Connection between Dark Matter and Flavor Anomalies

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Based on work in collaboration with , L. Calibbi, M. Fedele and F. Mescia

Motivations

Anomalies in semi-leptonic decays of B-mesons
(violation of lepton universality)

LHCb Collaboration 2103.11769
LHCb Collaboration JHEP 08 (2017) 055
Belle 1904.02440

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}$$

$$R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}$$

g-2 Anomaly

Muon g-2 Collaboration PRL 126 (2021) 141801

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

We need to explain the DM component of the Universe accounting for 27% of its energy budget.

Need for new Physics Beyond the Standard Model

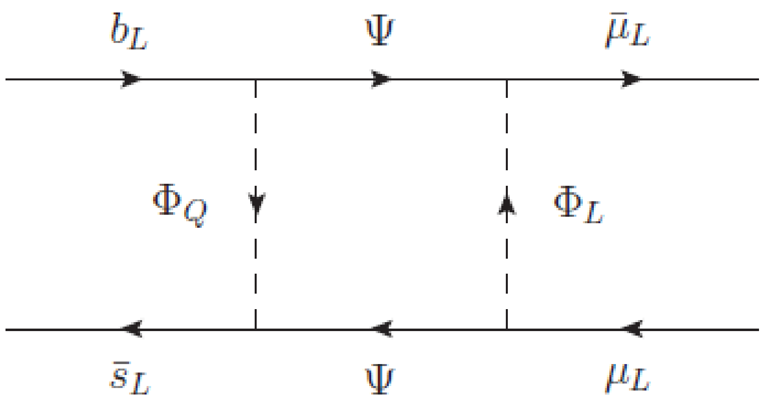
Model for DM, g-2 and B-anomalies

General requirements:

- Minimal NP field content. Interactions dictated by gauge invariance.
- Stable DM candidate achieving relic density through thermal freeze-out.
- Fit of B-anomalies;
- Fit of g-2;
- Evade other experimental constraints: DM Direct Detection, DM Indirect Detection, BSM searches at LHC;

Fit of B-anomalies

We need three NP states. Two class of models



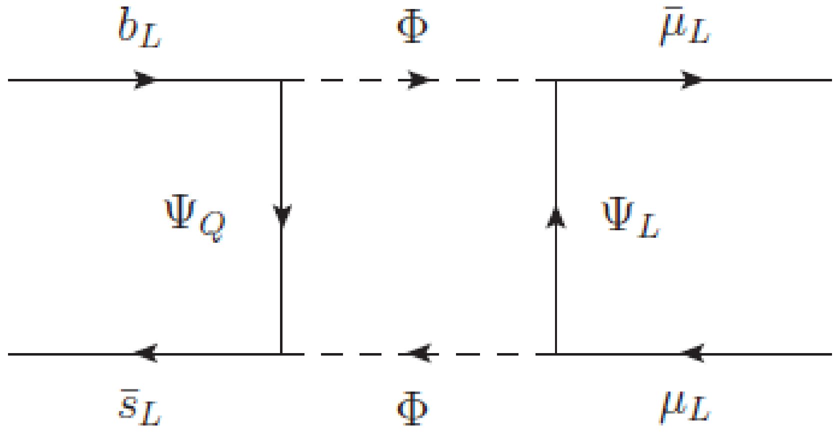
F-model (fermionic mediator)

$$L_F \supset \Gamma_i^Q \bar{Q}_i P_R \psi \phi_Q + \Gamma_i^L \bar{L}_i P_R \psi \phi_L + h.c.$$

Mediator=Field Coupled both with quarks and leptons

S-model (scalar mediator)

$$L_F \supset \Gamma_i^Q \bar{Q}_i P_R \psi_Q \phi + \Gamma_i^L \bar{L}_i P_R \psi_L \phi + h.c.$$



Models studied. (For a systematic classification see G.A., L. Calibbi, M. Fedele, F. Mescia PRD 104 (2021) 11, 115012)

$F_{IA;0}$

$\phi_Q: \left(3,2,\frac{1}{6}\right)$, $\phi_L: \left(1,2,-\frac{1}{2}\right)$, $\psi: (1,1,0)$

Dirac/Majorana DM

S_{IA}

$\psi_Q: \left(3,2,\frac{1}{6}\right)$; $\psi_L: \left(1,2,-\frac{1}{2}\right)$; $\phi: (1,1,0)$;

Complex Scalar DM

$F_{IB;-1/3}$

$\phi_Q: \left(1,2,\frac{1}{2}\right)$; $\phi_L: \left(\overline{3},2,-\frac{1}{6}\right)$; $\psi: \left(3,1,-\frac{1}{3}\right)$

Real Scalar DM

S_{IIB}

$\psi_Q: (1,1,0)$; $\psi_L: \left(\overline{3},1,-\frac{2}{3}\right)$; $\phi: \left(3,2,\frac{1}{6}\right)$;

Dirac/Majorana DM

$F_{IB;-1/3}$

$\phi_Q: \left(3,3,\frac{2}{3}\right)$; $\phi_L: (1,3,0)$; $\psi: \left(1,2,-\frac{1}{2}\right)$;

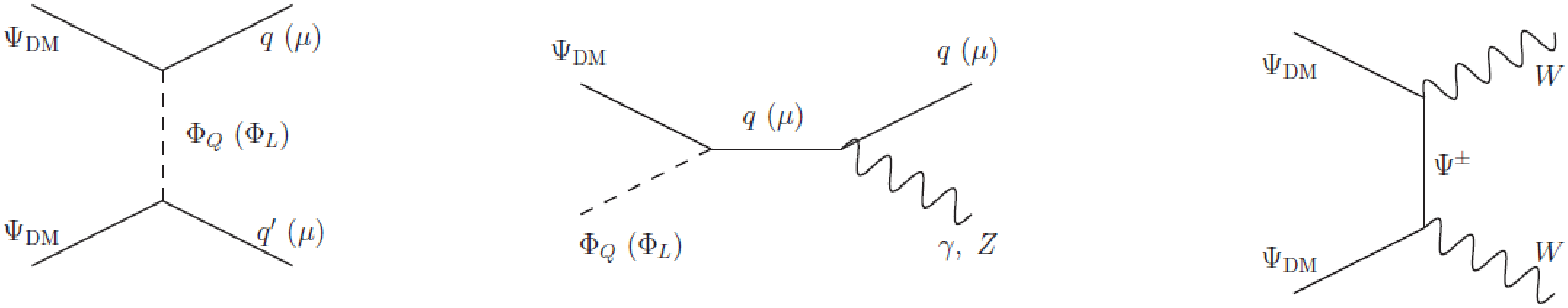
Real Scalar DM

$S_{IIIA;-1/2}$

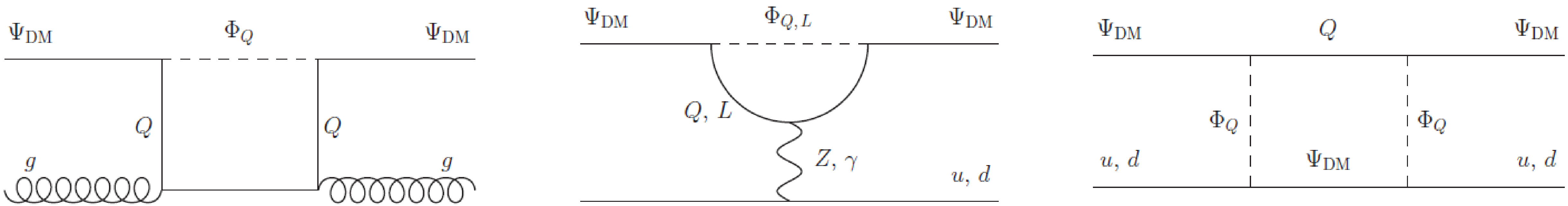
$\psi_Q: \left(3,3,\frac{2}{3}\right)$; $\psi_L: (1,3,0)$; $\phi: \left(1,2,-\frac{1}{2}\right)$;

Majorana DM

Relic density via conventional freeze-out



SI Scattering cross-section at one loop



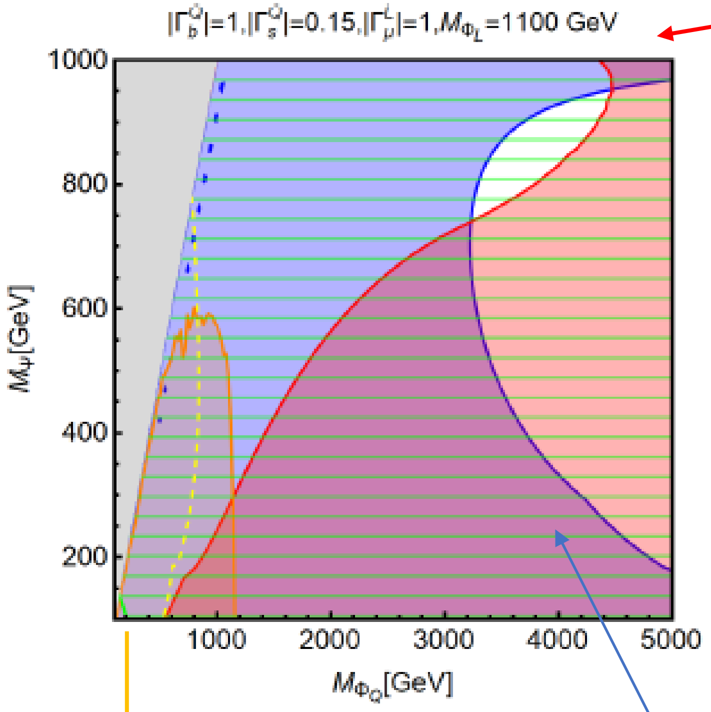
SM Singlet DM coupled with both leptons and quarks

F_{IA} dirac DM

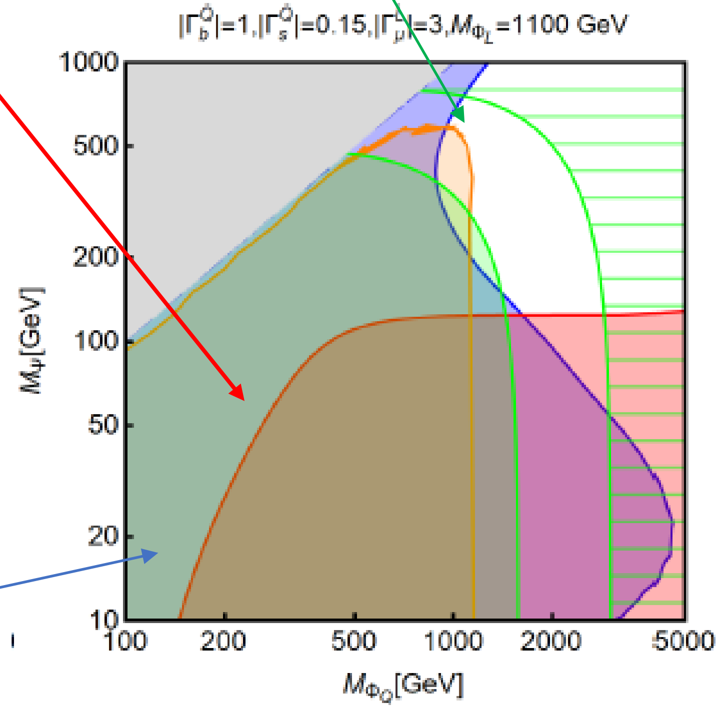
$\Omega h^2 > 0.12$

Viable fit of flavor anomalies

F_{IA} majorana DM



Dirac DM substantially ruled out by Direct Detection

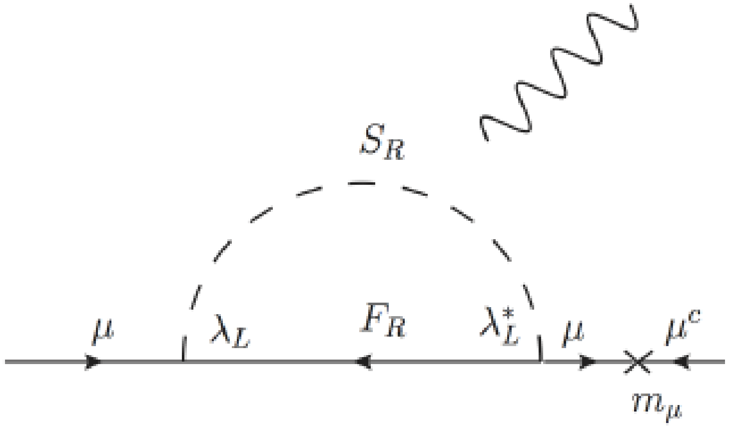


LHC excluded

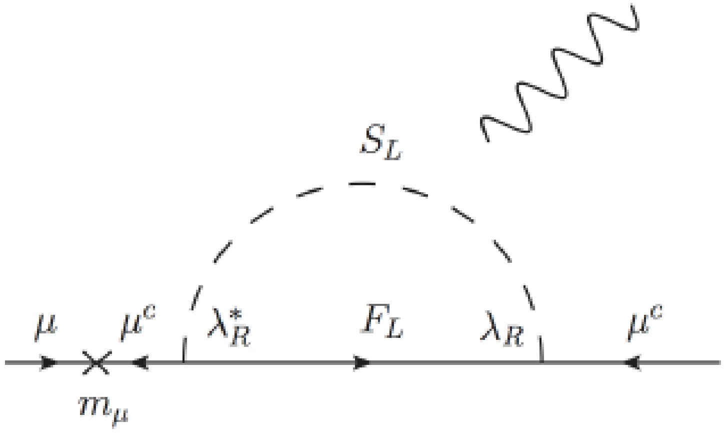
XENON1T Excluded

Adding g-2

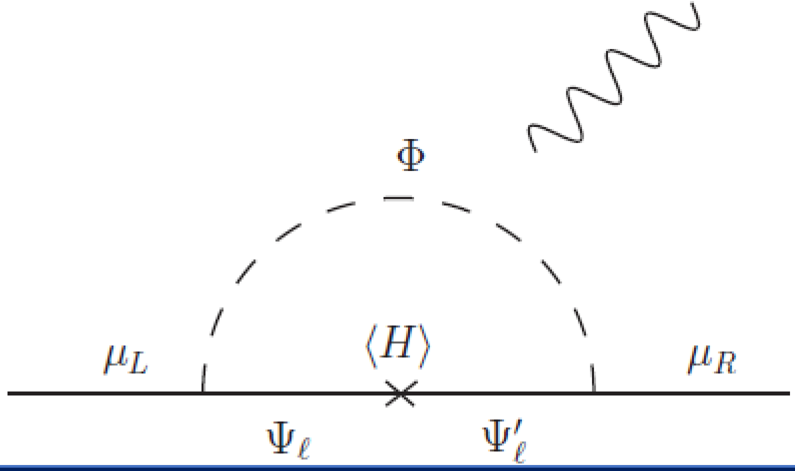
g-2 requires a chirality flip. If occurred only in the external lines, $\Delta a_\mu \propto m_\mu^2$, requiring light NP states excluded by other searches.

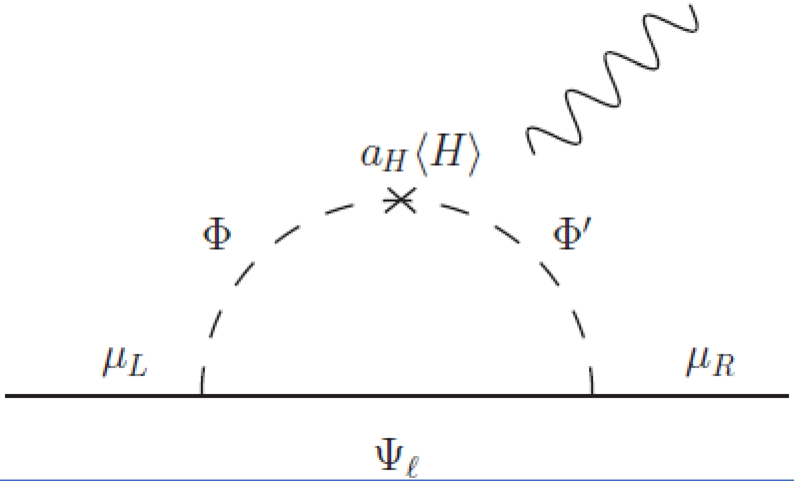


L. Calibbi, R. Ziegler, J. Zupan JHEP 07 (2018) 046



We need to trigger a chiral enhancement via NP.





We need a further NP field.....

New Class F: either $\{\phi_Q, \phi_L, \phi_L', \psi\}$ or $\{\phi_Q, \phi_L, \psi, \psi'\}$

New Class S: either $\{\psi_Q, \psi_L, \psi_L', \phi\}$ or $\{\psi_Q, \psi_L, \phi, \phi'\}$

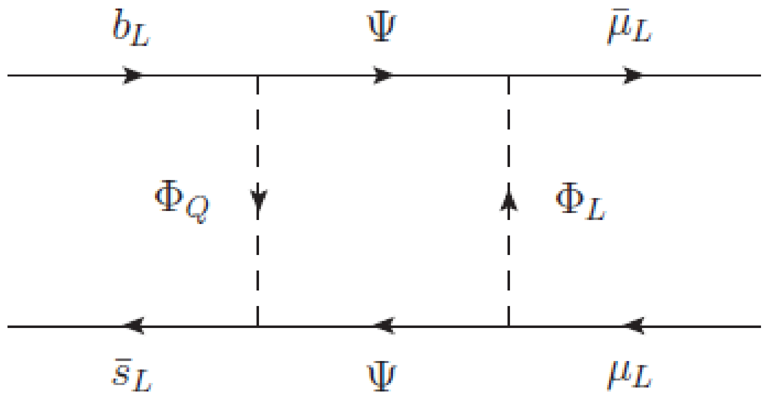
Label	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ	Φ_ℓ'/Ψ_ℓ'	Ψ'/Φ'
$\mathcal{F}_{\rm Ia}/\mathcal{S}_{\rm Ia}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{1},-1)$	–
$\mathcal{F}_{\rm Ib}/\mathcal{S}_{\rm Ib}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)$	–	$(\mathbf{1},\mathbf{2},-1/2)$
$\mathcal{F}_{\rm Ic}/\mathcal{S}_{\rm Ic}$	$(\mathbf{3},\mathbf{2},7/6)$	$(\mathbf{1},\mathbf{2},1/2)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{1},0)$	–
$\mathcal{F}_{\rm IIa}/\mathcal{S}_{\rm IIa}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{2},-1/2)$	–
$\mathcal{F}_{\rm IIb}/\mathcal{S}_{\rm IIb}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	–	$(\mathbf{1},\mathbf{1},-1)$
$\mathcal{F}_{\rm IIc}/\mathcal{S}_{\rm IIc}$	$(\mathbf{3},\mathbf{1},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)$	–	$(\mathbf{1},\mathbf{1},0)$
$\mathcal{F}_{\rm Va}/\mathcal{S}_{\rm Va}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{2},-1/2)$	–
$\mathcal{F}_{\rm Vb}/\mathcal{S}_{\rm Vb}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)$	$(\mathbf{1},\mathbf{2},-1/2)$	–	$(\mathbf{1},\mathbf{1},-1)$
$\mathcal{F}_{\rm Vc}/\mathcal{S}_{\rm Vc}$	$(\mathbf{3},\mathbf{3},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)$	–	$(\mathbf{1},\mathbf{1},0)$

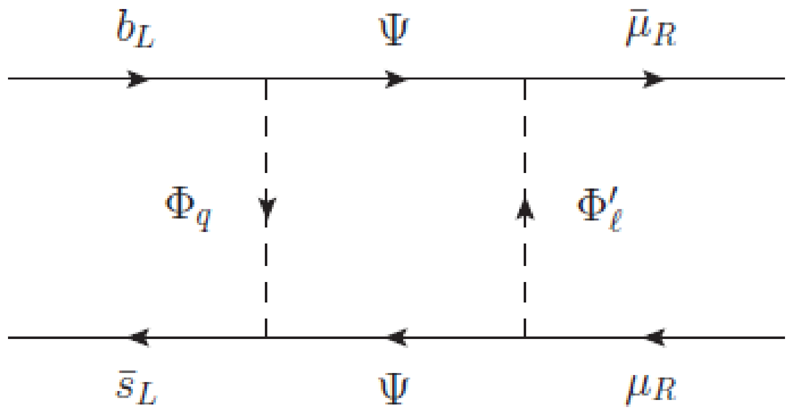
$SU(3)_c$	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ	Φ_ℓ'/Ψ_ℓ'	Ψ'/Φ'
A	3	1	1	1	1
B	1	$\bar{3}$	3	$\bar{3}$	3

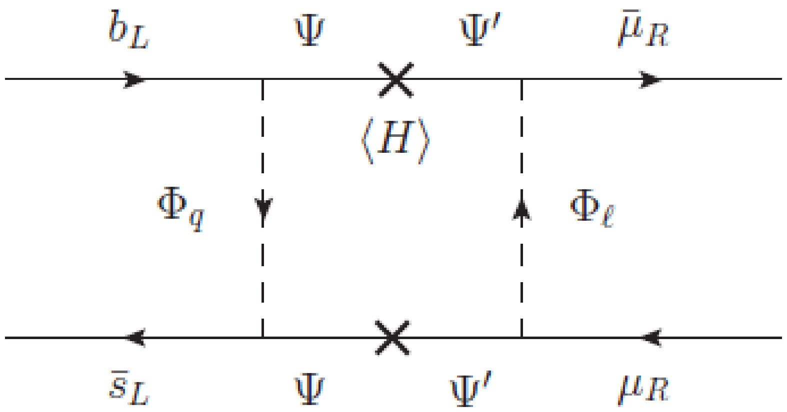
$SU(2)_L$	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ	Φ_ℓ'/Ψ_ℓ'	Ψ'/Φ'
I	2	2	1	1	2
II	1	1	2	2	1
III	3	3	2	2	3
IV	2	2	3	3	2
V	3	1	2	2	1
VI	1	3	2	2	3

$U(1)_Y$	Φ_q/Ψ_q	Φ_ℓ/Ψ_ℓ	Ψ/Φ	Φ_ℓ'/Ψ_ℓ'	Ψ'/Φ'
	$1/6-X$	$-1/2-X$	X	$-1-X$	$-1/2+X$

Additional contributions to B-meson decays







Specific example 1: FIb model. Singlet-doublet Majorana fermionic DM.

$$\phi_q:\left(3,2,\frac{1}{6}\right), \qquad \phi_l:\left(1,2,-\frac{1}{2}\right), \qquad \psi:(1,1,0), \qquad \psi':\left(1,2,-\frac{1}{2}\right)$$

$$L_{F_{Ib}} \supset \Gamma_i^Q \bar{Q}_i P_R \psi \phi_q + \Gamma_i^L \bar{L}_i P_R \psi \phi_l + \Gamma_i^E \bar{E}_i P_L \psi' \phi_l + \lambda_{HL} \bar{\psi} P_L \psi' H + \lambda_{HR} \bar{\psi} P_R \psi' + h.c.$$

$$V^T \begin{pmatrix} M_\psi & \lambda_{HL} v/\sqrt{2} & \lambda_{HR}^* v/\sqrt{2} \\ \lambda_{HL} v/\sqrt{2} & 0 & M_{\psi'} \\ \lambda_{HR}^* v/\sqrt{2} & M_{\psi'} & 0 \end{pmatrix} V = diag\left(M_1^{F_0}, M_2^{F_0}, M_3^{F_0}\right)$$

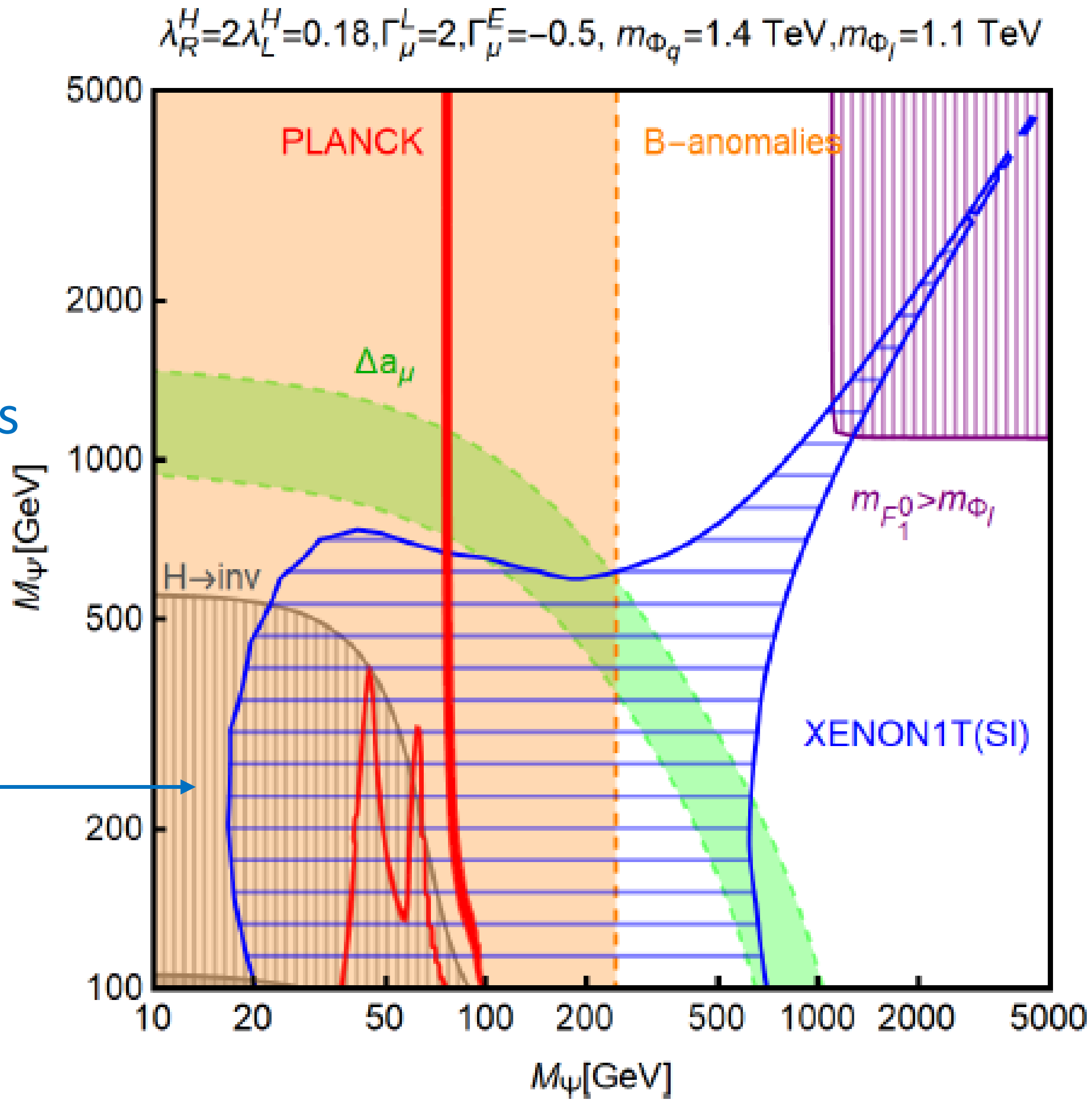
$$\delta C_\mu^9 = N \frac{\Gamma_s^{Q*}\Gamma_b^Q}{32\pi\alpha_{EM}} \sum_{i=1,2,3} \frac{V_{1i}V_{1j}}{\left(M_j^{F_0}\right)^2}\left(\left|\Gamma_\mu^L\right|^2 V_{1i}V_{1j} - \left|\Gamma_\mu^E\right|^2 V_{2i}V_{2j}\right)\left(F\left(\frac{M_{\phi_q}^2}{M_j^{F_0,2}}, \frac{M_{\phi_l}^2}{M_j^{F_0,2}}, \frac{M_i^{F_0,2}}{M_j^{F_0,2}}\right) + G\left(\frac{M_{\phi_q}^2}{M_j^{F_0,2}}, \frac{M_{\phi_l}^2}{M_j^{F_0,2}}, \frac{M_i^{F_0,2}}{M_j^{F_0,2}}\right)\right)$$

$$\delta C_\mu^{10} = -N \frac{\Gamma_s^{Q*}\Gamma_b^Q}{32\pi\alpha_{EM}} \sum_{i=1,2,3} \frac{V_{1i}V_{1j}}{\left(M_j^{F_0}\right)^2}\left(\left|\Gamma_\mu^L\right|^2 V_{1i}V_{1j} + \left|\Gamma_\mu^E\right|^2 V_{2i}V_{2j}\right)\left(F\left(\frac{M_{\phi_q}^2}{M_j^{F_0,2}}, \frac{M_{\phi_l}^2}{M_j^{F_0,2}}, \frac{M_i^{F_0,2}}{M_j^{F_0,2}}\right) + G\left(\frac{M_{\phi_q}^2}{M_j^{F_0,2}}, \frac{M_{\phi_l}^2}{M_j^{F_0,2}}, \frac{M_i^{F_0,2}}{M_j^{F_0,2}}\right)\right)$$

$$N^{-1} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^*$$

$$\Delta a_\mu \simeq -\frac{m_\mu}{2\pi^2 M_{\phi_l}^2} \sum_{j=1,2,3} M_j^{F_0} Re\left(\Gamma_\mu^L \Gamma_\mu^E V_{1j} V_{2j}\right) \widetilde{H}\left(\frac{M_j^{F_0 2}}{M_{\phi_l}^2}\right)$$

DD cross-section at tree-level via interactions with the Higgs



G.A., L. Calibbi, M. Fedele, F. Mescia Phys. Rev. Lett. 127 (2021) 061802

Specific example 2: FIIb model. SM Singlet Real scalar DM. Mass mixing in the NP field coupled with leptons.

$$\phi_q:\left(3,1,\frac{2}{3}\right),\qquad \phi_l=(1,1,0),\qquad \psi:\left(1,2,-\frac{1}{2}\right),\qquad \psi'=(1,1,-1)$$

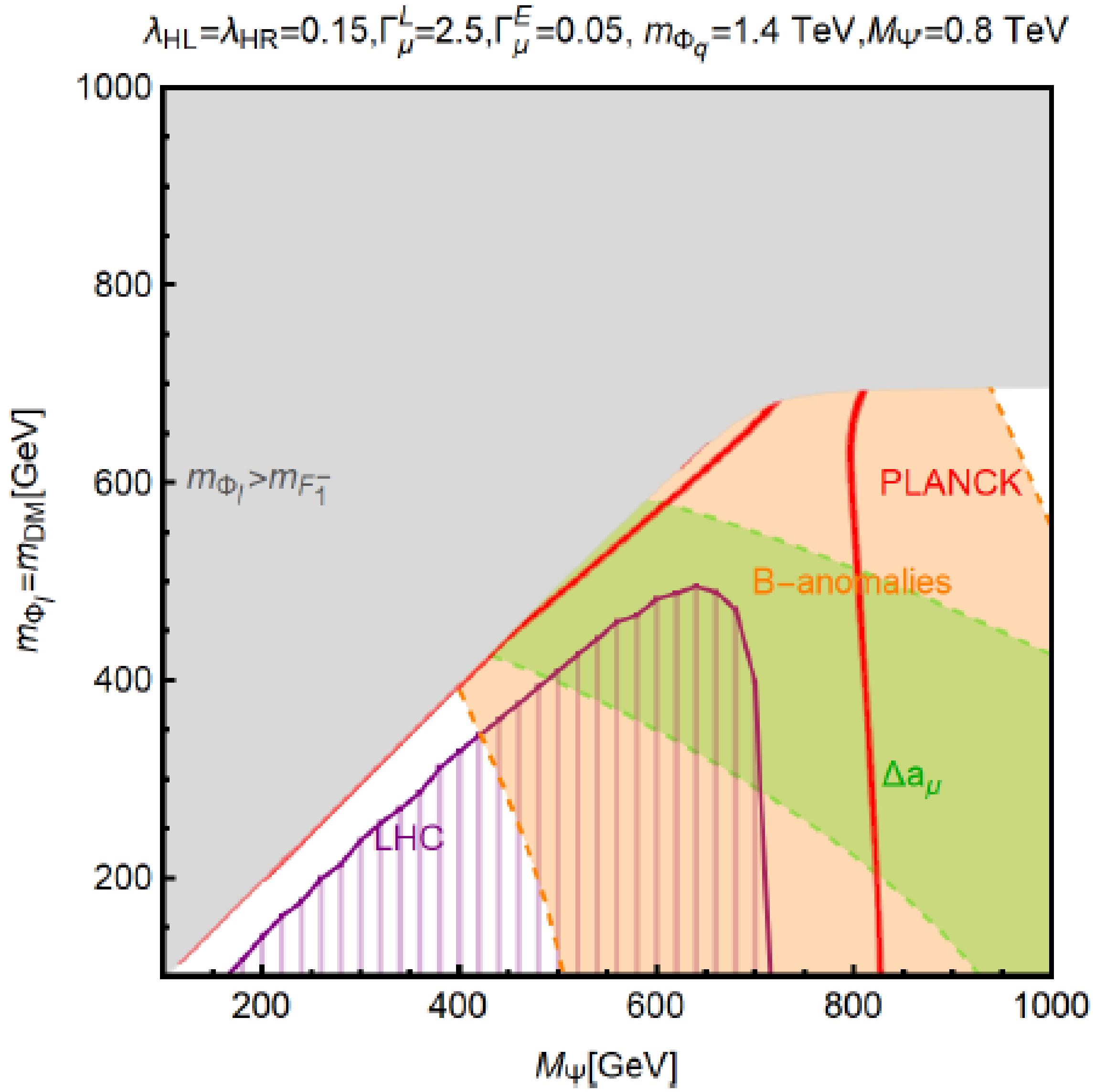
$$L_{F_{IIb}}\supset \Gamma_i^Q\bar{Q}_i P_R\psi\phi_q+\Gamma_\mu^L\bar{L}_\mu P_R\psi\phi_l+\Gamma_\mu^E\bar{E}_\mu P_L\psi'\phi_l+\lambda_{HL}\bar{\psi}P_L\psi' H+\lambda_{HR}\bar{\psi}P_R\psi' H+h.c.$$

$$M=\begin{pmatrix} M_{\psi'} & \lambda_{HR}^* v/\sqrt{2}\\ \lambda_{HL} v/\sqrt{2} & M_\psi\end{pmatrix}\qquad \left(U^{R\dagger}MU^L\right)_{ij}=M_i^{F-}\delta_{ij}$$

$$\delta C_\mu^9=N\frac{\Gamma_s^{Q*}\Gamma_b^Q}{32\pi\alpha_{EM}}\sum_{i,j=1,2}\frac{U_{2i}^R U_{2j}^{R*}}{\left(M_j^{F-}\right)^2}\left(\left|\Gamma_\mu^L\right|^2 U_{2i}^R U_{2j}^{R*} F\left(\frac{M_{\phi_q}^2}{(M_j^{F-})^2},\frac{M_{\phi_l}^2}{(M_j^{F-})^2},\frac{\left(M_i^{F-}\right)^2}{\left(M_j^{F-}\right)^2}\right)-\left|\Gamma_\mu^E\right|^2 U_{1i}^L U_{1j}^{R*} G\left(\frac{M_{\phi_q}^2}{(M_j^{F-})^2},\frac{M_{\phi_l}^2}{(M_j^{F-})^2},\frac{(M_i^{F-})^2}{\left(M_j^{F-}\right)^2}\right)\right)$$

$$\delta C_\mu^{10}=-N\frac{\Gamma_s^{Q*}\Gamma_b^Q}{32\pi\alpha_{EM}}\sum_{i,j=1,2}\frac{U_{2i}^R U_{2j}^{R*}}{\left(M_j^{F-}\right)^2}\left(\left|\Gamma_\mu^L\right|^2 U_{2i}^R U_{2j}^{R*} F\left(\frac{M_{\phi_q}^2}{(M_j^{F-})^2},\frac{M_{\phi_l}^2}{(M_j^{F-})^2},\frac{(M_i^{F-})^2}{(M_j^{F-})^2}\right)+\left|\Gamma_\mu^E\right|^2 U_{1i}^L U_{1j}^{R*} G\left(\frac{M_{\phi_q}^2}{(M_j^{F-})^2},\frac{M_{\phi_l}^2}{(M_j^{F-})^2},\frac{(M_i^{F-})^2}{(M_j^{F-})^2}\right)\right)$$

$$\Delta a_\mu\simeq\frac{m_\mu}{2\pi^2 M_{\phi_l}^2}\sum_{j=1,2}M_j^{F-}Re\left(\Gamma_\mu^L\Gamma_\mu^{E*}U_{2j}^R U_{1j}^{L*}\right)H\left(\frac{(M_j^{F-})^2}{M_{\phi_l}^2}\right)$$



$\lambda_{HL}=\lambda_{HR}=0.15,\Gamma_\mu^L=2.5,\Gamma_\mu^E=0.05,\ m_{\Phi_q}=1.4$ TeV$,M_\Psi=0.8$ TeV
$m_{\Phi_l}>m_{F_1^-}$
PLANCK
B−anomalies
Δa_μ
LHC
$m_{\Phi_l}=m_{DM}$[GeV]
M_Ψ[GeV]
200
400
600
800
1000

Conclusions

We have systematically classified and studied the minimal models which provide a combined interpretation of B- and g-2 anomalies and provide a viable WIMP DM candidate.

We have found interesting correlations between Dark Matter phenomenology and flavor observables.

Current constraints from LHC and Direct Detection experiments are already capable of favoring/ruling out different type of models.

Back up