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

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Based on JHEP 10 (2021) 155 [arXiv:2104.10709]
Michael Ramsey-Musolf, Jiang-Hao Yu & J.Z.

Outline

Search for New Physics in Higgs Studies

- Future e^+e^- machines offer opportunities for unprecendented high precision Higgs studies.
  - Projected uncertainties in Higgs coupling g_{hZZ} in κ framework at future e^+e^- colliders compared to that at HL-LHC.

Collider	$CEPC_{240}$	FCC-ee_{240}	ILC_{250}	HL-LHC
Lumi (ab^{-1})	5.6	5	2	3
$\delta g_{hZZ}/g_{hZZ}$	0.25%	0.2%	0.35%	1.3%

$\Rightarrow$ discovery potential for BSM associated with Higgs boson

- Extended scalar sectors in Zh & $h \to \gamma\gamma$ channels
  - New scalars modify the Higgs couplings to Z/γ pair via radiative corrections with new scalars running in loops.
  - Extract info on scalar potential by precision measurement for Zh and Higgs diphoton decay.

EW Scalar Multiplet Models

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

- Studied 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: $\overset{\mathcal{Z}_2}{\Longrightarrow}$ Dark Matter Studies

4: $\Longrightarrow$ 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

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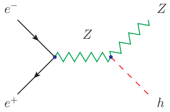
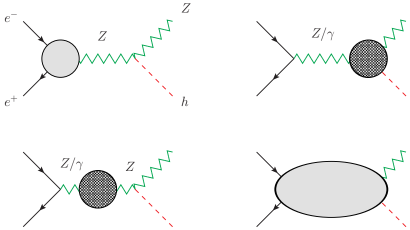
NLO Contribution from the Extended Scalar Sector

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



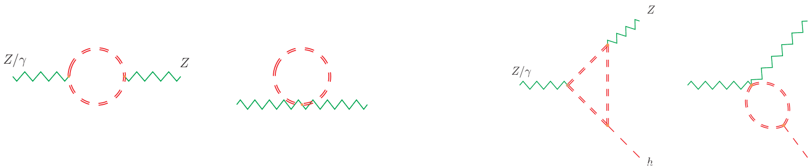
- One-loop corrections:



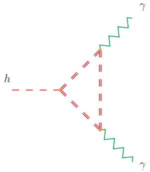
Hatched blobs: possible corrections induced by scalar-loop, assuming no interactions to the Fermion Fields (Yukawa interaction suppressed by $\mathcal{O}(M_f/M_W)$).

NLO Contribution from the Extended Scalar Sector

- New scalar 1-loop corrections:
  1. Zh



  2. $h \to \gamma\gamma$



- ▶ Charged scalar in loop

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}:

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

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

- 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

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

– Loop functions [1]:

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

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

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

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

Observables

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

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

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

$$\delta R_{h\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}^{\rm BSM+SM} - \Gamma_{h\to\gamma\gamma}^{\rm SM}}{\Gamma_{h\to\gamma\gamma}^{\rm SM}}$$

- 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})
$\sigma(Zh)$	0.50%	0.50%	0.71%
$\sigma \times \mathrm{BR}(h \to \gamma\gamma)$	6.8%	9.0%	12%

★ $|\delta\sigma_{Zh}| \leq 0.5\%$, $|\delta R_{h\gamma\gamma}| \leq 6.8\%$

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★ $|\delta\sigma_{Zh}| \leq 0.5\%, \quad |\delta R_{h\gamma\gamma}| \leq 6.8\%$

Complex Triplet

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

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

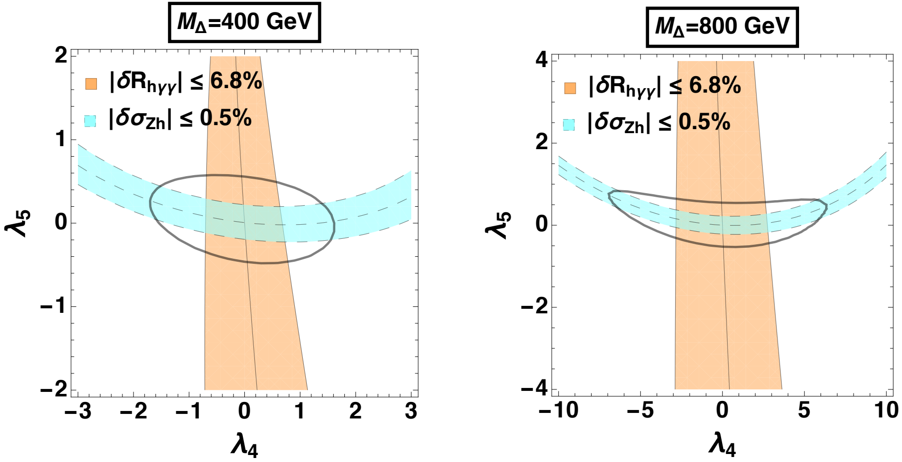
- Scalar components in mass eigenstates:
  - Doubly charged: $H^{\pm\pm}$, $M^2_{H^{\pm\pm}} = M^2_\Delta - \frac{\lambda_5 v_\phi^2}{2}$
  - Singly charged: $H^{\pm}$, $M^2_{H^{\pm}} = M^2_\Delta - \frac{\lambda_5 v_\phi^2}{4}$
  - Neutral CP-even/odd: H/A, $M_H = M_A = M_\Delta$

- ▶ We have omitted v_Δ since $v_\Delta / v_\phi \ll 1$ [2].
- ▶ Therefore, the scalar triplet can be deemed as unmixed with the SM Higgs doublet $\Rightarrow$ NLO scalar corrections are extracted from the SM one.

[2] $v_\Delta \lesssim 3$ 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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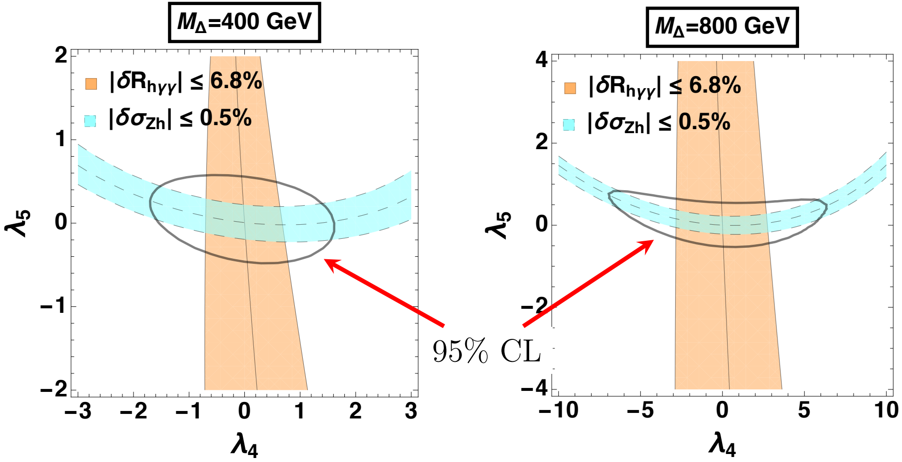


Complex Triplet – Complementarity in Parameter Space

- 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:

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

  – 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

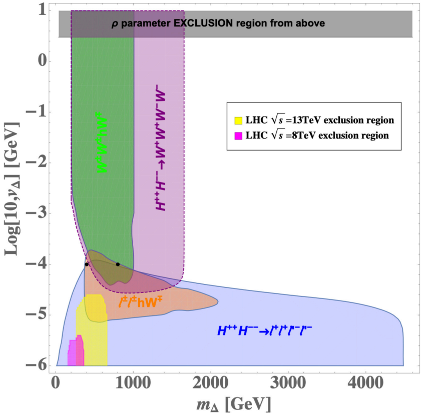
  – Combination of Planck 2018 and BAO data sets: $\sum m_\nu < 0.12$ eV

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

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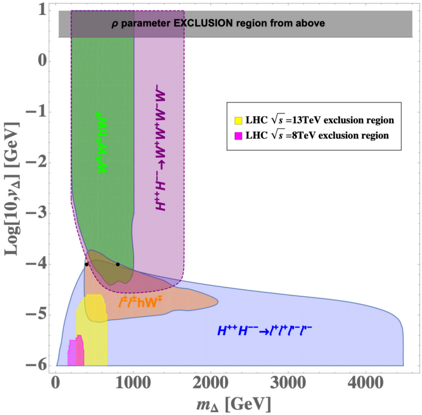

- In our study, one could further delineate the discovery regions in (M_Δ, v_Δ) for given values of neutrino masses
  - From the plots:

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

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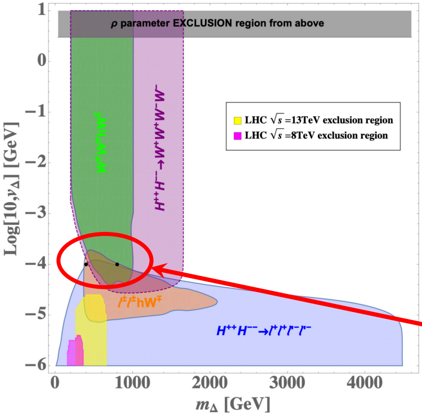

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- ▶ Two benchmark points:

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

Real Triplet

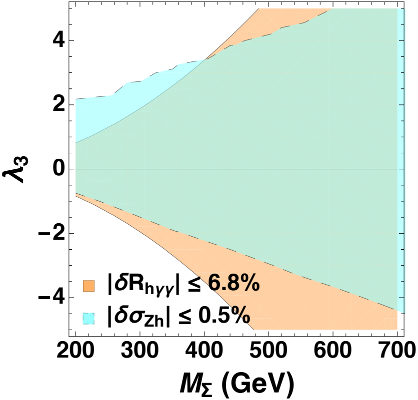
- Scalar potential:

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

- 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 $\delta R_{h\gamma\gamma}$: $\{M_\Sigma, \lambda_3\}$



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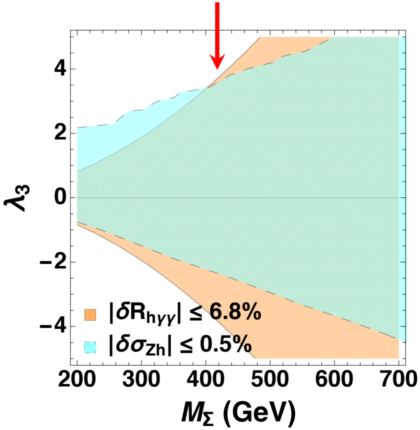
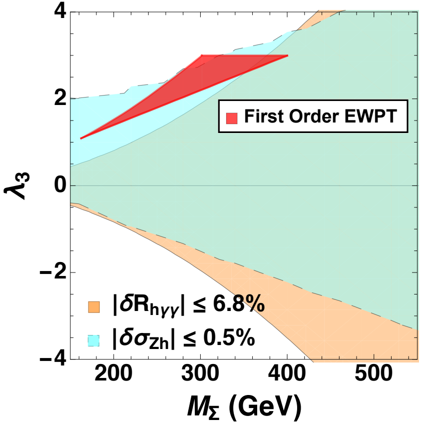
$M_\Sigma \sim 400$ GeV



Real Triplet

- Comparison with the first order EWPT region [3]



[3] L.Niemi, M.Ramsey-Musolf, T.V.Tenkanen and D.J.Weir, Phys.Rev.Lett.126, 171802 (2021) – uses DR3EFT method with non-perturbative lattice simulation

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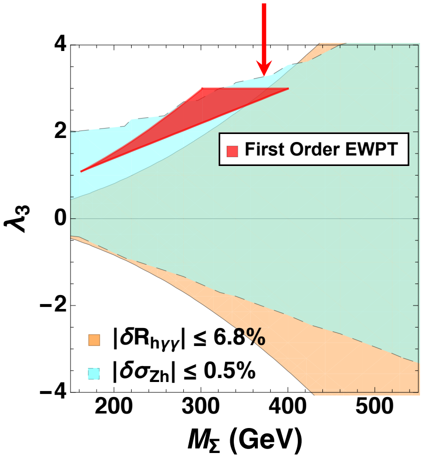
$M_\Sigma \sim 350$ GeV



[3] L.Niemi, M.Ramsey-Musolf, T.V.Tenkanen and D.J.Weir, Phys.Rev.Lett.126,

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:
  - $\sigma\,(Zh)$ 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.
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- 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). $\Rightarrow$ full 1-loop corrections (weak + QED) corrections are needed.

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Thank you!

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:

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

M. Gonderinger, H. Lim and M. J. Ramsey-Musolf, Phys. Rev. D 86 (2012) 043511
K. Riesselmann and S. Willenbrock, Phys. Rev. D 55 (1997) 311–321

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

- 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:

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

M. Gonderinger, H. Lim and M. J. Ramsey-Musolf, Phys. Rev. D 86 (2012) 043511
K. Riesselmann and S. Willenbrock, Phys. Rev. D 55 (1997) 311–321

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 $v_\Delta / v_\phi \ll 1$ [4].

▶ Therefore, the scalar triplet can be deemed as unmixed with the SM Higgs doublet ⇒ NLO scalar corrections are extracted from the SM one.

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

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:

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

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

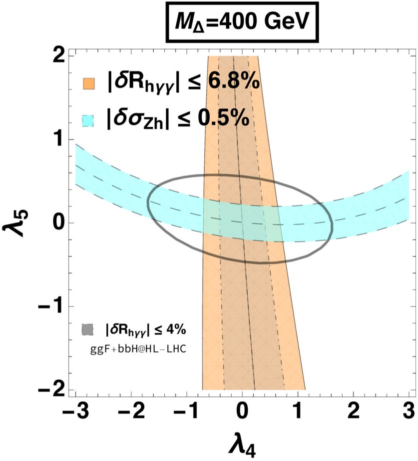
- In our study, one could further delineate the discovery regions in (M_Δ, v_Δ) for given values of neutrino masses
  - From the plots:

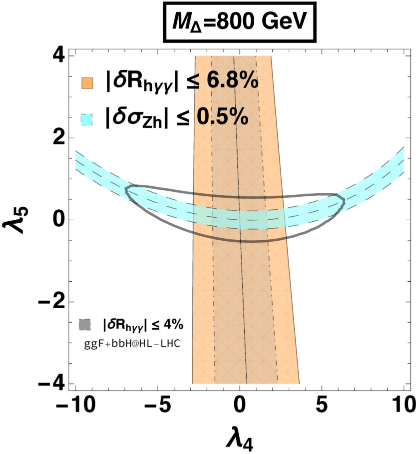
$$M_\Delta = 400(800)\ \mathrm{GeV}, |\lambda_4| \lesssim 1(3), |\lambda_5| \lesssim 0.2$$

  - 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

- Add contraint for $h \to \gamma\gamma$ measurement with HL-LHC precision at Higgs production channel via gluon-fusion plus $b\bar{b}H$
  - For each fixed M_Δ





Inert Doublet

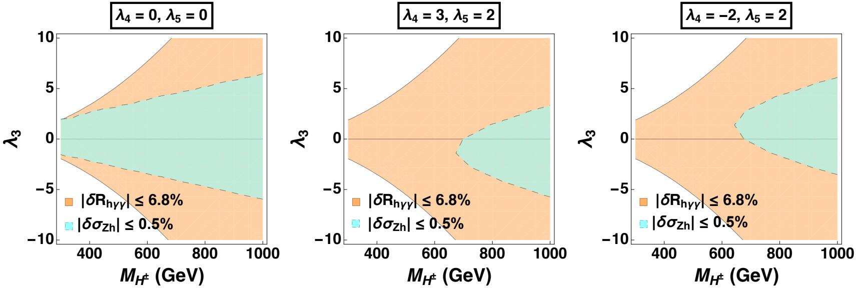
- Scalar potential involving SM Higgs and inert doublet $\mathbf{H}$,$\mathbf{\Phi}_2$

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

- 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

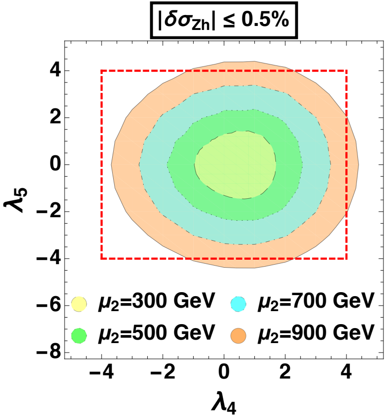
- Parameter dependence: $(M_{H^\pm}, \lambda_3, \lambda_4, \lambda_5)$
  - $\delta\sigma_{Zh}$ and $\delta R_{h\gamma\gamma}$ in the same plane (fixing λ_4, λ_5)



- ▶ 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



Inert Doublet

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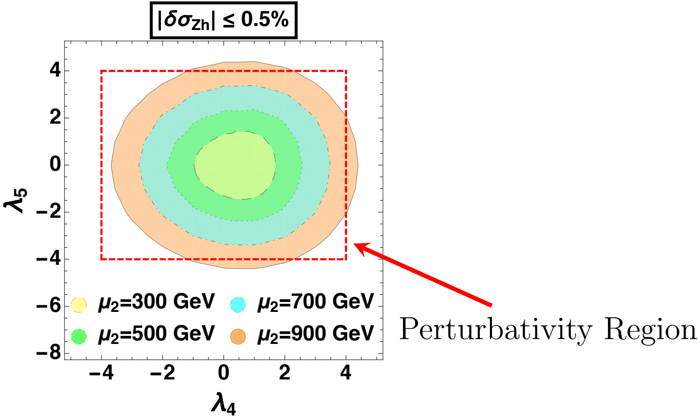


Inert Doublet

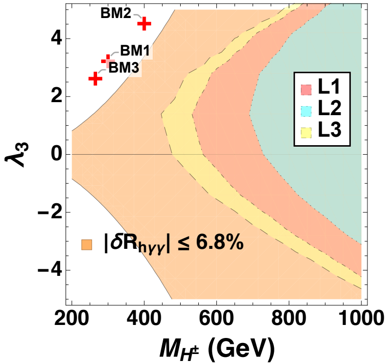
- Interplay between DM pheno and EW phase transition (EWPT) has been studied in a variety of spectra, and it shows
  - a strongly first order EWPT (SFOEWPT) requires a large mass splitting between the DM candidate particle and the other extended scalars;
  - when saturating the DM abundance, the Higgs 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.

Quintuplet & Septuplet $n = 5, 7$

- Scalar potential:

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

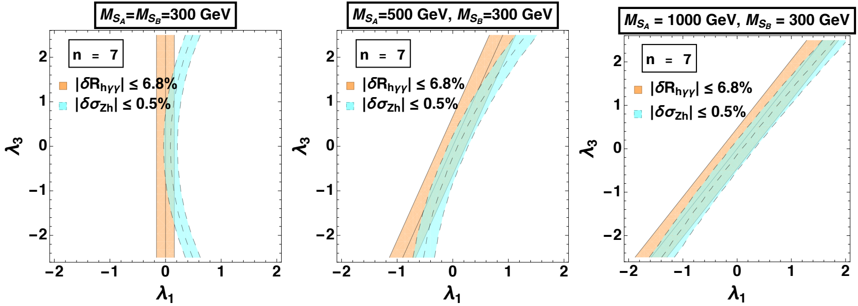
- $\lambda_2 = 0$
  - two real multiplets: $S_A,\ S_B,\ (j = \frac{n-1}{2})$
  - Scalar masses:

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

- 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

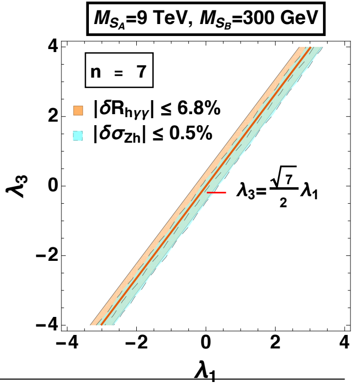


Degeneracy increases with $|M_{S_A} - M_{S_B}|$

- Similar for $n = 5$

Quintuplet & Septuplet $n = 5, 7$

- Connection to DM phenomenology
  - Effective coupling (e.g., n=7): $\lambda_{\text{eff}} = \lambda_1 - 2/\sqrt{7}\lambda_3$ is rather small when saturating the observed relic density and evading the direct dectection limits by LUX, PandaX-II and XENON1T [5].



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

▶ $\lambda_{\text{eff}} \sim 0$

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