A vector-like top quark portal to a minimal non-Abelian vector dark matter

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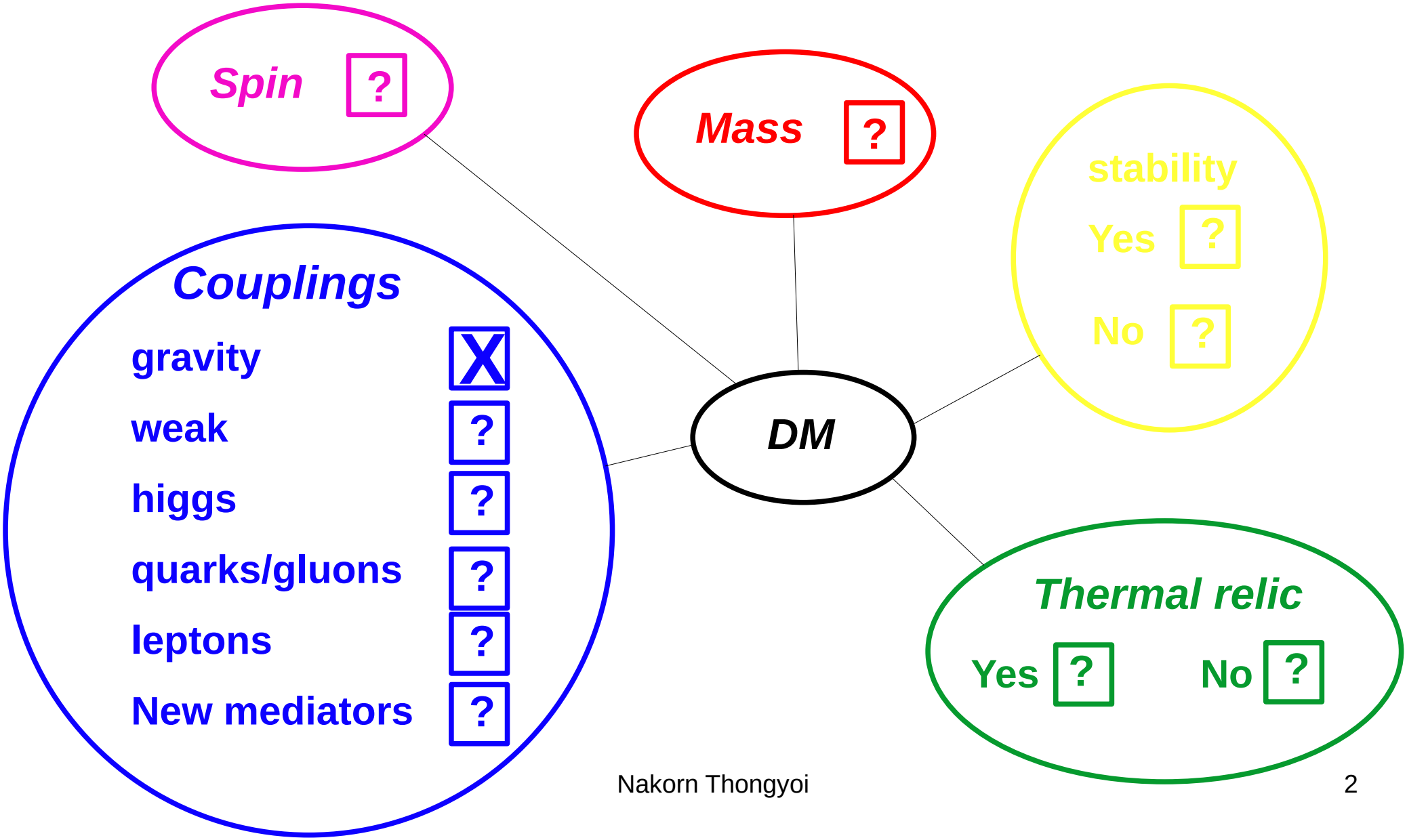
Based on 2203.04681 and 2204.03510 with
A. Belyaev, A. Deandrea, S. Moretti, L. Panizzi, D. Ross and NT

What do we know about DM?



How do we study DM?

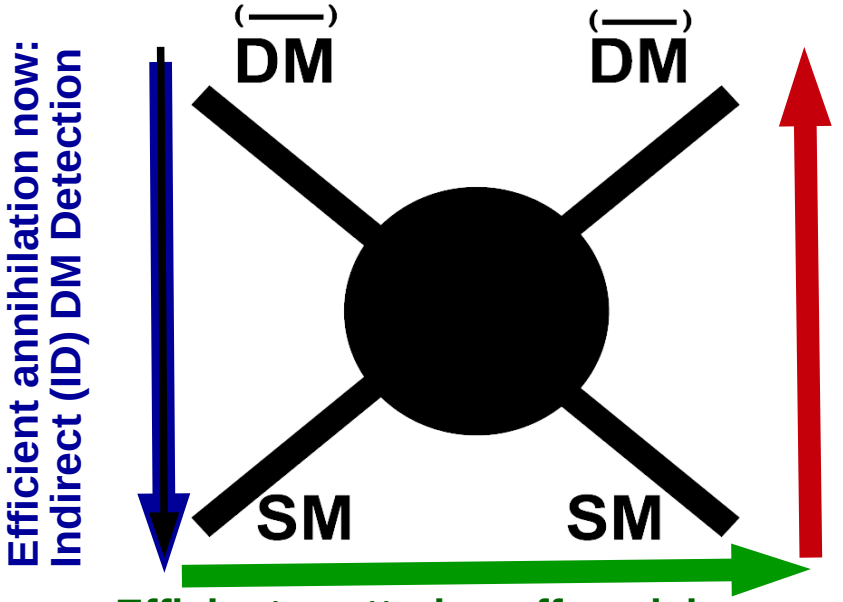
Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB

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

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

Neutrino telescopes:

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



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

LHC signatures

- **mono-jet**
- **mono-photon**
- **mono-Z**
- **mono Higgs**

- **VBF+MET**
- **soft leptons+MET**
- **….**

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

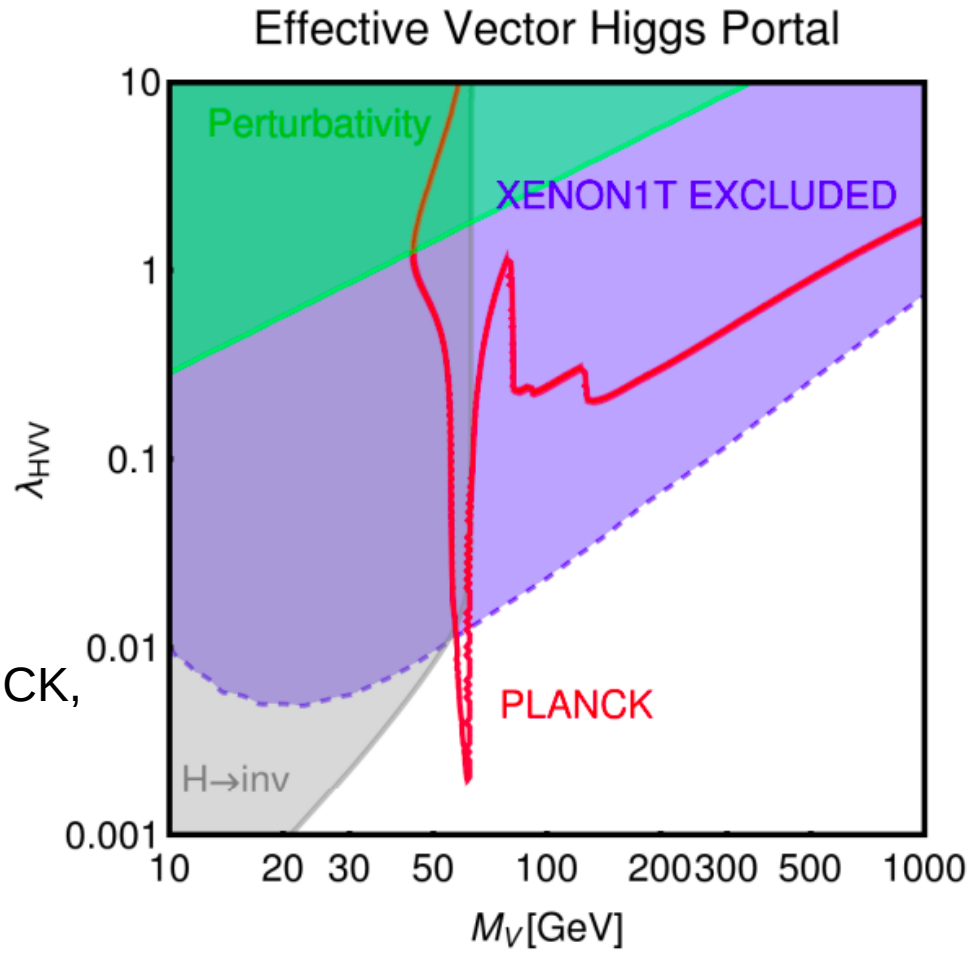
Why fermionic portal instead of a Higgs-portal model?

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 CONSTRAINTED* by PLANCK, XENON and LHC searches.



A Fermionic Portal to Vector Dark Matter (FPVDM)

We need new ingredients: $G_{SM}\times SU(2)_D\times U(1)_D^{Global}$

1. Gauge bosons V_μ^D
2. Complex scalar Φ_D
3. Fermion doublet Ψ

DSB: $SU(2)_D\times U(1)_{Y_D}^{Global}\rightarrow U(1)_{Q_D}^{Global}$

$Q_D = T_{3D} + Y_D$

D symmetry: $U(1)_{Q_D}^{Global}\supset Z_2$ $\quad Z_2:(-1)^{Q_D}$

D symmetry implies the DM stability

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

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

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

A Fermionic Portal to Vector Dark Matter (FPVDM)

The full scalar potential has the following form:

$$V(\Phi_H,\Phi_D) = -\mu^2\Phi_H^\dagger\Phi_H - \mu_D^2\Phi_D^\dagger\Phi_D + \lambda(\Phi_H^\dagger\Phi_H)^2 + \lambda_D(\Phi_D^\dagger\Phi_D)^2 + \lambda_{\Phi_H\Phi_D}(\Phi_H^\dagger\Phi_H)(\Phi_D^\dagger\Phi_D)$$

which is invariant under $SO(4)\sim SU(2)\times SU(2)$ global symmetry. One of them is gauged to $SU(2)_D$

$$\Phi_D = \begin{pmatrix} \varphi^0_{D+1/2} \\ \varphi^0_{D-1/2} \end{pmatrix} \longrightarrow \langle\Phi_D\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_D \end{pmatrix}$$

selects a direction in scalar field Φ_D space leaving 3 unbroken generators $SO(3)\sim SU(2)$ leading to stability of new gauge bosons

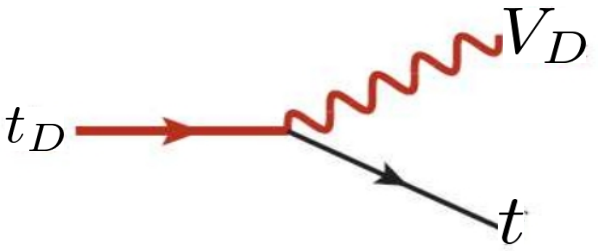
$SO(4)$ global symmetry is destroyed by Yukawa terms of the VL fermion

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

which makes the gauge boson unstable and cannot be DM candidate

The stability of DM can be restored by introducing the global $U(1)_D^{global}$ and it also get rid of one of the Yukawa terms

Only one Yakuwa term is allowed $y'\bar{\Psi}_L\Phi_D f_R^{\rm SM} + h.c$



A Fermionic Portal to Vector Dark Matter (FPVDM)

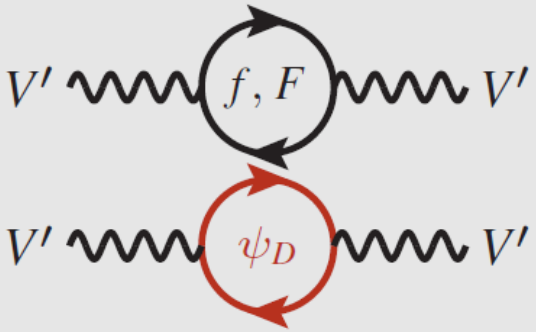
Mass spectrum of new gauge boson

- **At tree-level:**

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

- **At loop-level:**

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

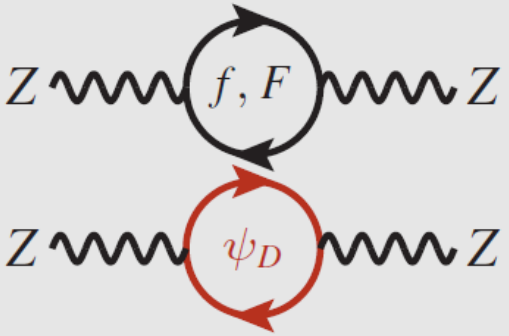


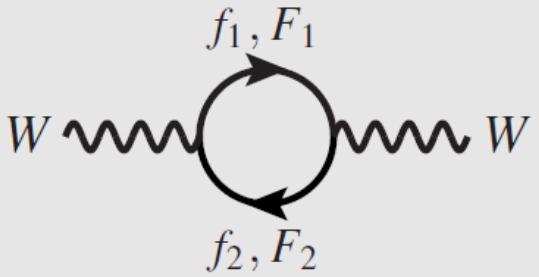
Similar diagrams appear for Kinetic mixing (backup slides)

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

- **Effect for W/Z boson masses**

Modifications to SM
different for Z and W



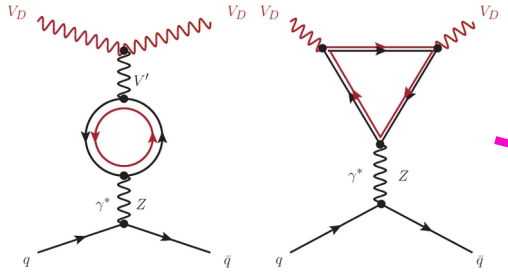


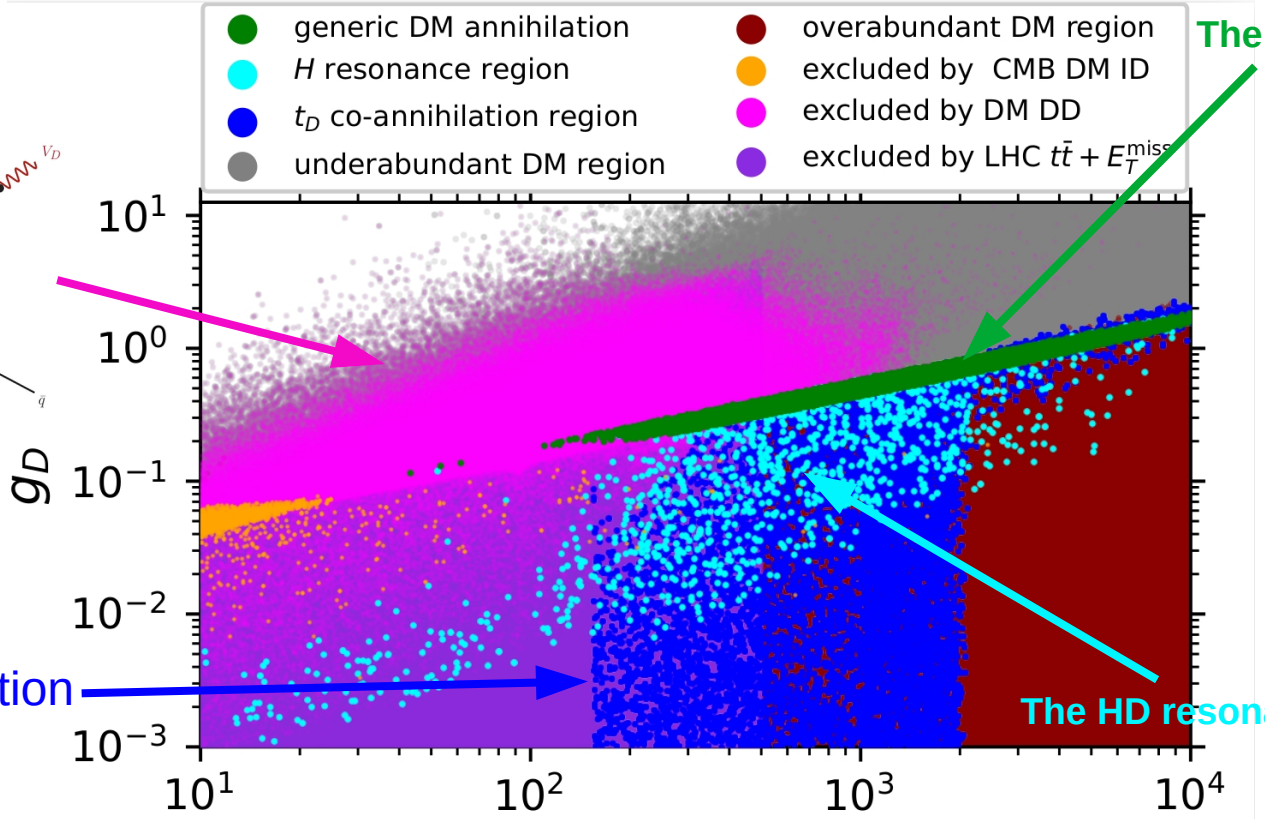
5D scatter plots

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

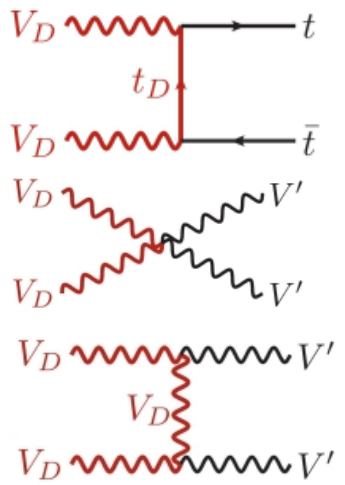
The VL fermion is composed of top partners and there is no mixing between scalars

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



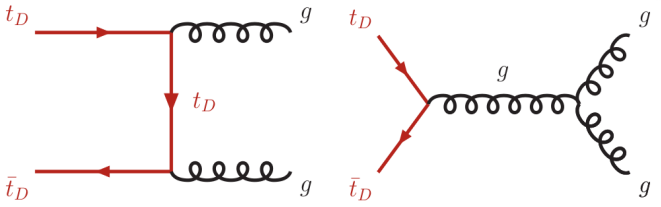


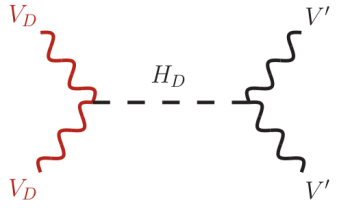
The generic annihilation



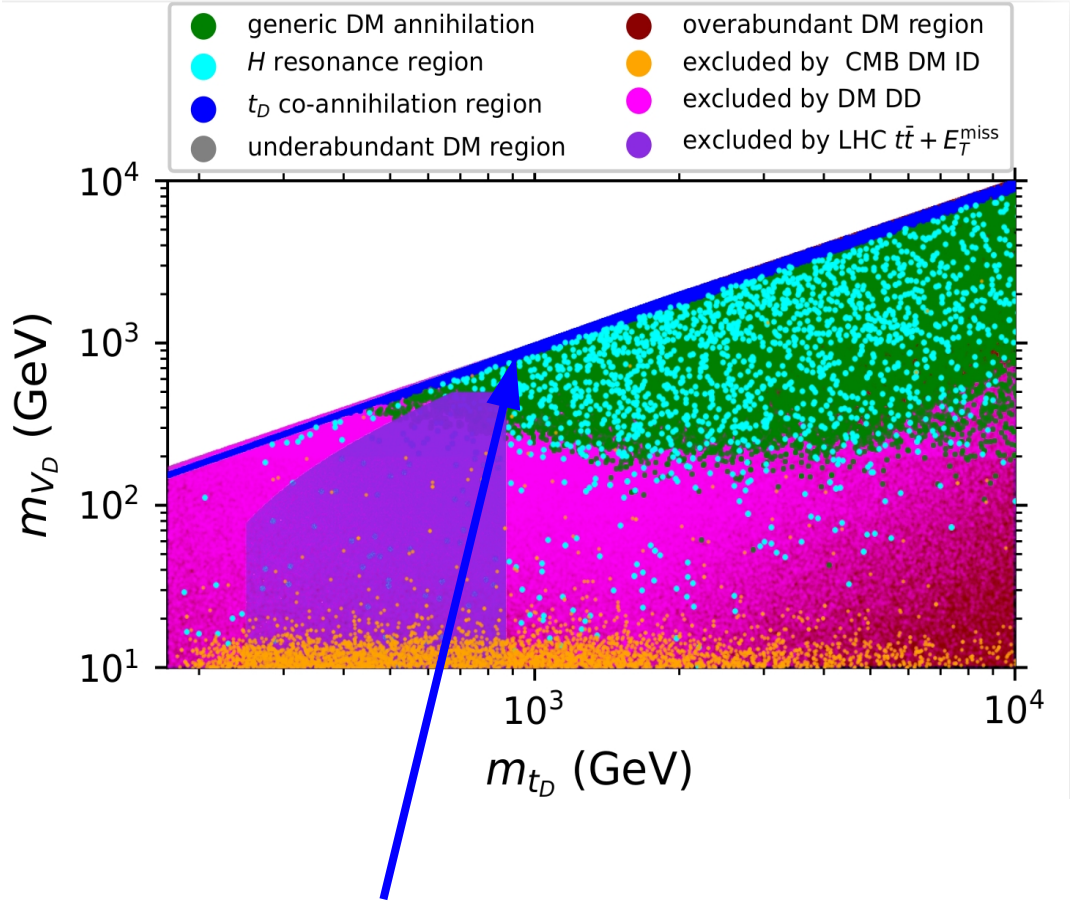
coannihilation

The HD resonance region

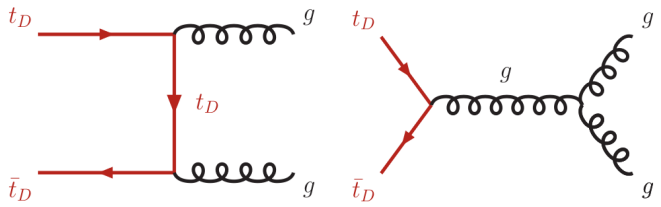


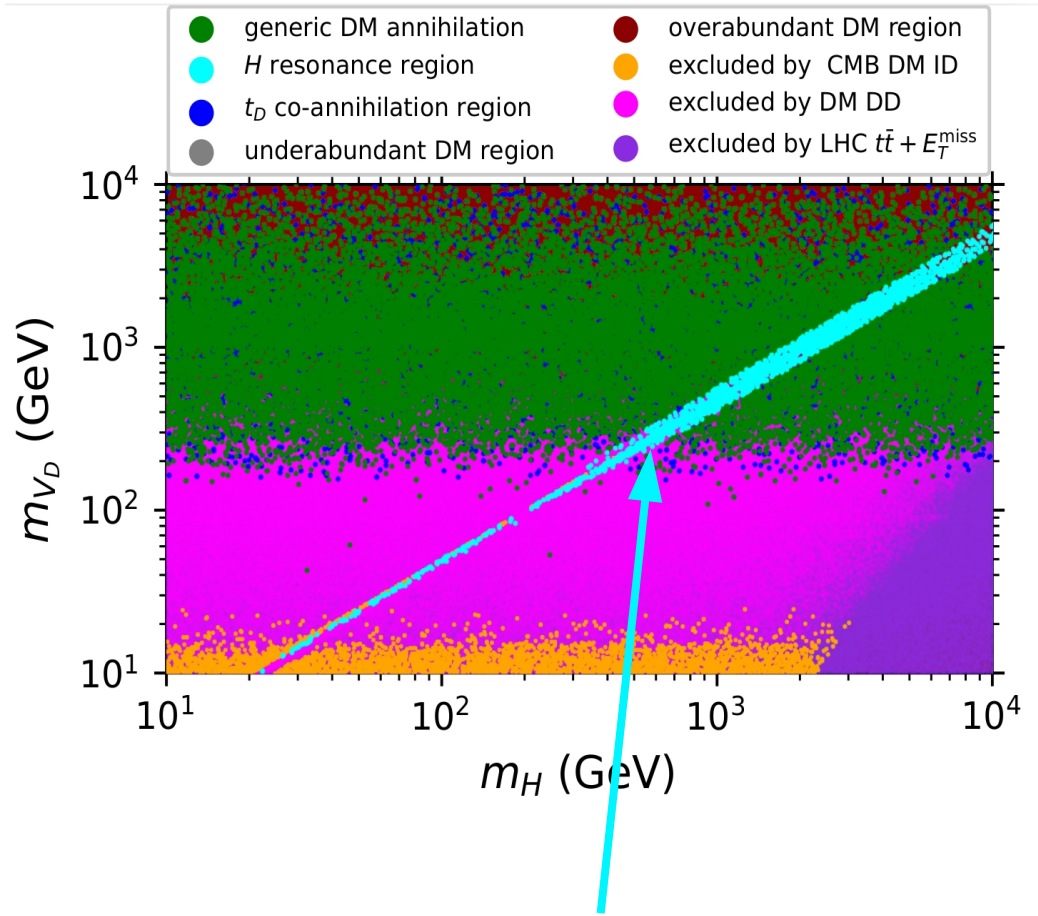


5D scatter plots

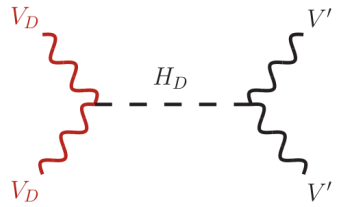


coannihilation





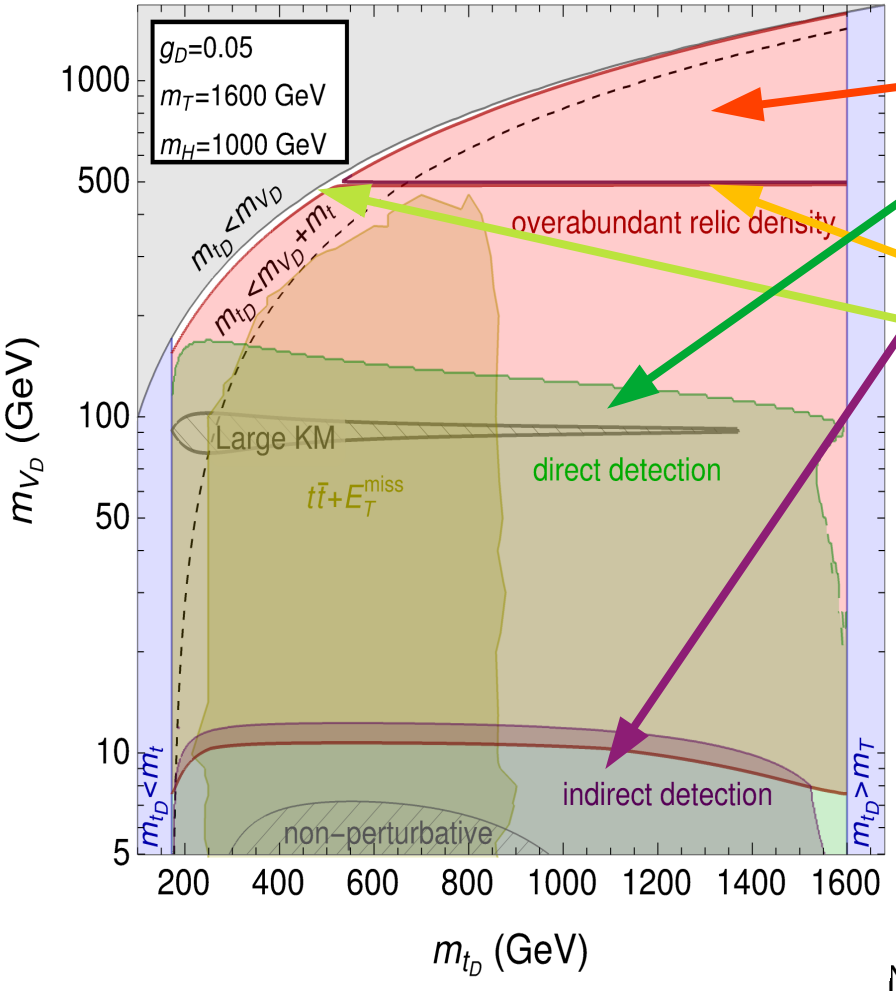
The HD resonance region



2D benchmark

We choose the benchmark points as follows:

- $g_D = 0.05, 0.5$ **reflect the weak or strong interaction between Dark and SM sector**
- $m_T = 1600$ **GeV avoid the LHC constraint on VL top**
- $m_{H_D} = 1000$ **GeV accommodate the dark Higgs resonance valley**

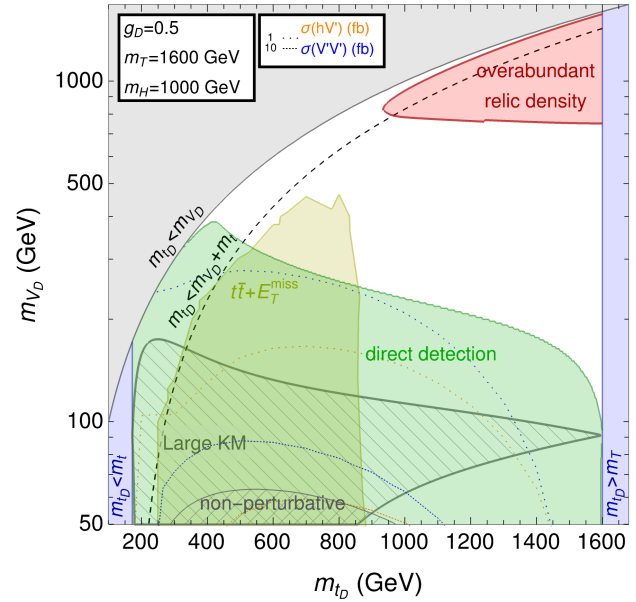


For gD=0.05, it is almost excluded by

- **Relic abundance**
- **Direct detection**
- **Indirect detection**

Except, the regions where

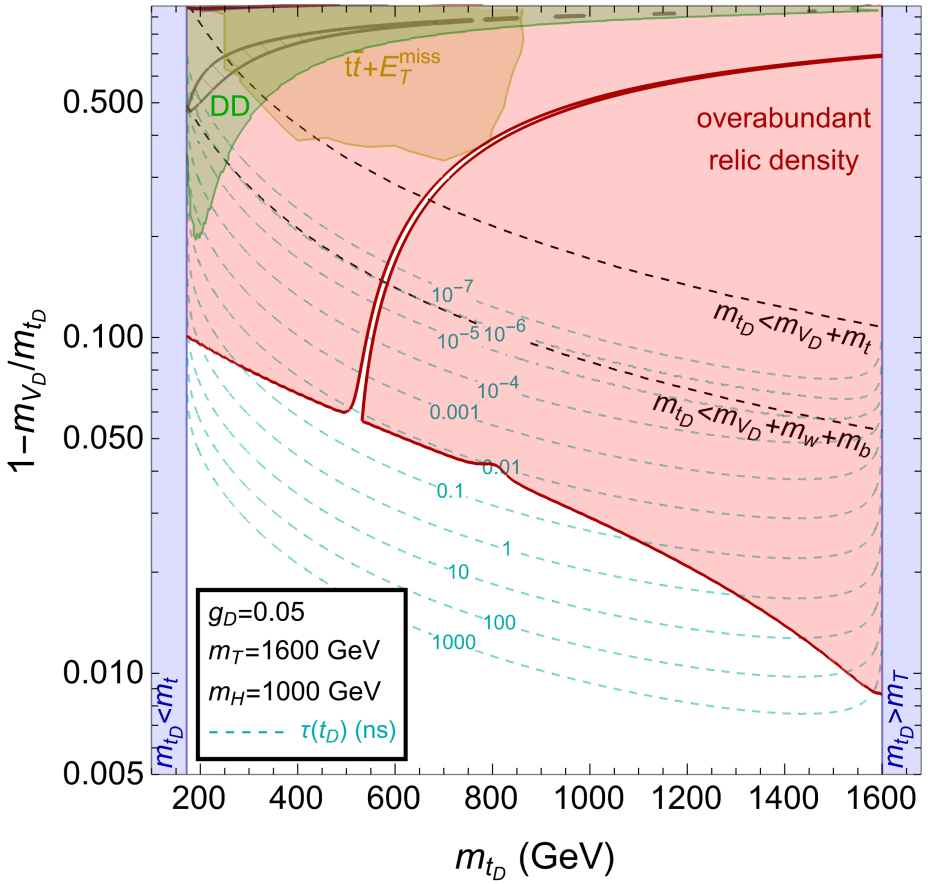
- **Higgs funnel**
- **Co-annihilation is dominant**

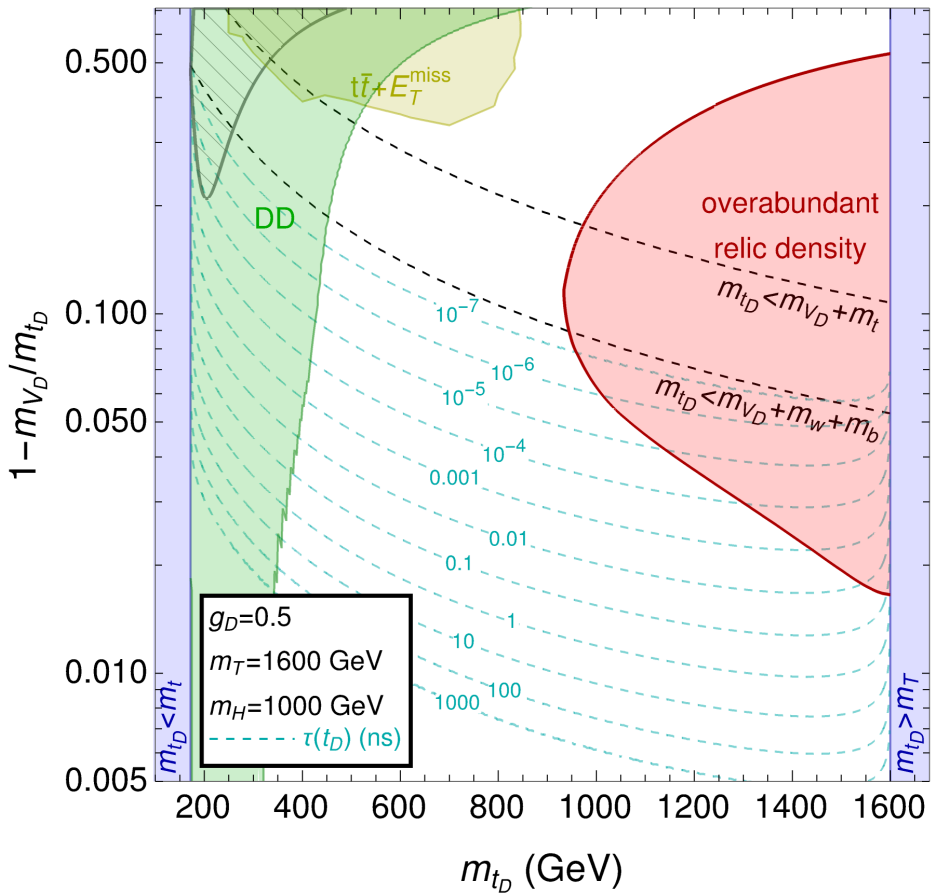


Decay of tD

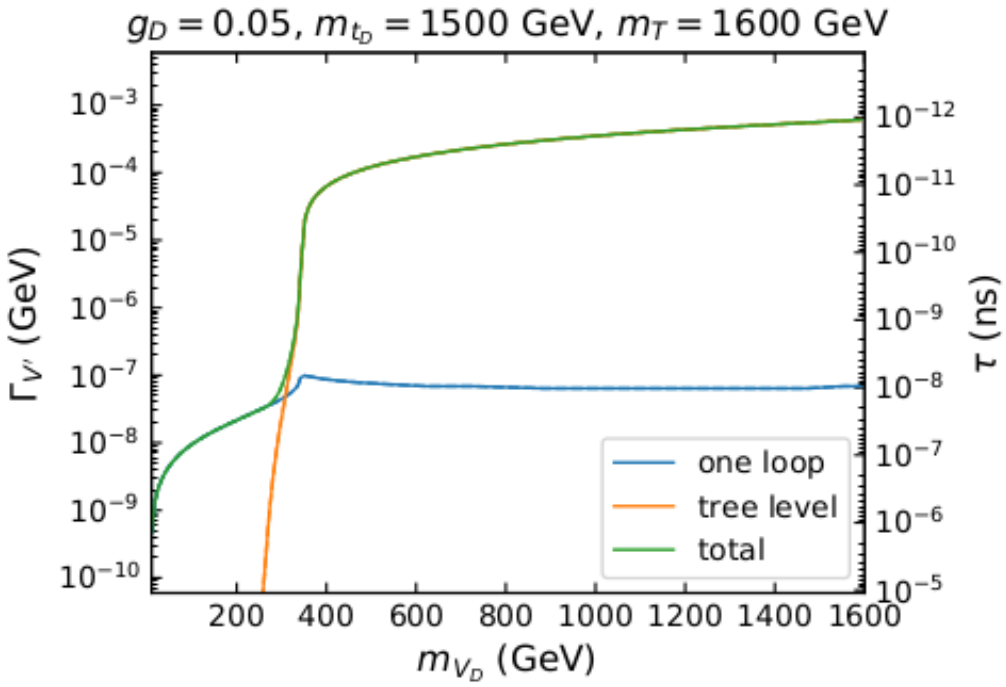
t_D can be long lived in two regimes:

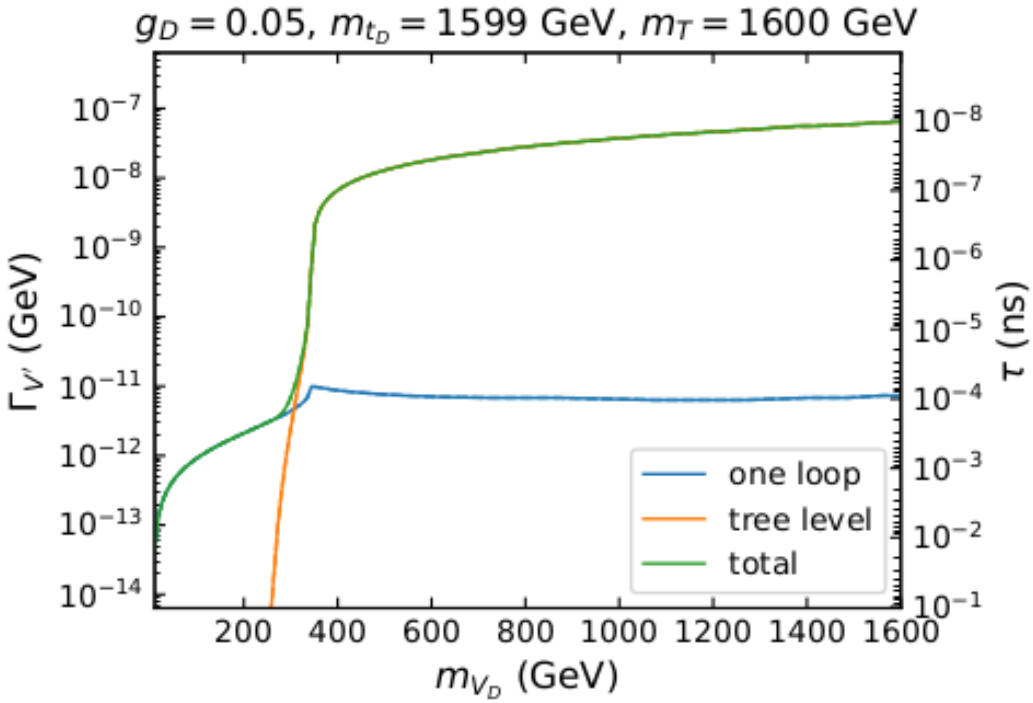
- $m_{t_D} < m_{V_D} + m_t$ **The lifetime goes from 10^{-7} – 10^{-6} ns**
- $m_{t_D} < m_{V_D} + m_W + m_b$ **The lifetime goes from 10^{-5} – 10^{3} ns**

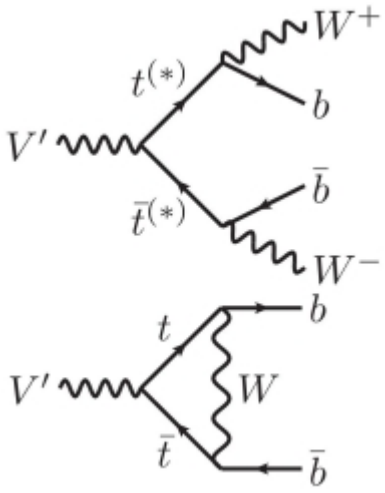




Decay width of V'







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

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
  - collider signatures: tt+Emiss, V', V'H, long-lived V' and t_D

Future directions:

- Muon g-2 anomaly (ongoing)
- Phase transition and Gravitational waves from DSB (ongoing)
- Freeze-in VDM (ongoing)
- Neutrino physics (ongoing)
- Flavour, W-mass anomalies etc.

THANK YOU