The gamma-ray Moon seen by the Fermi LAT

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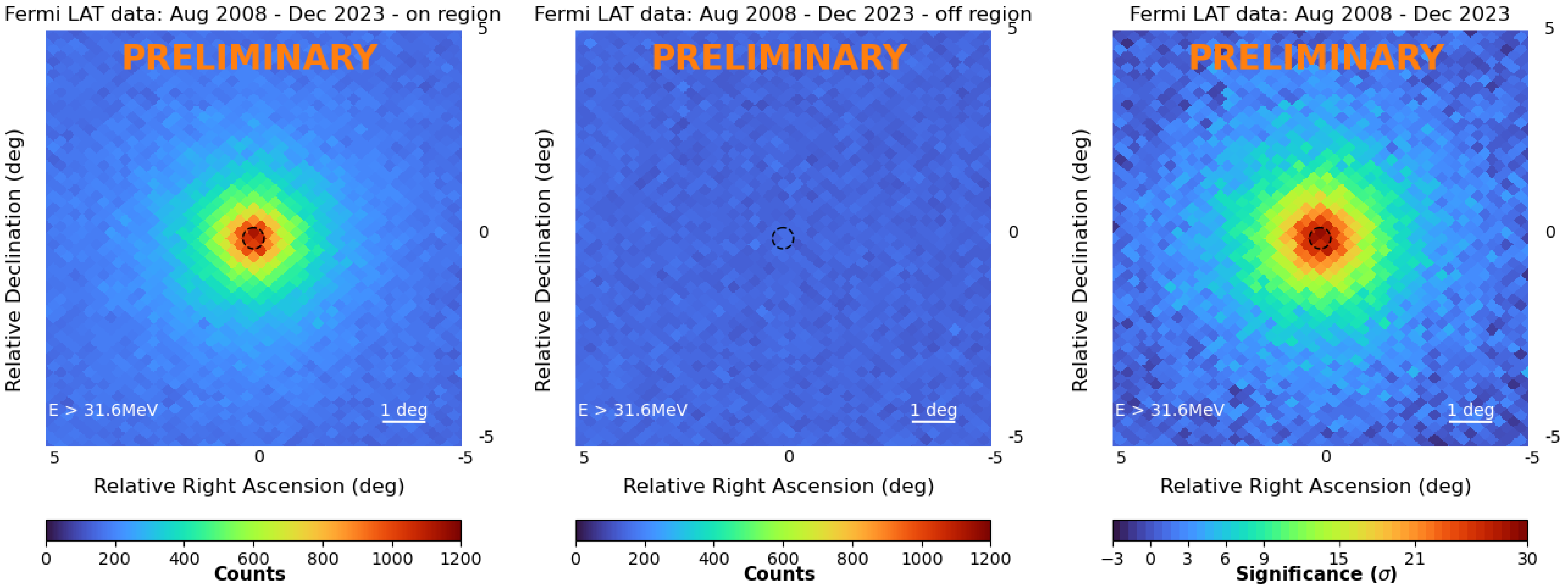
Gamma rays from the Moon

- The Moon is among the brightest sources in the gamma-ray sky
  - Gamma rays are produced in the hadronic interactions of cosmic rays with the regolith
- The gamma-ray flux from the Moon is sensitive to:
  - Cosmic-ray fluxes
  - Composition of the lunar surface
  - Mechanisms of the hadronic interactions
- The Fermi LAT has already measured the gamma-ray flux from the Moon using the data collected in its first 7 years of operation
  - For further details see Ackermann et al., PRD 93, 082001 (2016)
  - These results have been now updated using a 15.5-years dataset
- We have studied the time evolution of the lunar gamma-ray emission and its correlation with the solar activity

Data selection

- **Data sample:**
  - **Fermi-LAT Pass 8 SOURCE photon data with E>10 MeV**
  - **August 2008-December 2023**
  - **Same analysis procedure as in the 2016 PRD paper**
- **Signal region (Moon):**
  - **Cone centered on the Moon position with aperture** $\theta = \sqrt{[\theta_0 (E/E_0)^{-\delta}]^2 + \theta_{min}^2}$
    - $\theta_{min} = 1°, \theta_0 = 5°, E_0 = 100 MeV, \delta = 0.8$
    - **Reflects the energy dependence of the LAT PSF**
- **Background region (Time-offset Moon):**
  - **Cone centered on the time-offset Moon position, same aperture as the signal region**
  - **Time offset** Δt **= 14** $days$
- **Standard event selection cuts (details in the 2016 paper)**
  - **Moon outside the galactic plane:** $|b|$**>5°**
  - **Angular separation >20° between the Moon and the Sun and between the Moon and the brightest sources in the 4FGL catalog**
  - **Same selection cuts for the signal and background regions**

Count and significance maps



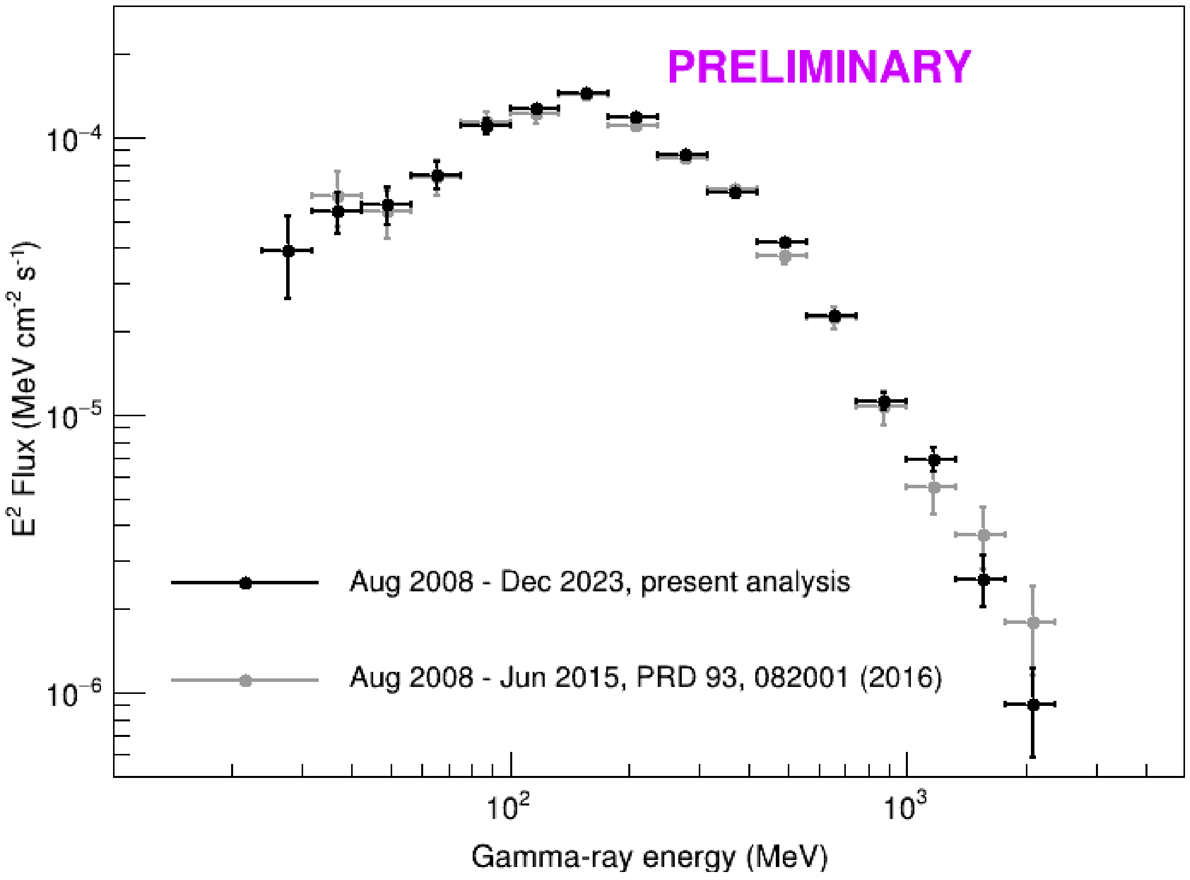
- **The significance map is built from the count maps in the signal and background regions with the Li&Ma approach, taking the different exposures into account**

Evaluation of the Moon gamma-ray energy spectrum

- The Moon is treated as a point source
  - The angular radius of the Moon is 0.25°
- The signal and background gamma-ray energy fluxes in each energy bin are evaluated by maximizing a Poisson likelihood function
  - The likelihood function is built from the photon counts in the Moon and in the time-offset Moon regions
    - Counts in the Moon region are originated from both signal and background gamma rays
    - Counts in the time-offset Moon region are originated from background gamma rays
  - The signal and background gamma-ray fluxes are reconstructed with a Bayesian procedure based on a Monte Carlo Markov Chain (MCMC) implemented in the software toolkit BAT

The Moon gamma-ray energy spectrum

- **The lunar gamma-ray emission is peaked at ~150 MeV and drops above 2 GeV**
- **No significant variations are observed with respect to previously published results**
  - **Present data cover ~1.4 solar cycles**
  - **Previous data covered ~0.65 solar cycles**



Gamma rays from the Moon and cosmic rays at Earth

- The intensity of gamma rays from the Moon is given by:

$$I_\gamma(E) = \sum_{i=p,He} Y(E|T_i) I(T_i) dT_i$$

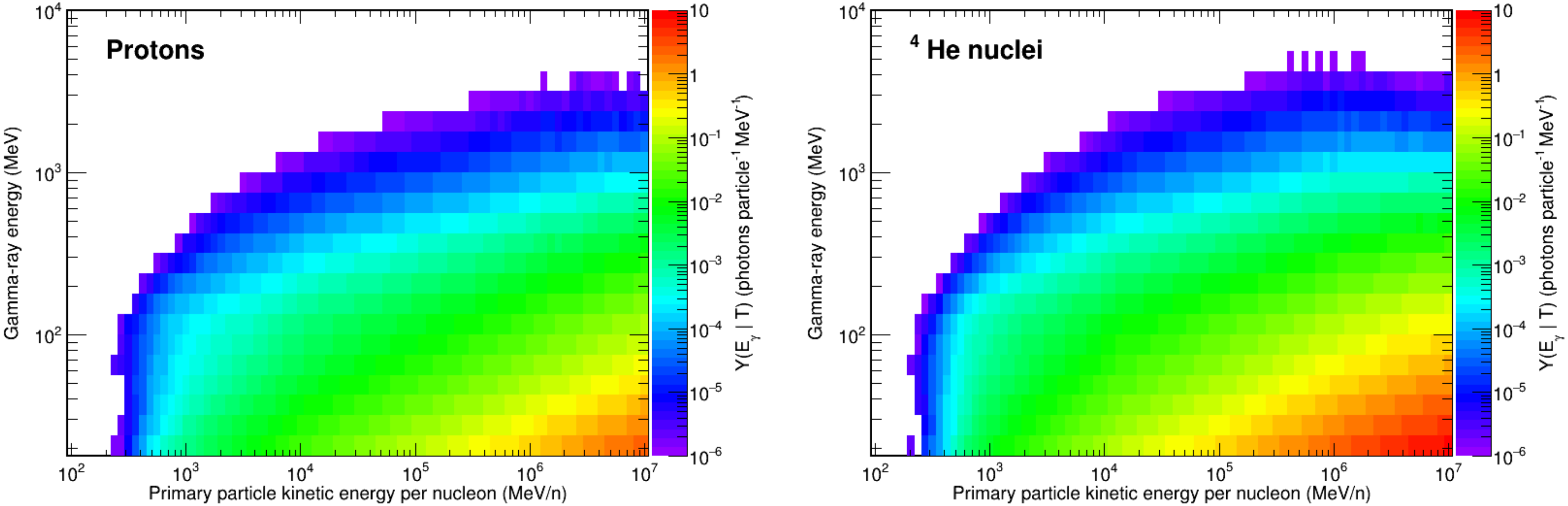
- The flux is given by:

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

  - $R = 1737km$ is the Moon radius, d is the Moon-LAT distance
  - $I(T_i)$ = intensity of CR particles of the i-th species ($i = p,\ {}^4He$) at the Moon
    - We assume that CR intensities at the Moon are the same as at the Earth
    - We use the p and ${}^4He$ intensities measured by AMS-02
  - $Y(E|T_i)$ = yield of gamma rays of energy E produced by the particles of the i-th CR species
    - The gamma-ray yields from p and ${}^4He$ interactions are evaluated using a simulation based on the FLUKA Monte Carlo code
      - In the present simulation the version 2024 1.0 is used
      - See http://www.fluka.org/fluka.php
    - The Moon is described as a sphere consisting of a mixture of 45% SiO_2, 22% FeO, 11% CaO, 10% Al_2O_3, 9% MgO, 3% TiO_2 with density $\rho = 1.8\ g/cm^3$(see PRD 93, 082001)

Gamma-ray yields from the Moon

Plots from PRD 93, 082001 (2016)

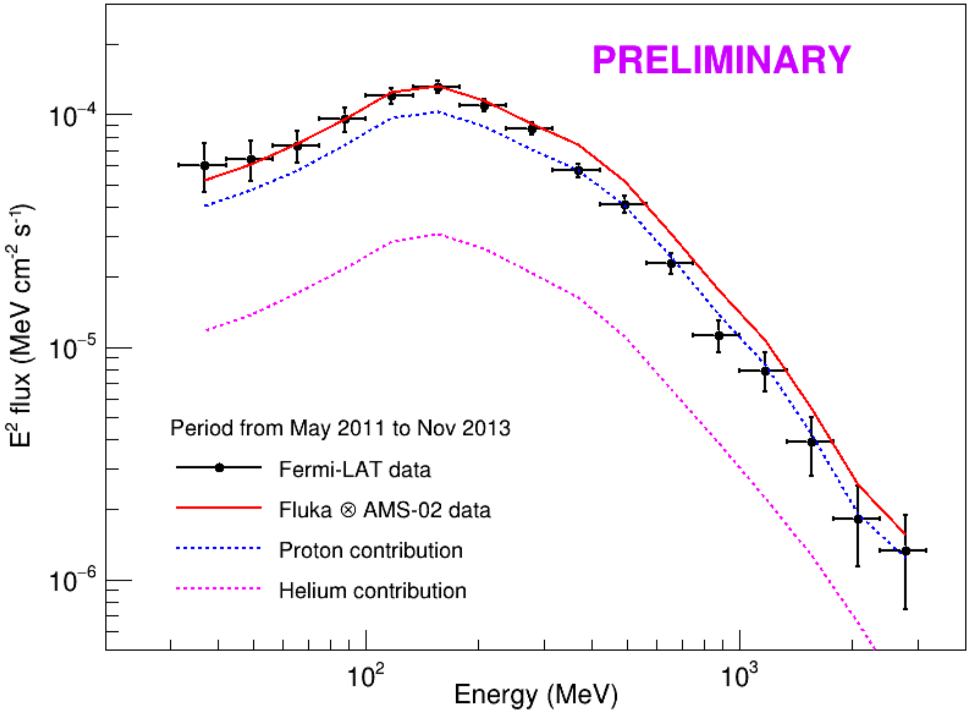


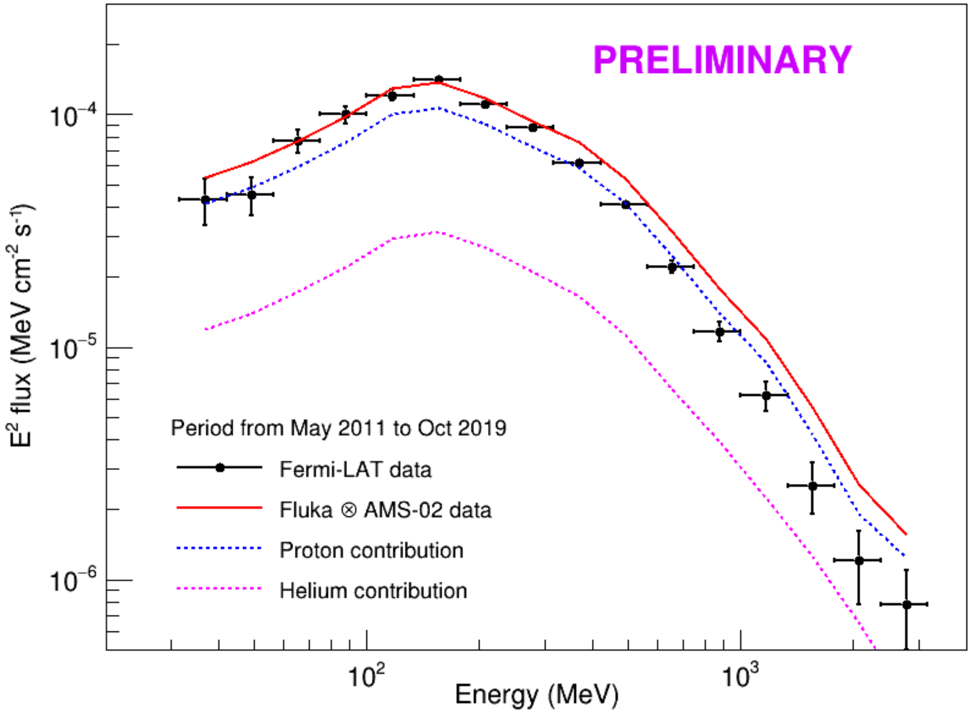
- **The yields have been evaluated with a full Monte Carlo simulation based on the FLUKA code**
  - **See http://www.fluka.org/fluka.php**

The AMS-02 and PAMELA datasets

- The AMS-02 data have been extracted from the SSDC cosmic-ray database https://tools.ssdc.asi.it/CosmicRays/
- AMS-02 provides p and ^{4}He fluxes on daily timescale in the period from May 20, 2011 to October 29, 2019 and extend to rigidities up to 100 GV
  - Missing data from Sepember 29, 2014 to November 29, 2014 (2 months) and from January 30, 2019 to March 05, 2019 (1 month)
    - The previous AMS dataset, used in the PRD paper, covered the period from May 20, 2011 to November 30, 2013
- PAMELA provides p and ^{4}He fluxes on time intervals corresponding to Carrington rotations in the period from the beginning of the LAT data taking on Aug 4, 2008 (CR 2072) to January 15, 2014 (CR 2145) and extend to rigidities above 500 GV
- AMS-02 and PAMELA data provide a benchmark for the Moon gamma-ray analysis

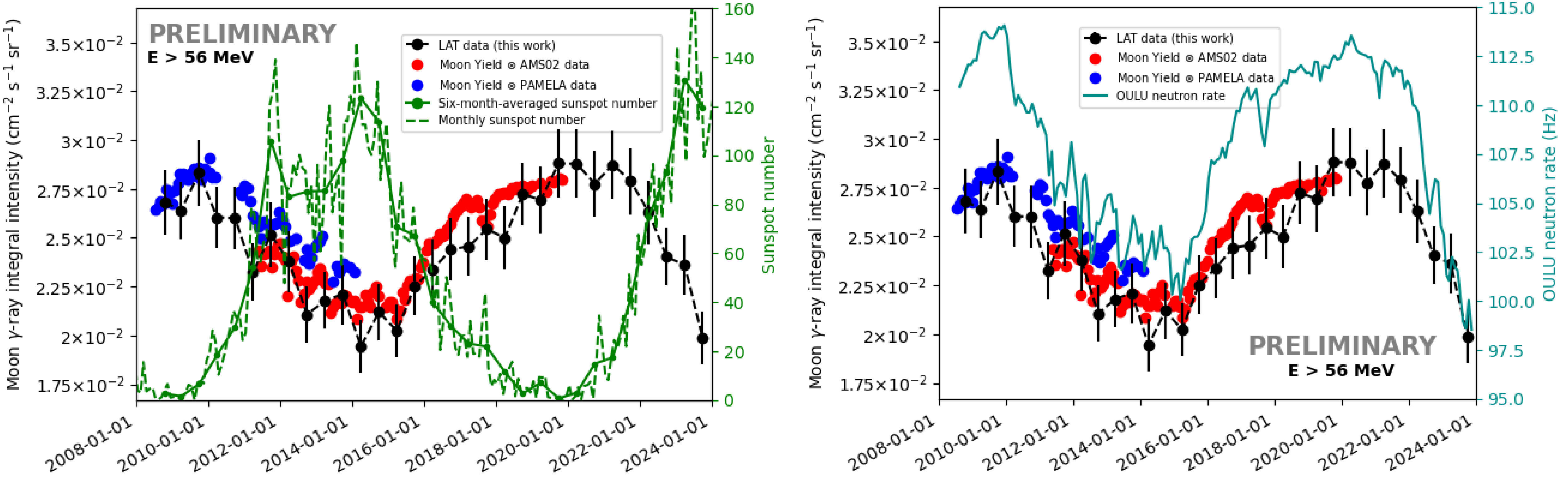
Comparison with the model





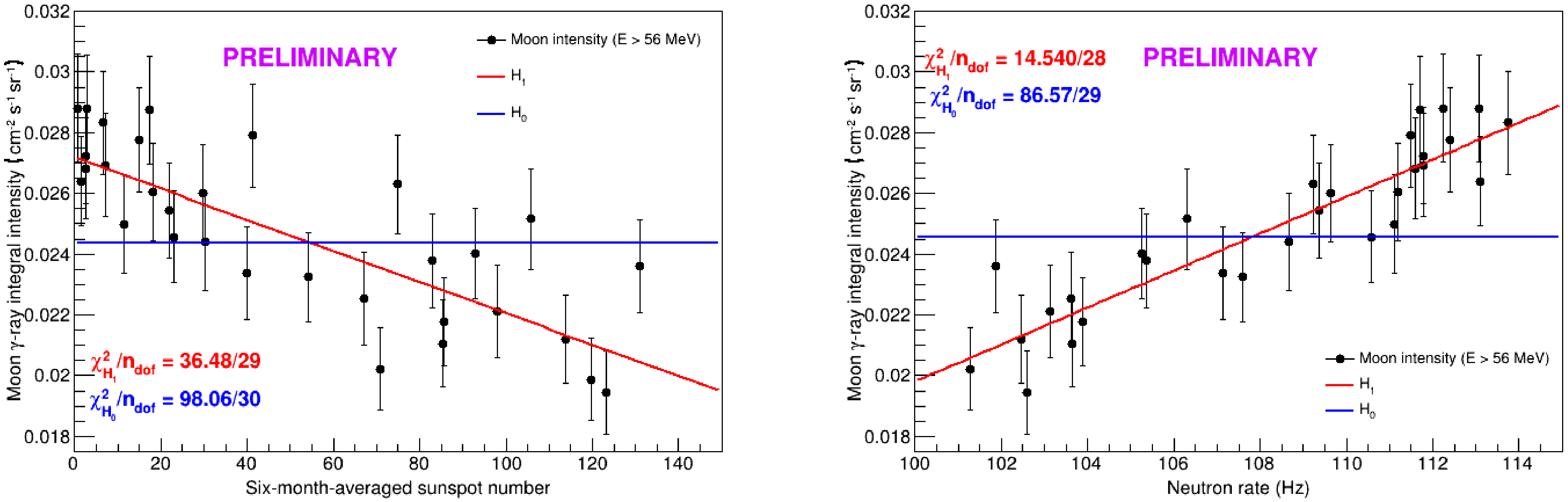
- **The data collected in the period May 2011-Nov 2013 are compared with MC predictions obtained by folding the p and ^{4}He spectra measured by AMS-02**
- **The simulation predicts a slightly higher flux than data at E>500 MeV**

Time evolution of the lunar gamma-ray flux



- **The Moon gamma-ray flux is evaluated in 6-months time intervals and is compared with the sunspot number and with the count rates of the Oulu neutron monitor**
  - **Sunspot number data taken from https://www.sidc.be/SILSO/datafiles**
  - **Oulu neutron monitor data taken from https://cosmicrays.oulu.fi/**

Correlation of the lunar gamma-ray emission with the solar activity



- **The intensity of the gamma-ray emission from the Moon is anticorrelated with the sunspot number and is correlated with the count rate observed by neutron monitors**
  - **Null hypothesis (H_0): constant Moon gamma-ray intensity**
  - **Alternative hypothesis (H_1): Moon gamma-ray intensity linearly dependent on sunspot number (neutron monitor count rate)**

Conclusions

- We have updated the measurement of the gamma-ray flux from the Moon using a 15.5-years dataset collected by the Fermi LAT
  - The observation period covers ~ 1.4 solar cycles, including two minima and two maxima
  - The average Moon gamma-ray fluxes are not significantly changed from the previously published LAT data analysis with a 7-years data sample
- We have studied the time evolution of the lunar gamma-ray emission
- The lunar gamma-ray flux is anticorrelated with the solar activity
- The trend of data is in agreement with the predictions obtained by folding the spectra of cosmic-ray protons and ^{4}He nuclei measured by AMS-02 and PAMELA with the gamma-ray yields evaluated with a MC simulation based on the FLUKA code

BACKUP

Likelihood function

- **The gamma-ray fluxes in each energy bin are evaluated from the counts in the signal and in the background regions by maximizing a Poisson likelihood function:**

$$\mathcal{L}(\vec{\phi}_s, \vec{\phi}_b; \vec{n}_s, \vec{n}_b) = \prod_{i=1}^{N} e^{-\mu_s(E_i)} \frac{\mu_s(E_i)^{n_s(E_i)}}{n_s(E_i)!} \prod_{i=1}^{N} e^{-\mu_b(E_i)} \frac{\mu_b(E_i)^{n_b(E_i)}}{n_b(E_i)!}$$

  - **Observed counts:** $\vec{n}_s = \{n_s(E_1), n_s(E_2), \ldots., n_s(E_N)\}$ **and** $\vec{n}_b = \{n_b(E_1), n_b(E_2), \ldots., n_b(E_N)\}$
  - **Expected counts:** $\vec{\mu}_s = \{\mu_s(E_1), \mu_s(E_2), \ldots., \mu_s(E_N)\}$ **and** $\vec{\mu}_b = \{\mu_b(E_1), \mu_b(E_2), \ldots., \mu_b(E_N)\}$

- **The expected counts depend on the signal and background fluxes and are given by:**

$$\mu_b(E_i) = \sum_{j=1}^{N} P_b(E_i|E_j)\phi_b(E_j) A t_b \Delta E_j$$

$$\mu_s(E_i) = \sum_{j=1}^{N} P_s(E_i|E_j)[\phi_s(E_j) + \phi_b(E_j)] A t_s \Delta E_j$$

  - t_s **and** t_b **are the live times of the two regions**
  - $P_s(E_i|E_j)$ **and** $P_b(E_i|E_j)$ **incorporate the IRF and the pointing history of the LAT**
  - $A = 6m^2$ **is the cross section of the sphere used for event generation in the MC simulation**