Direct measurement of the Higgs self-coupling in $e^+e^- \to ZH$.

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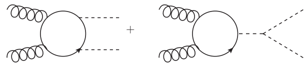
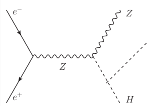
Introduction

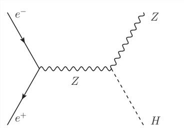
Introduction: the trilinear Higgs self-coupling measurement.

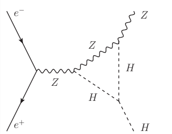
- The capabilities of the LHC and future e^+e^- colliders to measure the trilinear Higgs self-coupling λ_{HHH} have been seriously studied in recent years.
- The "direct" λ_{HHH} measurement from the di-Higgs productions (such as $gg \to HH$ and $e^+e^- \to ZHH$) is challenging, because of their very small cross sections.



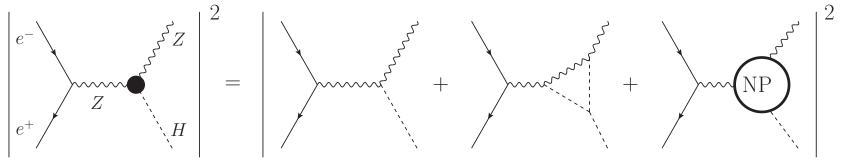


- "Indirect" constraint on λ_{HHH} may be obtained from the single-Higgs productions, because λ_{HHH} contributes to the EW one-loop correction (McCullough Phys.Rev.D90 (2014)).





The weak point of the "indirect" method is that the result highly depends on assumptions about unknown NP that does not modify λ_{HHH} itself:



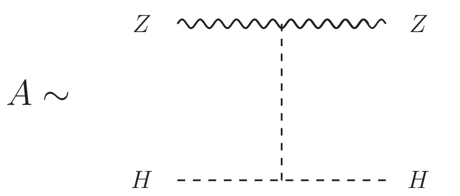
$$\text{Cross section} \propto \underbrace{|\bar{g}_{ZZH}|^2}_{\text{Input from Exp.}} = \underbrace{|g_{ZZH}|^2}_{LO} + \underbrace{g_{ZZH} \times \lambda_{HHH} + g_{ZZH} \times \text{NP}}_{NLO}$$

♠ Extraction of λ_{HHH} largely depends on NP.

Message: an "indirect" constraint on λ_{HHH} is very model-dependent.

In this work, a method of measuring "directly" the Higgs self-coupling λ_{HHH} in $e^+e^- \to ZH$ is proposed:

- we consider the process $e^+e^- \to Z(\to f\bar{f}) + H$.
- we use time-reversal-odd (T-odd) asymmetries.
- the T-odd asymmetries directly probe λ_{HHH}, because the former measure the tree-level $ZH \to ZH$ scattering:



Outline:

- ♠ General idea of time-reversal-odd (T-odd) quantities.
- ♠ T-odd asymmetries in $e^+e^- \to Z(\to f\bar{f}) + H$.
- ♠ Direct constraint on λ_{HHH} from the T-odd asymmetries.
- ♠ Conclusion.

General idea of time-reversal-odd (T-odd) quantities.

T-odd observables are generally define by (De Rujula et al Nucl.Phys.B35 (1971))

$$\mathcal{O} \equiv |\mathcal{M}_{fi}|^2 - |\mathcal{M}_{\tilde{f}\tilde{i}}|^2.$$

where $\tilde{i}$ ($\tilde{f}$) denotes the state obtained from i (f) by reversing momenta and spins. Using unitarity of S-matrix ($SS^\dagger = 1$), we may derive

$$\mathcal{O} = \underbrace{|\mathcal{M}_{if}|^2 - |\mathcal{M}_{\tilde{f}\tilde{i}}|^2}_{\text{vanishes when T-conserved}} -2Im\left(\mathcal{M}^\star_{fi}\mathcal{A}_{fi}\right) - |\mathcal{A}_{fi}|^2,$$

where

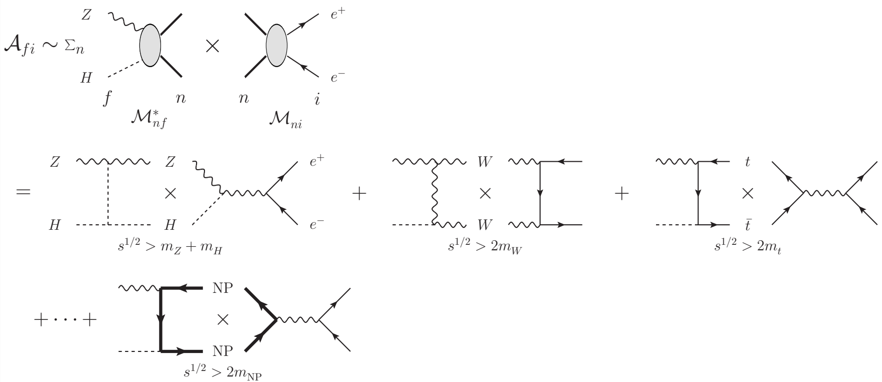
$$\mathcal{A}_{fi} \equiv (2\pi)^4 \sum_n \left[\left(\prod_j \int \frac{d^3p_j}{(2\pi)^3}\frac{1}{2E_j}\right)\delta^4(p_n - p_i)\mathcal{M}^\star_{nf}\mathcal{M}_{ni}\right]$$

is called the absorptive part of $\mathcal{M}_{fi}$ and the sum over all the possible asymptotic state n is performed. (also called re-scattering effects.)

> Message: If T (or equally CP) is conserved, T-odd observables are proportional to the absorptive part $\mathcal{A}_{fi}$.

General idea of T-odd quantities (II).

Schematic picture of the absorptive part $\mathcal{A}_{fi}$ for $e^+e^- \to ZH$:



- In the one-loop order, the absorptive part $\mathcal{A}_{fi}$ is simply $\mathcal{M}_{\rm tree} \times \mathcal{M}_{\rm tree}$.
- In case of $s^{1/2} < 2m_t$, only the ZH and WW states contribute to the absorptive part.

Message: Virtual heavy (NP) particles decouple from the T-odd observables.

T-odd asymmetries in $e^+e^- \to Z(\to f\bar{f}) + H$.

T-odd asymmetries in $e^+e^- \to Z(\to f\bar{f}) + H$ (I).

The differential cross section is

$$\frac{d^3\sigma(ee \to f\bar{f}H)}{d\cos\Theta d\cos\theta d\phi} = F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3\sin 2\theta\cos\phi + F_4\sin^2\theta\cos 2\phi + F_5\cos\theta + F_6\sin\theta\cos\phi + F_7\sin\theta\sin\phi + F_8\sin 2\theta\sin\phi + F_9\sin^2\theta\sin 2\phi,$$

where F_i ($i = 1$ to 9) are functions of only s, $\cos\Theta$. Note that

$$\frac{d\sigma(ee \to ZH)}{d\cos\Theta} = \int_{-1}^{1} d\cos\theta \int_0^{2\pi} d\phi \frac{d^3\sigma}{d\cos\Theta d\cos\theta d\phi} = \frac{16\pi}{3} F_1(\cos\Theta).$$

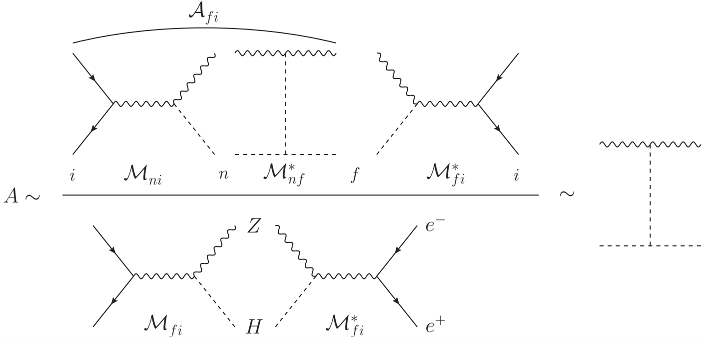
Under T transformation without interchanging the initial and final states,

$$\frac{d^3\sigma}{d\cos\Theta d\cos\theta d\phi} \to \underbrace{F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3\sin 2\theta\cos\phi + F_4\sin^2\theta\cos 2\phi}_{\text{T-even}} + \underbrace{F_5\cos\theta + F_6\sin\theta\cos\phi}_{\text{T-even}} \underbrace{-F_7\sin\theta\sin\phi - F_8\sin 2\theta\sin\phi - F_9\sin^2\theta\sin 2\phi}_{\text{T-odd}},$$

Define T-odd asymmetries (A_7, A_8, A_9) by

$$A_{(7,8,9)} \equiv \frac{F_{(7,8,9)}}{F_1}, \qquad A_7 \propto \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)} \text{ etc}$$

Diagrams contributing to the numerator and denominator in the T-odd asymmetries ($A_7 = F_7/F_1$ etc):

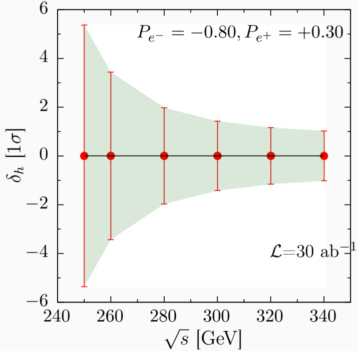


- ♠ The tree amplitude for $e^+e^- \to ZH$ drops from the ratio and only the tree diagram for the $ZH \to ZH$ scattering is left.
- ♠ The T-odd asymmetries are "direct" probes of the Higgs self-coupling λ_{HHH}, because λ_{HHH} is no longer a part of the loop.

Direct constraint on λ_{HHH} from the T-odd asymmetries

Introduce a real parameter δ_h as

$$\lambda_{HHH} = \lambda_{HHH}^{\rm SM}(1 + \delta_h).$$



Direct 1σ constraint on δ_h at several c.m. energies.

(The results have been obtained with FeynArts, FormCalc, LoopTools (FF) and BASES.)

Summary

Summary.

- The "indirect" method gives us only a highly model-dependent Higgs self-coupling λ_{HHH}.
- A "direct" measurement of λ_{HHH} is possible even in the single Higgs production process $e^- e^+ \to ZH$ by using the T-odd asymmetries.
- The T-odd asymmetries are direct probes of λ_{HHH}, because the former measure the tree-level $ZH \to ZH$ scattering.
- The method is found very difficult. But!, this is probably the only approach to measure λ_{HHH} directly in $e^+ e^-$ collisions, when a beam energy above the ZHH threshold is not available. (Imagine the case that the world faces an economical crisis when the ILC is running at 340 GeV...)

Thank you for your attention.

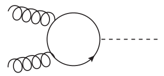
back up

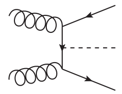
Direct and Indirect.

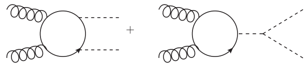
How can one distinguish "direct" from "Indirect"?

→ "Indirect" if the coupling enters intos a loop.

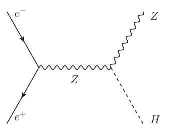
Examples:


: Indirect ttH.

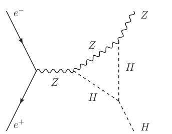

: Direct ttH.



: Indirect ttH & Direct HHH.



: Direct ZZH.



: Indirect HHH.

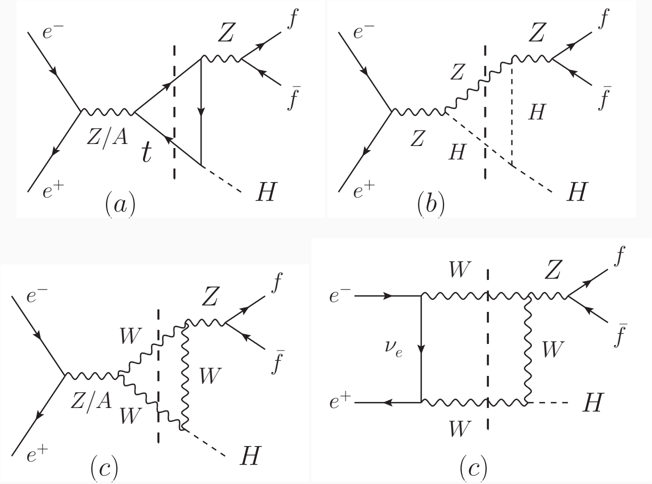


Figure 1: Representative one-loop Feynman diagrams that contribute to the T-odd distribution, (a) the top loop diagrams, (b) the Higgs loop diagram that depends on the coupling λ_{HHH}, and (c) a part of the gauge boson loop diagrams.

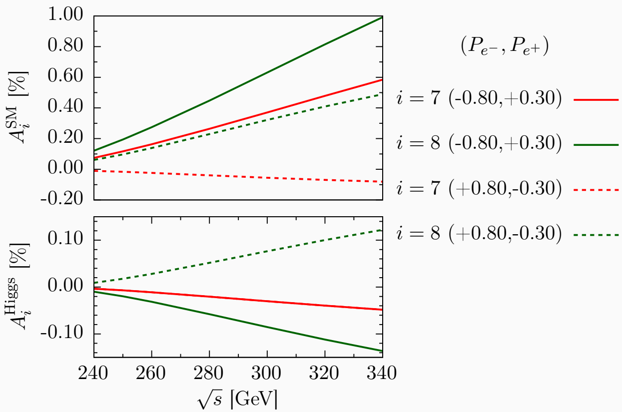


Figure 2: $(A_7^{\rm SM}, A_8^{\rm SM})$ in the upper plot and$(A_7^{\rm Higgs}, A_8^{\rm Higgs})$ in the lower plot as functions of the c.m. energy, for two choices of beam polarizations: $(-0.80, +0.30)$ (solid) and $(+0.80, -0.30)$ (dashed). $A_7^{\rm Higgs}$ for the two choices of polarizations are degenerate.