A fermionic portal to vector dark matter from a new gauge sector

Nakorn Thongyoi

University of Southampton

International Conference on High Energy Physics
6-13 July 2022

Based on 2203.04681 and 2204.03510 with
A. Belyaev, A. Deandrea, S. Moretti and L. Panizzi

What do we know about DM?

~~Mass ?~~

~~Spin ?~~

~~Stable ?~~

~~Symmetry ?~~

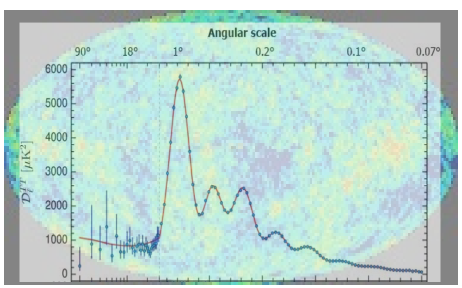
~~Thermal relic ?~~

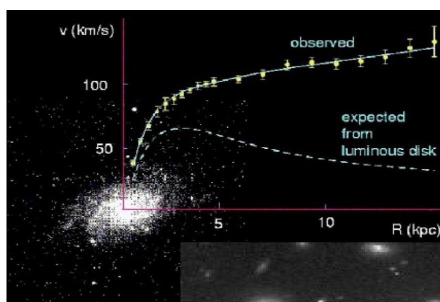
Interaction via Gravity

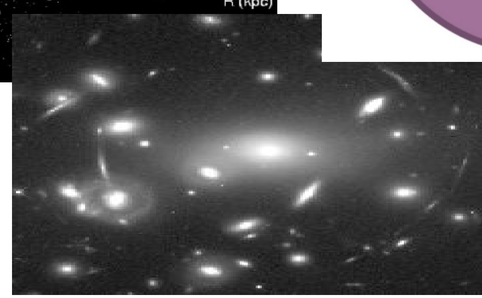
The invisible matter

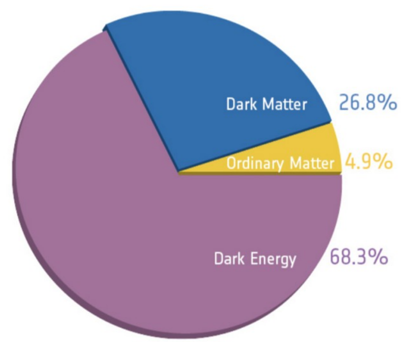
Interacting very weakly

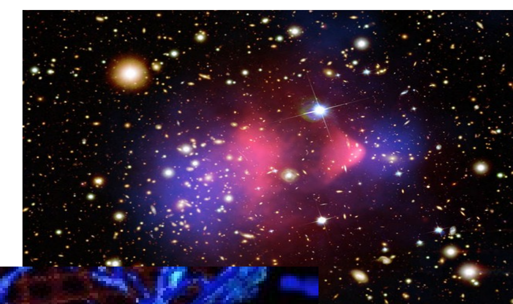
The energy density ~25%

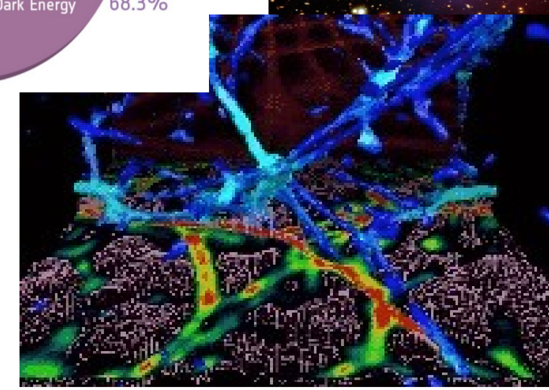


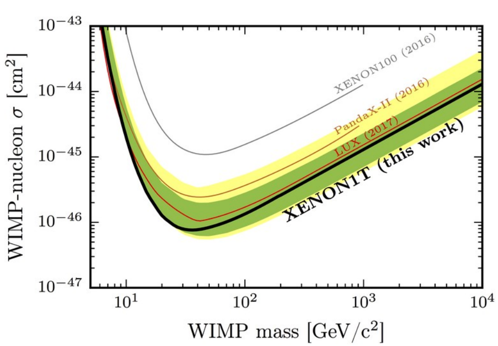












Vector DM

Scalar and fermionic DM models are extensively studied.

Vector DM models have been less studied.

VDM is well motivated by gauge principle like other gauge particles in SM.

VDM is quite interesting!

Abelian VDM

Extensively studied by many groups Lebedev, Lee, Mambrini 1111.4482

Baek, Ko, Park , Senaha 1212.2131 DiFranzo, Fox,Tait 1512.06853

Farzan, Akbarieh 1207.4272

Non-abelian VDM

Extensively studied by many groups Hambye 0811.0172 Diaz-Cruz & Ma 1007.2631

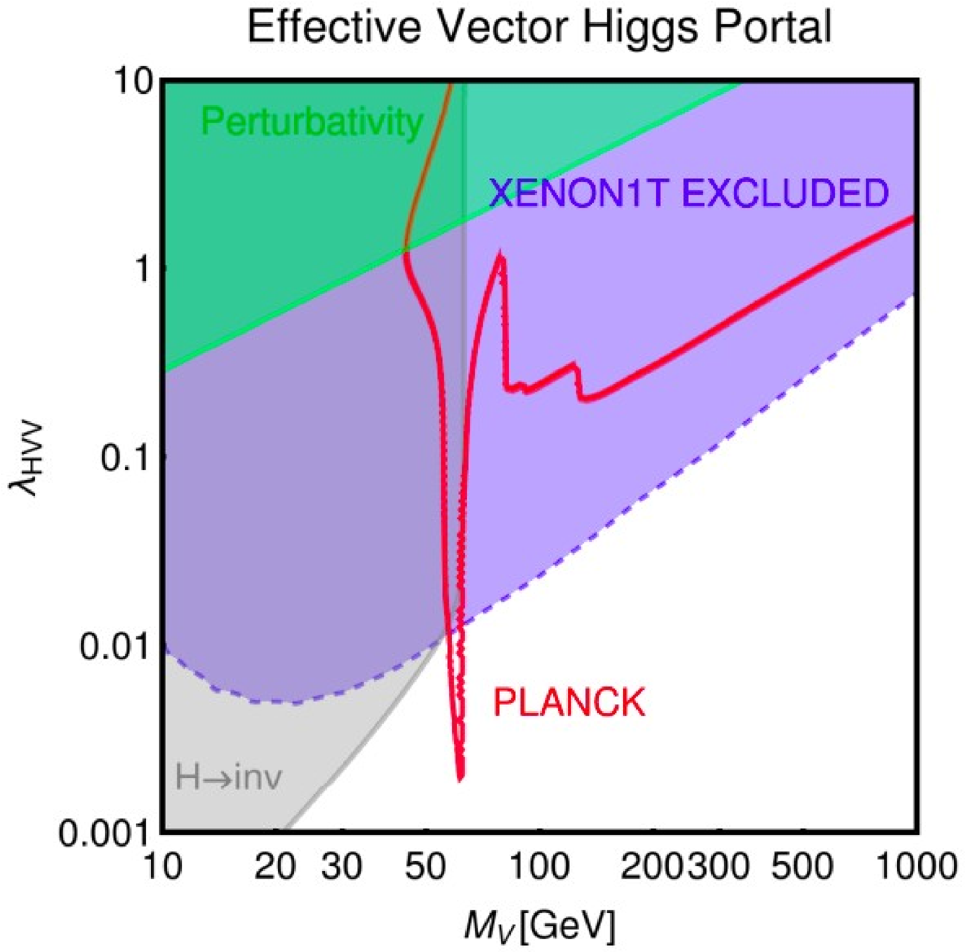
Fraser, Ma & Zakeri 1409.1162 Ko & Tang 1609.02307

Most of them rely on Higgs-portal to connect to dark sector!

Vector DM

Why fermionic portal instead of a Higgs-portal model?

Arcadi, Djouadi, Kado 2001.10750



The blue region excluded by constraint from XENON1T sets up The *upper* limit on the coupling.

The red line corresponds to the points that provide the correct relic density $\Omega h^2 = 0.12$ which set the *lower* limit on the coupling.

The allowed parameter space of Higgs portal VDM model is *very constrained* by PLANCK, XENON and LHC searches.

The Fermionic Portal to Vector Dark Matter (FPVDM)

New ingredients

- New gauge group $SU(2)_D$
- New scalar Φ_D charged under $SU(2)_D$
- New fermion doublet Ψ charged under $SU(2)_D$
- Discrete symmetry to stabilise DM

$$SU(2)_L \times U(1)_Y \times SU(2)_D$$

Fermions	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$f_L^{SM} = \begin{pmatrix} f_{u,\nu}^{SM} \\ f_{d,\ell}^{SM} \end{pmatrix}_L$	$\mathbf{2}$	$\frac{1}{6}, -\frac{1}{2}$	$\mathbf{1}$	$+$
u_R^{SM}, ν_R^{SM}	$\mathbf{1}$	$\frac{2}{3}, 0$	$\mathbf{1}$	$+$
d_R^{SM}, ℓ_R^{SM}	$\mathbf{1}$	$-\frac{1}{3}, -1$	$\mathbf{1}$	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	$\mathbf{1}$	Q	$\mathbf{2}$	$\begin{matrix} - \\ + \end{matrix}$

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

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

$V^0_{D0} \equiv V'$ $V^0_{D\pm} \equiv V_D$ **for compactness**

A case study: top-portal with no mixing between h and H

In this talk, we give a simple case study where only one VL doublet is required.
We choose the VL doublet of the top quark.

$$\Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} t_D \\ T \end{pmatrix}$$

VL partners of the top quark

$\boxed{\text{There is no mixing between scalars} \quad \sin\theta_S = 0}$

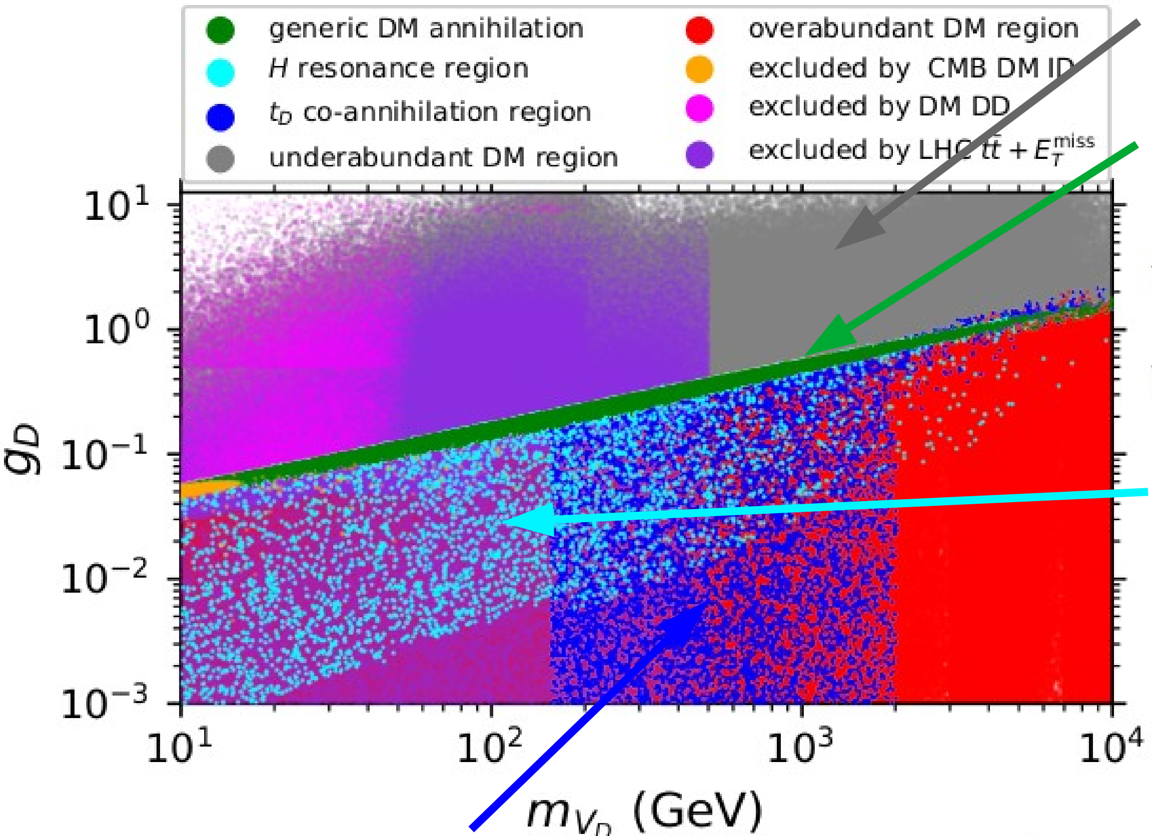
with mass hierarchy $m_t < m_{t_D} \leq m_T$

There are 5 input parameters in this model $g_D, m_{V_D}, m_T, m_{t_D}, m_H$

We did full scan of 5 parameters to understand where the model can live.

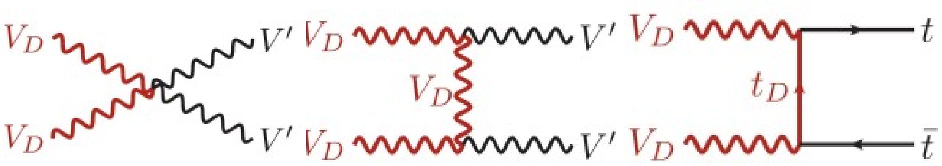
Results

Full 5D scan allows us to understand a big picture of parameter space



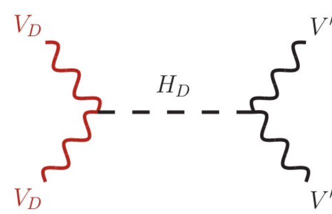
The underabundant region

The generic annihilation corresponds to the region where the relic density is +/-5% from the measured value.



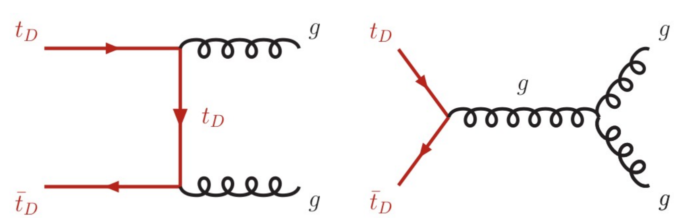
The H resonance region also provides good relic density because H resonance enhances the cross section.

$m_{V_D} \to m_H/2$



The region can give good relic density, even though the coupling is small, because of coannihilation processes.

$m_{V_D} \to m_{t_D}$

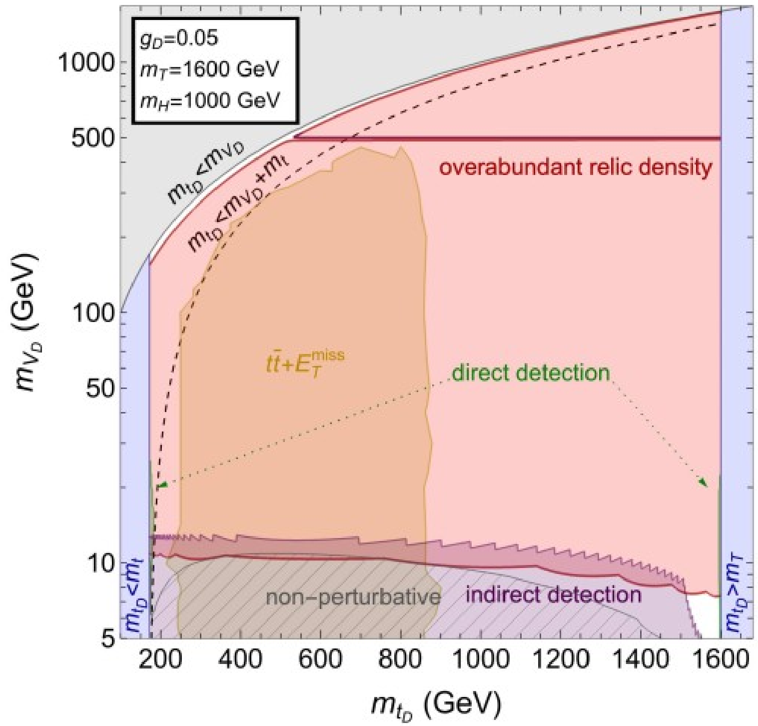


Results

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

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

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ \left.\begin{array}{l} m_T = 1600\ \text{GeV} \\ m_H = 1000\ \text{GeV} \end{array}\right\} & \text{heavy enough to evade LHC constraints} \end{cases}$



Mediator mass bounded from below and above

Light DM in non-perturbative region

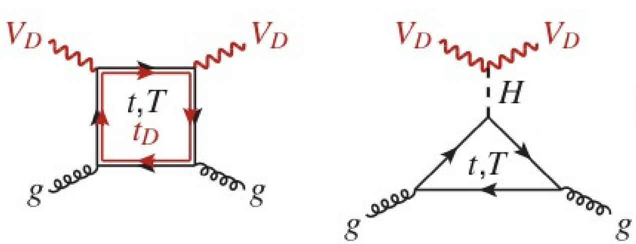
LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$
(bounds almost independent on g_D, m_T and m_H)

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

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

The direct detection excluded region is almost disappeared because of the scattering processes of DMs and partons happen at loop level.



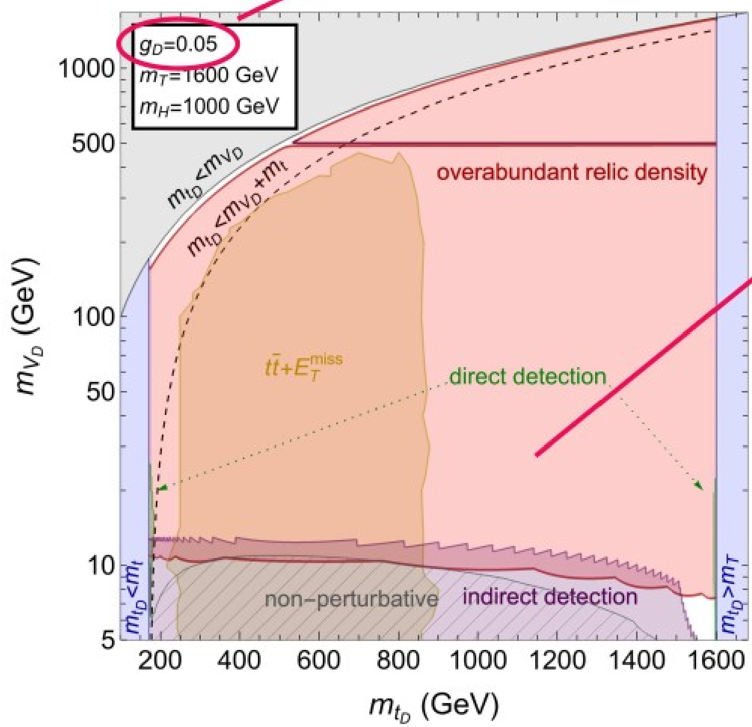
$\propto \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}$

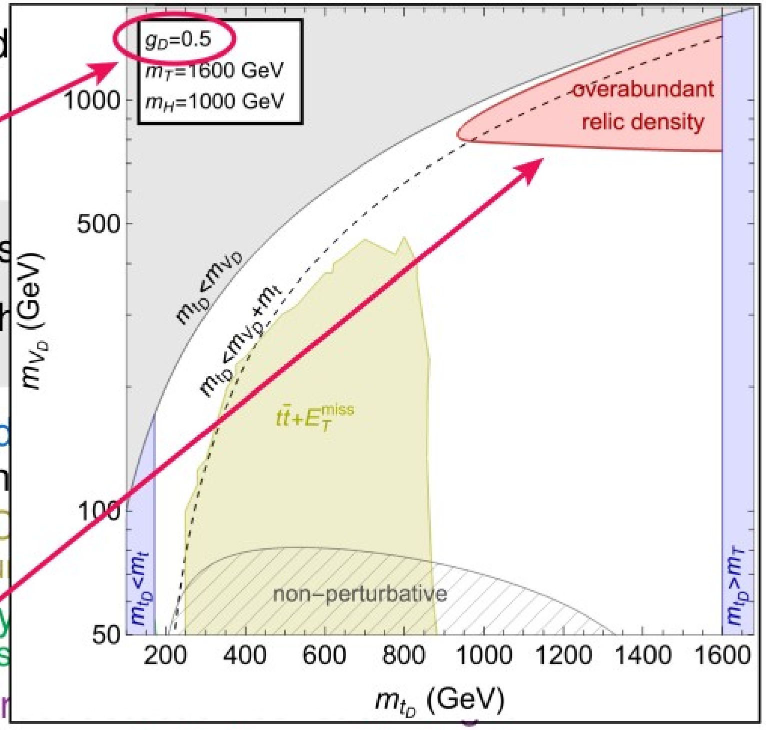
Results

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





Med
Ligh
LHC
(bou
Very
(mos
Indir

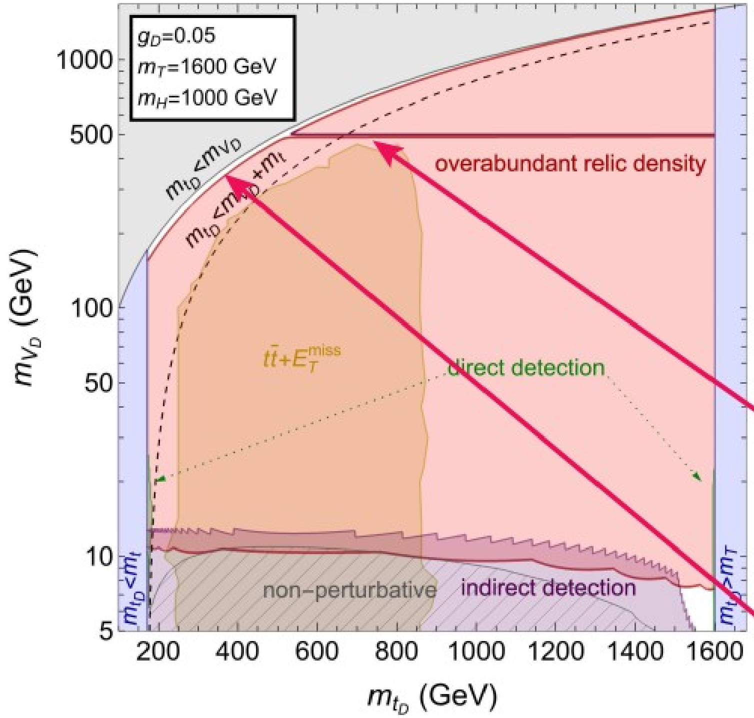
Strong constrain from relic density
→ the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)
→ overabundant region shrinks for larger g_D
→ and ID constraints vanish

Results

The $\boxed{\text{VL fermion is composed of top partners}}$ and there is $\boxed{\text{no mixing between scalars}}$

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

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ \left.\begin{matrix} m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{matrix}\right\} & \text{heavy enough to evade LHC constraints} \end{cases}$



Mediator mass bounded from below and above

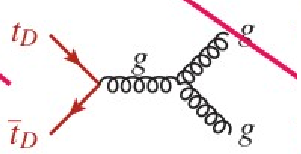
Light DM in non-perturbative region

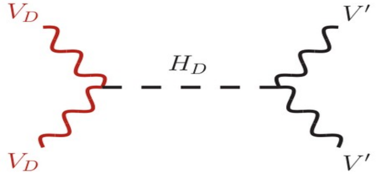
LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$
(bounds almost independent on g_D, m_T and m_H)

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

Strong constrain from relic density
→ the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)
→ overabundant region shrinks for larger g_D
→ and ID constraints vanish
→ effective (co-)annihilation processes



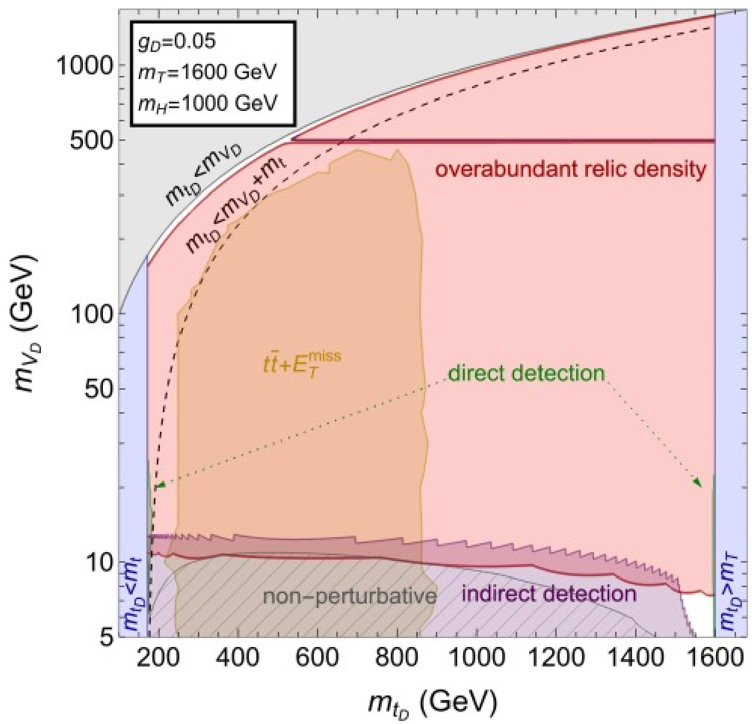


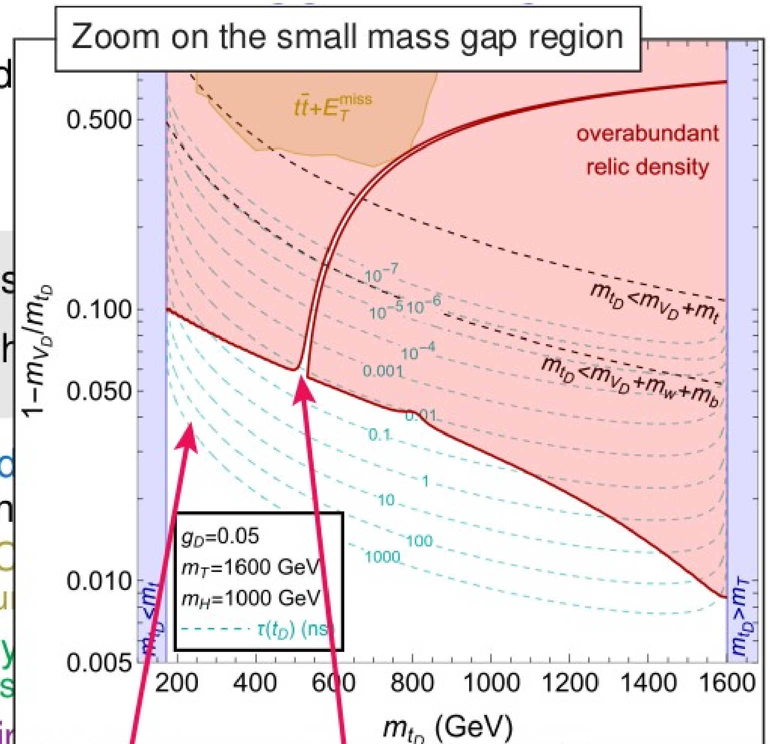
Results

The VL fermion is composed of top partners and

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

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





Med

Ligh

LHC

(bou

Very

(mos

Indir

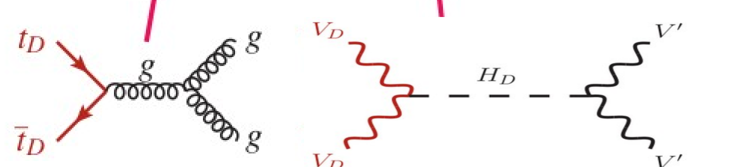
Strong constrain from relic density

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

→ overabundant region shrinks for larger g_D

→ and ID constraints vanish

→ effective (co-)annihilation processes

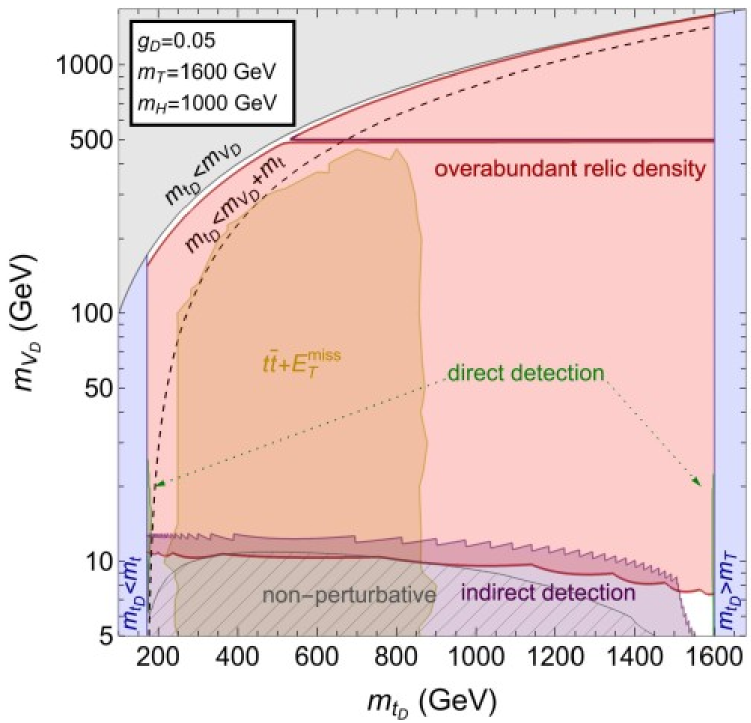


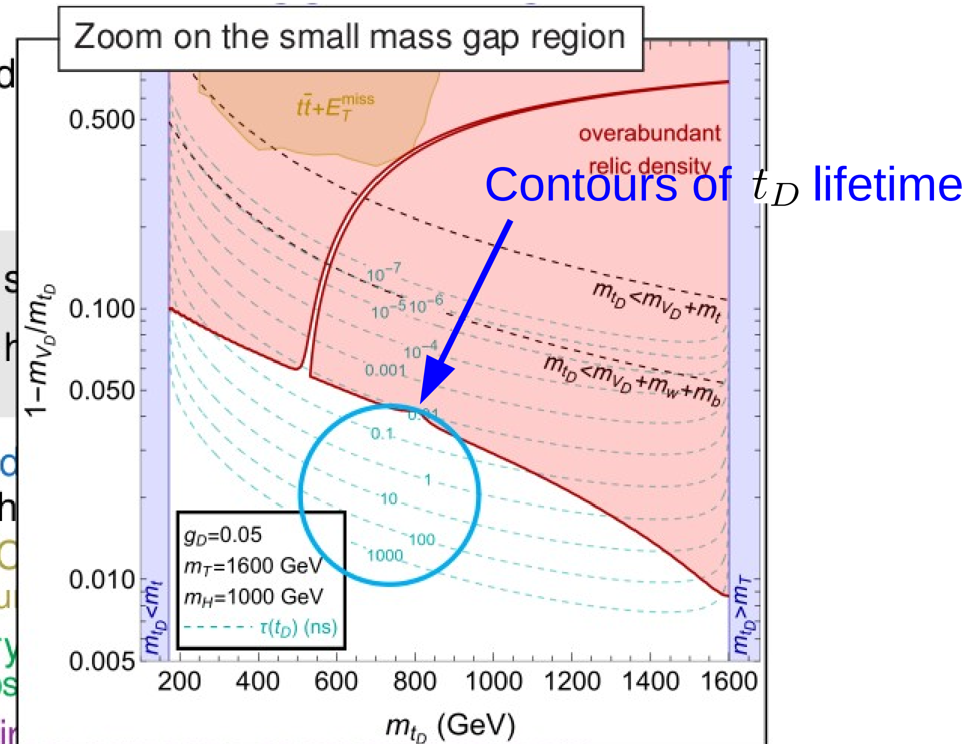
Results

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





Med

Ligh

LHC

(bou

Very

(mos

Indi

Strong constrain from relic density

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

→ overabundant region shrinks for larger g_D

→ and ID constraints vanish

→ effective (co-)annihilation processes

→ on the H_D pole, exclusion from ID

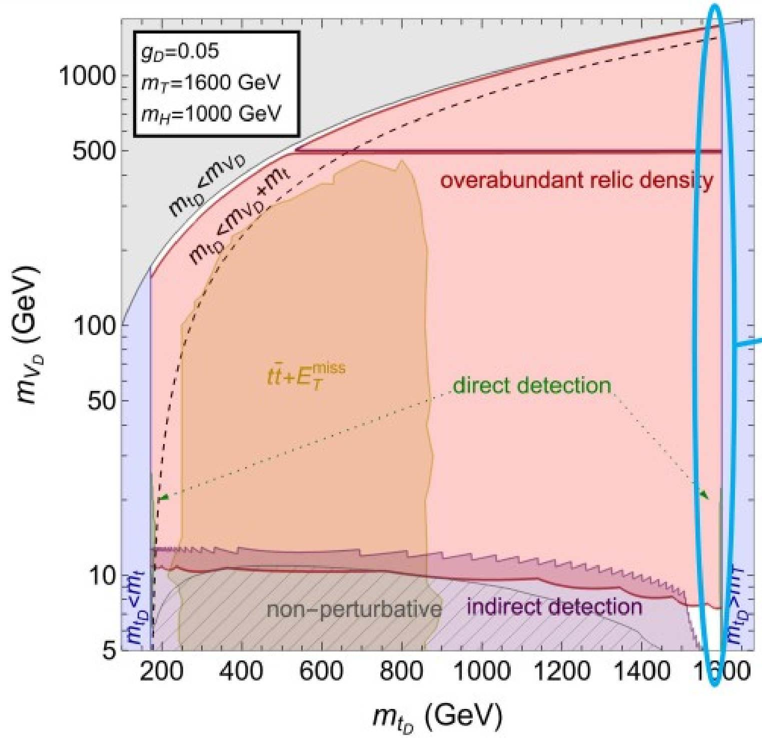
The mediator t_D can be long lived

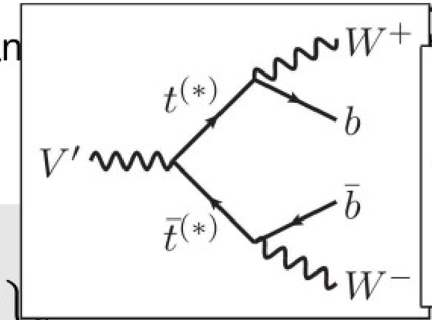
Results

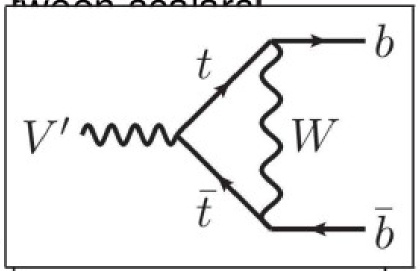
The VL fermion is composed of top partners an ... tween scalars

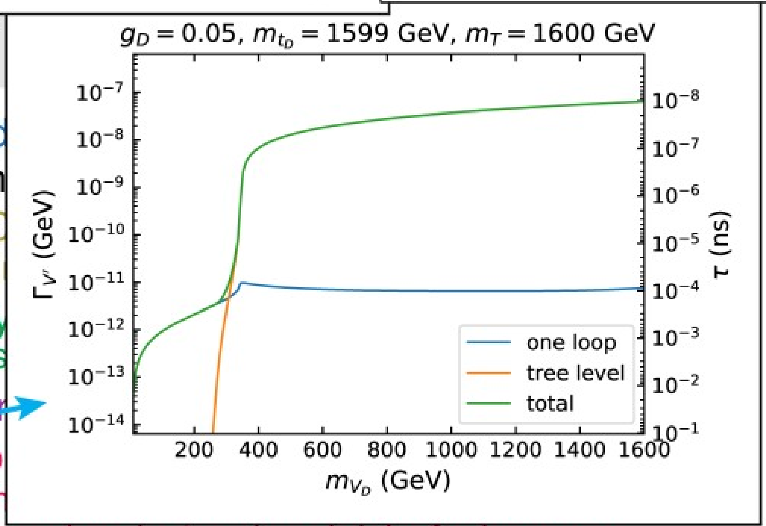
$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \le m_T$$

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









Med
Ligh
LHC
(bou
Very
(mos
Indi
Stro
→ th
→ overabundant region shrinks for larger g_D
→ and ID constraints vanish
→ effective (co-)annihilation processes
→ on the H_D pole, exclusion from ID

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

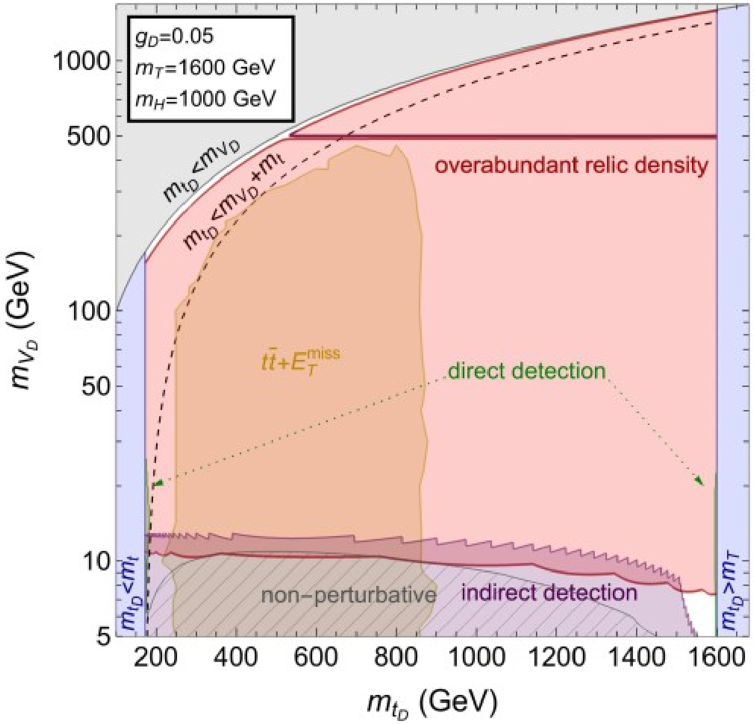
Two long-lived particles in a simple realisation!

Results

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

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

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

Strong constrain from relic density
- $\rightarrow$ the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)
- $\rightarrow$ overabundant region shrinks for larger g_D
  - $\rightarrow$ and ID constraints vanish
- $\rightarrow$ effective (co-)annihilation processes
  - $\rightarrow$ on the H_D pole, exclusion from ID

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

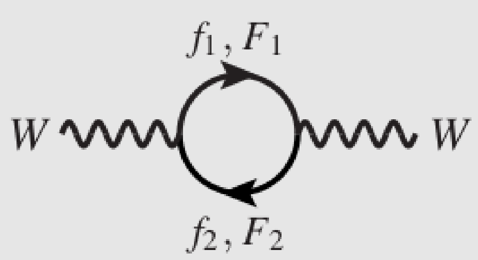
just a simple realization of the model template
multiple features and signatures

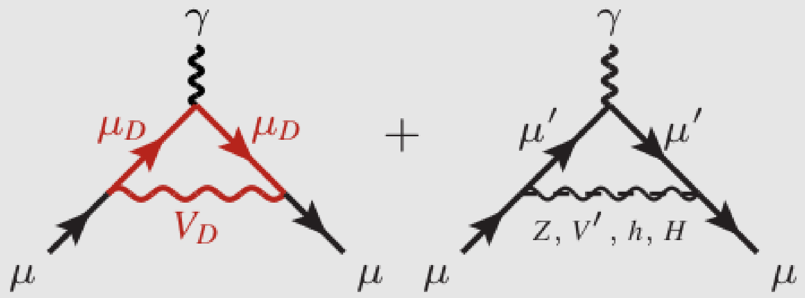
Summary & Outlook

- We propose a new class of model in which the Higgs-portal is not required.
- There are many possible implications in both collider and cosmological studies
- A case study on top-portal scenario provides multiple phenomenological predictions

Outlook

→ **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**

THANK YOU

BACK UP

Particle contents

$$SU(2)_L \times U(1)_Y \times SU(2)_D$$

We assign $\mathbb{Z}_2$ charge to component Of vector triplet according to $SU(2)_D$ isospin

These components carry $\mathbb{Z}_2$ odd charge because they have +1 and -1 isospin

They becomes stable **DM candidates**

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

Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} V^a_{\mu\nu} V^{a,\mu\nu}$$

From now on, we will call them

$$V^0_{D0} \equiv V' \;\; V^0_{D\pm} \equiv V_D$$

Particle contents

$$SU(2)_L \times U(1)_Y \times SU(2)_D$$

D-scalar doublet is charged under $SU(2)_D$ to give mass to DM.

The top component needs to have $\mathbb{Z}_2$odd charge becase it represents the longitunidal polarisation of DM.

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

The bottom component has $\mathbb{Z}_2$ even charge and acquires VEV to give mass to DM.

Lagrangian

$$\mathcal{L}_s = |D_\mu \Phi_D|^2 - \mu_D^2 \Phi_D^\dagger \Phi_D + \lambda_D (\Phi_D^\dagger \Phi_D)^2 + \boxed{\lambda_{\Phi_H \Phi_D} \Phi_H^\dagger \Phi_H \ \Phi_D^\dagger \Phi_D}$$

Higgs-portal term

Particle contents

$$SU(2)_L \times U(1)_Y \times SU(2)_D$$

The new fermion doublet which is charged Under $SU(2)_D$ is introduced to construct a portal to SM sector.

The fermion doublet is **vector-like**

Where the top component is $\mathbb{Z}_2$ -odd

while the bottom component is $\mathbb{Z}_2$ -even

Fermions	$SU(2)_L$	$U(1)_Y$	$SU(2)_{\rm D}$	$\mathbb{Z}_2$
$f_L^{\rm SM} = \begin{pmatrix} f_{u,\nu}^{\rm SM} \\ f_{d,\ell}^{\rm SM} \end{pmatrix}_L$	$\mathbf{2}$	$\frac{1}{6}, -\frac{1}{2}$	$\mathbf{1}$	$+$
$u_R^{\rm SM}, \nu_R^{\rm SM}$	$\mathbf{1}$	$\frac{2}{3}, 0$	$\mathbf{1}$	$+$
$d_R^{\rm SM}, \ell_R^{\rm SM}$	$\mathbf{1}$	$-\frac{1}{3}, -1$	$\mathbf{1}$	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	$\mathbf{1}$	Q	$\mathbf{2}$	$\begin{matrix} - \\ + \end{matrix}$

Lagrangian

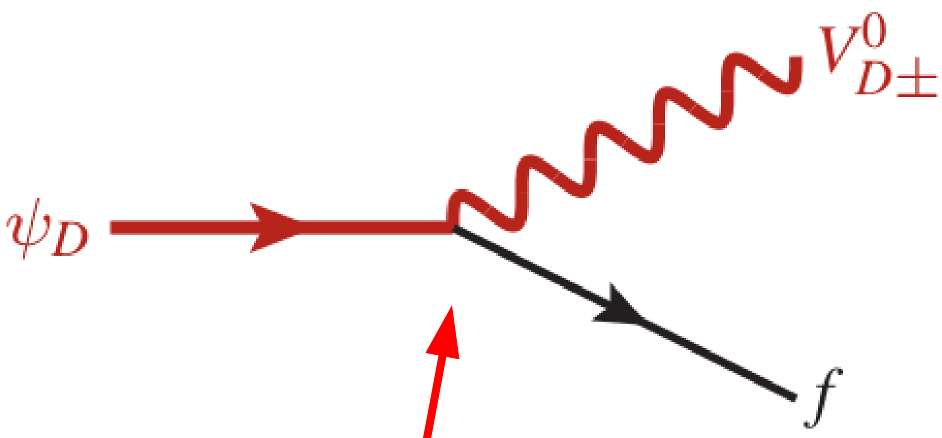
$$\mathcal{L}_F = \bar{\Psi} i \not{D} \Psi - (y \bar{f}_L^{\rm SM} \Phi_H f_R^{SM} + \boxed{y' \bar{\Psi}_L \Phi_D f_R^{\rm SM}} + h.c.) - M_\Psi \bar{\Psi}\Psi$$

This term connects D-fermion to SM-fermion

Particle contents

$$SU(2)_L \times U(1)_Y \times SU(2)_D$$

Connecting VDM, SM-fermion and D-fermion



Fermions	$SU(2)_L$	$U(1)_Y$	$SU(2)_\mathrm{D}$	$\mathbb{Z}_2$
$f_L^{\mathrm{SM}} = \begin{pmatrix} f_{u,\nu}^{\mathrm{SM}} \\ f_{d,\ell}^{\mathrm{SM}} \end{pmatrix}_L$	$\mathbf{2}$	$\frac{1}{6}, -\frac{1}{2}$	$\mathbf{1}$	$+$
$u_R^{\mathrm{SM}}, \nu_R^{\mathrm{SM}}$	$\mathbf{1}$	$\frac{2}{3}, 0$	$\mathbf{1}$	$+$
$d_R^{\mathrm{SM}}, \ell_R^{\mathrm{SM}}$	$\mathbf{1}$	$-\frac{1}{3}, -1$	$\mathbf{1}$	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	$\mathbf{1}$	Q	$\mathbf{2}$	$\begin{matrix} - \\ + \end{matrix}$

Lagrangian

$$\mathcal{L}_F = \bar{\Psi} i \not{D} \Psi - (y \bar{f}_L^{\mathrm{SM}} \Phi_H f_R^{SM} + \boxed{y' \bar{\Psi}_L \Phi_D f_R^{\mathrm{SM}}} + h.c.) - M_\Psi \bar{\Psi}\Psi$$

connecting D-fermion to SM-fermion

Results

We did full scan of 5 parameter with the ranges:

$$10^{-3} < g_D < 4\pi$$

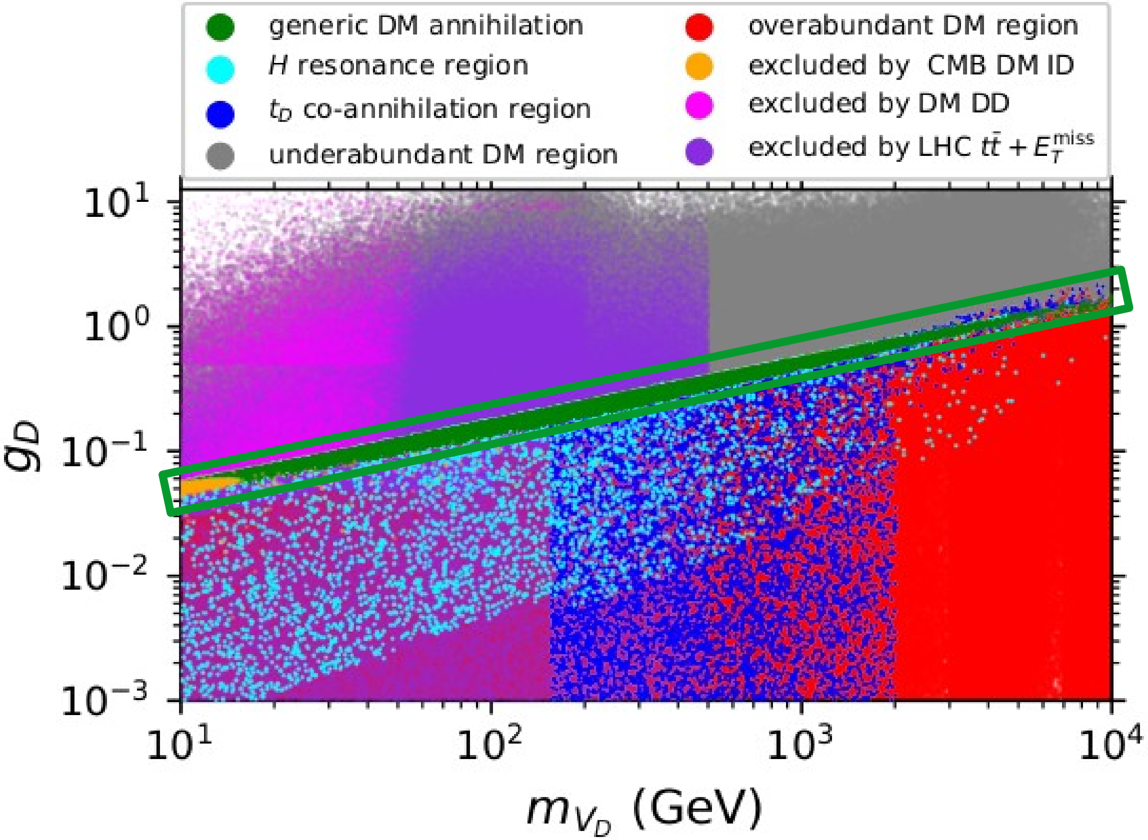
$$10 \text{ GeV} < m_{V_D} < m_{t_D}$$

$$m_t < m_{t_D} < m_T < 10^4 \text{ GeV}$$

$$10 \text{ GeV} < m_H < 10^4 \text{ GeV}$$

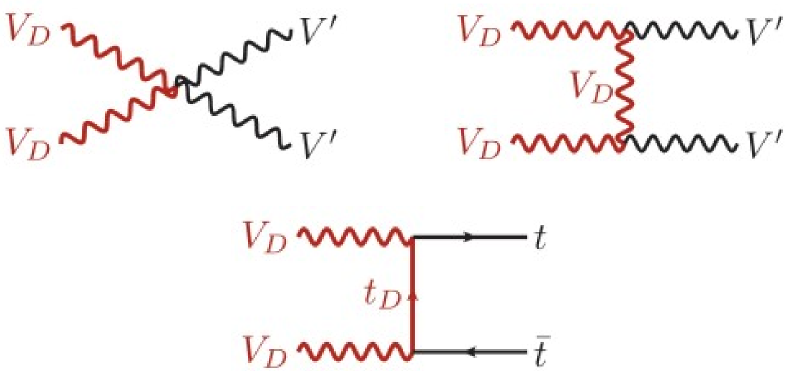
Results

Full 5D scan allows us to understand a big picture of parameter space



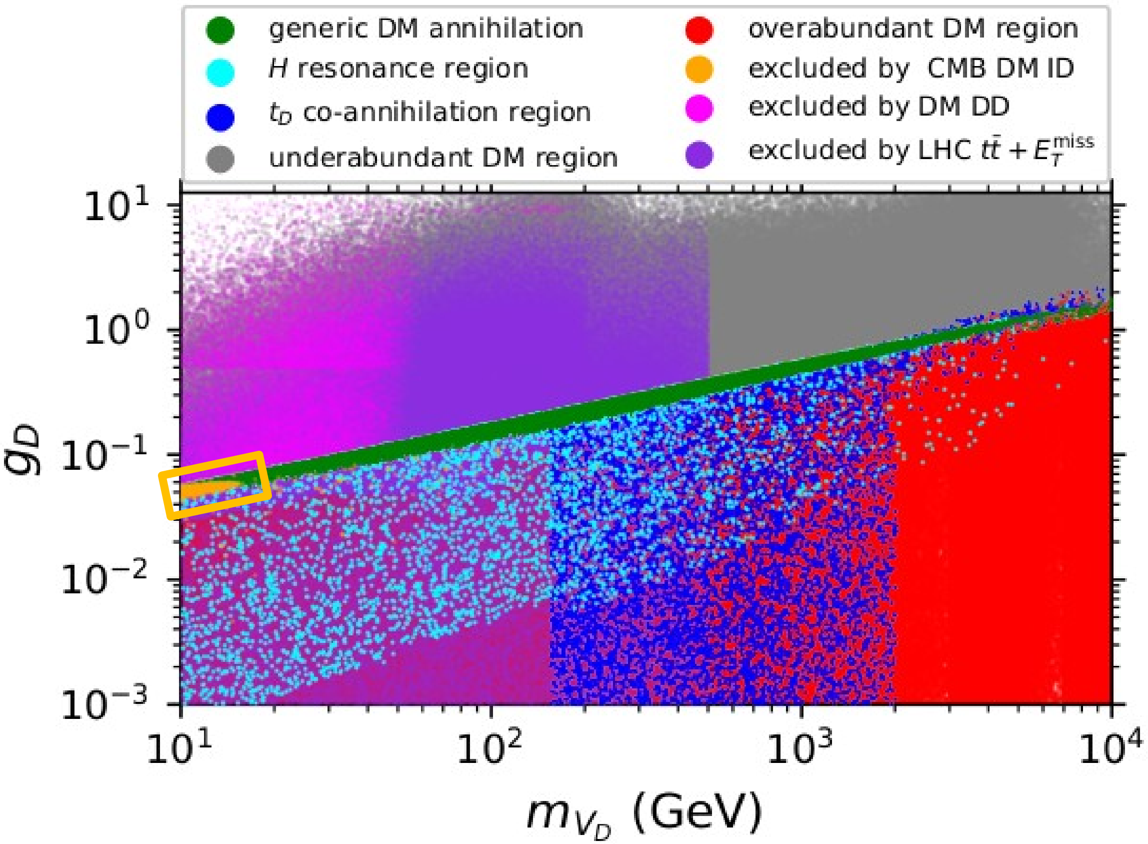
The generic annihilation corresponds to the region where the relic density is 5% from the measured value

$$\Omega h^2 \propto \frac{m_{DM}^3}{g_D^4}$$



Results

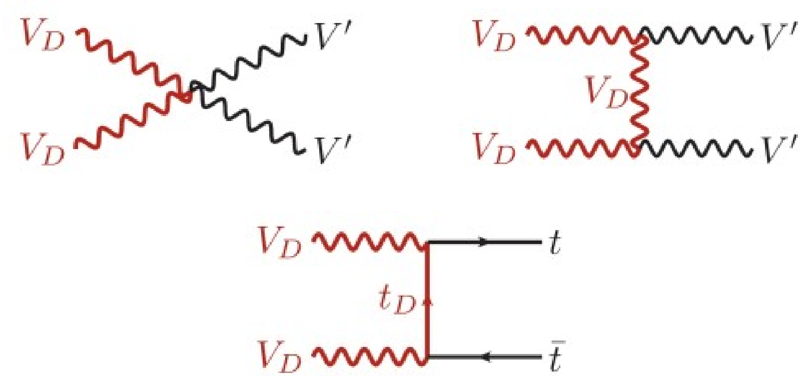
Full 5D scan allows us to understand a big picture of parameter space



The region is excluded by CMB dark matter indirect detection limit

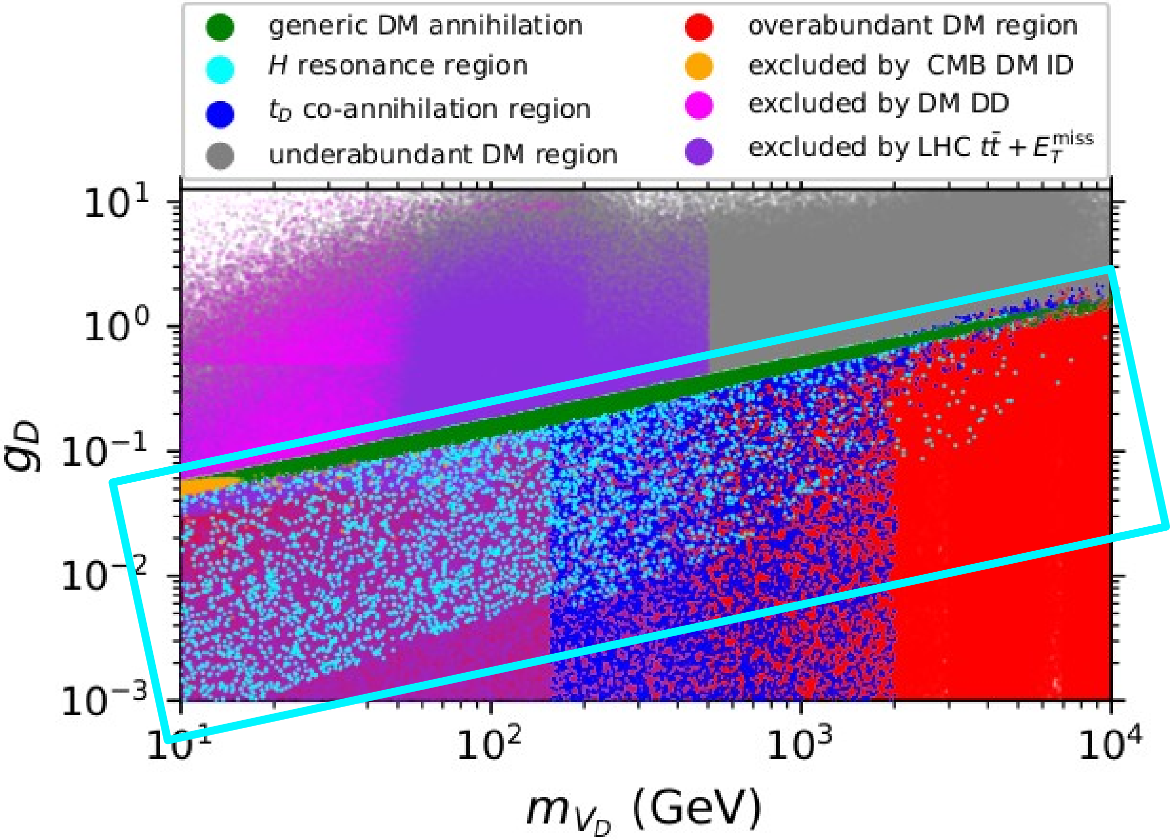
$$P_{\text{ann}} = \sum_j \frac{f_j^{\text{eff}} \langle \sigma v \rangle_j}{M_{\text{DM}}} \left(\frac{\Omega_{\text{DM}}}{\Omega_{\text{DM}}^{\text{Planck}}} \right)^2$$

$$P_{\text{ann}} < 3.2 \times 10^{-28} \ \frac{\text{cm}^3}{\text{s GeV}} \quad \text{at } 95\% \text{ C.L.}$$



Results

Full 5D scan allows us to understand a big picture of parameter space



The region can give the correct relic density even though the couplings is small because of H resonant processes

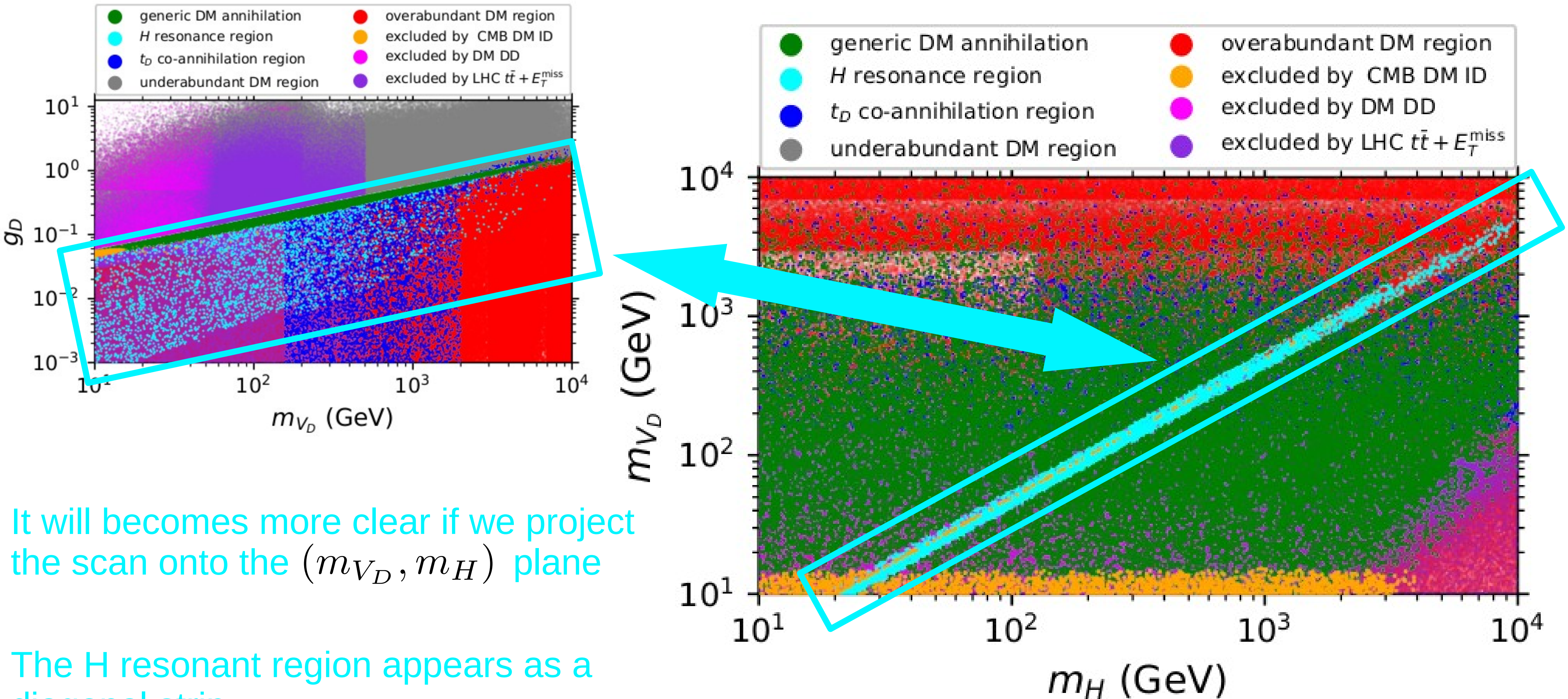
$$\langle \sigma v \rangle \propto \left(\frac{1}{4m_{DM}^2 - m_H^2} \right)^2$$

$$\text{as } m_{V_D} \to \frac{m_H}{2}$$

The relic density is suppressed!

Results

Full 5D scan allows us to understand a big picture of parameter space

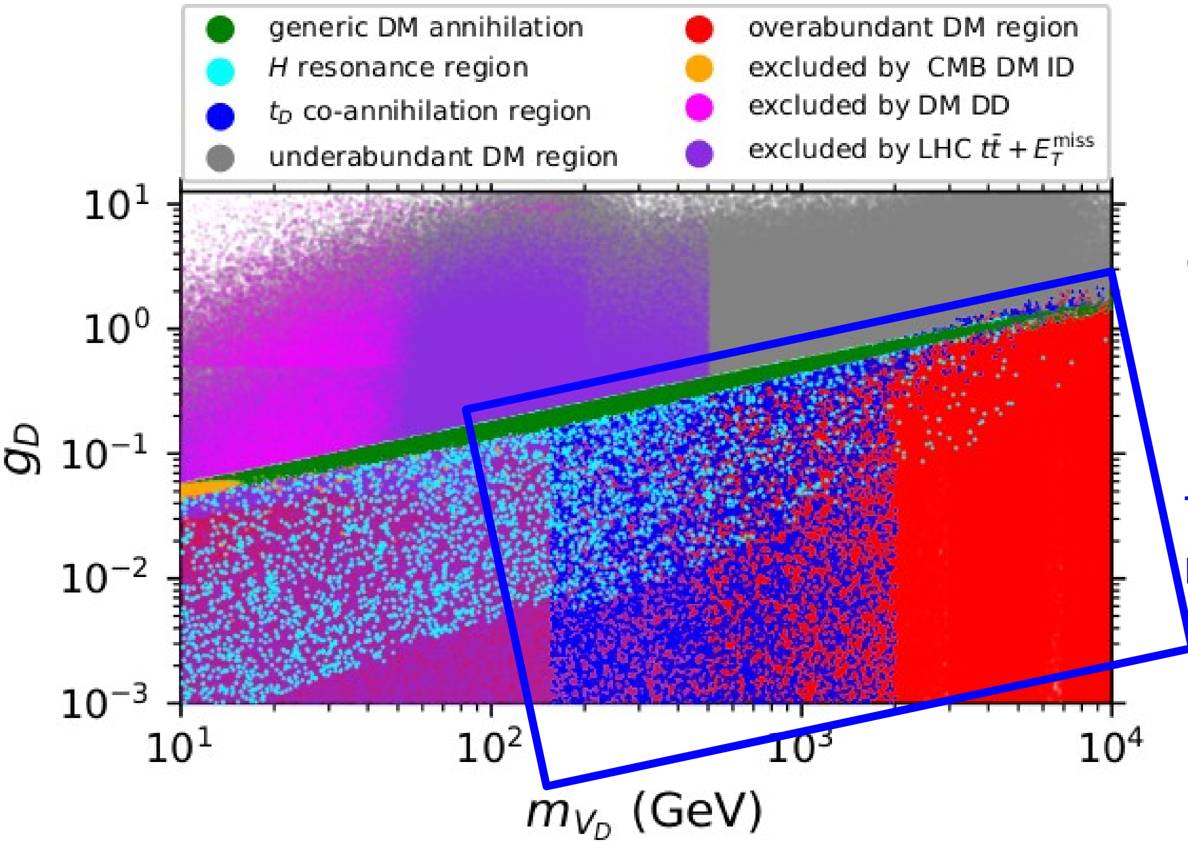


It will becomes more clear if we project the scan onto the (m_{V_D}, m_H) plane

The H resonant region appears as a diagonal strip.

Results

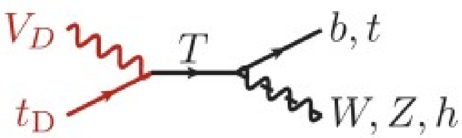
Full 5D scan allows us to understand a big picture of parameter space



Even though the coupling is 2 order of magnitude smaller than the generic processes(green region), the relic density is still very suppressed due to the co-annihilation processes with t_D

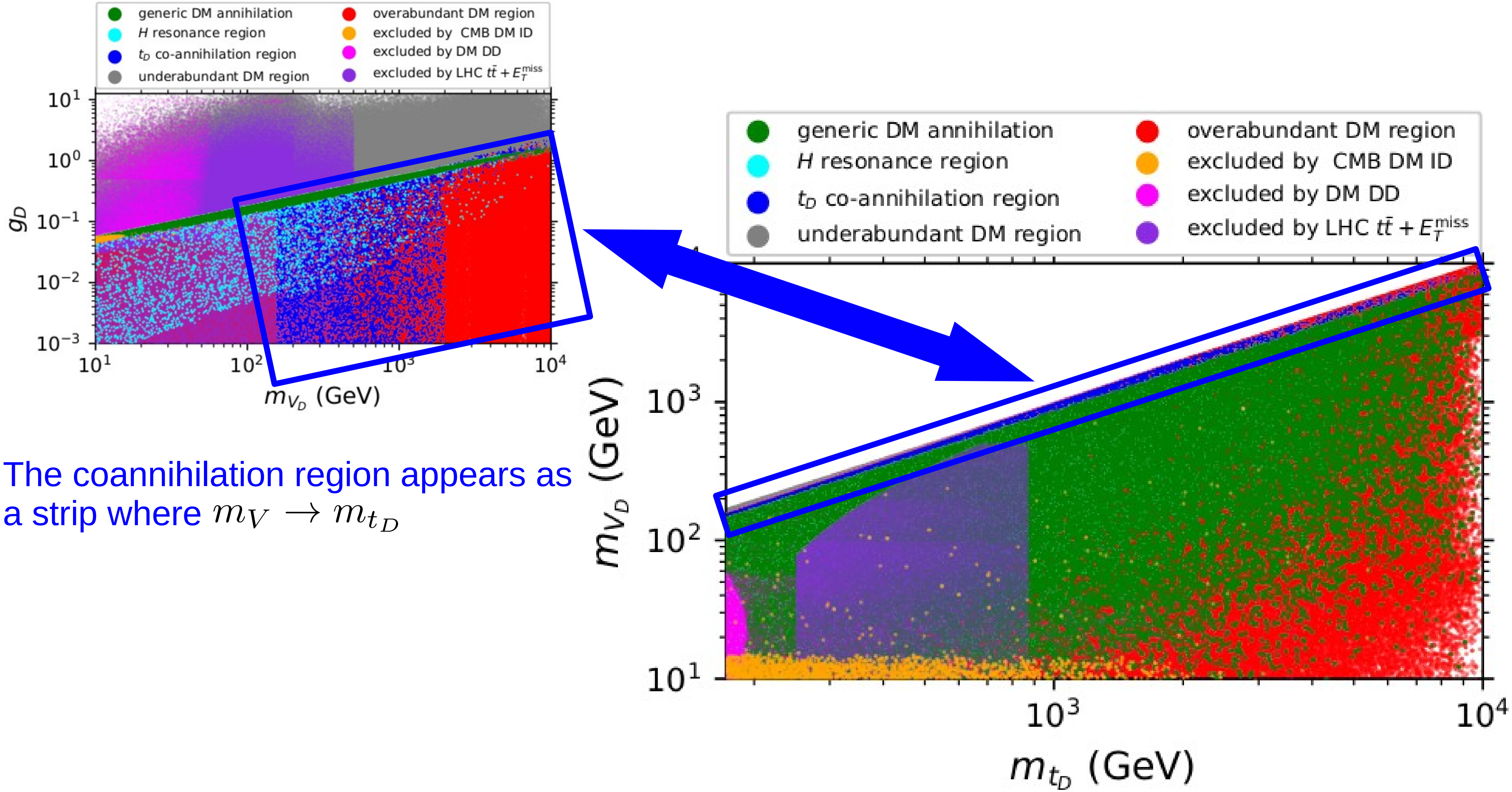
$$B_f \approx e^{-X_f\left(\frac{m_{t_D}-m_V}{m_V}\right)}$$

The coannihilation will becomes more relevant as $m_V \to m_{t_D}$



Results

Full 5D scan allows us to understand a big picture of parameter space



The coannihilation region appears as a strip where $m_V \to m_{t_D}$

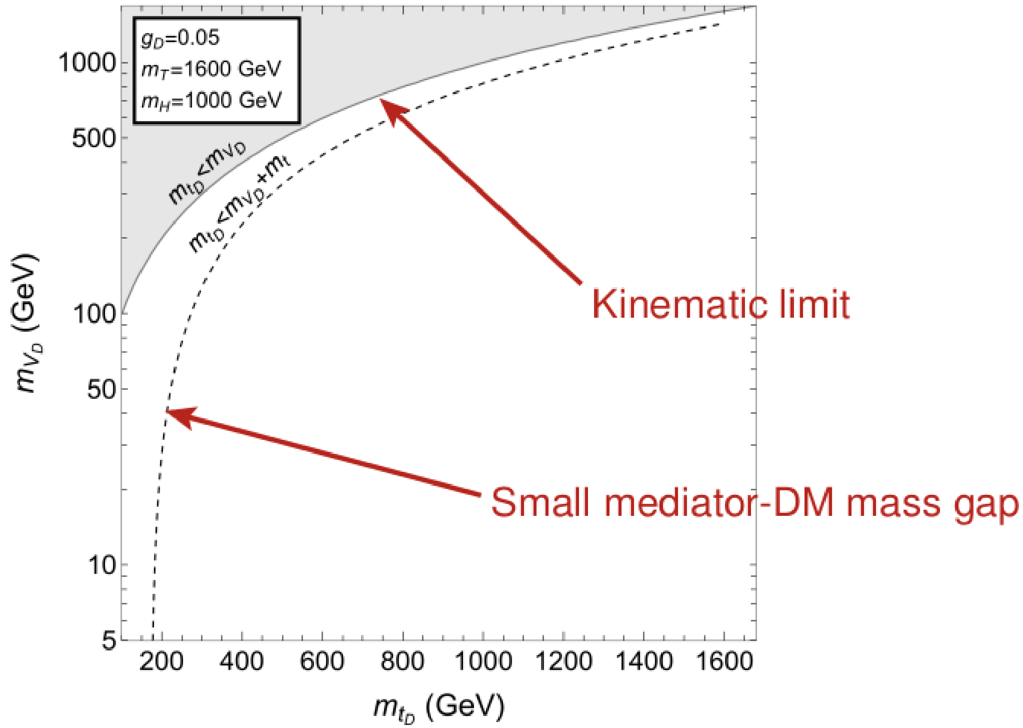
Results

The $\boxed{\text{VL fermion is composed of top partners}}$ and there is $\boxed{\text{no mixing between scalars}}$

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

$$\sin\theta_S = 0$$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ \left.\begin{array}{l} m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{array}\right\} & \text{heavy enough to evade LHC constraints} \end{cases}$



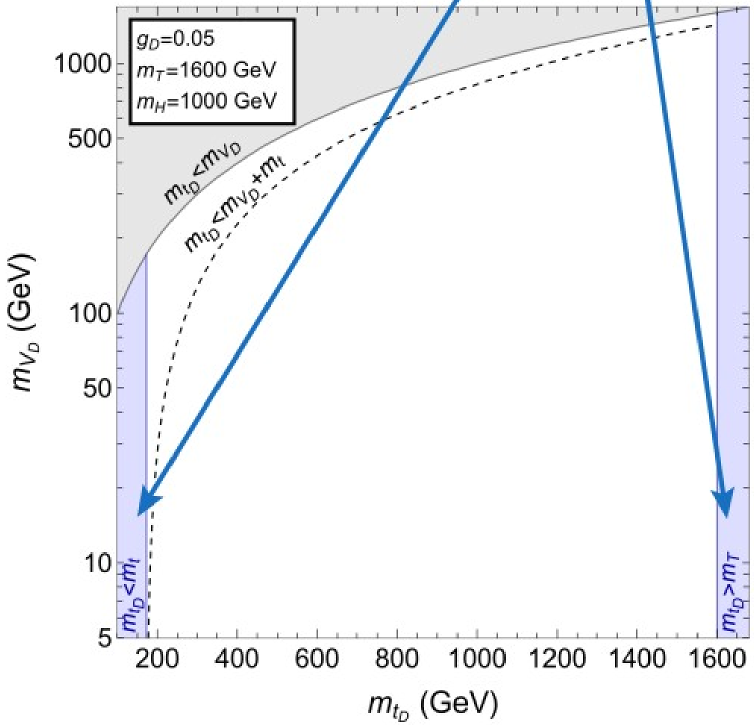
Results

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

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

$$\sin\theta_S = 0$$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases}$ strong or weak cosmological constraints; heavy enough to evade LHC constraints



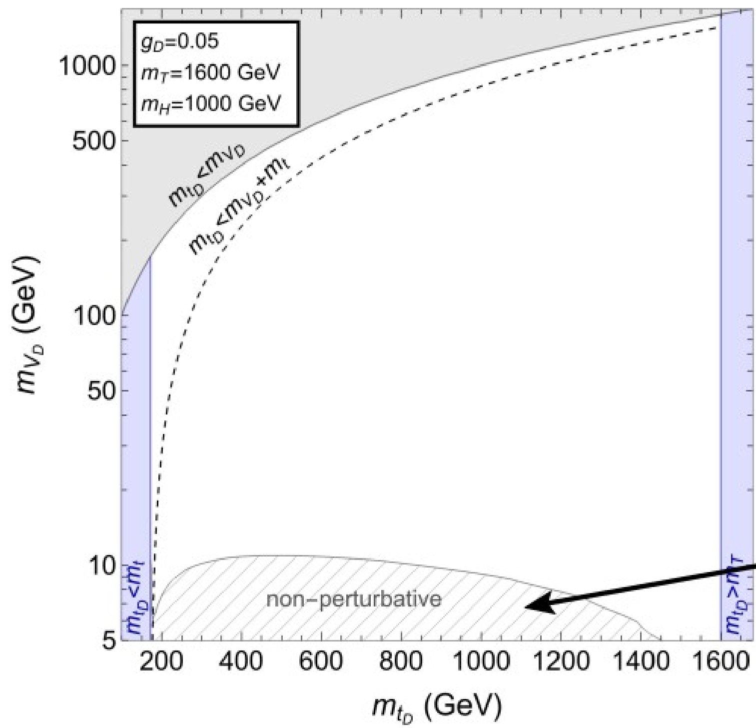
Mediator mass bounded from below and above

Results

The $\boxed{\text{VL fermion is composed of top partners}}$ and there is $\boxed{\text{no mixing between scalars}}$

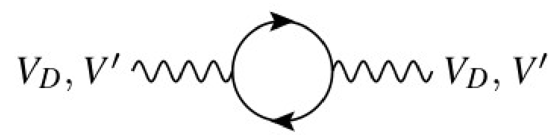
$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T \qquad\qquad \sin\theta_S = 0$$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ \left.\begin{array}{l} m_T = 1600\ \text{GeV} \\ m_H = 1000\ \text{GeV} \end{array}\right\} & \text{heavy enough to evade LHC constraints} \end{cases}$



Mediator mass bounded from below and above

Light DM in non-perturbative region



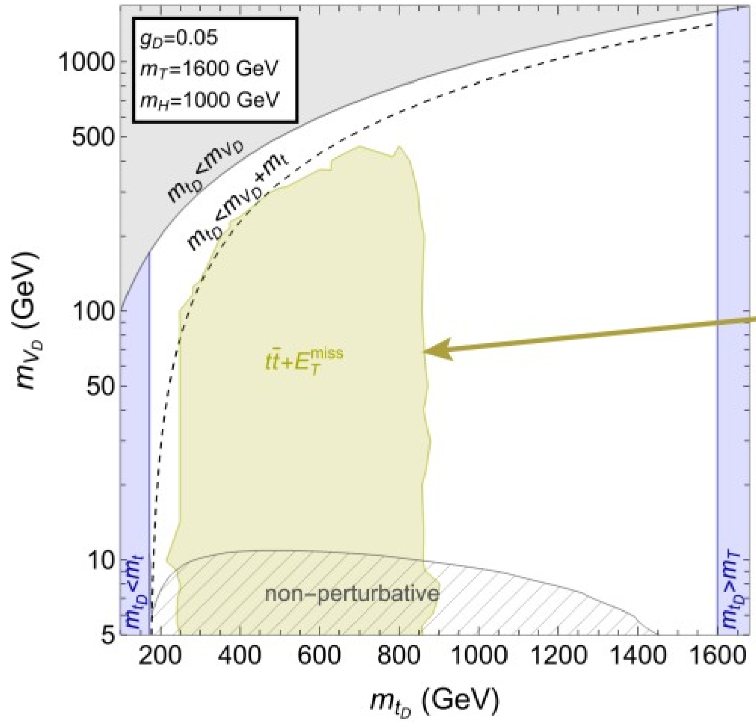
$$\frac{m_V^{\text{pole}} - m_V}{m_V} > 50\%$$

Results

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

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

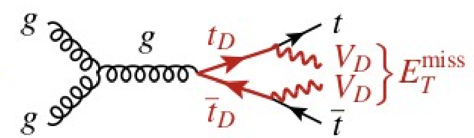
Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ m_T = 1600 \text{ GeV} & \\ m_H = 1000 \text{ GeV} & \end{cases}$ $\Big\}$ heavy enough to evade LHC constraints



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)



Recast

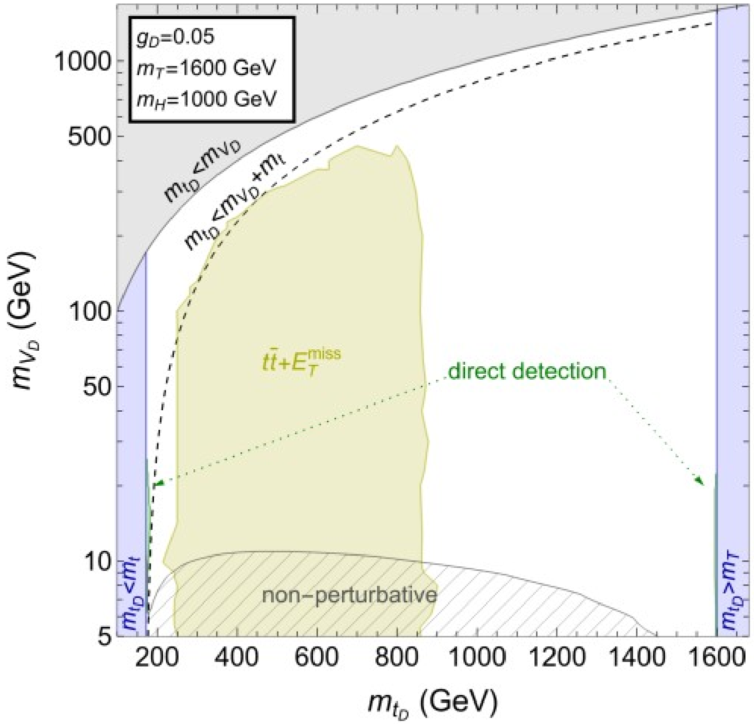
A. M. Sirunyan *et al.* [CMS], **Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV**, Phys. Rev. D **97** (2018) no.3, 032009, arXiv:1711.00752 [hep-ex]

Results

The $\boxed{\text{VL fermion is composed of top partners}}$ and there is $\boxed{\text{no mixing between scalars}}$

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

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ \left.\begin{array}{l} m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{array}\right\} & \text{heavy enough to evade LHC constraints} \end{cases}$

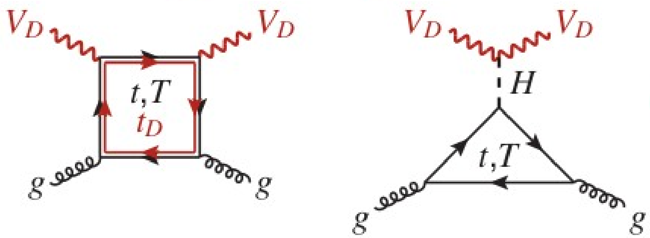


Mediator mass bounded from below and above

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)



$\propto \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}$

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]

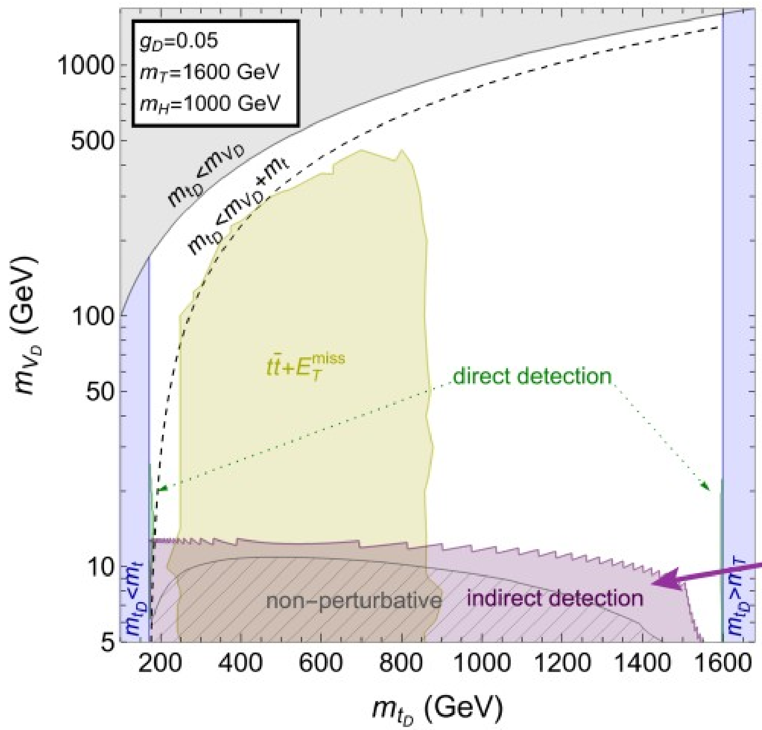
Results

The $\boxed{\text{VL fermion is composed of top partners}}$ and there is $\boxed{\text{no mixing between scalars}}$

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

$$\sin\theta_S = 0$$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases}$ strong or weak cosmological constraints; m_T, m_H: heavy enough to evade LHC constraints



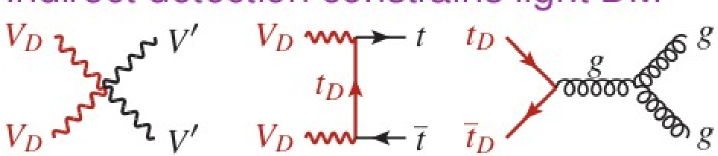
Mediator mass bounded from below and above

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



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

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

High energy physics tools

DM observables

LanHEP 0805.0555

↓

CalcHEP 1207.6082

↓

micrOMEGAs 1402.0787

LHC processes

FeynRules 1310.1921

↓

MG5_aMC 1405.0301

One-loop correction

LanHEP 0805.0555

↓

FeynArts 0012260

↓

FeynCalc 2001.04407

↓

FeynHelpers 1611.06793

+

Package-X 1612.00009

LanHEP and FeynRules implementations have been cross-validated within CalcHEP.

Package-X was used to cross-check the results from FeynCalc.

The origin of $\mathbb{Z}_2$ symmetry: A dark EW sector

This model can be embeded into a model with bigger gauge group like

$$SU(2)_L \times U(1)_Y \times SU(2)_D \times U(1)_{YD} \to U(1)_{\text{EM}} \times U(1)_D$$

After SSB, the conserved charge in dark EW

$$Q^D = T_3^D + Y^D$$

All SM particles carry no charge under the dark EW group.

In this dark EW sector, the discrete symmetry is not invoked to stabilise the dark matter.

Gauge boson mass

$$\Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \langle \Phi_H \rangle = \tfrac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \text{(scalar doublet breaking } SU(2)_L \times U(1)_Y) \;,$$

$$\Phi_D = \begin{pmatrix} \varphi^0_{D+1/2} \\ \varphi^0_{D-1/2} \end{pmatrix} \longrightarrow \langle \Phi_D \rangle = \tfrac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix} \qquad \text{(scalar doublet breaking } SU(2)_{\rm D}) \;.$$

Mass of weak gauge bosons

$$M_W = \frac{gv}{2} \qquad\qquad M_Z = \frac{v}{2}\sqrt{g^2 + g'^2}$$

Mass of new gauge bosons

$$m_{V'} = m_{V_D} = \frac{g_D v_D}{2}$$

New gauge bosons have degenrate mass at tree

Gauge boson mass

$$\Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \longrightarrow \langle \Phi_H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{(scalar doublet breaking } SU(2)_L \times U(1)_Y) ,$$

$$\Phi_D = \begin{pmatrix} \varphi^0_{D+1/2} \\ \varphi^0_{D-1/2} \end{pmatrix} \longrightarrow \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix} \quad \text{(scalar doublet breaking } SU(2)_{\mathrm{D}}) .$$

Mass of weak gauge bosons

New scalar does not affect
the mass of SM gauge bosons

$$M_W = \frac{gv}{2} \qquad M_Z = \frac{v}{2}\sqrt{g^2 + g'^2}$$

Mass of new gauge bosons

$$\cancel{m_{V'} = m_{V_D} = \frac{g_D v_D}{2}}$$

This is NOT the case
at loop level

BUT at one loop the mass splitting occur resulting from VL fermion

The mass splitting plays a role in
- relic density calculation
- ID constraint

Fermion mass and mixing

Fermion mass term

$$-\mathcal{L}_m^F = (\bar{f}_L^{\mathrm{SM}} \quad \bar{\psi}_L)\, \mathcal{M}_F \begin{pmatrix} f_R^{\mathrm{SM}} \\ \psi_R \end{pmatrix} \quad \Rightarrow \quad -\mathcal{L}_m^F = (\bar{f}_L \quad \bar{F}_L)\, \mathcal{M}_F^d \begin{pmatrix} f_R \\ F_R \end{pmatrix}$$

where $\mathcal{M}_F^d = V_{fL}^\dagger \mathcal{M}_F V_{fR}$

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

$$V_{fL} = \begin{pmatrix} \cos\theta_{fL} & \sin\theta_{fL} \\ -\sin\theta_{fL} & \cos\theta_{fL} \end{pmatrix} \qquad V_{fR} = \begin{pmatrix} \cos\theta_{fR} & \sin\theta_{fR} \\ -\sin\theta_{fR} & \cos\theta_{fR} \end{pmatrix}$$

$$m_{f,F}^2 = \frac{1}{4}\left[y^2v^2 + y'^2v_D^2 + 2M_\Psi^2 \mp \sqrt{(y^2v^2 + y'^2v_D^2 + 2M_\Psi^2)^2 - 8y^2v^2M_\Psi^2}\right]$$

Scalar mass and mixing

Scalar doublets in unitary gauge

$$\Phi_H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h_1 \end{pmatrix} \quad \Phi_D = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_D + \varphi_1 \end{pmatrix}$$

Scalar mass term

$$-\mathcal{L}_m^S = \begin{pmatrix} h_1 & \varphi_1 \end{pmatrix} \begin{pmatrix} \lambda v^2 & \frac{\lambda_{\Phi_H}\lambda_{\Phi_D}}{2} v v_D \\ \frac{\lambda_{\Phi_H}\lambda_{\Phi_D}}{2} v v_D & \lambda_D v_D^2 \end{pmatrix} \begin{pmatrix} h_1 \\ \varphi_1 \end{pmatrix}$$

Scalar mass

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

Scalar mixing matrix

$$V_S = \begin{pmatrix} \cos\theta_S & \sin\theta_S \\ -\sin\theta_S & \cos\theta_S \end{pmatrix}$$

Mass of new gauge at one loop

The mass of new gauge bosons are degenerate at tree level

But they are splitted at one loop level because of the VL-fermion

In the limit that

$$\epsilon = \frac{m_F^2 - m_{\psi_D}^2}{m_F^2}, \quad \epsilon_2 = \frac{m_f^2}{m_F^2}, \quad \epsilon_3 = \frac{m_{V_D}^2}{m_F^2} \ ,$$

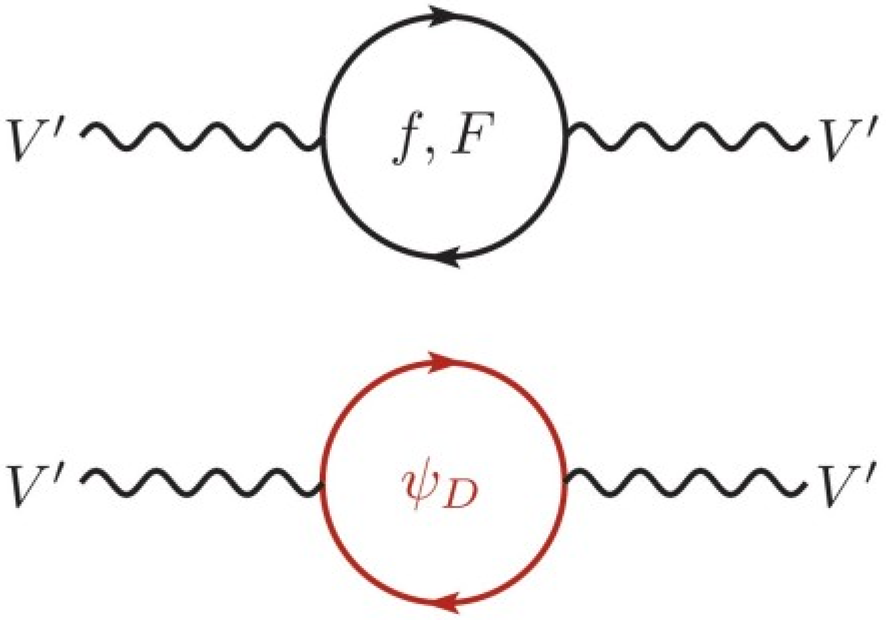
the mass difference is reduced to

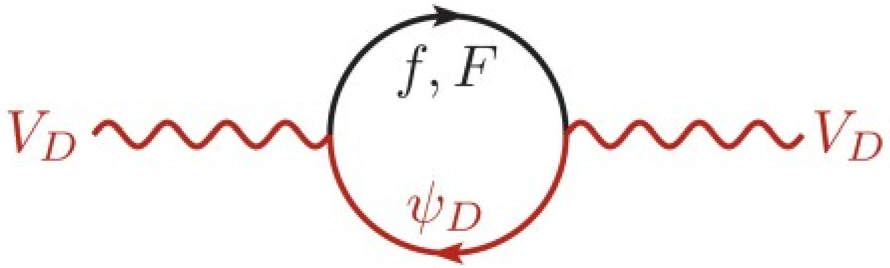
$$\Delta m'_V = \frac{1}{640\pi^2 m_{V_D}} \epsilon g_D^2 m_F^2 \left[(20 + 3\epsilon_3 - 15\epsilon_2 + 20\epsilon_2\epsilon_3) + 10(2\epsilon_2 - \epsilon_3 - 2\epsilon_2\epsilon_3)\log\epsilon_3\right] + o(\epsilon, \epsilon_2, \epsilon_3) \ .$$

$$\Delta m''_V = \frac{g_D^2 m_F^2}{32\pi^2 m_{V_D}} \epsilon = \frac{g_D^2 m_F^2}{32\pi^2 m_{V_D}} \frac{m_F^2 - m_{\psi_D}^2}{m_F^2}.$$

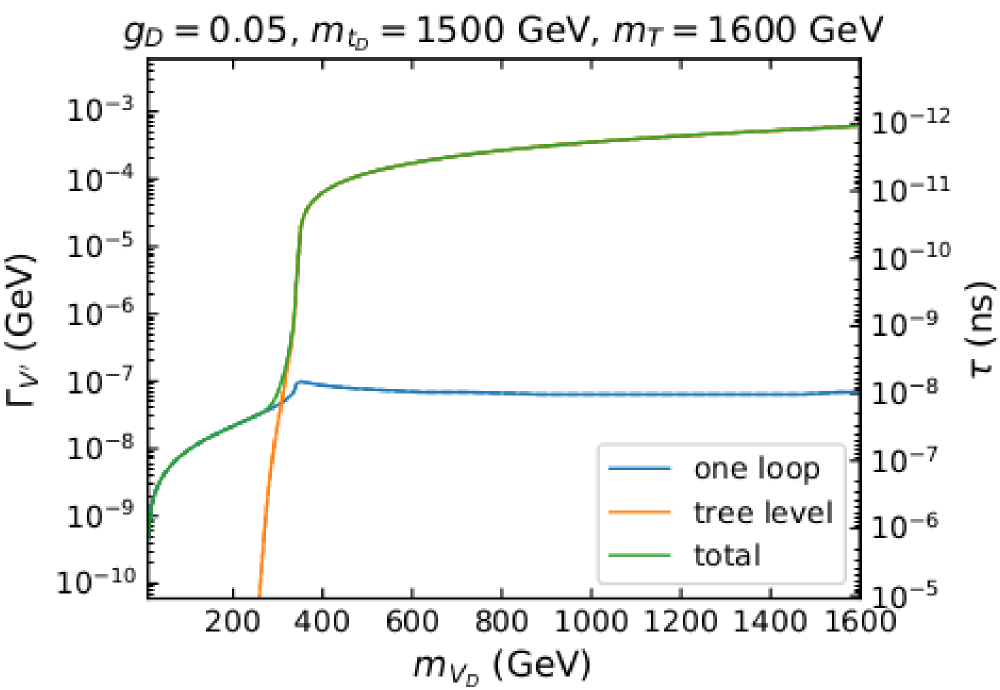
Mass of new gauge at one loop

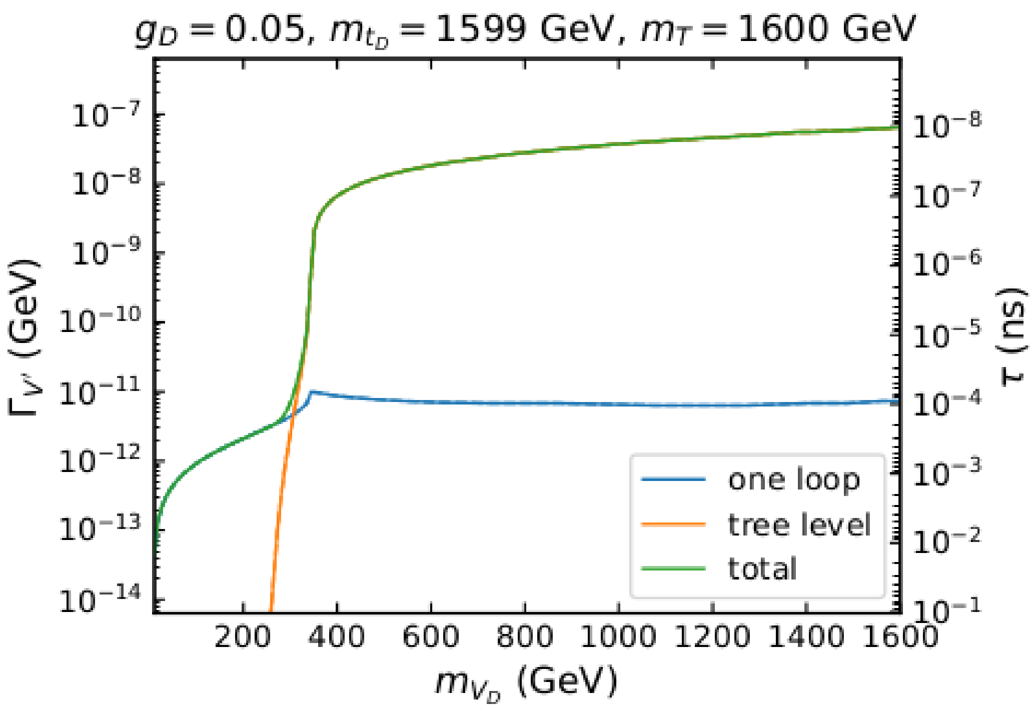
The relevant one loop diagrams

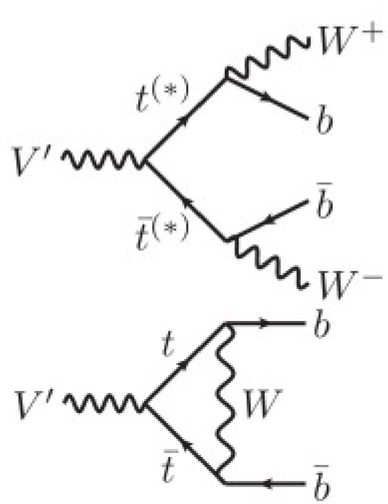




Decay width of V'







V' is a long-lived particle if its mass is small
And the mass difference of two VL quarks is small

The decay of V' does not spoil BBN because of one-loop induced processes

Mass of new gauge at one loop

The value of mass difference in (m_{t_D}, m_{V_D}) plane for a specific of g_D, m_T

The red line corresponds to exact formula
The blue and the green ones correspond to the approximated formulae

The mass splitting is small if the mass Difference of VL quarks is small and Tree-level mass of V_D is large.

The correction to the mass of V_D, V' becomes bigger than 50%