Probing Extended Scalar Sector Through $e^+e^- \rightarrow Zh$ Process at NLO

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Outline

1. Introduction
   - Motivations
   - Extended Scalar Sector

2. NLO Calculation

3. Numerical Results
   - Complementary with Higgs Diphoton
   - Degenerate with Higgs Diphoton

4. Conclusion
**Zh Production at Future Lepton Collider**

- Lepton Colliders at 240 GeV as a Higgs factory: CEPC, FCC-ee, LEP3; e.g., at CEPC it will produce \( \sim 1 \) million events with integrated luminosity \( \mathcal{L} = 5.6 \ ab^{-1} \) over 7 years

- Higgs production at lepton colliders

- Advantages of lepton colliders producing Higgs vs Hadron Colliders
  - a. Initial-states are well defined (point-like \( e^+e^- \), fixed \( \sqrt{S} \))
  - b. High precision Higgs studies
  - c. Clean experimental environment: no complex QCD background, no or less triggers needed, lower levels of radiation

Figure source: CEPC Conceptual Design Report, arXiv:1811.10545 [hep-ex]
Search for New Physics through Extended Scalar Sector

- Hints of extended scalar sector supported by a variety of experiments, e.g., $h \to \gamma\gamma$ enhancement [CMS-PAS-HIG-12-015]

- Extraction of the scalar potential needs scalar-induced loop contributions to well measured processes, e.g., $Zh$ production at future lepton colliders

<table>
<thead>
<tr>
<th>Property</th>
<th>Estimated Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H$</td>
<td>5.9 MeV</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>3.1%</td>
</tr>
<tr>
<td>$\sigma(ZH)$</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\sigma(\nu\bar{\nu}H)$</td>
<td>3.2%</td>
</tr>
</tbody>
</table>

Complementary constraints on scalar potential could be made through $h\gamma\gamma$ decay where charged scalars in loop results in the enhancement, meanwhile the precision at this channel would be improved with a relative precision $\sim 1\%$.

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L. Borgonovi et al, CERN-ACC-2018-0045
Scalar Multiplet Models

- Same gauge group as the SM: $SU(2)_L \times U(1)_Y$

- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable neutral component as DM candidate

- Vanishing v.e.v. of the extended scalar sector $\Rightarrow$ no mixing in neutral sector

- Extended scalar sector: $\Phi_n$; SM Higgs doublet: $H$

$$\mathcal{L}_{\text{scalar}}^{\text{int}} = \mathcal{L}_{\text{kin}} - V(H, \Phi_n), \quad \mathcal{L}_{\text{kin}} \propto (D_\mu \Phi_n) \dagger (D^\mu \Phi_n),$$

$$D_\mu = \partial_\mu + ig_1 \frac{Y}{2} B_\mu + ig_2 W^a_\mu T^a$$
Scalar Multiplet Models

Models:

1. Inert Doublet: \( n = 2, \ Y = 1 \)
2. Real Triplet: \( n = 3, Y = 0 \)
3. Quintuplet & Septuplet: \( n = 5, 7, Y = 0 \)
4. Complex Triplet: \( n = 3, Y = 2 \) \( \Rightarrow \) Type-II seesaw neutrino studies

Study goal: constraints to Higgs portal parameters via \( Zh \) NLO

- Complex Triplet: \( (\lambda_4, \lambda_5) \) get well constrained by \( Zh \) NLO and \( h\gamma\gamma \)
- Else multiplets: \( h\gamma\gamma \) overall give more stringent constraints upon the Higgs portal parameters
NLO Contribution from the Extended Scalar Sector

- \( Zh \) LO process: \( e^- (p_1) + e^+ (p_2) \rightarrow Z (k_1) + h (k_2) \)
- One-loop corrections:

  - Cyan blobs \( \Rightarrow \) possible corrections induced by scalar-loop
  - No interactions to the Fermion Fields (Yukawa interaction suppressed by \( \mathcal{O}(M_f/M_W) \))

- NLO amplitude:

\[
\begin{align*}
\mathcal{M}^{1-\text{loop}}_{e^+e^-\rightarrow Zh} &= \mathcal{M}^\text{tree}_{e^+e^-\rightarrow Zh} + \mathcal{M}^\text{self}_{e^+e^-\rightarrow Zh} + \mathcal{M}^\text{vert}_{e^+e^-\rightarrow Zh}
\end{align*}
\]
NLO Contribution from the Extended Scalar Sector

- In $\overline{\text{MS}}$ Renormalization Scheme ($^\wedge$ notation)

$$iM_{e^+e^-\rightarrow Zh}^{1-\text{loop}} = -i\frac{\hat{e}^2 \hat{M}_Z}{\hat{s}\hat{c}} \hat{\rho}_{NC}(s) \bar{v}(p_2) \gamma^\mu (g_v^{eff} - g_a^{eff} \gamma_5) u(p_1) \epsilon_\mu(k_1)$$

$$+ iM_{\gamma^*\rightarrow Zh}^{\text{vert}} + iM_{\gamma^*\rightarrow Zh}^{\text{vert}}$$

- Self energy absorption in $\hat{\rho}_{NC}(s)$ and $g_v^{eff}$:

$$\hat{\rho}_{NC}(s) = \frac{1}{s - \hat{M}_Z^2 + \hat{\Sigma}_{ZZ}^T(s)} \left( 1 + \frac{1}{2} \delta \hat{Z}_{ZZ} + \frac{1}{2} \delta \hat{Z}_h \right)$$

$$g_v^{eff} = \frac{I_{W,e}^3 - 2\hat{\kappa}(s) \hat{s}^2 Q_e}{2\hat{s}\hat{c}}$$

$$\hat{\kappa}(s) = 1 - \frac{\hat{c}}{\hat{s}} \hat{\Sigma}_{T}^{\gamma Z}(s)$$
Scalar Multiplet Contributions to Higgs Diphoton Decay

- \( h\gamma\gamma \) decay width including \( \mathcal{NP} \) contribution

\[
\Gamma_{h\to\gamma\gamma}^{\mathcal{NP+SM}} = \frac{G_F\alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 g_{hhf} A_{1/2}^h (\tau_f) + g_{hWW} A_f^h (\tau_W) - \sum_s \frac{M_W}{g_2} g_{s\gamma}^2 g_{ssh} A_0^h (\tau_s) \right|^2
\]

- Loop functions \( A_{1/2}^h, A_1^h, A_0^h \) with \( \tau_i = M_i^2 / M_h^2 \) (\( i = f, W, s \))

\[
A_{1/2}^h (\tau_i) = -2\tau_i [1 + (1 - \tau_i) F (\tau_i)]
\]
\[
A_1^h (\tau_i) = 2 + 3\tau_i + 3\tau_i (2 - \tau_i) F (\tau_i)
\]
\[
A_0^h (\tau_i) = -\tau_i [1 - \tau_i F (\tau_i)]
\]

\[
F (\tau_i) = \begin{cases} 
\sin^{-1} \left( \sqrt{\frac{1}{\tau_i}} \right)^2, & \tau_i \geq 1 \\
-\frac{1}{4} \left[ \ln \left( \frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} \right) - i\pi \right]^2, & \tau_i < 1 
\end{cases}
\]
Observables

- **$Zh$ production**: relative correction w.r.t. LO total cross section
  \[
  \delta \sigma_{Zh} = \frac{\sigma_{NP}^{1-\text{loop}}}{\sigma_{SM}^{\text{LO}}}
  \]

  - Precision measurement of $Zh$ cross section at future lepton collider (e.g., CEPC) $\sim 0.5\% \Rightarrow$ slot for $NP$ $|\delta \sigma_{Zh}| \leq 0.5\%$

- **$h\gamma\gamma$ decay**: $NP$ contribution to the decay rate
  \[
  \delta R_{h\gamma\gamma} = \frac{\Gamma_{NP+SM} - \Gamma_{SM}}{\Gamma_{SM}^{h\rightarrow\gamma\gamma}}
  \]

  - Future accuracy of $h\gamma\gamma$ decay rate at FCC-hh $\sim 1\% \Rightarrow NP$ to $|\delta R_{h\gamma\gamma}| \leq 1\%$
Complex Triplet

- Scalar masses:
  \[ M_{H^\pm \pm}^2 = M_\Delta^2 - \frac{\lambda_5 v^2}{2}, \quad M_{H^\pm}^2 = M_\Delta^2 - \frac{\lambda_5 v^2}{4}, \quad M_H^2 = M_A^2 = M_\Delta^2 \]

- Parameter dependence: \( \{M_\Delta, \lambda_4, \lambda_5\} \)
Summary on Complementary Results

- Reason: mass splitting depends on $\lambda_5$ solely; in $Z\ell h$ self energy $\hat{\Sigma}_{T}^{WW}(s)$ dominates as scalar mass increases; in $h\gamma\gamma$ minimization of $\delta R_{h\gamma\gamma}$ results in prominent dependence on $\lambda_4$

- $Z\ell h$ and $h\gamma\gamma$ could be used to best determine the parameter $\lambda_4, \lambda_5$ in Complex Triplet Model
Real Triplet

- Parameters in both $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$: $\{M_\Sigma, \lambda_3\}$
  
  \[
  (M_{\Sigma\pm} = M_{\Sigma 0} = M_\Sigma)
  \]
Inert Doublet

- Inert scalar masses: \( \lambda_{L,A} = \lambda_3 + \lambda_4 \pm \lambda_5 \)
  \( M_{H\pm}^2 = \mu_2^2 + \frac{1}{2} \lambda_3 v_\phi^2, \quad M_{H0}^2 = \mu_2^2 + \frac{1}{2} \lambda_L v_\phi^2, \quad M_{A0}^2 = \mu_2^2 + \frac{1}{2} \lambda_A v_\phi^2 \)
- \( \delta\sigma_{Zh} \) depends on \( \{\mu_2, \lambda_3, \lambda_4, \lambda_5\} \); \( \delta R_{h\gamma\gamma} \) on \( \{\mu_2, \lambda_3\} \)

- In \((\lambda_3, \mu_2)\) plane fixing \( \lambda_4, \lambda_5 \)

- In \((\lambda_4, \lambda_5)\) plane setting \( \lambda_3 = 0 \) to minimize \( \delta R_{h\gamma\gamma} \left( g_{H+H-h} \propto \lambda_3 \right) \)
Quintuplet & Septuplet $n = 5, 7$

- Scalar masses:
  \[ M_{S_A}^2 = M_A^2 + \frac{1}{2} \lambda_1 v^2 + \frac{2}{\sqrt{n}} M_B^2 + \frac{1}{\sqrt{n}} \lambda_3 v^2, \quad M_{S_B}^2 = M_A^2 + \frac{1}{2} \lambda_1 v^2 - \frac{2}{\sqrt{n}} M_B^2 - \frac{1}{\sqrt{n}} \lambda_3 v^2 \]
- Parameter dependence: \( \{ M_{S_A}, M_{S_B}, \lambda_1, \lambda_3 \} \)
- Fix physical masses \( \{ M_{S_A}, M_{S_B} \} \) and plot in \( (\lambda_1, \lambda_3) \) plane

Similar for $n = 5$
Summary on Degenerate Results

- **Real Triplet:**
  - complete degeneracy between $Zh$ and $h\gamma\gamma$; it relies on the Higgs diphoton process to better determine the parameters

- **Inert Doublet, Quintuplet & Septuplet:**
  - partial degeneracy between $Zh$ and $h\gamma\gamma$ depending on the choice of the parameter space and variation of the fixed input parameters; it helps to restrict the parameters to some extend with the combination of the two processes studied
Conclusion

- $e^+e^- \rightarrow Zh$ at lepton collider at 240GeV gives abundance of Higgs events ($\sim 1$ million) and unprecedented precision ($\sim 0.5\%$) to study the nature of this neutral scalar.

- Several models with extended scalar sector were studied through $e^+e^- \rightarrow Zh$ at NLO compared to the Higgs diphoton with new scalar loop contribution:
  - Sole constraints by $h\gamma\gamma$: Real Triplet
  - Moderate constraints by both $Zh$ and $h\gamma\gamma$: Inert Doublet, High dim multiplet ($n = 5, 7$)
  - Strong constraints by both $Zh$ and $h\gamma\gamma$: Complex Triplet
Inert Doublet

- Scalar potential involving SM Higgs $H$ and Inert Doublet $\Phi_2$

$$V(H, \Phi_2) = \mu_1^2 H^\dagger H + \mu_2^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

$$+ \lambda_3 (H^\dagger H) (\Phi_2^\dagger \Phi_2) + \lambda_4 (H^\dagger \Phi_2) (\Phi_2^\dagger H)$$

$$+ \left[ \frac{\lambda_5}{2} (H^\dagger \Phi_2)^2 + \text{h.c.} \right]$$

- Scalar DM studies with radiative corrections


S. Banerje and N. Chakrabarty, JHEP 05 (2019) 150
Real Triplet

- Scalar potential:
  \[
  V(H, \Phi_{3,R}) = \mu_1^2 H^\dagger H + \frac{\mu_2^2}{2} \Phi_{3,R}^\dagger \Phi_{3,R} + \lambda_1 \left( H^\dagger H \right)^2 \\
  + \frac{\lambda_2}{4} \left( \Phi_{3,R}^\dagger \Phi_{3,R} \right)^2 + \frac{\lambda_3}{2} \left( H^\dagger H \right) \left( \Phi_{3,R}^\dagger \Phi_{3,R} \right)
  \]

- DM studies, direct detection

- Precision measurement with Higgs triplet
Complex Triplet

- Complex triplet $\Delta$: $2 \times 2$ complex matrix
- Kinetic term:
  \[ \text{Tr} \left[ (D_\mu \Delta)^\dagger (D^\mu \Delta) \right], \quad D_\mu \Delta = \partial_\mu \Delta + i g_1 B_\mu \Delta + i g_2 \left[ \frac{\tau^a}{2} W^a_{\mu}, \Delta \right] \]
- Scalar potential:
  \[
  V (H, \Delta) = \mu_1^2 H^\dagger H + \mu_2^2 \text{Tr} (\Delta^\dagger \Delta) + \lambda_1 (H^\dagger H)^2 + \lambda_2 [\text{Tr} (\Delta^\dagger \Delta)]^2 \\
  + \lambda_3 \text{Tr} [\Delta^\dagger \Delta \Delta^\dagger \Delta] + \lambda_4 (H^\dagger H) \text{Tr} (\Delta^\dagger \Delta) + \lambda_5 H^\dagger \Delta \Delta^\dagger H
  \]
- Neutrino masses via Type-II seesaw mechanism
Quintuplet and Septuplet

- Scalar potential: \( n = 5, 7 \)

\[
V (H, \Phi_n) = \mu_1^2 H^\dagger H + M_A^2 (\Phi_n^\dagger \Phi_n) + [M_B^2 (\Phi_n \Phi_n)_0 + \text{h.c.}] + \lambda (H^\dagger H)^2 \\
+ \lambda_1 (H^\dagger H) (\Phi_n^\dagger \Phi_n) + \lambda_2 [(\bar{H}H)_1 (\bar{\Phi}_n \Phi_n)_1] \\
+ [\lambda_3 (\bar{H}H)_0 (\Phi_n \Phi_n)_0 + \text{h.c.}]
\]

- \( \lambda_2 = 0 \Rightarrow \text{two real multiplets: } S_A, S_B, (j = \frac{n-1}{2}) \)

\[
(\bar{H}H)_0 = -\frac{1}{\sqrt{2}} H^\dagger H, \quad (\Phi_n \Phi_n)_0 = \sum_{m=-j}^{j} C_{j,m;j,-m}^{0,0} \phi_{j,m} \phi_{j,-m}
\]

- Scalar Electroweak Multiplet Dark Matter

W. Chao, G. Ding, X. He and M. Ramsey-Musolf, JHEP 08 (2019) 058