Vector Dark Matter via a Fermionic Portal from a New Gauge Sector

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2203.04681 and 2204.03510 AB, Luca Panizzi, Aldo Deandrea, Stefano Moretti and Nakorn Thongyoi

Workshop on the Standard Model and Beyond
August 28 – September 8, 2022
The existence of Dark Matter is confirmed by several independent observations at cosmological scale.

Galactic rotation curves

CMB: WMAP and PLANCK

Large Scale Structures

Bullet cluster

Gravitational lensing

The existence of Dark Matter is confirmed by several independent observations at cosmological scale.
DM is very appealing even though we know almost nothing about it!

**Spin**
- ?

**Mass**
- ?

**Couplings**
- gravity: V
- weak: ?
- higgs: ?
- quarks/gluons: ?
- leptons: ?
- New mediators: ?

**Stable**
- Yes: ?
- No: ?

- Symmetry behind stability: ?

**Thermal relic**
- Yes: ?
- No: ?
Spectrum of Theory Space

- Effective Field Theories
- Dipole Interactions
- Simplified Models
- Minimal Consistent Models

Models:
- UED
- MSSM
- mSUGRA
- More Complete
- Little Higgs
- UV Complete Models
- Z' dark photon
- Contact Interactions
- Higgs portal
- "Squarks"

Universal building block for complete models
Cacciapaglia, Locke, Pukhov, AB
arXiv:2203.03660
Vector DM

- The abelian/non-abelian Vector DM with Higgs portal
  - $U(1)_D$ Group
Vector DM

- The abelian/non-abelian Vector DM with Higgs portal
  - $U(1)_D$ Group
  - $V^\mu_D \leftrightarrow -V^\mu_D$ Explicit $\mathbb{Z}_2$ 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 \( D_\mu \Phi \equiv \partial_\mu \Phi - gQ_\Phi V_\mu \Phi \)
The abelian/non-abelian Vector DM with Higgs portal

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

so one has

$$m_V^2 = g^2 Q_\Phi^2 v_\phi^2$$
Vector DM

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so one has $m_V^2 = g^2 Q_\Phi^2 v^2_\phi$

- Quite a few papers:
  - Lebedev, Lee, Mambrini 1111.4482, Farzan, Akbarieh 1207.4272
  - Baek, Ko, Park, Senaha 1212.2131, Duch, Grzadkowski, McGarrie 1506.08805
  - DiFranzo, Fox, Tait 1512.06853

...
Vector DM with the Higgs portal

- Since VDM ‘talks’ to SM via Higgs, $V_D V_D H$ coupling is **limited from above** by DM direct detection and $H \rightarrow$ DM DM $\text{Br}$
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- Since DM Relic density should be equal or below the PLANCK relic density limit, $V_D V_D H$ coupling is **limited from below**
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$\Omega h^2 \lesssim 0.1$

$\lambda_{HV}$

Arcadi, Djouadi, Kado 2001.10750
Vector DM with the Higgs portal

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- Since DM Relic density should be equal or below the PLANCK relic density limit $V_D V_D H$ 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 with the Higgs portal

- Non-abelian case
  - Generalisation to SU(N) case:
    Gross, Lebedev, Mambrini 1505.07480
    SSB with N-1 complex scalar N-plets in fundamental rep of SU(N) – gives mass to VDM and predicts \((N-1)^2\) scalars
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  - **electroweakly interacting non-abelian vector dark matter:**
    Abea, Fujiwara, Hisano, Matsushita 2004.00884
    $\text{SU}(2)_0 \times \text{SU}(2)_1 \times \text{SU}(2)_2 \times U(1)_Y : \text{SU}(2)_0 \leftrightarrow \text{SU}(2)_2$ symmetry provides stability for VDM, so there are VDM triplet + vector triplet of unstable $W'/Z'$ bosons

\[
V_{\text{scalar}} = m^2 H^\dagger H + m^2_\Phi \text{tr} \left( \Phi_1^\dagger \Phi_1 \right) + m^2_\Phi \text{tr} \left( \Phi_2^\dagger \Phi_2 \right) \\
+ \lambda (H^\dagger H)^2 + \lambda_\Phi \left( \text{tr} \left( \Phi_1^\dagger \Phi_1 \right) \right)^2 + \lambda_\Phi \left( \text{tr} \left( \Phi_2^\dagger \Phi_2 \right) \right)^2 \\
+ \lambda_{h\Phi} H^\dagger H \text{tr} \left( \Phi_1^\dagger \Phi_1 \right) + \lambda_{h\Phi} H^\dagger H \text{tr} \left( \Phi_2^\dagger \Phi_2 \right) + \lambda_{12} \text{tr} \left( \Phi_1^\dagger \Phi_1 \right) \text{tr} \left( \Phi_2^\dagger \Phi_2 \right)
\]
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\]

quite a non-minimal model
Vector like fermion Portal for Vector DM

- Higgs portal is very-well studied and the parameter space for minimal scenarios is almost excluded
- We are driven by curiosity and simplicity to find an alternative portal for Vector Dark Matter

SM + three ingredients:

- SU(2)_D new (dark) non-abelian new gauge group
- Complex scalar doublet charged under SU(2)_D
- Vector-Like fermion doublet of SU(2)_D
Vector like fermion Portal for Vector DM

The general form of the Yukawa terms of the new fermion sector reads

\[- \mathcal{L}_f = M_\Psi \bar{\Psi} \Psi + (y' \bar{\Psi}_L \Phi_D^c f_R^{SM} + y'' \bar{\Psi}_L \Phi_D^c f_R^{SM} + h.c) , \]

where \( \Phi_D^c = i\tau_2 \Phi^* \), while \( y' \) and \( y'' \) are new Yukawas, connecting SM fermions and new VL fermions.
Vector like fermion Portal for Vector DM

- The general form of the Yukawa terms of the new fermion sector reads:

\[ -\mathcal{L}_f = M_\Psi \bar{\Psi} \Psi + (y' \bar{\Psi}_L \Phi_D f^\text{SM}_R + y'' \bar{\Psi}_L \Phi^c_D f^\text{SM}_R + h.c) , \]

where \( \Phi^c_D = i\tau_2 \Phi^* \), while \( y' \) and \( y'' \) are new Yukawas, connecting SM fermions and new VL fermions.

- Problem: the presence of both \( y' \) and \( y'' \) breaks the stability of gauge bosons, since it breaks global SU(2) in the dark sector.
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- Problem: the presence of both $y'$ and $y''$ breaks the stability of gauge bosons, since it breaks global SU(2) in the dark sector.

- If we assign the “dark charge” to the components of the doublets, e.g. $Q_D = T_D^3 + Y_D$ and require its conservation, we will get

- $SU(2)_D \times U(1)_{glob} \rightarrow U(1)_{glob}^d$ pattern of dark sector breaking

- $\mathbb{Z}_2$ Subgroup can be defined as $\mathbb{Z}_2 : (-1)^{Q_D}$

- for $\Phi_D$ we choose, e.g., $Y_D = 1/2$ , then $y''$ is eliminated, stabilizing VDM.
Vector like fermion Portal for Vector DM

- So, we have: $SU(2)_D \times U(1)_{\text{glob}} \to U(1)^d_{\text{glob}}$, $Z_2 : (-1)^{Q_D}$, $Q_D = T^3_D + Y_D$

$Y_D = 1/2$ for the doublet and $Y_D = 0$ for the triplet

- Different components of the doublet and triplet will have different parities:

  - two scalar degrees of the doublet (i.e. upper part of the doublet) are $Z_2$ - odd – they become longitudinal component of DM
  - the lower part of scalar doublet is $Z_2$-even, it contains vev

  - this means that one of the components of the vector triplet is $Z_2$-even

  - the term, connecting dark scalar and VL fermion and SM RH fermion:

    $$ y' \Phi_L \bar{\Psi} f_{R}^{SM} $$

    one component of VL fermion doublet is $Z_2$-even and the other - $Z_2$-odd
Building VLF Portal for Vector DM: $V^{0}_{D^+} / V^{0}_{D^-}$ - Dark Matter

$SU(2)_{D}$

$V_{\mu}^{D} = \begin{pmatrix} V^{0}_{D^+} \\ V^{0}_{D^0} \\ V^{0}_{D^-} \end{pmatrix}$

$\Phi_{D} = \begin{pmatrix} \phi^{0}_{D^+ + \frac{1}{2}} \\ \phi^{0}_{D^- - \frac{1}{2}} \end{pmatrix}$

$\Psi = \begin{pmatrix} \psi_{D} \\ \psi \end{pmatrix}$

$\mathbb{Z}_2 : \{+,-\}$

The only* $\mathbb{Z}_2$-odd neutral massive particles are the D-charged gauge bosons $V^{0}_{D^\pm}$

dark matter

*unless $\psi$ is a neutrino partner

$SU(2)_{L} \times U(1)_{Y}$

$V_{\mu} = \begin{pmatrix} W^{+} \\ W_{3} \\ W^{-} \end{pmatrix}$, $B_{\mu}$

$\Phi_{H} = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix}$

$(u)_{L}$ $(d)_{L}$ $(\nu)_{L}$ $u_{R}$ $d_{R}$ $e_{R}$ $\psi_{D}$ $\psi$

$$
\mathcal{L} = -\frac{1}{4}(W_{\mu\nu}^{i})^{2} - \frac{1}{4}(B_{\mu\nu})^{2} + |D_{\mu} \Phi_{H}|^{2} + \mu^{2} \Phi_{H}^{\dagger} \Phi_{H} - \lambda(\Phi_{H}^{\dagger} \Phi_{H})^{2} + f^{SM}_{i} i \bar{\psi} f^{SM}_{j} - (y_{f_{L}}^{SM} \Phi_{H} f_{R}^{SM} + h.c.)

-\frac{1}{4}(V_{\mu\nu}^{D})^{2} + |D_{\mu} \Phi_{D}|^{2} + \mu_{D}^{2} \Phi_{D}^{\dagger} \Phi_{D} - \lambda_{D}(\Phi_{D}^{\dagger} \Phi_{D})^{2} + \bar{\Psi} i \bar{\psi} \Psi - M_{\Phi} \bar{\Phi} \Psi - (y' \bar{\Psi}_{L} \Phi_{D} f_{R}^{SM} + h.c.)

- \lambda \Phi_{H} \Phi_{D} \Phi_{H}^{\dagger} \Phi_{D}^{\dagger} \Phi_{D} \Phi_{D}^{\dagger} \Phi_{D}$
**VLF portal:** $\mathbb{Z}_2$-even fermions – RH SM ones and VL ones – mix

\[ -\mathcal{L}_f = (y f_L^{SM} \Phi_H f_R^{SM} + y' \bar{\psi}_L \Phi_D f_R^{SM} + h.c.) + M_\Psi \bar{\psi} \psi \text{ with } \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix} \]

\[ \langle \Phi_H \rangle \quad \times \quad \langle \Phi_D \rangle \]

\[ \begin{array}{c}
\uparrow f_L \\
y \\
\uparrow f_R \\
y' \\
\uparrow \psi_L \\
\uparrow M_\Psi \\
\downarrow \psi_R \\
\end{array} \]

\[ \mathcal{M}_F = \begin{pmatrix} y \frac{v}{\sqrt{2}} & 0 \\ y' \frac{v_D}{\sqrt{2}} & M_\Psi \end{pmatrix} \]

$\mathbb{Z}_2$-odd $\psi_D$ is DM-SM mediator

**$\mathbb{Z}_2$-even $\psi$ mixes with SM**

\[ (f^{SM}_L, \psi)_{L,R} = \begin{pmatrix} \cos \theta_{fL,R} & \sin \theta_{fL,R} \\ -\sin \theta_{fL,R} & \cos \theta_{fL,R} \end{pmatrix} \begin{pmatrix} f_L \\ F_R \end{pmatrix}_{L,R} \]

The hierarchy between mass eigenstates is always $m_f < m_\psi \leq m_F$
VLF portal: $Z_2$-even fermions – RH SM ones and VL ones – mix

\[-L_f = (y f^\text{SM}_L \Phi_H f^\text{SM}_R + y' \bar{\psi}_L \bar{\Phi}_D f^\text{SM}_R + h.c.) + M_\Psi \bar{\psi} \psi \quad \text{with} \quad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}\]

$Z_2$-odd $\psi_D$ is DM-SM mediator

$Z_2$-even $\psi$ mixes with SM

The hierarchy between mass eigenstates is always $m_f < m_\psi \leq m_F$

Potential to introduce flavour structure(s) with VL fermions, including VL leptons to explain various flavour anomalies, including $(g-2)_\mu$!
The gauge sector: $V'/V_D$ radiative mass split, no tree-level $V'$ – $Z$ mixing

- At tree-level: 
  
  $m_{V_D^0}^{D\pm} = m_{V_D^0}^0 = \frac{g_D}{2} v_D$
The gauge sector: $V' / V_D$ radiative mass split, no tree-level $V' – Z$ mixing

- At tree-level:
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- At loop-level:

  Different loop corrections:
  
  \( (V_{D\pm}^0 \equiv V_D \text{ and } V_{D0}^0 \equiv V') \)

  \[
  m_{V_D} - m_{V'} \simeq \frac{g_D^2}{32\pi^2} \frac{m_F^2 - m_{\psi_D}^2}{m_{V_D}} > 0 \quad \text{for} \quad m_F \gg m_F, m_{V_D}
  \]
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- **At loop-level:**
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  \]

- **Effect for \( W/Z \) boson masses**
  Modifications to SM different for \( Z \) and \( W \)
  Potential to explain \( W \)-boson mass anomaly
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.

\[ \Psi = \left( \begin{array}{c} t_D \\ T \end{array} \right) \quad \text{with} \quad m_t < m_{t_D} \leq m_T \]

\[ \sin \theta_S = 0 \]

5D parameter space:

\[ g_D, m_{V_D}, m_H, m_T, m_{t_D} \]

just a simple realization of the model template multiple features and signatures
Minimal VL top portal VDM: projections of 5D scan in $g_D, m_{V_D}, m_H, m_T, m_{\tilde{t}D}$
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## Minimal VL top portal VDM: collider signatures

<table>
<thead>
<tr>
<th>Process</th>
<th>Representative diagrams</th>
</tr>
</thead>
<tbody>
<tr>
<td>mono-jet (only loop)</td>
<td><img src="image1.png" alt="Diagram" /> + jet from ISR or from loop</td>
</tr>
<tr>
<td>$t\bar{t} + E_T^{miss}$</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>$t\bar{t}t\bar{t}$</td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>$hV'$ and $V'V'$ (only loop)</td>
<td><img src="image4.png" alt="Diagram" /></td>
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</table>
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

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$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix}$$ with \( m_t < m_{tD} \leq m_T \)

$$\sin \theta_S = 0$$

Representative benchmarks:

\[
\begin{align*}
  g_D &= 0.05, 0.5 \\
  m_T &= 1600 \text{ GeV} \\
  m_H &= 1000 \text{ GeV}
\end{align*}
\]

strong or weak cosmological constraints

heavy enough to evade LHC constraints

Mediator mass bounded from below and above

Light DM in non-perturbative region

LHC constrains \( m_{tD} \) for \( m_{tD} - m_{V_D} \gtrsim m_t \)

(bounds almost independent on \( g_D, m_T \) and \( m_H \))

Recast

Minimal VL top portal VDM: details of 2D space for chosen benchmarks

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Light DM in non-perturbative region

LHC constrains \( m_{t_D} \) for \( m_{t_D} - m_{V_D} \gtrsim m_t \) (bounds almost independent on \( g_D, m_T \) and \( m_H \))

Very weak direct detection constraints (mostly for \( m_{t_D} \sim m_t \) or \( m_{t_D} \sim m_T \) and light DM)

Indirect detection constrains light DM

Strong constrain from relic density → the model “lives” on the red contours (\( \Omega_{\text{Planck}}^{\text{DM}} \))
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

The VL fermion is composed of top partners and

\[
\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{tD} \leq m_T
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Representative benchmarks:

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\end{cases}
\]

Strong constrain from relic density

→ the model “lives” on the red contours \( \Omega_{\text{DM}}^{\text{Planck}} \)

→ overabundant region shrinks for larger \( g_D \)

→ and ID constraints vanish
Summary on Fermion Portal Vector Dark Matter (FPVDM)

- FPVDM is a new framework which does not require the Higgs portal
- Incorporates many possibilities with new collider and cosmological implications
- Case study with the top sector – multiple phenomenological predictions
  - great potential to explain dark matter
  - collider signatures: tt+miss, Z’, Z’H, long-lived Z’
  - great potential to explore flavour, was deliberately designed for this!

**Outlook**

→ Different realizations to study current anomalies (LFU, $(g - 2)_{\mu}, \mu W\ldots$)

→ Study of different theoretical embeddings

→ Further analysis of cosmological implications and scenarios for future colliders
Backup slides
Gauging the global $U(1)$
A dark electroweak sector

Extend the dark sector with a $U(1)_{YD}$ (dark hypercharge). Same scalars $\Phi_H$ and $\Phi_D$.

$$G = G_{SM} \times G_D = SU(2)_L \times U(1)_Y \times SU(2)_D \times U(1)_{YD} \rightarrow U(1)_{EM} \times U(1)_D$$

**Conserved charge** from the unbroken $U(1)_D$ symmetry: $Q_D = T^{3D} + Y_D$

One assumption: SM fields do not carry $Q_D$ charge

The only $Q_D$-charged state is $V_{D\pm}^0 \equiv W_D$ $\rightarrow$ stable $\rightarrow$ **DM candidate**

Renormalizable, gauge-invariant kinetic mixing between $U(1)_Y$ and $U(1)_{YD}$ can be generated

$$-\mathcal{L}_{KM} = \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{4} B^\nu_{D\mu\nu} B^\mu_{D\nu} + \frac{\xi}{2} B_{\mu\nu} B^\mu_{D\nu}$$

$$\left( \begin{array}{c} B_\mu^0 \\ B_{D\mu}^0 \end{array} \right) = \left( \begin{array}{c} \frac{1}{\sqrt{1-\varepsilon^2}} \\ 0 \end{array} \right) \left( \begin{array}{c} \cos \theta_k \\ \sin \theta_k \end{array} \right) \left( \begin{array}{c} \cos \theta_k \\ -\sin \theta_k \end{array} \right) \left( \begin{array}{c} B_\mu^0 \\ B_{D\mu}^0 \end{array} \right)$$

Mixing between all $Q$- and $Q_D$-neutral bosons

$$\begin{align*}
\begin{cases}
m_\gamma^2 = 0 \\
m_{\gamma D}^2 = 0
\end{cases} \\
\frac{m_Z^2}{4} = s^2 + g'^2 \left( 1 + \frac{(s^2 + g'^2)v^2 - s_D v_D^2}{(s^2 + g'^2)v^2 - (s_D^2 + g'^2)v_D^2} \right) + \mathcal{O}(\varepsilon^4)
\end{align*}$$

\begin{align*}
\frac{m_{Z'}^2}{4} = s_D^2 + g'^2 \left( 1 + \frac{g'^2 v^2 - (s_D^2 + g'^2)v_D^2}{(s^2 + g'^2)v^2 - (s_D^2 + g'^2)v_D^2} \right) + \mathcal{O}(\varepsilon^4)
\end{align*}

2 massless and 2 massive vectors

Connections with dark-photon phenomenology
The scalar sector: when the higgs portal is absent, the interactions become minimal

$$\begin{align*}
\text{Including Higgs portal} & \quad \begin{cases}
v = \pm \sqrt{\frac{4\lambda D \mu^2 - 2\lambda \Phi_H \Phi_D \mu_D^2}{4\lambda \lambda D - \lambda^2 \Phi_H \Phi_D}} \\
v_D = \pm \sqrt{\frac{4\lambda \mu_D^2 - 2\lambda \Phi_H \Phi_D \mu^2}{4\lambda \lambda D - \lambda^2 \Phi_H \Phi_D}}
\end{cases} \\
\text{Without Higgs portal} & \quad \begin{cases}
v = \pm \sqrt{\frac{\mu^2}{\lambda}} \\
v_D = \pm \sqrt{\frac{\mu_D^2}{\lambda_D}}
\end{cases}
\end{align*}$$

8 degrees of freedom, 6 massive gauge bosons, 2 physical scalars $h, H$

$$\mathcal{M}_S = \left( \frac{\lambda v^2}{2} \frac{\lambda \Phi_H \Phi_D}{v v_D} \right) \sin \theta_S = \sqrt{\frac{2m_H^2v^2 \lambda - m_h^2v_D^2 \lambda_D}{m_H^4 - m_h^4}}$$

$$m_{h,H}^2 = \lambda v^2 + \lambda_D v_D^2 \pm \sqrt{(\lambda v^2 - \lambda_D v_D^2)^2 + \lambda^2 \Phi_H \Phi_D v^2 v_D^2}$$
The scalar sector: when the higgs portal is absent, the interactions become minimal

\[
\begin{align*}
\text{Including Higgs portal} & \quad \begin{cases}
  v = \pm \sqrt{\frac{4\lambda_D\mu_D^2 - 2\lambda_{\Phi \Phi_D} \mu_D^2}{4\lambda_D^2 - \lambda_{\Phi \Phi_D}^2}} \\
v_D = \pm \sqrt{\frac{4\lambda_D^2 - 2\lambda_{\Phi \Phi_D} \mu_D^2}{4\lambda_D^2 - \lambda_{\Phi \Phi_D}^2}}
\end{cases} \\
\text{Without Higgs portal} & \quad \begin{cases}
  v = \pm \sqrt{\frac{\mu_D^2}{\lambda_D}} \\
v_D = \pm \sqrt{\frac{\mu_D^2}{\lambda_D}}
\end{cases}
\end{align*}
\]

8 degrees of freedom, 6 massive gauge bosons, 2 physical scalars \( h, H \)

\[
\mathcal{M}_S = \left( \frac{\lambda v^2}{2} \frac{\lambda_{\Phi \Phi_D}}{\lambda_D v_D^2} v v_D \right) \sin \theta_S = \sqrt{2 \frac{m_H^2 v^2 \lambda - m_H^2 v_D^2 \lambda_D}{m_H^4 - m_h^4}}
\]

\[
m_{h,H}^2 = \lambda v^2 + \lambda_D v_D^2 \pm \sqrt{(\lambda v^2 - \lambda_D v_D^2)^2 + \lambda_{\Phi \Phi_D}^2 v^2 v_D^2}
\]

If no Higgs portal, the interactions of the new scalar \( H \) are limited to:

\[
\begin{align*}
H & \rightarrow V' \\
H & \rightarrow V_D
\end{align*}
\]

\[
\begin{align*}
H & \rightarrow f \\
H & \rightarrow \psi_D \bar{\psi}_D
\end{align*}
\]
**VL portal VDM: the summary of particle content**

<table>
<thead>
<tr>
<th>Vectors</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
<th>$SU(2)_D$</th>
<th>$\mathbb{Z}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_\mu$ = $\begin{pmatrix} W_\mu^+ \ W_\mu^3 \ W_\mu^- \end{pmatrix}$</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>+ + +</td>
</tr>
<tr>
<td>$B_\mu$</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scalars</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
<th>$SU(2)_D$</th>
<th>$\mathbb{Z}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_H = \begin{pmatrix} \phi^+ \ \phi^0 \end{pmatrix}$</td>
<td>2</td>
<td>1/2</td>
<td>1</td>
<td>+</td>
</tr>
<tr>
<td>$\Phi_D = \begin{pmatrix} \phi^0 \ \phi^0_{D+\frac{1}{2}} \ \phi^0_{D-\frac{1}{2}} \end{pmatrix}$</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>− +</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fermions</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
<th>$SU(2)_D$</th>
<th>$\mathbb{Z}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \ V^0_{D0\mu} \ V^0_{D-\mu} \end{pmatrix}$</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>− +</td>
</tr>
<tr>
<td>$f^{SM}<em>L = \begin{pmatrix} f^{SM}</em>{u_L} \ f^{SM}<em>{d_L} \ f^{SM}</em>{t_L} \ f^{SM}_{e_L} \end{pmatrix}$</td>
<td>2</td>
<td>$\frac{1}{6}$, $-\frac{1}{2}$</td>
<td>1</td>
<td>+</td>
</tr>
<tr>
<td>$u^{SM}_R$, $d^{SM}_R$, $e^{SM}_R$</td>
<td>1</td>
<td>$\frac{2}{3}$, 0</td>
<td>1</td>
<td>+</td>
</tr>
<tr>
<td>$\Psi = \begin{pmatrix} \psi^D \ \psi \end{pmatrix}$</td>
<td>1</td>
<td>$Q$</td>
<td>2</td>
<td>− +</td>
</tr>
</tbody>
</table>
Kinetic Mixing in FPVDM models

\[ V' \sim f, F \sim V', Z, \gamma \]

\[ V' \sim \psi_D \sim V', Z, \gamma \]

\[ V_{KM} = \begin{pmatrix} 1 & 0 & -\frac{\epsilon_{AV}}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \\ 0 & 1 & -\frac{\epsilon_{ZV}}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \end{pmatrix} \]

\[ \epsilon_{ZV} = \frac{g g_D}{16 \pi^2 c_w} \left( \mathcal{F}_{ZV}^{T1+q_L}(r_f, r_{\psi_D}) + Q_f s_w^2 \mathcal{F}_{ZV}^{T2}(r_f, r_{\psi_D}) \right) \]

\[ \epsilon_{AV} = \frac{g_D e Q_f}{4 \pi^2} \mathcal{F}_{AV}(r_f, r_{\psi_D}) \]
Kinetic Mixing in FPVDM models

$$V' \sim f, F$$

$$V', Z, \gamma$$

$$\psi_D$$

$$\psi_D$$

$$V_D \sim f, F$$

$$\psi_D$$

$$V_D$$

$$g_\psi = 0.2$$

$$m_T = 1600 \text{ GeV}$$

$$m_N = 1000 \text{ GeV}$$

overabundant relic density

non-perturbative

Large KM

direct detection

200 400 600 800 1000 1200 1400 1600

$$m_{\tilde{b}}$$ (GeV)

$$m_{\tilde{\nu}_0}$$ (GeV)
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

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

\[ \Psi = \begin{pmatrix} iD \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{iD} \leq m_T \]

\[ \sin \theta_S = 0 \]

Representative benchmarks:

\[ \begin{aligned} g_D &= 0.05, 0.5 \\ m_T &= 1600 \text{ GeV} \\ m_H &= 1000 \text{ GeV} \end{aligned} \]

strong or weak cosmological constraints

heavy enough to evade LHC constraints
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

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

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix}$$

with

$$m_t < m_D \leq m_T$$

$$\sin \theta_S = 0$$

Representative benchmarks:

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\delta D = 0.05, 0.5 \\
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heavy enough to evade LHC constraints

Mediator mass bounded from below and above
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Heavy enough to evade LHC constraints

Mediator mass bounded from below and above

Light DM in non-perturbative region

\[ V_D, V' \sim \text{loop} \sim V_D, V' \]

\[ \frac{m_{V_{\text{pole}}}}{m_V} > 50\% \]
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

\[ \Psi = \left( \begin{pmatrix} iD \\ T \end{pmatrix} \right) \text{ with } m_t < m_{tD} \leq m_T \]

\[ \sin \theta_S = 0 \]

Representative benchmarks:
\[ \begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases} \]

Mediator mass bounded from below and above Light DM in non-perturbative region

LHC constrains \( m_{tD} \) for \( m_{tD} - m_{V_D} \gtrsim m_t \)

(bounds almost independent on \( g_D, m_T \) and \( m_H \))

Very weak direct detection constraints
(mostly for \( m_{tD} \sim m_t \) or \( m_{tD} \sim m_T \) and light DM)

E. Aprile et al. [XENON],
Dark Matter Search Results from a One Ton-Year Exposure of XENON1T,
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

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

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Indirect detection constrains light DM

\[ V_D \rightarrow V' \]
\[ V_D \rightarrow t_D \]
\[ V_D \rightarrow \bar{t}_D \]
\[ \chi \rightarrow \gamma\gamma \]

\[ \left( \frac{\Omega_{DM}}{\eta_{\text{planck}} \cdot \Omega_{DM}} \right)^2 \]

Minimal VL top portal VDM: details of 2D space for chosen benchmarks

The VL fermion is composed of top partners and

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix}$$

with

$$m_t < m_{tD} \leq m_T$$

Representative benchmarks:

$$\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases}$$

Strong constrain from relic density

- the model “lives” on the red contours ($\Omega_{DM}^{\text{Planck}}$)
- overabundant region shrinks for larger $g_D$
- and DM constraints vanish
- effective (co-)annihilation processes
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→ on the \( H_D \) pole, exclusion from ID
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\[ \rightarrow \text{on the } H_D \text{ pole, exclusion from ID} \]

The mediator \( t_D \) can be long lived
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

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

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Representative benchmarks:

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Representative benchmarks:
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    g_D = 0.05, 0.5 \\
    m_T = 1600 \text{ GeV} \\
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\end{cases}
\]

The mediator $t_D$ can be long lived, and $V'$ too.
**Minimal VL top portal VDM:** details of 2D space for chosen benchmarks

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

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\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{tD} \leq m_T 
\]

\[
\sin \theta_S = 0 
\]

Representative benchmarks:

\[
\begin{align*}
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\( \rightarrow \) on the \( H_D \) pole, exclusion from ID

The mediator \( t_D \) can be long lived, and \( V' \) too

\[
\text{just a simple realization of the model template} \\
\text{multiple features and signatures}
\]**