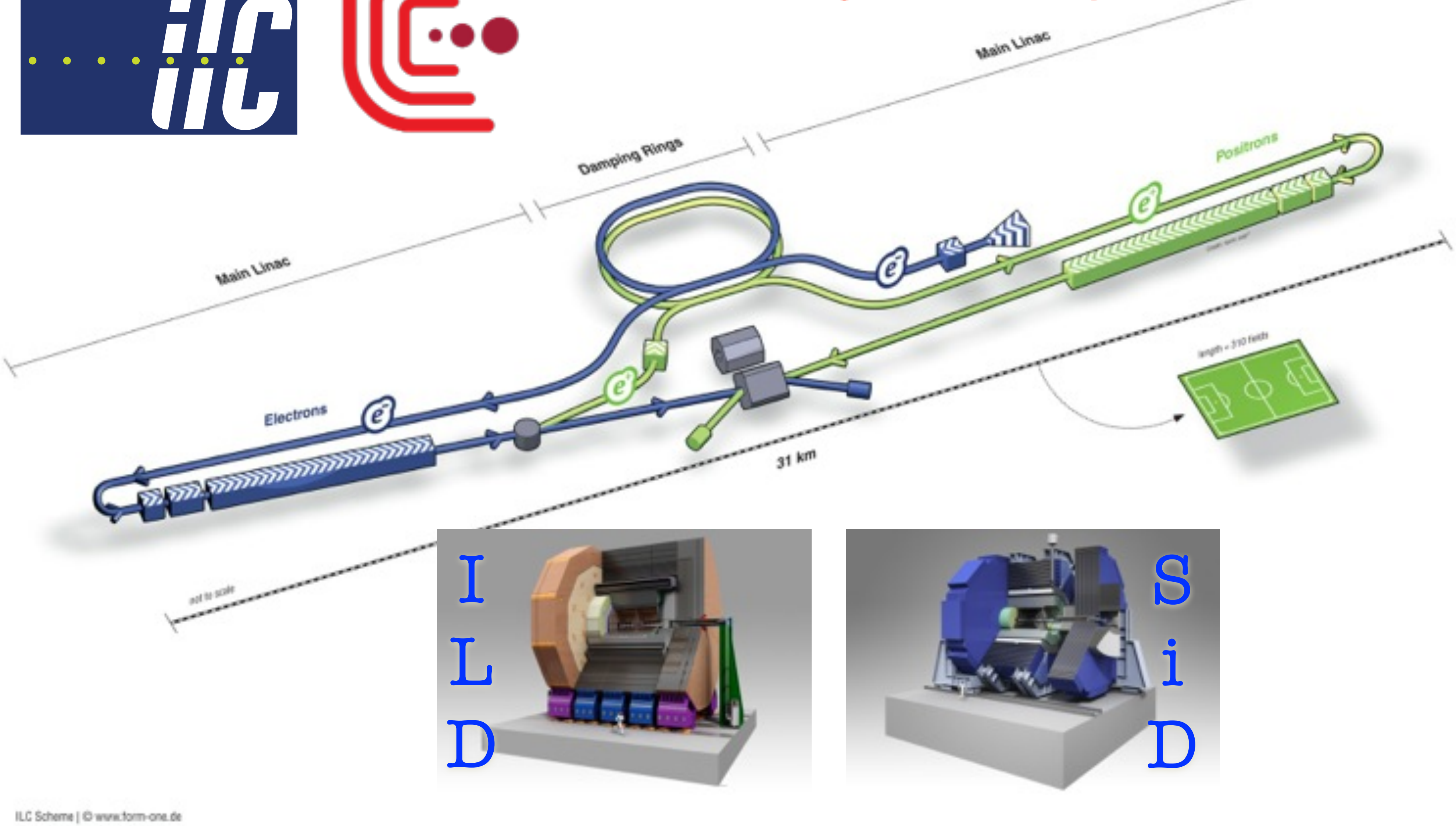
Measurement of Higgs couplings at the ILC

From Design to Reality



Technical Design Report

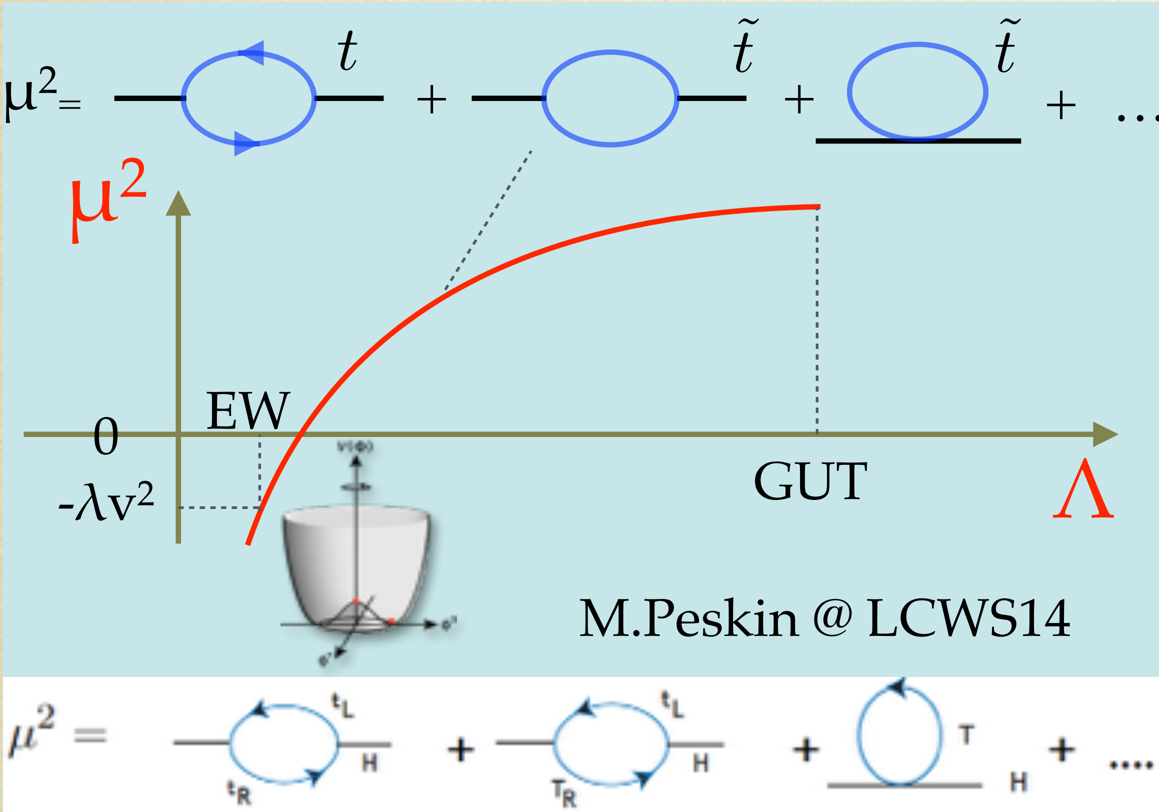
Junping Tian (KEK)

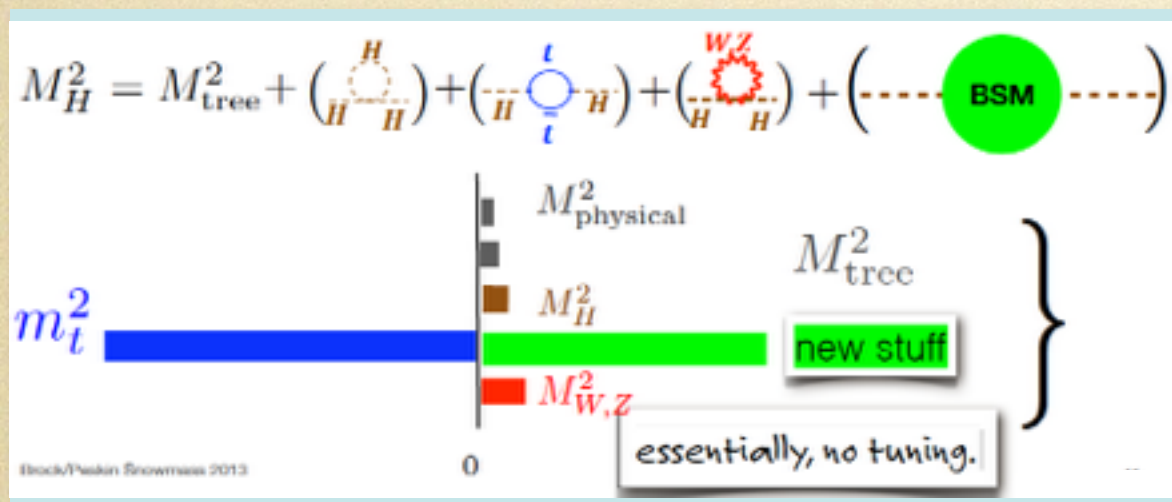
---on behalf of the ILC Physics & Detector Study

ICHEP 2014, Jul. 2-9 @ Valencia

For ILC Higgs Physics — TDR vol. 2 & vol. 4; ILC Higgs White Paper

Post discovery of a Higgs boson — What we want to know





C.Brock @ Snowmass 2013

1. H(125) = H_{SM}?
2. Why is μ^2 negative?
3. Is the cancelation in M_H radiative corrections natural?
4. What is the dynamics responsible for EWSB?

learn as much as possible about H(125)!

ILC is built to reveal the nature of H(125)

Why Precisions?

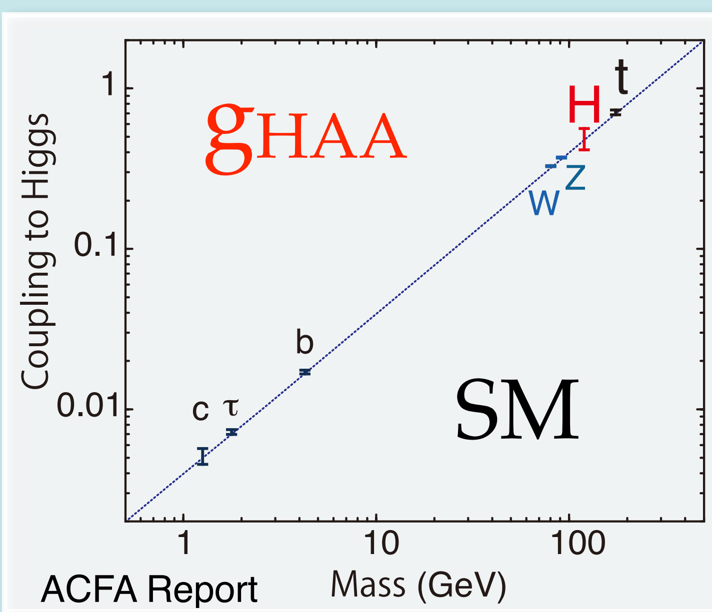
- Multiplet structure :
  - Additional singlet? (ϕ + S)
  - Additional doublet? (ϕ + ϕ')
  - Additional triplet? (ϕ + Δ)
- Underlying dynamics :
  - Why did the Higgs condense?
  - Weakly interacting or strongly interacting?
    = elementary or composite ?
- Relations to other questions of HEP :
  - ϕ + S → (B-L) gauge, DM, …
  - ϕ + ϕ' → Type I : m_ν from small vev, …
    → Type II : SUSY, DM, …
    → Type X: m_ν (rad.seesaw), …
  - ϕ + Δ → m_ν (Type II seesaw), …
  - $\lambda > \lambda_{SM}$ → EW baryogenesis ?
  - $\lambda \downarrow 0$ → inflation ?

K. Fuji @ Pheno2014

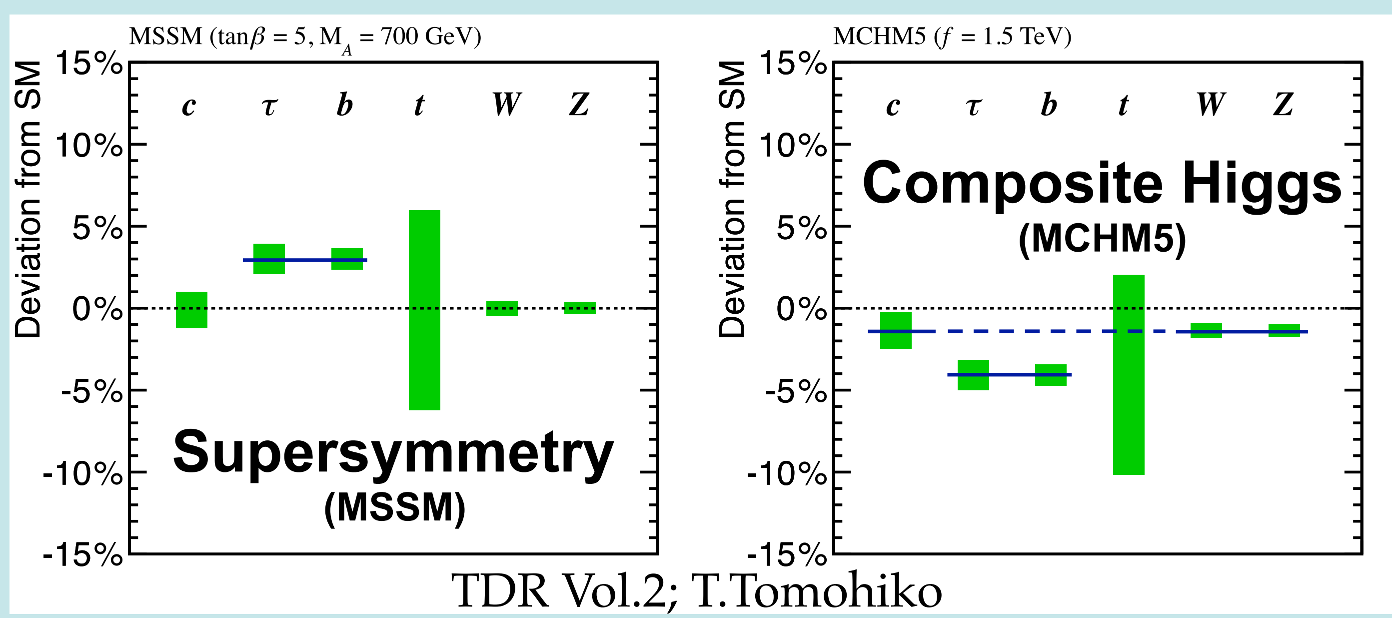
* SM is a minimal solution, there are many other possibilities! TeV scale new physics is strongly motivated.
* deviations on various Higgs couplings are window to see new physics.
* Haber's decoupling limit, deviation ~ m_h^2/M^2.

$\Delta g/g \sim O(1\%)$ @ 1 TeV

ILC comprehensive Higgs program, key is to measure mass coupling relation model independently



ACFA Report



TDR Vol.2; T.Tomohiko

A staged running program (Why 250—500 GeV?)

three well-known thresholds, a choice of physics

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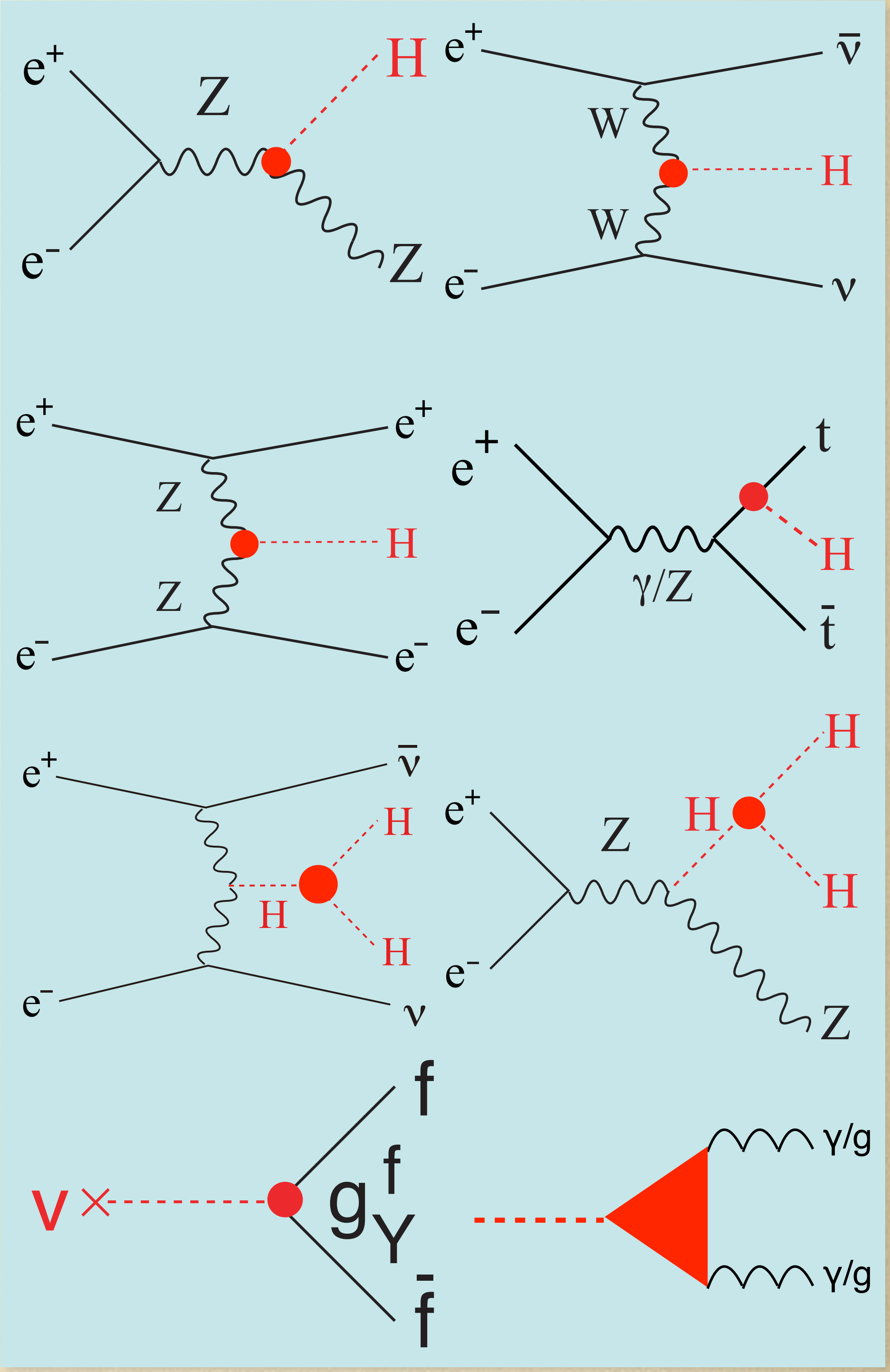

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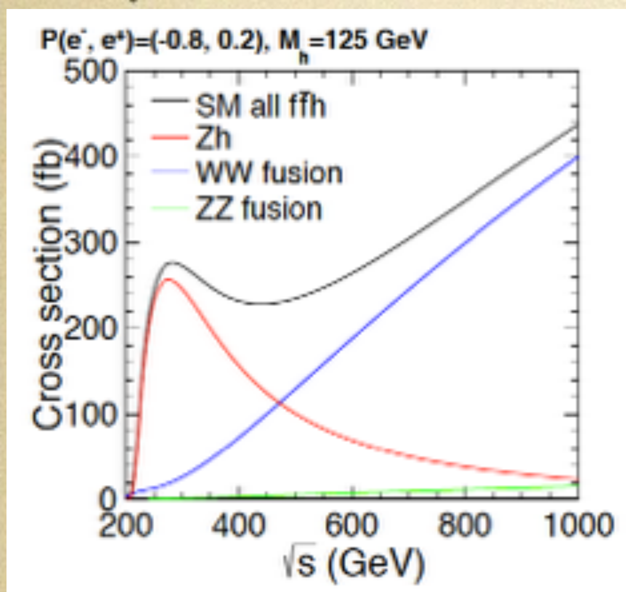

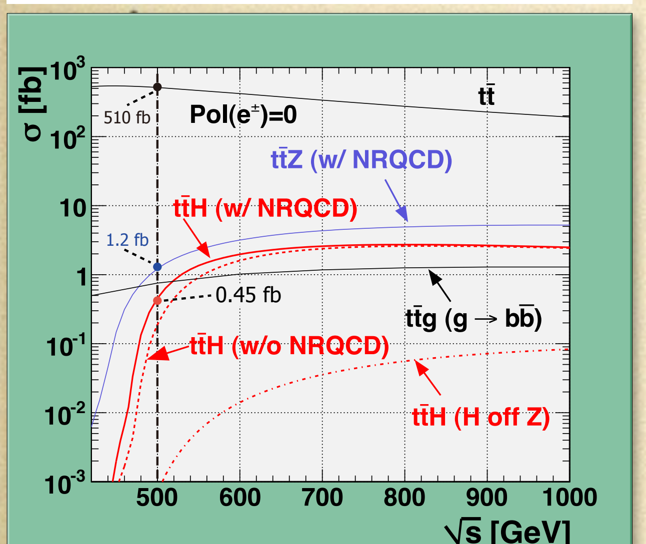

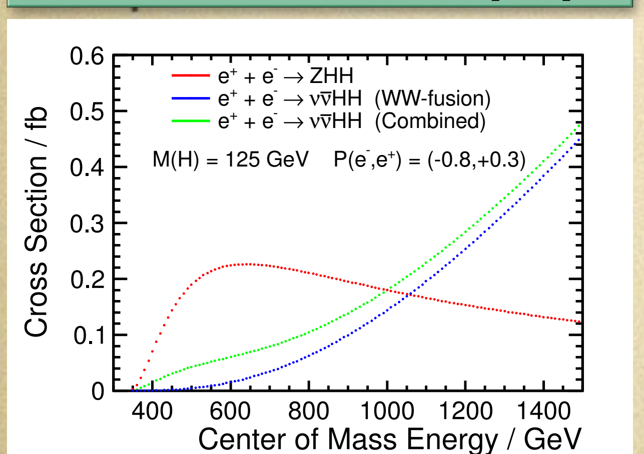

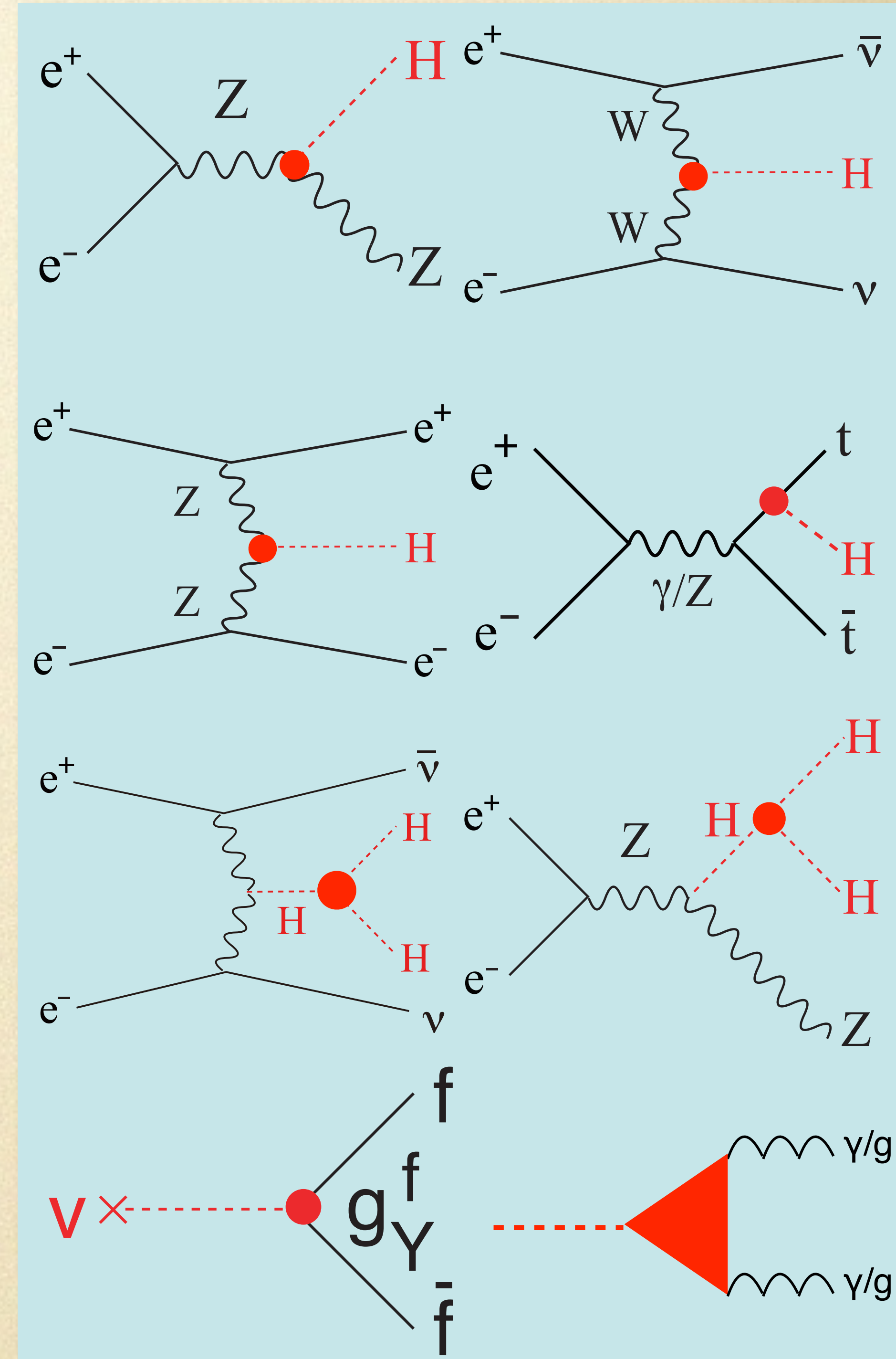

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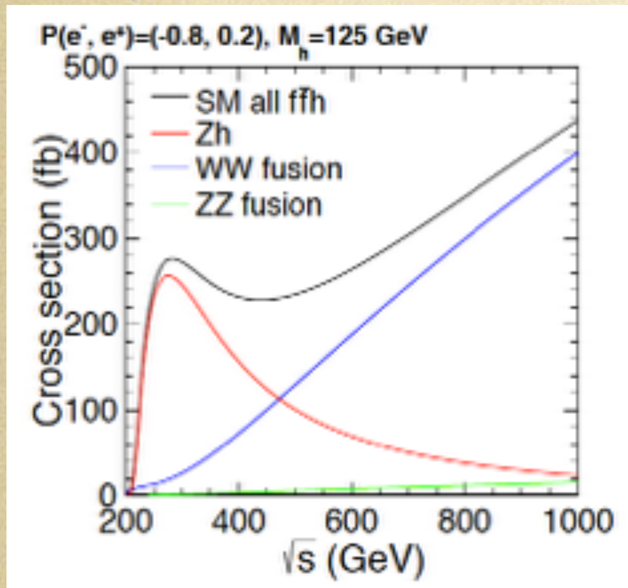
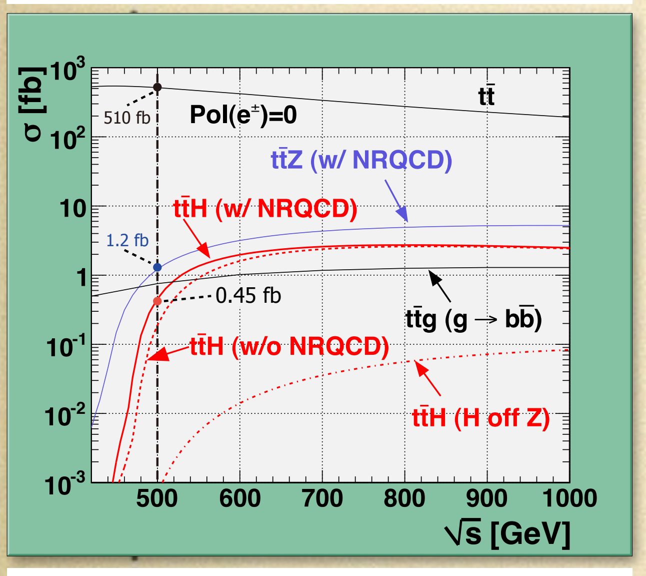
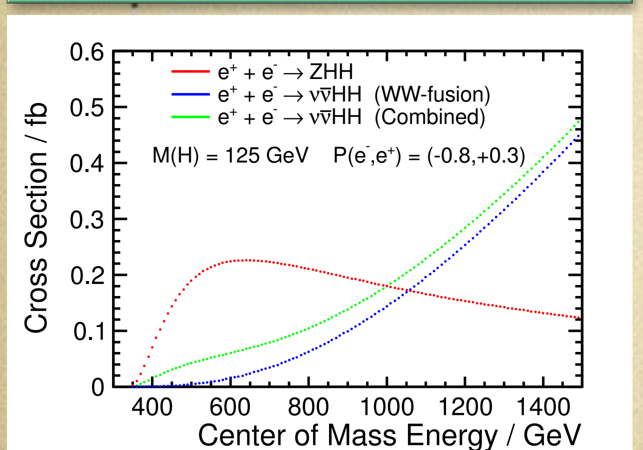
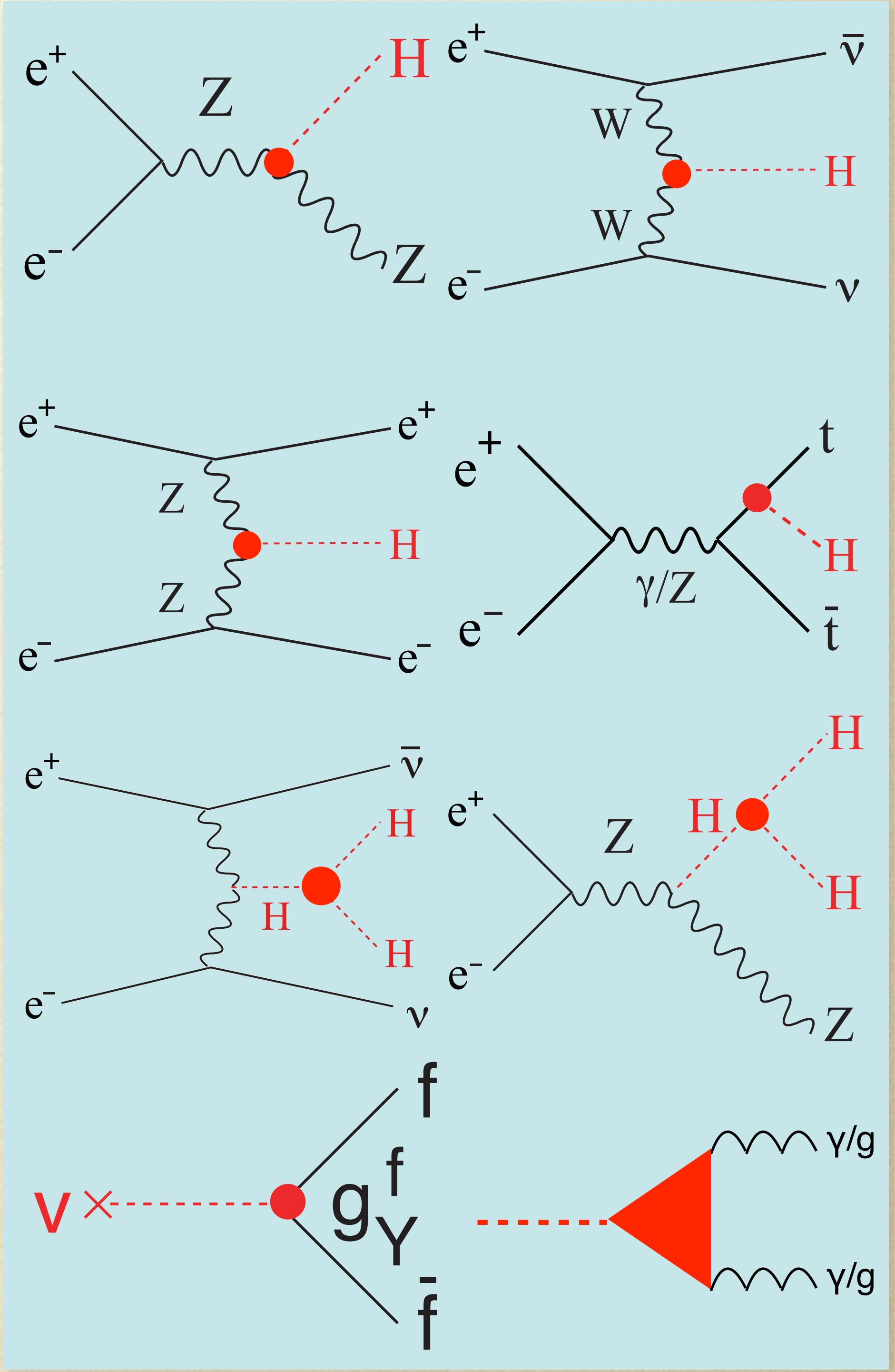






ZH @ 250 GeV

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



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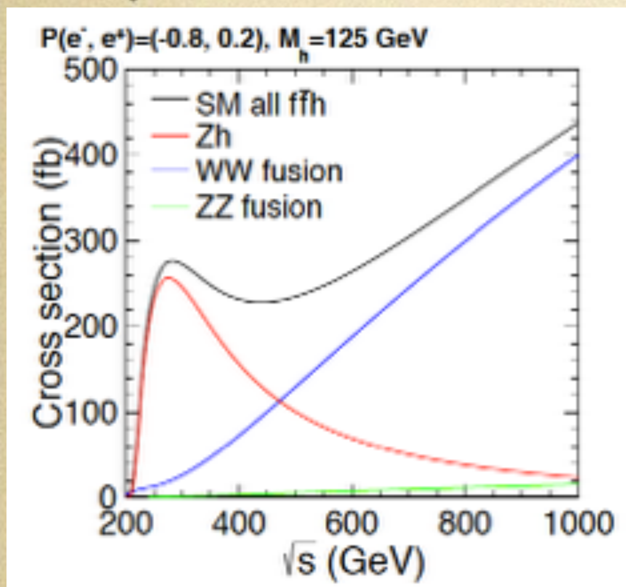

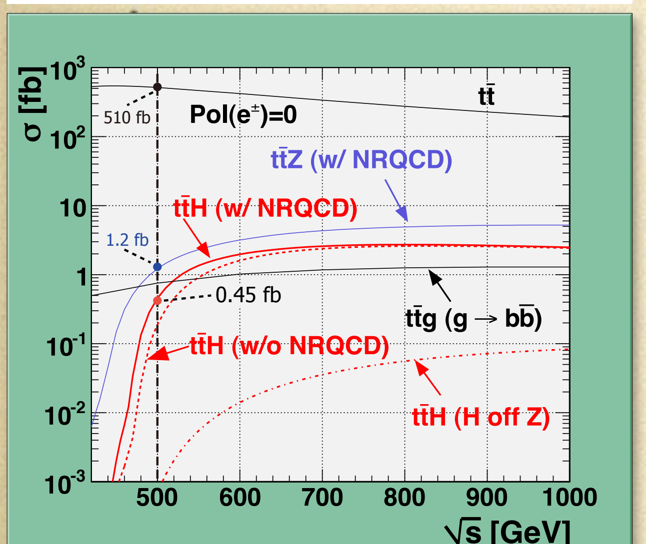

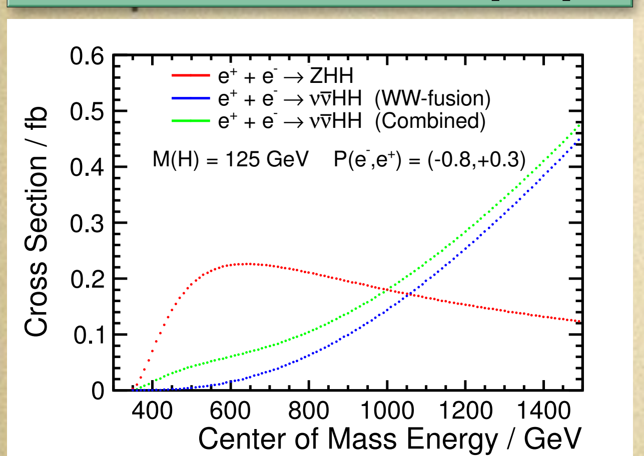

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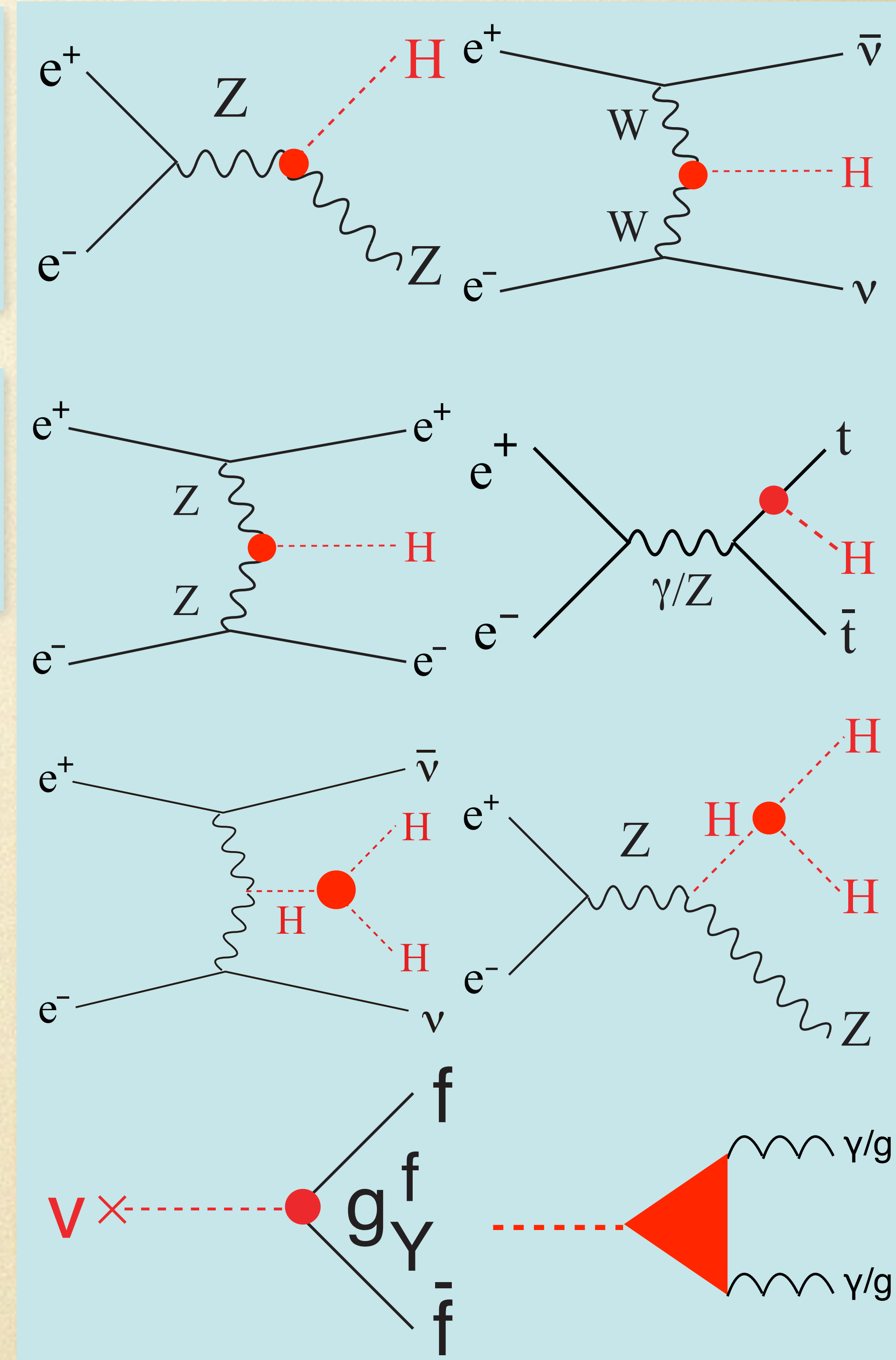
tt, ννH@ 350 GeV (talk by I.Garcia)

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



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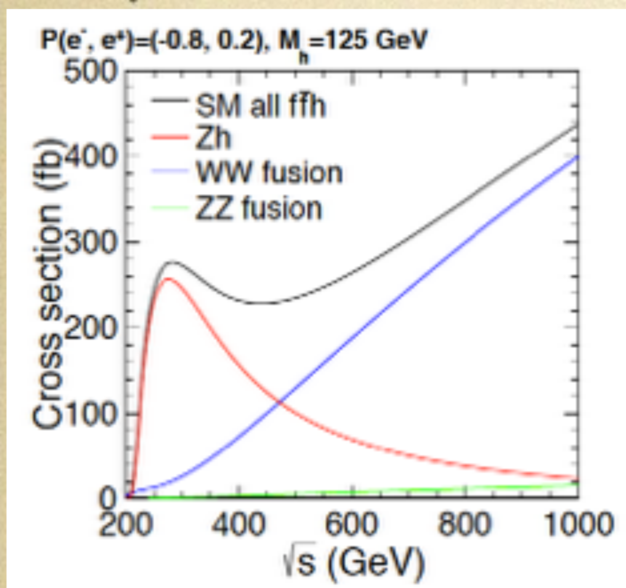

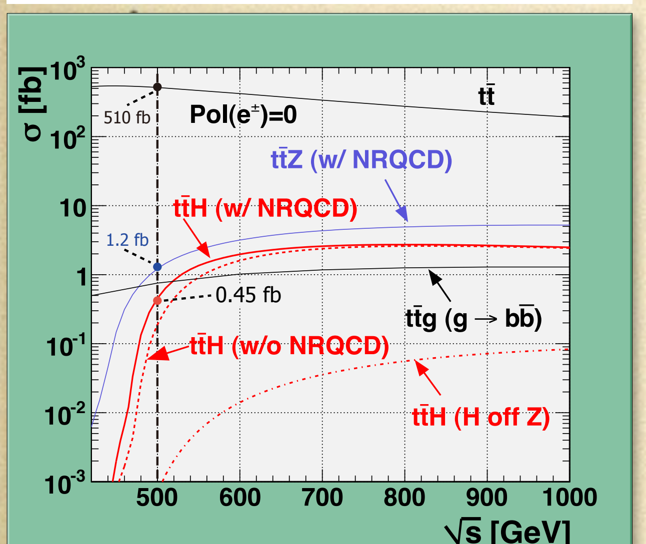

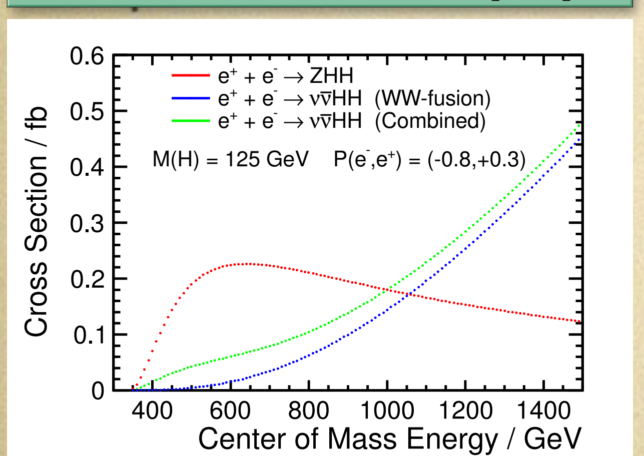

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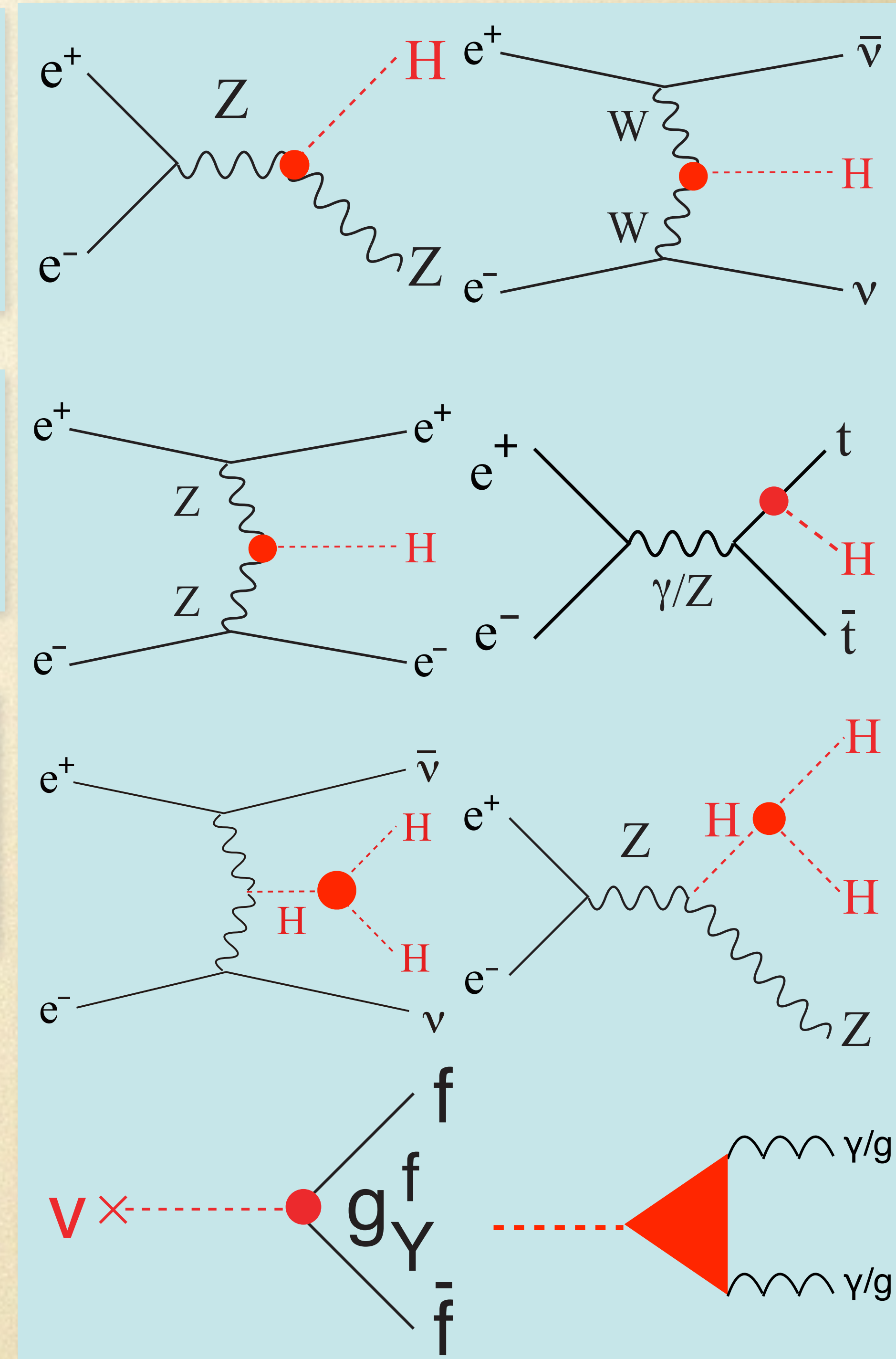
- Direct top-Yukawa coupling through ttH
- Higgs self-coupling through ZHH
- Total width —> all Higgs couplings



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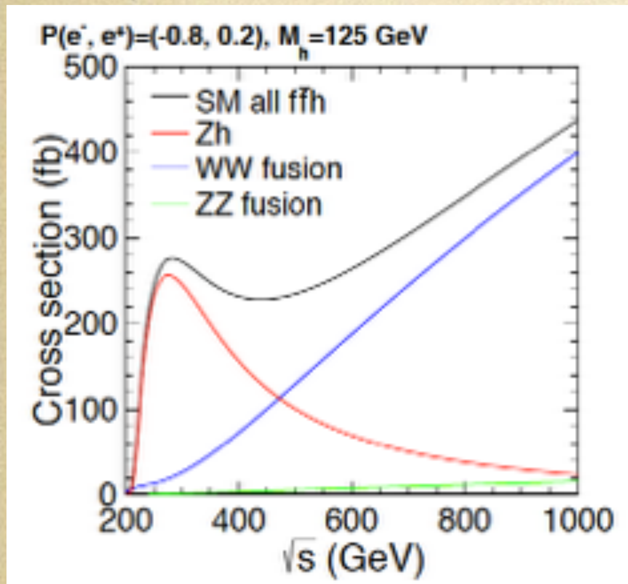

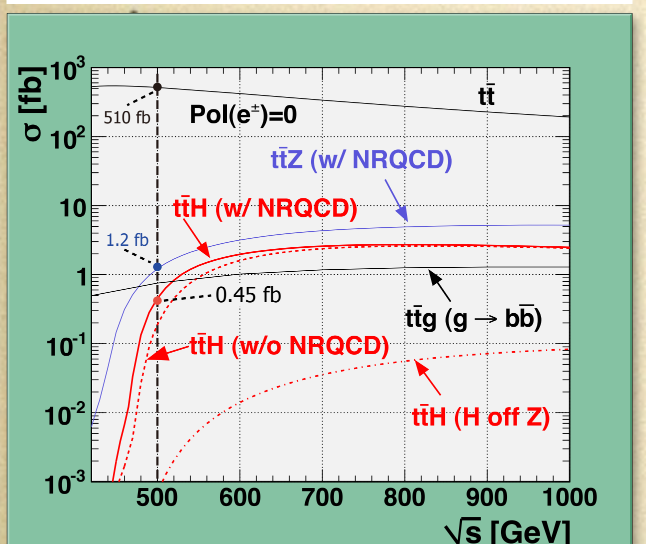

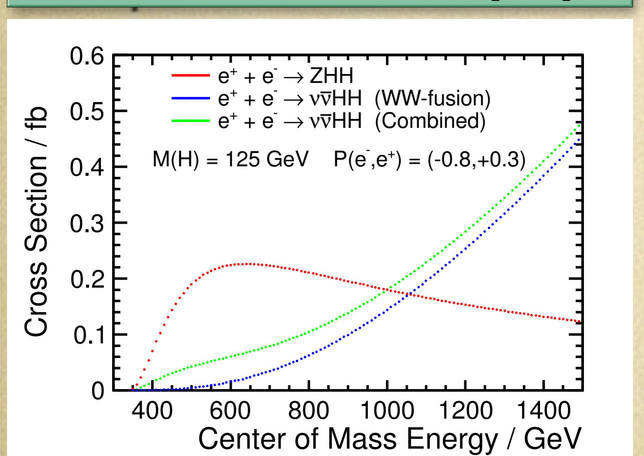

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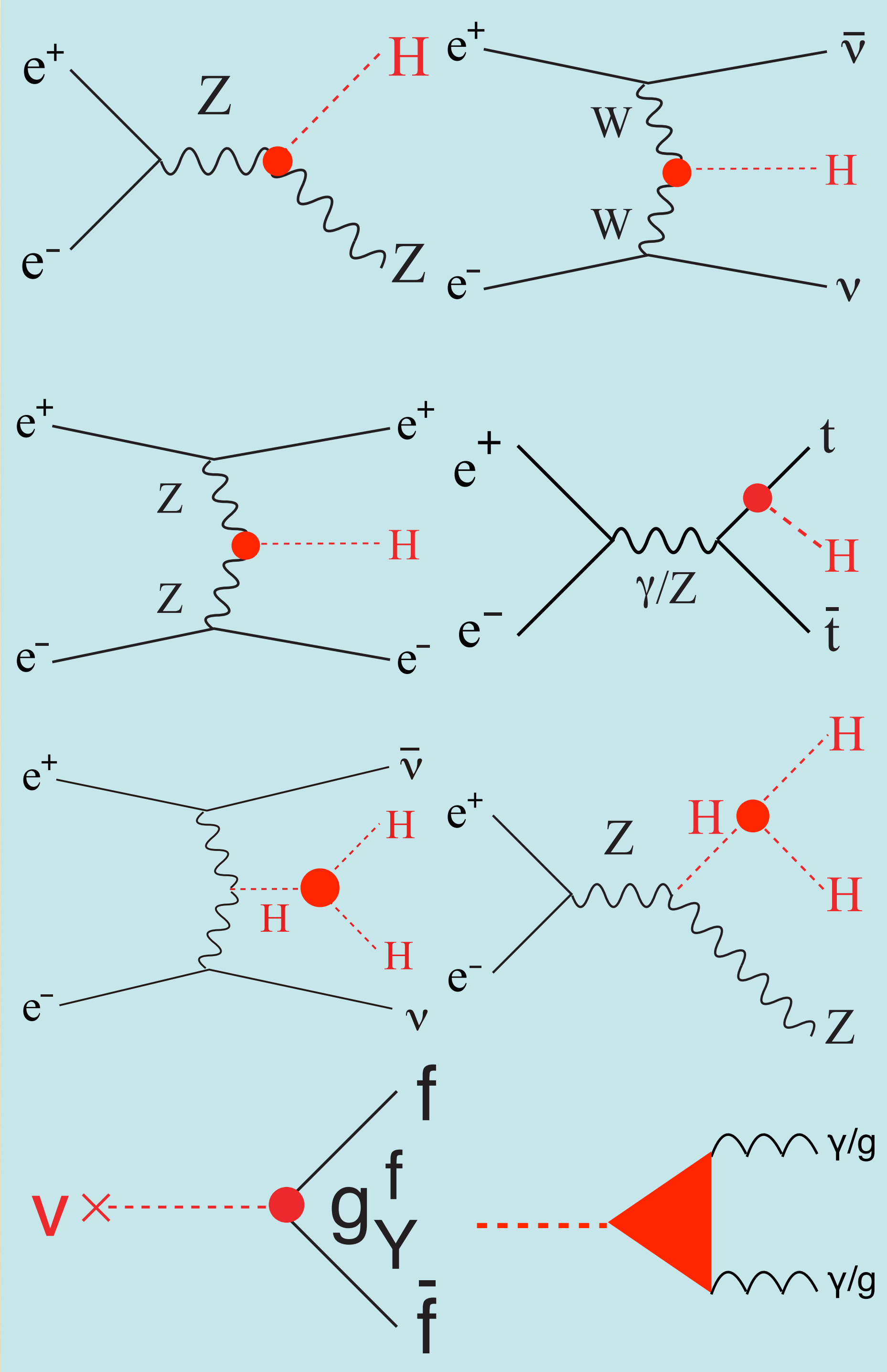
ννHH, ttH @ 1 TeV

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



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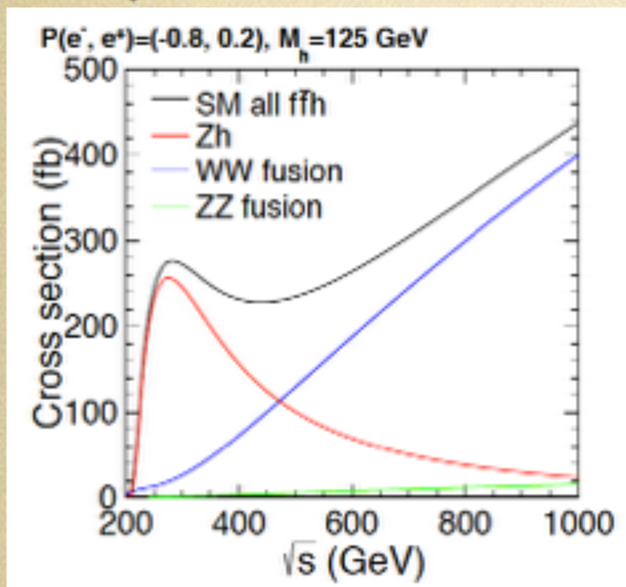

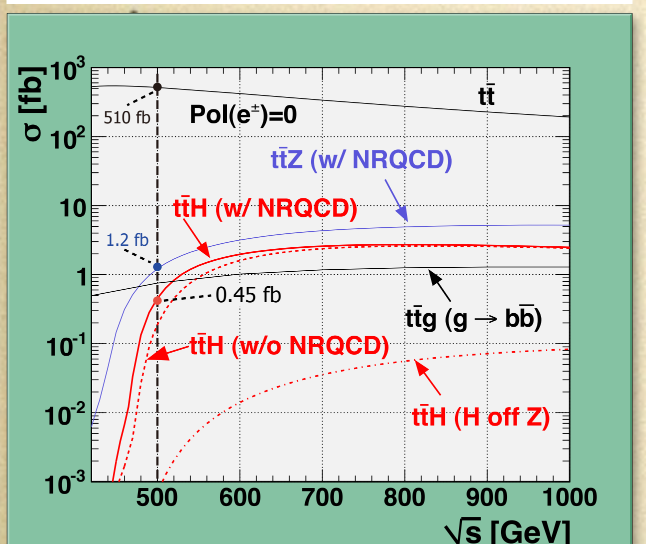

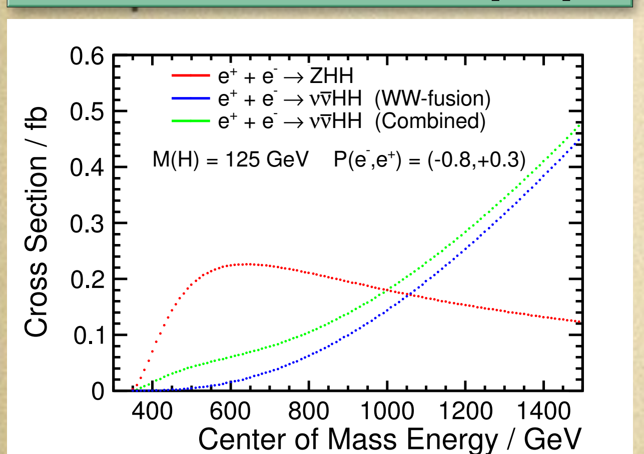

ZH @ 250 GeV $\int L\cdot dt = 250 \ / \ 1150 \ fb^{-1}$

- Higgs mass, spin, CP
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tt, ννH@ 350 GeV (talk by I.Garcia)

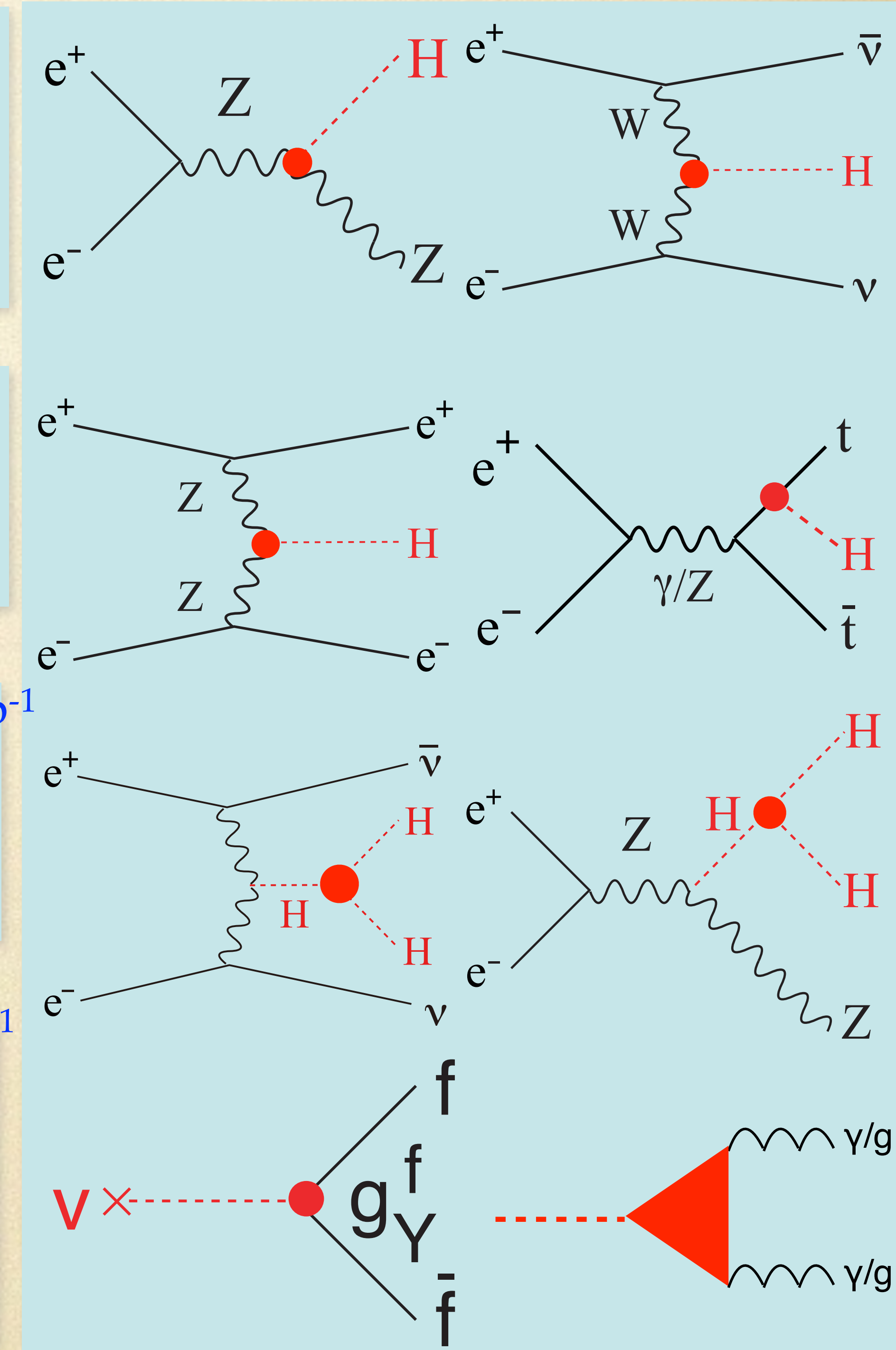
- top physics, indirect top-Yukawa
- HWW, Total width

ZHH, ttH @ 500 GeV $\int L\cdot dt = 500 \ / \ 1600 \ fb^{-1}$

- Direct top-Yukawa coupling through ttH
- Higgs self-coupling through ZHH
- Total width —> all Higgs couplings

ννHH, ttH @ 1 TeV $\int L\cdot dt = 1000 \ / \ 2500 \ fb^{-1}$

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



$\int L\cdot dt$ = Baseline (TDR is just beginning) / Luminosity Upgrade (increasing #bunch, collision rate)

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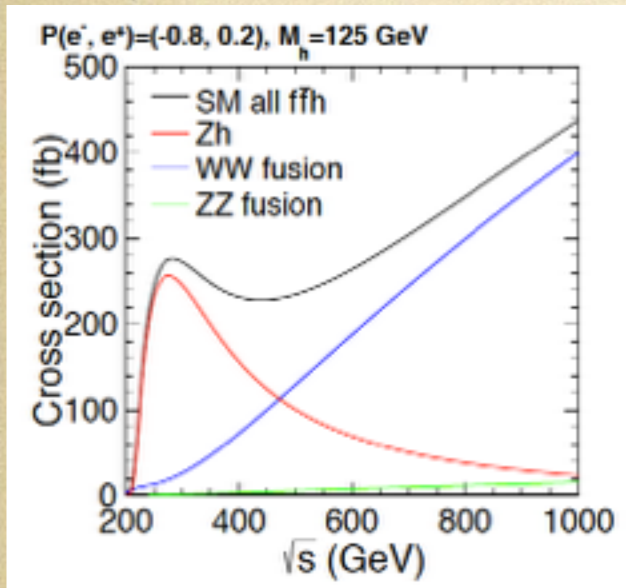

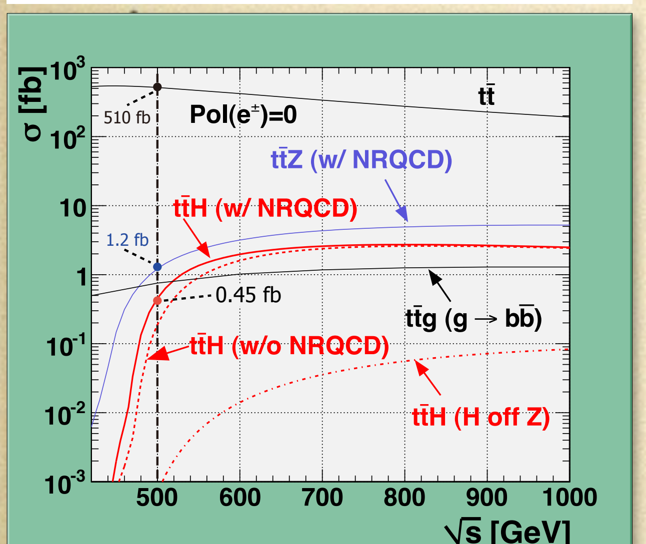

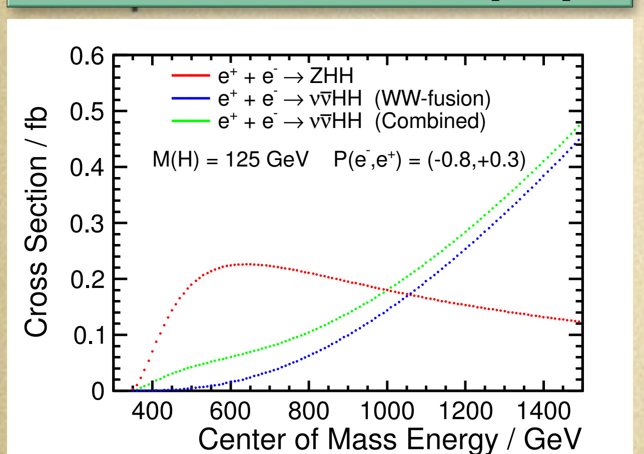

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ννHH, ttH @ 1 TeV $\int L\cdot dt = 1000\ /\ 2500\ fb^{-1}$

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- H-->μμ accessible
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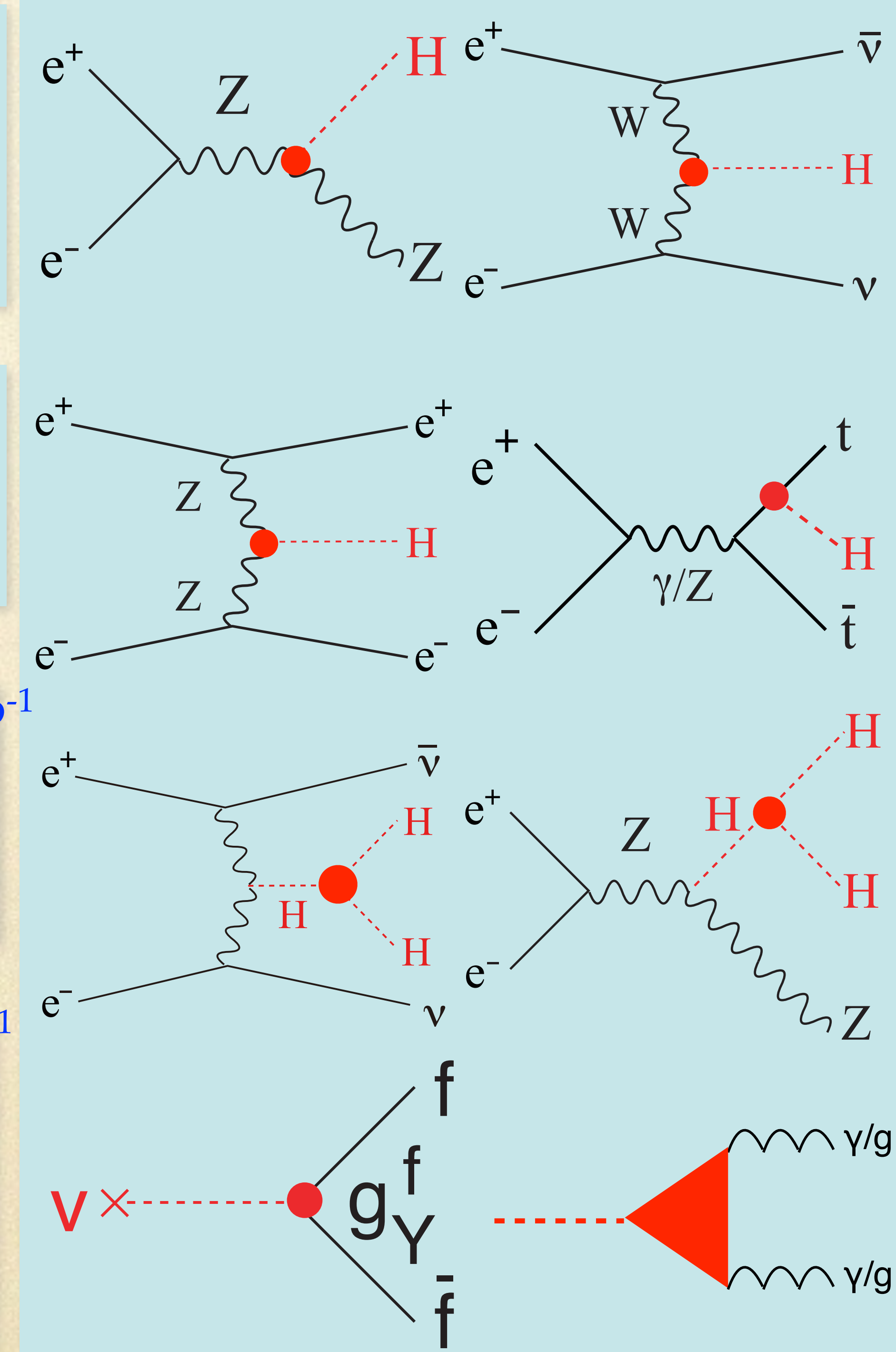


P(e-,e+)=(-0.8,+0.3) @ 250 - 500 GeV
P(e-,e+)=(-0.8,+0.2) @ 1 TeV

beam polarisation like a luminosity doubler (ννH)!

$\int L\cdot dt$ = Baseline (TDR is just beginning) / Luminosity Upgrade (increasing #bunch, collision rate)

Observables to measure at ILC

- σ_{ZH}
- $\sigma_{ZH} \times Br(H \rightarrow bb)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow bb)$
- $\sigma_{ZH} \times Br(H \rightarrow cc)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow cc)$
- $\sigma_{ZH} \times Br(H \rightarrow gg)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow gg)$
- $\sigma_{ZH} \times Br(H \rightarrow WW^*)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow WW^*)$
- $\sigma_{ZH} \times Br(H \rightarrow ZZ^*)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow ZZ^*)$
- $\sigma_{ZH} \times Br(H \rightarrow \tau\tau)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow \tau\tau)$
- $\sigma_{ZH} \times Br(H \rightarrow \gamma\gamma)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow \gamma\gamma)$
- $\sigma_{ZH} \times Br(H \rightarrow \mu\mu)$, $\sigma_{\nu\nu H} \times Br(H \rightarrow \mu\mu)$
- $\sigma_{ZH} \times Br(H \rightarrow Invisible)$
- $\sigma_{ttH} \times Br(H \rightarrow bb)$
- $\sigma_{ZHH} \times Br^2(H \rightarrow bb)$, $\sigma_{\nu\nu HH} \times Br^2(H \rightarrow bb)$

each running stage offers an independent set of measurements

Observables to measure at ILC

* σ_{ZH}
* $\sigma_{ZH}\times Br(H \to bb)$, $\sigma_{\nu\nu H}\times Br(H \to bb)$
* $\sigma_{ZH}\times Br(H \to cc)$, $\sigma_{\nu\nu H}\times Br(H \to cc)$
* $\sigma_{ZH}\times Br(H \to gg)$, $\sigma_{\nu\nu H}\times Br(H \to gg)$
* $\sigma_{ZH}\times Br(H \to WW^*)$, $\sigma_{\nu\nu H}\times Br(H \to WW^*)$
* $\sigma_{ZH}\times Br(H \to ZZ^*)$, $\sigma_{\nu\nu H}\times Br(H \to ZZ^*)$
* $\sigma_{ZH}\times Br(H \to \tau\tau)$, $\sigma_{\nu\nu H}\times Br(H \to \tau\tau)$
* $\sigma_{ZH}\times Br(H \to \gamma\gamma)$, $\sigma_{\nu\nu H}\times Br(H \to \gamma\gamma)$
* $\sigma_{ZH}\times Br(H \to \mu\mu)$, $\sigma_{\nu\nu H}\times Br(H \to \mu\mu)$
* $\sigma_{ZH}\times Br(H \to Invisible)$
* $\sigma_{ttH}\times Br(H \to bb)$
* $\sigma_{ZHH}\times Br^2(H \to bb)$, $\sigma_{\nu\nu HH}\times Br^2(H \to bb)$

each running stage offers an independent set of measurements

Full Detector Simulation of ILD & SiD

(see detector talks by T.Suehara & M.Oriunno)

Driven by Particle Flow Algorithm, High Granularity, ~4π Coverage

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

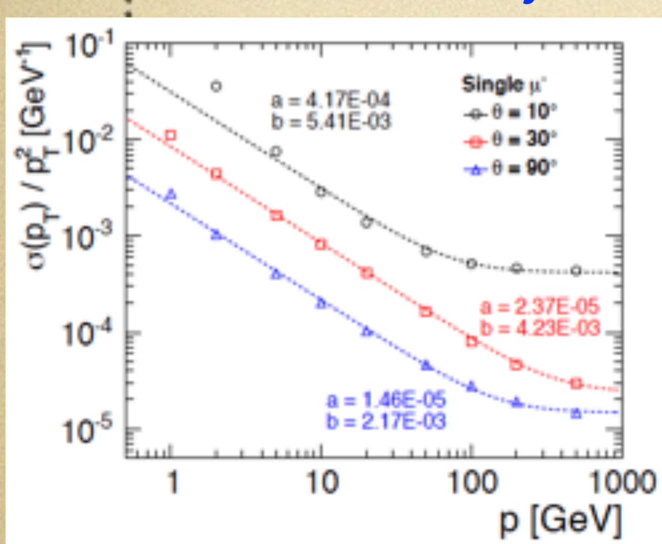
- driven by recoil mass measurement ZH-->l^+l^-X.

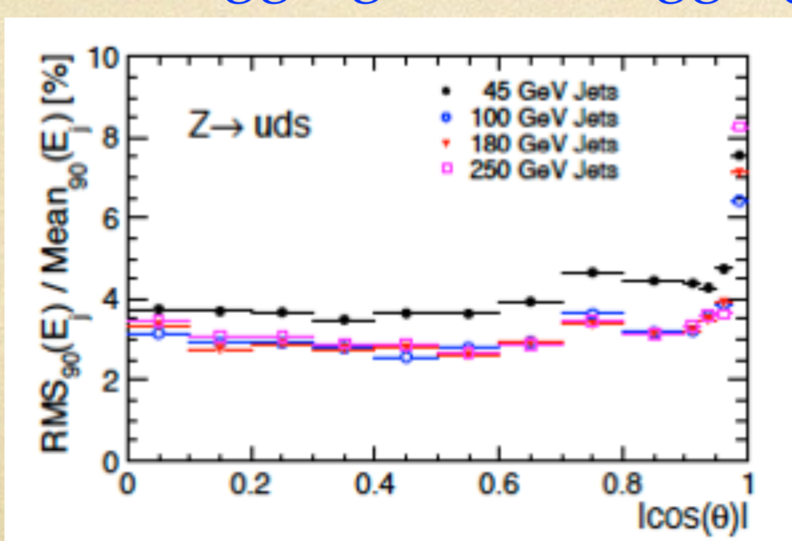
jet energy resolution: $\sigma_E/E \sim 30\%/\sqrt{E} \sim 3-4\%@100\mathrm{GeV}$

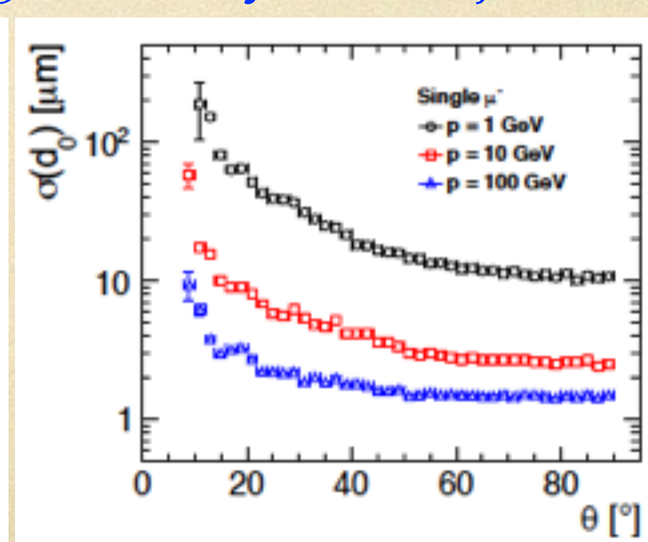
- driven by 3σ separation of the hadronic decay of W and Z bosons.

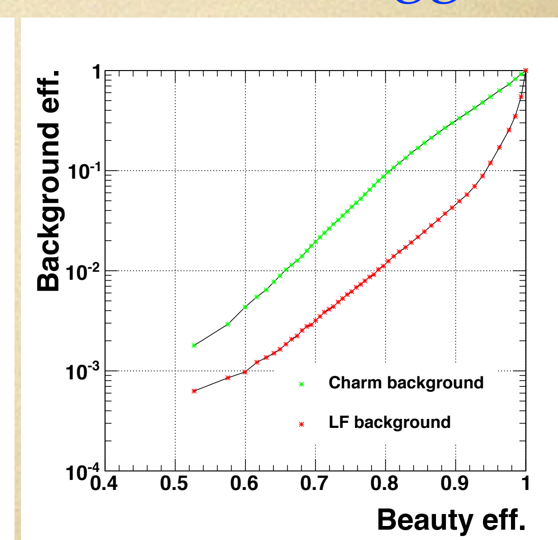
impact parameter resolution: $\sigma_{r\phi} = 5\ \mu\mathrm{m} \oplus \frac{10}{p(\mathrm{GeV}\sin^{3/2}\theta)}\ \mu\mathrm{m}$

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





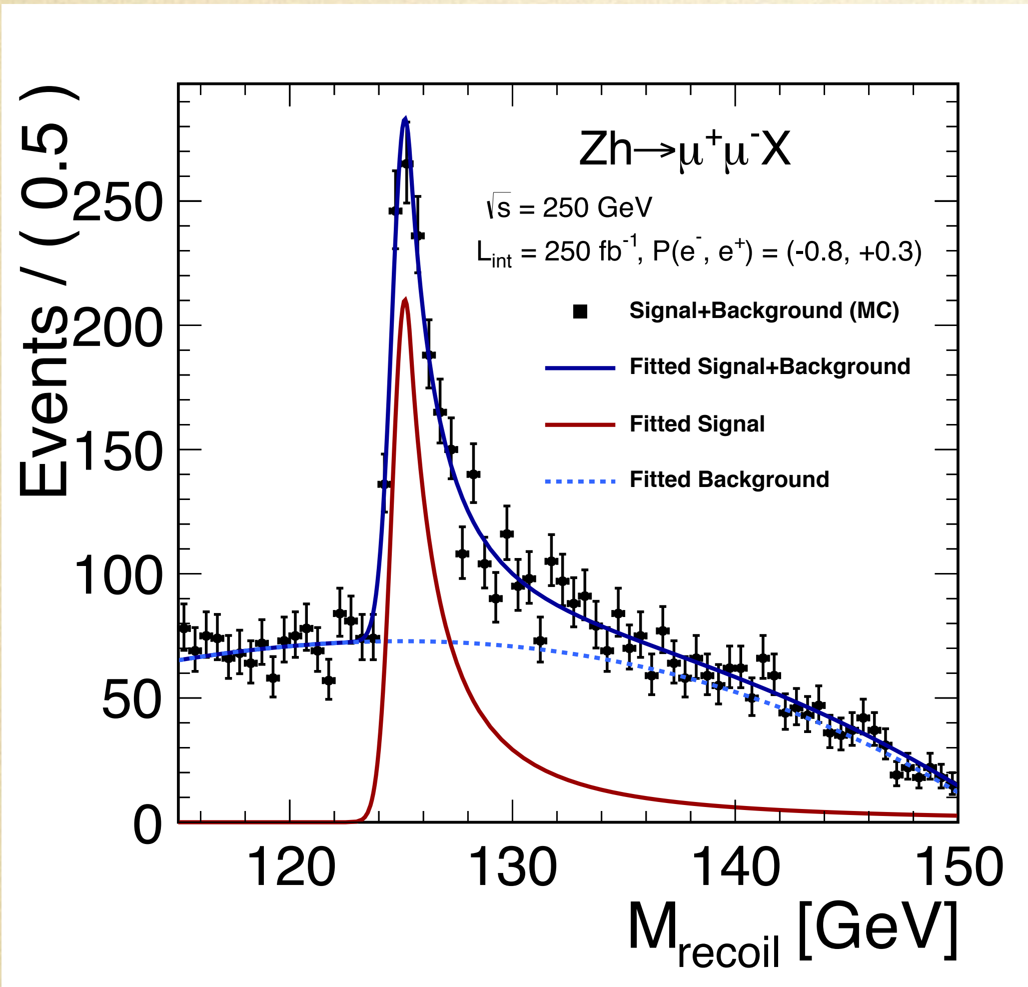


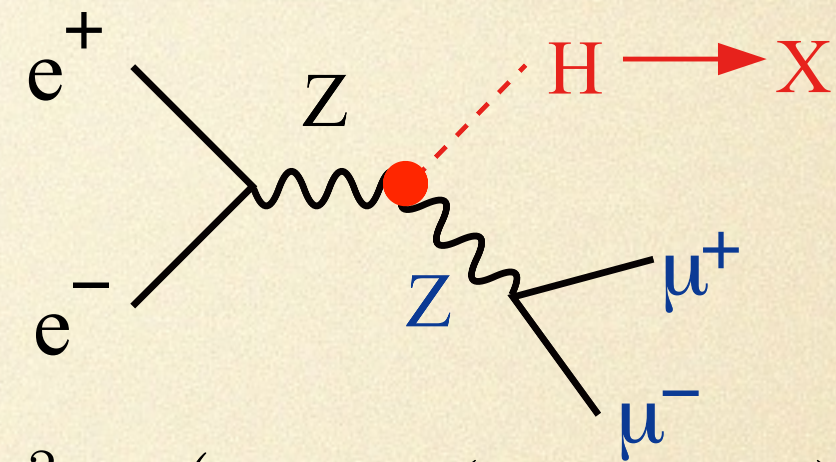


ILC 250 GeV

HZZ coupling

The flagship measurement of ILC250





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

- well defined initial states
- recoil mass technique
- tagged Higgs without looking into H decay
- precision mass measurement
- absolute cross section of e^+e^- —> ZH

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

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

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

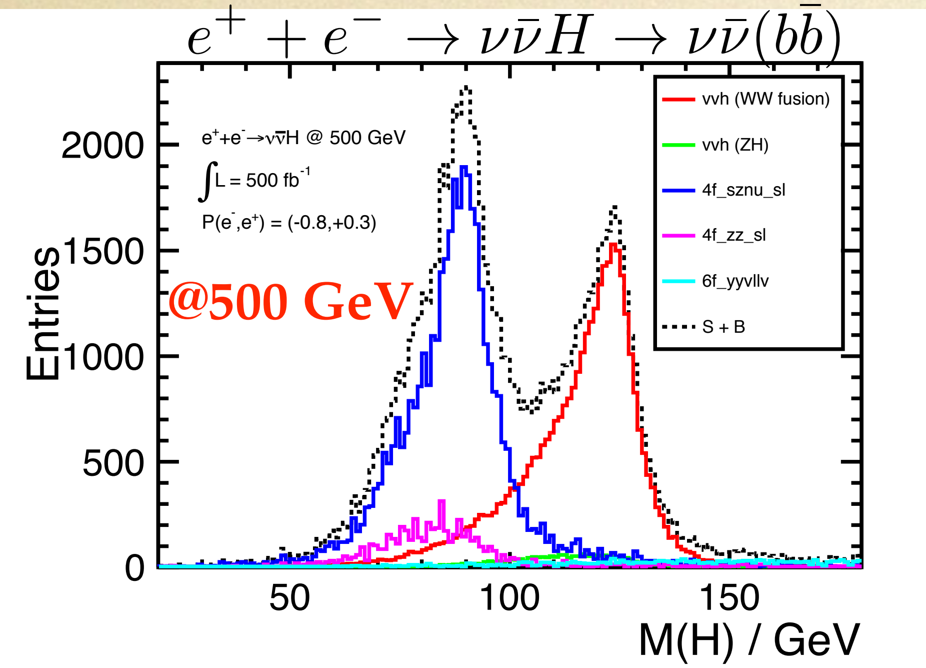
(Z—>e^+e^- combined, scaled from mH=120 GeV)

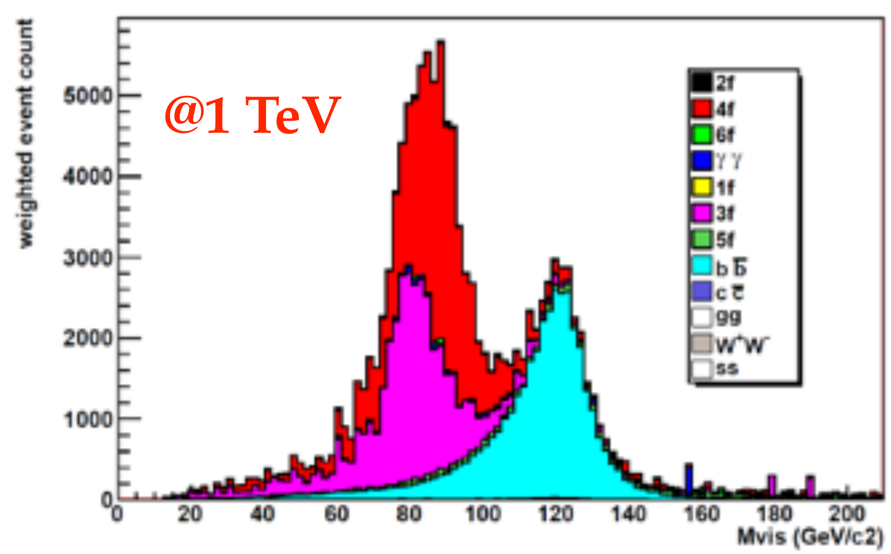
key ---> Model-independent measurement of σ_{ZH}, hence HZZ coupling

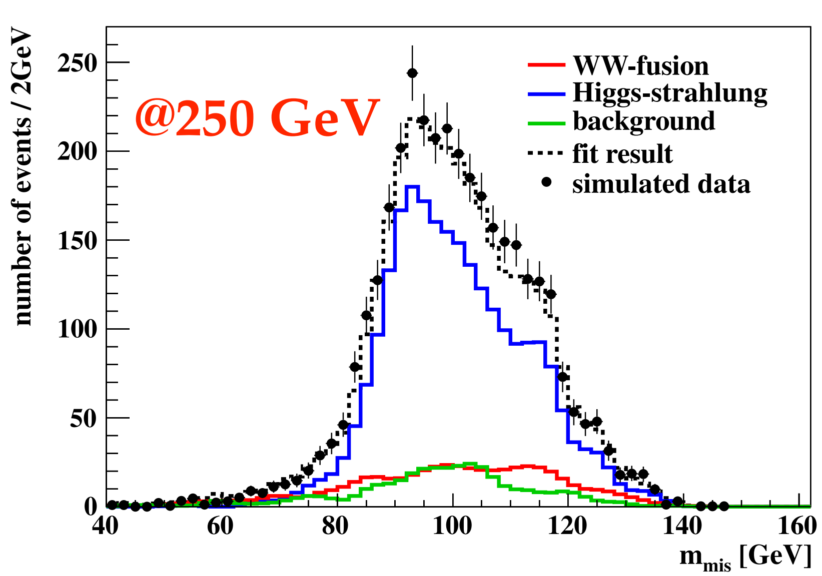
$$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$$

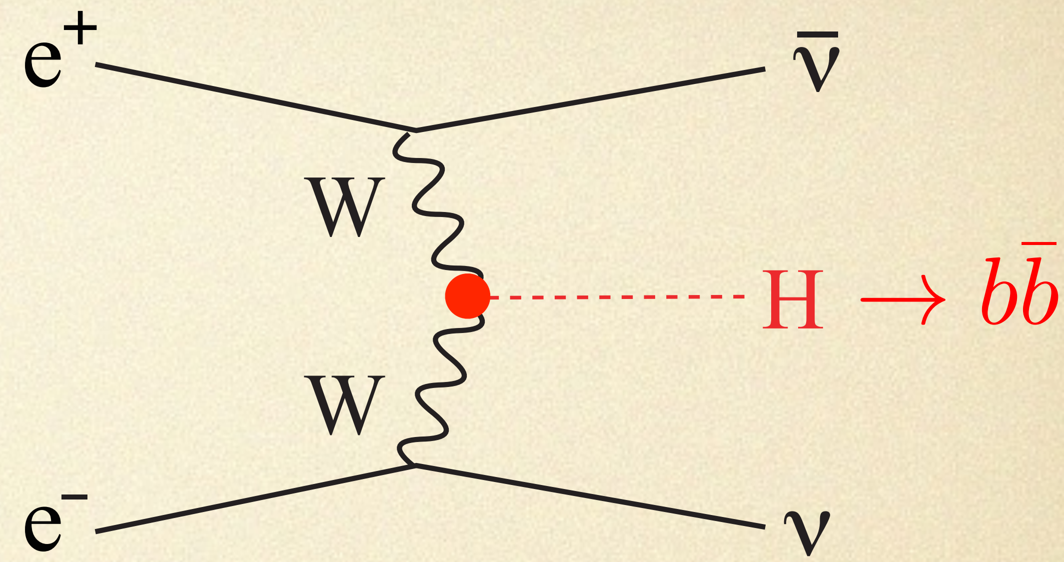
S.Watanuki @ LCWS13, H.Li, et. al, arXiv:1202.1439

HWW coupling









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

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

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

- it's essential to separate vvH from ZH at lower energy by fitting missing mass (+ angular distribution is ongoing).
- much better measured at higher energies.
- Δg_{HWW} is actually the limit to all other couplings precisions except g_{HZZ}.

C. Duerig, J. Tian, et al. LC-REP-2013-022, arXiv: 1403.7734
ILC Higgs White Paper, arXiv: 1310.0763

Higgs total width Γ_H

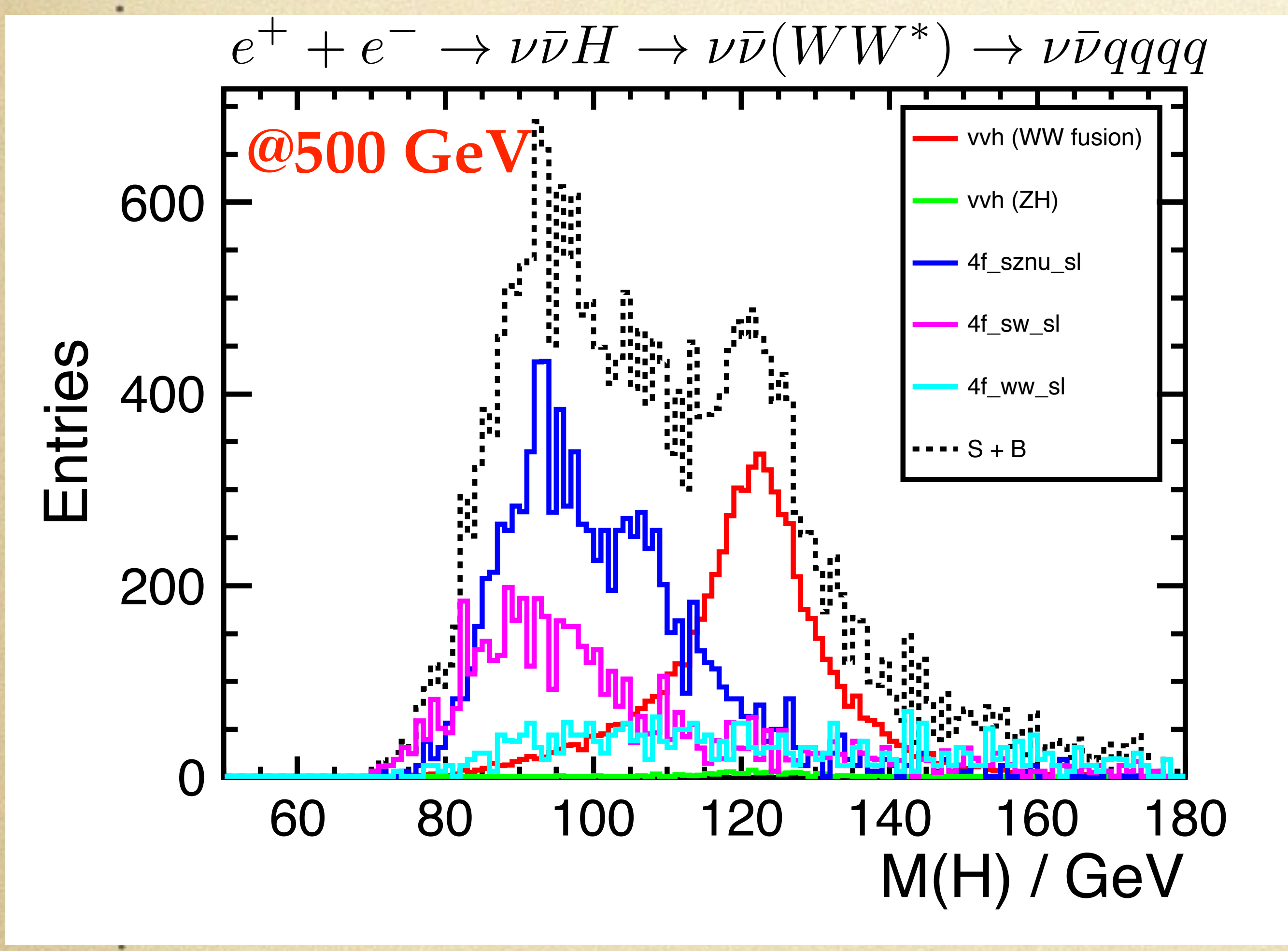
model free, one of the great advantages of ILC

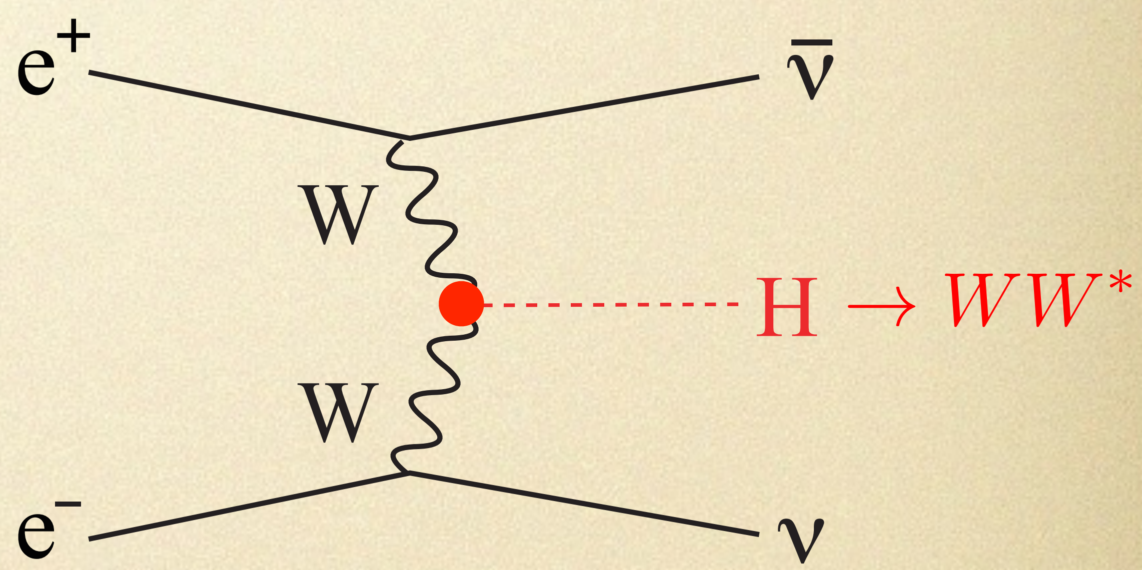
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

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!





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

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

C. Duerig, J. Tian, et al. LC-REP-2013-022, arXiv: 1403.7734

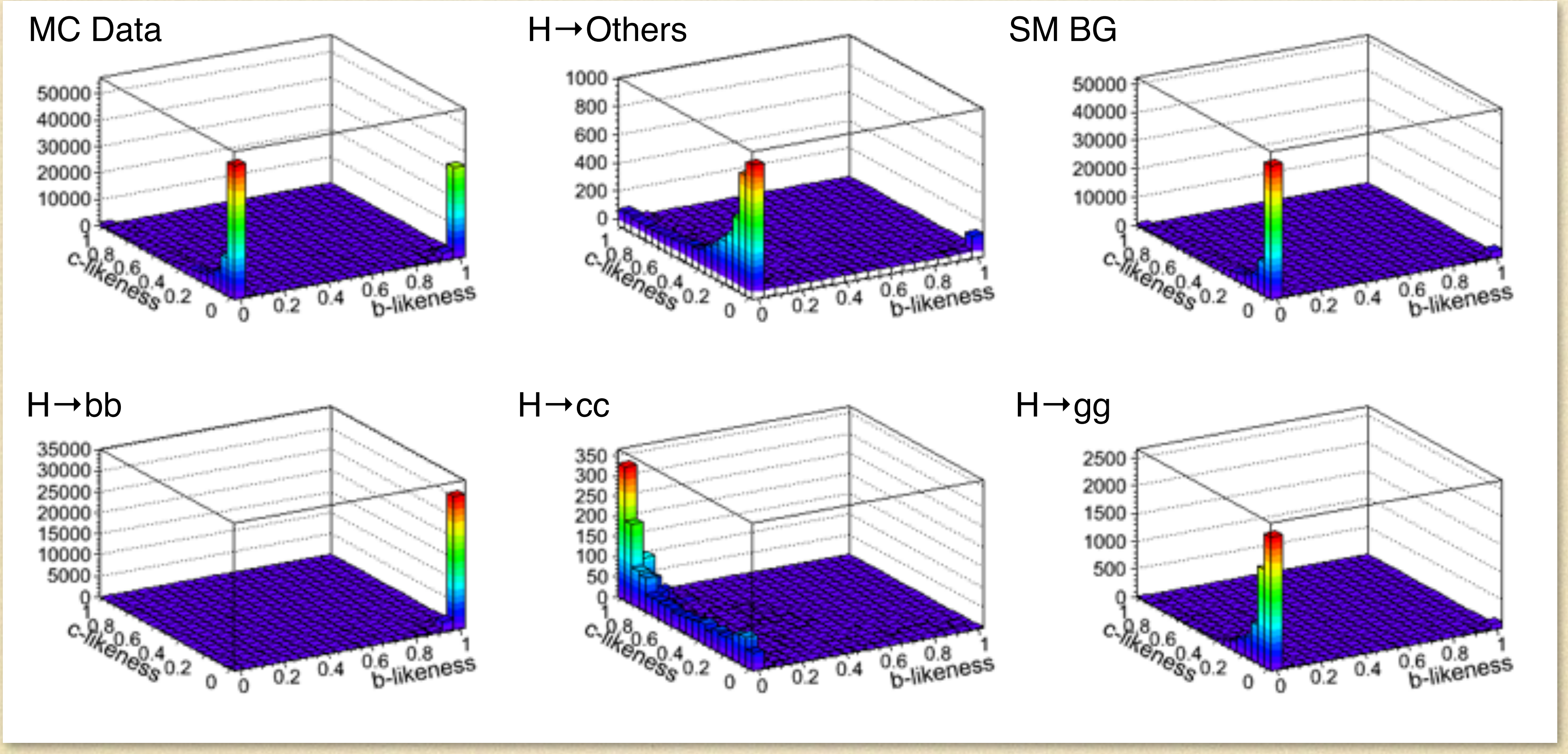
Higgs couplings to bb, cc and gg

b-vertices and c-vertices can be well reconstructed and separated @ ILC

$$e^+ + e^- \to ZH \to f\bar{f}(jj)$$

patterns of b-likeness versus c-likeness of the two jets from Higgs

flavor tagging by LCFIPlus
T.Suehara
T.Tanabe



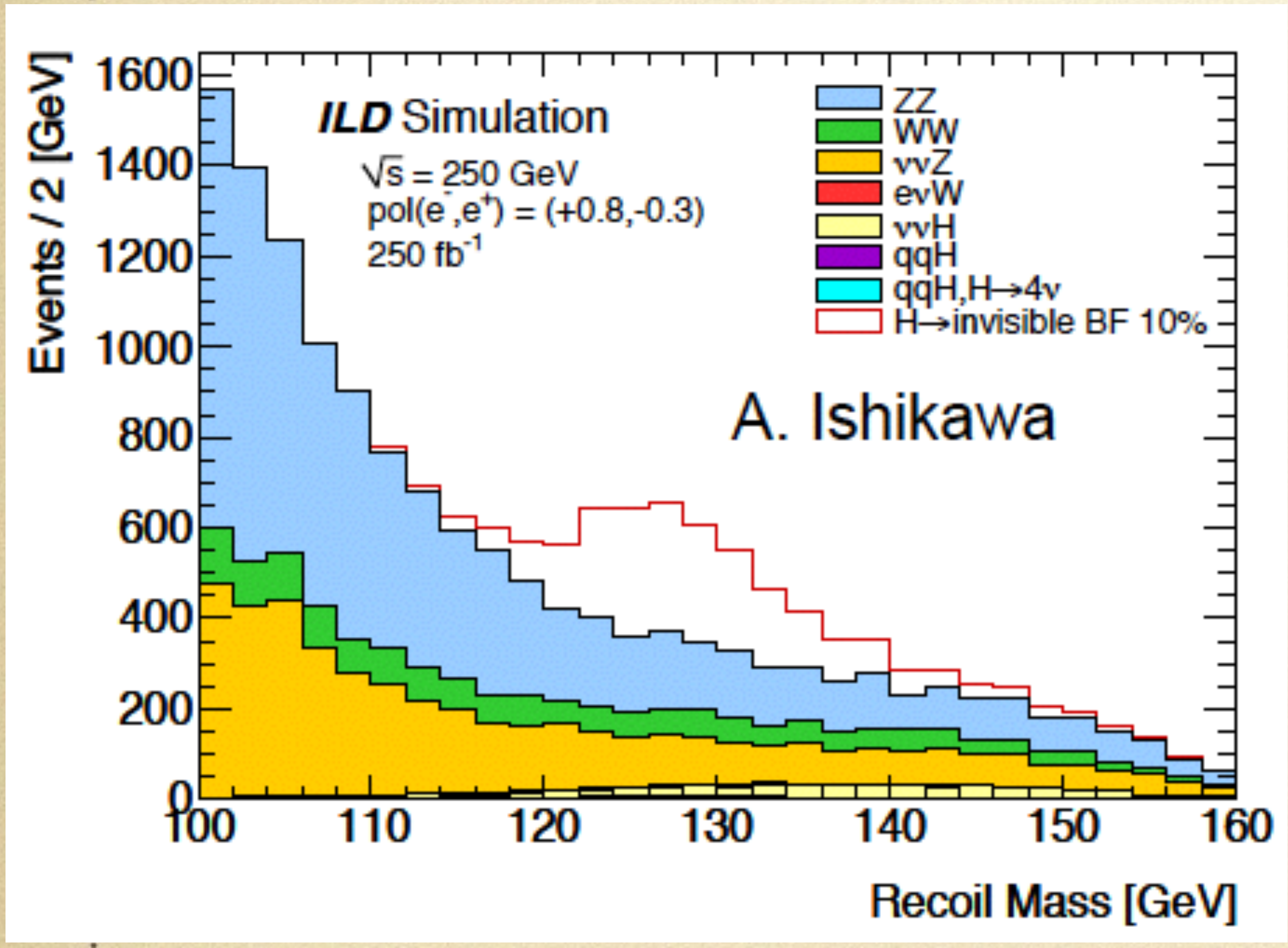
Template Fitting →

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg} / \Gamma_H$$

H. Ono, et. al, Euro. Phys. J. C73, 2343; LC-REP-2013-005

Invisible Higgs decay

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \mathrm{Missing}$$



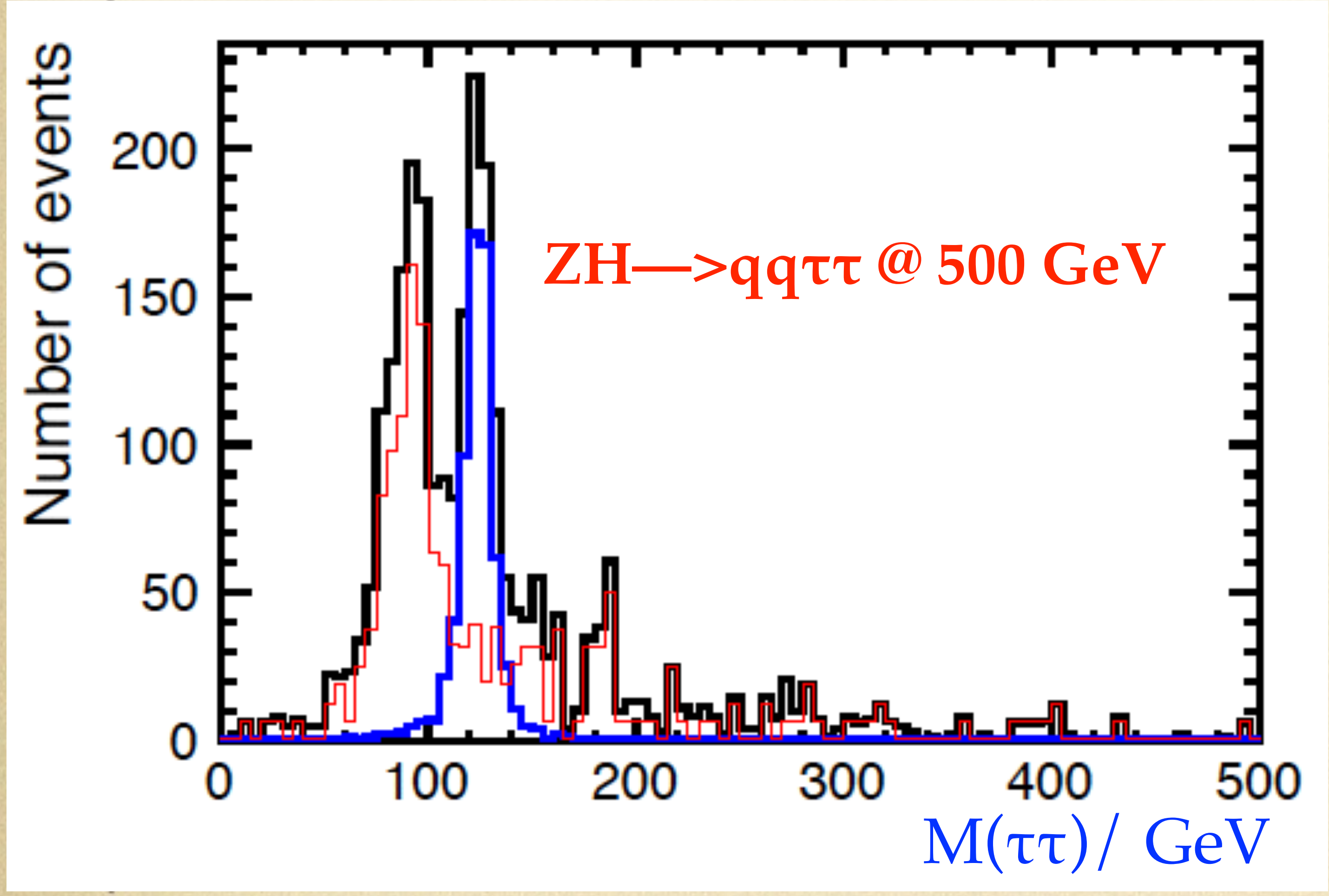
- Z—>ll or qq, initial state known
- recoil mass technique
- model independent
- Br(H—>Inv.) < 0.95% @ 95% C.L.

(ILC250 Baseline)

A. Ishikawa @ Snowmass Energy Frontier Workshop, Seattle, June 30 - July 3, 2013

Hττ coupling

$$e^+ + e^- \to ZH \to l^+l^- / q\bar{q} / \nu\bar{\nu} + \tau^+\tau^-$$

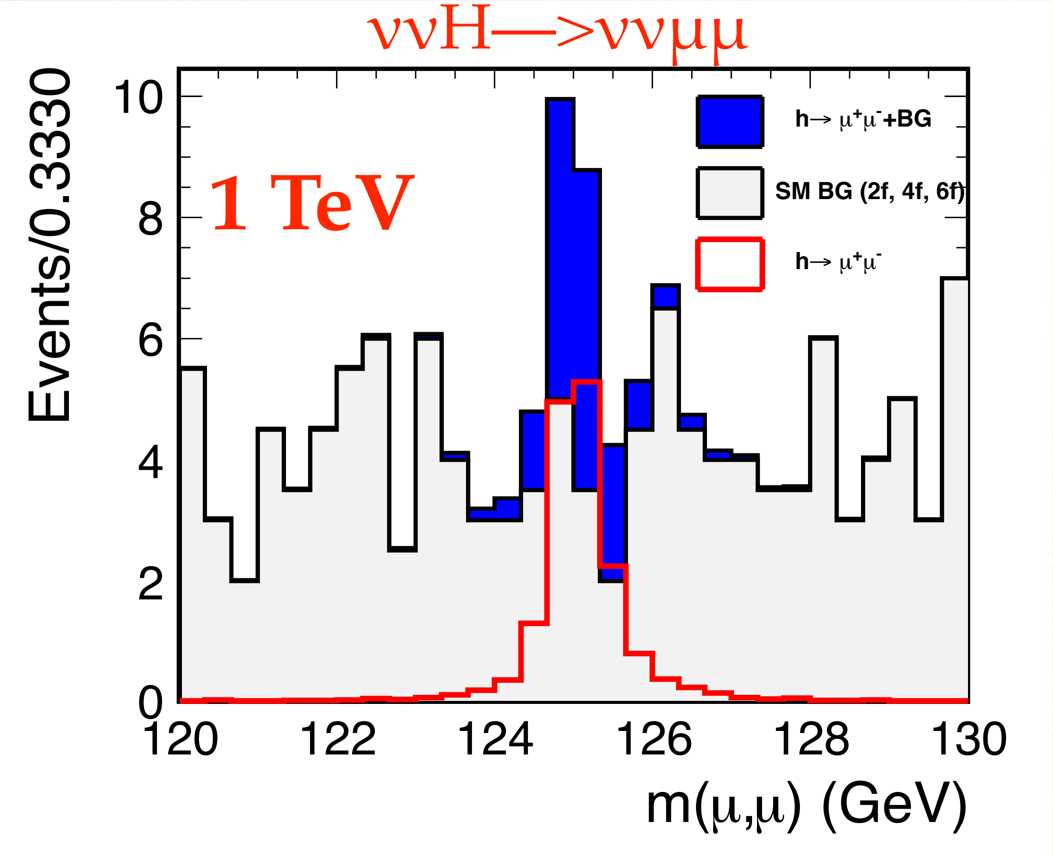


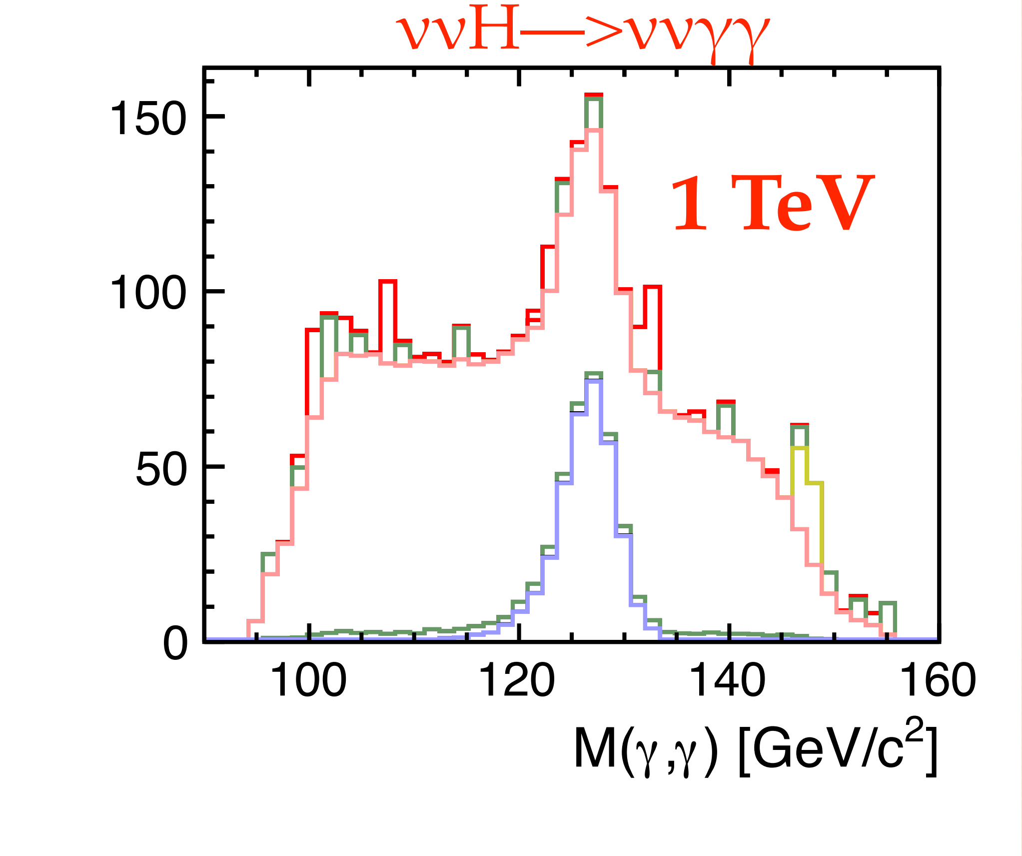
- sophisticated 1/3-prong τ finder.
- τ vertex detectable.
- neutrino momenta recoverable by using collinear approximation (or 6C fitting, ongoing) for Z—>ll, qq.

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to \tau^+\tau^-) \propto \frac{g^2_{HZZ} g^2_{H\tau\tau}}{\Gamma_H}$$

S. Kawada, et. al, LC-REP-2013-001, arXiv: 1403.7008

Higgs couplings to γγ and μμ





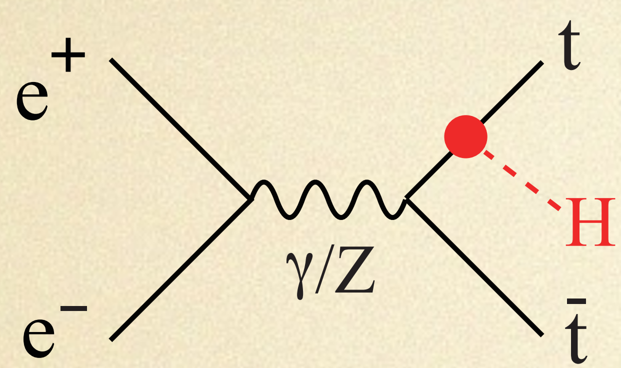
- limited by very small BRs, better at higher energies via WW-fusion production e^+e^- —> ννH.
- very characteristic signals (events with only two high energy muons or photons).
- background dominated by irreducible continuous SM process.
- limited by statistics, good synergy with LHC measurements.

$$\sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to \mu^+\mu^-) \propto \frac{g^2_{HWW} g^2_{H\mu\mu}}{\Gamma_H} \qquad \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to \gamma\gamma) \propto \frac{g^2_{HWW} g^2_{H\gamma\gamma}}{\Gamma_H}$$

C. Calancha @ LCWS13, LC-REP-2013-006

see poster by J.Strube @ ICHEP 2014

Top-Yukawa coupling

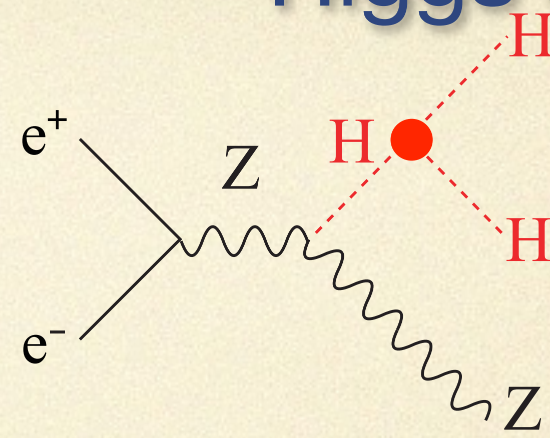


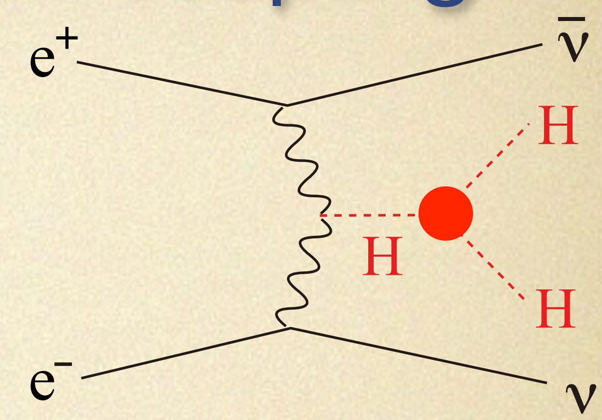
- largest Yukawa coupling.
- cross section significantly enhanced from QCD bound state effect at round threshold.
- counting experiment, $\sigma_{ttH} \propto g^2_{Htt}$ direct measurement of g_{Htt}.
- multi-jets final states, detector benchmark analyses.

$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Baseline	14%	3.2%
LumiUP	7.8%	2%

R. Yonamine, et. al, Phys.Rev. D84 (2011) 014033
T. Tanabe, T. Price, et. al, LC-REP-2013-004
P. Roloff, J. Strube, arXiv: 1307.6744

Higgs self-coupling





- force that makes vacuum condense.
- $\Delta\sigma/\sigma$ of double Higgs production measured well.
- significant irreducible diagrams effect (interference), $\Delta g/g = F \cdot \Delta\sigma/\sigma$, $F>0.5$
- new weighting method.
- challenging analysis, key is flavor tagging, jet-clustering, etc.

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Baseline	83%	21%
LumiUP	46%	13%

C.Duerig @ AWLC14 M. Kurata @ AWLC14
J. Tian, LC-REP-2013-003

Summary of observables @ ILC

Baseline

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 & SiD: 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%		11%	4.1%	2.3%
H-->WW*	6.4%		9.2%	2.4%	1.6%
H-->ττ	4.2%		5.4%	9%	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%
H-->Inv. (95% C.L.)	< 0.95%		-		

being updated by new studies with mH = 125 GeV

From observables to couplings — Global Fit

K.Fujii @ Pheno2014, Pittsburg

ILC Higgs White Paper
arXiv: 1310.0763

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

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t) \qquad (B_i = b, c, \tau, \mu, g, \gamma, Z, W \ : \text{decay})$$

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

$$F_i = S_i G_i$$

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

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

- It is the recoil mass measurement that 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.

Systematic Errors

	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

☆ theoretical calculations of Higgs particle widths are now at O(1%), and are expected to achieve per-mille level in next decade! (M.Peskin, et. al, arXiv:1404.0319)

Precisions of absolute Higgs couplings @ ILC

model independent global fit

coupling $\Delta g/g$	Baseline			LumiUP		
	250 GeV	+ 500 GeV	+ 1 TeV	250 GeV	+ 500 GeV	+ 1 TeV
HZZ	1.3%	1%	1%	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%
Hgg	6.4%	2.3%	1.6%	3%	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%	8.2%	4.5%	2.4%
$H\mu\mu$	-	-	16%	-	-	10%
Htt	-	14%	3.1%	-	7.8%	1.9%
Γ	11%	5%	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%

ILC Higgs White Paper, arXiv: 1310.0763

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Hγγ	18%	8.4%	4%	8.2%	4.5%	2.4%
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$H\tau\tau$	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
$H\gamma\gamma$	18%	8.4%	4%	8.2%	4.5%	2.4%
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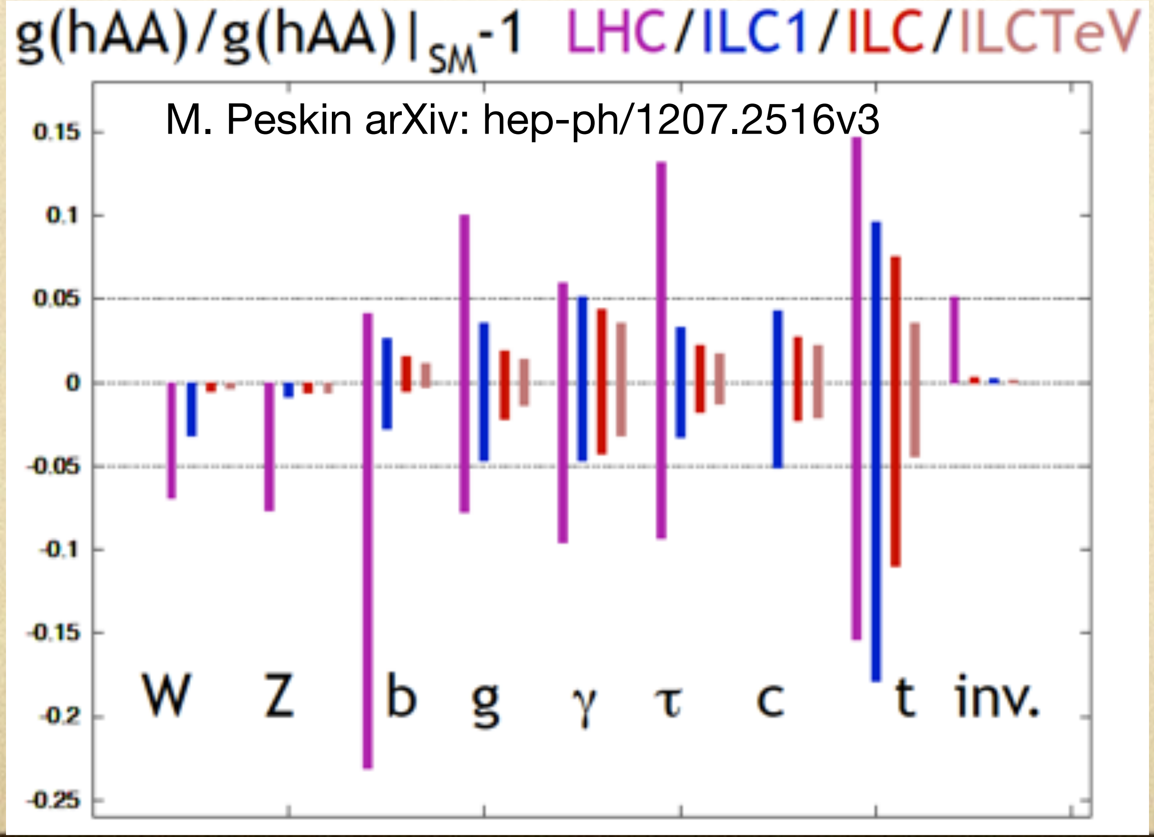
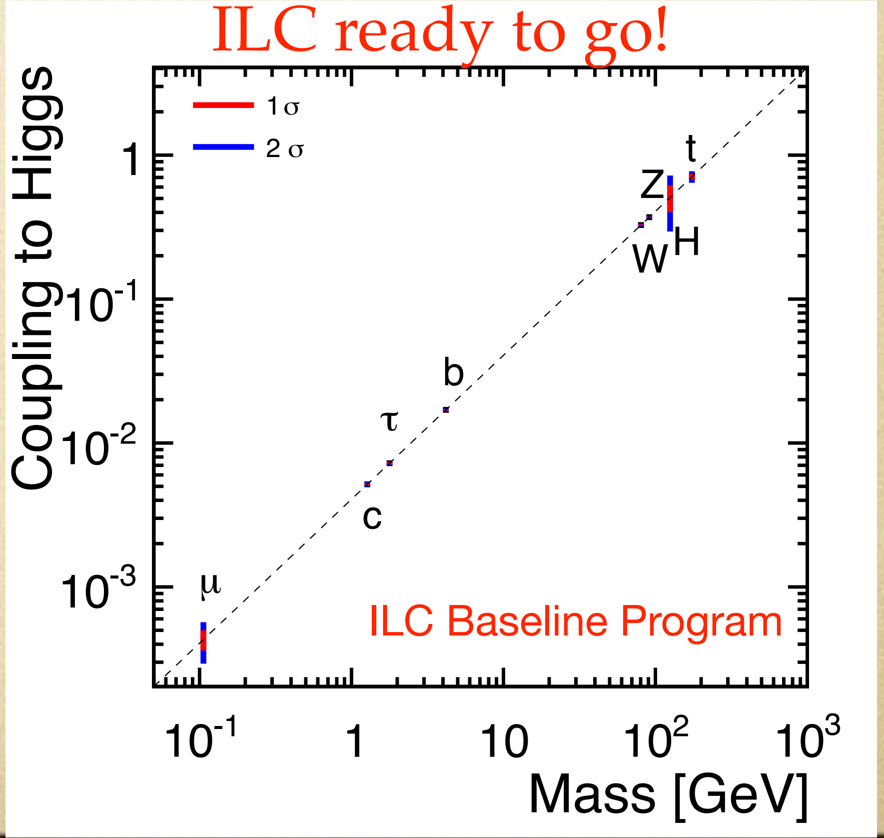
ILC Higgs White Paper, arXiv: 1310.0763

Summary

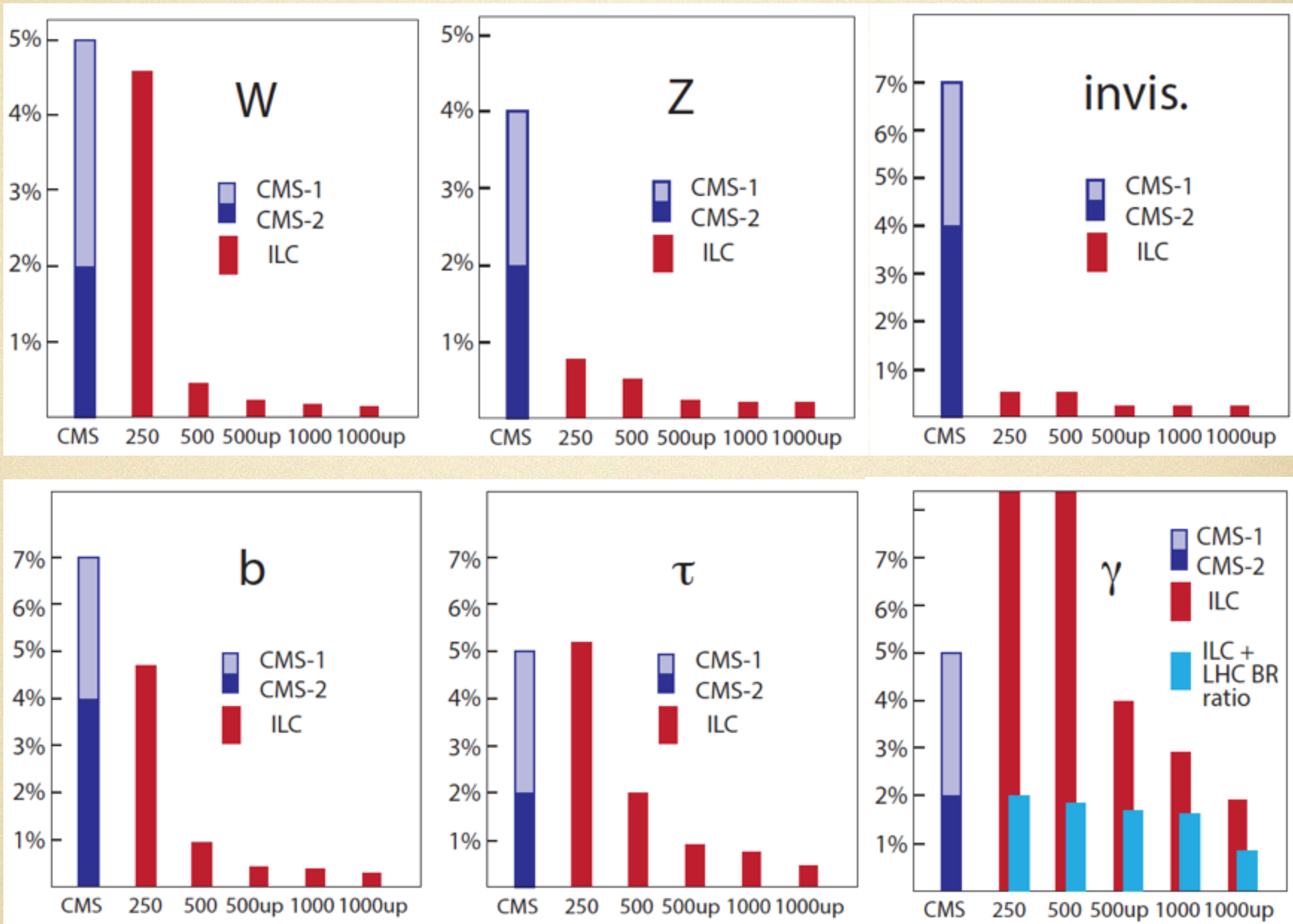
- ILC is the ideal machine to measure all Higgs boson couplings precisely and model independently, eventually to reveal the nature of EWSB and mass generation; performance of detectors ILD & SiD can meet the physics goal.
- Recoil mass measurement @ 250 GeV gives the absolute HZZ coupling, be able to model independently normalize all the Higgs couplings and total width; HWW coupling determination is crucial for precisions of all other couplings, and is essential to be improved significantly at higher ECM.
- It is essential to go to 500 GeV to directly measure top-Yukawa coupling and Higgs self-coupling which can be further improved at 1 TeV.
- Complementary to LHC, ability of energy scan and beam polarization can make ILC run at optimal energy and study in detail what LHC would discover.





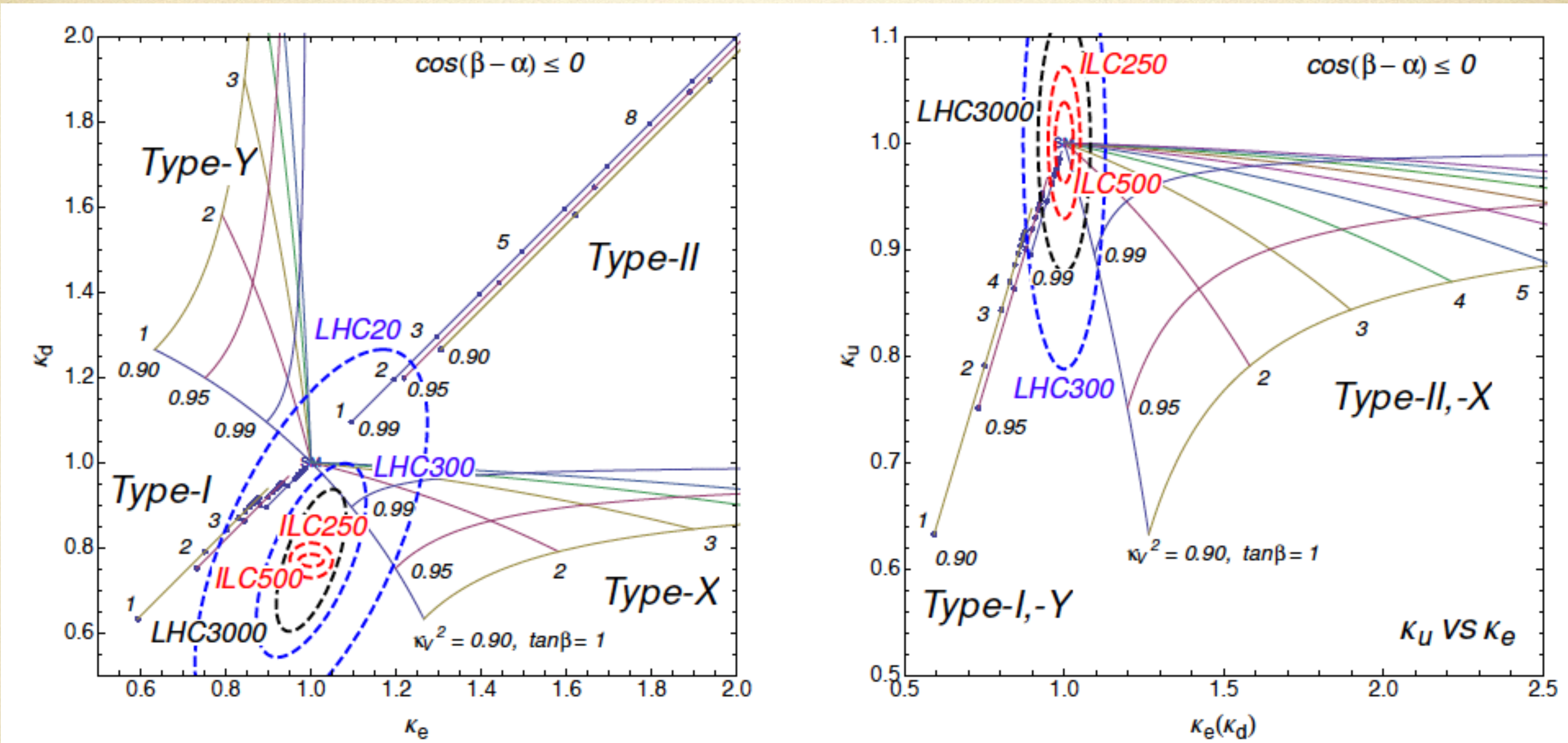
backup

LHC and ILC comparison / synergy



M.Peskin, arXiv:1312.4974

Fingerprinting non-minimal Higgs sector

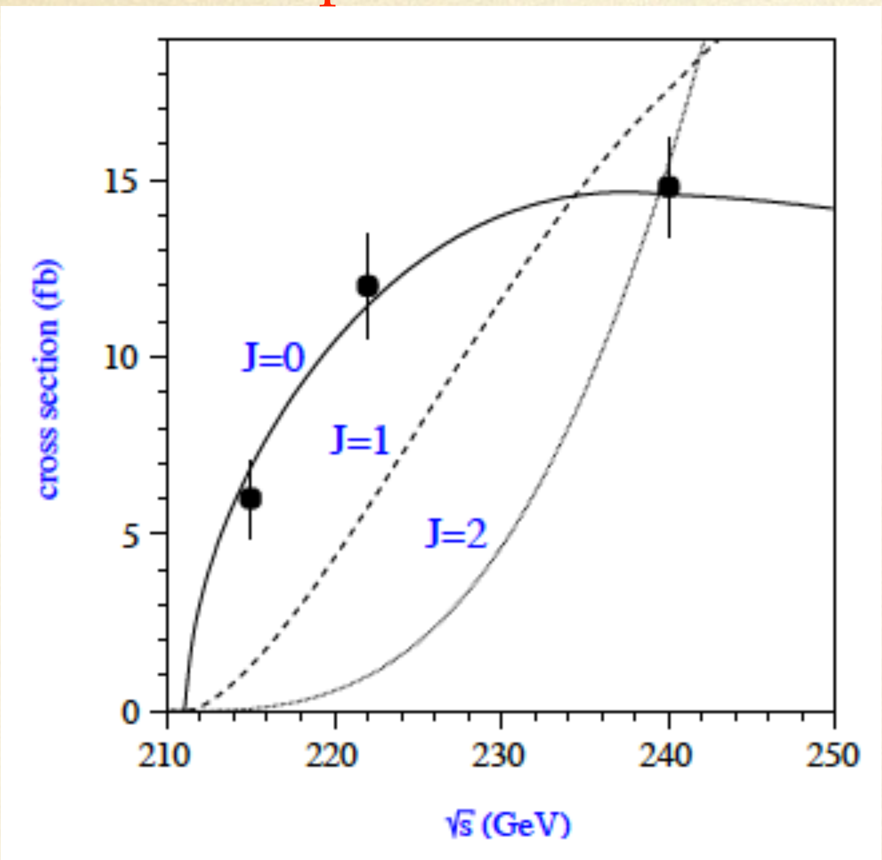


S.Kanemura, K.Yagyu, et al., arXiv: 1406.3294

Higgs Quantum Numbers J^{CP}

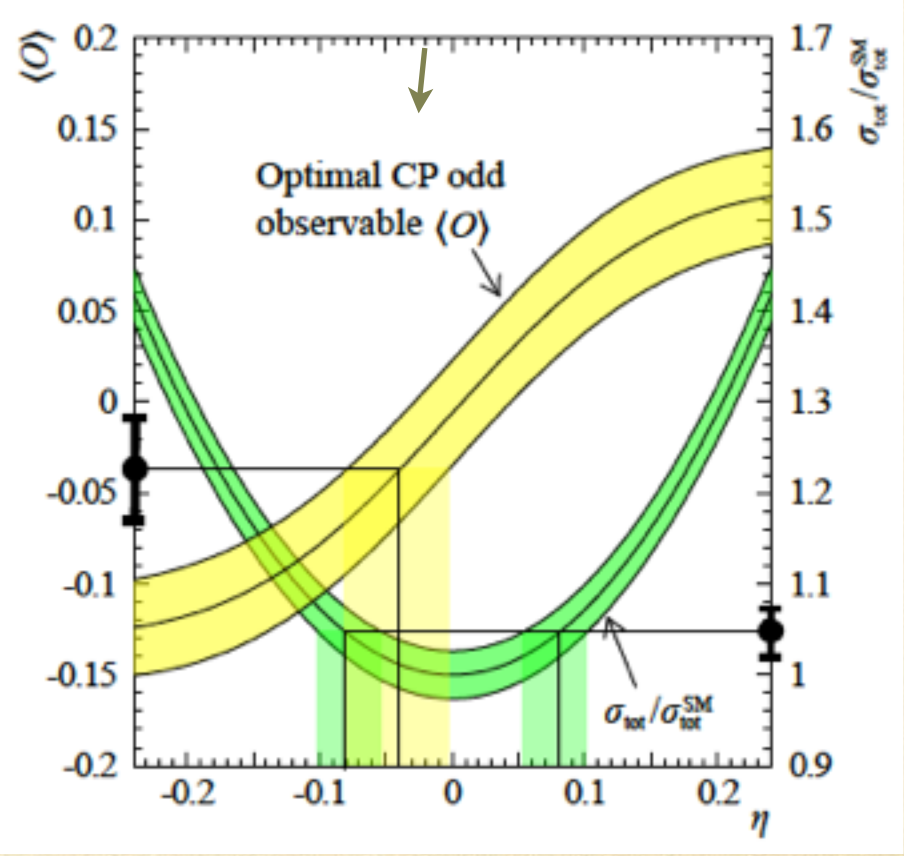
in addition to the spin study by H-->ZZ* and WW*, ILC offers an orthogonal way and be able to measure the mixture of CP

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



W.Lohmann, et al., arXiv: hep-ph/0302113

if a mixture of CP even and CP odd



--> few % of mixing angle

M. Schumacher, LC Note LC-PHSM-2001-003

a more complete CP search program

$$A(X_{J=0} \to VV) = v^{-1}\left(a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$A(X_{J=0} \to f\bar{f}) = \frac{m_f}{v}\bar{u}_2\,(b_1 + i b_2 \gamma_5)\,u_1$$

- via production channels e^+e^- —> ZH and e^+e^-H (ZZ-fusion): probe anomalous HZZ coupling.
- via decay H—>WW*: probe anomalous HWW coupling.
- via decay H—>$\tau^+\tau^-$: probe CP mixture for down-type coupling
- via production e^+e^- —> ttH: probe CP mixture up-type coupling.

(Snowmass Higgs Working Group Report, arXiv: 1310.8361)

limiting factors of coupling precisions

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

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g_{HWW}^2 g_{Hbb}^2}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g_{HZZ}^2 g_{Hbb}^2}{\Gamma_H}$$

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

$$\Delta g_{HZZ} \sim \frac{1}{2}\Delta Y_1$$

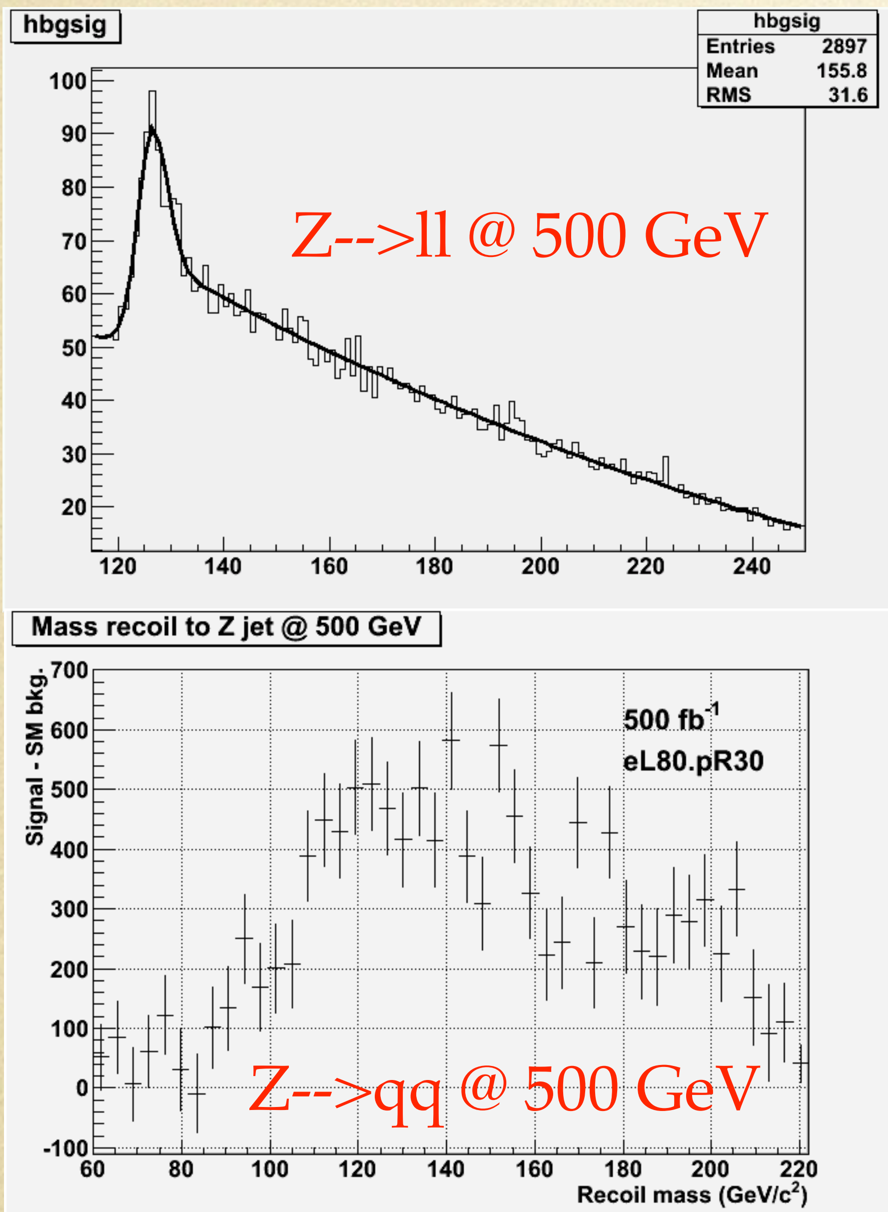
$$\Delta g_{HWW} \sim \frac{1}{2}\Delta Y_1 \oplus \frac{1}{2}\Delta Y_2 \oplus \frac{1}{2}\Delta Y_3$$

$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

$$\Delta \Gamma_H \sim 2\Delta Y_1 \oplus 2\Delta Y_2 \oplus 2\Delta Y_3 \oplus \Delta Y_4$$

both ZH and ννH productions matter!

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



S. Watanuki, T. Suehara,
A. Miyamoto, arXiv: 1311.2248

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 boosted at higher energy, better separation between Z and H decay products

$\Delta g_{HZZ}/g_{HZZ}$	250 GeV	+ 500 GeV
Baseline	1.3%	1%
LumiUP	0.61%	0.51%

recoil against Z-->qq at 250 GeV

study ongoing, preliminary

Cut efficiency (ex. 4-jet, 0-lepton) Cont.

mode	before	after	difference from mean	$\epsilon_n^i \times \frac{\Delta\epsilon_n^i}{\epsilon^i}$	$BR_n \times \epsilon_n^i \times \frac{\Delta\epsilon_n^i}{\epsilon^i}$
H->all (100%)	216,195 (41.2%)	53.0%	----	----	----
H->$b\bar{b}$ (55.6%)	128,085 (44.0%)	51.1%	-1.9%	-1.6%	-0.9%
H->WW (l) (2.4%)	1,331 (10.7%)	58.2%	+5.2%	+1.0%	0.0%
H->WW (sl) (10.0%)	13,588 (25.8%)	61.0%	+8.0%	+3.9%	+0.4%
H->WW (h) (10.5%)	16,471 (29.9%)	41.3%	-11.7%	-6.6%	-0.7%
H->gg (9.0%)	24,154 (51.0%)	52.8%	-0.2%	-0.2%	0.0%
H->$\tau\tau$ (6.7%)	18,354 (52.3%)	69.6%	+16.6%	+16.4%	+1.1%
H->ZZ (3.0%)	5,696 (36.4%)	54.0%	+1.0%	+0.7%	0.0%
H->$c\bar{c}$ (2.6%)	7,503 (54.2%)	54.0%	+1.0%	+1.0%	0.0%
H->$\gamma\gamma$ (0.4%)	1,135 (56.9%)	54.8%	+1.8%	+1.9%	0.0%

cut efficiencies are almost the same except for tau and W.

Americas Workshop on Linear Colliders 14/05/2014 : Tatsuhiko Tomita 14

T.Tomita @ AWLC14

model dependent fit (7 parameters @ LHC)

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

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

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

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

theory error (loop, parameter)

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

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

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)

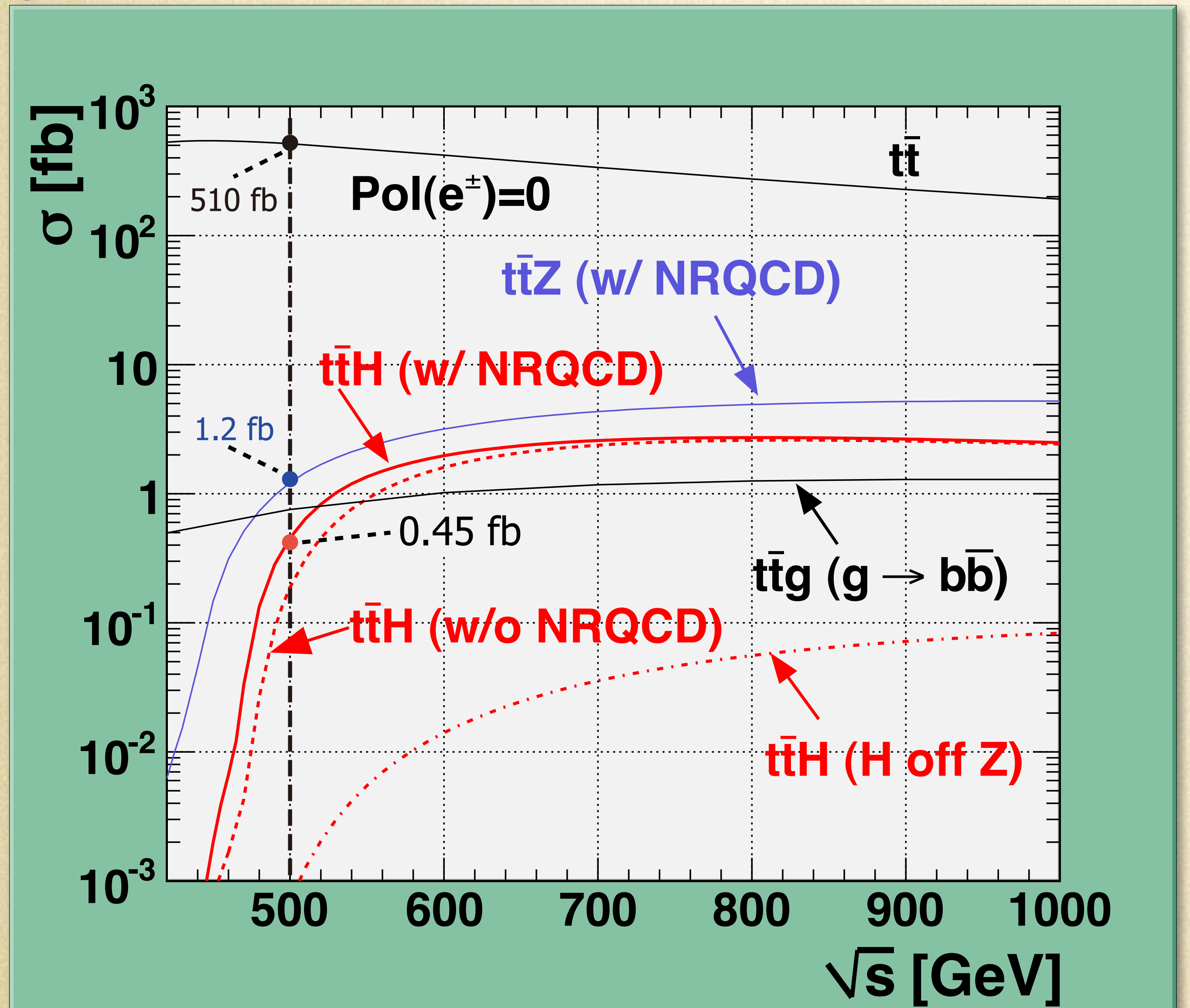
global fit --model dependent + sys + theory error (0.1%)

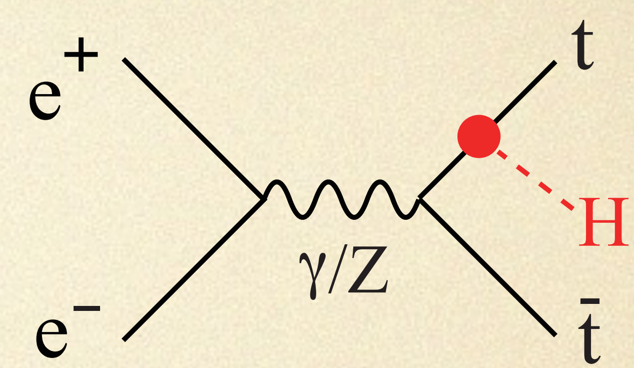
coupling $\Delta g/g$	baseline			luminosity upgrade		
	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.74%	0.49%	0.45%	0.36%	0.27%	0.25%
HWW	4.7%	0.43%	0.27%	2.2%	0.27%	0.2%
Hbb	4.7%	0.97%	0.57%	2.2%	0.55%	0.36%
Hcc	6.4%	2.5%	1.3%	3%	1.3%	0.78%
Hgg	6.1%	2%	1.1%	2.8%	1.1%	0.69%
$H\tau\tau$	5.2%	1.9%	1.3%	2.4%	1%	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%	0.89%
Htt	6.4%	2.5%	1.3%	3%	1.4%	0.87%
Γ	9%	1.7%	1.1%	4.2%	1%	0.8%
Br(Inv)	<0.95%	<0.95%	<0.95%	0.44%	0.44%	0.44%
HHH	-	83%	21%	-	46%	13%

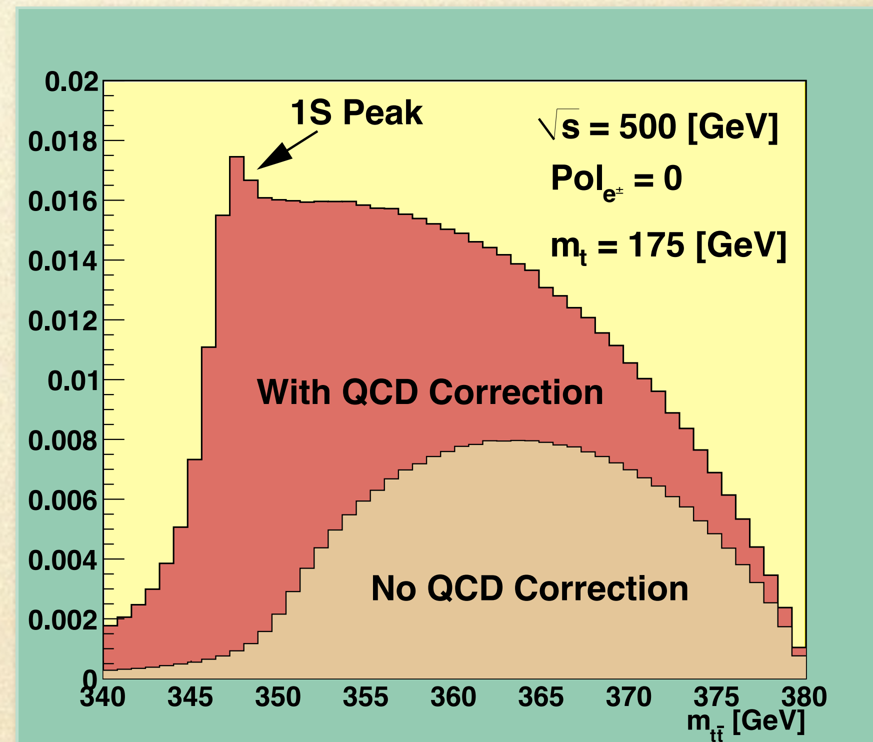
Top-Yukawa Coupling and Higgs

The largest among matter fermions

direct measurement!







A factor of 2 enhancement from QCD bound-state effects

8-jets mode and lv+6jets mode combined

$\Delta g_{ttH}/g_{ttH}$	500 GeV	500 GeV + 1 TeV
Baseline	14%	3.2%
LumiUP	7.8%	2%

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

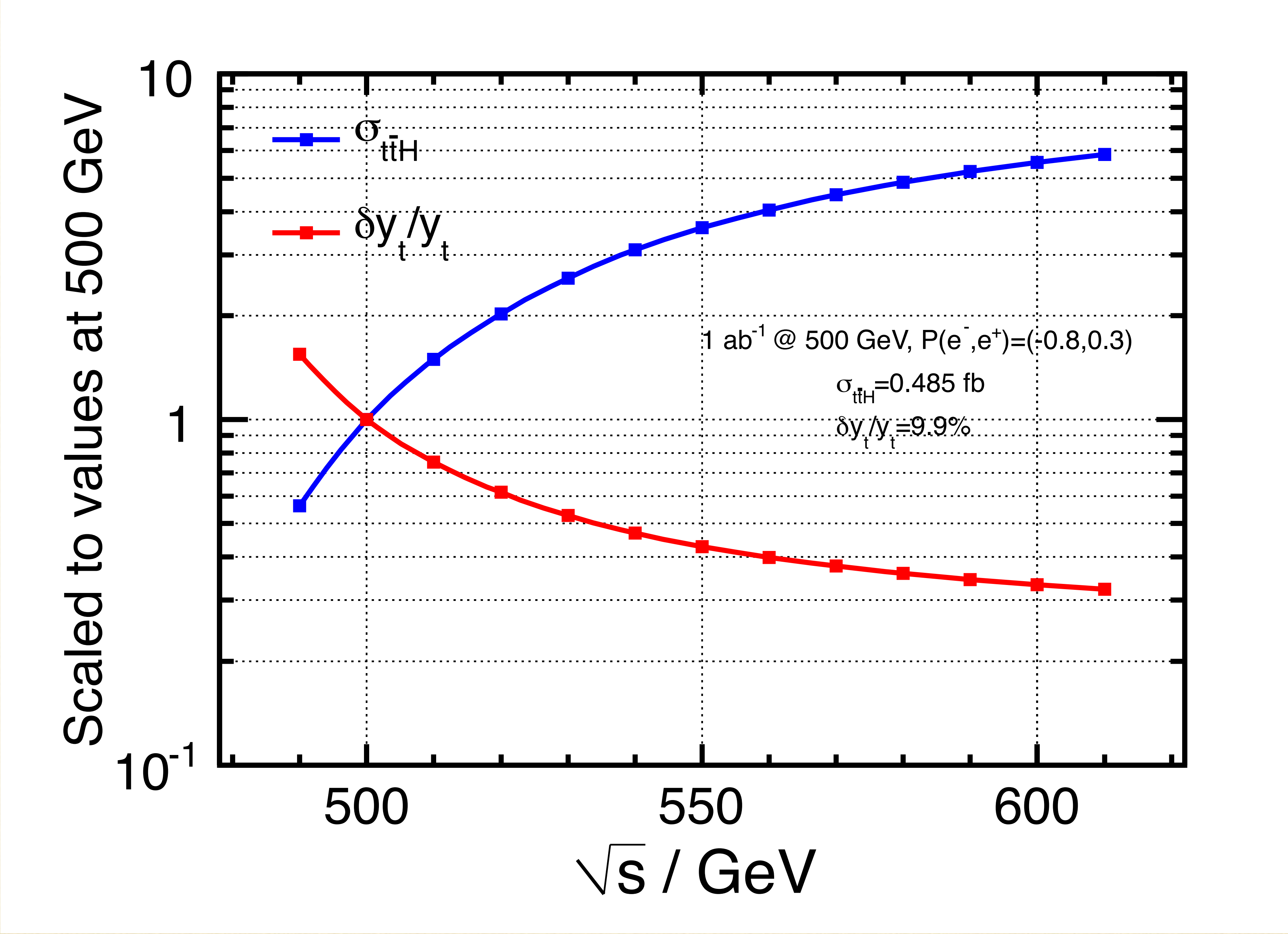
Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

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

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

see more details in poster by J.Strube

top-Yukawa coupling

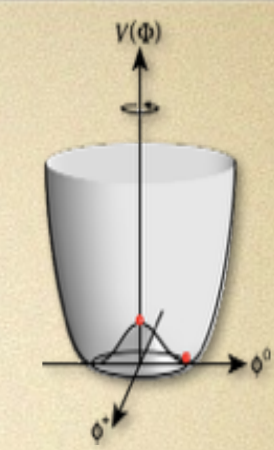


Y. Sudo

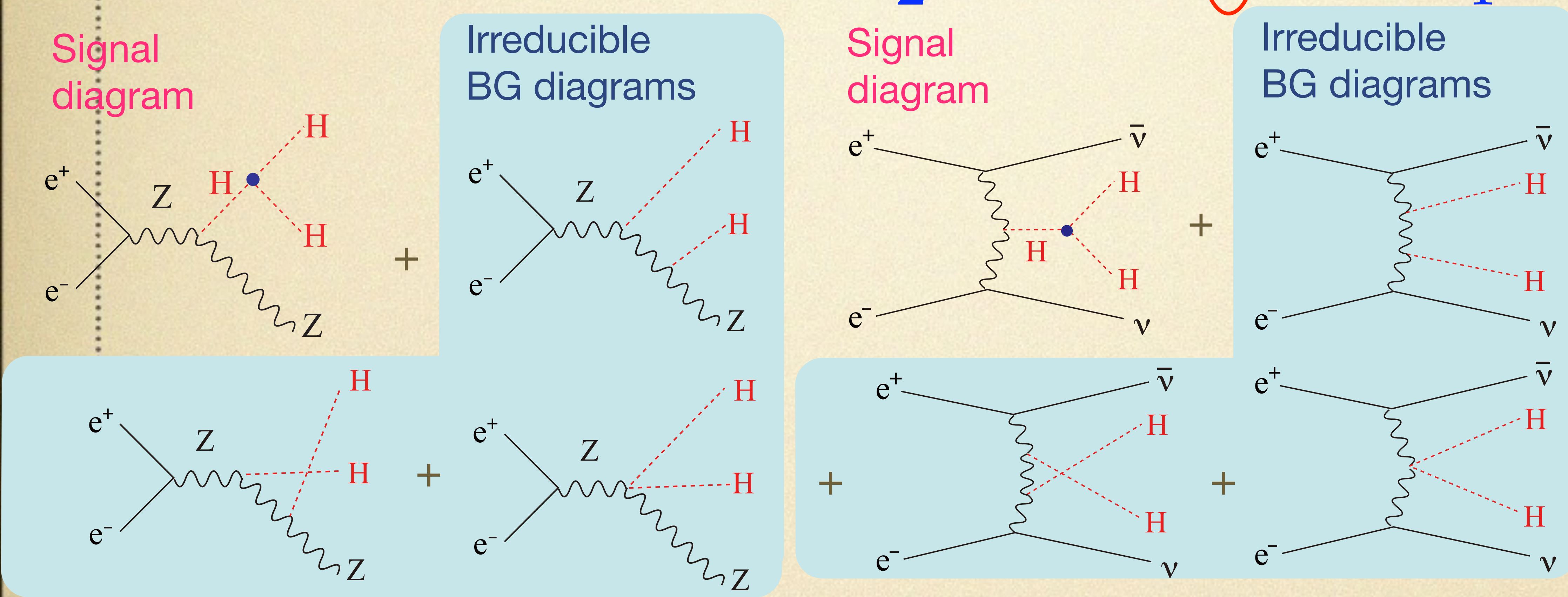
ILC 500 GeV & 1 TeV

Higgs Self-coupling

The force that makes Higgs boson condense in the vacuum



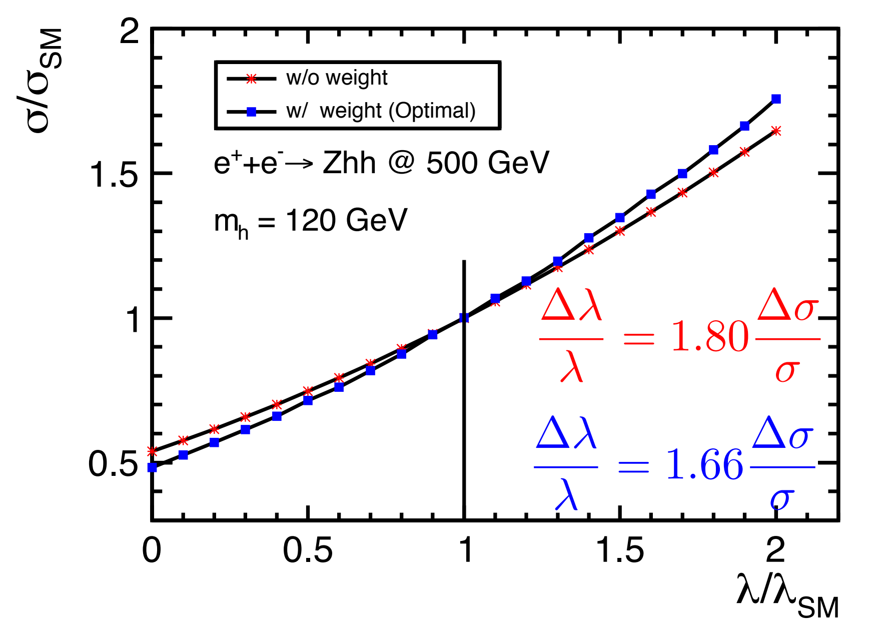
Higgs Potential: $V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$

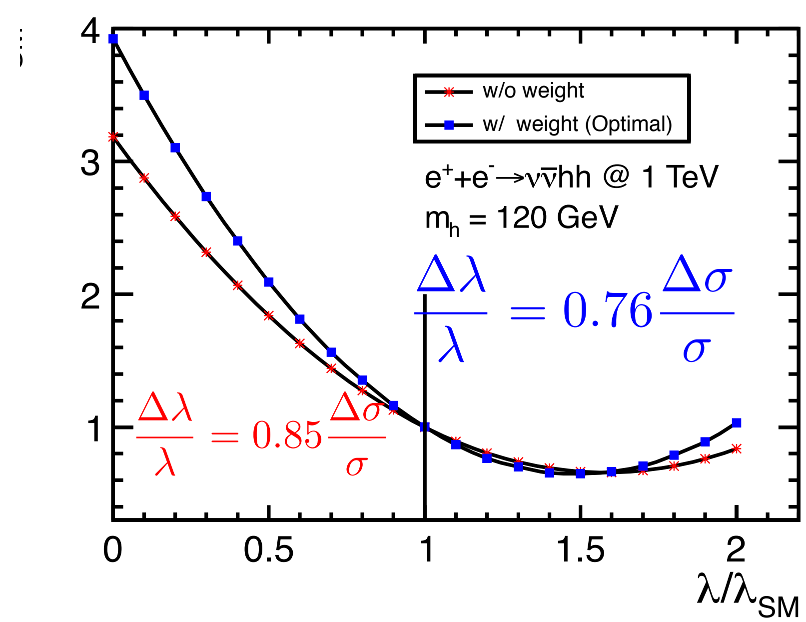


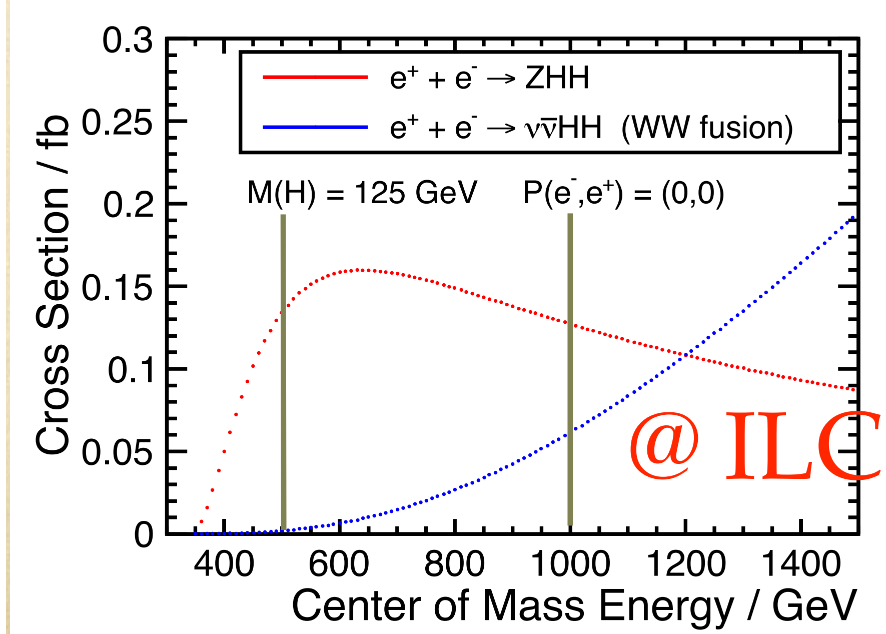
$\sigma = \lambda^2 S + \lambda I + B$

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

F=0.5 if no BG diagrams







Higgs Self-coupling Projections @ ILC

see more details in poster by J.Strube

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

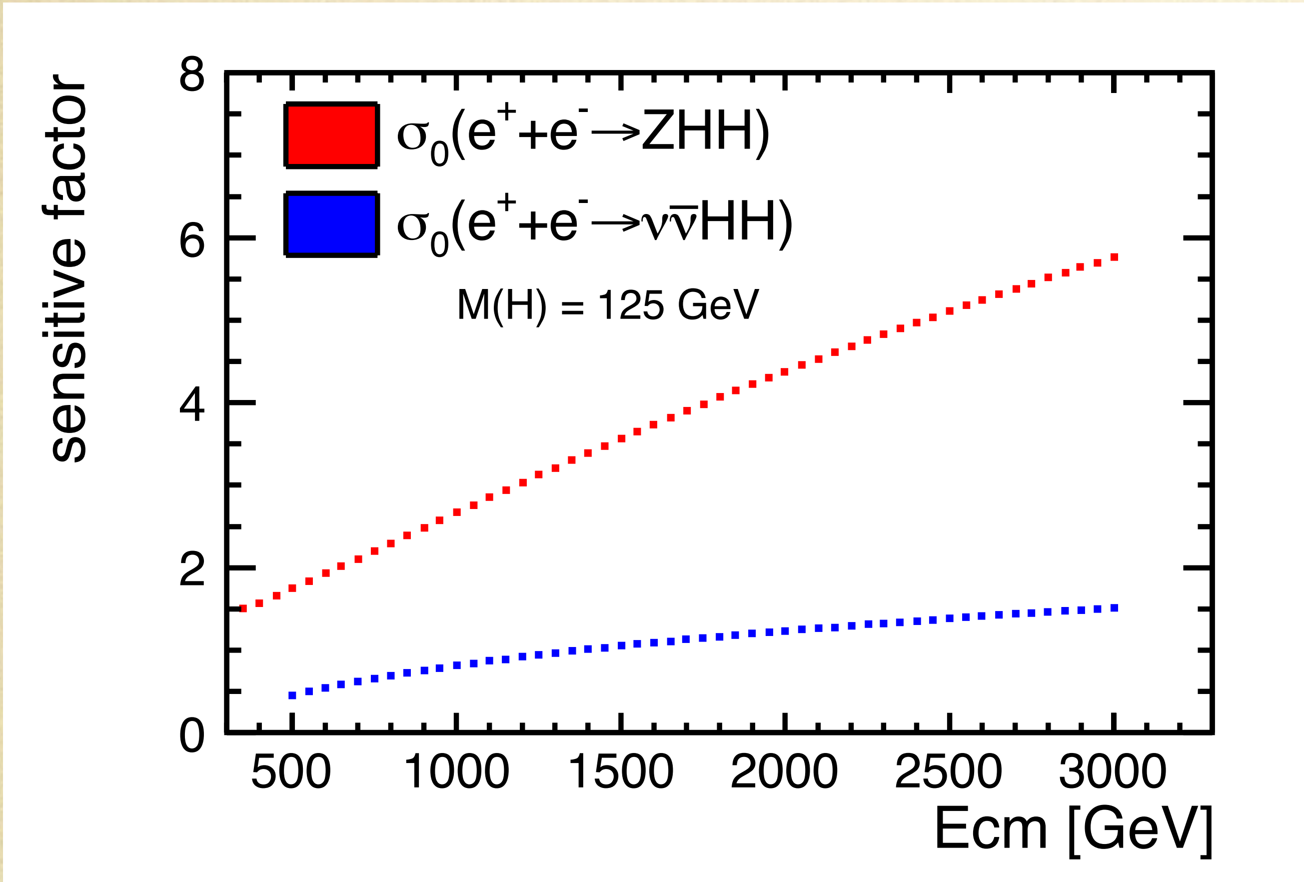
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV			500 GeV + 1 TeV		
Scenario	A	B	C	A	B	C
Baseline	104%	83%	66%	26%	21%	17%
LumiUP	58%	46%	37%	16%	13%	10%

Scenario A (done): HH-->bbbb, full simulation done
Scenario B (done): adding HH-->bbWW*, full simulation done, ~20% relative improvement
Scenario C (ongoing): color-singlet clustering, matrix element method, kinematic fitting, flavor tagging, expected ~20% relative improvement (conservative)

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

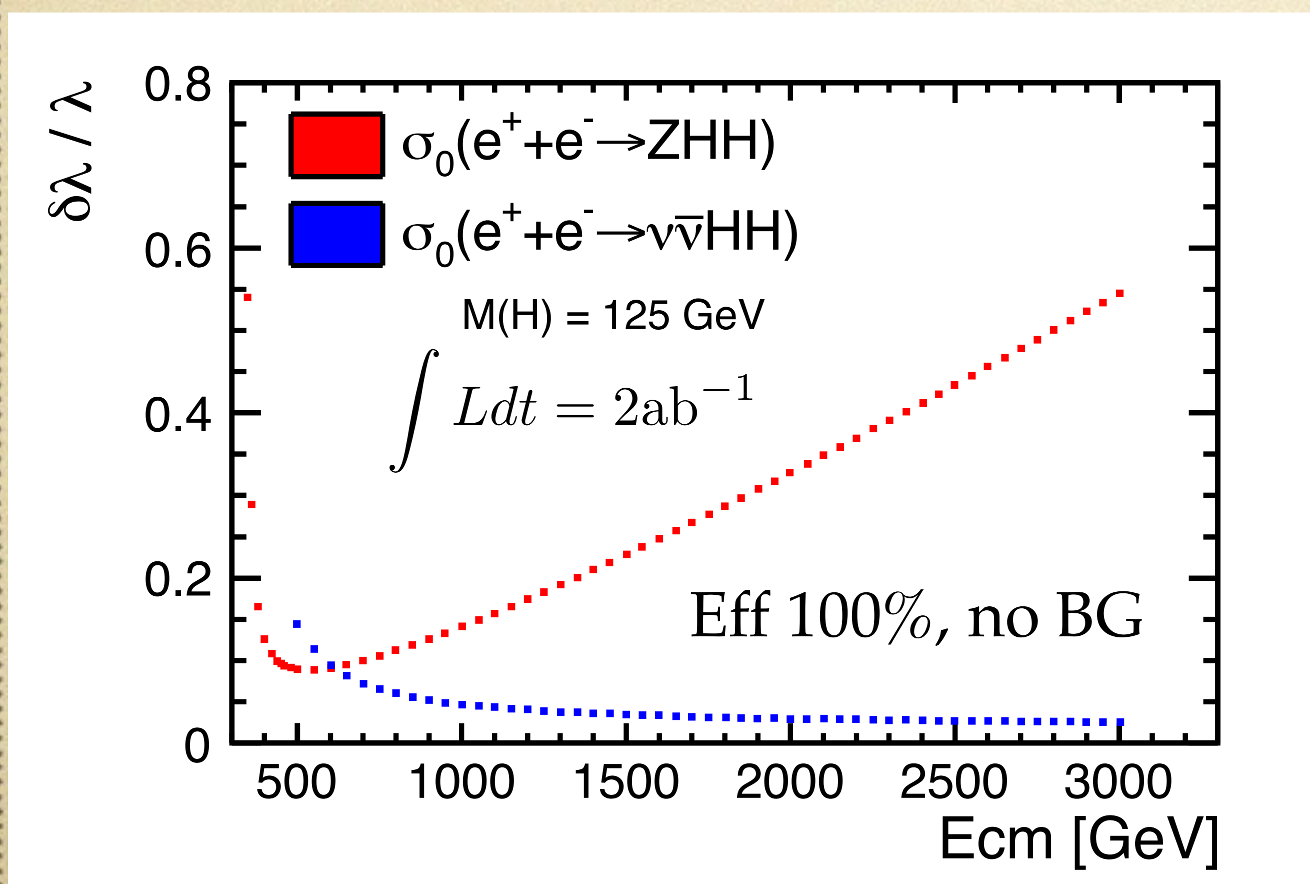
J. Tian, LC-REP-2013-003 M. Kurata @ ECFA2013 C.Duerig @ AWLC14

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



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

Factor increases quickly as going to higher energy

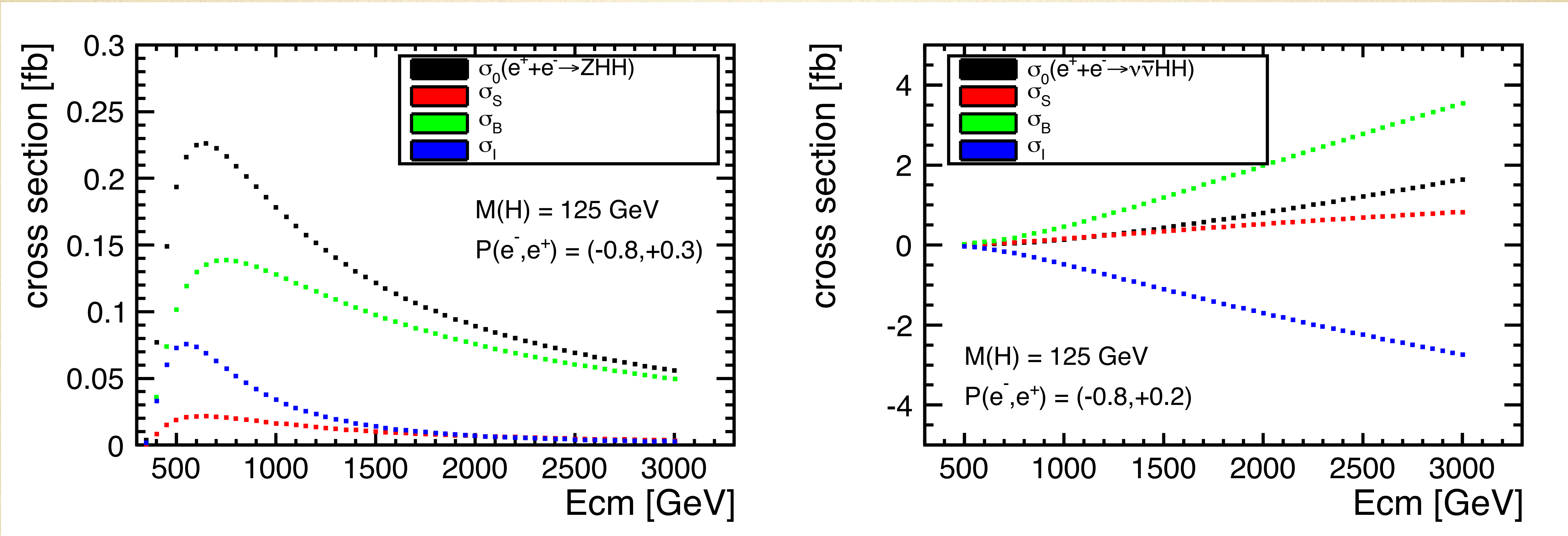


for ZHH, the expected optimal energy ~ 500 GeV (though cross section is maximum ~ 600 GeV)

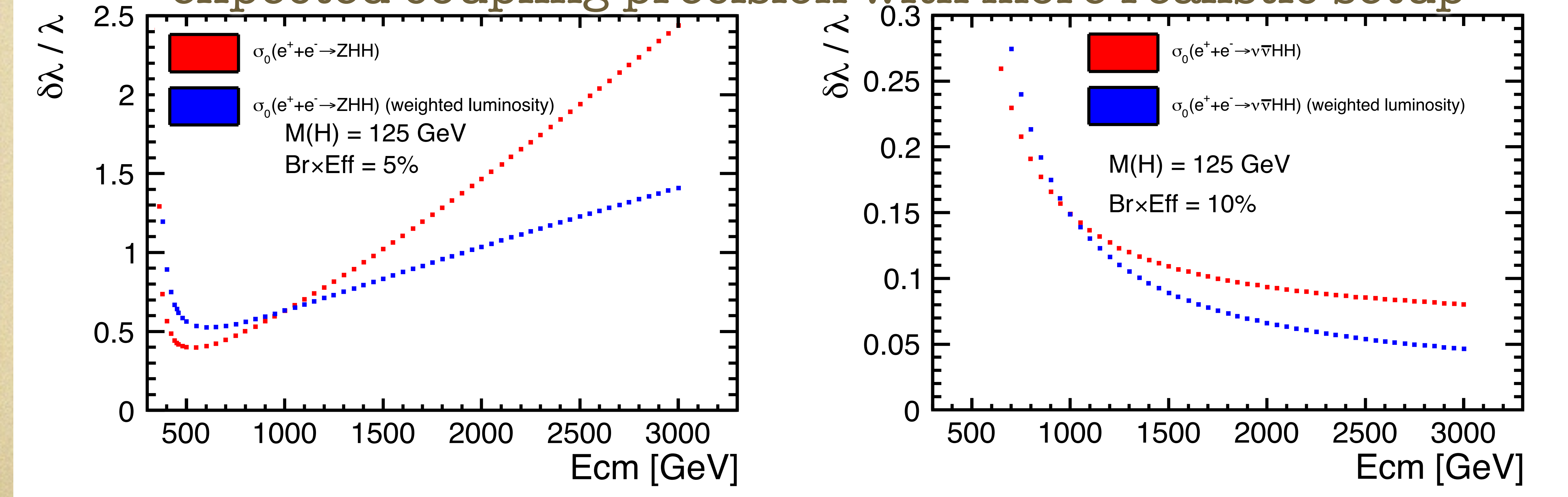
for ννHH, expected precision improves slowly as going to higher energy

General issue: cross sections of each contribution

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

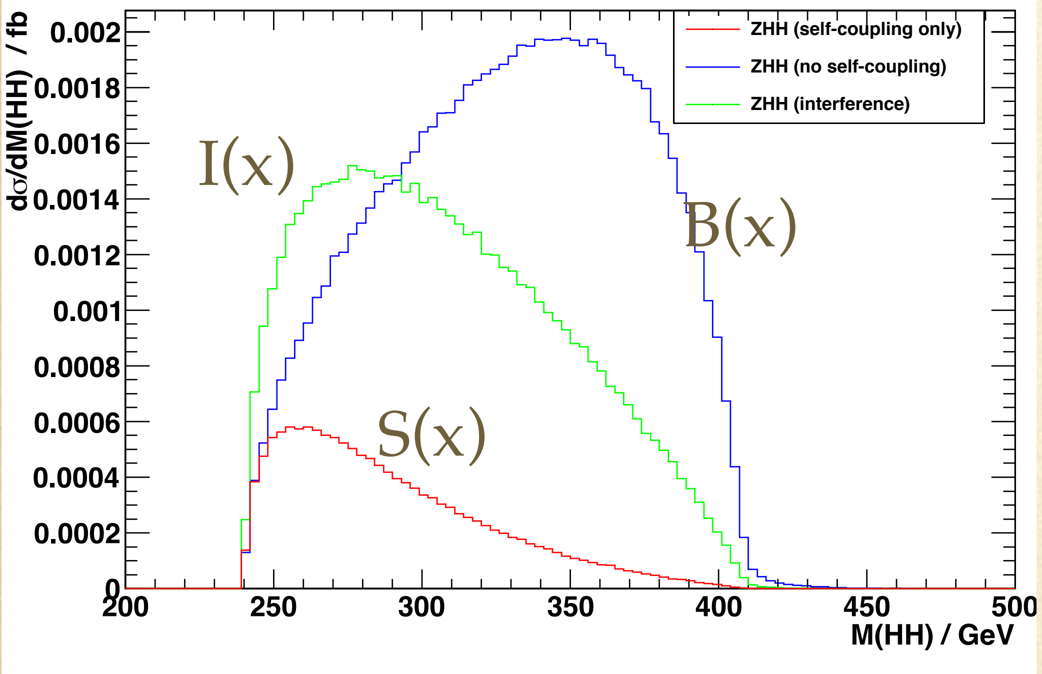


expected coupling precision with more realistic setup



new weighting method to enhance the coupling sensitivity

differential cross-section



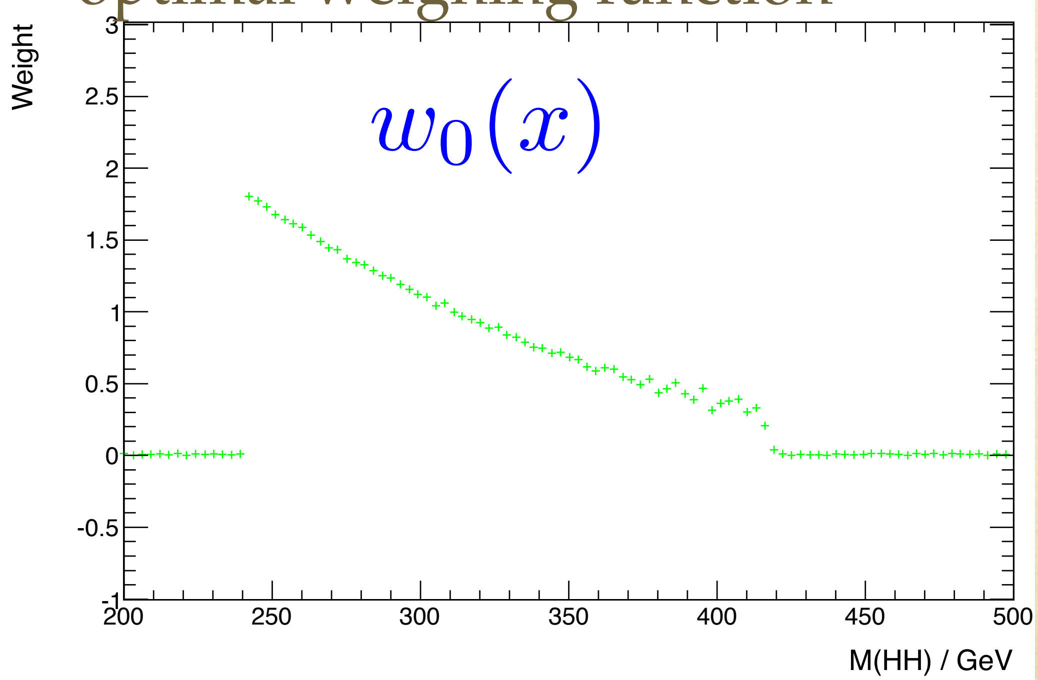
$$\frac{d\sigma}{dx} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

observable: weighted cross-section

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

optimal weighing function



equation of the optimal w(x) (variance principle):

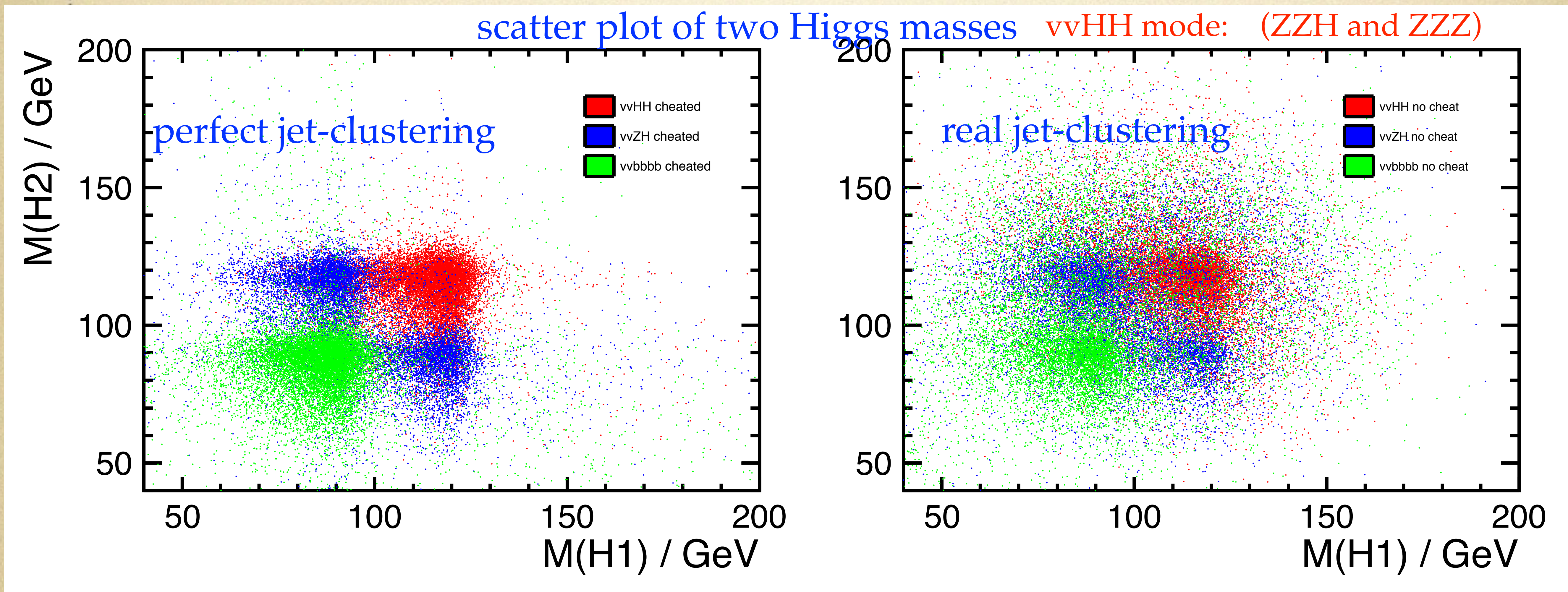
$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) dx = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) dx$$

general solution:

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

c: arbitrary normalization factor

prospect of Higgs self-coupling

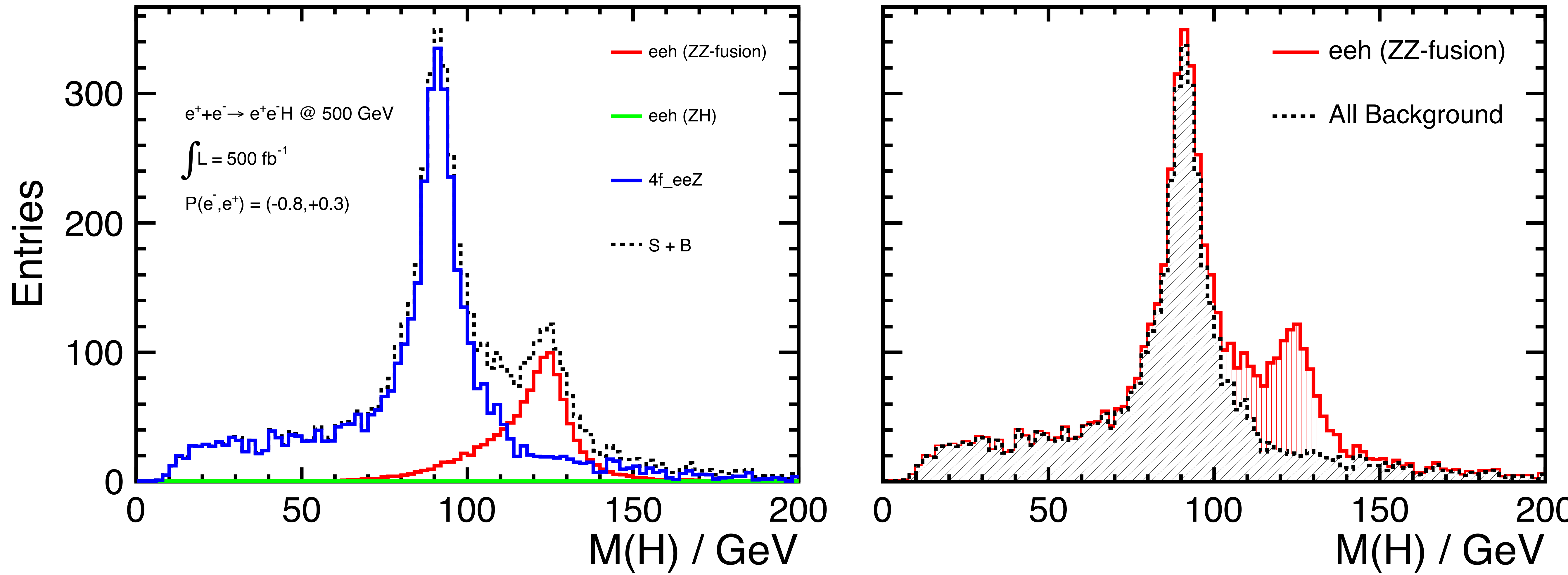


- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta\lambda/\lambda$ by 40%
- Mini-jet based clustering (Durham works when Np in mini-jet ~ 5, need better algorithm to combine the mini-jets, using such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

$$e^+ + e^- \to e^+e^-H \to e^+e^-b\bar{b}$$

(ZZ-fusion)

excess from BG (discovery by ZZ-fusion)



$$\frac{\delta(\sigma_{eeH} \cdot \mathrm{Br}(H \to b\bar{b}))}{\sigma \cdot \mathrm{Br}} = 3.9\% \quad (2.2\%)$$

(LumiUP)