Bounds on Gauge Bosons Coupled to Non-conserved Currents

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Light gauge bosons

• Well-motivated: can function as dark matter or mediators to dark sectors, have cosmological applications

• Scenarios with coupling to non-conserved currents are interesting:
  
  • due to anomaly, e.g., $U(1)_B$
  
  • due to fermion mass, e.g., $U(1)_{L_\mu-\nu}$

  e.g., Preskill '91, Fayet '06, Barger et al. '11, Karshenboim et al.’14, Dror et al. ’17 ...
Toy effective Lagrangian

• Consider chiral couplings of $A_X$ to a single Dirac fermion:

$$\mathcal{L} = -\frac{1}{4} F_X^2 + i \nu \left( \bar{\phi} - ig_X A_X P_L \right) \nu - m_\nu \bar{\nu} \nu + \frac{1}{2} m_X^2 A_X^2$$

• An EFT with the radial mode of the scalar field responsible for $m_X$ integrated out $\rightarrow$ Stueckelberg limit

• Primary questions:

  • High energy behavior of the above EFT?

  • Parameter space of an EFT with SM$+a$ light $U(1)_{L_\mu - L_\tau}$ boson?
High Energy Behavior
Toy effective Lagrangian after a chiral rotation

\[ \mathcal{L} = -\frac{1}{4} F_X^2 + i \bar{\nu} \left( \phi - ig_X A_X P_L \right) \nu - m_\nu \bar{\nu} \nu + \frac{1}{2} m_X^2 A_X^2 \]

- We consider scattering at \( E \gg m_X \) involving longitudinal polarization \( A_X^L \rightarrow \) Goldstone boson equivalence theorem.

- To isolate Goldstone coupling do a chiral transformation: \( \nu_L \rightarrow \exp(ig_X \phi/m_X) \nu_L \), mass term not gauge invariant*:

\[ V = m_\nu \bar{\nu} e^{ig_X P_L \phi/m_X} \nu = \sum_n \bar{\nu} \frac{m_\nu}{n!} \left( \frac{ig_X P_L \phi}{m_X} \right)^n \nu \]

*for Dirac mass, assume right-handed \( \nu \) to be uncharged
Bounding the growth in amplitudes

\[ V = m_\nu \bar{\nu} e^{igx P_L \phi / m_X} \nu = \sum_n \bar{\nu} \frac{m_\nu}{n!} \left( \frac{igx P_L \phi}{m_X} \right)^n \nu \]

- Higher-dimensional interactions → expect growth of amplitudes and the theory to break down at high-scale

- Study scattering amplitudes to estimate precisely:

\[ S = 1 + iT \]
\[ \langle P', \alpha' \mid T \mid P, \alpha \rangle = (2\pi)^4 \delta^4(P - P') \hat{M}_{\alpha \alpha'} \]

- Primary requirement: \( |\hat{M}_{\alpha \alpha'}| \leq 1 \) for all states \( \alpha \) and \( \alpha' \) at tree level

  e.g., Chang, Luty '19
\[ \nu + n\phi \to \nu + n\phi \text{ scattering} \]

\[ |\hat{M}(\nu + n\phi \to \nu + n\phi)| = \]

\[ \frac{g_X m_\nu}{2m_X (n + 1)!n!(n-1)!} \left( \frac{g_X E}{4\pi m_X} \right)^{2n-1} \]

- Naively grows for increasing \( n \), but for large enough \( n \) the \( 1/n! \) factorial suppression from final states dominates:

\[ n_{\text{opt}} \approx (g_X E/4\pi m_X)^{2/3} \]

- Demanding \( |\hat{M}_{\text{opt}}| < 1 \)

\[ E = \Lambda \approx \frac{4\pi m_X}{\sqrt{27} g_X} \log^{3/2} \left( \frac{m_X}{g_X m_\nu} \right) \]

same parametric was obtained first using \( \nu\nu \to n\phi \)

\[ \text{by Craig et al.,'19} \]
Strong Constraints on SM+$U(1)_{L_\mu - L_\tau}$ Boson EFT
Including flavor

- $U(1)_{L\mu - L\tau}$ model with Dirac* $\nu$ mass, assuming right
  handed $\nu'$s are uncharged: $\mathcal{L}_\nu^{mass} = \nu^c M_d U^\dagger P \nu_F + \text{h.c.}$:

$$\sum_{n,j} \frac{1}{n!} \left( \frac{ig_X \phi}{m_X} \right)^n \nu^c_j M_{d,j} \left( U^\dagger_{j\mu} \nu_{\mu} + (-1)^n U^\dagger_{j\tau} \nu_{\tau} \right)$$

$$P = \text{diag} \left( 1, e^{+ig_X \phi/m_X}, e^{-ig_X \phi/m_X} \right)$$

- 3-flavor results follow from 1-flavor result via the replacement,

$$m^2_\nu \rightarrow \sum_{j=1}^3 \left( |U_{\mu j}|^2 + |U_{\tau j}|^2 \right) m^2_j$$

*constraints for Majorana mass approximately obtained by $g_X \rightarrow 2g_X$
**W width**

- Emission of many **longitudinal** gauge modes,

\[
\Gamma(W \to l + \nu + n\phi) = \frac{g_2^2 M_W^{2n-1} \kappa_n^2}{(4\pi)^{2n}} \frac{1}{16\pi(n!)^2(n+2)!(n-1)}
\]

\[\Gamma_{BSM} \equiv \sum_{n>1} \Gamma(W \to l + \nu + n\phi) = \frac{1}{16\pi \times 96} \frac{g_2^2 m_\nu^2}{M_W} \left( \frac{M_W g_X}{4\pi m_X} \right)^4 {}_2F_4 \left( \{1,1\}, \{2,3,3,5\}, \left( \frac{M_W g_X}{4\pi m_X} \right)^2 \right)\]

- Requiring \(\Gamma_{BSM} < \Gamma_W\) gives

\[m_X/g_X > 54 \text{ MeV}\]

Can we do better?
Mono-lepton+MET search

Ekhterachian, Hook, SK, Tsai

- A process like $pp \rightarrow W^* \rightarrow l\nu$ involves,
$$\frac{i}{s - M_W^2 + \Sigma(s)}; \quad \text{Im}(\Sigma(s)) = M_W \Gamma_W(s)$$

- $\mathcal{O}(1)$ modification when $M_W \Gamma_W(s) \sim s$ → suppression of rates, but no excess up to $\sqrt{s} \geq M_T \simeq 2$ TeV.

- Constraint: $\sqrt{2s} \geq M_W \Gamma_W(s)$ at 2 TeV
$$m_X/g_X > 1.3 \text{ GeV}$$
Constraints

Ekhterachian, Hook, SK, Tsai

*Compatibility at the LHC from requiring perturbativity at 8 TeV
Conclusions

• **Growth** of amplitudes in SM+light gauge boson EFT for non-conservation due to mass term.

• Implies a **perturbative unitarity bound** before which the radial mode must come in.

• Generally applicable: benchmark model $U(1)_{L_\mu-L_\tau}$.

• **Mono-lepton+MET** LHC search best constraint for most masses below keV.
Thanks for your attention!
High mass constraints
Normalization

For $\nu + n \phi \rightarrow \nu + n \phi$ scattering,

$$| P, n, \alpha \rangle = C_n \int d^4 x e^{-i P x} \phi^{(-)}(x)^n \nu^{(-)}(x) \mid 0 \rangle$$

$$\langle P', n', \alpha' \mid P, n, \alpha \rangle = (2\pi)^4 \delta^4(P - P') \delta_{nn'} \frac{P^{\alpha \alpha'}}{E}$$

$$\frac{1}{|C_n|^2} = \frac{1}{2(n + 1)(n - 1)!} \left( \frac{E}{4\pi} \right)^{2n - 1}$$

The full amplitude:

$$\langle P', n, \alpha | (-i) \int d^4 x \bar{\nu}(x) \frac{m_\nu}{(2n)!} \left( \frac{ig x P_L \phi(x)}{m_X} \right)^{2n} \nu(x) \mid P, n, \alpha \rangle = (2\pi)^4 \delta^4(P - P') i \tilde{M}(\nu + n \phi \rightarrow \nu + n \phi)$$
UV completion

• How to obtain a separation between $m_X/g_X$ and $\Lambda$?

$$V = \frac{y \Phi^q}{\Lambda' q} H L \nu^c \quad m_\nu = \frac{y \nu f^q}{\Lambda' q}$$

$$m_\Phi \sim f; \quad m_X \sim g_X f / q$$

• Higgs does come in below $\Lambda$

$$\Lambda \approx \frac{4\pi m_X}{\sqrt{27} g_X} \log^{3/2} \left( \frac{m_X}{g_X m_\nu} \right) > m_\Phi$$