Physics at the ILC

with focus mostly on Higgs physics

Keisuke Fujii (KEK)

Electroweak Symmetry Breaking

Mystery of something in the vacuum

- The success of the SM is a success of gauge principle. We know that the transverse components of W and Z are gauge fields of the EW gauge symmetry.
- Since the gauge symmetry forbids explicit mass terms for W and Z, it must be broken by something condensed in the vacuum which carries EW charges:

$$\langle 0 \,|\, I_3, Y \,|\, 0 \rangle \neq 0 \quad \langle 0 \,|\, I_3 + Y \,|\, 0 \rangle = 0$$

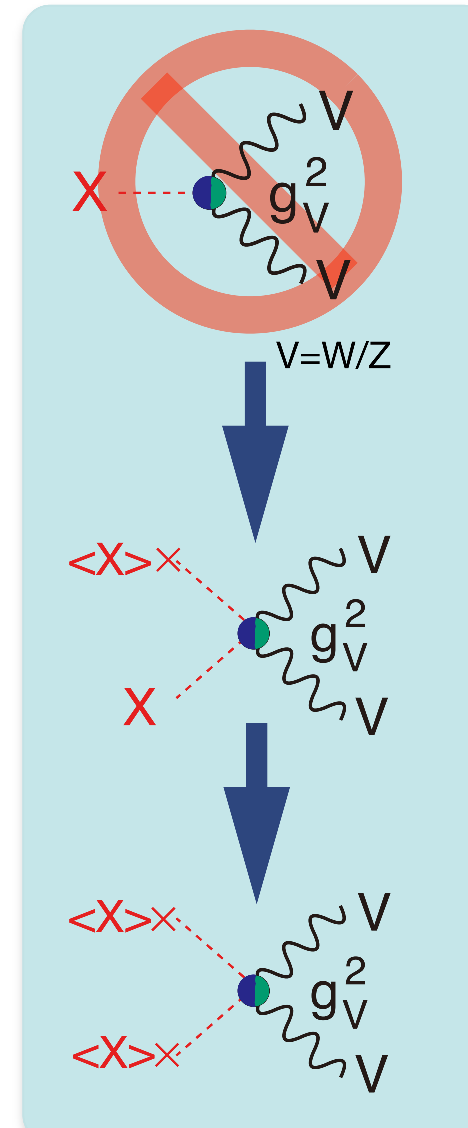
- This “something” supplies 3 longitudinal modes of W and Z:

$$W_L^+, W_L^-, Z_L \longleftarrow \chi^+, \chi^-, \chi_3$$: Goldstone modes

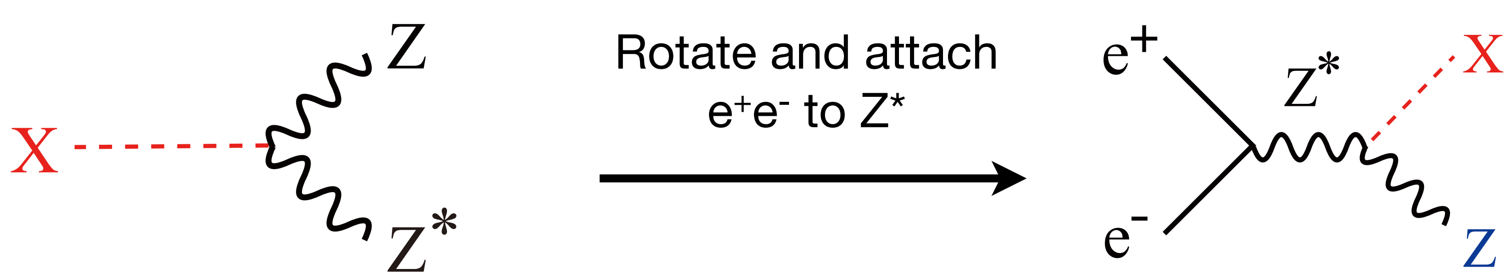
- Since Left- and right-handed matter fermions carry different EW charges, explicit mass terms are also forbidden for matter fermions by the EW gauge symmetry. Their masses have to be generated through their Yukawa interactions with some weak-charged vacuum.
- In the SM, the same “something” mixes the left- and right-handed matter fermions, consequently generating masses and inducing flavor-mixings among generations.
- In order to form the Yukawa interaction terms, we need a complex doublet scalar field. The SM identifies three real components of the doublet with the Goldstone modes that supply the longitudinal modes of W and Z.
- We need one more to form a complex doublet, which is the physical Higgs boson.
- This SM symmetry breaking sector is the simplest and the most economical, but there is no reason for it. The symmetry breaking sector (hereafter called the Higgs sector) might be more complex.
- We don’t know whether the “something” is elementary or composite.
- We knew it’s there in the vacuum with a vev of 246GeV. But other than that we did not know almost anything about the “something” until July 4, 2012.

Since the July 4th, the world has changed!

The discovery of the ~125 GeV boson at LHC could be called a quantum jump.

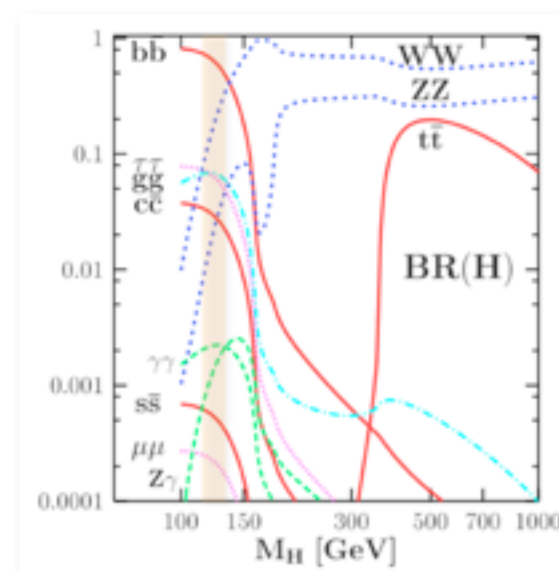


- X(125) -> γγ means X is a neutral boson and J ≠ 1 (Landau-Yang theorem).
- We know that the 125GeV boson decays to ZZ* and WW*, indicating the existence of XVV couplings: (V=W/Z: gauge bosons). There is no gauge coupling like XVV. There are only XXVV or XXV, hence XVV is most probably from XXVV with one X replaced by its vacuum expectation value <X> ≠ 0, namely <X>XVV.
  Then there must be <X><X>VV, a mass term for V, meaning that X is at least part of the origin of the masses of V=W/Z.
  --> This is a great step forward but we need to know whether <X> saturates the SM vev = 246GeV.
- X -> ZZ* means, X can be produced via e^+e^- -> Z* -> ZX



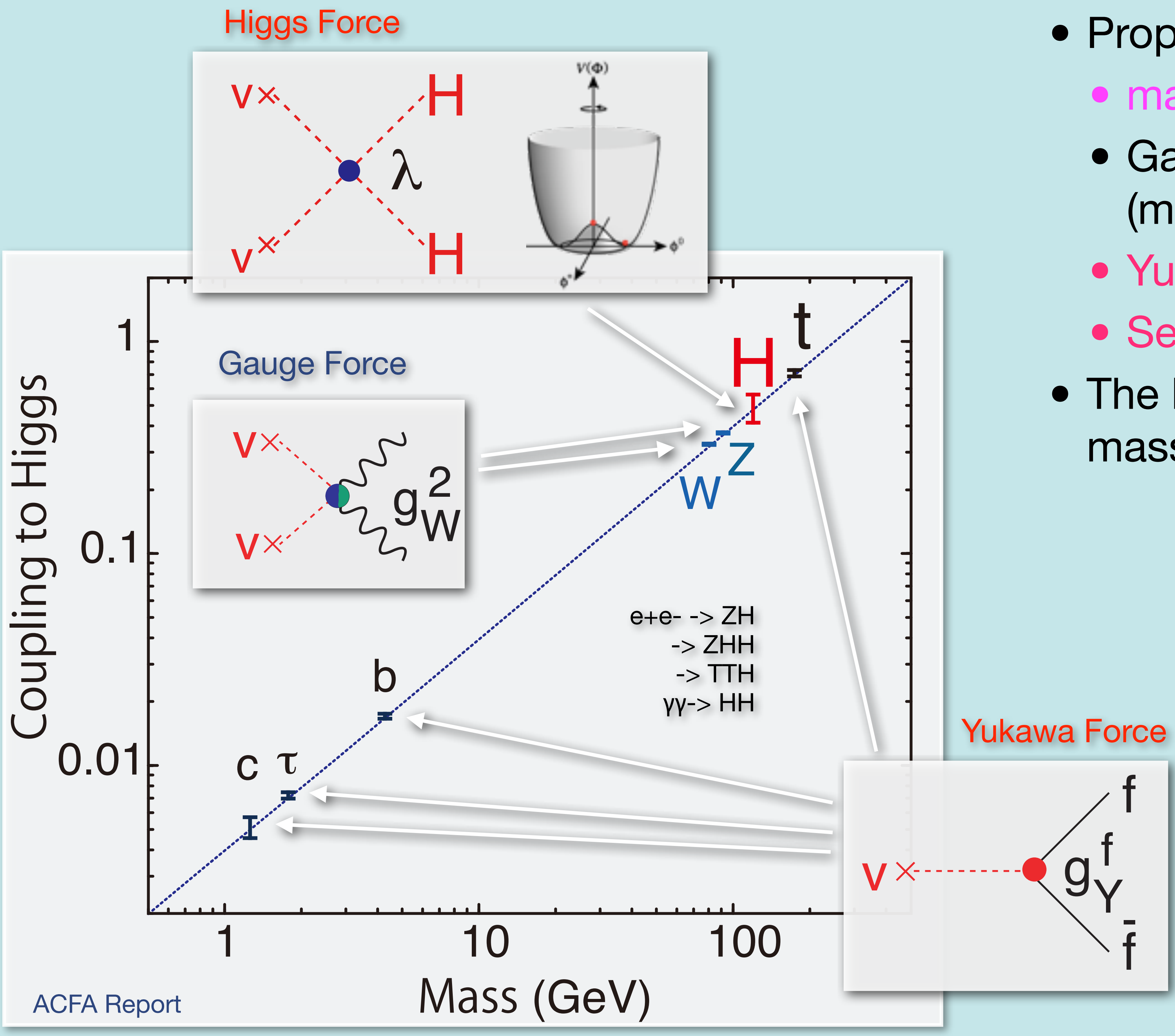
- By the same token, X -> WW* means, X can be produced via W fusion process: e^+e^- -> *ννX*

- We knew almost nothing about the “something” until July 4.
- We now know there is indeed “something” which seems to be condensed in the vacuum and can be produced in e^+e^- collisions. --> No lose theorem for the ILC.
- ~125GeV is the best place for the ILC, where variety of decay modes are accessible.
- We need to check this ~125GeV boson in detail to see if it has indeed all the required properties of the something in the vacuum.



The Mass Coupling Relation

Uncover the secret of the Electroweak Symmetry Breaking



- Properties to measure are
  - mass, width, J^{PC}
  - Gauge quantum numbers (multiplet structure)
  - Yukawa couplings
  - Self-coupling
- The key is to measure the mass-coupling relation

If the 125GeV boson is the one to give masses to all the SM particles, coupling should be proportional to mass.

Any deviation from the straight line signals BSM!

The Higgs is a window to BSM physics!

Precision Higgs Studies

The Mission = Bottom-up reconstruction of the EWSB sector

- Through the coupling measurements, determine the Electroweak Symmetry Breaking sector (bottom-up model-independent reconstruction of the Lagrangian for the Higgs and Yukawa sectors):

- 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?

There are many possibilities to discuss, and that's exactly why we are here!

- The July 4 was the opening of a new era which will last probably 20 years or more, where a 500 GeV LC such as ILC will / must play the central role.

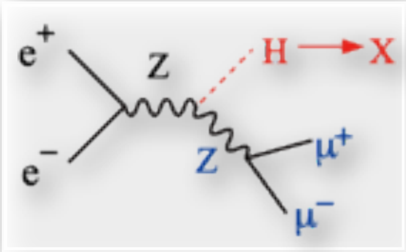
ILC 250-500

Why 250-500 GeV?

Three well known thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

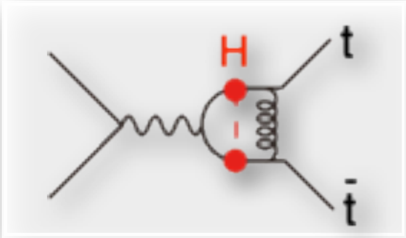
- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (recoil mass) -> couplings to H (other than top)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

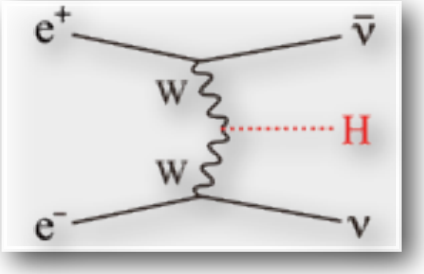


ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

- Threshold scan --> theoretically clean mt measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> indirect meas. of top Yukawa coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



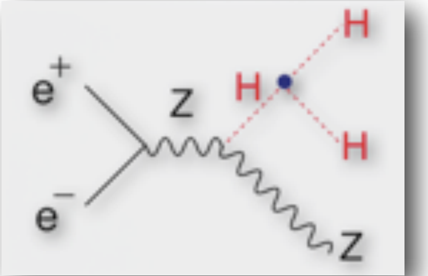


vvH @ 350 - 500GeV :

- HWW coupling -> total width --> absolute normalization of couplings

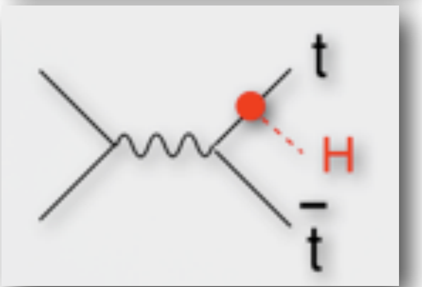
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> Higgs self-coupling



ttbarH @ 500GeV (~$2m_t+M_H$+30GeV) :

- Prod. cross section becomes maximum at around 700GeV.
- QCD threshold correction enhances the cross section -> top Yukawa measurable at 500GeV concurrently with the self-coupling



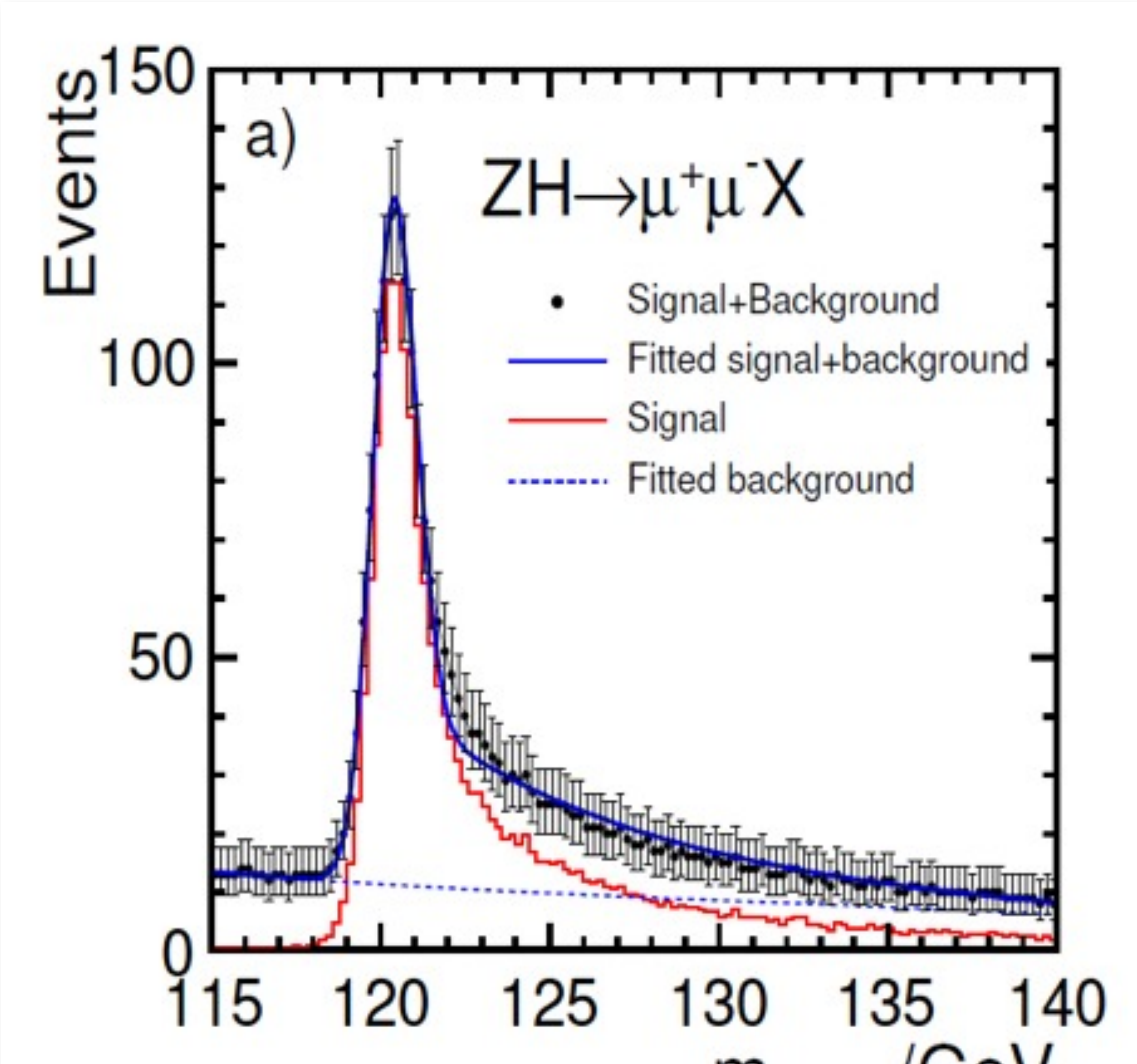
We can complete the mass-coupling plot at ~500GeV!

ILC 250

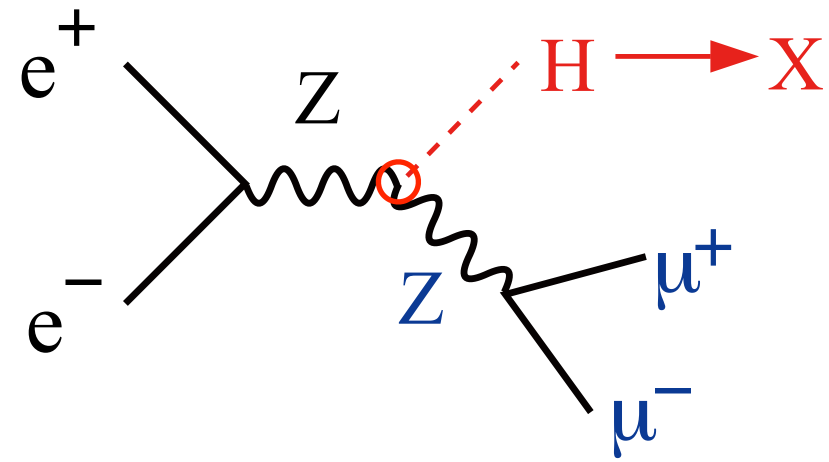
Recoil Mass Measurements

The flagship measurement of ILC 250

Recoil Mass



ILD LoI



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

Invisible decay detectable!

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

$$\Delta\sigma_H/\sigma_H = 2.5\%$$

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

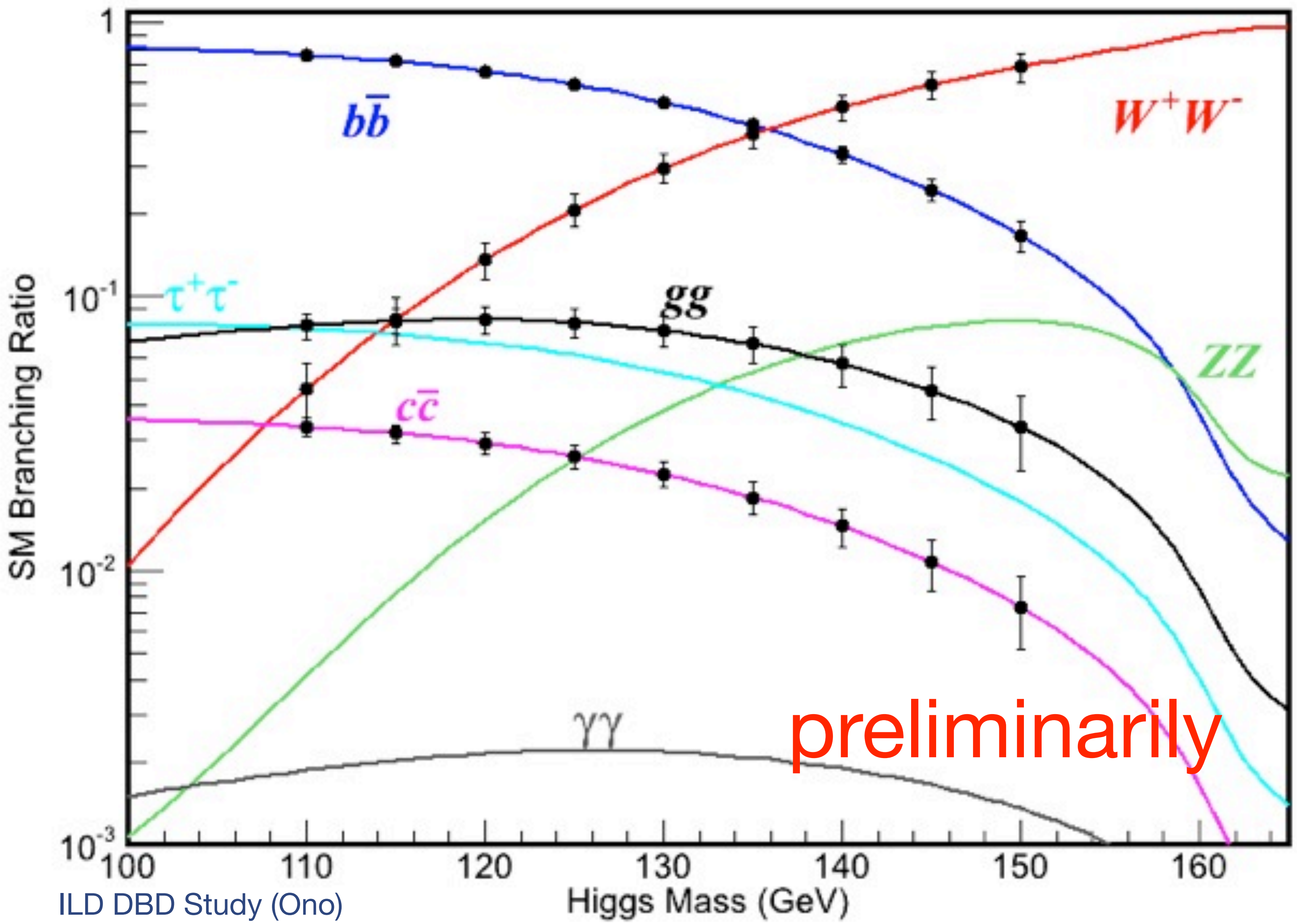
$$BR(\mathrm{invisible}) < 1\%\,@\,95\,\mathrm{C.L.}$$

Model-independent absolute measurement of the HZZ coupling

Branching Ratio Measurements

for b, c, g, tau, WW*

DBD Physics Chap.



ILD DBD Study (Ono)

$$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$$
$$m_H = 120\,\mathrm{GeV}$$

	@250GeV
process	ZH
Int. Lumi. [fb^{-1}]	250
Δσ/σ	2.5%
decay mode	ΔσBr/σBr
H --> bb	0.94%
H --> cc	6.5%
H --> gg	8.0%
H --> WW*	7.6%
H --> ττ	3.4%
H --> ZZ*	25%
H --> γγ	23-30%

preliminarily

Measurement accuracies extrapolated from Mh=120 GeV results

To extract BR from σxBR, however, we need σ from the recoil mass measurement.

--> Δσ/σ=2.5% eventually limits the BR measurements.

--> If we want to improve this, we need more data at 250GeV.

x2 lumi. upgrade is possible by increasing #bunches/train back to the RDR value.

Total Width and Coupling Extraction

One of the major advantages of the LC

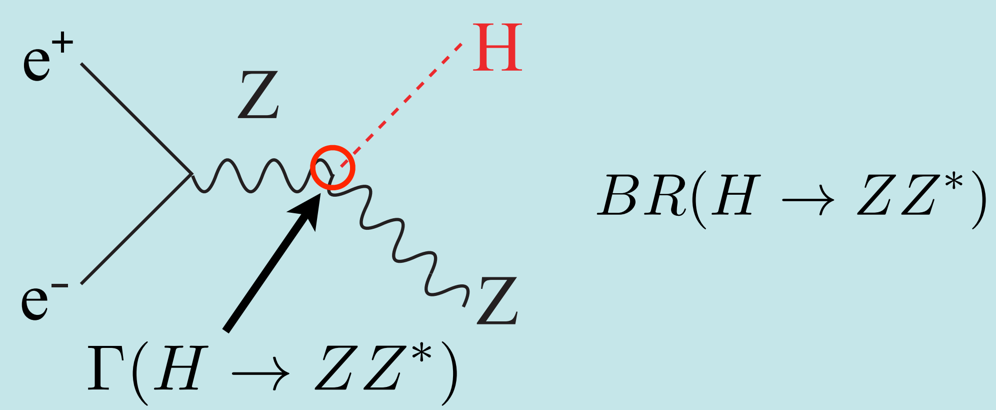
To extract couplings from BRs, we need the total width:

$$g_{HAA}^2 \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

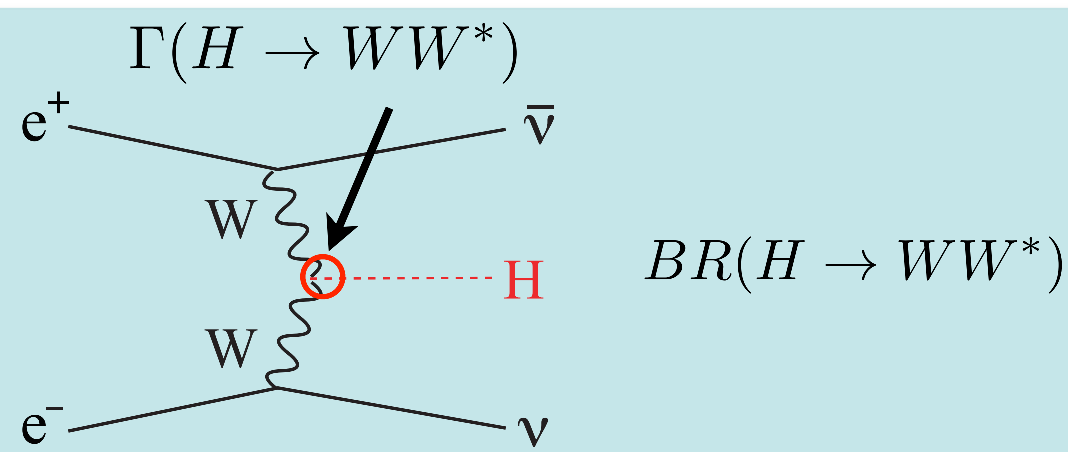
To determine the total width, we need at least one partial width and corresponding BR:

$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

In principle, we can use the A=Z, or W for which we can measure both the BRs and the couplings:



BR=O(1%): precision limited by low stat. for H->ZZ* events



More advantageous but not easy at low E

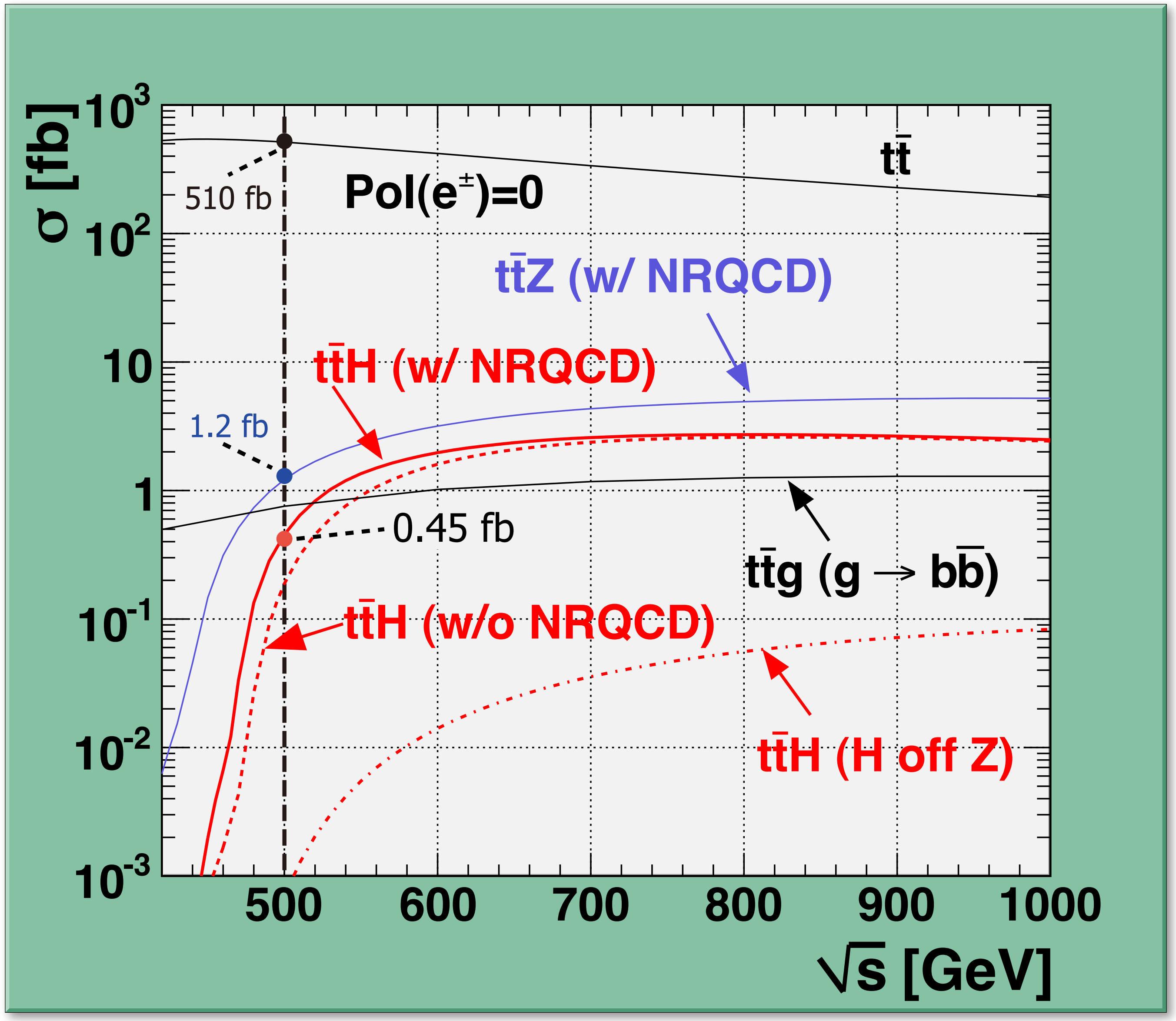
$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 11\%$

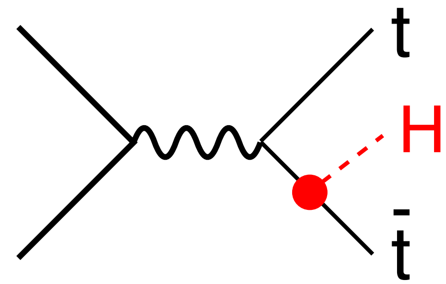
C.F.Durig, Helmholtz Alliance 6th WS, Dec. 2012

ILC 500

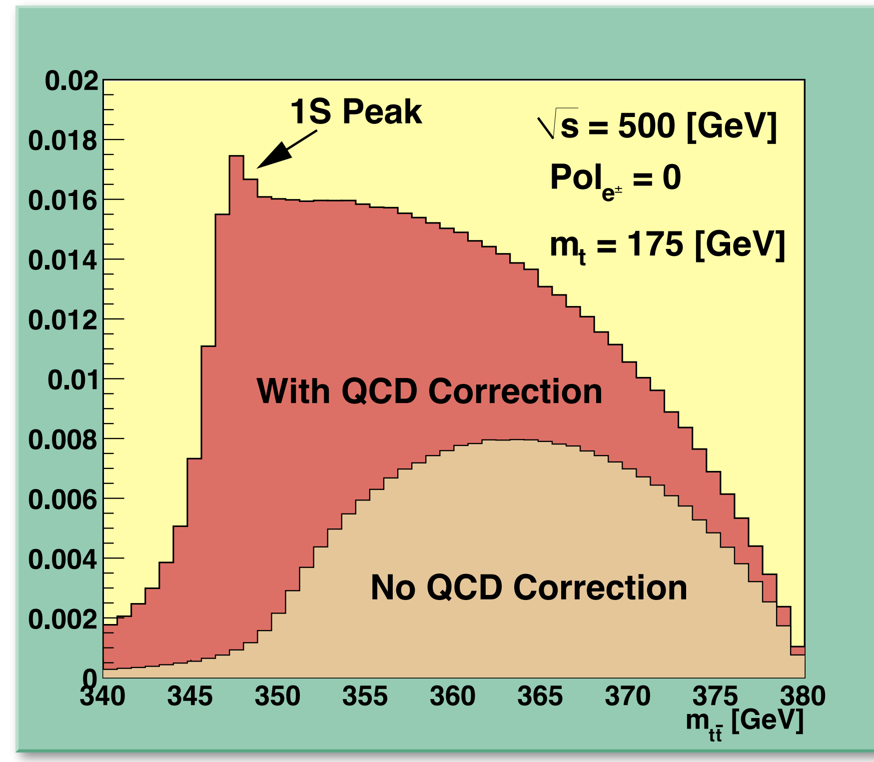
Top Yukawa Coupling

The largest among matter fermions, but not yet observed





H-> bb



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff, LCWS12
Tony Price, LCWS12

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV}$$

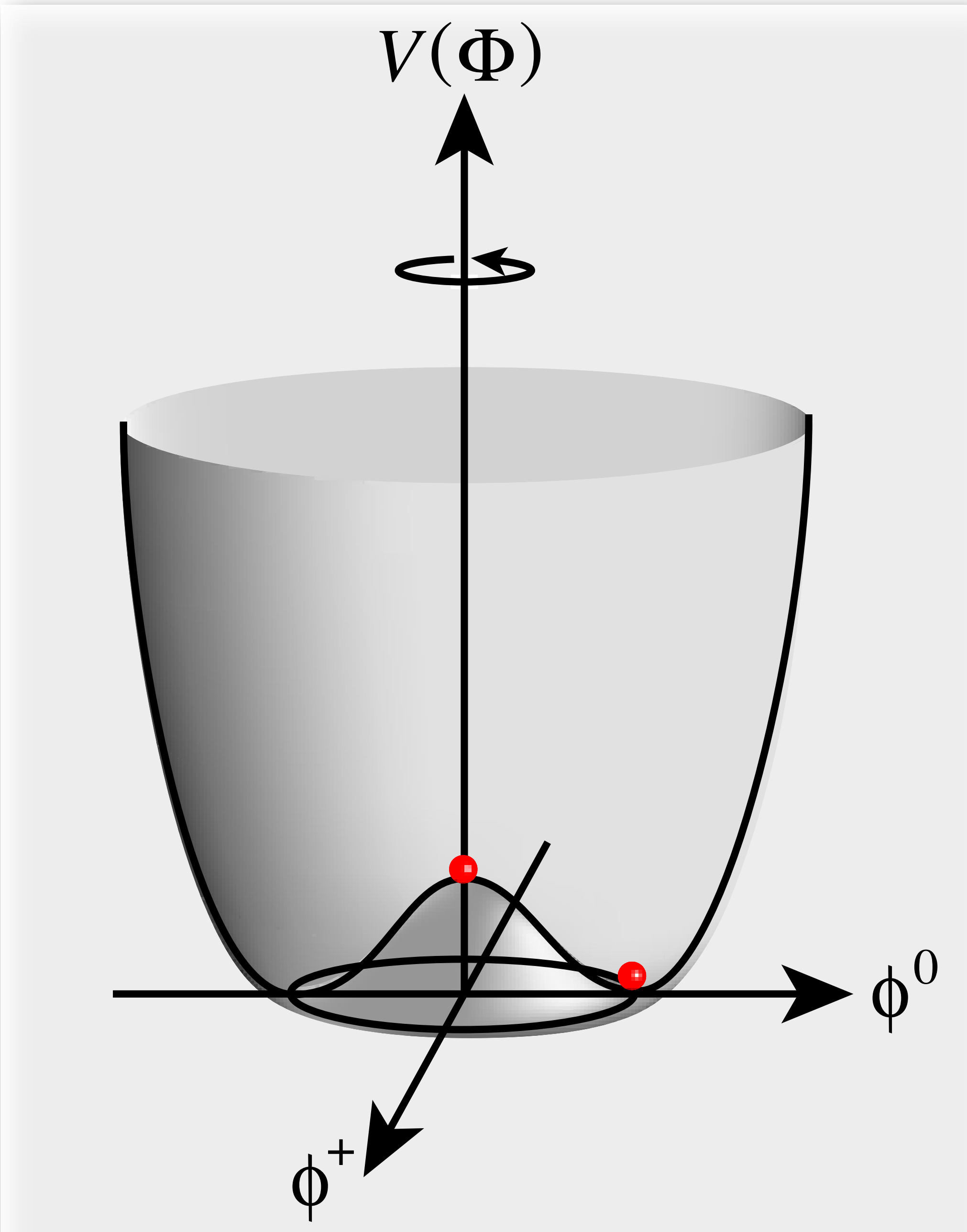
$$\Delta g_Y(t)/g_Y(t) = 10\,\%$$

Tony Price, LCWS12

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

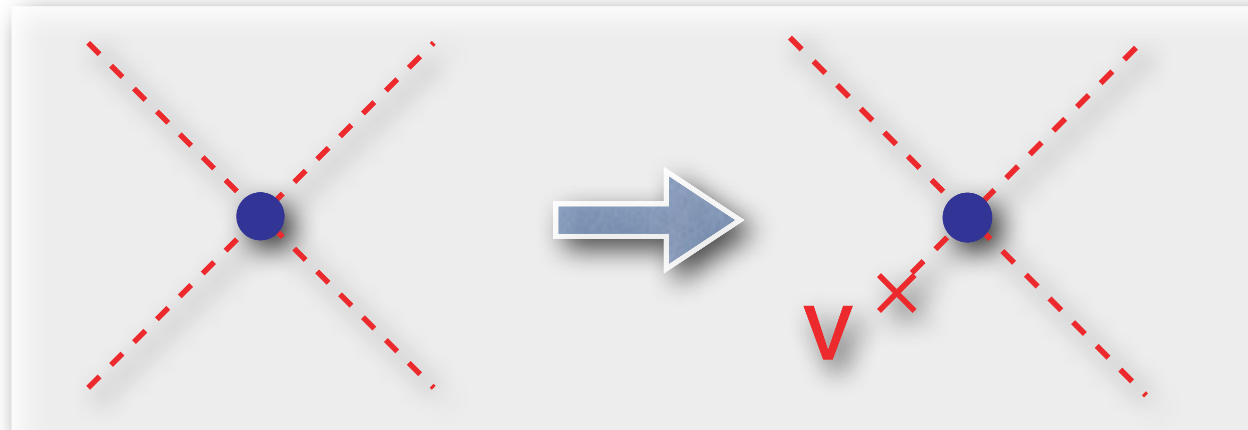
Higgs Self-coupling

What force makes the Higgs condense in the vacuum?

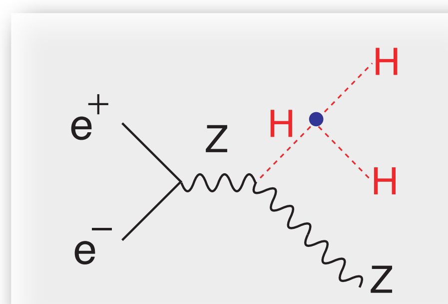


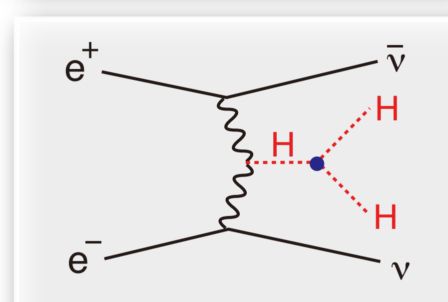
In order to uncover the secret of electroweak symmetry breaking, we need to observe the force that makes the Higgs condense in the vacuum!

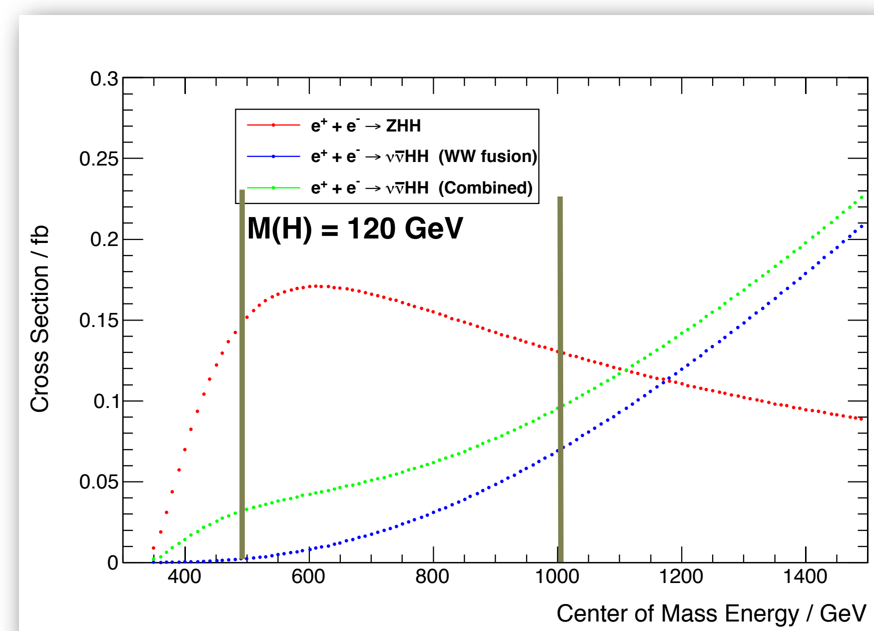
We need to measure the Higgs self-coupling



= We need to measure the shape of the Higgs potential







difficulties

fundamental:

- irreducible SM diagrams, significantly degrade the coupling sensitivity.
- very small cross section (σ_{ZHH}~0.22 fb with P_L) and we are only using ~40% of the signal (both H-->bb). large integrated luminosity needed. (high beam polarization helps a lot)
- huge SM background (tt/WWZ, ZZ/Zγ, ZZZ/ZZH), 3-4 orders higher.

technical:

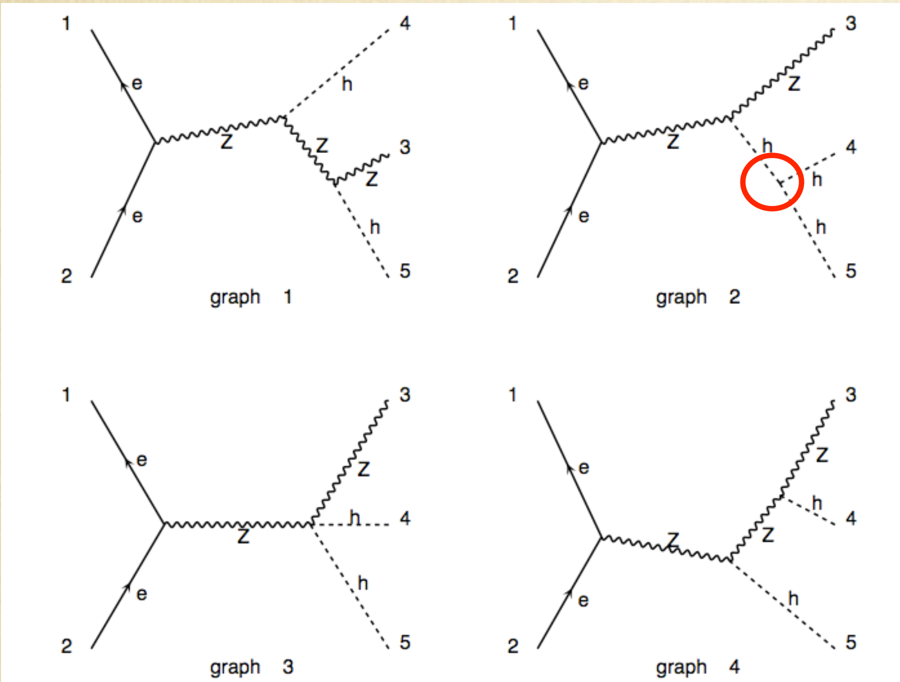
- Higgs mass reconstruction: mis-clustering, missing neutrinos, wrong pairing.
- flavor tagging and isolated-lepton selection: need very high efficiency and purity.
- neural-net training: separate neural-nets, huge statistics needed.

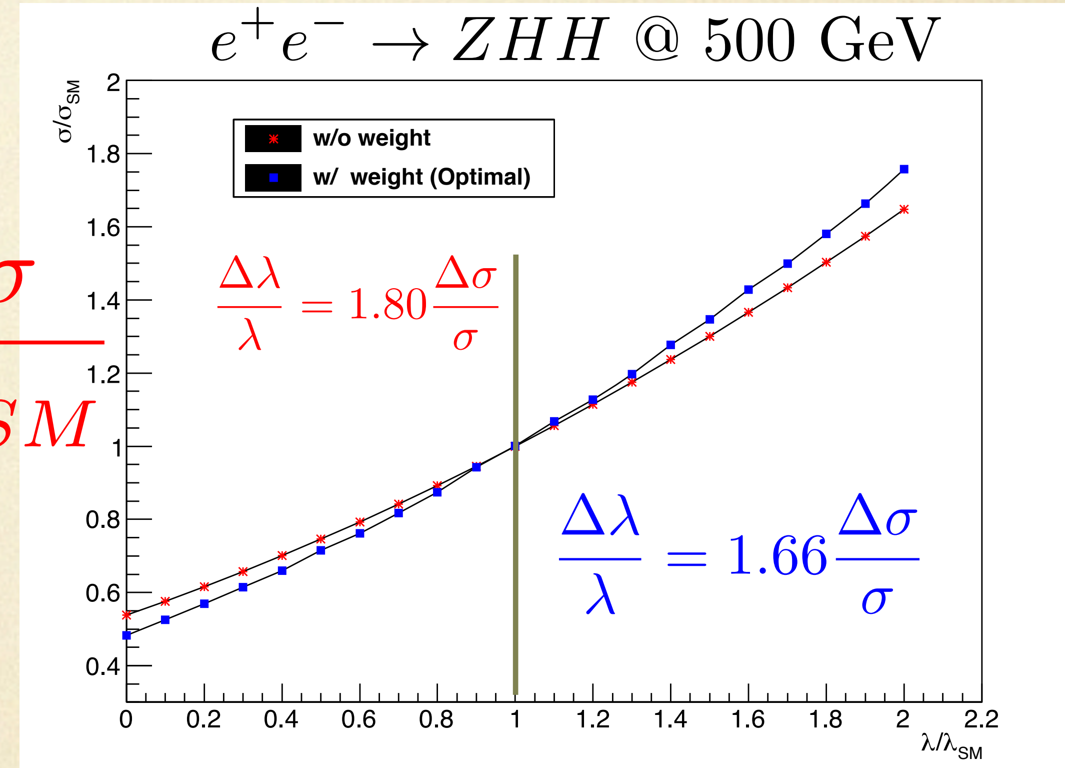
developments since LoI time

- LCFIPlus: Vertexing before jet-clustering --> flavor tagging much improved
- Improved data selection (neural-net optimization)
- Event weighting to enhance the signal diagram

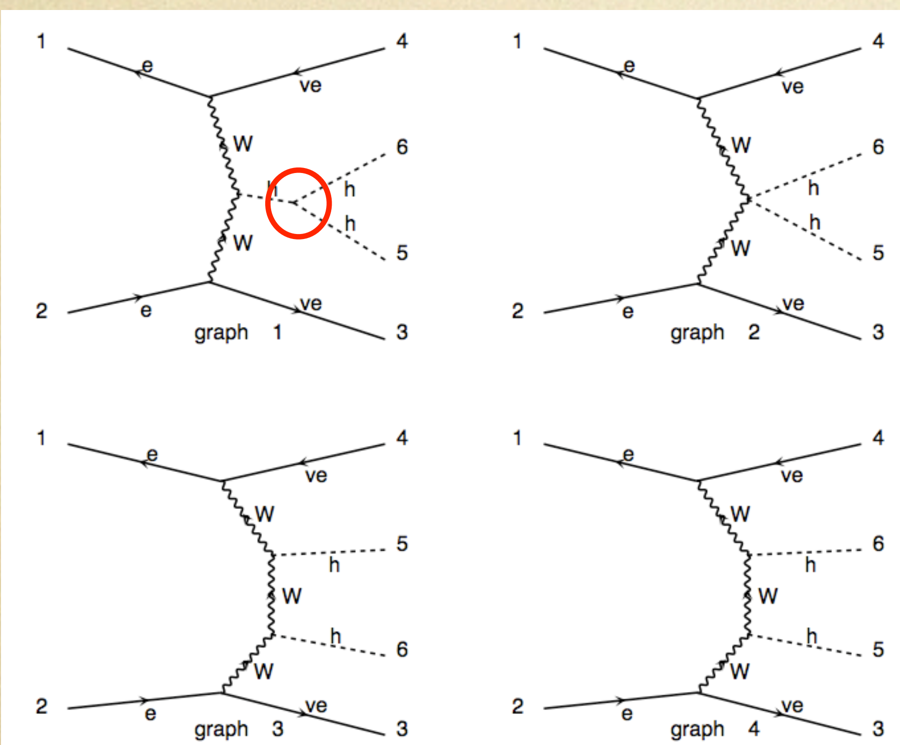
General issue: sensitivity to the cross section

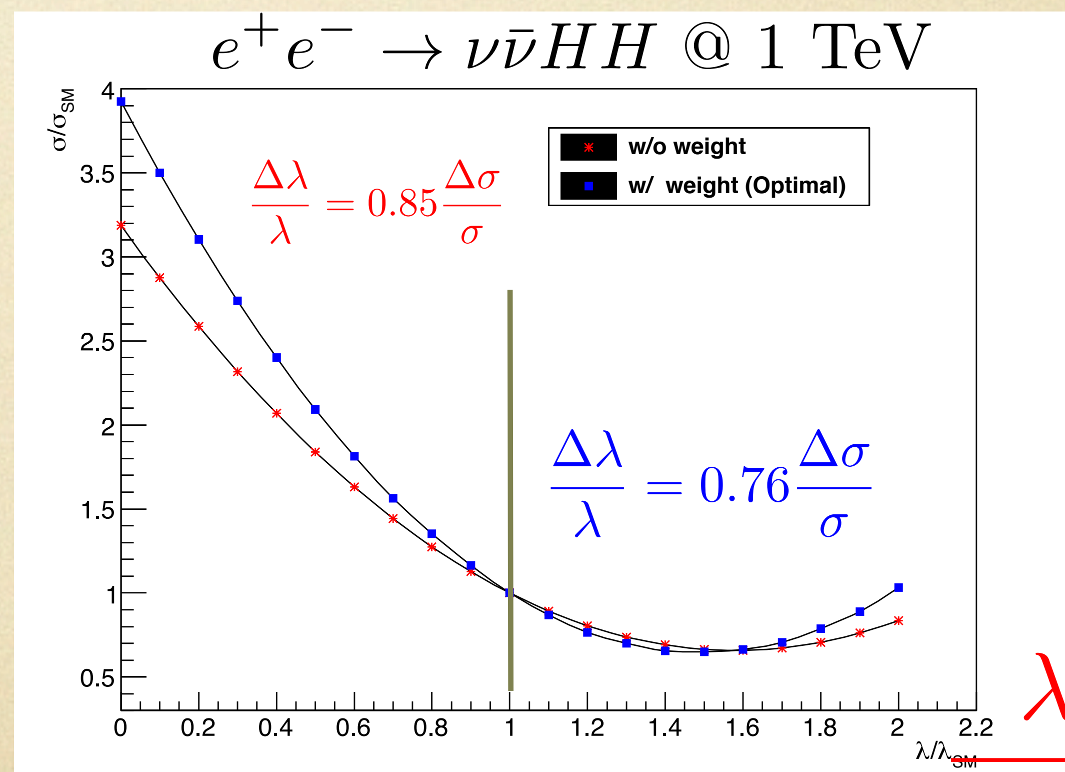
effect of irreducible diagrams





$\frac{\sigma}{\sigma_{SM}}$





$\frac{\lambda}{\lambda_{SM}}$

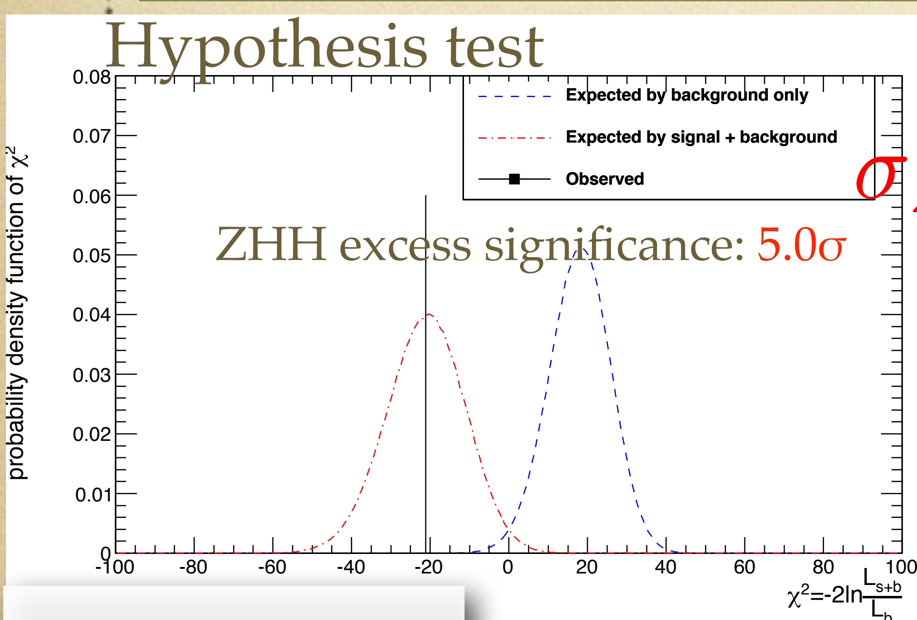
preliminary

DBD analysis at 500 GeV (combined)

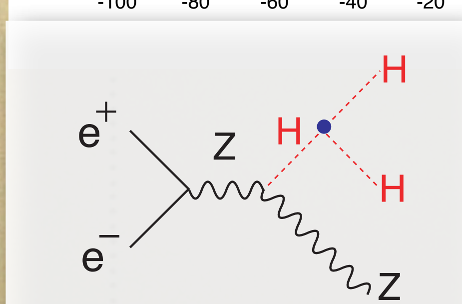
P(e-,e+)=(-0.8,0.3) $e^+ + e^- \to ZHH$ $M(H) = 120\mathrm{GeV}$ $\int Ldt = 2\mathrm{ab}^{-1}$

Energy (GeV)	Modes	signal	background	significance	
				excess (I)	measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	3.7	4.3	1.5σ	1.1σ
		4.5	6.0	1.5σ	1.2σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	8.5	7.9	2.5σ	2.1σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	13.6	30.7	2.2σ	2.0σ
		18.8	90.6	1.9σ	1.8σ

Hypothesis test



ZHH excess significance: 5.0σ

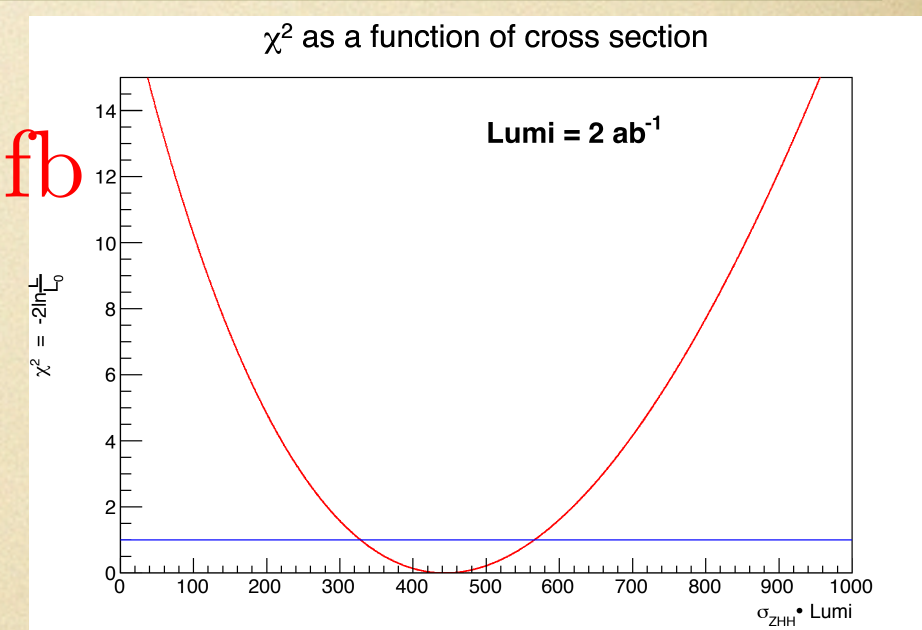


$$\sigma_{ZHH} = 0.22 \pm 0.06 \quad \mathrm{fb}$$

$$\delta\sigma/\sigma = 27\%$$

$$\delta\lambda/\lambda = 48\%$$

(cf. 80% for qqbbbb at the LoI time)



with weighting, it would be: $\frac{\delta\lambda}{\lambda} = 44\%$

ILC 250+500

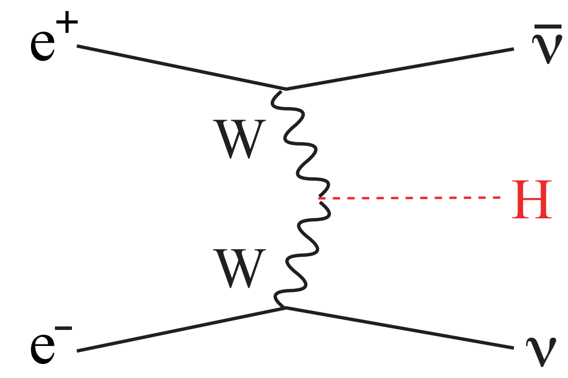
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

E_{cm} [GeV]	independent measurements	relative error
250	σ_{ZH}	2.5%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	0.94%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	6.5%
	$\sigma_{ZH} \cdot Br(H \to gg)$	8.0%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	7.6%
500	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.6%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	11%
	$\sigma_{ZH} \cdot Br(H \to gg)$	13%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	0.6%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to c\bar{c})$	5.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to gg)$	5.0%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to WW^*)$	3.0%

ILD DBD Study (Junping Tian)

$$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$$
$$+500\,\mathrm{fb}^{-1}@500\,\mathrm{GeV}$$
$$m_H = 120\,\mathrm{GeV}$$



comes in as a powerful tool!

$$\Delta\Gamma_H/\Gamma_H \simeq 6\%$$

Mode	ΔBR/BR
bb	2.6 (2.7)%
cc	4.6 (7.0)%
gg	4.8 (8.4)%
WW*	3.8 (8.0)%

preliminarily

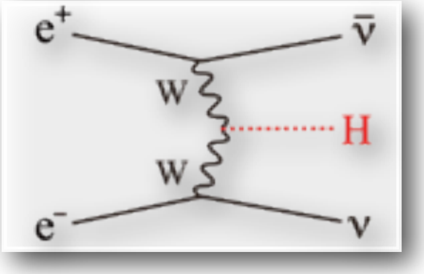
The numbers in the parentheses are as of $250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$

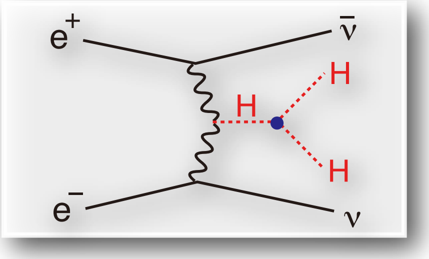
ILC >500

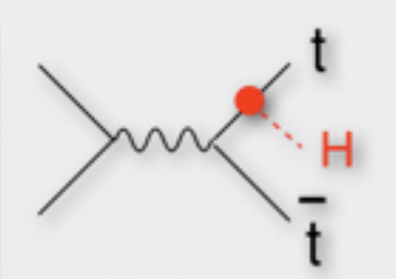
Higgs Physics at Higher Energy

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

- vvH @ at >1TeV : > 1ab^{-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)
  - cross section increases with Ecm but the sensitivity might not, because of background diagrams.
  - Nevertheless, the increased cross section probably compensates the higher BG diagram contributions and will give a better precision.
  - If possible, we want to see the running of the self-coupling (very very challenging).
- ttbarH @ 1TeV : 1ab^{-1}
  - Prod. cross section becomes maximum at around 800GeV.
  - CP mixing of Higgs can be unambiguously studied.





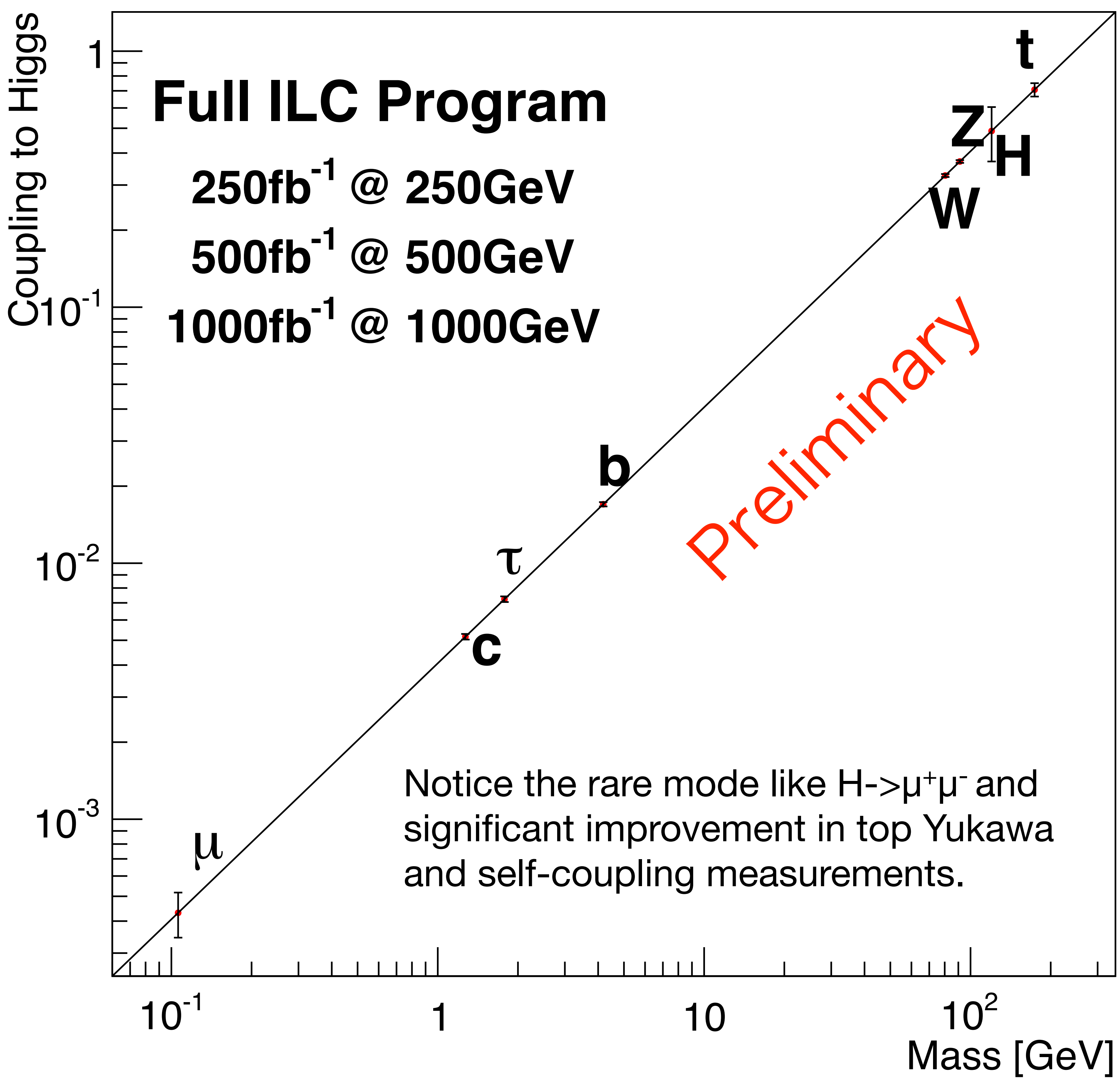


Obvious but most important advantage of higher energies in terms of Higgs physics is its higher mass reach to other Higgs bosons expected in an extended Higgs sector and higher sensitivity to $W_L W_L$ scattering to decide whether the Higgs sector is strongly interacting or not.

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

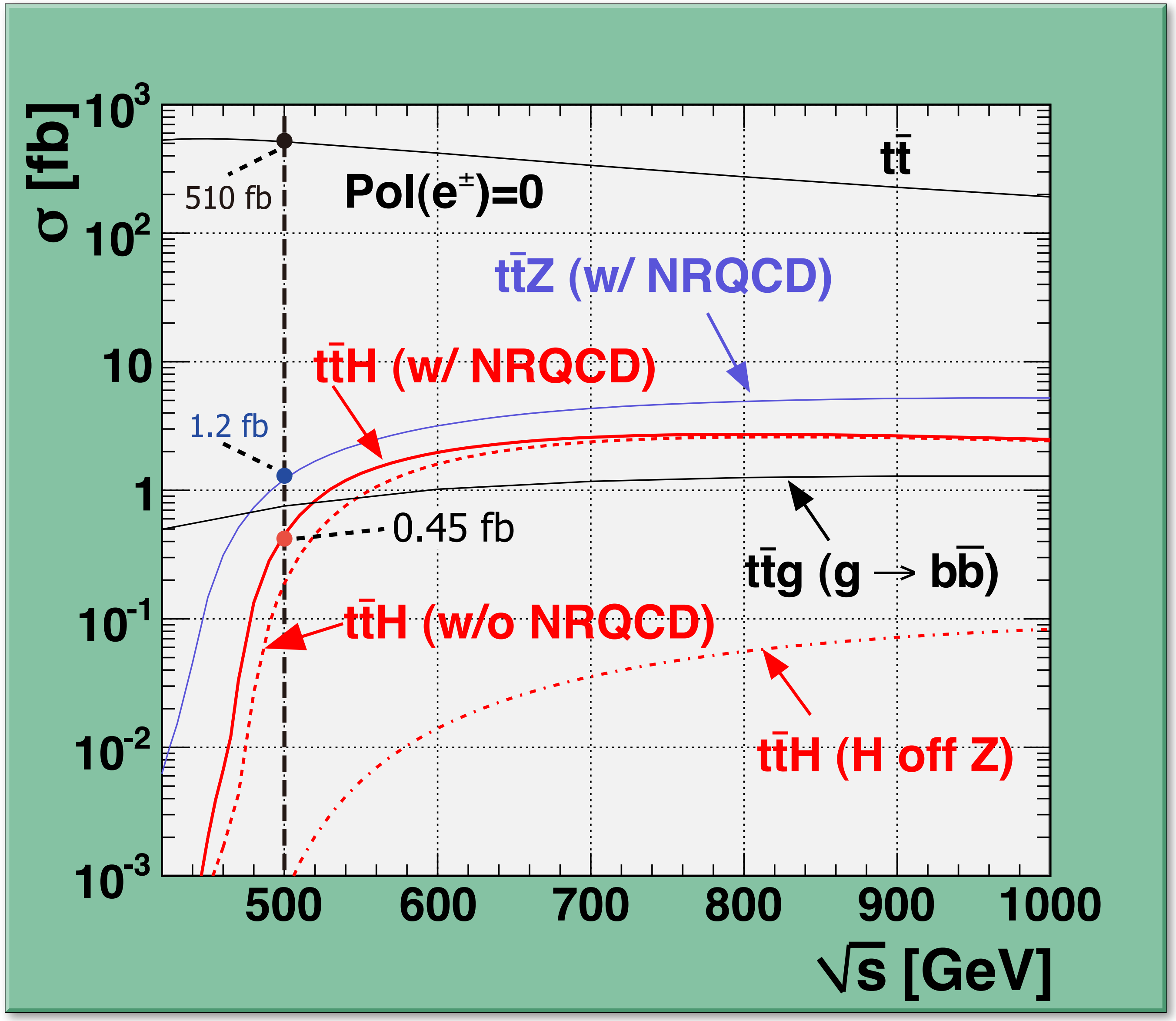
Mass Coupling Relation

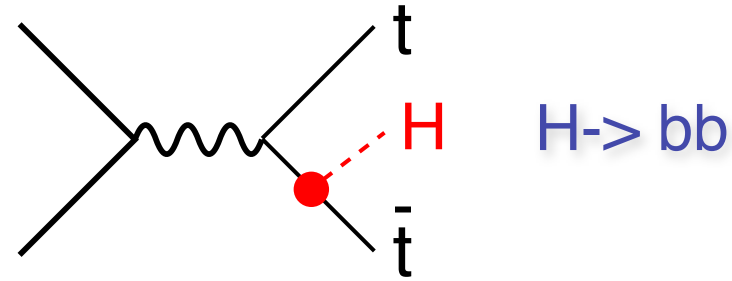
After Nominal Full ILC Program



Top Yukawa Coupling at 1TeV

The largest among matter fermions, but not yet observed





Similar significance in both modes

- 8-jet mode: 7.9σ (TMVA)
- L+6-jet mode: 8.4σ (TMVA)

Tony Price & Tomohiko Tanabe: ILD DBD Study

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV}$$
$$\Delta g_Y(t)/g_Y(t) = 10\,\%$$

Tony Price, LCWS12

$$1\,\mathrm{ab}^{-1}@1\,\mathrm{TeV}$$
$$\Delta g_Y(t)/g_Y(t) = 4.5\,\%$$

ILD / SiD DBD Studies

Cross section maximum at around Ecm = 800GeV

Tony Price & Tomohiko Tanabe: ILD DBD Study

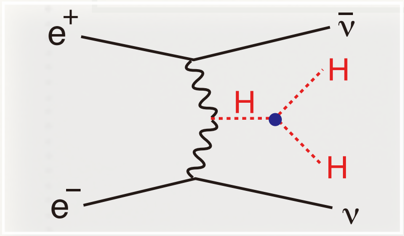
Philipp Roloff & Jan Strube: SiD DBD Dtudy

Higgs Self-coupling: ILC 1TeV: Full Sim.

signal and backgrounds (reduction table)

Polarization: (e-,e+)=(-0.8,+0.2) $E_{\rm cm} = 1$ TeV, $M_H = 120$ GeV $\int L = 2\ \mathrm{ab}^{-1}$

	Expected	Generated	pre-selction	cut1	cut2	cut3	cut4
ννhh (WW F)	272	1.05×10⁵	127	107	77.2	47.6	35.7
ννhh (ZHH)	74.0	2.85×10⁵	32.7	19.7	6.68	4.88	3.88
ννbbbb	650	2.87×10⁵	553	505	146	6.21	4.62
ννccbb	1070	1.76×10⁵	269	242	63.3	2.69	0.19
yyxyyx	3.74×10⁵	1.64×10⁶	18951	4422	38.5	26.7	1.83
yyxyeν	1.50×10⁵	6.21×10⁵	812	424	44.4	11.0	0.73
yyxylν	2.57×10⁵	1.17×10⁶	13457	4975	202	84.5	4.86
ννZH	3125	7.56×10⁴	522	467	257	30.6	17.6
BG	7.86×10⁵		34597	11054	758	167	33.7
significance	0.30		0.68	1.01	2.67	3.25	4.29



$\frac{\Delta\sigma}{\sigma} \approx 23\%$ $\frac{\Delta\lambda}{\lambda} \approx 20\% \rightarrow 18\%$ with weighting

ILD DBD Study (Junping Tian)

LHC + ILC

Why Precision?

Expected precision and deviation

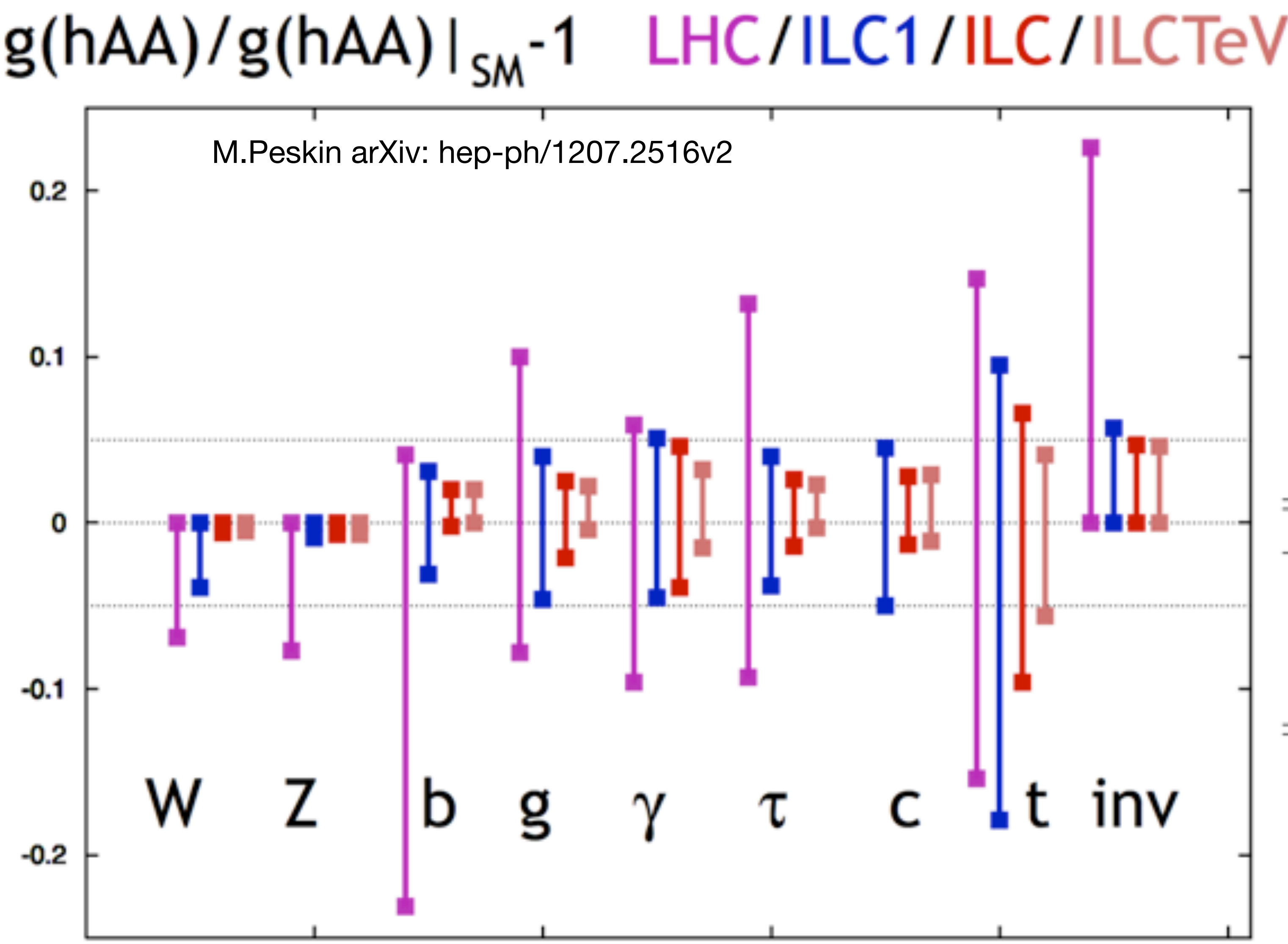


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

LC's precision provides important information on the energy scale for BSM physics.

Assumed Luminosities

LHC = LHC14TeV: 300fb^{-1}

HLC = ILC250: 250fb^{-1}

ILC = ILC500: 500fb^{-1}

ILCTeV = ILC1000: 1000fb^{-1}

Maximum deviation when nothing but the 125 GeV object would be found at LHC

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

R.S.Gupta, H.Rzehak, J.D.Wells arXiv: 1206.3560v1

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

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

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

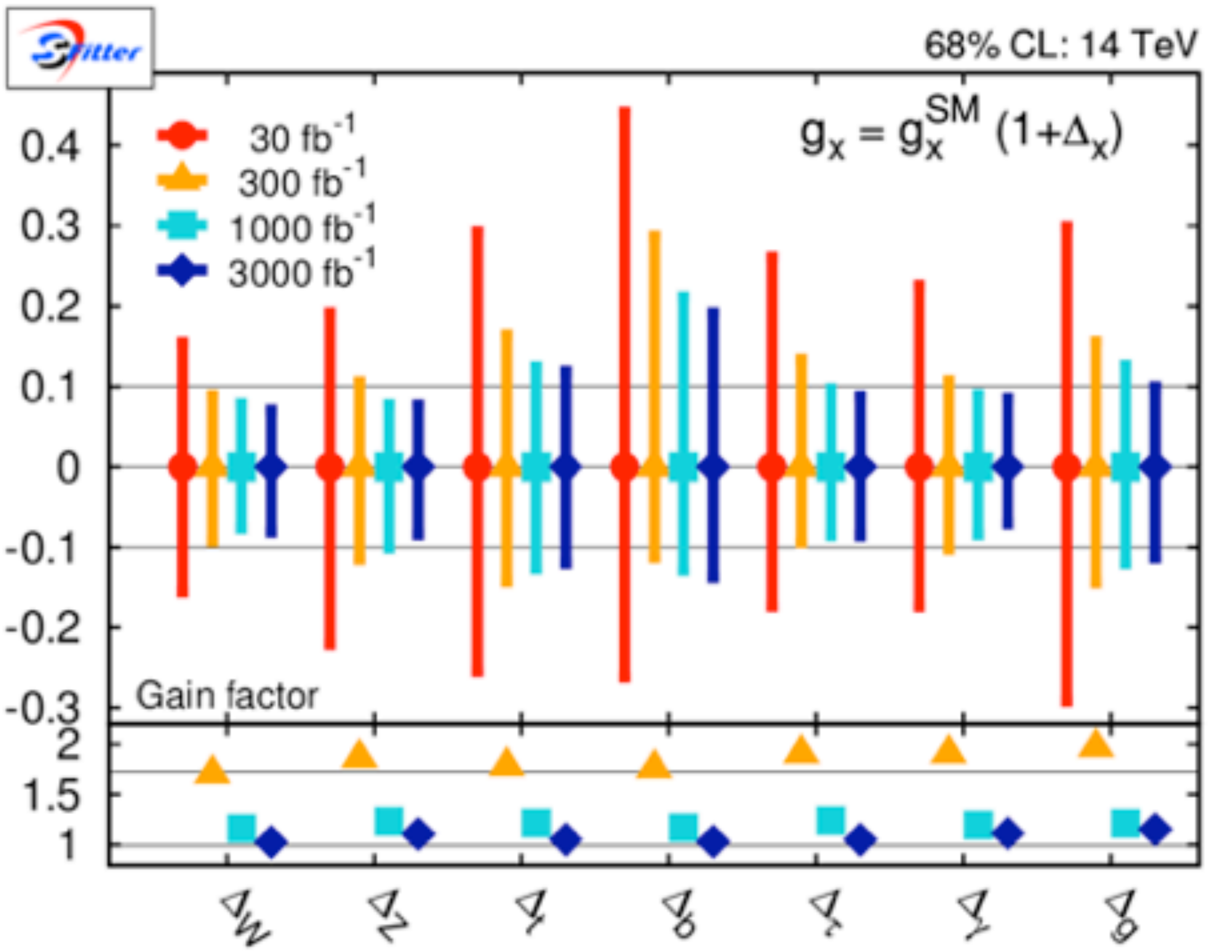
SUSY

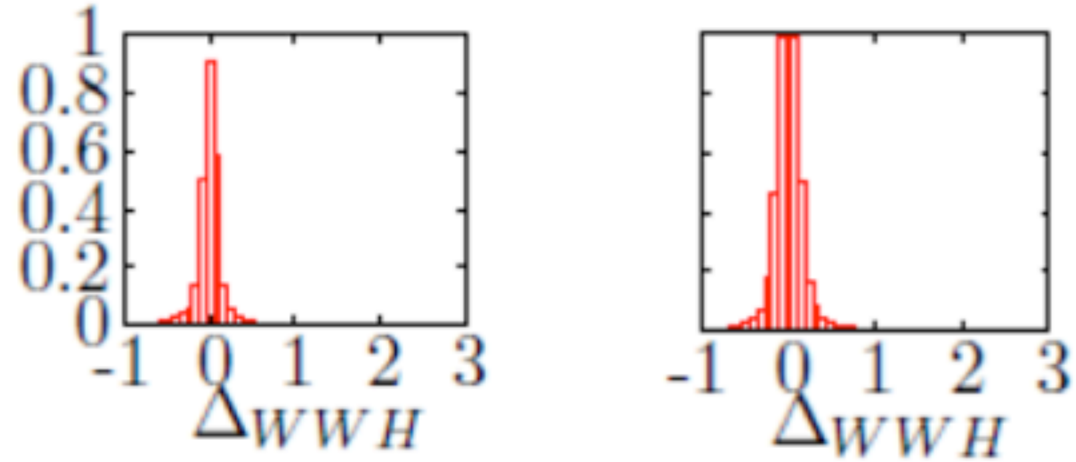
$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Different models predict different deviation patterns
--> Fingerprinting!

SFitter

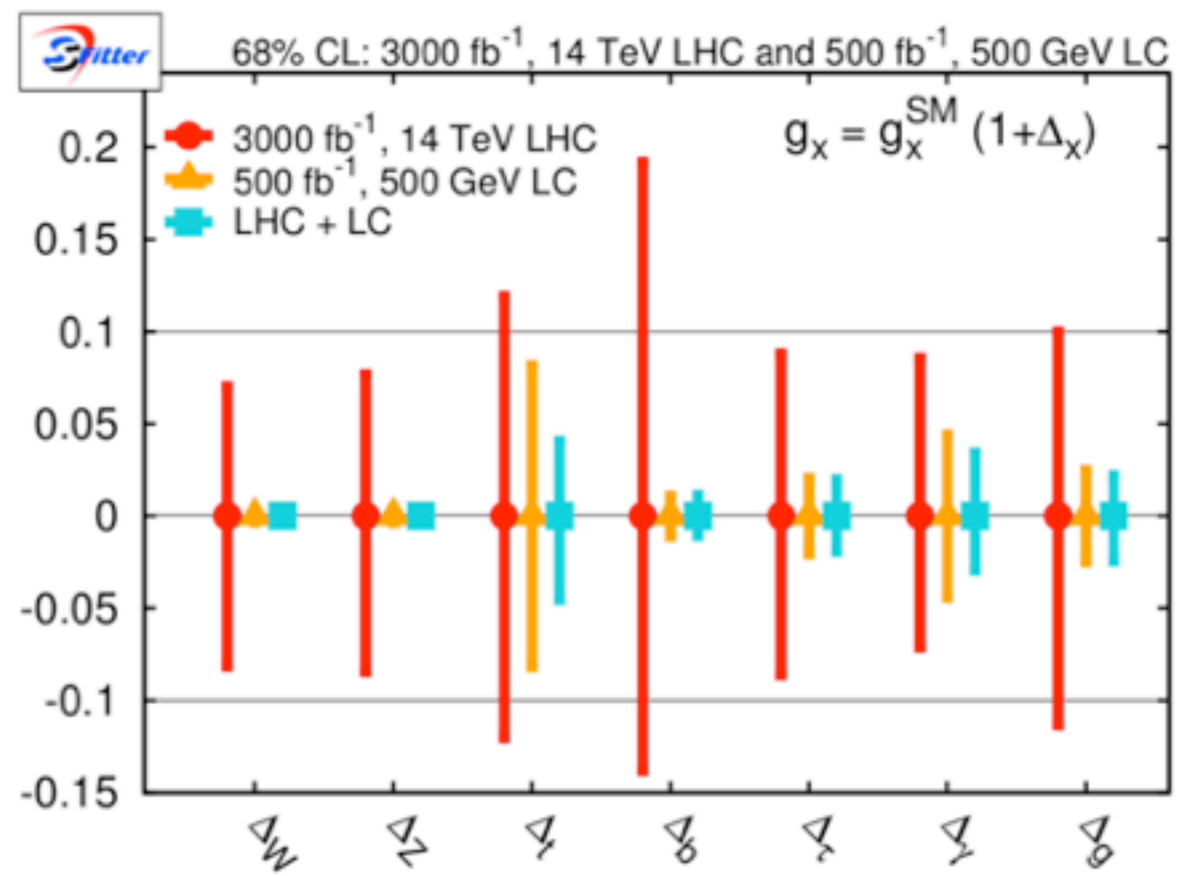
The Higgs sector precision





3000fb^{-1}:

- **extrapolate blindly**
- **full set including effective couplings**
- **flat top starting at order 100fb-1**
- **all errors on couplings <20%**
- **best order 10%**
- **gain factor less than sqrt(3), naïve sqrt(L) scaling**



LHC+ILC combined analysis:

- **ILC only Gauss errors (Keisuke Fujii/M. Peskin)**
- **clear improvement on Δt**
- **some improvement on D5 couplings Δγ, Δg**
- **LHC⊕ILC better than each machine alone**

similar effect to SUSY param determination (closes the circle)

Conclusions

- The primary goal for the next decades is to uncover the secret of the EW symmetry breaking. This will open up a window to BSM and set the energy scale for the E-frontier machine that follows LHC and ILC 500.
- Probably LHC will hit systematic limits at O(5-10%) for most of σ×Br measurements, being not enough to see the BSM effects if we are in the decoupling regime.
To achieve the primary goal we hence need a 500 GeV LC for self-contained precision Higgs studies to complete the mass-coupling plot
  - starting from e^+e^- -> ZH at Ecm = M_Z+M_H+20GeV,
  - then ttbar at around 350GeV,
  - and then ZHH and ttbarH at 500GeV.
- The ILC to cover up to Ecm=500 GeV is an ideal machine to carry out this mission (regardless of BSM scenarios) and we can do this with staging starting from Ecm at around 250GeV. We may need more data depending on the size of the deviation. Lumi-upgrade possibility should be always kept in our scope.
- If we are lucky, some extra Higgs boson or some other new particle might be within reach already at ILC 500. Let's hope that the upgraded LHC will make another great discovery in the next run from 2015.
- If not, we will most probably need the energy scale information from the precision Higgs studies. Guided by the energy scale information, we will go hunt direct BSM signals, if necessary, with a new machine. Eventually we will need to measure W_LW_L scattering to decide if the Higgs sector is strongly interacting or not.

Last but Not Least

- In this talk I have been focusing on the case where X(125GeV) alone would be the probe for BSM physics, but there is a good chance for the higher energy run of LHC to bring us more.
- It is also very important to stress that ILC, too, is an energy frontier machine. It will access the energy region never explored with any lepton collider. There can be a zoo of new uncolored particles or new phenomena that are difficult to find at LHC but can be discovered and studied in detail at ILC.
- Examples
  - Natural SUSY : naturalness prefers μ not far above 100GeV
    --> light chargino/neutralinos will be higgsino-dominant and nearly degenerate
    --> typically Δm of a few GeV or less (very difficult at LHC)
    --> Δm as small as 50MeV possible with ISR tagging at ILC
    --> If Δm=400MeV --> possible to measure m to 2GeV and Δm to 7MeV
    --> ILC will also be a Higgsino factory!
  - Possible anomalies in precision studies of properties of W/Z and top, two-fermion processes
- Whatever new physics is awaiting for us, clean environment, polarized beams, and excellent jet energy resolution to reconstruct W/Z/t/H in their hadronic decays will enable us to uncover the nature of the new physics through model-independent precision measurements.

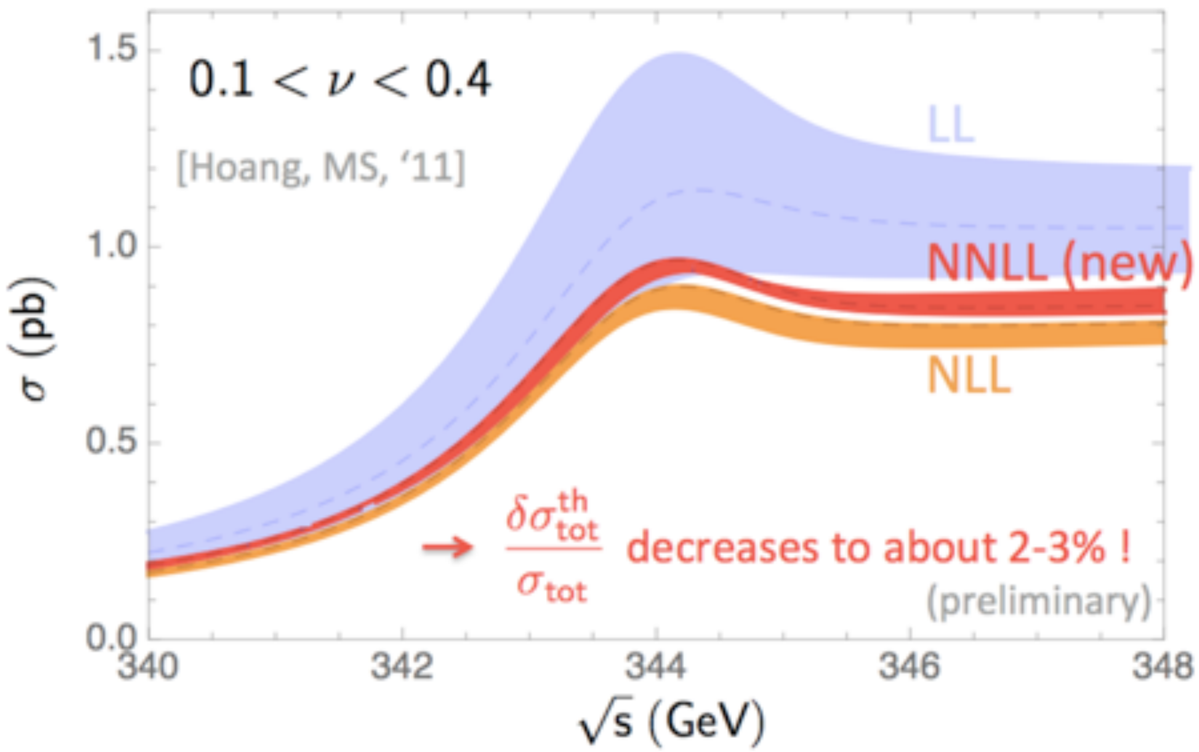
Backup

Other Probes for BSM

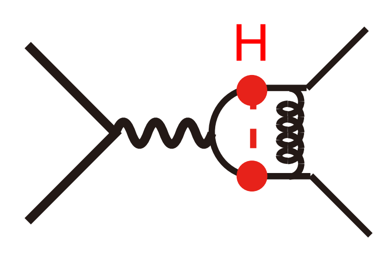
Top Quark

Threshold Region

M.Stahlhofen Top Phys WS 2012



Theory improving! →

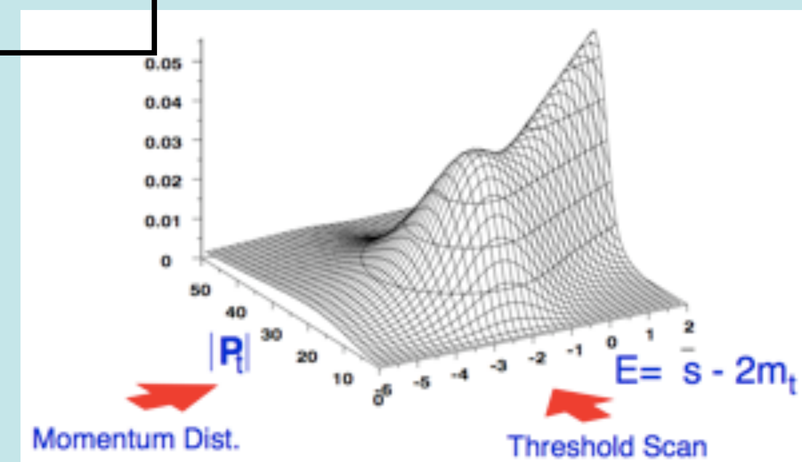


~10% effect

Expected accuracies

$$\Delta m_t = 34\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0023$$
$$\Delta\Gamma_t = 42\,\mathrm{MeV}$$

Threshold scan alone

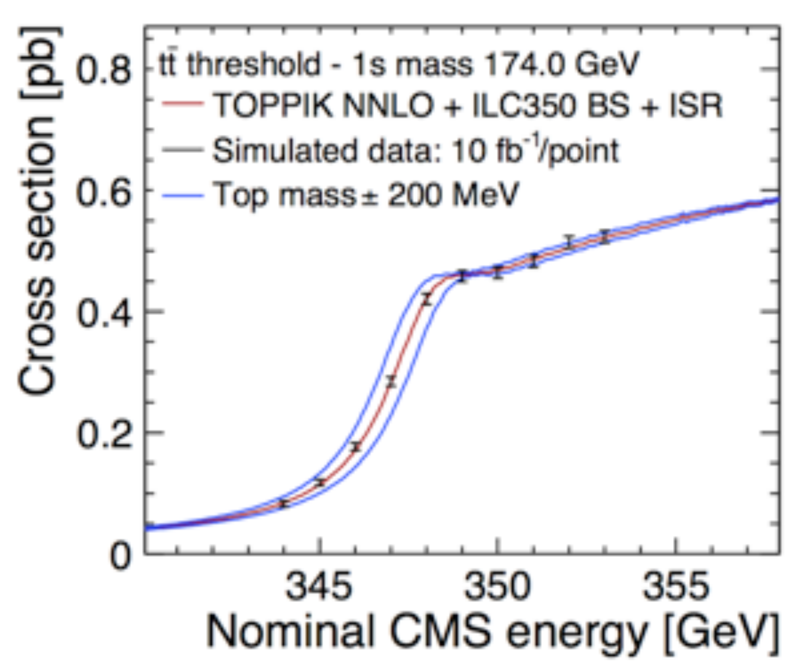


+ A_{FB} & Top Momentum

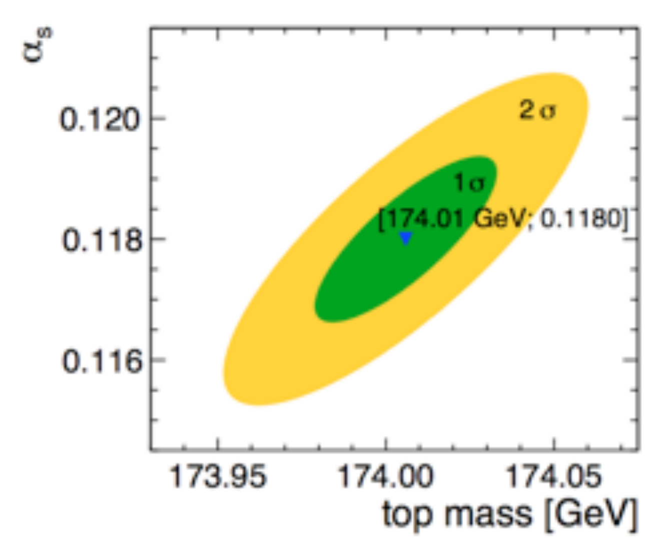
$$\Delta m_t = 19\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0012$$
$$\Delta\Gamma_t = 32\,\mathrm{MeV}$$

arXiv:hep-ph/0601112v2

$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$

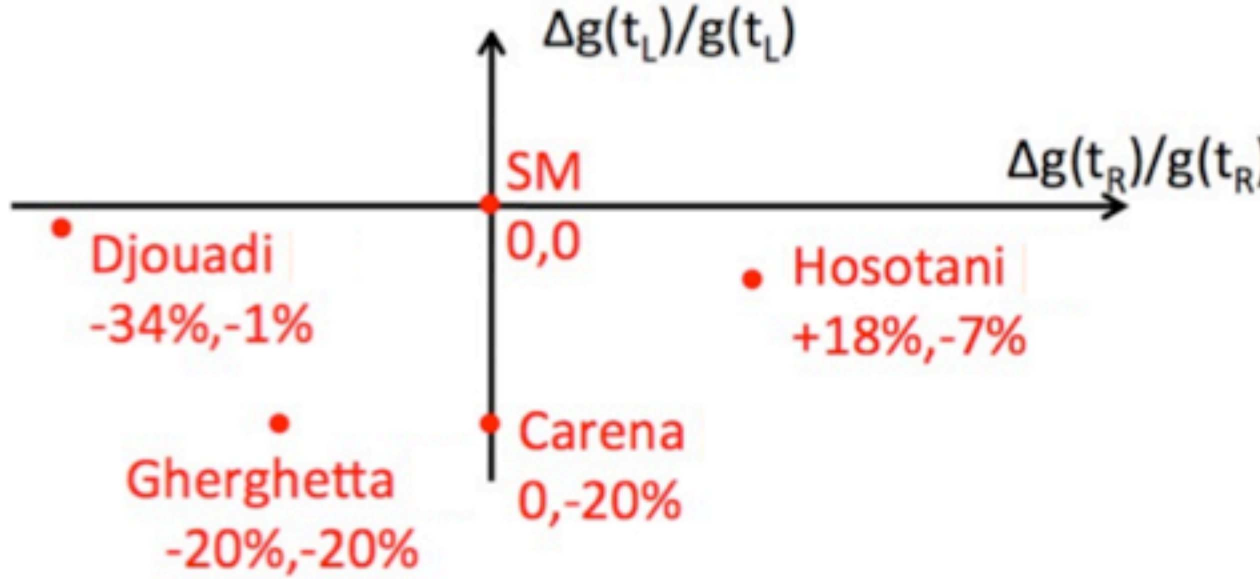


F.Simon Top Phys WS 2012



Top Quark

Anomalous Coupling



LAL 11-222

Figure 34: *Predictions of various groups [40,42–44] on deviations from Standard Model couplings of the t quark within Randall-Sundrum Models. The cartoon is taken from [47].*

coupling	LHC, 300 fb^{-1}	e^+e^- [23]	coupling	LHC, 300 fb^{-1}	e^+e^- [23]
$\Delta\widetilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}	$\Delta\widetilde{F}^{Z}_{1V}$	$^{+0.24}_{-0.62}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{1A}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}	$\Delta\widetilde{F}^{Z}_{1A}$	$^{+0.052}_{-0.060}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}	$\Delta\widetilde{F}^{Z}_{2V}$	$^{+0.27}_{-0.19}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2A}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}	$\Delta\widetilde{F}^{Z}_{2A}$	$^{+0.28}_{-0.27}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

Table 12: *Sensitivities achievable at 68.3% CL for the anomalous ttV ($V = \gamma, Z$) couplings $\widetilde{F}^{V}_{1V,A}$ and $\widetilde{F}^{V}_{2V,A}$ of Eq. (59) at the LHC for integrated luminosities of 300 fb^{-1}, and the ILC with $\sqrt{s} = 500$ GeV (taken from Ref. [23]). Only one coupling at a time is allowed to deviate from its SM value. Table and caption have been copied from [16].*

arXiv:hep-ph/0601112v2

Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

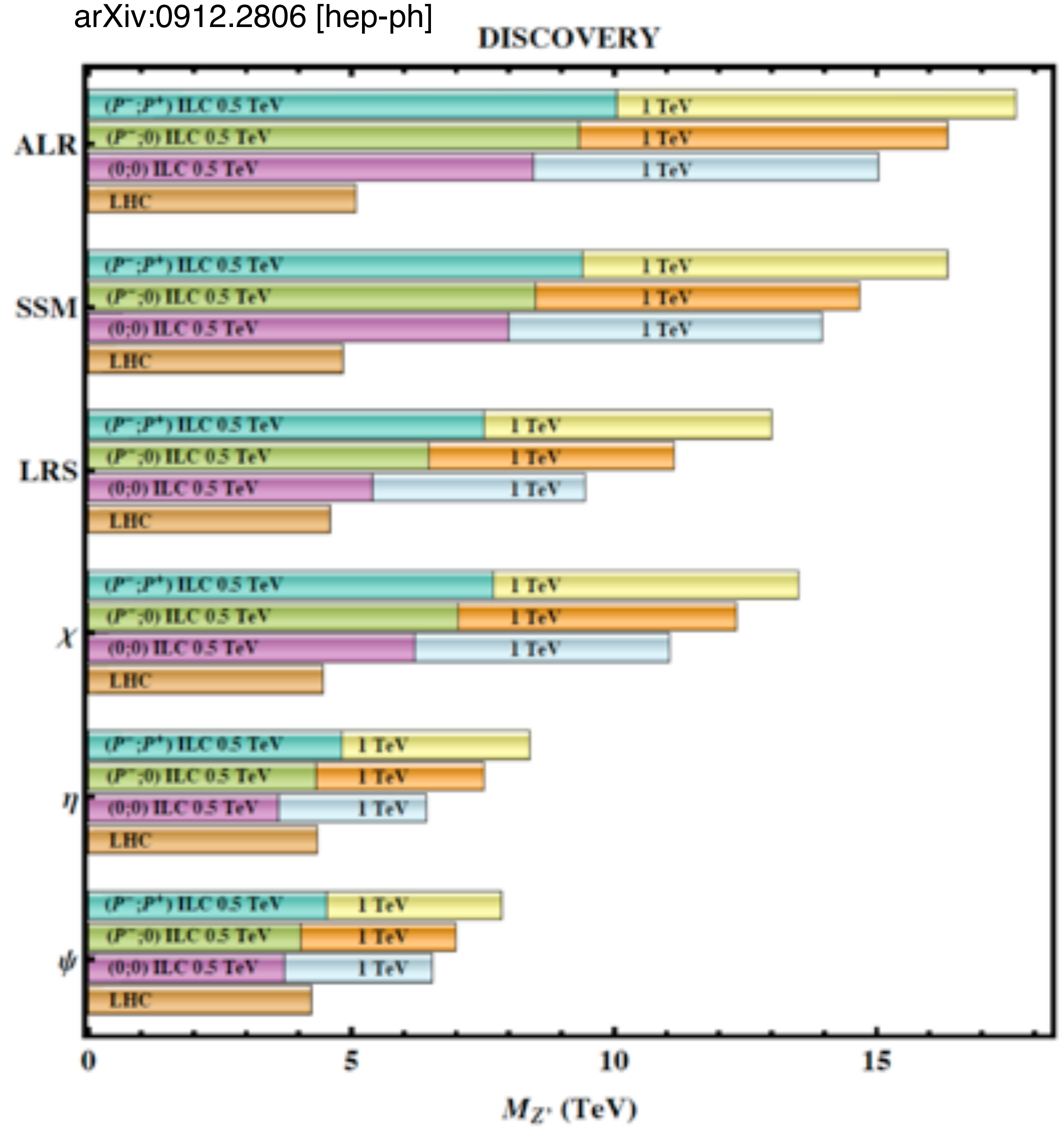
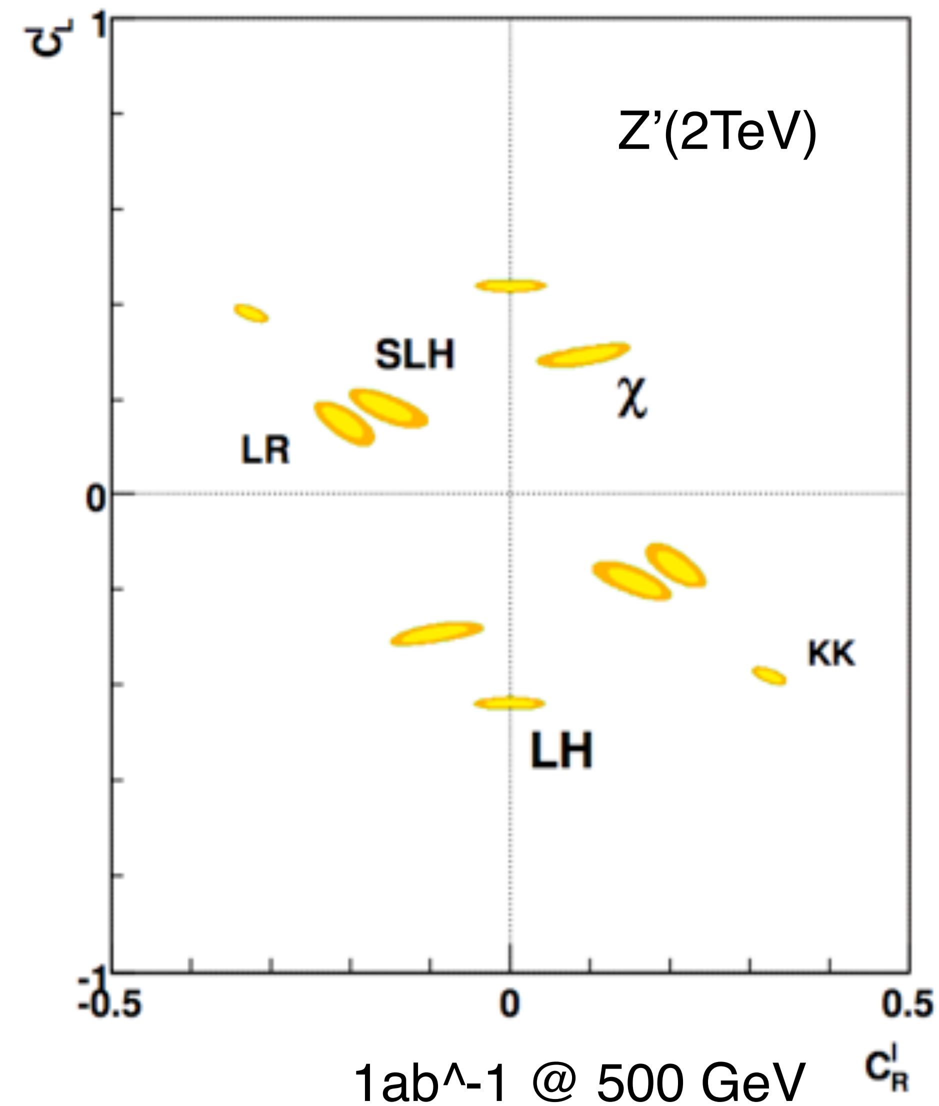


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For details, see [14].

hep-ph/0511335



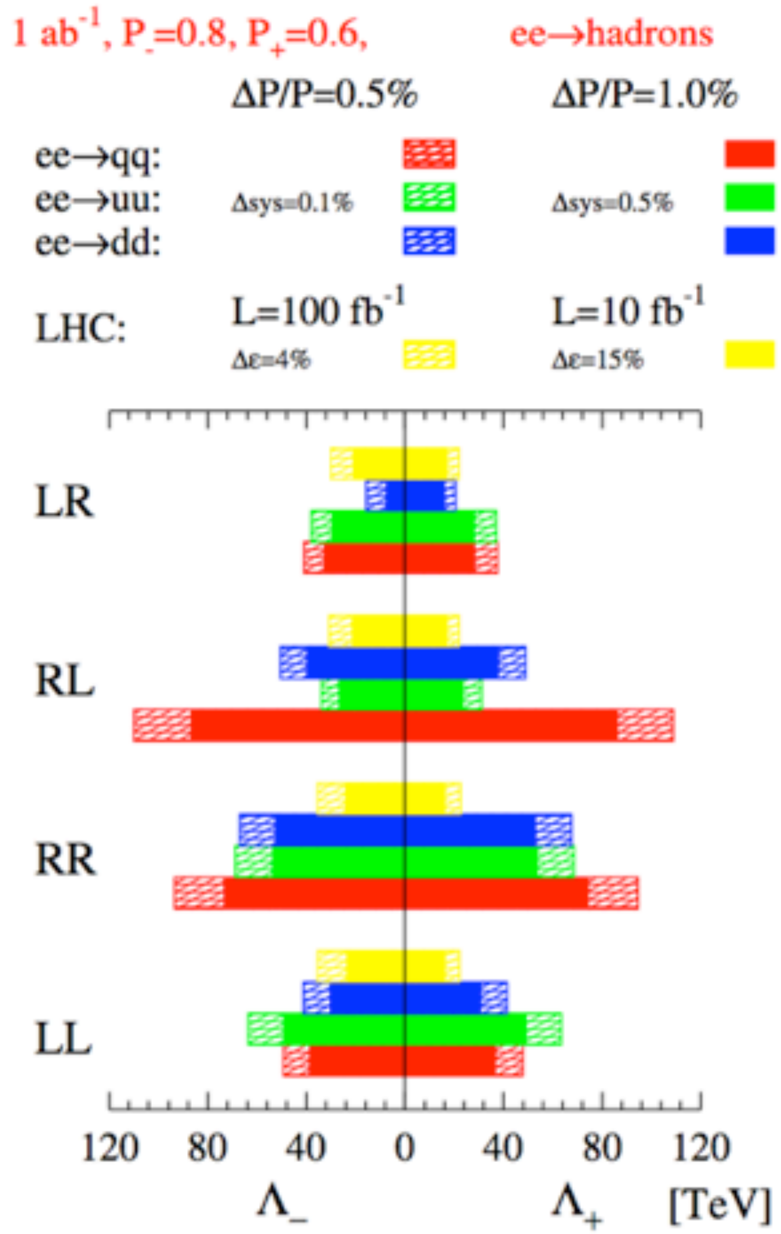
ILC's Model ID capability is expected to exceed that of LHC even if we cannot hit the Z' pole.

Beam polarization is essential to sort out various possibilities.

Two-Fermion Processes

Compositeness

S. Riemann, LC-TH-2001-007



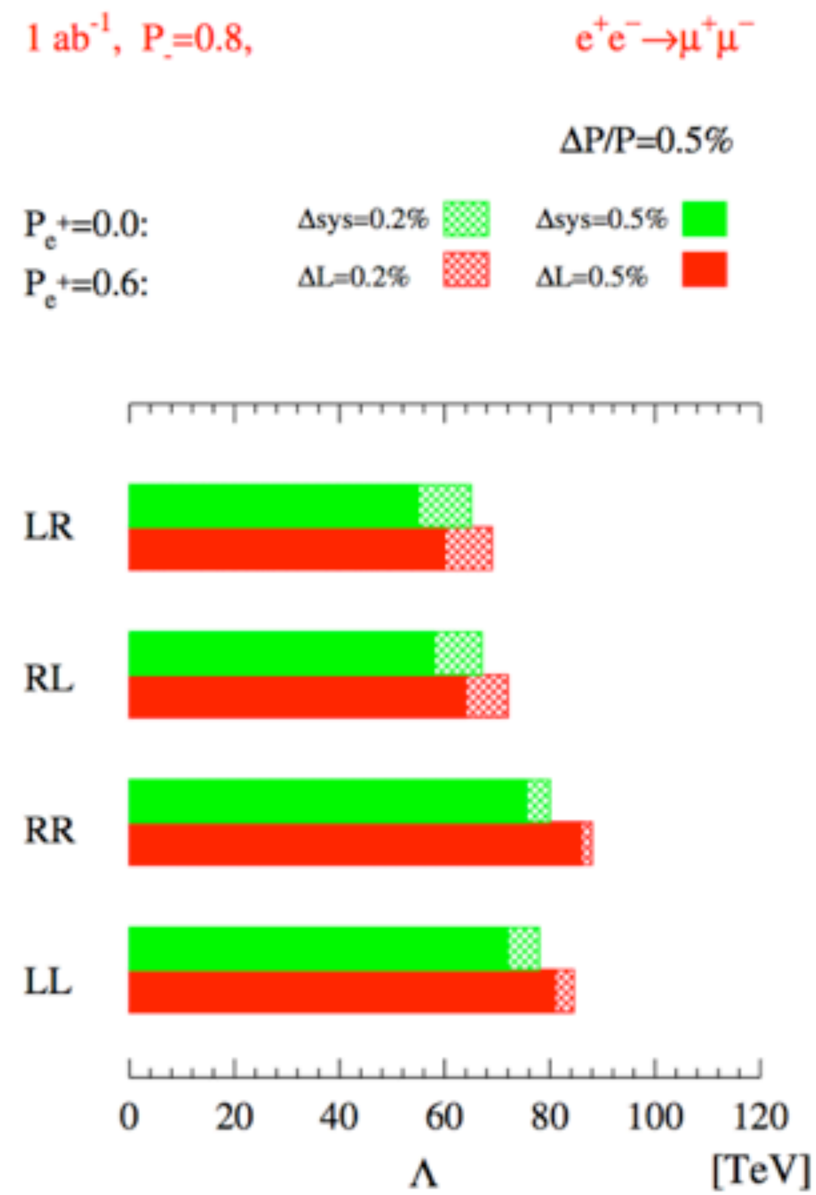


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.