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Hidden Gauged Dark Matter in Twin Higgs Scenarios

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JHY, work in progress

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Outline

1. **Vector Dark Matter (VDM)**
2. **Hidden Gauged W in Mirror Twin Higgs**
3. **VDM in Left-Right Twin Higgs**
4. **Summary**

Vector DM Theory

UV Model

Connection to Hierarchy Problem? Other UV model?

Focus on Twin Higgs model

Simplified Model

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + |D_\mu\phi|^2 + \overline{\psi}\gamma^\mu\psi V_\mu + \overline{\psi}\gamma^\mu q V_\mu + h.c.$$

EFT

$$V_\mu^\dagger V^\mu \bar{q}q \qquad V_\mu^\dagger V_\nu \bar{q} i\sigma^{\mu\nu} q \qquad i(V_\nu^\dagger \partial_\mu V^\nu - V^\nu \partial_\mu V_\nu^\dagger)\bar{q}\gamma^\mu q$$

$$V_\mu^\dagger V^\mu \bar{q} i\gamma^5 q \qquad V_\mu^\dagger V_\nu \bar{q}\sigma^{\mu\nu}\gamma^5 q \qquad (V_\nu^\dagger \partial_\mu V^\nu - V^\nu \partial_\mu V_\nu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$$

How to obtain VDM?

- **Higgs mechanism or Stueckelberg mechanism**

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + |D_\mu\phi|^2 + \overline{\psi}\gamma^\mu\psi V_\mu$$

Need Higgs portal or kinetic mixing to connect to SM

$$\mathcal{L} \supset \phi^2 H^2 + F^{\mu\nu}A_{\mu\nu}$$

For example U(1), SU(2), SU(3), etc

- **Another way:**

$$\mathcal{L} \supset \overline{\psi}\gamma^\mu q V_\mu + h.c.$$

Why VDM in Twin Higgs?

- **Mirror Twin Higgs**

Many kinds of dark matter candidate

Typically encounter Neff problem!

Need VDM?

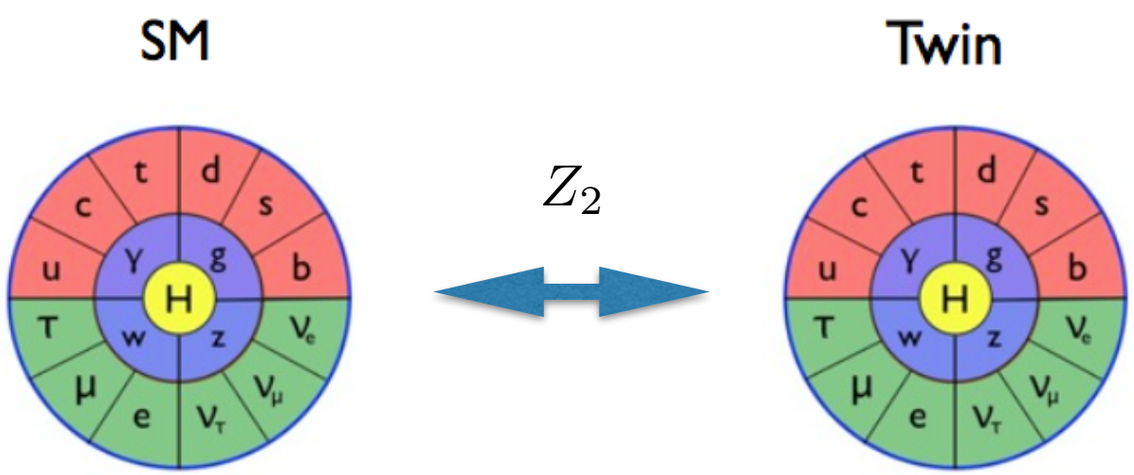
- **Left Right Twin Higgs**

No dark matter candidate!

VDM?

Mirror Twin Higgs

Mirror Standard Model



Chacko, Goh, Harnik 05

Sector A

Sector B

Accidental SU(4) symmetry in Higgs potential

$$H = \begin{pmatrix} H_{\rm SM} \\ H_{\rm twin} \end{pmatrix} \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix} \Big\} \; SU(4)$$

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Global symmetry breaking

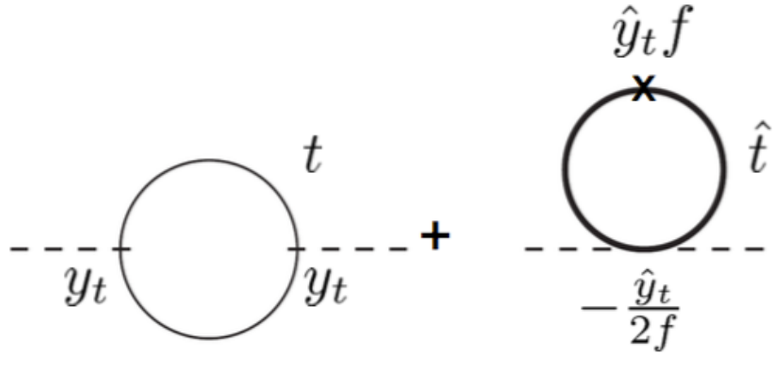
$$SU(4) : H = \begin{pmatrix} H_{\rm SM} \\ H_{\rm twin} \end{pmatrix} \rightarrow SU(3)$$

$$H \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix}$$

7 Goldstone Bosons,
Higgs as one of Goldstone Boson

Mirror Twin Higgs

Quadratic div. Cancellation



$$\mathcal{L} \supset y_A \overline{q_A} H_A t_A + y_B \overline{q_B} H_B t_B$$

$$\downarrow \qquad\qquad \downarrow$$

$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$

Dark matter candidate:

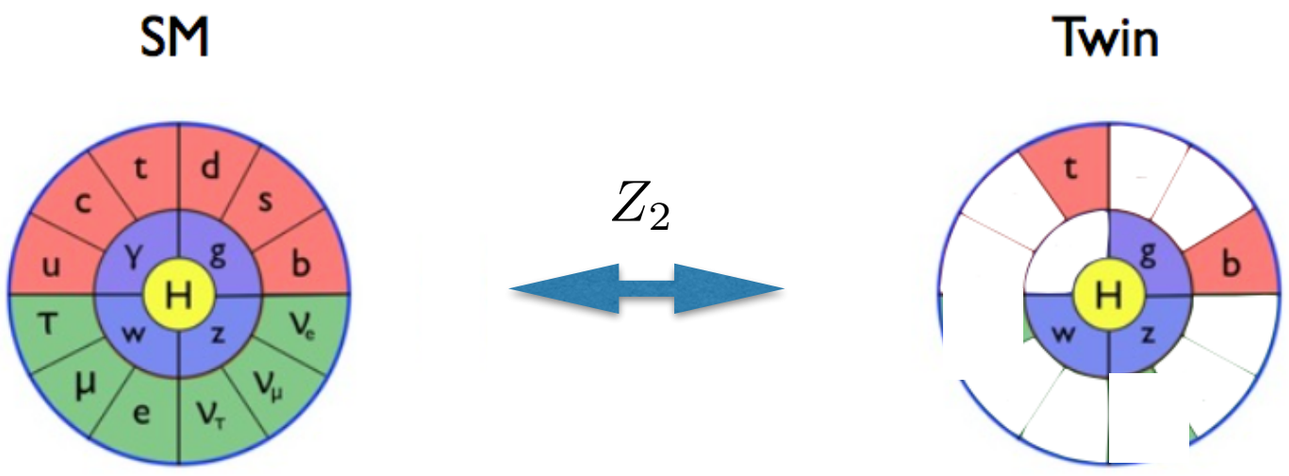
Naturally arise in hidden sector

twin tau, twin pion, twin baryon, etc

Twin neutrinos, twin photon, Neff constraint tight

Mirror Twin Higgs

Vectorlike dark fermion instead of chiral dark fermion



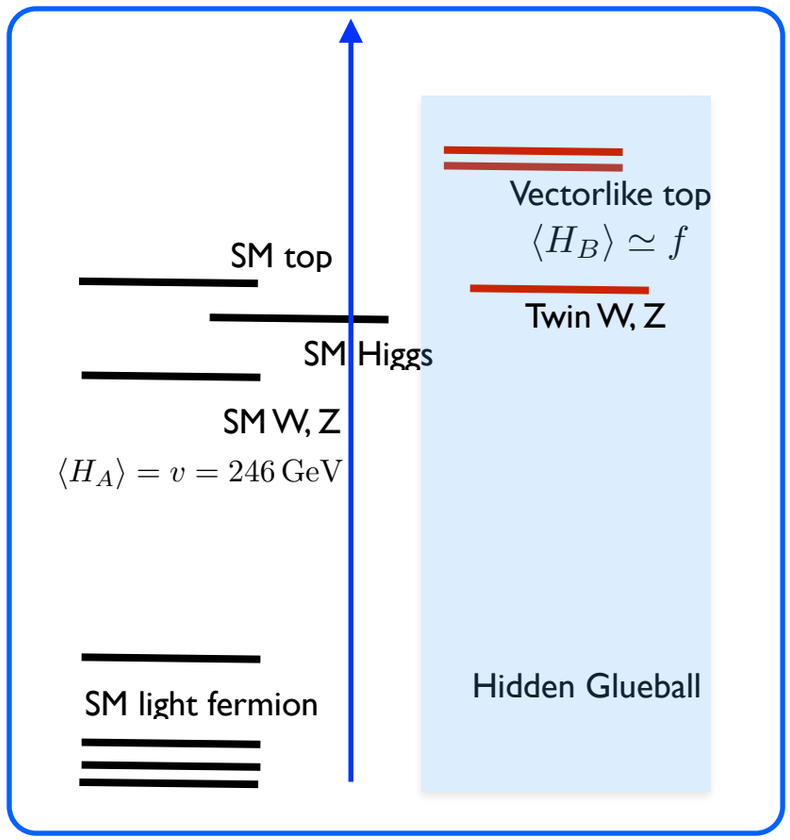
No twin neutrinos, global twin U(1), Neff constraint OK

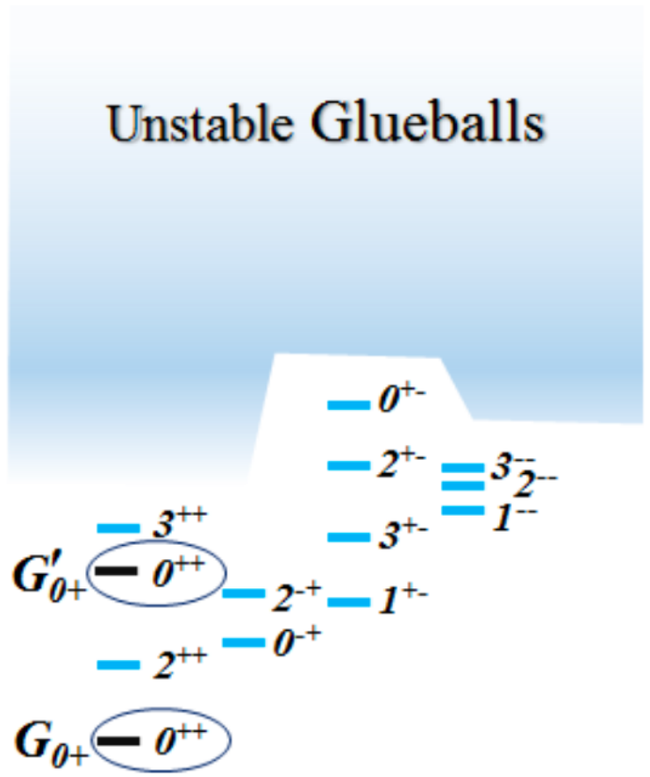
Twin top quark is typically heavier than twin W and twin Z

(Could have local twin U(1), with small masses via Stueckelberg)

Mirror Twin Higgs

Twin Spectrum: twin hadrons, twin glueball, and twin W/Z





Twin W is the WIMP dark matter candidate

Quirk hadrons

Chiral limit

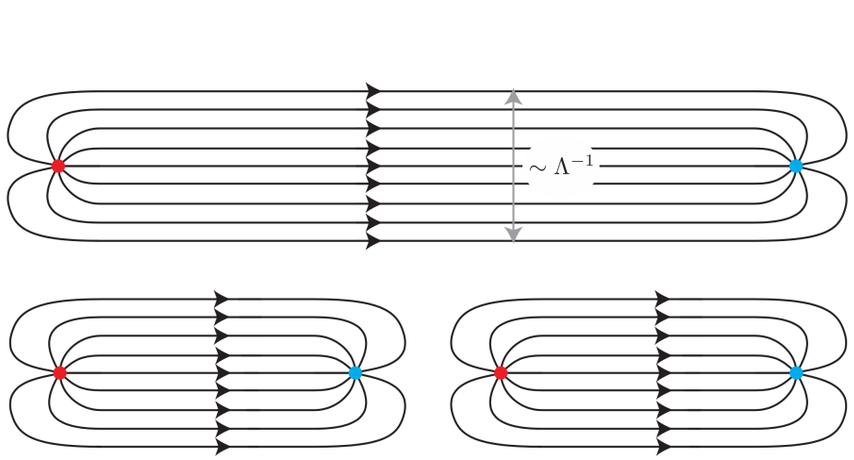
Darkonia

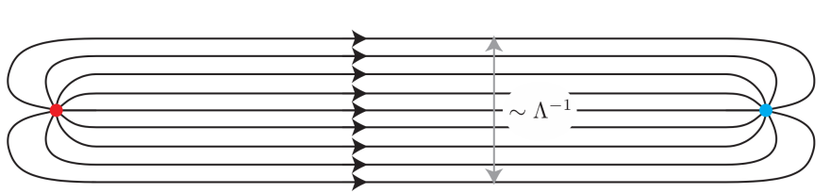
$m_q \ll \Lambda_{\rm dark}$

$m_q \gg \Lambda_{\rm dark}$

$\Lambda_{\rm dark}$

Vector-like





$\Gamma_{\rm break} \sim e^{-m_Q^2/\Lambda^2}$

QCD string with hadronization

Quark

Stable macroscopic string

Quirk

Dark Matter Candidate

- **WIMP dark W dark matter:**

Higgs portal dark matter

- **Adding U(1) dark photon:**

Self interacting dark matter

Solve small scale problems

Work in progress ….

Left Right Twin Higgs

Chacko, Goh, Harnik, 2005

- **Should we twin whole SM gauge group?**

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix}$$

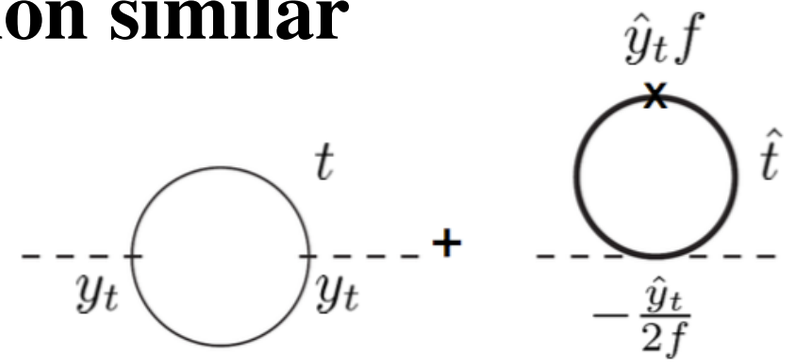
- **Only twin SU(2), but not QCD**

$SU(2)_L$		$SU(2)_R$
$H_A = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$		$H_B = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$
	Z_2	
$Q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$		$Q_R = \begin{pmatrix} t_R \\ b_R \end{pmatrix}$
$L_L = \begin{pmatrix} \nu_L \\ \tau_L \end{pmatrix}$		$L_R = \begin{pmatrix} \nu_R \\ \tau_R \end{pmatrix}$
T_L		T_R

Eat 6 GBs

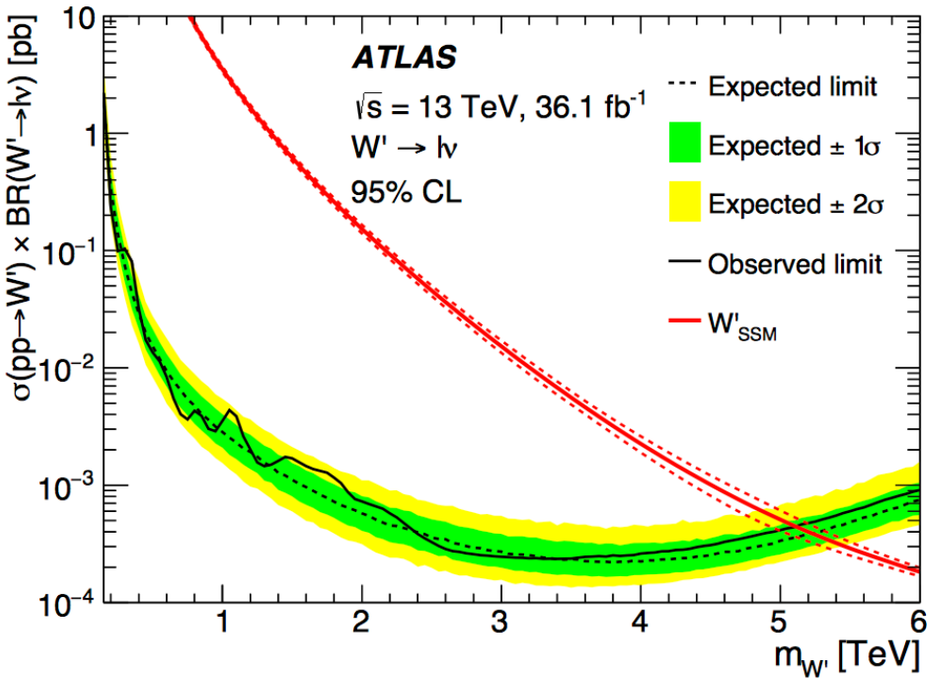
- **Quadratic divergence cancellation similar**

$$\mathcal{L} \supset -y_t \overline{Q}_L H_L T_L - y_t \overline{Q}_R H_R T_R$$

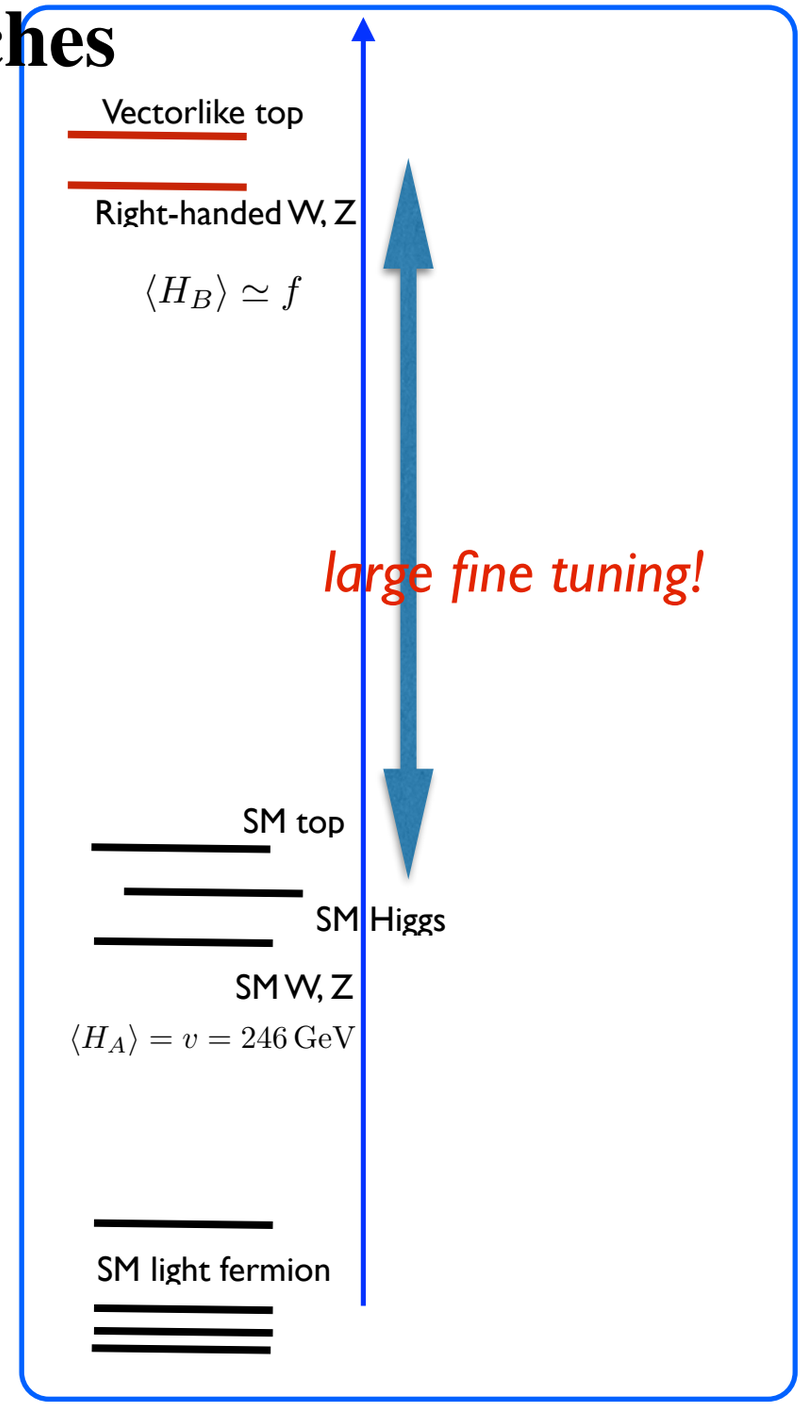


Left Right Twin Higgs

Problem 1: large fine tuning due to W' searches



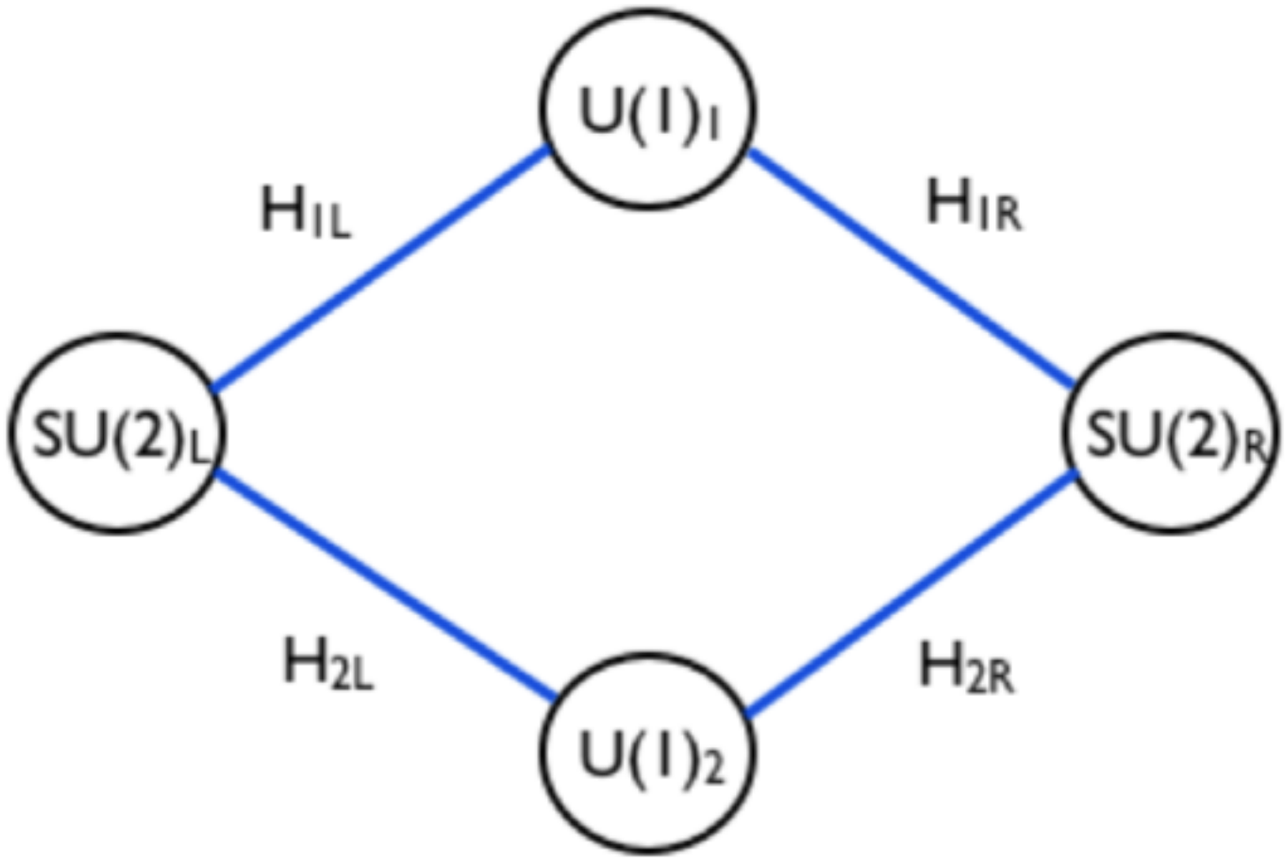
$$m_{W'} \sim gf \sim 5 \text{ TeV}$$



Problem 2: No dark matter candidate

Left Right Twin Higgs

J-H, Yu, 2017



$$H_1 = \begin{pmatrix} H_{1\mathrm{SM}} \\ H_{1\mathrm{twin}} \end{pmatrix} \leftrightarrow H_2 = \begin{pmatrix} H_{2\mathrm{SM}} \\ H_{2\mathrm{twin}} \end{pmatrix}$$

	$SU(2)_L$	$U(1)_1$	$U(1)_2$	$SU(2)_R$
H_{1L}	**2**	$\frac{1}{2}$	0	**1**
H_{1R}	**1**	$\frac{1}{2}$	0	**2**
H_{2L}	**2**	0	$\frac{1}{2}$	**1**
H_{2R}	**1**	0	$\frac{1}{2}$	**2**
q_L	**2**	$\frac{1}{6}$	$\frac{1}{6}$	**1**
q_R	**1**	$\frac{1}{6}$	$\frac{1}{6}$	**2**
ℓ_L	**2**	-1	-1	**1**
ℓ_R	**1**	-1	-1	**2**
$T_{1L,R}$	**1**	$+\frac{2}{3}$	0	**1**
$T_{2L,R}$	**1**	0	$+\frac{2}{3}$	**1**

T-parity

$$H = \frac{1}{\sqrt{2}}\left(H_1 + H_2\right), B^\mu = \frac{1}{\sqrt{2}}\left(B_1^\mu + B_2^\mu\right),$$
$$H' = \frac{1}{\sqrt{2}}\left(H_1 - H_2\right), B'^\mu = \frac{1}{\sqrt{2}}\left(B_1^\mu - B_2^\mu\right),$$
$$T_{L,R} = \frac{1}{\sqrt{2}}\left(T_{1L,R} + T_{2L,R}\right),$$
$$T'_{L,R} = \frac{1}{\sqrt{2}}\left(T_{1L,R} - T_{2L,R}\right).$$

$\mathbb{T}$-parity even fields: $H, B^\mu, T_{L,R}$, and $W^\mu_{L,R}$, $q_{L,R}$;

$\mathbb{T}$-parity odd fields: H', B'^μ, T' with $H' \leftrightarrow -H'$, $B' \leftrightarrow -B'$, $T' \leftrightarrow -T'$.

$$H \equiv \begin{pmatrix} H_L \\ H_R \end{pmatrix}, \qquad H' \equiv \begin{pmatrix} H'_L \\ H'_2 \end{pmatrix}.$$

Higgs Mechanism

$$\mathcal{L} = (D_\mu H_1)^\dagger D^\mu H_1 + (D_\mu H_2)^\dagger D^\mu H_2 - V(H_1, H_2).$$

$$D_\mu H_1 = \partial_\mu H_1 + ig\mathbf{W}_\mu H_1 + ig'\mathbf{B}_{1\mu} H_1,$$
$$D_\mu H_2 = \partial_\mu H_2 + ig\mathbf{W}_\mu H_2 + ig'\mathbf{B}_{2\mu} H_2,$$

$$\mathcal{L} = (D_\mu H^\dagger - ig' Y B'_\mu H'^\dagger)(D^\mu H + ig' Y B'_\mu H')$$
$$+(D_\mu H'^\dagger - ig' Y B'_\mu H^\dagger)(D^\mu H' + ig' Y B'_\mu H),$$

$$D^\mu H = \partial^\mu H + ig\mathbf{W}^\mu H + ig'\mathbf{B}^\mu H,$$
$$D^\mu H' = \partial^\mu H' + ig\mathbf{W}^\mu H' + ig'\mathbf{B}^\mu H'.$$

- In typical case, for example, the $\mathbb{T}$-even field B^μ absorbs the CP odd component of the T-even H and obtains its mass from its VEV $\langle H \rangle$;

- The terms $\partial^\mu H' B'_\mu H$ and $B'^\mu B'_\mu H^\dagger H$ indicate that the $\mathbb{T}$-odd field B'^μ absorbs the CP odd component of the T-odd H' but obtains its mass from VEV of the H.

Fermion Portal to Visible Sector

$$H = \frac{1}{\sqrt{2}}\left(H_1 + H_2\right), B^\mu = \frac{1}{\sqrt{2}}\left(B_1^\mu + B_2^\mu\right),$$

$$H' = \frac{1}{\sqrt{2}}\left(H_1 - H_2\right), B'^\mu = \frac{1}{\sqrt{2}}\left(B_1^\mu - B_2^\mu\right),$$

$$T_{L,R} = \frac{1}{\sqrt{2}}\left(T_{1L,R} + T_{2L,R}\right),$$

$$T'_{L,R} = \frac{1}{\sqrt{2}}\left(T_{1L,R} - T_{2L,R}\right).$$

$$\mathcal{L}_{\text{ferm}} = \overline{q_{L,R}}\gamma^\mu D_\mu q_{L,R} + \overline{\ell_{L,R}}\gamma^\mu D_\mu \ell_{L,R} + \overline{T_{1L,R}}\gamma^\mu D_\mu T_{1L,R} + \overline{T_{2L,R}}\gamma^\mu D_\mu T_{2L,R}$$

$$D^\mu T_{1,2} = \partial^\mu T_i + ig' Y B^\mu_{1,2} T_{1,2}$$

$$\mathcal{L} = \overline{T} i\gamma^\mu(\partial_\mu + ig' Y B_\mu)T + \overline{T'} i\gamma^\mu(\partial_\mu + ig' Y B_\mu)T' - g'\overline{T}\gamma^\mu B'_\mu T' - g'\overline{T'}\gamma^\mu B'_\mu T.$$

Higgs Potential

$$V_{\rm CW} \supset \frac{9\Lambda^2}{64\pi^2}(g_L^2|H_L|^2 + g_R^2|H_R|^2)$$

$$V_{\rm CW} \supset \frac{9\Lambda^2}{64\pi^2}(m_Z^2 + m_{Z'}^2) \simeq \Lambda^2 f^2,$$

$$V_{\rm CW} \supset -\frac{3\Lambda^2}{8\pi^2}(m_t^2 + m_T^2) \simeq \Lambda^2 f^2.$$

$$V(h^\dagger h) = a\sin^2\left(\frac{\sqrt{h^\dagger h}}{f}\right) + b\sin^4\left(\frac{\sqrt{h^\dagger h}}{f}\right)$$

$$a = -\frac{3}{8\pi^2}y^4 f^4\left(\log\frac{\Lambda^2}{M^2+y^2f^2}+1\right),$$

$$b = -a + \frac{3y_t^4 f^4}{16\pi^2}\left[\log\frac{M^2+y^2f^2}{m_t^2} - \frac{1}{2}\right],$$

Inert doublet, heavier than W'

$$H' = \begin{pmatrix} H'^+_L \\ H'^0_L + iA'^0_L \\ H'^+_R \\ H'^0_R + iA'^0_R \end{pmatrix}$$

$$m^2_{\text{all H' components}} \simeq \frac{1}{16\pi^2}g^4 f^2 \log\frac{\Lambda}{f}.$$

Relic Abundance

$$m_{B'} = \tfrac{1}{2} g' f$$

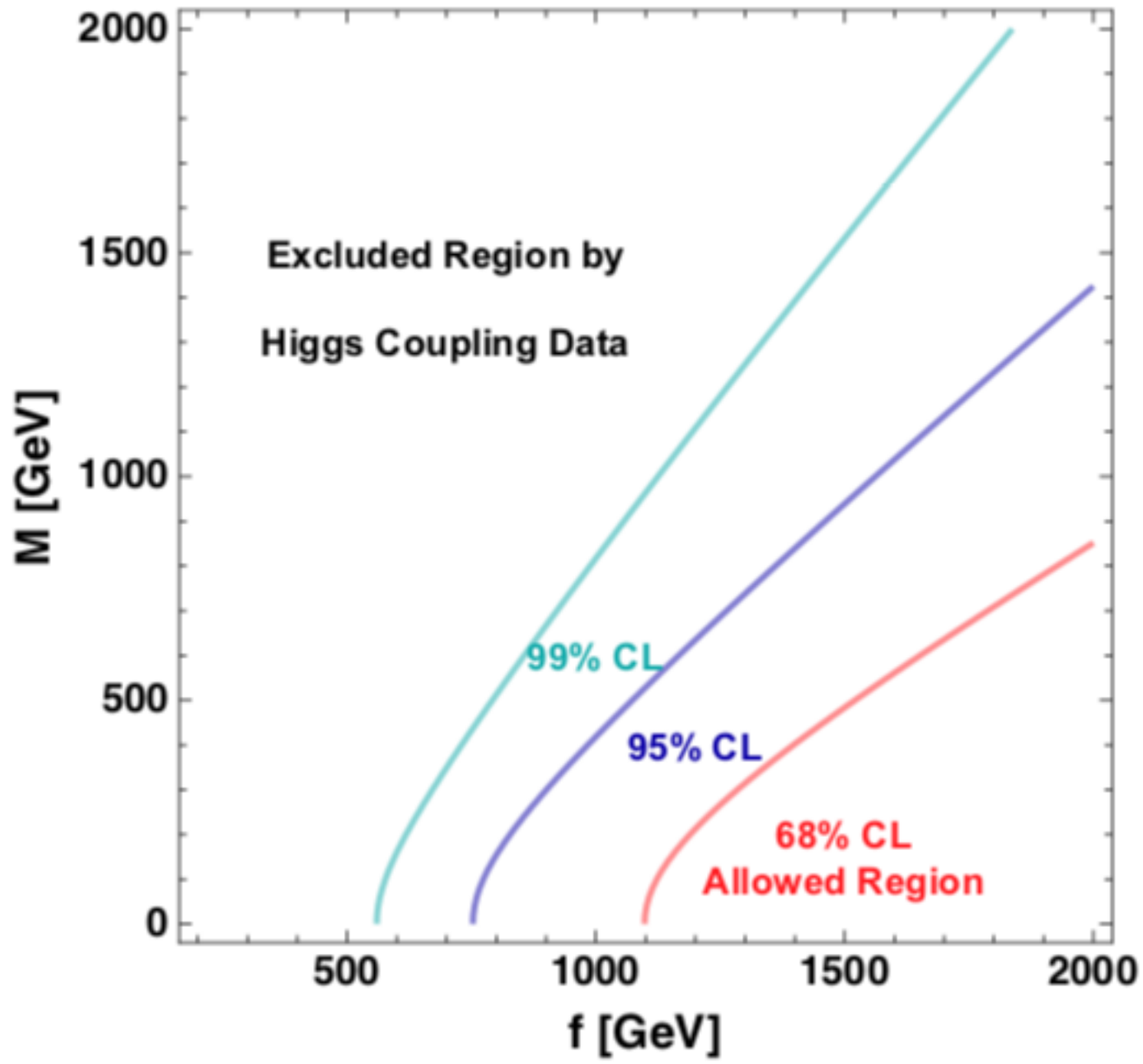
$$m_{T'} = M$$

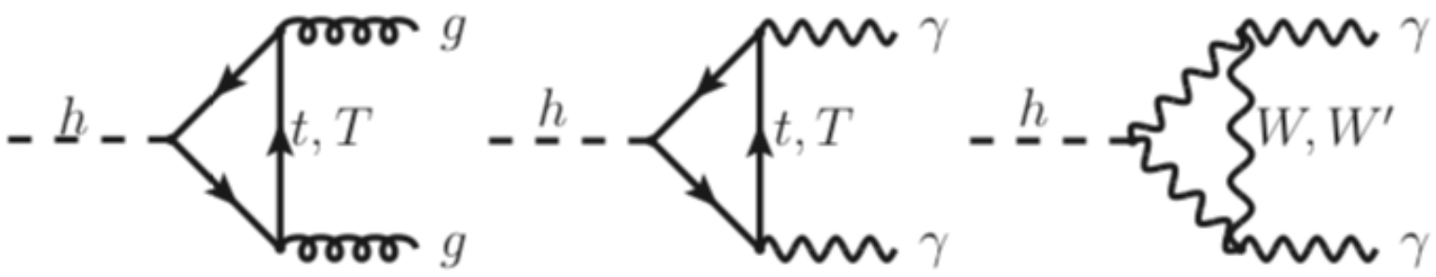
B' as dark matter candidate

- $B'B' \to W^+W^-/ZZ$ via t-channel exchange of $H_L^{\pm}(H_L^0)$;
- $B'B' \to t\bar{t}$ via t-channel exchange of T'.

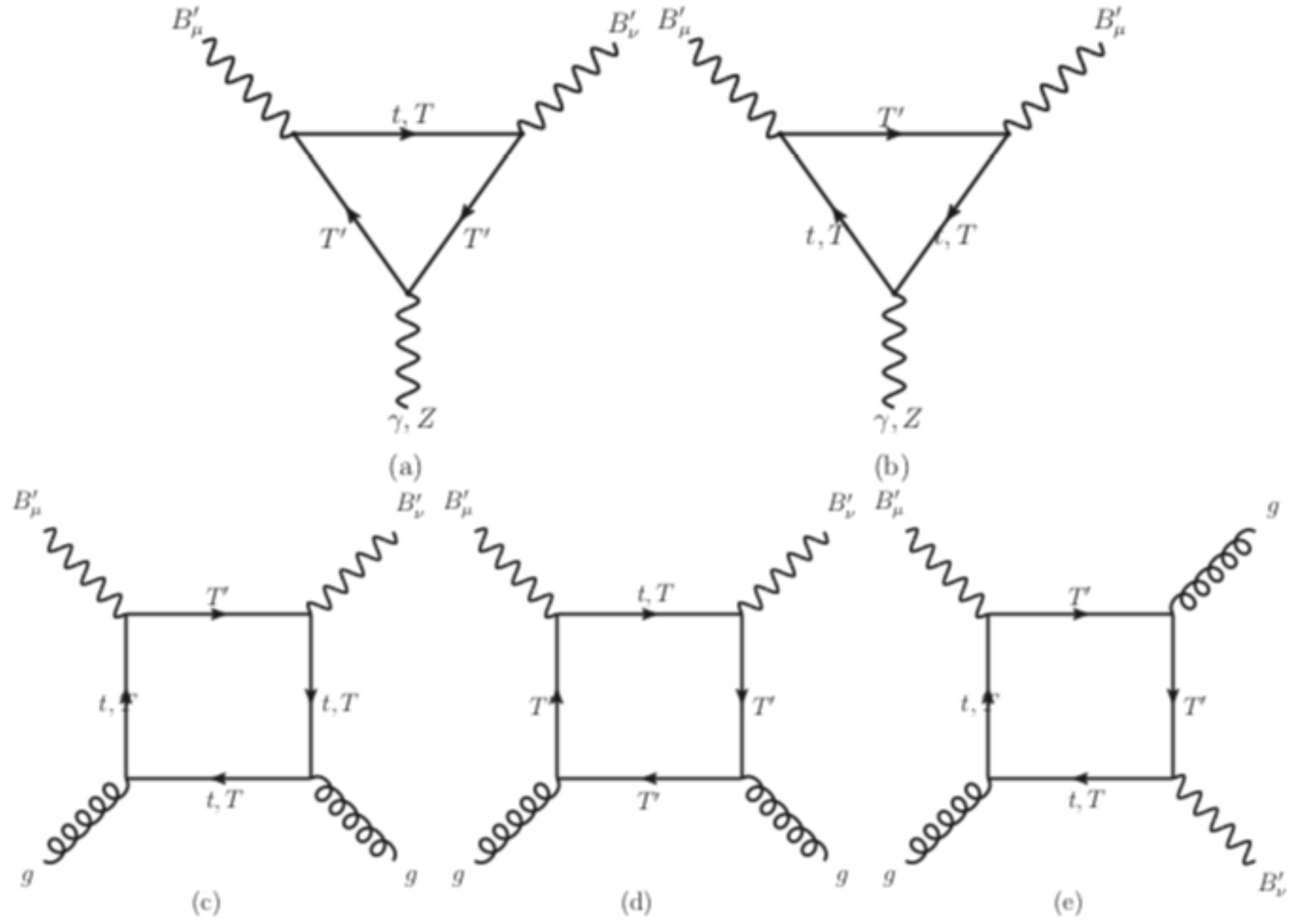
$$(\sigma v)_{B'B' \to t\bar{t}} \simeq \frac{2N_c g'^4 Y^2}{9\pi} \frac{m_{B'}^2}{(m_{B'}^2 + m_{T'}^2)^2}$$

Higgs Coupling Measurement





Direct Detection



Direct Detection

$$\mathcal{L} = \mathcal{C}_{\rm tri}\epsilon^{\mu\nu\rho\sigma}\left(B'_{\ \mu}\partial_\nu B'_{\ \rho}\right)\bar{q}\gamma_\sigma\gamma_5 q$$

$$\mathcal{C}_{\rm tri} \simeq N_c\frac{eQg'^2}{\pi^2}\frac{1}{6}\int_0^1 {\rm d}z\frac{z^3}{m_t^2+(m_{T'}^2-m_t^2)z+m_{B'}^2 z(z-1)} + (m_t \leftrightarrow m_{T'}). \quad (49)$$

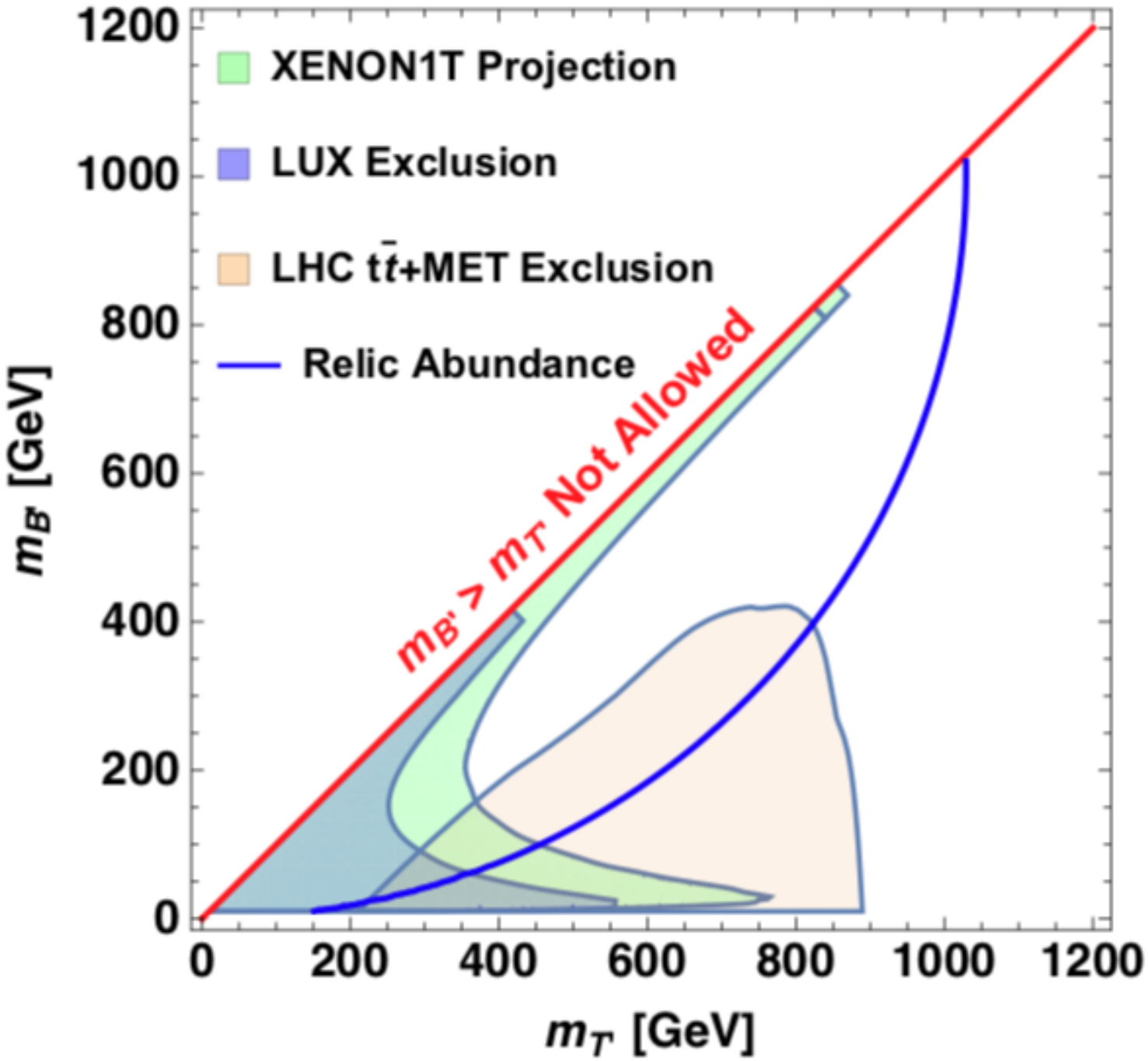
$$\mathcal{L} = \alpha_s \mathcal{C}_{\rm box} B'^{\rho} B'_{\ \rho} G^{a\mu\nu} G^a_{\mu\nu}$$

$$\mathcal{C}_{\rm box} = \frac{g'^2}{48\pi}\frac{3m_{T'}^2-2m_{B'}^2}{(m_{T'}^2-m_{B'}^2)^2}$$

$$\sigma_N^{\rm SI} = \frac{\mu_N^2}{\pi}\left(\frac{4}{9}f_{TG}^{(N)}\frac{m_N}{m_{B'}}\mathcal{C}_{\rm tri}\right)^2,$$

$$\sigma_N^{\rm SD} = \frac{16\mu_N^2}{\pi}\left(e\sum_q \Delta_q^N \mathcal{C}_{\rm box}\right)^2,$$

Parameter Space



$$pp \to T'\overline{T'} \to tB'\bar{t}B'$$

Conclusion

- **UV VDM realization is discussed**
- **VDM in Twin Higgs scenarios is natural**
- **VDM Pheno is very interesting**

Thank You!

Sorry, missing references