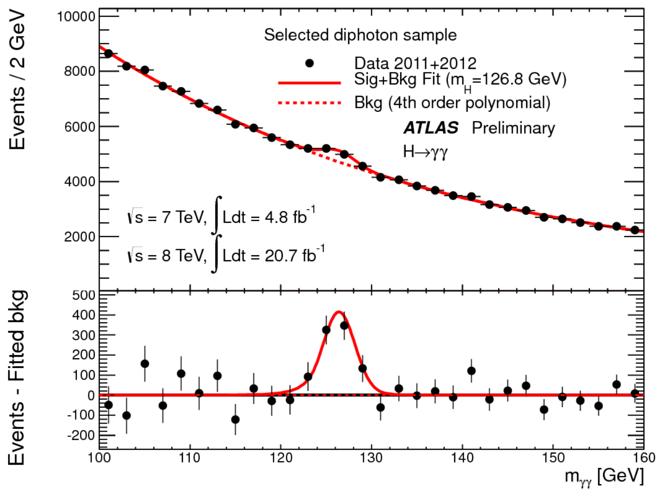
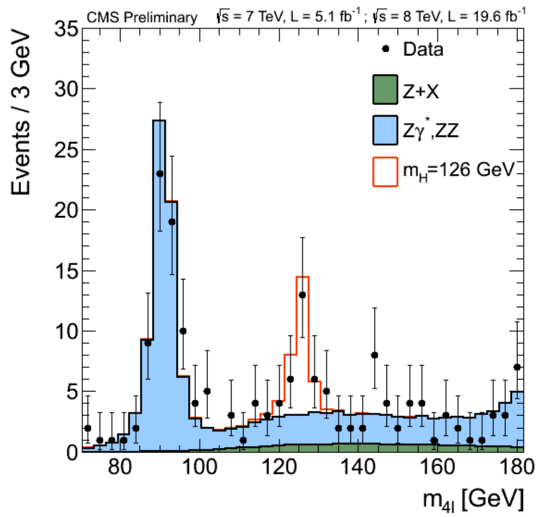
Higgs physics at ILC

1. The boson
2. The tools
3. What is good for?
4. The Higgs profile
5. Conclusions

The Boson





Landmark discovery of Boson H(125) marks the start of long-awaited new research line in the field of particle physics.

- a good candidate for the first fundamental scalar!
- is it the long-sought Higgs boson of the (minimal) Standard Model?
- is it responsible for EWSB? (i.e. is it the excitation of a scalar field with $v \neq 0$?
- does it cure the divergence of SM amplitudes at high E ($W_L W_L \rightarrow W_L W_L$ ...)?
- Is it embedded into a larger non-SM Higgs sector?
- Is it elementary or composite?
- Does it provide a window to BSM physics?

→ Study the particle with all possible experimental means to the greatest precision

Update of European Strategy

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) LHC → HL-LHC (until around 2030)

d) propose post-LHC machine at CERN by next update (~5y) → do R&D

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

f) neutrinos: pave the way for substantial European role in long-baseline expts

The Boson

An excess of events

A new boson in search for the Higgs

A Higgs-like boson

A Higgs boson ?

The Higgs boson ??

The SM Higgs boson ???

Where are we?

What do we need to know?

time

The Profile of the Higgs Boson

$$\mathcal{L}_{EW}^{SM} = -\frac{1}{4} W_{\mu\nu}^{a} W_{a}^{\mu\nu} - -\frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$
$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2} g\tau_a W_{\mu}^{a} - \frac{1}{2} g' Y B_{\mu}\right) L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - -\frac{1}{2} g' Y B_{\mu}\right) R$$
$$-\left|\left(i\partial_{\mu} - \frac{1}{2} g\tau_a W_{\mu}^{a} - \frac{1}{2} g' Y B_{\mu}\right)\Phi\right|^2$$
$$+\mu^2|\Phi|^2 - \lambda|\Phi|^4$$
$$-(\sqrt{2}\lambda_d \bar{L}\Phi R + \sqrt{2}\lambda_u \bar{L}\Phi_c R + h.c.)$$

Bottom-up reconstruction of the Higgs Lagrangian

- Higgs gauge couplings
- Higgs fermion couplings (largest # of SM par´s)
- Higgs mass (μ)
- Higgs self coupling (λ)
- Coupling structure (CP)

Are we ready to call it „a Higgs boson“ ? „the Higgs boson“ ?

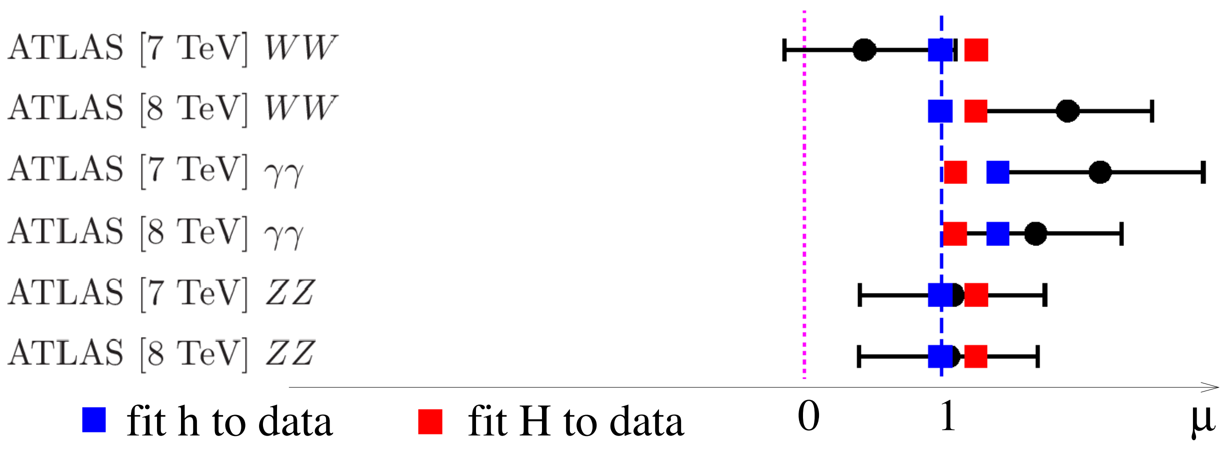
scientific goal: understand EWSB (!) through studying the new particle

The quest for precision – why?

Only one example (theory provides many...):

Fit LHC and Tevatron „signal strength“ parameters to the MSSM taking into account limits, B-physics constraints etc.

→ both h and H provide a reasonable fit

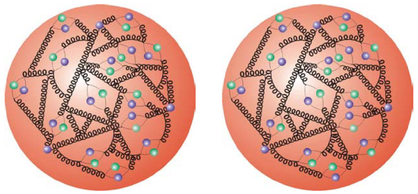


- tiny differences between best fit and SM
- tiny differences between h and H hypotheses
- $\Delta\mu/\mu \lesssim 5\%$-$20\%$

[Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein, Zeune arXiv:1211.1955]

The Tools

Proton proton collisions

p  p

LHC

Running!

Today: ~30 fb^{-1} @ 7/8 TeV

~2021 300 fb^{-1} @ 14 TeV

~2030 3000 fb^{-1} @ 14 TeV HL-LHC

Electron positron collisions

e^+ • • e^-

Linear colliders:

TDR ILC 250...500...1000 GeV

CDR CLIC 250...1400...3000 GeV

Circular colliders:

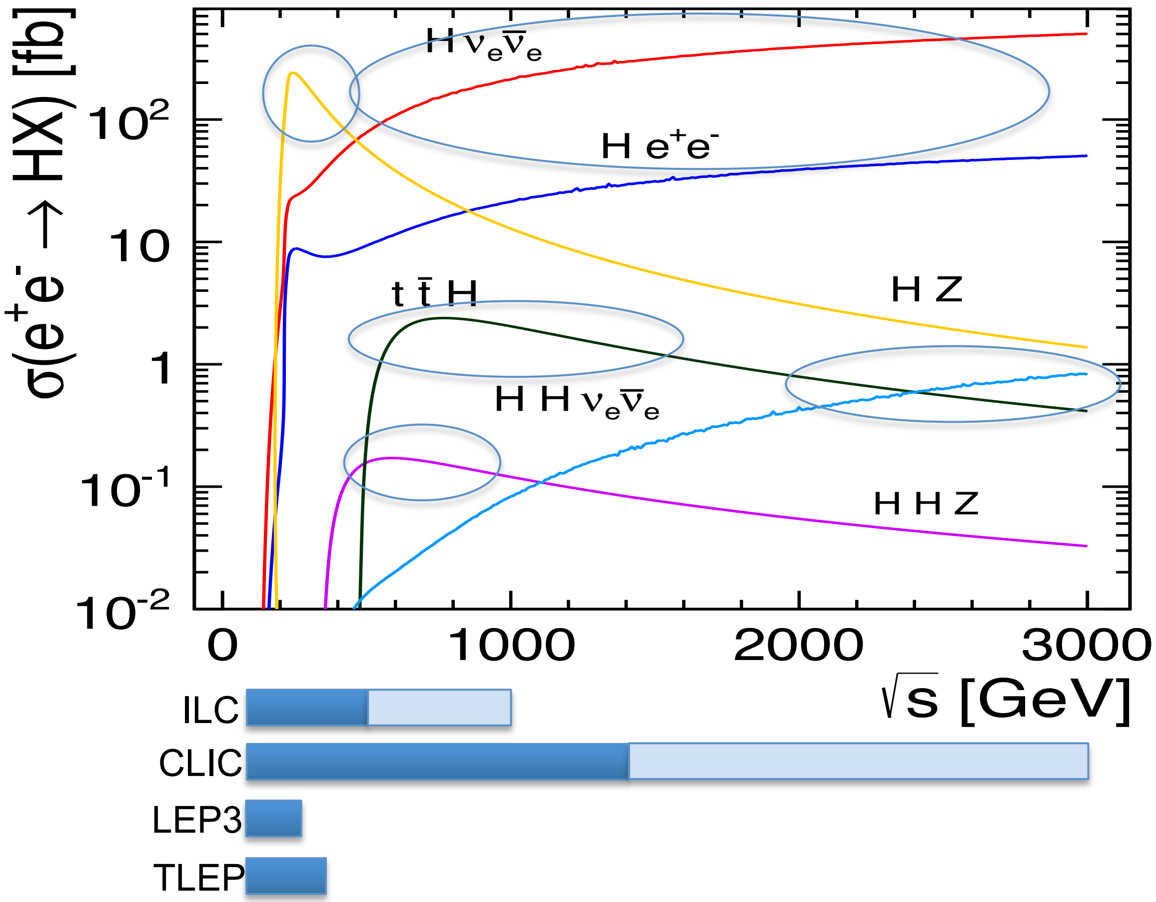
proposal

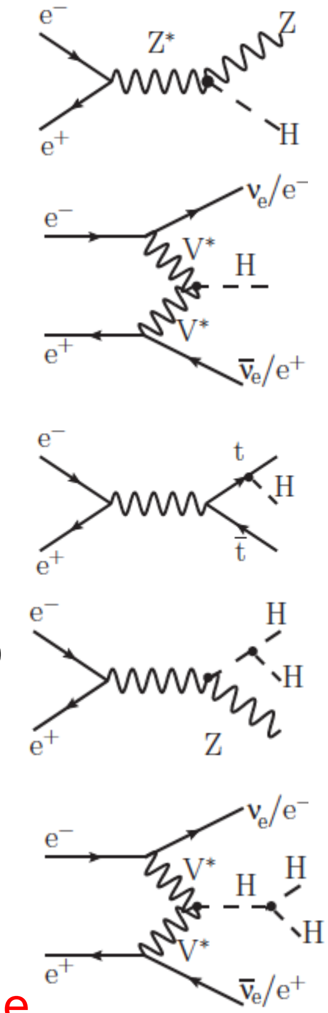
LEP3 90..240GeV (27 km)

TLEP 90..240..350GeV (80 km)

(other: $\gamma\gamma \rightarrow H$, $ep \rightarrow H+X$, $\mu\mu \rightarrow H$)

e^+e^- Higgs processes





Mass
g_Z (m.i.)
BR´s
(LHC)-invisible

Γ_{tot}

g_t (ILC,CLIC)

g_{HHH} (ILC500)

g_{HHH} (ILC1000, CLIC)

- Many processes at different $\sqrt{s}$ needed & accessible

Higgs mass

LHC now

m_H = 125.2 ± 0.3 (stat) ± 0.6 (syst) GeV (ATLAS)
m_H = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV (CMS)

preliminary

→ $\Delta m_H \approx$ 500 MeV (today)

LHC goal

→ $\Delta m_H \approx$ 100 MeV (syst. limited)

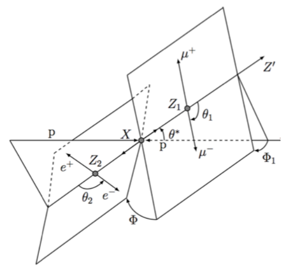
ILC

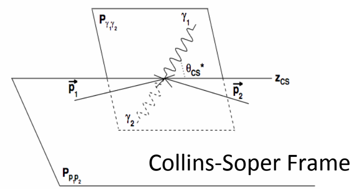
→ $\Delta m_H \approx$ 30 MeV

from recoil mass and/or
direct reconstruction (e.g. HZ→ bbqq, kin. fit)

fundamental SM parameter → measure as precisely as possible
however, compare to o(GeV) uncertainty of m_H prediction in MSSM
here Δm_{top} of utmost importance

Higgs spin/parity





LHC: Decay angle analysis in H→ZZ→4l and H→γγ

prefer J=0 over 2 and CP + over - at few σ level
LHC will do good job here

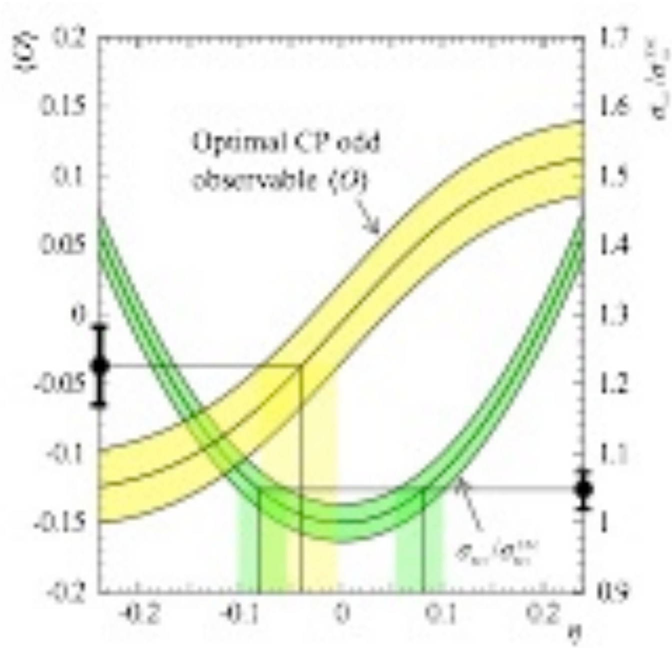
ILC:

In addition to H→ZZ→4l sensitivity:

- β vs β^3 rise of σ_{HZ} near threshold
- production angle in HZ
- spin correlations in H→ττ, ttH

unambigous exclusion of J=2

few % sensitivity to CP-odd admixture η



[Schumacher]

Towards Higgs couplings

Collider experiments measure rates / visible cross sections for certain final states

$$\sigma_{vis} = \sigma_{prod} \times BR(H \to f)$$

LHC:

Accessible production modes:
gg fusion
vector boson fusion
WH/ZH associated production
ttH production

LC:

Accessible production modes:

HZ (Higgs-strahlung)
vector boson fusion (WW/ZZ)
ttH

signal strength $\mu = \sigma_{vis}/\sigma_{vis}$ (SM)

ILC: „signal strength“

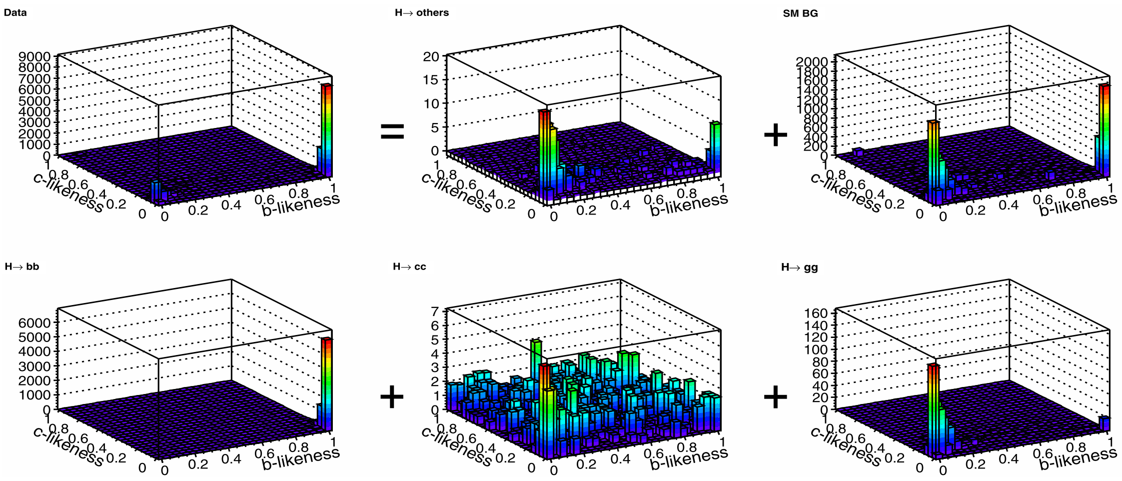
Table 2.6.4: Expected accuracies for cross section times branching ratio measurements for the 125 GeV h boson.

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	$250\,\mathrm{fb}^{-1}$ at 250 GeV (-0.8,+0.3)		$500\,\mathrm{fb}^{-1}$ at 500 GeV (-0.8,+0.3)		$1\,\mathrm{ab}^{-1}$ at 1 TeV (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

significant recent analysis effort towards ILC TDR (DBD)
all based on very detailed full detector simulation (ILD/SiD)
all are statistics limited (check bb) → push for luminosity!

[ILC DBD physics book - draft]

Hadronic (bb,cc,gg) Branching Ratios



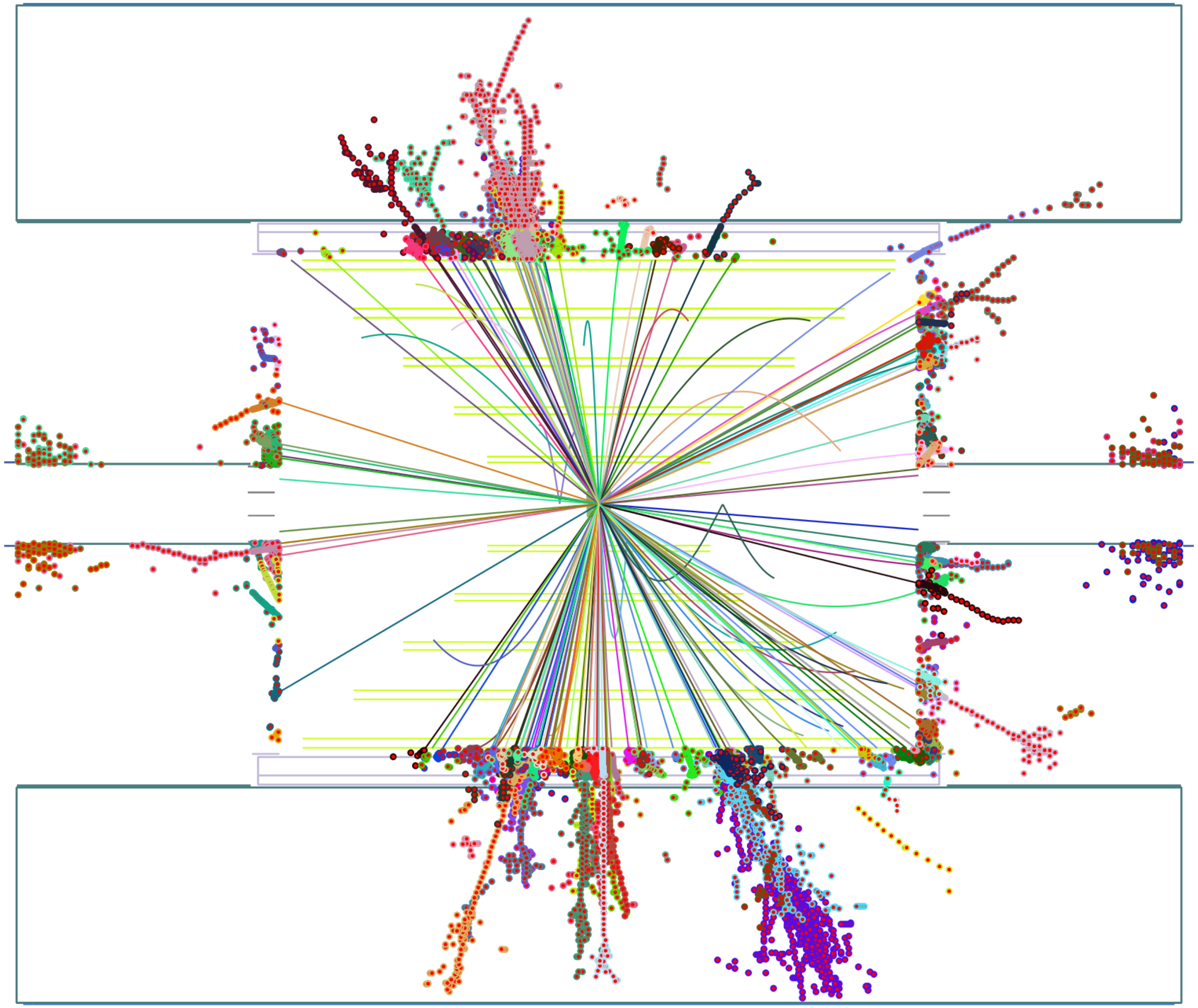
Full simulation ILD analysis: template fit to b- and c-tagging observables relies on excellent b/c separation (VXD)

Δ(σ*BR)/(σ*BR)	250 GeV/250 fb^{-1} P = (-0.8,+0,3)	350 GeV/250 fb^{-1} P = (-0.8,+0,3)	
H→bb	1.0%	1.0%	>factor 10 better than HL-LHC
H→cc	6.9%	6.2%	LC unique
H→gg	8.5%	7.3%	LC unique

[H.Ono, A: Miyamoto] EPJC (2013) 73

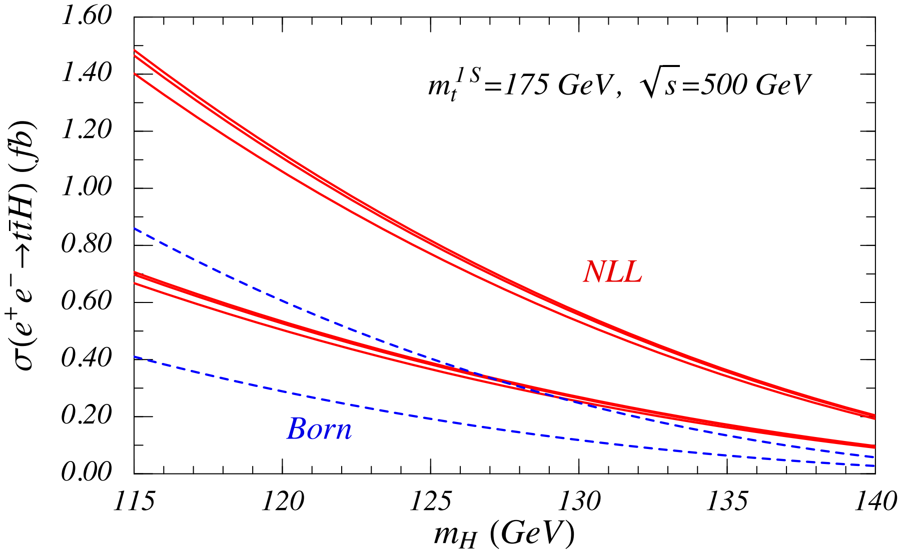
Top Yukawa coupling: ttH

8-jet signal
event in SiD



[P.Roloff, J.Strube, LCWS12]

Top Yukawa coupling: ttH



[C. Farrell, A. Hoang] PRD 74 (2006) 14008

significant enhancement from NRQCD near threshold
→ allows for measurement around $\sqrt{s}$ ~500 GeV

Full study for ILD (500/1000) and SiD(1000)

- $e^+e^- \to bq\bar{q}\,\bar{b}q\bar{q}\,b\bar{b}$ (hadronic)
- $e^+e^- \to bl\nu\,\bar{b}q\bar{q}\,b\bar{b}$ (semi lep)
- $e^+e^- \to bl\nu\,\bar{b}l\nu\,b\bar{b}$ (leptonic)

challenging final states → PFA

key variable: $$\frac{(M_{12}-M_{W^\pm})^2}{\sigma^2_{W^\pm}} + \frac{(M_{123}-M_t)^2}{\sigma^2_t} + \frac{(M_{45}-M_{W^\pm})^2}{\sigma^2_{W^\pm}} + \frac{(M_{456}-M_t)^2}{\sigma^2_t} + \frac{(M_{78}-M_H)^2}{\sigma^2_H}$$

[T. Price, N. Watson, V. Martin, H. Tabassam, T. Tanabe, R. Yonamine, K. Fujii]

[P.Roloff, J.Strube]

Top Yukawa coupling: ttH

Top Yukawa Coupling @ 500 GeV

R. Yonamine, T. Tanabe, K. Fujii

6 jet + lep	tth (6J+L)	bb4f	ttZ	ttbb	Sig
No Selection	246	9.09×10^5	1910	1060	
Cut-based	32	39	21	15	3.1
Likelihood	39	58	29	22	3.2

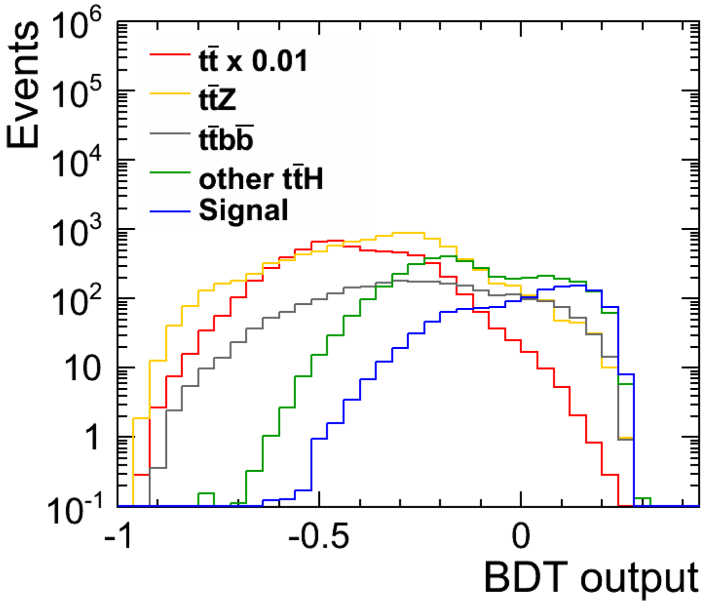
Semi Leptonic [E_{CM}=500 GeV, L=1 ab^{-1}, Pol=(-0.8,+0.3)]

8 jet	tth (8J)	bb4f	ttZ	ttbb	Sig
No Selection	235	9.09×10^5	1910	1060	
Cut-based	38	41	25	16	3.5
Likelihood	78	241	63	46	3.8

Hadronic [E_{CM}=500 GeV, L=1 ab^{-1}, Pol=(-0.8,+0.3)]

6 jet & 8 jet modes	Combined Sig	$\left(\frac{\Delta g_{ttH}}{g_{ttH}}\right)_{stat}$
Cut-based	4.7	11 %
Likelihood	5.0	10 %

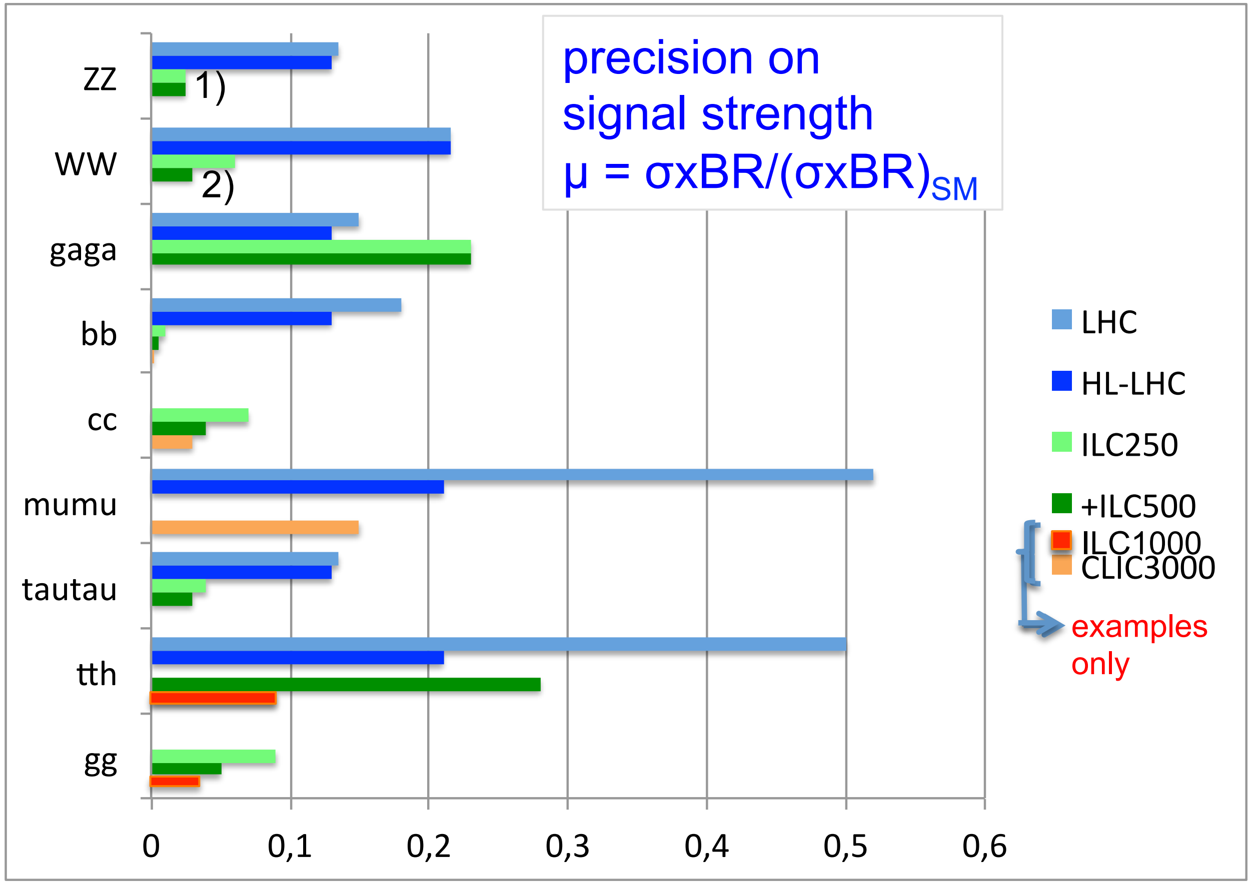
1 TeV SiD analysis



	500 GeV/ 1 ab^{-1}	1000 GeV/ 2 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$	10%	4.6%

note: σ(520 GeV)/σ(500) GeV ~ 2 (!)

LHC vs LC: „signal strength“



KD attempt to compile available experimental studies.
(best estimates)

HANDLE WITH CARE

fineprint:

ATLAS/CMS from Krakow notes
(= preliminary!)

LHC = (ATLAS+CMS)/2 (300 fb^{-1})
HL-LHC = ATLAS (3000 fb^{-1})
ILC250 = 250 fb^{-1} at 250 GeV
+ILC500 = 500 fb^{-1} at 500 GeV + 250 fb^{-1} at 250 GeV
ILC1000 + CLIC3000 are only examples

1) prec. on σ_{HZ}(total)
2) prec. on $\sigma_{WW\text{-}Fusion}$(total)

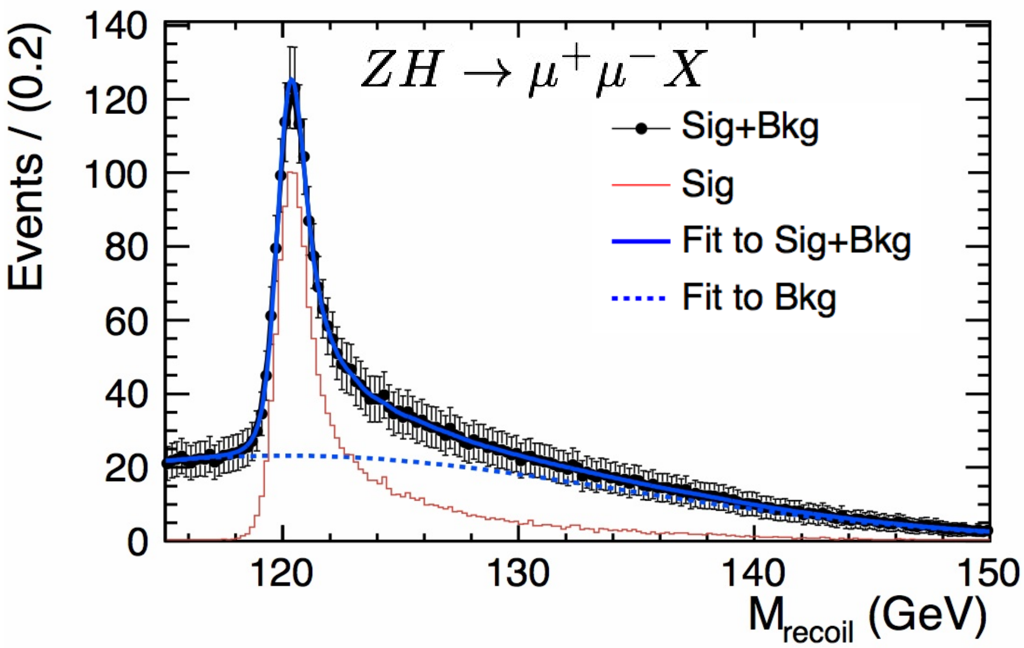
LHC – mostly syst. limited
LC – mostly stat. limited

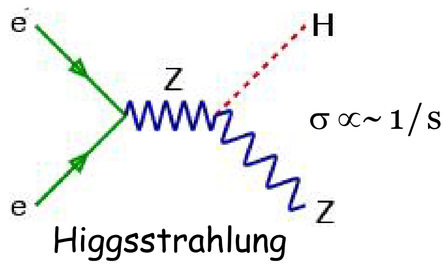
ILC1000/CLIC1400 further improves precision

Higgs branching ratios

<u>LHC:</u> no known (to me) method to extract absolute Higgs BRs

<u>LC:</u> Recoil mass technique in $e^+e^- \rightarrow HZ$ allows us to measure σ_{HZ} indep. of H-decay





$$m_H^2 = (p_{\ell\ell} - p_{initial})^2$$

250 GeV / 250 fb^{-1}

$\Delta\sigma/\sigma = 2.5$ %

$\Delta m_H/m_H = 30$ MeV

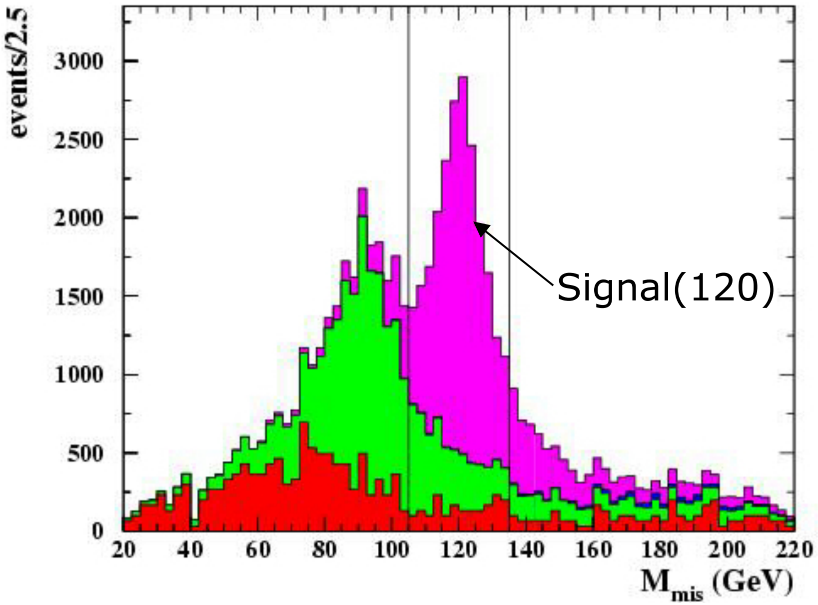
Once σ_{HZ} is known, any signal strength measurement can be turned into absolute BR´s measurement: $BR_X = (\sigma \times BR_X)_{meas} / \sigma(tot)_{meas}$

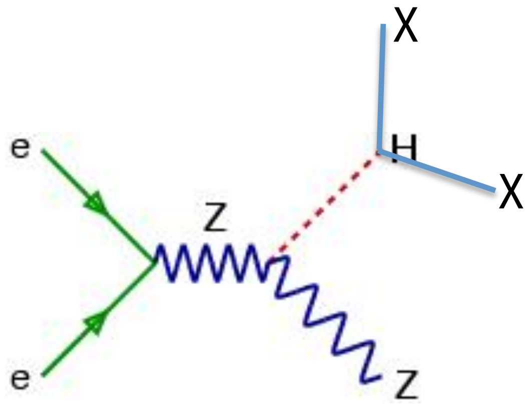
unique to lepton colliders (needs (E,p) constraint from initial state)

[Li, Poeschl]

Invisible Higgs

The recoil mass technique also allows for unbiased observation of any non-SM decay, e.g. H→invisible:





5σ observation for BR(H→inv.) = 2% (at $\sqrt{s}$=350 GeV/500 fb^{-1})

also applies to „LHC-invisible" decays, e.g. H→gg, H→qq etc.

[Schumacher]

Towards couplings: total width

LHC: no absolute couplings without assumptions on „invisible“ couplings

ILC: need to measure Γ_{tot} in addition to absolute BR´s to extract couplings in a model-independent way

$$\sigma_{vis} = \sigma_{prod} \times BR(H \to f)$$

$$\sigma_{prod} \sim g_{Hi}^2 \quad and \quad BR(H \to f) = \frac{\Gamma_f}{\Gamma_{tot}} \sim \frac{g_{Hf}^2}{\Gamma_{tot}}$$

$$\sigma_{vis} \sim \frac{g_{Hi}^2 g_{Hf}^2}{\Gamma_{tot}(g_{Hj}, j = 1 \ldots n)}$$

$$\Gamma_{tot} := \Gamma(g_{Hj}; j = 1 \ldots n_{vis}) \leftarrow$$

In general, σ_{vis} is a complicated function of all (including „invisible“) couplings.

The total width

Γ_{tot} (SM) ~ few MeV → no way to measure lineshape except maybe at a μC

→ In e^+e^- access total width through:

$$\Gamma_{tot} \sim \frac{BR(H \rightarrow X)}{g_{HX}^2}$$

→ a) measurement of BR(H→ZZ) (+ g_{HZ} from recoil mass) or
→ b) measurement of g_{HW} in WW-fusion (+ BR(H→WW))

Precision on Γ_{tot} directly enters into precision on (model-independent) couplings and may even dominate!

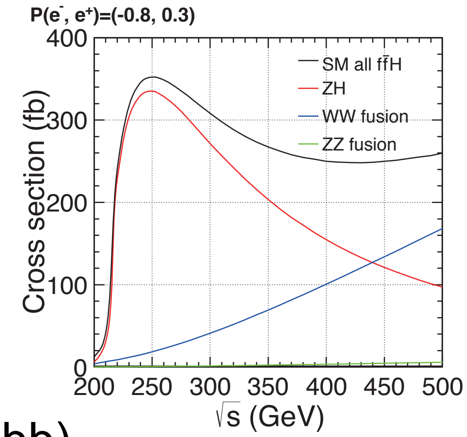
a) BR(H→ZZ;125 GeV) = 0.024 -- rather low statistics

b) the method of choice!

The total width

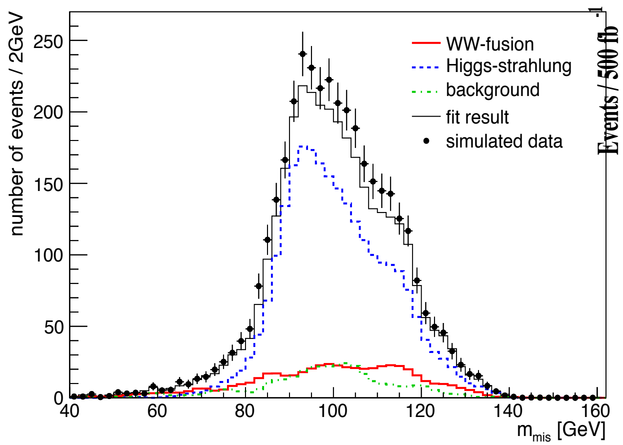
Need to measure WW-fusion cross section (e.g. $e^+e^- \rightarrow H\nu\nu \rightarrow bb\nu\nu$)

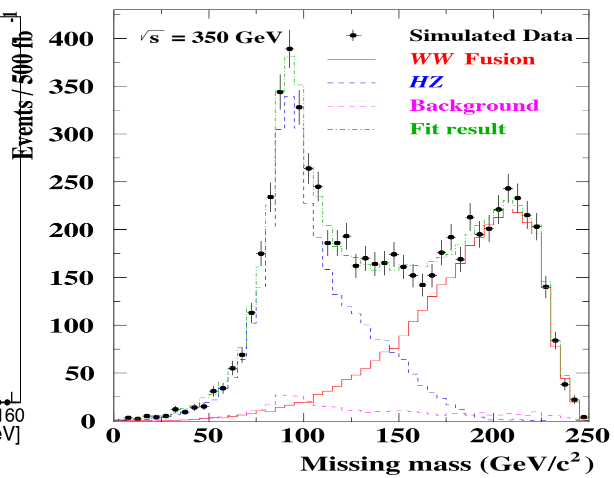
- need to separate from $HZ \rightarrow bb\nu\nu$ (+ handle interference)
- WW-fusion small at HZ threshold! → need higher $\sqrt{s}$

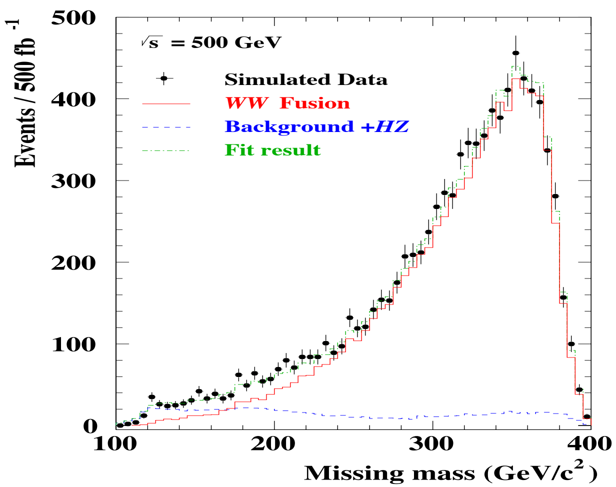


precision on $\sigma_{\text{WW-fusion}}$:

250 GeV	11.0 %	
350 GeV	3.6 %	} dominated by error on BR(H→bb)
500 GeV	3.2 %	



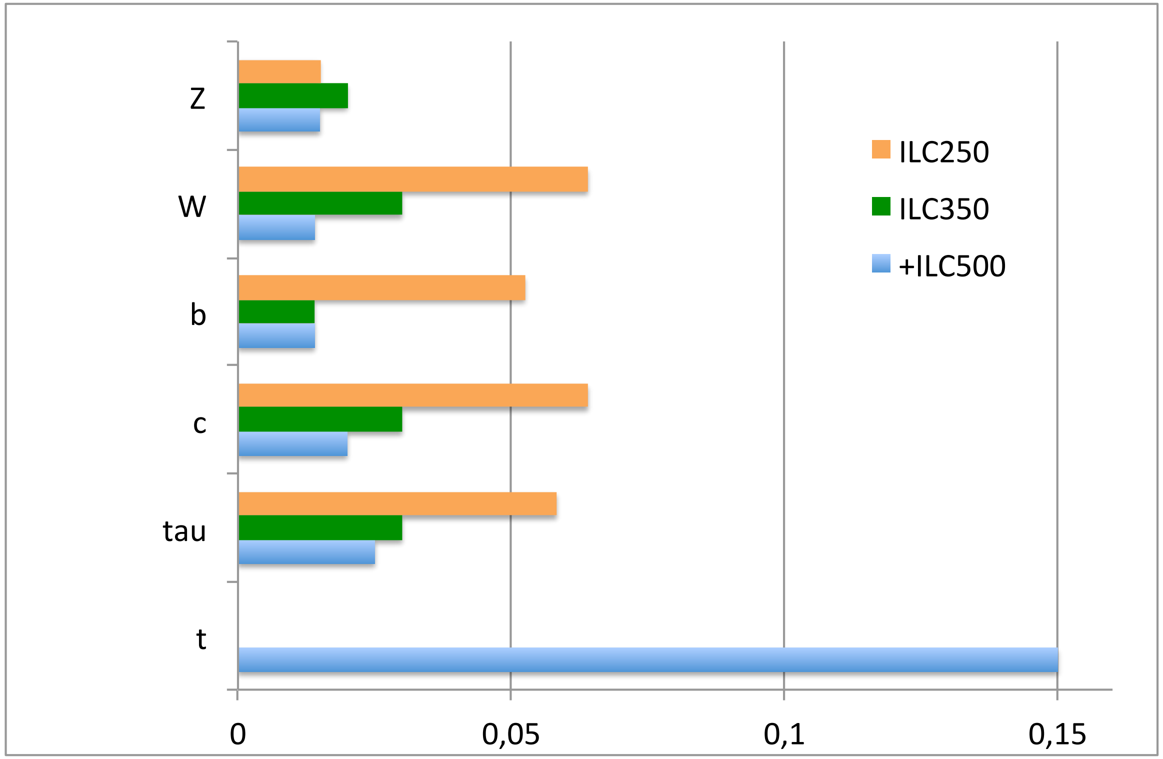




[Dürig; Meyer,KD]

Higgs couplings at LC

model-independent relative errors on Higgs couplings:



fineprint:

numbers mainly from LC Krakow report

ILC250: KD square-added 5% from $\Delta\Gamma_{tot}$ (omitted in Krakow report)

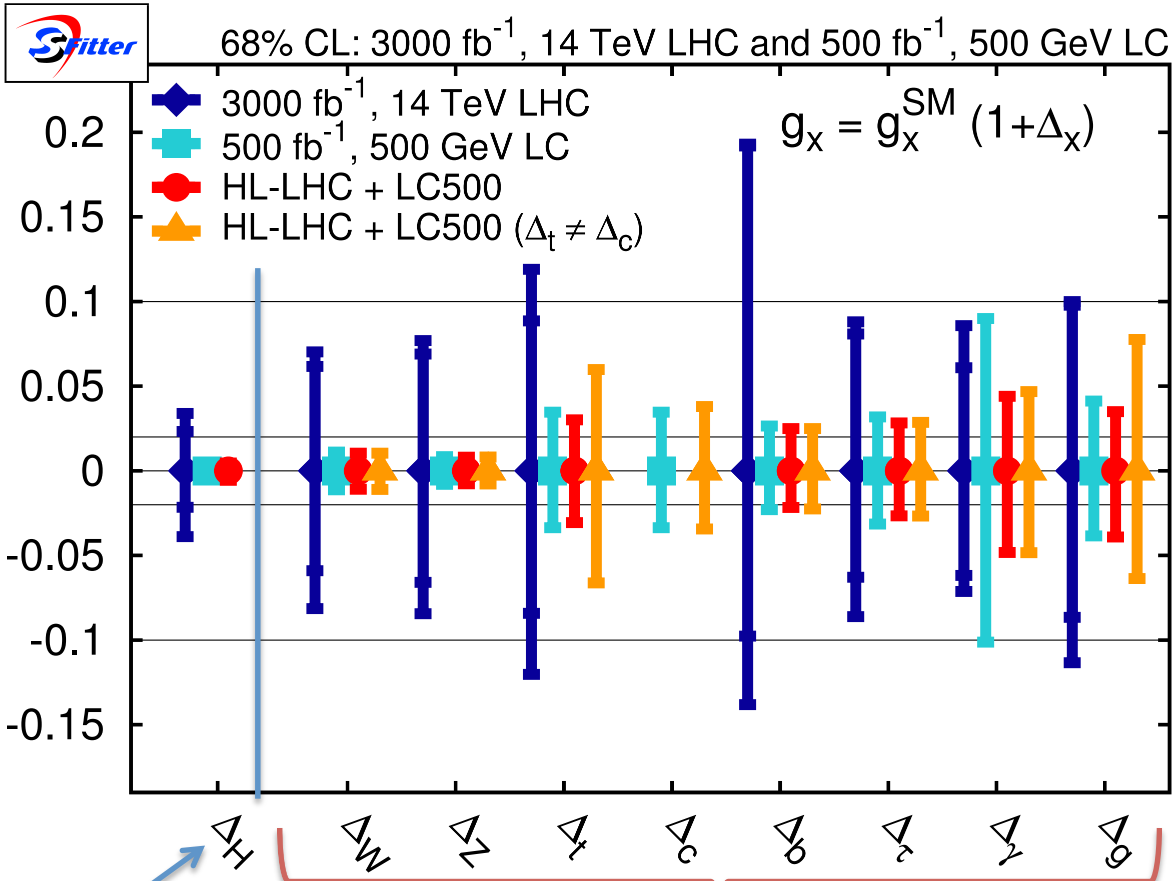
analysis are ongoing – KD expects further improvements

+ILC500 means ILC250 + ILC500

further improvements from ILC1000/CLIC1400/CLIC3000 (e.g. $\Delta g_t \approx 4\%$ at ILC1000)

Global Fits

Comparison of HL-LHC and ILC500 on equal footing within a constrained model (i.e. including the assumptions necessary for LHC):



note LHC+ILC synergy on some couplings

8-parameter model with effective loop-induced (g,γ) couplings

1 parameter model: scale all couplings by common factor

[Klute,Lafaye,Plehn,Rauch,D.Zerwas] arxiv:13.01.1322

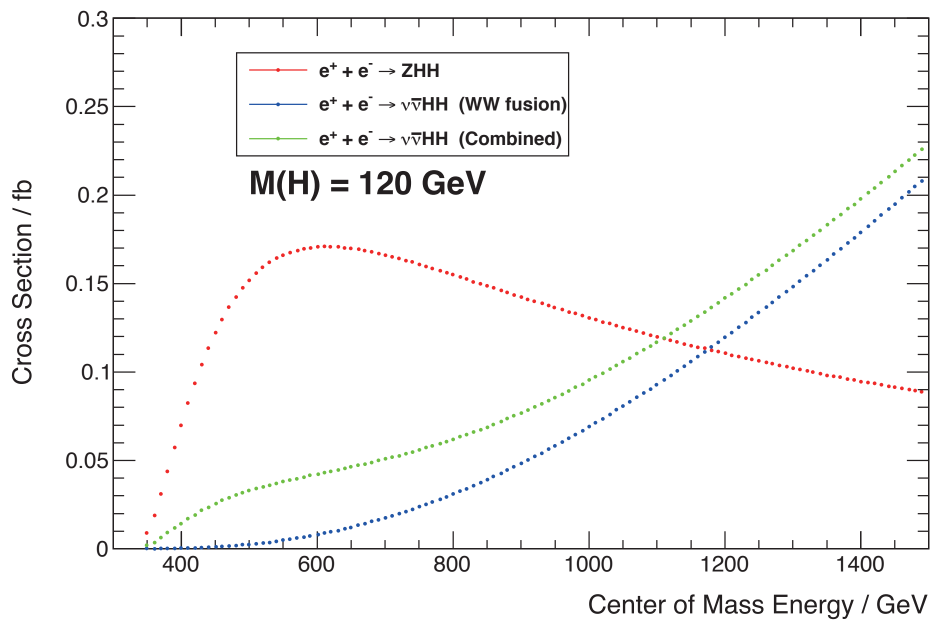
The Higgs self coupling

HL-LHC: prospects: 3σ observation of HH→bbγγ – hope for more channels

LC:
two choices:

$e^+e^- \rightarrow ZHH$
(maximum of σ around $\sqrt{s} \approx 600$ GeV)
→ ILC500 (~100 events in 500 fb^{-1})

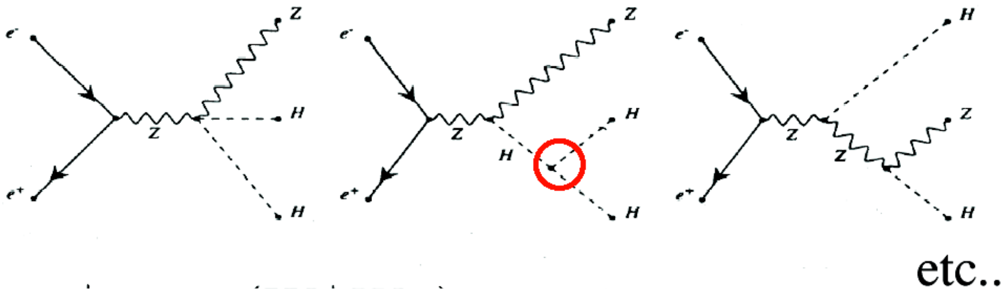
$e^+e^- \rightarrow HH\nu\nu$
(σ rising with $\sqrt{s}$)
→ ILC1000 (~140 events in1 ab^{-1})
→ CLIC1400 (~250 events in 1.5 ab^{-1})
→ CLIC3000 (~1250 events in 2 ab^{-1})



challenges:
- huge number of different final states (huge effort needed)
- „dilution“ due to interference with non-HHH diagrams (not sensitive to λ_{HHH})

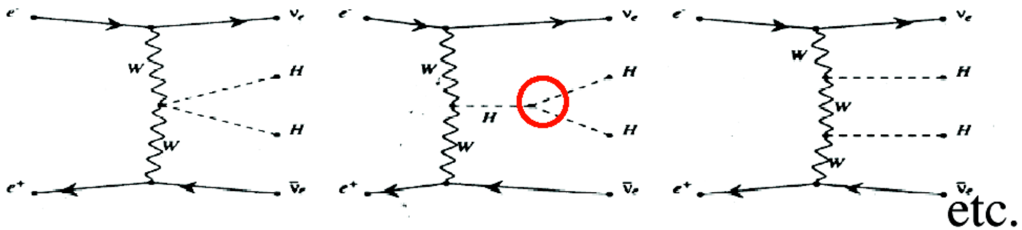
The Higgs self coupling: dilution

$\star\ e^+e^- \rightarrow ZHH$



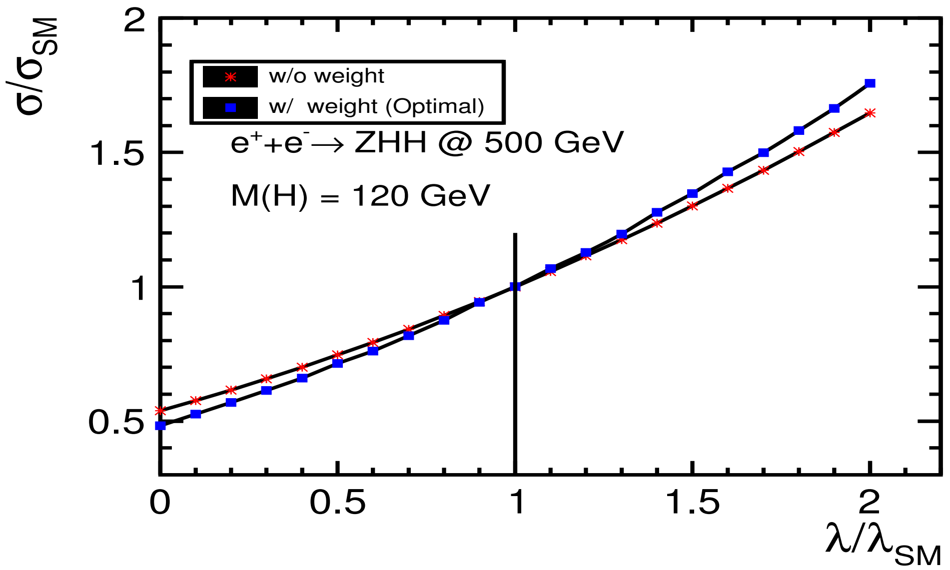
dλ/λ = 1.8 dσ/σ

$\star\ e^+e^- \rightarrow (W^+W^-)\nu\bar{\nu} \rightarrow HH\nu\bar{\nu}$



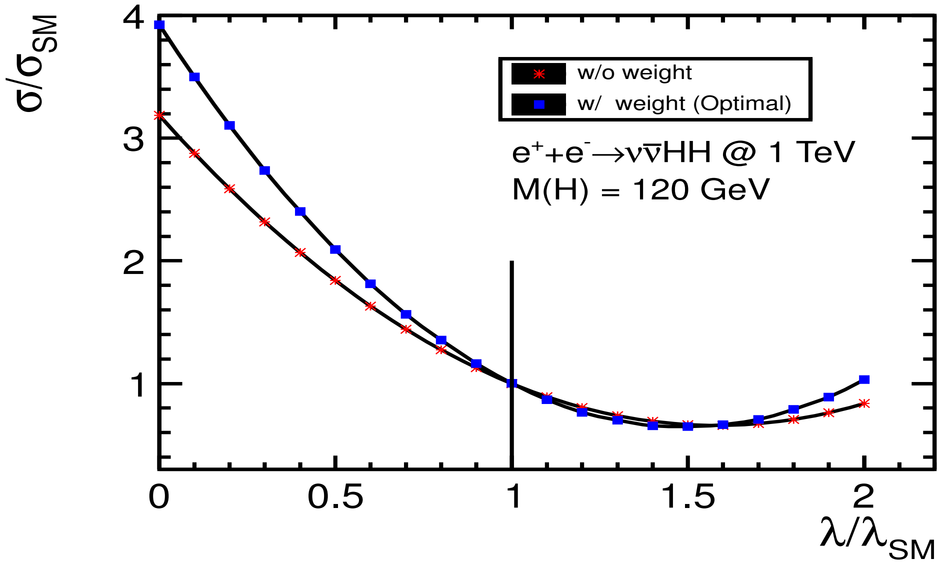
dλ/λ = 0.85 dσ/σ

The Higgs self coupling: weighting



$d\lambda/\lambda = 1.8\ d\sigma/\sigma$

→1.66 with weighting



$d\lambda/\lambda = 0.85\ d\sigma/\sigma$

→0.76 with weighting

[J.Tian LC-REP-2013-003]

ILC full simulation study

LC-REP-2013-003

Study of Higgs self-coupling at the ILC based on the full detector simulation at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV

Junping Tian

High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

(Dated: April 19, 2013)

In this analysis we investigated the feasibilities of the measurement of Higgs self-coupling at the International Linear Collider (ILC) during its two phases of operation with centre-of-mass energy of 500 GeV and 1 TeV. Three combinations of the decay modes of double Higgs strahlung process $e^+e^- \to ZHH$, where $Z \to l^+l^-$, $Z \to \nu\bar{\nu}$ and $Z \to q\bar{q}$ accompanying with both Higgs decay into $b\bar{b}$, were analyzed together at 500 GeV. The decay mode of WW fusion process $e^+e^- \to \nu\bar{\nu}HH$, where both Higgs decay into $b\bar{b}$ was analyzed at 1 TeV. Both the signal and background event samples are generated by a full detector simulation based on the International Large Detector (ILD). At

llbbbb
vvbbbb
qqbbbb

channels studied

multiple neural nets to reject backgrounds

full detector capabilities needed
- PFA (up to 6 jets)
- b-tagging with highest efficiency (4 b´s)

The Higgs self coupling

example: bbHH category

TABLE IV: The reduction table for the signal and backgrounds after the final selection for $bbHH$ dominant category, together with the number of expected events and generated events. The cuts names are explained in text.

Process	expected	generated	pre-selection	Cut1	Cut2	Cut3	Cut4	Cut5	Cut6
$qqHH$	310	3.73×10^5	111	26.9	25.1	23.0	22.4	21.1	13.6
$l\nu bbqq$	7.40×10^5	3.56×10^6	17240	363	103	18.7	15.9	12.8	0.03
$bbuddu$	1.56×10^5	8.87×10^5	565	11.4	11.3	10.0	7.65	6.92	0.55
$bbcsdu$	3.12×10^5	1.26×10^6	6109	89.0	78.4	67.6	51.2	45.1	1.01
$bbcssc$	1.56×10^5	1.17×10^6	12456	263	246	212	147	129	3.69
$bbbb$	4.02×10^4	7.19×10^5	22889	2319	733	16.5	15.0	11.8	5.25
$qqbbbb$	140	1.23×10^5	82.9	13.9	12.7	9.80	9.19	5.78	3.03
$qqqqh$	818	5.98×10^4	154	27.5	25.4	22.5	21.6	18.5	10.9
ttz	2.20×10^3	8.49×10^4	172	17.2	13.6	12.5	12.3	11.4	2.88
$ttbb$	2.11×10^3	8.25×10^4	450	47.8	29.9	26.0	24.5	22.6	3.40
BG			60119	3152	1253	395	304	264	30.7

1. Cut1: sum of b-likeness of the two jets from Z > 0.54.
2. Cut2: $MissPt < 60$ GeV, $Npfos < 245$, 30 GeV $< M(Z) <$ 139 GeV, 73 GeV $< M(H_1) <$ 170 GeV, 73 GeV $< M(H_2) <$ 148 GeV.
3. Cut3: $\mathrm{MLP}_{bbbb} > 0.47$.
4. Cut4: $\mathrm{MLP}_{bbqqqq} > 0.33$.
5. Cut5: $\mathrm{MLP}_{qqbbbb} > 0.16$.
6. Cut6: $Bmax3 + Bmax4 > 1.17$.

[J.Tian LC-REP-2013-003]

Self coupling: results

ZHH	500 GeV 2 ab^{-1} P=(-0,8,0,3)
significance for HH prod.	5.0σ
Δσ(ZHH)/σ(ZHH)	27%
Δλ/λ	44%

state-of-the-art today

	Δλ/λ
ILC 500/2ab^{-1}	44%
ILC 1000/2ab^{-1}	18%
CLIC1400/1.5 ab^{-1}	22%
CLIC3000/2 ab^{-1}	11%

CLIC study
tbc with full sim

Comments:

- Higgs self coupling is a huge challenge
- Signal efficiencies ≲ 10% → room for improvement? (e.g. jet finding, jetless vtx?)
- A case for ultimate luminosity...

Conclusions/Remarks

- Discovery of H(125) turns the physics case for ILC from „hypothetical“ to real!
- Bottom-up reconstruction of the Higgs profile requires high luminosity, precision detectors and a staged running up to at least 500+ GeV
- ILC provides many unique H measurements and is factor of 5-10 more precise where LHC can also contribute, synergy of LHC and ILC
- Strong additional physics case (top, EW gauge boson self couplings, BSM discovery potential for weak signals
- ILC Higgs case „stable“ since more than 1 decade. But: greatly improved realism through recent DBD fullsim studies
- This potential relies on (challenging) precision detectors → R&D mandatory

Realizing the ILC never was as timely as today!

Backup

Study EWSB beyond H at ILC

Beyond direct Higgs Physics at the future e^+e^- collider:

- Triple gauge Couplings
- Most precise m_t, m_W
- Unitarity of WW scattering at $\sqrt{s}_{e^+e^-} \approx 1$ TeV
- Invisible Higgs decays? Other (invisible?) Higgses?
- Any other sign for new physics . . .
- Much more . . .

H→ tautau

Table 3: The cut statistics of $Z \to q\bar{q}$ mode.

	qqH $H \to \tau\tau$	ZH with no τ	llH	$\tau\tau H$	$qqqq$	$qqll$	$qq\tau\tau$	$qql\nu$	$qq\tau\nu$	other SM bkg	signi.
No cut	4233	4.829×10^4	5377	2596	4.038×10^6	3.563×10^5	4.169×10^4	2.788×10^6	1.326×10^6	1.494×10^{10}	0.035
preselection	1647	578.8	2761	765.4	1.230×10^4	6.378×10^4	1.161×10^4	1.249×10^5	4.948×10^4	2.570×10^7	0.32
# of tracks	1644	549.8	2680	765.4	1.230×10^4	6.059×10^4	1.146×10^4	1.214×10^5	4.806×10^4	5.190×10^5	1.9
E_{vis}	1607	492.3	1015	744.2	4443	2.106×10^4	1.107×10^4	1.192×10^5	4.693×10^4	2.383×10^5	2.4
$\cos\theta_{\mathrm{miss}}$	1572	474.7	860.5	725.1	2127	8315	1.021×10^4	1.171×10^5	4.415×10^4	5939	3.6
M_Z	1440	376.1	791.3	682.8	778.6	4987	8674	8189	3288	997.3	8.3
E_Z	1429	352.0	782.7	528.7	505.0	4797	7857	7703	3061	609.9	8.6
$\cos\theta_{\tau^+\tau^-}$	1386	46.28	442.2	255.6	191.4	1468	2001	2831	1154	475.6	13.7
$d_0$sig	1338	30.29	235.1	244.3	131.4	854.9	1928	1786	1044	248.1	15.1
$z_0$sig	1287	19.54	105.0	234.7	81.77	408.2	1845	909.9	883.4	244.6	16.6
$M_{\tau^+\tau^-}$	1286	19.39	103.2	234.7	72.05	349.1	1837	883.5	883.4	243.9	16.7
$E_{\tau^+\tau^-}$	1282	19.39	103.0	234.7	72.05	324.7	1836	873.2	883.4	243.9	16.7
M_{colapp}	1065	3.074	18.76	47.94	10.28	72.83	616.9	150.8	137.0	0.746	23.1
E_{colapp}	1062	2.454	18.01	46.72	10.28	71.27	612.1	93.05	93.52	0.454	23.7
M_{recoil}	1026	2.144	14.54	21.24	9.938	57.07	366.3	39.64	43.31	0.161	25.8

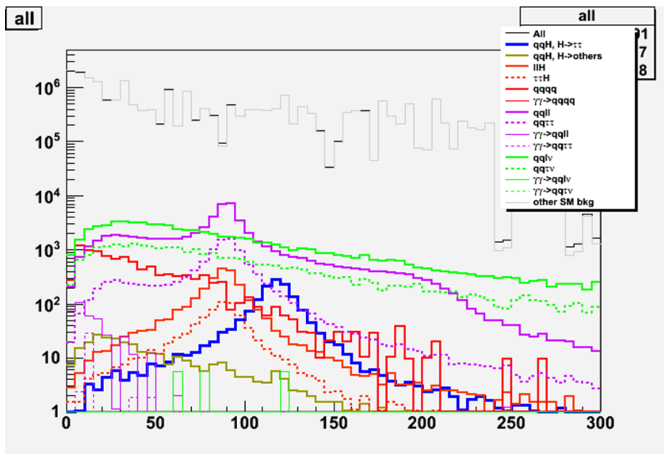
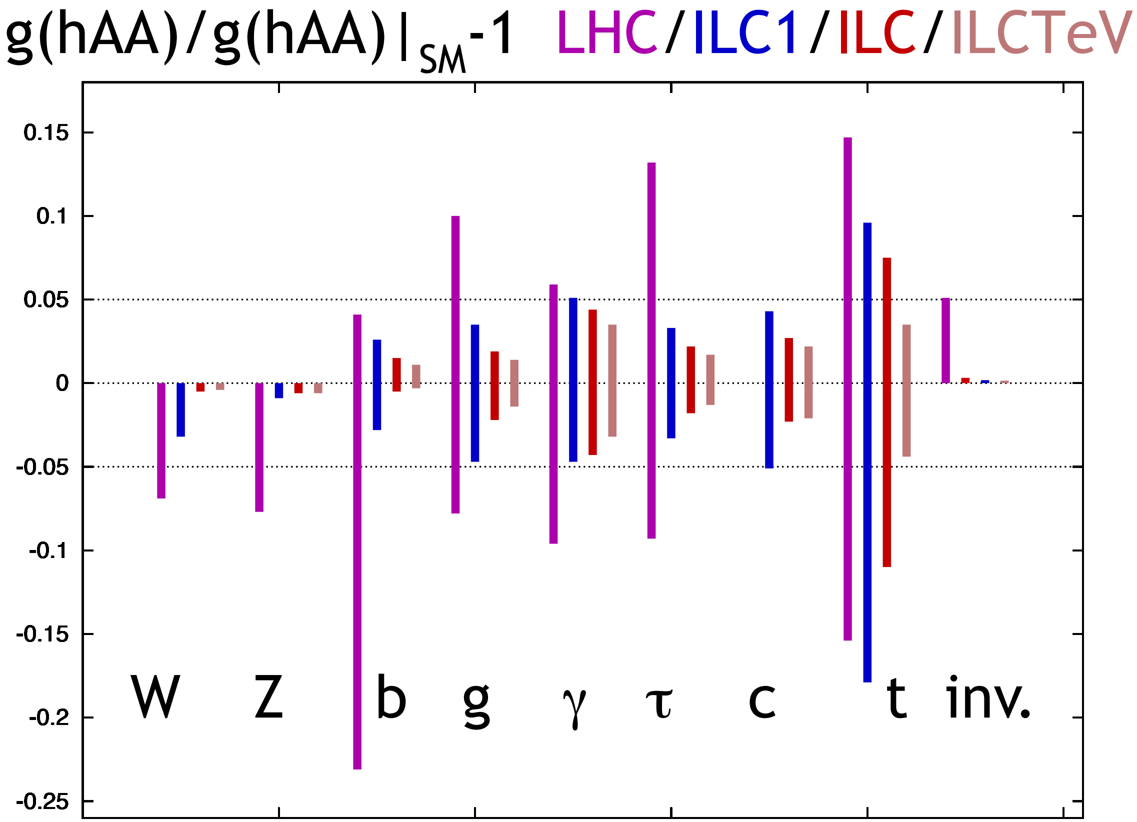


Table 5: The results of the extrapolation to $M_H = 125$ GeV.

$Z \to e^+e^-$	$Z \to \mu^+\mu^-$	$Z \to q\bar{q}$	Combined	$\frac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}}$
6.8σ	7.4σ	21.9σ	24.1σ	4.2 %

[S. Kawada, K. Fujii, T. Suehara, T. Takahashi, T. Tanabe, LC-REP-2013-001]

Higgs Couplings



[M. Peskin, arXiv:1207.2516]

„Required“ accuracy

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \text{GeV}}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2 . \qquad (13)$$

At the lower end of the range, the LHC experiments should see the deviation in the hbb or $h\tau\tau$ coupling. However, the heavy MSSM Higgs bosons can easily be as heavy as a TeV without fine tuning of parameters. In this case, the deviations of the gauge and up-type fermion couplings are well below the percent level, while those of the Higgs couplings to b and τ are at the percent level,

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2 . \qquad (14)$$

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

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

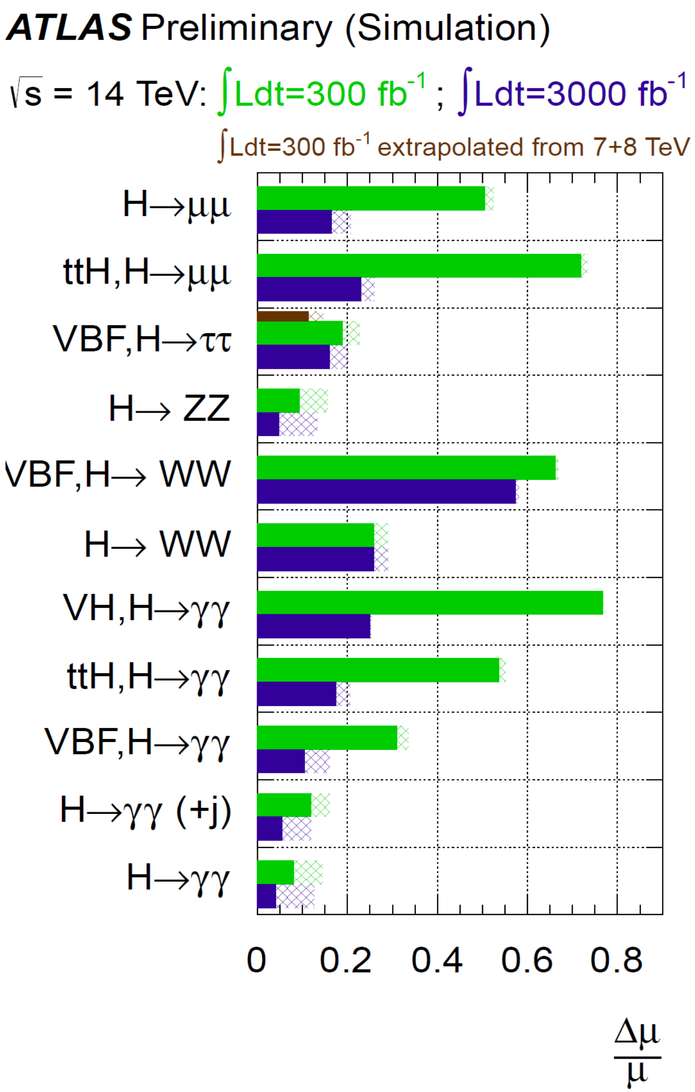
$$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 1.4\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2 , \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.4\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2 , \qquad (17)$$

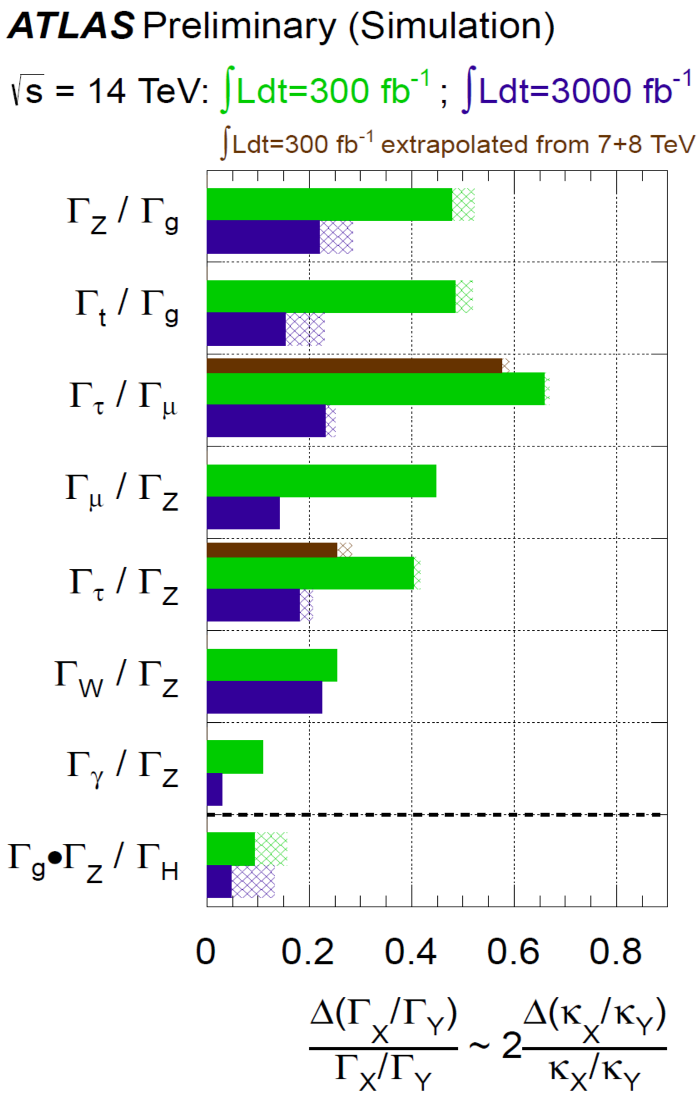
and for a fermionic top-partner,

$$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2 , \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2 . \qquad (18)$$

Peskin et al

High Lumi: precision





Other facilities for Higgs production

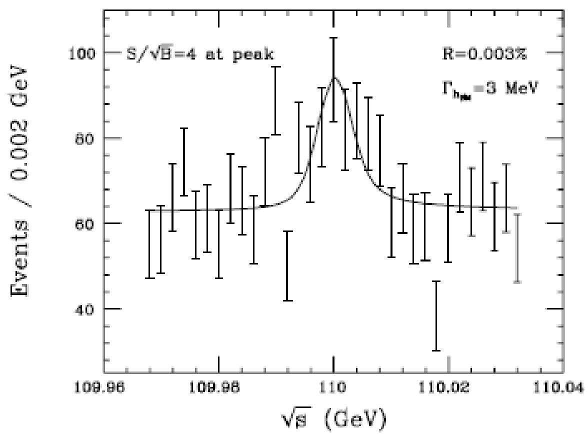
SAPPHIRE: $\gamma\gamma \rightarrow H$ at $\sqrt{s_{\gamma\gamma}} = m_H$ $L = 0.36\ 10^{34}\ cm^{-2}s^{-1}$

decay mode	raw events/year	S/B	ϵ_{sel}	$\mathcal{BR}$	$\Delta\Gamma_{\gamma\gamma}\mathcal{BR}/\Gamma_{\gamma\gamma}\mathcal{BR}$
$b\bar{b}$	11540	4.5	0.30	57.7%	2%
W^+W^-	4300	1.3	0.29	21.5%	5%
$\gamma\gamma$	45	—	0.70	0.23%	8%

LHeC: Vector boson fusion (CC,NC) $\Delta\sigma$ ($ep \rightarrow (H \rightarrow bb)+X \approx 8\%$ (stat.) + (pdf,NLO)

Muon Collider: $\mu^+ \mu^- \rightarrow H$ at $\sqrt{s} = m_H$ $\sigma \approx 50$ pb

10^7 s at $L = 10^{31}\ cm^{-2}s^{-1}$

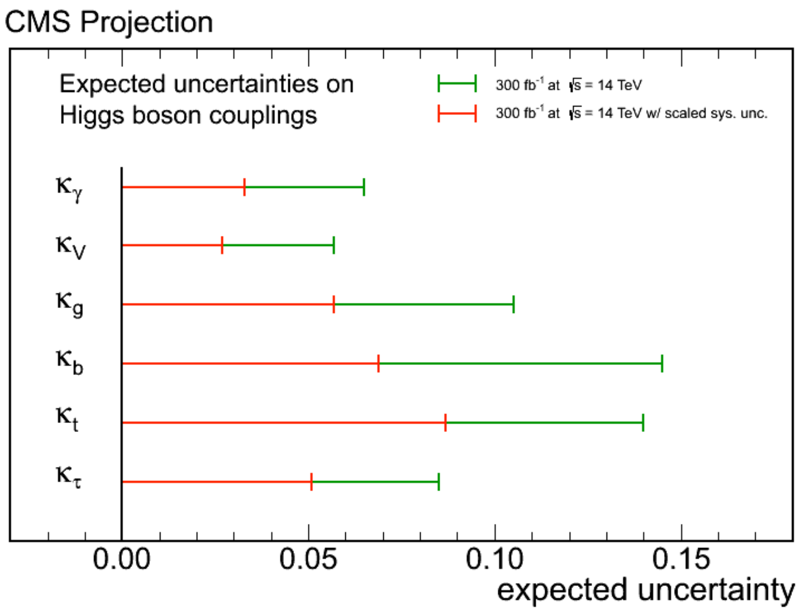


Further Higgs program at μCollider same as for e^+e^- if at same $\sqrt{s}$ and L

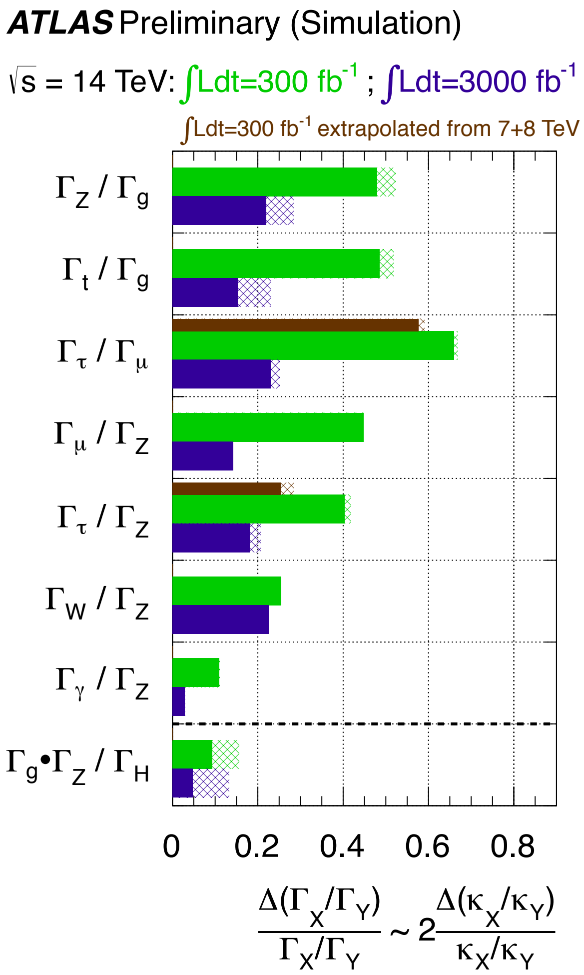
Higgs couplings at LHC

Need additional assumptions to convert the LHC μ measurements into couplings:

- assume no new particles contribute
- assume upper limit on Γ_{tot}
- assume non-observed final states to be either small or „coupled" to observed ones
- assume a fixed set of coupling parameters (e.g. κ_γ, κ_V, κ_g, κ_b, κ_t, κ_τ)



- Alternative: ratios of Γ´s (no theory assumptions):



Key Questions

<u>Experimental questions to the discovered particle:</u>

1. Mass
2. J – 0 (1) 2
3. CP – even / odd / admixture ?
4. Couplings to Bosons? (gauge couplings – Higgs mechanism)
   W/Z
5. Couplings to Fermions? (establish Yukawa mechanism)
   ~ to mass?
   up-type vs. down-type ?
   quarks vs. leptons ?
   2nd vs 3rd generation
6. Self coupling? (establish shape of Higgs potential)
7. Are there any non-SM particles relevant in production and/or decay
   - non-SM decays?
   - new particles in the loop

→ rich phenomenology of H(125) opens many windows to new physics

A window to New Physics?

- Multiplet structure:
  - Additional singlet?
  - Additional doublet?
  - Additional triplet?
- Underlying dynamics :
  - Weakly interacting or strongly interacting?
    = elementary or composite ?
- Relations to other problems :
  - DM
  - EW baryogenesis
  - neutrino mass
  - inflation?

Higgs spin/parity

LHC: Decay angle analysis in H→ZZ→4l and H→γγ

today: ATLAS + CMS prefer 0^+ over 0^- and 2^+ at the 1-2σ level

prospects: expect sensitivity to confirm 0^+ well within LHC300 programme
ATLAS study for CP violation in H→ZZ→4l:

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

Integrated Luminosity	Signal (S) and Background (B)	$6+6i$ a_1	$6i$ a_2	$4+4i$ a_3
100 fb^{-1}	$S = 158$; $B = 110$	3.0	2.4	2.2
200 fb^{-1}	$S = 316$; $B = 220$	4.2	3.3	3.1
300 fb^{-1}	$S = 474$; $B = 330$	5.2	4.1	3.8

number σ´s sensitivity
to different amplitudes

[ATLAS, Krakow report]

The Higgs self coupling: 1 TeV

TABLE VII: The reduction table for the signal and backgrounds after the final selection for $\nu\nu HH$ at 1 TeV mode, together with the number of expected events and generated events. The cuts names are explained in text.

Process	expected	generated	pre-selection	Cut1	Cut2	Cut3	Cut4
$\nu\nu HH$ $(fusion)$	272	1.05×10^5	127	107	77.2	47.6	35.7
$\nu\nu HH$ (ZHH)	74.0	2.85×10^5	32.7	19.7	6.68	4.88	3.88
$yyxye\nu$	1.50×10^5	6.21×10^5	812	424	44.4	11.0	0.73
$yyxyl\nu$	2.57×10^5	1.17×10^6	13457	4975	202	84.5	4.86
$yyxyyx$	3.74×10^5	1.64×10^6	18951	4422	38.5	26.7	1.83
$\nu\nu bbbb$	650	2.87×10^5	553	505	146	6.21	4.62
$\nu\nu ccbb$	1070	1.76×10^5	269	242	63.3	2.69	0.19
$\nu\nu qqh$	3125	7.56×10^4	522	467	257	30.6	17.6
BG	7.86×10^5		34597	11054	758	167	33.7

[J.Tian LC-REP-2013-003]

e^+e^- colliders

Table 2.2: Overview of electron-positron colliders (*different scenarios).

Facility	Year	E_{cm} [GeV]	Luminosity [$10^{34}\,cm^{-2}s^{-1}$]	Tunnel length [km]
ILC 250	$\ll$2030	250	0.75	
ILC 500		500	1.8	~ 30
ILC 1000		1000	4.9	~ 50
CLIC 500	>2030	500	2.3 (1.3)*	~ 13
CLIC 1400		1400 (1500)*	3.2 (3.7)*	~ 27
CLIC 3000		3000	5.9	~ 48
LEP3	>2024?	240	1	LEP/LHC
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

from European Strategy „Briefing Book" (red stuff added by KD)