Characterizing dark matter model with Higgs portal at the ILC

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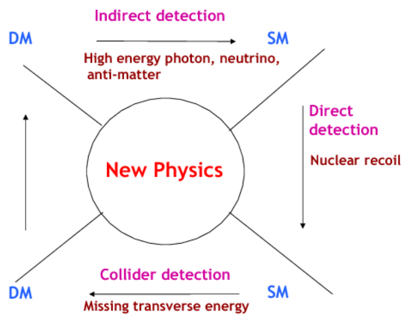
Outline

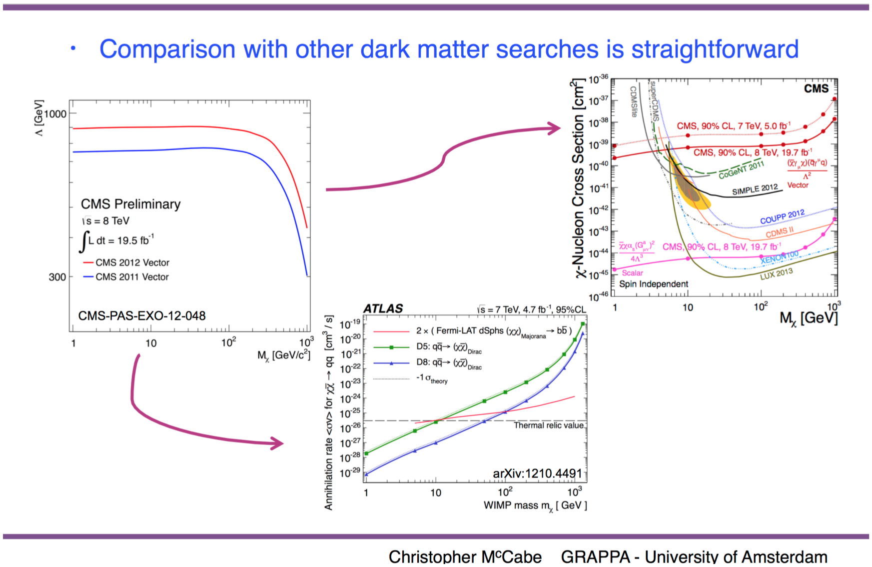
1. Theoretical frameworks for DM interaction
   - Effective Field Theory
   - Simplified model
   - Towards complete model (FDM, SDM, VDM)
2. Collider searches of UV-complete Higgs portal models (hadronic channel)
   - Features of DM spin
   - Discovery prospects
   - Spin characterization
3. The leptonic channel
4. Varying the coupling
5. Conclusion

Advantage of Effective Field Theory

Scalar operator for fermion DM:

$$\frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{f}f), \quad \frac{1}{\Lambda^3}(\bar{\chi}\chi)\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu})$$

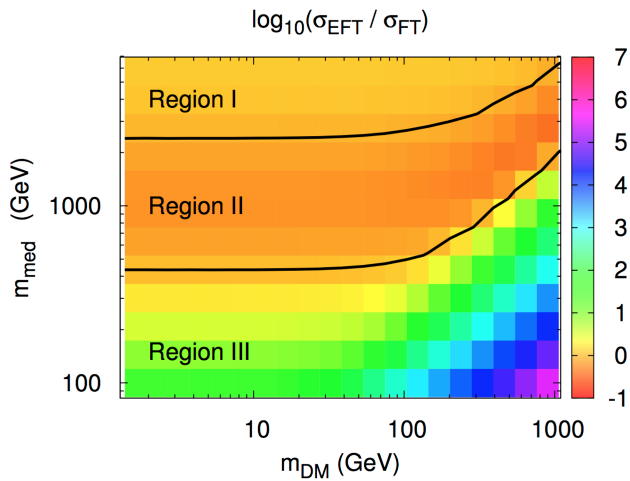




Validation of EFT

$$\sigma_{\mathrm{EFT/FT}}(pp \to \chi\chi)\text{@LHC}$$

O. Buchmueller, M. J. Dolan and C. McCabe JHEP **1401***, 025 (2014)*



- Region I: EFT limit is valid.
- Region II: EFT limit is too weak (Resonant enhancement).
- Region III: EFT limit is too strong (Off-shell suppression & Coupling change in EFT $1/m_{med}^2$ versus phase space factor in FT - mediator production).

Simplified model

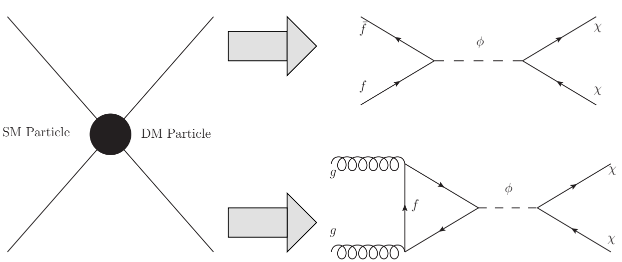
For fermion DM with scalar mediator:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi \bar{\chi}\chi - g_\chi \phi \bar{\chi}\chi - \sum_f g_v \frac{y_f}{\sqrt{2}} \phi \bar{f} f$$

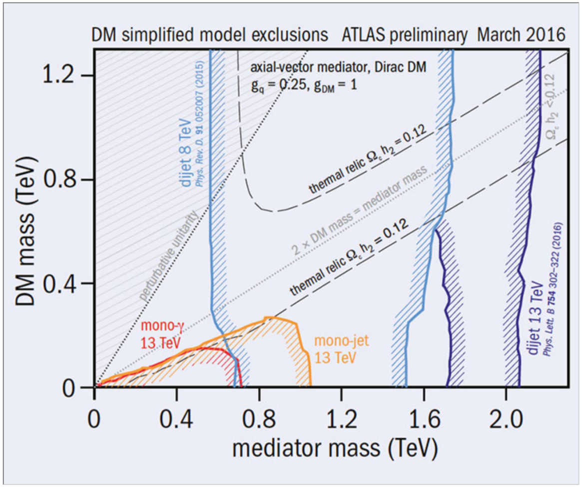
Four(Five) parameters:

$$m_\chi, \quad m_\phi, \quad g_\chi, \quad g_v, \quad \Gamma_\phi$$

Production process:

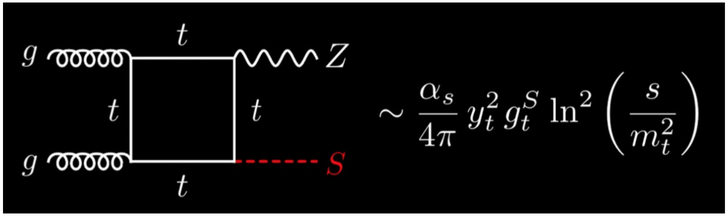


Bound are shown with fixing some parameters



Simplified model

- Unitarity:



U. Haisch

- Gauge symmetry,

$$\phi \cdot \bar{f} f = \phi \cdot (\bar{f}_L f_R + \bar{f}_R f_L)$$

- Lack of some gauge invariant interactions

$$S|H|^2, \quad S^2|H^2|, \quad S^3, \quad S^4$$

Towards complete model - Fermion DM

Simplest extension of the SM including fermion DM ($Z_2 : \ \chi \to -\chi$)

$$\mathcal{L}_{\text{FDM}} = \mathcal{L}_{\text{SM}} + \bar{\chi}(i\partial\!\!\!/ - m_\chi - g_\chi S)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2$$
$$- \lambda_{HS} H^\dagger H S^2 - \mu_0^3 S - \mu_1 S H^\dagger H - \frac{\mu_2}{3!}S^3 - \frac{\lambda_S}{4!}S^4$$

After EW symmetry breaking, portal includes two propagators:

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H2 \end{pmatrix}$$

Interacitions of DM and SM particles:

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

Towards complete model - Vector DM

Introduce an abelian dark gauge group $U(1)_X$ and a dark Higgs Φ

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

Z_2 symmetry: $V_\mu \to -V_\mu, \quad D_\mu = (\partial_\mu + i g_V Q_\Phi V_\mu)\Phi$

Interaction Lagrangian:

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

Towards complete model - Scalar DM

The SDM model can be constructed by simply introducing a new scalar S in addition to the SM

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

$$H \to (0, (v_h + h)/\sqrt{2})^T, \qquad \langle S \rangle = 0$$

Interaction Lagrangian:

$$\mathcal{L}_{\rm SDM}^{\rm int} = h \, [\frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v_h} Z_\mu Z^\mu] + \lambda_{HS} v_h \, h S^2$$

Outline

Benchmark points

- The relevant parameter in FDM for collider search: $g_\chi = 3, \ \sin\alpha = 0.3, \ m_\chi = 80$ GeV and $m_{H_2} = (200, \ 300, \ 400, 500)$ GeV.
- Parameters for the vector DM production are chosen accordingly: $\sin\alpha = 0.3, \ m_V = 80$ GeV and g_V is chosen such that the total decay width of H_2 is the same as benchmark points of FDM.

m_{H_2} [GeV]	200	300	400	500
$\Gamma_{\rm min}(H_2)$ [GeV]	14.2	60.1	103.0	144.5
g_V	3.53	3.07	2.37	1.91

- Fix $m_S = 80$ GeV and take appropriate λ_{HS} such that the production cross section of the signal process is the same with that in the FDM.

Features of DM spin at the ILC

The dominant DM production process:

$$e^+e^- \to Z(\to f f)\ H_{1,2}(\to DD)$$

DM pair four-momentum:

$$P^\mu_{DD} = P^\mu_{e^+} + P^\mu_{e^-} - P^\mu_Z = (\sqrt{s} - E_Z, -\vec{p}_Z)$$

DM pair invariant mass:

$$m^2_{DD} = s + m^2_Z - 2E_Z\sqrt{s}$$

Differential cross section:

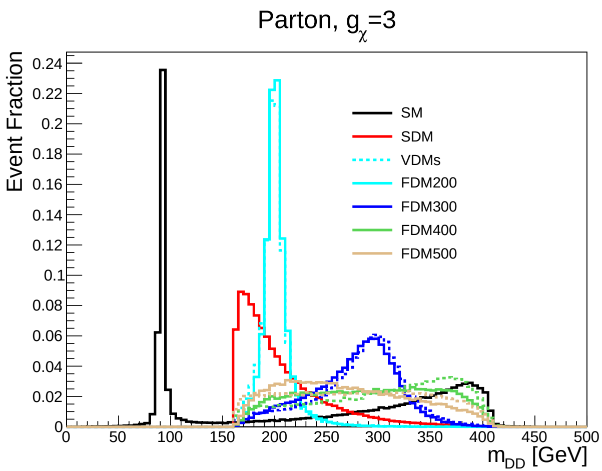
$$\frac{d\sigma_D}{dt} = \frac{1}{2\pi}\sigma_{h^*Z}(s,t) \cdot G_D(t)$$

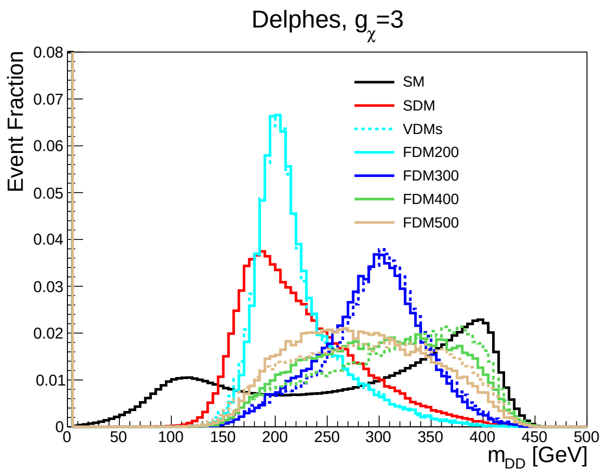
$$G_S(t) = \frac{\beta_S}{8\pi} \cdot \left|\frac{\lambda_{HS} v_h}{t - m_h^2 + i m_h \Gamma_h}\right|^2,$$

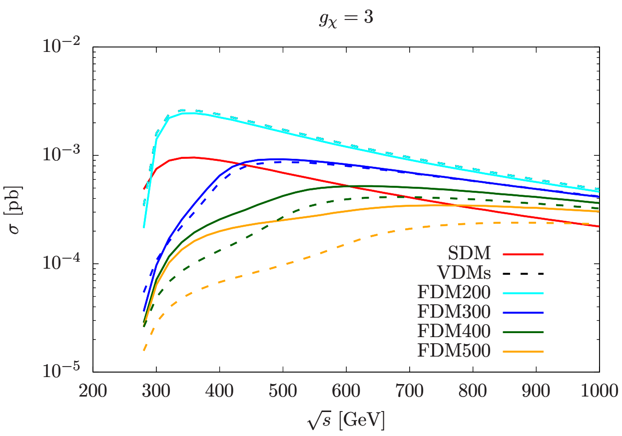
$$G_\chi(t) = \frac{\beta_\chi^3}{8\pi} 2 g_\chi t \cdot \left|\frac{1}{t - m^2_{H_1} + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m^2_{H_2} + i m_{H_2}\Gamma_{H_2}}\right|^2,$$

$$G_V(t) = \frac{\beta_V}{16\pi}\frac{g_V^2 t^2}{4m_V^2}\left(1 - \frac{4m_V^2}{t} + \frac{12 m_V^4}{t^2}\right) \cdot \left|\frac{1}{t - m^2_{H_1} + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m^2_{H_2} + i m_{H_2}\Gamma_{H_2}}\right|^2$$

Features of DM spin at the ILC

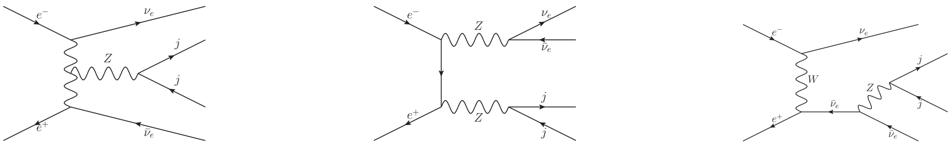




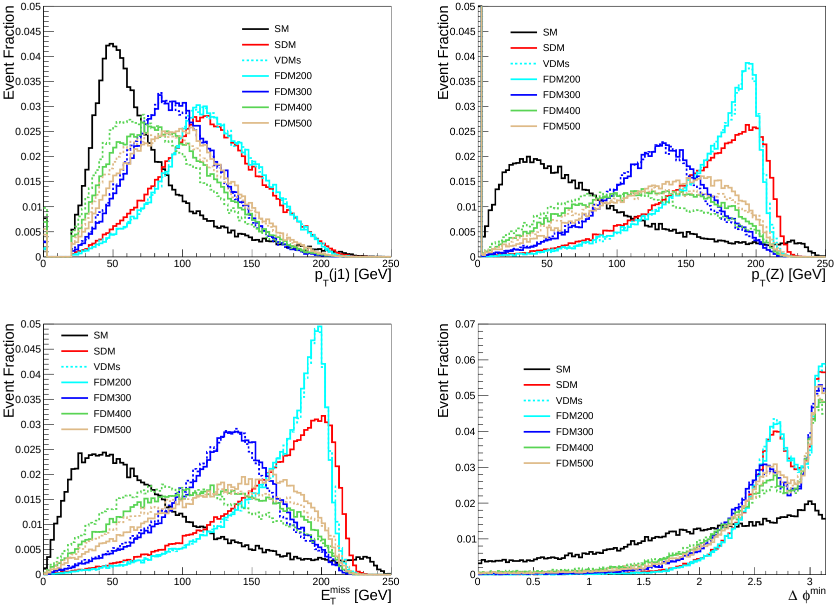


Discovery prospects of the hadronic channel

Dominant background processes:



Kinematic distributions:



$$\Delta\phi^{\min} = \min_{i=1,2} \Delta\phi(p_T^{\text{miss}}, p(j_i))$$

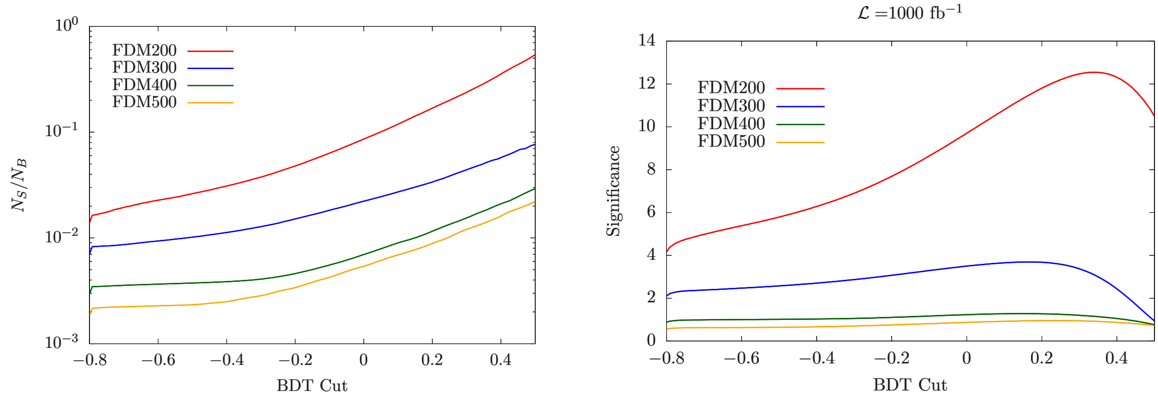
Discovery prospects of the hadronic channel (FDM)

Preselection cuts:

- Lepton veto
- Exactly two jets
- $E_T^{\text{miss}} > 50$ GeV

Boosted decision tree analysis with inputs:

$$m_{DD},\ p_T(j_1),\ p_T(Z),\ E_T^{\text{miss}},\ \Delta\phi^{\text{min}},\ p_T(j_2),\ m_{jj}$$



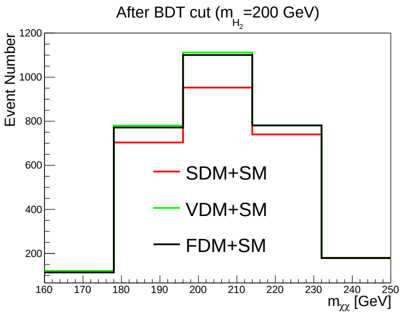
Discovery prospects of the hadronic channel (FDM)

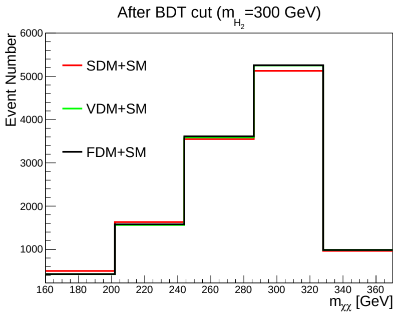
	FDM200	FDM300	FDM400	FDM500
σ^0 [fb]	1.643	0.9214	0.4221	0.2526
ϵ^{pre}	0.796	0.717	0.655	0.698
BDT	0.3615	0.2132	0.1929	0.2129
$N_S/1000\ \text{fb}^{-1}$	697.8	410.5	148	102
$N_B/1000\ \text{fb}^{-1}$	2248.5	11453.5	12736	10898
$N_S/\sqrt{N_S+N_B}$	12.85	3.769	1.31	0.97

Spin characterization

The same preselection and BDT cuts as used for FDM the benchmark point FDM200 (FDM300) are applied to the corresponding benchmark point SDM200 (SDM300) and VDM200 (VDM300).

	SDM200	SDM300	VDM200	VDM300
σ^0 [fb]	1.643	0.9214	1.734	0.8674
ϵ^{pre}	0.7875	0.7875	0.801	0.711
$N_S/1000\ \text{fb}^{-1}$	447	322.3	726	363.5
$\mathcal{S}$	4.4	3.3	0.59	0.44



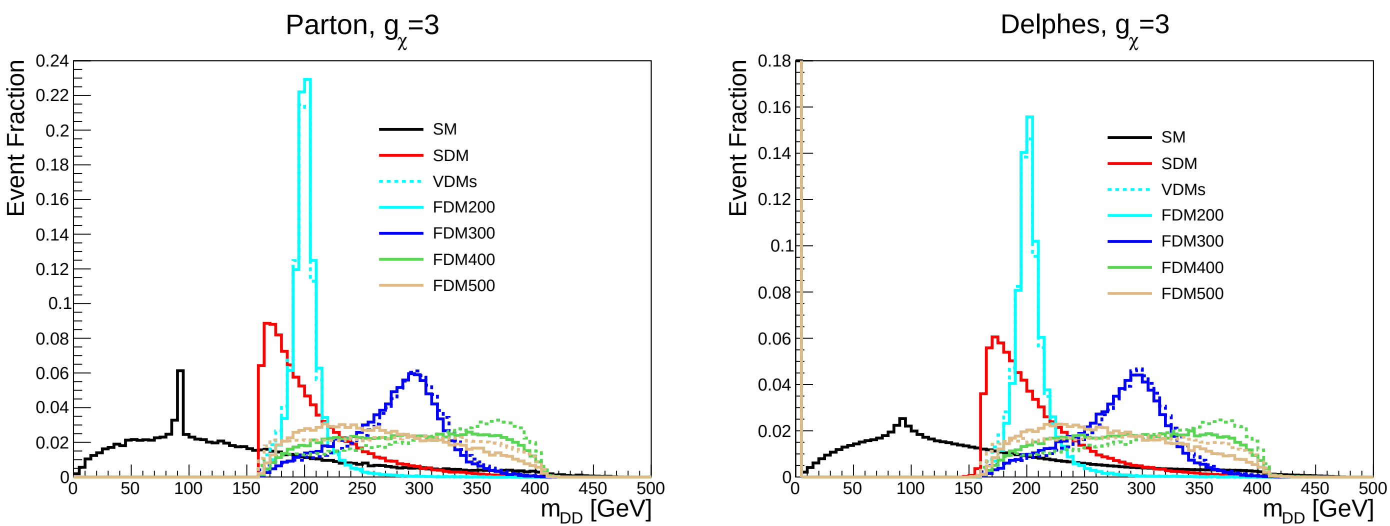


$$\text{SDM: } \delta\chi^2 = \sum_{i=1}^{5} \frac{N_i^{\text{FDM+SM}} - N_i^{\text{SDM+SM}}}{\sqrt{N_i^{\text{FDM+SM}}}}$$

$$\text{VDM: } \mathcal{S} = |N_S^{\text{FDM}} - N_S^{\text{VDM}}|/\sqrt{N_B}$$

The leptonic channel

- Smaller signal production rate: $\mathrm{Br}(Z \to \ell^+\ell^-) \sim 0.1{\times}\mathrm{Br}(Z \to qq)$
- Lager background cross section: signal and pair W prodution
- Better final state resolution



Discovery prospects of the leptonic channel

Preselection cuts:

- Jet veto
- Exactly two opposite sign same flavor leptons
- $E_T^{\text{miss}} > 50$ GeV
- Two leptons invariant mass $m_{\ell\ell} \in [75, 105]$ GeV
- Two DM invariant mass $m_{DD} > 160$ GeV

Boosted decision tree analysis with inputs:

$$p_T(\ell_1),\ p_T(\ell_2),\ E_T^{\text{miss}},\ m_{\ell\ell},\ m_{DD},\ p_T(Z),\ \Delta r(\ell,\ell),\ \Delta\phi^{\text{min}}$$

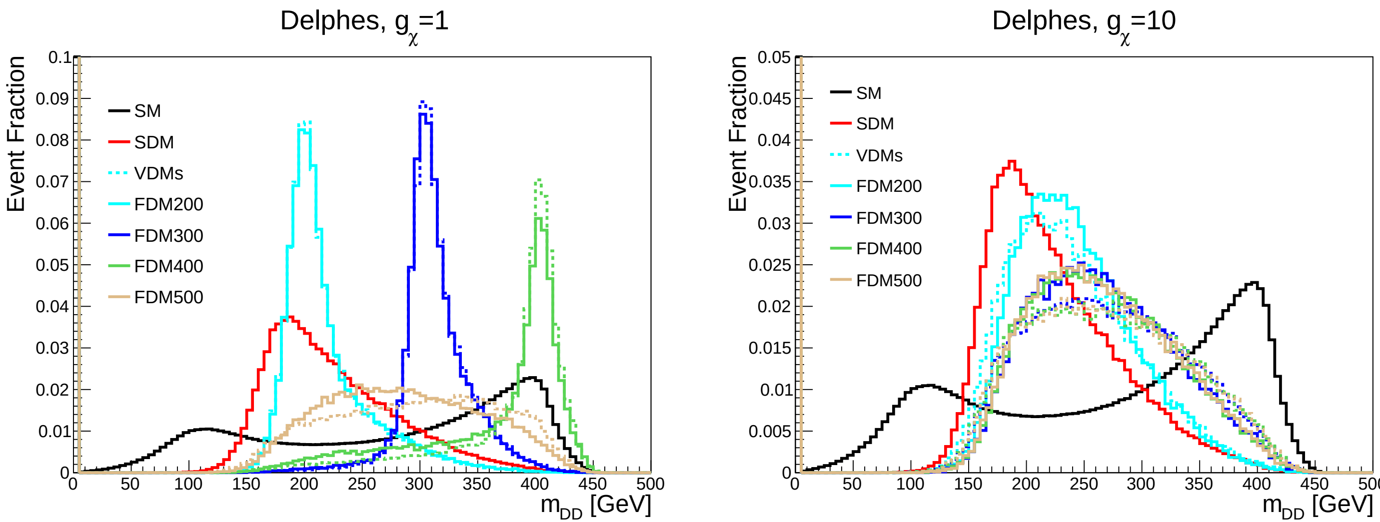
Leptonic channel	FDM200	FDM300	FDM400	FDM500
σ^0 [fb]	0.2101	0.1181	0.0541	0.0323
ϵ^{pre}	0.722	0.703	0.652	0.677
BDT	0.3775	0.25	0.26	0.335
$N_S/1000\ \text{fb}^{-1}$	85	47	16	9.72
$N_B/1000\ \text{fb}^{-1}$	151	1395	1376	830
$N_S/\sqrt{N_S+N_B}$	5.5	1.24	0.43	0.34

Spin characterization of the leptonic channel

Leptonic channel	SDM200	VDM200
σ^0 [fb]	0.2101	0.2217
$\epsilon^{\rm pre}$	0.716	0.726
$N_S/1000\ \rm fb^{-1}$	35.4	88.1
$\mathcal{S}$	2.7	0.25

Varying the coupling: $g_\chi = 1$, $g_\chi = 10$

- The benchmark points in VDM and SDM are chosen with the same strategy as before.
- Changing of the H_2 decay width
- Off-shell contribution become important when g_χ is large



Discovery prospects for varying g_χ

		FDM200	FDM300	FDM400	FDM500
$g_\chi = 1$	σ^0 [fb]	1.73	0.85	0.15	0.031
	ϵ^{pre}	0.799	0.700	0.334	0.686
	BDT	0.3391	0.2383	0.0564	0.2402
	$N_S/1000\ \text{fb}^{-1}$	774	374.6	38.1	10.8
	$N_B/1000\ \text{fb}^{-1}$	1922.2	6348.9	31910.6	9130.4
	$N_S/\sqrt{N_S+N_B}$	14.9	4.6	0.213	0.113
$g_\chi = 10$	σ^0 [fb]	1.78	1.88	1.80	1.76
	ϵ^{pre}	0.776	0.735	0.731	0.738
	BDT	0.2931	0.2610	0.2706	0.2816
	$N_S/1000\ \text{fb}^{-1}$	762.8	755	706.6	697
	$N_B/1000\ \text{fb}^{-1}$	5105	7416	7293	7194
	$N_S/\sqrt{N_S+N_B}$	9.96	8.35	7.9	7.8

Spin characterization for varying g_χ

- $g_\chi = 1$:

	SDM200	SDM300	VDM200	VDM300
σ^0 [fb]	1.73	0.85	1.74	0.84
$\epsilon^{\rm pre}$	0.787	0.787	0.803	0.697
$N_S/1000$ fb^{-1}	461.6	44.2	777.6	363.5
$\mathcal{S}$	6.7	3.1	-	-

- $g_\chi = 10$:

	SDM200	SDM300	SDM400	SDM500	VDM200	VDM300	VDM400	VDM500
σ^0 [fb]	1.78	1.88	1.80	1.76	2.08	1.77	1.02	0.643
$\epsilon^{\rm pre}$	0.7875	0.7875	0.7875	0.7875	0.774	0.725	0.720	0.718
$N_S/1000$ fb^{-1}	744.1	898.8	859.8	832.9	848.3	633.2	360.4	228
$\mathcal{S}$	3.3	6.1	5.7	5.4	10.0	8.4	7.9	7.8

Conclusion

- The gauge invariant DM simplified models for FDM and VDM require at least two mediators.
- For the benchmark scenario with $g_\chi = 3$: (1) $m_{H_2} \lesssim 300$ GeV can be probed at more than 3-σ level; (2) For those discoverable benchmark points in the FDM model, the spin discriminating against SDM can be made with $\gtrsim$3-σ level, spin discriminating against VDM is difficult.
- The leptonic channel has worse discovery potential than the hadronic channel.
- The smaller g_χ increase the difference between the $m_{\chi\chi}$ distributions of the FDM and the SDM models, achieve better signal significances and spin discriminating powers.
- For g_χ approaching the perturbative limit, benchmark points with H_2 in the full mass region of interest are discoverable and the spin discriminating against both the SDM and VDM are quite promising.