Flavour Phenomenology of Light Dark Vectors

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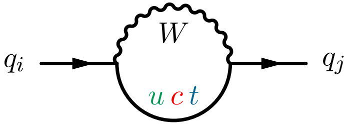
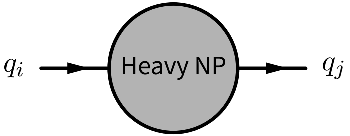
Quark flavour: SM vs NP

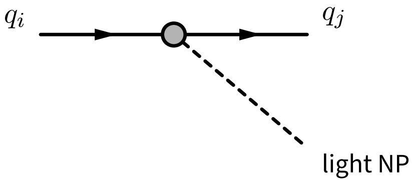
SM
loop induced, precision



Heavy NP
virtual, indirect probe
SUSY, Composite Higgs, Extra Dimensions, …



Light NP
decays to “invisible”
Axions, Dark Photons, …
[focus of this talk]



Flavour – the answer to all?

- Data from ongoing and planned experimental flavour program have the **potential** to provide at least some answers.

- **However**, there are no guarantees only best guesses and hopes.

  ➜FV in NP may be fully aligned to FV in SM

  ➜D.o.f. associated to BSM FV may be too heavy for discovery

  ➜our experiments may have blind spots (compressed spectra, missing energy, …)

➜ **Two (semi-orthogonal) strategies:**

- Expose deviations through precision and global fits

  (golden observables: EDMs, clean FCNCs, …; EFTs: WET, SMEFT, …)

  [focus of my talk at Discrete**2010**]

- Go beyond well established interpretation of data and observables

  (radiative modes, distributions, light-NP interpretations,…)

  [focus of this talk at Discrete**2024**]

From my Discrete2010 contribution

Rare K Decays

Discrete 2010
Rome

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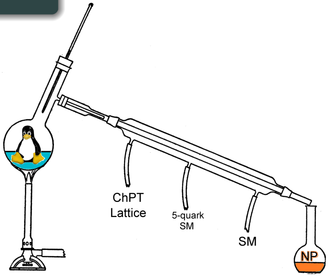
6 December 2010



Light-NP & flavour – example QCD Axion

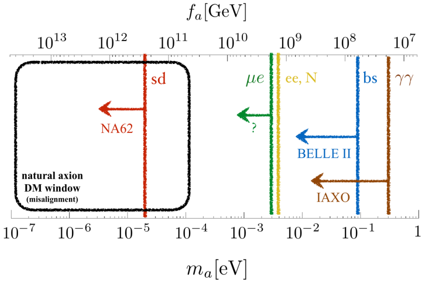
$$\Gamma_K^{\text{tot}} \sim M_K^5/M_W^4 \qquad \Gamma_B^{\text{tot}} \sim M_B^5/M_W^4$$

- Dimension-5 QCD axion couplings: $\frac{\partial^\mu a}{f_a}\,\bar{q}_i\gamma_\mu(\gamma_5)q_j$

$$\text{BR}(K \to \pi a) \propto \frac{M_W^4}{\boldsymbol{M_K^2} f_a^2}$$

$$\text{BR}(B \to \pi a) \propto \frac{M_W^4}{\boldsymbol{M_B^2} f_a^2}$$

➜ High sensitivity to light NP



(for $C_i = 1$)

[from R. Ziegler @ La Thuille]

Light NP

- **Scalars**
  QCD axion (best motivated light NP scenario), ALPs,...
- **Fermions**
  light sterile neutrinos, fermionic DM, ...
- **Vectors**
  dark Photons, light Z', ...

Phenomenology depends strongly on:
masses, lifetimes, and couplings to SM

Most promising search strategies may differ!

Outline

Flavourful light Vectors with “invisible” signatures

- Model-independent framework
  - Vector-type vs Dipole-type flavour-violating couplings
  - Model-dependence and scaling of couplings
- Bounds from two-body spectra
  - Form-factor dependence
  - Recast of available searches
- Unitarity constraints
  - Bad high-energy behaviour of $2 \to 2$ scattering, e.g., $q_i V' \to q_j V'$
  - Unitarity leads to bounds on flavour-violating couplings

Conclusions

EFTs for light, flavoured vectors V'

– Dipole interaction

$$\mathscr{L}^{D}_{\text{FCNC}} = \frac{\boldsymbol{C^{D}_{ij}}}{\boldsymbol{\Lambda}} \bar{f}_i \sigma^{\mu\nu} f_j F'_{\mu\nu} + \frac{\boldsymbol{C^{D5}_{ij}}}{\boldsymbol{\Lambda}} \bar{f}_i i \sigma^{\mu\nu} \gamma_5 f_j F'_{\mu\nu}$$

$*$ $SU(2)_L$ gauge invariance ➜ $\bar{Q}_L H \sigma^{\mu\nu} q_R F'_{\mu\nu}$ ➜dim-6 counting

– Vector interaction

$$\mathscr{L}^{V}_{\text{FCNC}} = \frac{\boldsymbol{m_{V'}}}{\boldsymbol{\Lambda}} \boldsymbol{C^{V}_{ij}} \bar{f}_i \gamma^{\mu} f_j V'_{\mu} + \frac{\boldsymbol{m_{V'}}}{\boldsymbol{\Lambda}} \boldsymbol{C^{V5}_{ij}} \bar{f}_i \gamma^{\mu} \gamma_5 f_j V'_{\mu}$$

$*$ gauge invariance ➜ no flavour violation for $m_{V'} = 0$ at dim-4

$*$ power, n, of $(m_{V'}/\Lambda)^n$ model dependent

UV motivation — quadratic scaling

Quadratic scaling $(n = 2)$

$$\left(\frac{\boldsymbol{m_{V'}}}{\boldsymbol{\Lambda}}\right)^{\boldsymbol{n}} C_{ij}^{V(5)} \, \bar{f}_i \gamma^\mu (\gamma_5) f_j V'_\mu$$

- Possible without charging SM fermions under $U(1)'$
- $S = v' \exp(iG/v)$ Goldstone parametrisation of $U(1)'$ breaking
- $\mathscr{L}^V_{\text{quadratic}} \supset \frac{c_{ij}}{\Lambda^2} (S^\dagger \partial_\mu S) \bar{f}_{Ri} \gamma^\mu f_{jR} \supset \frac{c_{ij}}{\Lambda^2} v' \partial_\mu G \bar{f}_{Ri} \gamma^\mu f_{jR}$
- GB equivalence theorem: $\partial_\mu G \to -m_{V'} V_\mu$

$$\mathscr{L}^V_{\text{quadratic}} \supset c_{ij} \frac{\boldsymbol{v' m_{V'}}}{\boldsymbol{\Lambda^2}} \bar{f}_{Ri} \gamma^\mu f_{jR}$$

[for details and explicit models see Folch, Klingel, ES, Tabet, Ziegler 24]

UV motivation — linear scaling

Linear scaling $(n = 1)$

$$\left(\frac{m_{V'}}{\Lambda}\right)^n C_{ij}^{V(5)}\, \bar{f}_i \gamma^\mu (\gamma_5) f_j V'_\mu$$

- SM fermions must be charged under $U(1)'$: $\mathscr{L}^V_{\text{linear}} \supset g' V'_\mu \bar{d}_R X_d \gamma^\mu d_R$
- Rotation to mass-eigenstates ➜FV couplings
  (for FV need non-universal X_d charges)
- Generic masses not possible at renormalisable level
  (for generic masses need S insertions, e.g. Ex. $X_d = \text{diag}(1,0)$ and $X_Q = X_H = 0$

$$\mathscr{L}^V_{\text{linear}} \supset -y_i Q_i H d_{R2} - z_i \frac{S^\dagger}{\Lambda} Q_i H d_{R1} \quad ➜ \quad Y_d \sim \begin{pmatrix} z_1 \frac{v'}{\Lambda} & y_1 \\ z_2 \frac{v'}{\Lambda} & y_2 \end{pmatrix}$$

- Rotation plus GB equivalence theorem: $\partial_\mu G \to -m_{V'} V_\mu$

$$\mathscr{L}^V_{\text{quadratic}} \supset i\bar{d}_{R1} \not{\partial} d_{R1} \to -\frac{\partial_\mu G}{v'} \bar{d}_{R1} \gamma^\mu d_{R1} \to \frac{g' v'}{\Lambda} \bar{V}'_\mu d_{Ri} \gamma^\mu d_{Rj}$$

[for details and explicit models see Folch, Klingel, ES, Tabet, Ziegler 24]

Flavour phenomenology of light Vectors

- dependence on mass of light Vector (& Form Factors)
  ➜recast of searches required
- multiple channels and experiments required to probe all couplings

Two-body decays to invisible V'

Pseudoscalar$\to$Pseudoscalar$+V'$

Pseudoscalar$\to$Vector$+V'$

Baryon$\to$Baryon$+V'$

	C_{ij}^{D}	C_{ij}^{D5}	C_{ij}^{V}	C_{ij}^{V5}
sd				
cu				
bs	depend on V' mass			
bd				

[Folch, Klingel, ES, Tabet, Ziegler 24]

[Kamenik, Smith 12]

Two-body decay modes

Pseudoscalar $\to$ Pseudoscalar $+V'$

- $\mathbb{C}_{ij}^{D}, \mathbb{C}_{ij}^{V}$ ✓ $\mathbb{C}_{ij}^{D5}, \mathbb{C}_{ij}^{V5}$ ✘
- $B^+ \to \pi^+, B^+ \to K^+, D^+ \to \pi^+, K^+ \to \pi^+, K_L \to \pi^0$

Pseudoscalar $\to$ Vector $+V'$

- $\mathbb{C}_{ij}^{D}, \mathbb{C}_{ij}^{D5}, \mathbb{C}_{ij}^{V}, \mathbb{C}_{ij}^{V5}$ ✓
- $B \to \rho, B \to K^*, D \to \rho$

Baryon $\to$ Baryon $+V'$

- $\mathbb{C}_{ij}^{D}, \mathbb{C}_{ij}^{D5}, \mathbb{C}_{ij}^{V}, \mathbb{C}_{ij}^{V5}$ ✓
- $\Sigma \to p, \Xi \to \Sigma, \Lambda \to n$

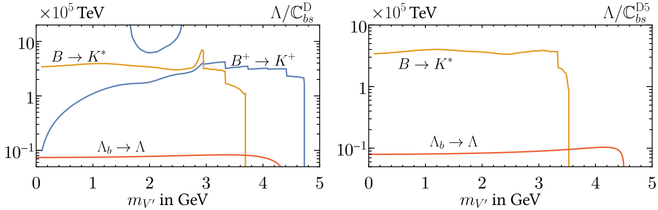
Summary of searches included

Quark Transition	Hadronic Process	Form Factors	Experimental Limit
$s \to d$	$K^+ \to \pi^+ + V'$	[65, 66]	NA62 [17, 38, 39]
	$\Sigma^+ \to p + V'$	[34, 67–69]	BES III [70], Lifetime$_r$[22, 63]
	$\Xi^- \to \Sigma^- + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
	$\Xi^0 \to \Sigma^0 + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
	$\Xi^0 \to \Lambda + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
	$\Lambda \to n + V'$	[34, 67–69]	Lifetime$_r$[22, 63]
$b \to s$	$B^+ \to K^+ + V'$	[71, 71]	BaBar$_r$ [41], Belle II$_r$ [44, 62]
	$B \to K^* + V'$	[71, 71]	BaBar$_r$ [41, 62]
	$\Lambda_b \to \Lambda + V'$	[72, 72]	Lifetime$_r$[22, 63]
$b \to d$	$B^+ \to \pi^+ + V'$	[71, 73]	BaBar$_r$ [40]
	$B \to \rho + V'$	[71, 71]	LEP$_r$ [60, 61]
	$\Lambda_b \to n + V'$	[72, 74]	Lifetime$_r$ [22, 63]
$c \to u$	$D^+ \to \pi^+ + V'$	[75, 76]	CLEO$_r$ [22, 42]
	$\Lambda_c \to p + V'$	[77, 77]	BES III [45], Lifetime$_r$ [22, 63]

[Folch, Klingel, ES, Tabet, Ziegler 24]

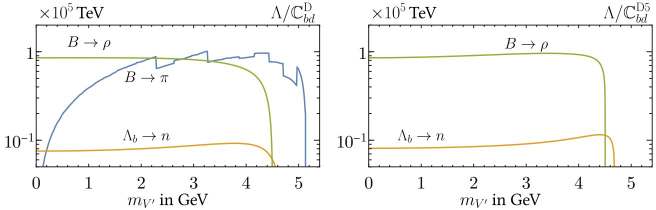
Dipole interaction — B sector

$b - s$ transition



$* \sim 2\sigma$ excess in 2023 $B \to K\nu\nu$ Belle2 measurement [recast from Altmannshofer et al 23]

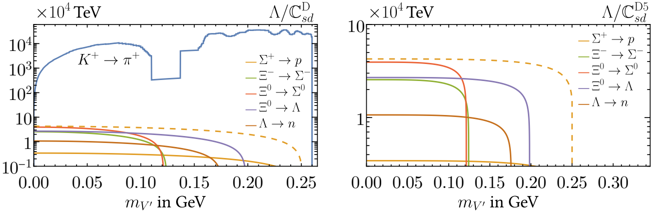
$b - d$ transition



pseudoscalar→pseudoscalar decays **insensitive to dipoles** for small $m_{V'}$!

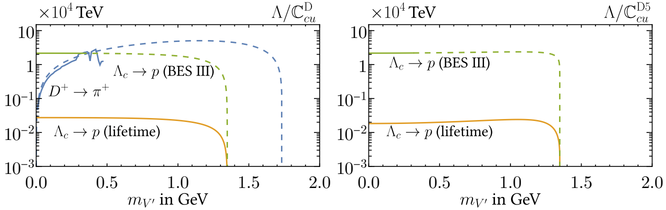
Dipole interaction — K, D sector

$s - d$ transition



$*$ not including a recast of the new NA62 measurement of $K^+ \to \pi^+\nu\nu$

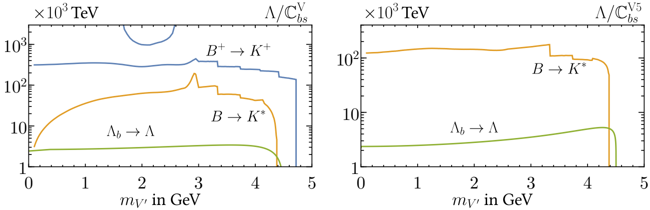
$c - u$ transition



pseudoscalar→pseudoscalar decays **insensitive to dipoles** for small $m_{V'}$!

Vector interaction — B sector

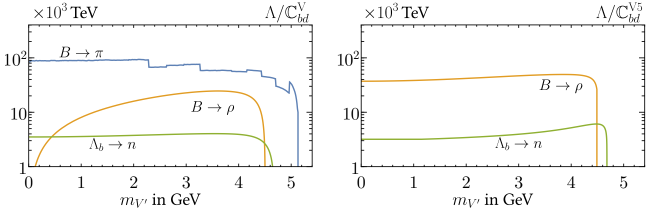
$b - s$ transition



pseudoscalar→pseudoscalar limits **survive for $m_{V'} \to 0$**

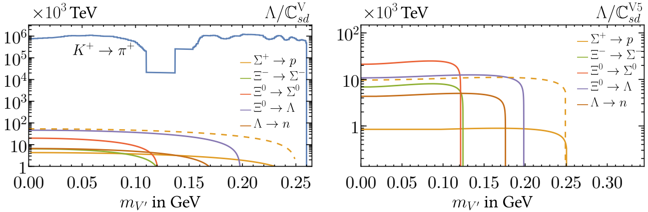
analogous to $t \to Wd$ decay in gauge-less limit in SM

$b - d$ transition



Vector interaction — K, D sector

$s - d$ transition



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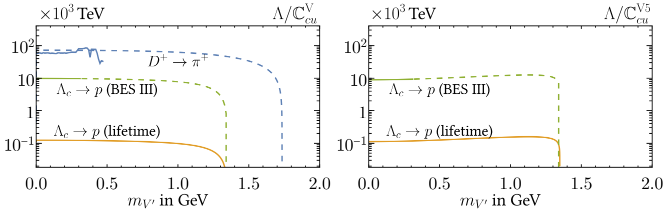


Flavour phenomenologoly of light, dark Vectors

Take-away messages

- FCNCs ➜ strong bounds on Λ (UV-completion scale)
- Constraining power depends on $m_{V'}$
- Different decays probe differently the Lorentz structure

➜ **Full picture requires two-body interpretations of spectra and combination of channels**

✘ Currently only rudimentary recasts and extrapolations

✘ Missing reliable dedicated exp. analyses

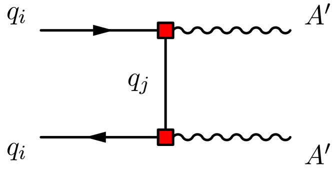
Question: what if the two-body decays kinematically inaccessible?

Perturbative-unitarity bounds on FV couplings

- Proca theory is **incomplete** [=massive vectors without Higgs modes]

➜ Place unitarity bounds on FV coupling from $2 \to 2$ **scattering**

[similar to unitarity bounds on Higgs mass prior to discovery]



- Partial-wave expansion of **massive** $2 \to 2$ helicity amplitudes

$$\mathcal{T}^J_{fi} = \frac{\beta_i^{1/4}\beta_j^{1/4}}{32\pi s}\int_0^\pi d\theta \sin\theta d^J_{\lambda_i\lambda_j}(\theta)\mathcal{T}_{fi;\lambda_i\lambda_j}(s,\theta)$$

- S-matrix unitarity implies bound for forward scattering $i = f$

$$\textbf{Im}[\boldsymbol{\mathcal{T}^l_{ii}}] \geq |\boldsymbol{\mathcal{T}^l_{ii}}|^2$$

[in progress with Folch, Tabet, Ziegler]

$2 \to 2$ scattering with FV couplings

$V'f \to V'f$ $\quad$ $ff \to V'V'$ $\quad$ $ff \to ff$

	$f_i f_j$	$\bar{f}_i f_j$	$f_i \bar{f}_j$	$\bar{f}_i \bar{f}_j$	$\bar{f}_i f_i$	$\bar{f}_j f_j$	$V'V'$	$V' f_i$	$V' f_j$	$V' \bar{f}_i$	$V' \bar{f}_j$
$f_i f_j$	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							
$\bar{f}_i f_i$							4×9				
$\bar{f}_j f_j$							4×9				
$V'V'$					9×4	9×4					
$V' f_i$								6×6			
$V' f_j$									6×6		
$V' \bar{f}_i$										6×6	
$V' \bar{f}_j$											6×6

- Diagonalisation corresponds to forwards scattering ($i = f$)
- Unitarity implies bound on largest eigenvalue $|\lambda_{\text{max}}| \leq 1$

➜ Bound on FV couplings

FV couplings and $2 \to 2$ unitarity

- Two origins
  - — **Standard pertubativity**
    Less relevant for UV completion (e.g. applicable also to QED)
  - — **Bad high-energy behaviour** $\mathcal{M} \propto (\sqrt{s})^n$
    Most interesting and numerically relevant

- Parametrics of badly-behaved amplitudes

— **Vector-type** from $V'V' \to \bar{f}f$ [no bad behaviour for $m_{i,j} \to 0$]

$$\left(\mathcal{T}_{00}^{\pm\pm}\right)^{J=0} \propto \frac{\sqrt{s}}{\Lambda^2}\sqrt{(m_i - m_j)^2\,|\mathbb{C}_{ij}^{V}|^4 + (m_i + m_j)^2\,|\mathbb{C}_{ij}^{V5}|^4 + \text{interference}}$$

— **Dipole-type** from $V'V' \to \bar{f}f$ [same for various $ff \to ff$ amplitudes]

$$\left(\mathcal{T}_{\pm\pm}^{\pm\mp}\right)^{J=1} \propto \frac{s}{\Lambda^2}\sqrt{|\mathbb{C}_{ij}^{D}|^4 + |\mathbb{C}_{ij}^{D5}|^4 + \text{interference}}$$

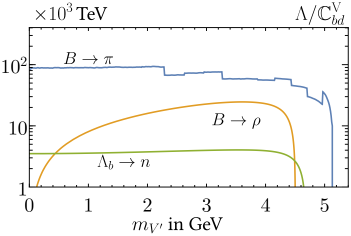
Assume unitarity up to $\sqrt{s_{\text{max}}} = 10$ TeV

➜Bound on $\mathbb{C}_{ij}^{V/D(5)}/\Lambda$

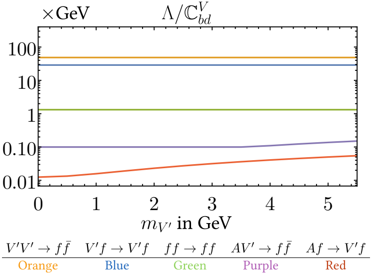
- ✘ Bounds on vector-type weak because $\propto m_{\text{fermion}}$
- ● Small dependence on $m_{V'}$ [leading approximation independent of it]
- ✓ Bounds valid for any $m_{V'}$ [no kinematic constraint as for decays]

Example: **bd-sector vector-type**

Flavour



Unitarity



[preliminary, in progress with Folch, Tabet, Ziegler]

Conclusions

- Possible to hide NP with **Light NP**
  ➜ QCD axions, sterile ν's, and dark-photons/light dark vectors
  ➜ Quark-flavour can provide competitive tests
  ➜ Look for interpretations of invisible signatures

- **Light Dark Vectors**
  ➜ Rich flavour phenomenology
  ➜ Considered vector- and dipole-type couplings
  ➜ Multiple channels and dedicated analyses needed for full picture

- **Unitarity Bounds**
  ➜ Constrain FV couplings from $2 \to 2$ scattering
  ➜ Much weaker if flavour bounds apply

backup

Leptons $\mu \to eV', \tau \to \mu V', \tau \to e$

$\tau \to \mu V'$ and $\tau \to e$

- Bounds from total rate of $\tau \to \mu/e +$ invis. from Belle2
- Only sensitive to combination $|\mathbb{C}_{\tau\ell}^{V/D}|^2 + |\mathbb{C}_{\tau\ell}^{V/D5}|^2$

$\mu \to eV'$

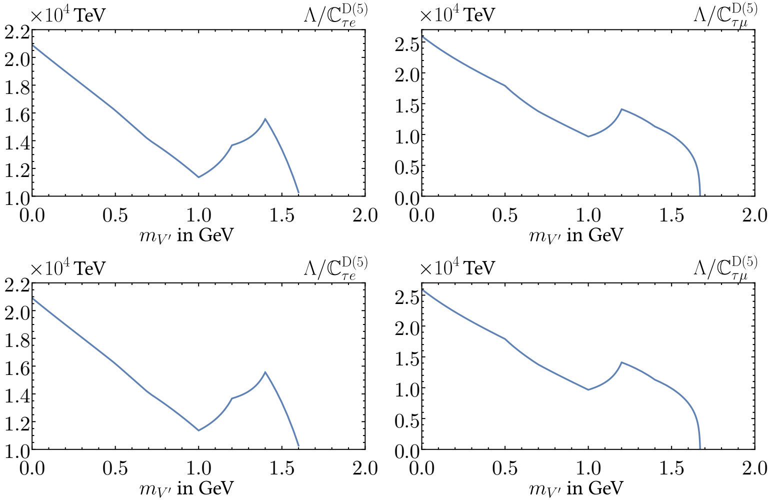
- Use polarisation to suppress SM backgrounds in Michel decays

$$\frac{d\Gamma}{d\cos\theta} \propto (1 + A\cos\theta)$$

θ : angle between muon spin and direction of electron
isotropic : $A = 0$ V-A : $A = -1$ V+A : $A = +1$

[see Callibi et al 20, Jho et al 22, Knapen et al 22/23, Hill et al 23, Folch et al 24]

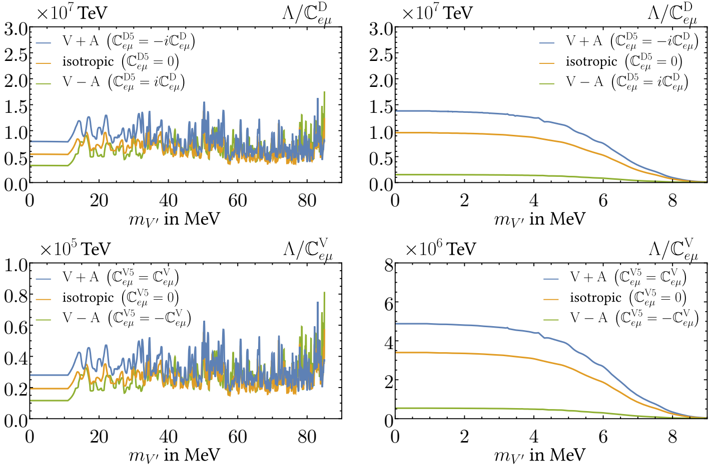
Bounds on τe and $\tau\mu$ couplings to V'



[Folch, Klingel, ES, Tabet, Ziegler 24]

Bounds on μe coupling to V'

TWIST$_r$ | Jodidio et al$_r$ @ TRIUMF



[Jodidio recast: Calibbi, Redigolo, Ziegler, Zupan 18]

[TWIST recast: Folch, Klingel, ES, Tabet, Ziegler 24]

Two theoretically motivated / minimal light-NP setups

- **QCD axion**

  – solution to Strong CP Problem

  – only requirement: $\frac{a}{f_a} G\widetilde{G}$, $m_a \ll \Lambda_{\text{QCD}}$

  [Peccei, Quinn 77; Wilczek 78; Weinberg 78]

- **Dark Photon**

  – minimal $U(1)'$ extention of SM

  [Holdom 86; Fayet 90; …]

  – kinetic mixing with photon: $\epsilon F F'$, massive or massless

But more couplings than $\frac{a}{f_a} G\widetilde{G}$ or $\epsilon F F'$

➜ **More discovery channels!**

➜ Comparison/correlations between experiments often misleading

Model-independent FCNC constraints on Axions

QCD axion

F^V_{ij}: constraints from $M \to Pa$

$K^+ \to \pi^+ a,\, D^+ \to \pi^+,\, B^+ \to K^+/\pi^+ a$

excellent prospects [NA62, Belle 2]

F^A_{ij}: $\Lambda \to na$ (SN), $B^+ \to K^{*+} a$

$M - \overline{M}$ (weak, UV dependent)

$$\mathcal{L}_{\text{FCNC}} = \frac{\partial_\mu a}{F^V_{ij}} \bar{f}_i \gamma^\mu f_j + \frac{\partial_\mu a}{F^A_{ij}} \bar{f}_i \gamma^\mu \gamma_5 f_j$$

	F^V_{ij} [GeV]	F^A_{ij} [GeV]
sd	6.8×10^{11}	5.4×10^{9}
cu	9.7×10^{7}	4.8×10^{7}
bs	3.3×10^{8}	1.3×10^{8}
bd	1.1×10^{8}	2.3×10^{6}

[Leading constraints from Camalich et al 20]