

# Cosmic Li, Be, B spectra with DAMPE and R&D for HERD

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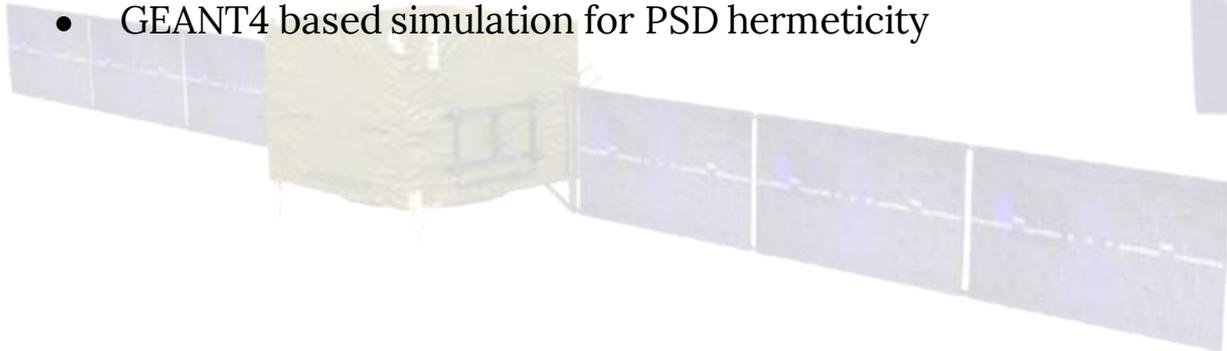
*Advisor: Ivan De Mitri*

## **Li-Be-B analysis with DAMPE:**

- Secondary cosmic rays
- CR direct detection in space with DAMPE
- Preliminary B spectrum
- Preliminary Li, Be spectrum

## **Simulation work for the HERD PSD**

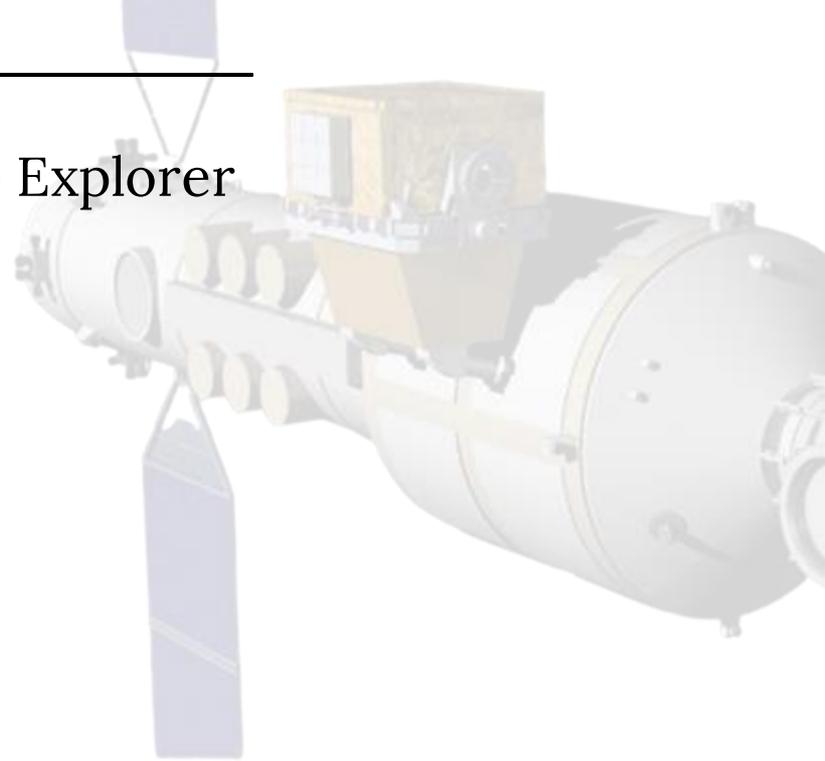
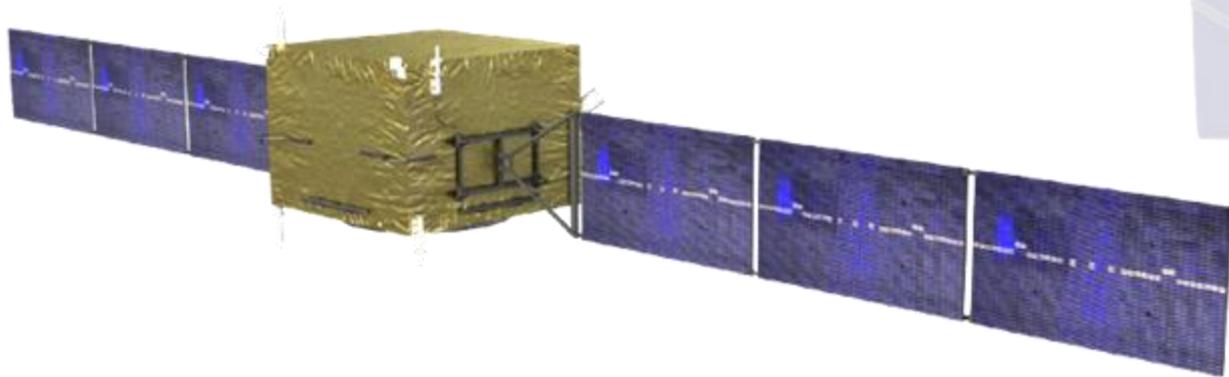
- The HERD mission
- GEANT4 based simulation for PSD hermeticity



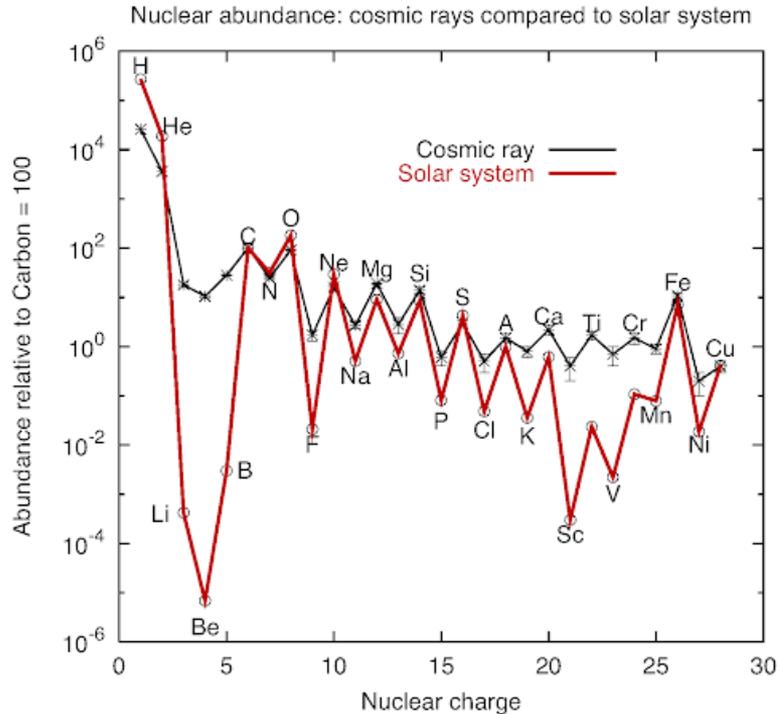
# DAMPE

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## Dark Matter Particle Explorer



# Secondary Cosmic Rays



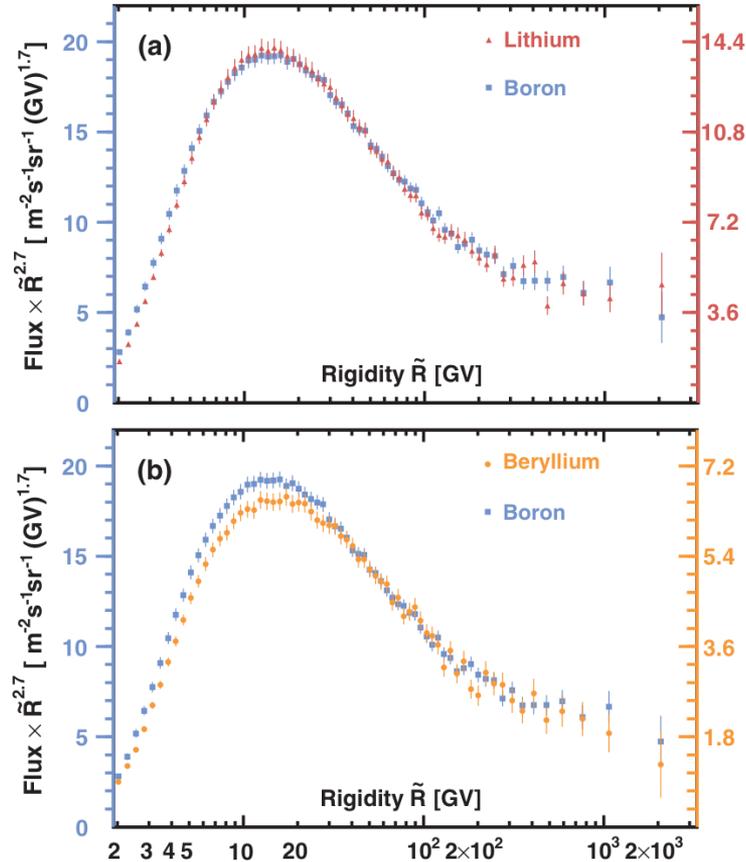
## Li, Be and B:

- Lithium, Beryllium and Boron (**secondaries**) are not produced in main stellar nucleosynthesis reactions
- Abundances of Li, Be, B are much higher in Cosmic Rays (CRs) than in the solar system
- Production: **cosmic ray spallation** with the ISM  
Mainly from C, O (**primaries**)

## CR propagation:

- Measuring the flux of secondaries can offer insight into:
  - Mechanisms of CR propagation
  - Origin of structures in the primaries spectra

# Current measurements



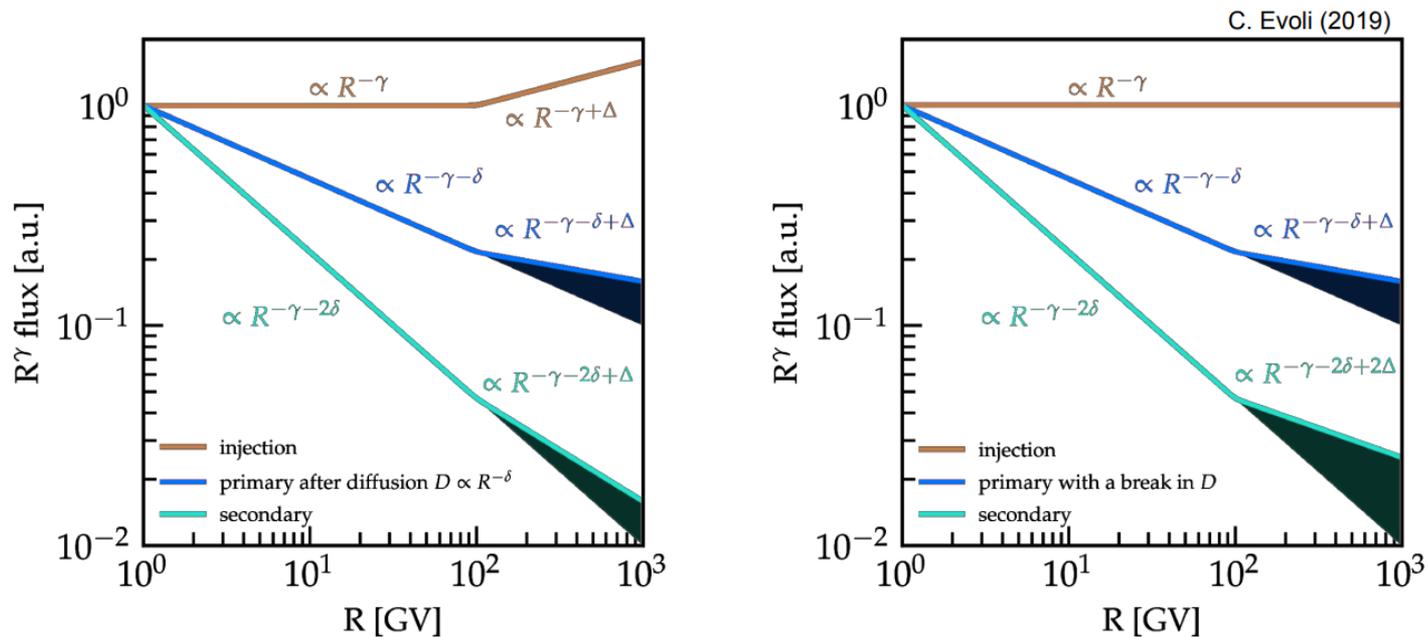
## AMS-02:

- Li, Be, B fluxes measured with first 5 years data
- Rigidity range: 1.9 GV - 3.3 TV
- Identical rigidity dependence over 30 GV
- Hardening at 200 GV observed in all three nuclei
- Rigidity dependencies of primaries and secondaries are significantly different

**New highlighted CR properties.**

**Extend measurement to higher energies.**

# Origin of observed hardening



- A spectral hardening at a few hundred GV has been observed for virtually all CR nuclei
- Is it a source or a propagation effect?
- Precisely measuring the hardening in the secondaries can provide an answer

# The DAMPE mission

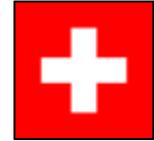
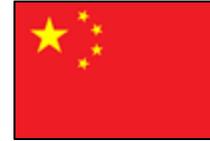
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## Launched in December 2015

- Sun-synchronous orbit
- Altitude: 500 km
- Payload: 1400 kg

## Collaboration:

- China
- Italy
- Switzerland

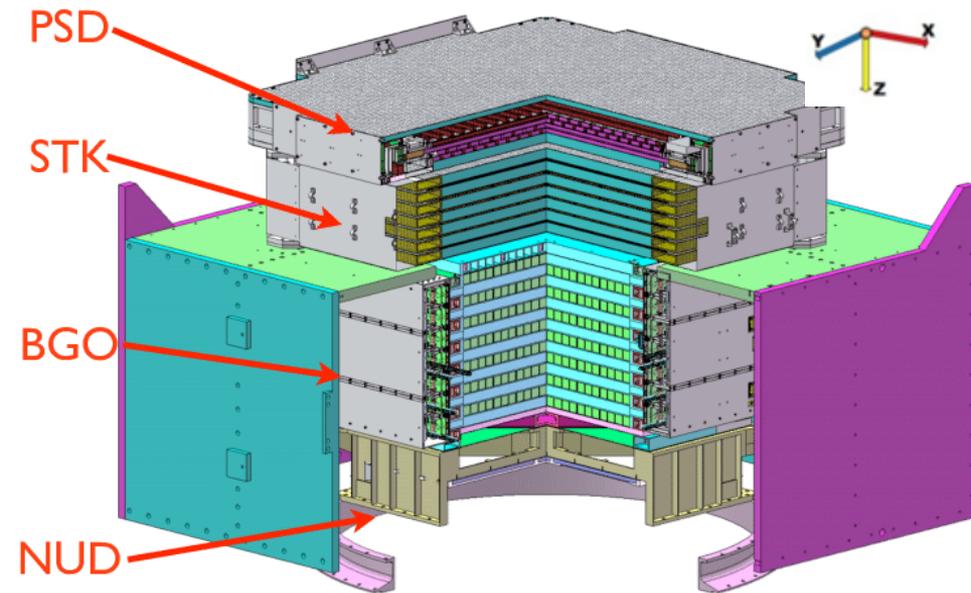


## Science goals:

- Cosmic all-electron spectrum
- **Cosmic protons and nuclei: spectrum and composition**
- High energy gamma-ray astronomy
- Gamma-ray line search



# The DAMPE detector



- **Plastic Scintillator Detector (PSD):**

- 2 X/Y planes of scintillator bars
- Charge measurement + Gamma-ray ID

- **Silicon Tracker (STK):**

- 6 Si planes + W converter
- Tracking + Additional charge measurement

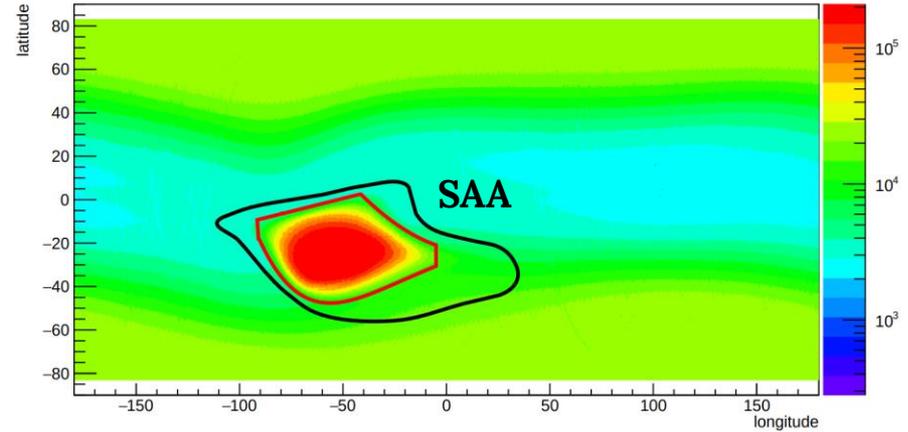
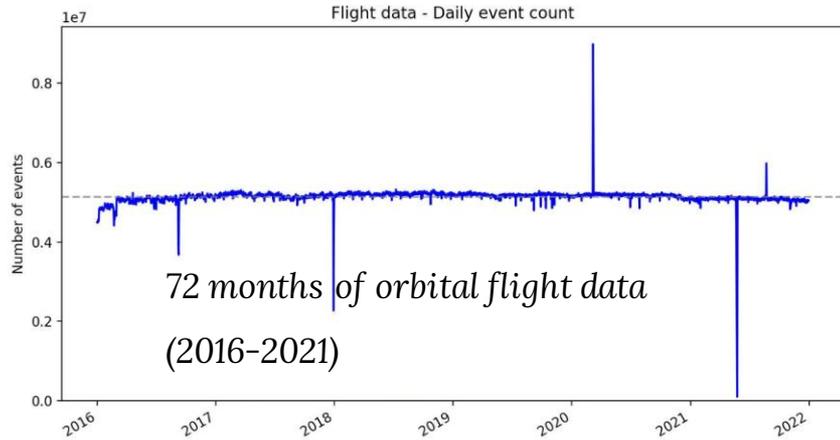
- **BGO calorimeter (BGO):**

- 14 layers of BGO bars ( $32 X_0$ )
- Energy measurement + e/p separation

- **Neutron detector (NUD):**

- 4 tiles of boron loaded scintillator
- Further e/p separation

# Event selection



## Preselection:

- Dead time (SAA, instrumental dead-time, calibration)
- Good event reconstruction
- Track quality check

## Trigger:

- **High energy trigger:** energy deposit  $> 10$  MIPs in each hit bar of the first 3 BGO layers



Specific selection for nucleus  
of interest (Li, Be, B)

# PSD charge measurement



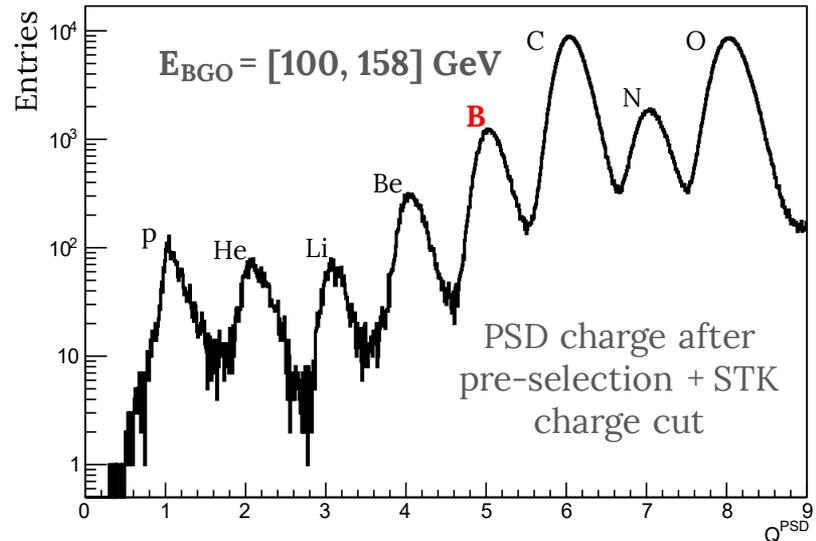
- Absolute value of the incoming CR charge can be estimated through the energy deposit in the PSD.
- Define one **global PSD charge** as:

$$Q^{PSD} = \frac{\sum_i Q_i^{PSD}}{\sum_i i}$$

- Index **i** goes over successive PSD planes with non - zero signal that satisfy the condition:

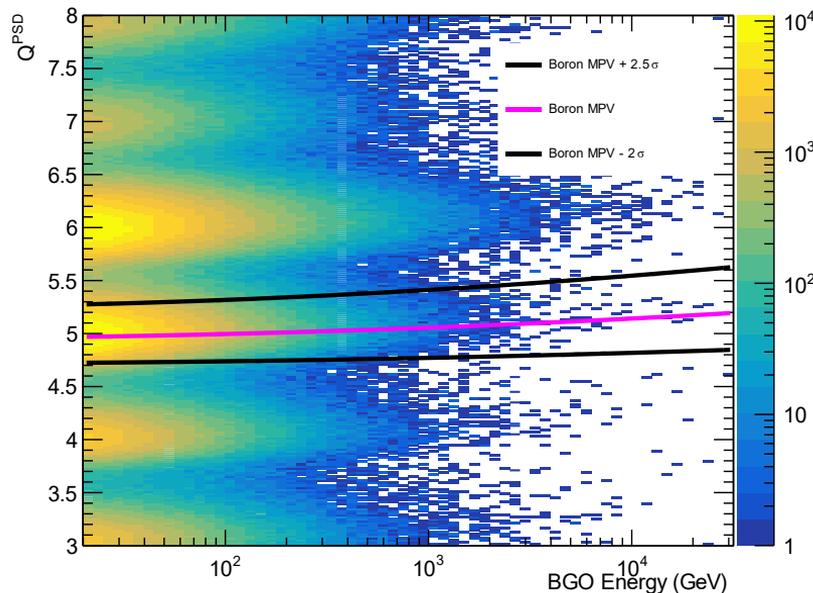
$$|Q_i^{PSD} - Q_{i+1}^{PSD}| < 1$$

- Specifically for **Boron**:  
STK charge X/Y (layer 0) > 600 ADC

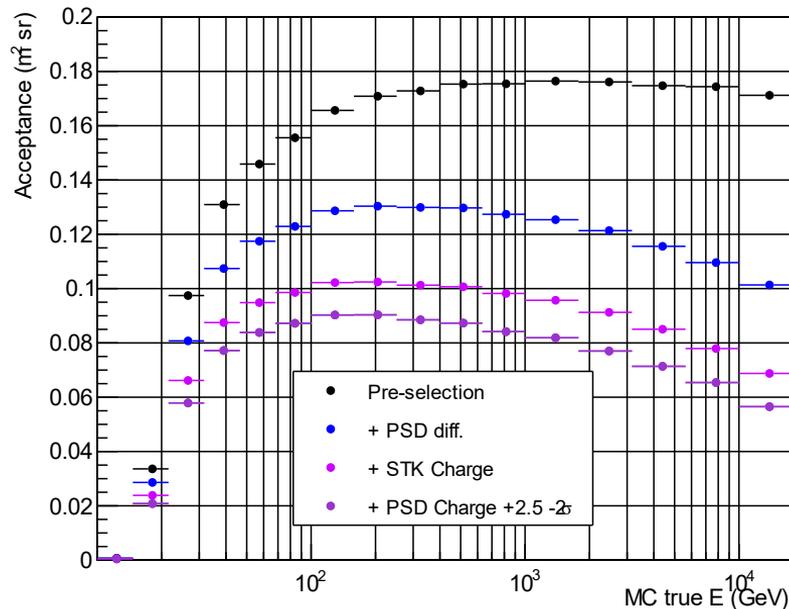


# Boron selection: PSD signal

## Boron analysis



*Overall acceptance estimated from  $^{10}\text{B} + ^{11}\text{B}$  MC*



Define PSD charge selection for B with functions obtained from fitting the PSD Boron peak:

$$f_{MPV} - 2 \cdot f_{Width} < Q^{PSD} < f_{MPV} + 2.5 \cdot f_{Width}$$

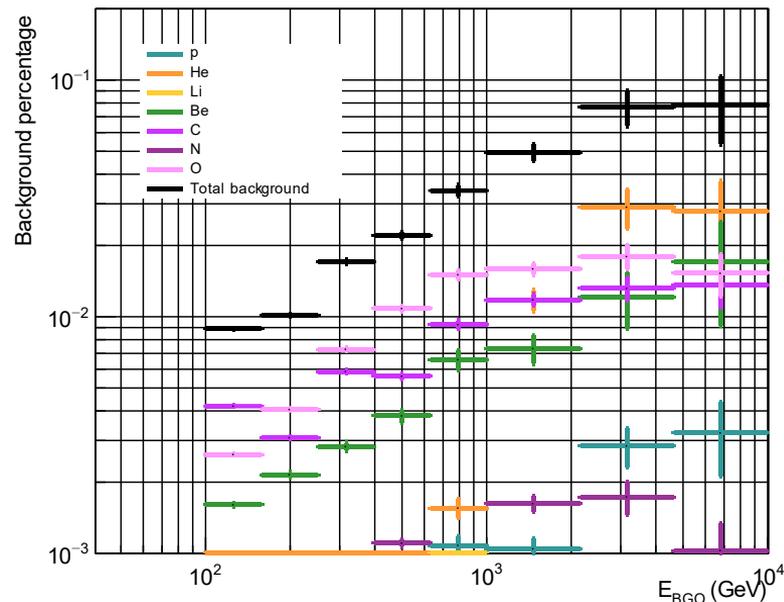
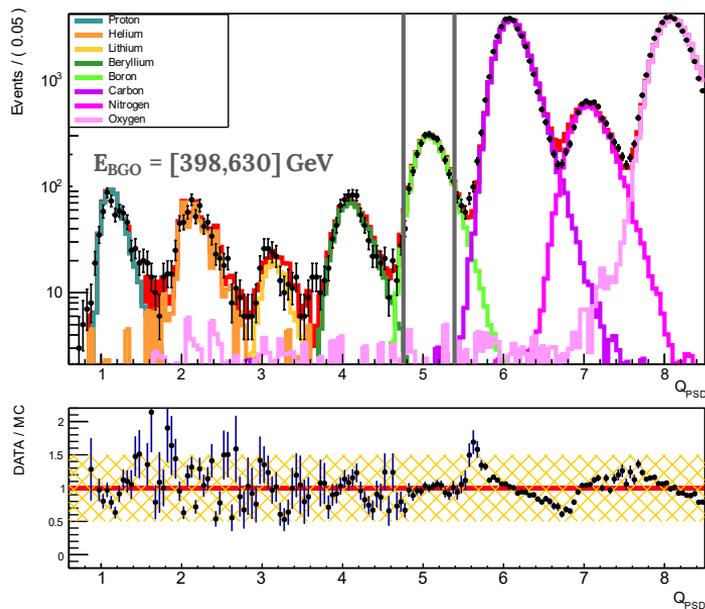
Sample selection is completed. Estimate residual background and compute preliminary spectrum

# MC template fit

## Templates:

- For each  $E_{BGO}$  bin, import MC PSD charge histograms for p up to O as a template (**h**)
- Construct **model** as the sum of the templates **h** with scaling factors **f**
- Use best fit value of the factors to estimate **background in signal region**

$$p(E_{BGO} | \mathbf{f}) \propto \sum_i f_i \cdot h_i(E_{BGO}) \quad i = p, He, \dots, O$$



# Boron preliminary spectrum

After the unfolding, the differential flux can be computed as:

$$J(E_i, E_i + \Delta E_i) = \frac{N(E_T^i)}{\epsilon_i \cdot A \cdot \Delta T \cdot \Delta E_i}$$

$N(E_T^i)$  Primary spectrum, estimated with **unfolding** of the observed counts

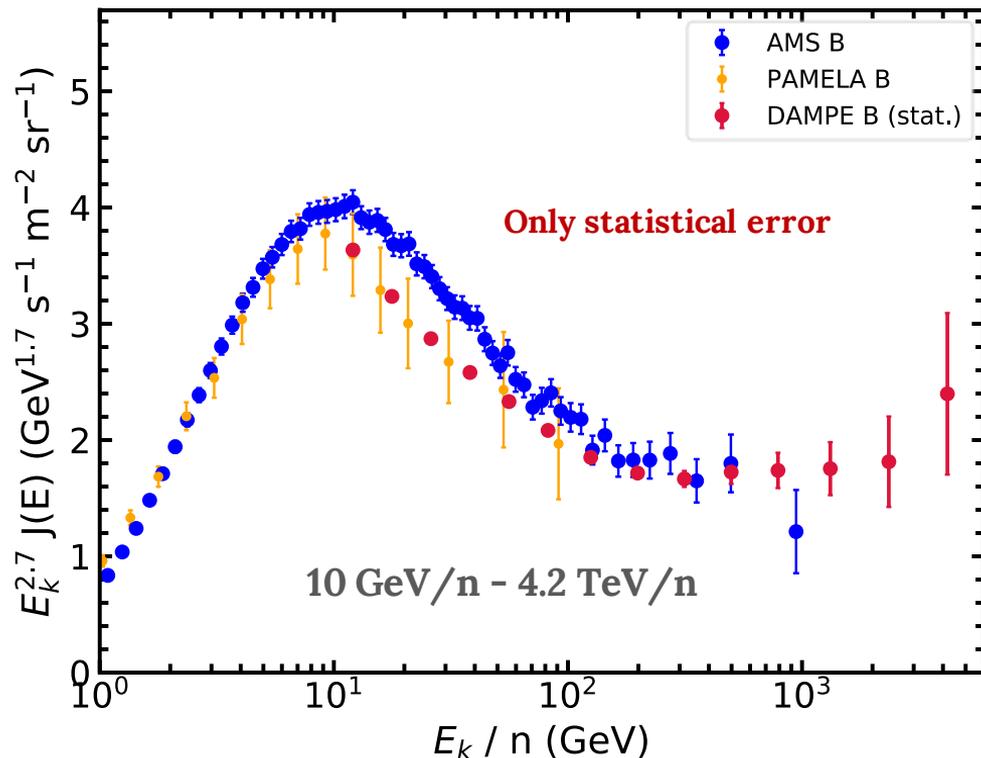
$\epsilon_i$  Detection efficiency

$A$  Generated MC acceptance

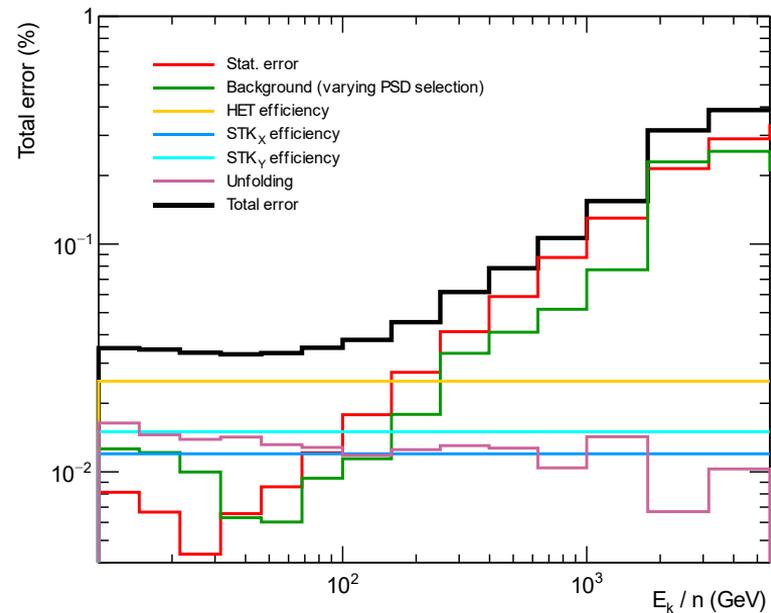
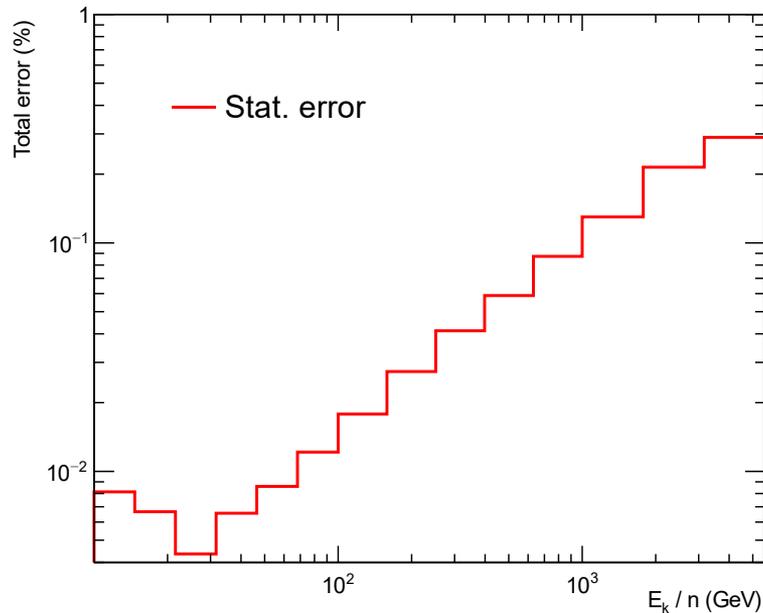
$\Delta T$  Exposure time

$\Delta E$  Energy bin width

B spectrum (x  $E^{2.7}$ )



# Boron: total uncertainty

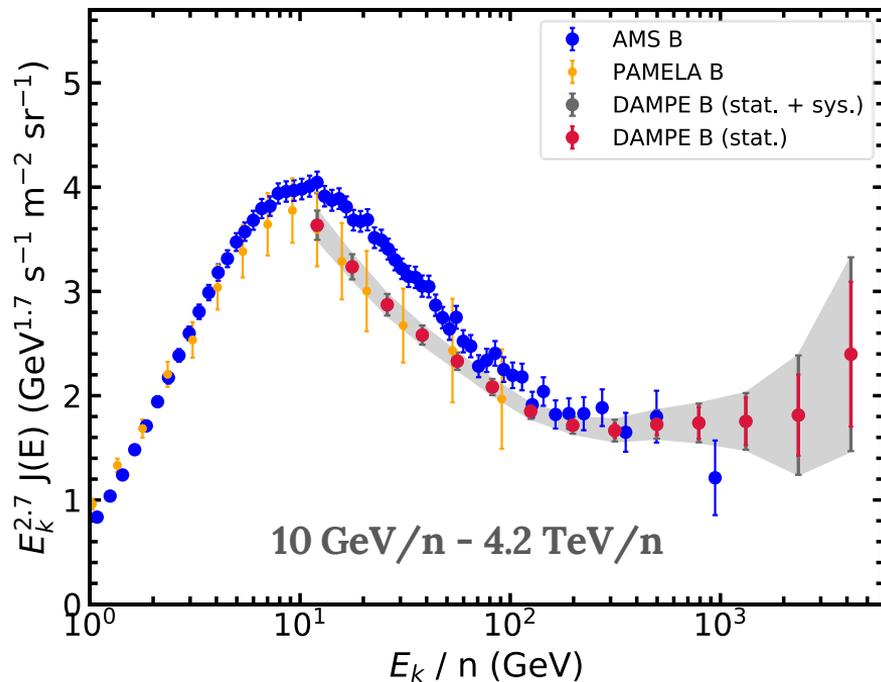


**Statistical** uncertainties estimated with a **toy MC**

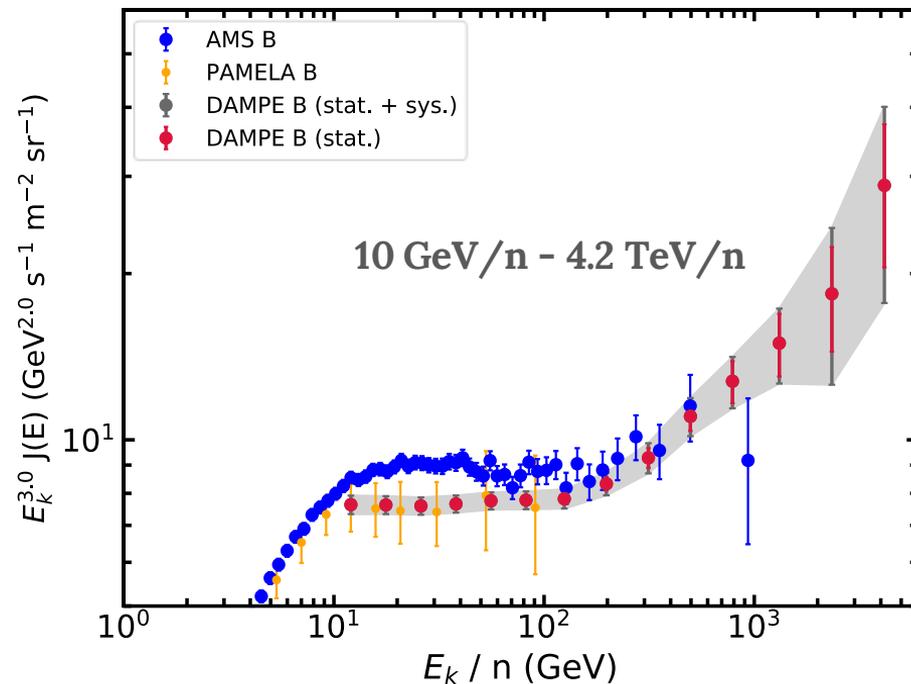
**Systematics** include also validation of the MC estimated acceptance: HET efficiency, STK charge selection efficiency, as well as contributions related to the unfolding procedure and the background contamination.

# Boron preliminary spectrum

B spectrum ( $\times E^{2.7}$ )



B spectrum ( $\times E^{3.0}$ )



Conversion to kinetic energy per nucleon done  
assuming an isotropic composition of :

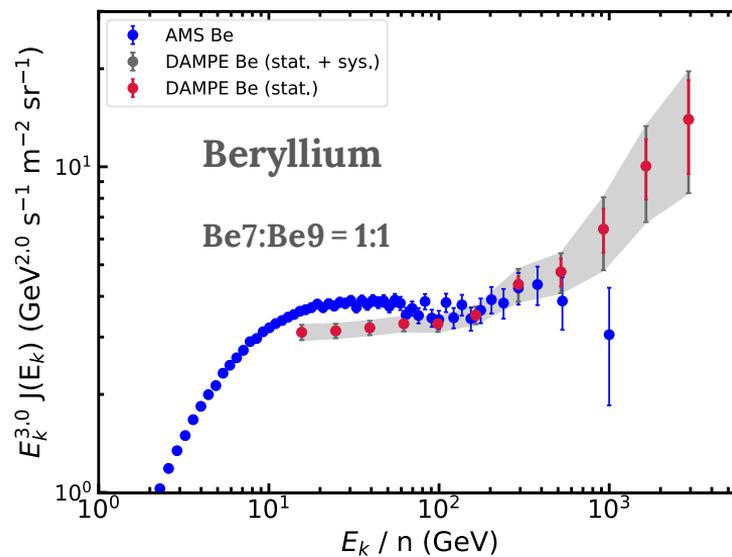
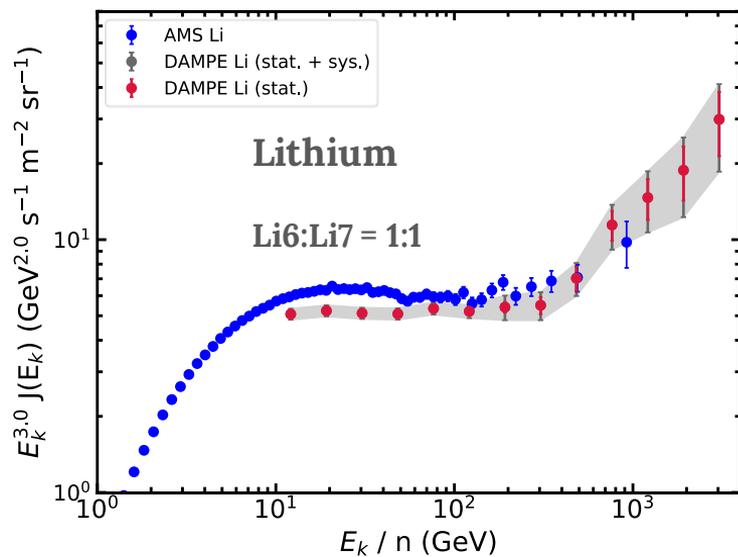
$$\mathbf{B10:B11 = 3:7} \quad \mathbf{n(B) = 10.7}$$

# Lithium and Beryllium preliminary spectra

Analyses for **Lithium** and **Beryllium** follow a similar strategy, with specific STK and PSD selections.

## Preliminary spectrum:

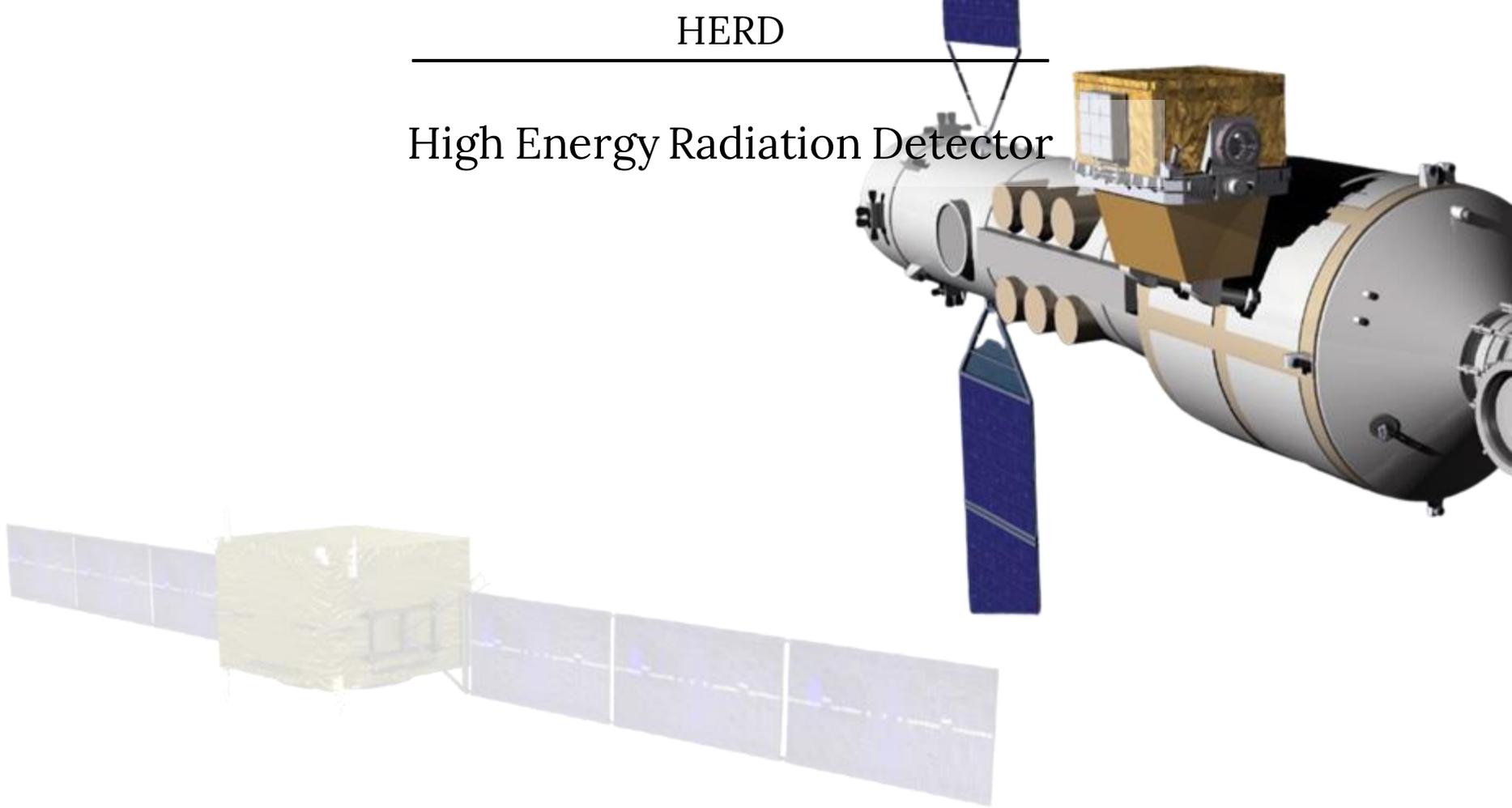
- Statistical uncertainty estimated with toy MC
- Preliminary systematics (full evaluation to be completed)
- Careful treatment of background needed



HERD

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## High Energy Radiation Detector



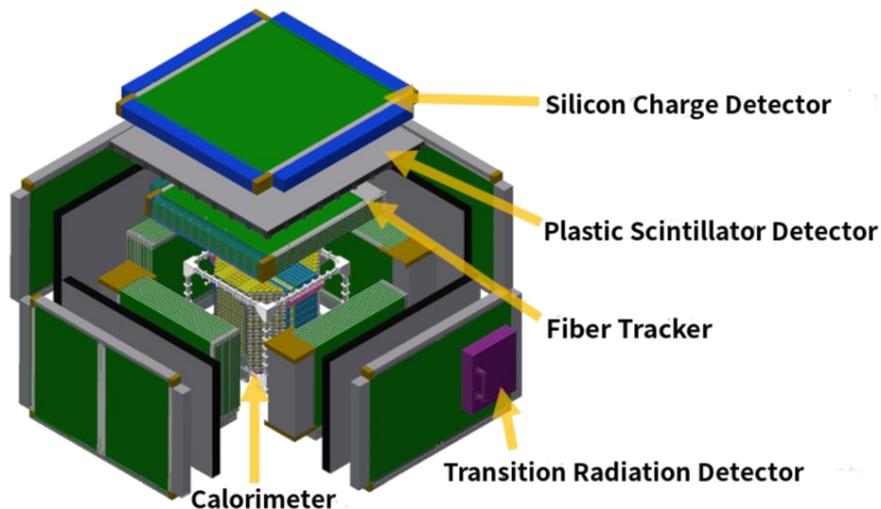
# The HERD mission

## Detector to be installed on CSS around 2027

- International collaboration between China, Italy, Switzerland and Spain

## Science goal:

- Push CR direct detection to the highest energies
- Reach the knee with direct measurement



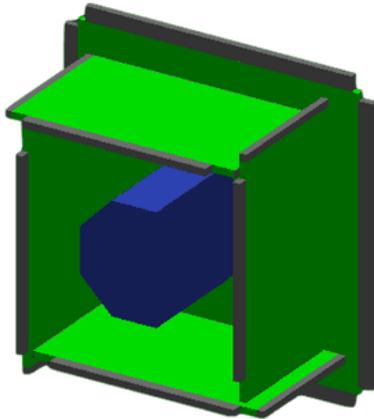
## Detector: 3D design concept

Lifetime	> 10 yr
FoV	$\pm 70^\circ$
Geom. Factor (e)	> 3 m <sup>2</sup> sr at 200 GeV
Geom. Factor (p)	> 2 m <sup>2</sup> sr at 100 GeV

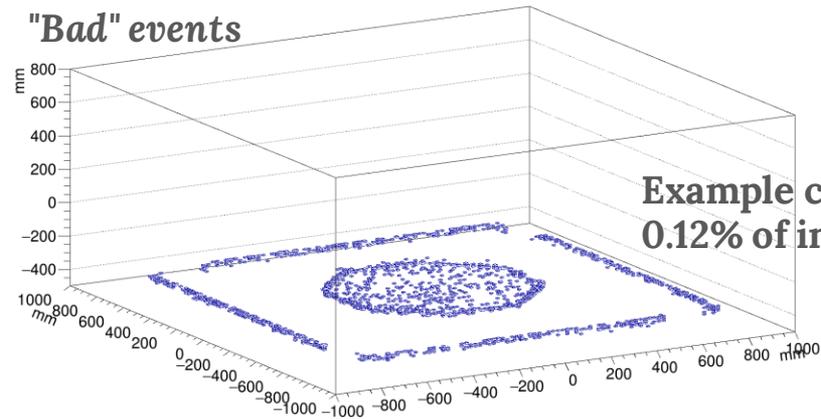
# The HERD PSD

**Geant4 simulation to quickly estimate hermeticity of the detector configuration. Important to avoid misidentification of charged particles as  $\gamma$ -rays.**

- Geometry imported from CAD (.stl) files
- Generate geantinos on a hemispherical surface
- Look at events that reach the CALO: did they also pass from the PSD?



**"Bad" events**



**Can be easily adapted to different geometries / experiments (Nuses, ...)**

# Conclusions

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## Li-Be-B analysis with DAMPE:

- Secondary CRs spectra are fundamental to better understand their propagation in the Galaxy
- **Boron analysis:**
  - Full sample selection
  - Evaluation of most systematics
  - **Preliminary spectrum in the 10 GeV/n to 4.2 TeV/n energy range**
  - Evaluate final systematics (hadronic model, track selection efficiency, isotopic composition)
- **Lithium and Beryllium:**
  - Full sample selection
  - **Preliminary spectra in the 10 GeV/n to ~3 TeV/n energy range**
  - Systematics to be evaluated, background suppression

## Simulations for HERD PSD:

- Future HERD mission on CSS will extend direct CR measurements to the highest energies
- PSD will be an anti-coincidence for gamma-ray detection. A Geant4 simulation was developed to determine the configuration with best hermeticity.

## Schools, conferences, outreach

- 6th International Symposium on Ultra High Energy Cosmic Rays UHECR2022
- Participation in outreach activity **SHARPER** 2021, 2022
- Cosmic Ray International Seminar CRIS 2022: accepted **talk** “Galactic Cosmic Rays: latest results from the DAMPE mission”
- GSSI interdisciplinary course: Physical and computational technologies applied to cultural heritage, environment and biomedicine
- 10th international DAMPE workshop: gave a **talk** with the title “Spectral measurements for the Li-Be-B group”
- INFN School of Statistics 2022
- Outreach lecture at Liceo Scientifico Castelnuovo, Firenze with the title “Raggi cosmici: particelle dallo spazio”
- HERD **test beam** at CERN PS 2021
- 107° Congresso Nazionale SIF: **talk** “Preliminary results on cosmic Li, Be and B with the DAMPE experiment”
- 10th International Conference on New Frontiers in Physics ICNFP 2021: **talk** “Latest results from the DAMPE mission”
- 37th International Cosmic Ray Conference ICRC 2021
- Collaboration meetings: DAMPE Europe 2020, HERD 2021, Nuses 2022
- Several **presentations** during internal DAMPE and HERD meetings

## Scientific publications:

- DAMPE collaboration, “**Measurement of the cosmic ray helium energy spectrum from 70 GeV to 80 TeV with the DAMPE space mission**”, Phys. Rev. Lett. 126, 201102 (2021)
- L. Wu, M. Cui, D. Kyratzis, A. Parenti and Y. Wei on behalf of the DAMPE collaboration, “**Towards the measurement of carbon and oxygen spectra in cosmic rays with DAMPE**”, PoS ICRC2021 128 (2021)
- I. De Mitri, A. Parenti and L. Silveri on behalf of the DAMPE collaboration, “**Selected results from the DAMPE mission**”, Phys. Atom. Nucl. 84, 947–955 (2021)
- DAMPE collaboration, “**Observations of Forbush Decreases of Cosmic-Ray Electrons and Positrons with the Dark Matter Particle Explorer**”, ApJL 920 L43 (2021)
- D. Kyratzis et al. for the HERD collaboration, “**The Plastic Scintillator Detector of the HERD space mission**”, PoS ICRC2021 053 (2021)
- DAMPE collaboration, “**Search for gamma-ray spectral lines with the Dark Matter Particle Explorer**” Sci. Bull. 677 (2022)
- DAMPE collaboration, “**Search for relativistic fractionally charged particles in space**”, Phys. Rev. D 106, 063026
- A. Parenti on behalf of the DAMPE collaboration, “**Latest results from the DAMPE space mission**” to be published on IJMPA
- A. Parenti on behalf of the DAMPE collaboration, “**Galactic cosmic rays: latest results from the DAMPE mission**”, to be published on Journal of Physics : Conference Series

# Backup slides

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# Data and MC samples

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- **Flight Data:**
  - 72 months (2016 - 2021)
- **MC:**
  - B-10 in range [10 GeV, 500 TeV]
  - B-11 in range [10 GeV, 500 TeV]
- **To be included:**
  - B MC wBGO quenching
  - B MC with FLUKA

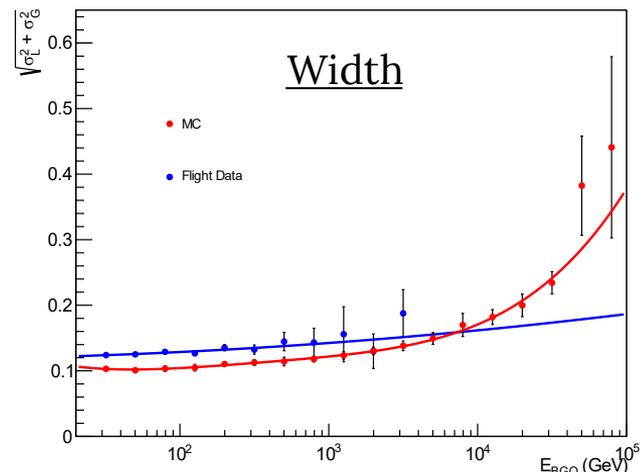
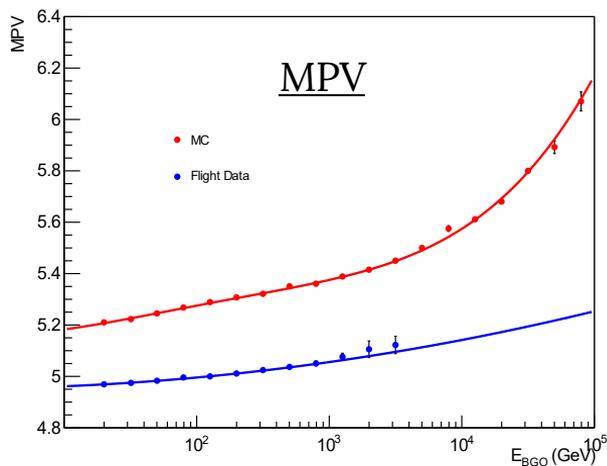
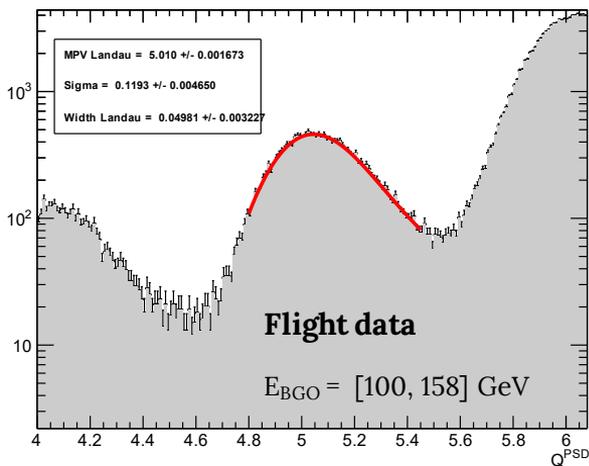
Sample	Size (M)	Sample	Size (M)
B10 10-100 GeV	~100	B11 10-100 GeV	~100
B10 100 GeV - 1 TeV	~ 50	B11 100 GeV - 1 TeV	~ 50
B10 1 - 10 TeV	~ 40	B11 1 - 10 TeV	~ 40
B10 10 - 100 TeV	~ 40	B11 10 - 100 TeV	~ 40
B10 100 - 500 TeV	~ 6	B11 100 - 500 TeV	~ 6

## Boron analysis

For both flight data and MC:

- Fit PSD **B charge peak** for different  $E_{\text{BGO}}$  bins with Landau distribution convoluted with a Gaussian
- Fit MPV and Width =  $\sqrt{(\sigma_L^2 + \sigma_G^2)}$  as a function of  $E_{\text{BGO}}$  with log-polynomial functions

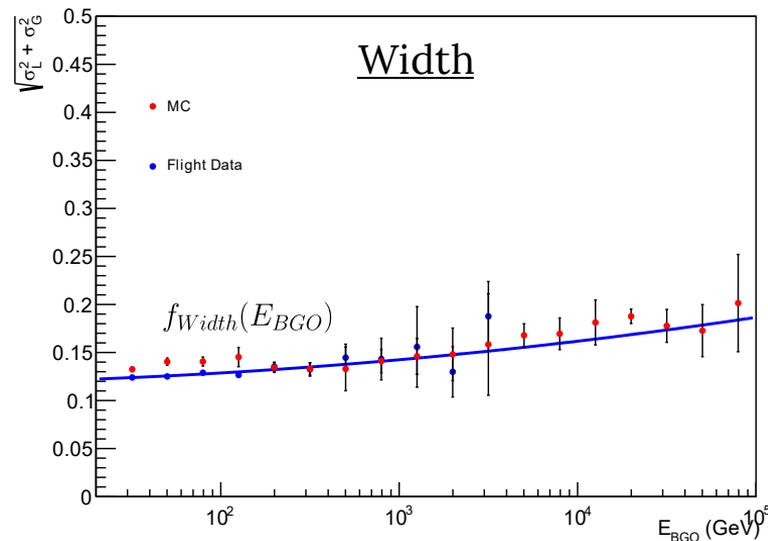
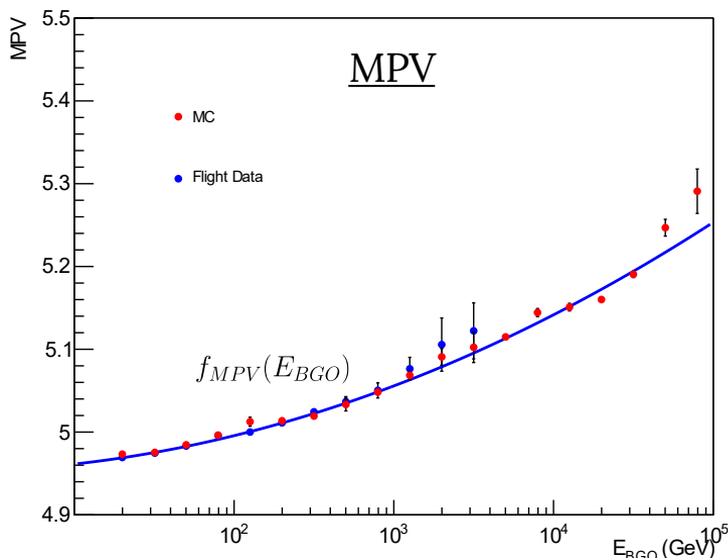
A PSD charge smearing is applied to reach agreement between MC and data.



# Boron: PSD charge smearing

- Correct MC PSD charge using log polynomial functions:

$$Q_{corr}^{PSD} = (Q^{PSD} - f_{MPV}^{MC}(E_{BGO})) \cdot \frac{f_{Width}^{FD}(E_{BGO})}{f_{Width}^{MC}(E_{BGO})} + f_{MPV}^{FD}(E_{BGO})$$



Good agreement between flight data and MC after the charge smearing correction.

# Unfolding of the spectrum

The DAMPE BGO calorimeter is 1.6 interaction lengths thick.  
CR nuclei will deposit only a fraction ( $\sim 1/3$ ) of their energy inside the calorimeter.

The primary energy can be estimated with an **iterative Bayesian unfolding**.

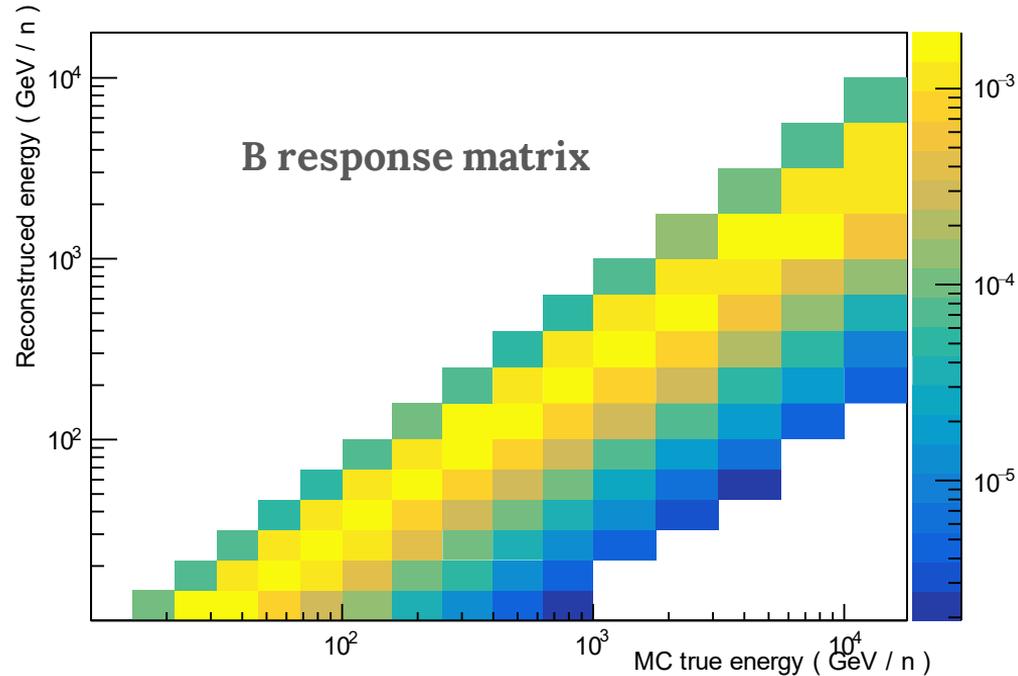
$$N(E_T^i) = \frac{1}{\epsilon_i} \sum_{j=0}^{n_o} P(E_T^i | E_O^j) N(E_O^j)$$

$N(E_T^i)$  Primary count spectrum

$N(E_O^j)$  Observed count spectrum

$P(E_T^i | E_O^j)$  Response matrix

$\epsilon_i$  Detection efficiency



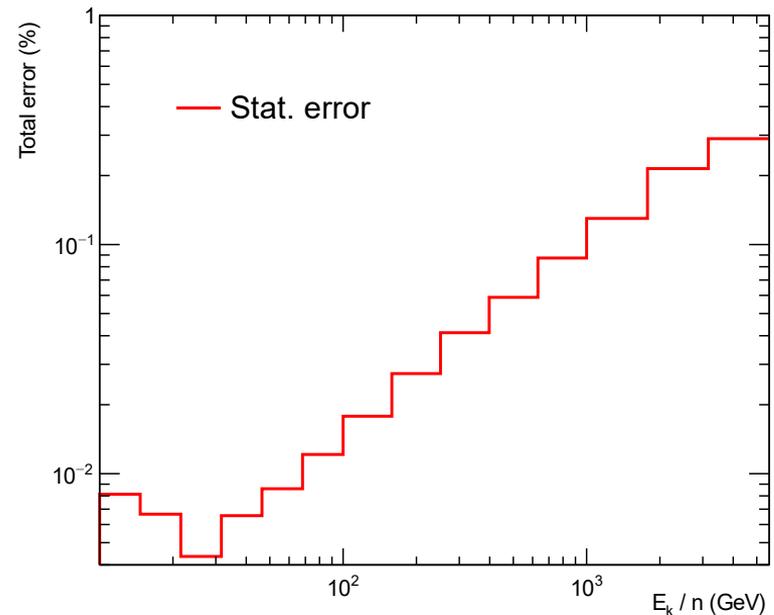
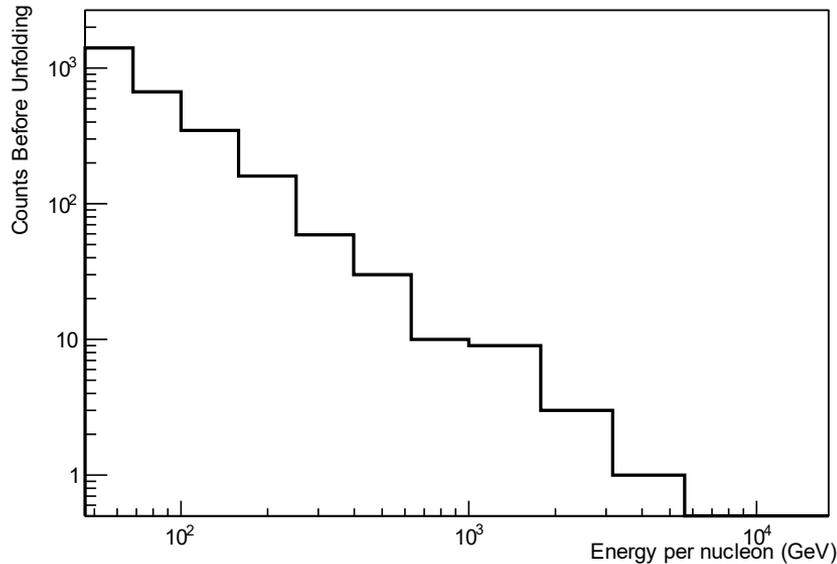
The **response matrix** is computed through an iterative Bayesian procedure which involves the choice of a prior distribution, number of iterations, stopping criteria.

# Statistical error: toy MC

$$N(E_T^i) = \frac{1}{\epsilon_i} \sum_{j=i}^{n_o} P(E_T^i | E_O^j) N(E_O^j)$$

**10'000 ToyMC:** extract counts for each bin from a **Poissonian** with mean equal to the observed counts.

**Stat. Error:** width from Gaussian fit of unfolded counts distribution for each bin



# Systematics: background

- Change PSD charge selection window.

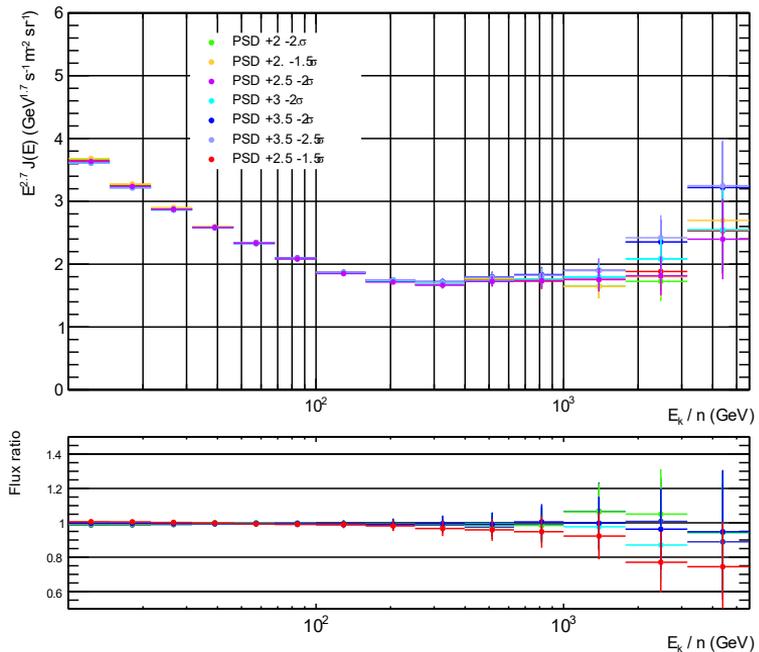
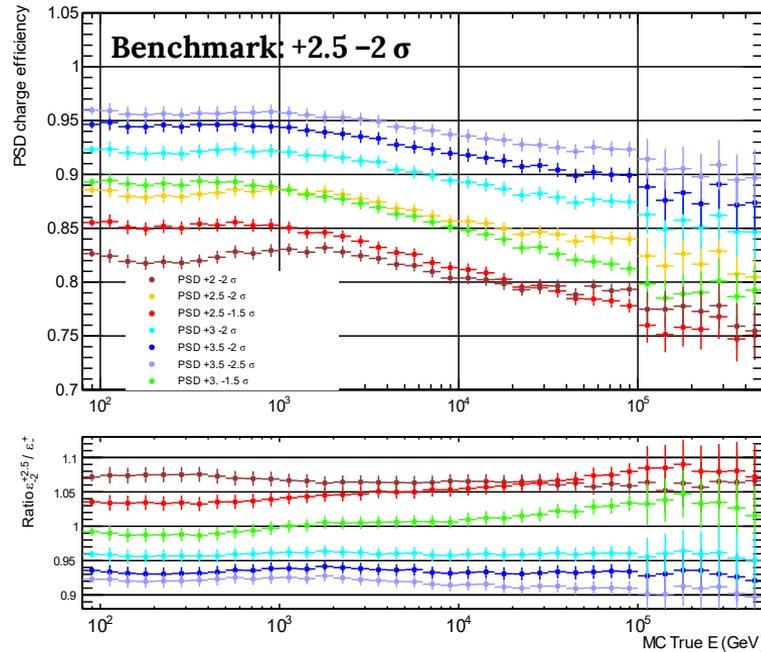
Shift upper and lower limit:

- from  $-1.5\sigma$  to  $-2.5\sigma$
- from  $+2.$  to  $+3.5\sigma$

- Look at how flux points change.

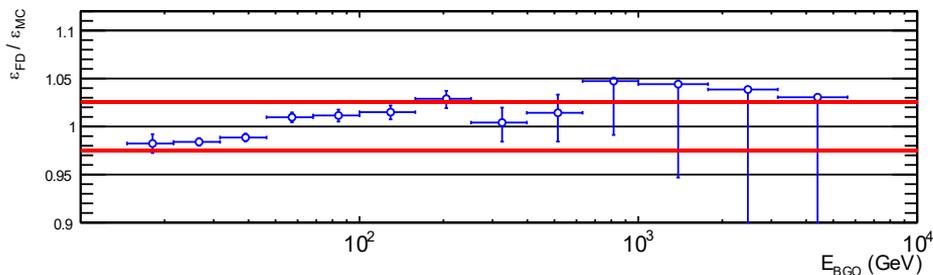
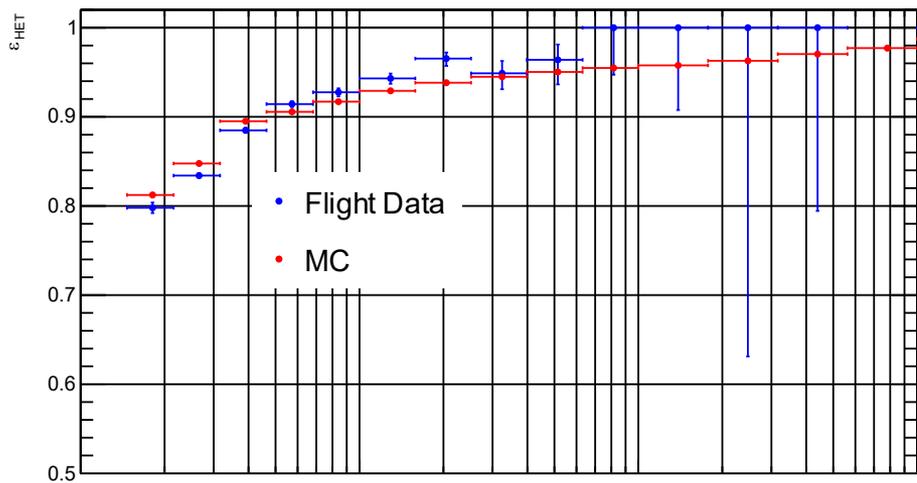
Assign difference as a **background related systematic**:

- Point in  $[1.7 - 3.2]$  TeV/n bin: 23 %
- Point in  $[3.2 - 5.6]$  TeV/n bin: 26 %



# Systematics: HET efficiency

- **HET efficiency:** apply B selection with Low Energy Trigger (LET) request



- **HET:** energy deposit > 10(2) MIPs in each hit bar of the first 3 BGO layers(4th BGO layer)
- **LET:** BGO layers 0, 1 (2, 3): energy deposit > 0.4 (2) MIPs. *Pre-scaled*
- 1 MIP ~ 23 MeV
- B MC weighted with  $E^{-3.0}$  power law

$$\epsilon_{HET} = \frac{N_{PSD|STK|LET|HET}}{N_{PSD|STK|LET}}$$

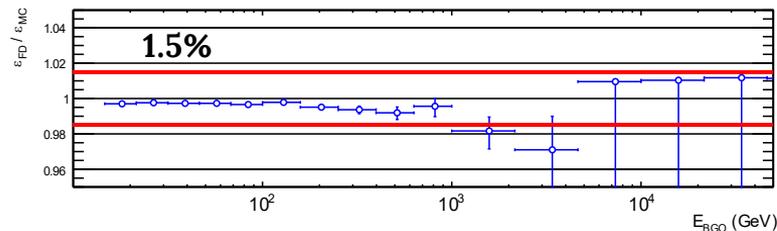
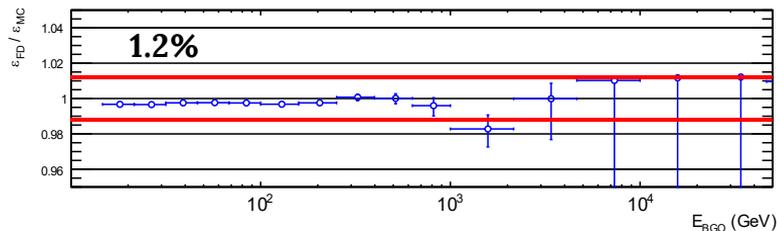
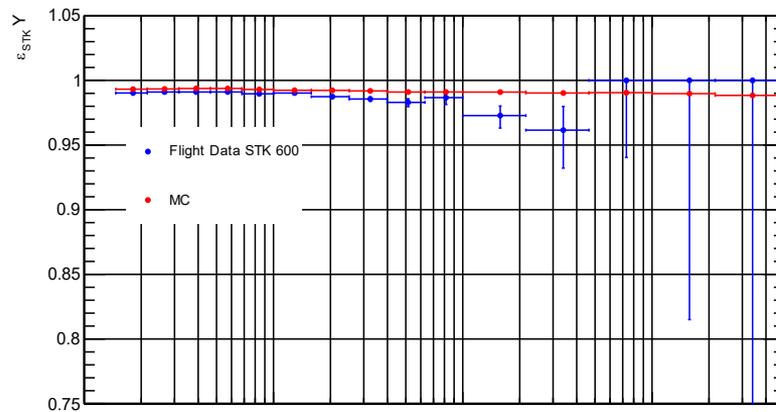
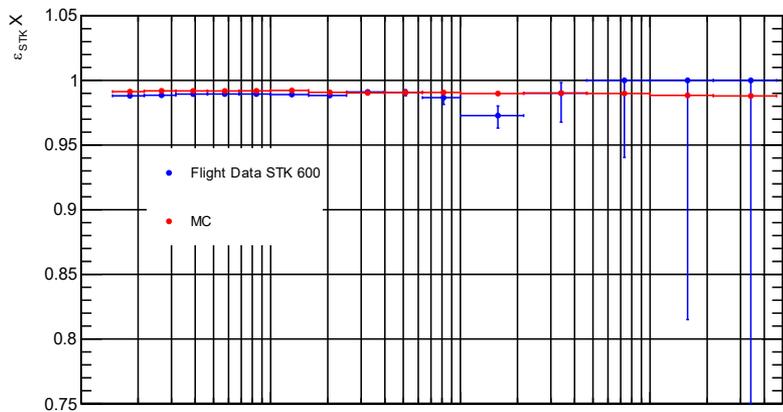
- Agreement between FD and MC within ~2.5%

# Systematics: STK charge efficiency

- **STK charge X/Y:** B selection with stricter PSD charge cut and STK charge selection in layer #1 and #2
- B MC weighted with  $E^{-3.0}$  power law

$$\epsilon_{STKX} = \frac{N_{PSD|STKlay1|STKlay2|STKY|STKX}}{N_{PSD|STKlay1|STKlay2|STKY}}$$

$$\epsilon_{STKY} = \frac{N_{PSD|STKlay1|STKlay2|STKX|STKY}}{N_{PSD|STKlay1|STKlay2|STKX}}$$



# Systematics: unfolding

$$N(E_T^i) = \frac{1}{\epsilon_i} \sum_{j=i}^{n_o} P(E_T^i | E_O^j) N(E_O^j)$$

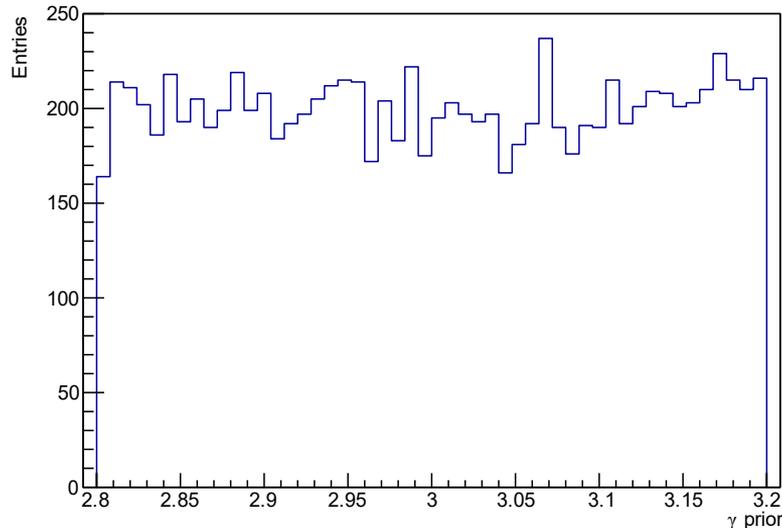
$$P(E_T^i | E_O^j) = \frac{P(E_O^j | E_T^i) P(E_T^i)}{\sum_{k=0}^{n_t} P(E_O^j | E_T^k) P(E_T^k)}$$

- Response matrix (MC ) entries sampled from a **Poissonian**

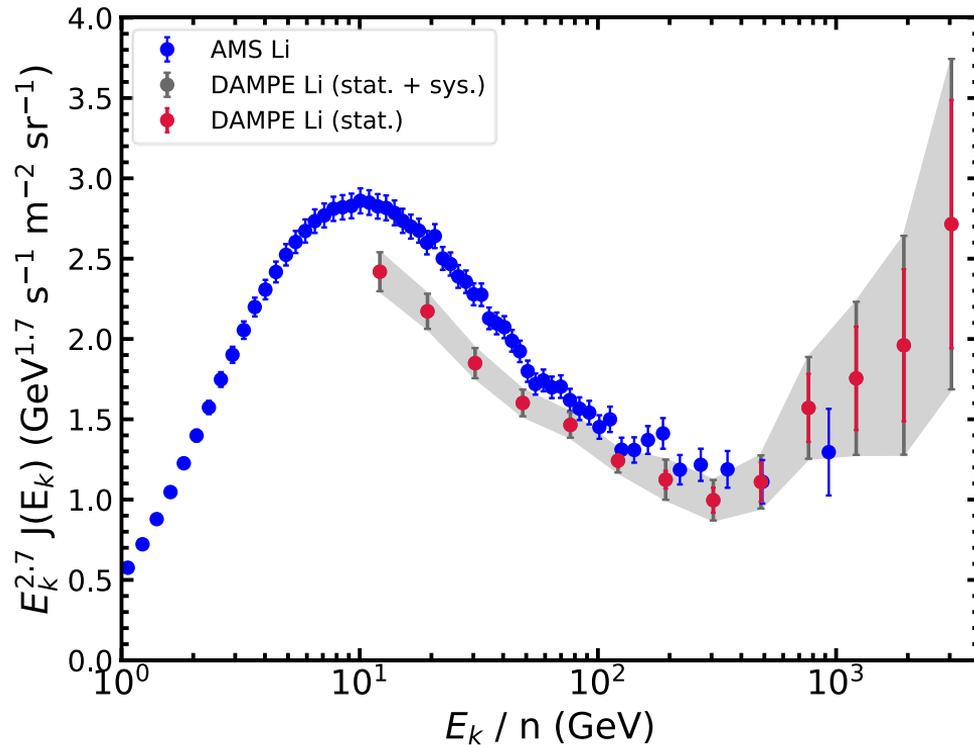
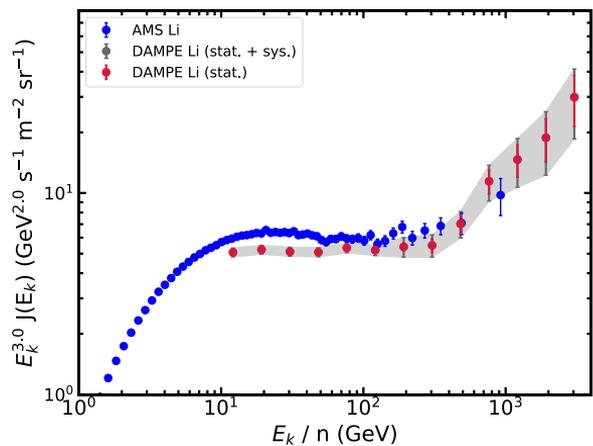
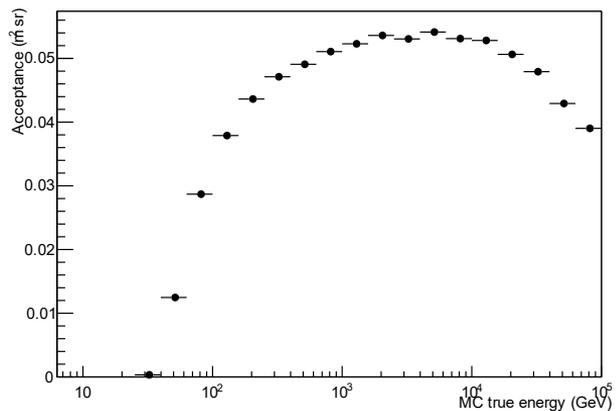
- Prior chosen as a power law with index  $\gamma$ . Index is extracted from a **uniform** distribution in the range (-3.2, -2.8)

- Benchmark value  $\gamma = -3.0$
- **10'000 toyMC**: fit unfolded counts for each true energy bin with a Gaussian to estimate unfolding systematic error
- Systematic uncertainty of **1.2-1.6 %** across the full energy range

Prior spectral index



# Lithium spectrum



# Beryllium spectrum

