Characterizing DM properties with (non)minimal Higgs portal at future colliders

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

Aug. 28, 2018

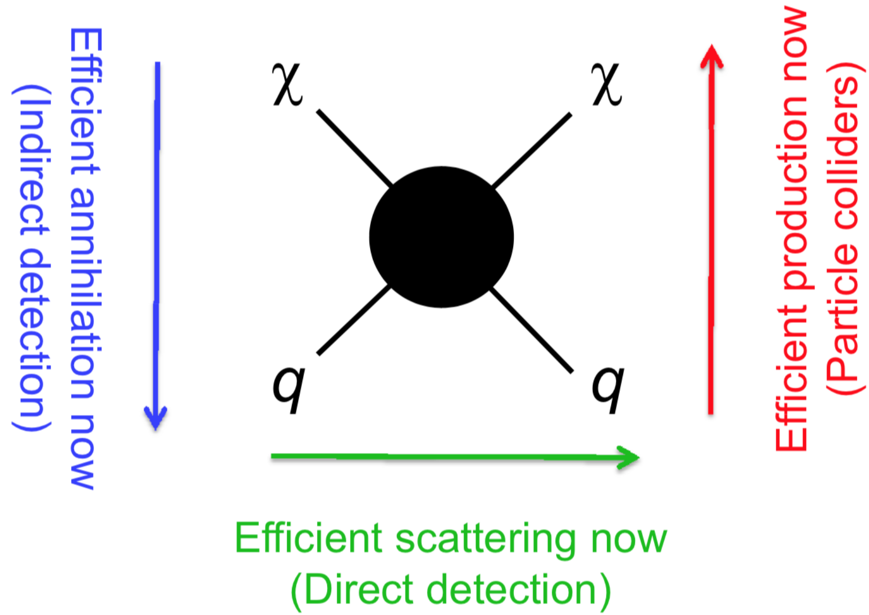
COSMO 2018

IBS, Daejon, Korea

Outline

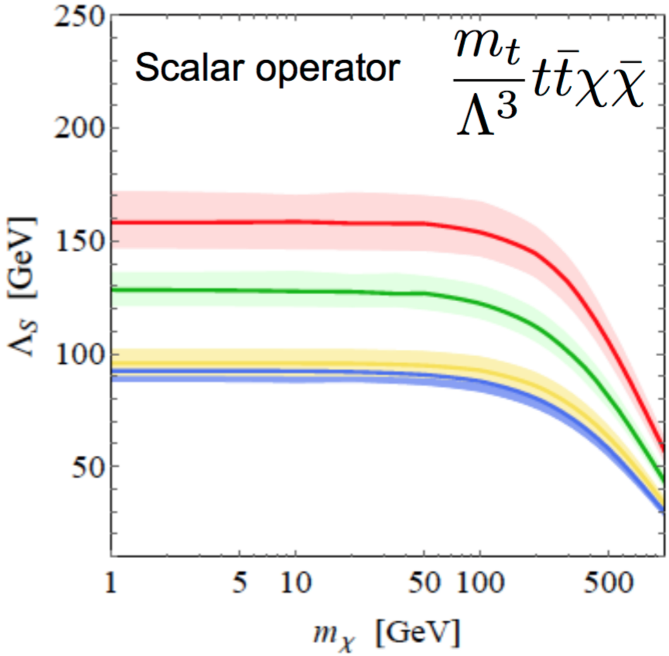
1. Generalities
2. Status of LHC searches for Higgs portal DM models
3. Prospects of searches at future colliders
   - 500 GeV ILC
   - 100 TeV FCC-pp/SppC
4. Conclusion

Crossing Relations and WIMP Detections



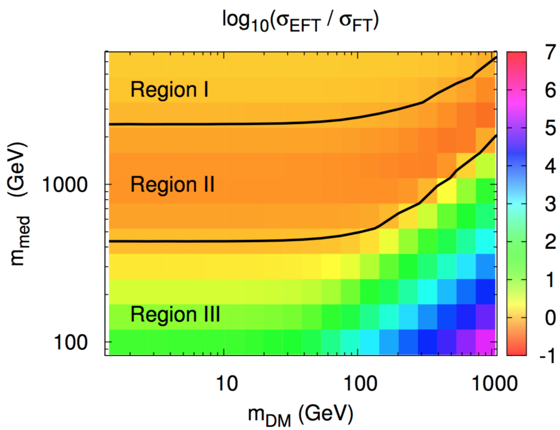
- Crossing sym is an exact sym of a single Lagrangian in QFT
- It should be applied to a model Lagrangian which is valid in all the relevant kinematic region
- One can not apply it to EFT or Simplified Models

1503.00691 (Ulrich Haisch, Emanuele Re)



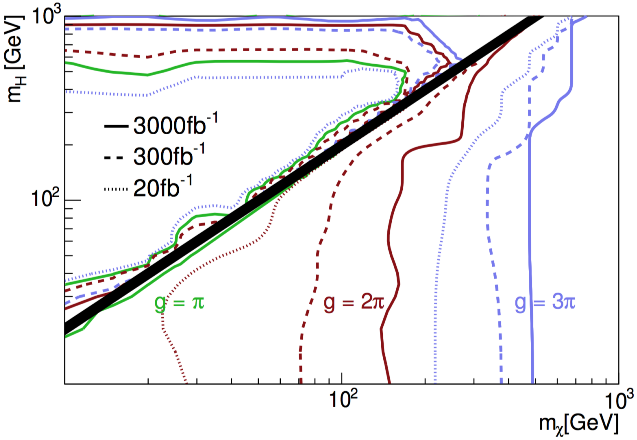
Limits after LHC run-1, red: mono-jet; green: one-lepton; yellow: two-leptons; blue: multi-jets.

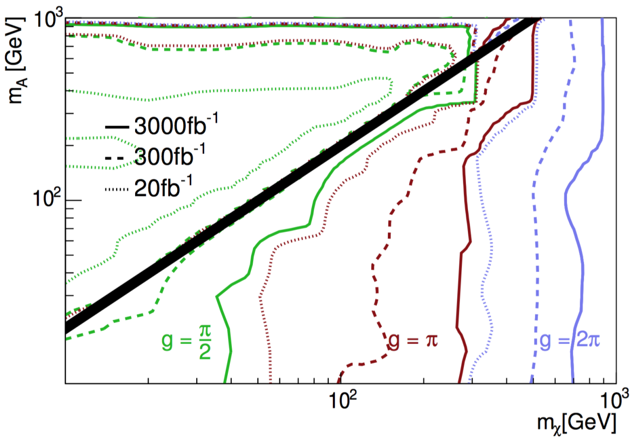
$\sigma_{\mathrm{EFT/FT}}(pp \to \chi\chi)$@LHC



- Region I: EFT limit is valid.
- Region II: Resonant enhancement in FT.
- Region III: $\sigma_{\mathrm{EFT}} \propto \frac{1}{m_{med}^2}$ VS phase space factor in FT

Scalar mediated simplified model





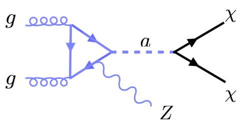
J. Brooke, M. Buckley, et. al. arXiv:1603.07739

$$\mathcal{L}_H \ni -g_\chi H\bar{\chi}\chi - \sum_f \frac{g_v y_f}{\sqrt{2}} H\bar{f}f$$

$$\mathcal{L}_A \ni -ig_\chi A\bar{\chi}\gamma^5\chi - \sum_f \frac{ig_v y_f}{\sqrt{2}} A\bar{f}\gamma^5 f$$

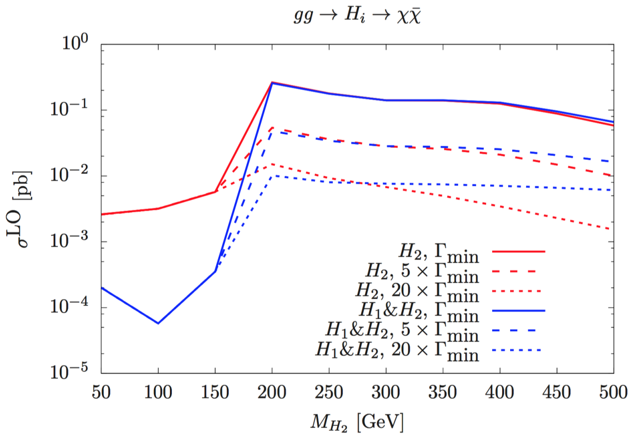
- Projected CMS invisible Higgs search in VBF
- Constraint on scalar is weaker than pseudoscalar, due to smaller cross section and a softer $E_T^{\rm miss}$.
- Requires sizeable coupling for detection ($g_v = g_\chi = g$), may not realistic, e.g. $\Gamma > m_{H/A}$.
- SM gauge symmetry is not conserved if H/A is an singlet.

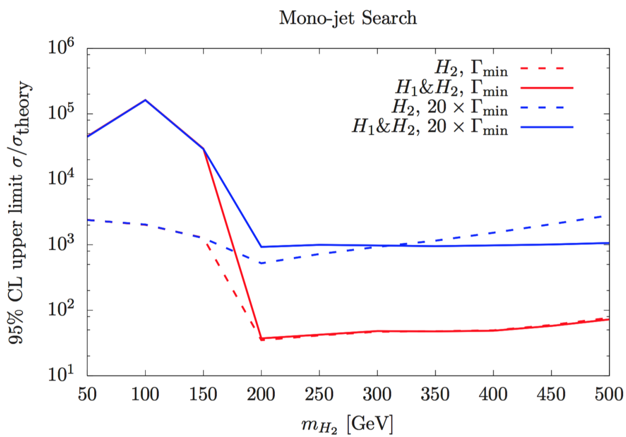
$$\phi \cdot \bar{f}f = \phi \cdot (\bar{f}_L f_R + \bar{f}_R f_L)$$

- 

$\propto \frac{\alpha_s}{4\pi} y_t\, g_t \log^2\left(\frac{s}{m_t^2}\right)$

Higgs portal dark matter model





$$\mathcal{L}_{\mathrm{FDM}} \ni -g_\chi S\bar{\chi}\chi - \lambda_{HS} H^\dagger H S^2 - \mu_0^3 S - \mu_1 S H^\dagger H - \frac{\mu_2}{3!} S^3 - \frac{\lambda_S}{4!} S^4$$

$$\mathcal{L}_{\mathrm{FDM}}^{\mathrm{int}} \ni -(H_1 \cos\alpha + H_2 \sin\alpha) \sum_f \frac{m_f}{v_h} \bar{f} f + g_\chi (H_1 \sin\alpha - H_2 \cos\alpha)\, \bar{\chi}\chi$$

- $g_\chi = 3,\ \sin\alpha = 0.3,\ m_\chi = 80$ GeV (Throughout the talk.)
- Production limited by SM Higgs-fermion couplings.
- Recast of the CMS invisible Higgs search in Mono-jet.
- Interference between two mediators (reduce the sensitivity at low M_{H_2}).
- All points way below the current LHC sensitivity.

P. Ko, J. Li. arXiv:1610.03997

Simplified vs. UV complete models

S. Baek, P. Ko, M.H. Park, W.I. Park, C. Yu, arXiv:1506.06556

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of $\mathcal{L}_{int} = \left(\frac{m_q}{v_H}\sin\alpha\right) S\bar{q}q - \lambda_s \cos\alpha S\bar{\chi}\chi$
- H.M.: A case where a Higgs is a mediator $\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right) H\bar{q}q - \lambda_s \sin\alpha H\bar{\chi}\chi$
- H.P.: Higgs portal model as in eq. (2).

$$\text{H.P.} \underset{m_{H_2}^2 \gg \hat{s}}{\longrightarrow} \text{H.M.},$$

$$\text{S.M.} \underset{m_S^2 \gg \hat{s}}{\longrightarrow} \text{EFT},$$

$$\text{H.M.} \neq \text{EFT}\,.$$

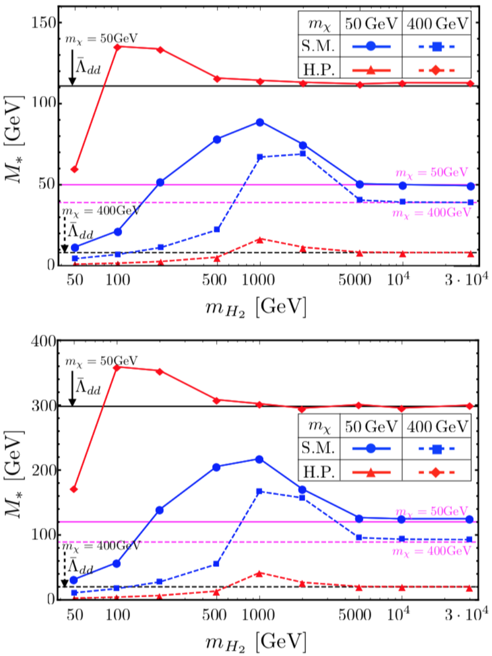


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass M_* through the Eq.(16)-(20). The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.

Outline

Minimal gauge invariant models: FDM, VDM and SDM

Lagrangians: Ko et al, arXiv:1112.1847 (SFDM), 1212.2131 (VDM)

- $\mathcal{L}_{\rm FDM} = \mathcal{L}_{\rm SM} + \bar{\chi}(i\partial\!\!\!/ - m_\chi - g_\chi S)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2 - \lambda_{HS} H^\dagger H S^2$
  $-\mu_0^3 S - \mu_1 S H^\dagger H - \frac{\mu_2}{3!} S^3 - \frac{\lambda_S}{4!} S^4$
- $\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi (\Phi^\dagger \Phi - \frac{v_\phi^2}{2})^2 - \lambda_{H\Phi}(H^\dagger H - \frac{v_h^2}{2})(\Phi^\dagger \Phi - \frac{v_\phi^2}{2})$
- $\mathcal{L}_{\rm SDM} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_0^2 S^2 - \lambda_{HS} H^\dagger H S^2 - \frac{\lambda_S}{4!} S^4$

Interaction Lagrangians:

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

Higgs portal DM within EFT

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

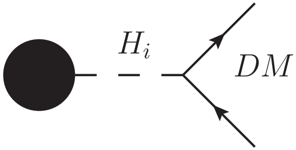
$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

- The models for the fermion and vector DM are not good, since
  - they are not renormalizable
  - not gauge invariant for vector DM case
  - thus they violate unitarity
- One cannot apply crossing relations for fermion or veector DM
- Need to work in (the simplest possible) UV completions
- In fact they are not even well-defined EFTs

General feature

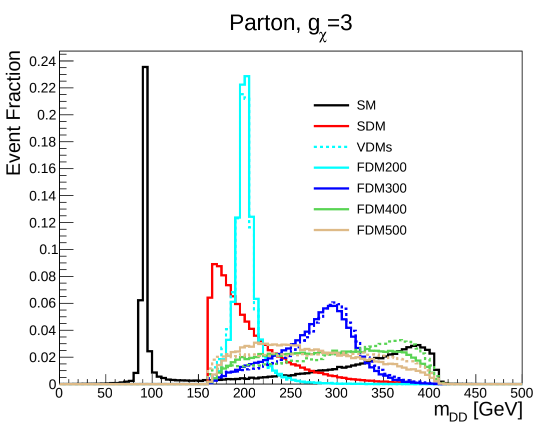


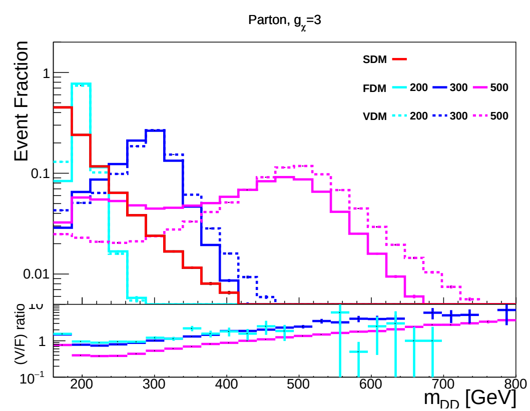
, $\quad t \equiv m_{DD}^2$

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

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

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





DM production at the ILC

The dominant DM production process:

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

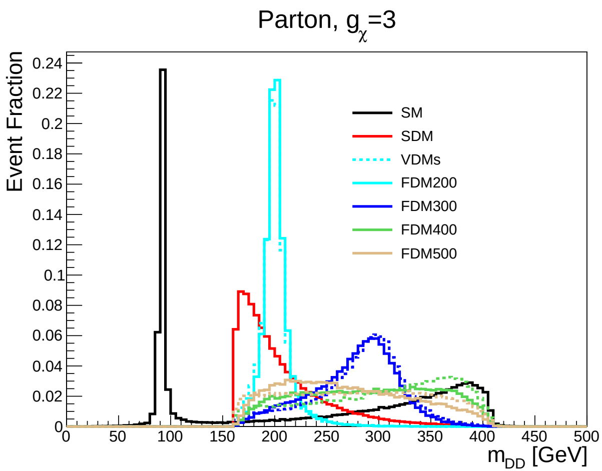
DM pair four-momentum:

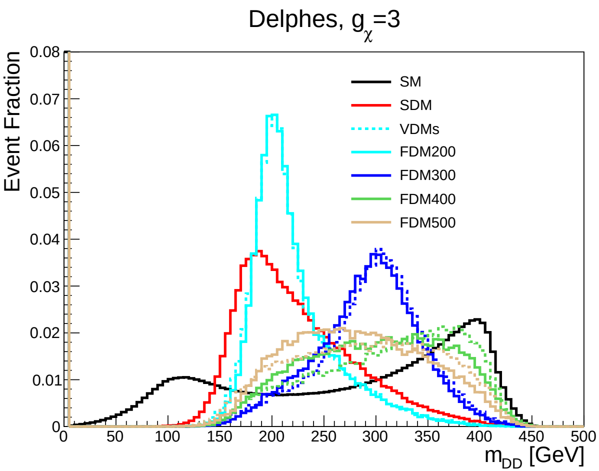
$$P^\mu_{DD} = P^\mu_{e^+} + P^\mu_{e^-} - P^\mu_Z = (\sqrt{s} - E_Z, -\vec{p}_Z)$$

DM pair invariant mass:

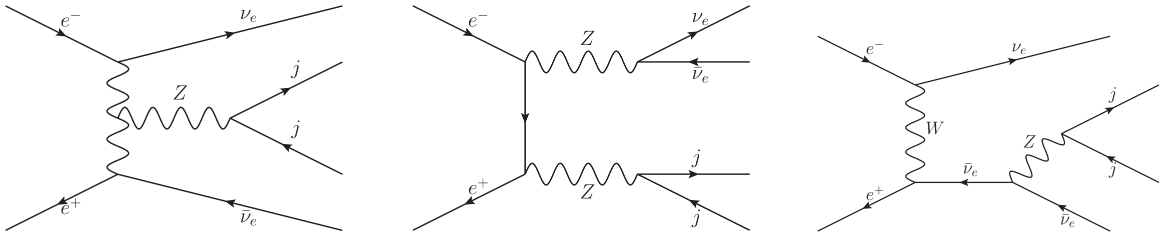
$$m^2_{DD} = s + m_Z^2 - 2E_Z\sqrt{s}$$

Features of DM production at the ILC

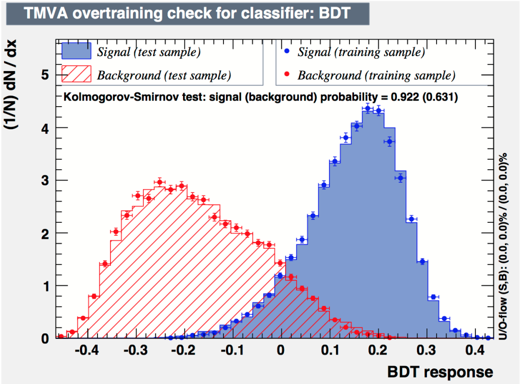




Dominant background processes:



Discovery prospects of the hadronic channel (FDM)

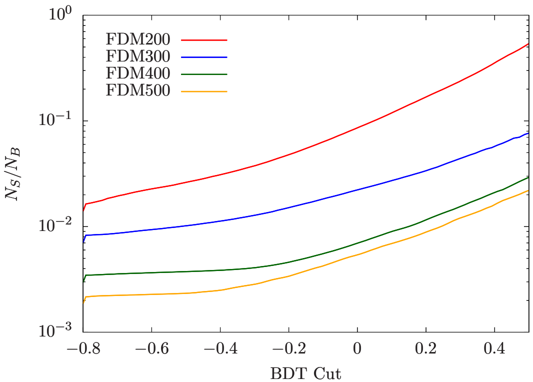


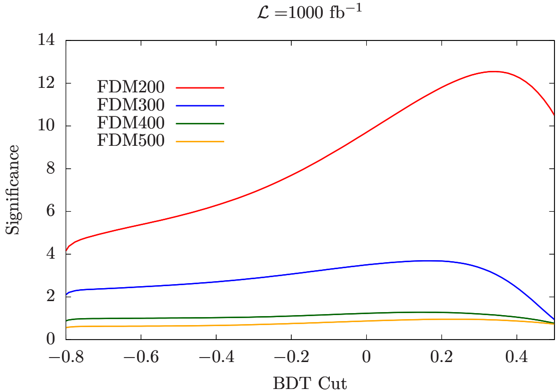
Preselection cuts:

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

Boosted decision tree analysis with inputs:

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





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

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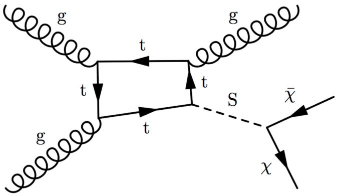
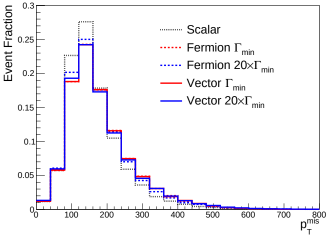
Signal: mono-jet?





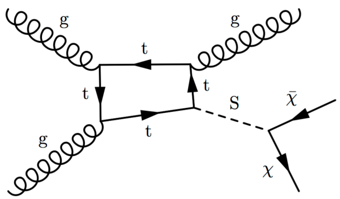
Signal: mono-jet?

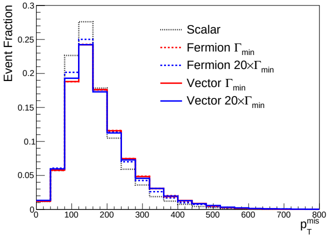
M. R Buckley et.al.;

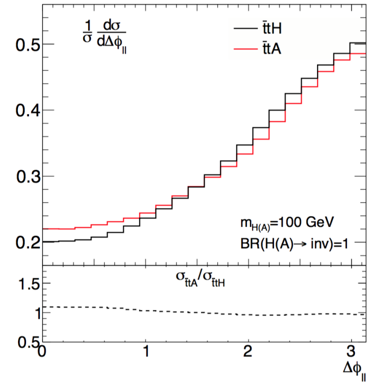
U. Haisch et.al.;

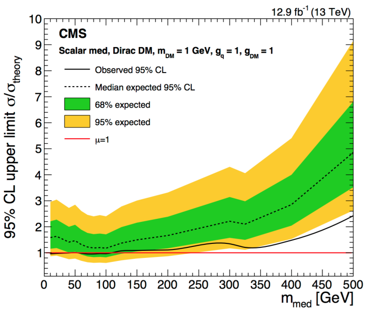
F.Boudjema et.al.;

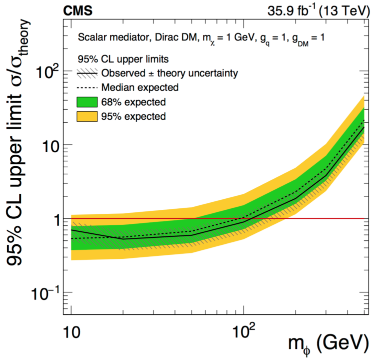
J. Ellis et.al. ...

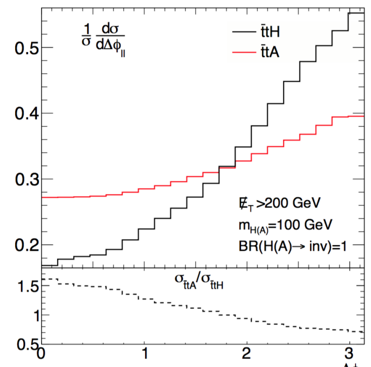








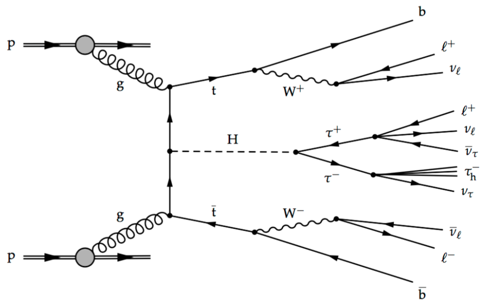




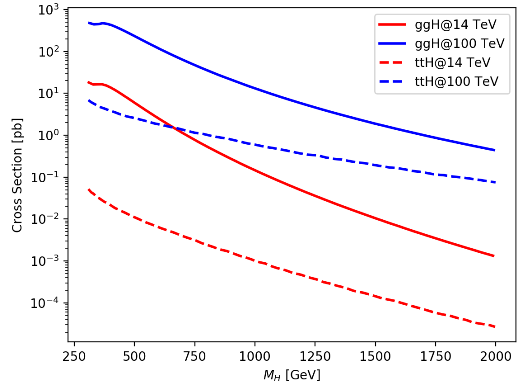
CMS mono-jet search, arXiv:1703.01651

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

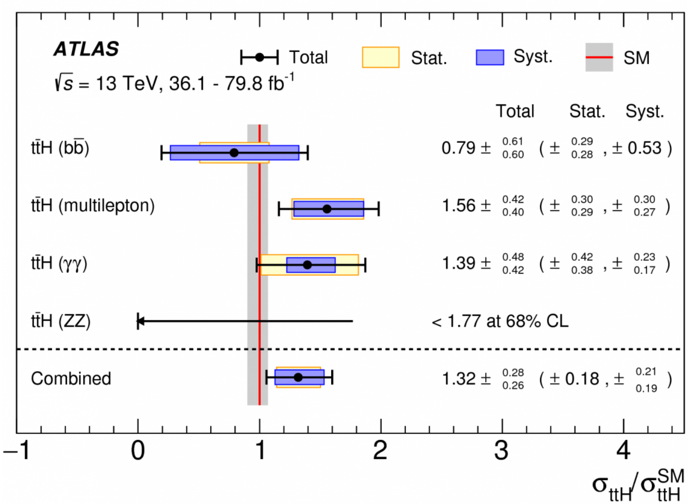
ttH channel is promising channel

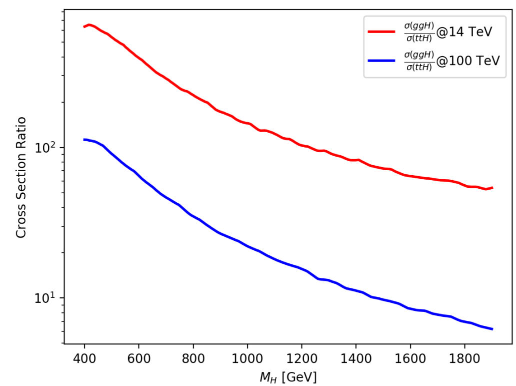


ttH cross section is enhanced more significantly with increasing collision energy.



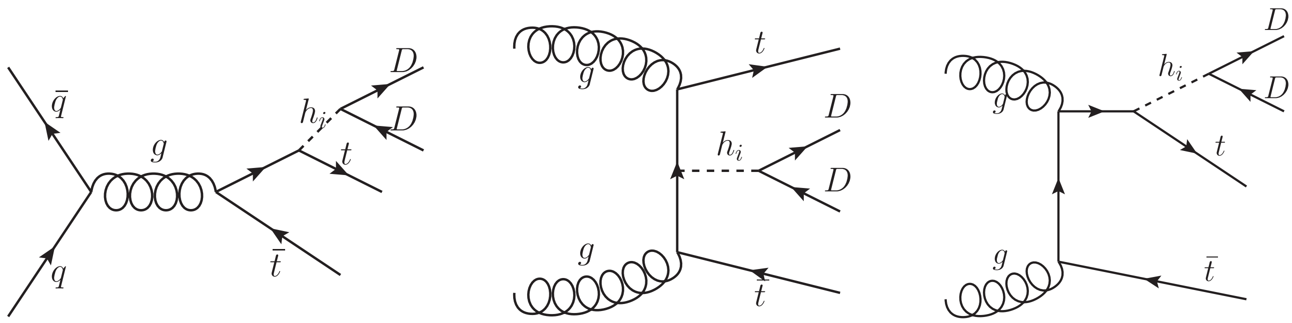
The observed (expected) significance of 5.8 (4.9) standard deviations





Signal and background

The dominant DM production process:



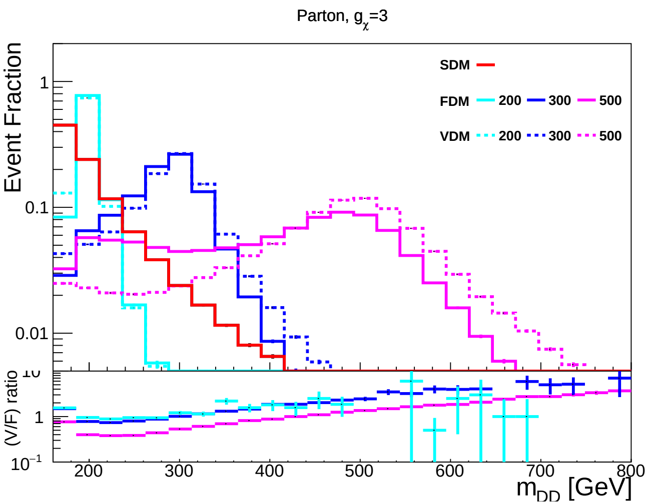
Dominant background processes:

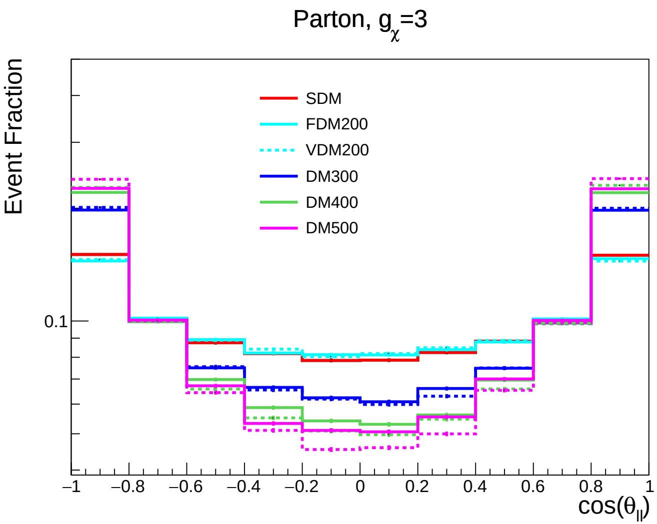
	Cross section (NLO)
$\bar{t}t$	1316.5 pb
$\bar{t}tW$	20.5 pb
$\bar{t}tZ$	64.2 pb
$W_\ell W_\ell b$	128.4 pb

Signal benchmark points:

	$t_\ell t_\ell +$ DM
FDM200	34.2 fb
FDM300	18.7 fb
FDM400	14.8 fb
FDM500	12.5 fb

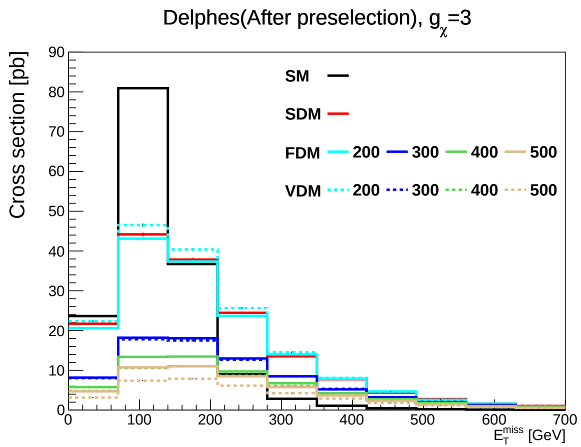
Features of DM spin

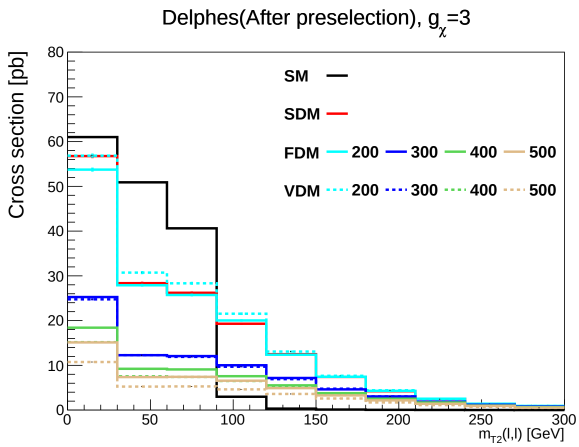




Analysis strategy

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





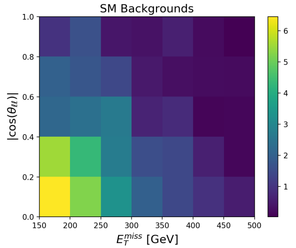
- $E_T^{miss} > 150$ GeV.
- $m_{T_2}(l, l) > 150$ GeV.

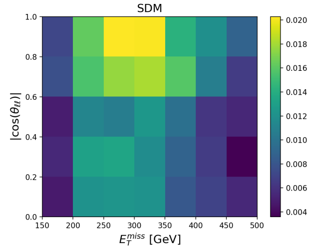
Cuts flow for SM processes and Signals

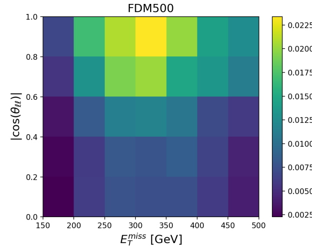
Backgrounds Cross section	$\bar{t}t$ 1316.5 pb	$\bar{t}tW$ 20.5 pb	$\bar{t}tZ$ 64.2 pb	$W_\ell W_\ell b$ 128.4 pb
Presections	63.76 pb	351.8 fb	1.9 pb	25.4 pb
$m_{\ell\ell} \notin [85, 95]$ GeV	59.8 pb	330.4 fb	1.05 pb	23.9 pb
$E_T^{miss} > 150$ GeV	17.76 pb	69.61 fb	261.14 fb	3.5 pb
$m_{T_2}(l, l) > 150$ GeV	23.83 fb	1.92 fb	32.1 fb	38.0 fb

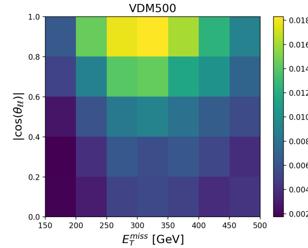
Signals Cross section	FDM200 34.2 fb	FDM300 18.7 fb	FDM400 14.8 fb	FDM500 12.5 fb
Presections	7.86 fb	3.99 fb	3.05 fb	2.55 fb
$m_{\ell\ell} \notin [85, 95]$ GeV	7.47 fb	3.82 fb	2.92 fb	2.44 fb
$E_T^{miss} > 150$ GeV	4.17 fb	2.44 fb	1.93 fb	1.63 fb
$m_{T_2}(l, l) > 150$ GeV	0.87 fb	0.62 fb	0.54 fb	0.47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

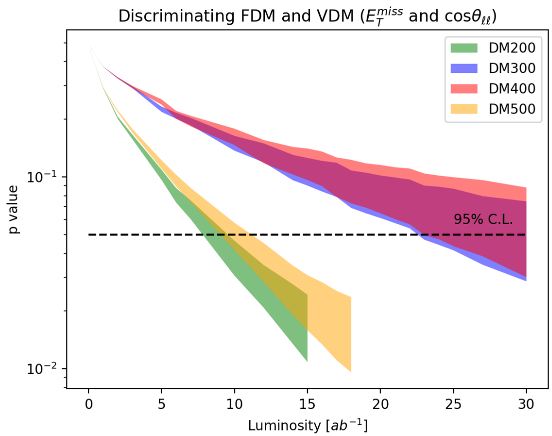
Two dimensional binned log-likelihood test: $\mathcal{L}(\text{data}|\mathcal{H}_\alpha) = \prod_{i,j} \frac{t_{ij}^{n_{ij}} e^{-t_{ij}}}{n_{ij}!}$

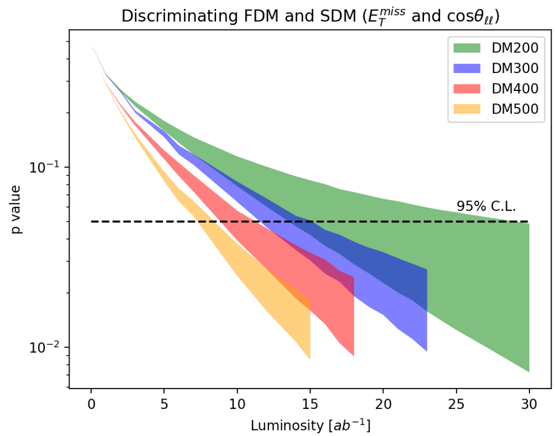












$\sigma^{sys.} = 0.5\%$

Conclusion

- 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, $m_{H_2} \lesssim 300$ GeV can be probed at more than 3-σ level.
- At the 100 TeV p-p collider, discovery/exclusion can be made with an integrated luminosity less than 1 ab^{-1} given a 1% systematic uncertainty, while the spin discrimination require integrated luminosity of a few $\mathcal{O}(10)$ ab^{-1} given a 0.5% systematic uncertainty.

Backup.

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.

$$\Gamma^{\rm FDM}_{\rm min}(H_2) = \Gamma(H_2 \to \chi\chi) + \Gamma(H_2 \to WW/ZZ) + \Gamma(H_2 \to ff)$$

$$= \cos^2\alpha \cdot g_\chi^2 \frac{m_{H_2}}{8\pi}(1 - \frac{4m_\chi^2}{m_{H_2}^2})^{3/2} + \sin^2\alpha \cdot \frac{G_\mu m_{H_2}^3}{16\sqrt{2}\pi}\delta_V \sqrt{1 - 4\frac{m_V^2}{m_{H_2}^2}}(1 - 4\frac{m_V^2}{m_{H_2}^2} + 12\frac{m_V^4}{m_{H_2}^4})$$

$$+ \sin^2\alpha \cdot (\frac{m_f}{v})^2 \frac{3m_{H_2}}{8\pi}(1 - \frac{4m_f^2}{m_{H_2}^2})^{3/2} ,$$

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

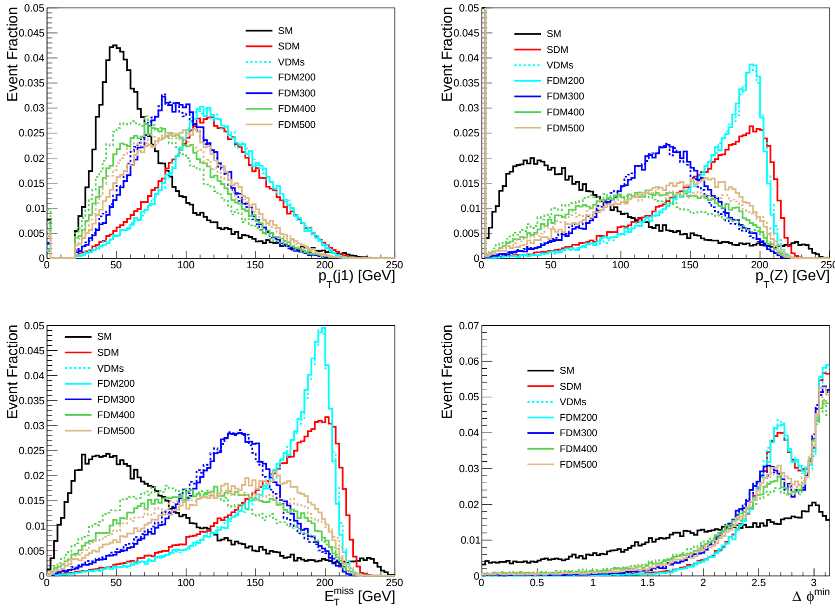
- Parameters for the vector DM production are chosen accordingly: $\sin\alpha = 0.3,\ m_V = 80$ GeV and g_V is chosen such that the total decay width of H_2 is the same as benchmark points of FDM.

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

Discovery prospects of the hadronic channel

Kinematic distributions:

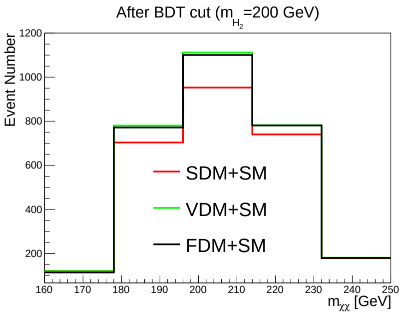


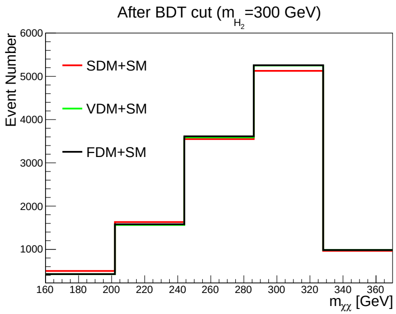
$$\Delta\phi^{\min} = \min_{i=1,2} \Delta\phi(p_T^{\text{miss}}, p(j_i))$$

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



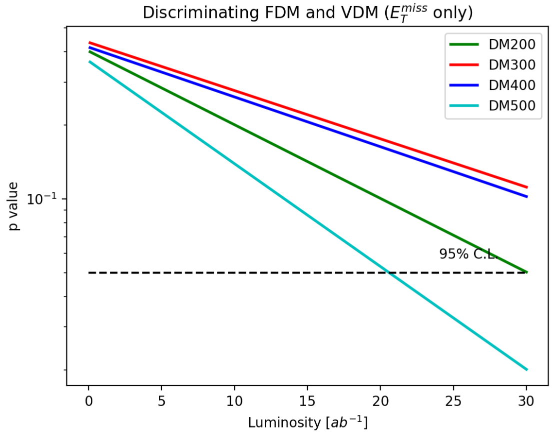


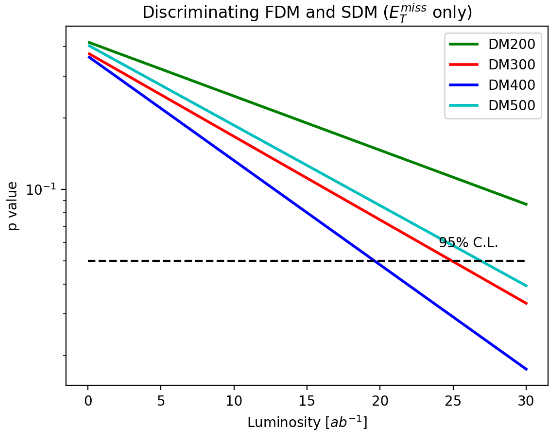
$$\text{SDM: } \delta\chi^2 = \sum_{i=1}^{5}\left(\frac{N_i^{\text{FDM+SM}} - N_i^{\text{SDM+SM}}}{\sqrt{N_i^{\text{FDM+SM}}}}\right)^2$$

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

Spin characterization

Using only the distribution of E_T^{miss}:
$\mathcal{H}_0$ is the FDM + SM, $\mathcal{H}_\alpha$ can be VDM/SDM + SM

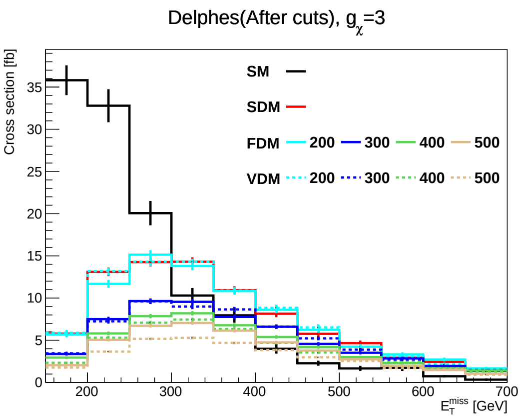


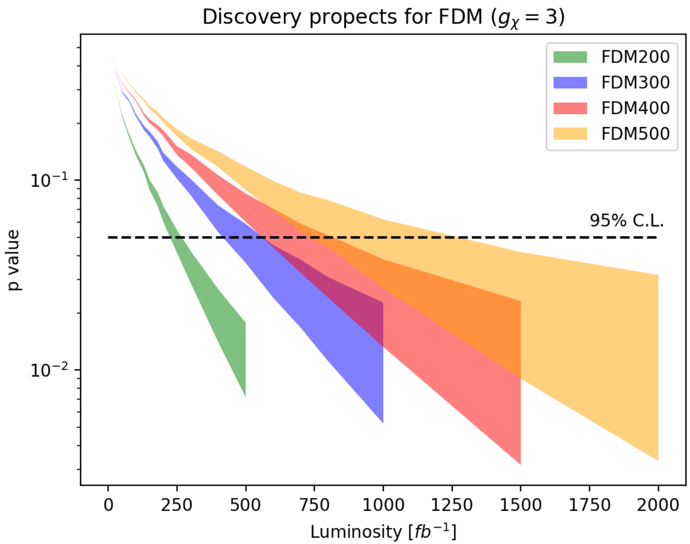


Discovery prospects

Binned log-likehood analysis:

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





$\sigma^{sys.} = 1\%$