Constraints on dark matter scattering with long-lived mediators using $\gamma$-rays from the Sun

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36th International Cosmic Ray Conference, ICRC 2019
29th July 2019 - Madison, WI, USA
The Sun as «Target» for DM searches

• DM particles from the galactic halo can be gravitationally trapped by the Sun through scattering interactions with the nuclei in the solar environment

• In those interactions DM particles continue to lose energy through subsequent scattering reaching the thermal equilibrium at the Sun core
  • The over density of DM in the core can result in annihilations into SM particles
  • However, SM particles produced in the Sun (with the exception of neutrinos), will be likely absorbed in the Sun interior

• We assume a model in which DM annihilates into a long-lived mediator that can escape and decay outside the Sun to produce gamma rays, electrons, or other SM particles:
  \[ \chi \chi \rightarrow \phi \phi \quad \phi \rightarrow \gamma \gamma, e^+e^- \ldots \]
\( \gamma \)-rays from DM annihilation: mediator case

- We investigate a scenario in which the light mediators decay into gamma rays that can therefore reach the Earth and be detected

\[ \chi \chi \rightarrow \phi \phi, \quad \phi \rightarrow \gamma \gamma \]

- This model predicts an enhancement of DM photon flux towards the Sun

- The resulting DM photon spectrum will have a "box-shape", where the center and the width of the box depend on \( m_\phi \) and \( m_\chi \)
  - If \( m_\phi << m_\chi \) the box extends up to \( m_\chi \)

- We also investigate the case of mediators that decay into cosmic-ray electrons and positrons (see Mazziotta’s Poster PS3-277)
DM $\gamma$-rays flux at Earth

• The DM $\gamma$-ray flux is given by:
  
  \[ \Phi_{DM}(E; m_\chi, \sigma, L, \ldots) = \Gamma_{cap} \frac{1}{4\pi D^2} \left( e^{-\frac{R_\odot}{L}} - e^{-\frac{D}{L}} \right) N_\gamma(E) \]
  
  • $L$ is the mediator decay length
  • $\Gamma_{cap}$ is the capture rate
  • $N_\gamma(E)$ is the DM $\gamma$ spectrum per decay:
    • In case of light mediators, $N_\gamma(E) = 2 \frac{H(m_\chi - E)}{m_\chi}$

• The capture rate has been calculated with the DARKSUSY code in case of Spin-Dependent and Spin-Independent cross sections
  
  • $\rho_\odot = 0.3 \text{ GeV/cm}^3$
  • Maxwellian velocity distribution with $<v> = 220 \text{ km/s}$ and $v_{\text{rms}} = 270 \text{ km/s}$
  • $\sigma = 10^{-40} \text{ cm}^2$ (indeed this is the parameter to be constrained)
Analysis approach

• A search for box-like features on the top of a smooth photon spectrum towards the Sun is implemented

• Dataset: 10-years of Fermi-LAT observations

• A Poisson maximum likelihood approach is used
  • Analysis performed in sliding energy windows with half-width of $w_E = 0.6E_W$

• ON/OFF technique analysis:
  • ON Region: RoI of 2° angular radius centered on the Sun
  • OFF Region: RoI of 2° angular radius centered on the 6 months time-offset Sun

• The OFF region is the control region to take systematic (instrumental) uncertainties into account
  • These effects could create extra features in the data that could mimic the “true” signal ones
Flux Models

• Flux models:
  • $\Phi^{ON}(E) = \Phi_{smooth}^{ON}(E) + \Phi_{feat}^{ON}(E) + \Phi^{extra}(E)$
  • $\Phi^{OFF}(E) = \Phi_{smooth}^{OFF}(E) + \Phi_{feat}^{OFF}(E)$

• Each flux-term consists of:
  • A continuous smooth term $\Phi_{smooth}(E) = k \left( \frac{E}{E_0} \right)^{-\alpha}$
  • A possible box-like feature $\Phi_{feat}(E) = s H(E_w - E)$

• Expected counts in a bin energy $E_j$:
  • $\mu^{ON/OFF}(E_j) = \int \mathcal{E}^{ON/OFF}(E_j|E) \Phi^{ON/OFF}(E)dE$

• The Poisson likelihood function is built combining the ON and OFF RoIs:
  • The extra feature (systematic uncertainties) is tied on the two regions

• The parameters of the models are calculated with MINUIT maximizing the likelihood
  • MINOS is used to evaluate the 95%CL intervals of the parameters
Significance of the signal features

- Null Hypothesis H0: \( \Phi_{\text{ON}}^{\text{feat}}(E) = 0 \)
- Alternative Hypothesis H1: \( \Phi_{\text{ON}}^{\text{feat}}(E) > 0 \)
- Local Test Statistic: \( TS_{\text{local}} = 2 (\ln \mathcal{L}(H_1) - \ln \mathcal{L}(H_0)) \)
- Expectation bands and global significance are evaluated with the pseudo-experiment technique
  - 1000 realization performed
  - Smoothly Broken Power Law model for the whole energy spectrum as template for the pseudo-experiment
  - Same analysis approach as for real data
  - Confidence band evaluated from the quantiles of the distributions of the fitted parameters
  - For each pseudo-experiment the largest value of the local Test Statistic \( TS_{\text{max}} \) is recorded
  - Global significance \( s_{\text{global}} \) evaluated with half-normal probability density function
The most significant features have global significances less than 1\(\sigma\).
DM - Nucleon cross section limits

- Using the DM flux at Earth (slide n.4), the limits on the box feature intensity can be converted into limits on the DM-nucleon cross section
  - Limits on the cross-sections depend on the decay length of the mediator
  - Limits scale linearly with local DM density $\rho_\odot$
Limits on the spin-dependent cross section for L = R⊙

- Current analysis: 10 years photon data of Fermi-LAT
- In the A. Albert at al. Paper (arXiv:1808.05624) the limits were calculated with the Fermi-LAT and HAWC data
  - 3 years in the high solar activity with a different approach
  - The e± channel with final state radiation (FSR γ) was also considered
- We also evaluated the limits with the LAT electron/positron (e±) data using an RoI of 30° (see Mazziotta’s poster P23-277)
Conclusions

• We have searched for possible box-like features in the solar gamma-ray spectrum as DM signatures
  • We consider a scenario in which DM particles in the Sun core annihilate into a long-lived mediator, which can escape the Sun and decay into photons
  • This scenario would yield a box-like feature in the gamma-ray spectrum

• A fit procedure in sliding energy windows has been implemented
  • A ON/OFF approach is used to take systematic effect into account

• We do not find any statistically significant feature in the energy spectra
  • The limits on the intensity of the feature have been converted into constraints on the DM-nucleon scattering cross section

• For further details see:
  • D. Serini at al., Constraint on dark matter scattering with long-lived mediators using gamma rays from the Sun, PoS (ICRC2019) 544
  • M.N. Mazziotta at al., Search for dark matter signatures in the cosmic-ray electron and positron spectrum measured by the Fermi Large Area Telescope, PoS (ICRC2019) 531, Poster Session PS23-277
  • M. N. Mazziotta et al., Search for features in the cosmic-ray electron and positron spectrum measured by the Fermi Large Area Telescope, Phys. Rev. D 98, 022006 [arXiv:1712.07005]