An Effective $Z'$

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Outline

• Adding Z’ to SM, usual approach
• Adding Z’ to SM, “effective” approach
• Simple UV completion
• Flavour and other (non-)issues
• DM
• One collider application
• Conclusions
Introduction

The SM has simple construction

- Renormalizable field theory
- Small gauge groups
- Chiral matter in fundamental reps.
- No anomalies, FCNC’s, B or L number violation

Perhaps new physics copies SM

Focus on new $U(1)'$ gauge group
Introduction

Easy to add a new $U(1)'$

Introduce a new vector and a Higgs: $Z'$, $\phi$

Couplings to SM fields?

Flavour universal couplings: anomalies, new heavy chiral fermions, non-standard representations

Flavour non-universal couplings: complicates Yukawa textures, makes some couplings non-renormalizable, forbids CKM entries
Effective Z’ approach

Leave the SM as intact as possible

$$L = L_{SM} + L_{Z', \phi} + L_{\text{higher dim.}} - \lambda |H|^2 |\phi|^2$$

$$\frac{c_i^j}{M^2} (\bar{q}_i \gamma^\mu q_j)(\phi^* D_\mu \phi) \supset g' \frac{c_i^j}{M^2} (\bar{q}_i \gamma^\mu q_j)(\phi^* Z'_\mu \phi)$$

SM “effectively” charged under $U(1)'$
(Toy) UV Model

$$\mathcal{L} \supset -\mu QQ^c - y\phi qQ^c$$

New “$\phi$-kawa” coupling mixes states

$$\tilde{Q} = \cos \theta Q + \sin \theta q \quad \tilde{q} = -\sin \theta Q + \cos \theta q$$

Generates effective $Z'$ coupling for SM quark

$$\bar{Q} \phi Q \supset g' \sin^2 \theta Z'_\mu \bar{q} \gamma^\mu \tilde{q}$$

$$g_{eff}$$
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$g_{\text{eff}}$
Effective $Z'$ approach

Only add vector-like matter in SM reps. Which reps. determine which $\phi$-kawa allowed

- Effective coupling $g_{eff} \leq g'$
- Only one linear combination SM quarks mix with $Q$. Rank of $c^i_j$ determined by # of $Q$
- Heavy quarks predicted at scale $\lesssim 4\pi M_{Z'}/g_{eff}$

$$M_{\tilde{Q}} = \frac{\lambda/\sqrt{2}}{g' \sin \theta} M_{Z'} = \frac{\lambda/\sqrt{2}}{\sqrt{g' g_{eff}}} M_{Z'}$$
Flavour

φ-kawa can lead to flavour violation

Good and bad.....

\[ \bar{q}(\lambda_u \lambda_u^\dagger + \lambda_d \lambda_d^\dagger) \gamma_\mu q \phi^* D^\mu \phi \]

\[ \frac{1}{v^2} \bar{u}_L V_{CKM} M_d^2 V_{CKM}^\dagger \gamma_\mu u_L \phi^* D^\mu \phi \]

\[ \frac{1}{v^2} \bar{d}_L V_{CKM}^\dagger M_u^2 V_{CKM} \gamma_\mu d_L \phi^* D^\mu \phi \]

\[ \propto m_c^4 \]
Kinetic Mixing

\[
\mathcal{L} \supset -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\chi}{2} b_{\mu\nu} (c_w A^{\mu\nu} - s_w Z^{\mu\nu}) \\
- \frac{1}{2} M_{Z'}^2 b_\mu b^\mu - \frac{1}{2} M_Z^2 Z_\mu Z^\mu
\]

\[
\chi = \frac{g_Y g'}{16\pi^2} \text{tr} Q_Y Q' \log \frac{\Lambda^2}{\mu^2}
\]
Kinetic Mixing

\[ \mathcal{L} \supset -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\chi}{2} b_{\mu\nu} (c_{w} A^{\mu\nu} - s_{w} Z^{\mu\nu}) - \frac{1}{2} M_{Z'}^{2} b_{\mu} b^{\mu} - \frac{1}{2} M_{Z}^{2} Z_{\mu} Z^{\mu} \]

\[ \chi = \frac{g Y g'}{16\pi^2 \text{tr} Q Y Q'} \log \frac{\Lambda^2}{\mu^2} \]
Kinetic Mixing

Removing kinetic mixing and going to mass basis
e.g. leptophobic at tree-level becomes:

\[
\frac{e}{c_w} \chi Z'_\mu \left( c_w^2 J_{em}^\mu - \frac{M_{Z'}^2}{M_{Z'}^2 - M_Z^2} J_Z^\mu \right)
\]

modified SM couplings

\[
g' \frac{s_w M_{Z'}^2}{M_{Z'}^2 - M_Z^2} J_{Z'}^\mu Z_\mu
\]

Can be removed by another pair of Q, non-mixing
(or non-abelian)
Fewer constraints, large Z’ invisible width

\[ \sigma \approx \frac{16 \pi \alpha_{Z'}^2 \mu_{\chi N}^2 Z_{eff}^2}{M_{Z'}^4} \sin^4 \theta \]

\[ \sigma \approx \frac{16 \pi \alpha_{Z'}^2 \mu_{\chi N}^2 Z_{eff}^2 \lambda^4 v^4}{g^4 v^4 M^4} = \lambda^4 \frac{\mu_{\chi N}^2 Z_{eff}^2}{M^4} \pi. \]

\[ f_p, f_n \text{“free parameters”} \]

\[ \bar{p} \left[ (2a_u + a_d) \gamma^\mu \frac{1 + \gamma_5}{2} + 3a_q \gamma^\mu \frac{1 - \gamma_5}{2} \right] p \]

\[ \bar{n} \left[ (a_u + 2a_d) \gamma^\mu \frac{1 + \gamma_5}{2} + 3a_q \gamma^\mu \frac{1 - \gamma_5}{2} \right] n. \]
Of course we do not expect φ to couple to all quarks, but we might still expect a cross section \( \sigma \approx \alpha'_{\text{eff}} \left( \frac{M_W^2}{\alpha_W} \right) \left( \frac{m_h^4}{m_\phi^4} \right) \times \sigma_h \).

Thus, even if the dark matter is a Majorana fermion and has no spin-independent scattering mediated by the \( Z \), the detection of an effective \( Z \) would give insight into the spin-independent cross section we might expect at a direct detection experiment.

### C. Indirect Detection

In addition to direct detection experiments, dark matter can be detected through its annihilation products. The annihilation through an effective \( Z \) can give rise to different final states, for instance \( \tau^+ + \tau^- \) that might occur rarely in conventional annihilation modes. While such models cannot avoid the usual helicity suppression for Majorana WIMPs annihilating into SM fermions, it does create a number of interesting new possibilities.

To begin with, let us consider the case of WIMPs annihilating after solar capture. If the coupling is dominantly to first generation quarks, then the light-flavor hadrons produced in annihilation \( \pi^\pm \) to point the solar interior before decaying lower in energy of the resultant neutrinos and weakening limits compared with heavy flavor.

Similarly, the \( Z \) could be dominantly leptophilic, and if coupling to \( \mu \) or \( e \) would also produce no interesting limits from solar capture. Such mechanisms to limit the solar capture signals can be important in models where the capture rate is high, such as inelastic dark matter and spin-dependent scattering, both of which can be realized with effective \( Z \).
Applications

- D0 dimuon asymmetry
- CDF Wjj excess
- CDF top forward-backward asymmetry
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**Wjj & effective Z’**

\[ \frac{c_j^i}{M^2} \left( \bar{q}_i \gamma^\mu q^j \right) (\phi^* D_\mu \phi) \]

\[ q \rightarrow q_L \]

Flavour constraints imply \( c_j^i \propto \delta_j^i \)

UV model respects flavour SU(3)

\[ \mathcal{L} \supset - (\mu Q_i^c Q_i + \lambda Q_i^c q_i \phi) \]

\[ g_{eff} = g' \sin^2 \theta \sim 0.37 \quad \text{for 4 pb x-sec} \]

\[ (~2 \text{ pb fits}) \]
Wjj & effective $Z'$

Existing constraints:

- couplings to leptons?
- dijet rate?
Wjj & effective Z’

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\[ g_{\text{eff}} \lesssim 0.23 \]
Wjj & effective Z’

Q around the corner?

\[ M_{\tilde{Q}} = \frac{\lambda/\sqrt{2}}{g' \sin \theta} M_{Z'} = \frac{\lambda/\sqrt{2}}{\sqrt{g' g_{\text{eff}}}} M_{Z'} \]

3 body resonances, potentially with sub-resonances
Conclusions

• $Z'$ very natural extension of SM, but adding one often feels very unnatural
  • removes many nice SM features
  • introduces weird matter content
• Keep nice features of SM, add $Z'$ through effective operators
• UV completion is simple, vectorlike matter in SM reps. mixes with SM states
• Tree-level couplings determined by vectorlike content
• New states to see at colliders