LHC monojets & direct detection

Felix Kahlhoefer

Rudolf Peierls Centre for Theoretical Physics

UNIVERSITY OF OXFORD

With: Mads Frandsen, Anthony Preston, Subir Sarkar, Kai Schmidt-Hoberg
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If dark matter particles scatter on nuclei to give a (direct detection) signal, we also expect to see related processes with distinctive signatures.

Experiments searching for these signatures can constrain the direct detection cross section.
Introduction

Problem: Separation of scales

• Dark matter direct detection probes the non-relativistic limit \( \nu_{DM} \approx 10^{-3} \), while the LHC probes the TeV scale.

• Interactions that look very similar at the LHC (e.g. coupling to the vector and axial current) may look very different in direct detection (spin-independent and spin-dependent).

talk by: E. Kolb
Effective operators

• To compare bounds from the LHC to direct detection, we describe interactions between DM and quarks with effective operators, e.g.

\[ \mathcal{L}_{\chi}^{\text{eff}} = \frac{1}{\Lambda^2} \bar{\chi} \gamma_\mu \chi \bar{q} \gamma^\mu q \]

• Such an interaction would arise from the exchange of a vector mediator with mass \( m_R \) and couplings \( g_q \) to quarks and \( g_\chi \) to DM:

\[ \Lambda = \frac{m_R}{\sqrt{g_q g_\chi}} \]
Effective interactions

• For sufficiently heavy mediators \( m_R > \) few TeV, effective interactions are valid even at the LHC
• We can directly compare LHC searches for dark matter to direct detection experiments
  \[ \sigma (j + \text{MET}) \sim \frac{1}{\Lambda^4} \sim \sigma_p \]
• Current monojet bounds give \( \Lambda > 700 \) GeV, corresponding to
  \[ \sigma_p \approx 10^{-39} \text{ cm}^2 \]
Two problems with EFT

1. Problems with perturbativity:
   From $g_q, g_\chi < (4\pi)^{1/2}$ we get $m_R < 2.5$ TeV for $\Lambda = 700$ GeV, so we require $\sqrt{s} < 2.5$ TeV.

2. Problems with unitarity:
   The requirement
   \[ |a^J(s)| = \left| \frac{1}{32\pi} \int_{-1}^{1} d(\cos \theta) P_J(\cos \theta) \mathcal{M}(s, \cos \theta) \right| < 1 \]
   holds only for $\sqrt{s} < 2.7 \Lambda \approx 1.9$ TeV.

Shoemaker, Vecchi, arXiv:1112.5457
Fox, Harnik, Primulando, Yu, arXiv:1203.1662
Resonant production

- Effective operators may *not* be valid at the LHC
- It is quite possible that the mediator mass is comparable to LHC energies ($m_R \sim \text{TeV}$)
- The LHC can produce such a mediator *on-shell*: 
  \[ \sigma (j + \text{MET}) \sim \sigma (pp \rightarrow R + j) \times \text{BR} (R \rightarrow \text{invisible}) \]
- As a consequence, the monojet cross section is *no longer proportional* to the direct detection cross-section and the analysis is more involved
How to get a bound

\[ \sigma_p \sim \frac{\mu_{\chi n}^2 g_q^2 g_X^2}{\pi m_R^4} \]

\[ \Gamma(R \rightarrow \chi \bar{\chi}) \sim \frac{m_R}{12\pi} g_X^2 \]

\[ \Gamma(R \rightarrow \chi \bar{\chi}) \leq \Gamma_R \times \text{BR}(R \rightarrow \text{inv}) \]

\[ \sigma_p \lesssim 12 \frac{\mu_{\chi n}^2 \Gamma_R}{m_R^5} g_q^2 \cdot \text{BR}(R \rightarrow \text{inv}) \]

\[ g_q: \text{ Coupling to quarks} \]
\[ g_X: \text{ Coupling to the DM particle} \]
\[ m_R: \text{ Mass of the mediator} \]
\[ \mu_{\chi n}: \text{ Reduced mass} \]

More difficult to constrain \hspace{1cm} \text{Constrained by monojet searches}
Decay channels

$R$ can decay into fermions, bosons and new hidden sector states.

$$\Gamma_R = \Gamma_{\chi \overline{\chi}} + \sum_q \Gamma_{q \overline{q}} + \sum_l \Gamma_{l \overline{l}} + \sum_\nu \Gamma_{\nu \overline{\nu}}$$

$$+ \Gamma_{W^+ W^-} + \Gamma_{ZZ} + \Gamma_{\gamma Z} + \Gamma_{ZH}$$

$$+ \Gamma^X$$

All of these channels can be constrained by the LHC!
Constraints: Fermions

\[ \frac{g_q^2 \times \text{BR}(R \rightarrow xy)}{10^0} \]

- \( xy = jj \) (yellow)
- \( xy = \bar{u} \bar{u} \) (green)
- \( xy = \text{inv (}j+\text{MET)} \) (cyan)
- \( xy = \text{inv (}\gamma+\text{MET)} \) (magenta)
- \( xy = ll \) (red dashed)
- \( xy = \tau\tau \) (red dashed)

\[ m_R / \text{GeV} \]

- \( 100, 200, 300, 500, 700, 1000, 2000 \)
Constraints: Bosons

\[ g_q^2 \times BR(R \rightarrow xy) \]

- \( xy = WW^{(*)} \)
- \( xy = ZZ^{(*)} \)
- \( xy = ZZ \) (high)
- \( xy = ZH \)
- \( xy = Z\gamma \)

\[ m_R / \text{GeV} \]

\[ 100 \quad 200 \quad 300 \quad 500 \quad 700 \quad 1000 \quad 2000 \]
Combined Constraints

- If $R$ decays only into SM particles or invisible states, we can obtain a bound on $\Gamma_R$.
Direct detection limits

\[ \sigma_p \lesssim 12 \frac{\mu^2_{\chi n} \Gamma_R}{m^5_R} g_q^2 \cdot \text{BR}(R \rightarrow \text{inv}) \]

\[ \sigma_p / \text{cm}^2 \]

\[ m_R / \text{GeV} \]

\[ f_n/f_p = 1 \]

excluded

DAMA

CoGeNT
There are strong constraints on the direct detection cross section for vector mediators with $m_R < 1 \text{ TeV}$.
Possible caveats

1. If the mediator is lighter than 300 GeV it becomes very difficult to constrain $\text{BR}(R \rightarrow qq)$.

2. If the DM mass is comparable to the mediator mass, decays of $R$ into $\chi\chi$ are suppressed.

3. If $R$ can decay into new hidden sector states with complicated decay modes, $\Gamma_R$ can be very large.

4. If $g_q << g_\chi$ the production of $R$ at LHC is insufficient to constrain $\Gamma_R$. 
Example: The dark $Z'$

- As an example we consider the case where $R$ is the gauge boson of a new $U(1)$ under which only the dark matter particle is charged.

\[
\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} m^2_{Z'} Z'_{\mu} Z'_{\mu} - \frac{1}{2} \sin \epsilon B_{\mu\nu} Z''_{\mu\nu} + \delta m^2 Z_{\mu} Z'_{\mu}
\]

Frandsen, F.K., Sarkar, Schmidt-Hoberg, JHEP 1109 (2011) 128
Example: The dark $Z'$

- Attractive feature: Isospin violation ($f_p \neq f_n$)
- $f_n/f_p = -0.7$ suppresses bounds from XENON100

Frandsen, F.K., Sarkar, Schmidt-Hoberg, JHEP 1109 (2011), 128
For $300 \text{ GeV} < m_{Z'} < 1500 \text{ GeV}$, we can use current LHC data to constrain direct detection cross sections.

$\sin \epsilon > 0.8$

$\sigma_p / \text{cm}^2$

$\sigma_p / \text{cm}^2$

$\delta m = m_Z/2$

$\sin \epsilon > 0.8$

$f_X^V = 0.1, \delta m = m_Z/2$
Conclusions

• If the LHC can resolve the mediator of dark matter interactions, effective operators are insufficient to interpret monojet bounds
  
• Heavy mediators ($m_R \geq 300$ GeV) can be tested and constrained by current LHC data
  
• Attractive model: Dark $Z'$ with mixing
  
• Lighter mediators are much more difficult to constrain experimentally
Backup
Non-standard interactions

- Collider bounds are largely independent of low-energy effects (e.g. nuclear coherence).
- Very strong bounds arise if $\sigma_p$ is suppressed.