Study of the cosmic-ray electron flux from the Sun with the Fermi LAT data

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Abstract

An excess of cosmic-ray electrons and positrons (CREs) from the Sun could be interpreted as a dark matter (DM) signature because in some DM models an observable flux of high-energy CREs is expected to be produced. We analyzed the CRE data sample collected by the Fermi LAT during its first year of operation to search for a possible flux excess correlated with the Sun's direction at high energies. We implemented two different analysis techniques, both yielding no evidence of a significant CRE flux excess correlated with the Sun's direction. The implications of our results on the DM theoretical models will be illustrated.

1.Introduction

The detection of an excess of high energy CREs from the Sun could be a DM signature. Recently [Schuster et al., PRD82, 115012 (2010)], two scenarios have been proposed in which an enhancement of the CRE flux from the Sun is predicted at energies of a few hundred GeV:

1. *"intermediate state scenario":* DM particles annihilate in the center of the Sun into an intermediate state which then decays to CREs outside the surface of the Sun.
2. *"iDM scenario":* Dark Matter captured by the Sun via inelastic scattering (iDM) remains on large orbits, then annihilates directly to CREs outside the surface of the Sun.

3.Flux asymmetry studies

This approach compares the CRE flux from the Sun with the flux from a fake source (fake Sun) located in the sky position opposite to that of the Sun.
The fluxes from individual pixels are evaluated as:

$$\frac{d\Phi_i(E)}{dE} = \frac{1}{\Delta E}\,\frac{N_i(E)\times[1-c(E)]}{\mathcal{E}_i(E)}$$

where $N_i(E)$ is the number of CRE events with energies in the range $[E,E+\Delta E]$ in the i-th pixel , $\mathcal{E}_i(E)$ is the exposure of the pixel and $c(E)$ is the residual hadron contamination [Ackermann et al., PRD82, 092004 (2010)]. The CRE flux $d\Phi_{Sun}(E|\Delta\Theta)/dE$ from a cone of angular radius $\Delta\Theta$ centered on the Sun is then evaluated by adding the fluxes from all the individual pixels within the cone. The CRE flux from the fake Sun is calculated in a similar way. The flux asymmetry is then defined as:

$$\frac{dA_\Phi(E|\Delta\Theta)}{dE} = \frac{d\Phi_{Sun}(E|\Delta\Theta)}{dE} - \frac{d\Phi_{Fake\ Sun}(E|\Delta\Theta)}{dE}$$

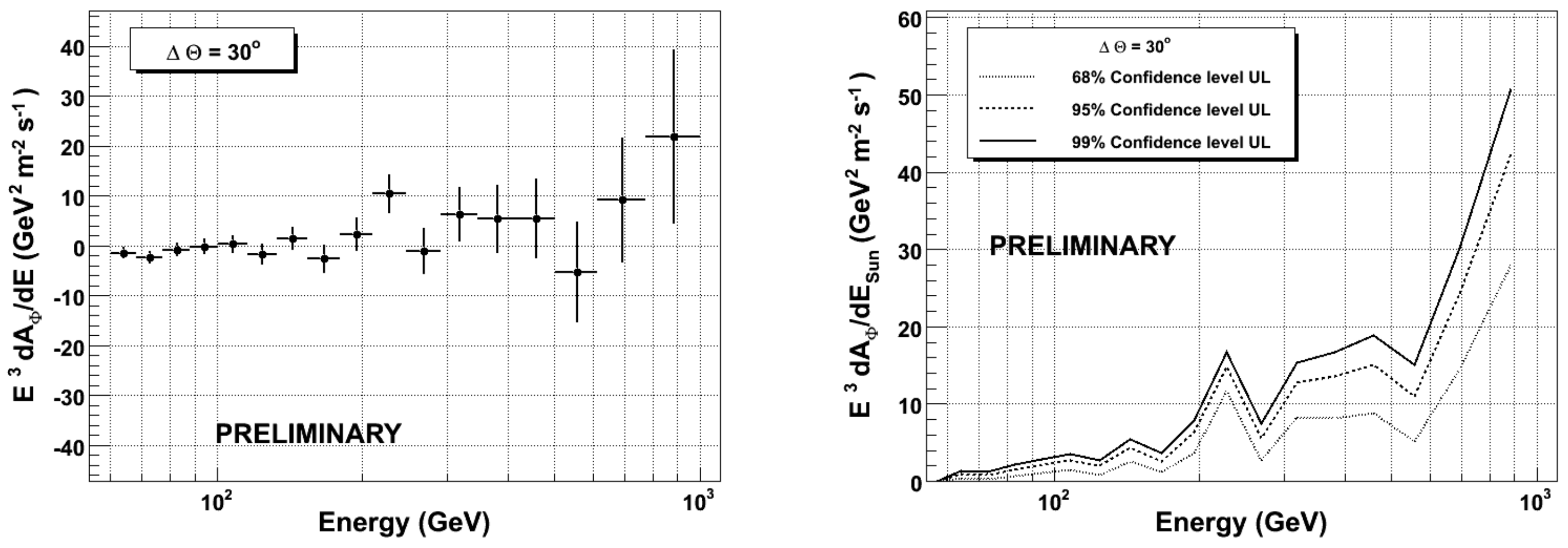

Figure 1: *Left panel: measured flux asymmetry between real and fake Sun in a cone with angular radius ΔΘ=30°. Right panel: statistical upper limits on the flux asymmetry at 68%, 95% and 99% confidence levels. The angular radius ΔΘ =30° has been chosen to account for the bending effects of both the Sun's and Earth's magnetic fields.*

5. DM annihilation through an intermediate state

In this scenario DM particles χ are captured by the Sun through elastic scattering interactions, then continue to lose energy through subsequent scatterings until they thermalize and eventually annihilate into a light intermediate state ϕ ($m_\phi \ll m_\chi$) through the process $\chi\chi \rightarrow \phi\phi$. The ϕ are assumed to escape the Sun without further interactions and to decay into e^+e^- pairs, which are able to reach the Earth. To evaluate the CRE fluxes from the Sun, we assume equilibrium between the capture and annihilation rates of DM particles. The solar capture rate as a function of m_χ is evaluated using DarkSUSY for both the spin dependent and spin independent scattering. A local DM density ρ_{DM}=0.3GeV/cm^3 was chosen. A Maxwell-Boltzmann velocity distribution is assumed, with the solar velocity relative to the DM rest frame $v_\odot$=220km/s and a DM velocity dispersion $\tilde{v}$=270km/s. The CRE fluxes within a ROI of angular radius $\Delta\Theta$=30° centered on the Sun for m_ϕ=1GeV were evaluated assuming different values of the ϕ decay length L. Comparing the theoretical fluxes with the upper limits on the measured ones, we derived upper limits on the scattering cross sections for both spin-dependent and spin-independent processes.

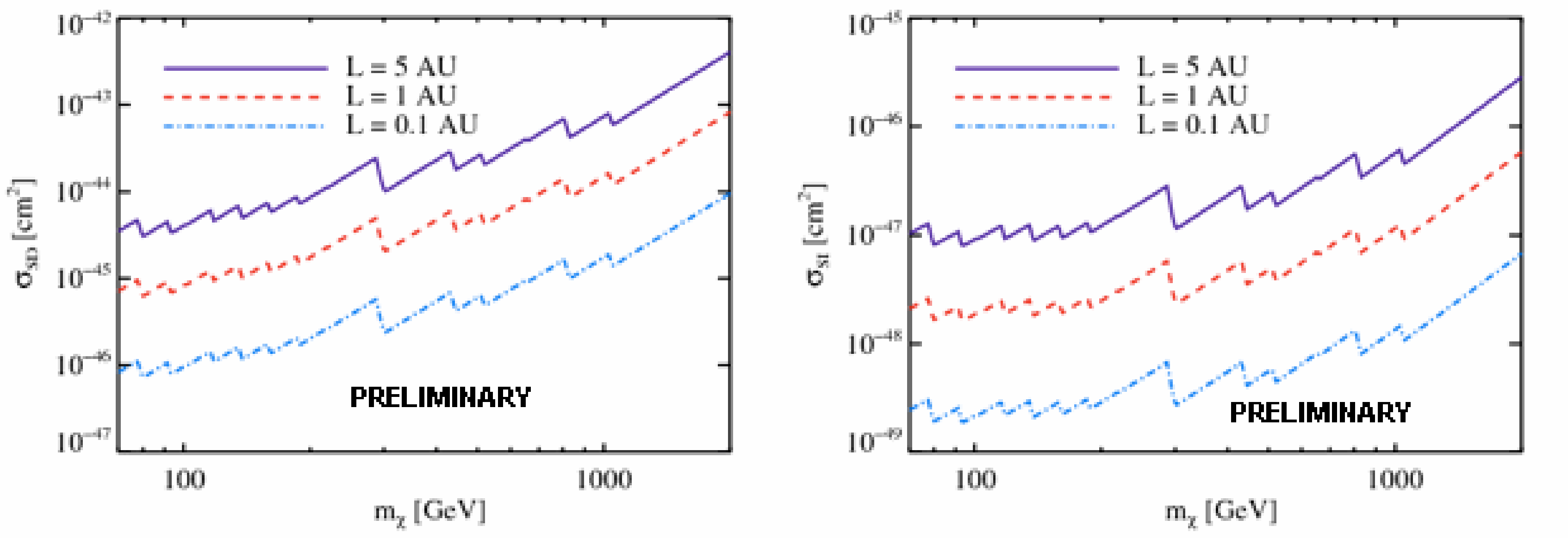

Figure 3: *Upper limits at 95% confidence level for the spin-dependent (left panel) and spin-independent (right panel) DM scattering cross sections, for different ϕ decay lengths L. These constraints were derived from the CRE flux upper limits shown in fig. 2.*

2.Data selection and analysis

We used the CRE events collected by the Fermi LAT during its first year of operation to search for a possible flux excess correlated with the Sun's direction. For this analysis we have selected CRE events with E>60GeV, which is significantly higher than the geomagnetic cutoff in any part of Fermi's orbit. A total of 1.35×10^6 events survived to the selection cuts. The analysis was performed in a custom reference frame derived from ecliptic coordinates and centered on the Sun's direction. The sky has been divided into 12288 equal area pixels, each covering a solid angle of about 10^{-3} sr, and CRE fluxes from extended regions of interest (ROIs) centered on the Sun with different angular radii have been studied, to take into account any magnetic field effects on CREs.

4.Comparison with an isotropic sky

This approach compares the real CRE flux from the Sun with the one expected from an isotropic distribution. To simulate an isotropic sample of CREs an event shuffling technique [Ackermann et al., PRD82, 092003 (2010)] was used. Simulated events are built from real ones by randomly coupling the arrival times and the arrival directions in the instrument reference frame of real events.
The difference between real and simulated counts in a cone of radius $\Delta\Theta$ centered on the Sun is given by $\Delta N(E|\Delta\Theta)=N_{real}(E|\Delta\Theta)-\alpha(E)N_{sim}(E|\Delta\Theta)$ where $\alpha(E)=N_{real}(E)/N_{sim}(E)$ is the ratio between the total real and simulated events with energy E. The count difference is then converted in a flux asymmetry according to the following equation:

$$\frac{dA'_\Phi(E|\Delta\Theta)}{dE} = \frac{\Delta N(E|\Delta\Theta)\times[1-c(E)]}{\mathcal{E}(E|\Delta\Theta)\Delta E}$$

Where $\mathcal{E}(E|\Delta\Theta)$ is the exposure of the sky region under investigation.
The results from this analysis are consistent with the ones from the flux asymmetry studies, discussed in section 3.

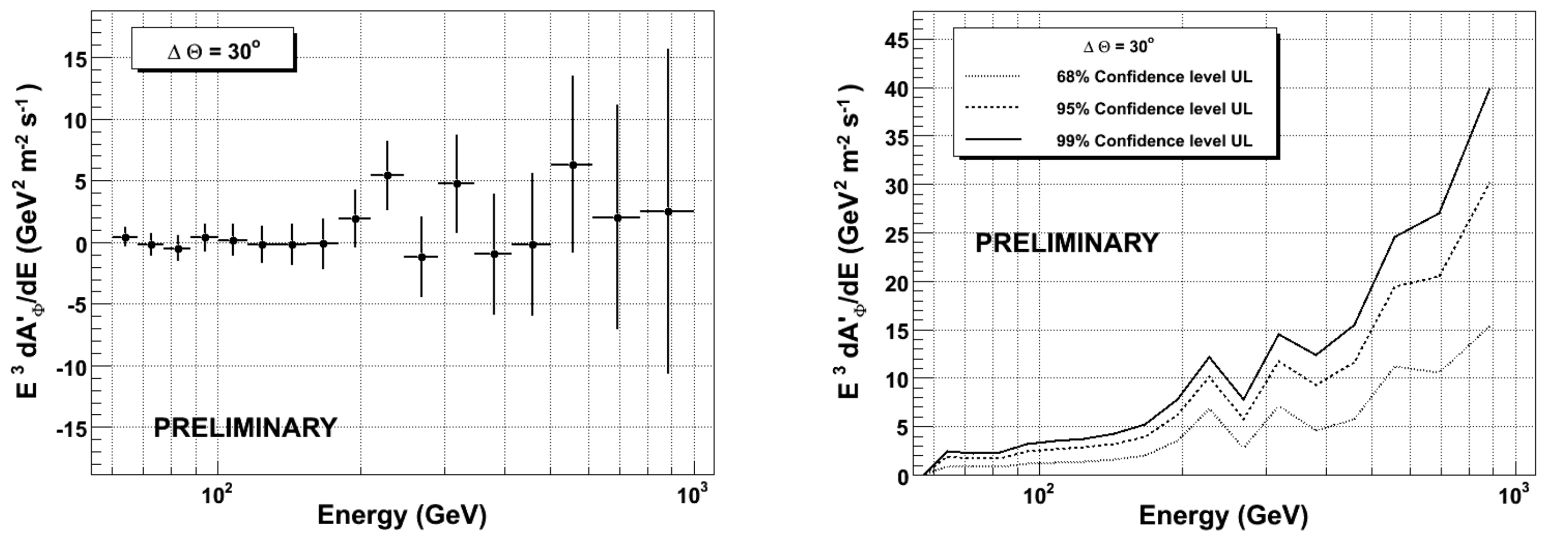

Figure 2: *Left panel: measured flux asymmetry between real and simulated events from the Sun in a cone with angular radius ΔΘ=30°. Right panel: statistical upper limits on the flux asymmetry at 68%, 95% and 99% confidence levels.*

6. Inelastic DM

In this scenario DM particles χ are captured by the Sun through inelastic scattering off of nuclei $\chi N \rightarrow \chi^* N$. This process requires a threshold energy $E_{th}=\delta(1+m_\chi/m_N)$ where $\delta=m_{\chi^*}-m_\chi$. DM particles captured after inelastic scattering lose their energy after a few interactions and, if the elastic scattering cross section is small, they are unable to thermalize and sink to the core of the Sun, remaining on large orbits that can take them outside the surface of the Sun and eventually annihilating into e^+e^- pairs. Assuming that the χ annihilate at rest, the CRE energy is equal to m_χ. Since the captured DM density falls off quickly with the distance from the Sun, we assume that all the annihilations take place at the surface of the Sun. We also assume equilibrium between the capture and annihilation rates. The inelastic capture rate of DM particles by the Sun was calculated in [Nussinov et al., JCAP 0908, 037 (2009); Menon et al., PRD82, 015011 (2010)] assuming $v_\odot$=250km/s, $\tilde{v}$=250km/s and ρ_{DM}=0.3GeV/cm^3. The fraction f_{out} of particles captured outside the Sun as a function of δ was calculated in [Schuster et al., PRD82, 115012 (2010)]. We derived constraints on the scattering cross section σ_0 by requiring that the predicted CRE flux in a 30° ROI centered on the Sun does not exceed the measured upper limits.

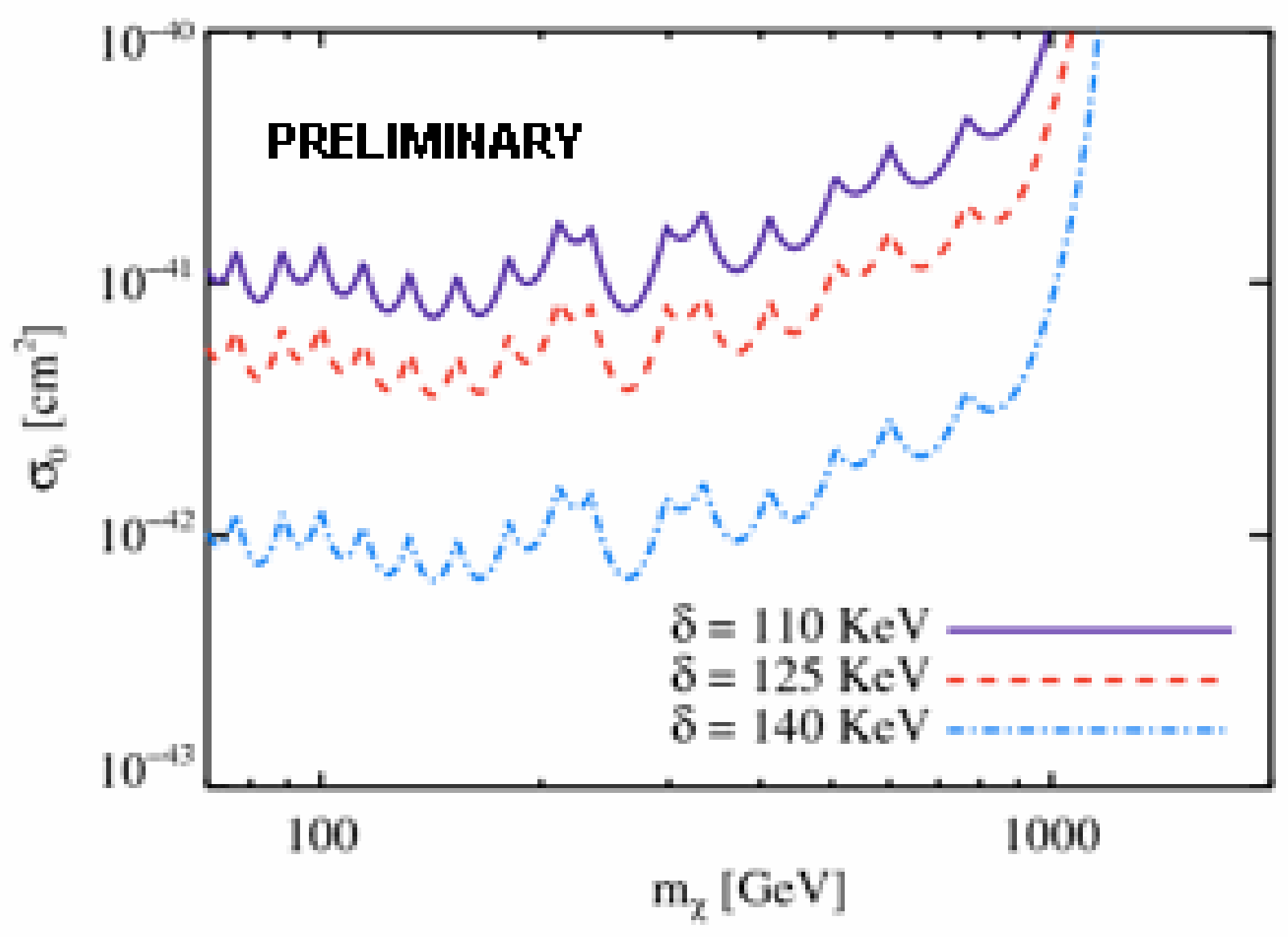

Figure 4: *Upper limits at 95% confidence level for the inelastic DM scattering cross sections σ_0 as a function of the DM mass for three different values of the mass splitting δ. These constraints were derived from the CRE flux upper limits shown in fig. 2.*