

Detecting dark matter spins at future colliders

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Based on B. Dutta, T. Kamon, P. Ko, JL, arXiv: 1705.02149, 1712.05123

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The Third China LHC Physic workshop

Nanjing University

- 1 Gauge invariant models: FDM, VDM and SDM
 - Benchmark points
- 2 Collider signals of benchmark points
 - ILC
 - 100 TeV FCC-pp/SppC
- 3 Conclusion

Gauge invariant models: FDM, VDM and SDM

Lagrangians:

- $\mathcal{L}_{\text{FDM}} = \mathcal{L}_{\text{SM}} + \bar{\chi}(i\not{\partial} - m_\chi - g_\chi S)\chi + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_0^2 S^2 - \lambda_{HS}H^\dagger HS^2 - \mu_0^3 S - \mu_1 SH^\dagger H - \frac{\mu_2^2}{3!}S^3 - \frac{\lambda_S}{4!}S^4$
- $\mathcal{L}_{\text{VDM}} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi - \lambda_\Phi(\Phi^\dagger\Phi - \frac{v_\phi^2}{2})^2 - \lambda_{H\Phi}(H^\dagger H - \frac{v_h^2}{2})(\Phi^\dagger\Phi - \frac{v_\phi^2}{2})$
- $\mathcal{L}_{\text{SDM}} = \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_0^2 S^2 - \lambda_{HS}H^\dagger HS^2 - \frac{\lambda_S}{4!}S^4$

Interaction Lagrangians:

- $\mathcal{L}_{\text{FDM}}^{\text{int}} = -(H_1 \cos \alpha + H_2 \sin \alpha) \left[\sum_f \frac{m_f}{v_h} \bar{f}f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right] + g_\chi(H_1 \sin \alpha - H_2 \cos \alpha) \bar{\chi}\chi$
- $\mathcal{L}_{\text{VDM}}^{\text{int}} = -(H_1 \cos \alpha + H_2 \sin \alpha) \left[\sum_f \frac{m_f}{v_h} \bar{f}f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right] - \frac{1}{2}g_V m_V (H_1 \sin \alpha - H_2 \cos \alpha) V_\mu V^\mu$
- $\mathcal{L}_{\text{SDM}}^{\text{int}} = h \left[\sum_f \frac{m_f}{v_h} \bar{f}f - \frac{2m_W^2}{v_h} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h} Z_\mu Z^\mu \right] + \lambda_{HS} v_h h S^2$

Benchmark points

- The relevant parameters 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.

$$\begin{aligned} \Gamma_{\min}^{\text{FDM}}(H_2) &= \Gamma(H_2 \rightarrow \chi\chi) + \Gamma(H_2 \rightarrow WW/ZZ) + \Gamma(H_2 \rightarrow ff) \\ &= \cos^2 \alpha \cdot g_\chi^2 \frac{m_{H_2}}{8\pi} \left(1 - \frac{4m_\chi^2}{m_{H_2}^2}\right)^{3/2} + \sin^2 \alpha \cdot \frac{G_\mu m_{H_2}^3}{16\sqrt{2}\pi} \delta_V \sqrt{1 - 4\frac{m_V^2}{m_{H_2}^2}} \left(1 - 4\frac{m_V^2}{m_{H_2}^2} + 12\frac{m_V^4}{m_{H_2}^4}\right) \\ &\quad + \sin^2 \alpha \cdot \left(\frac{m_f}{v}\right)^2 \frac{3m_{H_2}}{8\pi} \left(1 - \frac{4m_f^2}{m_{H_2}^2}\right)^{3/2}, \end{aligned}$$

where f is the SM fermion, $V = Z, W$ and $\delta_V = 1(2)$ for $Z(W^\pm)$.

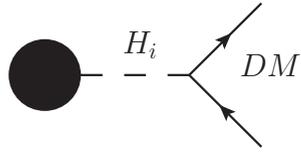
- Parameters for the vector DM production are chosen accordingly:
 $\sin \alpha = 0.3$, $m_V = 80$ GeV and g_V is chosen such that the total decay width of H_2 is the same as benchmark points of FDM.

m_{H_2} [GeV]	200	300	400	500
$\Gamma_{\min}(H_2)$ [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.

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General feature

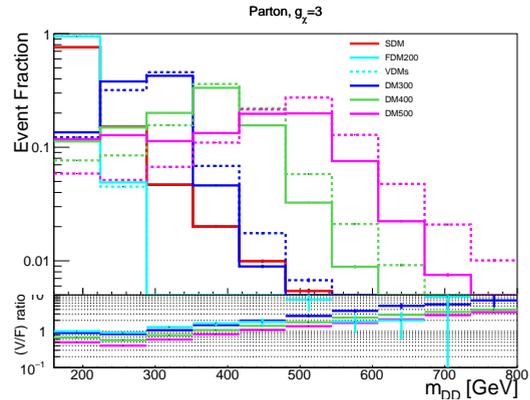
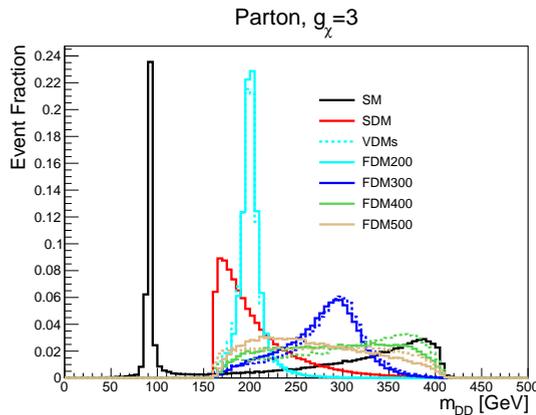


$$t \equiv m_{DD}^2$$

$$\frac{d\sigma_{\text{SDM}}}{dt} \propto \sigma_{\text{SDM}}^{h^*} \times \left| \frac{1}{t - m_h^2 + im_h\Gamma_h} \right|^2,$$

$$\frac{d\sigma_{\text{FDM}}}{dt} \propto \sigma_{\text{FDM}}^{h^*} \times \left| \frac{1}{t - m_{H_1}^2 + im_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + im_{H_2}\Gamma_{H_2}} \right|^2 \cdot (2t - 8m_\chi^2),$$

$$\frac{d\sigma_{\text{VDM}}}{dt} \propto \sigma_{\text{VDM}}^{h^*} \times \left| \frac{1}{t - m_{H_1}^2 + im_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + im_{H_2}\Gamma_{H_2}} \right|^2 \cdot \left(2 + \frac{(t - 2m_D^2)^2}{4m_V^4} \right).$$



Features of DM spin at the ILC

The dominant DM production process:

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

DM pair four-momentum:

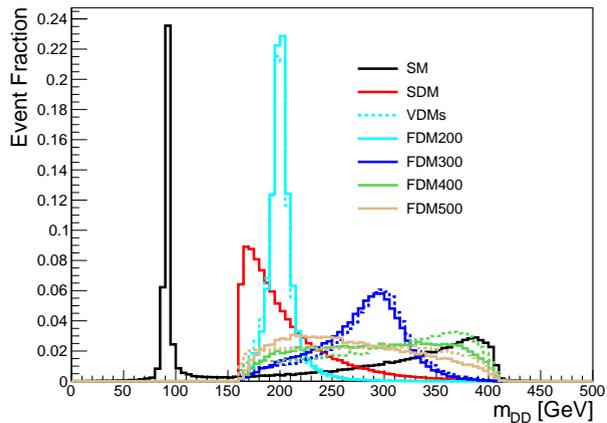
$$P_{DD}^\mu = P_{e^+}^\mu + P_{e^-}^\mu - P_Z^\mu = (\sqrt{s} - E_Z, -\vec{p}_Z)$$

DM pair invariant mass:

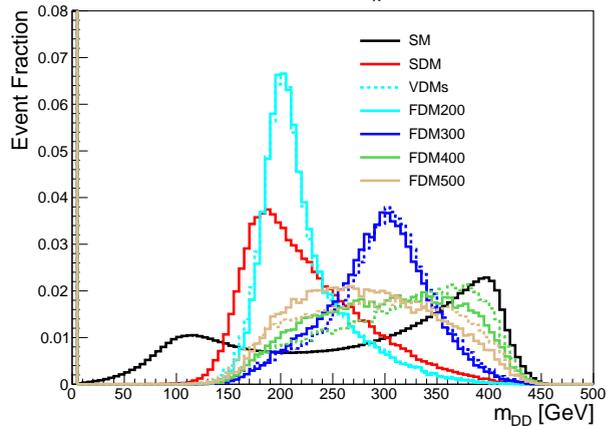
$$m_{DD}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$

Features of DM spin at the ILC

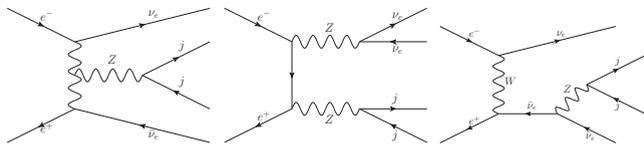
Parton, $g_\chi=3$



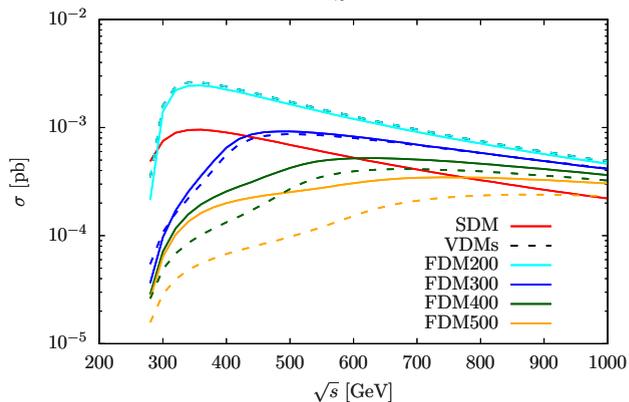
Delphes, $g_\chi=3$



Dominant background processes:

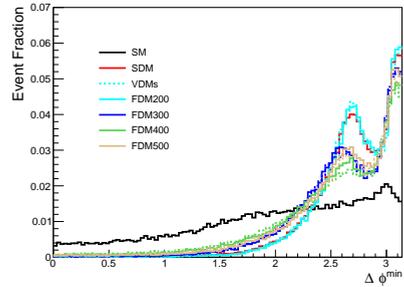
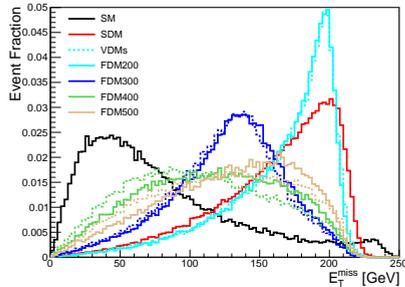
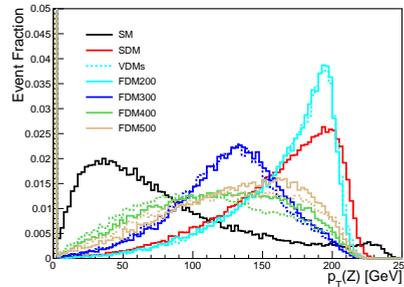
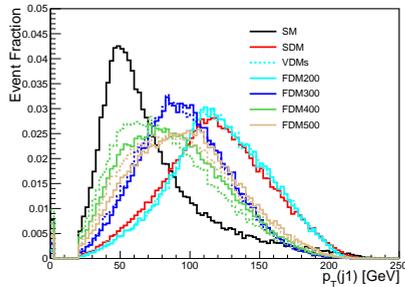


$g_\chi = 3$



Discovery prospects of the hadronic channel

Kinematic distributions:



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

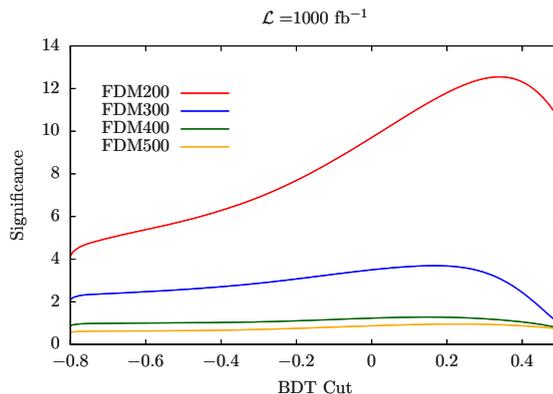
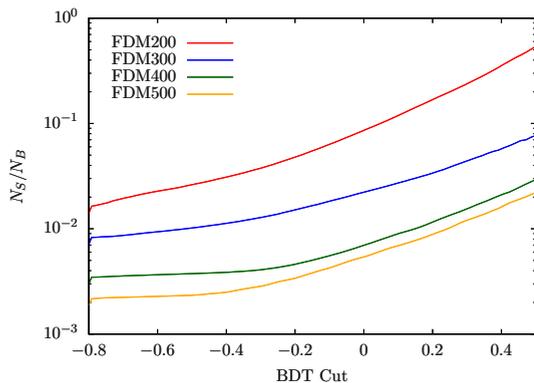
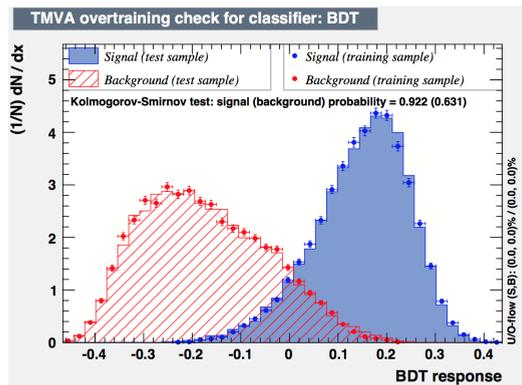
Discovery prospects of the hadronic channel (FDM)

Preselection cuts:

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

Boosted decision tree analysis with inputs:

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



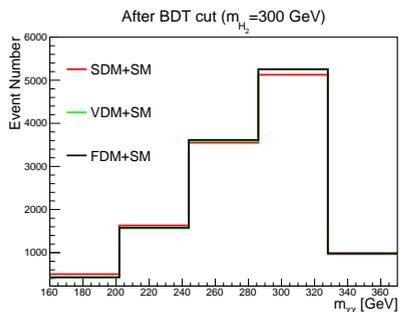
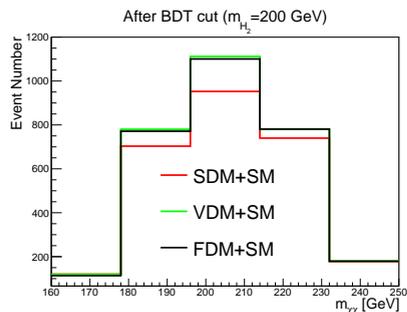
Discovery prospects of the hadronic channel (FDM)

	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

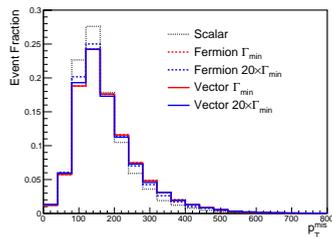
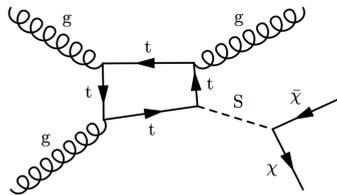


$$\text{SDM: } \delta\chi^2 = \sum_{i=1}^5 \left(\frac{N_i^{\text{FDM+SM}} - N_i^{\text{SDM+SM}}}{\sqrt{N_i^{\text{FDM+SM}}}} \right)^2$$

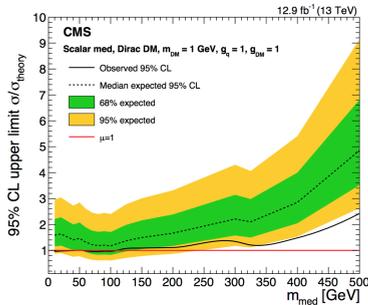
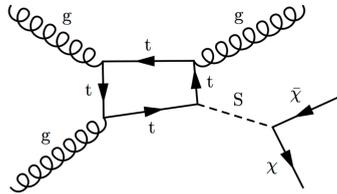
$$\text{VDM: } \mathcal{S} = |N_S^{\text{FDM}} - N_S^{\text{VDM}}| / \sqrt{N_B}$$

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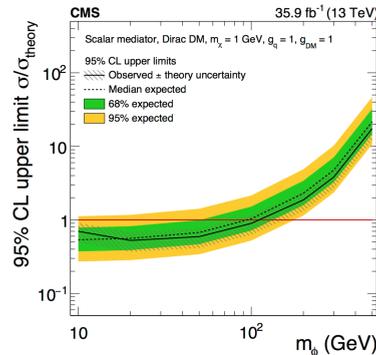
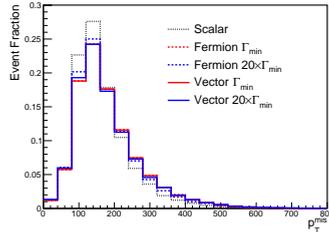
Signal: mono-jet?



Signal: mono-jet?



CMS mono-jet search,
arXiv:1703.01651



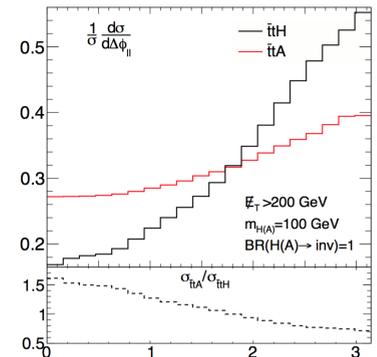
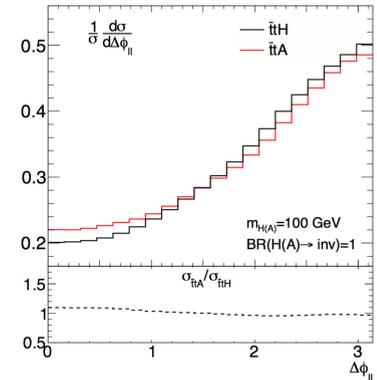
CMS $tt+DM$ search in dileptonic
channel,
arXiv:1711.00752

M. R Buckley et al.;

U. Haisch et al.;

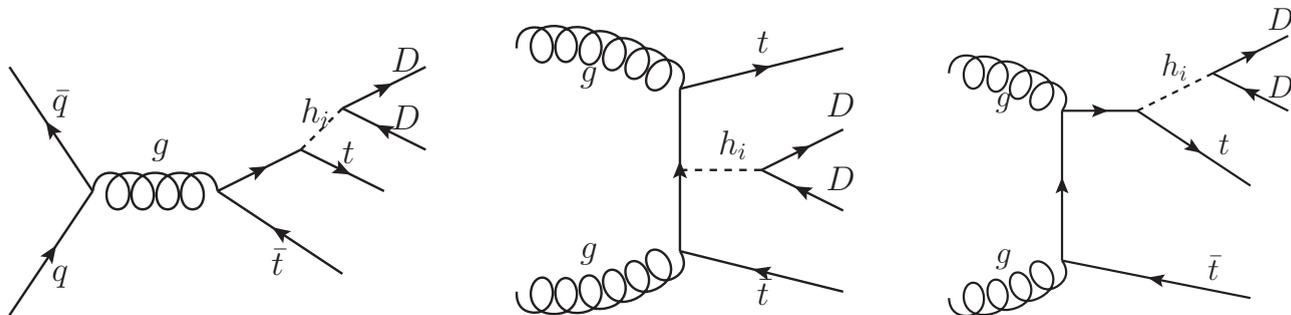
F. Boudjema et al.;

J. Ellis et al. ...



Signal and background

The dominant DM production process:

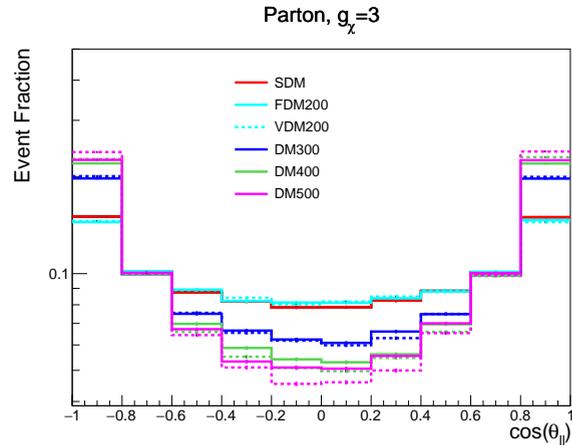
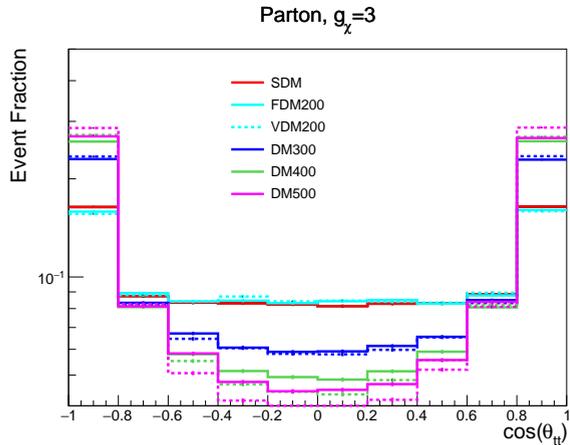
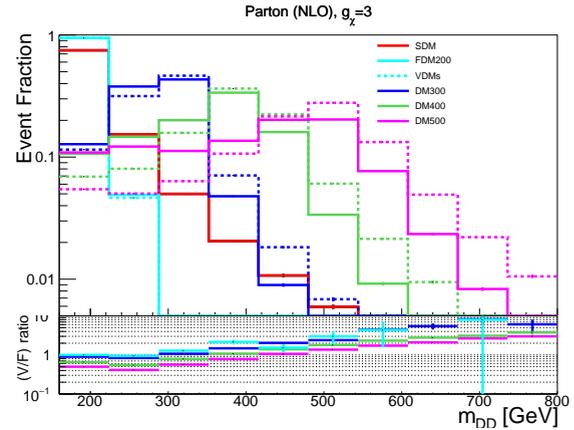
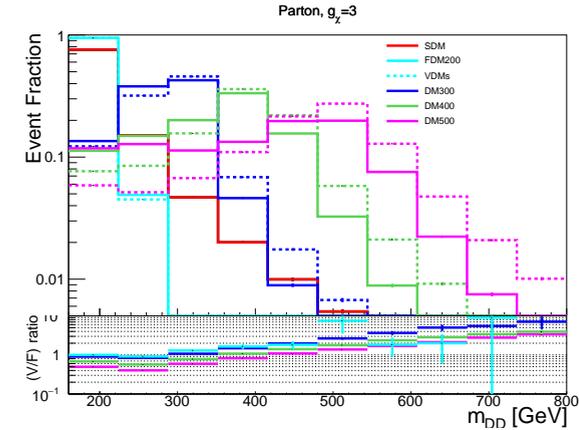


Dominant background processes:

	Cross section (NLO)
$\bar{t}t$	1316.5 pb
$\bar{t}tW$	20.5 pb
$\bar{t}tZ$	64.2 pb

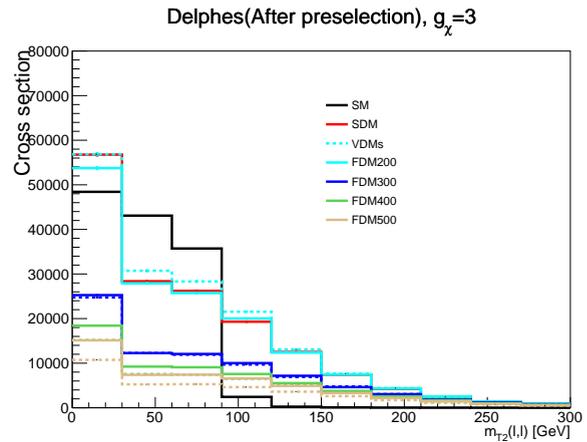
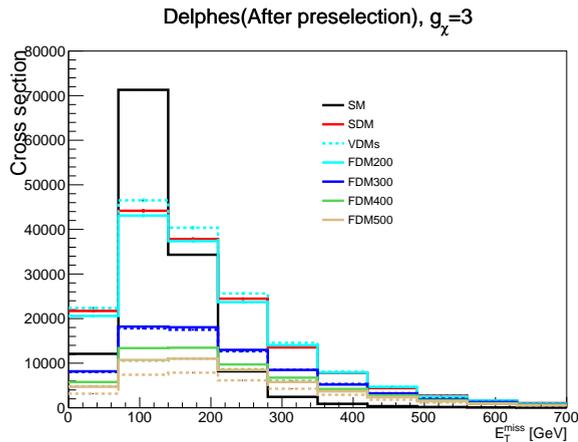
	$t(\rightarrow bl\nu)t(\rightarrow bl\nu) + \text{DM}$
FDM200	34.2 fb
FDM300	18.7 fb
FDM400	14.8 fb
FDM500	12.5 fb

Features of DM spin



Analysis strategy

- Preselection: Exactly two opposite sign lepton and at least one b jet in the final state.
- $m_{\ell\ell} \notin [85, 95] \text{ GeV}$.



- $E_T^{\text{miss}} > 150 \text{ GeV}$.
- $m_{T_2}(l,l) > 150 \text{ GeV}$.

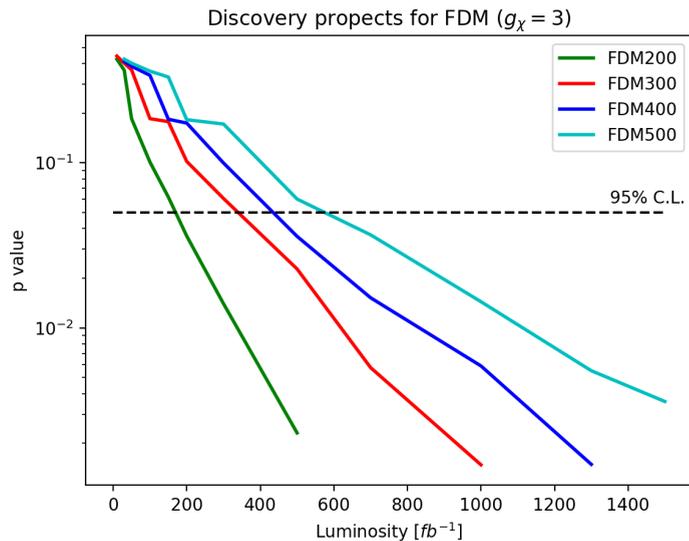
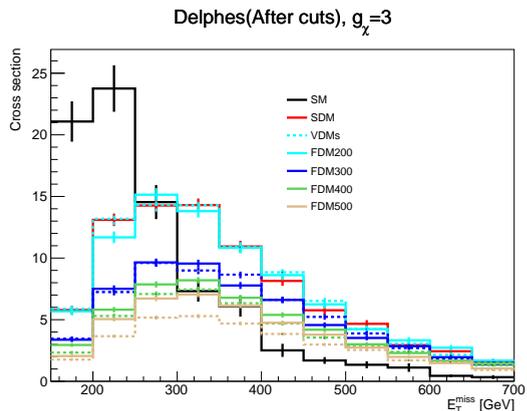
Cuts flow for SM processes and Signals

Backgrounds	$\bar{t}t$	$\bar{t}tW$	$\bar{t}tZ$
Cross section	1316.5 pb	20.5 pb	64.2 pb
Preselections	63.76 pb	351.8 fb	1.9 pb
$m_{\ell\ell} \notin [85, 95]$ GeV	59.8 pb	330.4 fb	1.05 pb
$E_T^{miss} > 150$ GeV	17.76 pb	69.61 fb	261.14 fb
$m_{T_2}(l, l) > 150$ GeV	23.83 fb	1.92 fb	32.1 fb

Signals	FDM200	FDM300	FDM400	FDM500
Cross section	34.2 fb	18.7 fb	14.8 fb	12.5 fb
Preselections	7.86 fb	3.99 fb	3.05 fb	2.55 fb
$m_{\ell\ell} \notin [85, 95]$ GeV	7.47 fb	3.82 fb	2.92 fb	2.44 fb
$E_T^{miss} > 150$ GeV	4.17 fb	2.44 fb	1.93 fb	1.63 fb
$m_{T_2}(l, l) > 150$ GeV	0.87 fb	0.62 fb	0.54 fb	0.47 fb
$\mathcal{L}^{95\%}$ [fb ⁻¹]	305	602	793	1047

Binned log-likelihood analysis:

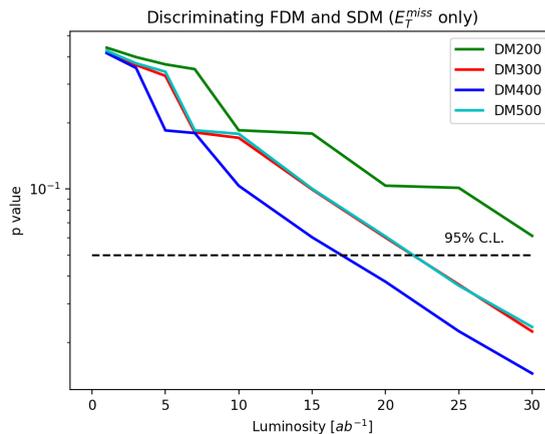
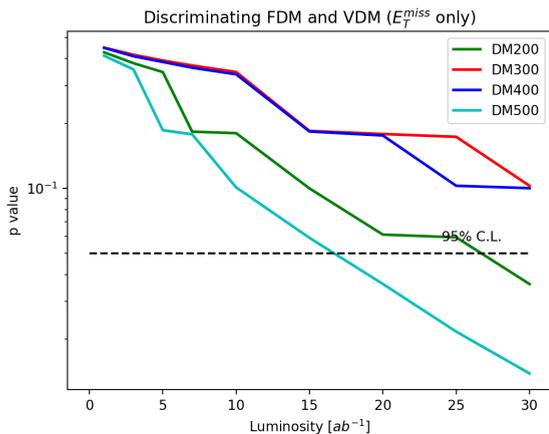
$$\mathcal{L}(\text{data}|\mathcal{H}_\alpha) = \prod_i \frac{t_i^{n_i} e^{-t_i}}{n_i!}, \quad \mathcal{Q} = -2 \log \left(\frac{\mathcal{L}(\text{data}|\mathcal{H}_\alpha)}{\mathcal{L}(\text{data}|\mathcal{H}_0)} \right).$$



Spin characterization

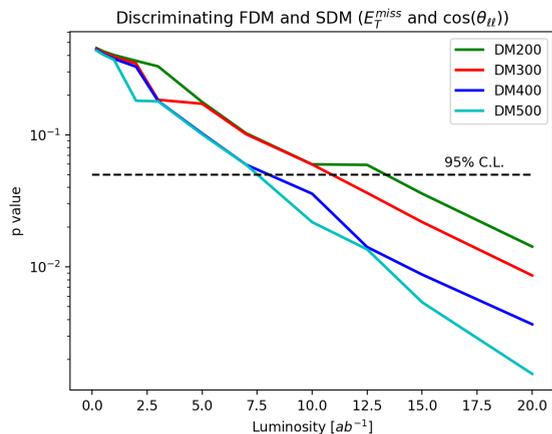
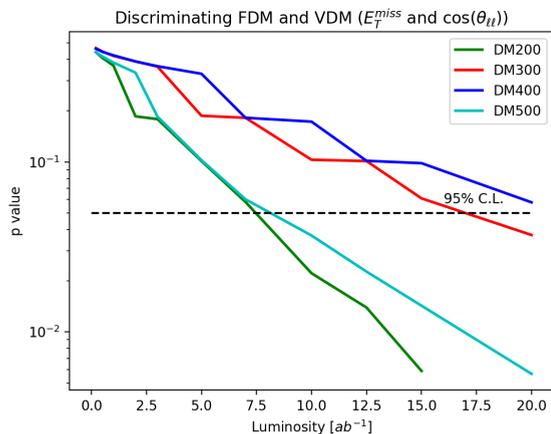
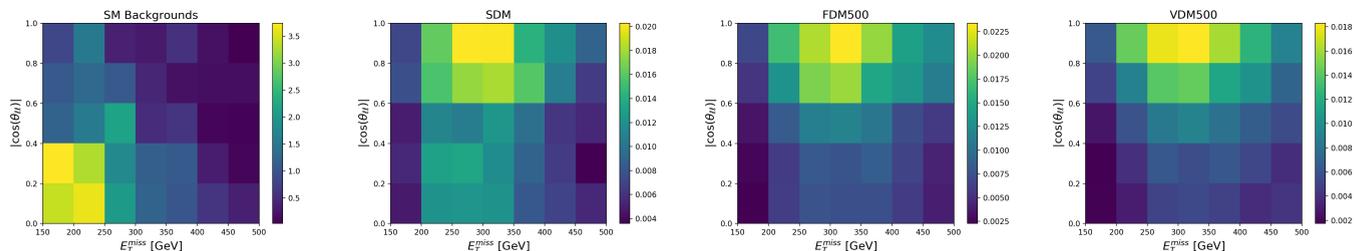
Using only the distribution of E_T^{miss} :

\mathcal{H}_0 is the FDM + SM, \mathcal{H}_α can be VDM/SDM + SM



Spin characterization (E_T^{miss} and $\cos(\theta_{\ell\ell})$)

Two dimensional binned log-likelihood test: $\mathcal{L}(\text{data}|\mathcal{H}_\alpha) = \prod_{i,j} \frac{n_{ij} e^{-t_{ij}}}{n_{ij}!}$



- The gauge invariant Higgs portal DM models for FDM and VDM require at least two mediators, while that of SDM only need one.
- At the ILC, (1) $m_{H_2} \lesssim 300$ GeV can be probed at more than $3\text{-}\sigma$ level; (2) For those discoverable benchmark points in the FDM model, the spin discriminating against SDM can be made with $\gtrsim 3\text{-}\sigma$ level, spin discriminating against VDM is difficult.
- At the 100 TeV $p\text{-}p$ collider, (1) All benchmark points should be probable at integrated luminosity of $\mathcal{O}(100)$ fb $^{-1}$ at 100 TeV $p\text{-}p$ collider; (2) The spin discriminations for our benchmark points are possible at $\mathcal{O}(10)$ ab $^{-1}$. (3) Those values are all below the targets luminosity of FCC-hh, which is ~ 20 ab $^{-1}$.