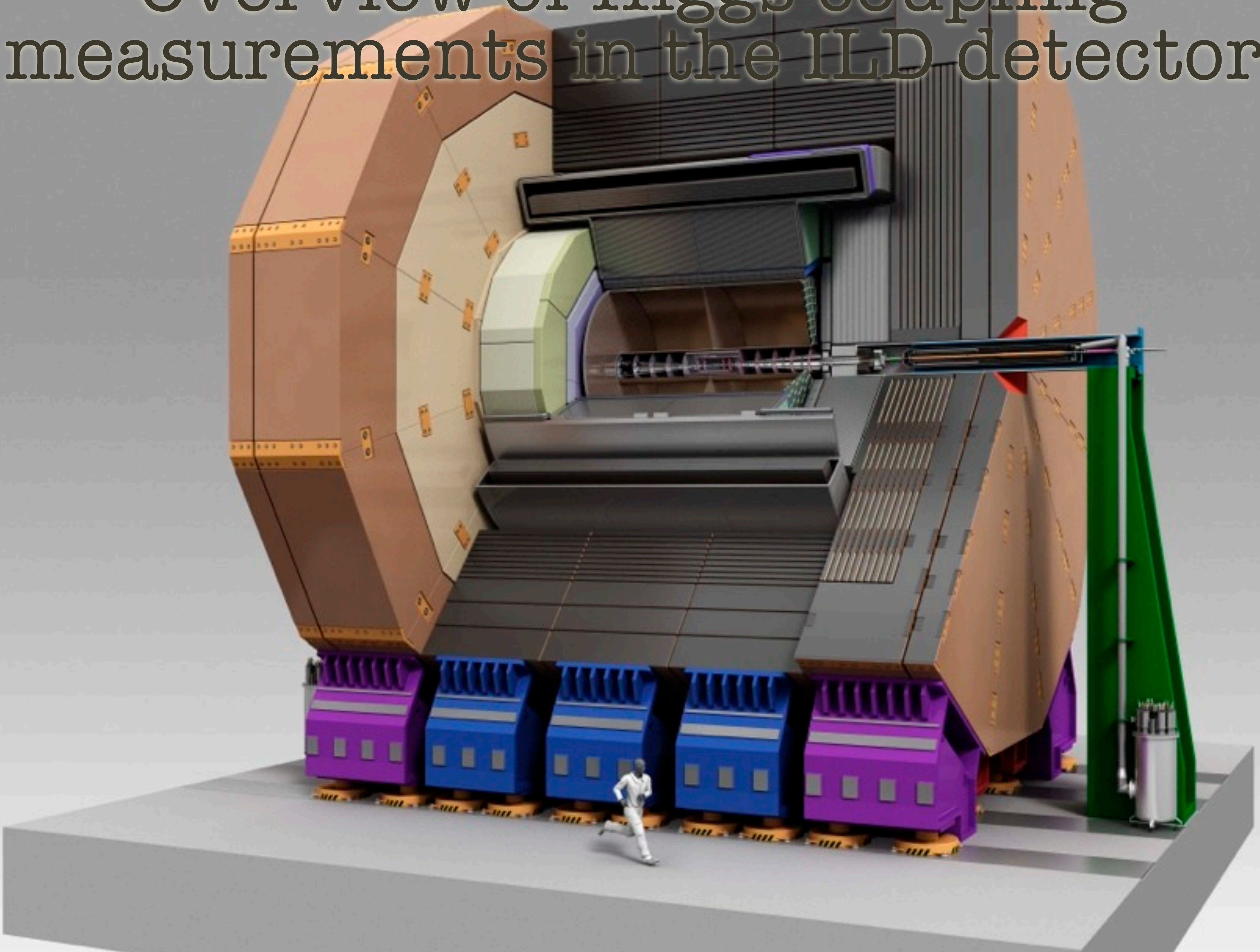
# Overview of Higgs coupling measurements in the ILD detector



**Junping Tian (KEK)**

**---on behalf of the ILD concept group**

**Snowmass Energy Frontier Workshop, Apr. 3-6, BNL**

# outline

- primary goals of ILC Higgs physics
- detector performance and simulation in ILD-DBD
- precision measurement @ 250 GeV as a Higgs factory
- physics opportunities @ 500 GeV and 1 TeV

specific topic on Higgs self-coupling

- ZHH @ 500 GeV
- $\nu\nu$HH (fusion) @ 1 TeV

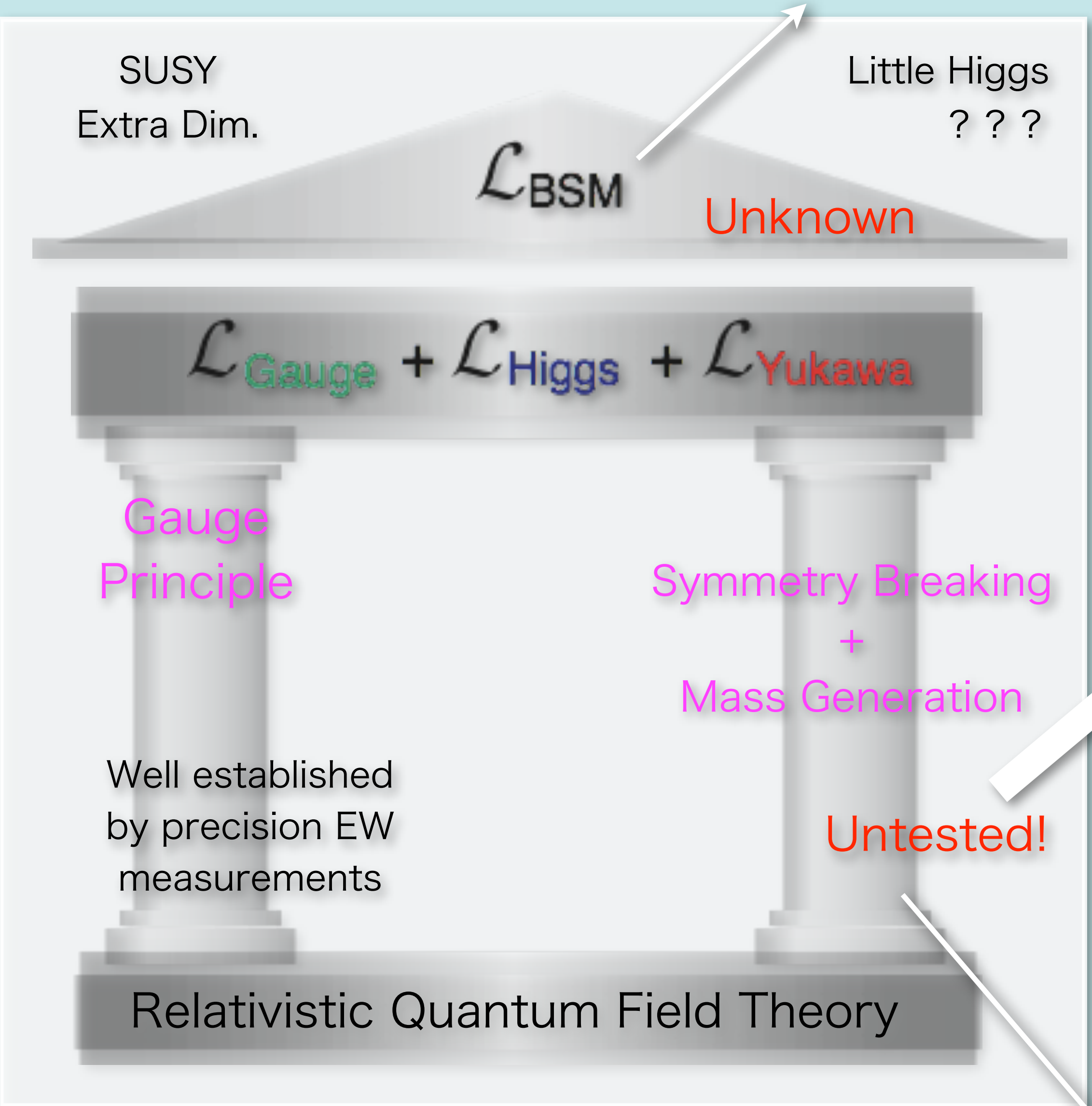
# Primary Goal

## 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


SUSY
Extra Dim.

Little Higgs
? ? ?

$\mathcal{L}_{BSM}$

Unknown

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

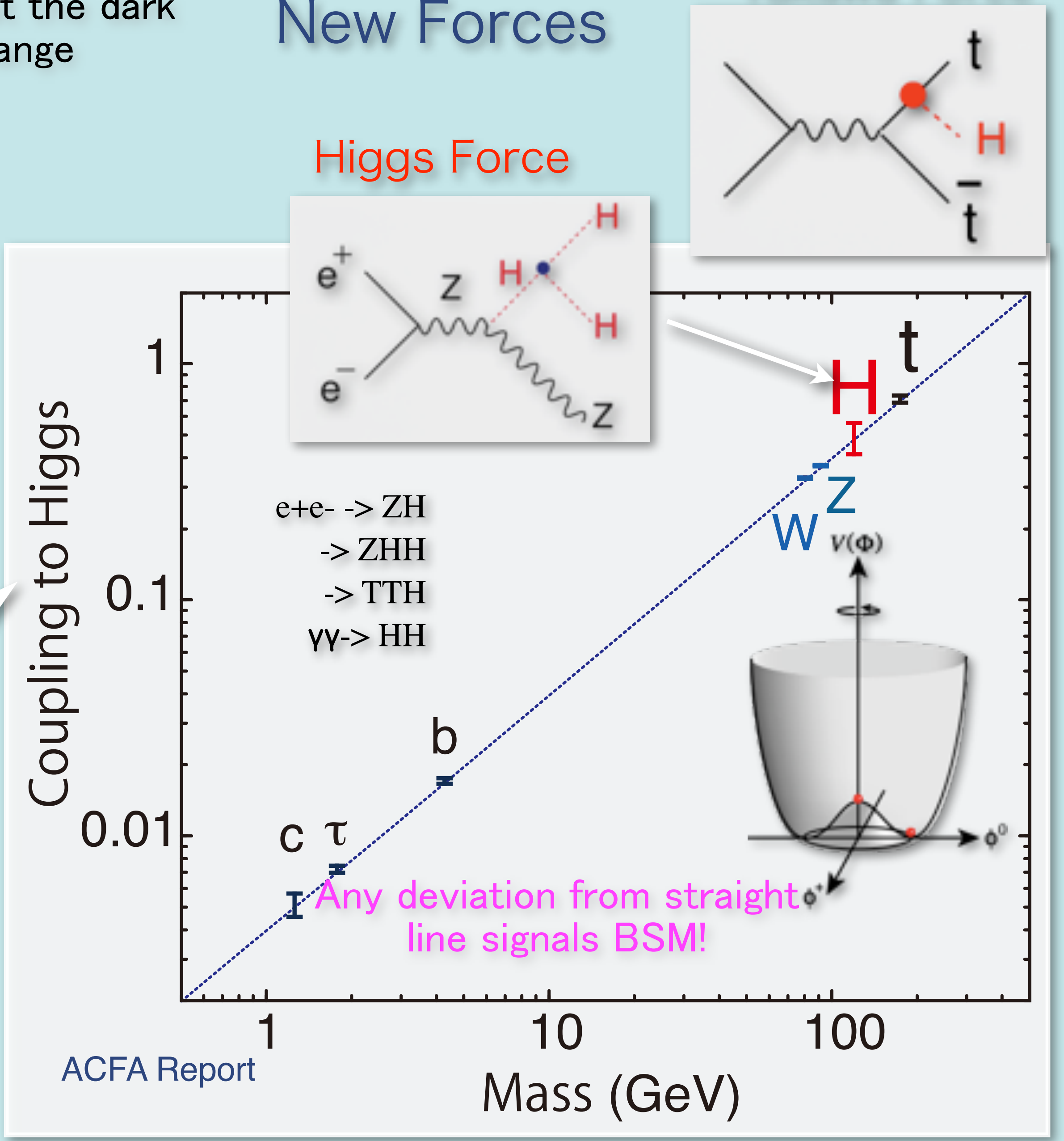
Gauge Principle

Symmetry Breaking
+
Mass Generation

Well established by precision EW measurements

Untested!

Relativistic Quantum Field Theory


Yukawa Force

Higgs Force

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!

# Precision determination of the absolute Higgs couplings

## (bottom-up reconstruction, model free)

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

test CP mixture

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

observe the force to make higgs condense

$L_{\text{Gauge}}$

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

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

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

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

crucial to test the mass coupling proportionality

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

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: DBD Physics Volume

**Decoupling limit:** deviation to SM $\sim \dfrac{m_h^2}{M^2}, \dfrac{m_t^2}{M^2}$

M: mass scale of new particle

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:

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

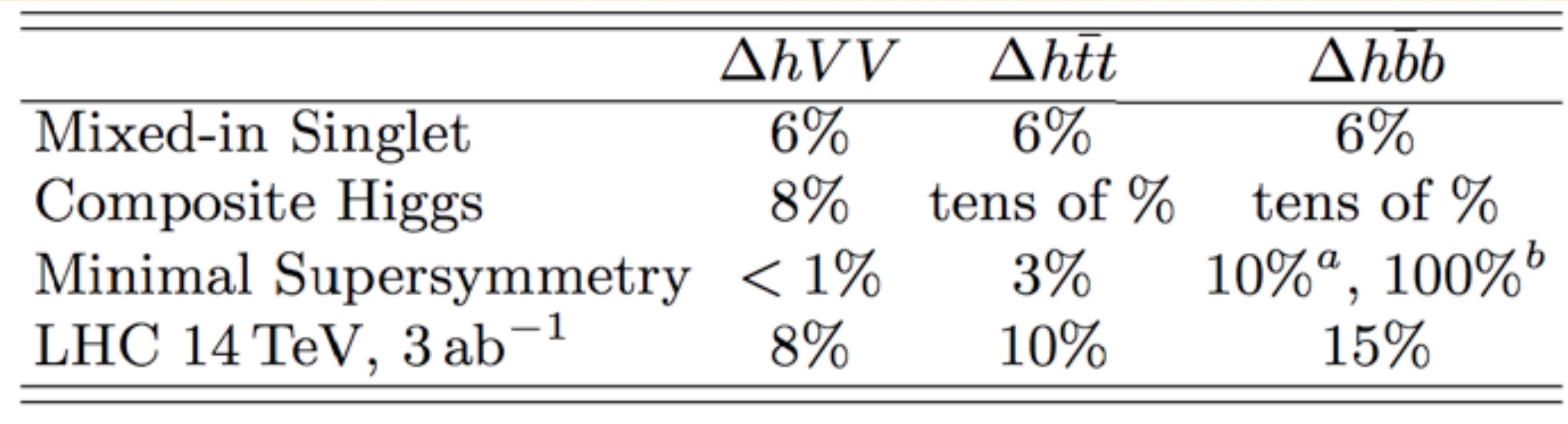
$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ {\rm TeV}/f)^2 & ({\rm MCHM4}) \\ 1 - 9\%(1\ {\rm TeV}/f)^2 & ({\rm MCHM5}) \end{cases}$$

SUSY:

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

Little Higgs:

$$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} = 1 - (5\% \sim 9\%) \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} = 1 - (5\% \sim 6\%)$$



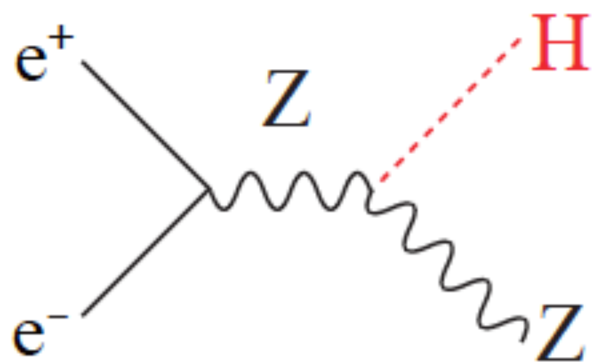
| | $\Delta hVV$ | $\Delta h\bar{t}t$ | $\Delta h\bar{b}b$ |
|---|---|---|---|
| Mixed-in Singlet | 6% | 6% | 6% |
| Composite Higgs | 8% | tens of % | tens of % |
| Minimal Supersymmetry | $< 1\%$ | 3% | $10\%^a$, $100\%^b$ |
| LHC 14 TeV, 3 $\mathrm{ab}^{-1}$ | 8% | 10% | 15% |

R.S.Gupta, H.Rzehak, J.D.Wells

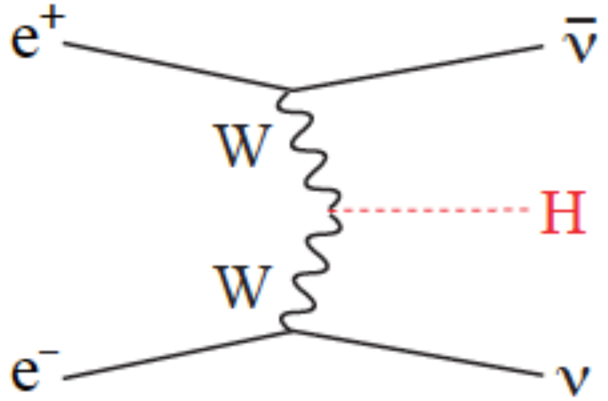
arXiv: 1206.3560v1

# Higgs Production and Decay @ ILC

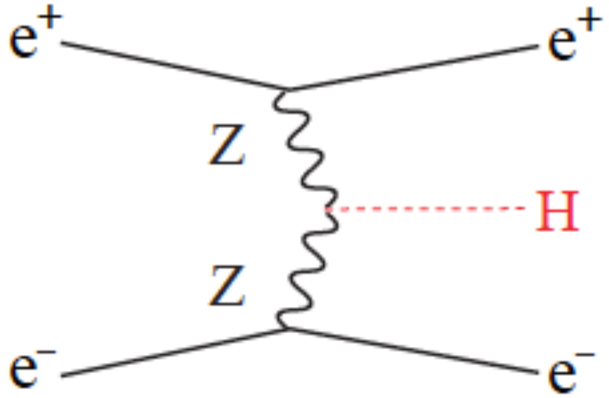
ref: DBD Physics Volume



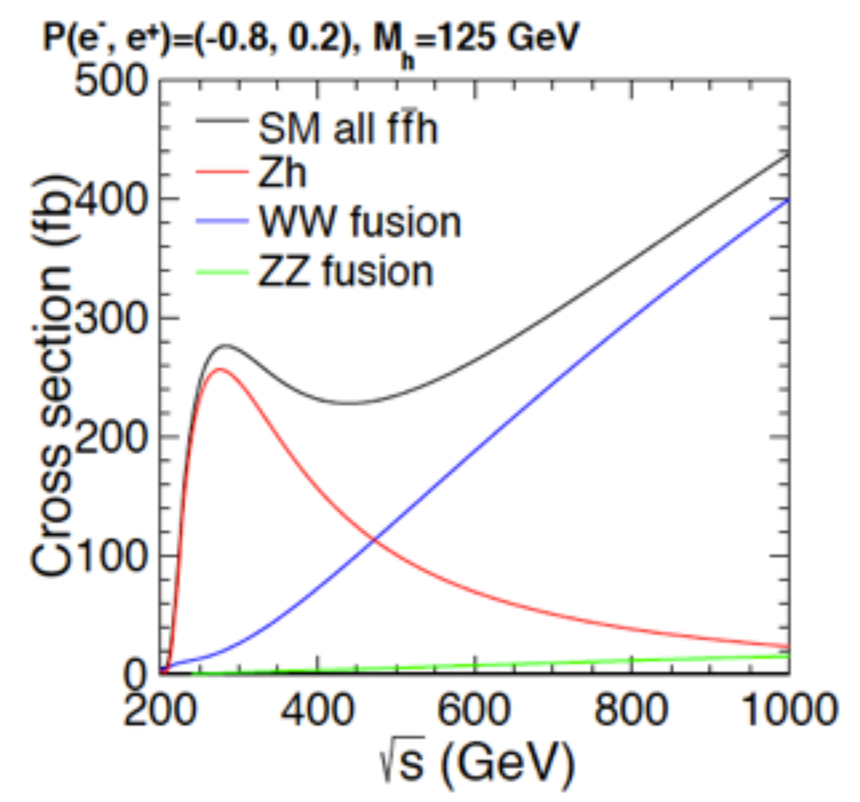
Higgs-strahlung

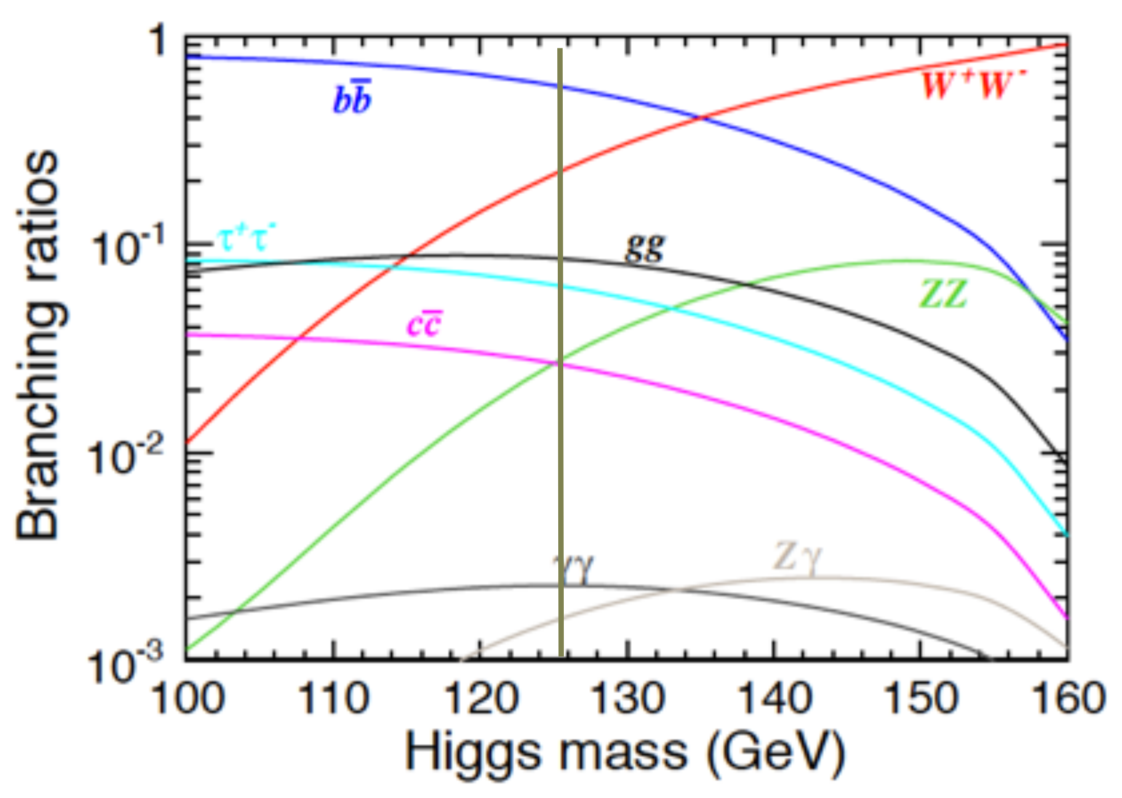


WW-fusion



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 canonical physics program (Higgs Part)

usually luminosity ∝ Ecm

## 250 $\mathrm{fb}^{-1}$ @ 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 mass
- Total width

## 500 $\mathrm{fb}^{-1}$ @ 500 GeV

- WW-fusion production, 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

## 1000 $\mathrm{fb}^{-1}$ @ 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: $\sigma_{1/p_T} \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$

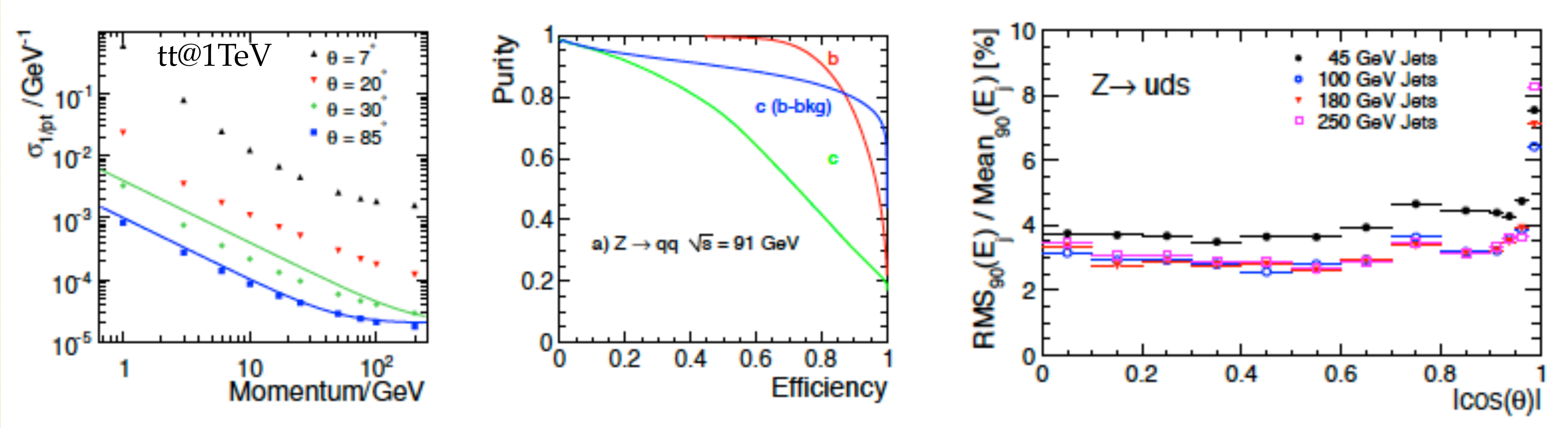
- driven by recoil mass measurement ZH-->$l^+l^-X$.

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

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



# framework of simulation in ILD-DBD (mokka and marlin)

## event generator

- $e^+ + e^-$--> up to 6f by Whizard, ttH (8f) by Physsim: completed SM background, full CKM-matrix, τ-polarisation, spin-color flow
- beam-beam effect by GuineaPig: beam energy spread, beamstrahlung
- hadronization by PYTHIA: parameters tuned to LEP data
- γγ-low-pt background: overlaid to each event (1TeV)

## detector simulator

- full simulation by GEANT4
- realistic material budget
- parameters from beam test

## key reconstruction algorithms

- particle flow: PandoraPFA
- flavor tagging: LCFIPlus

see Norman and Mikael's talk in detail

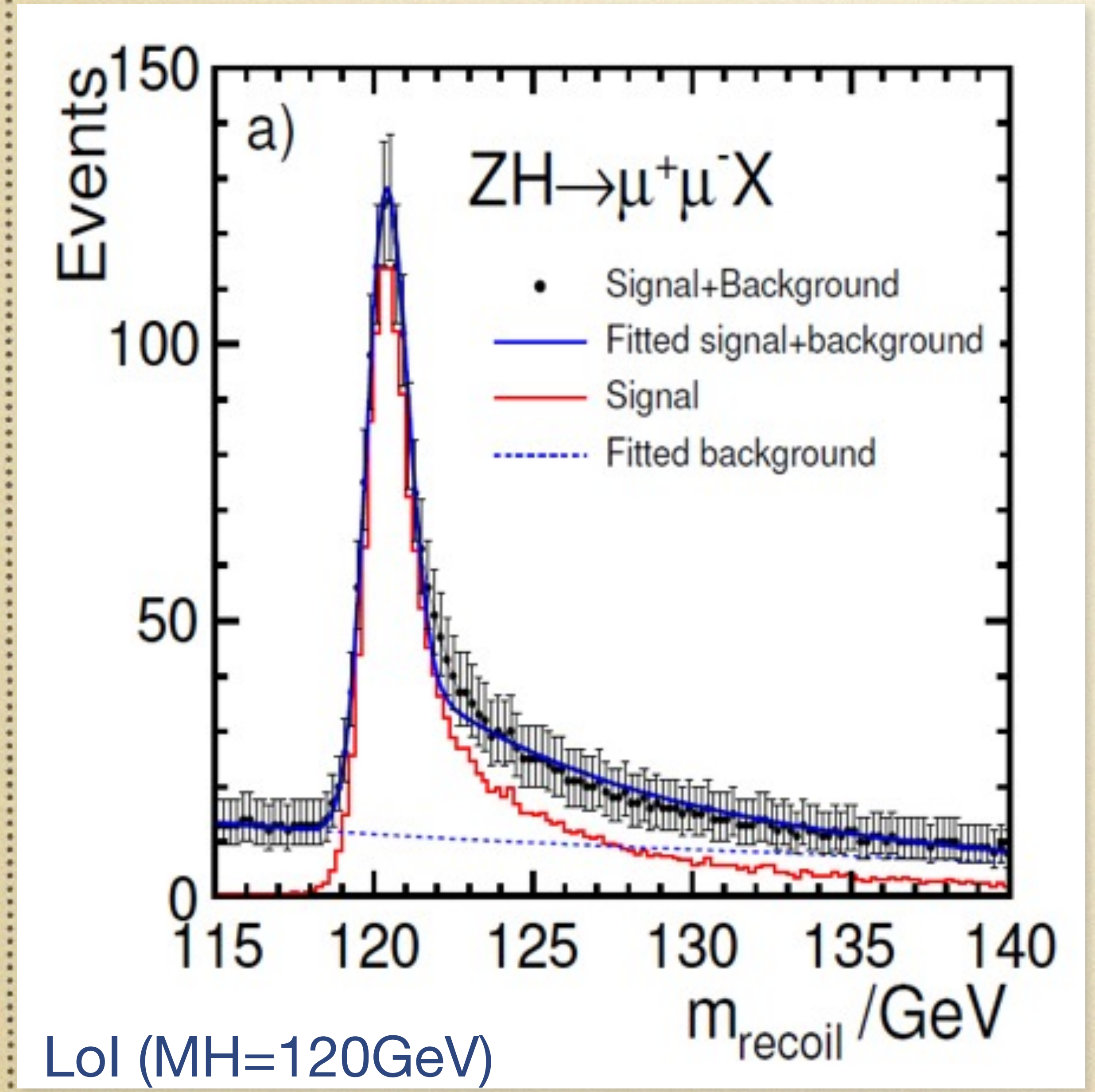
# ILC @ 250 GeV

ILC 250 GeV

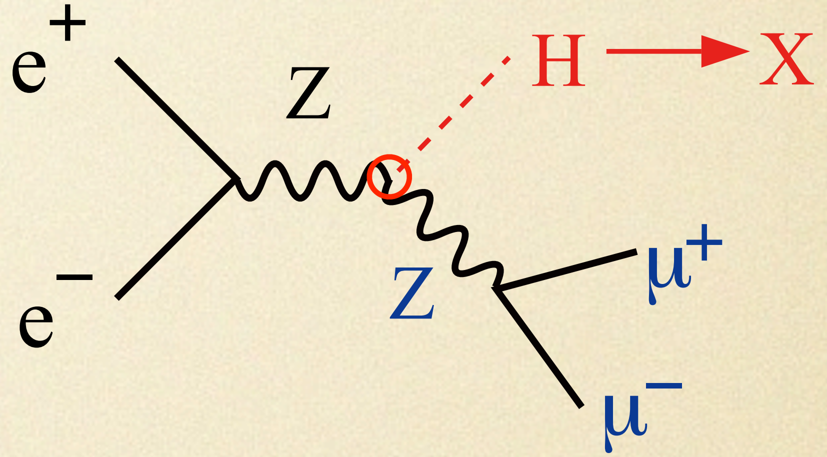
# Recoil Mass Measurements

The flagship measurement of LC 250

## Recoil Mass



LoI (MH=120GeV)



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

Invisible decay detectable!

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

$$\Delta\sigma_H/\sigma_H = 2.5\%$$

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

(Z-->ee combined)

Model-independent absolute measurement of the HZZ coupling

precision degrades with Ecm

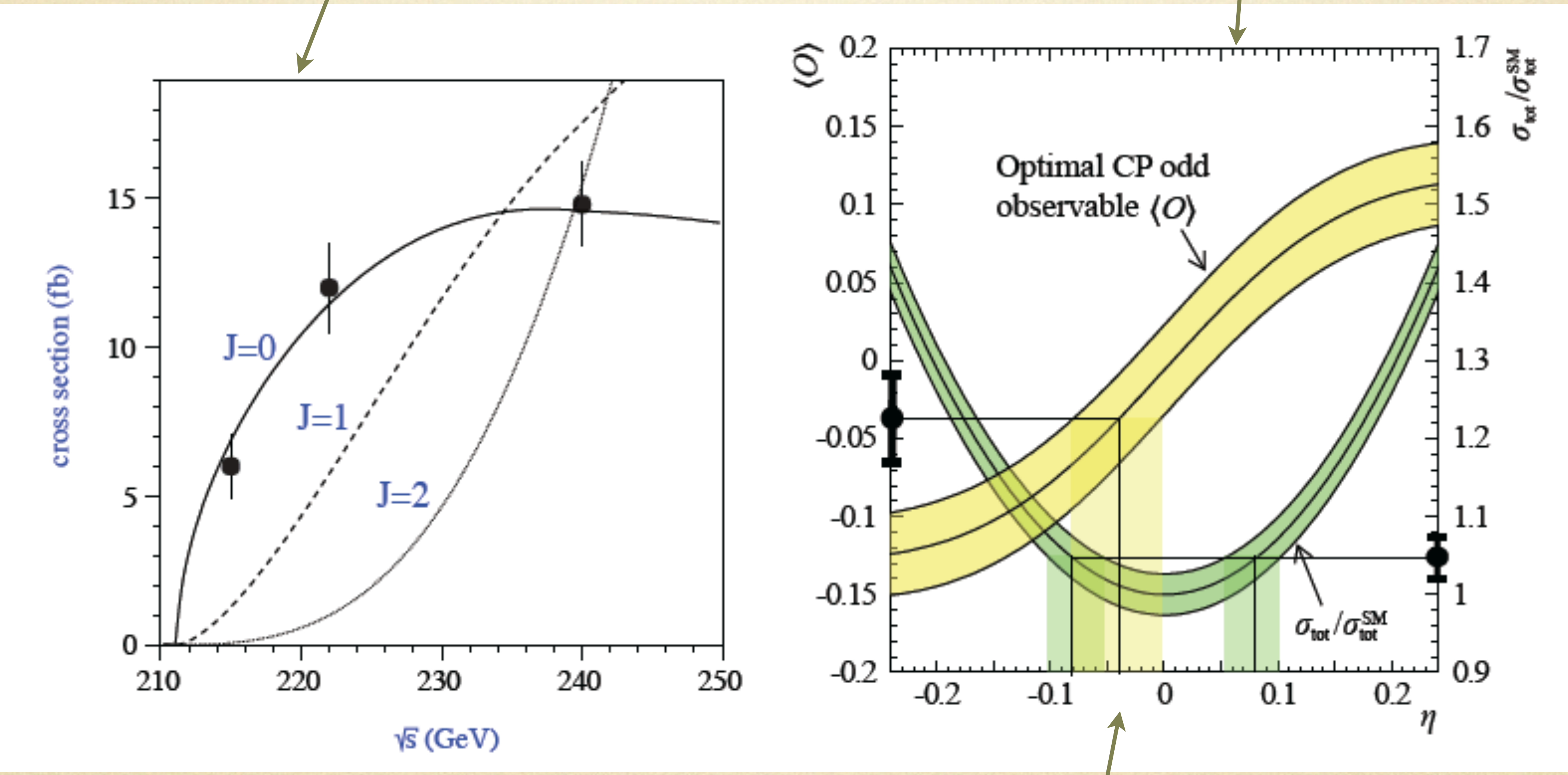
**ILC 250 GeV**

# 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: DBD Physics Volume

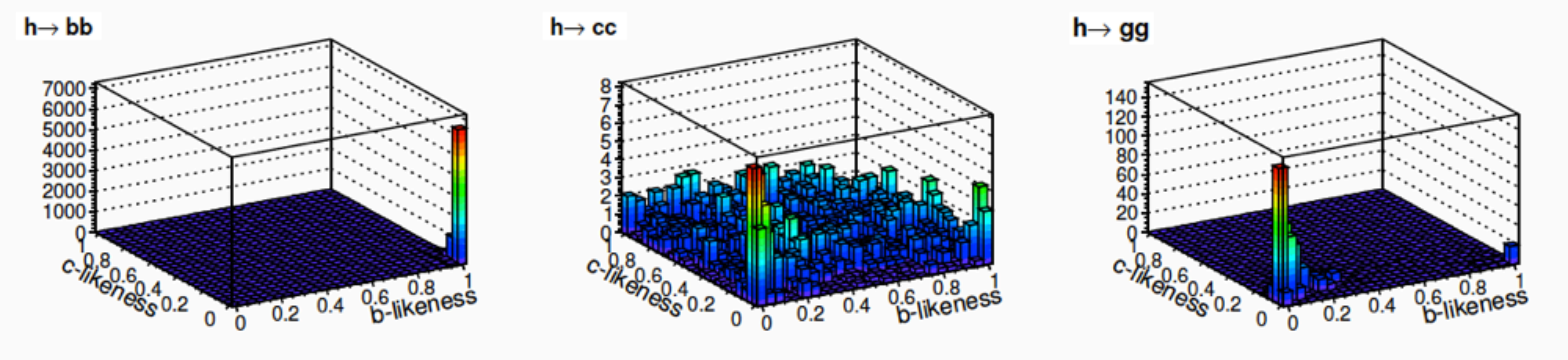
--> few % of mixing angle

**ILC 250 GeV**

# 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



precision

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

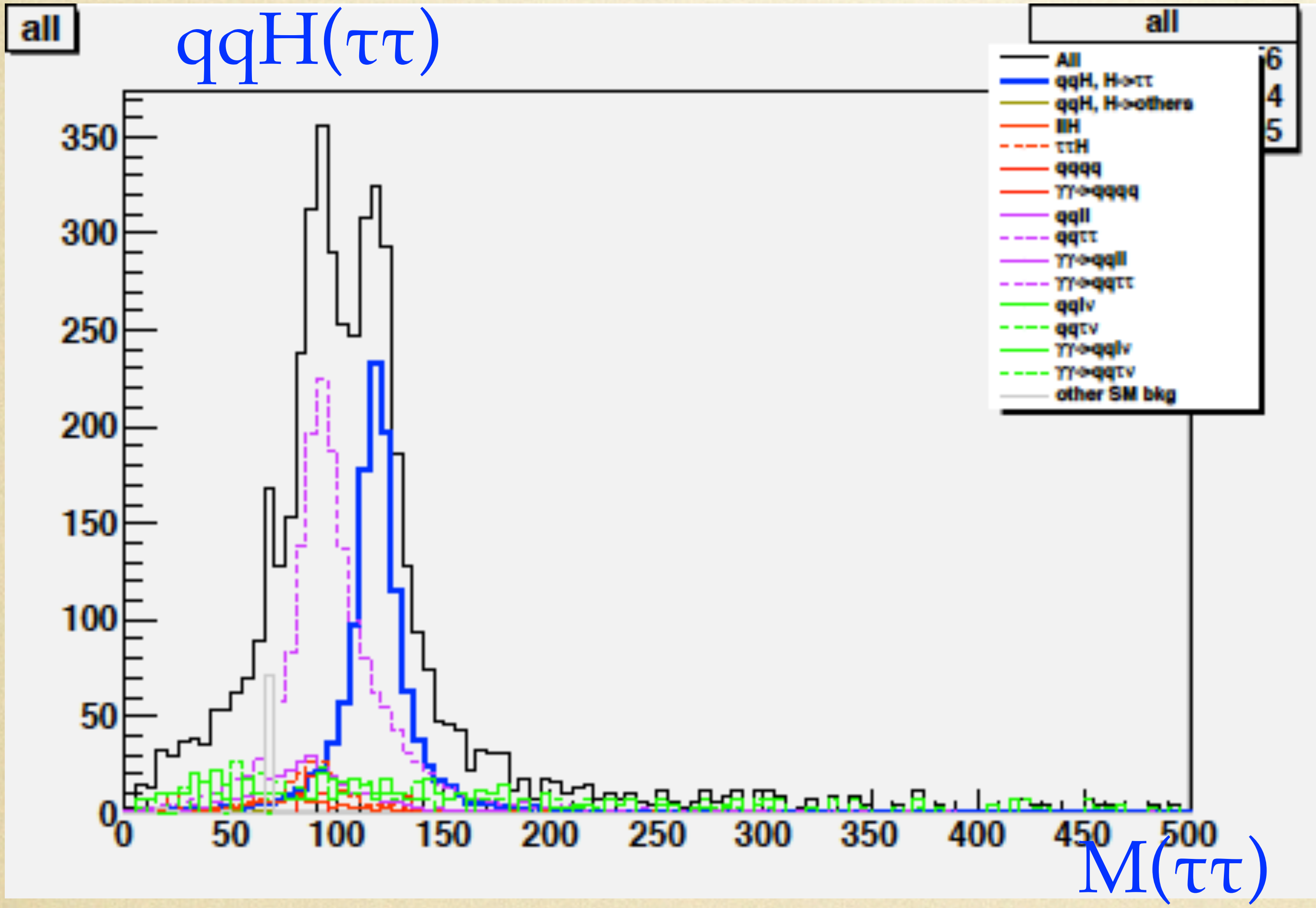
| | |
|---|---|
| $\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$ | 1.0% |
| $\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$ | 6.9% |
| $\sigma_{ZH} \cdot \mathrm{Br}(H \to g\bar{g})$ | 8.5% |

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

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

S. Kawada @ LCWS12

**ILC 250 GeV**

# Total width and absolute HVV, Hff coupling

**one of the main advantages of ILC**

see also Joshua's talk

$$\mathrm{Br}(H \to XX) = \frac{\Gamma(H \to XX)}{\Gamma_0} \propto \frac{g^2_{HXX}}{\Gamma_0}$$

★ couplings are always bundled together with the total width.

i) model independent: $\Gamma_0 = \dfrac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \dfrac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$ ~20%

ii) assuming SU(2) relation: $g_{HWW}/g_{HZZ} = \cos^2\theta_w$

$$\Gamma_0 = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to WW^*)}$$ ~9%

iii) model independent way to get the HWW coupling and total width

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

$$Y_2 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HZZ} \cdot g^2_{Hbb}}{\Gamma_0}$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HWW} \cdot g^2_{Hbb}}{\Gamma_0}$$

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

$$Y_5 = \sigma_{ZH} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^2_{HZZ} \cdot g^2_{HWW}}{\Gamma_0}$$

$$g^2_{HZZ} \propto Y_1$$

$$g^2_{HWW} \propto \frac{Y_1 \cdot Y_3}{Y_2}$$

$$g^2_{Hbb} \propto \frac{Y_1 \cdot Y_3^2}{Y_2 \cdot Y_4}$$

$$\Gamma_0 \propto \frac{Y_1^2 \cdot Y_3^2}{Y_2^2 \cdot Y_4} \propto \frac{Y_1^2 \cdot Y_3}{Y_2 \cdot Y_5}$$ ~11%

need go to higher energy for the precision HWW coupling measurement (WW-fusion)

# Total width and absolute HVV, Hff coupling @ 250 GeV

MH = 125 GeV
P(e-,e+)=(-0.8,+0.3)

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

**9 independent measurements**

$\sigma_{ZH}$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to g\bar{g})$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to WW^{*})$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to \tau^{+}\tau^{-})$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to \gamma\gamma)$
$\sigma_{ZH} \cdot \mathrm{Br}(H \to ZZ^{*})$
$\sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b})$

model free

| coupling | precision |
|---|---|
| HZZ | 1.3% |
| HWW | 4.8% |
| Hbb | 5.3% |
| Hcc | 6.5% |
| Hgg | 7.0% |
| Hττ | 5.7% |
| Hγγ | 25% |
| $\Gamma_0$ | 11% |

LHC can get better precision on Γ(Z)/Γ(γ) ~ 5%, with absolute HZZ here could improve Hγγ

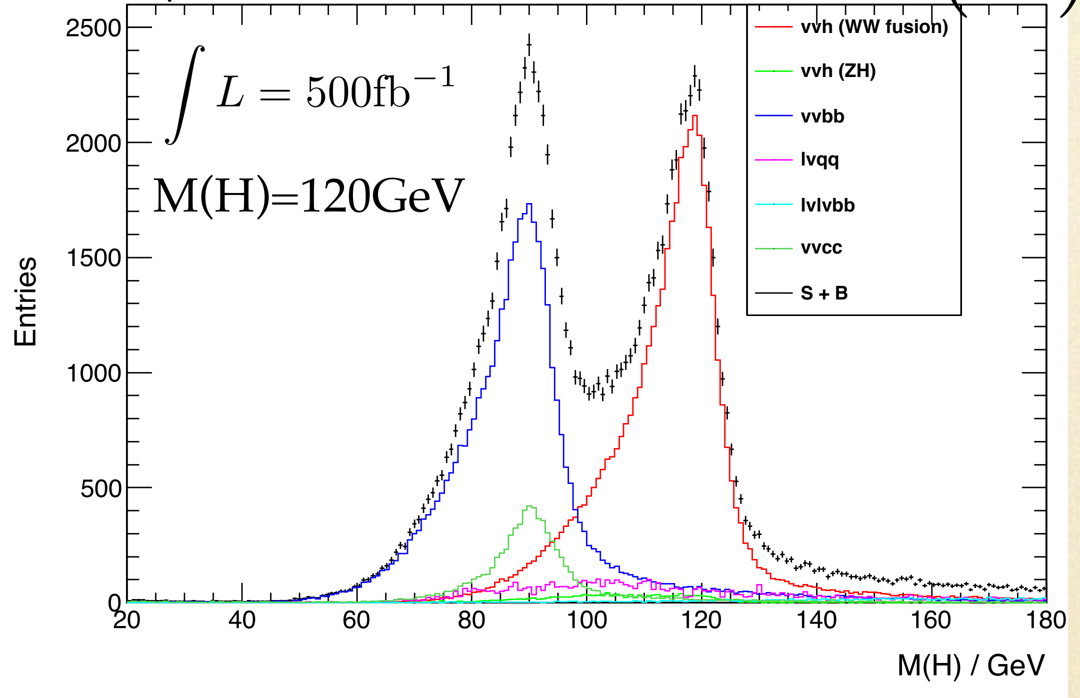
# ILC @ 500 GeV

# ILC 500 GeV

$$e^+ + e^- \rightarrow \nu\bar{\nu}H$$ (WW-fusion fully activated)

14 fb @ 250 GeV ---> 150 fb @ 500 GeV

$$e^+ + e^- \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}(b\bar{b})$$

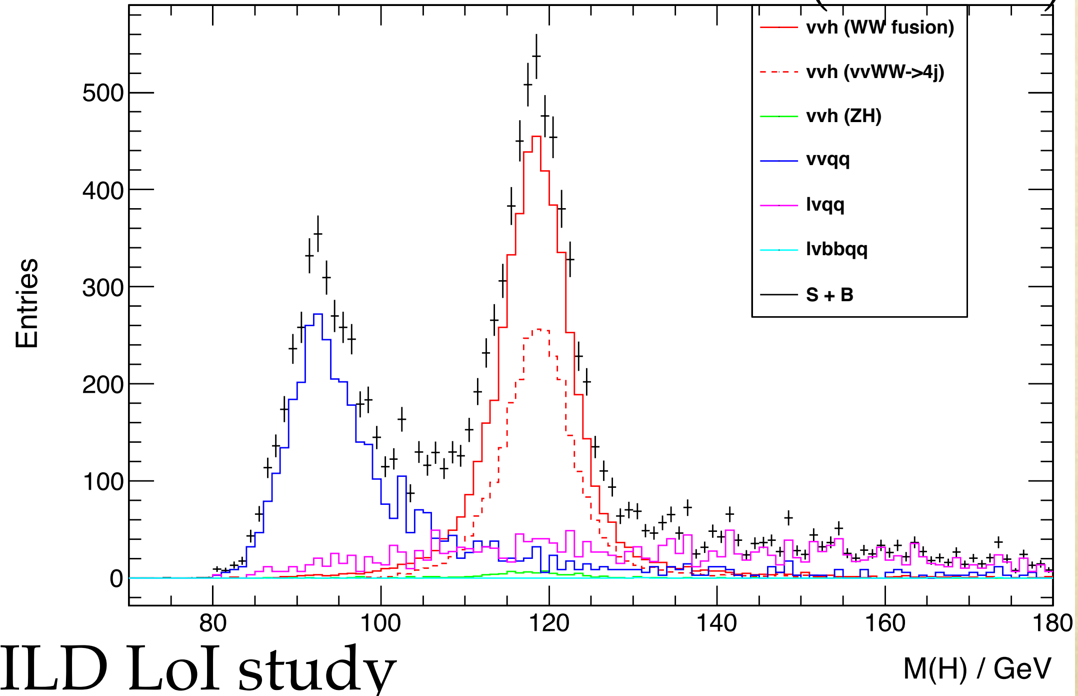


$$\sigma_1 = \sigma_0(\nu\bar{\nu}H)\cdot \mathrm{Br}(H \rightarrow b\bar{b}) \quad \frac{\delta\sigma_1}{\sigma_1} = 0.6\%$$

$$\frac{\delta\sigma_0}{\sigma_0} = 2.8\% \qquad \frac{\delta g_{HWW}}{g_{HWW}} = 1.4\%$$

$g_{HWW}/g_{HZZ}$ ➜ precision of 0.6%

$$e^+ + e^- \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}(WW^*)$$



ILD LoI study

$$\sigma_2 = \sigma_0(\nu\bar{\nu}H)\cdot \mathrm{Br}(H \rightarrow WW^*) \quad \frac{\delta\sigma_2}{\sigma_2} = 3.0\%$$

Higgs total width improved --> 6%

C. Durig & J. List @ LCWS12, J. Tian @ KILC12

# Total width and absolute HVV, Hff coupling @ 500 GeV

MH = 125 GeV    $250\ \mathrm{fb}^{-1}$ @ 250 GeV    $500\ \mathrm{fb}^{-1}$ @ 500 GeV

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

**9 measurements @ 250 GeV**

+

**14 measurements @ 500 GeV**

(7) $\sigma_{ZH} \cdot \mathrm{Br}(H \to XX)$

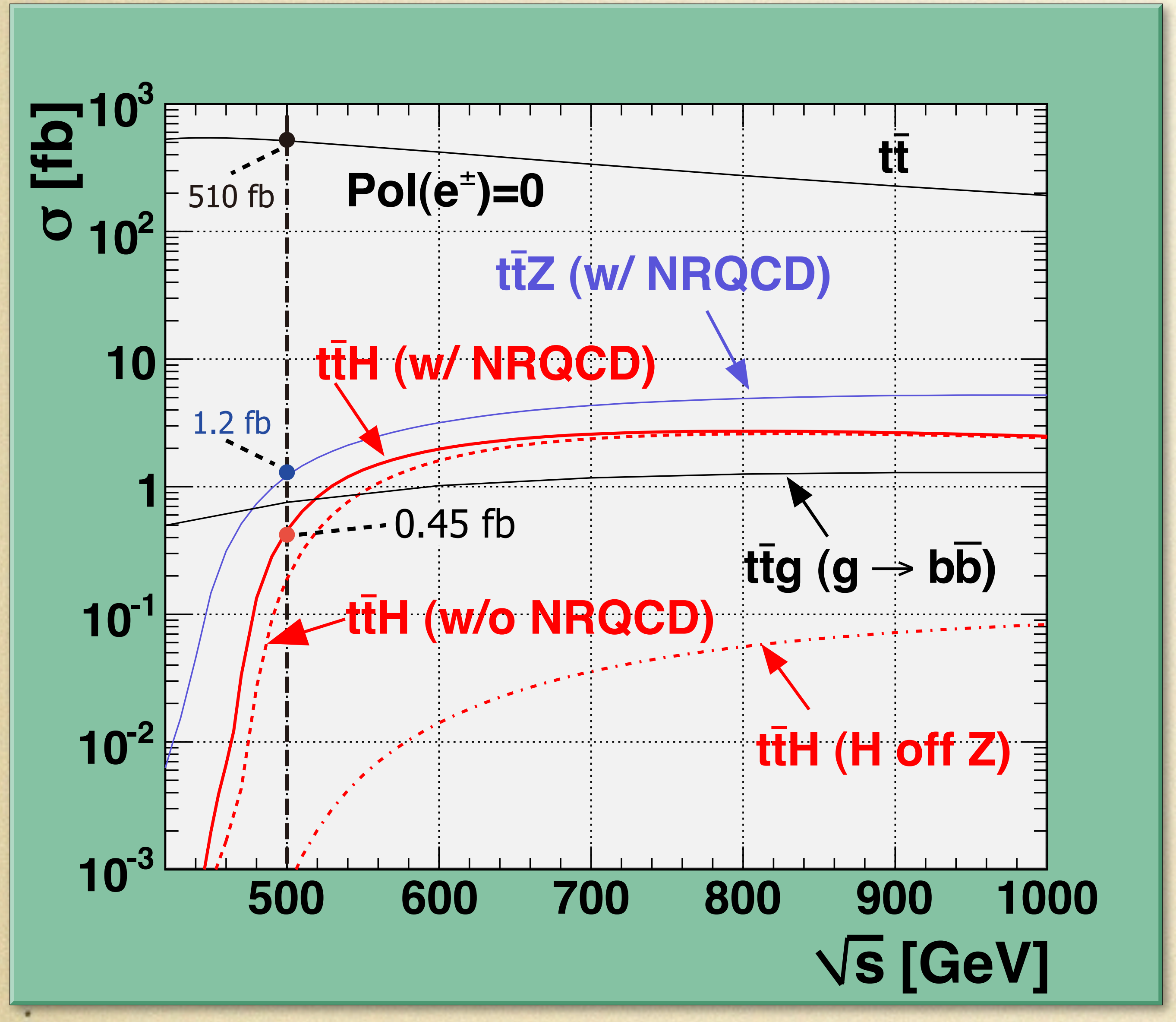
(7) $\sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to XX)$

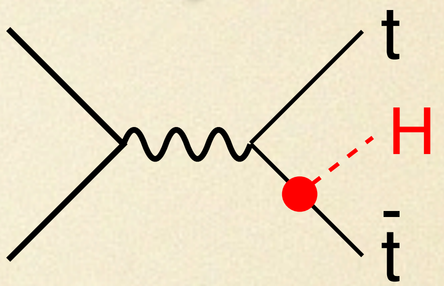
| coupling | 250 GeV | 250 GeV + 500 GeV |
|---|---|---|
| HZZ | 1.3% | 1.3% |
| HWW | 4.8% | 1.4% |
| Hbb | 5.3% | 1.8% |
| Hcc | 6.5% | 2.9% |
| Hgg | 7.0% | 2.5% |
| Hττ | 5.7% | 2.5% |
| Hγγ | 25% | 12% |
| $\Gamma_0$ | 11% | 5.9% |

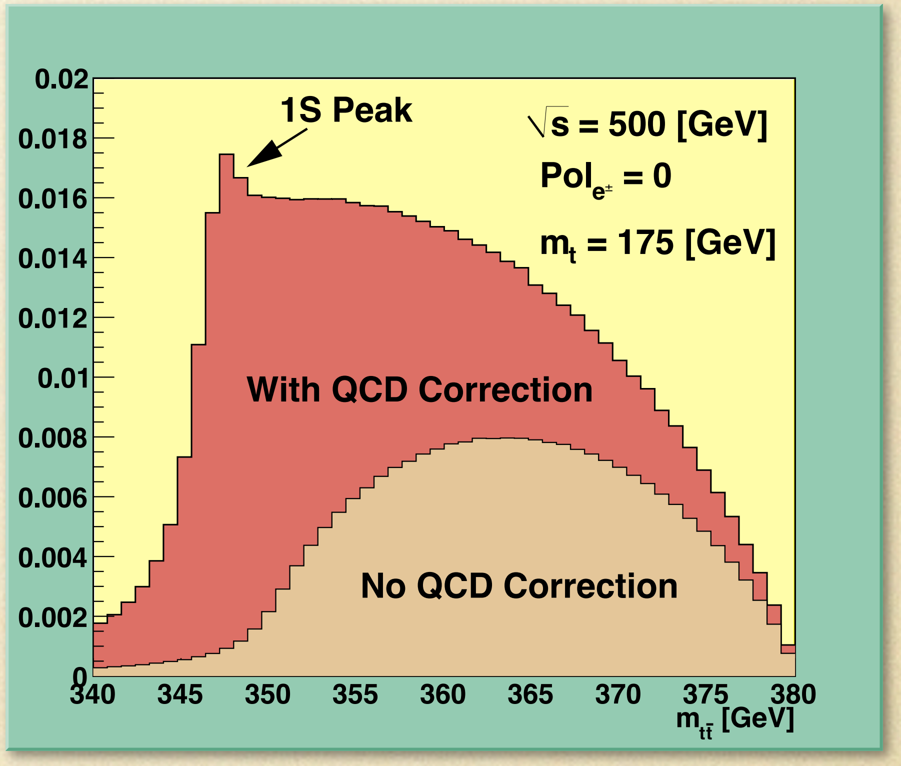
**benefit significantly from the WW-fusion production**

# Top Yukawa Coupling @ 500 GeV

## The largest among matter fermions, but not yet observed







A factor of 2 enhancement from QCD bound-state effects

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

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV}$$

$$\Delta g_Y(t)/g_Y(t) = 10\,\%$$

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

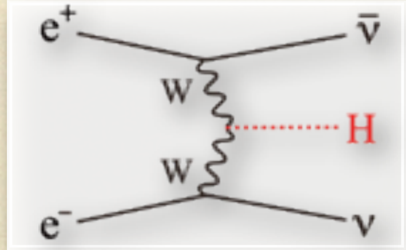
Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

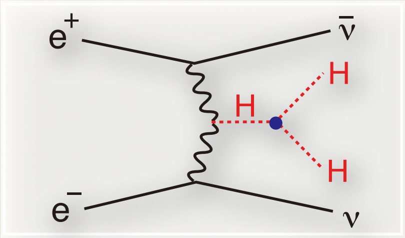
see also H. Yokoya's theory talk

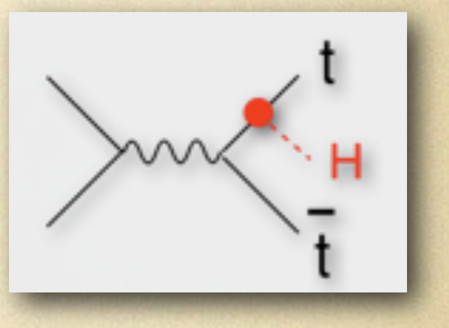
# Higgs Physics at Higher Energy

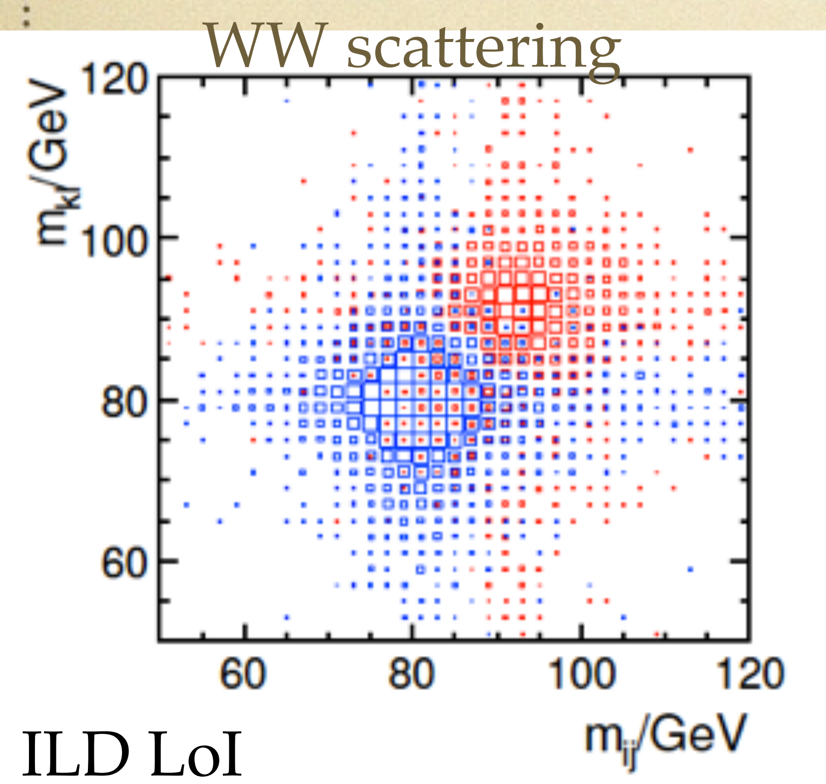
## Self-coupling with WBF, top Yukawa at xsection max., other higgses, ...

- 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

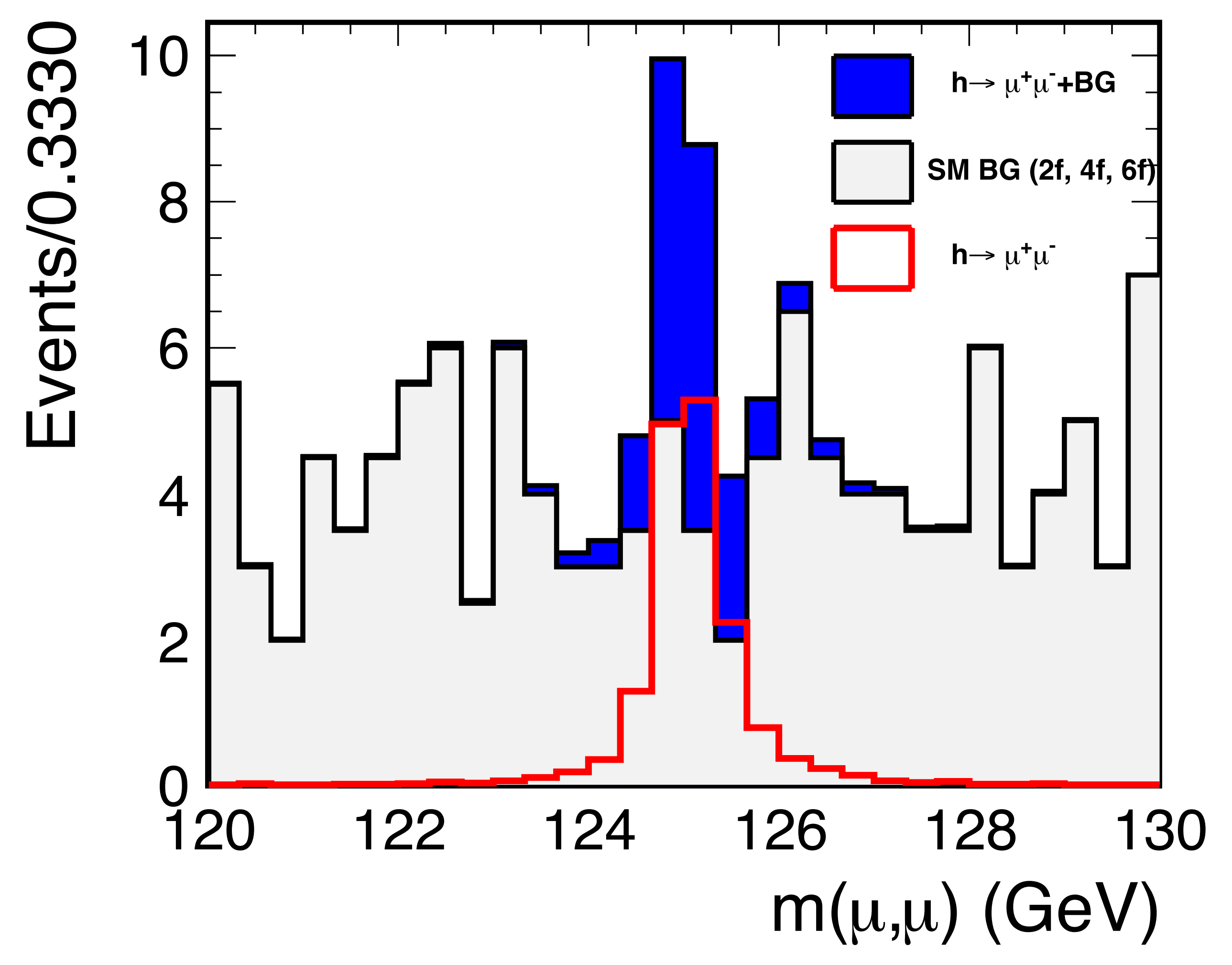
Obvious but most important advantage of higher energies in terms of Higgs physics is its higher mass reach to other Higgs bosons expected in an extended Higgs sector and higher sensitivity to $W_LW_L$ scattering to decide whether the Higgs sector is strongly interacting or not.

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

DBD full simulation

**ILC 1 TeV**

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



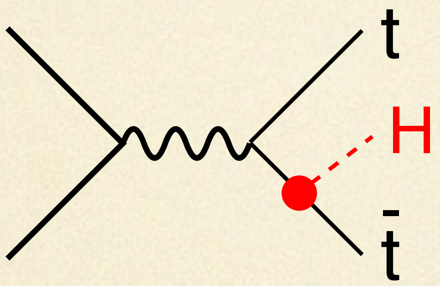
- rare decay
- low multiplicity
- clean and narrow mass peak
- main BG: ννZ, WW

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

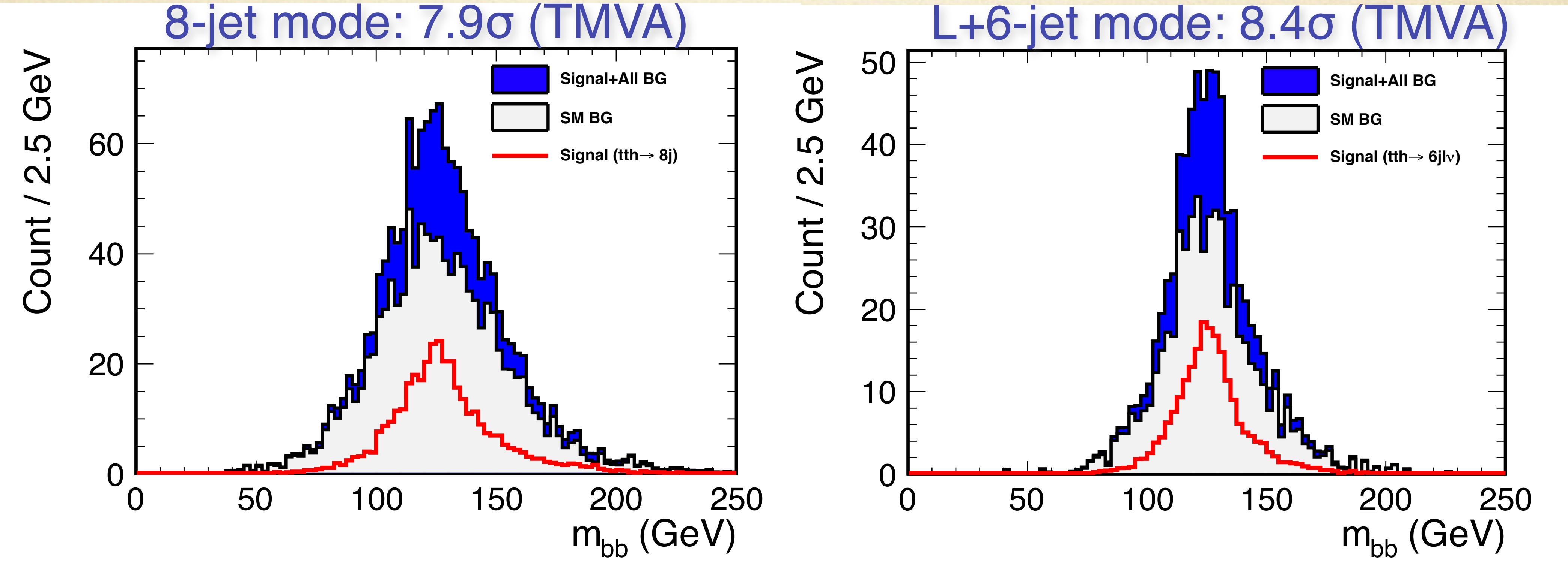
C. Calancha @ LCWS12

DBD full simulation

# Top Yukawa Coupling @ 1TeV



H-> bb



8-jet mode: 7.9σ (TMVA)

L+6-jet mode: 8.4σ (TMVA)

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV}$$
$$\Delta g_Y(t)/g_Y(t) = 10\,\%$$

(MH=120GeV)

$$1\,\mathrm{ab}^{-1}@1\,\mathrm{TeV}$$
$$\Delta g_Y(t)/g_Y(t) = 3.9\,\%$$

(MH=125GeV)

T. Tanabe & T. Price @ LCWS12

# Total width and absolute HVV, Hff coupling @ 1 TeV

MH = 125 GeV $250\ \mathrm{fb}^{-1}$ @ 250 GeV $500\ \mathrm{fb}^{-1}$ @ 500 GeV $1000\ \mathrm{fb}^{-1}$ @ 1000 GeV

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

**9 measurements @ 250 GeV**

+

**15 measurements @ 500 GeV**

+

**9 measurements @ 1 TeV**

$$\sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to XX)$$

| coupling | 250 GeV | 250 GeV + 500 GeV | 250 GeV + 500 GeV + 1 TeV |
|---|---|---|---|
| HZZ | 1.3% | 1.3% | 1.3% |
| HWW | 4.8% | 1.4% | 1.4% |
| Hbb | 5.3% | 1.8% | 1.5% |
| Hcc | 6.5% | 2.9% | 2.0% |
| Hgg | 7.0% | 2.5% | 1.8% |
| Hττ | 5.7% | 2.5% | 2.0% |
| Hγγ | 25% | 12% | 5.2% |
| Hμμ | - | - | 16% |
| $\Gamma_0$ | 11% | 5.9% | 5.6% |
| Htt | - | 16% | 3.8% |

eventual, all the precision limited by the recoil mass measurement
--> integrate more luminosity @ 250 GeV

# Higgs self-coupling @ ILC

# 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

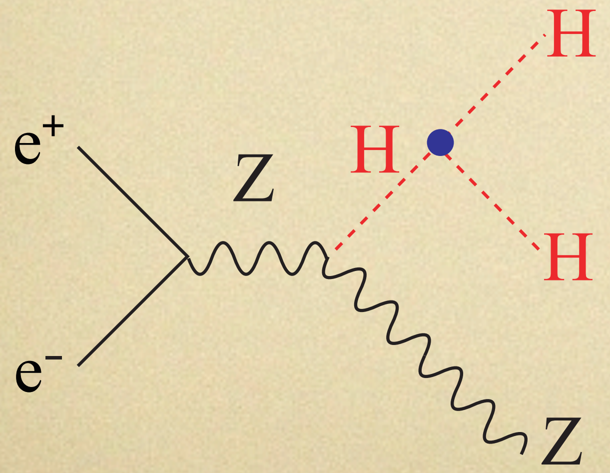
mass term

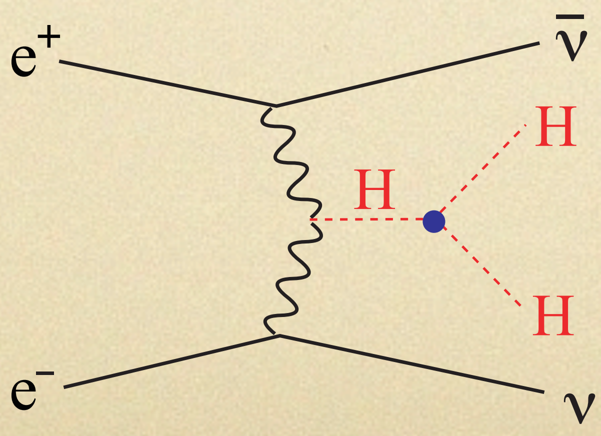
trilinear coupling

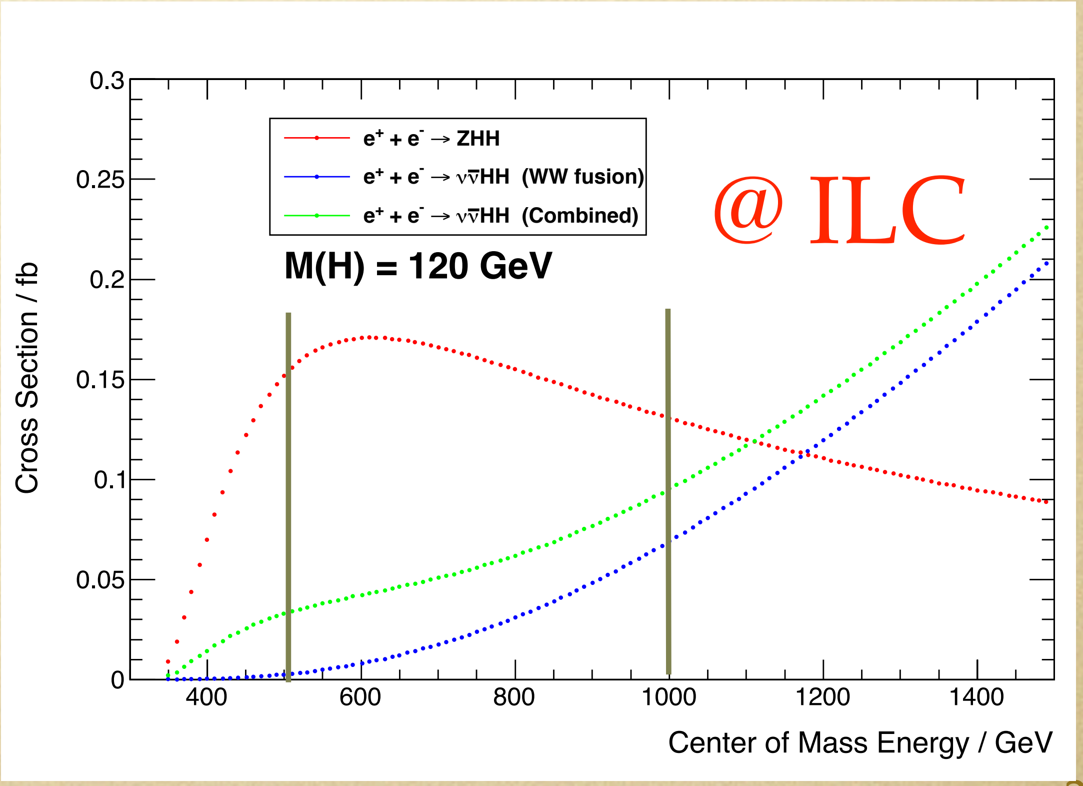
quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

SM: $\lambda = \lambda_{SM} = \frac{m_H^2}{2\upsilon^2}$ $\upsilon$ ~ 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.
- difficult to measure at LHC for a light Higgs.



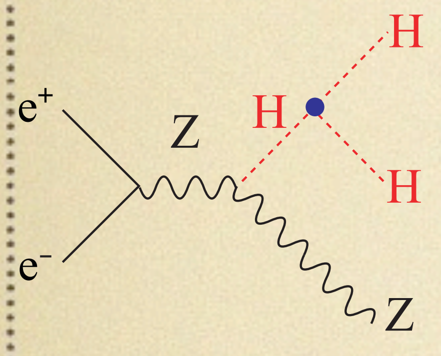




# General issue: sensitivity of coupling to the cross section

effect of irreducible diagrams

$$\sigma = a\lambda^2 + b\lambda + c$$



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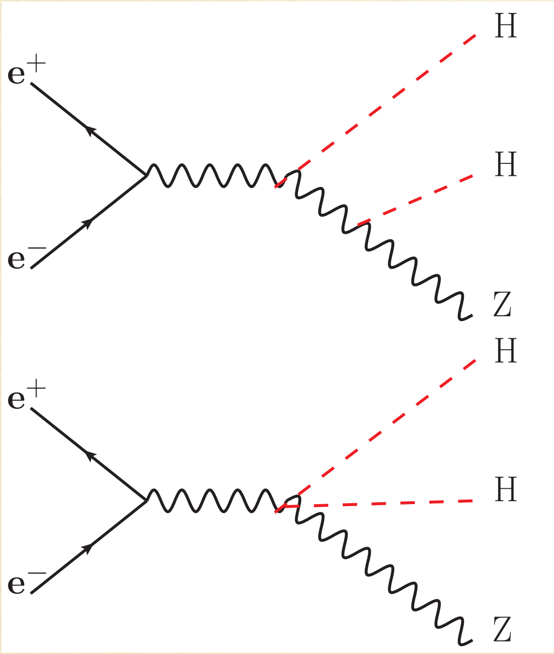

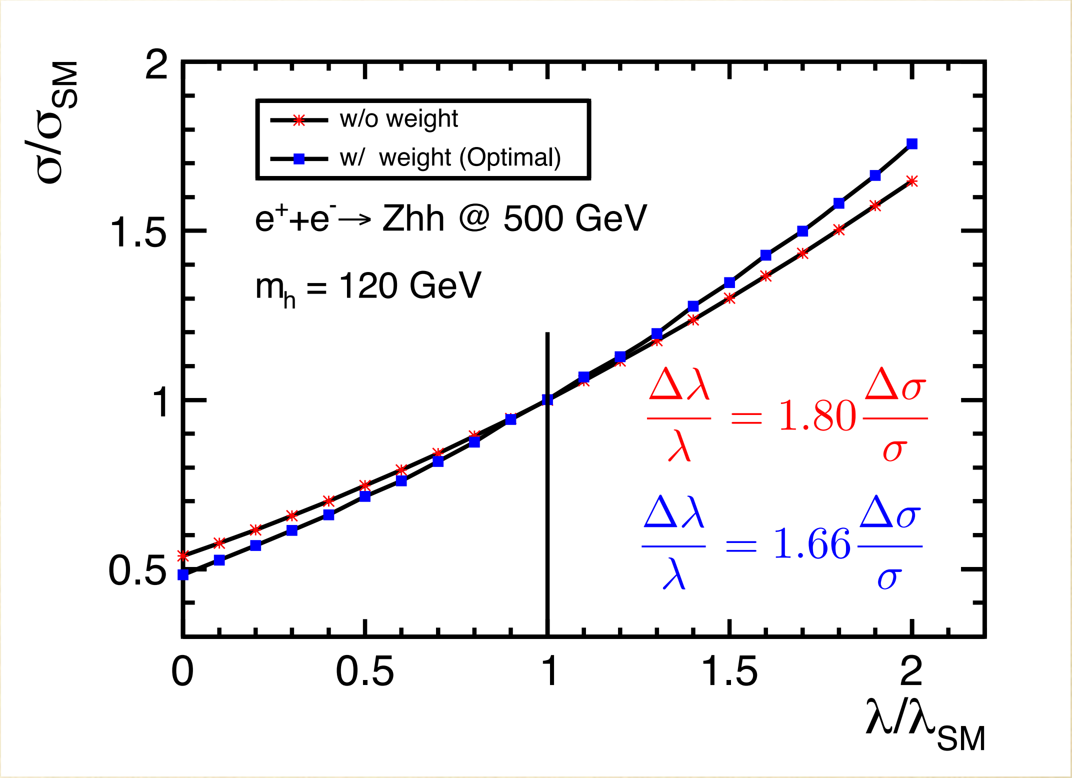

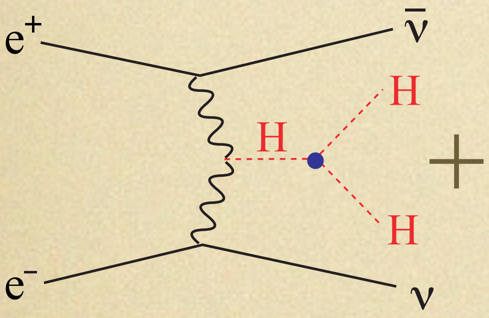

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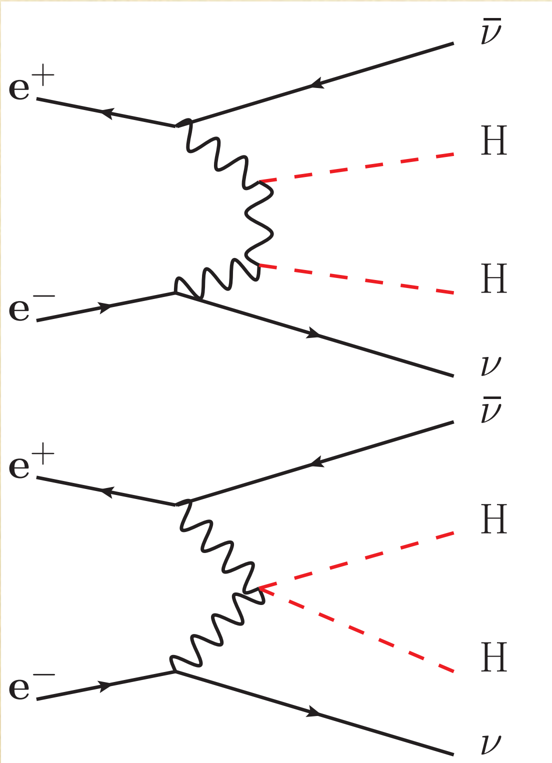
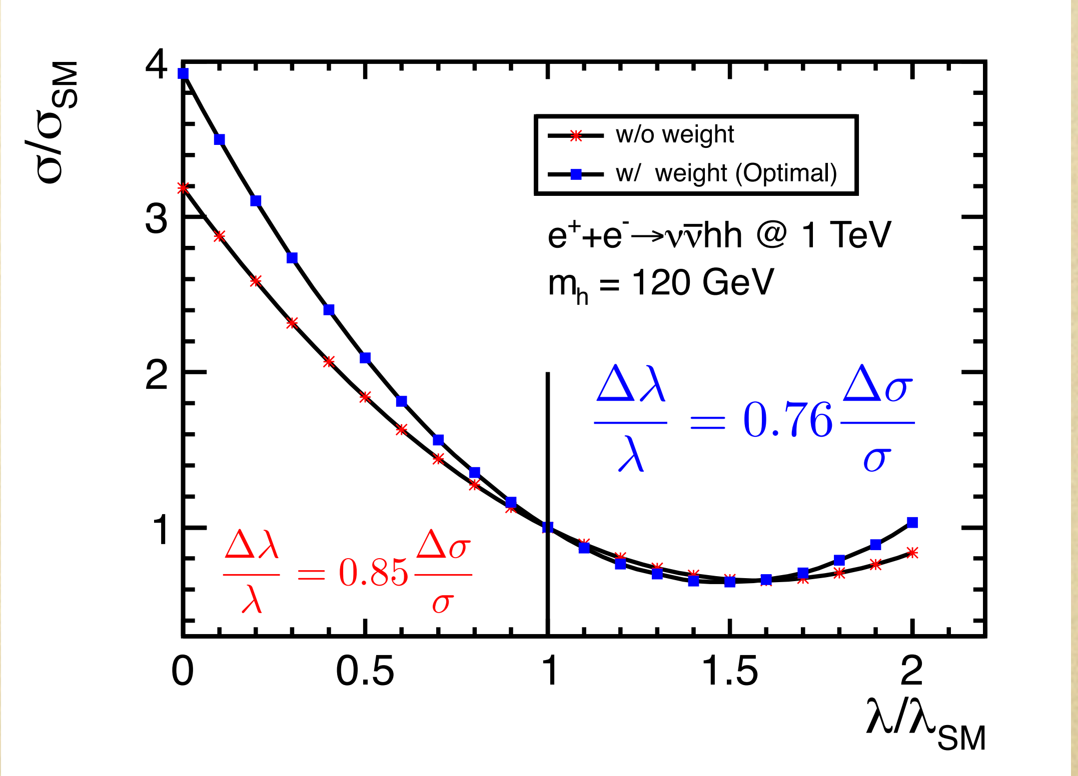
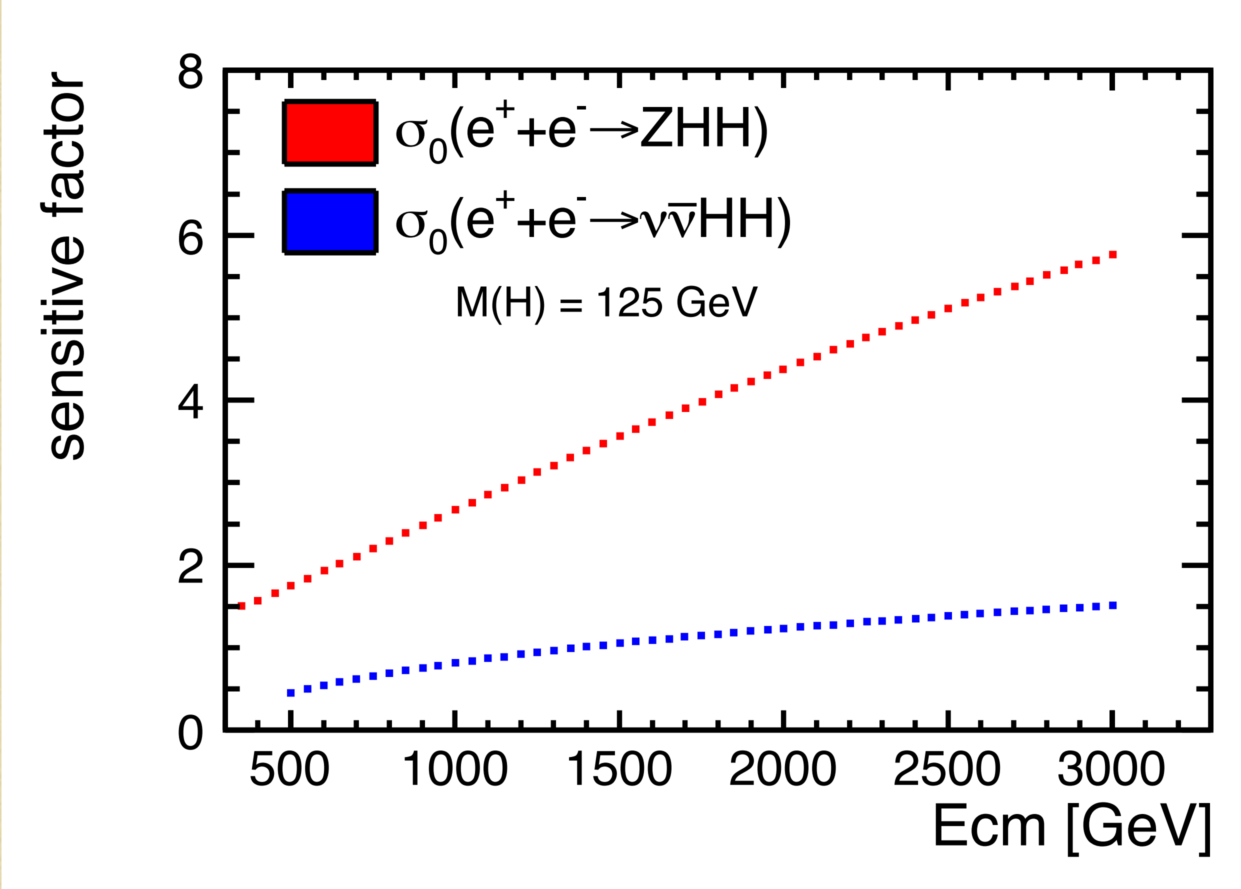




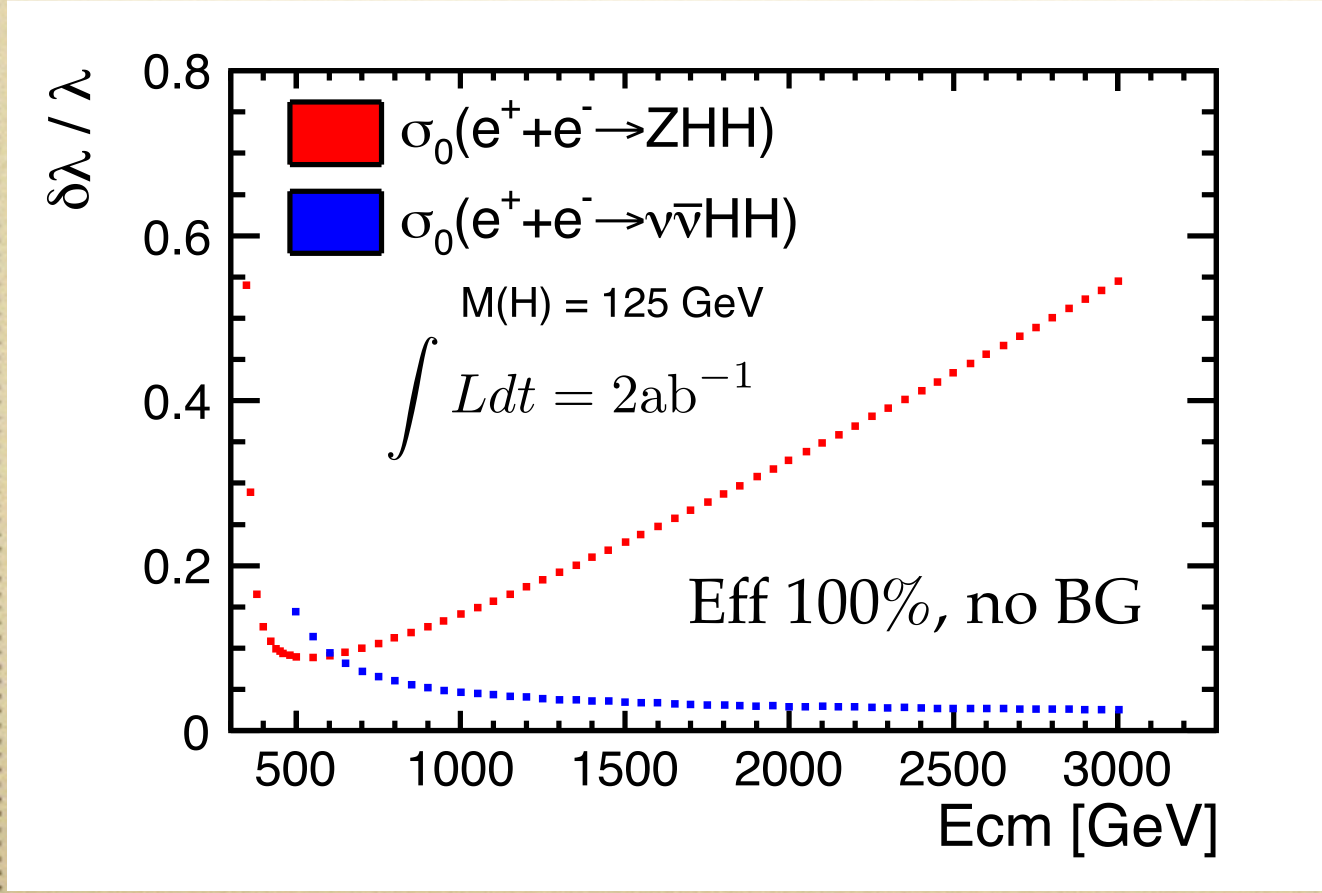
**these diagrams significantly degraded the sensitivity**

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



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

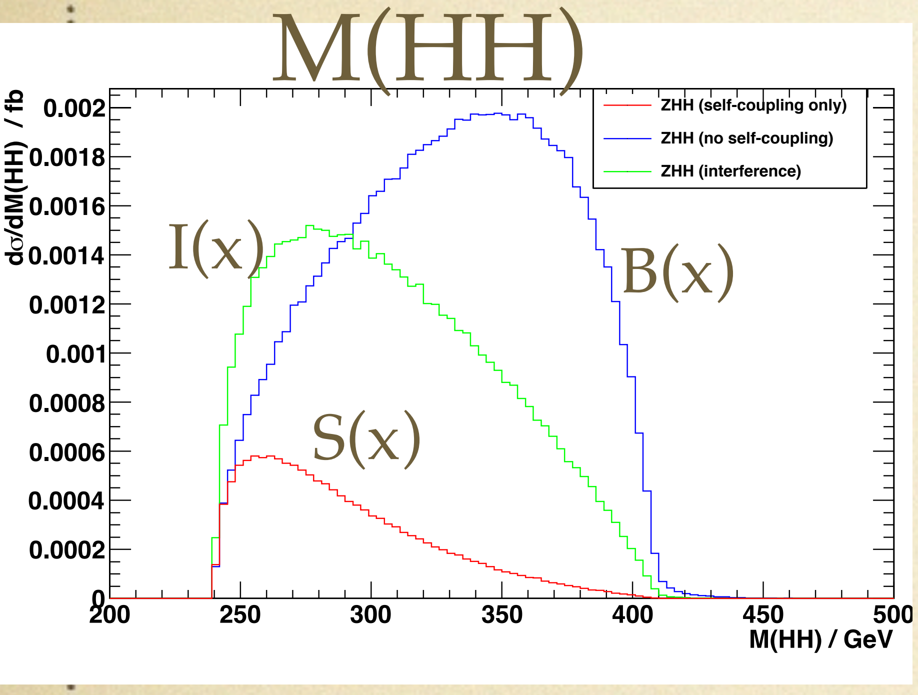
**Factor increases quickly as going to higher energy**



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

**for $\nu\nu$HH, expected precision improves slowly as going to higher energy**

# weighting method to enhance the coupling sensitivity

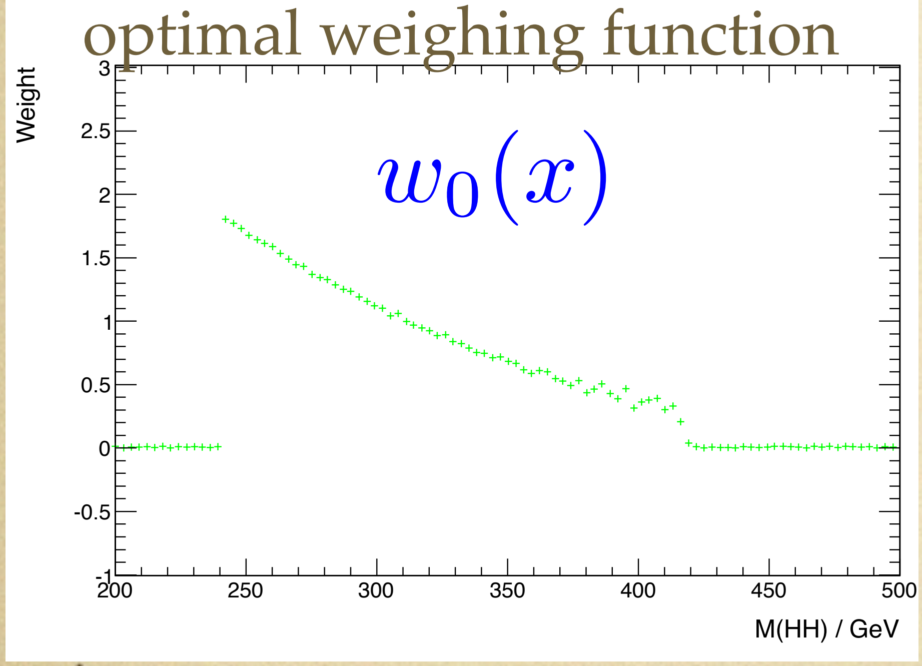


$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible interference self-coupling

**observable:** weighted cross-section

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



**equation 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**

# difficulties for the analysis

## fundamental:

- irreducible SM diagrams, significantly degrade the coupling sensitivity.
- very small cross section ($\sigma_{ZHH}$~0.22 fb with $P_L$) and we are only using ~40% of the signal (both H-->bb). large integrated luminosity needed. (high beam polarization helped a lot)
- huge SM background (tt/WWZ, ZZ/Z$\gamma$, ZZZ/ZZH), 3-4 orders higher.

## strategic:

- Higgs mass reconstruction: mis-clustering, missing neutrinos, wrong pairing.
- flavor tagging and isolated-lepton selection: need very high efficiency and purity.
- neural-net training: separated neural-nets, huge statistics needed.

# analysis strategy and status

$$e^+ + e^- \rightarrow ZHH \;@\; 500\; GeV$$

searching mode and main backgrounds in each mode:

- llHH: llbb (ZZ, γZ, bbZ), lνbbqq (tt-bar), llbbbb (ZZZ/ZZH)
- ννHH: bbbb (ZZ, γZ, bbZ), τνbbqq (tt-bar), ννbbbb (ZZZ/ZZH)
- qqHH: bbbb (ZZ, γZ, bbZ), bbqqqq (tt-bar), qqbbbb (ZZZ/ZZH)

event selection:

- isolated-lepton selection or rejection
- jet clustering and flavor tagging
- missing energy or visible energy requirement
- event reconstructed as from signal and dominant background
- each dominant background is suppressed by training a neural-net

**to make the result stable, high statistics (~10 $ab^{-1}$) is used**

**strategy for ννHH @ 1 TeV is quite similar**

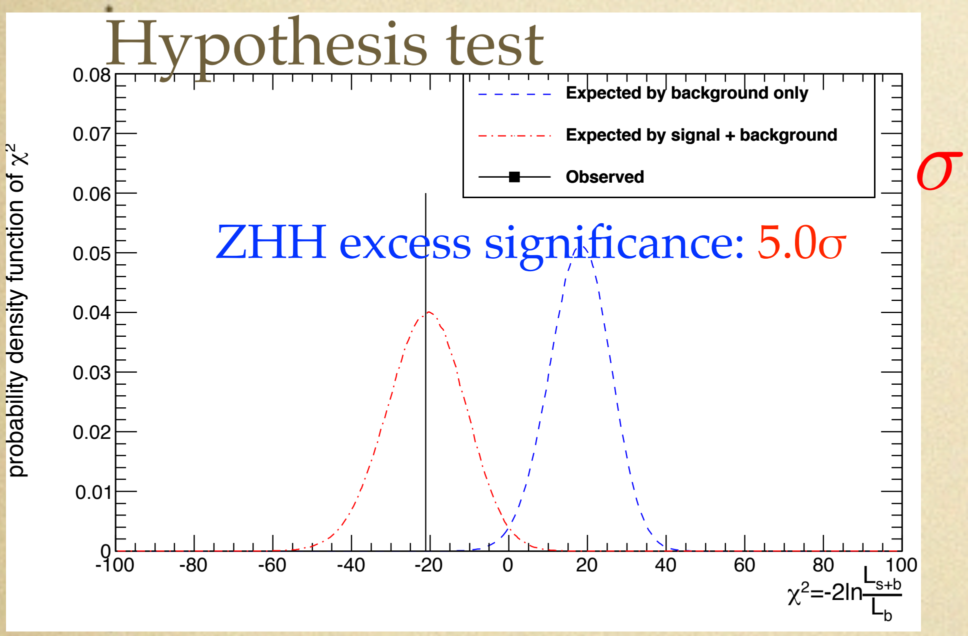
DBD full simulation

# 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 |

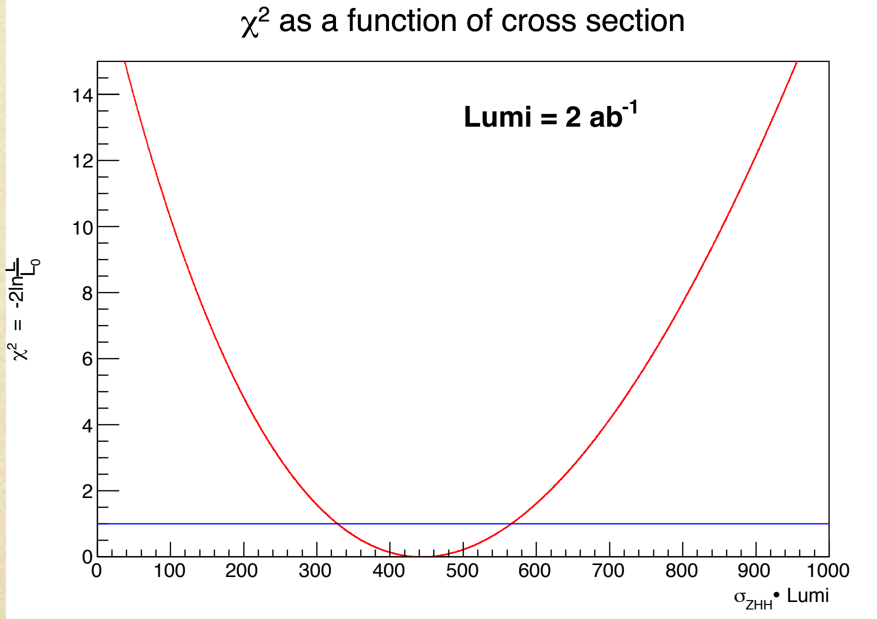
Hypothesis test



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

| | Expected | After Cut |
|---|---|---|
| ννhh (WW F) | 272 | 35.7 |
| ννhh (ZHH) | 74.0 | 3.88 |
| BG (tt/ννZH) | $7.86\times10^5$ | 33.7 |
| significance | 0.30 | 4.29 |

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

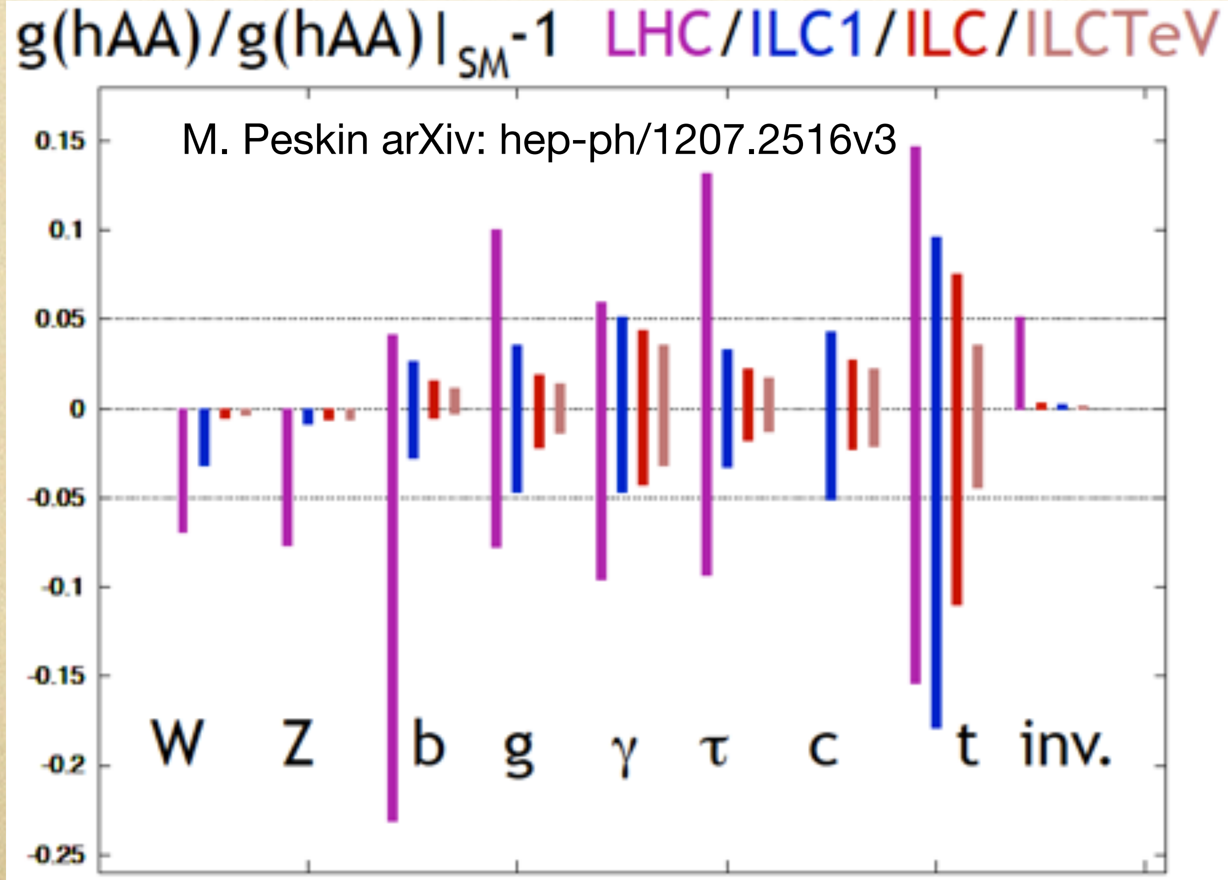
$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: > 7σ

Higgs self-coupling significance: > 5σ

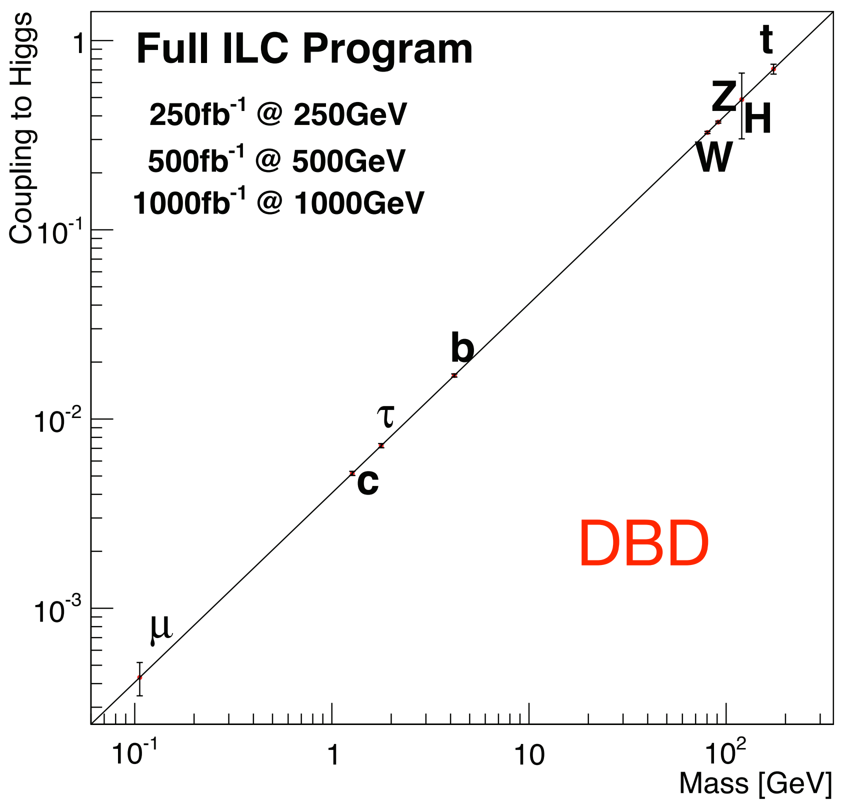
# Summary

- ILC offers the unique precision physics opportunities 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.



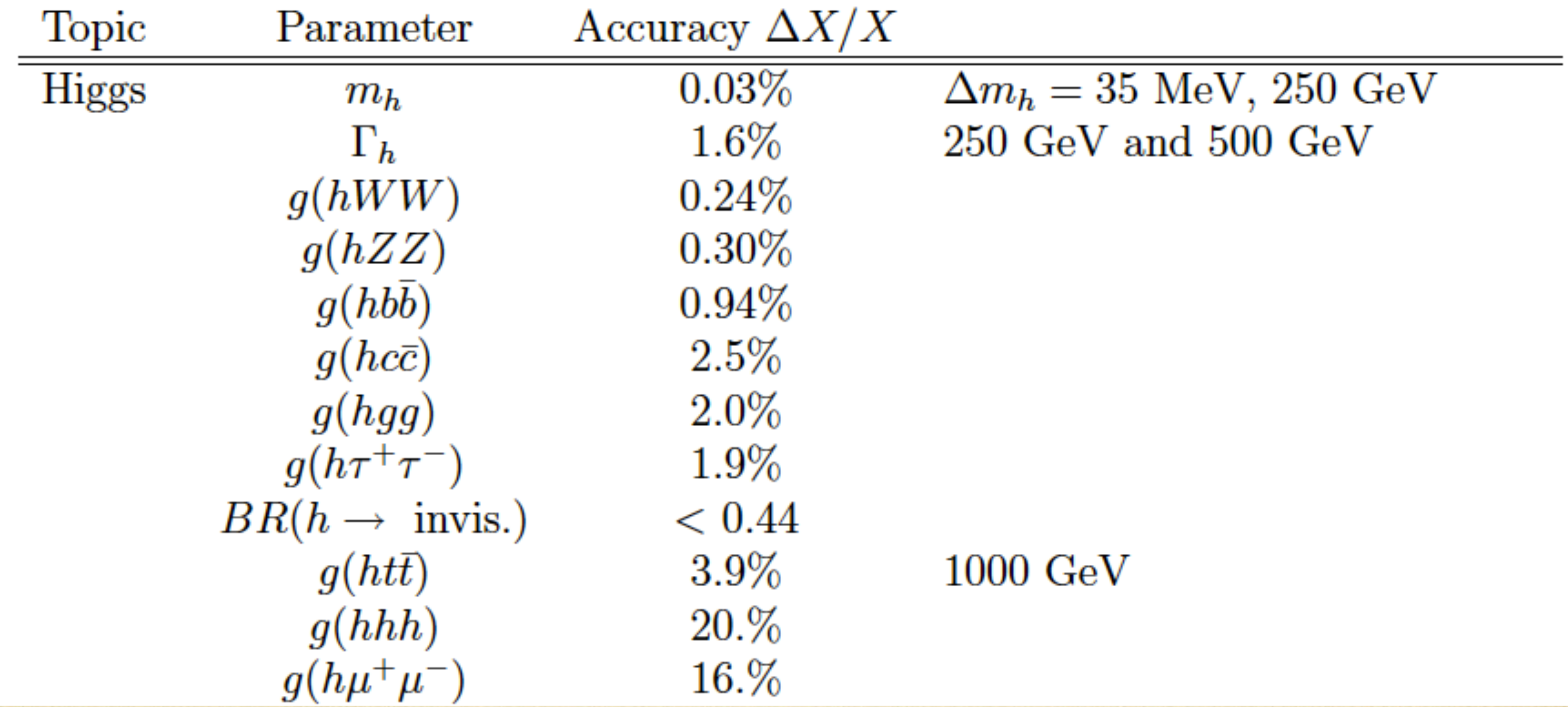
M. Peskin arXiv: hep-ph/1207.2516v3

ILC ready to go!



# backup

# executive summary of DBD
# (M. Peskin)



| Topic | Parameter | Accuracy $\Delta X/X$ | |
|---|---|---|---|
| Higgs | $m_h$ | 0.03% | $\Delta m_h = 35$ MeV, 250 GeV |
| | $\Gamma_h$ | 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.% | |

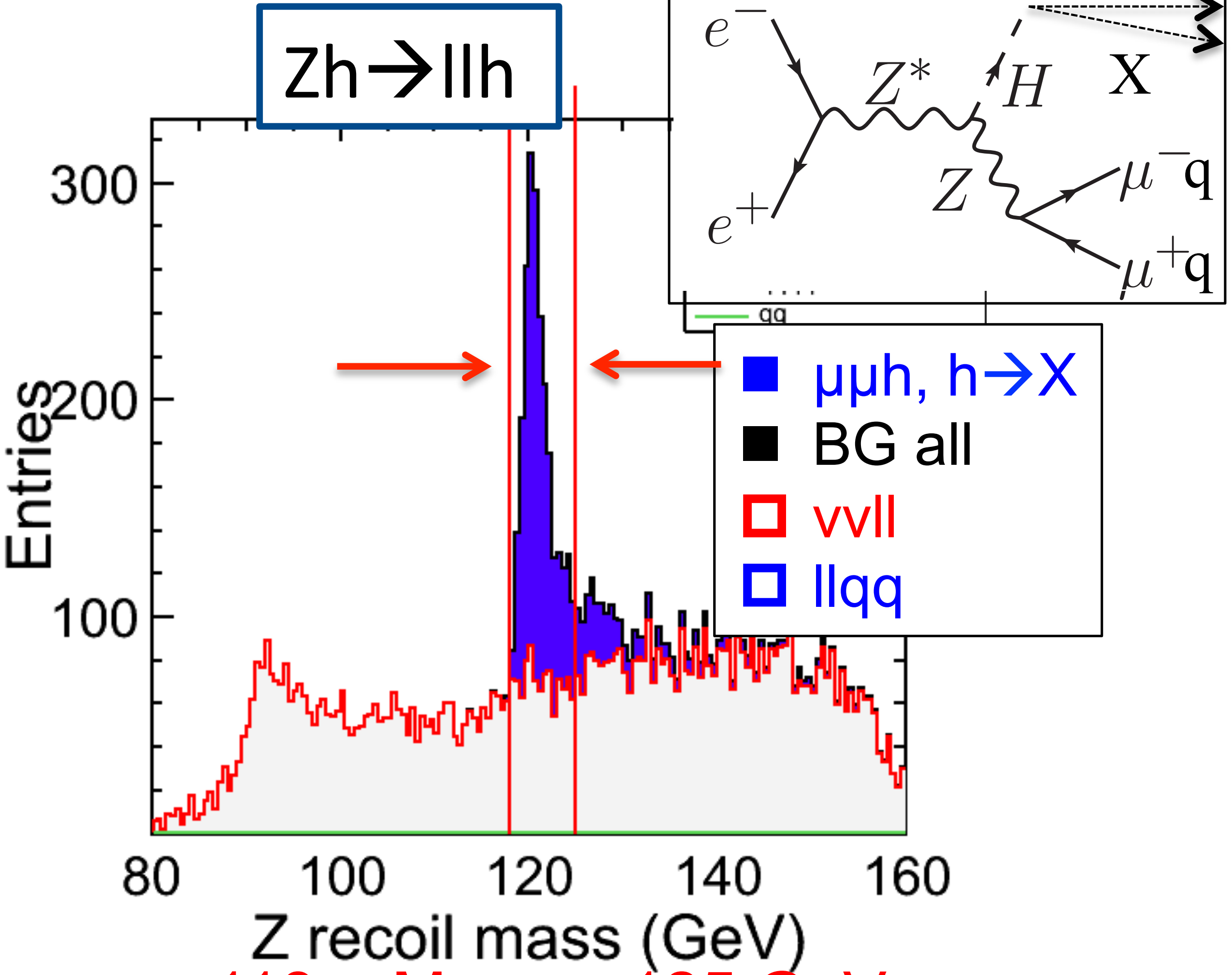
almost model-free fitting, constraint:

Branching ratios sum up to 1

# h→Invisible decay

h→ZZ→νννν pseudo signal is used with full simulation

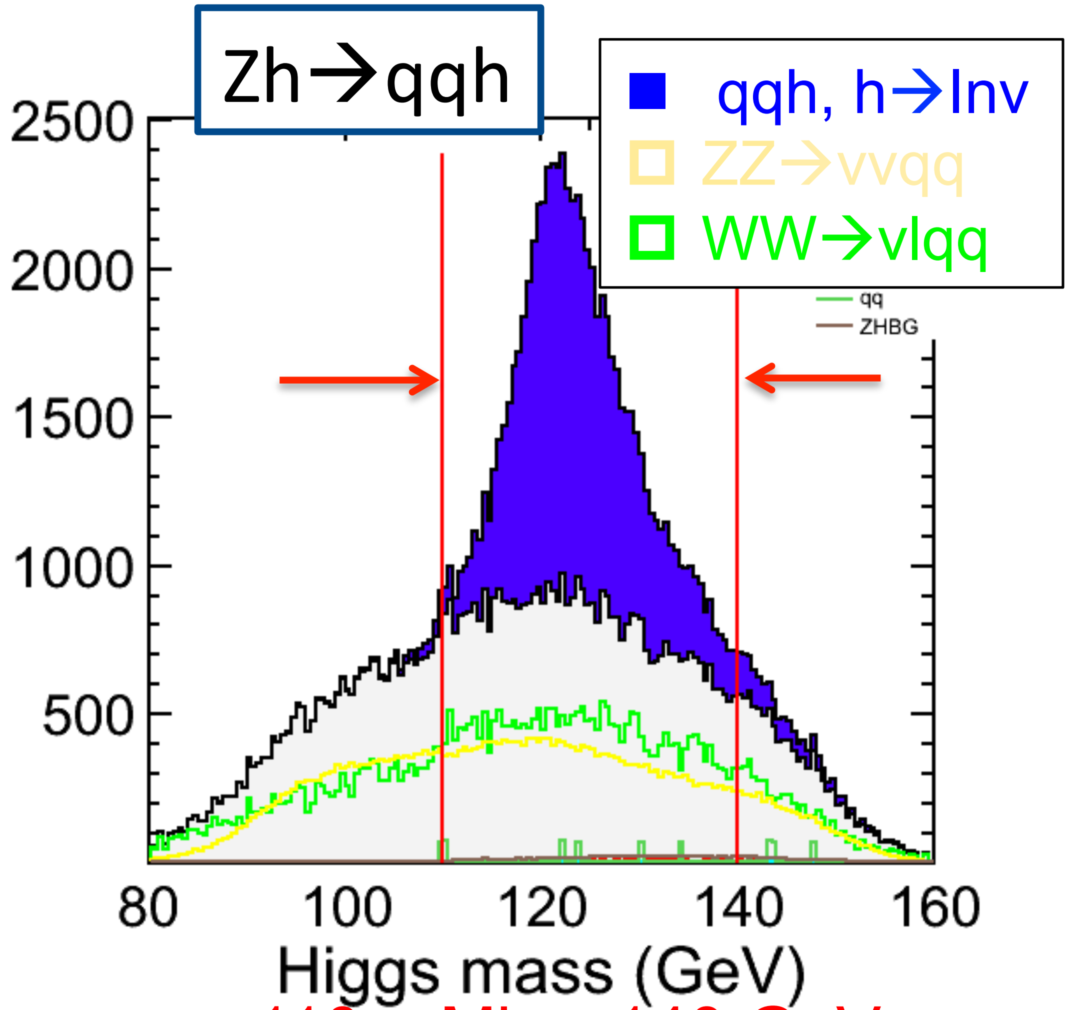
Require Z→ll,qq + nothing at Ecm=250 GeV, L=250 fb-1



$118 < M_{recoil} < 125$ GeV

CL 95% upper limit: 5.7%

in BR(h→Inv)=100%



110 < Mh < 140 GeV

CL 95% upper limit: 1.1%

in BR(h→Inv)=100%

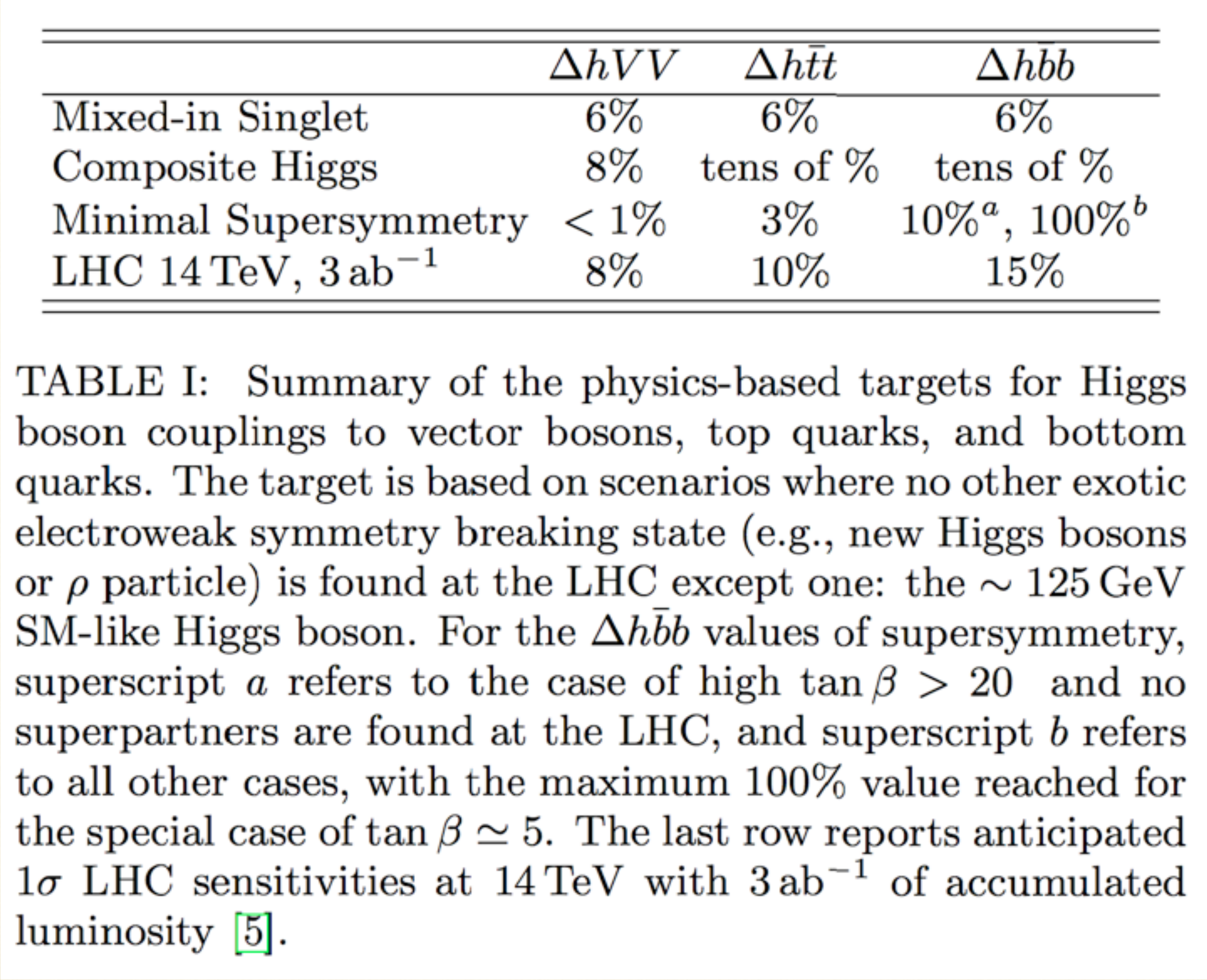
# Independent Higgs measurements @ ILC

## (MH = 125 GeV)

| ECM | @ 250 GeV | | @ 500 GeV | | @ 1 TeV |
|---|---|---|---|---|---|
| luminosity · fb | 250 | | 500 | | 1000 |
| polarization (e-,e+) | (-0.8, +0.3) | | (-0.8, +0.3) | | (-0.8, +0.2) |
| process | ZH | vvH(fusion) | ZH | vvH(fusion) | vvH(fusion) |
| cross section | 2.6% | - | - | | |
| | σ·Br | σ·Br | σ·Br | σ·Br | σ·Br |
| H-->bb | 1.1% | 10.5% | 1.8% | 0.66% | 0.32% |
| H-->cc | 7.4% | | 12% | 6.2% | 3.1% |
| H-->gg | 9.1% | | 14% | 4.1% | 2.3% |
| H-->WW* | 6.4% | | 9.2% | 2.6% | 1.6% |
| H-->ττ | 4.2% | | 5.4% | 14% | 3.5% |
| H-->ZZ* | 19% | | 25% | 8.2% | 4.1% |
| H-->γγ | 48% | | 48% | 33% | 11% |

# arXiv: 1206.3560v1

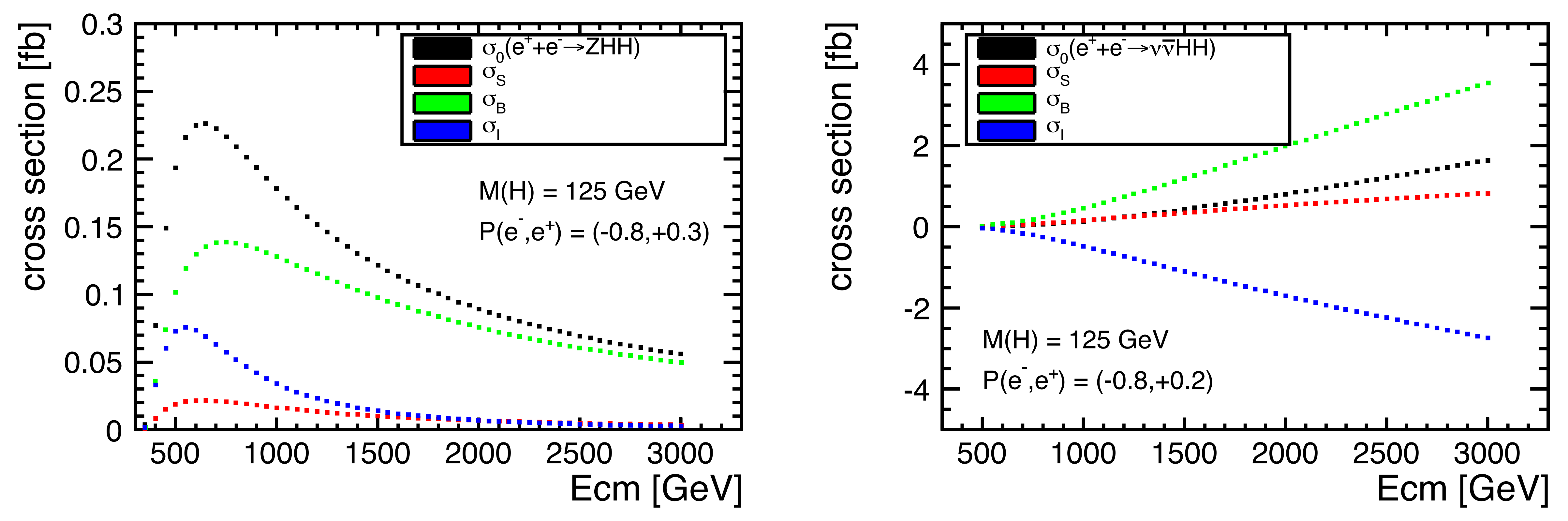
## R.S.Gupta, H.Rzehak, J.D.Wells

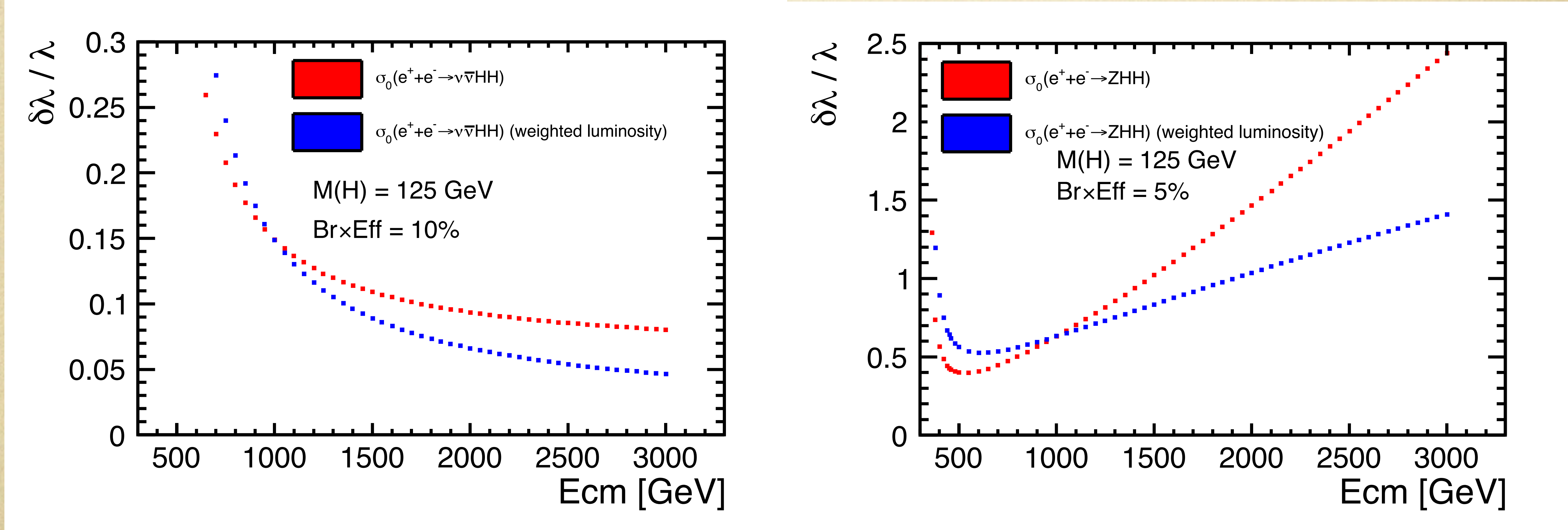


| | $\Delta hVV$ | $\Delta h\bar{t}t$ | $\Delta h\bar{b}b$ |
|---|---|---|---|
| Mixed-in Singlet | 6% | 6% | 6% |
| Composite Higgs | 8% | tens of % | tens of % |
| Minimal Supersymmetry | $< 1\%$ | 3% | $10\%^a$, $100\%^b$ |
| LHC 14 TeV, $3\,\mathrm{ab}^{-1}$ | 8% | 10% | 15% |

TABLE I: Summary of the physics-based targets for Higgs boson couplings to vector bosons, top quarks, and bottom quarks. The target is based on scenarios where no other exotic electroweak symmetry breaking state (e.g., new Higgs bosons or $\rho$ particle) is found at the LHC except one: the $\sim 125\,\mathrm{GeV}$ SM-like Higgs boson. For the $\Delta h\bar{b}b$ values of supersymmetry, superscript $a$ refers to the case of high $\tan\beta > 20$ and no superpartners are found at the LHC, and superscript $b$ refers to all other cases, with the maximum 100% value reached for the special case of $\tan\beta \simeq 5$. The last row reports anticipated $1\sigma$ LHC sensitivities at 14 TeV with $3\,\mathrm{ab}^{-1}$ of accumulated luminosity [5].

# General issue: expected coupling precision at different Ecm

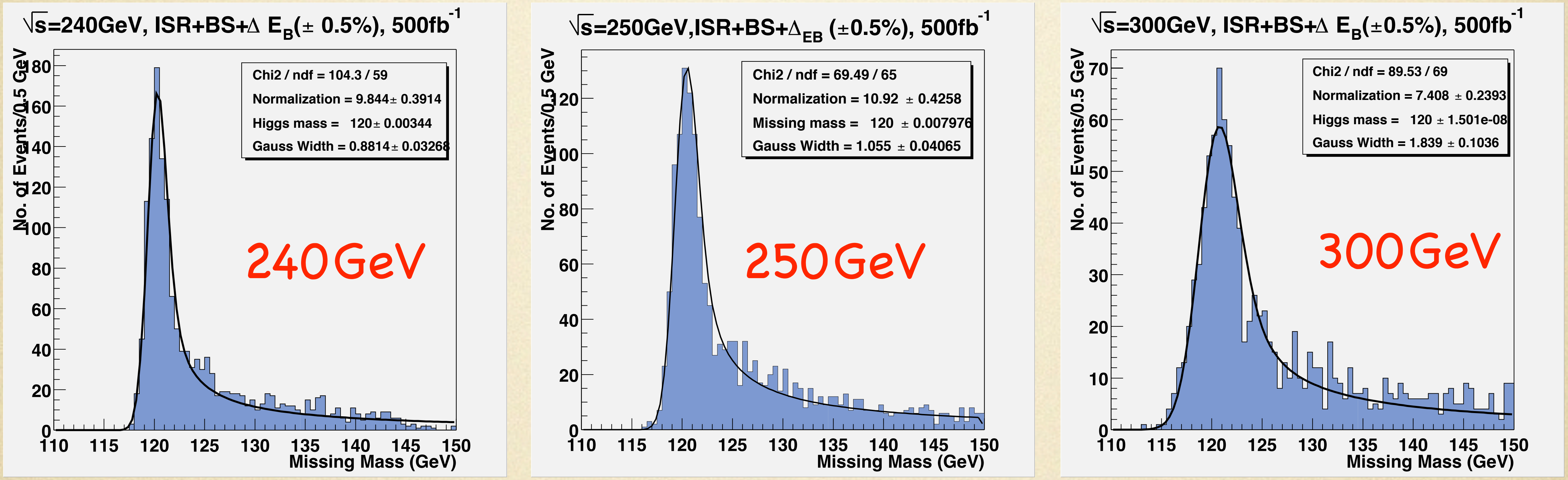


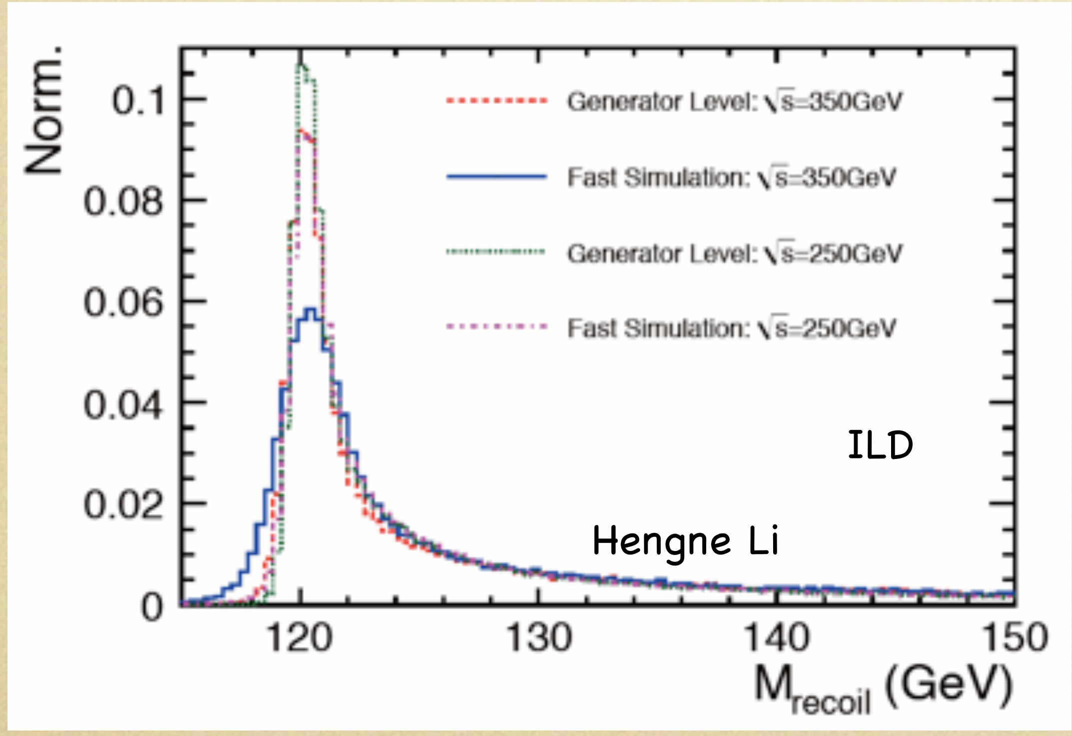


# Recoil Mass Resolution

## Estimation by simulation

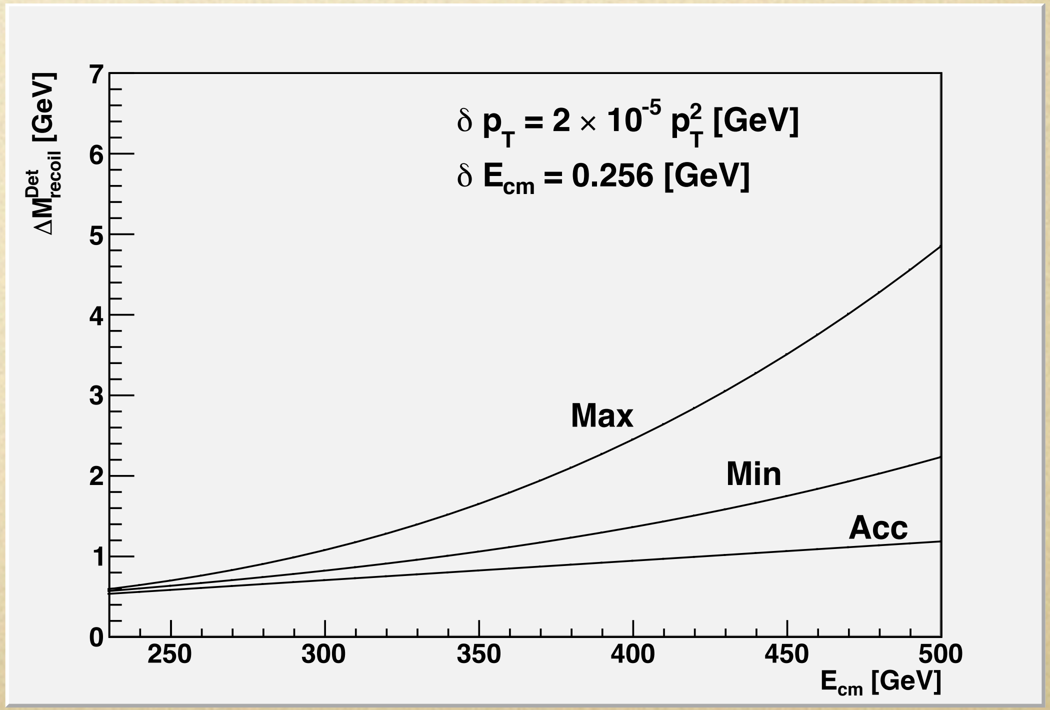
Old ACFA Study
by Akiya Miyamoto





Degrades with energy

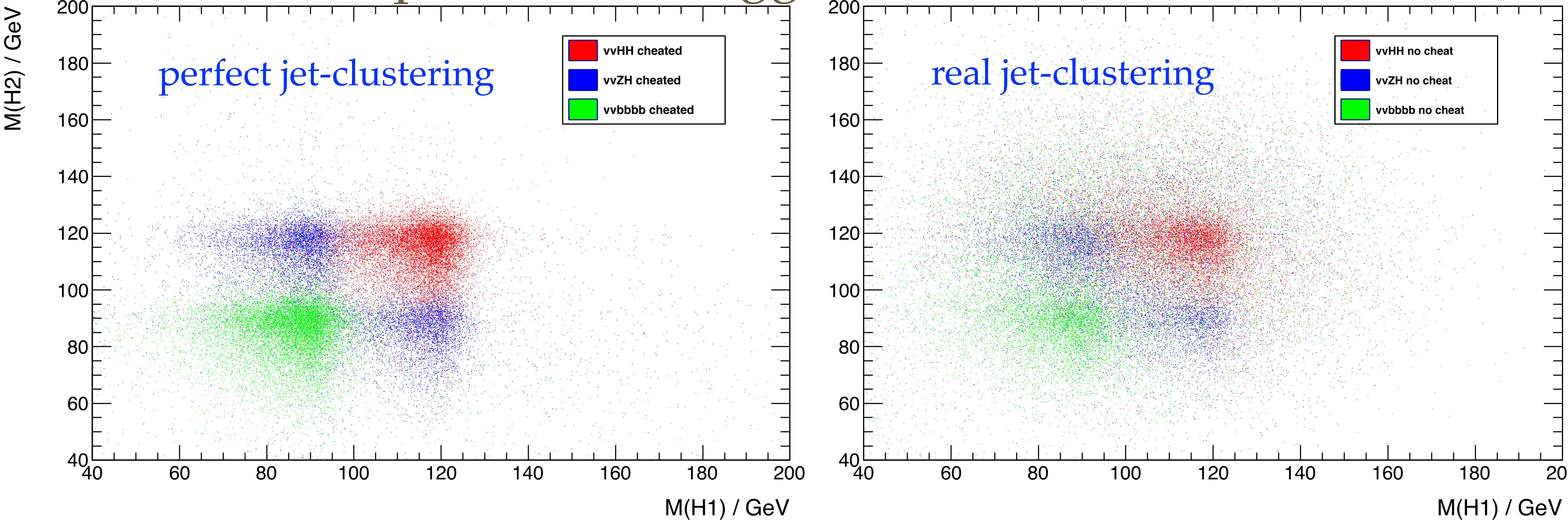
## Rough analytic estimate



# prospect of Higgs self-coupling

## scatter plot of two Higgs masses

vvHH mode: (ZZH and ZZZ)



perfect jet-clustering

real jet-clustering

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

# P value and Significance

large statistics

**excess:** assuming there is no signal, the probability of observing events equal or more than the expected number of events (S+B).

$$p = \int_{S+B}^{+\infty} f(x, B, \sqrt{B})\mathrm{dx} \qquad \frac{S}{\sqrt{B}}$$

**measure:** assuming signal exists, the probability of observing events equal or less than the expected number of background events (B).

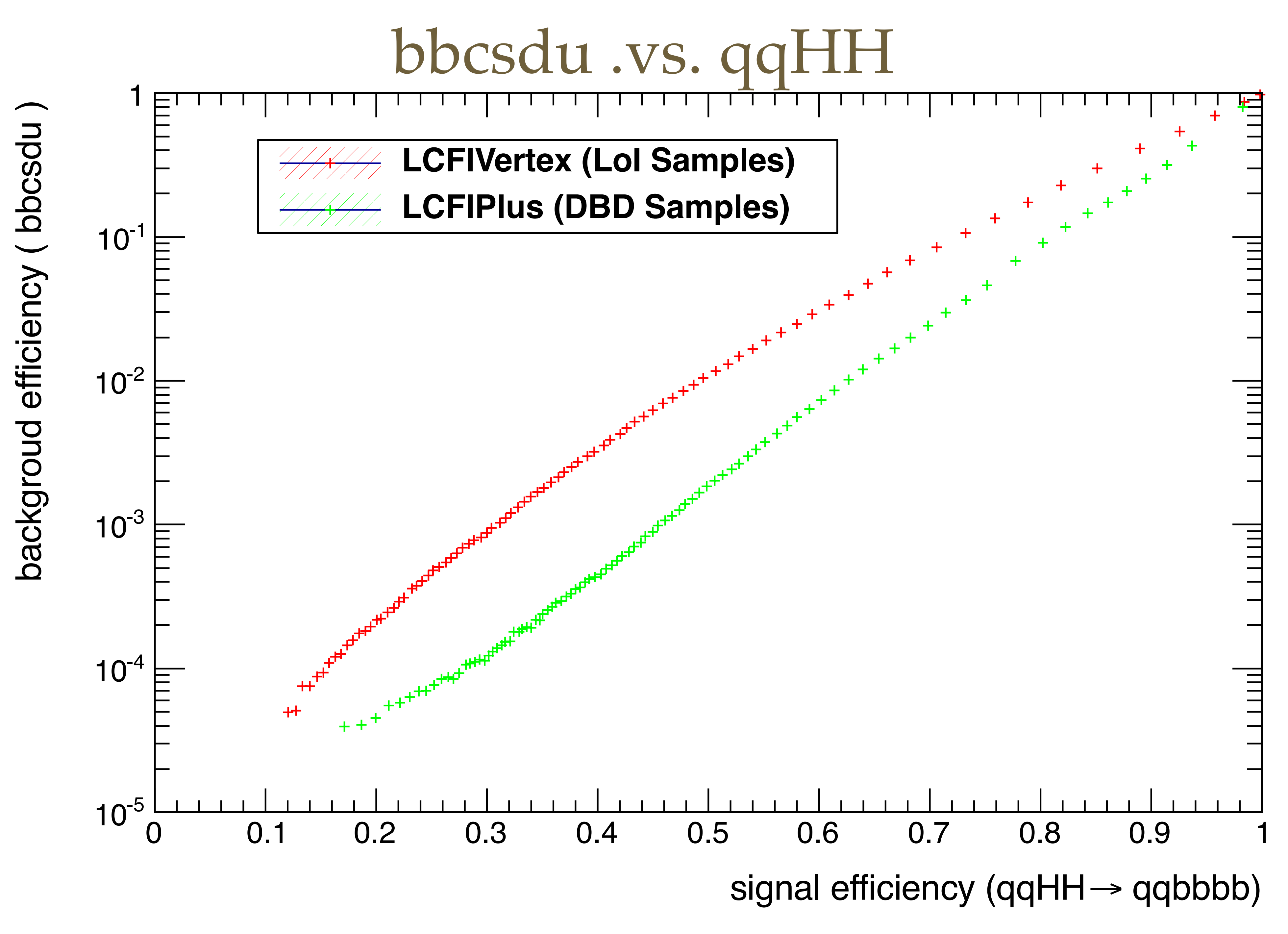
$$p = \int_{-\infty}^{B} f(x, S+B, \sqrt{S+B})\mathrm{dx} \qquad \frac{S}{\sqrt{S+B}}$$

convert to gaussian significance (s):

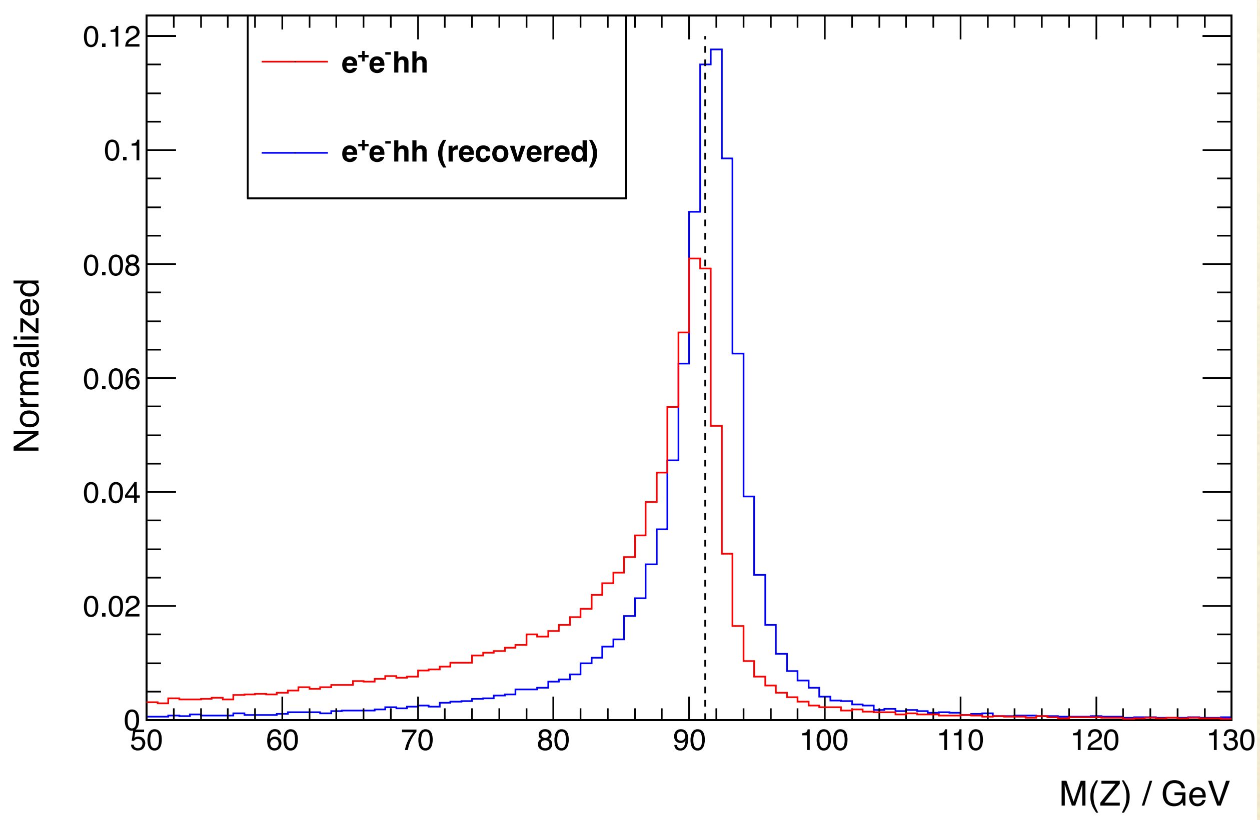
$$1 - p = \int_{-\infty}^{\mathrm{s}\sigma} N(x; 0, 1)\mathrm{dx}$$

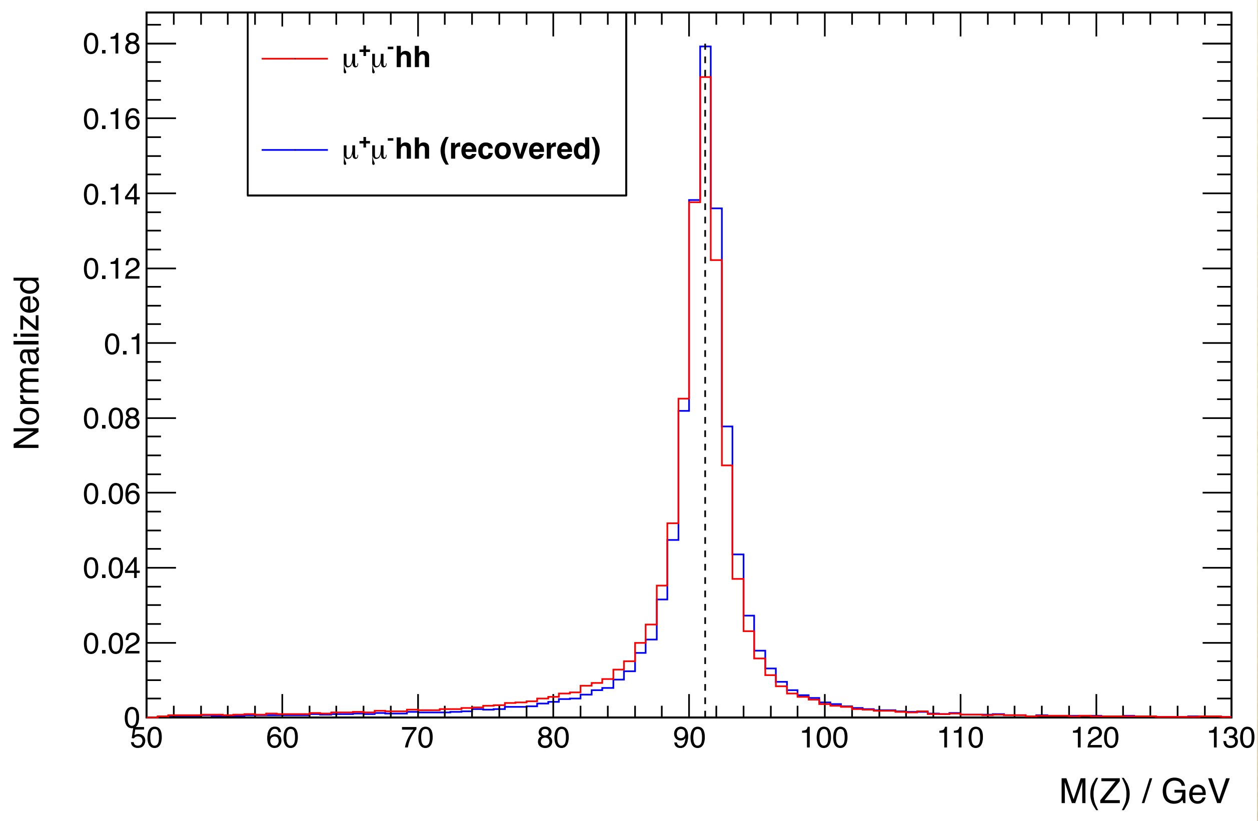
# flavor tagging performance in qqHH mode

Thanks to developers of LCFIPlus (T. Tanabe and T. Suehara)



# Isolated lepton selection (llHH)





(Etot = Eecal + Ehcal)

| | electron ID | muon ID |
|---|---|---|
| ✦ | Eecal / Etot > 0.9 | Eyoke > 1.2 |
| ✦ | 0.5 < Etot / P < 1.3 | Etot / P < 0.3 |
| ✦ | from primary vertex | from primary vertex |
| ✦ | P > 12.2 + 0.87Econe | P > 12.6 + 4.62Econe |

BS and FSR recovery adapted from ZFinder

efficiency of two isolated lepton selection

**(much better for DBD)**

| Eff (%) | eeHH | μμHH | bbbb | eνbbqq | μνbbqq |
|---|---|---|---|---|---|
| DBD | 85.7 | 88.4 | 0.028 | 1.44 | 0.10 |
| LoI | 81.9 | 85.4 | 0.43 | 2.71 | 1.94 |