Global Spline Fit (GSF) 2024

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Introduction

The cosmic-ray flux is used as an input to calculate the atmospheric neutrino flux, so it is important to quantify the uncertainty of the cosmic-ray flux reflecting the experimental uncertainties.

The **Global Spline Fit (GSF)** [1] is a **data-driven model of the cosmic-ray flux and mass composition.** The GSF combines direct and indirect measurements of cosmic rays from 1 GeV to 10^{11} GeV **considering their uncertainties**.

In this work, we **update the GSF with recent experimental data**.

Dataset

References of updated/new data are shown in **bold**.

Data set 1

ACE-CIRS [2]*	ISS-CREAM [**10**]	HESS [19]	TUNKA [25, 26]
HEAO [3]**	NUCLEON-KLEM (NK) [**11**, **12**]*	VERITAS [**20**]	IceCube [27, 28]
PAMELA [4, 5]	CALET [**13**, **14**, **15**]*	HAWC [**21**, **22**]	KASCADE Grande [29]
AMS-02 [**6**, **7** ,**8** ,**9**]	DAMPE [**16**, **17**, **18**]	GRAPES-3 [**23**]	TA [30, 31]
		LHAASO [**24**]	Auger [**32**, **33**, **34**, 35]

* Fe of ACE-CRIS, Fe-group elements of NK, B, C, O and Fe of CALET are in tension with AMS-02 data, and they are not included in Data set 1 but included in Data set 2.

** For a given element, use AMS-02 measurements if available; otherwise, use HEAO measurements. In Data set 2, all HEAO measurements are used instead of AMS-02.

- To demonstrate the impacts and assess the mutual combability of new data, four variant data sets are prepared in addition to the Data set 1:

Data set 2:
+) CREAM I+III (proton, He) [36]
-) ISS-CREAM, CALET, DAMPE, NK, GRAPES-3

Data set 3:
+) all HEAO, ACE-CRIS (Fe), CALET (B, O, C, Fe, Ni) [**37**, **38**, **39**, **40**], NK (Ne, Mg, Si, Fe, Ni) [**41**]
-) AMS-02

Data set 4:
-) LHAASO

Data set 5:
Use the same Auger data [42] as GSF 2019, the previous model presented in [43], instead of that used in Data set 1.

Method

- Flux of leading elements L of four mass groups (p, He, O*, Fe*) are described with smooth spline curves.

Flux of leading element L : $$J_L(R) = (R/\mathrm{GV})^{-3} \sum_k \underbrace{a_{Lk}}_{\text{amplitude}} \underbrace{b_k(\ln(R/\mathrm{GV}))}_{\text{spline curve}}$$

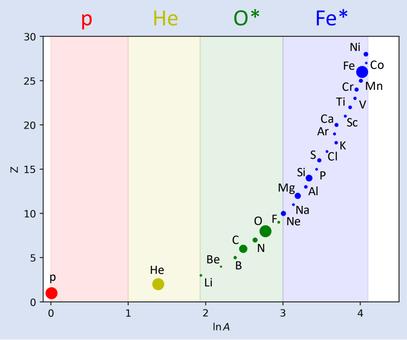
- Other elements flux in a group are kept constant at high energies where mass-group fractions are measured.

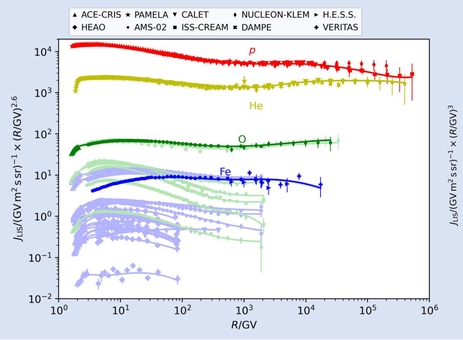
Total flux : $$J(E) = \sum_L \sum_j \underbrace{w_{Lj}}_{\text{flux ratio}} J_L\left(R_j(E)\right) \left(\frac{\mathrm{d}R}{\mathrm{d}E}\right)_j$$

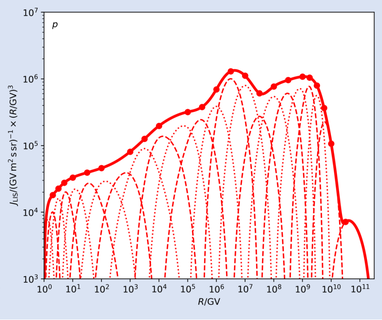
- Energy-scale offset z_E is introduced to adjust energy-scale of each experiment.
- Fitting to minimize the residual S, which consists of flux residuals, <lnA> residuals (of LHAASO data), and the energy-scale offset residuals.

$$S = \underbrace{\sum_i z_i^2}_{\substack{\text{Flux and <lnA>} \\ \text{residuals}}} + \underbrace{\sum_j \left(\frac{z_{E_j}}{(\sigma[\mathrm{E}]/E)_j}\right)^2}_{\substack{\text{Energy-scale offset} \\ \text{residuals}}}$$

- Experimental uncertainties are propagated to the model uncertainty with covariance matrix.



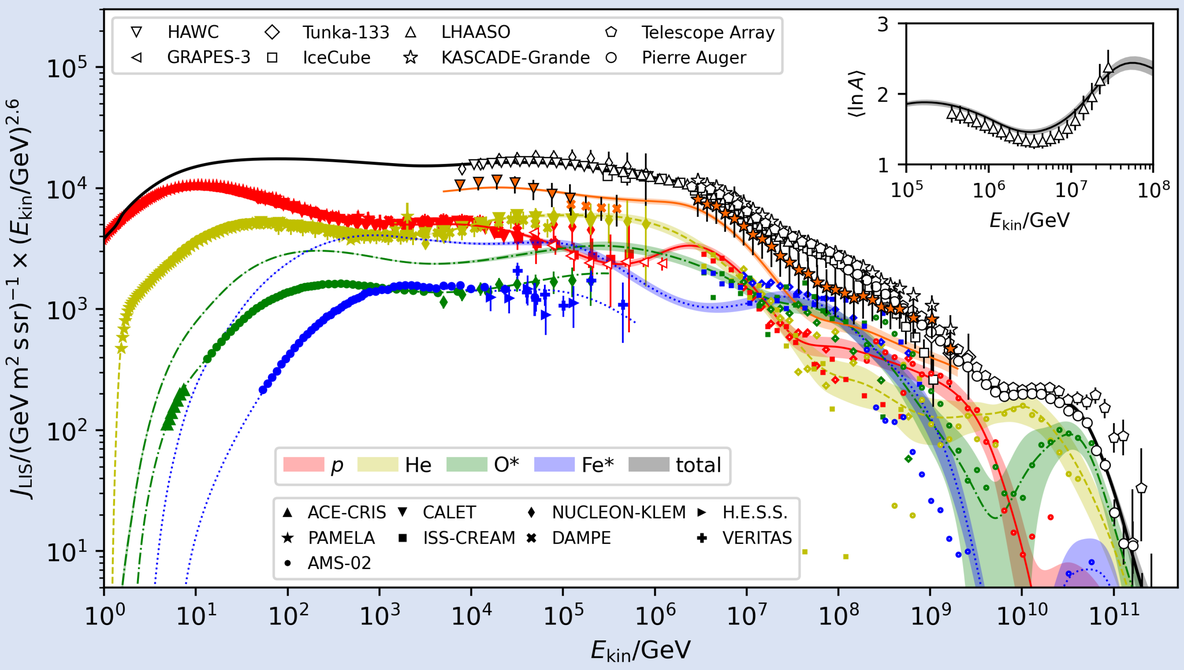




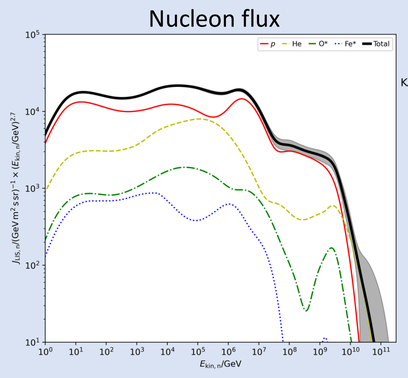
Results

GSF 2024 model (Data set 1)

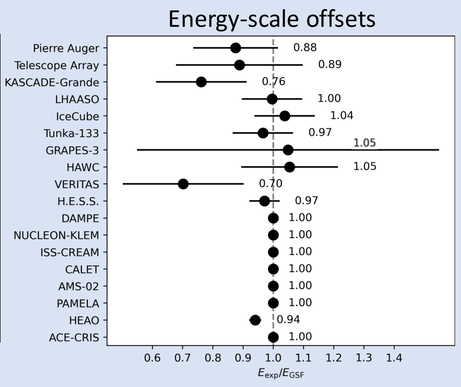
χ^2/ ndf = 1034 / 1072 = 0.96



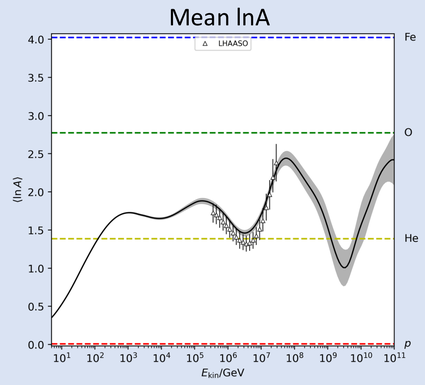
Nucleon flux



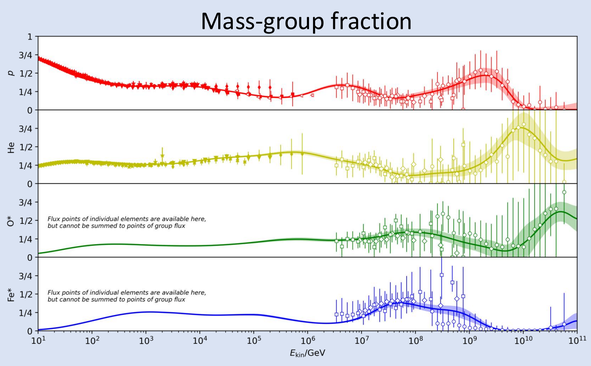
Energy-scale offsets



Mean lnA



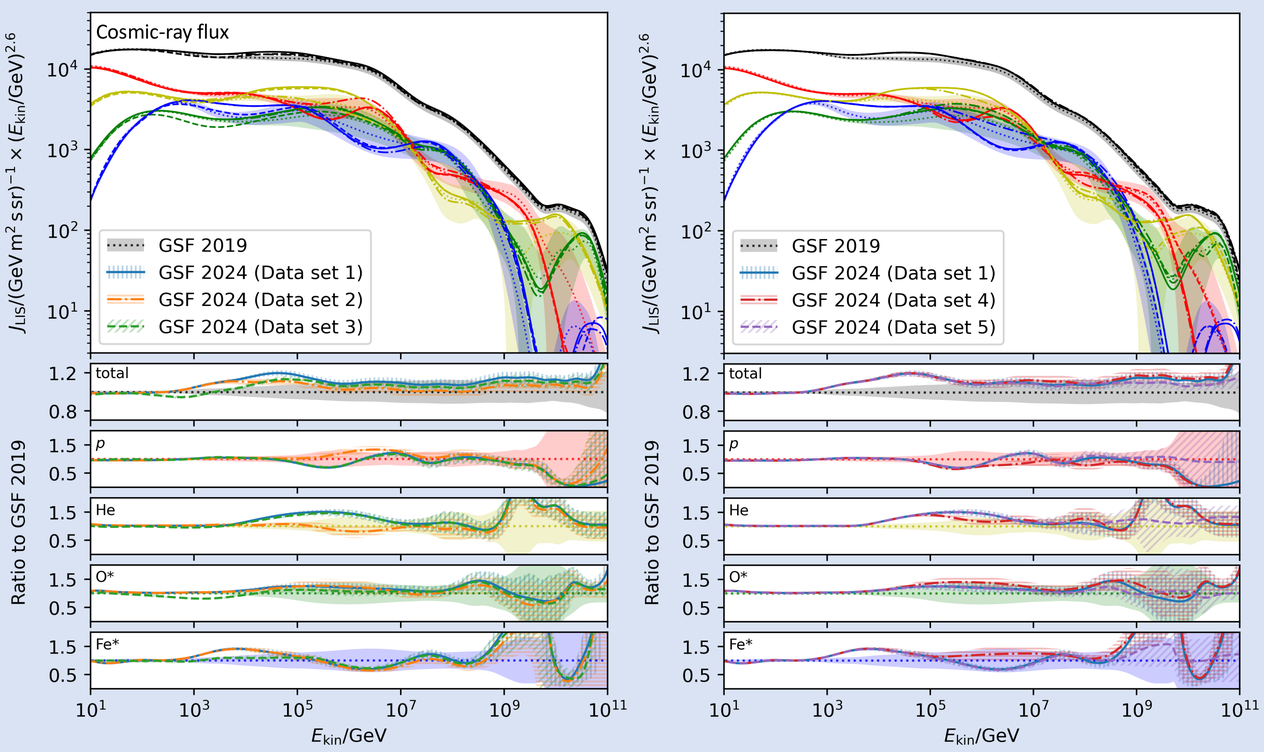
Mass-group fraction

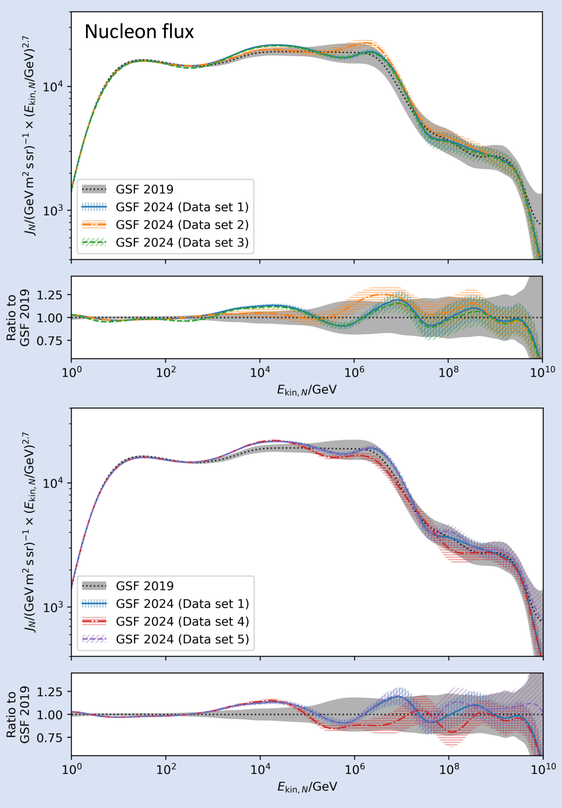


- New data from 100 GeV to PeV (Data set 1 vs. 2):
  - Spectrum hardening around 300 GV and softening around tens of TV for proton and helium.
  - These result in new features in the nucleon flux: bump around 10 TeV/n and dip around hundreds of TeV/n.
- New AMS-02 data (Data set 1 vs. 3):
  - Higher flux of heavy elements compared with GSF2019.
- LHAASO (Data set 1 vs. 4):
  - Lighter mean lnA at the knee.

Model comparisons

"GSF 2019" is the previous GSF model presented in [43].





Summary

- Updates the Global Spline Fit [1], a data-driven model of cosmic ray flux and mass composition, with recent data sets.
- The overall features of the spectra of the previous model re confirmed with the updated fit
- Smaller uncertainties reflecting recent precise cosmic-ray measurements.
- New features in cosmic-ray flux and nucleon flux.

Outlook

- Further study on the impact of new measurements.
- Calculate the atmospheric neutrino flux with the updated GSF model.
- Publish the updated GSF model and provide code for download.

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