Spin discrimination of Higgs Portal DM at the Muon Collider
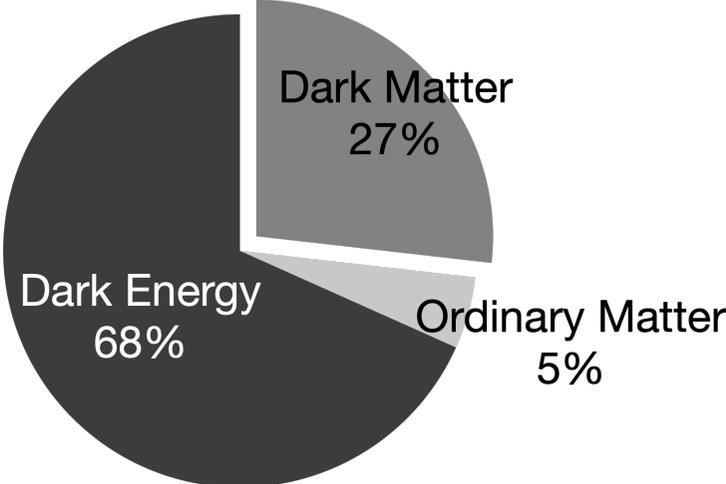
JK, Xu Deng, Jeonghan Kim, Pyungwon Ko, Jinmian Li

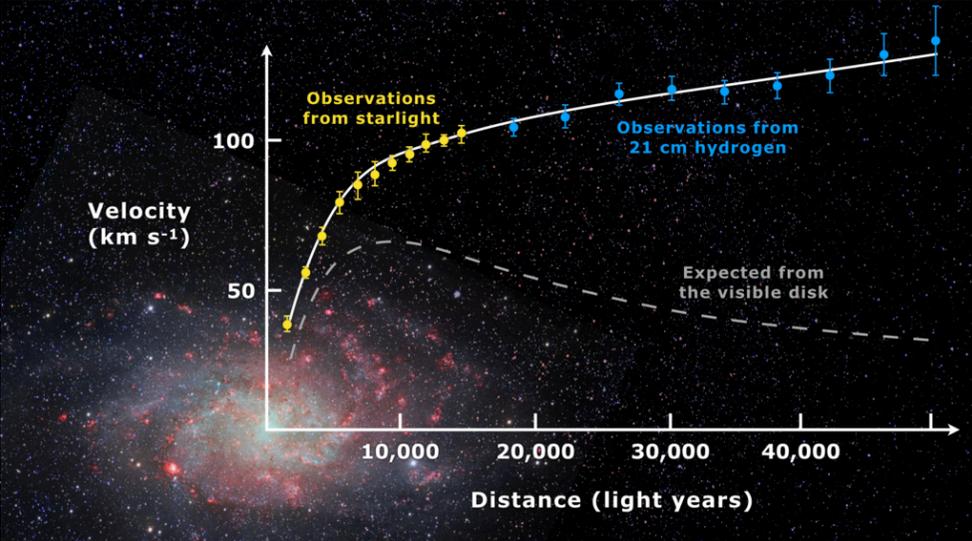Jinheung Kim

KIAS

Introduction

$$\Omega_{\mathrm{DM}} h^2 = 0.1188 \pm 0.0022$$

Higgs Portal DM

- Portal model

$$\text{Standard Model } n, p, e, \dots \iff_{\text{Portal}} \text{ Dark Sector } \chi, V, \dots$$

- The SM particles can interact with the dark matter throught the mediator particles.
- In the Higgs Portal model case, the mediator particles are the Higgs bosons.
- DM spin: 0 (SDM), 1/2 (FDM), 1 (VDM)

Higgs Portal DM

- SDM: $Z_2 : S \to -S$, $\langle S \rangle = 0$

$$\mathcal{L}_{\text{SDM}} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2 - \lambda_{HS} H^\dagger H S^2 - \frac{\lambda_S}{4!}S^4$$

$$\mathcal{L}_{\text{SDM}} \supset -h\left(\sum_f \frac{m_f}{v_h}\overline{f}f - \frac{2m_W^2}{v}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v}Z_\mu Z^\mu\right) - \lambda_{HS}vhS^2.$$

- FDM: $Z_2 : \chi \to -\chi$, $\langle S \rangle = v_s$

$$\mathcal{L}_{\text{FDM}} = \overline{\chi}(i\slashed{\partial} - m_\chi - g_\chi S)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2 - \lambda_{HS}H^\dagger H S^2 - \mu_{HS}SH^\dagger H - \mu_0^3 S - \frac{\mu_S}{3!}S^3 - \frac{\lambda_S}{4!}S^4$$

$$\mathcal{L}_{\text{FDM}} \supset -(H_1\cos\alpha + H_2\sin\alpha)\left(\sum_f \frac{m_f}{v_h}\overline{f}f - \frac{2m_W^2}{v_h}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right) + g_\chi(H_1\sin\alpha - H_2\cos\alpha)\overline{\chi}\chi$$

$$\begin{pmatrix} h \\ S \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

Higgs Portal DM

- VDM: Dark gauge $U(1)_X$, Dark Higgs field Φ, $D_\mu \Phi = \left(\partial_\mu - ig_V Q_\Phi V_\mu \right) \Phi$

$$\mathcal{L}_{\text{VDM}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{H\Phi} \left(H^\dagger H - \frac{v_H^2}{2} \right) \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)$$

$$\mathcal{L}_{\text{VDM}} \supset -(H_1 \cos\alpha + H_2 \sin\alpha) \left(\sum_f \frac{m_f}{v_h} \bar{f} f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right) - \frac{1}{2} g_V m_V (H_1 \sin\alpha - H_2 \cos\alpha) V_\mu V^\mu$$
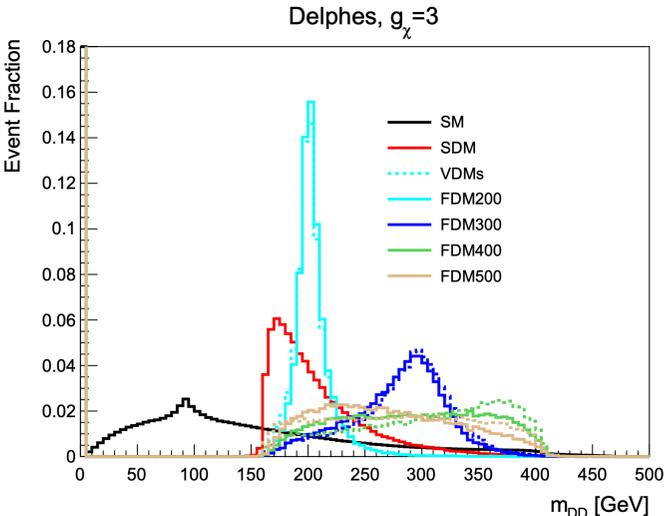
- $H_1 = h \ M_h = 125 \ \text{GeV}, \ H_2 = H, \ M_H > 125 \ \text{GeV}$
- Can we distinguish the FDM and VDM at the collider?

$$\begin{pmatrix} h \\ S \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$
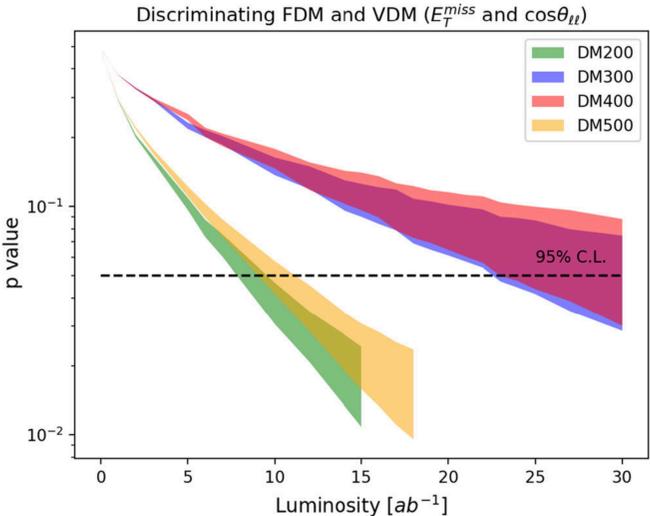
Previous study

- Previous studies of spin discrimination between FDM and VDM were conducted at the ILC and LHC.

ILC [1]

FCC [2]

- SDM vs FDM discrimination is possible
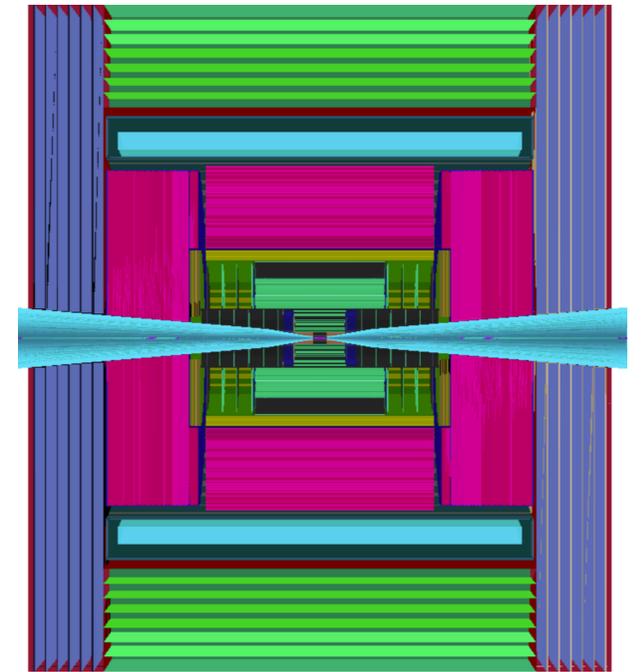- FDM vs VDM discrimination is not possible

- Both SDM vs FDM and FDM vs VDM discrimination are possible
- Only for $M_H < 500$ GeV

Why Muon Collider?

- e^+e^- collider: Low backgrounds, low CM energy.
- $pp(p\overline{p})$ collider: High CM energy, huge backgrounds.

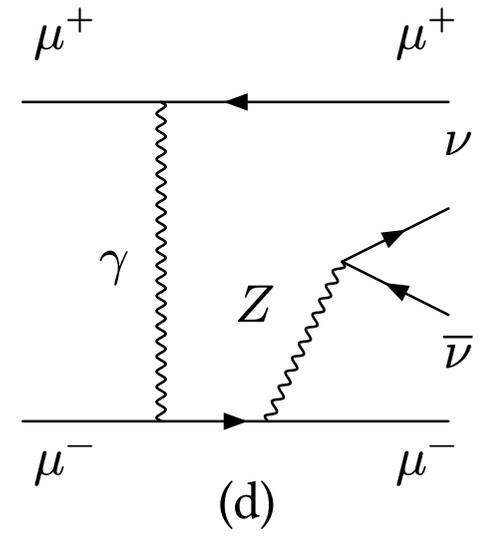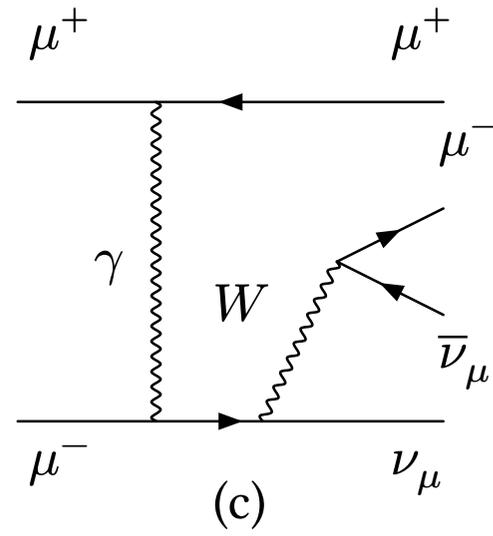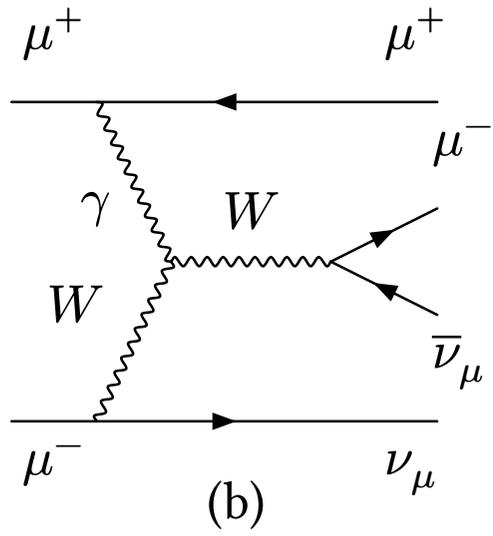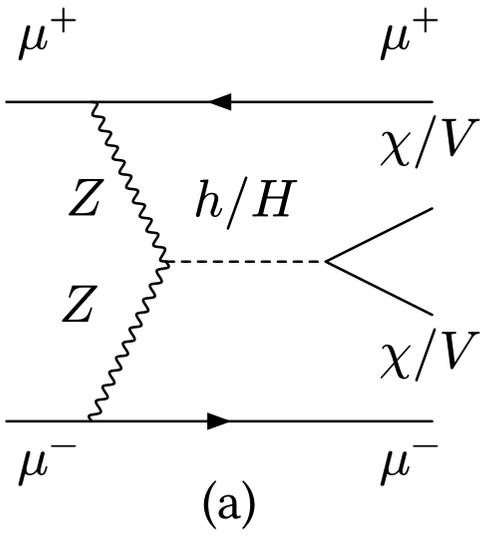- $\mu^+\mu^-$ collider: **Low backgrounds, high CM energy.**

$\rightarrow$ We can study TeV scale H_2.

- CM energy: $\sqrt{s} = 3, 10$ TeV, $\mathcal{L}_{\text{tot}} : 1, 10$ ab^{-1}
- Angular coverage:
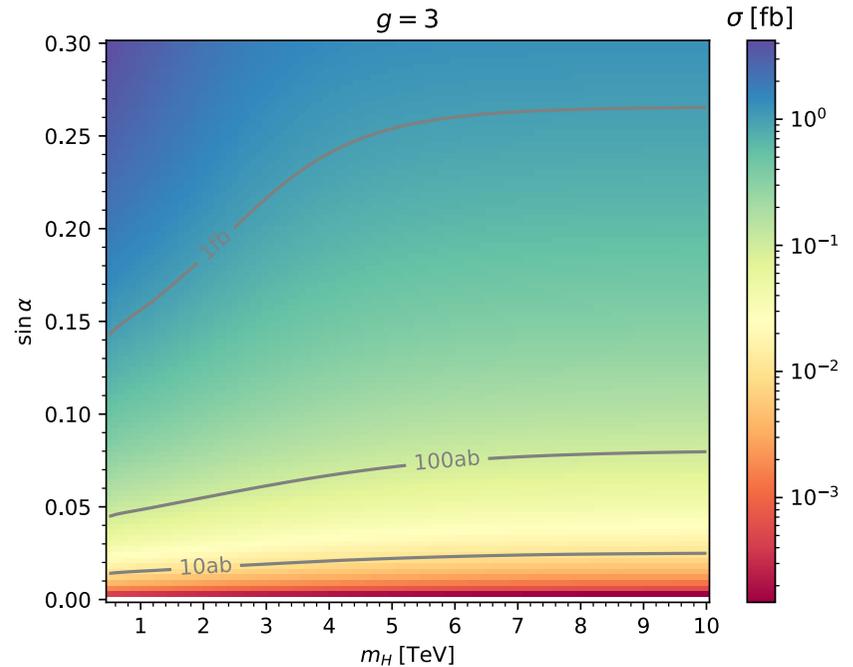 - Central: $|\eta| < 2.5$
  - Forward: $|\eta(\mu)| < 8$

Muon collider detector concept [3]

Production of FDM and VDM at MuC

(a)   (b)   (c)   (d)

Production of FDM and VDM at MuC

- FDM production cross section at $\sqrt{s} = 10$ TeV MuC.
- $\mu^+\mu^- \to \mu^+\mu^- \chi\overline{\chi}$, $\eta(\mu) < 8$
- $M_\chi = 150$ GeV, $g_\chi = 3$
- Increasing $\sin\alpha$ gives an increasing σ.
- Increasing M_H gives a decreasing σ.
  - For large M_H, σ becomes constant.
- SM cross section: $\sigma(\mu\mu\nu\overline{\nu}) \sim 2$ pb
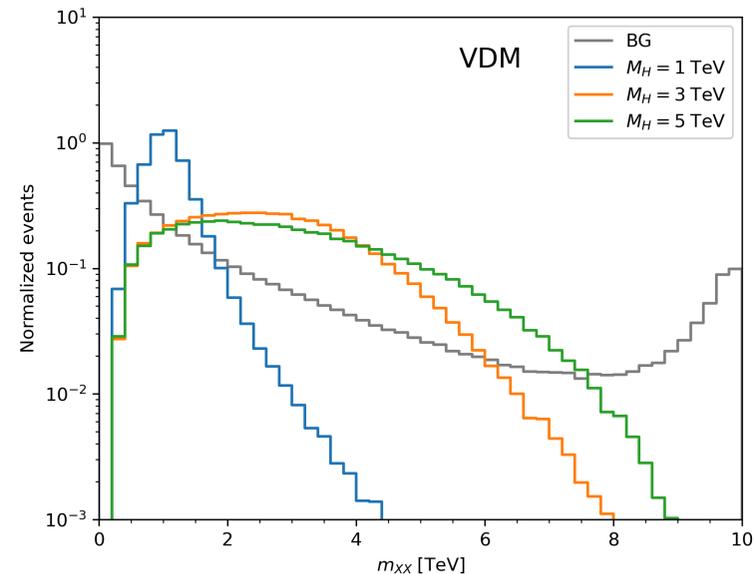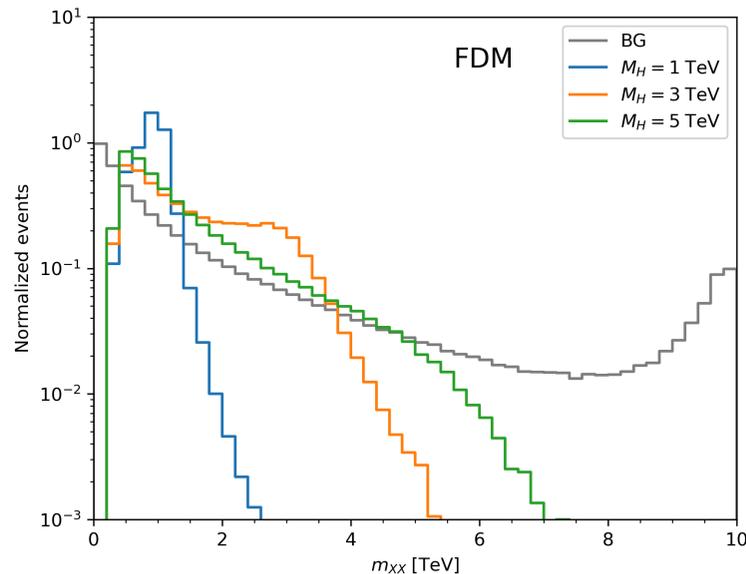- g_V: $\sigma_{\text{VDM}}(g_V) = \sigma_{\text{FDM}}(g_\chi = 1, 3)$

Production of FDM and VDM at MuC

- Recoil Mass

$$m_{\text{rec}}^2 = s + m_{\mu\mu}^2 - 2E_{\mu\mu}\sqrt{s}$$

- m_{rec}: Recoil mass, Invariant mass of the DM pair (or neutrino pair)
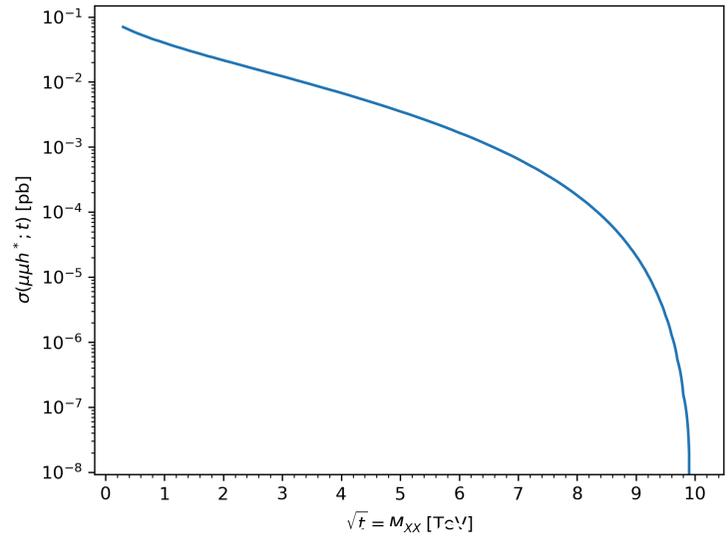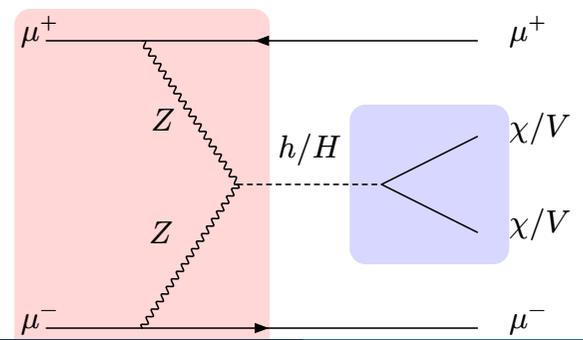- $m_{\mu\mu}$, $E_{\mu\mu}$: Invariant mass and energy of the muon pair

Production of FDM and VDM at MuC

The DM production cross section at MuC is given by:

$$\sigma(\mu\mu \to \mu\mu XX) = \int_{\sqrt{4m_X^2}}^{\sqrt{s}} d\sqrt{t}\ \sigma(\mu\mu h^*; t)\ \left| \frac{1}{t - m_h^2 + im_h\Gamma_h} - \frac{1}{t - m_H^2 + im_H\Gamma_H} \right|^2 \times \frac{2t}{\pi}\ \Gamma_{h^* \to XX}(t)\ s_\alpha^2 c_\alpha^2$$

- t: Squared recoil mass m_{XX}^2
- $\sigma(\mu\mu h^*; t)$: production cross section with mediator scalar mass $m_\phi = \sqrt{t}$
- $\Gamma_{h^* \to XX}(t)$: Decay width of the mediator scalar to the DM pair. $XX = \overline{\chi}\chi,\ VV$

- $\Gamma(h^* \to \overline{\chi}\chi) = g_\chi^2\ \dfrac{M_{h^*}}{8\pi}\ \left(1 - \tau_\chi\right)^{\frac{3}{2}}$

- $\Gamma(h^* \to VV) = \dfrac{g_V m_V}{2048\pi}\ \dfrac{M_{h^*}^3}{m_V^2}\ \left(1 - \tau_V\right)^{\frac{1}{2}} \left(4 - 4\tau_V + 3\tau_V^2\right)$

ML approach

- For a given $m_{XX} \left(= \sqrt{t}\right)$, the distributions of all kinematic variables $(P^T(\mu), \eta(\mu), m_{\mu\mu}, ...)$ are independent of the choice of BSM parameters (spin, M_H, $\sin\alpha$, g, ...).

- If the NN can discriminate signal and background for the full range of t, this network can be used for any parameter choice.

- Training
  - ▸ Kinematic Variables:
    - – $E(\mu), \eta(\mu), \phi(\mu)$ of $\mu_0, \mu_1, \mu\mu$, $\Delta R(\mu_0, \mu_1), \Delta\phi(\mu_0, \mu_1), \Delta\eta(\mu_0, \mu_1)$
    - – $p_T^{\mathrm{miss}}, \phi^{\mathrm{miss}}, M(\mu^+\mu^-), m_{XX}$
  - ▸ 100k events each of signal and background, with flat m_{XX} distribution.
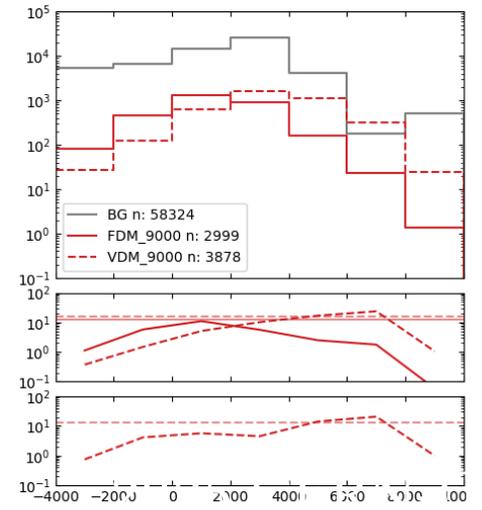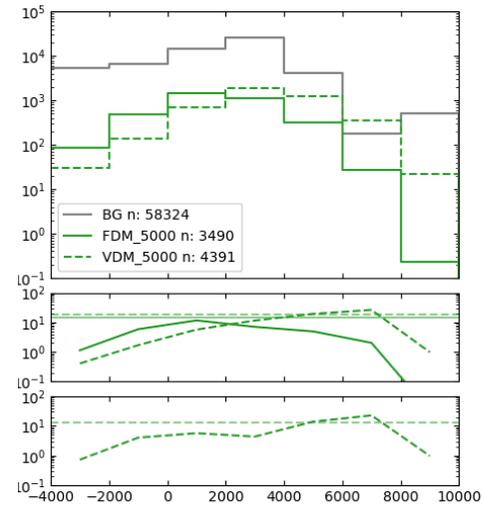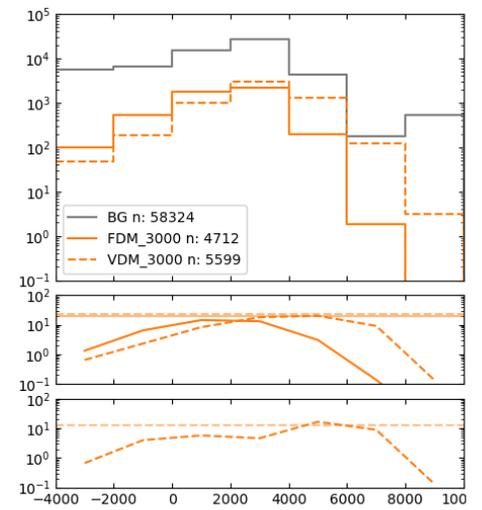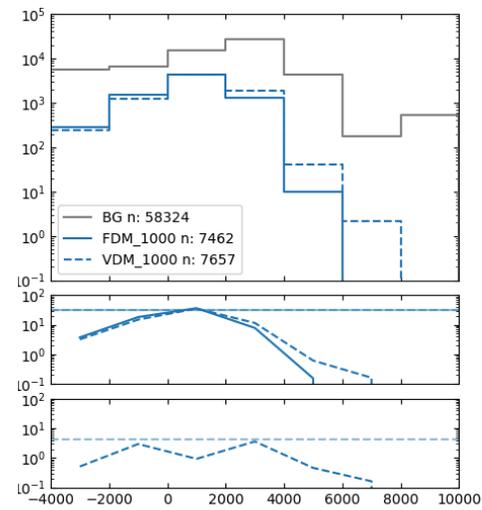 - ▸ 70%, 15%, 15% for training, validation, and test

Results

- Network
  - ‣ FC Layer [128, 64, 32]
  - ‣ 1 Output
  - ‣ Layer Norm, ReLU, Dropout(0.25)

- Signal efficiency and background refaction
  - ‣ $\varepsilon_{\text{Signal}} = 0.6$
  - ‣ $1/\varepsilon_{\text{Bakcgourn}} = 483$
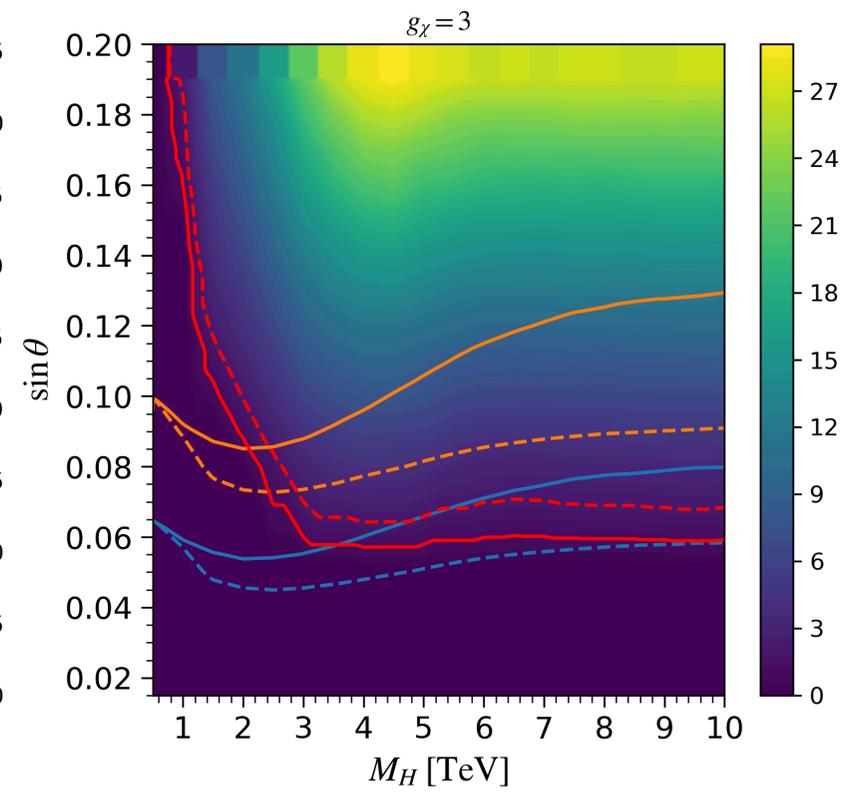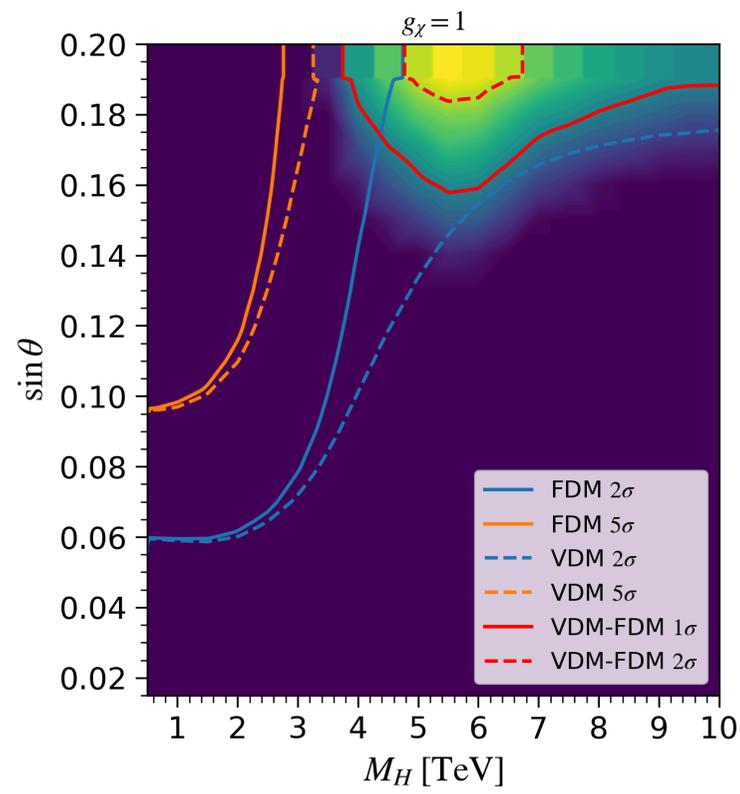
- FDM/VDM signal vs SM background
  - ‣ $S = \dfrac{N^{\text{FDM(VDM)}}}{\sqrt{N^{\text{SM}}}}$

- Spin discrimination
  - ‣ $\delta\chi^2 = \sum_i^{\text{nbin}} \left(\dfrac{N_i^{\text{VDM}} - N_i^{\text{FDM}}}{\sqrt{N_i^{\text{FDM+SM}}}} \right)^2$
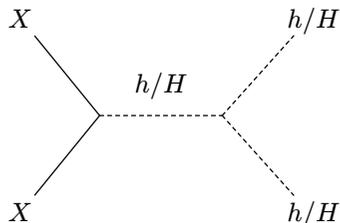
Results

Dark Matter Phenomenology

- Relic Density Constraints
  - ▸ $\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$
  - ▸ $\lambda_{hhH}, \lambda_{hHH}, \lambda_{HHH}$

- Direct Detection
  - ▸ To avoid DD constraints, small σ_{DN} is needed
  - ▸ Small g_X, small $|\sin\alpha|$, large m_H.

- Other Explanations
  - ▸ Uncertainty in local DM density
  - ▸ Excited Dark Matter (P. Ko)
    - $\mathcal{L} \supset \sum \overline{\chi}_i (i\slashed{D} - m_i - y_i S)\chi_i - \left[\overline{\chi}_1 (y_S + iy_p\Gamma_5) S\chi_2 + \text{h.c} \right]$
      $-\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu S D^\mu S - \frac{1}{2} m_S^2 S^2 - V(H, S)$
    - $\chi_2 \to \chi_1 \gamma_D$

Conclusion

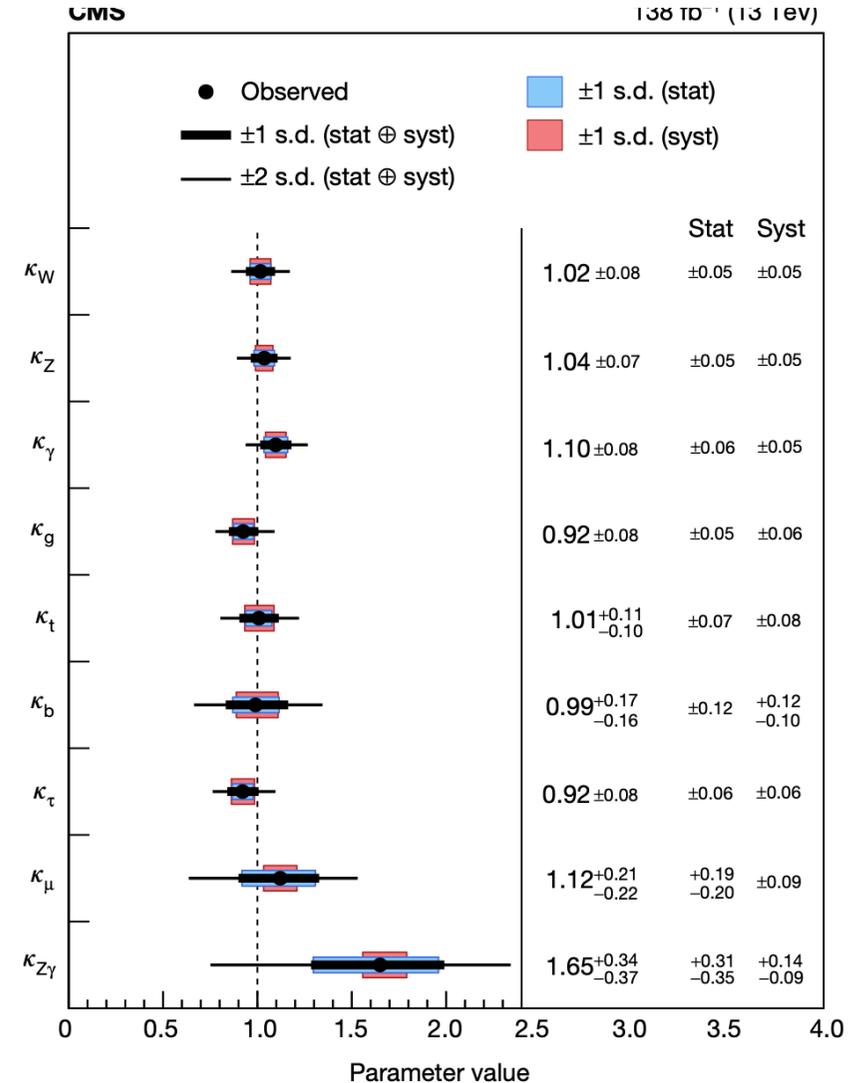- We study the spin discrimination of Higgs Portal DM at the Muon Collider.

- At the muon collider, the recoil mass m_{XX} is a useful variable to measure dark matter properties.

- Due to the different growth of FDM and VDM with M_H, the FDM and VDM show different distributions in m_{XX}.

- For $g_\chi = 1$, the separation of FDM and VDM is limited and it is challenging to discriminate the spin of DM. For $g_\chi = 3$ with $\sin \alpha \gtrsim 0.05$, we can observe the signal above 2σ. For most of this region, we can discriminate the spin of DM.

- The parameter space is excluded by direct detection constraints. However, this may be evaded by introducing Excited Dark Matter.
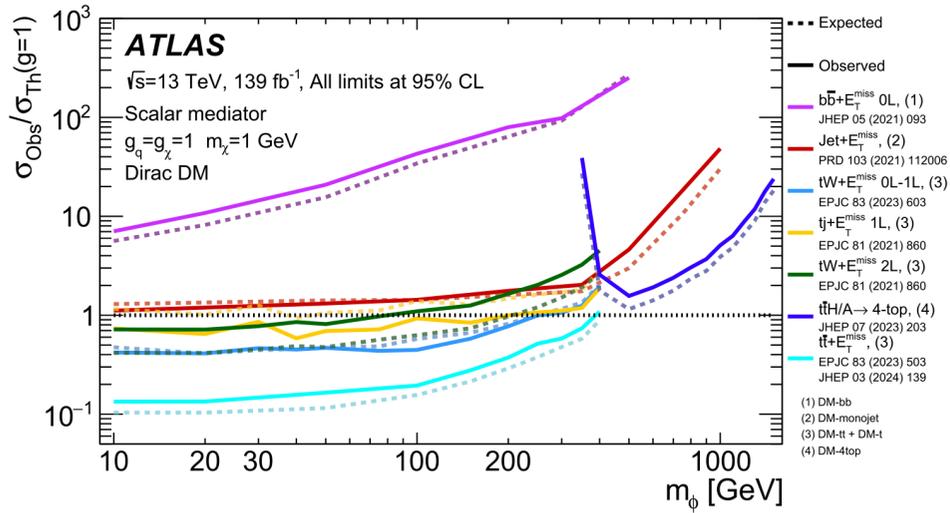
Thank you for your attention!

Backup

Mixing angle $\sin\alpha$

- The properties of the 125 GeV Higgs boson is well agree with SM prediction.
- CMS[4]
  - ‣ $\kappa_W = 1.02 \pm 0.08$, $\kappa_Z = 1.04 \pm 0.07$
- ATLAS[5]
  - ‣ $\kappa_W = 1.05 \pm 0.06$, $\kappa_Z = 0.99 \pm 0.06$
- HL-LHC[6]
  - ‣ $\kappa_W \approx 1.7\%$, $\kappa_Z \approx 1.5\%$
  - ‣ $\sin\alpha \lesssim 0.24$
- MuC [7]
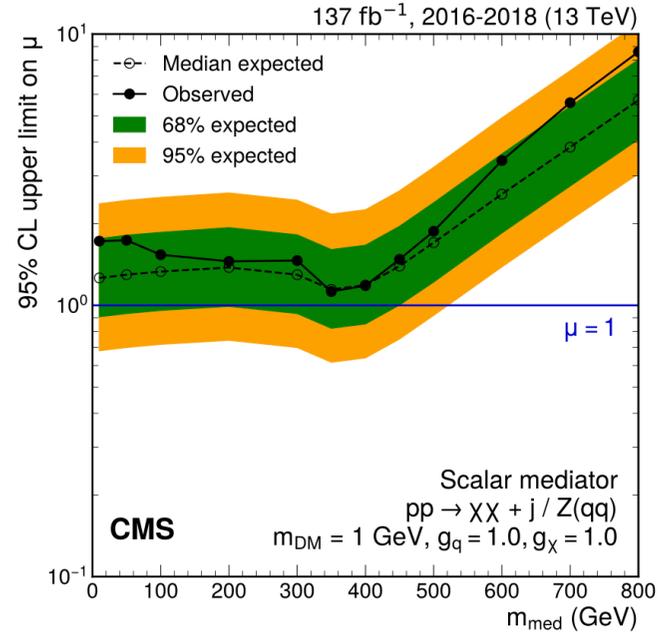 - ‣ $\kappa_W = 0.1\%$, $\kappa_Z = 0.4\%$
  - ‣ $\sin\alpha \lesssim 0.06$

Mono-X search

(a)

2404.15930

2107.13021

- Mono-X search may constrain the parameter when $M_H < 500$ GeV

References

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[2] B. Dutta, T. Kamon, P. Ko, and J. Li, "Prospects for discovery and spin discrimination of dark matter in Higgs portal DM models and their extensions at 100 TeV pp collider", *Eur. Phys. J. C*, vol. 78, no. 7, p. 595, 2018, doi: 10.1140/epjc/s10052-018-6071-y.

[3] C. Accettura and others, "Interim report for the International Muon Collider Collaboration (IMCC)," *CERN Yellow Rep. Monogr.*, p. 176, 2024, doi: 10.23731/CYRM-2024-002.

[4] A. Tumasyan and others, "A portrait of the Higgs boson by the CMS experiment ten years after the discovery.," *Nature*, vol. 607, no. 7917, pp. 60–68, 2022, doi: 10.1038/s41586-022-04892-x.

[5] G. Aad and others, "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery," *Nature*, vol. 607, no. 7917, pp. 52–59, 2022, doi: 10.1038/s41586-022-04893-w.

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[6] J. de Blas and others, "Higgs Boson Studies at Future Particle Colliders," *JHEP*, vol. 1, p. 139, 2020, doi: 10.1007/JHEP01(2020)139.

[7] C. Accettura and others, "Towards a muon collider," *Eur. Phys. J. C*, vol. 83, no. 9, p. 864, 2023, doi: 10.1140/epjc/s10052-023-11889-x.