

Radiative corrections to Higgs Strahlung from the Real Triplet Model

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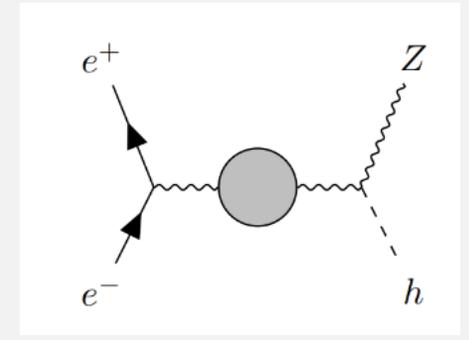
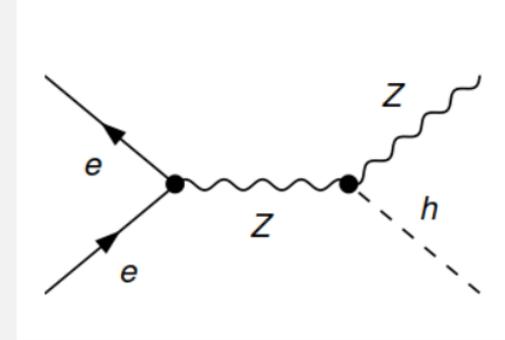


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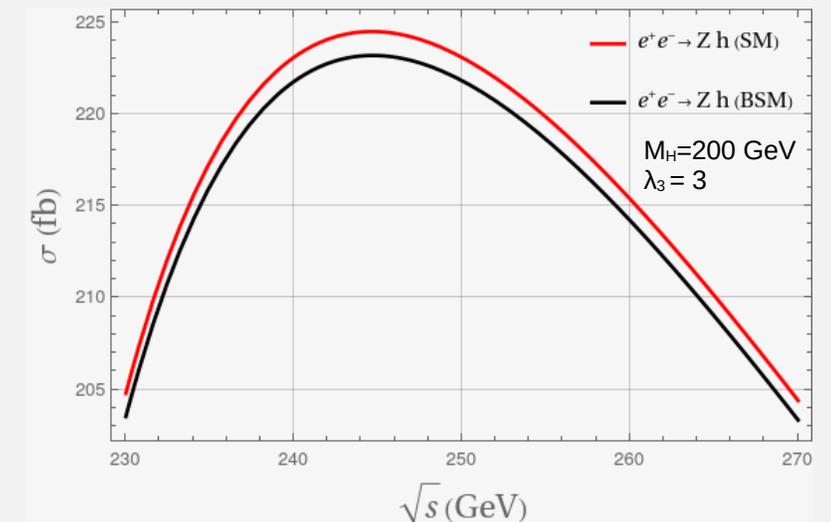
● Motivation and main idea

- Future electron positron colliders will measure the **Higgs Strahlung production cross section with very high precision $> 0.26\%$ ***
- **BSM scalar models** can influence this process via **NLO radiative corrections**.

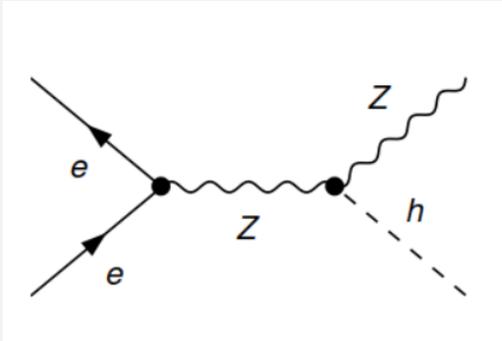


Calculating the **deviation from the SM** caused by BSM models provides a **strong indirect probe** on BSM physics

In this talk, we discuss these **radiative corrections** for the case of the **Real Triplet Scalar Model**, and show how future experimental precise Higgs Strahlung measurements can **constrain the parameter space of this model**.



• The SM cross section at tree level



$$|M_{e^+e^- \rightarrow Zh}^{LO}|^2 = \frac{2e^4(g_v^2 + g_a^2)}{s_W^2 c_W^2} \frac{tu + 2sm_Z^2 - m_h^2 m_Z^2}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}, \quad s_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

To compute the cross section we need inputs for the parameters: e , m_Z , m_W , m_h

- Already at tree-level, the value of the cross section depends heavily on the chosen input scheme

Different experimental input schemes

$\alpha(0), m_Z, m_W, m_h$

$$\alpha(0) = \frac{e^2(0)}{4\pi} = \frac{1}{137.036}$$

$\alpha(m_Z), m_Z, m_W, m_h$

$$\alpha(m_Z) = \frac{e^2(m_Z)}{4\pi} = \frac{1}{128.943}$$

G_μ, m_Z, m_W, m_h

$$G_\mu = \frac{\sqrt{2}e^2}{8m_W^2 s_W^2} \quad \text{From muon decay}$$

• The SM cross section at tree level

\sqrt{s}	schemes	σ_{LO} (fb)
240	$\alpha(0)$	223.14 ± 0.47
	$\alpha(M_Z)$	252.03 ± 0.60
	G_μ	239.64 ± 0.06

[1609.03995]

- Comparison of different results for the cross section at LO with **different input schemes is not meaningful**, since different schemes “absorb” higher order corrections already at LO.
- A **full NLO** result using the same schemes is, however, **input scheme independent** (up to possible NNLO effects).

Moreover, future Higgs factories will measure this cross section with 0.26%* precision

→ **Need a precise determination of the SM cross section and calculations of higher order corrections**

NLO Nucl. Phys. B216 (1983), Z. Phys. C55 (1992), Z. Phys. C56 (1992)

NNLO (Mixed EW-QCD) [1609.03995], [1609.03955]

NNLO (fermionic-EW) [2209.07612], polarized [2305.16547]

● The SM cross section at higher orders

\sqrt{s}	schemes	σ_{LO} (fb)	σ_{NLO} (fb)	σ_{NNLO} (fb)
240	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$

[1609.03995]

The cross section at NNLO has almost the same value for all input schemes.

Future Higgs factories can measure this cross section with a relative precision of 0.26% (CEPC).

—————> Perfect probe for BSM models

● Contributions to Higgs Strahlung

- The cross section of the Higgs Strahlung will be measured up to **0.26% precision** in future electron positron colliders such as the **CEPC**.
- **Deviations** from the **SM predictions** can be attributed to **BSM physics**.
- **No deviations** from the SM predictions up to the experimental precision can be used to **constrain BSM physics**.

—————→ **Quantum corrections provide an indirect test on BSM models**

Goal: Calculate the deviation of σ_{Zh} in the Real Triplet Model from the SM value.

$$\delta\sigma_{Zh} = \frac{\sigma_{SM+BSM}^{NLO} - \sigma_{SM}^{NLO}}{\sigma_{SM}^{NLO}}$$

Captures the pure Real Triplet Model contributions to this process.

• The Inert Real Triplet Model

We extend the SM Scalar sector with an $SU(2)_L$ Real Triplet $\Sigma(1,3,0)$

$$\Sigma = \frac{1}{2} \begin{pmatrix} H^0 & \sqrt{2}H^+ \\ \sqrt{2}H^- & -H^0 \end{pmatrix}$$

$$\mathcal{L}_{scalar} = (D_\mu \Phi)^\dagger (D^\mu \Phi) + \text{Tr} (D_\mu \Sigma)^\dagger (D^\mu \Sigma) - V(\Phi, \Sigma)$$

$$V(h, \Sigma) = -\mu_h^2 \Phi^\dagger \Phi + \lambda_h (\Phi^\dagger \Phi)^2 - \mu_\Sigma^2 \text{Tr} \Sigma^\dagger \Sigma + \lambda_\Sigma (\text{Tr} \Sigma^\dagger \Sigma)^2 + \lambda_3 (\Phi^\dagger \Phi) \text{Tr} \Sigma^\dagger \Sigma$$

Only the SM Higgs doublet acquires a non zero vacuum expectation value \rightarrow No mixing between the SM Higgs and Real triplet scalars.

Particle spectrum : SM Higgs h , Neutral triplet H^0 , and charged H^\pm .

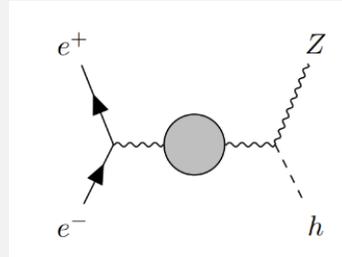
For $\langle \Sigma \rangle = 0$, both H^0 and H^\pm have degenerate masses at tree level ($\Delta_m = 166$ MeV loop correction).

Can act as a dark matter candidate [0811.3957]

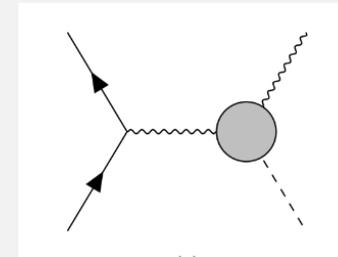
Since there is no scalar mixing, effects from this model in the Higgs Strahlung process only enter through loop corrections
 \rightarrow precision calculations of e^+e^- to Zh is a good probe for this model.

● Real Triplet contributions to Higgs Strahlung at NLO

1) Generate the loop diagrams related to the Real Triplet Model using **FeynArts**.



Self energy contributions



Vertex contributions

2) Calculate the Feynman diagrams and express them in terms of Passarino-Veltman functions (**FeynCalc**).

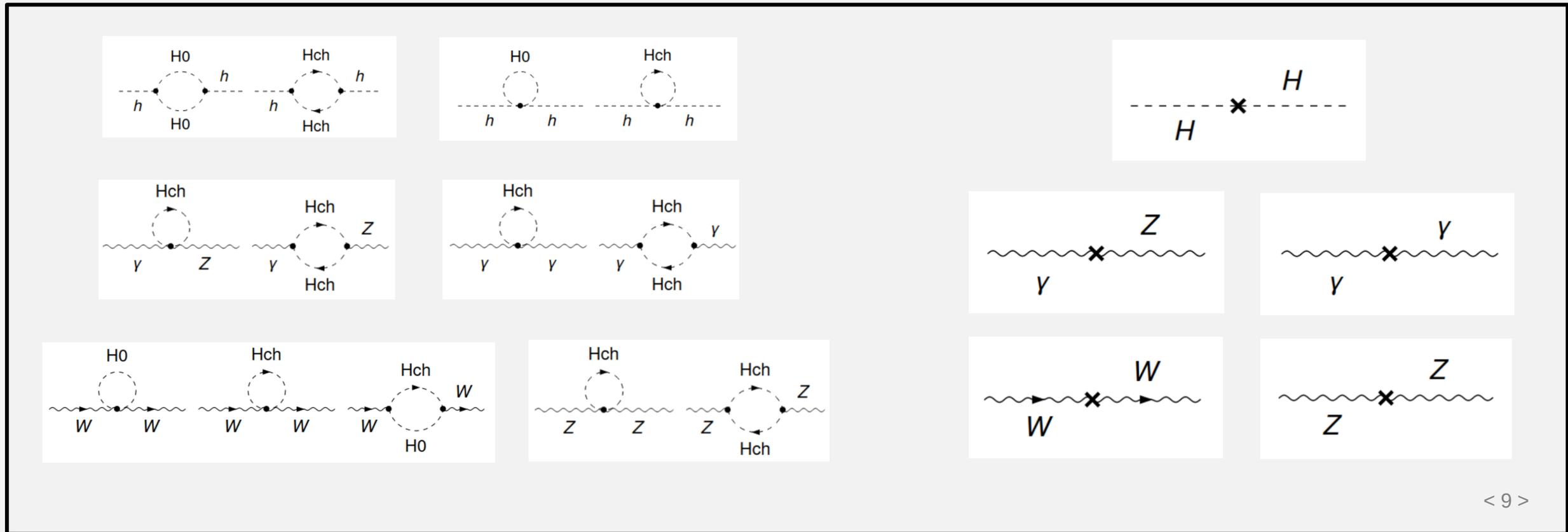
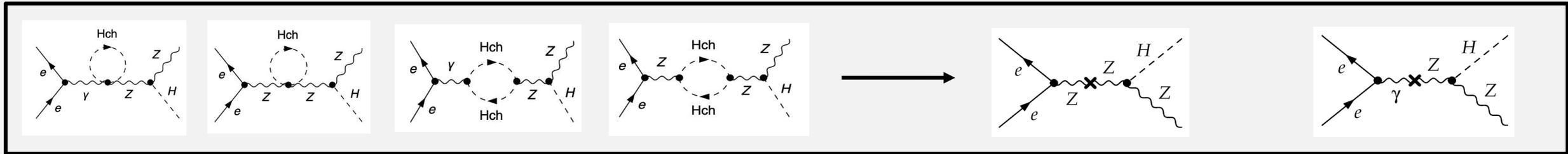
3) Absorb the UV divergences in counterterms using either the **On-Shell** or **MS-bar renormalization schemes**.

4) Calculate the UV-finite NLO cross section and compute the parameter space region of the Real Triplet Model that can be excluded in future collider (**Package X**).

Loop Contributions to Higgs Strahlung

Self energy loops

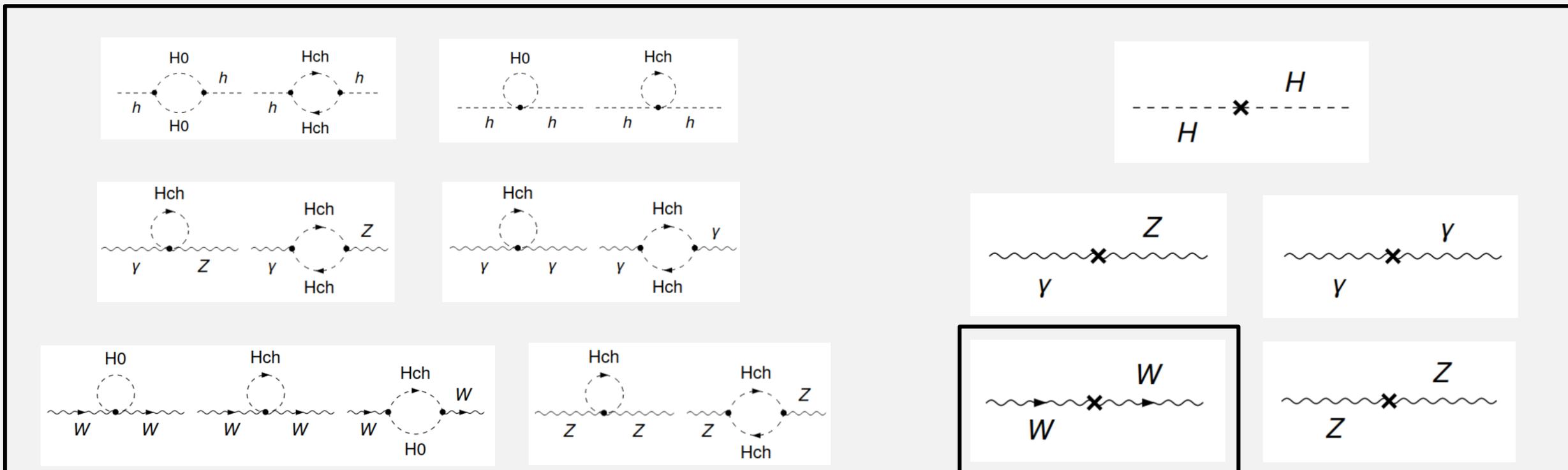
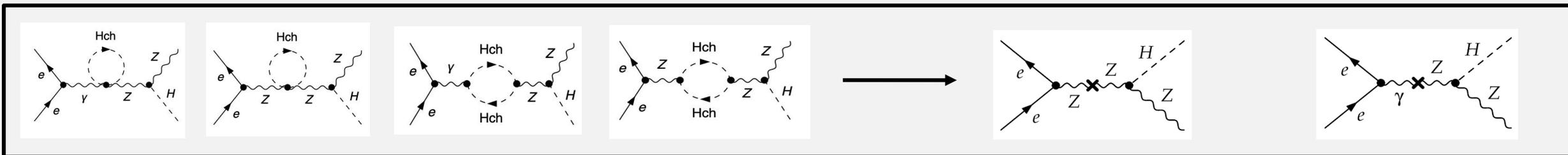
Counterterms



Loop Contributions to Higgs Strahlung

Self energy loops

Counterterms

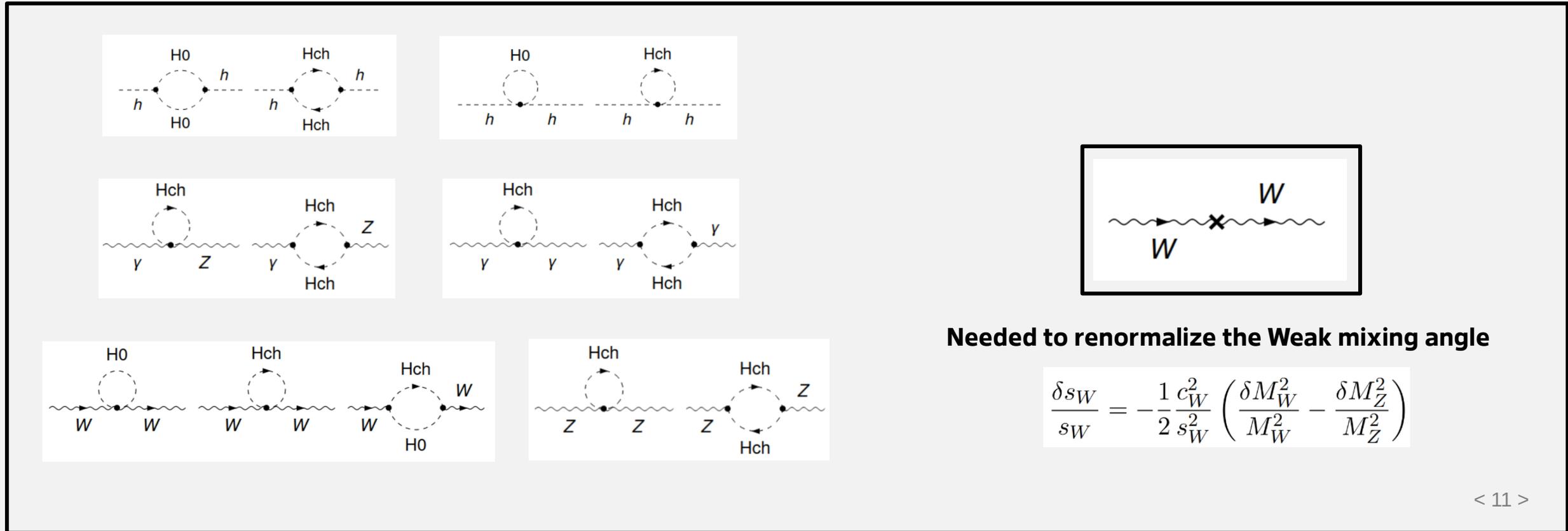
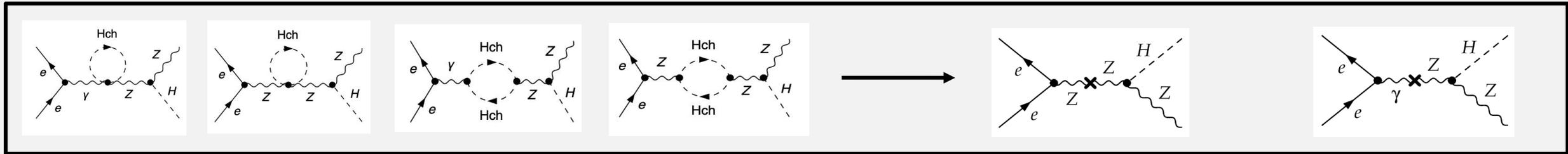


Needed to renormalize the Weak mixing angle

Loop Contributions to Higgs Strahlung

Self energy loops

Counterterms

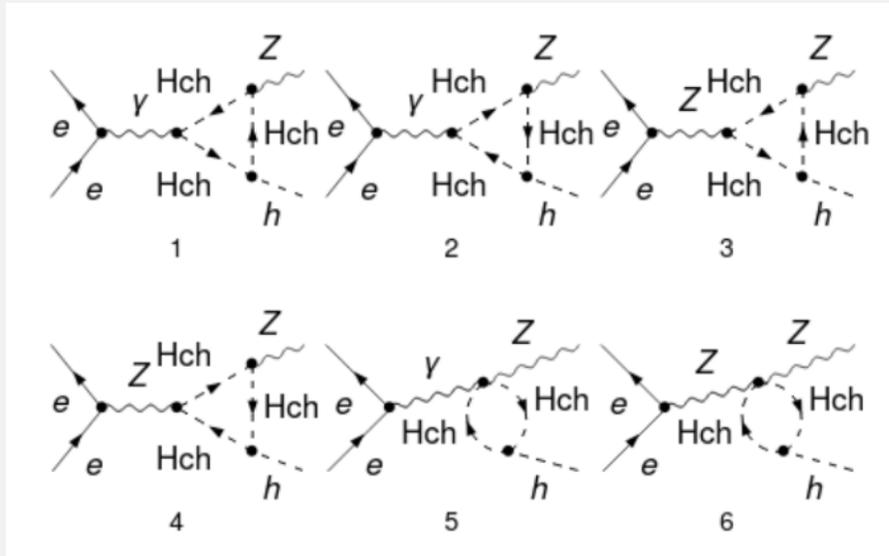


Needed to renormalize the Weak mixing angle

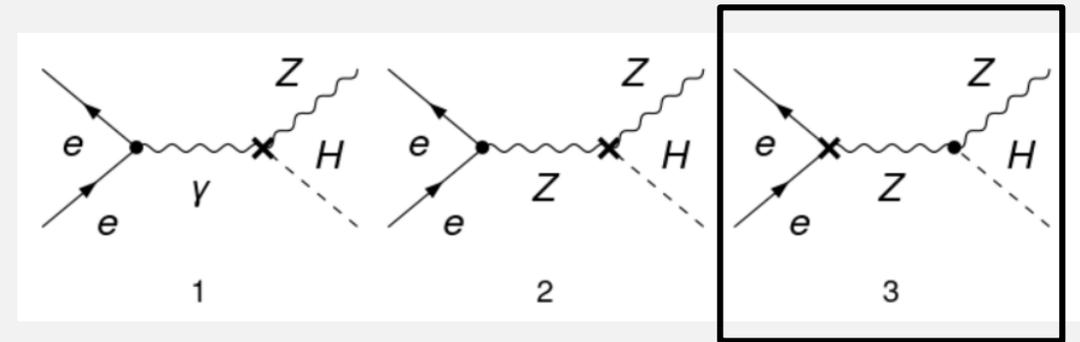
$$\frac{\delta s_W}{s_W} = -\frac{1}{2} \frac{c_W^2}{s_W^2} \left(\frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2} \right)$$

Loop Contributions to Higgs Strahlung

Vertex Diagrams



Counterterms needed for the BSM calculation



Why is this initial vertex counterterm needed even though we don't have initial vertex loop diagrams (from BSM scalars) ?

Renormalisation of the Lagrangian

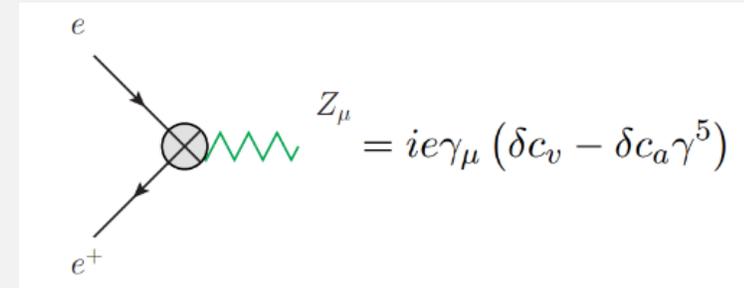
Bare parameters

Renormalized parameters

Counterterms parameters

$$\mathcal{L}_{bare}(g_0, \lambda_0, m_0) = \mathcal{L}_{ren}(g, \lambda, m) + \delta\mathcal{L}(\delta g, \delta\lambda, \delta m)$$

Using the OS- Scheme, this generates such a vertex counterterm:



[2104.10709]

$$\delta c_v = \delta g_v + \frac{g_v}{2} \delta Z_{ZZ} - \frac{Q_e}{2} \delta Z_{\gamma Z},$$

$$\delta c_a = \delta g_a + \frac{g_a}{2} \delta Z_{ZZ},$$

$$\delta g_v = \frac{I_{W,e}^3}{2s_W c_W} \left(\delta Z_e + \frac{s_W^2 - c_W^2}{c_W^2} \frac{\delta s_W}{s_W} \right) - \frac{s_W}{c_W} Q_e \left(\delta Z_e + \frac{1}{c_W^2} \frac{\delta s_W}{s_W} \right),$$

$$\delta g_a = \frac{I_{W,e}^3}{2s_W c_W} \left(\delta Z_e + \frac{s_W^2 - c_W^2}{c_W^2} \frac{\delta s_W}{s_W} \right),$$

The Real Triplet scalars influence the renormalization of the Z-boson wave function as well as the renormalization of the Weak mixing angle → BSM triplet scalars contribute **(with finite contribution)** into this counterterm.

● Renormalization

Renormalization has two important aspects:

1) Absorbing the UV divergences in radiative corrections to some process.

2) Determines the physical meaning of the model parameters. This is renormalization scheme dependent.

$$\mathcal{L}_{bare}(g_0, \lambda_0, m_0) = \mathcal{L}_{ren}(g, \lambda, m) + \delta\mathcal{L}(\delta g, \delta\lambda, \delta m)$$

$$\begin{array}{ccccccc}
 \text{-----} & + & \text{---}\bigcirc\text{---} & + & \text{---}\times\text{---} & + & \dots \\
 p^2 - m_h^2 & & \Sigma_h(p^2) & & -\delta m_h^2 + (p^2 - m_h^2)\delta Z_h & &
 \end{array}$$

Propagator:

$$\frac{1}{p^2 - m_h^2 + \Sigma_h(p^2) - \delta m_h^2 + (p^2 - m_h^2)\delta Z_h}$$

● Renormalization in the OS-Scheme

$$\frac{1}{p^2 - m_h^2 + \Sigma_h(p^2) - \delta m_h^2 + (p^2 - m_h^2)\delta Z_h}$$

The OS-scheme defines the pole of this propagator to be equal to the measured physical mass m_h .

In all renormalization schemes, counterterms absorb the divergences, but how do we define our renormalized parameters ?

Different meaning for the parameters in different renormalization schemes (MS-bar, On-shell, Complex mass, ect...)

This leads to the renormalization condition:

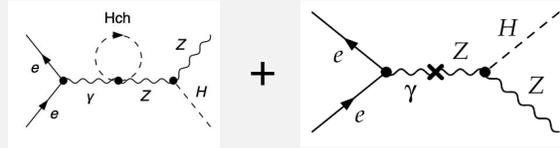
$$\begin{aligned}\delta m_h^2 &= \text{Re } \Sigma_h(p^2 = m_h^2) \\ \delta Z_h &= -\text{Re } \frac{\partial \Sigma_h(p^2)}{\partial p^2} \Big|_{p^2 = m_h^2}\end{aligned}$$



$$\delta m_h^2 = \frac{A}{\epsilon} + \textit{finite}$$

Similar procedure for the rest of the parameters needed for the calculations.

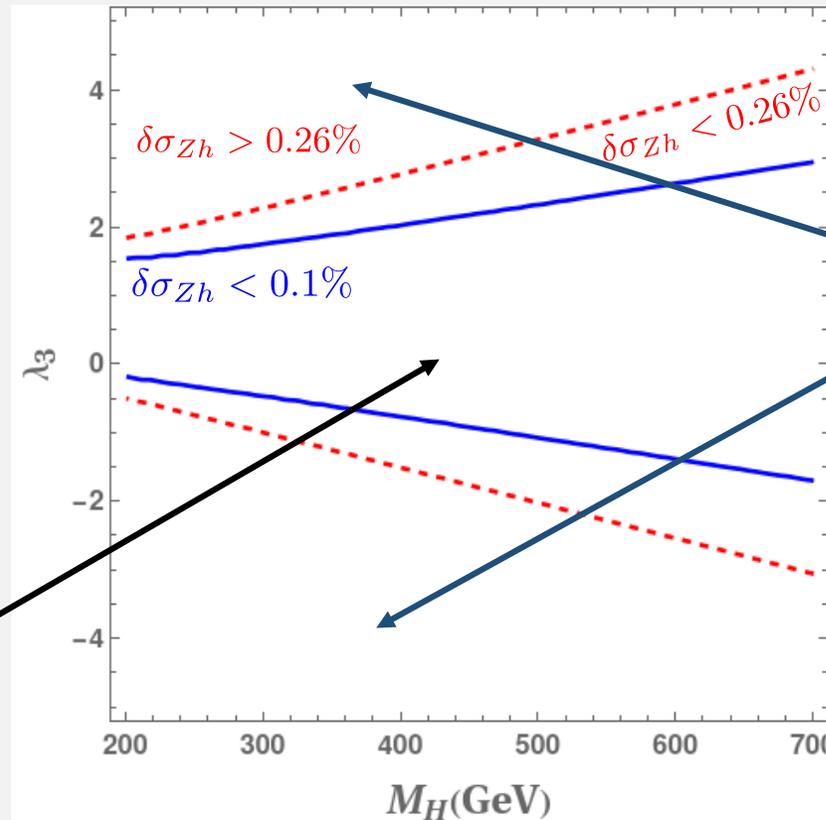
Renormalization in the OS-Scheme



$$|M_{BSM}^{NLO}|^2 = 2\text{Re} \left[(\hat{M}_{BSM}^{\gamma Z} + \hat{M}_{BSM}^{ZZ}) \cdot \overline{M}_{LO} \right] + 2\text{Re} \left[\hat{M}_{BSM}^{vertex} \cdot \overline{M}_{LO} \right]$$

$$\delta\sigma_{Zh} = \frac{\sigma_{SM+BSM}^{NLO} - \sigma_{SM}^{NLO}}{\sigma_{SM}^{NLO}}$$

Region of parameter space where the deviation caused by the real Triplet scalars are smaller than the experimental precision.

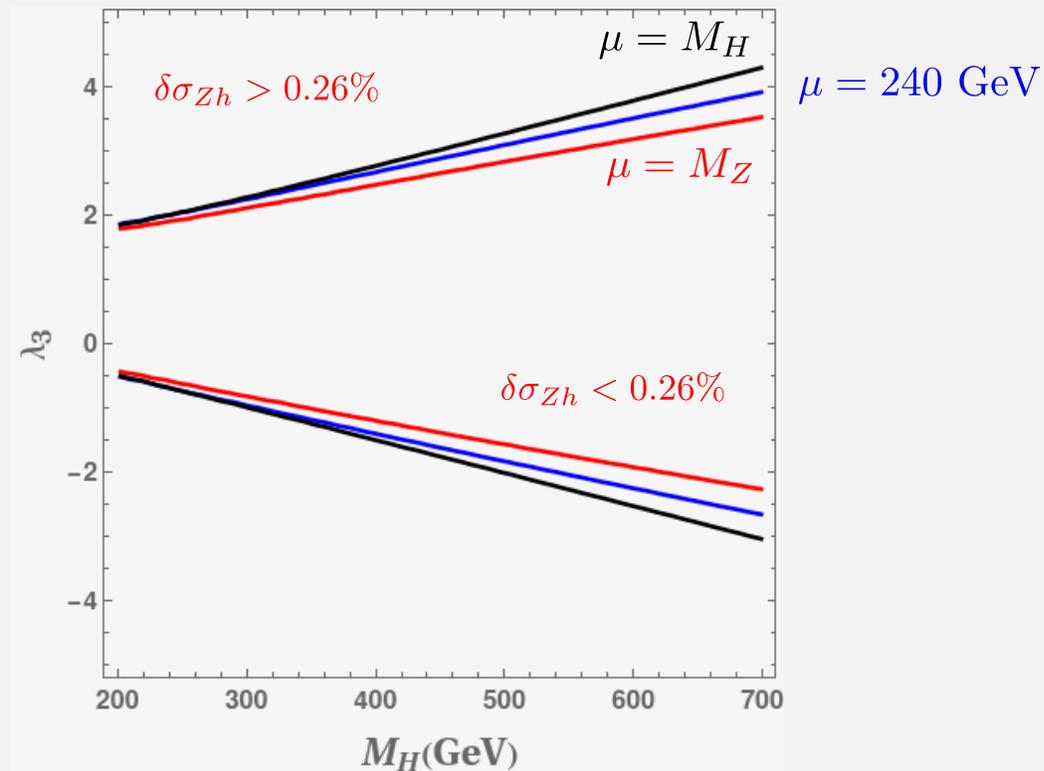


Region of parameter space where the real Triplet scalars can induce an observable deviation from SM.

Effects from varying λ_Σ enter at NNLO, since there is no mixing between the Real Triplet and the SM Doublet

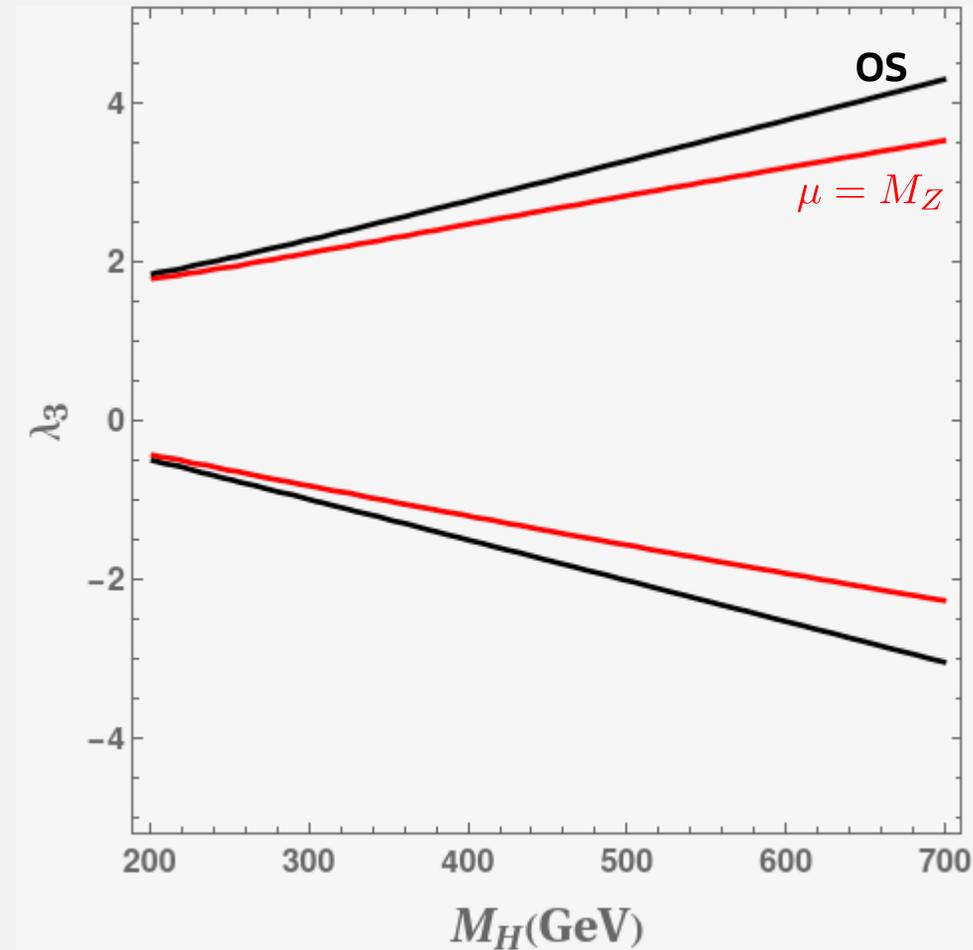
● Renormalization in the $\overline{\text{MS}}$ Scheme

- In the $\overline{\text{MS}}$ scheme, the counterterms are constructed to **only absorb the divergences** and the finite term $(\log(4\pi) + \gamma_E)$.
- The renormalized self energies and model parameters depend on the **renormalization scale μ** .



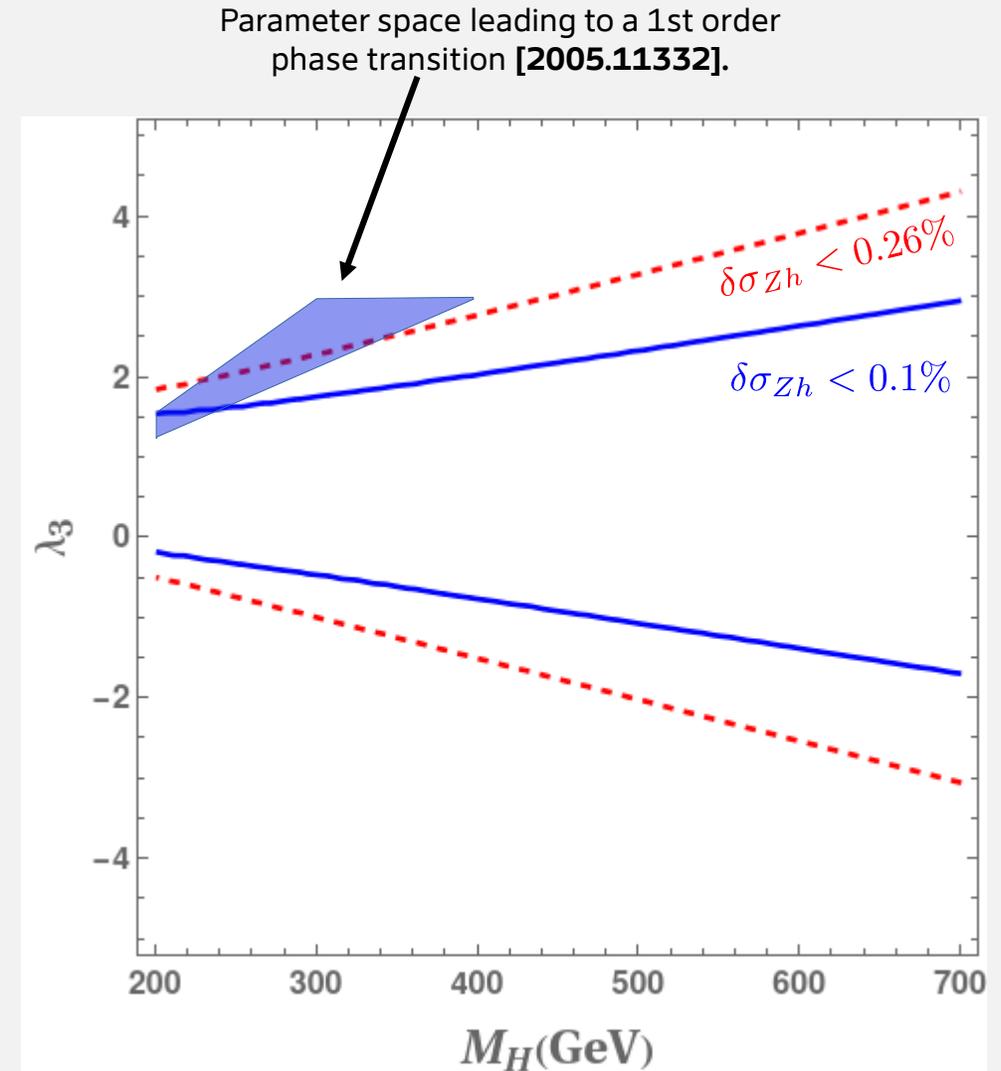
Comparison of the two schemes

- Both schemes have good agreement at **lower masses** for the triplet scalar.
- The renormalization scale dependance in the MS-bar is related to terms **$\log(\mu^2/M_H^2)$** .
- No difference in the results for **$\mu = M_H$**



• Synergies with Electroweak Phase Transitions

- The real triplet model can induce a **1st order EW phase transition** in the early universe [2005.11332] (Niemi, Ramsey-Musolf, Tenkanen, Weir).
- By measuring the Higgs Strahlung cross section with **> 0.1% precision**, one can rule out large region of parameter space with a **1st order phase transition**.
- For more on the **synergy between colliders and EW baryogenesis**, see Yanda Wu's talk (Tuesday, 3:20PM)

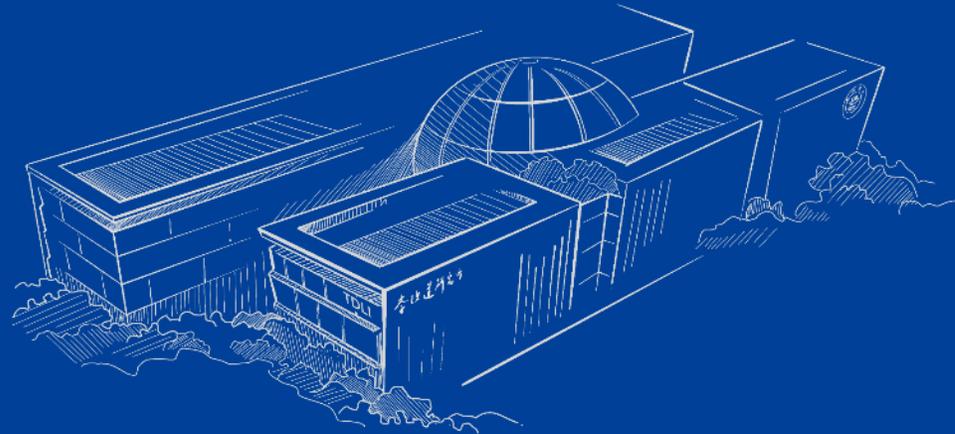


● Summary and outlook

- **Precision measurements** of the **Higgs Strahlung** process e^+e^- to Zh in future Higgs factories provides a **strong probe for scalar BSM models** such as the Real Triplet Model.
- The **choice of renormalization scheme** is detrimental in determining deviation from the SM value, and therefore the **allowed/excluded parameter points** of the real triplet model.
- These precision measurements also allow to probe parameter points leading to **1st order phase transition**.
- In the future, possible directions include checking the constraint on the model from **Higgs decays to $\Upsilon\Upsilon$, ΥZ , ect...**
- Provide the community with an **automated tool** to use **precise cross section measurements of the Higgs Strahlung** in order to probe the parameter space of BSM scalar models.



—— 谢谢! ——

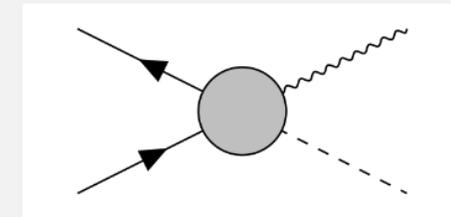
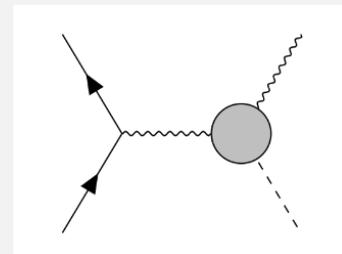
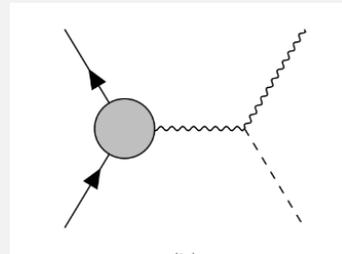
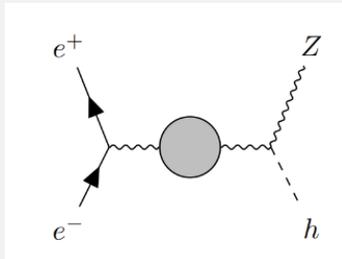


— Backup —

• The SM cross section at higher orders

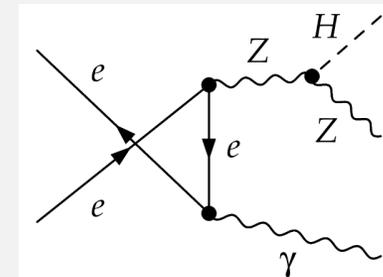
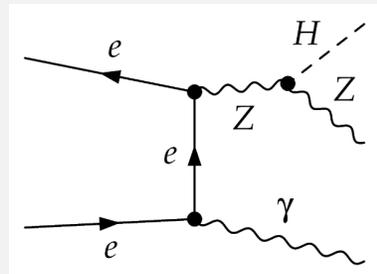
$$\sigma_{e^+e^- \rightarrow Zh}^{NLO} = \int_{2 \rightarrow 2} d\sigma_{virtual}^{NLO} + \int_{2 \rightarrow 3} d\sigma_{real}^{NLO}$$

- Virtual corrections: Compute self energy, vertex and box diagrams.



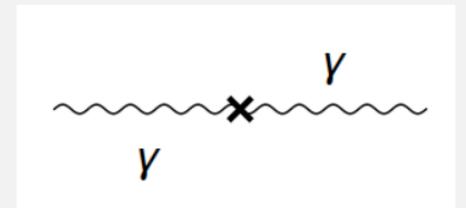
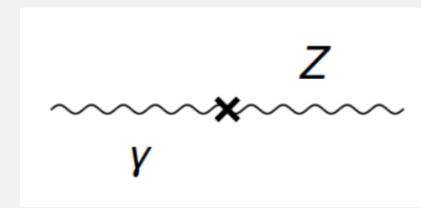
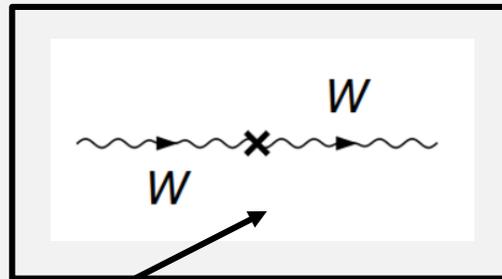
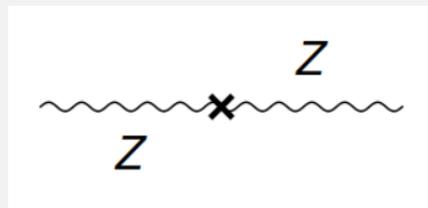
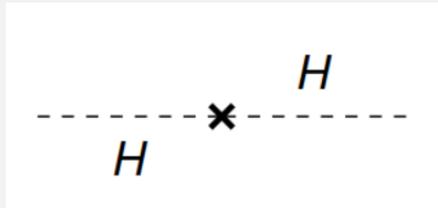
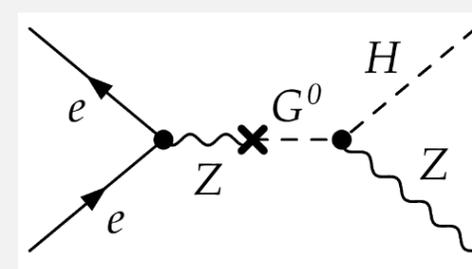
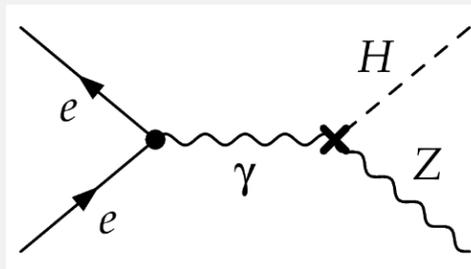
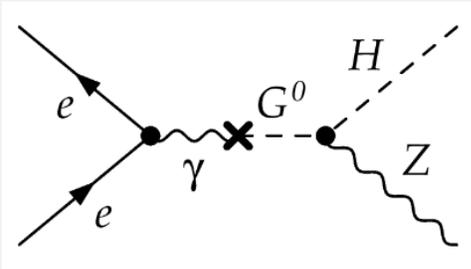
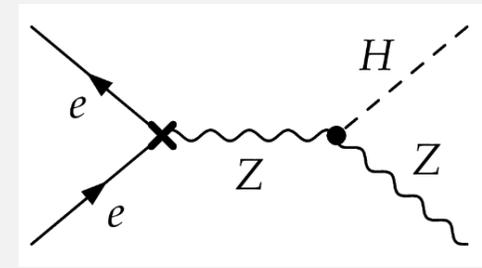
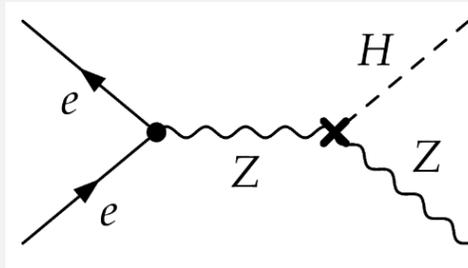
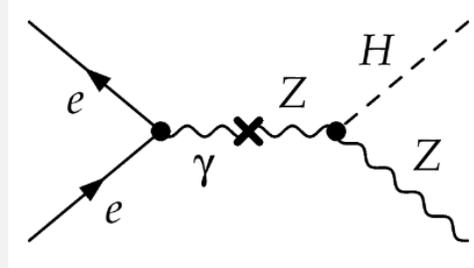
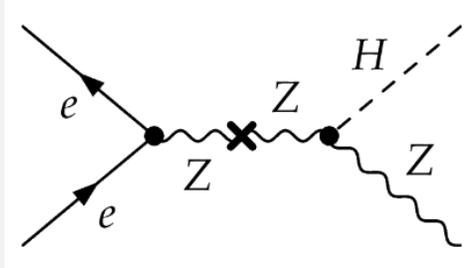
[Figs. from 2109.02884]

- Real corrections: Compute contributions from the real emission of photons by initial state electrons.



• The SM cross section at higher orders

- Loop contributions are UV divergent → Absorb these divergences in counterterms



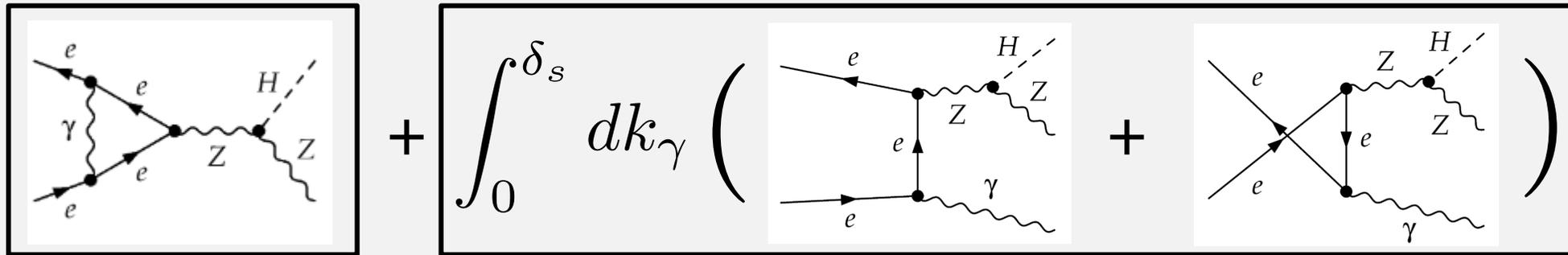
Needed to renormalize the Weak mixing angle

$$\frac{\delta s_W}{s_W} = -\frac{1}{2} \frac{c_W^2}{s_W^2} \left(\frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2} \right)$$

• The SM cross section at higher orders

- Contributions from initial photon loop as well as the real photon emission also cause IR divergences.

$$\sigma_{e^+e^- \rightarrow Zh}^{NLO} = \int_{2 \rightarrow 2} d\sigma_{virtual}^{NLO} + \int_{2 \rightarrow 3}^{soft, col} d\sigma_{real}^{NLO} + \int_{2 \rightarrow 3}^{hard} d\sigma_{real}^{NLO}$$



$$\frac{A}{\epsilon_{IR}}$$

$$-\frac{A}{\epsilon_{IR}}$$

→ The IR divergences from the loop corrections is cancelled exactly by the contribution from the emission of soft photons off initial electrons. **[Kinoshita, Lee, Nauenberg Theorem]**