Light vectors from baryonic and lepton family numbers with harmless Wess-Zumino terms

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based on the work with Marco Nardecchia and Luca Di Luzio

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Light vectors from abelian SM extension

- Light vectors provide a possible solution to many low-energy anomalies (e.g. muon's g-2) or a good candidate as mediator to dark sectors.
- Many BSM models including a light vector have been proposed in the past few years.

- We proposed a BSM extension including a light vector coming from the gauging of a new abelian symmetry.
- The gauge group of our model is then:

$$G_{SM} \times U(1)_X = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$$

- For simplicity, we assumed the SM Yukawa sector to be invariant under the new gauge symmetry.
- X is then a combination of the SM incidental symmetries, i.e. the baryonic number and lepton family numbers:

$$X = \alpha_B B + \sum_{i=e,\mu,\tau} \alpha_i L_i$$

Light vectors and anomalous currents

- Unless few specific cases, if no new fermions are introduced, the new gauge current is conserved at tree level but broken at loop by chiral anomaly.
- An example is the current of the baryon number:

$$\partial^\mu J_\mu^{\text{baryon}} = \frac{\mathcal{A}}{16\pi^2}\left(g^2 W^a_{\mu\nu}(\tilde{W}^a)^{\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- If a light vector couples to a non conserved current, there are (energy/vector mass)^2 enhanced processes involving the longitudinal mode of the new vector.
- Such energy-enhanced processes can be the dominant production mechanism in high-energy experiments, and can place strong constraints on its coupling.

Example: let's consider a light vector with m = 1 MeV emitted in a physical process whose energy is around 1 GeV → Enhanced by a factor of (1 GeV/1 MeV)^2 = 10^6!

WZ coefficient at 1-loop matching

- For example, a model of gauged baryon number requires anomalons to be consistent.
- Once integrated out, anomaly cancellation is preserved by WZ terms.

$$SU(2)_L^2 U(1)_B = \frac{3}{2}$$

$$U(1)_Y^2 U(1)_B = -\frac{3}{2}$$

$$\mathcal{L} \supset C_B g_X g'^2 \epsilon^{\mu\nu\rho\sigma} X_\mu B_\nu \partial_\rho B_\sigma + C_W g_X g^2 \epsilon^{\mu\nu\rho\sigma} X_\mu (W_\nu^a \partial_\rho W_\sigma^a + \frac{1}{3} g \epsilon^{abc} W_\nu^a W_\rho^b W_\sigma^c)$$

- Only the combinations $L_e - L_\mu$, $L_\tau - L_\mu$ and $L_e - L_\tau$ are free-anomaly in the SM.
- The gauging of a general linear combination of SM accidental symmetries is anomalous.

$$\mathrm{SU}(2)_L^2 \times \mathrm{U}(1)_X$$

$$\mathrm{U}(1)_Y^2 \times \mathrm{U}(1)_X$$

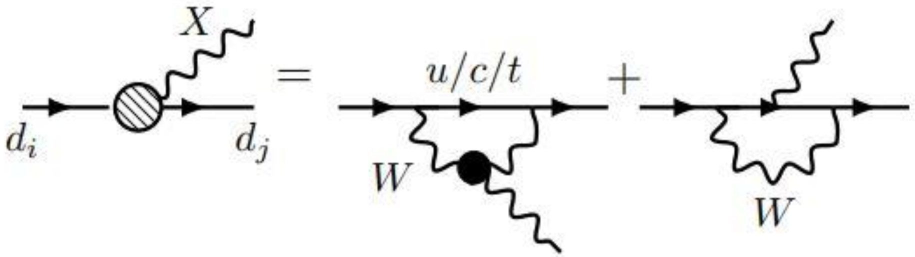
proportional to $3\alpha_B + \alpha_e + \alpha_\mu + \alpha_\tau \equiv 3\alpha_{B+L}$

- The values of the WZ coefficients depend on the UV completion.

FCNC from WZ terms

- XWW operator leads to flavor changing neutral current (FCNC) interactions

$$\mathcal{L} \supset g_{X d_i d_j} X_\mu \bar{d}_j \gamma^\mu \mathcal{P}_L d_i + \text{h.c.} + \ldots$$



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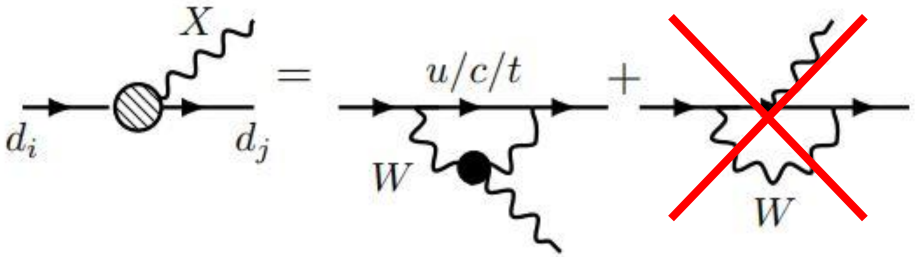

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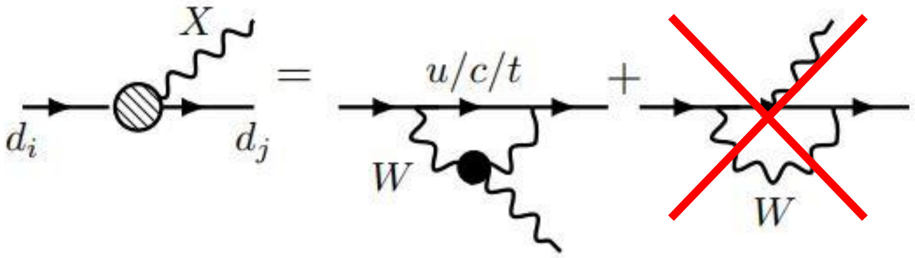

- Meson decay rates trough longitudinal light vector emission
- $g_{d_i d_j X}$ are the effective FCNC couplings originated from WZ operators

$$\Gamma(B \to KX) \simeq \frac{m_B^3}{64\pi m_X^2} |g_{bsX}|^2 \left(1 - \frac{m_K^2}{m_B^2}\right)^2 |f_K(m_X^2)|^2 \frac{2Q}{m_B}$$

$$\Gamma(B \to K^*X) \simeq \frac{m_B^3}{64\pi m_X^2} |g_{bsX}|^2 |f_{K^*}(m_X^2)|^2 \left(\frac{2Q}{m_B}\right)^3$$

$$\Gamma(K^\pm \to \pi^\pm X) \simeq \frac{m_{K^\pm}^3}{64\pi m_X^2} \left(1 - \frac{m_{\pi^\pm}^2}{m_{K^\pm}^2}\right)^2 |g_{sdX}|^2 \frac{2Q}{m_{K^\pm}}$$

$$\Gamma(K_L \to \pi^0 X) \simeq \frac{m_{K_L}^3}{64\pi m_X^2} \left(1 - \frac{m_{\pi^0}^2}{m_{K_L}^2}\right)^2 \text{Im}(g_{sdX})^2 \frac{2Q}{m_{K_L}}$$

Gauging the accidental symmetries

- The main question of our work was: can we avoid such strong constrains?
- The answer is yes: mostly chiral anomalons suppress the coefficients of the WZ terms involving the electroweak gauge bosons, thus relaxing the bounds!

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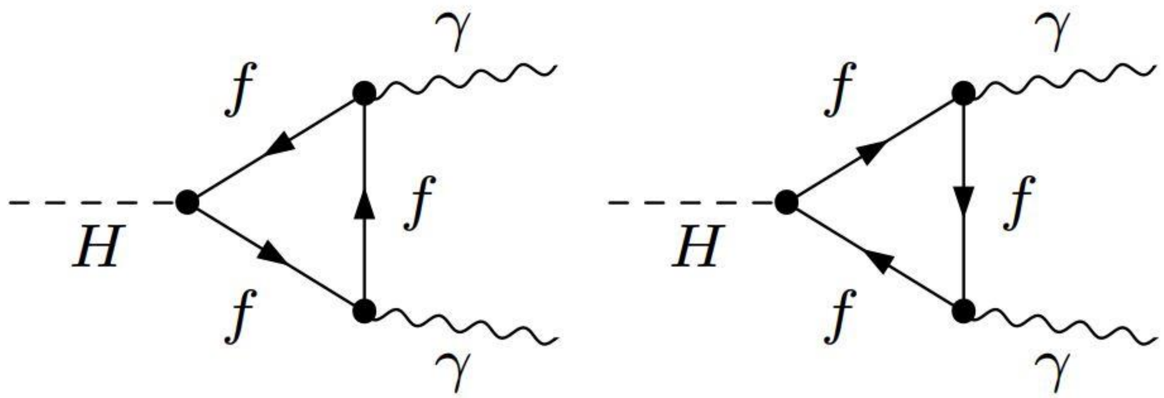
- However, mostly chiral fermions would modify the SM prediction of the Higgs decay channels.



- The goal is then to introduce a UV completion made of mostly chiral anomalons while being compatible with experimental measurements of Higgs decays.

UV completion

Field	Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_L^i	$(\frac{1}{2},0)$	3	2	1/6	$\alpha_B/3$
u_R^i	$(0,\frac{1}{2})$	3	1	2/3	$\alpha_B/3$
d_R^i	$(0,\frac{1}{2})$	3	1	$-1/3$	$\alpha_B/3$
ℓ_L^i	$(\frac{1}{2},0)$	1	2	$-1/2$	α_i
e_R^i	$(0,\frac{1}{2})$	1	1	-1	α_i
H	$(0,0)$	1	2	1/2	0
$\mathcal{L}_L$	$(\frac{1}{2},0)$	1	2	$\mathcal{Y}-1/2$	$X_{\mathcal{L}_L}$
$\mathcal{L}_R$	$(0,\frac{1}{2})$	1	2	$\mathcal{Y}-1/2$	$X_{\mathcal{L}_L}+3\alpha_{B+L}$
$\mathcal{E}_L$	$(\frac{1}{2},0)$	1	1	$\mathcal{Y}-1$	$X_{\mathcal{L}_L}+3\alpha_{B+L}$
$\mathcal{E}_R$	$(0,\frac{1}{2})$	1	1	$\mathcal{Y}-1$	$X_{\mathcal{L}_L}$
$\mathcal{N}_L$	$(\frac{1}{2},0)$	1	1	$\mathcal{Y}$	$X_{\mathcal{L}_L}+3\alpha_{B+L}$
$\mathcal{N}_R$	$(0,\frac{1}{2})$	1	1	$\mathcal{Y}$	$X_{\mathcal{L}_L}$
ν_R^α	$(0,\frac{1}{2})$	1	1	0	$X_{\nu_R}^\alpha$
$\mathcal{S}$	$(0,0)$	1	1	0	$X_\mathcal{S}$

- Anomaly-cancelling fermions are highlighted in pink.
- Anomalon $U(1)_X$ charges were chosen by the requirement that the electroweak-charged anomalons pick up mass from the SM Higgs

$$-\mathscr{L}_Y = y_1\overline{\mathcal{L}}_L\mathcal{E}_R H + y_2\overline{\mathcal{L}}_R\mathcal{E}_L H + y_3\overline{\mathcal{L}}_L\mathcal{N}_R\tilde{H} + y_4\overline{\mathcal{L}}_R\mathcal{N}_L\tilde{H} + \text{h.c.}$$

- A SM-singlet Higgs is added to give mass to the new gauge bosons but not to the electroweak-charged anomalons.

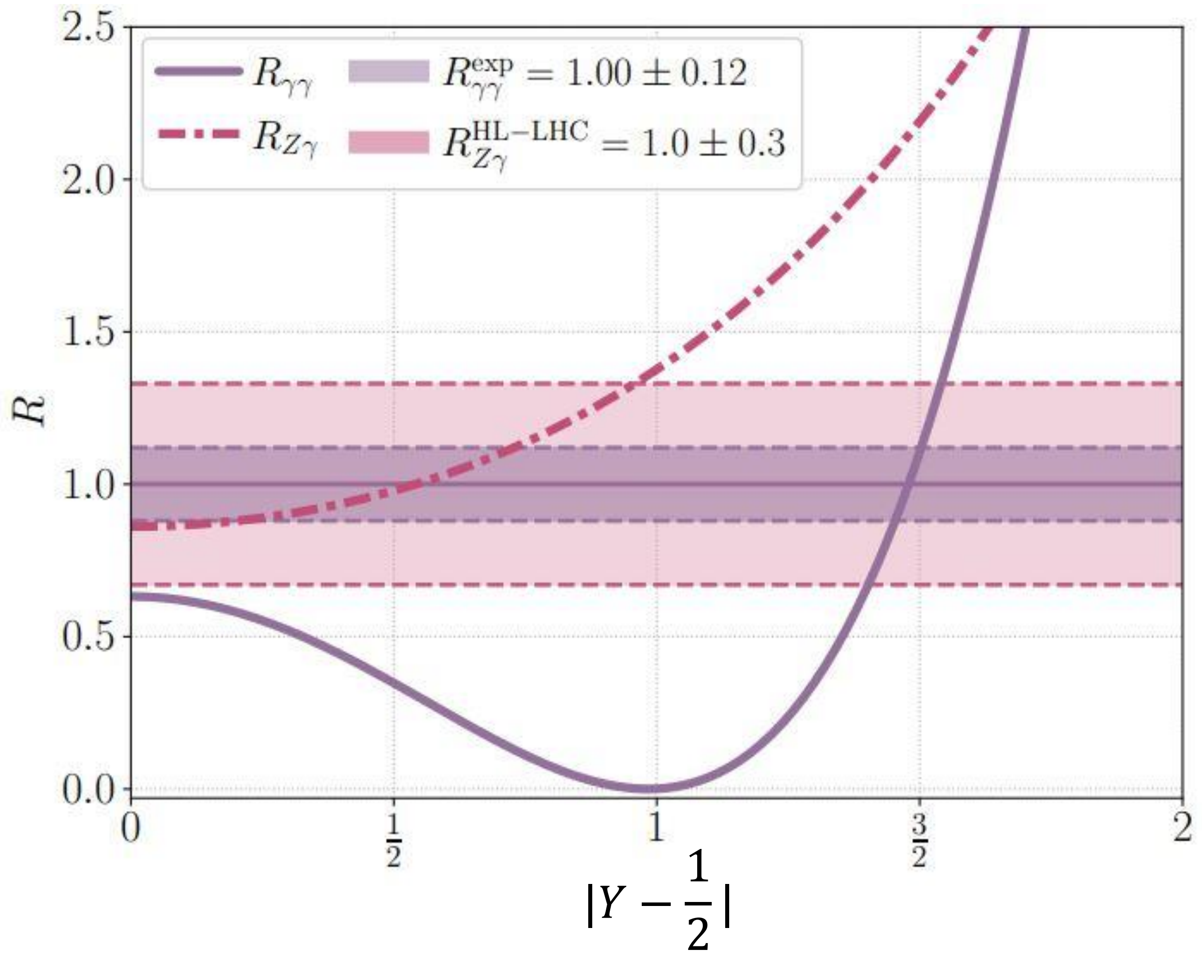
Higgs decay channels

- Mostly-chiral electroweak anomalons, needed to decouple dangerous WZ terms, would produced a signal in Higgs decays

$$R_{\gamma\gamma} = \frac{|\mathcal{A}^{SM}_{\gamma\gamma} + \mathcal{A}^{NP}_{\gamma\gamma}|^2}{|\mathcal{A}^{SM}_{\gamma\gamma}|^2}$$

$$\mathcal{A}^{NP}_{\gamma\gamma} \approx -2\mathcal{A}^{SM}_{\gamma\gamma}$$

- In the limit of heavy fermions, the anomalon contribution to the decays depends on the Y parameter.
- Our prediction is compatible with the di-photon channel for $|Y - 1/2| \approx 3/2$, while leading a large deviation to the correlated signal in the γZ channel to be tested at the High Luminosity phase at LHC.



Direct searches

Stable anomalons

- $|Y-1/2|\approx 3/2$ but $|Y-1/2|\neq 3/2$
- EW anomalon-SM mixing terms are forbidden and the lightest state of the electroweak anomalons is electrically charged and stable
- Need to invoke low-scale inflation to avoid cosmological problems
- Stable charged particles yield striking signatures at colliders in the forms of charged track, anomalous energy loss in calorimeters, longer time of flights, etc
- Actual experimental limits from CMS at 13 TeV LHC yielding $m\geq 800$ GeV

Unstable anomalons

- $|Y-1/2|=3/2$
- EW anomalons can actually mix with the SM leptons, opening new decay channels
- Anomalons with electric charge $|Q|=2$ can decay into a W and a $|Q|=1$ fermion, while the latter can mix with SM leptons and decay into $Z\ell$ or $h\ell$
- Bounds appear to be of the same order of those obtained in the case of stable charged leptons.

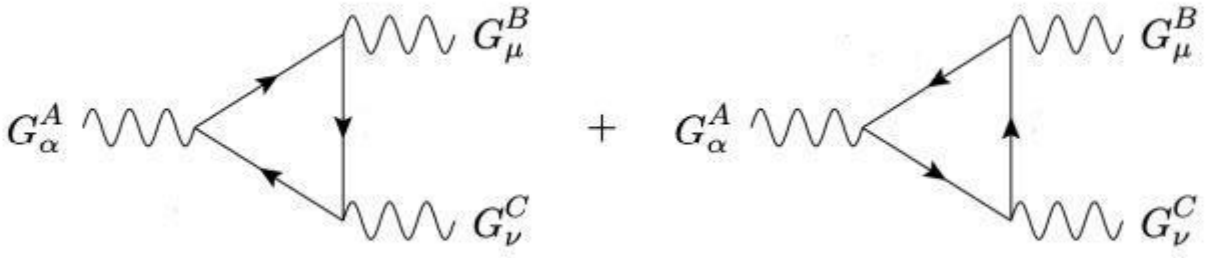
Yukawas of the anomalons to the boundary of perturbativity!

THANKS FOR THE ATTENTION!

BACK UP

Chiral anomaly and anomalon fermions

- At quantum level, chiral anomaly can break classical symmetry.
- Chiral anomaly occurs at one-loop level trough triangle with fermion fields:



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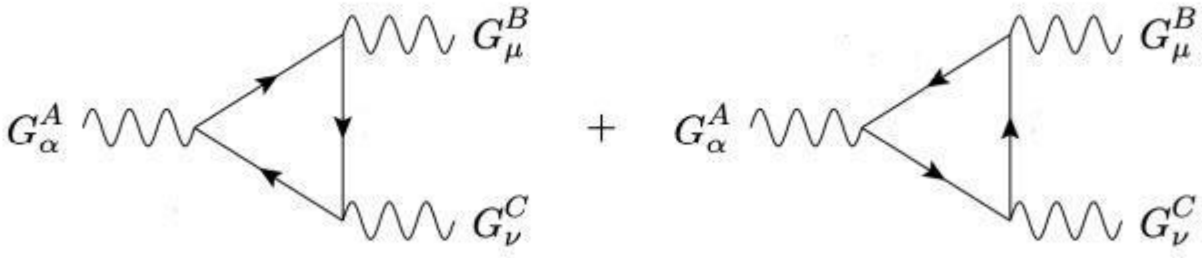

$$\partial_\mu J^\mu_{Q^A} = \sum_{BC} \frac{g_B g_C}{48\pi^2} \left[\mathrm{Tr}\, Q_R^A \{Q_R^B, Q_R^C\} - \mathrm{Tr}\, Q_L^A \{Q_L^B, Q_L^C\} \right] \partial_\alpha G_\mu^B \partial_\beta G_\nu^C \epsilon^{\alpha\mu\beta\nu}$$

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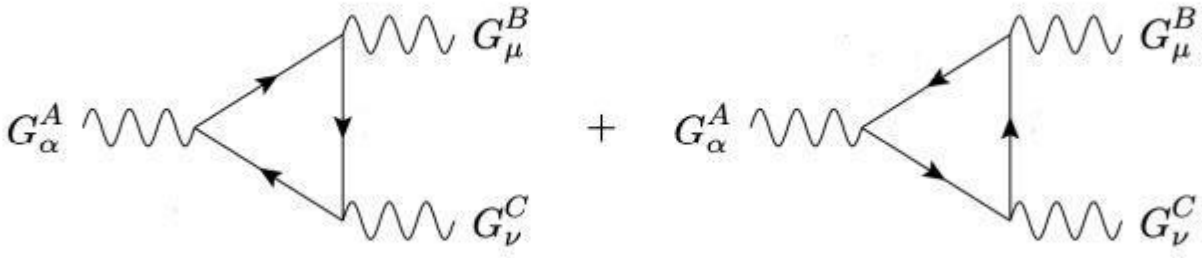

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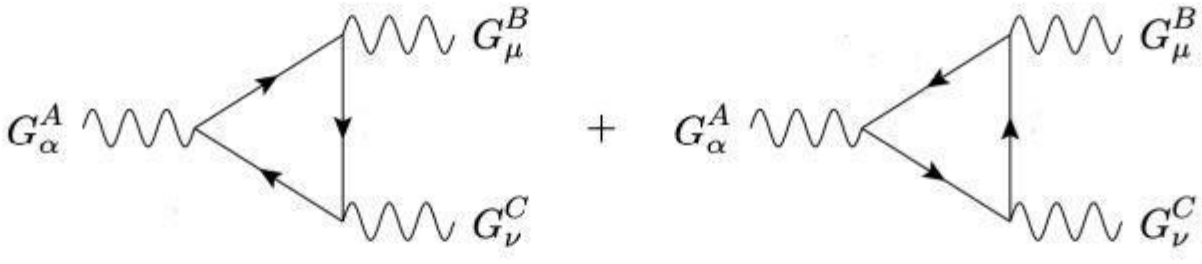

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- A gauge symmetry is conserved (and hence the theory is consistent) if

$$\sum_{\text{fermions}} \left[\mathrm{Tr}\, Q_R^A\{Q_R^B, Q_R^C\} - \mathrm{Tr}\, Q_L^A\{Q_L^B, Q_L^C\}\right] = 0$$

- Uncancelled chiral anomalies requires new fermions to have a consistent gauge theory!

Anomaly matching and WZ operators

- One of the most important EFT operator is the Wess-Zumino (WZ) term Γ_{WZ}.
- The WZ term is a functional of gauge vector bosons and Goldstone fields of the theory.
- WZ operators appear once we integrate out a fermion field from the theory.

$$\mathcal{L}_{UV} \supset \sum_i \bar{\psi}_i i\partial\!\!\!/ \psi_i - \sum_{i,j} (\bar{\psi}_{iL} \mathcal{M}_{ij} \psi_{jR} + \text{h.c.}) - \sum_{a,i,j} \tilde{H}_a (\bar{\psi}_{iL} \mathcal{Y}^a_{ij} \psi_{jR} + \text{h.c.})$$
$$- \sum_{i,j,A} g_A G^A_\mu \left[\bar{\psi}_{iL} \gamma^\mu (Q^A_L)_{ij} \psi_{jL} + \bar{\psi}_{iR} \gamma^\mu (Q^A_R)_{ij} \psi_{jR} \right]$$

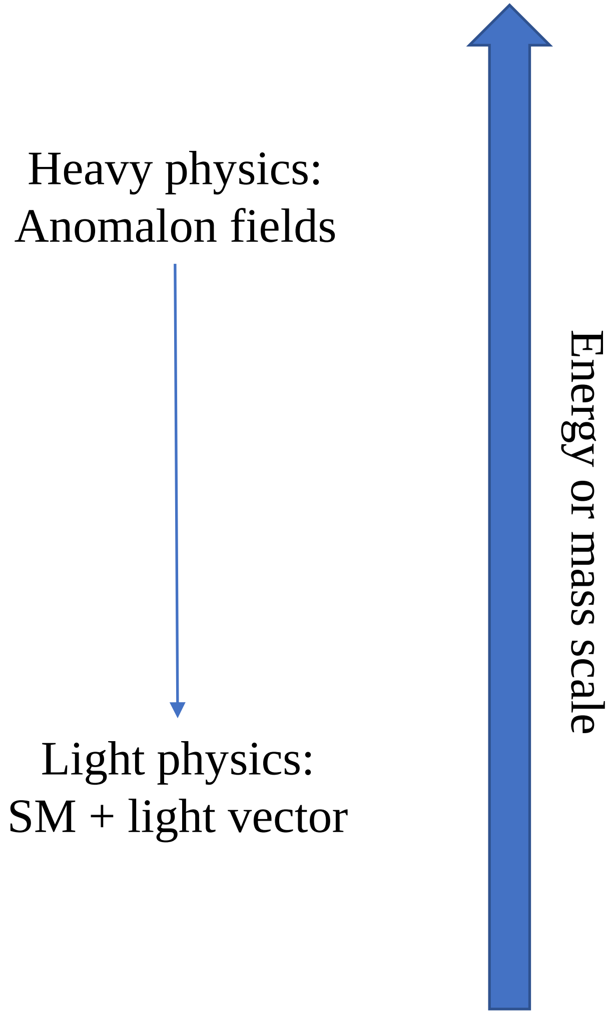
$$\Rightarrow \quad \mathcal{S}_{eff} \supset \Gamma_{WZ}(G^A_\mu, \tilde{H}^a)$$

- The WZ term matches the chiral anomaly of the UV fermions we integrated out from the theory.
- They are crucial to keep the theory free-anomaly and hence consistent.

$$\delta\Gamma_{WZ}|_{Q^A} = \sum_{BC} \frac{g_B g_C}{48\pi^2} \left[\text{Tr}\, Q^A_R \{Q^B_R, Q^C_R\} - \text{Tr}\, Q^A_L \{Q^B_L, Q^C_L\} \right] \int \mathrm{d}^4 x\, \alpha_A \partial_\alpha G^B_\mu \partial_\beta G^C_\nu \epsilon^{\alpha\mu\beta\nu}$$

EFT framework

- Uncancelled anomalies requires new fermion fields (the “anomalons”) otherwise no gauging is possible.
- Anomalon fermions are supposed to be heavy, masses above hundreds of GeV, since we have not observed them so far.



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↓

- At low energy, we work with Effective Field Theory (EFT).
- Anomalon fields are integrated out.
- EFT operators are introduced to match the UV physics.

~~Heavy physics:~~
~~Anomalon fields~~

↓

Light physics:
SM + light vector

$$\mathscr{L}_{\mathrm{EFT}} = \sum_{\mathscr{D}\geq 0,i} \frac{c_i^{(\mathscr{D})} O_i^{(\mathscr{D})}}{\Lambda^{\mathscr{D}-d}}$$

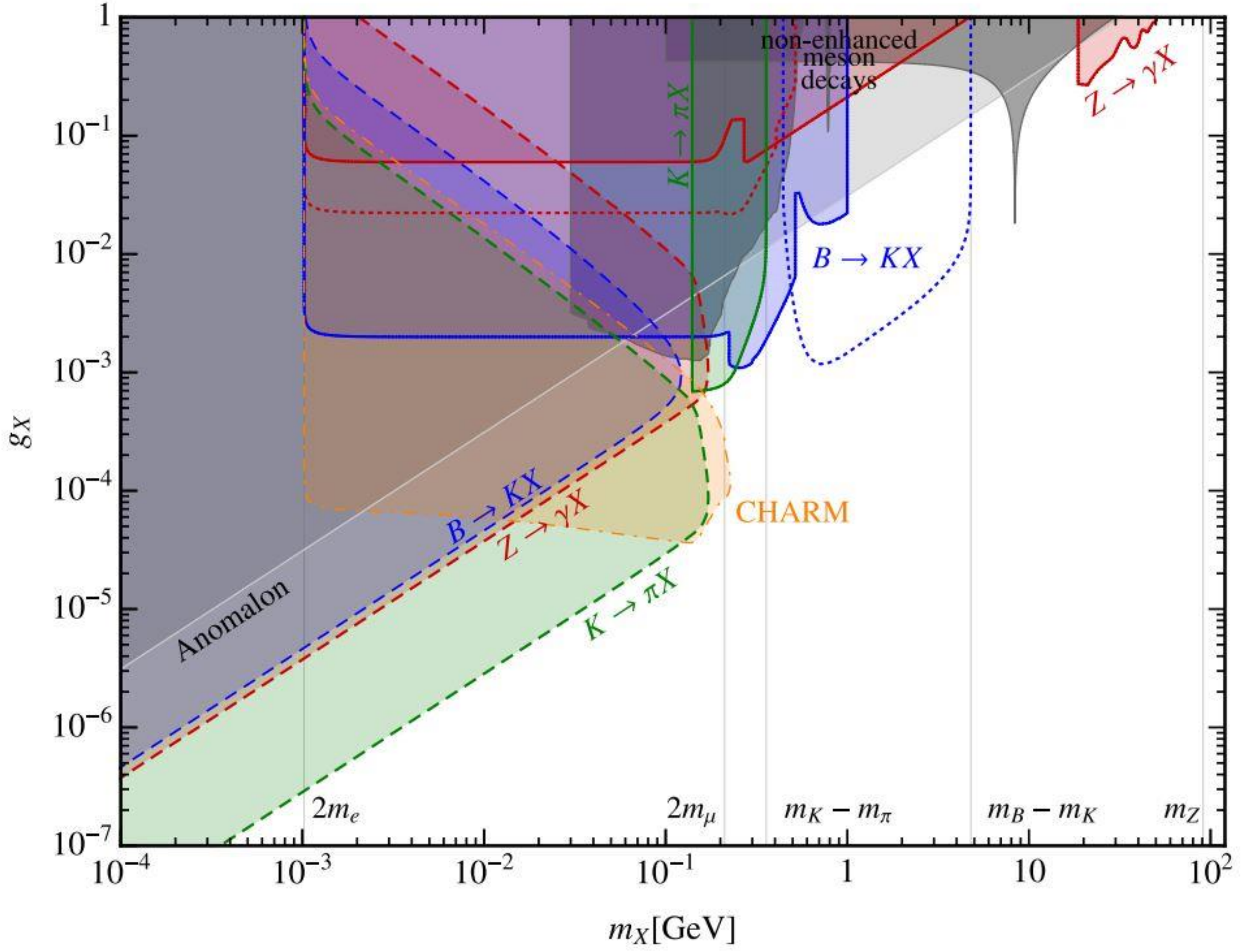
Energy or mass scale

FCNC from WZ terms

- Collection of experimental bounds from arxiv:1705.06726
- Here is considered the case of gauged baryonic number with SM-vector-like UV anomalon fields

$$g_{Xd_id_j} = -\frac{3g^4\mathcal{A}}{(16\pi^2)^2} g_X \sum_{\alpha\in\{u,c,t\}} V_{\alpha i}V^*_{\alpha j} F\left(\frac{m_\alpha^2}{m_W^2}\right)$$

Assumed kinetic mixing $\epsilon \sim e g_X/(4\pi)^2$



Neutrino masses

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ℓ_L^i	$(\frac{1}{2},0)$	1	2	$-1/2$	α_i
e_R^i	$(0,\frac{1}{2})$	1	1	-1	α_i
H	$(0,0)$	1	2	1/2	0
$\mathcal{L}_L$	$(\frac{1}{2},0)$	1	2	$\mathcal{Y}-1/2$	$X_{\mathcal{L}_L}$
$\mathcal{L}_R$	$(0,\frac{1}{2})$	1	2	$\mathcal{Y}-1/2$	$X_{\mathcal{L}_L}+3\alpha_{B+L}$
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ν_R^α	$(0,\frac{1}{2})$	1	1	0	$X_{\nu_R}^\alpha$
$\mathcal{S}$	$(0,0)$	1	1	0	$X_\mathcal{S}$

- SM Higgs and SM-singlet Higgs yield Dirac and Majorana masses respectively for neutrinos

$$-\mathcal{L}_Y^{\nu_R} = y_D^{i\beta}\bar{\ell}_L^i\nu_R^\beta\tilde{H} + \frac{1}{2}y_{\nu_R}^{\alpha\beta}\nu_R^\alpha\nu_R^\beta\mathcal{S}^* + \text{h.c.}$$

$$\longrightarrow \quad m_D^{i\beta}\bar{\ell}_L^i\nu_R^\beta + \frac{1}{2}M_R^{\alpha\beta}\nu_R^\alpha\nu_R^\beta + \text{h.c.}$$

- Our model can accommodate a type-I see-saw mechanism:

$$m_\nu = m_D M_R^{-1} m_D^T$$