A fermionic portal to a non-abelian dark sector

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Based on 2203.04681 and 2204.03510 with
A. Belyaev, A. Deandrea, S. Moretti and N. Thongyoi

A still unresolved issue

What is dark matter?

And if it is composed of new particle(s), what are their properties?

Thousands of papers, multiple experiments, no clue yet

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One possibility: build a dark sector using the same fundamental principles of SM

The SM is a gauge theory $\longrightarrow$ $\begin{cases} \text{Dark sector} \longrightarrow \text{new gauge group} \\ \text{Dark matter} \longrightarrow \text{(massive) mediator of a new force} \end{cases}$

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One possibility: build a dark sector using the same fundamental principles of SM

The SM is a gauge theory ⟶ { Dark sector ⟶ new gauge group; Dark matter ⟶ (massive) mediator of a new force }

Ingredients:

- **a new gauge symmetry**
- **a way to break it spontaneously** ⟶ massive gauge boson(s)
- **a residual $\mathbb{Z}_2$ parity** ⟶ make the lightest $\mathbb{Z}_2$-odd particle stable

and that would be enough in theory. But we'd like to detect it. . .

- **a portal with the SM**

Which kind of gauge group?

Abelian

- A $U(1)_D$ group: $\mathcal{L} = V_{D\mu\nu} V_D^{\mu\nu}$

A problem:

Abelian ➔ kinetic mixing ➔ not stable

Solution:

- Sequester $U(1)_D$ ➔ an exact $\mathbb{Z}_2$

$$V_D^\mu \to -V_D^\mu \quad \text{(Charge conjugation)}$$

V_D is stable, now make it massive:

- SSB ➔ complex singlet S ($S \xrightarrow{\mathbb{Z}_2} S^*$)

$$\mathcal{L} = |D_\mu S|^2 + \mu_S^2 |S|^2 - \lambda_S |S|^4$$
$$m_{V_D} = \sqrt{2} g_D v_D$$

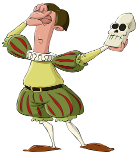
V_D^μ is a DM candidate

Need to interact with the SM:

- **Higgs portal** ➔ $V(\Phi_H, S) = \lambda |\Phi_H|^2 |S|^2$

Widely studied

Lebedev, Lee & Mambrini 1111.4482,
Farzan & Akbarieh 1207.4272,
Baek, Ko, Park & Senaha 1212.2131, ...



Non-abelian

- Various possible gauge groups

$$\mathcal{L} = V^a_{D\mu\nu} V_D^{\mu\nu a}$$

- No renormalizable kinetic mixing

Limiting to $SU(N)$:

- complete SSB with $N-1$ complex scalars ➔ preserved $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetries

Gross *et al* 1505.07480

$V_D^{\mu a}$ are all DM candidates

- Still can have **Higgs portal**

$$V(\Phi_H, S_{i,j,\dots}) = \sum_{i,j} \lambda_{ij} |\Phi_H|^2 S_i^\dagger S_j + h.c.$$

Also widely studied

Hambye 0811.0172, Diaz-Cruz & Ma 1007.2631,
Fraser, Ma & Zakeri 1409.1162, Ko & Tang 1609.02307, ...

Minimal vector DM scenario
where the Higgs portal can be small or absent*?

Non-abelian with fermion portal

* No *need* to avoid Higgs portal, but new fermions can address current anomalies

Connecting the dark sector to the SM

$SU(2)_D$ $\quad \mathcal{V}^D_\mu = \begin{pmatrix} V^0_{D+} \\ V^0_{D0} \\ V^0_{D-} \end{pmatrix}$

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

Different member of $SU(2)_D$ multiplets
transform differently under $\mathbb{Z}_2$
(we'll get back to this)

$SU(2)_L \times U(1)_Y$ $\quad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\quad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad u_R$, $d_R\ e_R$

$$\mathcal{L} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 + |D_\mu \Phi_H|^2 + \mu^2 \Phi_H^\dagger \Phi_H - \lambda(\Phi_H^\dagger \Phi_H)^2 + \bar{f}^{\rm SM}\, i\not{D}\, f^{\rm SM} - (y\, \bar{f}_L^{\rm SM}\, \Phi_H\, f_R^{\rm SM} + h.c.)$$
$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2$$

Connecting the dark sector to the SM

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

SSB: $\langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}$

$SU(2)_L \times U(1)_Y$ $\quad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\quad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad u_R$ $\; d_R \; e_R$

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Higgs portal: $\Phi_H^\dagger \Phi_H \Phi_D^\dagger \Phi_D$

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

Kinetic mixing: $\mathcal{V}_D^{\mu\nu a} W^b_{\mu\nu}$

$SU(2)_L \times U(1)_Y \qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad u_R \quad d_R \; e_R$

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

Kinetic mixing: $\frac{\kappa_W}{\Lambda^4} \mathcal{V}^{\mu\nu a}_D W^b_{\mu\nu} \Phi^\dagger_{Dk} (\sigma^a)_{kl} \Phi_{Dl} \Phi^\dagger_{Hi} (\sigma^b)_{ij} \Phi_{Hj}$

$SU(2)_L \times U(1)_Y$ $\qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \begin{matrix} u_R \\ d_R \; e_R \end{matrix}$

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$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu^2_D \Phi^\dagger_D \Phi_D - \lambda_D (\Phi^\dagger_D \Phi_D)^2$$

$$-\lambda_{\Phi_H \Phi_D} \Phi^\dagger_H \Phi_H\; \Phi^\dagger_D \Phi_D - \mathcal{V}^{\mu\nu a}_D \Phi^\dagger_{Dk} (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi^\dagger_{Hi} (\sigma^b)_{ij} \Phi_{Hj} + \frac{\kappa_B}{\Lambda^4} B_{\mu\nu} \Phi^\dagger_H \Phi_H \right)$$

Connecting the dark sector to the SM

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- **fundamental of** $SU(2)_D$
  $\rightarrow$ interacts with $\mathcal{V}^D_\mu$

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

Introducing a fermion

$SU(2)_L \times U(1)_Y$ $\qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\qquad u_R$, $d_R\ e_R$

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$SU(2)_D$ $\quad \mathcal{V}^D_\mu = \begin{pmatrix} V^0_{D+} \\ V^0_{D0} \\ V^0_{D-} \end{pmatrix}$ $\quad \Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$ $\quad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$ $\quad -M_\Psi \bar{\Psi}\Psi$

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

Introducing a fermion

- **fundamental of $SU(2)_D$**
  $\rightarrow$ interacts with $\mathcal{V}^D_\mu$
- **Vector-like***
  $\rightarrow$ no anomalies

* abelian case with VL fermions in DiFranzo, Fox & Tait 1512.06853

$SU(2)_L \times U(1)_Y$ $\quad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\quad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad u_R$, d_R e_R

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$$-\lambda_{\Phi_H\Phi_D} \Phi_H^\dagger \Phi_H\, \Phi_D^\dagger \Phi_D - \mathcal{V}_D^{\mu\nu a} \Phi^\dagger_{Dk} (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi^\dagger_{Hi} (\sigma^b)_{ij} \Phi_{Hj} + \frac{\kappa_B}{\Lambda^4} B_{\mu\nu} \Phi_H^\dagger \Phi_H \right)$$

Connecting the dark sector to the SM

$SU(2)_D$ $\qquad \mathcal{V}^D_\mu = \begin{pmatrix} V^0_{D+} \\ V^0_{D0} \\ V^0_{D-} \end{pmatrix}$ $\qquad \Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$ $\qquad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$ $\quad \boxed{-M_\Psi \bar{\Psi}\Psi}$

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

Introducing a fermion

- **fundamental of $SU(2)_D$**
  $\rightarrow$ interacts with $\mathcal{V}^D_\mu$
- **Vector-like**
  $\rightarrow$ no anomalies
- **Charged under $U(1)_Y$**
  $\rightarrow$ interacts with SM

doublet of $SU(2)_D$

singlets of $SU(2)_L$

$SU(2)_L \times U(1)_Y$ $\qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad u_R \; d_R \; e_R$ $\quad \psi_D \; \psi$

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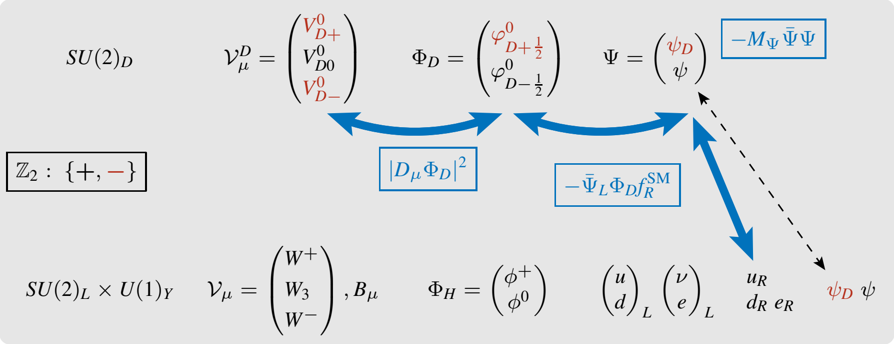
Connecting the dark sector to the SM



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can be small — suppressed

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

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

→ dark matter

* unless Ψ is a neutrino partner

$SU(2)_L \times U(1)_Y$ $\quad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\quad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad \begin{matrix} u_R \\ d_R \; e_R \end{matrix}$ $\quad \psi_D \; \psi$

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$\mathbb{Z}_2 : \{+, -\}$ ← Reminder: what is the origin of $\mathbb{Z}_2$?

$SU(2)_L \times U(1)_Y \qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \begin{matrix} u_R \\ d_R \; e_R \end{matrix} \qquad \psi_D \; \psi$

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can be small $\qquad\qquad$ suppressed

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If $y' = 0$ the Φ_D potential has a global custodial symmetry $SU(2)'_D$

$SU(2)_L \times U(1)_Y$ $\qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\qquad u_R \; d_R \; e_R$ $\qquad \psi_D \; \psi$

$$\mathcal{L} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 + |D_\mu \Phi_H|^2 + \mu^2 \Phi_H^\dagger \Phi_H - \lambda(\Phi_H^\dagger \Phi_H)^2 + \bar{f}^{SM}\, i\not{D}\, f^{SM} - (y\, \bar{f}_L^{SM}\, \Phi_H\, f_R^{SM} + h.c.)$$

$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D}\Psi - M_\Psi \bar{\Psi}\Psi - \cancel{(y'\, \bar{\Psi}_L \Phi_D f_R^{SM} + h.c)}$$

$$-\lambda_{\Phi_H\Phi_D}\, \Phi_H^\dagger \Phi_H\, \Phi_D^\dagger \Phi_D - \mathcal{V}_D^{\mu\nu a} \Phi^\dagger_{Dk} (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi^\dagger_{Hi} (\sigma^b)_{ij} \Phi_{Hj} + \frac{\kappa_B}{\Lambda^4} B_{\mu\nu} \Phi_H^\dagger \Phi_H \right)$$

can be small — suppressed

Connecting the dark sector to the SM

$SU(2)_D$ $\qquad \mathcal{V}^D_\mu = \begin{pmatrix} V^0_{D+} \\ V^0_{D0} \\ V^0_{D-} \end{pmatrix} \qquad \Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix} \qquad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$

When $y' \neq 0$ Explicit breaking: $SU(2)'_D \to U(1)_c$ ← global charge conjugation

$SU(2)_L \times U(1)_Y \qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \begin{matrix} u_R \\ d_R\ e_R \end{matrix} \qquad \psi_D\ \psi$

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$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D}\Psi - M_\Psi \bar{\Psi}\Psi - (y' \bar{\Psi}_L \Phi_D f_R^{\rm SM} + h.c)$$

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When $\langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}$ SSB: $SU(2)_D \times U(1)_c \to$ global $U(1)$ — $\mathbb{Z}_2$ is a subgroup of $U(1)$

diagonal part: exp$(i\phi\tau_3)$

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can be small $\qquad$ suppressed

Gauging the global $U(1)$

A dark electroweak sector

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

$$\mathcal{G} = \mathcal{G}_{\rm SM} \times \mathcal{G}_D = SU(2)_L \times U(1)_Y \times SU(2)_D \times U(1)_{YD} \longrightarrow U(1)_{\rm EM} \times U(1)_D$$

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 $V^0_{D\pm} \equiv W_D$ ⟶ stable ⟶ **DM candidate**

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

$$-\mathcal{L}_{\text{KM}} = \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{4} B_{D\mu\nu} B_D^{\mu\nu} + \frac{\varepsilon}{2} B_{\mu\nu} B_D^{\mu\nu} \qquad \begin{pmatrix} B^\mu \\ B^{0\mu}_{D0} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon^2}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_k & -\sin\theta_k \\ \sin\theta_k & \cos\theta_k \end{pmatrix} \begin{pmatrix} B_1^\mu \\ B_2^\mu \end{pmatrix}$$

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Mixing between all Q- and Q_D-neutral bosons

$$\begin{cases} m_\gamma = 0 \\ m_{\gamma_D} = 0 \end{cases} \qquad \begin{cases} m_Z^2 = \frac{v^2}{4}\left[g^2 + g'^2\left(1 + \frac{(g^2+g'^2)v^2 - g_D^2 v_D^2}{(g^2+g'^2)v^2 - (g_D^2+g_D'^2)v_D^2}\varepsilon^2\right)\right] + \mathcal{O}(\varepsilon^4) \\ m_{Z'}^2 = \frac{v_D^2}{4}\left[g_D^2 + g_D'^2\left(1 + \frac{g^2 v^2 - (g_D^2+g_D'^2)v_D^2}{(g^2+g'^2)v^2 - (g_D^2+g_D'^2)v_D^2}\varepsilon^2\right)\right] + \mathcal{O}(\varepsilon^4) \end{cases}$$

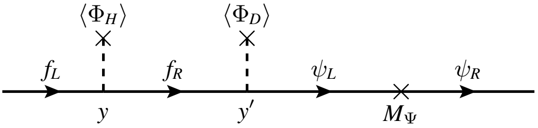
2 massless and 2 massive vectors

Connections with dark-photon phenomenology

The fermionic portal

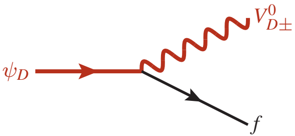
The $\mathbb{Z}_2$-even fermions mix due to the SM and new Yukawas

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



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

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



$\mathbb{Z}_2$-even ψ mixes with SM

$$\begin{pmatrix} f^{\rm SM} \\ \psi \end{pmatrix}_{L,R} = \begin{pmatrix} \cos\theta_{fL,R} & \sin\theta_{fL,R} \\ -\sin\theta_{fL,R} & \cos\theta_{fL,R} \end{pmatrix} \begin{pmatrix} f \\ F \end{pmatrix}_{L,R}$$

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

The portal can be with any SM fermion(s) and with any number of VL fermions

maybe a portal in the lepton sector can explain anomalies and muon $(g-2)$?

Case study: top portal w/o Higgs mixing

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

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

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and there is no mixing between scalars

$$\sin\theta_S = 0$$

Representative benchmarks:

$$\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases}$$

(m_T, m_H): heavy enough to evade LHC constraints

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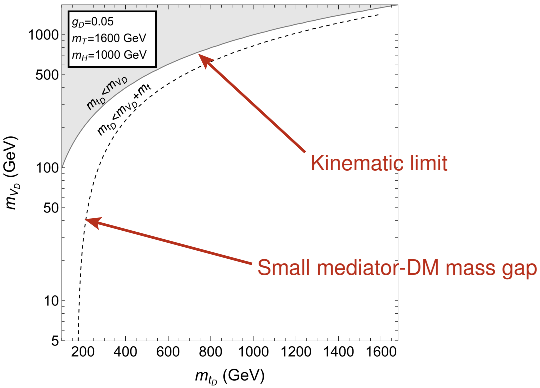

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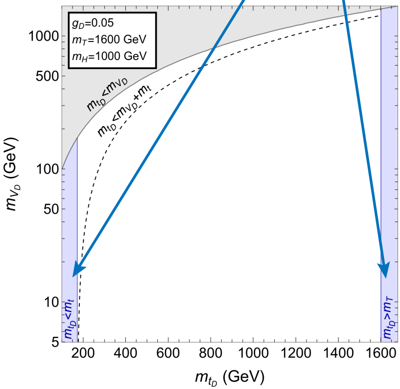

Mediator mass bounded from below and above

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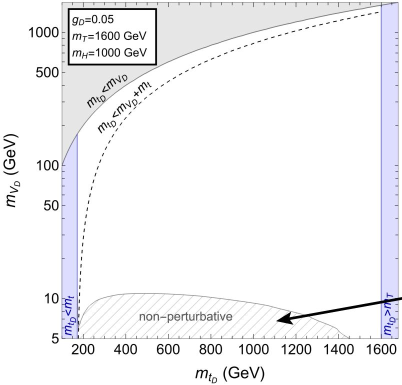
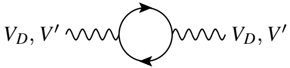


Mediator mass bounded from below and above

Light DM in non-perturbative region



$$\frac{m_V^{\text{pole}} - m_V}{m_V} > 50\%$$

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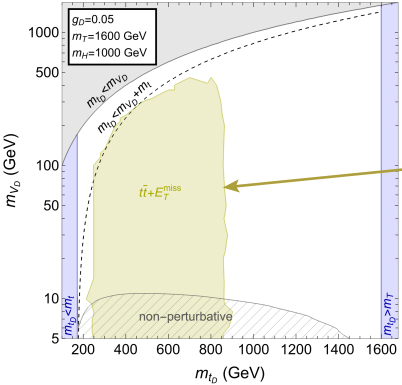

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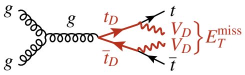
LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$
(bounds almost independent on g_D, m_T and m_H)



Recast

A. M. Sirunyan *et al.* [CMS], **Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV**, Phys. Rev. D **97** (2018) no.3, 032009, arXiv:1711.00752 [hep-ex]

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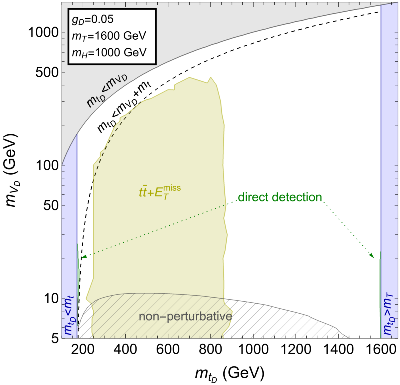

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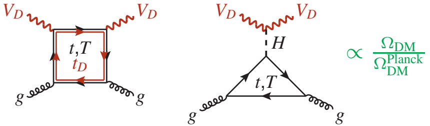
Very weak direct detection constraints
(mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM)



E. Aprile *et al.* [XENON],
Dark Matter Search Results from a One Ton-Year Exposure of XENON1T,
Phys. Rev. Lett. **121** (2018) no.11, 111302, arXiv:1805.12562 [astro-ph.CO]

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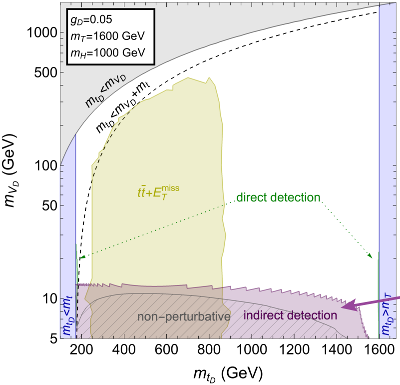

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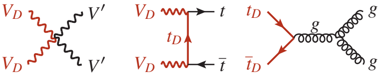
Indirect detection constrains light DM



$$\propto \left(\frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}\right)^2$$

N. Aghanim *et al.* [Planck],
Planck 2018 results. VI. Cosmological parameters,
Astron. Astrophys. **641** (2020), A6, arXiv:1807.06209 [astro-ph.CO]

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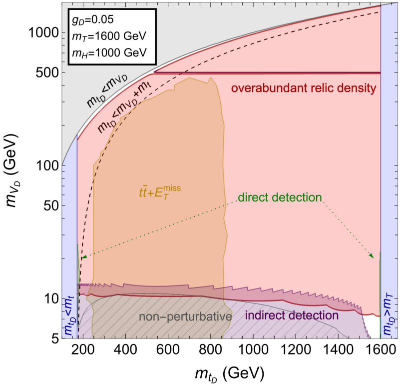

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Strong constrain from relic density
→ the model "lives" on the red contours $(\Omega_{\rm DM}^{\rm Planck})$

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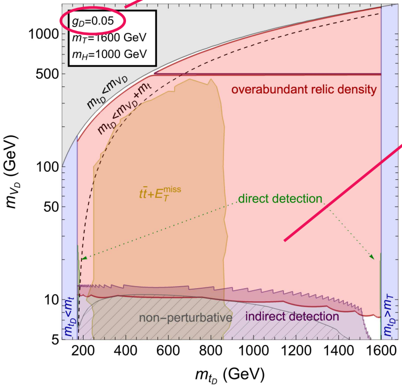

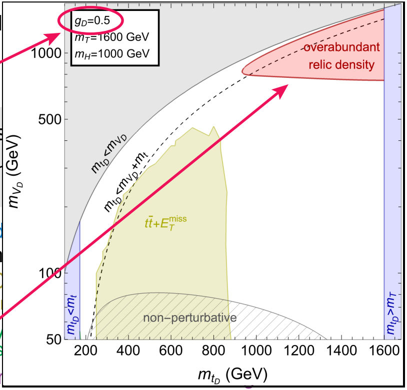

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Strong constrain from relic density

→ the model "lives" on the red contours (Ω_{DM}^{Planck})

→ overabundant region shrinks for larger g_D

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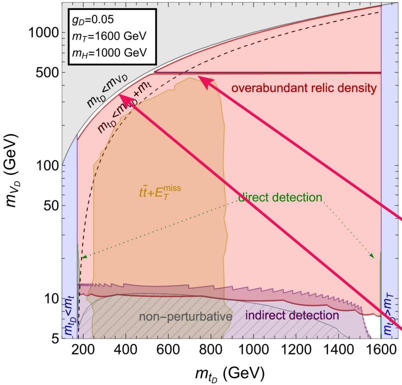

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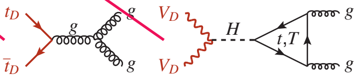
→ and ID constraints vanish
→ effective (co-)annihilation processes

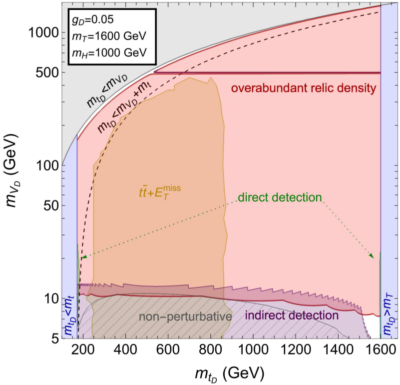


Case study: top portal w/o Higgs mixing

The VL fermion is composed of top partners and

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

Representative benchmarks: $\left\{ \begin{array}{l} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{array} \right\}$ s h



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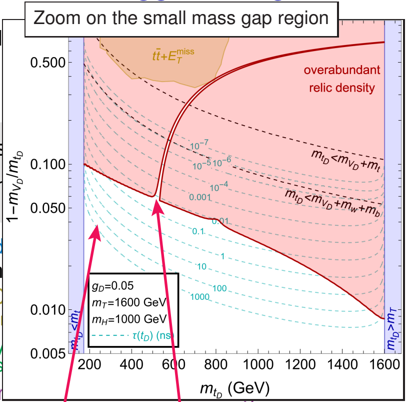

Strong constrain from relic density

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

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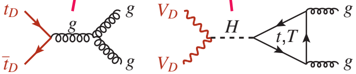

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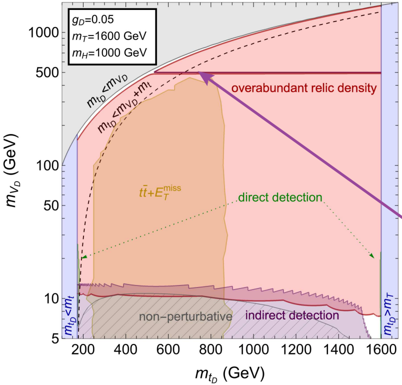

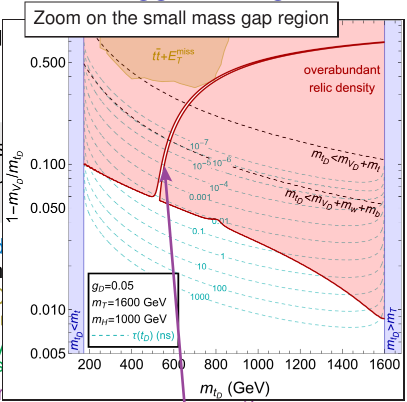

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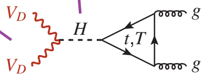

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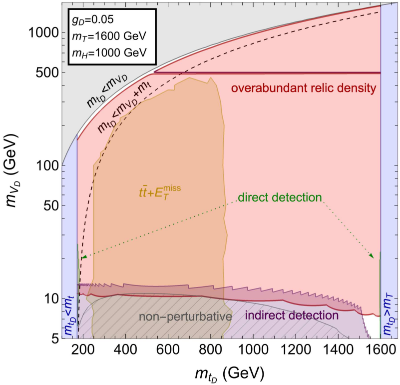

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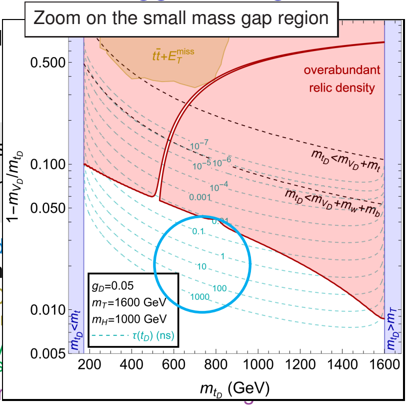

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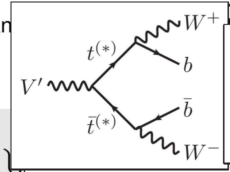

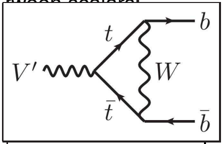

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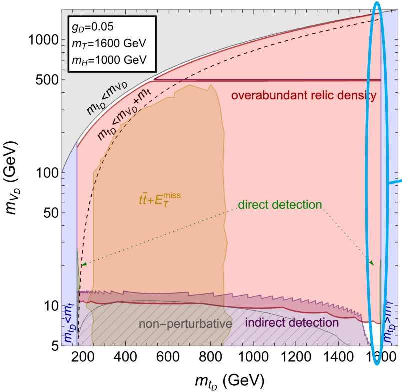

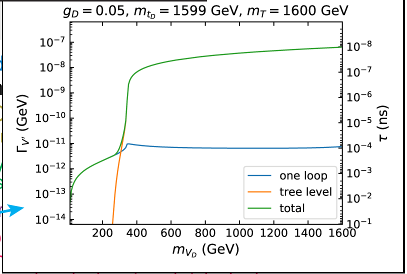

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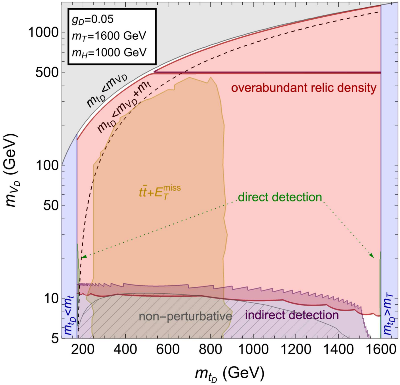
$$\sin\theta_S = 0$$

Representative benchmarks:
$g_D = 0.05, 0.5$ — strong or weak cosmological constraints
$m_T = 1600$ GeV, $m_H = 1000$ GeV — heavy enough to evade LHC constraints



Mediator mass bounded from below and above

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

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just a simple realization of the model template
multiple features and signatures

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Full five-dimensional parameter space: $g_D, m_{V_D}, m_H, m_T, m_{t_D}$

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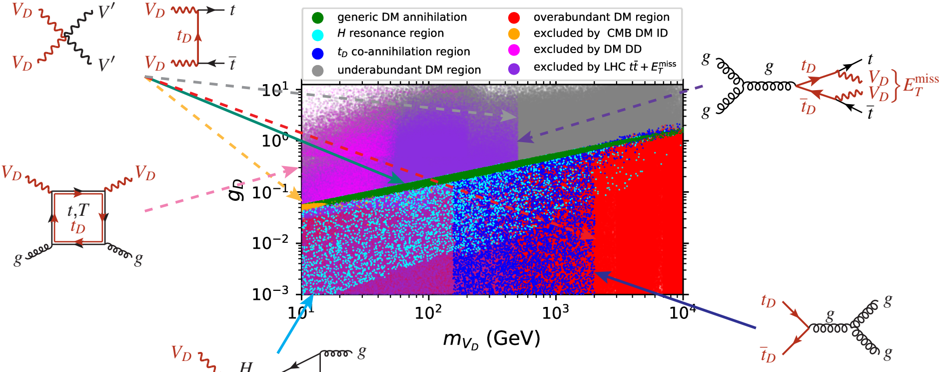

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Fermion Portal Vector Dark Matter

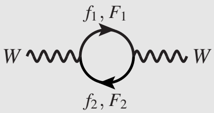
FPVDM

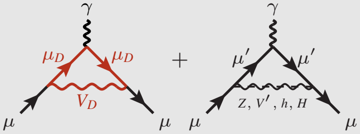
Summary

- A model of **non abelian vector DM** with a **fermion portal** which does not require the Higgs portal
- A **template scenario** with new collider and cosmological implications
- Case study in the **top sector** with multiple phenomenological predictions
- Different possible **origins of the $\mathbb{Z}_2$ parity**

Outlook

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





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

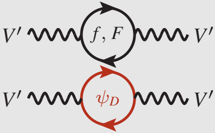
Backup

The gauge sector

Φ_H and Φ_D are only charged under their gauge groups → No gauge mixing at tree-level

$$m_{V^0_{D\pm}} = m_{V^0_{D0}} = \frac{g_D}{2} v_D$$

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



$$m_{V_D} - m_{V'} \simeq \frac{g_D^2}{32\pi^2} \frac{m_F^2 - m_{\psi_D}^2}{m_{V_D}} > 0 \quad \text{for} \quad m_F \gg m_f, m_{V_D}$$

The $\mathbb{Z}_2$-even gauge boson V' can only decay to $f\bar{f}$, or $V_D V_D^*$ if $m_F^2 - m_{\psi_D}^2$ is large enough

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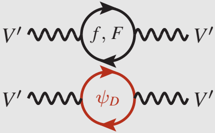

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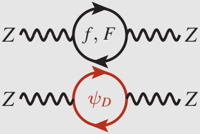
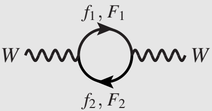
Modifications to SM
different for Z and W





Possible explanation of W mass discrepancy?

The scalar sector

EW + Dark symmetry breaking $\longrightarrow$

Including Higgs portal

$$\begin{cases} v = \pm\sqrt{\dfrac{4\lambda_D\mu^2 - 2\lambda_{\Phi_H\Phi_D}\mu_D^2}{4\lambda\lambda_D - \lambda_{\Phi_H\Phi_D}^2}} \\ v_D = \pm\sqrt{\dfrac{4\lambda\mu_D^2 - 2\lambda_{\Phi_H\Phi_D}\mu^2}{4\lambda\lambda_D - \lambda_{\Phi_H\Phi_D}^2}} \end{cases}$$

Without Higgs portal

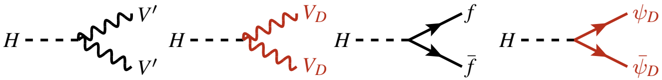
$$\begin{cases} v = \pm\sqrt{\dfrac{\mu^2}{\lambda}} \\ v_D = \pm\sqrt{\dfrac{\mu_D^2}{\lambda_D}} \end{cases}$$

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

$$\mathcal{M}_S = \begin{pmatrix} \lambda v^2 & \frac{\lambda_{\Phi_H\Phi_D}}{2} v v_D \\ \frac{\lambda_{\Phi_H\Phi_D}}{2} v v_D & \lambda_D v_D^2 \end{pmatrix} \qquad \sin\theta_S = \sqrt{2\frac{m_H^2 v^2\lambda - m_h^2 v_D^2 \lambda_D}{m_H^4 - m_h^4}}$$

$$m_{h,H}^2 = \lambda v^2 + \lambda_D v_D^2 \mp \sqrt{(\lambda v^2 - \lambda_D v_D^2)^2 + \lambda_{\Phi_H\Phi_D}^2 v^2 v_D^2}$$

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



With the Higgs portal, the superposition with h allows for other SM decays

Summary of particle content

Scalars	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$\Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	**2**	1/2	**1**	$+$
$\Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$	**1**	0	**2**	$-$ $+$

Vectors	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$W_\mu = \begin{pmatrix} W^+_\mu \\ W^3_\mu \\ W^-_\mu \end{pmatrix}$	**3**	0	**1**	$+$ $+$ $+$
B_μ	**1**	0	**1**	$+$
$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \\ V^0_{D0\mu} \\ V^0_{D-\mu} \end{pmatrix}$	**1**	0	**3**	$-$ $+$ $-$

Fermions	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$f^{\text{SM}}_L = \begin{pmatrix} f^{\text{SM}}_{u,\nu} \\ f^{\text{SM}}_{d,\ell} \end{pmatrix}_L$	**2**	$\frac{1}{6}, -\frac{1}{2}$	**1**	$+$
$u^{\text{SM}}_R, \nu^{\text{SM}}_R$	**1**	$\frac{2}{3}, 0$	**1**	$+$
$d^{\text{SM}}_R, \ell^{\text{SM}}_R$	**1**	$-\frac{1}{3}, -1$	**1**	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	**1**	Q	**2**	$-$ $+$