Constraining Elko Dark Matter at the LHC with Monophoton events

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Summary

- D. Vir Ahluwalia, D. Grumiller arXiv:0412080[hep-th].
- The Dirac and Majorana spinors in the Weyl representation are

$$\psi(\mathbf{p}) = \begin{pmatrix} \phi_R(\mathbf{p}) \\ \phi_L(\mathbf{p}) \end{pmatrix}. \tag{1}$$

The right hand component has the following transformation

$$\phi_R(\mathbf{p}) \longrightarrow e^{1/2\sigma\cdot\Phi}\phi_R(\mathbf{0}), \tag{2}$$

corresponding to the representation $(1/2, 0)$ of the Lorentz group. The left component

$$\phi_L(\mathbf{p}) \longrightarrow e^{-1/2\sigma\cdot\Phi}\phi_L(\mathbf{0}) \tag{3}$$

corresponding to the representation $(0, 1/2)$.

How to relate the representation spaces? In the framework of full Lorentz group we have:

- Rotations
- *Boosts*
- *Discretes Symmetries:* P, T *(and* PT*)*

It is easy to see that $P\phi_R \sim \phi_L$. Therefore $P\phi_R = \phi_L$ (and vice-versa) up to a global phase.

- The action of P on ψ must be interchange the components of the representation space.

- Therefore, as far as we use the Weyl spinors as eigenspinors of the P operator we arrive at a usual Dirac dynamics (from the relativistic point of view).
- The parity operator, then, plays a key role in the usual formalism.
- Let us propose the following exercise: how to (re)build the relativistic spinor theory without parity? There is another operator relating both sides of the representation space: let θ be the Wigner matrix

$$\Theta = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

- Now we can apreciate the Magic of the Pauli Matrices:

$$\Theta\vec{\sigma}\Theta^{-1} = -\vec{\sigma}^{*} \tag{4}$$

Remember that

$$\phi_R(p^\mu) = \exp(+\vec{\sigma}/2 \cdot \varphi)\phi_R(k^\mu).$$

Conjugating the above equation and using Eq (4) we have

$$\Theta\phi_R^*(p^\mu) = \exp(-\vec{\sigma}/2 \cdot \varphi)\Theta\phi_R^*(k^\mu) \tag{5}$$

Playing the same game we have

$$\Theta\phi_L^*(p^\mu) = \exp(\vec{\sigma}/2 \cdot \varphi)\Theta\phi_L^*(k^\mu) \tag{6}$$

- If ϕ_R is *right-handed*, then $\Theta\phi_R^*$ is *left-handed*;
- If ϕ_L is *left-handed*, then $\Theta\phi_L^*$ is *right-handed*.

- Therefore it is possible to construct new elements of $(0,1/2)\oplus(1/2,0)$ whitout parity:

$$\lambda(p^\mu) = \begin{pmatrix} \epsilon\Theta\phi_L^*(p^\mu) \\ \phi_L(p^\mu) \end{pmatrix},$$
$$\rho(p^\mu) = \begin{pmatrix} \phi_R(p^\mu) \\ \chi\Theta\phi_R^*(p^\mu) \end{pmatrix}$$

- The physics related to both spinors is quite similar;
- In order to fix the arbitrary phase let us require that $C\lambda = \pm\lambda$
- where C is the charge conjugation operator:

$$C = \begin{pmatrix} 0 & i\Theta \\ -i\Theta & 0 \end{pmatrix} K \tag{7}$$

- $C\lambda^S(p^\mu) = +\lambda^S(p^\mu)$:

$$\lambda^S(p^\mu) = \begin{pmatrix} +i\Theta\phi_L^*(p^\mu) \\ \phi_L(p^\mu) \end{pmatrix}.$$

- $C\lambda^A(p^\mu) = -\lambda^A(p^\mu)$:

$$\lambda^A(p^\mu) = \begin{pmatrix} -i\Theta\phi_L^*(p^\mu) \\ \phi_L(p^\mu) \end{pmatrix}.$$

- A short pause: We have at hands a spinor field candidade (not quantized yet) (matter) which cannot interact with the electromagnetic field (dark). This is being a worthwhile exercise.

- In order to provide a specific example of Elko spinor let us require ϕ_L as eingenstates of the helicity operetor (at the rest frame):

$$(\vec{\sigma}\cdot\hat{p})\phi_L^{\pm}(k^\mu) = \pm\phi_L^{\pm}(k^\mu),$$

whose solution (with suitable choice of phases) is given by

$$\phi_L^{+}(k^\mu) = \sqrt{m}\begin{pmatrix} cos(\theta/2)e^{-i\phi/2} \\ sin(\theta/2)e^{i\phi/2} \end{pmatrix}$$

$$\phi_L^{-}(k^\mu) = \sqrt{m}\begin{pmatrix} -sin(\theta/2)e^{-i\phi/2} \\ cos(\theta/2)e^{i\phi/2} \end{pmatrix},$$

- Notice that $(\vec{\sigma}\cdot\hat{p})\left(\Theta[\phi_L^{\pm}(k^\mu)]^*\right) = \mp\left(\Theta[\phi_L^{\pm}(k^\mu)]^*\right)$ and, therefore, each λ is a dual helicty object.

Elko:

$$\begin{pmatrix} \pm i \Uparrow \\ \Downarrow \end{pmatrix}, \begin{pmatrix} \mp i \Downarrow \\ \Uparrow \end{pmatrix}$$

Dirac:

$$\begin{pmatrix} \uparrow \\ \uparrow \end{pmatrix}, \begin{pmatrix} \downarrow \\ \downarrow \end{pmatrix}$$

$$\lambda_{+}^{S}(p^{\mu}) = \sqrt{\frac{E+m}{2m}}\left(1-\frac{p}{E+m}\right)\begin{pmatrix} i\Theta\left[\phi_{L}^{+}(k^{\mu})\right]^{*} \\ \phi_{L}^{+}(k^{\mu}) \end{pmatrix}$$

$$\lambda_{-}^{S}(p^{\mu}) = \sqrt{\frac{E+m}{2m}}\left(1+\frac{p}{E+m}\right)\begin{pmatrix} i\Theta\left[\phi_{L}^{-}(k^{\mu})\right]^{*} \\ \phi_{L}^{-}(k^{\mu}) \end{pmatrix}$$

$$\lambda_{+}^{A}(p^{\mu}) = \sqrt{\frac{E+m}{2m}}\left(1+\frac{p}{E+m}\right)\begin{pmatrix} -i\Theta\left[\phi_{L}^{-}(k^{\mu})\right]^{*} \\ \phi_{L}^{-}(k^{\mu}) \end{pmatrix}$$

$$\lambda_{-}^{A}(p^{\mu}) = \sqrt{\frac{E+m}{2m}}\left(1-\frac{p}{E+m}\right)\begin{pmatrix} -i\Theta\left[\phi_{L}^{+}(k^{\mu})\right]^{*} \\ \phi_{L}^{+}(k^{\mu}) \end{pmatrix}$$

- Thus, we have four spinors $\lambda_{+}^{S}, \lambda_{-}^{S}, \lambda_{+}^{A}$ and λ_{-}^{A}.

$\frac{1}{\Lambda}\varepsilon_{\alpha\beta}\bar{\nu}_{\alpha}\nu_{\beta}\ \stackrel{\neg}{\eta}\ \eta\ \frac{1}{\Lambda}\varepsilon_{\alpha\beta}\bar{\nu_{\alpha}}l_{\beta}\ \stackrel{\neg}{\eta}\ \eta$

IMPORTANT!

$$
\begin{aligned}
\gamma_\mu p^\mu \lambda_+^S(p^\mu) &= \sqrt{\frac{E+m}{2m}}\left(1-\frac{p}{E+m}\right) \\
&\times \left[E\gamma_0 + p\begin{pmatrix} 0 & \vec{\sigma}\cdot\hat{p} \\ -\vec{\sigma}\cdot\hat{p} & 0 \end{pmatrix}\right]\lambda_+^S(k^\mu) \\
&= im\underbrace{\sqrt{\frac{E+m}{2m}}\left(1+\frac{p}{E+m}\right)\lambda_-^S(k^\mu)}_{\lambda_-^S(p^\mu)}
\end{aligned}
$$

Therefore $\gamma_\mu p^\mu \lambda_+^S(p^\mu) = im\lambda_-^S(p^\mu)$ and the Dirac operator does not annihilate λ.

- The aplication of $\gamma_\nu p^\nu$ once again gives

$$
(\eta_{\mu\nu}p^\mu p^\nu I - m^2 I)\lambda(p^\mu) = 0 \tag{8}
$$

- Hence the $\lambda's$ obey just the Klein-Gordon wave equation.

A small course in Elko phenomenology

- The quantum field is

$$\eta(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2mE(\mathbf{p})}} \sum_\beta [a_\beta(\mathbf{p})\lambda^S_\beta(\mathbf{p})e^{-ip_\mu x^\mu} + b^\dagger_\beta(\mathbf{p})\lambda^A_\beta(\mathbf{p})e^{ip_\mu x^\mu}]$$

  with

$$\{a_\beta(\mathbf{p}), a^\dagger_{\beta'}(\mathbf{p}')\} = (2\pi)^3\delta^3(\mathbf{p}-\mathbf{p}')\delta_{\beta\beta'}$$
$$\{a^\dagger_\beta(\mathbf{p}), a^\dagger_{\beta'}(\mathbf{p}')\} = \{a_\beta(\mathbf{p}), a_{\beta'}(\mathbf{p}')\} = 0$$

  and similarly for $b_\alpha(\vec{p})$.

- The Feynman-Dyson propagator $S_{FD}(x'-x) = i\langle|T(\eta(x')\,\overset{\neg}{\eta}(x))|\rangle$ is

$$S_{FD}(x'-x) = -\int \frac{d^4p}{(2\pi)^4} e^{-ip^\mu(x'_\mu - x_\mu)} \left[\frac{\mathbb{I}_4}{p^2 - m^2 + i\varepsilon}\right]$$

- So, the field has mass dimension 1 instead of $\frac{3}{2}$.

A small course in Elko phenomenology

The interactions for this field are:

$$\mathcal{L}_{int}(x) = -g_\phi \stackrel{\neg}{\eta}(x)\eta(x)\phi^2(x) - g_e \stackrel{\neg}{\eta}(x)[\gamma^\mu, \gamma^\nu]\eta(x)F_{\mu\nu}(x) - g_a(\stackrel{\neg}{\eta}(x)\eta(x))^2$$

The Feynman Rules (external lines):

- $\frac{\lambda^S_{\beta'}(\mathbf{k})}{\sqrt{m}}$ - For the S particle incoming the vertex;
- $\frac{\stackrel{\neg}{\lambda}^A_{\beta'}(\mathbf{k})}{\sqrt{m}}$ - For the A incoming the vertex;
- $\frac{\stackrel{\neg}{\lambda}^S_{\beta'}(\mathbf{k})}{\sqrt{m}}$ - For the S outgoing the vertex;
- $\frac{\lambda^A_{\beta'}(\mathbf{k})}{\sqrt{m}}$ - For the A outgoing the vertex.

The interaction vertex is $\Gamma = 2ig_e[\gamma_\sigma, \not{q}]$.

Cross Sections - Unitarity

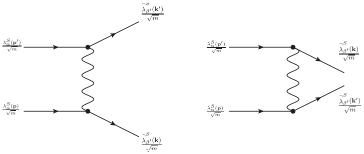

Figura: Möller scattering for Elkos with the external legs explicited.

$$\mathcal{M} = -\left(\overset{\neg S}{\lambda}_{\beta}(\mathbf{k})\frac{2g_e}{m}[\gamma^{\nu},\gamma^{\mu}]q_{\nu}\lambda^{S}_{\alpha}(\mathbf{p})\right)\frac{-ig_{\mu\rho}}{q^2}\left(\overset{\neg S}{\lambda}_{\beta'}(\mathbf{k}')\frac{2g}{m}[\gamma^{\sigma},\gamma^{\rho}]q_{\sigma}\lambda^{S}_{\alpha'}(\mathbf{p}')\right)$$
$$+\left(\overset{\neg S}{\lambda}_{\beta'}(\mathbf{k}')\frac{2g_e}{m}[\gamma^{\nu},\gamma^{\mu}]r_{\nu}\lambda^{S}_{\alpha}(\mathbf{p})\right)\frac{-ig_{\mu\rho}}{r^2}\left(\overset{\neg S}{\lambda}_{\beta}(\mathbf{k})\frac{2g}{m}[\gamma^{\sigma},\gamma^{\rho}]r_{\sigma}\lambda^{S}_{\alpha'}(\mathbf{p}')\right).$$

$$\sigma = \frac{24g_e^4(6E^4 - 6m^2E^2 + m^4)}{\pi E^2 m^4}. \quad (9)$$

- At high energies the cross-section grows indefinitely with energy. Unitarity of the $\mathcal{S}$ matrix is violated.

- through the partial wave analysis it is possible to obtain the region of the parameters space in which the process remains unitary.
-

$$a_0(\hat{s}) = \frac{1}{32\pi}\int_{-1}^{1} d(\cos\theta)\mathcal{M}(\hat{s}). \tag{10}$$

- Unitarity of the scattering amplitude requires that $|\text{Re}a_0| \leq \frac{1}{2}$, reflecting the fact that the amplitude is bounded. Therefore the condition (10) implies

$$a_0 = \frac{3g_e^2\hat{s}}{\pi m^2} \leq \frac{1}{2}, \tag{11}$$

leading to the the bound

$$\frac{g_e}{m_\lambda} \leq \sqrt{\frac{\pi}{6\hat{s}}}\ . \tag{12}$$

- The most stringent absolute bound for a collider search is obtained by fixing $\sqrt{\hat{s}} = \sqrt{S}$, the CM energy of the collider, in our case, 8 TeV.

Monophoton Channel

- In order to simulate the monophoton events at the LHC, we implemented the model in `Madgraph5` using the `FeynRules` package. We have also modified the `Source/DHELAS/aloha_functions.f` by the inclusion of the Elko field.
- The `CheckMate` program was used to verify, for a given set of coupling constants and masses, whether the model is excluded or not at 95% C.L. by comparing the result with the experimental analysis. The cuts implemented by `CheckMate` require

$$\not{E}_T > 150 \text{ GeV}, p_T^\gamma > 125 \text{ GeV}$$

$$|\eta^\gamma| < 1.37, \Delta R(\not{E}_T, \gamma) > 0.4$$

$$\text{veto electrons with: } p_T^e > 7 \text{ GeV}, |\eta^e| < 2.47$$

$$\text{veto muons with: } p_T^\mu > 6 \text{ GeV}, |\eta^\mu| < 2.5\,.$$

The Feynman graphs for the monophoton channel are depicted in Fig.2.

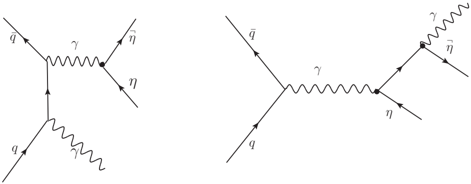

Figura: Elko production in monophoton events. Notice that in terms of the coupling constant, g_e, the graph at the right is of order g_e^2, but the the dominant contribution, at the left, is of order g_e.

Using the ATLAS constraints for these events, the 95Łlimit imposed on the coupling g_e, as a function of Elko mass m_λ, with CheckMATE is shown in theThe main background to this process is $Z\gamma$, where the Z-boson decays to neutrino pairs.

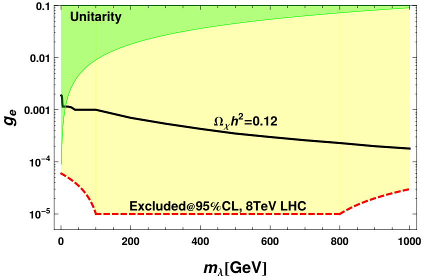

Figura: The constraints on the Elko-photon coupling for a range of Elko masses, m_λ, and coupling constants, g_e. The yellow shaded region is the 95%CL exclusion region from the 8 TeV LHC data from monophoton events. The green shaded region corresponds to the points where the unitary of Möller scattering of Elkos is violated. The black solid represents the points compatible with the dark matter relic density.

A. Alves, M. Dias, F. de Campos, L. Duarte and J. M. Hoff da Silva, EPL **121**, no. 3, 31001 (2018) doi:10.1209/0295-5075/121/31001 [arXiv:1712.05180 [hep-ph]].

OBRIGADA! THANKS! GRACIAS!