Flavour Phenomenology and Unitarity of Light Dark Vectors

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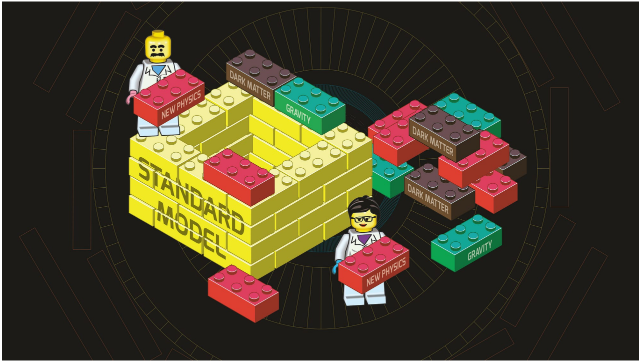
LHCb meeting 2024

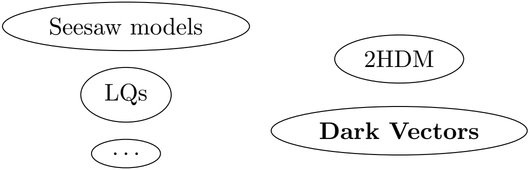
technische universität dortmund

Part I

Beyond the Standard Model, Flavour and Light Dark Vectors



Beyond the Standard Model (BSM) and Flavour



Beyond the Standard Model (BSM) and Flavour

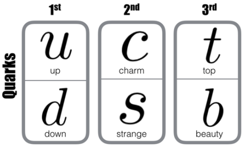
Seesaw models

2HDM

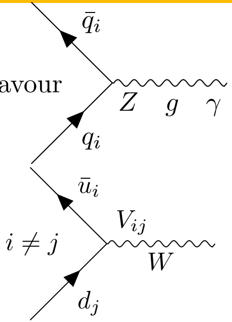
LQs

Dark Vectors

...



Same flavour



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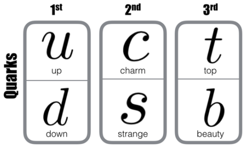
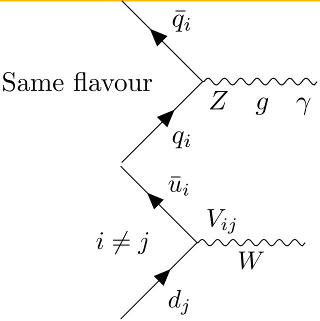
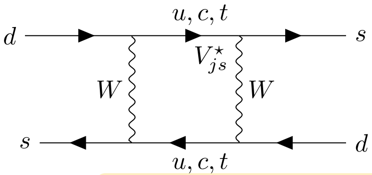
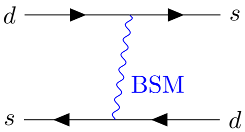




Flavour changing neutral currents (FCNCs) are **suppressed**



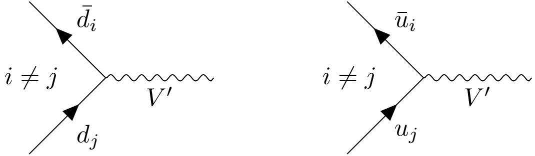
New BSM field with FCNCs



FCNCs are a good probe for BSM physics

Light Dark Vectors (LDV) with FCNCs

- Consider adding a **massive neutral spin-1** vector boson V'_μ to the SM
- We focus on **FCNC interactions** between SM matter and the LDV



$$\mathcal{L}_D = \frac{1}{\Lambda}\bar{q}_i \sigma^{\mu\nu}\left(\mathbb{C}^D_{ij} + i\gamma_5 \mathbb{C}^{5D}_{ij}\right) q_j F'_{\mu\nu} \quad \text{Dipole (dim-5)}$$

$$\mathcal{L}_V = \left(\frac{m_{V'}}{\Lambda}\right)\bar{q}_i \gamma^\mu \left(\mathbb{C}_{ij} + \gamma_5 \mathbb{C}^5_{ij}\right) q_j V'_\mu \quad \text{Vector (dim-4)}$$

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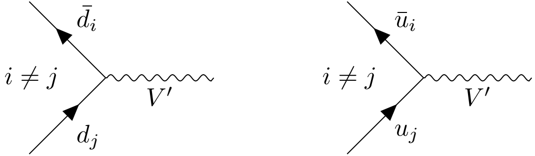

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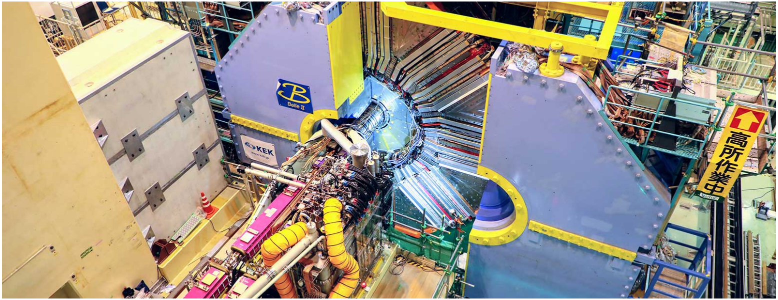
$$\mathcal{L}_V = \left(\frac{m_{V'}}{\Lambda}\right)\bar{q}_i\gamma^\mu\left(\mathbb{C}_{ij} + \gamma_5\mathbb{C}^5_{ij}\right)q_j V'_\mu \quad \text{Vector (dim-4)}$$

Objective: Constrain $\{\mathbb{C}^D_{ij}, \mathbb{C}^{5D}_{ij}, \mathbb{C}_{ij}, \mathbb{C}^5_{ij}\}$ for $i \neq j$ via 2-body decays with experimental limits and with unitarity

Part II

Phenomenology



LDV Searches

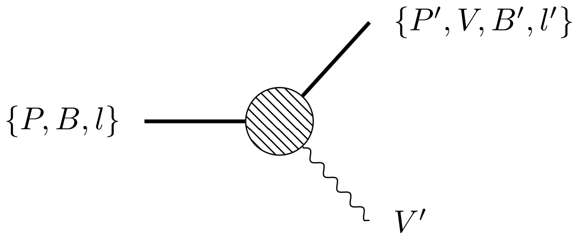
- Rich phenomenology with experimental searches with siganture SM $\rightarrow$ SM $+$ invisible
  - Belle II ($B \rightarrow \rho +$ inv)
  - NA62 ($K \rightarrow \pi +$ inv)
  - BaBar ($B \rightarrow \pi +$ inv)
  - ...
- Future upgrades and searches: KOTO, BESIII, ...

  $\Rightarrow$ Potential discovery via FCNCs

- Constrain couplings via 2-body decays+experimental bounds on BR

2-body decays

$P^{(\prime)} \equiv$ pseudoscalar, $V \equiv$ vector, $B^{(\prime)} \equiv$ baryon, $l^{(\prime)} \equiv$ lepton



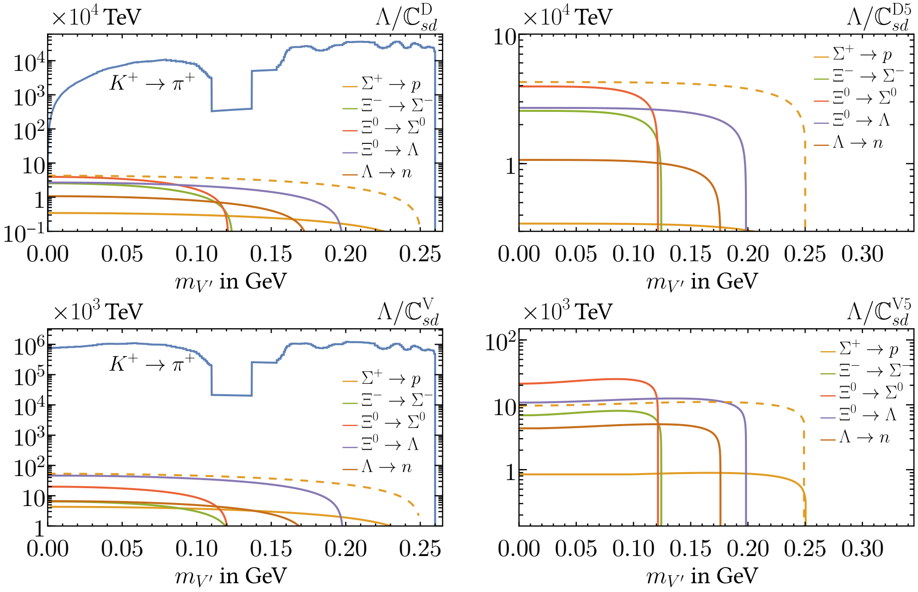
- Two relevant elements
  - **Form factors** for hadronic decays, which depend on the LDV mass, $F(m^2_{V'})\rightarrow$ typically computed on the lattice
  - **Recast** of experimental data for 2-body decays$\rightarrow$ BaBar, Belle II, CLEO

Analysis

Quark Transition	Hadronic Process	Form Factors	Experimental Limit
$s \to d$	$K^+ \to \pi^+ + V'$	[60, 61]	NA62 [17, 33, 34]
	$\Sigma^+ \to p + V'$	[32, 62–64]	BES III [65], Lifetime$_r$[22, 58]
	$\Xi^- \to \Sigma^- + V'$	[32, 62–64]	Lifetime$_r$[22, 58]
	$\Xi^0 \to \Sigma^0 + V'$	[32, 62–64]	Lifetime$_r$[22, 58]
	$\Xi^0 \to \Lambda + V'$	[32, 62–64]	Lifetime$_r$[22, 58]
	$\Lambda \to n + V'$	[32, 62–64]	Lifetime$_r$[22, 58]
$b \to s$	$B^+ \to K^+ + V'$	[66, 66]	BaBar$_r$ [36], Belle II$_r$ [39, 57]
	$B \to K^* + V'$	[66, 66]	BaBar$_r$ [36, 57]
	$\Lambda_b \to \Lambda + V'$	[67, 67]	Lifetime$_r$[22, 58]
$b \to d$	$B^+ \to \pi^+ + V'$	[66, 68]	BaBar$_r$ [35]
	$B \to \rho + V'$	[66, 66]	LEP$_r$ [55, 56]
	$\Lambda_b \to n + V'$	[67, 69]	Lifetime$_r$ [22, 58]
$c \to u$	$D^+ \to \pi^+ + V'$	[70, 71]	CLEO$_r$ [22, 37]
	$\Lambda_c \to p + V'$	[72, 72]	BES III [40], Lifetime$_r$ [22, 58]

LFV Transition	Experimental Limit
$\mu \to e$	TWIST [41], Jodidio$_r$ [18, 73]
$\tau \to e$	Belle II [38]
$\tau \to \mu$	Belle II [38]

Constraints *sd* sector



Part III
(in progress)

Unitarity

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Unitarity

Derivation of gauge invariance from high-energy unitarity bounds on the S matrix*

John M. Cornwall,[†] David N. Levin, and George Tiktopoulos
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024
(Received 21 March 1974)

Weak interactions at very high energies: The role of the Higgs-boson mass

Benjamin W. Lee,* C. Quigg,[†] and H. B. Thacker
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Improved unitarity constraints in Two-Higgs-Doublet-Models

Mark D. Goodsell[1,*] and Florian Staub[2,3,†]

Perturbative Unitarity Constraints on a Supersymmetric Higgs Portal

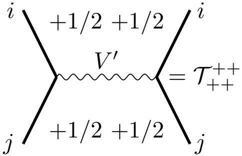
Kassahun Betre, Sonia El Hedri and Devin G. E. Walker
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, U.S.A.

Unitarity Constraints on Dimension-Six Operators

Tyler Corbett*

Unitarity with FCNCs from 2 $\rightarrow$ 2 helicity partial waves

$f_i f_j \rightarrow f_i f_j$
$\lambda_f = \{\pm 1/2\}$



Unitarity with FCNCs from 2 $\rightarrow$ 2 helicity partial waves

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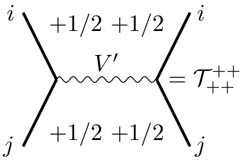
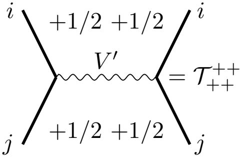


- Given the helicity amplitudes $\mathcal{T}_{\lambda_1\lambda_2}^{\lambda_3\lambda_4}$ compute their partial waves

$$\mathcal{T}_{\lambda_1\lambda_2}^{\lambda_3\lambda_4,l} \propto \int_0^{\pi} d\theta \sin\theta \underbrace{d_{\lambda_i\lambda_f}^{l}}_{\text{Wigner d}}(\theta)\mathcal{T}_{\lambda_1\lambda_2}^{\lambda_3\lambda_4}(s,\theta)$$

Unitarity with FCNCs from $2 \to 2$ helicity partial waves

$f_i f_j \to f_i f_j$
$\lambda_f = \{\pm 1/2\}$



- Given the helicity amplitudes $\mathcal{T}^{\lambda_3\lambda_4}_{\lambda_1\lambda_2}$ compute their partial waves

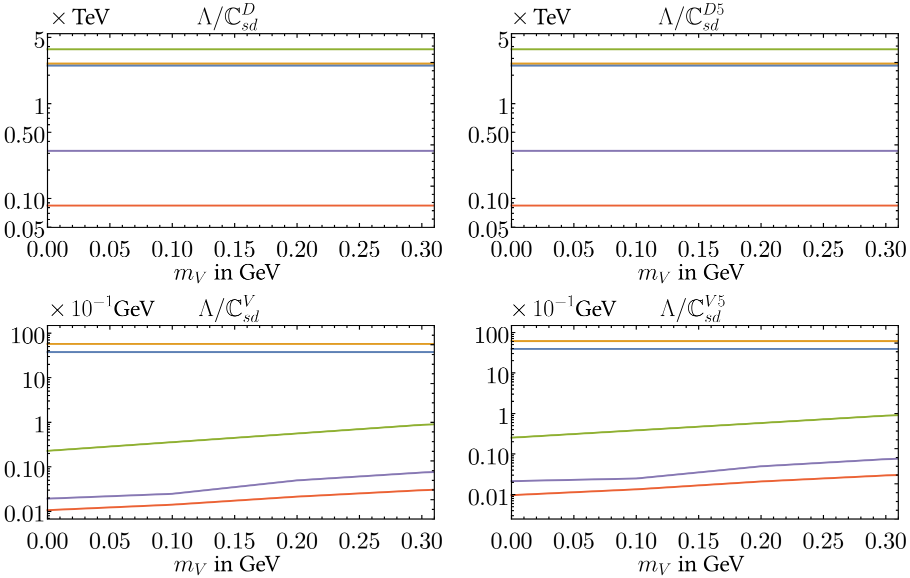
$$\mathcal{T}^{\lambda_3\lambda_4,l}_{\lambda_1\lambda_2} \propto \int_0^\pi d\theta \sin\theta \underbrace{d^l_{\lambda_i\lambda_f}}_{\text{Wigner d}}(\theta)\mathcal{T}^{\lambda_3\lambda_4}_{\lambda_1\lambda_2}(s,\theta)$$

- Unitarity implies $|\mathcal{T}^{\lambda_3\lambda_4,l}_{\lambda_1\lambda_2}| \leq 1$

$$\{ff \to ff, V'f \to V'f, V'V' \to \bar{f}f, Af \to V'f, AV' \to \bar{f}f\}$$

Constraints *sd* sector at high energy $\sqrt{s} = 10$ TeV

$ff \to ff$, $V'f \to V'f$, $V'V' \to \bar{f}f$, $Af \to V'f$, $AV' \to \bar{f}f$

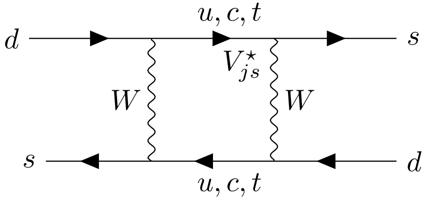


Conclusions and outlook

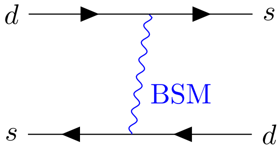
- LDV is a minimal extension of the SM and a DM candidate
- Flavour gives us a guide; potential of discovery with current (and future) searches
- Constrained FCNC couplings via
  - 2-body decays with experimental limits
  - Unitarity of $2 \to 2$ scattering
- Baryon decays are the least constraining but sometimes the only available
- Phenomenology bounds are much stronger than unitarity bounds (but have kinematical endpoint)
- Unitarity$\to$ much to learn about high energy behaviour, role of FCNCs (masses), Stückelberg mechanism and GBET

Backup slides

FCNCs can occur at loop level



New BSM field with FCNCs



FCNC processes are very suppressed in the SM:

- Arise at loop level $\left(\sim 1/16\pi^2\right)$
- Smallness of CKM elements $(V_{ij} \ll 1, i \neq j)$
- GIM mechanism $\left(\sim (m_u - m_c)^2 / M_W^2; V_{td}, V_{ts} \ll 1\right)$

FCNCs are a good probe for BSM physics

LDV mass

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{V'}^2}{2}V'_\mu V'^\mu \quad \text{Proca theory} \tag{1}$$

Is not (explicitly) gauge invariant. Use Stückelberg trick:

$$V'_\mu \to X_\mu - \frac{\partial_\mu \pi}{m_{V'}} \Rightarrow \mathcal{L}_{\text{St}} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_{V'}^2}{2}\left(X_\mu - \frac{\partial_\mu \pi}{m_{V'}}\right)^2 . \tag{2}$$

The Lagrangian is now manifestly $U(1)$ gauge invariant under

$$\begin{aligned} X_\mu &\to X_\mu + \partial_\mu \alpha(x)\,, \\ \pi &\to \pi + m_{V'}\alpha(x) \end{aligned} \tag{3}$$

Stückelberg is nothing else than the **affine Higgs mechanism** (i.e. Higgs is decoupled)

LDV can get mass through a $U(1)'$ Dark Higgs

LDV with kinetic mixing

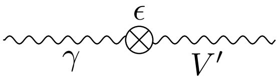
Consider adding a **neutral spin 1** field (V'_μ) to QED (A_μ)

$$\mathcal{L} = -\frac{1}{4}F^2_{\mu\nu} - \frac{1}{4}F'^2_{\mu\nu} + eJ_\mu A^\mu + e'J'_\mu V'^\mu + \frac{m^2_{V'}}{2}V'_\mu V'^\mu$$

J_μ SM matter
J'_μ dark sector (DS) matter

We can also write a kinetic mixing term!

$$\mathcal{L}_{KM} = -\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}, \quad \epsilon \ll 1$$



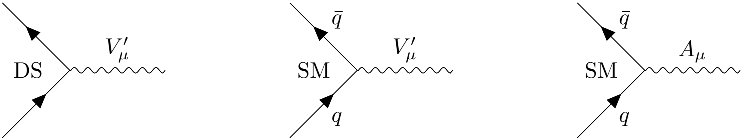
Due to kinetic mixing the LDV can interact with SM matter

LDV and SM matter

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F_{\mu\nu}'^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + eJ_\mu A^\mu + e'J'_\mu V'^\mu + \frac{m_{V'}^2}{2}V'_\mu V'^\mu$$

Diagonalisation of the kinetic mixing

$$\mathcal{L}_{\text{int}} = \left(e'J'_\mu - \boldsymbol{e\epsilon J_\mu}\right)V'^\mu + eJ_\mu A^\mu$$



Minimal model with kinetic mixing and no flavour-changing couplings

Kinetic mixing with SM hypercharge boson

$$\mathcal{L} = \mathcal{L}_{EW} + \mathcal{L}_{Higgs} + \mathcal{L}_{KM}$$

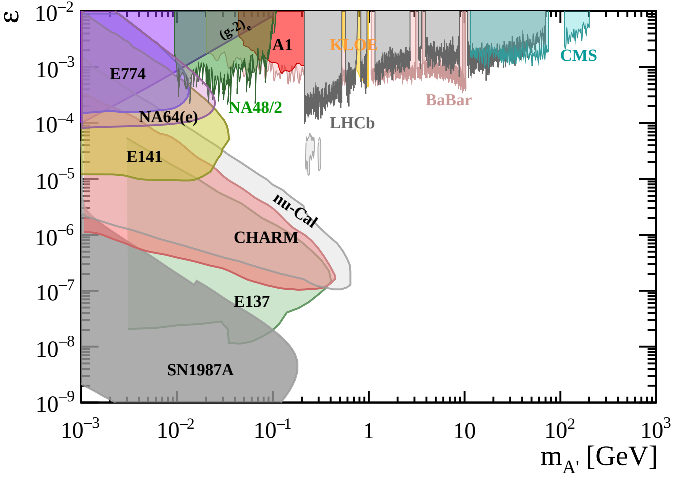
Kinetic mixing term for LDV and SM $U(1)_Y$ boson

$$\mathcal{L}_{KM} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$$

Diagonalisation+SSB+gauge mass basis

$$\begin{pmatrix} B_\mu \\ W^3_\mu \\ V'_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\epsilon t \\ 0 & 1 & 0 \\ 0 & 0 & t \end{pmatrix} \begin{pmatrix} c_W & -s_W c_\xi & s_W s_\xi \\ s_W & c_W c_\xi & c_W s_\xi \\ 0 & s_\xi & c_\xi \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ V'_\mu \end{pmatrix}$$

$$\tan 2\xi = -\frac{2\eta s_W}{1 - s_w^2 \eta^2 - \delta} \quad \text{with} \quad t = 1/\sqrt{1-\epsilon^2}, \quad \eta = \epsilon t, \quad \delta = m_{V'}^2/m_Z^2$$



Di-lepton searches (LHCb, NA48, BaBar, etc); Beam dump (NA64, E774 at Fermilab, etc); Supernova (1987A)

Origin of flavour violating couplings

- $\mathcal{L}_V$ comes from the interaction $V'_\mu J^\mu$

$$J^\mu = \sum_{ij} \bar{Q}^i Y'^{ij}_Q \gamma^\mu Q^j + \sum_{ij} \bar{u}^i_R Y'^{ij}_u \gamma^\mu u^j_R + \sum_{ij} \bar{d}^i_R Y'^{ij}_d \gamma^\mu d^j_R$$

Going to the Yukawa mass basis we infer:

FV couplings are induced if the hypercharges Y'_x are **not** universal

- $\mathcal{L}_D$ comes from the interaction $\frac{1}{\Lambda^2} F'_{\mu\nu} J^{\mu\nu}$

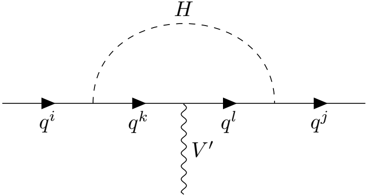
$$J^{\mu\nu} = \sum_{ij} \bar{Q}^i \tilde{H} C^{ij}_u \sigma^{\mu\nu} u^j_R + \sum_{ij} \bar{Q}^i H C^{ij}_d \sigma^{\mu\nu} d^j_R + \text{h.c}$$

Going to the Yukawa mass basis we infer:

FV couplings are induced if couplings C_x are **not** aligned with SM Yukawas

Flavour-changing couplings from RGEs

FCNCs can be induced from the couplings RGEs (1310.4838v3)



$$\mu \frac{dC}{d\mu} = \gamma^T C$$

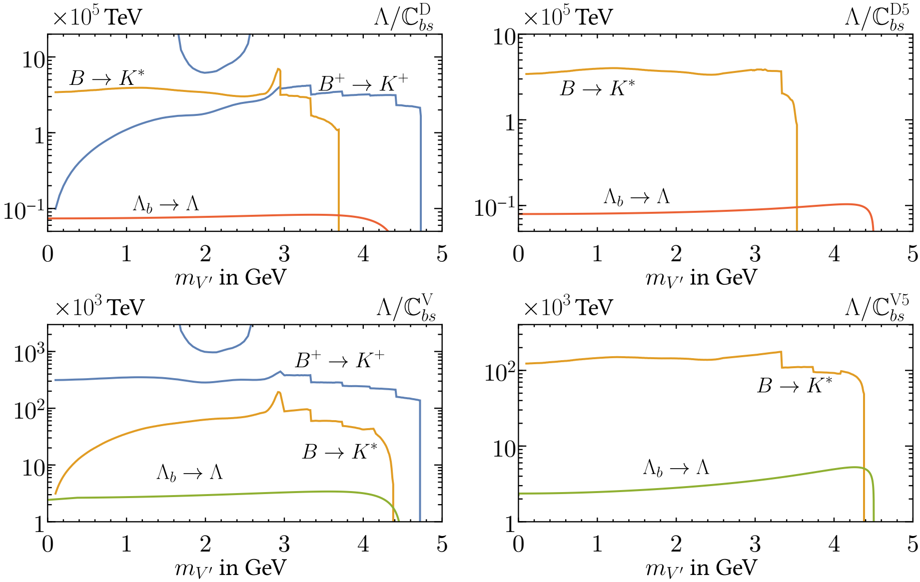
Taking into account 1-loop Yukawa corrections we find

Starting with flavour-diagonal interactions at a high scale Λ FCNCs are induced at the low scale μ

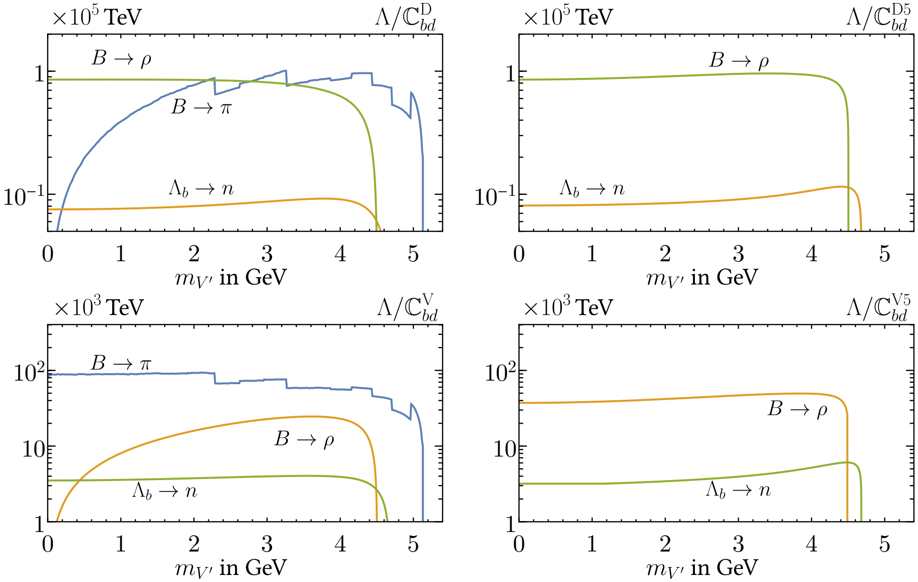
Top contributions yield

$$C_{ij}(\mu) \sim \delta_{ij} C_{ij}(\Lambda) + m_t^2 V_{tj} V_{ti}^{\star} \log\left(\frac{\mu}{\Lambda}\right)$$

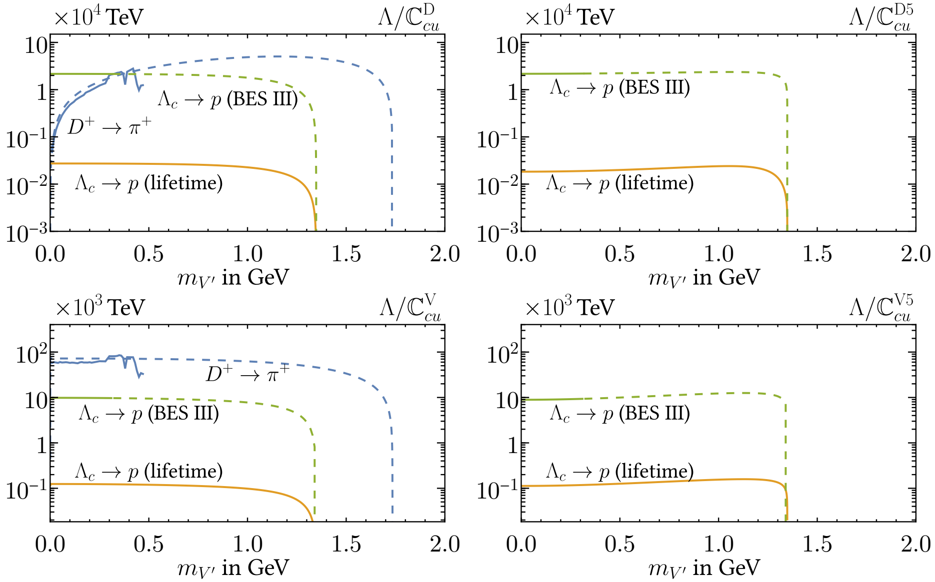
Constraints bs sector



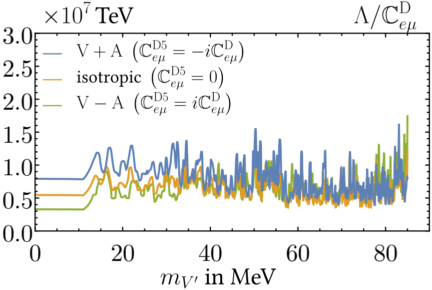
Constraints *bd* sector

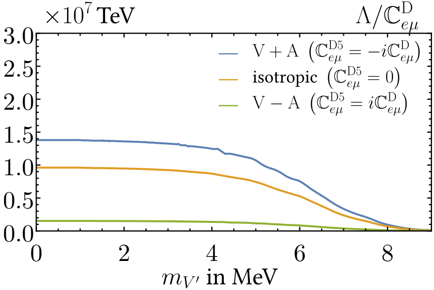


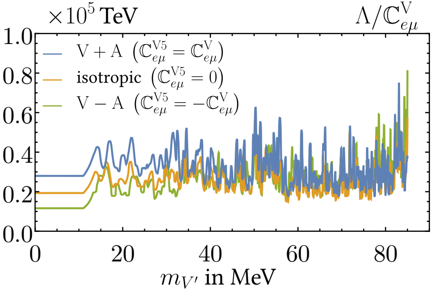
Constraints *cu* sector

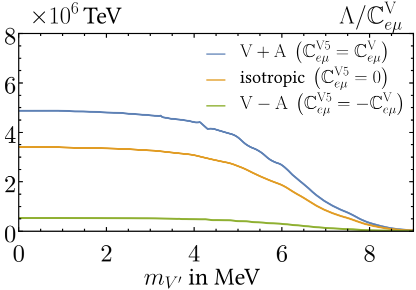


Constraints $e\mu$ sector

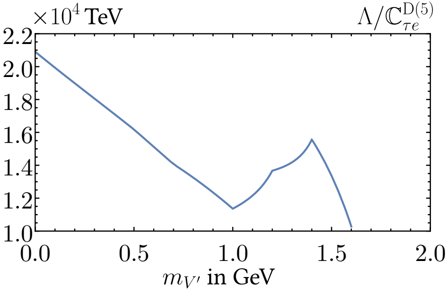


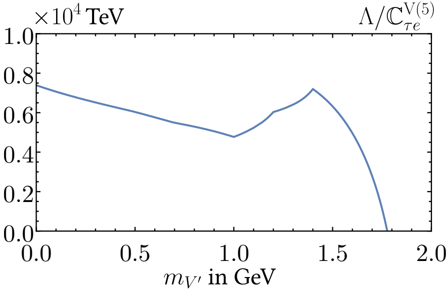


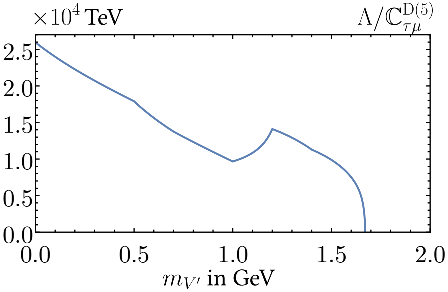


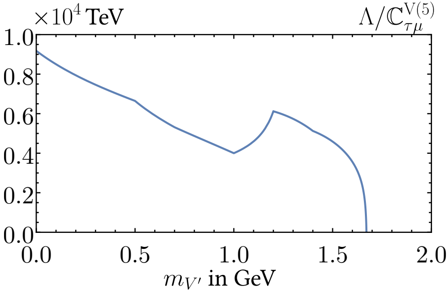


Constraints $\tau \to \mu/e$ sector





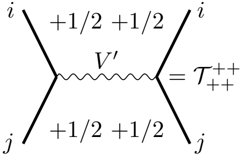




Unitarity with FCNCs from $2 \to 2$ partial waves

$f_i f_j \to f_i f_j$

$\lambda_f = \{\pm 1/2\}$



- Given the helicity amplitudes $\mathcal{T}^{\lambda_3\lambda_4}_{\lambda_1\lambda_2}$ compute their partial waves

$$\mathcal{T}^{\lambda_3\lambda_4, l}_{\lambda_1\lambda_2} \propto \int_0^\pi d\theta \sin\theta \underbrace{d^l_{\lambda_i\lambda_f}}_{\text{Wigner d}}(\theta)\mathcal{T}^{\lambda_3\lambda_4}_{\lambda_1\lambda_2}(s,\theta) \xrightarrow{\text{Unitarity}} |\mathcal{T}^{\lambda_3\lambda_4, l}_{\lambda_1\lambda_2}| \leq 1$$

$$\{ff \to ff, V'f \to V'f, V'V' \to \bar{f}f, Af \to V'f, AV' \to \bar{f}f\}$$

- $\mathcal{T}^{\lambda_3\lambda_4, l}_{\lambda_1\lambda_2}$ are matrices in flavour (and helicity) space $\to$ diagonalise

In flavour space

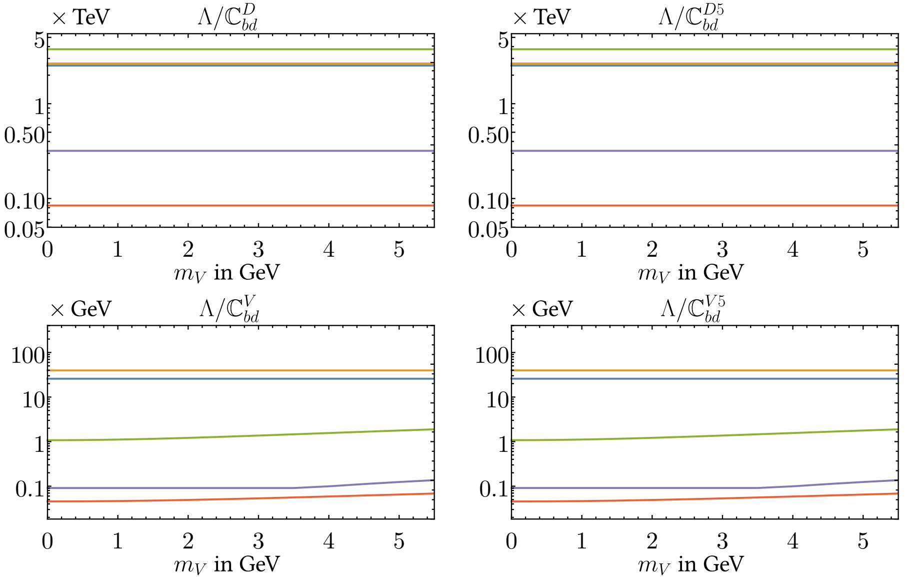
	$f_i f_j$	$\bar{f}_i f_j$	$f_i \bar{f}_j$	$\bar{f}_i \bar{f}_j$
$f_i f_j$	4×4			
$\bar{f}_i f_j$		4×4	4×4	
$f_i \bar{f}_j$		4×4	4×4	
$\bar{f}_i \bar{f}_j$				4×4

In helicity space

$$\begin{pmatrix} \mathcal{T}^{++}_{++} & \mathcal{T}^{+-}_{++} & \mathcal{T}^{-+}_{++} & \mathcal{T}^{--}_{++} \\ \mathcal{T}^{++}_{+-} & \mathcal{T}^{+-}_{+-} & \mathcal{T}^{-+}_{+-} & \mathcal{T}^{--}_{+-} \\ \mathcal{T}^{++}_{-+} & \mathcal{T}^{+-}_{-+} & \mathcal{T}^{-+}_{-+} & \mathcal{T}^{--}_{-+} \\ \mathcal{T}^{++}_{--} & \mathcal{T}^{+-}_{--} & \mathcal{T}^{-+}_{--} & \mathcal{T}^{--}_{--} \end{pmatrix}$$

Constraints bd sector at high energy $\sqrt{s} = 10$ TeV

$ff \to ff$, $V'f \to V'f$, $V'V' \to \bar{f}f$, $Af \to V'f$, $AV' \to \bar{f}f$



High energy behaviour

- From Ward identities, we find that the processes with $\mathcal{L}_V$ vertices violating unitarity are $V'V' \to \bar{f}f$, $V'f \to V'f$, i.e., $\mathcal{T}^{\lambda_3\lambda_4}_{\lambda_1\lambda_2} \propto s^\alpha$ with $\alpha > 0$
- For $\mathcal{L}_D$ amplitudes grow with energy because it is a dim-5 operator in the EFT.
- At high energies $s \gg m_i^2 \quad \forall i$, scattering longitudinal V' is equivalent to scattering scalars
- Stückelberg decomposition is equivalent to GBET, $(V'_\mu)_{\text{longitudinal}} \propto -\partial_\mu \pi$
  - $(\mathcal{L}_V)_{\text{longitudinal}} = i\frac{\pi}{\Lambda}\bar{f}_i\left(\mathbb{C}^V_{ij}(m_i - m_j) + \gamma_5\mathbb{C}^{V5}_{ij}(m_i + m_j)\right)f_j \to$ masses!
  - $(\mathcal{L}_D)_{\text{longitudinal}} = 0$