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

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May 5, 2020

PHENO 2020

4 – 6 May 2020 @ University of Pittsburgh

Virual Meeting due to COVID 19 Pandemic

In collaboration with

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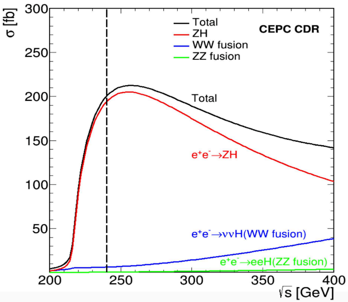
Outline

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 ~ 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]

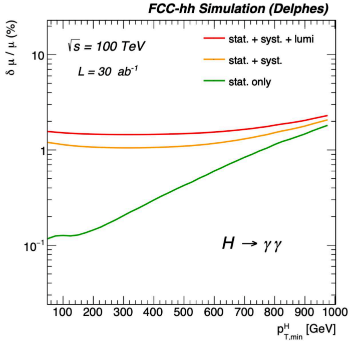
- Extraction of the scalar potential needs scalar-induced loop contributions to well measured processes, e.g., Zh production at future lepton colliders

Property	Estimated Precision
m_H	5.9 MeV
Γ_H	3.1%
$\sigma(ZH)$	0.5%
$\sigma(\nu\bar{\nu}H)$	3.2%

CEPC Conceptual Design Report, arXiv:1811.10545 [hep-ex]

Search for New Physics through Extended Scalar Sector

- Complementary contraints 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 $\sim 1\%$.



L. Borgonovi *et al*, CERN-ACC-2018-0045

Scalar Multiplet Models

- Same gauge group as the SM: $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y$
- $\mathcal{Z}_2$ 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: $\mathbf{\Phi}_n$; SM Higgs doublet: $\mathbf{H}$

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

$$D_\mu = \partial_\mu + i g_1 \frac{Y}{2} B_\mu + i g_2 W_\mu^a T^a$$

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: $n = 3,\ Y = 2$

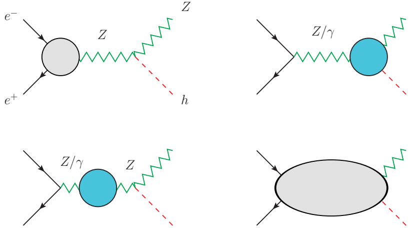
  (1–3) $\Rightarrow$ Dark Matter Studies

  (4) $\Longrightarrow$ Type-II seesaw neutrino studies

- Study goal: constraints to Higgs portal parameters via Zh NLO
  - Complex Triplet: (λ_4, λ_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: $e^{-}(p_1) + e^{+}(p_2) \to Z(k_1) + h(k_2)$
- 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:

$$i\mathbf{M}^{1-\text{loop}}_{e^+e^-\to Zh} = i\mathbf{M}^{\text{tree}}_{e^+e^-\to Zh} + i\mathbf{M}^{\text{self}}_{e^+e^-\to Zh} + i\mathbf{M}^{\text{vert}}_{e^+e^-\to Zh}$$

NLO Contriubtion from the Extended Scalar Sector

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

$$i\mathbf{M}^{1-\text{loop}}_{e^+e^-\to Zh} = -\,i\frac{\hat{e}^2\hat{M}_Z}{\hat{s}\hat{c}}\hat{\rho}_{NC}\left(s\right)\bar{v}\left(p_2\right)\gamma^\mu\left(g_v^{eff} - g_a^{eff}\gamma_5\right)u\left(p_1\right)\epsilon_\mu\left(k_1\right) + i\mathbf{M}^{\text{vert}}_{Z^*\to Zh} + i\mathbf{M}^{\text{vert}}_{\gamma^*\to Zh}$$

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

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

$$g_v^{eff} = \frac{I^3_{W,e} - 2\hat{\kappa}\left(s\right)\hat{s}^2 Q_e}{2\hat{s}\hat{c}} \qquad \hat{\kappa}\left(s\right) = 1 - \frac{\hat{c}}{\hat{s}}\frac{\hat{\Sigma}_T^{\gamma Z}\left(s\right)}{s}$$

Scalar Multiplet Contributions to Higgs Diphoton Decay

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

$$\Gamma^{\mathcal{NP}+\text{SM}}_{h\to\gamma\gamma} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 g_{hff} A^h_{1/2}(\tau_f) + g_{hWW} A^h_f(\tau_W) - \sum_s \frac{M_W}{g_2} g^2_{ss\gamma} g_{ssh} A^h_0(\tau_s) \right|^2$$

- Loop functions $A^h_{1/2}$, A^h_1, A^h_0 with $\tau_i = M_i^2/M_h^2$ $(i = f, W, s)$

$$A^h_{1/2}(\tau_i) = -2\tau_i\left[1 + (1-\tau_i)\mathcal{F}(\tau_i)\right]$$
$$A^h_1(\tau_i) = 2 + 3\tau_i + 3\tau_i(2-\tau_i)\mathcal{F}(\tau_i)$$
$$A^h_0(\tau_i) = -\tau_i\left[1 - \tau_i\mathcal{F}(\tau_i)\right]$$

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

Observables

- Zh production: relative correction w.r.t. LO total cross section

$$\delta\sigma_{Zh} = \frac{\sigma_{\mathcal{NP}}^{1-\text{loop}}}{\sigma_{\text{SM}}^{\text{LO}}}$$

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

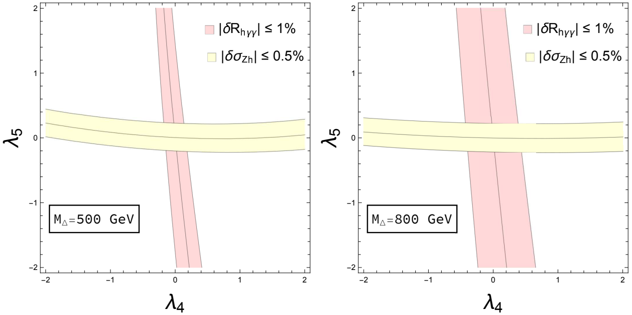
- $h\gamma\gamma$ decay: $\mathcal{NP}$ contribution to the decay rate

$$\delta R_{h\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}^{\mathcal{NP}+\text{SM}} - \Gamma_{h\to\gamma\gamma}^{\text{SM}}}{\Gamma_{h\to\gamma\gamma}^{\text{SM}}}$$

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

Complex Triplet

- scalar masses:
  $M^2_{H^{\pm\pm}} = M^2_\Delta - \frac{\lambda_5 v_\phi^2}{2},\ M^2_{H^\pm} = M^2_\Delta - \frac{\lambda_5 v_\phi^2}{4},\ M^2_H = M^2_A = M^2_\Delta$
- Parameter dependence: $\{M_\Delta, \lambda_4, \lambda_5\}$



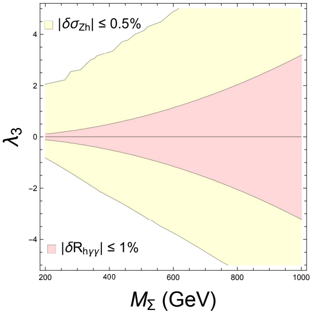
Summary on Complementary Results

- Reason: mass splitting depends on λ_5 solely; in Zh self energy $\hat{\Sigma}_T^{WW}(s)$ dominates as scalar mass increases; in $h\gamma\gamma$ minimization of $\delta R_{h\gamma\gamma}$ resluts in prominent dependence on λ_4

- Zh and $h\gamma\gamma$ could be used to best determine the parameter λ_4, λ_5 in Complex Triplet Model

Real Triplet

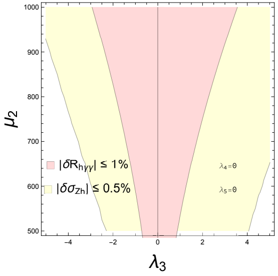
- Parameters in both $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$: $\{M_\Sigma, \lambda_3\}$ $\left(M_{\Sigma_\pm} = M_{\Sigma_0} = M_\Sigma\right)$



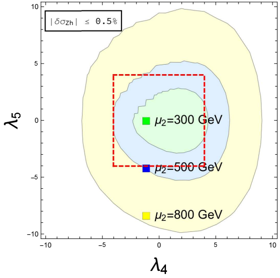
Inert Doublet

- Inert scalar masses: $\lambda_{L,A} = \lambda_3 + \lambda_4 \pm \lambda_5$
  $M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v_\phi^2,\ M_{H^0}^2 = \mu_2^2 + \frac{1}{2}\lambda_L v_\phi^2,\ M_{A^0}^2 = \mu_2^2 + \frac{1}{2}\lambda_A v_\phi^2$
- $\delta\sigma_{Zh}$ depends on $\{\mu_2,\ \lambda_3,\ \lambda_4,\ \lambda_5\}$; $\delta R_{h\gamma\gamma}$ on $\{\mu_2, \lambda_3\}$

- In (λ_3, μ_2) plane fixing λ_4, λ_5



- In (λ_4, λ_5) plane setting $\lambda_3 = 0$ to minize $\delta R_{h\gamma\gamma}$ $(g_{H^+H^-h} \propto \lambda_3)$



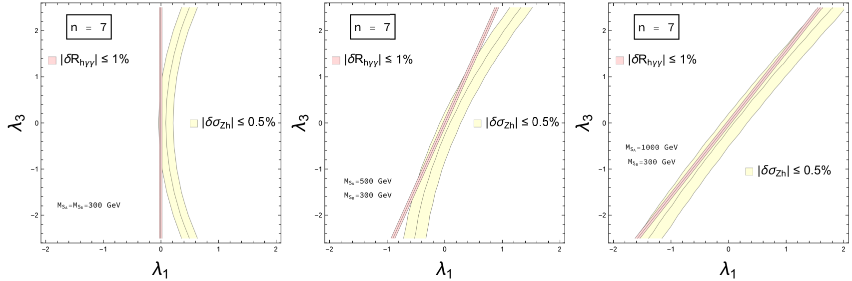
Quintuplet & Septuplet $n = 5, 7$

- Scalar masses:

$$M_{S_A}^2 = M_A^2 + \frac{1}{2}\lambda_1 v^2 + \frac{2}{\sqrt{n}} M_B^2 + \frac{1}{\sqrt{n}}\lambda_3 v^2,\ M_{S_B}^2 = M_A^2 + \frac{1}{2}\lambda_1 v^2 - \frac{2}{\sqrt{n}} M_B^2 - \frac{1}{\sqrt{n}}\lambda_3 v^2$$

- Parameter dependence: $\{M_{S_A}, M_{S_B}, \lambda_1, \lambda_3\}$

▶ Fix physical masses $\{M_{S_A}, M_{S_B}\}$ and plot in (λ_1, λ_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

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

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

Inert Doublet

- Scalar potential involving SM Higgs $\mathbf{H}$ and Inert Doublet $\mathbf{\Phi}_2$

$$
\begin{aligned}
V(\mathbf{H}, \mathbf{\Phi}_2) = \mu_1^2\, \mathbf{H}^\dagger \mathbf{H} + \mu_2^2\, \mathbf{\Phi}_2^\dagger \mathbf{\Phi}_2 + \lambda_1 \left(\mathbf{H}^\dagger \mathbf{H}\right)^2 + \lambda_2 \left(\mathbf{\Phi}_2^\dagger \mathbf{\Phi}_2\right)^2 \\
+ \lambda_3 \left(\mathbf{H}^\dagger \mathbf{H}\right)\left(\mathbf{\Phi}_2^\dagger \mathbf{\Phi}_2\right) + \lambda_4 \left(\mathbf{H}^\dagger \mathbf{\Phi}_2\right)\left(\mathbf{\Phi}_2^\dagger \mathbf{H}\right) \\
+ \left[\frac{\lambda_5}{2} \left(\mathbf{H}^\dagger \mathbf{\Phi}_2\right)^2 + \text{h.c.}\right]
\end{aligned}
$$

- Scalar DM studies with radiative corrections

S. Kanemura, M. Kikuchi and K. Sakurai, Phys. Rev. D 94 (2016) 11, 115011

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

Real Triplet

- Scalar potential:

$$V\left(\mathbf{H},\mathbf{\Phi}_{3,R}\right)=\mu_1^2\ \mathbf{H}^\dagger\mathbf{H}+\frac{\mu_2^2}{2}\ \mathbf{\Phi}_{3,R}^\dagger\mathbf{\Phi}_{3,R}+\lambda_1\left(\mathbf{H}^\dagger\mathbf{H}\right)^2+\frac{\lambda_2}{4}\left(\mathbf{\Phi}_{3,R}^\dagger\mathbf{\Phi}_{3,R}\right)^2+\frac{\lambda_3}{2}\left(\mathbf{H}^\dagger\mathbf{H}\right)\left(\mathbf{\Phi}_{3,R}^\dagger\mathbf{\Phi}_{3,R}\right)$$

- DM studies, direct detection

  P. F. Perez, H. H. Patel, M. J. Ramsey-Musolf and K.Wang, Phys. Rev. D, 79:055024, 2009
  C.-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, and M. J. Ramsey-Musolf, arXiv:2003.07867 [hep-ph]

- Precision measurement with Higgs triplet

  T. Blank and W. Hollik, Nucl. Phys. B, 514:113–134, 1998
  M.-C. Chen, S. Dawson, and C.B. Jackson, Phys. Rev. D, 78:093001, 2008

Complex Triplet

- Complex triplet Δ: 2×2 complex matrix
- Kinetic term:
  $\mathrm{Tr}\left[(D_\mu\Delta)^\dagger(D^\mu\Delta)\right]$, $D_\mu\Delta = \partial_\mu\Delta + ig_1 B_\mu\Delta + ig_2\left[\frac{\tau^a}{2}W_\mu^a, \Delta\right]$
- Scalar potential:

$$V(\mathbf{H},\Delta) = \mu_1^2\mathbf{H}^\dagger\mathbf{H} + \mu_2^2\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \lambda_1\left(\mathbf{H}^\dagger\mathbf{H}\right)^2 + \lambda_2\left[\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + \lambda_3\mathrm{Tr}\left[\Delta^\dagger\Delta\Delta^\dagger\Delta\right] + \lambda_4\left(\mathbf{H}^\dagger\mathbf{H}\right)\mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \lambda_5\mathbf{H}^\dagger\Delta\Delta^\dagger\mathbf{H}$$

- Neutrino masses via Type-II seesaw mechanism
  Y. Du, A. Dunbrack, M. J. Ramsey-Musolf and J. Yu, JHEP 01 (2019) 101

Quintuplet and Septuplet

- Scalar potential: $n = 5, 7$

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

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

$$\left(\bar{\mathbf{H}}\mathbf{H}\right)_0 = -\frac{1}{\sqrt{2}} \mathbf{H}^\dagger \mathbf{H}, \quad \left(\mathbf{\Phi}_n \mathbf{\Phi}_n\right)_0 = \sum_{m=-j}^{j} \underbrace{C^{0,0}_{j,m;j,-m}}_{\text{CG Coeff}} \phi_{j,m}\phi_{j,-m}$$

- Scalar Electroweak Multiplet Dark Matter

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