# COSMIC RAY HELIUM SPECTRUM MEASURED BY THE DAMPE EXPERIMENT

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On behalf of the DAMPE Collaboration

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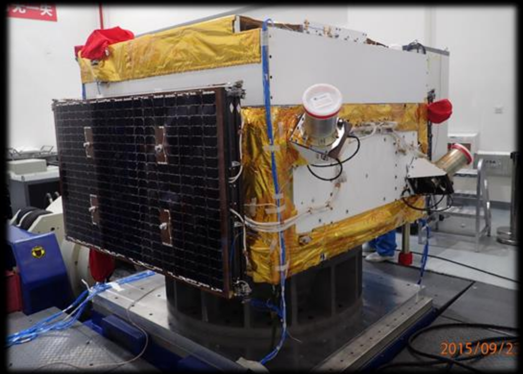
# The DArk Matter Particle Explorer




DAMPE is a satellite-borne particle detector proposed in the framework of the Strategic Pioneer Program on Space Science, promoted by the Chinese Academy of Sciences (CAS).

- LAUNCH: 17th Dec. 2015, CZ-2D rocket
- ALTITUDE: 500 km
- PERIOD: 95 minutes
- ORBIT: Sun-synchronous
- LIFETIME > 3 years

PHYSICS GOALS

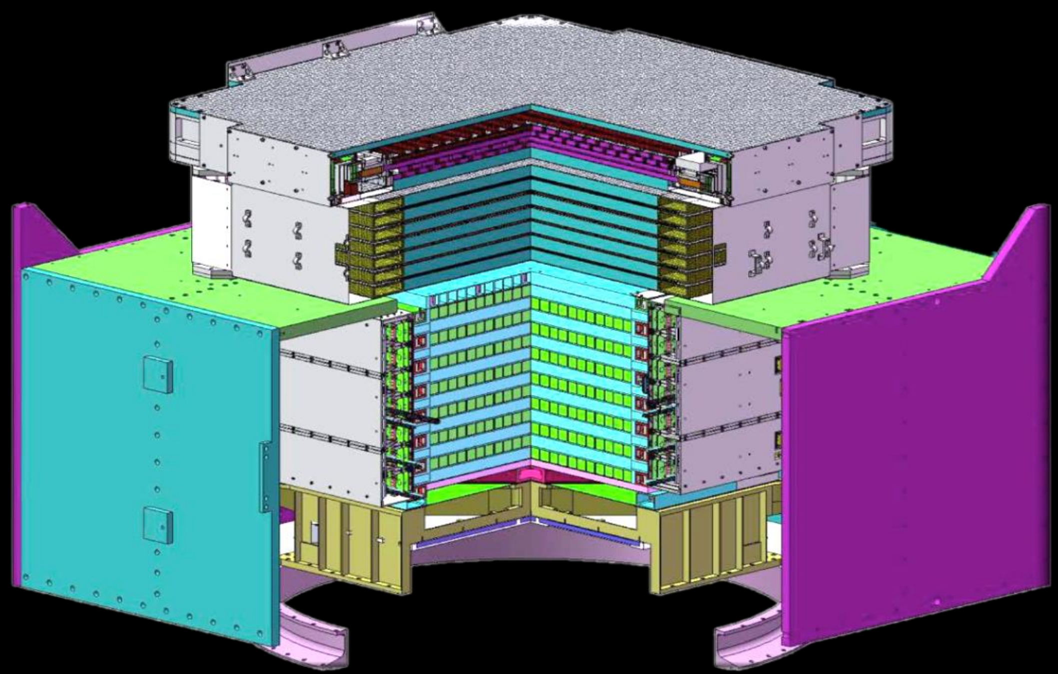
- Study of Cosmic Ray composition, origin and propagation
- Search for Dark Matter signatures in lepton and photon spectra
- High Energy Gamma-Ray Astronomy

- **Purple Mountain Observatory**
- **University of Science and Technology**
- **Institute of High Energy Physics**
- **Institute of Modern Physics**
- **National Space Science Center**

- **INFN Lecce and University of Salento**
- **INFN Bari and University of Bari**
- **INFN Perugia and University of Perugia**
- **INFN LNGS and Gran Sasso Science Institute**

- **Geneva University**

# The DAMPE detector



J. Chang et al., Astrop. Phys. 95 (2017) 6-24

## Plastic Scintillator Detector (PSD)

- 2 planes with double layer configuration (2D )
- 82 plastic scintillator bars EJ-200 ( Eljen Technology Corporation)
- ❑ CHARGE MEASUREMENT ($Z<28$, $Z \propto \sqrt{E}$)
- ❑ $\gamma$-RAY VETO

## Silicon Tungsten tracKer-converter (STK)

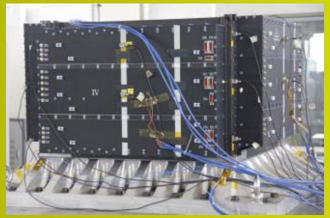
- 6 planes with 2 single-sided silicon layers
- 3 thin tungsten layers (for $\gamma$ conversion in $e^+/e^-$)

- ❑ TRACK RECONSTRUCTION
  - ❑ spatial resolution <70 $\mu$m for CR ($\theta_{inc} < 60°$)
  - ❑ angular resolution ~0.2° for $\gamma$ at 10 GeV
- ❑ CHARGE MEASUREMENT ( $Z \propto \sqrt{ADC}$)

## BGO Calorimeter (BGO)

- 14 layers, each one with 22 bars of $Bi_4Ge_3O_{12}$ ,~32 $X_0$

- ❑ ENERGY MEASUREMENT
  - ❑ 1 GeV - 10 TeV for electrons and $\gamma$
  - ❑ 50 GeV - 100 TeV for nuclei



## NeUtron Detector (NUD)

- 1 layer, 4 boron-doped plastic scintillators

- ❑ DETECTION OF NEUTRONS generated in the BGO for hadron/e.m. showers discrimination

# Data Sample

- ON-ORBIT DATA SAMPLE:

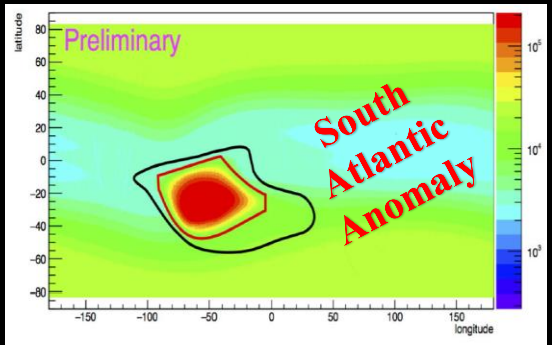
54 months of on-orbit data from January 1st, 2016 to June 30th 2020

Dead time

South Atlantic Anomaly (SAA) (~4.9% of O.T.)

On-orbit calibration (~1.7% of O.T.)

Instrumental dead time (~17.2% of O.T.)




- EXPOSURE TIME:

$1.08 \cdot 10^8$ s , 76% of the O.T.

- SIMULATION DATA SAMPLE:

**HELIUM:**

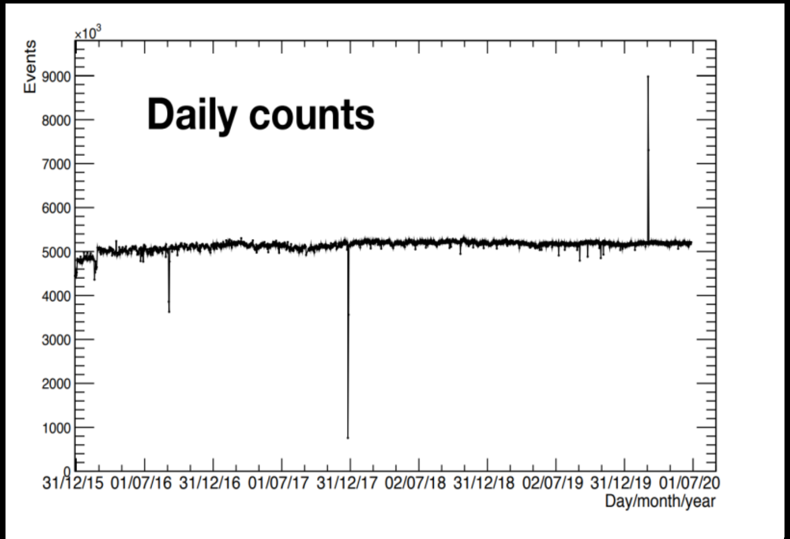
GEANT4 FTFP_BERT from 10GeV to 500TeV

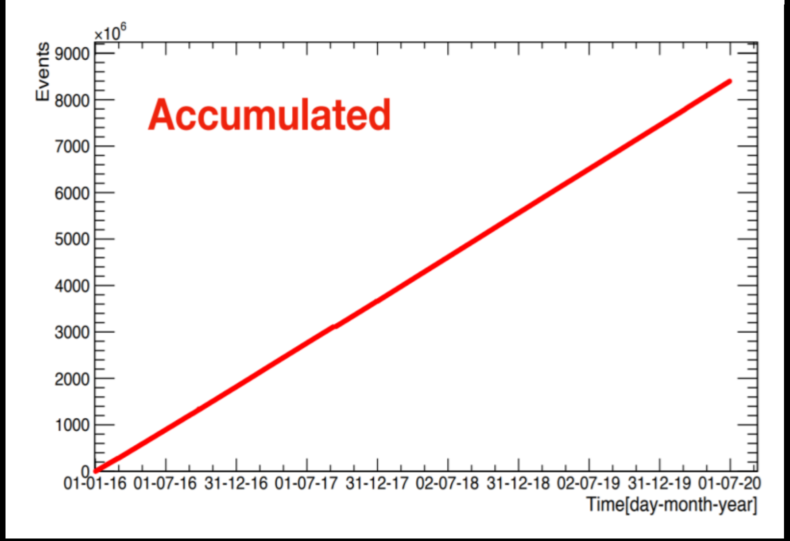
FLUKA 10GeV-500TeV

**PROTONS:**

GEANT4 FTFP_BERT from 10GeV to 100TeV

CRMC-GEANT4 from 100TeV to 1PeV



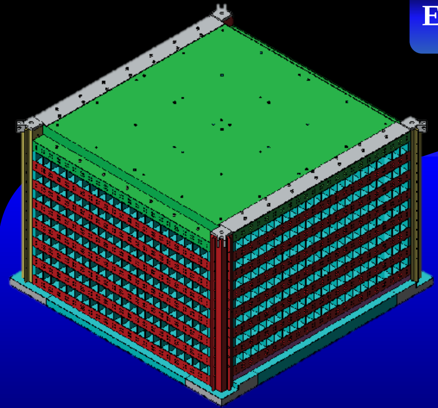



# Event selection (I)

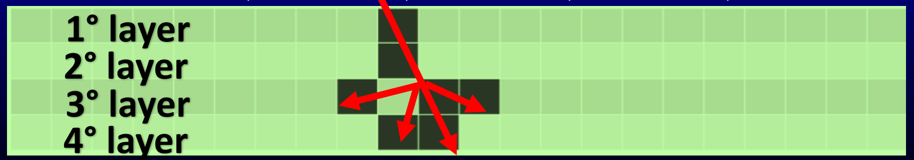
Pre-Selection

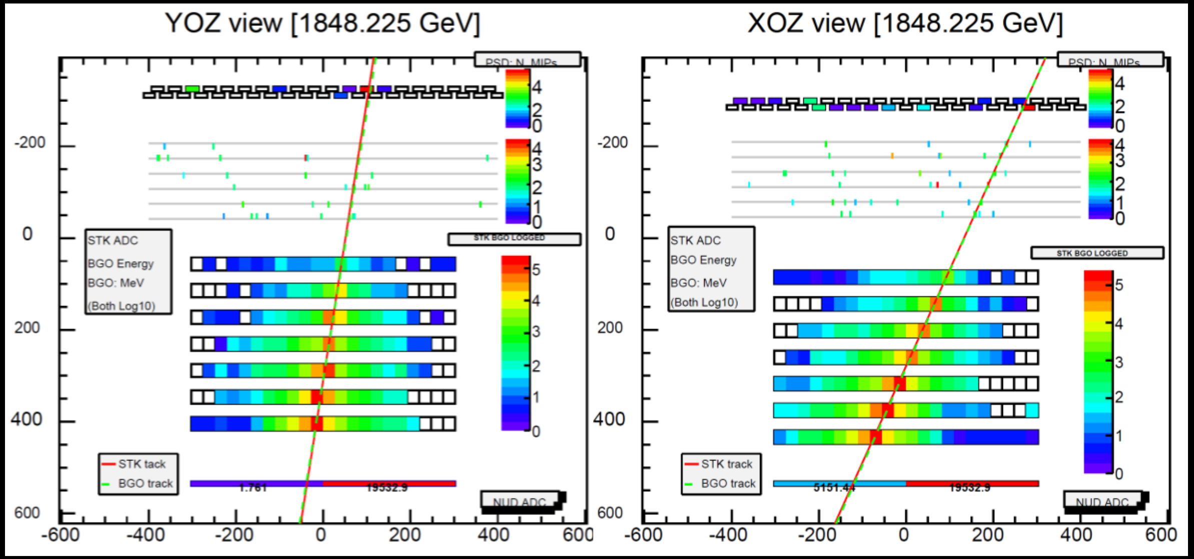
- $E_{dep}$> 20 GeV inside the BGO calorimeter && High Energy Trigger Activation
- South Atlantic Anomaly events exclusion
- Nhits>=3 && Chi2Ndof< 35 && Maximum total ADC of track
- $\Delta_{diff}$<25 mm between STK and first 4 BGO layers, $\Delta_{diff}$<90 mm between BGO and STK track on the PSD
- Selected STK track crossing the full detector
- Elayermax<35% && Top-down development of the shower

HET activation:
$E_{dep}$ > 13MIPs in first 3 BGO Layers
&& $E_{dep}$ > 2.4 MIPs in 4th BGO Layer
(1 $MIP_{BGO}$ = 23 MeV)



$$E_{BGO,1} + E_{BGO,2} < E_{BGO,3} + E_{BGO,4}$$



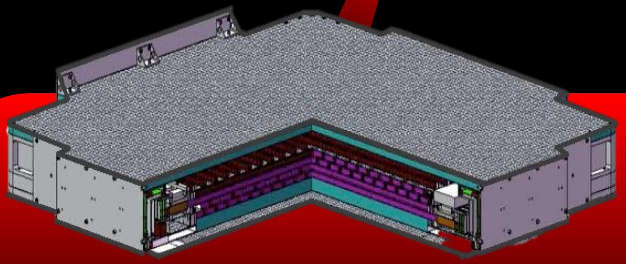
# Event selection (II)

Three independent charge measurements provided by the 2 layers of the PSD and by the first layer of the STK.

**Charge selection**

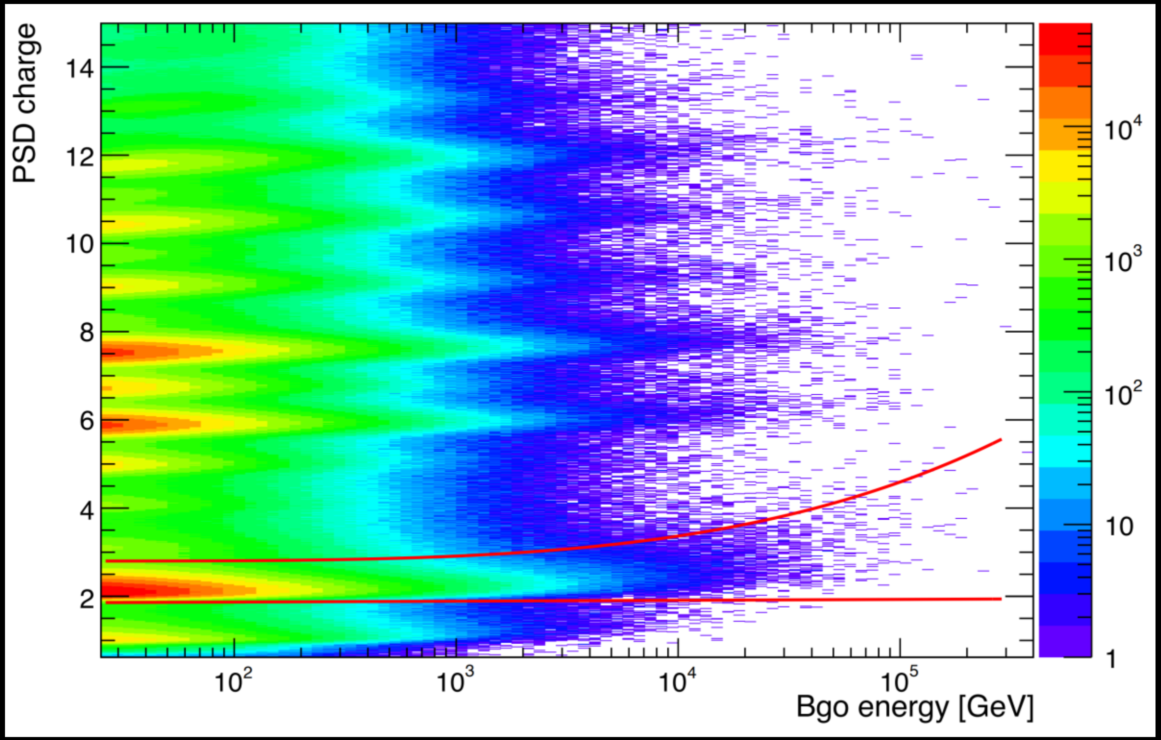
**PSD Charge Selection :** $1.85 + 0.02\, log \frac{E_{dep}}{10\ GeV} < Z_{Y(X)} < 2.8 + 0.007 \left( log \frac{E_{dep}}{10\ GeV} \right)^4$

**STK Charge Selection :** $ADC_{firstpoint} > 120$

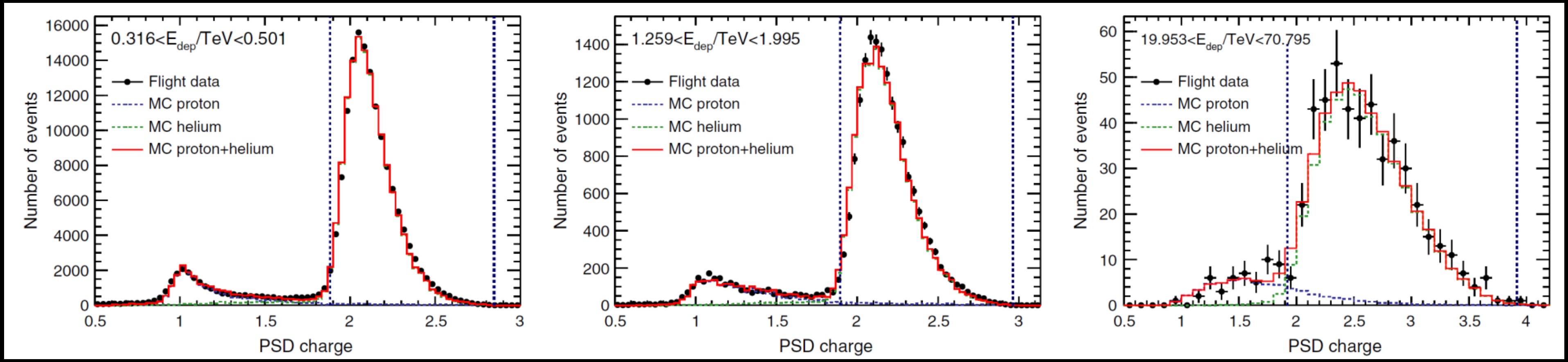



According to the Bethe-Bloch formula, the energy released through ionization inside the PSD by a crossing CR is proportional to the square of its charge.

**BETHE-BLOCH FORMULA** $\frac{dE}{dx} \propto Z^2$

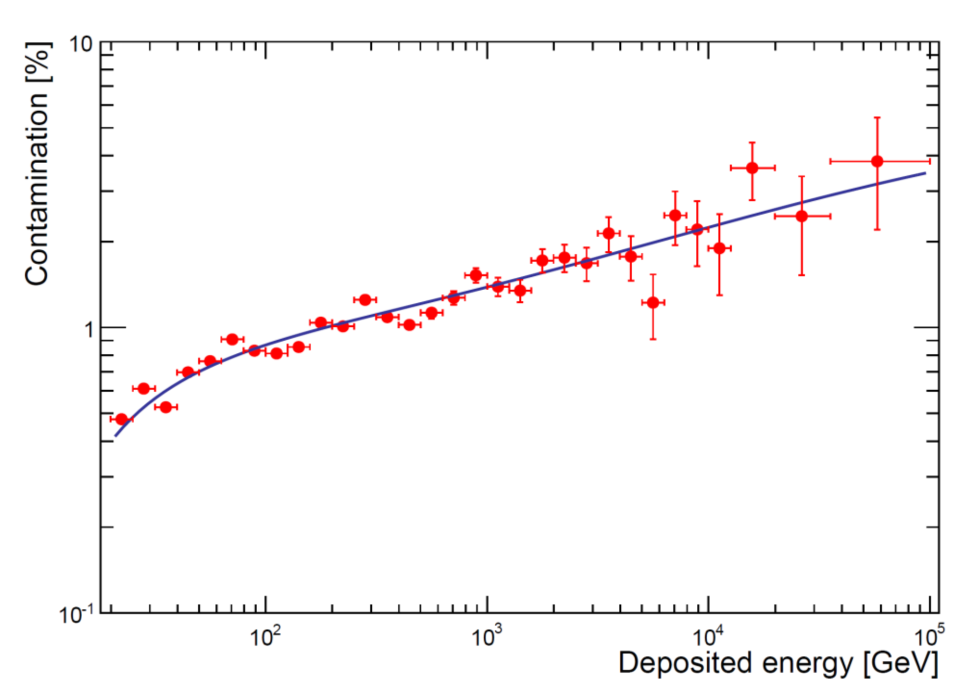


# Systematics: Proton background




Template-Fit based on MC simulation data.
Systematic uncertainty due to proton background $\sigma_{bg}$:

proton background ranges from ~0.05% for deposited energy of 20 GeV to ~4% for 60 TeV



# Systematics: High Energy Trigger efficiency

Unbiased Trigger: $E_{dep}$>0.4 MIPs in first 2 BGO layers

Pre-scaling factors of Unbiased Trigger:

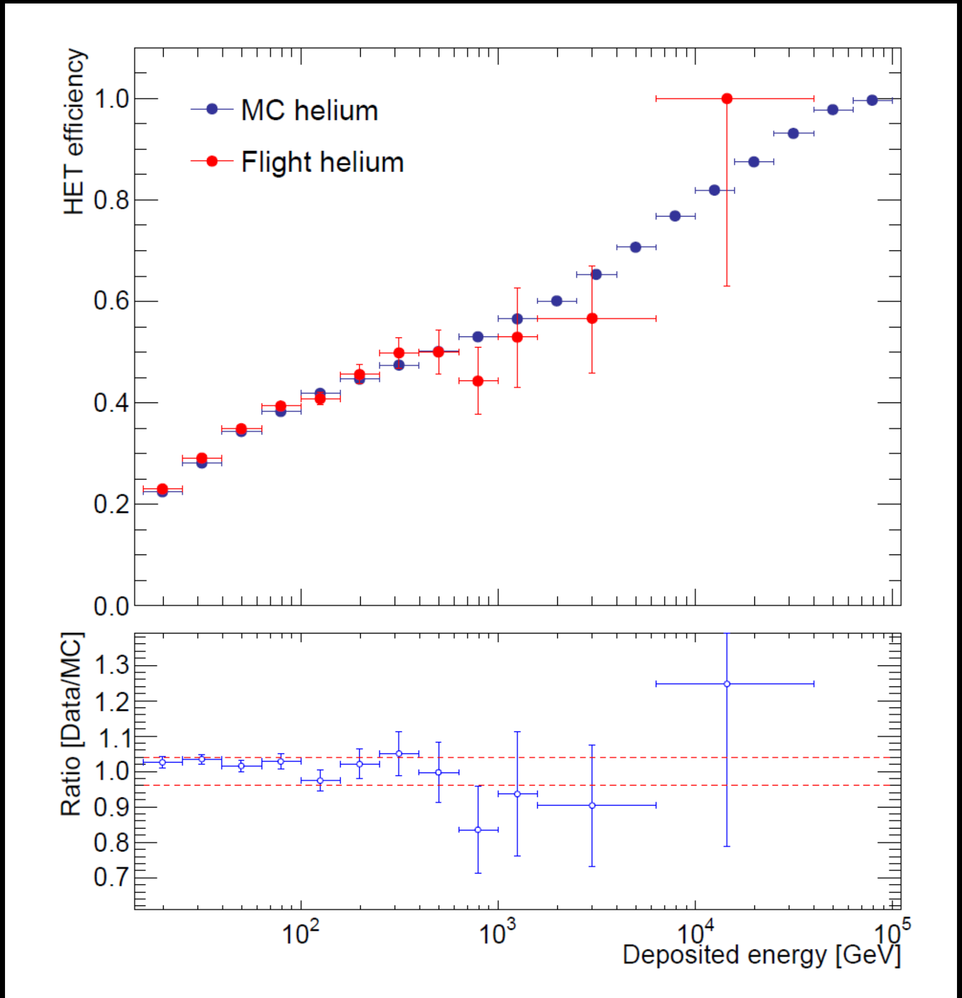
- 1/512 in the latitude range [-20°;20°]
- 1/204 at higher latitudes

$$\varepsilon_{HET} = \frac{N_{HET|Unb}}{N_{Unb}}$$

- $N_{HET|Unb}$ : HE & Unb triggers activated
- $N_{Unb}$ : Unb trigger activated

Systematic uncertainty due to HET:

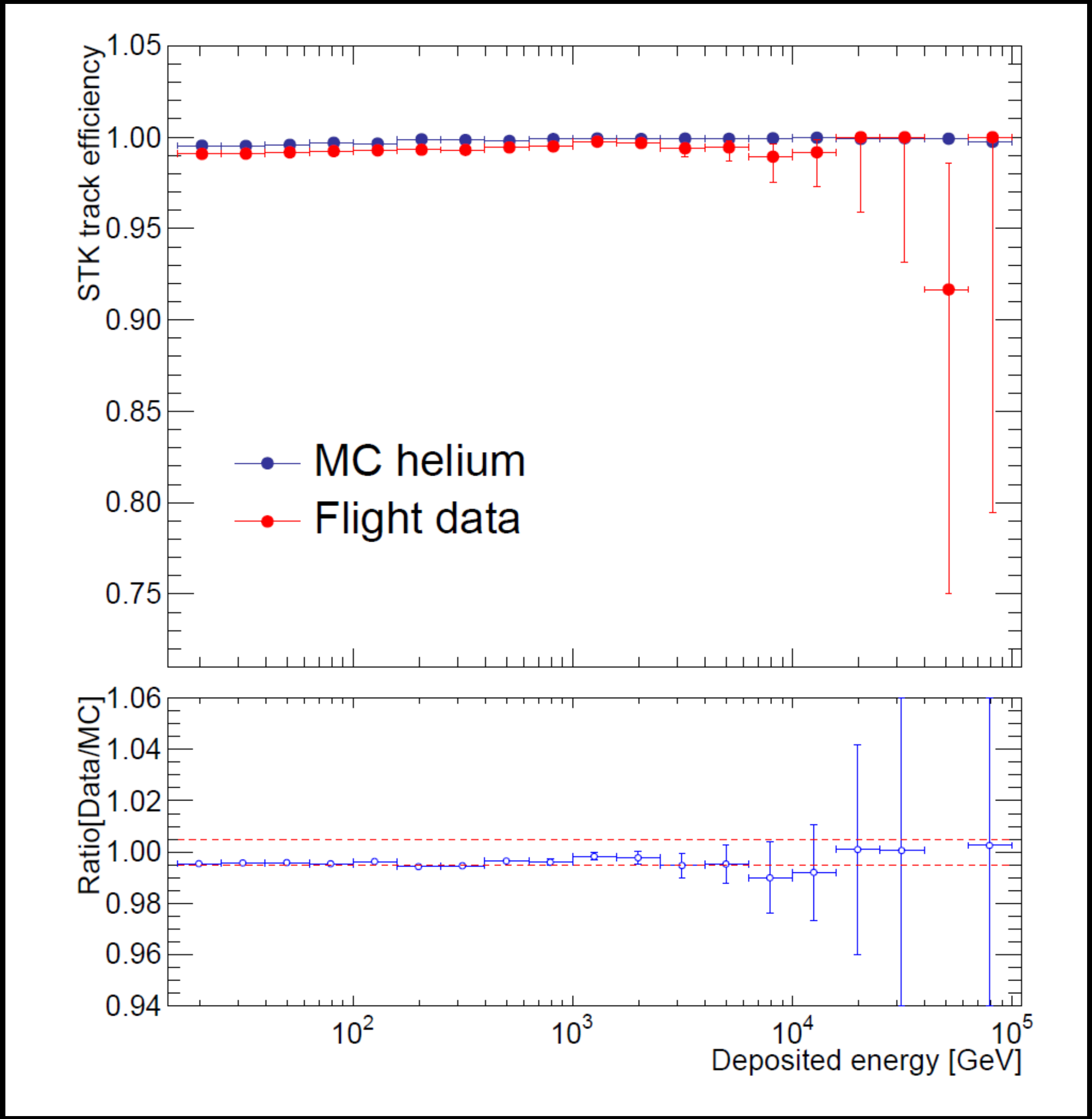
$\sigma_{HET} \sim 4\%$ **up to ~ 1 TeV**



# Systematics: Track reconstruction efficiency

$$\varepsilon_{Track} = \frac{N_{PSD|STK|BGO}}{N_{PSD|BGO}}$$

- $N_{PSD|STK|BGO}$ : number of events selected by the analysis
- $N_{PSD|BGO}$ : number of events selected by using track information provided only by PSD and BGO

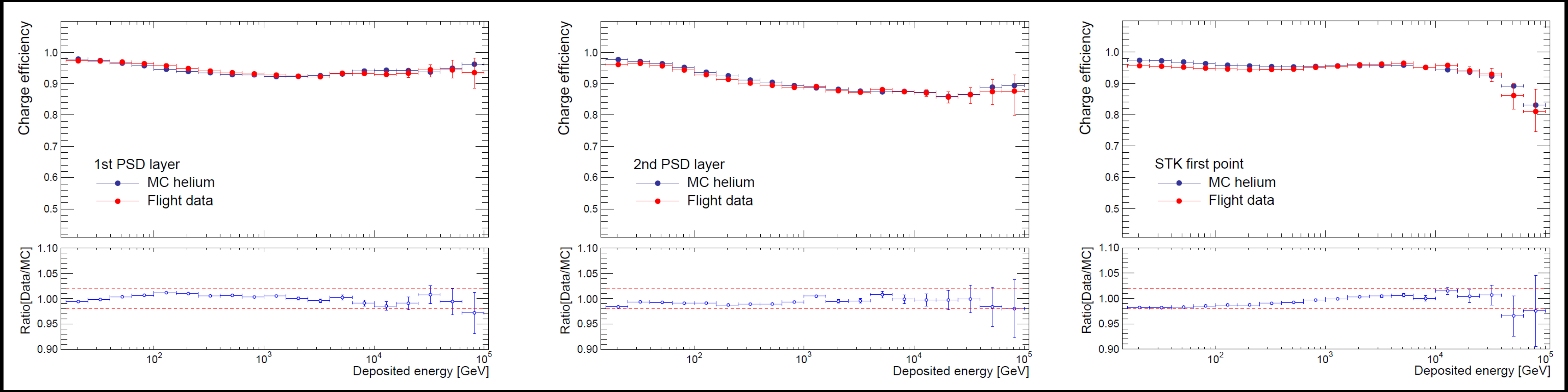



**Systematic uncertainty due to Track selection:**

**$\sigma_{Track}$ found to be within 0.5% up to 100 TeV**

# Systematics: Charge reconstruction efficiency

Charge reconstruction efficiency computed for both the PSD layers separately with the help of the 1st STK layer.




$$\varepsilon_{PSD1st} = \frac{N_{PSD1st|PSD2nd|STK1st}}{N_{PSD2nd|STK1st}}$$

$$\varepsilon_{PSD2nd} = \frac{N_{PSD1st|PSD2nd|STK1st}}{N_{PSD1st|STK1st}}$$

$$\varepsilon_{STK1st} = \frac{N_{PSD|STK1st}}{N_{STK1st}}$$

Combined systematic uncertainty due to Charge reconstruction:

$\sigma_{charge} \sim 3.5\%$ up to 10 TeV

# Effective Acceptance

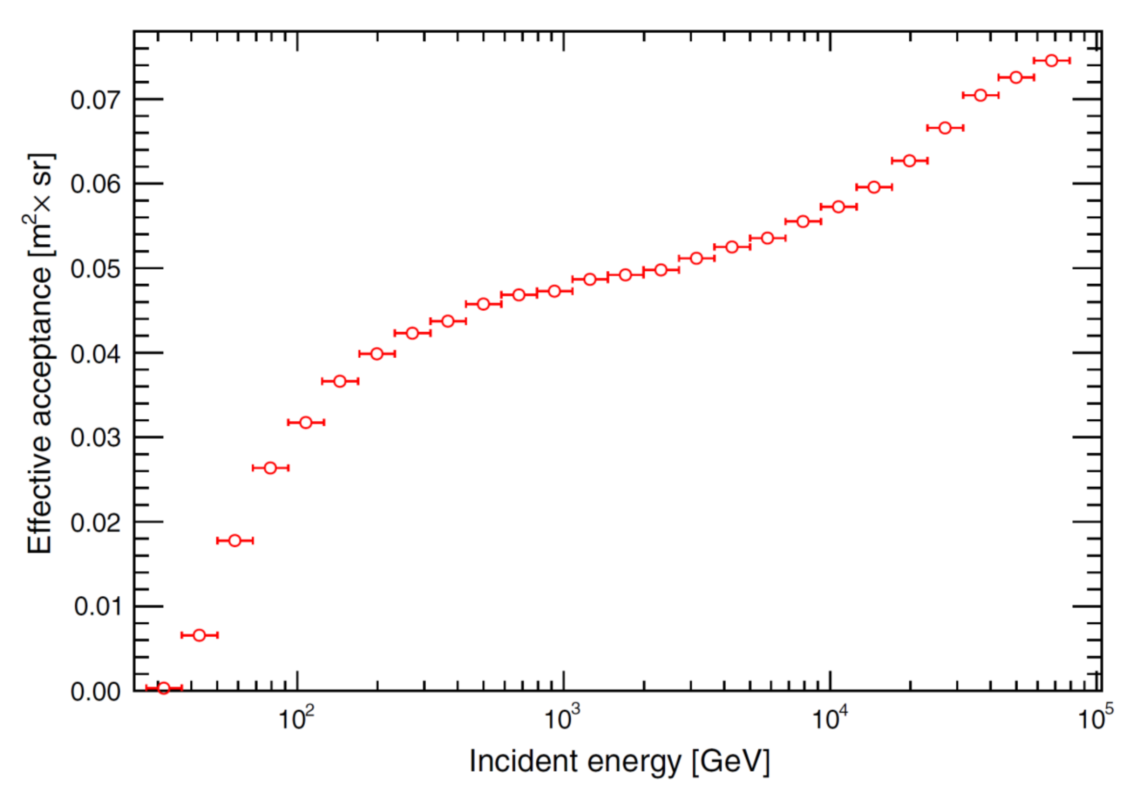
Differential flux in the *i*-th bin of primay energy:

$$\Phi(E_i, E_i + \Delta E_i) = \frac{\Delta N_i}{\Delta E_i \; \mathrm{A}_{\mathrm{eff},i} \; \Delta \mathrm{T}}$$

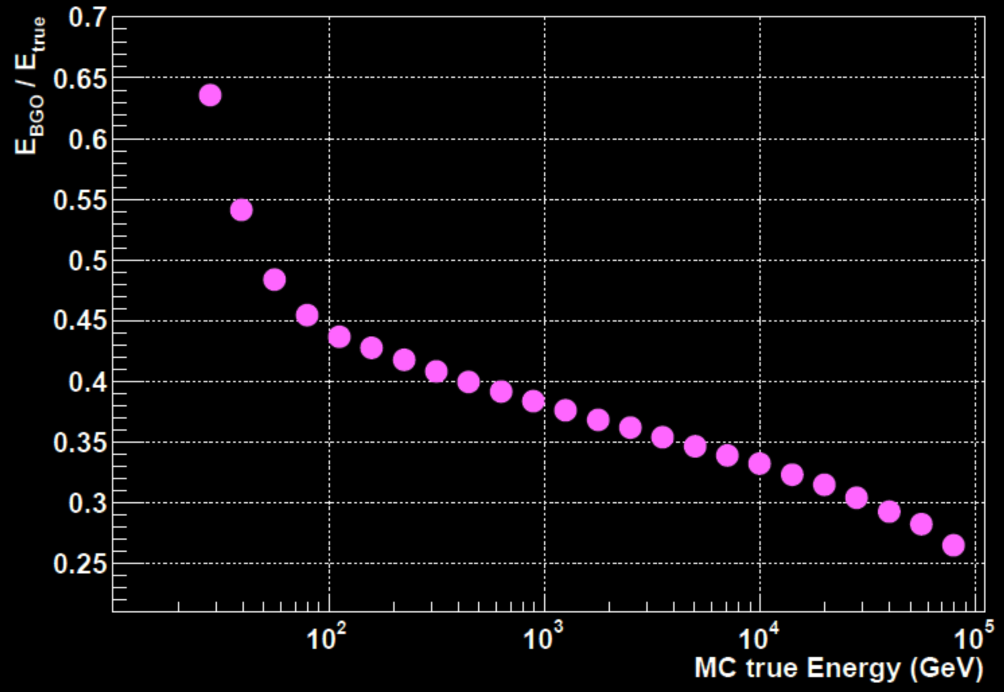
- **$\Delta N_i$** : number of detected incident helium nuclei in the *i*-th primary energy bin of width $E_i$
- **$\Delta T$ :** is the total detector livetime which is $1.08 \cdot 10^8$ s
- **$A_{eff,i}$ :** effective acceptance of the DAMPE detector as a function of the primary energy for the incoming CR helium nuclei at a given *i*-th bin of incident energy

$$\mathrm{A}_{\mathrm{eff},i} = \mathrm{A}_{\mathrm{gen}} \times \frac{\mathrm{N}_{\mathrm{pass},i}}{\mathrm{N}_{\mathrm{gen},i}}$$

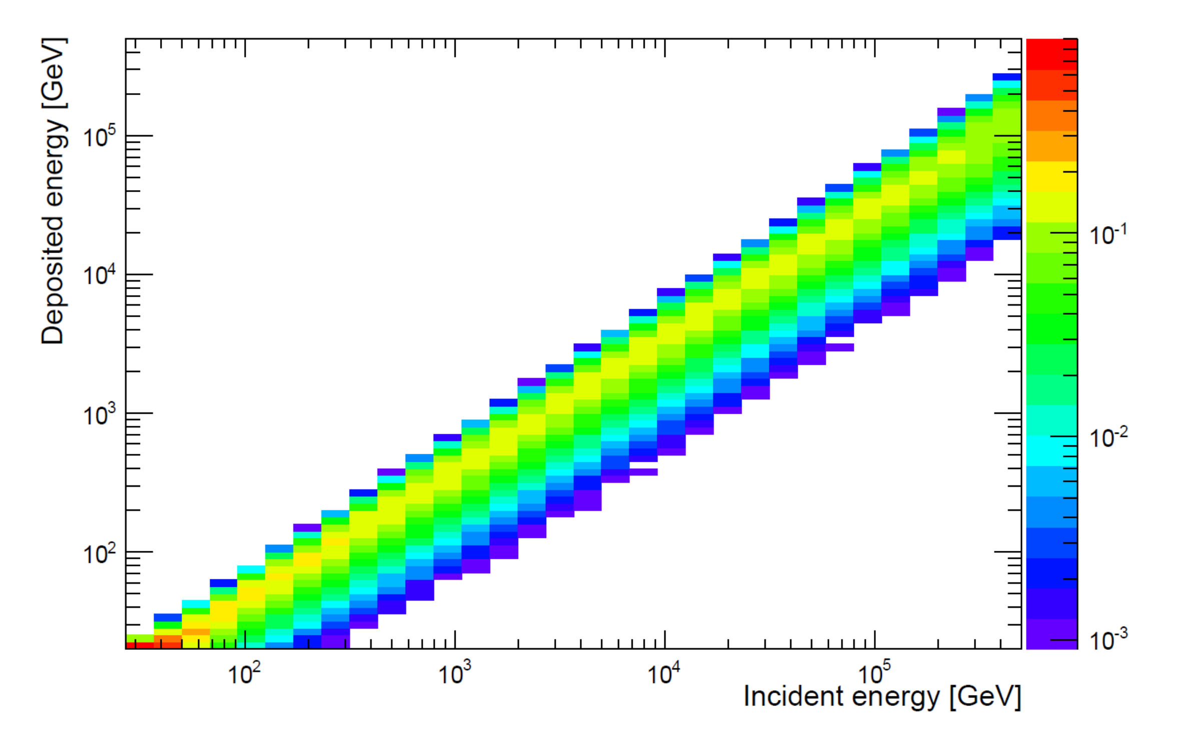
- **$A_{gen}$** : geometrical factor used in MC simulation of an isotropic CR helium flux generated above a sphere with R=1.0 m
- **$N_{gen,i}$** : total number of generated events in the *i*-th of primary energy
- **$N_{pass,i}$** : number of events selected by the  the analysis, in a given *i*-th of primary energy



# Unfolding procedure for energy estimate



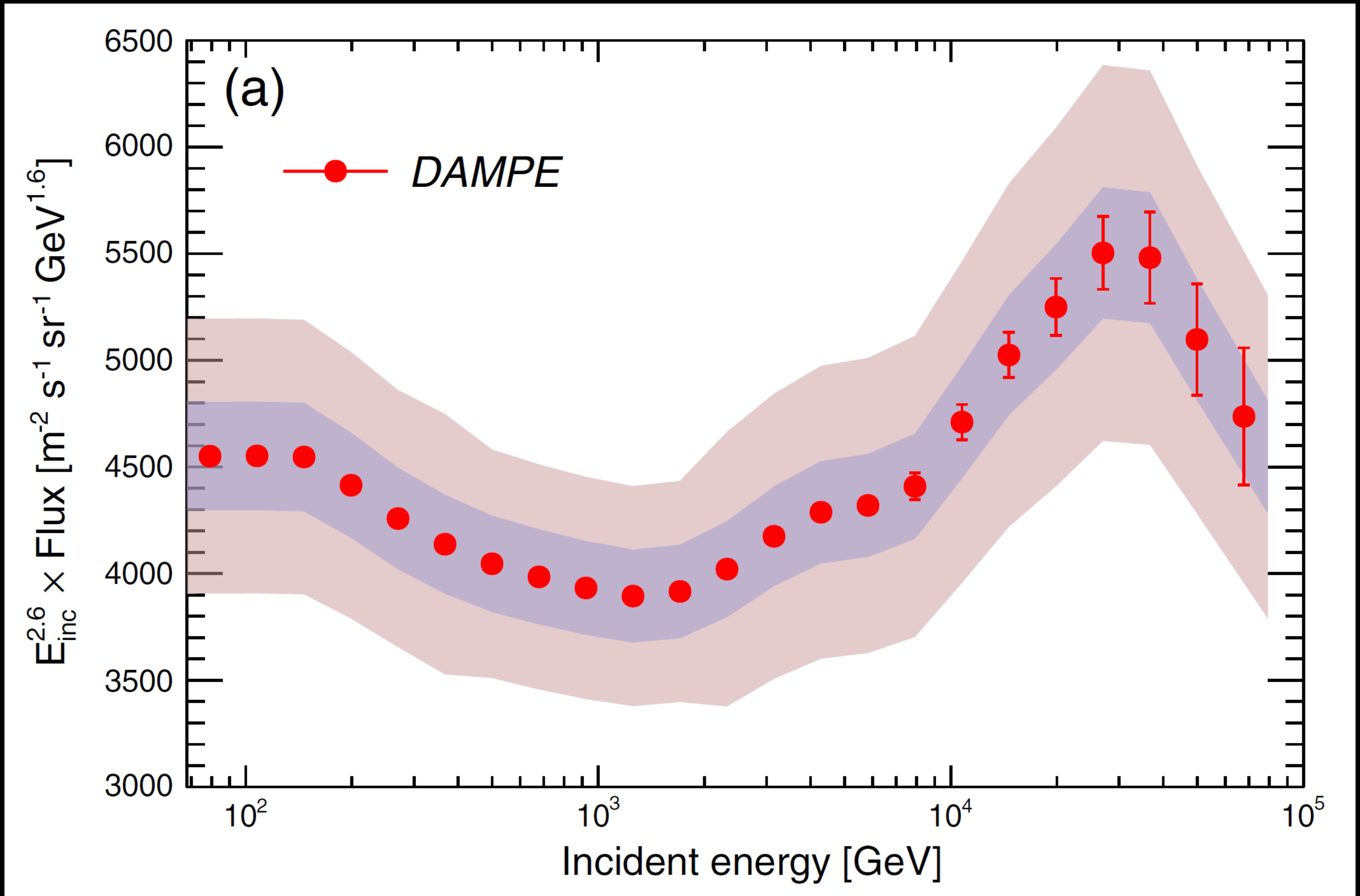

The limited thickness of the DAMPE calorimeter (~ 1.62 nuclear interaction lengths) significantly affects the energy response. In fact, only a part of the total particle energy is deposited inside the detector (~ 40% at 10 TeV), decreasing with the true energy due to a deeper development of the showers inside the calorimeter.

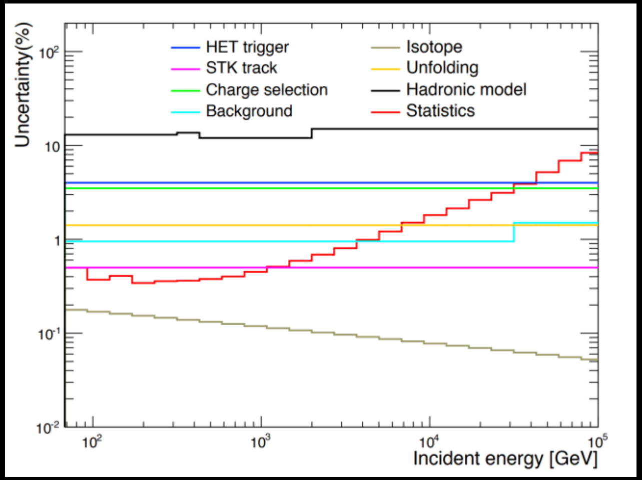



We use an *Unfolding* procedure by adopting a *Bayesian* method.

**G. D'Agostini, Nucl. Instrum. Meth. A 362 (1995)**

# Helium energy spectrum




**Error bars:** statistical uncertainties

**Inner deshed band:** $\sigma_{ana} = \sqrt{\sigma_{HET}^2 + \sigma_{Charge}^2 + \sigma_{track}^2 + \sigma_{bg}^2 + \sigma_{unf}^2 + \sigma_{iso}^2}$

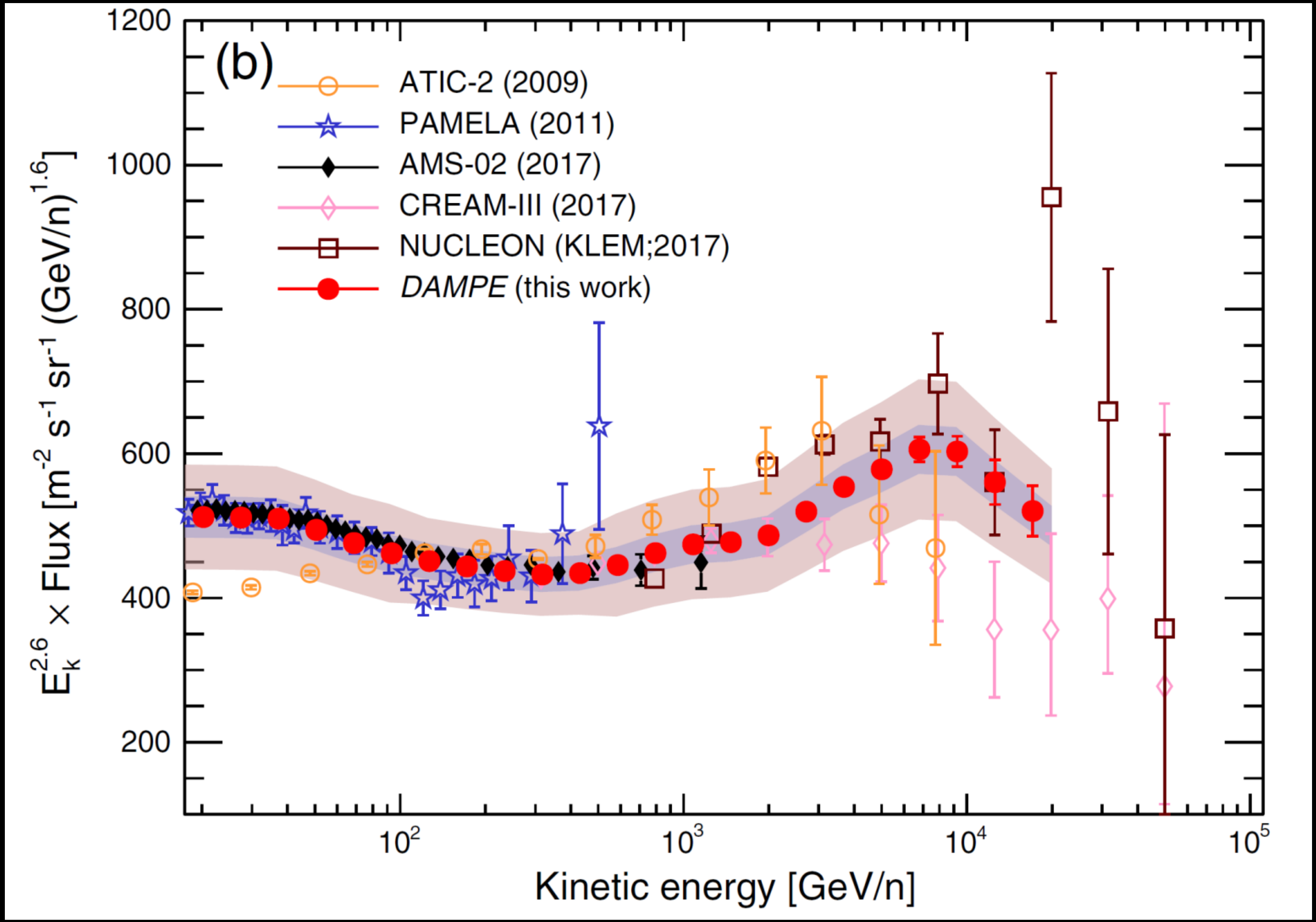
$\sigma_{iso}^2$ ~ 0.2% isotope uncertainty obtained by varing the ratio of $He^3$ and $He^4$ measured by AMS-02 by 5%.

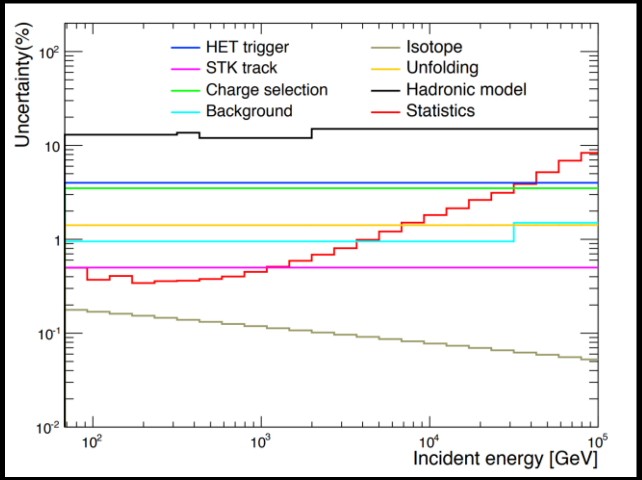
$\sigma_{unf}$ ~ 1% unfolding uncertainty evaluated both re-weighting the MC simulations by varying the spectral index from 2.0 to 3.0 and checking the differences with the result obtained by repeating the analysis with 14 BGO layers.

**Outer shaded band:** $\sqrt{\sigma_{ana} + \sigma_{had}}$ , $\sigma_{had}$ obtained from the comparison with FLUKA MC simulations.

**The DAMPE measurement of the helium energy spectrum confirms the observation of a spectral hardening at TeV-energies previously highlighted by other experiments and clearly shows an evidence of a spectral softening at tens of TeV.**

# Helium energy spectrum

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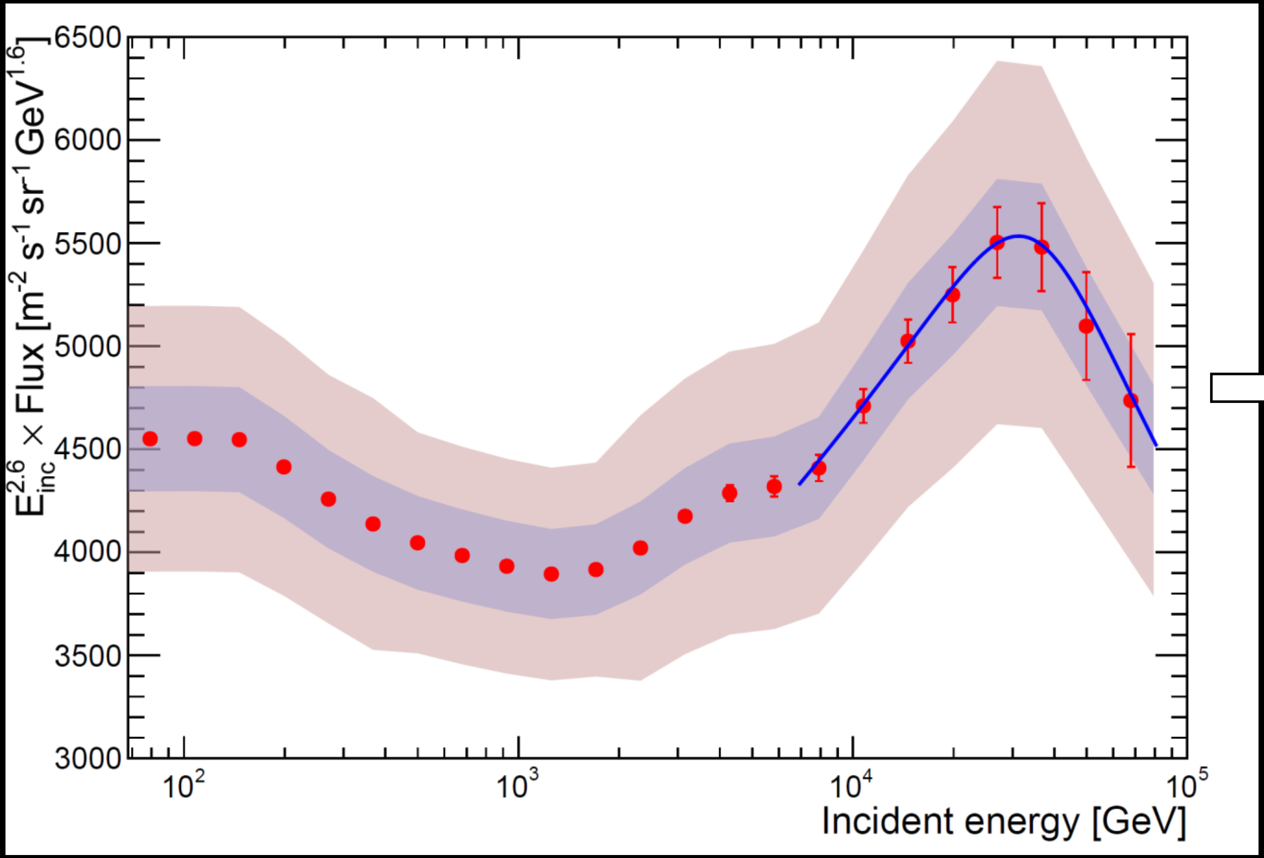
# Helium flux fit - Softening

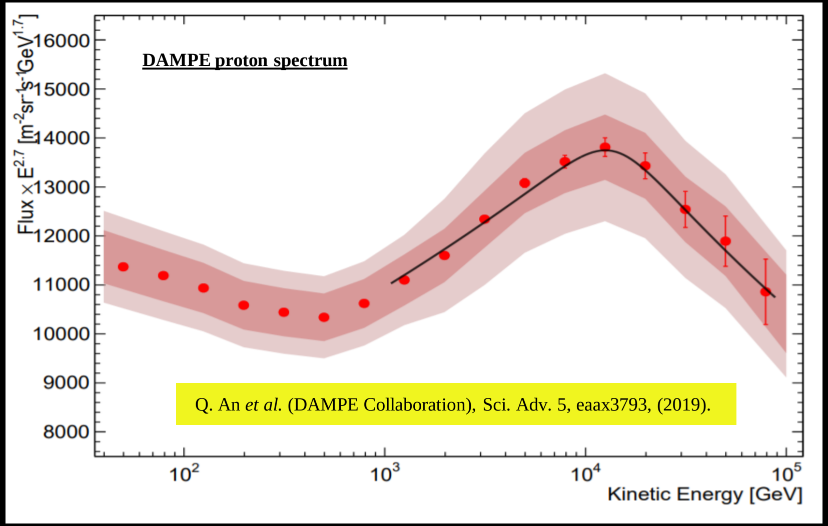



Fit of the softening structure with a Smoothly Broken Power-Law (SBPL) in the energy range [6.8 TeV - 80 TeV].

$$\Phi(E) = \Phi_0 \left(\frac{E}{\mathrm{TeV}}\right)^{\gamma} \left[1 + \left(\frac{E}{E_b}\right)^{s}\right]^{\Delta\gamma/\omega}$$

$$E_b = 34.4^{+6.7}_{-9.8}\ \mathrm{TeV}$$
$$\gamma = 2.41^{+0.02}_{-0.02}$$
$$\Delta\gamma = -0.51^{+0.18}_{-0.20}$$
$$s = 5.0\ (fixed)$$

**Significance of the softening: $\sim 4.3\ \sigma$**




By comparing the implications of this result with the softening observed by DAMPE in the proton energy spectrum at ~13.6 TeV, it turns out a charge-dependent softening energy, even if a mass-dependence of the structure cannot be ruled out.

# Conclusions

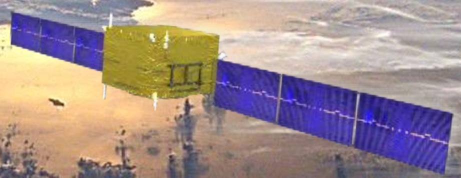
- The measurement of the Galactic CR Helium flux from 70 GeV up to 80 TeV has been obtained by analyzing the on-orbit data provided by the DAMPE satellite during 54 months of data-taking

- The result shows a good agreement with other experiments within the uncertainties

- A spectral *hardening* has been observed, confirming previous results by other experiments but with higher energy resolution

- A *softening* structure has been clearly observed at energy $E_b \sim 34$ TeV for the first time with a significance of ~4.3 σ

- This measurement has been validated by three independent analyses which are consistent within the analysis uncertainty



# Thank you!