Flavourful vector FIPs for $B \to K$ and $(g-2)_\mu$ anomalies

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Based on 2002.11150 and 2106.xxxxx with M. Fedele, K. Kowalska and E. Sessolo

Why always the muons …

- Experimental anomalies in muon-related observables have been gaining traction in recent months

Flavour-violation in $B \to K^{(*)}$ (mostly LHCb)

→Form a consistent picture in WET

→Focus in this talk on the $b \to s$ signatures

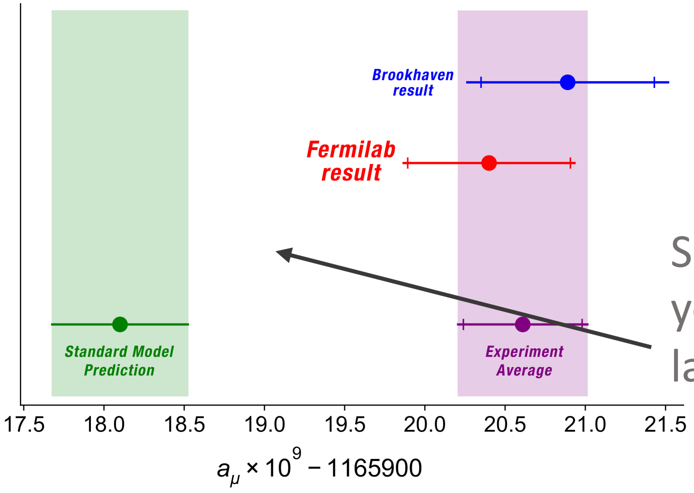
$$R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}(B^+ \to K^+e^+e^-)} = 0.846\ {}^{+0.042}_{-0.039}\ (\mathrm{stat})\ {}^{+0.013}_{-0.012}\ (\mathrm{syst})$$

LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
[LHCb-PAPER-2021-004]

And many other observables: R_{K^*} , Angular obs., etc…

Unexpectedly large $(g-2)_\mu$

w.r.t data-driven theory estimates



SM goes here if you trust BMW lattice QCD

- Both are "low energy precision observables"

→ A great many models with heavy new particles, in this this talk we try to find a common "low scale" NP explanation

Feebly-Interacting Particles

- FIPs= "new neutral particle which interact with the SM via suppressed new interactions"

  → Appear in many NP solution to the SM challenges

The hierarchy problem	pNGB / ALPs
What is the origin of flavour?	pNGB / ALPs
The nature of dark matter?	Light Dark Matter
Origin of the ν masses?	Heavy Neutral Leptons
Why does QCD respect CP ?	QCD axion

+ dark photons, dark Higgs…

- In many cases, flavourful interactions are possible and even expected
  - → pNGB from flavour syms.
  - →HNL and dark Higgs, etc…

In this talk we focus also on MeV to tens of GeV scale

Dark EFT approach → DEFT

- Goal: fitting the anomalies with the "tree-level" exchange of a light mediator
- Provide additionally solution to $(g-2)_\mu$
- Inputs from WET global fits: we want a negative interference with SM in $\bar{s}\gamma^\mu P_L b$

→ The anomalies as a true "low scale" effect

→ Couplings to muons

→ Use spin-1 FIP, V, with $\bar{s}\gamma^\mu P_L b$

- We construct an EFT description of SM (cf. SM+X, Portal EFT, etc …), for this talk we pick:

Pospelov, Dror, Lasenby Arina, Hajer , Klose and many others

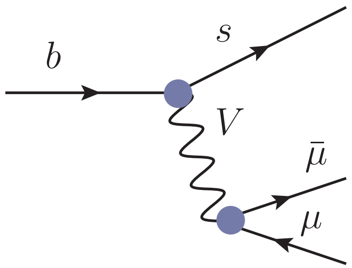
"4 4" model	$Q_4^{bsV} = (\bar{s}\gamma_\rho P_L b)\, V^\rho\,,$	$Q_4^{\mu\mu V} = (\bar{\mu}\gamma_\rho \mu)\, V^\rho,$	$\widetilde{Q}_4^{\mu\mu V} = (\bar{\mu}\gamma_\rho\gamma^5 \mu)\, V^\rho,$
"6 4" model	$Q_6^{bsV} = (\bar{s}\gamma_\rho P_L b)\, \partial_\sigma V^{\rho\sigma}$	$Q_4^{\mu\mu V} = (\bar{\mu}\gamma_\rho \mu)\, V^\rho,$	$\widetilde{Q}_4^{\mu\mu V} = (\bar{\mu}\gamma_\rho\gamma^5 \mu)\, V^\rho,$

There are of course many other operators…

Fitting the anomalies

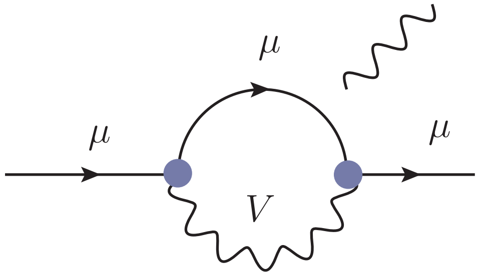
- As a simple scaling, the anomalies require

$B \to K$ anomalies



$$\mathcal{C}^{bsV}_{4+\delta_1}\,\mathcal{C}^{\mu\mu V}_{4+\delta_2}\left(\frac{q}{\Lambda}\right)^{\delta_1+\delta_2} \approx 10^{-9}$$

$(g-2)_\mu$ anomalies



Around the GeV

$$\sqrt{(\mathcal{C}_4^{\mu\mu V})^2 - 5\,(\widetilde{\mathcal{C}}_4^{\mu\mu V})^2} \sim 0.05\left(\frac{1\,\mathrm{GeV}}{m_V}\right)^2$$

- In details though: explicit momentum dependence of the $bs\mu\mu$ vertex

$$C_9 = \frac{4\pi\mathcal{N}}{\alpha_{\rm em}}\frac{(\mathcal{C}_4^{bsV} - \frac{q^2}{\Lambda^2}\mathcal{C}_6^{bsV})(\mathcal{C}_4^{\mu\mu V} - \frac{q^2}{\Lambda^2}\mathcal{C}_6^{\mu\mu V})}{q^2 - M_V^2 + i\Gamma_V M_V}$$

We assume that V has an invisible decay width
→ left as free parameter

- Since we have q^2-dependent observables complete fit needed
  - →Dependence on the width important for M_V in the GeV range

Fitting the anomalies

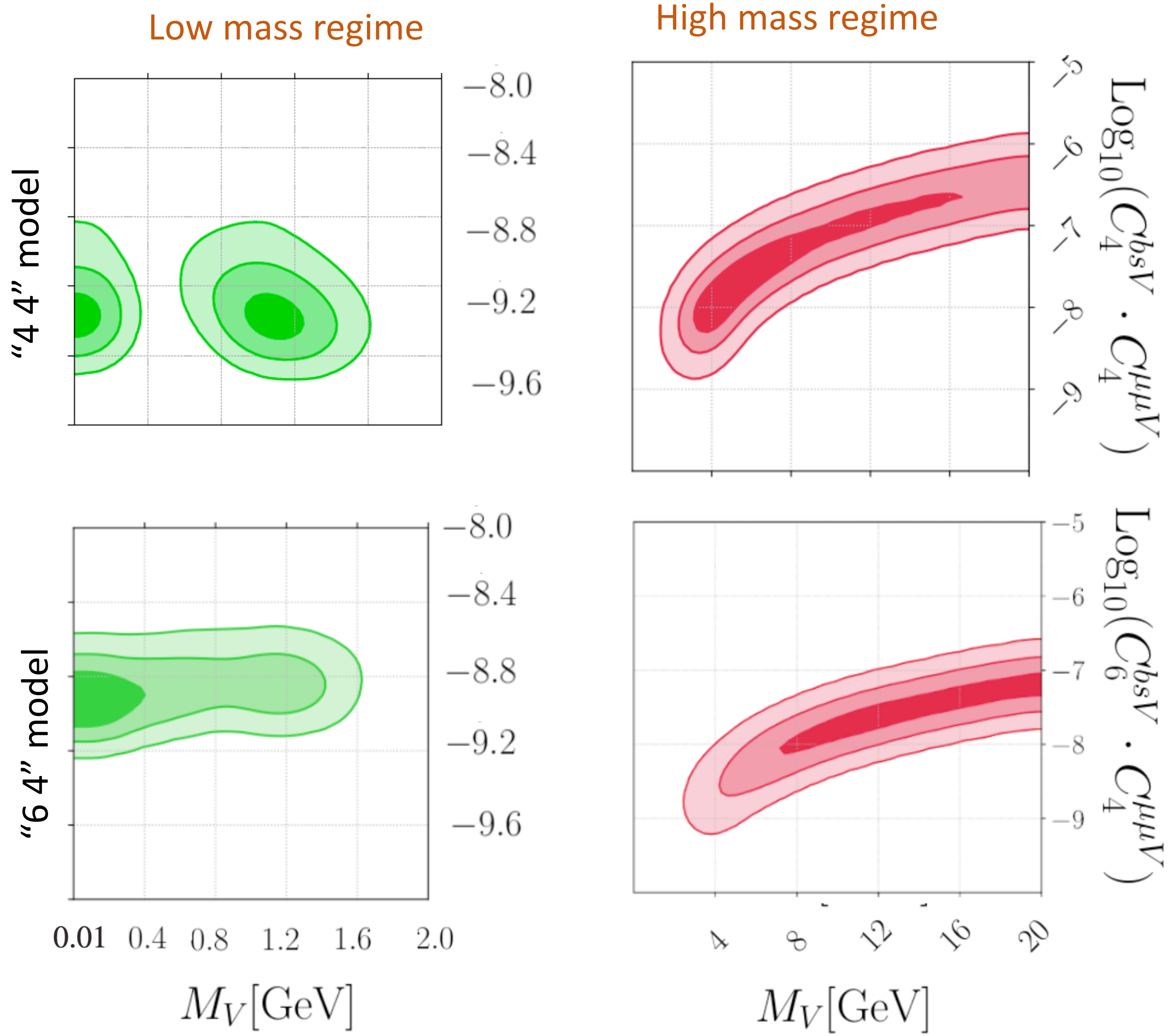
- We implemented the model in HEPfit to account for the q^2 , tested various combinations

  → Included LFUV ratios R_K, R_{K^*} and the angular observables in $B \to K^* \mu\mu$

  → Significant differences between C_4 and C_6 case (q^2 dependence)

- From fit point of view, both "low" and "high" masses are achievable

  → Resonance + width effects are important!



The troubles with non-conserved currents...

- The interaction between vector FIP and SM can be represented via a "current"

$$\mathcal{L}_{\rm int} \supset V_\mu \, \mathcal{J}_V^\mu$$

→ It does not corresponds a priori to a SM global symmetry

- Non-conserved SM currents leads to strong signatures, particularly at small vector masses

Pospelov, Dror, Lasenby

→ Most processes scale as $\frac{E^2}{M_V^2}$, since any on-shell vector leads to as $M^\mu \sim \frac{q^\mu}{M_V}$

- We have

→ Tree-level flavour violation, both critical to the anomalies and very strongly constrained

  - B_s -mixing, $\mathrm{B}_s \to \mu\mu$
  - $B \to K^{(*)}V$ on-shell processes, with subsequent visible/invisible V decay

→Weak-isospin violation (no coupling to neutrinos)

  - Strong flavour-dependent modification of W decay rates

→Axial-coupling interaction to the SM fermions

The GeV-FIP windows "6-4"

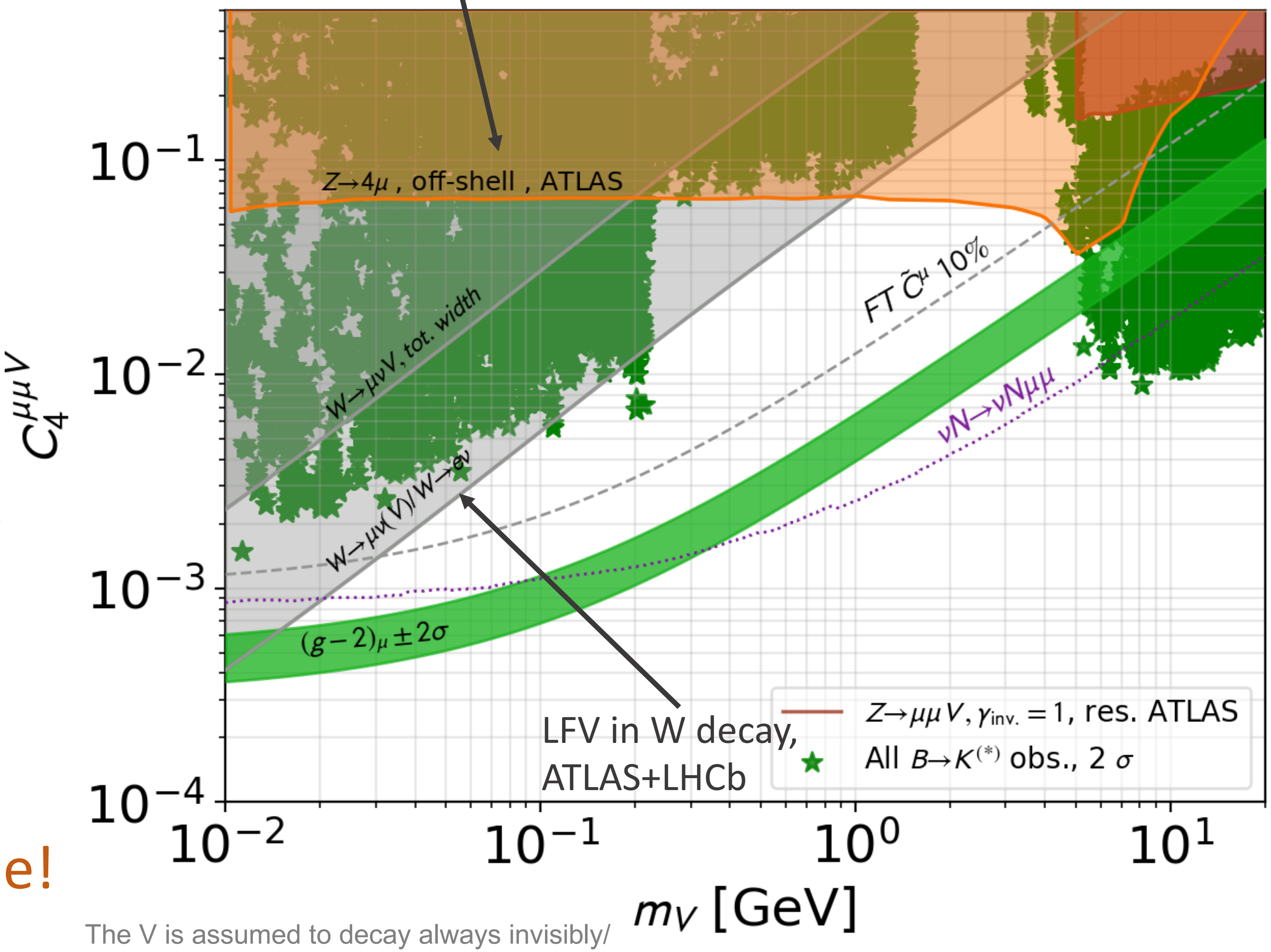
$$\mathcal{Q}_6^{bsV} = (\bar{s}\gamma_\rho P_L b)\,\partial_\sigma V^{\rho\sigma}$$
$$\mathcal{Q}_4^{\mu\mu V} = (\bar{\mu}\gamma_\rho \mu)\,V^\rho,$$

- Low masses very constrained
  - → Green points show fit $B \to K^{(*)}$ observables at 2σ (including invisible decays)
  - → Several other subdominant low mass constraints not shown
  - → Combined with W decays rules out the low mass region
- Above the B mass, large open parameter space
  - → Similar effect for a "4-4" model

→ LHC searches play a critical role!

Multi-leptons search, ATLAS 2103.01918

PRELIMINARY 2006.xxxxx -- LD, M. Fedele, K. Kowalska, E. Sessolo

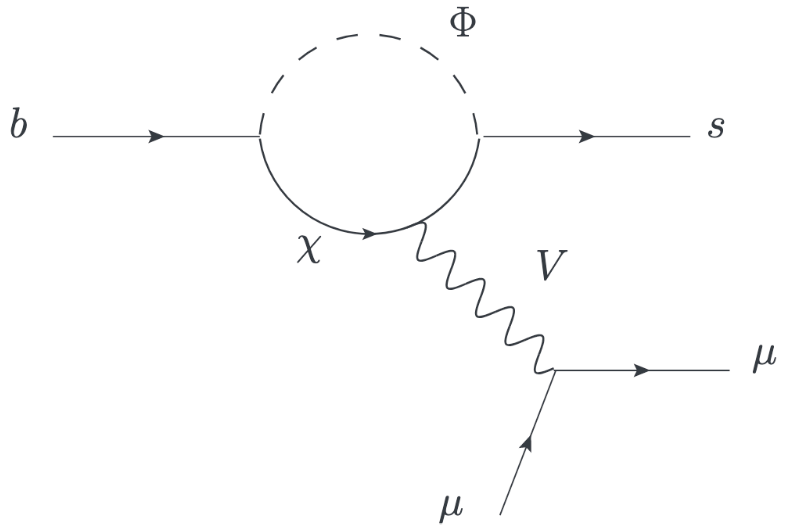


The V is assumed to decay always invisibly/ remains stable below the dimuon threshold

An (partial) UV realisation

- Aim: realise an effective bsV vertex via a loop of heavy scalar/light dark fermion

  → Log-enhancement of the loop from scale mismatched



$$\tilde{g} = -\frac{g_D\, Q_\Phi}{16\pi^2 m_\Phi^2} \sum_i y_s^{i*} y_b^i\, \mathcal{F}(x_i)$$

- The mediator is the gauge boson of a dark U(1), after SSB in the dark sector

$$\mathcal{L} \supset y_{s(b)} \phi^* \bar{\chi} P_L s(b) + \mathrm{H.c.}$$

$$\mathcal{L} \supset \left(g_\mu^V \bar{\mu}\gamma_\nu\mu + g_\mu^A \bar{\mu}\gamma_\nu\gamma_5\mu\right) V^\nu$$

$\Phi : (\mathbf{3}, \mathbf{2}, 1/6, Q_\Phi)$ → Colored “squark”

$\chi : (\mathbf{1}, \mathbf{1}, 0, -Q_\Phi)$ → U(1)-charged Dirac dark fermion

- Generating the tree-level muon-coupling in a non-anomalous fashion requires additional model building

Conclusion

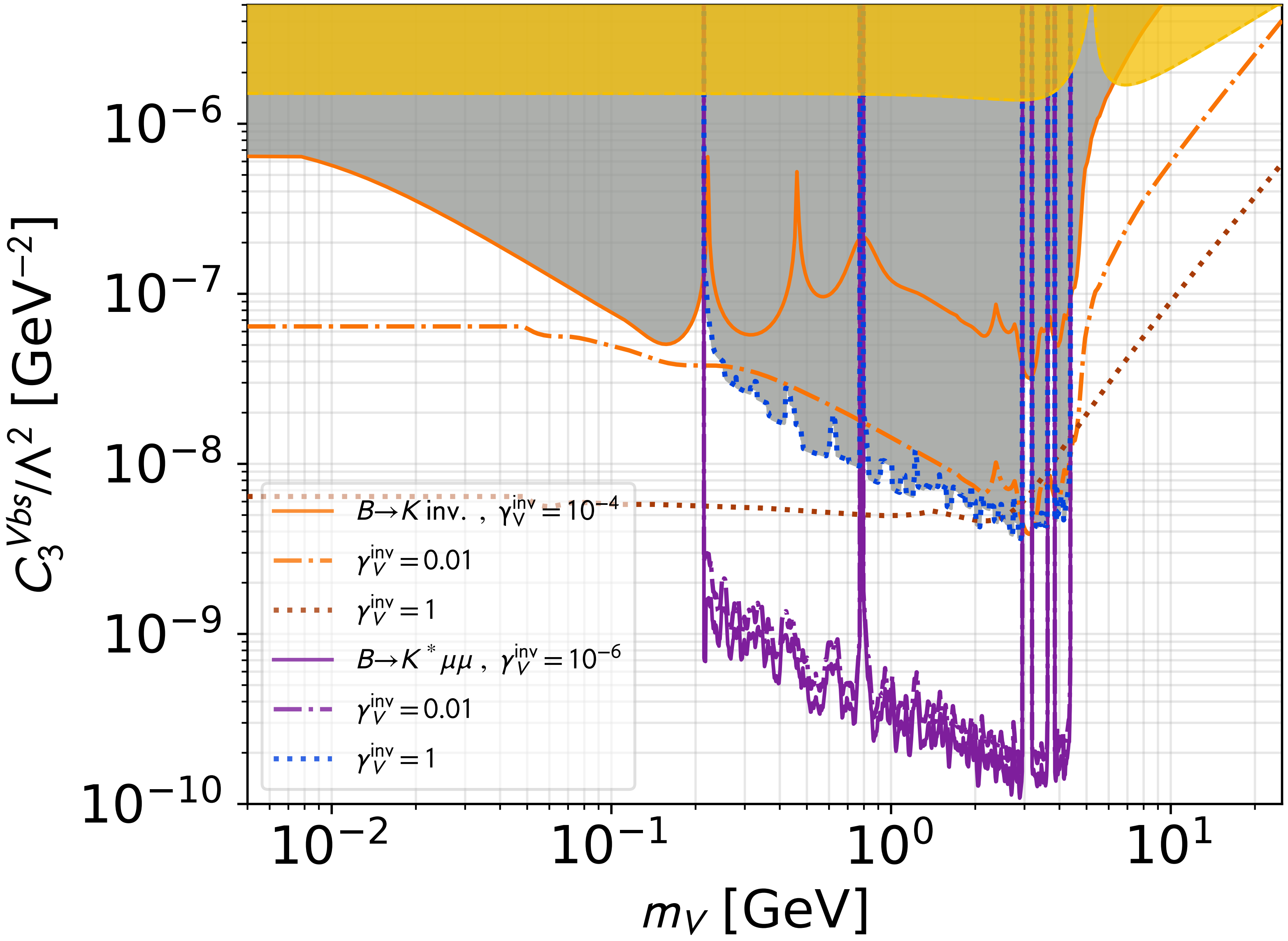
- Flavoured FIPs have been long used to fit various "precision anomalies"
- We have constructed an dark "EFT" approach to test the compatibility between MeV to GeV FIP with
  - Flavoured $B \to K$ anomalies
  - $(g-2)_\mu$ experimental results
  - All relevant precision physics constraints, both in flavourful and flavour-blind analyses
- The low mass regime is not-favoured by anomaly fits+constraints
- The GeV FIP windows turns out to be particularly interesting

  →Simultaneous fit possible to both anomalies without tuning
- LHC searches are relevant for this region → exciting experimental targets for Run-3 and HL-LHC

Backup slides

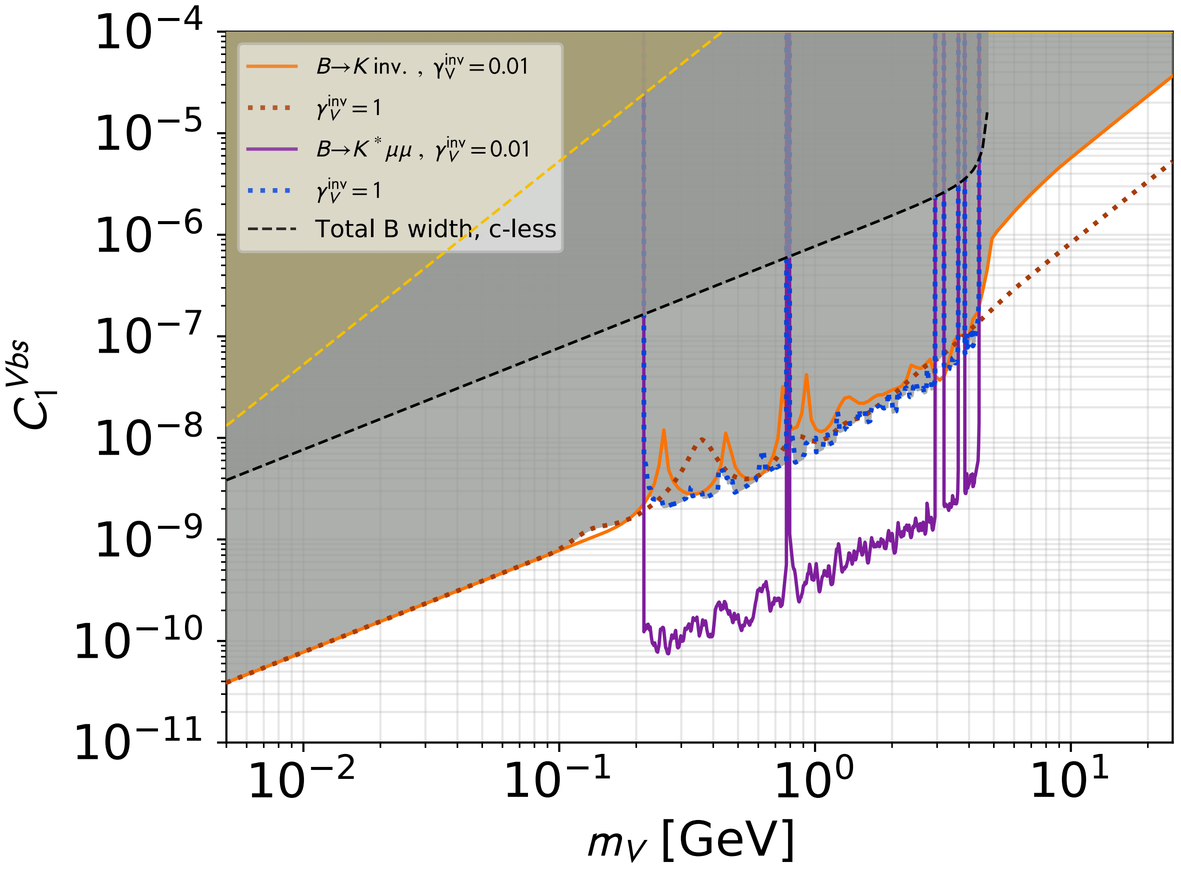
B -> K limits in "4 6" model

- Strongest constraints are from "visible" decays
  - → large invisible width for V is typically required
- Invisible limits from $B \to K \nu\nu$ can be re-casted
  - → Care must me taken since different kinematics
  - → "Off-shell" component dominates at low masses



B -> K limits in “4 4” model

- Strongest constraints are from “visible” decays
  - → large invisible width for V is typically required
- No suppression of the on-shell decay $B \to K^{(*)} V$ leads to very strong constraints at small V masses

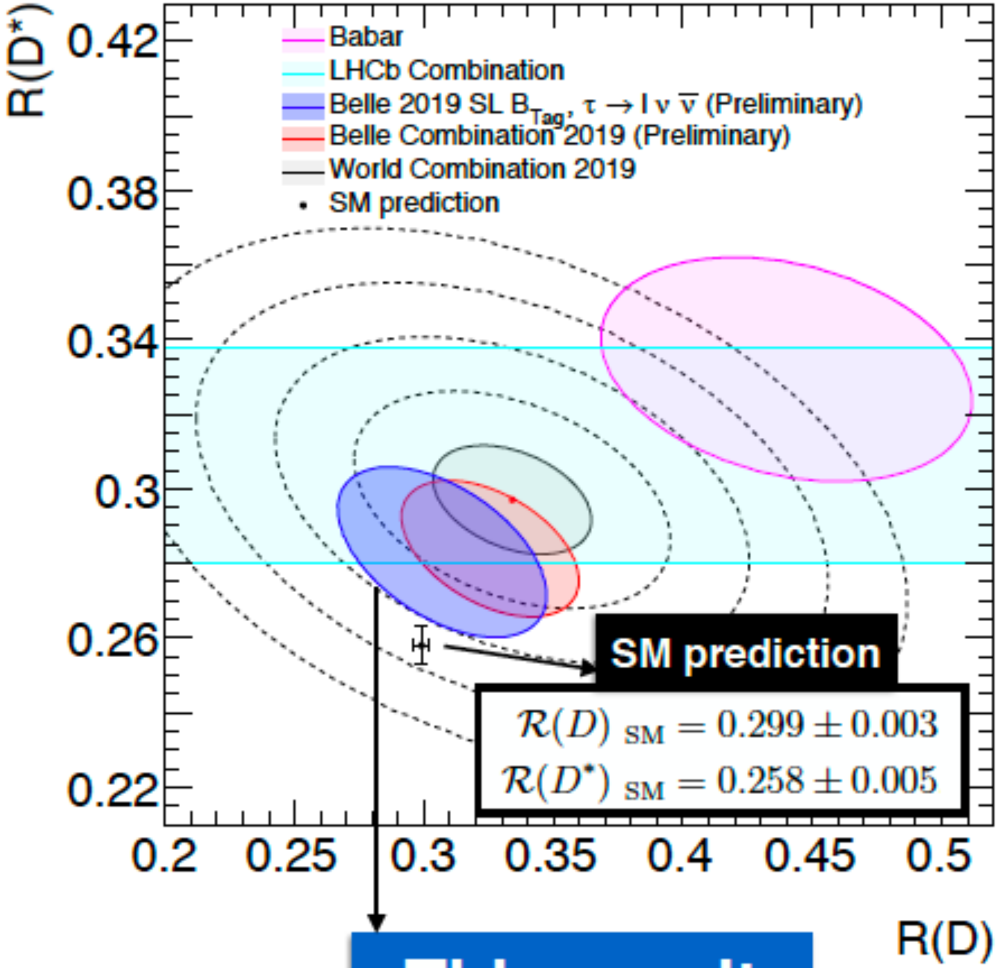


Current status B-anomalies

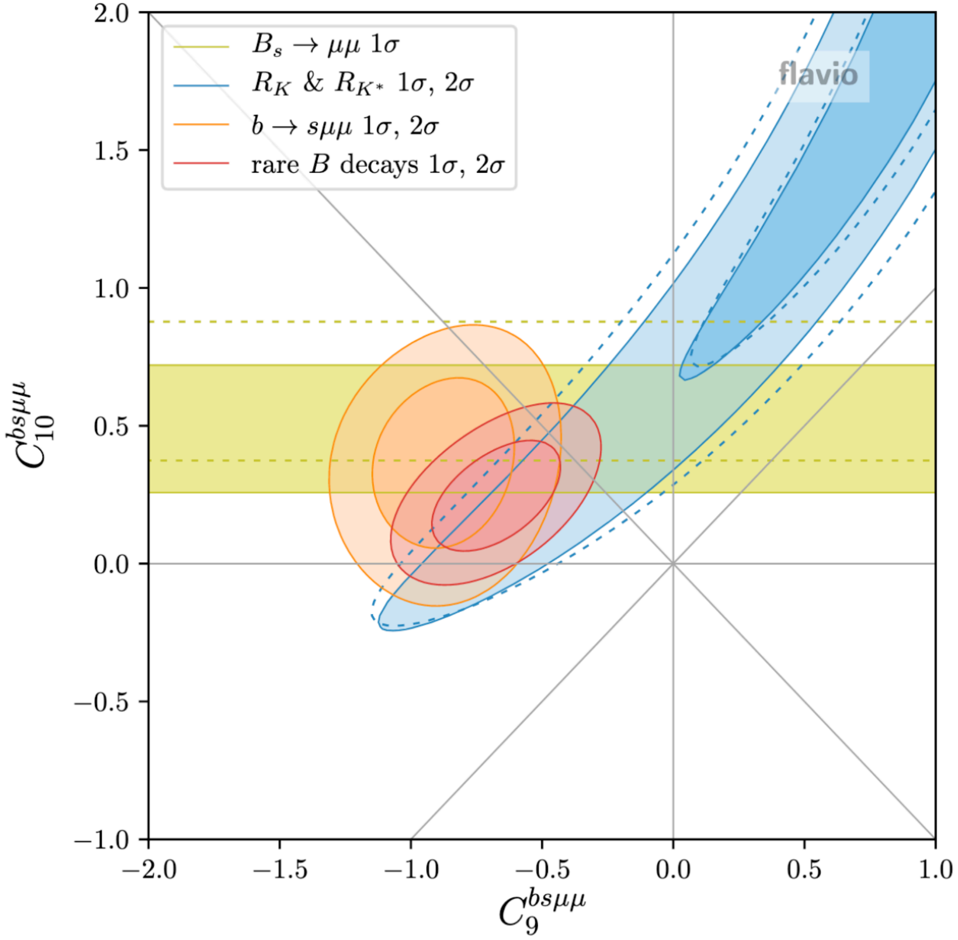
Altmannshofer, Stangl, 2103.13370

1. Updated Belle measurement of R_{K^*} Talk by M. Prim

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu\mu)}{\mathrm{BR}(B \to K^* ee)} = \begin{cases} 0.90^{+0.27}_{-0.21} \pm 0.10\,, & \text{for } 0.1\,\mathrm{GeV}^2 < q^2 < 8\,\mathrm{GeV}^2 \\ 1.18^{+0.52}_{-0.32} \pm 0.10\,, & \text{for } 15\,\mathrm{GeV}^2 < q^2 < 19\,\mathrm{GeV}^2 \end{cases}$$



G. Ciara's talk @ MoriondEW2019



2. Updated LHCb measurement of R_K Talk by T. Humair

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)} = 0.846\ ^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}\,,$$

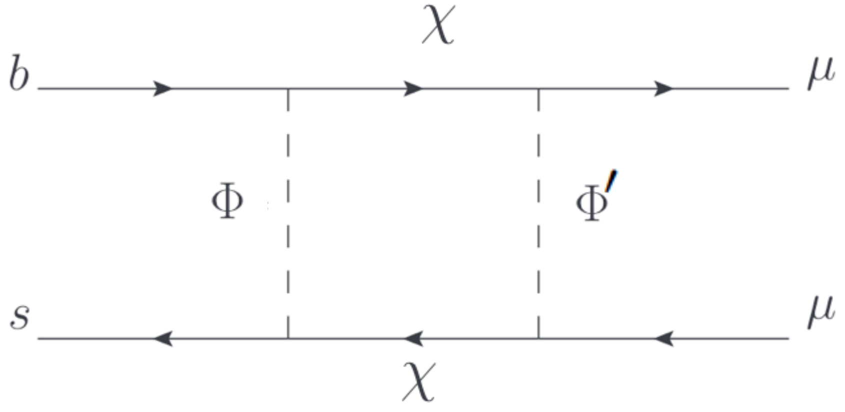
LHCb 5 fb^{-1}
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
[PRL122191801]

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
[LHCb-PAPER-2021-004]

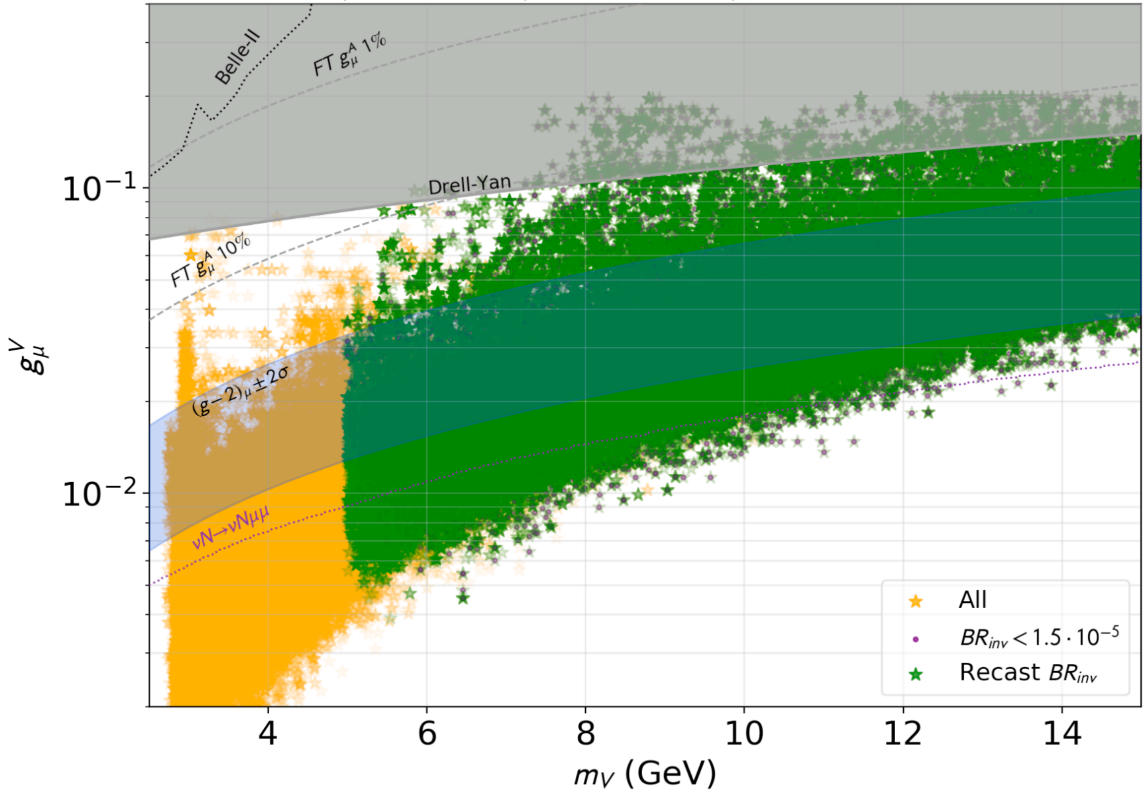
Flavour physics and split dark sectors

- Loop-based models of flavour anomalies can feature light particles
- Box diagram based (e.g. with (colored) scalar doublets and light fermions)

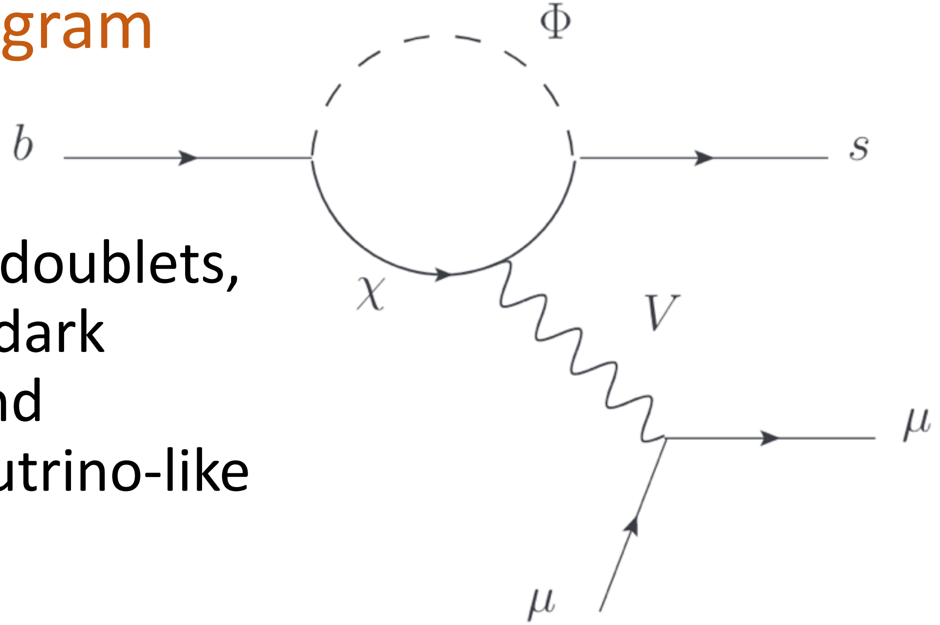


See e.g. Arnan, Crivellin, Fedele, Mescia (2019)

2002.11150 -- LD, M. Fedele, K. Kowalska, E. Sessolo



- Penguin diagram based
  - E.g with a colored doublets, plus new dark photon and sterile neutrino-like fermion



See e.g. LD, Fedele, Kowalska, Sessolo (2020)

Feebly-Interaction Particles and portals

- FIPs= "new (quasi-) neutral particle which interact with the SM via suppressed new interactions" → assumed light (MeV to few GeVs)
- Appear in various NP models aiming at dark matter, neutrino masses, strong CP problem, flavour etc …

	SM operator		FIPs / dark sector	examples …
Scalar portal	$\|H\|^2 \quad (d=2)\,,$	⟷	$\|S\|^2$	Dark Higgs
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	⟷	$F'^{\mu\nu}$	Dark photon
Neutrino portal	$LH \quad (d=5/2)$	⟷	N	Sterile neutrino/HNL
Axion portal / fermion portal	$\bar{f}_i\,\Gamma^\mu f_j \quad (d=3)$	→	$\partial_\mu a$	Axion/ALP
		→	$\Psi\Gamma_\mu\Psi$	Dark fermions