The gamma-ray Moon seen by the Fermi LAT over a full solar cycle

S. De Gaetano (Bari University and INFN Bari), F. Loparco (Bari University and INFN Bari), M. N. Mazziotta (INFN Bari) and N. Giglietto (Politecnico di Bari and INFN Bari)
on behalf of the Fermi Large Area Telescope Collaboration

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Abstract

The Moon is among the brightest gamma-ray sources in the sky. We have reconstructed its gamma-ray spectrum in the energy range from 30 MeV up to a few GeV using the data collected by the Fermi Large Area Telescope during its first 12.5 years of operation since its launch in 2008, a period covering the duration of a whole solar cycle. We have also studied the evolution of the lunar gamma-ray emission by measuring the spectra in 6 months time intervals. The data show a strong correlation with the solar activity. Gamma rays produced on the lunar surface are in fact originated in the interactions of cosmic rays (mainly proton and helium), whose fluxes are affected by solar modulation. We have also developed a model based on the FLUKA simulation code to evaluate the yields of photons produced by cosmic-ray protons and helium nuclei impinging on the Moon. We have then folded the gamma-ray yields obtained from the model with the primary proton and helium spectra measured by the AMS-02 and PAMELA experiments in different time intervals and we have compared the simulation results with the experimental data, showing that the simulation reproduces correctly the time evolution of the lunar gamma-ray flux.

1. Introduction

High-energy gamma rays emitted from the Moon are produced in inelastic collisions of cosmic-ray nuclei (CRs) with the lunar surface [1]. The major contribution to the gamma-ray emission comes from the production and subsequent decay of neutral pions in hadronic interactions. The gamma-ray flux from the Moon will be therefore sensitive to the primary CR energy spectra, to the composition of the lunar surface and to the mechanisms of hadronic interactions of CR nuclei with the lunar surface.

In this work, we have reconstructed the gamma-ray flux from the Moon using the data collected by the Large Area Telescope onboard the Fermi satellite [2] in its first 12.5 years of operation. The analysis procedure is the same as in Ref. [3], with an update in the calculation of the Moon position.

2. Data selection

The analysis has been performed using a sample of the newest version (P305) of Pass 8 LAT data collected from August 2008 to December 2020 and selecting P8_SOURCE photon events, starting from a minimum energy of 10 MeV. As in Ref. [3], we have identified a signal region and a background region:

- signal region = cone centered on the Moon position
- background region = cone centered on a time-offset Moon position (Δt = 14 days)

The angular radius of the two regions is given by:

$$\theta = \sqrt{[\theta_0 (E/E_0)^{-\delta}]^2 + \theta_{min}^2}$$

with $\theta_{min} = 1°$, $\theta_0 = 5°$, $\delta = 0.8$ and $E_0 = 100$ MeV. This choice reflects the energy dependence of the 68% PSF of the LAT and maximizes the signal-to-noise ratio. The value of θ_{min} accounts for the angular size of the Moon (0.25° angular radius).

The good time intervals (GTIs) for the analysis have been chosen by requiring the following conditions, applied to the Moon or the time-offset-Moon as appropriate:

- LAT taking data in its standard science operation configuration and outside the South Atlantic Anomaly;
- angular separation < 100° between a cone of 15° angular radius centered on the Moon direction and the zenith direction;
- Moon observed with off-axis angle (i.e. angle between the Moon direction and the LAT z-axis) < 66.4°;
- Moon at galactic latitudes $|b| > 5°$;
- angular separation > 20° between the Moon and the Sun;
- angular separation > 20° between the Moon and the brightest sources in the 4FGL catalog.

The Moon position is obtained from its ephemeris using a software interfaced to the JPL libraries [4], which provides the Moon right ascension (ra) and declination (dec) with respect to an observer located at the Earth center, and correcting for Fermi orbital parallax. In this work, the apparent coordinates (with respect to the spacecraft) have been obtained from the coordinates of the spacecraft in the GTIs used for the analysis. This method is more precise than the one used in the previous work, in which the parallax correction was implemented by using tabulated values provided in Ref. [5]. This method was validated by performing a cross-check with the Astropy package [6]. The maximum angular separation between the Moon positions evaluated with the two methods is about 0.01°.

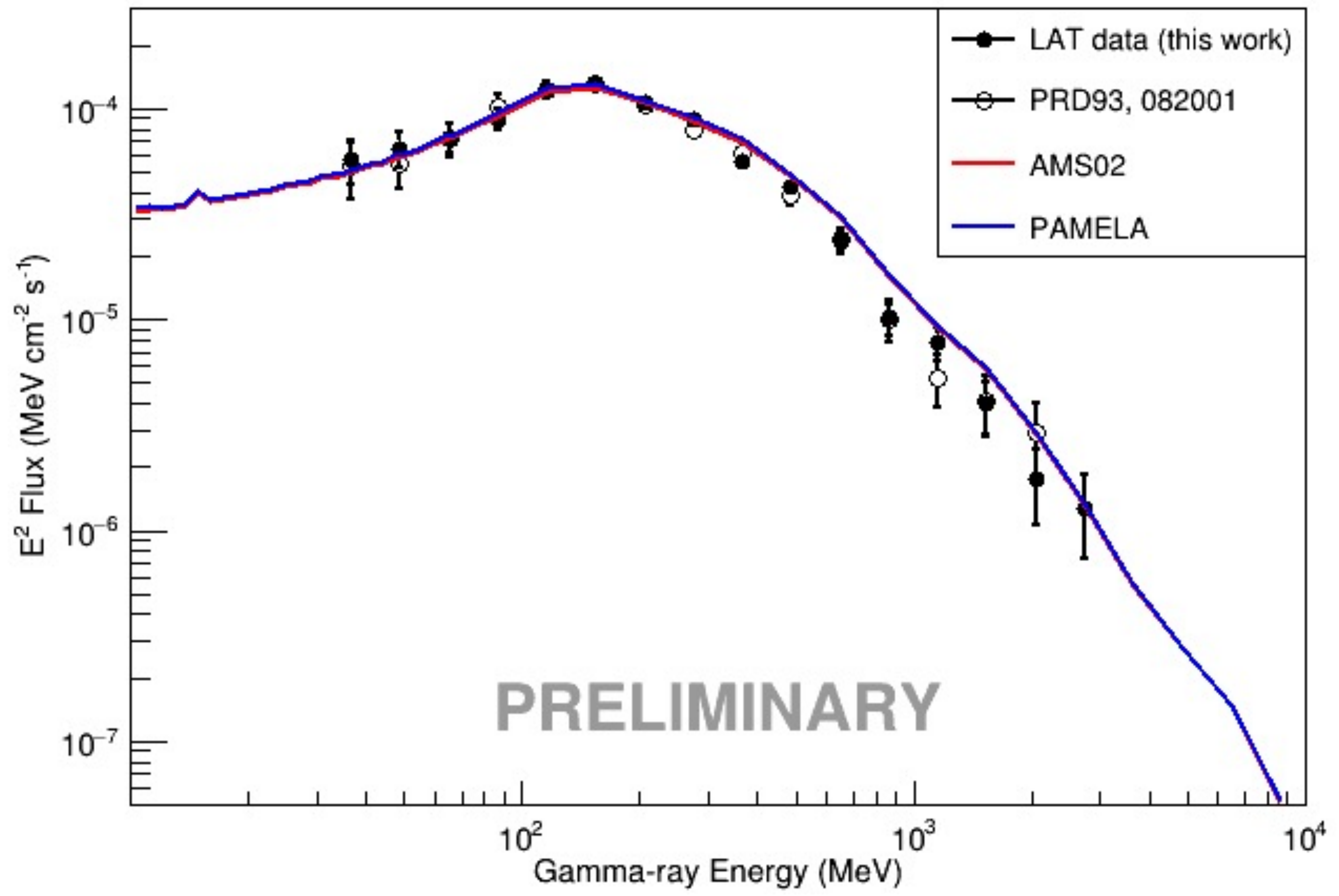

Figure 1 *Gamma-ray flux from the Moon. The flux reconstructed with the latest version of Pass-8 LAT data (P305) is compared with the flux reconstructed with the previous version of Pass-8 LAT data (P302). The blue and the red curves correspond to the fluxes obtained by folding the gamma-ray yield computed with FLUKA with the proton and He spectra measured by PAMELA and AMS-02 in the period from May 2011 to November 2013.*

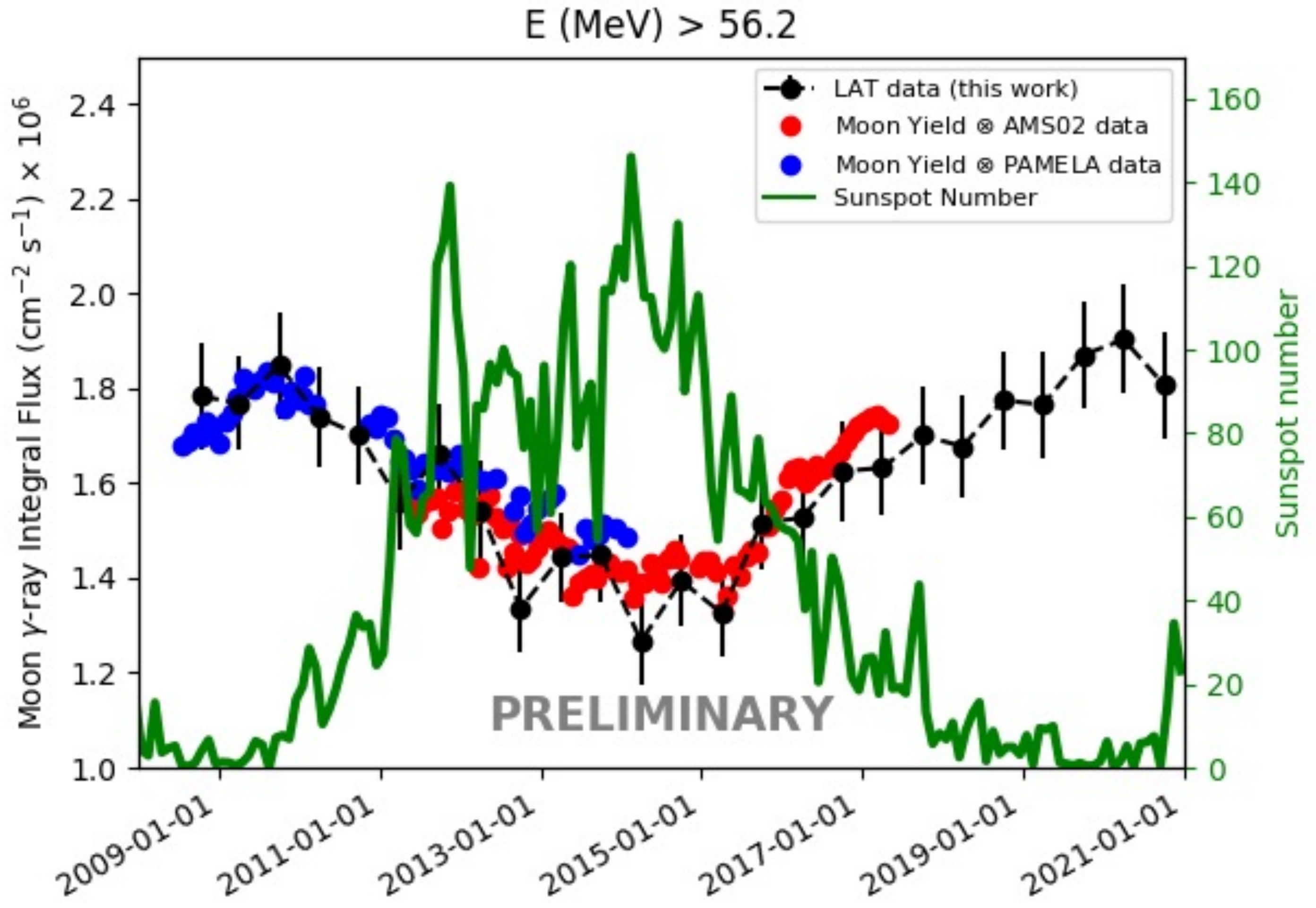

Figure 2: *Time evolution of the Moon gamma-ray flux (left y-axis) and of the number of sunspots (right y-axis). Black points indicate the flux measured by the LAT, while blue and red points correspond to the flux computed by folding the gamma-ray yield obtained with FLUKA with the CR spectra measured by AMS-02 and PAMELA respectively.*

3. Comparison with expected flux

The gamma-ray flux $\varphi_\gamma(E_\gamma)$ from the Moon can be evaluated starting from the CR proton and ^{4}He intensities in the solar system, $I_p(T_p)$ and $I_{He}(T_{He})$, as:

$$\varphi_\gamma(E_\gamma) = \frac{\pi R^2}{d^2} \sum_{i=p,He} \int Y(E_\gamma|T_i) I(T_i) dT_i = \frac{\pi R^2}{d^2} I_\gamma(E_\gamma)$$

where $Y(E_\gamma|T_i)$ is the gamma-ray yield from the i-th species of CR primaries, d is the LAT-Moon distance and R is the Moon radius. To evaluate the gamma-ray yield, we used the FLUKA code [7] in which we implemented a MC simulation of the interactions of CR protons and ^{4}He nuclei with the lunar surface. In the simulation, the Moon is described as a sphere of radius R = 1737.1 km, consisting of a mixture of different oxides (45% SiO_2, 22% FeO, 11% CaO, 10% Al_2O_3, 9% MgO, 3%) with a density $\rho = 1.8$ g/cm^3 [8]. In order to compute the lunar flux, we folded the gamma-ray yield with the proton and He spectra measured by the AMS-02 and Pamela experiments from May 2011 to November 2013 [9]. In Figure 1, the computed γ-ray spectra are plotted against the LAT reconstructed flux obtained with the latter version of Pass-8 data (P305) and with the previous one (P302). The lunar gamma-ray fluxes evaluated starting from the measured CR intensities reproduce correctly the LAT data.

4. Time evolution studies

We have studied the time evolution of the gamma-ray emission from the Moon dividing the dataset into subsamples, corresponding to periods of 6 months duration. The total time interval exceeds the duration of a full solar cycle. Figure 2 shows the time evolution of lunar gamma-ray flux (E > 56 MeV) measured by the LAT compared with the predictions obtained by folding the gamma-ray yield evaluated with FLUKA with the CR spectra measured by AMS-02 and PAMELA. The time evolution of the number of sunspots, provided by the WDC-SILSO [10], is also shown. We find that the lunar gamma-ray flux is anticorrelated with the solar activity, as already shown in Ref. [3] for a 7-years data sample. This is due to the fact that the intensity of the solar magnetic field increases with the solar activity. As a consequence, the flux of charged CRs impinging on the Moon surface, and therefore also the flux of lunar gamma rays at Earth, is anticorrelated with solar activity. From Figure 2 we see that the gamma-ray flux from the Moon has reached a maximum at the end of 2019 and is now starting to decrease, while an increase in the sunspot number is observed, corresponding to the beginning of the 25th Solar Cycle.

References

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