Higgs Measurements at the ILC

Junping Tian (KEK)

Tohoku Forum for Creativity Oct. 21-25, 2013 @ Sendai

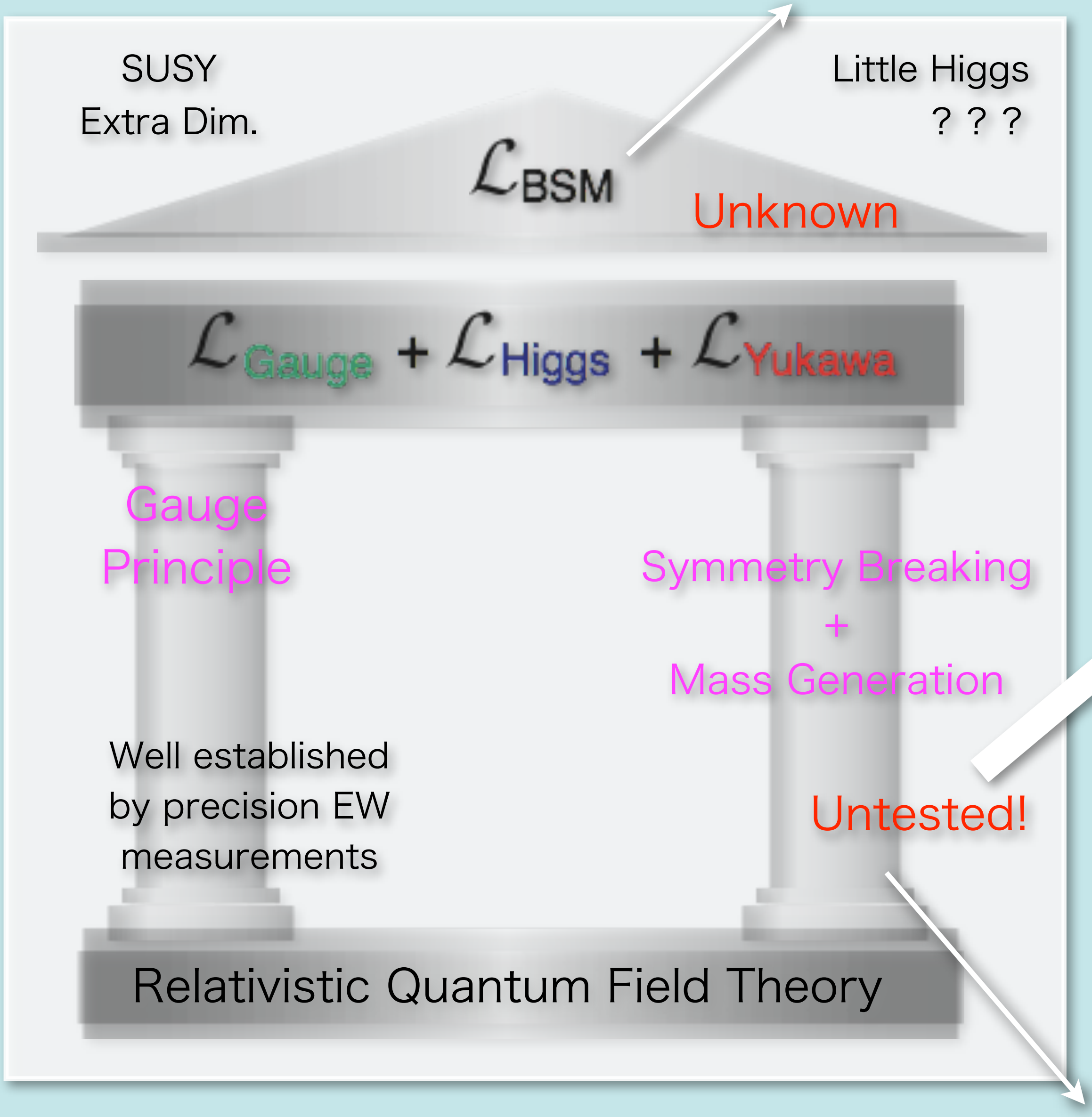
Ref: ILC TDR Physics Volume, ILC Higgs White Paper

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

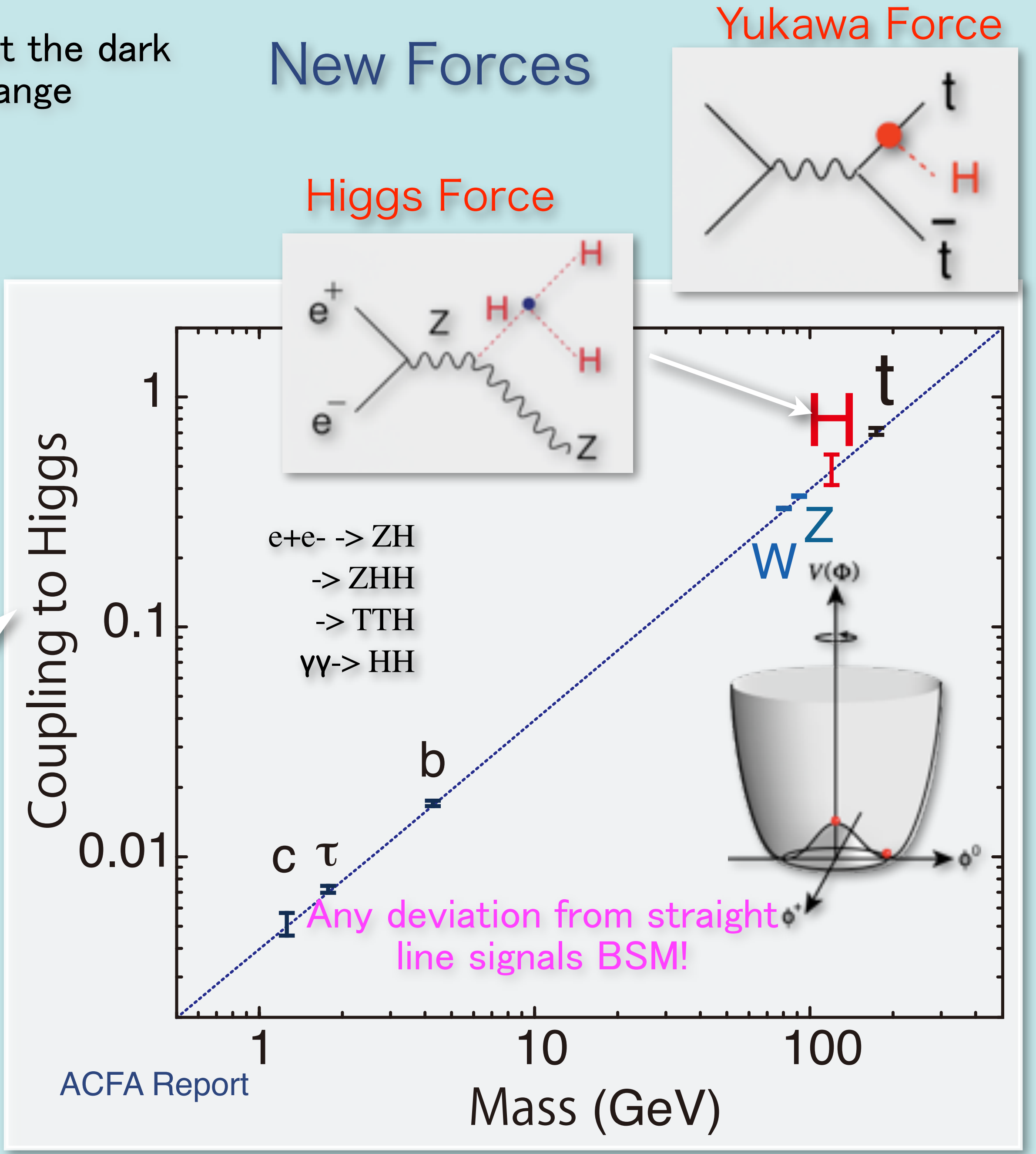
Symmetry Breaking
+
Mass Generation

Well established by precision EW measurements

Untested!

Relativistic Quantum Field Theory

New Forces



e+e- -> ZH
-> ZHH
-> TTH
γγ-> HH

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!

not necessary the minimal solution

- 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?

	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
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

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

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

Mixing with singlet

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

Composite Higgs

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

SUSY

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

Expected deviations are small --> Precision!

see Shinya's talk

Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

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

test new decay, CP mixture

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

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

crucial to test the mass coupling proportionality

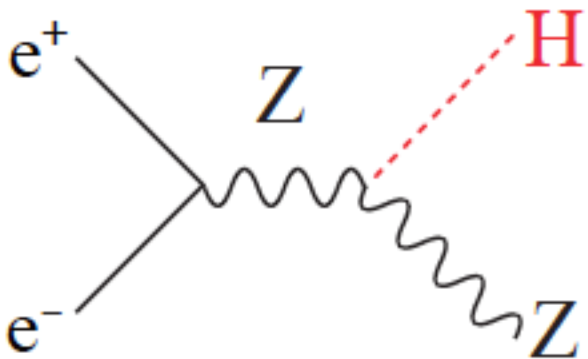
L_{Loop} $h\gamma\gamma \quad hgg \quad h\gamma Z$

sensitive to the new particles in the loop

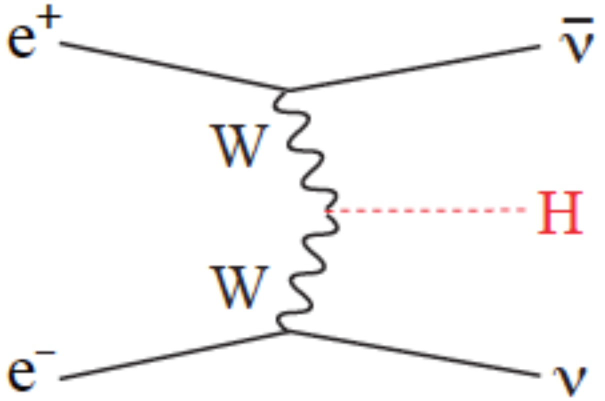
the second pillar, secret of EWSB, will be fully uncovered

Higgs Production and Decay @ ILC

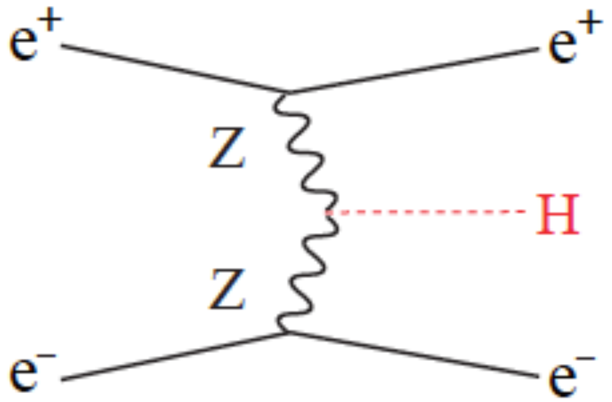
no lose theorem



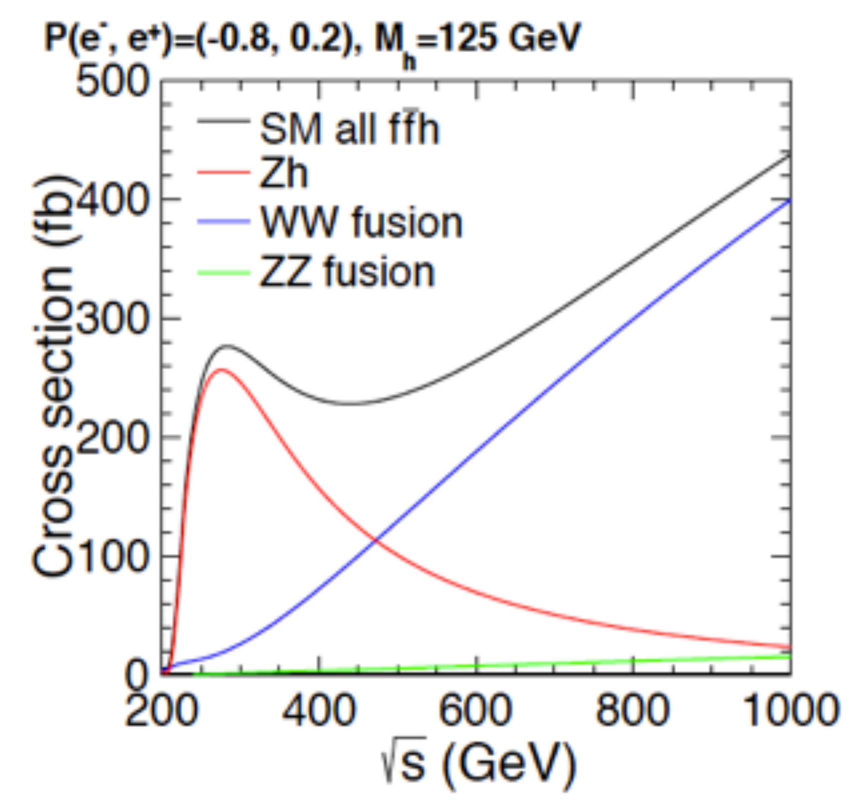
Higgs-strahlung

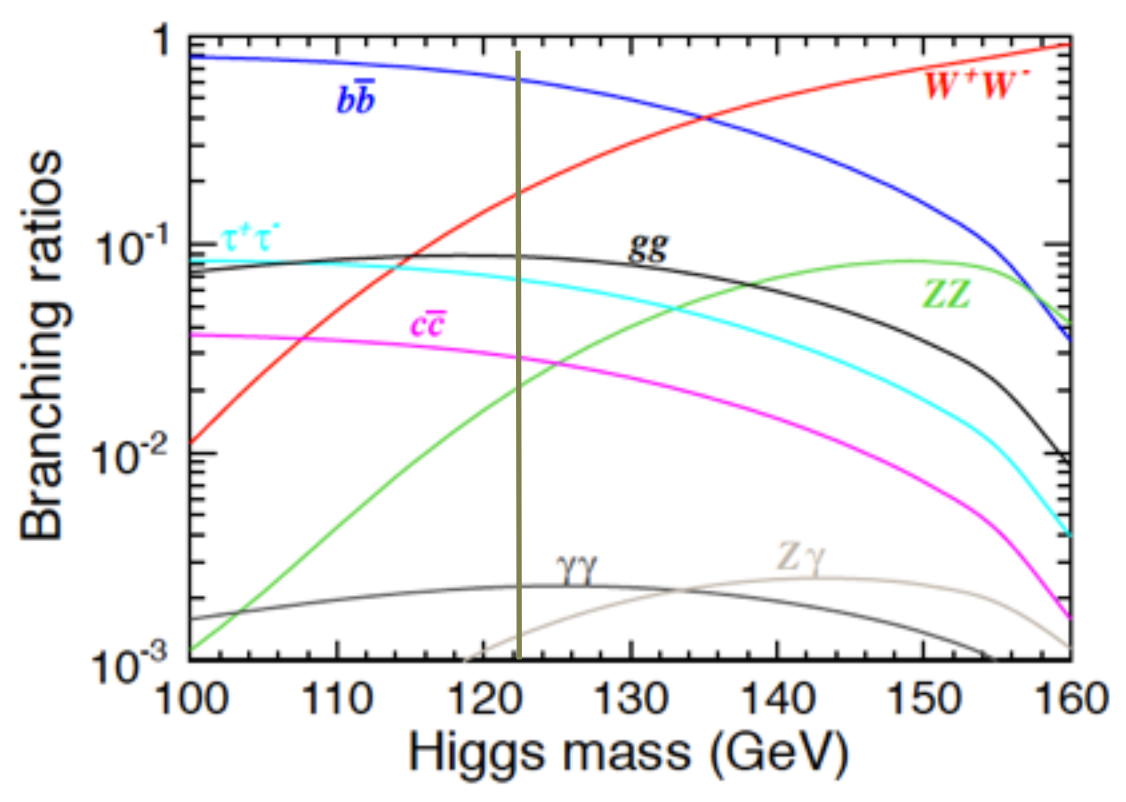


WW-fusion



ZZ-fusion





- ✓ HZZ, HWW observed at LHC --> sufficient production rate
- ✓ 125 GeV + clean environment --> most decay modes accessible

expected branching ratio values from LHC Higgs cross section working group

A staged running program (why 250-500 GeV?)

three well-known threshold

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

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

beam polarisation like a luminosity doubler!

(canonical / upgraded luminosity)

state-of-art detector performance achievable by ILD

Particle Flow Algorithm, High Granularity, ~4π Coverage

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

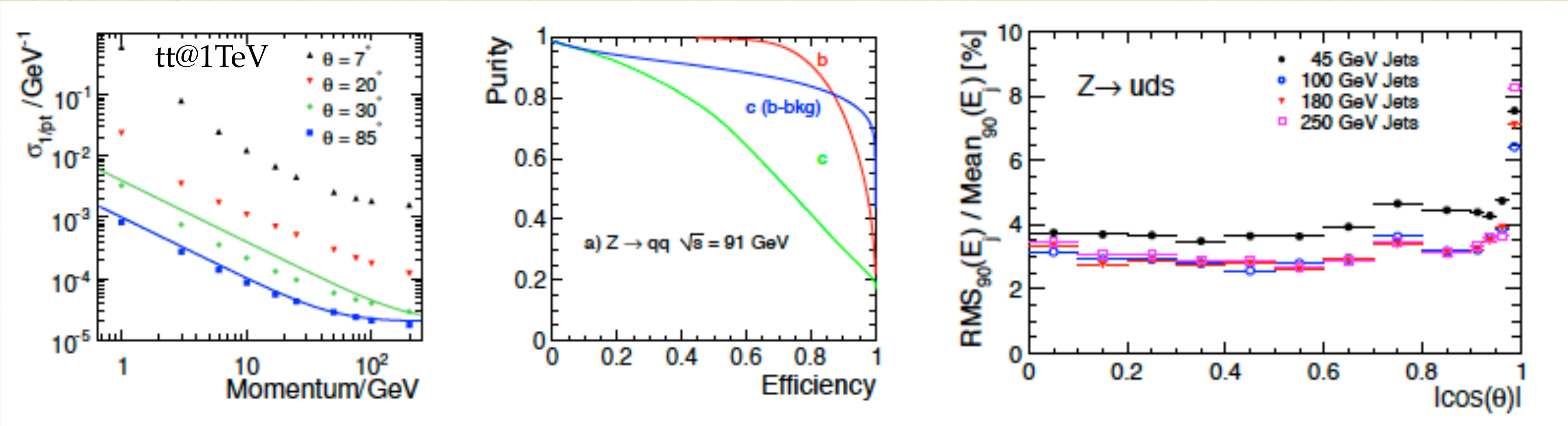
- driven by recoil mass measurement ZH-->l^+l^-X.

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).

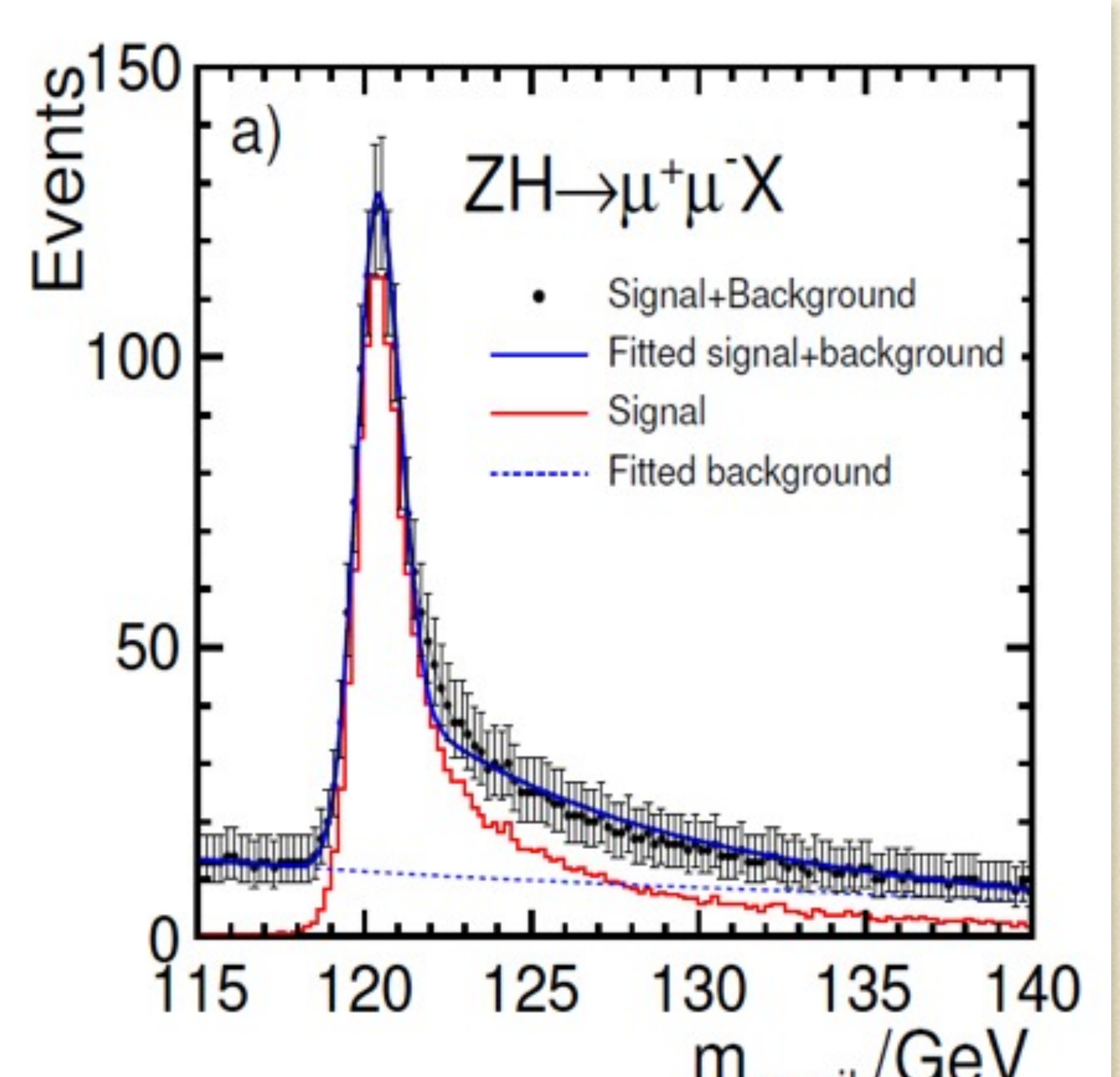


ILC 250 GeV

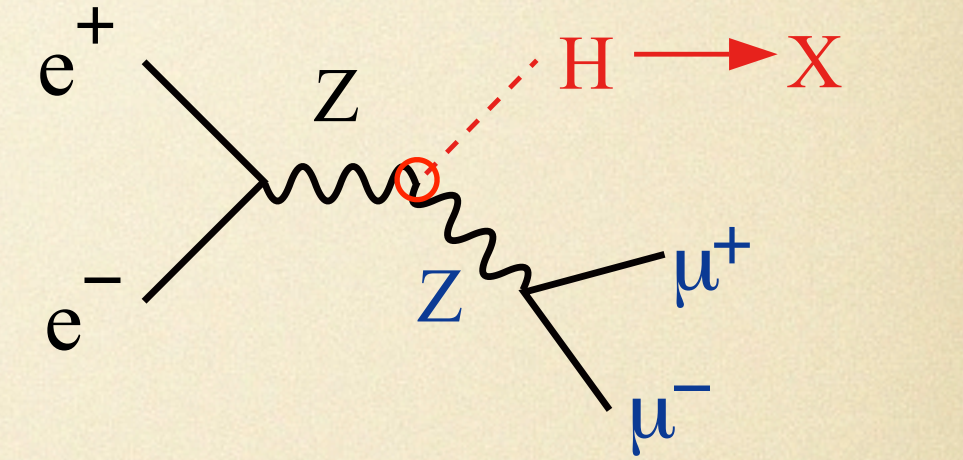
mass and HZZ coupling

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!

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

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

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

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

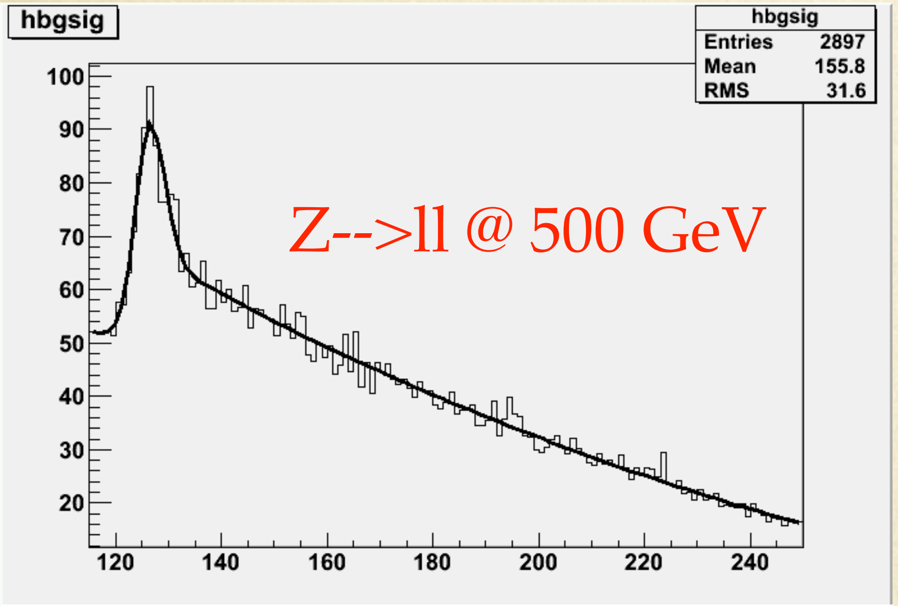
(Z-->ee combined)

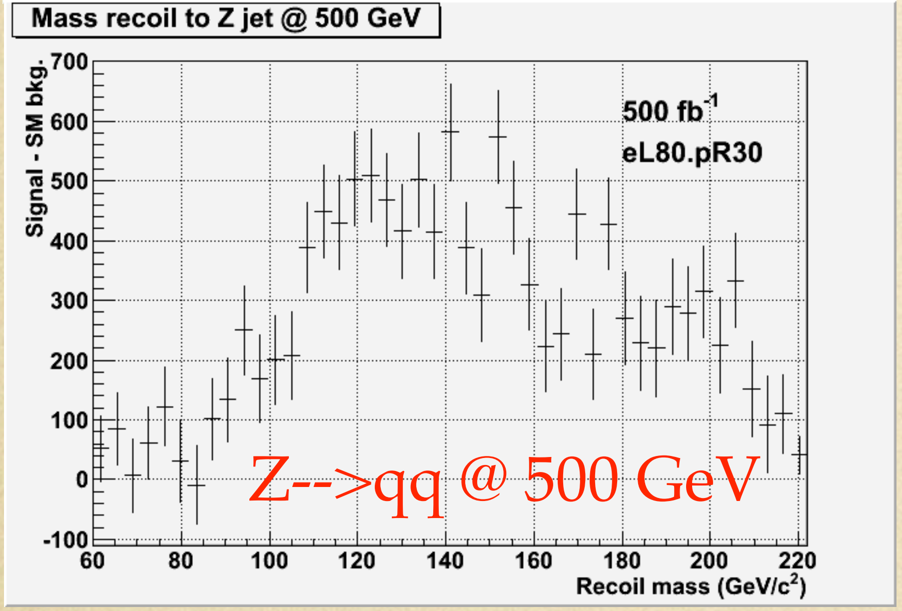
$Y_1 = \sigma_{ZH} \propto g_{HZZ}^2$ ---> Model-independent absolute measurement of the HZZ coupling

$g_{HZZ} \propto \sqrt{Y_1}$

H-->invisible: A. Ishikawa @ Snowmass-seattle

recoil against Z-->ll,qq at 500 GeV





S. Watanuki, T. Suehara,
A. Miyamoto

study ongoing, preliminary

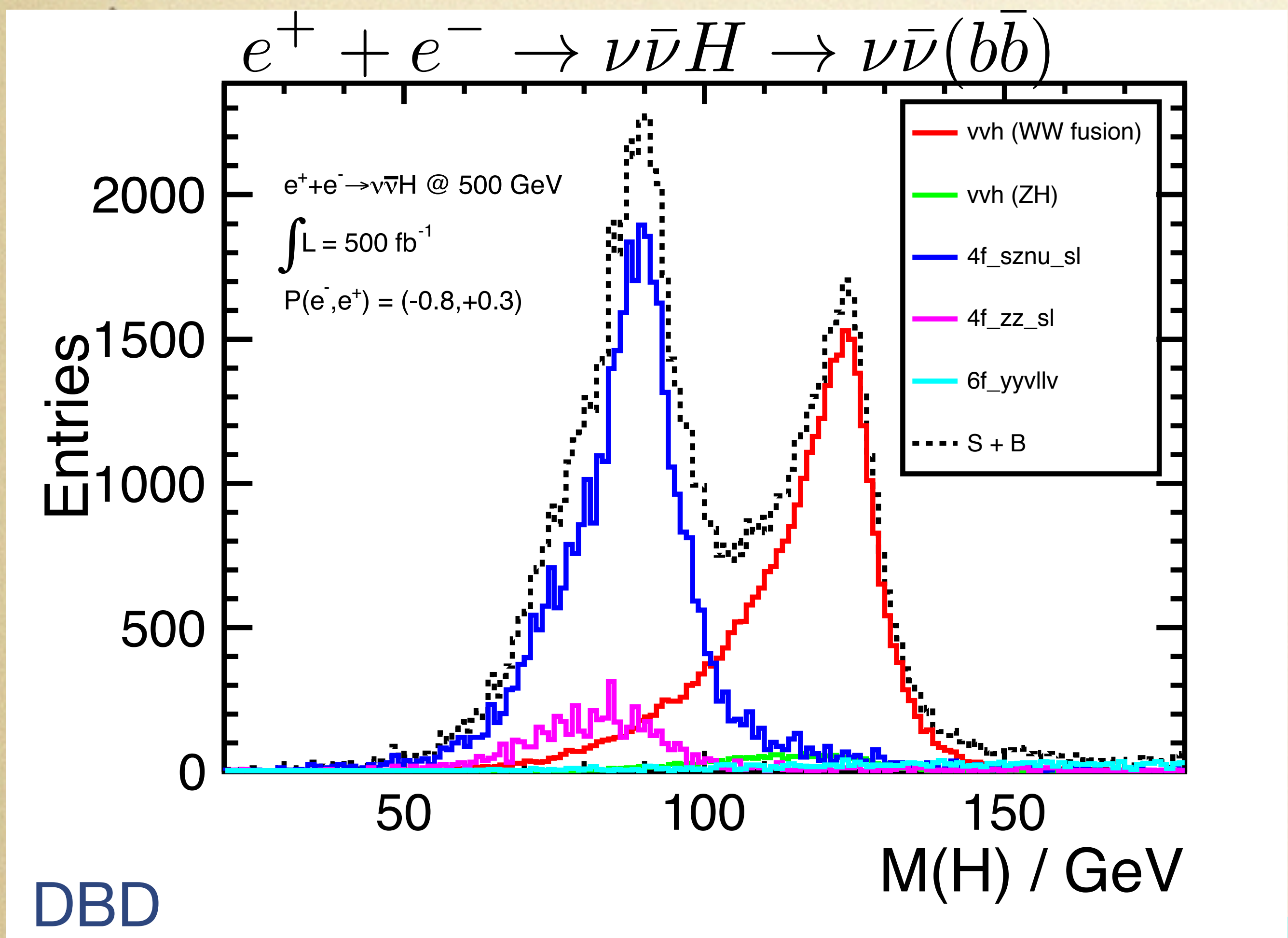
- performance using Z-->ll depends on momentum resolution, which is usually worse at higher energy, but partly compensated by higher luminosity
- recoil technique can be also applied to Z-->qq mode, more boostted at higher energy, better separation between Z and H decay products

$\Delta g_{HZZ}/g_{HZZ}$	250 GeV	+ 500 GeV
Baseline	1.3%	1.0%
LumiUP	0.61%	0.51%

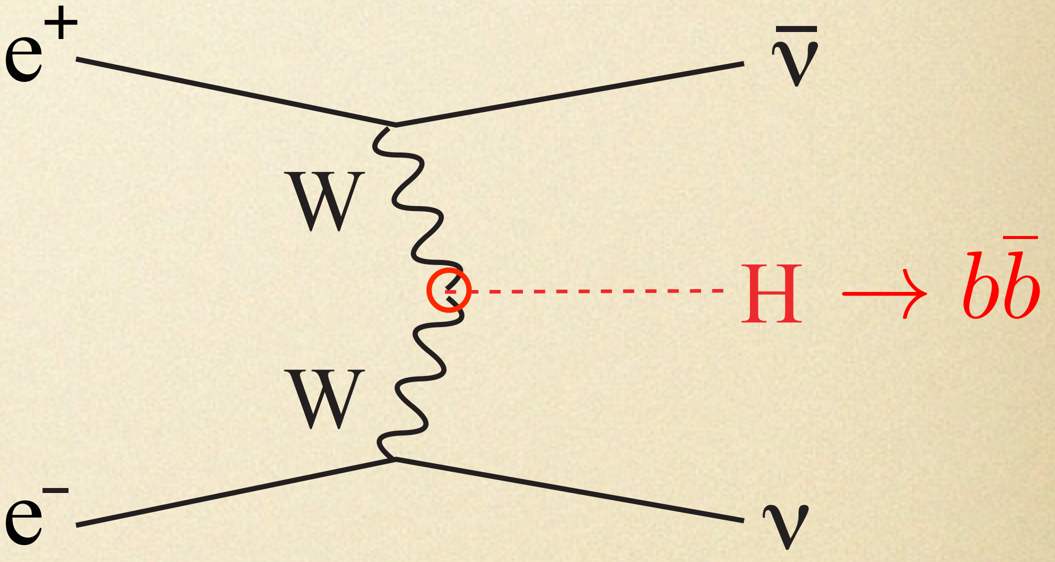
ILC 500 GeV

HWW coupling

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



DBD



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

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

Y_2/Y_3 gives accurate test of g_{HWW}/g_{HZZ}, and with g_{HZZ} gives absolute normalization of g_{HWW}.

$\Delta g_{HWW}/g_{HWW}$	250 GeV	+ 500 GeV
Baseline	4.8%	1.2%
LumiUP	2.3%	0.58%

$$g_{HWW} \propto \sqrt{\frac{Y_2}{Y_3}} \cdot g_{HZZ} \propto \sqrt{\frac{Y_1 Y_2}{Y_3}}$$

C. Durig, J. Tian, et al. LC-REP-2013-022

ILC 500 GeV

Higgs total width Γ_H

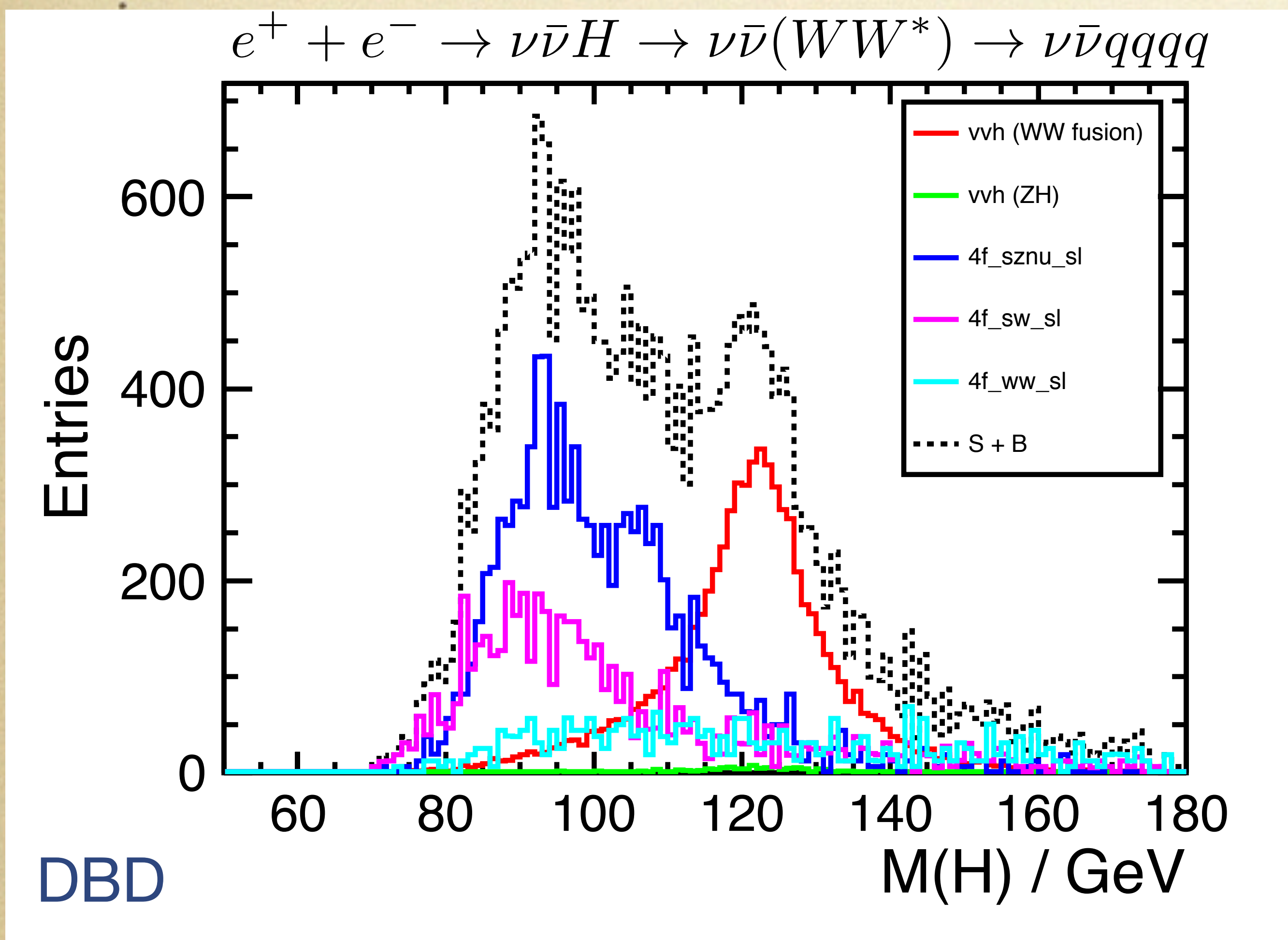
model free, one of the great advantages of ILC

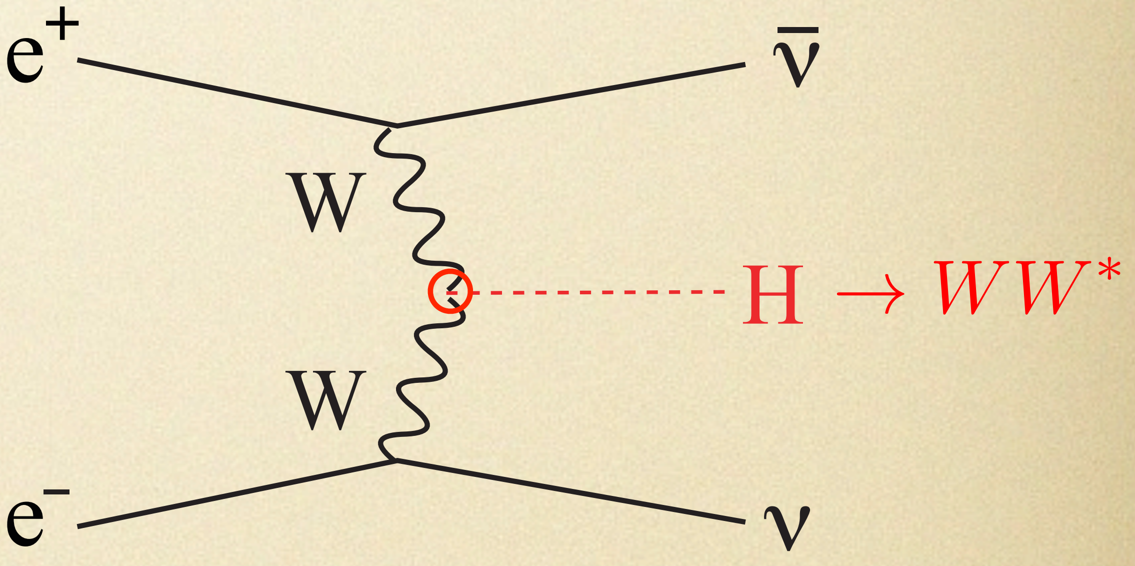
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

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

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

better option





$$Y_4 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_0}$$

Y_4 and g_{HWW} gives Higgs total width --> absolute normalization of other couplings.

$\Delta\Gamma_H/\Gamma_H$	250 GeV	+ 500 GeV
Canonical	11%	5.0%
LumiUP	5.4%	2.5%

$$\Gamma_H \propto \frac{g^4_{HWW}}{Y_4} \propto \frac{Y_1^2 Y_2^2}{Y_3^2 Y_4}$$

C. Durig, J. Tian, et al. LC-REP-2013-022

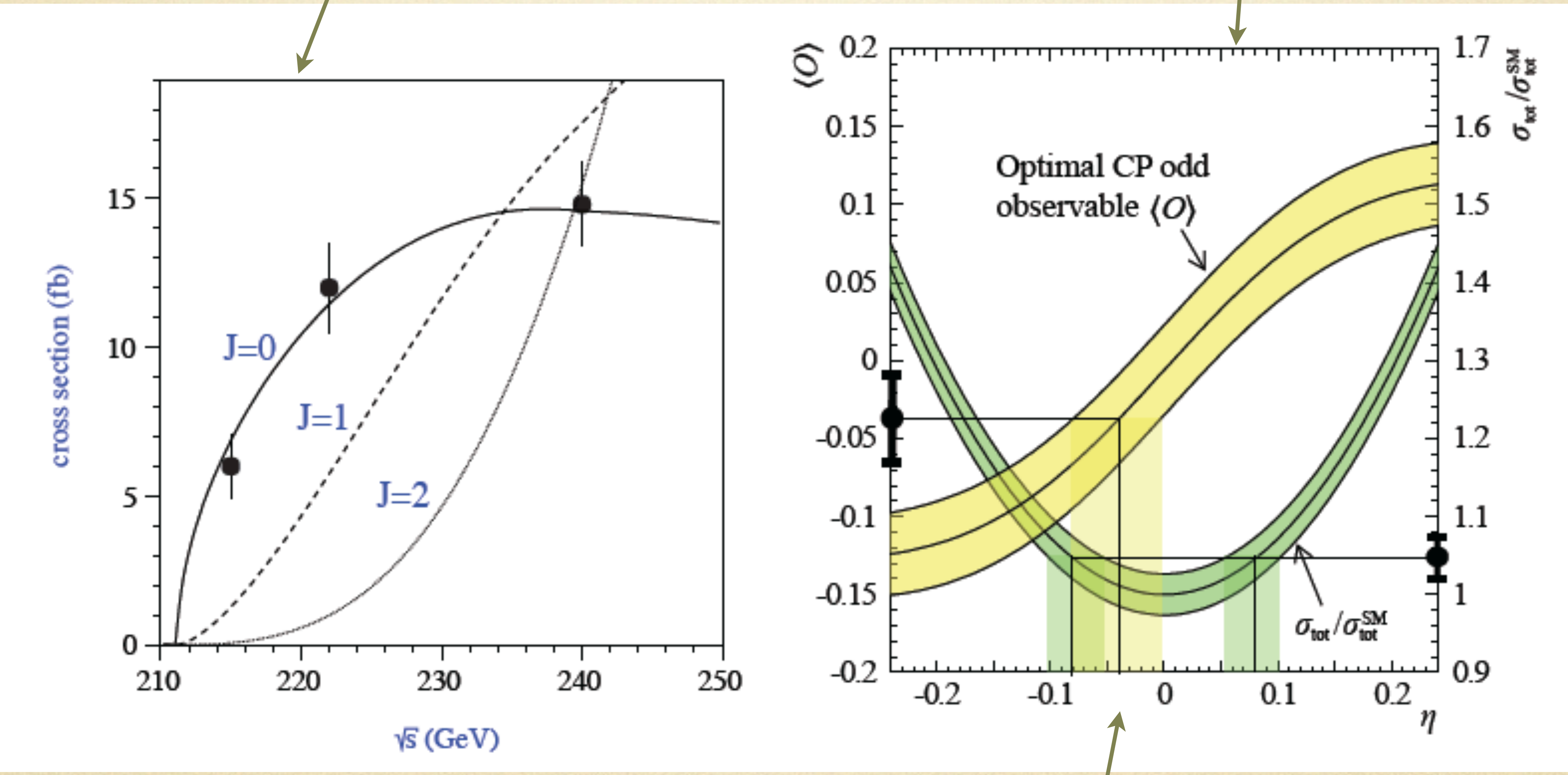
ILC 250 GeV

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: Physics Volume

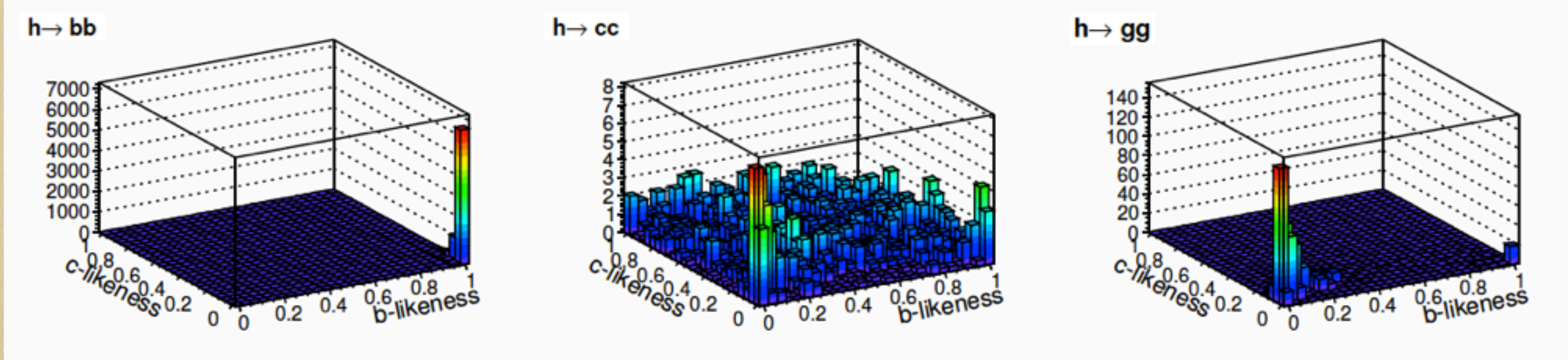
--> few % of mixing angle

ILC 250 GeV

H-->bb,cc,gg

b-tagging and c-tagging performance is crucial

patterns of the b-likeness .vs. c-likeness



template fitting can give the fractions of Higgs to bb, cc, gg events

	accuracy
$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$	1.2%
$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$	8.3%
$\sigma_{ZH} \cdot \mathrm{Br}(H \to g\bar{g})$	7.0%

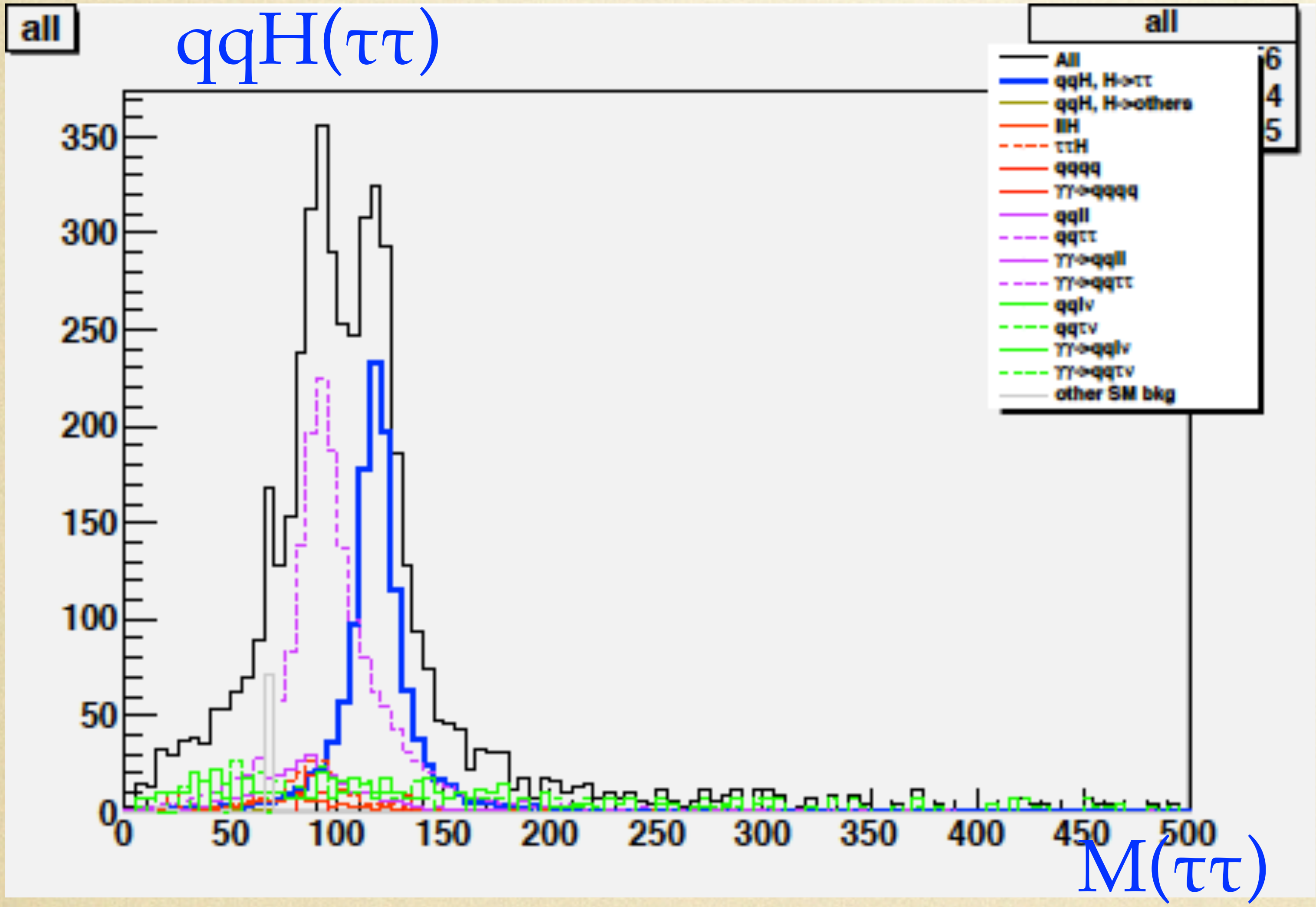
(Baseline)

H. Ono, A. Miyamoto
Euro. Phys. J. C, 73, 2343

ILC 250 GeV

H-->ττ

CP study ongoing



- 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

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

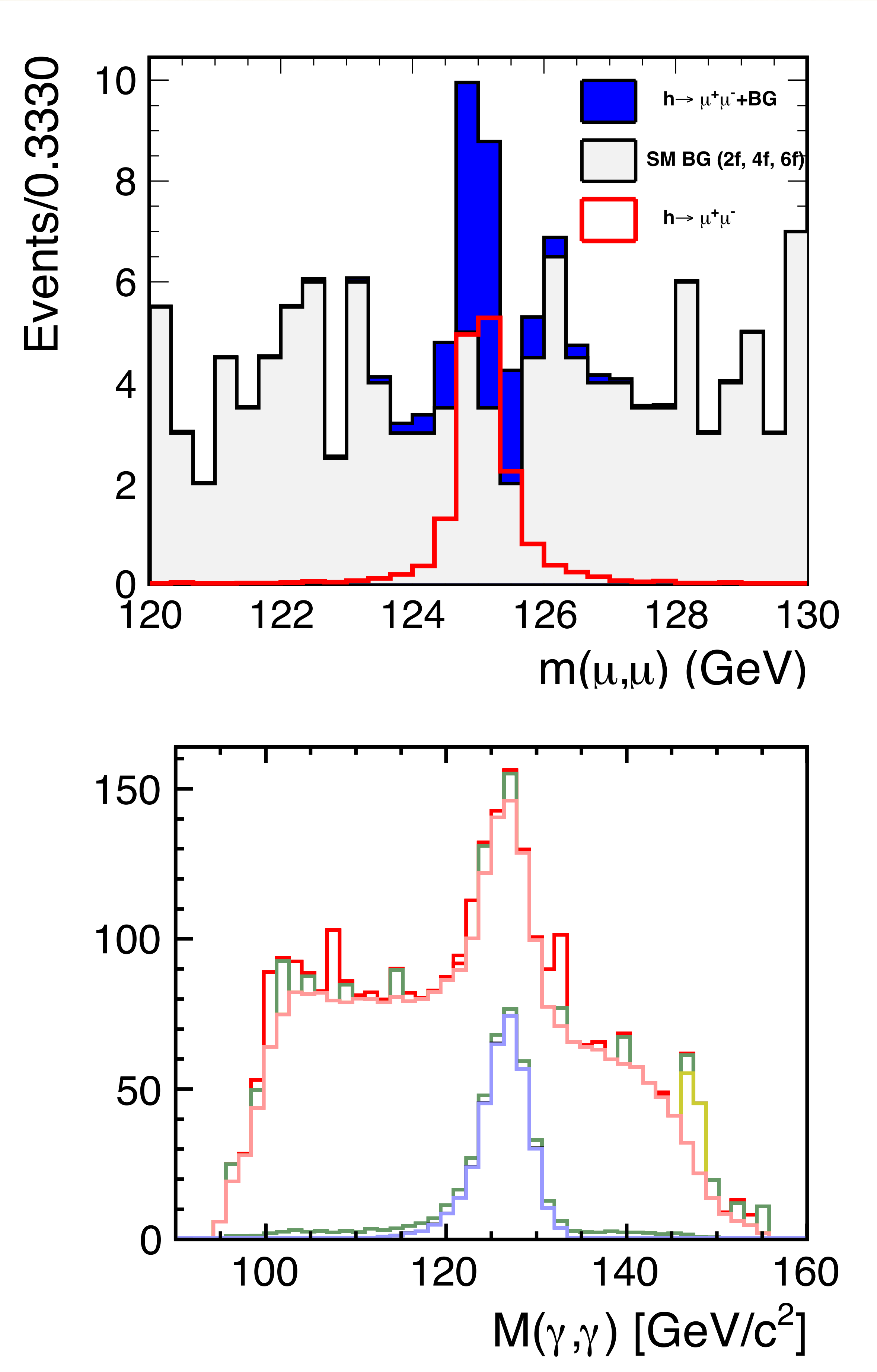
(Baseline)

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

ILC 1 TeV

H-->γγ, $\mu^+\mu^-$

ongoing, preliminary



- rare decay
- low multiplicity
- clean and narrow mass peak
- need enough statistics

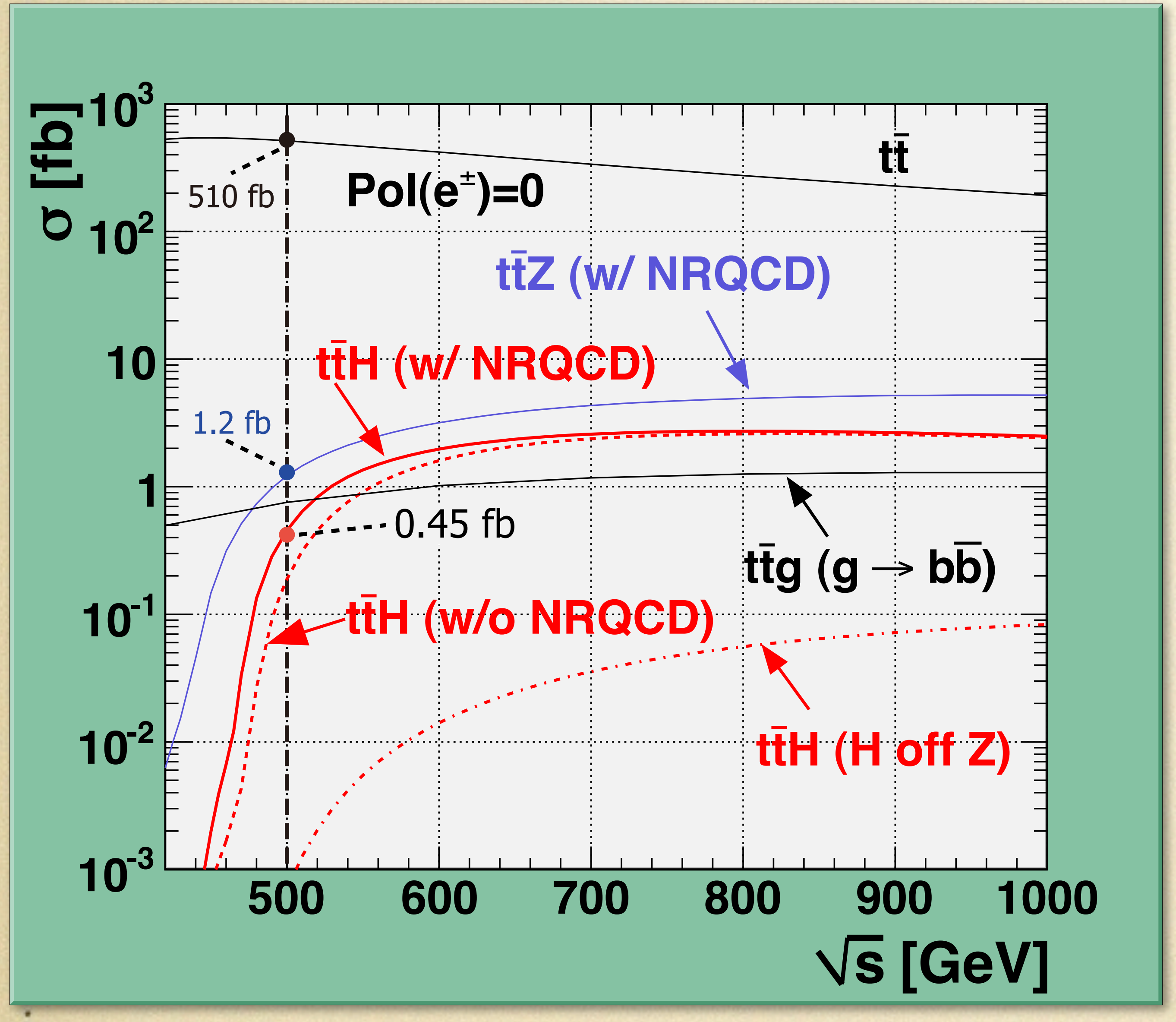
Baseline	accuracy
$\sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to \mu^+\mu^-)$	31%
$\sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to \gamma\gamma)$	10%

C. Calancha, LC-REP-2013-006

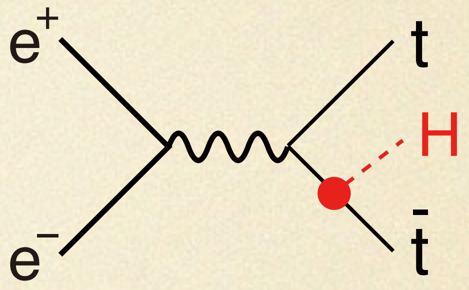
ILC 500 GeV & 1 TeV

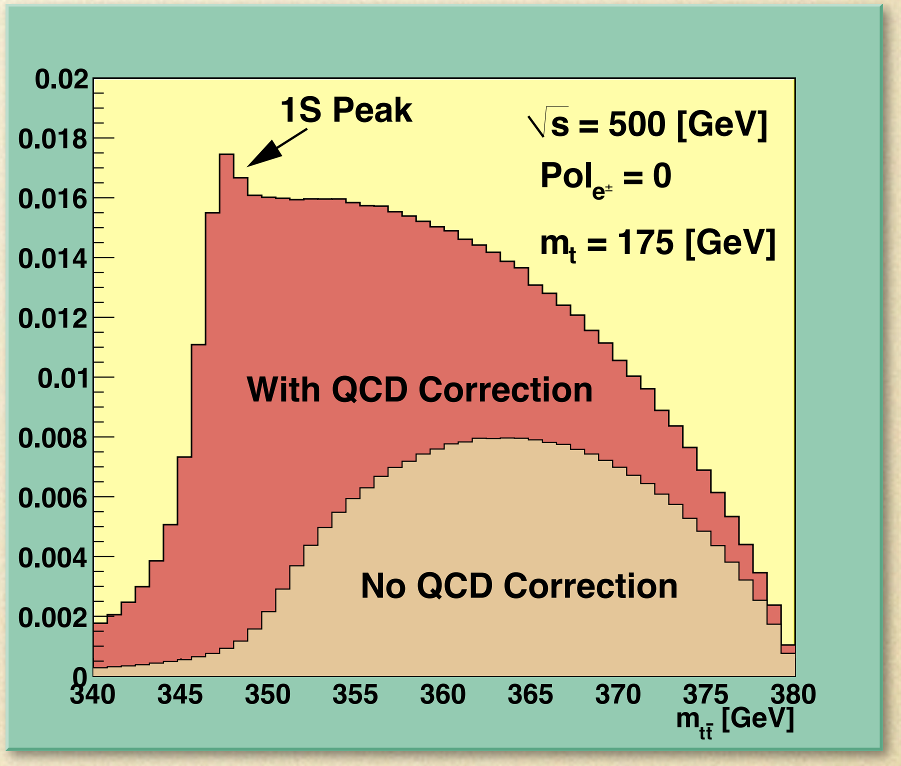
Top Yukawa Coupling

The largest among matter fermions



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





A factor of 2 enhancement from QCD bound-state effects

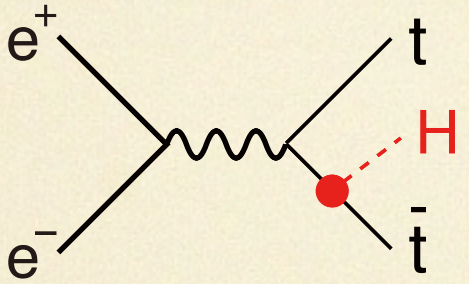
R. Yonamine, et. al, Phys.Rev. D84 (2011) 014033, confirmed by full simulation

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

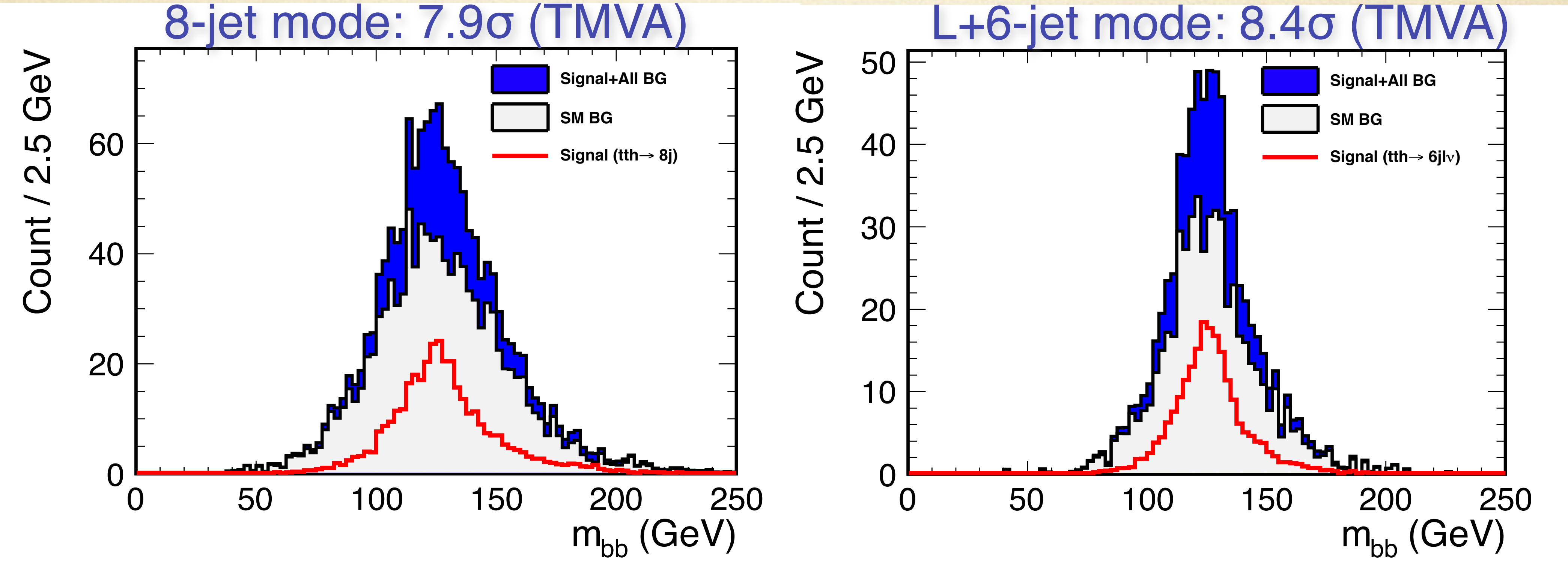
ILC 1 TeV

Top Yukawa Coupling

The largest among matter fermions



H-> bb


8-jet mode: 7.9σ (TMVA)

L+6-jet mode: 8.4σ (TMVA)

$\Delta g_{Htt}/g_{Htt}$	500 GeV	+ 1 TeV
Baseline	14%	3.1%
LumiUP	7.8%	1.9%

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

Higgs self-coupling measurement

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

physical Higgs field

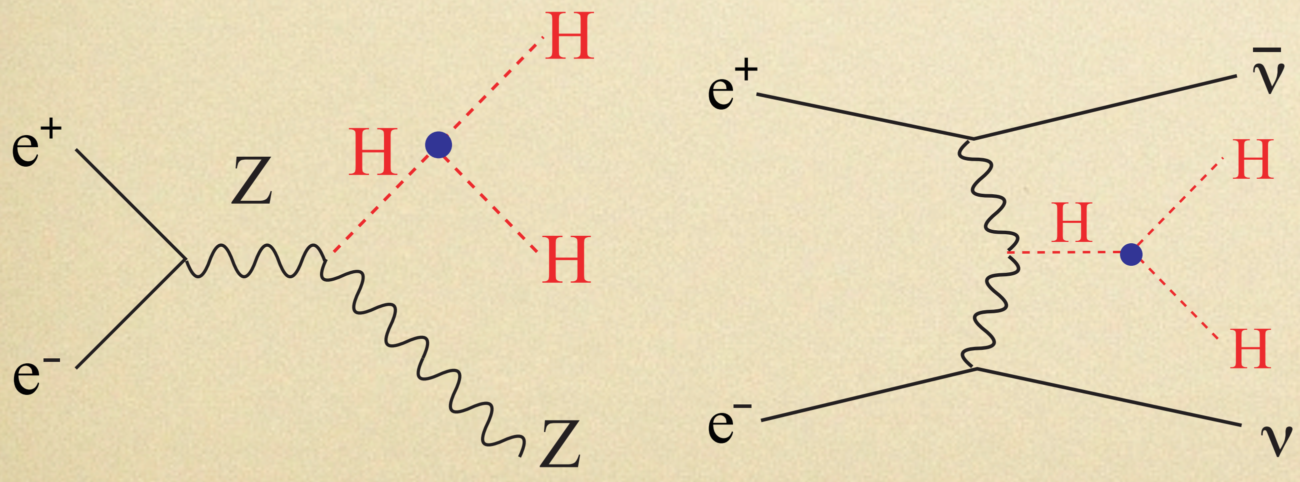
mass term

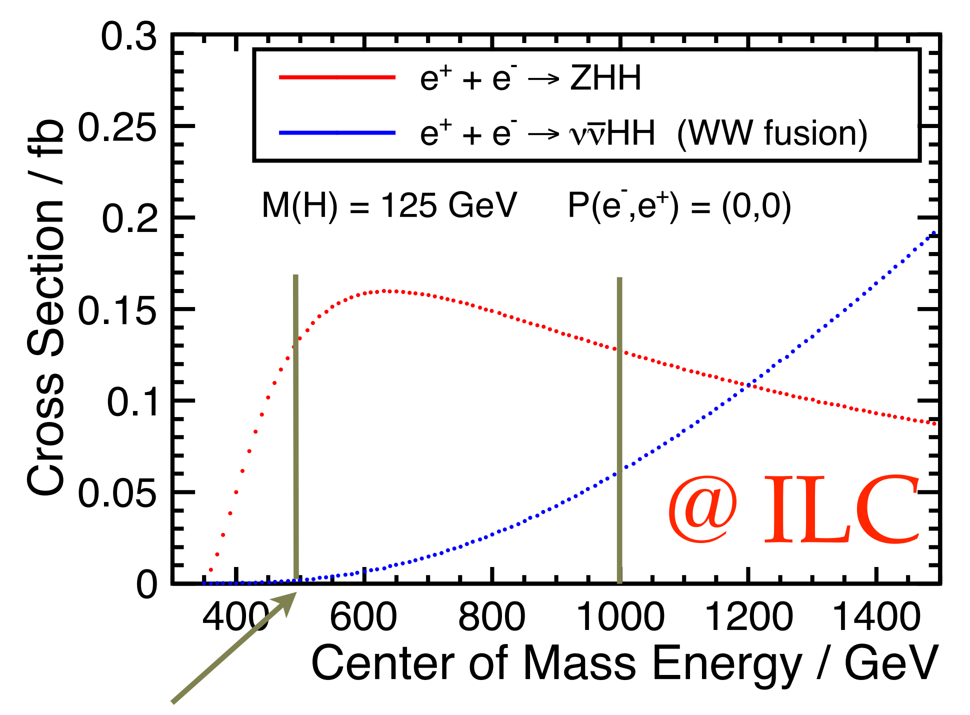
trilinear coupling

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.





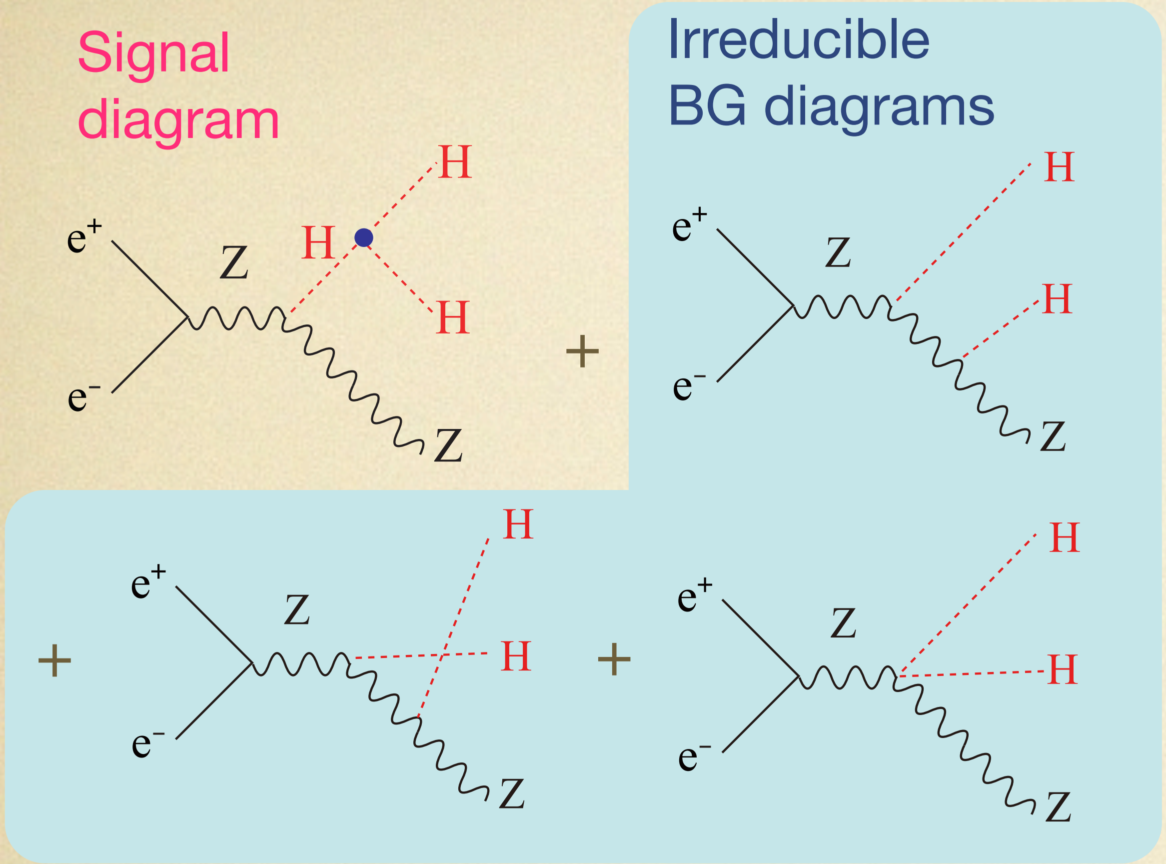
one of the reasons why 500 GeV

General issue: sensitivity of coupling to the cross section

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

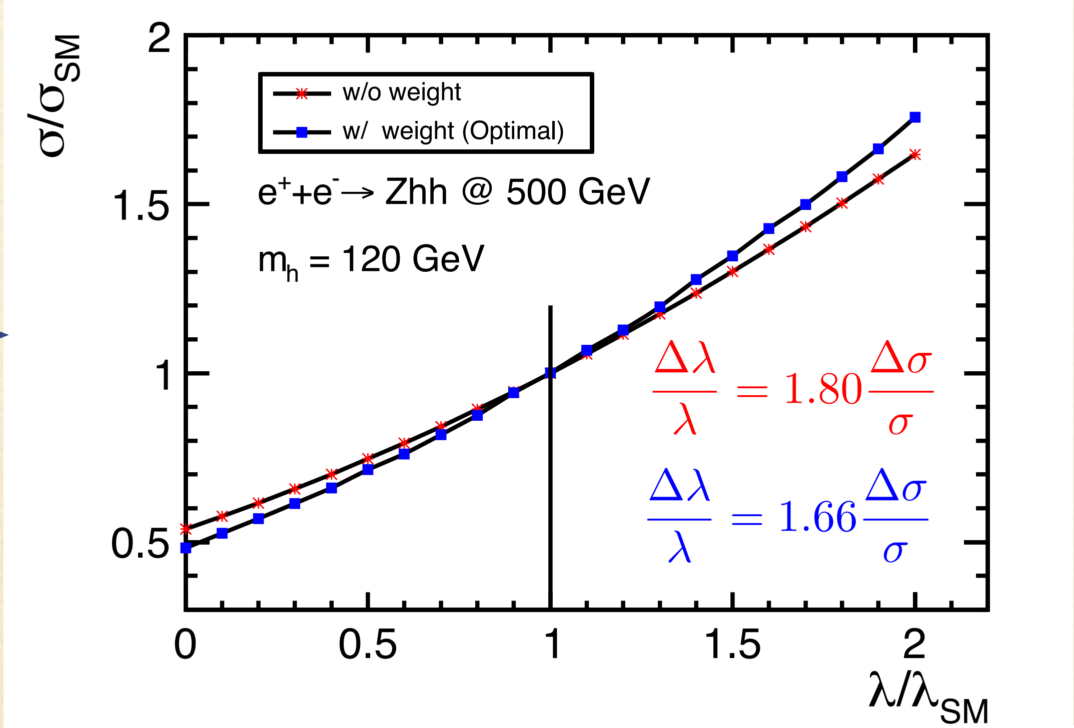
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

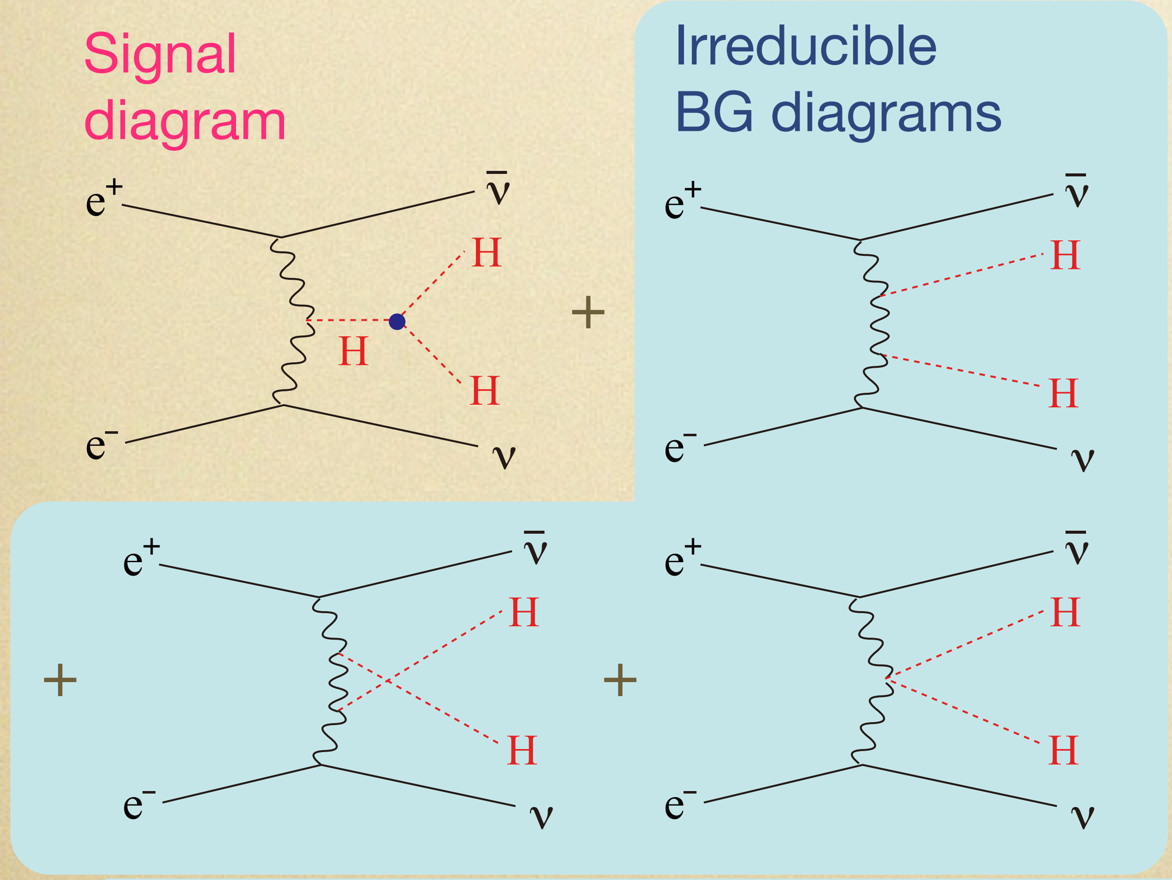
F=0.5 if no BG diagrams



Signal diagram

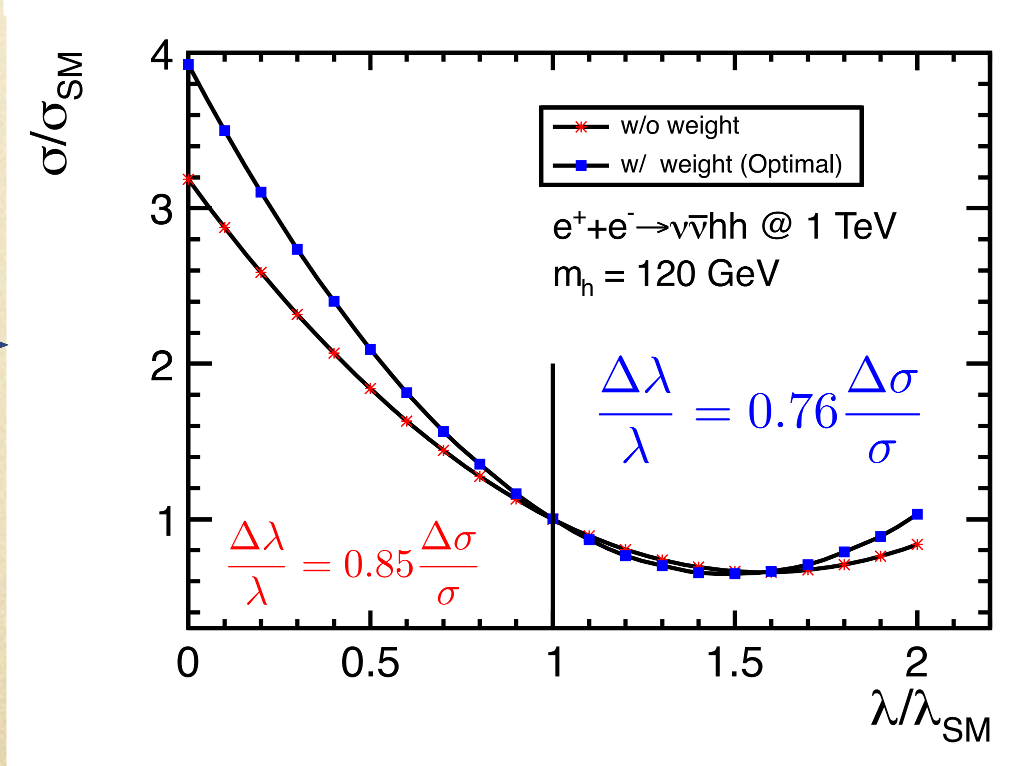
Irreducible BG diagrams





Signal diagram

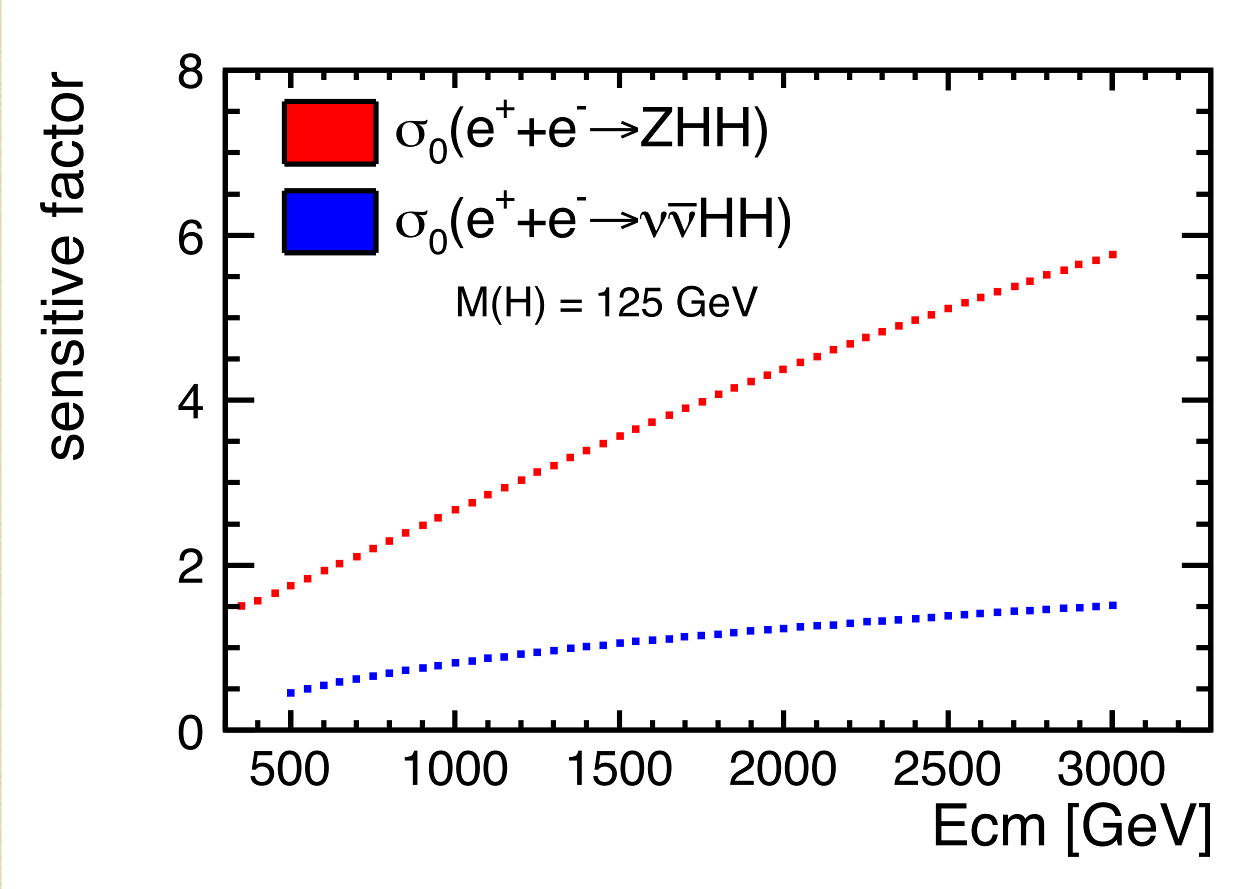
Irreducible BG diagrams

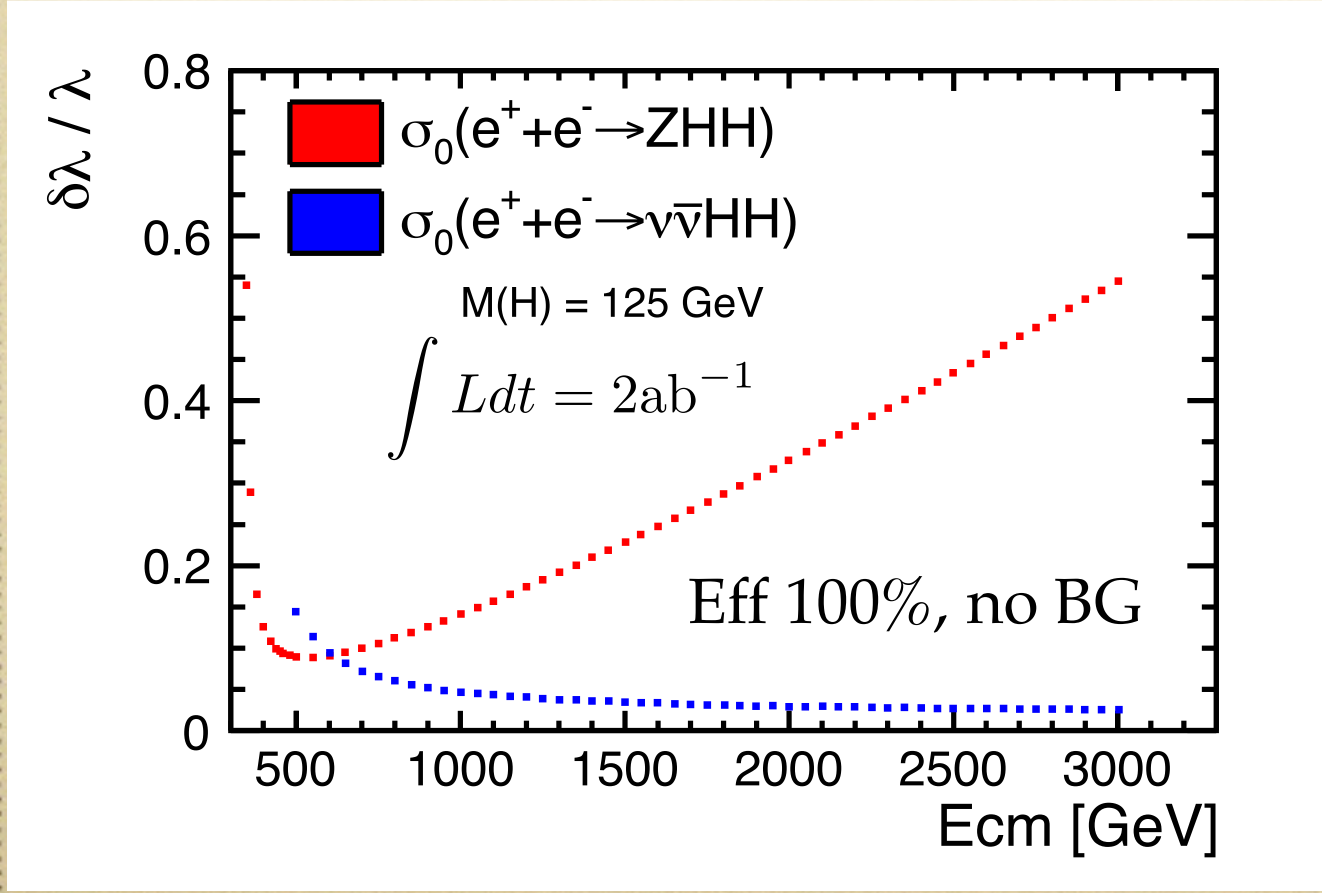


these diagrams significantly degraded the sensitivity

J. Tian, LC-REP-2013-003

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





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

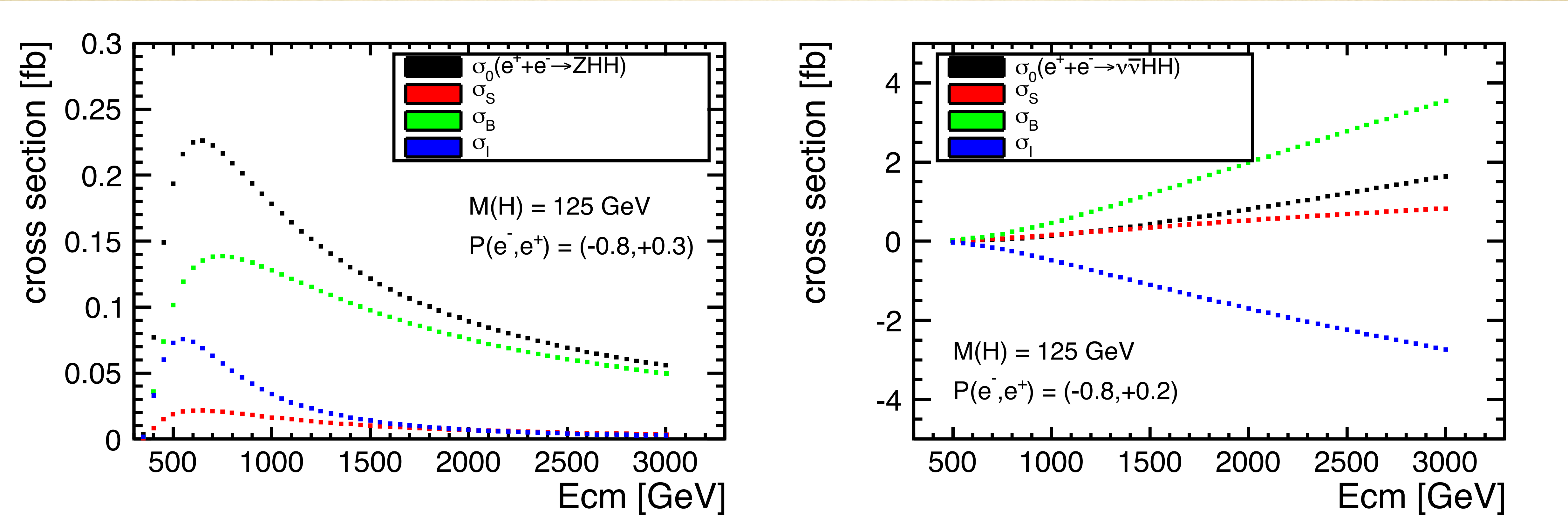
Factor increases quickly as going to higher energy

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

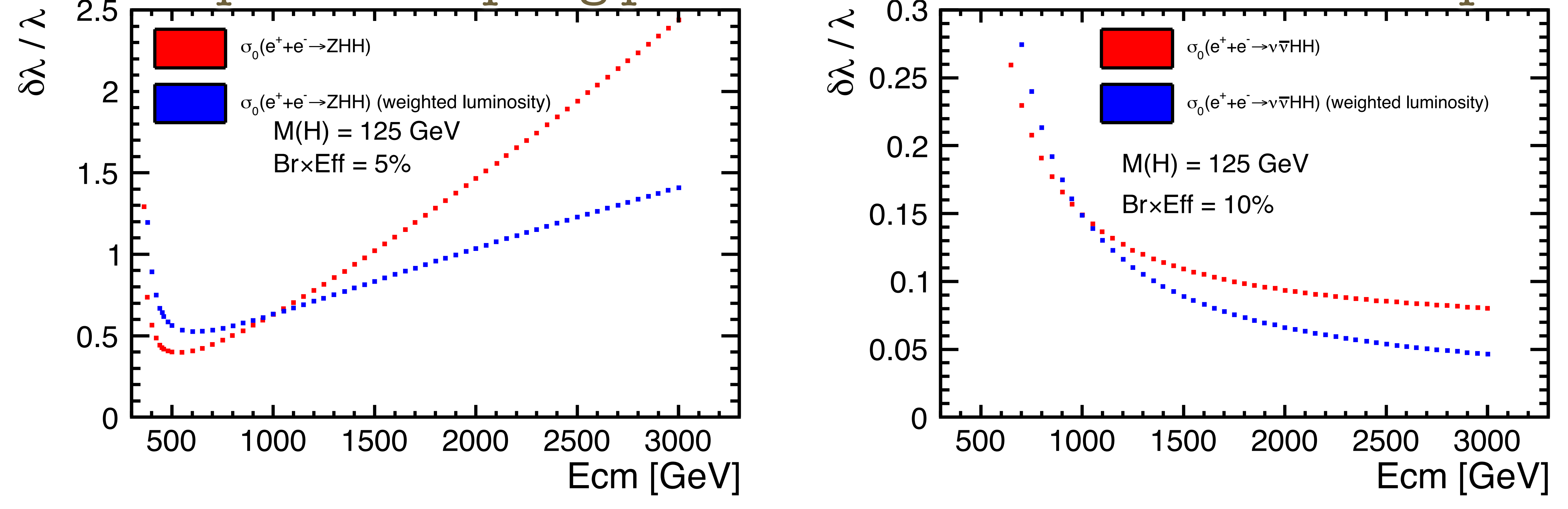
for ννHH, expected precision improves slowly as going to higher energy

General issue: cross sections of each contribution

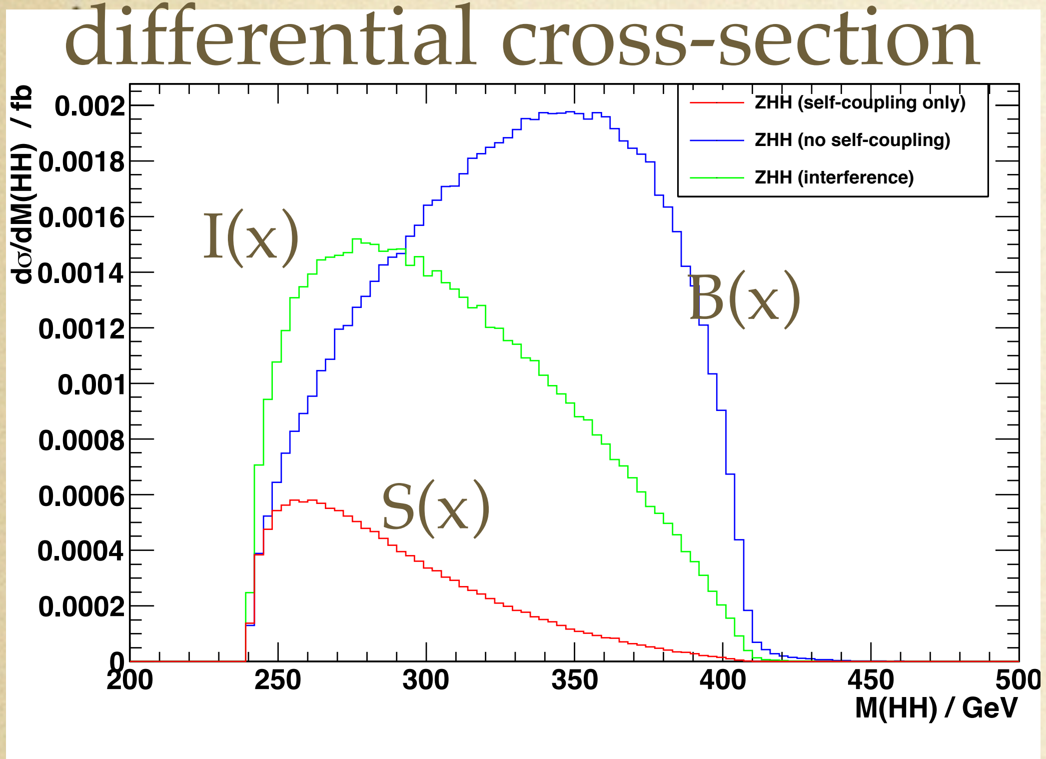
$$\sigma_0 = a\lambda^2 + b\lambda + c = \sigma_S + \sigma_I + \sigma_B$$



expected coupling precision with more realistic setup



new weighting method to enhance the coupling sensitivity

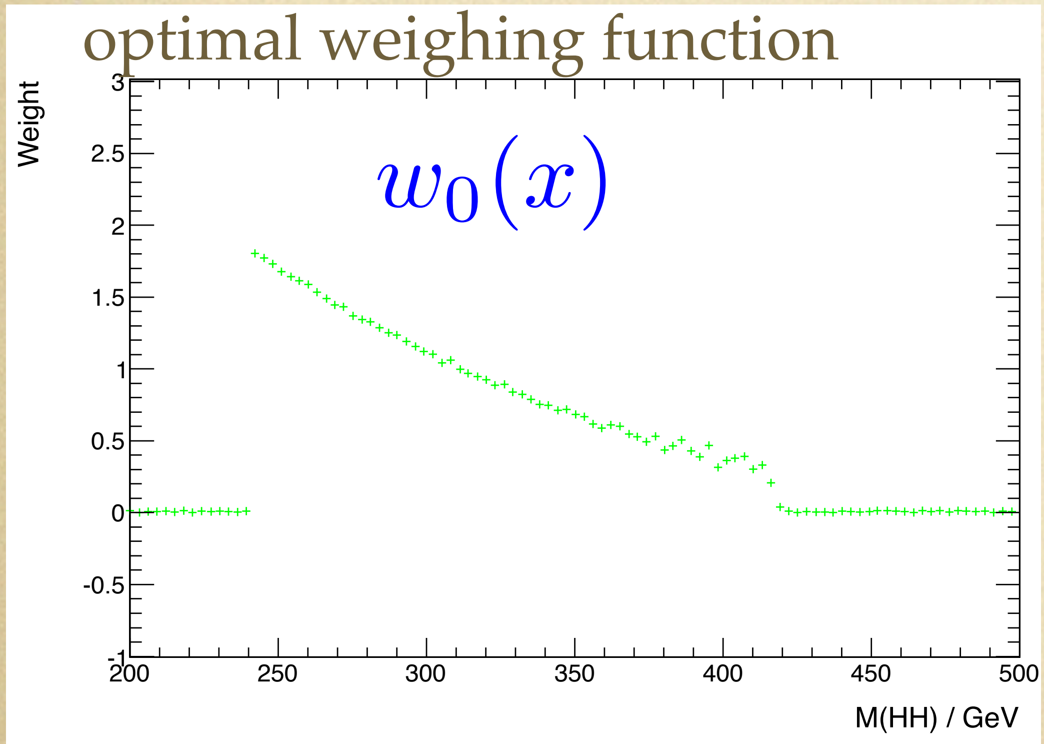


differential cross-section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \underset{\text{irreducible}}{B(x)} + \lambda \underset{\text{interference}}{I(x)} + \lambda^2 \underset{\text{self-coupling}}{S(x)}$$

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

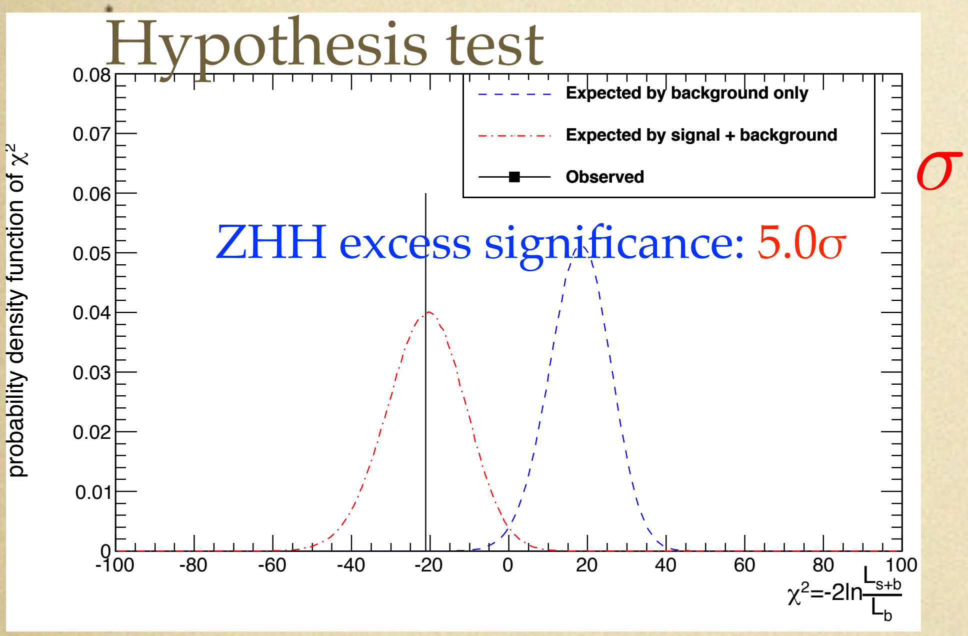
DBD full simulation

Higgs self-coupling @ 500 GeV (combined)

P(e-,e+)=(-0.8,+0.3) $e^+ + e^- \rightarrow ZHH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

Energy (GeV)	Modes	signal	background (tt, ZZ, ZZH/ZZZ)	significance	
				excess (I)	measurement (II)
500	$ZHH \rightarrow (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6.0	1.5σ	1.2σ
500	$ZHH \rightarrow (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \rightarrow (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

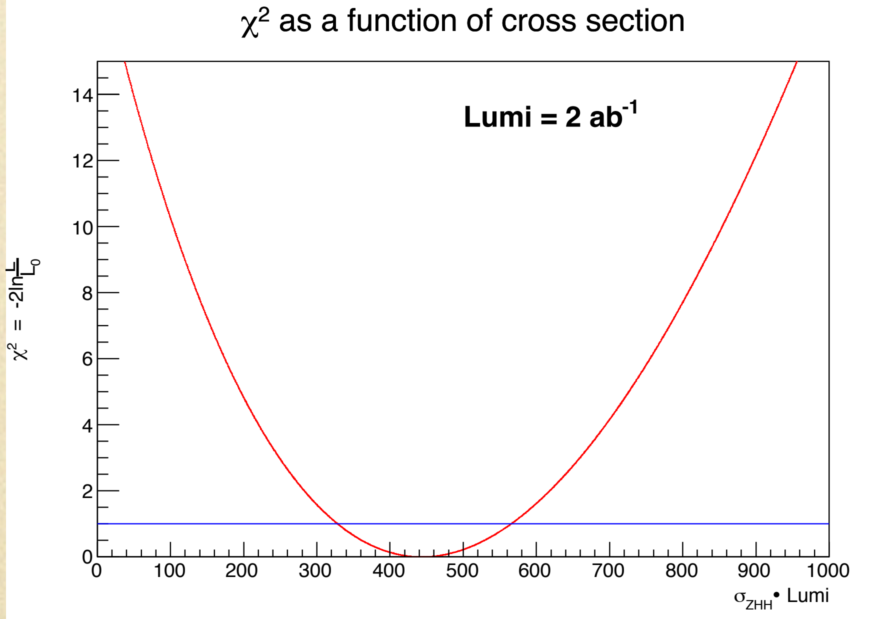
Hypothesis test



ZHH excess significance: 5.0σ

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

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



Higgs self-coupling: $$\frac{\delta\lambda}{\lambda} = 44\%$$

DBD full simulation

Higgs self-coupling @ 1 TeV

P(e-,e+)=(-0.8,+0.2) $e^+ + e^- \to \nu\bar{\nu}HH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

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

- better sensitive factor
- benefit more from beam polarisation
- BG tt x-section smaller
- more boosted b-jets

$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: $> 7\sigma$

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

SENSITIVITY

DBD full simulation

- HH→(bb)(WW)
  - As mentioned, categorized with decay tipes of Z and W boson
    - Z→bb, cc or ll
  - b-tagging strategy – introduce looser b-tag category
    - 4-btag & 3-btag
  - E_{CM}=500GeV, L=2ab-1
  - **Significance ~1.91σ**

Modes	Z decay	b tag	Signal	Background	Significance
All hadronic	Z→bb	4btag	15.20	87.52	1.50σ
		3btag	19.43	3099.49	0.35σ
	Z→cc		11.29	366.13	0.58σ
Lepton + jets	Z→bb		1.65	17.62	0.38σ
	Z→cc		1.50	819.61	0.05σ
Dilepton	Z→ll		2.24	8.44	0.69σ
Trilepton	Z→ll		1.05	2.60	0.55σ
Combined					**1.91σ**

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
Baseline	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)

J. Tian, LC-REP-2013-003 M. Kurata, LC-REP-2013-025

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%	-	3.0%		
	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

Combine all the measurement: Global Fit

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

F_i is what we can calculate

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

2 absolute σ_{ZH} measurements, which can be predicted by

$$\chi^2 = \sum_{i=1}^{i=34} (\frac{Y_i - Y_i'}{\Delta Y_i})^2$$

$$Y_{33}' = F_{33} \cdot g^2_{HZZ} \qquad Y_{34}' = F_{34} \cdot g^2_{HZZ}$$

define a $\chi2$, which can be parameterized with 9 couplings and Higgs total width

$$\chi^2 = \sum_{i=1}^{i=34} (\frac{Y_i - Y_i'}{\Delta Y_i})^2$$

ΔY_i is the measurement error

global fit: minimize the $\chi2$ ---> get the 10 parameters

model independent, no theoretical errors included

Global Fit: Higgs Couplings @ ILC

model independent fit

coupling $\Delta g/g$	Baseline			LumiUP		
	250 GeV	+ 500 GeV	+ 1 TeV	250 GeV	+ 500 GeV	+ 1 TeV
HZZ	1.3%	1.0%	1.0%	0.61%	0.51%	0.51%
HWW	4.8%	1.2%	1.1%	2.3%	0.58%	0.56%
Hbb	5.3%	1.6%	1.3%	2.5%	0.83%	0.66%
Hcc	6.8%	2.8%	1.8%	3.2%	1.5%	1.0%
Hgg	6.4%	2.3%	1.6%	3.0%	1.2%	0.87%
$H\tau\tau$	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
$H\gamma\gamma$	18%	8.4%	4.0%	8.2%	4.5%	2.4%
$H\mu\mu$	-	-	16%	-	-	10%
Htt	-	14%	3.1%	-	7.8%	1.9%
Γ_0	11%	5.0%	4.6%	5.4%	2.5%	2.3%
Br(Inv)	<0.95%	<0.95%	<0.95%	0.44%	0.44%	0.44%
HHH	-	83%	21%	-	46%	13%

model dependent fit (7 parameters @ LHC)

$$\chi^2 = \sum_{i=1}^{i=33} (\frac{Y_i - Y_i'}{\Delta Y_i})^2 + (\frac{\xi_{ct}}{\Delta \xi_{ct}})^2 + (\frac{\xi_{\mu\tau}}{\Delta \xi_{\mu\tau}})^2 + (\frac{\xi_\Gamma}{\Delta \xi_\Gamma})^2$$

$$\xi_{ct} = \kappa_c - \kappa_t \qquad \xi_{ct} = \kappa_\mu - \kappa_\tau$$

$$\xi_\Gamma = \kappa_H - \sum_i \kappa_i^2 \mathrm{Br}_i|_{\mathrm{SM}}$$

$$\Delta\xi_{ct} = \Delta\xi_{\mu\tau} = 0.5\% \qquad \Delta\xi_\Gamma = 0.5\% \times 0.63$$

theory error

$$\Delta_{\mathrm{Theory}} = 0\ ;\ 0.1\%\ ;\ 0.5\%$$

$$\Delta Y_i^2 = \Delta Y_i^2(\mathrm{exp}) + (\Delta_{\mathrm{Theory}} Y_i')^2$$

systematic error

	Baseline	LumiUP
luminosity	0.1%	0.05%
polarisation	0.1%	0.05%
b-tag efficiency *	0.3%	0.15%

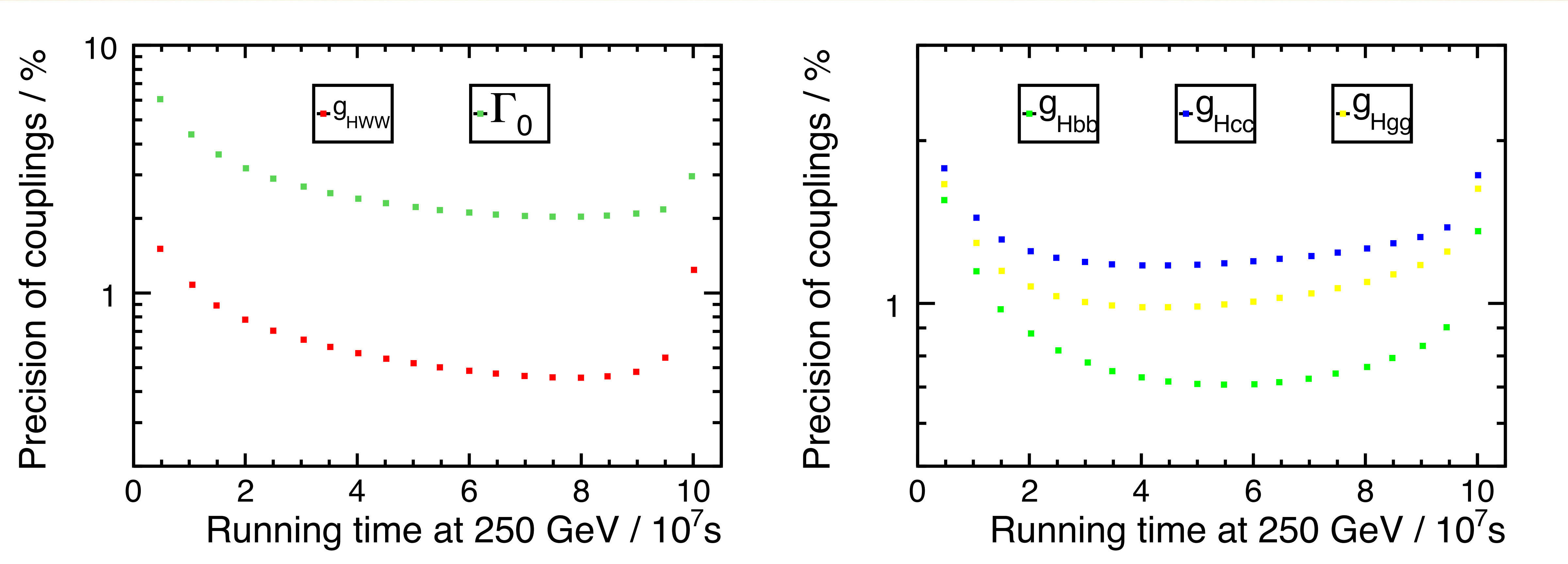
(* only for H-->bb)

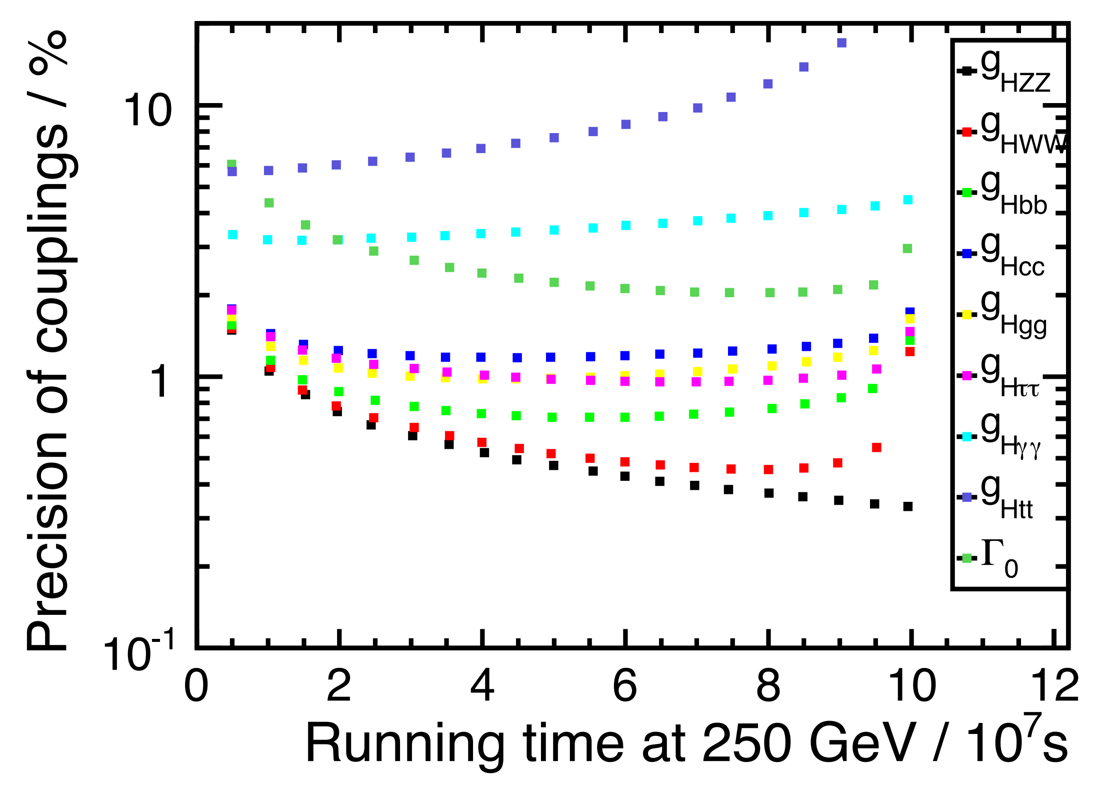
global fit --model dependent + sys + theory error (0.1%)

coupling $\Delta g/g$	baseline			luminosity upgrade		
	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.74%	0.49%	0.45%	0.36%	0.27%	0.25%
HWW	4.7%	0.43%	0.27%	2.2%	0.27%	0.20%
Hbb	4.7%	0.97%	0.57%	2.2%	0.55%	0.36%
Hcc	6.4%	2.5%	1.3%	3.0%	1.3%	0.78%
Hgg	6.1%	2.0%	1.1%	2.8%	1.1%	0.69%
$H\tau\tau$	5.2%	1.9%	1.3%	2.4%	1.0%	0.74%
$H\gamma\gamma$	17%	8.3%	3.8%	8.1%	4.4%	2.3%
$H\mu\mu$	5.2%	1.9%	1.4%	2.4%	1.0%	0.89%
Htt	6.4%	2.5%	1.3%	3.0%	1.4%	0.87%
Γ_0	9.0%	1.7%	1.1%	4.2%	1.0%	0.80%
Br(Inv)	<0.95%	<0.95%	<0.95%	0.44%	0.44%	0.44%
HHH	-	83%	21%	-	46%	13%

example: Power of Staged Running

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





Finger Printing

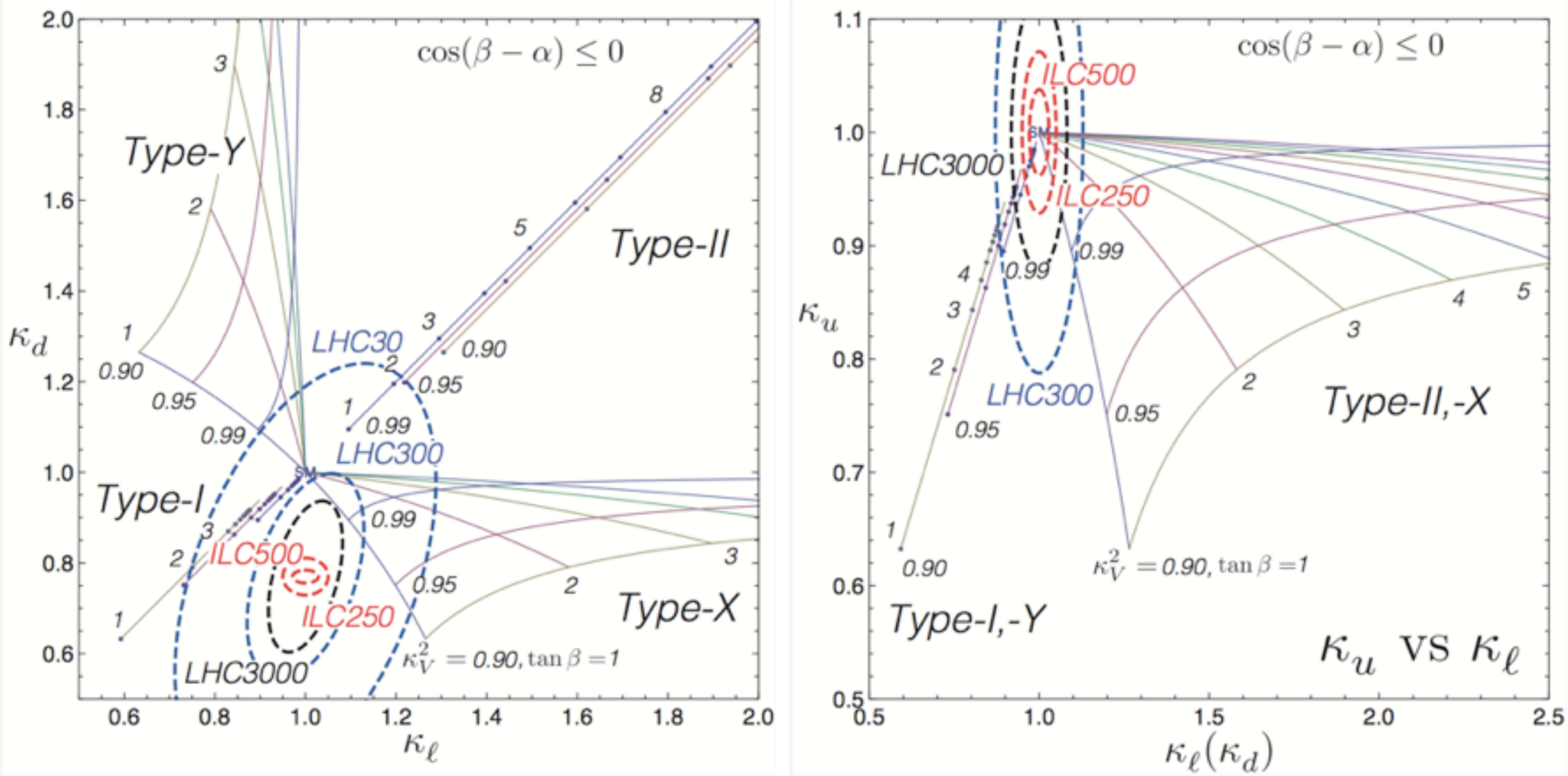


Figure 1.17. The deviation in $\kappa_f = \xi_h^f$ in the 2HDM with Type I, II, X and Y Yukawa interactions are plotted as a function of $\tan\beta = v_2/v_1$ and $\kappa_V = \sin(\beta-\alpha)$ with $\cos(\beta-\alpha) \le 0$. For the illustration purpose only, we slightly shift lines along with $\kappa_x = \kappa_y$. 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)

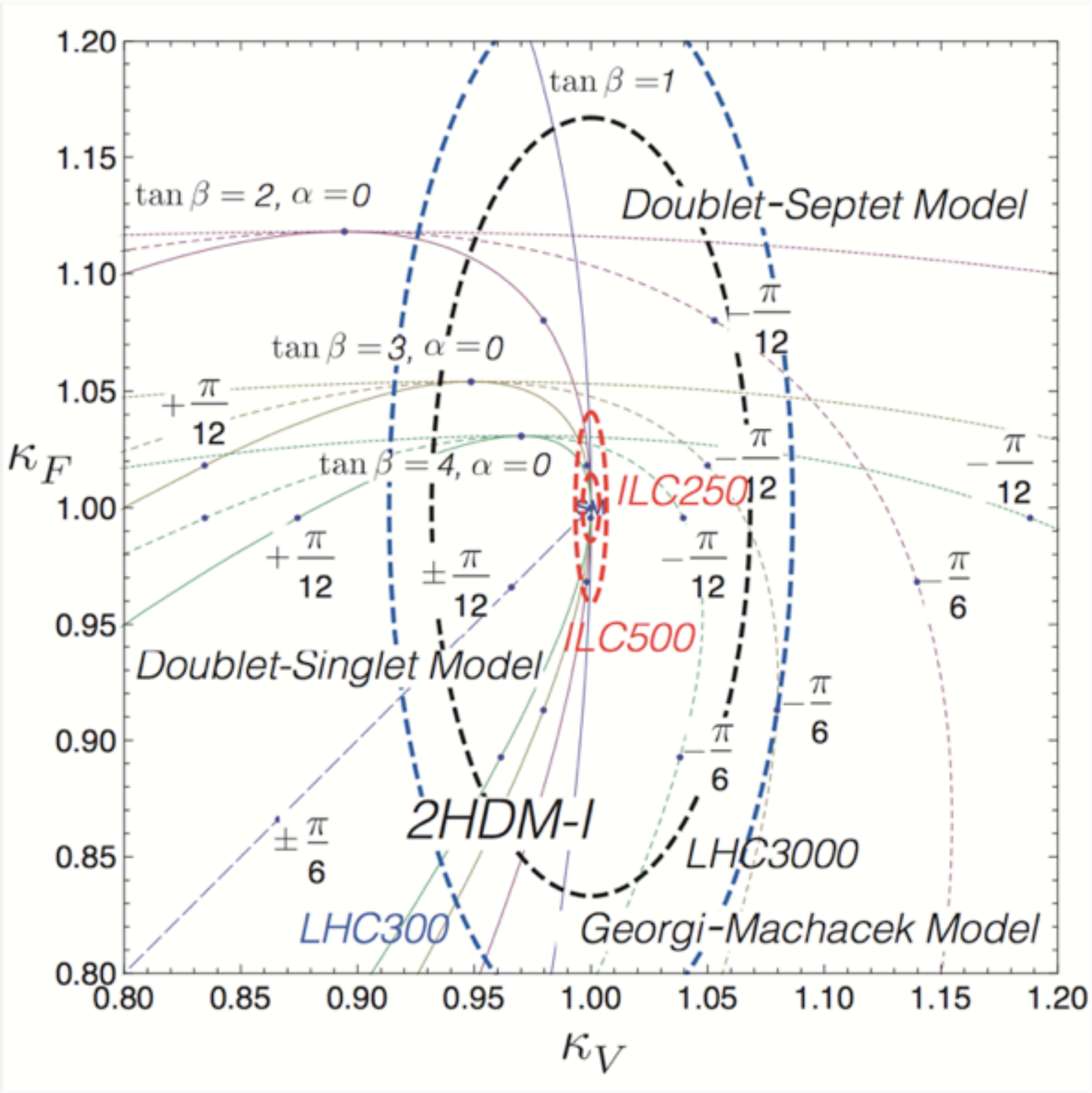
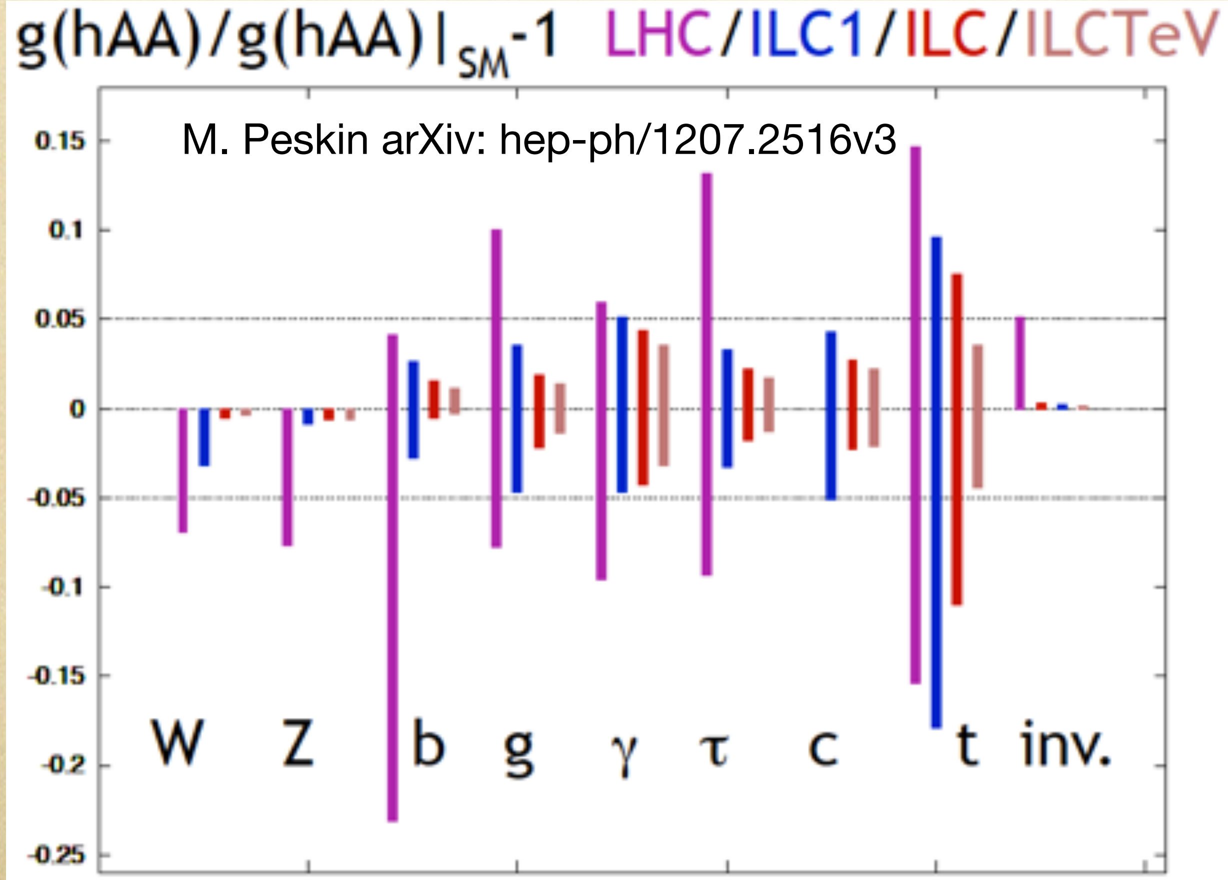


Figure 1.18. The scaling factors in models with universal Yukawa coupling constants.

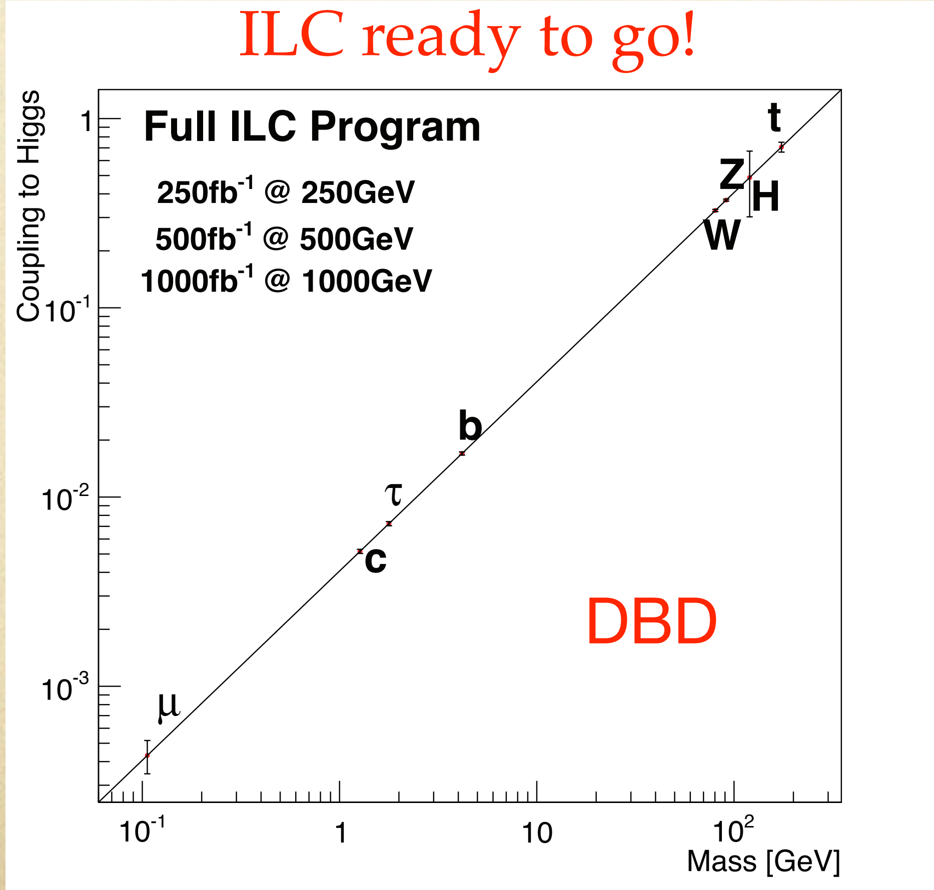
Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

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.
- capability of energy scan can make ILC run at optimal energy and complementary to what LHC would discover.

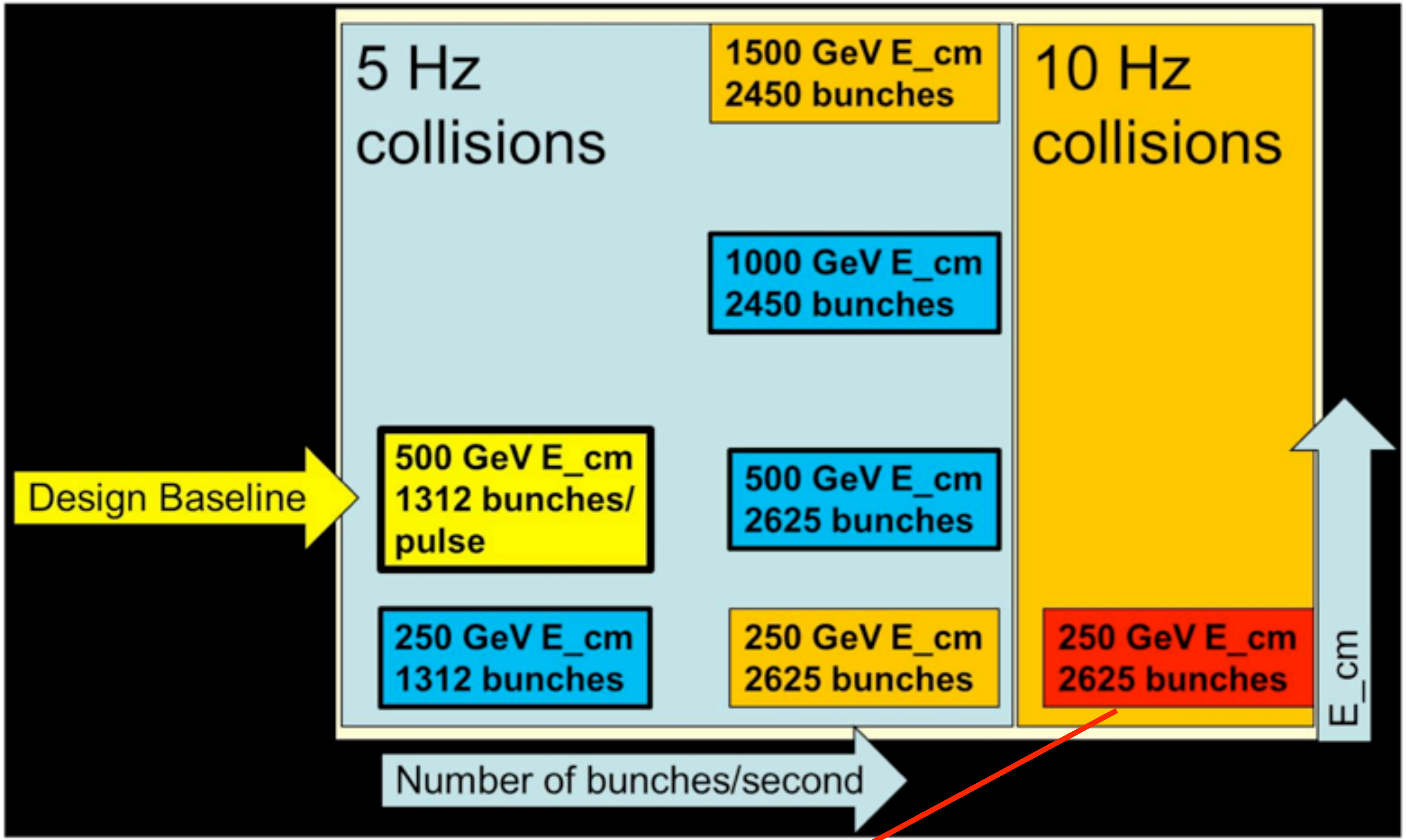

$g(hAA)/g(hAA)|_{SM}-1$ LHC/ILC1/ILC/ILCTeV

M. Peskin arXiv: hep-ph/1207.2516v3


ILC ready to go!

backup

ILC Stages and Upgrades



5 Hz collisions

10 Hz collisions

Design Baseline

500 GeV E_cm
1312 bunches/ pulse

250 GeV E_cm
1312 bunches

1500 GeV E_cm
2450 bunches

1000 GeV E_cm
2450 bunches

500 GeV E_cm
2625 bunches

250 GeV E_cm
2625 bunches

250 GeV E_cm
2625 bunches

Number of bunches/second

E_cm

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

x4 upgrade
@250GeV

Blue: upgrade described in TDR

The current ILC design is rather conservative!

Model-independent Global Fit for Couplings

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

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

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

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

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

$$F_i = S_i G_i$$

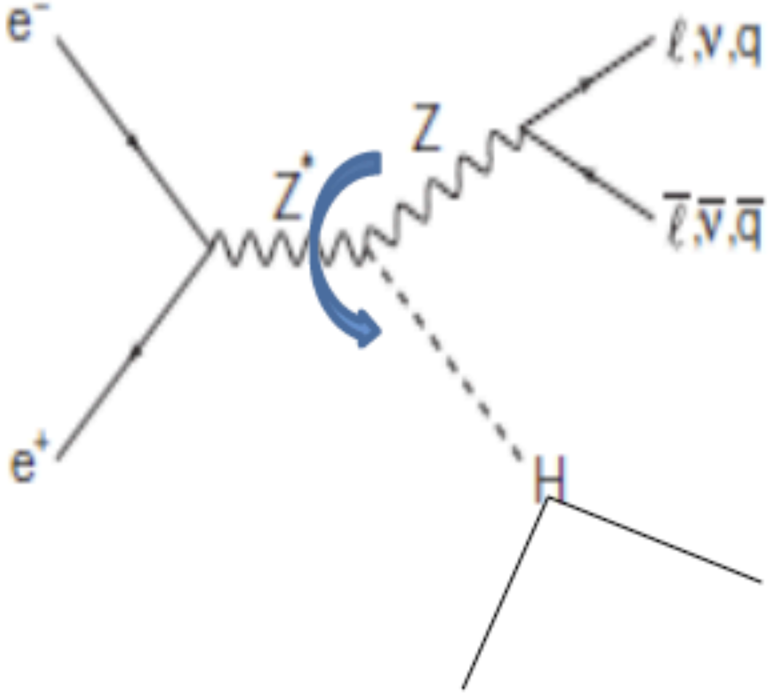
$$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

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

- The recoil mass measurement 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.

Invisible Higgs Decay



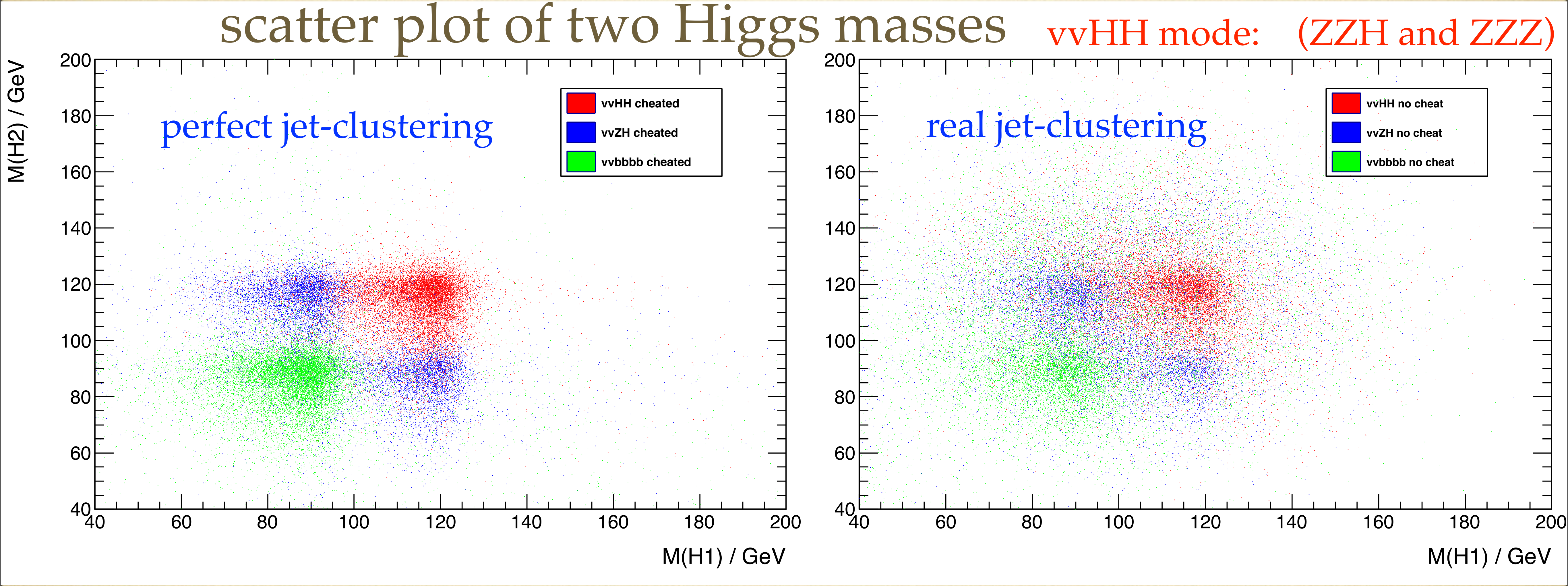
- In the SM, an invisible Higgs decay is H → ZZ* →4ν process and its BF is small ~0.1%
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - The decay products are dark matter candidates.

- 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

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

A. Ishikawa @ Snowmass, Seattle

prospect of Higgs self-coupling



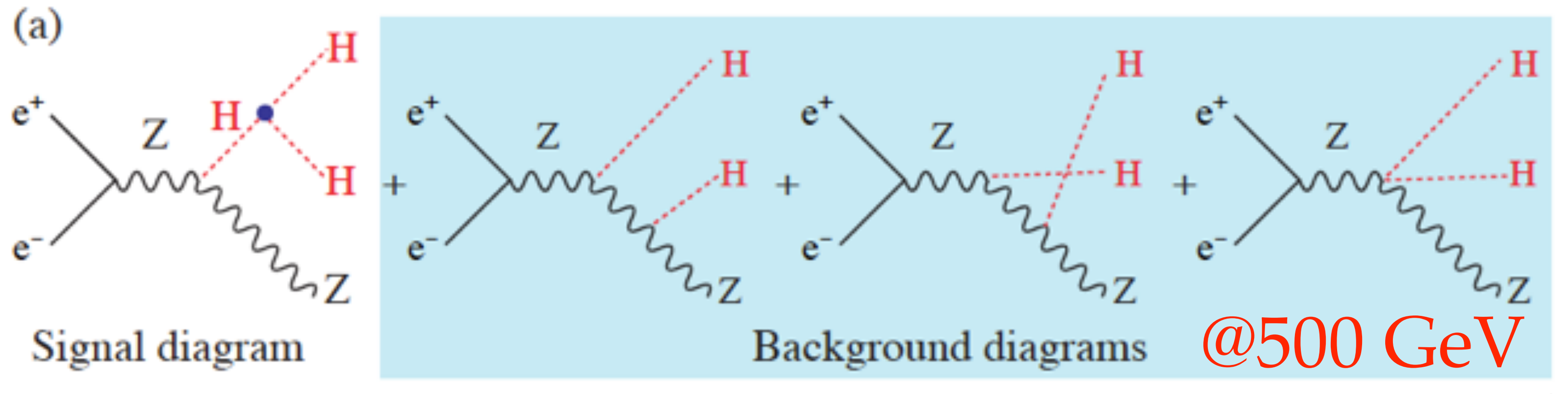
scatter plot of two Higgs masses

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 $\delta\lambda \sim 40\%$
- 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

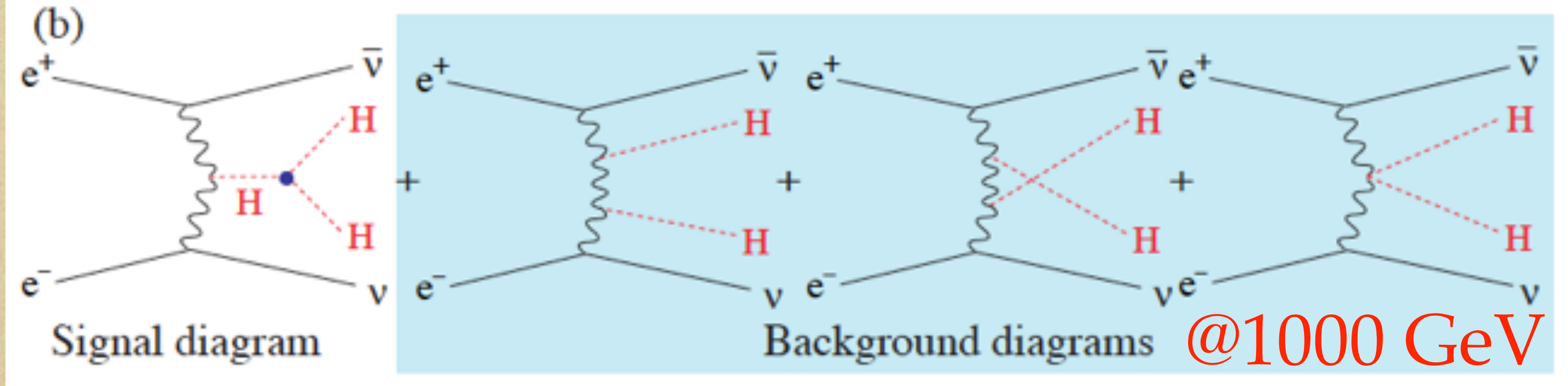
new couplings to be added: g_{ZZHH}, g_{WWHH}

---would be unique at Linear Collider



@500 GeV

more sensitive!



@1000 GeV

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

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

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

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

preliminary! correlation with HHH not included