TDLI-PKU BSM workshop 2022

August 2nd 2022

Muon g-2 and B anomalies from Dark Matter

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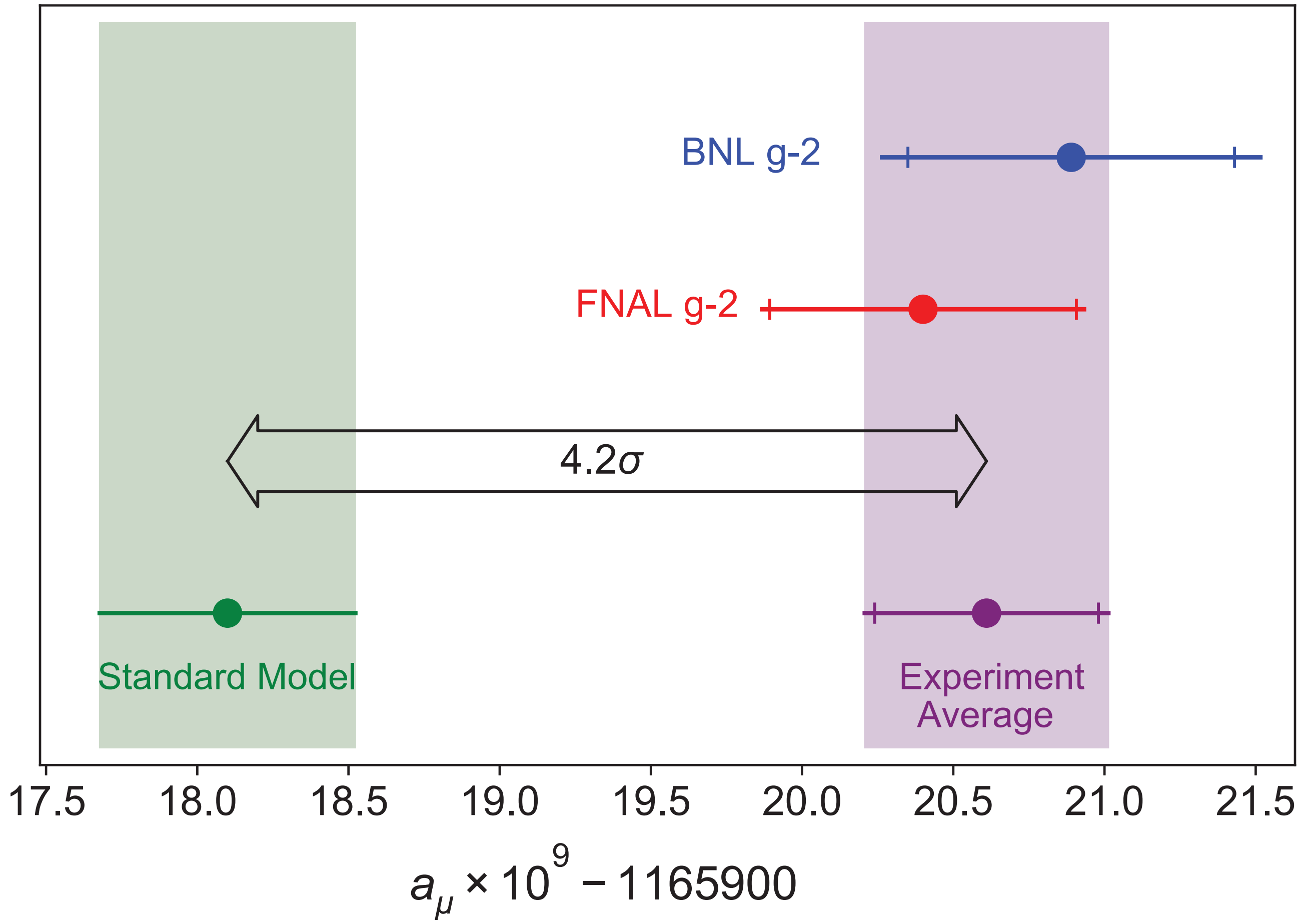
mainly based on Phys.Rev.D 104 (2021) 11, 115012
and Phys.Rev.Lett. 127 (2021) 6, 061802
in collaboration with G. Arcadi, M. Fedele, F. Mescia

Motivation: what's going on with muons? (I)

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



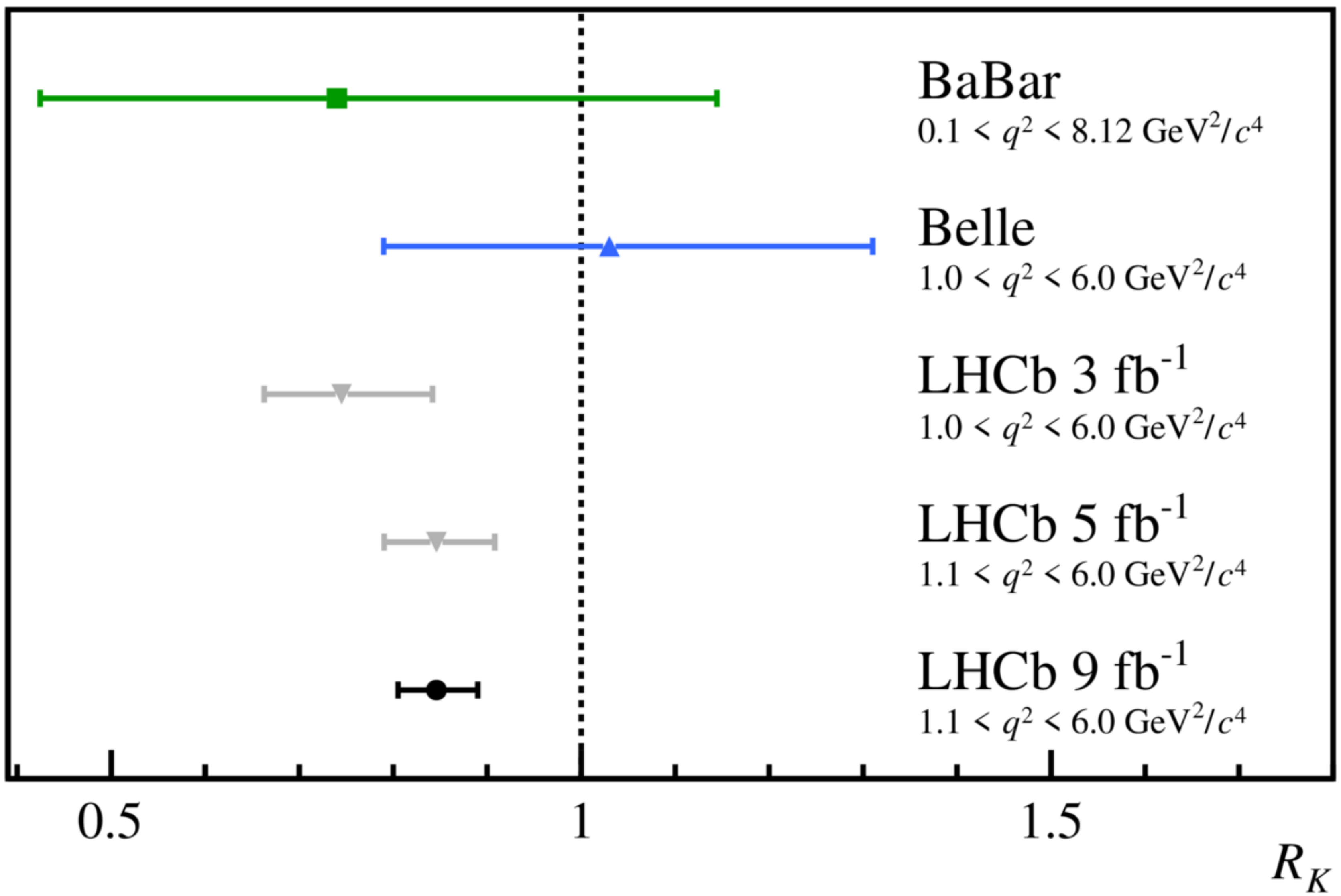
$$a_\mu \equiv (g-2)_\mu/2$$

Muon g-2 Phys.Rev.Lett. 126 (2021) 141801

- The FNAL Muon g-2 confirmed the BNL results: very unlikely that the discrepancy is due to a fluctuation or unaccounted systematic effects
- Only two possible explanations: underestimated hadronic contributions (cf. dispersive methods vs lattice QCD) or *new physics*

Test of lepton flavour universality in semileptonic B mesons decays

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

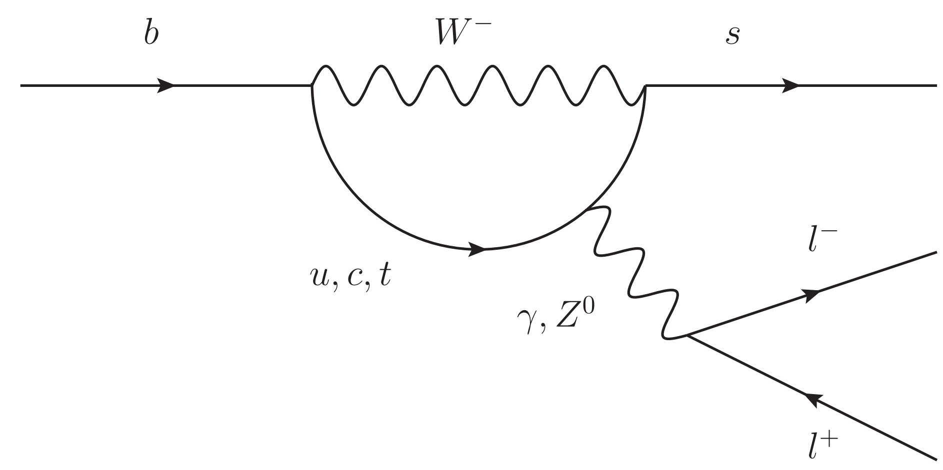


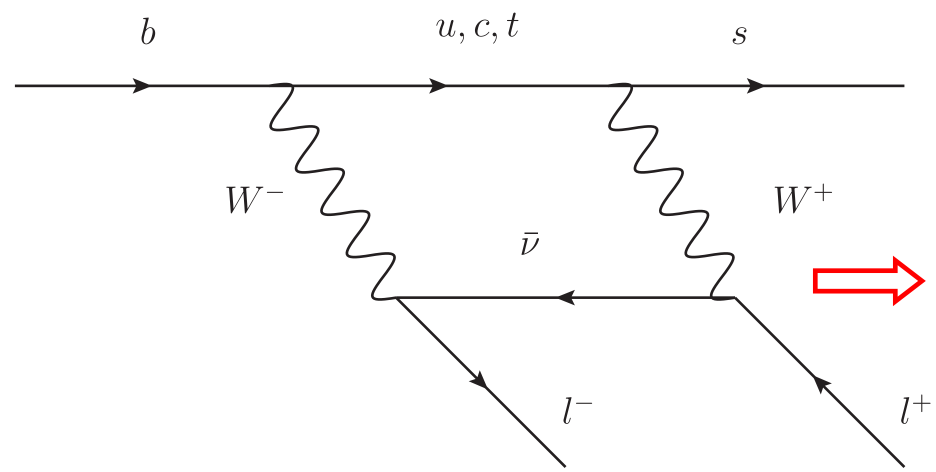
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+\,0.042}_{-\,0.039}\,^{+\,0.013}_{-\,0.012} \qquad (3.1\,\sigma)$$

LHCb arXiv:2103.11769

The SM predicts R_K =1±0.01 in the SM → lepton flavour universality

Bordone et al. '16





$\Rightarrow C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4.1$

Another deviation in a theoretical clean observable in the same class (neutral-current $b \to s\ell^+\ell^-$ transitions):

$$R_{K^*} = \left.\frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^* e^+ e^-)}\right|_{1.1<q^2<6\,\mathrm{GeV}^2} = 0.69^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$$

LHCb '17

Few sigma discrepancies in other obs with larger hadronic uncertainties:

Angular observables in $B \to K^*\mu^+\mu^-$

Some $b \to s\mu^+\mu^-$ BRs

Motivation and strategy

Assuming they are hints of new physics (NP), both the μ g-2 discrepancy and the B anomalies require new fields coupling to muons at scales $\lesssim$ O(100) TeV

Di Luzio Nardecchia '17, Capdevilla et al. '20, Buttazzo Paradisi '20, Allwicher et al. '21 …

a common explanation?

Since Dark Matter (DM) is the most compelling call for new physics, our goal is systematically building the *simplest* extensions of the SM that, *simultaneously*,

(i) address the B anomalies, (ii) explain the muon g-2 anomaly,
(iii) provide a DM candidate (a thermal relic WIMP)

How do we define our "minimal" models?

- Minimal field content (and minimal spin, quantum numbers, number of relevant couplings etc)
- DM field "*induces*" the NP contributions to semileptonic B decays and to the muon g-2 (i.e. directly enters the diagrams)

Assuming they are hints of new physics (NP), both the μ g-2 discrepancy and the B ...) TeV

al. '21 ...

DM stability → couplings SM-SM'-NP must be forbidden (or very suppressed) e.g. by a Z_2 symmetry:

- ⋆ New fields (Z_2 odd) do not mix with SM fields (Z_2 even)
- ⋆ We only have interactions of the kind NP-NP'-SM

→ B anomalies only at 1 loop

Gripaios et al. '15,
Arnan et al. '16, '19

Since I ... goal is system... eously,

How do we define our "minimal" models?

- Minimal field content (and minimal spin, quantum numbers, number of relevant couplings etc)
- DM field "*induces*" the NP contributions to semileptonic B decays and to the muon g-2 (i.e. directly enters the diagrams)

B anomalies from DM

Global fits to $b \to s\ell^+\ell^-$data

The anomalies in semileptonic B mesons decays suggest a deficit of muon events

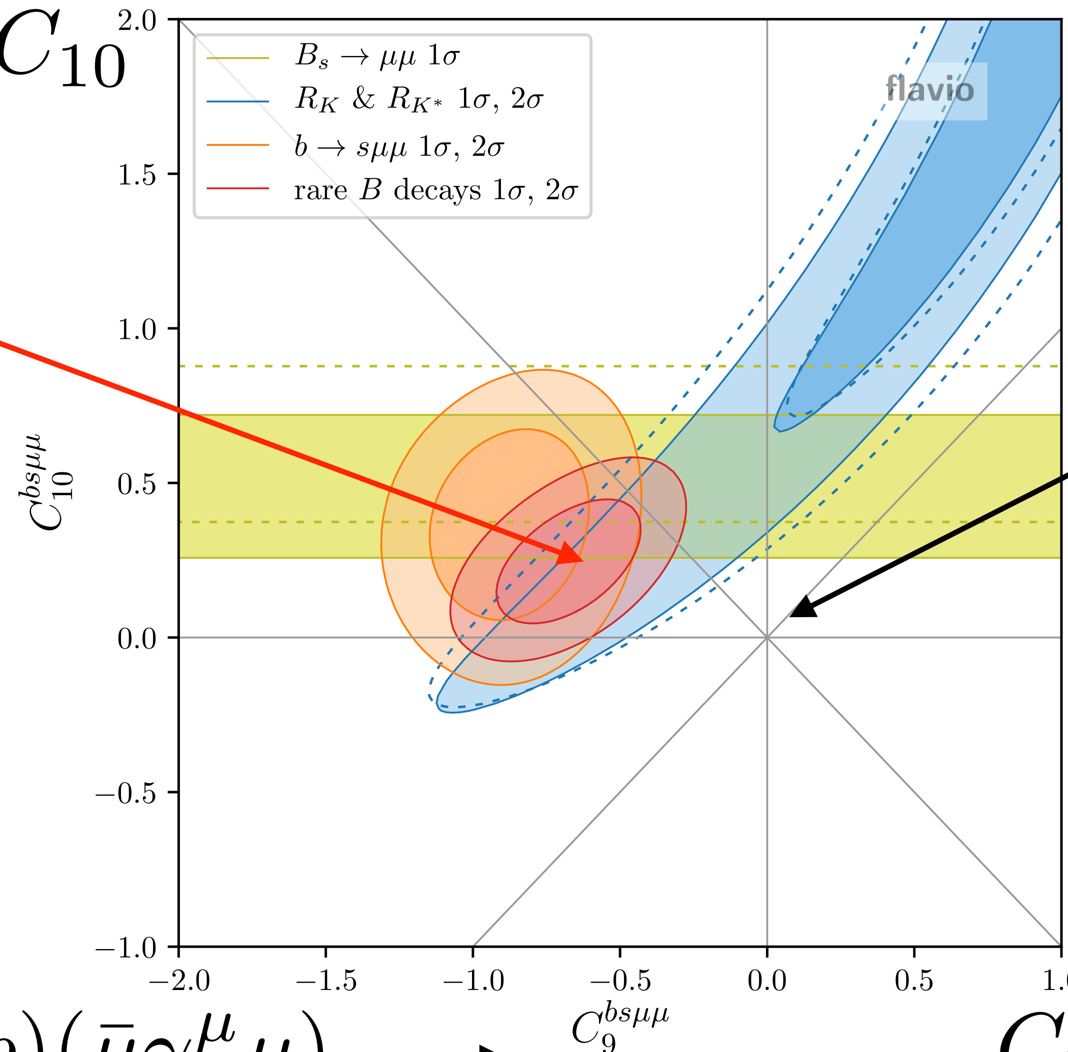
$$\mathcal{O}_9^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{\ell(\prime)} \sim (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

C_{10}

Best fit

SM point

New physics contribution to → $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$



Altmannshofer Stangl
2103.13370

New physics contribution to (negative) $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$ → C_9

Fits to the data: NP contributions preferred to SM at the ~5σ level

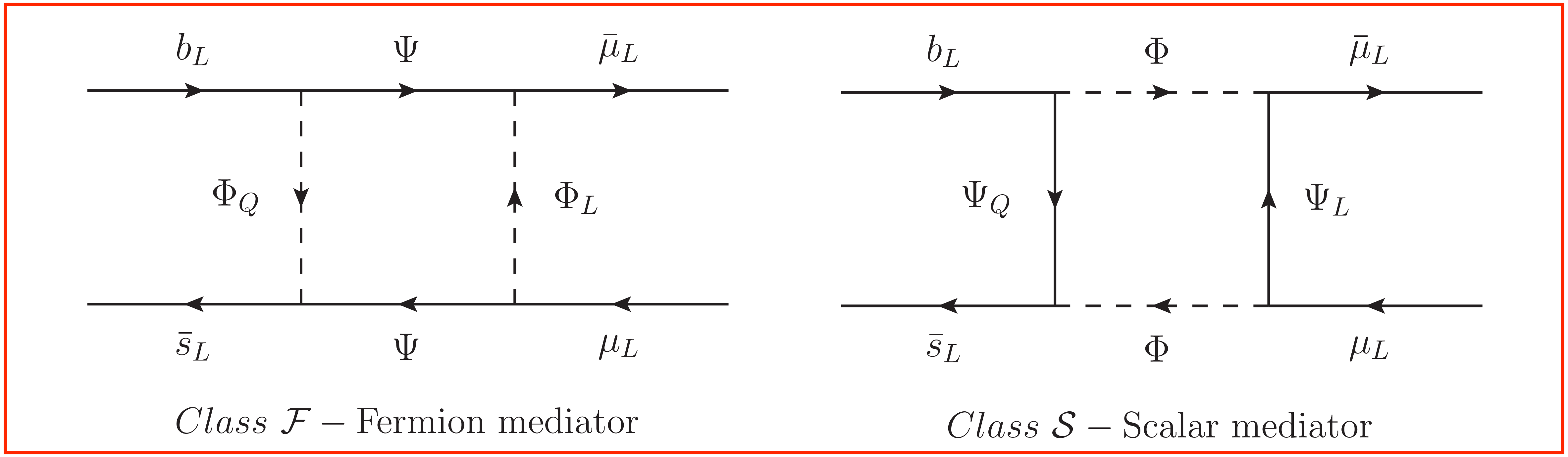
Geng Li-Sheng et al. '21, Cornella et al. '21, Ciuchini et al. '20 + many older refs.

The simplest possibility is to introduce fields that couple to LH fields only

$$\mathcal{H}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\left[C_\mu^9\,(\bar{s}\gamma_\mu P_L b)(\overline{\mu}\gamma^\mu\mu) + C_\mu^{10}\,(\bar{s}\gamma_\mu P_L b)(\overline{\mu}\gamma^\mu\gamma_5\mu) + \text{h.c.}\right]$$

➡ NP contribution: $\delta C_\mu^9 = -\delta C_\mu^{10} \approx -0.5$

Only 3 heavy fields (scalars and VL fermions) need to be added to the SM:



If neutral, the lightest state in the loop can be our DM candidate

For models of B anomalies and DM belonging to this class see:

Kawamura et al. '17, Cline Cornell '17, Barman et al. '18, Cerdeño et al. '19, Huang et al. '20

The simplest possibility is to introduce fields that couple to LH fields only

On … M:

Gauge invariance requires →

[only possibilities for *SU(3)*, irrep with *d*≤3 for *SU(2)*]

We select combinations with at least one state that is:

- colorless
- EM neutral
- *Y*=0, if fermion (to avoid huge contributions to direct detection from Z exchange)

$SU(3)_c$	Φ_Q, Ψ_Q	Φ_L, Ψ_L	Ψ, Φ
A	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
B	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$

$SU(2)_L$	Φ_Q, Ψ_Q	Φ_L, Ψ_L	Ψ, Φ
I	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
II	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$
III	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{2}$
IV	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{3}$
V	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$
VI	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$

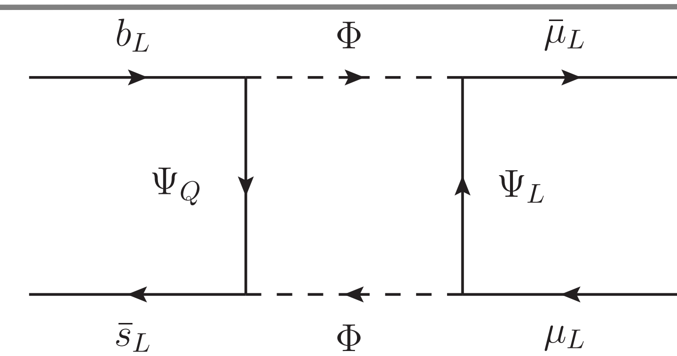
$U(1)_Y$	Φ_Q, Ψ_Q	Φ_L, Ψ_L	Ψ, Φ
	$1/6 - X$	$-1/2 - X$	X

If neutral, the lightest state in the loop can be our DM candidate

For models of B anomalies and DM belonging to this class see:

Kawamura et al. ’17, Cline Cornell ‘17, Barman et al. ‘18, Cerdeño et al. ‘19, Huang et al. ‘20

Minimal models for DM and B anomalies



Label	Ψ_Q	Ψ_L	Φ
$\mathcal{S}_{\rm IA}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{1},0)^\star$
$\mathcal{S}_{\rm IIA;\,-1/2}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)^\star$
$\mathcal{S}_{\rm IIA;\,1/2}$	$(\mathbf{3},\mathbf{1},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)^\star$
$\mathcal{S}_{\rm IIB}$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$
$\mathcal{S}_{\rm IIIA;\,-1/2}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)^\star$
$\mathcal{S}_{\rm IIIA;\,1/2}$	$(\mathbf{3},\mathbf{3},-1/3)$	$(\mathbf{1},\mathbf{3},-1)$	$(\mathbf{1},\mathbf{2},1/2)^\star$
$\mathcal{S}_{\rm IIIB}$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\bar{\mathbf{3}},\mathbf{3},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$
$\mathcal{S}_{\rm IVA;\,-1}$	$(\mathbf{3},\mathbf{2},7/6)$	$(\mathbf{1},\mathbf{2},1/2)$	$(\mathbf{1},\mathbf{3},-1)^\star$
$\mathcal{S}_{\rm IVA;\,0}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)$	$(\mathbf{1},\mathbf{3},0)^\star$
$\mathcal{S}_{\rm IVA;\,1}$	$(\mathbf{3},\mathbf{2},-5/6)$	$(\mathbf{1},\mathbf{2},-3/2)$	$(\mathbf{1},\mathbf{3},1)^\star$
$\mathcal{S}_{\rm VA;\,-1/2}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)^\star$
$\mathcal{S}_{\rm VA;\,1/2}$	$(\mathbf{3},\mathbf{3},-1/3)$	$(\mathbf{1},\mathbf{1},-1)$	$(\mathbf{1},\mathbf{2},1/2)^\star$
$\mathcal{S}_{\rm VB}$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$
$\mathcal{S}_{\rm VIA;\,-1/2}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)^\star$
$\mathcal{S}_{\rm VIA;\,1/2}$	$(\mathbf{3},\mathbf{1},-1/3)$	$(\mathbf{1},\mathbf{3},-1)$	$(\mathbf{1},\mathbf{2},1/2)^\star$
$\mathcal{S}_{\rm VIB}$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\bar{\mathbf{3}},\mathbf{3},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$

Label	Φ_Q	Φ_L	Ψ
$\mathcal{F}_{\rm IA;\,-1}$	$(\mathbf{3},\mathbf{2},7/6)$	$(\mathbf{1},\mathbf{2},1/2)^\star$	$(\mathbf{1},\mathbf{1},-1)$
$\mathcal{F}_{\rm IA;\,0}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)^\star$	$(\mathbf{1},\mathbf{1},0)^\star$
$\mathcal{F}_{\rm IB;\,-1/3}$	$(\mathbf{1},\mathbf{2},1/2)^\star$	$(\bar{\mathbf{3}},\mathbf{2},-1/6)$	$(\mathbf{3},\mathbf{1},-1/3)$
$\mathcal{F}_{\rm IB;\,2/3}$	$(\mathbf{1},\mathbf{2},-1/2)^\star$	$(\bar{\mathbf{3}},\mathbf{2},-7/6)$	$(\mathbf{3},\mathbf{1},2/3)$
$\mathcal{F}_{\rm IIA}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)$
$\mathcal{F}_{\rm IIB}$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$
$\mathcal{F}_{\rm IIIA;\,-3/2}$	$(\mathbf{3},\mathbf{3},5/3)$	$(\mathbf{1},\mathbf{3},1)^\star$	$(\mathbf{1},\mathbf{2},-3/2)$
$\mathcal{F}_{\rm IIIA;\,-1/2}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)$
$\mathcal{F}_{\rm IIIA;\,1/2}$	$(\mathbf{3},\mathbf{3},-1/3)$	$(\mathbf{1},\mathbf{3},-1)^\star$	$(\mathbf{1},\mathbf{2},1/2)$
$\mathcal{F}_{\rm IIIB;\,-5/6}$	$(\mathbf{1},\mathbf{3},1)^\star$	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	$(\mathbf{3},\mathbf{2},-5/6)$
$\mathcal{F}_{\rm IIIB;\,1/6}$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\bar{\mathbf{3}},\mathbf{3},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$
$\mathcal{F}_{\rm IIIB;\,7/6}$	$(\mathbf{1},\mathbf{3},-1)^\star$	$(\bar{\mathbf{3}},\mathbf{3},-5/3)$	$(\mathbf{3},\mathbf{2},7/6)$
$\mathcal{F}_{\rm IVA;\,-1}$	$(\mathbf{3},\mathbf{2},7/6)$	$(\mathbf{1},\mathbf{2},1/2)^\star$	$(\mathbf{1},\mathbf{3},-1)$
$\mathcal{F}_{\rm IVA;\,0}$	$(\mathbf{3},\mathbf{2},1/6)$	$(\mathbf{1},\mathbf{2},-1/2)^\star$	$(\mathbf{1},\mathbf{3},0)^\star$
$\mathcal{F}_{\rm IVB;\,-1/3}$	$(\mathbf{1},\mathbf{2},1/2)^\star$	$(\bar{\mathbf{3}},\mathbf{2},-1/6)$	$(\mathbf{3},\mathbf{3},-1/3)$
$\mathcal{F}_{\rm IVB;\,2/3}$	$(\mathbf{1},\mathbf{2},-1/2)^\star$	$(\bar{\mathbf{3}},\mathbf{2},-7/6)$	$(\mathbf{3},\mathbf{3},2/3)$
$\mathcal{F}_{\rm VA}$	$(\mathbf{3},\mathbf{3},2/3)$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)$
$\mathcal{F}_{\rm VB;\,-5/6}$	$(\mathbf{1},\mathbf{3},1)^\star$	$(\bar{\mathbf{3}},\mathbf{1},1/3)$	$(\mathbf{3},\mathbf{2},-5/6)$
$\mathcal{F}_{\rm VB;\,1/6}$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$
$\mathcal{F}_{\rm VB;\,7/6}$	$(\mathbf{1},\mathbf{3},-1)^\star$	$(\bar{\mathbf{3}},\mathbf{1},-5/3)$	$(\mathbf{3},\mathbf{2},7/6)$
$\mathcal{F}_{\rm VIA;\,-3/2}$	$(\mathbf{3},\mathbf{1},5/3)$	$(\mathbf{1},\mathbf{3},1)^\star$	$(\mathbf{1},\mathbf{2},-3/2)$
$\mathcal{F}_{\rm VIA;\,-1/2}$	$(\mathbf{3},\mathbf{1},2/3)$	$(\mathbf{1},\mathbf{3},0)^\star$	$(\mathbf{1},\mathbf{2},-1/2)$
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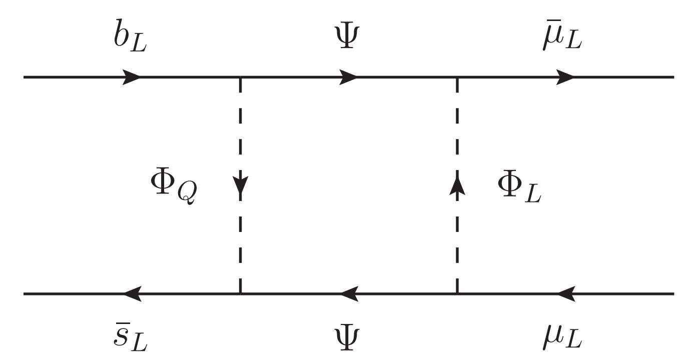
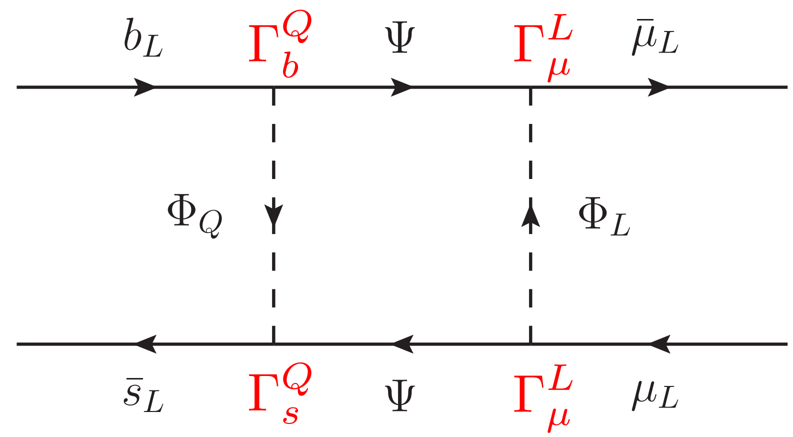
$\mathcal{F}_{\rm VIB}$	$(\mathbf{1},\mathbf{1},0)^\star$	$(\bar{\mathbf{3}},\mathbf{3},-2/3)$	$(\mathbf{3},\mathbf{2},1/6)$

$\star$ *DM candidate*



Arcadi et al. 2103.09835

Fit to B physics data



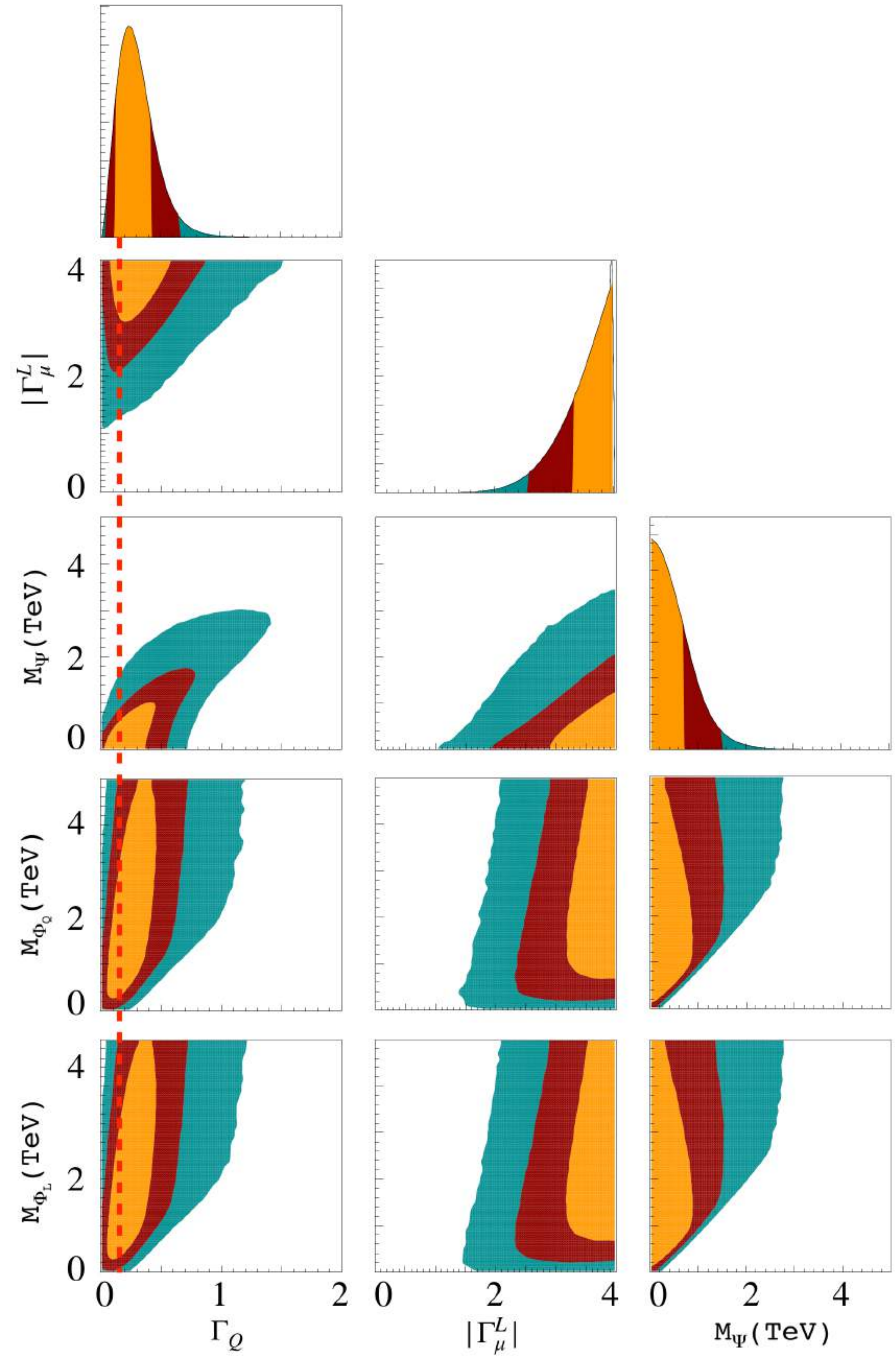
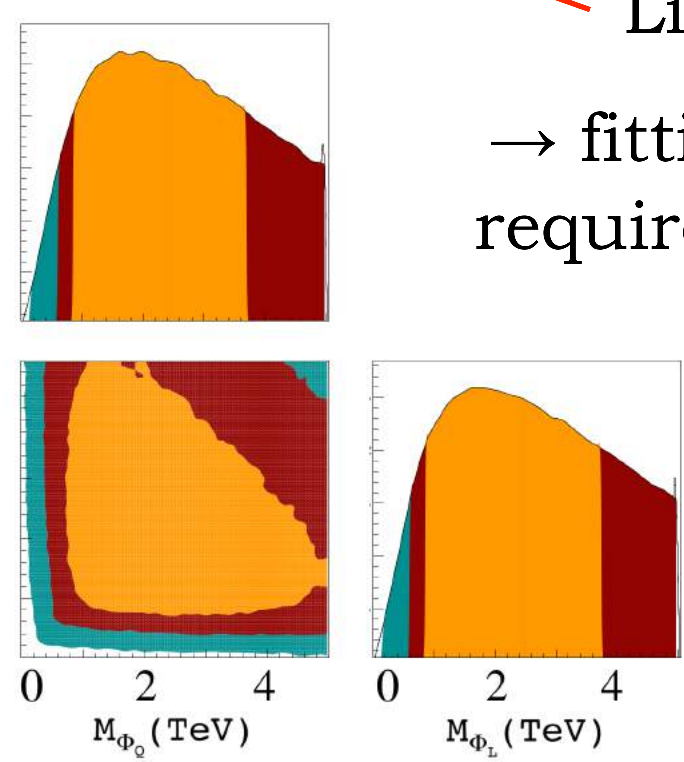
$$\mathcal{L}_\mathcal{F} \supset \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_Q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_L$$

Only 5 parameters:

$$\Gamma_Q \equiv \Gamma_b^Q \Gamma_s^{Q*},\ |\Gamma_\mu^L|,\ M_\Psi,\ M_{\Phi_Q} \text{ and } M_{\Phi_L}$$

Limited by $B_s - \bar{B}_s$

→ fitting the B anomalies requires large coupling to muons ≳ 2-3

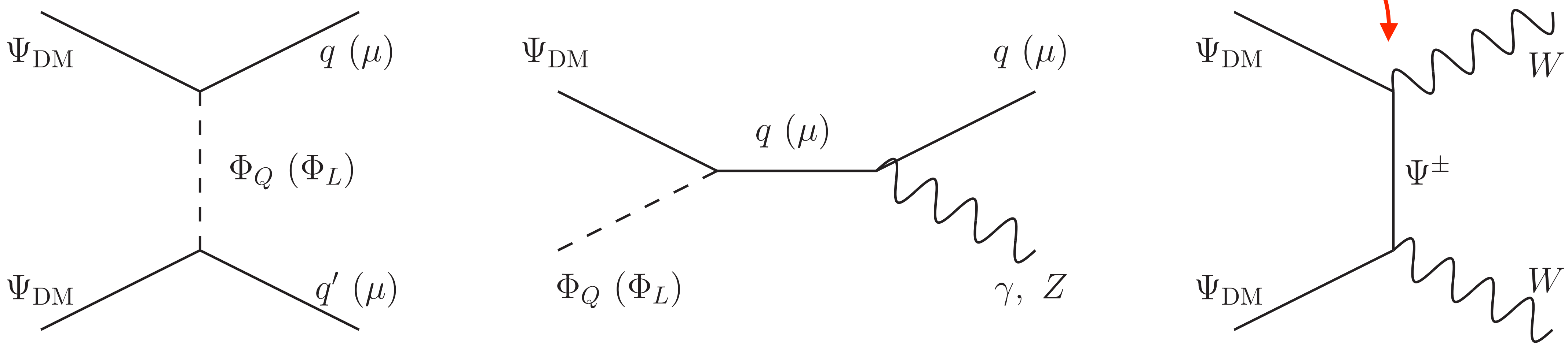



Arcadi et al. 2103.09835

DM phenomenology

DM (co-)annihilations controlled by the same coupling as C_9 and C_{10}
(unless it belongs to an SU(2) multiplet)

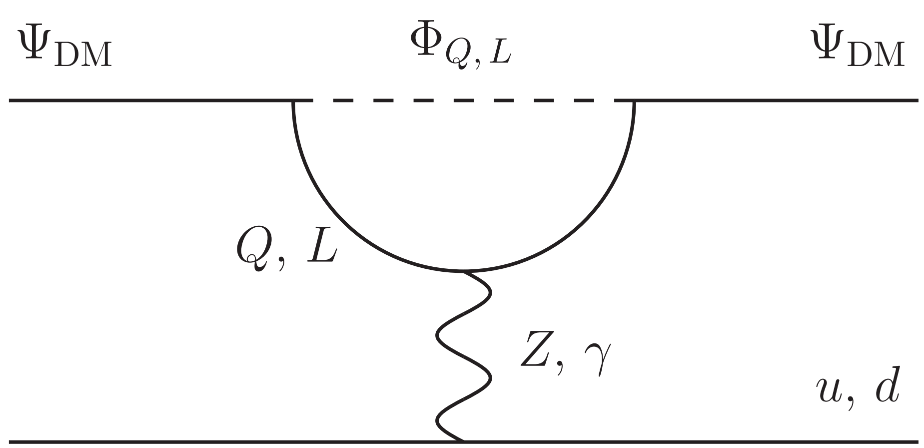
e.g. :



If DM couples to muons *t*-channel annihilation very efficient (given the large coupling)

Relic density constraint, $\Omega h^2 \lesssim 0.12$, easy to fulfil (such as the fit to the B anomalies)

For the same reason these models are challenged by bounds from DM *direct detection*:



$$c^q\, \bar\Psi_{\rm DM}\gamma_\mu\Psi_{\rm DM}\bar q\gamma^\mu q$$

or

$$c^q \left(\Phi^\dagger_{\rm DM} i\overleftrightarrow{\partial}_\mu \Phi_{\rm DM}\right) \bar q\gamma^\mu q$$

However, these operators *vanish* if DM is a Majorana fermion or a real scalar

Combined constraints (including LHC searches)

Working example with Majorana DM (same model as in Cerdeño et al. ‘19):

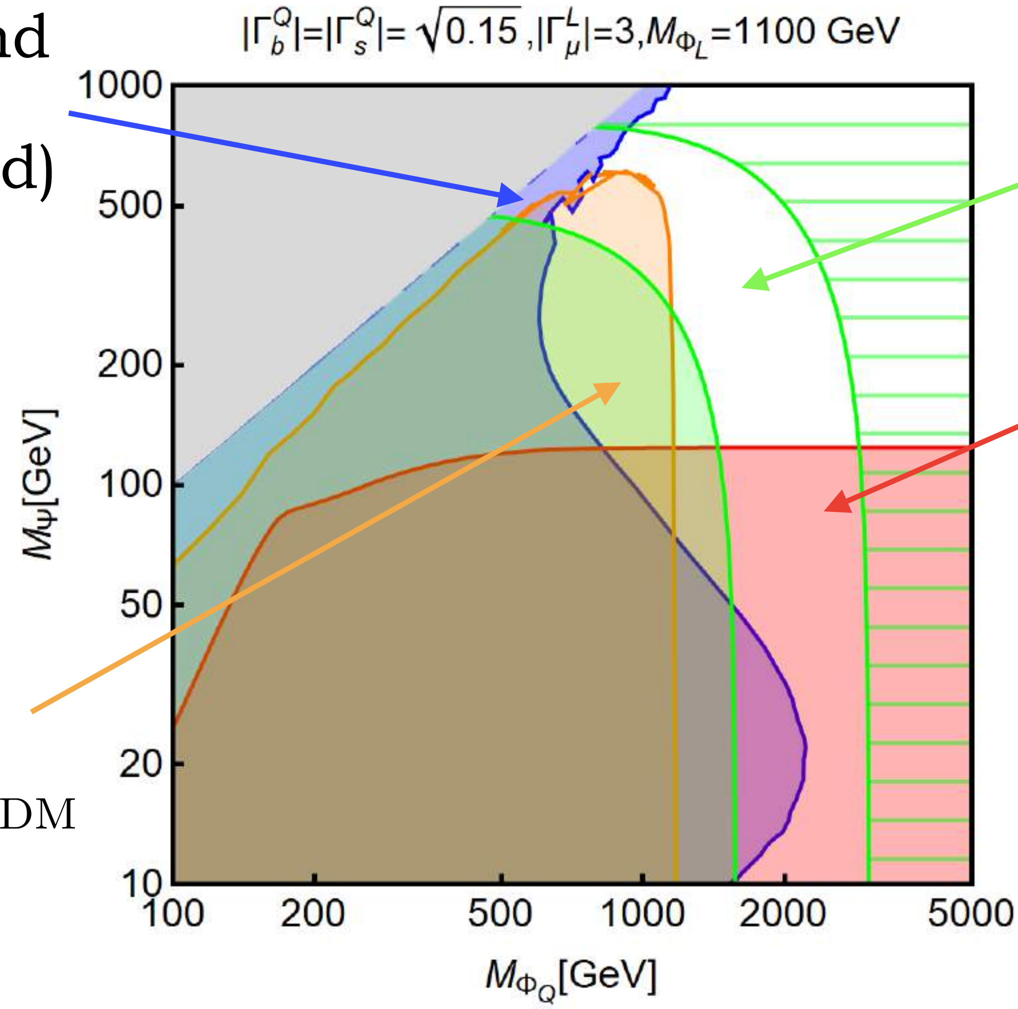
DM direct detection bound (the plane for Dirac DM would *completely* excluded)

$M_{\rm DM}$

Excluded by the LHC

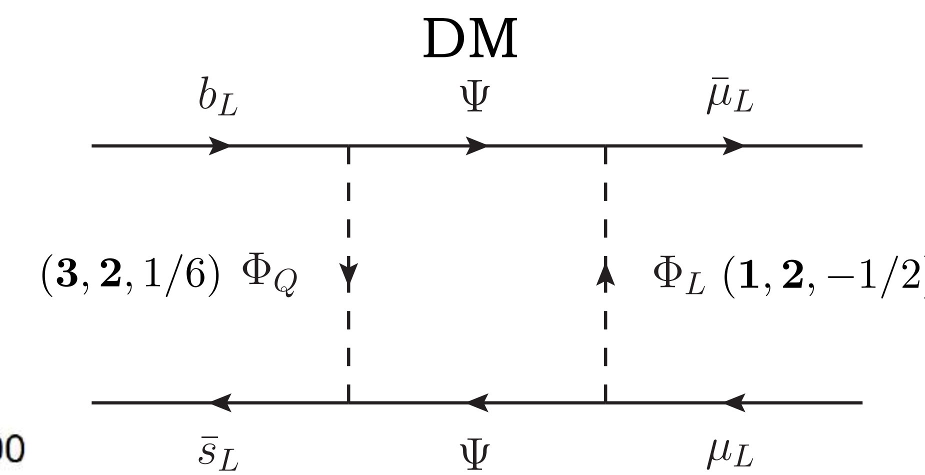
$pp \to \Phi_Q \Phi_Q \to q q' + \Psi_{\rm DM} \Psi_{\rm DM}$

i.e. (b-) jets + MET



2σ solution to B anomalies

$\Omega_{\Psi_{\rm DM}} h^2 > 0.12$



We found *natural* solutions to the B anomalies with a thermal DM candidate if:

1. DM from an SU(2) singlet (underproduced otherwise + serious LHC bounds)
2. DM couples to muons, i.e. in Ψ/Φ or Φ_ℓ/Φ_ℓ (overproduced otherwise)
3. DM is a Majorana fermion or a real scalar (direct detection)

Arcadi et al. 2103.09835

Adding the muon g-2 …

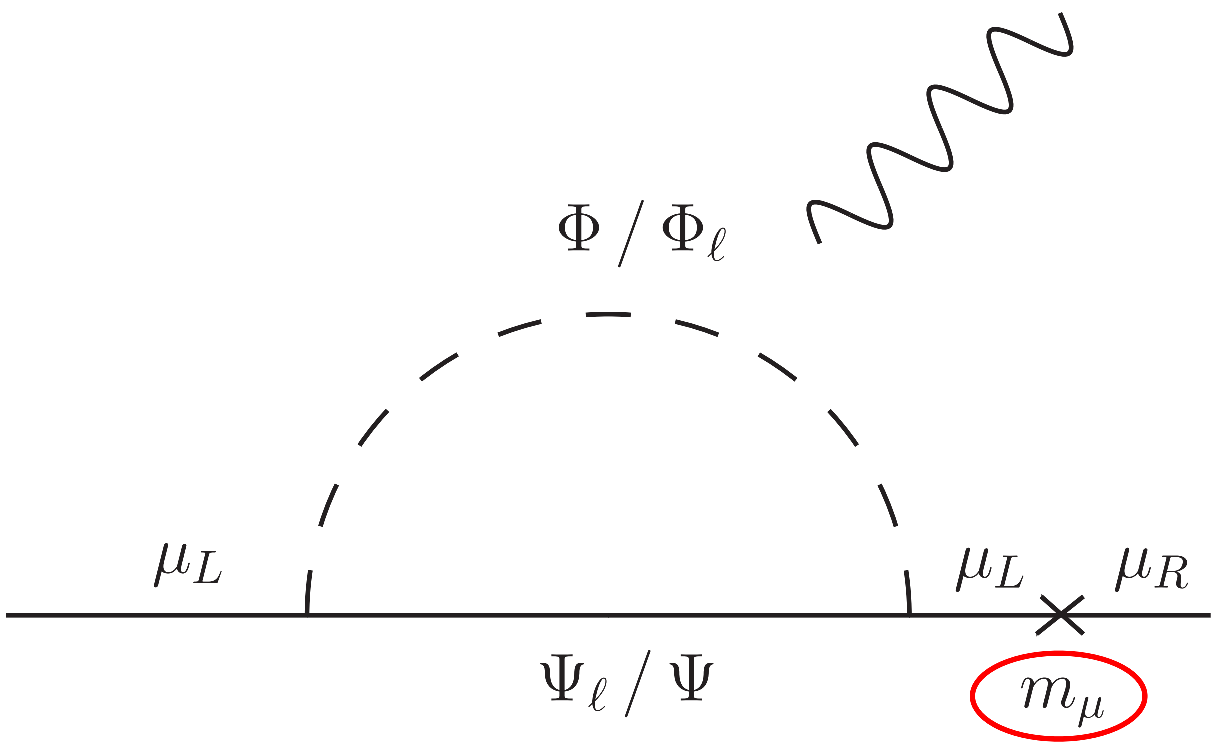
The goal is generating the usual dipole operator:

$$\frac{v}{\Lambda^2}\,\bar{\mu}_L \sigma^{\mu\nu} \mu_R\, F_{\mu\nu}$$

EW vev from a Higgs insertion to provide gauge invariant chirality flip

(I) Higgs insertion on the external line:

- Suppression from the (small) muon Yukawa coupling



The goal is generating the usual dipole operator:

EW

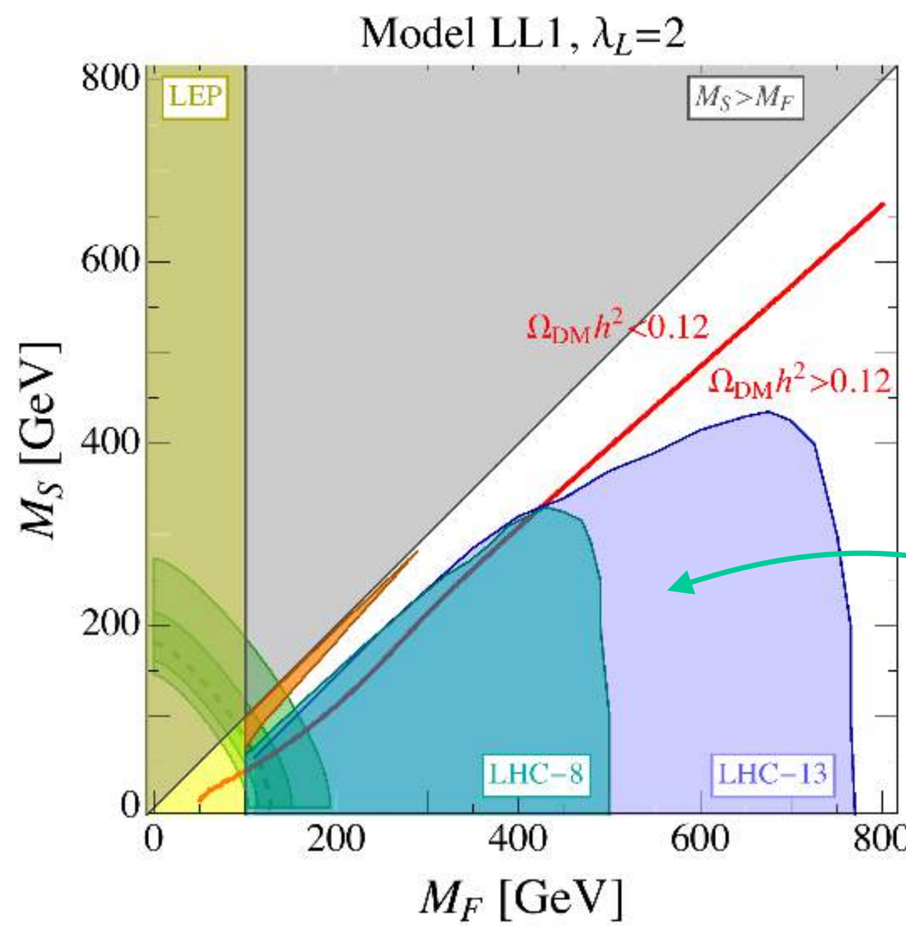
ip

(I)

•

Without adding extra fields, muon g-2 from DM is possible only in tuned regions of the parameter space

e.g.:



LC Ziegler Zupan 1804.00009

excluded by LHC searches

see also Kowalska Sessolo '17, Athron et al. '21

$\Psi_\ell \,/\, \Psi$

m_μ

The goal is generating the usual dipole operator:

$$\frac{v}{\Lambda^2}\,\bar{\mu}_L \sigma^{\mu\nu} \mu_R\, F_{\mu\nu}$$

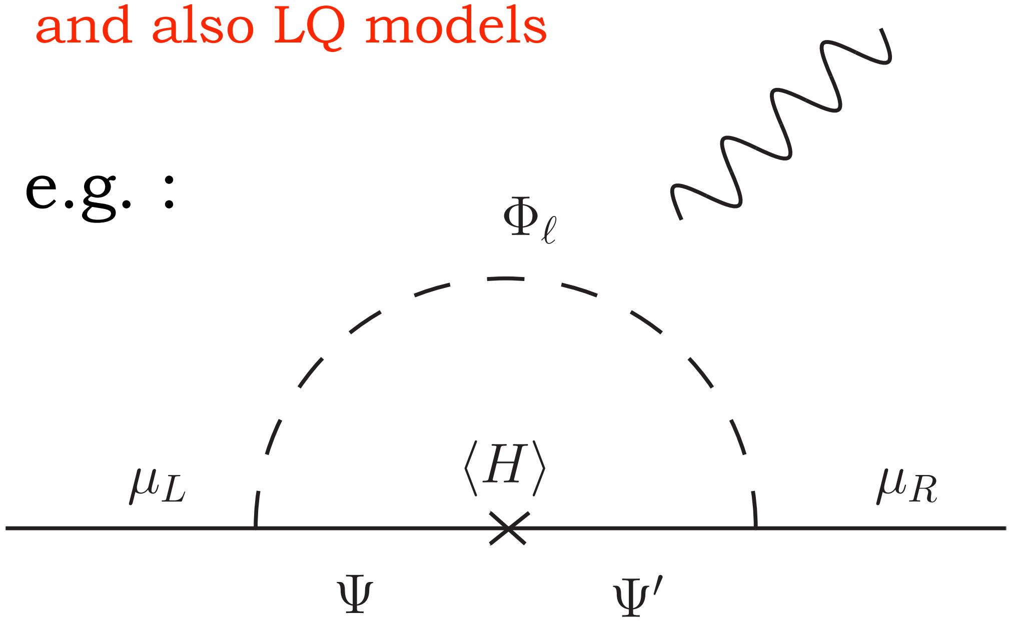
EW vev from a Higgs insertion to provide gauge invariant chirality flip

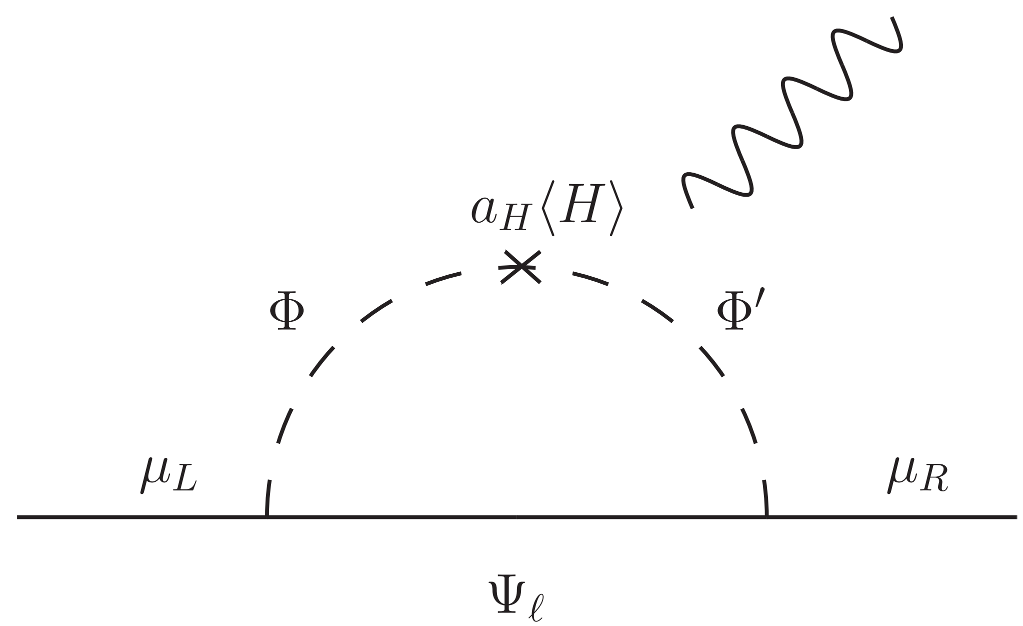
(II) Higgs insertion inside the loop:

- We add a field that mixes with our scalar or fermion via a Higgs vev
- No suppression from light Yukawas → *chiral enhancement*

see e.g. Crivellin Hoferichter '18 and '21, Kowalska Sessolo '17, LC Ziegler Zupan '18, …
and also LQ models

e.g. :





Minimal models for DM, B anomalies and g-2

We have to add a *4th field* to couple to both LH and RH muons. As we said, DM needs to directly couple to muons and to be singlet (or mixed with a singlet)

The only possibilities are: Arcadi et al. 2104.03228

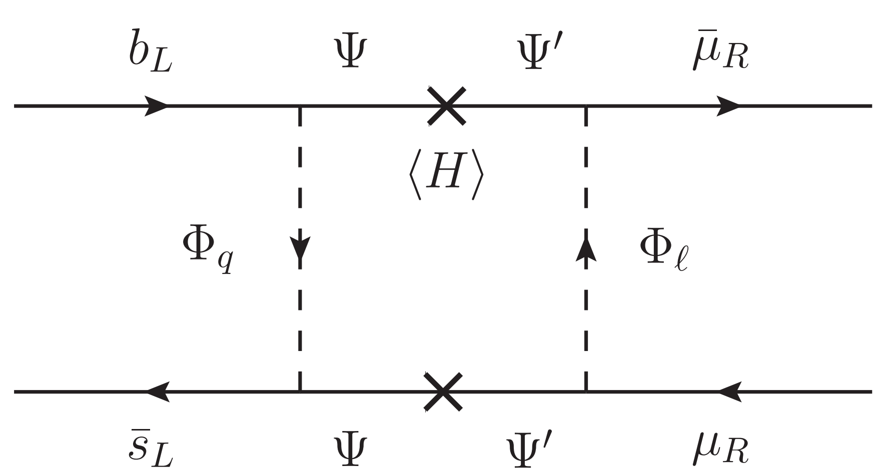
Singlet DM

the two examples

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

Mixed singlet-doublet DM

Also additional contributions breaking the relation C_9=-C_{10}, e.g.:

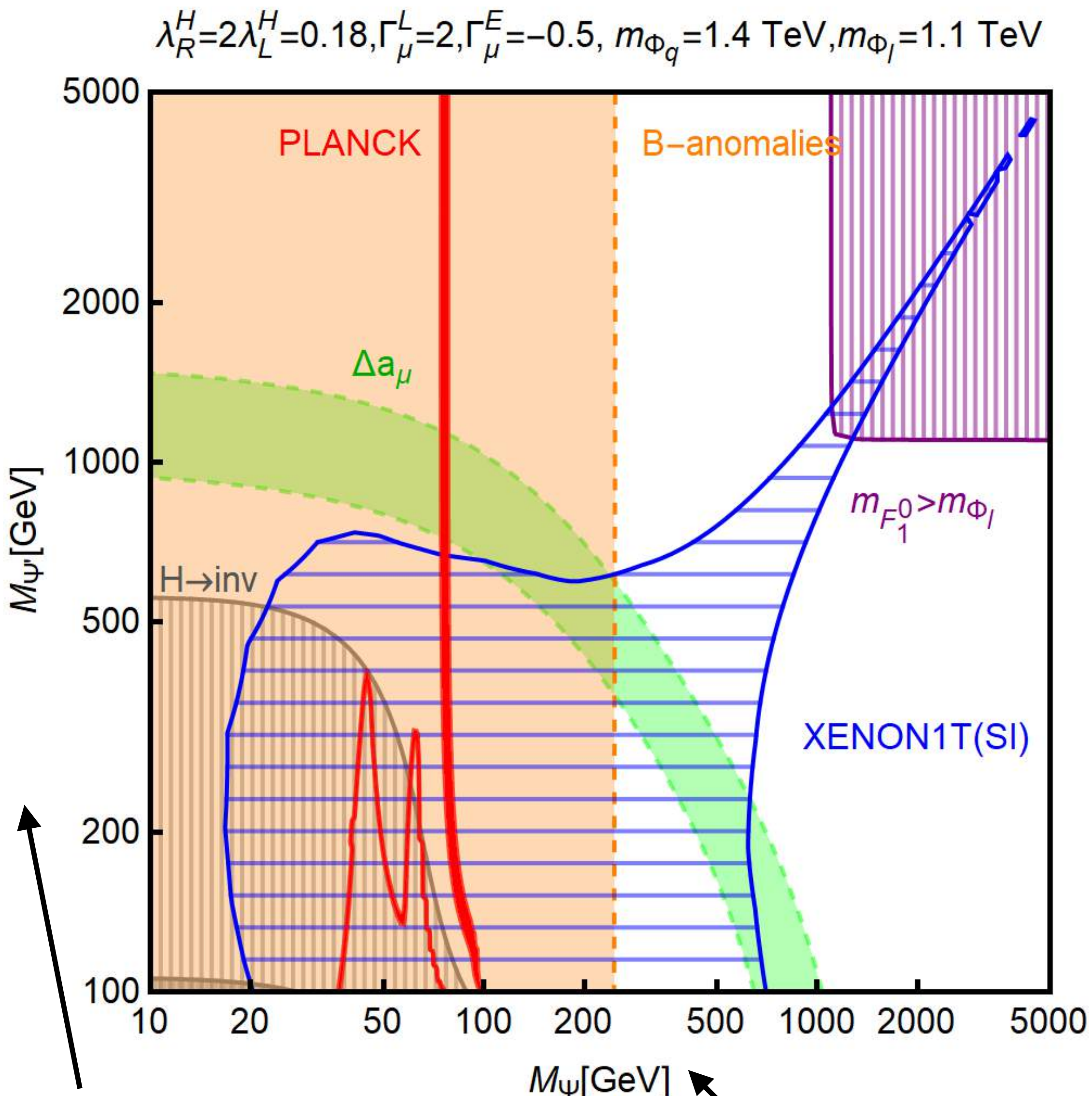


Combining everything together

Two examples: Arcadi et al. 2104.03228

$$\mathcal{L}_{\mathcal{F}}^{\Psi\Psi'} \supset \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_\ell + \Gamma_i^E \bar{E}_i P_L \Psi' \Phi_\ell + \lambda_{HL} \bar{\Psi} P_L \Psi' H + \lambda_{HR} \bar{\Psi} P_R \Psi' H + \text{h.c.}\,,$$

Fermion singlet-doublet DM



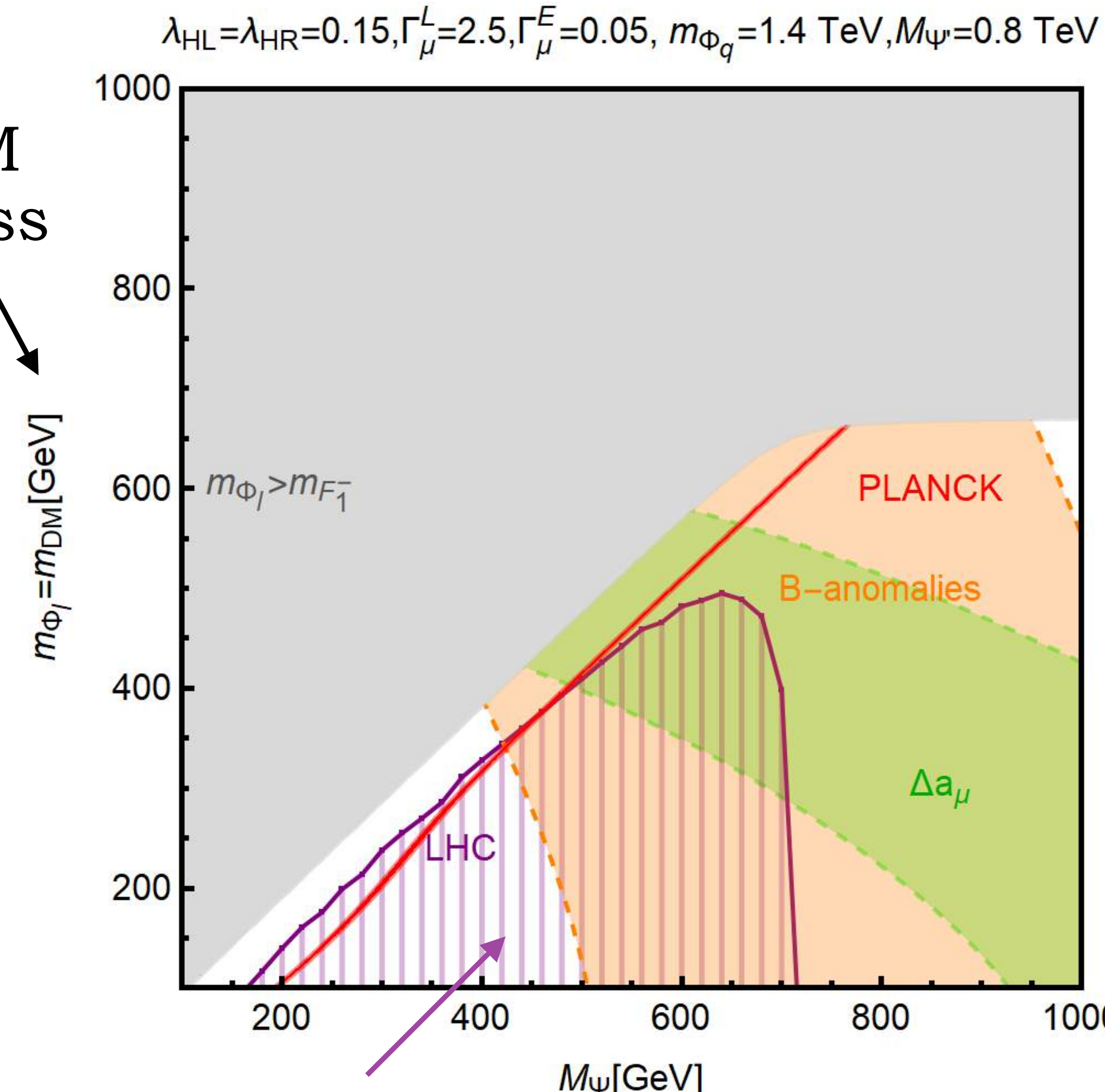
doublet mass

singlet mass

(DM is the lightest Majorana state)

Real scalar DM

DM mass



LHC bound from

$pp \to \Psi\Psi \to \mu^+\mu^- + \not{E}_T$

We systematically built models addressing the muon g-2 and the B anomalies through loops involving a thermal DM candidate accounting for 100% of the observed DM abundance

This can be achieved by introducing 4 new fields, at the price of a large coupling to LH muons ($\gtrsim$ 2-3) and a (moderate) chiral enhancement of the g-2 contribution

Rather than "realistic" models, this exercise showed the minimal ingredients that a fully fledged theory may need to incorporate (e.g. large muon couplings imply a Landau pole below ~2500 TeV)

These minimal solutions seem to be in the reach of future direct detection and/or LHC searches (and definitely of a muon collider) + possible correlated effects from H/Z decays into muons (Crivellin Hoferichter '21)

Thank you!

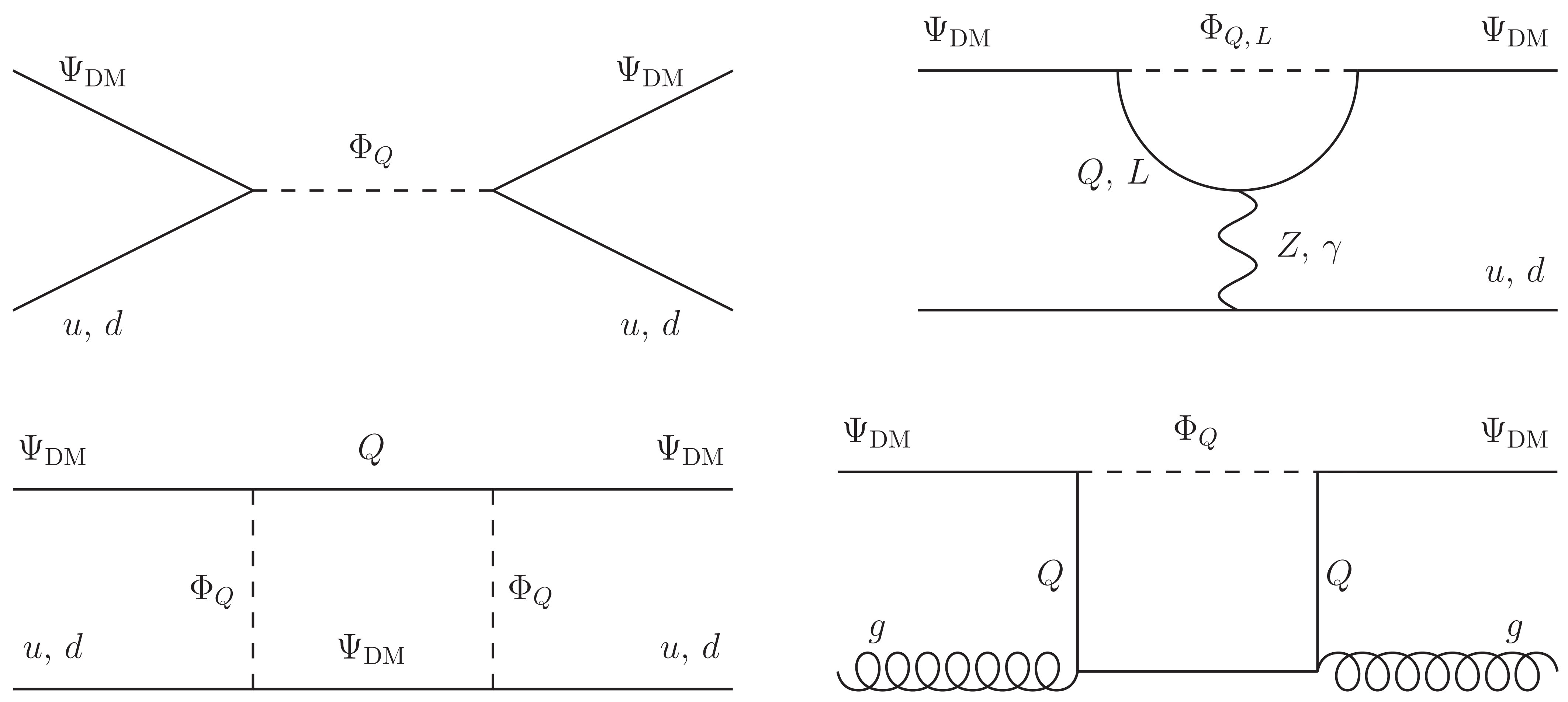
谢谢大家!

Additional slides

DM annihilation and direct detection

$$\langle \sigma v \rangle^{\rm Complex}_{\rm DM\,DM} = \sum_f N_c \frac{\lambda_f^4 M^2_{\Phi_{\rm DM}} v^2}{48\pi \left(M^2_{\Phi_{\rm DM}} + M^2_{F_f} \right)^2}, \qquad \langle \sigma v \rangle^{\rm Dirac}_{\rm DM\,DM} = \sum_f N_c \frac{\lambda_f^4 M^2_{\Psi_{\rm DM}}}{32\pi \left(M^2_{\Psi_{\rm DM}} + M^2_{S_f} \right)^4},$$

$$\langle \sigma v \rangle^{\rm Real}_{\rm DM\,DM} = \sum_f N_c \frac{\lambda_f^4 M^6_{\Phi_{\rm DM}} v^4}{60\pi \left(M^2_{\Phi_{\rm DM}} + M^2_{F_f} \right)^4}, \qquad \langle \sigma v \rangle^{\rm Majorana}_{\rm DM\,DM} = \sum_f N_c \frac{\lambda_f^4 M^2_{\Psi_{\rm DM}} \left(M^4_{\Psi_{\rm DM}} + M^4_{S_f} \right) v^2}{48\pi \left(M^2_{\Psi_{\rm DM}} + M^2_{S_f} \right)^4}$$



Singlet-doublet mixing

$\mathcal{F}_{\rm Ib}$: Singlet-doublet fermionic DM

$$\mathcal{L}_{\mathcal{F}_{\rm Ib}} \supset \Gamma_i^Q \, \bar{Q}_i \, P_R \Psi \, \Phi_q + \Gamma_i^L \, \bar{L}_i \, P_R \Psi \, \Phi_\ell + \Gamma_i^E \, \bar{E}_i \, P_L \Psi' \cdot \Phi_\ell + \lambda_{HL} \bar{\Psi} \, P_L \Psi' \cdot H + \lambda_{HR} \bar{\Psi} P_R \Psi' \cdot H + \text{h.c.}\,.$$

$$\Psi = (\mathbf{1},\mathbf{1},0) \quad \Psi' = (\mathbf{1},\mathbf{2},-1/2) = (\Psi'^0, \Psi'^-) \quad \Phi_\ell = (\mathbf{1},\mathbf{2},-1/2),\ \Phi_q = (\mathbf{3},\mathbf{2},1/6)$$

$$\begin{pmatrix} \Psi_R^{0\,c} \equiv \Psi_L^0 \\ \Psi_L'^0 \\ \Psi_R'^{0\,c} \end{pmatrix}_i = V_{ij} F^0_{L,j}\,, \quad V^T \begin{pmatrix} M_\Psi & \lambda_{HL} v/\sqrt{2} & \lambda^*_{HR} v/\sqrt{2} \\ \lambda_{HL} v/\sqrt{2} & 0 & M_{\Psi'} \\ \lambda^*_{HR} v/\sqrt{2} & M_{\Psi'} & 0 \end{pmatrix} V = \begin{pmatrix} m_1^{F^0} & & \\ & m_2^{F^0} & \\ & & m_3^{F^0} \end{pmatrix}$$

$\mathcal{F}_{\rm IIb}$: Real scalar DM

$$\mathcal{L}_{\mathcal{F}_{\rm IIb}} \supset \Gamma_i^Q \, \bar{Q}_i \, P_R \Psi \, \Phi_q + \Gamma_\mu^L \, \bar{L}_\mu \, P_R \Psi \, \Phi_\ell + \Gamma_\mu^E \, \bar{E}_\mu \, P_L \Psi' \, \Phi_\ell + \lambda_{HL} \bar{\Psi} P_L \Psi' H + \lambda_{HR} \bar{\Psi} P_R \Psi' H + \text{h.c.}\,,$$

$$\Phi_q = (\mathbf{3},\mathbf{1},2/3),\ \Phi_\ell = (\mathbf{1},\mathbf{1},0),\ \Psi = (\mathbf{1},\mathbf{2},-1/2) = (\Psi^0, \Psi^-) \text{ and } \Psi' = (\mathbf{1},\mathbf{1},-1).$$

$$\mathcal{M}_\Psi = \begin{pmatrix} M_{\Psi'} & \frac{v}{\sqrt{2}} \lambda^*_{HR} \\ \frac{v}{\sqrt{2}} \lambda_{HL} & M_\Psi \end{pmatrix} \qquad (U^{R\dagger} \mathcal{M}_\Psi U^L)_{ij} = m_i^{F^-} \, \delta_{ij}$$