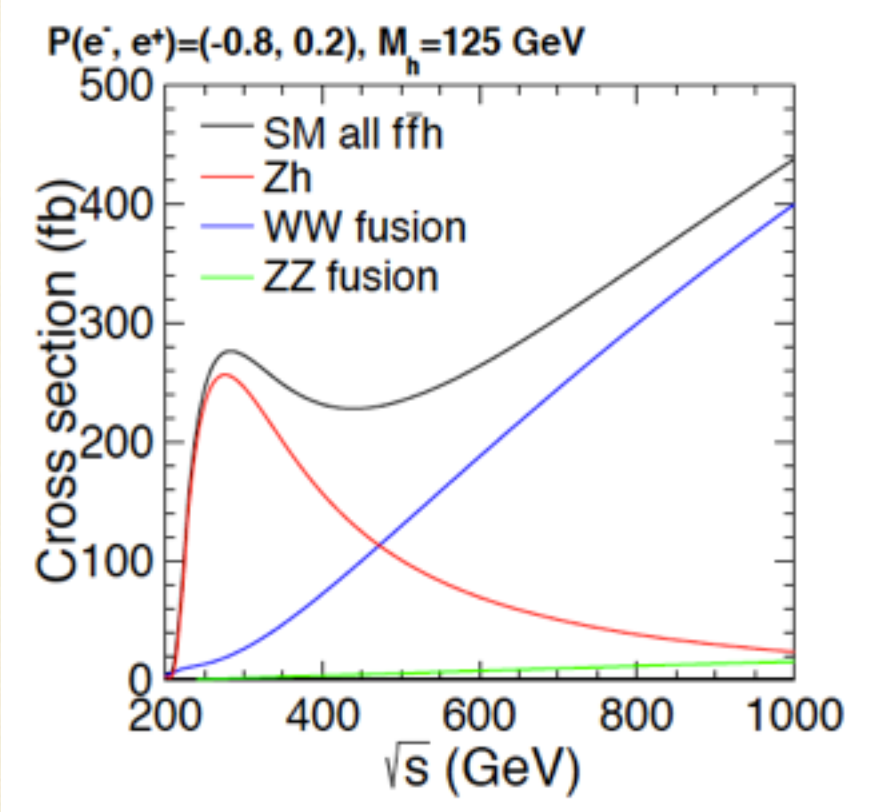
Gupta, Rzehak, Wells, arXiv:1206.3560

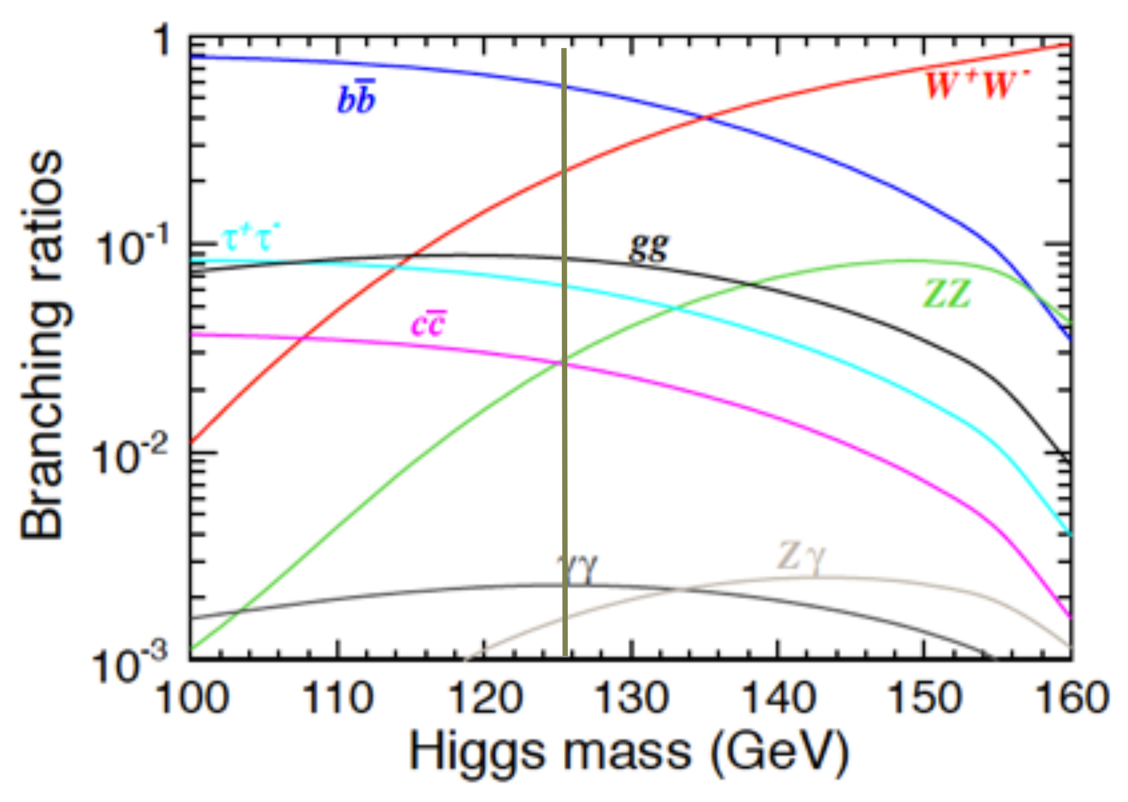
Higgs Production and Decay @ ILC

ref: TDR Physics Volume



Higgs-strahlung WW-fusion ZZ-fusion





- ✓ sufficient production rate solidified by what observed at LHC
- ✓ very clean signal making most of the decay modes accessible

expected branching ratio values from LHC Higgs cross section working group
arxiv:1101.0593

A staged running program (Higgs Part)

(canonical / upgraded luminosity)

250/1150 fb^{-1} @ 250 GeV (as a Higgs Factory)

- Higgs mass, spin, CP
- Absolute HZZ coupling
- Br(H-->bb, cc, gg, ττ, WW*, ZZ*, γγ, γZ)
- Total width (initial)

@ 350 GeV

- precision top physics, indirect top-Yukawa
- Total width

500/1600 fb^{-1} @ 500 GeV

- WW-fusion full activated, Absolute HWW coupling
- Total Higgs width --> absolute normalization of all other couplings
- BRs with high statistics
- Top-Yukawa coupling through ttH
- Higgs self-coupling through ZHH

beam polarisation likes a luminosity doubler

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

1000/2500 fb^{-1} @ 1 TeV

- accumulate much more Higgs events
- H-->μμ accessible
- improve Top-Yukawa coupling
- Higgs self-coupling through ννHH

state-of-art detector performance achievable by ILD

Particle Flow Algorithm, High Granularity, ~4π Coverage

momentum resolution: $\sigma_{1/p_T} \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$

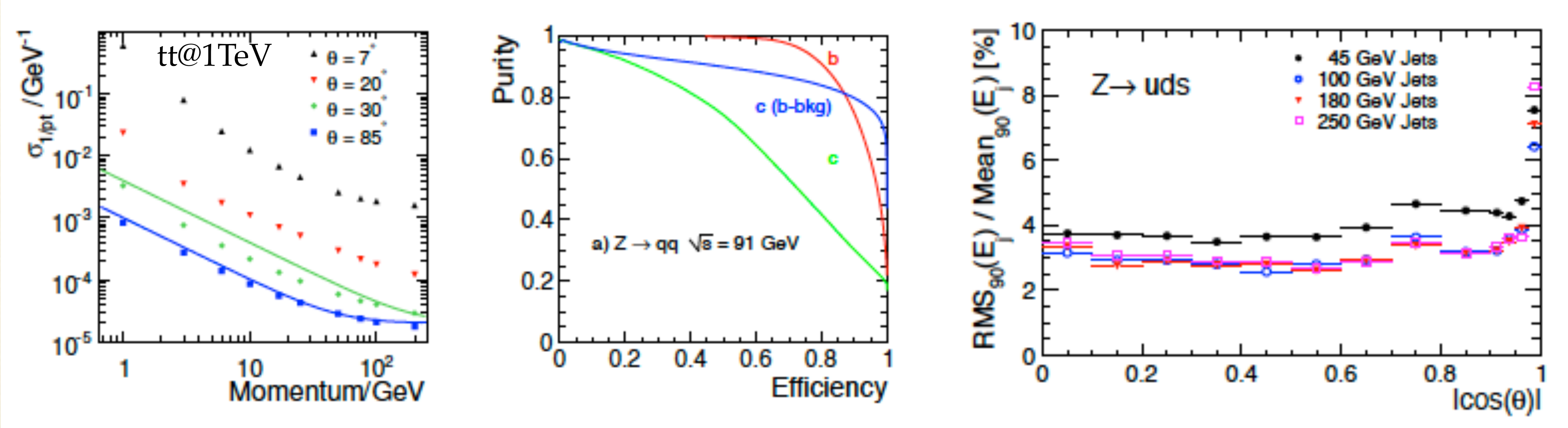
- driven by recoil mass measurement ZH-->l^+l^-X.

jet energy resolution: $\sigma_E/E \sim 3-4\% \sim 30\%/\sqrt{E}$ @100GeV

- driven by 3σ separation of the hadronic decay of W and Z bosons.

impact parameter resolution: $\sigma_{r\phi} = 5\ \mu\mathrm{m} \oplus \frac{10}{p(\mathrm{GeV}\sin^{3/2}\theta)}\ \mu\mathrm{m}$

- driven by excellent tagging and untagging of heavy flavor jets (H-->bb, cc and gg).

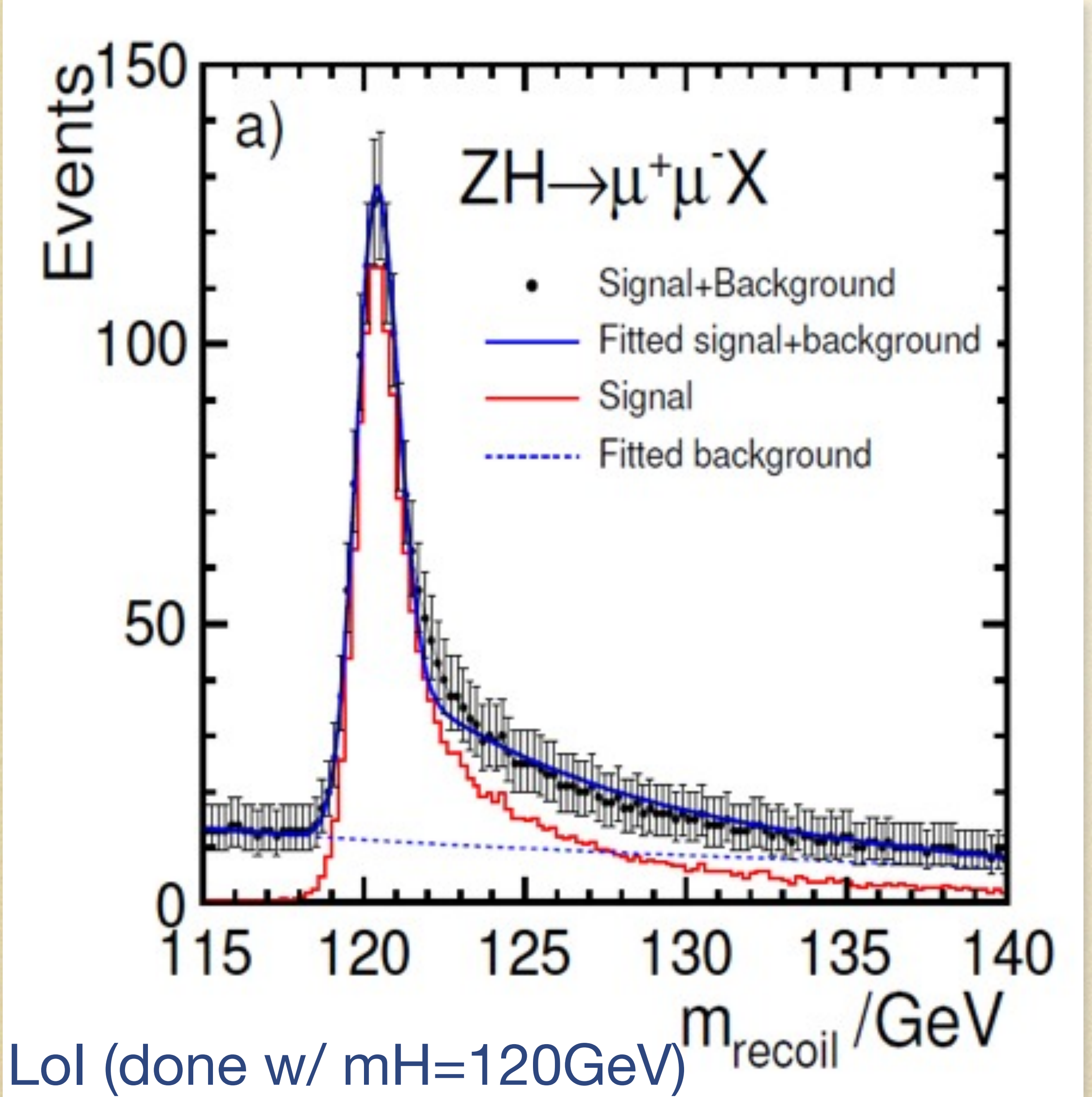


ILC 250 GeV

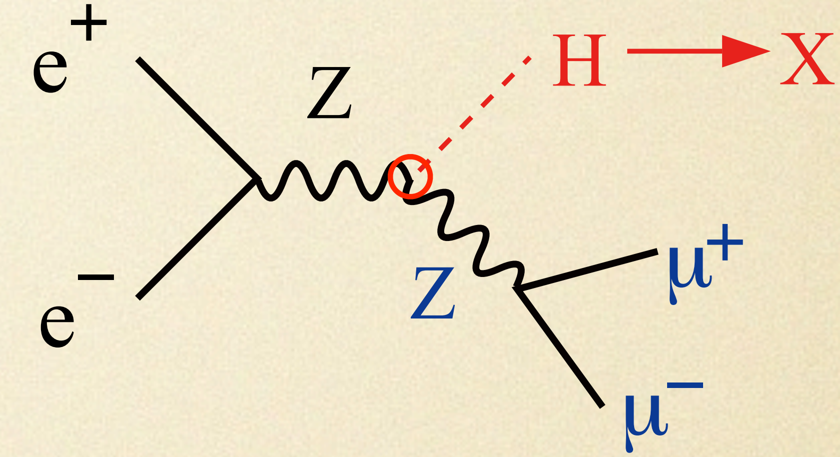
g_{HZZ}

The flagship measurement of LC 250

Recoil Mass



LoI (done w/ mH=120GeV)



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

Invisible decay detectable!

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

$$\Delta\sigma_{ZH}/\sigma_{ZH} = 2.6\%$$

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

$$BR(\mathrm{invisible}) < 0.95\%\ @\ 95\%\ \mathrm{C.L.}$$

(Z-->ee combined) scaled from mH=120 GeV

$\sigma_{ZH} \propto g_{HZZ}^2$ ---> Model-independent absolute measurement of the HZZ coupling

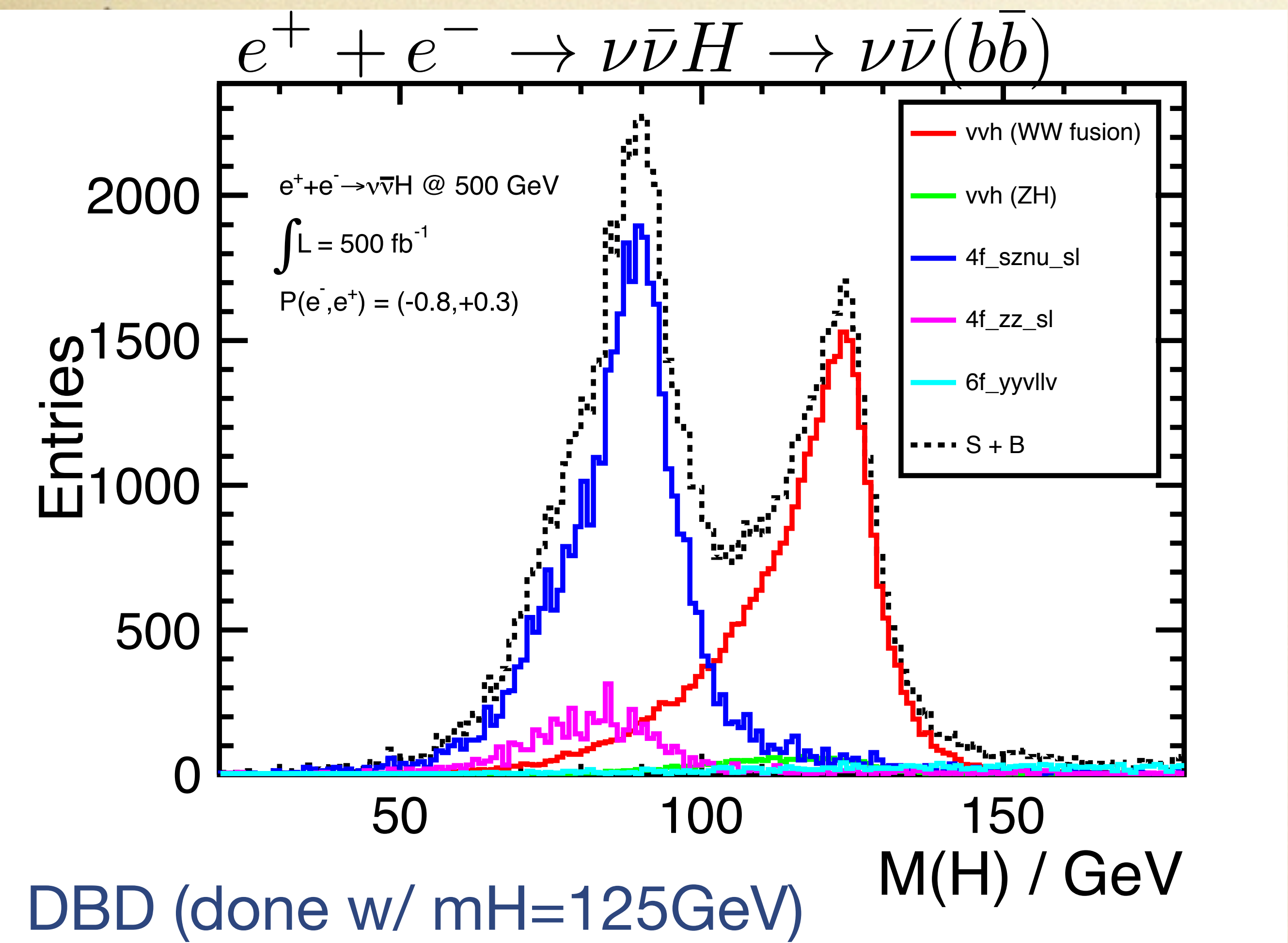
$\frac{\Delta g_{HZZ}}{g_{HZZ}}$	Canonical	1.3%
	LumiUP	0.61%

250 GeV is the optimal energy for g_{HZZ}

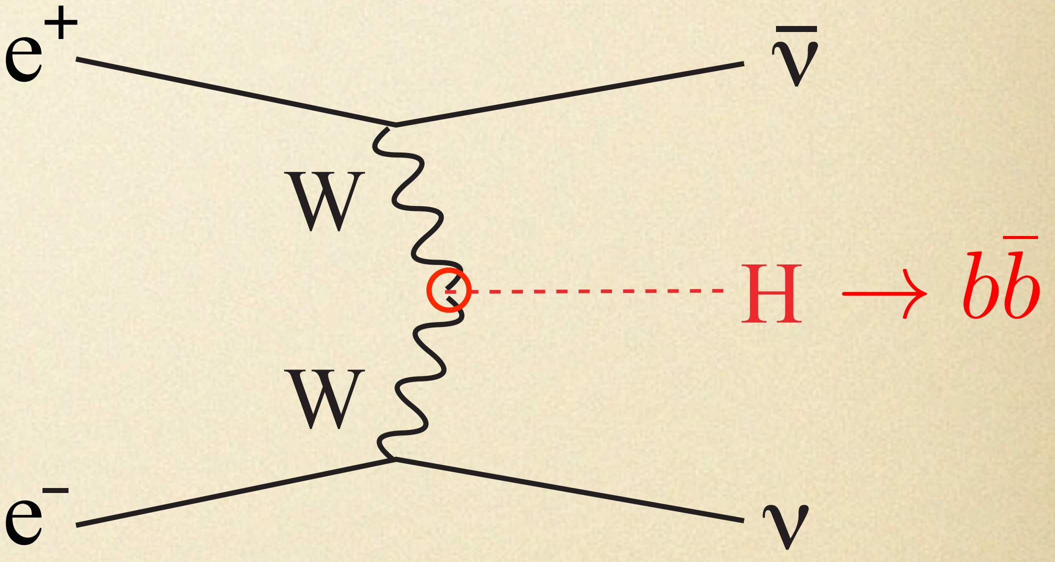
ILC 500 GeV

g_{HWW}

WW-fusion production fully activated: 14 fb @ 250 GeV ---> 150 fb @ 500 GeV



DBD (done w/ mH=125GeV)



$$Y_1 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HWW} \cdot \mathrm{Br}(H \to b\bar{b})$$

$$Y_2 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} \cdot \mathrm{Br}(H \to b\bar{b})$$

$\Delta g_{HWW}/g_{HWW}$	250 GeV	250 GeV + 500 GeV
Canonical	4.8%	1.4%
LumiUP	2.3%	0.67%

Y_1/Y_2 gives accurate test of SU(2), and with g_{HZZ} gives absolute normalization of g_{HWW}.

(Y_2 done at 250 GeV)

C. Durig @ LCWS12, J. Tian @ KILC12 and new DBD study

ILC 500 GeV

Higgs total width Γ_0

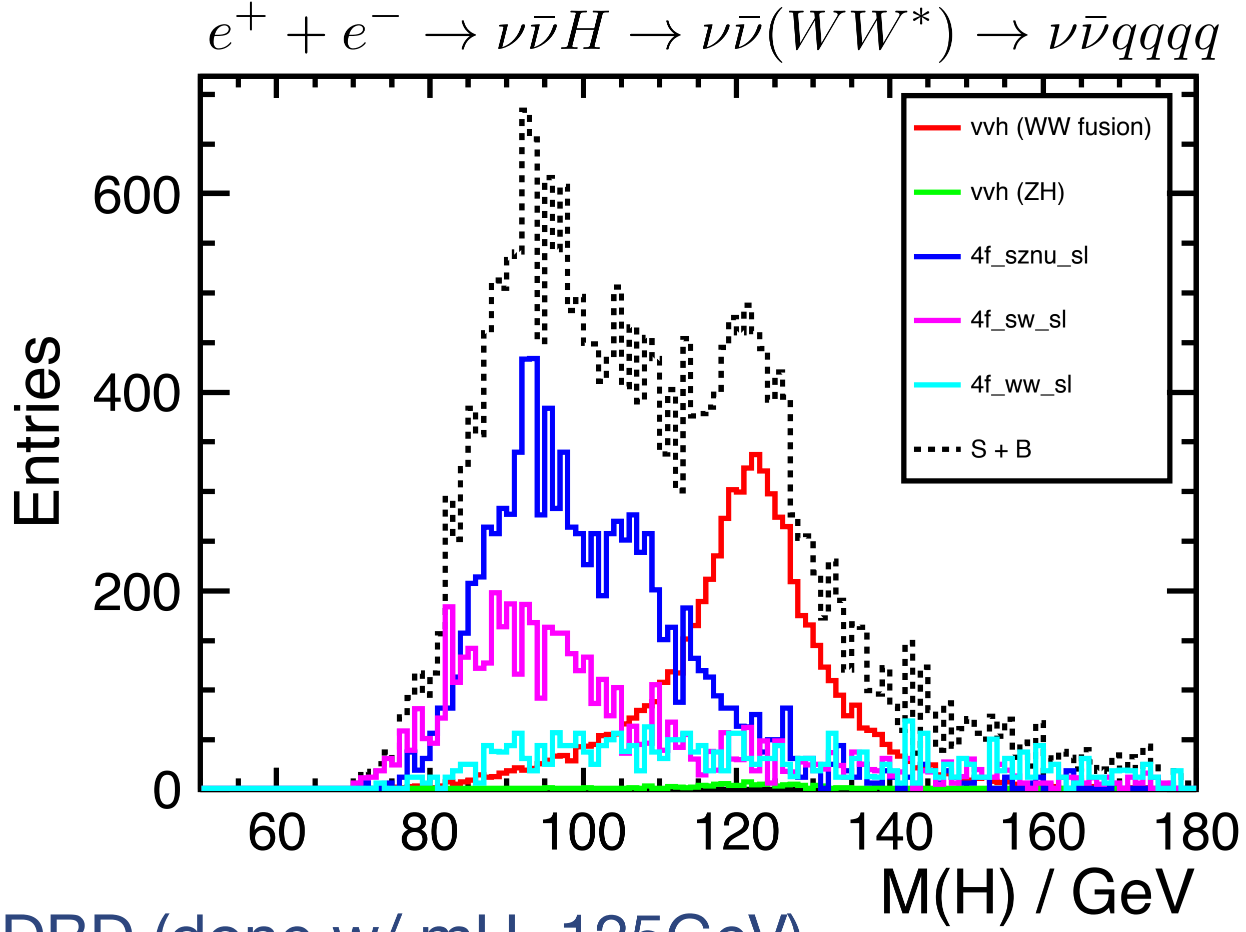
model free, one of the main advantages of ILC

$$\Gamma_0 = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

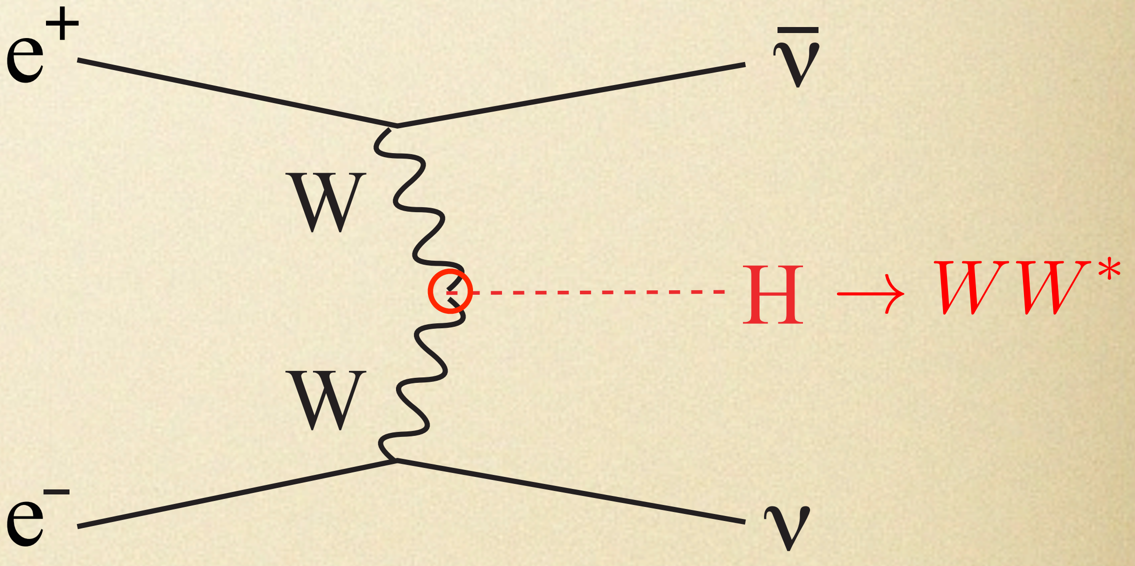
Br(H->ZZ*) very small, not very precisely measured

$$\Gamma_0 = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

Br(H->WW*) much larger, more precisely measured



DBD (done w/ mH=125GeV)



$$Y_1 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HWW} \cdot \mathrm{Br}(H \to b\bar{b})$$

$$Y_2 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} \cdot \mathrm{Br}(H \to b\bar{b})$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_0}$$

Y_3 and g_{HWW} gives Higgs total width --> absolute normalization of other couplings.

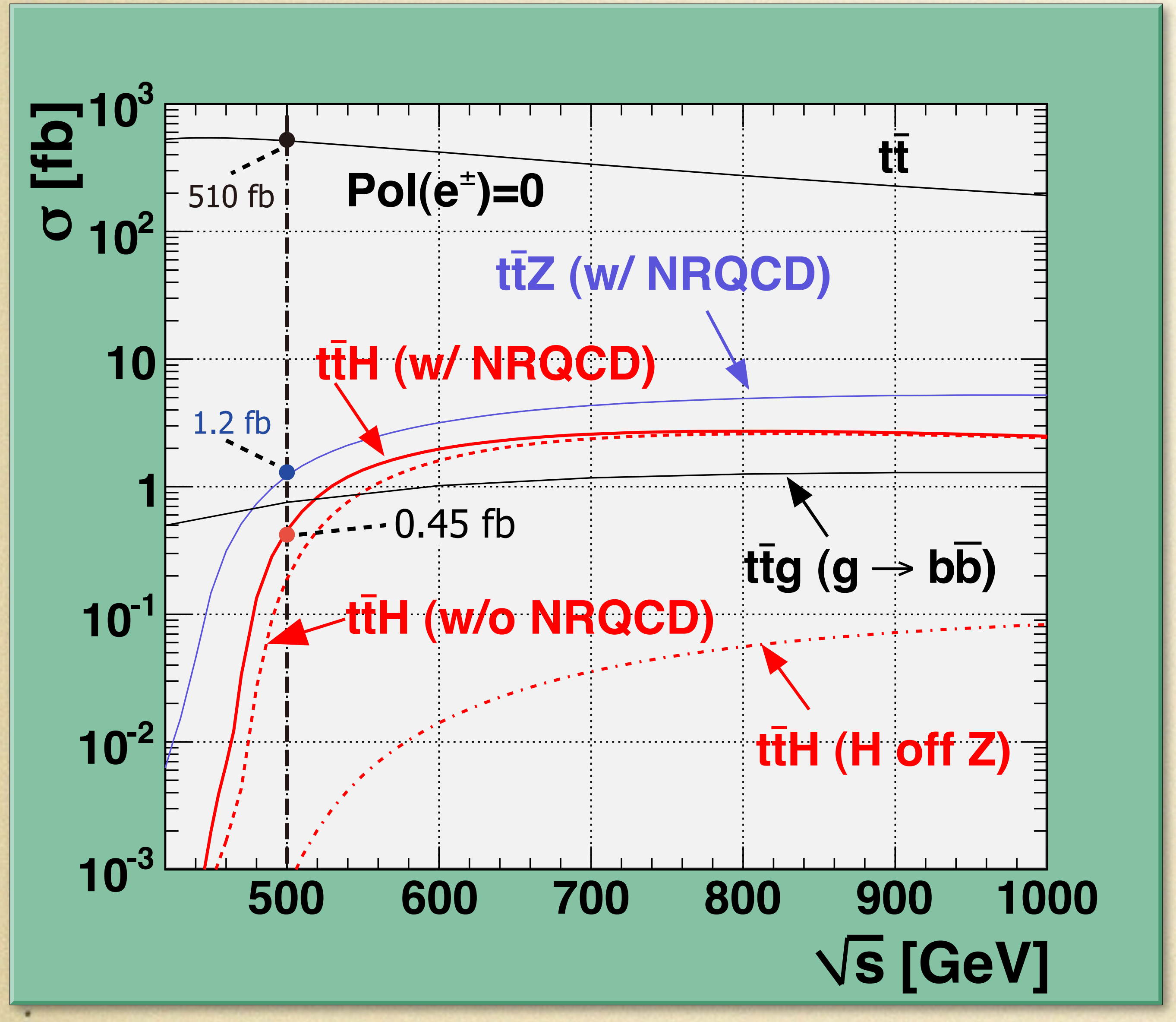
$\Delta\Gamma_0/\Gamma_0$	250 GeV	250 GeV + 500 GeV
Canonical	11%	5.9%
LumiUP	5.4%	2.8%

J. Tian, new DBD study

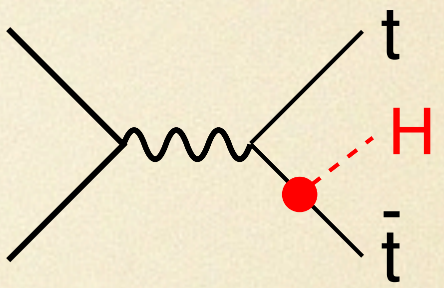
(Y_2 done at 250 GeV)

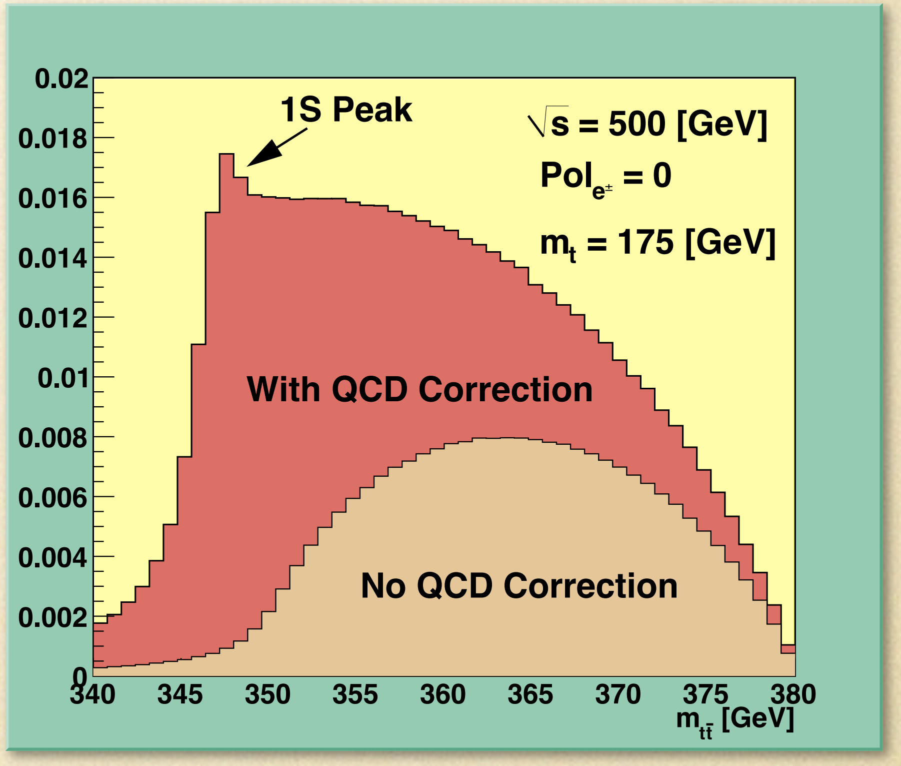
Top Yukawa Coupling

The largest among matter fermions



main BG: ttZ / ttg (g-->bb)





A factor of 2 enhancement from QCD bound-state effects

$\Delta g_{ttH} / g_{ttH}$	500 GeV	500 GeV + 1 TeV
Canonical	14%	3.2%
LumiUP	7.8%	2.0%

R. Yonamine, et. al, Phys.Rev. D84 (2011) 014033, confirmed by full simulation

T. Tanabe, T. Price, et. al, LC-REP-2013-004

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

Higgs self-coupling measurement

Higgs Potential: $V(\eta_H) = \frac{1}{2}m_H^2\eta_H^2 + \boxed{\lambda}\upsilon\eta_H^3 + \frac{1}{4}\lambda\eta_H^4$

physical Higgs field

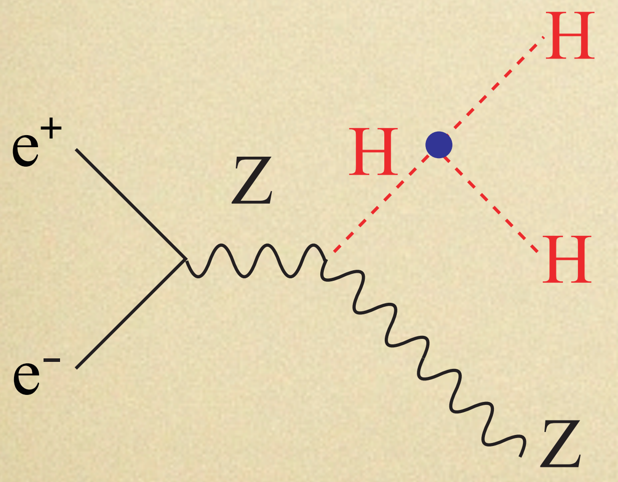
mass term

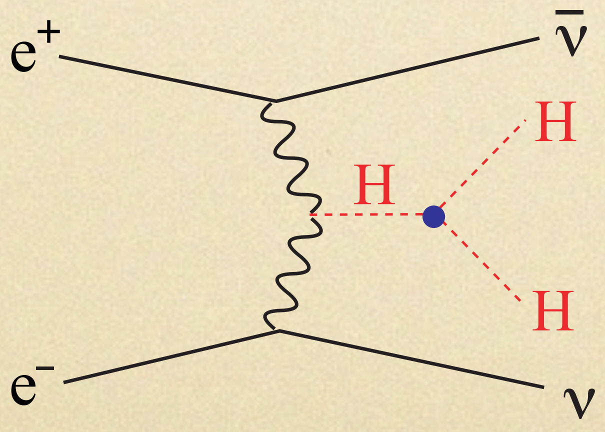
trilinear coupling

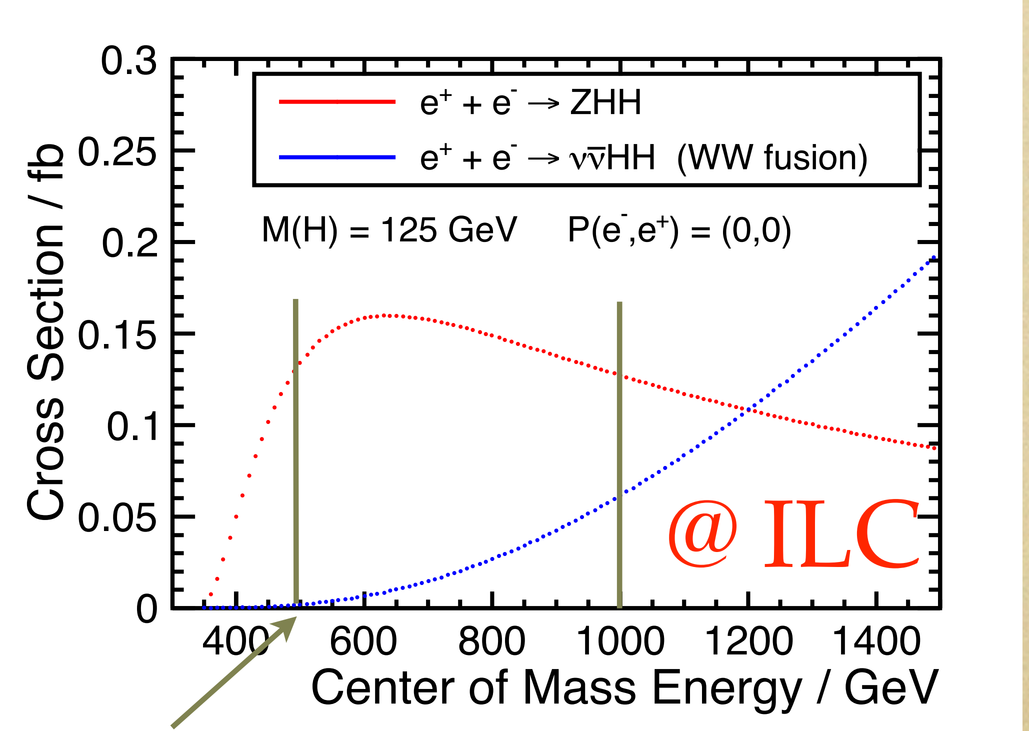
quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2\upsilon^2}$ υ ~ 246 GeV

- just the force that makes the Higgs boson condense in the vacuum (a new force, non-gauge interaction).
- direct determination of the Higgs potential.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like 2HDM and SUSY.







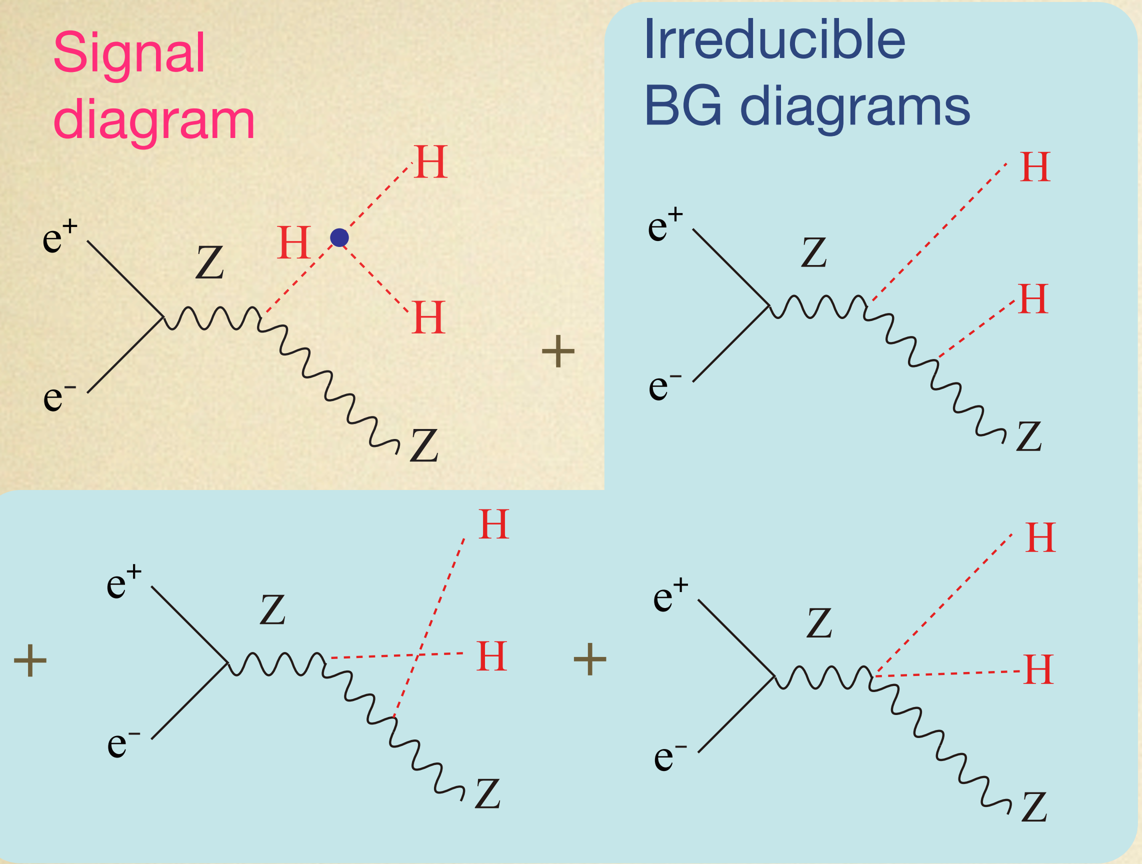
one of the reasons why 500 GeV

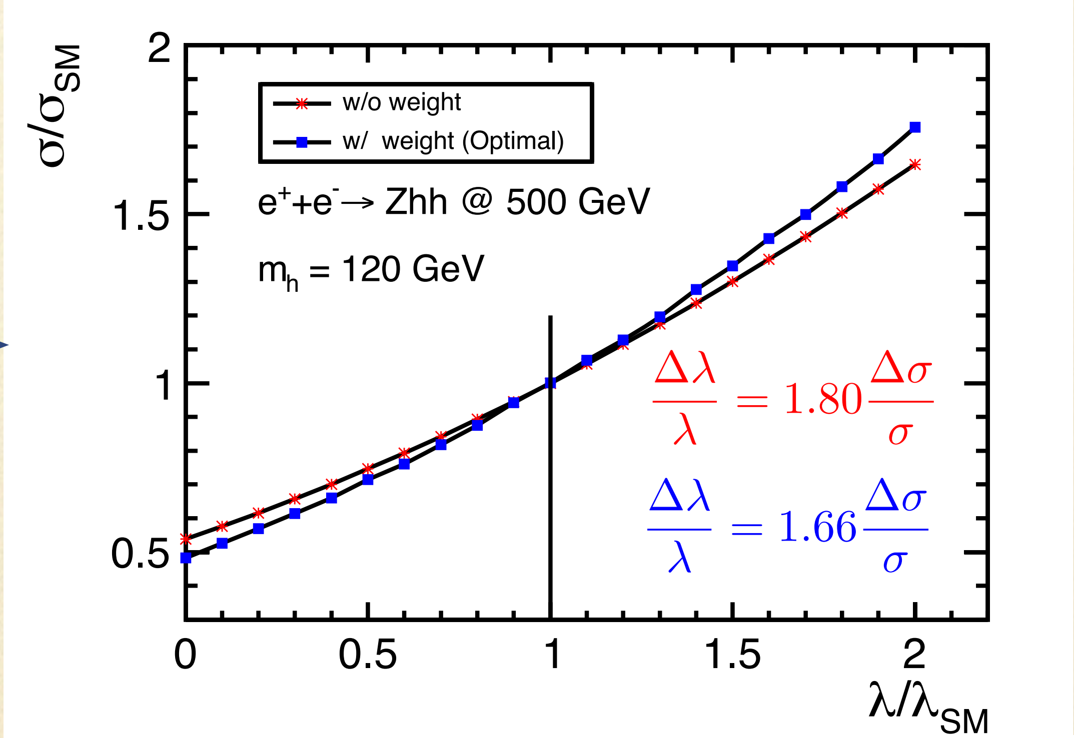
General issue: sensitivity of coupling to the cross section

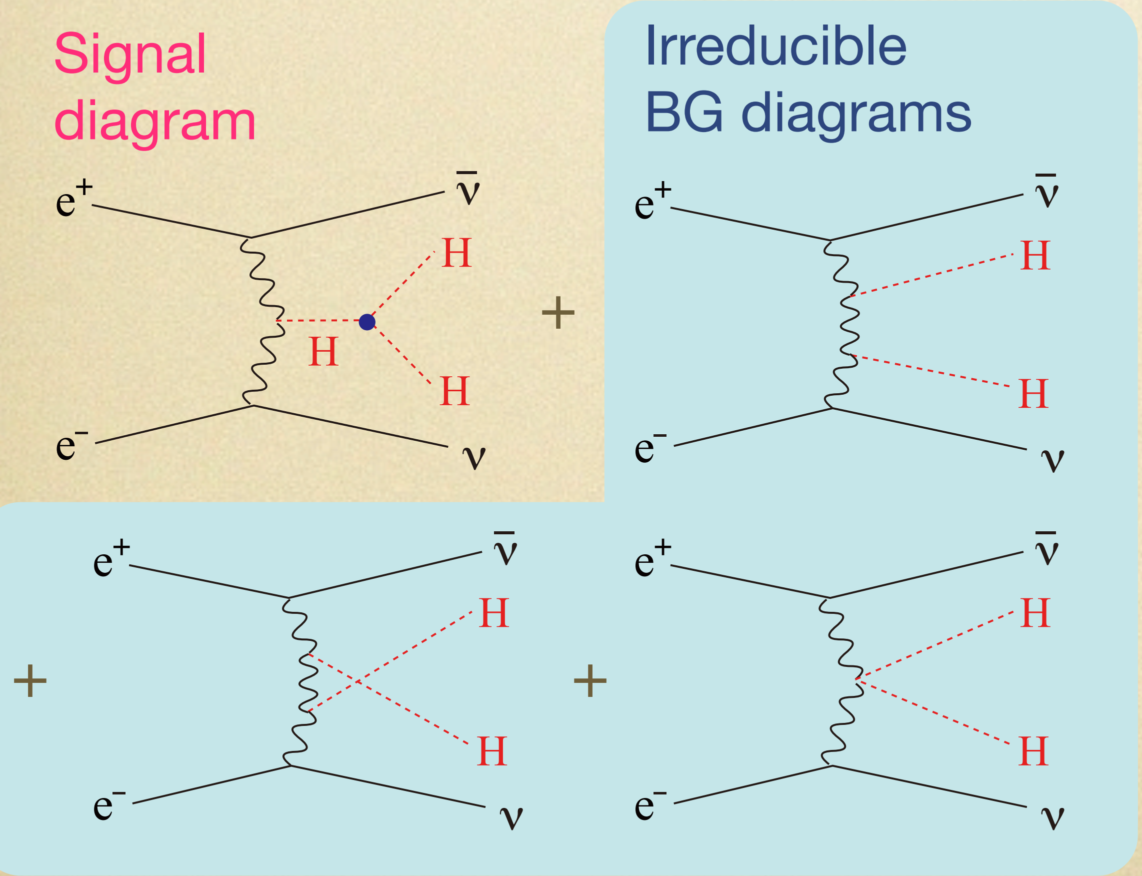
$$\sigma = \lambda^2 S + \lambda I + B$$

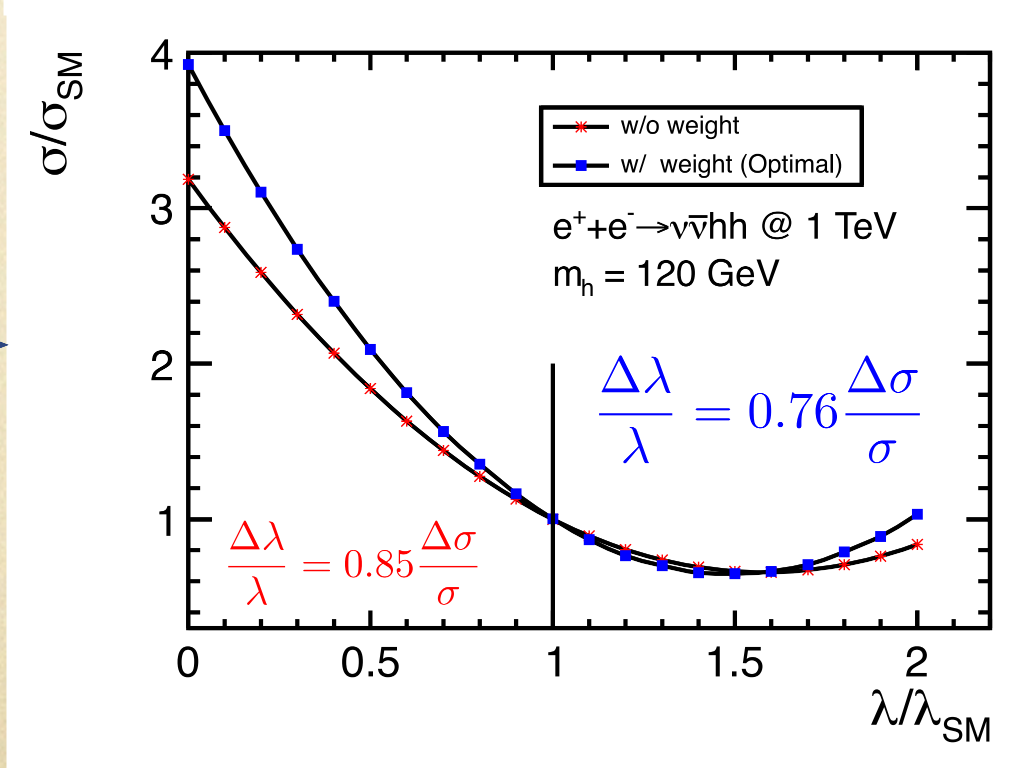
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams









these diagrams significantly degraded the sensitivity

J. Tian, LC-REP-2013-003

Higgs Self-coupling Projections @ ILC

full simulation done w/ mH = 120 GeV, extrapolated to mH = 125 GeV

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV			500 GeV + 1 TeV		
Scenario	A	B	C	A	B	C
Canonical	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

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)

if positron polarisation 30%(20%) --> 60%(40%), gain relatively 10% improvement

J. Tian, LC-REP-2013-003

M. Kurata @ ECFA2013

Summary table of Higgs measurements @ ILC

250 GeV: 250 fb-1
500 GeV: 500 fb-1
1 TeV: 1000 fb-1

MH = 125 GeV
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

ILD-DBD

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	2.6%	-	-		
	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	7.0%		11%	4.1%	2.3%
H-->WW*	6.4%		9.2%	2.4%	1.6%
H-->ττ	4.2%		5.4%	9.0%	3.1%
H-->ZZ*	19%		25%	8.2%	4.1%
H-->γγ	29-38%		29-38%	20-26%	7-10%
H-->μμ	-		-		31%
ttH, H-->bb	-		28%		6.0%
H-->Inv. (95% C.L.)	< 0.95%		-		

being updated by new studies with mH = 125 GeV

Global Fit

32 $Y_i=\sigma\times Br$ measurements, each of which can be predicted by

F_i is what we can calculate

$$Y_i' = F_i \cdot \frac{g^2_{HZZ} g^2_{HXX}}{\Gamma_0} \quad \text{or} \quad Y_i' = F_i \cdot \frac{g^2_{HWW} g^2_{HXX}}{\Gamma_0} \quad \text{or} \quad Y_i' = F_i \cdot \frac{g^2_{Htt} g^2_{HXX}}{\Gamma_0}$$

1 $Y_{33}=\sigma_{ZH}$ measurements, which can be predicted by

$$Y_{33}' = F_{33} \cdot g^2_{HZZ}$$

define a $\chi 2$, which can be parameterized with 9 couplings and Higgs total width

$$\chi^2 = \sum_{i=1}^{i=33} (\frac{Y_i - Y_i'}{\Delta Y_i})^2$$

ΔY_i is the measurement error

global fit: minimize the $\chi 2$ ---> get the 10 parameters

model independent, no theoretical errors included

Absolute Higgs Couplings @ ILC

250 GeV: 250 fb-1
500 GeV: 500 fb-1
1 TeV: 1000 fb-1

MH = 125 GeV
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

Canonical

<table>
<tr><th>coupling $\Delta g/g$</th><th>250 GeV</th><th colspan="2">250 GeV + 500 GeV</th><th colspan="2">250 GeV + 500 GeV + 1 TeV</th></tr>
<tr><td>HZZ</td><td>1.3%</td><td colspan="2">1.3%</td><td colspan="2">1.3%</td></tr>
<tr><td>HWW</td><td>4.8%</td><td colspan="2">1.4%</td><td colspan="2">1.4%</td></tr>
<tr><td>Hbb</td><td>5.3%</td><td colspan="2">1.8%</td><td colspan="2">1.5%</td></tr>
<tr><td>Hcc</td><td>6.8%</td><td colspan="2">2.9%</td><td colspan="2">2.0%</td></tr>
<tr><td>Hgg</td><td>6.4%</td><td colspan="2">2.4%</td><td colspan="2">1.8%</td></tr>
<tr><td>$H\tau\tau$</td><td>5.7%</td><td colspan="2">2.4%</td><td colspan="2">1.9%</td></tr>
<tr><td>$H\gamma\gamma$</td><td>18%</td><td colspan="2">8.4%</td><td colspan="2">4.1%</td></tr>
<tr><td>$H\mu\mu$</td><td>-</td><td colspan="2">-</td><td colspan="2">16%</td></tr>
<tr><td>Γ_0</td><td>11%</td><td colspan="2">5.9%</td><td colspan="2">5.6%</td></tr>
<tr><td>Htt</td><td>-</td><td colspan="2">14%</td><td colspan="2">3.2%</td></tr>
<tr><td>Br(H-->Inv.) 95% C.L.</td><td>< 0.95%</td><td colspan="2">< 0.95%</td><td colspan="2">< 0.95%</td></tr>
<tr><td>HHH</td><td>-</td><td>104%</td><td>66%(*)</td><td>26%</td><td>17%(*)</td></tr>
</table>

(*): including H-->WW* and better jet-clustering

model independent fit

Absolute Higgs Couplings @ ILC

250 GeV: 1150 fb-1
500 GeV: 1600 fb-1
1 TeV: 2500 fb-1

MH = 125 GeV
P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

LumiUP

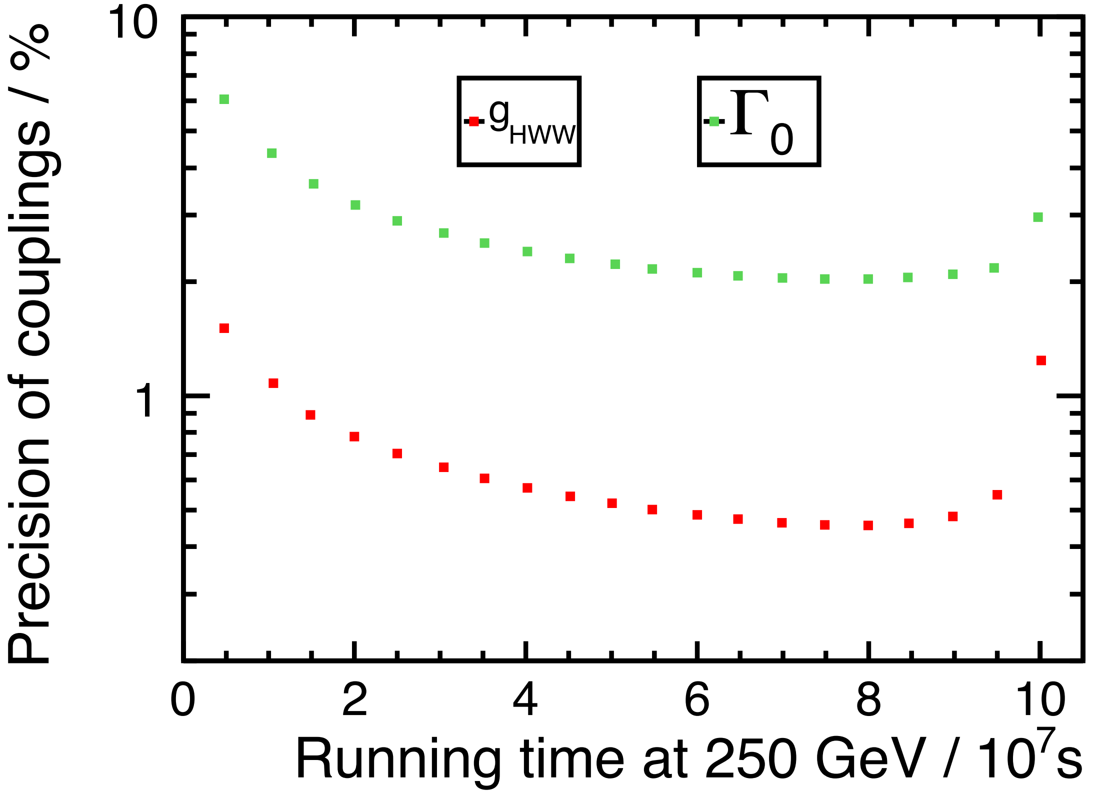
<table>
<tr><th>coupling Δg/g</th><th>250 GeV</th><th colspan="2">250 GeV + 500 GeV</th><th colspan="2">250 GeV + 500 GeV + 1 TeV</th></tr>
<tr><td>HZZ</td><td>0.61%</td><td colspan="2">0.61%</td><td colspan="2">0.61%</td></tr>
<tr><td>HWW</td><td>2.3%</td><td colspan="2">0.67%</td><td colspan="2">0.65%</td></tr>
<tr><td>Hbb</td><td>2.5%</td><td colspan="2">0.90%</td><td colspan="2">0.74%</td></tr>
<tr><td>Hcc</td><td>3.2%</td><td colspan="2">1.5%</td><td colspan="2">1.1%</td></tr>
<tr><td>Hgg</td><td>3.0%</td><td colspan="2">1.3%</td><td colspan="2">0.93%</td></tr>
<tr><td>Hττ</td><td>2.7%</td><td colspan="2">1.2%</td><td colspan="2">0.99%</td></tr>
<tr><td>Hγγ</td><td>8.2%</td><td colspan="2">4.5%</td><td colspan="2">2.4%</td></tr>
<tr><td>Hμμ</td><td>-</td><td colspan="2">-</td><td colspan="2">10%</td></tr>
<tr><td>Γ_0</td><td>5.4%</td><td colspan="2">2.8%</td><td colspan="2">2.7%</td></tr>
<tr><td>Htt</td><td>-</td><td colspan="2">7.8%</td><td colspan="2">2.0%</td></tr>
<tr><td>Br(H-->Inv.) 95% C.L.</td><td>< 0.44%</td><td colspan="2">< 0.44%</td><td colspan="2">< 0.44%</td></tr>
<tr><td>HHH</td><td>-</td><td>58%</td><td>37%(*)</td><td>16%</td><td>10%(*)</td></tr>
</table>

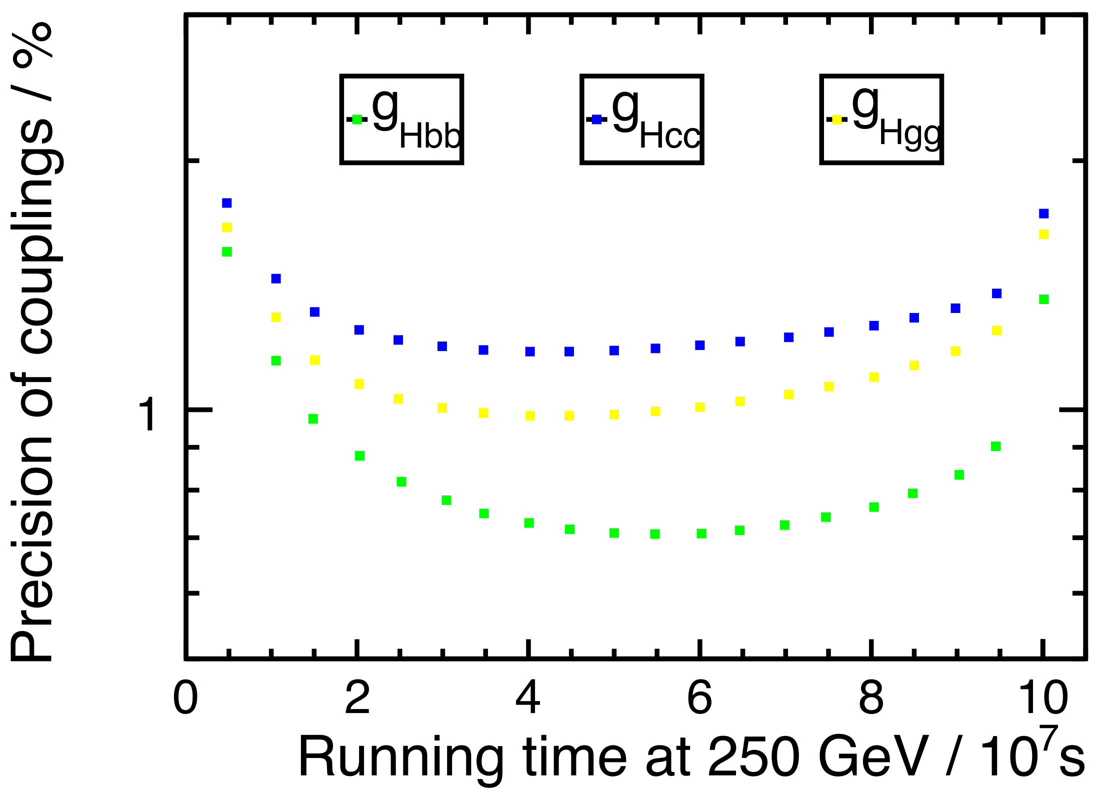
(*): including H-->WW* and better jet-clustering

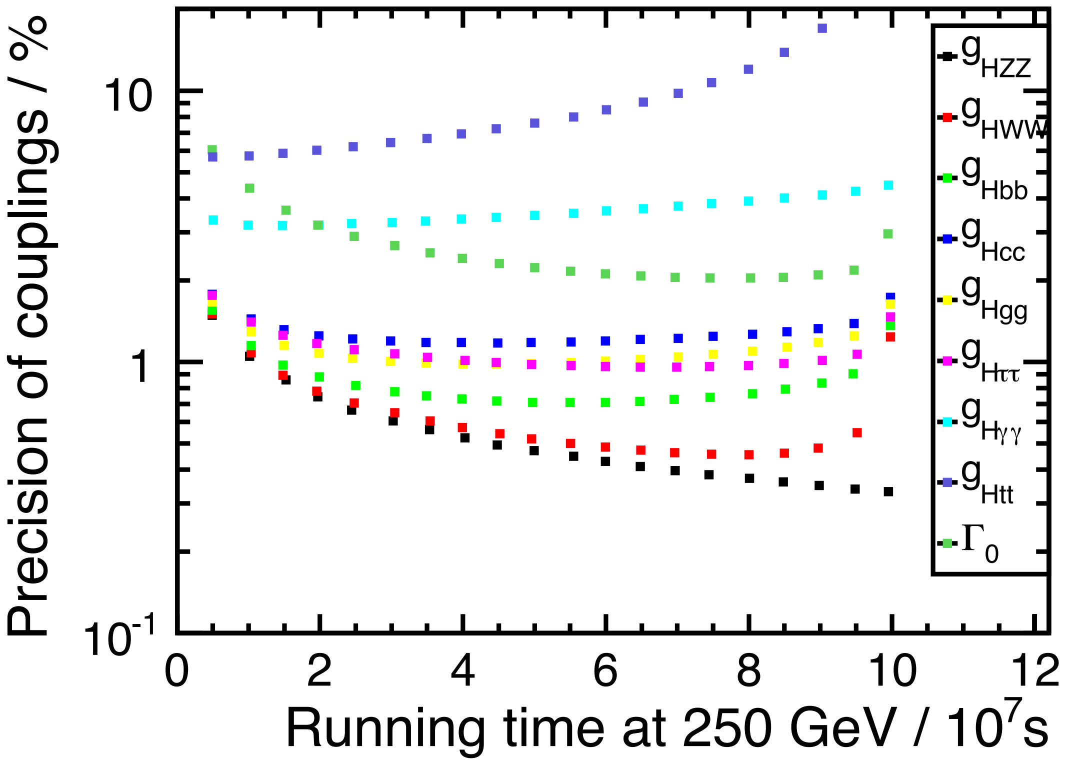
model independent fit

Power of Staged Running

e.g., assuming 10y running at 250 GeV + 500 GeV

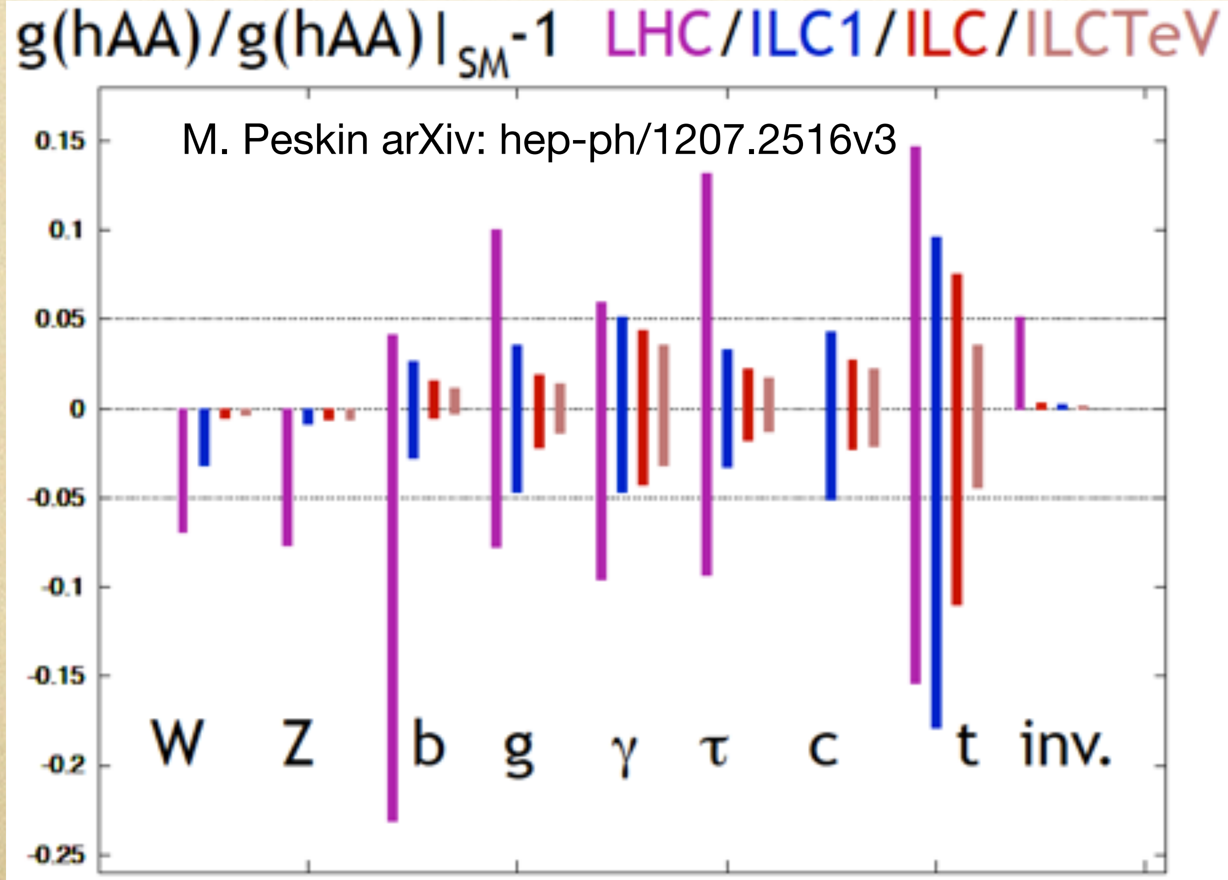




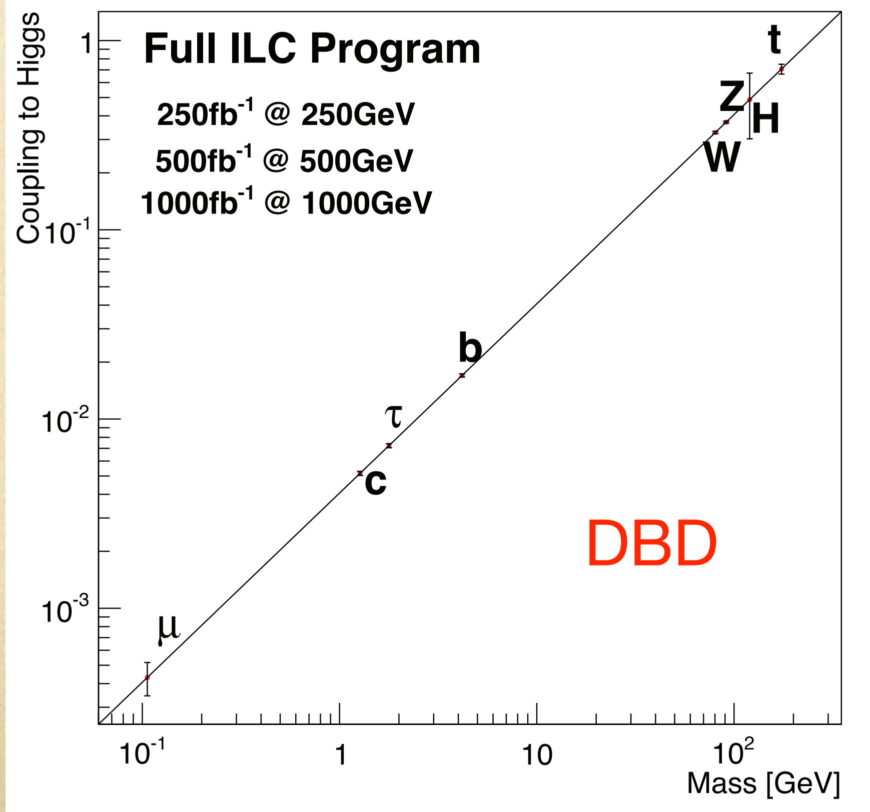


Summary

- ILC is the ideal precision machine complementary to LHC discovery power, to reveal the mechanism of EWSB and mass generation; performance of ILD can exactly meet the physics goal.
- recoil mass measurement @ 250 GeV gives the absolute HZZ coupling, be able to model independently normalize all the Higgs couplings and total width.
- ILC @ 500 GeV and 1 TeV is essential to significantly improve precision and access top-Yukawa coupling and Higgs self-coupling.
- ability of energy scan can make ILC run at optimal energy and complementary to whatever LHC would discover.

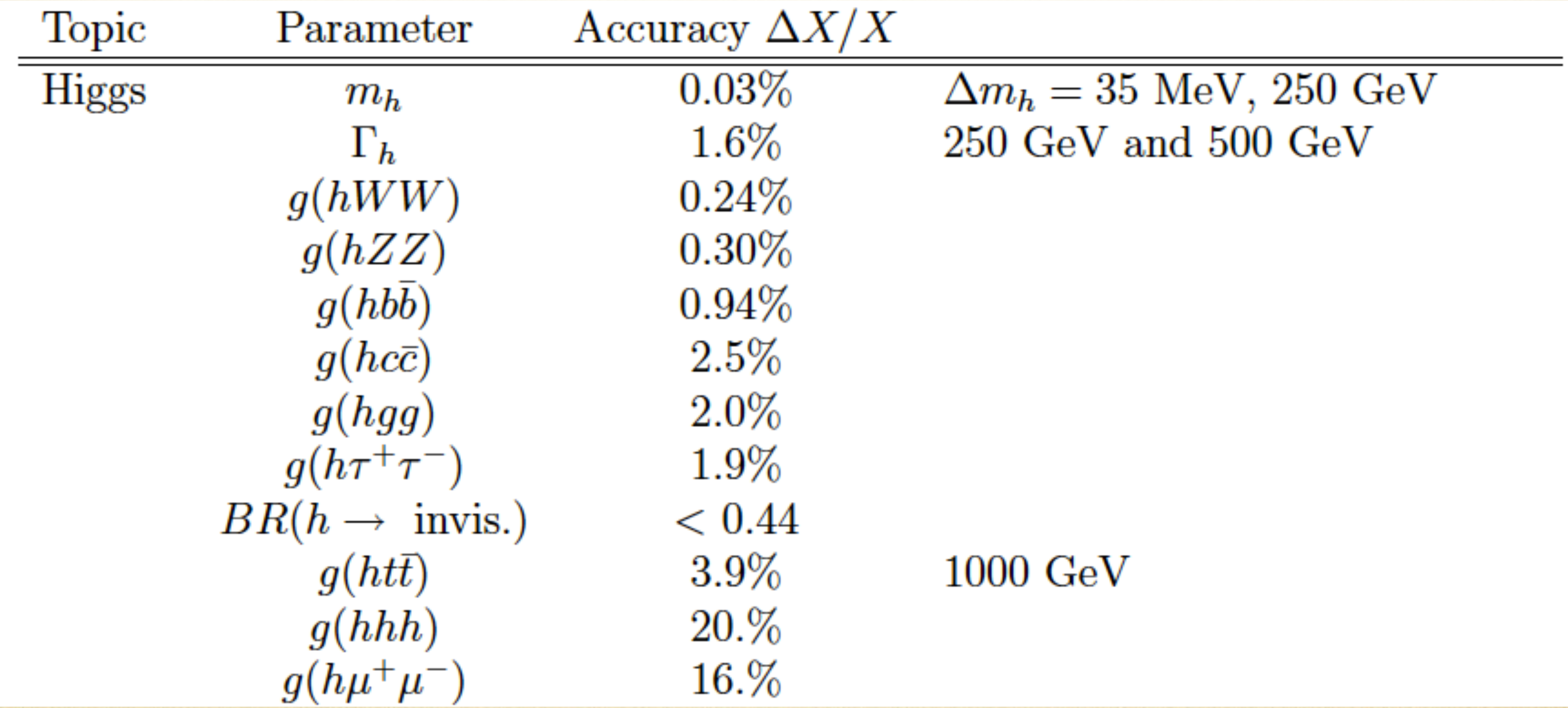


ILC ready to go!



backup

executive summary of TDR
(M. Peskin)

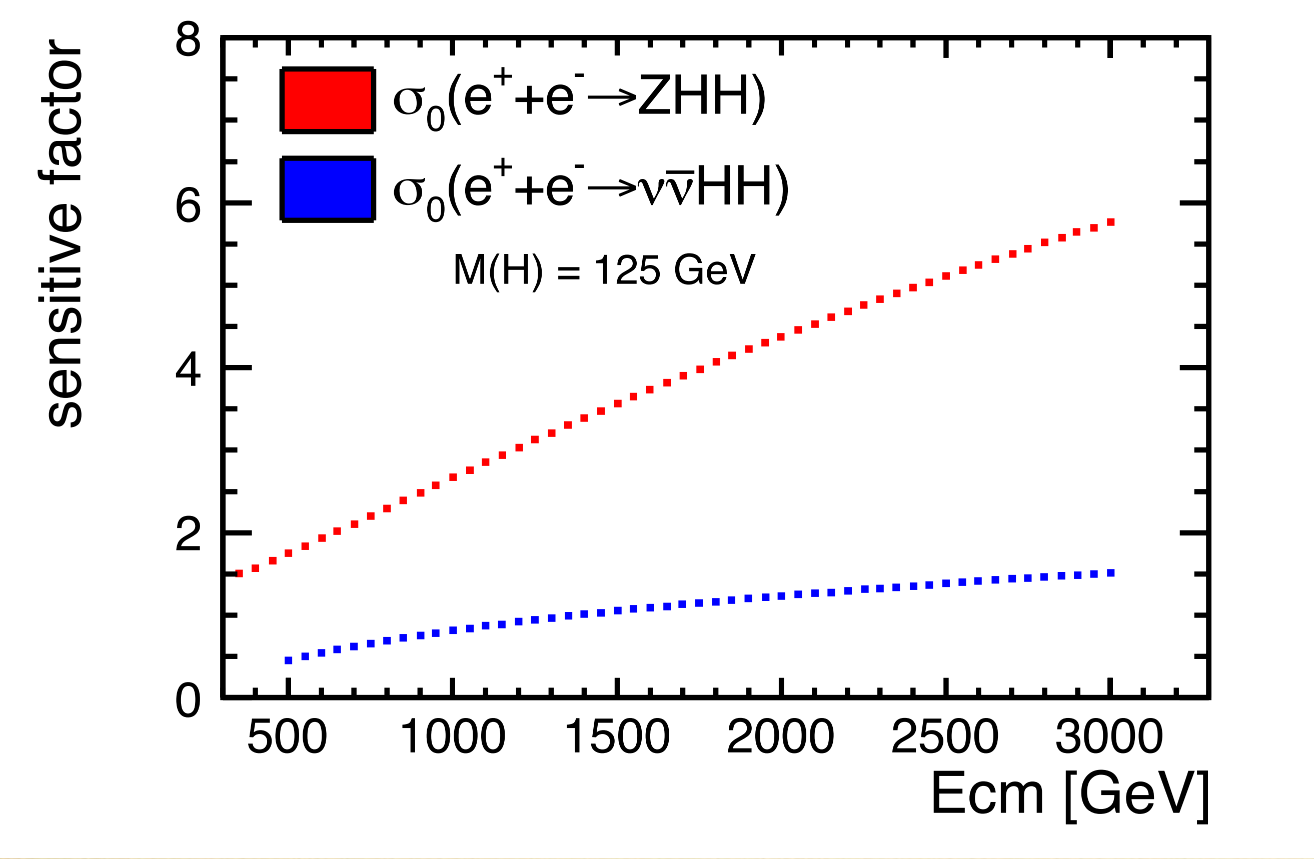


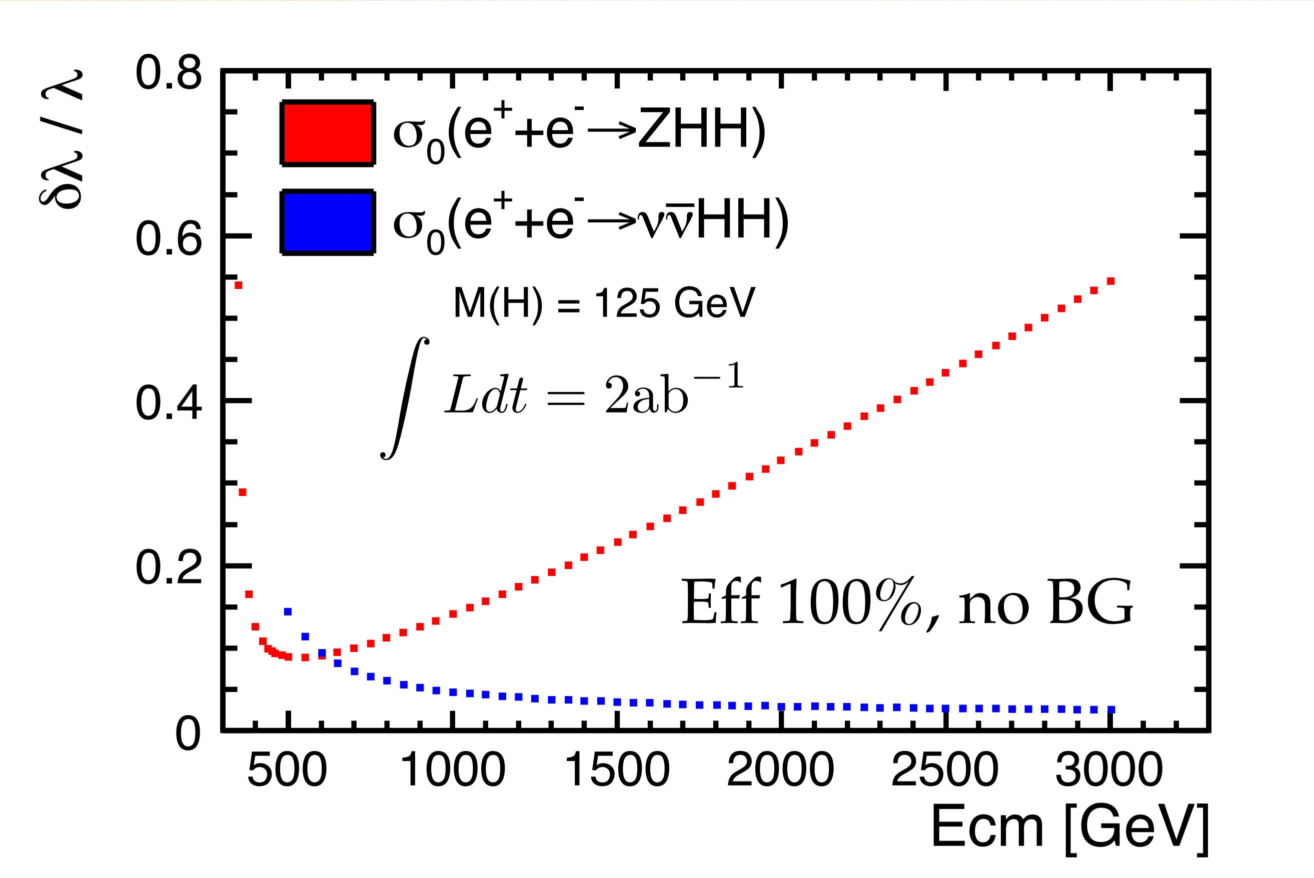
Topic	Parameter	Accuracy $\Delta X/X$	
Higgs	m_h	0.03%	$\Delta m_h = 35$ MeV, 250 GeV
	Γ_h	1.6%	250 GeV and 500 GeV
	$g(hWW)$	0.24%	
	$g(hZZ)$	0.30%	
	$g(hb\bar{b})$	0.94%	
	$g(hc\bar{c})$	2.5%	
	$g(hgg)$	2.0%	
	$g(h\tau^+\tau^-)$	1.9%	
	$BR(h \to \text{ invis.})$	< 0.44	
	$g(ht\bar{t})$	3.9%	1000 GeV
	$g(hhh)$	20.%	
	$g(h\mu^+\mu^-)$	16.%	

almost model-free fitting, constraint:

Branching ratios sum up to 1

General issue: running of the sensitive factor and expected coupling precision at different Ecm





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

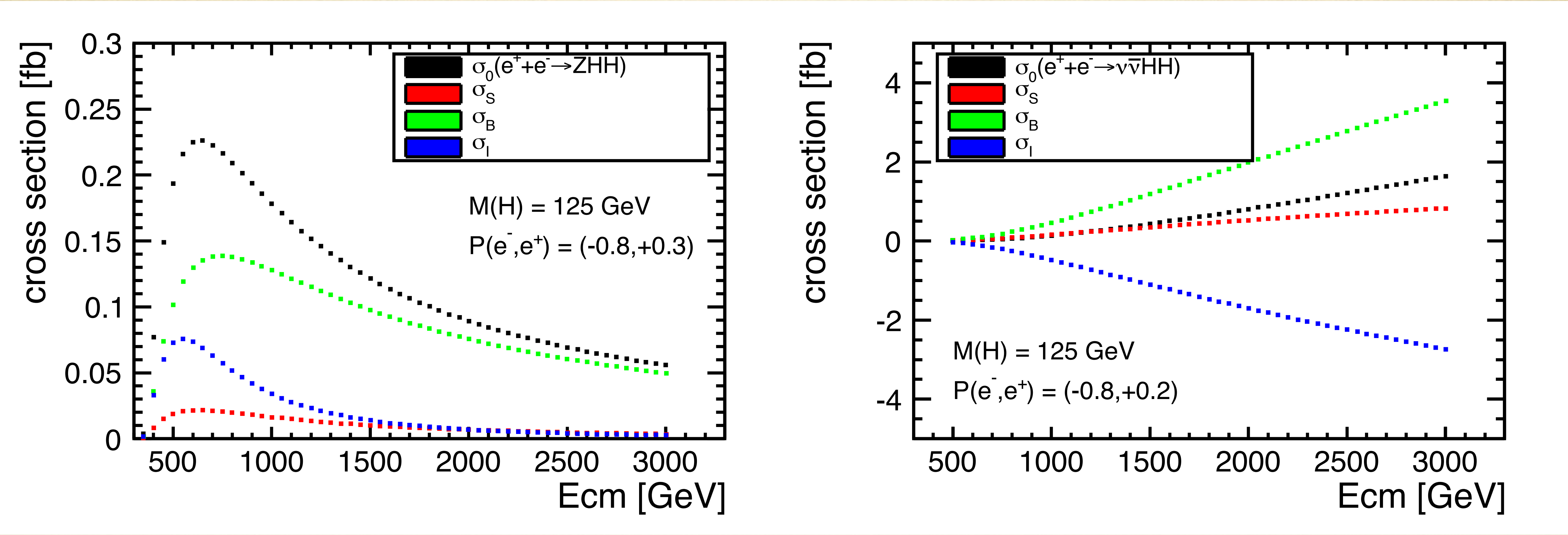
Factor increases quickly as going to higher energy

for ZHH, the expected optimal energy ~ 500 GeV (though cross section is maximum ~ 600 GeV)

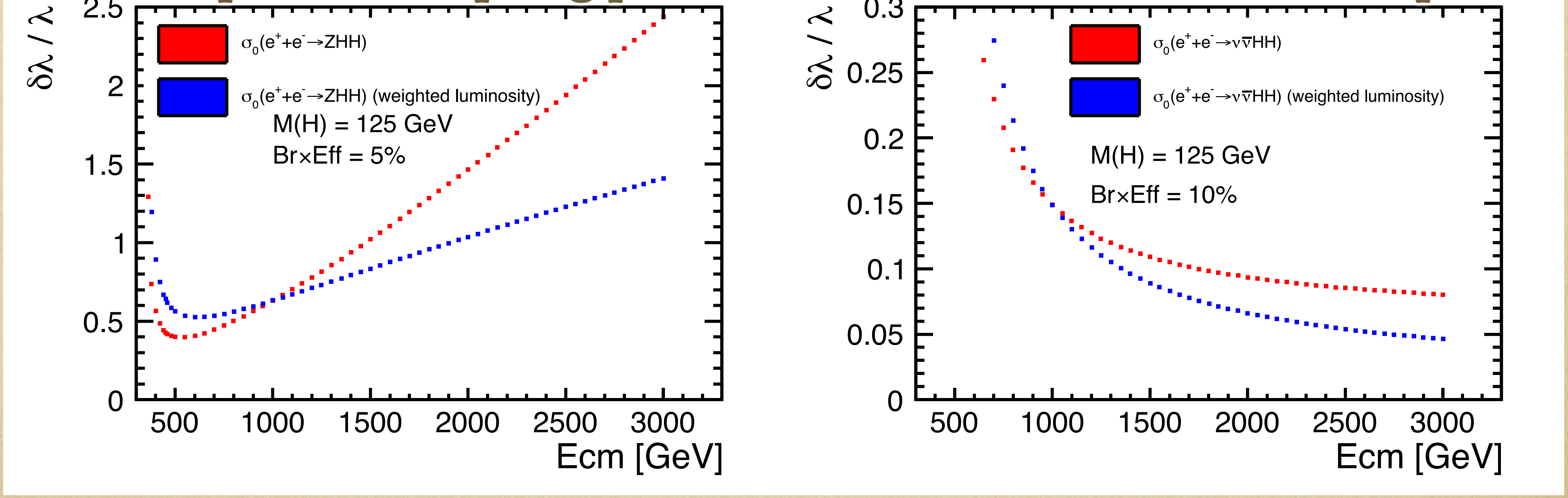
for ννHH, expected precision improves slowly as going to higher energy

General issue: cross sections of each contribution

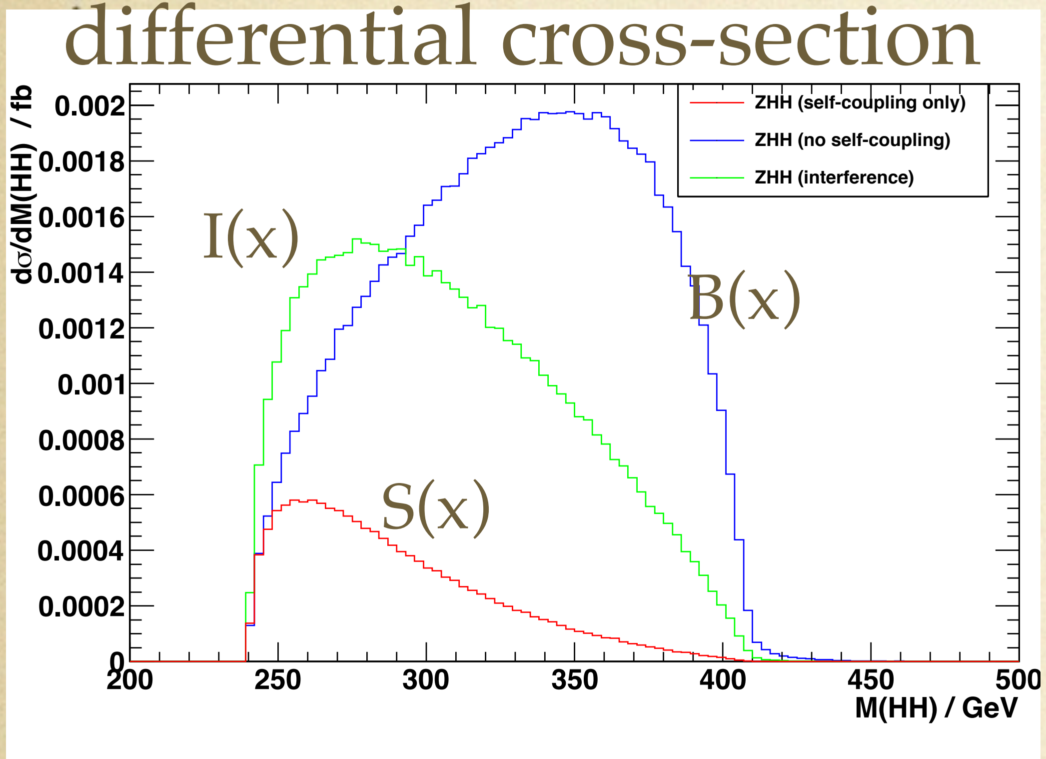
$$\sigma_0 = a\lambda^2 + b\lambda + c = \sigma_S + \sigma_I + \sigma_B$$



expected coupling precision with more realistic setup



new weighting method to enhance the coupling sensitivity

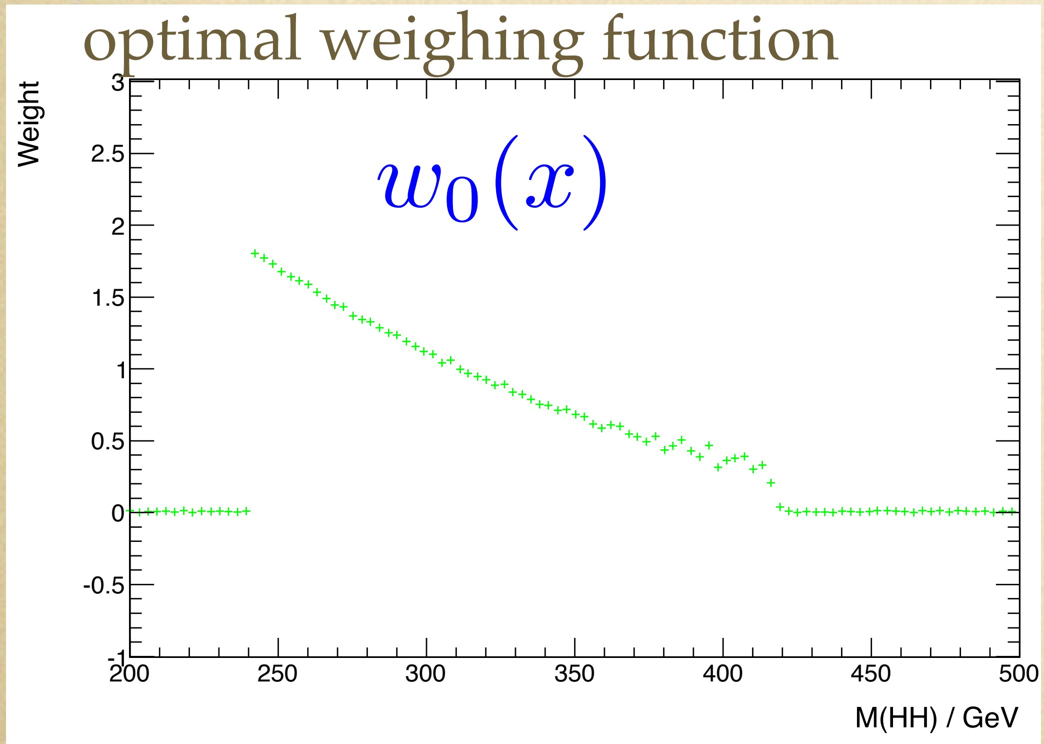

differential cross-section

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

irreducible interference self-coupling

observable: weighted cross-section

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


optimal weighing function

equation of the optimal w(x) (variance 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

Higgs Physics at Higher Energy

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

vvH @ at >1TeV : 2ab^-1 (pol e+, e-)=(+0.2,-0.8)

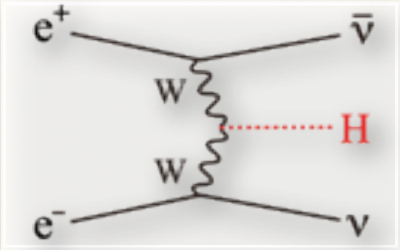
- allows us to measure rare decays such as H -> $\mu^+\mu^-$, ...
- further improvements of coupling measurements

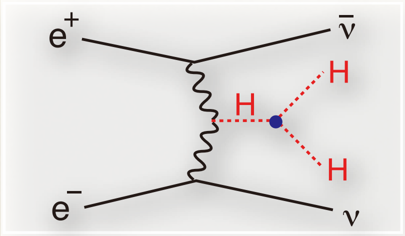
vvHH @ 1TeV or higher : 2ab^-1 (pol e+, e-)=(+0.2,-0.8)

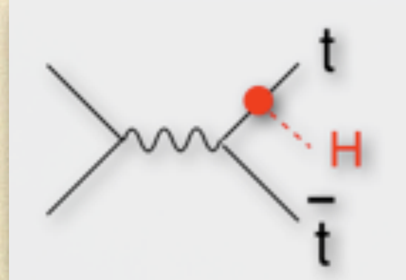
- self-coupling through WW-fusion.
- If possible, we want to see the running of the self-coupling (very very challenging).

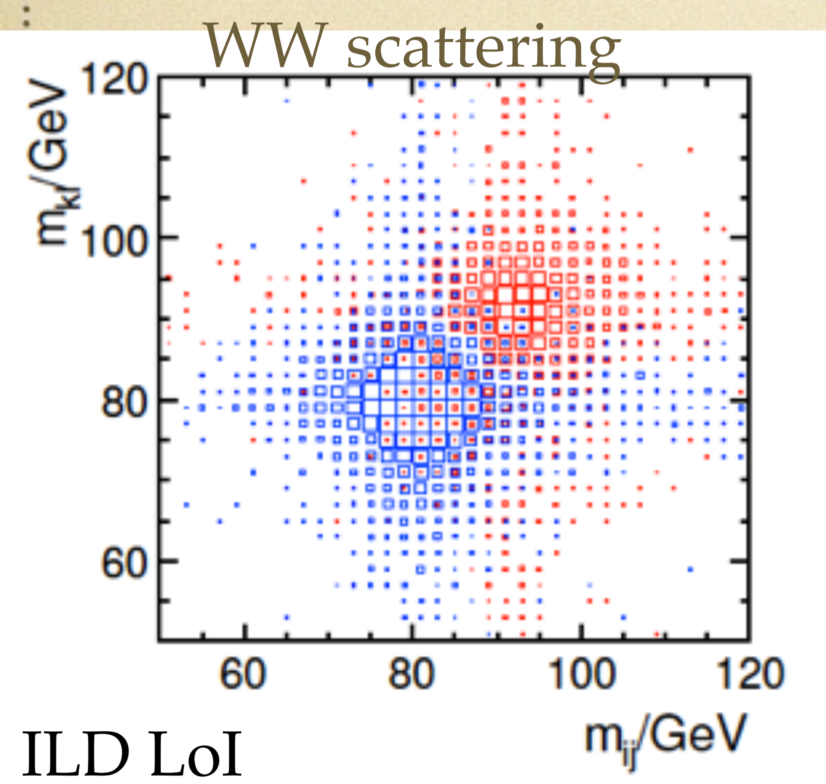
ttH @ 1TeV : 1ab^-1

- improve the top-Yukawa coupling









ILD LoI

Obvious but most important advantage of higher energies in terms of Higgs physics is its higher mass reach to other Higgs bosons expected in an extended Higgs sector and higher sensitivity to $W_L W_L$ scattering to decide whether the Higgs sector is strongly interacting or not.

In any case we can improve the mass-coupling plot by including the data at 1TeV!

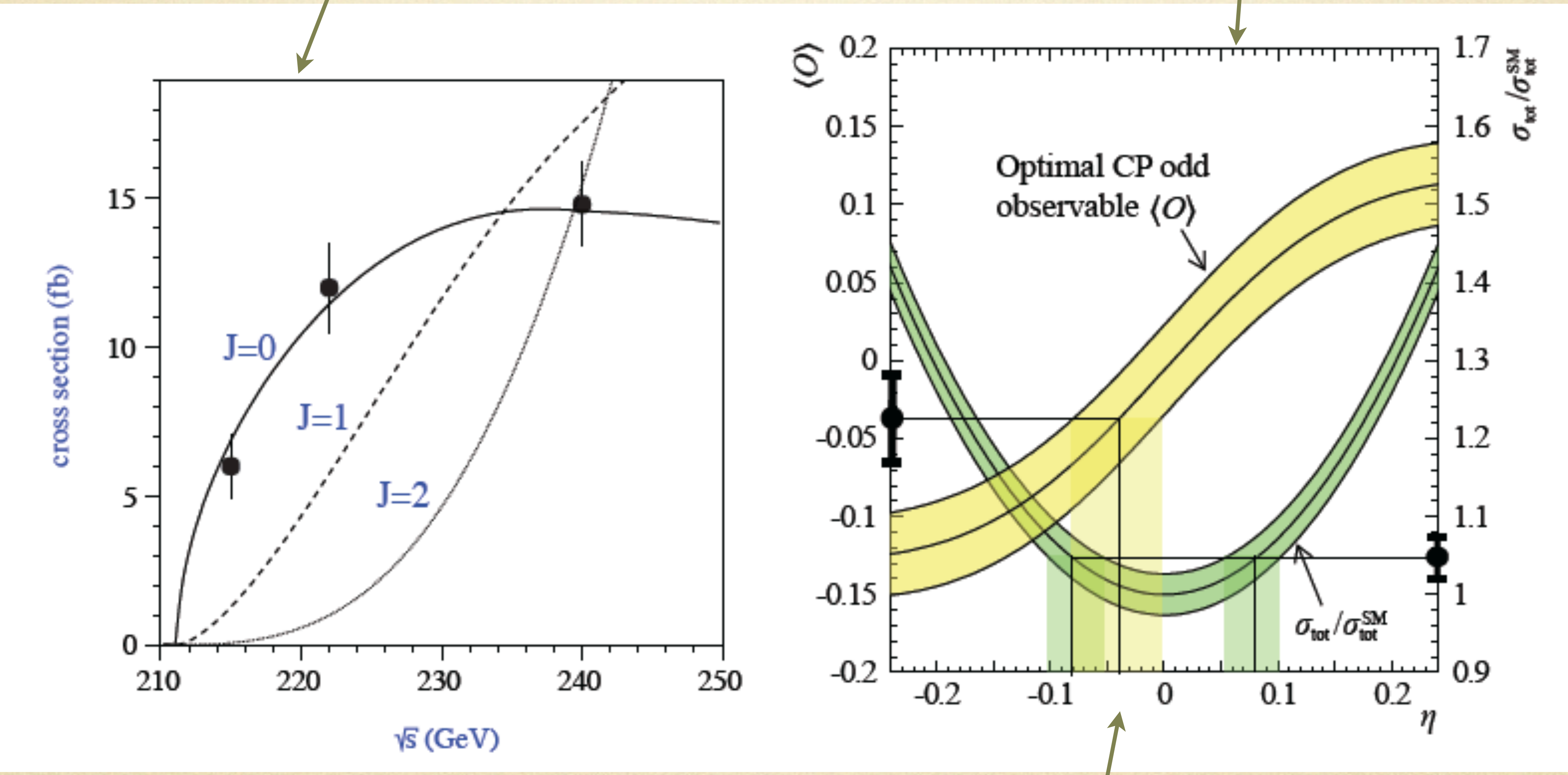
ILC 250 GeV

Quantum Numbers J^{CP}

in addition to the spin study by H-->ZZ* and WW*, ILC offers an orthogonal way and be able to measure the mixture of CP even and CP odd

three-20 fb^{-1}-points threshold scan

if a mixture of CP even and CP odd



precision measurement of the HZZ coupling, 500 fb^{-1} @ 350 GeV

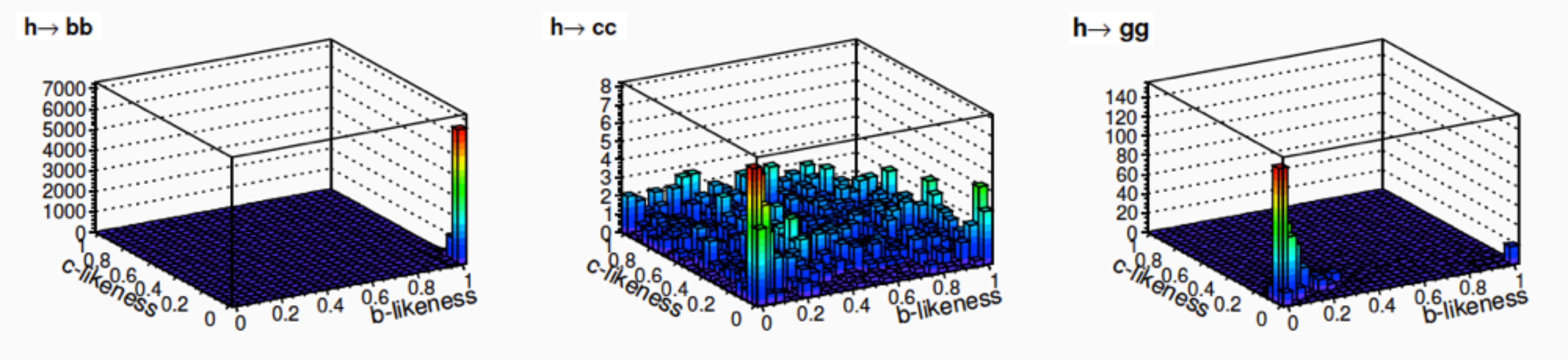
ref: DBD Physics Volume

--> few % of mixing angle

Branching ratios of H-->bb,cc,gg

each jet is tagged by a b-likeness and a c-likeness

patterns of the 2-D b-likeness and c-likeness



excellent b-tagging and c-tagging -->
template fitting can give the fractions
of Higgs to bb, cc, gg events

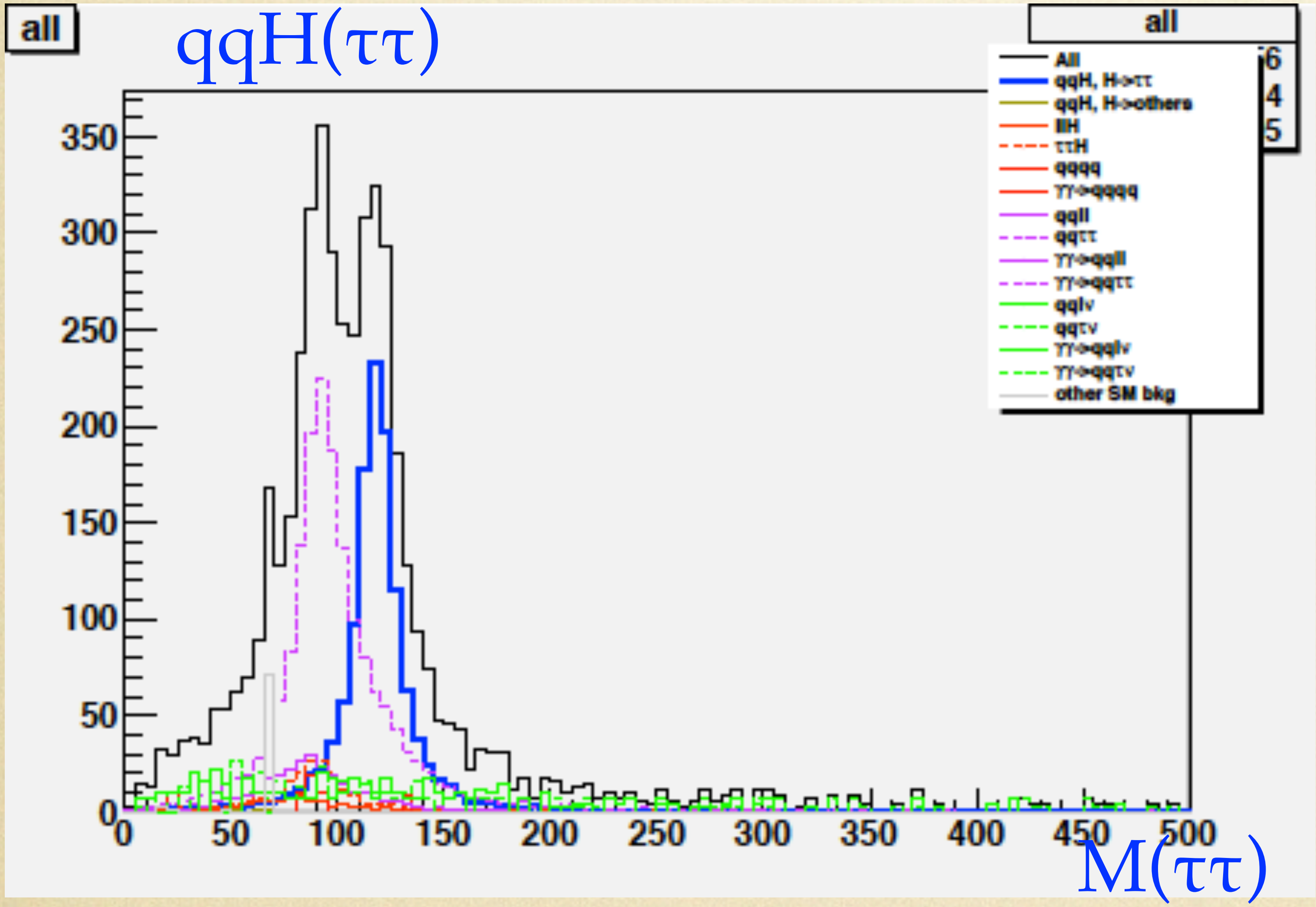
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to g\bar{g})$$

H. Ono @ LCWS12
Euro. Phys. J. C, 73, 2343

(LoI study, MH=120 GeV)

ILC 250 GeV

Branching ratios of H-->ττ



- full simulation (LoI study, MH = 120 GeV)
- 1-prong and 3-prongs τ-finder
- Z-->ll: recoil mass
- Z-->qq: collinear approximation

	$Z \to ee$	$Z \to \mu\mu$	$Z \to qq$	$Z \to \nu\nu$
significance	8.0σ	8.8σ	25.7σ	3.0σ

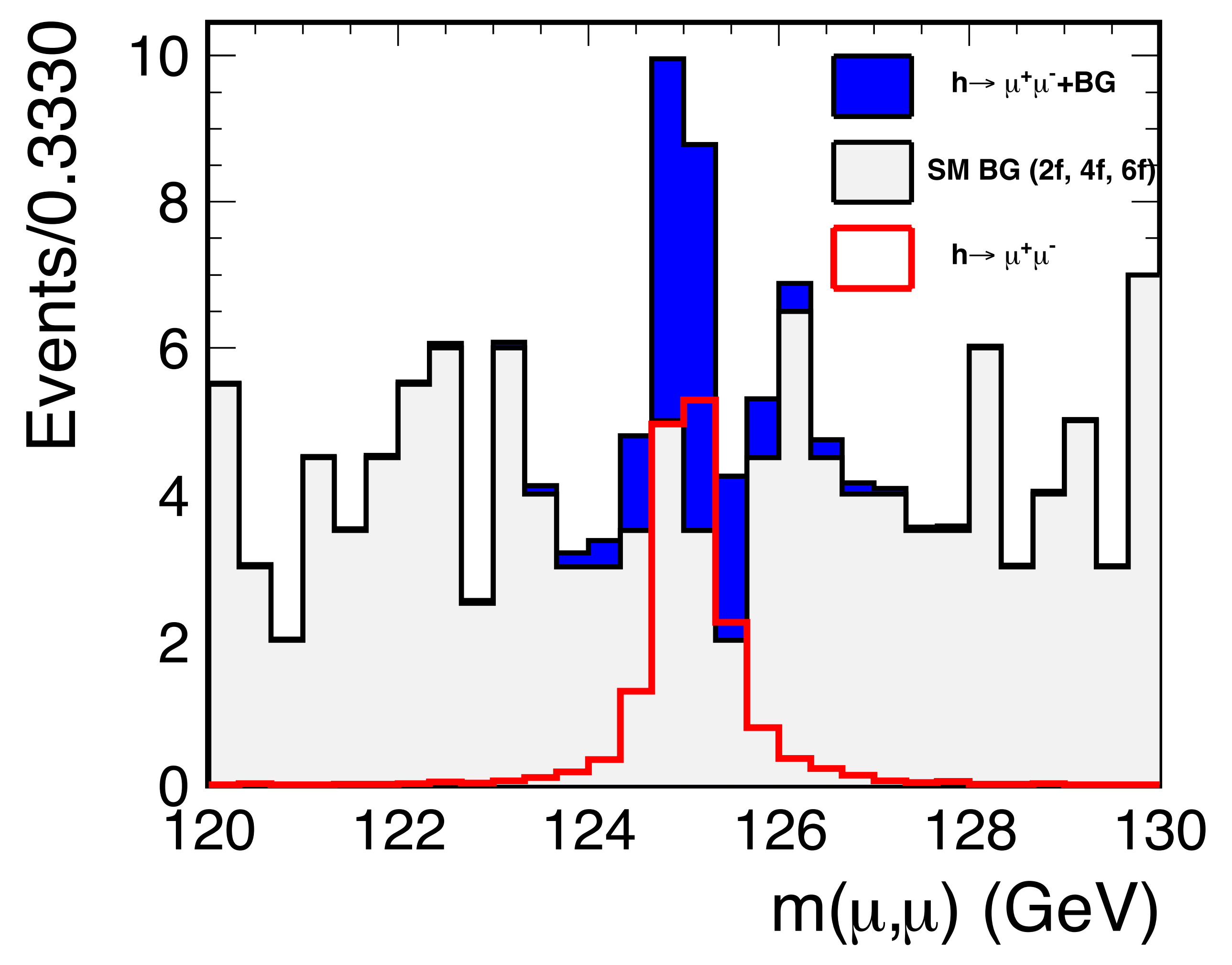
$$\frac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}} = 3.5\%$$

S. Kawada, et. al, LC-REP-2013-001

DBD full simulation

ILC 1 TeV

Branching ratio of H-->$\mu^+\mu^-$



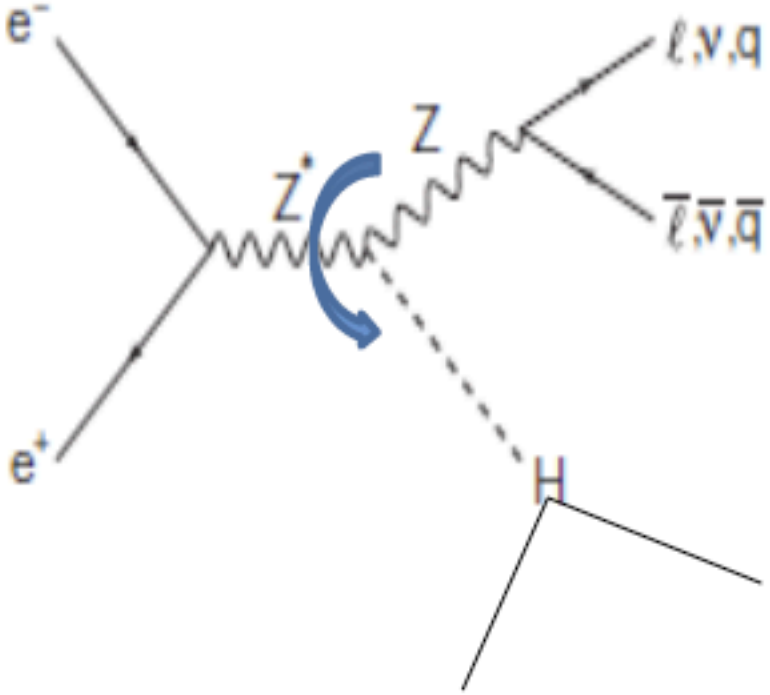
- rare decay
- low multiplicity
- clean and narrow mass peak
- main BG: ννZ, WW

C. Calancha @ LCWS12

$$\frac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}} = 31\% \text{ @ } 1\ \mathrm{ab}^{-1}$$

Invisible Higgs Decay

- In the SM, an invisible Higgs decay is H → ZZ* →4ν process and its BF is small ~0.1%
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - The decay products are dark matter candidates.



- At the LHC, one can search for invisible Higgs decays by using recoil mass from Z or summing up BFs of observed decay modes with some assumptions.
  - The upper limit is O(10%).
- At the ILC, we can search for invisible Higgs decays using a recoil mass technique with model independent way!
  - e+e- → ZH

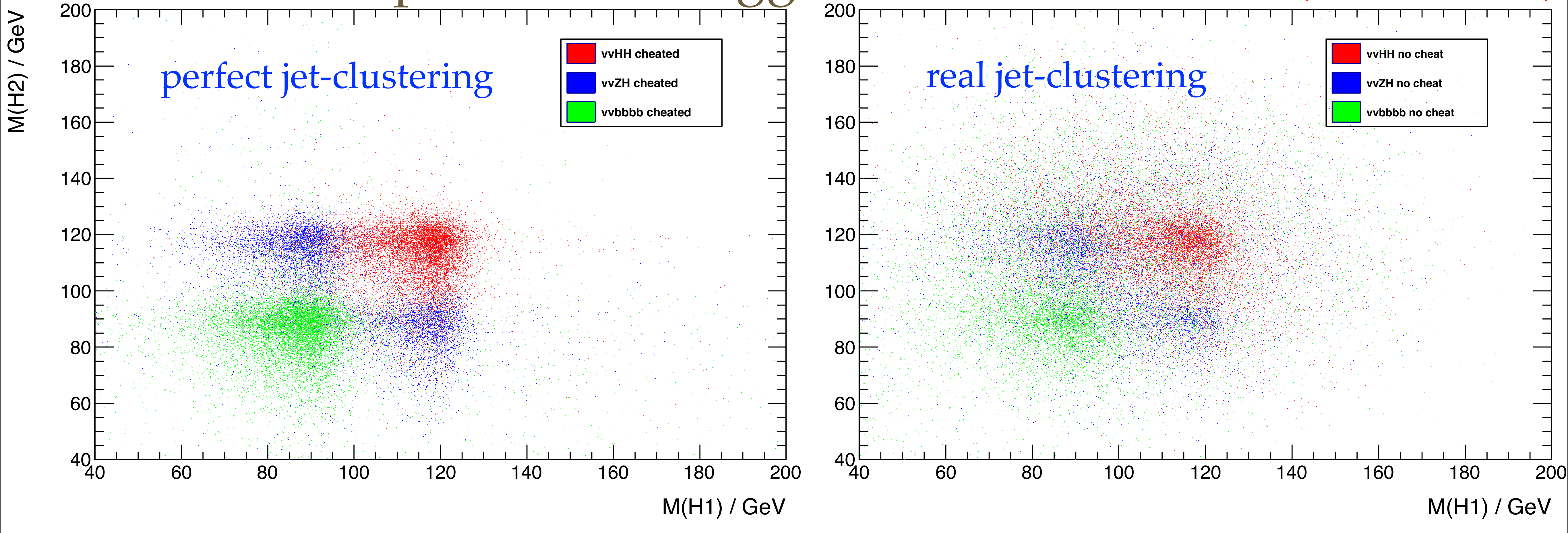
$$P_H = \underset{\text{known}}{\underset{\uparrow}{P_{e+e-}}} - \underset{\text{measured}}{\underset{\uparrow}{P_Z}}$$

A. Ishikawa @ Snowmass, Seattle

prospect of Higgs self-coupling

scatter plot of two Higgs masses

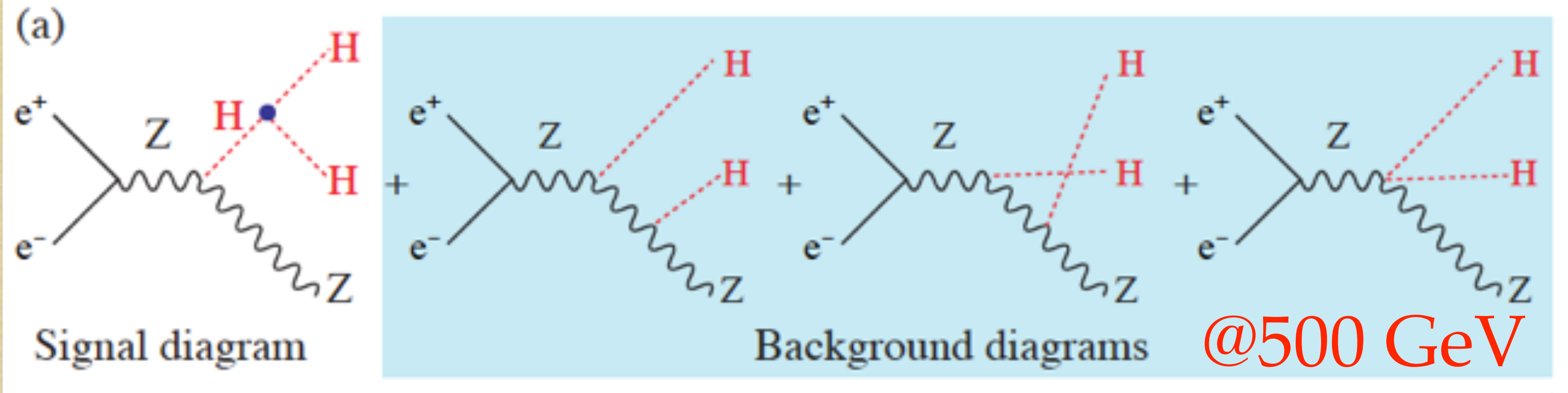
vvHH mode: (ZZH and ZZZ)



- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve δλ ~ 40%
- Mini-jet based clustering (Durham works when Np in mini-jet ~ 5, need better algorithm to combine the mini-jets, using such as color-singlet dynamics)
- looks very challenging now...
- including H-->WW* (ongoing)
- kinematic fitting

new couplings to be added: g_{ZZHH}, g_{WWHH}

---would be unique at Linear Collider



Signal diagram

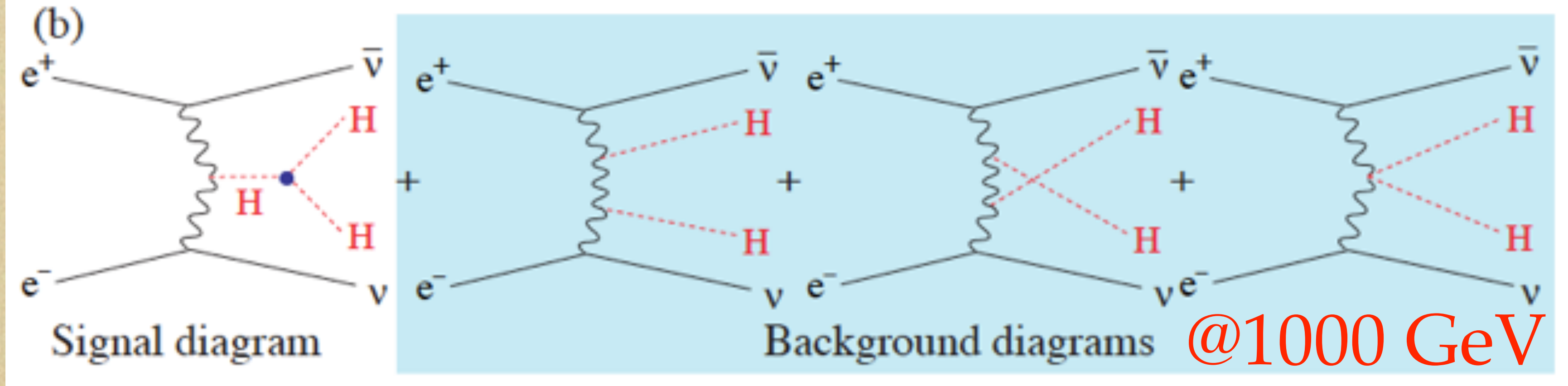
Background diagrams

@500 GeV

more sensitive!

$$\frac{\delta\lambda_{HHH}}{\lambda_{HHH}} = 1.8\frac{\delta\sigma_{ZHH}}{\sigma_{ZHH}}$$

$$\frac{\delta g_{ZZHH}}{g_{ZZHH}} = 0.97\frac{\delta\sigma_{ZHH}}{\sigma_{ZHH}}$$



Signal diagram

Background diagrams

@1000 GeV

$$\frac{\delta\lambda_{HHH}}{\lambda_{HHH}} = 0.85\frac{\delta\sigma_{\nu\bar{\nu}HH}}{\sigma_{\nu\bar{\nu}HH}}$$

$$\frac{\delta g_{WWHH}}{g_{WWHH}} = 0.29\frac{\delta\sigma_{\nu\bar{\nu}HH}}{\sigma_{\nu\bar{\nu}HH}}$$

coupling	500 GeV		500 GeV + 1 TeV	
HHH	104%	58%(LU)	26%	16% (LU)
ZZHH	62%		30%	
WWHH	-		11%	

preliminary! correlation with HHH not included