Dark Matter searches in models with extended Higgs sector at lepton colliders

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The Two Higgs Doublet model extended with a complex scalar singlet (2HDMS) is a well-motivated Beyond Standard Model candidate addressing several open problems of nature. In this work, we focus on the dark matter (DM) phenomenology of the complex scalar singlet where the real part of the complex scalar obtains a vacuum expectation value. The model is characterized by an enlarged Higgs spectrum comprising six physical Higgs bosons and a pseudoscalar DM candidate. We address the impact of accommodating the 95 GeV excess on the 2HDMS parameter space and DM observables after including all theoretical and experimental constraints. Finally, we look into the prospects of this scenario at different lepton colliders such as electron-positron colliders as well as a muon collider.

Based on [arXiv: 2308.05653] and forthcoming study

2HDM with complex singlet extension

Two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix},$$

Additional complex singlet

$$S = \frac{v_S + \rho_S + i\eta_S}{\sqrt{2}}$$

Mass eigenstate:

- Neutral scalar: $h_1,\ h_2,\ h_3$
- Neutral pseudoscalar: A, A_S(DM candidate)
- Charged scalar: $H^\pm$

Symmetry

	Φ_1	Φ_2	S	
$\mathbb{Z}_2$	$+1$	-1	$+1$	Suppress the FCNC
$\mathbb{Z}_2'$	$+1$	$+1$	-1	Stabilize the dark matter candidate

Higgs potential :

$$\begin{aligned} V = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}] \\ & + m_S^2 S^*S + (\frac{m_S^{2\prime}}{2}S^2 + \text{h.c.}) + \frac{\lambda_1''}{6}\left(\frac{S^4}{4} + S^2S^*S + \text{h.c.}\right) + \frac{\lambda_3''}{4}(S^*S)^2 \\ & + S^*S[\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2] + [S^2(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2) + \text{h.c.}]. \end{aligned}$$

Mass matrices:

$$M_{ij} = \frac{\partial^2 V}{\partial\phi_i\partial\phi_j}\bigg|_{\substack{\Phi=\langle\Phi\rangle \\ S=\langle S\rangle}}$$

Diagonalization of the mass matrices:

$$\begin{aligned} \text{diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2) &= R(\alpha_1,\alpha_2,\alpha_3)M_{\text{Scalar}}^2R^T(\alpha_1,\alpha_2,\alpha_3) \\ \text{diag}(m_{H^\pm}^2, m_{G^\pm}^2) &= R_\pm M_{\text{Charged}}^2 R_\pm^T \\ \text{diag}(m_A^2, m_{G^0}^2) &= R_A M_{\text{Pseudoscalar}}^2 R_A^T \end{aligned}$$

Dark matter mass:

$$m_{A_S}^2 = \frac{\partial^2 V}{\partial\eta_S^2}\bigg|_{\substack{\Phi=\langle\Phi\rangle \\ S=\langle S\rangle}} = -(2m_S'^2 + v_S^2\frac{2\lambda_1''}{3} + 2(\lambda_4'v_1^2 + \lambda_5'v_2^2))$$

- Because of the $\mathbb{Z}_2'$ symmetry, the CP-odd singlet field would not mix with the doublet field
- The model has 15 free parameters:
  $m_{h_{1,2,3}}, m_A, m_{H^\pm}, m_{A_S}, m_{12}, v_S,$ tan $\beta, \alpha_{1,2,3}, \lambda_1'', \lambda_4', \lambda_5'$

Couplings for the Higgs bosons

Types of Yukawa couplings:

	type I	type II	lepton-specific	type IV (flipped)
c_{h_itt}	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$
c_{h_ibb}	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$
$c_{h_i\tau\tau}$	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$R_{i1}/\cos\beta$	$R_{i2}/\sin\beta$

Couplings to gauge bosons:

$$c_{h_iVV} = \cos\beta R_{i1} + \sin\beta R_{i2}\,.$$

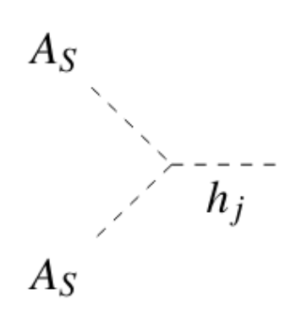
- Because of the absence of the mixing, $c_{A_Sff} = 0$
- Because of the CP-odd structure, $c_{A_SVV} = c_{A_Sh_ih_j} = 0$

The input parameters $\alpha_{1,2,3}$ can be extracted by

$$c_{h_1tt} = \frac{s_{\alpha_1}}{s_\beta}c_{\alpha_2}, \quad c_{h_1bb} = \frac{c_{\alpha_1}}{c_\beta}c_{\alpha_2},$$
$$\text{alignm} = \cos(\beta - \alpha_1 - \text{sgn}(\alpha_2)\alpha_3)$$

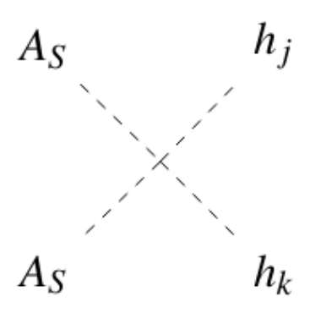
Dark matter portal coupling

Trilinear coupling:



$$\frac{\lambda_{h_jA_SA_S}}{v} = -[(\lambda_1' - 2\lambda_4')c_\beta R_{j1} + (\lambda_2' - 2\lambda_5')s_\beta R_{j2} - \frac{v_S}{2v}(\lambda_1'' - \lambda_3'')R_{j3}]$$

Quartic coupling:



$$\lambda_{h_jh_kA_SA_S} = -[(\lambda_1' - 2\lambda_4')R_{j1}R_{k1} + (\lambda_2' - 2\lambda_5')R_{j2}R_{k2} - \frac{1}{2}(\lambda_1'' - \lambda_3'')R_{j3}R_{k3}]$$

- The dark matter only couple to the Higgs bosons, where the couplings dominate the DM co-annihilation and scattering process
- When all the masses and Higgs couplings are fixed, the dark matter couplings can be changed by the parameter combinations $\lambda_1' - 2\lambda_4'$, $\lambda_2' - 2\lambda_5'$ and $\lambda_1'' - \lambda_3''$

Testing against the constraints

Theoretical constraints

- Tree-level perturbative unitarity [J. Horejsi, M. Kladiva arXiv.0510154]
- Boundedness from below [K.G. Klimenko Theor. Math. Phys. 62, 58–65 (1985)]
- Vaccum stability ⟶ `Evade` [J. Wittbrodt arXiv:1812.04644]

Experimental constraints

- LEP, Tevatron & LHC Higgs searches ⟶ `HiggsBounds` [T.Stefaniak et al. 2006.06007]
- 125 GeV Higgs couplings ⟶ `HiggsSignals` [T.Stefaniak et al. 2012.09197]
- Electroweak precision observables ⟶ $S,\ T,\ U$ parameters [M. Baak et al. 1209.2716]
- Flavor physics constraint ⟶ $m_{H^\pm} > 800$ GeV, tan $\beta > 1.5$ [J. Haller et al. 1803.01853]

Require for the 95 GeV excess [T.Biekoetter et al. 23’]

$$\mu_{\gamma\gamma}^{ggH} = 0.24^{+0.09}_{-0.08}, \qquad \mu_{bb}^{ZH} = 0.117 \pm 0.057$$

Benchmark Scenarios

BP1

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	900	900	900	8.0456×10^4	325.86	239.86
tan β	c_{h_1bb}	c_{h_1tt}	alignm	$\lambda_1' - 2\lambda_4'$	$\lambda_2' - 2\lambda_5'$	$\lambda_1'' - \lambda_3''$	Ωh^2
10	0.2096	0.4192	0.02	12.3327	-0.3109	-1.3645	8.71×10^{-3}

BP2

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	700	700	700	7.2576×10^4	325.86	239.86
tan β	c_{h_1bb}	c_{h_1tt}	alignm	$\lambda_1' - 2\lambda_4'$	$\lambda_2' - 2\lambda_5'$	$\lambda_1'' - \lambda_3''$	Ωh^2
6.6	0.258	0.372	0.02	12.75	-0.3135	-1.0112	3.16×10^{-4}

BP55

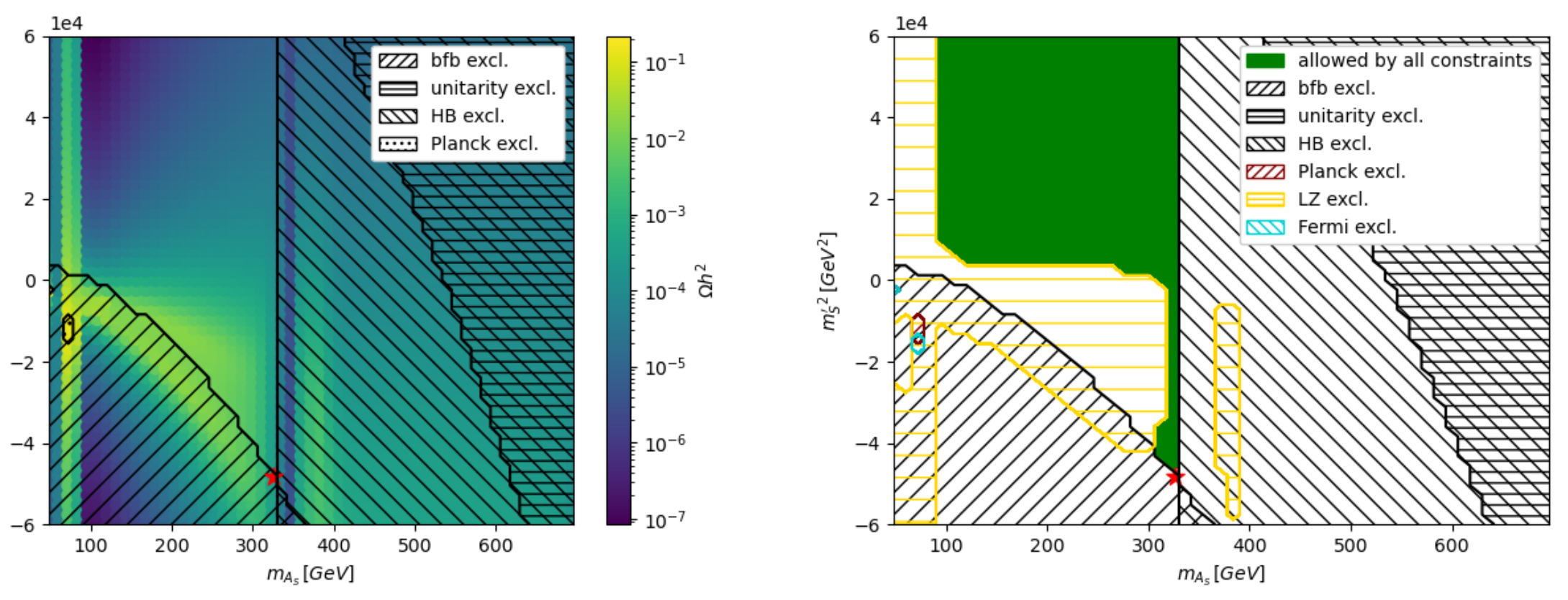
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	650	800	800	1.69×10^5	55.596	300
tan β	c_{h_1bb}	c_{h_1tt}	alignm	$\lambda_1' - 2\lambda_4'$	$\lambda_2' - 2\lambda_5'$	$\lambda_1'' - \lambda_3''$	Ωh^2
2	0.2323	0.3105	0.03	0.00209	0.000746	-0.025735	0.11

BP2900

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	m_{12}^2	m_{A_S}	v_S
95	125.09	2900	2900	2900	1.6173×10^6	1000	1000
tan β	c_{h_1bb}	c_{h_1tt}	alignm	$\lambda_1' - 2\lambda_4'$	$\lambda_2' - 2\lambda_5'$	$\lambda_1'' - \lambda_3''$	Ωh^2
5	0.3669	0.3393	5.5×10^{-5}	7.616	0.0	-0.4632	0.111

Parameter space scan

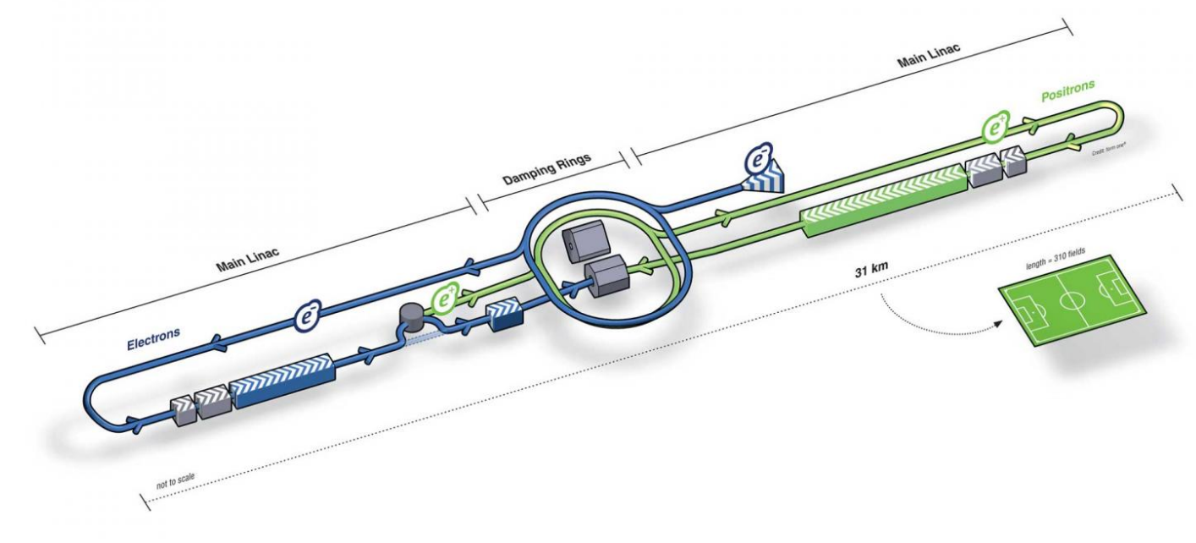
Scan around the benchmark point BP2 (red star)



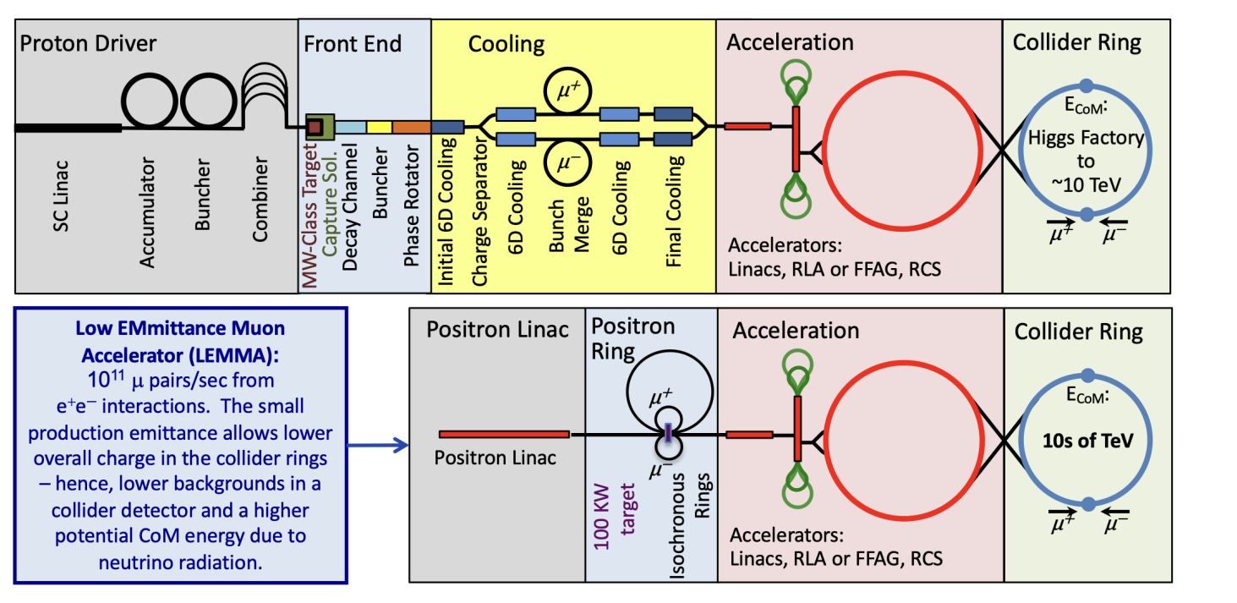
- The DM relic density has a dip at $2m_{A_S} \sim m_{h_3}$, where the resonant annihilation channel via h_3 opens up.
- The DM direct detection limits from LZ relaxes for underabundant DM due to the rescaling factor $\zeta = \Omega h^2/(\Omega h^2_{\text{PLANCK}})$ rescaled by DM relic density.
- Further stringent constraints on portal couplings $\lambda_1', \lambda_2', \lambda_4', \lambda_5'$, tan β, v_S. [arXiv: 2308.05653]

The lepton colliders

The ILC



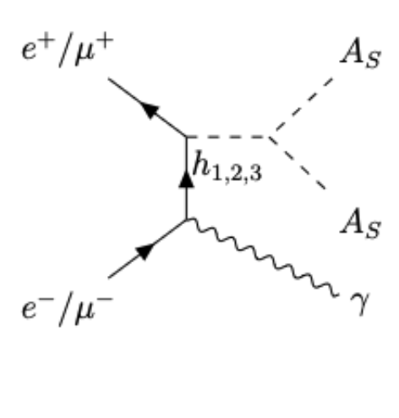
The muon-collider



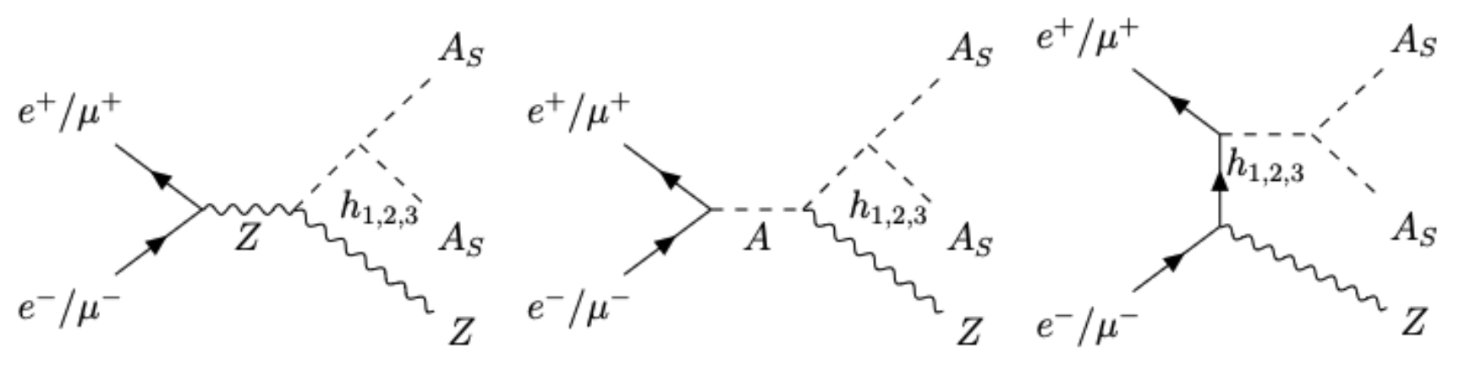
Low EMmittance Muon Accelerator (LEMMA): 10^{11} μ pairs/sec from e$^+$e$^-$ interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

Dark matter searches at lepton colliders

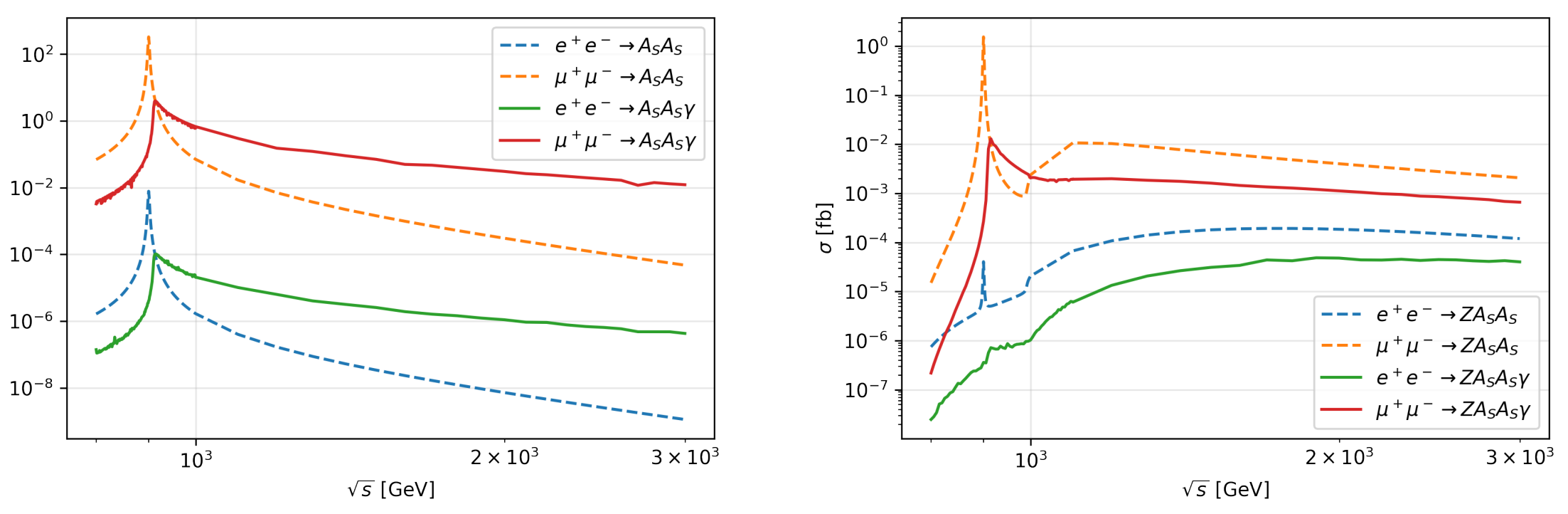
Mono-γ



Mono-Z



The cross-sections of mono-photon and mono-Z processes



- The muon-collider has larger cross-section of the mono-photon and mono-Z processes than the e^+e^- collider

	Process	Production cross-section [fb] 250 GeV	 1 TeV
BP55	$e^-e^+ \to Z\chi\chi$	4.24	0.227
BP55	$e^-e^+ \to \chi\chi\gamma$	2.28×10^{-3}	1.20×10^{-4}
BP55	$\mu^-\mu^+ \to Z\chi\chi$	4.24	0.227
BP55	$\mu^-\mu^+ \to \chi\chi\gamma$	95.9	5.09

	Process	Production cross-section [fb] 3 TeV	 14 TeV
BP2900	$e^-e^+ \to Z\chi\chi$	8.33×10^{-8}	1.29×10^{-7}
BP2900	$e^-e^+ \to \chi\chi\gamma$	7.28×10^{-8}	2.60×10^{-10}
BP2900	$\mu^-\mu^+ \to Z\chi\chi$	2.44×10^{-4}	1.76×10^{-6}
BP2900	$\mu^-\mu^+ \to \chi\chi\gamma$	3.08×10^{-3}	1.11×10^{-5}

Mono-photon cut:

$$E_\gamma > 10 \text{ GeV}, \qquad |\eta_\gamma| < 2.5$$

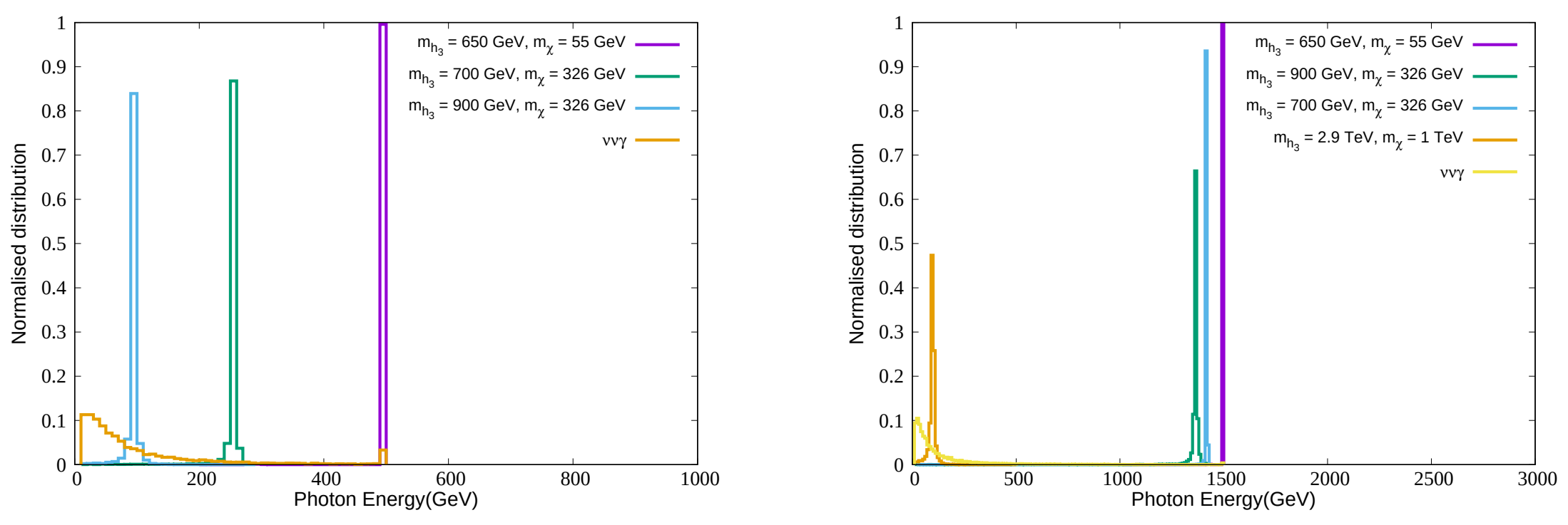
Background estimation

Process	Production cross-section (pb) at $\sqrt{s} =$ 1 TeV	 3 TeV
$\gamma\nu\bar{\nu}$	2.447	2.964

Signal Significance

Benchmark	$\mathcal{S}$(1 TeV)	$\mathcal{S}$(3 TeV)
BP1	0.34 (10 ab^{-1})	0.05 (10 ab^{-1})
BP2	1.24 (10 ab^{-1})	0.3 (10 ab^{-1})
BP55	26(10 ab^{-1}),8.2(1 ab^{-1})	8.1(10 ab^{-1}), 2.1(1 ab^{-1})
BP2900	–	0.14 (10 ab^{-1})

$\sqrt{s} = 1$ TeV at ILC $\qquad$ $\sqrt{s} = 3$ TeV at muon-collider



- The signal of mono-photon process can be well seperated from the background

Summary

- We performed the analysis of dark matter portal couplings and scan the corresponding parameter space.
- We obtained four benchmark points for phenomenology study, including light dark matter scenario and heavy dark matter scenarios. Both points are allowed by all the constraints and accommodating the 95 GeV excess.
- We estimated the cross-sections for the dark matter searches at muon-collider and e^+e^- collider
- We estimated the background contribution and calculated the signal significance for both benchmark points.