Unifying flavor and Dark Matter puzzles with $SU(2)_D$ lepton portals

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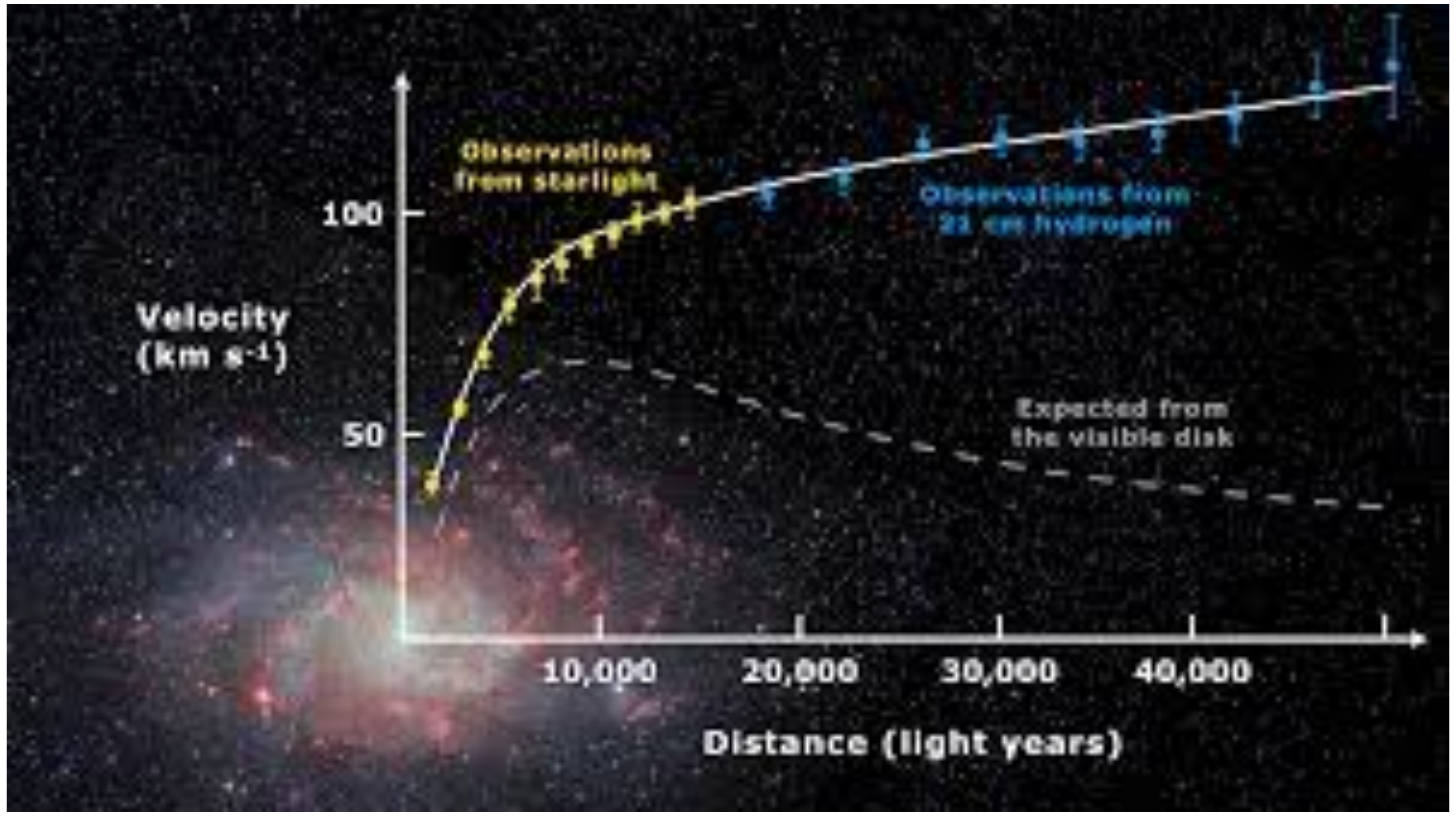
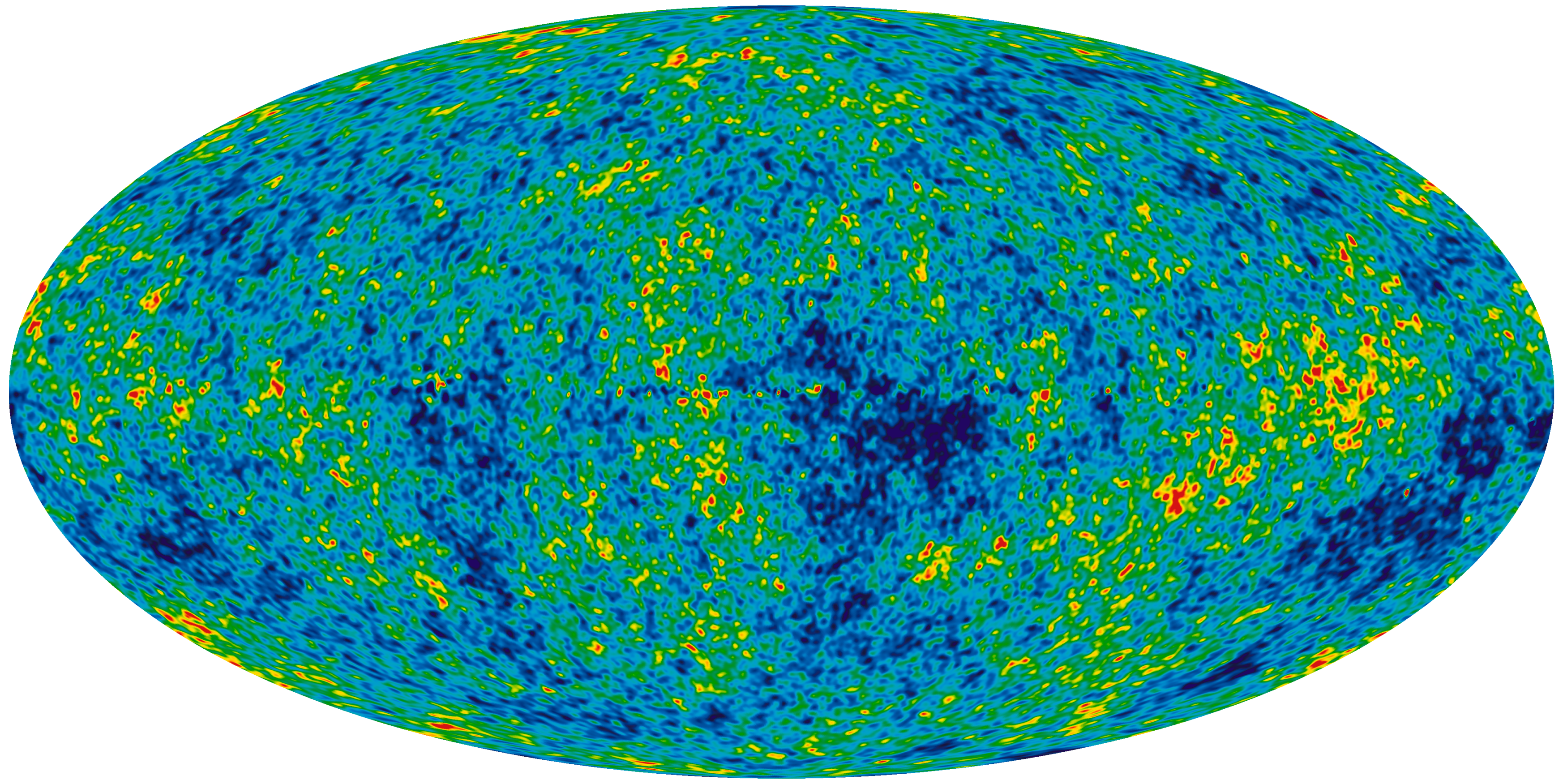
Evidence for Dark Matter



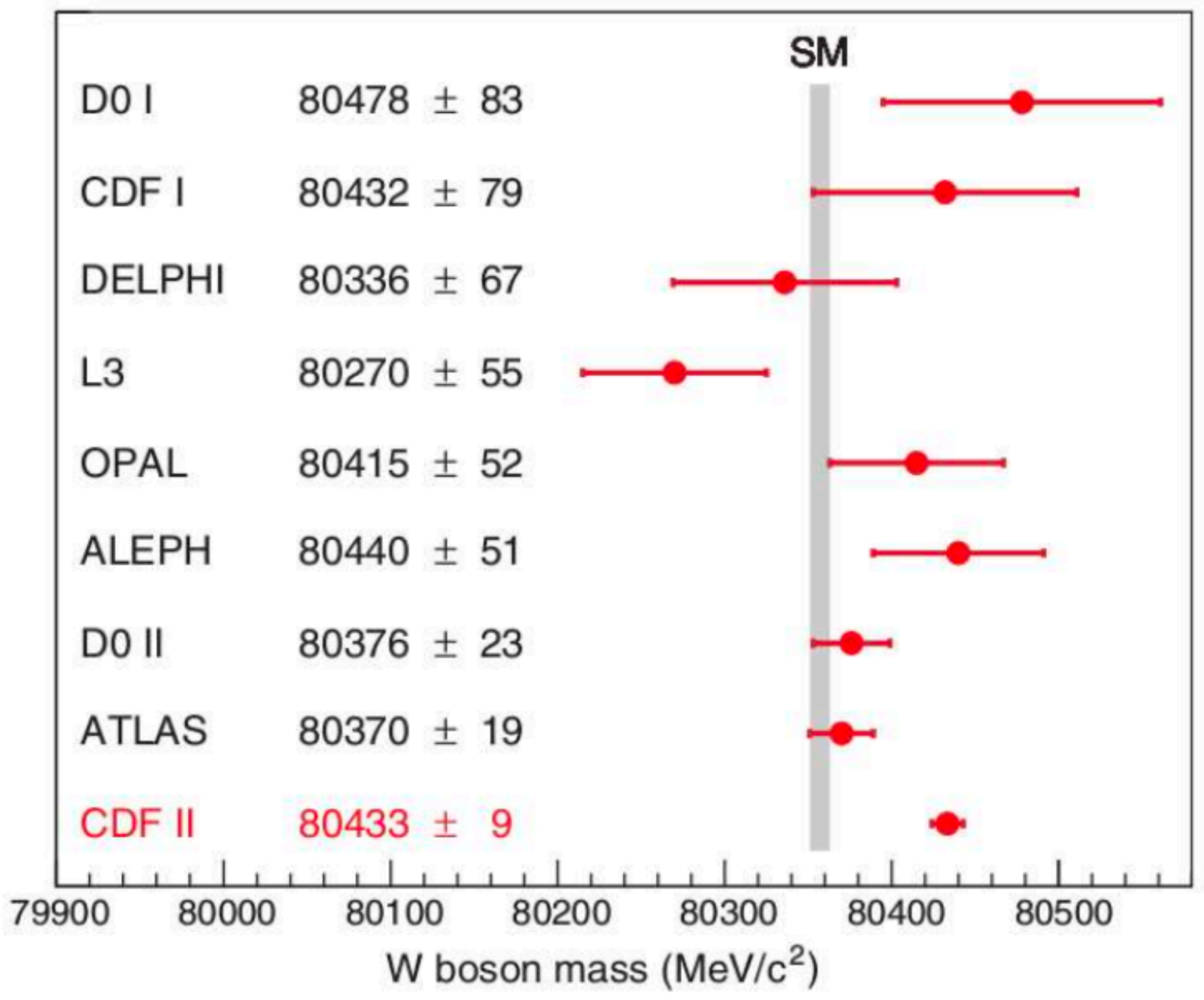
Dispersions of galaxies in clusters [Zwicky 1933]

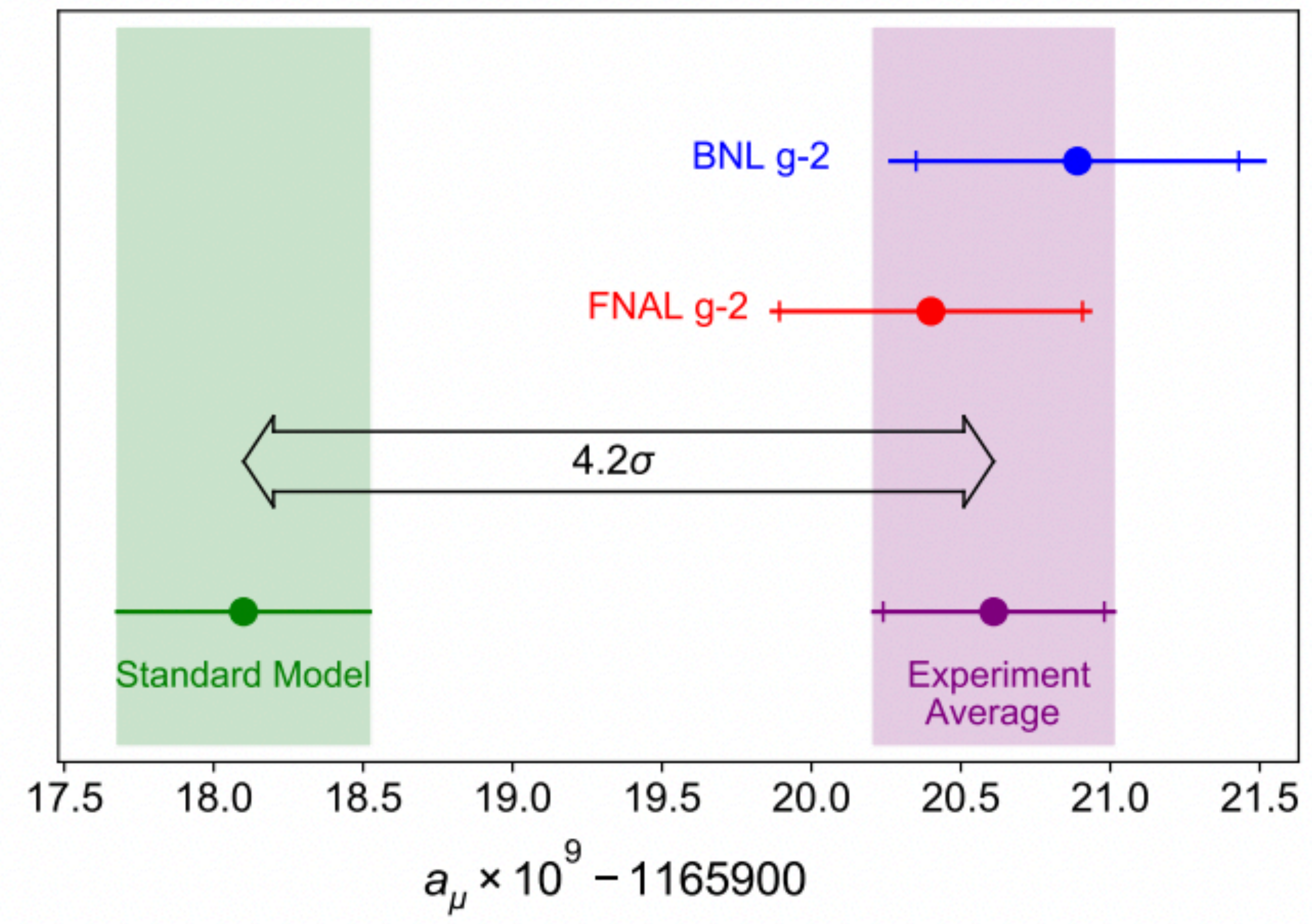


CDM is needed to explain the observed CMB temperature and polarization anisotropies.

The big question now, of course, is what actually is dark matter

M_W and $(g-2)_\mu$ measurements





$$M_W^{CDFII} = 80.4335 \text{ GeV} \pm 9.4 \text{ MeV}$$

$$M_W^{SM} = 80.357 \text{ GeV} \pm 6 \text{ MeV}$$

7σ **deviation**

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-11}$$

4.2σ **deviation**

What kind of new physics can explain simultaneously the $(g-2)_\mu$ and the W boson mass anomaly and also accommodate Dark Matter?

Our model

We consider the SM + an extra local $SU(2)_D$ symmetry.

	ν_R	$H' = \begin{pmatrix} \hat{\phi}_2^+ & \phi_2^+ \\ \hat{\phi}_2^0 & \phi_2^0 \end{pmatrix}$	$\Psi = \begin{pmatrix} E' \\ E \end{pmatrix}$	$\Phi_D = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}$	$V = \begin{pmatrix} V^+ \\ V^0 \\ V^- \end{pmatrix}$
$SU(2)_D \times G_{\rm EW}$	$(1,1)_0$	$(2,2)_{+\frac{1}{2}}$	$(2,1)_{-1}$	$(2,1)_0$	$(3,1)_0$
Z_2	$+$	$\begin{pmatrix} - & + \\ - & + \end{pmatrix}$	$\begin{pmatrix} - \\ + \end{pmatrix}$	$\begin{pmatrix} - \\ + \end{pmatrix}$	$\begin{pmatrix} - \\ + \\ - \end{pmatrix}$
		Higgs bi-doublet	$SU(2)_D$ **VL doublet**	$SU(2)_D$ **Higgs doublet**	

$$\mathscr{L}_{\rm VLSM} = -y_d \bar{q}_L d_R H - y_u \bar{q}_L u_R \tilde{H} - y_l \bar{l}_L e_R H - y_\nu \bar{l}_L \nu_R \tilde{H} - M_R \overline{\nu_R^c} \nu_R - M_E \bar{\Psi}\Psi - \lambda_E \bar{\Psi}_L \Phi_D e_R - y_E \bar{l}_L H' \Psi_R + \mathrm{h.c.}$$

$$\mathscr{L}_{\rm DM} = -\frac{1}{2}\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right) + i\bar{\Psi}\gamma^\mu D_\mu \Psi + |D_\mu \Phi_D|^2 + \mathrm{Tr}\left(|D_\mu H'|^2\right) - V(\Phi_D, H', H)$$

$$V(\Phi_D, H, H') = \mu_1^2 H^\dagger H + \mu_2^2 \mathrm{Tr}(H'^\dagger H') - (\mu_3 H^\dagger H' \Phi_D + \mathrm{h.c.}) + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\mathrm{Tr} H'^\dagger H')^2 + \lambda_3 (H^\dagger H)\mathrm{Tr}(H'^\dagger H')$$
$$+\mu_\phi^2 \Phi_D^\dagger \Phi_D + \lambda_\phi (\Phi_D^\dagger \Phi_D)^2 + \lambda_{H\Phi} H^\dagger H \Phi_D^\dagger \Phi_D + \lambda_{H'\Phi} \mathrm{Tr}(H'^\dagger H') \Phi_D^\dagger \Phi_D$$

$$Z_2 = e^{i\pi(G + I_3^D)}$$

The Z2 parity, originates from a combination of the dark isospin symmetry and a global $U(1)_G$ symmetry in the Higgs sector

Seesaw lepton masses.

$$\mathscr{L}_{L,\mathrm{mass}} = -M_E \bar{E}'E' - [(\bar{e}_L, \bar{E}_L)\mathscr{M}_L \begin{pmatrix} e_R \\ E_R \end{pmatrix} + \mathrm{h.c.}]$$

- After diagonalization: $\begin{pmatrix} e_L \\ E_L \end{pmatrix} = U_L \begin{pmatrix} l_{1L} \\ l_{2L} \end{pmatrix}, \quad \begin{pmatrix} e_R \\ E_R \end{pmatrix} = U_R \begin{pmatrix} l_{1R} \\ l_{2R} \end{pmatrix}$

$$\mathscr{M}_L = \begin{pmatrix} m_0 & m_L \\ m_R & M_E \end{pmatrix}$$

m_0: **bare lepton mass**

m_R, m_L: **mixing masses**

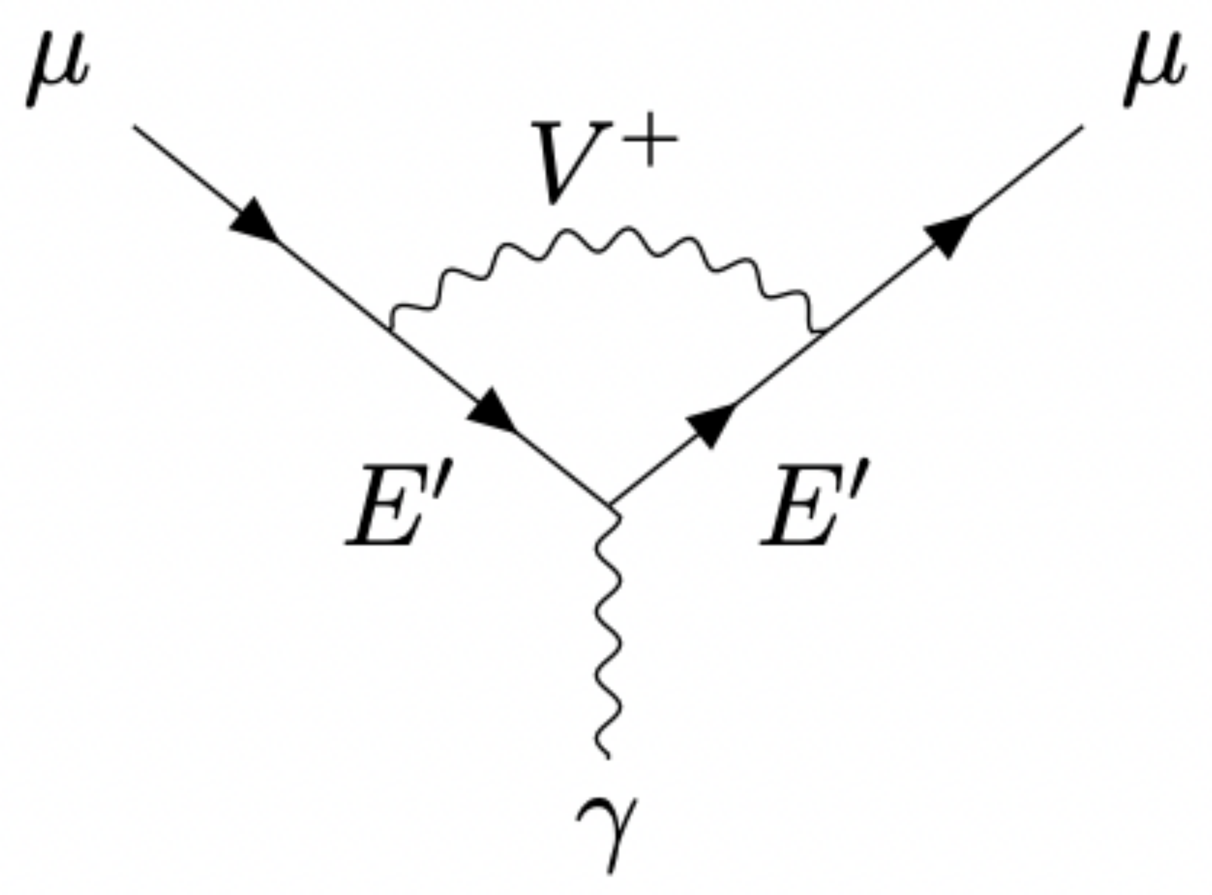
$$\mathscr{L}_{L,\mathrm{mass}} = -m_{l_1}\bar{l}_1 l_1 - m_{l_2}\bar{l}_2 l_2 - M_E \bar{E}'E'$$

$$m_{l_1} \approx m_0 - \frac{m_R m_L}{M_E}$$

$$m_{l_2} \approx (M_E^2 + m_L^2 + m_R^2)^{1/2}$$

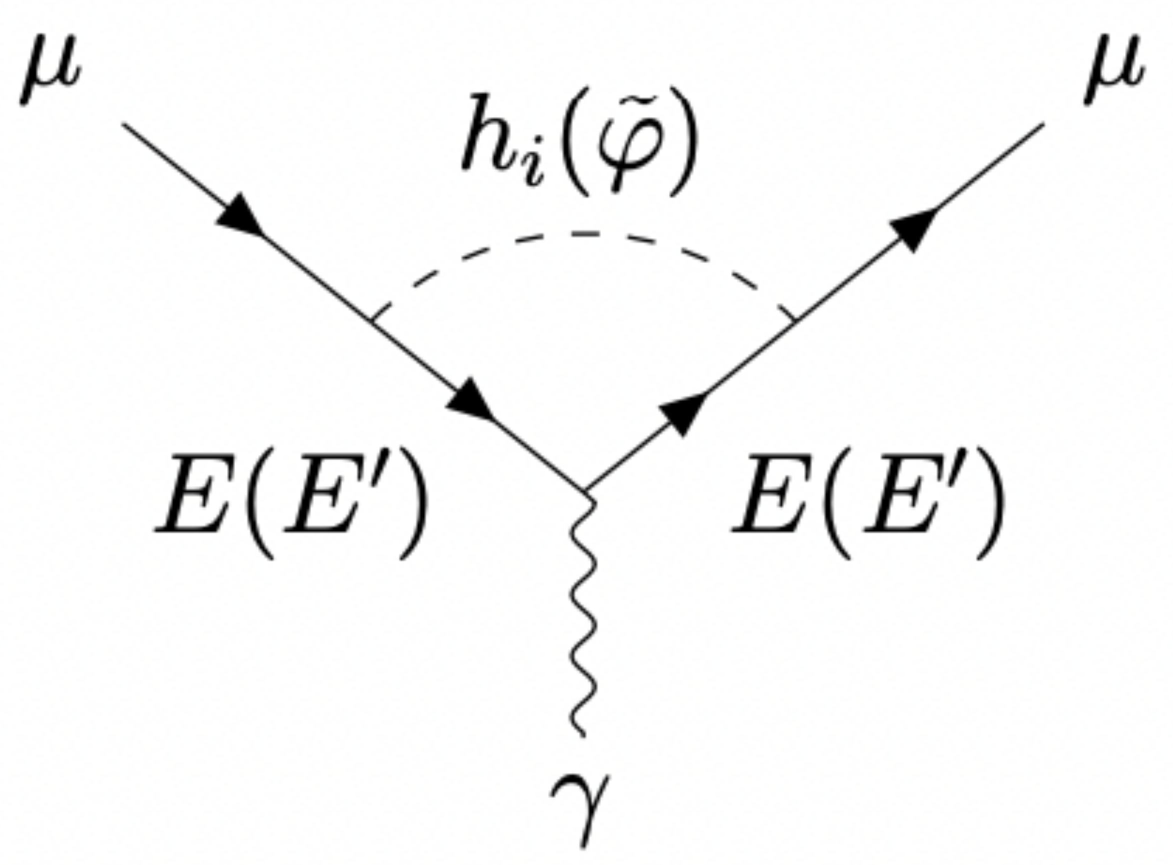
- Lepton masses are naturally small since they are a result of a simultaneous symmetry breaking of $SU(2)_D$ and the EW gauge symmetry, $m_L \neq 0$ and $m_R \neq 0$.

$(g-2)_\mu$ from V and h



$$\Delta a_\mu^{V,E} \simeq \begin{cases} \frac{g_D^2 M_E m_\mu}{16\pi^2 m_{V^0}^2}\left(c_V^2 - c_A^2\right) + \frac{g_D^2 M_E m_\mu}{32\pi^2 m_{V^0}^2}\left(\hat{c}_V^2 - \hat{c}_A^2\right), & M_E \gg m_{V^0}, \\ \frac{g_D^2 M_E m_\mu}{4\pi^2 m_{V^0}^2}\left(c_V^2 - c_A^2\right) + \frac{g_D^2 M_E m_\mu}{8\pi^2 m_{V^0}^2}\left(\hat{c}_V^2 - \hat{c}_A^2\right), & m_\mu \ll M_E \ll m_{V^0}. \end{cases}$$

The contributions from V^0 and the Z boson are negative, but subdominant due to the small mixing angles

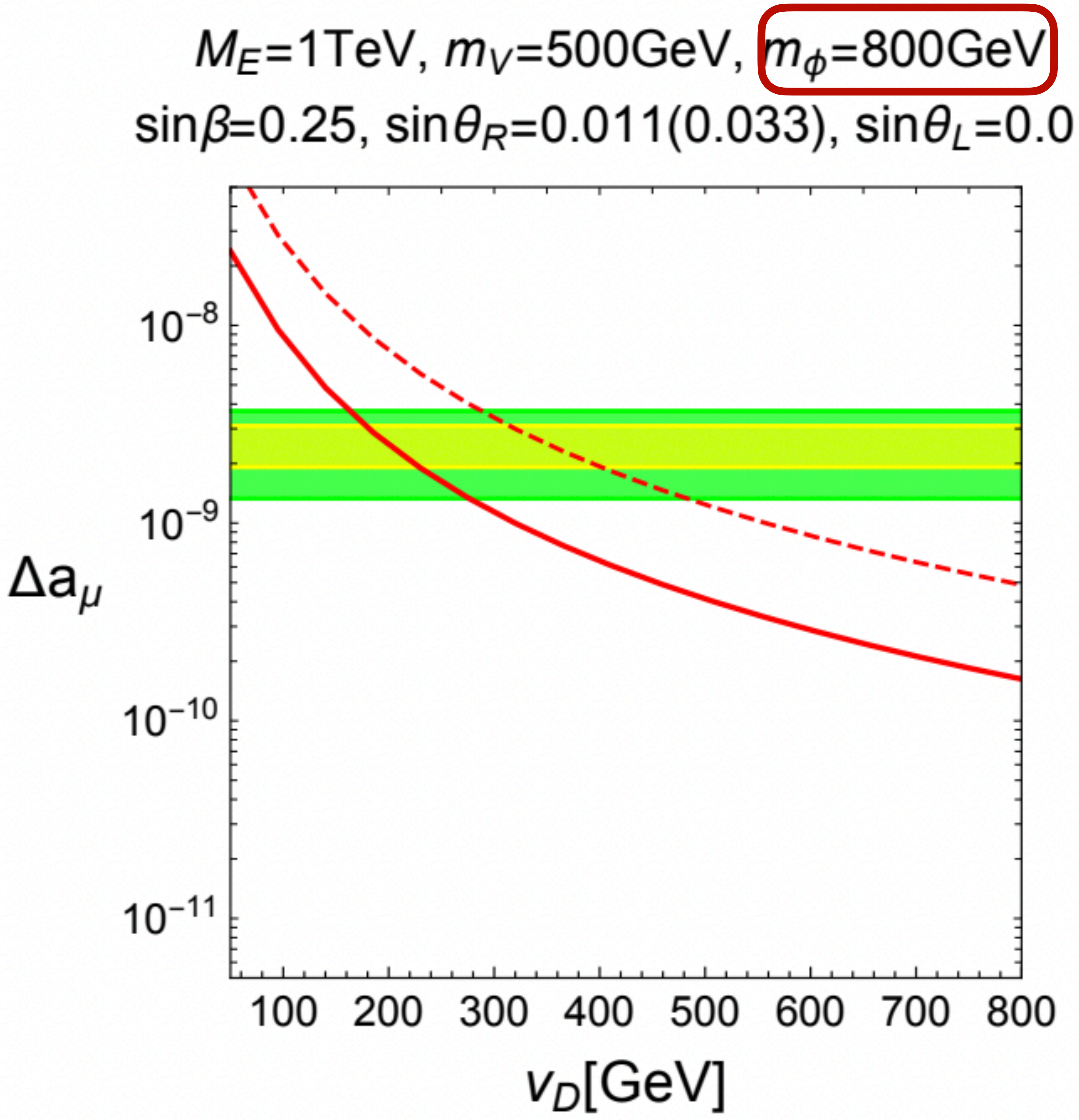


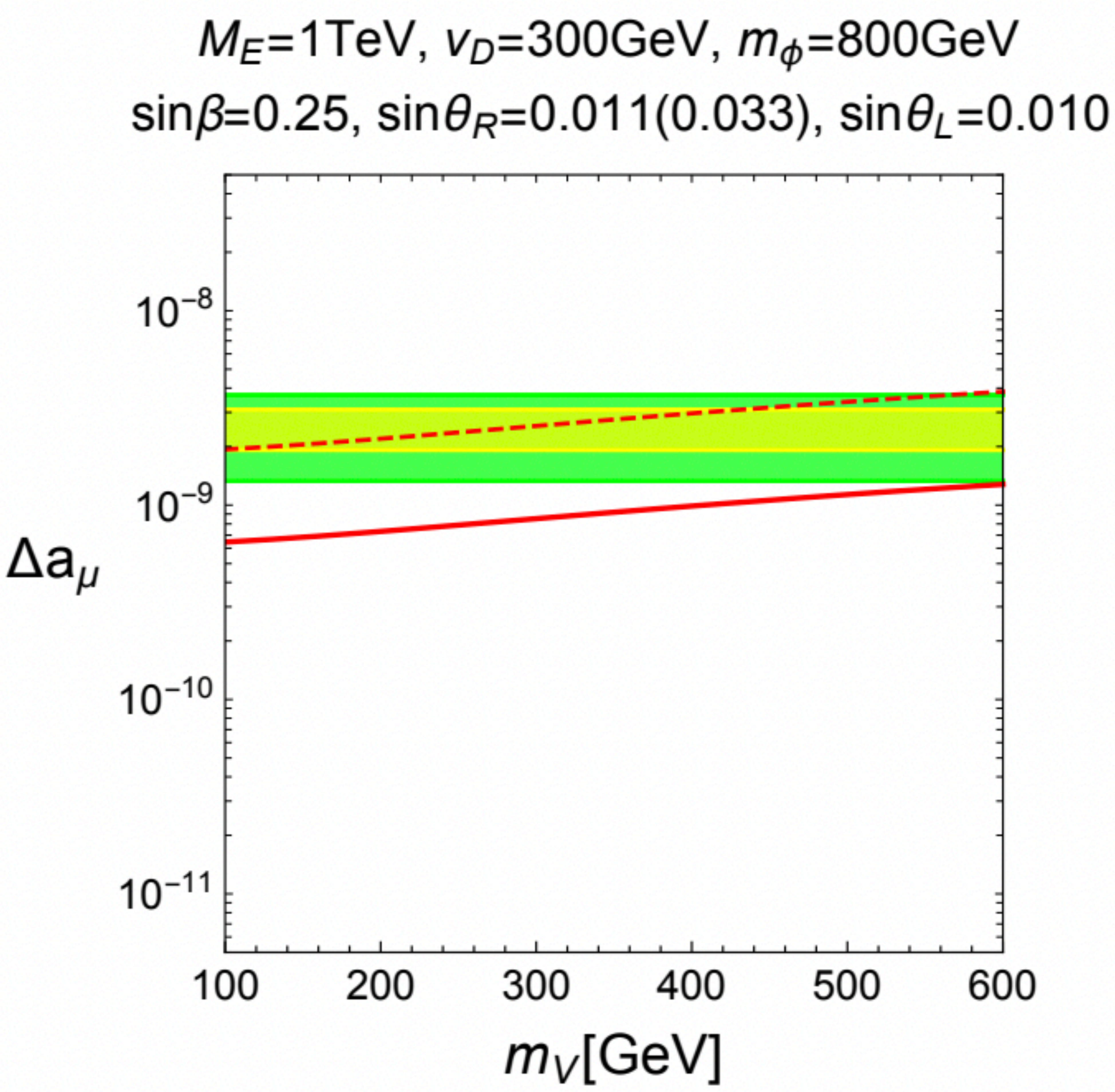
$$\Delta a_\mu^{h,E} \simeq \frac{m_\mu^2}{24\pi^2 m_{h_i}^2}\left[|v_i^E|^2 + |a_i^E|^2 + \frac{3M_E}{m_\mu}\left(|v_i^E|^2 - |a_i^E|^2\right)\left(\ln\left(\frac{m_{h_i}^2}{M_E^2}\right) - \frac{3}{2}\right)\right]$$

The contribution from $\tilde{\varphi}$ is not suppressed by the mixing angles,
But, the chirality-enhanced contribution is negative and enhanced by the VL lepton mass

$(g-2)_\mu$ from V^0 and h

For the favored correction,
m_ϕ **close to the TeV scale**





Contributions to the M_W

The W mass is determined by experimental inputs as

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}\cos\theta_L\left(1+\frac{\Delta r}{\cos\theta_L}\right)$$

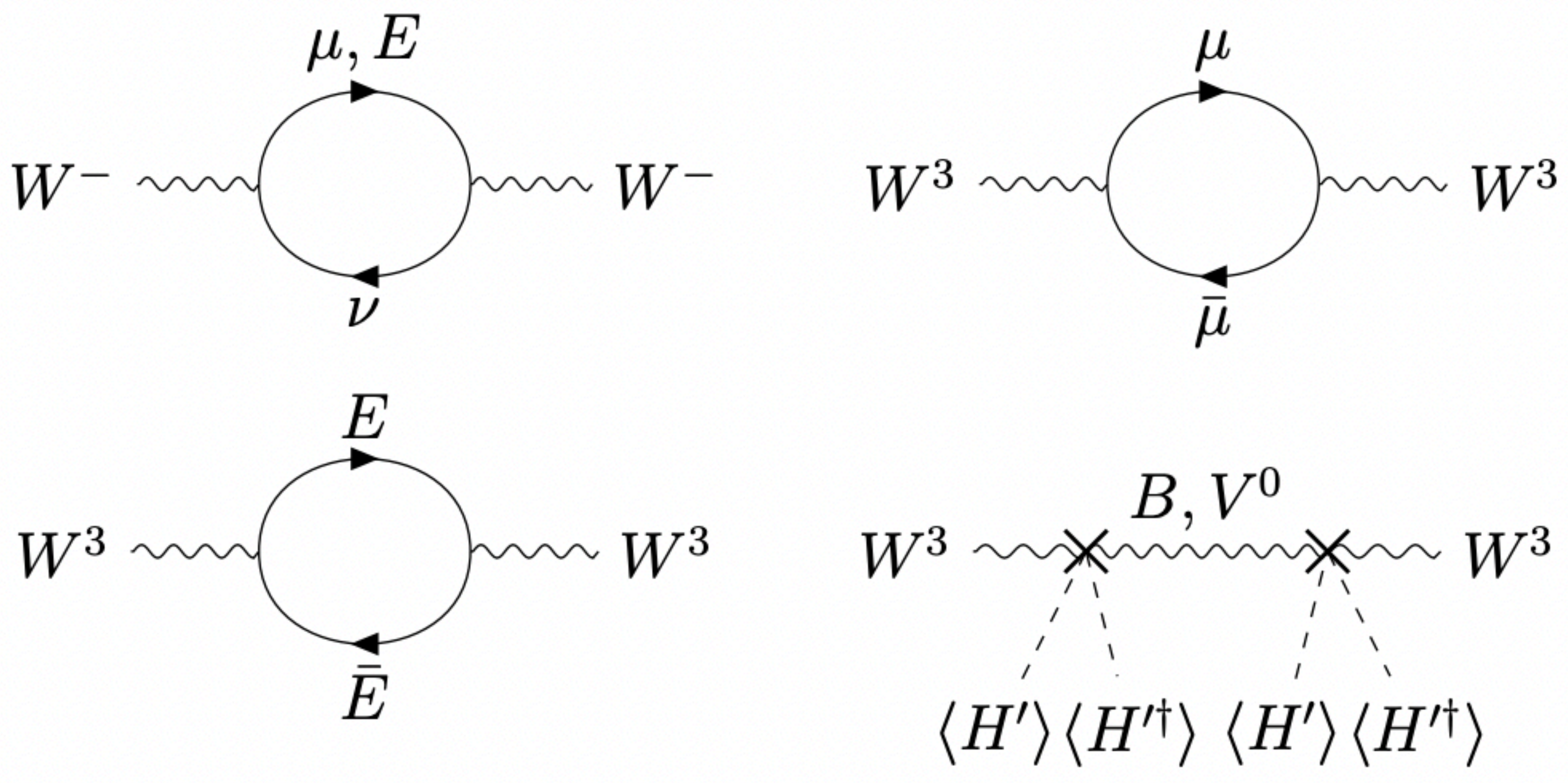
New contributions

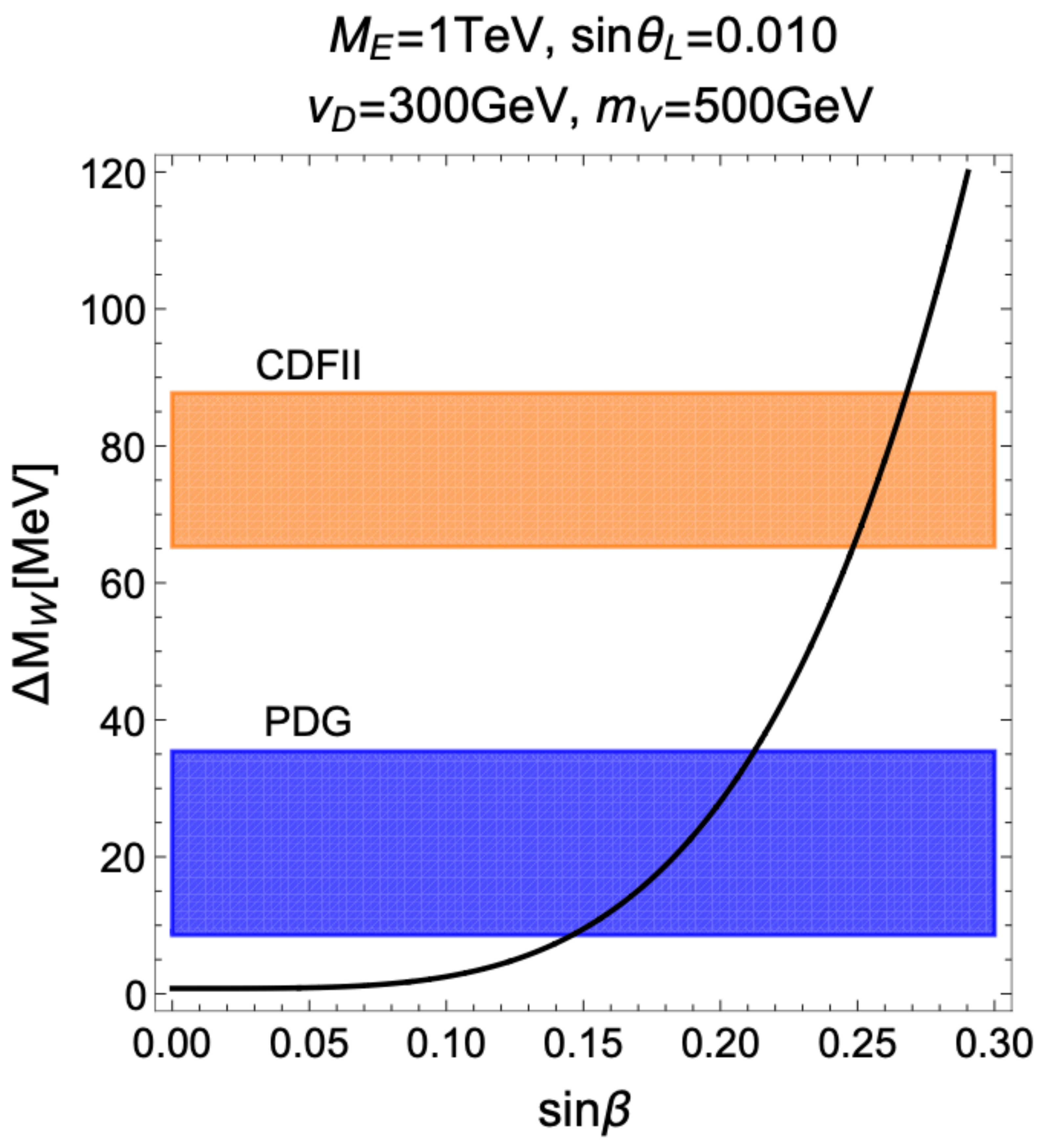
$$\Delta M_W \simeq \frac{1}{2}M_W\,\frac{s_W^2}{c_W^2-s_W^2}\left(1-\cos\theta_L+\frac{c_W^2}{s_W^2}\left(\Delta\rho_L+\Delta\rho_H\right)\right).$$

$$\Delta\rho_L \simeq \frac{\alpha M_E^2}{16\pi s_W^2 c_W^2 M_Z^2}\sin^4\theta_L.$$ **Vector-like lepton**

$$\Delta\rho_H = \frac{M_W^2}{M_{Z_1}^2\cos^2\theta_W}\cos^2\zeta-1$$ **Mixing between V^0 and Z after symmetry breaking**

Contributions to the M_W

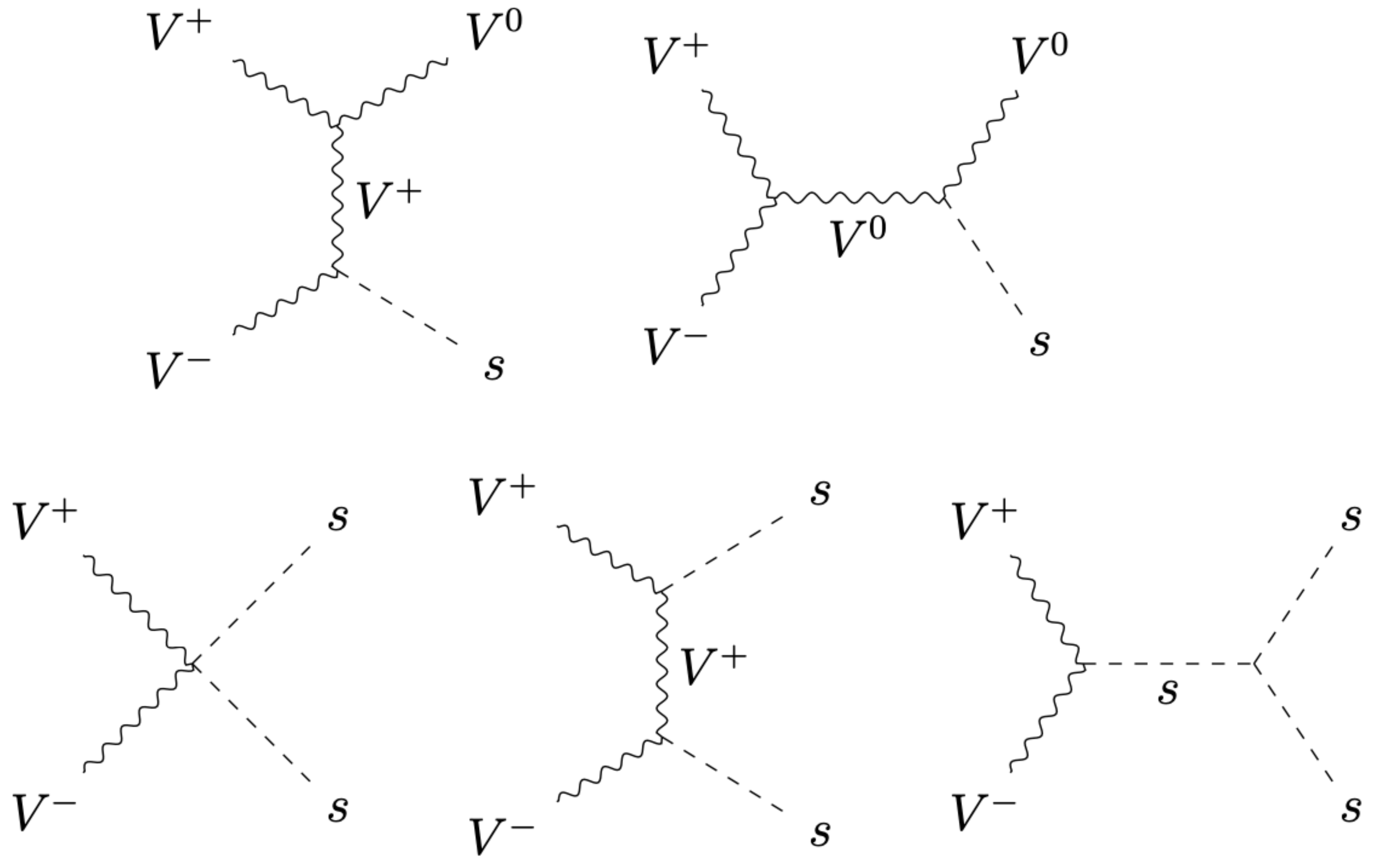




$$\Delta\rho_H \simeq \begin{cases} \frac{s_W^2 g_D^2}{g_Y^2}\frac{M_Z^2}{m_{V^0}^2}\sin^4\beta, & m_{V^0} \gg M_Z, \\ -\frac{s_W^2 g_D^2}{g_Y^2}\sin^4\beta, & m_{V^0} \ll M_Z. \end{cases}$$

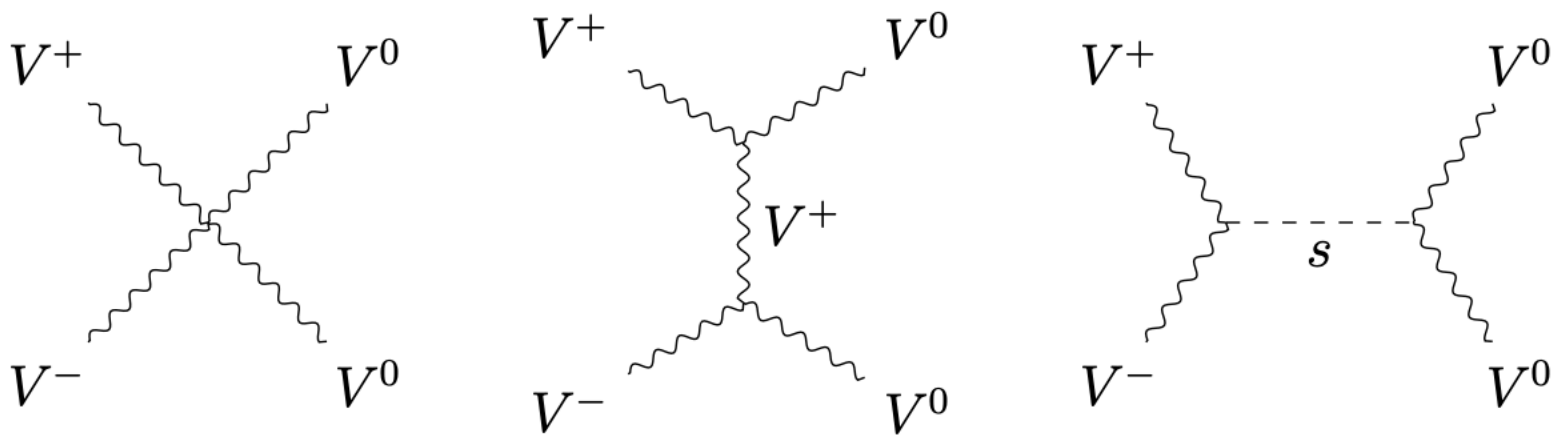
Dark Matter

$$V^+V^- \to V^0 s, ss$$



Closed for heavy s (as favored for XENON1T)

$$V^+V^- \to V^0V^0$$



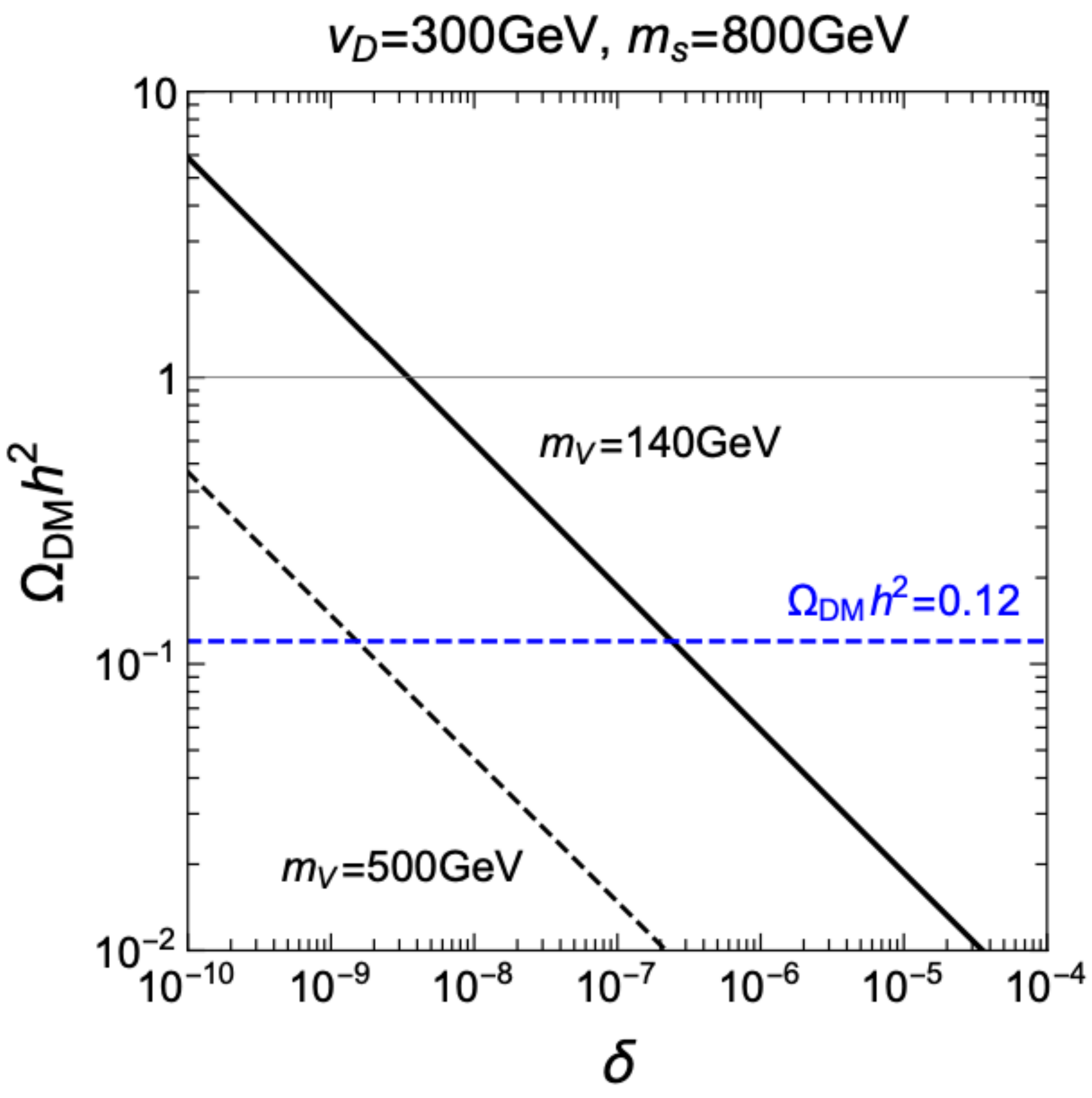
Because of the Z-V mass mixing, m_{V^0} is slightly larger than $m_{V^\pm}$

The channel is allowed due to a non-zero DM velocity at F.O.

Dark Matter

$$\Omega_{\rm DM}h^2 = 0.2745\left(\frac{Y_{\rm DM}}{10^{-11}}\right)\left(\frac{m_{V^+}}{100\,{\rm GeV}}\right)$$

$$\delta \simeq 2.2\times 10^{-5}\left(\frac{\Delta\rho_H}{1.3\times 10^{-3}}\right)\left(\frac{500\,{\rm GeV}}{m_{V^0}}\right)^2$$

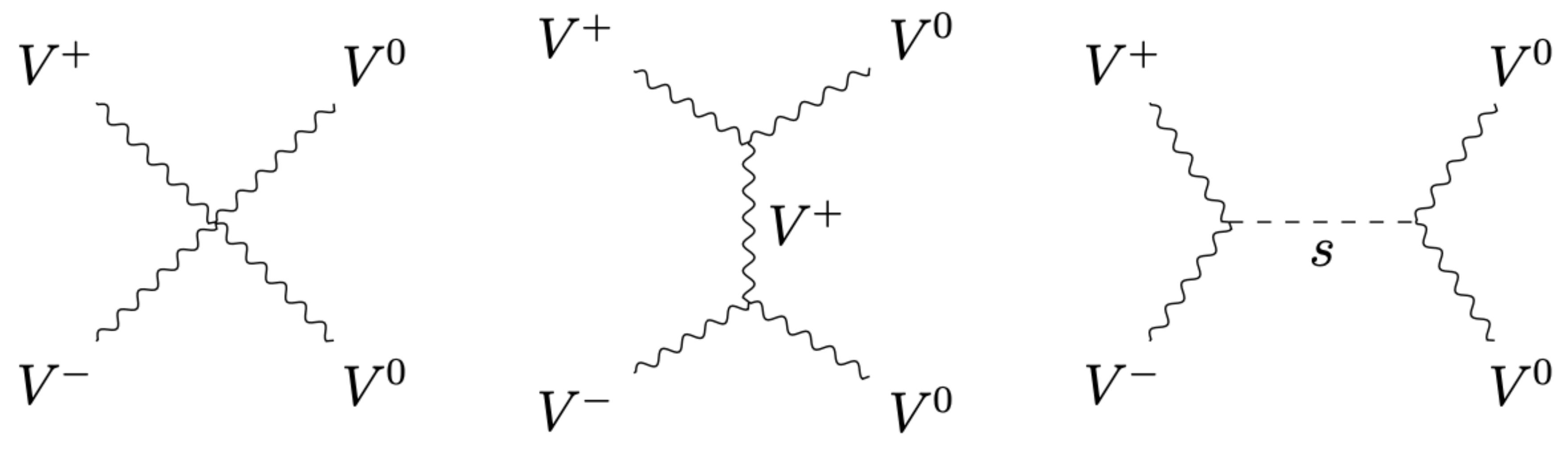


- The relic abundance condition is insensitive to m_s and mixing angles

- Crucially dependent on the mass splitting $\delta \equiv m_{V^0}/m_{V^+} - 1$

- For a fixed v_D, a larger $SU(2)_D$ dark coupling (larger mass) leads to a larger annihilation cross-section so the relic density decreases.

Forbidden channel



Closed for $v_{rel} \lesssim \sqrt{8\delta} \approx 220\,\mathrm{km}/s$

Does not lead to observable signatures for $\delta \gtrsim 6 \times 10^{-7}$

$$V^+V^- \to hh$$
$$V^+V^- \to V^0Z$$
$$V^+V^- \to SMSM$$

Subdominant channels

- Suppressed by small mixing angles
- They may lead to signals in CMB or cosmic rays.

Direct detection

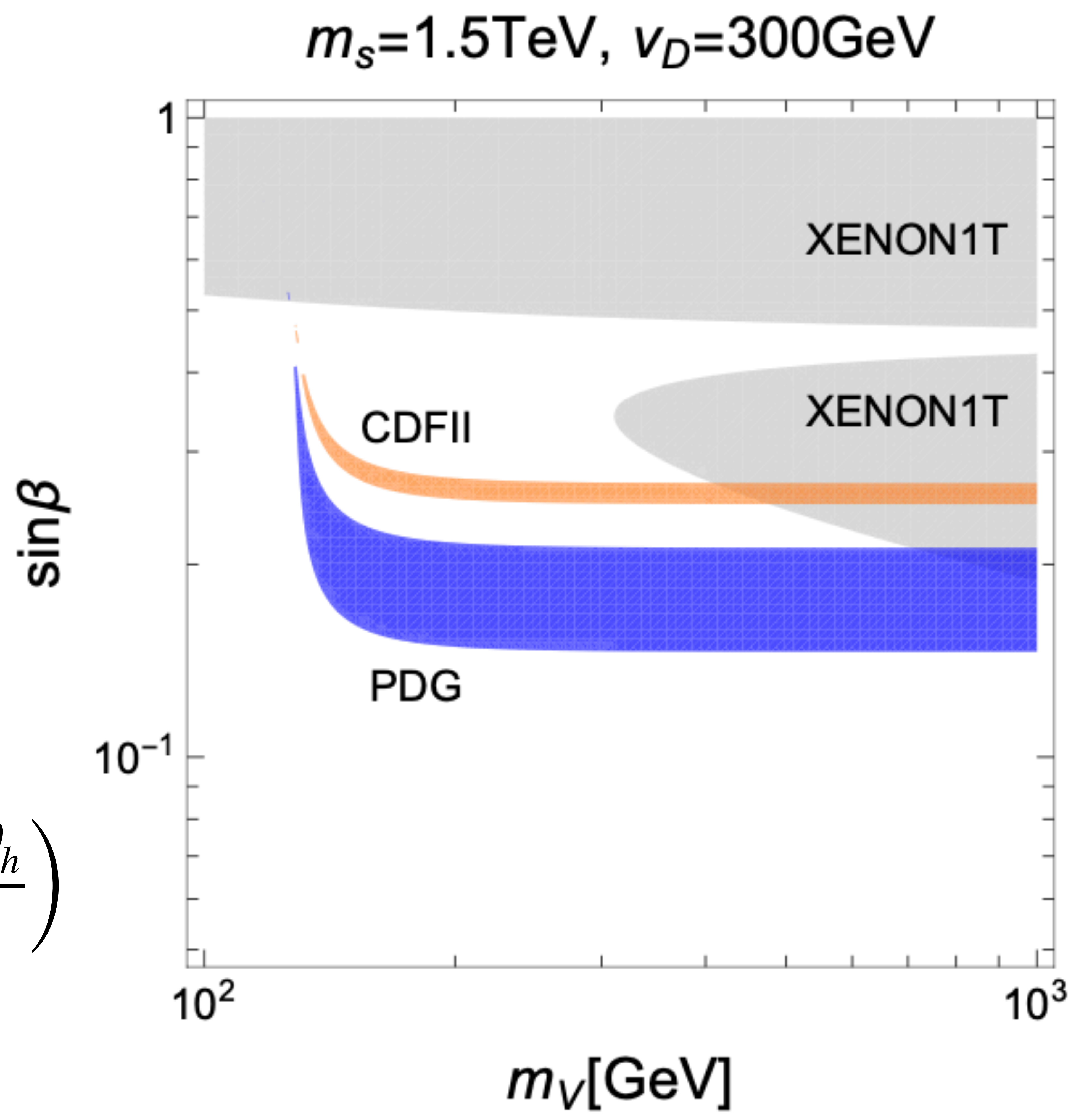
$$V^{\pm}q \to V^{\pm}q$$

- Possible through SM Higgs and singlet scalar exchanges.
- It is subdominant but can be constrained by the direct detection.
- Spin-independent elastic scattering:

$$\mathcal{L}_{V^{\pm}-q} = \lambda_{\text{eff}} m_q V^{+}_{\mu} V^{-\mu} \bar{q} q$$

$$\lambda_{\text{eff}} = \frac{\sqrt{2}}{2v} v_D g_D^2 \sin\theta_h \cos\theta_h \left(\frac{1}{m_s^2} - \frac{1}{m_h^2}\right) - \frac{1}{2} g_D^2 \sin^2\beta \left(\frac{\sin^2\theta_h}{m_s^2} + \frac{\cos^2\theta_h}{m_h^2}\right)$$

Alignment limit $\sin\theta_h = -\frac{v}{\sqrt{2}v_D}\sin^2\beta,\qquad m_s \gg m_h$



Summary

- We extended the SM with an extra $SU(2)_D$ gauge symmetry.
- The vector-like leptons and $SU(2)_D$ gauge bosons contribute to the muon g – 2.
- The mass mixing between the Z boson and the dark V^0 contributes to the W boson mass.
- A combination of the $U(1)_G$ in the Higgs sector and the dark isospin leads to a Z2 parity allowing for stable candidates for DM.
- The forbidden annihilation channel explains the correct relic density.
- Direct detection bounds can be satisfied in the alignment limit of the mixing between the SM Higgs and the singlet scalar of $SU(2)_D$.