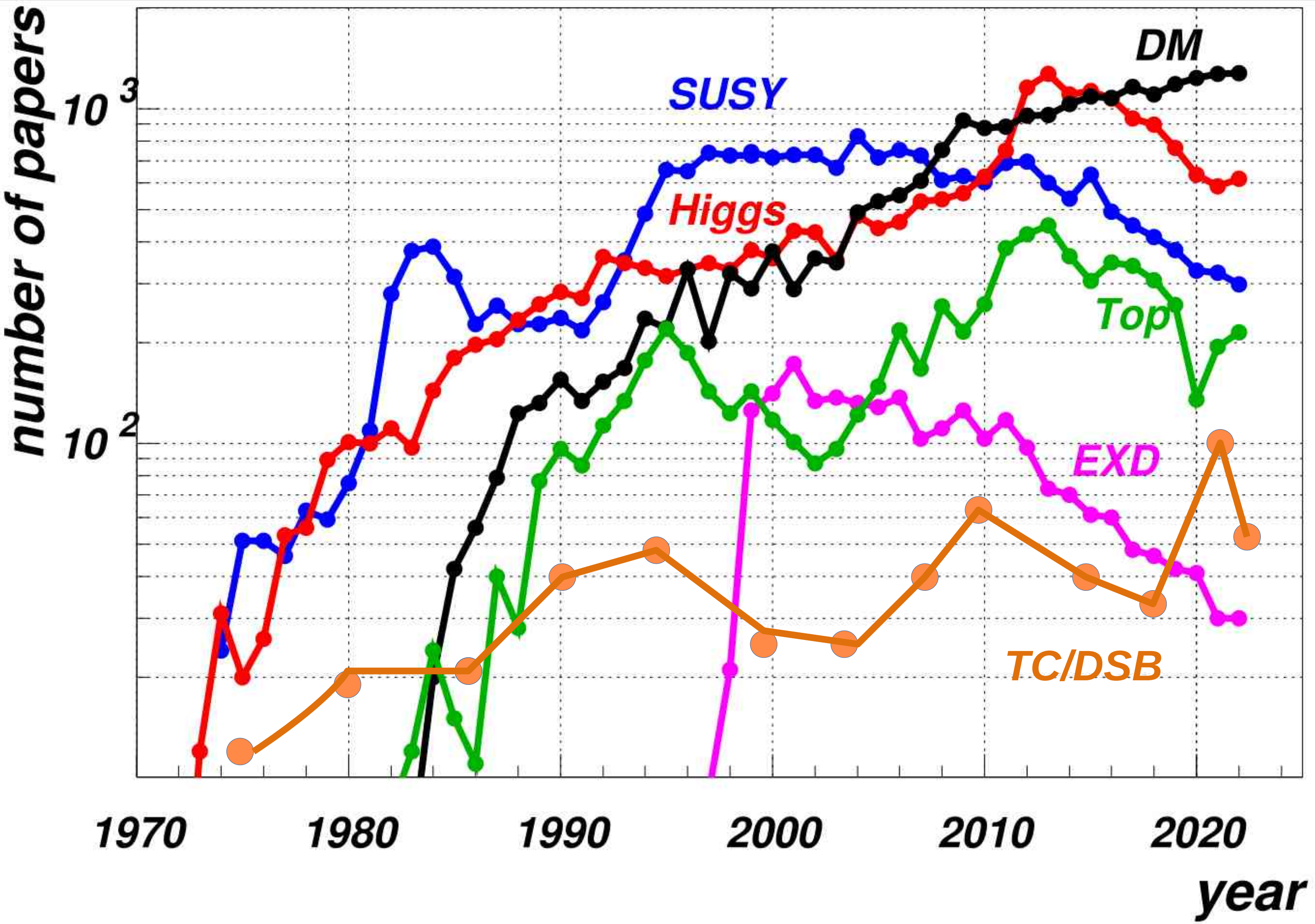
Towards decoding the nature of Dark Matter

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

International Conference
on
Particle Physics and Cosmology
October 02-07, 2023
Yerevan, Armenia

Popular directions in Particle Physics.



DM is very appealing even though we know almost nothing about it!

Spin ?

Mass ?

Stable

Yes ? No ?

symmetry behind stability ?

Couplings

gravity	V
weak	?
higgs	?
quarks/gluons	?
leptons	?
New mediators	?

Thermal relic

Yes ? No ?

How we can explore & decode the nature of Dark Matter?

We need a DM signal first!

But at the moment we can:

* understand what kind of DM is already excluded
* explore and systematise the DM theory space
* prepare ourselves to discovery and decoding of DM

DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB

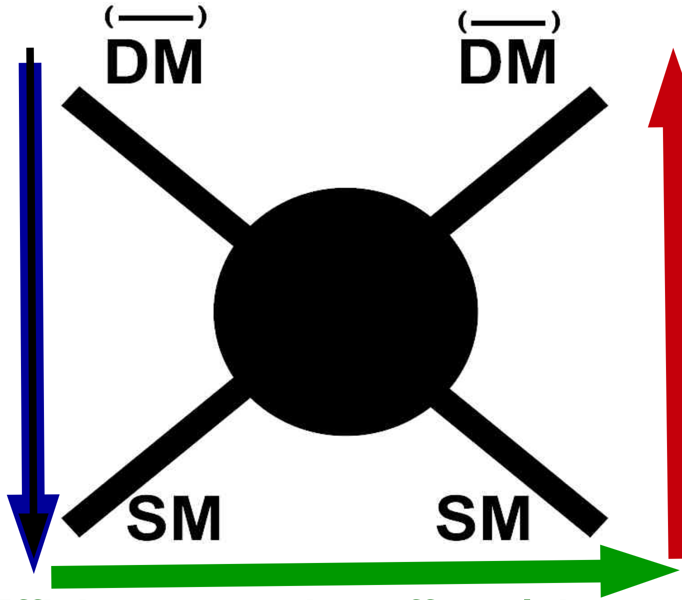
Signatures from neutralino annihilation in halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:

- **Amanda**
- **Icecube**
- **Antares**

Efficient annihilation now:
Indirect (ID) DM Detection



Efficient production at colliders

LHC signatures

- **mono-jet**
- **mono-photon**
- **mono-Z**
- **mono Higgs**
- **VBF+MET**
- **soft leptons+MET**
- **….**

Efficient scattering off nuclei:
DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

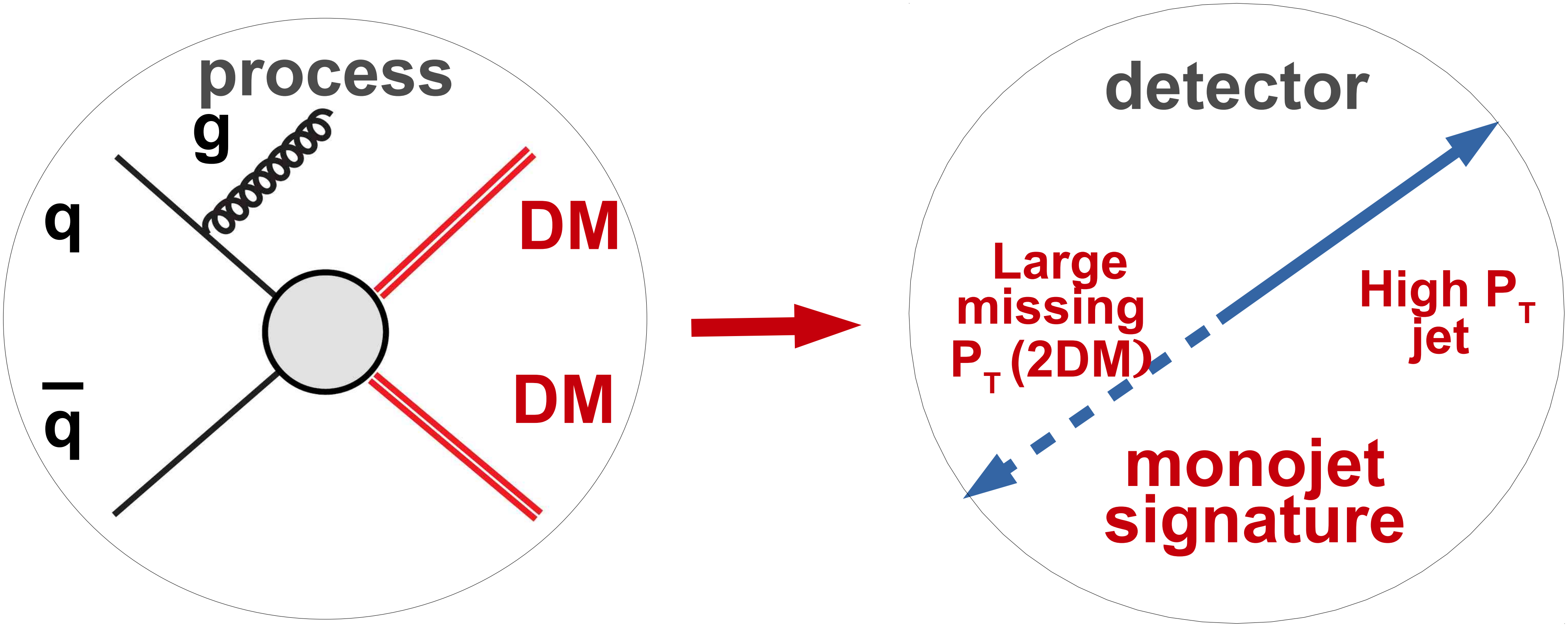
Note: **there is no 100%correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!**

Actually there is a great complementarity in this:

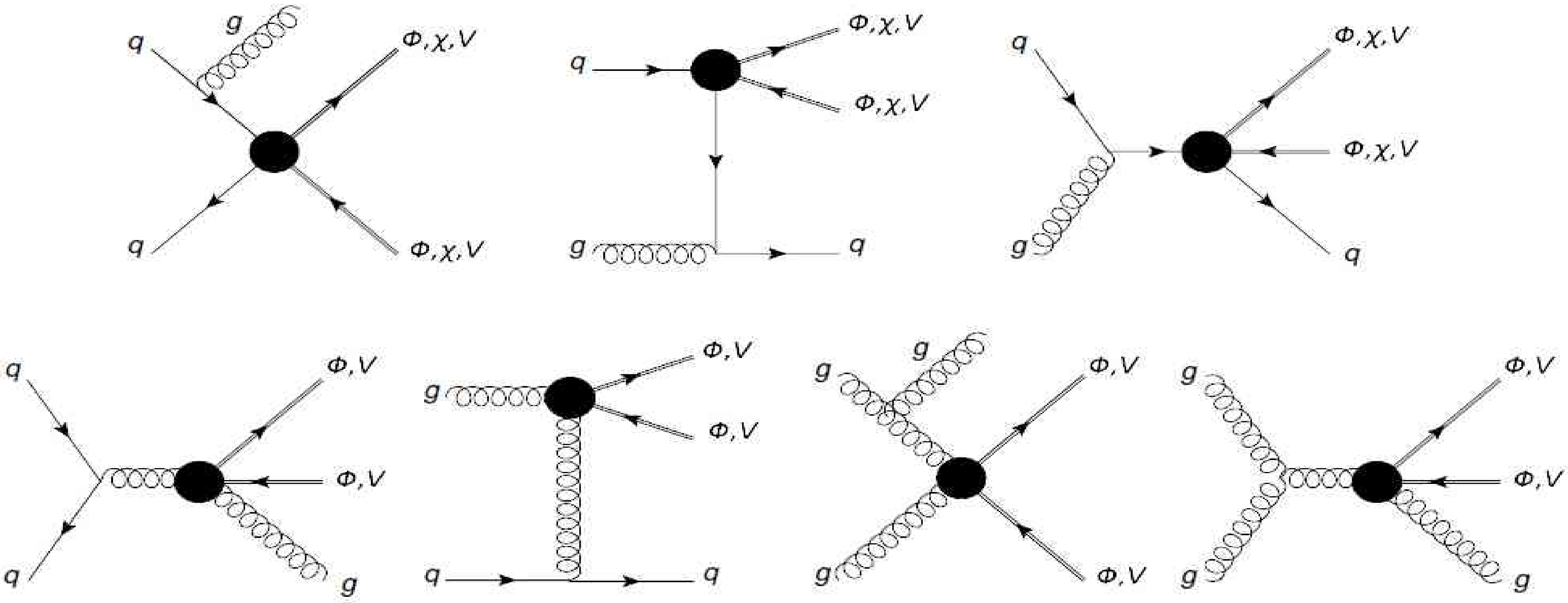
- **In case of NO DM Signal – we can efficiently exclude DM models**
- **In case of DM signal – we can efficiently determine the nature of DM**

The LHC potential to probe DM

Monojet – the most generic DM signature

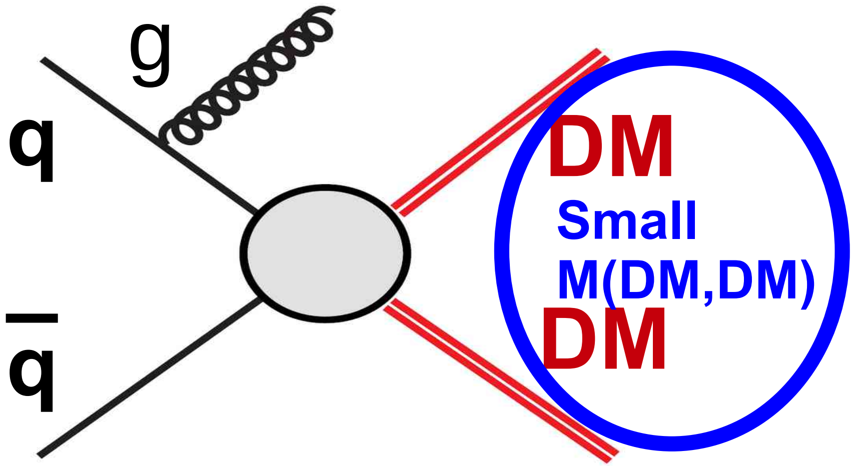


Mono-jet diagrams from EFT operators
Can we test DM properties at the LHC?



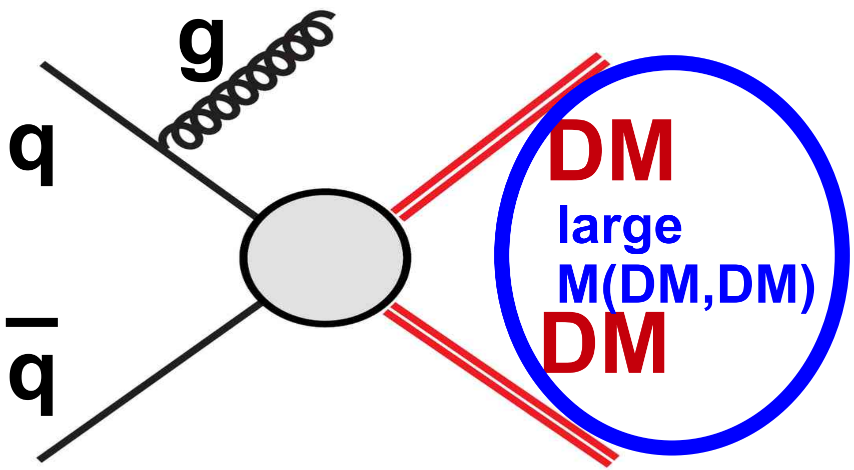
Properties of MET distributions:

MET distributions are the same for the fixed mass of DM pair [M(DM,DM)] & fixed SM operator
With the increase of M(DM,DM), MET slope decreases (PDF effect)



P_T(g) small → P_T(g)large

Δ (x1 x2)/(x1 x2) is large
and MET slope is steep

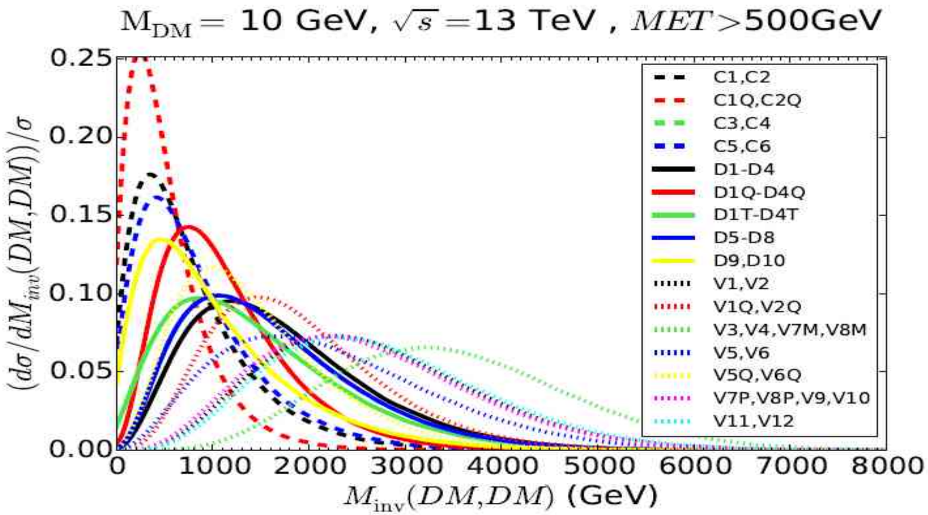


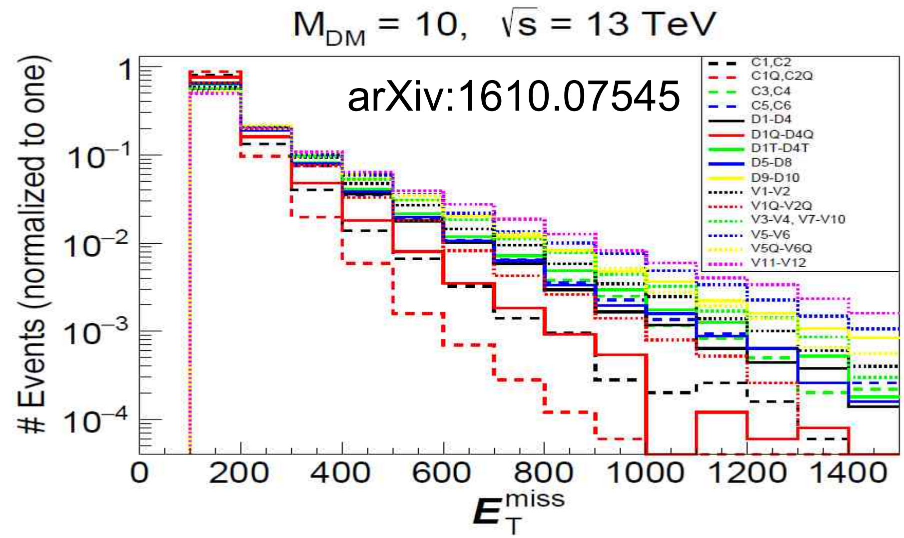
P_T(g) small → P_T(g)large

Δ (x1 x2)/(x1 x2) is small
and MET slope is gradual

Distinguishing DM operators/theories

The harder M(DM,DM) distributions ⟷ **The flatter MET shapes**





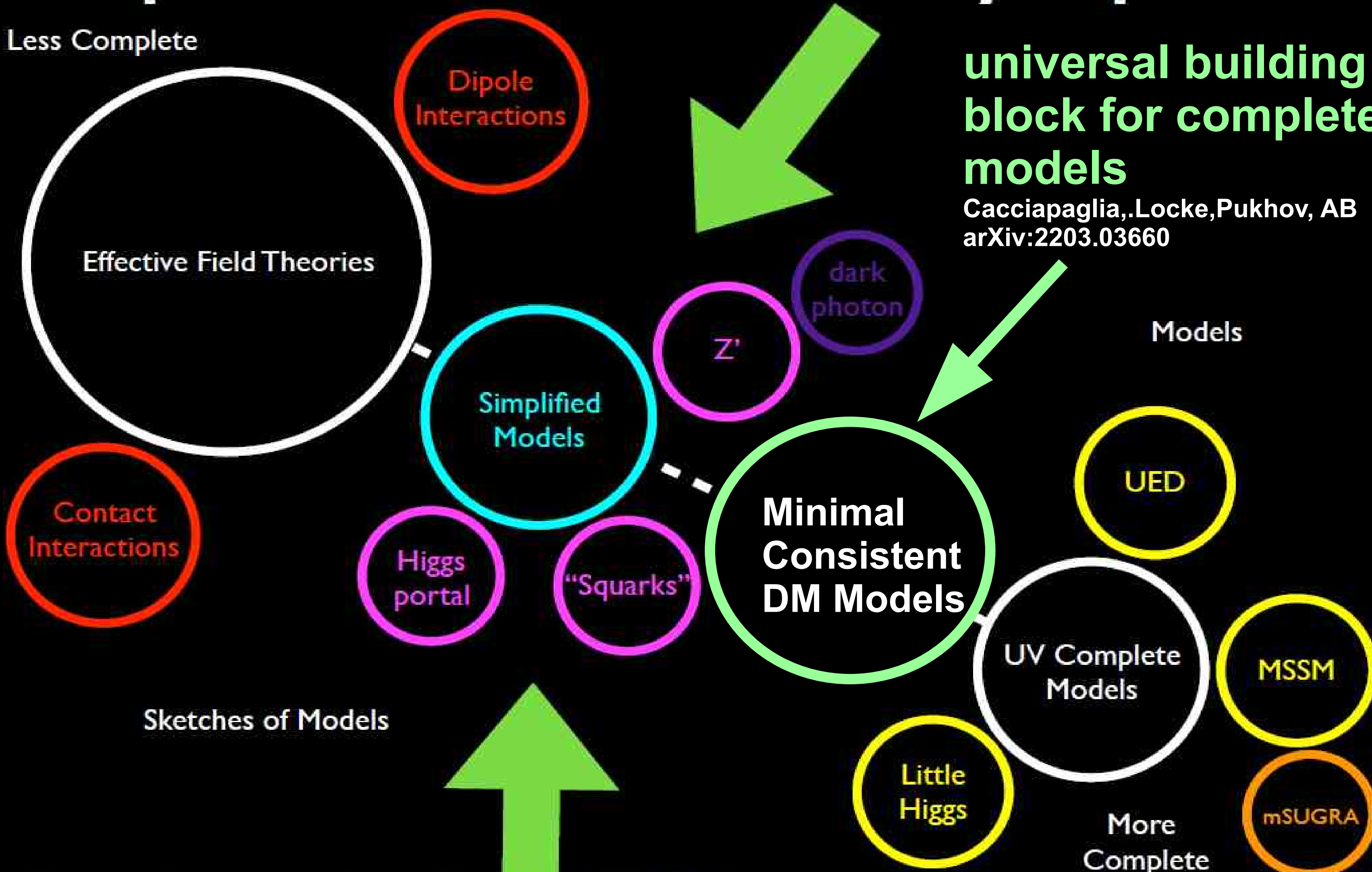
operator energy dependence → M_{DMDM} shape → MET shape

➪ projection for 300 fb^{-1}: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other

➪ Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

DM classification:
minimal consistent dark matter models (MCDMs)

Spectrum of Theory Space



Minimal Consistent DM (MCDM) Models

Properties

- gauge-invariant
- renormalisable
- anomaly-free
- can also be a building block of a bigger theory (e.g. SUSY)

Z_2 odd or even

spin $\rightarrow$ $\tilde{X}^{i}_{y}$ $\leftarrow$ isospin, hypercharge

Classification

- DM is a part of EW multiplet
  - Radiative mass split
  - Disappearing track (DT) signatures
- at most one mediator multiplet

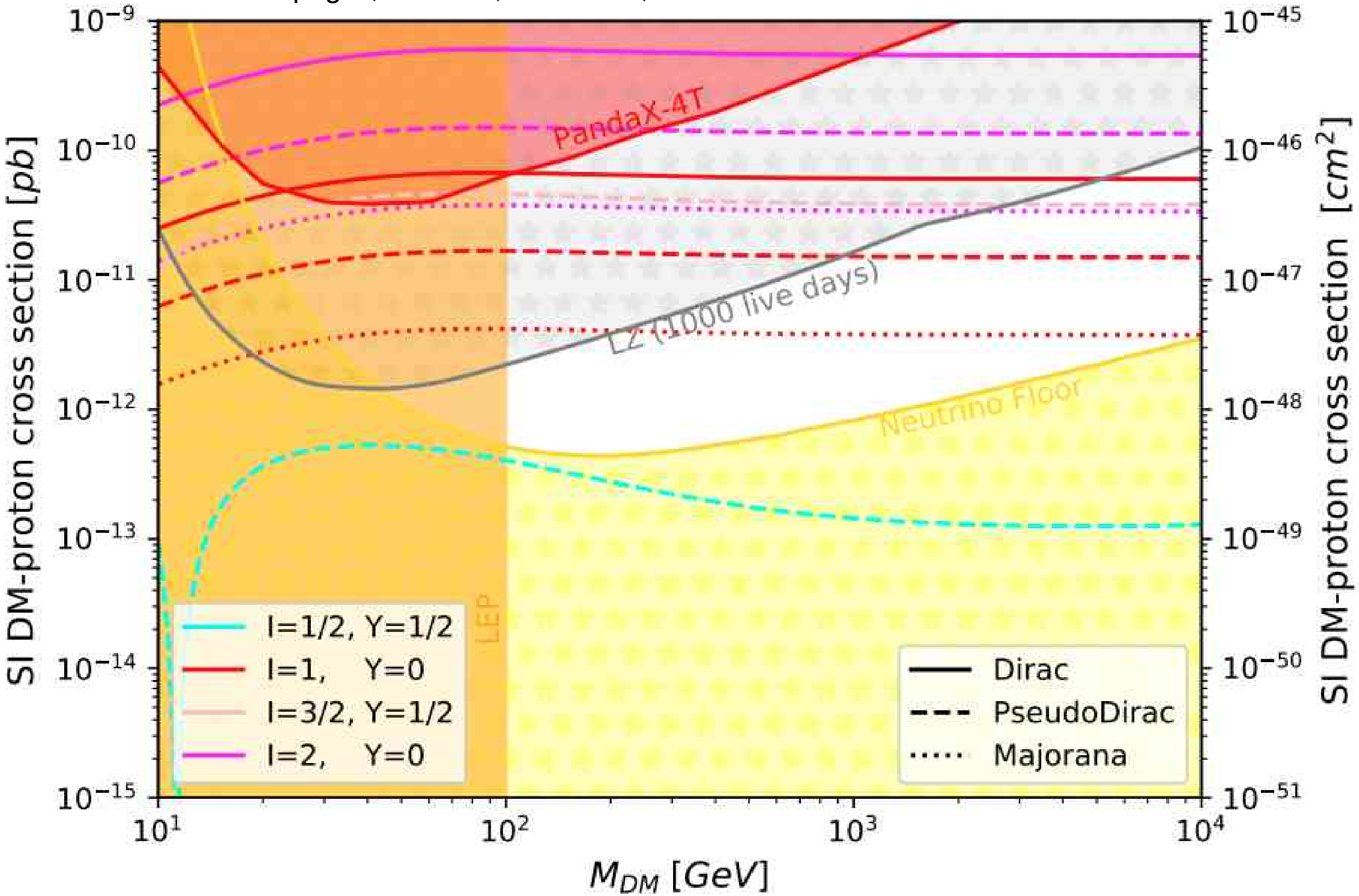
Spin of Mediator \ Spin of Dark Matter	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\tilde{F}^I_Y S^{I'}_0$	$\tilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\tilde{S}^I_Y \tilde{S}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{S}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{S}^{I'c}_{Y'}$ **MSSM!**	$\tilde{V}^I_Y \tilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}^I_Y F^{I'}_{Y'}$ $\tilde{S}^I_Y F^{I'c}_{Y'}$	$\tilde{F}^I_Y F^{I\pm1/2}_{Y\pm1/2}$	$\tilde{V}^I_Y F^{I'}_{Y'}$ $\tilde{V}^I_Y F^{I'c}_{Y'}$
spin 1 even mediator	$\tilde{S}^I_Y V^{I'}_0$	$\tilde{F}^I_Y V^{I'}_0$	$\tilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\tilde{S}^I_Y \tilde{V}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{V}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{V}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{V}^{I'}_{Y'}$

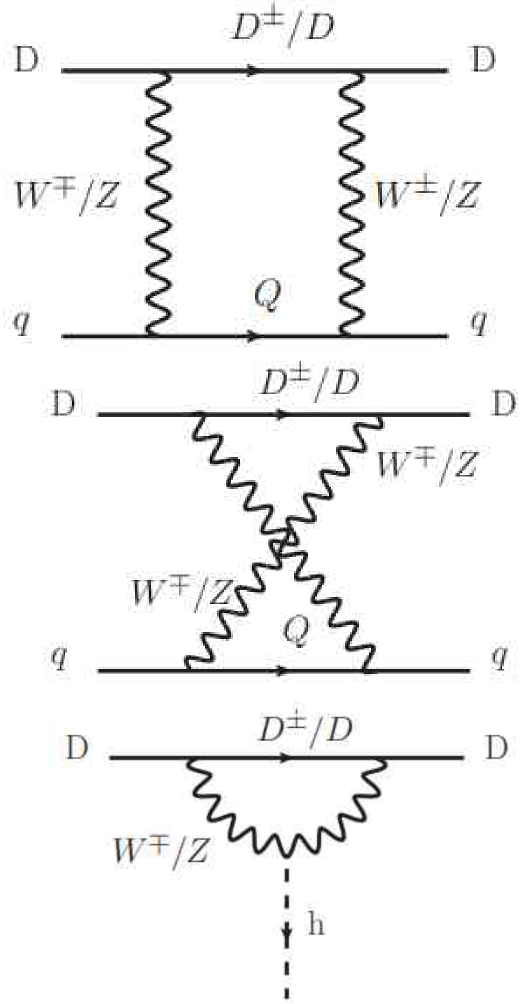
an important step for consistent exploration of DM theory space

G.Cacciapaglia, D.Locke, A.Pukhov, AB **2203.03660**

The role of loops in DM DD

G.Cacciapaglia, D.Locke, A.Pukhov, AB **2203.03660**





Y=0 minimal candidates may be discovered or ruled out at next generation of DD experiments. But there is a cancellation in amplitudes and some models could be accessible only at colliders!

[**Initially noted by Hisano, Ishiwata, Nagata arXiv:1004.4090**]

$\tilde{F}^0_0 S^0_0 (CP - odd)$

Minimal fermion DM model with pseudo-scalar mediator

new model, has not been explored previously

two-component DM model (pseudoscalar is accidentally stable)

Z2 odd

isospin

$\tilde{X}^i_y$

spin

hypercharge

$$\mathcal{L} \supset iY_\psi a \bar{\psi}\gamma^5\psi - \frac{\lambda_{aH}}{4}|a|^2 \phi^\dagger_H \phi_H$$

Fermion DM Singlet

pseudoscalar

SM Higgs doublet

- a does not acquire VEV → no linear coupling to Higgs
- $m_a < 2m_\psi$ → “secluded DM”
- Model implemented in LanHEP, and numerical scan performed using micrOMEGAs.

4 relevant parameters:

$$m_\psi,\ Y_\psi,\ m_a,\ \lambda_{aH}$$

G.Cacciapaglia, D.Locke, A.Pukhov, AB arXiv:**2203.03660**

B.Diaz, P. Escalona,S.Norrero,A. Zerwekh arXiv:**2105.04255**

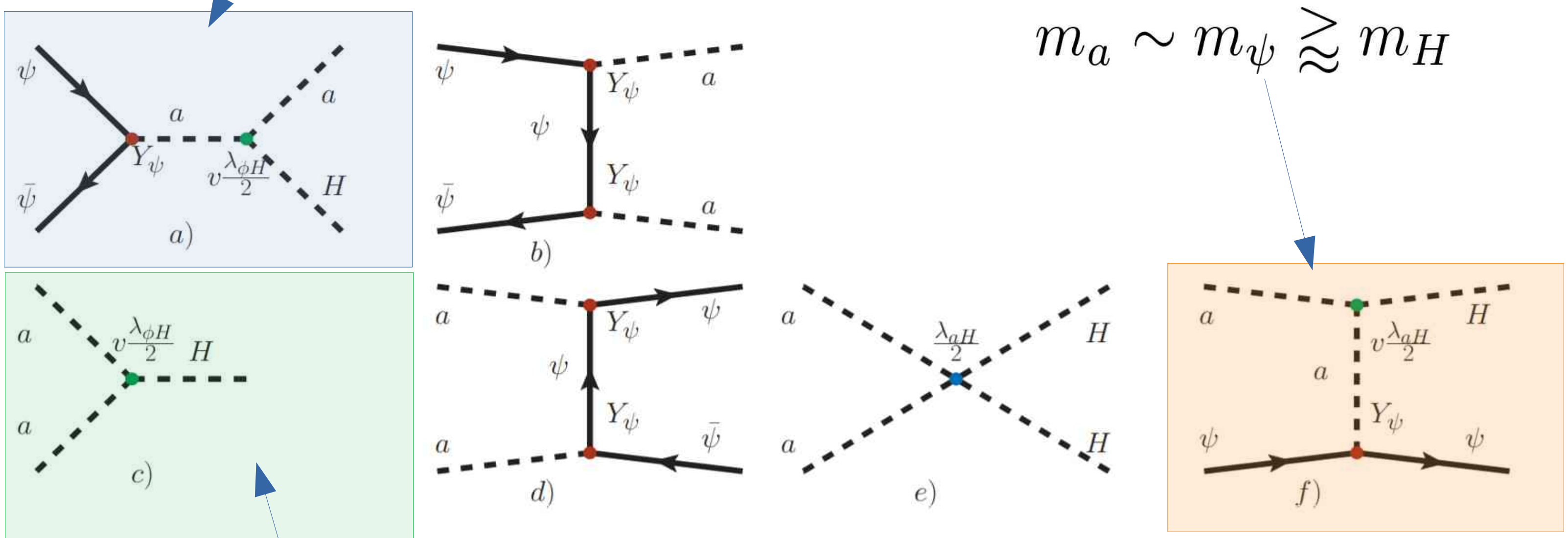
Spin of Mediator \ Spin of Dark Matter	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\boxed{\tilde{F}^I_Y S^{I'}_0}$	$\tilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\tilde{S}^I_Y \tilde{S}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{S}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{S}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{S}^I_Y \tilde{F}^{I'c}_{Y'}$	$\tilde{F}^I_Y \tilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\tilde{V}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{V}^I_Y \tilde{F}^{I'c}_{Y'}$
spin 1 even mediator	$\tilde{S}^I_Y V^{I'}_0$	$\tilde{F}^I_Y V^{I'}_0$	$\tilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\tilde{S}^I_Y \tilde{V}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{V}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{V}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{V}^{I'}_{Y'}$

Minimal fermion DM model with pseudo-scalar mediator

rich phenomenology: relic density, DD, colliders

(co)Annihilation channels

$$m_\psi \gtrsim \frac{m_a + m_h}{2} \gtrsim \frac{3m_H}{4} \sim 90GeV$$

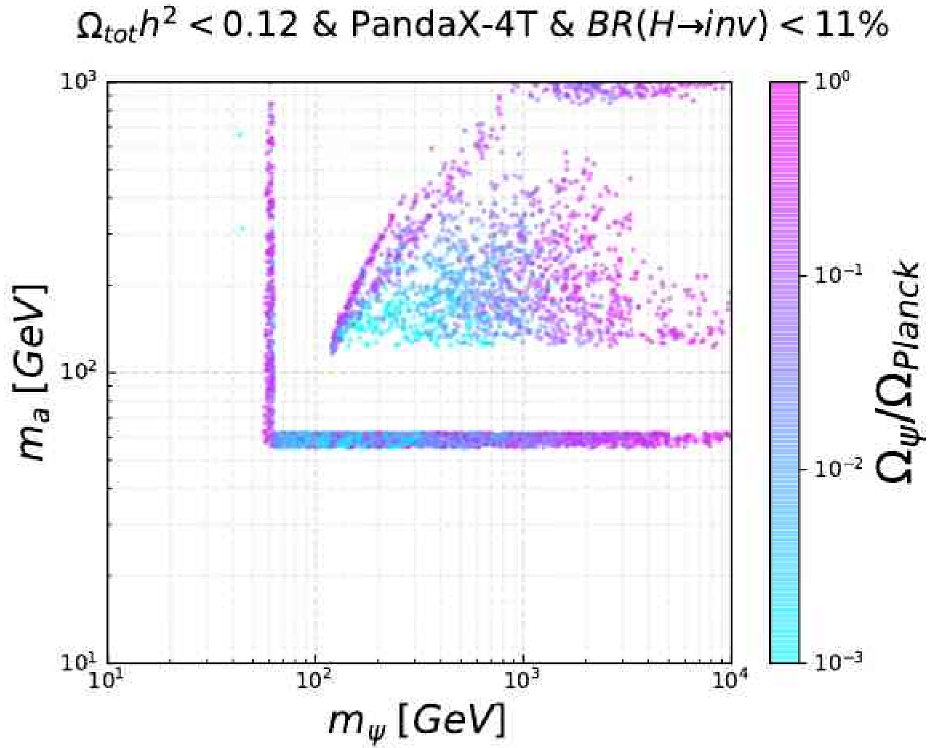


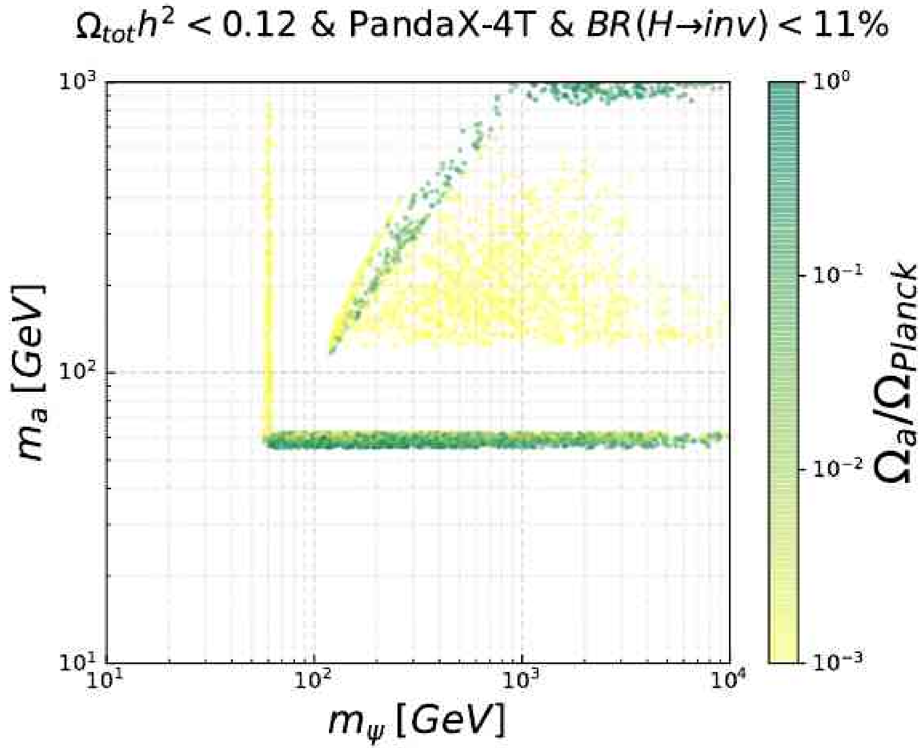
$$m_a \sim m_\psi \gtrsim m_H$$

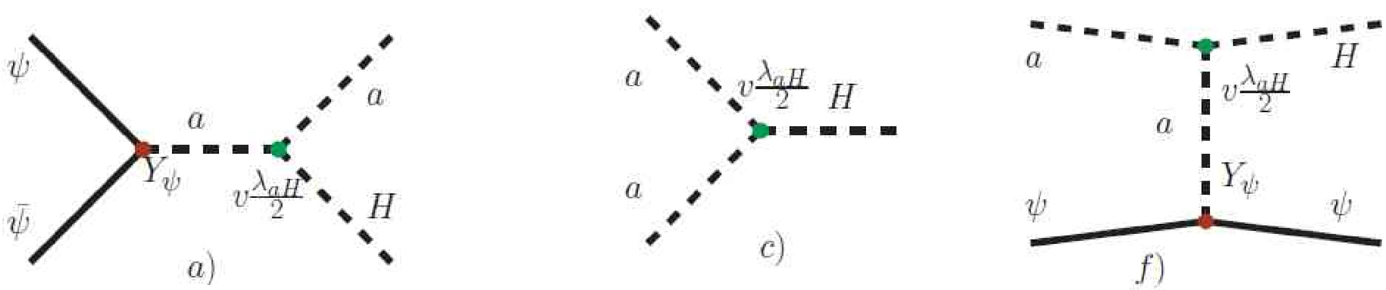
aa → WW
ma>80GeV
aa → ZZ
ma>90GeV
aa → tt
ma>173GeV

$$\sigma^{ann}_{aa\to ff} v \sim \frac{\lambda^2 m_f^2}{(4m_a^2 - m_H^2)^2 + m_H^2 \Gamma_H^2)}$$

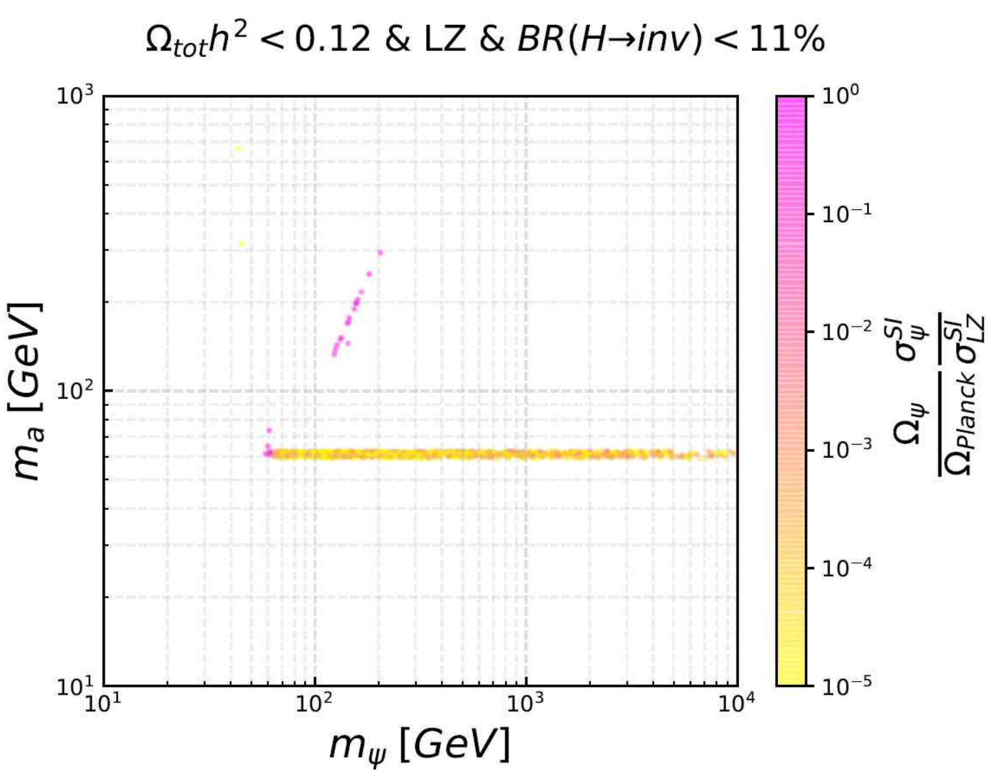
Minimal fermion DM model with pseudo-scalar mediator
PandaX-4T exclusion

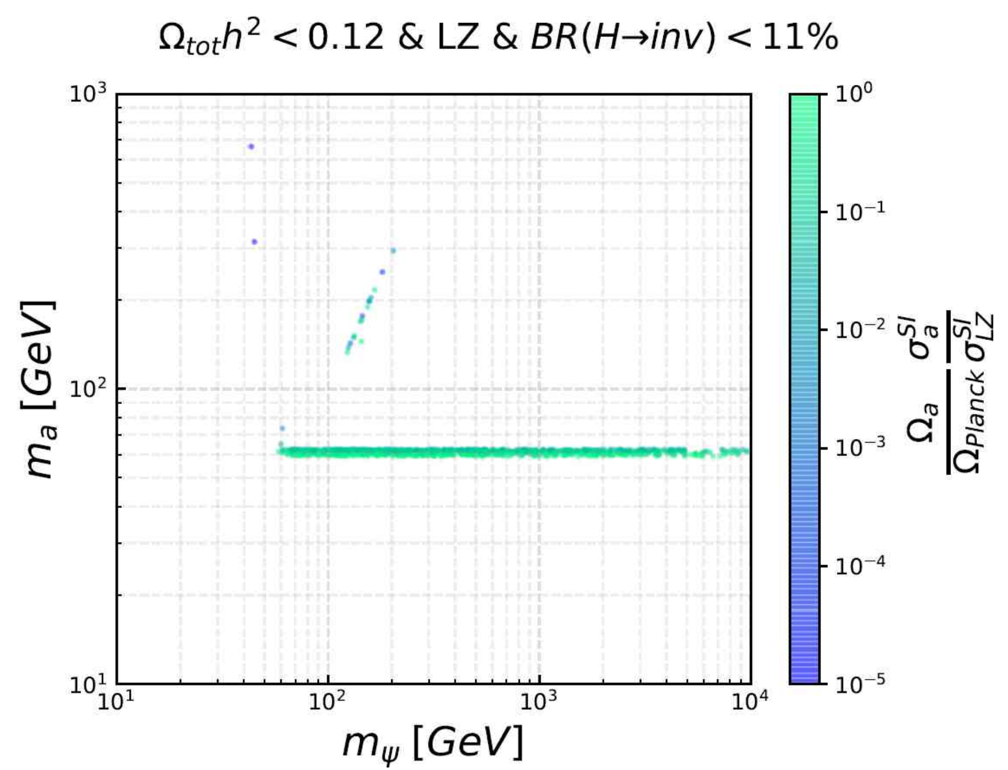


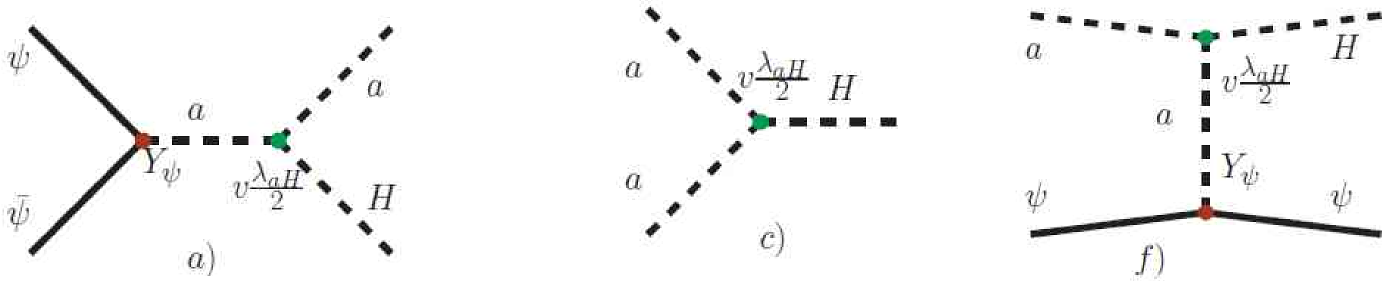




Minimal fermion DM model with pseudo-scalar mediator
LZ exclusion (projection)







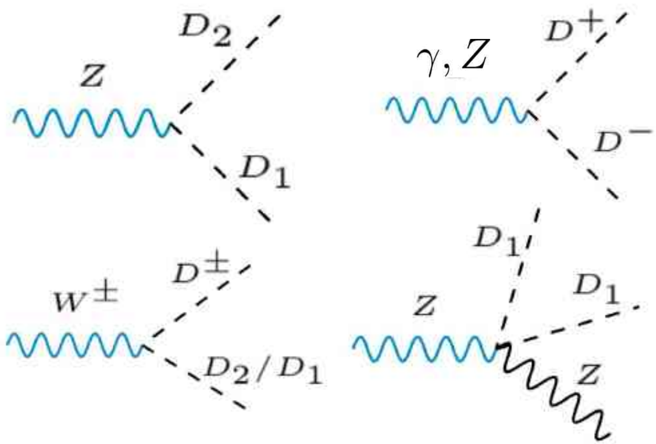
Decoding Dark Matter at future e^+e^- colliders

Inert 2 Higgs Doublet model (i2HDM)

$\tilde{S}^{1/2}_{1/2}$

$$\mathcal{L}_\phi = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - V(\phi_1, \phi_2)$$

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} D^+ \\ D_1 + i D_2 \end{pmatrix}$$



M_{D1}, $\Delta M^+ = M_{D+} - M_{D1}$, $\Delta M^0 = M_{D2} - M_{D+}$

Minimal fermion DM model (MFDM)

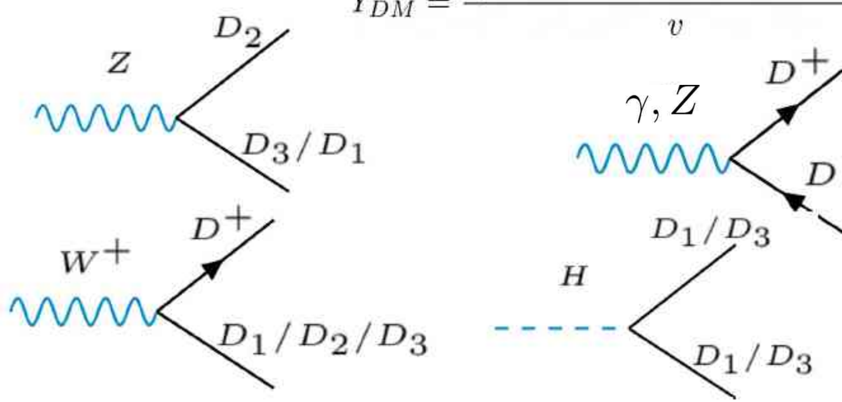
$\widetilde{F}^{1/2}_{1/2} \widetilde{M}^0_0$

$$\mathcal{L}_{FDM} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m_\psi)\psi + \frac{1}{2}\bar{\chi}^0_s(i\not{\partial} - m_s)\chi^0_s - (Y_{DM}(\bar{\psi}\Phi\chi^0_s) + h.c.)$$

$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(\chi^0_1 + i\chi^0_2) \end{pmatrix}$$

Majorana singlet χ^0_s

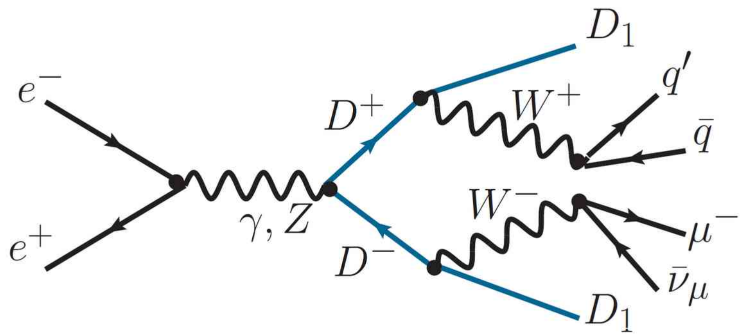
$$Y_{DM} = \frac{\sqrt{(m_{D3} - m_{D+})(m_{D+} - m_{D1})}}{v}$$



M_{D1}, $\Delta M^+ = M_{D+} - M_{D1}$, $\Delta M^0 = M_{D3} - M_{D+}$

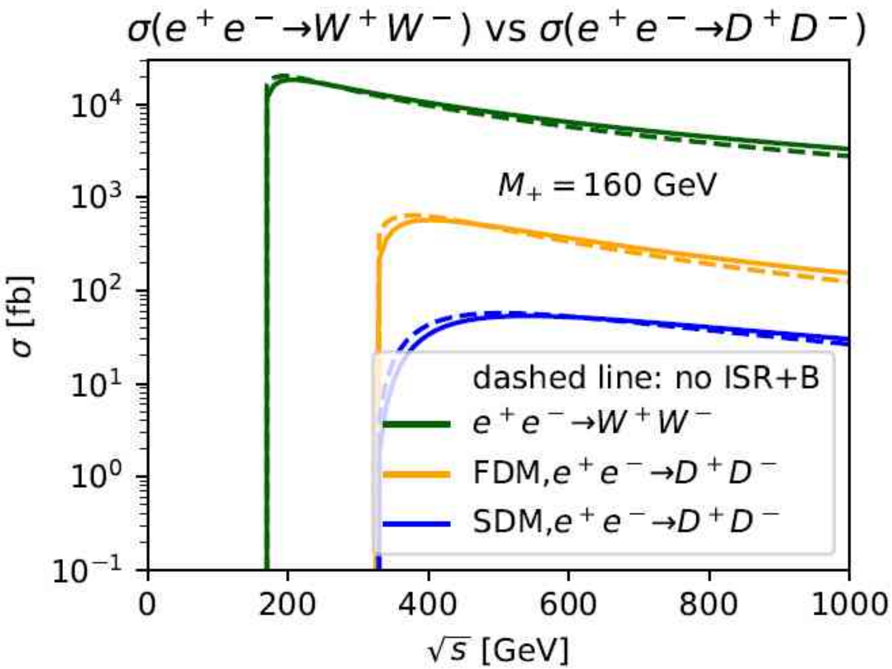
The process under study

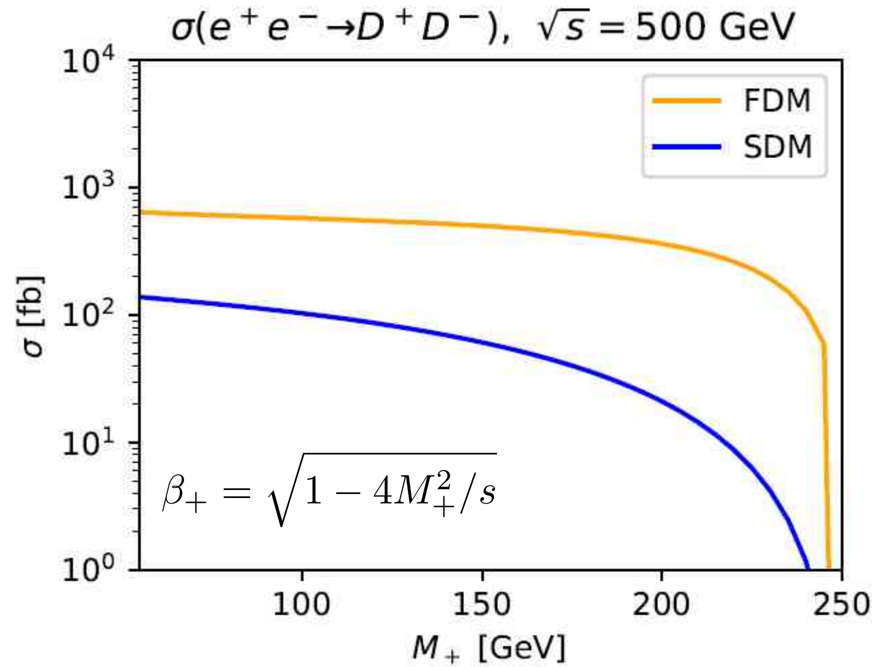
$$e^+e^- \to D^+D^- \to D_1 D_1 W^+W^- \to D_1 D_1 q'\bar{q}\mu\bar{\nu}$$



- Di-jet + muon + MET signature

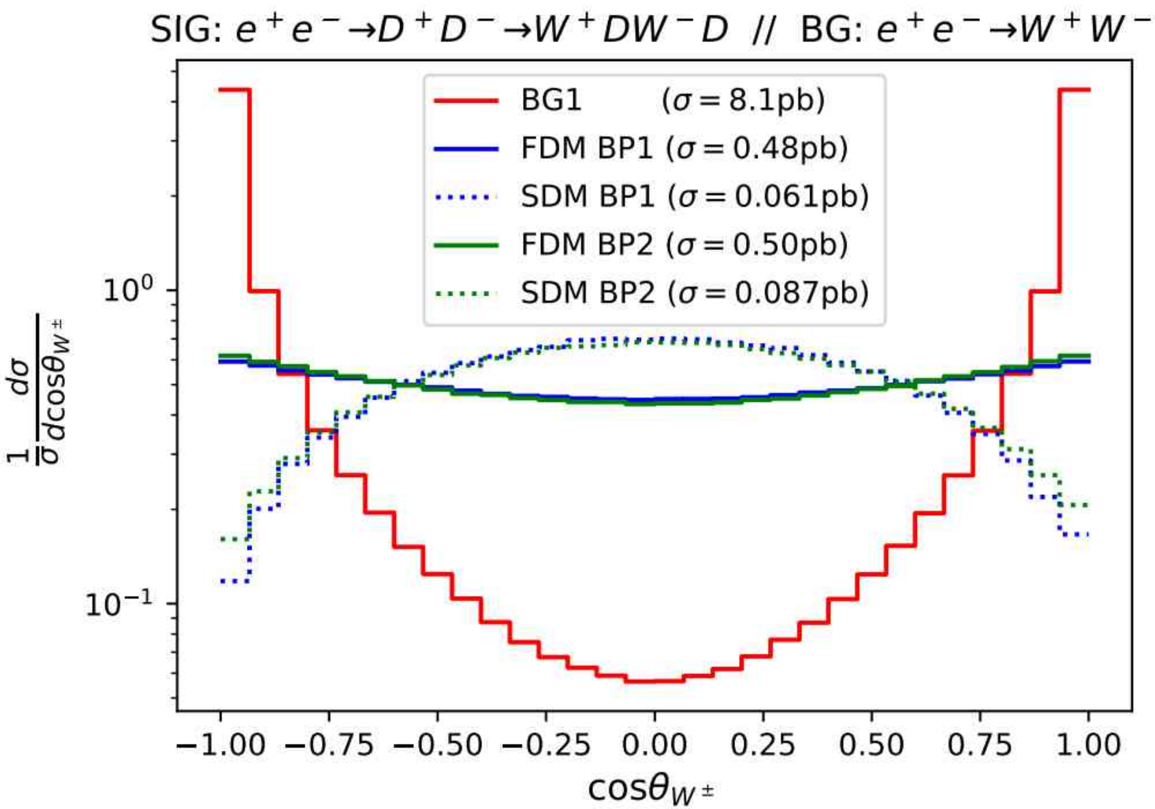
$$\sigma_{\gamma\gamma} = \begin{cases} \sigma_0 \beta_+ \left[1 + \frac{2M_+^2}{s}\right] & \text{if } s_D = \frac{1}{2} \\ \sigma_0 \frac{\beta_+^3}{4} & \text{if } s_D = 0 \end{cases}$$





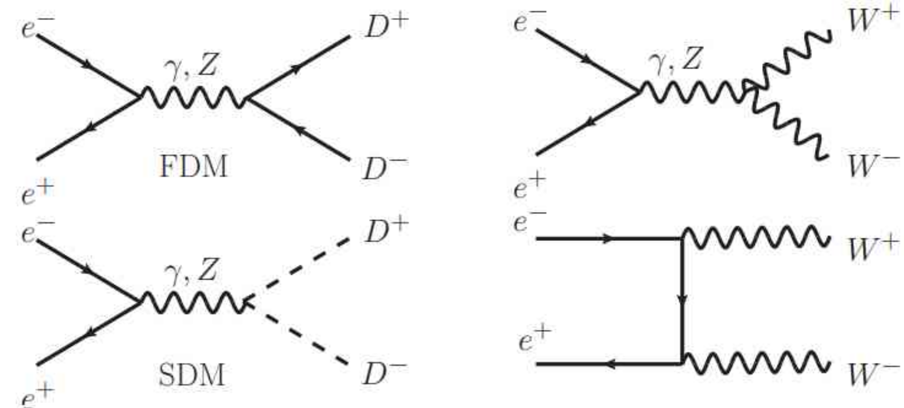
The role of the ILC in decoding the spin of DM

e+e- → D+ D- → DM DM W+ W- → DM DM jj μ ν



AB, Ginzburg, Locke, Freegard, Pukhov arXiv:**2112.15090**

$$\frac{d\sigma}{d\cos\theta_{D\pm}} \propto \begin{cases} 1-\cos^2\theta_{D\pm}, & \text{for SDM} \\ 1+\dfrac{s-4M_+^2}{s+4M_+^2}\cos^2\theta_{D\pm}, & \text{for FDM} \end{cases}$$



- The angular W-boson distribution (either for real or virtual W) is found to be very important discriminator between DM spin as well as the main BG
- The shape of angular W-boson distribution is the same for different benchmarks for DM of the same spin

Beyond the weak interactions: Vector Dark Matter (VDM) from dark SU(2)

Deandrea, Moretti, Panizzi, Ross, Thongyoi,AB arXiv:**2204.03510,2203.04681**

Vector DM

- The abelian/non-abelian Vector DM with Higgs portal
  - $U(1)_D$ Group
  - $V_D^\mu \leftrightarrow -V_D^\mu$ Explicit Z_2 symmetry plus a Higgs portal to provide the stability and the mass for VDM and connect it to the SM

$$\mathcal{L} \supset -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) + \lambda_P \, |H|^2 |\Phi|^2$$

with $D_\mu \Phi \equiv \partial_\mu \Phi - g Q_\Phi V_\mu \Phi$, after SSB → $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \varphi(x))$

so one has $m_V^2 = g^2 Q_\Phi^2 \; v_\phi^2$

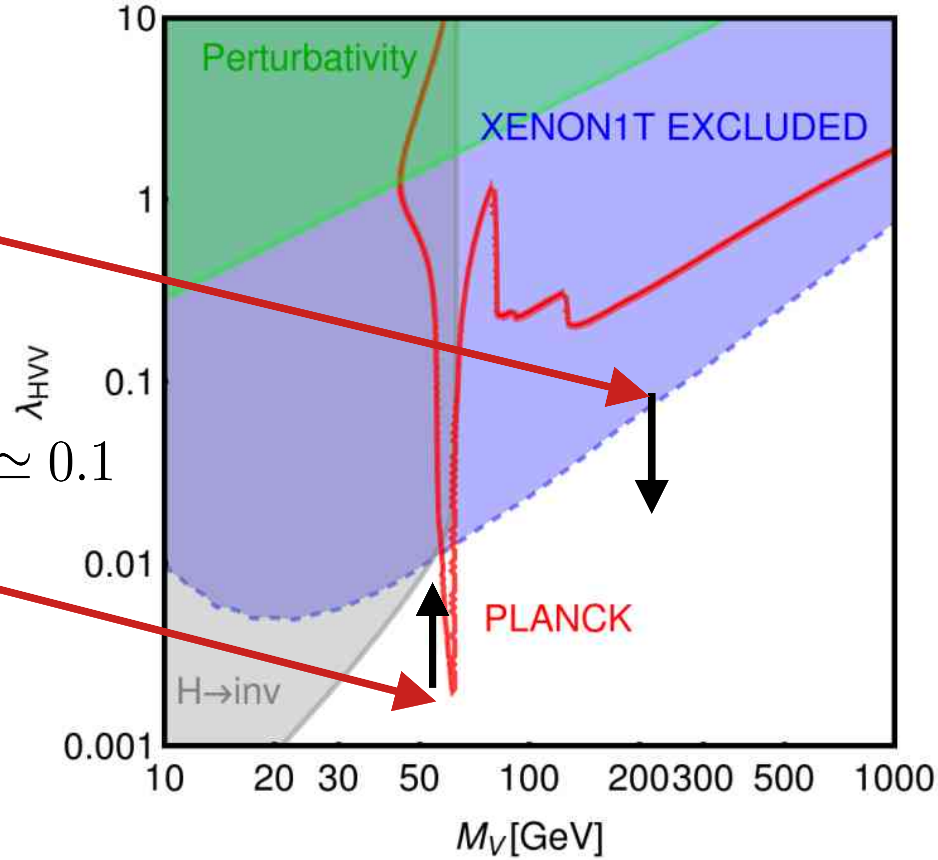
  - Quite a few papers:

Lebedev, Lee, Mambrini 1111.4482,
Baek, Ko, Park , Senaha 1212.2131
DiFranzo, Fox,Tait 1512.06853
Farzan, Akbarieh 1207.4272
Duch, Grzadkowski, McGarrie 1506.08805
…………………………

Vector DM with the Higgs portal

Arcadi, Djouadi, Kado 2001.10750

- Since VDM 'talks' to SM via Higgs, $V_D V_D H$ coupling is **limited from above** by DM direct detection and H→ DM DM Br
- Since DM Relic density should be equal or below the PLANCK relic density limit $\Omega h^2 \simeq 0.1$ $V_D V_D H$ coupling is **limited from below**
- The Higgs portal VDM parameter space is very limited by interplay of collider, DD and DM relic density



Vector DM and Vector-Like Fermionic Portal

- Higgs portal : the parameter space for minimal scenarios is almost excluded
- **Vector Like(VL) fermionic portal for Vector Dark Matter** (also in Nakorn's talk)
  - $SU(2)_D$ gauge triplet (new dark gauge) V_μ^D
  - Complex scalar doublet charged under $SU(2)_D$ Φ_D – to break gauge group
  - Vector-Like fermion doublet of $SU(2)_D$ Ψ – to “talk” to SM

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  - Vector-Like fermion doublet of $SU(2)_D$ Ψ – to "talk" to SM
  - we assign the "dark charge" to the components of the doublets, e.g. $Q_D = T_D^3 + Y_D$ and require its conservation
  - $SU(2)_D \times U(1)_{\rm glob} \to U(1)^d_{\rm glob}$ pattern of dark sector breaking
  - $\mathbb{Z}_2$ subgroup can be defined as: $(-1)^{Q_D}$

Vector DM and Vector-Like Fermionic Portal

- If we chose $Y_D = +1/2$ for Φ_D and Ψ then we have

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	Q_D	Z_2
$\varphi_D = \begin{pmatrix}\varphi_{D+\frac{1}{2}} \\ \varphi_{D-\frac{1}{2}}\end{pmatrix} \to \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ H_D + v_D\end{pmatrix}$	1	0	2	$\begin{matrix}+1 \\ 0\end{matrix}$	$\begin{matrix}- \\ +\end{matrix}$
$\Psi = \begin{pmatrix}\psi_D \\ \psi\end{pmatrix} = \begin{pmatrix}\tilde{F} \\ F\end{pmatrix}$	1	Q_{EM}	2	$\begin{matrix}+1 \\ 0\end{matrix}$	$\begin{matrix}- \\ +\end{matrix}$
$V_\mu^D = \begin{pmatrix}V_\mu^{D+} \\ V_\mu^{D0} \\ V_\mu^{D-}\end{pmatrix} = \begin{pmatrix}\tilde{V}_D^+ \\ V' \\ \tilde{V}_D^-\end{pmatrix}$	1	0	3	$\begin{matrix}+1 \\ 0 \\ -1\end{matrix}$	$\begin{matrix}- \\ + \\ -\end{matrix}$

Vector DM and Vector-Like Fermionic Portal

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	Q_D	Z_2
$\Phi_D = \begin{pmatrix} \varphi_{D+\frac{1}{2}} \\ \varphi_{D-\frac{1}{2}} \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H_D + v_D \end{pmatrix}$	1	0	2	$\begin{matrix} +1 \\ 0 \end{matrix}$	$\begin{matrix} - \\ + \end{matrix}$
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- If we chose $Y_D = +1/2$ for Φ_D and Ψ then we have

$$y' \bar{\Psi}_L \Phi_D f_R^{\rm SM} + \cancel{y'' \bar{\Psi}_L \Phi_D^c f_R^{\rm SM}} + h.c$$

y'' **eliminated, DM is stabilised!**

Fermionic Portal for Vector Dark Matter (FPVDM)

- It is the framework, representing the class of models
  (Deandrea, Moretti, Panizzi, Ross, Thongyoi, AB – arXiv:2204.03510,2203.04681)

- Various realisations are possible, including one or several VL fermions

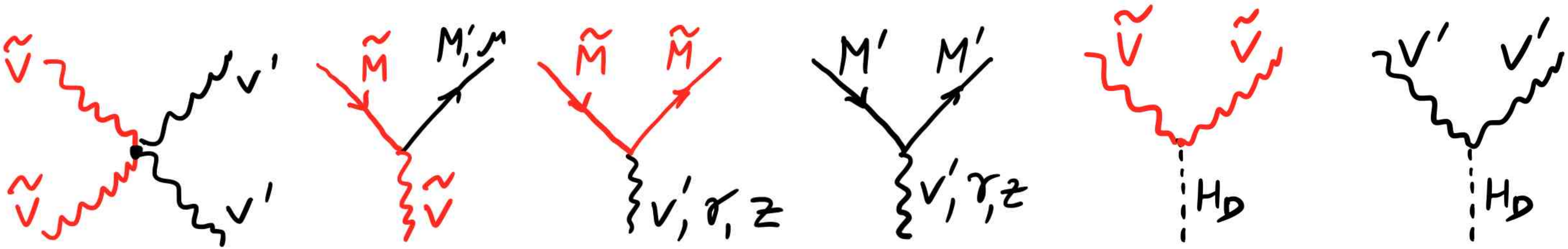
$$
\begin{aligned}
\mathcal{L}_{FPVDM} &= -\frac{1}{4}(V^i_{D\mu\nu})^2 + \bar{\Psi} i \not{D} \Psi + |D_\mu \Phi_D|^2 - V(\Phi_H, \Phi_D) \\
&- \underline{(y'_{\alpha\beta} \bar{\Psi}^{i\alpha}_L \Phi_D f^{\mathrm{SM}\beta}_R} + h.c) - M_\Psi{}^{ij} \bar{\Psi}^i \Psi^j \\
V(\Phi_H, \Phi_D) &= -\mu_H^2 \Phi_H^\dagger \Phi_H - \mu_D^2 \Phi_D^\dagger \Phi_D + \lambda_H (\Phi_H^\dagger \Phi_H)^2 \\
&+ \lambda_D (\Phi_D^\dagger \Phi_D)^2 + \lambda_{HD} (\Phi_H^\dagger \Phi_H)(\Phi_D^\dagger \Phi_D)
\end{aligned}
$$

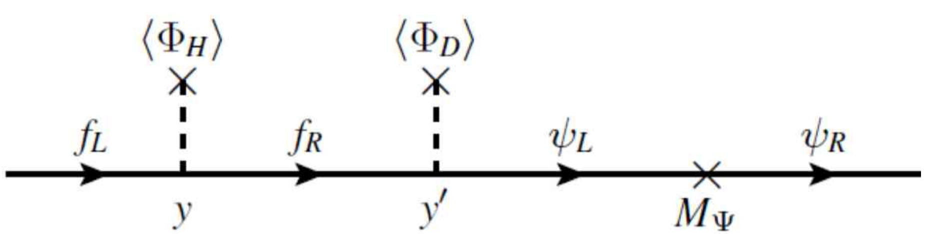
- $y'_{\alpha\beta}$ can have a flavour structure – to explain flavour anomalies
- λ_{HD} can be zero at tree-level, DM can be well-generated via FP
- the model with $\Psi = \begin{pmatrix} \tilde{T} \\ T \end{pmatrix}$ and $\lambda_{HD} = 0$ was explored as an example

FPVDM model with $\Psi_M = \begin{pmatrix} \tilde{M} \\ M' \end{pmatrix}$, the partner of muon

$$\mathcal{L}_{\mu PVDM} \supset -y'\bar{\Psi}_{ML}\Phi_D\mu_R + h.c \qquad \text{with} \quad \tilde{V}_D, \ V', \ H_D, \ M', \ \tilde{M}$$

- has potential to explain DM relic density and $(g\text{-}2)_\mu$ anomaly
- one should ensure
  - consistency with DD and ID DM search experiments
  - consistency with collider searches
- Parameter space ($\lambda_{HD} = 0$ for simplicity): $\boxed{g_D, m_{V_D}, m_{H_D}, m_{M'}, m_{\tilde{M}}}$
- Interactions+mixing:





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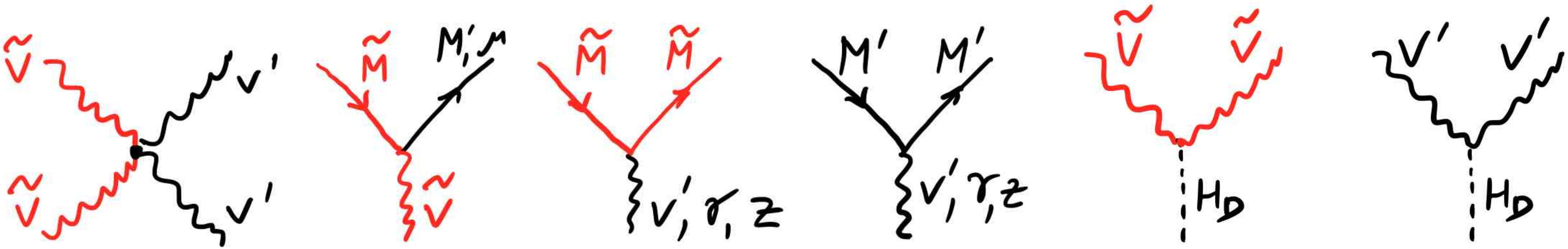
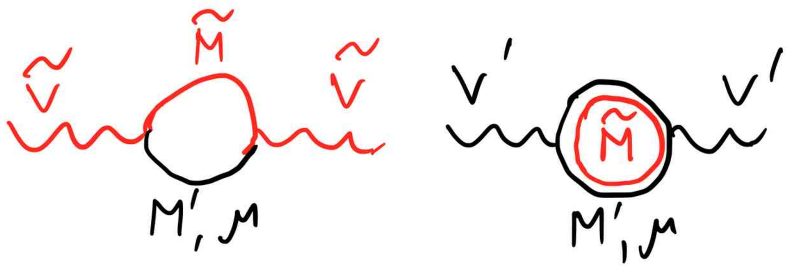
- Interactions+mass corrections:





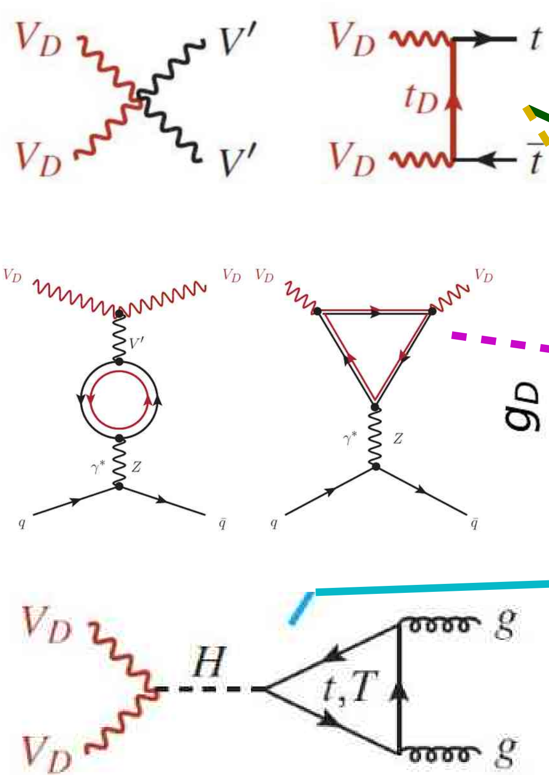
$$m_{V_D} - m_{V'} = \frac{g_D^2 m_{M'}^2}{32\pi^2 m_{V_D}} \left(\frac{m_{M'}^2 - m_{\tilde{M}}^2}{m_{M'}^2} \right)^2$$

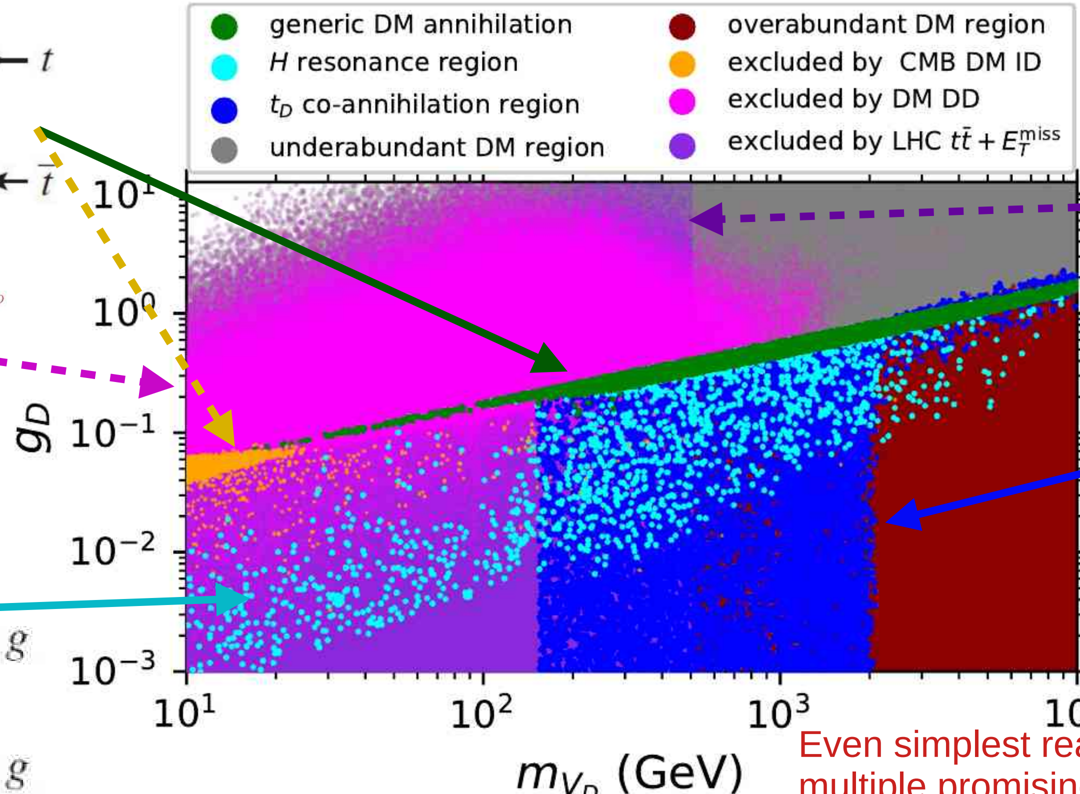
Minimal VL top portal VDM: VL top portal without higgs portal mixing

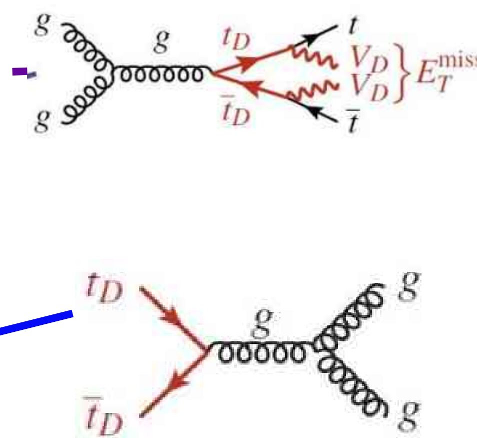
The VL fermion is composed of top partners and there is no mixing between scalars

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T \qquad\qquad \sin\theta_S = 0$$

5D parameter space: $g_D, m_{V_D}, m_H, m_T, m_{t_D}$

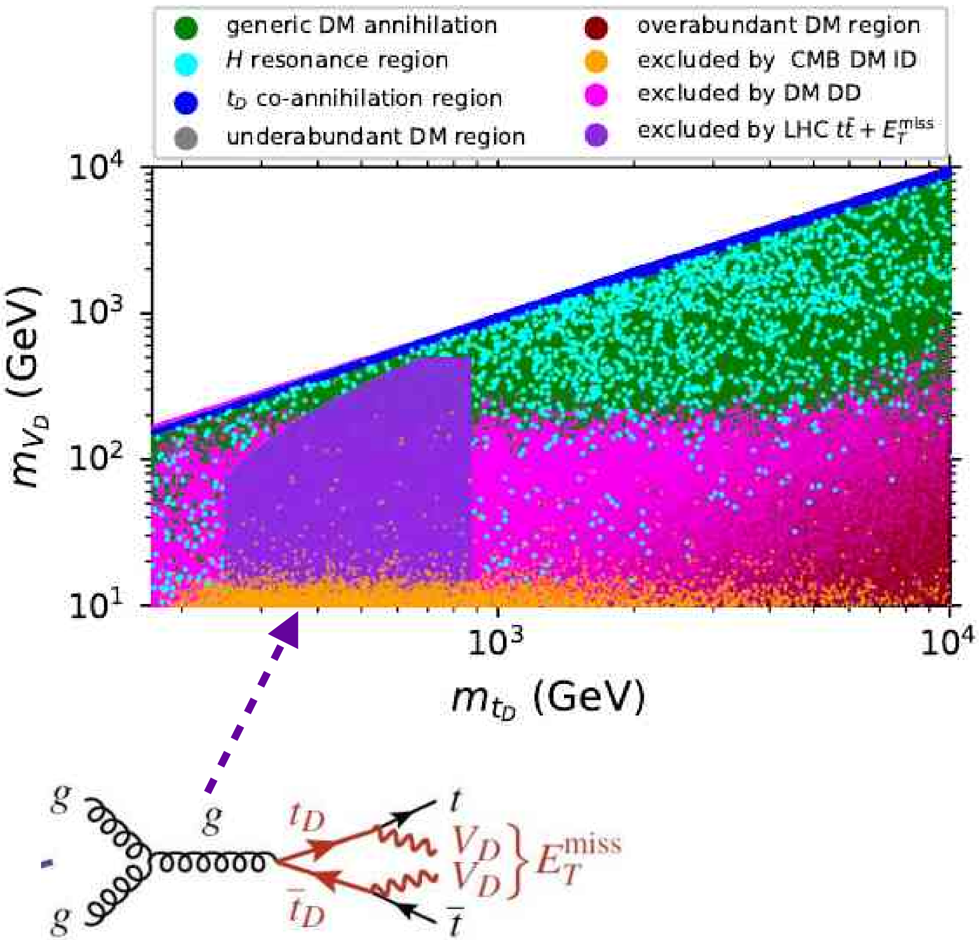


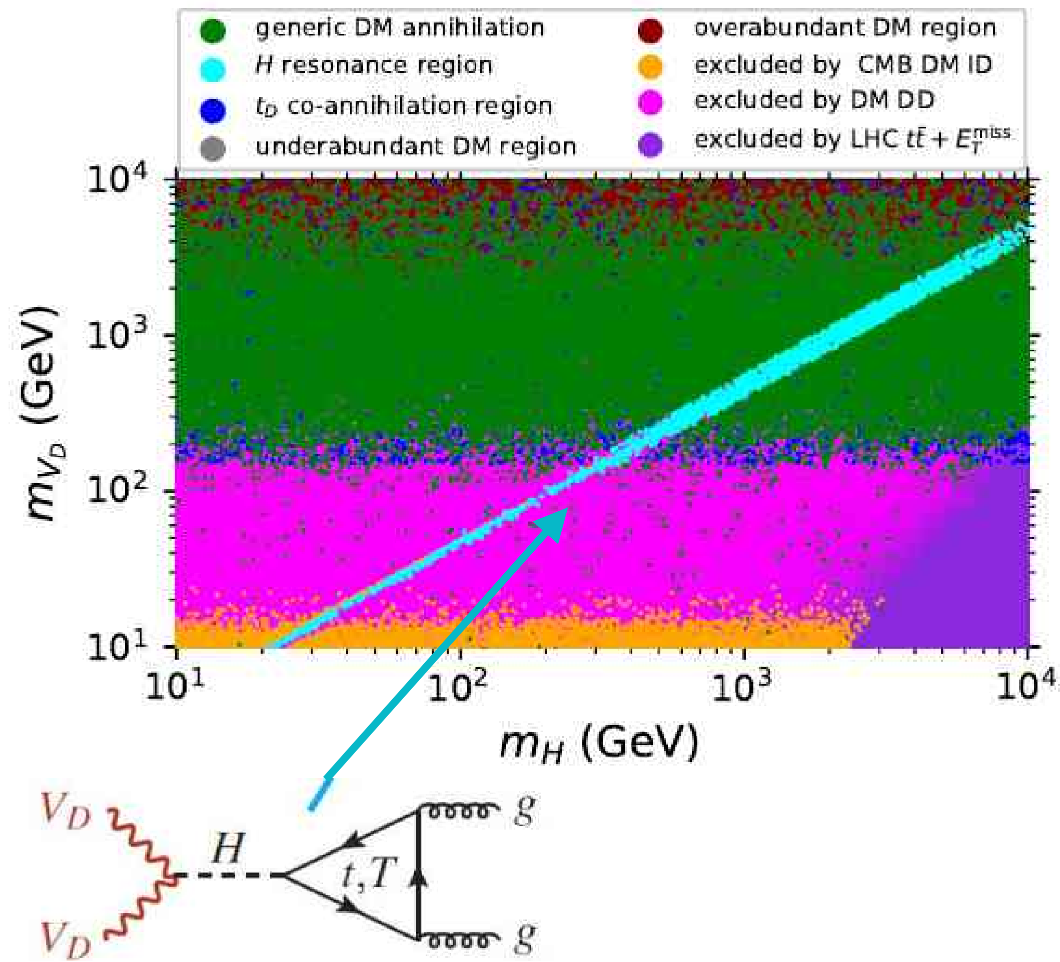




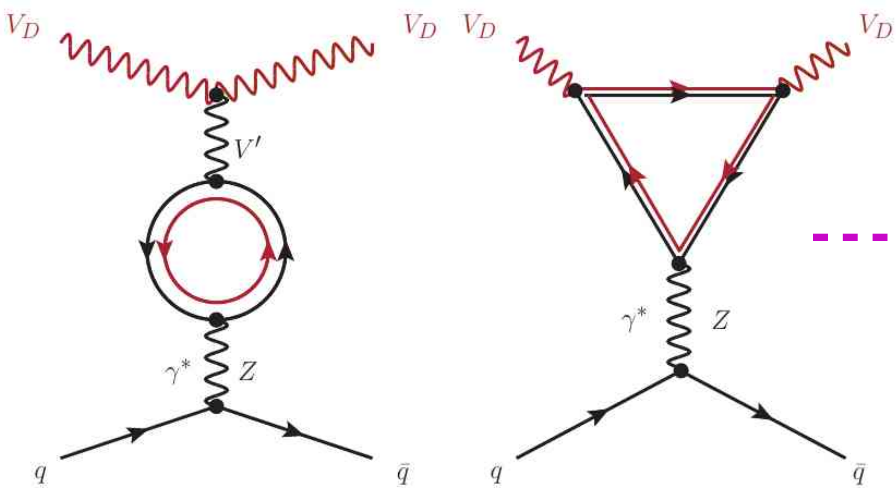
Even simplest realisation of the framework has multiple promising features and signatures

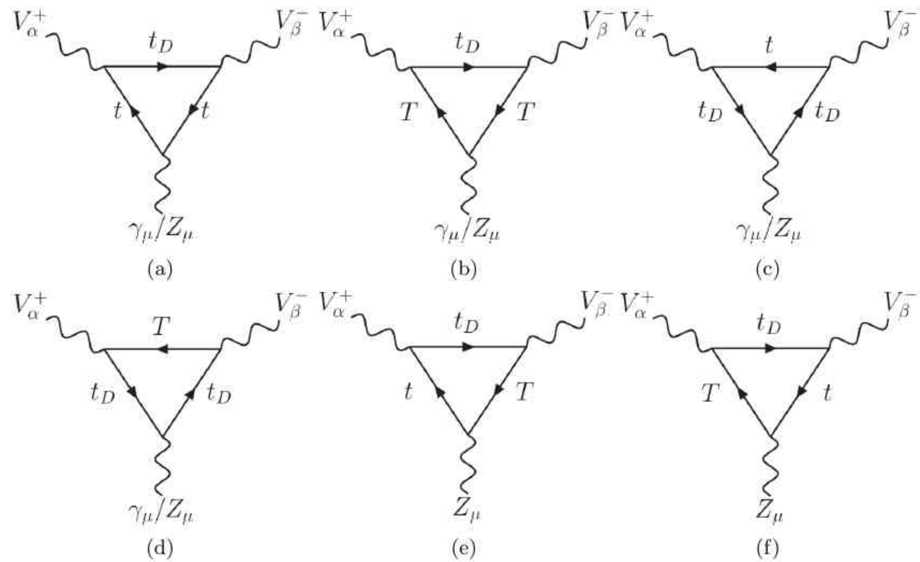
Minimal VL top portal VDM: projections of 5D scan in $g_D, m_{V_D}, m_H, m_T, m_{t_D}$





The role of quantum corrections for DM direct detection





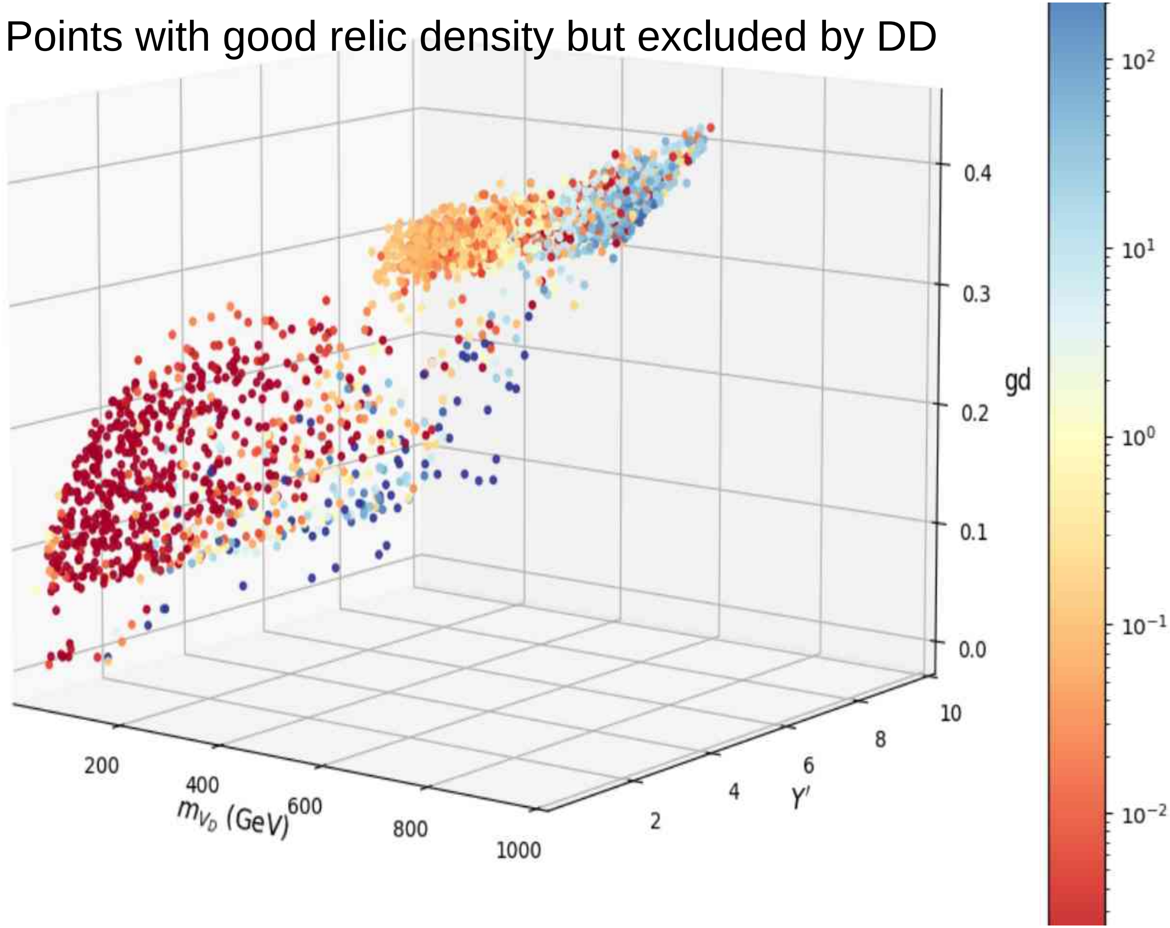
$$V_V^{\alpha\beta\mu}(p_1,p_2,q) = f_1^V (p_1-p_2)^\mu g^{\alpha\beta} + \frac{f_2^V}{M_{V^\pm}^2}(p_1-p_2)^\mu q^\alpha q^\beta + f_3^V (q^\alpha g^{\mu\beta} - q^\beta g^{\mu\alpha})$$

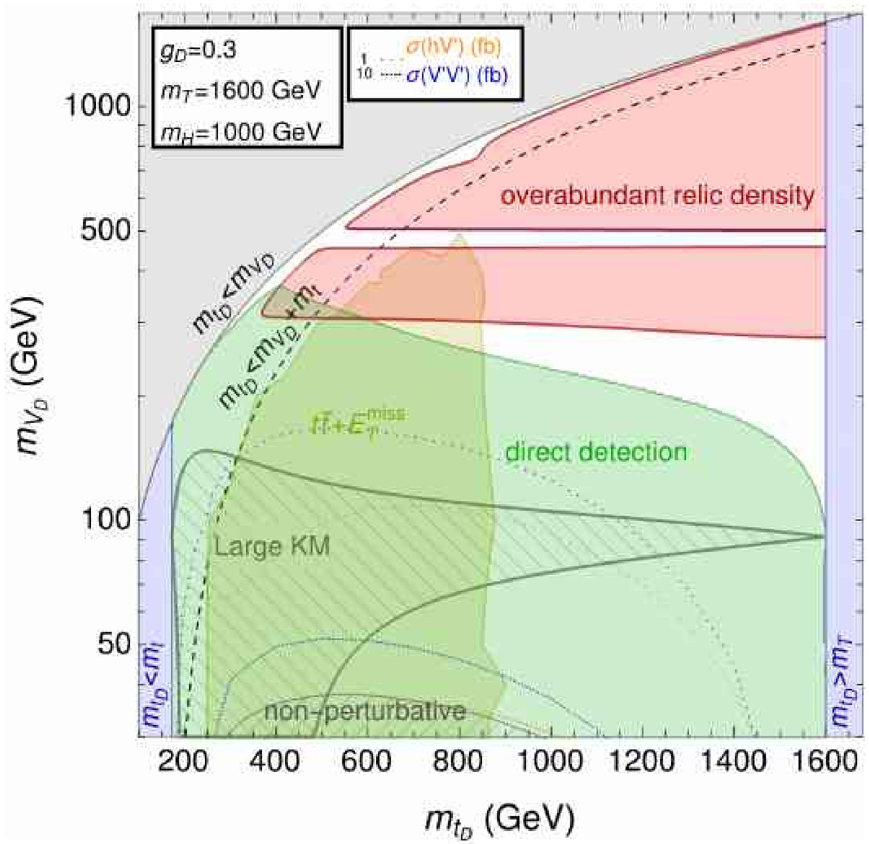
$$+ i f_5^V \epsilon^{\alpha\beta\mu\rho}(p_1-p_2)_\rho + i\frac{f_8^V}{M_{V^\pm}^2}(p_1-p_2)_\rho q_\sigma (\epsilon^{\mu\alpha\rho\sigma} q^\beta - \epsilon^{\mu\beta\rho\sigma} q^\beta)$$

There five CP - conserving Lorentz structures and the respective form-factors for DM multipole interactions from triangle diagrams

The role of quantum corrections for DM direct detection

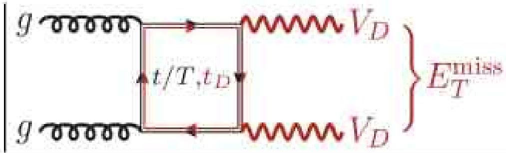
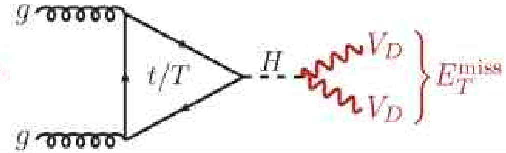
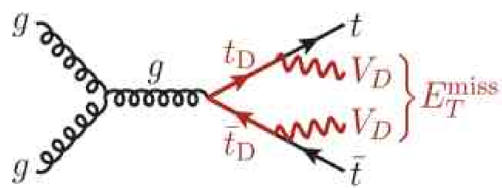
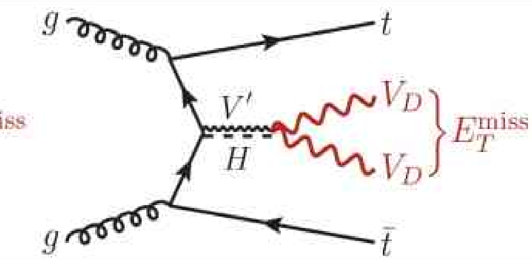
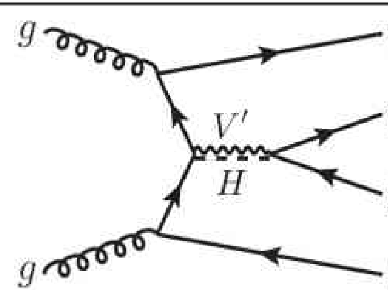
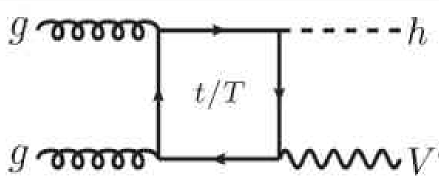
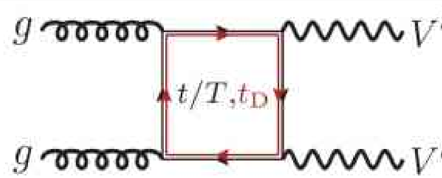
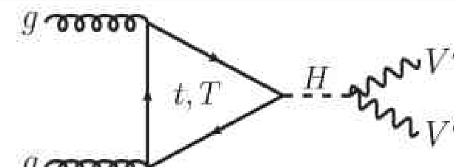
Points with good relic density but excluded by DD



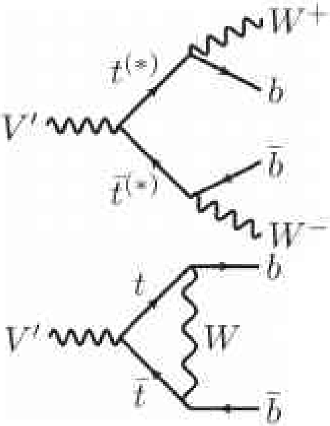


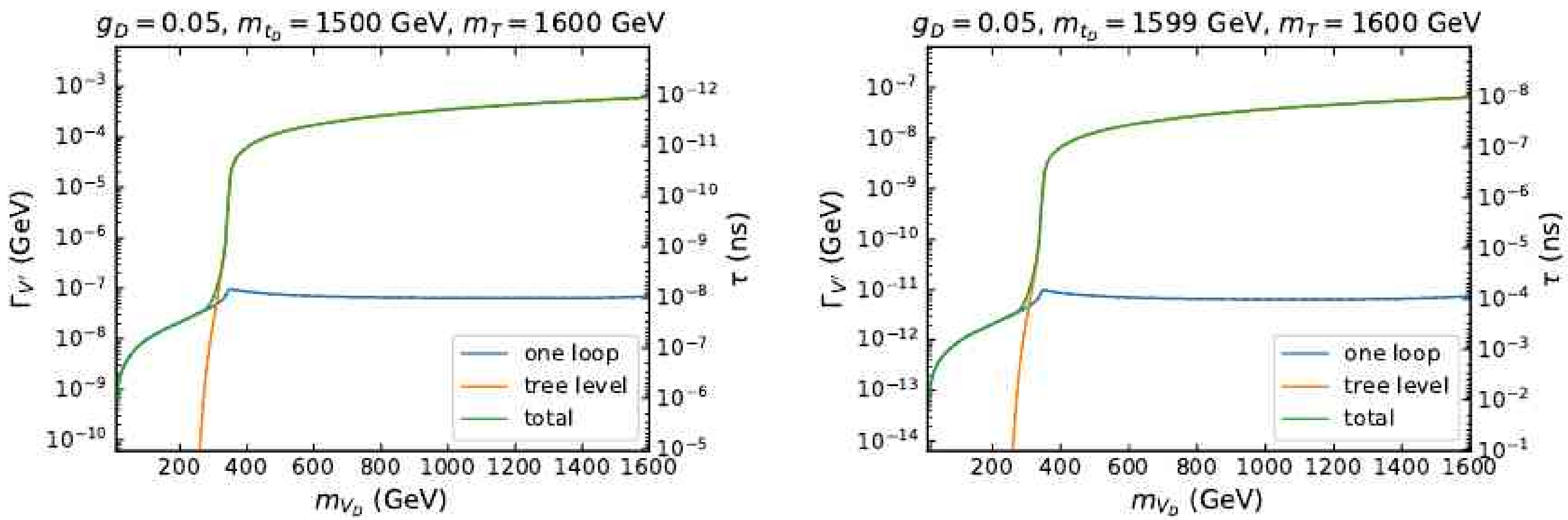
Both kinetic mixing and DM multipole interactions play a crucial role for DM direct detection!

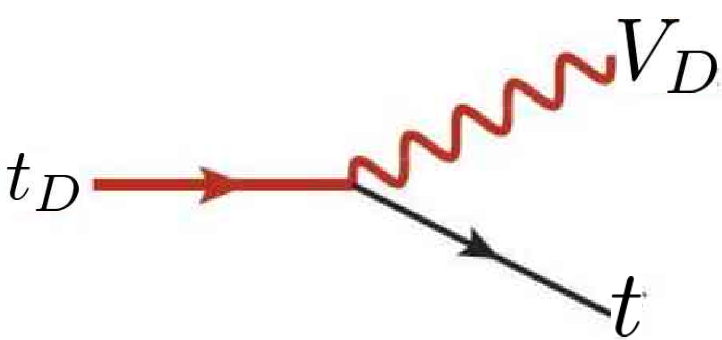
Minimal VL top portal VDM: collider signatures

Process	Representative diagrams
mono-jet (only loop)	  + jet from ISR or from loop
$t\bar{t} + E_T^{miss}$	 
$t\bar{t}t\bar{t}$	
hV' and $V'V'$ (only loop)	  

V′ and t_D can be naturally long-lived







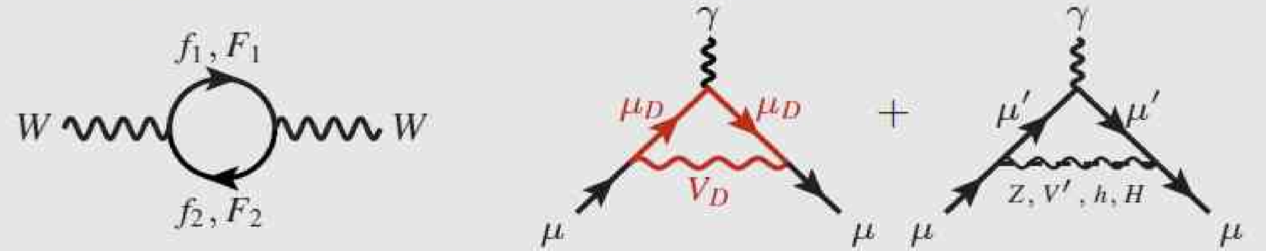
If V’ is light enough, its radiative decay will be dominant, so V’ could be naturally long-lived

If the mass gap between odd-fermion (t_D) and DM is below the top-quark mass, t_D can also be naturally long-lived

Summary on Fermion Portal Vector Dark Matter (FPVDM)

- FPVDM is a new framework which does not require the Higgs portal
- Has new features with new collider and cosmological implications
- Simple realisation of the top sector – several promising predictions and signatures
  - great potential to explain dark matter
  - collider signatures: tt+miss, V', V'H, long-lived V' and t_D
  - Gravitational waves from the interplay of EW and dark Higgs potentials
  - great potential to explain flavour anomalies, $(g\text{-}2)_m$, baryogenesis, W-mass, … while it was not deliberately designed to do this!

→ **Different realizations** to study **current anomalies** (LFU, $(g-2)_\mu$, $m_W \ldots$)



→ Study of different **theoretical embeddings**
→ Further analysis of **cosmological implications** and scenarios for **future colliders**

Note on DM Decoding Problem

- This is the problem of finding of **the link between signatures and underlying theory**

- probably the most challenging problem to solve
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signature from data with the pattern of the signature from the theory

- **HEPMDB (High Energy Physics Model Database)** was created in 2011 **hepmdb.soton.ac.uk**
  - convenient centralized storage environment for HEP models
  - you can upload there your own model and perform its analysis
  - It is an important framework for decoding the underlying theory

Conclusions and Outlook

- **To decode the nature of DM** we need a signal first! But at the moment we can
  - understand what kind of DM is already excluded
  - systematically explore theory/parameter space and prepare ourselves for DM discovery and interpretation
- **MCDM models:** consistent but simple – one can explore the entire parameter space
- **Systematic classification**: new models can be found even for simplest cases
- **Probing DM space**
  - non-singlets can be probed via DT searches or multi-lepton signatures at colliders
  - DM DD is sensitive to the loop-induced diagrams but does not exclude all models
  - rich phenomenology, complementarity of DM DD, collider signals and relic density
- **FPVDM** framework offers an elegant solution solution of DM , $(g\text{-}2)_\mu$ and flavour problems via VL fermion portal, new signatures and many promising projects
- **Decoding the underlying theory** is crucial problem to solve: requires joint effort of theorists and experimentalists, models' classification, ML approach