Light vectors coupled to anomalous currents with harmless Wess-Zumino terms

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based on the work with Marco Nardecchia and Luca Di Luzio

published in Phys.Rev.D 105 (2022) 11, 115042

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.

- Our work considered the case of 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:

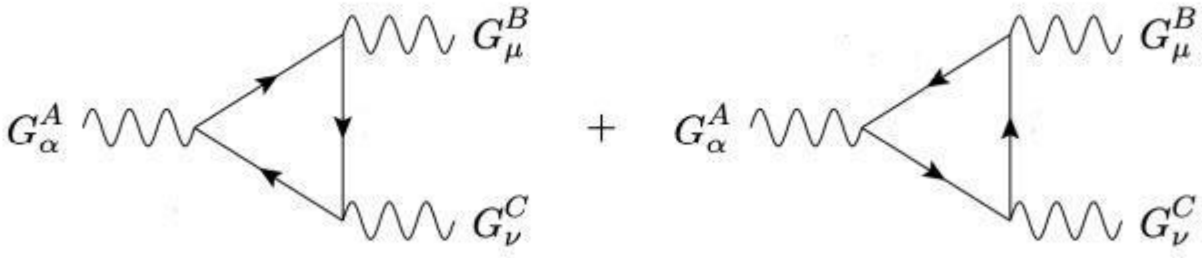
$$\partial^\mu J_\mu^{\text{baryon}} = \frac{\mathcal{A}}{16\pi^2}\left(g^2 W^a_{\mu\nu}(\tilde{W}^a)^{\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- 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!

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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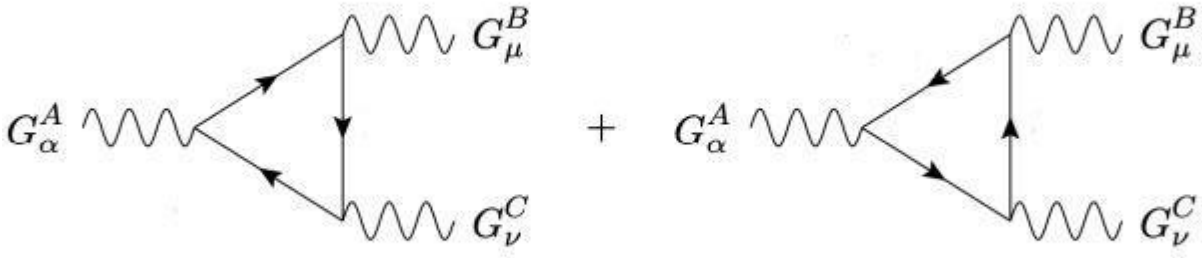

$$\partial_\mu J^\mu_{Q^A} = \sum_{BC} \frac{g_B g_C}{48\pi^2} \left[\mathrm{Tr}\, Q^A_R\{Q^B_R, Q^C_R\} - \mathrm{Tr}\, Q^A_L\{Q^B_L, Q^C_L\}\right] \partial_\alpha G^B_\mu \partial_\beta G^C_\nu \epsilon^{\alpha\mu\beta\nu}$$

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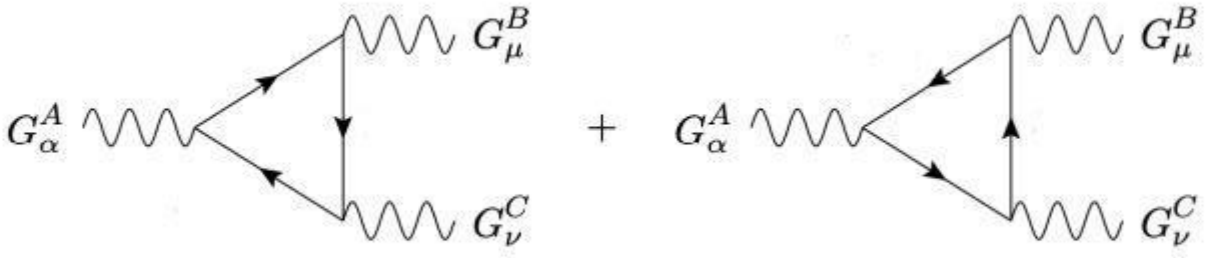

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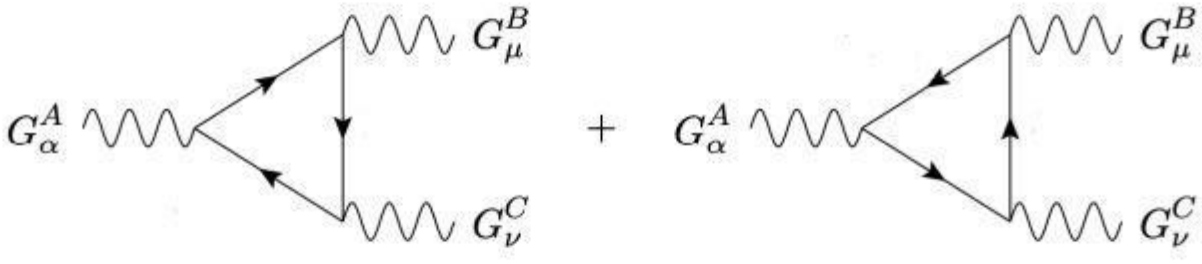


$$\partial_\mu J^\mu_{Q^A} = \sum_{BC} \frac{g_B g_C}{48\pi^2} \left[\mathrm{Tr}\, Q_R^A \{Q_R^B, Q_R^C\} - \mathrm{Tr}\, Q_L^A \{Q_L^B, Q_L^C\}\right] \partial_\alpha G_\mu^B \partial_\beta G_\nu^C \epsilon^{\alpha\mu\beta\nu}$$

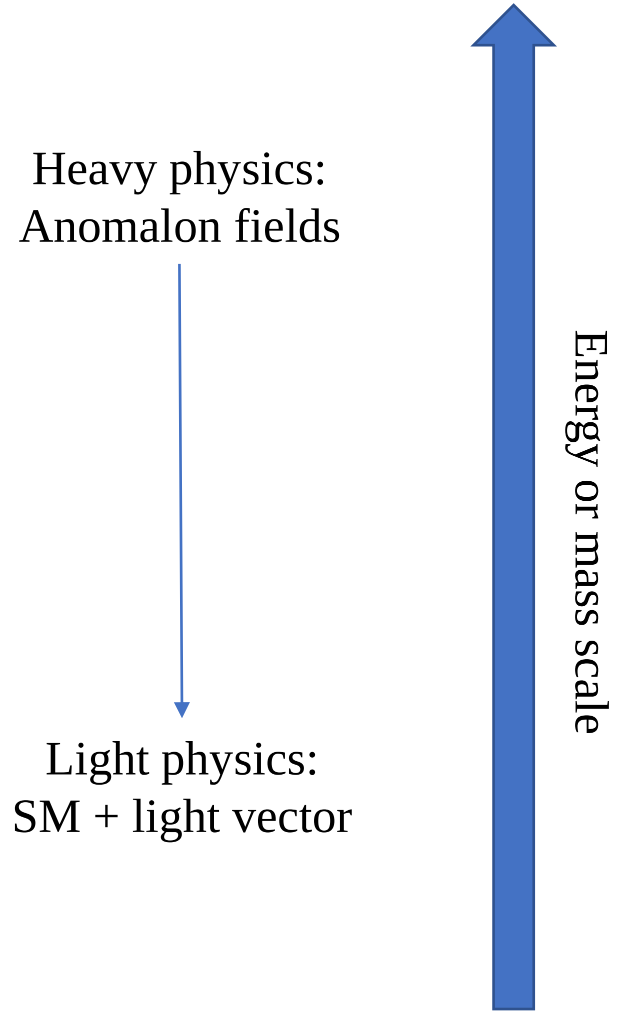
- A gauge symmetry is conserved (and hence the theory is consistent) if

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

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

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

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.

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

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.

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

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

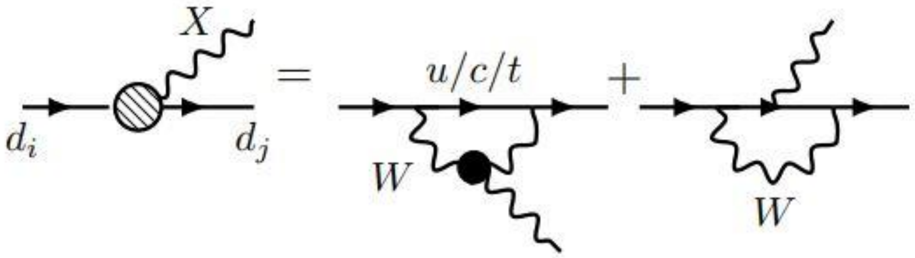
proportional to $3\alpha_B + \alpha_e + \alpha_\mu + \alpha_\tau \equiv 3\alpha_{B+L}$

- 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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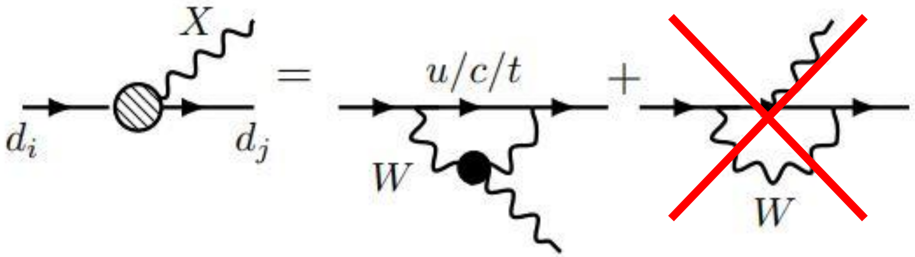

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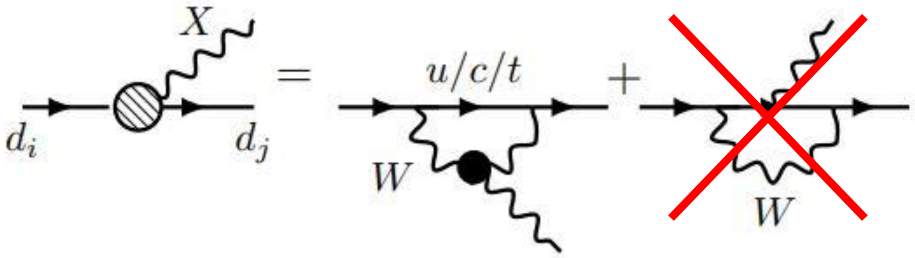


- Meson decay rates trough longitudinal light vector emission
- $g_{d_i d_j X}$ are the effective FCNC couplings originated from WZ operators

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

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

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

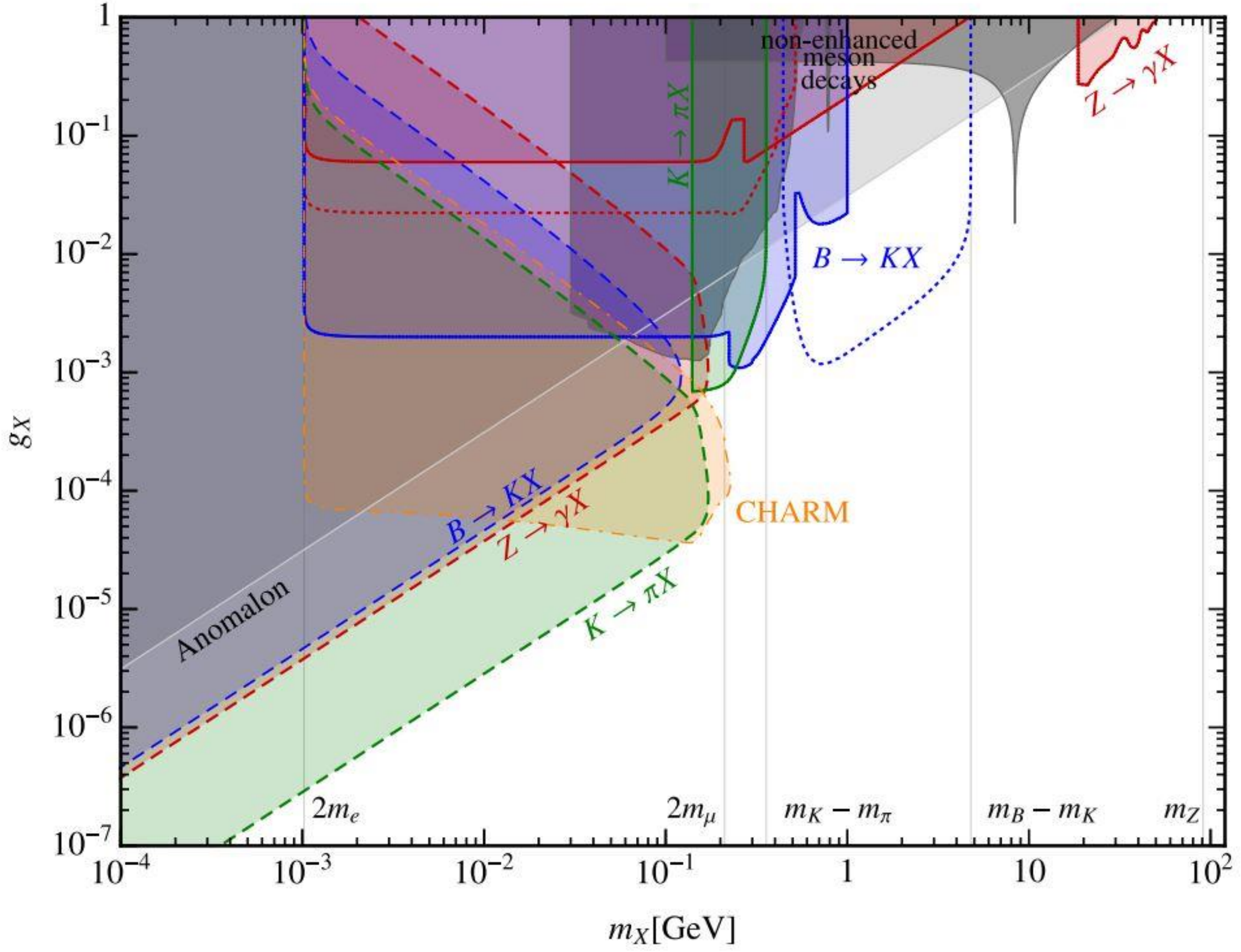
$$\Gamma(K_L \to \pi^0 X) \simeq \frac{m_{K_L}^3}{64\pi m_X^2} \left(1 - \frac{m_{\pi^0}^2}{m_{K_L}^2}\right)^2 \text{Im}(g_{sdX})^2 \frac{2Q}{m_{K_L}}$$

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

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

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



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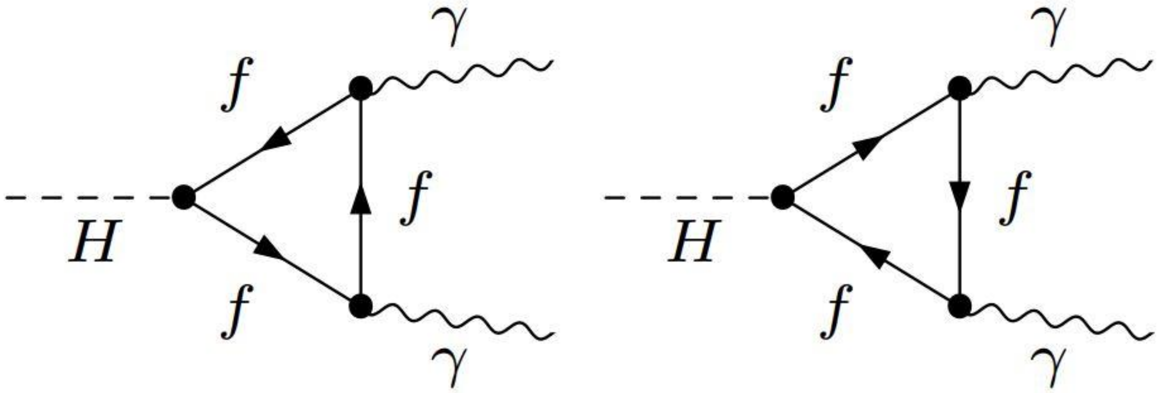
- However, mostly chiral fermions would modify the SM prediction of the Higgs decay channels.



- 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.

Neutrino masses

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	$X_\mathcal{S}$

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

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

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

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

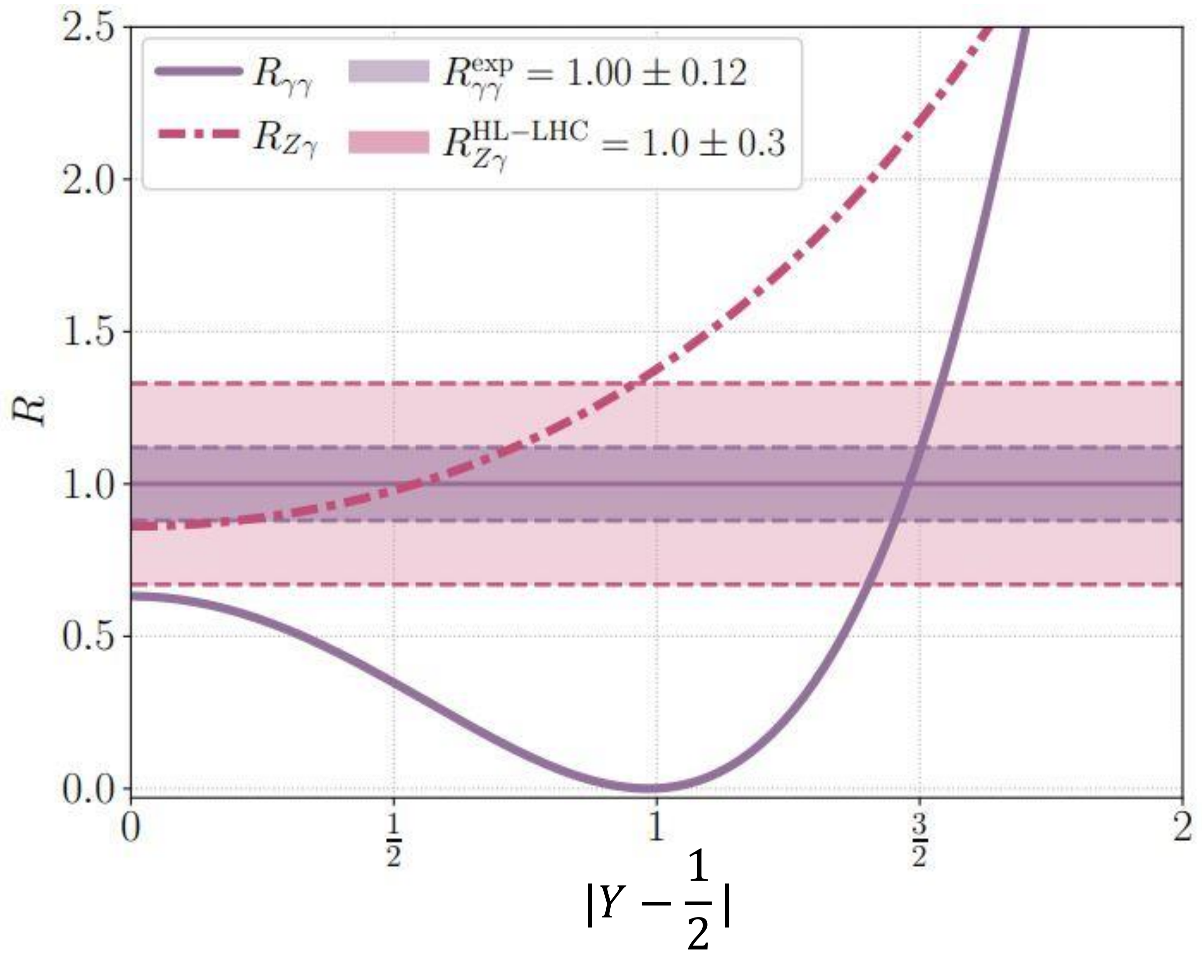
$$m_\nu = m_D M_R^{-1} m_D^T$$

Higgs decay channels

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

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

- 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!

Conclusion

- Our work considered a BSM model with a light vector coming from the gauging of the SM accidental symmetries.
- We enlarged the SM gauge group by an abelian symmetry.

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \qquad X = \alpha_B B + \sum_{i=e,\mu,\tau} \alpha_i L_i$$

- Chiral anomaly spoils the conservation of the new gauge current unless new fermions (anomalons) are introduced.
- In EFT gauge symmetry is preserved by Wess-Zumino term once we integrated out anomalon fields.
- Wess-Zumino term contains a XWW effective vertex, leading to strong constrains on the coupling and mass of light vectors due to FCNC interactions.
- Such constrains are suppressed if anomalon fields are mostly chiral fermions.

- We proposed a UV completion of mostly chiral anomaly-cancelling fermions.
- Our prediction of the di-photon decay channel of the Higgs boson is adjusted to be SM-like.
- A large deviation is then expected in the correlated signal in the γZ channel.
- Direct searches push the Yukawas of the anomalons at the boundary of perturbativity.