Constraints on non-conserved gauge currents

why UV consistency matters

1705.06726, 1707.01503, 180X.XXXXX

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Introduction
Outline

- Why **light vectors**?
  - Hidden sectors
  - Experimental hints
- **Generalizing the vector portal**
- Gauging **anomalous symmetries**
  - Non-decoupling heavy fermions
  - Example: baryon number vector
  - Constraints
- Gauging symmetries **broken at tree-level**
  - Axial couplings
  - Weak-isospin violating
  - Mass-mixed with the $Z$
- “Real life” applications
  - Beryllium anomaly
The energy frontier has driven the field for the several decades.

Standard Model (SM) able to explain all current data.

Looking in the wrong place?

New particles below the electroweak scale?

1. Light particle could be a mediator to dark sector.

2. Useful to explain experimental anomalies.

3. Be open minded: “Who ordered that?”
Dark sector portals

- Scalar portal, $\phi$,
  \[ \phi |H|^2, \phi^2 |H|^2, \ldots \]
- Fermionic portal, $N$,
  \[ HLN, \ldots \]
- Vector portal, $X^\mu$,
  \[ F_{\mu\nu}X^{\mu\nu}, X_\mu J^\mu_{B-L}, X_\mu J^\mu_{L_\mu-L_\tau}, \ldots \]
- SM: **EM, $B - L$, $L_\mu - L_\tau$, etc. are conserved**
- Coupling to **conserved** currents $\rightarrow$ straightforward but restrictive
- Relax this requirement?
Many experimental hints for **new light states**

- Others: proton radius puzzle, 3.5 keV line, ...
- $^8\text{Be}$ anomaly models - **fun application of new constraints**
How to introduce these particles?

- Fundamental spin-1 particles are tricky
- Cause amplitudes to grow with energy ($\Rightarrow$ unitarity violation)
- e.g.,

\[ M^\mu \propto \frac{q^\mu}{m_X} \sim \frac{E}{m_X} \]

- $1/m_X$ behaviour consequence of non-conserved current:

\[ \partial_\mu j^\mu 5 = 2im_\psi \bar{\psi}\gamma^5 \psi \]

- Avoid growth by choosing charges of a symmetry
- Safe choices $\rightarrow$ good symmetries of SM
Gauging “bad” symmetries

- We can gauge symmetries **broken in the SM!**
- Breaking can be
  - at **quantum-level** (e.g., baryon number vector)
    
    ![Triangle Diagram]
    
    
    broken by triangle diagrams
  - at **tree level** (e.g., axial couplings)
    
    ![Tree Diagram]
    
    broken by $m_\psi$
  - $\partial_{\mu}J_{\mu}^X \neq 0$ leads to rates enhanced by $(E/m_X)^2$
    - $\Rightarrow$ unitarity violation
Loop-level breaking

- Focus on symmetries violated by the chiral anomaly
- Can see breaking at amplitude level using Ward Identity:

\[ q_\rho \mathcal{M}^\rho(q) = 0 \]

- **Chiral anomaly:**

\[ \mathcal{M}^{\mu\nu\rho} = X_f Y_f^2 \epsilon^{\mu\nu\rho\sigma} k_\rho p_\sigma \]

- UV divergent: chose regulator which preserves SM

- Now study assumption further
Theory needs “fixing”

- Introduce heavy $U(1)_X$ chiral fermions (SM-chiral ruled out)

$$E \quad m_F \lesssim \frac{4\pi m_X}{g_X}$$

[ - Preskill (1991)]

$$\sum_f X_f Y_f^2 = - \sum_F X_F Y_F^2$$

[ - D'Hoker, Farhi (1984)]

- But these fermions don’t decouple!
- For $E \ll m_F$ have effective interactions:
UV theory

- Massless SM + new fermions, $F$:

$$- q_\rho \mathcal{M}^{\mu\nu\rho} = \left( 0 + \frac{g^f g_X}{12\pi^2} \sum_F 2m_F^2 I_{00}(m_F) X_F Y_F^2 \right) \epsilon^{\nu\rho\lambda\sigma} p_\lambda k_\sigma$$

$$\lim_{m_F \gg m_X} q_\rho \mathcal{M}^{\mu\nu\rho} = - \frac{g^f g_X}{12\pi^2} \sum_F X_F Y_F^2 \epsilon^{\nu\rho\lambda\sigma} p_\lambda k_\sigma$$

Anomaly cancelled

Constant value for $m_F \gg m_X$!
3-pt vertex
Building SM+$X$ effective theory

- How to derive 3-pt interaction in SM+$X$ EFT?
- Regulator uniquely determines assumption about UV
- In full theory chose regulator valid for energy $\rightarrow \infty$
- Impossible in the SM+$X$ EFT
- Can choose:
  1. EFT breaks $SU(2)_L \times U(1)_Y$ (heavy fermions are SM-chiral)
  2. EFT breaks $U(1)_X$ (heavy fermions are $U(1)_X$-chiral)
- If EFT breaks EW symmetry
  - Heavy fermions get mass from Higgs
  - ruled out
- Alternatively, EFT breaks $U(1)_X$
  - leads to amplitudes growing with $\text{energy}/m_X$!
Effective interactions

○ Longitudinal model dominates, $X_\mu \rightarrow \partial_\mu \varphi / m_X$

○ Triangle diagrams arise from (assuming EFT breaks $U(1)_X$),

$$\mathcal{L}_{\text{eff}} = \frac{g_X}{16\pi^2 m_X} \left[ \sum_f X_f Y_f^2 \right] \varphi \left( g^2 W^a \tilde{W}^a - g'^2 B \tilde{B} \right)$$

○ Need to add to $\mathcal{L}_X$!

○ New processes: [JD, Pospelov, Lasenby - 1705.06726]

○ These grow with energy, $\mathcal{M} \propto E / m_X$!
1. What happens with $B - L$ below $m_t$?

- Theory appears anomalous
- $B - L$ is good symmetry $\rightarrow$ can’t exist “anomalous” interactions
- Integrating out top breaks EW (top is EW chiral)
- Below $m_t$, $\partial_\mu J_{\text{EW}}^\mu \neq 0$ but $\partial_\mu J_{X}^\mu = 0$
- Rates “enhanced” by $E^2/m_W^2$ (not $E^2/m_X^2$!)

2. What if $m_F \ll m_Z$?

- No 3-pt diagram but collider constraints $\Rightarrow m_F \gtrsim 100$ GeV

3. What about $\varphi \tilde{F}F$ and $\varphi \tilde{G}G$?

- All interactions are vector-like $\rightarrow$ no chiral anomaly
The $X$ Lagrangian looks like,

\[
\frac{m_X^2}{2} X^2 + \frac{g_X}{3} X \mu \sum_i \bar{q}_i \gamma_\mu q_i + \frac{3g_X}{32\pi^2} \frac{\varphi}{m_X} (g^2 W^a \tilde{W}^a - g'^2 B \tilde{B})
\]

$X$ can decay:

[1404.4370 - Tulin]
$B$ vector constraints

- Non-enhanced limits:

![Diagram of $B$ vector constraints with mass limits and decay modes.]

[Carone, Murayama - hep-ph/9501220]

[Tulin - 1404.4370]
Direct searches for heavy fermions:

[Dobrescu, Frugiuele - 1404.3947]
$B$ vector constraints

- $Z \rightarrow X\gamma$

[JD, Pospelov, Lasenby - 1705.06726]

![Diagram showing constraints on $m_X$ and $g_X$ with regions for visible decays and missing energy](image-url)
$B$ vector constraints

- $B \rightarrow KX$ (not just $K^*!$), $K \rightarrow \pi X$:

\[
\text{[JD, Pospelov, Lasenby - 1705.06726]}
\text{[Recast of - Babar, Belle, LHCb]}
\]
\section*{$B$ vector constraints}

- Beam dump:

[JD, Pospelov, Lasenby - 1705.06726]
Limit summary \((U(1)_B)\)

- Summary of all limits
- Significant improvement over old limits (gray)

**X** decays to SM

**X** decays to dark sector
Tree-level breaking
Amplitudes grow with energy... **even at tree-level**

- Need modification of EW sector

\[ \Delta \lesssim m_X / g_X \]

- Below this scale, \( \partial_\mu J_\mu^X \neq 0 \! \)
- For \( E \ll \Lambda \):
  \[ \mathcal{M} \propto E / m_X \]
Axially-coupled vector

- $X$ can have axial couplings to SM fermions
- $m_f$ are $U(1)_X$
- Still have $U(1)_X$-chiral anomaly (now with $F\tilde{F}$ and $G\tilde{G}$)

[Fayet - hep-ph/0607318]

[JD, Pospelov, Lasenby - 1705.06726]

[JD, Pospelov, Lasenby - 1707.01503]

[JD, Pospelov, Lasenby - 1707.01503]
Axially-coupled UV completions

- SM+axial, e.g.,
  \[ \mathcal{L} \supset H \bar{L} L e_R + X_\mu \bar{e}_R \gamma^\mu e_R \]

- Not UV complete
- Need to charge Higgs under $U(1)_X$
- **Benchmark model:** $U(1)_R$
- Still need heavy fermions to cure anomaly

References:
- [1609.02188 - Ismail, Keung, Tsao, Unwin]
- [1609.09072 - Kahn, Krnjaic, Mishra-Sharma, Tait]
Example: $U(1)_R$-coupled vector

- Non-enhanced limits:

  - [Fayet - hep-ph/0702176]
  - [Babar - 1406.2980]
  - [Dobrescu, Frugiuele - 1404.3947]

### Graph

- $pp \rightarrow F\bar{F}$
- $e^+e^- \rightarrow X\gamma$
- $e + Ce \rightarrow e + Ce$
- (more model-dependent)

### Axes

- $\phi_X$: $10^{-4}$ to $10^1$
- $m_X$: $10^{-4}$ to $10^2$ (in GeV)
- $2m_e$: $10^{-4}$ to $10^{-2}$
- $2m_{\mu}$: $10^{-2}$ to $10^{-1}$
- $m_K - m_{\pi}$: $0$ to $1$
- $m_B - m_K$: $0$ to $10$

### Sections

- Introduction
- Tree-level breaking
- Applications
Example: $U(1)_R$-coupled vector

- $\Upsilon \rightarrow X\gamma$:

[Ref: Fayet - hep-ph/0702176]
[Ref: JD, Pospelov, Lasenby - 1707.01503]
Example: $U(1)_R$-coupled vector

- Monojet (using $\varphi \tilde{G} G$): [JD, Pospelov, Lasenby - 1707.01503]
Example: $U(1)_R$-coupled vector

- $Z \to X\gamma$:

[JD, Pospelov, Lasenby - 1705.06726]
○ FCNC:

[JD, Pospelov, Lasenby - 1705.06726]
Beam dump:

[JD, Pospelov, Lasenby - 1705.06726]
Limit summary $(U(1)_R)$

- Summary of all limits
- Significant improvement over old limits (gray)

**$X$ decays to SM**

**$X$ decays to dark sector**
Weak-isospin violation

- Can build models that charged current violates $U(1)_X$
- Occurs if couple only one particle of SU(2) doublet to $X$
- Enhanced processes:
  - $W \ell^+ \nu X$
  - $W \pi^+ \ell^+ X$
  - $W \pi^+ \nu X$

$\pi^+ \to e^+ \nu X$ is particularly stringent

- SM rate for $\pi^+ \to e^+ \nu (\gamma^* \to e^+ e^-) \propto m_e^2$ (at tree-level)
- Not the case for $X$ rate

[Karshenboim, McKeen, Pospelov - 1401.6154]  [JD, Pospelov, Lasenby - 1707.01503]
EW coupling

- $X$ could couple to EW sector (other than kinetic mixing)
- Such couplings are not $U(1)_X$ invariant
- Prominent example: mass-mixing:

$$\mathcal{L} \supset \varepsilon_Z m_Z^2 X_{\mu} Z^{\mu}$$

- Typical for generic light vector model
- Enhanced rates, $\propto \varepsilon_Z$

[JD, Pospelov, Lasenby - 180X, XXXXX]

[JD, Pospelov, Lasenby - 1705.06726]
- Constraints on a mass-mixing are tricky
- Mixing is not EW-gauge invariant!
- Leads to log-enhanced FCNCs
- 2HDM for mass-mixing
- \( m_H \gg m_W \gg m_X \)
- standard motivation for APV
- FCNC from IR and UV
- \( g_{d_i d_j X} \propto \mathcal{I}_{IR} + \mathcal{I}_{UV} \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>SM</th>
<th>U(1) ( X )</th>
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</thead>
<tbody>
<tr>
<td>( H_1 )</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>( H_2 )</td>
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<td>✓</td>
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<tr>
<td>( H_d )</td>
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<td>✓</td>
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</tbody>
</table>

- Introduction
- 3-pt vertex
- Constraints
- Tree-level breaking
- Applications
Applications
Beryllium anomaly

- Excess in $^8\text{Be}^\ast \rightarrow \text{Be} e^+ e^-$ in $m_{ee}$ (or $\theta_{ee}$) [1504.01527 - Krasznahorkay et al] [1604.0741 - Feng et al]

- New physics explanation: vector/pseudoscalar

- Unusual vector: $\mathcal{L} \supset \sum \epsilon_{f} \bar{f} \gamma^\mu f X_\mu$ “anomalies to fix anomalies” [1608.03591 - Feng et al]

- Claim: $\geq 5\sigma$ [1609.01669 - Ellwanger, Moretti]

- Constraints

- Introduction

- 3-pt vertex

- Applications
Explaining the Beryllium anomaly requires some vector gymnastics.

Requires $|\epsilon_e| \sim \epsilon_u \simeq -2\epsilon_d$, $\epsilon_\nu \simeq 0$.

Idea: gauge baryon number with introduce kinetic mixing.

- Sets $\epsilon_\nu \to 0!$
- Can tune $\epsilon_u$ to cancel $\epsilon_d$

But predicts...

$$\text{Br}(K \to \pi (X \to \text{inv})) \simeq 10^{-5} \left( \frac{g_X}{10^{-3}} \right)^2 \left( \frac{17 \text{ MeV}}{m_X} \right)^2$$

Limit: $\text{Br}(K \to \pi + \text{inv}) \simeq (2 \pm 1) \times 10^{-10}$

Ref: [1608.03591 - Feng et al]
Idea: $B - L$ without neutrino coupling can explain anomaly

Use mass-mixing to eliminate neutrino coupling

Require $g_X \sim 10^{-3}$

Model has weak-isospin violation ($W\ell\nu$ does not preserve $U(1)_X$)

\[
\text{Br}(\pi^+ \rightarrow e^+\nu(X \rightarrow e^+e^-)) \simeq 10^{-7} \left( \frac{17\text{MeV}}{m_X} \right)^2 \left( \frac{g_X}{10^{-3}} \right)^2
\]

\[
\text{Limit: } \text{Br}(\pi^+ \rightarrow e^+\nu e^+e^-) \simeq \lesssim 3 \times 10^{-9}
\]

[SINDRUM Collaboration - 1989]
8Be - axially coupled vector

- Idea: axially-coupled vector
- Changes all the constraints
- Allows for somewhat smaller couplings $g^u_X \sim g^d_X \sim 10^{-4.5}$
- But...

$$\text{Br}(B \rightarrow K(X \rightarrow e^+ e^-)) \simeq 0.1 \left( \frac{17\text{MeV}}{m_X} \right)^2 \left( \frac{g_X}{10^{-5}} \right)^2$$

$$\left[ \text{Limit} : \delta\text{Br}(B \rightarrow Ke^+ e^-) \lesssim 10^{-7} \right]$$

[BaBar Collaboration - 0807.4119]
Take home message

- Can gauge non-conserved currents
- Broken at loop level?
  - Dangerous!
- Broken at tree level?
  - More dangerous!
- Constraints grow with energy!
- FCNC’s dominate for $m_X \lesssim m_B$
- Rule out most $^8\text{Be}$ anomaly models
- Moral:

  careful what you gauge!