Polynomial spectral features from dark matter

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Outline

• Part I: Motivation
  Box-shaped gamma-ray spectra

• Part II: Another example
  Neutrino features from DM annihilating into SM gauge bosons

• Part III: General case
  Polynomial spectral features

• Part IV: Connection to the diphoton resonance

• Conclusions
Gamma-ray spectral features

Smoking gun signature for dark matter: no astrophysical process is known to produce a sharp feature in the gamma-ray spectrum.

Annihilation into Photons
Virtual Internal Bremsstrahlung (VIB)
Box-shaped spectra
Gamma-ray spectral features

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Originally studied for scalar mediators
Gamma-ray spectral features

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- Annihilation into Photons
- Virtual Internal Bremsstrahlung (VIB)
- Box-shaped spectra

Originally studied for scalar mediators

This talk: Generalize this to an arbitrary intermediate state
The same applies to neutrinos
The same applies to neutrinos
The same applies to neutrinos.

What about?
Connection to the diphoton resonance

Its simplest explanation assumes a spin-0 or spin-2 particle $R$ of mass 750 GeV

Landau-Yang theorem

Spin-one is not possible
Connection to the diphoton resonance

Its simplest explanation assumes a spin-0 or spin-2 particle $R$ of mass 750 GeV

Landau-Yang theorem $\rightarrow$ Spin-one is not possible

TeV-DM would likely annihilate or decay into the resonance
Box-shaped spectra from intermediary scalars

\begin{align*}
\phi_\gamma &= \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \\
E_\gamma &= \text{GeV}
\end{align*}

centre region

\[ m_{\text{DM}} = 100 \text{ GeV} \]

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

Ibarra et al. 2010
The case of gauge bosons
The case of gauge bosons

\[ m = -1, 0, +1 \]
The case of gauge bosons

\[ \frac{d\Phi_\nu}{dE_\nu} = \Phi_\nu \sum_m \text{Br}_m \frac{dN_{\nu,m}}{dE_\nu}, \quad \Phi_\nu = \frac{(\sigma v)}{8\pi M_{DM}^2} \bar{J}_{\text{ann}} \]
The case of gauge bosons

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The case of gauge bosons

DM DM → W^-W^+, W^+ → e^+ν with M_W/M_{DM} = 0.01

DM DM → W^-W^+, W^+ → e^+ν with M_W/M_{DM} = 0.75

Φ_γ^- dφ_γ^-/dx

x = E_γ/M_{DM}

transverse W

unpolarized W

longitudinal W

transverse W

unpolarized W

longitudinal W
The case of gauge bosons

Gauge bosons produced in DM annihilations are typically polarized

Above the electroweak scale, Majorana DM with $SU(2)_L$ quantum numbers produce gauge bosons that are mostly transverse.

Scalar DM, also singlet under $SU(2)_L$, produces gauge bosons that are mostly longitudinally polarized.
General case
General case
General case

\[ \theta_0 \langle m', S|m, S \rangle = \langle m', S|R(\theta_0)|m, S \rangle \equiv d_{m', m}(\theta_0) \]
General case

\[ \theta_0 \langle m', S | m, S \rangle = \langle m', S | R(\theta_0) | m, S \rangle \equiv d_{m', m}^S(\theta_0) \]

\[
(\Phi_A)^{-1} \frac{d\Phi_A}{dE_A} = \frac{1}{n} \sum_m \text{Br}_m \frac{dN_{A,m}}{dE_A}
\]

\[
= \frac{1}{M_{DM}} \sum_m \text{Br}_m f_m^S \left( \frac{E_A}{M_{DM}}, \frac{E_X}{M_{DM}} \right)
\]
General case

\[ \theta_0 \langle m', S|m, S \rangle = \langle m', S|R(\theta_0)|m, S \rangle \equiv d_{m,m_0}^S \]

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\]

\[
f_m^S(x, y) = \frac{(2S + 1)}{\sqrt{y^2 - r_X^2}} \Theta (x - x^-(y)) \Theta (x^+(y) - x) \times \sum_{m'} C_{m'} \left| d_{m'm}^S \left( \arccos \left( \frac{2x - y}{\sqrt{y^2 - r_X^2}} \right) \right) \right|^2
\]
General case

Almost everything fixed by angular momentum.

The dependence on the DM Model is encoded in two quantities

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**General case**

Fixed by the DM model. It determines the degree of polarization.

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Fixed by the DM model. It determines the degree of polarization

Fixed by the properties of the particle X and the final state
Example with particles of Spin-2

For spin-2 particles coupled to the energy-momentum tensor

\[
\begin{align*}
\text{final state } AB & \quad |C_{-2}| \quad |C_{-1}| \quad |C_0| \quad |C_1| \quad |C_2| \\
\gamma\gamma & \quad \frac{1}{2} \quad 0 \quad 0 \quad \frac{1}{2} \\
ZZ & \quad \frac{6}{13} \quad 0 \quad \frac{1}{13} \quad 0 \quad \frac{6}{13} \\
W^+W^- & \quad \frac{6}{13} \quad 0 \quad \frac{1}{13} \quad 0 \quad \frac{6}{13} \\
hh & \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \\
\nu_L\bar{\nu}_L & \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \\
\nu_R\bar{\nu}_R & \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \\
\nu\bar{\nu} \text{ (Dirac or Majorana)} & \quad 0 \quad \frac{1}{2} \quad 0 \quad \frac{1}{2} \quad 0
\end{align*}
\]

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Fixed by the properties of the particle X and the final state.
Are spin-2 particles arising in DM annihilations polarized?

Are they coupled to the energy-momentum tensor?
Are spin-2 particles arising in DM annihilations polarized?

Boosted regime \( M_T^2 \ll p^2 \)

\[
\begin{align*}
\varepsilon^{\mu\nu}(\pm 2) &= \varepsilon^{\mu}(\pm)\varepsilon^{\nu}(\pm), \\
\varepsilon^{\mu\nu}(\pm 1) &\approx \frac{1}{\sqrt{2} M_T} [p^\nu \varepsilon^{\mu}(\pm) + p^\mu \varepsilon^{\nu}(\pm)] \\
\varepsilon^{\mu\nu}(0) &\approx \frac{\eta^{\mu\nu}}{\sqrt{6}} + \sqrt{\frac{2}{3}} \frac{p^\mu p^\nu}{M_T^2}.
\end{align*}
\]

Are they coupled to the energy-momentum tensor?

No

The spin-2 particles are mostly polarized with \( m = 0 \)

\[ \text{Br}_{0,0} = 1 \]
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Are they coupled to the energy-momentum tensor?  
- Yes
- No

- States with $m = \pm 1$ naturally decouple. Is there a selection rule forbidding $m = 0$?

The spin-2 particles are mostly polarized with $m = 0$

$\mathcal{B}_{0,0} = 1$
Are spin-2 particles arising in DM annihilations polarized?

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\[ \text{Br}_{2,2} = \text{Br}_{-2,-2} = \frac{1}{2} \]
DM DM → TT, T → γγ with \( M_T/M_{DM} = 0.01 \)

\[ \phi^{-1}_{\gamma} \, d\phi_{\gamma}/dx \]

\[ \text{unpolarized} \]

\[ \text{Br}_{0,0} = 1 \]

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\[ x = E_{\gamma}/M_{DM} \]

DM DM → TT, T → γγ with \( M_T/M_{DM} = 0.75 \)

\[ \text{unpolarized} \]

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\[ x = E_{\gamma}/M_{DM} \]
Connection to the diphoton resonance

\[ M_{\text{DM}} = 5 \text{ TeV}, \quad M_T = 0.75 \text{ TeV} \]

\[ \Delta E/E = 15\% \]

\[ \text{Br}_{\theta} = 1, \quad \text{Br}_{\pm} = \frac{1}{2} \]
Connection to the diphoton resonance

$M_{\text{DM}} = 5 \text{ TeV}, M_T = 0.75 \text{ TeV}$

$\Delta E/E = 15\%$

$\text{Br}_{\nu,\theta} = 1$

$\text{Br}_{\nu,2} = 1/2$

$\Delta E/E = 5\%$

$\text{Br}_{\nu,\theta} = 1$

$\text{Br}_{\nu,2} = 1/2$
Connection to the diphoton resonance

H.E.S.S. Limits on spectral features

\[ M_T = 0.75 \text{ TeV} \]

\[ \sigma (\text{DM DM} \rightarrow \gamma \gamma) \quad (\text{cm}^3/\text{s}) \]

\[ 2 \sigma (\text{DM DM} \rightarrow \gamma \gamma) \]

\[ M_{\text{DM}} \quad (\text{TeV}) \]

\[ \text{unpolarized} \]

\[ \text{Br}_{0, 0} = 1 \]

\[ \text{Br}_{2, -2} = \text{Br}_{-2, 2} = \frac{1}{2} \]
Conclusions

- DM annihilations into arbitrary particles that subsequently decay into photons or neutrinos lead to polynomial spectral features.

- Such features are generic and can be studied using a model-independent approach.

- Using this, high resolution of gamma-ray or neutrinos telescopes could tell the spin of the decaying particle.

- We calculate the annihilation spectrum that the associated to 750 GeV resonance if DM annihilates or decays into it.