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Fermi LAT observation of the Moon

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The gamma-ray Moon

- The Moon is among the brightest sources in the gamma-ray sky
- Lunar 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 PRD 93, 082001 (2016)
- The previous results have been now updated using a 14-years dataset
  - The observation period exceeds the duration of a solar cycle

Data selection (1/2)

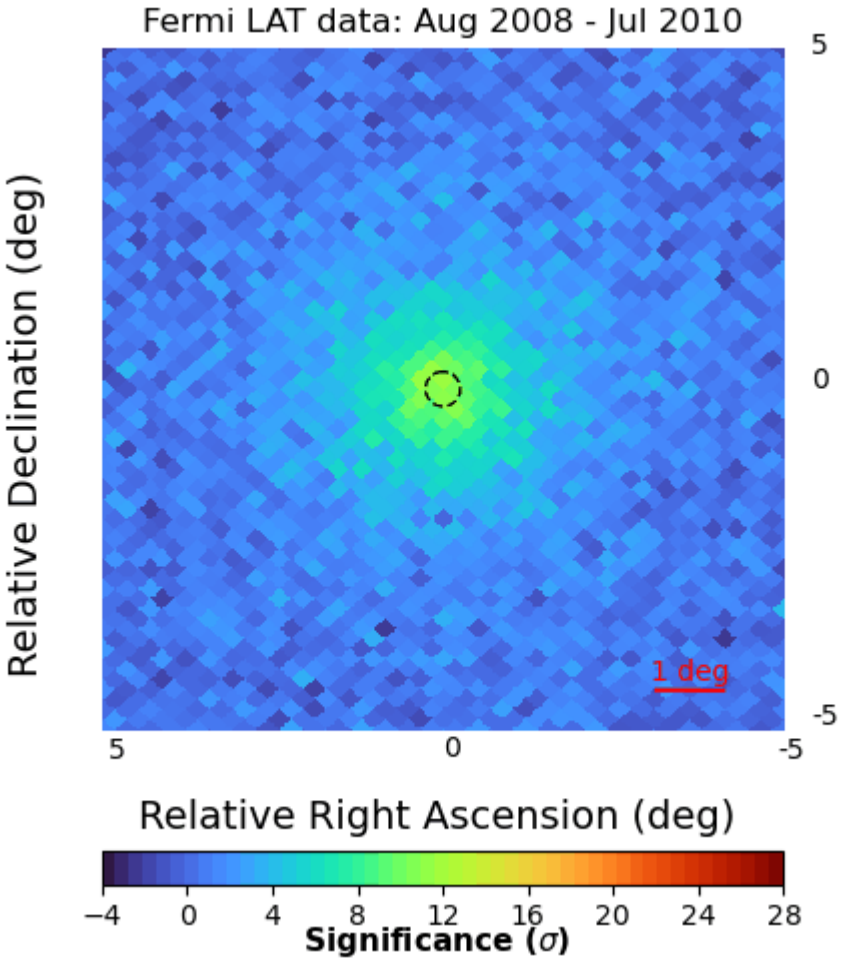
- Data sample:
  - Fermi-LAT Pass 8 SOURCE photon data with E>10 MeV
  - August 2008-June 2022
- Signal region:
  - Cone centered on the Moon position
  - Angular radius $\theta = \sqrt{[\theta_0 (E/E_0)^{-\delta}]^2 + \theta_{min}^2}$
    - $\theta_{min} = 1°, \theta_0 = 5°, E_0 = 100 MeV, \delta = 0.8$
    - Reflects the energy dependence of the LAT PSF
- Background region:
  - Cone centered on the time-offset Moon position
  - Time offset $\Delta t = 14\ days$
  - Same angular radius as the signal region

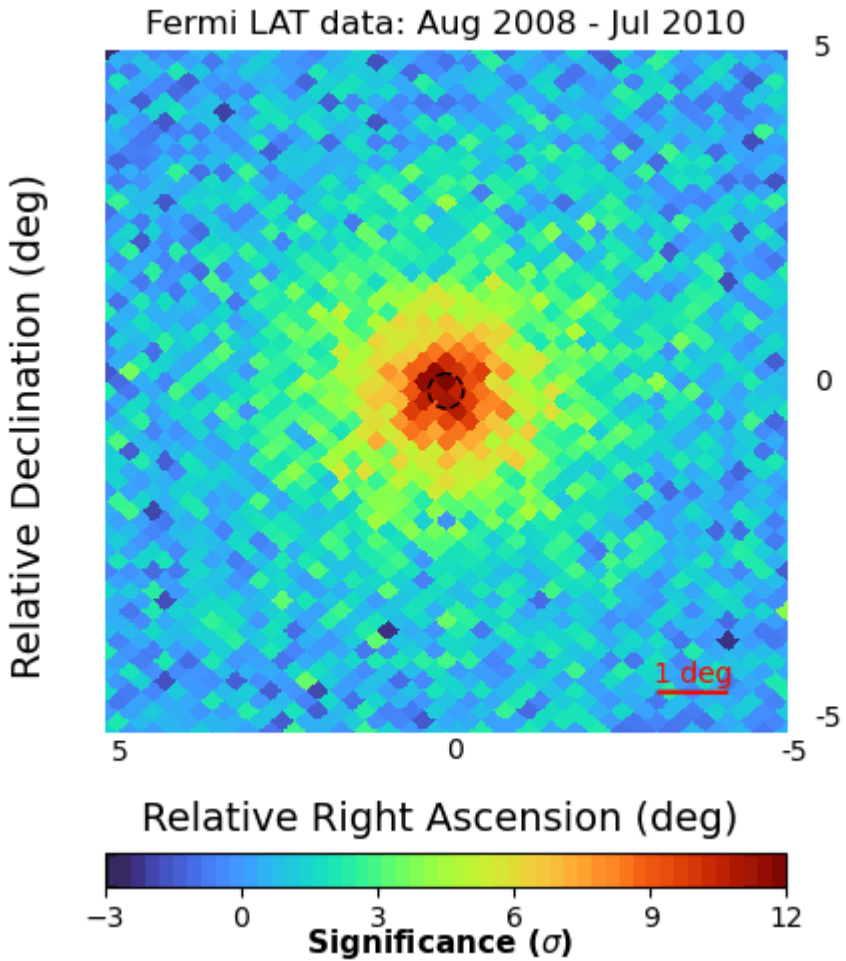
Data selection (2/2)

- Event selection:
  - LAT in standard science operation configuration and outside the SAA
  - angular separation $< 100°$ between a cone of $15°$ radius centered on the Moon direction and the zenith direction
  - Moon observed with off-axis angle $< 66.4°$
  - 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
  - Same selection cuts for the signal and background regions

Significance maps of the Moon

- The significance maps are built from the counts in the signal and background regions with the Li&Ma approach
  - The significance increases as the time interval increases
  - The significance evaluated over 2-years time intervals changes due to solar modulation





Reconstruction of the gamma-ray energy spectrum

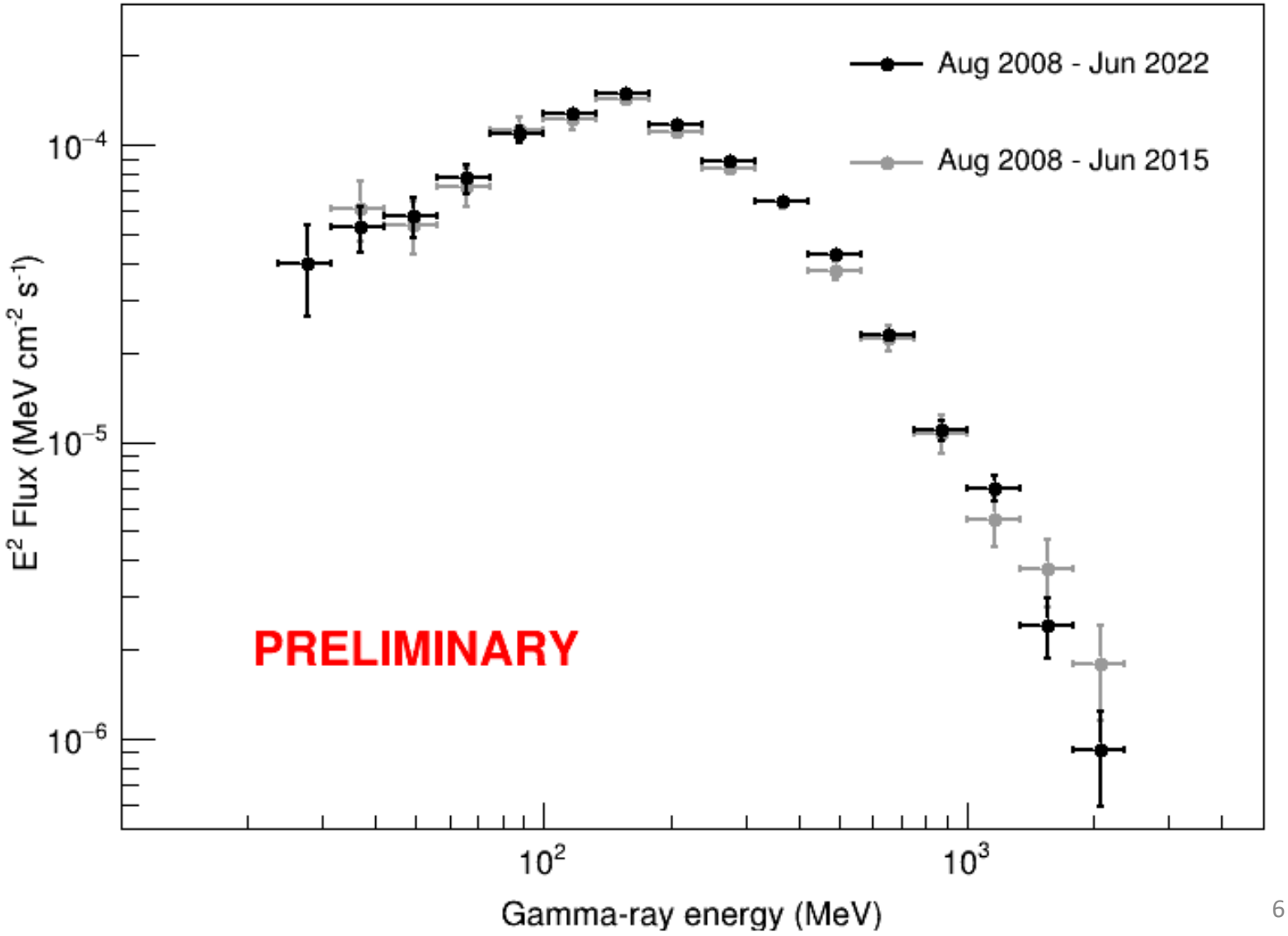
- The gamma-ray fluxes are evaluated from the counts in the signal and in the background region by maximizing a Poisson likelihood function:

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

  - 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 are given by:
  - $\mu_b(E_i) = \sum_{j=1}^{N} P_b(E_i|E_j)\phi_b(E_j)At_b\Delta E_j$
  - $\mu_s(E_i) = \sum_{j=1}^{N} P_s(E_i|E_j)\left[\phi_s(E_j) + \phi_b(E_j)\right]At_s\Delta E_j$
    - t_s and t_b are the signal and background live times
    - $P_s(E_i|E_j)$ 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
- The signal and the background 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 spectrum

- The lunar gamma-ray emission is peaked at ~150 *MeV*
- No significant variations are observed with respect to previously published results



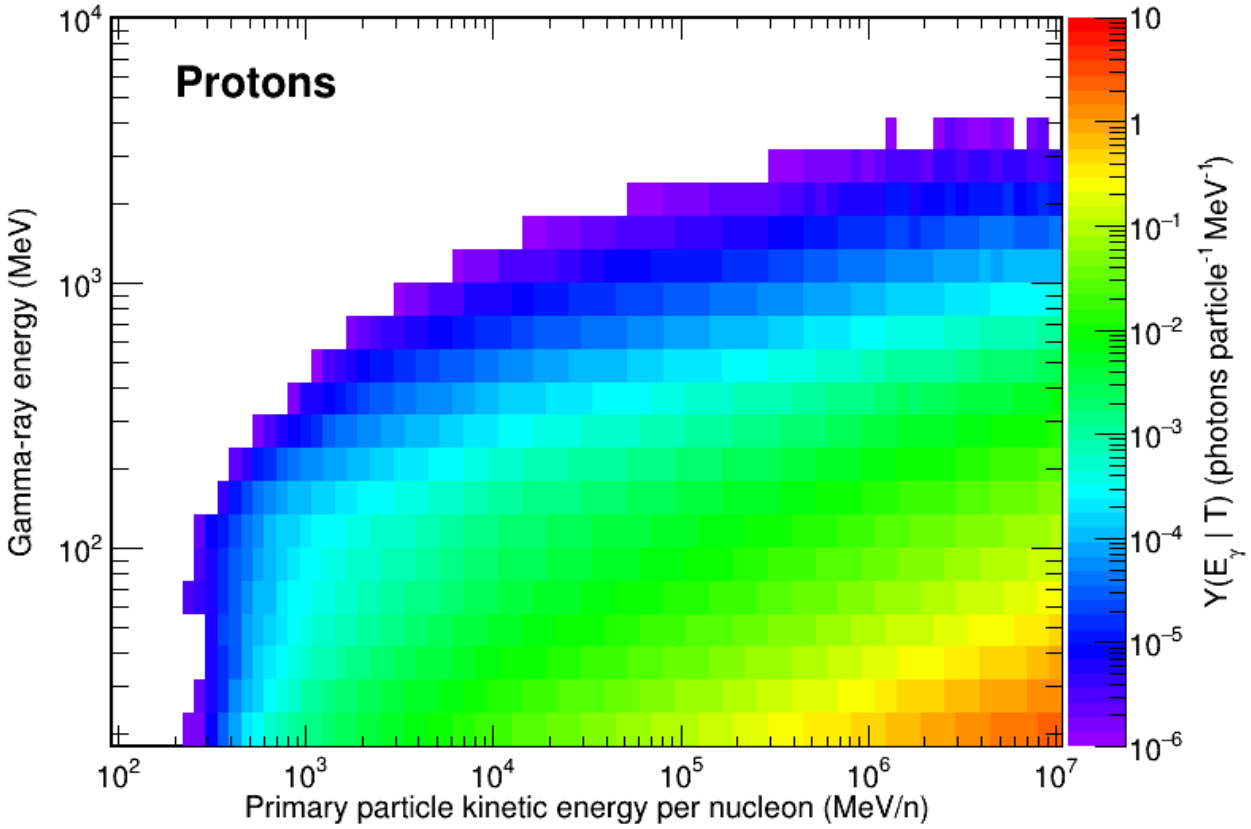
Evaluation of the expected gamma-ray fluxes

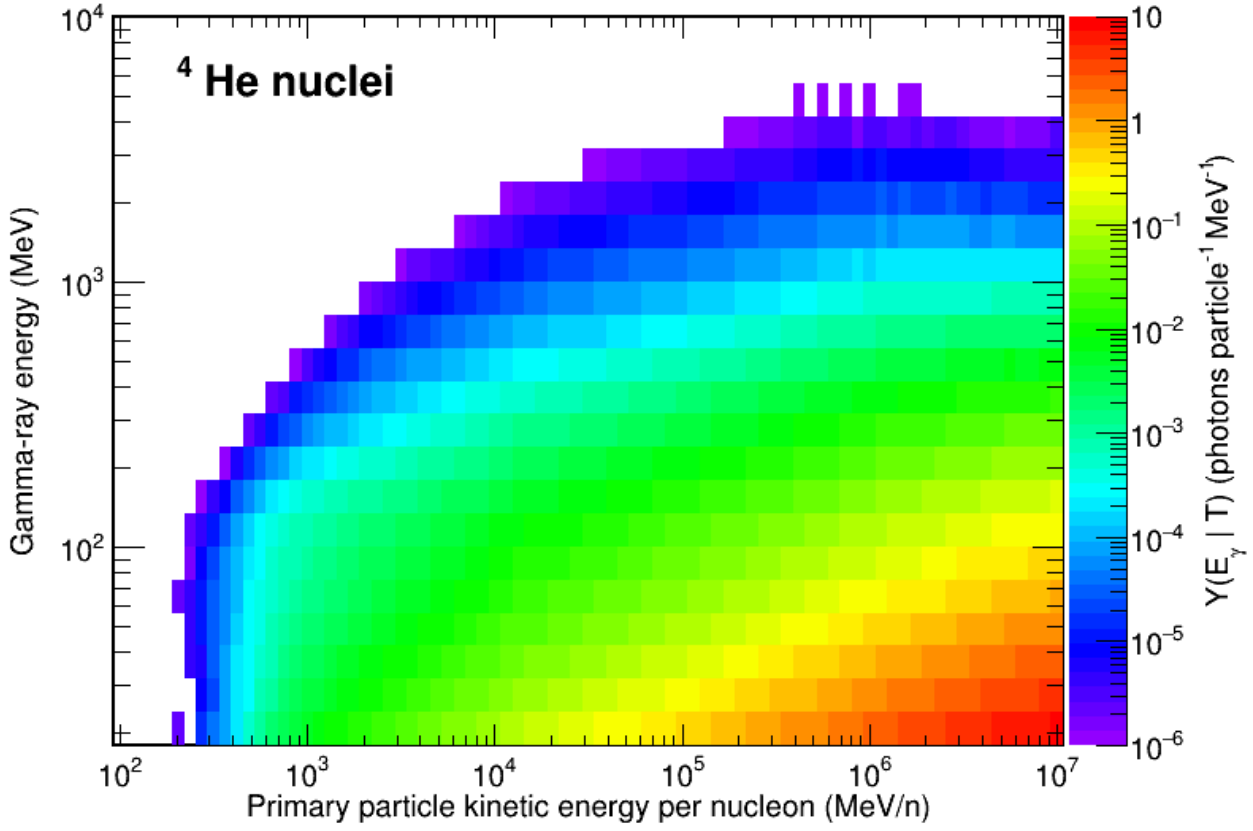
- The lunar gamma-ray flux is given by:

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

  - $R = 1737 km$ is the Moon radius
  - d is the Moon-LAT distance
    - It is known from the LAT pointing history
  - $I(T_i)$ = intensity of CR particles of the i-th species
    - We use the p and ^{4}He 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 ^{4}He interactions are evaluated using a simulation based on the FLUKA Monte Carlo code
    - 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 a density $\rho = 1.8\ g/cm^3$ (see PRD 93, 082001 (2016))

Gamma-ray yields from protons and ^{4}He nuclei



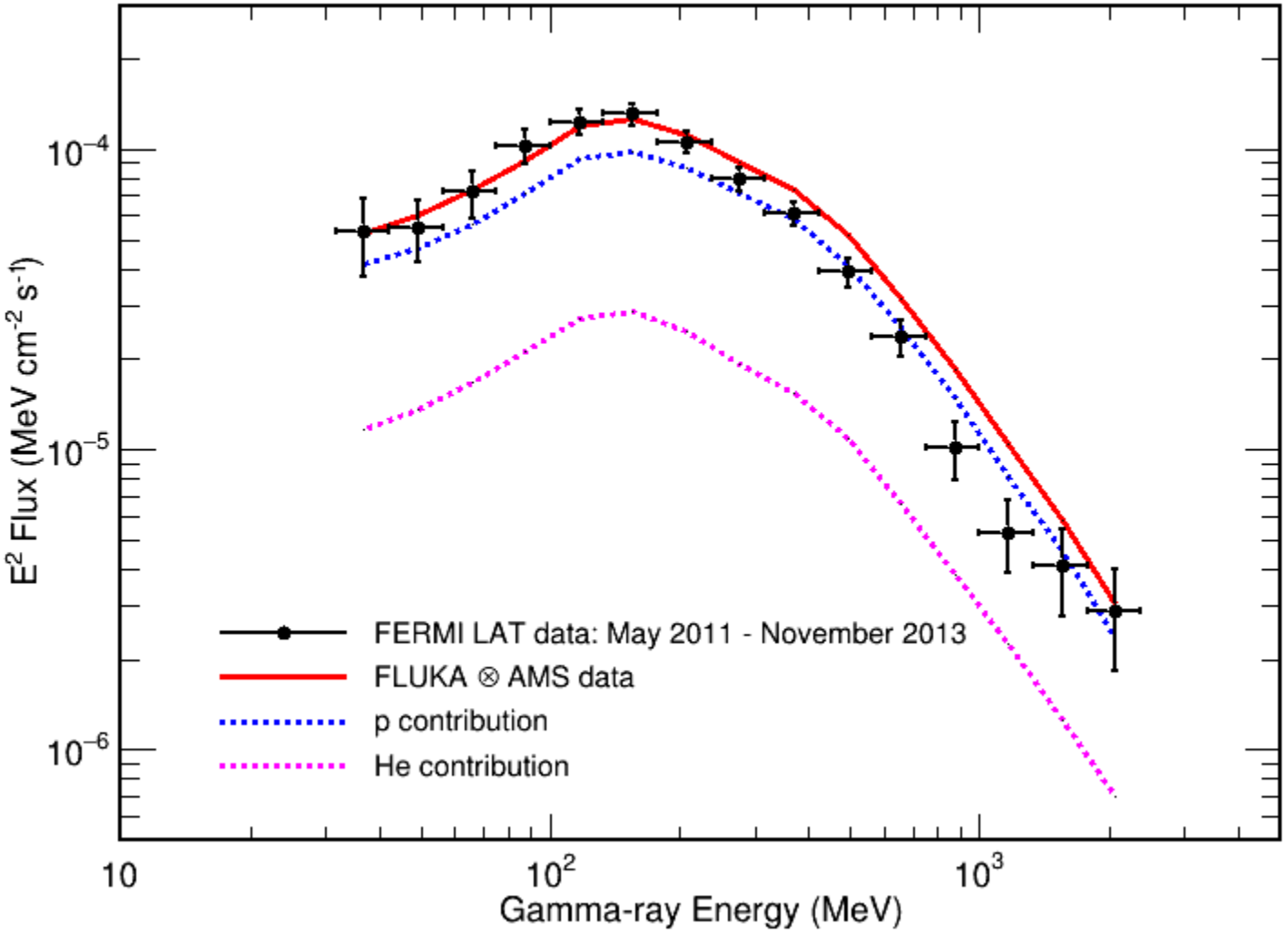


Plots from PRD 93, 082001 (2016)

Data-model comparison

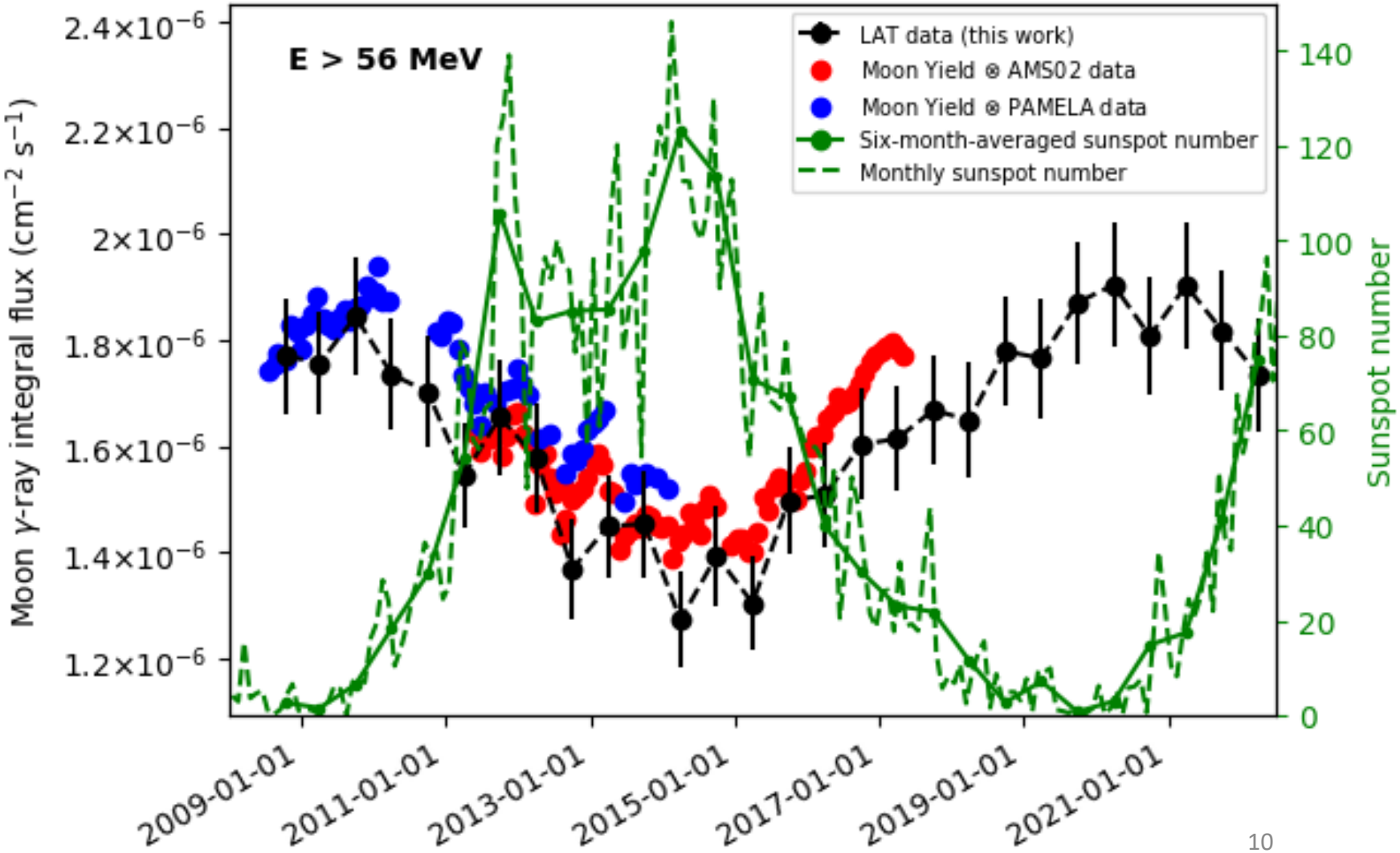
- The data collected in the period May 2011-Nov 2013 are compared with MC predictions obtained by folding the p and ^{4}He spectra measured by AMS-02 with the gamma-ray yield evaluated with FLUKA

Plot from PRD93, 082001 (2016)



Time evolution of the lunar gamma-ray flux

- The Moon gamma-ray flux is evaluated in 6-months time intervals and compared with the model predictions based on CR measurements
- Predictions are obtained by folding the AMS-02 and PAMELA data with the gamma-ray yields evaluated with FLUKA
- The Moon gamma-ray flux is anticorrelated with the solar activity



Conclusions

- We have updated the measurement of the gamma-ray flux from the Moon using a 14-years dataset collected by the Fermi LAT
  - The observation period exceeds the duration of a whole solar cycle
- 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 measurements are in agreement with the predictions obtained by folding the measured spectra of cosmic-ray protons and ^{4}He nuclei with the gamma-ray yields evaluated with a MC simulation based on the FLUKA code