Higgs Physics @ ILC250

11th Annual Meeting of the Helmholtz Alliance
"Physics at the Terascale"

Hamburg, 28-11-2017

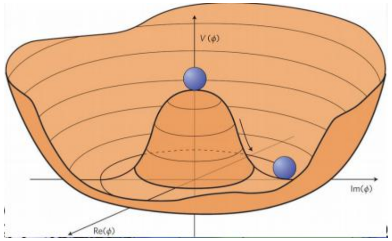
Yan Wang (DESY, IHEP)

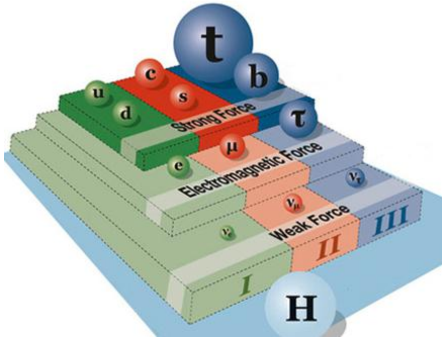
Higgs itself is the New Physics

The Higgs boson is found at the LHC in 2012, but it was just a beginning

Higgs not only the first elementary spin-0 particle, but also new interactions, involves two New Interactions

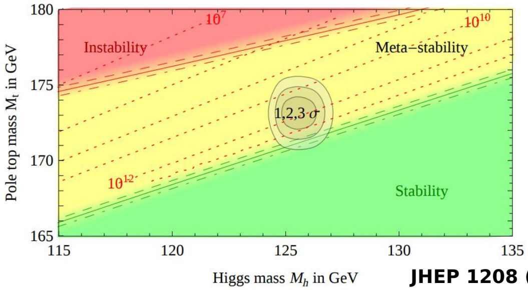
- **Higgs Yukawa coupling**
- **Higgs self-interaction**





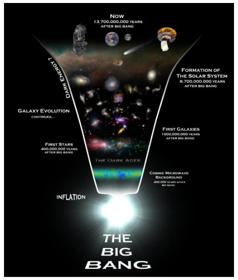
Related to

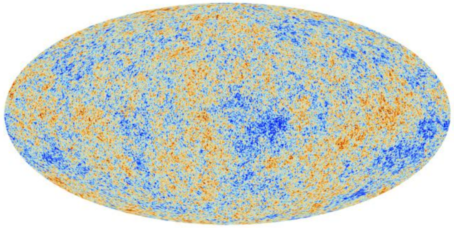
- **mass puzzle**
  - ✓ **W,Z masses --- SM Higgs mechanism?**
  - ✓ **fermion mass --- why large hierarchy?**
  - ✓ **higgs boson mass --- naturalness?**
- **vacuum stability? vacuum energy?**
- **inflation --- higgs involved inflation?**
- **dark matters --- higgs portal?**



JHEP 1208 (2012) 098

Precision Measurements may open the gate of NP world!





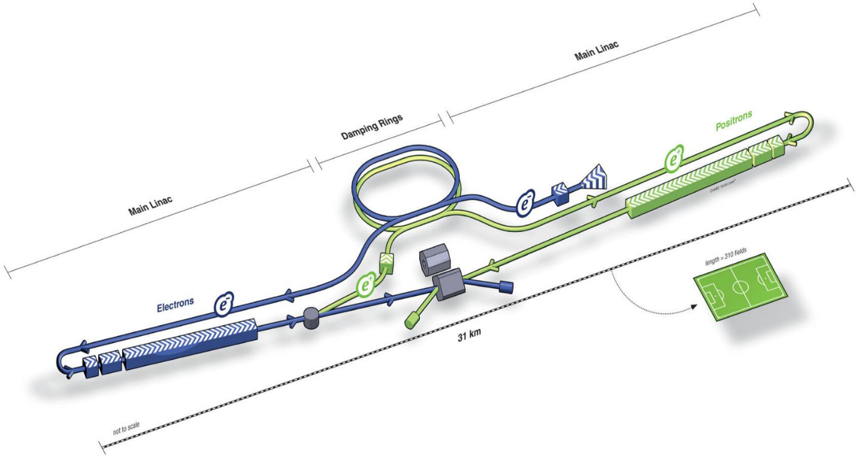
ILC

The International Linear Collider

ILC properties:

- polarized beams (e^-: ∓ 0.8, e^+: ∓ 0.3)
- center-of-mass energy = 250 GeV for the first stage
- Energy-upgrade capability

  --- 350 GeV, 500 GeV, even 1 TeV

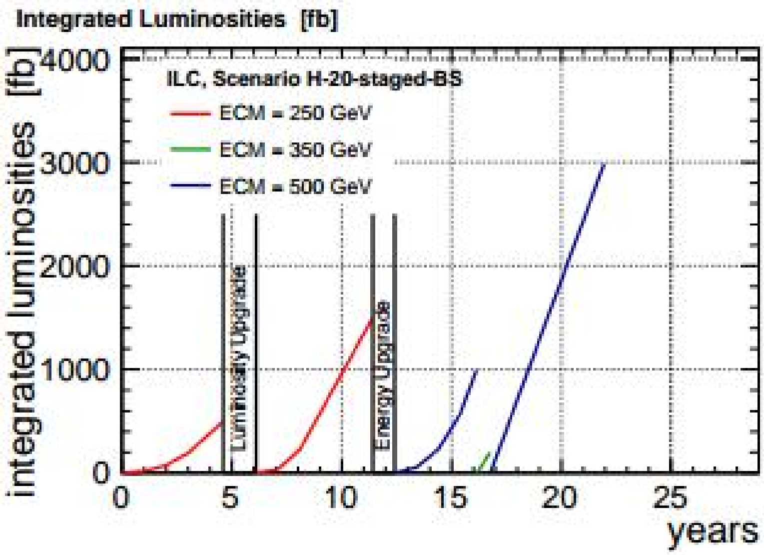


ILC Running Scenario:

one scenario for 22 years

- 2/ab @ 250 GeV
- 0.2/ab @ 350 GeV
- 4/ab @ 500 GeV

if possible 1 TeV upgrade ...



arXiv: 1710.07621 [hep-ex]

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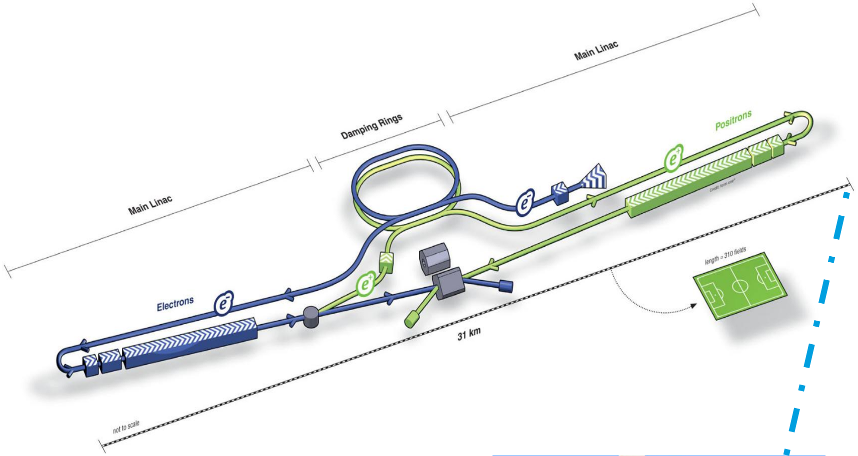


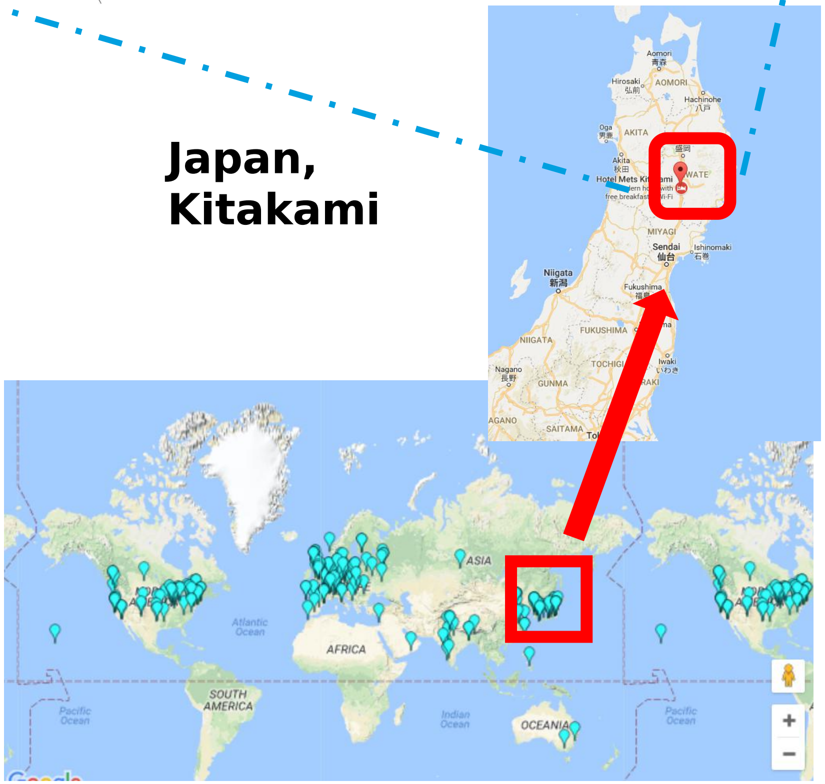
ILC Running Scenario:

new scenario for 22 years

- 2/ab @ 250 GeV
- 0.2/ab @ 350 GeV
- 4/ab @ 500 GeV

if possible 1 TeV upgrade ...

Japan,
Kitakami



Waiting for finally decision

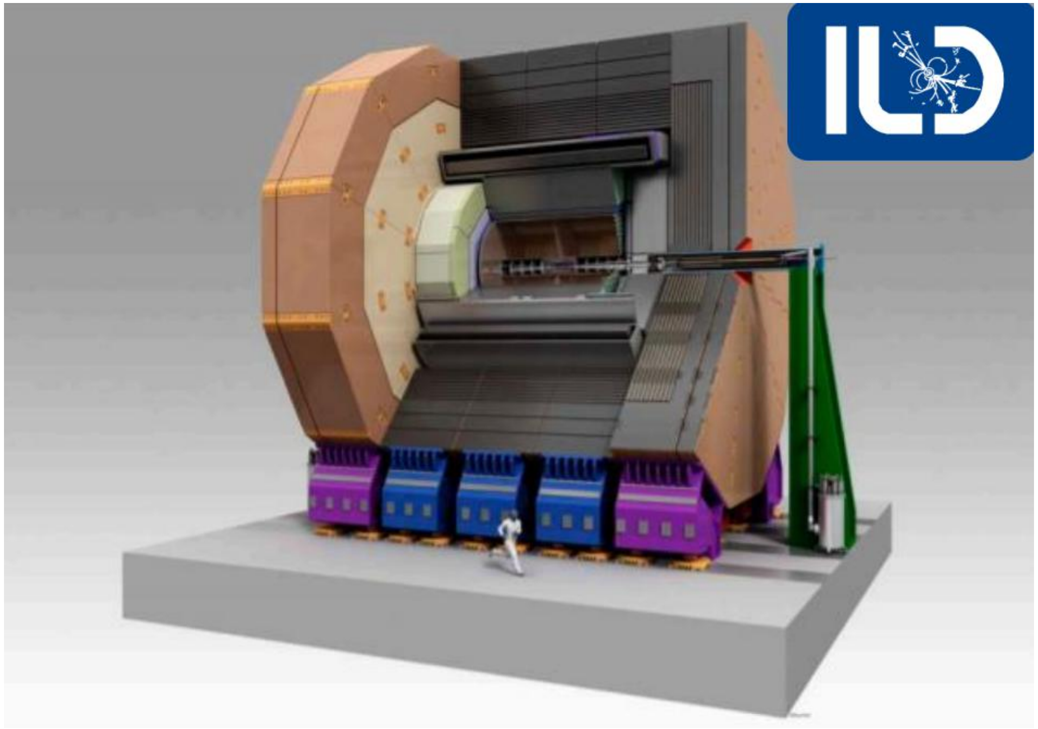
--- in 2018!

arXiv: 1710.07621 [hep-ex]

Detector Concept at the ILC

ILD (International Large Detector)

- Tracker:
  - Vertex, TPC
- Calorimeter:
  - ECAL, HCAL
- 3.5T magnetic field
- Yoke for muon, Forward system

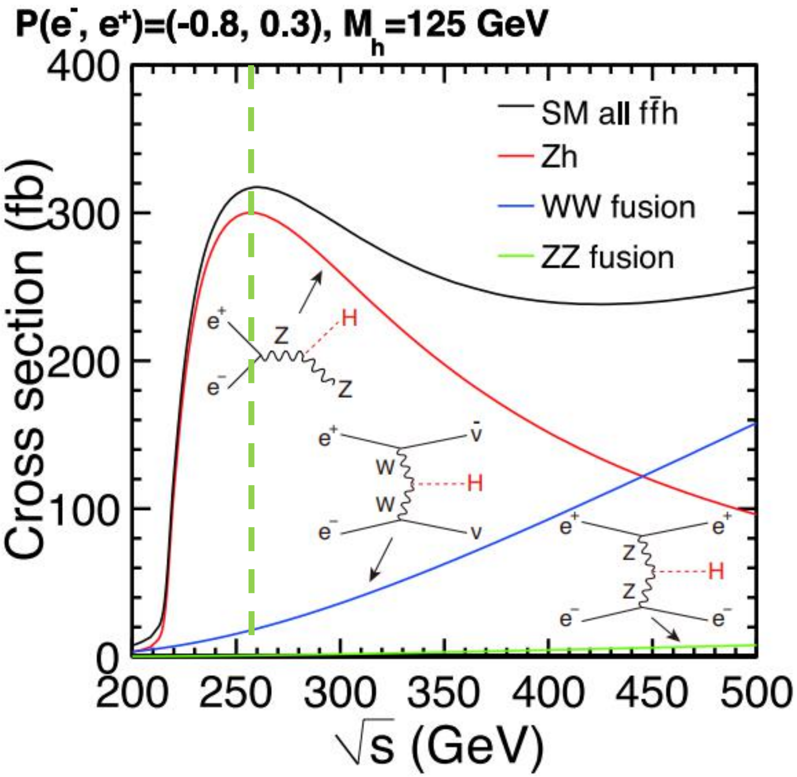


Requirements:

- Impact parameter resolution
  - $\sigma_{r\Phi} < 5 \oplus 10/(p^{*}\sin^{3/2}\theta)\mu m$
- Momentum resolution
  - $\sigma_{1/pt} < 2^{*}10^{-5}\ GeV^{-1}$
- Energy resolution
  - $\sigma_{E}/E = 3 - 4\%$

arXiv:1506.05992 [hep-ex]

Higgs production



- clean environment, known initial state
- @ILC250, Higgs-strahlung dominant, better to measure σ_{Zh}
  - ✓ larger cross section
  - ✓ less beamstrahlung effect
- measure σ_{Zh} model-independently
  - ➢ the key to determinate absolute couplings!
- recoil technique

$$M_{rec}^2 = (\sqrt{s} - E_{l^+l^-})^2 - |\vec{p}_{l^+l^-}|^2$$

  - ➢ No Higgs reconstruction required ---model-independent and precise measurement

Phys. Rev. D 94, 113002 (2016)

Higgs cross section & mass

Key measurement
model independent & accurate

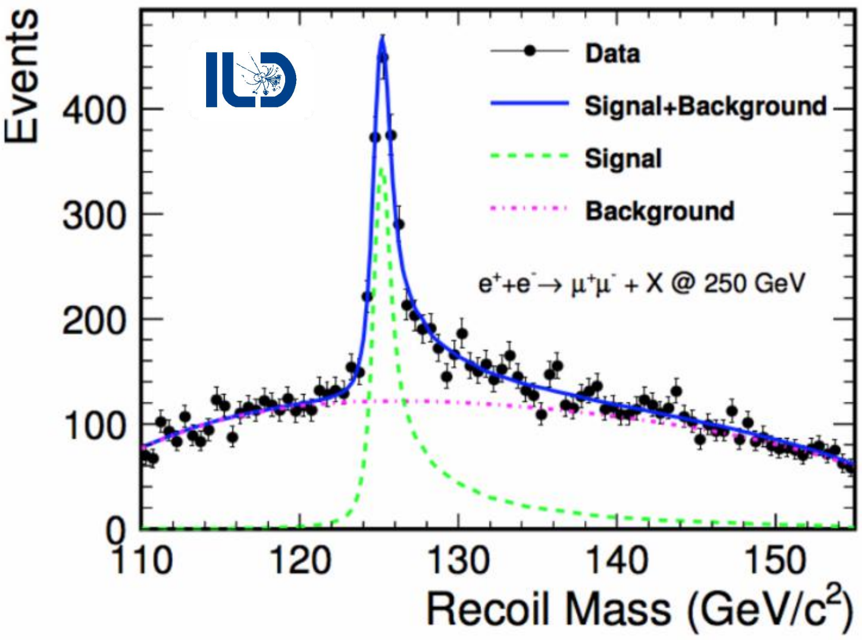
the expected precisions

$$\frac{\Delta\sigma_{Zh}}{\sigma_{Zh}} = 0.8\%, \frac{\Delta g_{hZZ}}{g_{hZZ}} = 0.4\%$$

relative bias of the different Higgs decay modes:

$\mu^+\mu^-H < 0.1\%$
$e^+e^-H < 0.2\%$

(-+)(+-) initial polarization states @ 250GeV + 2/ab



$\delta m_h \sim O(0.2\%)$ @LHC

already accuracy, but not enough.

e.g. $h \to ZZ^*$, $h \to WW^*$ partial width sensitive to m_h due to phase space!

relative errors for effective couplings are

$$\delta_W = 6.9 \cdot \delta m_h, \quad \delta_Z = 7.7 \cdot \delta m_h$$

$\delta_{Z/W} \sim O(1\%)$

@ILC250 $\delta m_h \sim$ 14 MeV

$\delta_{Z/W} \sim O(0.1\%)$

Higgs decay branching ratio

with recoil technique

- σ_{Zh} ·BR for various decay modes
- BR_{bb} ~ O(0.89%), $BR_{\tau\tau}$ ~ O(1.4%) BR_{cc} ~ O(3.2%), BR_{gg} ~ O(2.7%)
- BR_{WW} ~ O(1.9%), BR_{ZZ} ~ O(6.7%), $BR_{\gamma\gamma}$ ~ O(13%), $BR_{\mu\mu}$ ~ O(27%)
- BR_{inv}~ O(0.32%)

in κ-framework

$$\Gamma_{ZZ} \propto \kappa_Z^2 \propto \sigma_{Zh} \quad (\Gamma_{WW} \propto \kappa_W^2 \propto \sigma_{\nu\nu h}).$$

$$\Gamma_h = \boxed{\frac{\Gamma_{ZZ}}{BR_{ZZ}}} = \frac{\Gamma_{WW}}{BR_{WW}},$$

$$\kappa_A^2 \propto \Gamma_{AA} = \Gamma_h \cdot BR_{AA}. \quad A = b, c, g, \tau, \mu, \gamma$$

but $\sigma_{\nu\nu h}$ is small @ILC250

BR_{zz}~ O(6.7%) is too large

most couplings (except κ_z) > O(2%)

κ-framework is model dependent

$$\kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H$$

missing in κ-framework

$$\delta\mathcal{L} = \frac{m_Z^2}{v}(1+\eta_Z)hZ_\mu Z^\mu + \boxed{\zeta_Z \frac{1}{v} hZ_{\mu\nu}Z^{\mu\nu}}$$

$$\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$$
$$\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)\ .$$

So we change to EFT framework

Higgs Effective Theory: Definition

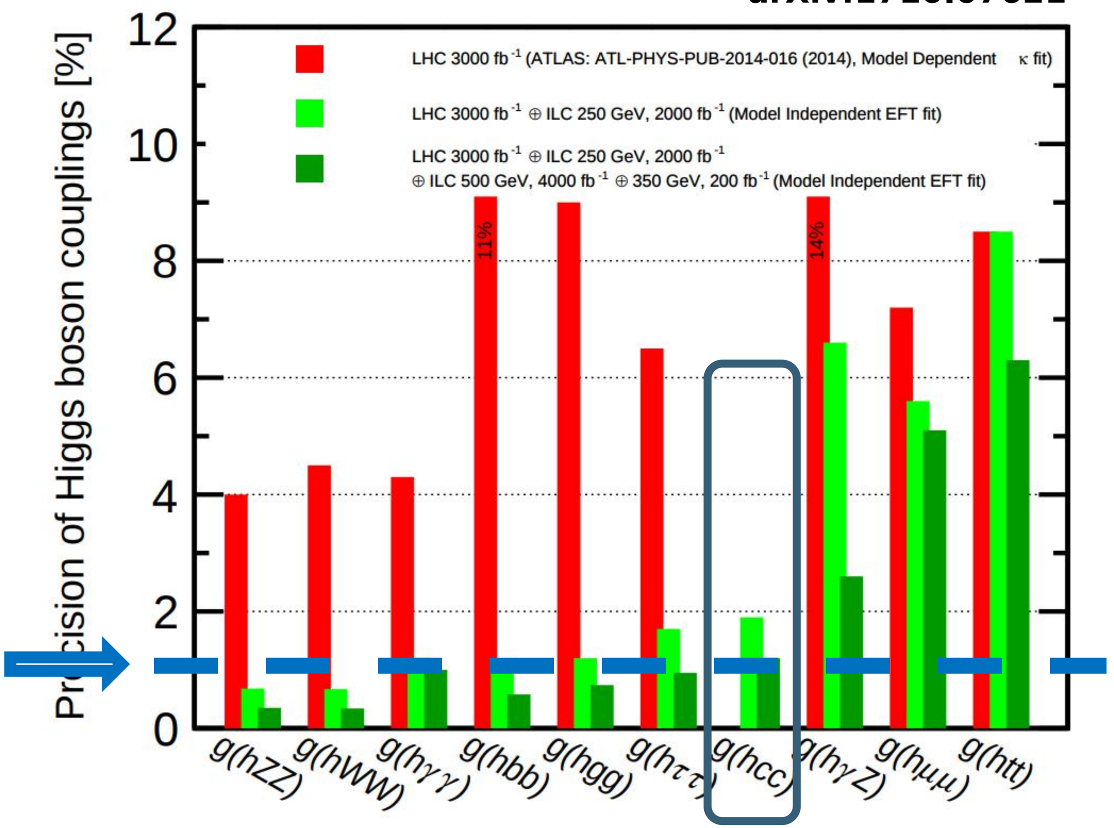
EFT-based framework

- **most general set of SU(3)xSU(2)xU(1) invariant dim-6 operators**
- **10+7 parameters --- available at the ILC**
- **model independent**
- **the best way to parametrize deviations from the SM in Higgs physics**
- **couplings extracted by global fit**
- **combining channels**
  - **$e^+e^- \to Zh$, $e^+e^- \to WW$,**
  - **EW precise measurement, TGC ...**

Higgs Decay Channel and Couplings

- **Compared to HL-LHC, ILC250 provide quantitative and qualitative improvement.**
  - ✓ **O(1%) for many couplings**
  - ✓ **model independent**
  - ✓ **measurement for 2nd generation**
- **ILC500 improves a factor of 2**

arXiv:1710.07621



2/ab 250 GeV,
(−+; +−; −−; ++) = (45%; 45%; 5%; 5%)
4/ab 500 GeV,
(−+; +−; −−; ++) = (40%; 40%; 10%; 10%)

ILC TDR Volume 2: Physics, PRD 90, 095017 (2014)

New Physics model discrimination

How accurate we need for BSM?

Littlest higgs

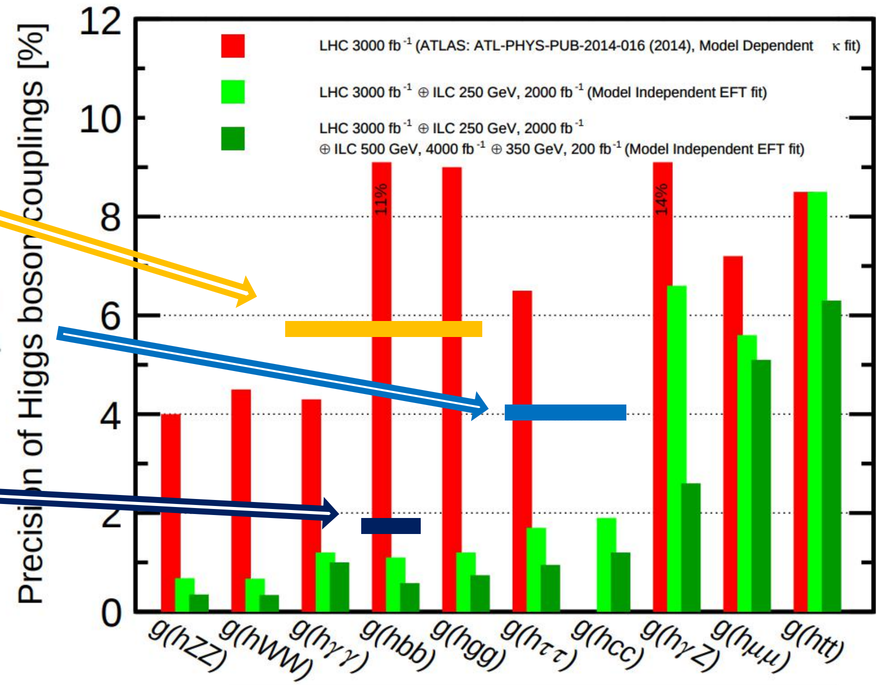
$$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} = 1-(5\% \sim 9\%)$$
$$\frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} = 1-(5\% \sim 6\%),$$

Composite higgs

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

MSSM

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



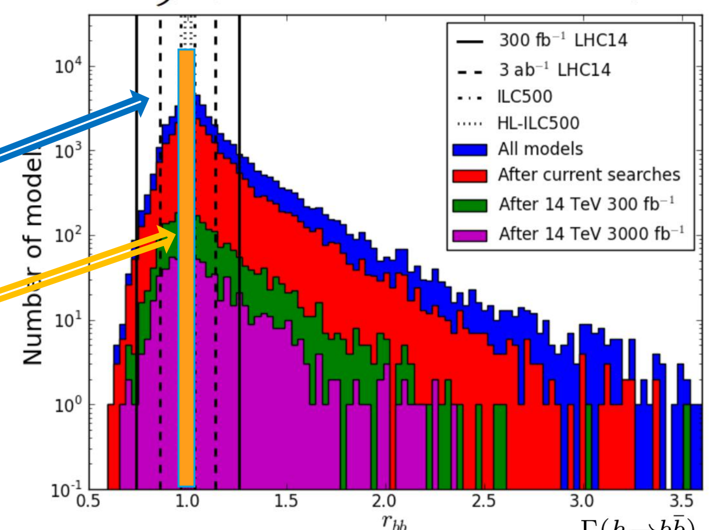
pMSSM model

scan 19 parameter sets with a neutralino/gravitino LSP

survive from direct LHC SUSY search and other constrains

after HL-LHC projection for direct SUSY search and Higgs coupling measurement, still many sets remain

δg(hbb)~1.1% @ILC250



$$r_{bb} = \frac{\Gamma(h\to b\bar{b})}{\Gamma(h\to b\bar{b})_{SM}}$$

New physics model discrimination

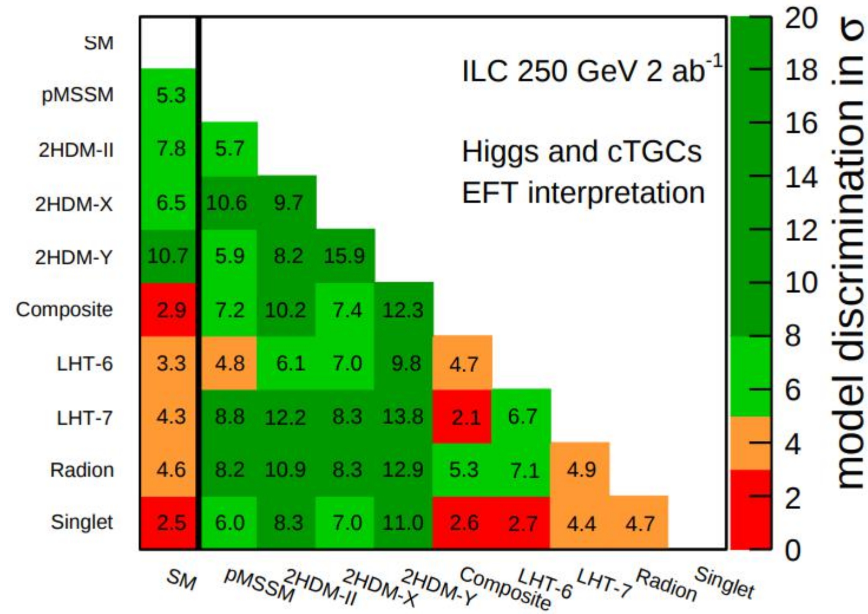
combine Higgs and EW (TGC) measurement

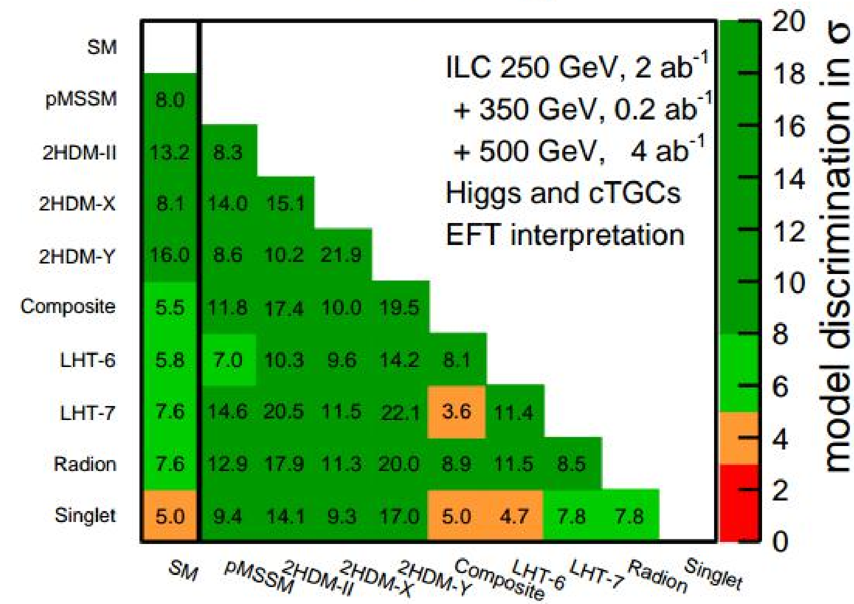
assume no new physics associated with EWSB is found at the HL-LHC

maximum deviations for higgs coupling in different models

	$\Delta g(hVV)$	$\Delta g(ht\bar{t})$	$\Delta g(hb\bar{b})$
Composite Higgs	10%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	tens of %
Mixed-in Singlet	6%	6%	6%

illustrates the ability of ILC measurements to distinguish the Higgs boson couplings in these models

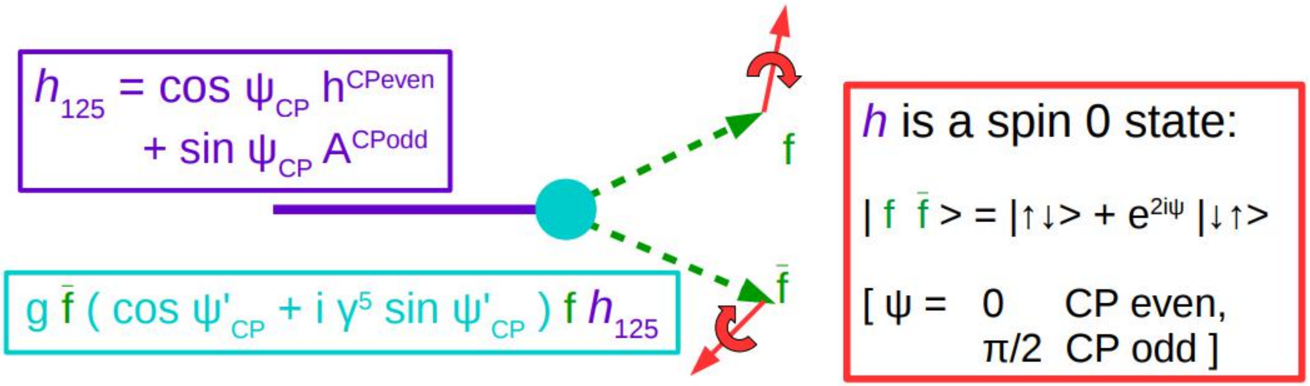




Higgs CP

Nucl.Instrum.Meth. A810 (2016) 51-58
Daniel Jeans's talk at LCWS2016

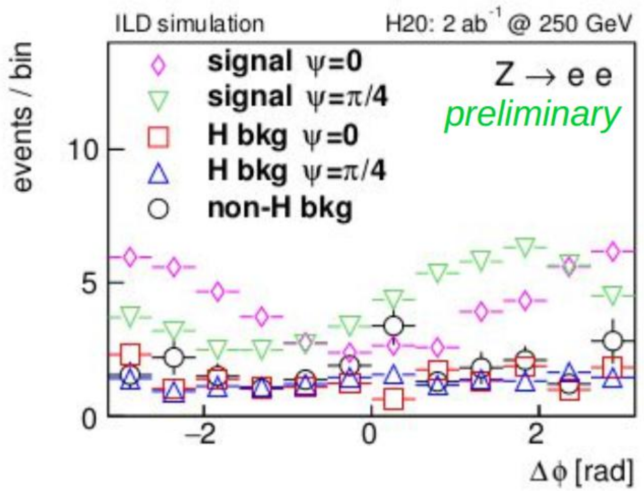
Higgs CP --- Hττ channel



fermion must be unstable
kinematics of fermion's daughter → polarisation of fermion→ CP of higgs and coupling

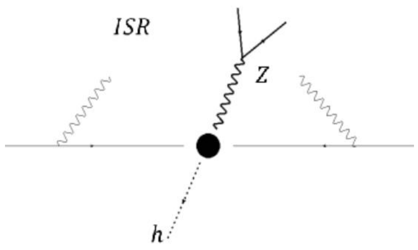
τ best for fermions
- **decays in detector**
- **no QCD between taus**

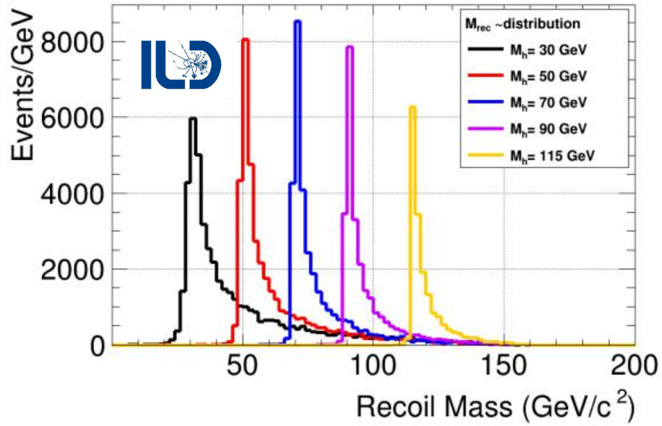
CP δψ ~ 3.8◦

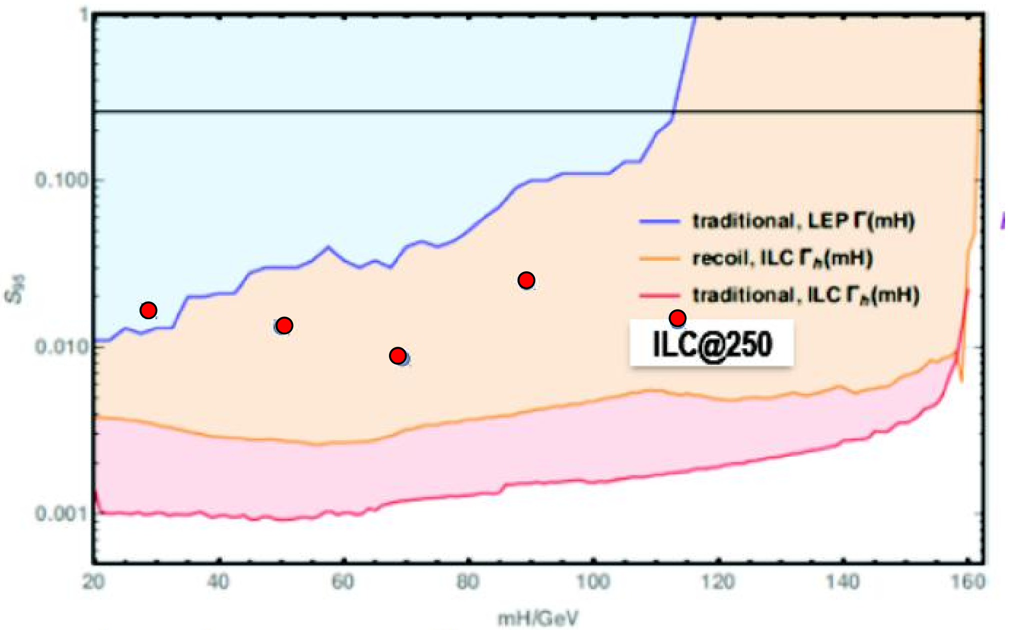


Direct search --- light higgs

(-80%, +30%) initial polarization states @250GeV, 2/ab







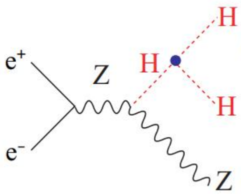
$$S_{95} = \left[\frac{\hat{\sigma}_{ee\to\phi_i Z}}{\sigma^{\rm ref}_{ee\to\tilde{h}Z}}\right]_{\substack{g_{\tilde{h}ZZ}=g_{hZZ} \\ m_{\tilde{h}}=m_{\phi_i}}} = \frac{\hat{n}}{n_{\rm ref}} = \frac{\hat{g}^2_{\phi_i ZZ}}{g^2_{hZZ}}$$

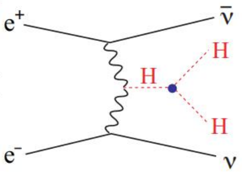
- **Many BSM models favor a low mass higgs (2HDM, NMSSM)**
- **LEP and LHC constrains --- coupling strongly reduced!**
- **A model-independent analysis with light higgs recoiling against Z**
- **mass range [10, 125) GeV with full ILD detector simulation @ILC250 is ongoing**
- **five benchmark point for illustration m_h=30, 50, 70, 90, 115 GeV**
- **spliting higgs decay mode into visible and invisible will lead to a better results**

ILC upgrade

@ILC 500/550 GeV, WW-fusion dominant

H^3 ~ O(27%) ~ 3σ





WW-fusion cross section

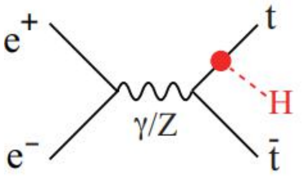
Higgs width

$$\Gamma_H = \frac{\Gamma(H \to WW^*)}{\mathrm{BR}(H \to WW^*)},$$

$$\frac{\Delta g_{hWW}}{g_{hWW}} = 0.42\%$$

$$\frac{\Delta\Gamma^h_{\mathrm{total}}}{\Gamma^h_{\mathrm{total}}} = 1.8\%$$

ttH ~O(3% - 6%)



improve precision of Higgs coupling by a factor of 2

Summary

- Higgs properties is the key to many essential physics questions.
- ILC with polarised beams offer supremely accurate measurements.
- Higgs gauge & Yukawa couplings & self-interaction

  model-independent measurement.

  HZZ, HWW, Hγγ, Hgg, Hbb, Hττ ... reach O(1%).
- Discriminate BSM models.
- Direct search for new light higgs bosons.
- ILC is upgradable, 250 GeV is a first step!
- ILC should be treated as the priority task and to be constructed as soon as possible!

backup

Higgs Decay Channel and Couplings

	ILC250		+ILC500	
	κ fit	EFT fit	κ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
$g(h\mu\mu)$	5.6	5.6	5.1	5.1
$g(h\gamma Z)$	16	6.6	16	2.6
$g(hbb)/g(hWW)$	0.88	0.86	0.47	0.46
$g(h\tau\tau)/g(hWW)$	1.0	1.0	0.65	0.65
$g(hWW)/g(hZZ)$	1.7	0.07	0.26	0.05
Γ_h	3.9	2.5	1.7	1.6
$BR(h \to inv)$	0.32	0.32	0.29	0.29
$BR(h \to other)$	1.6	1.6	1.3	1.2

arXiv:1710.07621

Major physics processes @ILC

Energy	Reaction	Physics Goal	Polarization
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak	A
160 GeV	$e^+e^- \to WW$	ultra-precision W mass	H
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings	H
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings	A
	$e^+e^- \to WW$	precision W couplings	H
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings	L
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'	A
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top	H
	$e^+e^- \to Zhh$	Higgs self-coupling	H
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry	B
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states	B
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling	L
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector	L
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top	L
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry	B

Higgs CP Hττ detail

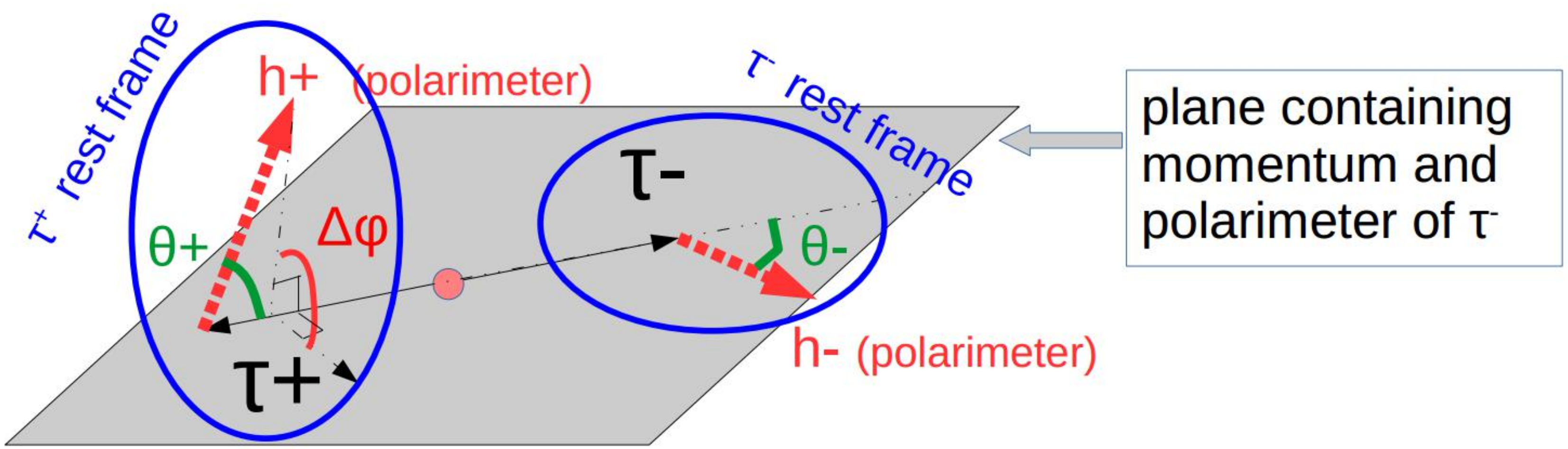
Nucl.Instrum.Meth. A810 (2016) 51-58

with visible Z decay products
- ✓ **τ production vertex**
- ✓ **pT of τ-τ system**

the impact parameters of charged tau decay products

→ **full reconstruction of τ decay products, including the neutrino(s)**

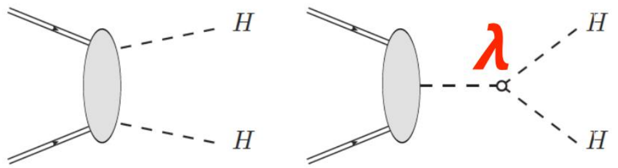
→ **reconstruct τ polarimeter**



θ±, φ±	direction of h± with respect to τ- boost in τ± rest frame
Δφ	angle between polarimeter planes
ψ_{CP}	CP mixing angle we want to measure

arxiv:1506.07830, arxiv:1708.09079

HHH coupling



non-trivial relations between cross sections and λ

@ILC500, ZHH

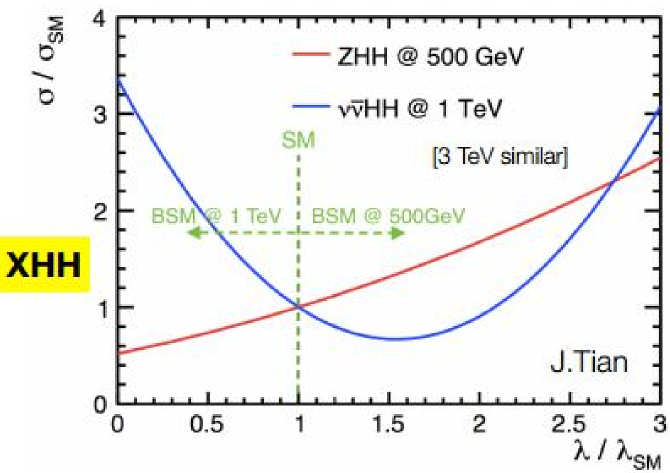
- **Observation of HH with 8σ**
- **extract $\delta\lambda_{SM}$ ~ O(27%)**

@ILC1 TeV, 4ab-1, vvHH

- **$\delta\lambda_{SM}$ = 10%**

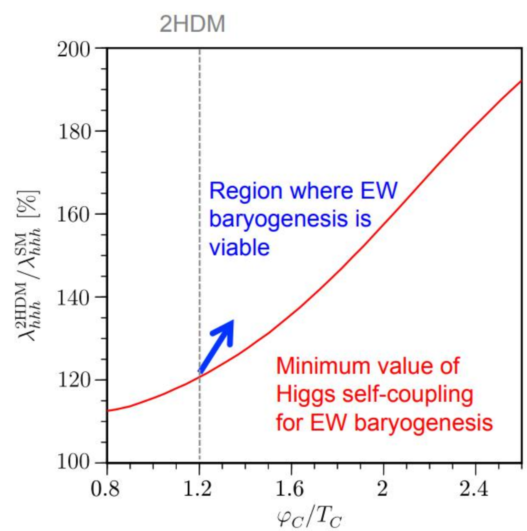
precision depends strongly on actual value of λ

e^+e^- -> XHH



many BSM models will lead to a large λ O(100%) even if other couplings are SM-like [Phys.Lett. B558 (2003) 157-164]

electroweak baryogenesis requires λ > 1.2 λ_{SM}



Major physics processes @ILC

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	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry	**B**

10 dim-6 CP-conserving operator

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

4 dim-6

$$\Delta\mathcal{L}_{CP} = +\frac{g^2\tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} + \frac{4gg'\tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}\widetilde{B}^{\mu\nu}$$
$$+\frac{g'^2\tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{g^3\tilde{c}_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho\widetilde{W}^{c\rho\mu}$$

Higgs related dim-6 operators

Table 1. List of dimension-6 effective operators for the present study.

Higgs	EW Gauge Bosons	Fermions
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$	$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}_{BB} = g^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{LL}^{(3)} = (\overline{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
	$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\Psi}_L \gamma^\mu \Psi_L)$
Gluon	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\overline{\psi}_R \gamma^\mu \psi_R)$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_y^u = \lvert H\rvert^2 \overline{\Psi}_L^q \tilde{H} u_R$
	$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D_\nu W^{a\mu\nu}$	$\mathcal{O}_y^d = \lvert H\rvert^2 \overline{\Psi}_L^q H d_R$
	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) D_\nu B^{\mu\nu}$	$\mathcal{O}_y^\ell = \lvert H\rvert^2 \overline{\Psi}_L^\ell H \ell_R$