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

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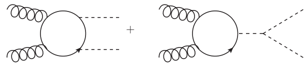
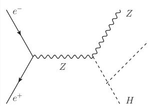
Introduction

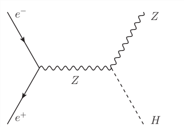
Introduction: the trilinear Higgs self-coupling measurement.

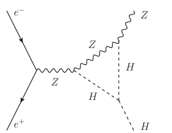
- The capabilities of the LHC and future e^+e^- colliders to measure the trilinear Higgs self-coupling λ have been seriously studied in recent years.
- The "direct" measurement from the di-Higgs productions (such as $gg \to HH$ and $e^+e^- \to ZHH$) is challenging, because of their very small cross sections.





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

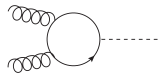


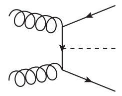


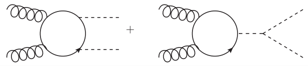
How can one distinguish "direct" from "Indirect"?

→ "Indirect" if the coupling constitutes a loop.

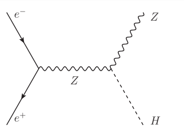
Examples:


: Indirect ttH.

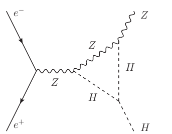

: Direct ttH.



: Indirect ttH & Direct HHH.

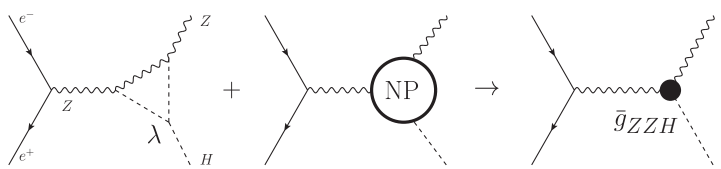


: Direct ZZH.



: Indirect HHH.

The weak point of the "indirect" method is that the result highly depends on assumptions about unknown NP at UV scale:

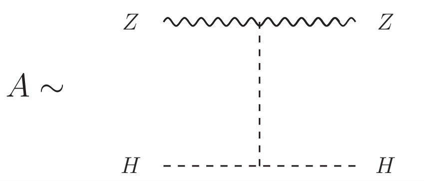


- Both the *ZHH* triangle-loop (left) and the one-loop correction due to heavy NP particles (middle) reduce to the same effective *ZZH* coupling (right).
- "NP at UV scale" and "λ" may contribute to the cross section with the same magnitude.
- A virtual heavy fermion does not decouple from the cross section measured at low energy (Fleischer et al Nucl.Phys.B216 (1983)).

Message: a "indirect" constraint is very model-dependent.

In this work, a method of measuring "directly" the Higgs self-coupling λ 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, because the former measure the tree-level diagram for the $ZH \to ZH$ 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_H from the T-odd asymmetries.
- ♠ Conclusion.

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

General idea of T-odd quantities (I).

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

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

where

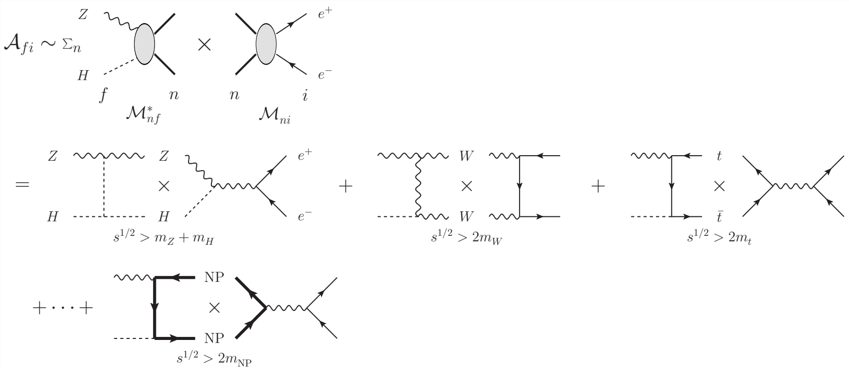
$$\mathcal{A}_{fi} \equiv (2\pi)^4 \sum_n \left[\left(\prod_j \int \frac{d^3p_j}{(2\pi)^3}\frac{1}{2E_j}\right)\delta^4(p_n - p_i)\mathcal{M}^\star_{nf}\mathcal{M}_{ni}\right]$$

is called the absorptive part of $\mathcal{M}_{fi}$ and the sum over all the possible asymptotic state n is performed. (also called 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 $\mathcal{M}_{\rm tree} \times \mathcal{M}_{\rm tree}$.
- Unknown virtual heavy NP particles never contribute to the absorptive part!, unless the c.m. energy is large enough to directly produce these NP particles.

Message: NP at higher scale completely decouples 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

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

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

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

Under T transformation without interchanging the initial and final states,

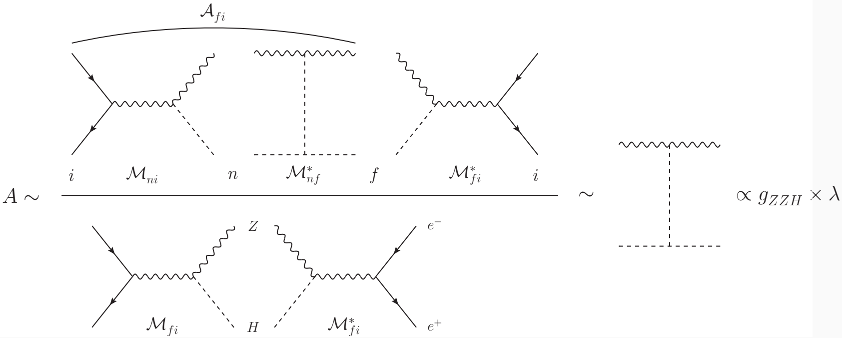
$$\frac{d^3\sigma}{d\cos\Theta d\cos\theta d\phi} \to \underbrace{F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3\sin 2\theta\cos\phi + F_4\sin^2\theta\cos 2\phi}_{\text{T-even}} + \underbrace{F_5\cos\theta + F_6\sin\theta\cos\phi}_{\text{T-even}} \underbrace{-F_7\sin\theta\sin\phi - F_8\sin 2\theta\sin\phi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

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

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

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

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



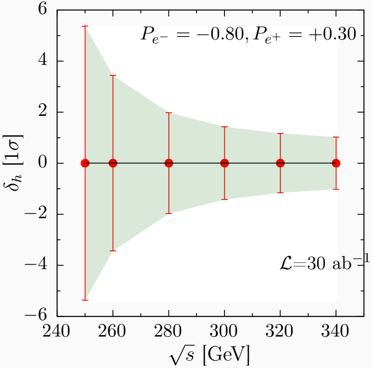
- ♠ The tree amplitude for $e^+e^- \to ZH$ drops from the ratio and only the tree diagram for the $ZH \to ZH$ scattering is left.
- ♠ The T-odd asymmetries measure "$g_{ZZH} \times \lambda$", and this is a "direct" probe of the Higgs self-coupling λ.

Direct constraint on λ from the T-odd asymmetries

Direct constraint on λ from the T-odd asymmetries.

Introduce a real parameter δ_h as

$$\lambda = \frac{m_H^2}{2v^2}(1 + \delta_h).$$



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

Summary

Summary.

- The indirect Higgs self-coupling λ measurement suffers from large dependence on unknown NP scenarios that do not necessarily influence λ itself.
- In this work, a method of measuring λ ”directly” in $e^+e^- \to ZH$ is discussed.
- The T-odd asymmetries directly probe λ, because (1) the former measure the tree-level diagram for the $ZH \to ZH$ scattering and (2) NP at higher scale completely decouples from the former.
- The method is found very difficult. But!, this is probably the only method to constrain λ directly in e^+e^- collisions, when a beam energy below the ZHH threshold is only available. (Imagine the case that Japan faces an economical crisis when the ILC is running at 340 GeV...)