Anomalous Couplings of the Higgs Boson

Tao Han

Univ. of Wisconsin–Madison

(ILC Workshop, Snowmass, Aug. 17, 2005)

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Standard Model as An Effective Theory

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Standard Model as An Effective Theory

Parameterize Physics Beyond the SM

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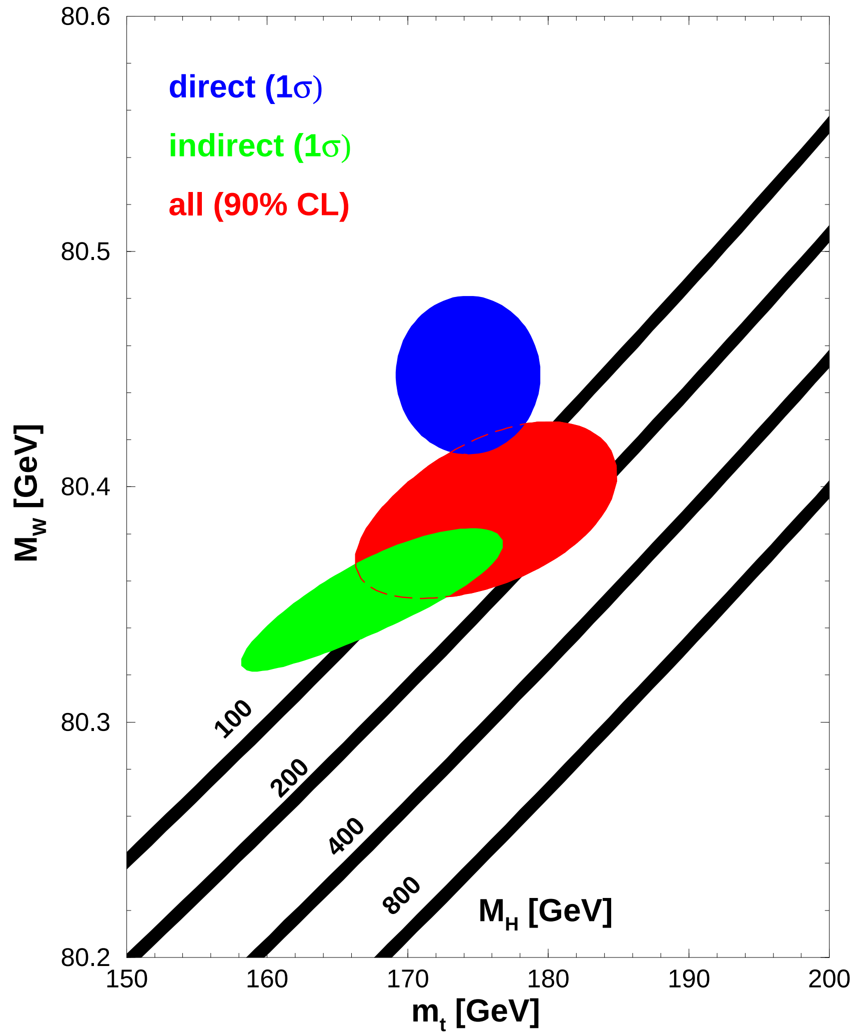
- Standard Model as An Effective Theory
- Parameterize Physics Beyond the SM
- Collider Sensitivities
- Concluding Remarks

SM with a light Higgs ?



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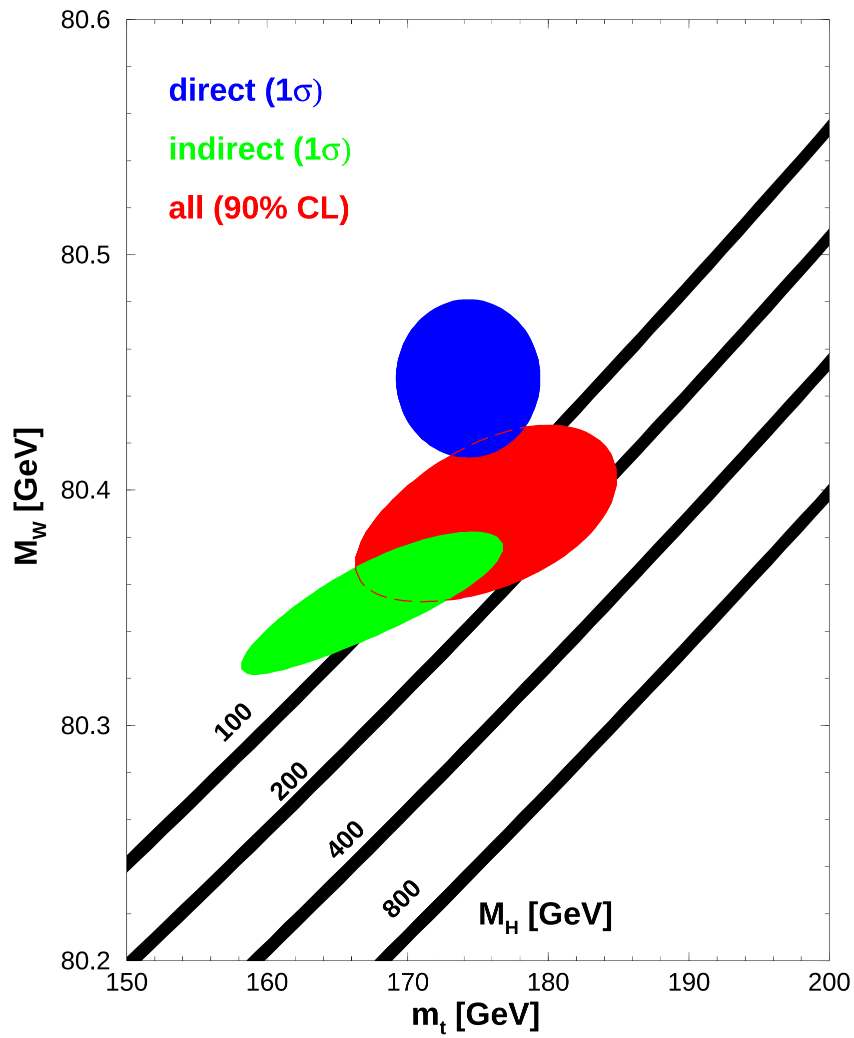


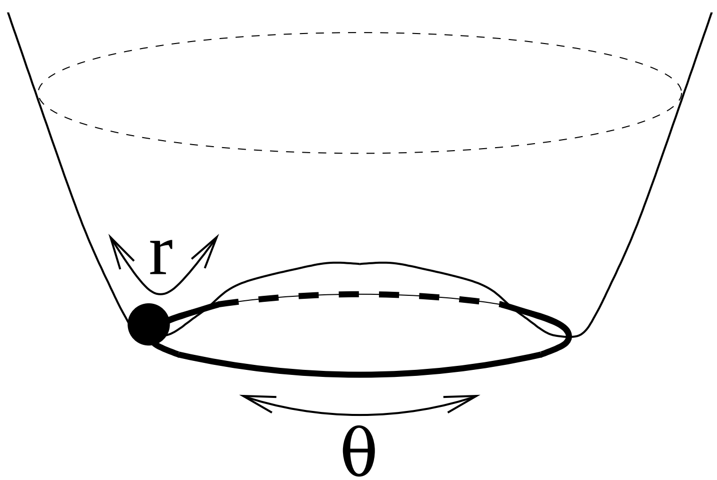
EW precision data: $m_H < 186$ GeV at 95% CL;*

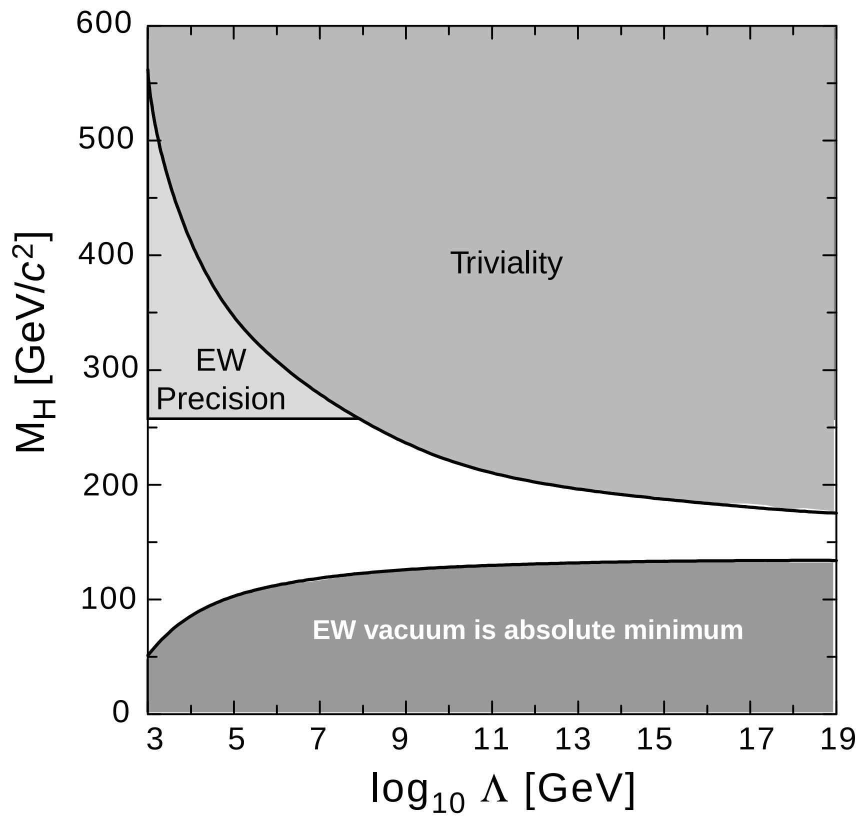
*Recent fit with new m_t.

SM as an effective theory ?

$$V = -\mu^2\Phi^2 + \lambda\Phi^4, \quad <\Phi> = \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{2\lambda}}, \quad v^{-2} = \sqrt{2}\; G_F$$

$$m_H = \sqrt{2\lambda}\; v$$





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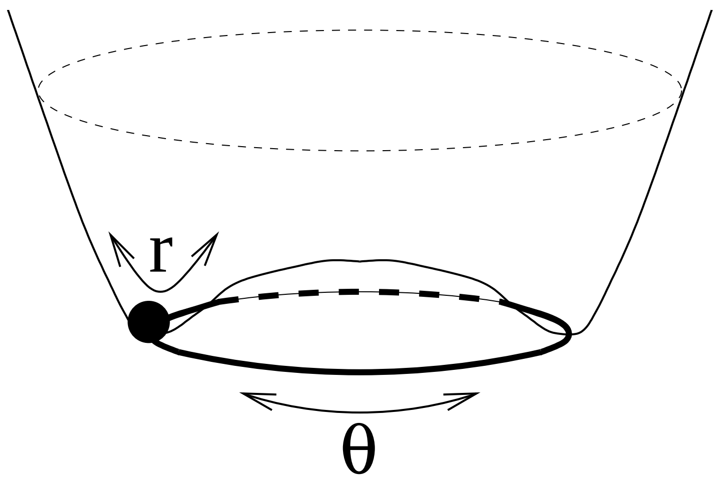
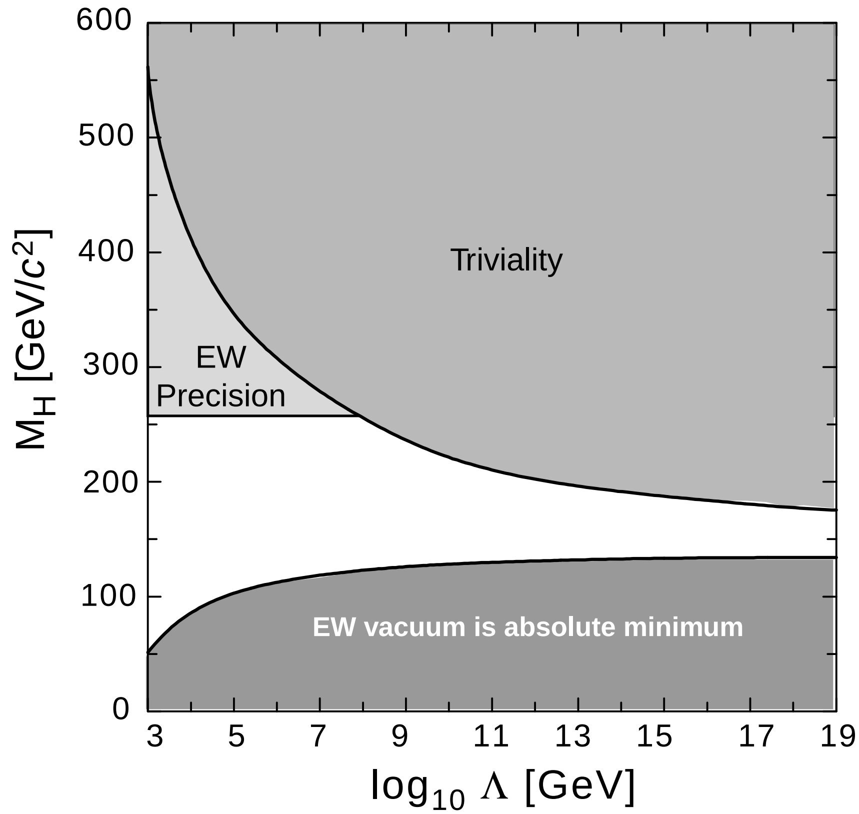




SM with a light H could be an effective theory to $\Lambda \sim M_{pl}$.

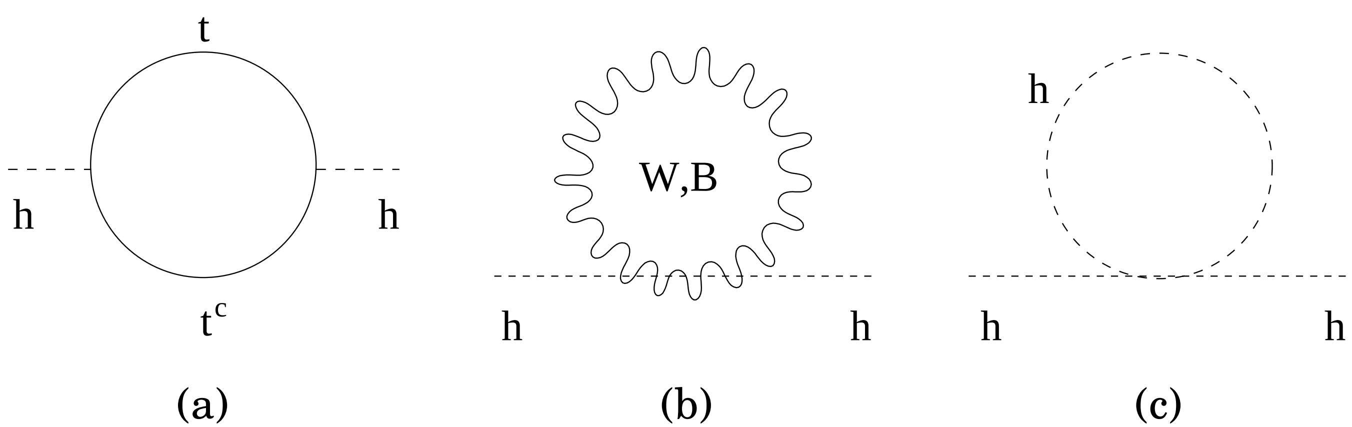
a stable vacuum;

non-trivial interactions;

renormalizability ...

Unnatural ?

Due to quantum corrections, the Higgs mass is quadratically sensitive to the new physics (cutoff) scale: $\sim \Lambda^2$.



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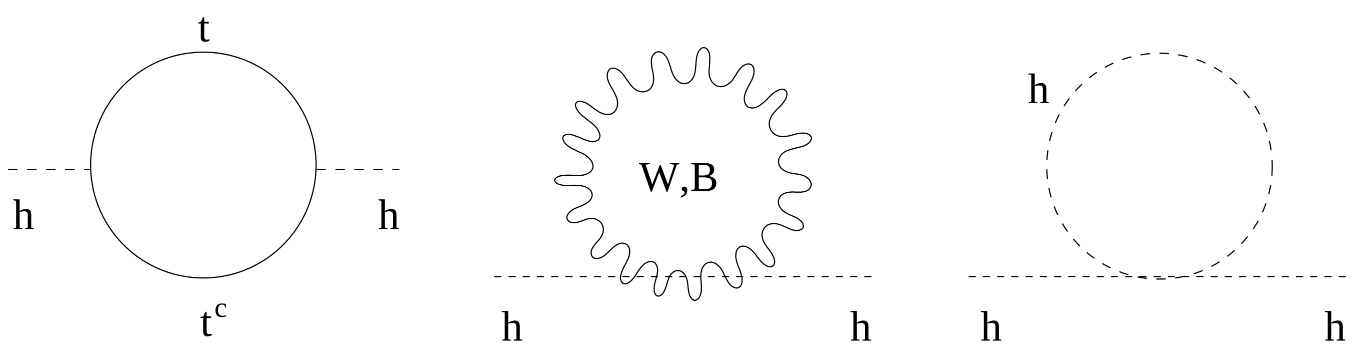

(a) (b) (c)

$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

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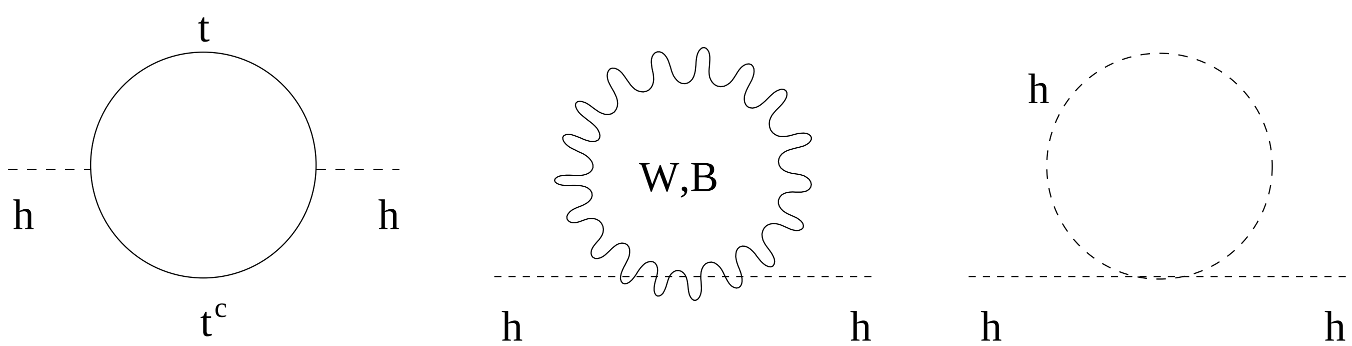

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$$(200\ \text{GeV})^2 = m_{H0}^2 + \left[-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2 \right] \left(\frac{\Lambda_{t,W,H}}{10\ \text{TeV}} \right)^2$$

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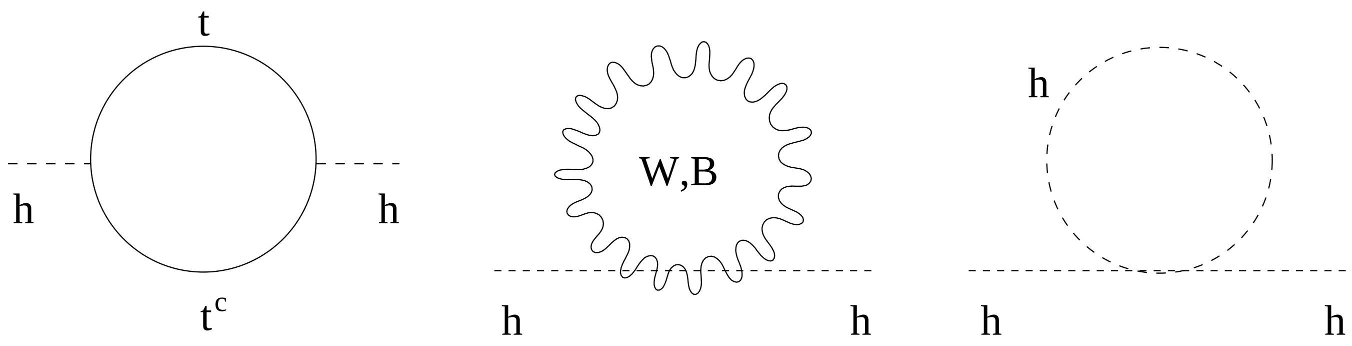

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Naturalness requirement: less than 90% cancellation on m_H^2

$$\Lambda_t \lesssim 3\ \text{TeV} \quad \Lambda_W \lesssim 9\ \text{TeV} \quad \Lambda_H \lesssim 12\ \text{TeV}$$

Beyond the SM ϕ^4 Theory

Blow a new physics scale Λ, the effective interactions at the NLO

$$\mathcal{L}_{\text{eff}}^{\text{dim-6}} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n,$$

where f_n's are dimensionless "anomalous couplings".

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There are eleven SM gauge-invariant bosonic operators;*
eight of them involving H.

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<u>Class I</u>

Among those, two of them contribute to two-point functions:

$$\begin{aligned} \mathcal{O}_{BW} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi && \Longrightarrow S, \\ \mathcal{O}_{\Phi,3} &= (D_\mu \Phi)^\dagger \Phi^\dagger \Phi \, (D^\mu \Phi) && \Longrightarrow T. \end{aligned}$$

Tight constraints, at 95% CL:†

$$-1 < \frac{f_{BW}}{(\Lambda/\text{TeV})^2} < 8, \quad -0.07 < \frac{f_{\Phi,3}}{(\Lambda/\text{TeV})^2} < 0.6.$$

will not persue them further.

*K. Hagiwara et al., PRD48, 2182 (1993); ...

†M.C. Gonzalez-Garcia, hep-ph/9902321.

Class II

Four of them lead to $V - H$ interactions:

$$\begin{aligned}
\mathcal{O}_{WW} &= \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \\
\mathcal{O}_{BB} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \\
\mathcal{O}_{W} &= (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \\
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\end{aligned}
$$

as

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{H} = \quad & g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g^{(1)}_{HZ\gamma} A_{\mu\nu} Z^{\mu} \partial^{\nu} H + g^{(2)}_{HZ\gamma} H A_{\mu\nu} Z^{\mu\nu} \\
& + g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu} \partial^{\nu} H + g^{(2)}_{HZZ} H Z_{\mu\nu} Z^{\mu\nu} \\
& + g^{(1)}_{HWW} (W^{+}_{\mu\nu} W^{-\mu} \partial^{\nu} H + \text{h.c.}) + g^{(2)}_{HWW} H W^{+}_{\mu\nu} W^{-\mu\nu},
\end{aligned}
$$

with

$$
g_{H\gamma\gamma} = -\frac{s^2(f_{BB} + f_{WW})}{2} K, \;\; g^{(1)}_{HZ\gamma} = \frac{s(f_W - f_B)}{2c} K, \;\; g^{(2)}_{HZ\gamma} = \frac{s(s^2 f_{BB} - c^2 f_{WW})}{c} K,
$$

$$
g^{(1)}_{HZZ} = \frac{c^2 f_W + s^2 f_B}{2c^2} K, \quad g^{(2)}_{HZZ} = -\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} K,
$$

$$
g^{(1)}_{HWW} = \frac{1}{2} f_W K, \quad g^{(2)}_{HWW} = -f_{WW} K,
$$

where $s \equiv \sin\theta_W$, $c \equiv \cos\theta_W$ and $K = g m_W / \Lambda^2 \approx 0.053\ \text{TeV}^{-1} \approx 1/(19\ \text{TeV})$.

Current constraints not strong:

By precision electroweak data and one-loop calculations:

$$-4 < \frac{f_B}{(\Lambda/\mathrm{TeV})^2} < 2, \quad -6 < \frac{f_W}{(\Lambda/\mathrm{TeV})^2} < 5,$$
$$-17 < \frac{f_{BB}}{(\Lambda/\mathrm{TeV})^2} < 20, \quad -5 < \frac{f_{WW}}{(\Lambda/\mathrm{TeV})^2} < 6.$$

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- LEP II Higgs search bound, but for $m_H < 113$ GeV;
- Triple gauge boson coupling constraints weaker — will improve;
- Partial wave unitarity bounds weaker as well.

Class III

The last two are pure H terms:

$$\mathcal{O}_{\Phi,1} = \frac{1}{2}\partial^{\mu}\left(\Phi^{\dagger}\Phi\right)\partial_{\mu}\left(\Phi^{\dagger}\Phi\right),$$
$$\mathcal{O}_{\Phi,2} = \frac{1}{3}\left(\Phi^{\dagger}\Phi\right)^{3}.$$

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In terms of the canonically normalized Higgs field (via $a_1 = f_{\Phi,1}v^2/\Lambda^2$) and the physical Higgs mass (via a_1, a_2),[‡]

$$\mathcal{L}_{VH} = (M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}M_Z^2 Z_\mu Z^\mu)\left((1-\frac{a_1}{2})\frac{2H}{v} + (1-a_1)\frac{H^2}{v^2}\right),$$
$$\mathcal{L}_{H^3} = -\frac{m_H^2}{2v}\left((1-\frac{a_1}{2}+\frac{2a_2}{3}\frac{v^2}{m_H^2})H^3 - \frac{2a_1 H\partial_\mu H\partial^\mu H}{m_H^2}\right),$$
$$\mathcal{L}_{H^4} = -\frac{m_H^2}{8v^2}\left((1-a_1+\frac{4a_2v^2}{m_H^2})H^4 - \frac{4a_1H^2\partial_\mu H\partial^\mu H}{m_H^2}\right).$$

[‡]V. Barger et al., hep-ph/0301097.

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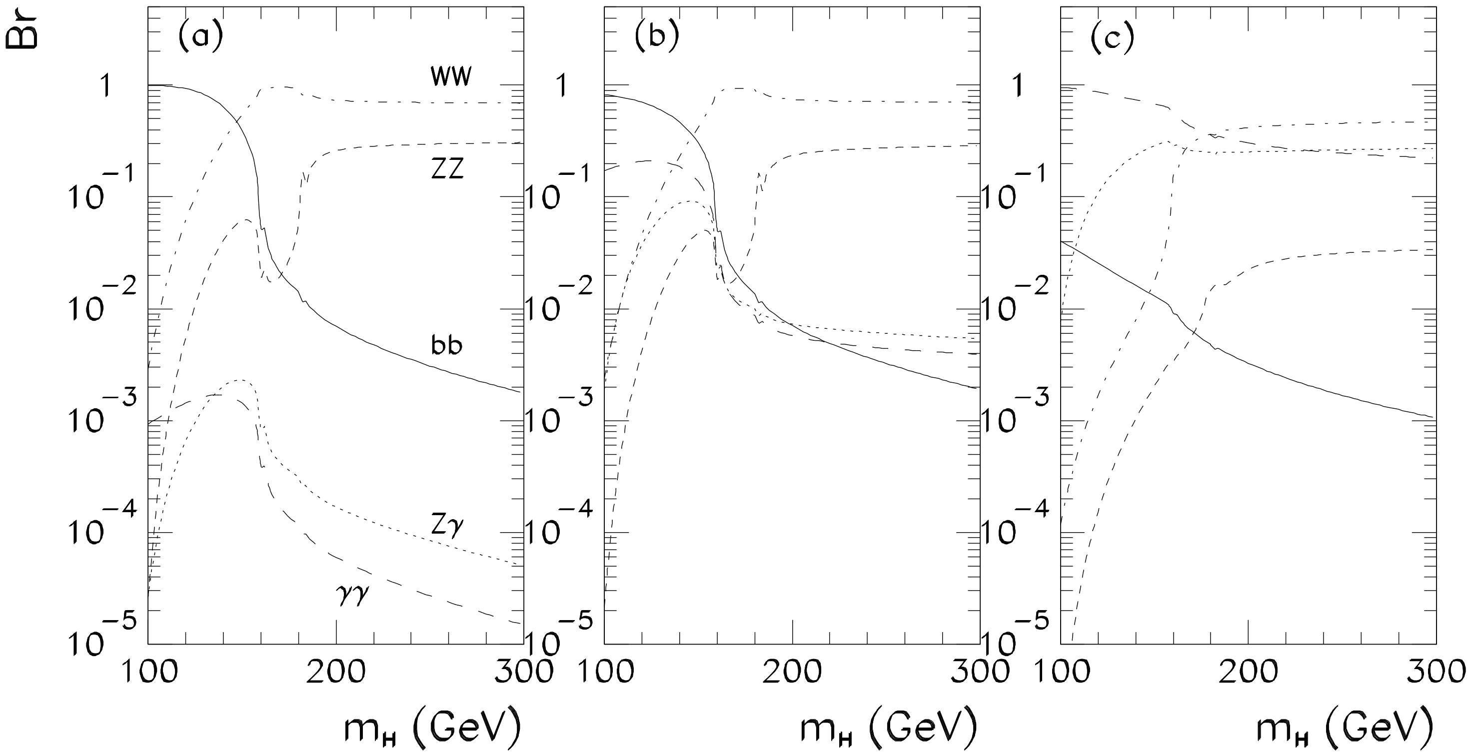
- Gauge-invariant formulation important !
- Not only a change in Higgs potential, but also kinetic corrections !
- VVH probe $f_{\Phi,1}$; H^3 (related to H^4) probes $f_{\Phi,2}$ ($f_{\Phi,1}$ as well).

[‡]V. Barger et al., hep-ph/0301097.

Collider Sensitivity to the anomalous Couplings

In the case of Class II: g_{HVV}

H decays modified:



where (a)=SM; (b)=$f/\Lambda^2 = 10/\text{TeV}^2$; (c)=$f/\Lambda^2 = 100/\text{TeV}^2$.

H Production Changed:

$$
\begin{aligned}
pp(\bar{p}) &\rightarrow jjH \rightarrow jj\ \gamma\gamma, \\
&\rightarrow jjH \rightarrow jj\ Z\gamma, \\
&\rightarrow \gamma\gamma\gamma,\ \gamma\gamma Z, \\
&\rightarrow \gamma\gamma + \not{E}_T.
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Tevatron with 1 fb^{-1} [10 fb^{-1}]

m_H(GeV)	f/Λ^2(TeV^{-2})
	COMBINED
100	(−7.6 , 19)[−3 , 5.6]
120	(−7.4 , 18)[−3.3 , 5.9]
140	(−9.1 , 20)[−4.0 , 8.7]
160	(−9.9 ,22) [−5.1 , 13]
180	(−24 , 33) [−16 , 24]
200	(−32 , 39) [−17 , 23]
220	(−42 , 45) [−19 , 26]

LHC $WW \to WW$,[§]

$$
-1.4 < \frac{f_W}{\Lambda^2} \le 1.2, \quad -2.2 \le \frac{f_{WW}}{\Lambda^2} < 2.2.
$$

[§] B. Zhang, Y.-P. Kuang et al., Phys.Rev.**D67**, 114024 (2003.

$$
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e^+e^- &\to jjH \to jj\ \gamma\gamma, \\
&\to jjH \to jj\ Z\gamma, \\
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&\to W^+W^-\gamma,\ ZZ\gamma.
\end{aligned}
$$

ILC with $\sqrt{s} = 500$ GeV 100 fb^{-1}¶

m_H(GeV)	f/Λ^2(TeV^{-2})	
	$e^+e^- \to W^+W^-\gamma$ at NLC	$e^+e^- \to Z^0Z^0\gamma$ at NLC
170	(−2.3 , 3.7)	(— , —)
200	(−3.2 , 4.0)	(−2.6 ,3.9)
250	(−4.3 , 4.8)	(−3.2 , 4.3)
300	(−6.3 , 6.3)	(−4.7 , 5.2)
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¶M.C. Gonzalez-Garcia, hep-ph/9902321.

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$$\gamma\gamma \ \to\ ZZ$$

For $\sqrt{s_{ee}} = 500$ GeV ($m_H = 115 - 200$ GeV) :[‖]

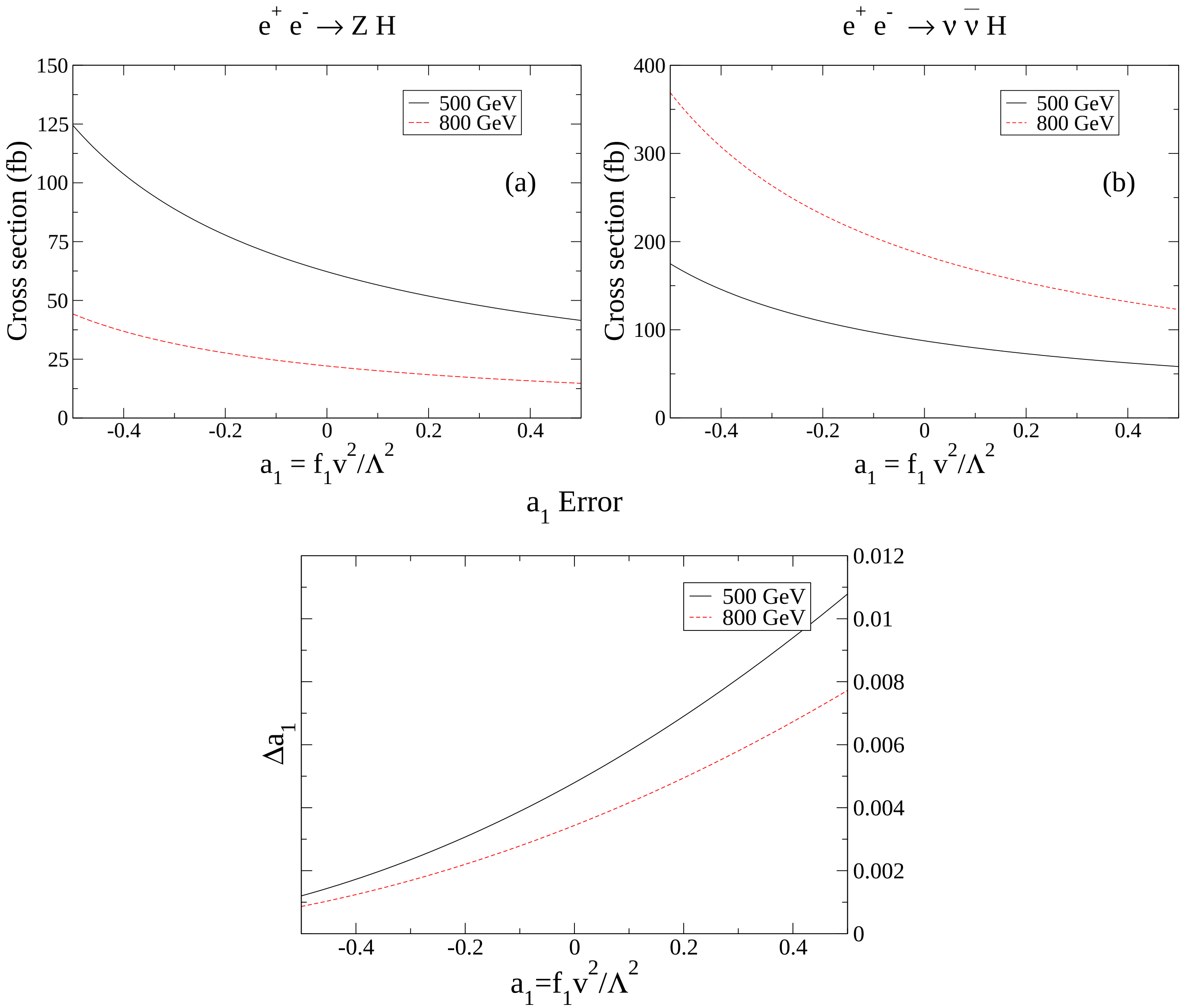
$$-0.65\ \text{TeV}^{-2} < f/\Lambda^2 < 1.7\ \text{TeV}^{-2} \quad at\ 2\sigma.$$

[¶]M.C. Gonzalez-Garcia, hep-ph/9902321.

[‖]B.Zhang, Y.-P. Kuang, et al. in progress.

In the case of Class III

$$\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right):\quad\left(M_W^2 W_\mu^+ W^{-\mu}+\frac{1}{2}M_Z^2 Z_\mu Z^\mu\right)\frac{2H}{v}\left(1-\frac{a_1}{2}\right)$$



a_1 determined better than 2%.

Genuine self-couplings:

$$\left(\Phi^\dagger\Phi\right)^3: \qquad (M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)\ \frac{H^2}{v^2}\ (1-a_1) - \frac{m_H^2}{2v}\left((1-\frac{a_1}{2} + \frac{2a_2}{3}\frac{v^2}{m_H^2})H^3 - \frac{2a_1 H\partial_\mu H\partial^\mu H}{m_H^2}\right)$$

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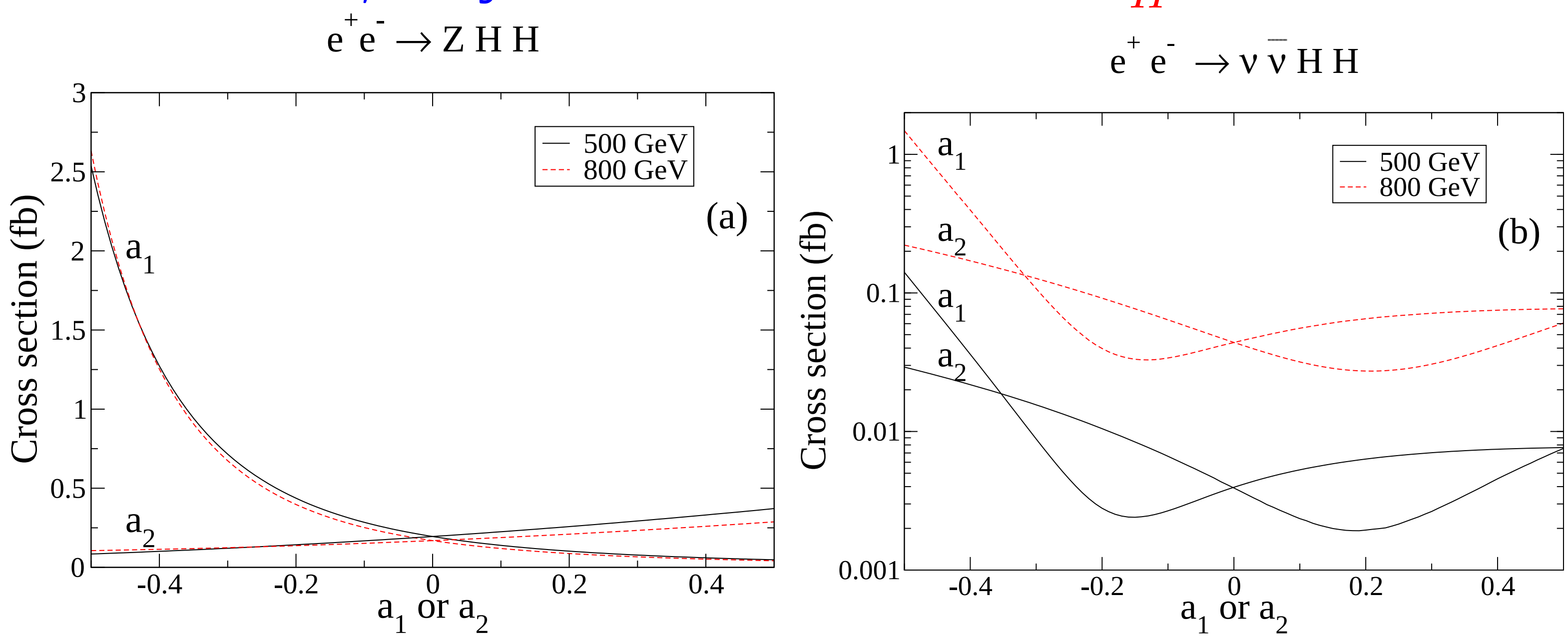
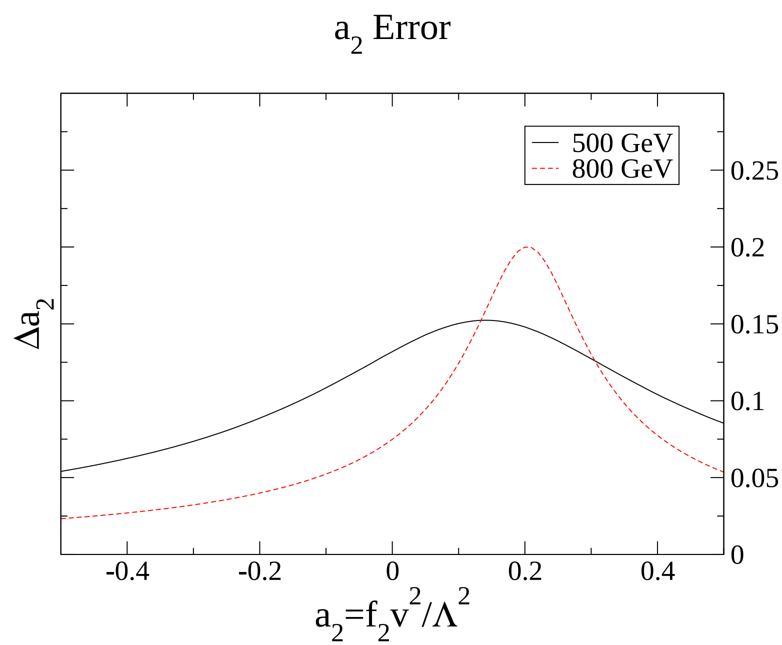
At the LHC: very hard to observe HH, unless $H \to WW,\ ZZ$.*

At the ILC, only event rate matters. $m_H = 120$ GeV:



*U.Baur, T.Plehn, D.Rainwater, Phys.Rev.**D67**, 033003 (2003);
ibid. **D68**, 033001 (2003).



Translate to the effective triple coupling:

$$\frac{\delta g_{HHH}}{g_{HHH}} = \frac{2v^2\delta a_2}{3m_H^2 + 2v^2 a_2} \approx 2.8\Delta a_2.$$

SM corresponds to $g_{HHH}|_{a_2=0}$,

so at the ILC with $\sqrt{s} = 500$ GeV $m_h = 120$ GeV,**

Luminosity	500 fb^{-1}	1 ab^{-1}	2 ab^{-1}
$\delta g_{HHH}/g_{HHH}$	42%	30%	20%
Δa_2	0.15	0.11	0.073

**C. Castanier, P. Gay, P. Lutz and J. Orloff, `hep-ex/0101028`.

Concluding Remarks

- Consider only a light Higgs below $\Lambda \lesssim 4\pi v$:
  BSM $\Longrightarrow$ "anomalous Higgs coupling".

- Emphasize the gauge-invariant formulation in $1/\Lambda^2$-expansion:
  Unify our language !

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- Studies should be systematically updated/sharpened.

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- Fermionic operators should be included in further studies.

Still more to do ...