Theoretical frameworks for dark matter searches

Jinmian Li

Korea Institute for Advanced Study

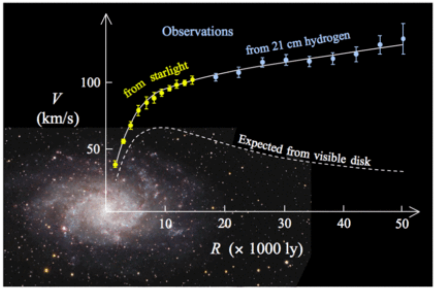
May 26th, 2017

2nd KR-LHC TH-EXP cross seminar

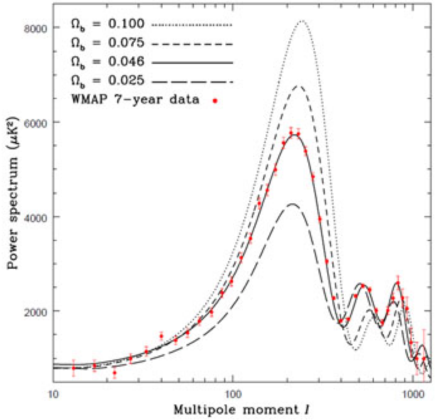
Seoul National University

Outline

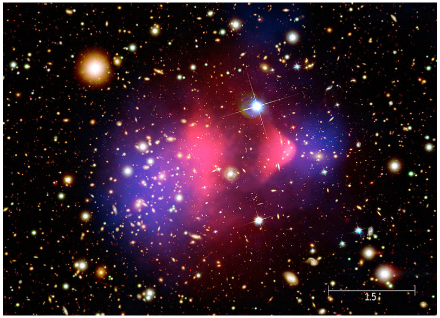
Dark Matter evidences



Rotation curve



CMB Anisotropy



Bullet Cluster

Complete set of lowest-dimension effective operators:

Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$

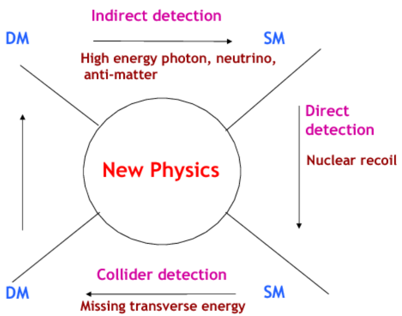
Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde G$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde G$	$i\alpha_s/8M_*^3$	γ_5	-

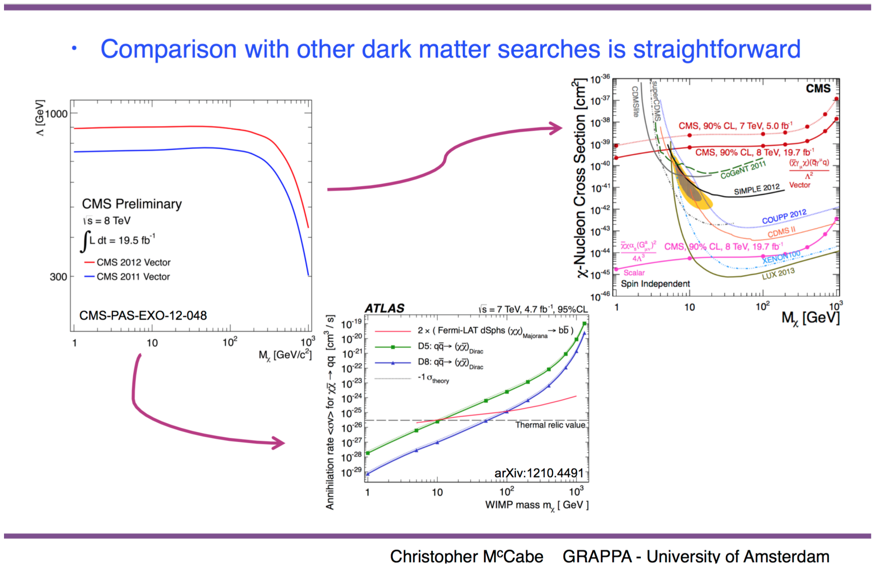
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar q q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar q\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar q q$	$m_q/2M_*^2$
R2	$\chi^2\bar q\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^2$

$\frac{\tilde m}{\Lambda^2}V_\mu^\dagger V^\mu\bar q q$	[V1]
$\frac{\tilde m}{\Lambda^2}V_\mu^\dagger V^\mu\bar q i\gamma^5 q$	[V2]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar q\gamma^\mu q$	[V3]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar q i\gamma^\mu\gamma^5 q$	[V4]
$\frac{\tilde m}{\Lambda^2}V_\mu^\dagger V_\nu\bar q i\sigma^{\mu\nu} q$	[V5]
$\frac{\tilde m}{\Lambda^2}V_\mu^\dagger V_\nu\bar q\sigma^{\mu\nu}\gamma^5 q$	[V6]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar q\gamma^\mu q$	[V7P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar q i\gamma^\mu q$	[V7M]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar q\gamma^\mu\gamma^5 q$	[V8P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar q i\gamma^\mu\gamma^5 q$	[V8M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar q\gamma_\mu q$	[V9P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar q i\gamma_\mu q$	[V9M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar q\gamma_\mu\gamma^5 q$	[V10P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar q i\gamma_\mu\gamma^5 q$	[V10M]
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu G^{\rho\sigma}G_{\rho\sigma}$	[$V11$]
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu\tilde G^{\rho\sigma}G_{\rho\sigma}$	[$V12$]

Scalar operator for fermion DM:

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

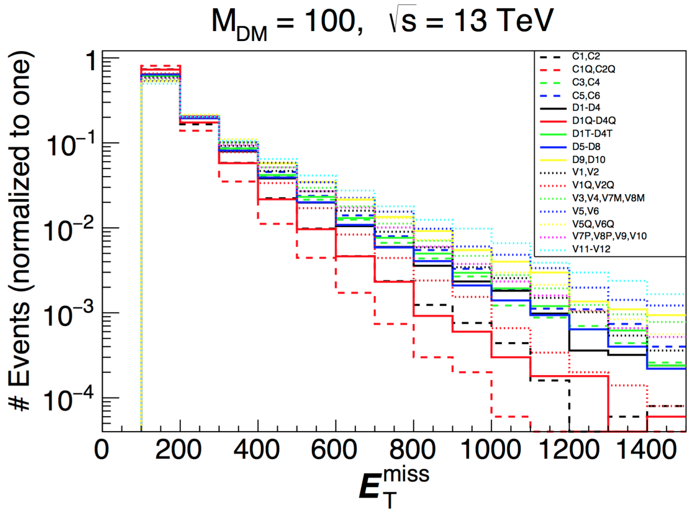


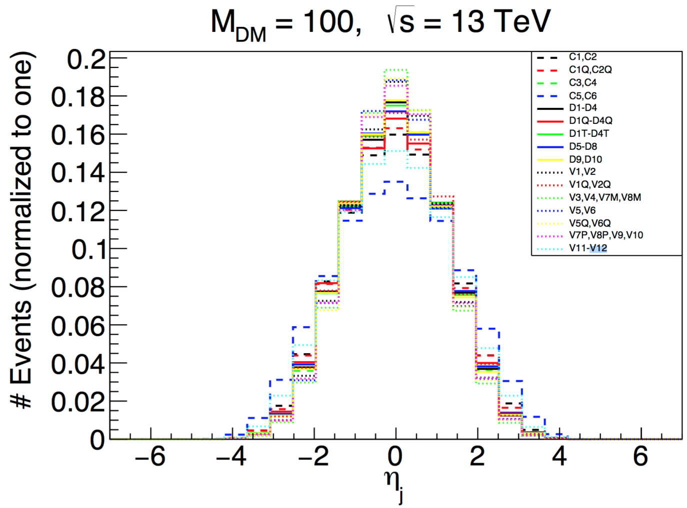


Operator characterization

A. Belyaev, L. Panizzi, A. Pukhov and M. Thomas, JHEP **1704**, *110 (2017)*

$$pp \to DDj$$

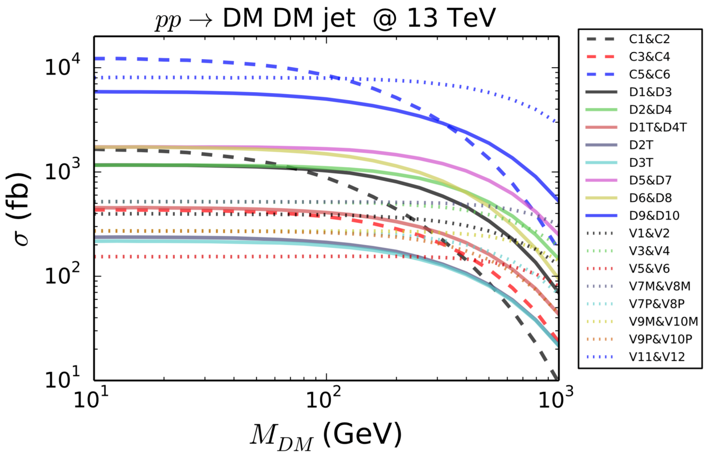




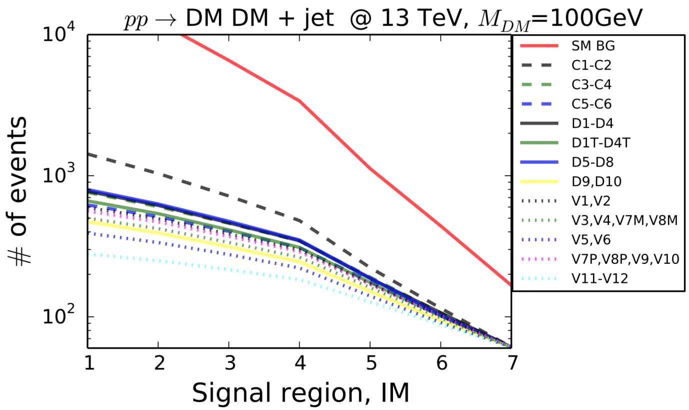
Operator characterization

A. Belyaev, L. Panizzi, A. Pukhov and M. Thomas, JHEP **1704**, *110 (2017)*

Fixing $\Lambda = 1$ TeV



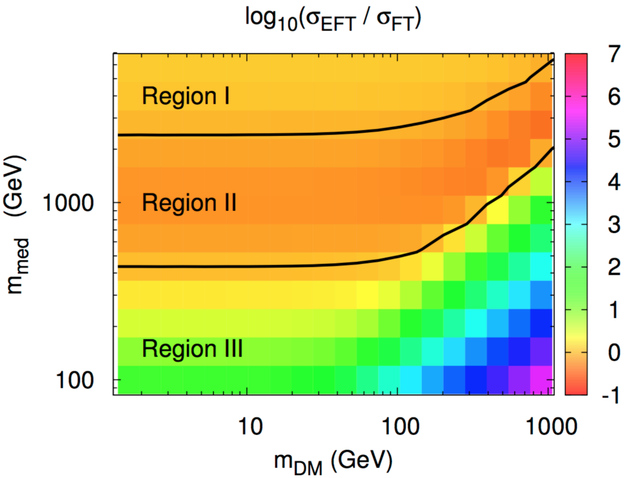
Event number normalized to 61 in IM7 SR



Validation of EFT

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

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

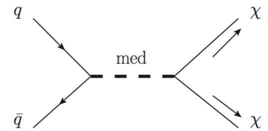


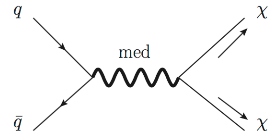
- Region I: EFT limit is valid.
- Region II: EFT limit is too weak (Resonant enhancement).
- Region III: EFT limit is too strong (Off-shell suppression & Coupling change in EFT $1/m_{med}^2$ versus phase space factor in FT - mediator production).

Simplified models

- s-channel mediator
  - Fermion DM

$$\mathcal{L}_{\rm S} \supset -\frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j + \text{h.c.}\,,$$
$$\mathcal{L}_{\rm S'} \supset -\frac{1}{2}M_{\rm med}^2 S'^2 - y'_\chi S'\bar{\chi}\gamma_5\chi - y_q'^{ij} S\bar{q}_i\gamma_5 q_j + \text{h.c.}\,,$$
$$\mathcal{L}_{\rm V} \supset \frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu\bar{\chi}\gamma^\mu\chi - g_q^{ij} V_\mu\bar{q}_i\gamma^\mu q_j\,,$$
$$\mathcal{L}_{\rm V'} \supset \frac{1}{2}M_{\rm med}^2 V'_\mu V'^\mu - g'_\chi V'_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - g_q'^{ij} V'_\mu\bar{q}_i\gamma^\mu\gamma_5 q_j\,.$$





  - Scalar DM

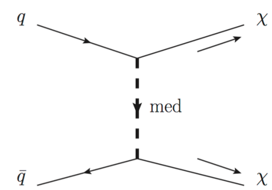
$$\mathcal{L}_{\rm SSDM}^{\rm EFT} = \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4!}S^4 - \frac{\lambda_{HS}}{2}S^2 H^\dagger H$$

  - Vector DM

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

- t-channel mediator

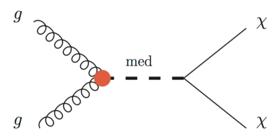
$$\mathcal{L} = \mathcal{L}_{SM} + g_M \sum_{i=1,2}\left(\widetilde{Q}_L^i \bar{Q}_L^i + \tilde{u}_R^i \bar{u}_R^i + \tilde{d}_R^i \bar{d}_R^i\right)\chi + \text{mass terms} + c.c.$$



- DM gluon simplified model

$$\mathcal{L} \supset y_\chi S\bar{\chi}\chi + \frac{\alpha_s}{\Lambda_S}SG_{\alpha\beta}G^{\alpha\beta}$$

$$\mathcal{L} \supset iy'_\chi S'\bar{\chi}\gamma_5\chi + \frac{\alpha_s}{\Lambda}S'G_{\mu\nu}G_{\alpha\beta}\epsilon^{\mu\nu\alpha\beta}$$



Simplified model

For fermion DM with scalar mediator:

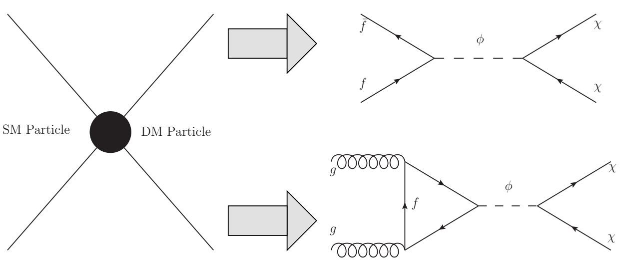
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - g_\chi\phi\bar{\chi}\chi - \sum_f g_v\frac{y_f}{\sqrt{2}}\phi\bar{f}f$$

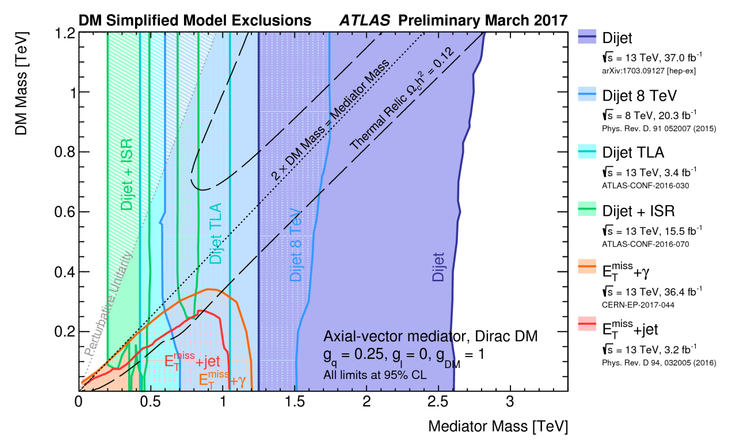
Four(Five) parameters:

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

Bound are shown with fixing some parameters

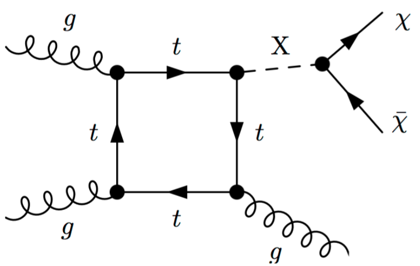
Production process:

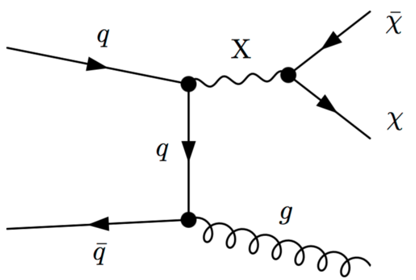


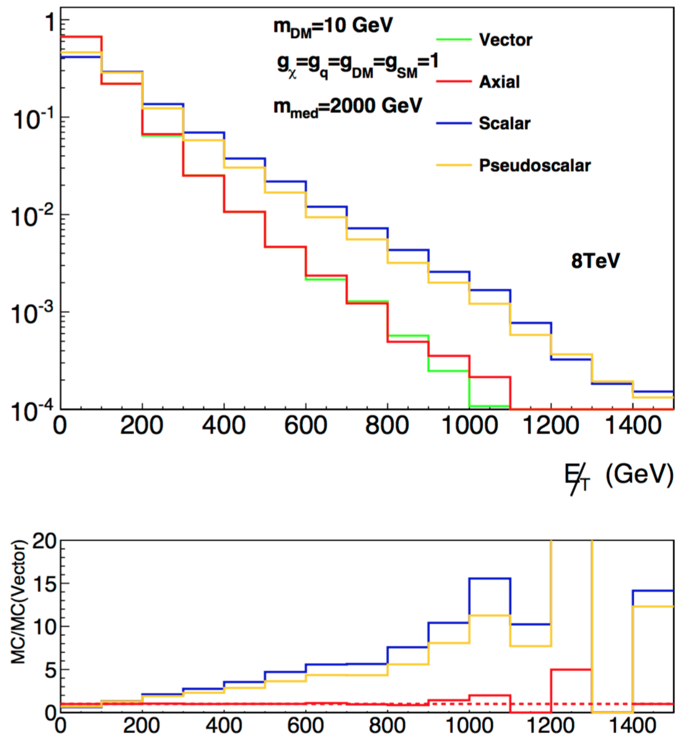


Mediator characterization

P. Harris, V. V. Khoze, M. Spannowsky and C. Williams, Phys. Rev. D **91**, *055009 (2015)*







Mediator characterization

M. J. Dolan, M. Spannowsky, Q. Wang and Z. H. Yu, Phys. Rev. D **94***, no. 1, 015025 (2016)*

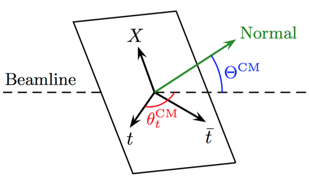
$$pp \to t_h t_\ell X$$

$$\chi^2 = \frac{(m_{jj}-m_W)^2}{m_W^2} + \frac{(m_{t,\text{had}}-m_t)^2}{m_t^2} \to b_1$$

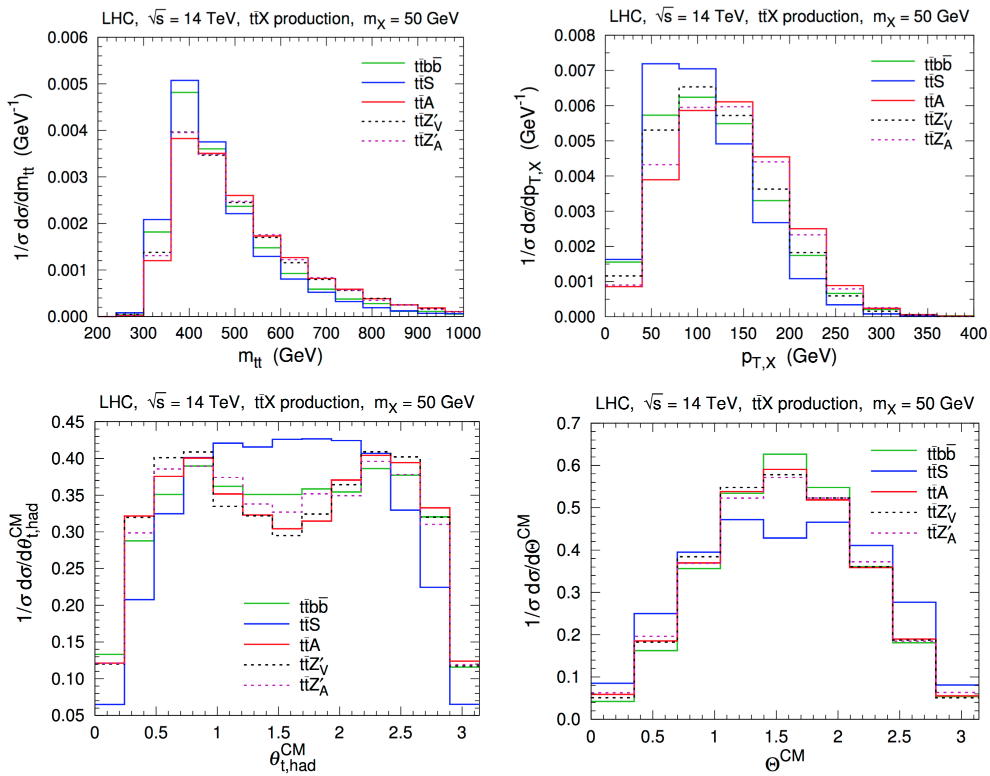
$$\chi^2 = \frac{(m_{t,\text{lep}}-m_t)^2}{m_t^2} \to b_2$$

$$p_{t,\text{had}} = p_{b_1} + p_{j_1} + p_{j_2},$$
$$p_{t,\text{lep}} = p_{b_2} + p_\ell + \not{p}_{\text{T}},$$
$$p_X = p_{b_3} + p_{b_4}.$$

$$\mathbf{p}_{t,\text{had}} + \mathbf{p}_{t,\text{lep}} + \mathbf{p}_X = 0 \to \text{CM frame}$$

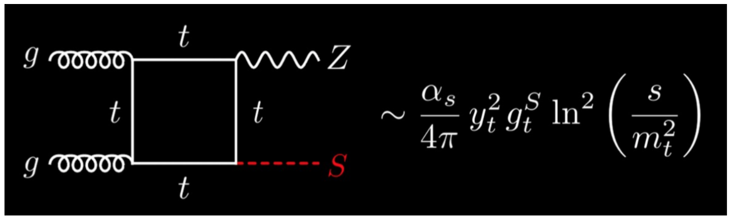


$t\bar{t}X$ CM frame



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

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

Outline

Towards complete model

- Supersymmetry with R-partity
  - Neutralino
  - Sneutrino
  - Gravitino
- Extra-dimensional theories with KK-parity: B^1
- Axion-like particle: QCD axion, string inspired
- Sterile Neutrinos: light & slightly mixed with active neutrino
- Higgs portal dark matter models
- Two-Higgs-doublet extension
- ...

Higgs portal - Fermion DM

S. Baek, P. Ko and W. I. Park, JHEP **1202**, *047 (2012)*

Simplest extension of the SM including fermion DM

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

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:

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

Higgs portal - Vector DM

S. Baek, P. Ko, W. I. Park and E. Senaha, JHEP **1305**, *036 (2013)*

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

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

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

Interaction Lagrangian:

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

Higgs portal - Scalar DM

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

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

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

Interaction Lagrangian:

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

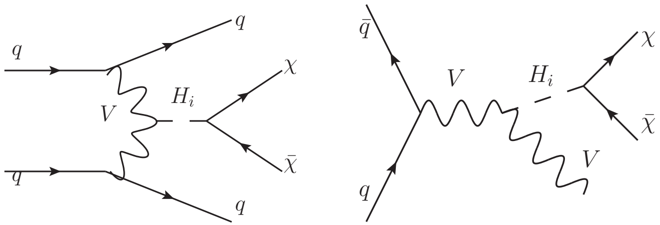
Higgs portal - Fermion DM

Consequences of gauge symmetry:

- Couplings suppressed by scalar mixing angle:

$$g_\chi \to g_\chi \cos\alpha, \quad g_{\rm SM} \to -\sin\alpha$$

- Higgs invisible decay for $m_\chi < m_h/2$ and Higgs precision measurement
- Vector boson fusion (VBF) and Higgs Strahlung (VH) DM production



- Interference effect of two propagators
  - DM direct detection blind window at $m_{H_1} \sim m_{H_2}$
  - Collider phenomenology

S. Baek, et.al, arXiv:1506.06556; P. Ko, H. Yokoya, arXiv:1603.04737

Minimal pseudoscalar portal

S. Baek, P. Ko and J. Li, Phys. Rev. D **95**, *no. 7, 075011 (2017)*

$$\mathcal{L} = \bar{\chi}(i\partial\cdot\gamma - m_\chi - ig_\chi a\gamma^5)\chi + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2$$
$$- (\mu_a a + \lambda_{Ha} a^2)\left(H^\dagger H - \frac{v_h^2}{2}\right) - \frac{\mu'_a}{3!}a^3 - \frac{\lambda_a}{4!}a^4 - \lambda_H\left(H^\dagger H - \frac{v_h^2}{2}\right)^2$$

Mixing between H_0 and A:

$$H_0 = h\cos\alpha + a\sin\alpha \ ,$$
$$A = -h\sin\alpha + a\cos\alpha \ .$$

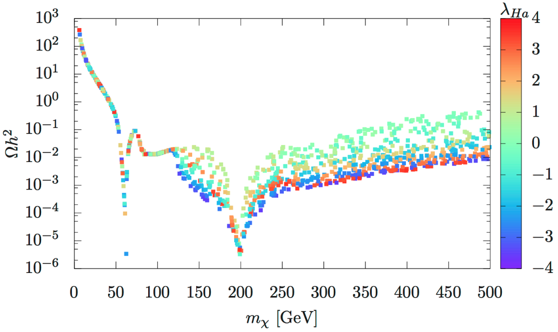
Interaction Lagrangian:

$$\mathcal{L}_{\rm int} = -ig_\chi(H_0\sin\alpha + A\cos\alpha)\ \bar{\chi}\gamma^5\chi - (H_0\cos\alpha - A\sin\alpha)$$
$$\times\left[\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right]$$

DM properties

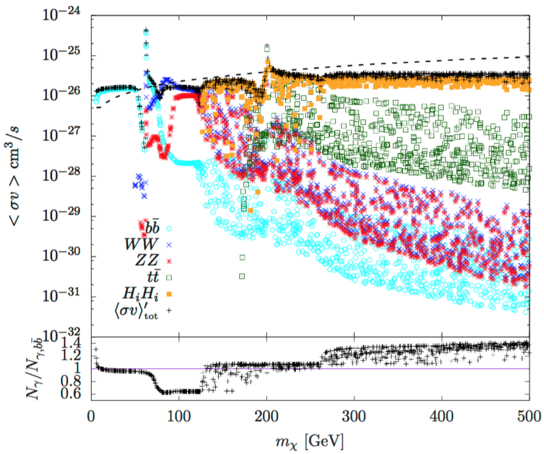
DM relic density:

$g_\chi = 1, \ \alpha = 0.3, \ m_A = 400$ GeV



DM indirect detection:

Varying g_χ to obtain correct Ωh^2

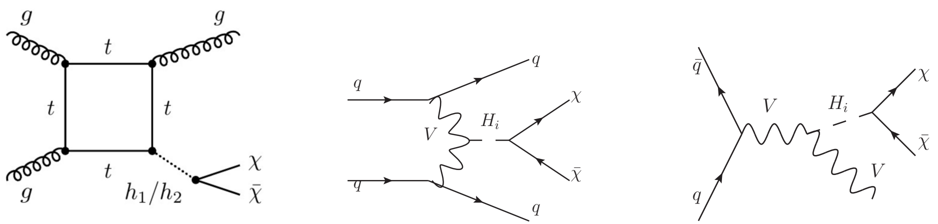


DM direct detection:

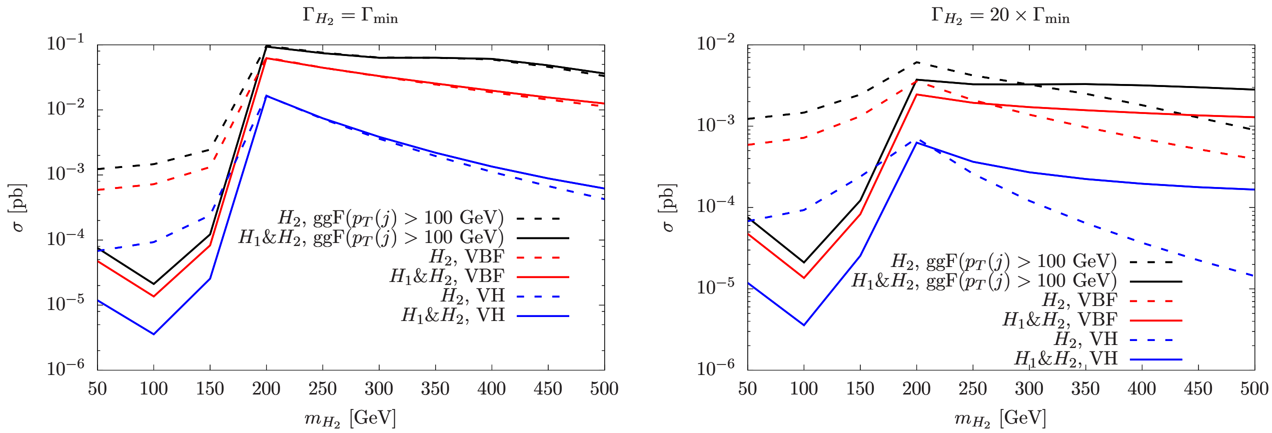
$$\mathcal{M} \propto \mathcal{M}_\chi \cdot \mathcal{M}_f = -2q^i(\xi_\chi^\dagger \hat{S}^i \xi_\chi) \times$$
$$[2m_f(\xi_f^\dagger \xi_f) + i\frac{\mu}{m_f}\epsilon^{ijk} q^i v^j (\xi_f^\dagger \hat{S}^k \xi_f)]$$

Interference in DM search at the LHC

*P. Ko and J. Li, Phys. Lett. B **765**, 53 (2017)*



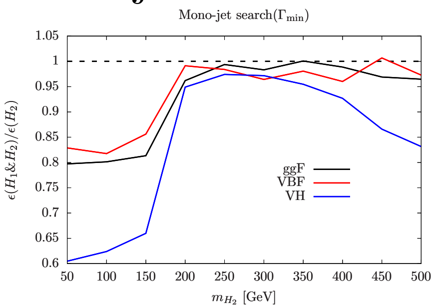
Production cross section($m_\chi = 80$ GeV):

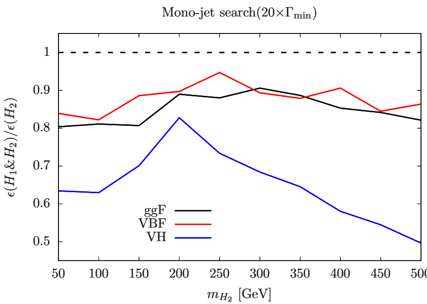


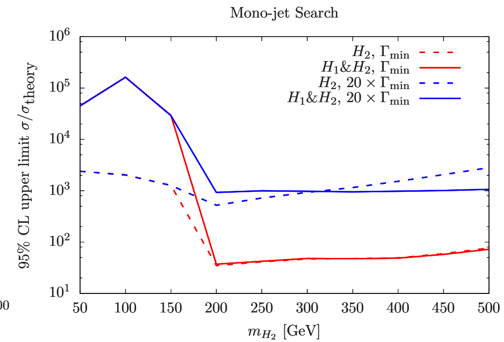
Application to CMS analysis

CMS-PAS-EXO-16-037

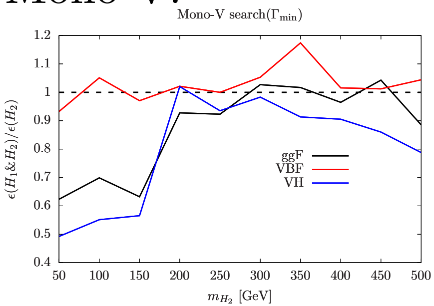
Mono-jet:

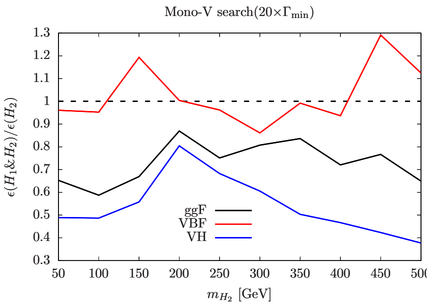


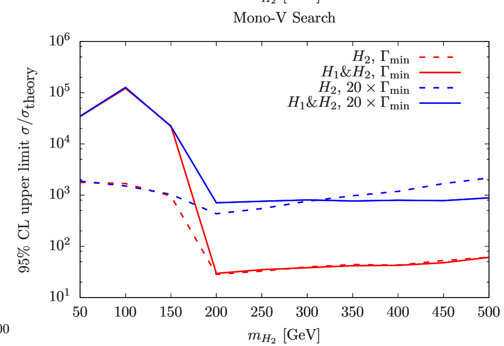




Mono-V:

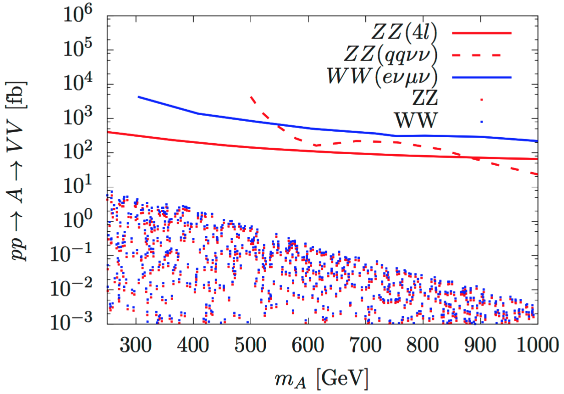




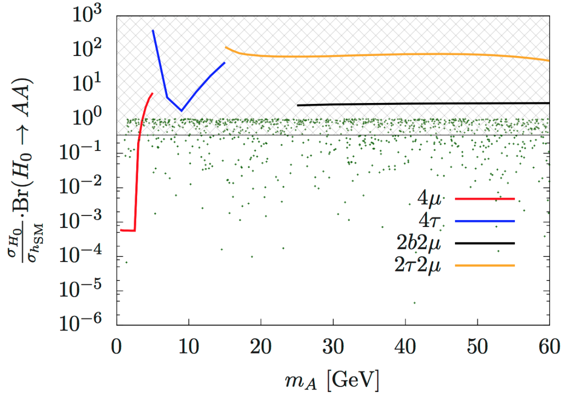


Mediator searches at the LHC($m_\chi = 80$ GeV)

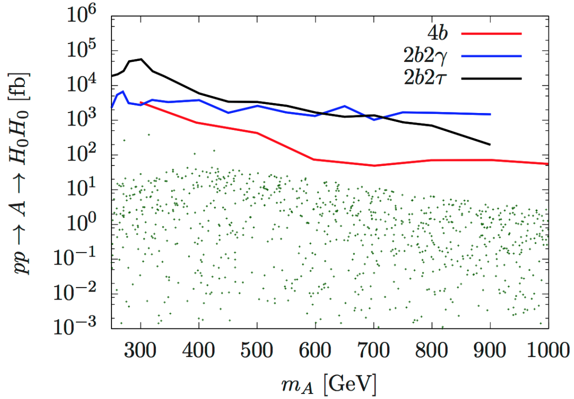
Vector boson pair production:



SM Higgs decay:



Scalar-to-Scalar process:



DM spin discrimination for Higgs portal DM models

T. Kamon, P. Ko and J. Li, arXiv:1705.02149

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

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

$$\mathcal{L}^{\text{int}}_{\text{SDM}} = h\ [\frac{2m_W^2}{v_h} W^+_\mu W^{-\mu} + \frac{m_Z^2}{v_h} Z_\mu Z^\mu - \sum_f \frac{m_f}{v_h} \bar{f} f] + \lambda_{HS} v_h\ h S^2$$

- 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.
- 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
$\Gamma_{\text{min}}(H_2)$ [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.

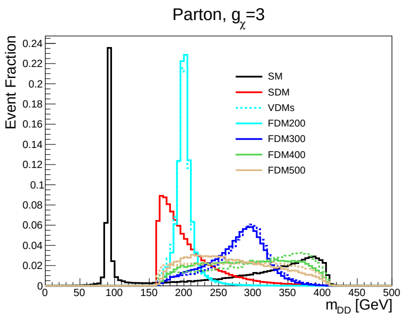
DM spin discrimination for Higgs portal DM models

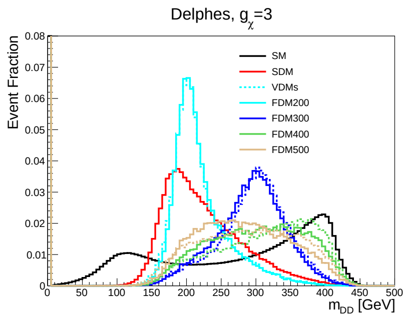
$$e^+e^- \to Z(\to f f)\ H_{1,2}(\to DD)$$
$$m_{DD}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$
$$\frac{d\sigma_D}{dt} = \frac{1}{2\pi}\sigma_{h^*Z}(s,t)\cdot G_D(t)$$

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

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

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





Discovery prospects of FDM

Preselection cuts:

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

Boosted decision tree analysis with inputs:

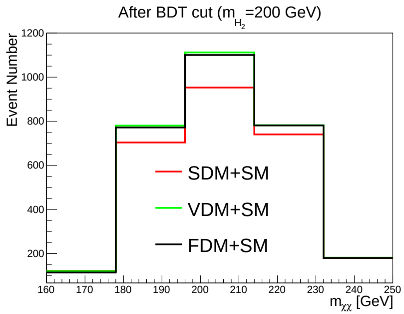
$$m_{DD},\ p_T(j_1),\ p_T(Z),\ E_T^{\text{miss}},\ \Delta\phi^{\text{min}},\ p_T(j_2),\ m_{jj}$$

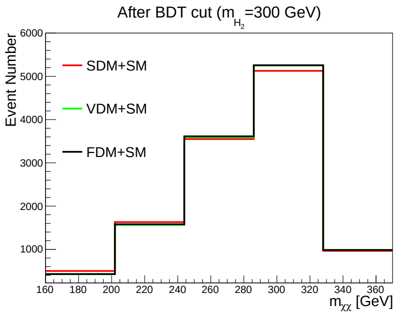
	FDM200	FDM300	FDM400	FDM500
σ^0 [fb]	1.643	0.9214	0.4221	0.2526
ϵ^{pre}	0.796	0.717	0.655	0.698
BDT	0.3615	0.2132	0.1929	0.2129
$N_S/1000\ \text{fb}^{-1}$	697.8	410.5	148	102
$N_B/1000\ \text{fb}^{-1}$	2248.5	11453.5	12736	10898
$N_S/\sqrt{N_S+N_B}$	12.85	3.769	1.31	0.97

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
$\epsilon^{\rm pre}$	0.7875	0.7875	0.801	0.711
$N_S/1000\ {\rm fb}^{-1}$	447	322.3	726	363.5
$\mathcal{S}$	4.4	3.3	0.59	0.44





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

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

Conclusion

- There are three kinds of theoretical frameworks for describing the DM phenomenology at the LHC.
- Effective field theory is minimal but is only valid when the momentum transfer is much lower than the suppression scale ($\propto$ mediator mass); DM effective operators can be distinguished in the mono-jet channel by the distribution of MET.
- Simplified model introduces a new mediator particle and keep interactions renormalizable, but often violates SM gauge symmetry and unitarity; the nature of the mediator can be characterized in both the mono-jet channel and $t\bar{t}X$ channel.
- A UV-complete model is more realistic but has limited applications, and constraints from many aspects become relevant: DM relic density, DM direct (indirect) detection, searches solely related to the mediator.
  - Considering the Higgs portal DM models, 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.