Measurements of Hadronic Cross Section for Proton and Nuclei in Space with the DAMPE Experiment

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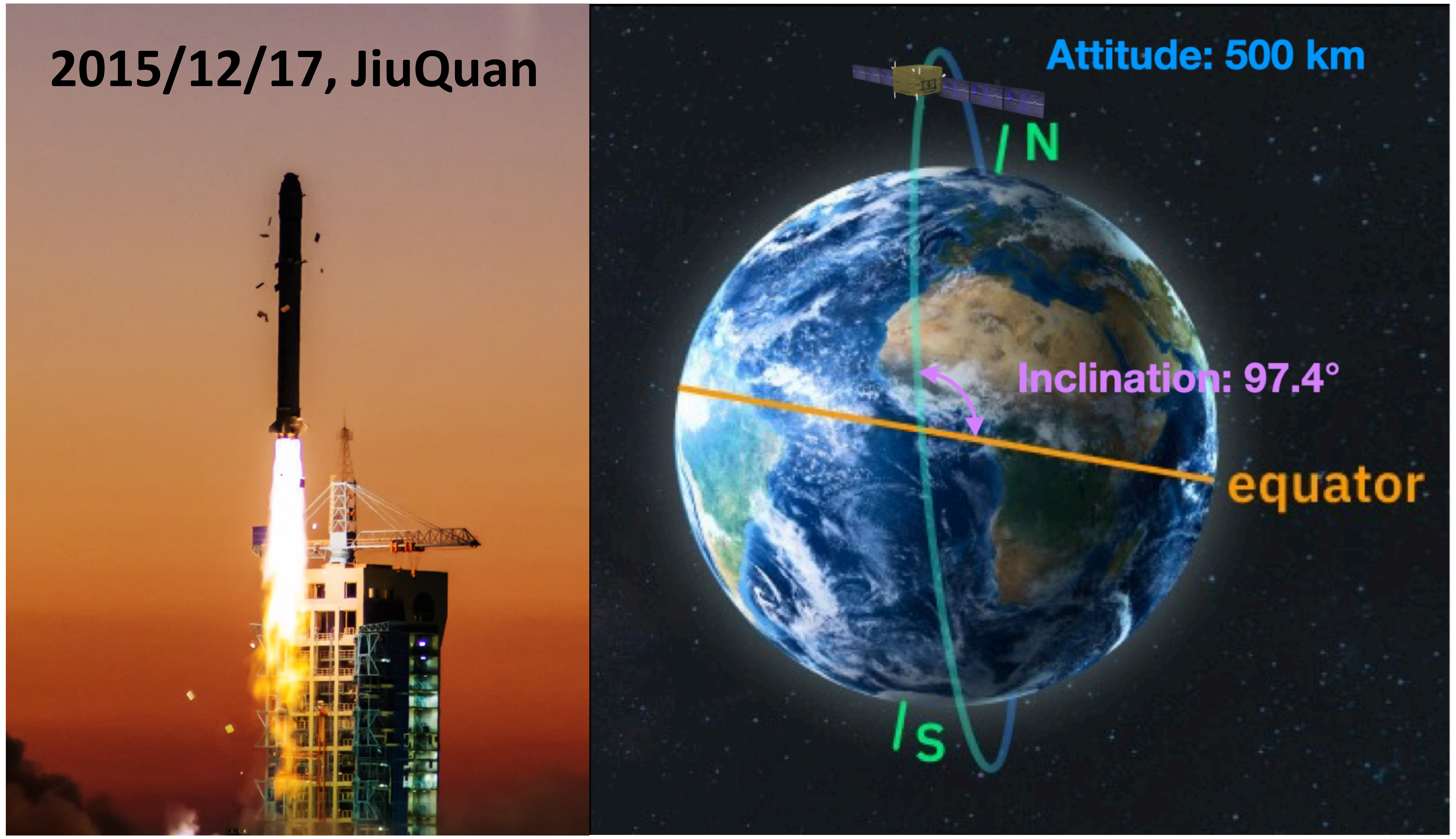
Outline

- DAMPE experiment
- Results of hadronic cross section of **Proton** & **Helium** on a BGO target (Machine learning method)
- Results of Hadronic cross section of **Carbon** & **Oxygen** on a BGO target (Classical method)
- Summary

DArk Matter Particle Explorer (DAMPE)

- **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).



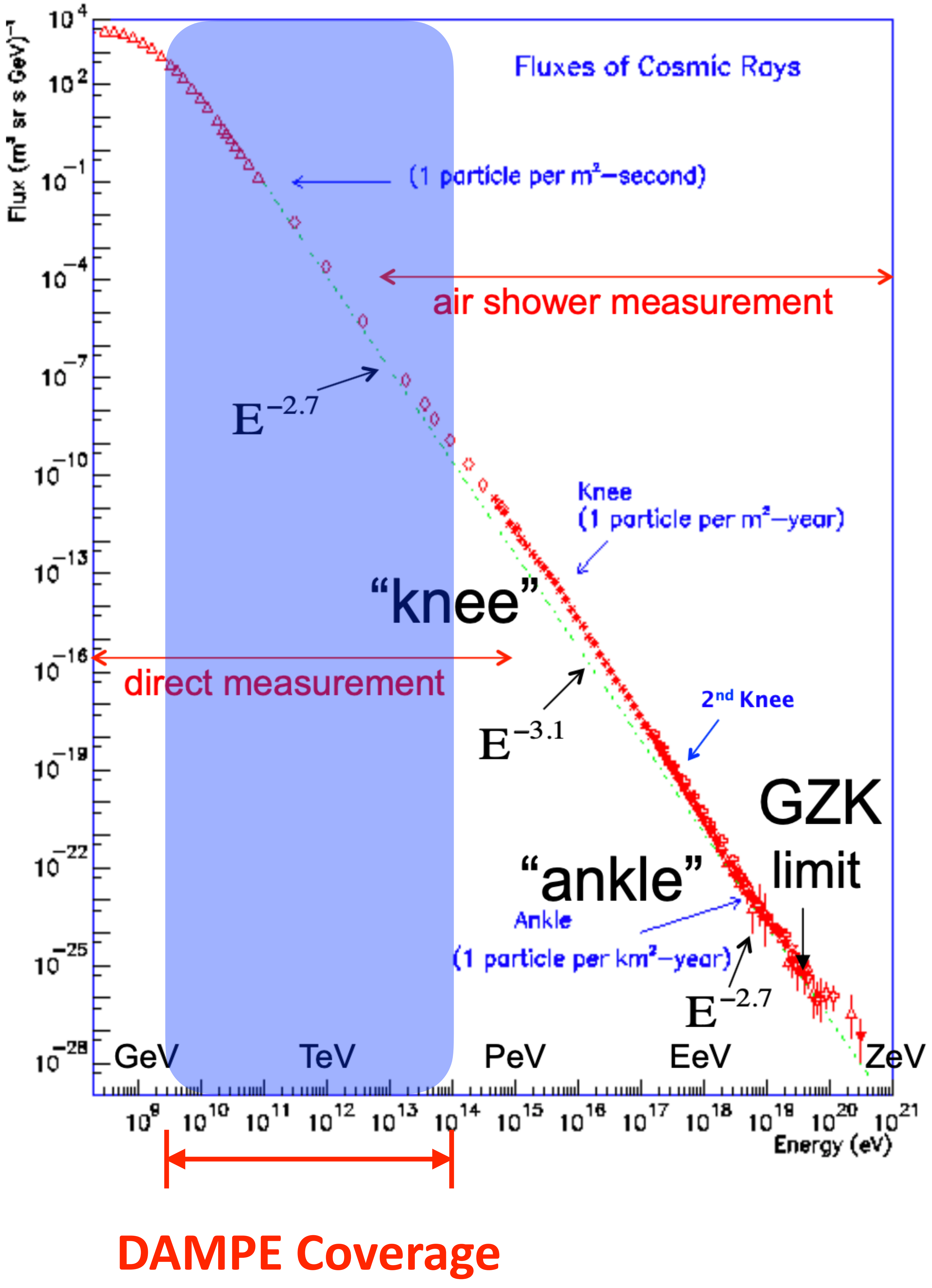
CNINA
- **Purple Mountain Observatory, CAS**
- **University of Science and Technology of China**
- **Institute of High Energy Physics, CAS**
- **Institute of Modern Physics, CAS**
- **National Space Science Center, CAS**

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**

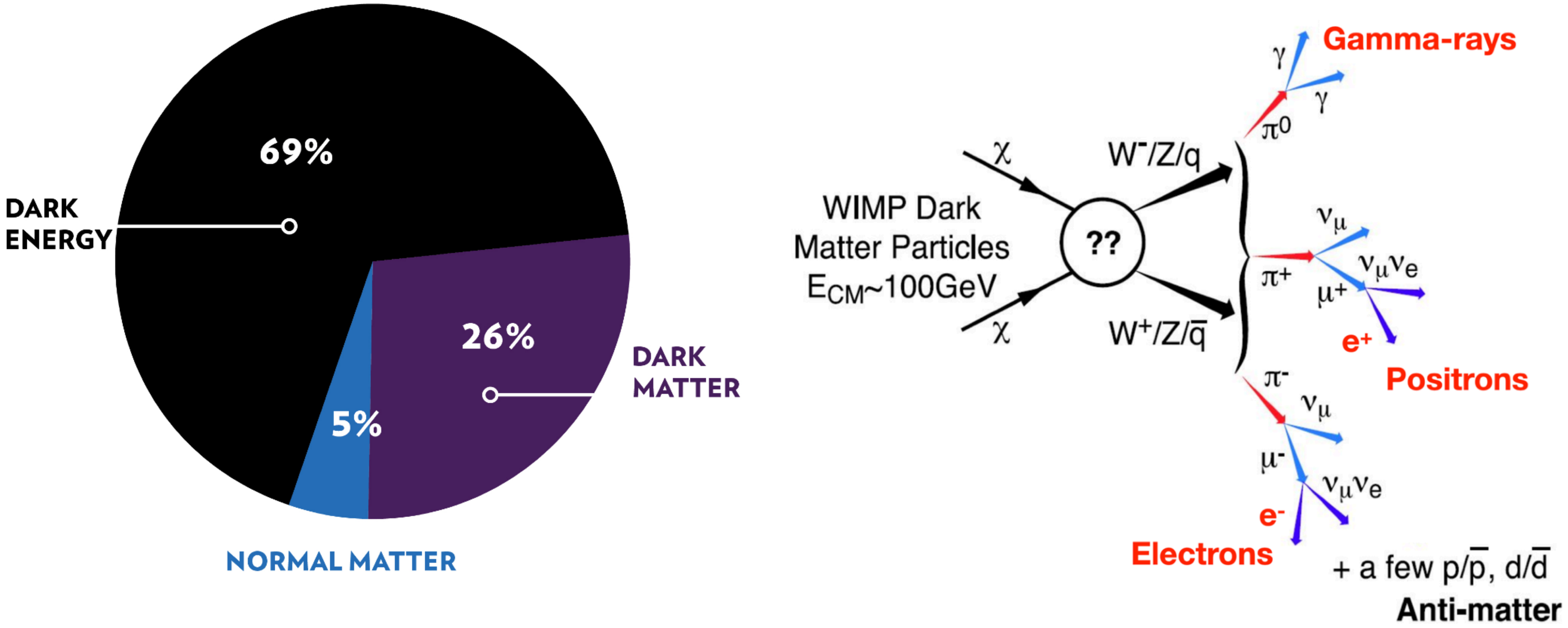
SWITZERLAND
- **University of Geneva**

Scientific Objects

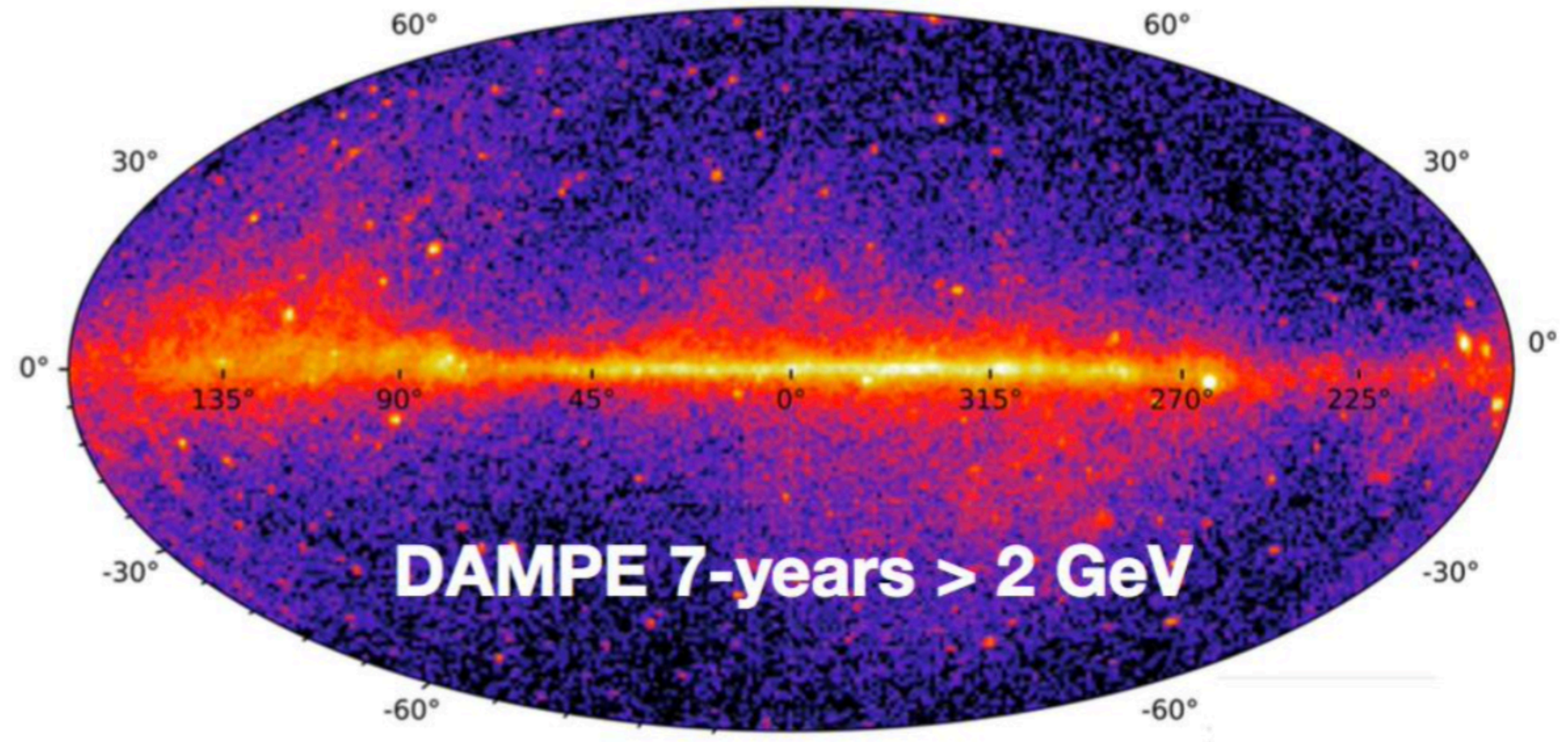
- **Cosmic ray physics**



- **Dark matter indirect detection**

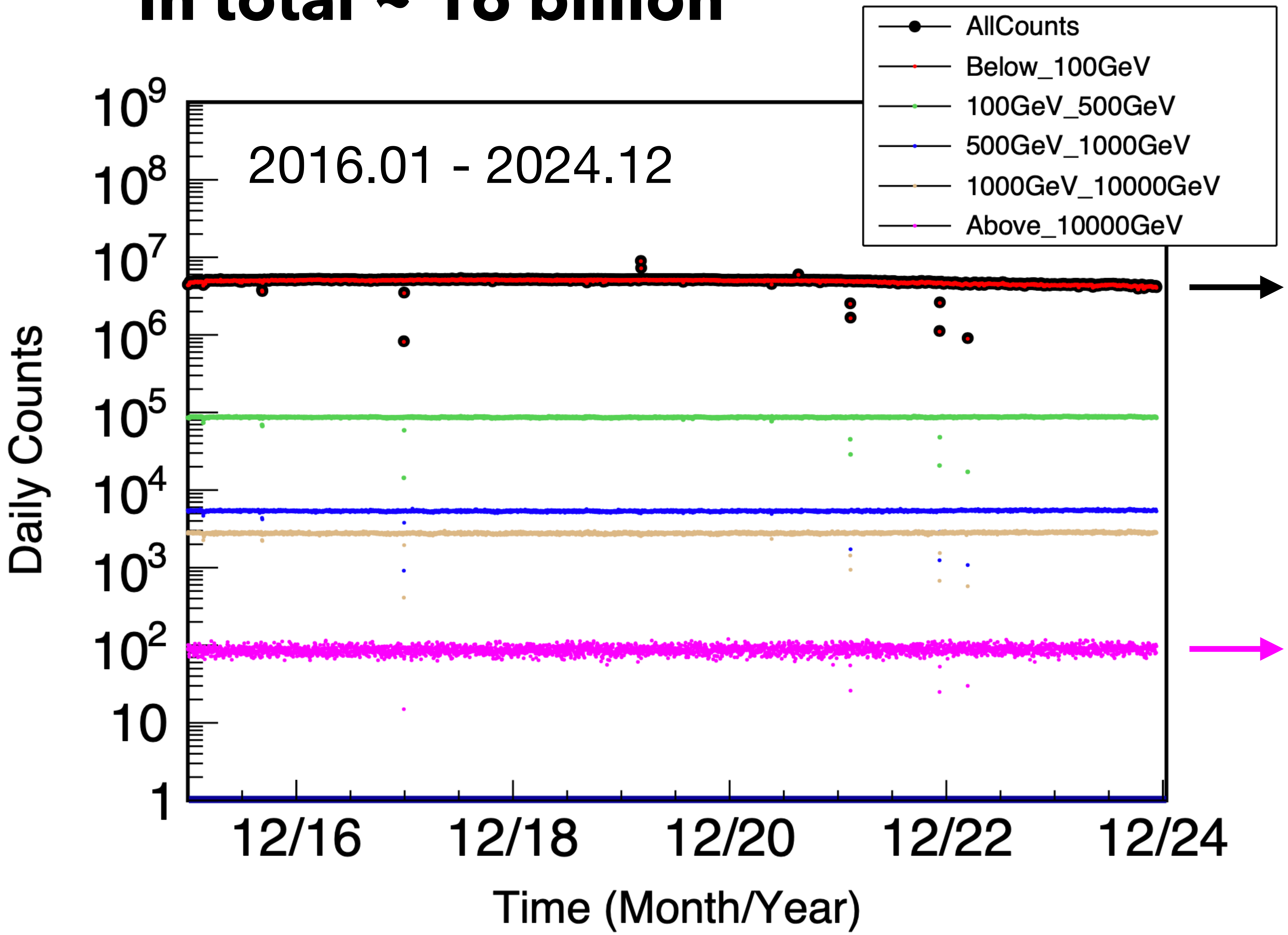


- **Gamma ray astronomy**



In-orbit Operation

In total ~ 16 billion

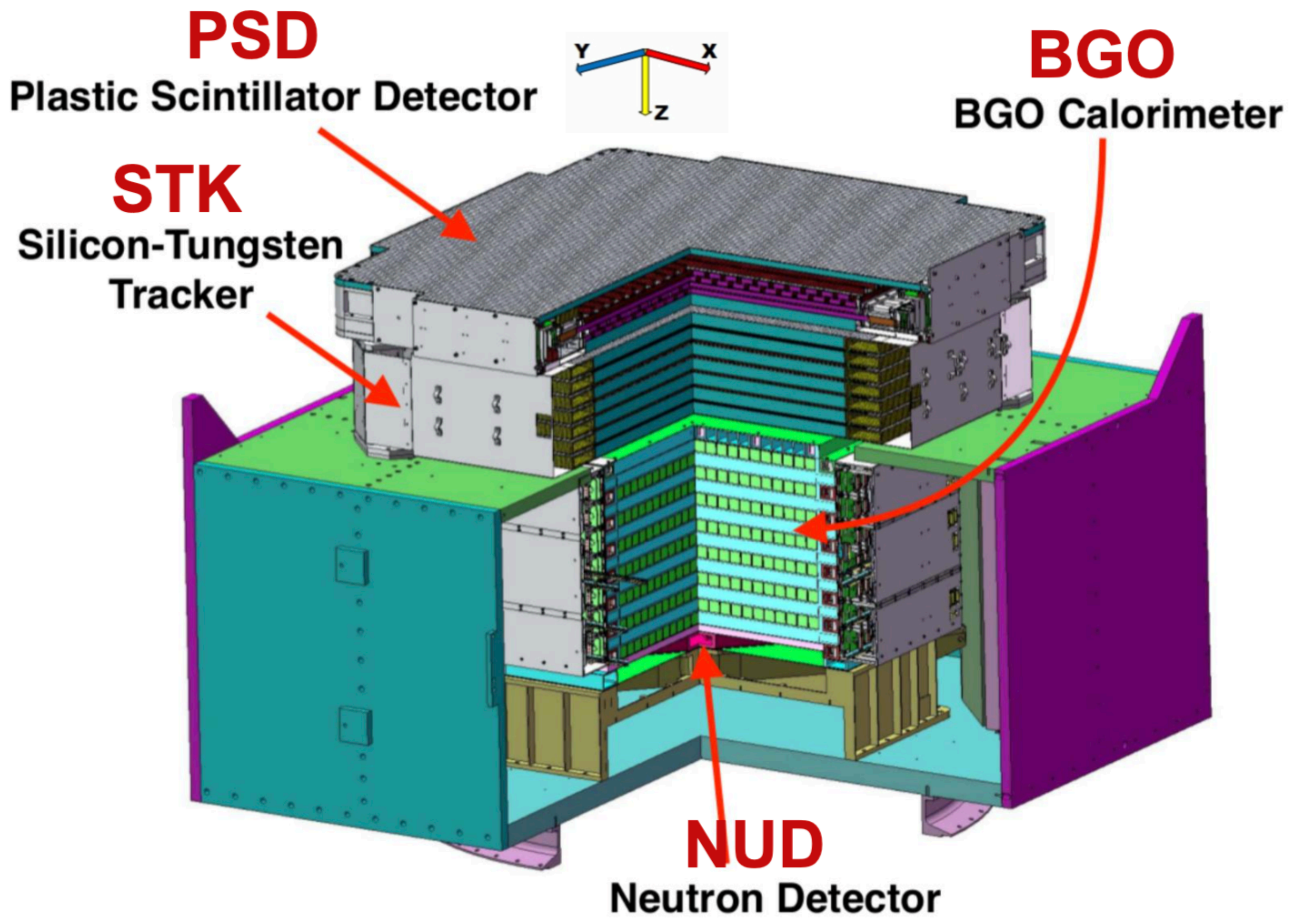


Smooth operation over 9 years since launch in Dec. 2017

→ Daily counts: ~ 5 million/day

→ > 10 TeV count: ~ 90 events/day

DArk Matter Particle Explorer



DAMPE sub-detectors:

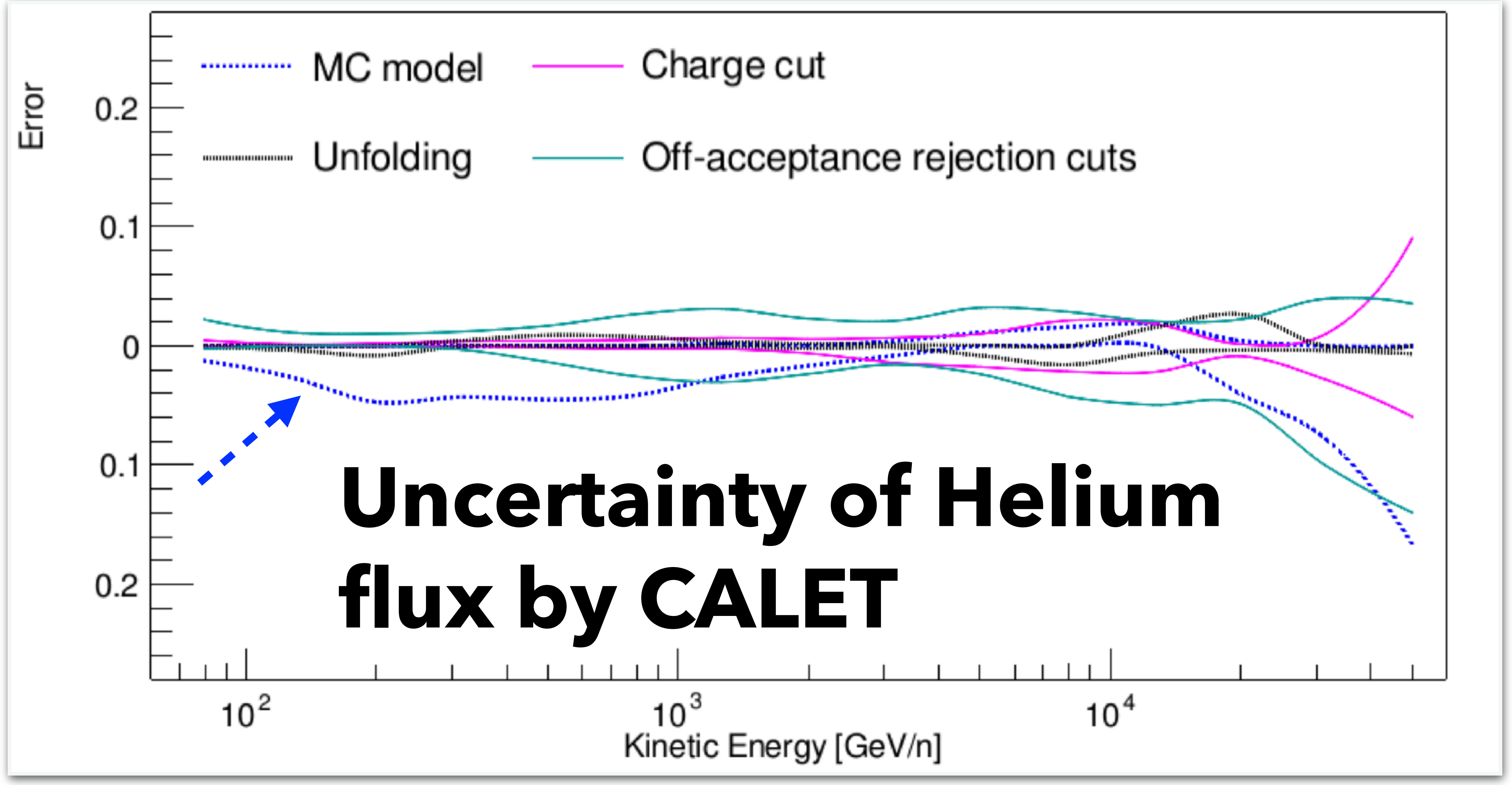
- Charge measurement (dE/dx in PSD, STK)
- Tracking and Gamma-ray converting (STK and BGO)
- Precise energy measurement (BGO)
- Electron-hadron separation (BGO and NUD)

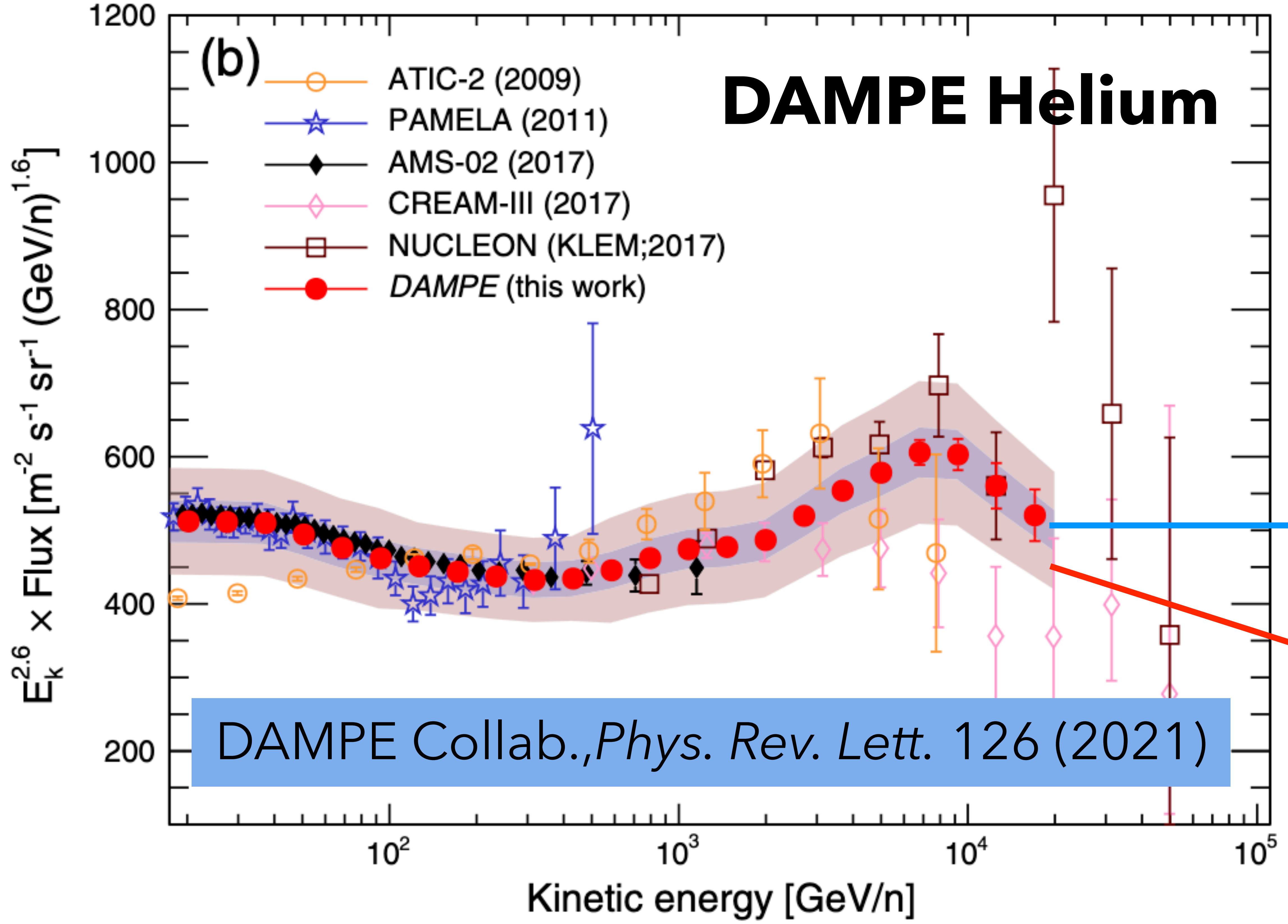
DAMPE Collab., *Astropart.Phys.* 95 (2017)

Motivation

- Hadronic model uncertainty: main source of total uncertainty in **space calorimetric experiments** like DAMPE

CALET Collab.,*Phys. Rev. Lett.* 130 (2023)





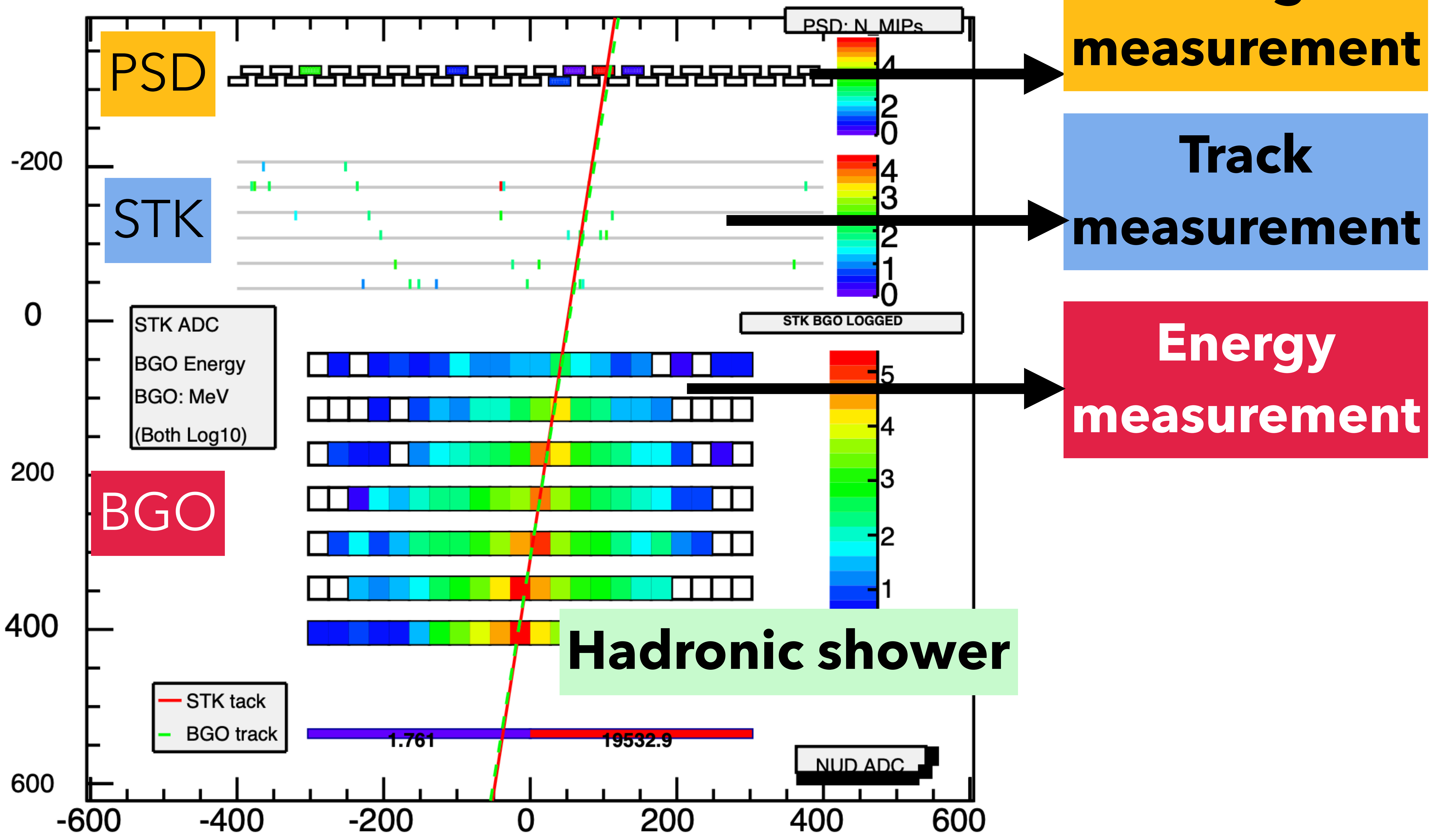
DAMPE Collab.,*Phys. Rev. Lett.* 126 (2021)

Other uncertainties ~ 5%

Uncertainty from MC Hadronic Model ~ 15%

A Typical Event in DAMPE

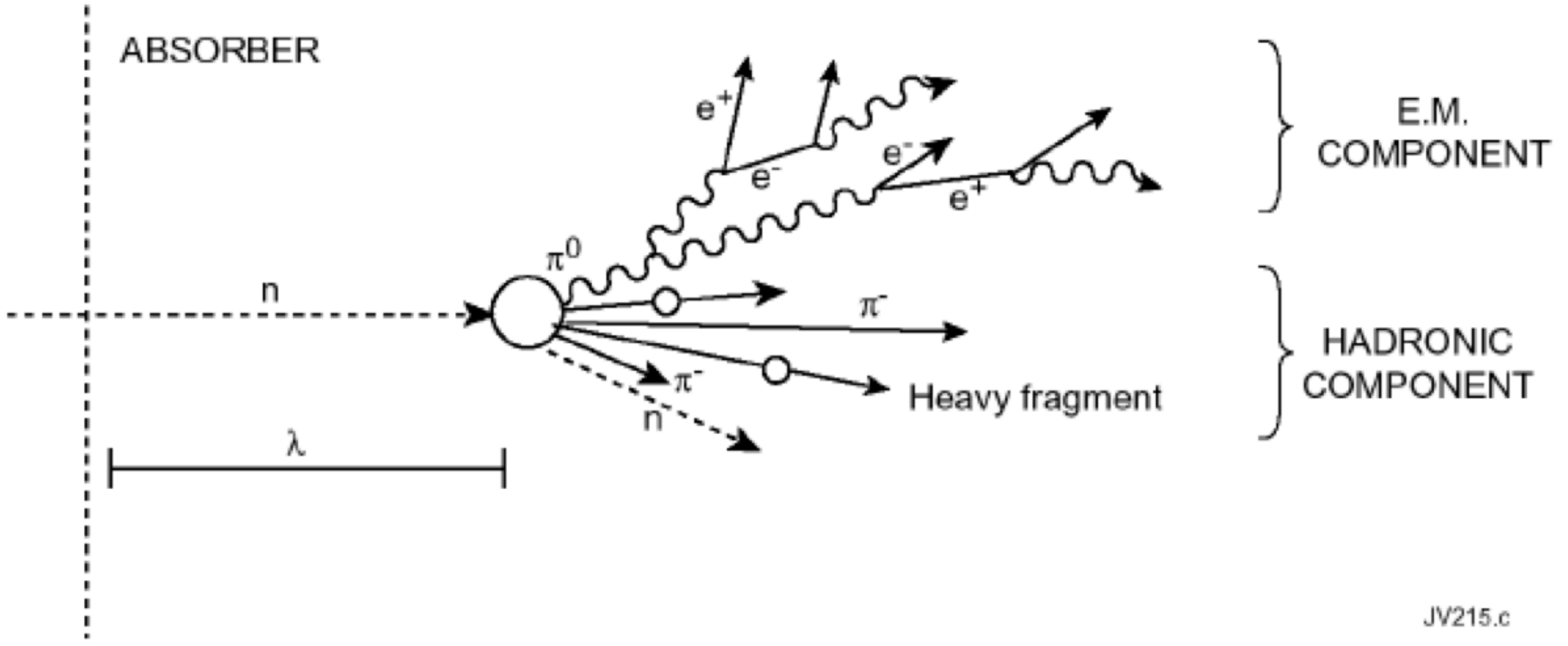
Helium event (1.8 TeV in BGO)

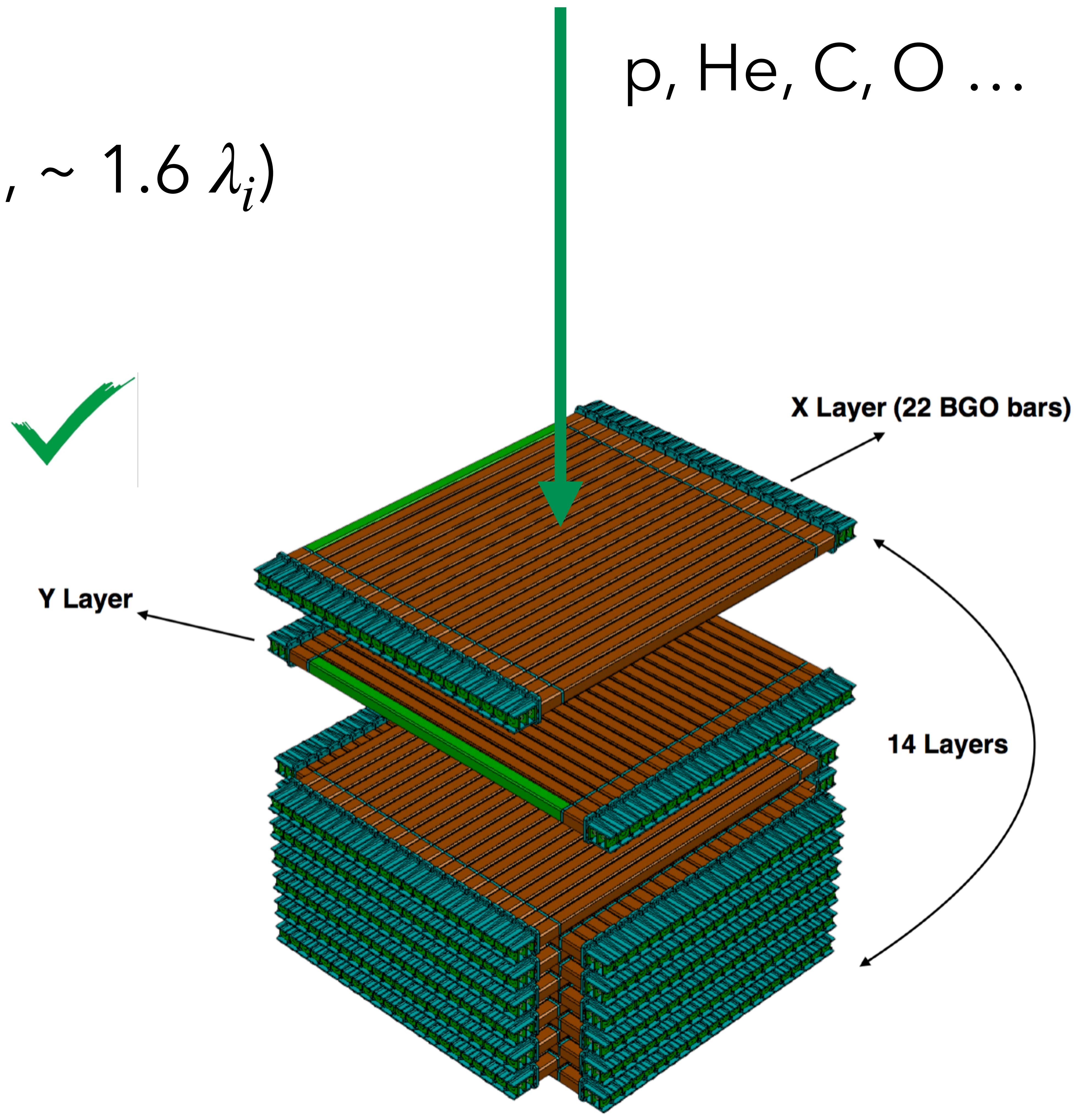


- Hadronic interaction model introduces effects in various aspects
  - Energy response
  - Trigger efficiency
  - Reconstruction and selections related to the calorimeter
  - Backsplash
  - …

What Can We Do in DAMPE

- A beam-target experiment
- Target material: **$Bi_4Ge_3O_{12}$** (35 cm in depth, ~ 1.6 λ_i)
- What can we measure in DAMPE:
  - Inelastic interaction point (cross section) ✓
  - Detailed shower development ✗



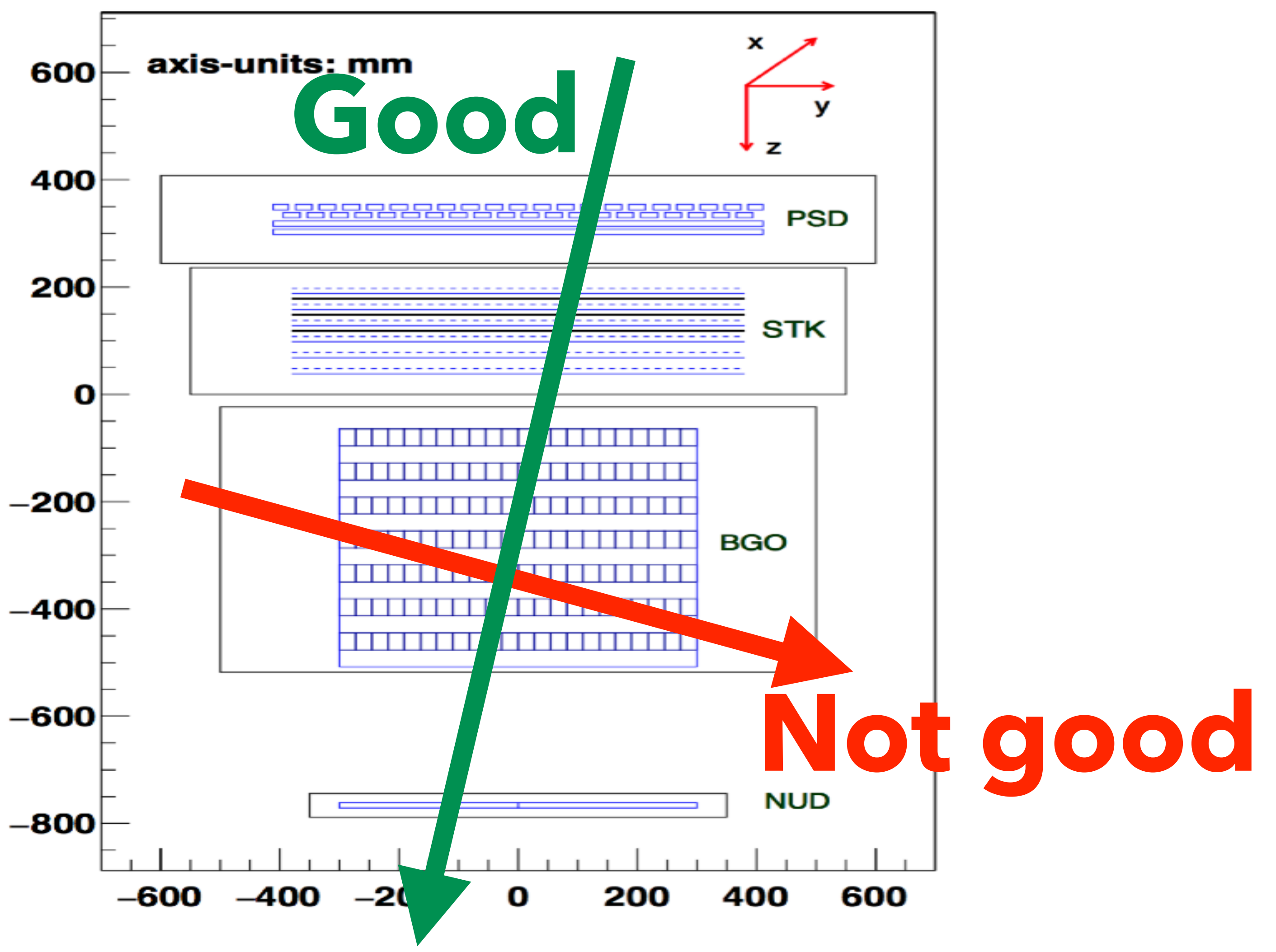


P & He Cross Section

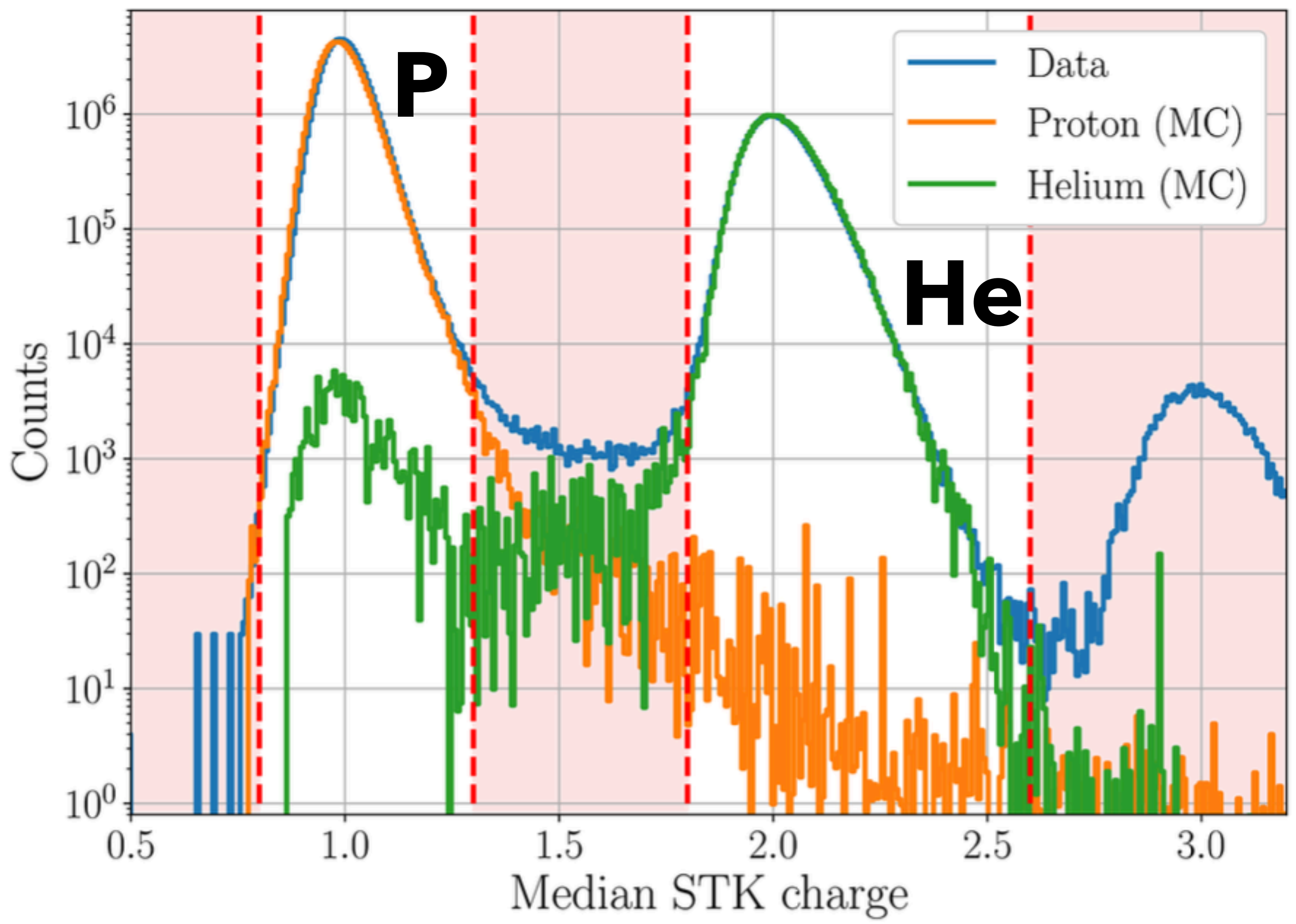
Criteria for Sample Selection

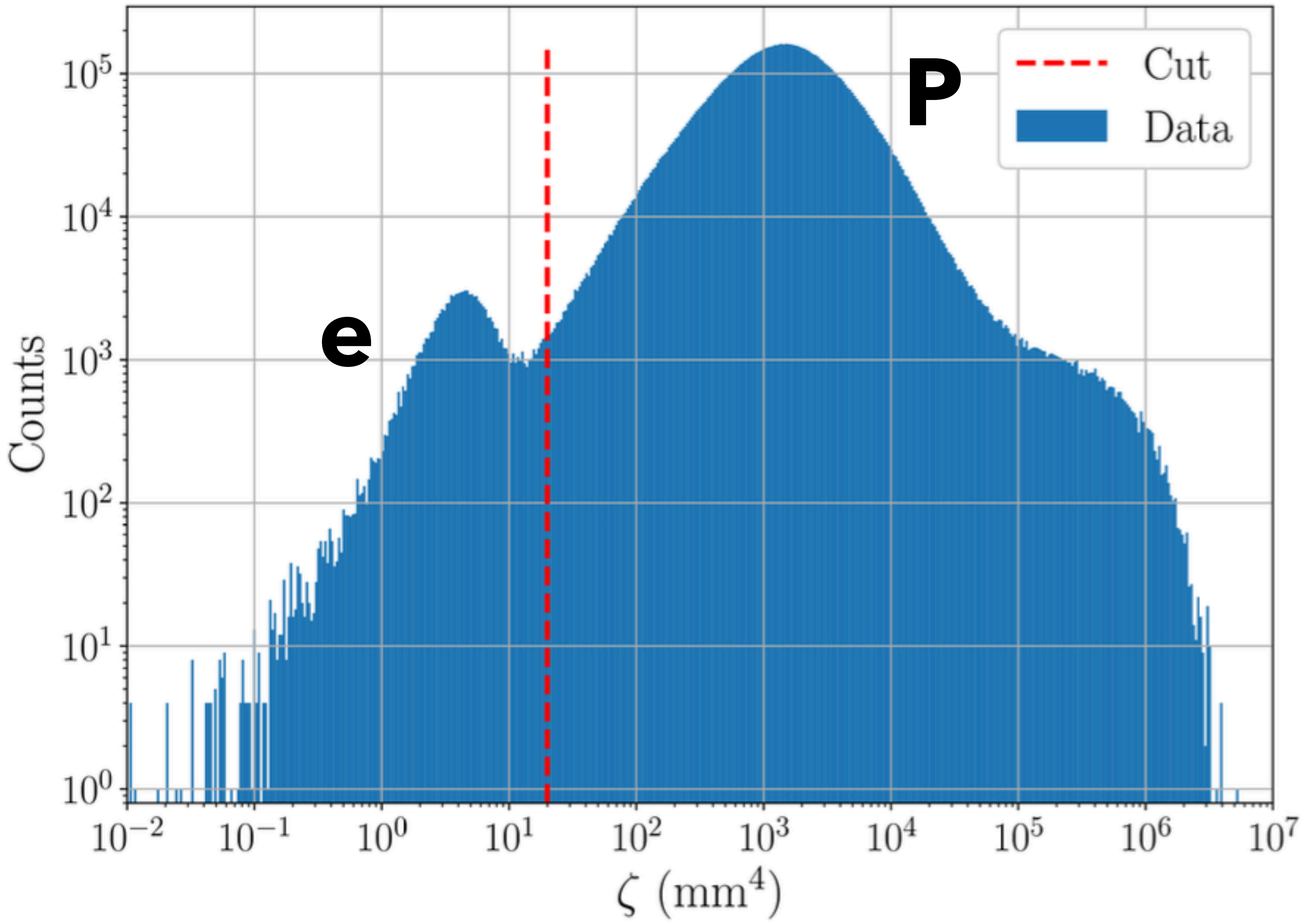
- Data sample:
  - Flight data: 84 months
- Energy range: > 10 GeV
- MIP Trigger

- Track finding (ML)
- Pre-Selection:
  - Event containment
  - Interact after reaching the calorimeter



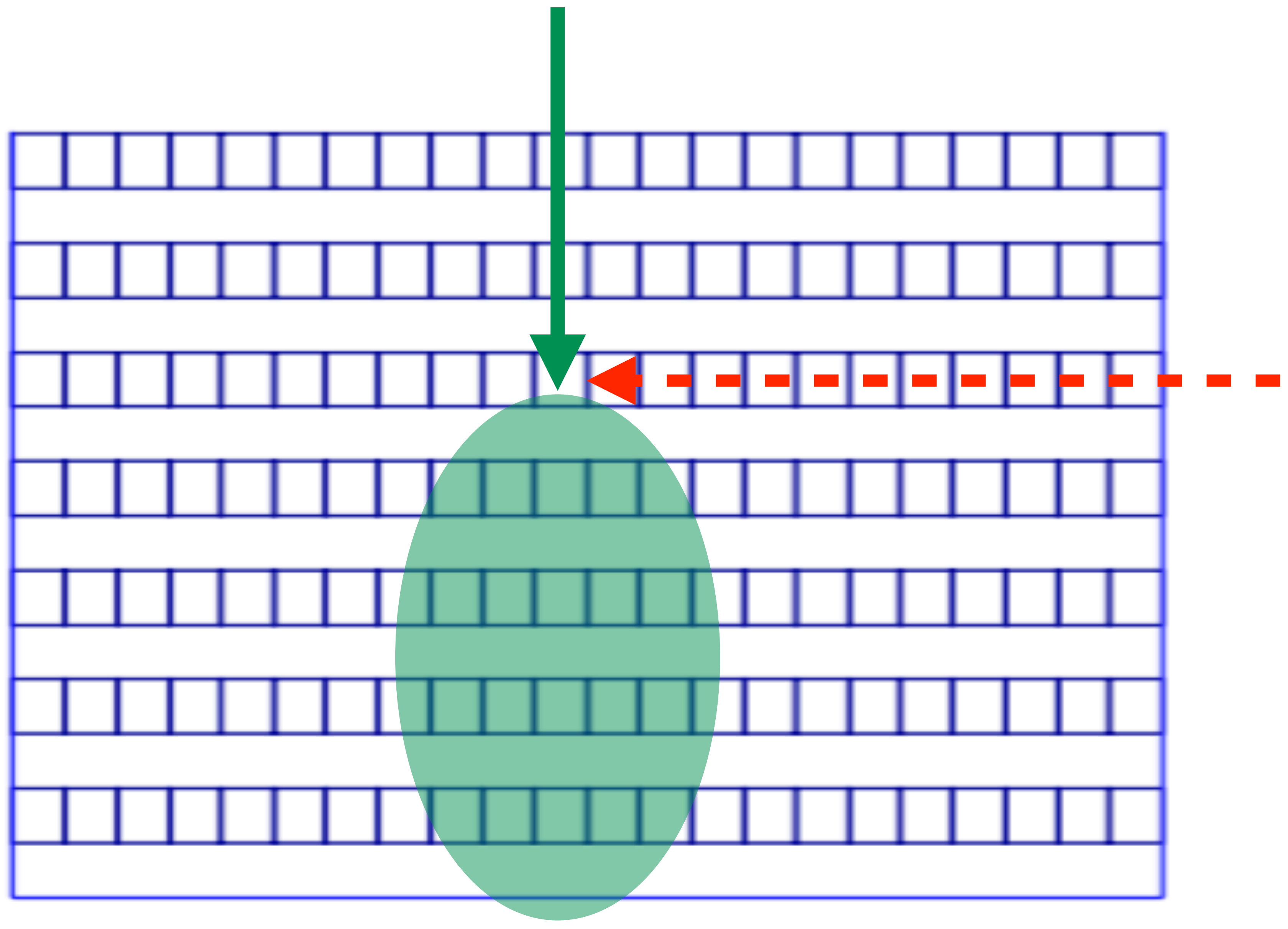
- Select P & He sample
  - Charge signal
  - Shower profile information (ζ)
- ~ 85% efficiency , while background ≤ 0.2%





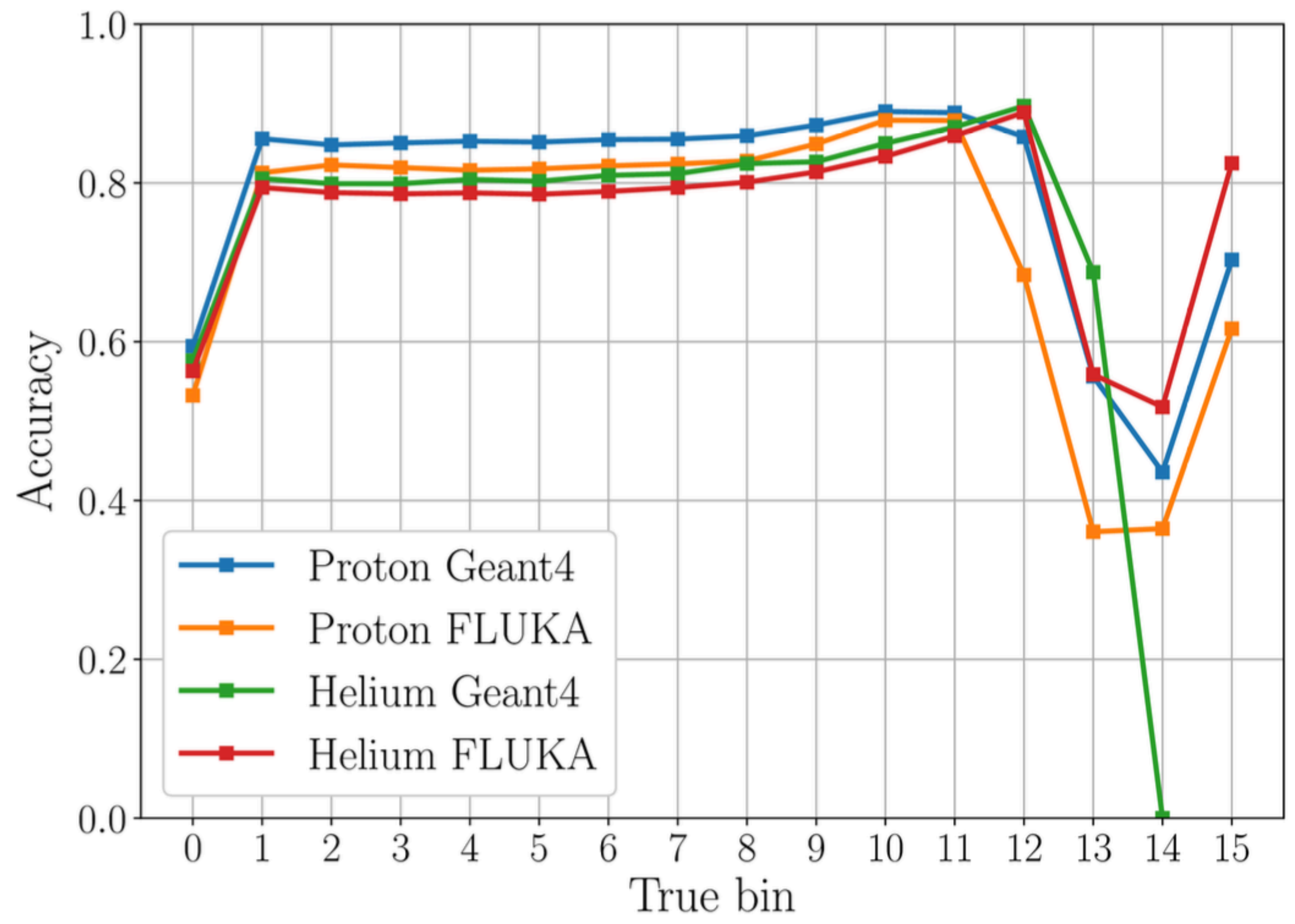
Cross Section Measurement

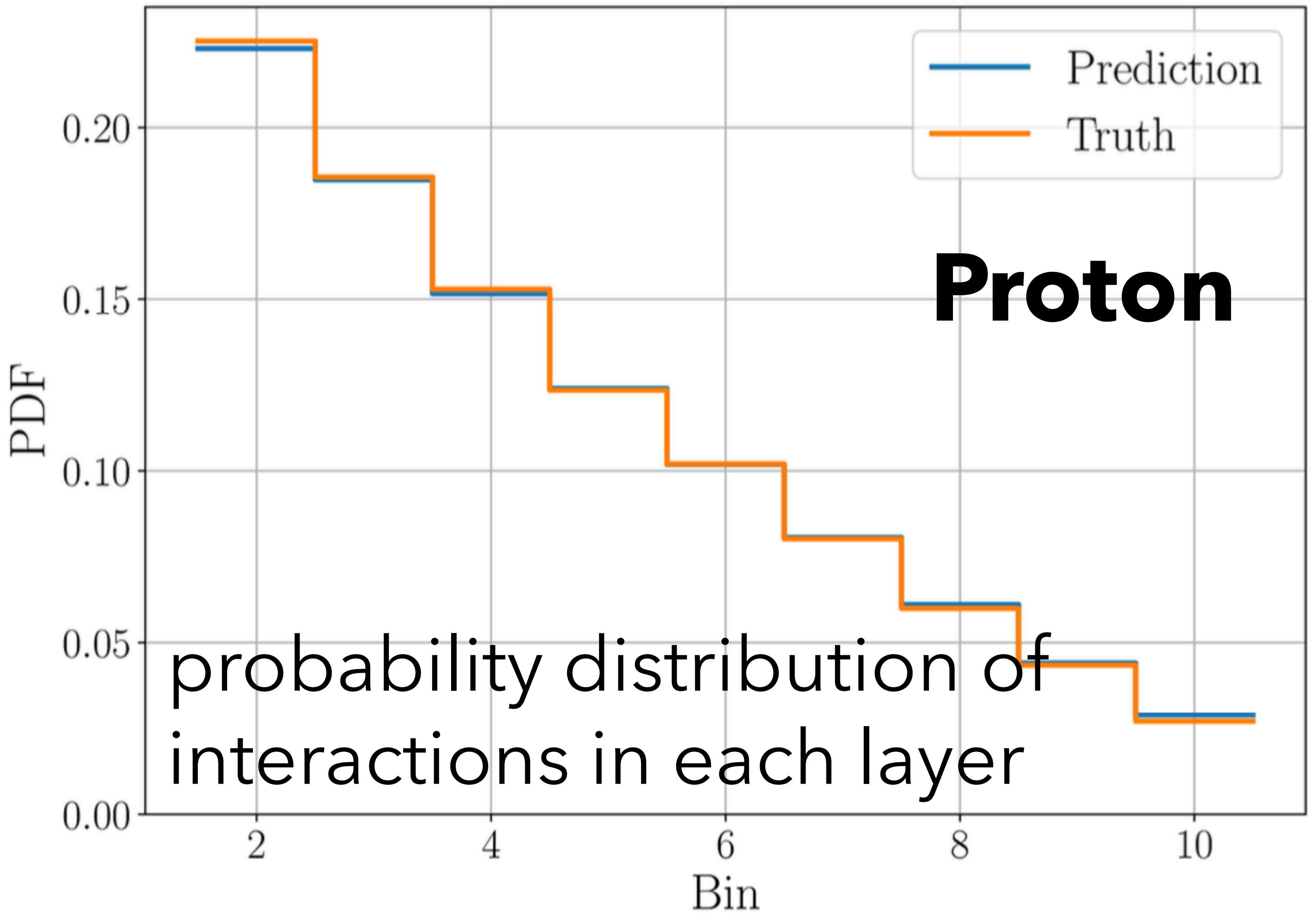
- Point of inelastic interaction → Cross section
- True interaction point is given by MC
- **Interaction depth classifier** was trained based on XGBoost (70 input variables)



Which layer does the inelastic interaction point take place in?

Multi-class Classification





Cross Section Measurement

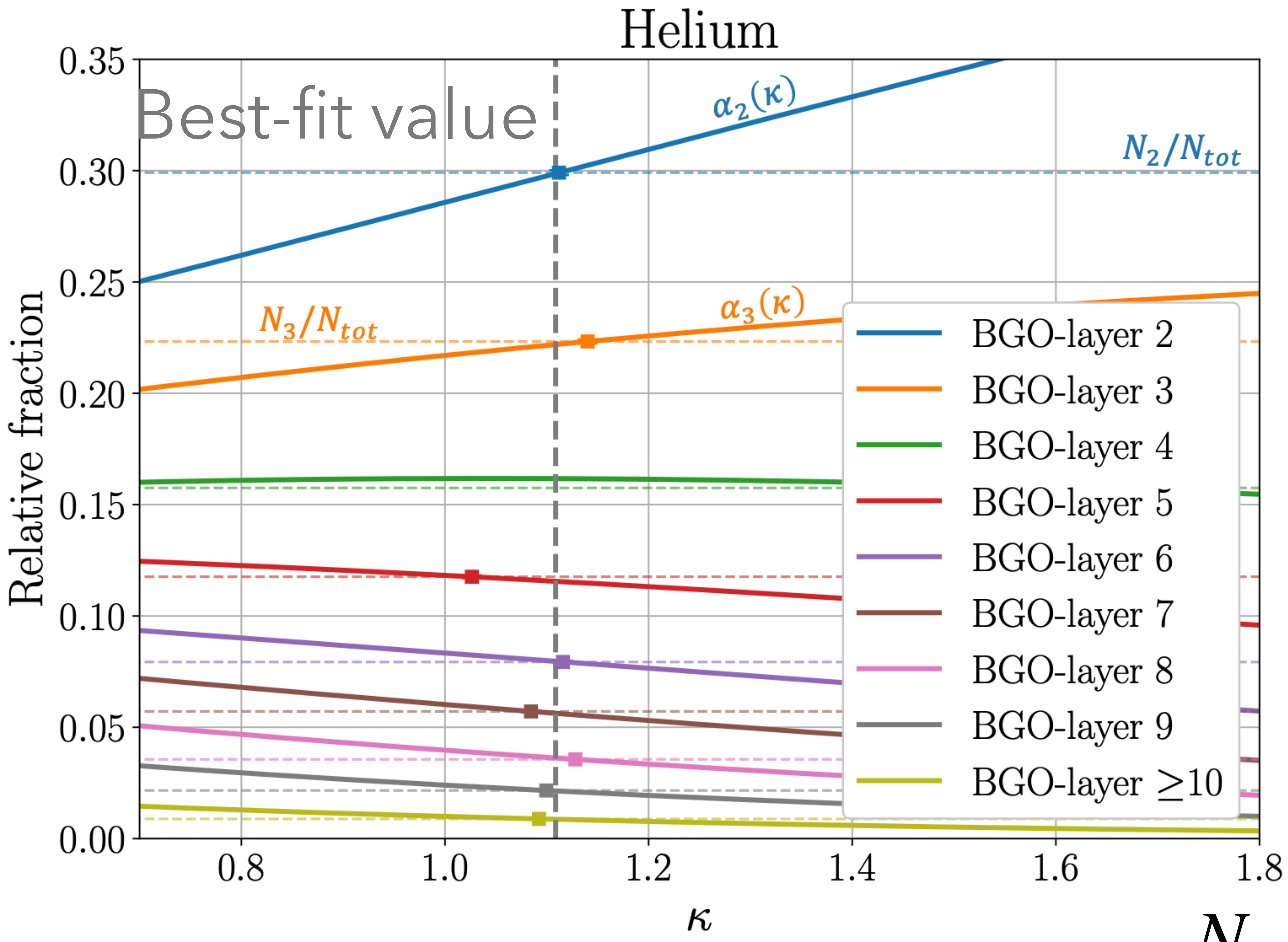
- N_i , the number of events interacting in layer i, given by the classifier
- A relative fraction is defined as follows:

$$\alpha_i = \frac{N_i}{\sum_{j=2}^{10} N_j} \qquad 2 \leq i \leq 10$$

- Assume the true cross section is the MC cross section scaled by a constant factor.

$$\sigma_{true} = (1+\kappa) \cdot \sigma_{MC}$$

- κ determination: modify MC cross section until it matches data



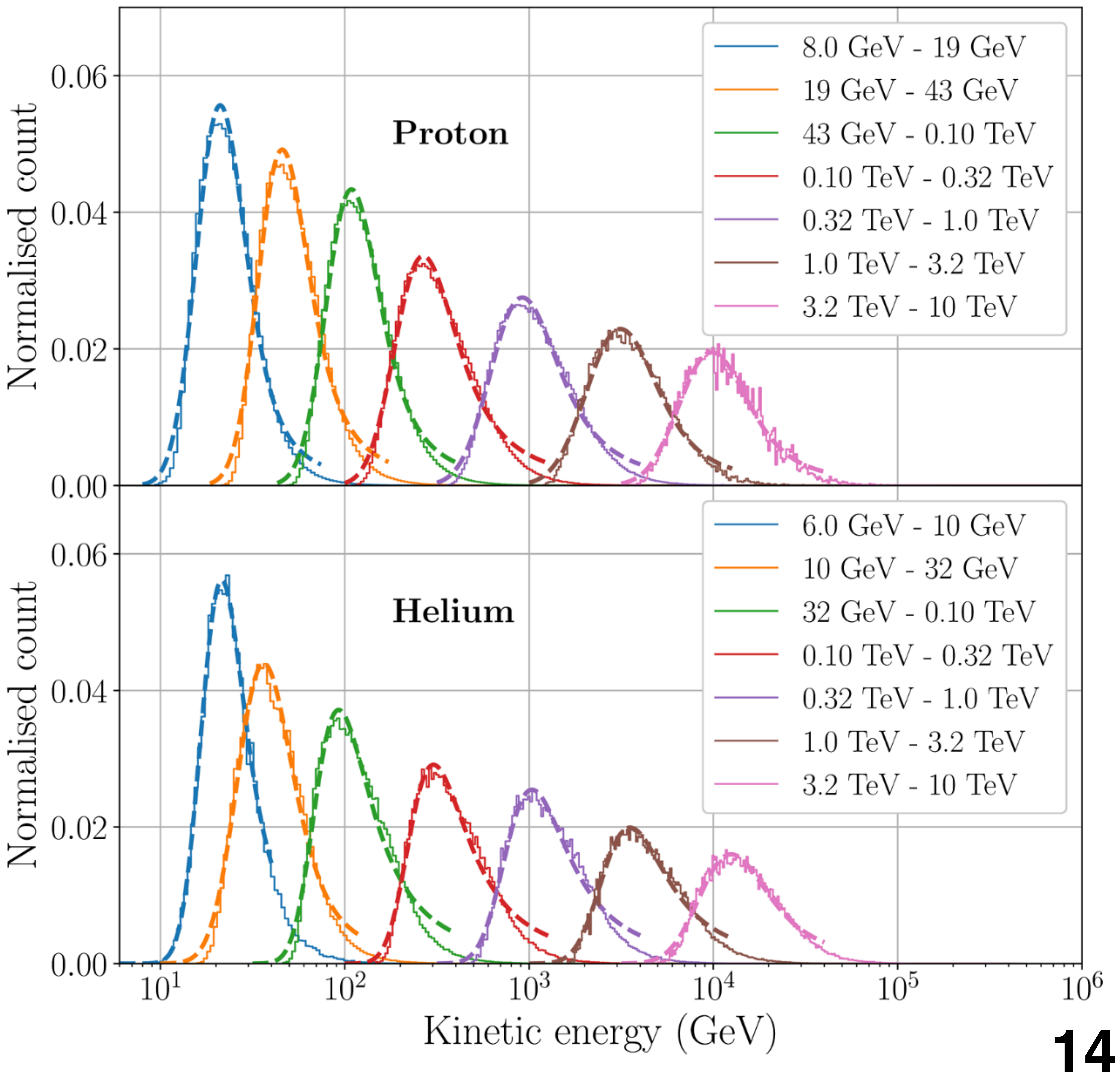
- Dash lines: measured fractions ($\frac{N_i}{N_{tot}}$)
- Solid lines: MC (α_i) obtained by scanning κ

Energy Dependence

- Cross section measured as function of particle's kinetic energy
  - Bin events in total energy deposited in calorimeter
  - Determine corresponding kinetic energies from MC
  - Fit Landau+Gaussian

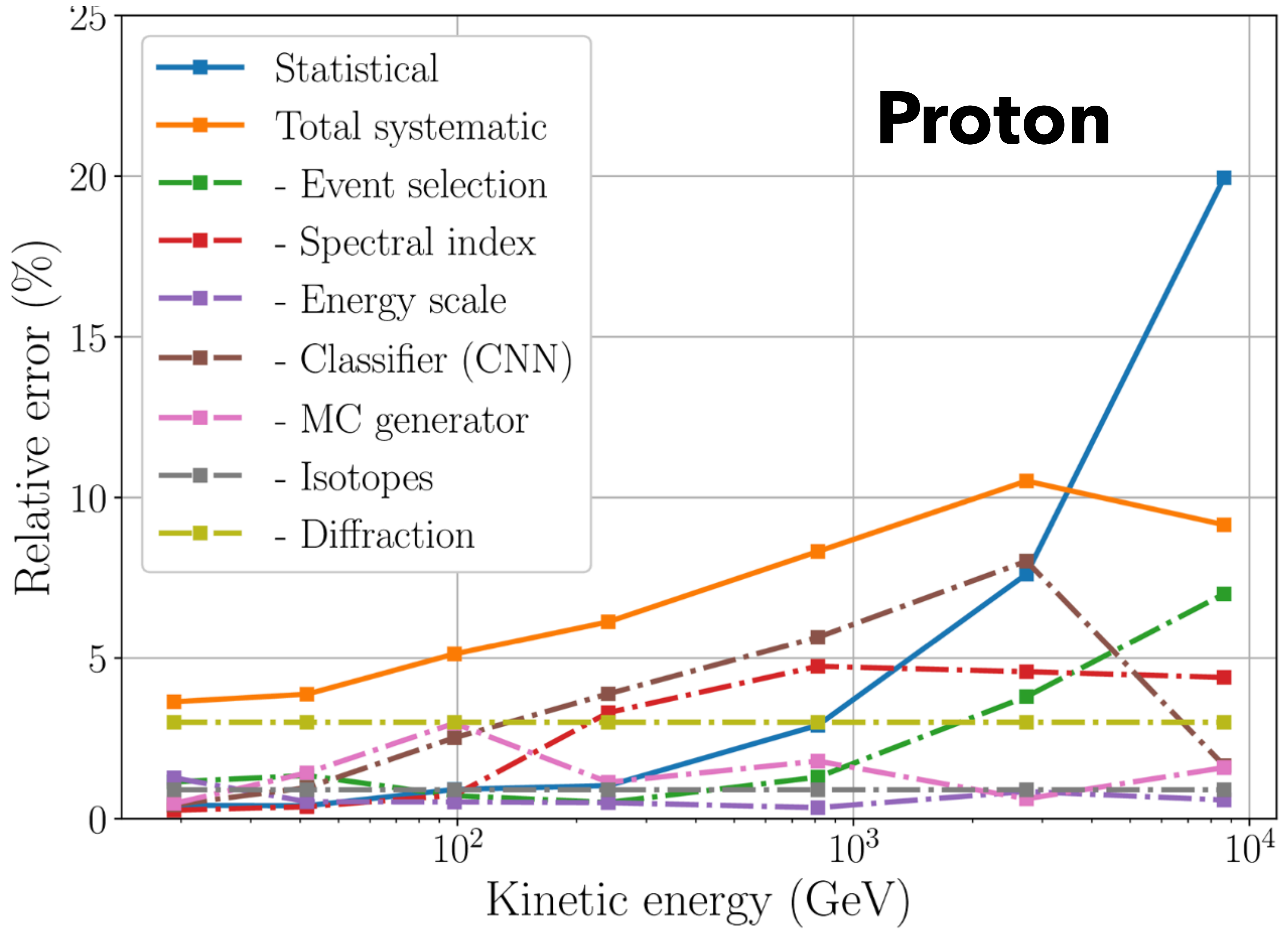
    → peak: reference value

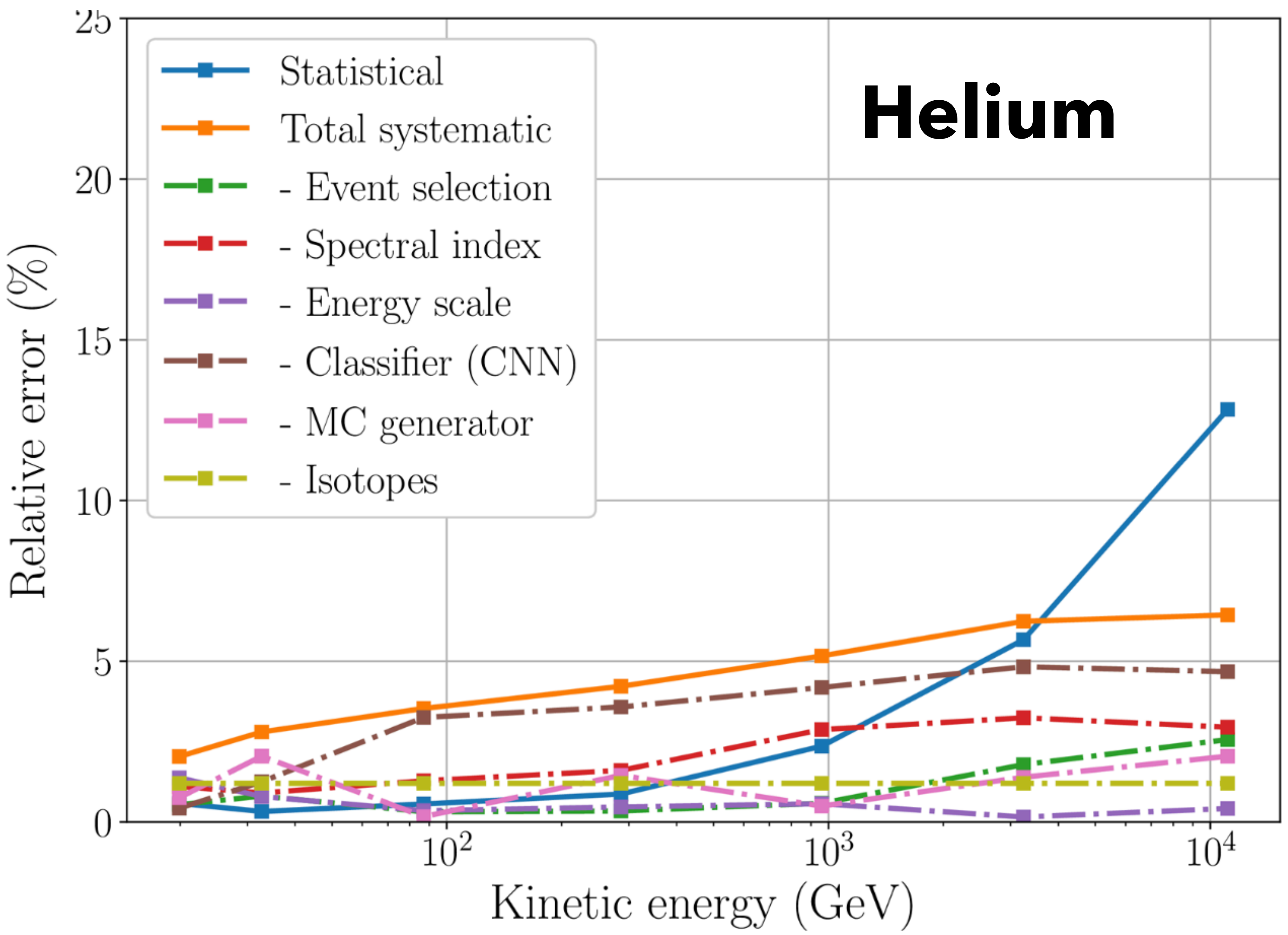
    → width: uncertainty



Uncertainties

- Statistical uncertainty dominates in last bin
- Systematic uncertainty
- Main contributions: Classifier, spectral index, event selection and isotopes

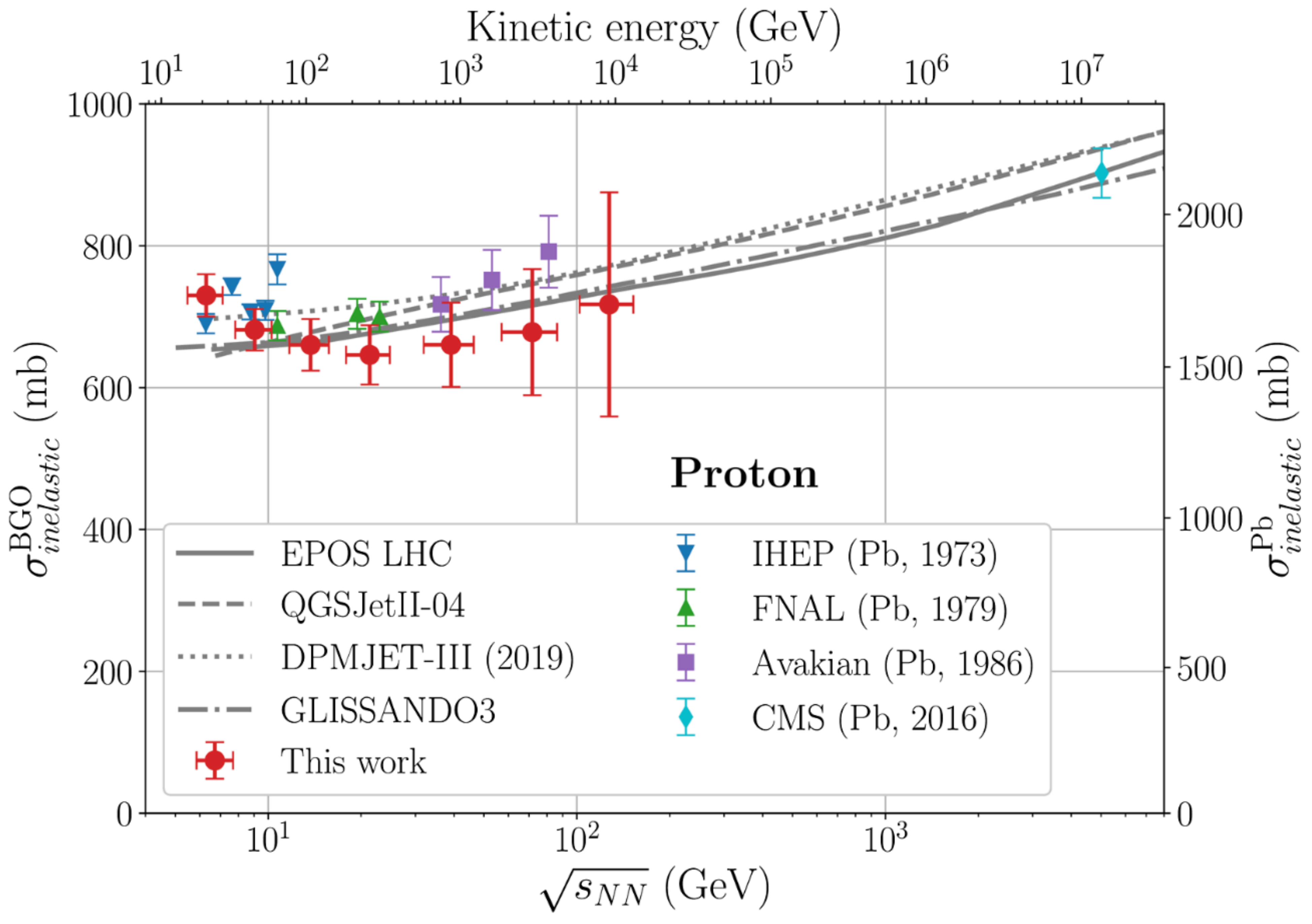


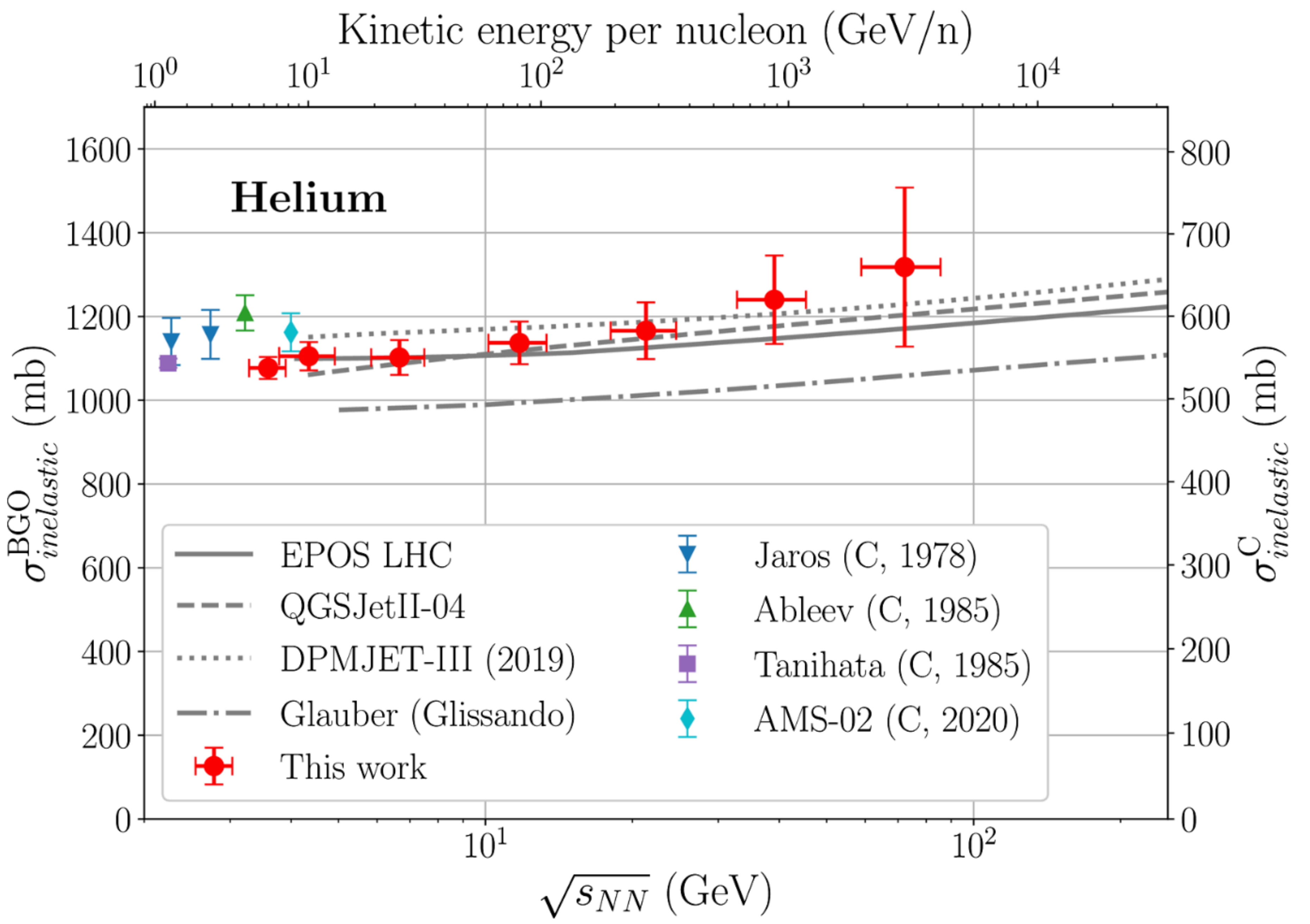


P & He Results

- Model comparisons: EPOS-LHC, QGSJetII-04, DPMJET3 …
- Other measurements not for BGO, so scaled: $\sigma_{target}^{EPOS-LHC}/\sigma_{BGO}^{EPOS-LHC}$

Proton: Within error-band of measurements at same energy; but slightly lower normalization.





Helium-4: Good agreement with other measurements. Slightly steeper rise, but models within analysis uncertainty.

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

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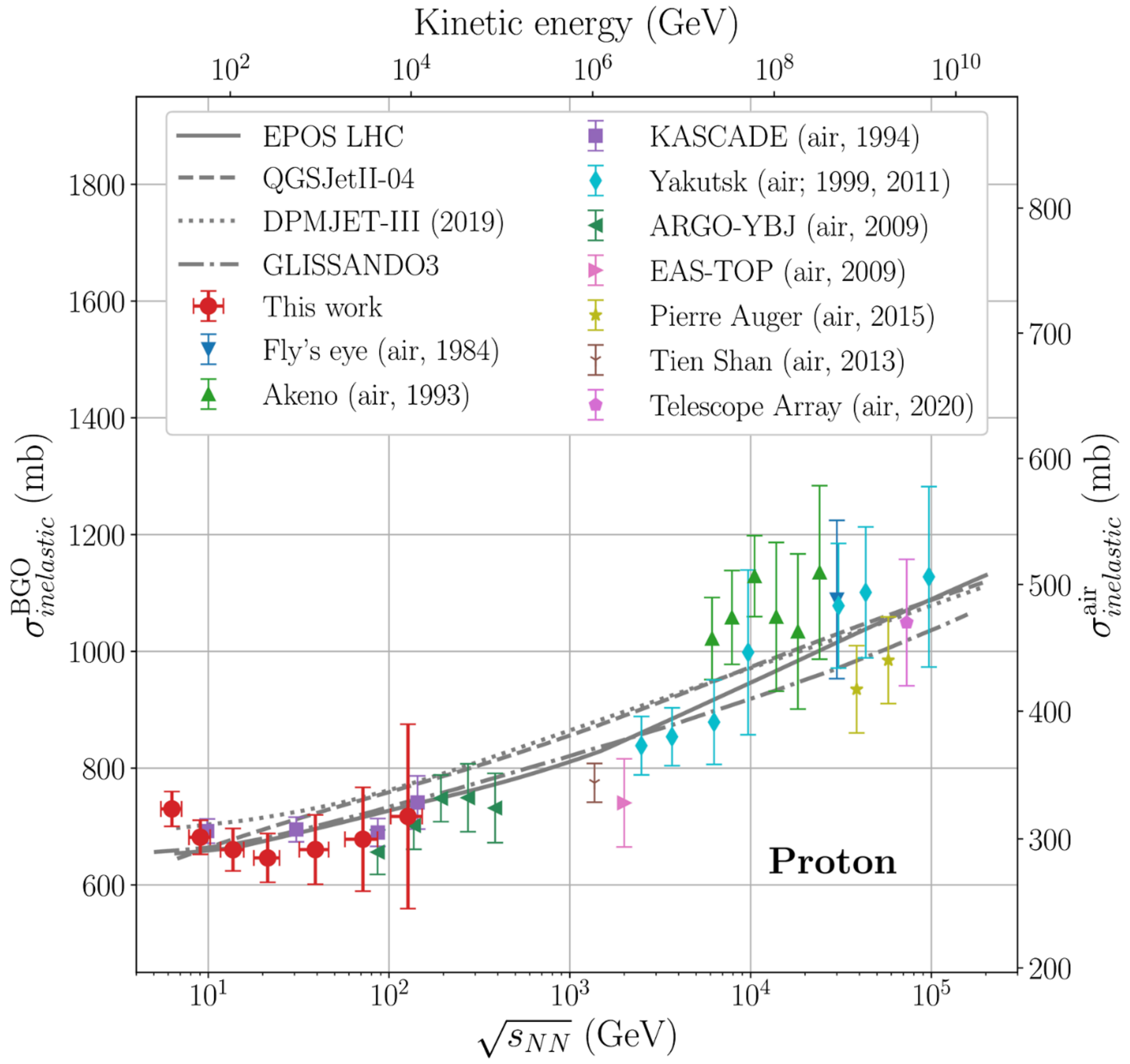

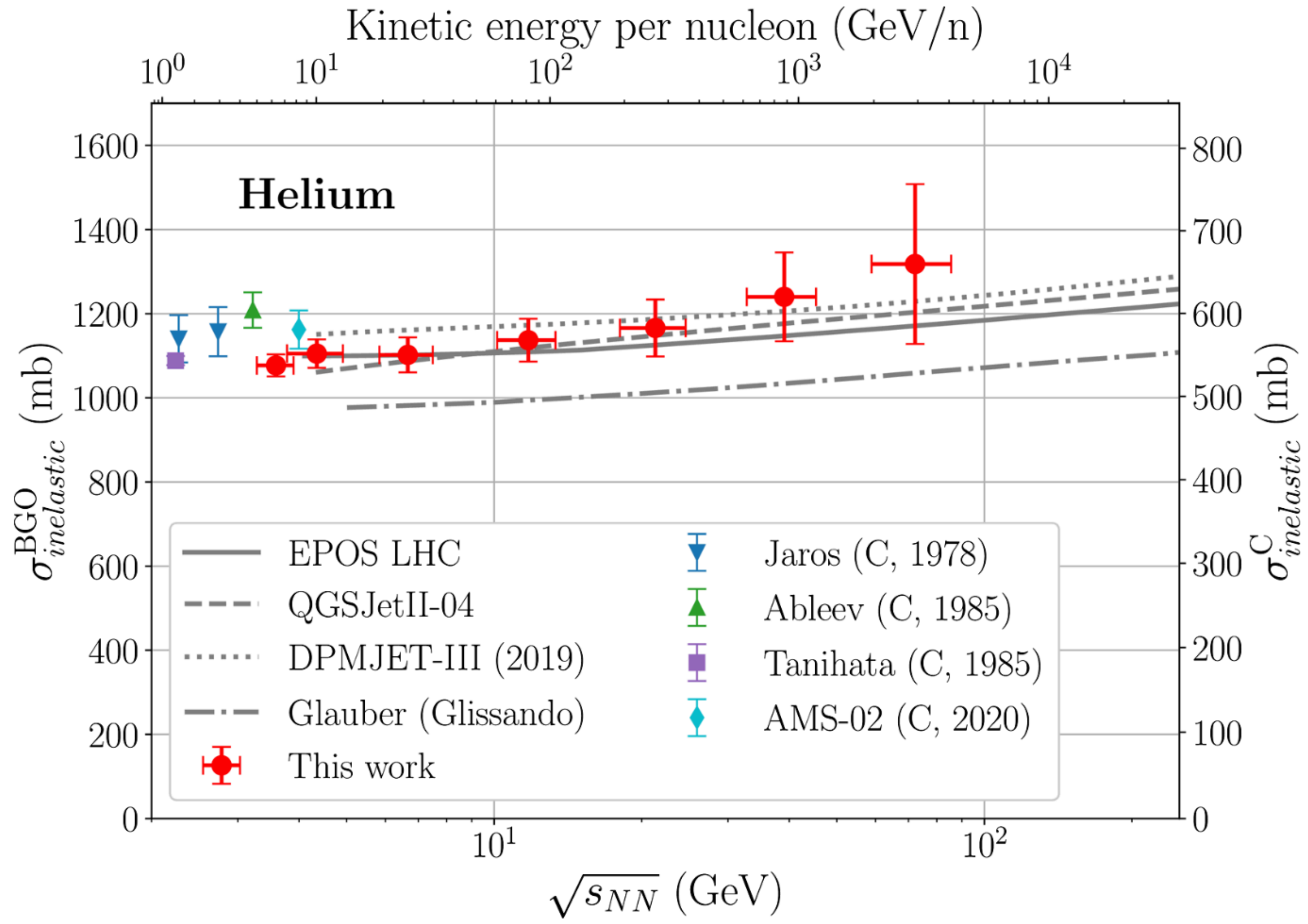

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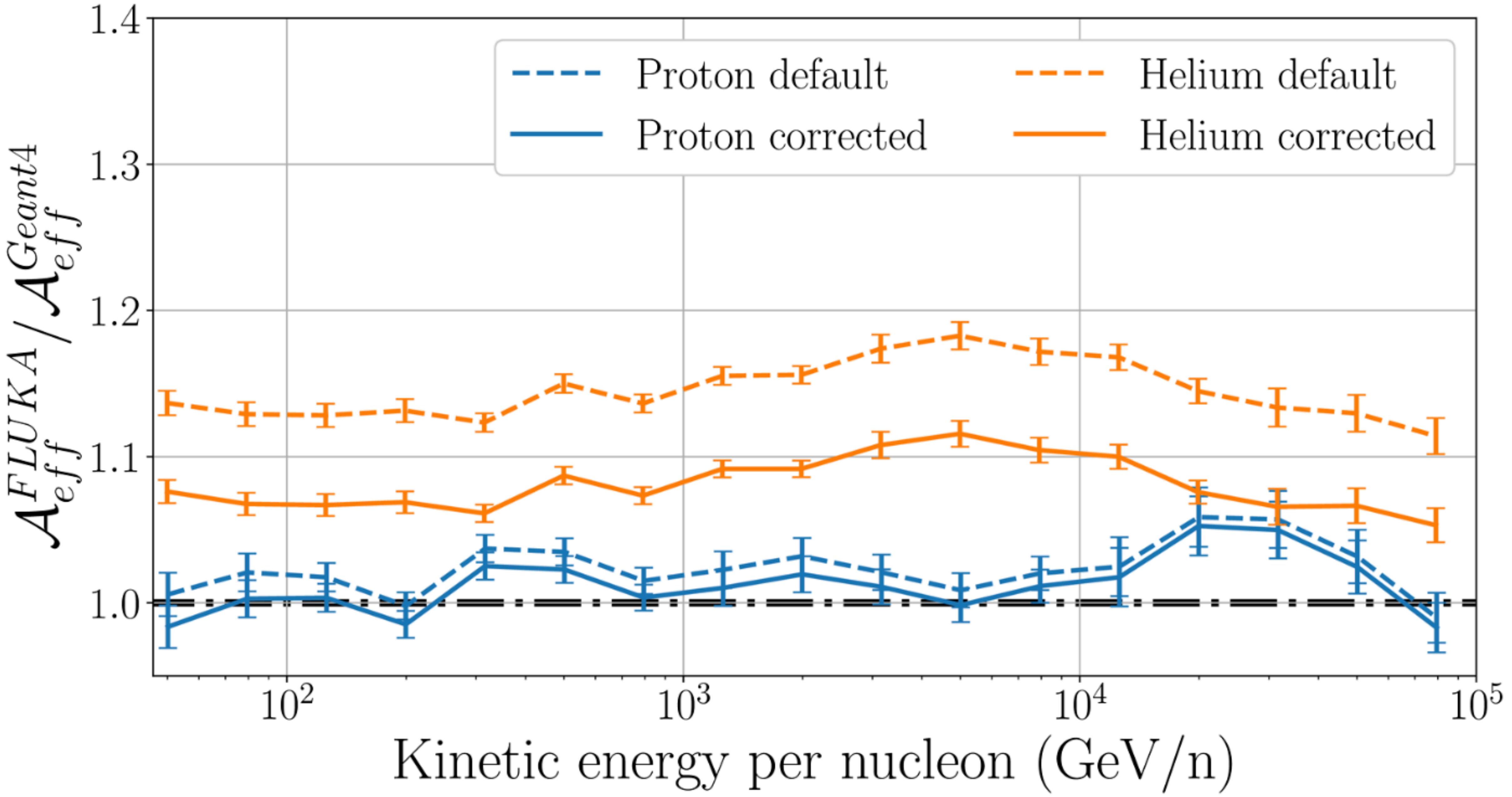
Effect on Flux Normalization

- Effective detector acceptance depends on cross section:

$$\Phi(E \to E + \Delta E) = \frac{N}{\mathcal{A}_{\text{eff}} \cdot \Delta E \cdot \delta t}$$

- Higher cross section → lower flux (and vice versa)

- Compare acceptances, FLUKA over Geant4
  - Correcting cross section in MC to measured result significantly improves agreement
  - Minor effect for proton, major effect for helium

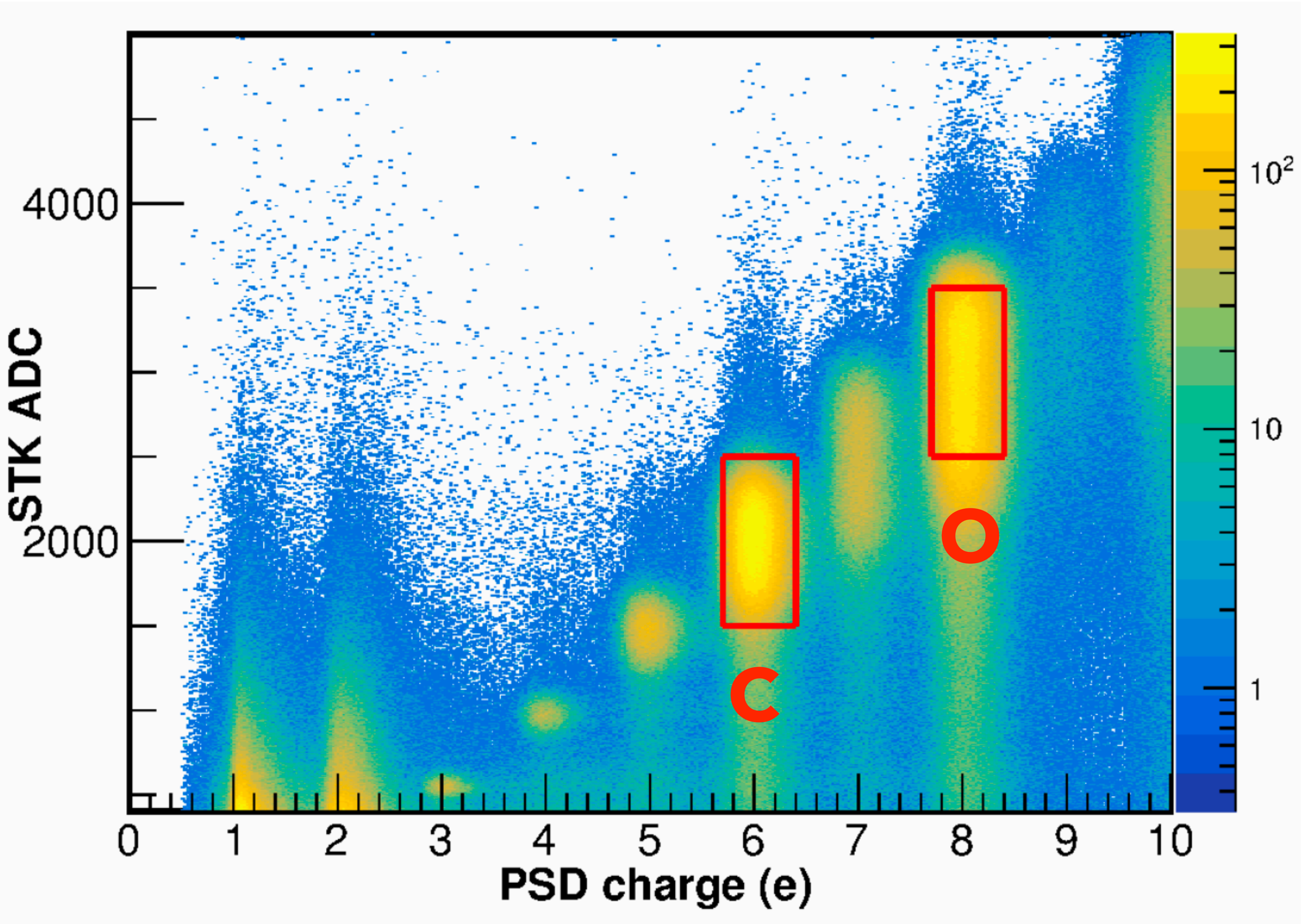


C & O Cross Section

Criteria for Sample Selection

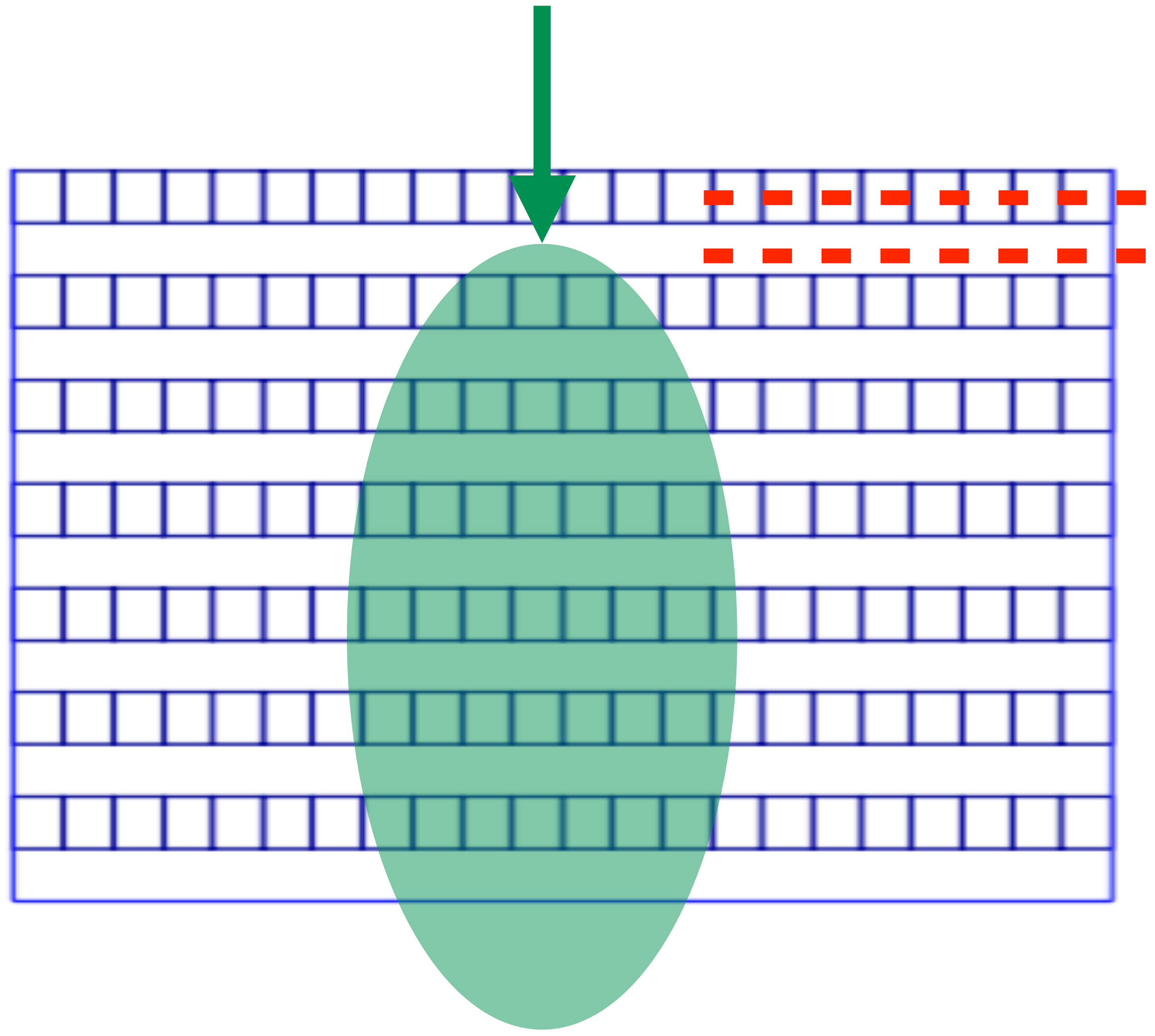
- Data sample:
  - Flight data: 96 months
- Energy range: > 50 GeV
- HET trigger
- Track finding (Kalman Filter)
- Pre-Selection:
  - Event containment
  - Interact after reaching the calorimeter

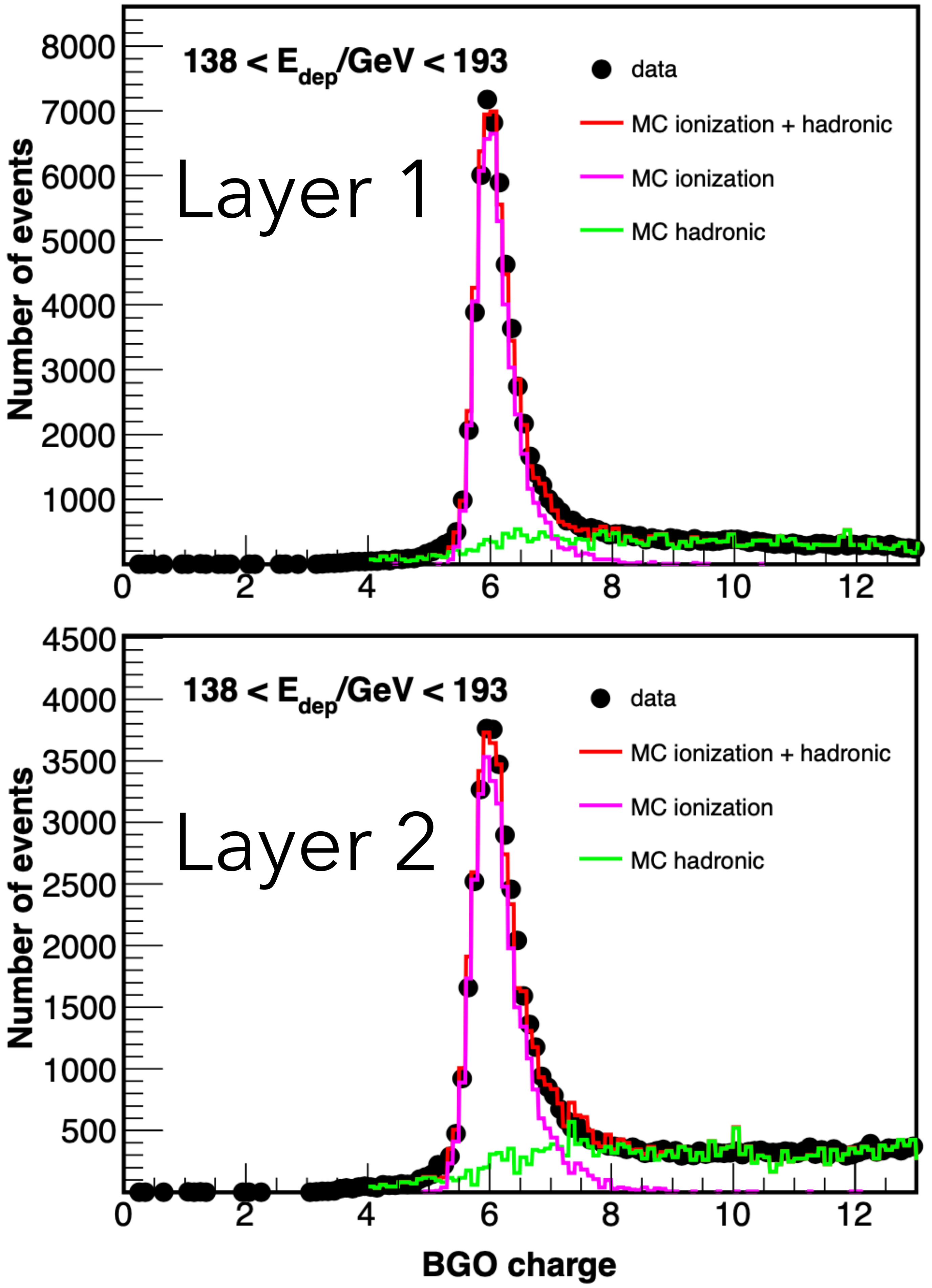
- Select C & O sample
  - Charge signal (with both PSD and STK)
- background: 0.1 ~ 0.2 %



Cross Section Measurement

- Point of nuclei fragmentation → Cross section
- Determine whether the nucleus survives through a layer by **changes in charge**





- Pink: ionization energy loss component (non-fragmented)
- Green: hadronic component (fragmented)

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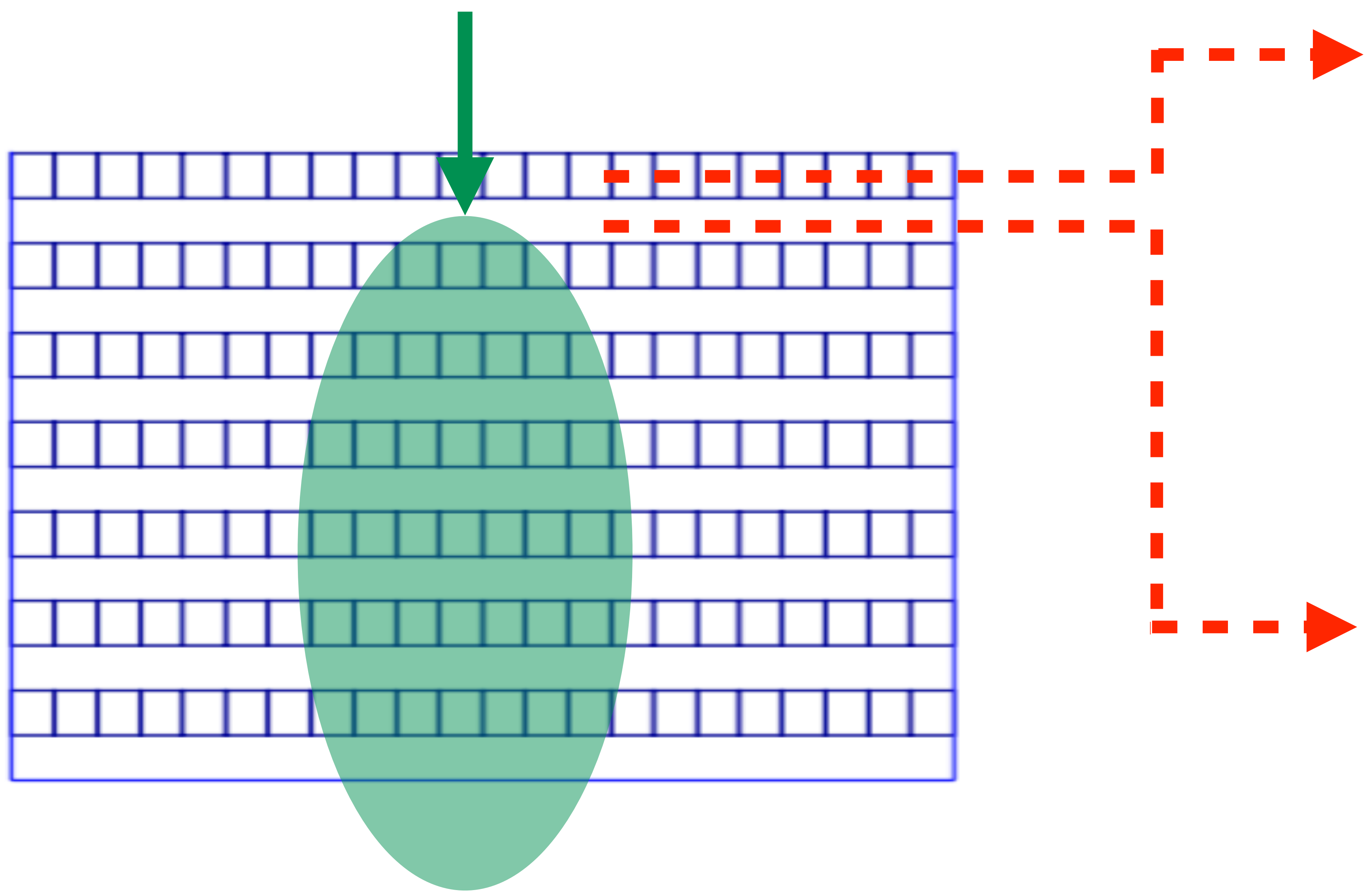
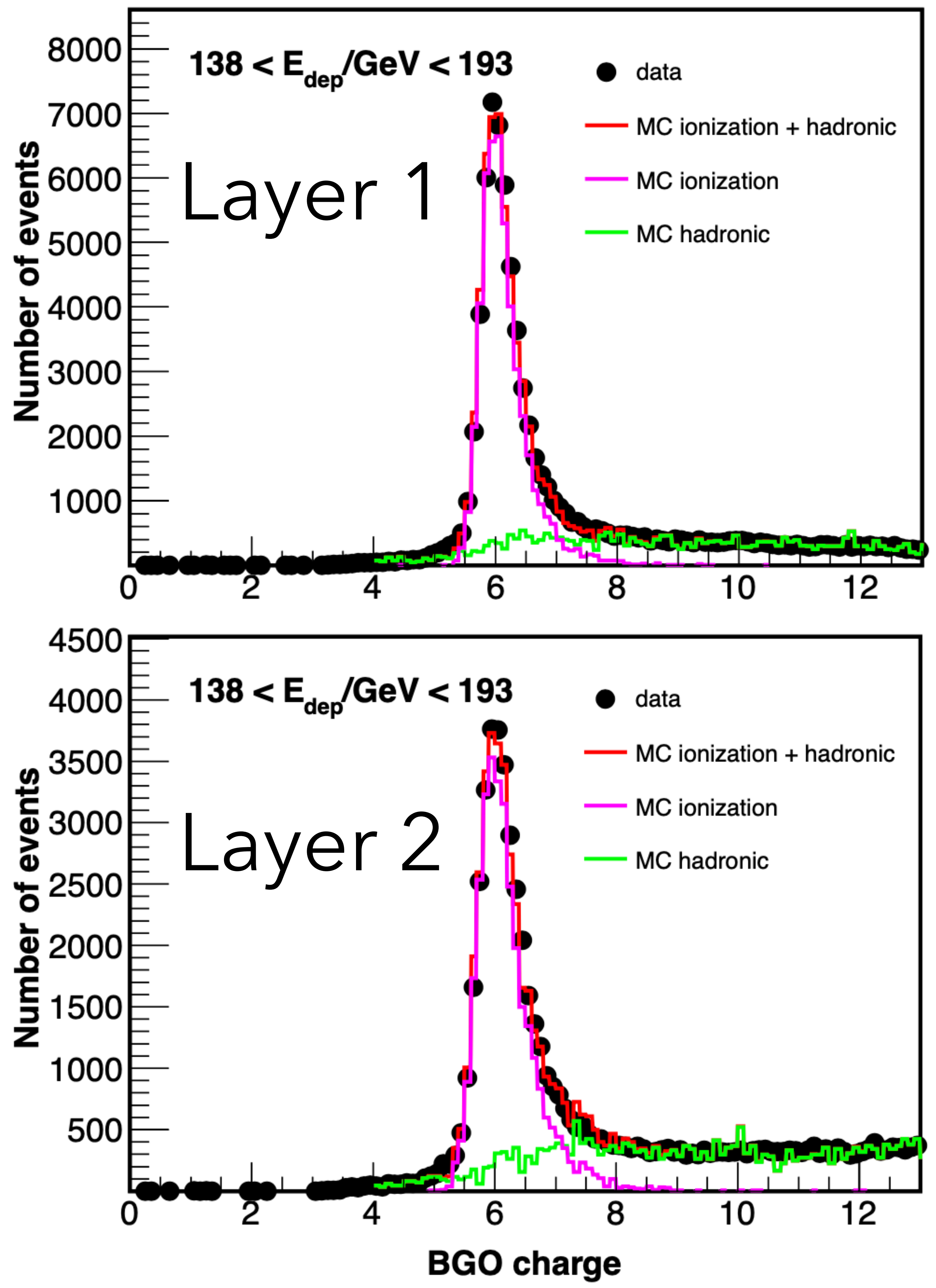




- Survival rates of a layer (The ratio of particles leaving the layer to those entering it.):

$$\varepsilon_{sur}(E, \Delta l) = \frac{N_{leave}(E, \Delta l)}{N_{enter}(E, \Delta l)}$$
$$= \exp(-n \cdot \Delta l \cdot \sigma_{BGO}(E))$$

E : Energy, Δl : Path length in BGO

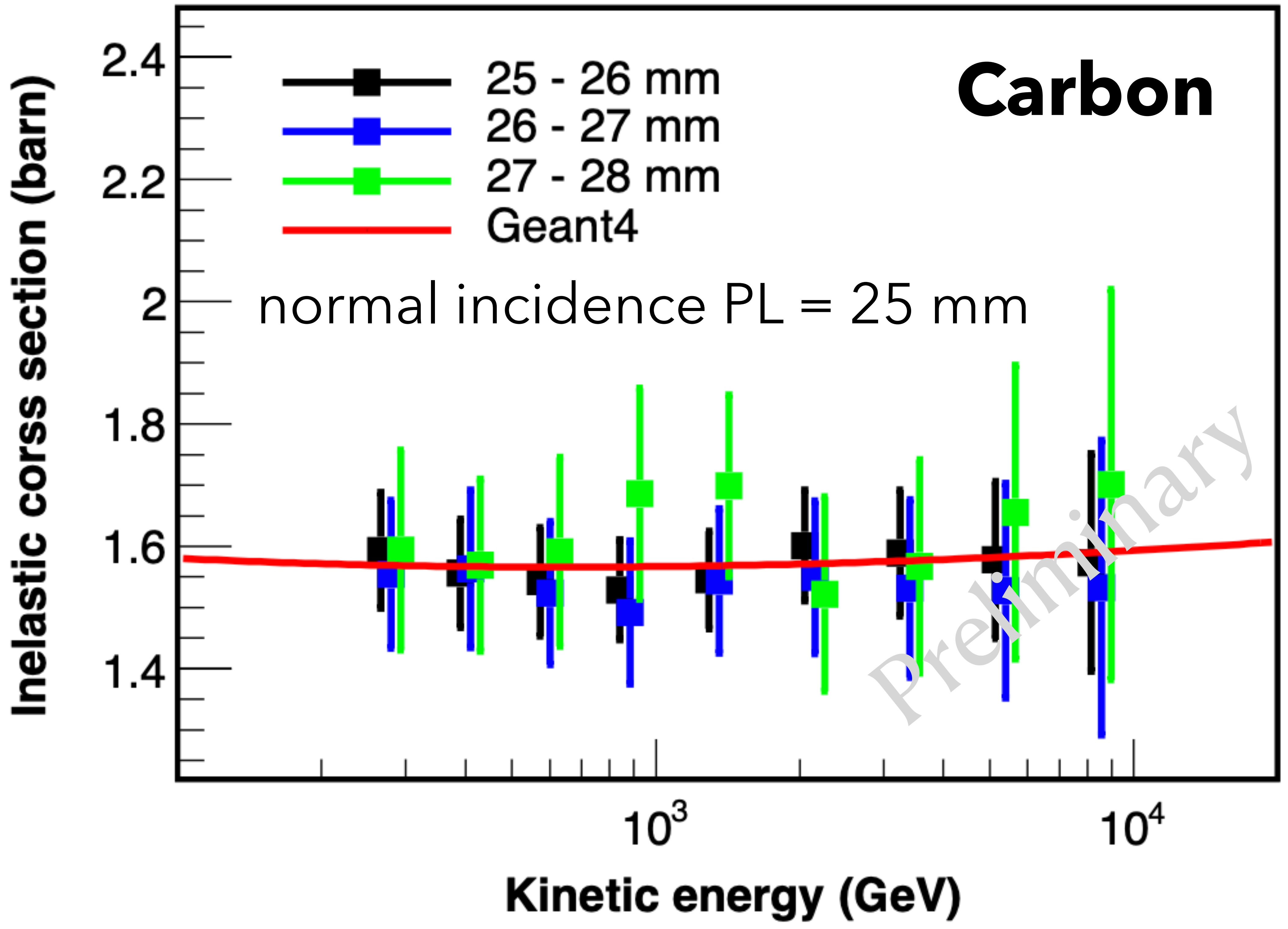
- Then calculate the cross section:

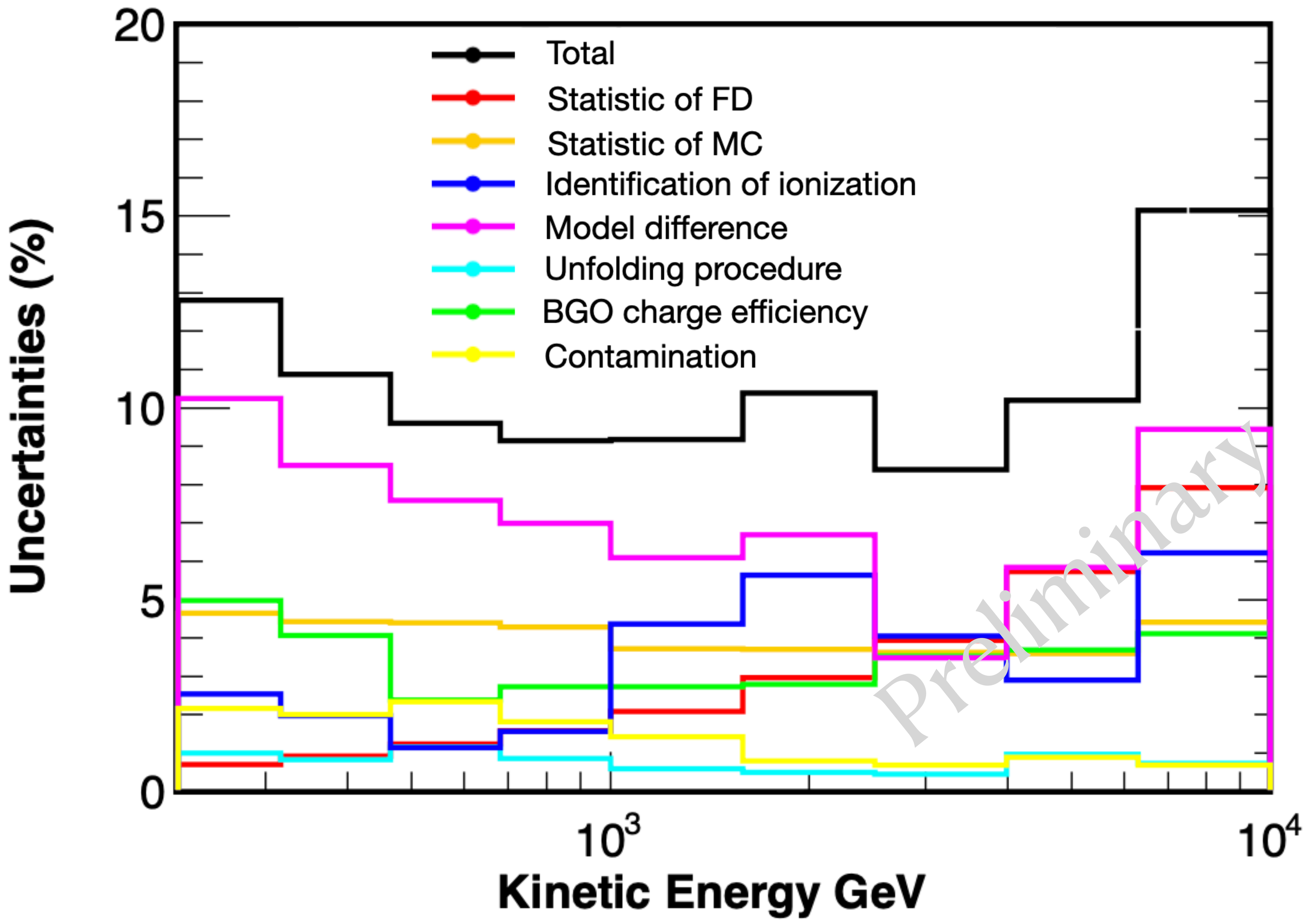
$$\sigma_{BGO}^{FD}(E, \Delta l) = \sigma_{BGO}^{MC}(E, \Delta l) \cdot \frac{\ln(\varepsilon_{sur}^{FD}(E, \Delta l))}{\ln(\varepsilon_{sur}^{MC}(E, \Delta l))}$$

Cross Section Measurement

- Inelastic hadronic cross sections of carbon on BGO target with varying path lengths

- Systematic uncertainty
- Main contributions: model difference (G4 & FLUKA), statistic of MC, identification of ionization, BGO charge efficiency

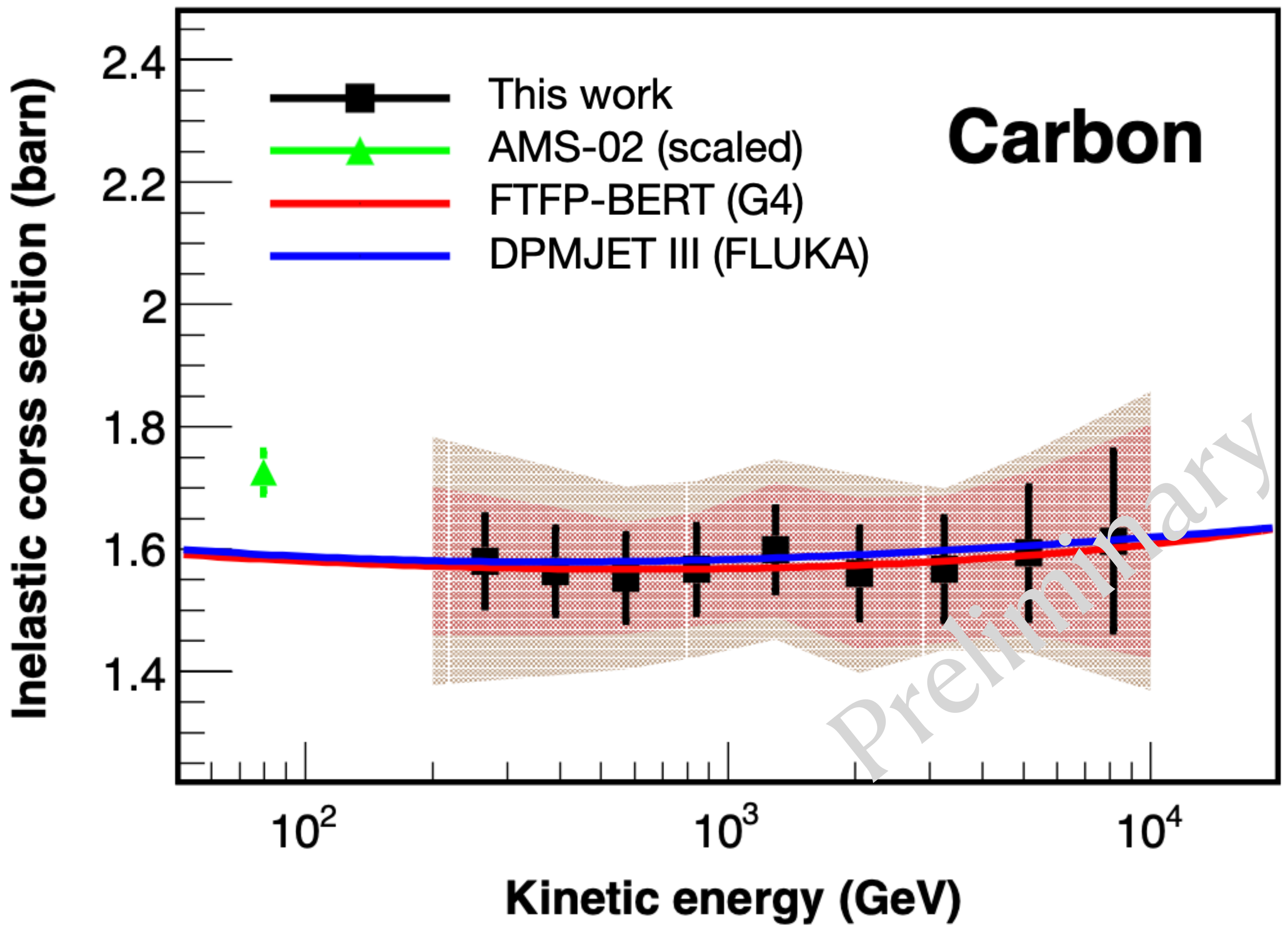


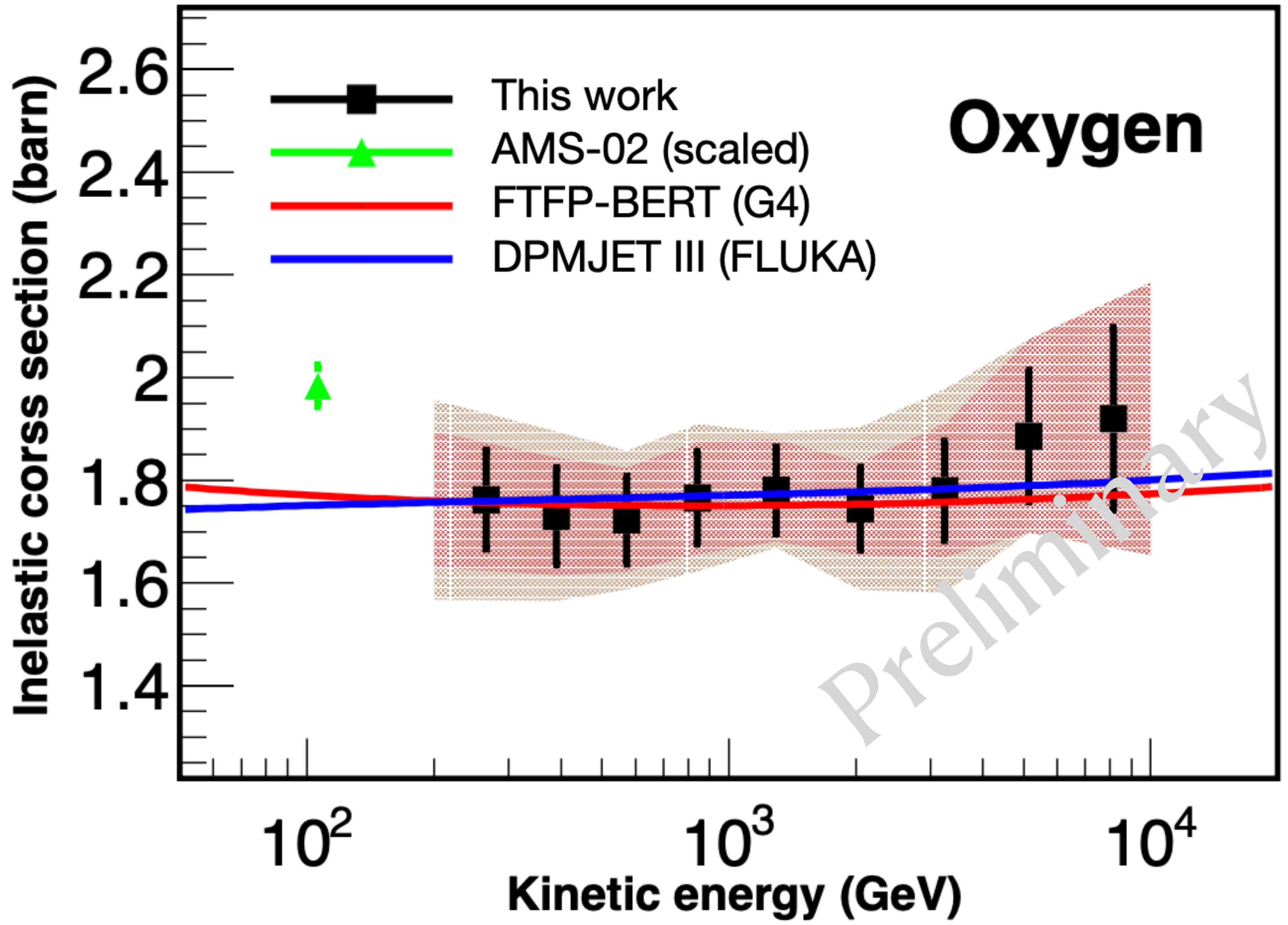


C & O Results

- Model comparisons: FTFP_BERT, DPMJET3
- AMS02 measurement not for BGO, so scaled: $\sigma^{AMS}_{target}/\sigma^{AMS}_{BGO}$

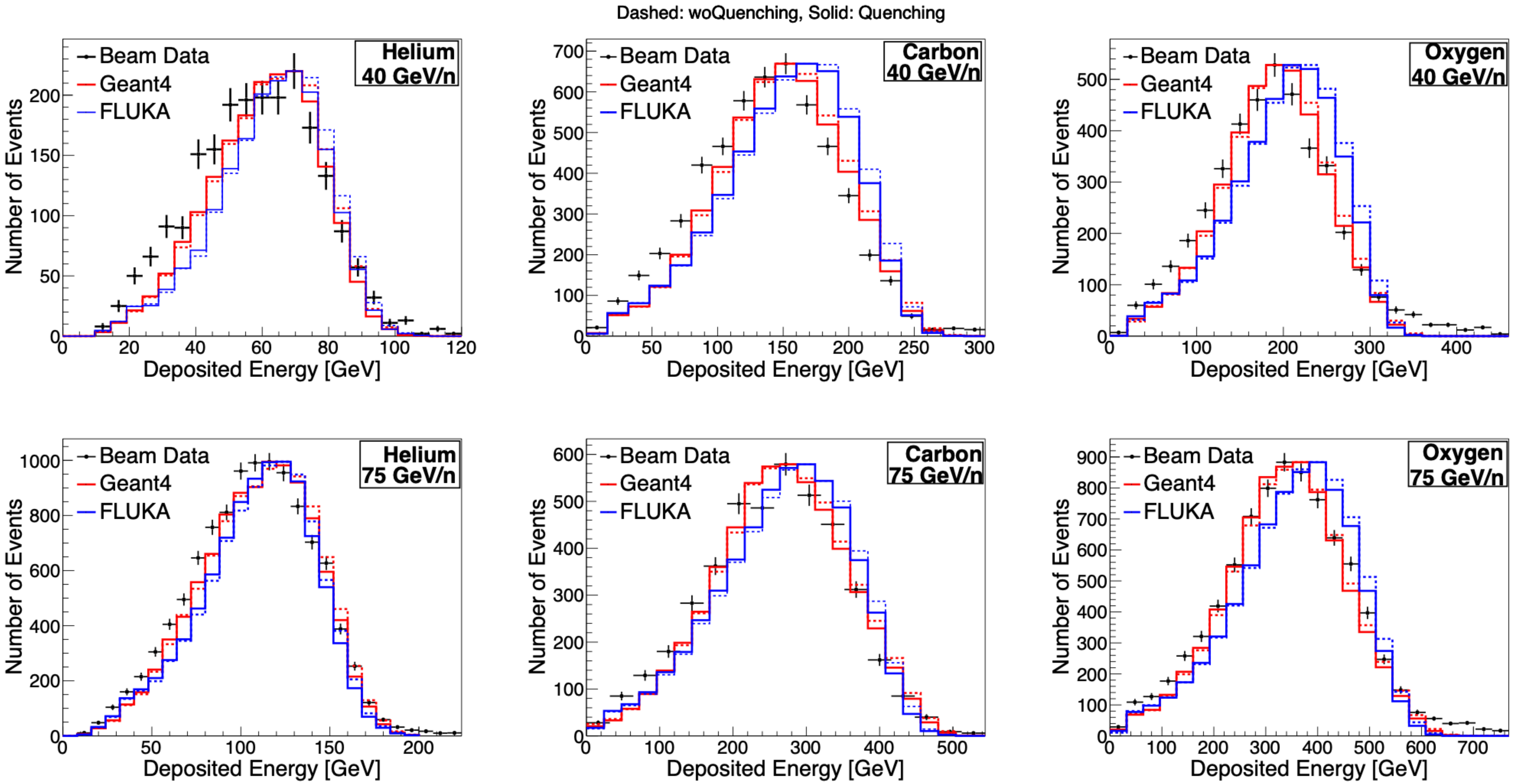
C & O: Measured inelastic hadronic cross sections are in excellent agreement with the models





Beam Test

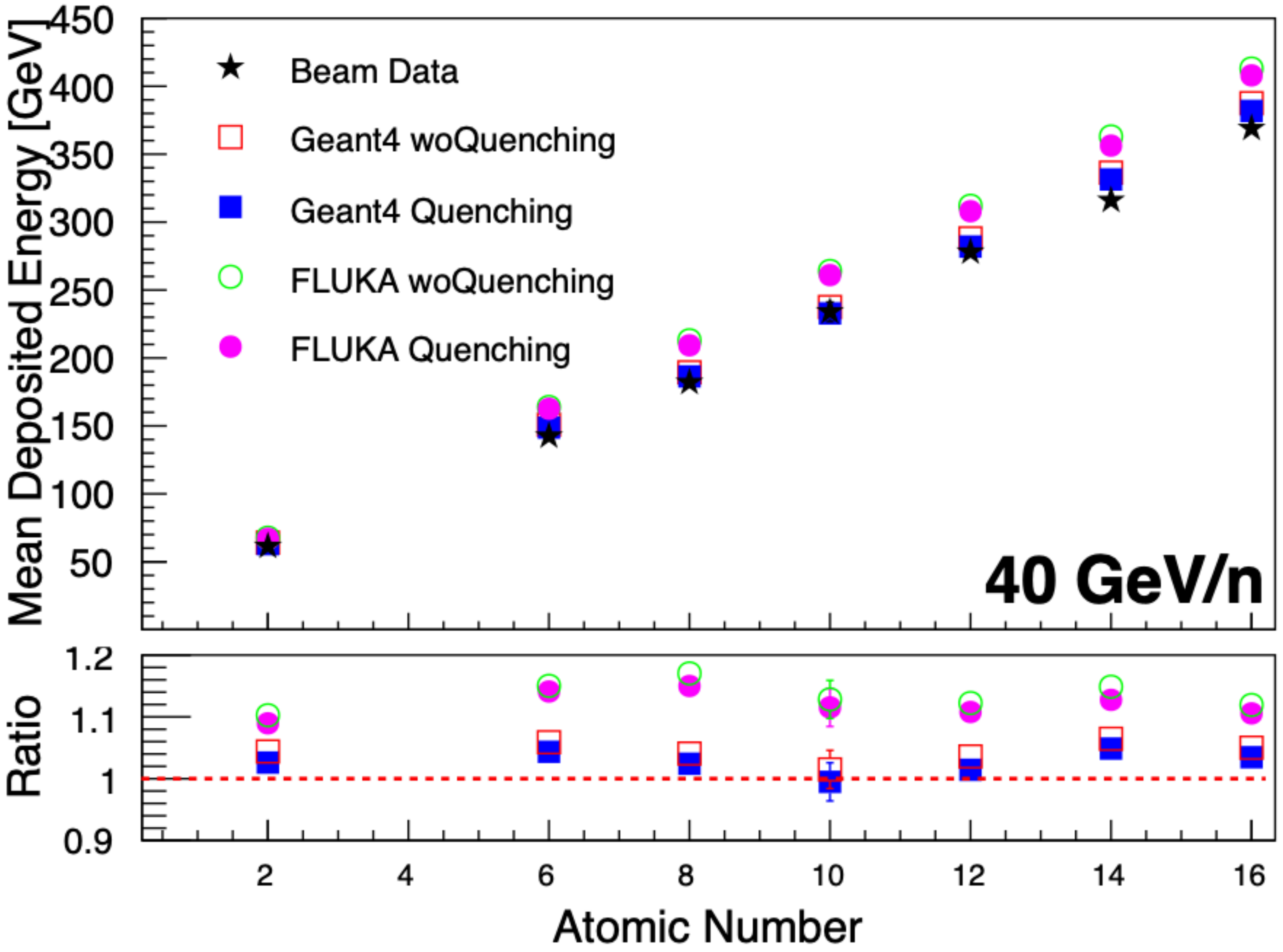
- Ion beam test @ CERN
- Remove the ionization component, just study the energy deposition of hadronic shower
- Geant4 shows better agreement with data compared to FLUKA

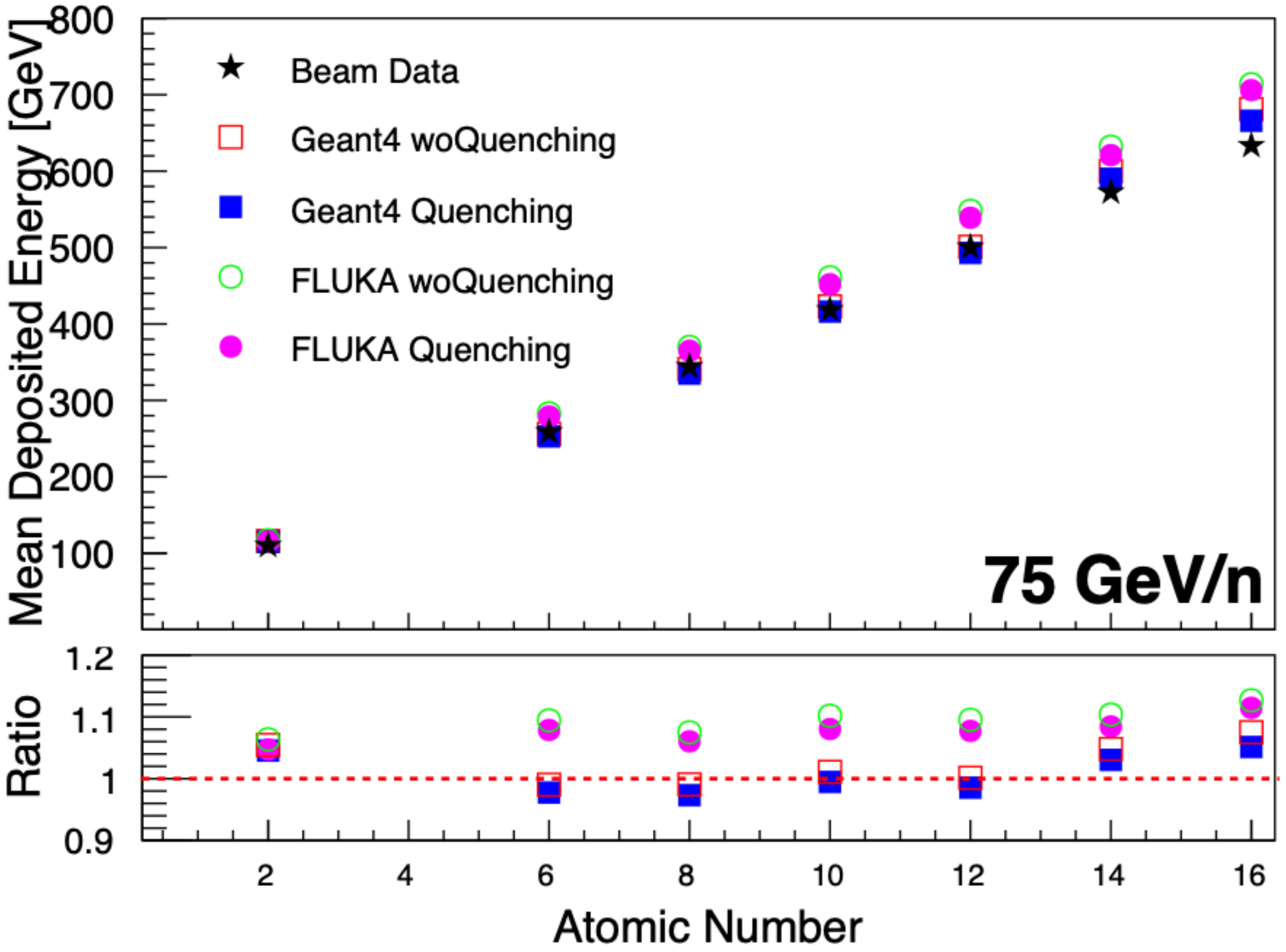


Z, Chen, et al., *NIMA.* 1055 (2023)

Beam Test

- Ion beam test @ CERN
- **Geant4/BT ~ 0.98**: the flux uncertainty would be affected by **~ 4%**





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Summary

- Hadronic inelastic cross section is important systematic affecting CR ion-flux measurement
- We presented hadronic cross section measurement
  - $Bi_4Ge_3O_{12}$ target
  - Proton: 18 GeV - 9 TeV
  - Helium: 20 GeV - 12 TeV
  - Carbon & Oxygen: 200 GeV - 10 TeV

✓ First measurement at these high energies!

- In DAMPE, Geant4 shows better agreement with data compared to FLUKA

Thank you !