Constraints on dark matter scattering with long-lived mediators using γ-rays from the Sun

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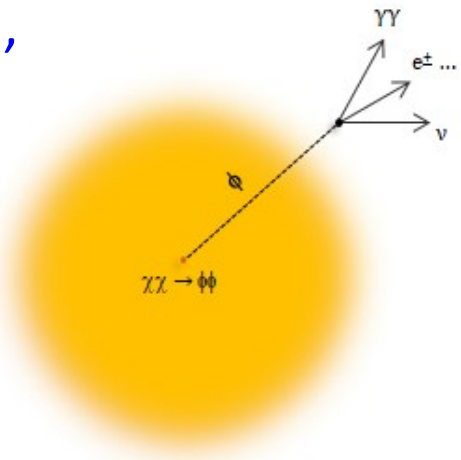
The Sun as «Target» for DM searches

- 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:

$$\chi\chi \rightarrow \phi\phi \qquad \phi \rightarrow \gamma\gamma, e^{+}e^{-} \ldots$$

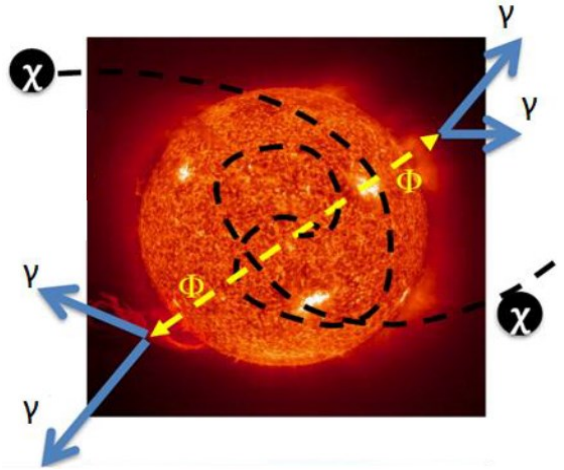


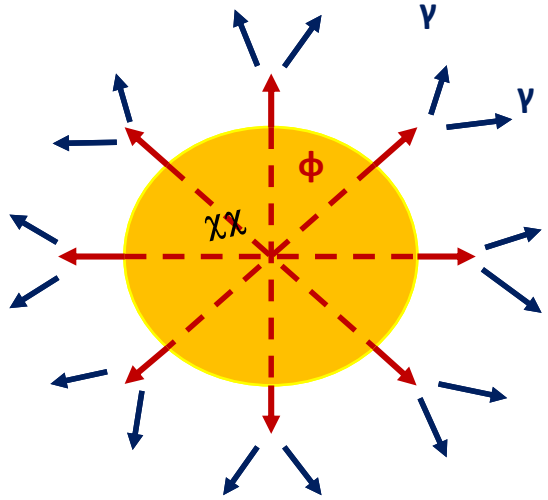
γ-rays from DM annihilation: mediator case

- 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 predict 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_ϕ and m_χ
  - If $m_\phi << m_\chi$ the box extends up to m_χ
- We also investigate the case of mediators that decay into cosmic-ray electrons and positrons (see Mazziotta's Poster PS3-277)

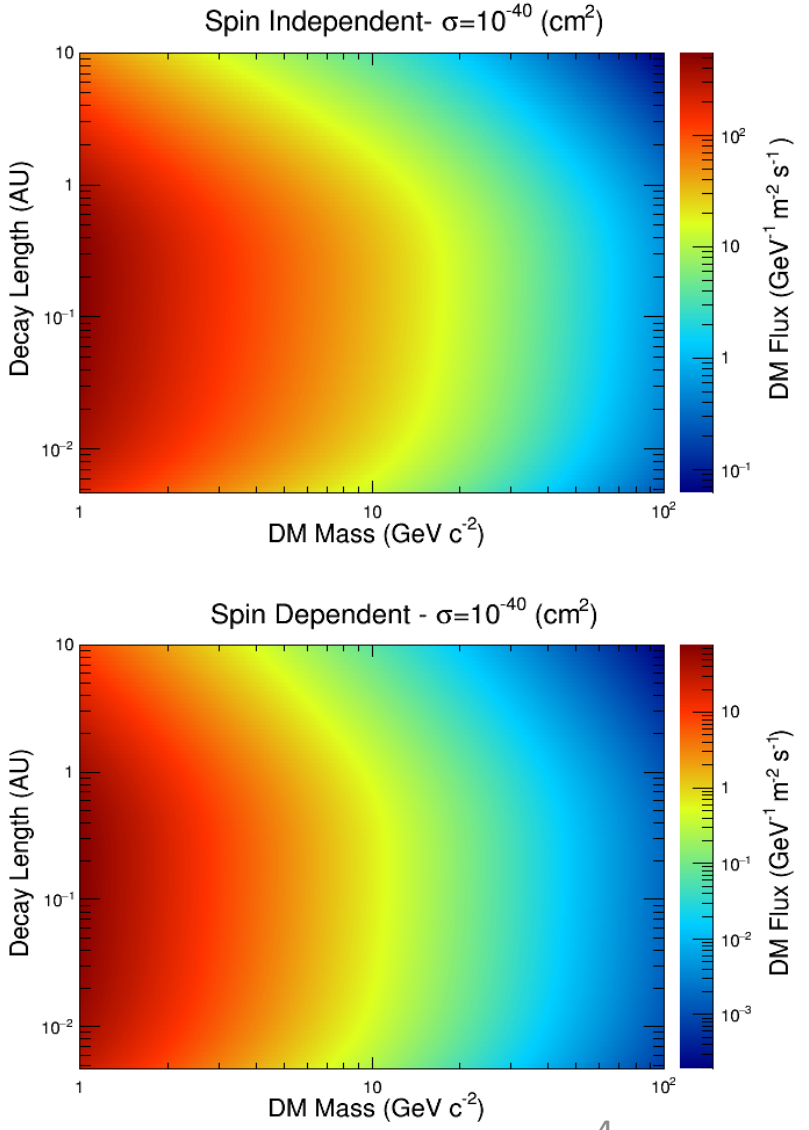




$$E_\gamma = [0\,;\, m_\chi]$$

DM γ-rays flux at Earth

- The DM γ-ray flux is given by:
  - $\Phi_{DM}(E;\, m_\chi, \sigma, L, \dots) = \Gamma_{cap}\, \frac{1}{4\pi D^2} \left(e^{-\frac{R_\odot}{L}} - e^{-\frac{D}{L}}\right) N_\gamma(E)$
  - L is the mediator decay length
  - Γ_{cap} is the capture rate
  - N_γ (E) is the DM γ 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 GeV/cm^3
  - Maxwellian velocity distribution with <v> = 220 km/s and v_{rms} = 270 km/s
  - σ = 10^{-40} cm^2 (indeed this is the parameter to be constrained)

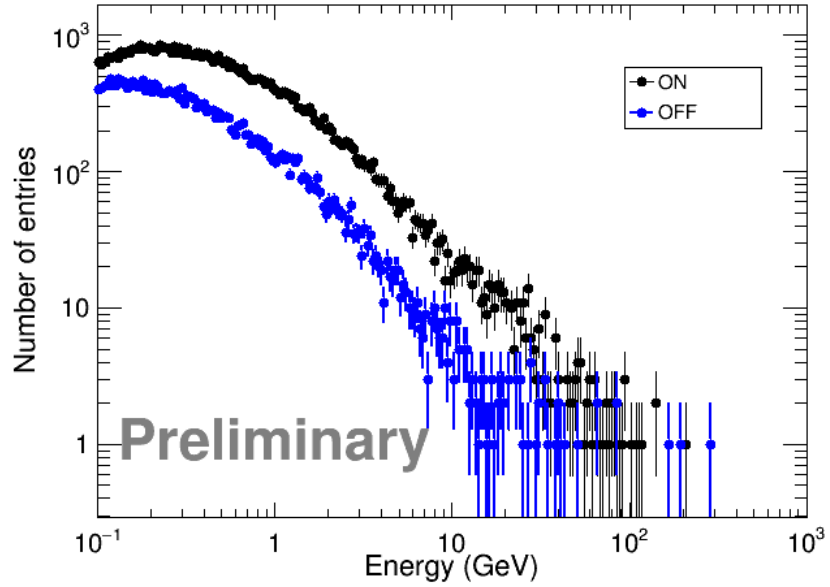


Analysis approach

- 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:
  - $\Phi^{ON}(E) = \Phi^{ON}_{smooth}(E) + \Phi^{ON}_{feat}(E) + \Phi^{extra}_{feat}(E)$
  - $\Phi^{OFF}(E) = \Phi^{OFF}_{smooth}(E) + \Phi^{extra}_{feat}(E)$
- 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:
  - $\mu^{ON/OFF}(E_j) = \int \mathcal{E}^{ON/OFF}(E_j|E)\,\Phi^{ON/OFF}(E)dE$

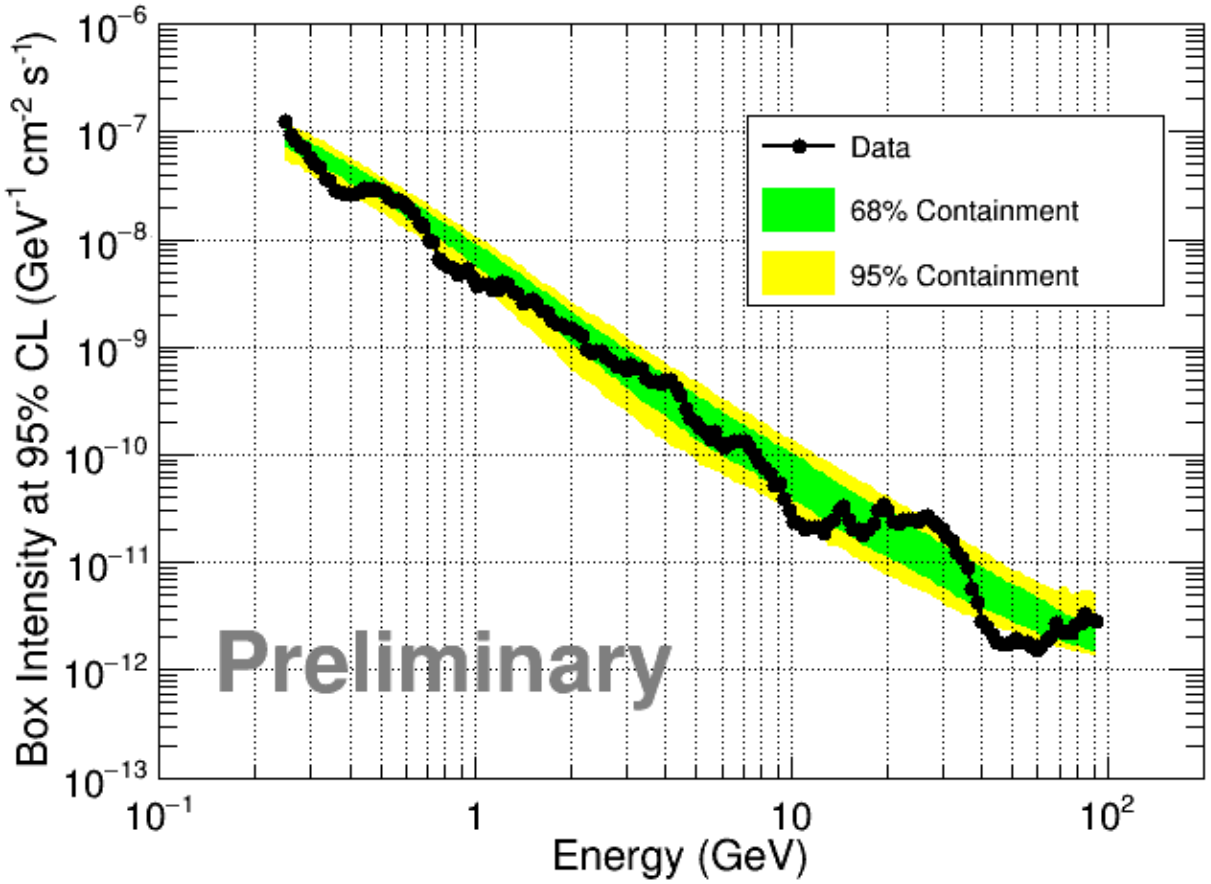


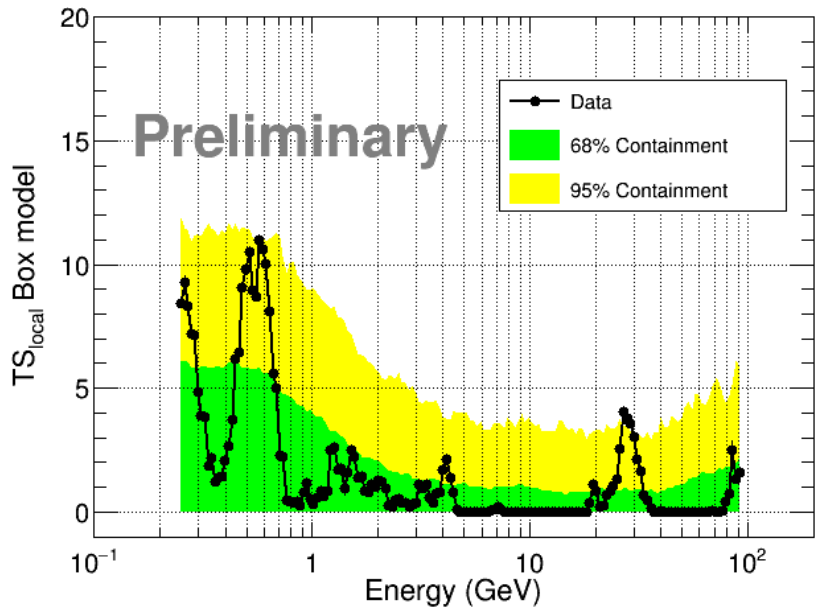
- The Poisson likelihood function is built combining the ON and OFF RoIs:
  - The extra feature (systematic uncertainties) is tied on the two regions
- The parameters of the models are calculated with MINUIT maximizing the likelihood
  - MINOS is used to evaluate the 95%CL intervals of the parameters

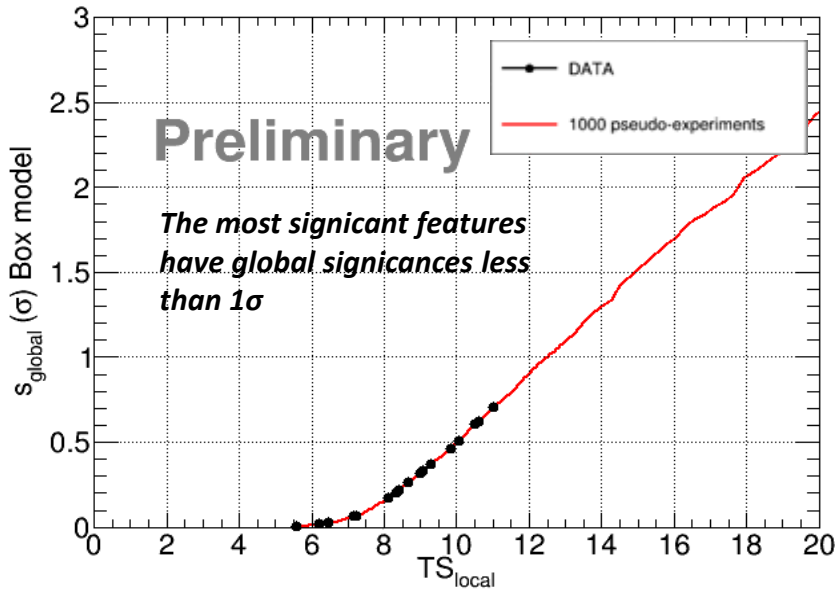
Significance of the signal features

- Null Hypothesis H0: $\Phi_{feat}^{ON}(E) = 0$
- Alternative Hypothesis H1: $\Phi_{feat}^{ON}(E) > 0$
- Local Test Statistic: $TS_{local} = 2\,(\ln \mathcal{L}(H_1) - \ln \mathcal{L}(H_0))$
- 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_{max} is recorded
  - Global significance s_{global} evaluated with half-normal probability density function

Analysis results

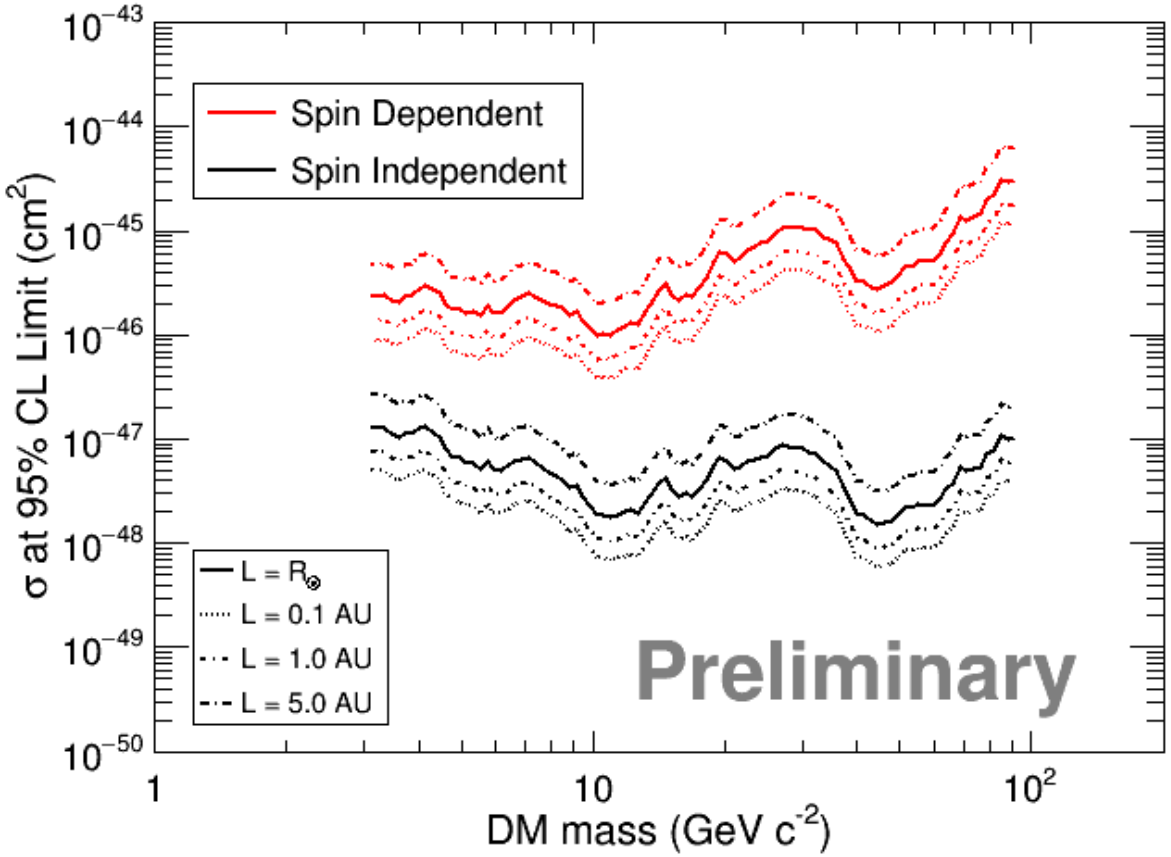






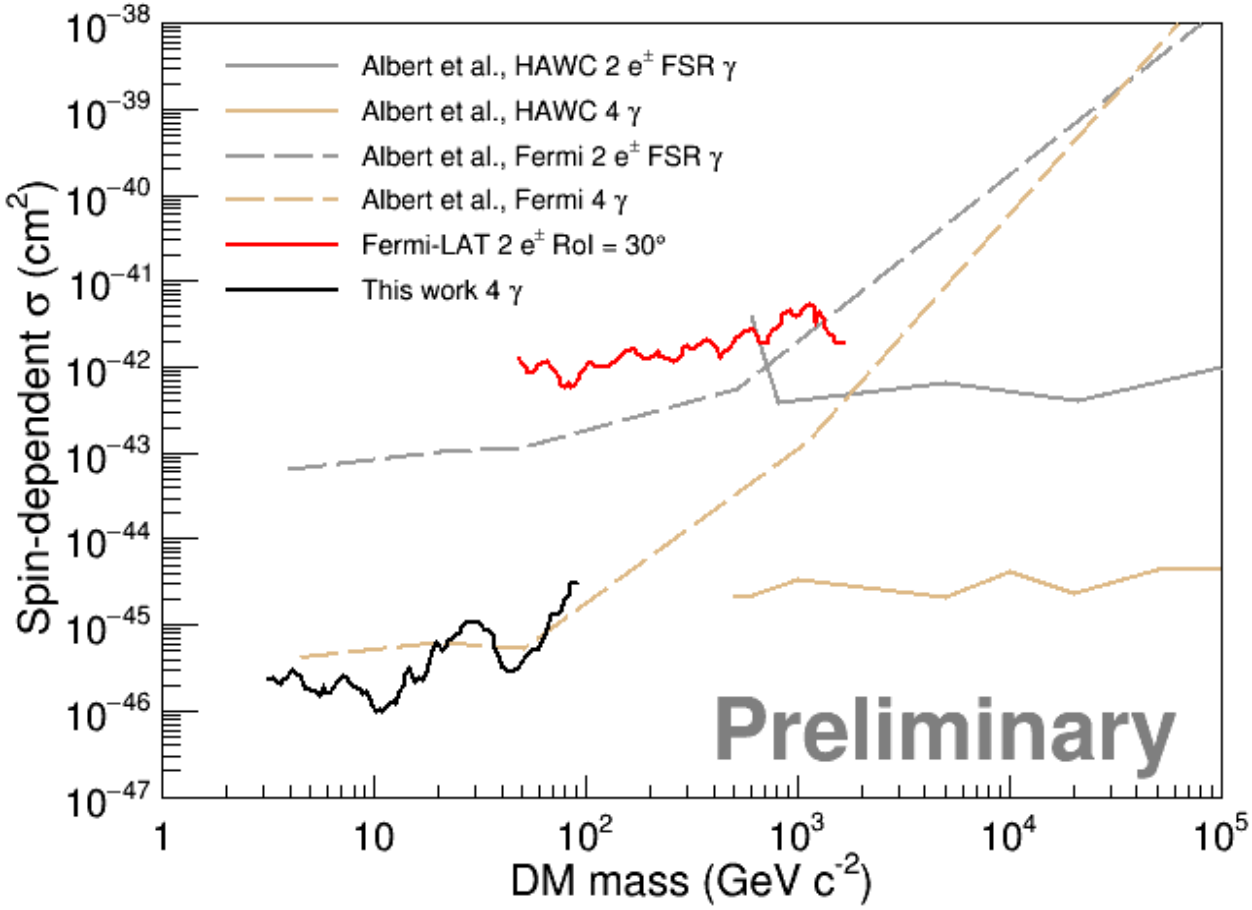
DM - Nucleon cross section limits

- 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 with local DM density $\rho_{\odot}$



Limits on the spin-dependent cross section for L = $R_\odot$

- 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 $e^{\pm}$ channel with final state radiation (FSR γ) was also considered
- We also evaluated the limits with the LAT electron/positron ($e^{\pm}$) 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]