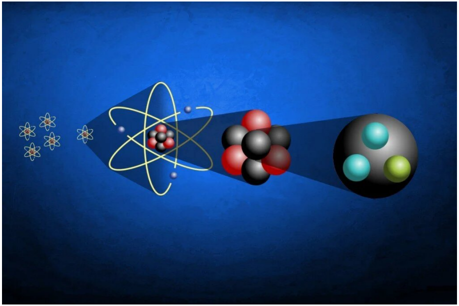
Physics Beyond the Standard Model
Flavour and Dark Photons

Jordi Folch Eguren
w/ E. Stamou (TUD), M. Tabet (TUD), R. Ziegler (KIT)

ICCUB Winter Meeting 2023

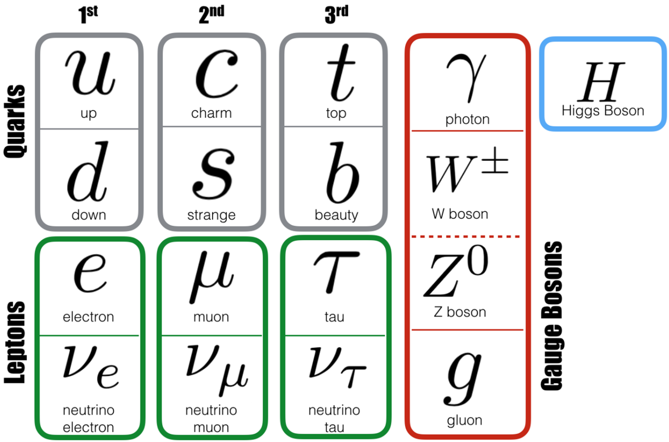
Part I

Standard Model, Flavour and Beyond

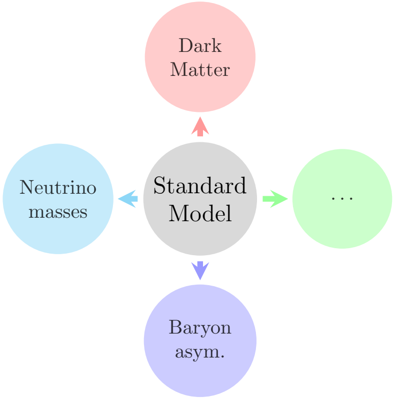


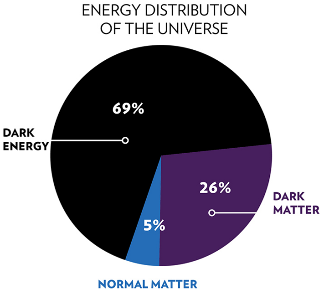
Standard Model: Flavour

Quarks come in three copies (generations), and 6 flavours: $\underbrace{u, c, t}_{u^i}, \underbrace{d, s, b}_{d^i}$.



Beyond the Standard Model (BSM)





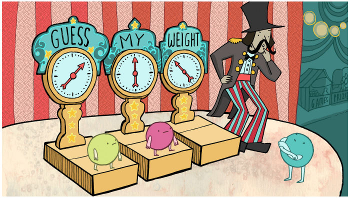
Seesaw models

SUSY

. . .

WIMPs

Dark Photon



Flavour and BSM connection

How can flavour physics help?

Flavour physics allows to probe new phenomena $\rightarrow$ BSM searches!

But why?

Flavour and BSM connection

How can flavour physics help?

Flavour physics allows to probe new phenomena $\rightarrow$ BSM searches!

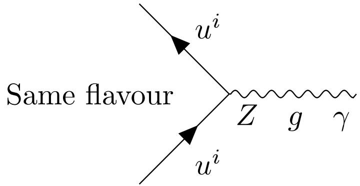
But why?

Because of the **suppression** of flavour-changing neutral currents (**FCNCs**) in the SM

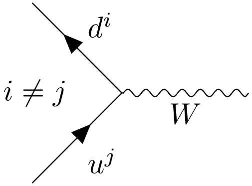
SM and flavour changing currents

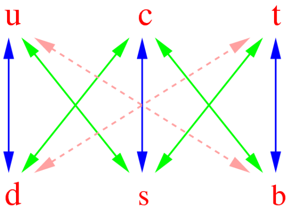
There are neutral (γ, g, Z) and charged $(W^{\pm})$ interactions with quarks

- (γ, g, Z) do not change flavour $\rightarrow$ **no** flavour changing **neutral** currents (FCNCs) $\quad u^i \equiv (u, c, t)$, $d^i \equiv (d, s, b)$



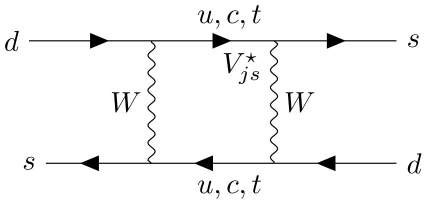
- $W^{\pm}$ bosons change flavour $\rightarrow$ flavour changing **charged** currents



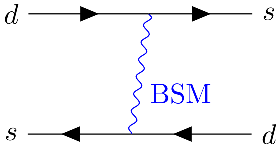


SM, FCNCs and BSM

FCNCs can occur at loop level



New BSM field with FCNCs



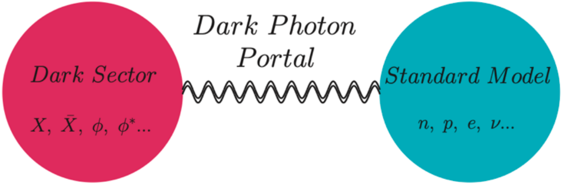
FCNC processes are very suppressed in the SM:

- 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

Part II

Dark Photon



The Dark Photon (DP) with kinetic mixing

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

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

J_μ SM matter

J'_μ dark sector (DS) matter

The Dark Photon (DP) with kinetic mixing

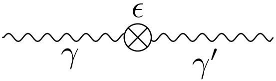
Consider adding a **neutral spin 1** field (A'_μ) to QED (A_μ)

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

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

We can also write a kinetic mixing term!

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



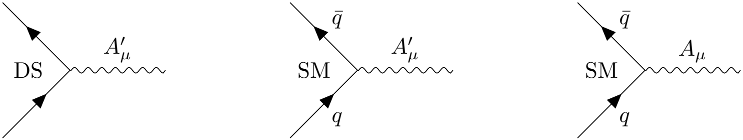
Due to kinetic mixing the DP can interact with SM matter

DP and SM matter

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

Diagonalisation of the kinetic mixing

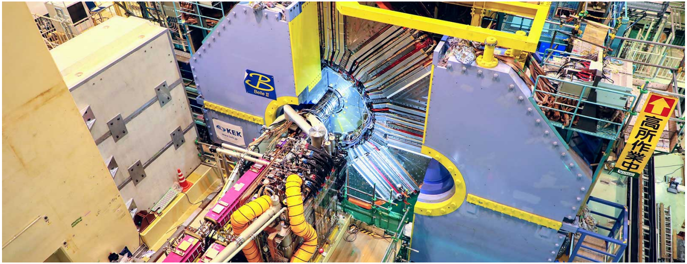
$$\mathcal{L}_{\text{int}} = \left(e'J'_\mu - \boldsymbol{e\epsilon J_\mu}\right)A'^\mu + eJ_\mu A^\mu$$

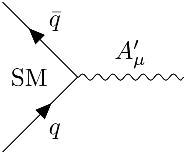


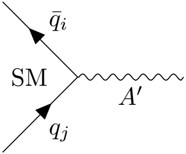
Minimal model with kinetic mixing and no flavour-changing couplings

Part III

Flavour and Dark Photon







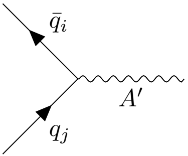
We considered kinetic mixing, now we go beyond!

Why flavour and the Dark Photon

- SM has non-trivial flavour interactions, DP could behave similarly
- Rich phenomenology with experimental searches at colliders (2-body decays)
  - Belle II ($B \to \rho$)
  - NA62 ($K \to \pi$)
  - BaBar ($B \to \pi$)
  - ...
- Future upgrades and searches: KOTO, KLEVER, BESIII, ...

$\Rightarrow$ Potential discovery via FCNCs

Flavour-changing couplings with the Dark Photon



$$\mathcal{L} = \mathcal{L}_D + \mathcal{L}_V$$

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

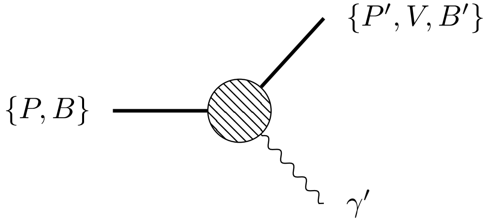
$$\mathcal{L}_V = \left(\frac{m_{\gamma'}}{\Lambda}\right)^2 \bar{q}_i\left(\mathbb{C}_{ij} + \gamma_5\mathbb{C}_{ij}^{5}\right)q_j \not{A}' \quad \text{Vector (dim-4)}$$

Objective

Constrain $\{\mathbb{C}_{ij}^{D}, \mathbb{C}_{ij}^{5D}, \mathbb{C}_{ij}, \mathbb{C}_{ij}^{5}\}$ with flavour-changing 2-body decays ($m_{\gamma'} \ll m_{EW}$; EFT)

2-body decays

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



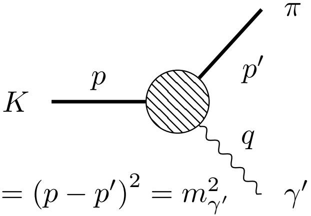
Type	Example	$\mathbb{C}_{ij}^{D}$	$\mathbb{C}_{ij}^{5D}$	$\mathbb{C}_{ij}$	$\mathbb{C}_{ij}^{5}$
$P \to P'\gamma'$	$K \to \pi\gamma'$	✓	✗	✓	✗
$P \to V\gamma'$	$B \to K^{\star}\gamma'$	✓	✓	✓	✓
$B \to B'\gamma'$	$\Sigma \to p\gamma'$	✓	✓	✓	✓

Sector	Example
sd	$K \to \pi\gamma'$
bs	$B \to K^{\star}\gamma'$
bd	$B \to \pi\gamma'$
cu	$D \to \pi\gamma'$

Form factors (FFs): $K \to \pi\gamma'$ example

$$\mathcal{L}_V = \left(\frac{m_{\gamma'}}{\Lambda}\right)^2 \bar{q}_i \not{A}' \mathbb{C}_{ij} q_j$$

$$\mathcal{M} = \langle \gamma' \pi(p') | \, \mathcal{L}_V \, | K(p) \rangle$$

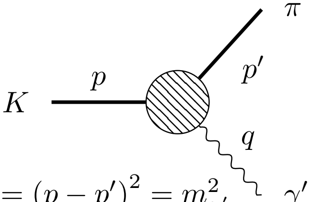


$$q^2 = (p - p')^2 = m_{\gamma'}^2$$

Form factors (FFs): $K \to \pi\gamma'$ example

$$\mathcal{L}_V = \left(\frac{m_{\gamma'}}{\Lambda}\right)^2 \bar{q}_i \not{A}' \mathbb{C}_{ij} q_j$$

$$\mathcal{M} = \langle \gamma' \pi(p') | \mathcal{L}_V | K(p) \rangle$$



$$q^2 = (p - p')^2 = m_{\gamma'}^2$$

- $\mathcal{M} = \left(\frac{m_{\gamma'}}{\Lambda}\right)^2 \mathbb{C}_{ij} \langle \pi(p')\gamma' | \bar{q}_i A'_\mu \gamma^\mu q_j | K(p) \rangle$

$\langle \pi(p') | \bar{q}_i \gamma^\mu q_j | K(p) \rangle \sim f\left(m_{\gamma'}^2\right)$ is the form factor

$$\langle \pi(p') | \bar{q}_i \gamma^\mu q_j | K(p) \rangle = (p + p')^\mu \, \boldsymbol{f_{ij}^+}\left(\boldsymbol{m_{\gamma'}^2}\right) + (p - p')^\mu \, \boldsymbol{f_{ij}^-}\left(\boldsymbol{m_{\gamma'}^2}\right)$$

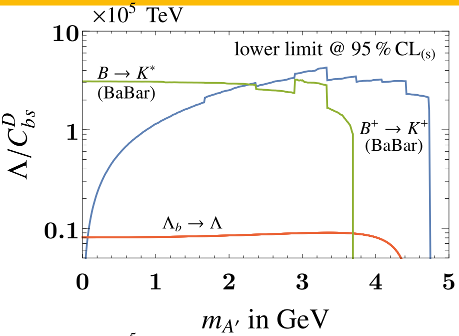
Mass dependence and non-perturbative effects in FFs

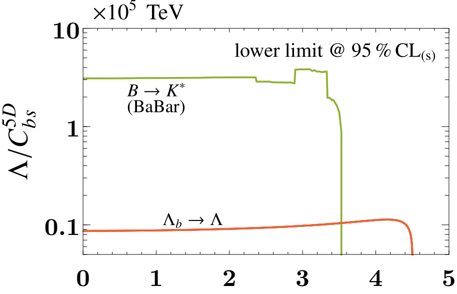
Equivalently for $\langle B(p') | \bar{q}_i \gamma_\mu q_j | B(p) \rangle$, $\langle V(p', \epsilon_\alpha) | \bar{q}_i \sigma_{\mu\nu} \gamma_5 q_j | P(p) \rangle$, etc

Part IV

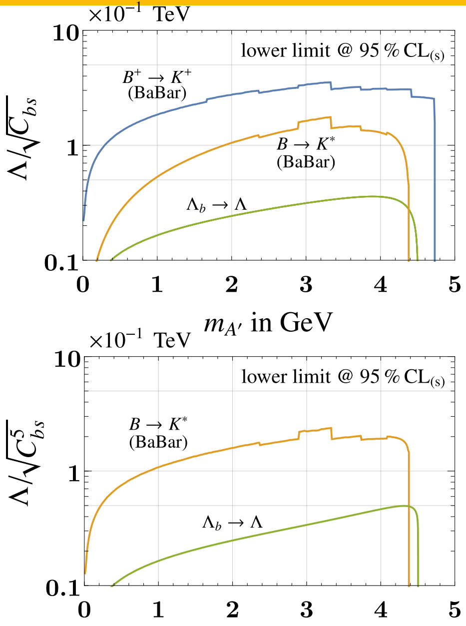
Constraining Dark Photon FCNCs

Constraints bs sector Dipole $\mathbb{C}_{bs}^{D}, \mathbb{C}_{bs}^{5D}$

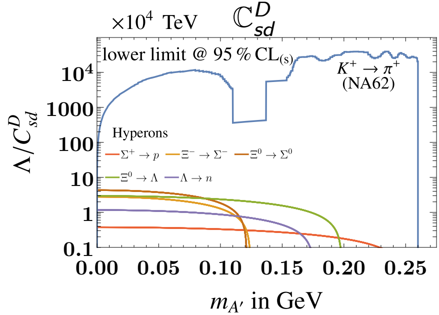


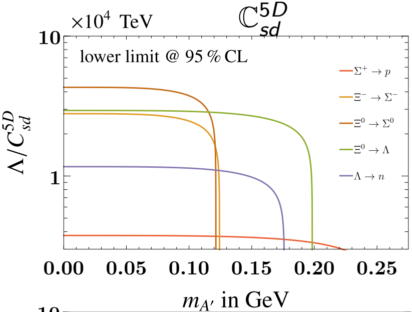


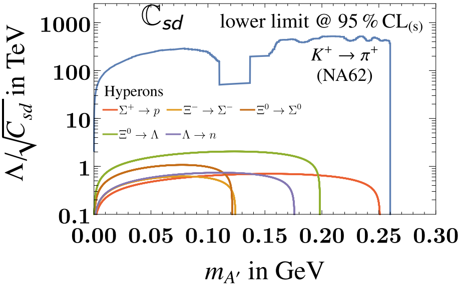
Constraints *bs* sector Vector $\mathbb{C}_{bs}, \mathbb{C}_{bs}^5$

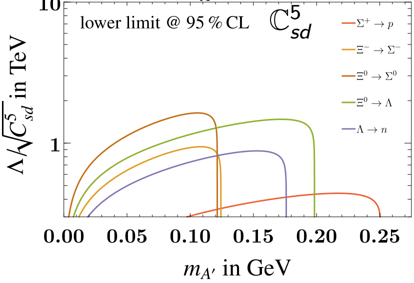


Constraints *sd* sector









Towards a global picture of FCNC bounds

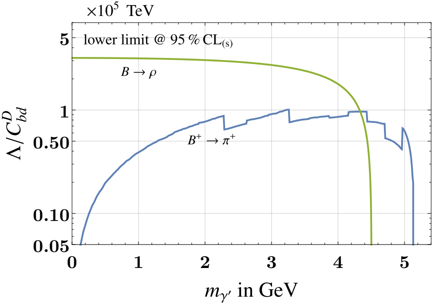
- Recast of data, experiments needed!
- DP mass dependence, with $m_{A'} \ll m_{EW}$
- $K \to \pi$ sets the strongest contraint (*sd* sector)
- Baryon decays are the least constraining but sometimes the only available (no current experimental searches, but planned ones).
- Two more sectors: *bd* and *cu*

Conclusions and outlook

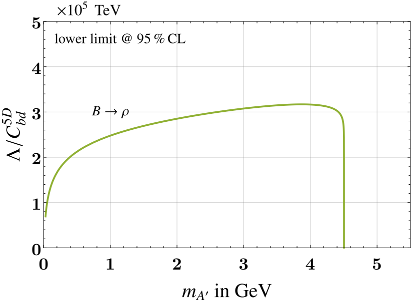
- SM must be extended, flavour gives us a guide
- Dark Photon is a minimal extension of the SM and a DM candidate
- Discovery potential via FCNCs searches: constrained flavour-violating couplings with 2-body decays
    - $P \to P'\gamma'$
    - $P \to V\gamma'$
    - $B \to B'\gamma'$
- Future:
    - Astrophysical and cosmological constraints
    - Dark sector matter

Backup slides

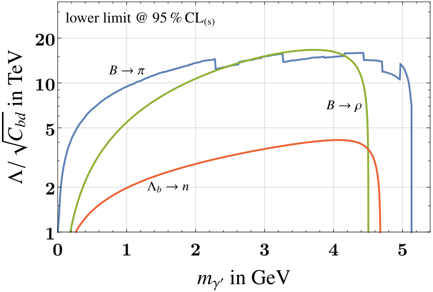
bd sector



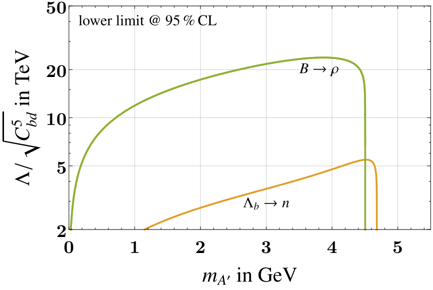
$\times 10^5$ TeV
lower limit @ 95 % $CL_{(s)}$
$B \to \rho$
$B^+ \to \pi^+$
Λ / C_{bd}^{D}
5
1
0.50
0.10
0.05
0
1
2
3
4
5
$m_{\gamma'}$ in GeV



$\times 10^5$ TeV
lower limit @ 95 % CL
$B \to \rho$
Λ / C_{bd}^{5D}
5
4
3
2
1
0
0
1
2
3
4
5
$m_{A'}$ in GeV

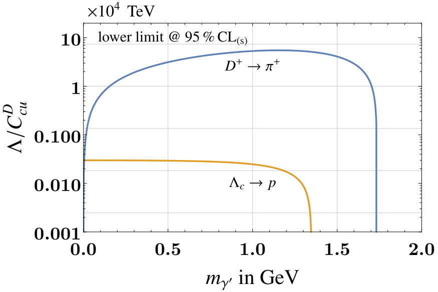


lower limit @ 95 % $CL_{(s)}$
$B \to \pi$
$B \to \rho$
$\Lambda_b \to n$
$\Lambda / \sqrt{C_{bd}}$ in TeV
20
10
5
2
1
0
1
2
3
4
5
$m_{\gamma'}$ in GeV

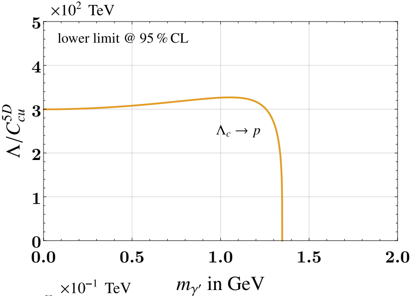


lower limit @ 95 % CL
$B \to \rho$
$\Lambda_b \to n$
$\Lambda / \sqrt{C_{bd}^{5}}$ in TeV
50
20
10
5
2
0
1
2
3
4
5
$m_{A'}$ in GeV

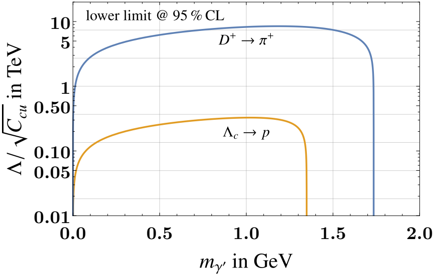
cu sector



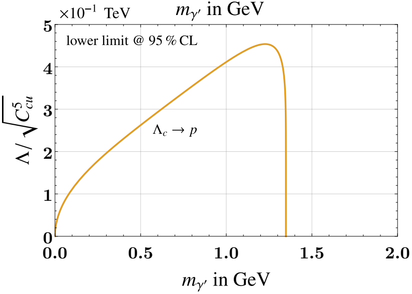
×10^4 TeV
lower limit @ 95 % CL(s)
$D^+ \to \pi^+$
$\Lambda_c \to p$
Λ/C^D_{cu}
10
1
0.100
0.010
0.001
0.0
0.5
1.0
1.5
2.0
$m_{\gamma'}$ in GeV



×10^2 TeV
lower limit @ 95 % CL
$\Lambda_c \to p$
Λ/C^{5D}_{cu}
5
4
3
2
1
0
0.0
0.5
1.0
1.5
2.0
$m_{\gamma'}$ in GeV



lower limit @ 95 % CL
$D^+ \to \pi^+$
$\Lambda_c \to p$
$\Lambda/\sqrt{C_{cu}}$ in TeV
10
5
1
0.50
0.10
0.05
0.01
0.0
0.5
1.0
1.5
2.0
$m_{\gamma'}$ in GeV



×10^-1 TeV
lower limit @ 95 % CL
$\Lambda_c \to p$
$\Lambda/\sqrt{C^5_{cu}}$
5
4
3
2
1
0
0.0
0.5
1.0
1.5
2.0
$m_{\gamma'}$ in GeV

Dark Photon mass and gauge invariance

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{m^2}{2}A_\mu A^\mu \quad \text{Proca theory}$$

The mass term $\frac{m^2}{2}A_\mu A^\mu$ is gauge invariant in a **hidden** manner

Consider doing a field redefinition $A_\mu \to A_\mu + \partial_\mu \phi$, then the theory is invariant under

$$A_\mu \to A_\mu + \partial_\mu \Lambda$$
$$\phi \to \phi - \Lambda$$

This is known as the Stueckelberg procedure, which is nothing else than the **affine Higgs mechanism** (i.e. Higgs is decoupled)

DP can get mass through a Dark Higgs

Kinetic mixing with SM hypercharge boson

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

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

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

Diagonalisation+SSB+gauge mass basis

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

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

Interactions

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

- dim-5 operator, DP can be massive/massless

$$\mathcal{L}_V = \bar{q}_i \not{A}' \left(\mathbb{C}_{ij} + \gamma_5 \mathbb{C}^5_{ij}\right) q_j \quad \text{Vector}$$

- dim-4 operator, DP **cannot** be massless, Ward identity is not satisfied $(p_\mu M^{\mu\nu} \neq 0)$. Rescale $\mathcal{L}_V \to \left(\frac{m_{\gamma'}}{\Lambda}\right)^2 \mathcal{L}_V$ so $\mathcal{L}_V = 0$ if $m_{\gamma'} = 0$

	$\mathcal{L}_D$	$\mathcal{L}_V$
Massive	✓	✓
Massless	✓	×

Massless DP couples to SM only through higher dimensional operators

Origin of flavour violating couplings

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

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

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 $\frac{1}{\Lambda^2} F'_{\mu\nu} J^{\mu\nu}$

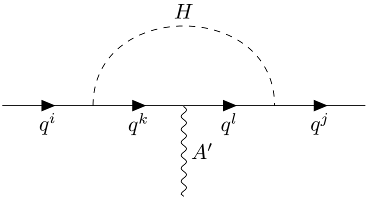
$$J^{\mu\nu} = \sum_{ij} \bar{Q}^i \tilde{H} C^{ij}_u \sigma^{\mu\nu} u^j_R + \sum_{ij} \bar{Q}^i H C^{ij}_d \sigma^{\mu\nu} d^j_R + \text{h.c}$$

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)



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

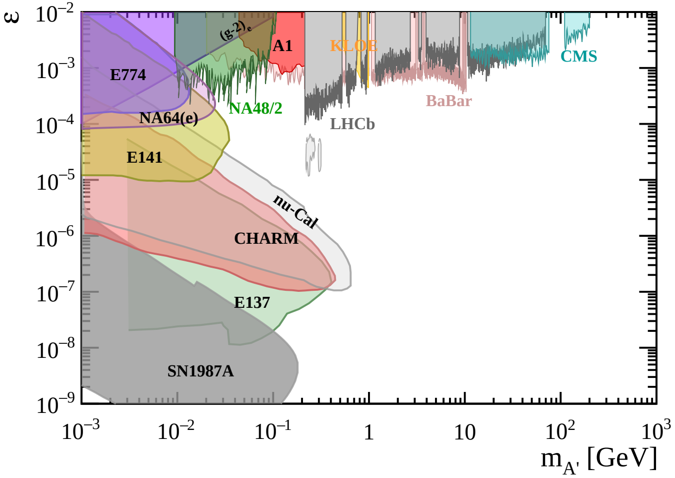
Taking into account 1-loop Yukawa corrections we find

> 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



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