Probing Extended Scalar Sectors with Precision $e^+e^- \to Zh$ and Higgs Diphoton Studies

Jia Zhou

Amherst Center for Fundamental Interactions, Department of Physics,
University of Massachussetts Amherst, MA 01003, USA.

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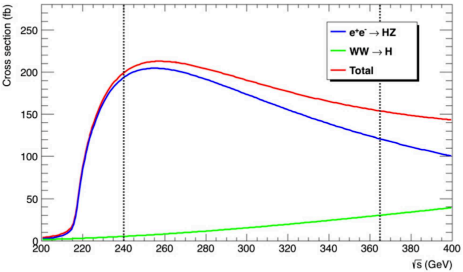
Based on arXiv: 2104.10709
Michael Ramsey-Mosulf, Jiang-Hao Yu & J.Z.

Outline

Zh Production at Future Lepton Colliders

- Lepton Colliders at 240 – 250 GeV as a Higgs factory: FCC-ee, CEPC, ILC; e.g., at FCC-ee it will produce ~ 1 million events with integrated luminosity of at least $\mathcal{L} = 5\ \text{ab}^{-1}$ at 240 GeV.

– 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: FCC-ee CDR Vol 2, Eur.Phys.J.Special Topics 228, 261–623(2019)

Search for New Physics through Extended Scalar Sector

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

- In $Zh\,(h \to \gamma\gamma)$, the new scalars modify the Higgs couplings to Z/γ pair via radiative corrections with new scalars running in loops. Once scalar mass spectra are determined (through direct detection at HL-LHC), one could extract info on the scalar Higgs couplings by precision measurement for Zh and Higgs diphoton decay.
  - 1-σ statisitical uncertainties for $\sigma\,(Zh)$ and $h \to \gamma\gamma$ at e^+e^- colliders

Measurement	CEPC (240 GeV, 5.6 ab^{-1})	FCC-ee (240 GeV, 5 ab^{-1})	ILC (250 GeV, 2 ab^{-1})
$\sigma\,(Zh)$	0.50%	0.50%	0.71%
$\sigma \times \mathrm{BR}\,(h \to \gamma\gamma)$	6.8%	9.0%	12%

Scalar Multiplet Models

- $\mathbf{\Phi}_n$ transfers under same gauge group as the SM: $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$

- Generic kinetic term

$$\mathcal{L}_{\text{kin}} = (D_\mu \mathbf{H})^\dagger (D^\mu \mathbf{H}) + (D_\mu \mathbf{\Phi}_n)^\dagger (D^\mu \mathbf{\Phi}_n), \quad D_\mu = \partial_\mu + i g_1 \frac{Y}{2} B_\mu + i g_2 W_\mu^a T^a$$

- Scalar potential is representation dependent
  - Imposition of $\mathcal{Z}_2$ symmetry $\Rightarrow$ stable neutral component as dark matter (DM) candidate
  - Higgs portal term $|\mathbf{\Phi}|^2 |\mathbf{H}|^2$ could allow for a first order EW phase transition (EWPT)

★ E.g., real triplet

C.-W.Chiang *et. al.*, JHEP 01 (2021) 198

1. DM direct search: disappearing charge tracks search $\Sigma_\pm \to \Sigma_0 \pi_\pm$
2. Higgs portal term $\frac{\lambda_3}{2} (\mathbf{H}^\dagger \mathbf{H}) \left(\mathbf{\Phi}_3^\dagger \mathbf{\Phi}_3 \right) \Rightarrow \lambda_3$ plays a role in EWPT

L.Niemi, M.Ramsey-Musolf, T.V.Tenkanen and D.J.Weir, Phys.Rev.Lett.126, 171802 (2021)

Scalar Multiplet Models

- Studied models:
  1. Inert Doublet: $n = 2,\ Y = 1$
  2. Real Triplet: $n = 3, Y = 0$
  3. Quintuplet & Septuplet: $n = 5, 7\ , Y = 0$

  (1–3) $\overset{\mathcal{Z}_2}{\Longrightarrow}$ Dark Matter Studies

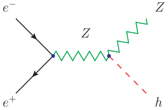
  4. Complex Triplet: $n = 3,\ Y = 2$ $\Longrightarrow$ Type-II seesaw neutrino studies

  – 1-3: zero VEV; 4: tiny VEV (omitted)

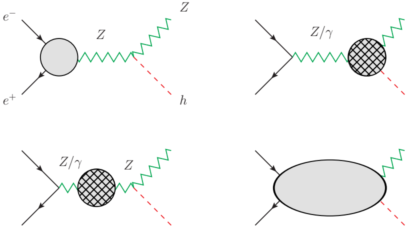
  $\Rightarrow$ new scalar loop contributions can be extracted from the SM one

NLO Contribution from the Extended Scalar Sector

- Zh LO process: $e^-(p_1) + e^+(p_2) \to Z(k_1) + h(k_2)$



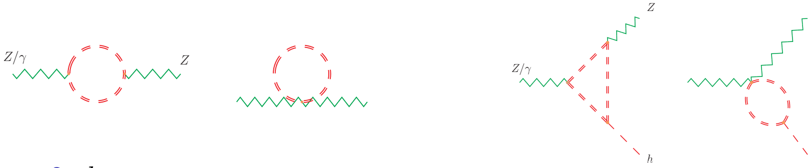
- One-loop corrections:



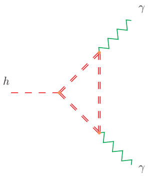
Hatched blobs: possible corrections induced by scalar-loop, assuming no interactions to the Fermion Fields (Yukawa interaction suppressed by $\mathcal{O}\left(M_f/M_W\right)$).

NLO Contribution from the Extended Scalar Sector

- New scalar 1-loop corrections:
  1. Zh



  2. $h \to \gamma\gamma$



- Charged scalar in loop

Observables

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

$$\delta\sigma_{Zh} = \frac{\sigma^{1-\text{loop}}_{\text{BSM}}}{\sigma^{\text{LO}}_{\text{SM}}}$$

- $h \to \gamma\gamma$ decay: scalar-induced loop contribution to the decay rate

$$\delta R_{h\gamma\gamma} = \frac{\Gamma^{\text{BSM+SM}}_{h\to\gamma\gamma} - \Gamma^{\text{SM}}_{h\to\gamma\gamma}}{\Gamma^{\text{SM}}_{h\to\gamma\gamma}}$$

- Estimated precision for $\sigma(Zh)$ and $h \to \gamma\gamma$ at future lepton colliders

Measurement	CEPC (240 GeV, 5.6 ab^{-1})	FCC-ee (240 GeV, 5 ab^{-1})	ILC (250 GeV, 2 ab^{-1})
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★ $|\delta\sigma_{Zh}| \leq 0.5\%$, $|\delta R_{h\gamma\gamma}| \leq 6.8\%$

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⋆ $|\delta\sigma_{Zh}| \le 0.5\%,\ \ |\delta R_{h\gamma\gamma}| \le 6.8\%$

Complex Triplet

- Scalar potential with a 2×2 complex triplet Δ:

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

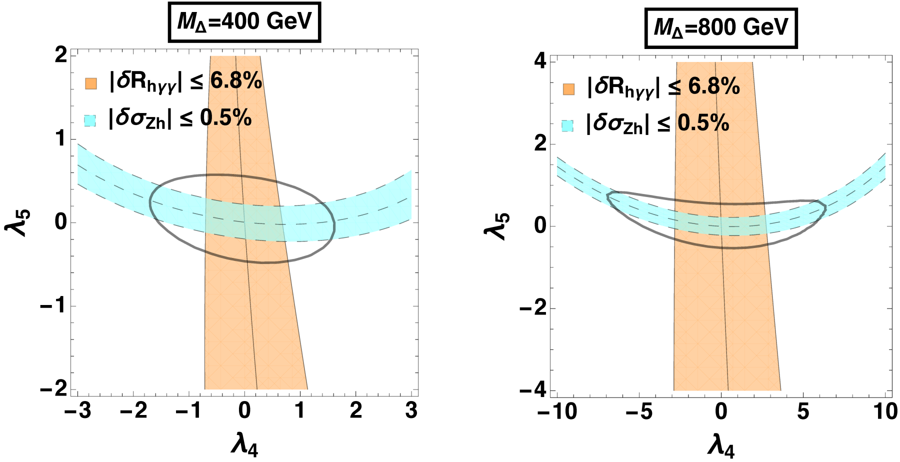
- Scalar components in mass eigenstates:
  - Doubly charged: $H^{\pm\pm}$, $M^2_{H^{\pm\pm}} = M^2_\Delta - \frac{\lambda_5 v_\phi^2}{2}$
  - Singly charged: $H^{\pm}$, $M^2_{H^{\pm}} = M^2_\Delta - \frac{\lambda_5 v_\phi^2}{4}$
  - Neutral CP-even/odd: H/A, $M_H = M_A = M_\Delta$

- We have omitted v_Δ since $v_\Delta / v_\phi \ll 1$ [1].
- Therefore, the scalar triplet can be deemed as unmixed with the SM Higgs doublet $\Rightarrow$ NLO scalar corrections are extracted from the SM one.

[1] $v_\Delta \lesssim 3$ GeV by contraints on ρ parameter.

Complex Triplet

- Parameter dependence: $\{M_\Delta, \lambda_4, \lambda_5\}$
  - For each fixed M_Δ



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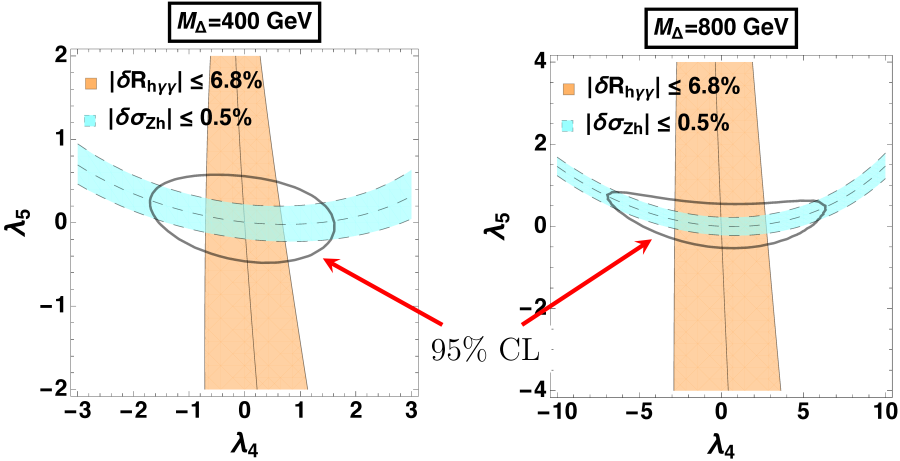


Complex Triplet – Complementarity in Parameter Space

- Complemenatarity between $\sigma(Zh)$ & $h \to \gamma\gamma$ decay rate realized in two aspects:

1. The scalar triplet contribution to $\sigma(Zh)$ is dominated by the WW self energy via differently charged scalar in loops which is susceptible to the variation of the mass splitting parameter (λ_5), compared to other types of corrections.

2. The scalar triplet contribution to $h \to \gamma\gamma$ decay rate involves triple Higgs couplings with two charged Higgs that have a stronger dependence on the parameter λ_4 than on the other couplings $(g_{H^{++}H^{--}h} = -\lambda_4 v_\phi,\ g_{H^+H^-h} = -(\lambda_4 + \lambda_5/2)v_\phi)$, making it more susceptible to variation in λ_4.

Complex Triplet

- Complex triplet $\subset$ type-II seesaw model – connection to neutrinos?
  - Neutrinos acquire masses in type-II seesaw model through Yukawa interaction after EWSB:

$$\mathcal{L}_{\rm Yuk} = h_{ij}\overline{L^{Ci}}i\tau_2\Delta L^j + \text{h.c.},$$

  - Neutrino mass matrix:

$$m_{\nu,ij} = \sqrt{2}h_{ij}v_\Delta,$$

h_{ij} – neutrino Yukawa coupling & v_Δ – triplet VEV.

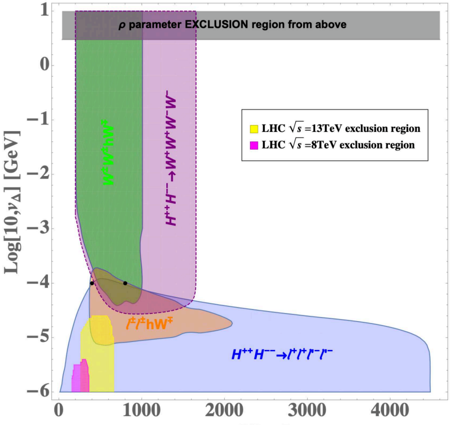
  - Constrained by the ρ parameter: $v_\Delta \lesssim 3$ GeV
  - Combination of Planck 2018 and BAO data sets: $\sum m_\nu < 0.12$ eV

Planck Collaboration 2020; Particle Data Group Collaboration 2020

Complex Triplet

Y.Du, A.Dunbrack, M.J.Ramsey-Musolf and J.-H.Yu, JHEP 01 (2019) 101

- Interplay of h_{ij} and v_Δ affects the sensitivity of collider probes of the complex triplet model
  - Discovery channels at a 100 TeV pp machine



- Decay modes & parameter space
  - $H^{++}H^{--}$:
    Br $\left(H^{\pm\pm} \to l^\pm l^\pm / W^\pm W^\pm\right)$
    $\Rightarrow$ $(M_\Delta, \lambda_5, v_\Delta)$
  - $H^{\pm\pm}H^{\mp}$:
    Br $\left(H^{\pm\pm} \to l^\pm l^\pm / W^\pm W^\pm\right)$
    Br $\left(H^{\pm} \to hW^\pm\right)$
    $\Rightarrow$ $(M_\Delta, \lambda_4, \lambda_5, v_\Delta)$

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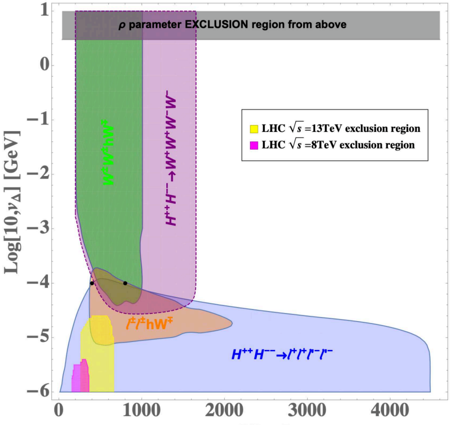

- In our study, one could further delineate the discovery regions in (M_Δ, v_Δ) for given values of neutrino masses
  - From the plots:

$$M_\Delta = 400(800)\ \text{GeV},$$
$$|\lambda_4| \lesssim 1(3), |\lambda_5| \lesssim 0.2$$

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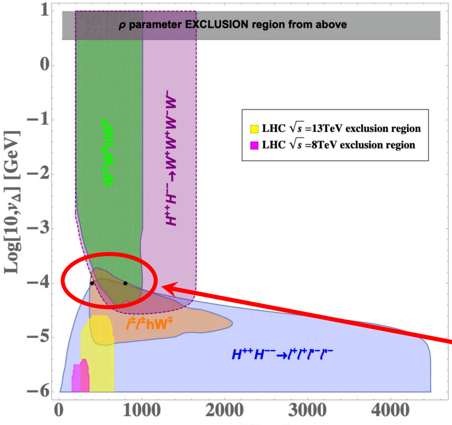

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  - From the plots:

$$M_\Delta = 400(800)\ \text{GeV},$$
$$|\lambda_4| \lesssim 1(3), |\lambda_5| \lesssim 0.2$$

- Two benchmark points:

$$\lambda_4 = 0, \lambda_5 = -0.1$$

Inert Doublet

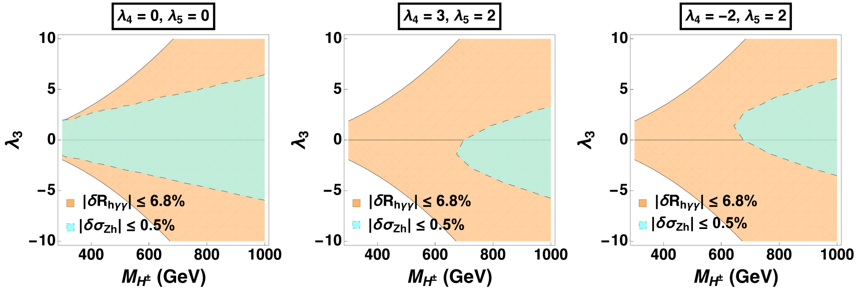
- Scalar potential involving SM Higgs and inert doublet $\mathbf{H},\mathbf{\Phi}_2$

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

- Scalar components and masses:
  - Charged: $H^\pm,\ M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v_\phi^2$
  - Neutral: $H^0, A_0,\ M_{H^0/A^0}^2 = \mu_2^2 + \frac{1}{2}\lambda_{L,A} v_\phi^2$ with $\lambda_{L,A} = (\lambda_3 + \lambda_4 \pm \lambda_5)$.
- Z_2 symmetry $\Rightarrow$ lightest neutral component coulde be a WIMP dark matter candidate
- Parameter dependency in loop contribution:
  - $\delta\sigma_{Zh}$: $\left\{\mu_2^2, \lambda_3, \lambda_4, \lambda_5\right\}$
  - $\delta R_{h\gamma\gamma}$: $\left\{\mu_2^2, \lambda_3\right\}$ – only charged component couples to photon

Inert Doublet

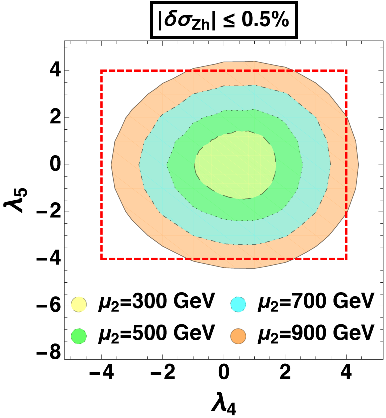
- $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$ in the same plane (fixing λ_4, λ_5)



- Positive/negative λ_4 shifts $\delta\sigma_{Zh}$ down/upward
- Non-zero λ_5 gives lower bound of $M_{H^\pm}$ vs $\lambda_5 = 0$ (contour of $\delta\sigma_{Zh}$ is not affected by the sign of λ_5)

Inert Doublet

- Minimize $\delta R_{h\to\gamma\gamma}$ by setting $\lambda_3 = 0$ since $g_{H^+H^-h} \propto \lambda_3$ – in the (λ_4, λ_5) plane
  - $M_{H^\pm} = \mu_2$ for vanishing λ_3



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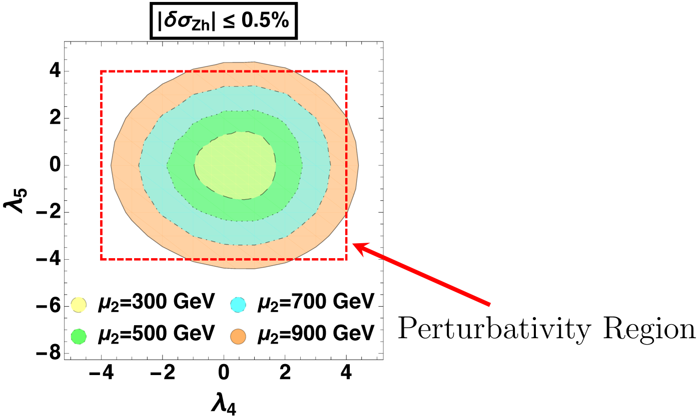


Inert Doublet

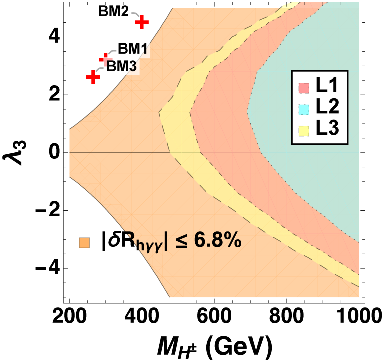
- Interplay between DM pheno and EW phase transition (EWPT) has been studied in a variety of spectra, and it shows
  - a strongly first order EWPT (SFOEWPT) requires a large mass splitting between the DM candidate particle and the other extended scalars;
  - when saturating the DM abundance, the Higgs funnel regime ($M_{H^0} \sim M_h/2$) is the only region of parameter space to provide a SFOEWPT.
- Compare the parameter space in our study with the region the SFOEWPT ocucurs
  - Three benchmark points in three benchmark models (BMs):

	M_{H^0}	M_{A^0}	$M_{H^\pm}$	λ_3	λ_4	λ_5
BM1	66	300	300	3.3	-1.7	-1.5
BM2	200	400	400	4.6	-2.3	-2.0
BM3	5	265	265	2.7	-1.4	-1.2

N. Blinov, S. Profumo and T. Stefaniak, CAP 07 (2015) 028

Inert Doublet

- Constraints on parameter space for $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$ vs benchmark points for SFOEWPT in the $(\lambda_3, M_{H^\pm})$ plane



- L1, L2, L3
  - contours for $|\delta\sigma_{Zh}| < 0.5\%$ with $\lambda_{4,5}$ in accordance with BM1, BM2, BM3

- with projected precision at the future lepton colliders it may further exclude some region for SFOEWPT permitted phenomenologically elsewhere.

Real Triplet

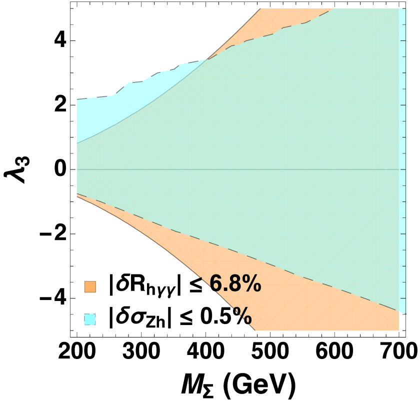
- Scalar potential:

$$V\left(\mathbf{H},\mathbf{\Phi}_3\right)=\mu_1^2\ \mathbf{H}^\dagger\mathbf{H}+\frac{\mu_2^2}{2}\ \mathbf{\Phi}_3^\dagger\mathbf{\Phi}_3+\lambda_1\left(\mathbf{H}^\dagger\mathbf{H}\right)^2+\frac{\lambda_2}{4}\left(\mathbf{\Phi}_3^\dagger\mathbf{\Phi}_3\right)^2+\frac{\lambda_3}{2}\left(\mathbf{H}^\dagger\mathbf{H}\right)\left(\mathbf{\Phi}_3^\dagger\mathbf{\Phi}_3\right)$$

- Scalar components and masses
  - Charged and neutral: $\Sigma_\pm,\ \Sigma_0,\ M_{\Sigma_\pm}=M_{\Sigma_0}=M_\Sigma$
  - Mass splitting between charged and neutral components due to loop corrections is omitted ($\Delta M\simeq 166$ MeV) for $M_\Sigma\gg M_W$
- Neutral component could be a potential WIMP dark matter candidate
  - Direct search: e.g., disappearing charge tracks search $\Sigma_\pm\to\Sigma_0\pi_\pm$
- The Higgs portal coupling λ_3 may play a role in EWPT
  - Recent study is done using dimensional reduction - a three dimensional effective field theory (DR3EFT) that allows non-perturbative lattice simulation.

Real Triplet

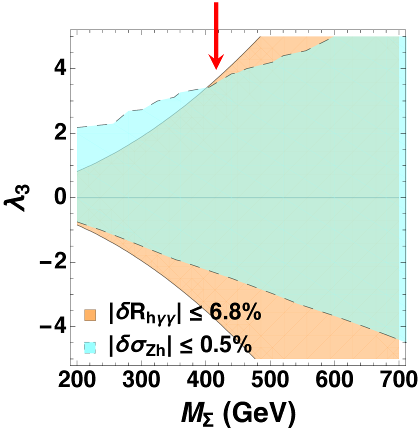
- Parameters in both $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$: $\{M_\Sigma, \lambda_3\}$



Real Triplet

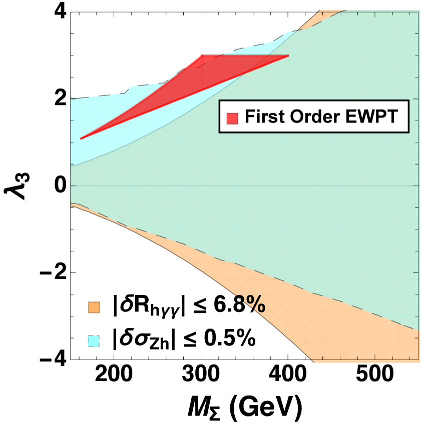
- Parameters in both $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$: $\{M_\Sigma, \lambda_3\}$

$M_\Sigma \sim 400$ GeV



Real Triplet

- Comparison with the first order EWPT region [2]

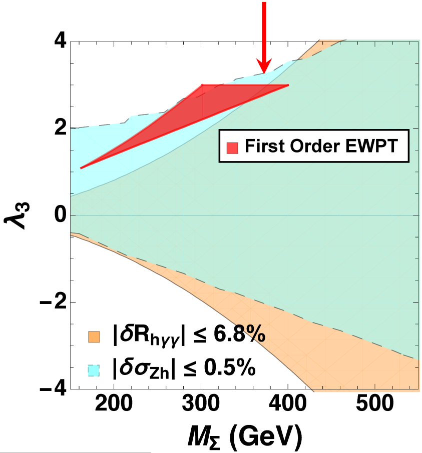


[2] L.Niemi, M.Ramsey-Musolf, T.V.Tenkanen and D.J.Weir, Phys.Rev.Lett.126, 171802 (2021)

Real Triplet

- Comparison with the first order EWPT region [2]

$M_\Sigma \sim 350$ GeV



[2] L.Niemi, M.Ramsey-Musolf, T.V.Tenkanen and D.J.Weir, Phys.Rev.Lett.126, 171802 (2021).

Quintuplet & Septuplet $n = 5, 7$

- Scalar potential:

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

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

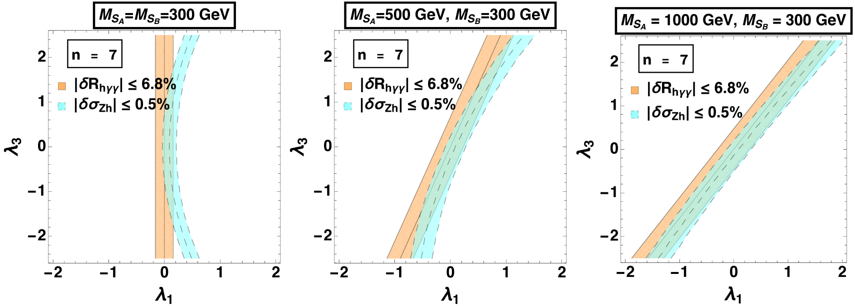
$$M_{S_A}^2 = M_A^2 + \frac{1}{2}\lambda_1 v^2 + \frac{2}{\sqrt{n}}M_B^2 + \frac{1}{\sqrt{n}}\lambda_3 v^2,\ M_{S_B}^2 = M_A^2 + \frac{1}{2}\lambda_1 v^2 - \frac{2}{\sqrt{n}}M_B^2 - \frac{1}{\sqrt{n}}\lambda_3 v^2$$

- High dimensional EW multiplets with $Y = 0 \Rightarrow$ neutral component a potential WIMP DM candidate (neutral component of S_A)

Quintuplet & Septuplet $n = 5, 7$

- 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

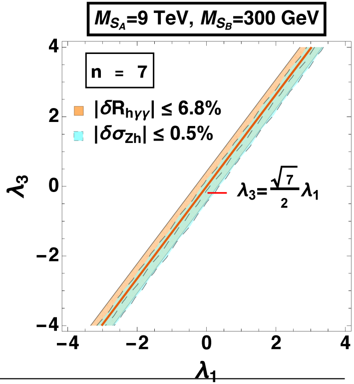


Degeneracy increases with $|M_{S_A} - M_{S_B}|$

▶ Similar for $n = 5$

Quintuplet & Septuplet $n = 5, 7$

- Connection to DM phenomenology
  - Effective coupling (e.g., n=7): $\lambda_{\rm eff} = \lambda_1 - 2/\sqrt{7}\lambda_3$ is rather small when saturating the observed relic density and evading the direct dectection limits by LUX, PandaX-II and XENONT1 [3].



If septuplet is the only DM, $M_{S_A} \sim 9$ TeV

▶ $\lambda_{\rm eff} \sim 0$

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

Conclusion

- We calculated 1-loop corrections to $e^+e^- \to Zh$ in the presence of an extended scalar sector (inert doublet, real/complex triplet, EW HD multiplets $n = 5, 7$).

- The BSM contribution can be computed separately from the SM EW corrections due to zero or tiny VEV for the neutral components, which makes the calculation simpler.

- Based on the numerical results:
  1. $\sigma(Zh)$ is sensitive to the mass splitting between different components of the multiplet, similar to the oblique T parameter.
     - no mass splitting (real triplet, quintuplet & septuplet): $\sigma(Zh)$ & $h \to \gamma\gamma$ are sensitive to similar regions of parameter space.
     - mass splitting (complex triplet): $\sigma(Zh)$ & $h \to \gamma\gamma$ measurements provide complementary parameter space probes.

Conclusion

- We calculated 1-loop corrections to $e^+e^- \to Zh$ in the presence of an extended scalar sector (inert doublet, real/complex triplet, EW HD multiplets $n = 5, 7$).

- The BSM contribution can be computed separately from the SM EW corrections due to zero or tiny VEV for the neutral components, which makes the calculation simpler.

- Based on the numerical results:
  1. $\sigma(Zh)$ is sensitive to the mass splitting between different components of the multiplet, similar to the oblique T parameter.
     - no mass splitting (real triplet, quintuplet & septuplet): $\sigma(Zh)$ & $h \to \gamma\gamma$ are sensitive to similar regions of parameter space.
     - mass splitting (complex triplet): $\sigma(Zh)$ & $h \to \gamma\gamma$ measurements provide complementary parameter space probes.

Conclusion

- Based on the numerical results:
    2. The scalar loop contributions depend on the new scalar masses, gauge couplings (fixed by gauge invariance), and extended scalar potential couplings. If the mass spectrum in the multiplet has been identified at a hadron collider, one could further extract info on the new scalar-Higgs couplings from the precision Higgs observables in our study.
        - It may further constrain the mass and interactions of some portion of the DM if the neutral components contribute to the DM relic density.

- Outlook: One may also perform the analysis for other versions of the extended scalar models which may obtain a non-zero VEV (e.g., 2HDM, singlet). ⇒ full 1-loop corrections (weak + QED) corrections are needed.

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Thank you!

NLO Contriubtion from the Extended Scalar Sector

- NLO amplitude in $\overline{\text{MS}}$ Renormalization Scheme ($\hat{}$ notation)

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

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

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

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

- One-loop corrections from the extended scalar sector:

$$
\frac{d\sigma^{1-\text{loop}}_{\text{BSM}}}{dt} = \frac{1}{16\pi s^2}\overline{\sum_{\text{spin}}}|\mathbf{M}|^2_{\text{corr}} = \frac{1}{16\pi s^2}\overline{\sum_{\text{spin}}}\left(\left|\mathbf{M}^{\text{NLO}}_{e^+e^-\to Zh}\right|^2 - \left|\mathbf{M}^{\text{LO}}_{e^+e^-\to Zh}\right|^2\right)
$$

NLO Contriubtion from the Extended Scalar Sector

- $h \to \gamma\gamma$ decay width including scalar-induced loop contribution

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

  - Loop functions [4]:

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

$$A^h_1(\tau_i) = 2 + 3\tau_i + 3\tau_i(2-\tau_i)\mathcal{F}(\tau_i)$$

$$A^h_0(\tau_i) = -\tau_i\left[1 - \tau_i \mathcal{F}(\tau_i)\right]$$

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

with $\tau_i = M_i^2/M_h^2$ $(i = f, W, s)$.

[4] A. Djouadi, Phys. Rept. 459 (2008) 1–241 [hep-ph/0503173]

Settings

- SM input parameters:

$$\alpha^{-1} = \left(\frac{e^2}{4\pi}\right)^{-1} = 137.036,$$
$$M_W = 80.385 \text{ GeV},\ M_Z = 91.1876 \text{ GeV},\ \Gamma_Z = 2.4952 \text{ GeV},\ M_h = 125.1 \text{ GeV}.$$

- At one-loop level in $\overline{\text{MS}}$:

$$\hat{M}_V^2 = M_V^2 + \text{Re}\hat{\Sigma}_T^{VV}\left(M_V^2\right),$$
$$\hat{c}^2 = 1 - \hat{s}^2 = \frac{\hat{M}_W^2}{\hat{M}_Z^2}, \quad \hat{e} = e\left(1 - \frac{1}{2}\delta\hat{Z}_{\gamma\gamma} - \frac{1}{2}\frac{\hat{s}}{\hat{c}}\delta\hat{Z}_{Z\gamma}\right).$$

- Constraints on quartic Higgs couplings by perturbativity:

$$\lambda_i(\mu) \lesssim \frac{\lambda_{\text{FP}}}{3}, \quad \mu \in [M_Z, \Lambda], \quad \lambda_{\text{FP}} = 12.1\ldots.$$

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Complex Triplet

Y.Du, A.Dunbrack, M.J.Ramsey-Musolf and J.-H.Yu, JHEP 01 (2019) 101

- Interplay of h_{ij} and v_Δ affects the sensitivity of collider probes of the complex triplet model
  - Dominant discovery channels at LHC and a 100 TeV pp machine:

$$H^{++}H^{--}: \mathrm{Br}\left(H^{\pm\pm} \to l^\pm l^\pm / W^\pm W^\pm\right) \Rightarrow \boxed{(M_\Delta, \lambda_5, v_\Delta)}$$

$$H^{\pm\pm}H^{\mp}: \mathrm{Br}\left(H^{\pm\pm} \to l^\pm l^\pm / W^\pm W^\pm\right),\ \mathrm{Br}\left(H^{\pm} \to hW^\pm\right) \Rightarrow (M_\Delta, \lambda_4, \lambda_5, v_\Delta)$$

- In our study, one could further delineate the discovery regions in (M_Δ, v_Δ) for given values of neutrino masses
  - From the plots:

$$M_\Delta = 400(800)\ \mathrm{GeV}, |\lambda_4| \lesssim 1(3), |\lambda_5| \lesssim 0.2$$

  - Two benchmark points from Ref:

M_Δ	M_Z	M_h	m_ν	v_Δ	λ_2	λ_3	λ_4	λ_5
400 & 800 GeV	91.1876 GeV	125 GeV	0.01 eV	10^{-4} GeV	0.2	0	0	-0.1