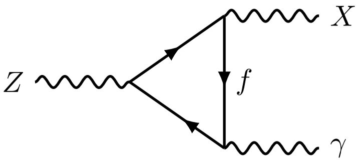
Constraints on non-conserved gauge currents

why UV consistency matters

1705.06726, 1707.01503, 180X.XXXXX

Jeff Dror, Robert Lasenby, Maxim Pospelov



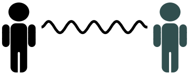
Introduction

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

Light particles

- 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 **mediator** to dark sector



  2. Useful to **explain experimental-anomalies**
  3. Be open minded: **“Who ordered that?”**

- Scalar portal, ϕ,

$$\phi \left|H\right|^2, \phi^2 \left|H\right|^2, \ldots$$

- Fermionic portal, N,

$$HLN, \ldots$$

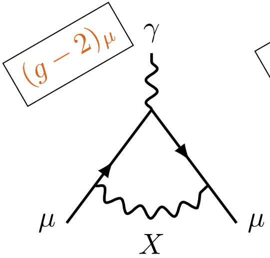
- **Vector portal**, X^μ,

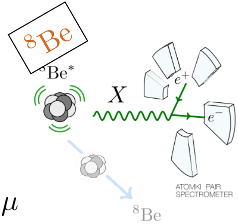
$$F_{\mu\nu} X^{\mu\nu}, X_\mu J^\mu_{B-L}, X_\mu J^\mu_{L_\mu - L_\tau}, \ldots$$

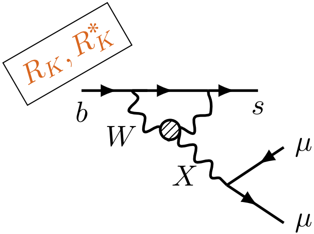
- SM: **EM, $B-L$, $L_\mu - L_\tau$, etc. are conserved**
- Coupling to **conserved** currents → straightforward but restrictive
- Relax this requirement?

Experimental hints

- Many experimental hints for **new light states**



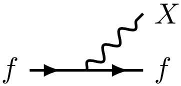




- Others: proton radius puzzle, 3.5 keV line, ...
- ^{8}Be anomaly models - **fun application of new constraints**

How to introduce these particles?

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



$$\Rightarrow \mathcal{M}^{\mu} \propto \frac{q^{\mu}}{m_X} \sim \frac{E}{m_X}$$

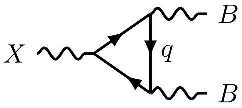
- $1/m_X$ behavoir consequence of non-conserved current:

$$\partial_{\mu} j^{\mu 5} = 2 i m_{\psi} \bar{\psi} \gamma^5 \psi$$

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

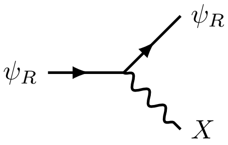
Gauging "bad" symmetries

- We can gauge symmetries **broken in the SM!**
- Breaking can be
  - at **quantum-level** (e.g., baryon number vector)



$\rightarrow$ broken by triangle diagrams

  - at **tree level** (e.g., axial couplings)



$\rightarrow$ broken by m_ψ

- $\partial_\mu J^\mu_X \neq 0$ leads to rates enhanced by $(E/m_X)^2$
  - $\Rightarrow$ unitarity violation

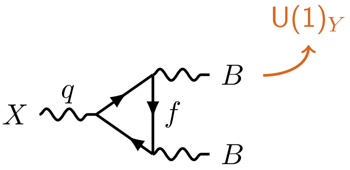
Loop-level breaking

- 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**:

$$\mathcal{M}^{\mu\nu\rho} =$$



- UV divergent: chose regulator which preserves SM

$$q_\rho \mathcal{M}^{\mu\nu\rho} = \frac{g_X g'^2}{12\pi^2} \sum_{f \in \text{quarks}} X_f Y_f^2 \epsilon^{\mu\nu\rho\sigma} k_\rho p_\sigma$$

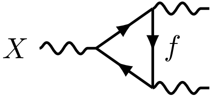
- Now study assumption further

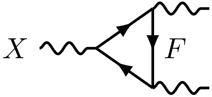
Theory needs "fixing"

- Introduce heavy $\mathrm{U}(1)_X$ chiral fermions (SM-chiral ruled out)

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

[- Preskill (1991)]

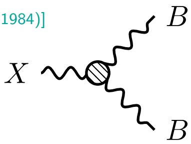




Cancel anomaly: $$\sum_f X_f Y_f^2 = -\sum_F X_F Y_F^2$$

[- D'Hoker, Farhi (1984)]

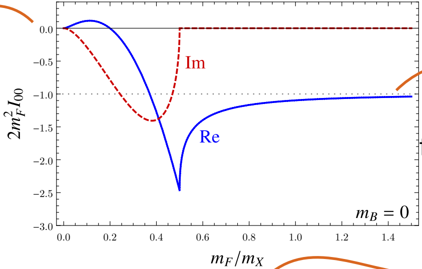
- But these fermions don't decouple!
- For $E \ll m_F$ have effective interactions:



- Massless SM + new fermions, F:

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

anomaly cancelled



constant value for $m_F \gg m_X$!

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

$$= -\sum_f X_f Y_f^2$$

3-pt vertex

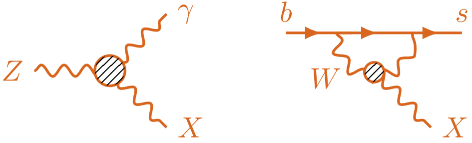
Building SM+X effective theory

- How to derive 3-pt interaction in SM+X EFT?
- Regulator uniquely determines assumption about UV
- In full theory chose regulator **valid for energy $\to \infty$**
- 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 energy$/m_X$!

- Longitudinal model dominates, $X_\mu \to \partial_\mu \varphi / m_X$
- Triangle diagrams arise from (assuming EFT breaks U(1)$_X$),

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

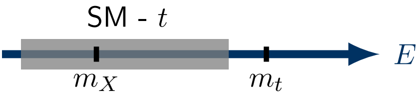
- Need to add to $\mathcal{L}_X$!
- New processes: [JD, Pospelov, Lasenby - 1705.06726]



- These grow with energy, $\mathcal{M} \propto E/m_X$!

Frequently Asked Questions (FAQ)

① What happens with $B-L$ below m_t?



- Theory appears anomalous
- $B-L$ is good symmetry → can't exist "anomalous" interactions
- Integrating out top breaks EW (**top is EW chiral**)
- Below m_t, $\partial_\mu J^\mu_{\text{EW}} \neq 0$ but $\partial_\mu J^\mu_X = 0$
- 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 $\varphi\tilde{G}G$?

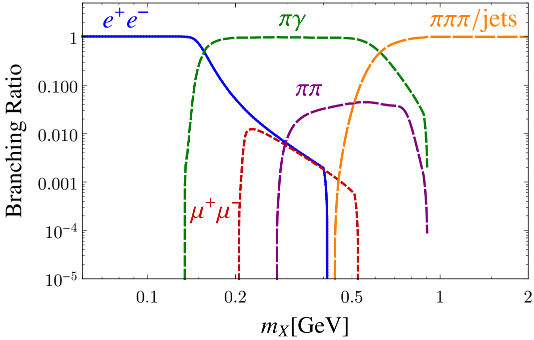
- All interactions are vector-like → no chiral anomaly

Baryon number vector

- The X Lagrangian looks like,

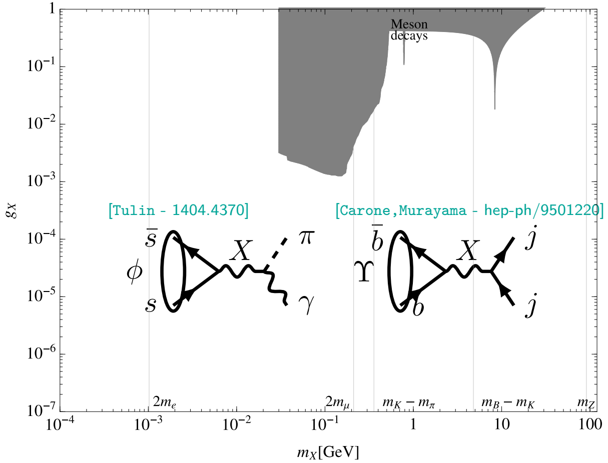
$$\frac{{m_X}^2}{2}X^2 + \frac{g_X}{3}X^\mu \sum_i \bar{q}_i\gamma_\mu q_i + \frac{3g_X}{32\pi^2}\frac{\varphi}{m_X}\left(g^2 W^a \tilde{W}^a - g'^2 B\tilde{B}\right)$$

- X can decay: [1404.4370 - Tulin]



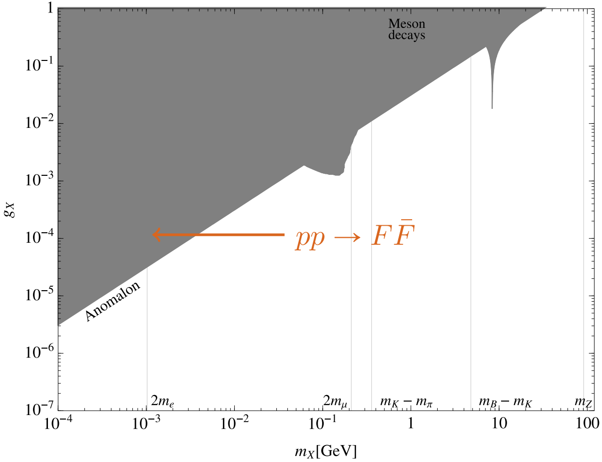
Constraints

- Non-enhanced limits:



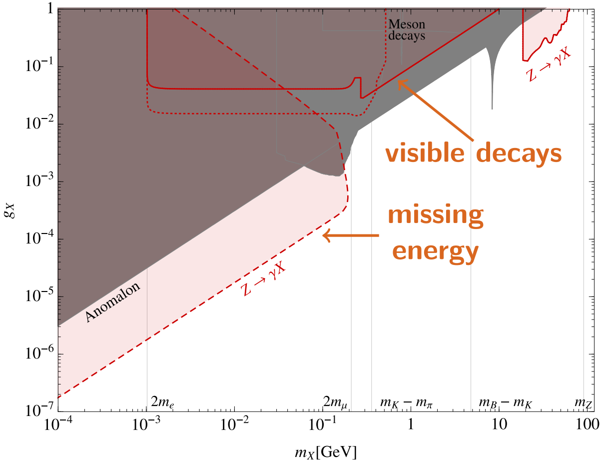
- Direct searches for heavy fermions:

[Dobrescu,Frugiuele - 1404.3947]



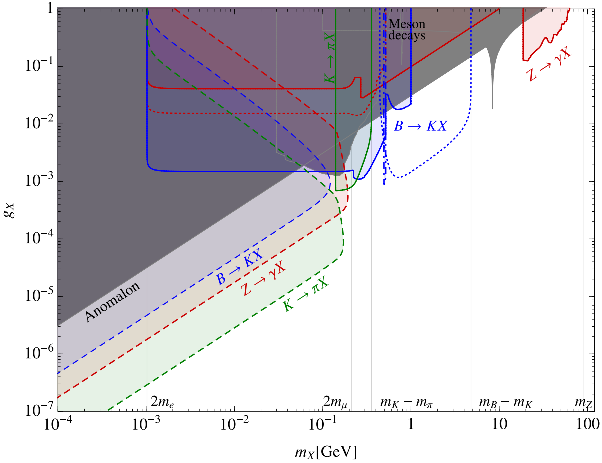
- $Z \to X\gamma$:

[JD,Pospelov,Lasenby - 1705.06726]



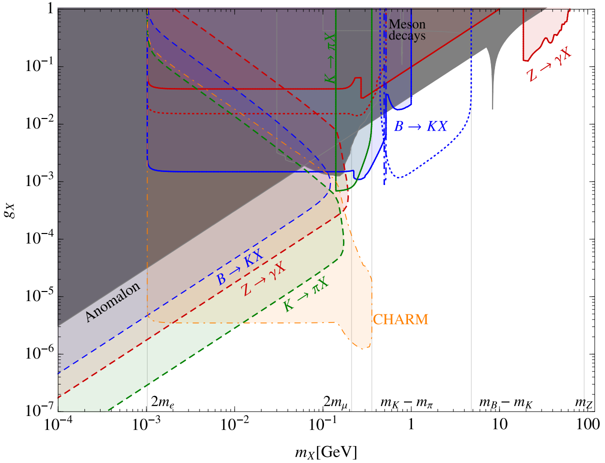
- $B \to KX$ (not just K^*!), $K \to \pi X$:

[**JD**,Pospelov,Lasenby - 1705.06726]
[Recast of - Babar,Belle,LHCb]



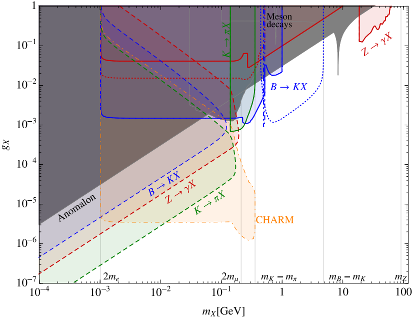
- Beam dump:

[**JD**,Pospelov,Lasenby - 1705.06726]

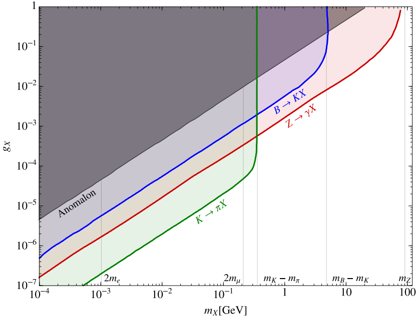


- Summary of all limits
- Significant improvement over old limits (gray)

X decays to SM

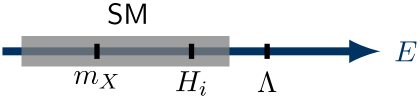


X decays to dark sector



Tree-level breaking

- Ampliudes grow with energy... **even at tree-level**
- Need modification of EW sector



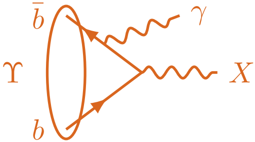
$$\Lambda \lesssim m_X/g_X$$

- Below this scale, $\partial_\mu J_X^\mu \neq 0$!
- For $E \ll \Lambda$:

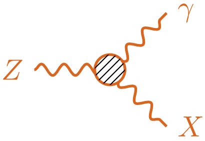
$$\mathcal{M} \propto E/m_X$$

Axially-coupled vector

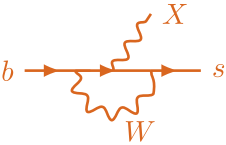
- X can have axial couplings to SM fermions
- m_f are $\cancel{\mathrm{U}(1)_X}$
- Still have $\cancel{\mathrm{U}(1)_X}$-chiral anomaly (now with $F\tilde{F}$ and $G\tilde{G}$)



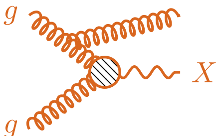
[Fayet - hep-ph/0607318]



[**JD**,Pospelov,Lasenby - 1705.06726]



[**JD**,Pospelov,Lasenby - 1707.01503]



[**JD**,Pospelov,Lasenby - 1707.01503]

Axially-coupled UV completions

- SM+axial, e.g.,

$$\mathcal{L} \supset H\bar{L}_L e_R + X_\mu \bar{e}_R \gamma^\mu e_R$$

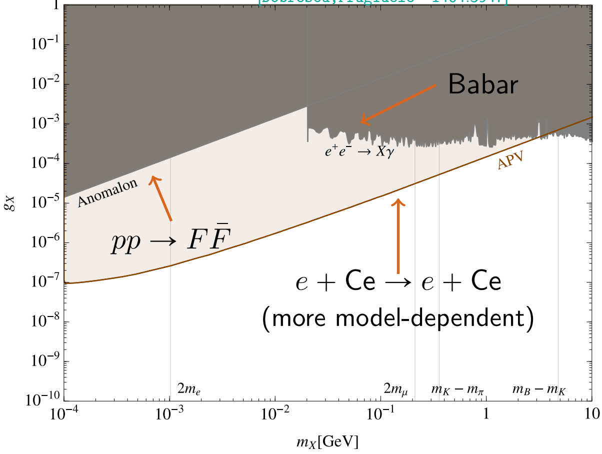
- Not UV complete

[1609.02188 - Ismail,Keung,Tsao,Unwin]
[1609.09072 - Kahn,Krnjaic,Mishra-Sharma,Tait]

- Need to charge Higgs under U(1)$_X$
- **Benchmark model: U(1)$_R$**
- Still need heavy fermions to cure anomaly

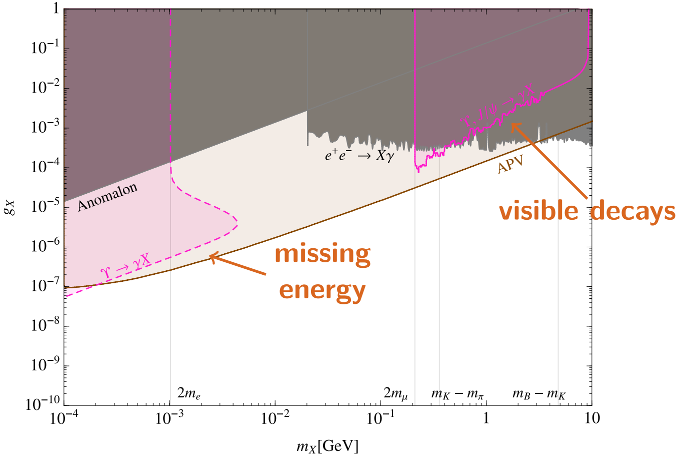
- Non-enhanced limits:

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

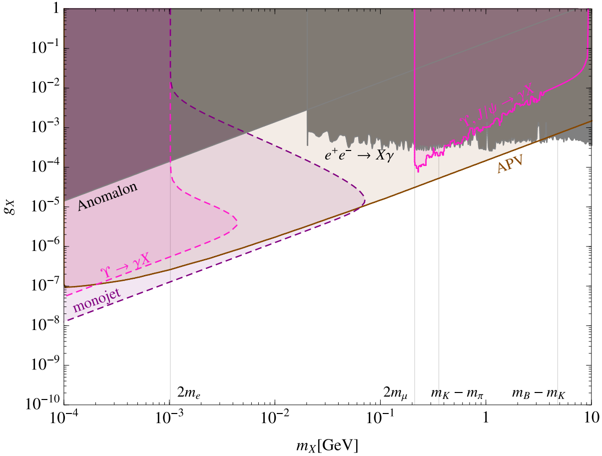


- $\Upsilon \to X\gamma$:

[Fayet - hep-ph/0702176]
[**JD**,Pospelov,Lasenby - 1707.01503]



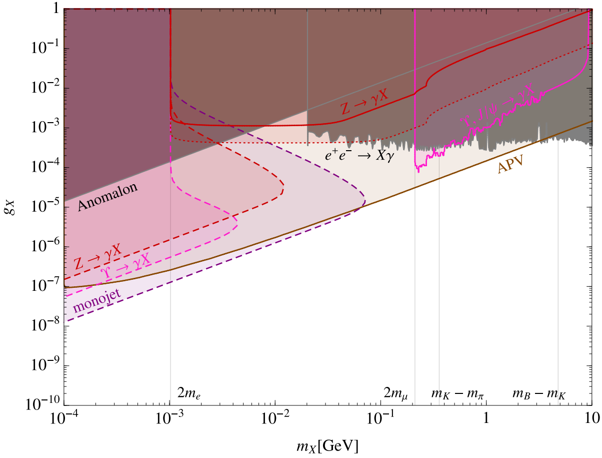
- Monojet (using $\varphi\tilde{G}G$): [JD,Pospelov,Lasenby - 1707.01503]



Example: U(1)$_R$-coupled vector

- $Z \to X\gamma$:

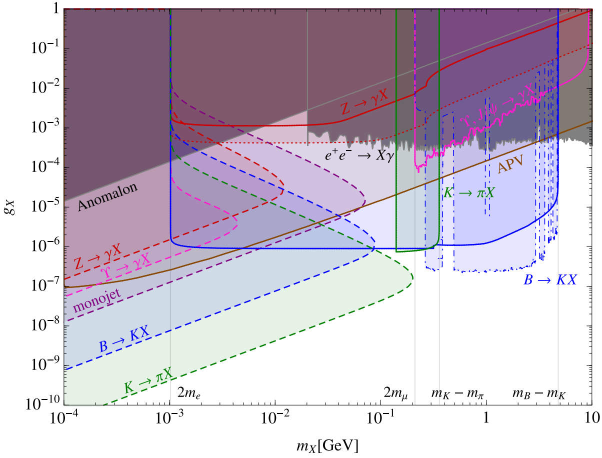
[JD,Pospelov,Lasenby - 1705.06726]



Example: U(1)$_R$-coupled vector

- FCNC:

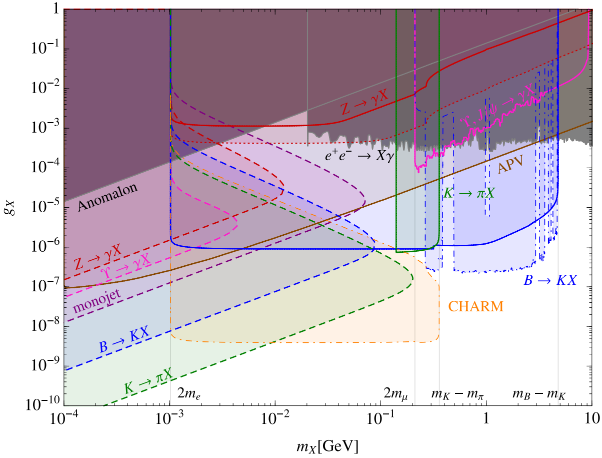
[JD,Pospelov,Lasenby - 1705.06726]



Example: U(1)$_R$-coupled vector

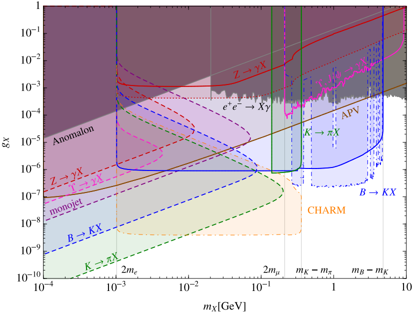
- Beam dump:

[**JD**,Pospelov,Lasenby - 1705.06726]

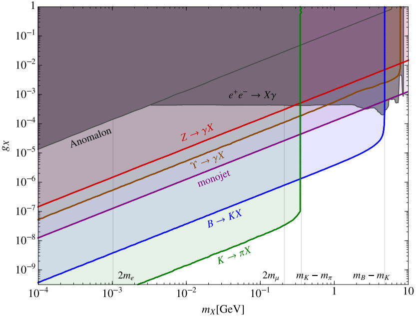


- Summary of all limits
- Significant improvement over old limits (gray)

X decays to SM

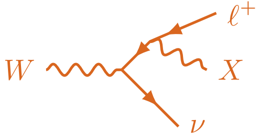


X decays to dark sector

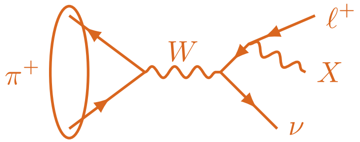


Weak-isospin violation

- Can build models that charged current violates $\mathrm{U}(1)_X$
- Occurs if couple only one particle of SU(2) doublet to X
- Enhanced processes:



[Karshenboim, McKeen, Pospelov - 1401.6154]



[**JD**,Pospelov,Lasenby - 1707.01503]

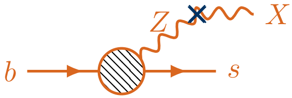
- $\pi^+ \to e^+ \nu X$ is particularly stringent
- SM rate for $\pi^+ \to e^+ \nu (\gamma^* \to e^+ e^-) \propto m_e^2$ (at tree-level)
- Not the case for X rate

EW coupling

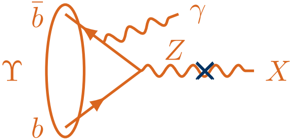
- X could couple to EW sector (other then kinetic mixing)
- Such couplings are not $\mathrm{U}(1)_X$ invariant
- Prominent example: mass-mixing:

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

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



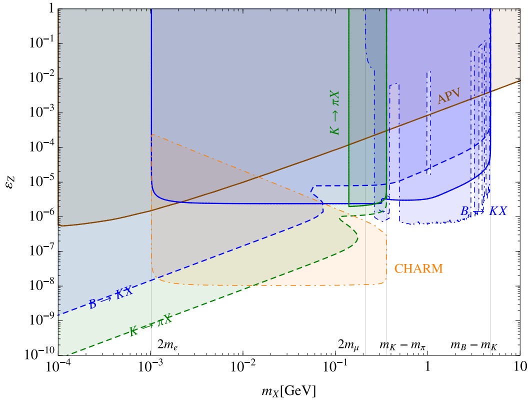
[**JD**,Pospelov,Lasenby - 180X,XXXXX]



[**JD**,Pospelov,Lasenby - 1705.06726]

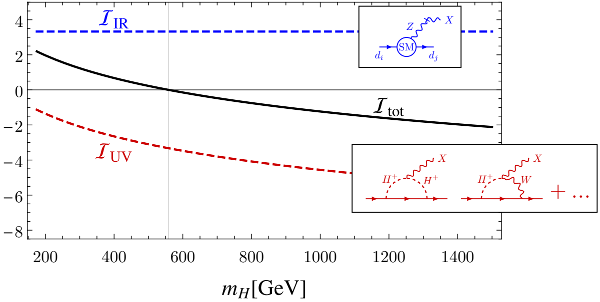
Mass-mixing

- Constraints on a mass-mixing are tricky
- Mixing is not EW-gauge invariant!
- Leads to log-enhanced FCNCs



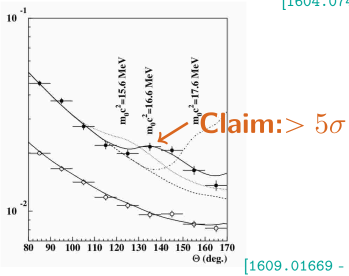
- 2HDM for mass-mixing
  [1203.2947 - Davoudiasl et al]
- $m_H \gg m_W \gg m_X$
- standard motivation for APV
- FCNC from IR and UV
- $g_{d_i d_j X} \propto \mathcal{I}_{\rm IR} + \mathcal{I}_{\rm UV}$

Particle	SM	$U(1)_X$
H_1	✓	×
H_2	✓	✓
H_d	×	✓



Applications

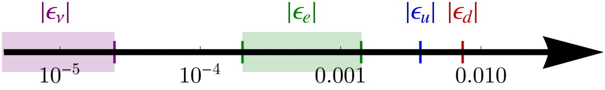
- Excess in ${}^{8}\mathbf{Be}^{*} \to \mathbf{Be}\, e^{+}e^{-}$ in m_{ee} (or θ_{ee}) [1504.01527 - Krasznahorkay et al] [1604.0741 - Feng et al]



[1609.01669 - Ellwanger, Moretti]

- New physics explanation: **vector**/pseudoscalar
- Unusual vector: $\mathcal{L} \supset \sum e\epsilon_f \bar{f}\gamma^{\mu} f X_{\mu}$ "anomalies to fix anomalies"

[1608.03591 - Feng et al]



^{8}Be - baryon number model

- 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.
  [1608.03591 - Feng et al]
  - Sets $\epsilon_\nu \to 0$!
  - Can tune ϵ_u to cancel ϵ_d
- But predicts...

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

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

[E949 - 2008]

^{8}Be - modified $B-L$ model

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

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

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

[SINDRUM Collaboration - 1989]

- Idea:axially-coupled vector [1612.01525 - Kozaczuk,Morrissey,Stroberg]
- Changes all the constraints
- Allows for somewhat smaller couplings $g_X^u \sim g_X^d \sim 10^{-4-5}$
- But...

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

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

[BaBar Collaboration - 0807.4119]

- 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}Be anomaly models
- Moral:

careful what you gauge!