Anomalies and Dark Matter: arXiv:1704.03850 & arXiv:1705.03447

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Overview

- Simplified models of Dark Matter (DM)
- Gauge anomalies
- Anomaly-free simplified models
- Anomaly-free models for LHCb flavour excess

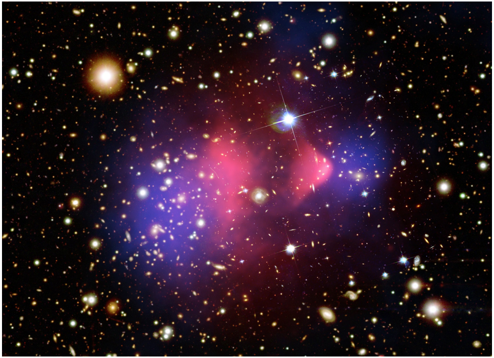


Fig: the bullet cluster, one piece of evidence for DM

Simplified Models

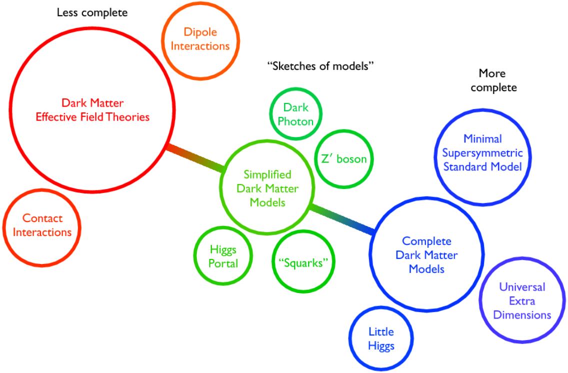


Fig: sketch of DM model space – Credit: arXiv:1506.03116.

EFT breaks down at high (LHC) energies → Simplified Model needed

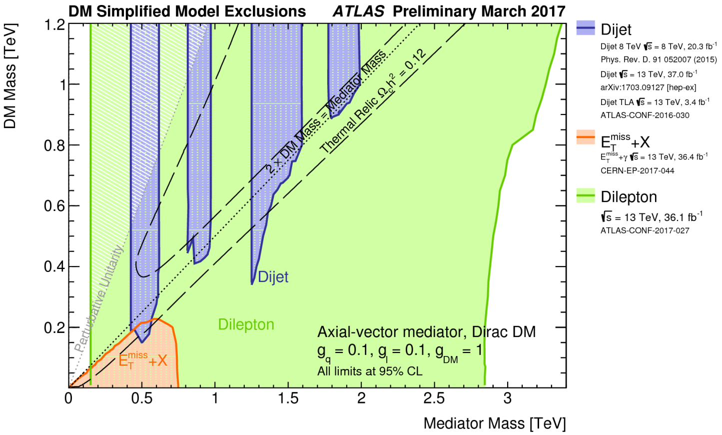
Simplified Models

Focus on a spin-one mediator:

$$\mathcal{L} = Z'_\mu \left[\bar{\chi}\gamma^\mu \left(g_{\chi,V} + g_{\chi,A}\gamma^5 \right) \chi + \sum_{f=q,l} \bar{f}\gamma^\mu (g_{f,V} + g_{f,A}\gamma^5) f \right] \tag{1}$$

- Z' mediates interactions between SM fermions f and DM
- Assume only one DM particle (χ)
- Typically assume no lepton couplings to evade dilepton searches
- Universal quark couplings to evade flavour constraints

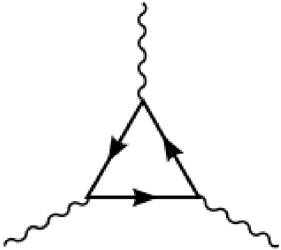
Dilepton Constraints



With same size quark and lepton couplings, dilepton constraints overcome almost all other LHC bounds. Credit: ATLAS exotics.

Gauge Anomalies

- Anomalies arise when a classical symmetry is broken by quantum effects.
- Chiral gauge theories will produce anomalies from diagrams involving three external gauge bosons.
- To preserve gauge symmetry, all anomalies must vanish or be cancelled by additional chiral fermions.



Gauge Anomalies: The case of a U(1)'

When you extend the SM gauge group with a $U(1)'$ with charge Y', the following anomaly conditions must be satisfied:

(a) $[\mathrm{SU}(3)_C]^2 \times [\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\{\mathcal{T}^i, \mathcal{T}^j\} Y'] = 0$.

(b) $[\mathrm{SU}(2)_W]^2 \times [\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\{T^i, T^j\} Y'] = 0$.

(c) $[\mathrm{U}(1)_Y]^2 \times [\mathrm{U}(1)_{Y'}]$, which implies $\mathrm{Tr}[\mathrm{Y}^2 Y'] = 0$.

(d) $[\mathrm{U}(1)_Y] \times [\mathrm{U}(1)_{Y'}]^2$, which implies $\mathrm{Tr}[Y Y'^2] = 0$.

(e) $[\mathrm{U}(1)_Y']^3$, which implies $\mathrm{Tr}[Y'^3] = 0$.

(f) Gauge-gravity, which implies $\mathrm{Tr}[Y'] = 0$.

with $\mathcal{T}^i$ a generator of $SU(3)$, T^i a generator of $SU(2)$, Y the SM hypercharge, Y' the exotic $U(1)'$ charge which will give the Z' couplings to fermions.

Example: All exotic fermions are singlets

Assuming just dark sector + SM: all exotic fermions are uncharged under SM gauge group

$$\begin{aligned}
&\text{(a)} \quad 3(2Y'_q - Y'_u - Y'_d) = 0\,,\\
&\text{(b)} \quad 9Y'_q + 3Y'_l = 0\,,\\
&\text{(c)} \quad 2Y'_q - 16Y'_u - 4Y'_d + 6\left(Y'_l - 2Y'_e\right) = 0\,,\\
&\text{(d)} \quad 6\left(Y'^2_q - 2Y'^2_u + Y'^2_d\right) - 6\left(Y'^2_l - Y'^2_e\right) = 0\,,\\
&\text{(e)} \quad 9\left(2Y'^3_q - Y'^3_u - Y'^3_d\right) + \left(2Y'^3_l - Y'^3_e\right) + \mathrm{Tr}_{\mathrm{BSM}}(Y'^3) = 0\,,\\
&\text{(f)} \quad 9\left(2Y'_q - Y'_u - Y'_d\right) + \left(2Y'_l - Y'_e\right) + \mathrm{Tr}_{\mathrm{BSM}}(Y') = 0\,.
\end{aligned}$$

where q LH quark doublet, u, d RH quark singlets, l LH quark doublet, e RH charged leptons.

$(b) \to$ either $Y'_l \neq 0$ or *all* $Y' = 0$ (trivial theory)

SM Yukawa conditions

Standard Model Yukawa terms:

$$\mathcal{L}_{\text{Yukawa}} = \bar{q}_L \Phi u_R + \ldots \tag{2}$$

Gauge invariance of these terms under the $U(1)'$ implies:

$$Y'_\Phi = Y'_q - Y'_u = Y'_d - Y'_q = Y'_e - Y'_l \,, \tag{3}$$

One exotic fermion

Take example of just one exotic fermion (χ).

Only possible solution is that DM has a vectorial coupling to the Z', and *SM* charges completely determined:

$$Y'_l = -3Y'_q, \quad Y'_e = -6Y'_q, \quad Y'_d = -2Y'_q,$$
$$Y'_u = 4Y'_q, \quad Y'_\Phi = -3Y'_q.$$

- Strong dilepton bounds from LHC

Adding non-singlet fermions

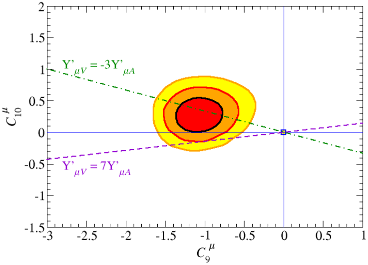
In order to get a leptophobic Z', need to alter the $[\mathrm{SU}(2)_W^2] \times [\mathrm{U}(1)_{Y'}]$ anomaly $\rightarrow$ at least one exotic field transforming non-trivially under $\mathrm{SU}(2)_W$.

In fact need A, B and χ transforming in the ($\mathrm{SU}(2)_W$, $\mathrm{U}(1)_Y$, $\mathrm{U}(1)_{Y'}$) representations ($\mathbf{2}$, Y_A, $\mathrm{Y}'_{A,L/R}$), ($\mathbf{1}$, Y_B, $\mathrm{Y}'_{B,L/R}$), and ($\mathbf{1}$, 0, $\mathrm{Y}'_{\chi,L/R}$) respectively, where L/R signifies the field is chiral.

- Dilepton constraints absent.
- New bounds depend on exotic fermion masses, but exotic fermions cannot be completely decoupled.

Generation dependent charges

- Generation dependent charges gives a flavour changing Z'.
- This can explain the tentative excess seen at LHCb in semi-leptonic B decays.
- Models in the literature as they stand contain anomalies.
- DM or other exotics needed to cancel the anomalies.



$C_{10}^{\mu} \equiv$ Axial muon coupling,
$C_{9}^{\mu} \equiv$ Vectorial muon coupling,
lines show anomaly free models,
shaded region is favoured by flavour excess

Conclusion

- At some scale, a theory must be gauge-invariant and renormalizable
- All anomalies must vanish, imposing severe restrictions on the exotic charges & field content of the theory.
- Lepton couplings cannot vanish without additional exotic fermions, some of which are charged under the SM.
- DM can help to give you an anomaly-free theory of the flavour anomaly.
- In general, simplified models of dark matter are not so simples!