Galactic cosmic ray studies with the DAMPE space mission

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3rd year activity report
10/10/2024

Overview

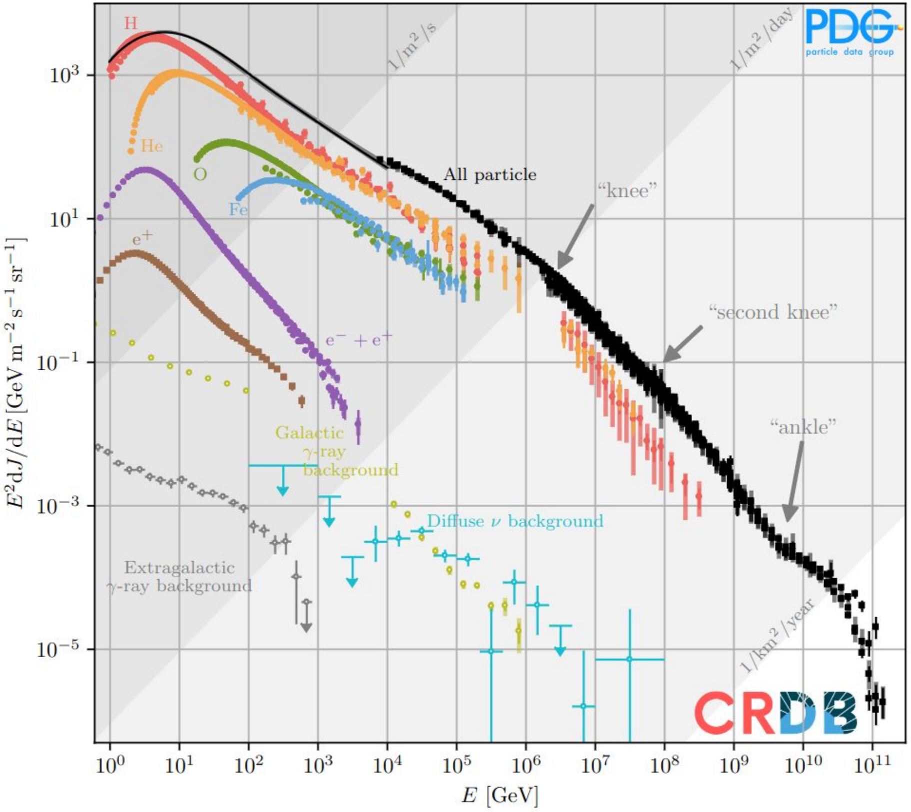
Measurements of CRs spectra with DAMPE:

- The relevance of the all-particle spectrum
- The DAMPE space mission
- Analysis and a preliminary result
- Next short-term and long-term project activities

Hardware R&D of the HERD PSD:

- the HERD future space mission
- Activities on the PSD hardware

The all-particle spectrum towards the knee



The all-particle spectrum up to ~1 PeV

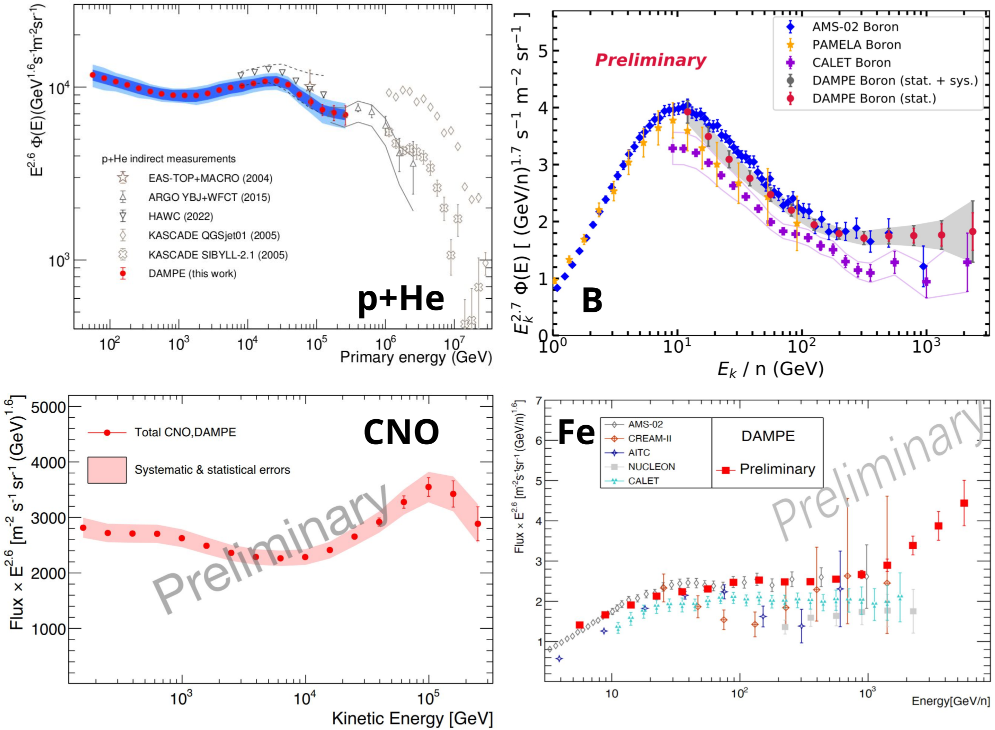
- Space-based and ground-based measurements can overlap:
  - establish a **link**
  - **cross-calibration** with ground-based measurements (normalization)
- Combine all particle species using a **loose charge cut selection**
  - to **minimize cross-contamination** among individual element spectra
  - to **increase the statistics and reach higher energies** wrt individual nuclei spectra

The DAMPE space mission

- Collaboration of Chinese, Italian and Swiss scientific institutions
- Launched on 17 December 2015

Acceptance	>0.1 m^2sr
Energy resolution	1.2% at 100 GeV (e/γ) < 40% at 800 GeV (nuclei)
e/γ angular resolution	0.2° at 100 GeV
Detection	20 GeV - 10 TeV (e/γ) 50 GeV - 400 TeV (nuclei)

- The primary scientific goals:
  - Study of (e- + e-), CD protons and nuclei spectra
  - HE gamma ray astronomy
  - Indirect search of DM signatures



The DAMPE detector

Plastic Scintillator Detector (PSD)

- **Charge** measurement + **anti-coincidence** for γ ID
- 4 layers of PS bars (2 Y & 2 X oriented)

Silicon TracKer (STK)

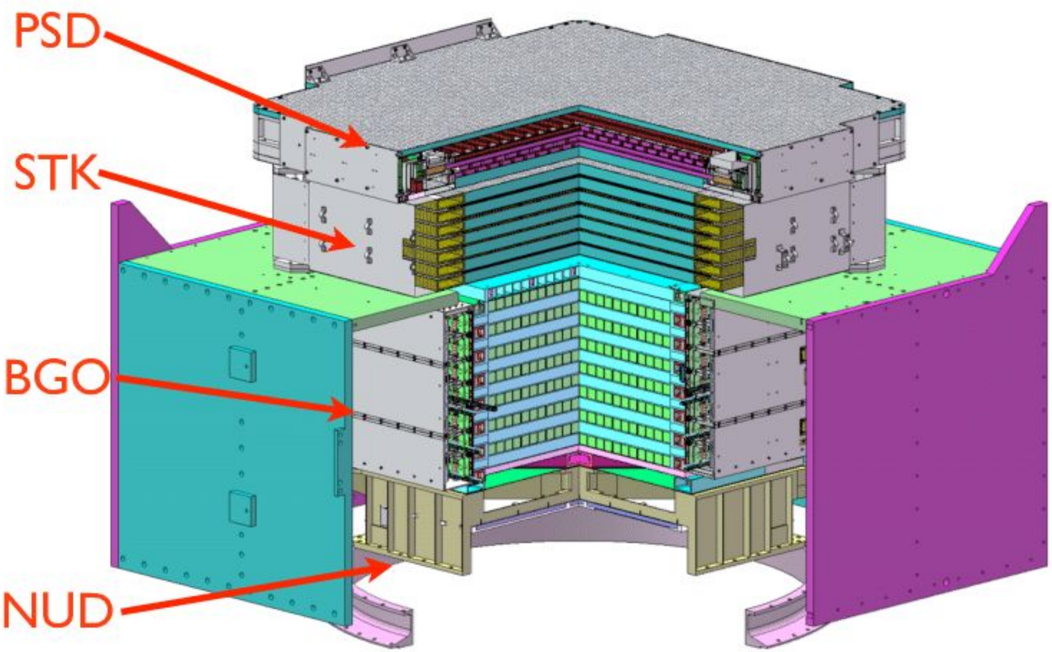
- **Track** reconstruction + additional **charge** measurement
- 6 planes of Si microstrip detectors + 3 W layers

BGO calorimeter (BGO)

- **Energy** measurement + **em/had showers** discrimination
- 14 layers of BGO crystal bars
- 32 X_0 and 1.6 λ_I

NeUtron Detector (NUD)

- Further em/had showers separation
- 4 boron-doped scintillator tiles



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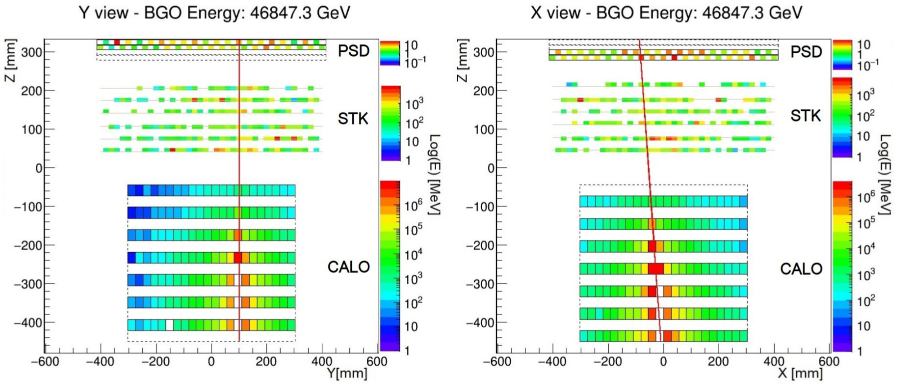
Analysis selection & procedure

Primary goal: not use charge cut selection to increase the statistics (& the energy reach)



Experimental data

- 8 years of flight data (01/2016 - 12/2023)
- Total live time ~1.9 10^8 s

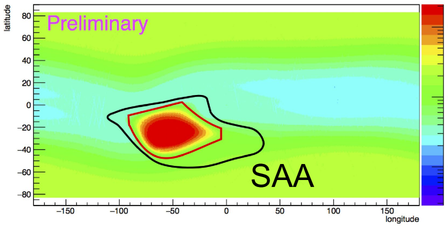
Monte-Carlo simulations

- p, He, C, O, Ne, Mg, Si, Fe
  - [100 GeV - 500 TeV] range
  - GEANT4v4.10.5 with FTFP_BERT and EPOS-LHC
- Assumed a mass composition model
  - To build the weighted mean acceptance and response matrix
  - Different models considered to evaluate the model dependence of the output spectra

In a first investigation

No charge selection + No composition model assumption

Significant differences in the detector response between light & heavy nuclei

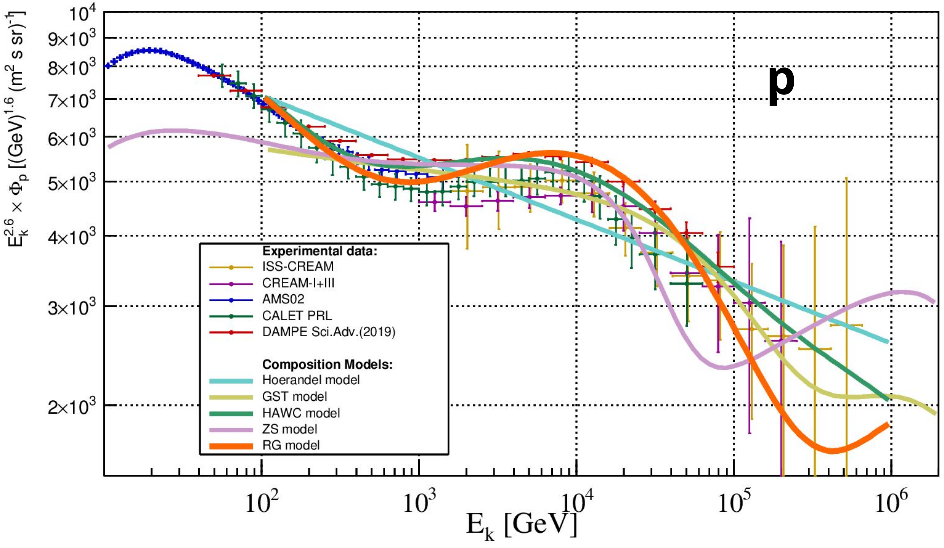


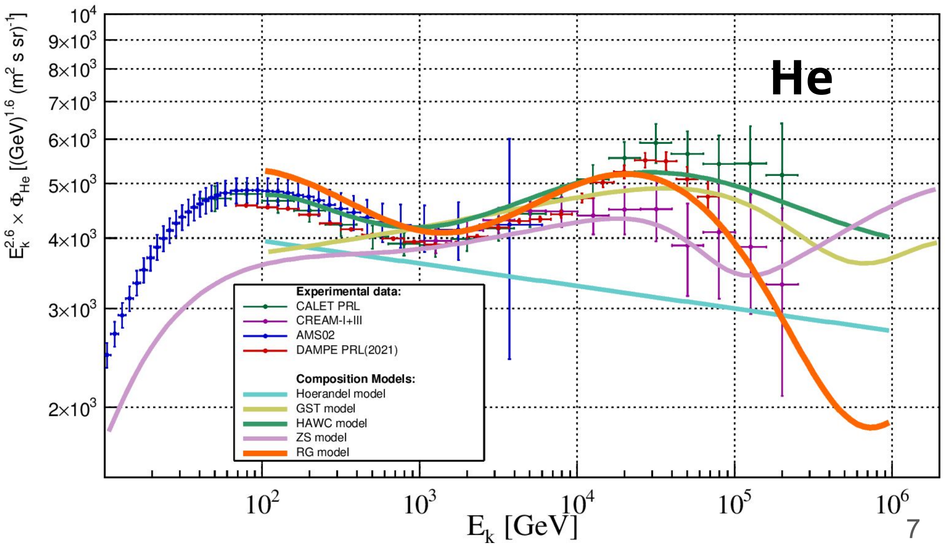
Selection cuts

- SAA exclusion
- E_{depo} in each BGO layer < 35% E_{BGO}
- HET trigger ON
- E_{BGO} > 100 GeV
- BGO fiducial cuts
  - Reconstructed shower axis inside the fiducial volume
  - ∀ layer: max E_{depo} inside the fiducial volume
- No charge/track selection cuts

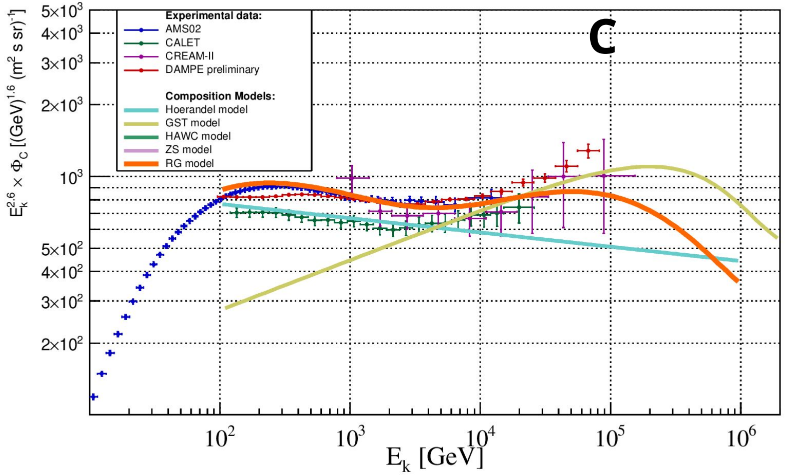
Composition models

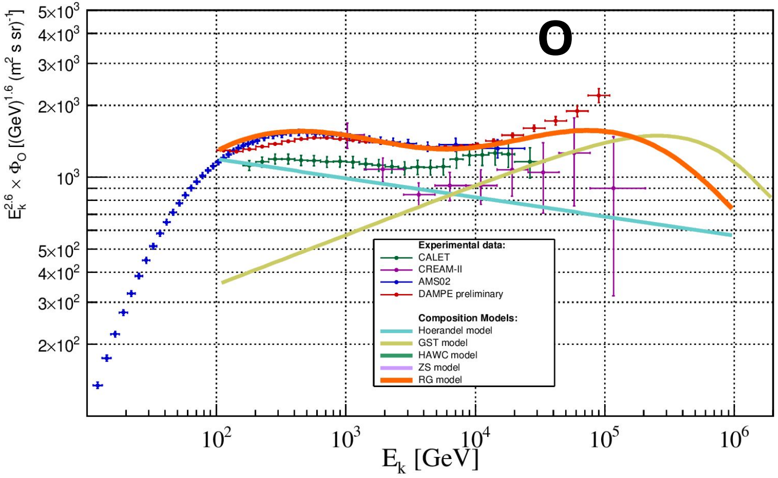
Model	Application E range	Reference
Hoerandel (poly-gonato) model	[10 GeV - 10^9 GeV]	*J. R. Hörandel, Astropart.Phys. 19 (2003) 193-220*
HAWC model	[10^2 GeV - 10^6 GeV]	*HAWC, PoS ICRC (2023) 299*
Recchia-Gabici (RG) model	[~GeV - multi PeV]	*S. Recchia, S. Gabici (2023) arXiv:2312.11397*
Zatsepin-Sokolskaya (ZS) model	[10 GeV - 10^8 GeV]	*V. I. Zatsepin, N. V. Sokolskaya, A&A 458 (2006) 1*
GST model	[10^5 GeV - 10^{11} GeV]	*T. K. Gaisser, T. Stanev, S. Tilav, Front. Phys. 8 (2013) 748–758*

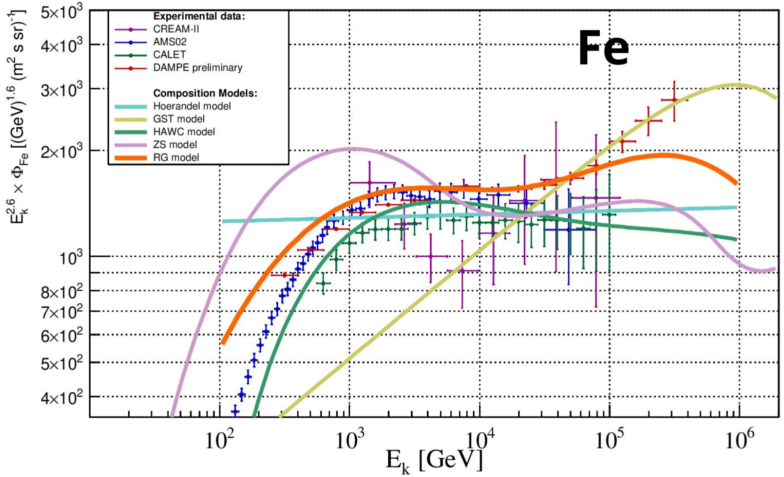




Composition models



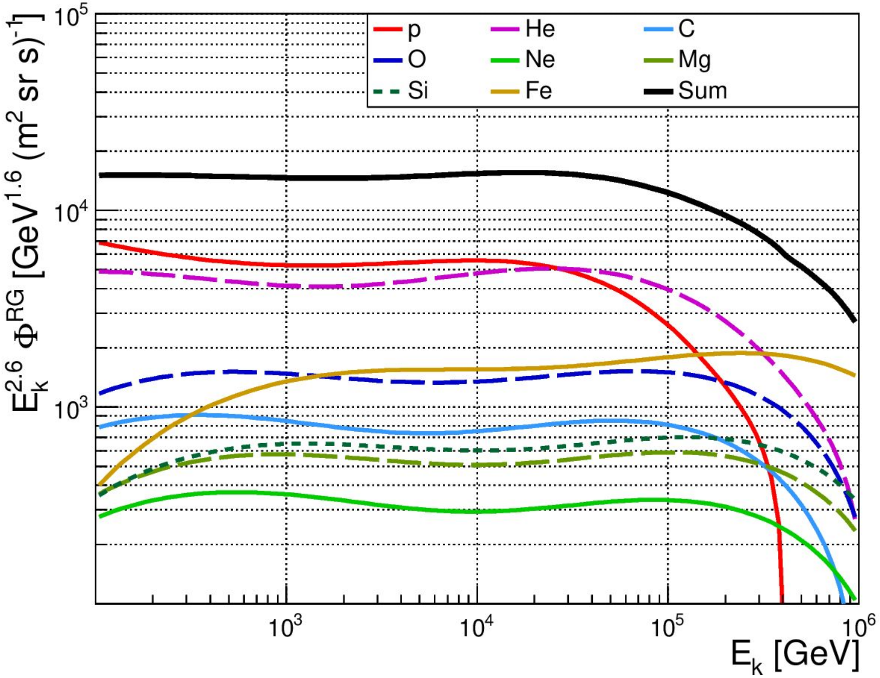




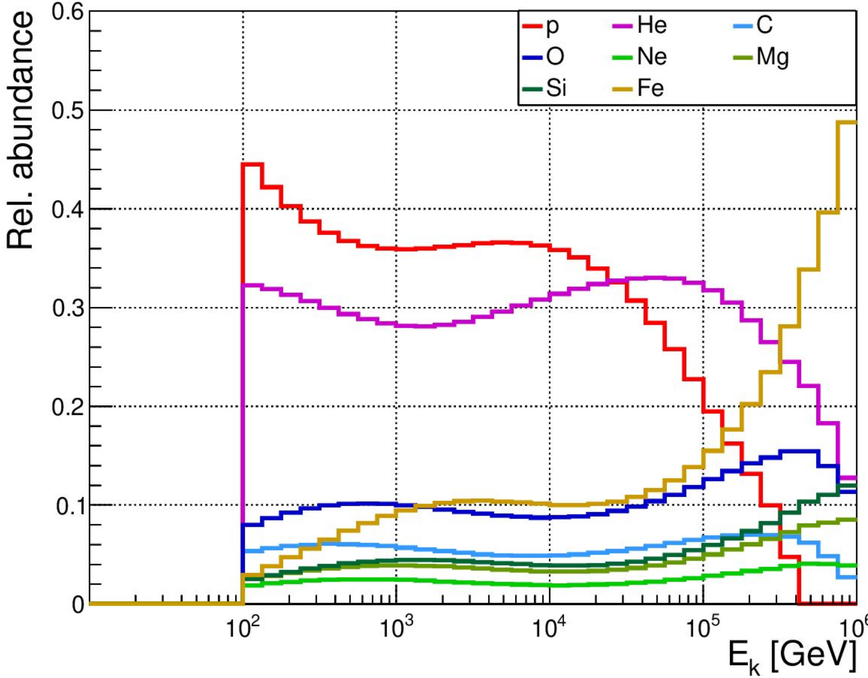
The **RG model** accurately reproduces the single nuclei spectra: **assumed as the composition model for the analysis**

Implementation of the Recchia-Gabici model

RG flux for each element



Relative abundances



∀ element *X*

- its flux is described by the RG model
- its rel. abundance is computed and used as a weight to compute the mean acceptance & response matrix

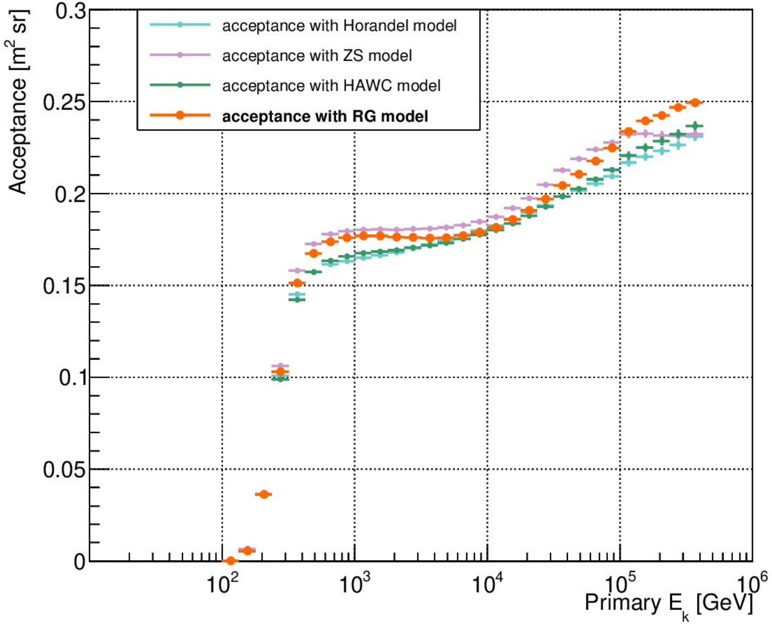
$$w_i^X = \frac{\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^X(E)dE}{\sum_{el}\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^{el}(E)dE}$$

$el = \mathrm{p, He, C, O, Ne, Mg, Si, Fe}$

Acceptance and unfolding

Weighted mean acceptance

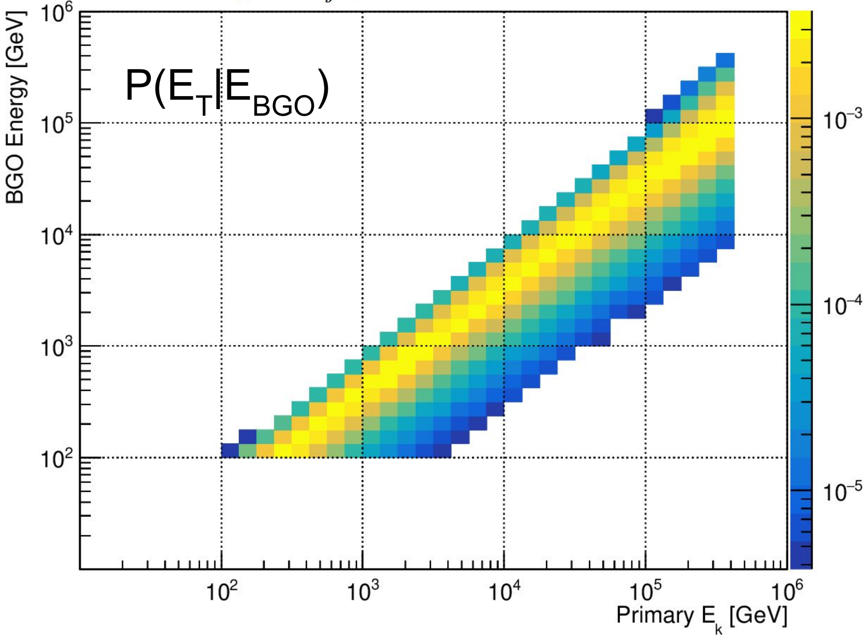
$$A_i = \sum_{el} w^{el} \; G^{el}_{gen} \; \frac{N^{el}_{sel}(E^i_T)}{N^{el}_{gen}(E^i_T)}$$



Weighted mean response matrix

for the unfolding: iterative Bayesian procedure is adopted to reconstruct the primary energy of the events

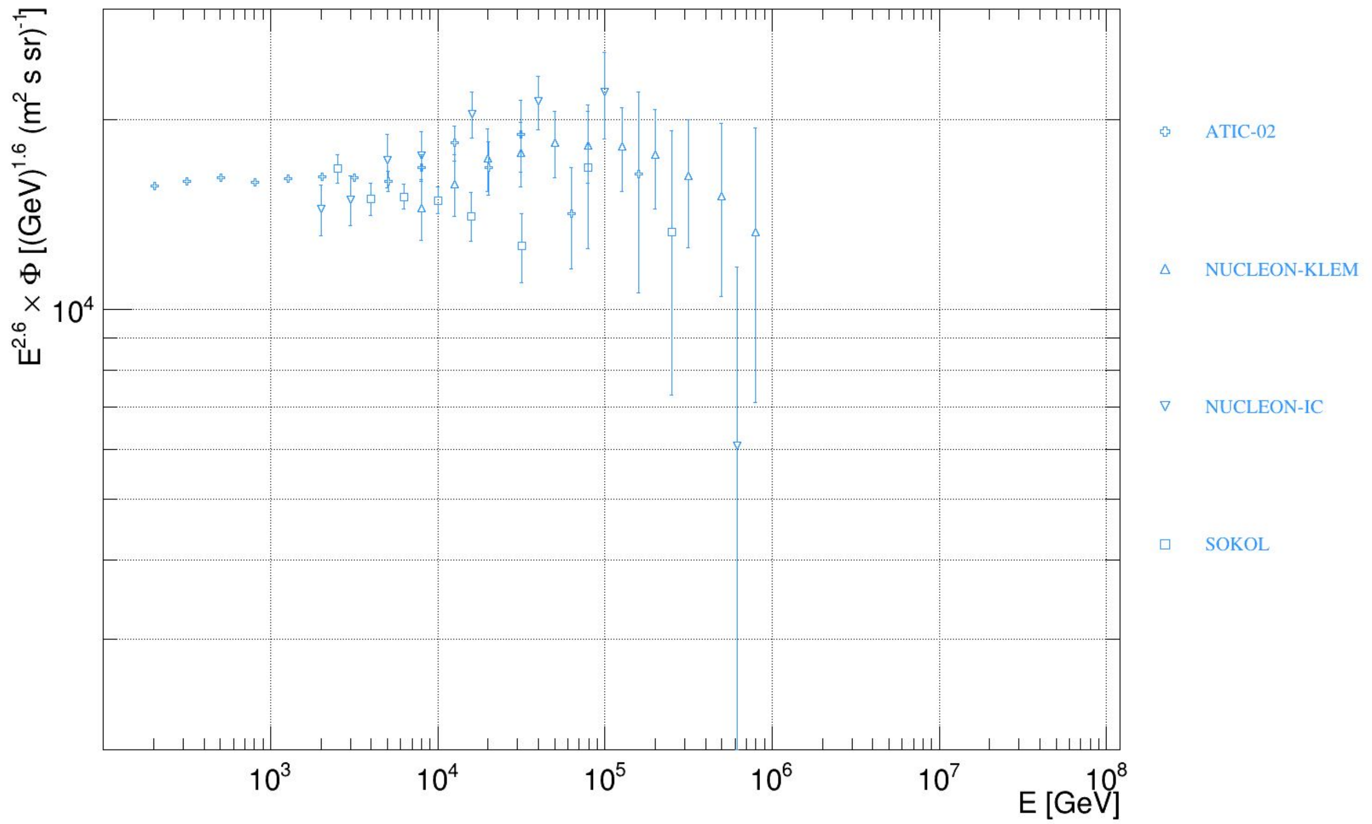
$$N_i = \sum_{el} w^{el} \sum_{j=1}^{n} P^{el}(E^i_T|E^j_{BGO}) \; N^{el}(E^j_{BGO})$$



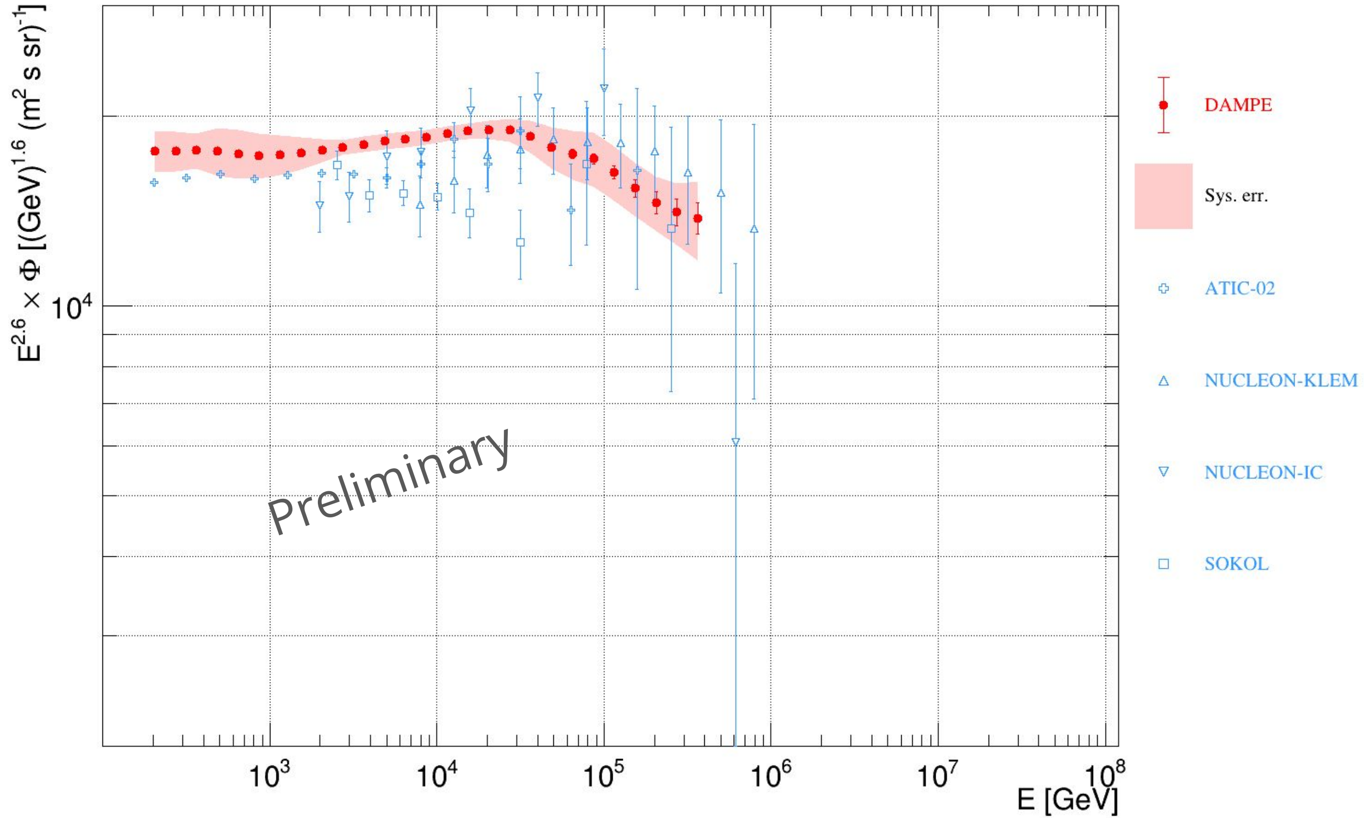
Output flux
∀ i^{th} E_k bin

$$\Phi_i = \frac{N_i}{\Delta T \times A_i \times \Delta E_i}$$

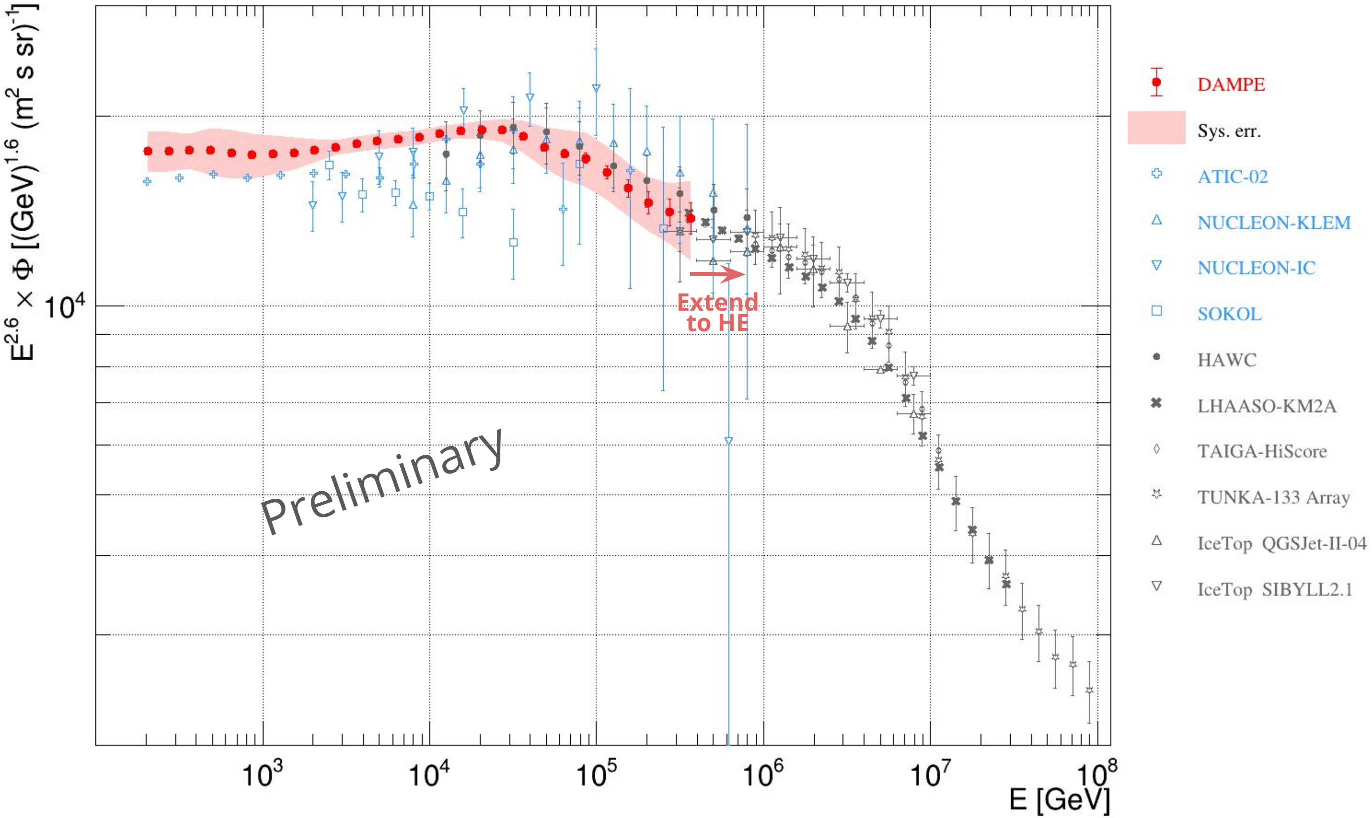
All-particle flux



All-particle flux



All-particle flux



- Spectrum from 200 GeV - 400 TeV using 8 years of data (2016-2023)
- Evaluated systematics
  - Unfolding
  - Composition model
- Contribution from hadronic model is under evaluation
- In agreement with indirect experiments results
- Structure at tens TeV (possible convolution of different nuclei softening?)

Future plans with DAMPE

All-particle spectrum

- complete the systematic uncertainties estimation
- investigation of the structure at tens TeV (smoothly broken power law fit)
- extend the measurement up to 0.7/0.8 PeV

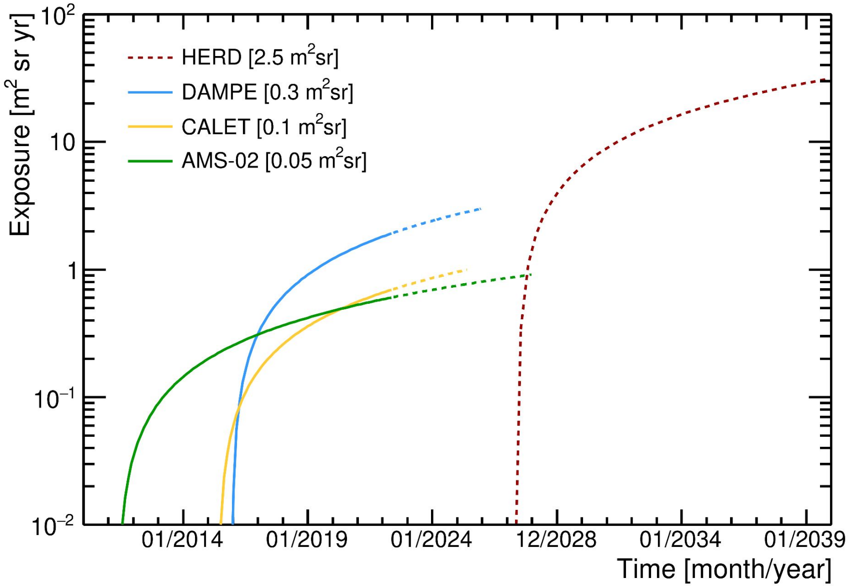
Global analysis of DAMPE p+He, CNO, Fe

- evaluate the consistency between the all-particle spectrum and the combined total of the three spectra
- study the overall picture that involve the spectral features of these spectra

The High Energy cosmic-Radiation Detection mission

- International scientific collaboration led by China and with relevant contributions from Italian, Spanish & Swiss institutes

- The HERD facility is planned to be installed in 2027 on board of the China's Space Station (CSS)



Payload mass	< 4t
Power consumption	< 1.5 kW
FOV	± 70°
Calorimeter	55 X_0 (~3 λ_I)
Geometric acceptance	>2 m^2sr at 100 TeV (nuclei) >3 m^2sr at 200 GeV (e) >0.2 m^2sr at 200 GeV (γ)
Detection	30 GeV - 3 PeV (nuclei) 10 GeV - 100 TeV (e) 0.5 GeV - 100 TeV (γ)
Energy resolution	1% at 200 GeV (e/γ) ~20% at 100 GeV - 1 PeV (nuclei)
Angular resolution	0.1 deg. at 10 GeV

The Detector

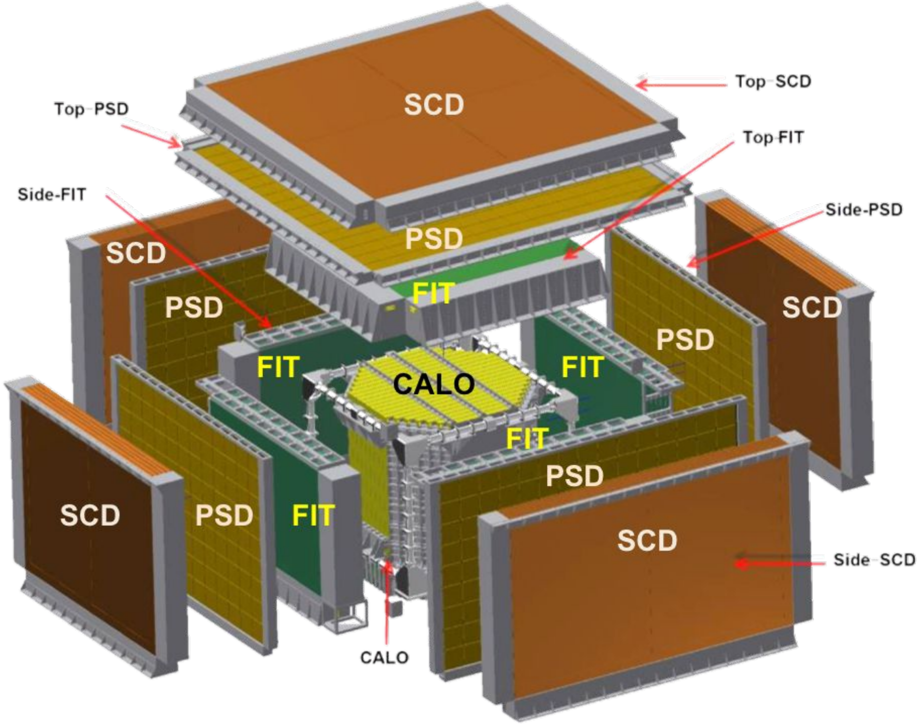
From inside to outside

CALOrimeter
- Energy reconstruction
- EM/HAD showers discrimination

FIT (FIber Tracker)
- Charge particles track reconstruction
- Conversion of γ to e+e- pairs
- Additional charge measurement

PSD (Plastic Scintillator Detector)
- Anti-coincidence for γ ID
- Charge measurement up to Z=26
- Charged particle triggers

SCD (Silicon Charge Detector)
- Charge measurement up to Z=28



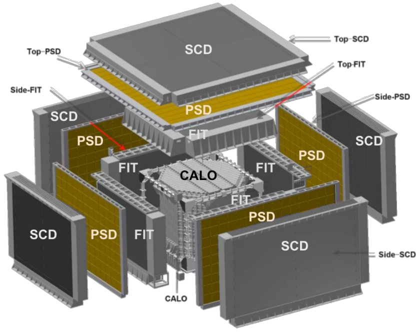
TRD (Transition Radiation Detector)
- Calibration of CALO response for TeV p

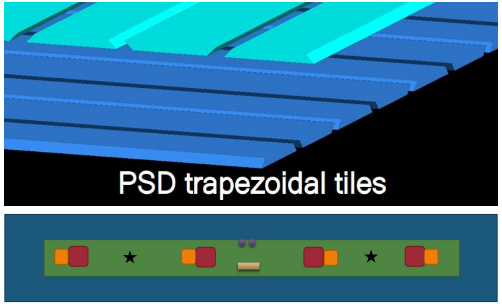
Plastic Scintillator Detector (PSD)

Requirements
- High detection efficiency (>99.98%)
- Wide dynamic range in nuclei ID
- Highly segmented

For all 5 sectors: 2 double X-Y layers of scintillating bars, each readout by multiple SiPMs

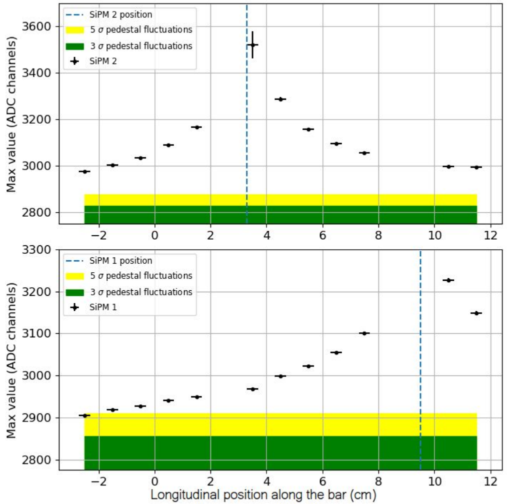
Test beam campaigns at CERN and CNAO to
- Study the uniformity response of light collection
- Evaluate nuclei ID performances
- Optimise SiPM-based readout





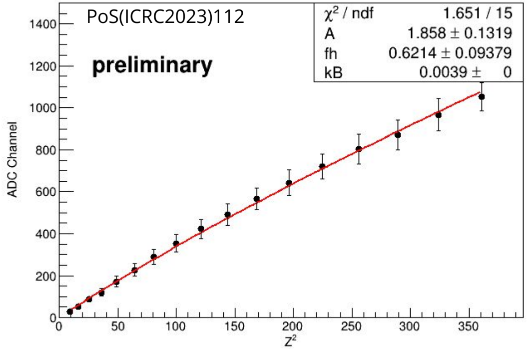
4 SiPM (3.0x3.0 mm² - 50 μm cell) Low Z
4 SiPM (1.3x1.3 mm² - 15 μm cell) High Z
Led for calibration
Coaxial cable
★ Temperature sensor

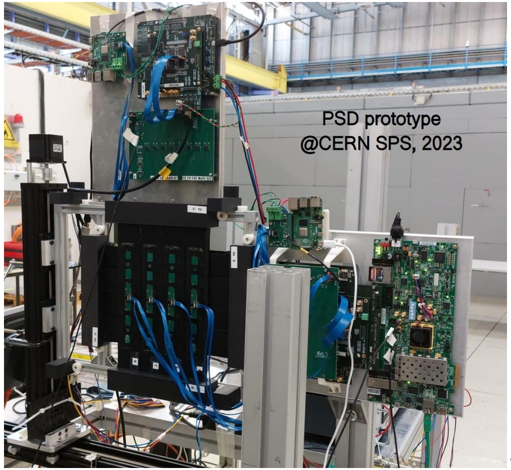
PSD prototype attenuation test



PSD prototype quenching effects test

PSD L2 Bar: S14160-1315 TOP PCB





GSSI

Summary

All-particle analysis with DAMPE:

- Derivation the all-particle spectrum with DAMPE investigating possible spectral breaks and the agreement with other experiments
- No charge cut selection is applied to increase statistics, application of a composition model to account for different nuclei responses (RG model)
- Preliminary result of the all-particle spectrum in the 200 GeV - 0.4 PeV energy range
- **The next steps involve finalizing systematic uncertainties, extending measurements up to 0.7/0.8 PeV, exploring a possible spectral break at tens of TeV, and conducting a global analysis of CR nuclei spectra**

Hardware R&D of the HERD PSD:

- tests on hardware and prototypes construction for beam tests at CERN and CNAO
- Finalize prototypes and performances tests

GSSI

Workshops and conferences

- 6th International Symposium on Ultra High Energy Cosmic Rays (UHECR2022), L'Aquila, 3-7 oct. 2022
- 38th International Cosmic Ray Conference (ICRC2023), virtual, 26 jul. - 3 aug. 2023
- 109 Congresso Nazionale SIF, Salerno, 11-15 sept. 2023
  talk:"Latest results from the DAMPE space experiment"
- Incontri di Fisica delle Alte Energie 2024 (IFAE 2024), Firenze, 3-5 apr. 2024
  talk:"Misura dello spettro all-particle con l'esperimento DAMPE"
- 16th Pisa Meeting on Advances Detectors, La Biodola Isola d'Elba, 26 may - 1 jun. 2024
  poster:"HERD space mission: Probing the Galactic Cosmic Ray frontier"
- COSPAR 2024 45th Scientific Assembly, 13-21 jul. 2024
  talk:"Measurement of the all-particle energy spectrum with the DAMPE mission"
- 28th European Cosmic Ray Symposium (ECRS 2024), 23-27 sept. 2024
  talk 1:"The HERD space mission"
  talk 2 (as a substitute speaker):"Measurement of the iron energy spectrum with the DAMPE space mission"
- Conference in memory of Vienamin Sergeyevich Beresinsky, L'Aquila, 1-3 Oct. 2024

Collaboration meetings

- 11th international DAMPE workshop, virtual, 12-15 jun. 2023
- Talks during biweekly working group online meetings of DAMPE

Schools

- NBIA PhD School "Here, There & Everywhere", Copenhagen, 11-15 jul. 2022
- 6th HEP C++ course and hands-on training - Essential, virtual, 6-10 mar. 2023
- 12th international IDPASC school and workshop, Granada, 18-28 sept. 2023
- GEANT4 beginners course "First steps with Geant4 2024", virtual, 15-19 apr. 2024

Other activities

- Test beam at CERN SPS for the HERD PSD, 17-25 nov. 2022
- Test beam at CNAO for the HERD PSD, 10-12 jan. 2023
- Test beam at CNAO for the HERD PSD, 21-23 may 2023
- Working in Bari to test the DAQ of the HERD PSD, 10-15 jul. 2023
- Test beam at CERN PS for the HERD PSD, 3-12 sept. 2023
- Test beam at CERN SPS for the HERD PSD, 6-11 oct. 2023

Outreach activities

- Participation in SHARPER (European Researcher's nigh), L'Aquila, 30 sept. 2022
- Volunteer in UHECR2022 conference, L'Aquila, 3-7 oct. 2022
- 9th GSSI Astroparticle physics Science Fair, L'Aquila, 21-23 feb. 2023
  talk:"Galactic Cosmic Rays with the DAMPE space mission"
- Participation to "Corso formazione ed addestramento Preposti per visite in underground",
- Assergi-LNGS, 10 may 2023, obtaining the tour guide qualification for underground lab. visits in LNGS
- 10th GSSI Astroparticle physics Science Fair, L'Aquila, 13 feb. 2024
  poster:"DAMPE: study of high energy cosmic electrons, photons and nuclei in space"
- Volunteer & Guide for the LNGS lab. underground visit for the SST - PhD National Days, L'Aquila, 6-8 jun. 2024
- Participation in SHARPER (European Researcher's nigh), L'Aquila, 27 sept. 2024

Scientific publications

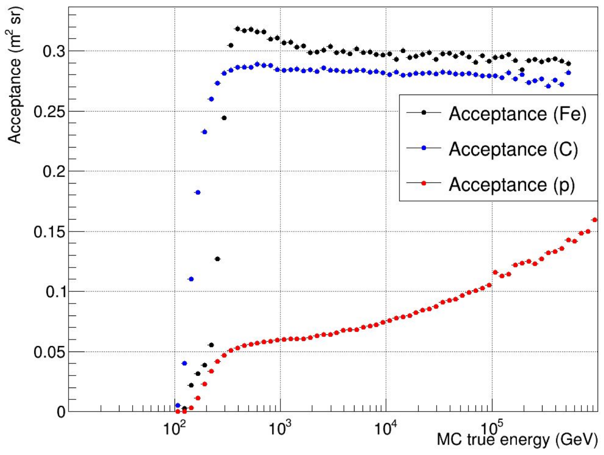
- PoS ECRS (2023) 064
- EPJ Web Conf. 280 (2023) 01001
- Astroparticle Physics 146 (2023) 102795
- PoS ICRC2023 (2023) 142
- PoS ICRC2023 (2023) 161
- PoS ICRC2023 (2023) 163
- PoS ICRC2023 (2023) 130
- PoS ICRC2023 (2023) 174
- PoS ICRC2023 (2023) 165
- PoS ICRC2023 (2023) 170
- PoS ICRC2023 (2023) 138
- PoS ICRC2023 (2023) 115
- PoS ICRC2023 (2023) 137
- PoS ICRC2023 (2023) 149
- PoS ICRC2023 (2023) 168
- PoS ICRC2023 (2023) 131
- PoS ICRC2023 (2023) 159
- PoS ICRC2023 (2023) 670
- PoS ICRC2023 (2023) 391
- PoS ICRC2023 (2023) 1316
- PoS ICRC2023 (2023) 139
- IWASI (2023) pp. 184-189, doi: 10.1109/IWASI58316.2023.10164305
- PRD 109 (2024) L121101
- arXiv: 2408.17224 [hep-ex]
- NIM-A 1068 (2024) 169788
- NIM-A 1069 (2024) 169888

Backup

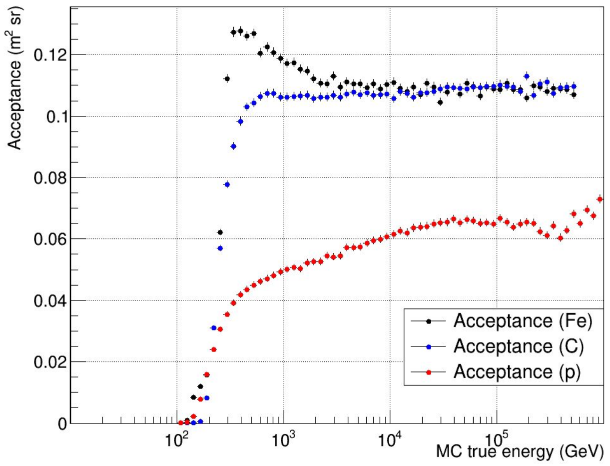
First analysis investigation (no composition model)

Selection cuts

- SAA exclusion
- E_{depo} in each BGO layer < 35% E_{BGO}
- HET trigger ON
- E_{BGO} > 100 GeV
- BGO fiducial cuts
  - Reconstructed shower axis inside the fiducial volume
  - ∀ layer: max E_{depo} inside the fiducial volume
- No charge/track selection cuts

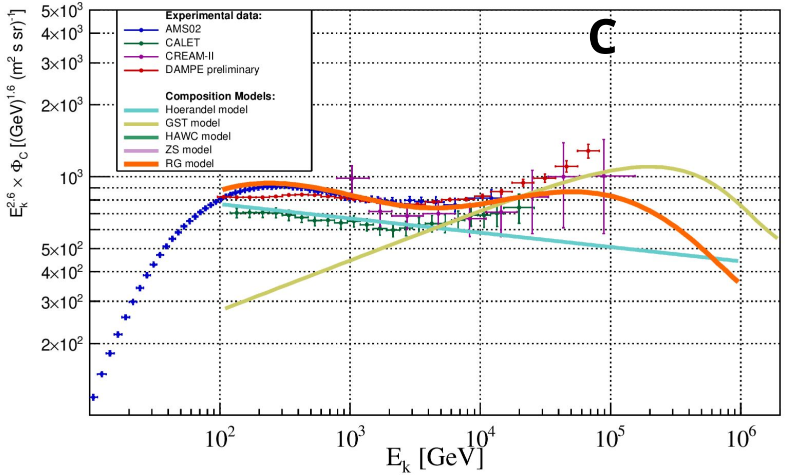


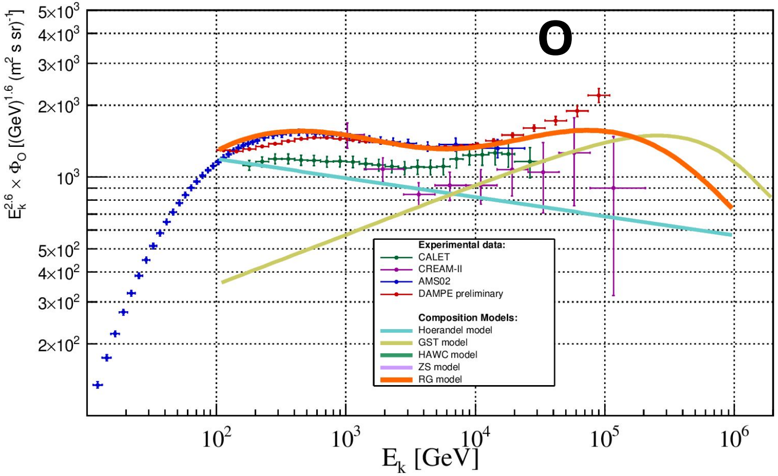
- LET trigger on
- Additional cut to maximize the agreement between the p,Fe acceptances
  - Studying the distribution of the shower energy deposit in the BGO bars of each layer

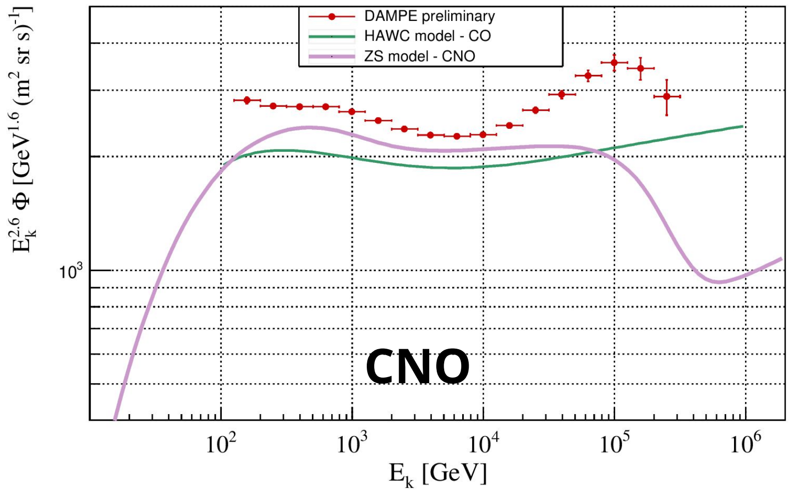


the uncertainty in the unfolded flux would be too large

Composition models



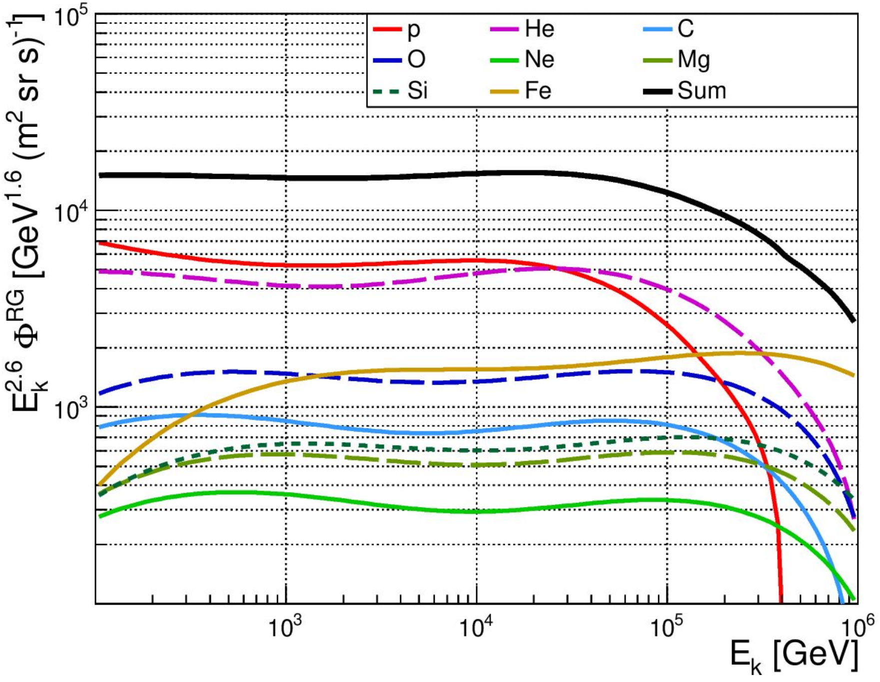




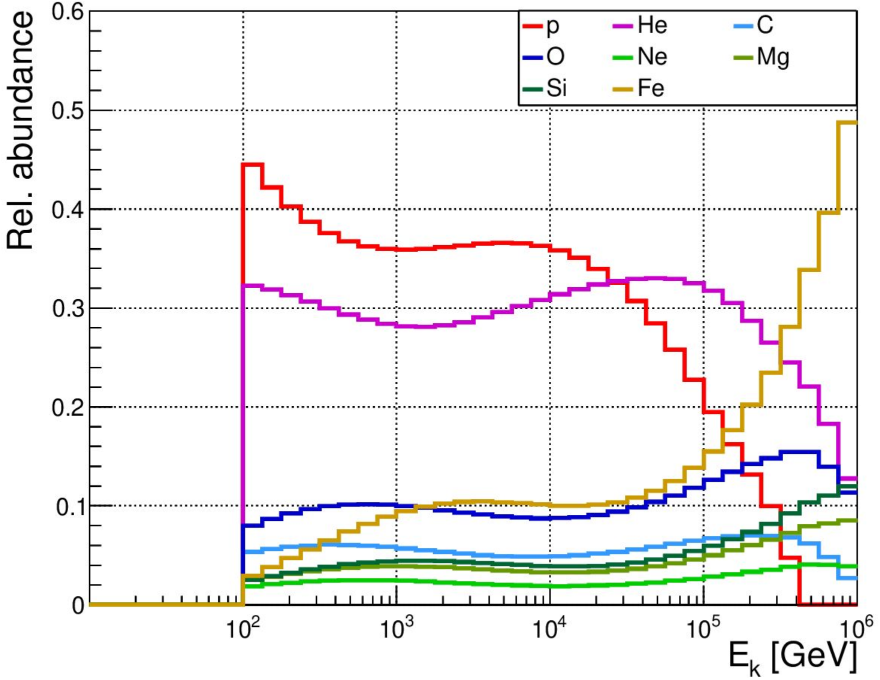
RG Composition model

- Analitic solution derived from the transport equations describe the single element fluxes.
- Transport equations are obtained assuming 2 populations of CR sources:
  - the majority of SN that are expected to accelerate up to a maximum rigidity of 15 TV
  - a 10% fraction of SN is expected to accelerate up to PetaVolt

RG flux for each element



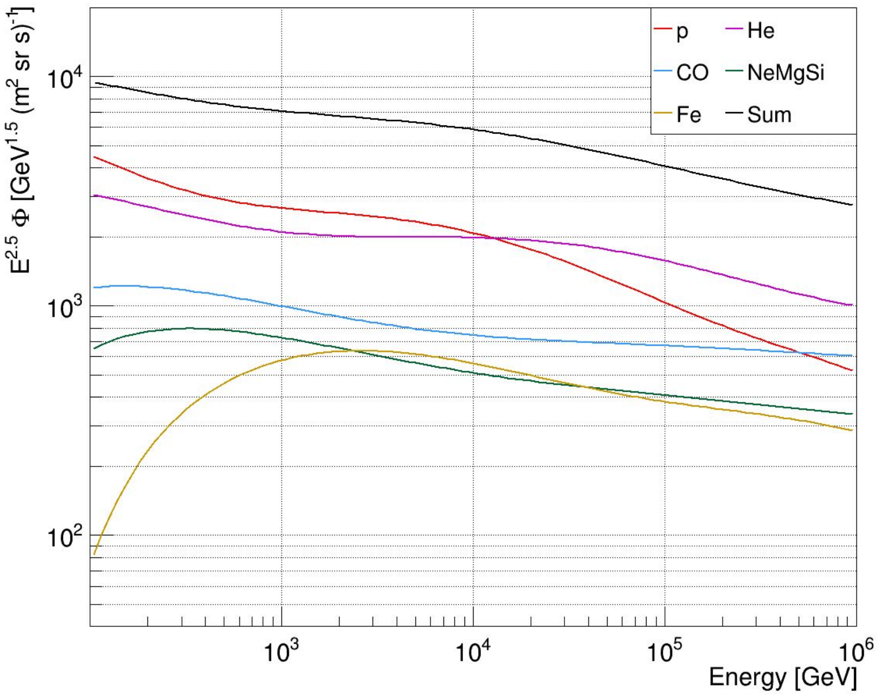
Relative abundances



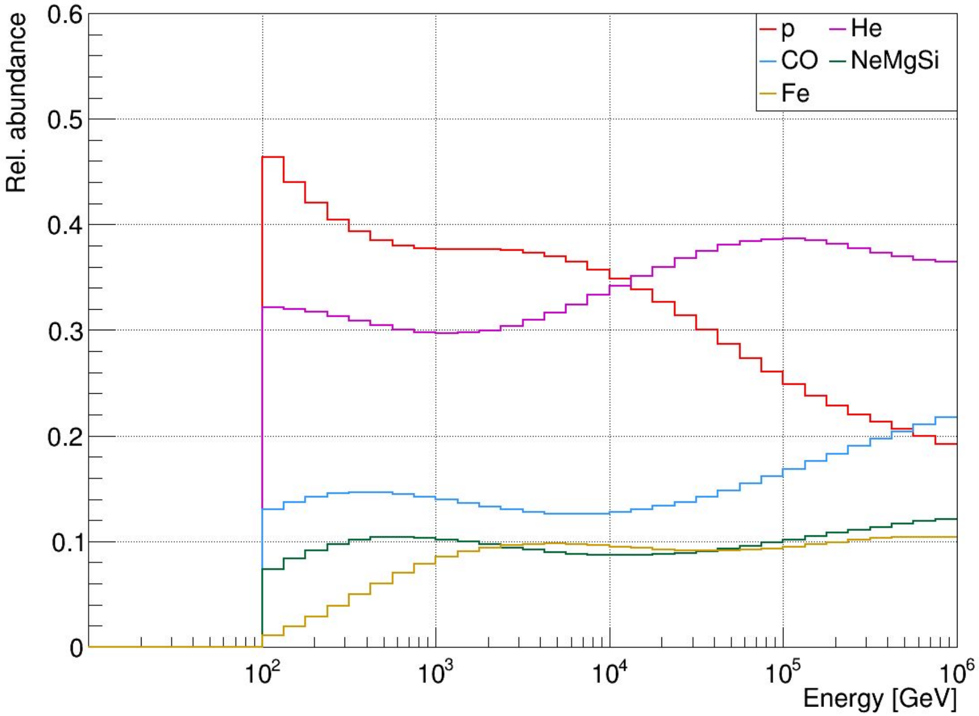
HAWC composition model

- Derived by fitting BPL functions to data from ATIC-2, CREAM, PAMELA, AMS-2, NUCLEON, CALET, DAMPE, KASCADE

HAWC flux for each element



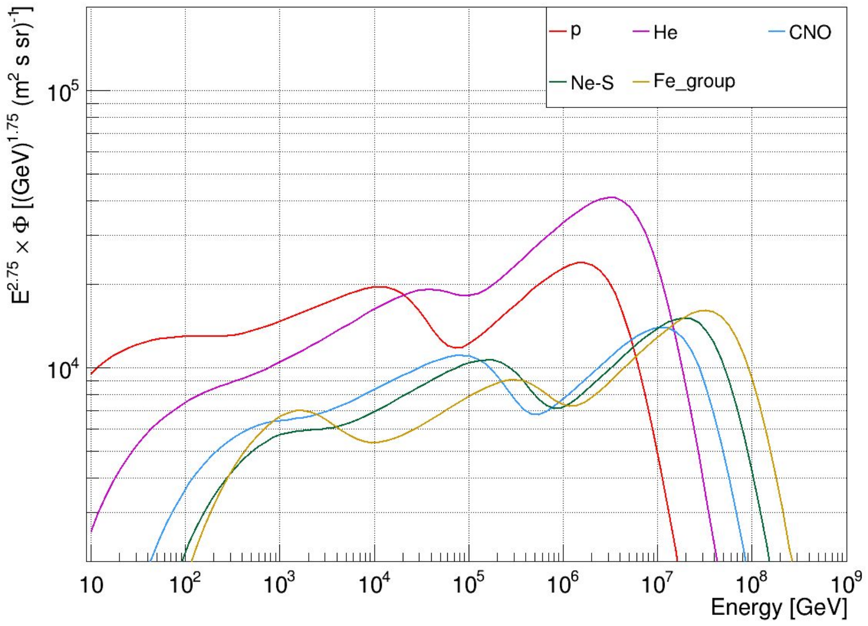
Relative abundances



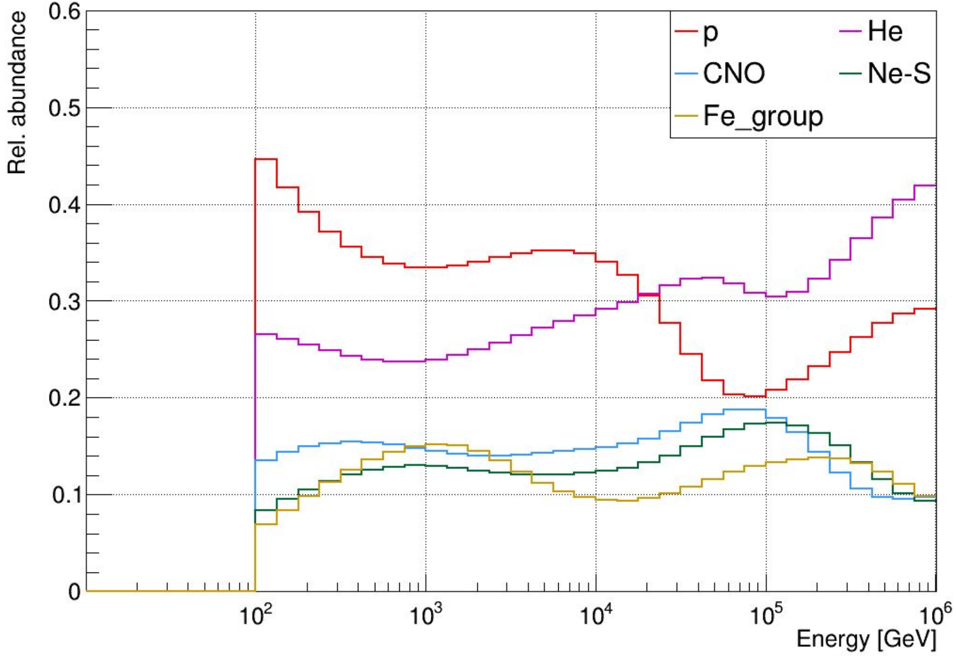
ZS composition model

- 3 different classes of sources: each class prod. a spectrum for 5 nuclear group that
  - is simple power-law after termination of effective acceleration
  - with specific spectral-index γ_k & Rmax
- Nuclear groups: p, He, CNO, Ne-S, Fe-group(Z>17)
- Solar modulation is taken into account
- Model fitted on experimental direct & EAS data

ZS flux for each element

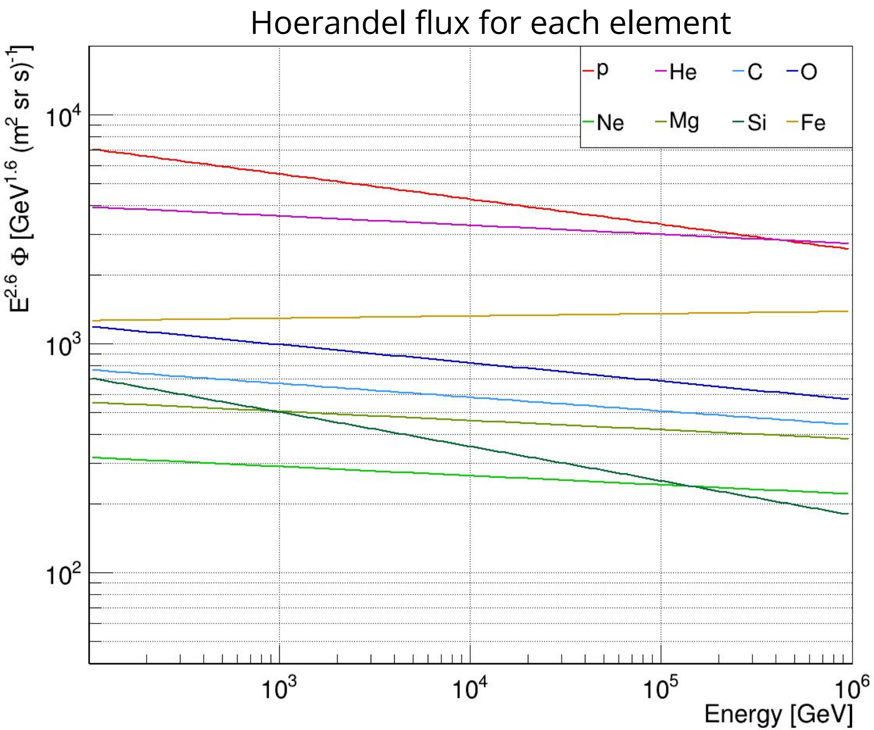


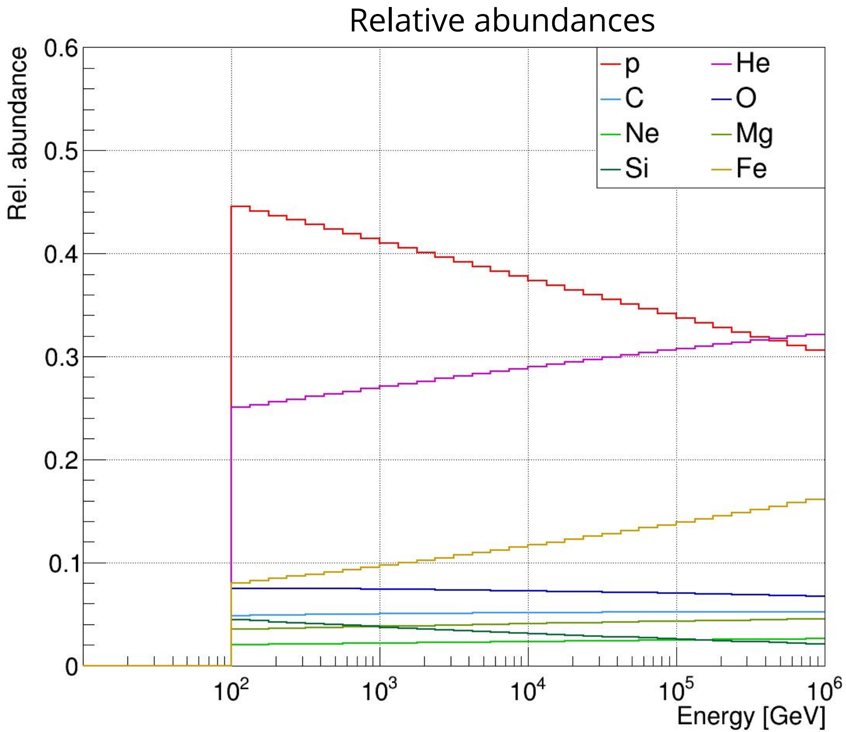
Relative abundances



Hoerandel composition model

- Spectra of individual elements obtained from direct observations and extrapolated to high energies
- Direct experiments data fitted with SPL functio $\Phi(E) = \Phi^0 \left(\frac{E}{1TeV} \right)^{\gamma}$



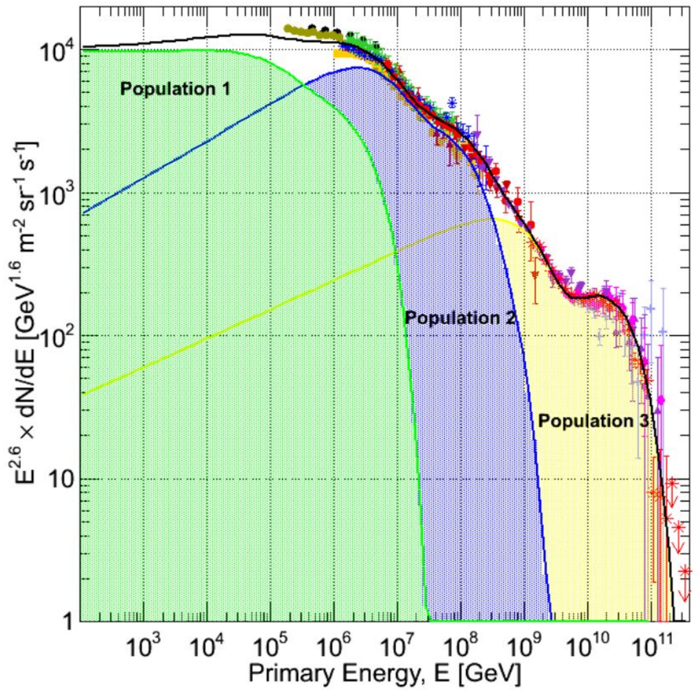


GST composition model

- Performed 2 different fits to experimental data
  - each assuming 3 populations of particles
  - different assumptions for the rigidity cut off for each population
  - 3 populations: pop. 1 & 2 of galactic origin, pop. 3 is extragalactic
  - Each population (j) is contains 5 groups of nuclei (i)

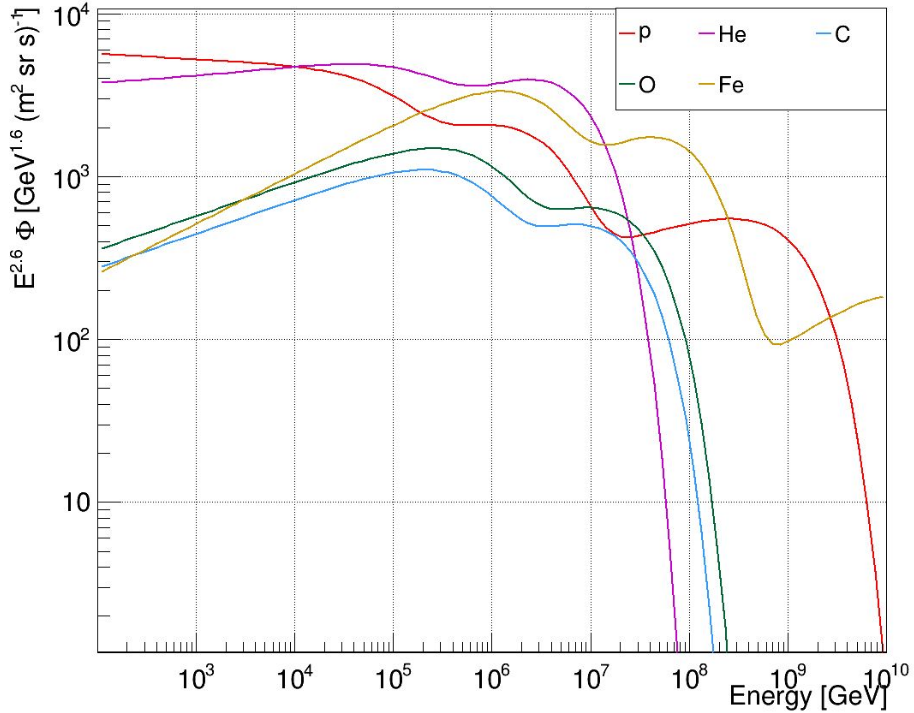
$$\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

	p	He	C	O	Fe
Pop. 1:	7000	3200	100	130	60
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3
Pop. 2:	150	65	6	7	2.3
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2
Pop. 3:	14				0.025
$R_c = 1.3$ EV	1.4				1.2

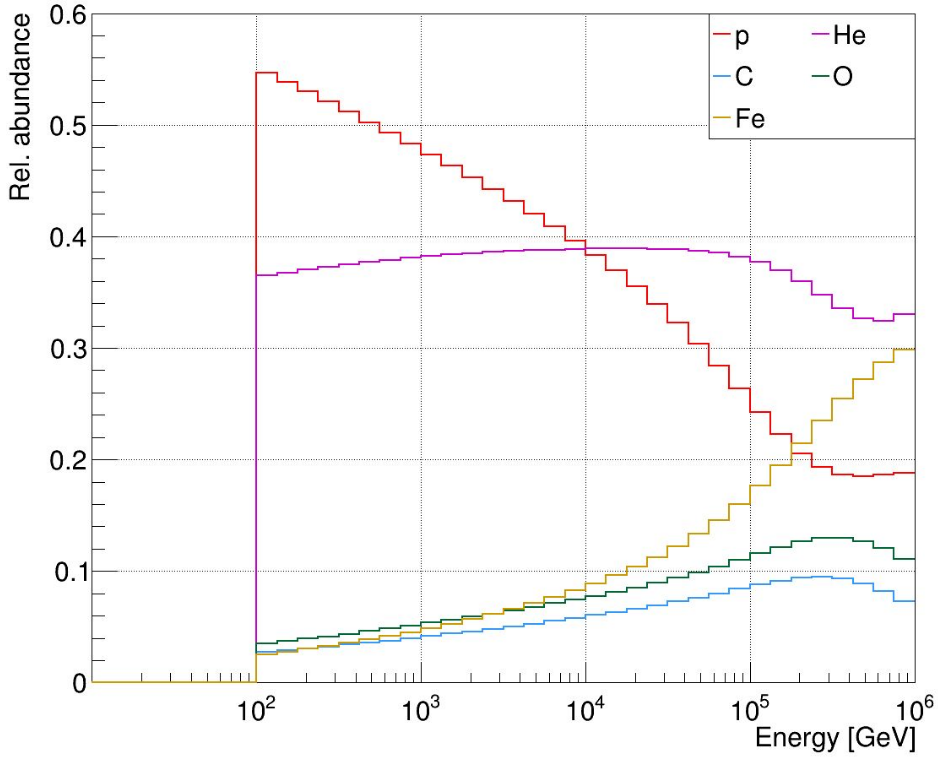


GST composition model

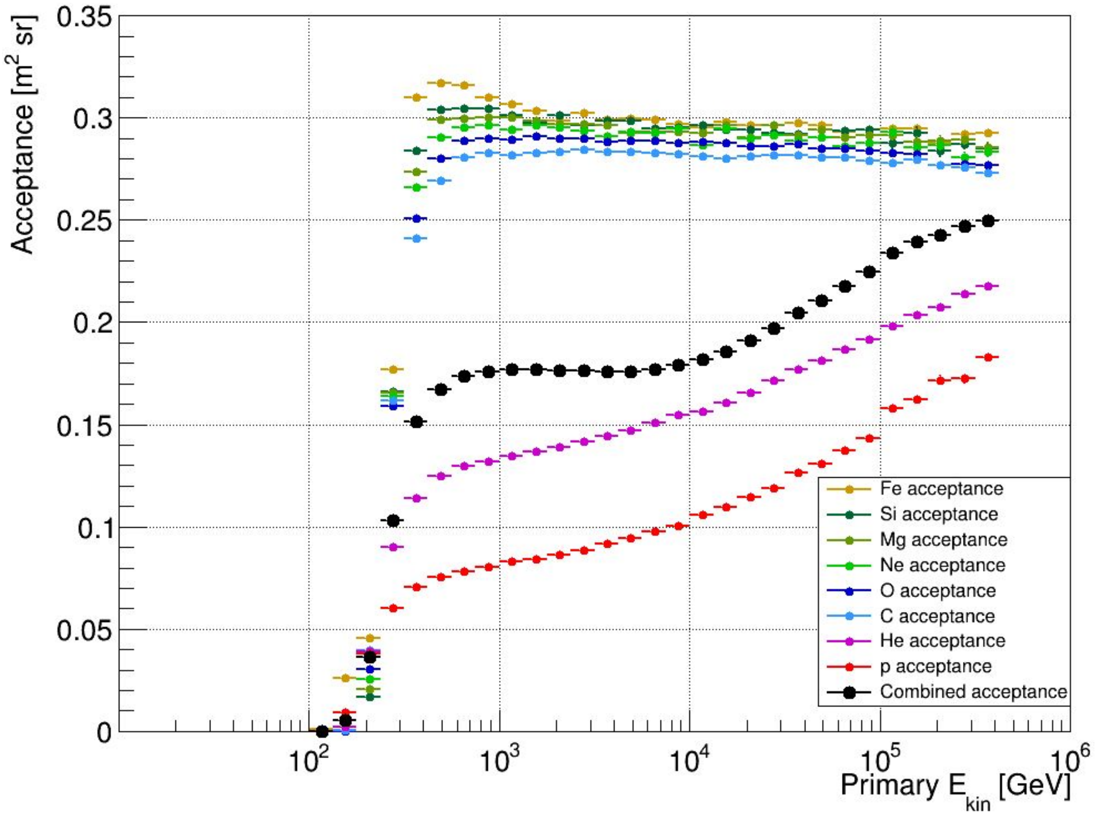
GST flux for each element



Relative abundances



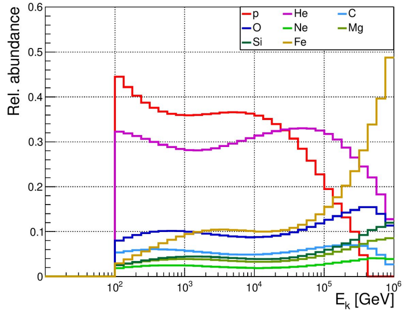
Single elements acceptances



Rel. abund. computed using the RG model

$$w_i^X = \frac{\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^X(E)dE}{\sum_{el}\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^{el}(E)dE}$$

$$el = \mathrm{p, He, C, O, Ne, Mg, Si, Fe}$$



Weighted mean acceptance

$$A_i = \sum_{el} w^{el} \; G_{gen}^{el} \; \frac{N_{sel}^{el}(E_T^i)}{N_{gen}^{el}(E_T^i)}$$