# Galactic CRs spectra with DAMPE and R&D activities for HERD

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Second year activity report
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GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
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# Overview

**Measurements of CRs spectra with DAMPE:**

- The DAMPE space mission
- The all-particle spectrum
- Preliminary analysis for the all-particle spectrum
- Next steps

**Hardware R&D of the HERD PSD:**

- the HERD future space mission
- Activities focused on the PSD hardware development and test

# The DAMPE space mission

- Collaboration of Chinese, Italian and Swiss scientific institutions
- Launched in December 2015
  - Sun-synchronous orbit
  - At 500 km altitude
  - Payload of 1400 kg
- The primary scientific goals:
  - Study of cosmic ($e^+ + e^-$) spectrum
  - Study of CR protons and heavier nuclei
  - High energy γ-ray astronomy
  - Indirect search for Dark Matter signatures
- The main features

| | |
|---|---|
| Acceptance | ~0.3 $m^2sr$ |
| Energy resolution | 1.2% at 100 GeV (e/γ)<br>< 40% at 800 GeV (nuclei) |
| e/γ angular resolution | 0.2° at 100 GeV |
| Detection | 10 GeV - 10 TeV (e/γ)<br>50 GeV - 200 TeV (nuclei) |

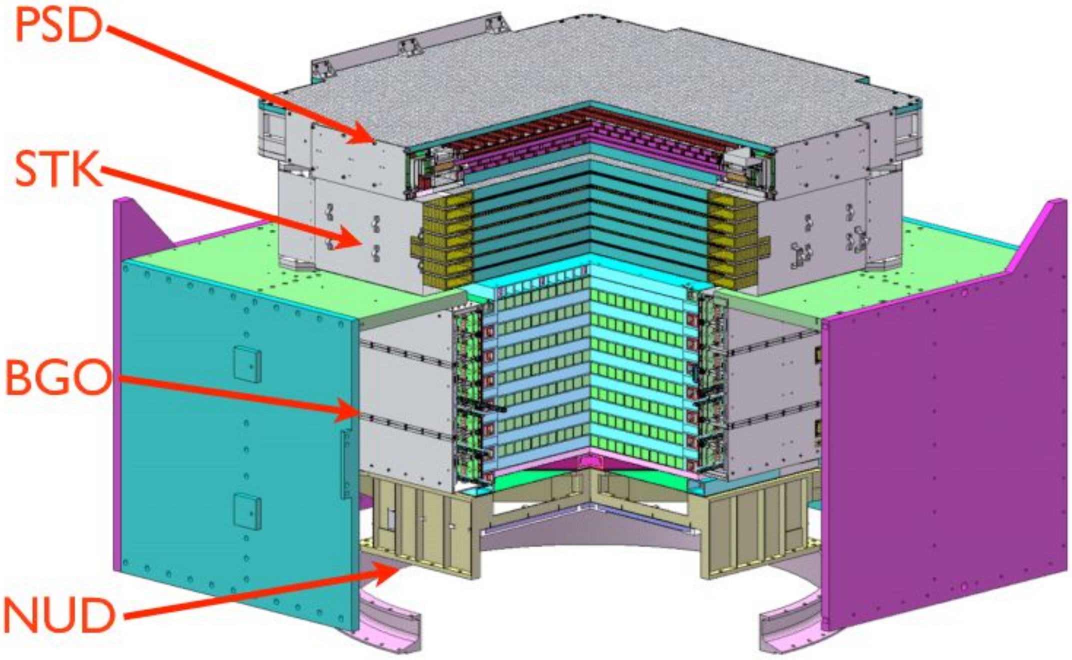
# The detector

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

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

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

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



# All-particle spectrum

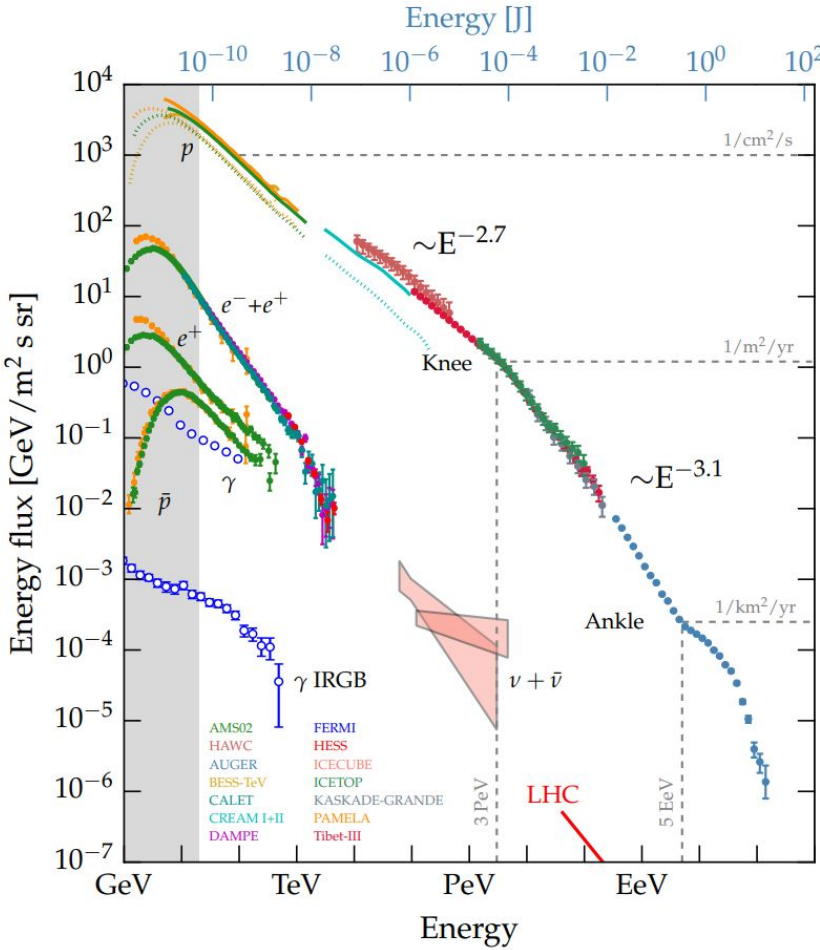
Direct CRs experiments

- Precise measurement of CRs spectra
- Difficulty in measuring CRs spectra > hundreds TeV
  - Limited acceptance
  - Rapidly falling CRs flux with energy

Indirect CRs experiments

- Measurements above the ‘knee’
- More model dependent
- Have larger uncertainties

**The measure of the all-particle spectrum between 100 GeV -1 PeV would provide a link between direct and indirect CRs detectors**




10.5281/zenodo.1468852

# Analysis objectives and progress

**Use loose charge cut selection to increase the statistics (and the energy reach)**

**First investigation**

- No charge selection
- No composition model assumption
- Need to assume the same acceptance and response matrix for all Z
- Study for dedicated analysis cuts to limit the systematics

**Current investigation**

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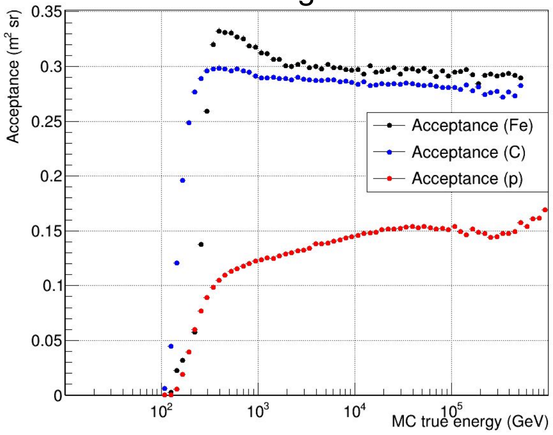
# Analysis objectives and progress

**Use loose charge cut selection to increase the statistics (and the energy reach)**

## First investigation

- No charge selection
- No composition model assumption
- **Problem**: p and Fe acceptances remain very different

→ the uncertainty in the unfolded flux would be too large



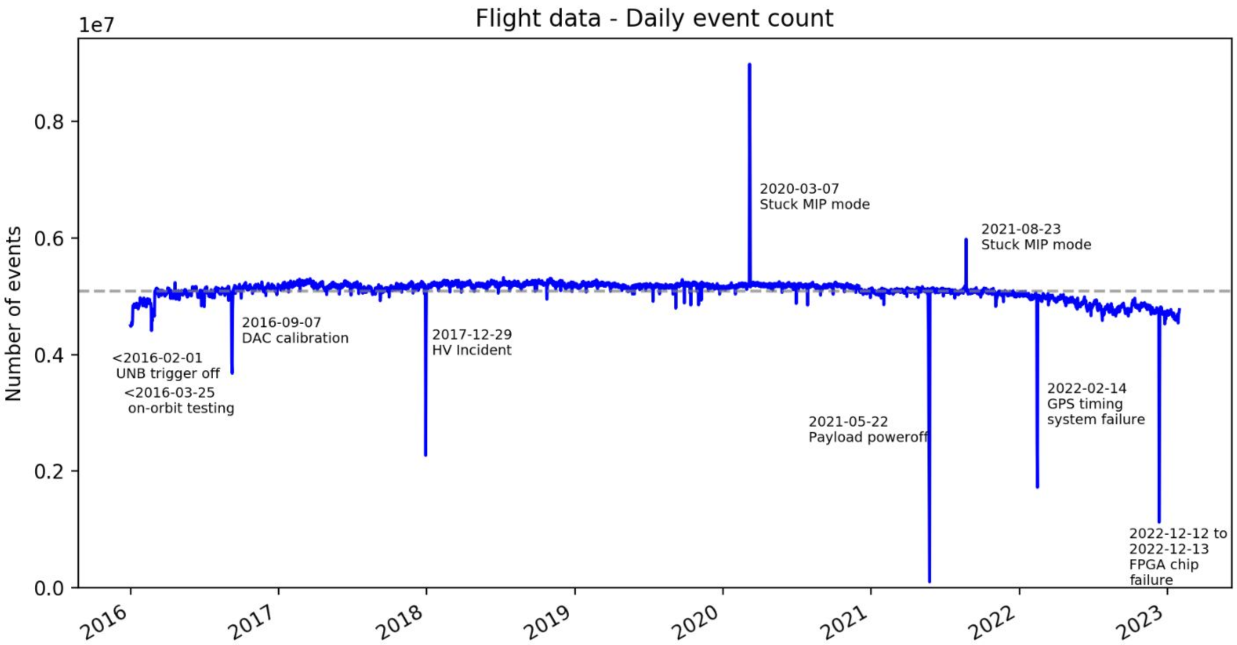

## Current investigation

- Assume a mass composition model
- Evaluate the systematics due to the assumption of a composition model
- Method typically used by ground-based experiments

# Data sets

Flight data

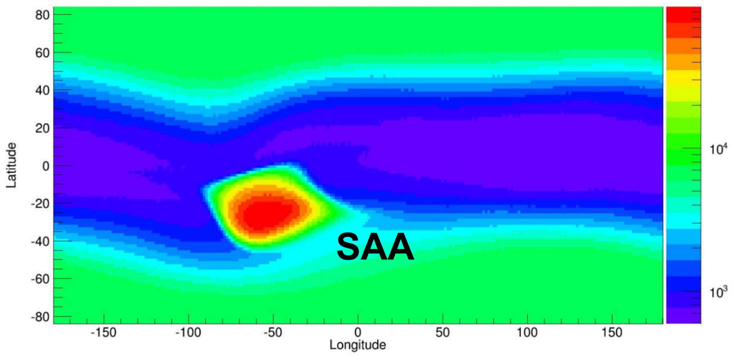
- 1/01/2016 - 31/12/2021
- 6 years of data
- ~ 5.2 M events /day




MC data

- Proton, He: [100 GeV - 1 PeV] energy range
- C, N, O, Mg, Fe: [100 GeV - 500 TeV] energy range

# Event selection - MC & flight data

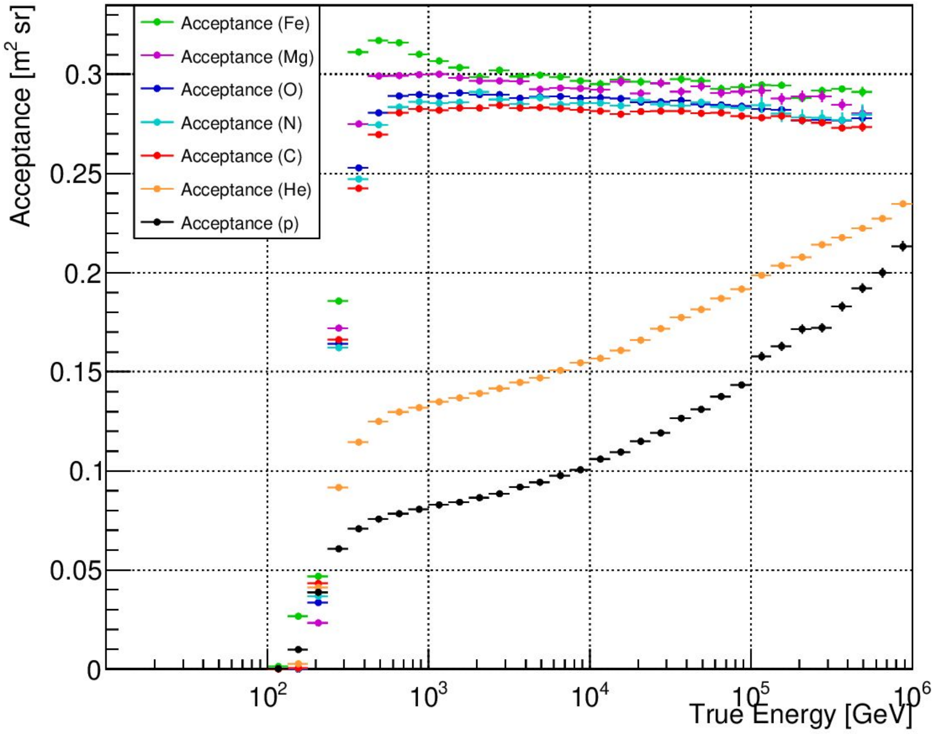



pre-selection

- Rejection of SAA flight data
- No side-in events
- Good shower containment in the BGO

Analysis selection

- BGO $E_{DEPO}$ > 100 GeV
- High Energy Trigger activated



# Composition model

- Use the same elements considered for MC dataset
- **First attempt** with Hoerandel poly-gonato model

Table 7: Absolute flux $\Phi_Z^0$ $[(\mathrm{m^2\ sr\ s\ TeV})^{-1}]$ at $E_0$ = 1 TeV/nucleus and spectral index $\gamma_Z$ of cosmic–ray elements.

| Z | | $\Phi_Z^0$ | $-\gamma_Z$ | Z | | $\Phi_Z^0$ | $-\gamma_Z$ | Z | | $\Phi_Z^0$ | $-\gamma_Z$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $1^2$ | H | $8.73 \cdot 10^{-2}$ | 2.71 | $32^4$ | Ge | $4.02 \cdot 10^{-6}$ | 2.54 | $63^4$ | Eu | $1.58 \cdot 10^{-7}$ | 2.27 |
| $2^2$ | He | $5.71 \cdot 10^{-2}$ | 2.64 | $33^4$ | As | $9.99 \cdot 10^{-7}$ | 2.54 | $64^4$ | Gd | $6.99 \cdot 10^{-7}$ | 2.25 |
| $3^3$ | Li | $2.08 \cdot 10^{-3}$ | 2.54 | $34^4$ | Se | $2.11 \cdot 10^{-6}$ | 2.53 | $65^4$ | Tb | $1.48 \cdot 10^{-7}$ | 2.24 |
| $4^3$ | Be | $4.74 \cdot 10^{-4}$ | 2.75 | $35^4$ | Br | $1.34 \cdot 10^{-6}$ | 2.52 | $66^4$ | Dy | $6.27 \cdot 10^{-7}$ | 2.23 |
| $5^3$ | B | $8.95 \cdot 10^{-4}$ | 2.95 | $36^4$ | Kr | $1.30 \cdot 10^{-6}$ | 2.51 | $67^4$ | Ho | $8.36 \cdot 10^{-8}$ | 2.22 |
| $6^3$ | C | $1.06 \cdot 10^{-2}$ | 2.66 | $37^4$ | Rb | $6.93 \cdot 10^{-7}$ | 2.51 | $68^4$ | Er | $3.52 \cdot 10^{-7}$ | 2.21 |
| $7^3$ | N | $2.35 \cdot 10^{-3}$ | 2.72 | $38^4$ | Sr | $2.11 \cdot 10^{-6}$ | 2.50 | $69^4$ | Tm | $1.02 \cdot 10^{-7}$ | 2.20 |
| $8^3$ | O | $1.57 \cdot 10^{-2}$ | 2.68 | $39^4$ | Y | $7.82 \cdot 10^{-7}$ | 2.49 | $70^4$ | Yb | $4.15 \cdot 10^{-7}$ | 2.19 |
| $9^3$ | F | $3.28 \cdot 10^{-4}$ | 2.69 | $40^4$ | Zr | $8.42 \cdot 10^{-7}$ | 2.48 | $71^4$ | Lu | $1.72 \cdot 10^{-7}$ | 2.18 |
| $10^3$ | Ne | $4.60 \cdot 10^{-3}$ | 2.64 | $41^4$ | Nb | $5.05 \cdot 10^{-7}$ | 2.47 | $72^4$ | Hf | $3.57 \cdot 10^{-7}$ | 2.17 |
| $11^3$ | Na | $7.54 \cdot 10^{-4}$ | 2.66 | $42^4$ | Mo | $7.79 \cdot 10^{-7}$ | 2.46 | $73^4$ | Ta | $2.16 \cdot 10^{-7}$ | 2.16 |
| $12^3$ | Mg | $8.01 \cdot 10^{-3}$ | 2.64 | $43^4$ | Tc | $6.98 \cdot 10^{-8}$ | 2.46 | $74^4$ | W | $4.16 \cdot 10^{-7}$ | 2.15 |
| $13^3$ | Al | $1.15 \cdot 10^{-3}$ | 2.66 | $44^4$ | Ru | $3.01 \cdot 10^{-7}$ | 2.45 | $75^4$ | Re | $3.35 \cdot 10^{-7}$ | 2.13 |
| $14^3$ | Si | $7.96 \cdot 10^{-3}$ | 2.75 | $45^4$ | Rh | $3.77 \cdot 10^{-7}$ | 2.44 | $76^4$ | Os | $6.42 \cdot 10^{-7}$ | 2.12 |
| $15^3$ | P | $2.70 \cdot 10^{-4}$ | 2.69 | $46^4$ | Pd | $5.10 \cdot 10^{-7}$ | 2.43 | $77^4$ | Ir | $6.63 \cdot 10^{-7}$ | 2.11 |
| $16^3$ | S | $2.29 \cdot 10^{-3}$ | 2.55 | $47^4$ | Ag | $4.54 \cdot 10^{-7}$ | 2.42 | $78^4$ | Pt | $1.03 \cdot 10^{-6}$ | 2.10 |
| $17^3$ | Cl | $2.94 \cdot 10^{-4}$ | 2.68 | $48^4$ | Cd | $6.30 \cdot 10^{-7}$ | 2.41 | $79^4$ | Au | $7.70 \cdot 10^{-7}$ | 2.09 |
| $18^3$ | Ar | $8.36 \cdot 10^{-4}$ | 2.64 | $49^4$ | In | $1.61 \cdot 10^{-7}$ | 2.40 | $80^4$ | Hg | $7.43 \cdot 10^{-7}$ | 2.08 |
| $19^3$ | K | $5.36 \cdot 10^{-4}$ | 2.65 | $50^4$ | Sn | $7.15 \cdot 10^{-7}$ | 2.39 | $81^4$ | Ti | $4.28 \cdot 10^{-7}$ | 2.06 |
| $20^3$ | Ca | $1.47 \cdot 10^{-3}$ | 2.70 | $51^4$ | Sb | $2.03 \cdot 10^{-7}$ | 2.38 | $82^4$ | Pb | $8.06 \cdot 10^{-7}$ | 2.05 |
| $21^3$ | Sc | $3.04 \cdot 10^{-4}$ | 2.64 | $52^4$ | Te | $9.10 \cdot 10^{-7}$ | 2.37 | $83^4$ | Bi | $3.25 \cdot 10^{-7}$ | 2.04 |
| $22^3$ | Ti | $1.14 \cdot 10^{-3}$ | 2.61 | $53^4$ | I | $1.34 \cdot 10^{-7}$ | 2.37 | $84^4$ | Po | $3.99 \cdot 10^{-7}$ | 2.03 |
| $23^3$ | V | $6.31 \cdot 10^{-4}$ | 2.63 | $54^4$ | Xe | $5.74 \cdot 10^{-7}$ | 2.36 | $85^4$ | At | $4.08 \cdot 10^{-8}$ | 2.02 |
| $24^3$ | Cr | $1.36 \cdot 10^{-3}$ | 2.67 | $55^4$ | Cs | $2.79 \cdot 10^{-7}$ | 2.35 | $86^4$ | Rn | $1.74 \cdot 10^{-7}$ | 2.00 |
| $25^3$ | Mn | $1.35 \cdot 10^{-3}$ | 2.46 | $56^4$ | Ba | $1.23 \cdot 10^{-6}$ | 2.34 | $87^4$ | Fr | $1.78 \cdot 10^{-8}$ | 1.99 |
| $26^2$ | Fe | $2.04 \cdot 10^{-2}$ | 2.59 | $57^4$ | La | $1.23 \cdot 10^{-7}$ | 2.33 | $88^4$ | Ra | $7.54 \cdot 10^{-8}$ | 1.98 |
| $27^3$ | Co | $7.51 \cdot 10^{-5}$ | 2.72 | $58^4$ | Ce | $5.10 \cdot 10^{-7}$ | 2.32 | $89^4$ | Ac | $1.97 \cdot 10^{-8}$ | 1.97 |
| $28^3$ | Ni | $9.96 \cdot 10^{-4}$ | 2.51 | $59^4$ | Pr | $9.52 \cdot 10^{-8}$ | 2.31 | $90^4$ | Th | $8.87 \cdot 10^{-8}$ | 1.96 |
| $29^4$ | Cu | $2.18 \cdot 10^{-5}$ | 2.57 | $60^4$ | Nd | $4.05 \cdot 10^{-7}$ | 2.30 | $91^4$ | Pa | $1.71 \cdot 10^{-8}$ | 1.94 |
| $30^4$ | Zn | $1.66 \cdot 10^{-5}$ | 2.56 | $61^4$ | Pm | $8.30 \cdot 10^{-8}$ | 2.29 | $92^4$ | U | $3.54 \cdot 10^{-7}$ | 1.93 |
| $31^4$ | Ga | $2.75 \cdot 10^{-6}$ | 2.55 | $62^4$ | Sm | $3.68 \cdot 10^{-7}$ | 2.28 | | | | |

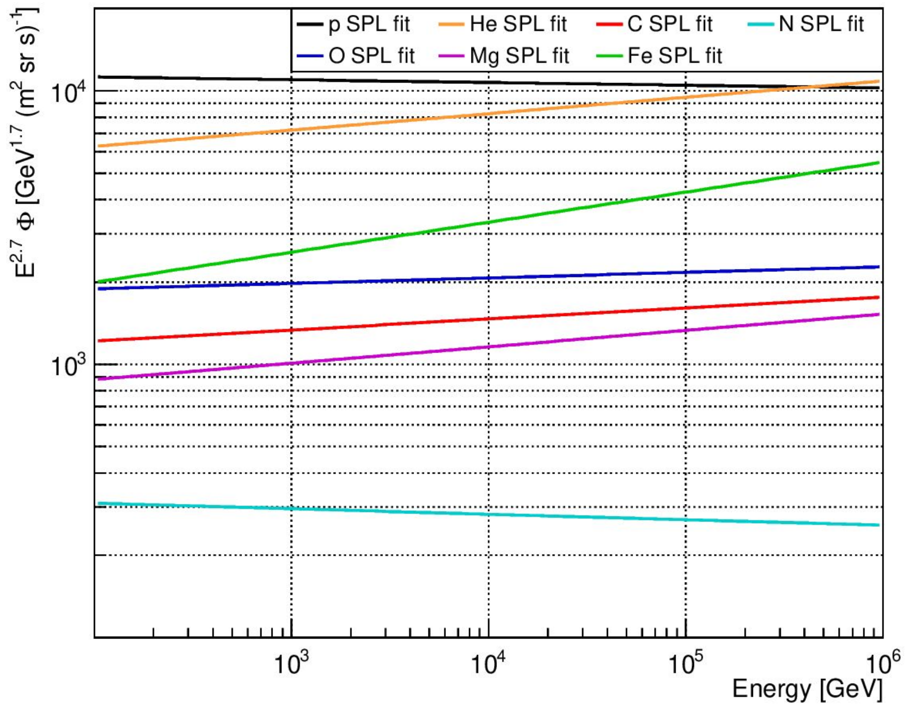
arXiv:astro-ph/0210453v1

Fit parameters (for H-Ni) derived as the best **fit to the spectra of different direct and indirect experiments** according to a **single power law (SPL)**

Using

- the Single Power Law fit function $$\Phi(E) = \Phi^0 \left(\frac{E}{1TeV}\right)^{\gamma}$$
- the Hoerandel parameters ($\Phi^0$, $\gamma$) (table)

The SPL for each element has been reproduced



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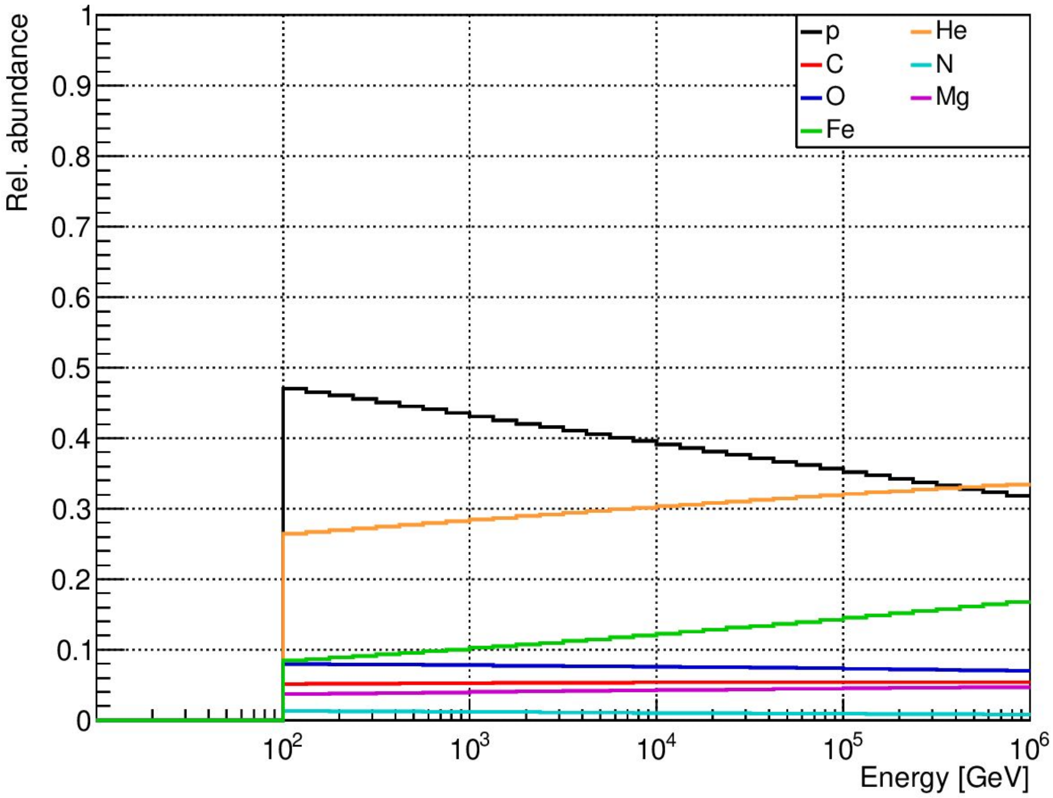
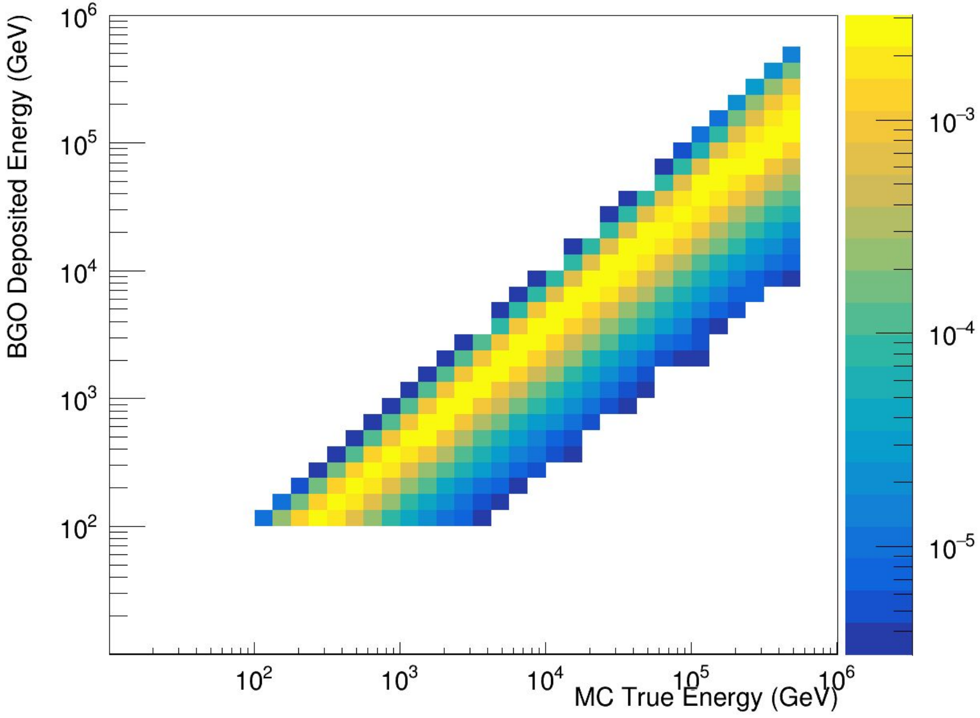
# Composition model - Hoerandel poly-gonato model

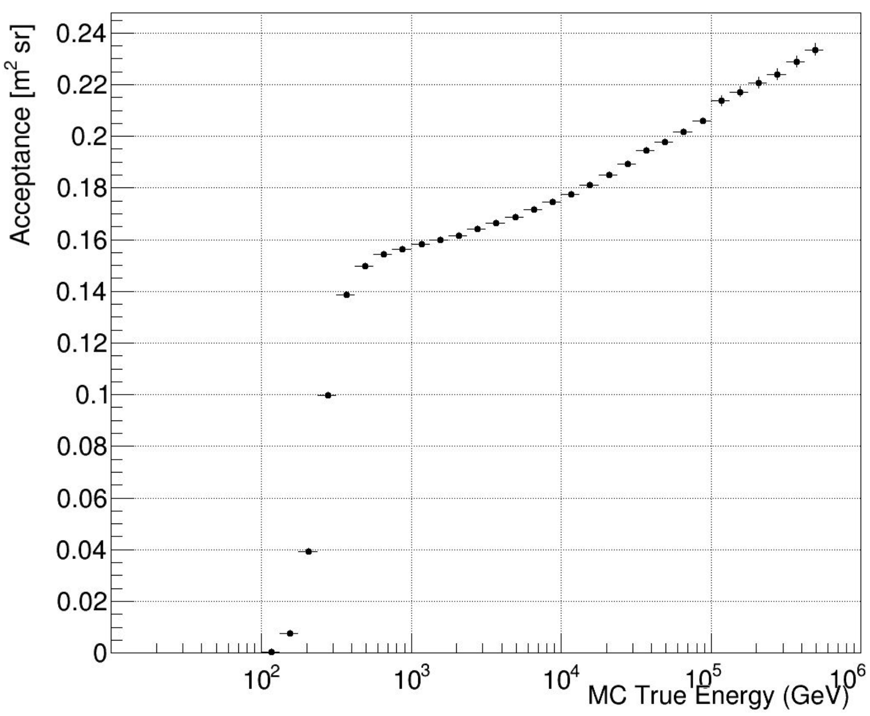
The relative abundances between 100 GeV - 1 PeV



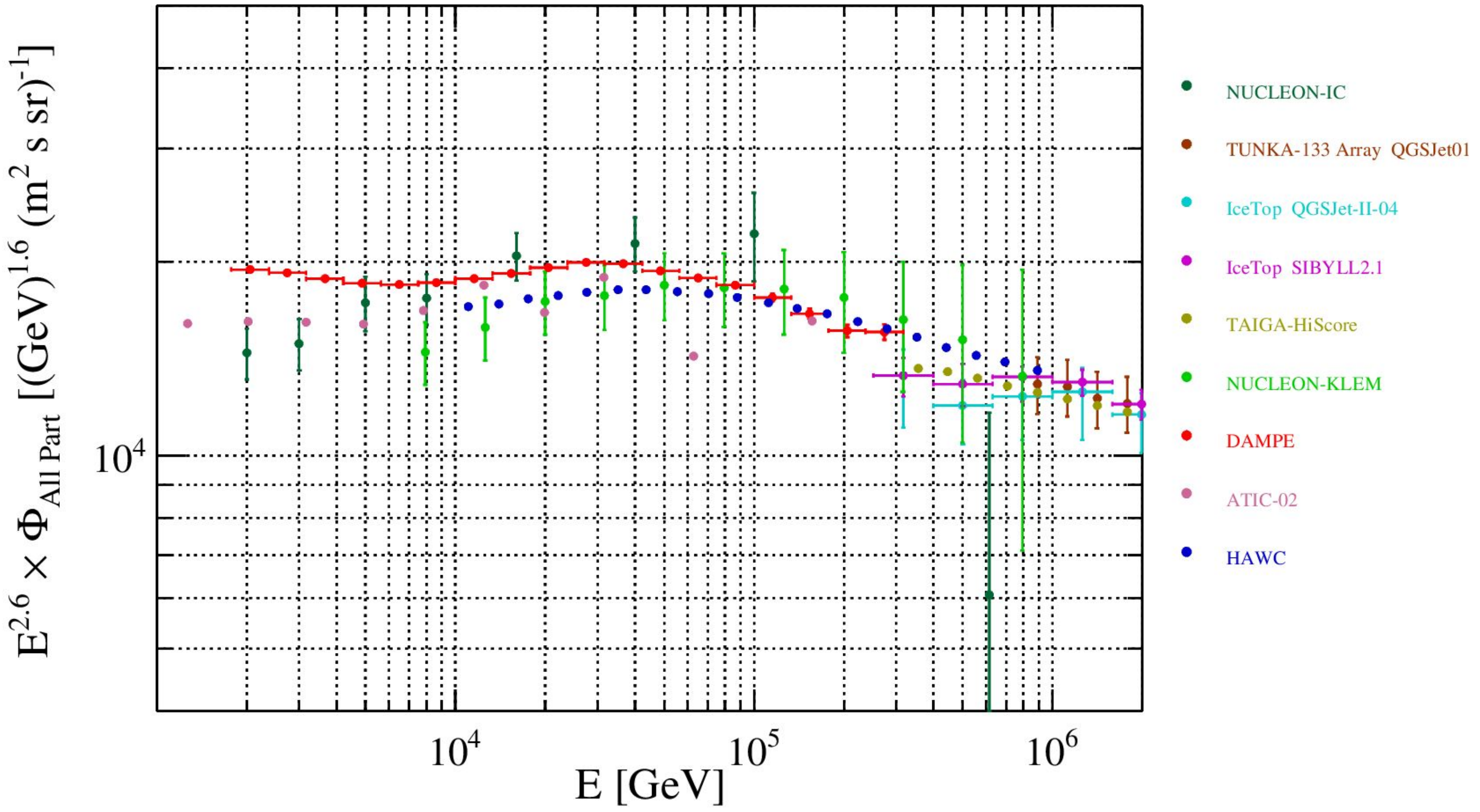
# MC data - using weights from Hoerandel model

Total acceptance (response matrix) obt. as the weighted sum of all the elements histograms (matrices) using weights derived from the Hoerandel model



# Output flux - first attempt with Hoerandel model



# Next steps

For the all-particle analysis

- Use other composition models to evaluate the systematics due to the composition model assumption
- Derive a composition model by fitting data from direct experiments
- Study better the possible systematics that could affect the flux at low (<1 TeV) and high energies (>200 TeV)

Perform other spectral analyses with DAMPE

- p/He flux ratio
- spectral measurement of the heavy mass elements combined group

# The HERD space mission

- Collaboration of Chinese, Italian, Swiss and Spanish institutes
- Launch planned for 2027
  - Onboard the China’s Space Station
  - Lifetime ~10 years
  - Payload of ~4000 kg
- The primary scientific goals:
  - Precise CR spectra and composition at the ‘knee’
  - High energy γ-ray astronomy and transient studies
  - Electrons spectra up to tens of TeV
  - Indirect search for Dark Matter signatures
- The expected performances

| | |
|---|---|
| Acceptance | ~2.5 $m^2sr$ |
| Energy resolution | 1.2% at 200 GeV (e/γ)<br>20-30% at 0.1 - $10^3$ TeV (nuclei) |
| e/γ angular resolution | 0.1° at 10 GeV |
| Detection | 10 GeV - tens TeV (e/γ)<br>30 GeV - 3 PeV (nuclei) |

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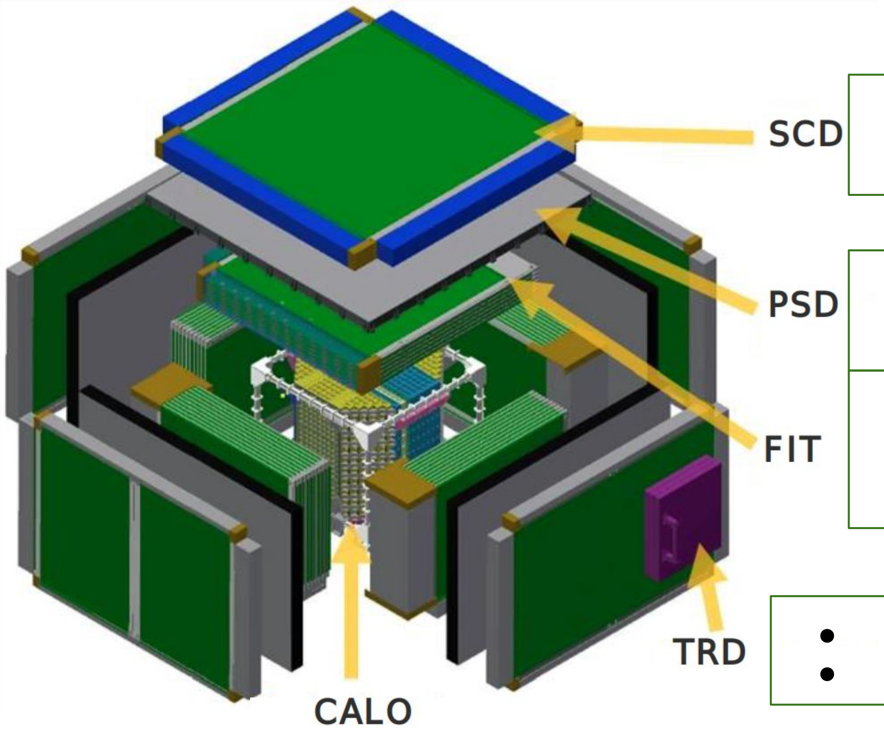
# The detector design




- Charge measurement
- Based on silicon micro-strip detectors

- Charge measurement + anti-coincidence for γ
- Based on plastic scintillator bars

- Charged particles track reconstruction + conversion for γ -rays
- Based on scintillating fiber mat

- Energy calibration of nuclei (TeV region)
- Installation on a lateral face

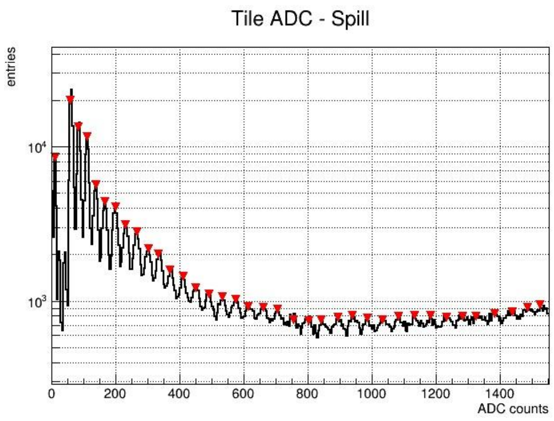
- Particle energy measurement + e/p separation
- ~7500 LYSO crystals
- 55 $X_0$ and 3 $\lambda_I$

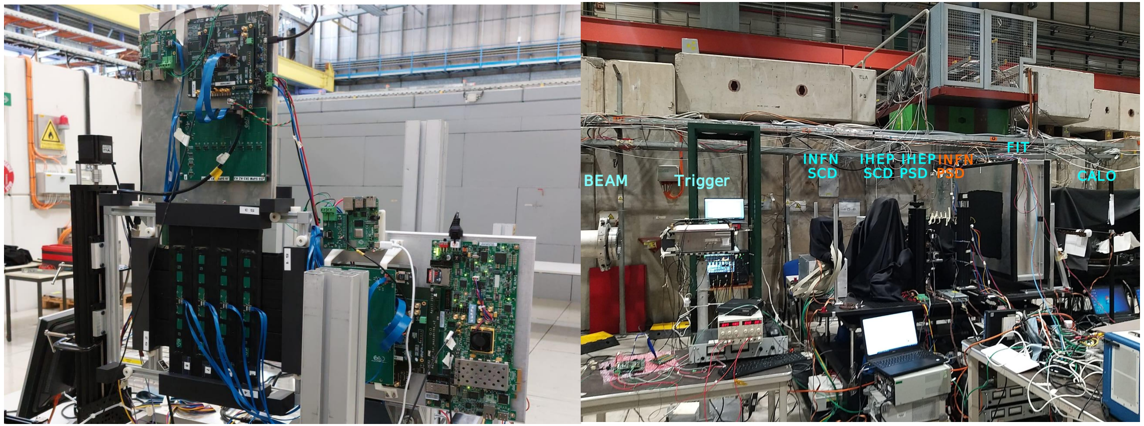
# The HERD PSD

- Design: 4 layers of trapezoidal bars readout by SiPMs
- Requirements
  - High detection efficiency: ~99.9%
  - Good charge resolution < 30% at low Z
  - Wide dynamic range in identifying nuclei (at least up to Z = 30)

Test beam campaigns at CERN and CNAO to

- optimise SiPM-based readout
- evaluate the overall performance of the prototypes




Experimental setup @CERN SPS, Oct 2023

PSD Prototype & Tile (in the Trigger)

- made of BC404 plastic scintillator
- SiPMs ($3 \times 3$ mm$^2$ & $1.3 \times 1.3$ mm$^2$ )
- HERD-BETA chip

Ion beam

- Derived from a 150 GeV/A primary lead beam impinging onto a Beryllium target

# Summary

**All-particle analysis with DAMPE:**

- Importance of the all-particle spectrum to provide a link between direct and indirect CRs experiments
- Analysis status
  - Built a preliminary structure for the analysis
  - Assumption of the Hoerandel model to obtain the composition model
  - Obtained a preliminary result for the all-particle

**Hardware R&D of the HERD PSD:**

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

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## 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

## Collaboration meetings

- 11th international DAMPE workshop, virtual, 12-15 jun. 2023
- Some talks during periodical 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

## 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

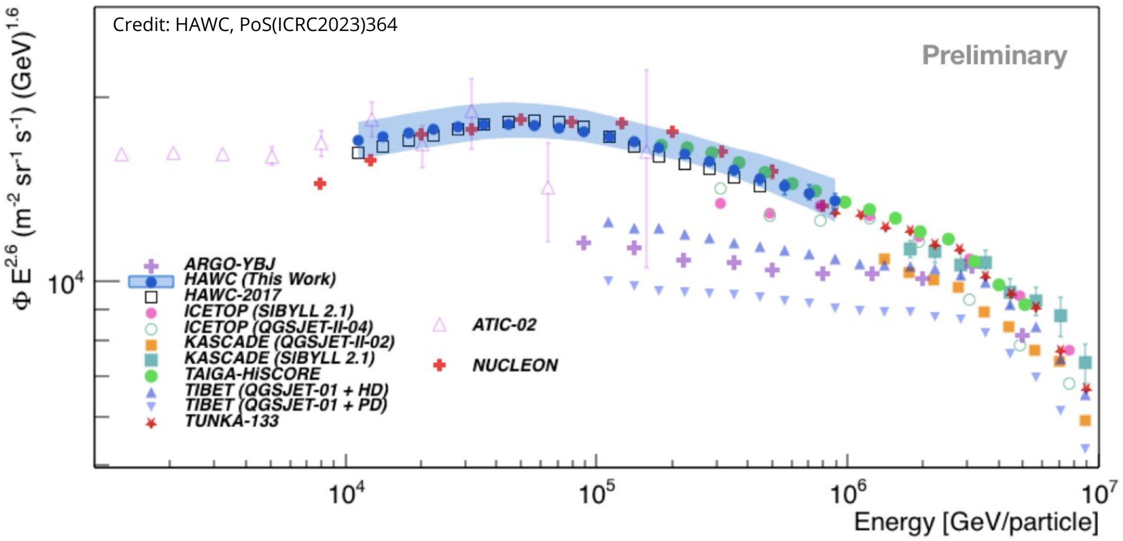
- Participation in SHARPER (European Researchers nigh), L'Aquila, 30 sept. 2022
- Volunteer in UHECR2022 conference, L'Aquila, 3-7 oct. 2022
- 9th GSSI Astroparticle physics Science Fair, L'Aquila, 21-23 feb. 2023
- Participation to "Corso formazione ed addestramento Preposti per visite in underground",Assergi-LNGS, 10 may 2023

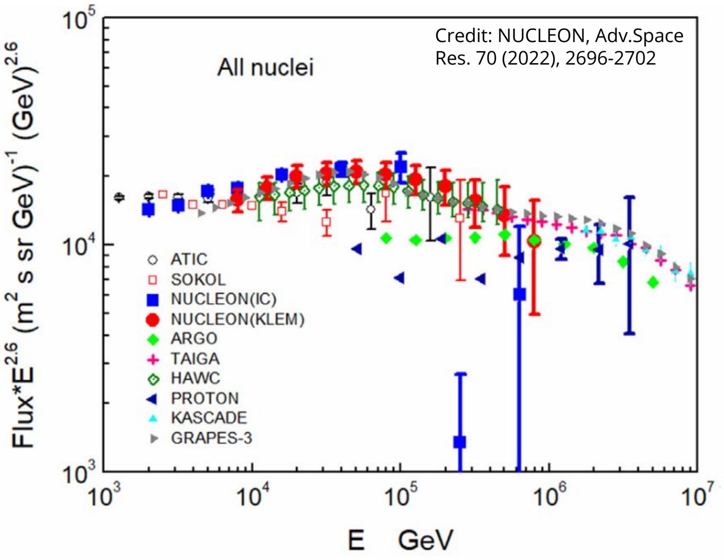
# Backup slides

# All-particle spectrum recent measurements

**HAWC:**
Data from 01/2017 to 12/2020
Energy range 10 TeV - 1 PeV
A Break at 28.1 TeV with 4.2 $\sigma$

**NUCLEON:**
~3 yrs of data
Energy range 8 TeV - 800 TeV
A bend observed in the spectrum

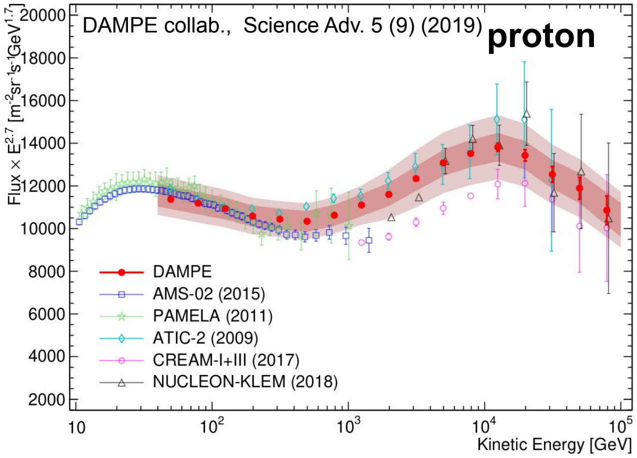


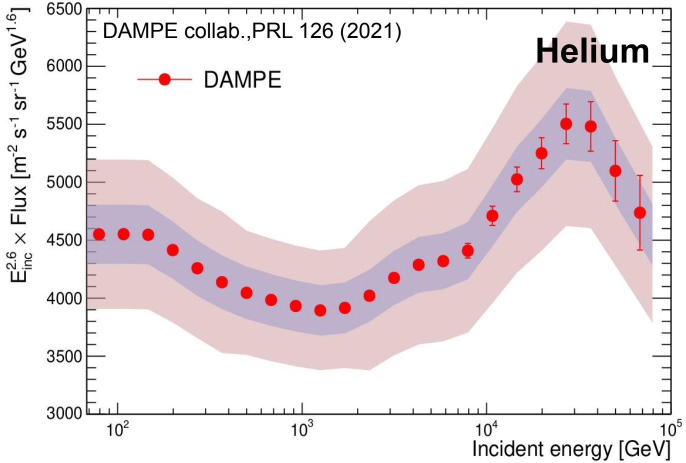




## Measuring the spectrum between 100 GeV -1 PeV

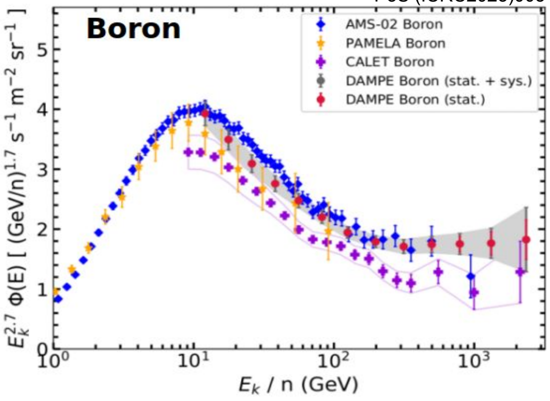
- **to test the paradigm of a unique power law energy spectrum below the knee**
- **to provide a link between direct and indirect CRs detectors**

# Individual CR nuclei spectra

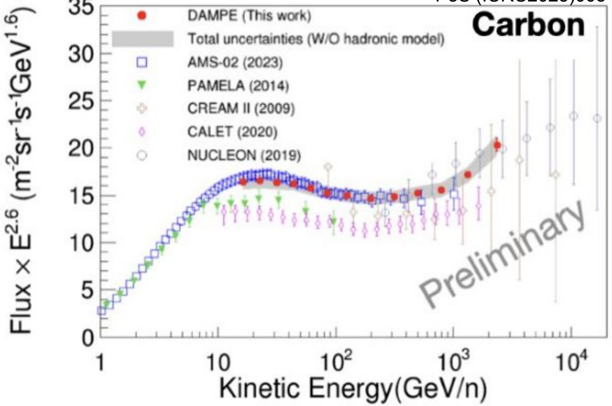


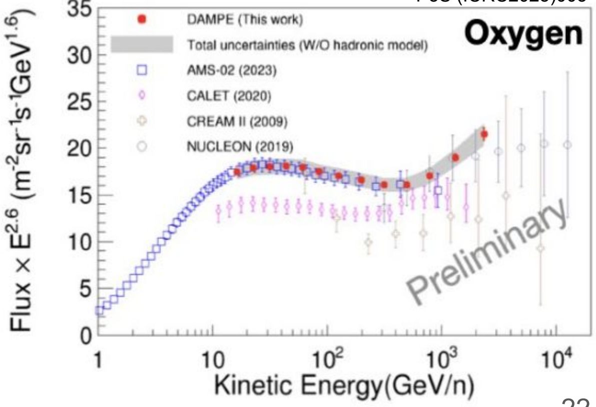

PoS (ICRC2023)003




PoS (ICRC2023)003




PoS (ICRC2023)003



# The HERD PSD

PSD Prototype

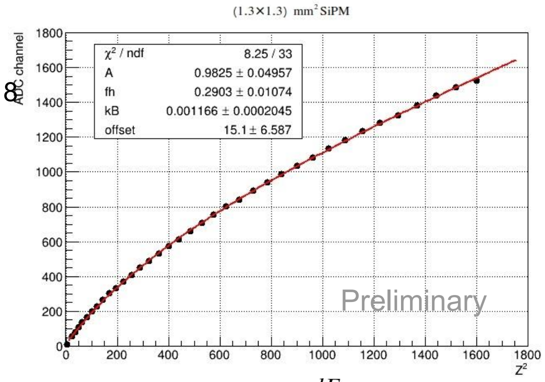
- 8 bars made of BC404 plastic scintillator
- 8 Printed Circuit Boards (PCBs) housing 8 Hamamatsu SiPMs
  - 4 of size 3 × 3 mm$^2$
  - 4 of size 1.3 × 1.3 mm$^2$
- HERD-BETA chip as read-out electronics (by ICCUB-SiUB)

Tile (in the Trigger)

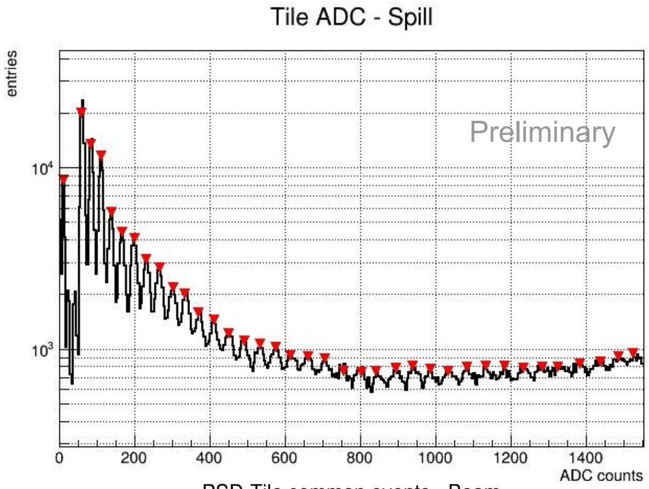
- BC404 plastic scintillator
- 2 SiPMS (3 × 3 mm$^2$ & 1.3 × 1.3 mm$^2$ )
- HERD-BETA chip

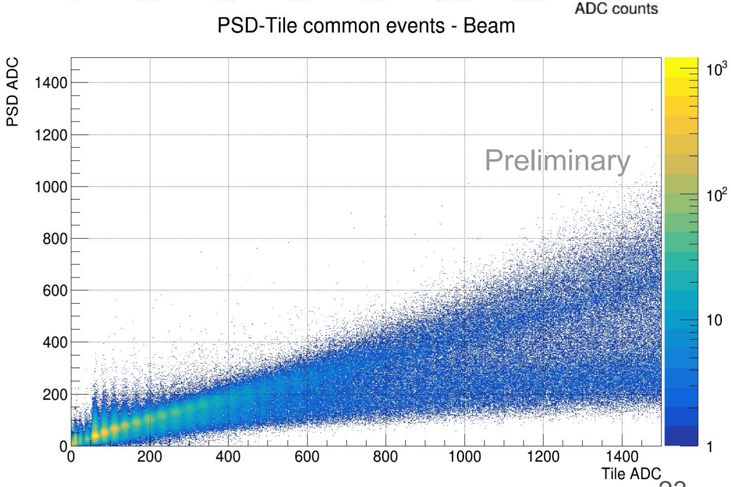
Ion beam

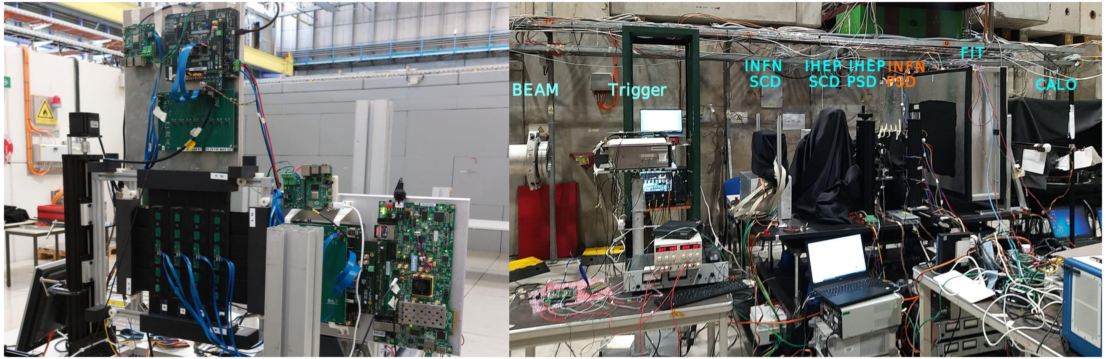
- Derived from a 150 GeV/A primary lead beam impinging onto a Beryllium target




$$\frac{dL}{dx} = A \cdot \frac{(1 - f_h) \cdot \frac{dE}{dx}}{1 + k_b \cdot \frac{dE}{dx}} + A \cdot f_h \frac{dE}{dx}$$

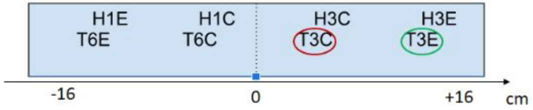


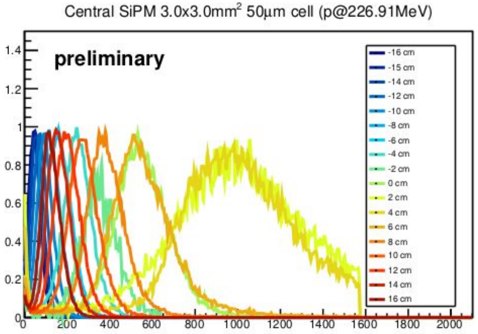

Experimental setup @CERN SPS, Oct 2023

# The HERD PSD




Prototype

- 1 bar of plastic scintillator
- Equipped with Hamamatsu SiPMs
    - size 6 x 6 mm$^2$
    - size 3 × 3 mm$^2$
    - size 1.3 × 1.3 mm$^2$
- HERD-BETA chip as read-out electronics (by ICCUB-SiUB)

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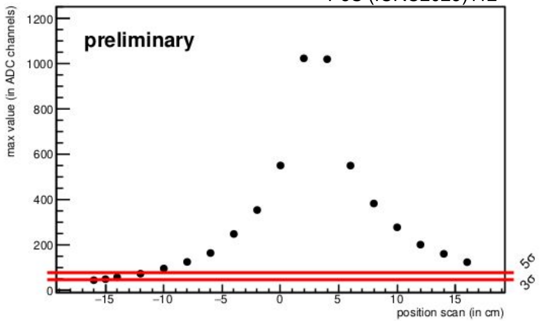


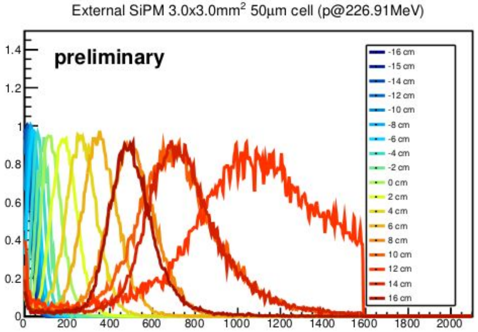


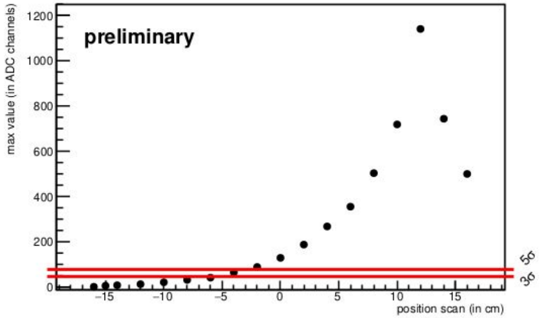


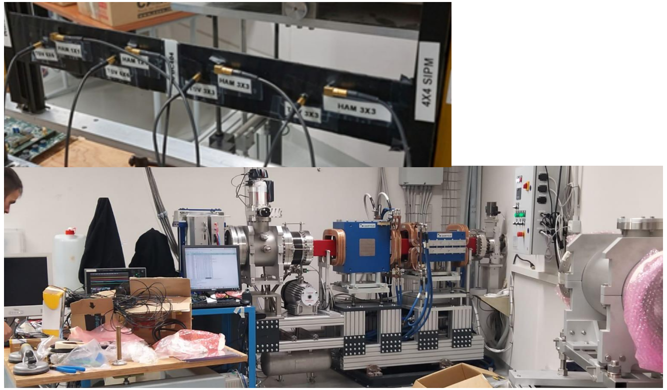


Experimental setup @CNAO, May 2023