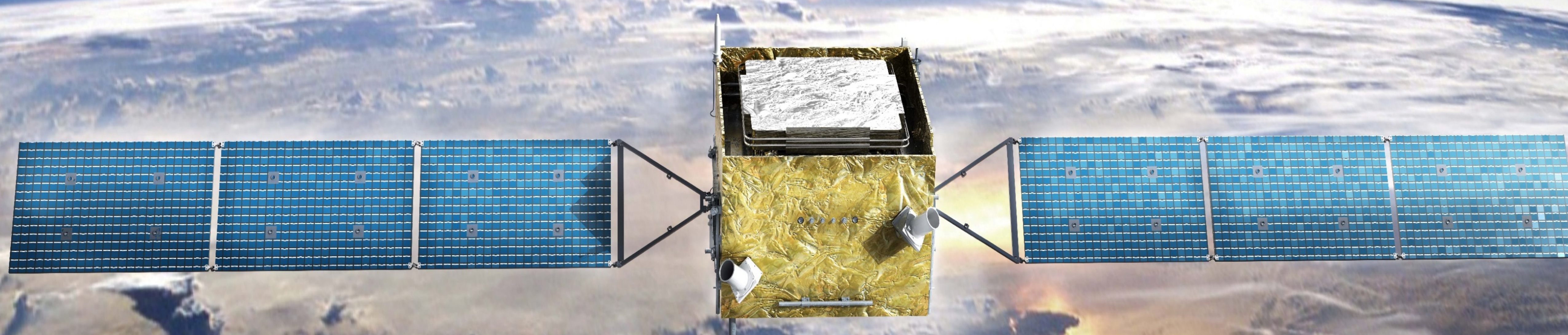
2021 TEV Particle Astrophysics Conference

Measurements of the cosmic ray proton and helium spectra with the DAMPE experiment



Yue, Chuan

Purple Mountain Observatory, CAS

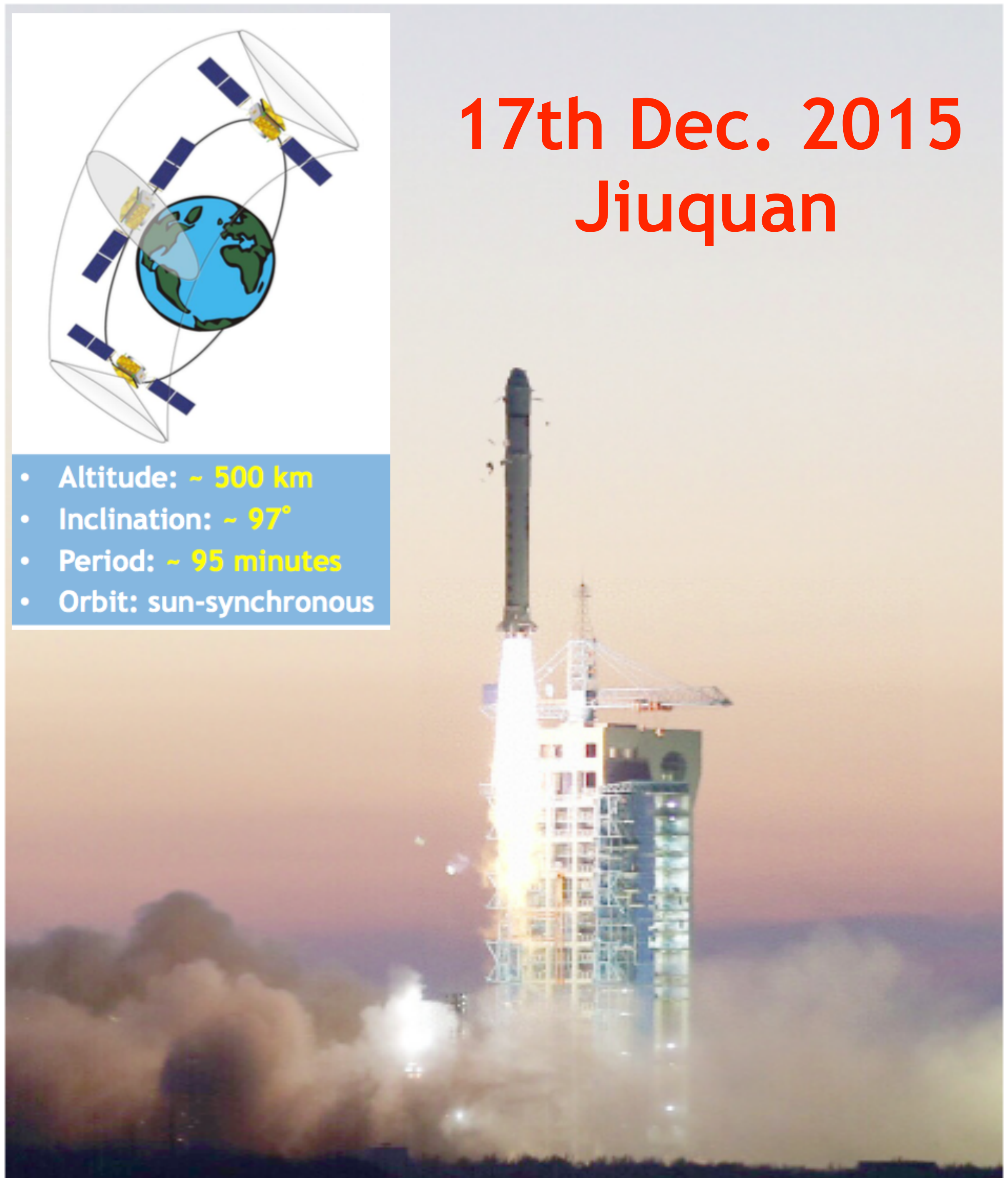
(on behalf of the DAMPE Collaboration)

2021 TeV Particle Astrophysics Conference

Chengdu, China 2021.10.26

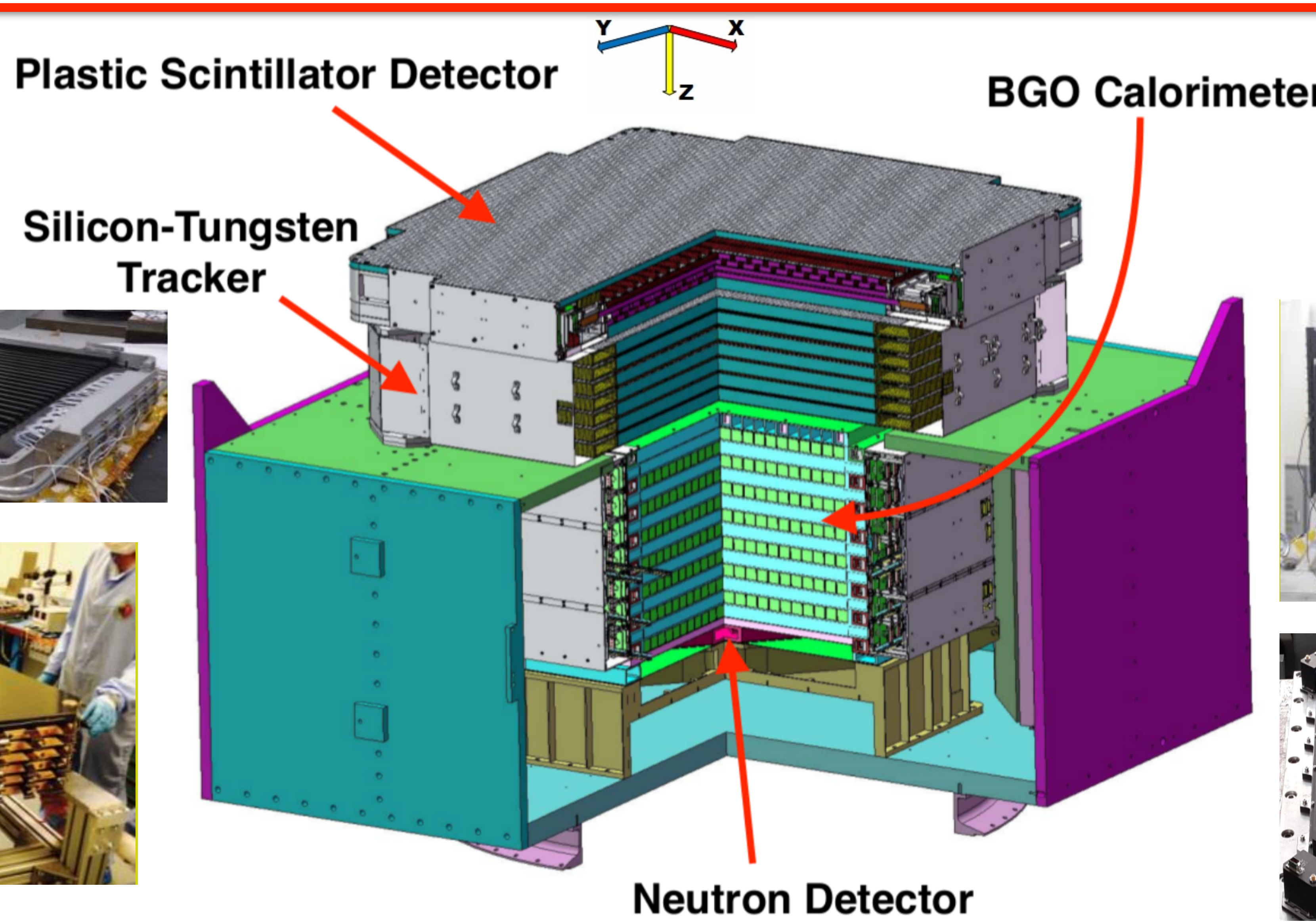
The DArk Matter Particle Explorer

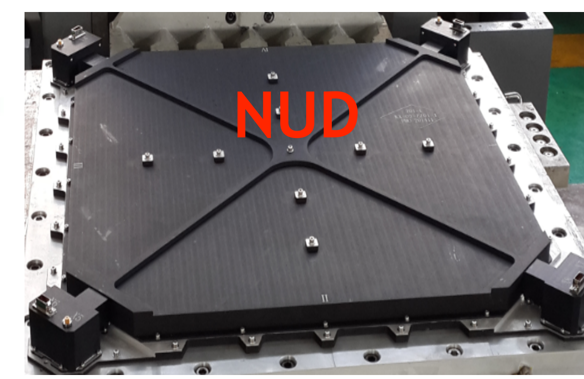
DAMPE is a satellite-borne particle detector proposed in the framework of the Strategic Pioneer Program on Space Science, promoted by the Chinese Academy of Sciences (CAS).



- CHINA
  - Purple Mountain Observatory, CAS
  - University of Science and Technology of China
  - Institute of High Energy Physics, CAS
  - Institute of Modern Physics, CAS
  - National Space Science Center, CAS
- ITALY
  - INFN Perugia and University of Perugia
  - INFN Bari and University of Bari
  - INFN Lecce and University of Salento
  - INFN LNGS and Gran Sasso Science Institute
- SWITZERLAND
  - University of Geneva

The DAMPE detector





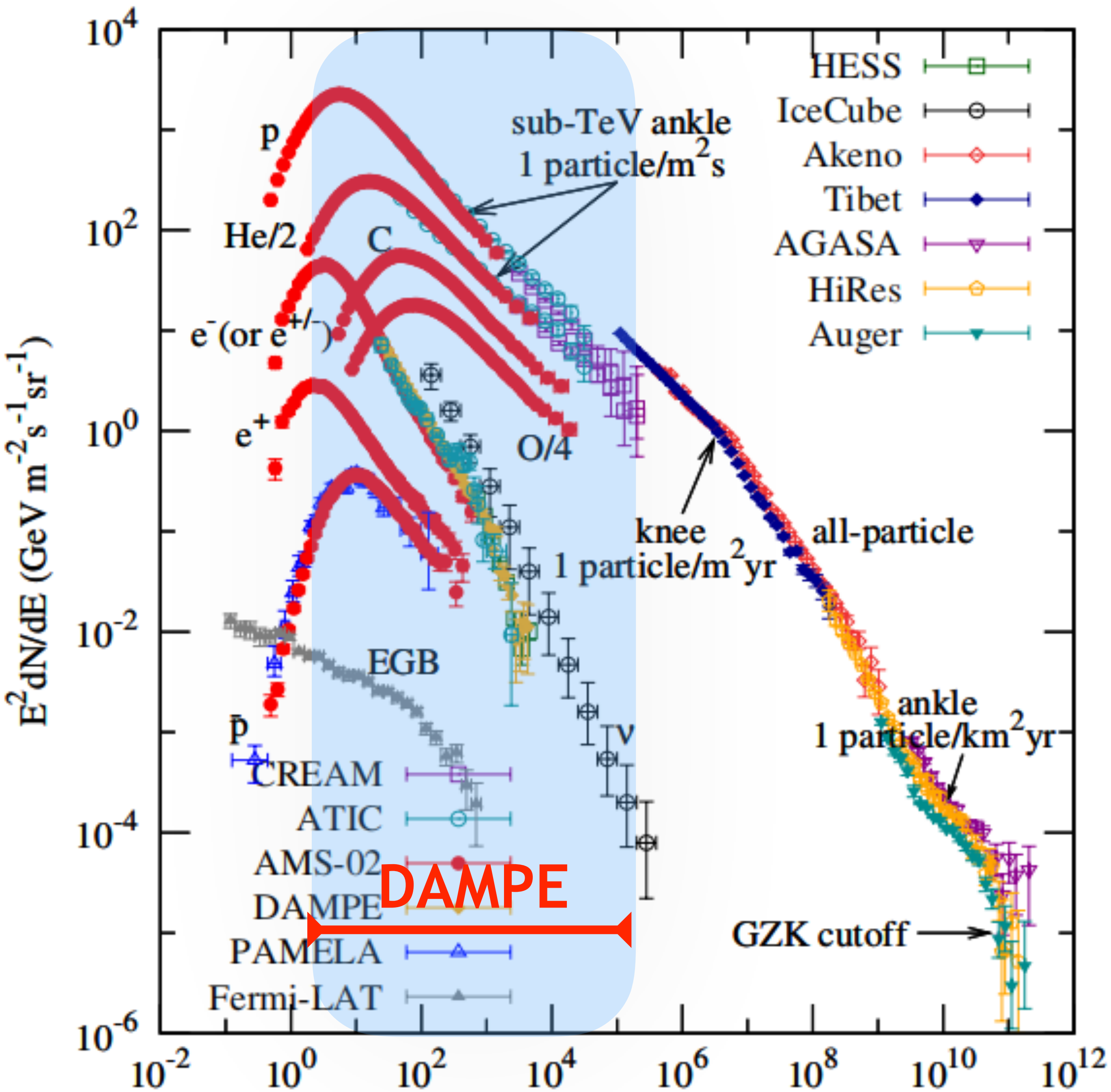
Main Scientific Goals:

- Dark Matter Indirected Detection
- Cosmic-Ray Origin and Acceleration
- High Energy Gamma-ray Astronomy

- Charge measurement (dE/dx in PSD, STK)
- Gamma-ray converting and tracking (STK)
- Precise energy measurement (BGO ECAL)
- Hadron rejection (BGO and Neutron Detector)

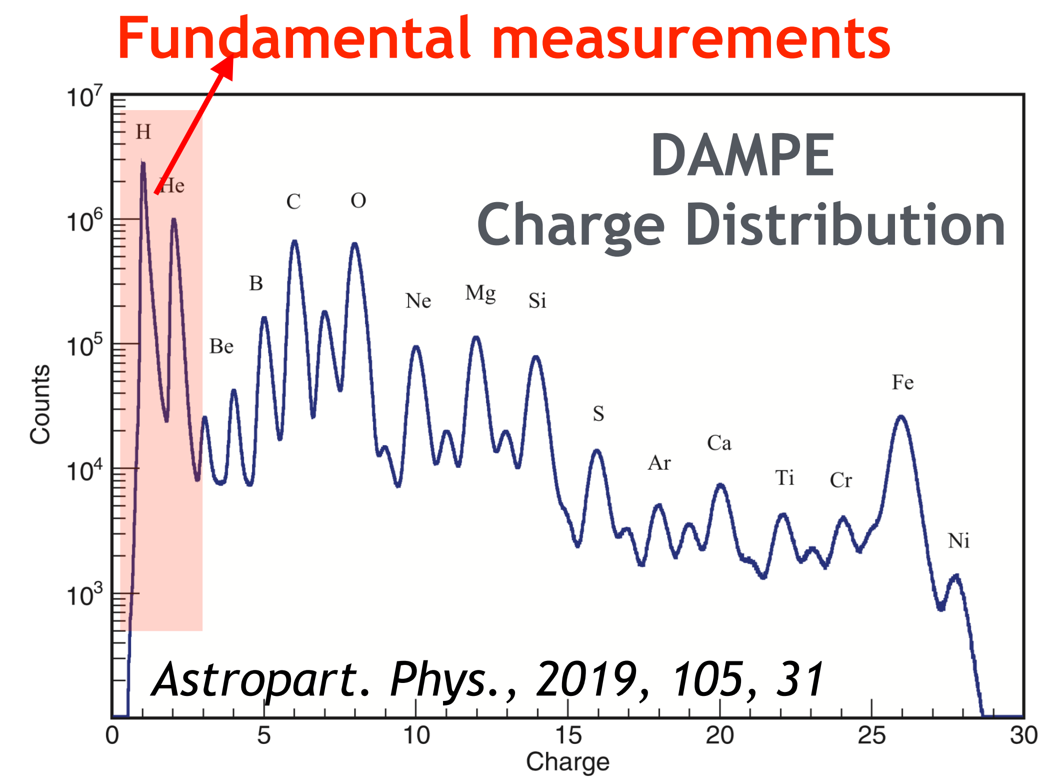
(Chang et al. Astropart.Phys. 2017, 95, 6-24)

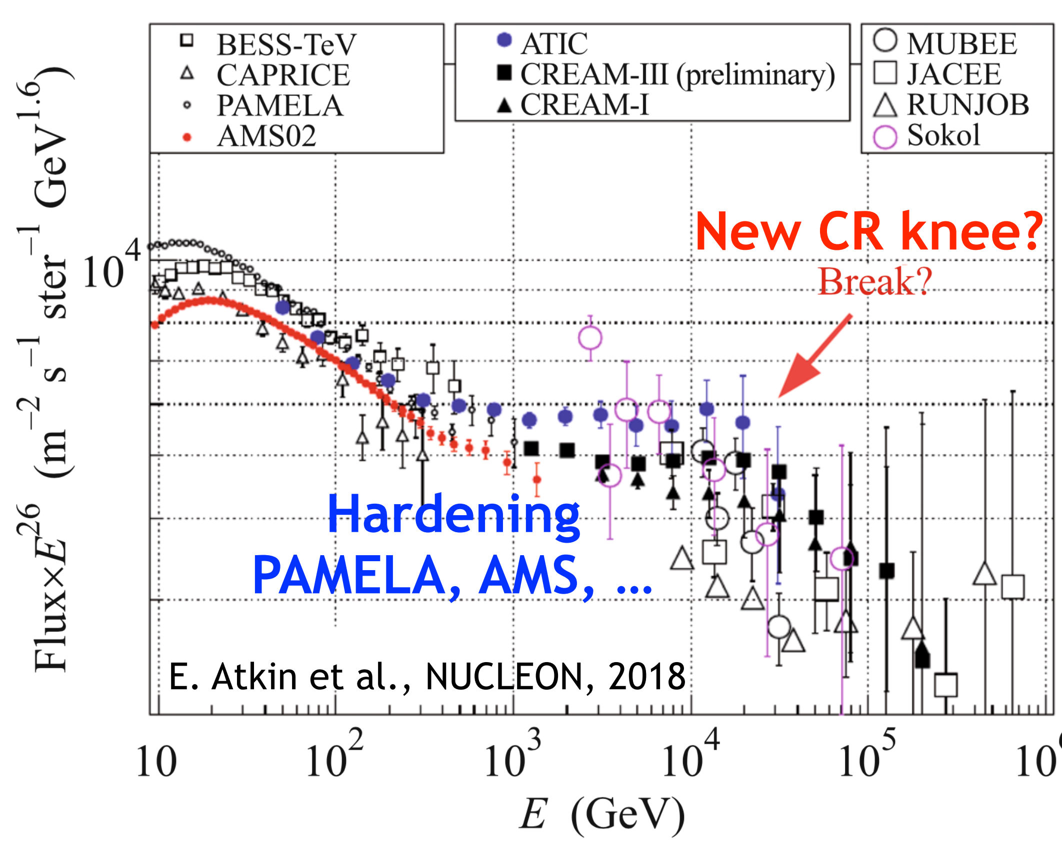
Introduction



Space-based experiments (direct measurements)

Ground-based experiments (indirect measurements)





Data sample

Proton:

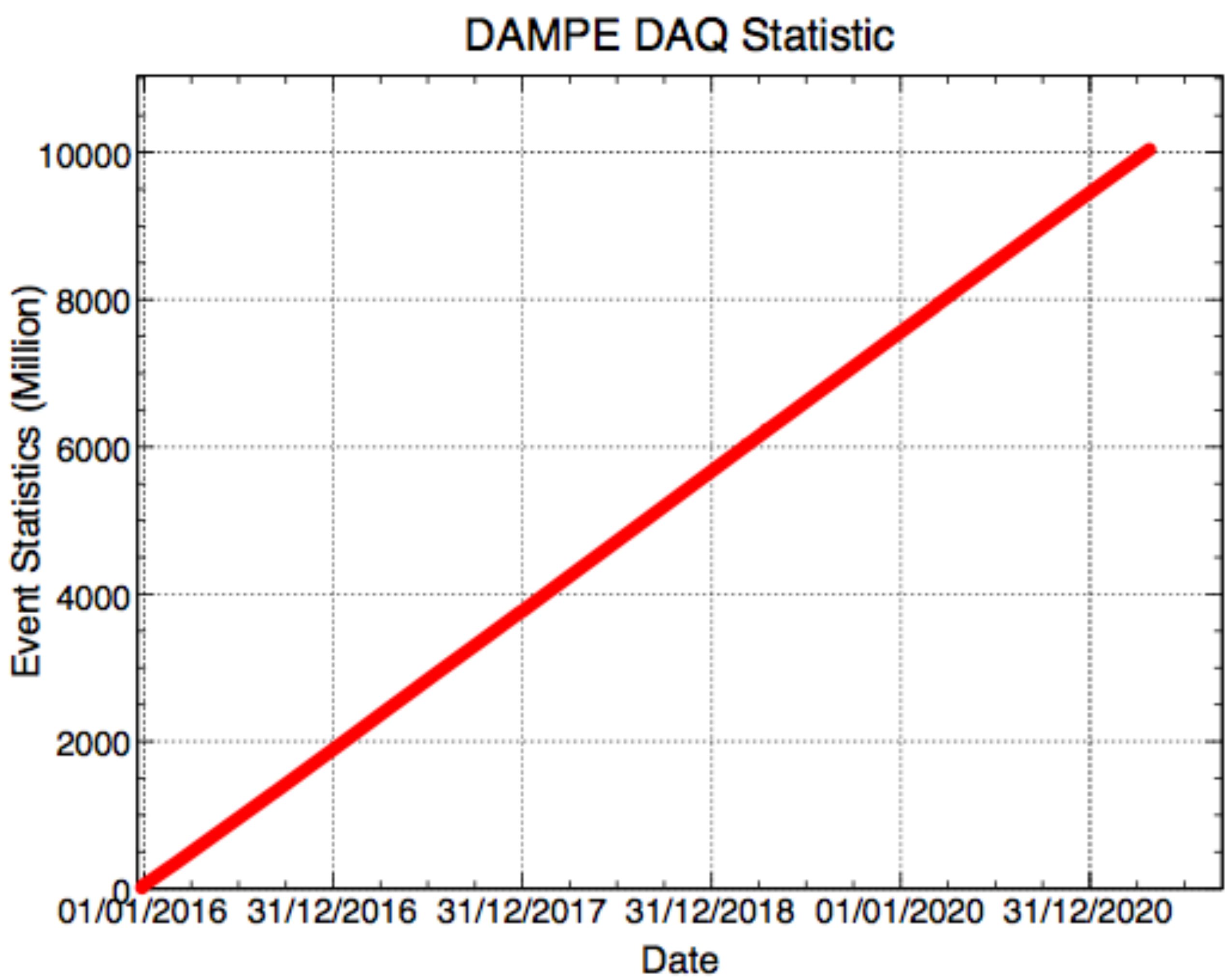
2016/01/01-2018/06/30 (30 month)

5.98×10^7s ~76% of orbit time

Helium:

2016/01/01-2020/06/30 (54 month)

1.08×10^8s ~76% of orbit time



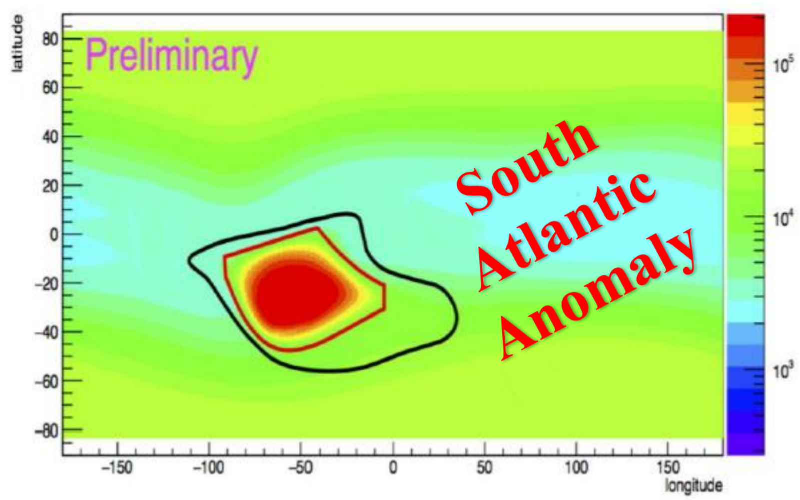
Dead Time

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

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

South Atlantic Anomaly (~4.9% o O.T.)

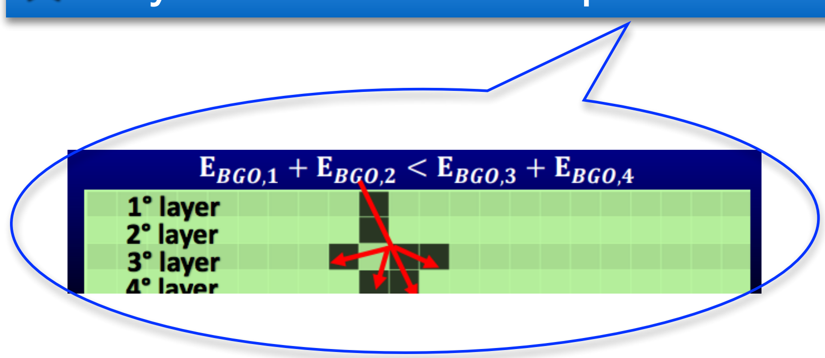
X Solor Flare in Sep. 2017



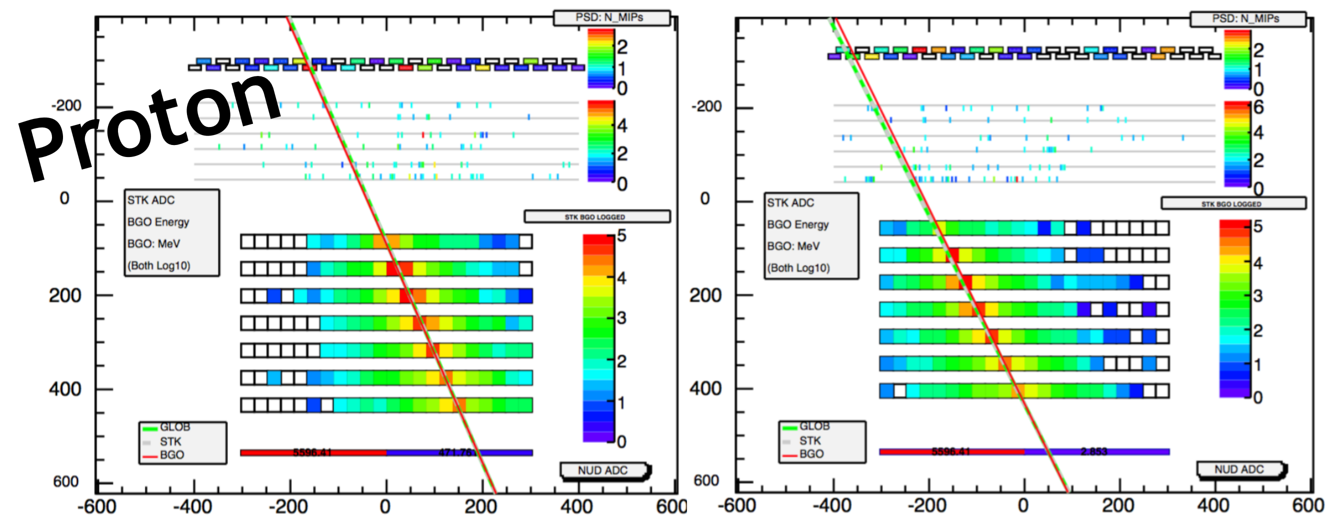
Pre-selection

Target - Good reco events

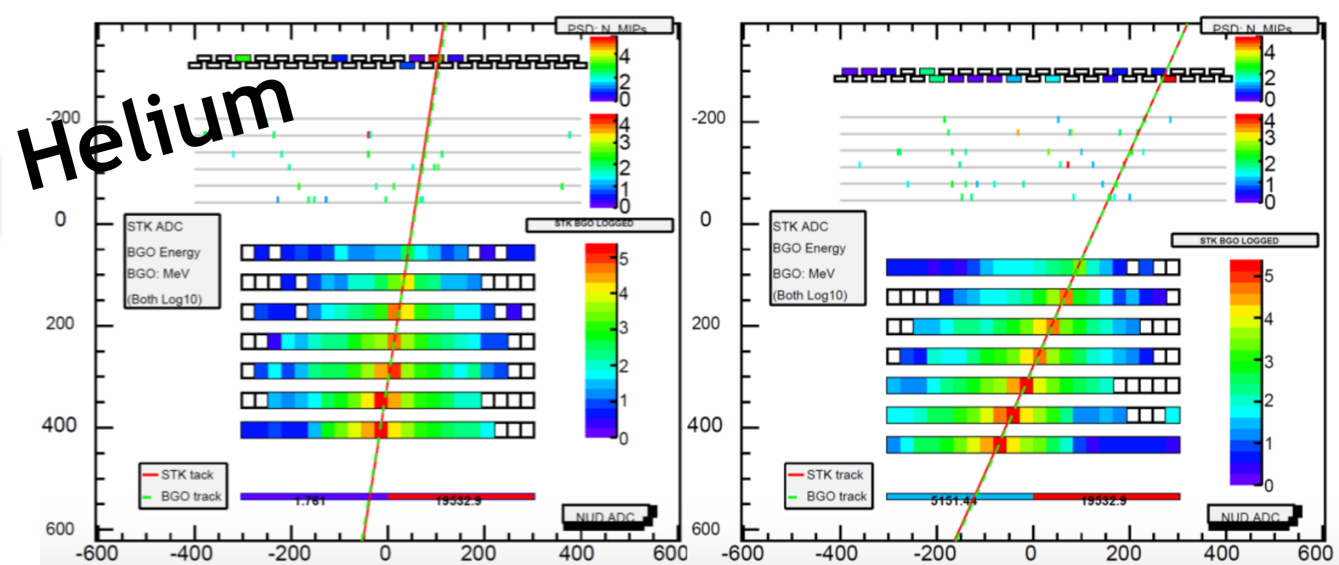
- ★South Atlantic Anomaly (SAA) events exclusion
- ★High Energy Trigger (HET) generation
- ★STK track optimisation
  p: NhitsXY>=4 && Chi2ndof<25 && Maximum total signal of tack
  He: NhitsXY>=4 && Chi2ndof<25 && Maximum total signal of tack
  △diff<25 mm between track and c.o.g. of first 4 BGO layers
- ★Fiducial cut: STK track crossing PSD and BGO
- ★ElayerMax<35% & Top-down shower development



Orbit Proton (BGO-Energy: 1.2 TeV)



Orbit Helium (BGO-Energy: 1.8 TeV)

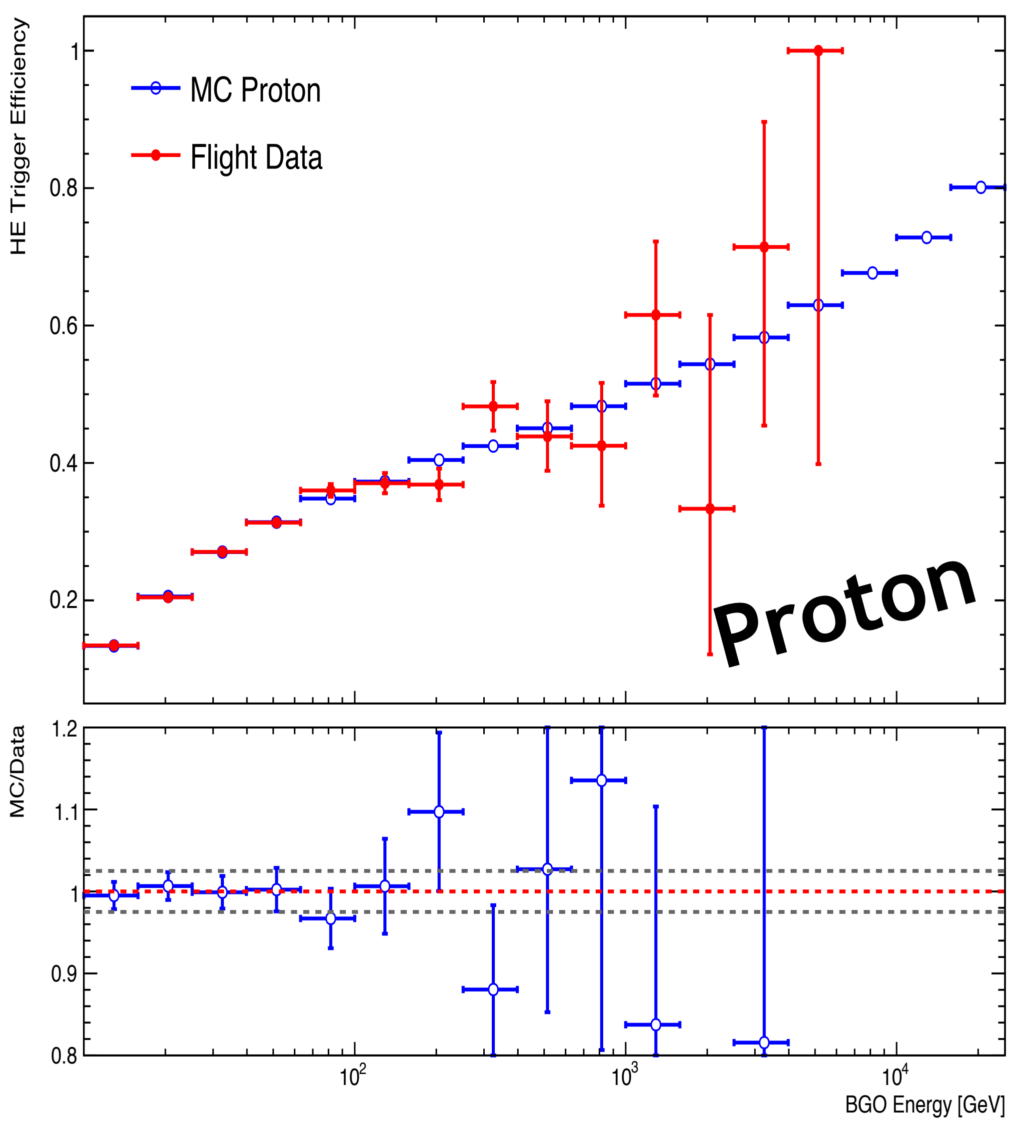


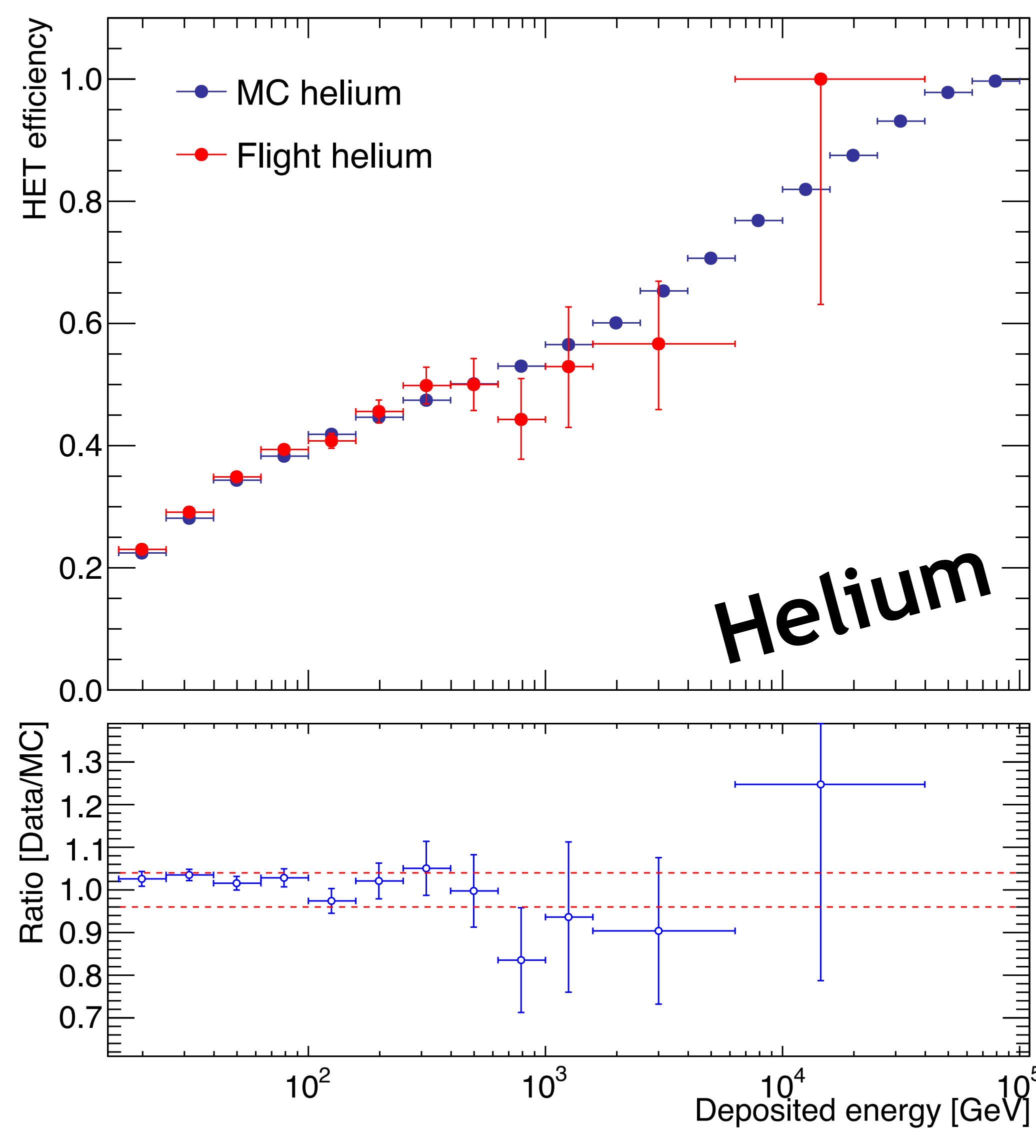
HE trigger efficiency

- ☐ Unbias Trigger (G0)
- ☑ High Energy Trigger (G3)
- ☐ MIPs Trigger (G1&G2)
- ☐ Low Energy Trigger (G4)

High-Energy (G3) trigger efficiency can be obtained by applying all other proton selections ("N-1") to unbias (G0) sample

$$\varepsilon_{\mathrm{trigger}} = \frac{N_{\mathrm{he|unb}}}{N_{\mathrm{unb}}}$$



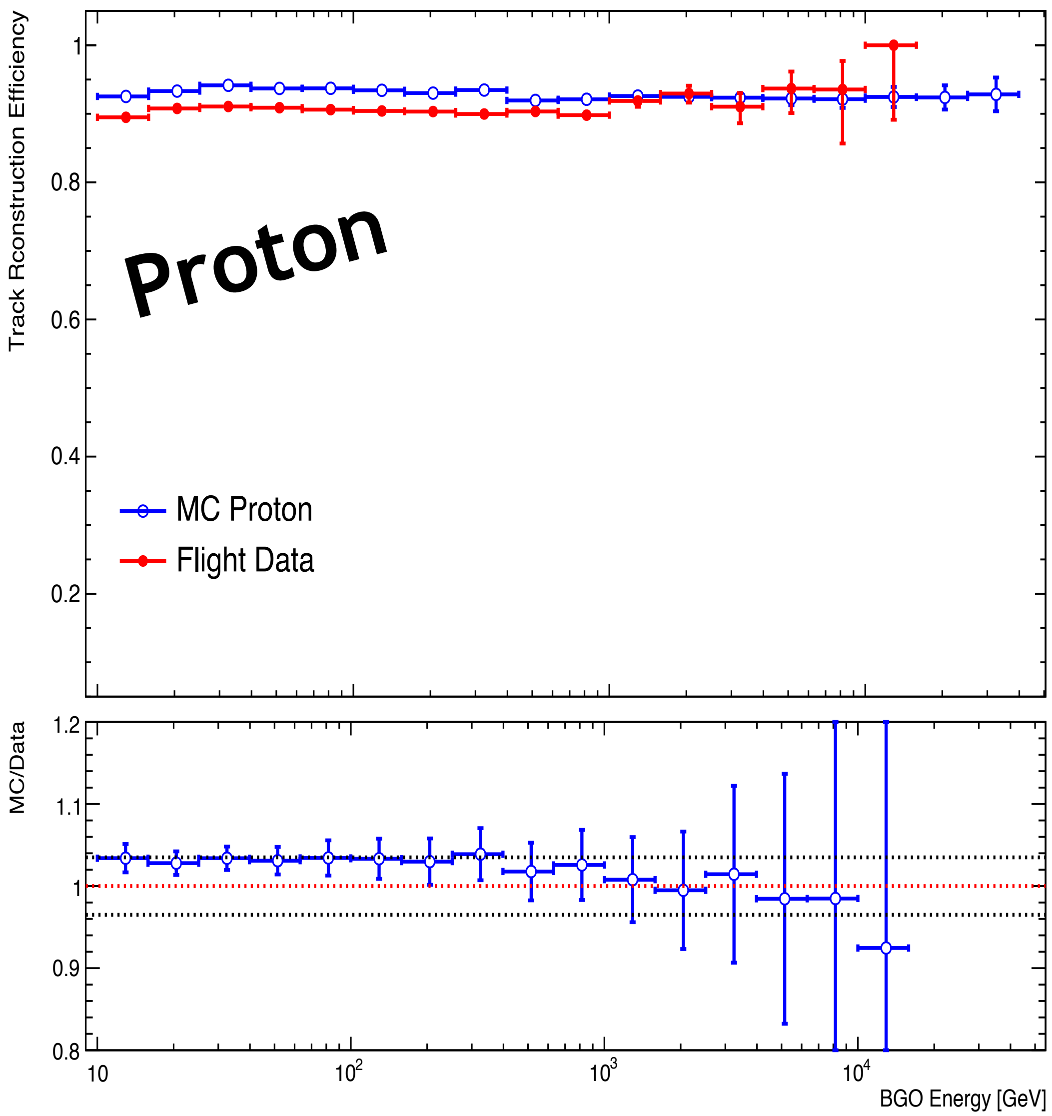


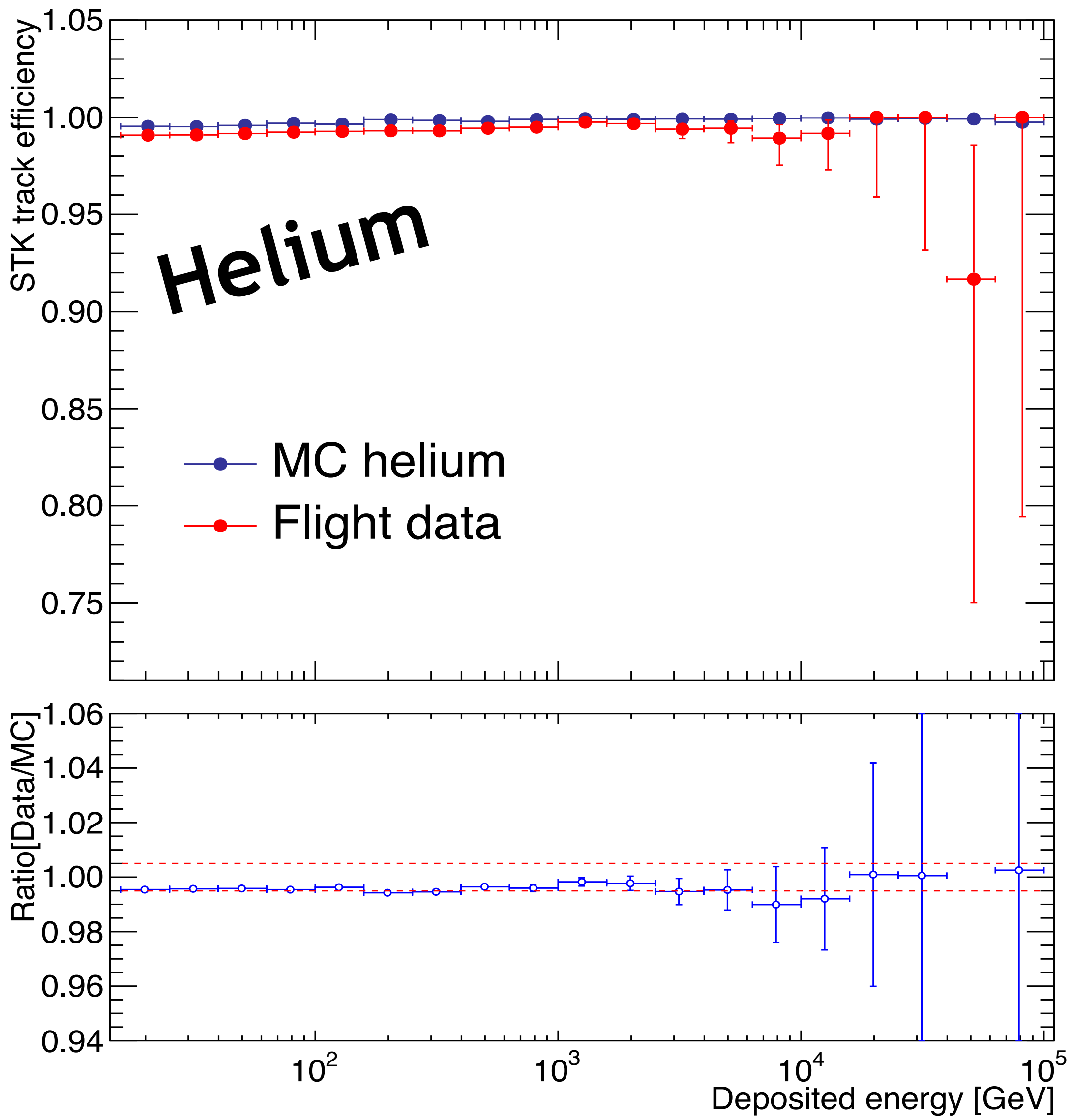
Systematic uncertainty due to HET: ~2.5% (proton), ~4% (Helium)

STK track efficiency

Selecting a "pure" proton (helium) sample by applying BGO shower-axis based proton (helium) selections ("N-1") to estimate STK track reconstruction efficiency.

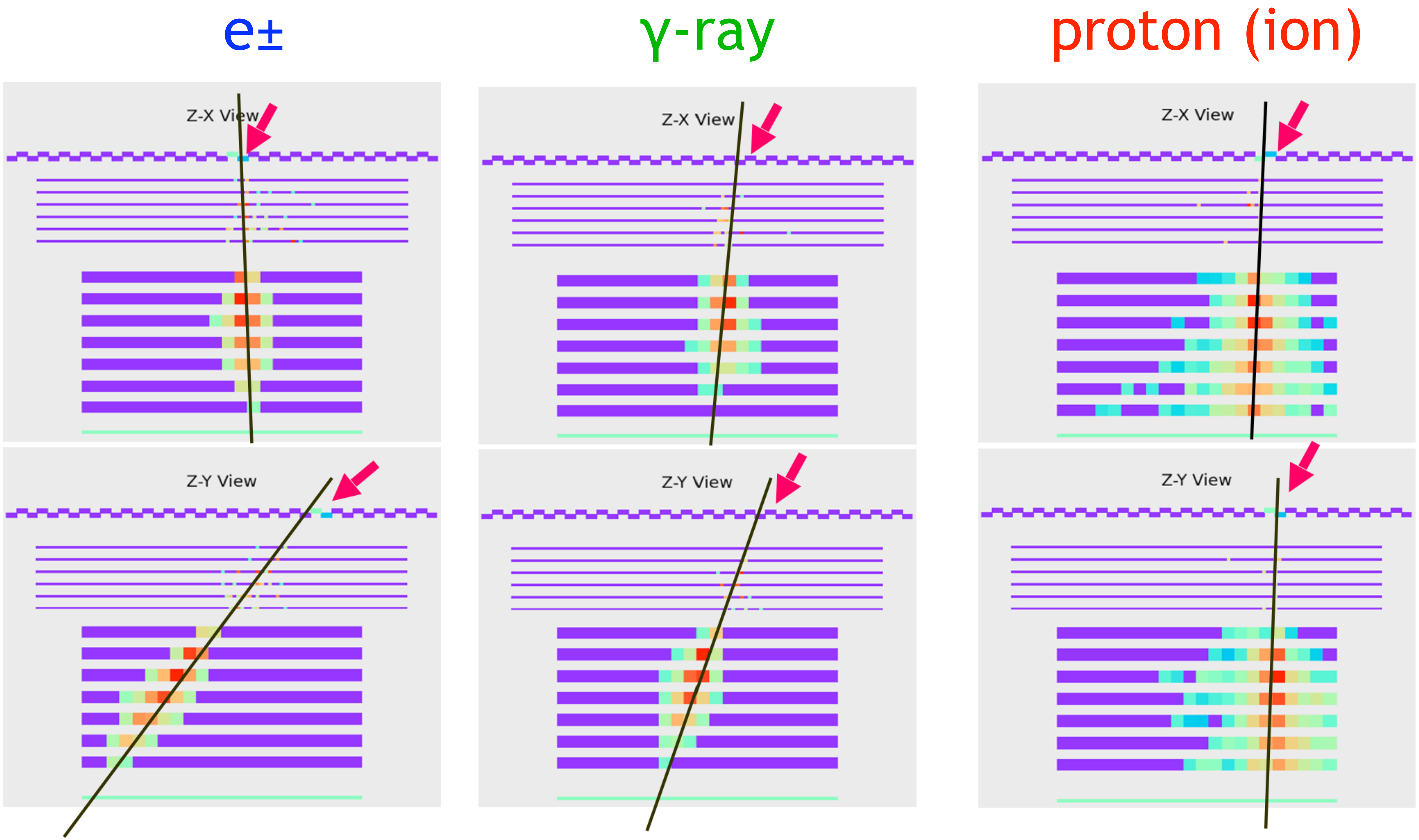
$$\varepsilon_{track} = \frac{N_{track|BGOtrack}}{N_{BGOtrack}}$$



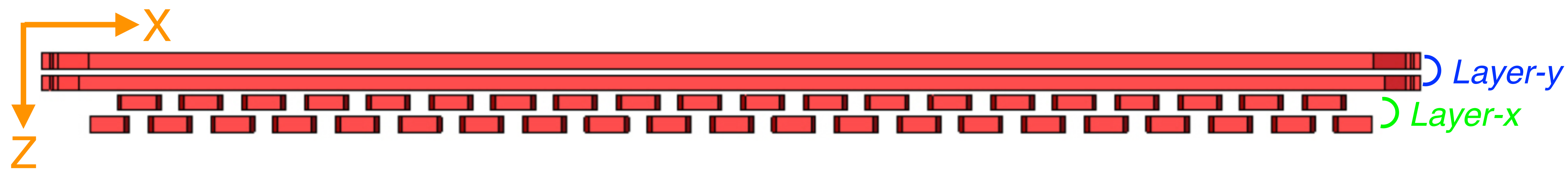


Systematic uncertainty due to STK-track: ~3.5% (proton), ~0.5% (Helium)

Particle identification of DAMPE



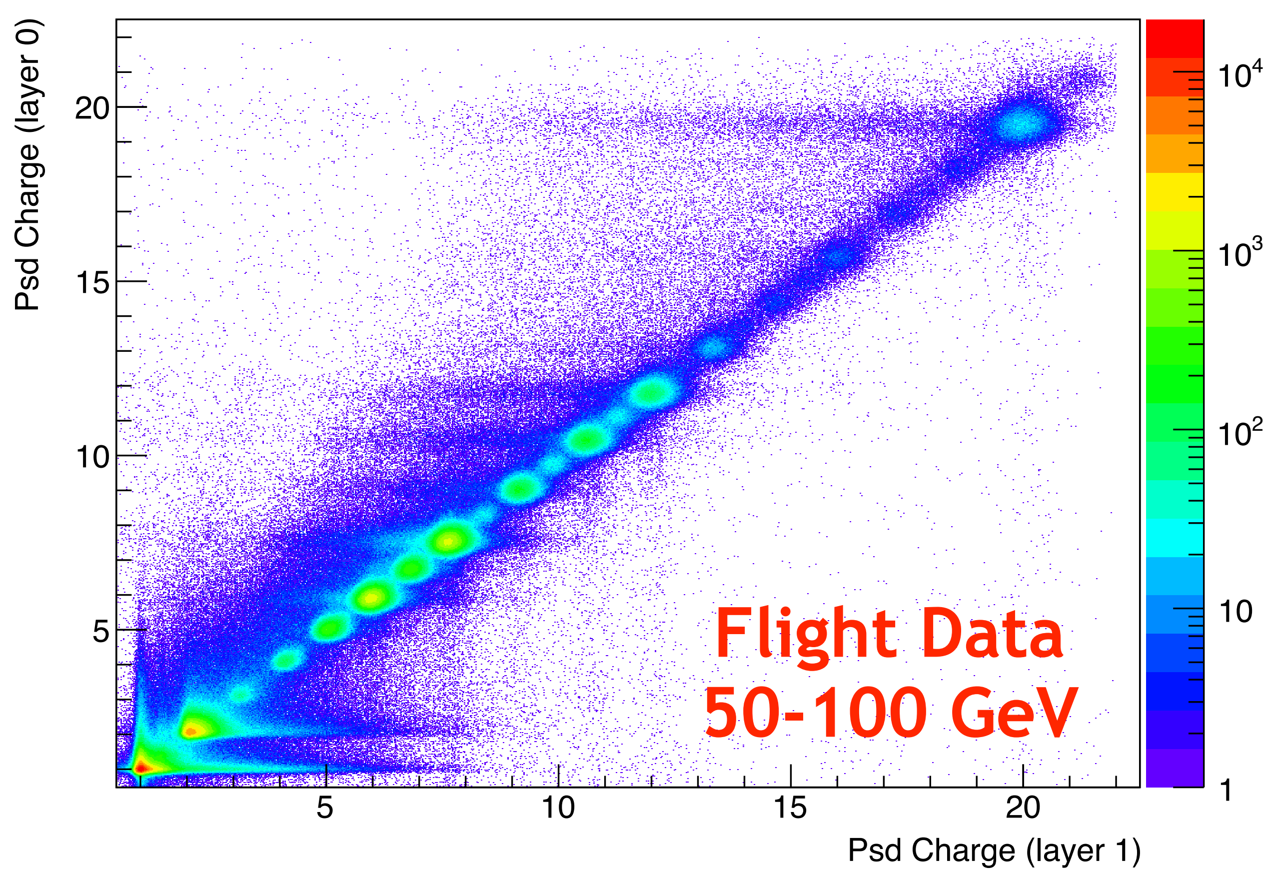
Charge selection

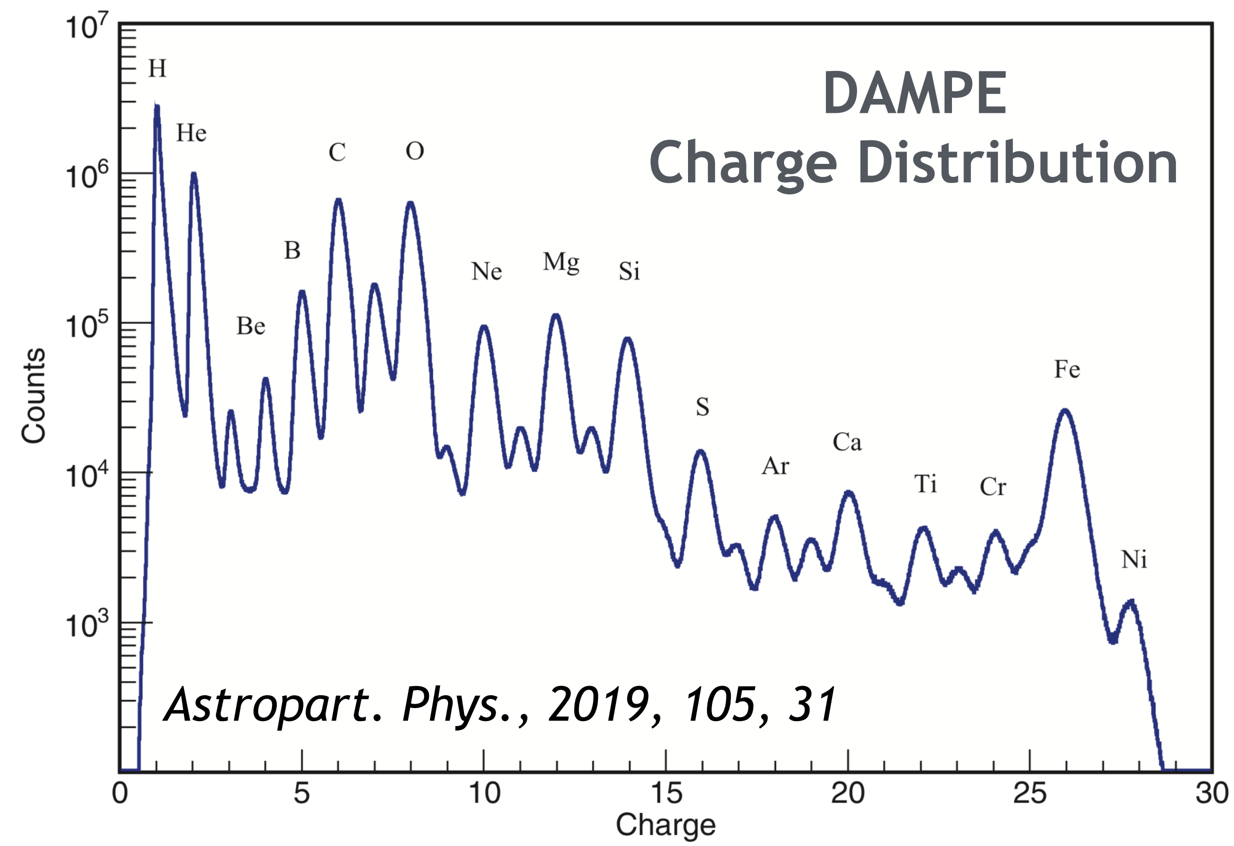


Bethe-Bloch

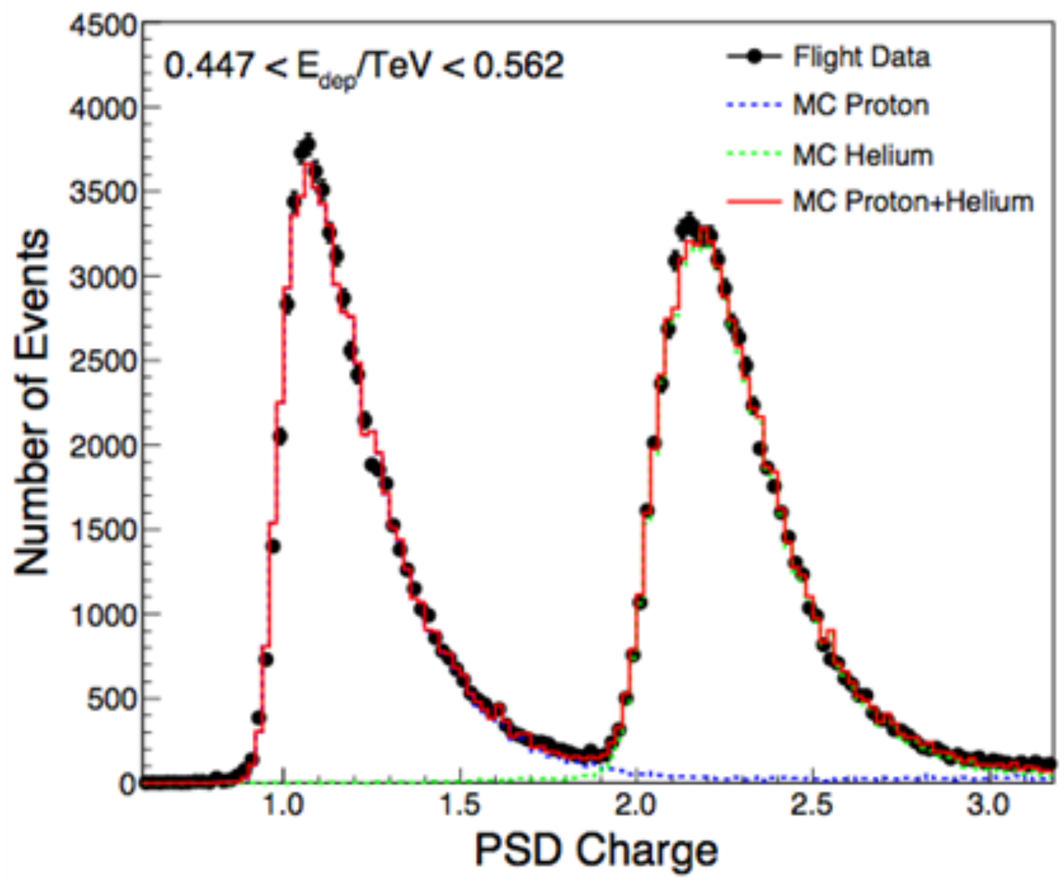
$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

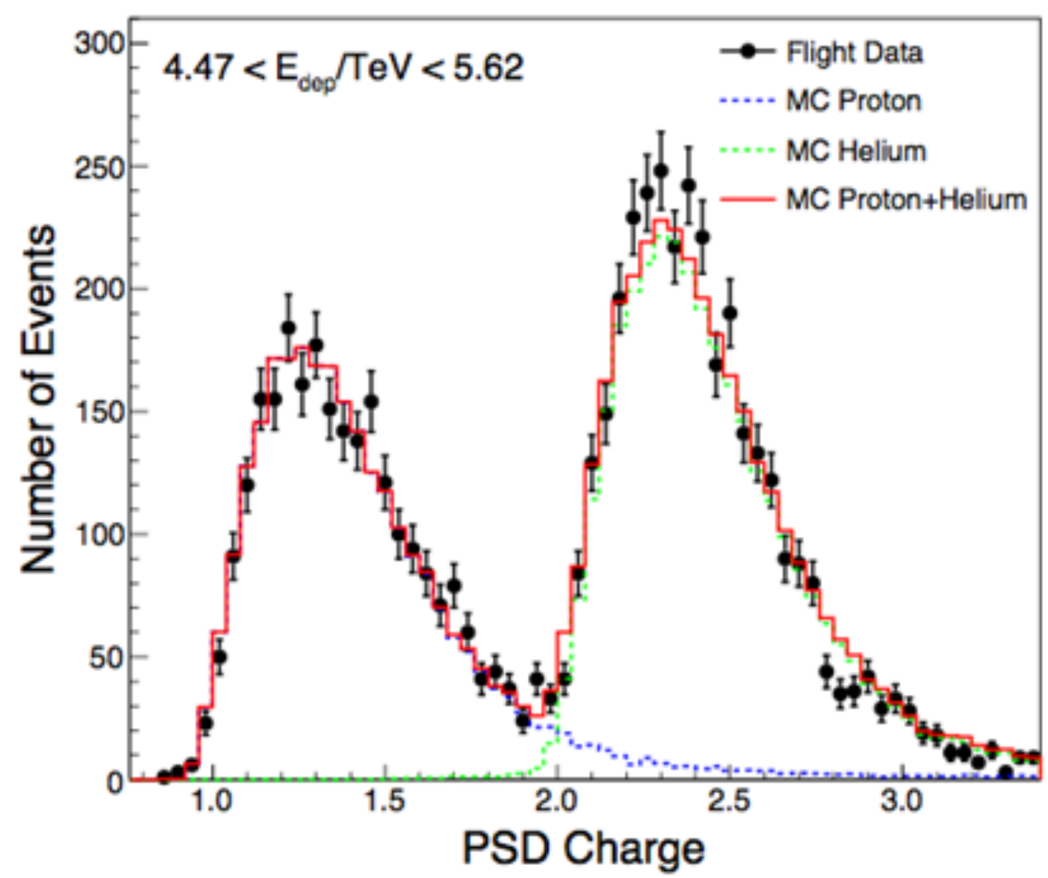
$$Z_y = \sqrt{PsdE_y/MipE} \quad Z_x = \sqrt{PsdE_x/MipE} \quad Z_{PSD} = (Z_y + Z_x)/2$$





Charge selection



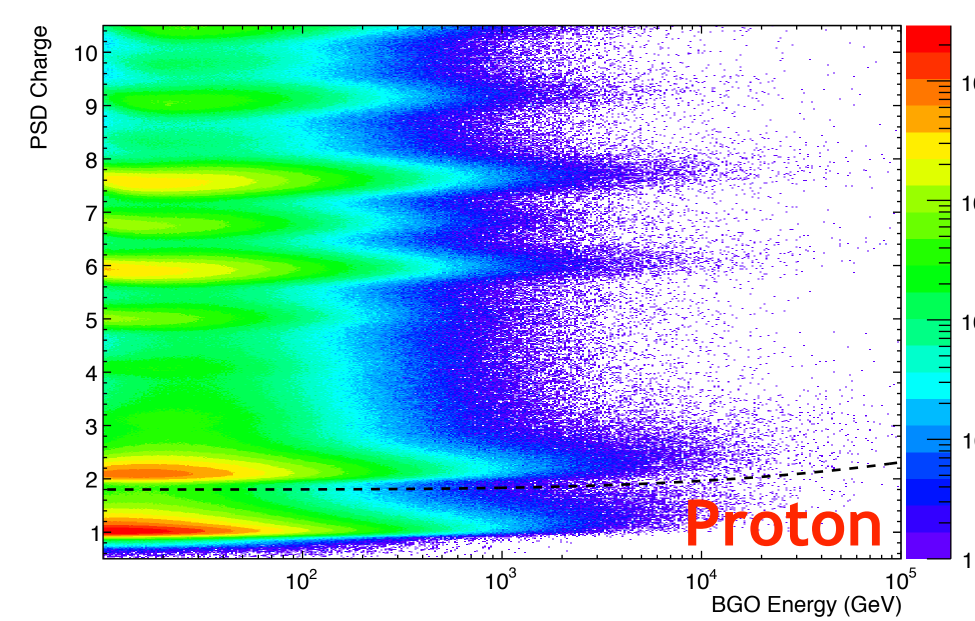


Proton selection:

$$0.6 + 0.05 \cdot log\frac{E_{dep}}{10GeV} < Z_{PSD} < 1.8 + 0.002 \cdot (log\frac{E_{dep}}{10GeV})^4$$

Helium selection:

$$1.85 + 0.02 \cdot log\frac{E_{dep}}{10GeV} < Z_{PSD,Y(X)} < 2.8 + 0.007 \cdot (log\frac{E_{dep}}{10GeV})^4$$



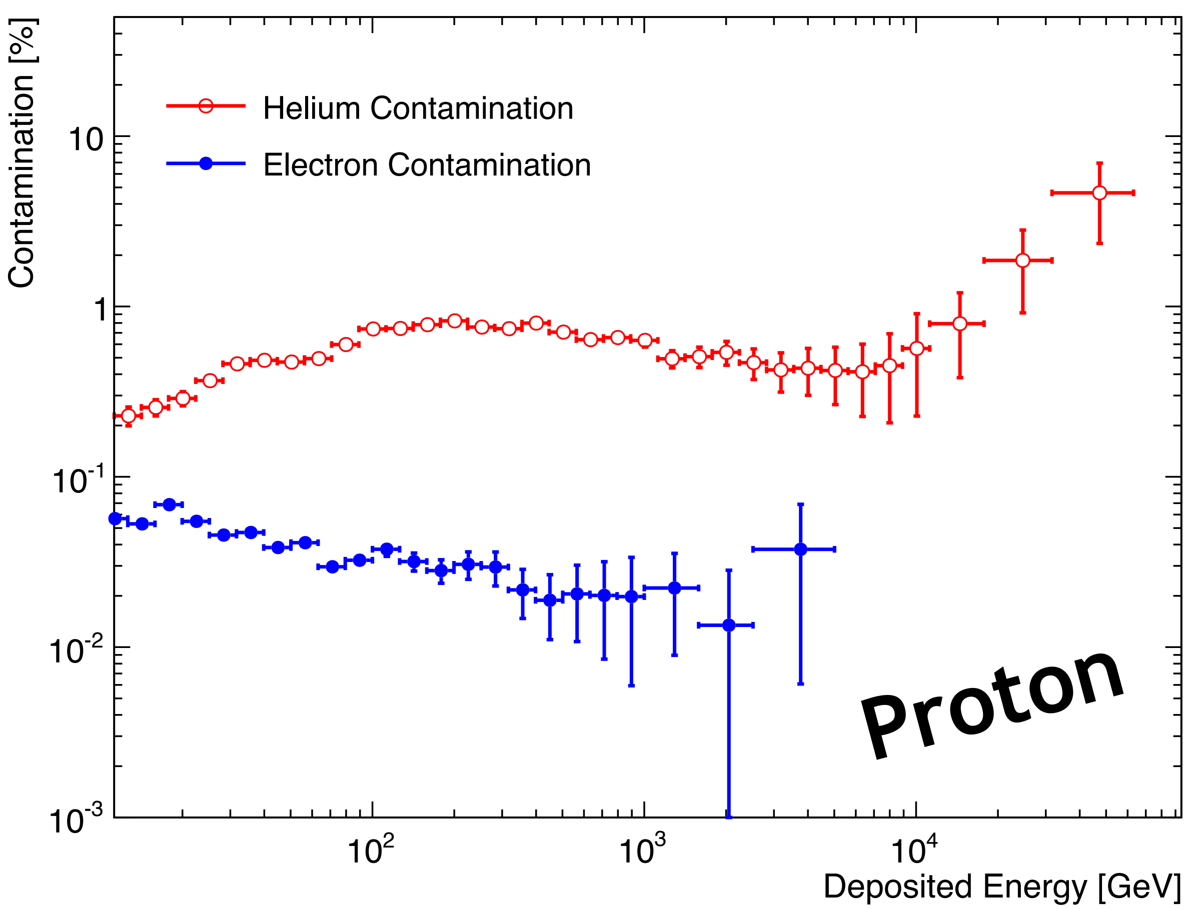
Contamination

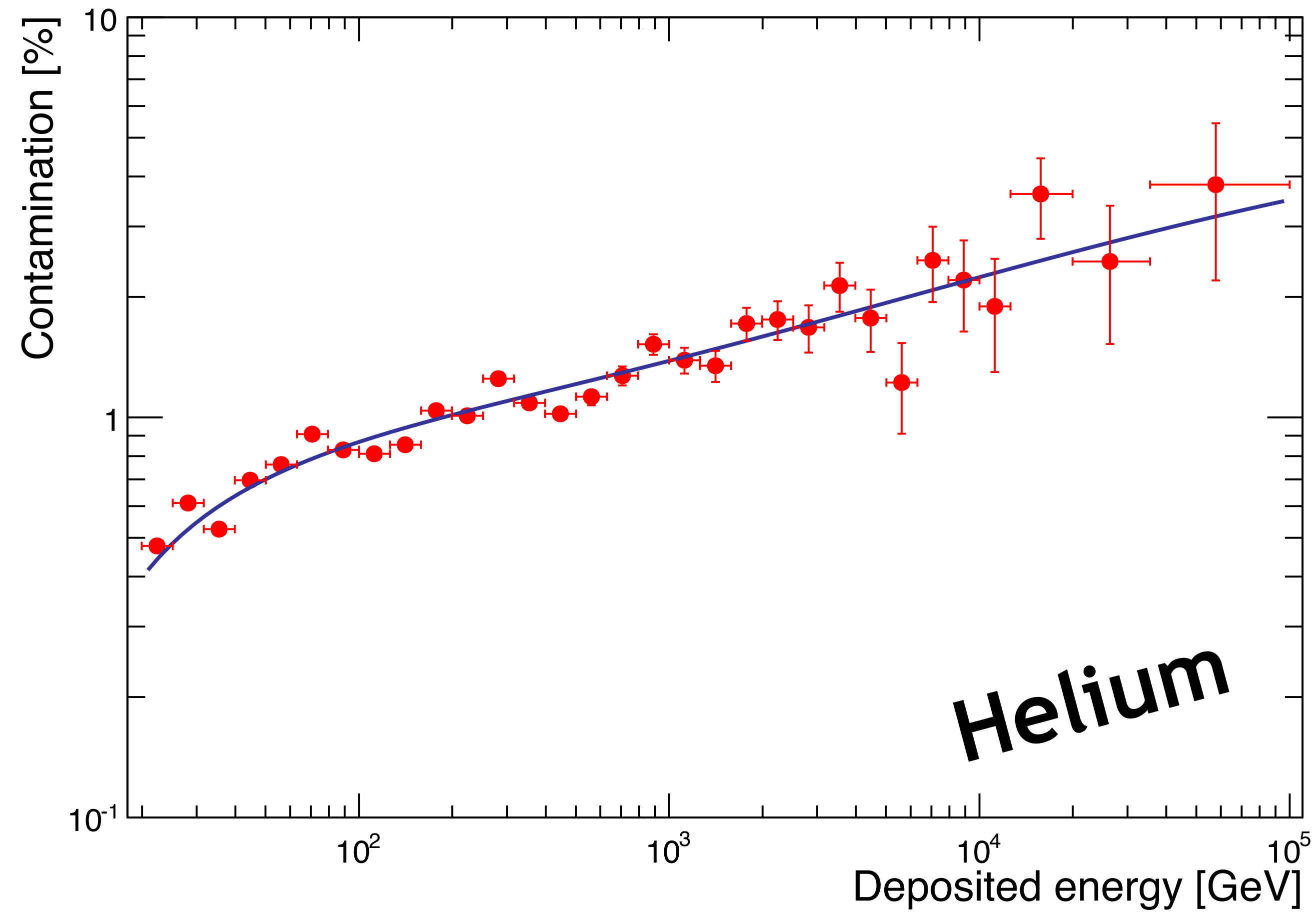
Proton selection:

$$0.6 + 0.05 \cdot log\frac{E_{dep}}{10GeV} < Z_{PSD} < 1.8 + 0.002 \cdot (log\frac{E_{dep}}{10GeV})^4$$

Helium selection:

$$1.85 + 0.02 \cdot log\frac{E_{dep}}{10GeV} < Z_{PSD,Y(X)} < 2.8 + 0.007 \cdot (log\frac{E_{dep}}{10GeV})^4$$





Spectral unfolding procedure

The limited thickness of the DAMPE calorimeter (~ 1.62 nuclear interaction lengths) significantly affects the energy response of hadronic particles. The energy resolution for proton is found to be about 25%-35% for incident energies from 100 GeV to 10 TeV. An unfolding procedure to reconstruct the incident energy distribution is thus necessary.

Iterative Bayesian Unfolding Method
[Giulio D'Agostini, NIM A362(1995), 487]

$$N_i = \sum_{j=1}^{n} \alpha_{ij} M_j (1 - \beta_j)$$

$$\alpha_{ij} = \frac{P(E_{d,j}|E_{0,i})\hat{N}_i}{\epsilon_i \sum_{i=1}^{n} P(E_{d,j}|E_{0,i})\hat{N}_i}$$

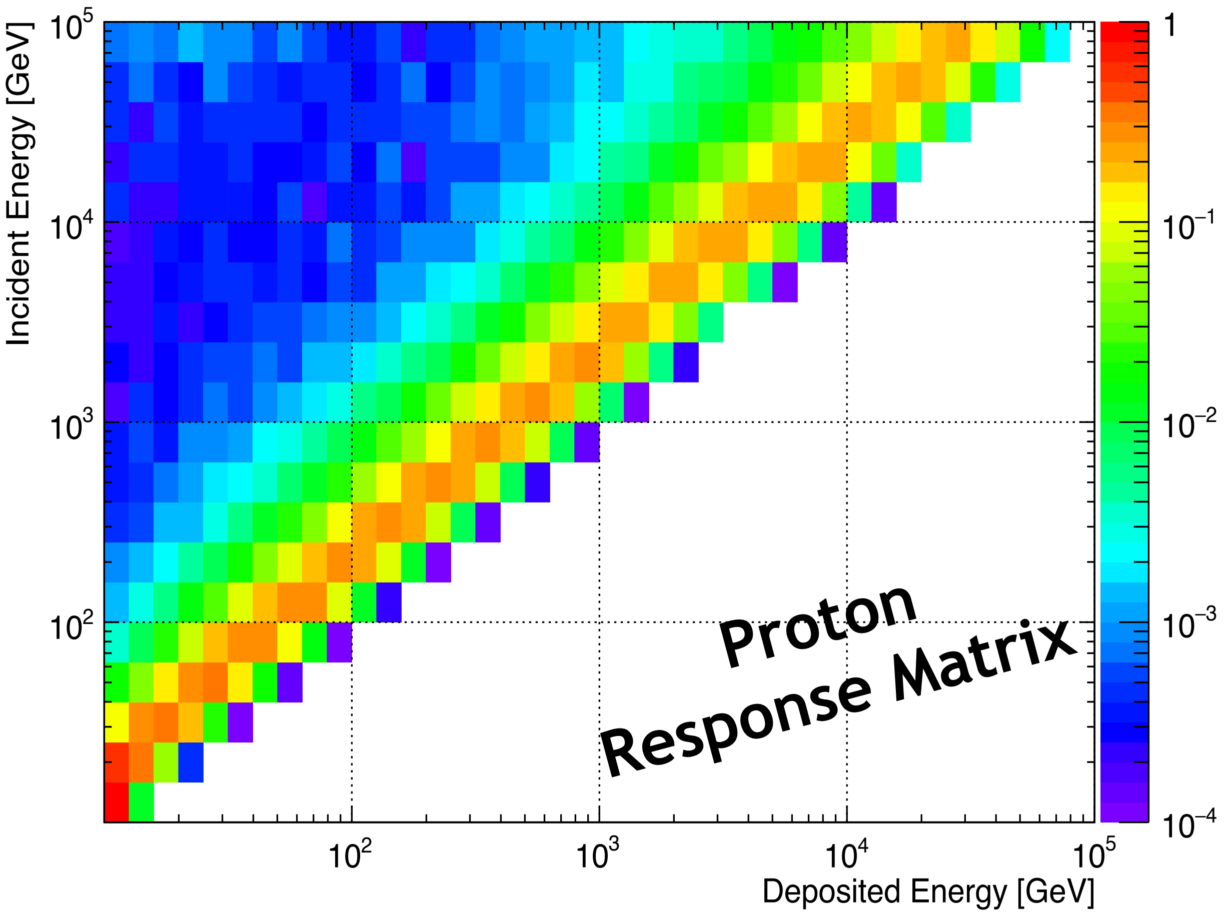
N_i : **Unfolded event number**

M_j : **Measured event number**

β_j : **Background**

$P(E_{d,j}|E_{0,i})$: **Response Matrix (MC)**

$\hat{N}_i$: **Prior ($E^{-2.7}$)**



Effective acceptance

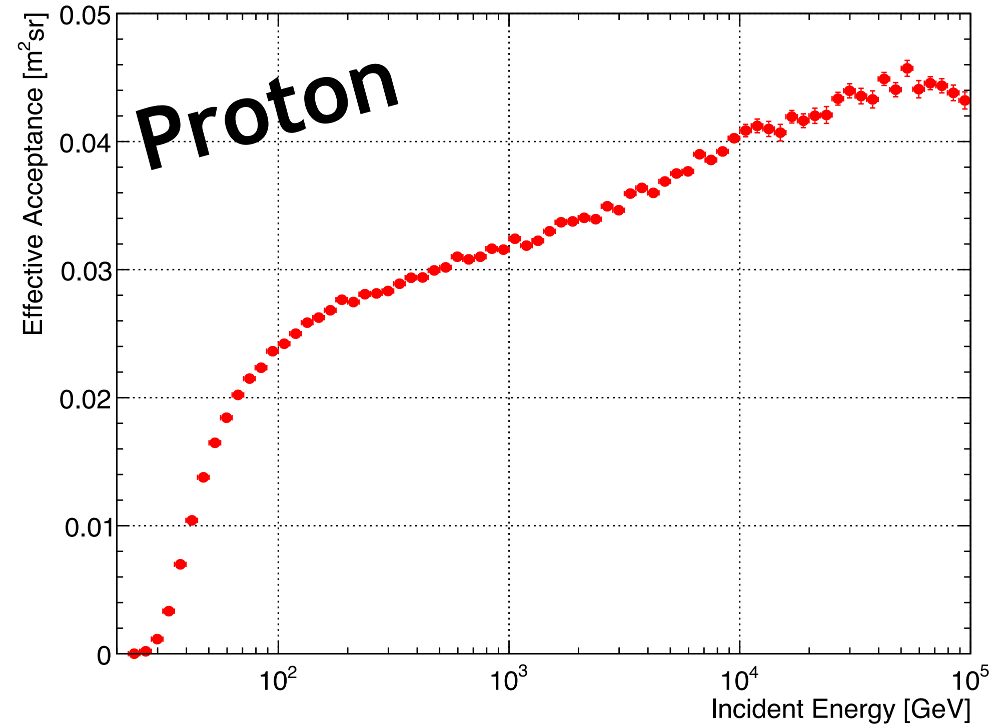
Differential flux in the i-th primay energy bin:

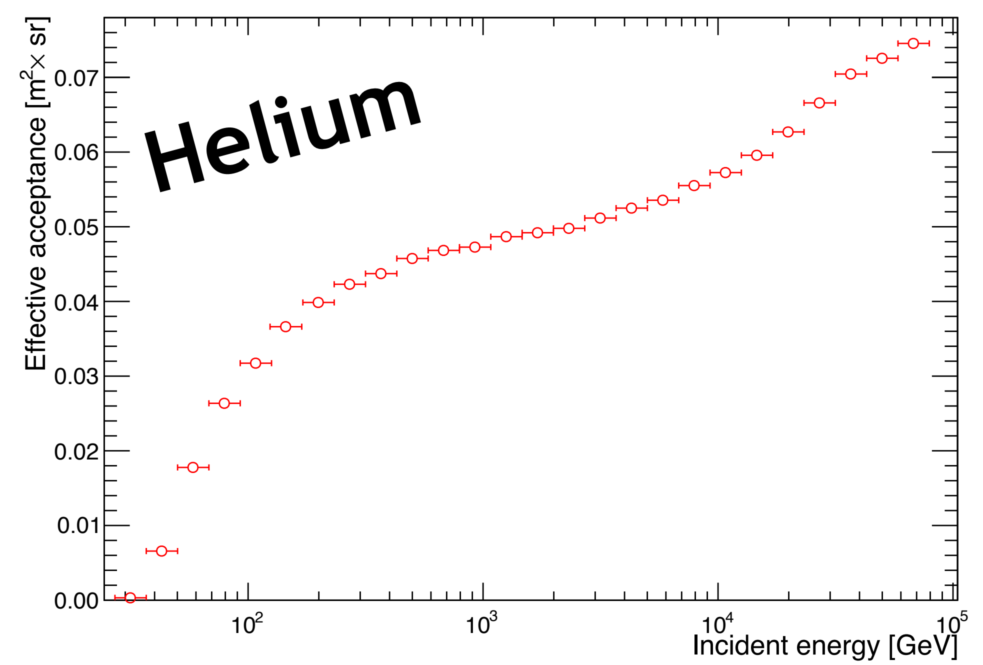
$$\Phi(E_i, E_i + \Delta E_i) = \frac{\Delta N_i}{\Delta E_i \ A_{eff,i} \ \Delta T}$$

ΔN_i : number of detected incident particle in the i-th primary energy bin of width E_i
ΔT : total livetime
$A_{eff,i}$: effective acceptance of the DAMPE detector as a function of the primary energy for the incoming particle at a given i-th bin of incident energy

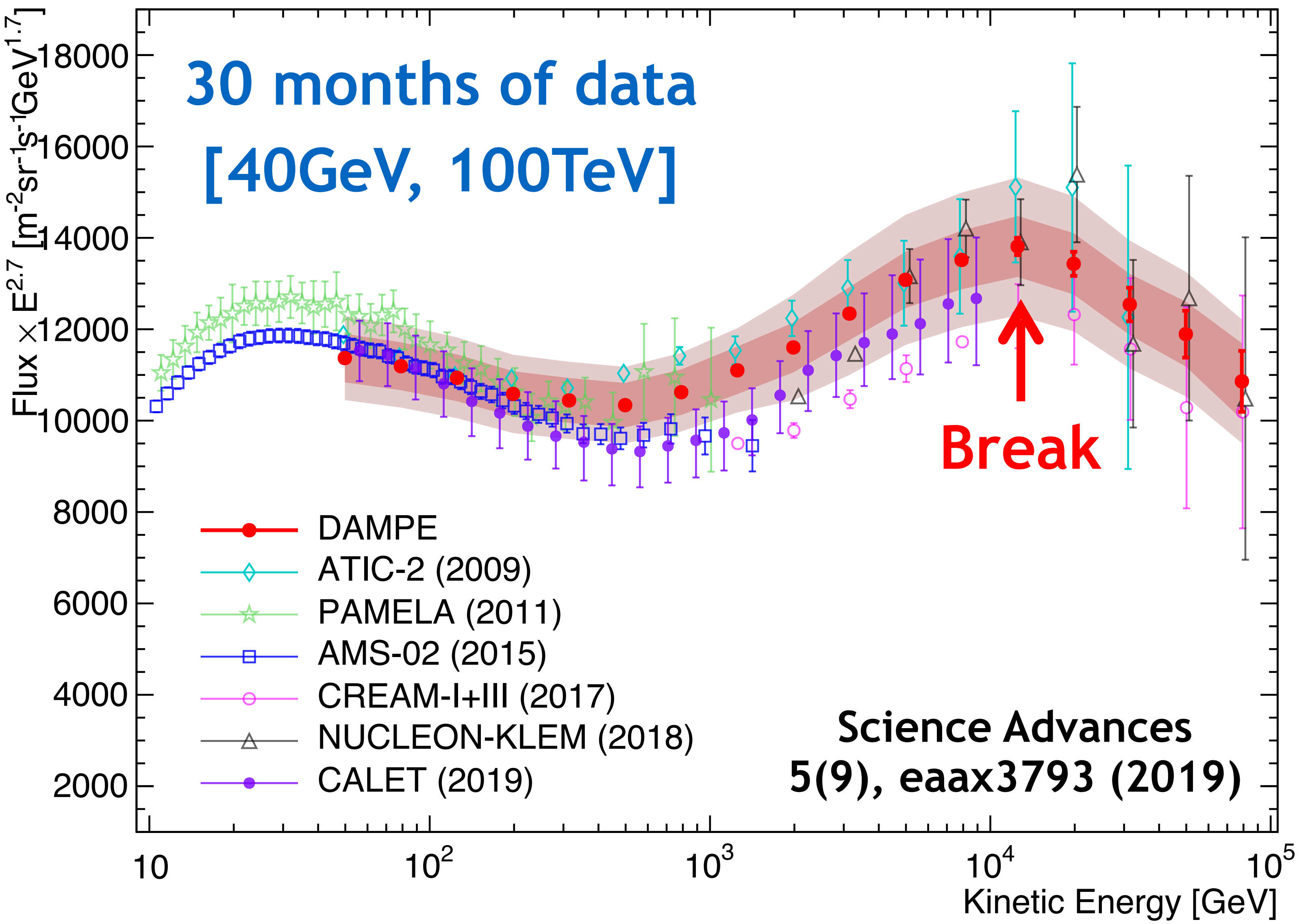
$$A_{eff,i} = A_{gen} \times \frac{N_{pass,i}}{N_{gen,i}}$$

A_{gen} : geometrical factor of the particle source in MC simulations
$N_{gen,i}$: total number of generated events in the i-th primary energy bin
$N_{pass,i}$: number of events selected by the the analysis, in a given i-th primary energy bin

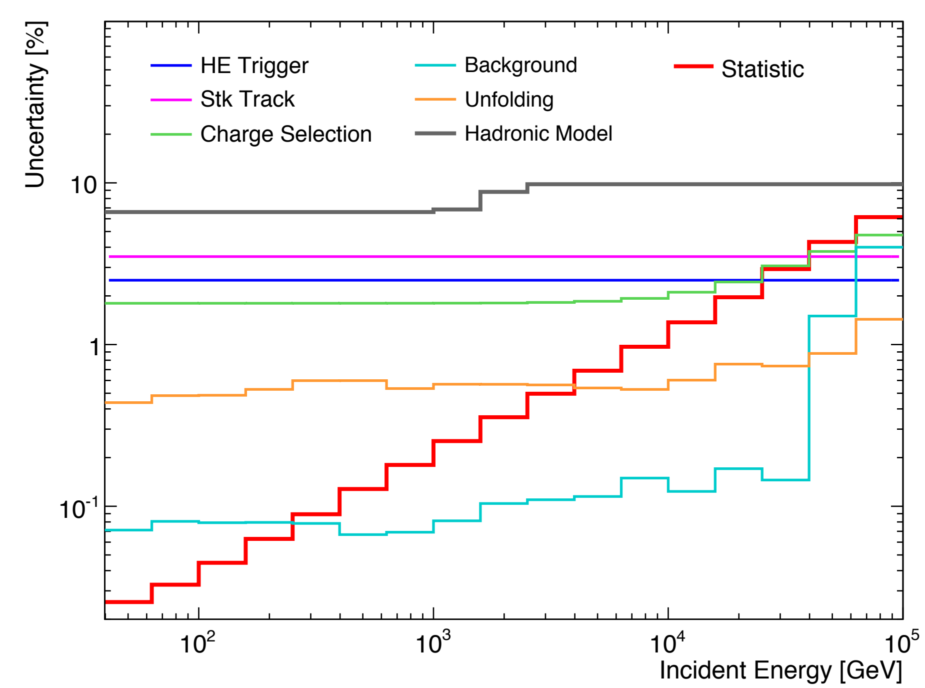




Proton spectrum of DAMPE



Uncertainties



Error bars: statistical uncertainties

Inner dashed band:

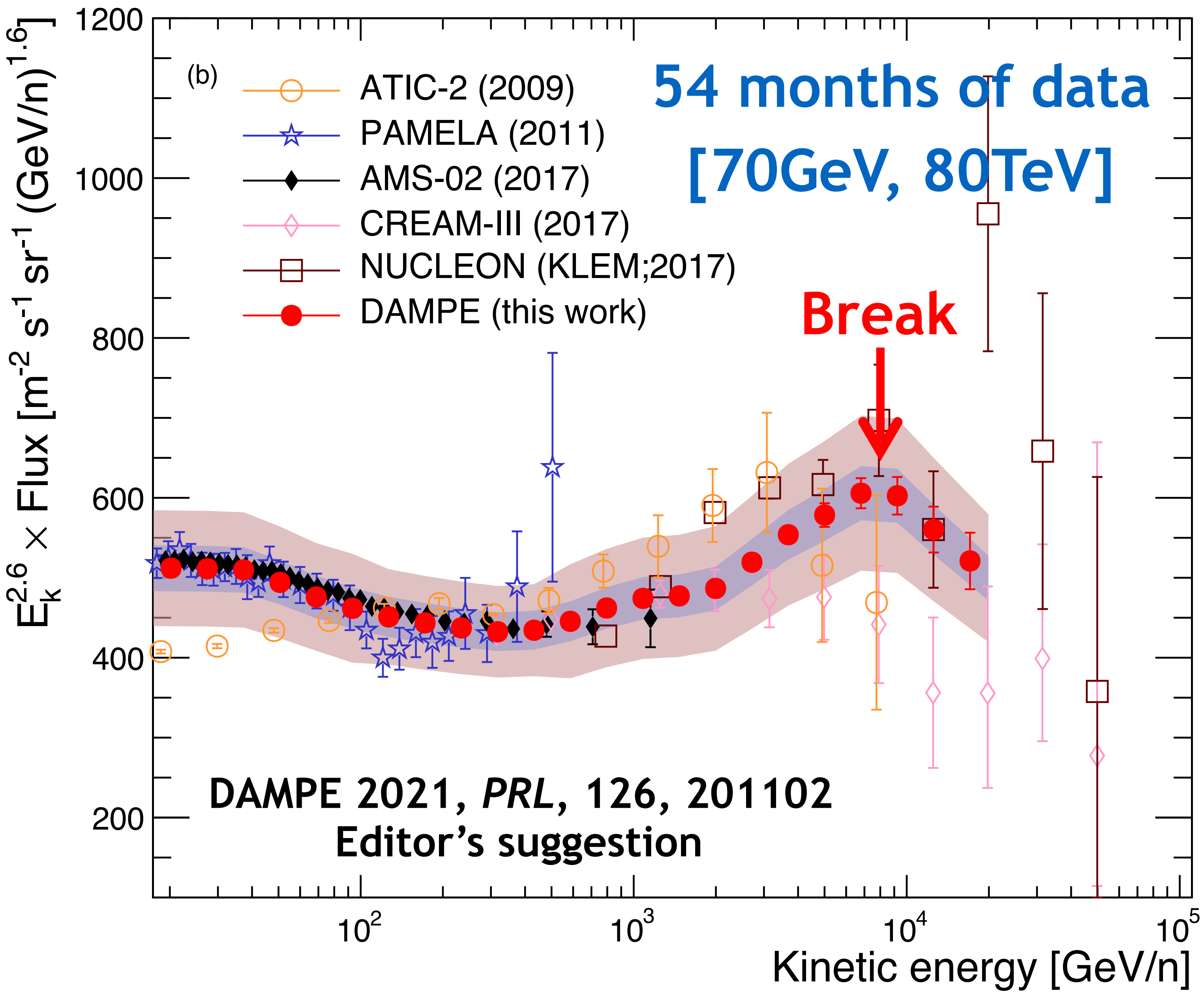
$$\sigma_{ana} = \sqrt{\sigma^2_{HET} + \sigma^2_{track} + \sigma^2_{charge} + \sigma^2_{bg} + \sigma^2_{unfold}}$$

Outer dashed band:

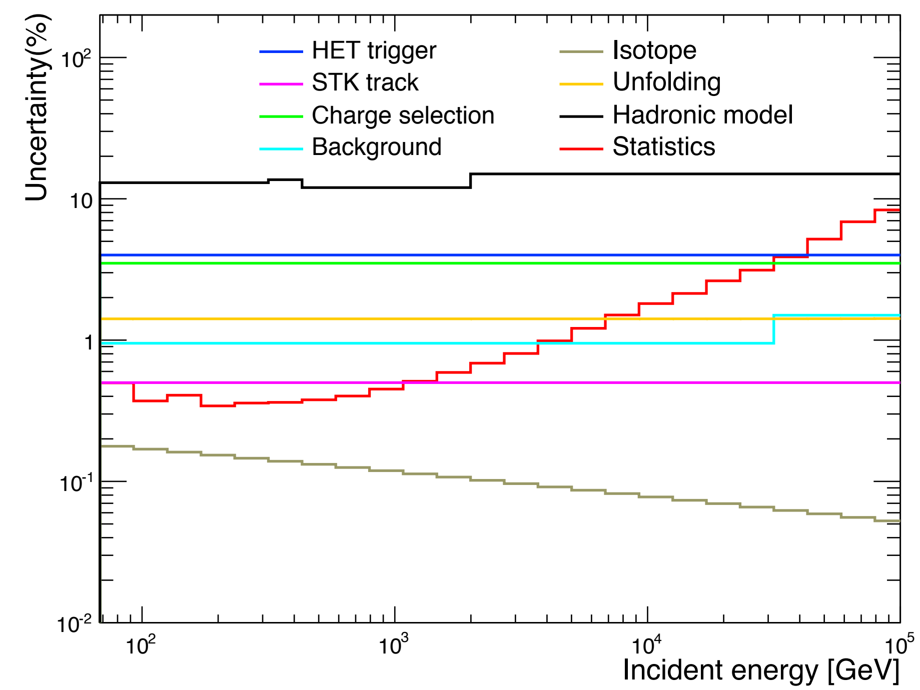
$\sqrt{\sigma^2_{ana} + \sigma^2_{had}}$, σ_{had} obtained from the comparison between Geant4 and FLUKA MC simulations.

The DAMPE measurement confirms the spectral hardening at a few hundreds of GeVs found by previous experiments, and more importantly, it reveals a spectral softening feature at ~14 TeV.

Helium spectrum of DAMPE



Uncertainties



Error bars: statistical uncertainties

Inner dashed band:

$$\sigma_{ana} = \sqrt{\sigma^2_{HET} + \sigma^2_{track} + \sigma^2_{charge} + \sigma^2_{bg} + \sigma^2_{unfold} + \sigma^2_{iso}}$$

$\sigma_{iso} \sim 0.2\%$ isotope uncertainty by varing the ratio of He3/He4 measured by AMS-02.

Outer dashed band:

$\sqrt{\sigma^2_{ana} + \sigma^2_{had}}$, σ_{had} obtained from the comparison between Geant4 and FLUKA MC simulations.

The DAMPE measurement confirms the spectral hardening at TeV-energies found by previous experiments, and more importantly, it reveals a spectral softening feature at a few decades of TeVs.

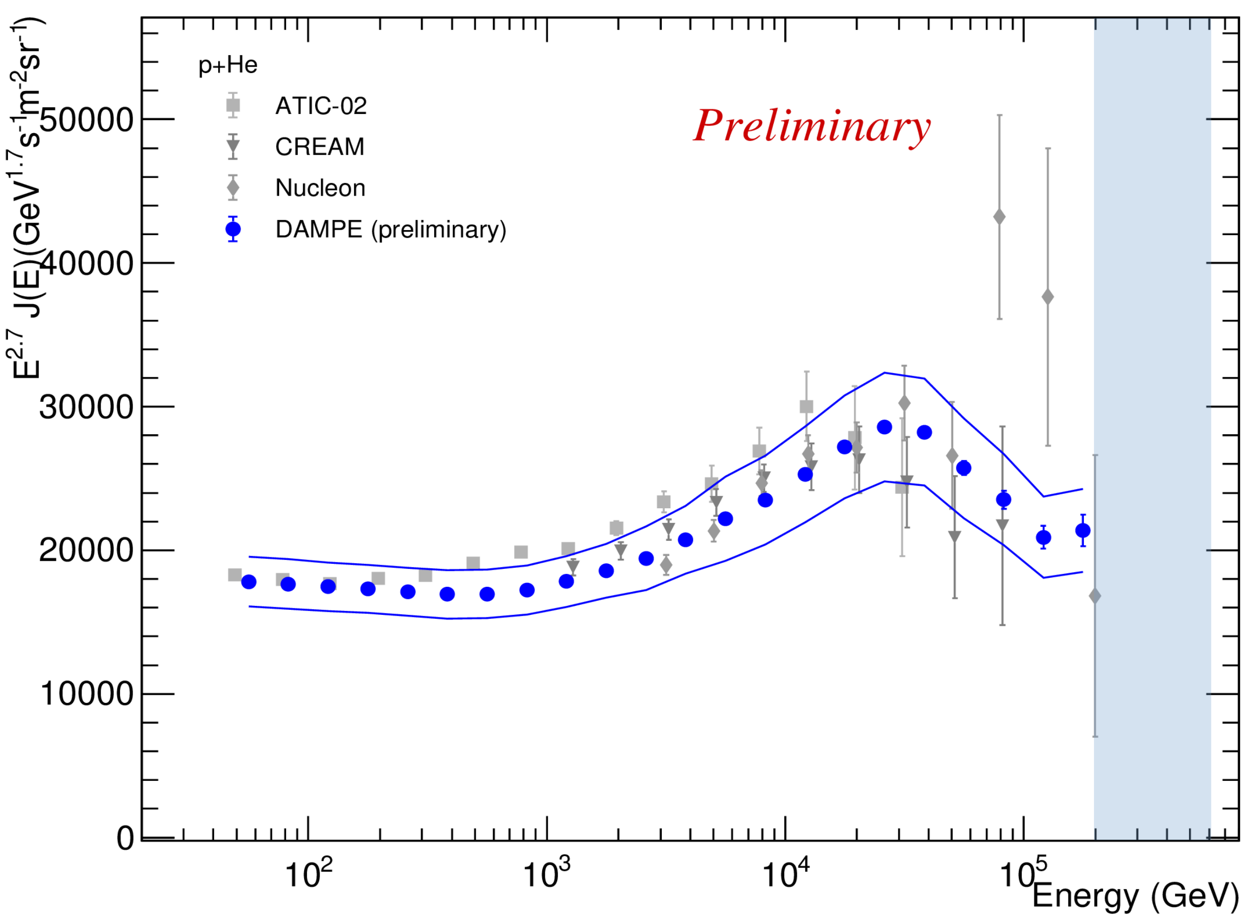
p+He spectrum of DAMPE

Independent analysis of p+He spectrum in the collaboration

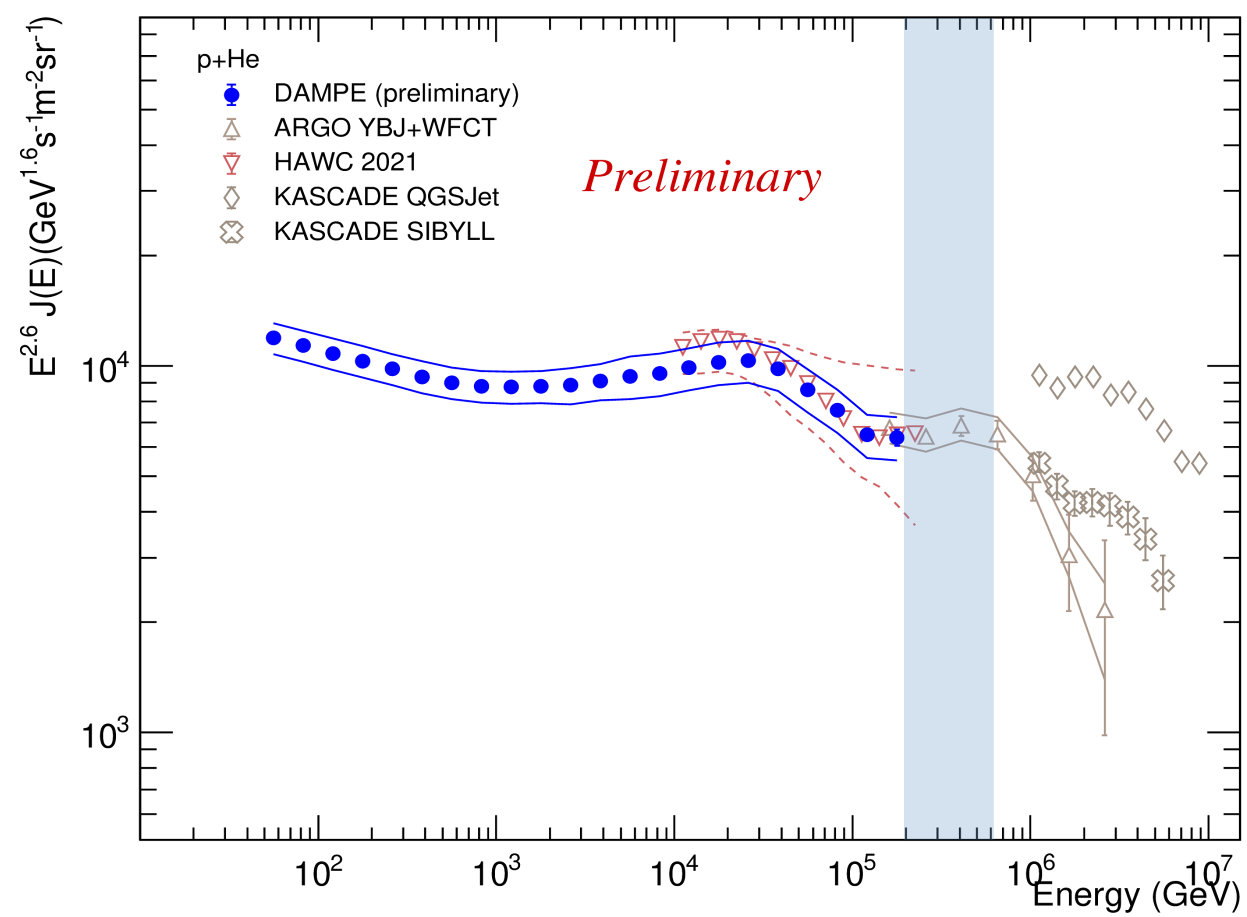
Very low contamination + Very large statistics ==> High upper limit of measurement

The p+He spectrum shows a spectral hardening at ~ 600 GeV and a softening at ~ 25 TeV

DIRECT MEASUREMENTS



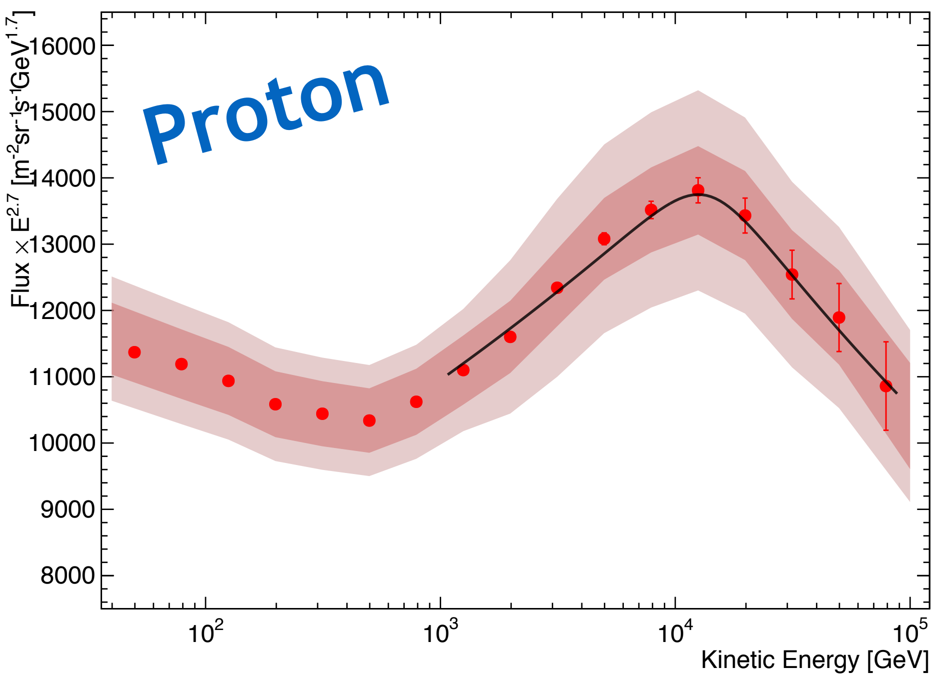
INDIRECT MEASUREMENTS



The extension of the p+He spectrum to higher energies (~500 TeV) is ongoing

Spectral fitting

Smoothly Broken Power-Law (SBPL) : $\Phi(E) = \Phi_0 \left(\frac{E}{\mathrm{TeV}}\right)^{-\gamma} \left[1 + \left(\frac{E}{E_B}\right)^{s}\right]^{\Delta\gamma/s}$



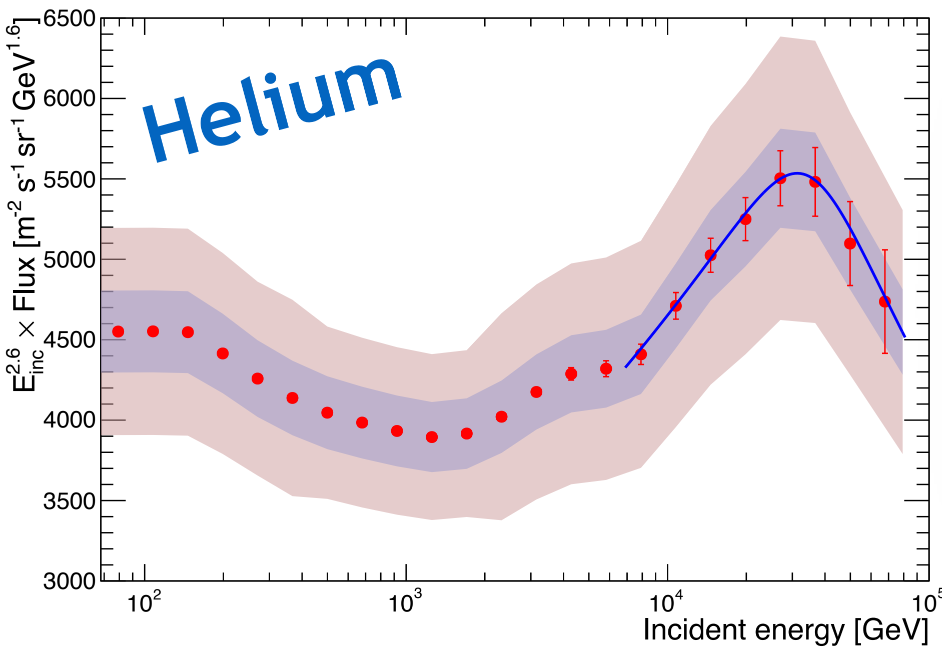
$E_b = 13.6^{+4.1}_{-4.8}\ TeV$

$\gamma = 2.60 \pm 0.01$

$\Delta\gamma = -0.25 \pm 0.07$

$s = 5$ (fixed)

Significance of softening: ~4.7σ



$E_b = 34.4^{+6.7}_{-9.8}\ TeV$

$\gamma = 2.41 \pm 0.02$

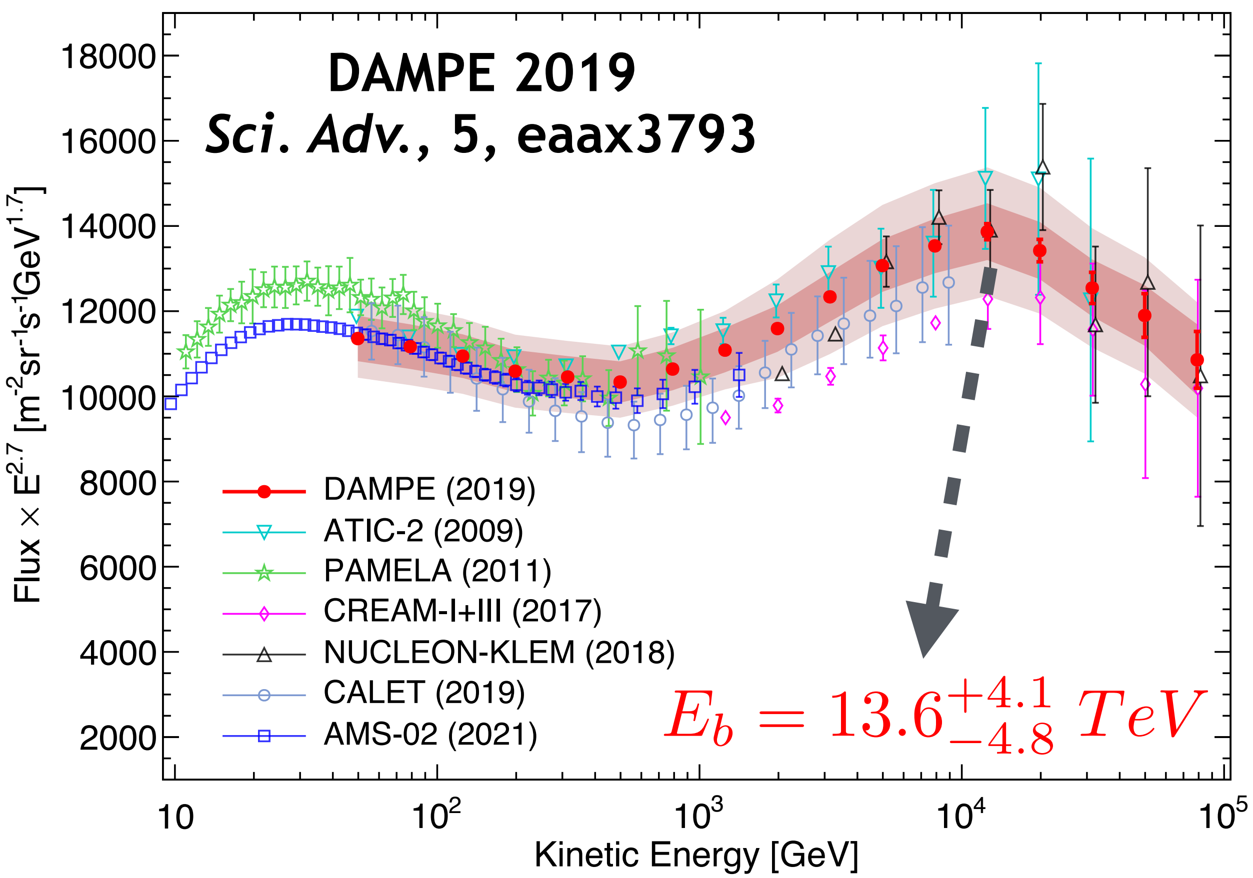
$\Delta\gamma = -0.51^{+0.18}_{-0.20}$

$s = 5$ (fixed)

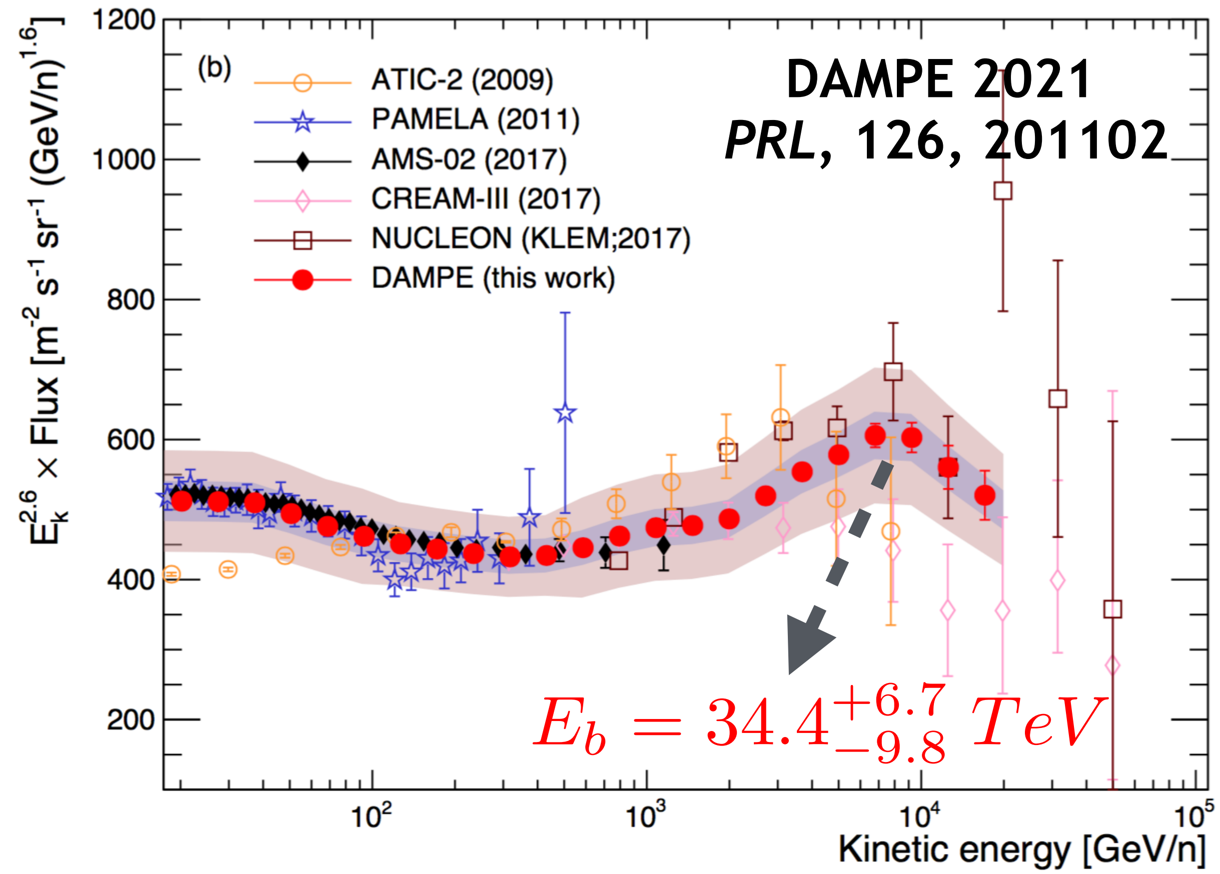
Significance of softening: ~4.3σ

Discussion

CR Proton



CR Helium



✳ The spectra of CR proton and helium measured by DAMPE show a very similar softening feature at tens of TeVs.

✳ The softening energies are well consistent with a dependence on particle charge, although a dependence on particle mass can not be ruled out yet.

✳ The results implicate a Z-dependent spectral break (e.g. “knee”) in CR nuclei, which is likely an imprint of a nearby cosmic ray source.

Summary

- Since launch on Dec. 17th, 2015, DAMPE("Wukong") has been operated stably for almost six years
- The analyses of CR proton spectrum in [40GeV, 100TeV] and CR helium spectrum in [70GeV, 80TeV] with DAMPE experiment are presented.
- For the first time in space, DAMPE measures the proton and helium spectra individually in a wide energy range from tens of GeV to ~100TeV with a single experiment.
- The DAMPE measurements reveal a similar spectral softening feature in proton spectrum (Eb~13.6TeV) and helium spectrum(Eb~34TeV) with a very high significance.
- More results of nuclei spectra from DAMPE are forthcoming, and we would like to see if such a softening is an universal feature (e.g. knee) for all nuclei with Z-dependence or A-dependence.

Thanks for your attention!

中国科学院紫金山天文台

Purple Mountain Observatory Chinese Academy of Sciences