Measurement of the all-particle energy spectrum with the DAMPE mission

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on behalf of the DAMPE collaboration
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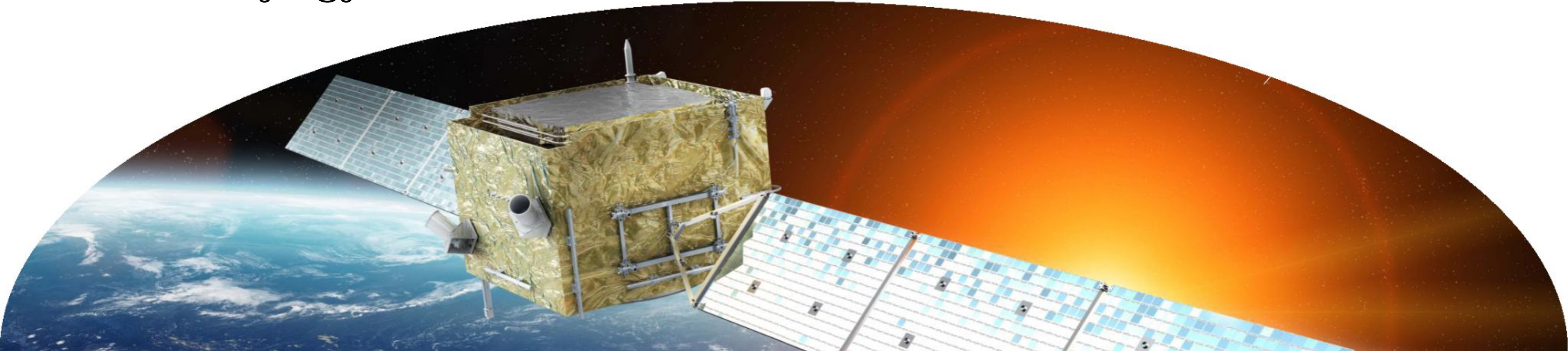
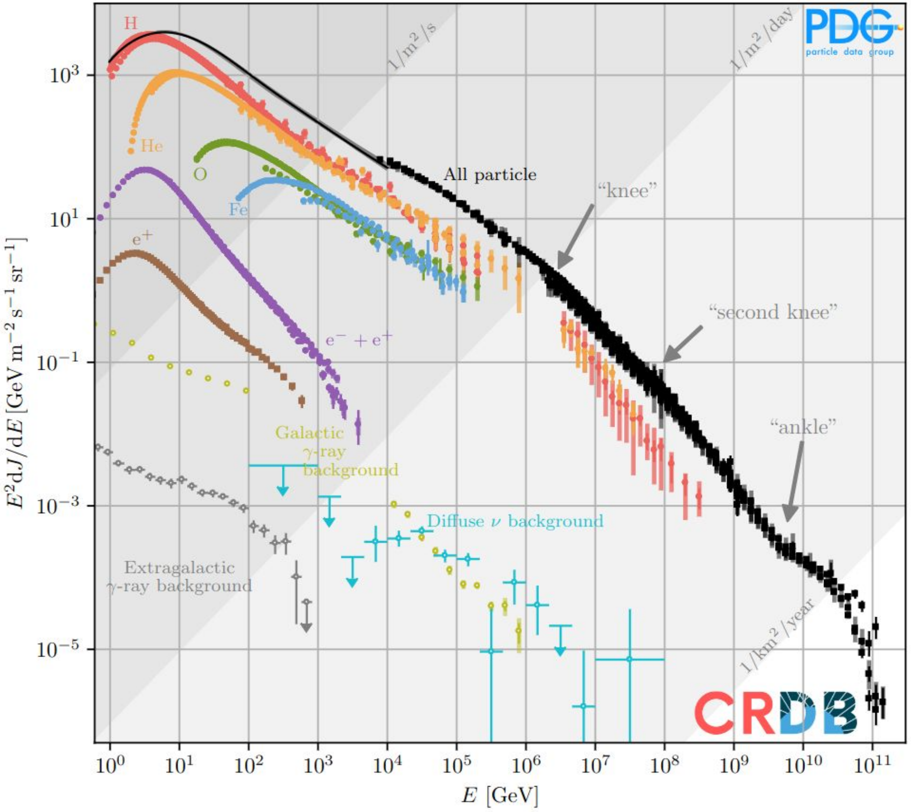


The all-particle spectrum towards the knee



Scientific motivations for measuring the all-particle spectrum up to ~1 PeV

- Use **loose charge cut selection**
  - to **minimize cross-contamination** among individual element spectra, which could arise from a sum of them
  - to **increase the statistics and the energy reach**
- Establish a **link between direct and indirect CRs experiments**: facilitate a unified understanding of CR properties across different energy ranges
- **Cross-calibration** with ground-based measurements (hadronic interaction models and other systematics)

The DAMPE space mission

- Collaboration of Chinese, Italian and Swiss scientific institutions
- Launched on 17 December 2015
- The primary **scientific goals**:
  - Study of (e^- + e^+), CR protons and nuclei spectra
  - High energy gamma ray astronomy
  - Indirect search for dark matter signatures in lepton spectra
- The main features

Acceptance	~0.3 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	10 GeV - 10 TeV (e/γ) 50 GeV - 200 TeV (nuclei)

GSSI

The DAMPE detector

Plastic Scintillator Detector (PSD)

- **Charge** measurement + **anti-coincidence** for γ ID
- 2 planes (X/Y) of plastic scintillator bars

Silicon TracKer (STK)

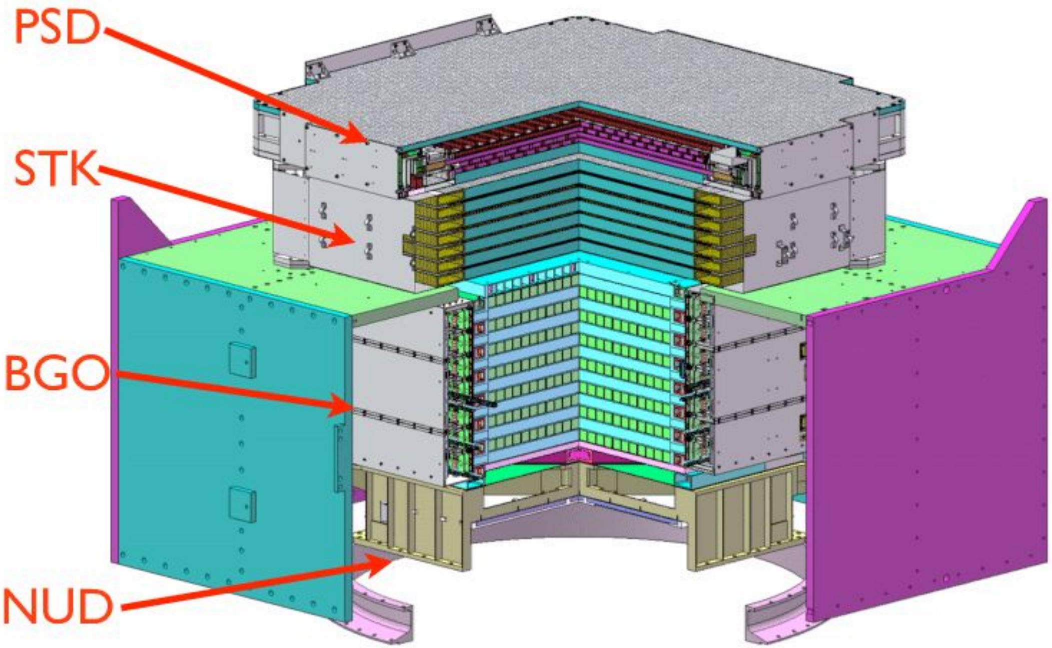
- **Track** reconstruction + additional **charge** measurement
- 6 planes of Si microstrip detectors + 3 W layers

BGO calorimeter (BGO)

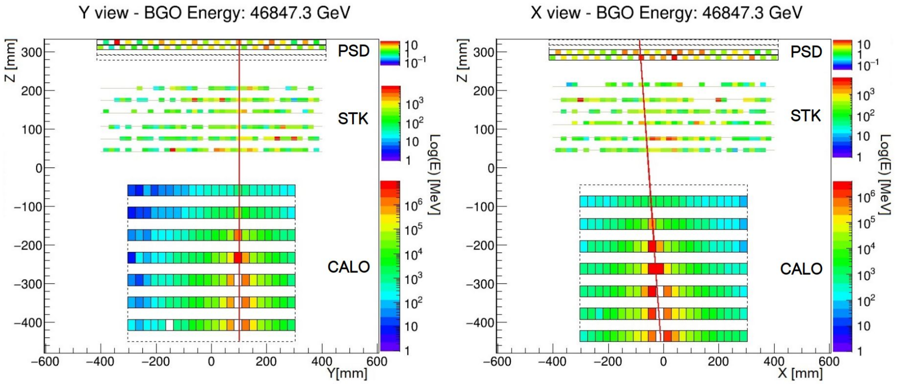
- **Energy** measurement + **em/had showers** discrimination
- 14 layers of BGO crystal bars
- 32 X_0 and 1.6 λ_I

NeUtron Detector (NUD)

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



Analysis selection & procedure



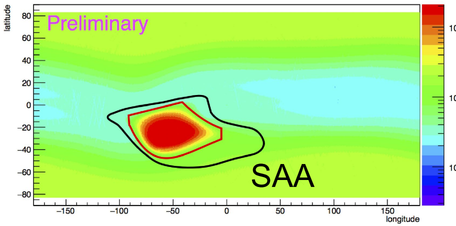
Experimental data

- 96 months of flight data (January 2016 - December 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

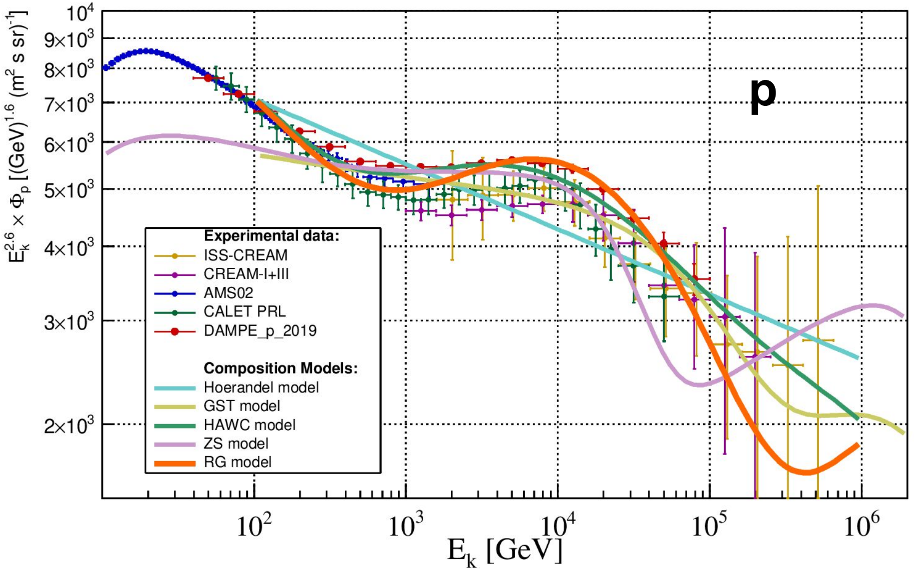
Selection cuts

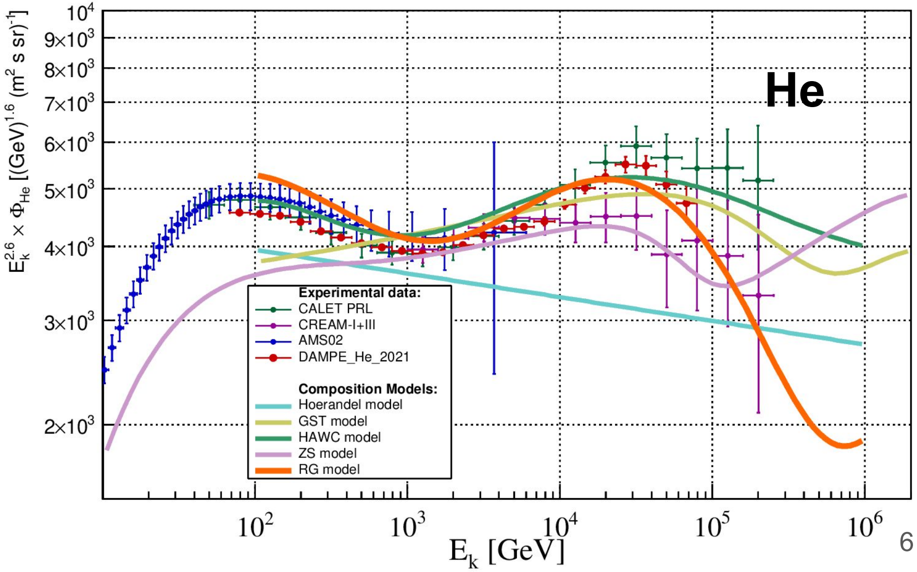


- SAA exclusion
- E_{depo} in each BGO layer < 35% E_{BGO}
- HET trigger ON
- E_{BGO} > 100 GeV
- BGO fiducial cuts
  - Reconstructed shower axis inside the fiducial volume
  - $\forall$ layer: max E_{depo} inside the fiducial volume
- No charge/track selection cuts

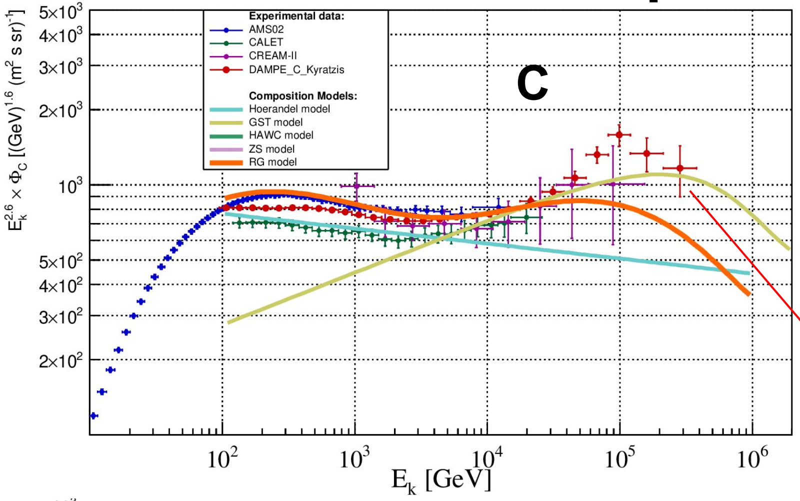
Composition models

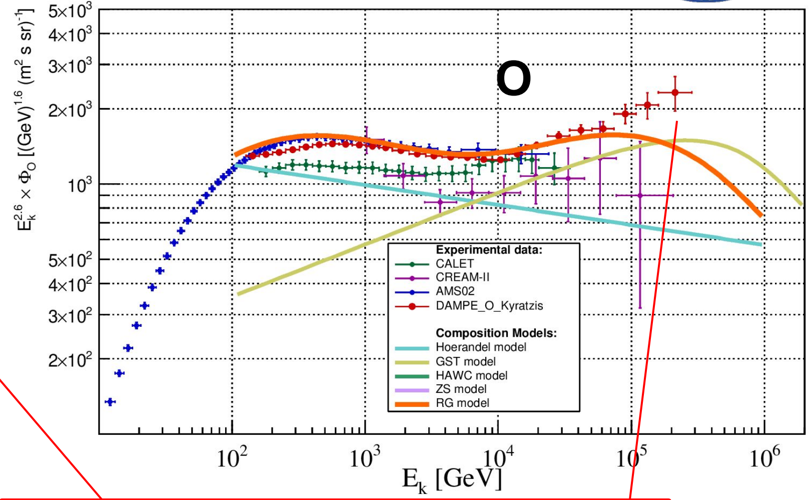
Model	Application E range	Reference
Hoerandel (poly-gonato) model	[10 GeV - 10^9 GeV]	*J. R. Hörandel, Astropart.Phys. 19 (2003) 193-220*
HAWC model	[10^2 GeV - 10^6 GeV]	*HAWC, PoS ICRC (2023) 299*
Recchia-Gabici (RG) model	[~GeV - multi PeV]	*S. Recchia, S. Gabici (2023) arXiv:2312.11397*
Zatsepin-Sokolskaya (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*

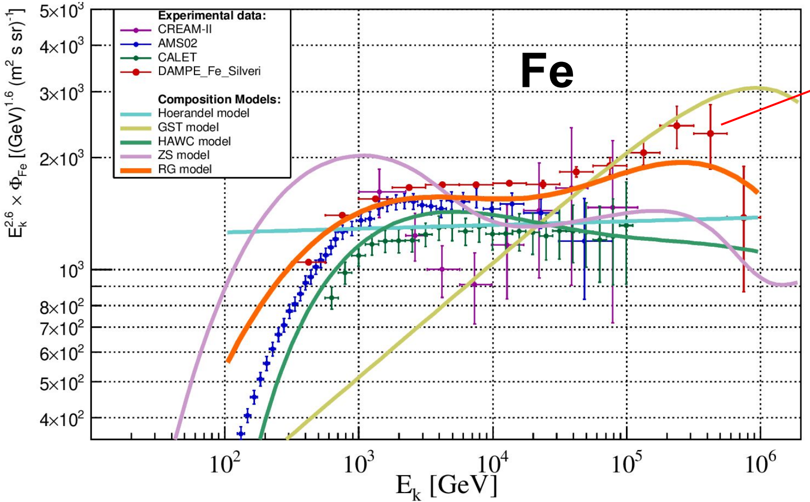




Composition models





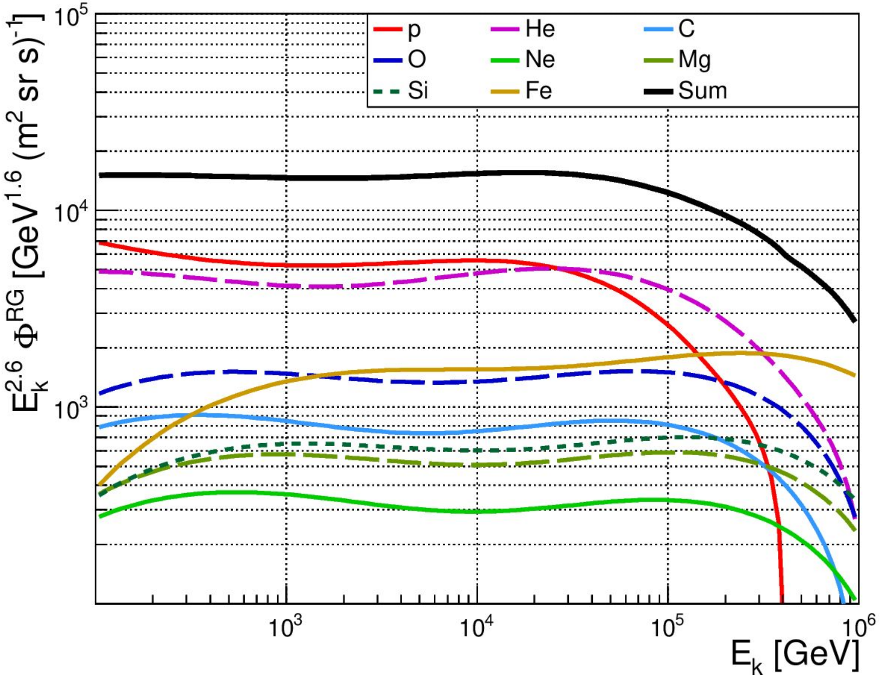


DAMPE DATA To be updated with the spectra that will be shown at COSPAR

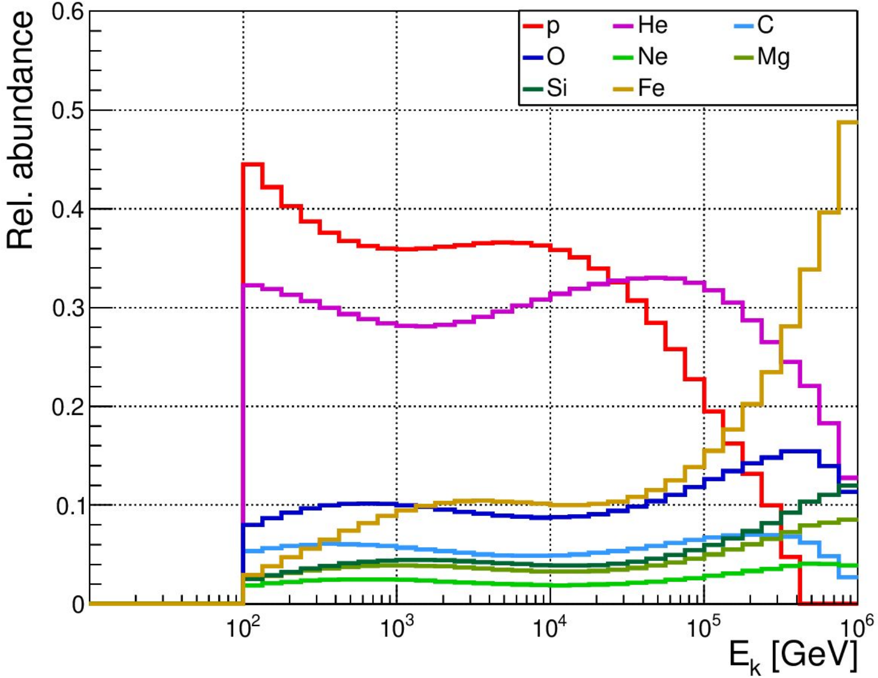
The **RG model** accurately reproduces the single nuclei spectra: **assumed as the composition model for the analysis**

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

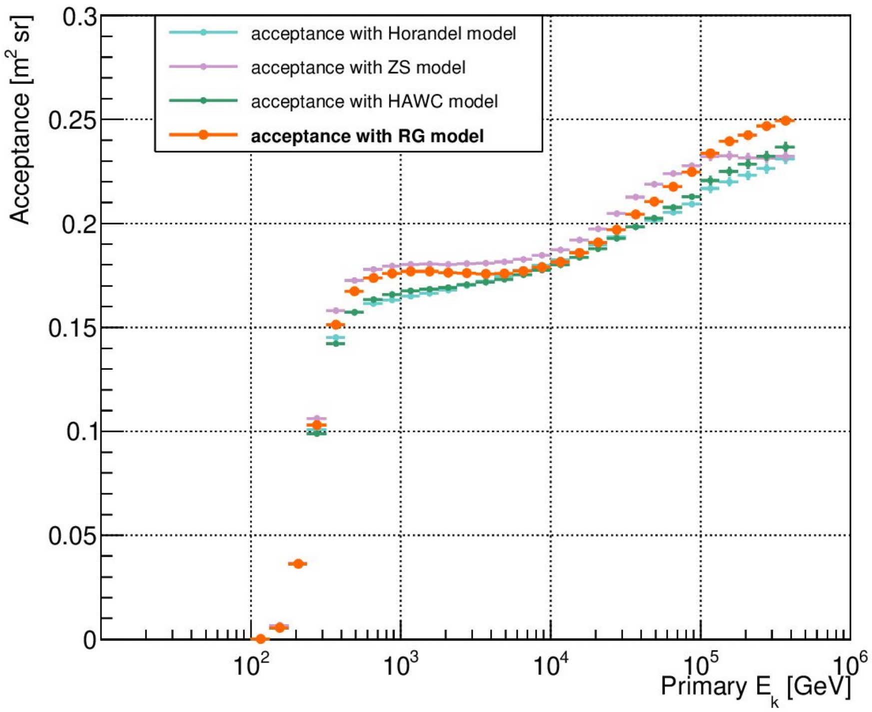
$$w_i^X = \frac{\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^X(E)dE}{\sum_{el}\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^{el}(E)dE}$$

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

Acceptance and unfolding

Weighted mean acceptance

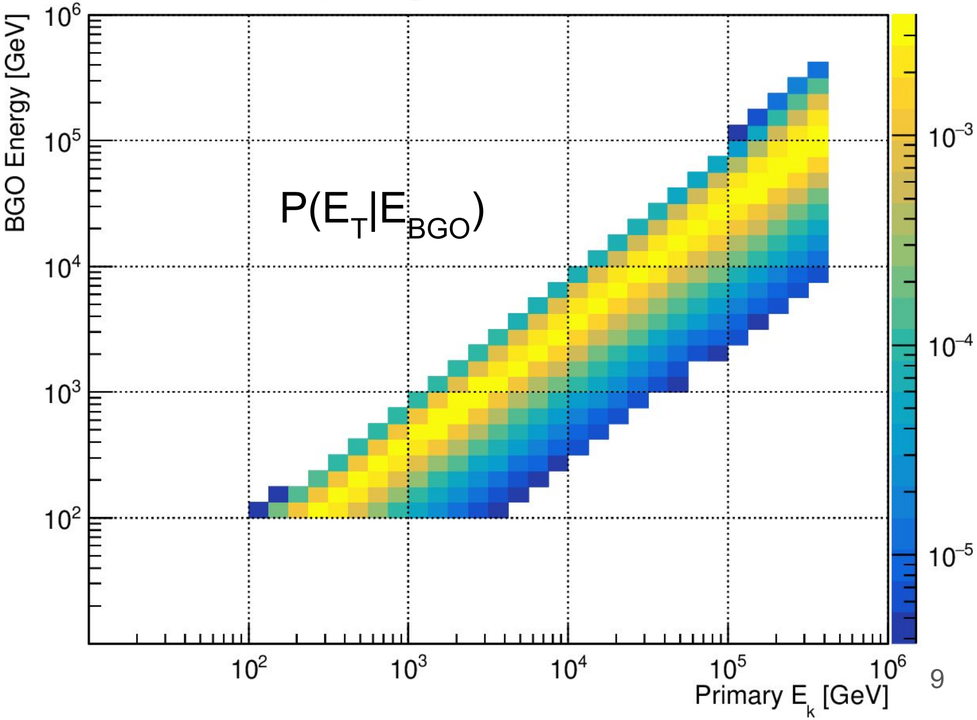
$$A_i = \sum_{el} w^{el} \; G^{el}_{gen} \; \frac{N^{el}_{sel}(E^i_T)}{N^{el}_{gen}(E^i_T)}$$



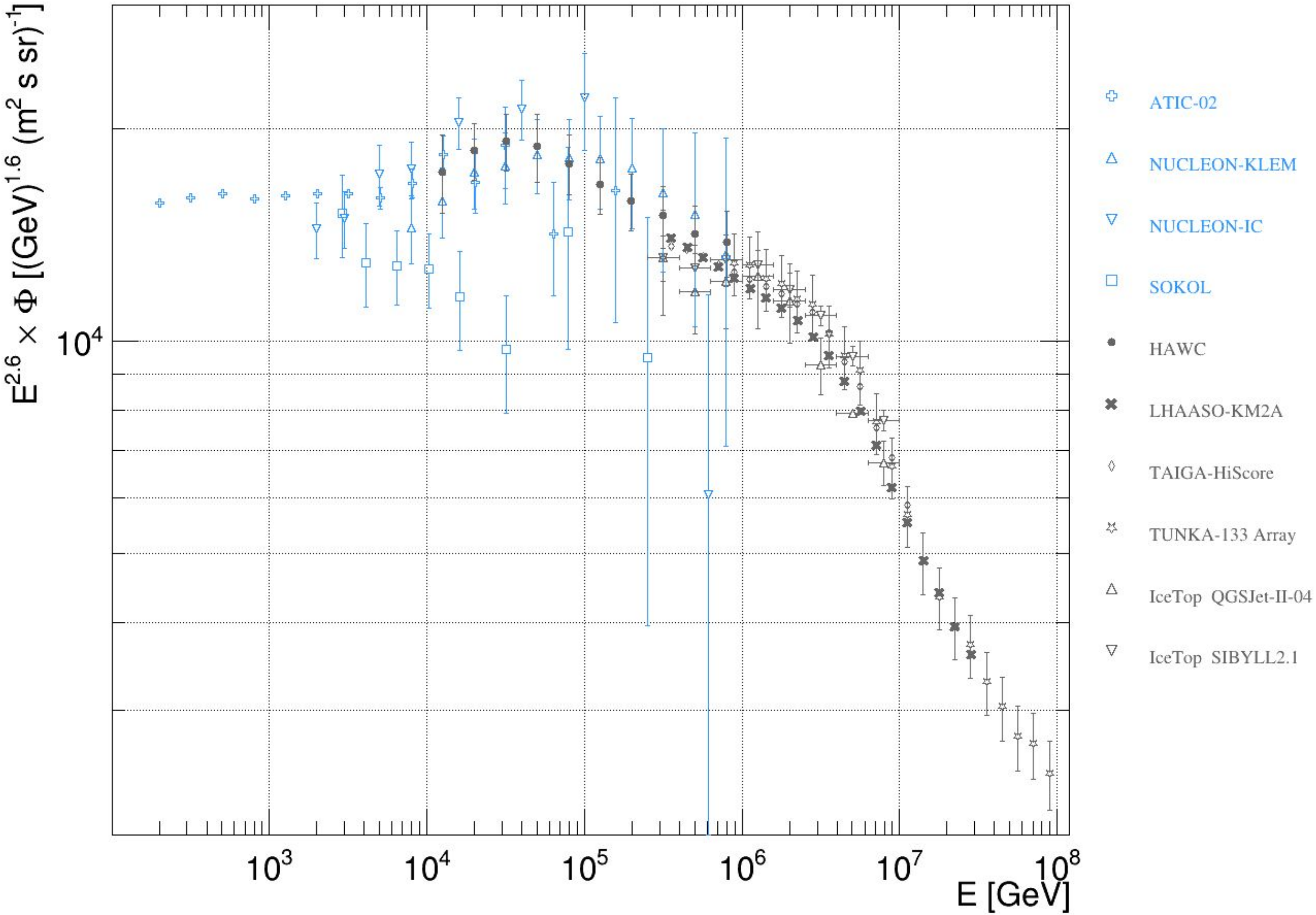
Weighted mean response matrix

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

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



All-particle flux



- Differential flux:

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

- Evaluated systematics
  - Unfolding
  - Composition model
- Contribution from hadronic model is under evaluation
- In agreement with indirect experiments results
- Structure at tens TeV (convolution of the softening of different nuclei?)
- Work in progress to extend the measurement up to 0.7/0.8 PeV

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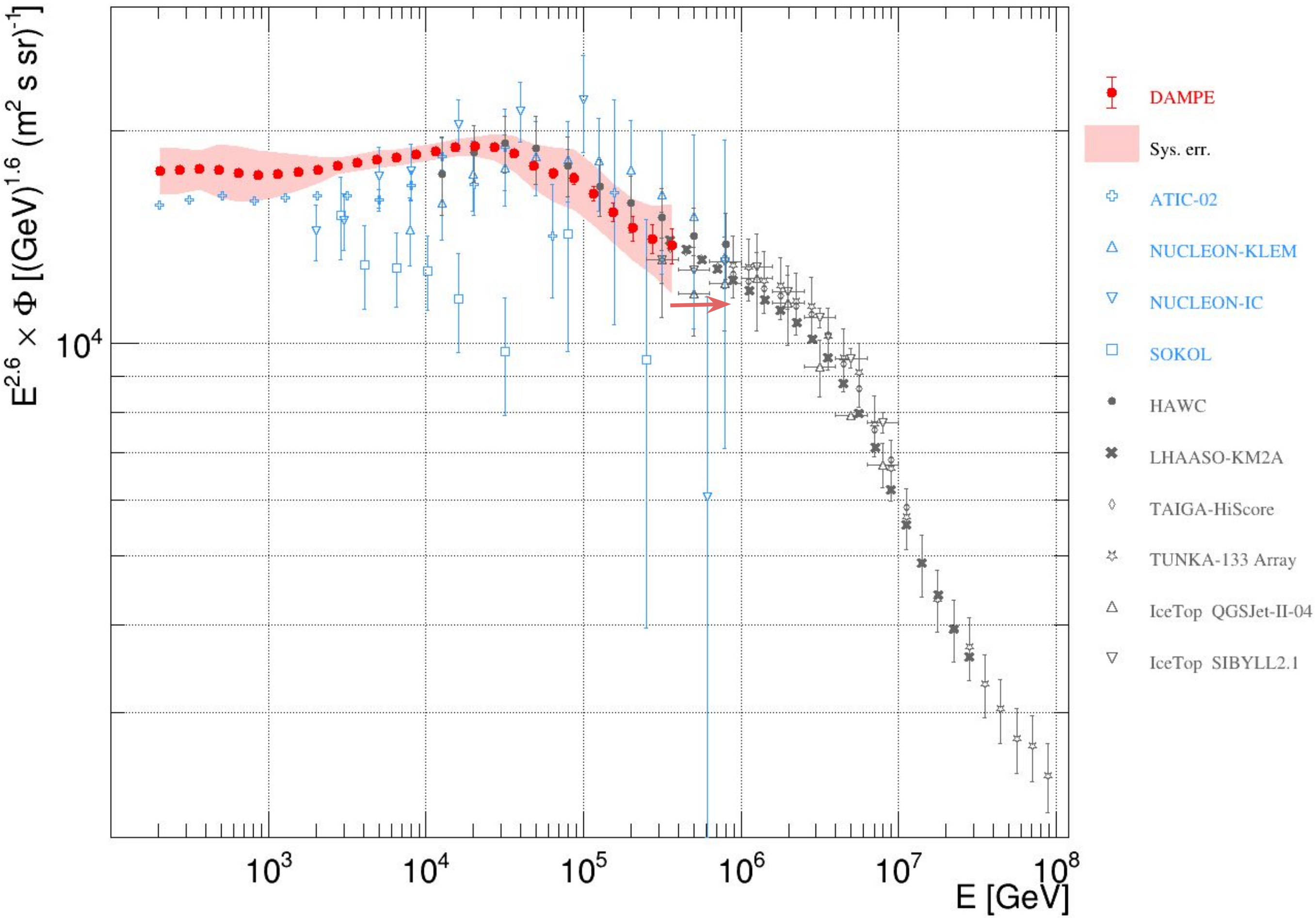

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Conclusions

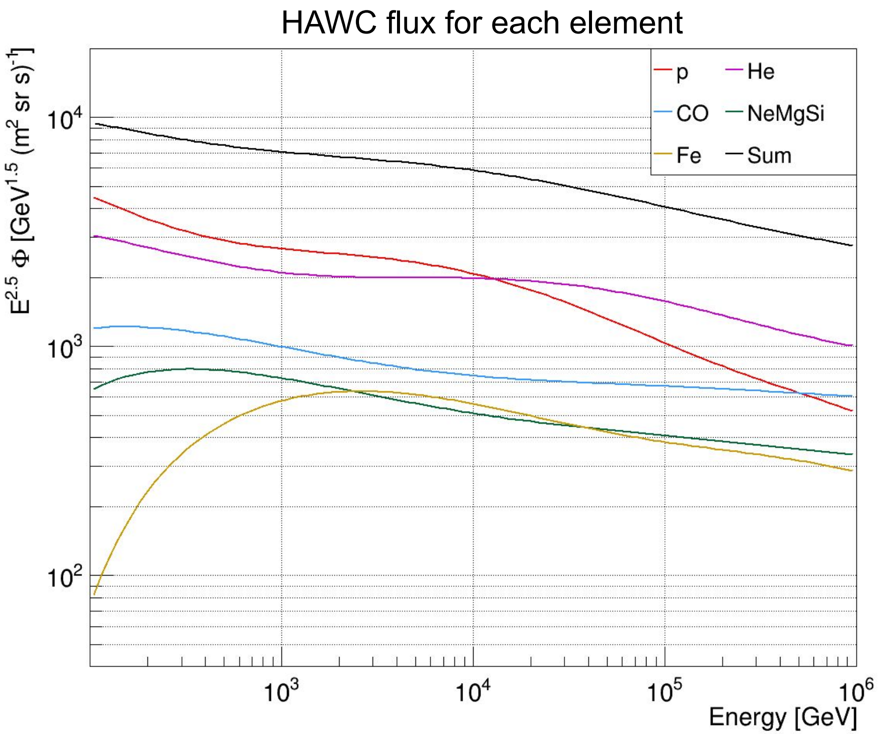
Preliminary result of the all-particle spectrum in the 200 GeV - 0.4 PeV energy range

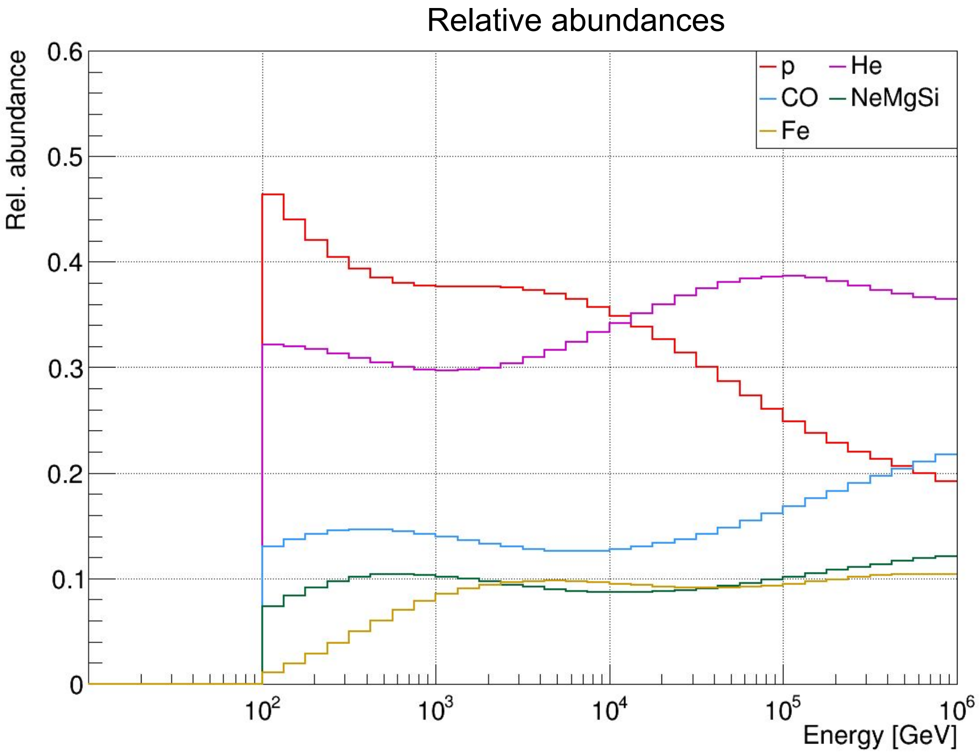
- Loose charge cut selection to increase the statistics
- Assumed a composition model: Recchia-Gabici model
- Systematics evaluation ongoing (limited dependence on the composition model)
- In agreement with other experiments data

Backup

HAWC composition model

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

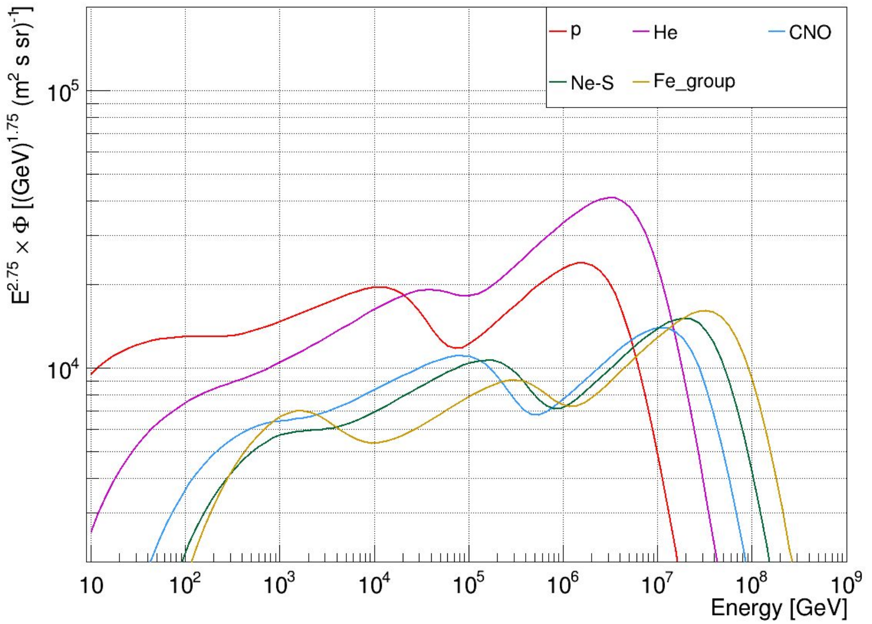




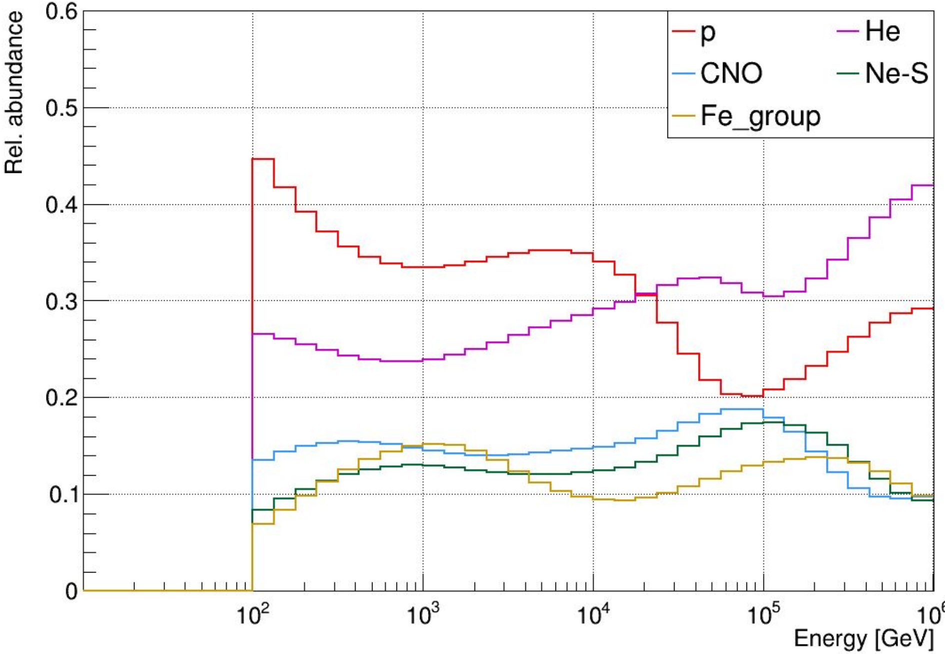
ZS composition model

- 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

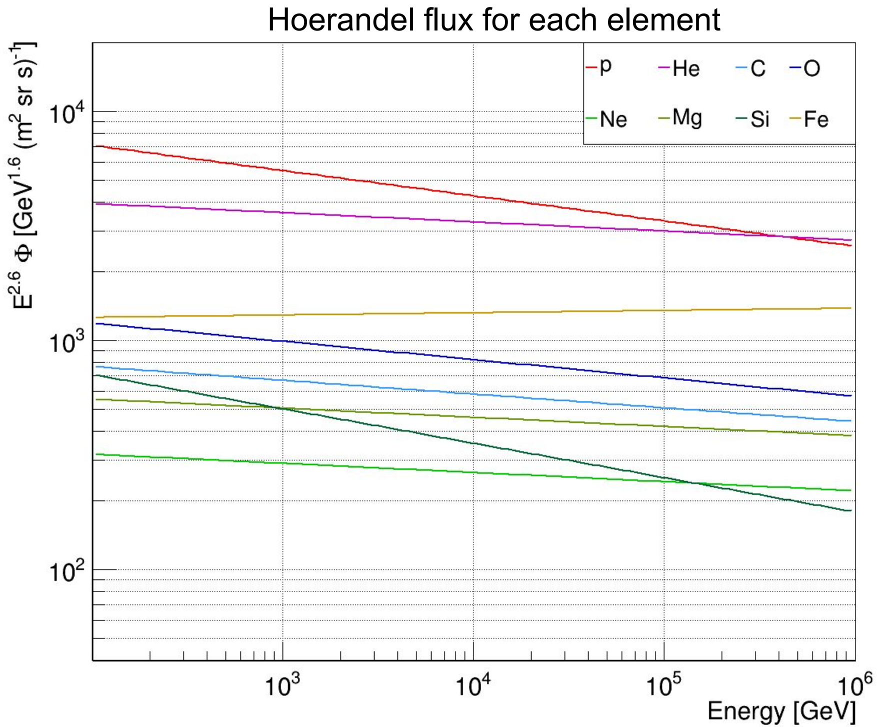


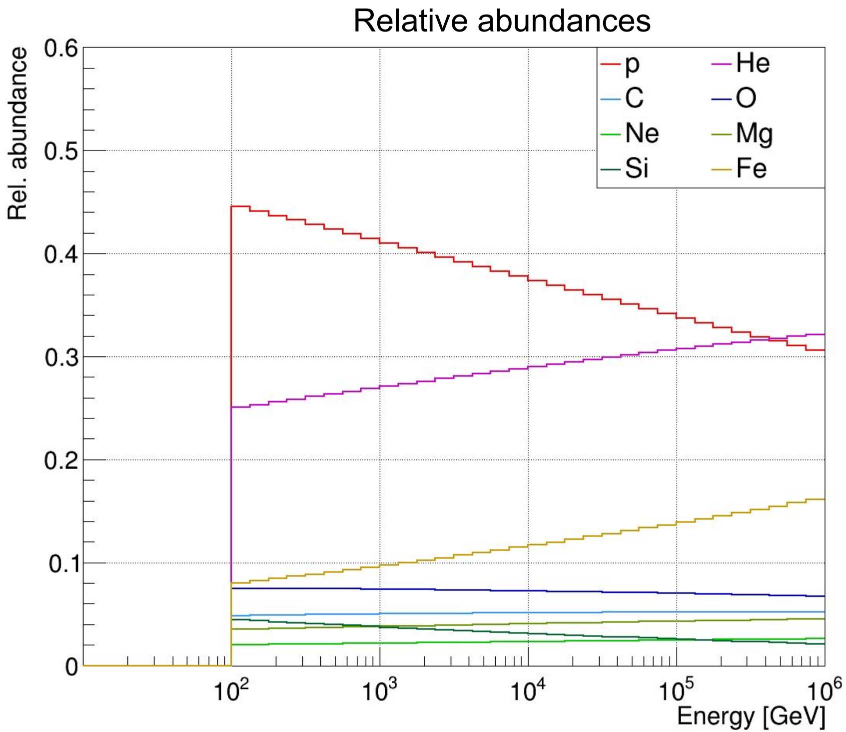
Relative abundances



Hoerandel composition model

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



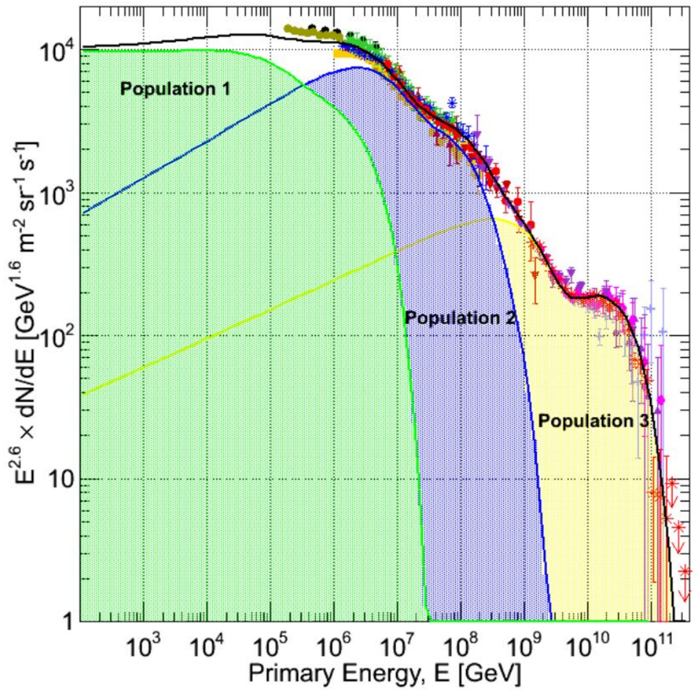


GST composition model

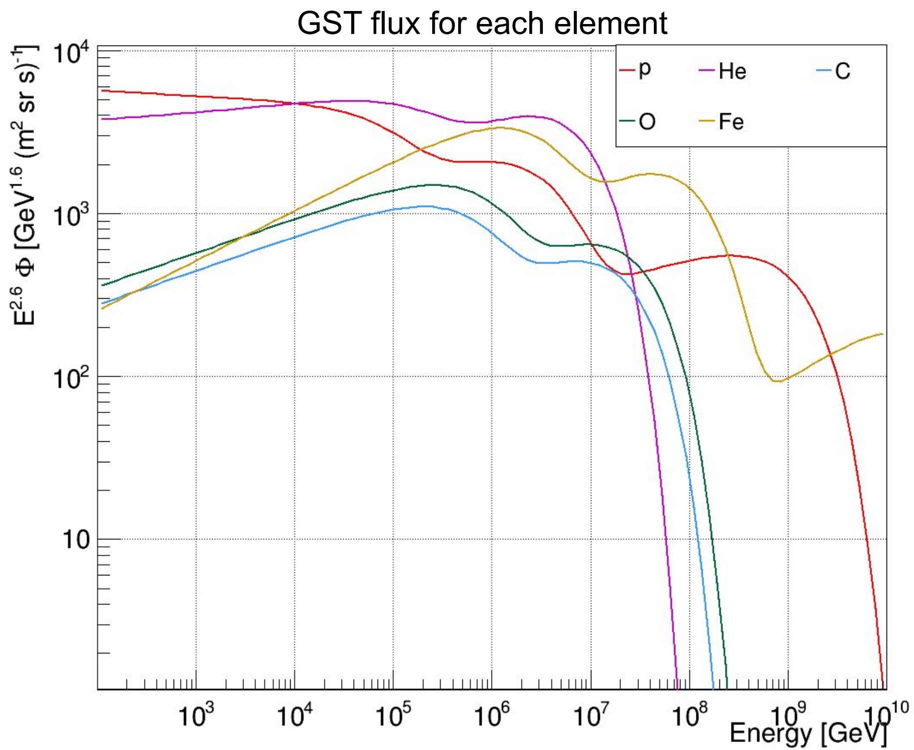
- Performed 2 different fits to experimental data
  - each assuming 3 populations of particles
  - different assumptions for the rigidity cut off for each population
  - 3 populations: pop. 1 & 2 of galactic origin, pop. 3 is extragalactic
  - Each population (j) is contains 5 groups of nuclei (i)

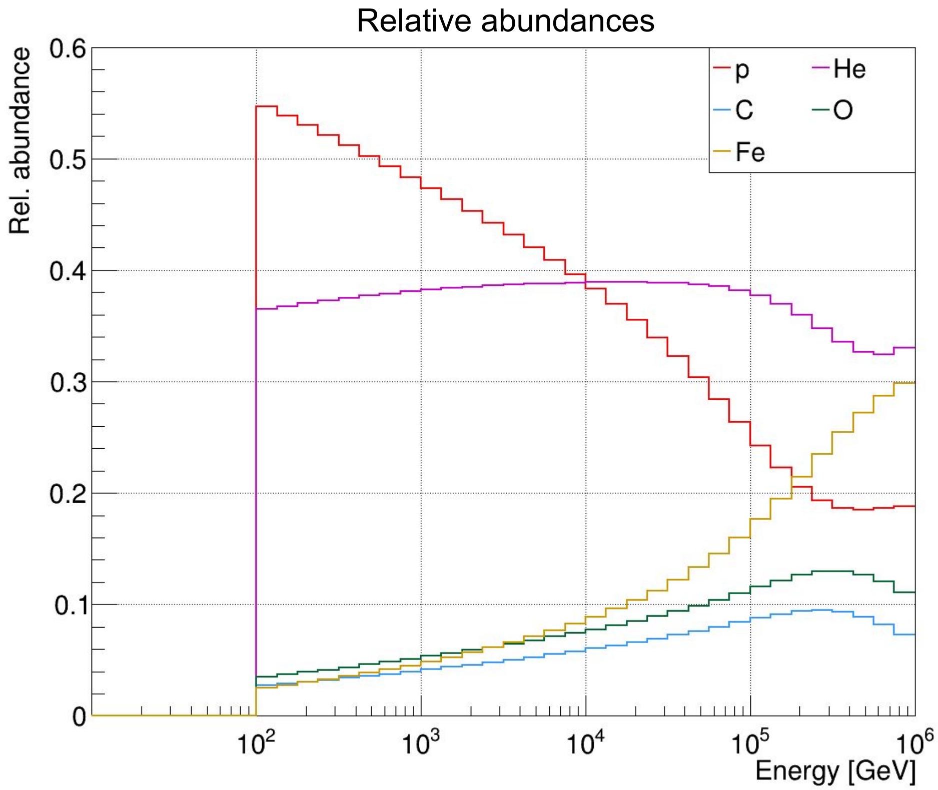
$$\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

	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

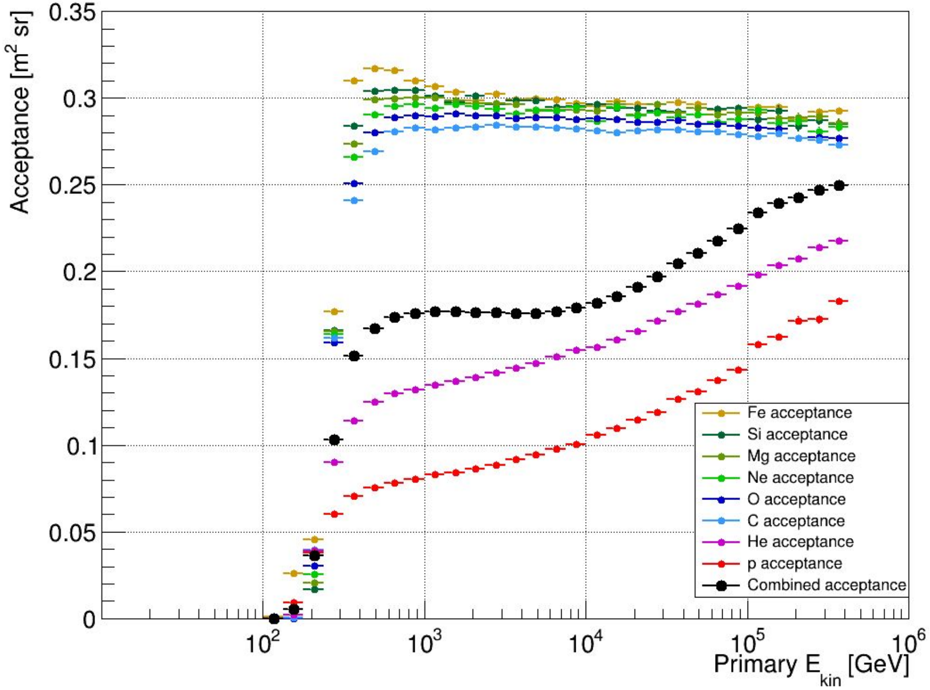




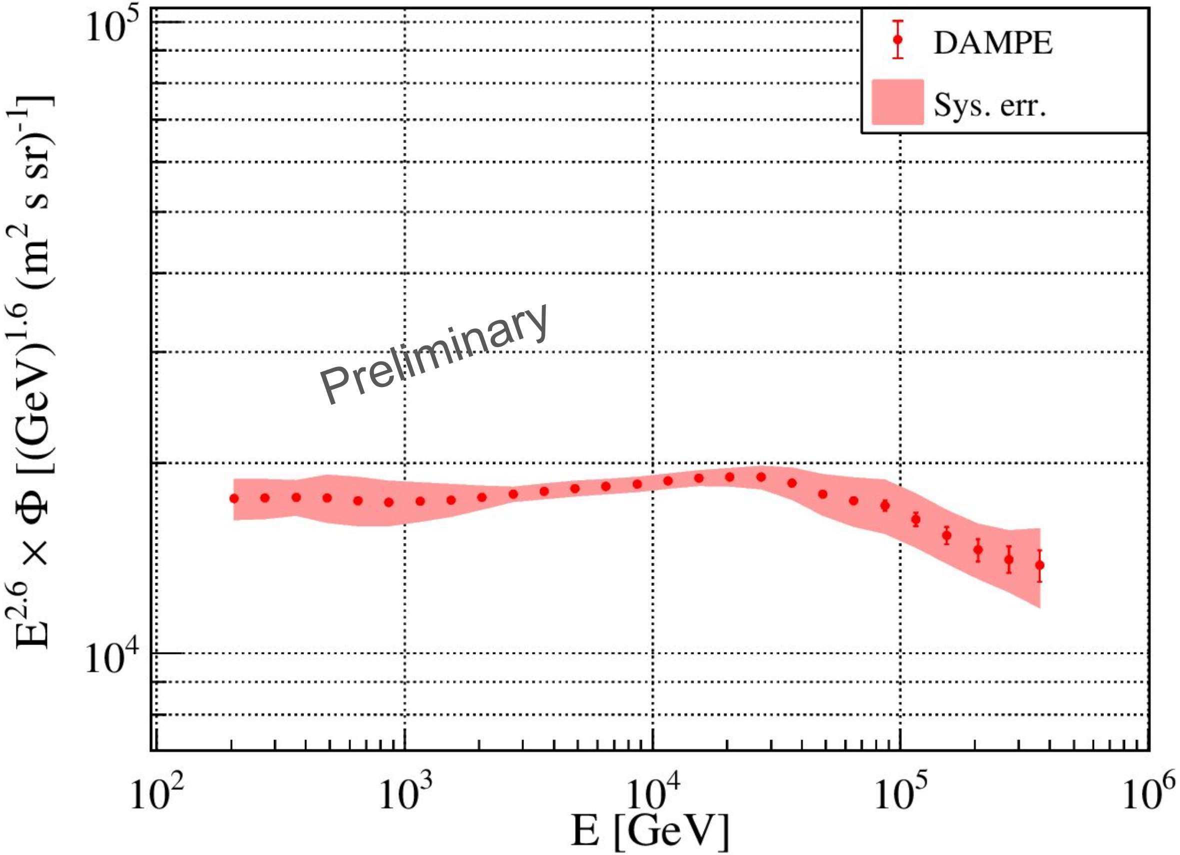
Combined acceptance

Weighted mean acceptance with RG model

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



All-particle flux



Differential flux:

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

Evaluated systematics

- Unfolding
- Composition model

Contribution from hadronic model is under evaluation