The Higgs Program at the International Linear Collider.

on behalf of the ILC Physics and Detector Study

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EPS-HEP Vienna, July 22-29 2015

PIER

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Introduction

- discovery of Higgs-like boson at LHC is milestone in history of particles physics
- **main task**: identify boson and its connection to the SM → last particle of SM?
  → first particle beyond the SM?
  - now test symmetry breaking and mass generation
  - open door to new physics?
- **our goal**: model-independent reconstruction of EWSB sector through precision measurements
  - investigate mass-coupling relation
  - any deviation clear indication of BSM
- **needed**: comprehensive program of model-independent and direct Higgs boson measurements

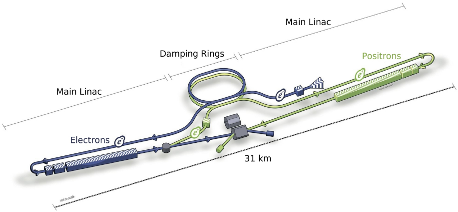
$$m_H,\ g_{HZZ},\ g_{HWW},\ g_{Hb\bar{b}},\ g_{Hgg},\ g_{H\gamma\gamma},\ g_{H\tau\tau},\ g_{Hc\bar{c}},\ g_{Ht\bar{t}},\ g_{H\mu\mu},\ g_{HHH},\ \Gamma_H^{tot},\ \Gamma_{invis}$$

- ILC is ideally situated to give a full understanding of new boson, whatever nature it is

Chip Brock, Snowmass 2013

The International Linear Collider

- energy range: $\sqrt{s} = 250$ GeV $-$ 500 GeV, upgradeable to 1 TeV
- about 31 km site length for $\sqrt{s} = 500$ GeV
- polarised beams ($\approx$ 80% for e^- and $\approx$ 30% $-$ 60% for e^+)



Japan showed great interest to host ILC

REFERENCES PICTURES MISSING

COMMENT ON MEXT

PHOTO OF MEN WEARING SUITS

ILC Operating Scenario

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

- studied impact of running scenarios on physics output

  optimise

  - Higgs precision measurements
  - top physics
  - new physics searches

- energy stages between (500 - 250) GeV

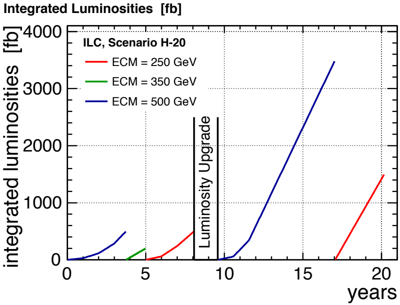
- following LHC and early ILC results:

  - best combination of dataset sizes
  - other energies may be required

- limited to 20 years before possible 1TeV upgrade

final $\mathcal{L}$ and real time required for each stage of running

Stage	ILC500			ILC500 LumiUP		
$\sqrt{s}$ [GeV]	500	350	250	500	350	250
$\mathcal{L}$ [fb^{-1}]	500	200	500	3500	-	1500
time [a]	3.7	1.3	3.1	7.5	-	3.1



Single Higgs Production Processes

LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

at $\sqrt{s} \geq$ 250 GeV

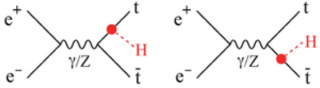
- Higgs-strahlung dominant production process
- beneficial for measuring σ_{ZH} and m_H
  $\rightarrow$ limited sensitivity to g_{HWW}

at $\sqrt{s} \geq$ 450 GeV

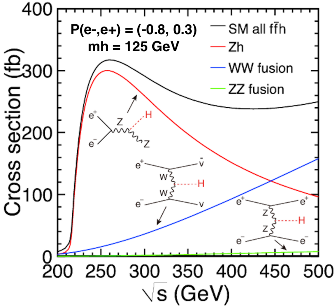
- WW-fusion process of similar size
  $\rightarrow$ balanced sensitivity g_{HZZ} and g_{HWW}

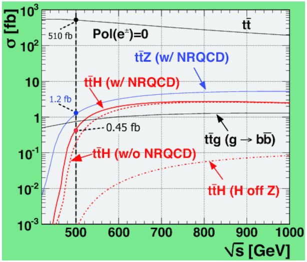
at $\sqrt{s} \geq$ 500 GeV

- process $e^+e^- \rightarrow t\bar{t}H$ accessible
  $\rightarrow$ probe top-Yukawa coupling g_{Htt}



Due to these three production processes, Higgs physics exhibits the most complex interplay between different energies





Recoil Mass Technique: $m_H \to \sigma_{ZH} \to g_{HZZ}$

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex], LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

$$m_H \to \sigma_{ZH} \propto g^2_{HZZ}$$

model-independent measurement of coupling

→ g_{HZZ} without Γ_H assumptions

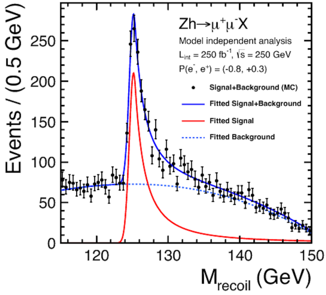
→ no Higgs reconstruction required

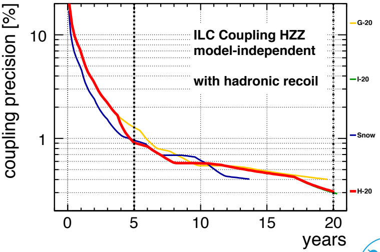
- well-known p_{cm} of initial e^+e^- system allows measurement of **inclusive** σ_{ZH}
- **recoil technique**: reconstruct Z of ZH event
  → recoil mass of decay products give m_H

$$M_X^2 = (p_{cm} - (p_{l^+} + p_{l^-}))^2 , \quad (l^\pm = e^\pm, \mu^\pm)$$

	ILC500	ILC500 LumiUP
Δm_H	25 MeV	15 MeV
$\Delta g_{HZZ}/g_{HZZ}$	0.58 %	0.31 %

- detect $H \to$ invisible/exotic
- precise m_H and σ_{ZH} (sub-% level)
- fixes the overall scale for all couplings





WW-fusion and 500 GeV: $g_{HWW} \rightarrow \Gamma_H$

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex], LCC Physics Working Group, arXiv:1506.05992v2 [hep-ex]

- compare Higgs rate measurements to SM predictions assumptions on Γ_H made

$$\mathrm{BR}(H \rightarrow AA) = \Gamma(H \rightarrow AA)/\Gamma_H^{tot}$$

→ total width too narrow to be measured directly

↓

needed to learn absolute sizes of Higgs couplings

↓

ILC measurements give model-independent determination of Γ_H

- WW-fusion production dominant at 500 GeV

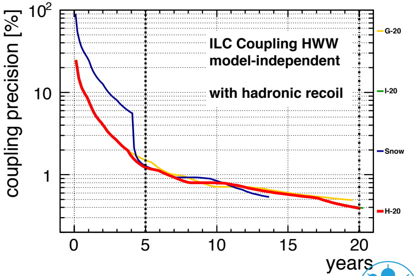
$$e^+e^- \rightarrow \nu\bar{\nu}H \quad \text{with} \quad H \rightarrow b\bar{b}$$

using relation

$$\sigma_{\nu\nu H} \cdot \mathrm{BR}(H \rightarrow b\bar{b}) \propto g_{HWW}^2 \cdot \mathrm{BR}(H \rightarrow b\bar{b})$$
$$\propto \Gamma(H \rightarrow WW) \cdot \mathrm{BR}(H \rightarrow b\bar{b})$$

	ILC500	ILC500 LumiUP
$\Delta\Gamma_H$	3.8 %	1.8 %
$\Delta g_{HWW}/g_{HWW}$	0.81 %	0.42 %

- g_{HZZ} → absolute normalization of g_{HWW}
- Γ_H → absolute normalization of couplings
- g_{HWW}^2/g_{HZZ}^2 represents test of SU(2)



Top-Yukawa Coupling at 500 GeV

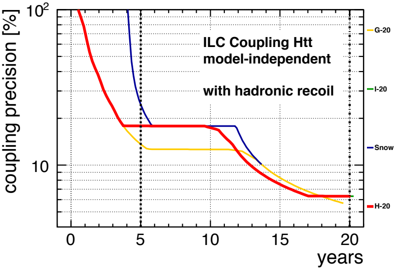
ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

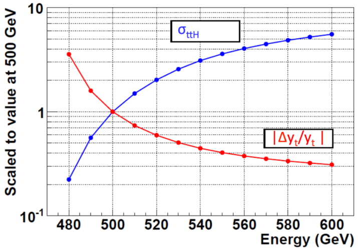
- top quark heaviest particle in SM
  - couples most strongly to Higgs sector
  - g_{Htt} could contain special effects
  - should be measured model-independently
- at ILC directly accessible through

  $e^+e^- \rightarrow t\bar{t}H$ (with $H \rightarrow b\bar{b}$)
- enhanced cross section at $\sqrt{s} = 500$ GeV
  - need full energy $\rightarrow$ close to production threshold
- at $\sqrt{s} = 550$ GeV better precision on g_{Htt}
  - by factor 4 enhanced cross section
  - main backgrounds decrease

$\Delta g_{Htt}/g_{Htt}$	ILC500	ILC500 LumiUP
500 GeV	18 %	6.3 %
550 GeV	$\sim$ 9 %	$\sim$ 3 %

increasing $\sqrt{s}$ by 10%, precision improves by factor two for same integrated luminosity





Precision on Relevant Higgs Couplings

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

- model-independent global fit to extract Higgs couplings and width

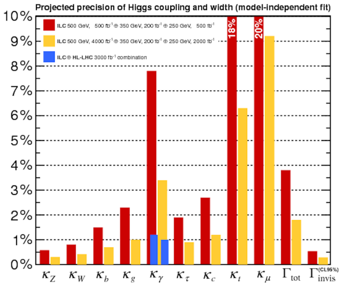
  input to coupling fit:

  - staged running and various production processes provide direct independent measurements of

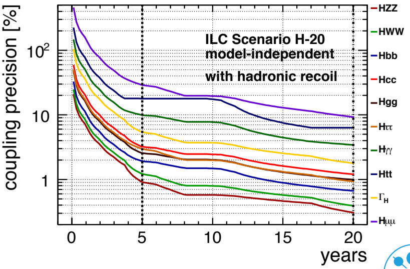
    $$\sigma \times \mathrm{BR}(H \to XX)$$

  - independent of Higgs decay mode recoil mass measurement provides direct measurement of

    $$\sigma(ZH)$$



- most couplings reach required precision of 1 % or better during ILC program
- running at 550GeV instead of 500GeV gives g_{Htt} precision of 3 %
- precision matters: detect deviations due to extended Higgs sectors (SUSY, composite,...)



Precision Matters

references of figures still need to be added

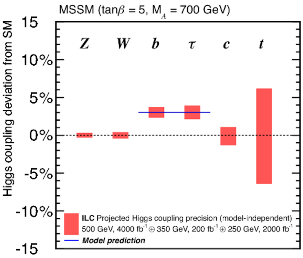
- for new physics searches important to get couplings precision into 1 % range
- all Higgs properties predicted by SM

  → any deviation clear indication of BSM

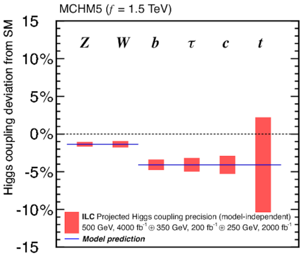
  → largest deviations typically 5%-10% (BSM model dependent)

  → BSM models have different patterns of deviation from predicted couplings

Supersymmetry



Composite Higgs



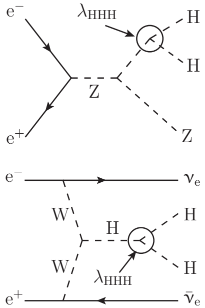
Higgs couplings give proof wether Higgs is fundamental scalar or composite of more fundamental constituents

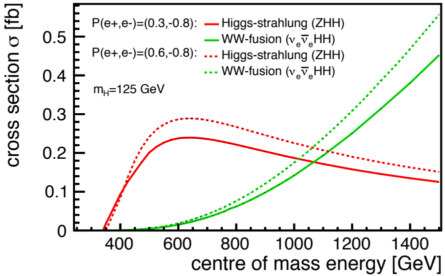
Higgs Self-Coupling Measurement at the ILC

- precise measurement of SM Higgs potential via Higgs self-coupling

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

- existence of HHH coupling → direct evidence of vacuum condensation
- one must observe double Higgs production
- very challenging measurement
  - → small production cross section, i.e. $\sigma(\mathrm{ZHH}) \approx 0.2$fb at 500GeV
  - → many jets in final state
  - → interference terms due to irreducible diagrams





Higgs Self-Coupling Measurement at the ILC

ILC Parameters Joint Working Group, arXiv:1506.07830v1 [hep-ex]

Existing full simulation analyses

@ 500 GeV

- ZHH→Z(bb)(bb) for $m_H = 125$ GeV
- ZHH→Z(bb)(WW) for $m_H = 125$ GeV

@ 1 TeV

- $\nu\nu$HH →$\nu\nu$(bb)(bb) for $m_H = 125$ GeV
- $\nu\nu$HH →$\nu\nu$(bb)(WW) for $m_H = 125$ GeV

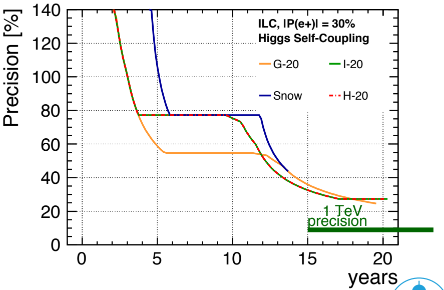
ongoing studies

there are several key points for potential improvement in analyses (kinematic fitting, jet-clustering, etc)

before luminosity upgrade precision of 77 % on Higgs self-coupling

after full ILC program precision of 27% can be achieved

possible energy upgrade to 1 TeV could improve precision to 10% or better

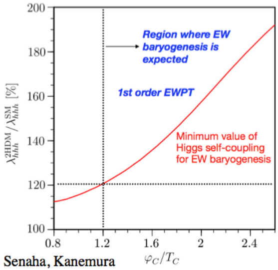


Sensitivity of Higgs self-coupling λ in BSM

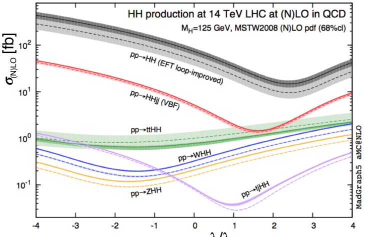
references of figures still need to be added

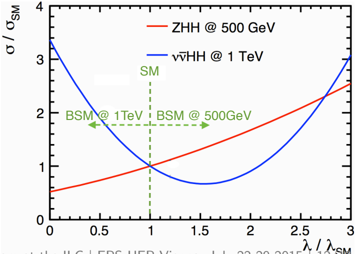
- in many BSM models large deviations expected in other Higgs couplings, not only λ_{SM}
- electroweak baryogenesis (THDM) large deviation expected **only** in λ ($\lambda \geq 1.2 \cdot \lambda_{SM}$)
- such physics scenario difficult to be observed at LHC
- at ILC possible at 500 GeV with ZHH

example: $\lambda = 2 \cdot \lambda_{SM}$
- σ_{ZHH} enhanced by 60%
- interference term reduced
- $\Delta\lambda/\lambda$ improved by factor of 2



estimated physics outcome
- λ can be measured to 14% precision
- 7σ discovery
- more than 3σ deviation from SM





Summary

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BACKUP SLIDES

Summary Table - Projected Precisions for H-20

Summary Table - Input Precisions to Higgs Coupling Fit

Running Scenarios - Summary Table

Advantageous of ee Linear Collider

Higgs Boson Production rates

Measured Parameters

$$\sigma_{ZH}$$

$$\sigma_{ZH} \times BR(H \to invisible)$$

$$\sigma_{ZH} \times BR(H \to VV), \sigma_{\nu} \times BR(H \to VV)$$

$$\sigma_{ZH} \times BR(H \to bb/cc), \sigma_{\nu} \times BR(H \to bb/cc)$$

$$\sigma_{ZH} \times BR(H \to \tau\tau/\mu\mu), \sigma_{\nu} \times BR(H \to \tau\tau/\mu\mu)$$

$$\sigma_{ZH} \times BR(H \to \gamma\gamma/gg), \sigma_{\nu} \times BR(H \to \gamma\gamma/gg)$$

$$\sigma_{ttH} \times BR(H \to bb)$$

$$\sigma_{ZHH} \times BR^2(H \to bb), \sigma_{\nu\nu HH} \times BR^2(H \to bb)$$

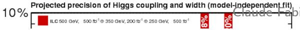
Global fit - Model-Independent Results

- staged running and various production processes provide many independent measurements $Y_i = \sigma \times BR(H \to XX)$, with error ΔY_i
- predicted values of measurements Y_i' can always be parametrized by couplings g_{HZZ}, g_{HWW}, g_{Htt} and Γ_H
- additional recoil mass measurement provide absolute cross section measurement of σ_{ZH}, independent of Higgs decay mode, all modes at iLC
- combined all measurements to extract 9 couplings (hzz, hww, hbb, hcc, hgg, htautau,hmumu,htt,hgamma) and width Γ_H
- model-independent global fit by constructing χ^2

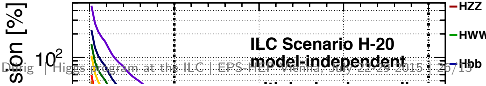
$$\chi^2 = \sum_{i=1}^{i=N} (\frac{Y_i - Y_i'}{\Delta Y_i})^2$$

- estimated uncertainties from the ILC for a model-independent fit to the Higgs couplings in which all Higgs couplings, including couplings to invisible and exotic modes are separately taken as free parameters.
- in these model-independent determinations, most couplings reach the required precision of 1 percent or better in the course of the ILC program.
- as noted before, running the ILC at 550GeV rather than 500GeV would give precisions of 9pc and 3pc in the two entries for the tty coupling
- one important Higgs coupling not discussed so far.

relative precisions for the various Higgs couplings extracted from a model-.independent fit



time development of available Higgs coupling studies interpreted in fully model-indecent fit



Sensitivity of Higgs self-coupling λ in BSM

BSM scenario: improved accuracy expected

(i.e. electroweak baryogenesis: $\lambda > \lambda_{SM}$)

$\lambda < \lambda_{SM} \rightarrow \nu\nu HH$ at 1 TeV

example: $\lambda = 0.5 \cdot \lambda_{SM}$

$\lambda > \lambda_{SM} \rightarrow ZHH$ at 500 GeV

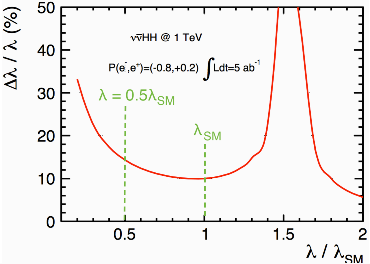
example: $\lambda = 2 \cdot \lambda_{SM}$

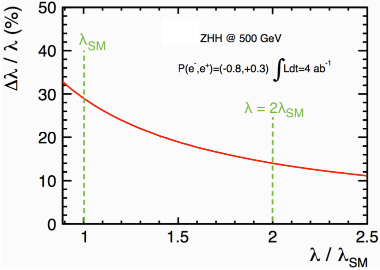
- σ_{ZHH} enhanced by 60%
- sensitivity factor reduced ($1.73 \rightarrow 1.08$)
- $\Delta\lambda/\lambda$ improved by factor of 2

both cases:

- λ can be measured to 14% precision
- 7σ discovery
- more than 3σ deviation from SM

extrapolated measurement accuracy of current λ_{SM} measurement (J. Tian)





Higgs Self-Coupling Analyses at ILC

Existing DBD full simulation analyses

studies performed **with** low-p_T $\gamma\gamma \longrightarrow$ hadrons beam background
without low-p_T $\gamma\gamma \longrightarrow$ hadrons beam background

@ 500 GeV

- ZHH→Z(bb)(bb) for $m_H = 125$ GeV
- ZHH→Z(bb)(WW) for $m_H = 125$ GeV

@ 1 TeV

- $\nu\nu$HH →$\nu\nu$(bb)(bb) for $m_H = 125$ GeV
- $\nu\nu$HH →$\nu\nu$(bb)(WW) for $m_H = 125$ GeV

ILC white paper: Higgs self-coupling projections
(full simulation w/ $m_H = 120$ GeV, extrapolated to $m_H = 125$ GeV)

	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%

500 GeV: 500 (1600)fb^{-1} $P(e^+e^-)=(0.3,-0.8)$
1 TeV: 1000 (2500)fb^{-1} $P(e^+e^-)=(0.2,-0.8)$

Scenario A: HH → bbbb ✔
Scenario B: adding HH → bbWW ✔, expect 20% relative improvement
Scenario C: analysis improvement (jet-clustering, kinematic fit, flavor tagging, matrix element method, etc.), expect 20% relative improvement (**ongoing**)