# 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

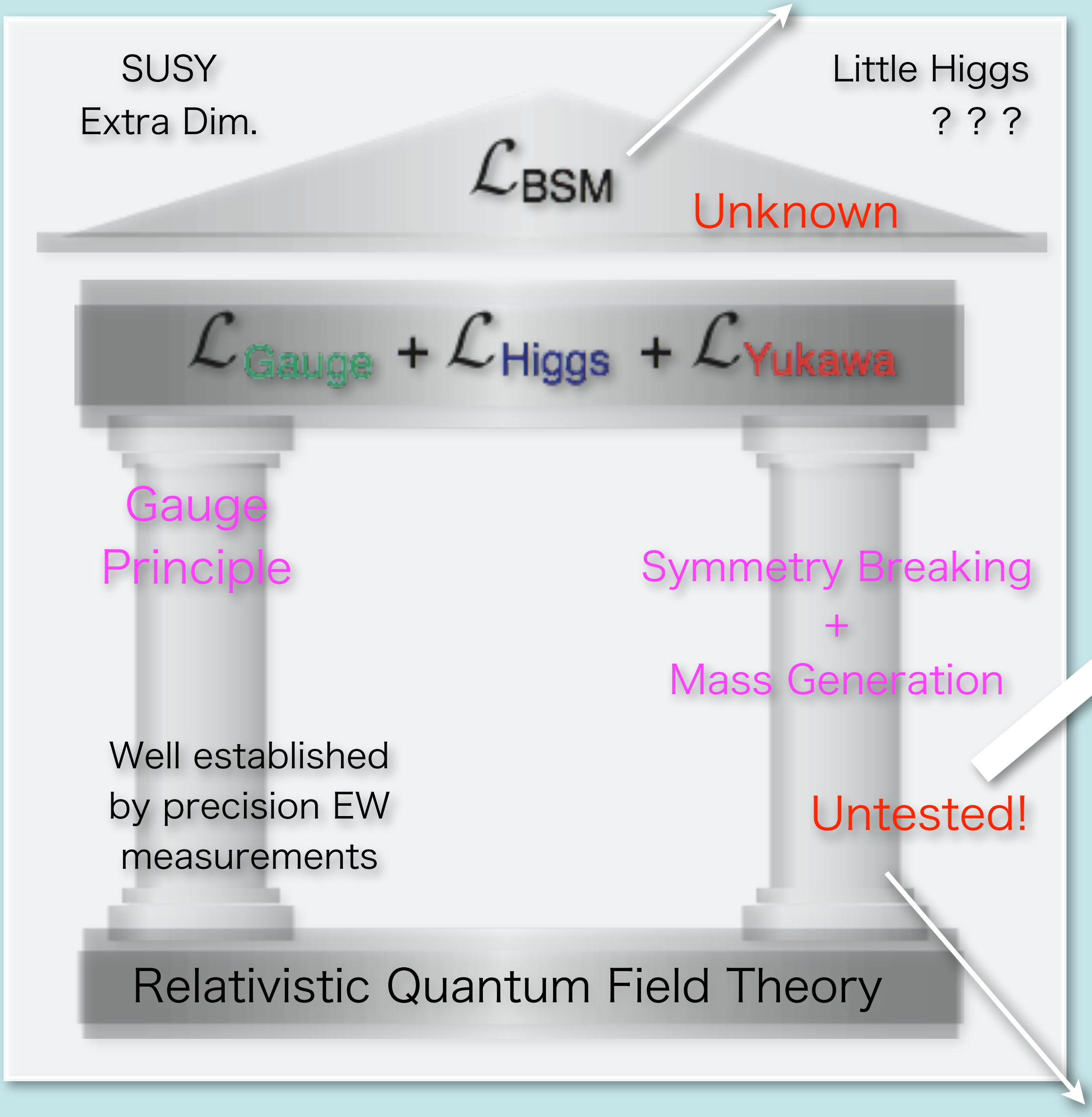
# Primary Goal

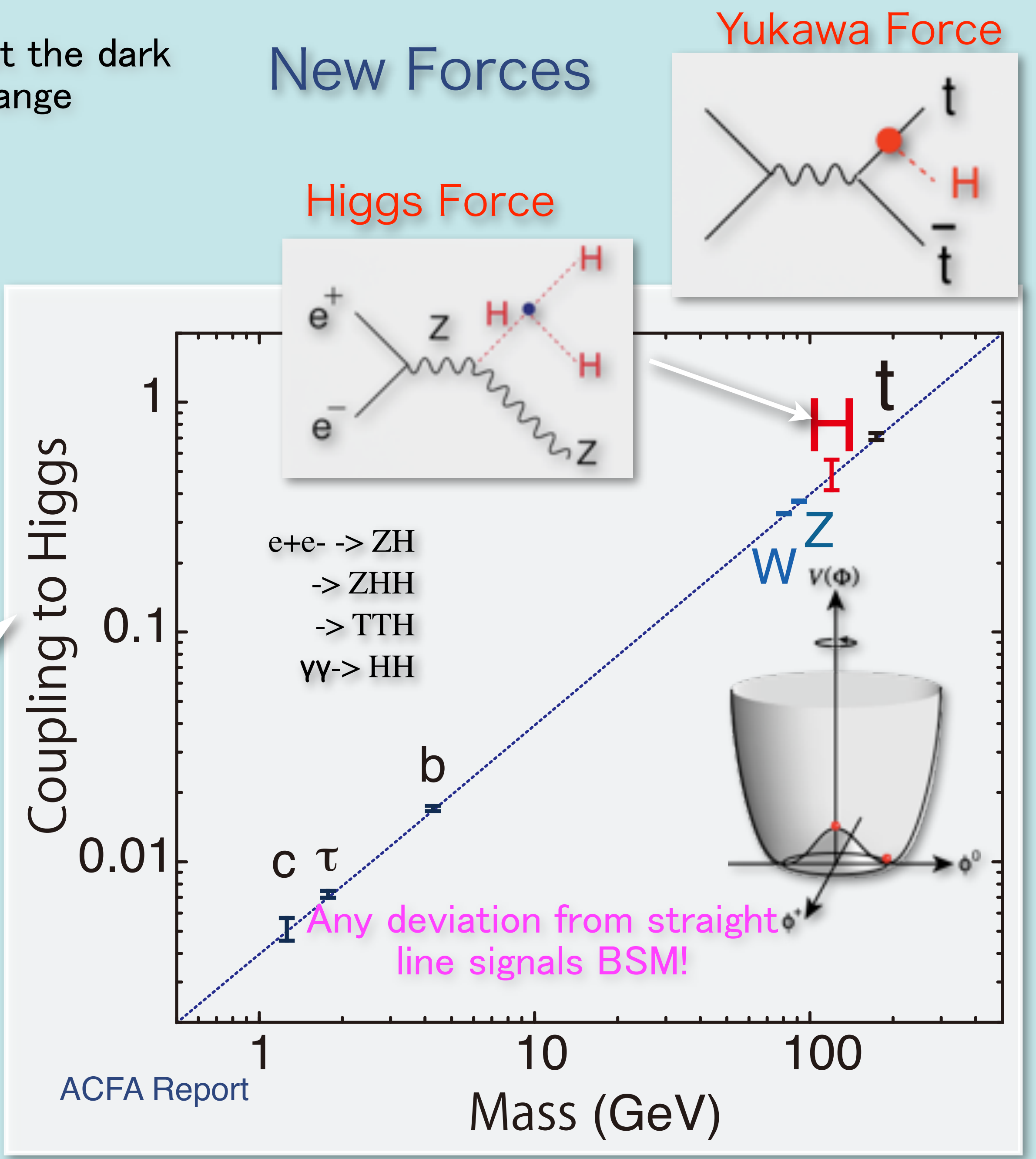
## Mystery Test of the 2nd pillar, then BSM

2 Main Pillar of SM

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

New Forces





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 | $\mu$ | $\tau$ | $b$ | $c$ | $t$ | $g_V$ |
|---|---|---|---|---|---|---|
| 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

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

SUSY

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

Expected deviations are small --> Precision!

see Shinya's talk

# Bottom-up Model-Independent Reconstruction of the EWSB Sector

## through Precision Higgs Measurements

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

test new decay, CP mixture

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

observe the force to make higgs condense

$L_{\mathrm{Gauge}}$

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

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

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

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

crucial to test the mass coupling proportionality

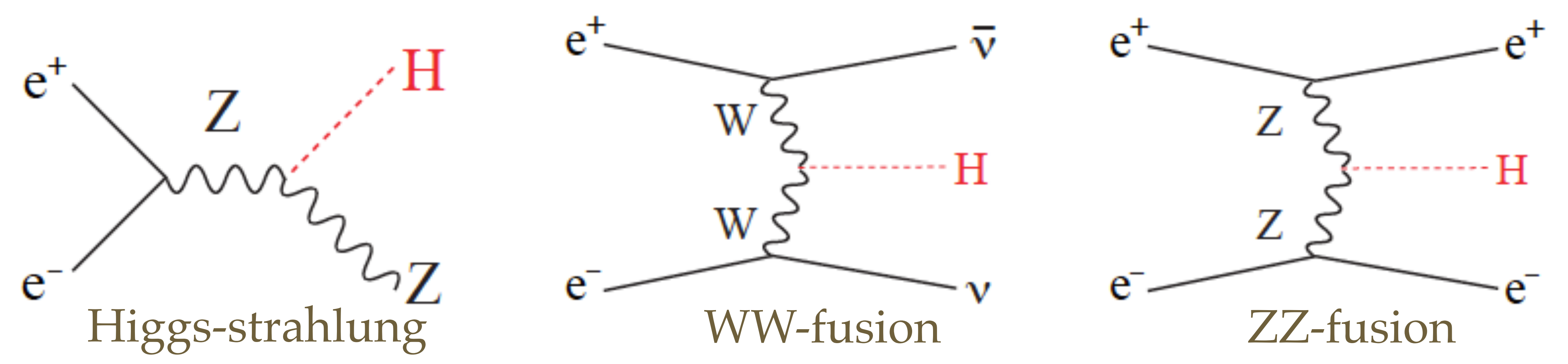
$L_{\mathrm{Loop}}$ $\quad h\gamma\gamma \quad hgg \quad h\gamma Z$

sensitive to the new particles in the loop

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

# Higgs Production and Decay @ ILC

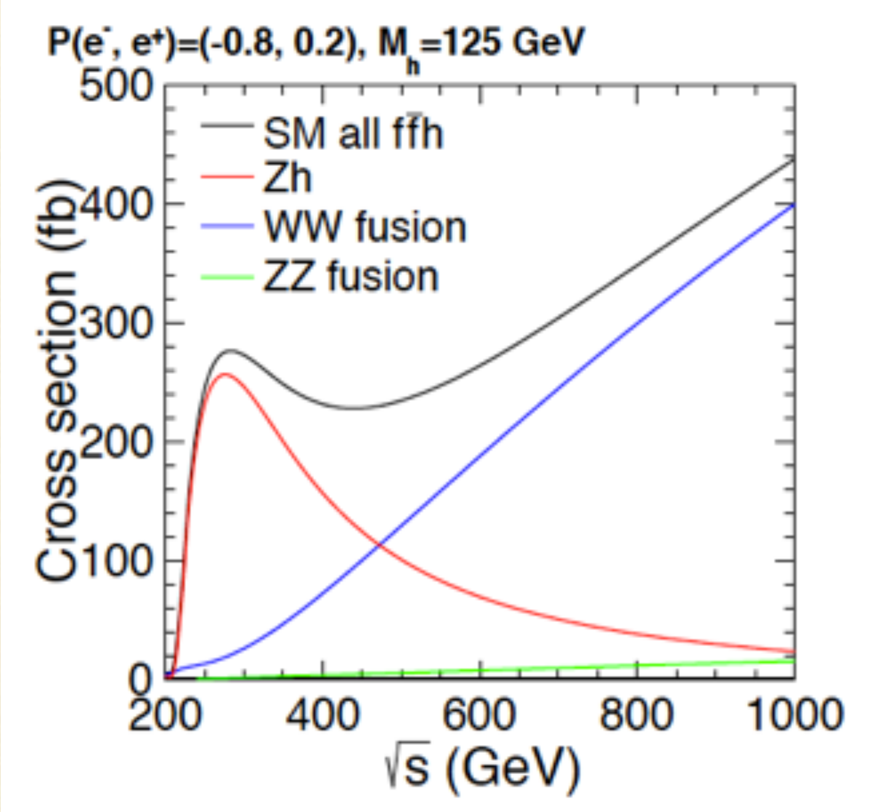
no lose theorem

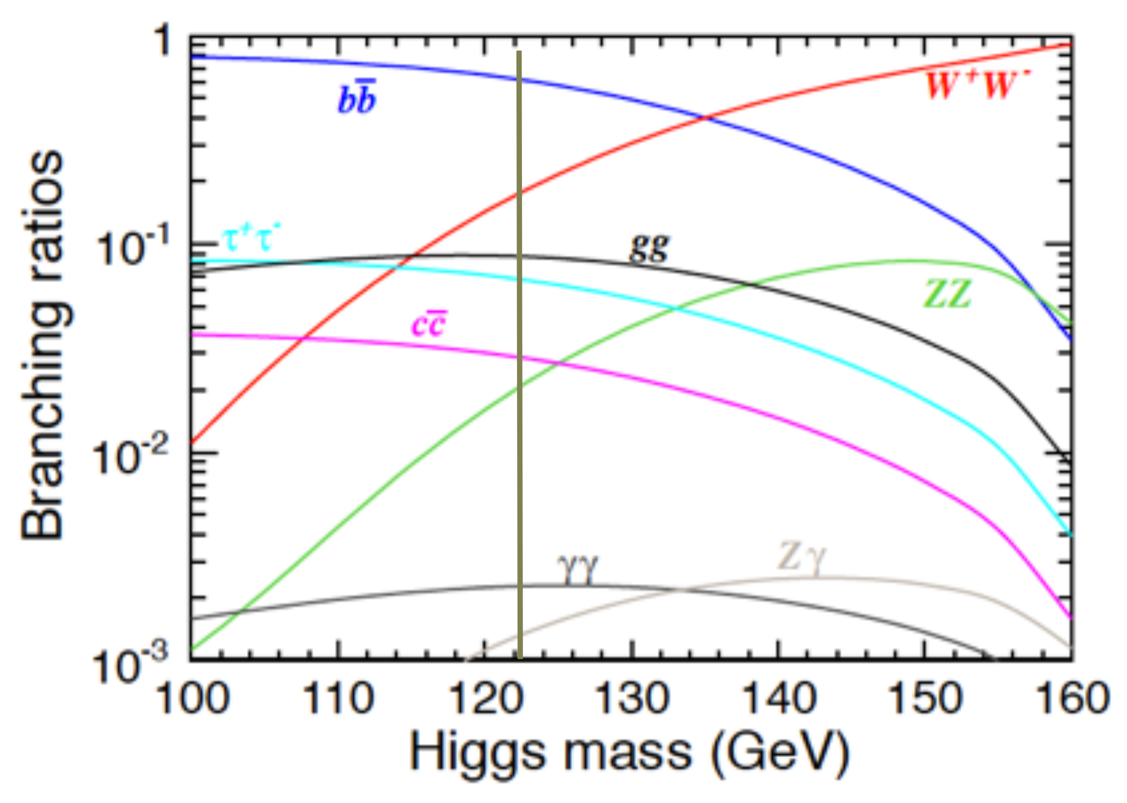


Higgs-strahlung

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 $\text{fb}^{-1}$ @ 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 $\text{fb}^{-1}$ @ 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 $\text{fb}^{-1}$ @ 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: $\sigma_{1/p_T} \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$

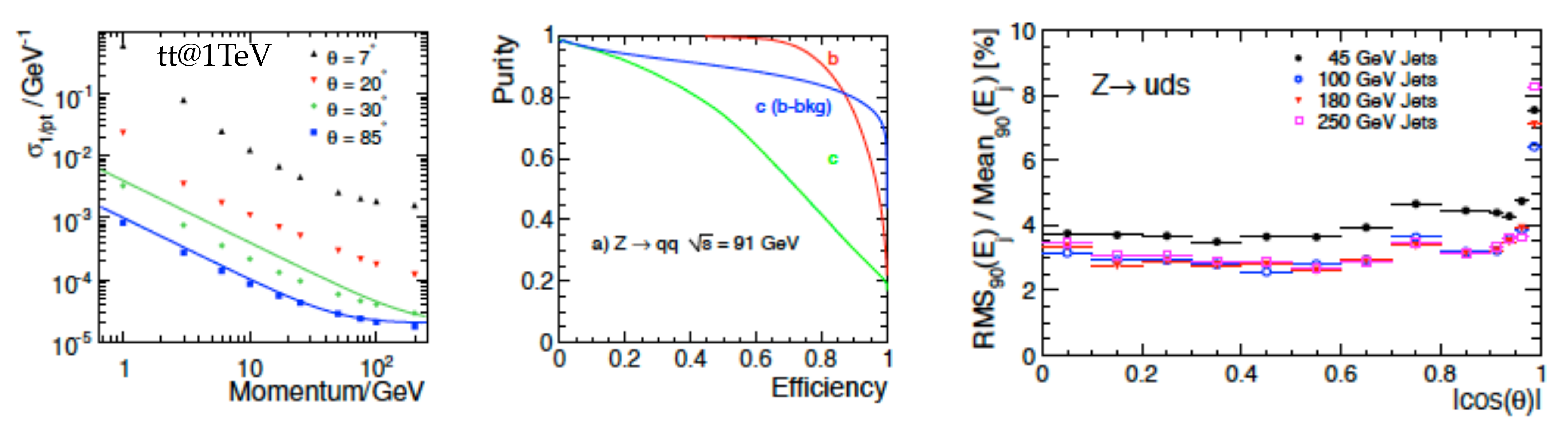
- driven by recoil mass measurement ZH-->$l^+l^-X$.

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).

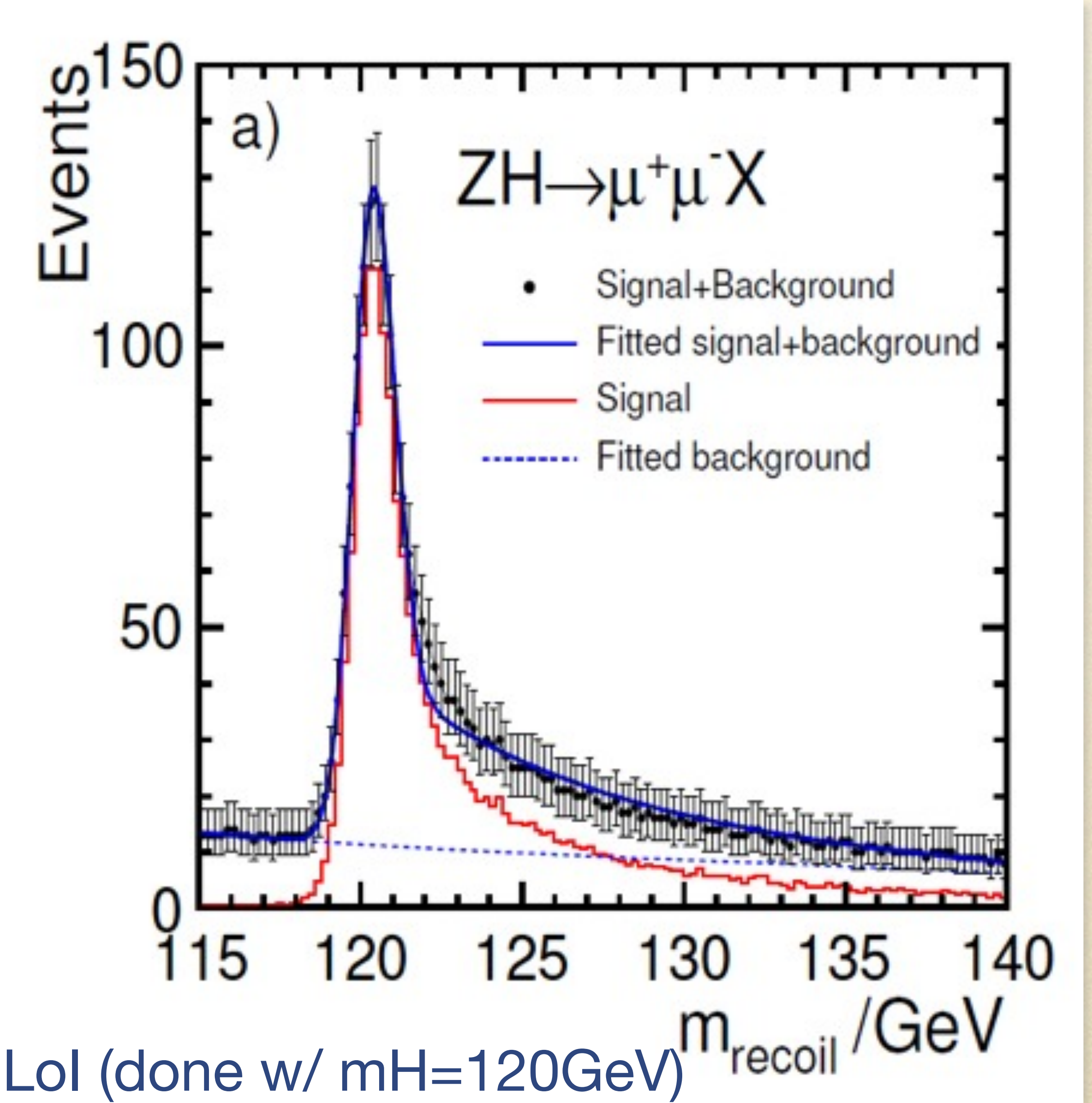


**ILC 250 GeV**

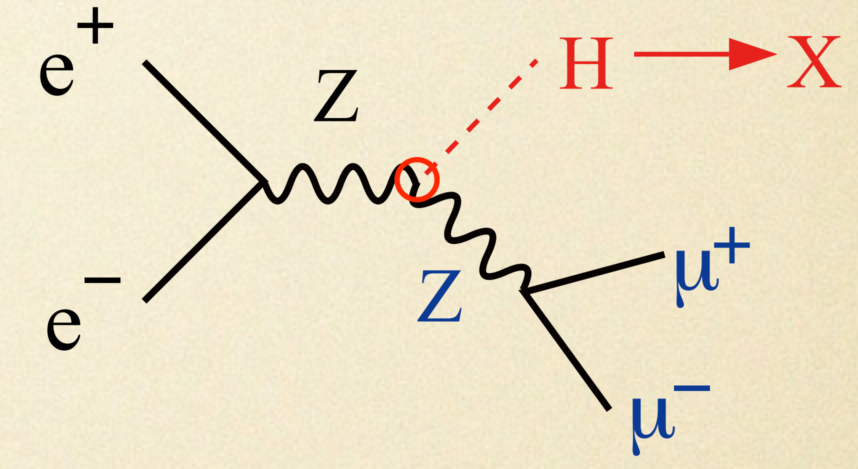
# mass and HZZ coupling

## 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!

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

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

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

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

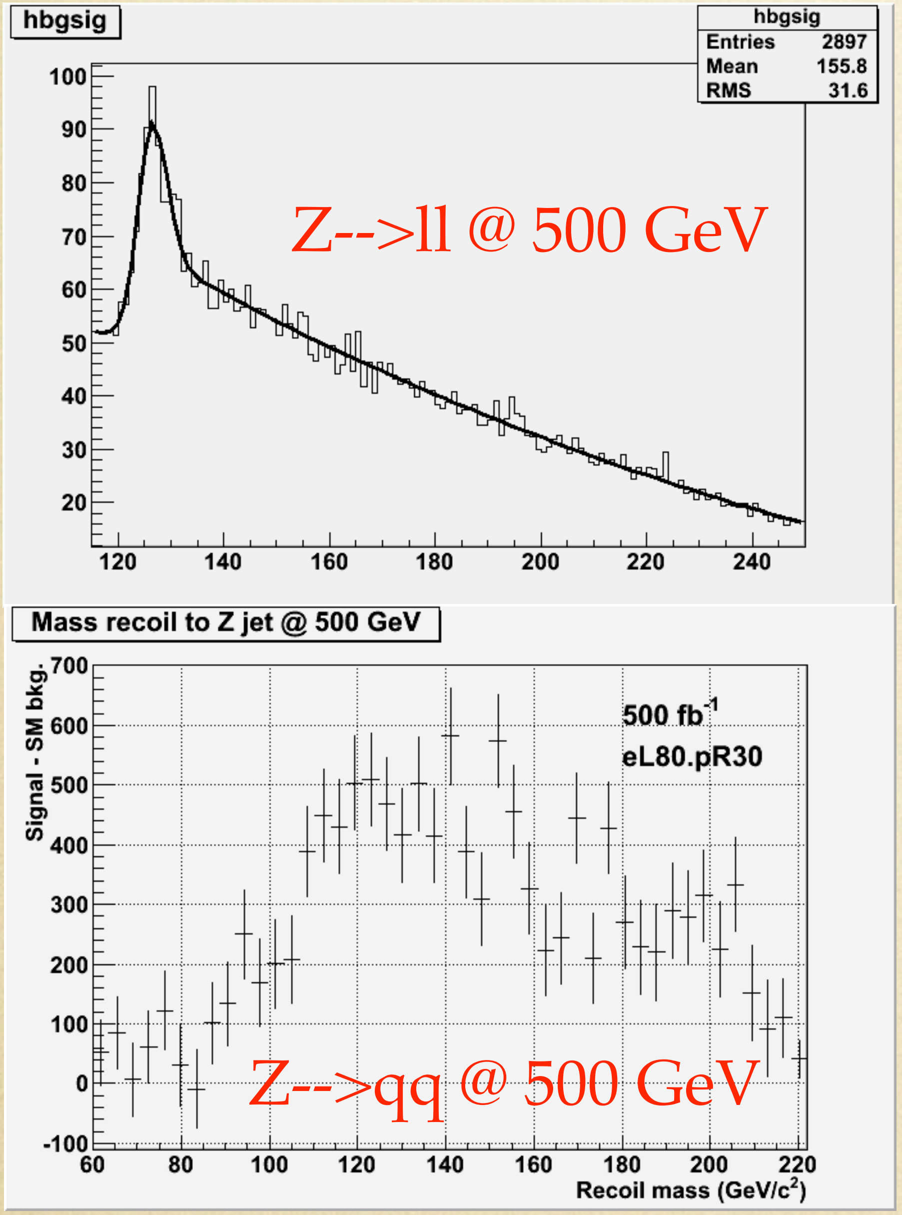
(Z-->ee combined)

$Y_1 = \sigma_{ZH} \propto g_{HZZ}^2$ ---> 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

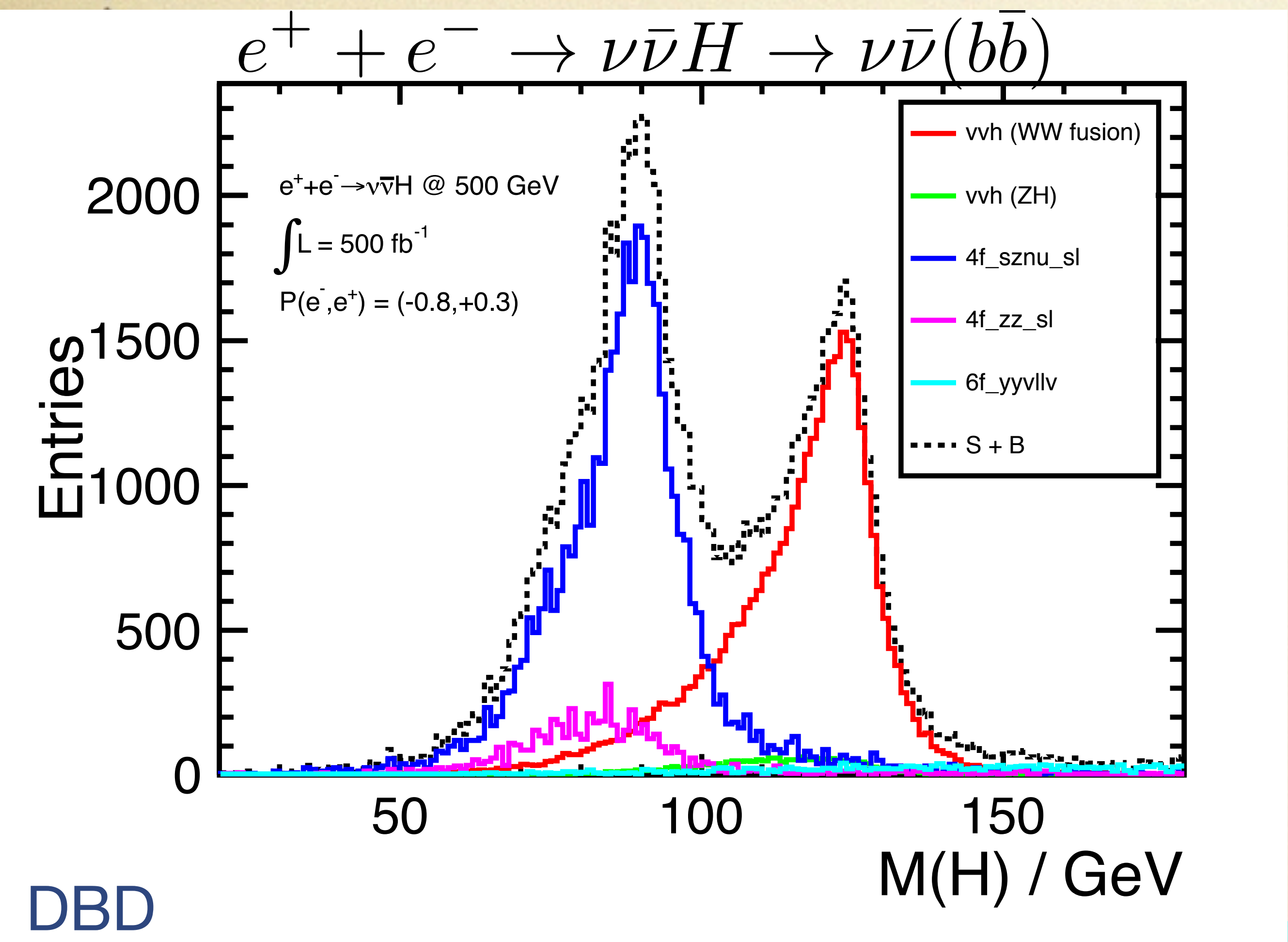
- recoil technique can be also applied to Z-->qq mode, more boostted at higher energy, better separation between Z and H decay products

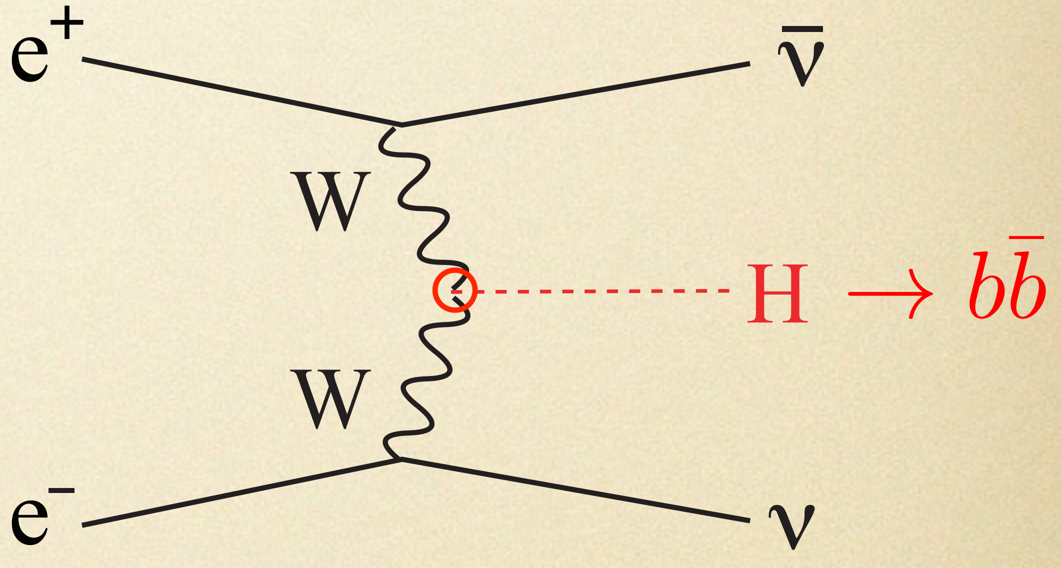
| $\Delta g_{HZZ}/g_{HZZ}$ | 250 GeV | + 500 GeV |
|---|---|---|
| Baseline | 1.3% | 1.0% |
| LumiUP | 0.61% | 0.51% |

**ILC 500 GeV**

# HWW coupling

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





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

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

$Y_2/Y_3$ 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 $\Gamma_H$

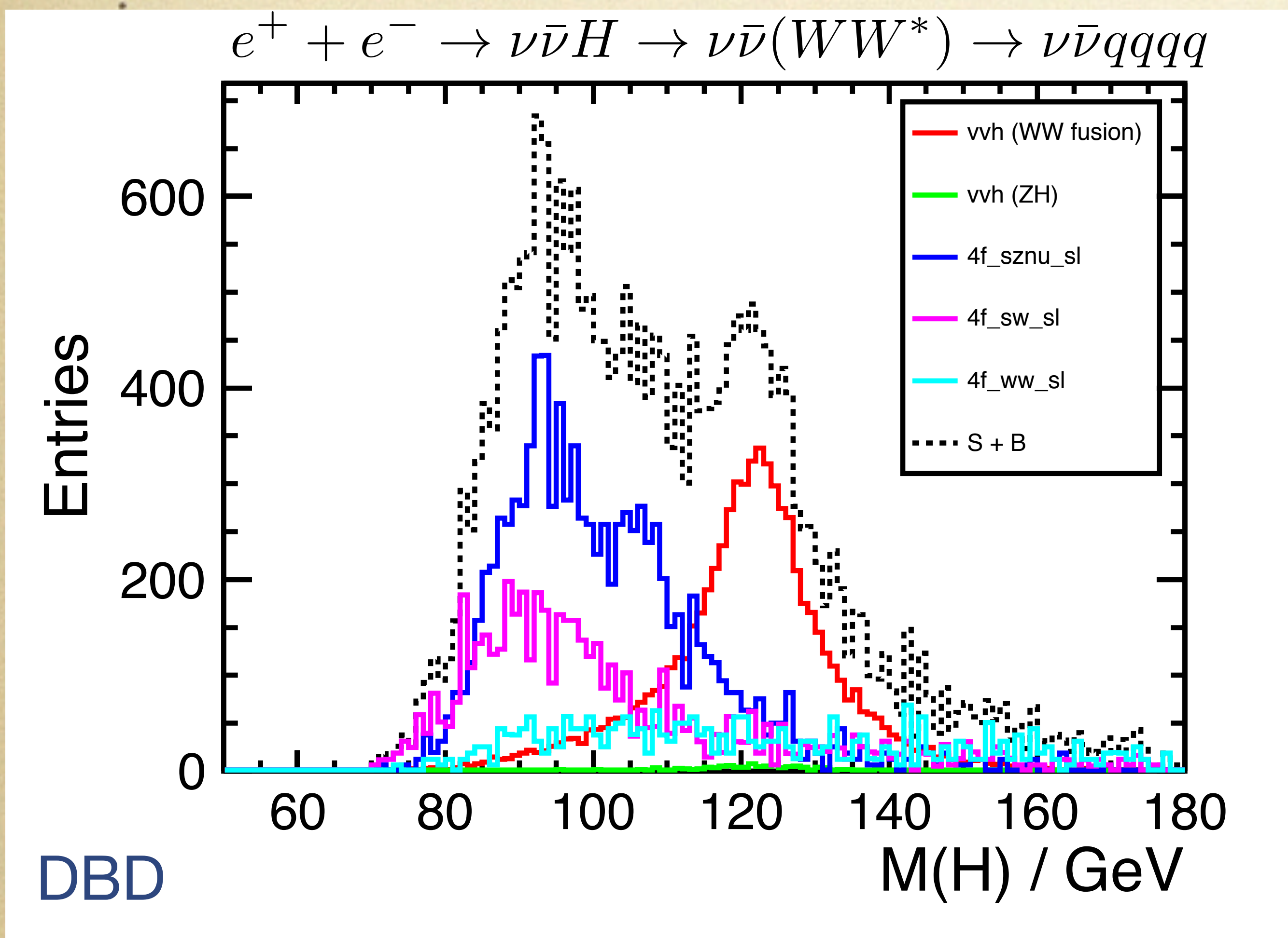
**model free, one of the great advantages of ILC**

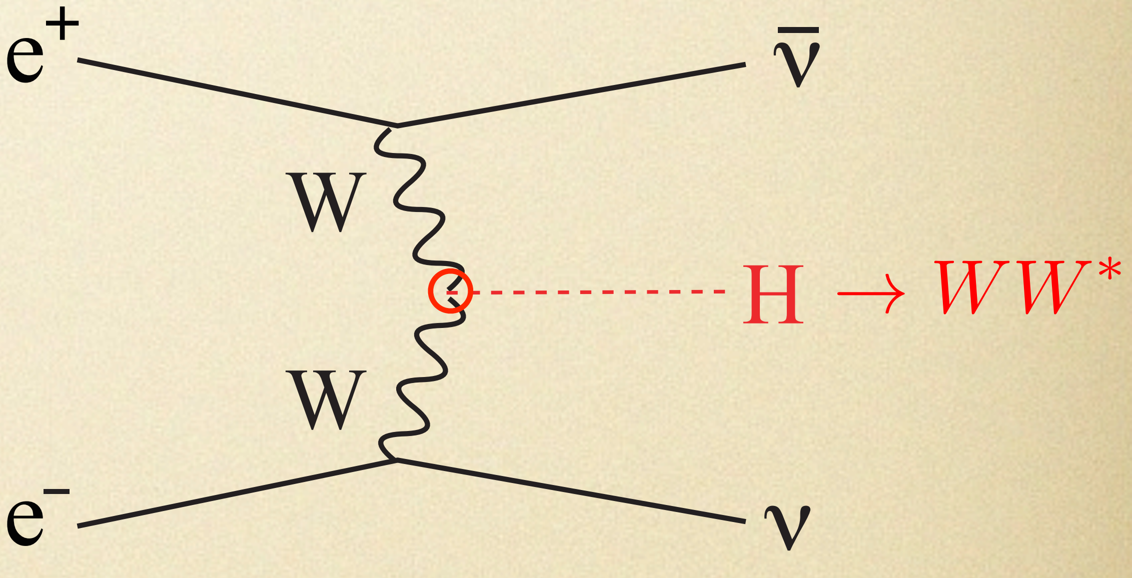
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

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

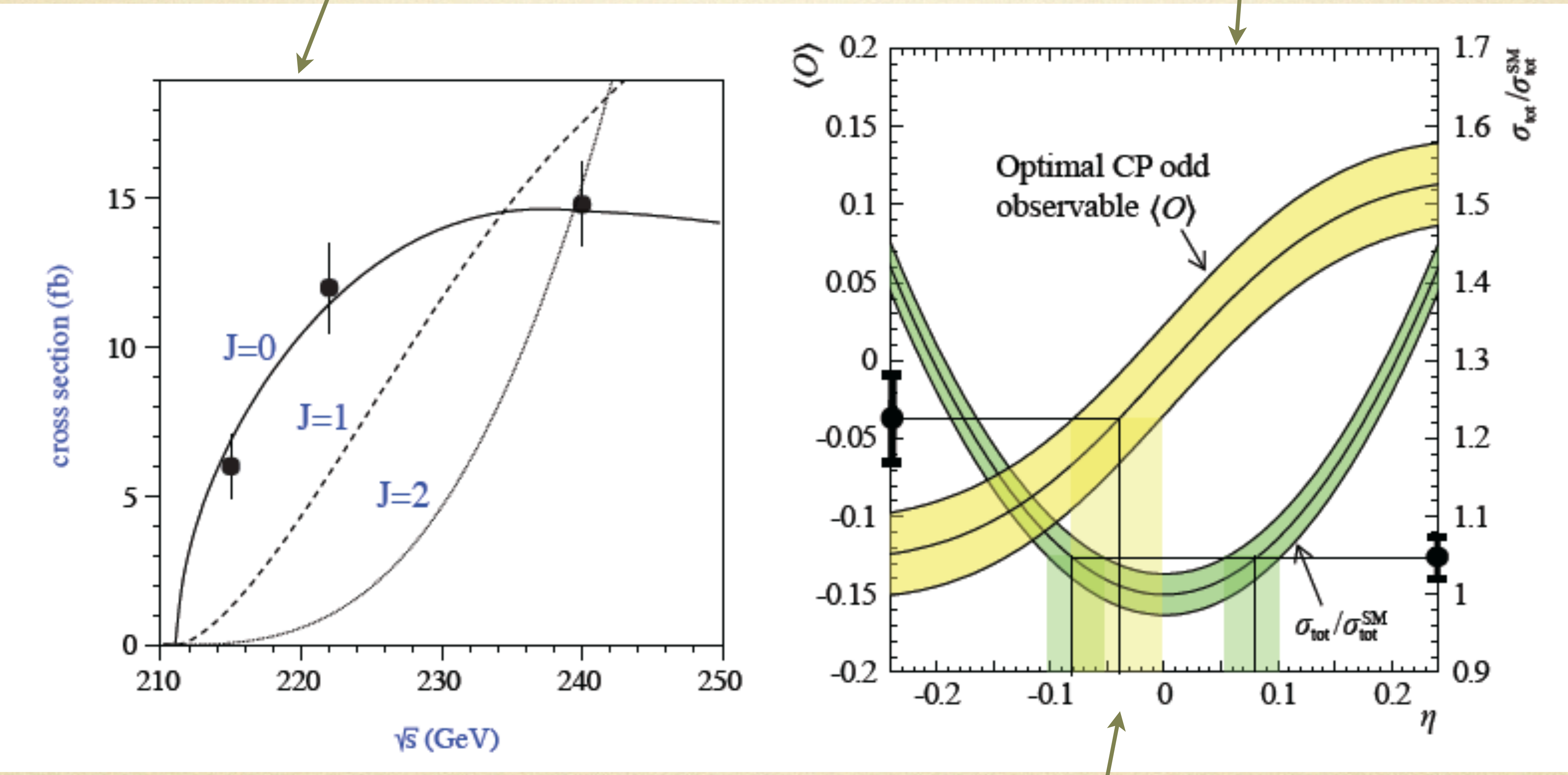
**ILC 250 GeV**

# Quantum Numbers $J^{\mathrm{CP}}$

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 $\mathrm{fb}^{-1}$-points threshold scan

if a mixture of CP even and CP odd



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

ref: Physics Volume

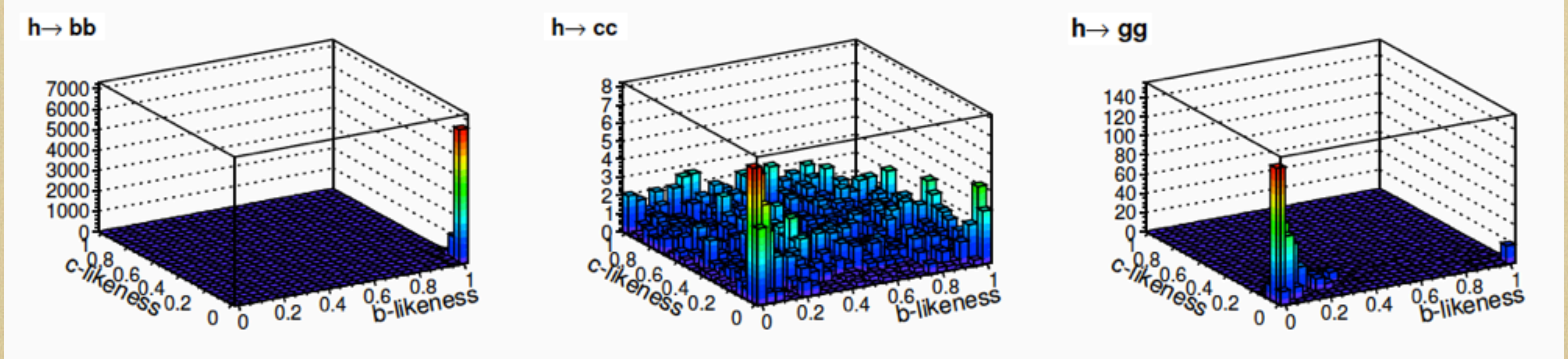
## --> few % of mixing angle

**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% |

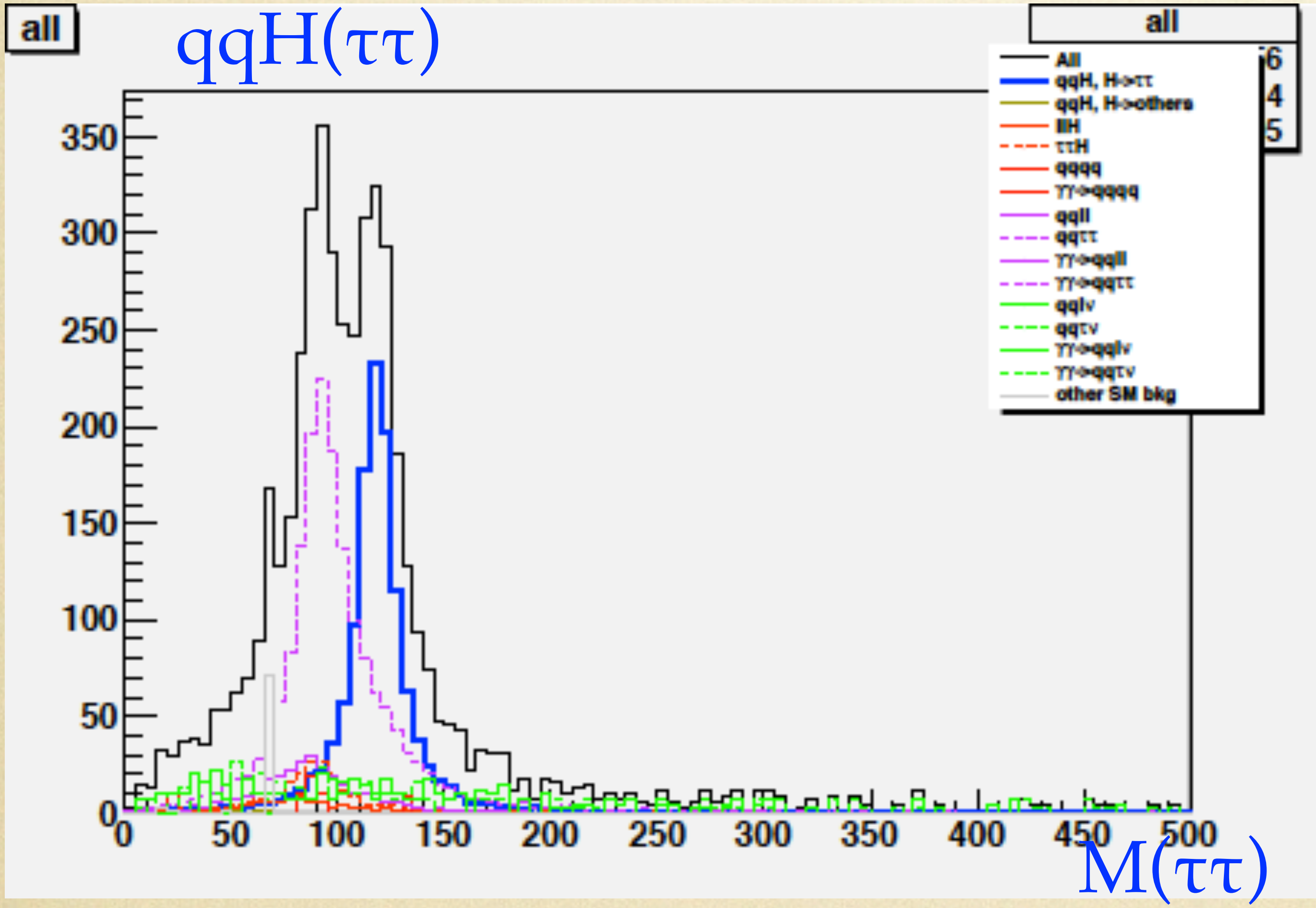
(Baseline)

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 | $8.0\sigma$ | $8.8\sigma$ | $25.7\sigma$ | $3.0\sigma$ |

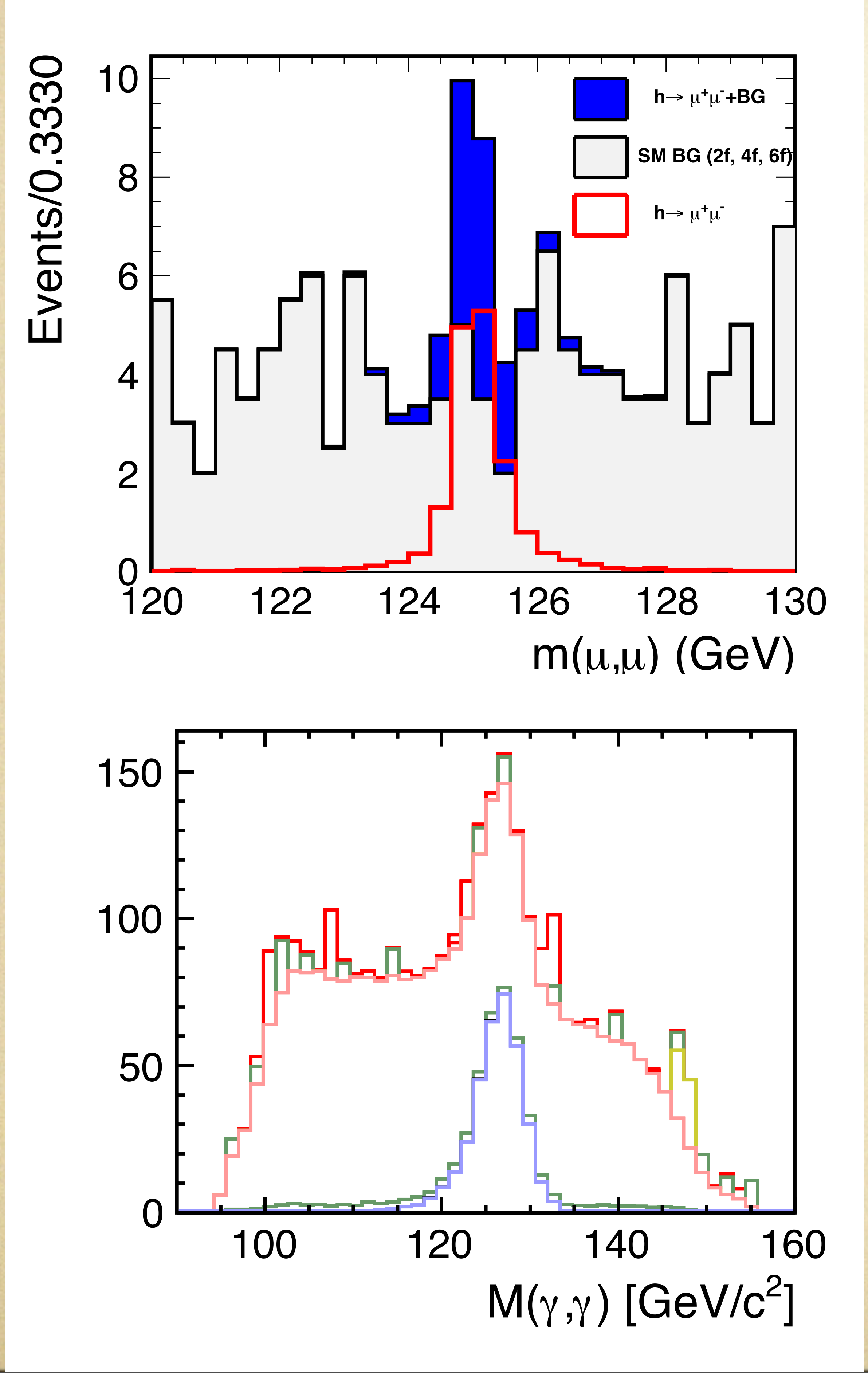
$$\frac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}} = 3.5\%$$

(Baseline)

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

**ILC 1 TeV**

# H-->γγ, $\mu^+\mu^-$



ongoing, preliminary

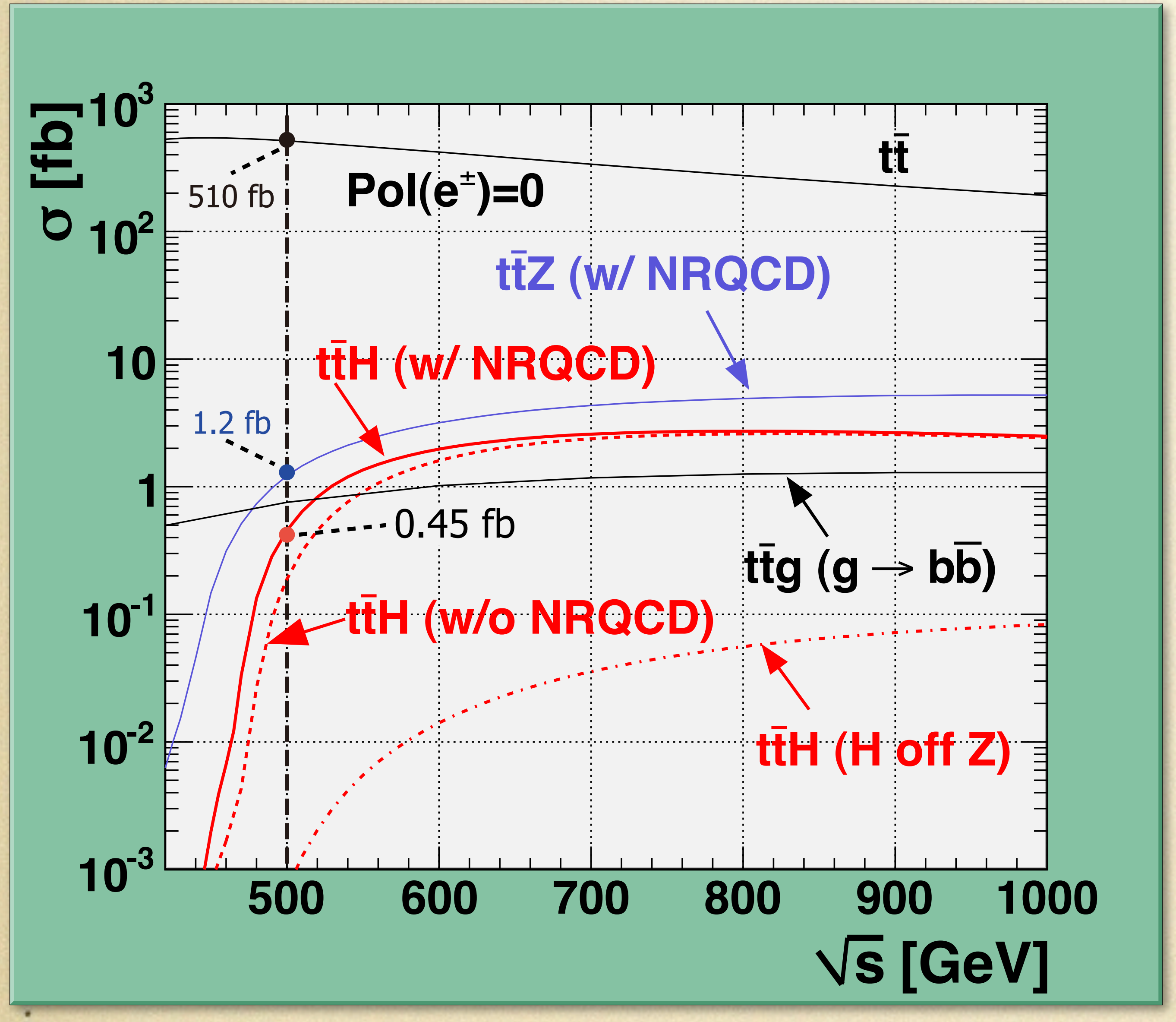
- rare decay
- low multiplicity
- clean and narrow mass peak
- need enough statistics

| 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% |

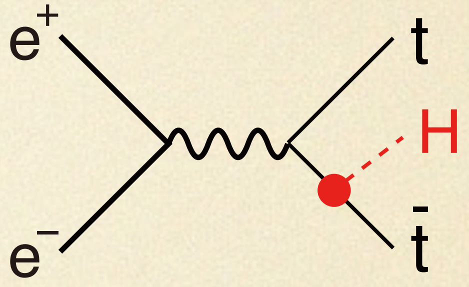
C. Calancha, LC-REP-2013-006

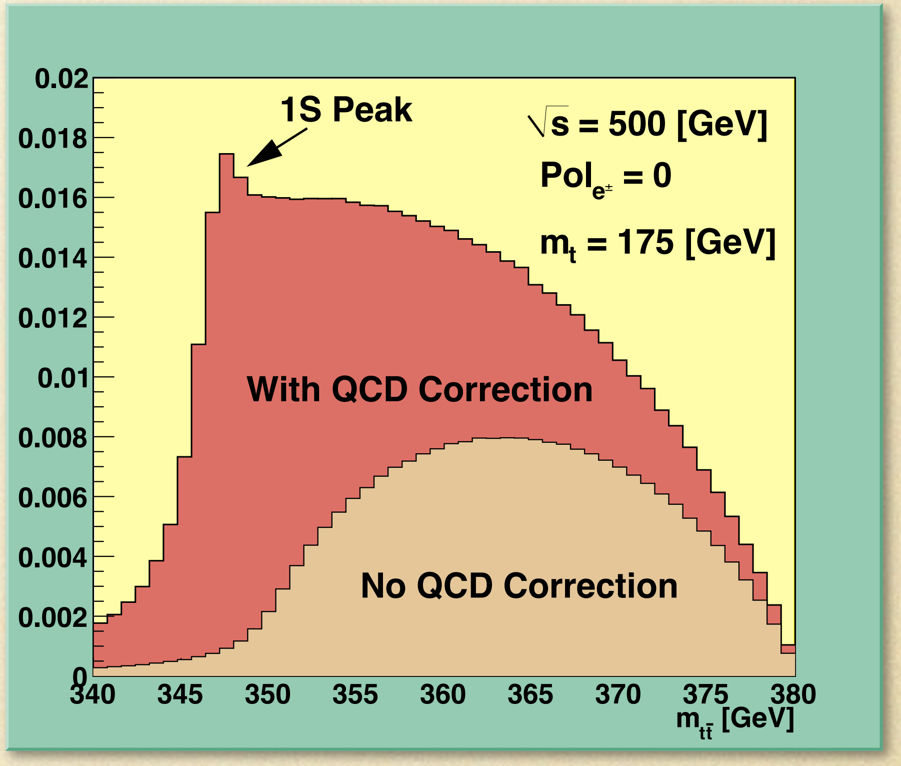
# Top Yukawa Coupling

## The largest among matter fermions



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





A factor of 2 enhancement from QCD bound-state effects

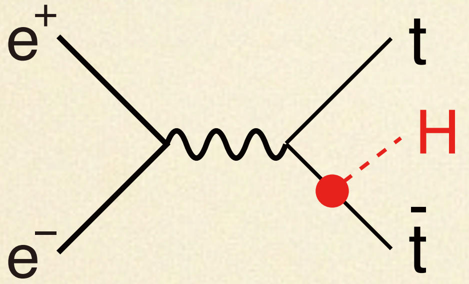
R. Yonamine, et. al, Phys.Rev. D84 (2011) 014033, confirmed by full simulation

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

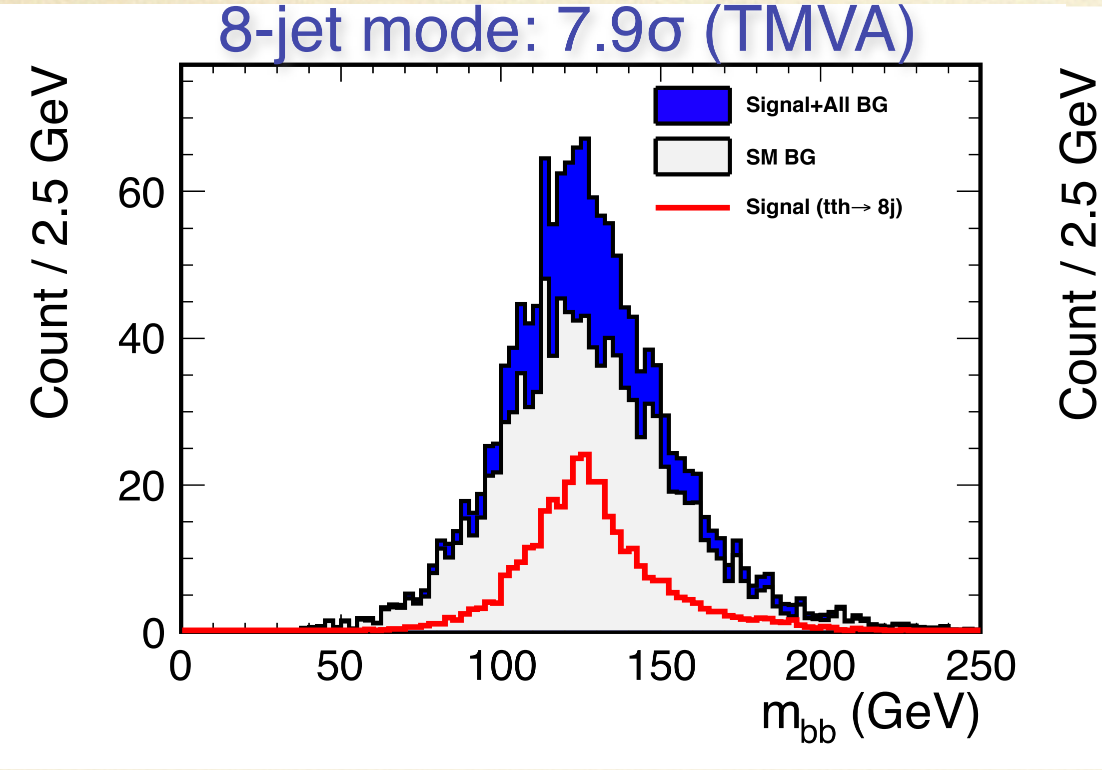
**ILC 1 TeV**

# Top Yukawa Coupling

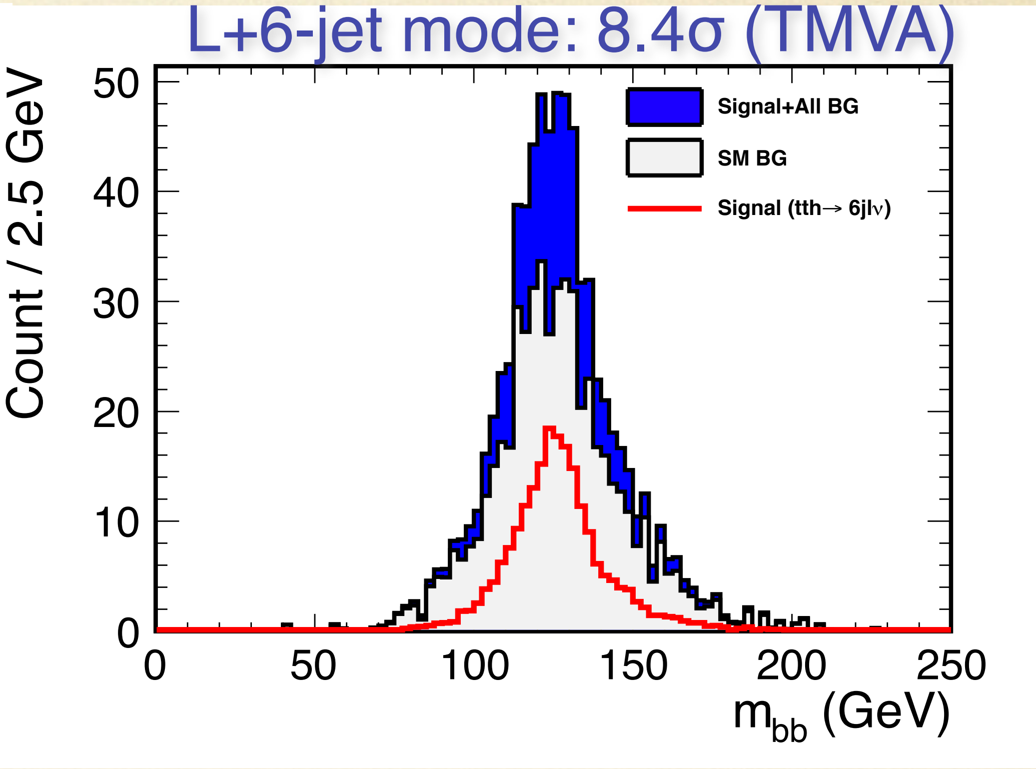
## The largest among matter fermions



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

physical Higgs field

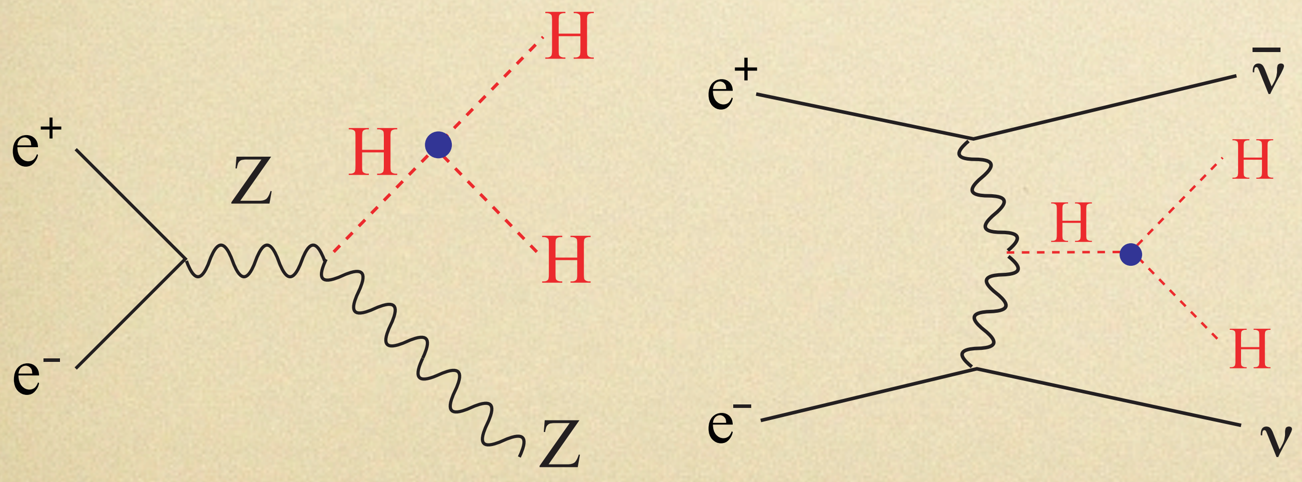
mass term

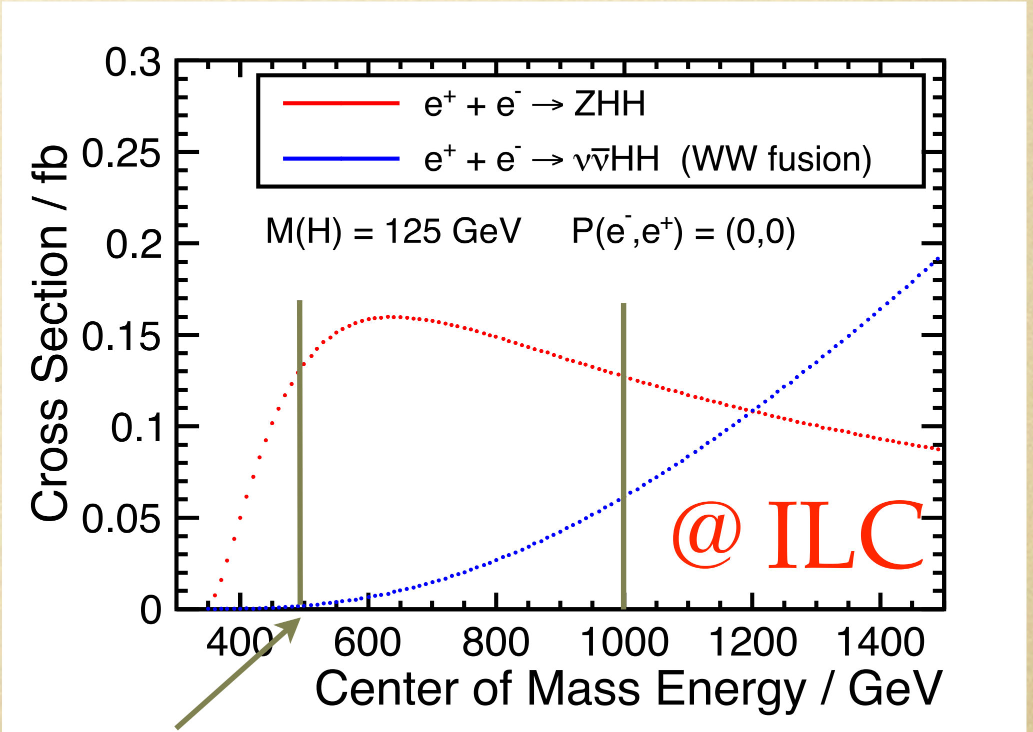
trilinear coupling

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

SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2\upsilon^2}$ $\upsilon$ ~ 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.





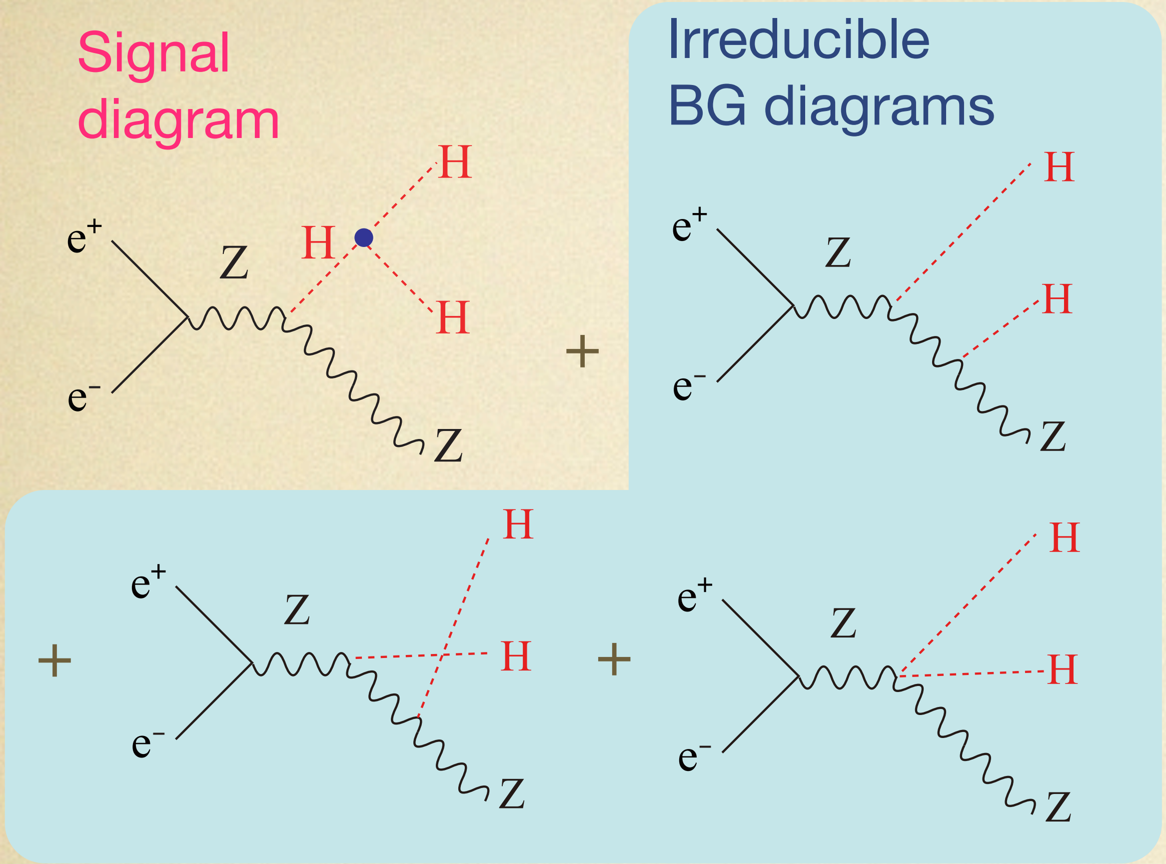
one of the reasons why 500 GeV

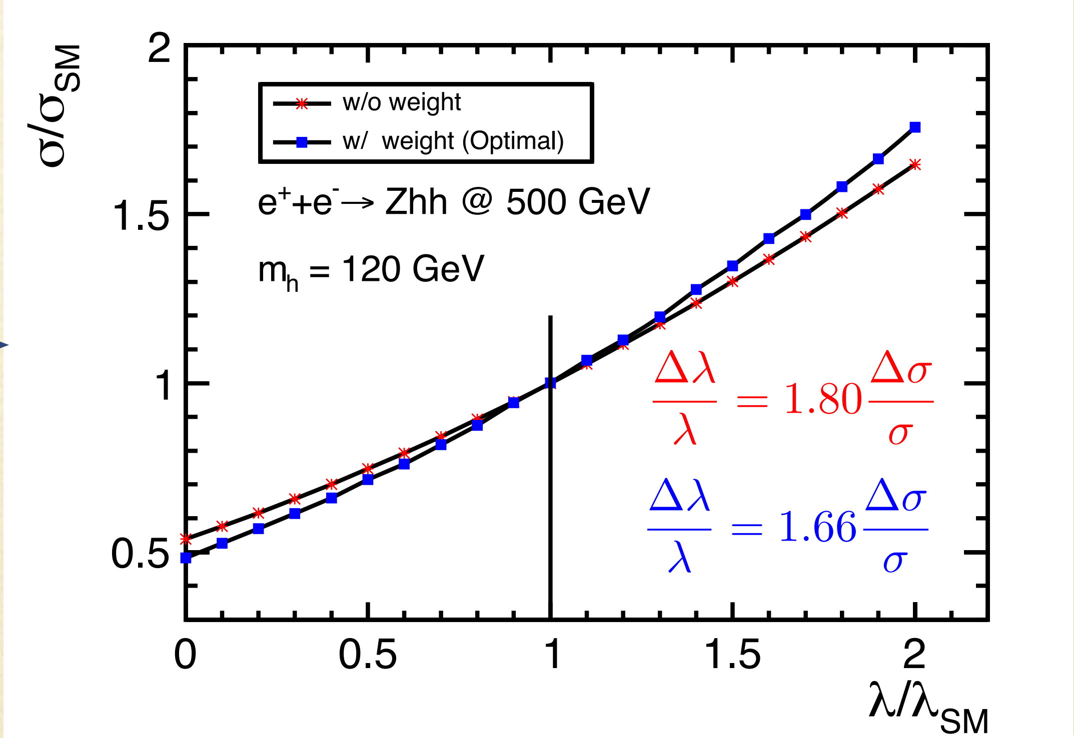
# General issue: sensitivity of coupling to the cross section

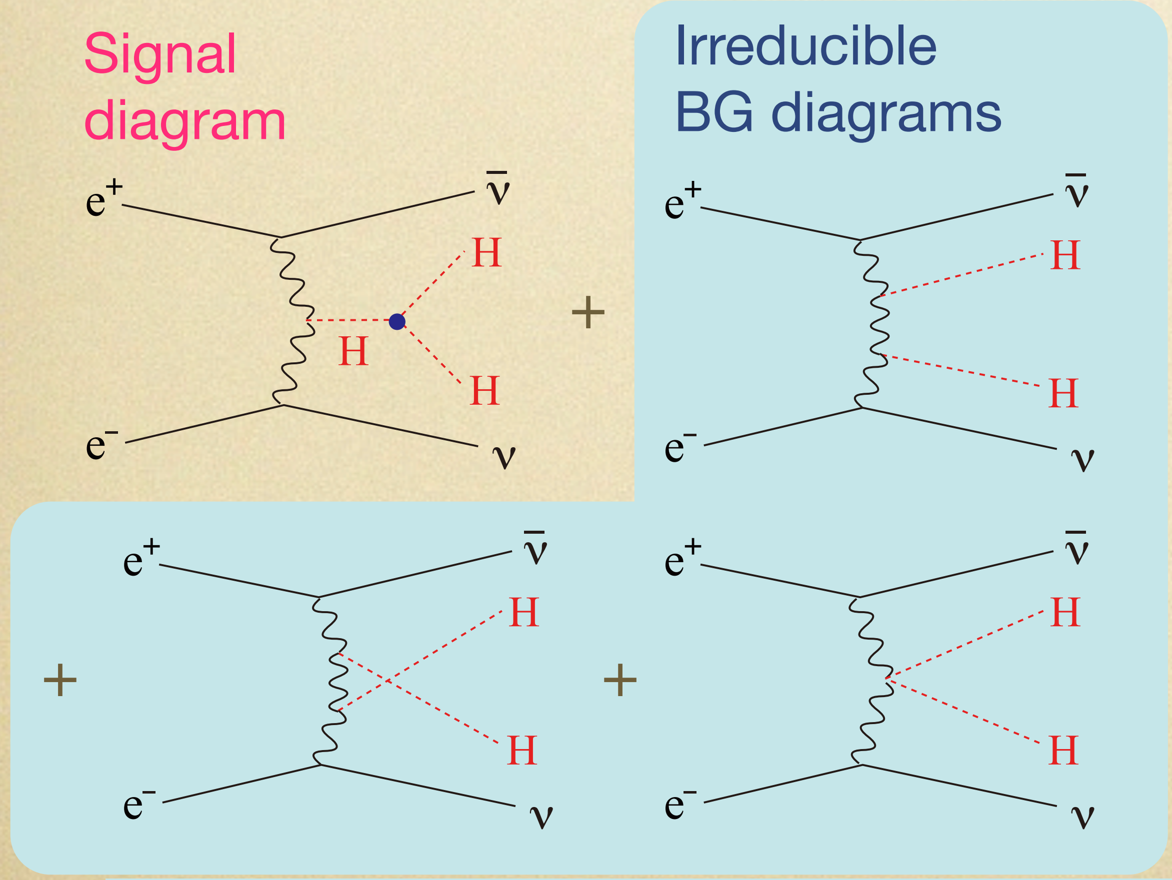
$$\sigma = \lambda^2 S + \lambda I + B$$

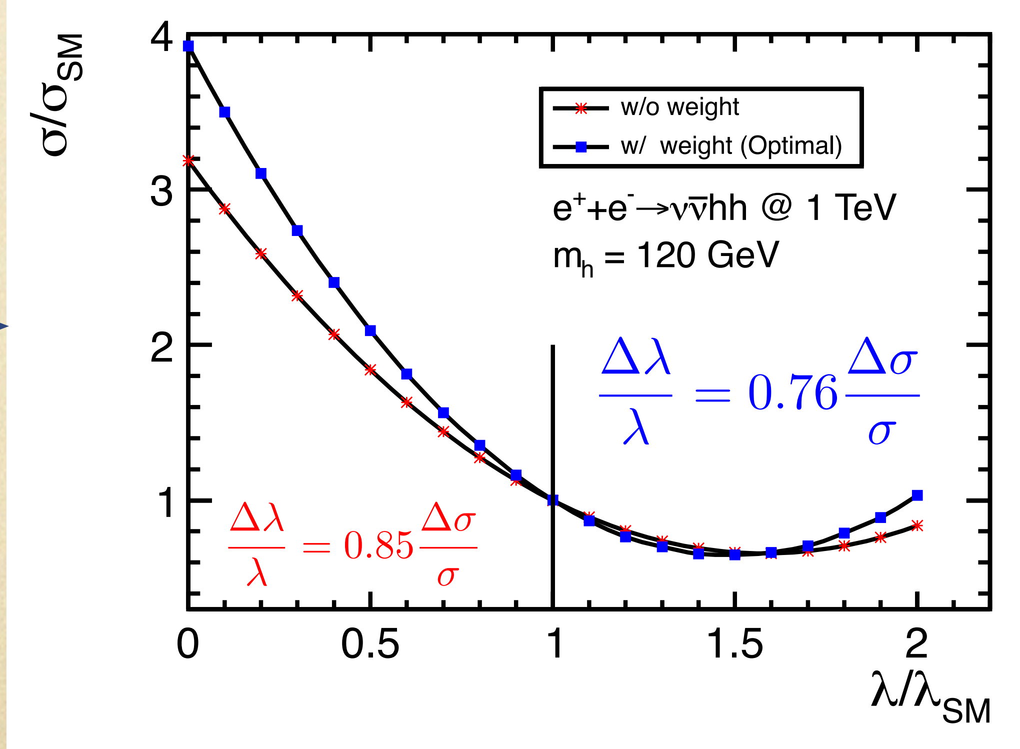
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

**F=0.5 if no BG diagrams**





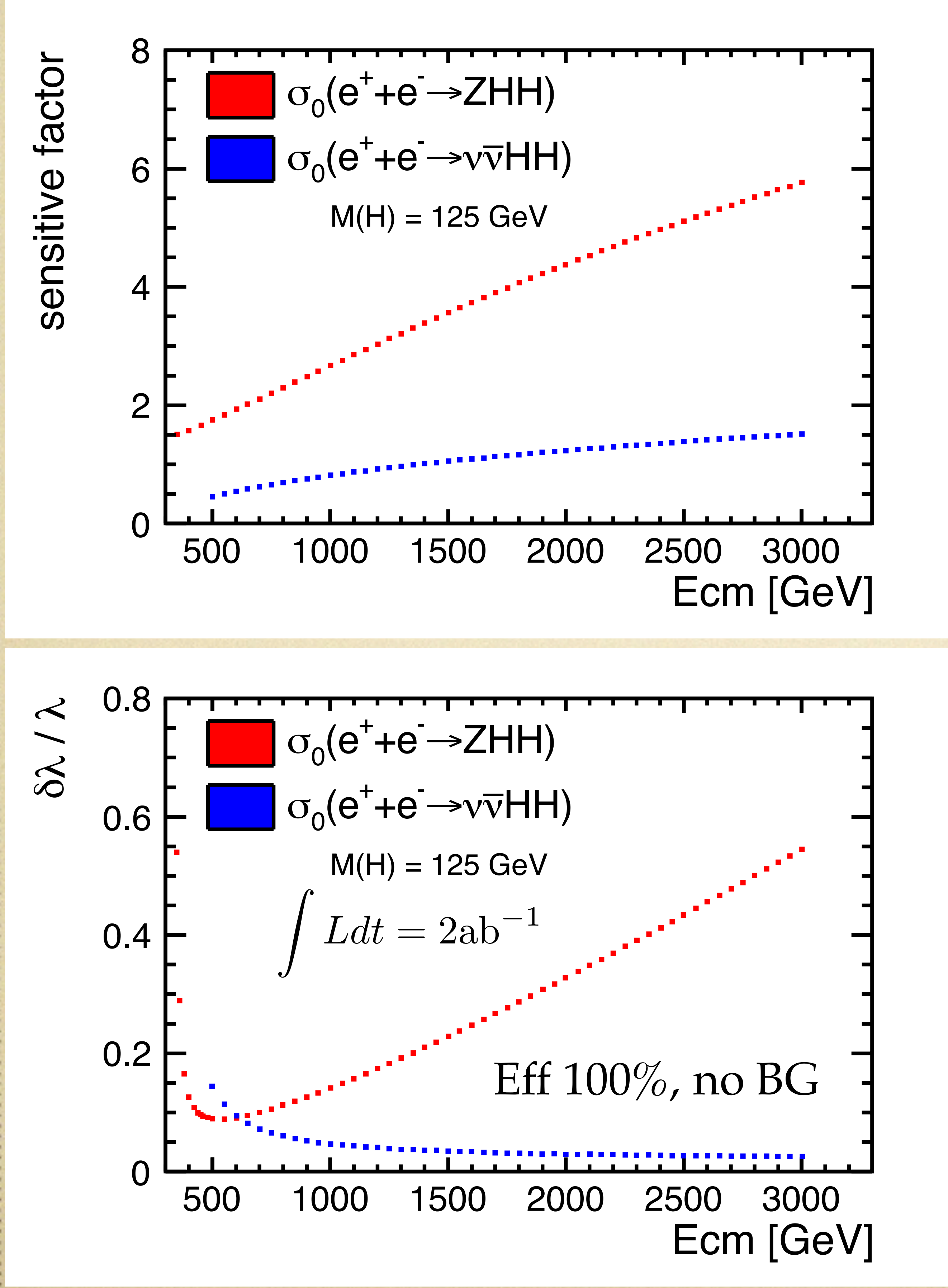




**these diagrams significantly degraded the sensitivity**

J. Tian, LC-REP-2013-003

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



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

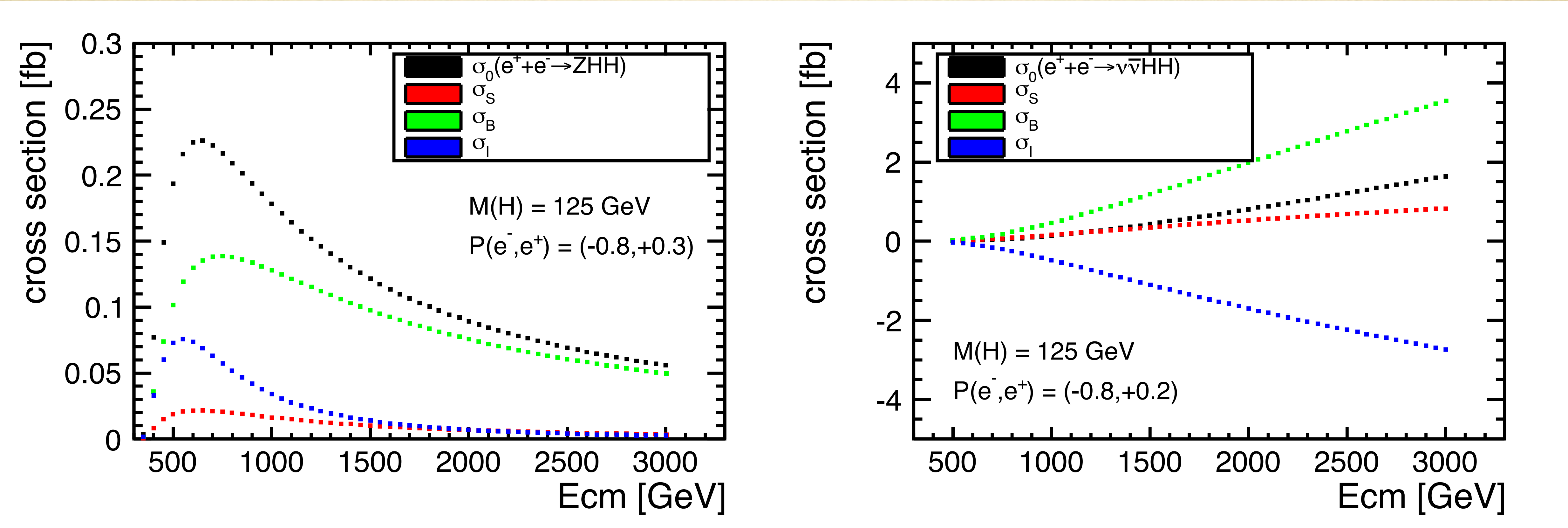
**Factor increases quickly as going to higher energy**

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

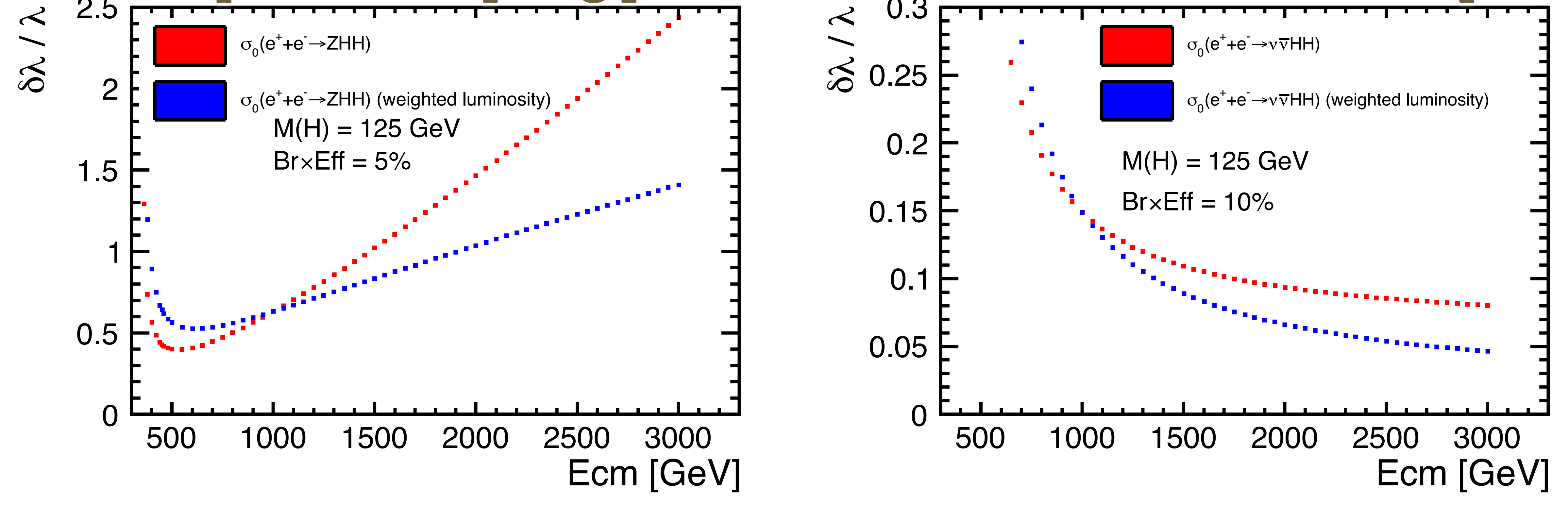
**for ννHH, expected precision improves slowly as going to higher energy**

# General issue: cross sections of each contribution

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

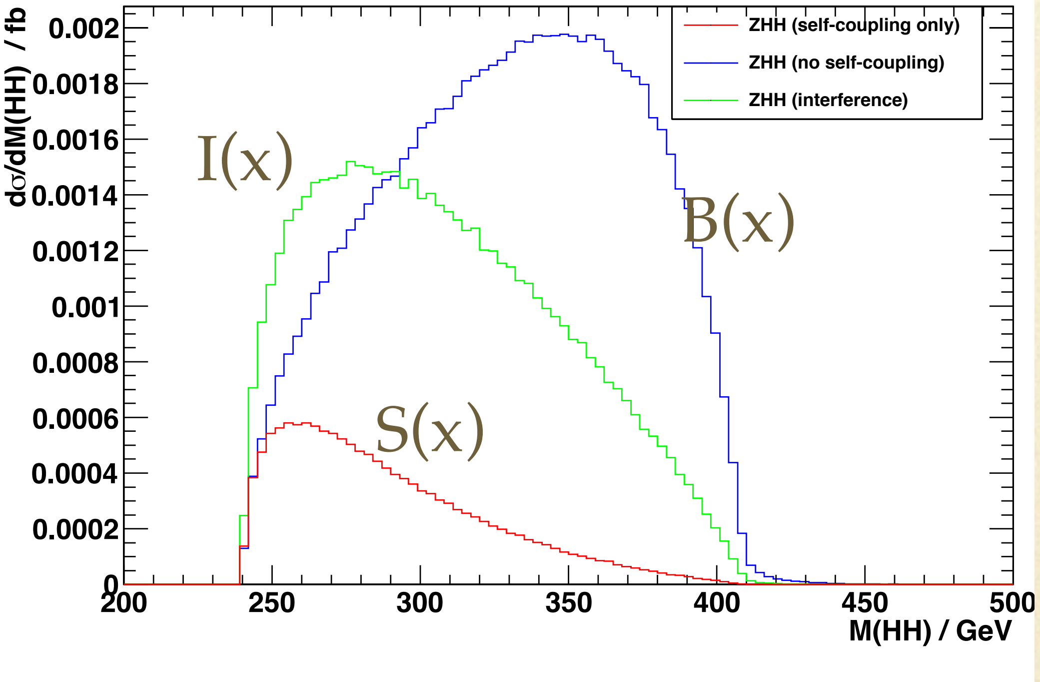


# expected coupling precision with more realistic setup



# new weighting method to enhance the coupling sensitivity

differential cross-section



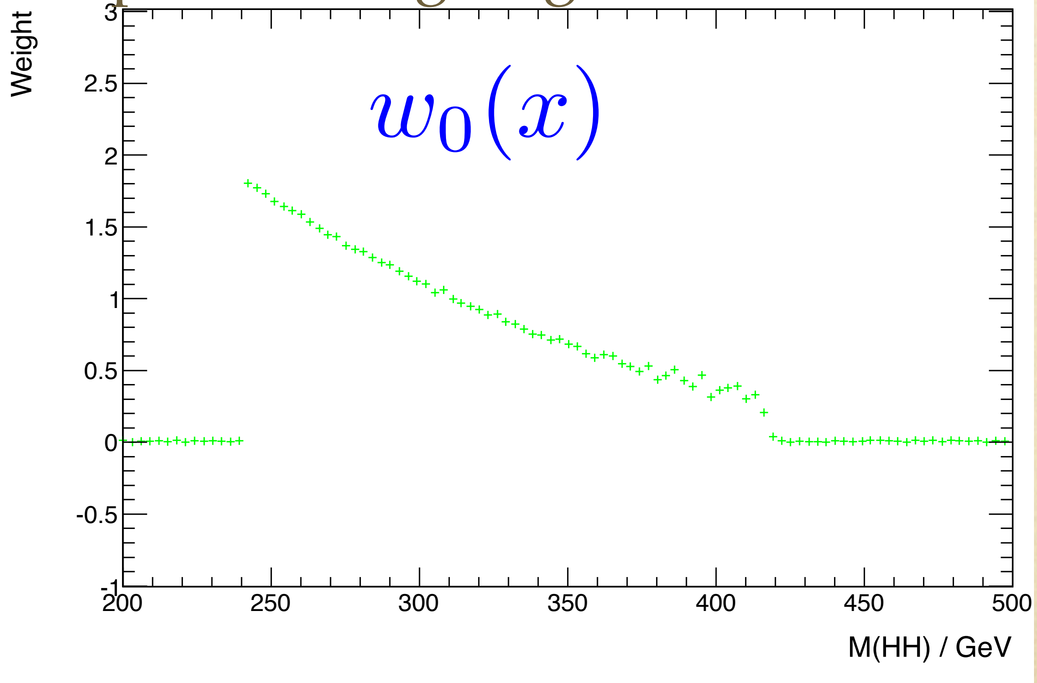
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

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:**

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

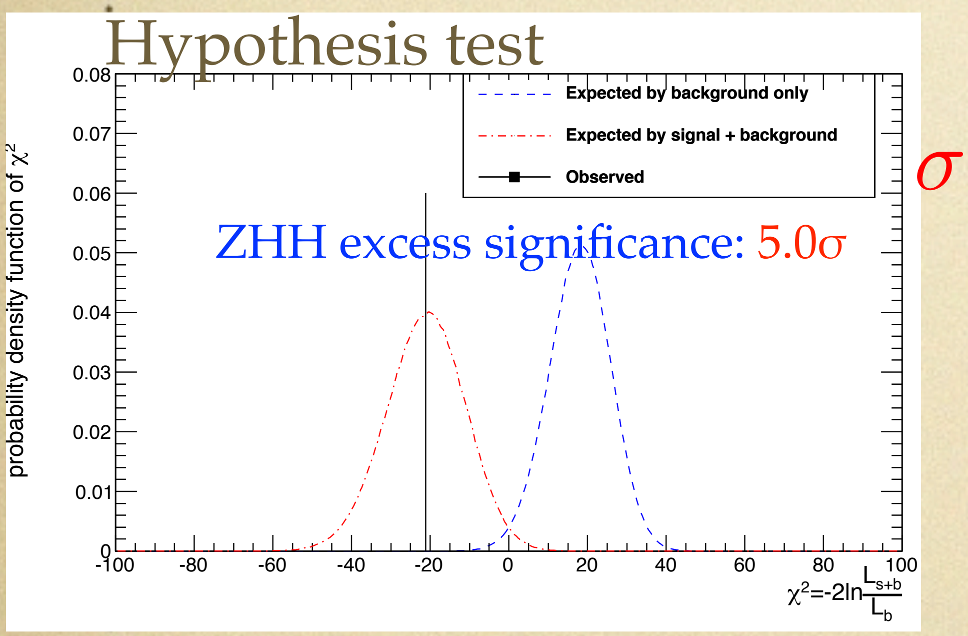
**c: arbitrary normalization factor**

DBD full simulation

# Higgs self-coupling @ 500 GeV (combined)

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

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

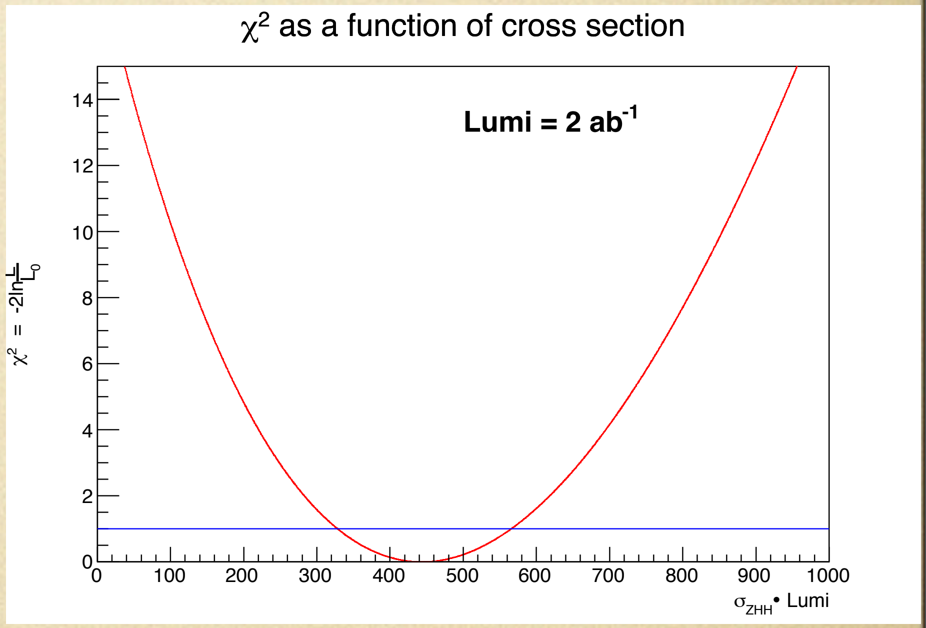


Hypothesis test

ZHH excess significance: 5.0σ

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

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



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

DBD full simulation

# Higgs self-coupling @ 1 TeV

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

| | Expected | After Cut |
|---|---|---|
| vvhh (WW F) | 272 | 35.7 |
| vvhh (ZHH) | 74.0 | 3.88 |
| BG (tt/vvZH) | $7.86\times10^5$ | 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)

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

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 $\sigma_{ZH}$ 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 χ2, which can be parameterized with 9 couplings and Higgs total width

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

$\Delta Y_i$ is the measurement error

global fit: minimize the χ2 ---> 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% |
| $\Gamma_0$ | 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% |

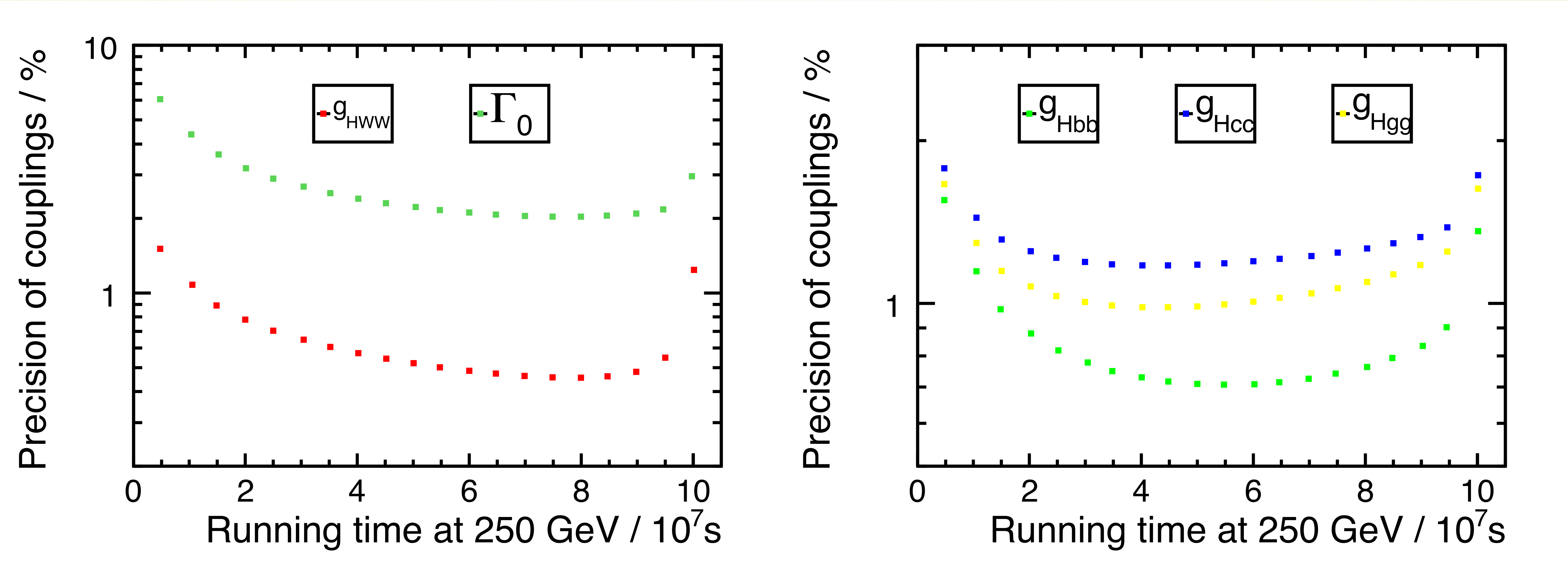
(* only for H-->bb)

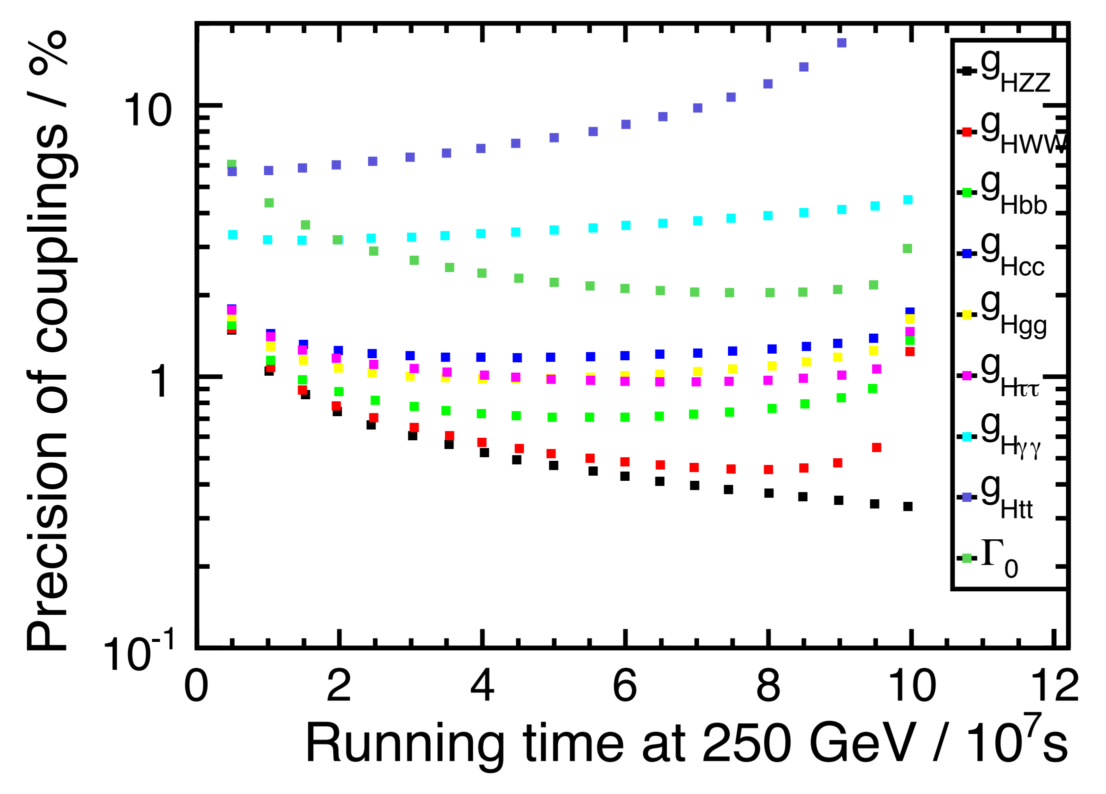
# global fit --model dependent + sys + theory error (0.1%)

| coupling Δg/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% |
| Hττ | 5.2% | 1.9% | 1.3% | 2.4% | 1.0% | 0.74% |
| Hγγ | 17% | 8.3% | 3.8% | 8.1% | 4.4% | 2.3% |
| Hμμ | 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% |
| $\Gamma_0$ | 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

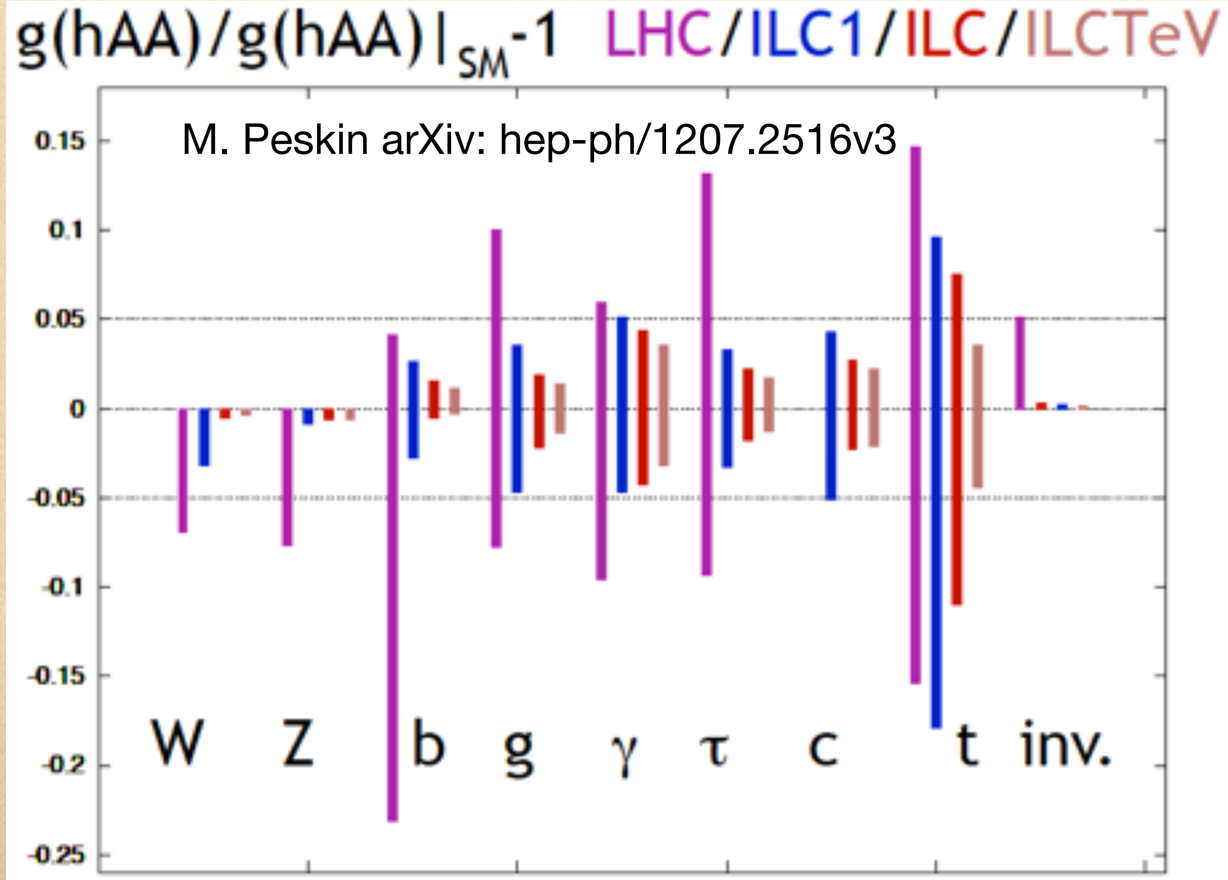
## e.g., assuming 10y running at 250 GeV + 500 GeV

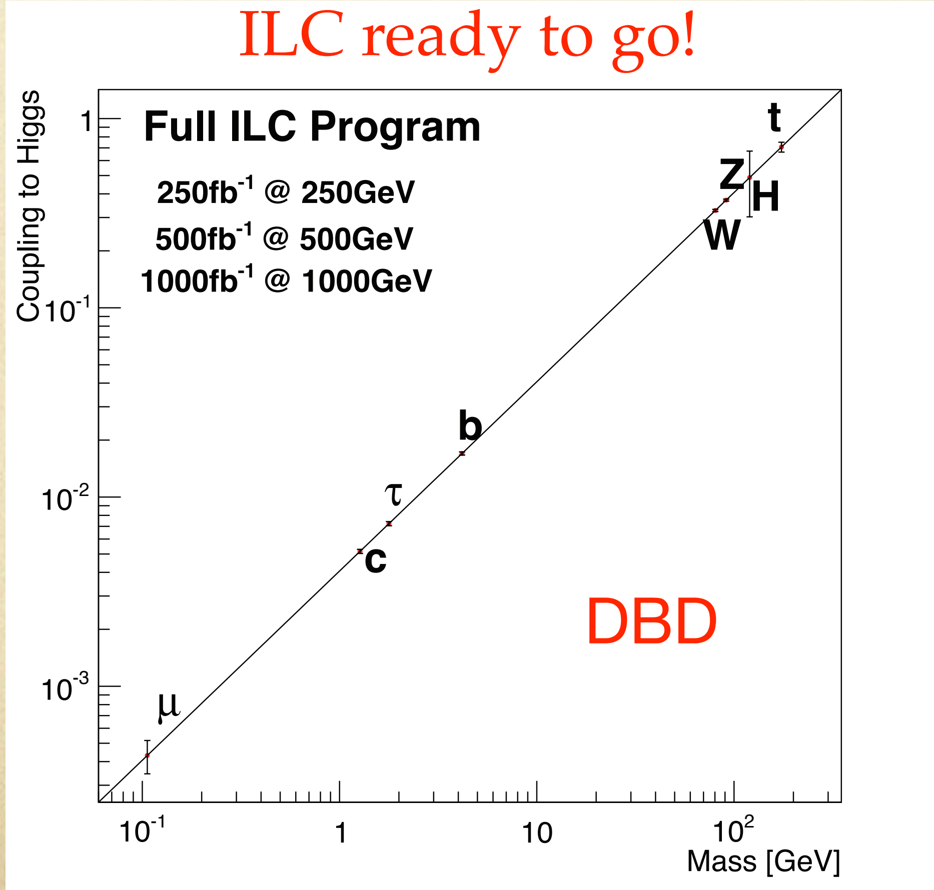




# Summary

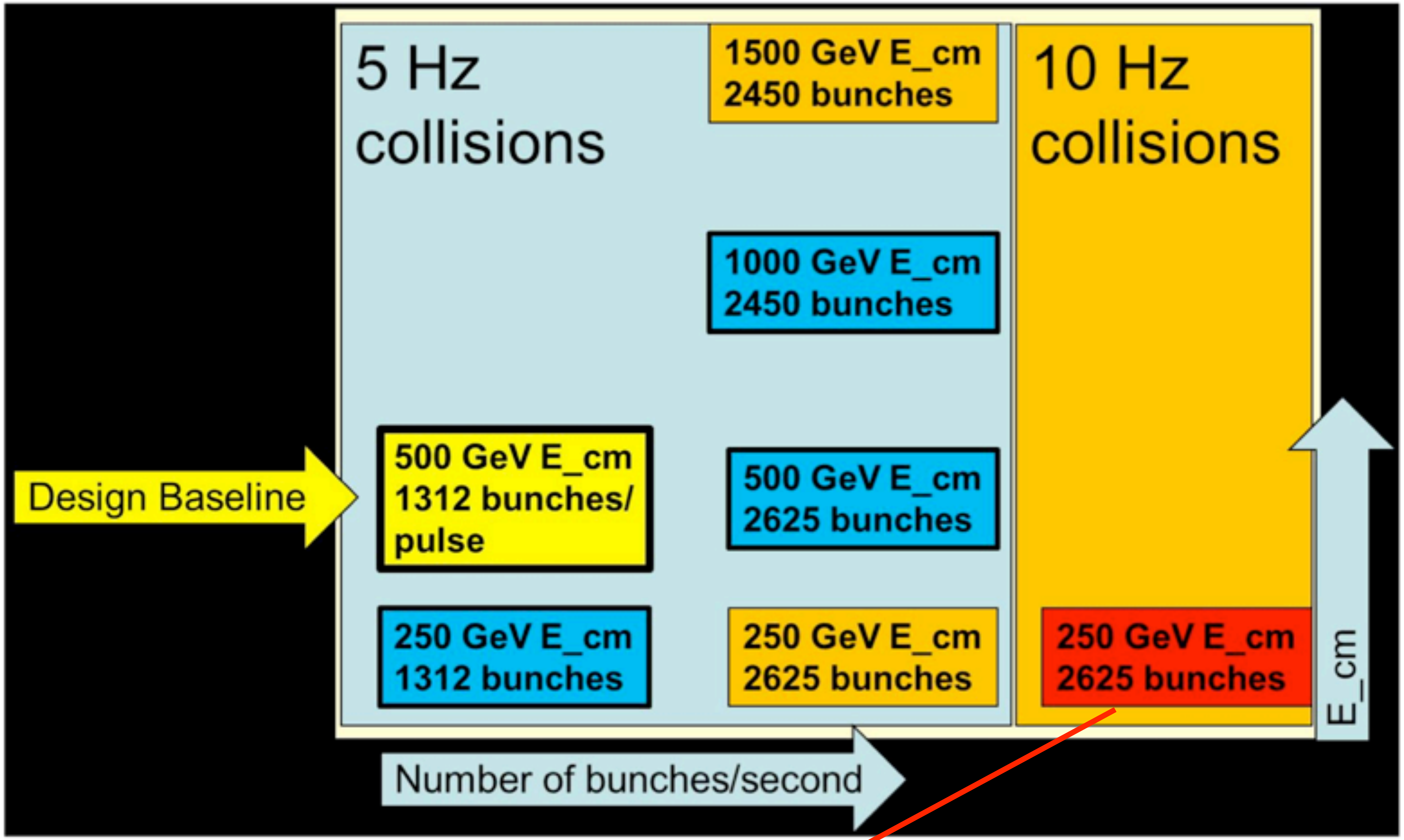
- ILC is the ideal precision machine complementary to LHC discovery power, to reveal the mechanism of EWSB and mass generation; performance of ILD can exactly meet the physics goal.
- recoil mass measurement @ 250 GeV gives the absolute HZZ coupling, be able to model independently normalize all the Higgs 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.





# backup

# ILC Stages and Upgrades



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

**x4 upgrade @250GeV**

Blue: upgrade described in TDR

The current ILC design is rather conservative!

# Model-independent Global Fit for Couplings

## 33 σxBR measurements ($Y_i$) and $\sigma_{ZH}$ ($Y_{34,35}$)

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

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

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

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

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

$$F_i = S_i\, G_i$$

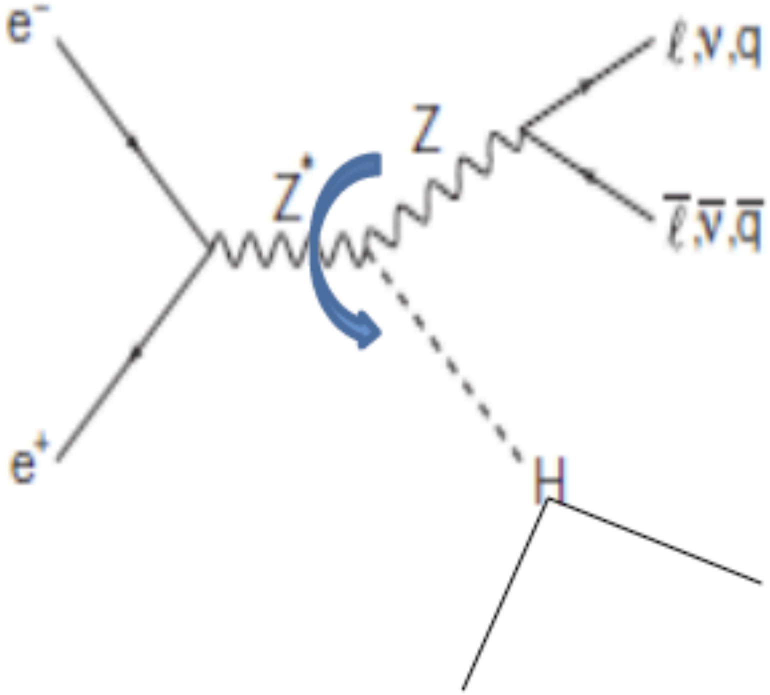
$$S_i = \left( \frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left( \frac{\sigma_{\nu\bar{\nu}H}}{g^2_{HWW}} \right), \text{ or } \left( \frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right)$$

- 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

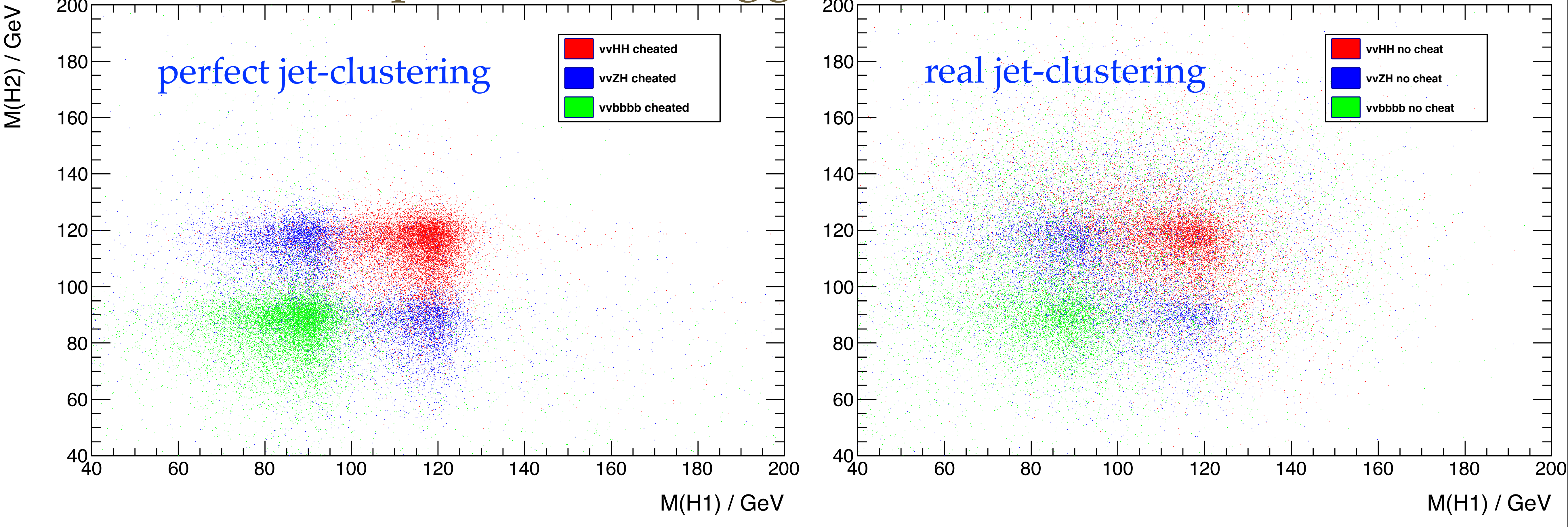
$$P_H = \underset{\uparrow \atop \text{known}}{P_{e+e-}} - \underset{\uparrow \atop \text{measured}}{P_Z}$$

A. Ishikawa @ Snowmass, Seattle

# prospect of Higgs self-coupling

## scatter plot of two Higgs masses

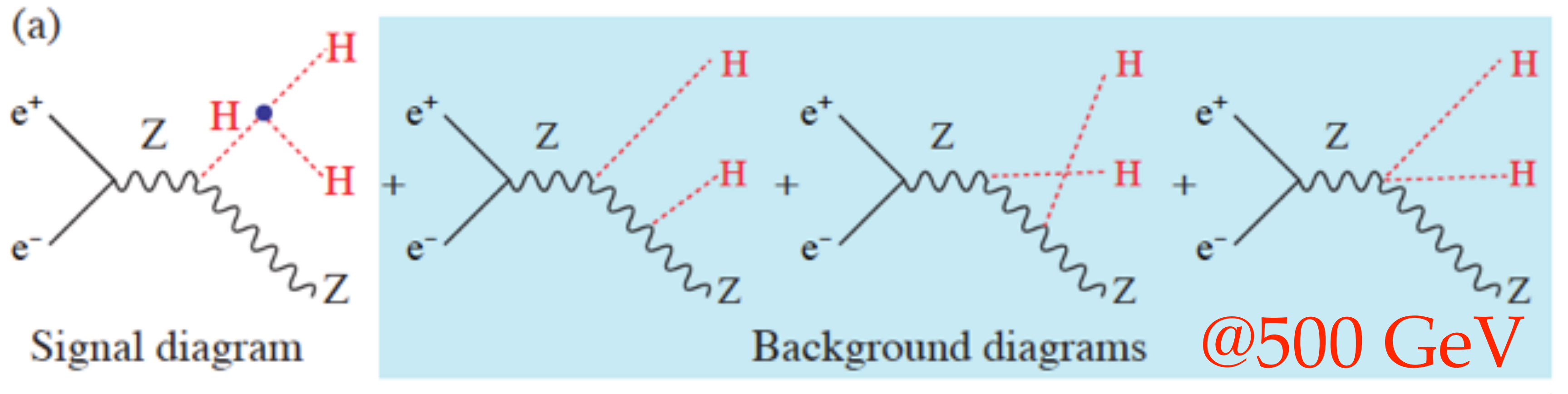
vvHH mode: (ZZH and ZZZ)



- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve 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

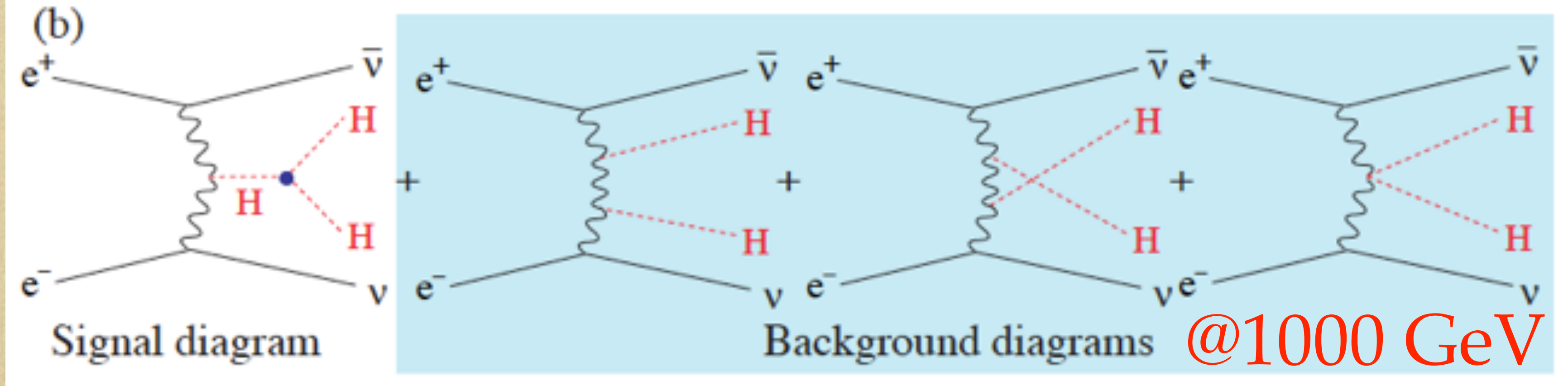


@500 GeV

more sensitive!

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

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



@1000 GeV

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

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

preliminary! correlation with HHH not included