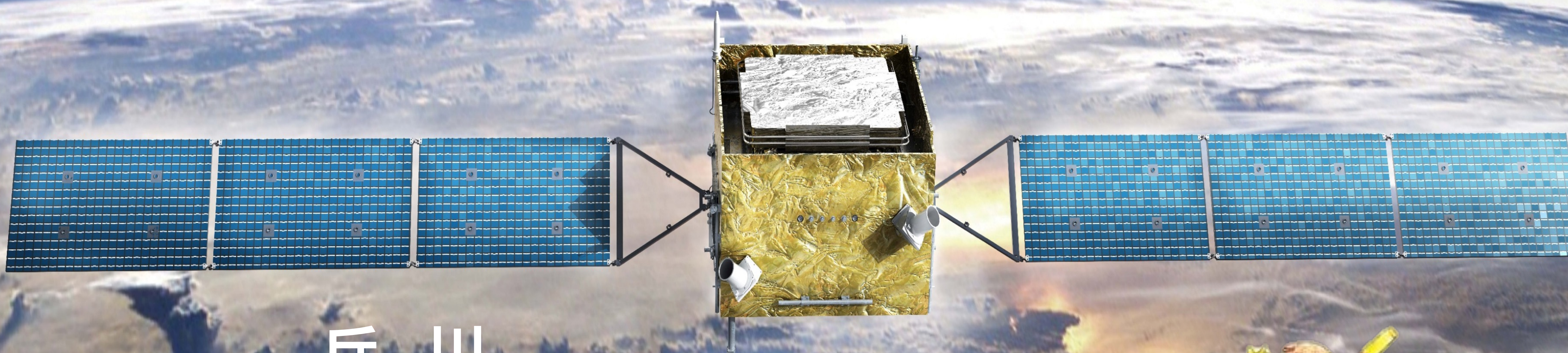
中国科学院稳定支持基础研究领域青年团队计划

“宇宙线起源”青年团队

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



岳 川

中国科学院紫金山天文台

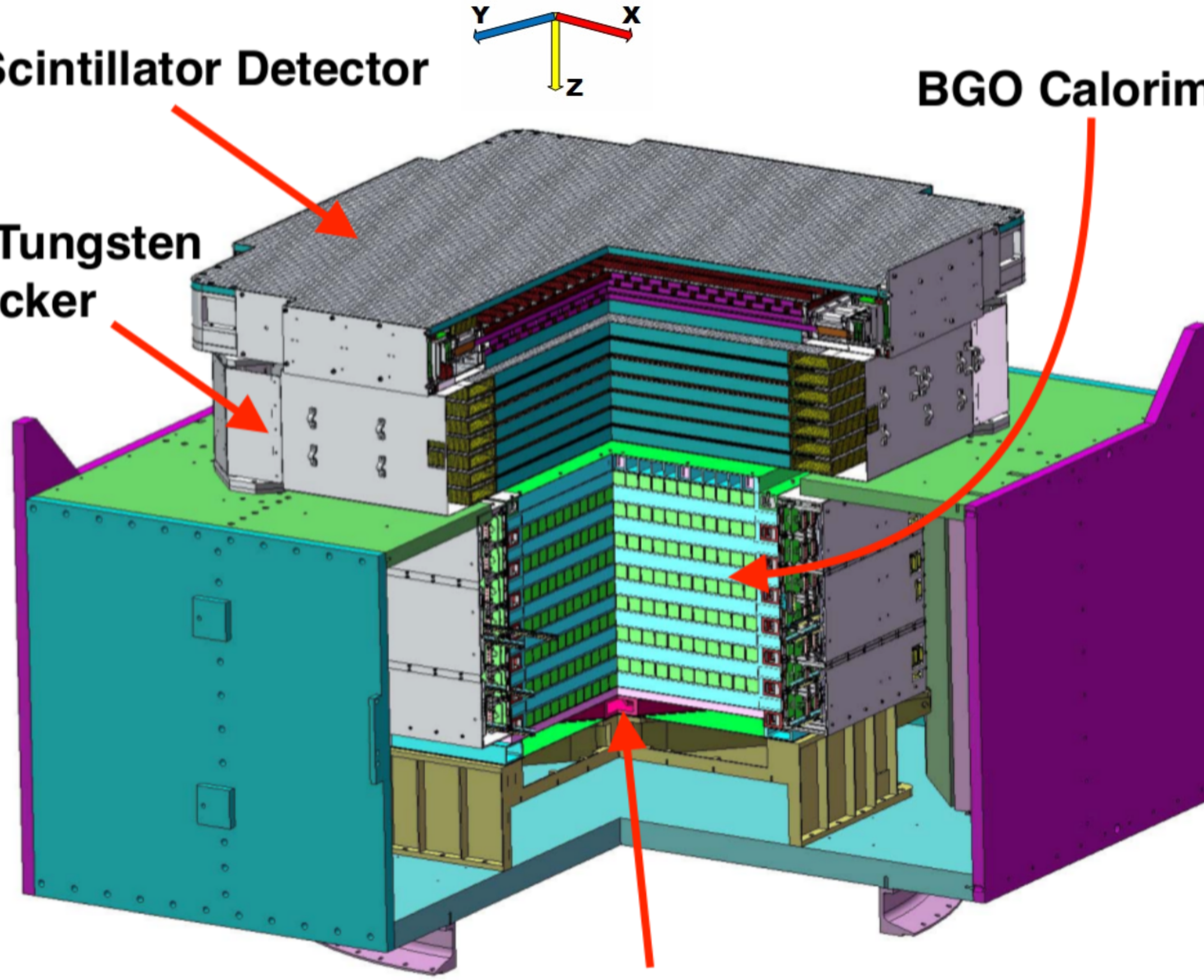
(on behalf of the DAMPE Collaboration)

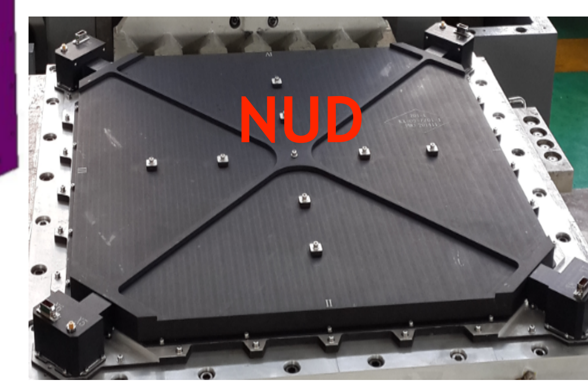
*2023*弥散伽马射线与宇宙线研讨会

“宇宙线起源”青年团队年度总结会议

Oct 23, 2023 | 合肥

DAMPE detector





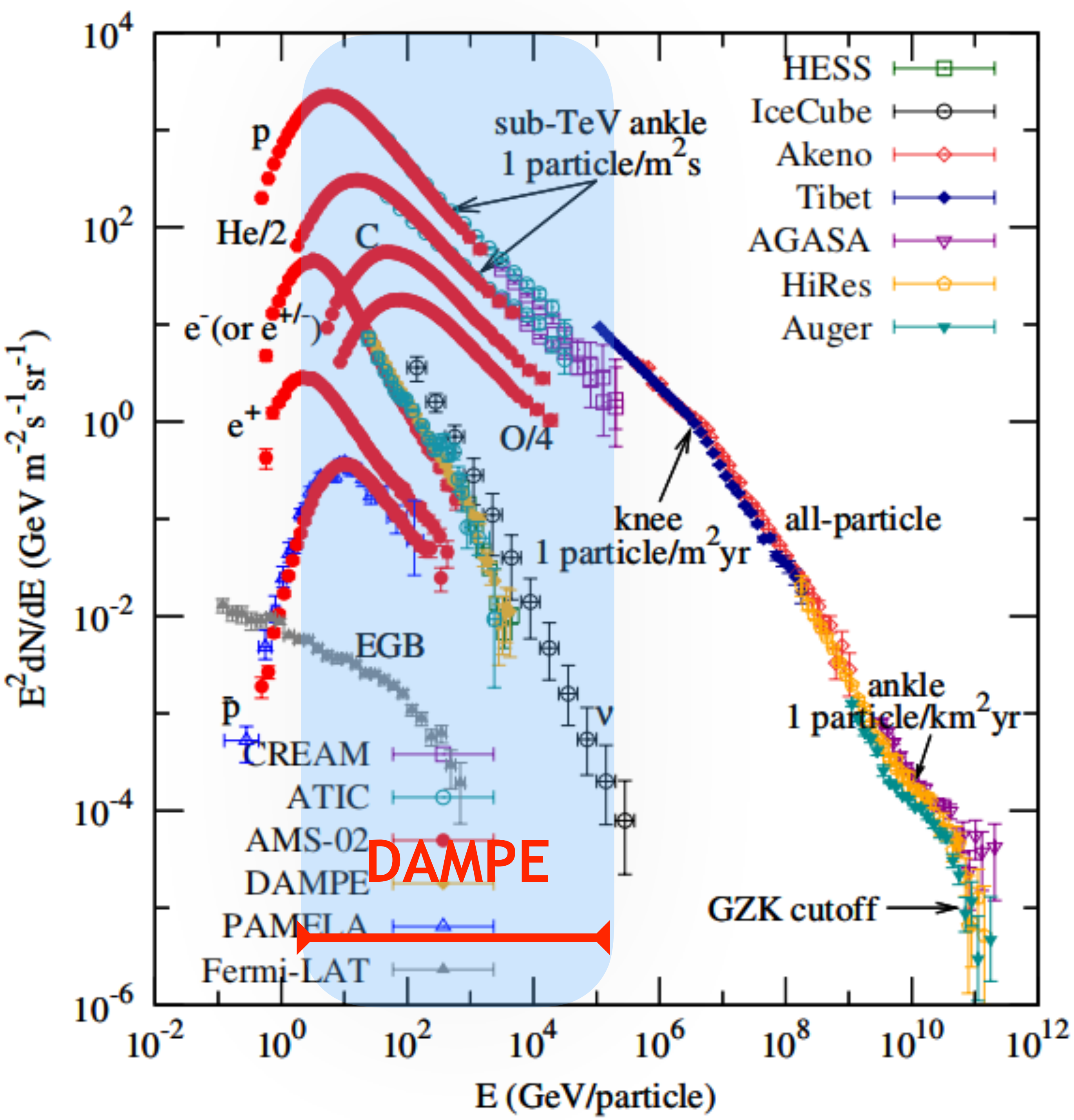
Main Scientific Goals:

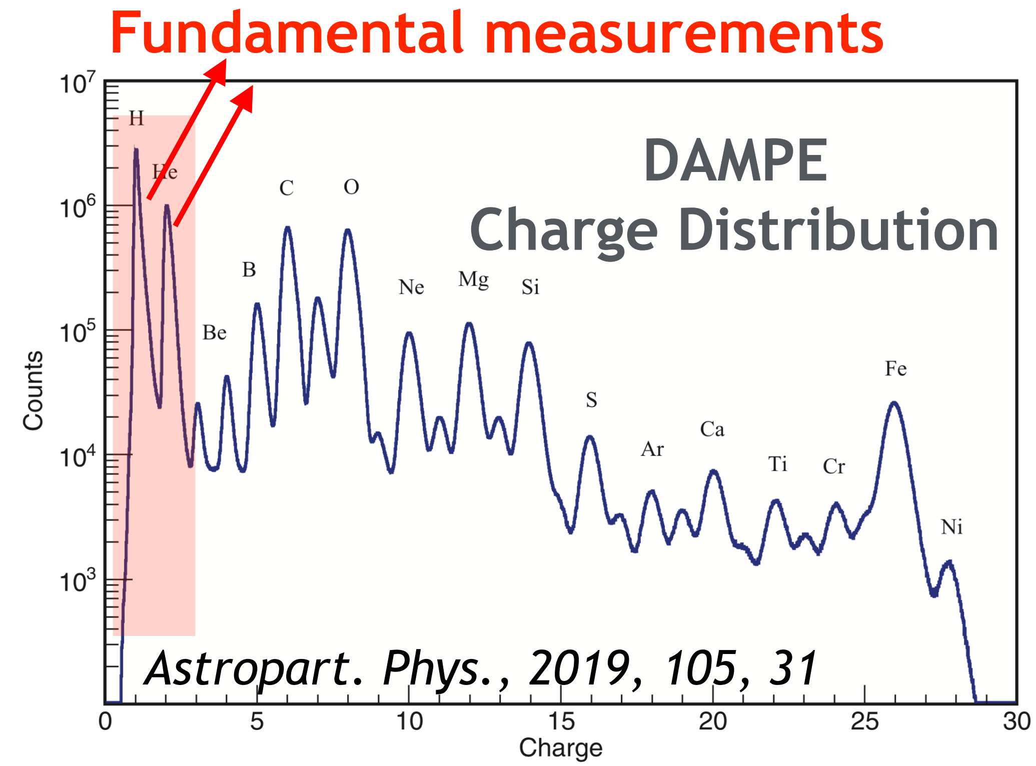
- Dark Matter Indirected Detection
- Cosmic-Ray Origin and Acceleration
- High Energy Gamma-ray Astronomy

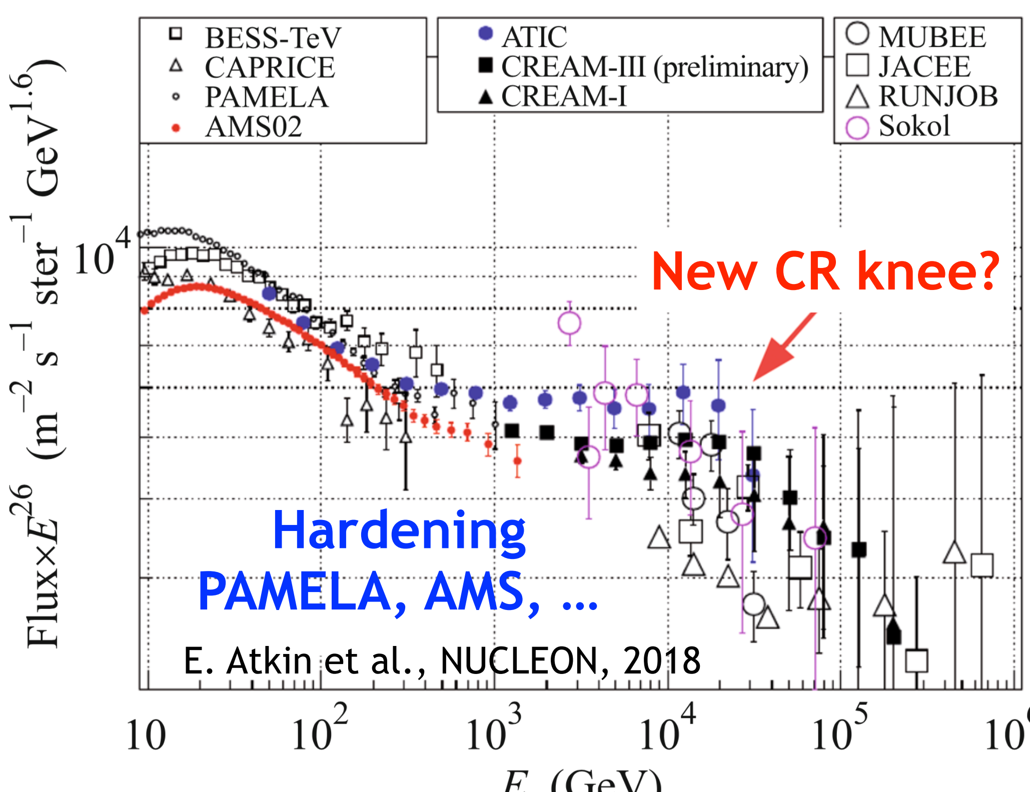
- Charge measurement (dE/dx in PSD, STK)
- Gamma-ray converting and tracking (STK)
- Precise energy measurement (BGO ECAL)
- Hadron rejection (BGO and Neutron Detector)

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

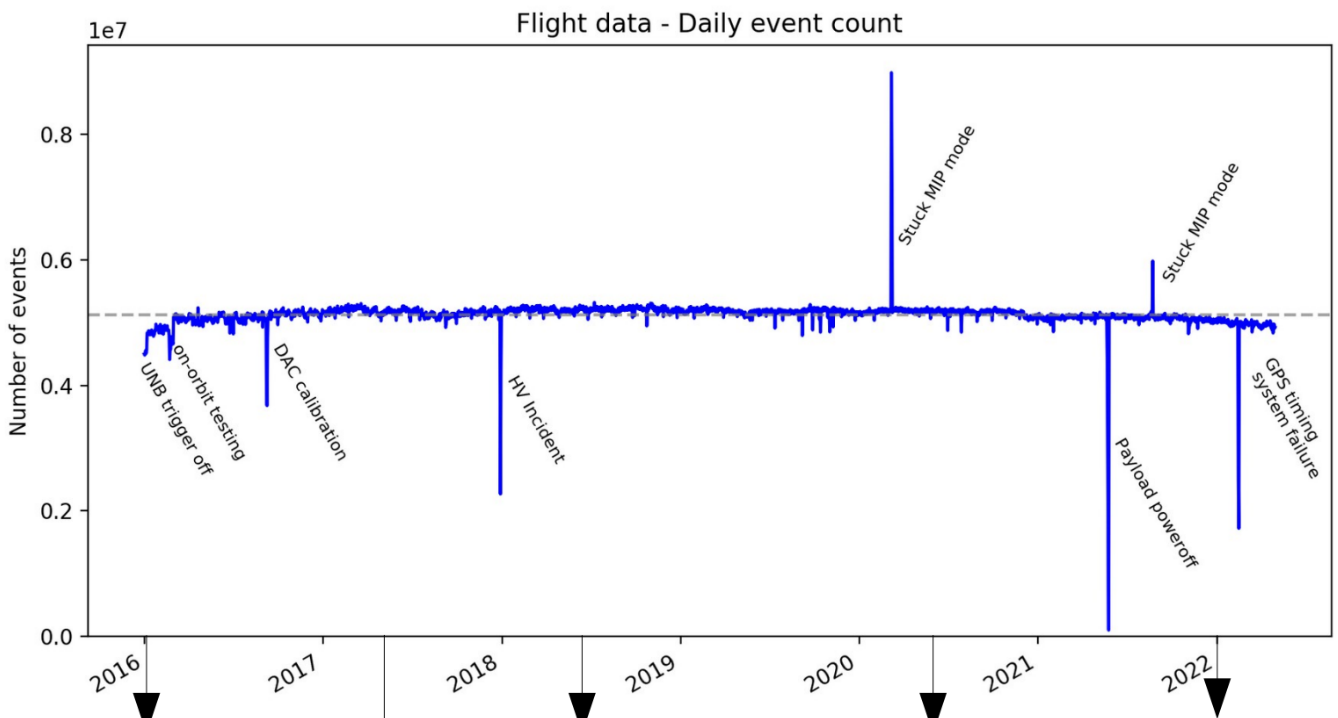
Introduction







Data sample



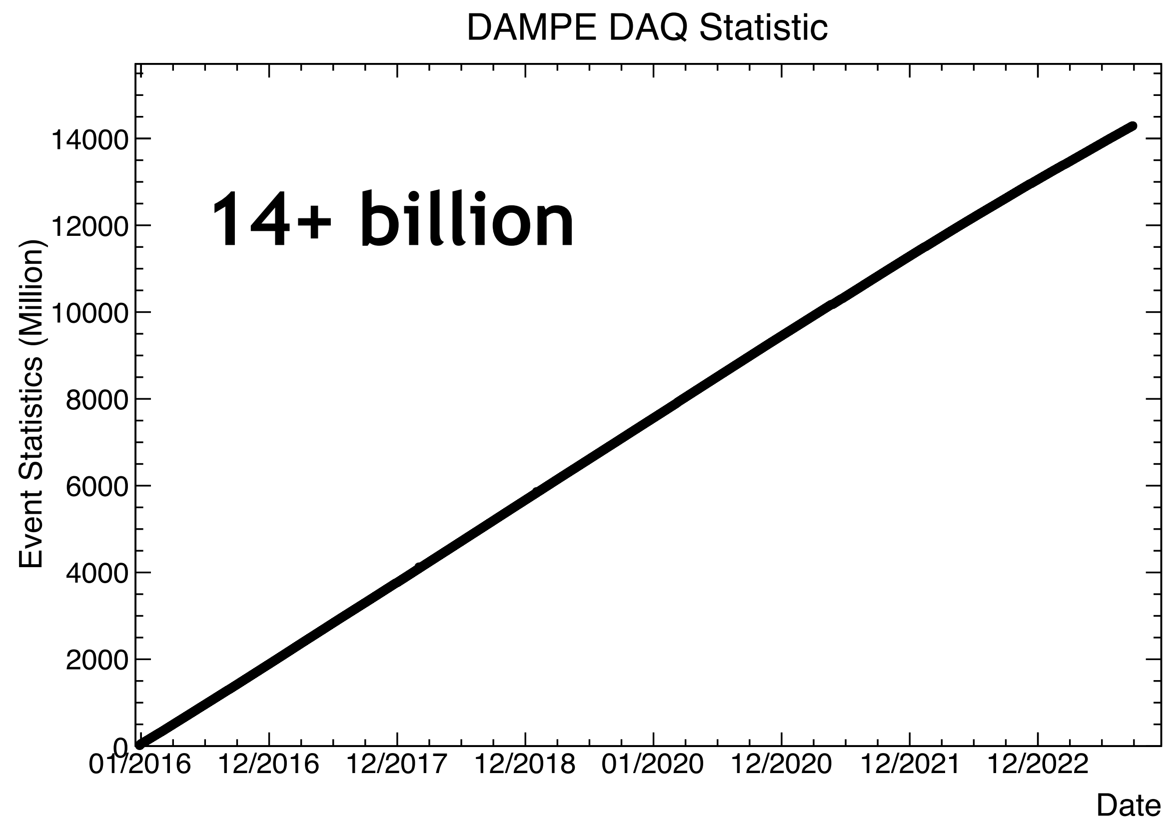
START

18 months
Electron-positron spectrum

30 months
Proton spectrum

54 months
Helium spectrum

72 months
p+He spectrum
B/C and B/O flux ratio



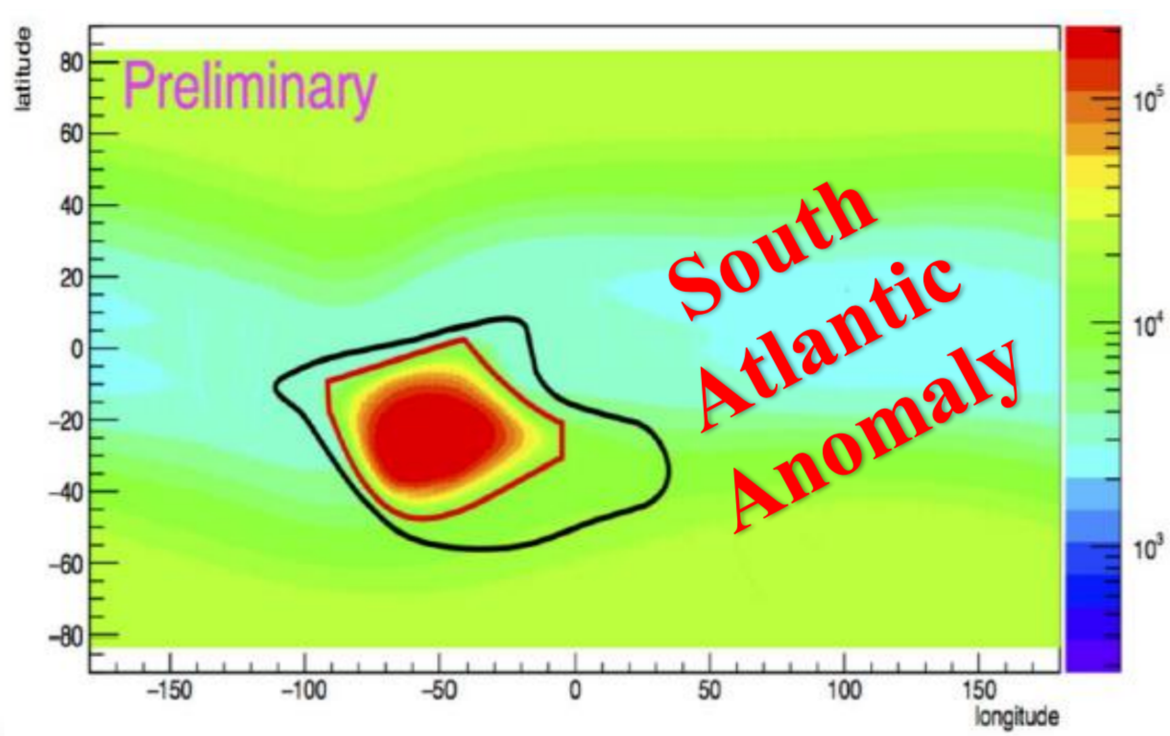
Dead Time

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

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

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

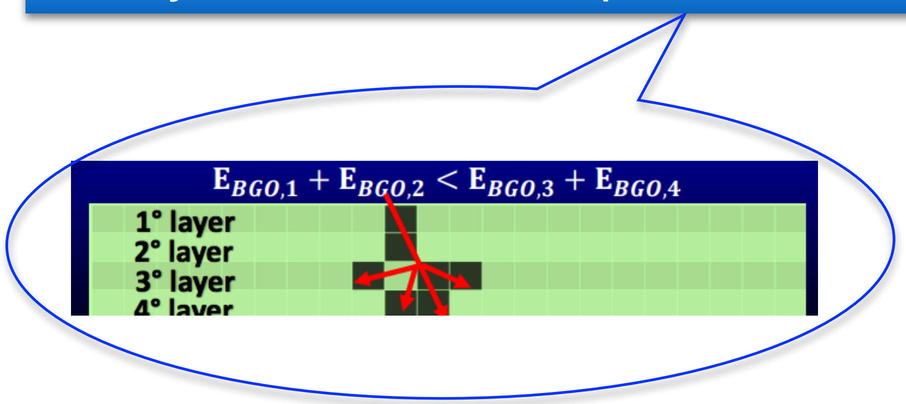
X Solor Flare in Sep. 2017



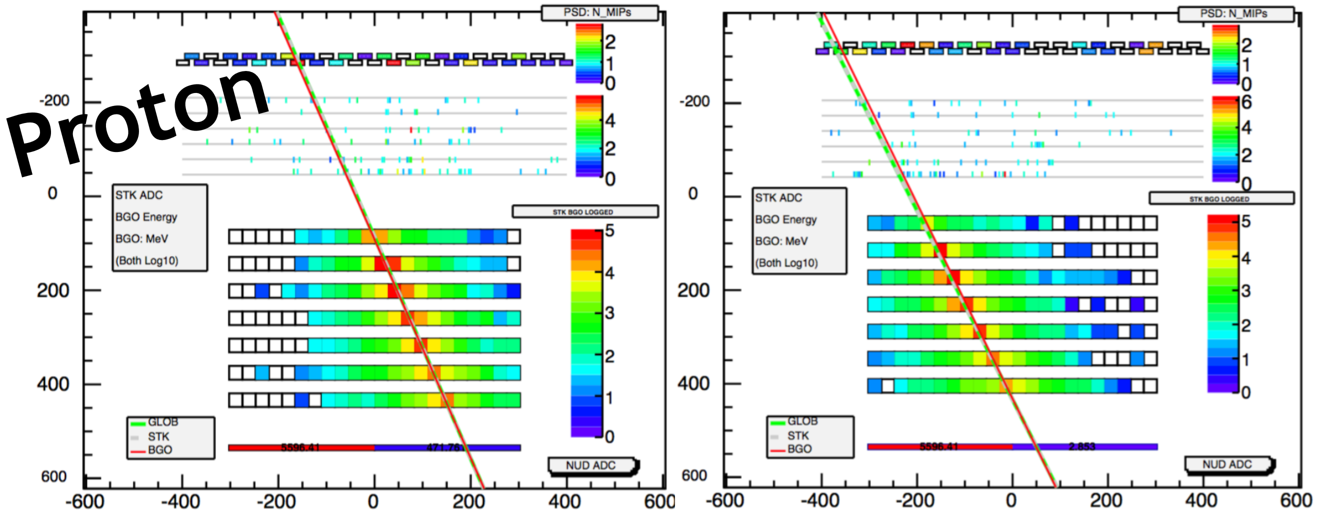
Pre-selection

Target: Good-reco events

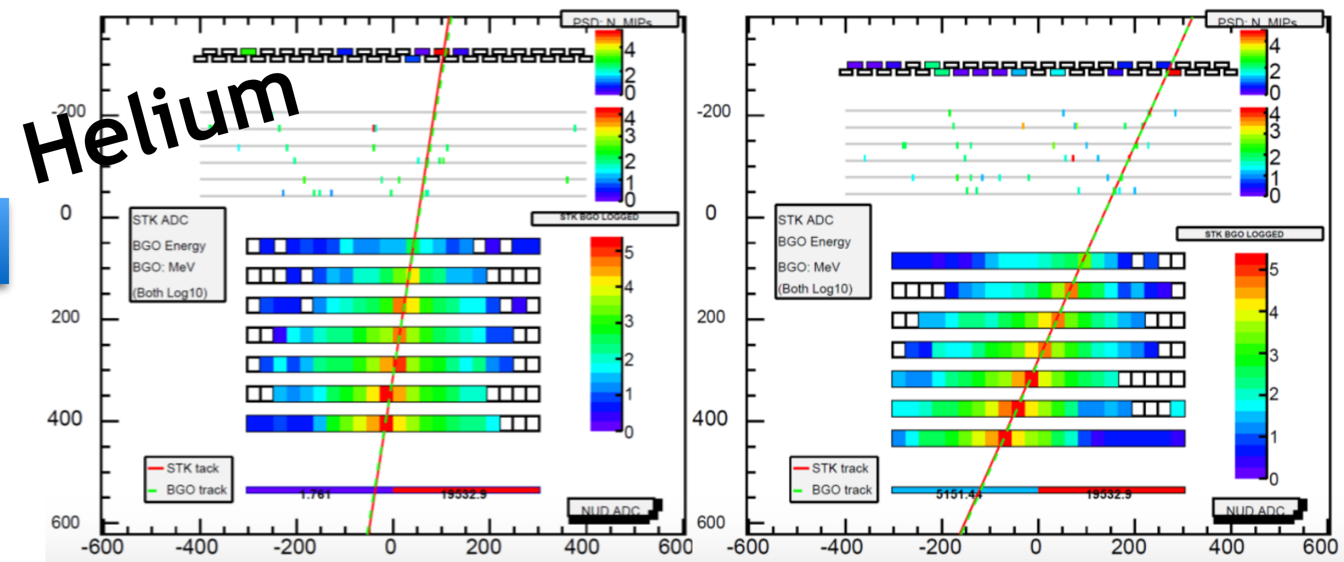
- ★South Atlantic Anomaly (SAA) events exclusion
- ★High Energy Trigger (HET) generation
- ★STK track optimisation
  p: NhitsXY>=4 && Chi2ndof<25 && Maximum energy
  He: NhitsXY>=4 && Chi2ndof<25 && Maximum energy
  △diff<25 mm between track and c.o.g. of first 4 BGO layers
- ★Fiducial cut: STK track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



Orbit Proton (BGO-Energy: 1.2 TeV)



Orbit Helium (BGO-Energy: 1.8 TeV)

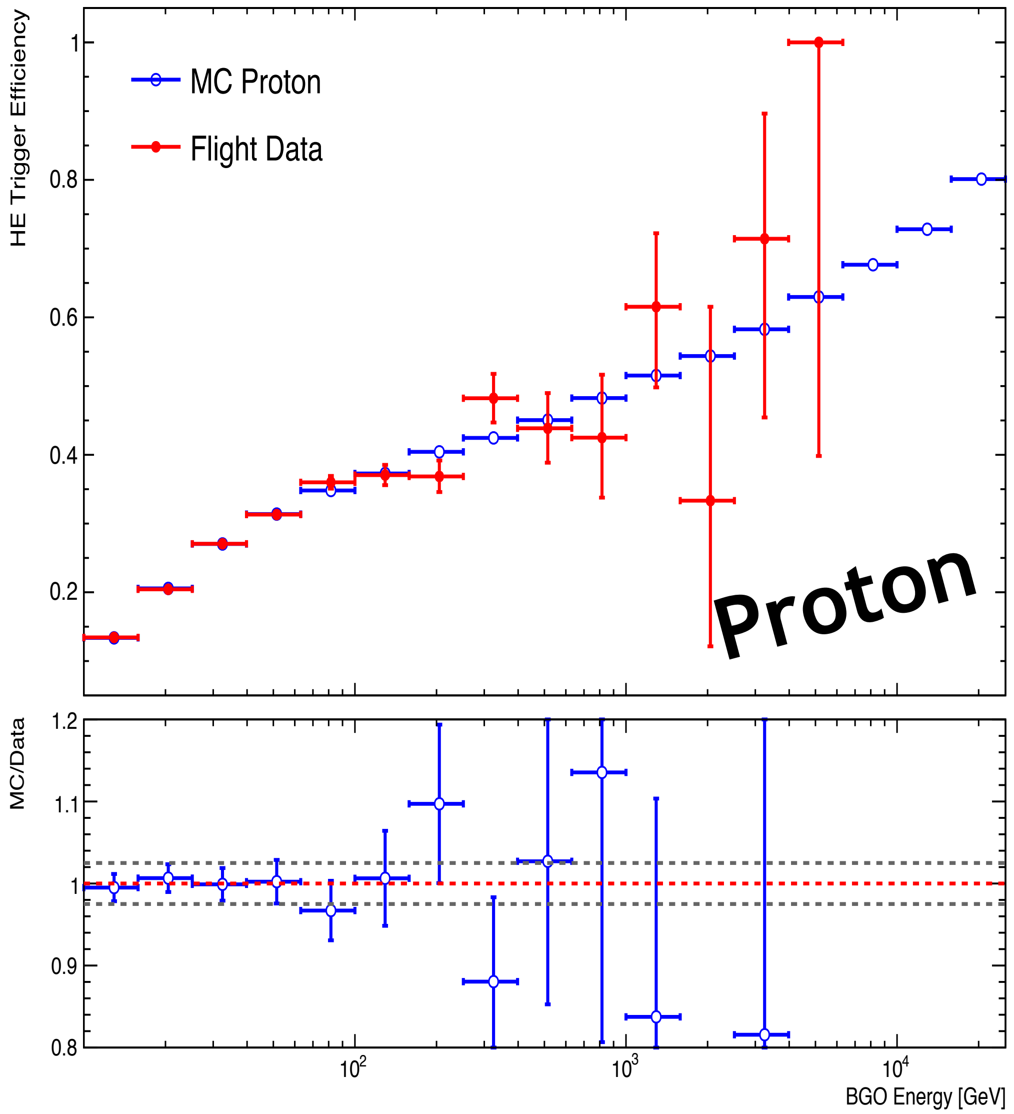


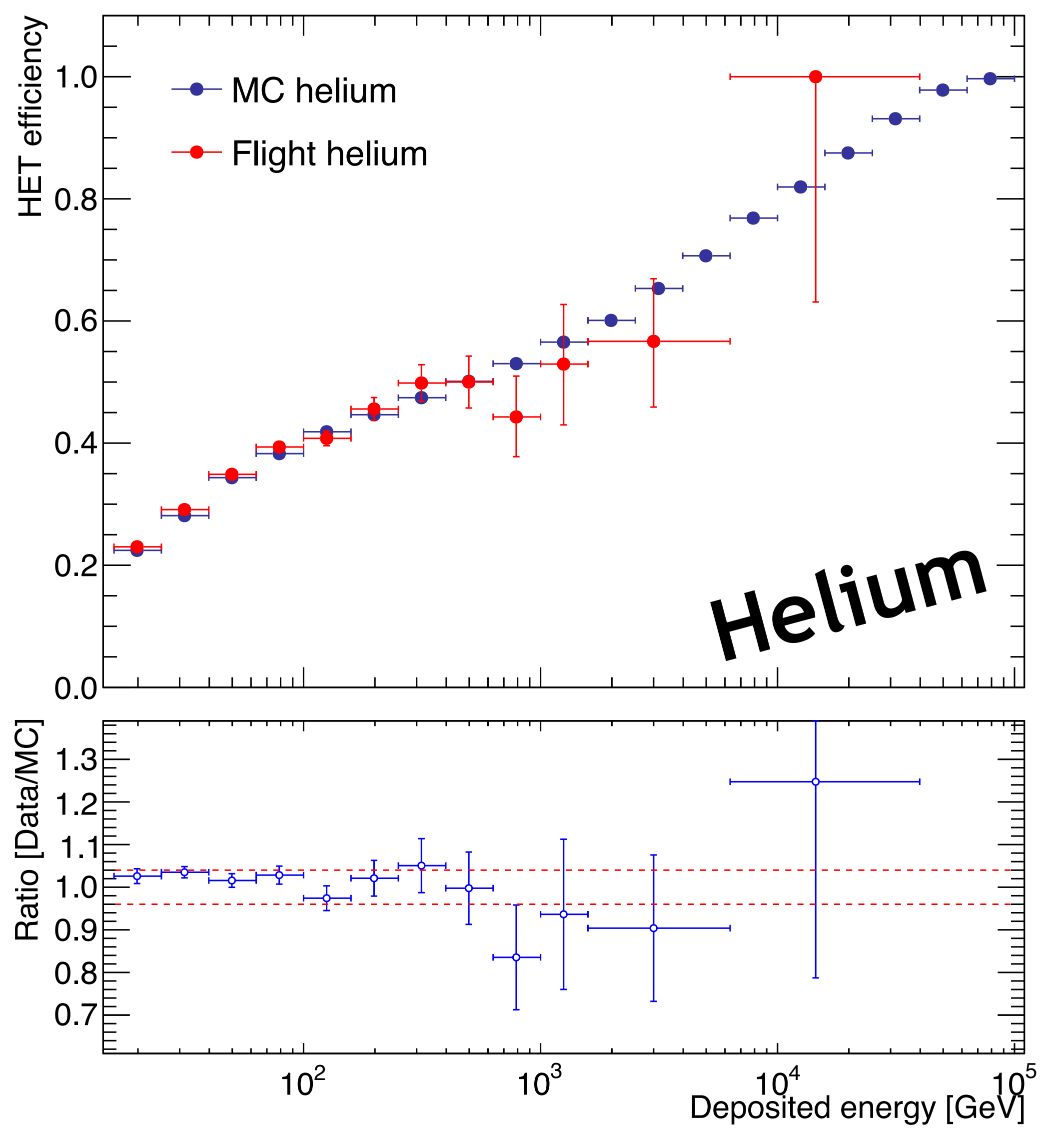
Trigger efficiency

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

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

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



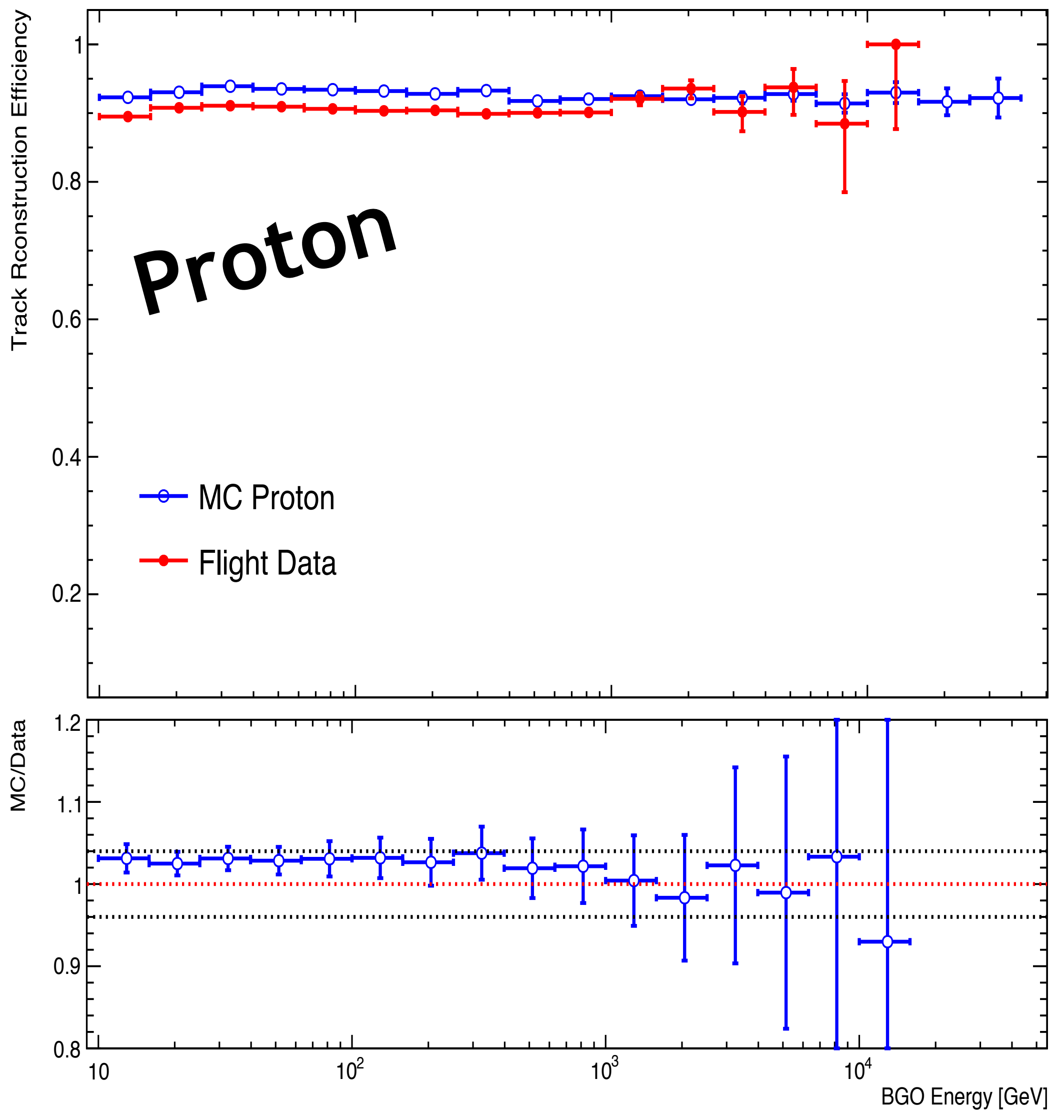


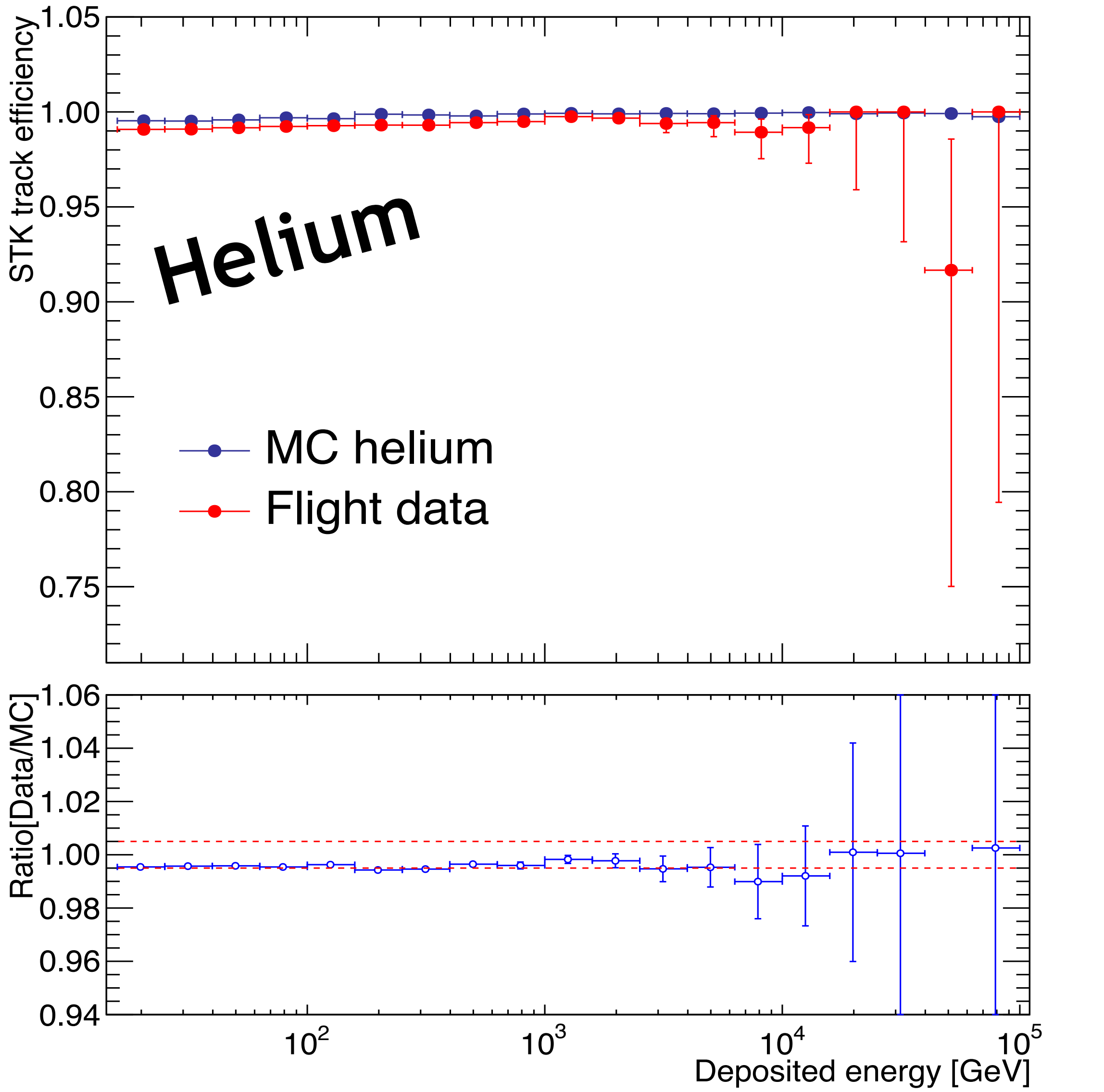
Systematic uncertainty due to HET: ~2.5% (proton), ~4% (Helium)

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.

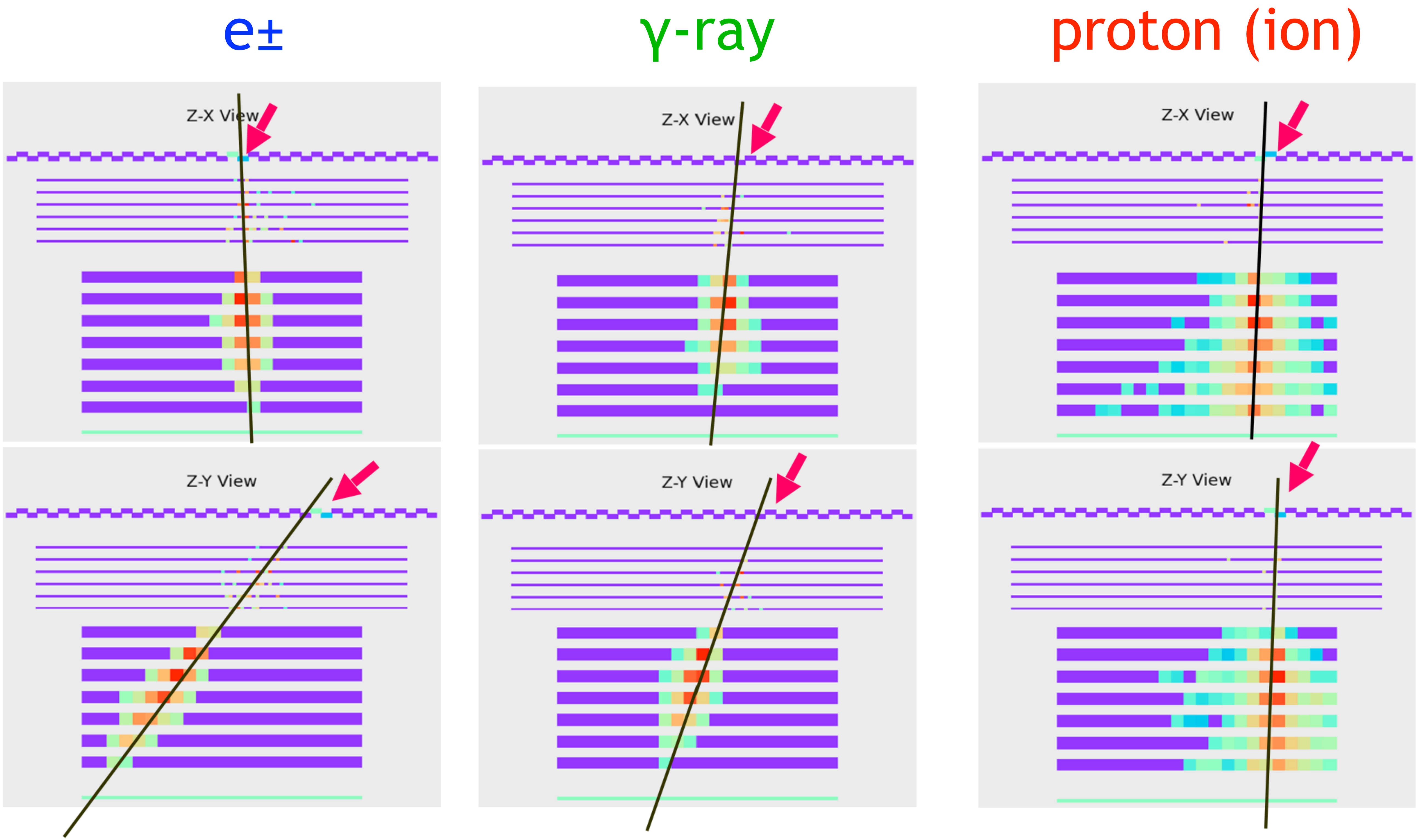
$$\varepsilon_{track} = \frac{N_{track|BGOtrack}}{N_{BGOtrack}}$$



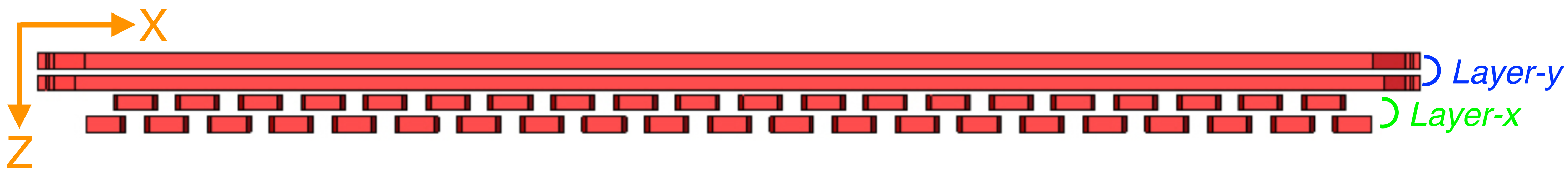


Systematic uncertainty due to STK-track: ~3.5% (proton), ~0.5% (Helium)

Particle identification



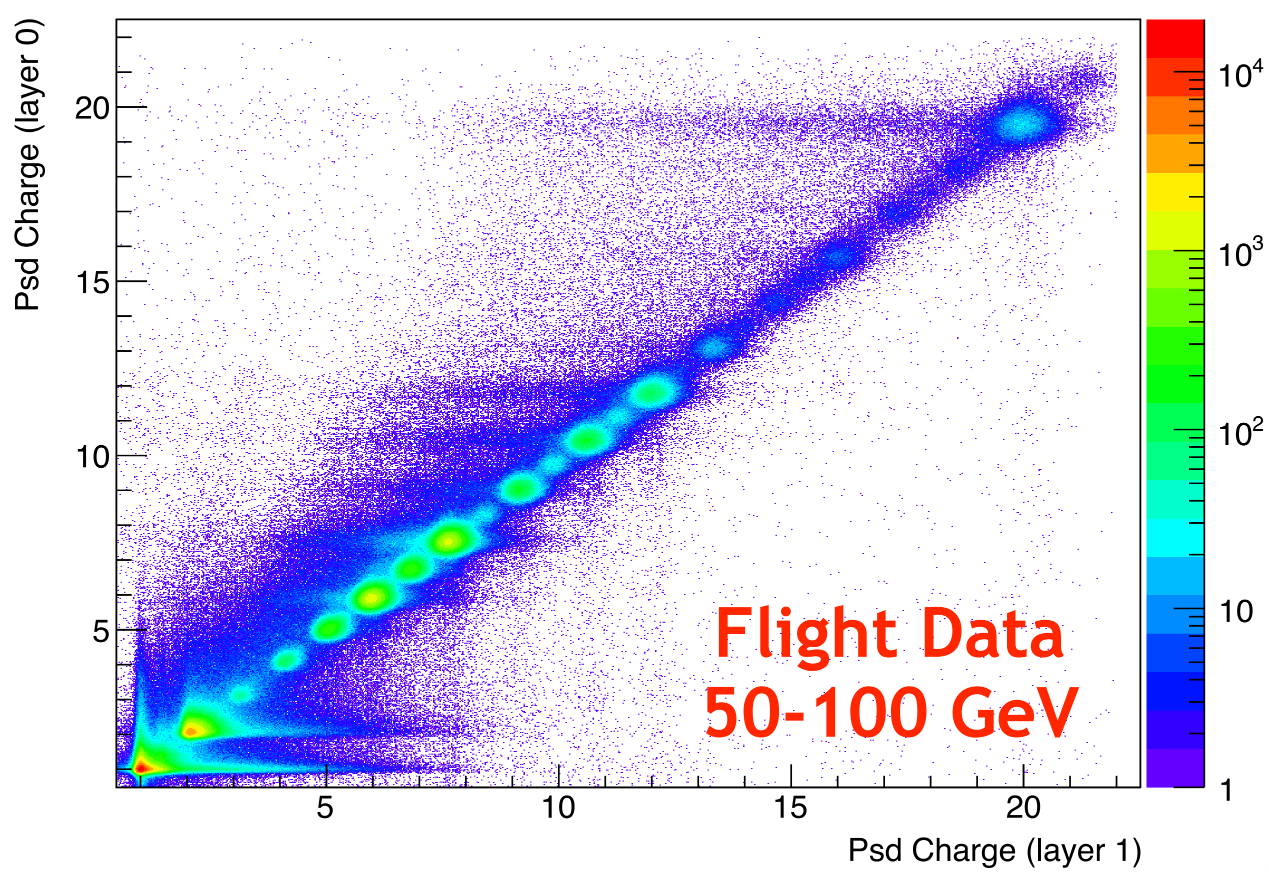
Charge selection

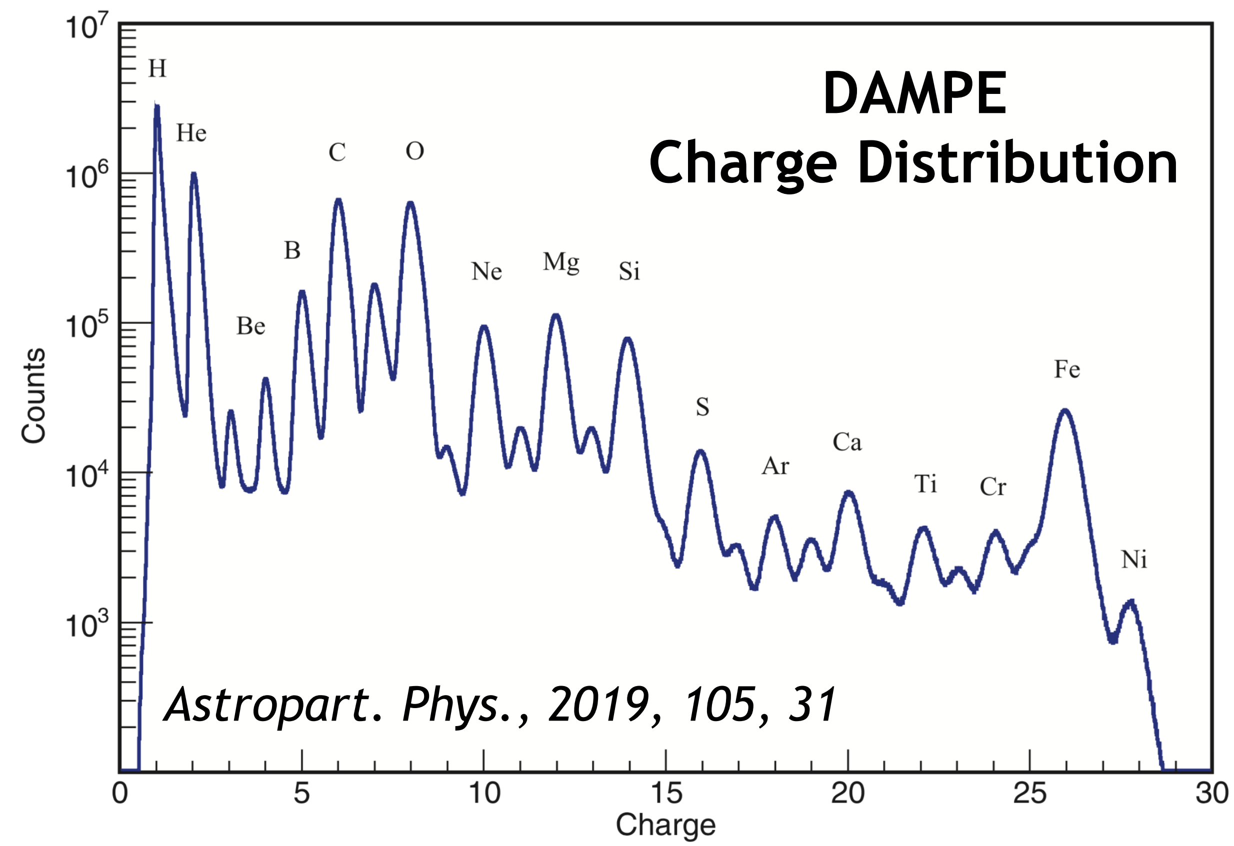


Bethe-Bloch

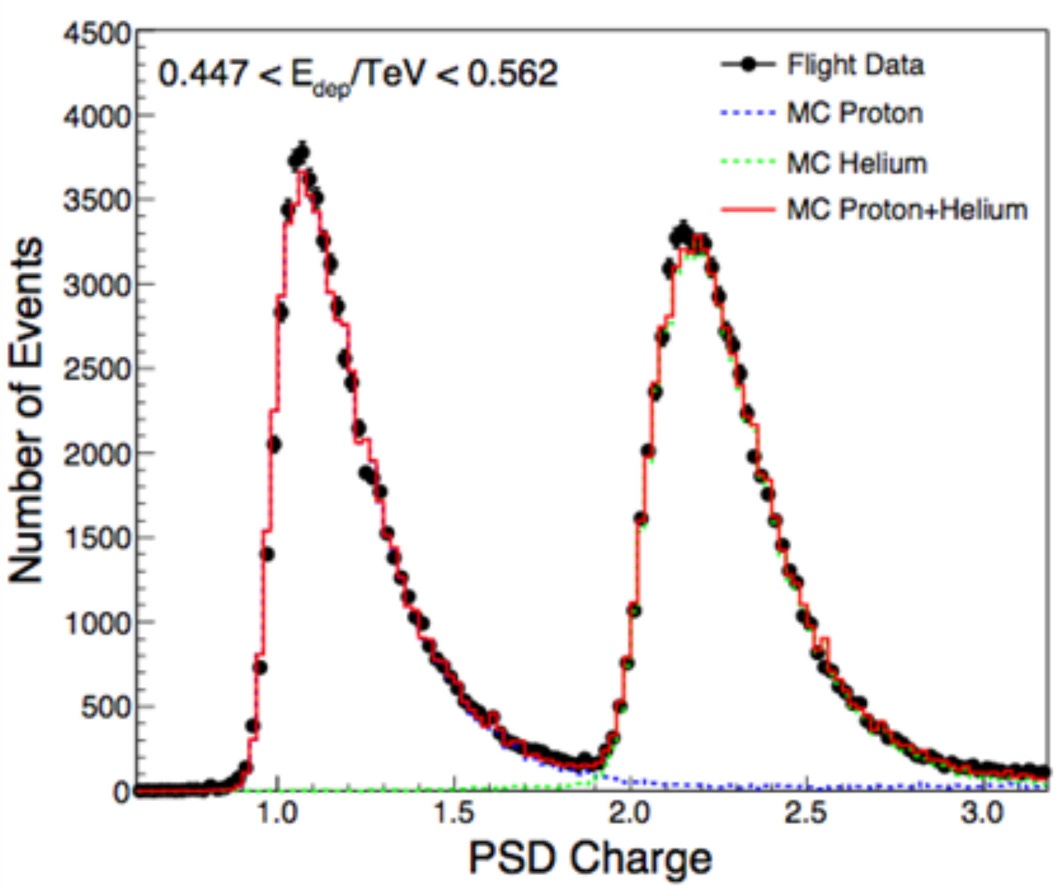
$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

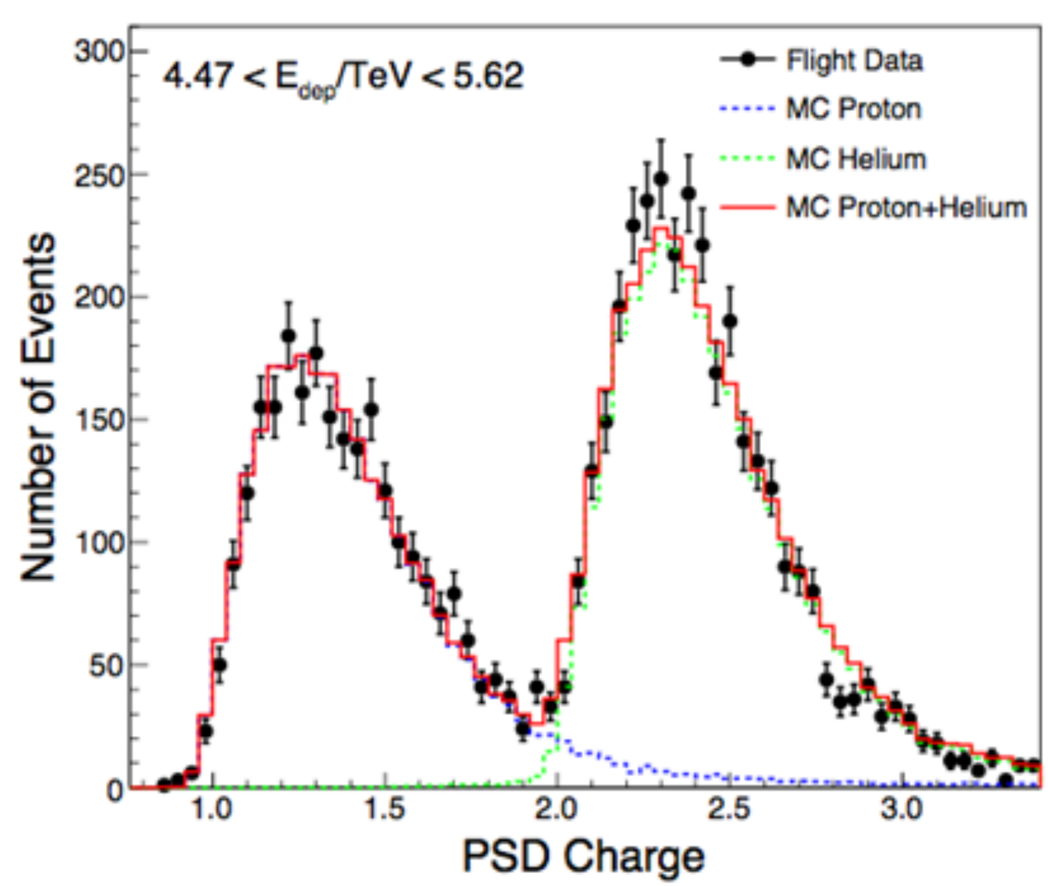
$$Z_y = \sqrt{PsdE_y/MipE} \quad Z_x = \sqrt{PsdE_x/MipE} \quad Z_{PSD} = (Z_y + Z_x)/2$$





Charge selection



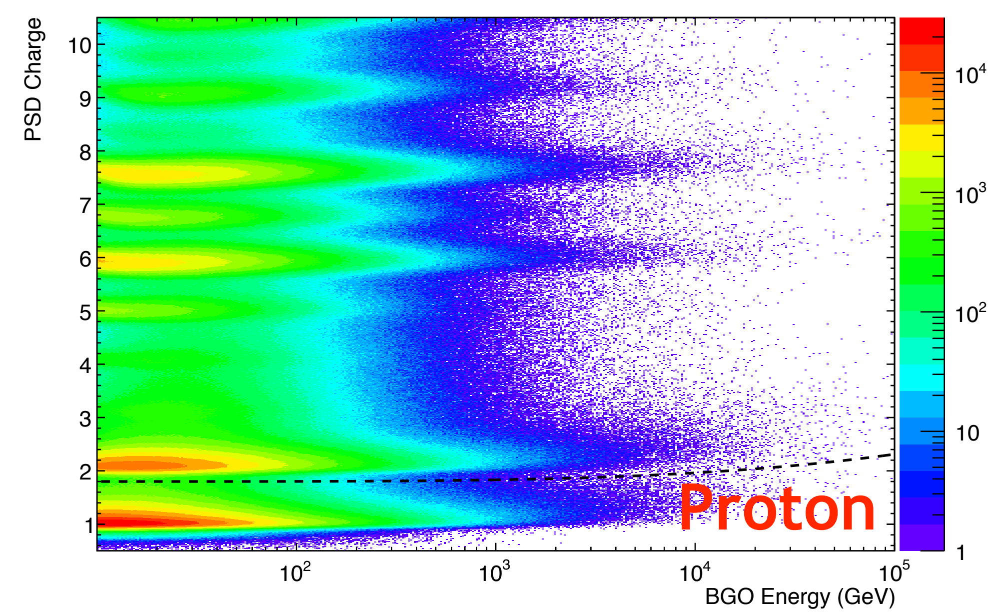


Proton selection:

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

Helium selection:

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



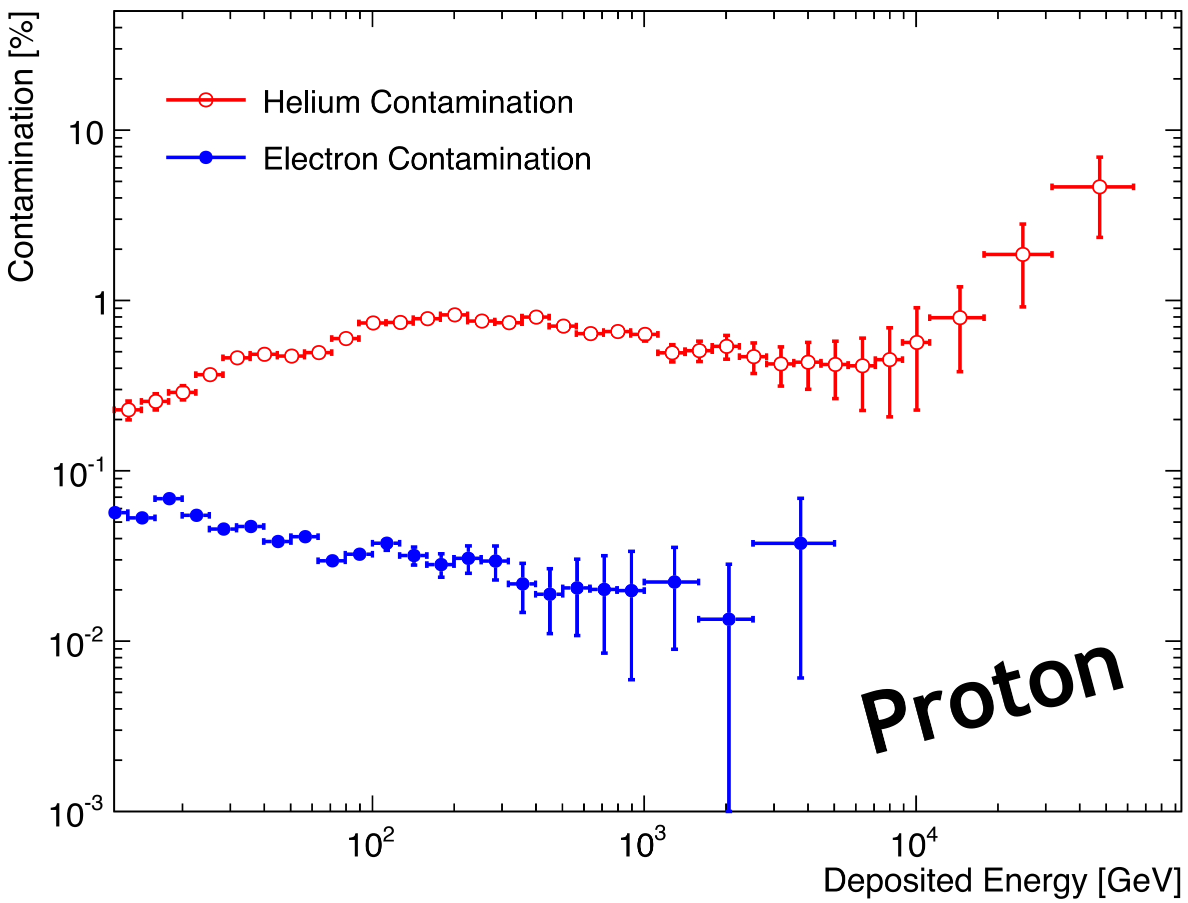
Background

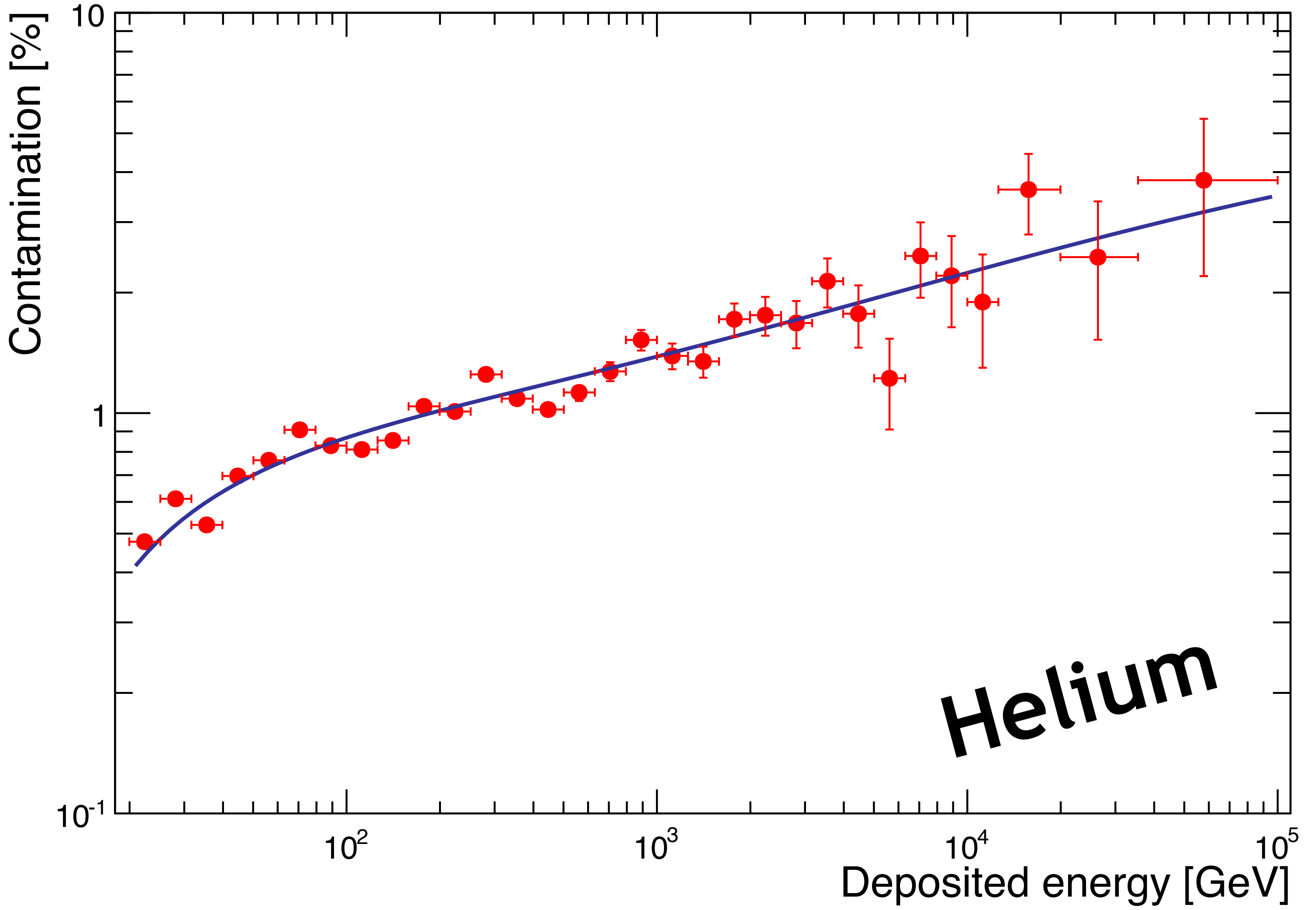
Proton selection:

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

Helium selection:

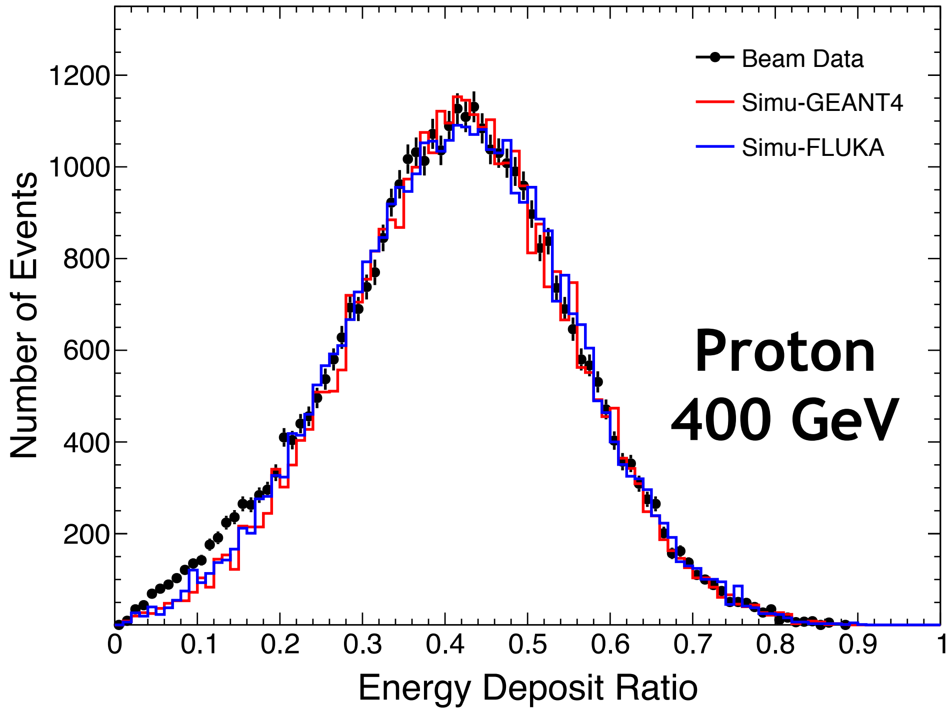
$$1.85 + 0.02 \cdot log\frac{E_{dep}}{10GeV} < Z_{PSD,Y(X)} < 2.8 + 0.007 \cdot (log\frac{E_{dep}}{10GeV})^4$$

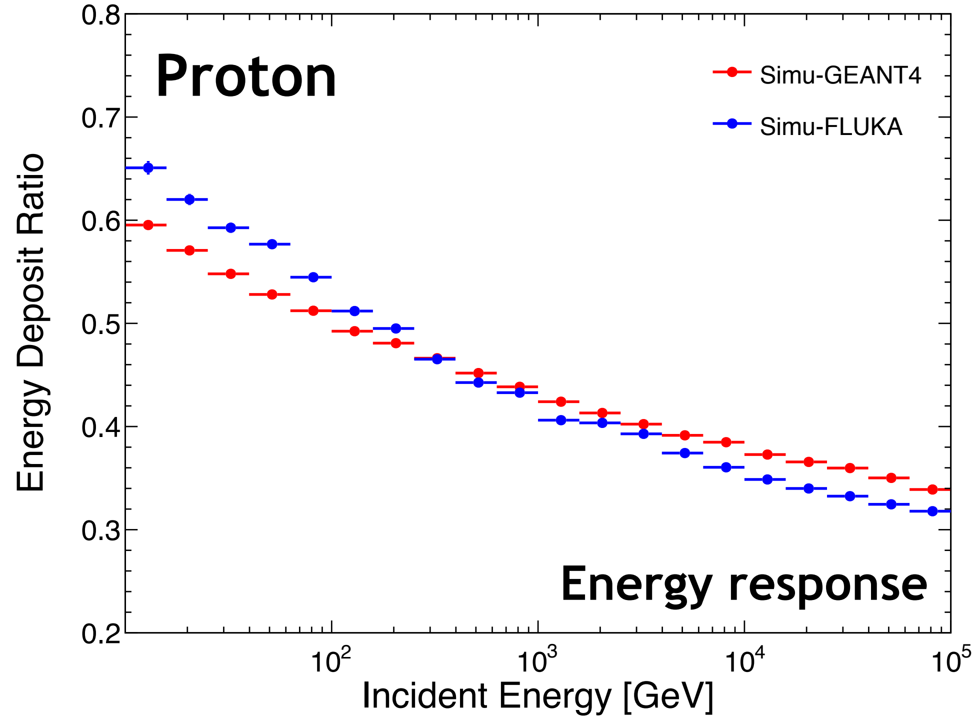


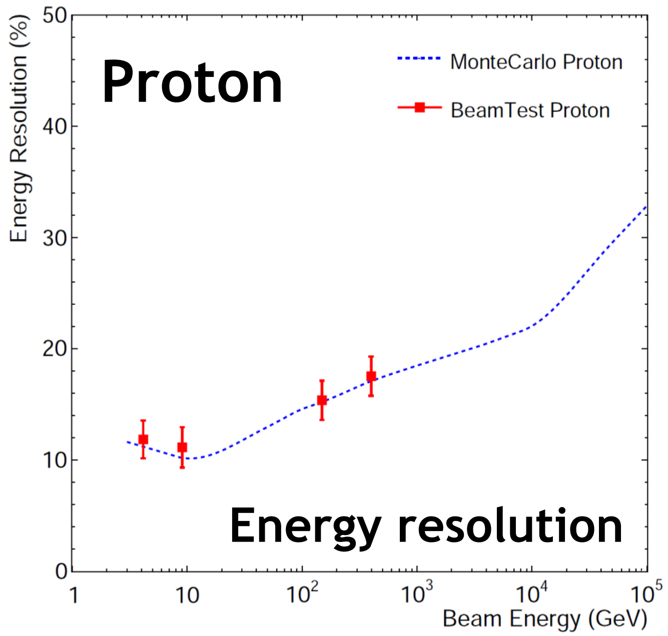


Energy measurement

Beam test @ CERN SPS

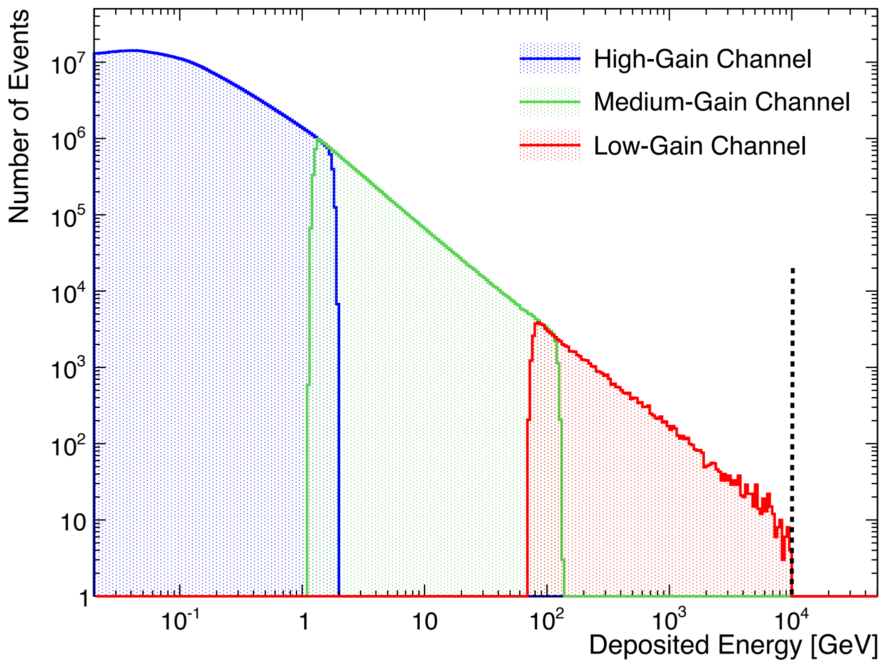


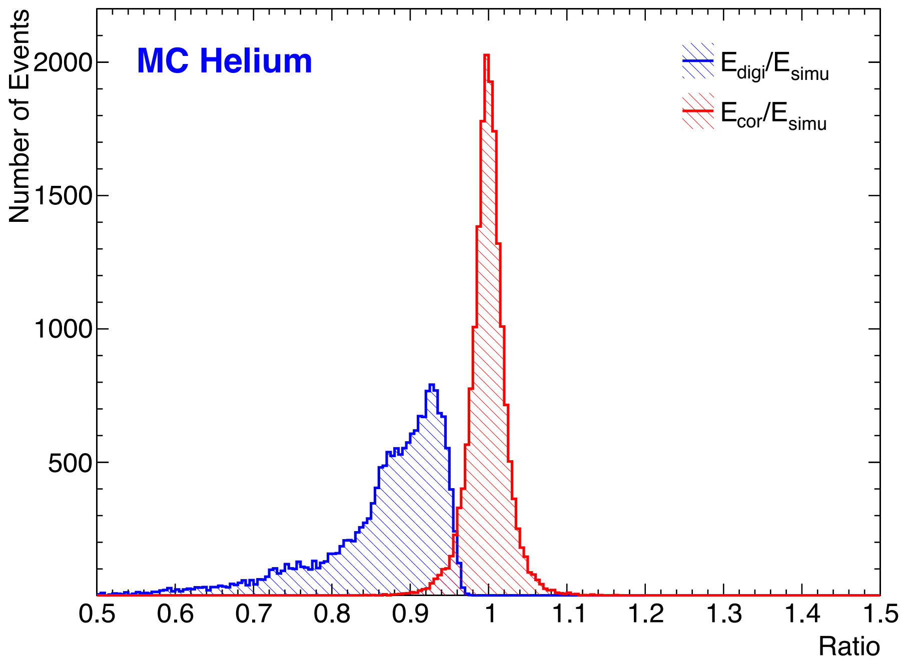


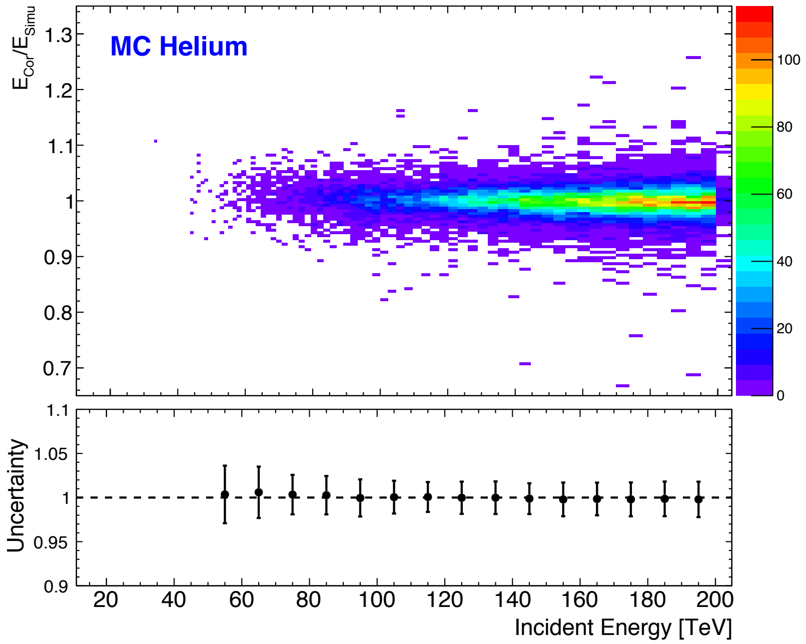


BGO readout saturation correction

C. Yue et al., NIMA 984 (2020), 164645







Spectral unfolding

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**

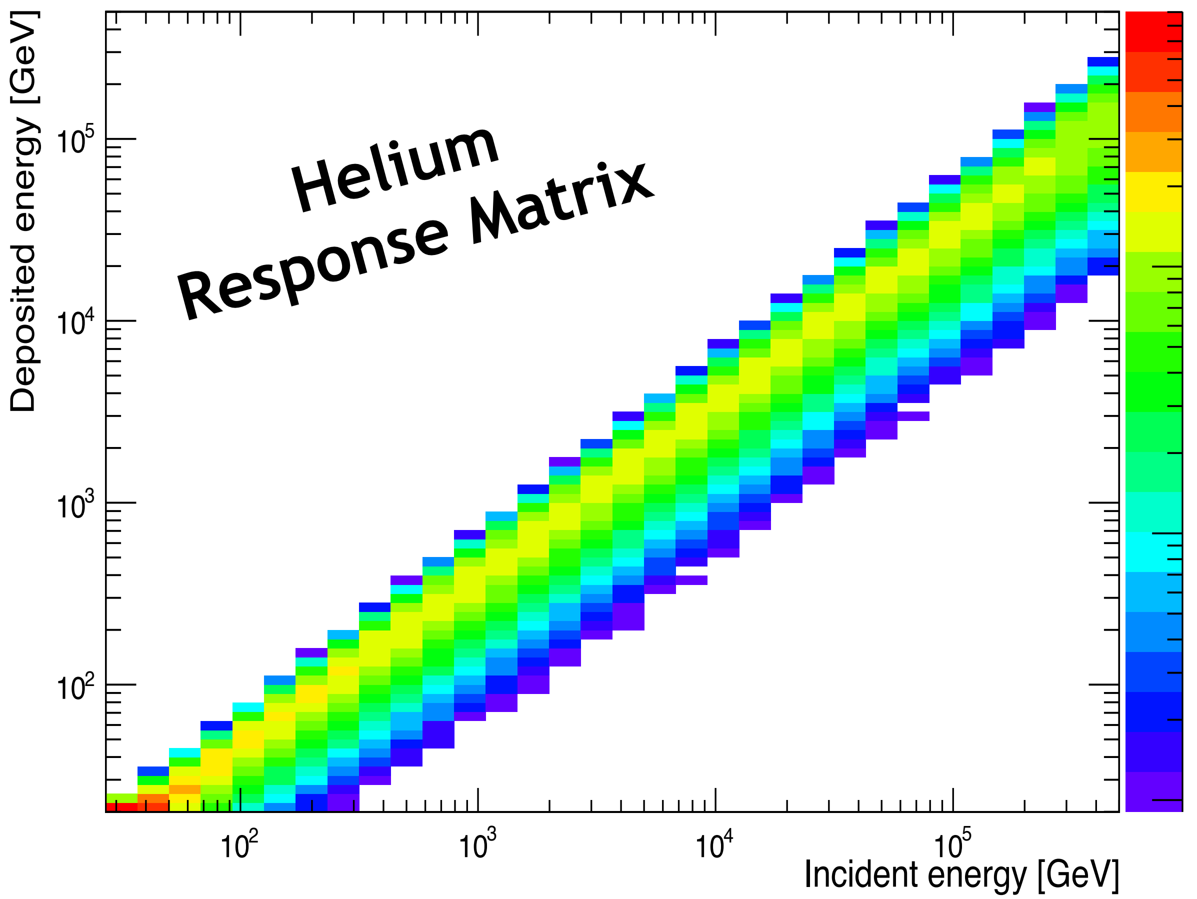
M_j: **Measured event number**

β_j : **Background**

$P(E_{d,j}|E_{0,i})$: **Energy response matrix**

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

$$V_{kl} = V_{kl}(\mathbf{n}(E)) + V_{kl}(\mathbf{M})$$



Flux calculation

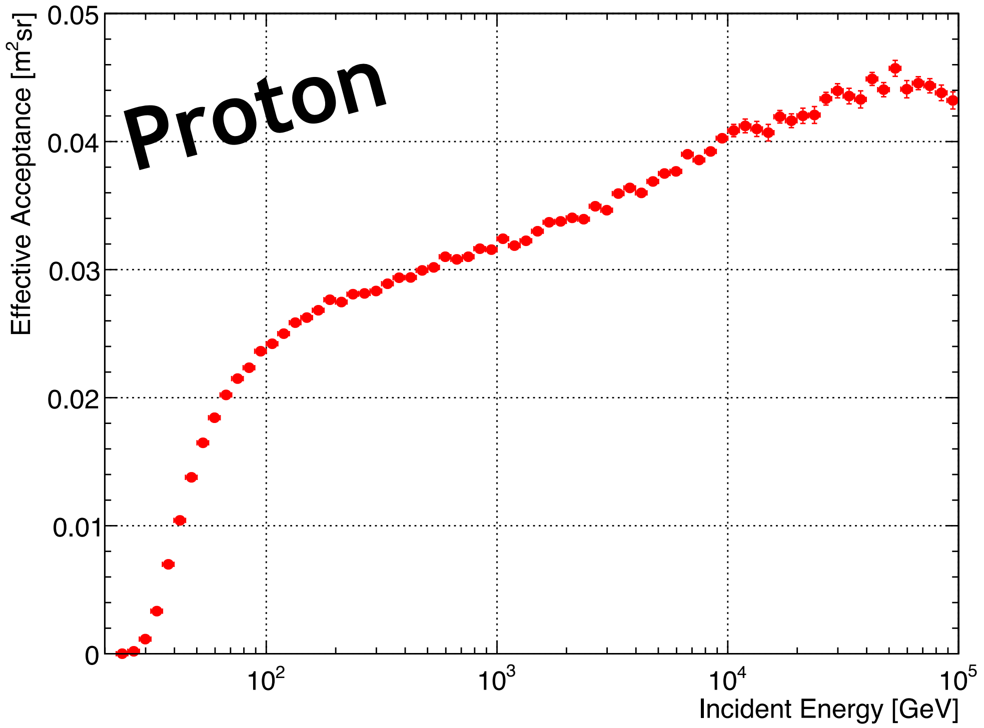
Differential flux in the i-th primay energy bin:

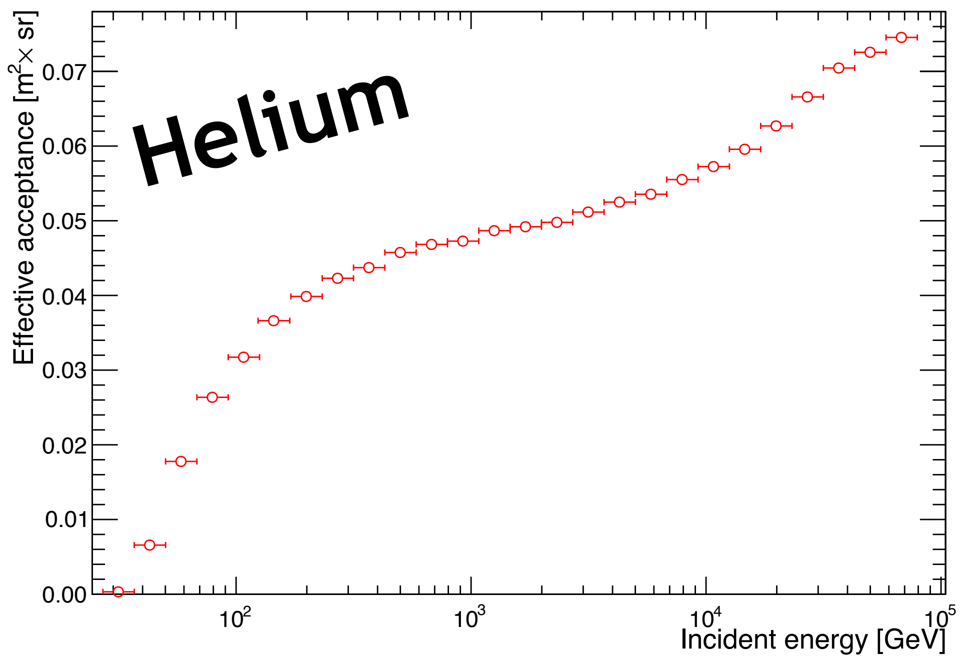
$$\Phi(E_i, E_i + \Delta E_i) = \frac{\Delta N_i}{\Delta E_i \; A_{eff,i} \; \Delta T}$$

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

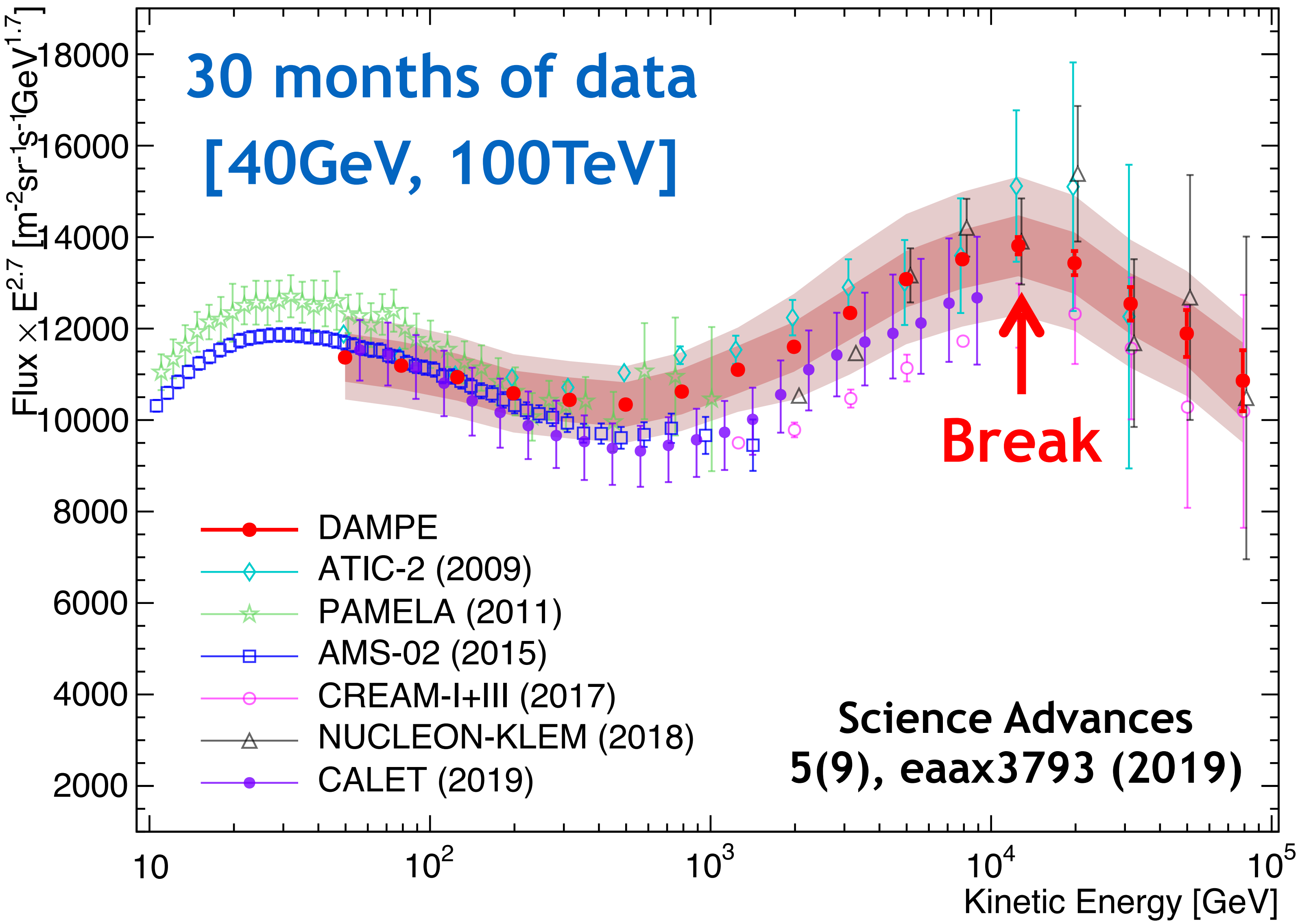
$$A_{eff,i} = A_{gen} \times \frac{N_{pass,i}}{N_{gen,i}}$$

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

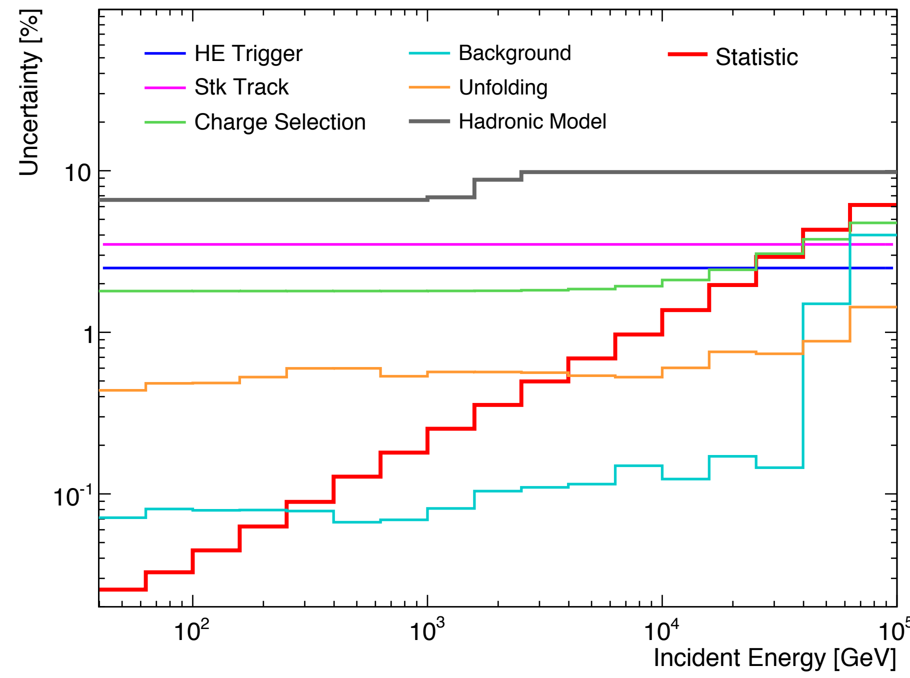




Proton spectrum



Uncertainties



Error bars: statistical uncertainties

Inner dashed band:

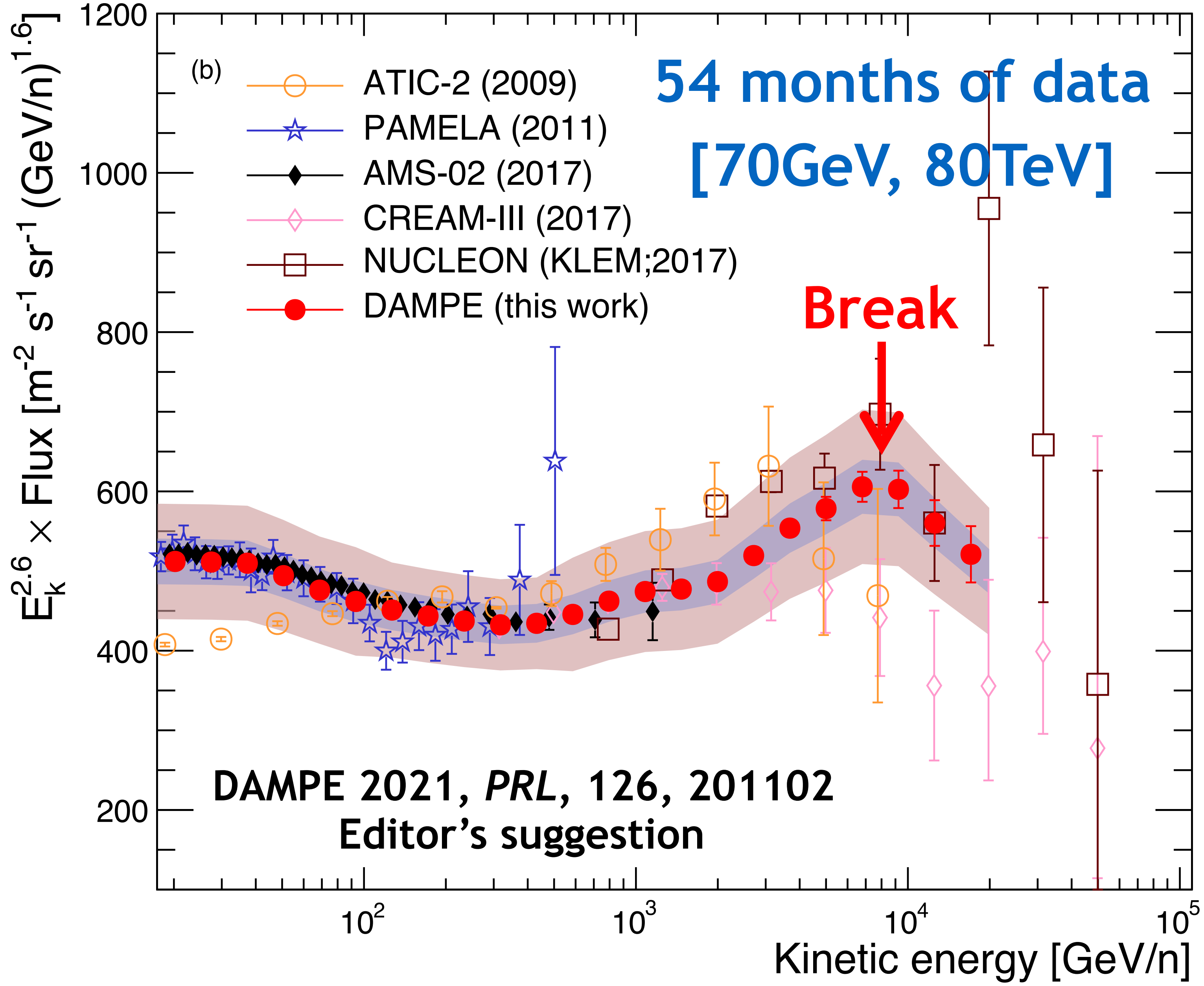
$$\sigma_{ana} = \sqrt{\sigma_{HET}^2 + \sigma_{track}^2 + \sigma_{charge}^2 + \sigma_{bg}^2 + \sigma_{unfold}^2}$$

Outer dashed band:

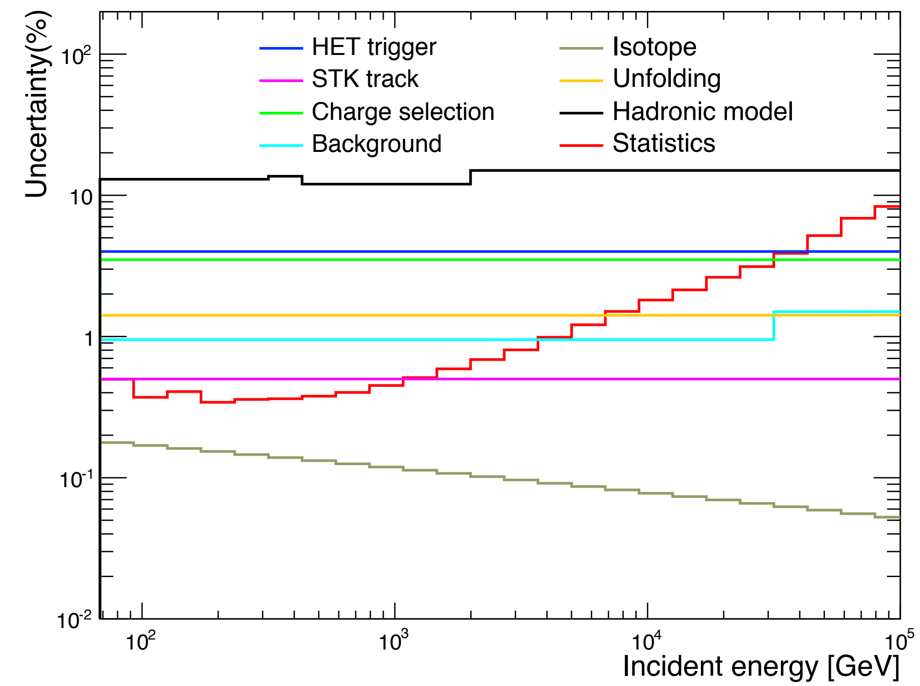
$\sqrt{\sigma_{ana}^2 + \sigma_{had}^2}$, σ_{had} obtained from the comparison between Geant4 and FLUKA MC simulations.

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



Uncertainties



Error bars: statistical uncertainties

Inner dashed band:

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

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

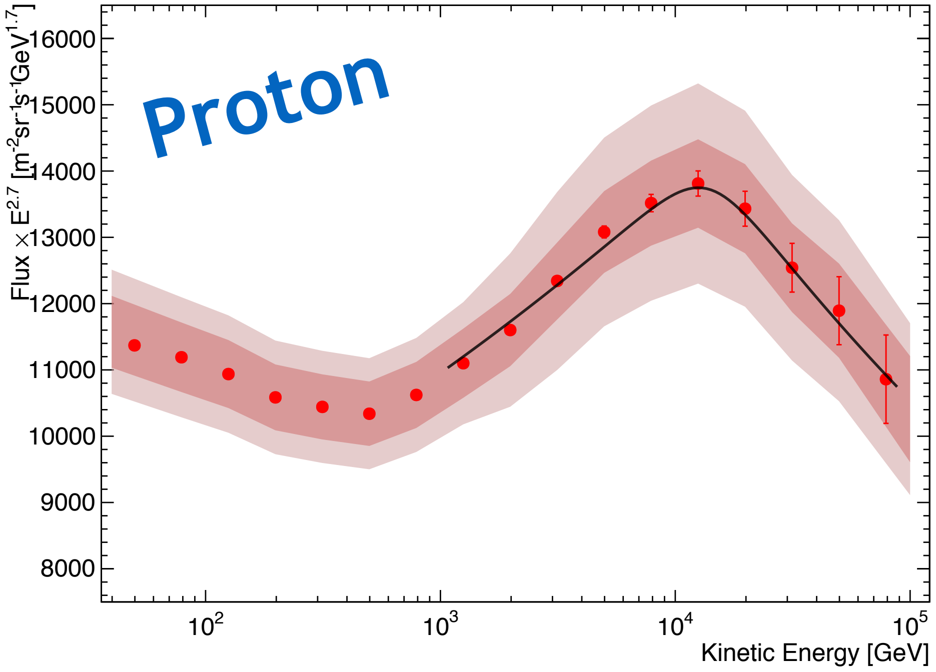
Outer dashed band:

$\sqrt{\sigma_{ana}^2 + \sigma_{had}^2}$, 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.

Softening feature

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



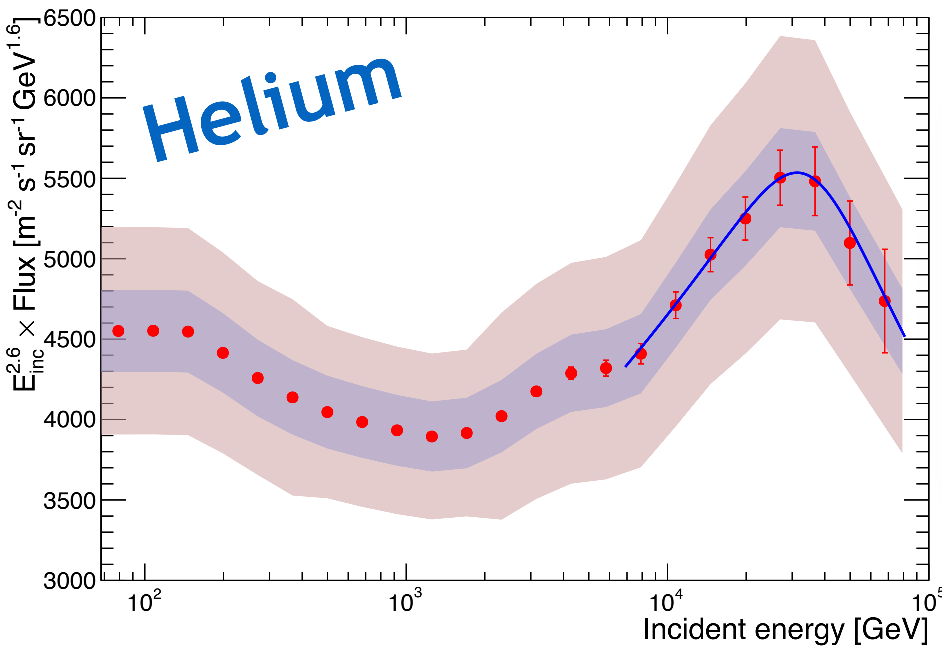
$E_b = 13.6^{+4.1}_{-4.8}\ TeV$

$\gamma = 2.60 \pm 0.01$

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

$s = 5$ (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)

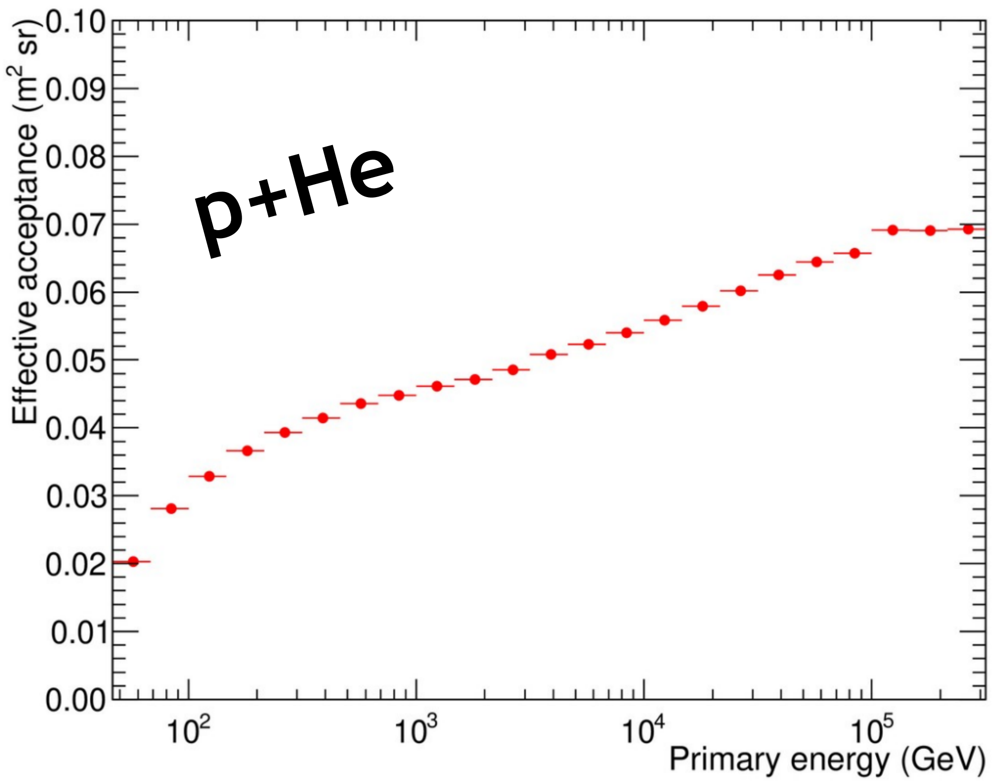
Significance of softening: ~4.3σ

p+He spectrum

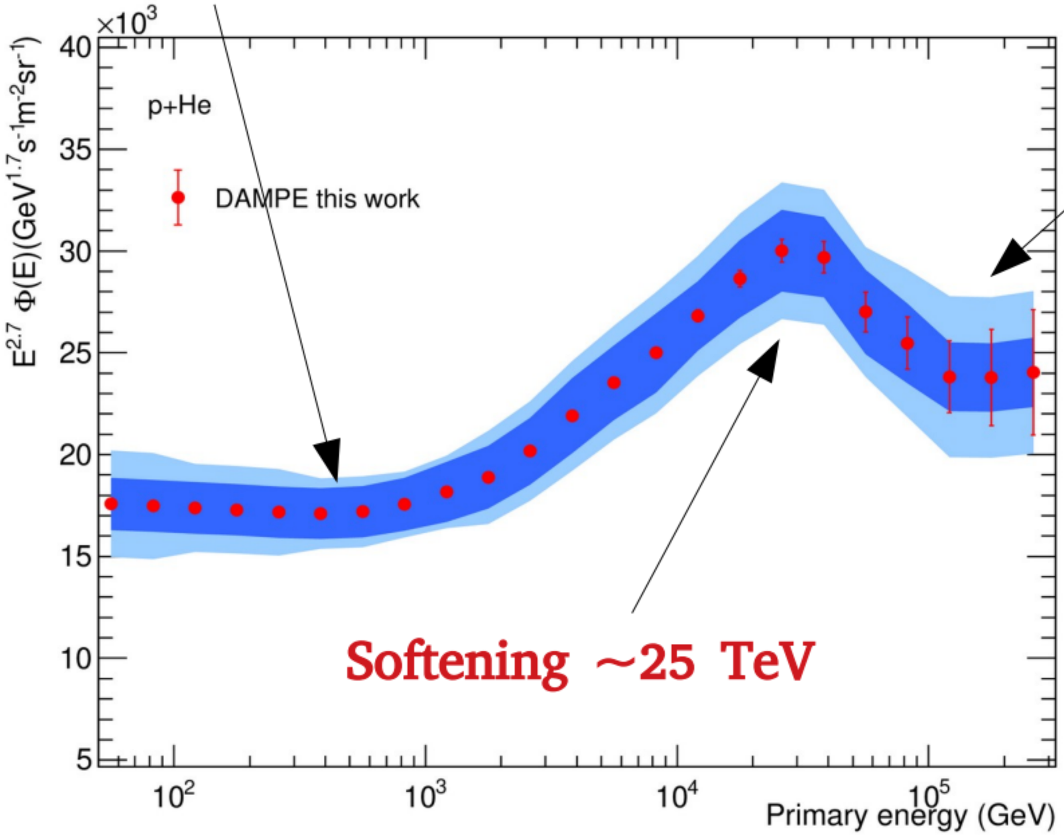
Independent analysis of p+He spectrum in the collaboration

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

Effective acceptance



Hardening ~600 GeV



Softening ~25 TeV

Second hardening >100 TeV ?

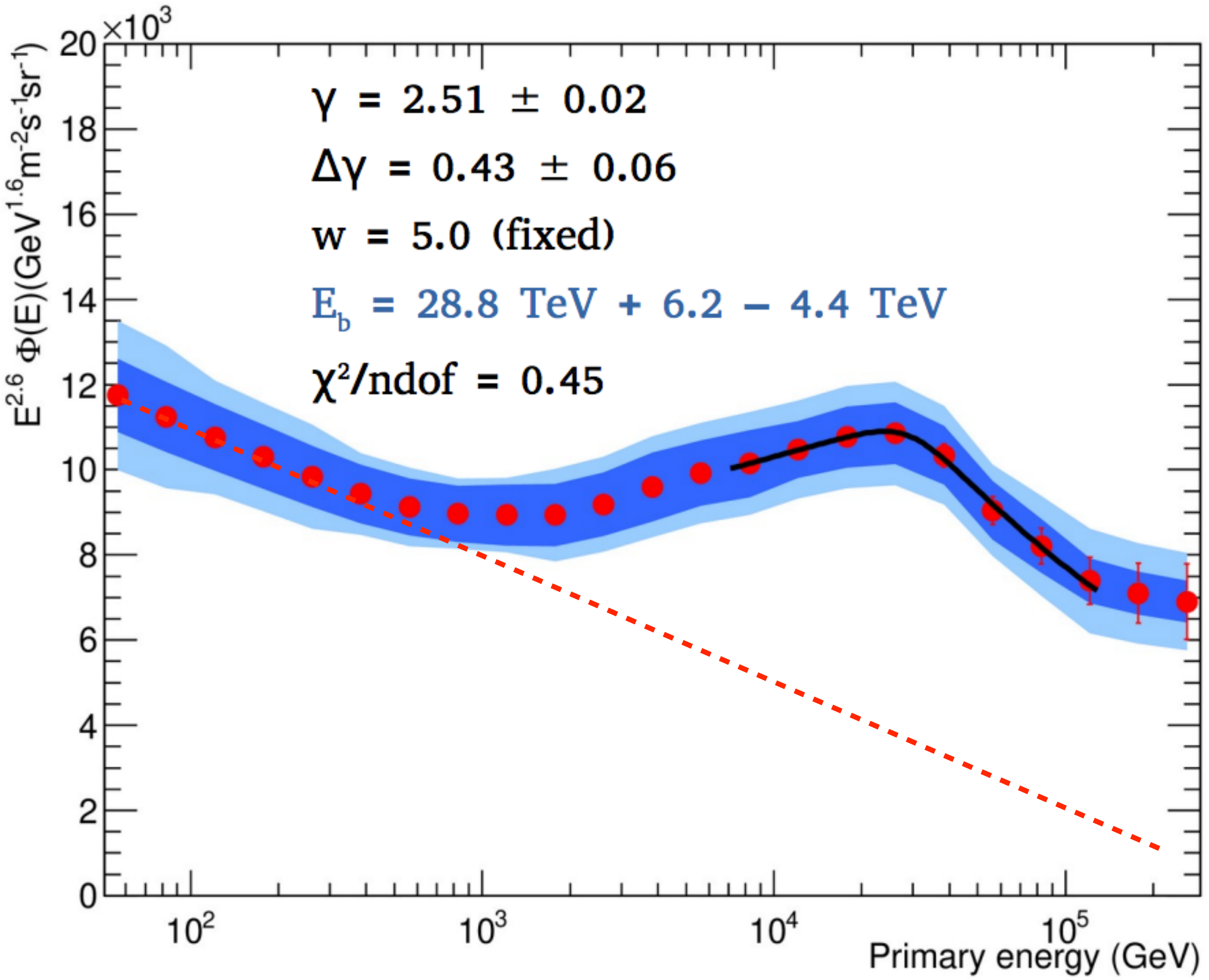
Outer band: total systematic uncertainties

Inner band: without the hadronic model

p+He spectrum

Independent analysis of p+He spectrum in the collaboration

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



Smoothly-broken power-law model (SBPL)

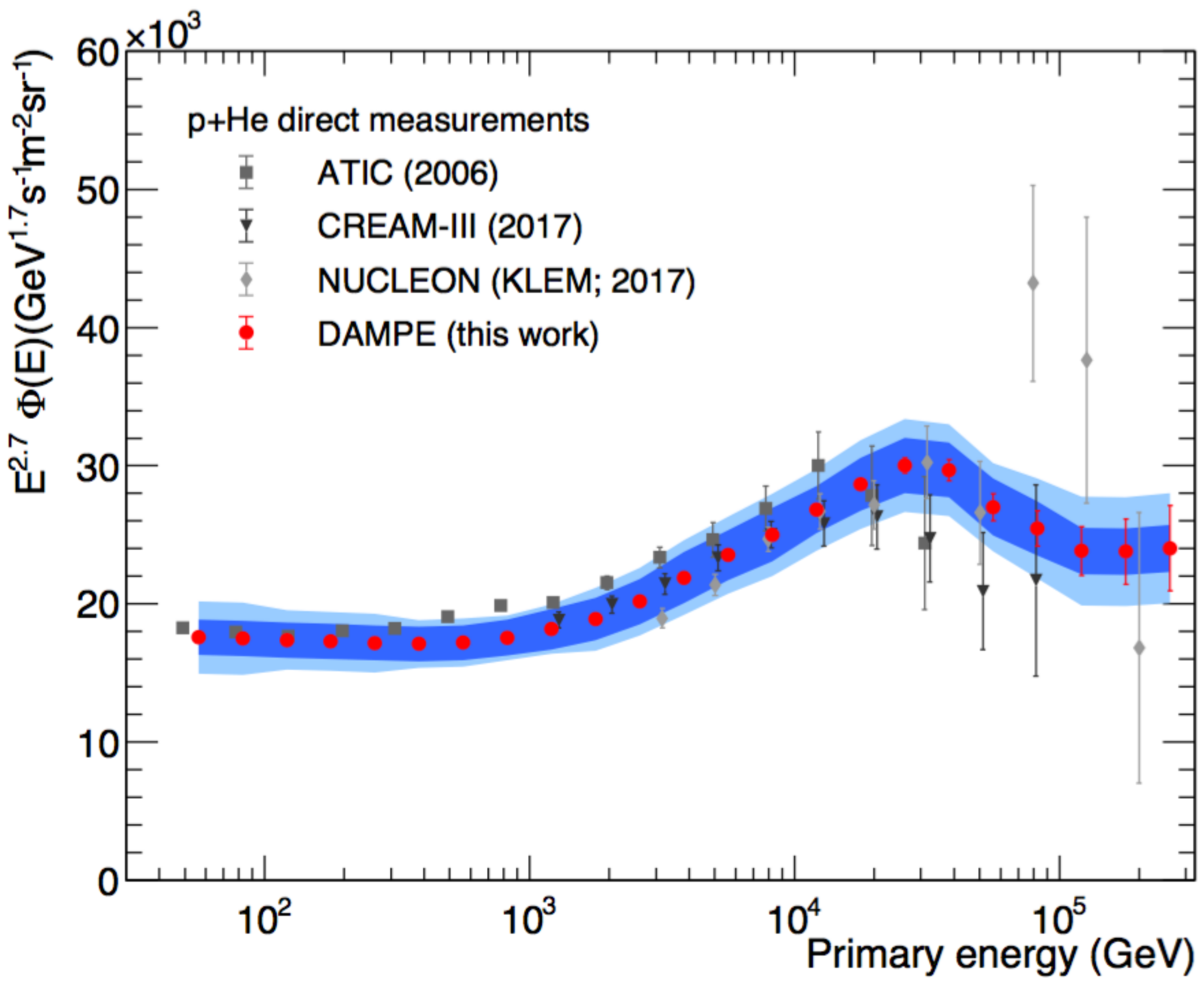
$$\Phi(\mathrm{E}) = \Phi_0 \left(\frac{\mathrm{E}}{\mathrm{TeV}}\right)^{-\gamma} \left[1 + \left(\frac{\mathrm{E}}{\mathrm{E_b}}\right)^{1/w}\right]^{-\Delta\gamma \cdot w}$$

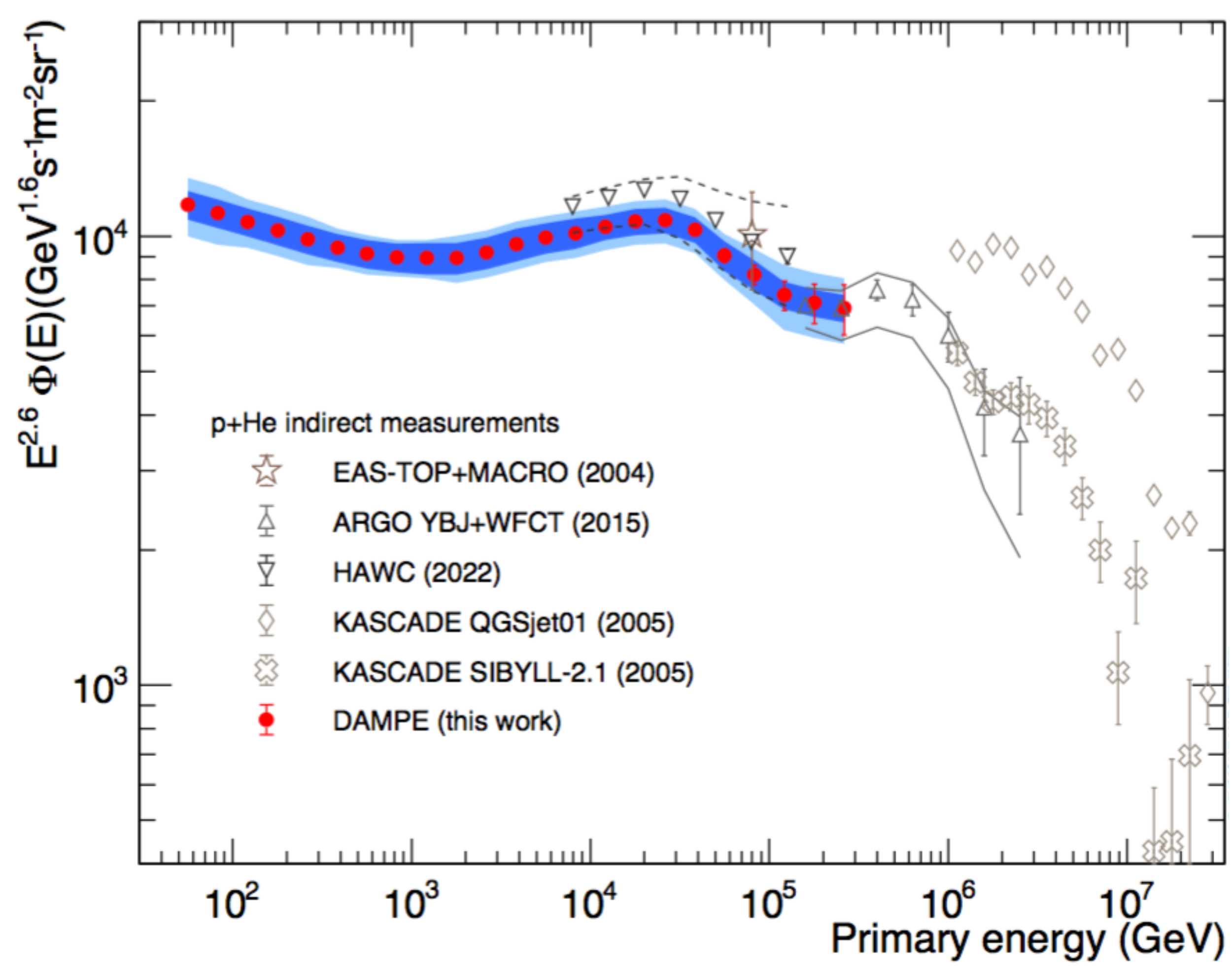
	Proton	Helium	Proton+Helium
E_b (TeV)	$13.6^{+4.1}_{-4.8}$	$34.4^{+6.7+11.6}_{-9.8-0.0}$	$28.8^{+6.2+2.9}_{-4.4-0.0}$
γ	2.60 ± 0.01	$2.41^{+0.02+0.02}_{-0.02-0.00}$	$2.51^{+0.021+0.01}_{-0.024-0.00}$
$\Delta\gamma$	-0.25 ± 0.07	$-0.51^{+0.18+0.01}_{-0.20-0.00}$	$0.43^{+0.066+0.066}_{-0.057-0.00}$

SBPL model favored on the PL model with a significance of 6.6σ

p+He spectrum

Independent analysis of p+He spectrum in the collaboration





- Link between direct/indirect CR measurements
- **Hint of new spectral hardening at ~150 TeV**

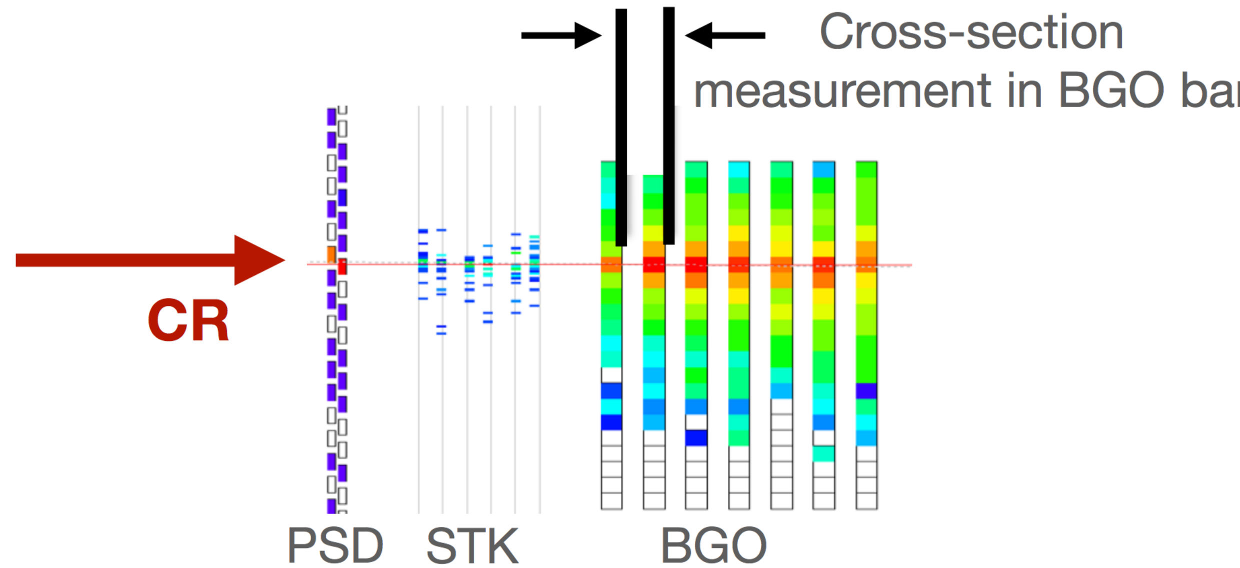
DAMPE collab.,
arxiv:2304.00137 (2023)

p(He)-BGO cross-section

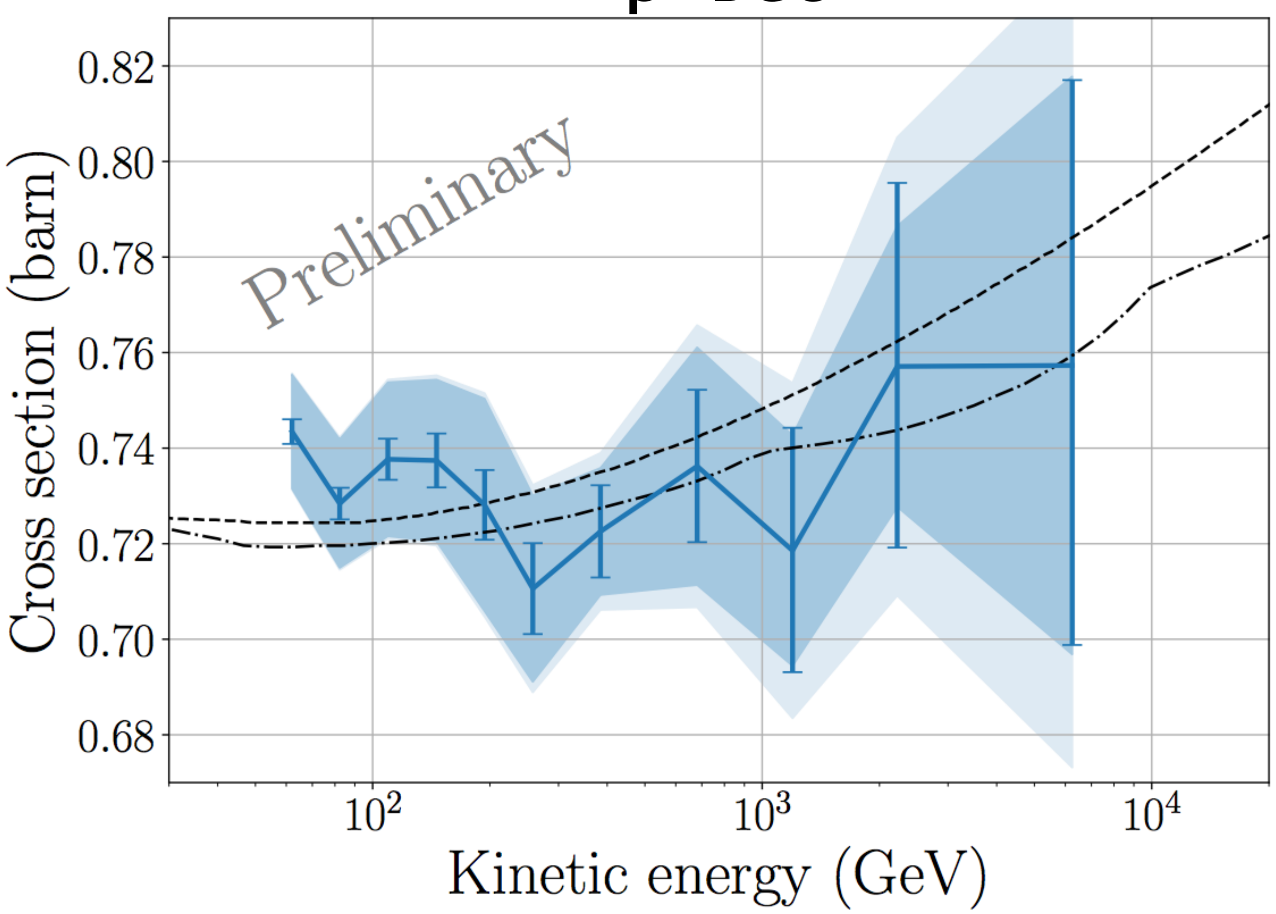
Inelastic hadronic cross section:
→ Determines the survive possibility in BGO

Fraction of events f that interacts after small distance δx follows exponential decay

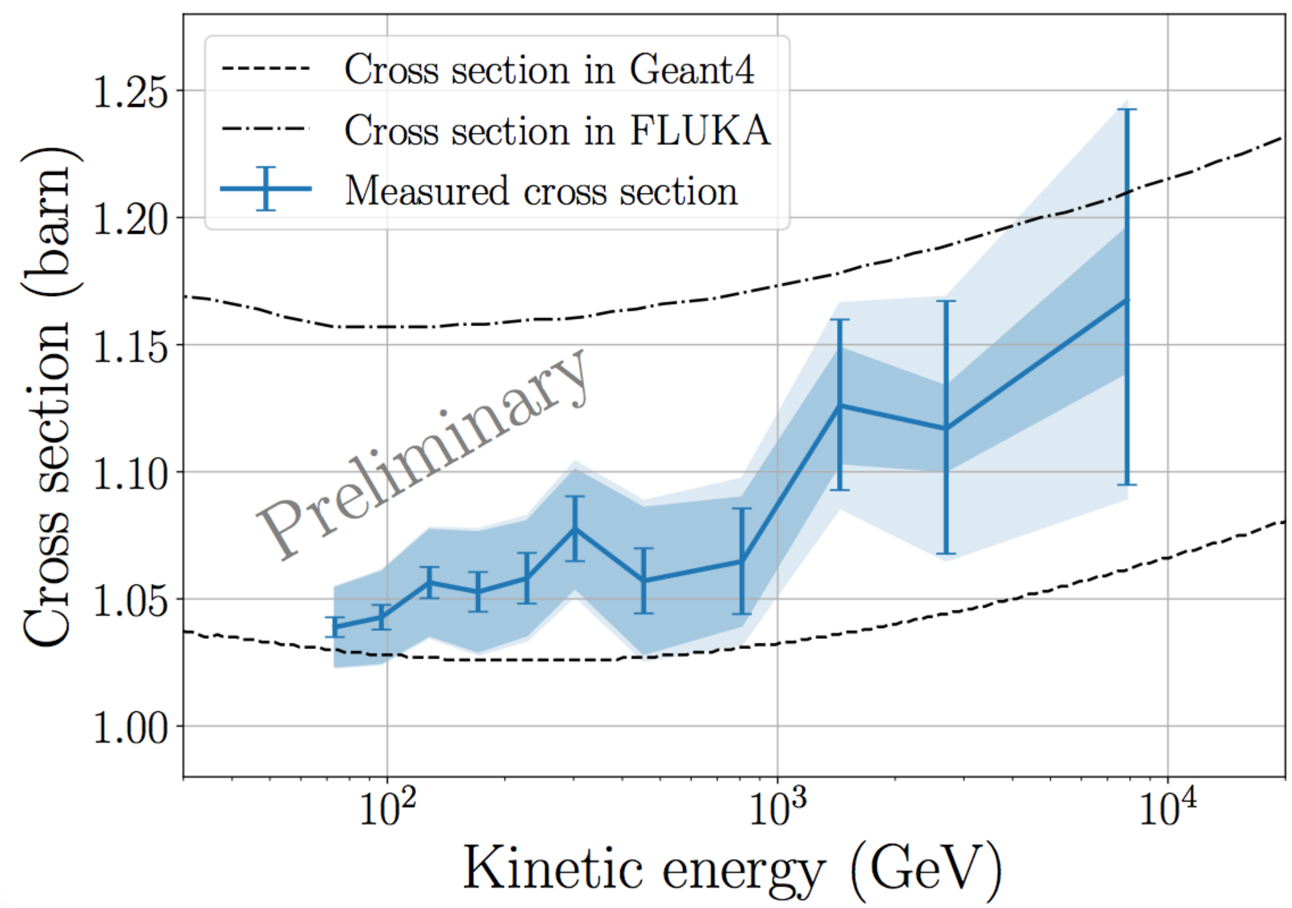
$$f = 1 - e^{\sigma(x)\cdot\rho(x)\cdot\delta x}$$



p—BGO



He—BGO



Summary

- The DAMPE measurements reveal similar **spectral softening features** in proton spectrum **(Eb~14 TeV)** and helium spectrum **(Eb~34 TeV)** with very high significances, which indicate **a Z-dependent spectral break (e.g. "knee")** in CR nuclei.

- The latest measurement of the **p+He spectrum up to 300 TeV** confirms the significant hardening (~600 GeV) and softening (~25 TeV) features and shows **a hint of hardening above 100 TeV**.

- 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.

Thank You!