Spin discrimination of Higgs Portal DM at the Muon Collider

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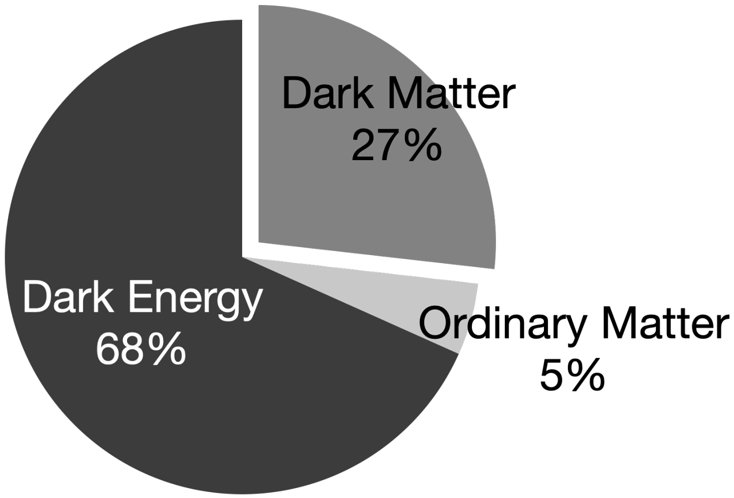
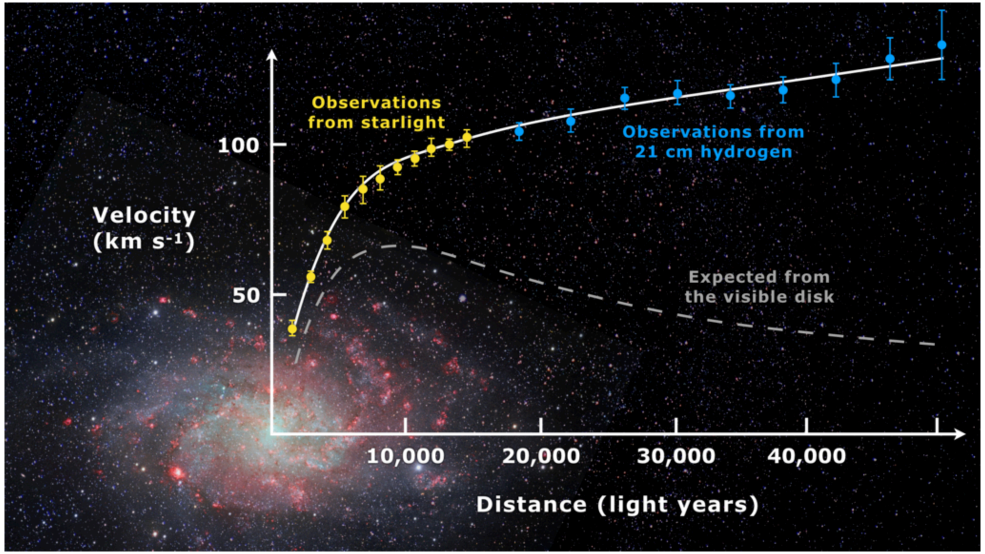
Introduction

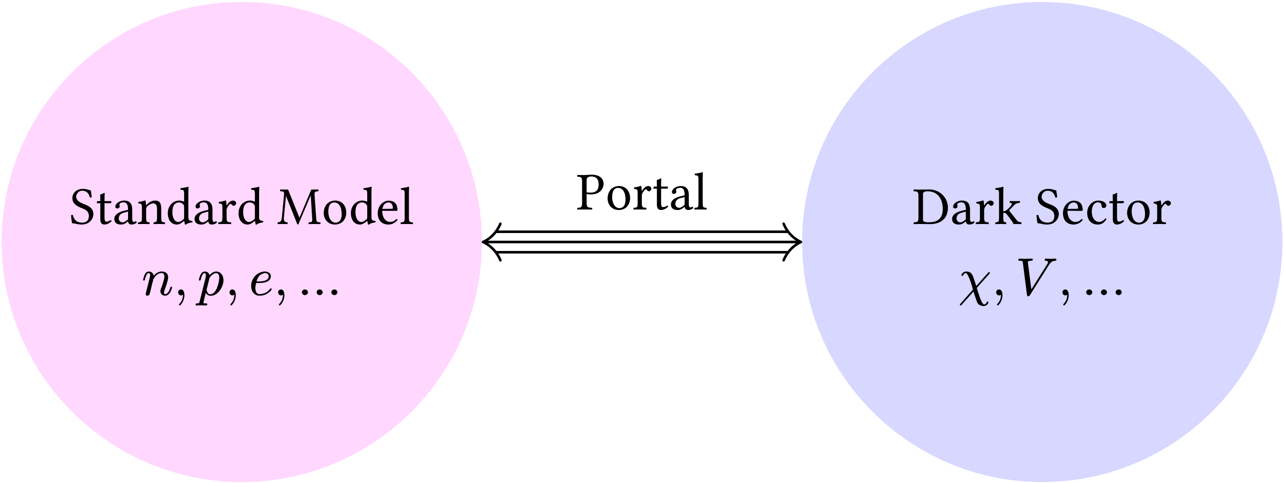


$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0022$$



Higgs Portal DM

- Portal model



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

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

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

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

$$\mathcal{L}_{\text{FDM}} = \overline{\chi}(i\not\partial - m_\chi - g_\chi S)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2 - \lambda_{HS} H^\dagger H S^2 - \mu_{HS} S H^\dagger H - \mu_0^3 S - \frac{\mu_S}{3!}S^3 - \frac{\lambda_S}{4!}S^4$$

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

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

Higgs Portal DM

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

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

$$\mathcal{L}_{\text{VDM}} \supset -(H_1\cos\alpha + H_2\sin\alpha)\left(\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W_\mu^+W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right) - \frac{1}{2}g_V m_V(H_1\sin\alpha - H_2\cos\alpha)V_\mu V^\mu$$

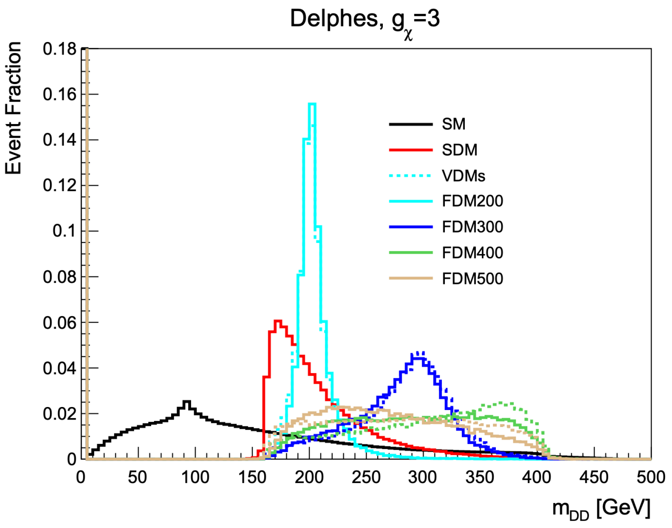
- $H_1 = h$ $M_h = 125$ GeV, $H_2 = H$, $M_H > 125$ GeV
- Can we distinguish the FDM and VDM at the collider?

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

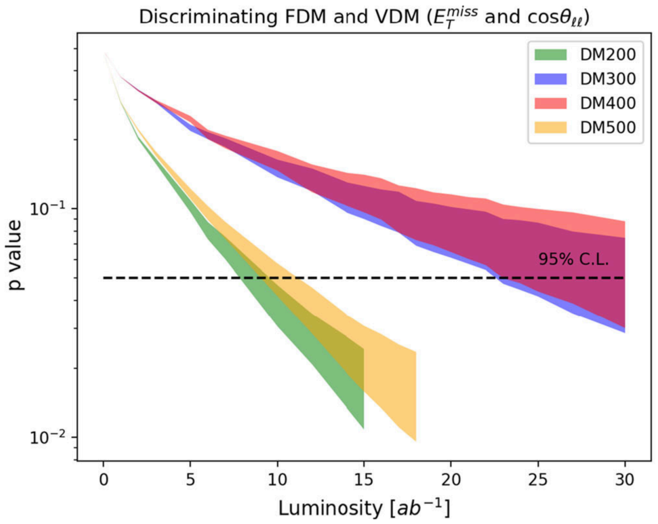
Previous study

- 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

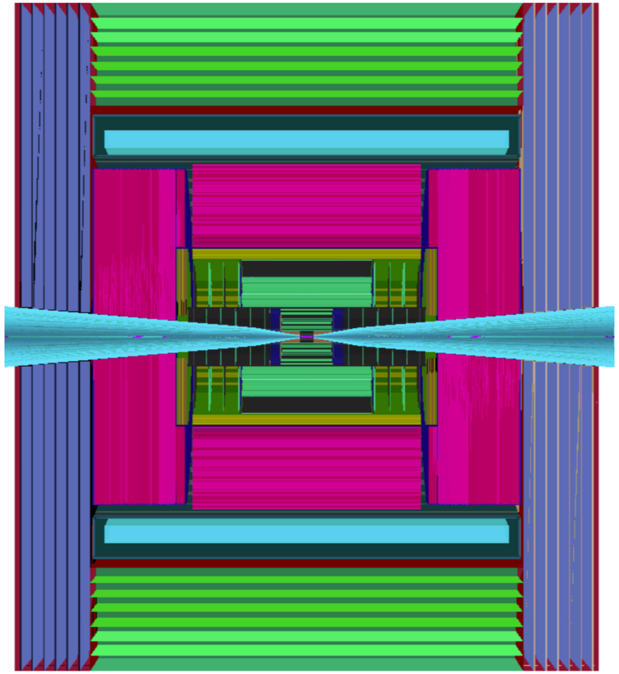
Why Muon Collider?

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

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

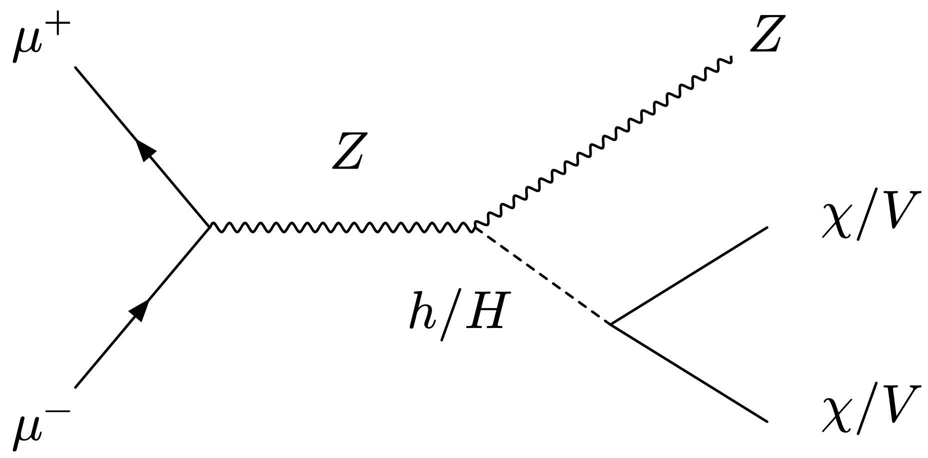
$\rightarrow$ We can study TeV scale H_2.

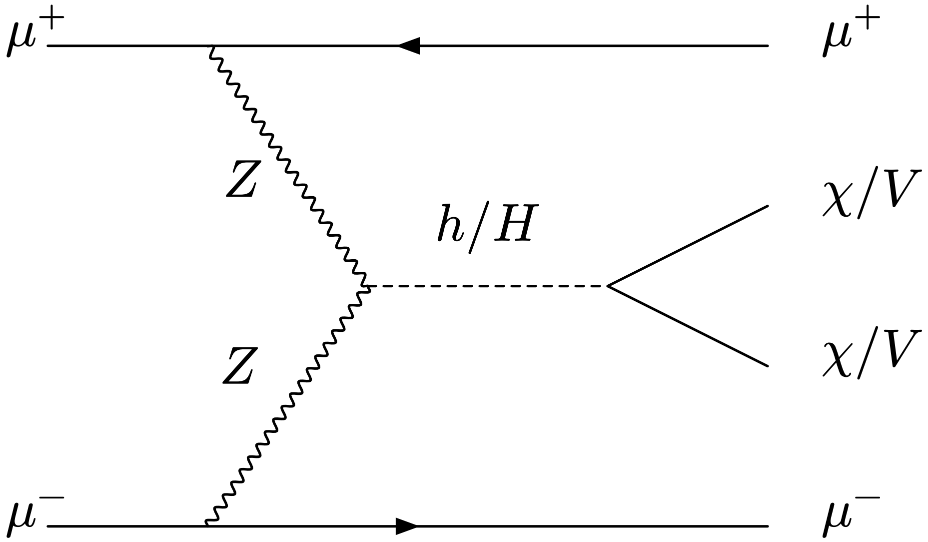
- CM energy: $\sqrt{s} = 3, 10$ TeV, $\mathcal{L}_{\text{tot}}$: $1, 10$ ab^{-1}
- Angular coverage:
  - Central: $|\eta| < 2.5$
  - Forward: $|\eta(\mu)| < 8$



Muon collider detector concept [3]

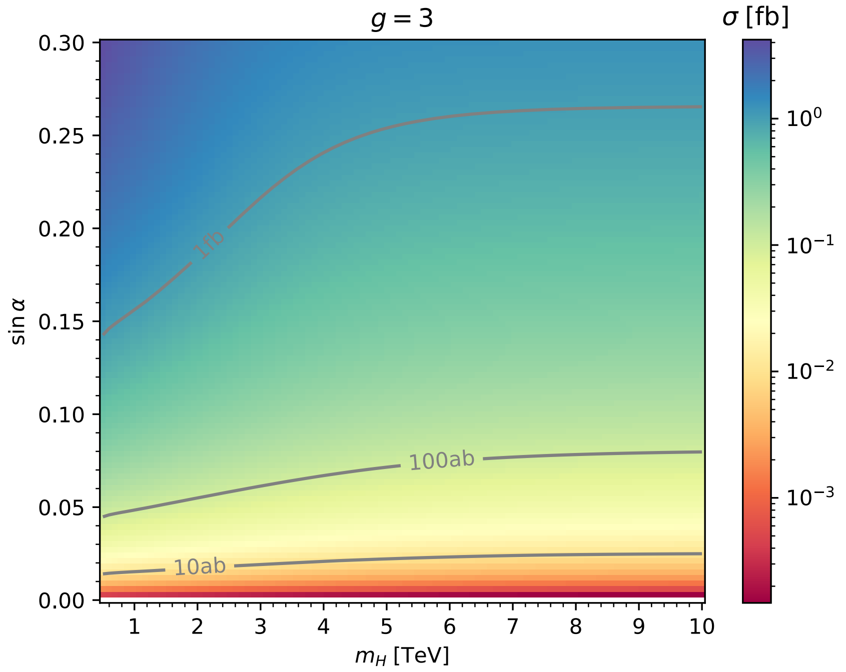
Production of FDM and VDM at MuC





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: $\sigma_{\text{VDM}}(g_V) = \sigma_{\text{FDM}}(g_\chi = 1, 3)$

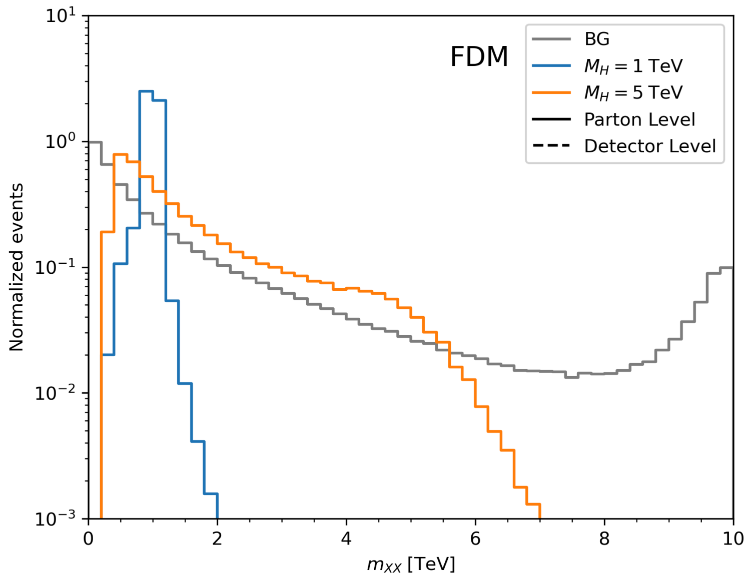


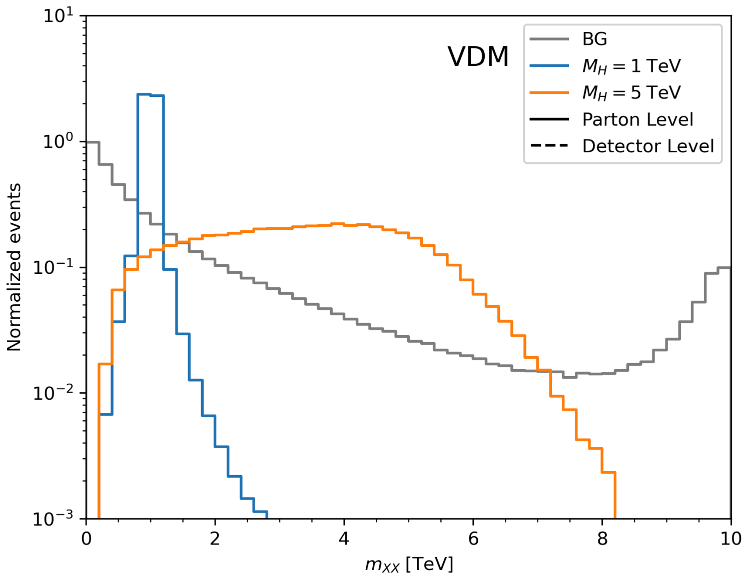
Production of FDM and VDM at MuC

- Recoil Mass

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

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





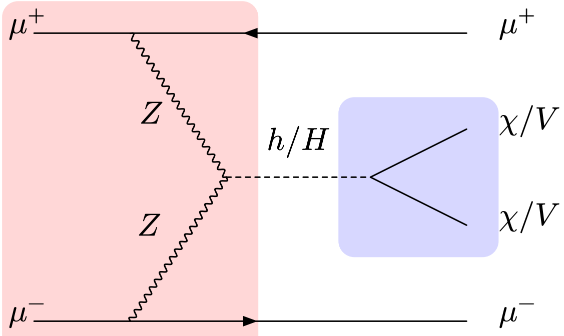
Production of FDM and VDM at MuC

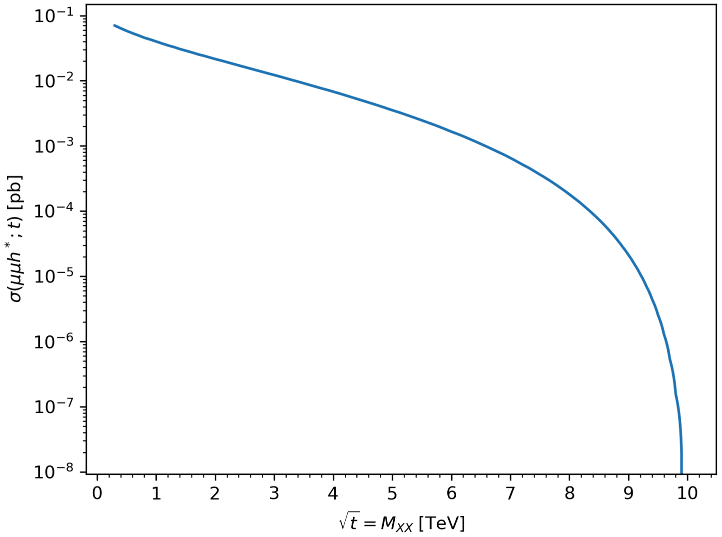
The DM production cross section at MuC is given by:

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

- 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. $XX = \chi\overline{\chi}, VV$

- $\Gamma(H \to \overline{\chi}\chi) = g_\chi^2\ \frac{M_H}{8\pi}\ (1 - \tau_\chi)^{\frac{3}{2}}$
- $\Gamma(H \to VV) = \frac{g_V m_V}{2048\pi}\ \frac{M_H^3}{m_V^2}\ (1 - \tau_V)^{\frac{1}{2}} (4 - 4\tau_V + 3\tau_V^2)$



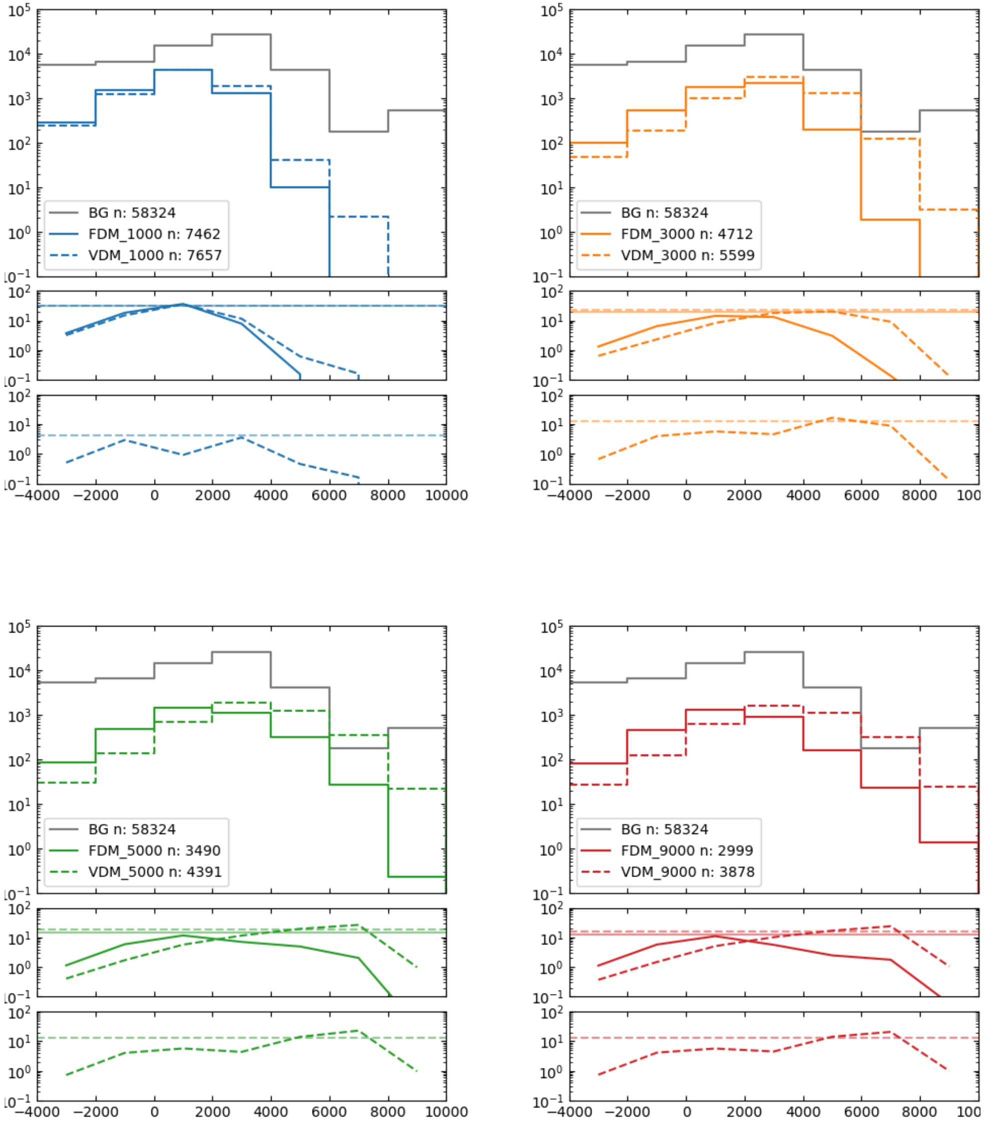


ML approach

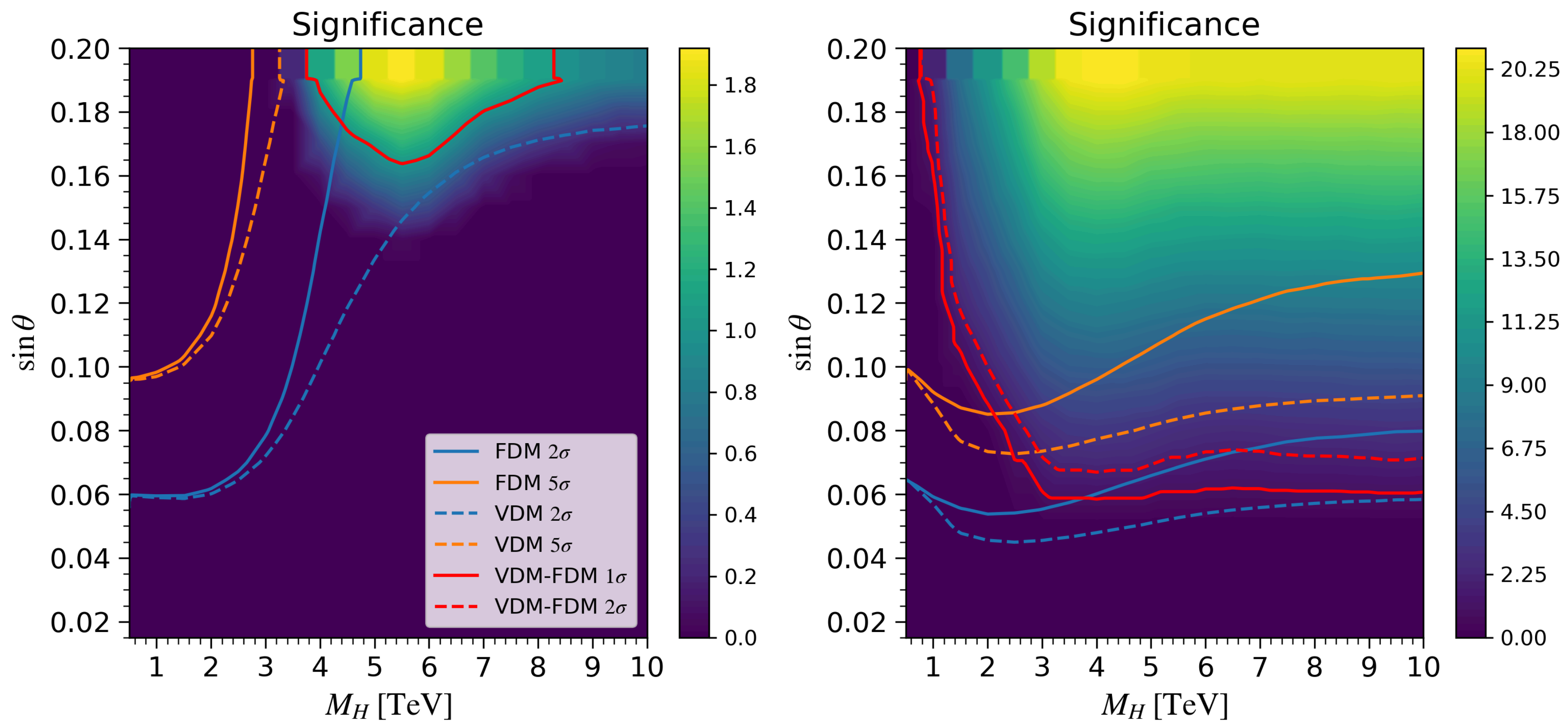
- For a given $m_{XX}\left(=\sqrt{t}\right)$, the distributions of all kinematic variables ($P^T(\mu), \eta(\mu), m_{\mu\mu}, \ldots$) are independent of the choice of BSM parameters (spin, M_H, $\sin\alpha$, g, ...).
- If the NN can discriminate signal and background for the full range of t, this network can be used for any parameter choice.
- Training
  - Kinematic Variables:
    - $E(\mu), \eta(\mu), \phi(\mu)$ of $\mu_0, \mu_1, \mu\mu$, $\Delta R(\mu_0, \mu_1), \Delta\phi(\mu_0, \mu_1), \Delta\eta(\mu_0, \mu_1)$
    - $p_T^{\text{miss}}, \phi^{\text{miss}}$, $M(\mu^+\mu^-), m_{XX}$
  - 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
  - $\varepsilon_{\text{Signal}} = 0.6$
  - $1/\varepsilon_{\text{Bakcgourn}} = 483$
- Spin discrimination
  - $\delta\chi^2 = \sum_i^{\text{nbin}} \left(\frac{N_i^{\text{VDM}} - N_i^{\text{FDM}}}{\sqrt{N_i^{\text{VDM+SM}}}} \right)^2$

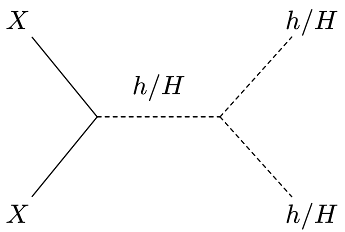


Results

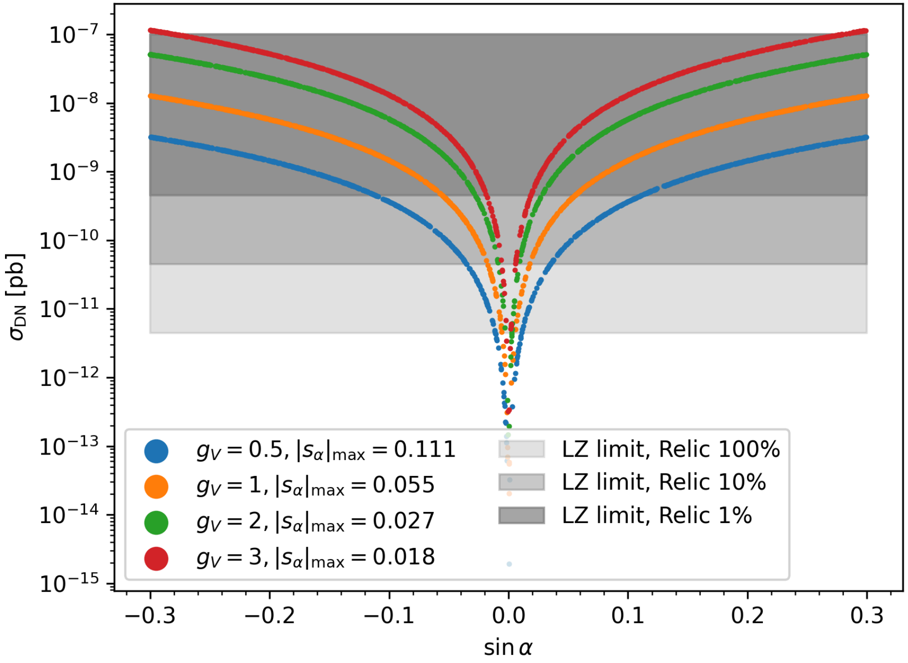

Significance
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
$\sin\theta$
1 2 3 4 5 6 7 8 9 10
M_H [TeV]
FDM 2σ
FDM 5σ
VDM 2σ
VDM 5σ
VDM-FDM 1σ
VDM-FDM 2σ
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
Significance
0.00 2.25 4.50 6.75 9.00 11.25 13.50 15.75 18.00 20.25

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 [4]
    - $\mathcal{L} \supset \sum \overline{\chi}_i (i\not{D} - m_i - y_i S)\chi_i - \left[\overline{\chi}_1 \left(y_S + i y_p \Gamma_5\right) S \chi_2 + \mathrm{h.c}\right]$

      $-\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu S D^\mu S - \frac{1}{2} m_S^2 S^2 - V(H, S)$
    - $\chi_2 \to \chi_1 \gamma_D$

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 $\sin\alpha \gtrsim 0.5$, 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!

References

[1] T. Kamon, P. Ko, and J. Li, "Characterizing Higgs portal dark matter models at the ILC," *Eur. Phys. J. C*, vol. 77, no. 9, p. 652, 2017, doi: 10.1140/epjc/s10052-017-5240-8.

[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] J. L. W.-I. P. S. Baek P. Ko, "(Paper in preparation)."