Cosmic-Ray Nuclei Flux Measurements with the DAMPE Experiment

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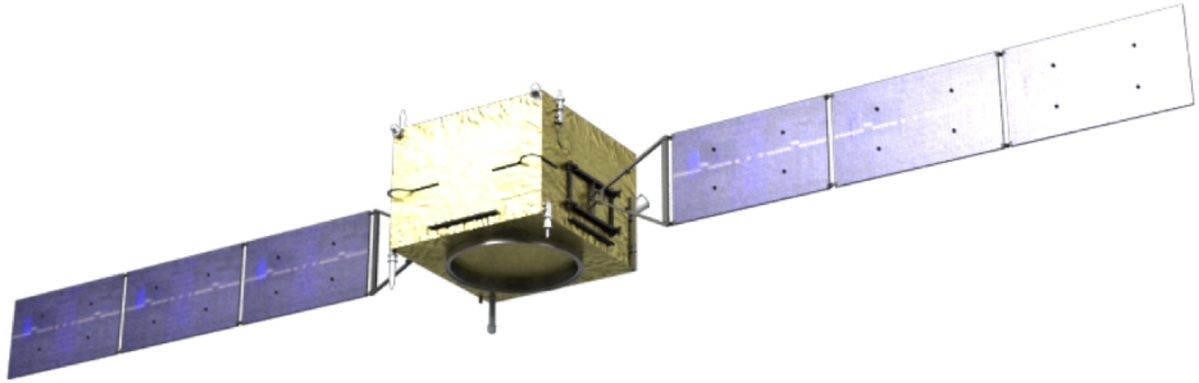
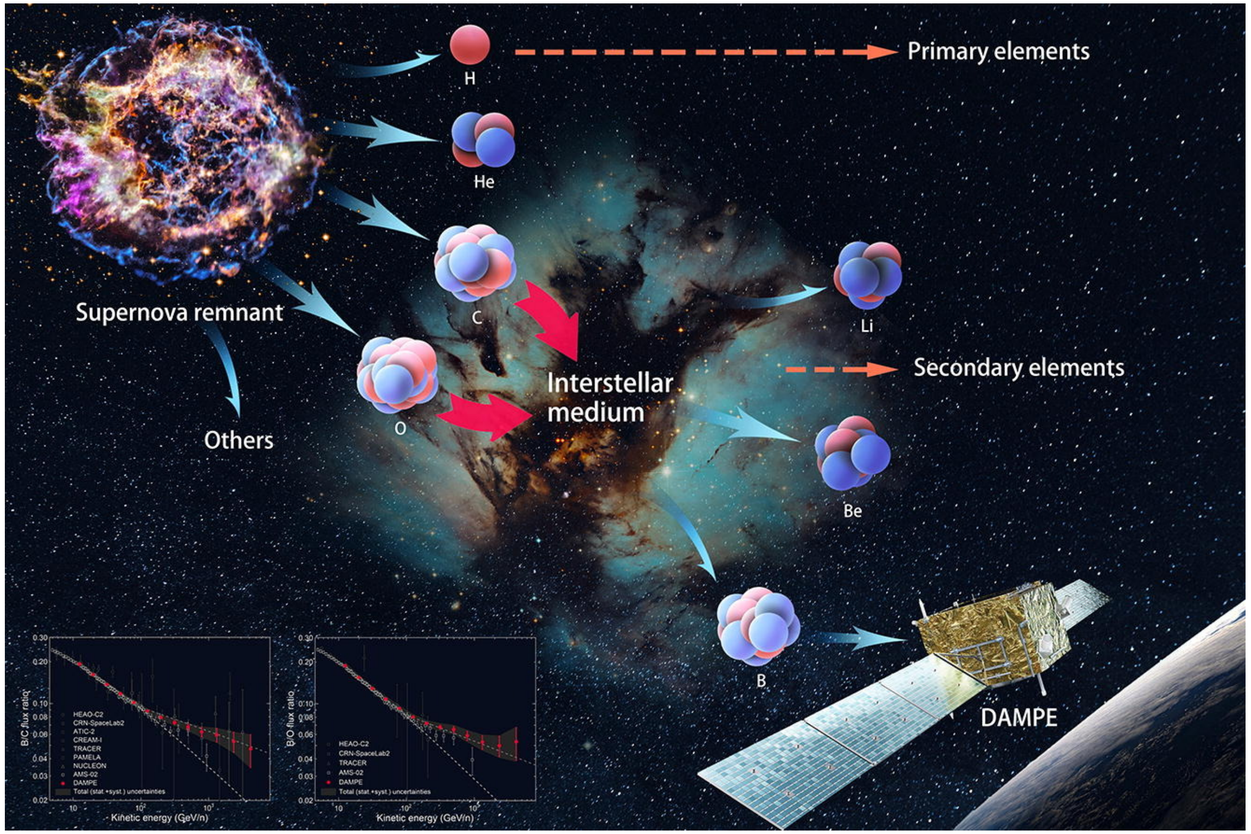
Outline

- Motivation
- DAMPE Experiment
- Method
- Latest results
- Summary



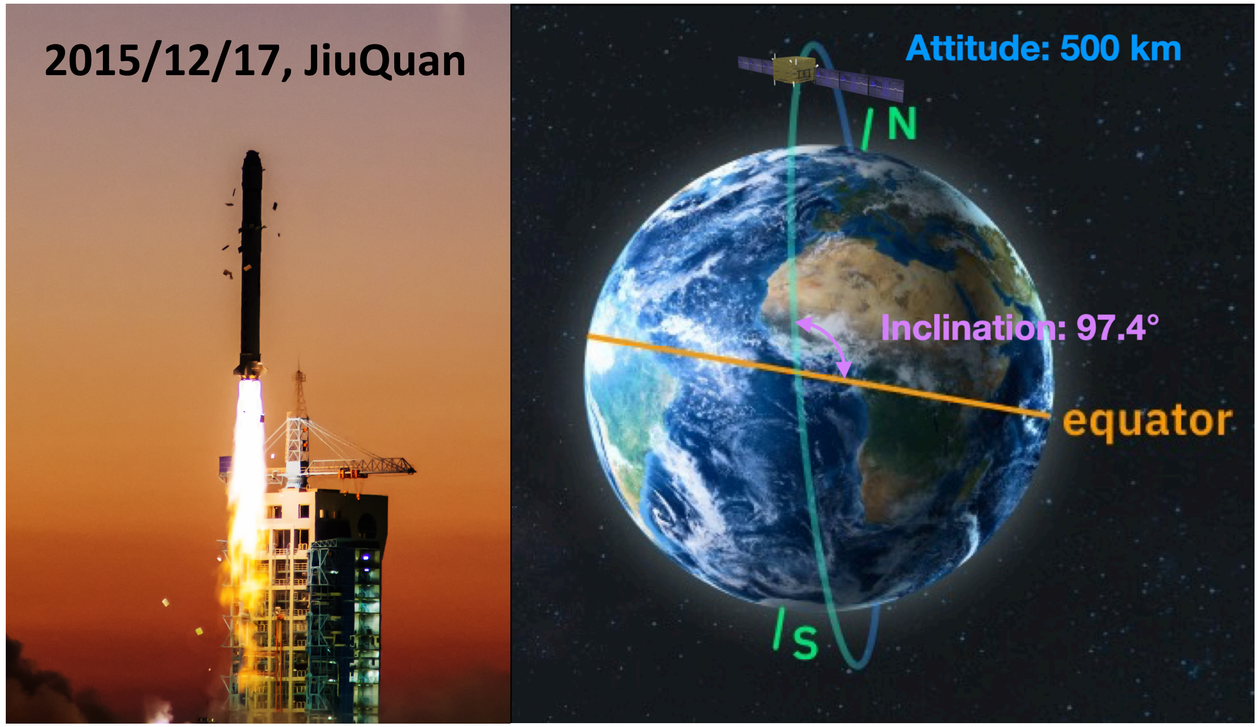
Motivation

- CR nuclei
  - **Primary components** (p, He, C, O, …, Fe, …) : Studying the **origin and acceleration of cosmic rays**
  - **Secondary components** (Li, Be, B, …) : Studying the **propagation of cosmic rays**
  - **Elements beyond Iron** (Ni, Zn, …): Studying the **the origin of elements beyond ion**



DAMPE Mission

- **DAMPE (悟空)** 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).



CNINA
- **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**

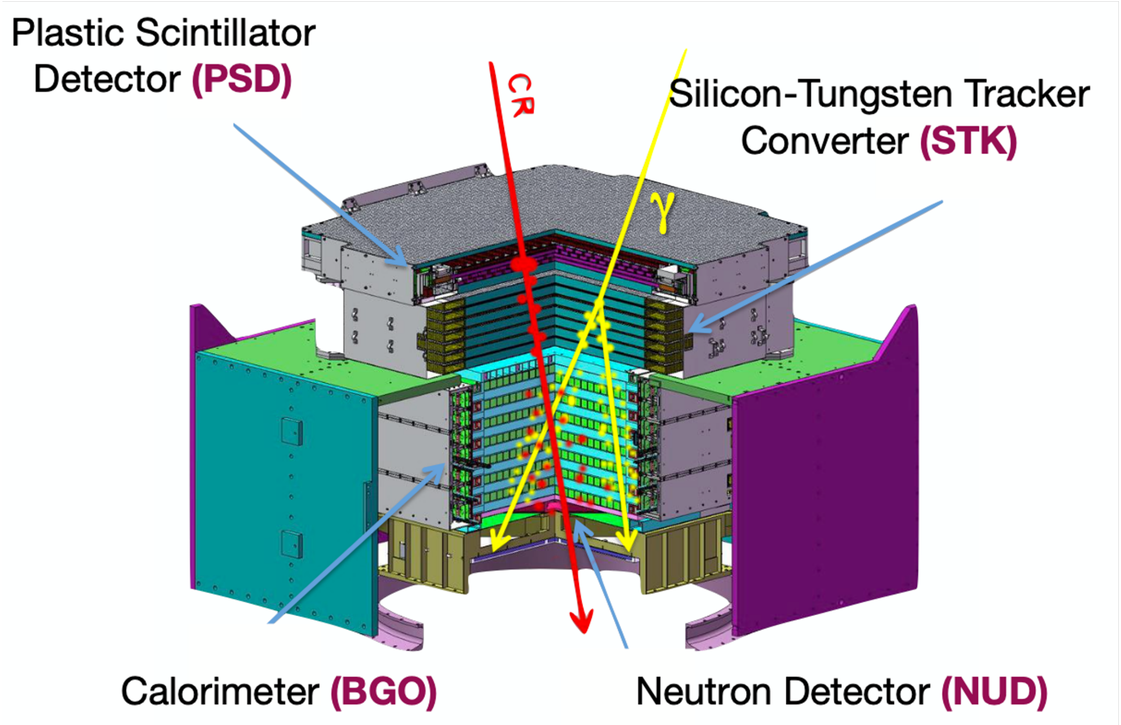
SWITZERLAND
- **University of Geneva**

DAMPE Detector

Functions of sub-detectors:

- Charge measurement (dE/dx in PSD, STK)
- Tracking and Gamma-ray conversion (STK and BGO)
- Precise energy measurement (BGO)
- Electron-hadron separation (BGO and NUD)

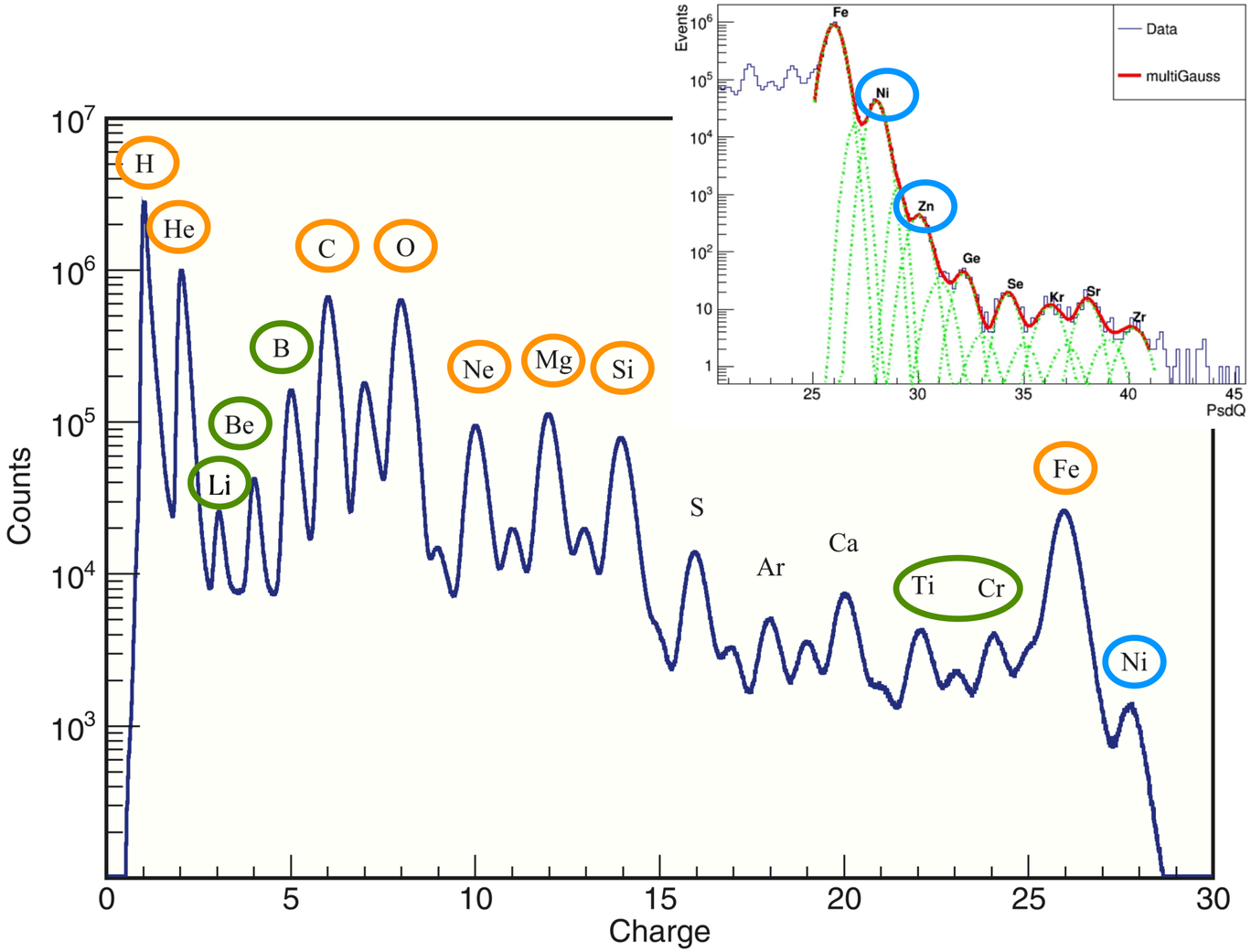
DAMPE Collab., *Astropart.Phys.* 95 (2017)



Parameter	Value
Energy range (e/γ)	5 GeV to 10 TeV
Energy resolution (e/γ)	1.5% at 800 GeV
Energy range (p/nuclei)	50 GeV to 500 TeV
Energy resolution (p)	~30% at 800 GeV
Charge resolution (p)	0.06 charge unit
Geometric factor (e)	0.3 m^2sr above 30 GeV
Angular resolution (γ)	0.1 degree at 100 GeV

CR Proton & Nuclei Measurement with DAMPE

DAMPE Charge Distribution



Primary CRs:

CR origin / acceleration

- proton, Helium, p+He
- C, O, Ne, Mg, Si, Fe, …

Secondary CRs:

CR propagation

- Li, Be, B, …
- Sub-Iron

Elements beyond Iron:

- Ni, Zn, …

All particle spectrum

Flux Measurement

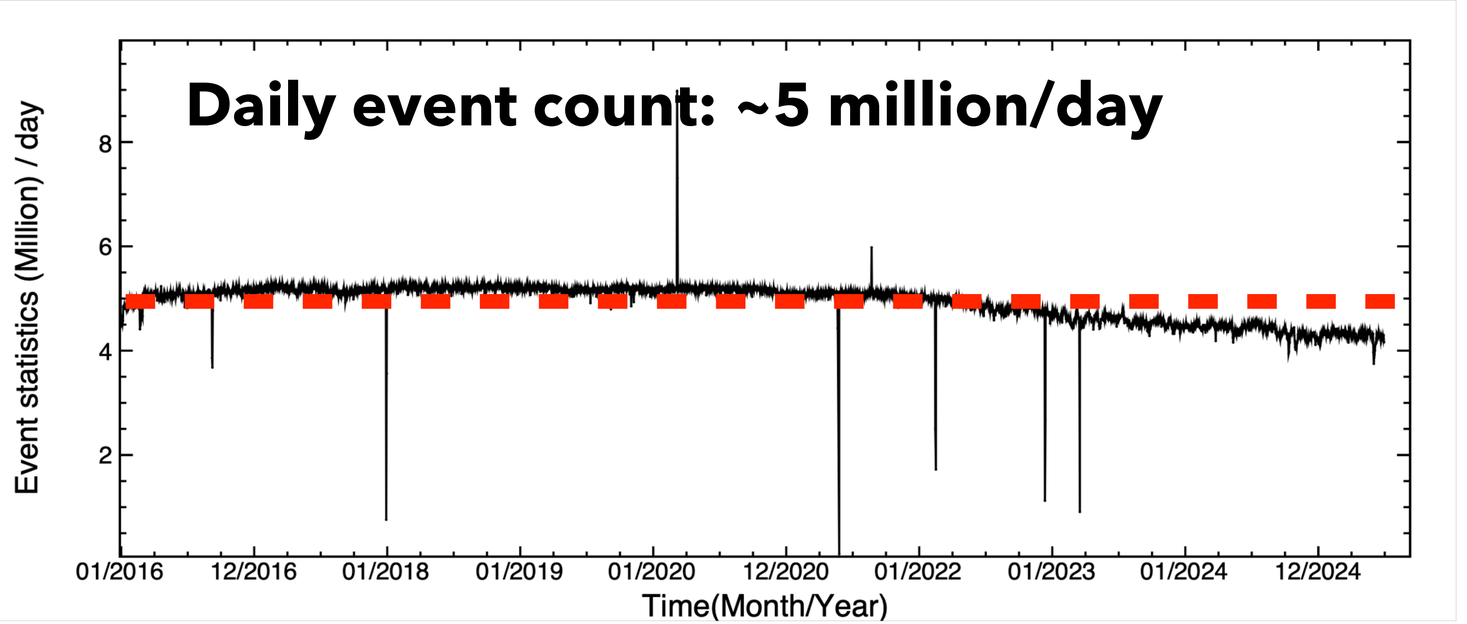
- Flux in i-th incident energy bin:

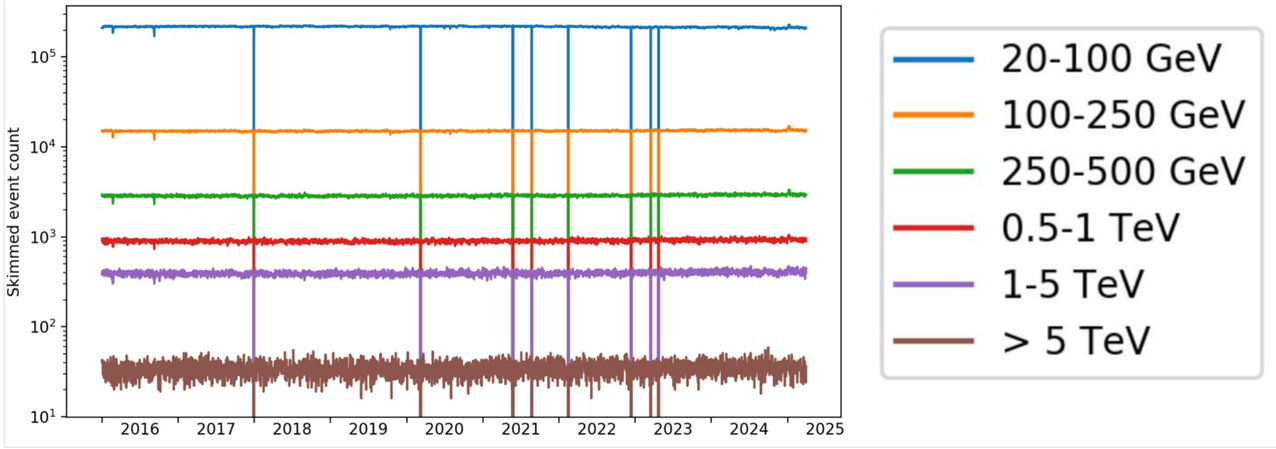
$$\Phi(E_i, E_i + \Delta E) = \frac{N_{obs}(E_i, E_i + \Delta E)}{A_{eff,i} T_{exp} \Delta E_i}$$

  - Φ : Absolute differential flux ($m^{-2}sr^{-1}GeV^{-1}s^{-1}$)
  - N_{obs} : Number of observed events
  - $A_{eff,i}$: Effective acceptance (m^2sr), $A_{eff} = \varepsilon_{trig}\varepsilon_{sel1} \cdots \varepsilon_{selN} A_{geo}$
  - T_{exp} : Exposure time (s)
  - ΔE_i : Width of energy bin (GeV)

Data Sample

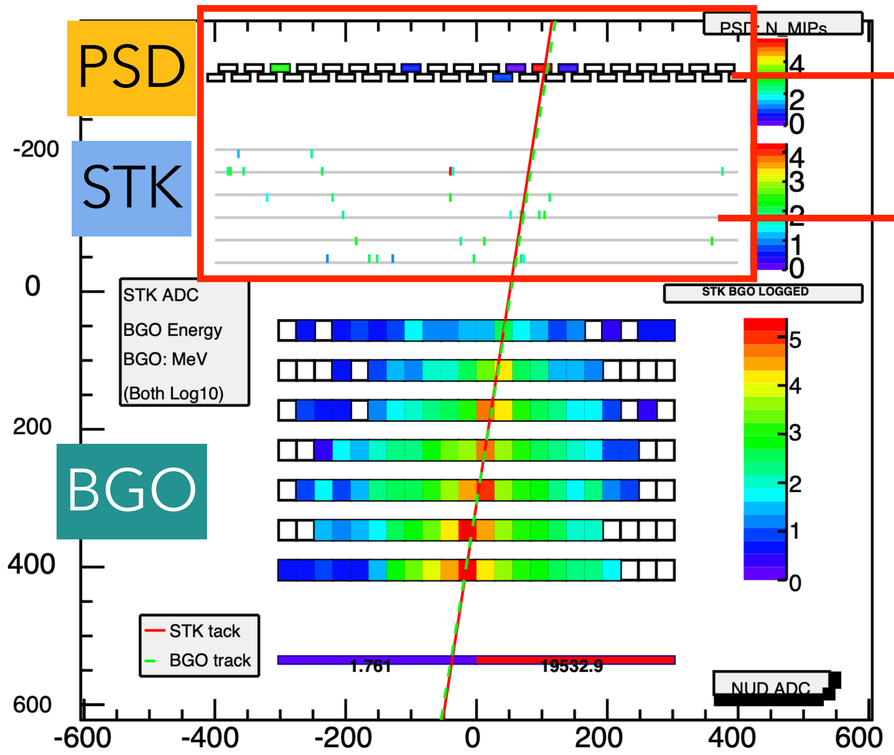
- 9 years flight data
- Data in South Atlantic Anomaly (SAA) region are excluded
- Data during Sep.2017 Solar Flare are excluded
- Detector's dead time is excluded
- T_{exp} ~2.18 × 10^8 s (~76.8% live time)

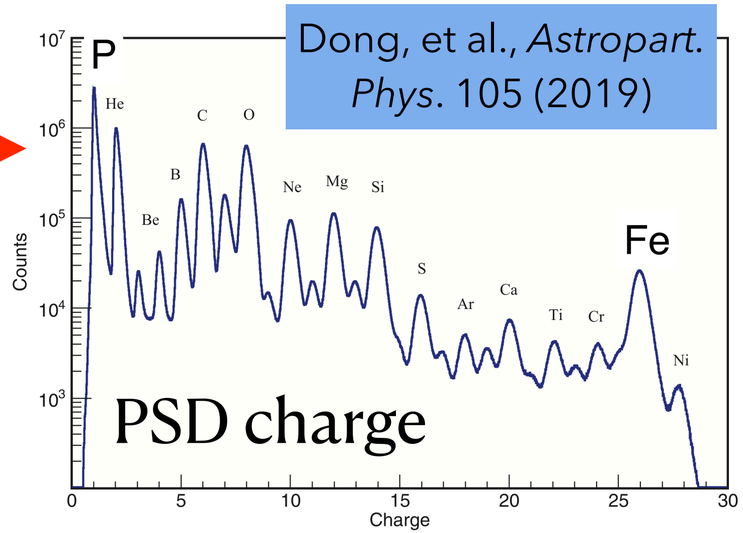




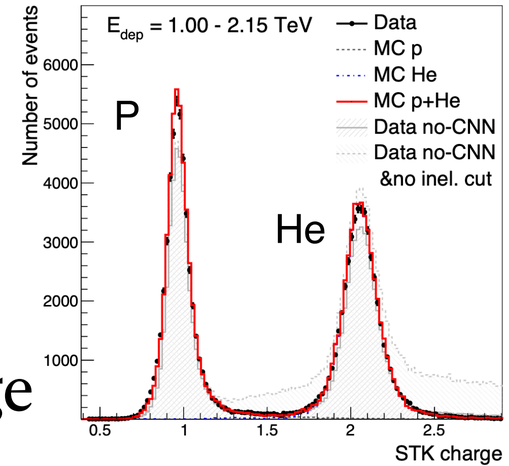
Key Point I : Charge Identification

N_{obs} : Determined by the charge ID





Dong, et al., *Astropart. Phys*. 105 (2019)



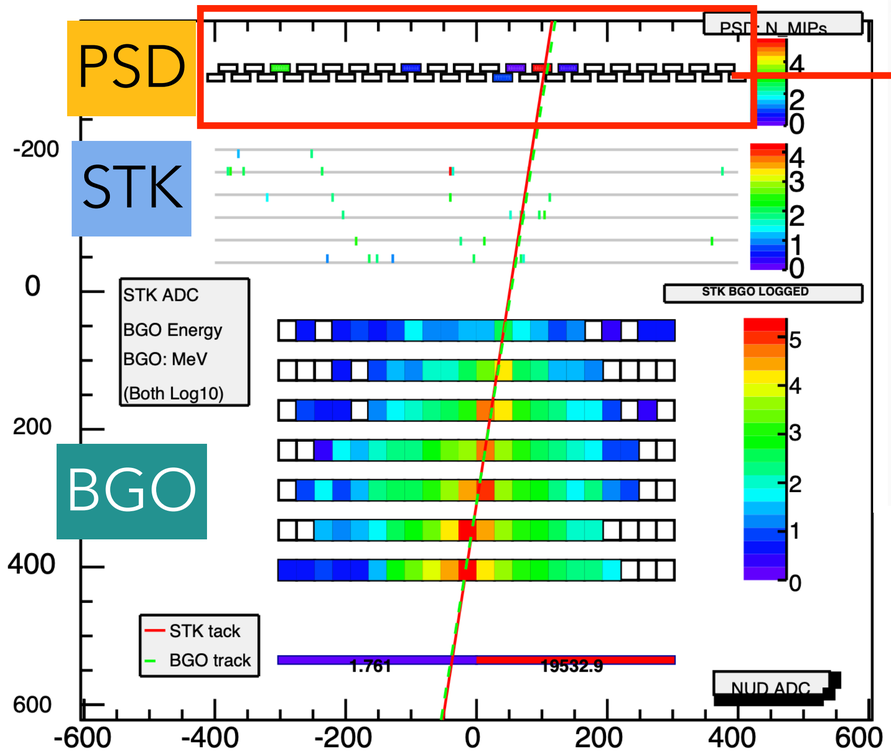
STK charge

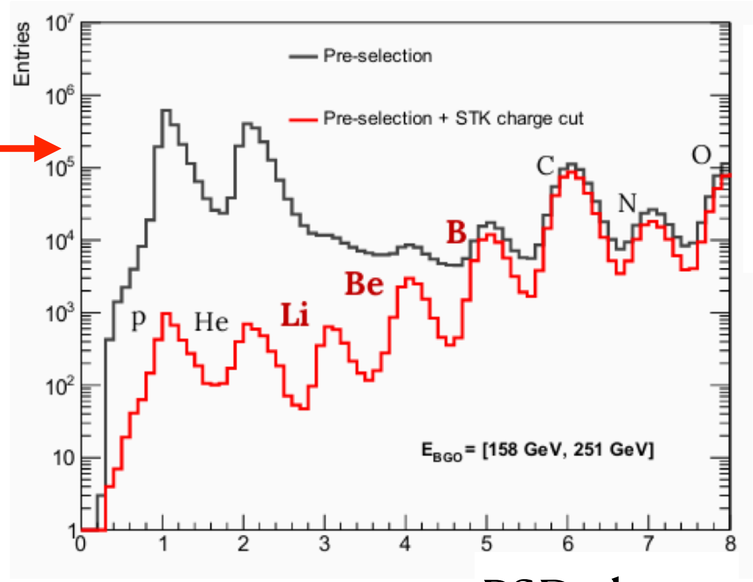
- **For P & He:** both PSD and STK provide charge measurement

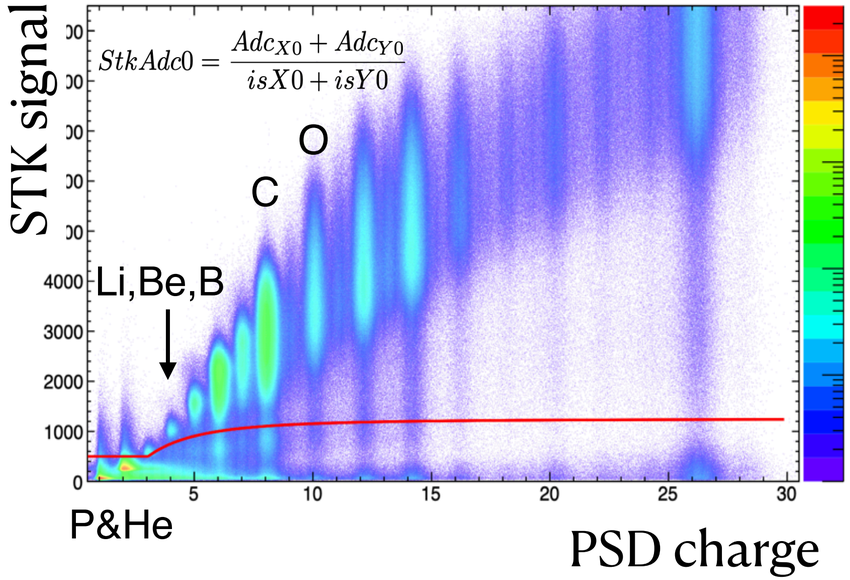
	PSD charge resolution (Charge unit, c.u.)	STK charge resolution (Charge unit, c.u.)
Proton	0.06	0.04
Helium	0.10	0.07

Key Point I : Charge Identification

N_{obs} : Determined by the charge ID



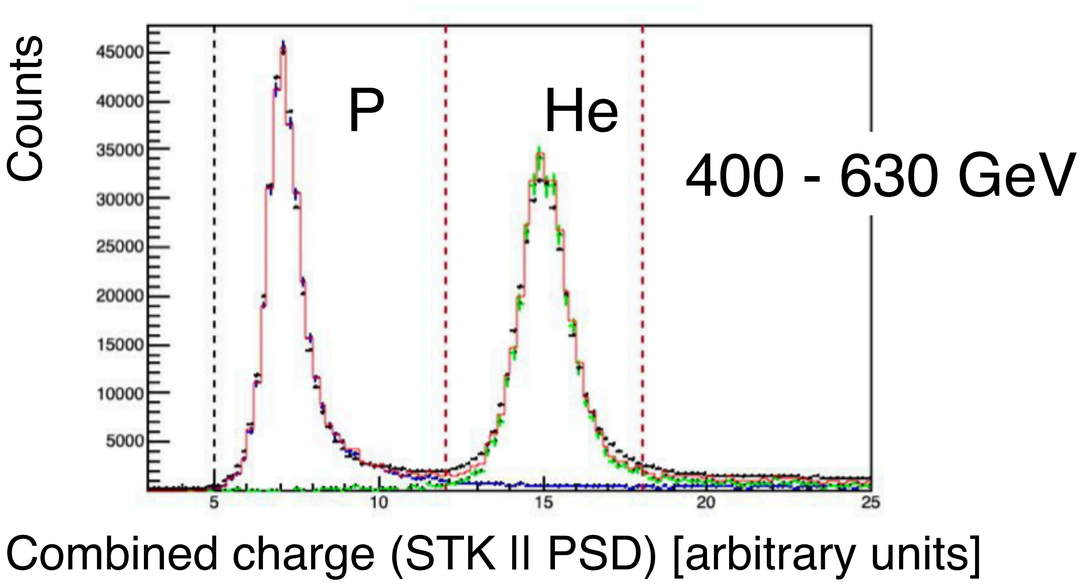


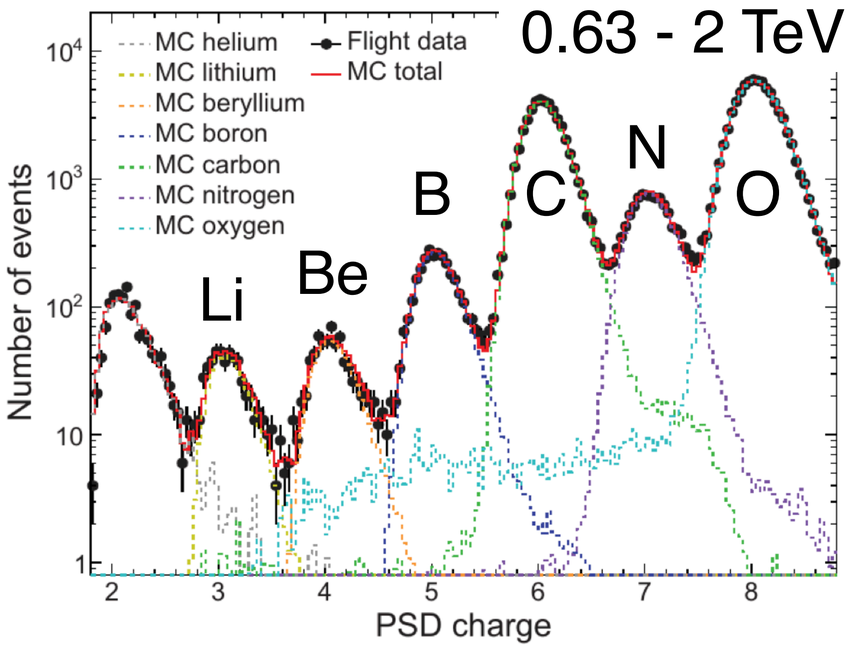


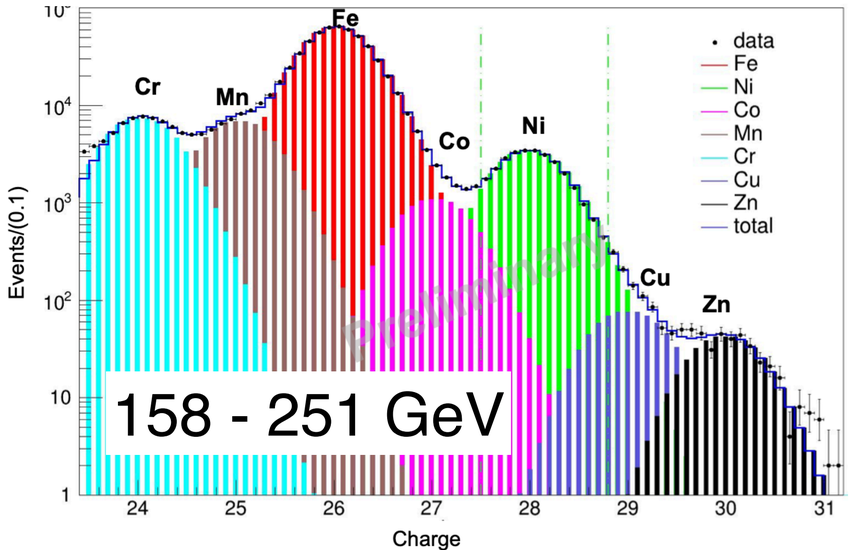
- **For Li and heavier nuclei:**
  - PSD serves as the main charge detector
  - P & He background is suppressed by the STK

Key Point I : Charge Identification

- N_{obs} : Number of events falling within the charge signal range
- Charge selection efficiency and contamination are determined by the template fit.

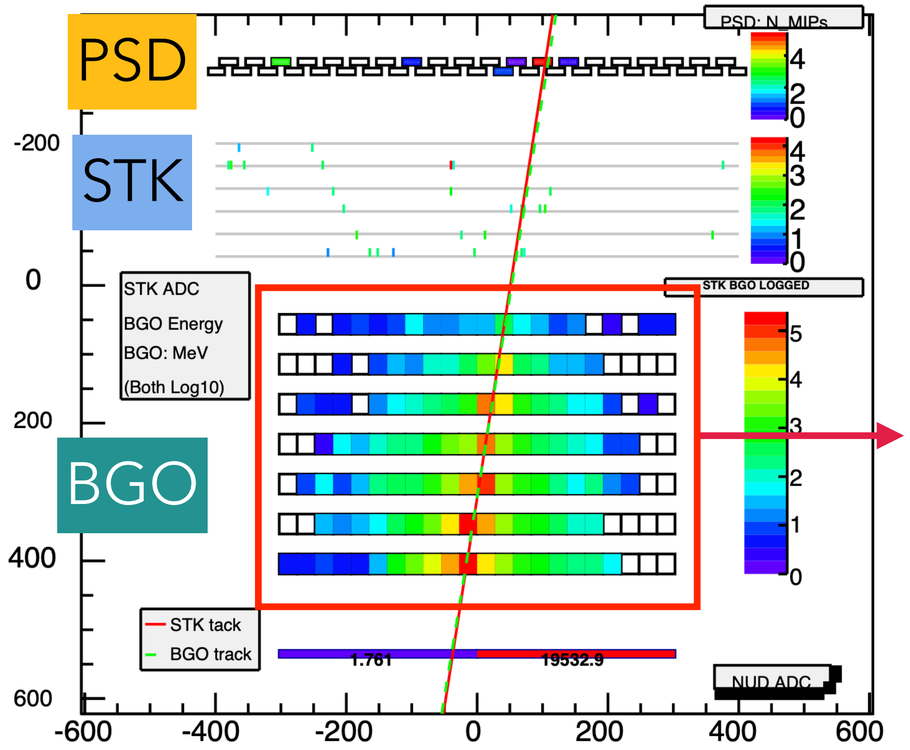




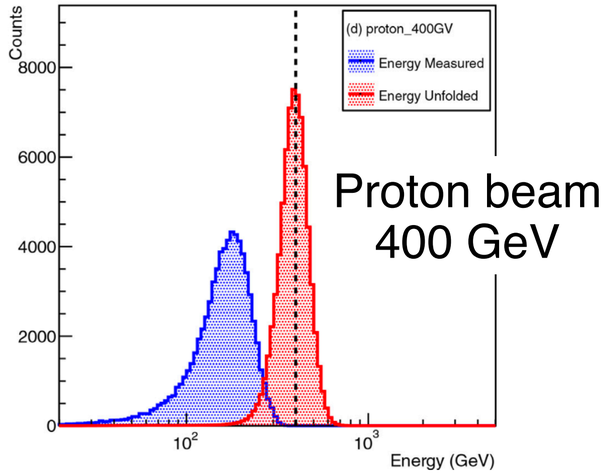


Key Point II : Energy Measurement

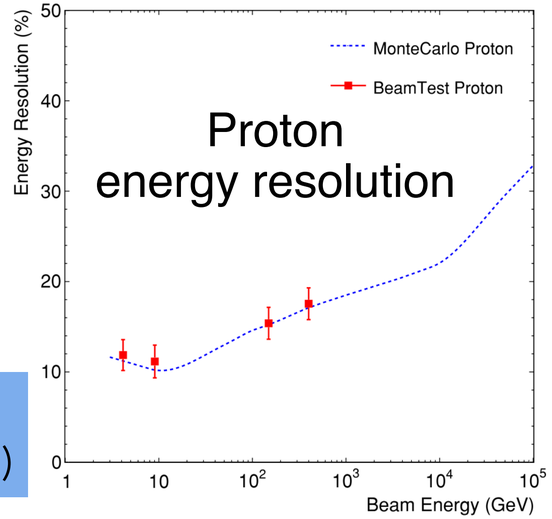
E : Measured by the calorimeter



DAMPE Collab.,
Astropart.Phys. 95 (2017)

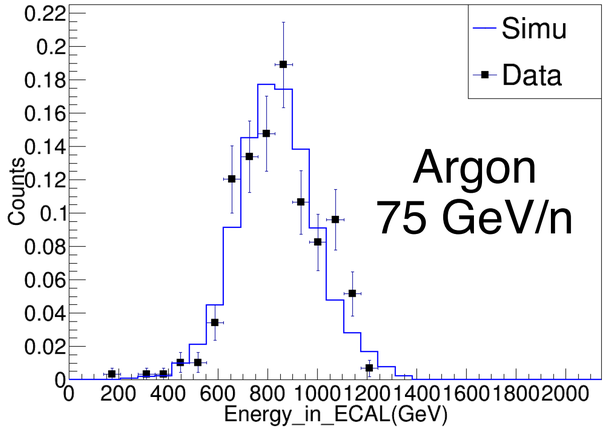


Proton beam
400 GeV

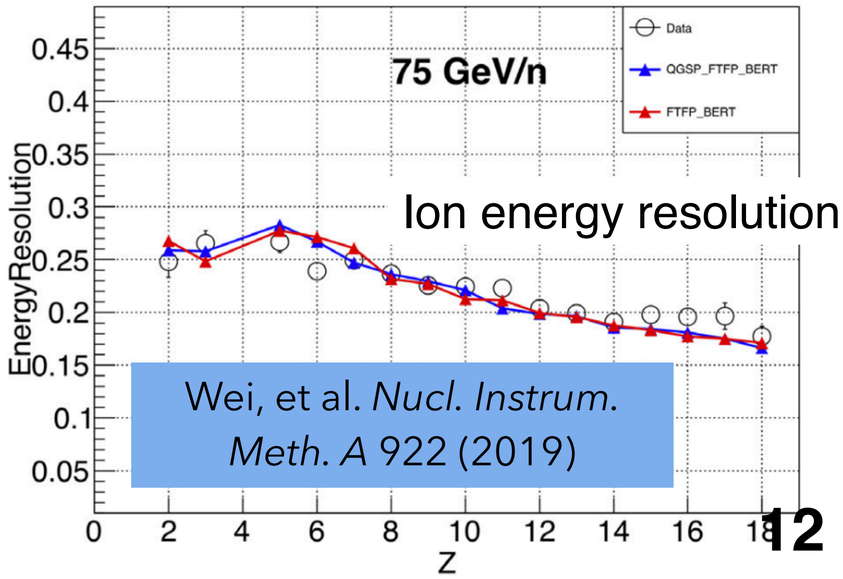


Proton
energy resolution

Ion beam:



Argon
75 GeV/n



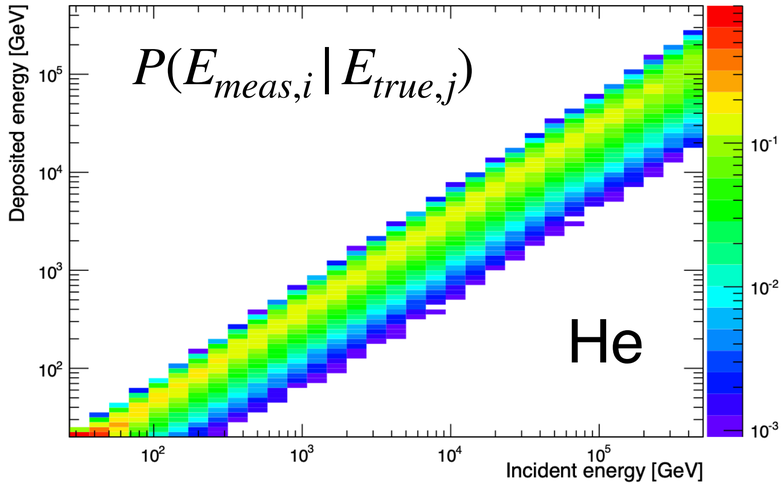
Ion energy resolution

Wei, et al. *Nucl. Instrum. Meth. A* 922 (2019)

Key Point II : Energy Measurement

- Bayesian unfolding method is used to obtain event counts as a function of CR kinetic energy

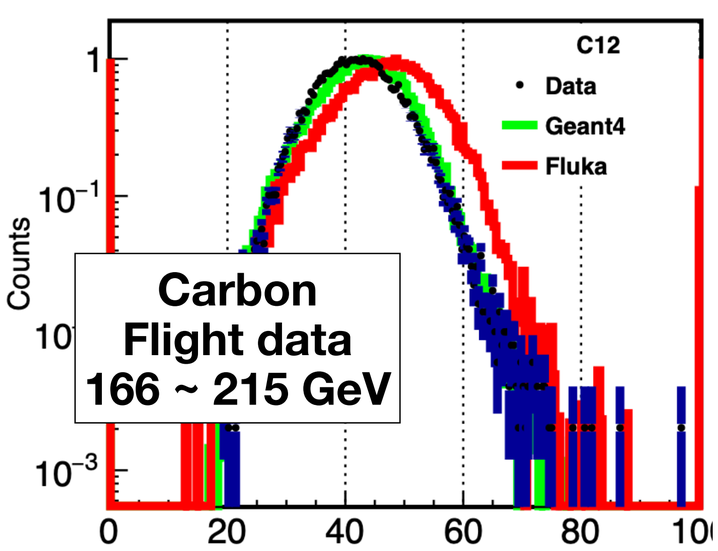
$$P(E_{true,j}\,|\,E_{meas,i}) = \frac{P(E_{meas,i}\,|\,E_{true,j})P(E_{true,j})}{\Sigma_k P(E_{meas,i}\,|\,E_{true,k})P(E_{true,k})}$$

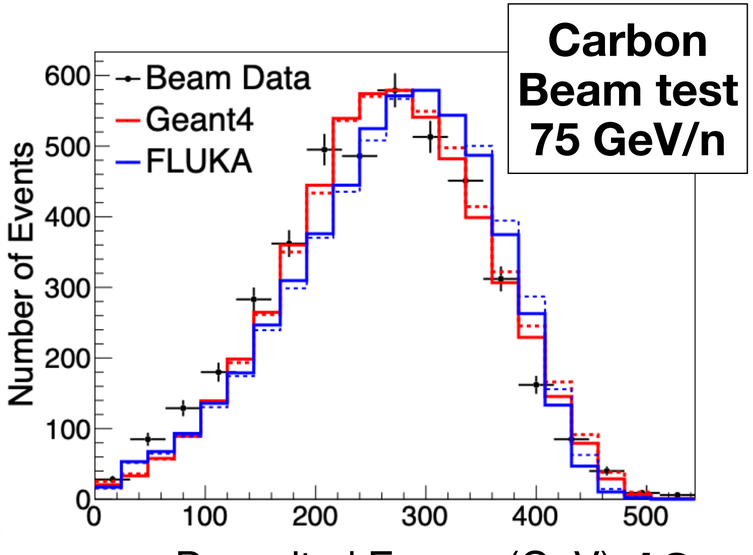


Probability matrix

(MC simulation)

- Baseline simulation: GEANT4
  - FTFP_BERT model
  - EPOS-LHC (> 100 TeV)
- FLUKA (DPMJET III) is used for comparison





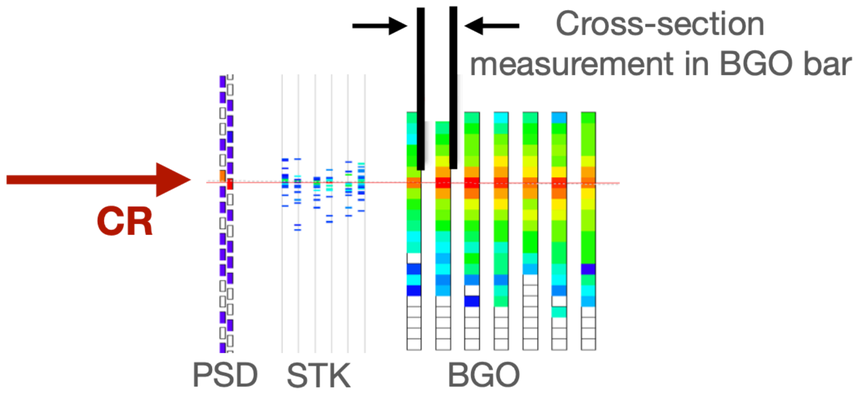
Key Point II : Energy Measurement

- Measure and validate hadronic cross sections for p, He, C, and O up to 10 TeV

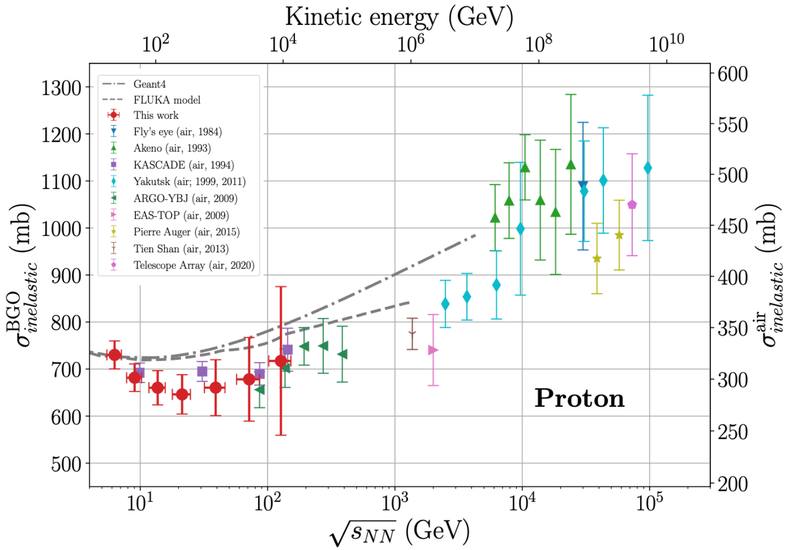
A beam-target experiment

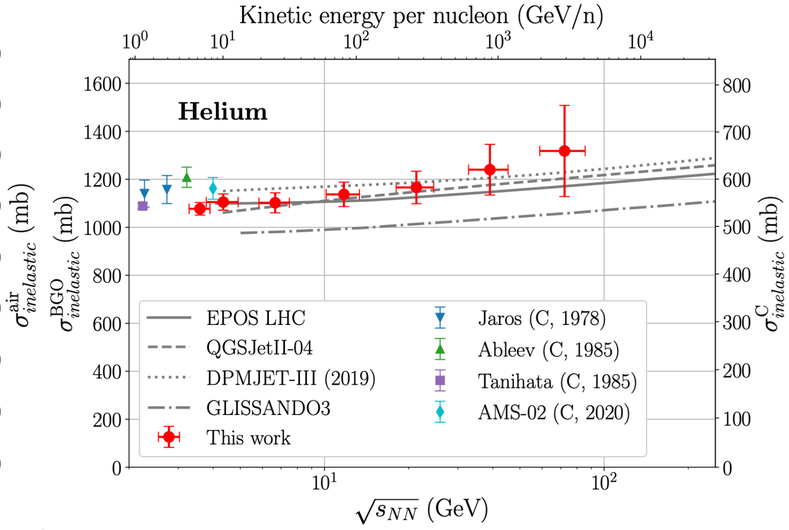
Beam: CR nuclei

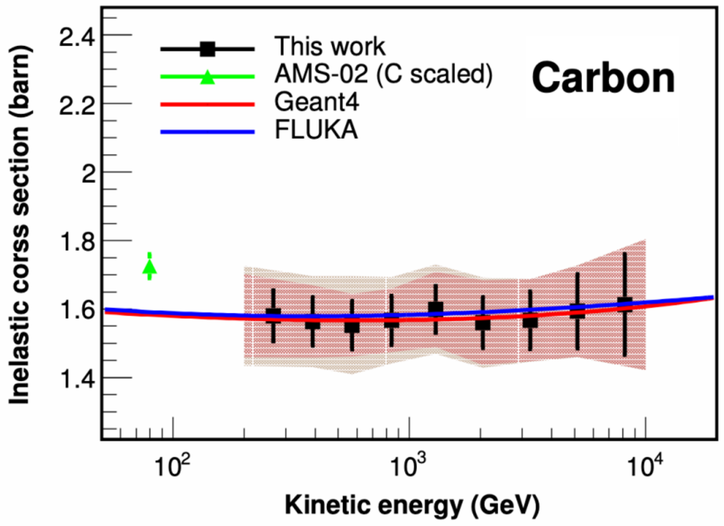
Target: BGO ($Bi_4Ge_3O_{12}$)

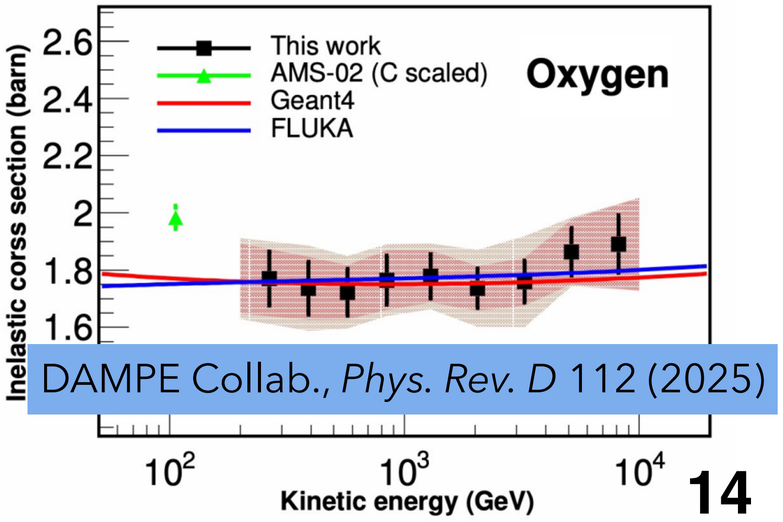


DAMPE Collab., *Phys. Rev. D* 111 (2025)









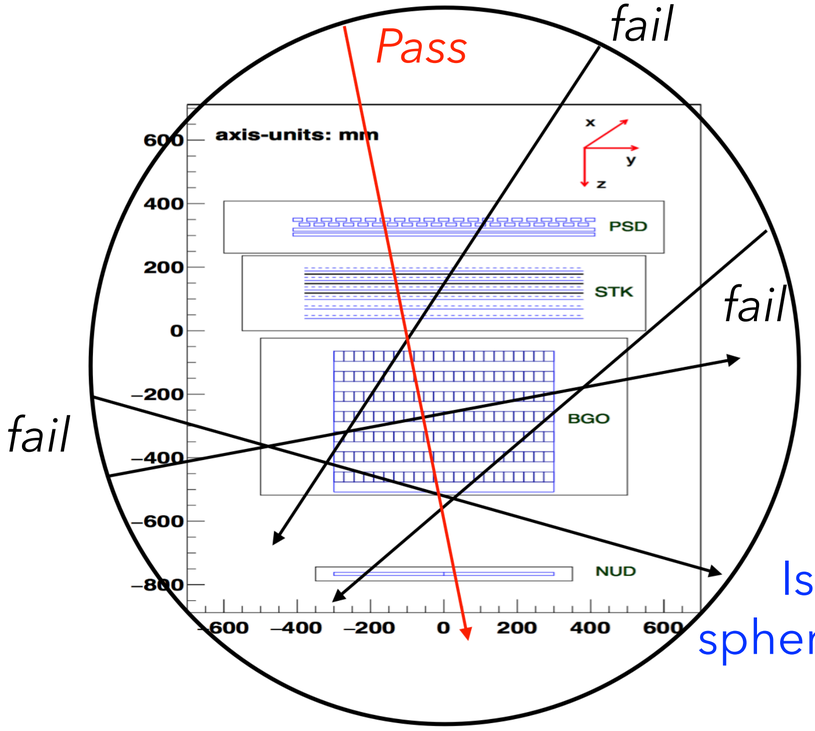
DAMPE Collab., *Phys. Rev. D* 112 (2025)

Acceptance

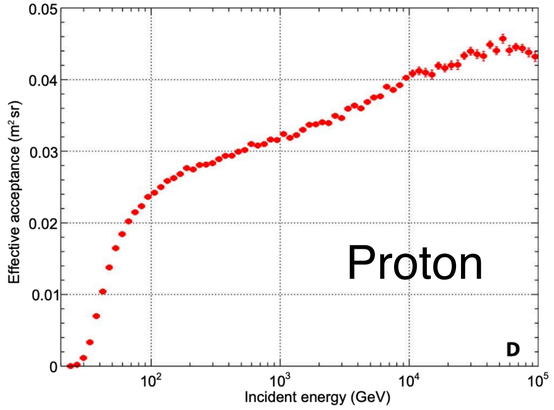
$$\Phi(E_i, E_i + \Delta E) = \frac{N_{obs}(E_i, E_i + \Delta E)}{A_{eff,i} T_{exp} \Delta E_i}$$

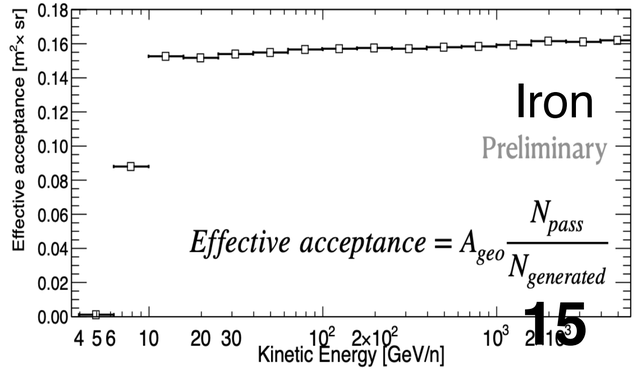
$$A_{eff,i} = A_{gen} \times \frac{N_{pass,i}}{N_{gen,i}}$$

- A_{gen} : the geometrical factor of the MC generation, for a sphere source $A_{gen} = 4\pi^2 r^2$
- N_{gen} : the numbers of generated events
- N_{pass} : the numbers of events passing all selections



Isotropic spherical source

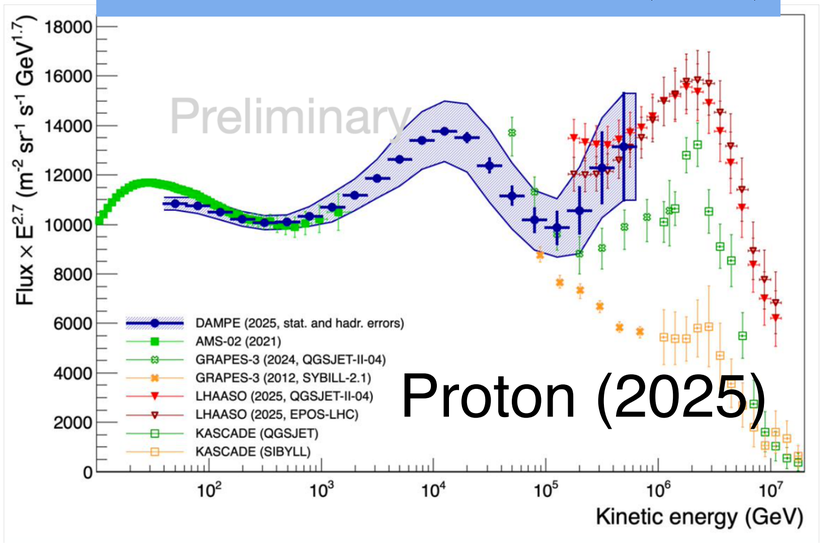


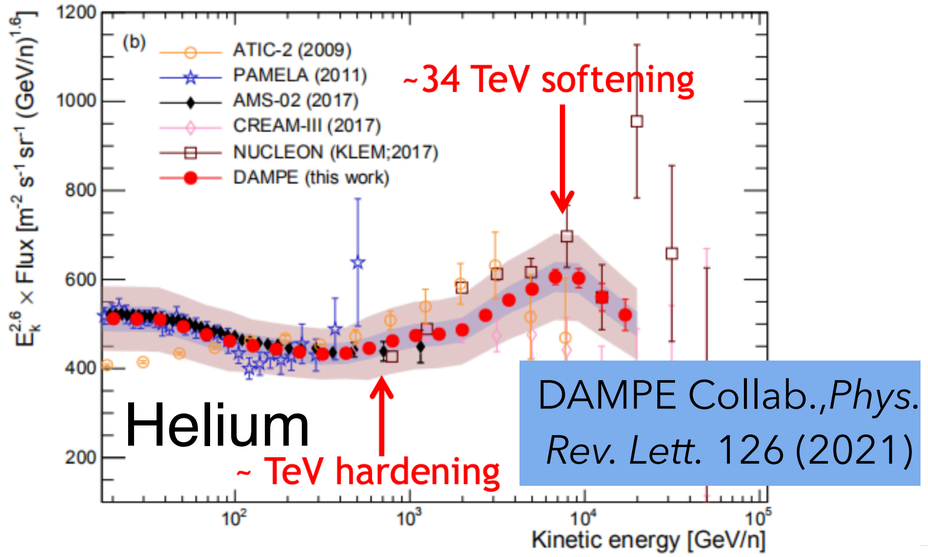


Physical Results

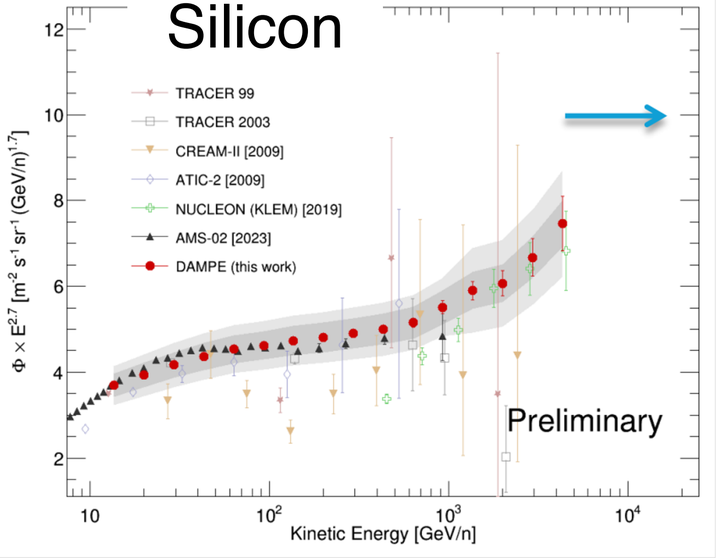
Primary CRs

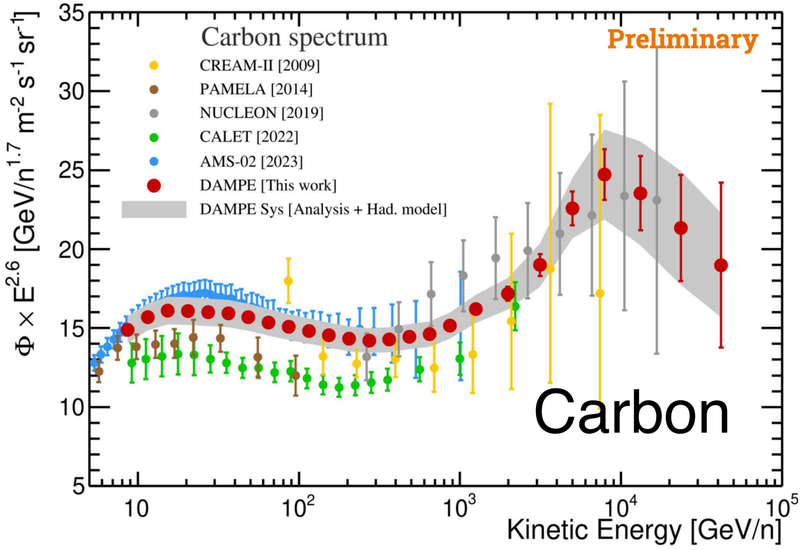
DAMPE Collab., *Sci. Adv.* 5.9 (2019)

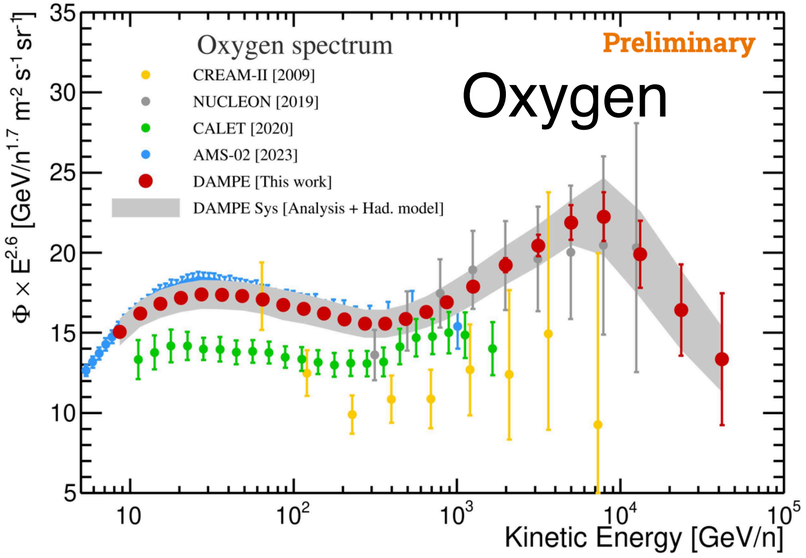


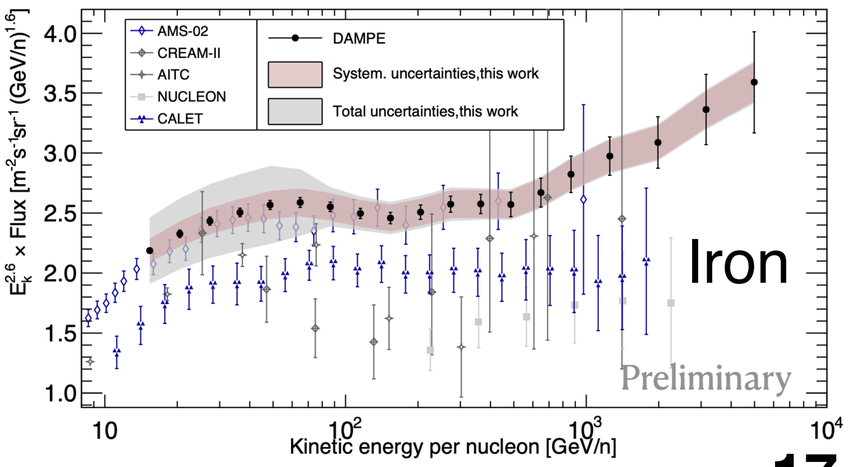


DAMPE Collab.,*Phys. Rev. Lett.* 126 (2021)



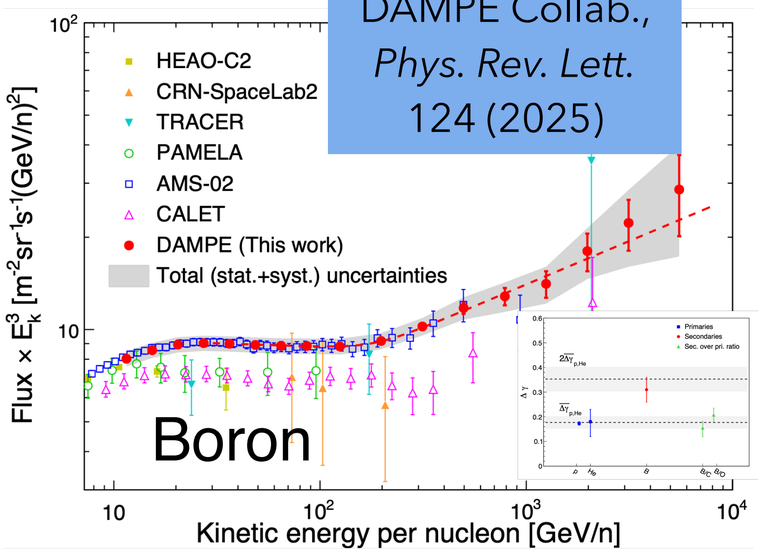


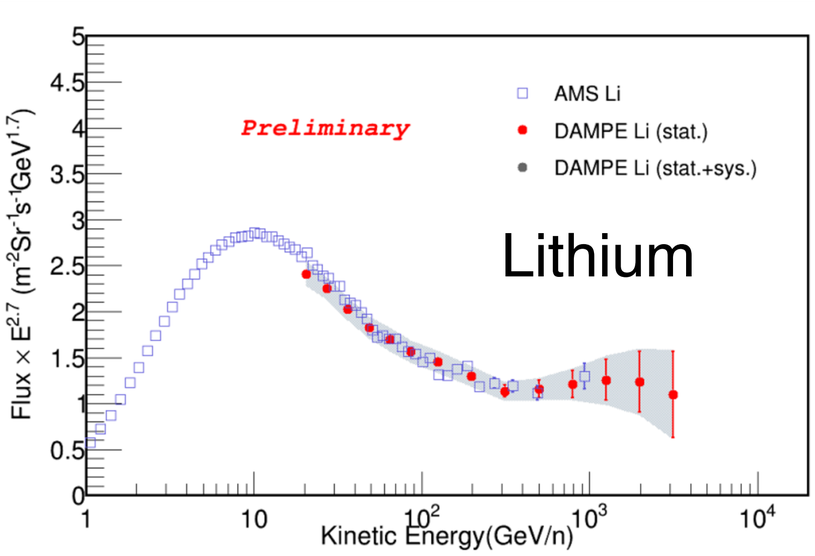


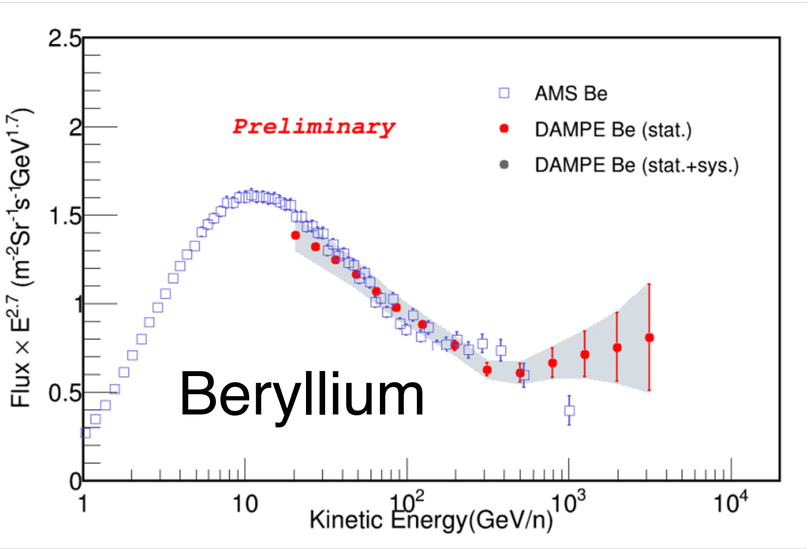


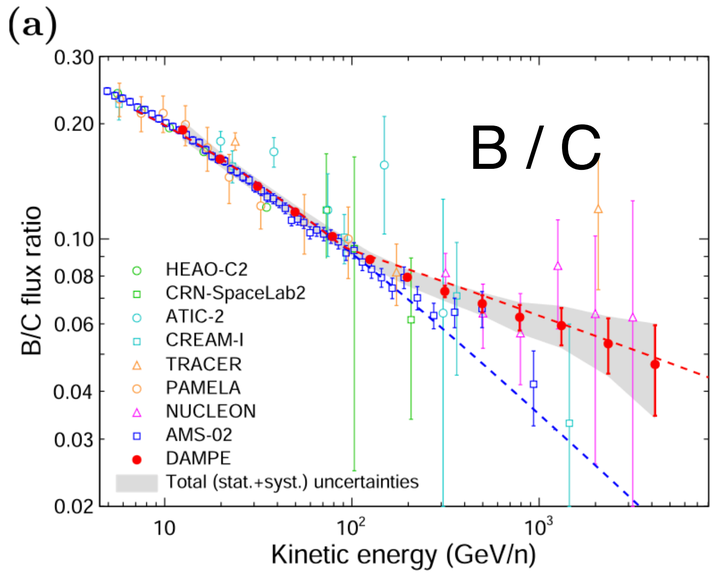
Secondary CRs & Ratios

DAMPE Collab., *Phys. Rev. Lett.* 124 (2025)

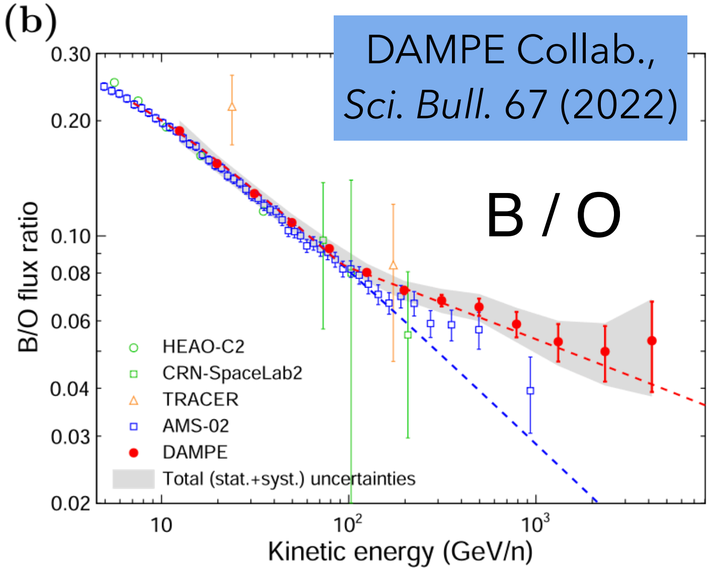


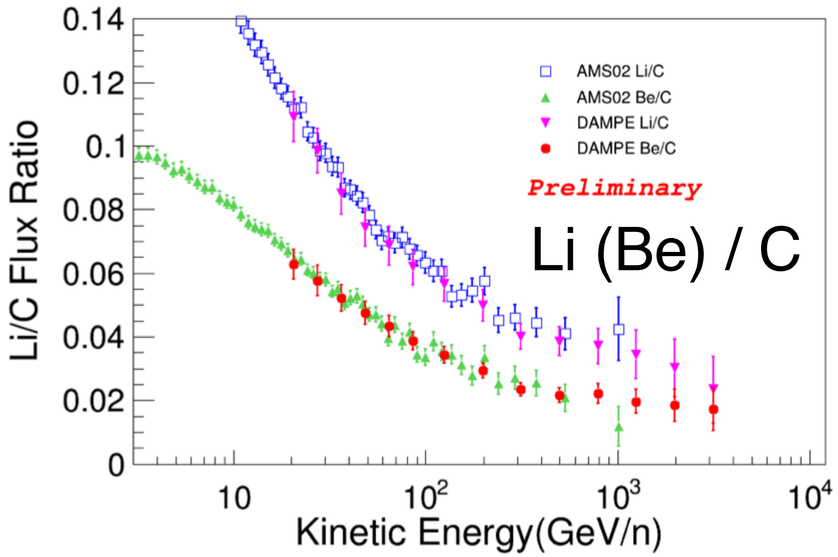




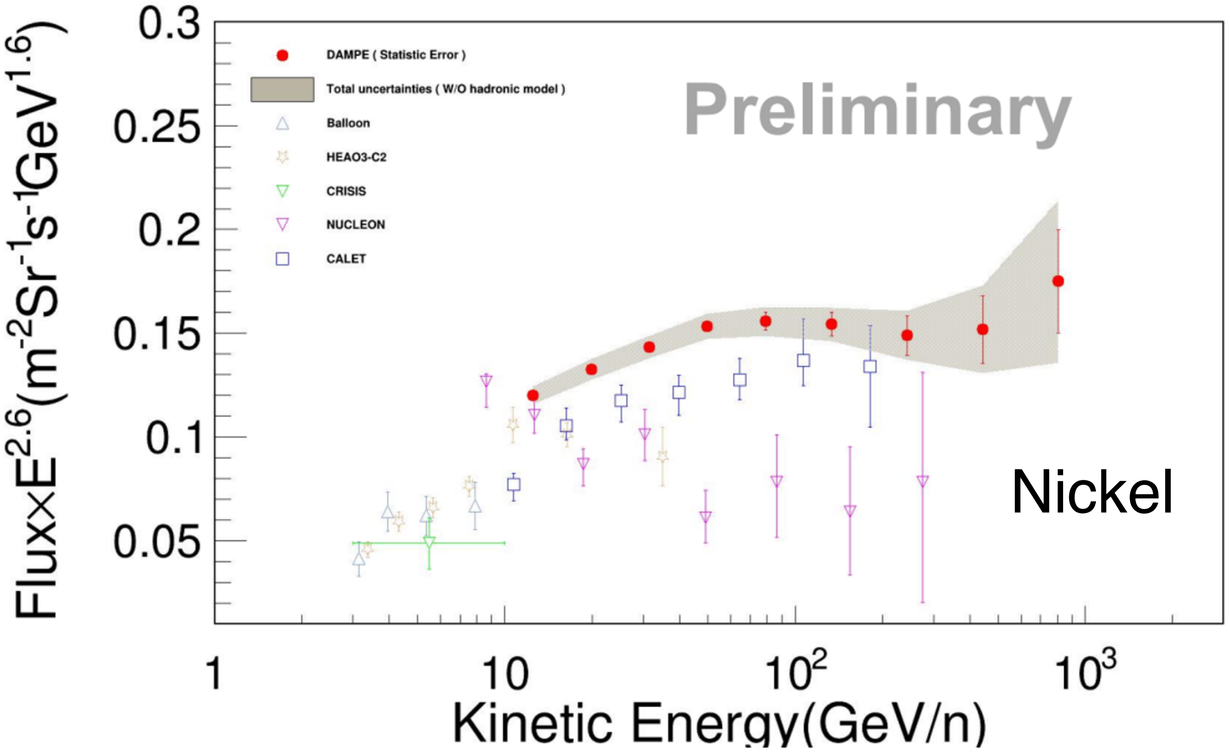


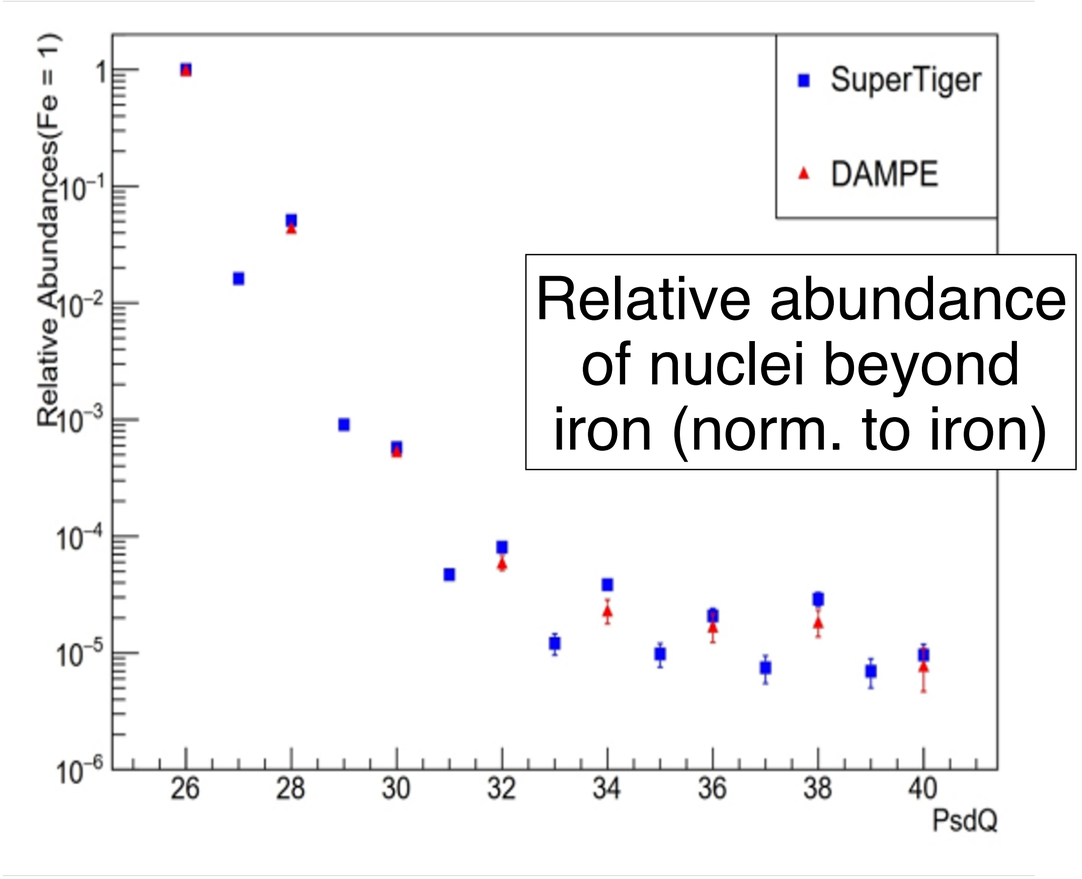
DAMPE Collab., *Sci. Bull.* 67 (2022)





Elements beyond Iron





Relative abundance of nuclei beyond iron (norm. to iron)

Summary

DAMPE Experiment

- Smooth on-orbit operation for 9.5 years
- An analysis method for cosmic-ray nuclei was presented
- Key results obtained. Ongoing analysis continues.

Physical program

- **p, He, p+He** – universal softening at ~15 TV, approaching the PeV frontier
- **C, O, CNO** – observation of hardening, evident softening at ~ 15 TV (vs. p, He)
- **Ne, Mg, Si, Fe** – observation of hardening, extending to above 10 TeV/n
- **Secondaries: Li, Be, B, B/C, B/O** – secondary hardening twice that of primaries.

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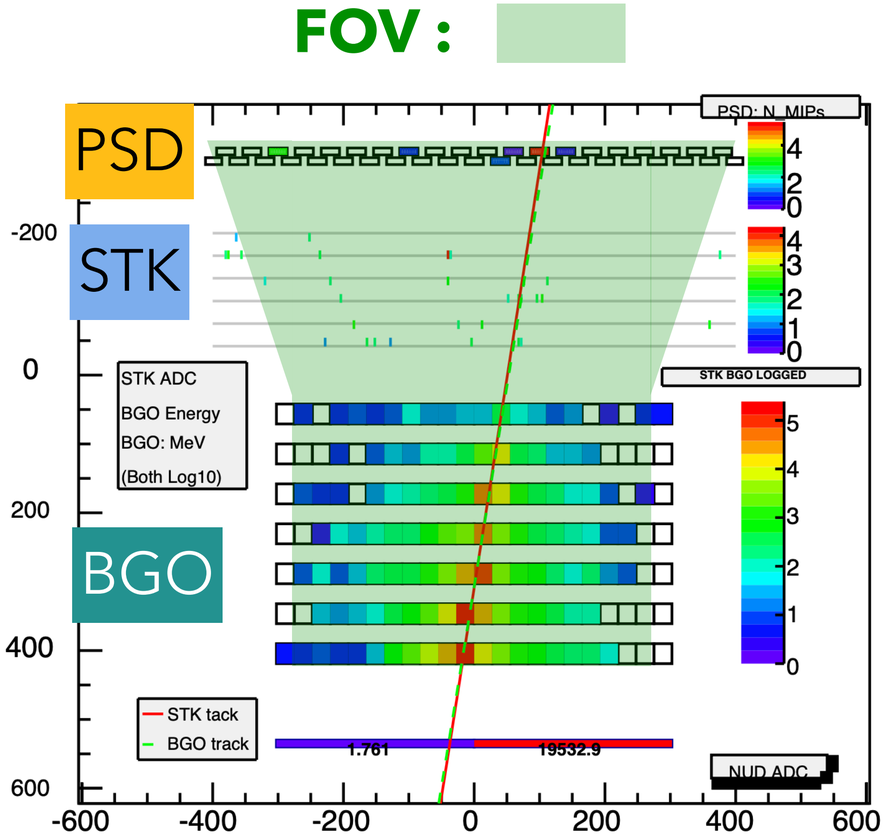
Thank you !

Backup

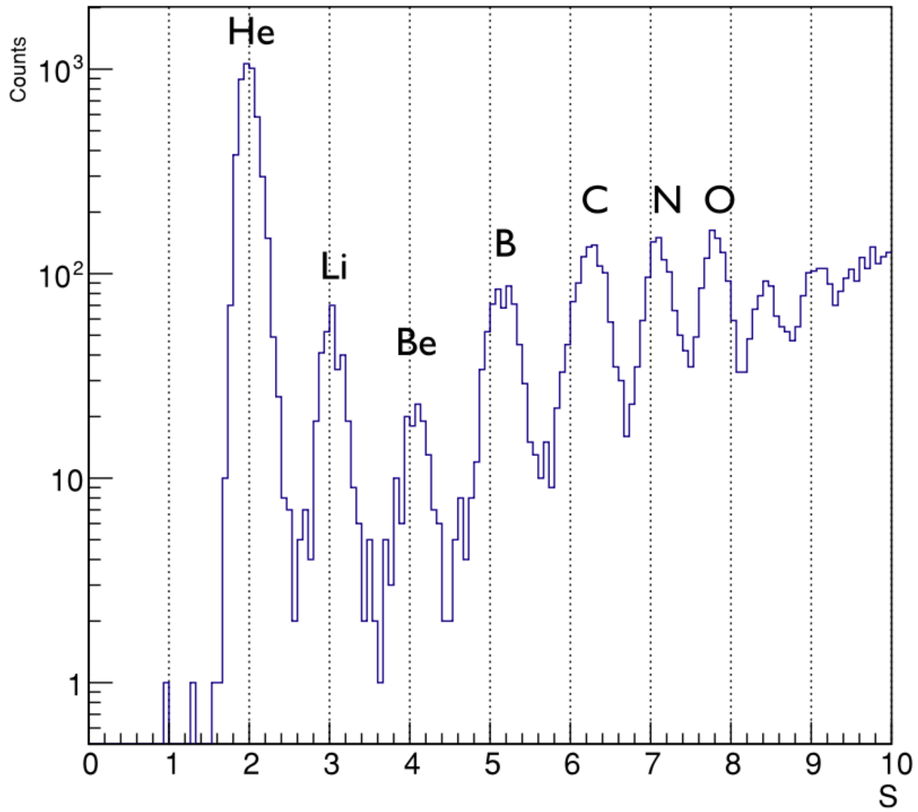
Fiducial Selection

- High energy trigger
- Select events with energy above the geomagnetic cutoff
- Select events that fall within the field of view (FOV).
  - Reliance on the reconstructed track (two methods: Kalman filter & Machine learning)

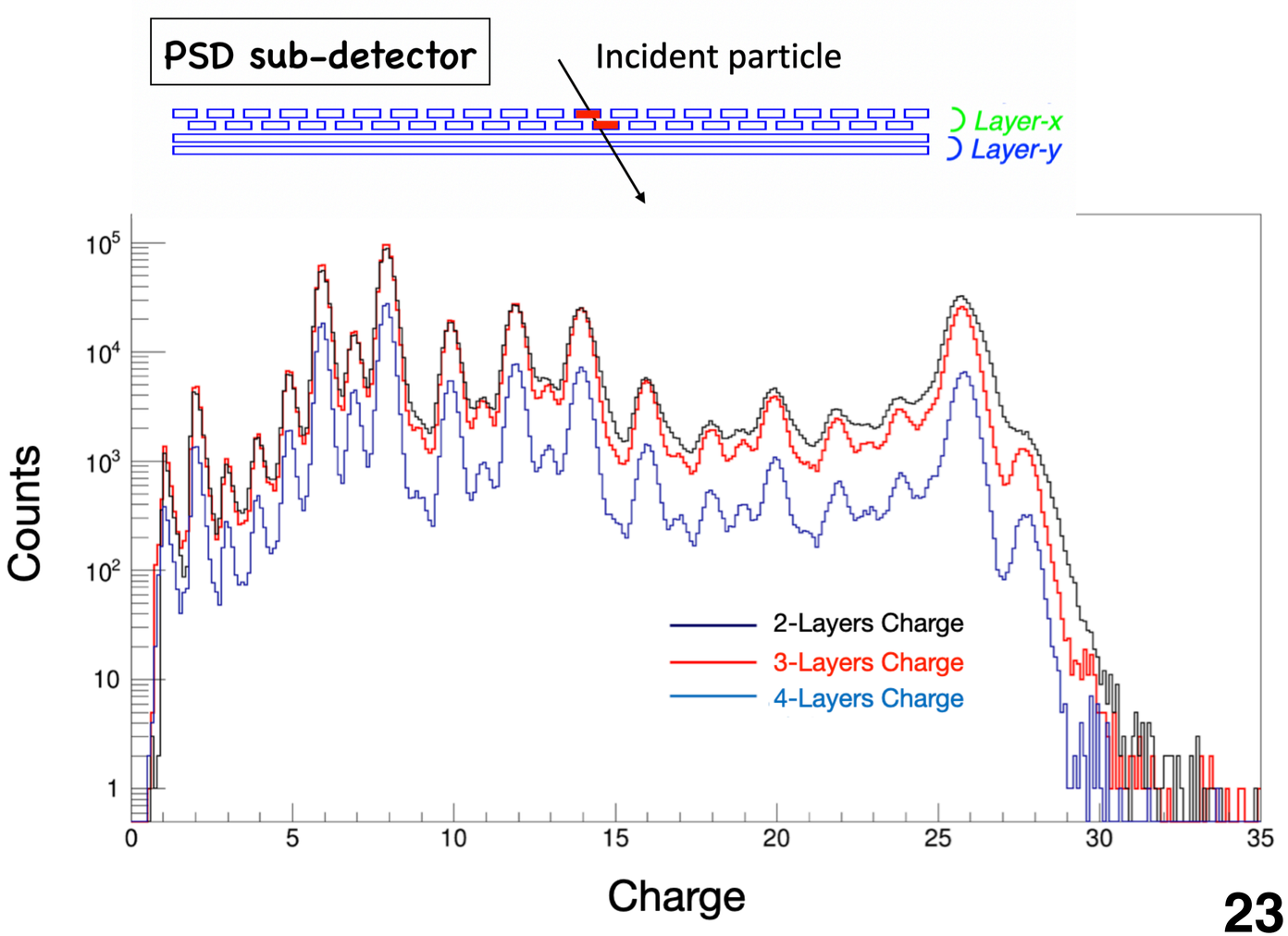


Charge Measurement

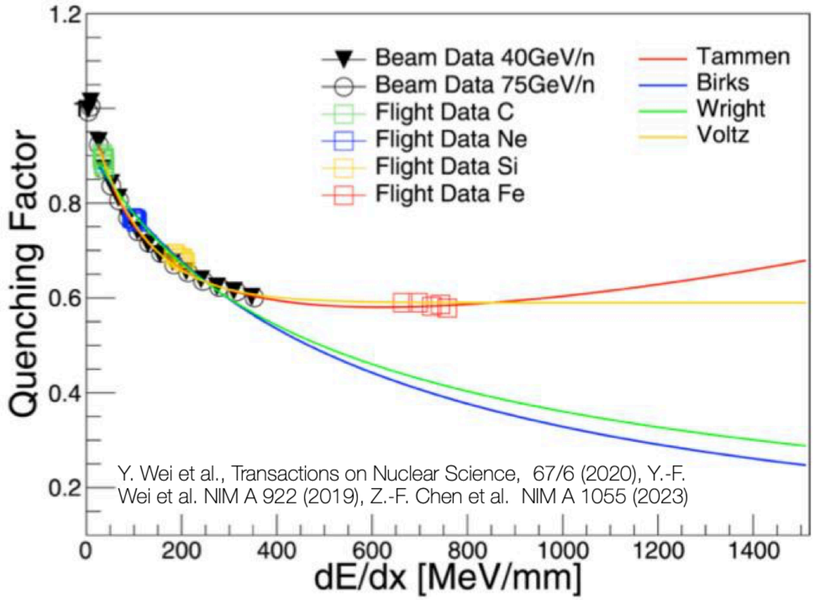
- STK beam test



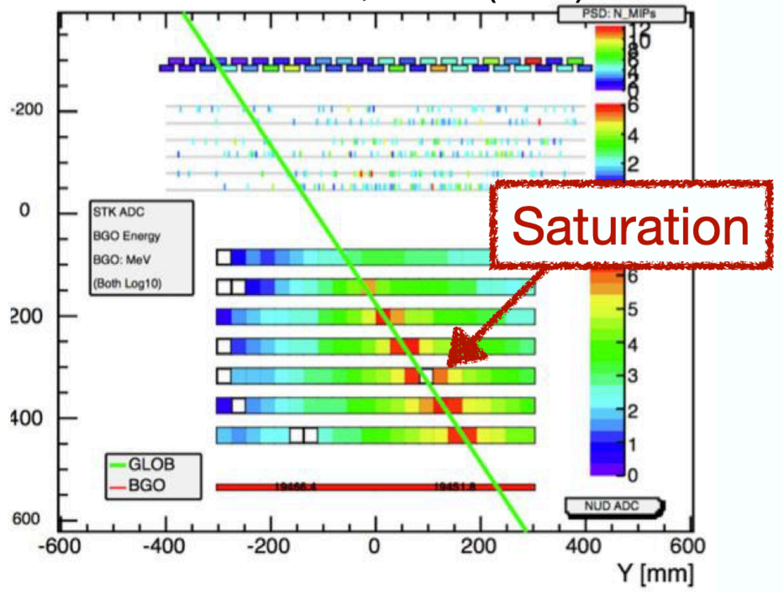
- Using multi-layer charge reconstruction



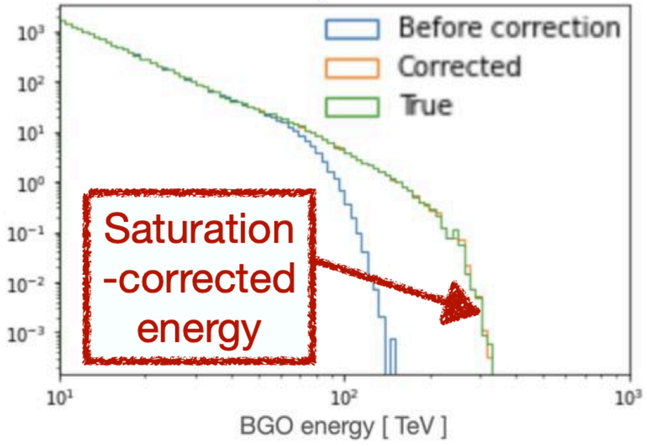
Corrections in Energy Measurement



C. Yue at al. NIM, A 984 (2020) 164645



M. Stolpovskiy et al. JINST (2022)



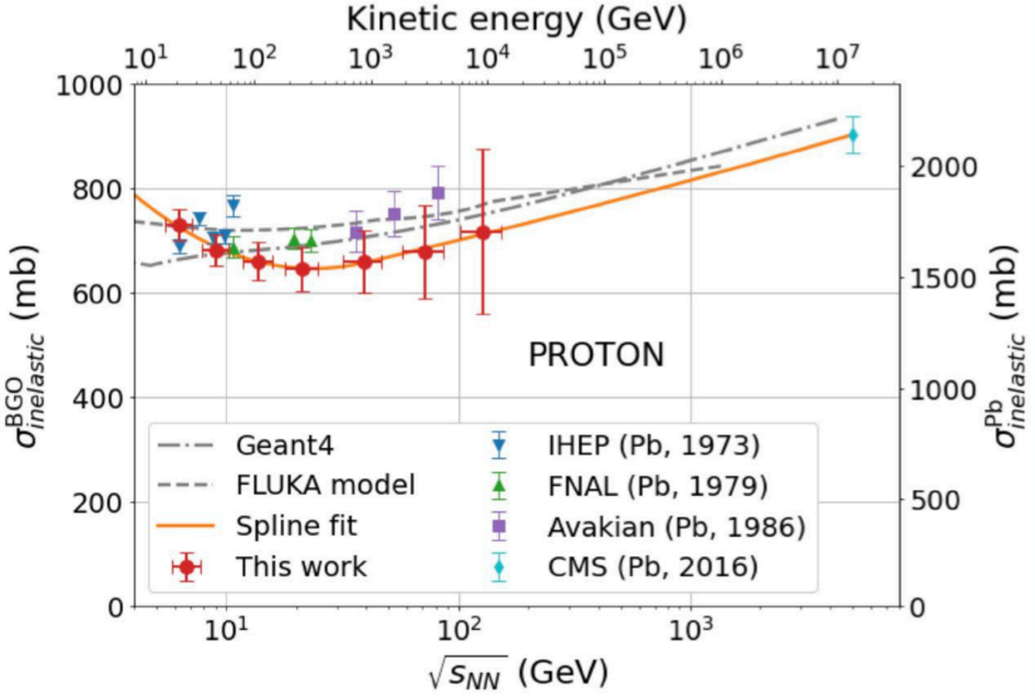
Quenching — nonlinear fluorescence response of BGO for large ionization

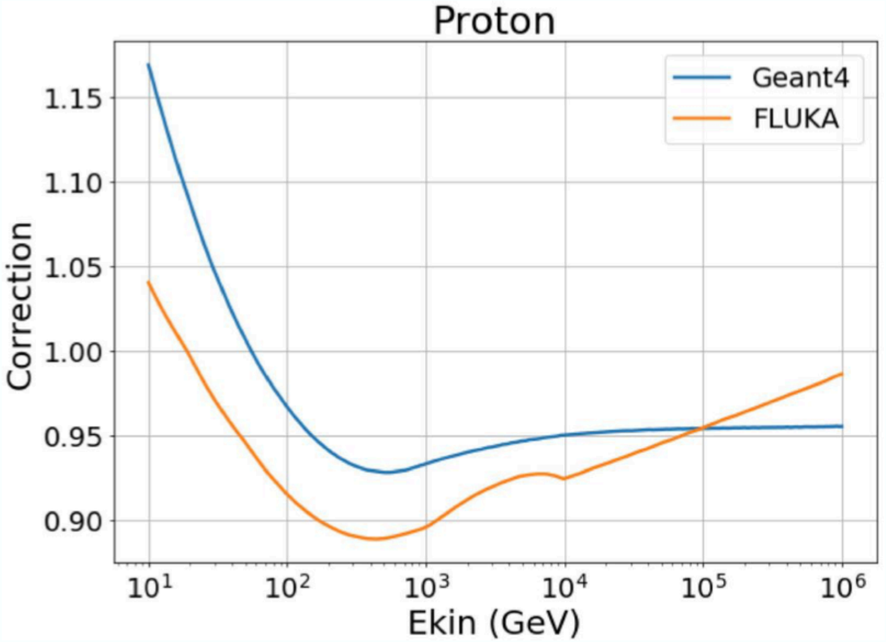
- correction derived from beam test and flight data
- implemented in the detector simulation, **~3%** effect for *p* at 10 GeV

Saturation of BGO bars at ~100 TeV CR kinetic energy:

- corrections derived using analytical and ML methods

Corrections in Energy Measurement





We use the measured DAMPE values to correct inelastic cross sections in Monte-Carlo