

Surveying the Landscape of Axially-Coupled Dark Forces

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Work with Yoni Kahn, Gordan Krnjaic and Tim Tait [1609.09072]

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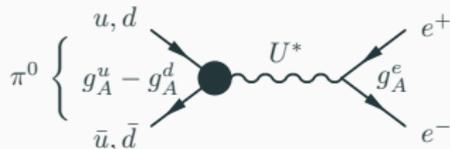


Why axial couplings?

$$\mathcal{L}_{A'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{m_{A'}^2}{2}A'_\mu A'^\mu + A'_\mu \sum_f \bar{f} (c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5) f,$$

Rare pseudoscalar decays: $\pi^0 \rightarrow e^+ e^-$

- Loop and helicity suppressed in the SM
- $\left\{ \begin{array}{l} \text{Br}(\pi^0 \rightarrow e^+ e^-)_{\text{meas}} = 7.48 \pm 0.38 \times 10^{-8} \\ \text{Br}(\pi^0 \rightarrow e^+ e^-)_{\text{SM}} \simeq 6.20 - 6.35 \times 10^{-8} \end{array} \right.$
- Axially coupled A' contributes at tree level [Kahn et al 0712.0007]:



$$\mathcal{L}_{\text{kin}} \supset -\frac{1}{4} \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} + \frac{\epsilon}{2c_W} \hat{B}^{\mu\nu} \hat{F}'_{\mu\nu} - \frac{1}{4} \hat{F}'^{\mu\nu} \hat{F}'_{\mu\nu}$$

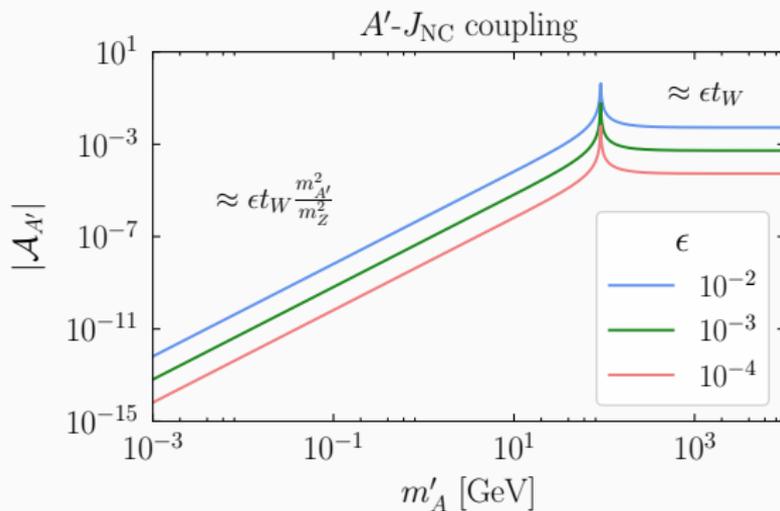
1. **Diagonalize away the kinetic mixing** by shifting the $U(1)_Y$ field
2. **Rotate into the mass basis** $\{Z, A'\}$ with mixing angle ζ .

Coupling to SM currents

$$\begin{cases} e \hat{A}_\mu J_{\text{EM}}^\mu = e [A_\mu + \epsilon (-\sin \zeta Z_\mu + \cos \zeta A'_\mu)] J_{\text{EM}}^\mu \\ g_Z \hat{Z}_\mu J_{\text{NC}}^\mu = g_Z [(\cos \zeta + \epsilon t_W \sin \zeta) Z_\mu + \underbrace{(\sin \zeta - \epsilon t_W \cos \zeta)}_{\equiv \mathcal{A}_{A'}} A'_\mu] J_{\text{NC}}^\mu \end{cases}$$

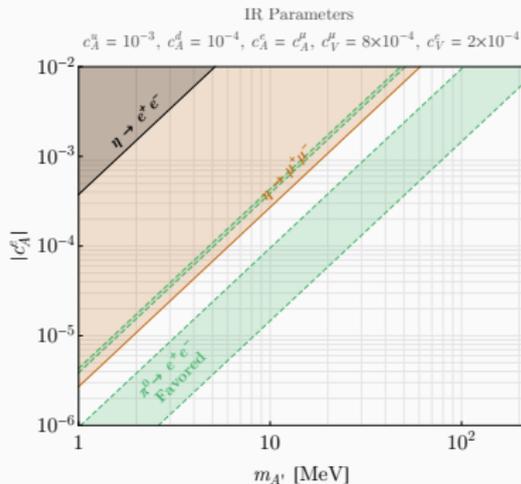
Coupling to SM neutral current

$$\mathcal{A}_{A'} = \sin \zeta - \epsilon t_W \cos \zeta$$



$$\mathcal{L}_{A',\text{int}} = A'_\mu \sum_f \bar{f} (c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5) f$$

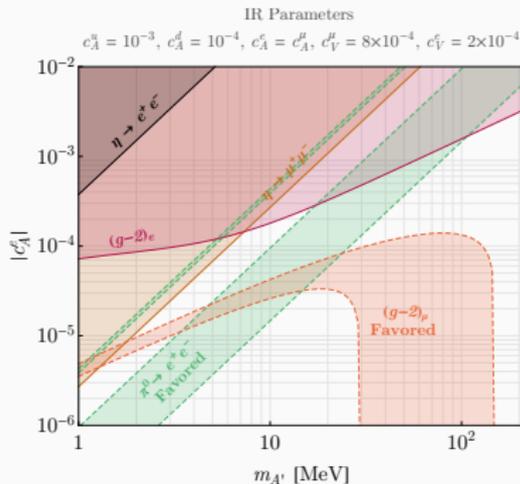
- Pseudoscalar decays:
 $\mathcal{M}_{A'} \sim c_A^e (c_A^u - c_A^d)$



$$\mathcal{L}_{A',\text{int}} = A'_\mu \sum_f \bar{f} (c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5) f$$

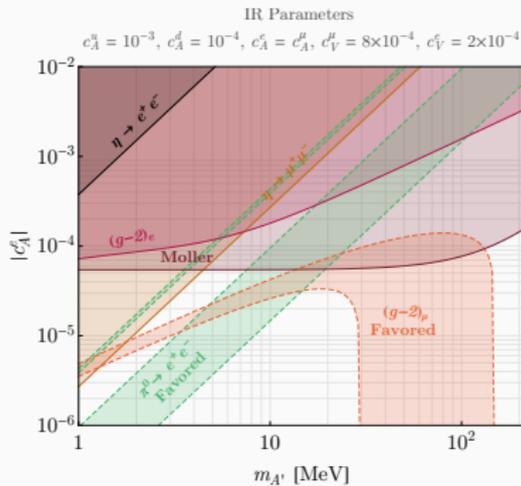
- $(g-2)_{e,\mu}$:

$$\delta a \sim (c_V^\ell)^2 - \frac{m_{A'}^2}{m_\ell^2} (c_A^\ell)^2$$



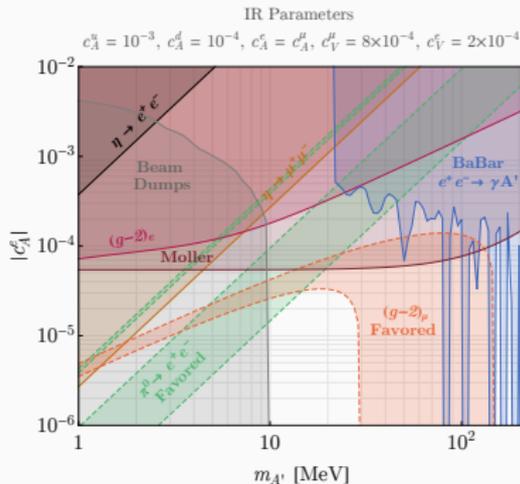
$$\mathcal{L}_{A',\text{int}} = A'_\mu \sum_f \bar{f} (c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5) f$$

- Moller: $A_{PV} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim c_V^e c_A^e$



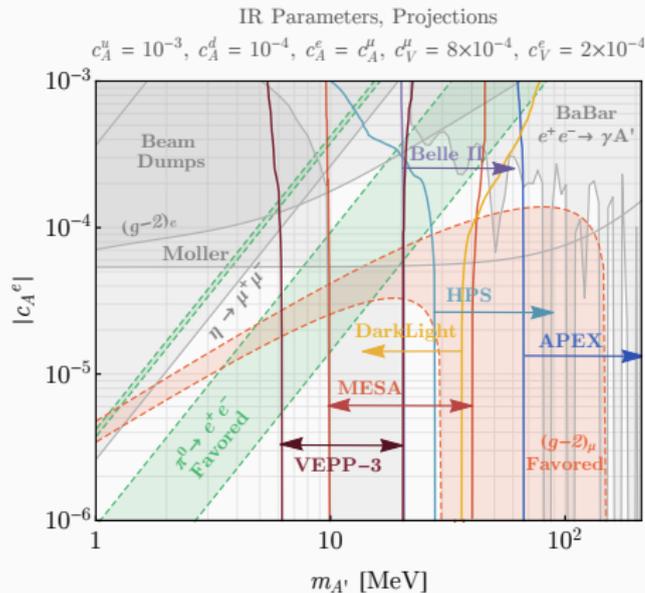
$$\mathcal{L}_{A',\text{int}} = A'_\mu \sum_f \bar{f} (c_V^f \gamma^\mu + c_A^f \gamma^\mu \gamma^5) f$$

- *Colliders and beam dumps:*
 $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-$
 $\mathcal{M}_{A'} \sim (c_A^e)^2 + (c_V^e)^2$
- *Other*
 - *Atomic parity violation:* $c_V^q c_A^e$
 - *Electron-neutrino scattering:*
 $c_V^\nu c_{A,V}^e$



IR constraints: future prospects

Future experiments will robustly sample the IR axial-couplings space.



Require gauge – invariant SM Yukawas

Fermion vector and axial currents:

$$\begin{cases} J_V^\mu \equiv \bar{f} \gamma^\mu f = f_L^\dagger \bar{\sigma}^\mu f_L - f^{c\dagger} \bar{\sigma}^\mu f^c \\ J_A^\mu \equiv \bar{f} \gamma^\mu \gamma^5 f = f_L^\dagger \bar{\sigma}^\mu f_L + f^{c\dagger} \bar{\sigma}^\mu f^c \end{cases}$$

corresponding to **vector** (c_V^f) and **axial** (c_A^f) couplings to the A' :

$$\begin{cases} c_V^f \equiv \frac{1}{2} g_D (q_{f_L} - q_{f^c}) \\ c_A^f \equiv \frac{1}{2} g_D (q_{f_L} + q_{f^c}) \end{cases}$$

Single Higgs doublet

$$\mathcal{L}_{y,\text{SM}} = y_u H Q u^c + y_d H^\dagger Q d^c + y_e H^\dagger L e^c + h.c.$$

Gauge-invariant charge assignments

$$\underbrace{c_A^d = c_A^e = -c_A^u = \frac{1}{2} g_D q_H}_{c_A^f = -g_D q_H T_f^3} \quad (\text{before EWSB})$$

After mass-mixing + rotating into physical basis

$$c_A^f \rightarrow c_A^f + \Delta c_A^f = 0 + \mathcal{O}(g_D^3) + \mathcal{O}(\hat{m}_{A'}^2 / \hat{m}_Z^2) \quad (\text{EWSB})$$

Two Higgs doublets (Type-II 2HDM)

$$\mathcal{L}_{\mathcal{Y},2\text{HDM}} = y_u H_u Q u^c + y_d H_d Q d^c + y_e H_d L e^c + \text{h.c.}$$

$$c_A^u = -\frac{1}{2}g_D q_{H_u}, \quad c_A^d = c_A^e = -\frac{1}{2}g_D q_{H_d} \quad (\text{before EWSB})$$

1. As before, Higgs vevs ($\langle H_u \rangle = \frac{1}{\sqrt{2}}(0, v_u)$ and $\langle H_d \rangle = \frac{1}{\sqrt{2}}(v_d, 0)$) contribute to **mass mixing**,

$$\frac{1}{2}(\hat{Z}_\mu \quad \hat{A}'_\mu) \begin{pmatrix} \hat{m}_Z^2 & -g_D(q_{H_u} v_u^2 - q_{H_d} v_d^2) \hat{m}_Z / v \\ -g_D(q_{H_u} v_u^2 - q_{H_d} v_d^2) \hat{m}_Z / v & g_D^2(q_{H_u}^2 v_u^2 + q_{H_d}^2 v_d^2) + \hat{m}_{A'}^2 \end{pmatrix} \begin{pmatrix} \hat{Z}_\mu \\ \hat{A}'_\mu \end{pmatrix}$$

Two Higgs doublets (Type-II 2HDM)

2. **Rotate** to mass basis (mixing angle θ_D):

$$\sin \theta_D \simeq \theta_D \simeq \frac{g_D(q_{H_u} v_u^2 - q_{H_d} v_d^2)}{\hat{m}_{ZV}} = \frac{2g_D(q_{H_u} v_u^2 - q_{H_d} v_d^2)}{g_Z v^2} \equiv \frac{2g_D}{g_Z} \tilde{\theta}_D$$

$\hat{Z} - \hat{A}'$ mixing after rotating into the mass basis:

$$\hat{Z}_\mu J_{\text{NC}}^\mu = (\cos \theta_D Z_\mu + \sin \theta_D A'_\mu) J_{\text{NC}}^\mu \simeq \left(Z_\mu + \frac{2g_D}{g_Z} \tilde{\theta}_D A'_\mu \right) J_{\text{NC}}^\mu$$

$$c_A^u = -\frac{1}{2} g_D q_{H_u} + \frac{1}{2} g_D \tilde{\theta}_D, \quad c_A^d = c_A^e = -\frac{1}{2} g_D q_{H_d} - \frac{1}{2} g_D \tilde{\theta}_D \quad (\text{EWSB})$$

Anomalons and charge assignments

$$\mathcal{L} = \mathcal{L}_{y,2\text{HDM}} + y_U H'_u U U^c + y_D H'_d D D^c + y_E H'_d E E^c + \text{h.c.}$$

- LHC heavy-fermion searches: $m_\psi \gtrsim 1 \text{ TeV}$
- Perturbativity: $y_\psi \lesssim 4\pi$
- Dark Higgs: $m_{A'} \gtrsim g_D q_H V'$

⇓

$$m_{A'} \gtrsim 80 \text{ MeV} \times \left(\frac{g_D q_H}{10^{-3}} \right) \times \left(\frac{4\pi}{y_\psi} \right)$$

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{RH}$
H_u	1	2	$+\frac{1}{2}$	$+q_{H_u}$
H_d	1	2	$-\frac{1}{2}$	$+q_{H_d}$
u^c	$\bar{3}$	1	$-\frac{2}{3}$	$-q_{H_u}$
d^c	$\bar{3}$	1	$+\frac{1}{3}$	$-q_{H_d}$
e^c	1	1	+1	$-q_{H_d}$
U	3	1	$+\frac{2}{3}$	$+q_{H_u}$
U^c	$\bar{3}$	1	$-\frac{2}{3}$	0
\mathcal{D}	3	1	$-\frac{1}{3}$	$+q_{H_d}$
\mathcal{D}^c	$\bar{3}$	1	$+\frac{1}{3}$	0
\mathcal{E}	1	1	-1	$+q_{H_d}$
\mathcal{E}^c	1	1	+1	0
H'_u	1	1	0	$-q_{H_u}$
H'_d	1	1	0	$-q_{H_d}$

2HDM: additional ingredients

- $U(1)_{\kappa(L_\mu-L_\tau)}$: generation dependent vector couplings
- Kinetic mixing ϵ between $U(1)_D$ and $U(1)_Y$

$$\{g_D, q_{H_u}, q_{H_d}, \tilde{\theta}_D, \epsilon, \kappa\},$$

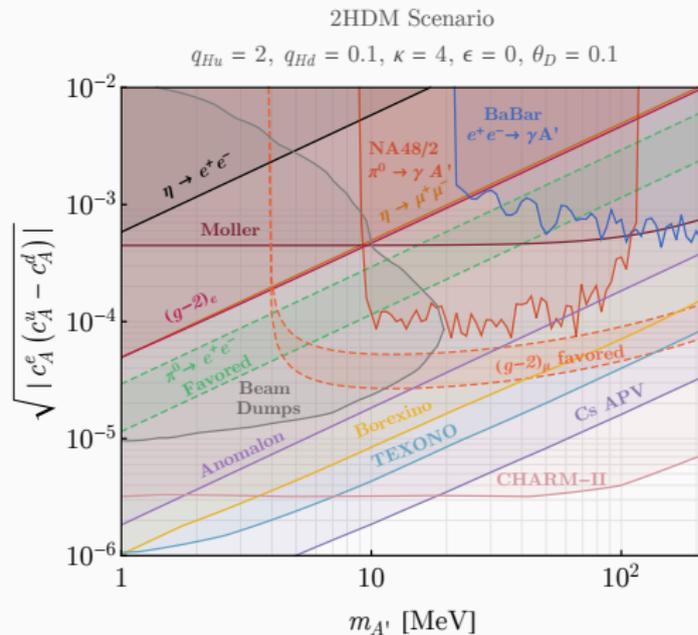
SM lepton	e	μ, τ
c_V^l	$\frac{1}{2}g_D q_{H_d} - \epsilon e + g_D \tilde{\theta}_D (-\frac{1}{2} + 2s_W^2)$	$g_D (\frac{1}{2} q_{H_d} \pm \kappa) - \epsilon e + g_D \tilde{\theta}_D (-\frac{1}{2} + 2s_W^2)$
c_A^l	$-\frac{1}{2}g_D q_{H_d} - \frac{1}{2}g_D \tilde{\theta}_D$	$-\frac{1}{2}g_D q_{H_d} - \frac{1}{2}g_D \tilde{\theta}_D$

SM quark	u, c, t	d, s, b
c_V^q	$\frac{1}{2}g_D q_{H_u} + \frac{2}{3}\epsilon e + g_D \tilde{\theta}_D (\frac{1}{2} - \frac{4}{3}s_W^2)$	$\frac{1}{2}g_D q_{H_d} - \frac{1}{3}\epsilon e + g_D \tilde{\theta}_D (-\frac{1}{2} + \frac{2}{3}s_W^2)$
c_A^q	$-\frac{1}{2}g_D q_{H_u} + \frac{1}{2}g_D \tilde{\theta}_D$	$-\frac{1}{2}g_D q_{H_d} - \frac{1}{2}g_D \tilde{\theta}_D$

SM neutrino	ν_e	ν_μ	ν_τ
$c^\nu \equiv c_V^\nu = c_A^\nu$	$\frac{1}{2}g_D \tilde{\theta}_D$	$\frac{1}{2}g_D (\tilde{\theta}_D + \kappa)$	$\frac{1}{2}g_D (\tilde{\theta}_D - \kappa)$

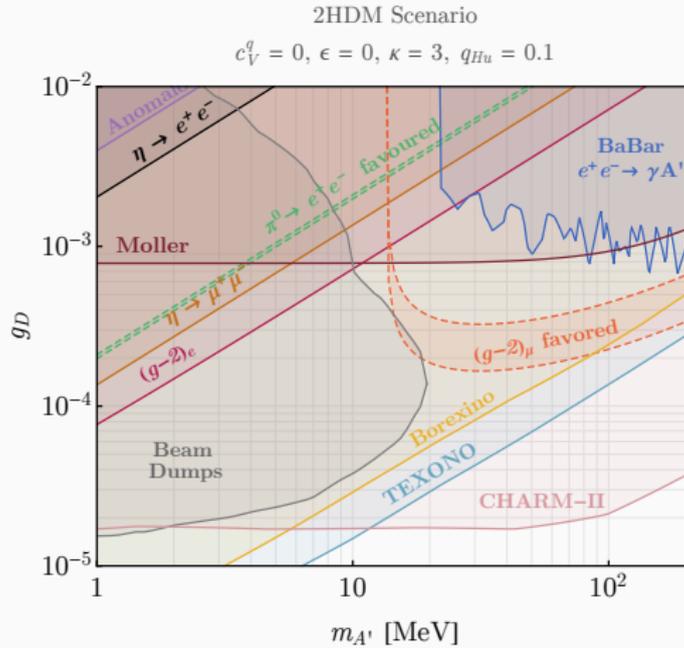
2HDM: constraints

Turn on c_V^q



2HDM: constraints

Turn off c_V^q



Non-renormalizable SM Yukawas

- SM Higgs uncharged under $U(1)_D$ – $y_u H Q u^c$ not allowed
- Generate SM Yukawas through mixing with new vector-like fermions:

$$\mathcal{L} = -M_Q Q_i^c Q_i - y H' Q_i^c Q_i - H Q y' u^c$$

Integrating out vector-like quarks:

$$y_{\text{eff}} = y y' \frac{v'}{M_Q}$$

Bound from needing to realize top Yukawa:

$$|c_A^t| \lesssim 10^{-3} \times \left(\frac{y y'}{(4\pi)^2} \right) \times \left(\frac{m_{A'}}{10 \text{ MeV}} \right) \times \left(\frac{1 \text{ TeV}}{M_Q} \right)$$

Generation-dependent couplings

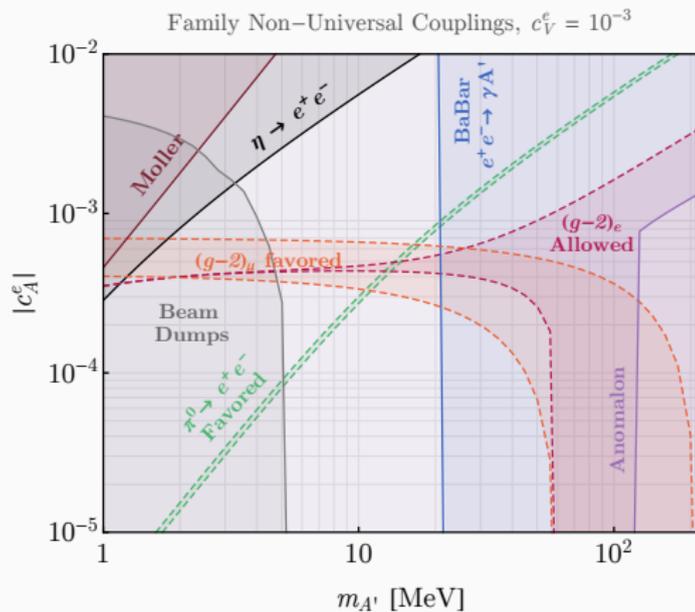
- Charge only RH gen-1 fermions under $U(1)_D$
- Assume flavour violating effects cancel in physical basis

$$\begin{aligned}c_V^e &= -\frac{1}{2}g_D q_e - \epsilon e, & c_A^e &= \frac{1}{2}g_D q_e, \\c_V^u &= -\frac{1}{2}g_D q_u + \frac{2}{3}\epsilon e, & c_A^u &= \frac{1}{2}g_D q_u, \\c_V^d &= -\frac{1}{2}g_D q_d - \frac{1}{3}\epsilon e, & c_A^d &= \frac{1}{2}g_D q_d.\end{aligned}$$

- Extra dark Higgses contribute to Anomalon bound:

$$m_{A'} \gtrsim g_D \sqrt{q_u^2 + q_d^2 + q_e^2} \times \left(\frac{4\pi}{y_\psi} \right)$$

Generation-dependent couplings



Conclusions

- We have examined constraints on MeV-scale, axially-coupled dark force carriers from a low-energy experimental perspective
- Non-trivial relationship with UV physics imposes interesting constraints on axial couplings which robustly excludes parameter space consistent with $\pi^0 \rightarrow e^+e^-$ and $(g - 2)_\mu$
- Scenarios where SM Yukawas are generated by integrating out new messenger states remain constrained

Questions?

Backup: $U(1)_D$

$$\mathcal{L}_{\text{kin}} \supset -\frac{1}{4}\hat{B}^{\mu\nu}\hat{B}_{\mu\nu} + \frac{\epsilon}{2c_W}\hat{B}^{\mu\nu}\hat{F}'_{\mu\nu} - \frac{1}{4}\hat{F}'^{\mu\nu}\hat{F}'_{\mu\nu}$$

1. Diagonalize away the kinetic mixing by shifting the $U(1)_Y$ field

$$\hat{B}_\mu \rightarrow \hat{B}_\mu + \frac{\epsilon}{c_W}\hat{A}'_\mu \implies \underbrace{\begin{cases} \hat{A}_\mu \rightarrow \hat{A}_\mu + \epsilon\hat{A}'_\mu \\ \hat{Z}_\mu \rightarrow \hat{Z}_\mu - \epsilon t_W\hat{A}'_\mu \\ A'_\mu \rightarrow A'_\mu \end{cases}}_{\text{IR eigenstates}}$$

$$\begin{cases} e\hat{A}_\mu J_{\text{EM}}^\mu \rightarrow e(\hat{A}_\mu + \epsilon\hat{A}'_\mu)J_{\text{EM}}^\mu \\ g_Z\hat{Z}_\mu J_{\text{NC}}^\mu \rightarrow g_Z(\hat{Z}_\mu - \epsilon t_W\hat{A}'_\mu)J_{\text{NC}}^\mu \end{cases}$$

Backup: $U(1)_D$

$$\mathcal{L}_{\text{kin}} \supset -\frac{1}{4} \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} + \frac{\epsilon}{2c_W} \hat{B}^{\mu\nu} \hat{F}'_{\mu\nu} - \frac{1}{4} \hat{F}'^{\mu\nu} \hat{F}'_{\mu\nu}$$

2. Induces mass mixing between \hat{Z} and \hat{A}' . **Diagonalize into the mass basis** $\{Z, A'\}$:

$$\begin{cases} \hat{Z}_\mu = \cos \zeta Z_\mu + \sin \zeta A'_\mu \\ \hat{A}'_\mu = -\sin \zeta Z_\mu + \cos \zeta A'_\mu \end{cases}$$

with $\sin \zeta \simeq \epsilon t_W g_Z \left(1 - \epsilon^2 t_W^2 - \frac{\hat{m}_{A'}^2}{\hat{m}_Z^2} \right)$ for $\hat{m}_{A'} \ll \hat{m}_Z$.

Coupling to SM currents

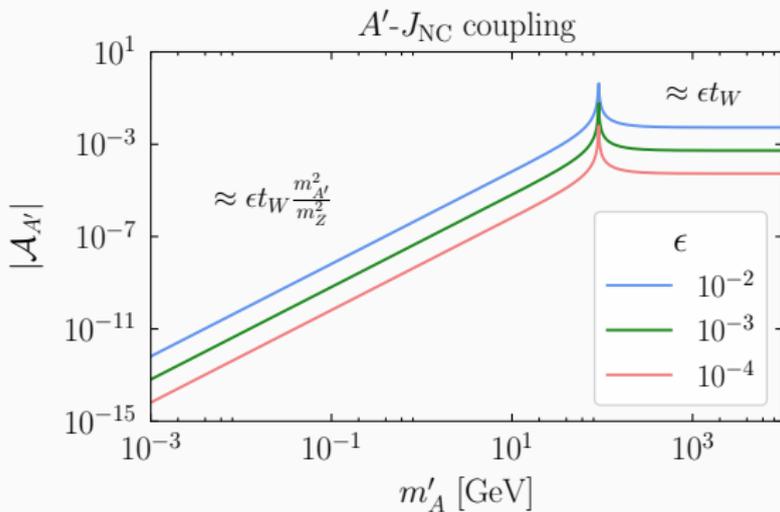
$$\begin{cases} e \hat{A}'_\mu J_{\text{EM}}^\mu = e [A_\mu + \epsilon (-\sin \zeta Z_\mu + \cos \zeta A'_\mu)] J_{\text{EM}}^\mu \\ g_Z \hat{Z}_\mu J_{\text{NC}}^\mu = g_Z [(\cos \zeta + \epsilon t_W \sin \zeta) Z_\mu + \underbrace{(\sin \zeta - \epsilon t_W \cos \zeta)}_{\equiv A'} A'_\mu] J_{\text{NC}}^\mu \end{cases}$$

Backup: $U(1)_D$

$$\mathcal{L}_{\text{int}} = -(\epsilon \cos \zeta e J_{\text{EM}}^\mu + \mathcal{A}_{A'} g_Z J_{\text{NC}}^\mu) A'_{\mu}$$

Coupling to SM neutral current

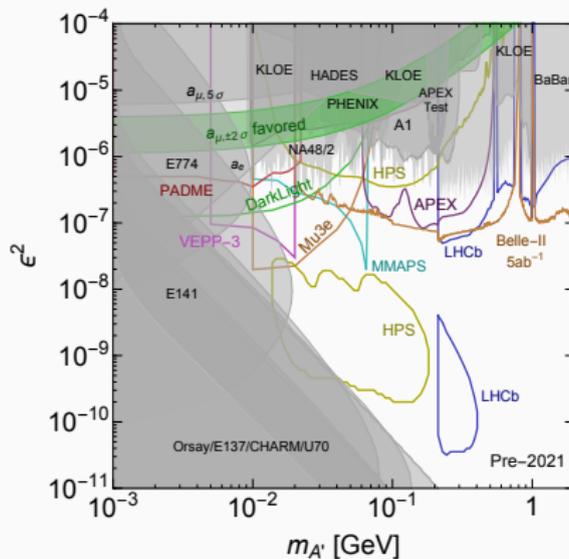
$$\mathcal{A}_{A'} = \sin \zeta - \epsilon t_W \cos \zeta$$



Backup: $U(1)_D$

Regularly invoked to explain anomalies hinting at new physics:

- PAMELA/AMS positron excess
- $(g - 2)_\mu$ deviation
- ATOMKI $Be-8$ anomaly



Backup: Single Higgs doublet

$$\mathcal{L}_{y,\text{SM}} = y_u H Q u^c + y_d H^\dagger Q d^c + y_e H^\dagger L e^c + h.c.$$

Gauge-invariant charge assignments

$$\underbrace{c_A^d = c_A^e = -c_A^u = \frac{1}{2} g_D q_H}_{c_A^f = -g_D q_H T_f^3} \quad (\text{before EWSB})$$

1. Higgs carries non-zero $U(1)_D$ charge – contributes to **mass mixing**

$$\mathcal{L} = \frac{1}{2} \begin{pmatrix} \hat{Z}_\mu & \hat{A}'_\mu \end{pmatrix} \begin{pmatrix} \hat{m}_Z^2 & -g_D q_H v \hat{m}_Z \\ -g_D q_H v \hat{m}_Z & g_D^2 q_H^2 v^2 + \hat{m}_{A'}^2 \end{pmatrix} \begin{pmatrix} \hat{Z}_\mu \\ \hat{A}'_\mu \end{pmatrix}$$

Backup: Single Higgs doublet

2. Diagonalize into **physical basis**:

$$\begin{pmatrix} \hat{Z}_\mu \\ \hat{A}'_\mu \end{pmatrix} = \begin{pmatrix} \cos \eta & \sin \eta \\ -\sin \eta & \cos \eta \end{pmatrix} \begin{pmatrix} Z_\mu \\ A'_\mu \end{pmatrix}$$

$$\sin \eta \simeq \frac{g_D q_{HV}}{\hat{m}_Z} + \mathcal{O}(g_D^3) + \mathcal{O}(\hat{m}_{A'}^2 / \hat{m}_Z^2)$$

Mixing-induced axial coupling:

$$\hat{Z}_\mu J_{\text{NC}}^\mu = (\cos \eta Z_\mu + \underbrace{\sin \eta A'_\mu}_{\Delta c_A^f}) J_{\text{NC}}^\mu$$
$$\Delta c_A^f = \sin \eta c_{A, \text{SM}}^f \simeq +g_D q_H T_f^3$$

$$c_A^f \rightarrow c_A^f + \Delta c_A^f = 0 + \mathcal{O}(g_D^3) + \mathcal{O}(\hat{m}_{A'}^2 / \hat{m}_Z^2) \quad (\text{EWSB})$$

Backup: Mixing with new vector-like Fermions

- SM fermions uncharged under $U(1)_D$
- Mix with A' through new **vector-like fermions** charged under $U(1)_D$

$$\mathcal{L} = -M_Q Q_i^c Q_i - M_U U_i^c U_i - y_L H' Q_i^c Q_i - y_R H' U_i U_i^c$$

- MFV: generation-independent $M_{Q,U}, y_{L,R}$
- Mixing for LH and RH up-quarks:

$$\theta_L \sim \frac{y_L v'}{M_Q}, \quad \theta_R \sim \frac{y_R v'}{M_U}$$

Backup: Mixing with new vector-like Fermions

$$c_V^u = -\frac{1}{2}ag_D (\theta_L^2 + \theta_R^2), \quad c_A^u = -\frac{1}{2}ag_D (\theta_L^2 - \theta_R^2)$$

Natural size of couplings

- Lower bounds on $M_{Q,U} \gtrsim 1 \text{ TeV}$
- Perturbativity of Yukawas: $y_{L,R} \lesssim 4\pi$
- Dark Higgs: $m_{A'} \gtrsim g_D q_{HV'}$

$$c_V, c_A \sim \frac{10^{-8}}{ag_D} \times \left(\frac{y}{4\pi}\right)^2 \times \left(\frac{m_{A'}}{10 \text{ MeV}}\right)^2 \times \left(\frac{1 \text{ TeV}}{M}\right)^2$$