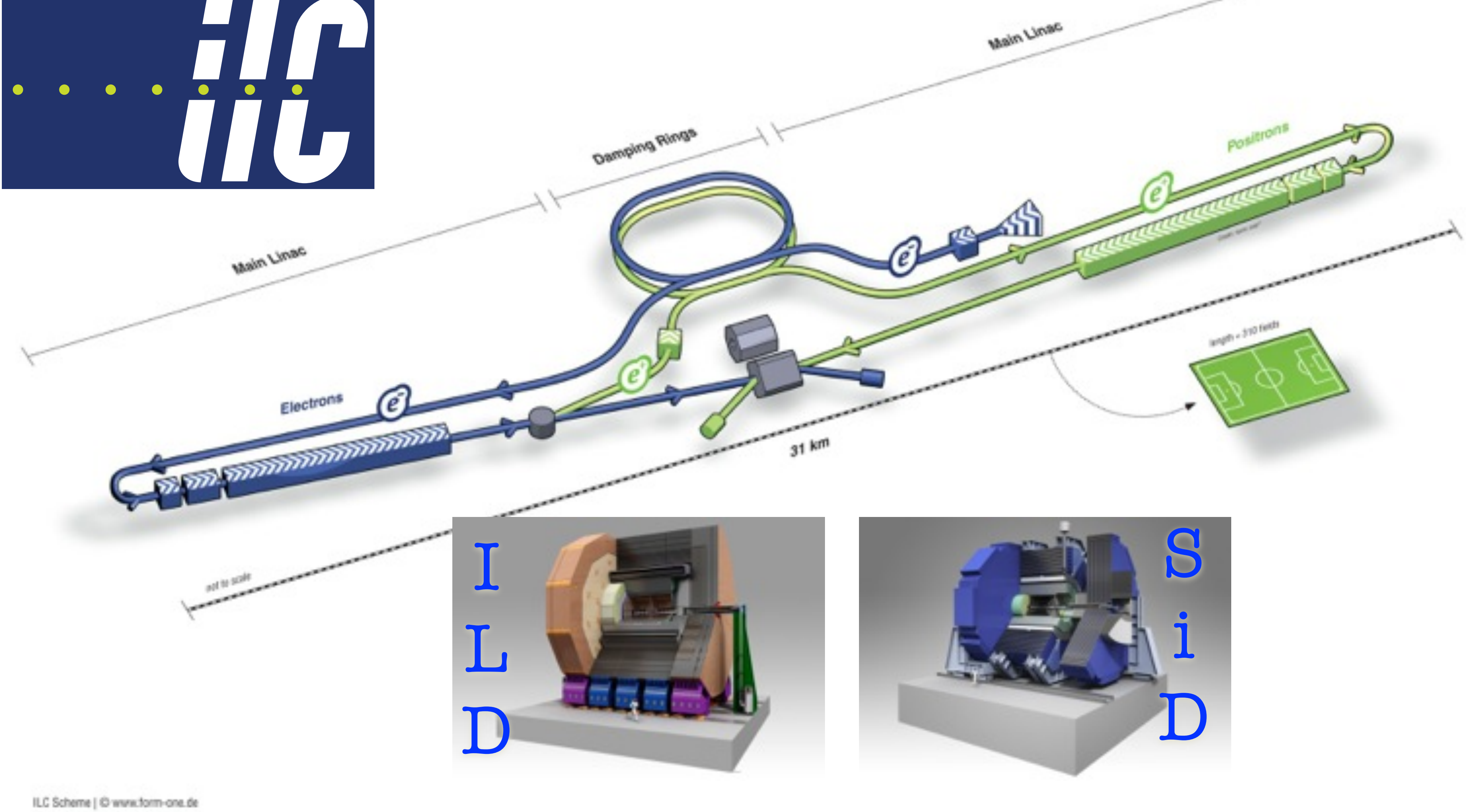
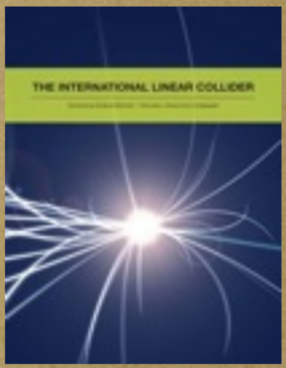
Measurement of Higgs couplings at the ILC

From Design to Reality



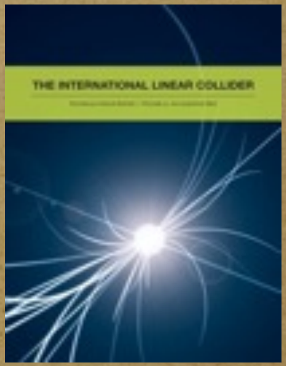
Technical Design Report

1 - Executive Summary



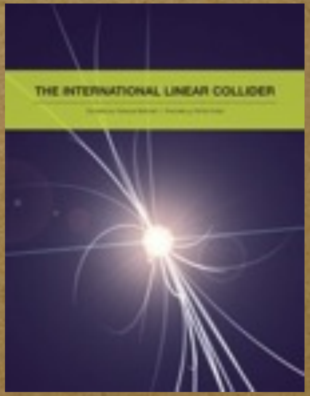
2 - Physics

3 - Accelerator I



3 - Accelerator II

4 - Detector



Junping Tian (KEK)

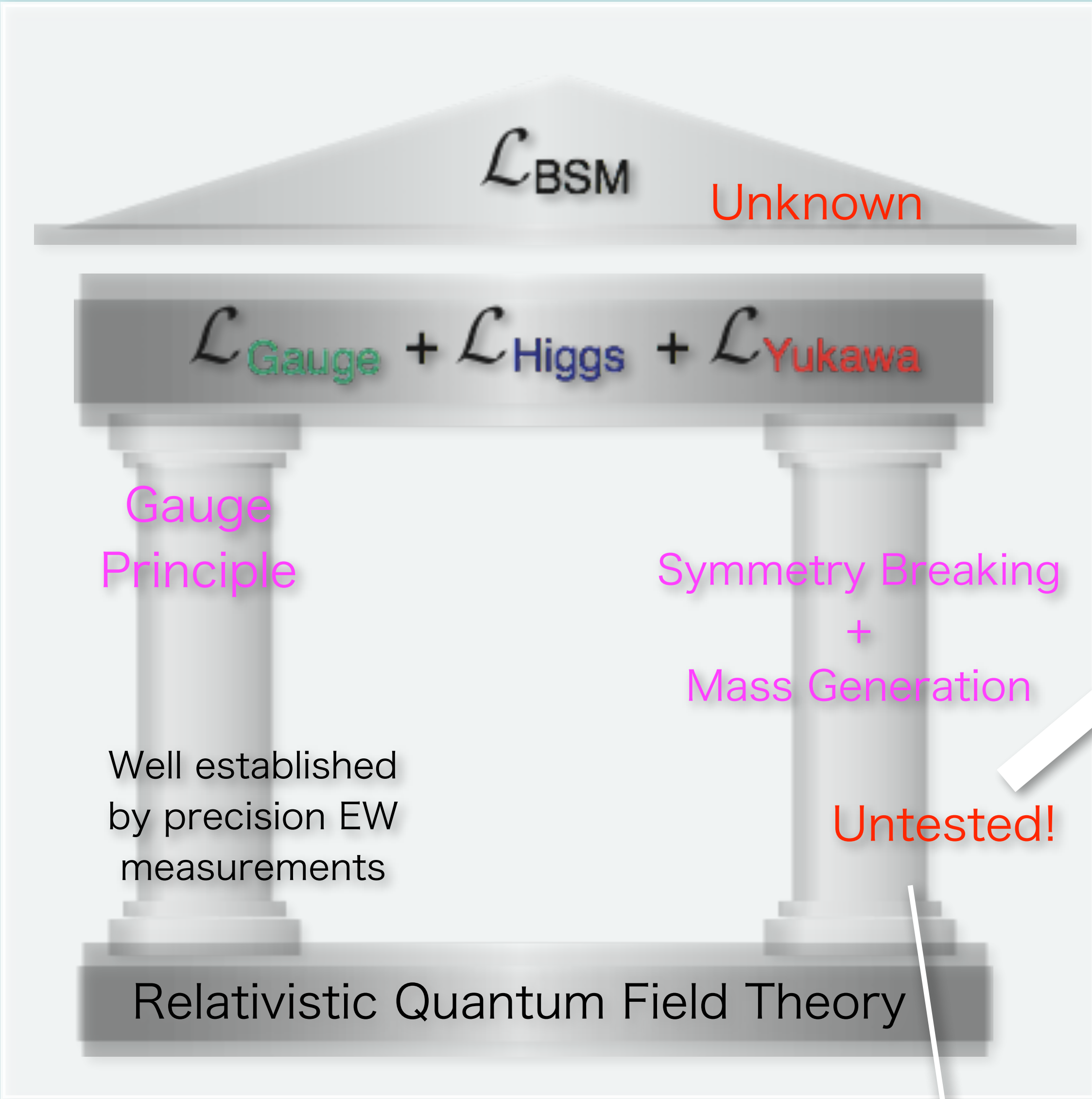
---on behalf of the ILC Physics & Detector Group

ICHEP 2014, Jul. 2-9 @ Valencia

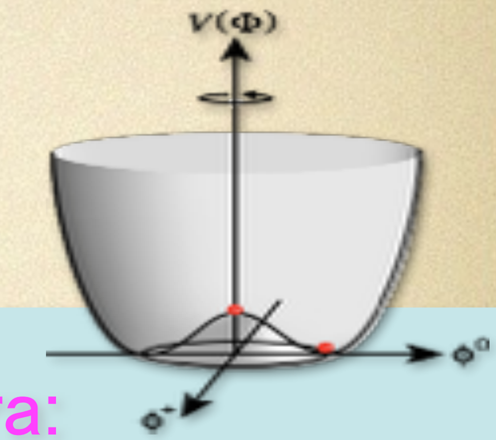
main references of this talk— TDR vol. 2 & vol. 4; ILC Higgs White Paper

Post discovery of a Higgs-like boson

2 Main Pillar of SM



The answer surely lines in the TeV Region



beginning of a new era:

1. Is this Higgs–like boson "the" Higgs boson?

2. What is the dynamics responsible for the EWSB?

ILC is built to nail down the first question, and provides good opportunity to answer the second one

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

through Precision Higgs Measurements

Mass & J^{CP}	$M_h \quad \Gamma_h \quad J^{\rm CP}$	determine spin and CP mixture
$L_{\rm Higgs}$	$hhh: \quad -6i\lambda v = -3i\frac{m_h^2}{v}$, $\quad hhhh: \quad -6i\lambda = -3i\frac{m_h^2}{v^2}$	observe the force to make higgs condense
$L_{\rm Gauge}$	$W_\mu^+ W_\nu^- h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W_\mu^+ W_\nu^- hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$ $Z_\mu Z_\nu h: \; i\frac{g^2+g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2+g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$	test the SSB, SU(2), saturation to <vev>
$L_{\rm Yukawa}$	$h\bar{f}f: \quad -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$	crucial to test the mass coupling proportionality
$L_{\rm Loop}$	$h\gamma\gamma \quad hgg \quad h\gamma Z$	sensitive to the new particles in the loop

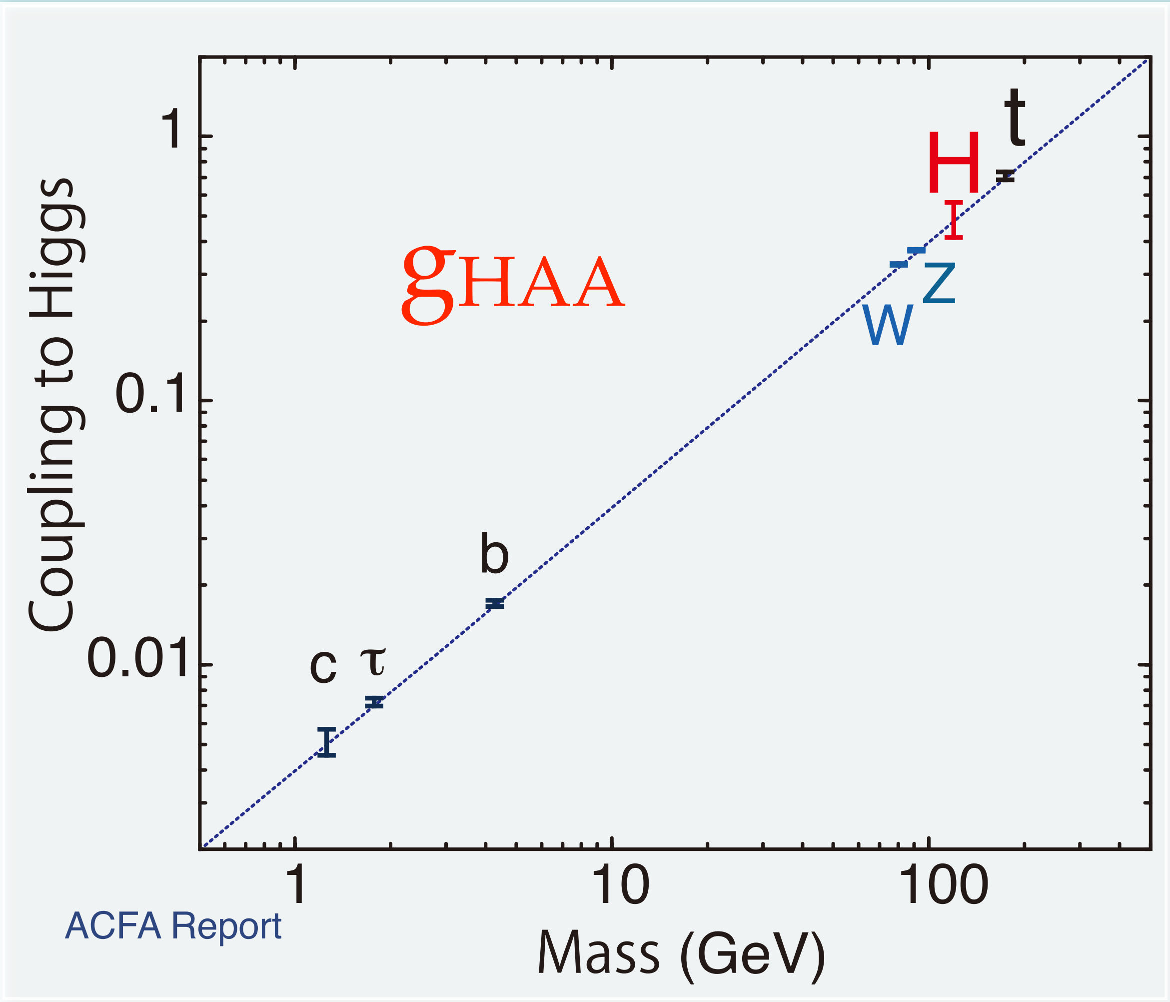
comprehensively reveal the Higgs nature

Why Precisions? (I)

within Standard Model

Degrassi, et. al, arXiv:1205.6479

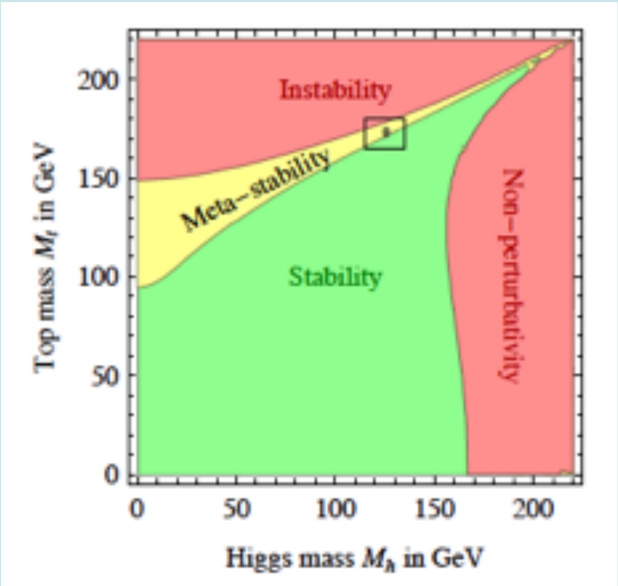
coupling strength

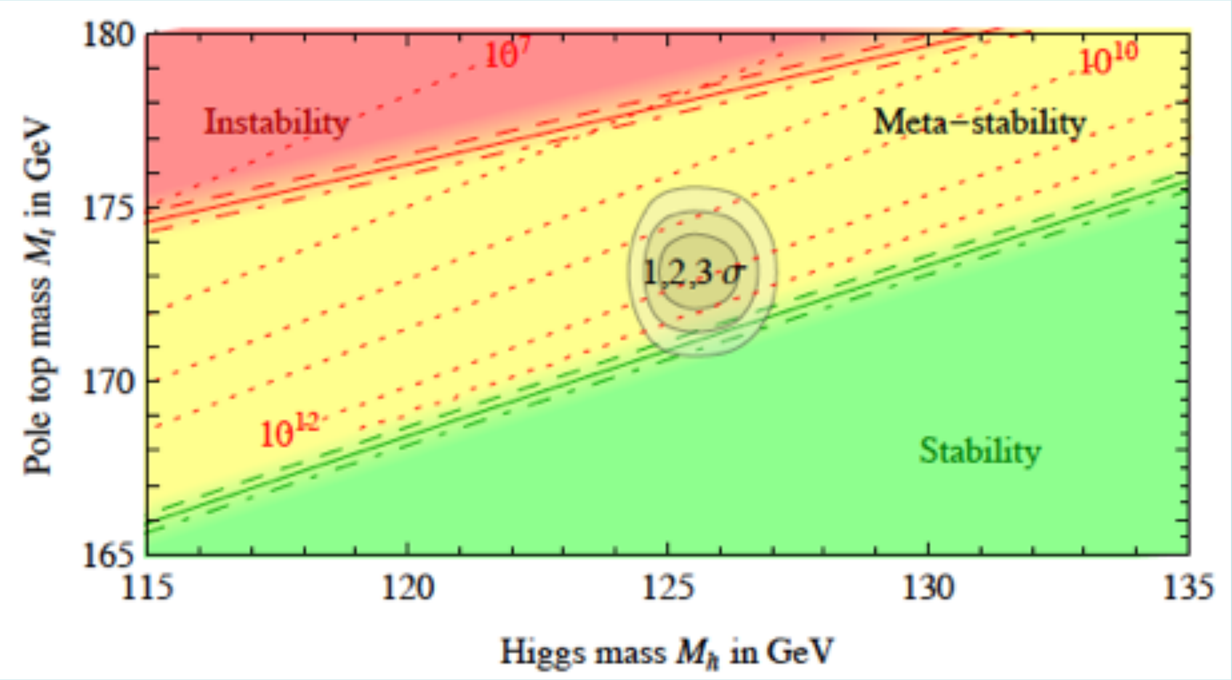


No deviation is expected from straight line in SM!

vacuum stability

M_H





- theoretical predictions of Higgs couplings are now at O(1%), and are expected to achieve per-mille level in next decade!

M.Peskin, et. al, arXiv:1404.0319

Beyond Standard Model

Why Precisions? (II)

- Multiplet structure :
  - Additional singlet? ($\phi + S$)
  - Additional doublet? ($\phi + \phi'$)
  - Additional triplet? ($\phi + \Delta$)
- Underlying dynamics :
  - Composite Higgs (PNGB)?
  - Supersymmetry?
- Relations to other questions of HEP :
  - $\phi + S$ → (B-L) gauge, DM, …
  - $\phi + \phi'$ → Type I : m_ν from small vev, …
    → Type II: SUSY, DM, …
    → Type X: m_ν (rad.seesaw), …
  - $\phi + \Delta$ → m_ν (Type II seesaw), …
  - $\lambda > \lambda_{SM}$ → EW baryogenesis ?
  - $\lambda \downarrow 0$ → inflation ?

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

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

Mixing with singlet

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

Composite Higgs

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

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

SUSY

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

Expected deviations are small --> Precision!

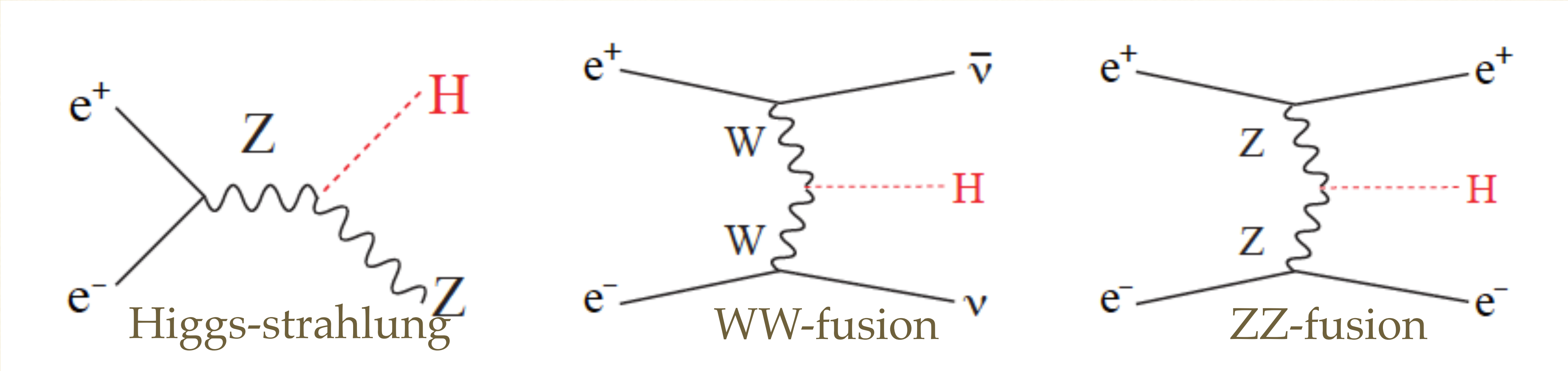
K. Fuji @ Pheno2014

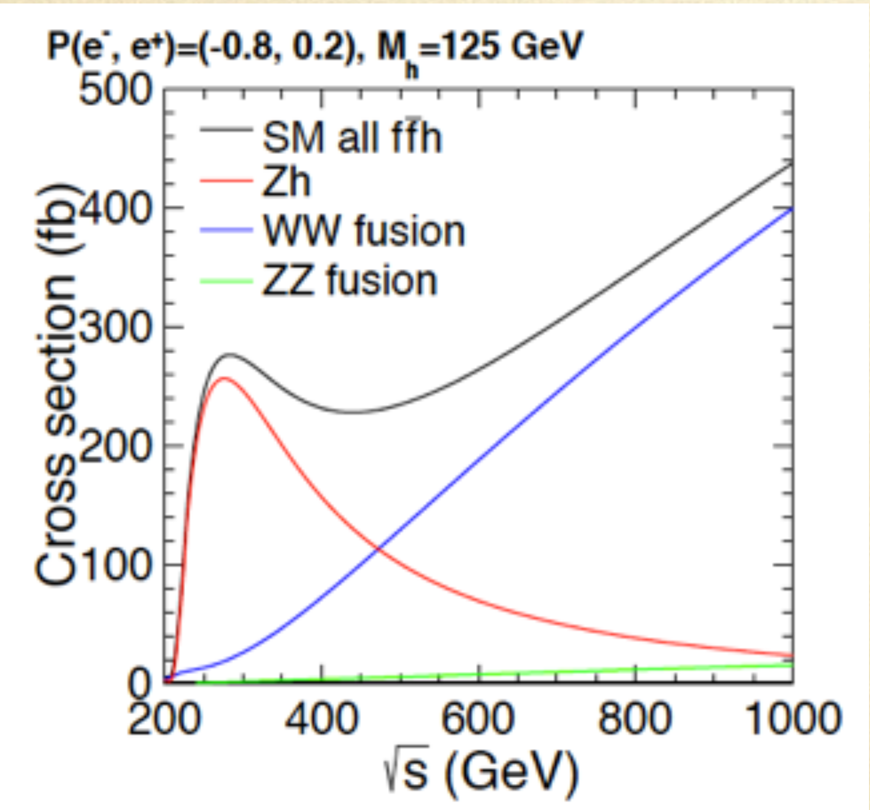
	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

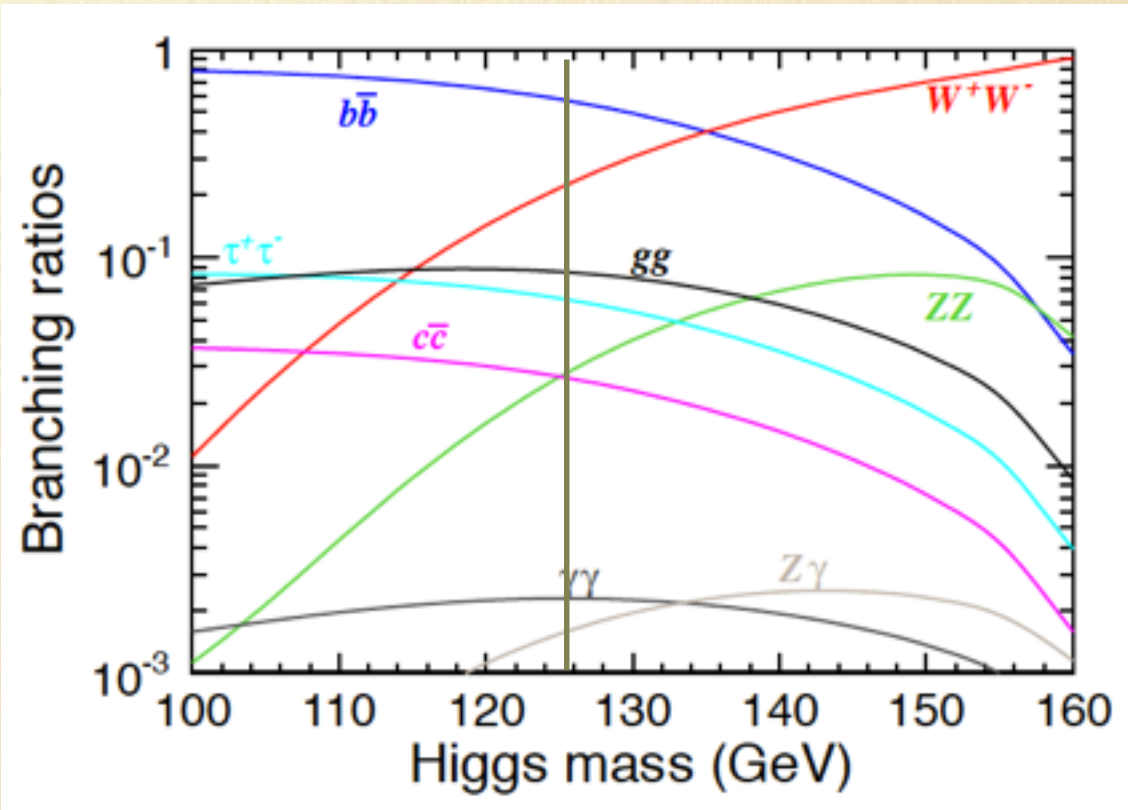
Gupta, Rzehak, Wells, arXiv:1206.3560

Higgs Production and Decay @ ILC

no lose theorem







- ✓ HZZ, HWW observed at LHC --> sufficient production rate
- ✓ 125 GeV + clean environment (1% of total cross section) --> all major decay modes accessible

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

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

three well-known threshold, a choice driven by physics

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

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

@ 350 GeV

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

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

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

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

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

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

beam polarisation like a luminosity doubler!

Baseline (TDR is just beginning) / Luminosity Upgrade (increasing #bunch, collision rate)

State-of-art Detector Performance by ILD & SiD

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

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

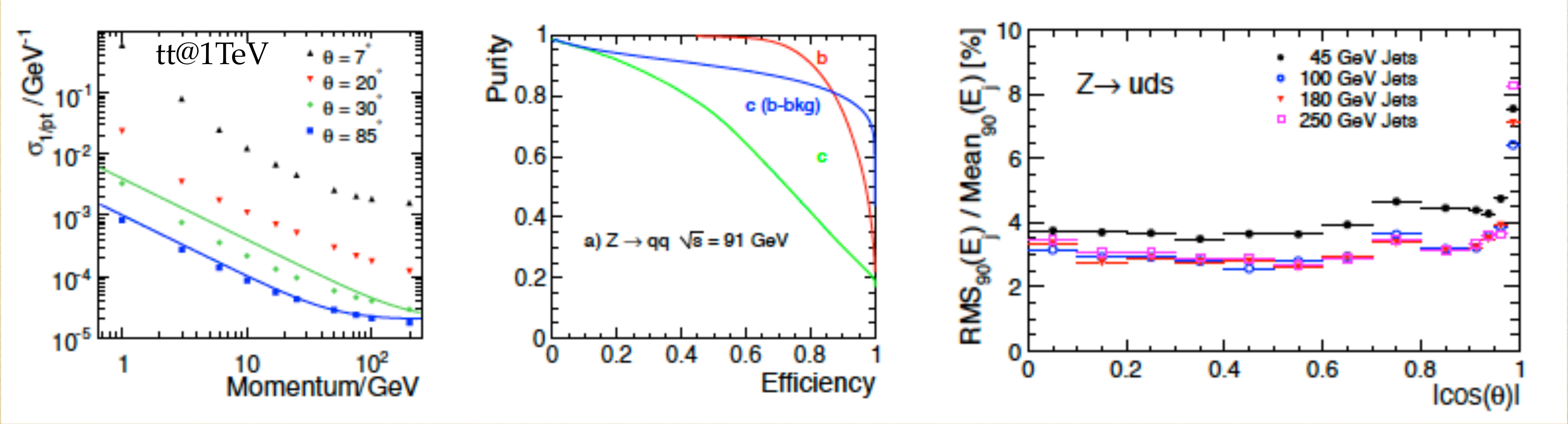
- driven by recoil mass measurement ZH-->l^+l^-X.

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).

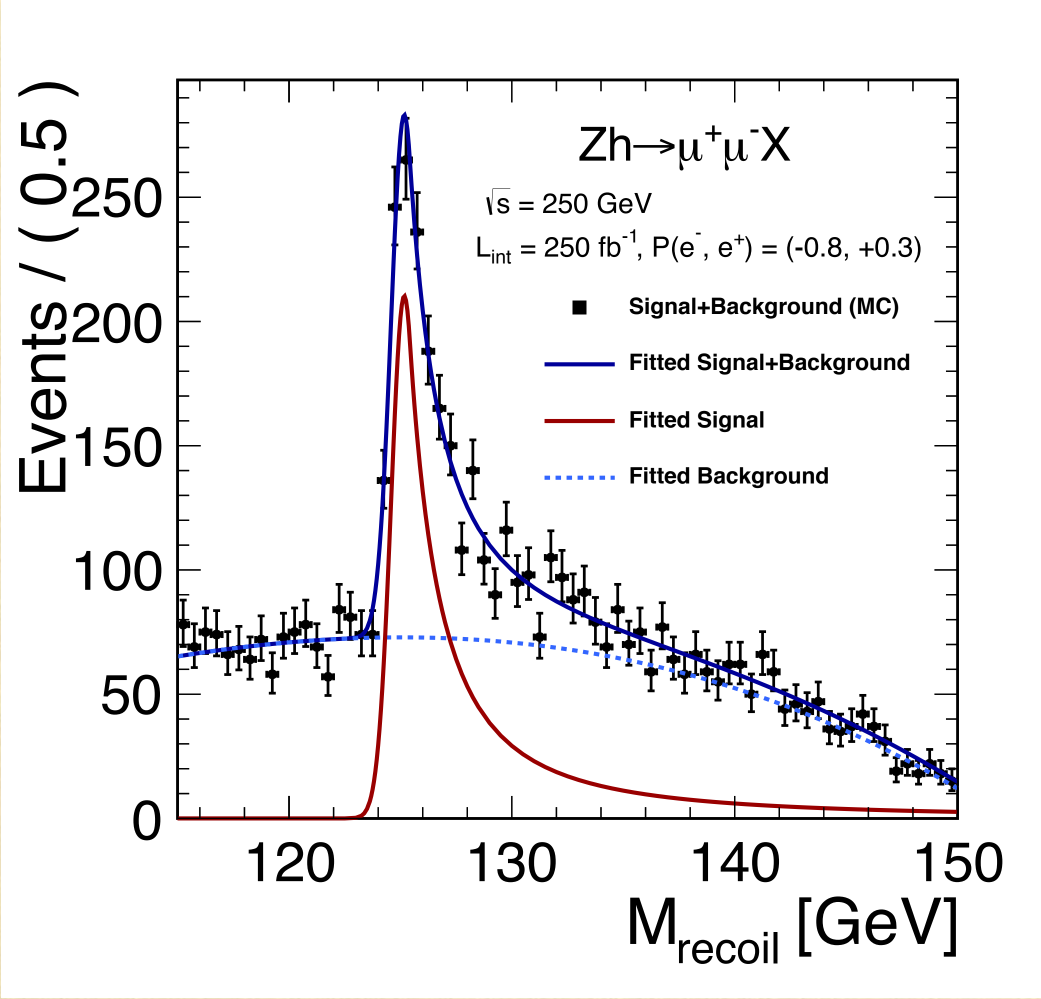


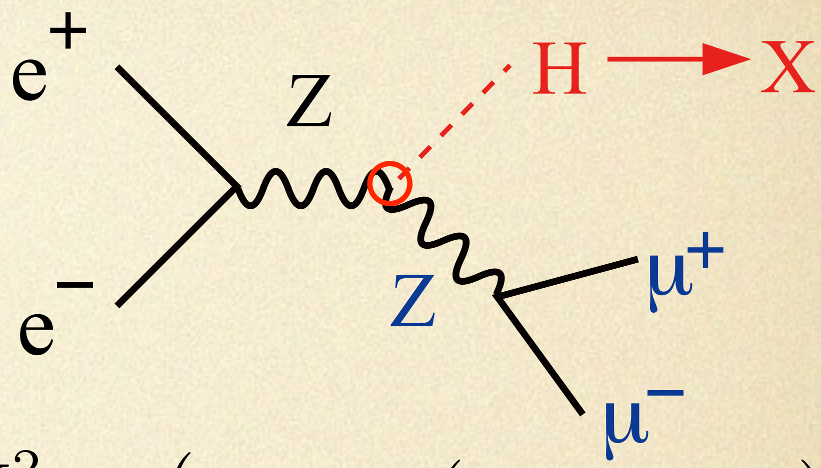
the following measurements are all based on full detector simulation!

mass and HZZ coupling

The flagship measurement of ILC250

Recoil Mass against Z without looking into H decay!





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

Invisible decay detectable!

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

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

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

($Z \to e^+e^-$ combined, scaled from mH=120 GeV)

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

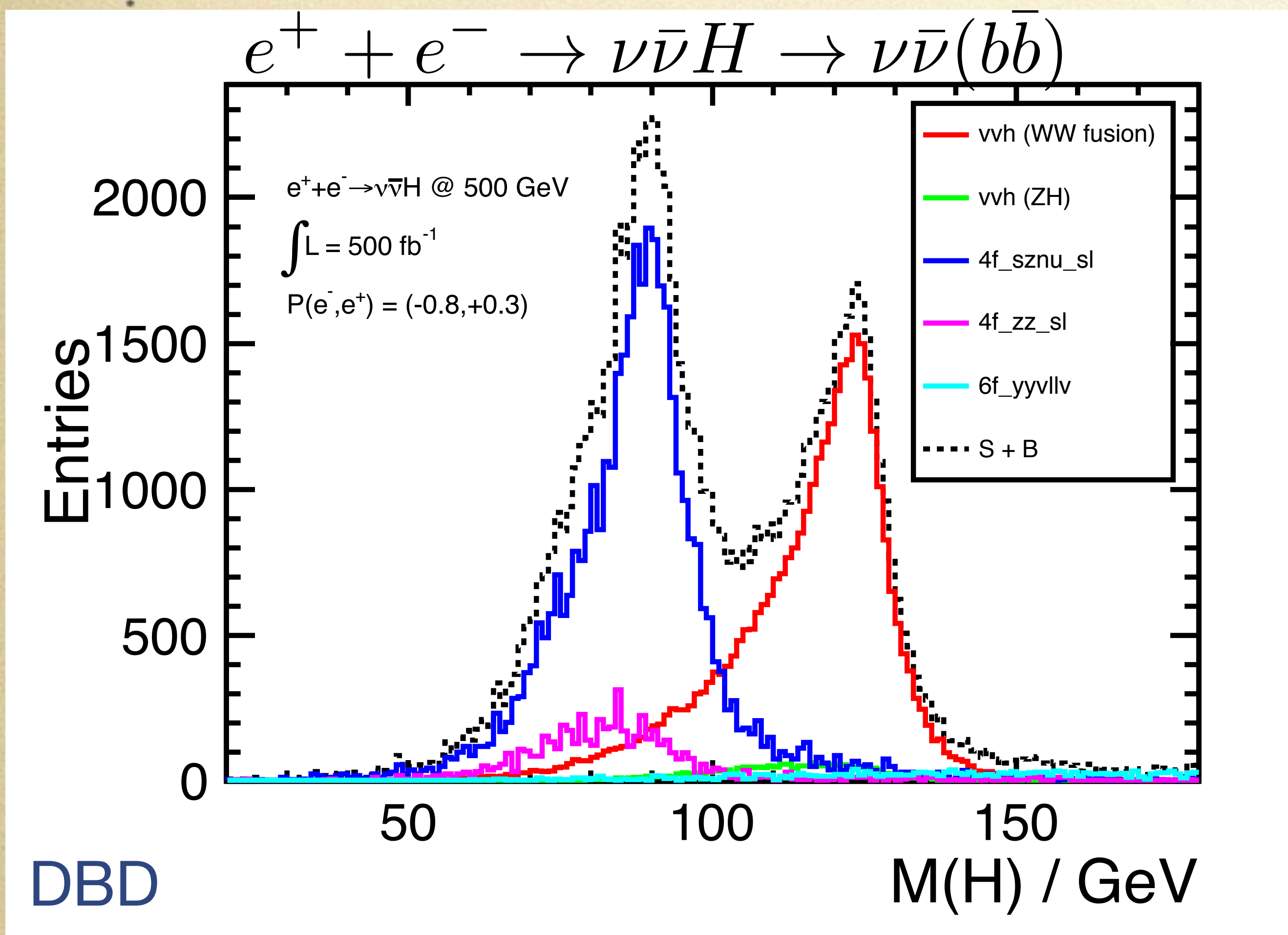
$Y_1 = \sigma_{ZH} \propto g_{HZZ}^2$ ---> Model-independent measurement of the absolute HZZ coupling

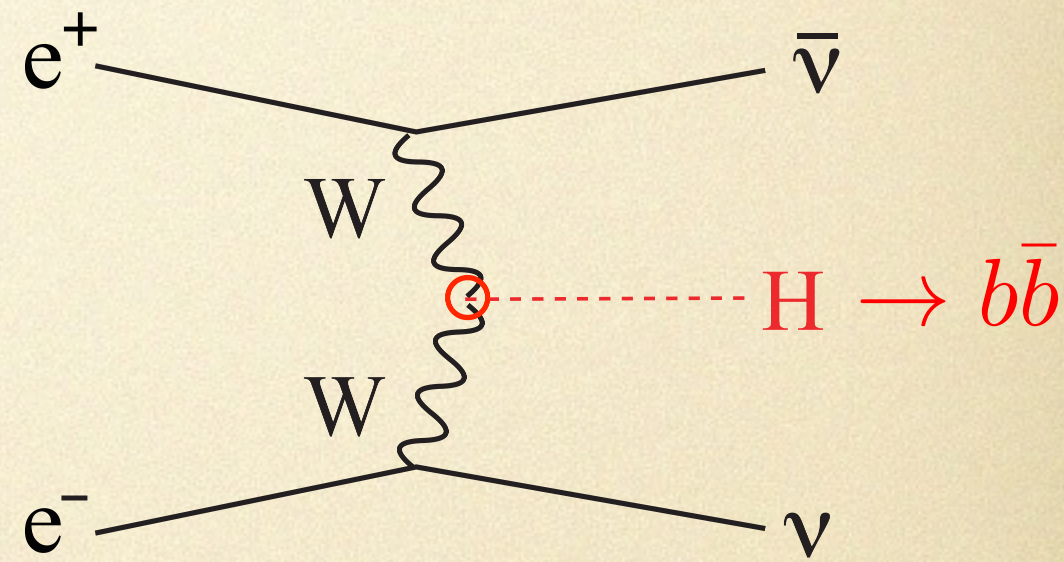
- invisible decay? no problem!
- other new scalar particles? will be captured in same way if they would be missed at LHC.
- measured to be small than SM value? Z mass must be provided together with additional Higgs boson! sin(β-α)!
- Δm_H is important source of $\Delta\Gamma(H \to WW/ZZ)$!
- 250 GeV is optimal energy for m_H and g_{HZZ}

$\Delta g_{HZZ}/g_{HZZ}$	250 GeV
Baseline	1.3%
LumiUP	0.61%

HWW coupling

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





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

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

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

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

- it's essential to separate vvH from ZH at lower energy by fitting missing mass (+ angular distribution is ongoing).
- Δg_{HWW} is actually the limit to all other couplings precisions except for g_{HZZ}.
- well constrained by unitarity in W_LW_L—>W_LW_L scattering.

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

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

ILC 500 GeV

Higgs total width Γ_H

model free, one of the great advantages of ILC

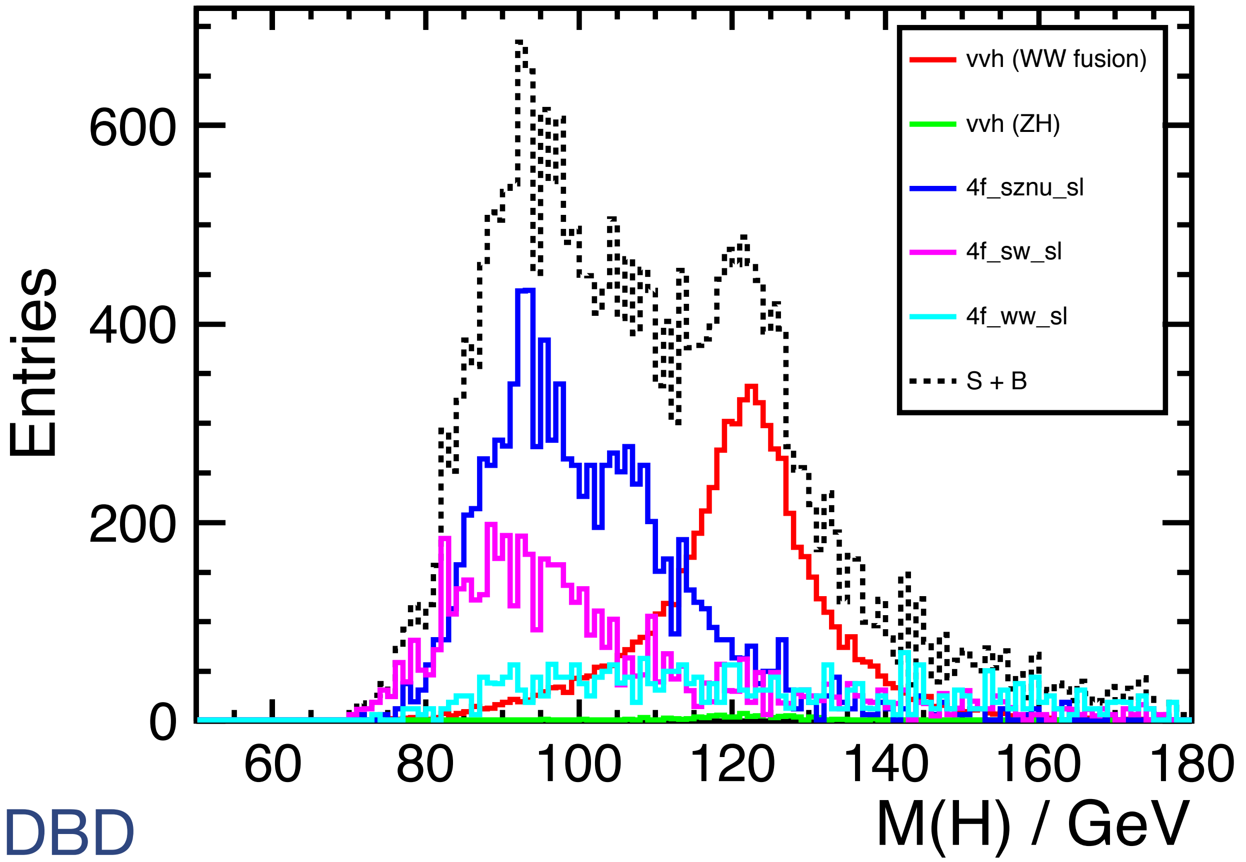
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

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

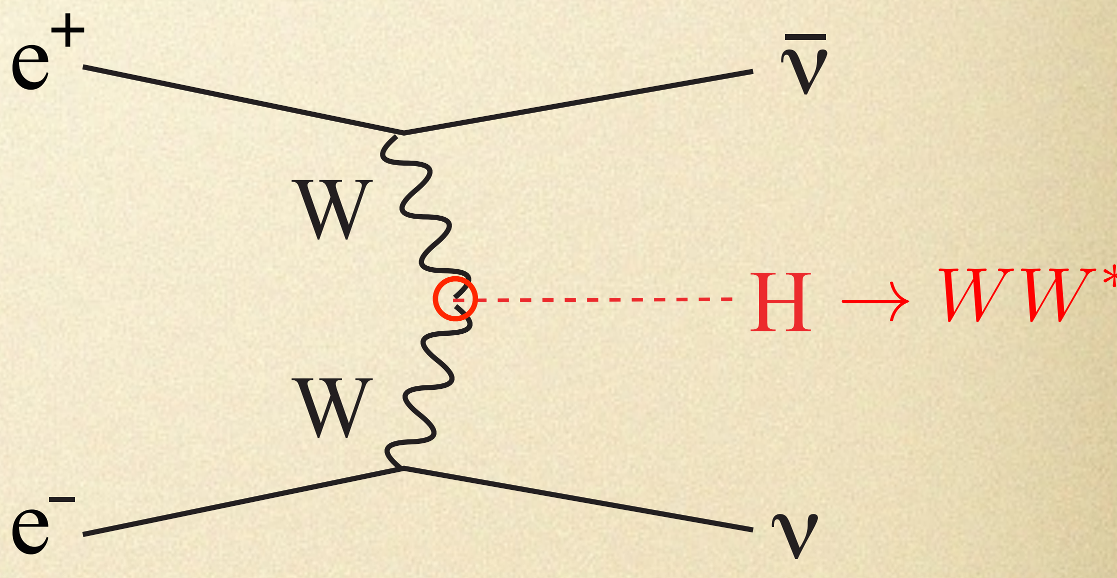
$$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

better option!

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



DBD



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

$\Delta\Gamma_H/\Gamma_H$	250 GeV	+ 500 GeV
Baseline	11%	5%
LumiUP	5.4%	2.5%

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

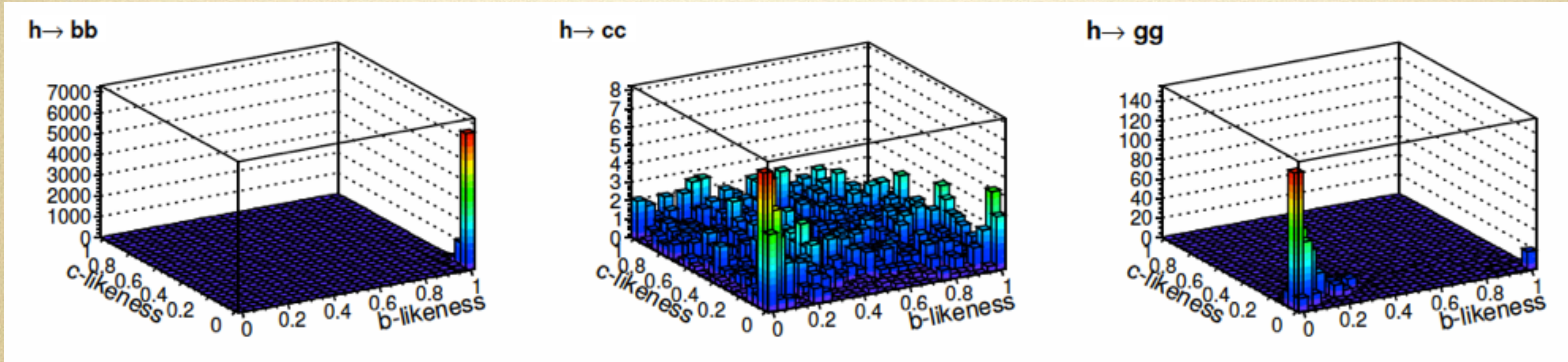
$$\Gamma_H \propto \frac{g^4_{HWW}}{Y_4} \propto \frac{Y_1^2 Y_2^2}{Y_3^2 Y_4}$$

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

Higgs couplings to bb, cc and gg

state-of-art vertex detector is as close as 2 cm to the beam + clean electroweak background
—> b-vertices and c-vertices can be well reconstructed

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



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

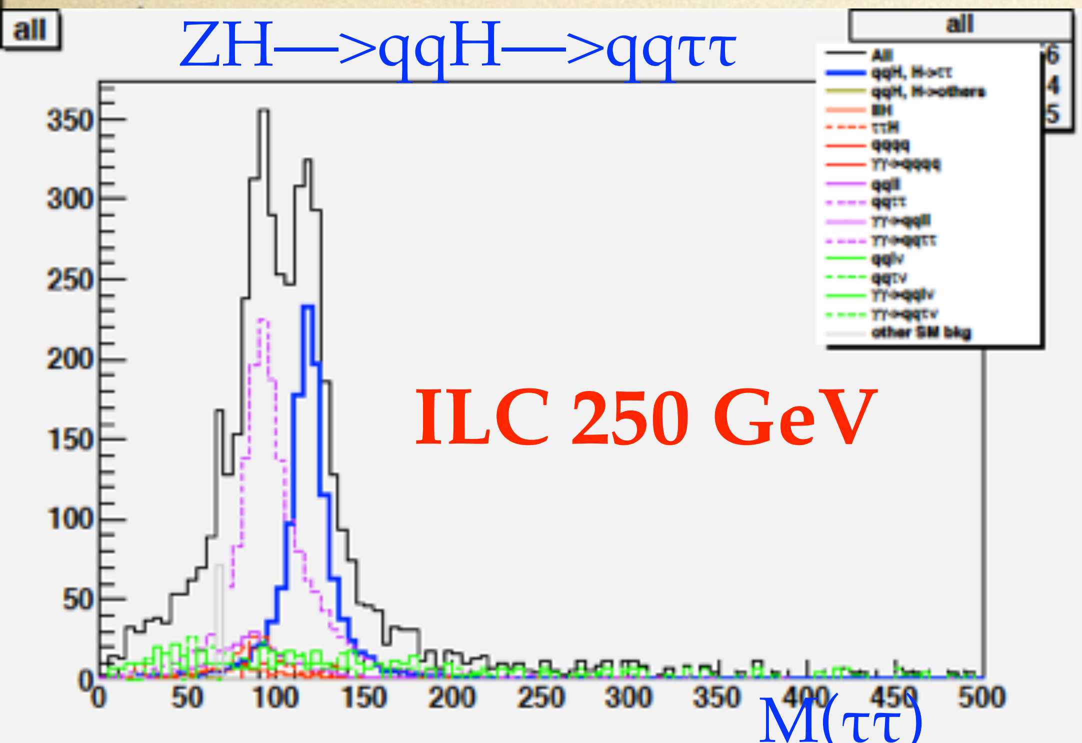
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb}/\Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc}/\Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg}/\Gamma_H$$

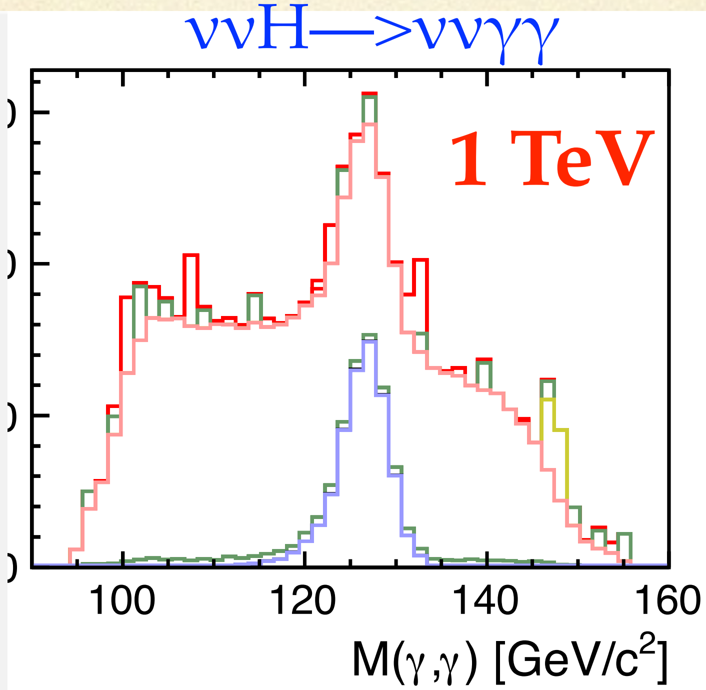
(results of couplings precision by global fit shown in following slides)

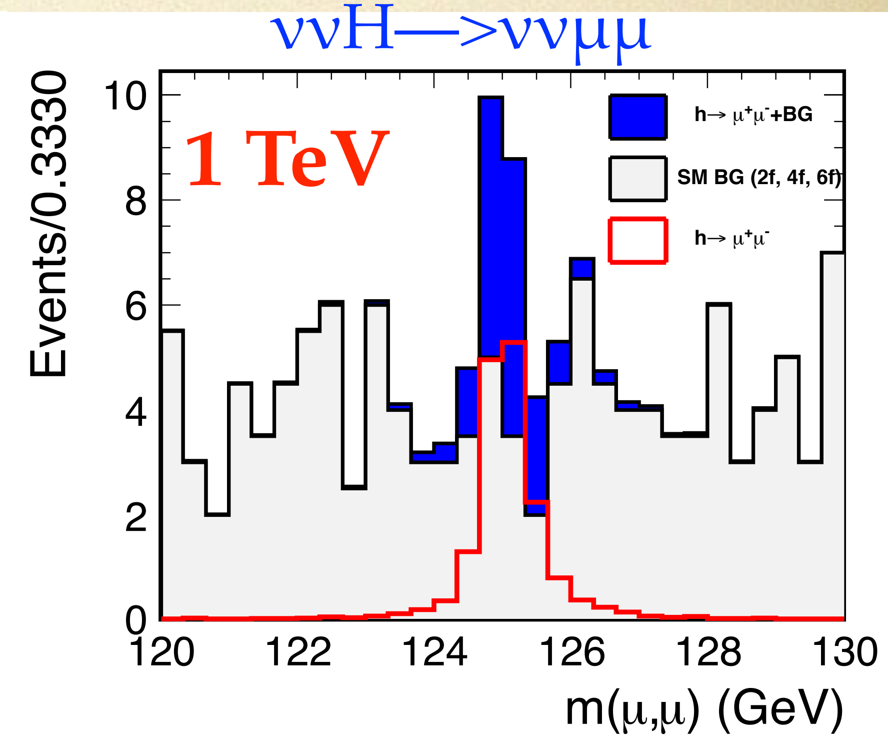
H. Ono, et. al, Euro. Phys. J. C73, 2343 (LoI study, done w/ mH=120 GeV, scaled to 125 GeV)

Higgs couplings to ττ, γγ and μμ

keys: IP resolution (tau finder) + ECAL single photon energy resolution + Tracking







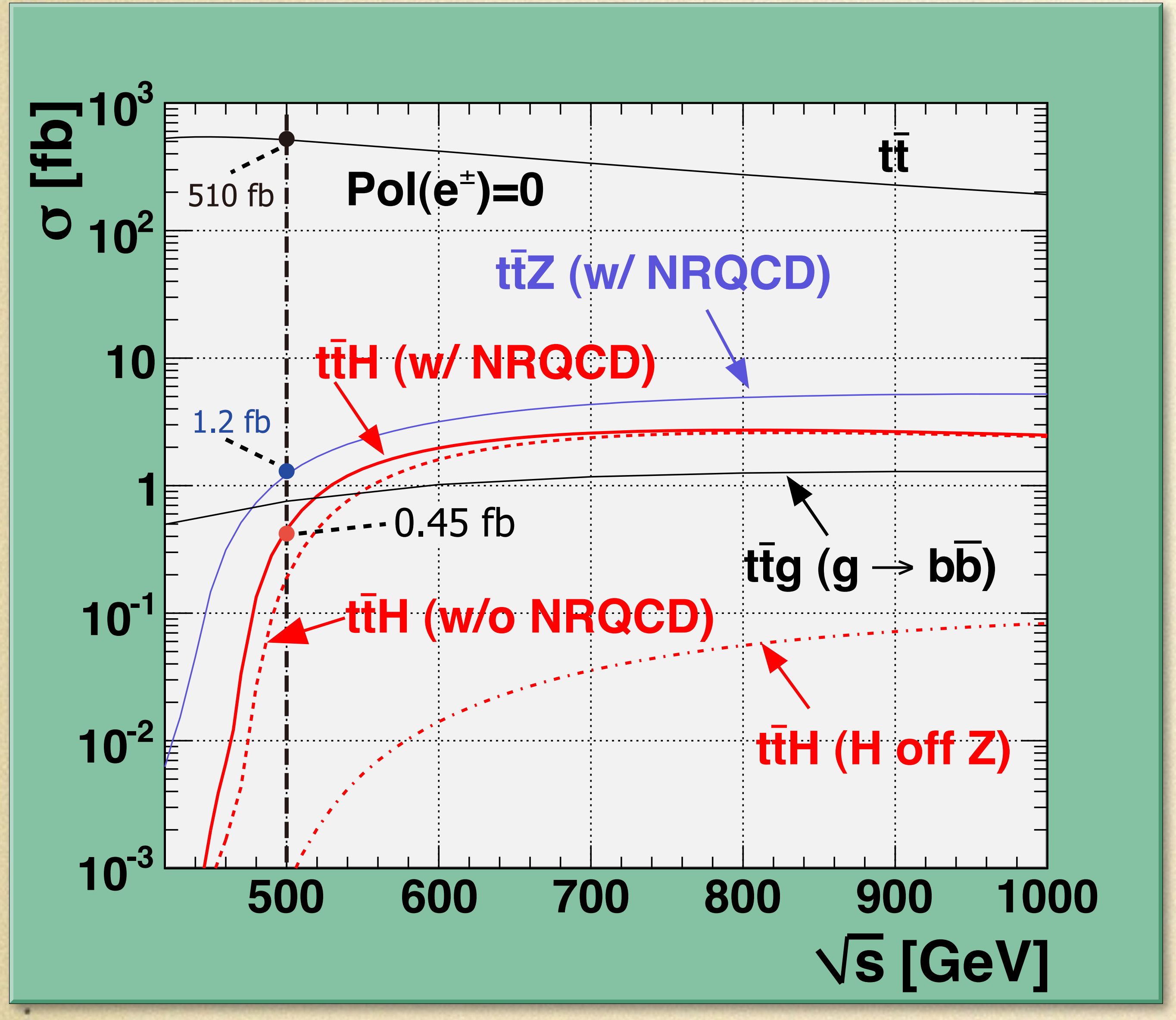
- H—>ττ done with all decay modes of ZH; very sophisticated tau-finder developed; benefit greatly from well defined initial state, in some case tau momentum can be fully recovered (i.e. 6C fit for Z->ll,qq mode); main BG from ZZ.
- H—>γγ and μμ mainly done with WW-fusion production; Isolated photon and lepton finder; low-multiplicities signal events, very narrow peak, BG mainly from continuous channel; very small branching ratios, limited by statistics.
- results of couplings precision by global fit shown in following slides.

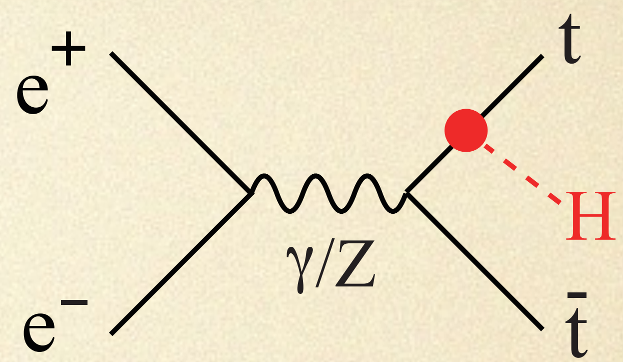
S. Kawada, et. al, LC-REP-2013-001, arXiv: 1308.5489 C. Calancha, LC-REP-2013-006

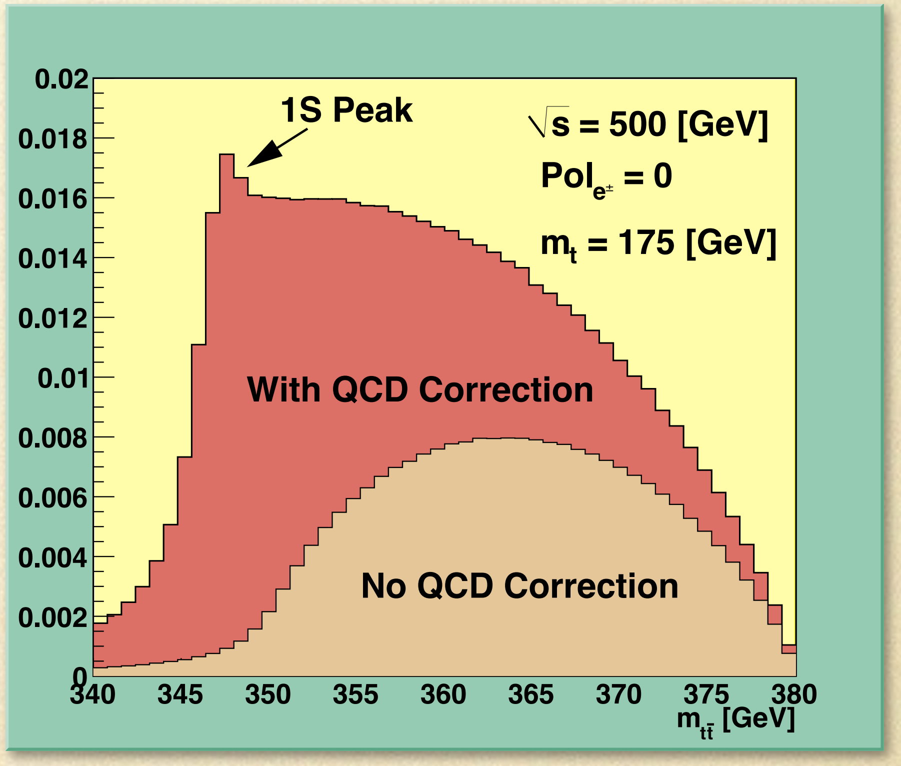
Top-Yukawa Coupling

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

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

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

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

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

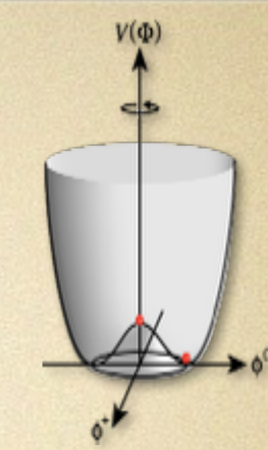
T. Tanabe, T. Price, et. al, LC-REP-2013-004

see more details in poster by J.Strube

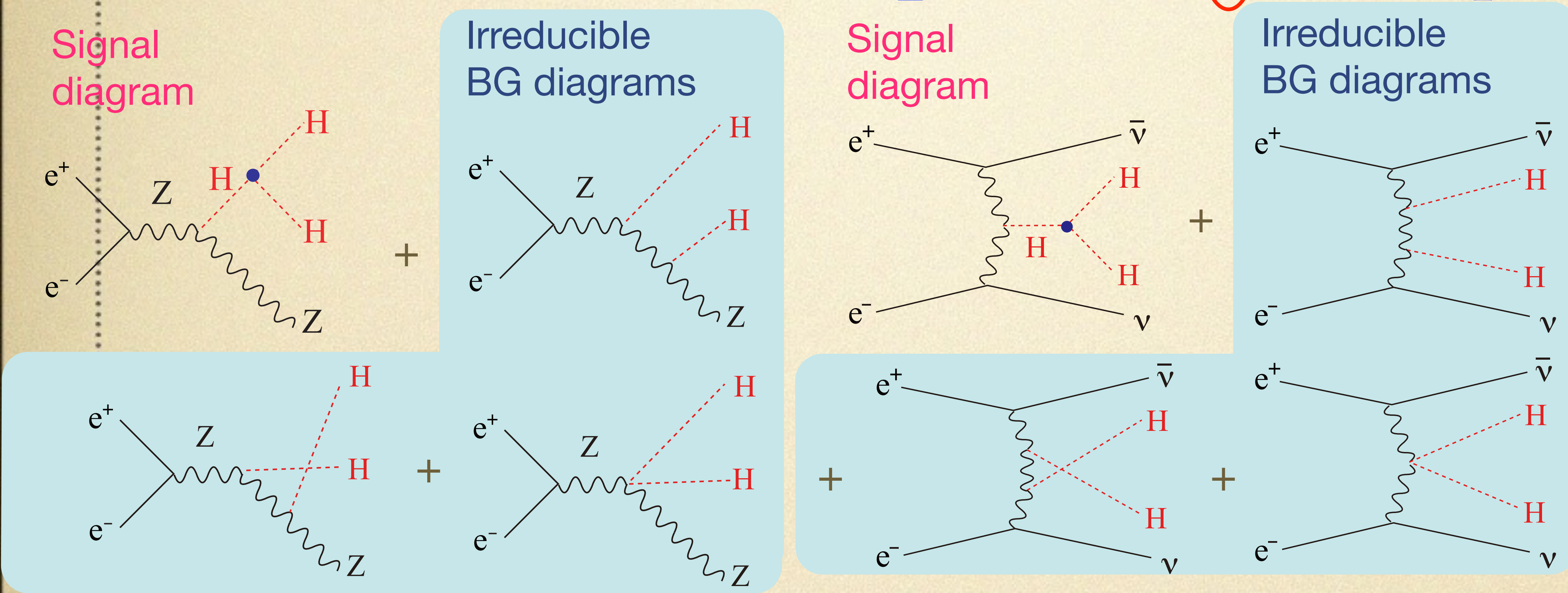
ILC 500 GeV & 1 TeV

Higgs Self-coupling

The force that makes Higgs boson condense in the vacuum



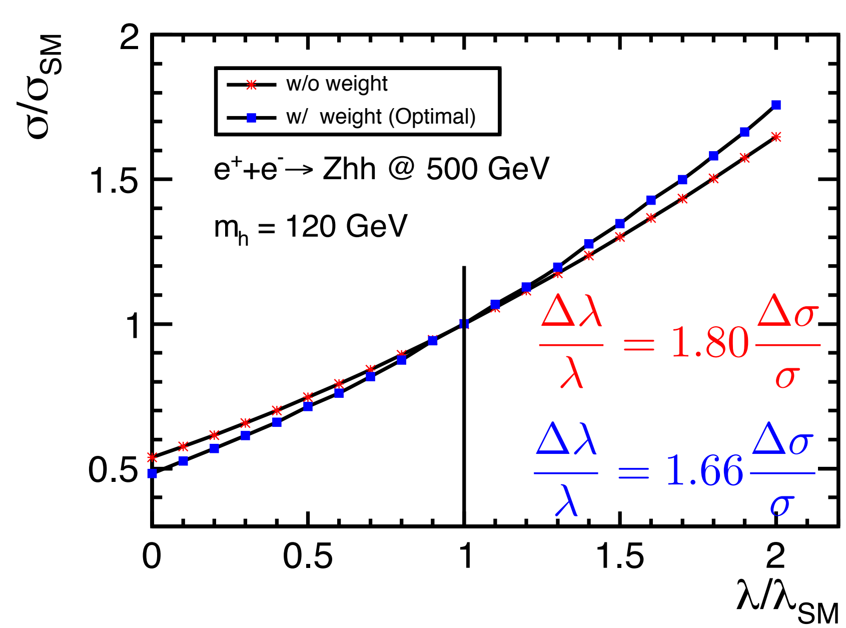
Higgs Potential: $$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

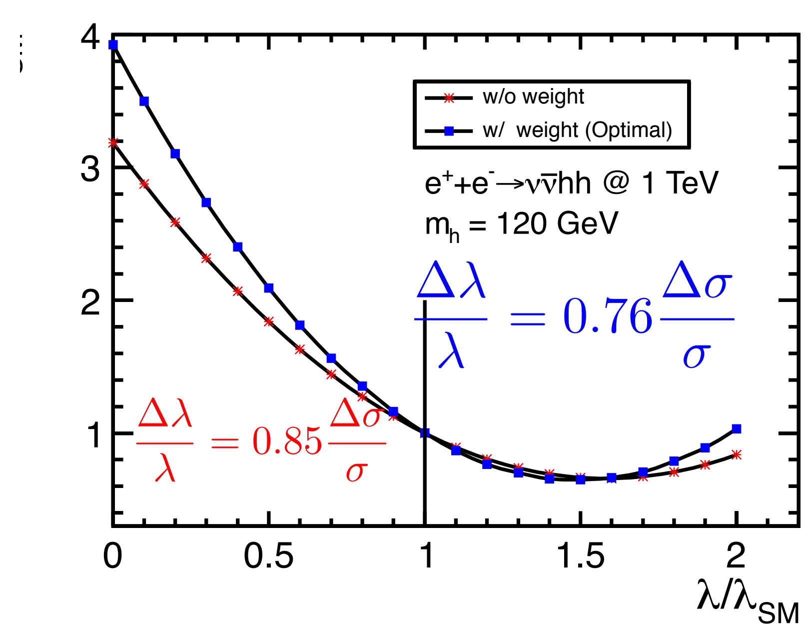


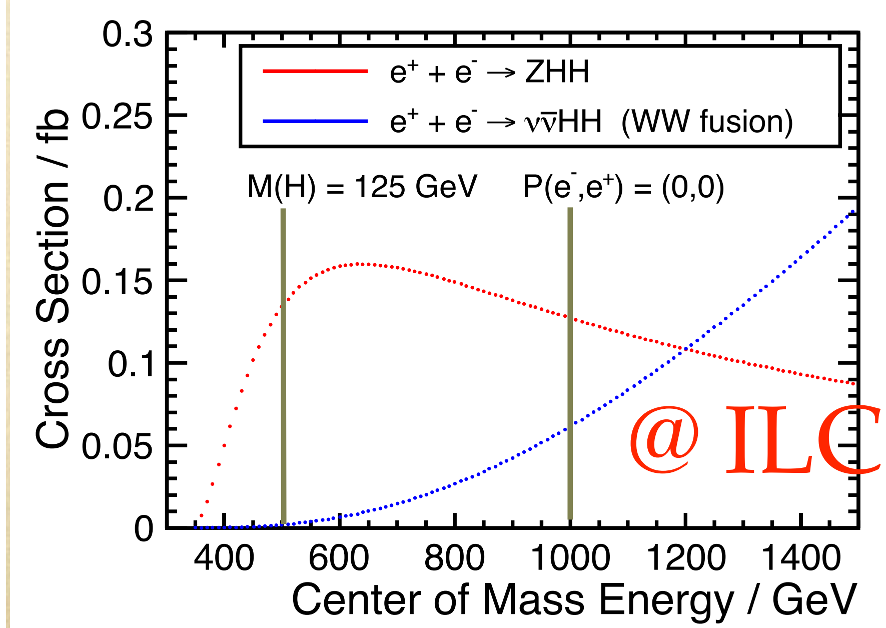
$$\sigma = \lambda^2 S + \lambda I + B$$

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

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

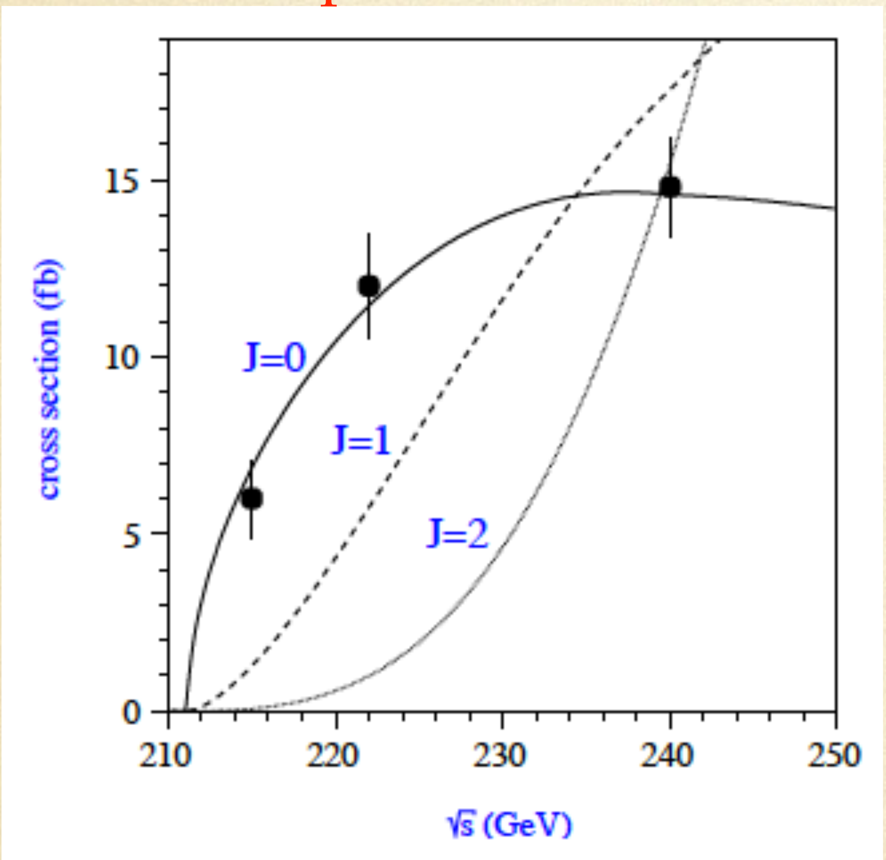
J. Tian, LC-REP-2013-003 M. Kurata @ ECFA2013 C.Duerig @ AWLC14

ILC

Higgs Quantum Numbers J^{CP}

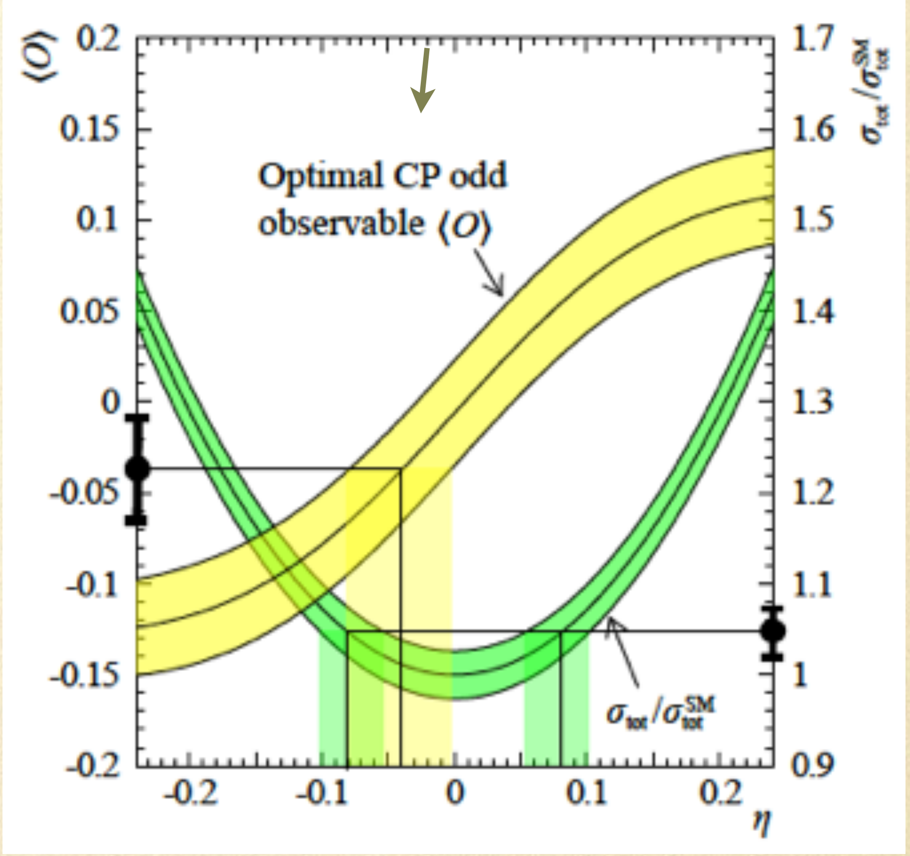
in addition to the spin study by H-->ZZ* and WW*, ILC offers an orthogonal way and be able to measure the mixture of CP

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

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

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

- 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—>τ+τ-: 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)

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%	-	-		
	$\sigma \cdot Br$	$\sigma \cdot Br$	$\sigma \cdot Br$	$\sigma \cdot Br$	$\sigma \cdot Br$
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

Model-independent Global Fit to extract couplings

K.Fujii @ Pheno2014, Pittsburg

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

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

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

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

$$F_i = S_i \, G_i$$

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

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

- 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) will be 0.1% level in next decade (arXiv: 1404.0319).

Systematic Errors

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

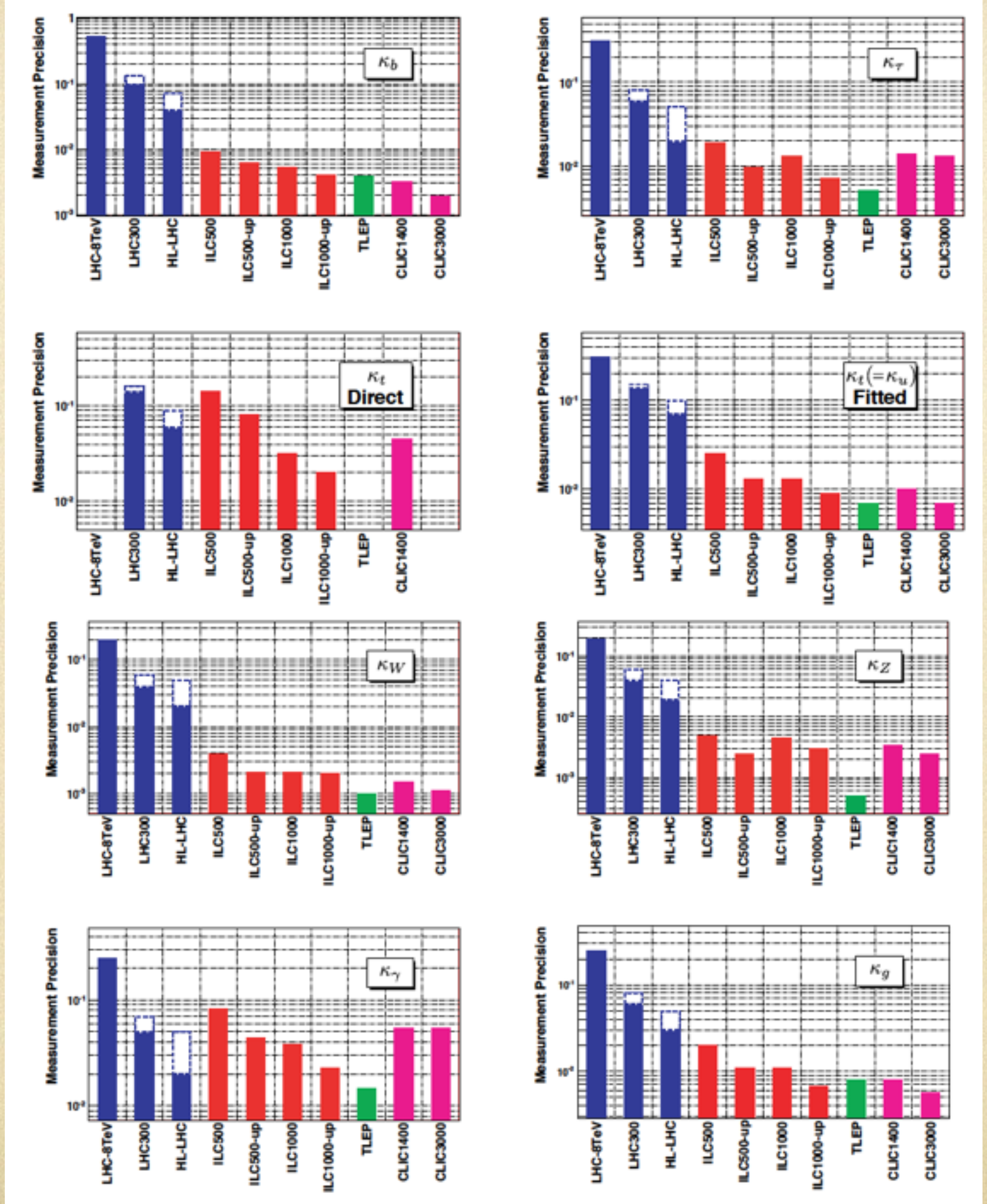
ILC Higgs White Paper. arXiv: 1310.0763

Precisions of Absolute Higgs Couplings @ ILC

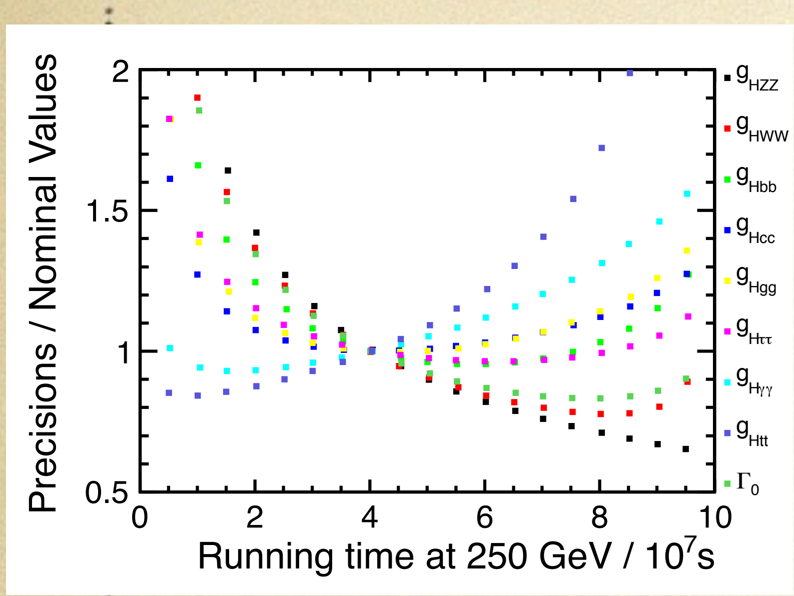
model independent fit

coupling $\Delta g/g$	Baseline			LumiUP		
	250 GeV	+ 500 GeV	+ 1 TeV	250 GeV	+ 500 GeV	+ 1 TeV
HZZ	1.3%	1%	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


Measurement Precision
κ_b
κ_τ
κ_t Direct
$\kappa_t(=\kappa_u)$ Fitted
κ_W
κ_Z
κ_γ
κ_g
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000

limiting factors of coupling precisions



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

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

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

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

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

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

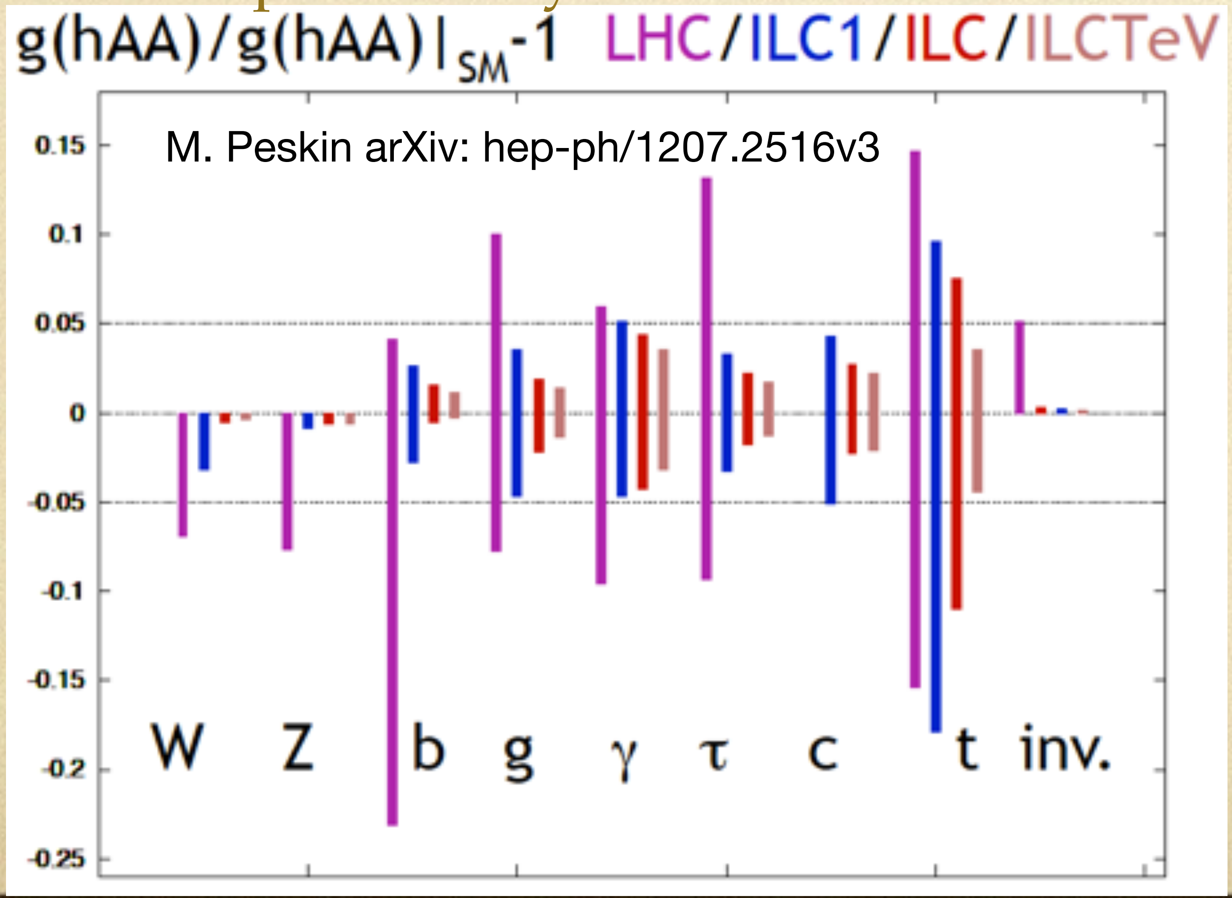
$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

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

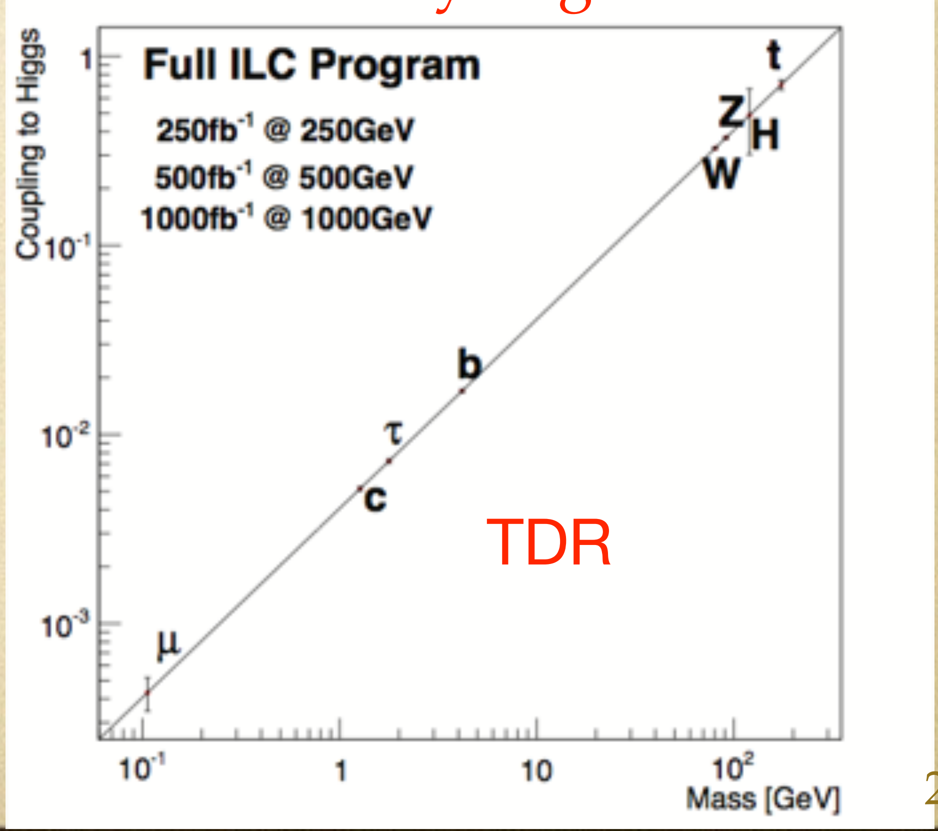
both ZH and ννH productions matter!

Summary

- ILC is the ideal precision machine complementary to LHC discovery power, to reveal the mechanism of EWSB and mass generation; performance of ILD & SiD 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; HWW coupling determination is crucial for precisions of all other couplings, and is essential to be improved significantly at higher ECM.
- ILC @ 500 GeV and 1 TeV is essential to measure direct top-Yukawa coupling and Higgs self-coupling.
- ability of energy scan can make ILC run at optimal energy and complementary to whatever LHC would discover.



ILC ready to go!



backup

executive summary of TDR (M. Peskin)

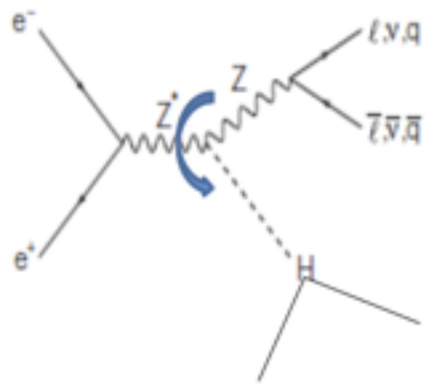
Topic	Parameter	Accuracy $\Delta X/X$	
Higgs	m_h	0.03%	$\Delta m_h = 35$ MeV, 250 GeV
	Γ_h	1.6%	250 GeV and 500 GeV
	$g(hWW)$	0.24%	
	$g(hZZ)$	0.30%	
	$g(hb\bar{b})$	0.94%	
	$g(hc\bar{c})$	2.5%	
	$g(hgg)$	2.0%	
	$g(h\tau^+\tau^-)$	1.9%	
	$BR(h \to \text{ invis.})$	< 0.44	
	$g(ht\bar{t})$	3.9%	1000 GeV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

almost model-free fitting, constraint:

Branching ratios sum up to 1

Invisible Higgs Decay

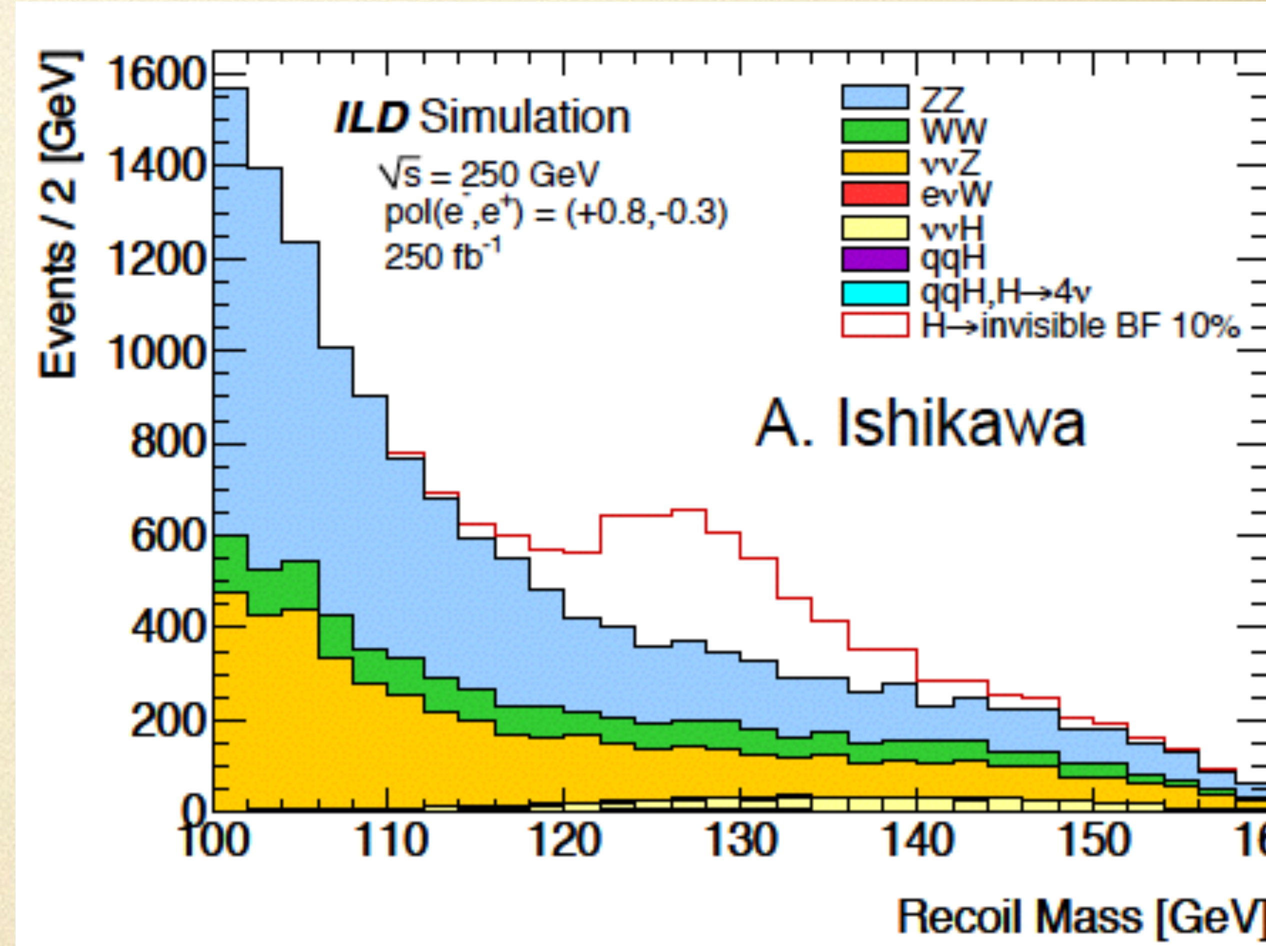
- In the SM, an invisible Higgs decay is H → ZZ* → 4ν process and its BF is small ~0.1%
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - The decay products are dark matter candidates.



- 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

$$P_H = P_{e+e-} - P_Z$$

known measured



A. Ishikawa @ Snowmass Energy Frontier Workshop, Seattle, 2013

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)

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

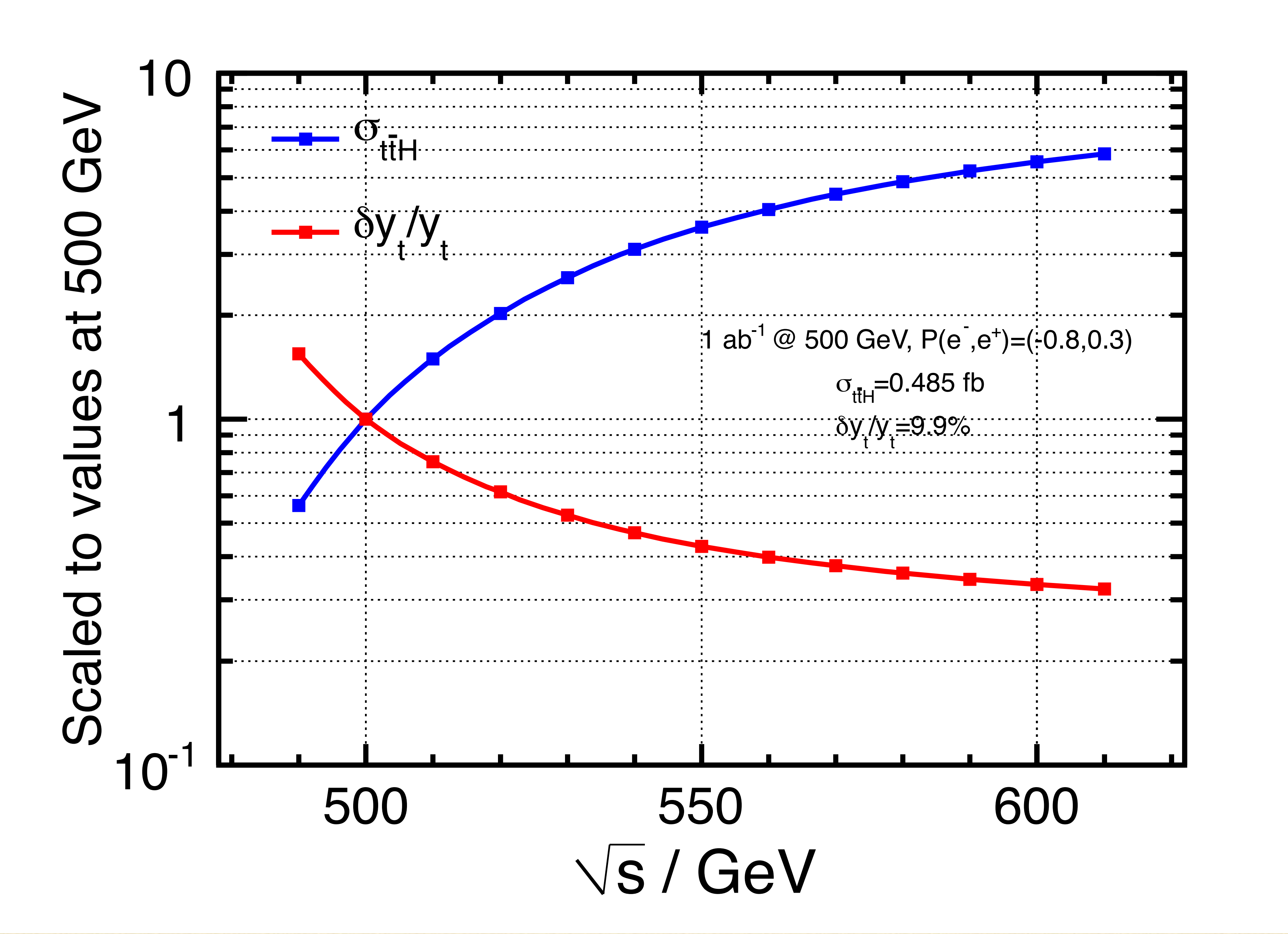
$$\Delta Y_i^2 = \Delta Y_i^2(\mathrm{exp}) + (\Delta_{\mathrm{Theory}} Y_i')^2$$

systematic error

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

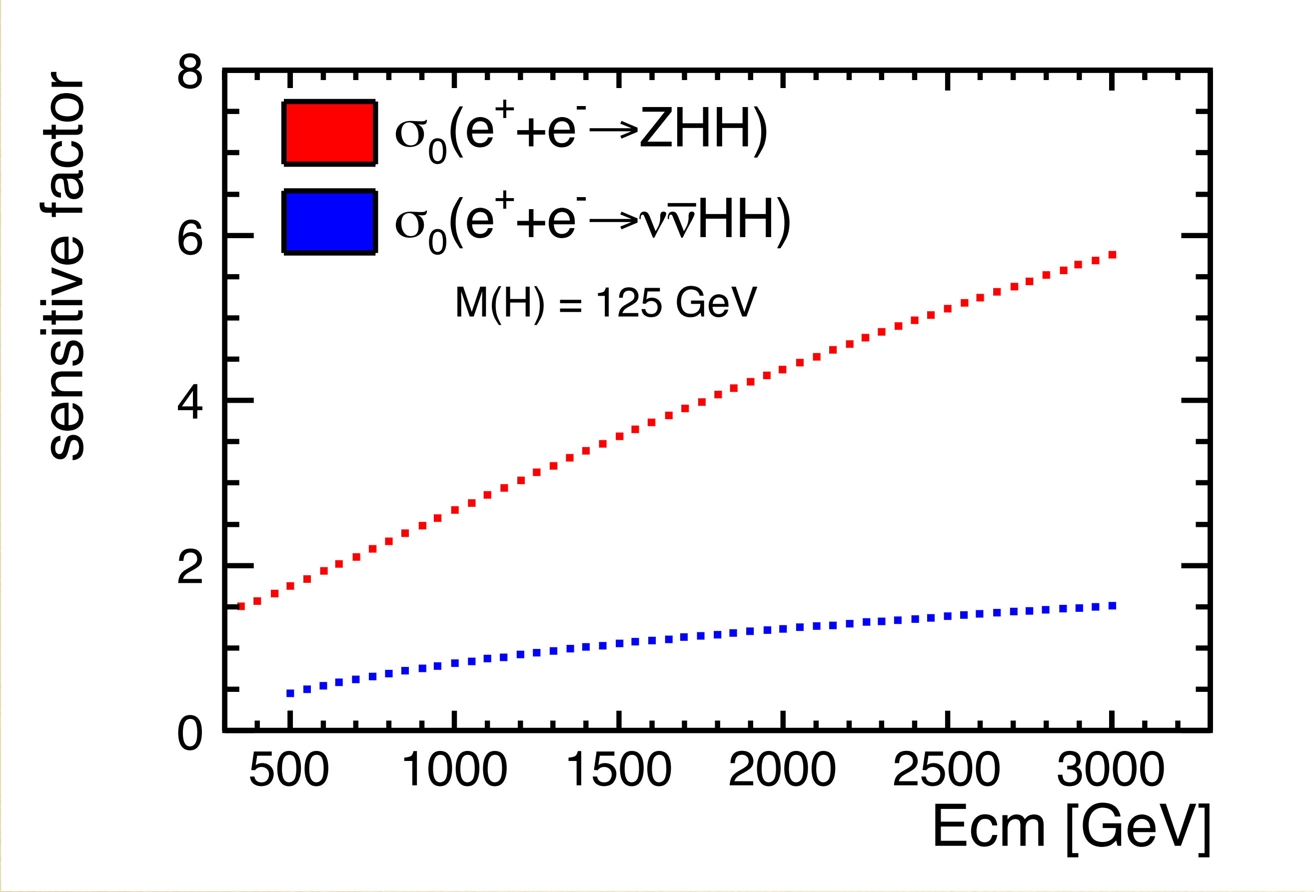
(* only for H-->bb)

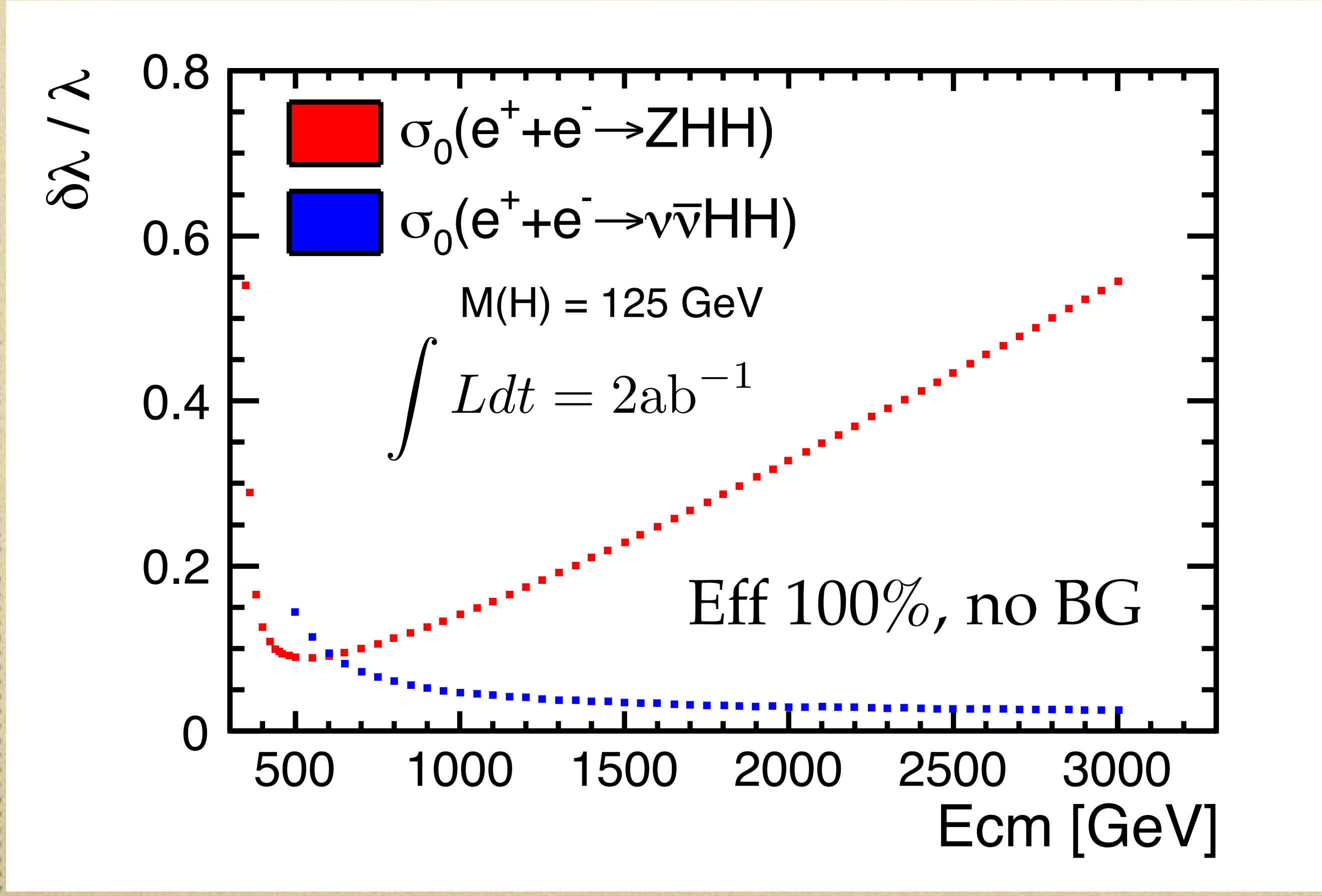
top-Yukawa coupling



many thanks to Y. Sudo!

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





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

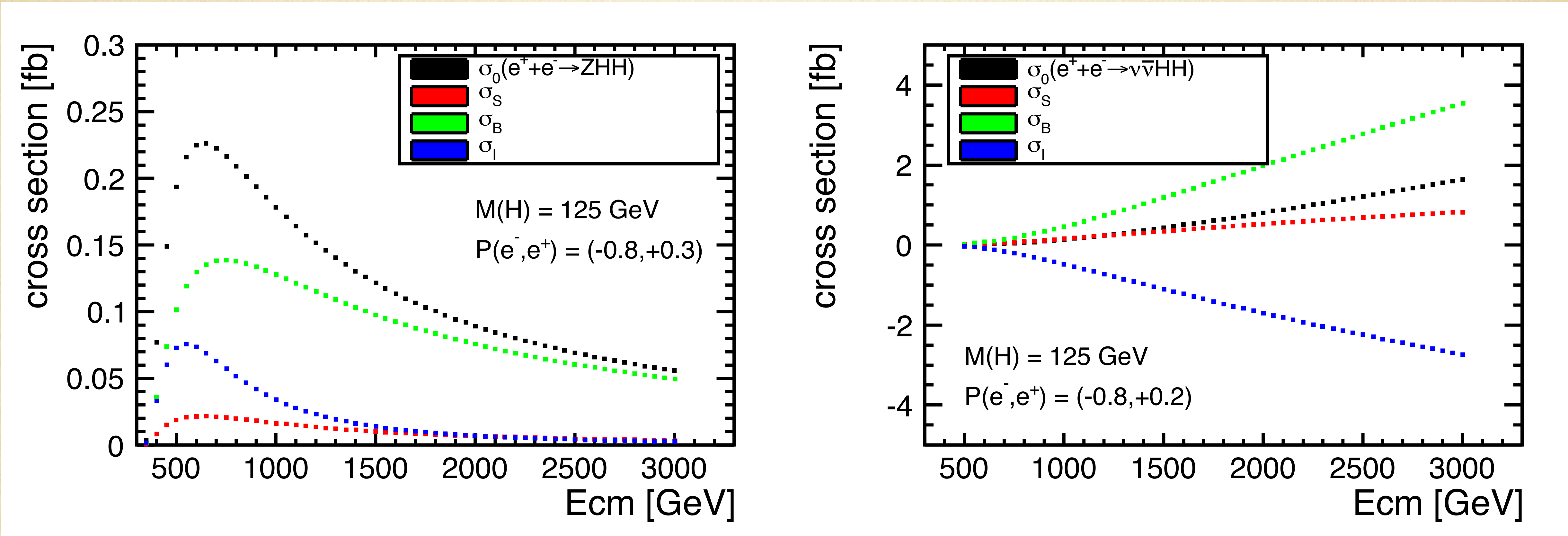
Factor increases quickly as going to higher energy

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

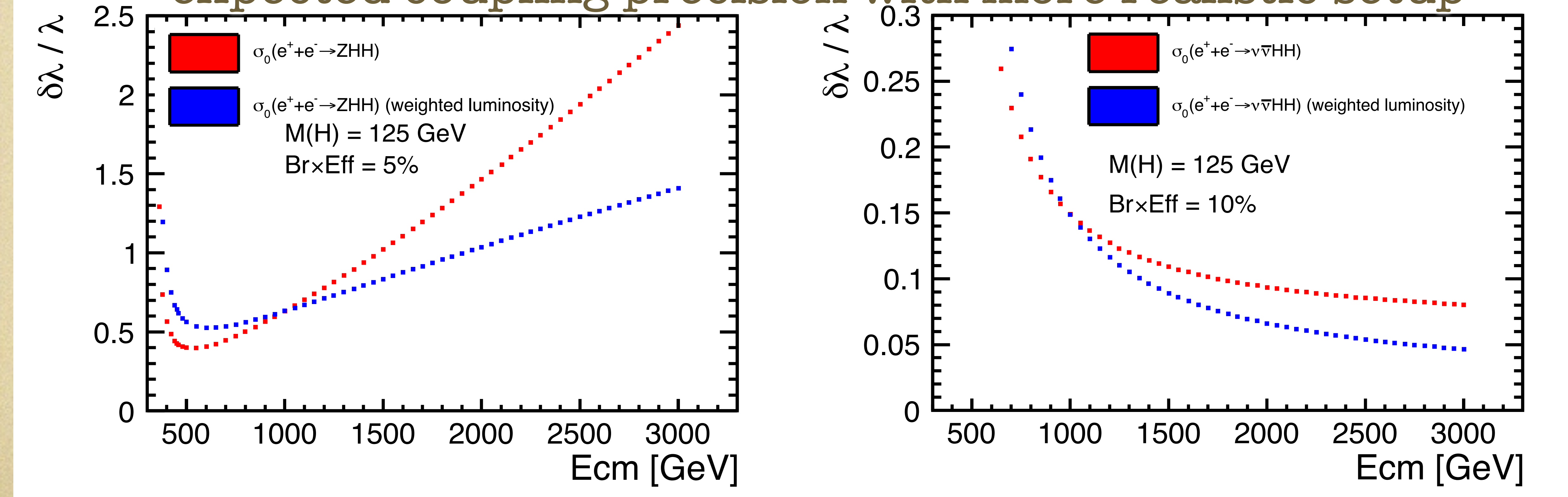
for νvHH, expected precision improves slowly as going to higher energy

General issue: cross sections of each contribution

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

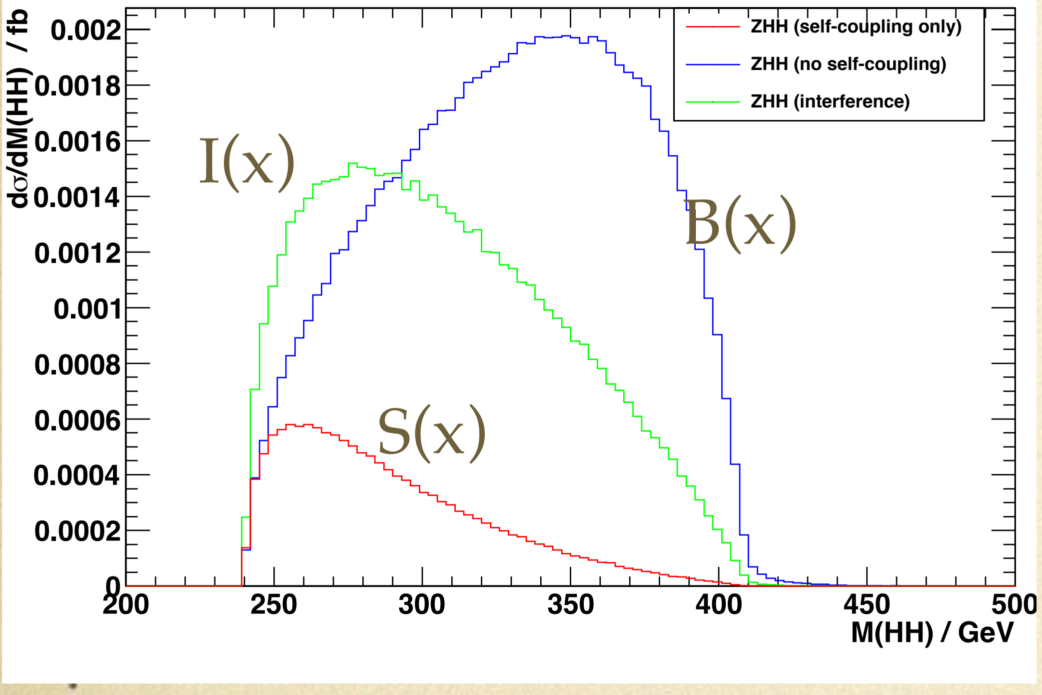


expected coupling precision with more realistic setup



new weighting method to enhance the coupling sensitivity

differential cross-section



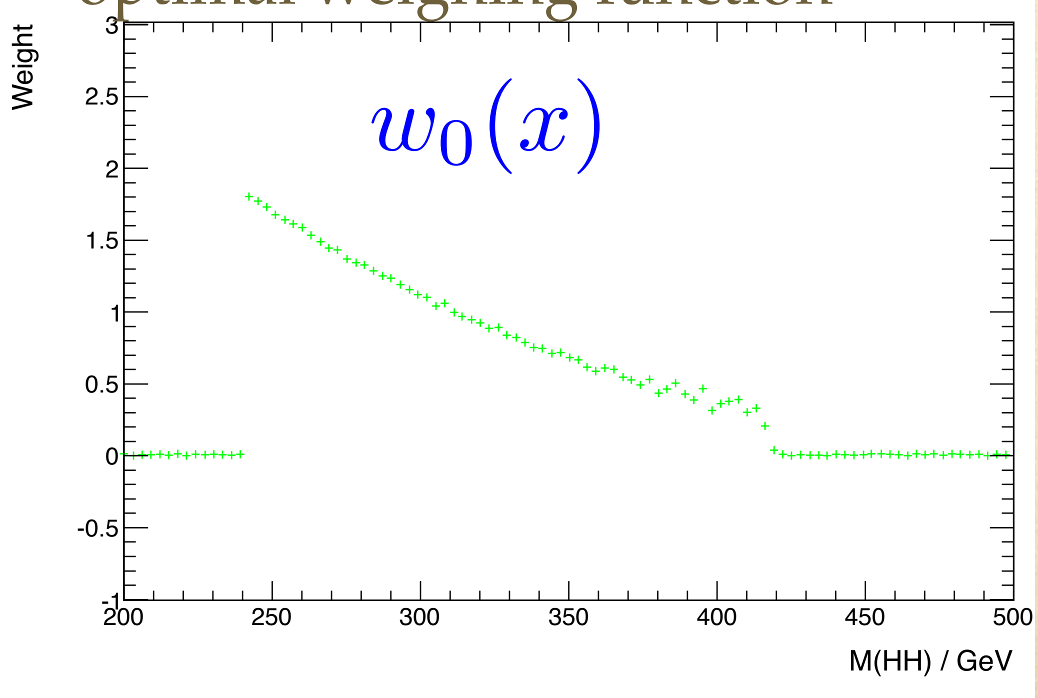
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = B(x) + \lambda I(x) + \lambda^2 S(x)$$

irreducible — interference — self-coupling

observable: weighted cross-section

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

optimal weighing function



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

$$\sigma(x) w_0(x) \int (I(x) + 2S(x)) w_0(x) \mathrm{d}x = (I(x) + 2S(x)) \int \sigma(x) w_0^2(x) \mathrm{d}x$$

general solution:

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

c: arbitrary normalization factor

Higgs Physics at Higher Energy

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

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

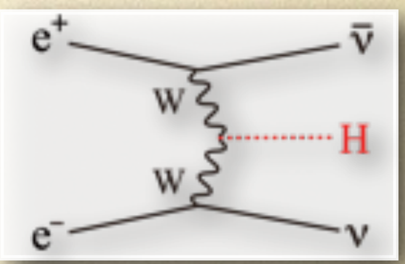
- allows us to measure rare decays such as H -> $\mu^+\mu^-$, ...
- further improvements of coupling measurements

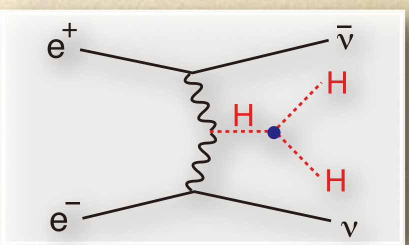
vvHH @ 1TeV or higher : 2ab^-1 (pol e+, e-)=(+0.2,-0.8)

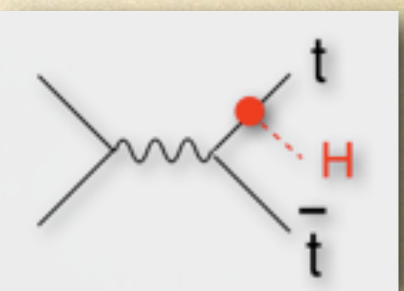
- self-coupling through WW-fusion.
- If possible, we want to see the running of the self-coupling (very very challenging).

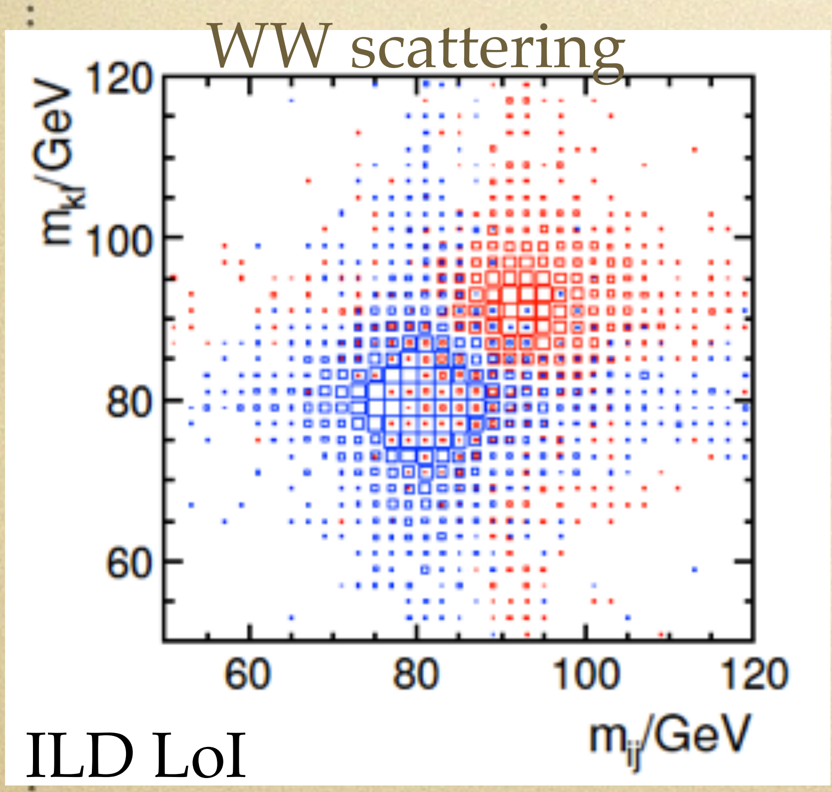
ttH @ 1TeV : 1ab^-1

- improve the top-Yukawa coupling









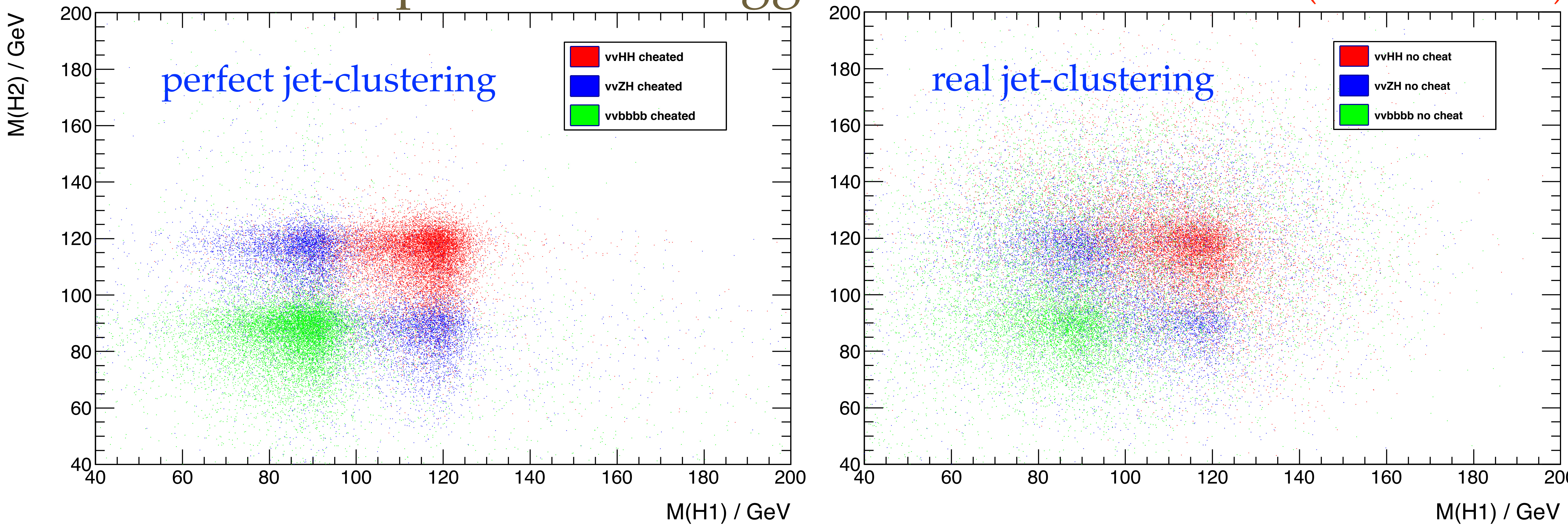
Obvious but most important advantage of higher energies in terms of Higgs physics is its higher mass reach to other Higgs bosons expected in an extended Higgs sector and higher sensitivity to W_LW_L scattering to decide whether the Higgs sector is strongly interacting or not.

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

prospect of Higgs self-coupling

scatter plot of two Higgs masses

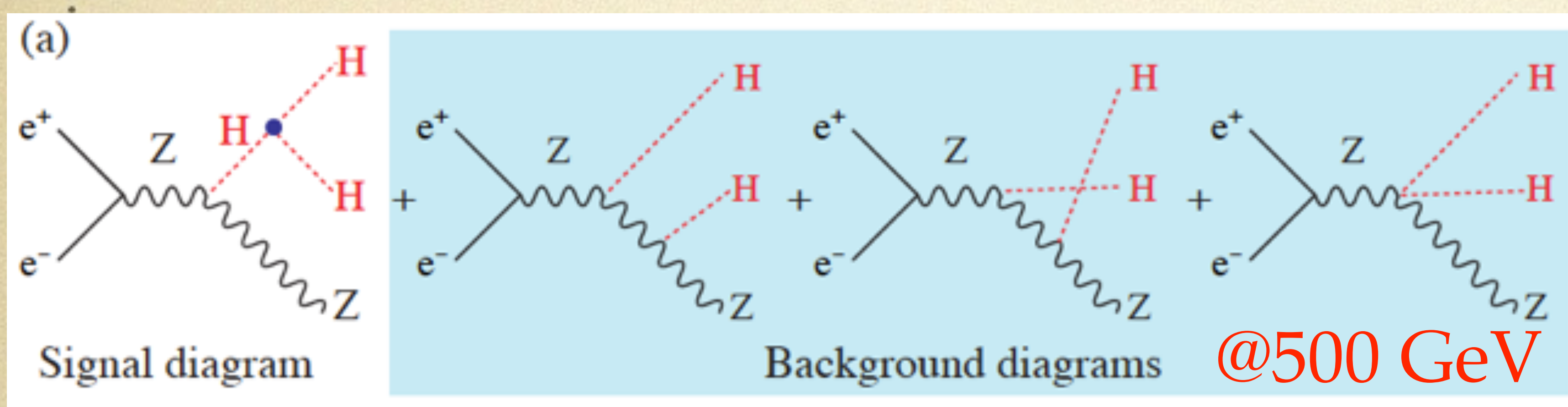
vvHH mode: (ZZH and ZZZ)



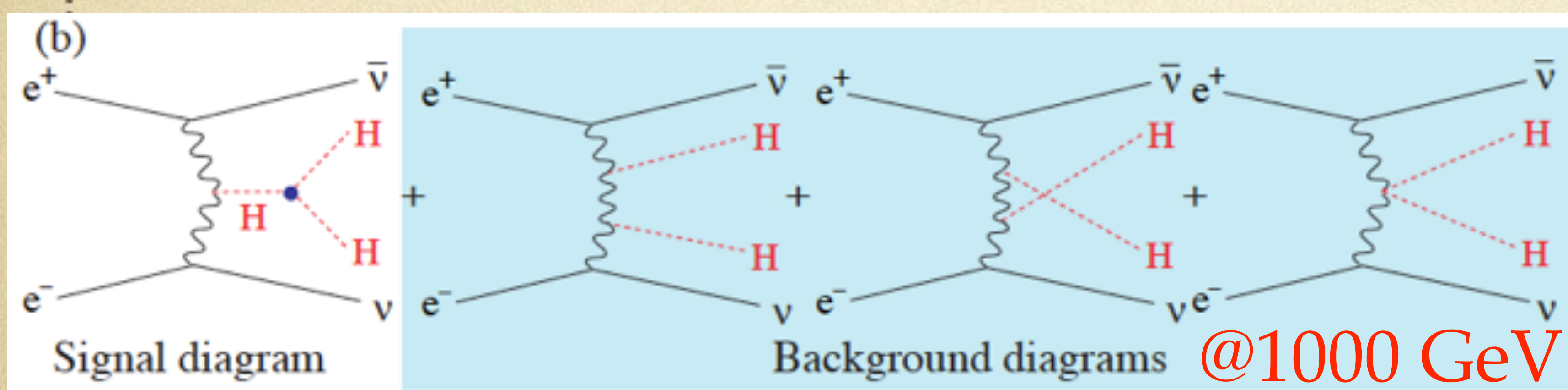
- the mis-clustering of particles degrades the mass resolution very much
- it is studied using perfect color-singlet jet-clustering can improve $\delta\lambda$ ~ 40%
- Mini-jet based clustering (Durham works when Np in mini-jet ~ 5, need better algorithm to combine the mini-jets, using such as color-singlet 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



more sensitive!



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

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

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

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

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

preliminary! correlation with HHH not included