Chromo-Rayleigh Interactions of Dark Matter

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Introduction

Rayleigh Interactions: $\sim X^\dagger X\, F_{\mu\nu} F^{\mu\nu}$.
Chromo-Rayleigh Interactions: $\sim X^\dagger X G^a_{\mu\nu} G^{a\,\mu\nu}$.

- Complementarity of direct detection, collider searches.
- Gluon fusion dominant at hadron colliders.
- Leads to alternative searches to simple monojet + MET.
- May boost the discovery potential of DM at the LHC.

Chromo-Rayleigh Interactions

We consider a complex scalar DM particle (X) - however, in principle X could be fermionic, fundamental, or composite.

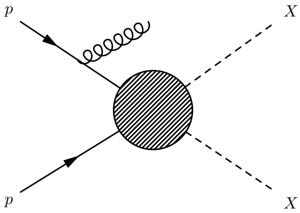
- Neutral under the SM gauge group $SU(3) \otimes SU(2) \otimes U(1)$.
- Stabe: enforce a dark $\mathcal{Z}_2$ symmetry under which X is odd.
- May interact with the SM through the following dimension 6, CP-conserving operators:

$$\mathcal{O}_1^{\text{cRayleigh}} = \frac{\alpha_s}{4\pi\Lambda_1^2} X^\dagger X \, G^a_{\mu\nu} G^{a\,\mu\nu} \,,$$

$$\mathcal{O}_2^{\text{cRayleigh}} = \frac{\alpha_s}{4\pi\Lambda_2^2} \left(XX - X^\dagger X^\dagger \right) G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu} \,.$$

LHC Monojet Search

- The universal collider signature for these operators comes from monojets with $E_{\mathrm{T}}^{\mathrm{miss}}$.
- Using background estimates from the CMS collaboration at $\sqrt{s} = 8$ TeV and 19.7 fb^{-1} luminosity, using an optimized cut of $E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV, we find



M_X (GeV)	Λ_1 (GeV)	Λ_2 (GeV)
1	130	170
10	120	180
100	120	180
200	110	160
400	90	130

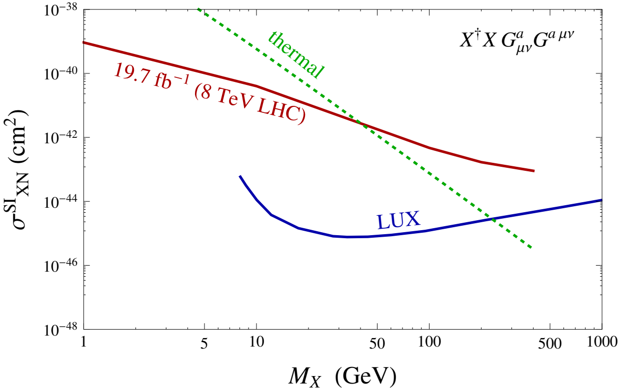
CMS Collaboration: [arXiv:1408.3583], ATLAS Collaboration: [arXiv:1502.01518]

Note: different normalization conventions.

Direct Detection Bounds

$\mathcal{O}_1^{\text{cRayleigh}}$ translated to spin-independent scattering:

$$\sigma^{\text{SI}}_{X\,N} = \frac{\kappa^2 m_N^4}{4\pi\Lambda_1^4(m_N + M_X)^2}\,, \quad \kappa \approx -0.20\,,$$

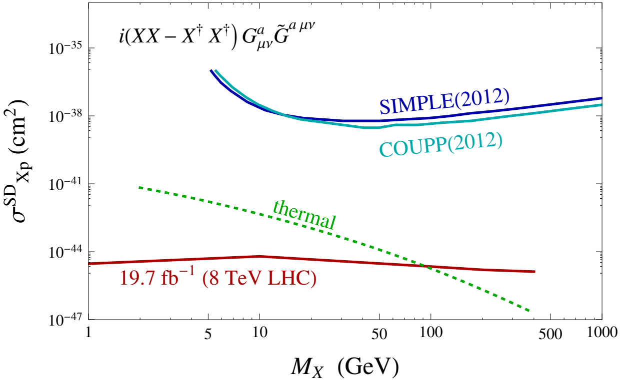


Direct Detection Bounds

$\mathcal{O}_2^{\mathrm{cRayleigh}}$ translated to spin-dependent scattering:

$$\frac{d\sigma^{\mathrm{SD}}_{X\,N}}{d\,\cos\theta} = \frac{\eta_N^2 m_N^2}{2\pi\Lambda_2^4}\frac{q^2}{(m_n + M_X)^2}\,, \quad \eta_p\,(\eta_n) \approx 0.41\,(-0.0021)\,.$$

$q \approx \mu_{X\,A} v$, with $v = 10^{-3}$ and $m_A = 100$ GeV.



Consistency

Requirements for EFT description:

- In the simplest models, $\Lambda = m_M/\sqrt{g_s\, g_X}$.
- EFT requires $q_{\mathrm{Tr}} < m_M$.
- If $\sqrt{g_s\, g_X} \approx 1$, we require $\Lambda > q_{\mathrm{Tr}}$.

At the LHC, q_T can be much larger than $\mathcal{O}(100\ \mathrm{GeV})$.

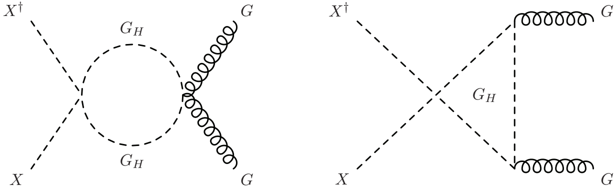
- Questionable interpretation of the limits placed by this mono-jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ search.
- Study specific UV completions of the chromo-Rayleigh operators.

Note: Higgs portal covers these operators.

UV Completion of $\mathcal{O}_1^{\mathrm{cRayleigh}}$

Introduce a real color-octet, electroweak-singlet scalar (G_H^a) coupling to DM:

$$\mathcal{L} \supset -\frac{\lambda}{2} G_H^a G_H^a X^\dagger X \,.$$



$$\mathcal{O}_1^{\mathrm{cRayleigh}} = F(\tau) \frac{\lambda}{8 M_{G_H}^2} \frac{\alpha_s}{4\pi} X^\dagger X G^a_{\mu\nu} G^{a\,\mu\nu} \,,$$

Form factor: $F(\tau) \to 1$ as $\tau = \hat{s}/(4M_{G_H}^2) \to 0$.

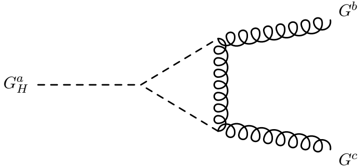
Matching: $\Lambda_1^2 = \frac{8}{\lambda} M_{G_H}^2 \,.$

UV Completion of $\mathcal{O}_1^{\text{cRayleigh}}$

G_H can be pair produced at the LHC.

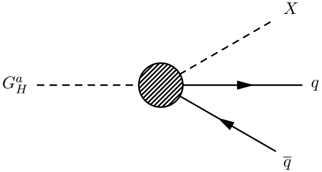
- For a $\mathcal{Z}_2$-even G_H^a, the dominant signature would be paired dijet resonances:

$$\mu_G d_{abc} G_H^a G_H^b G_H^c$$



- For a $\mathcal{Z}_2$-odd G_H^a, its decay must include a DM particle X. The dominant signature would be:
  4 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, 2 jets + 2 top + $E_{\mathrm{T}}^{\mathrm{miss}}$, or 4 top + $E_{\mathrm{T}}^{\mathrm{miss}}$.

$$\frac{g_s}{\Lambda_1'^2} G_H^a \partial_\nu (X + X^\dagger)\, \overline{q} \gamma^\nu t^a q$$



UV Completion of $\mathcal{O}_1^{\mathrm{cRayleigh}}$

- The multi-jet + MET (paired dijet) searches at the 8 TeV LHC constrain the mediator mass to be

$$\boxed{m_{G_H} \gtrsim 600\ (520)\ \text{GeV}}.$$

- For $\lambda = 1$, the matching condition then gives

$$\boxed{\Lambda_1 \gtrsim 1.5 - 1.7\ \text{TeV}}.$$

- Recalling from contact operators we found $\Lambda_1 \gtrsim 120$ GeV, this UV completion is dramatically more constrained.

UV Completion of $\mathcal{O}_2^{\mathrm{cRayleigh}}$

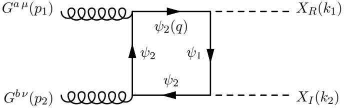
Introduce two color-triplet Dirac fermions (ψ_1, ψ_2) coupling to DM:

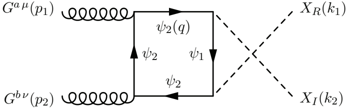
$$\mathcal{L} \supset -\left(X + X^\dagger\right)\left(y_1 \overline{\psi}_1 \psi_2 + y_1^* \overline{\psi}_2 \psi_1\right) - \left(X - X^\dagger\right)\left(y_2 \overline{\psi}_1 \gamma_5 \psi_2 + y_2^* \overline{\psi}_2 \gamma_5 \psi_1\right) .$$

- Field redefinitions allow us to set $y_1 = y_1*$.
- If $y_2 = y_2^*$, CP symmetry is satisfied.
- If $y_2 \neq y_2^*$, P is conserved while C is broken (CP violating).

UV Completion of $\mathcal{O}_2^{\text{cRayleigh}}$

$\mathcal{O}_2^{\text{cRayleigh}}$ conserves P but breaks C $\rightarrow$ require $\text{Im}(y_1 y_2) \neq 0$.





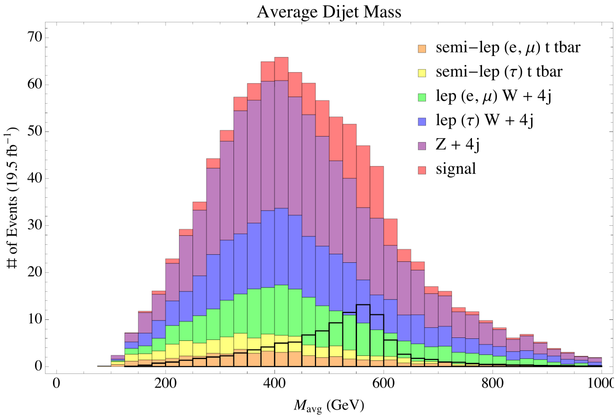
$$\text{Matching: } \Lambda_2^2 = \frac{2 m_{\psi_1} m_{\psi_2}}{\text{Im}(y_1 y_2)} \,.$$

- For $m_{\psi_2} > m_{\psi_1}$, ψ_2 $\mathcal{Z}_2$-odd, and ψ_1 $\mathcal{Z}_2$-even, signature is pair produced ψ_2 decaying into 4 jets + $E_{\text{T}}^{\text{miss}}$:

$$\frac{g_s^2}{4\pi\Lambda_2'} \overline{\psi}_{1,L} \sigma^{\mu\nu} t^a u_R G^a_{\mu\nu} \qquad\qquad \psi_2 \rightarrow X + \psi_1 \rightarrow X + 2j$$

UV Completion of $\mathcal{O}_2^{\mathrm{cRayleigh}}$

- Other iterations of $\mathcal{Z}_2$ with different signatures, more work is necessary.
- A sneak peak at $m_{\psi_1} = 600$ GeV, $m_{\psi_2} = 800$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV:



Future Work

- Complete analysis of $\mathcal{O}_2^{\mathrm{cRayleigh}}$.
- 14 TeV LHC reach.
- Other simplified UV models under the framework of Chromo-Rayleigh Dark Matter?

Conclusion

- Studying simplified completion models can fix the validity problem of the EFT operator analysis.
- The UV models can provide interesting signatures beyond standard searches.
- Both the 8 TeV and 14 TeV LHC have great discovery potential for the classes of models considered here.
- We will learn more about "chromo-Rayleigh" interactions in the coming years.