Measurement of Cross Sections in Space with DAMPE

Paul Coppin
on behalf of the DAMPE collaboration

Motivation

- Astroparticle physics enters precision era
- Nuclear cross sections limit accuracy
  - Propagation models
    $\rightarrow$ production secondary CRs
  - Measurement nuclei fluxes

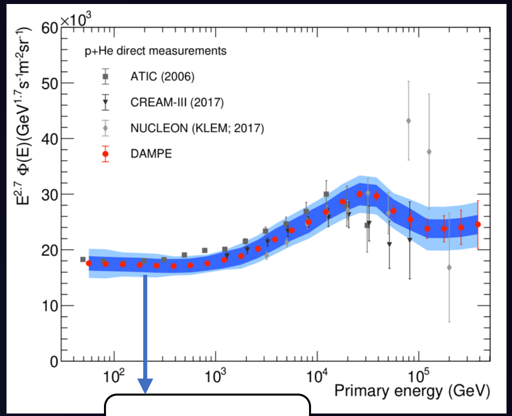
Motivation (space)

- Astroparticle physics enters precision era
- Nuclear cross sections limit accuracy
  - Propagation models
    → production secondary CRs
  - Measurement nuclei fluxes

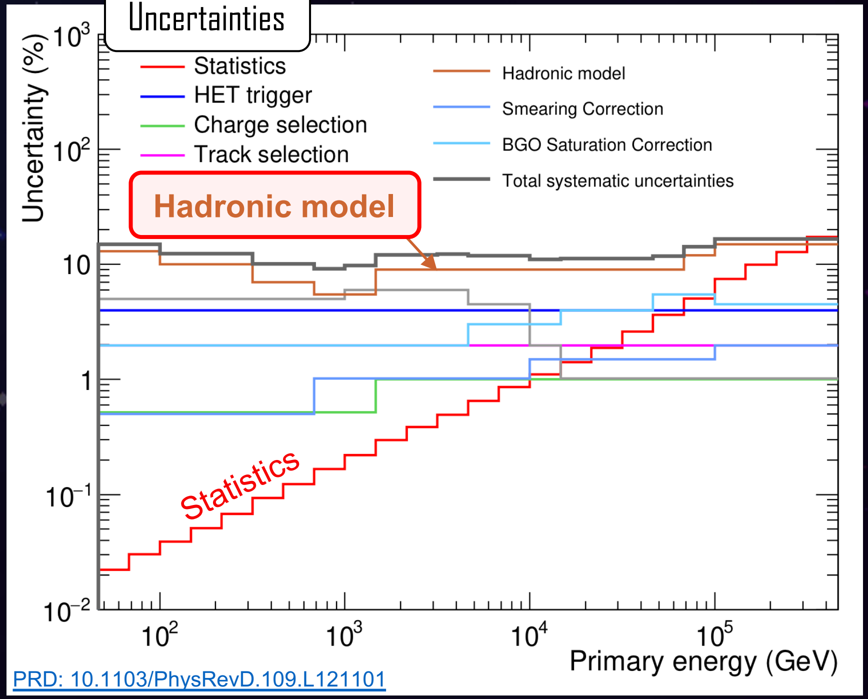
    → Cross section affects acceptance!

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

Flux of proton+helium

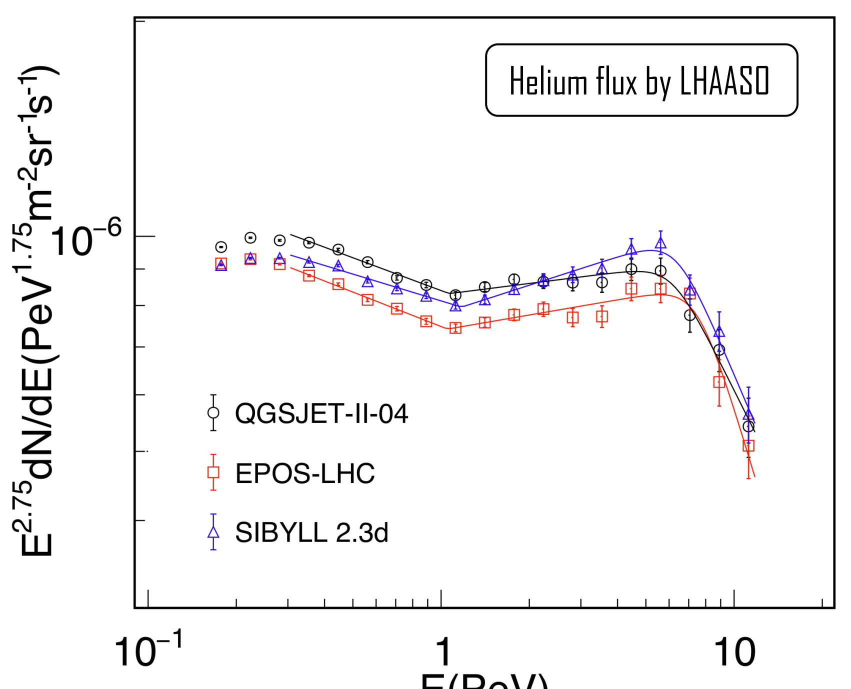


Uncertainties



Motivation (ground)

- Astroparticle physics enters precision era → E.g. helium flux measurement without unfolding by LHAASO
- Nuclear interaction models dominate accuracy of the result



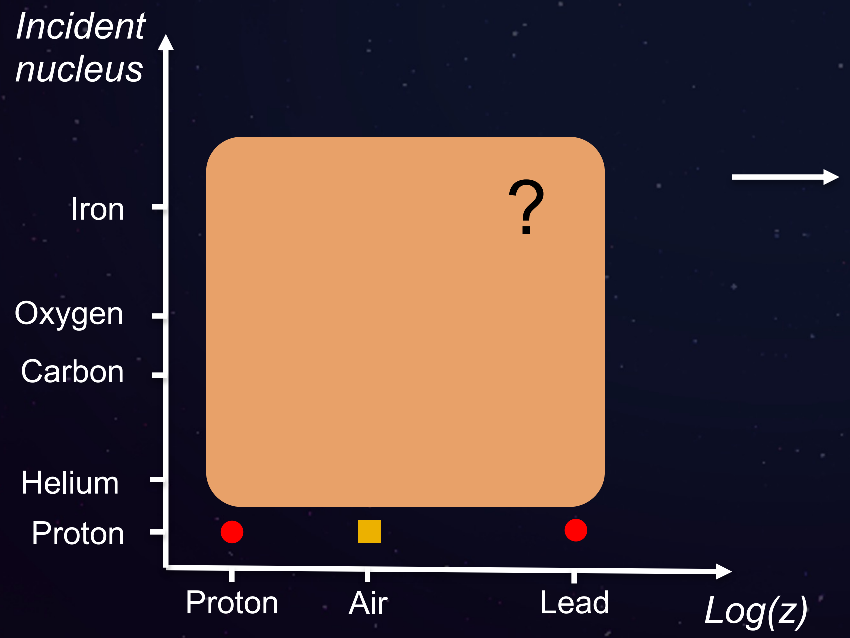
arXiv.2511.05013

"The largest systematic uncertainty is associated with the hadronic interaction model used in the simulation of shower development in the atmosphere and detector response."

Motivation

Inelastic cross section at TeV energies and above

- Accelerators: proton-proton, proton-lead (●)
- Ground-based CR experiments: proton-air (■)



Measurements available only for proton. Extrapolation leads to >20% uncertainty on nucleus cross section of other ions

Solution: Measurement with DAMPE!

The DAMPE experiment

- Also called *Wukong*
- Satellite launched in December 2015
- Sun-synchronous orbit
  (Altitude - 500 km, Period - 95 minutes, Oriented toward zenith)
- Records $\sim 5\times10^{6}$ events per day
- Large effective area and deep calorimeter (32 radiation lengths)
  - Electrons / photons:
    5 GeV to 10 TeV ; acceptance $\sim 0.3\ \mathrm{m^2\ sr}$
  - CR ions:
    10 GeV to ~500 TeV; acceptance $\sim 0.1\ \mathrm{m^2\ sr}$

Collaboration between:

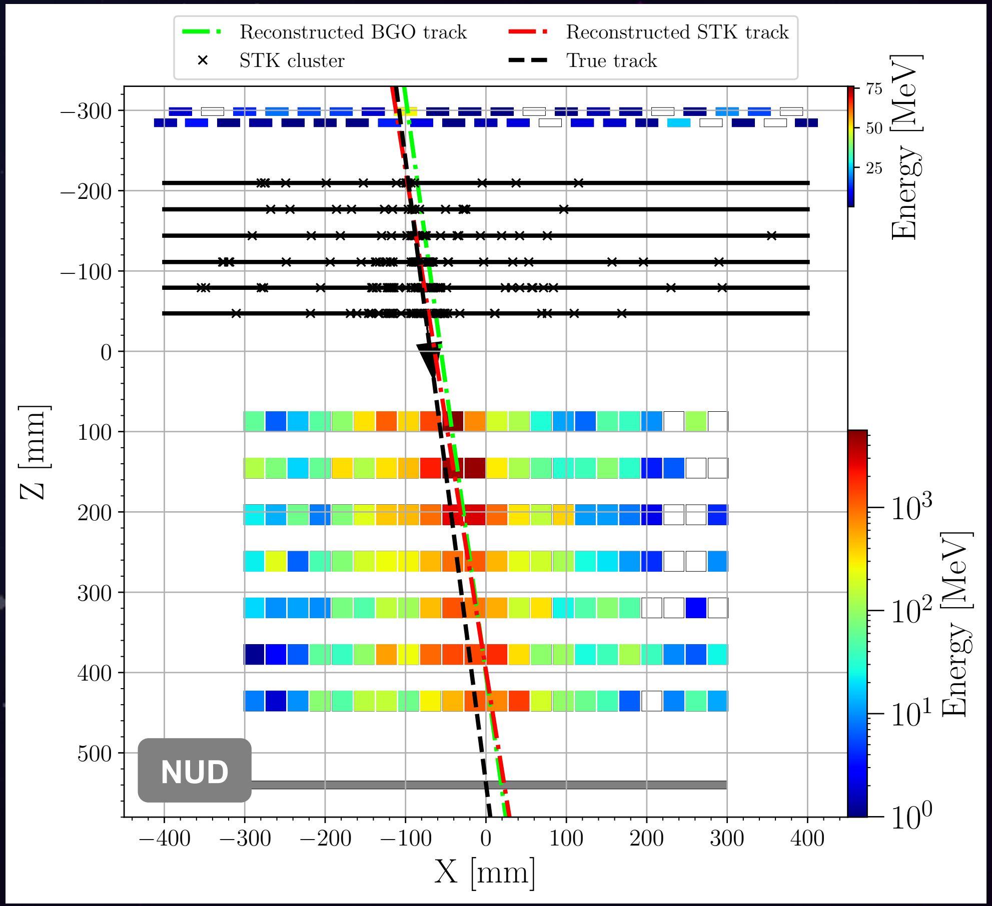
China
- Purple Mountain Observatory, CAS, Nanjing
- University of Science and Technology of China, Hefei
- Institute of High Energy Physics, CAS, Beijing
- Institute of Modern Physics, CAS, Lanzhou
- National Space Science Center, CAS, Beijing

Switzerland
- University of Geneva

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

The DAMPE experiment

- Layered design with 4 sub-detectors:
  - Plastic scintillator detector (PSD)
    → Charge
  - Silicon-Tungsten tracKer-converter (STK)
    → Tracking + charge
  - Calorimeter (BGO)
    → Energy
  - NeUtron detector, NUD
    → Electron/proton separation



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    → Inelastic interaction point
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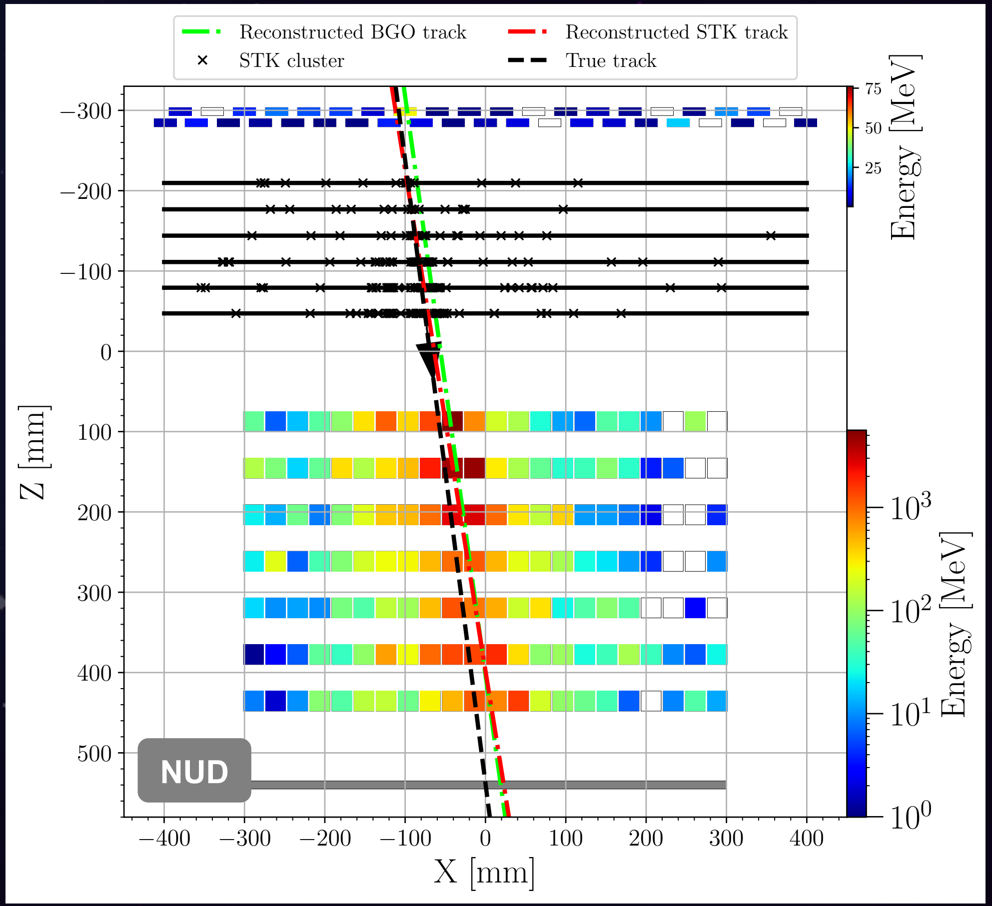
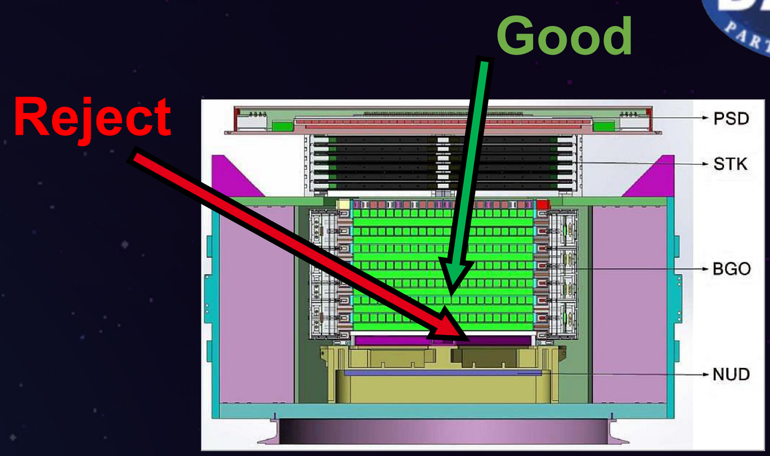


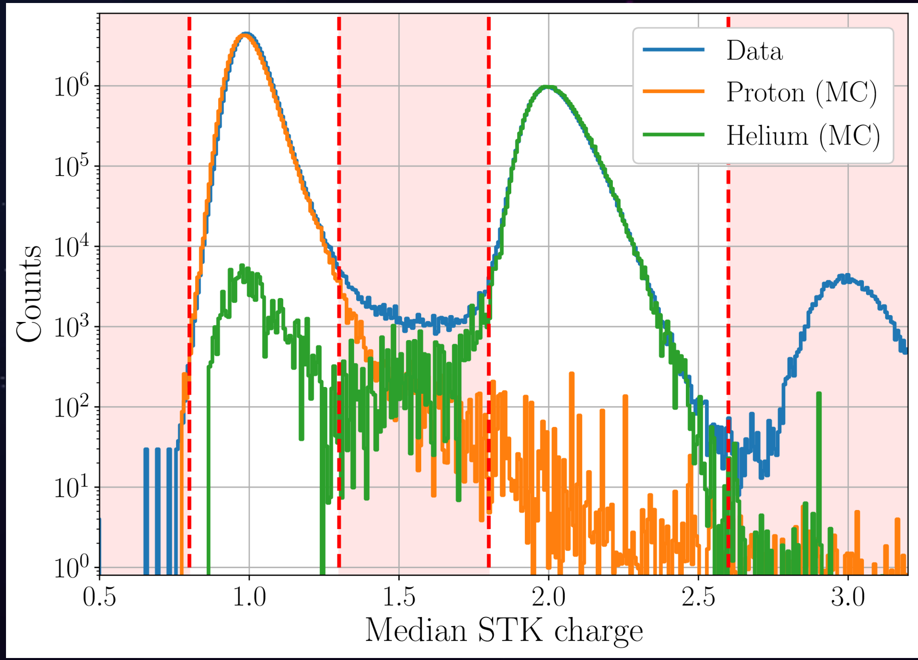
Proton and Helium-4

Selection

1. MIP trigger
2. Pre-cuts → contained events
   10.1016/j.astropartphys.2022.102795
3. Criteria:
   1. Basic quality cuts
   2. Remove electrons
   3. Interact after reaching calorimeter
   4. Fall P or He charge window

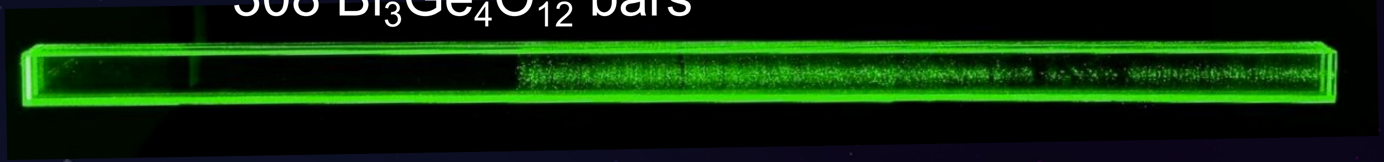
⇒ > 85% signal efficiency,
≲ 0.2% background

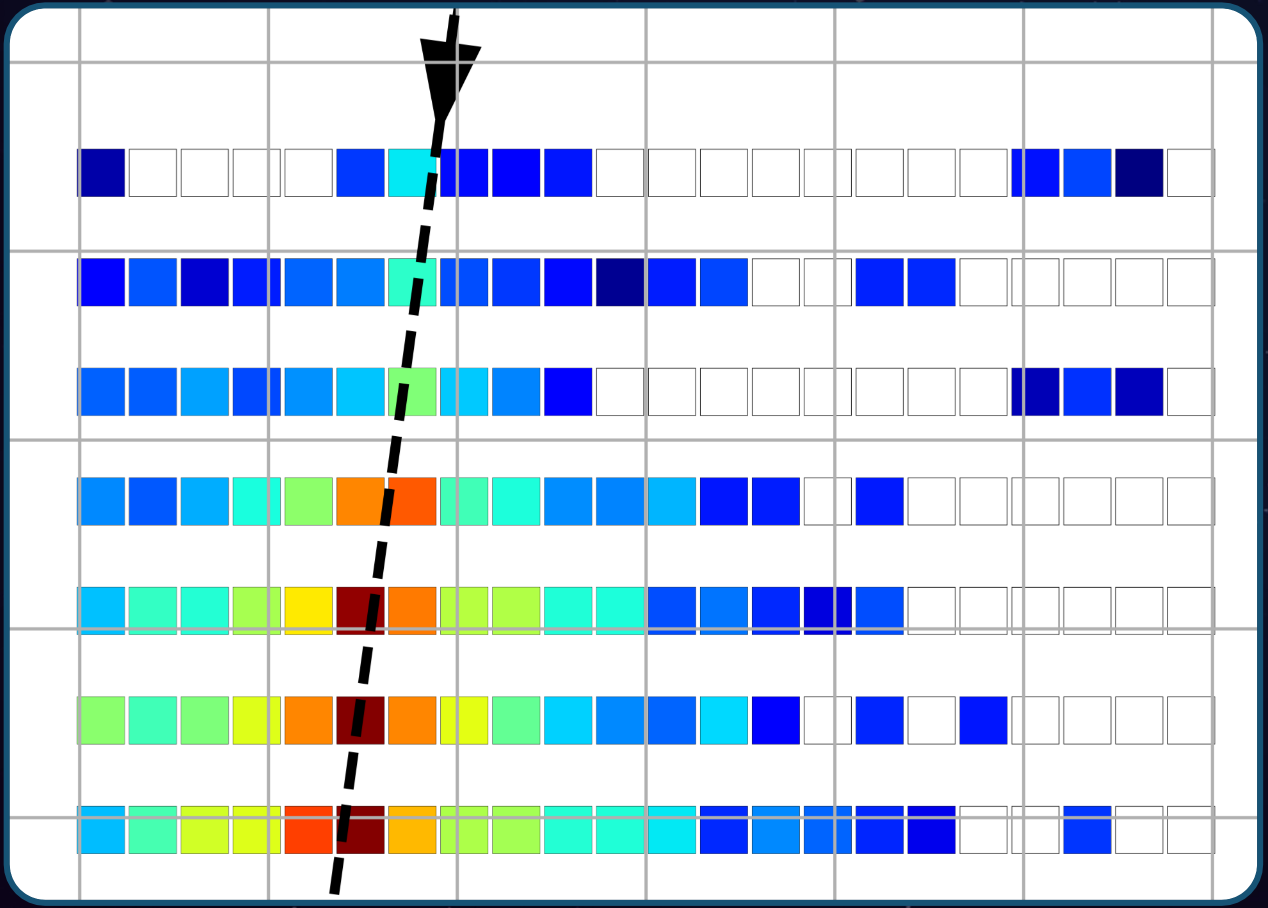




Methodology

Calorimeter with
308 $Bi_3Ge_4O_{12}$ bars





- Measurement:
  - Inelastic hadronic cross section
  - Proton and helium primary
  - $Bi_4Ge_3O_{12}$ target (calorimeter)

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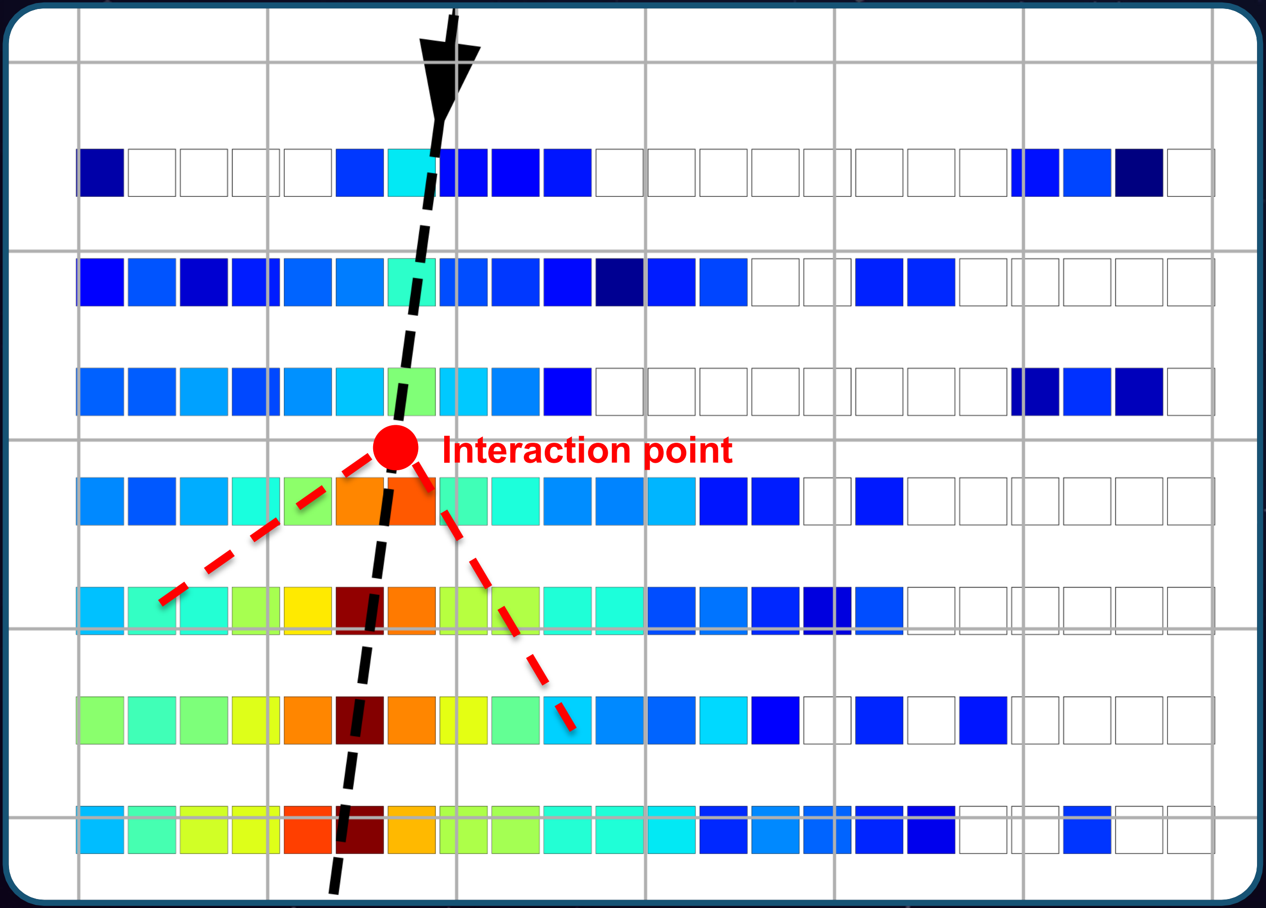
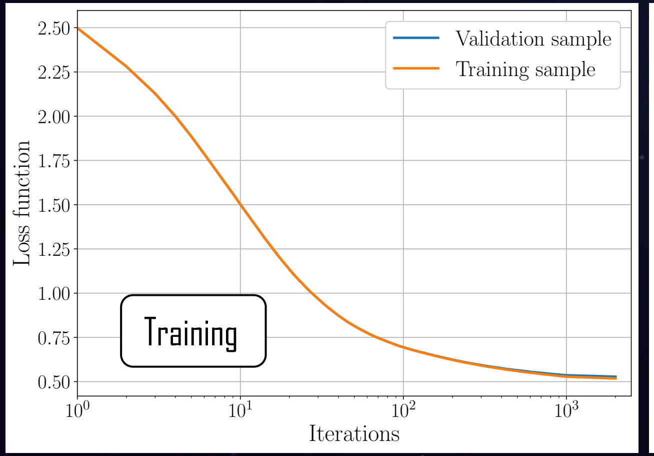


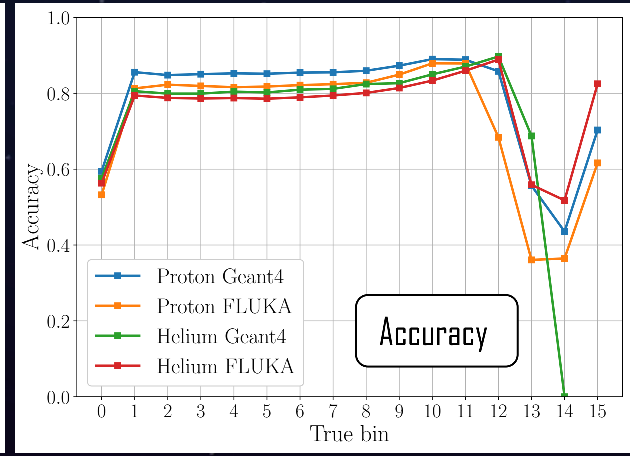
- Measurement:
  - Inelastic hadronic cross section
  - Proton and helium primary
  - $Bi_4Ge_3O_{12}$ target (calorimeter)

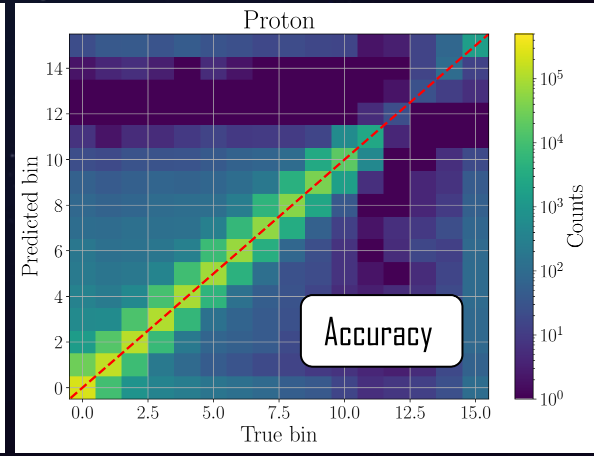
⇒ Determine depth of interaction point

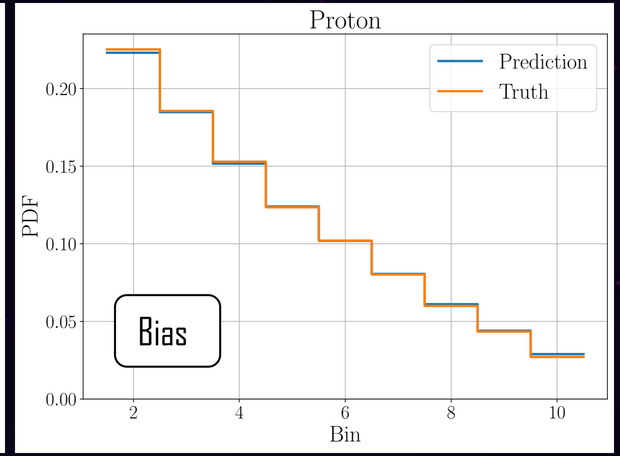
Interaction depth classifier

- Cross section ⟷ point of inelastic interaction
- Gradient boosted decision tree (XGB)
  - 16 output classes:
    - Before calorimeter
    - One per layer (14x)
    - After calorimeter
  - ~80% accuracy

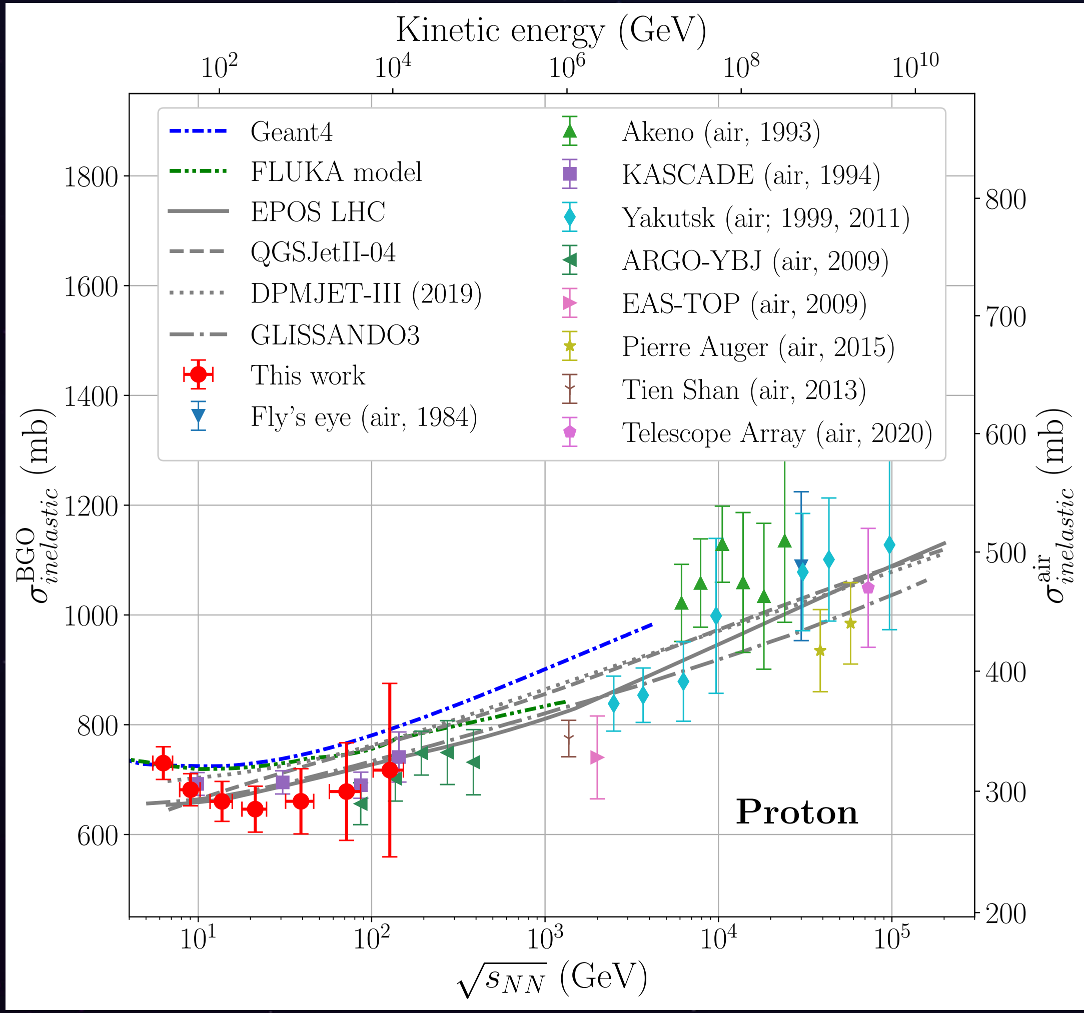






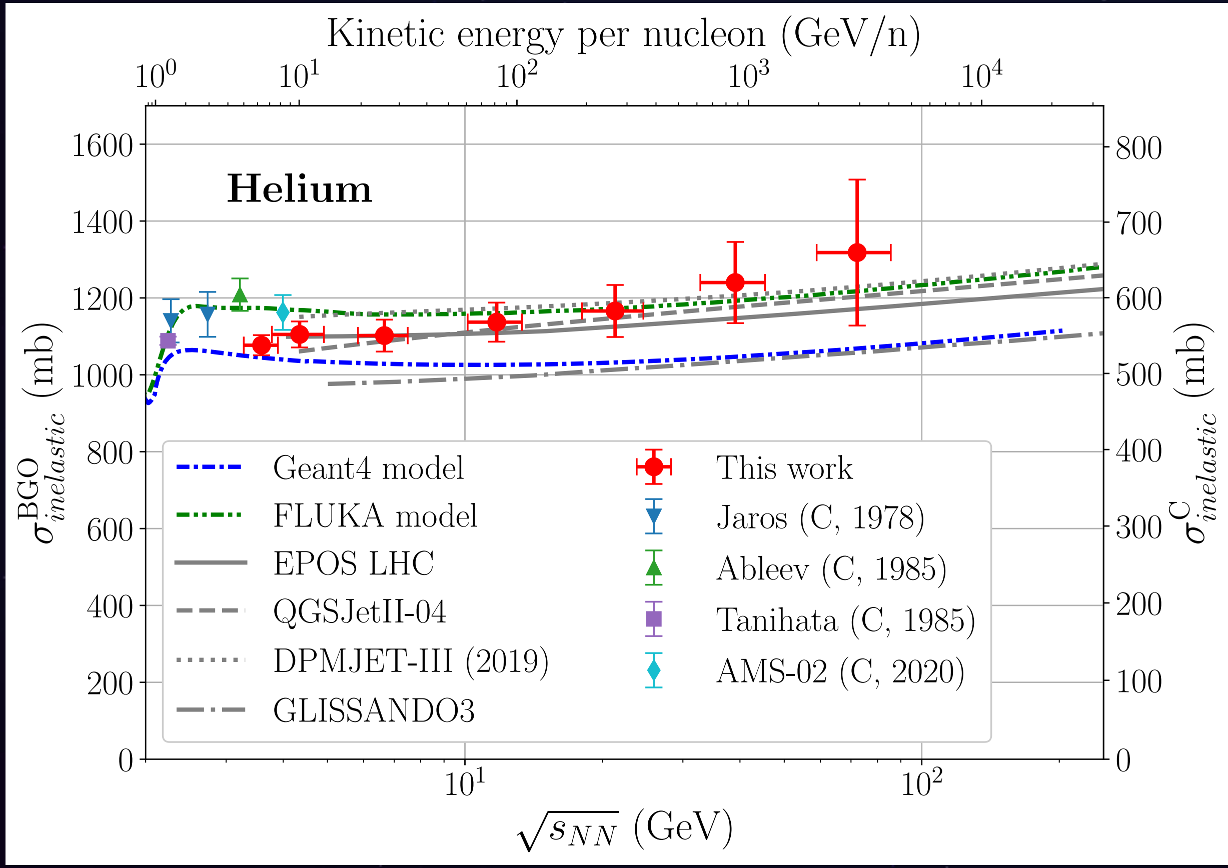


Results - Proton



- 19 GeV – 10 TeV
- Below model predictions
- Excellent agreement with ground-based CR observatories

Results - Helium



- 5 GeV/n – 3 TeV/n
  → First result at TeV!
- Within model predictions
- Good agreement with previous results

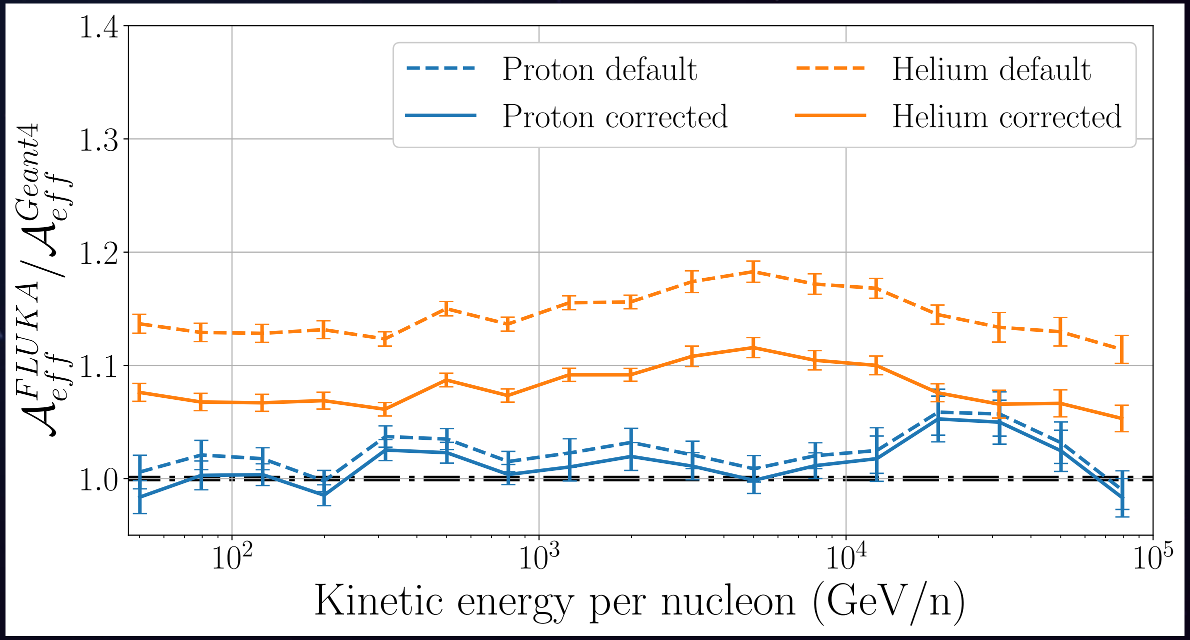
Effect on flux normalisation

- Effective detector acceptance depends on cross section:

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

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

- Our results significantly improve Geant4-FLUKA agreement
  - Minor effect for proton
  - Major effect for helium

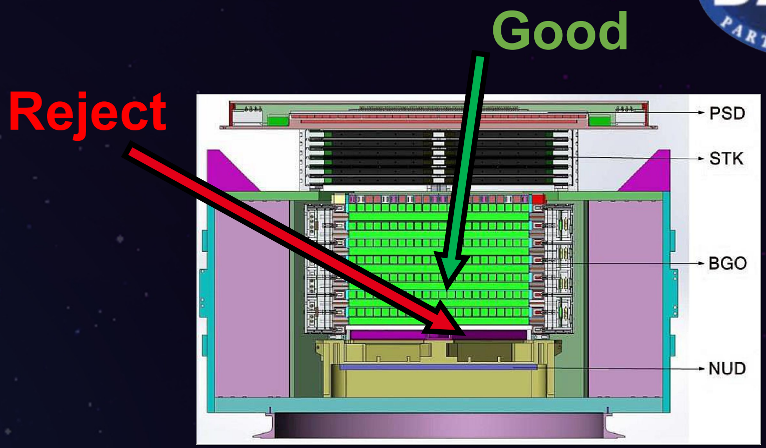


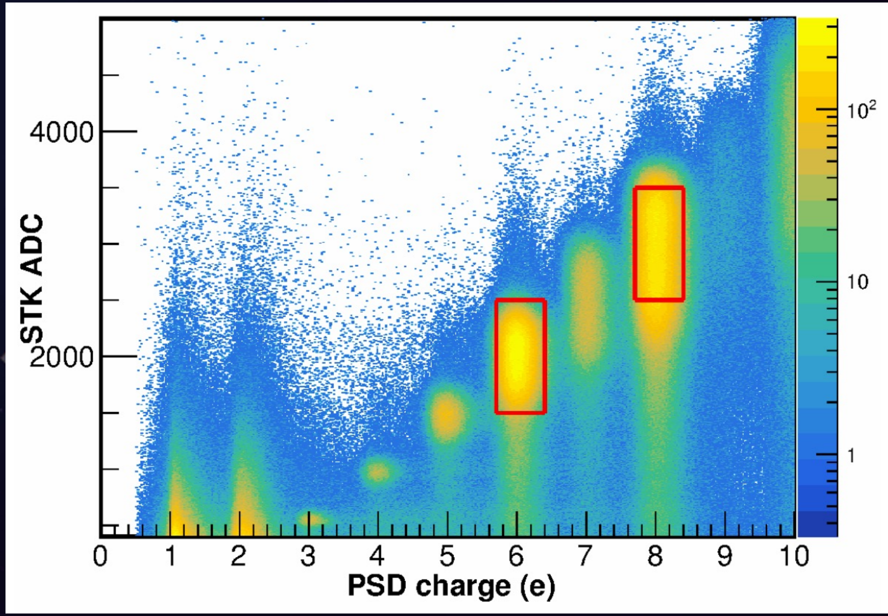
Carbon and Oxygen

Selection

1. High-energy trigger
2. Pre-cuts → contained events
   10.1016/j.astropartphys.2022.102795
3. Criteria:
   1. Basic quality cuts
   2. Energy > 50 GeV
   3. Interact after reaching calorimeter
   4. Charge signal (PSD & STK)

⇒ Background: 0.1~0.2%

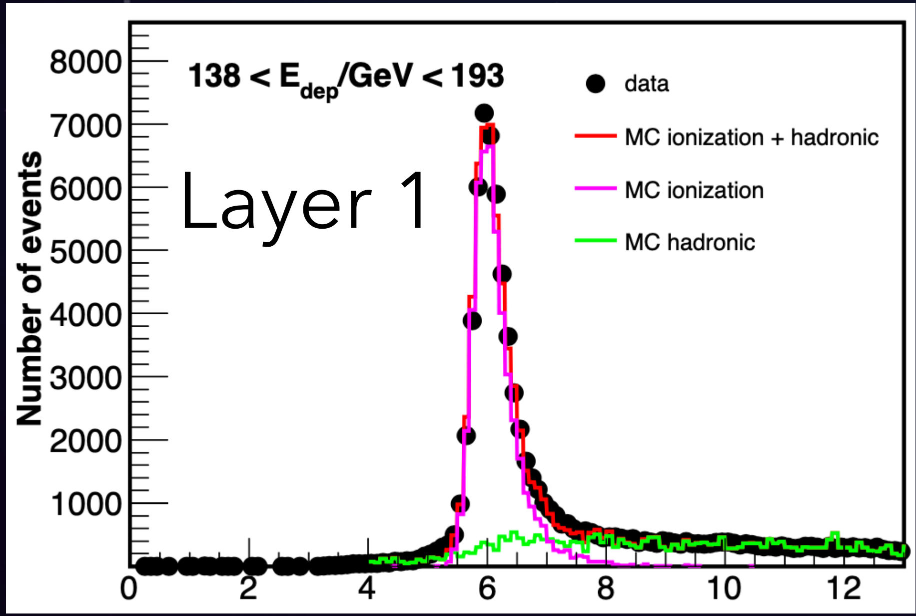


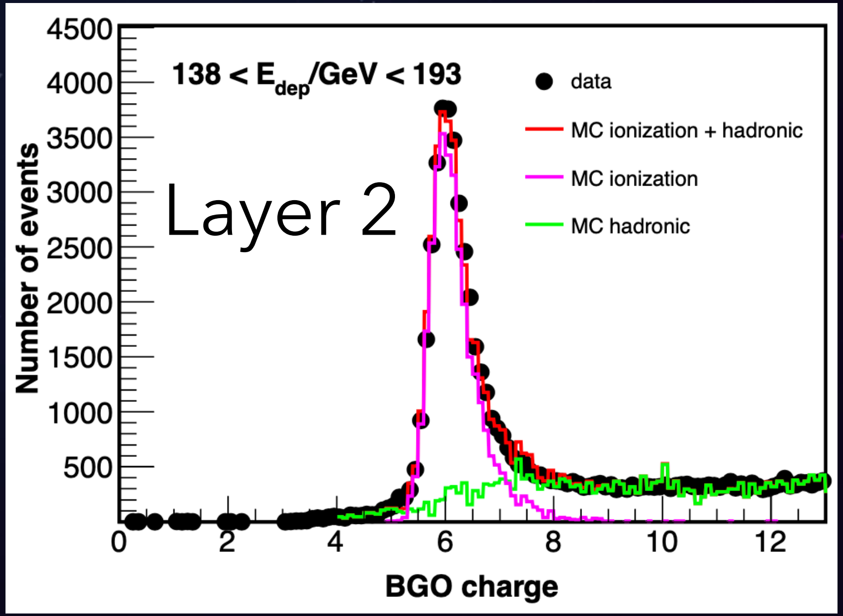


Methodology

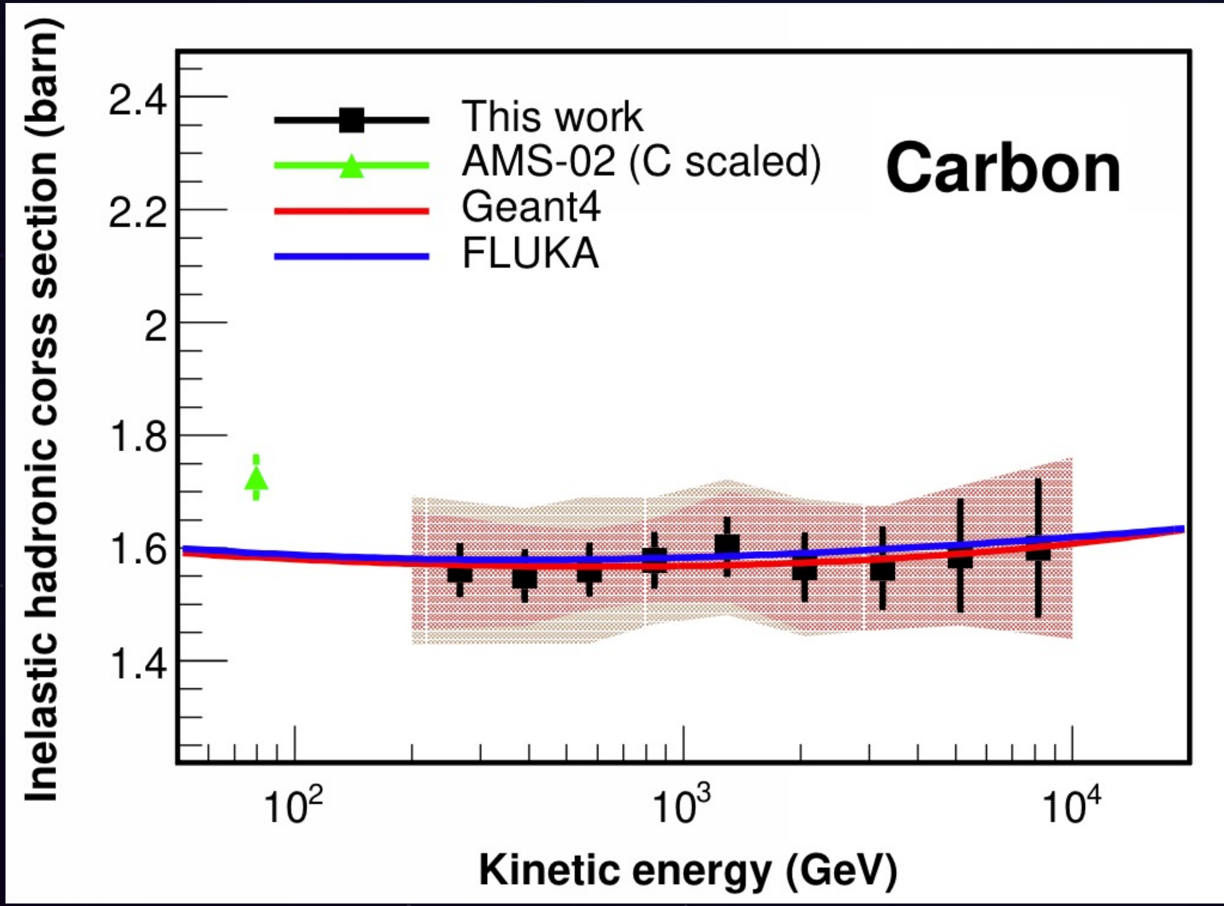
- Monitor change in charge to see if a nucleus interacts
- Survival probability $\leftrightarrow$ cross section:

$$\epsilon = N_{L_2}^{MIP} / N_{L_1}^{MIP} = \exp(-n \cdot \Delta l \cdot \sigma) \quad \Rightarrow \quad \boxed{\sigma = \sigma_{MC} \cdot \frac{\ln \epsilon_{\mathrm{data}}}{\ln \epsilon_{\mathrm{MC}}}}$$



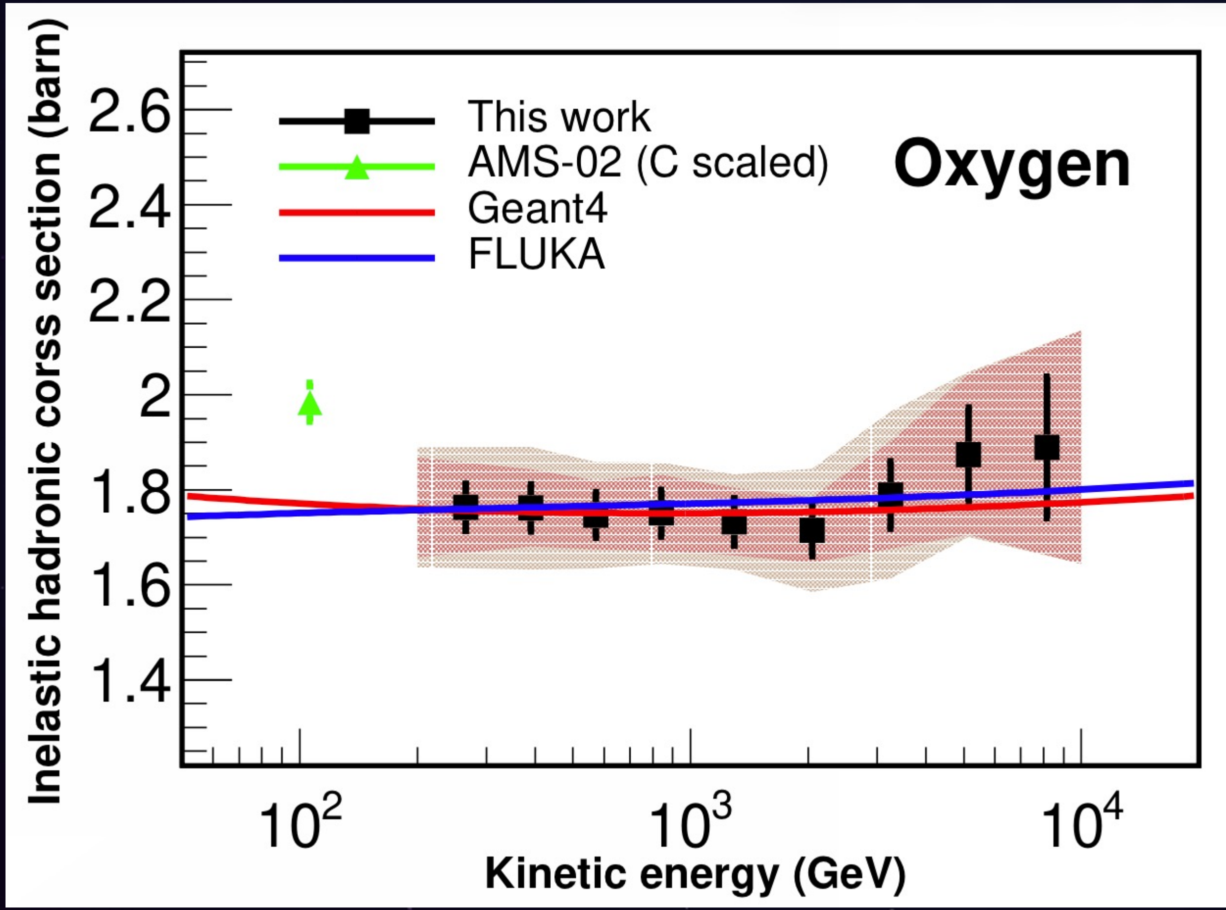


Results - Carbon



- Kinetic energy (fixed target): $200\ \mathrm{GeV} - 10\ \mathrm{TeV}$ → First results at TeV!
- Excellent agreement with model predictions

Results - Oxygen



- Kinetic energy (fixed target): $200\ \mathrm{GeV} - 10\ \mathrm{TeV}$ → First results at TeV!
- Excellent agreement with model predictions

Conclusion & outlook

- Inelastic cross section measurement
  → Improves accuracy ion fluxes
- Published this year!
  - Proton and Helium-4
    PRD: 10.1103/PhysRevD.111.012002
  - Carbon-12 and Oxygen-16
    PRD: 10.1103/k2wp-c3hb

  → First measurement at these energies for He, C, and O!
- Outlook:
  - Extend approach to other ions

Backup slides

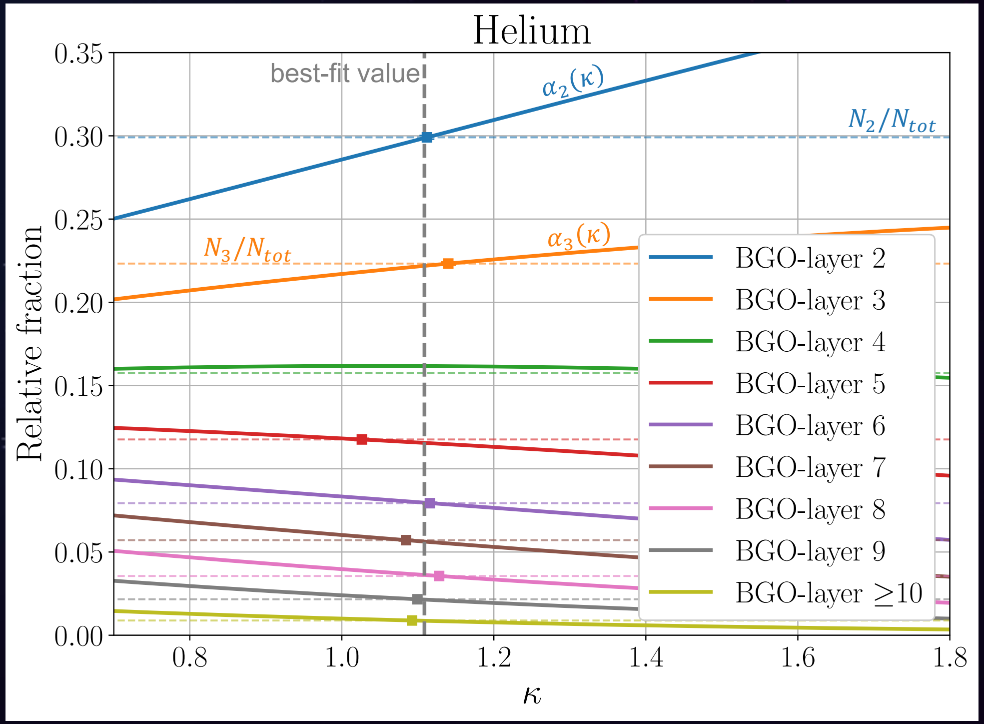
Proton-helium: Method

- Cross section ⟷ point of inelastic interaction
- Modify MC cross section until it matches data:

$$\sigma_{true} = \kappa \cdot \sigma_{MC}$$

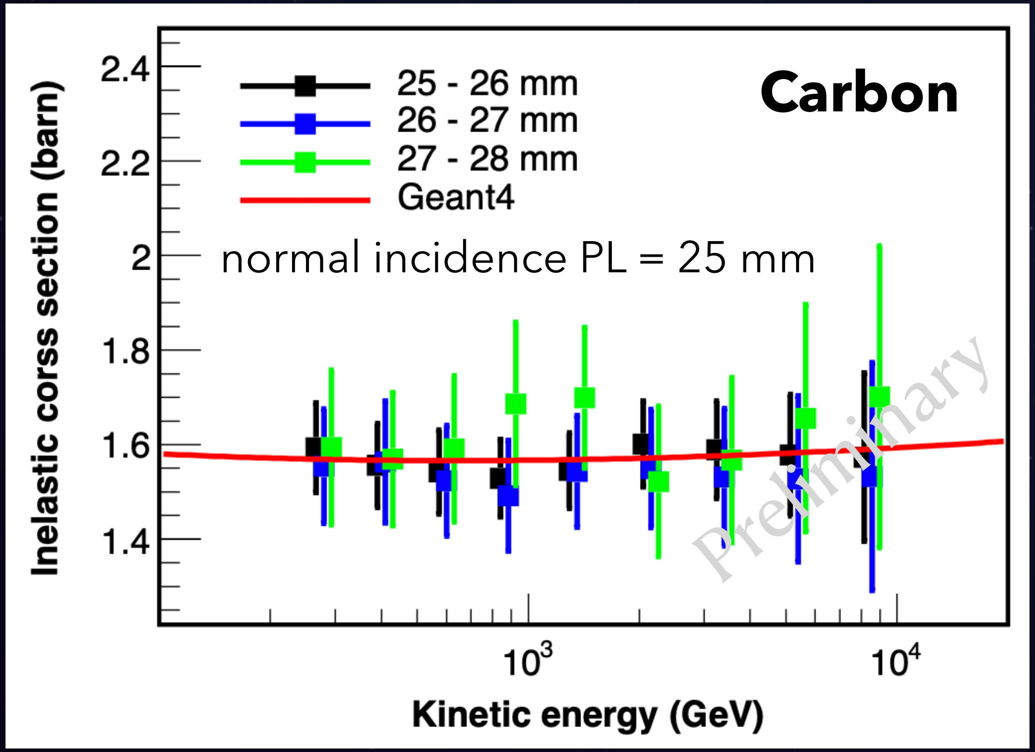
- Compare MC (α_i) to data $\left(\frac{N_i}{N_{tot}}\right)$:

$$\mathcal{L}(\kappa) = \frac{N_{tot}!}{N_2!\,N_3!\ldots N_{10}!}\prod_{i=2}^{10}\alpha_i^{N_i}(\kappa)$$



Carbon-oxygen: Method

- Accounting for path-length difference due to different incidence angles



- Normal incidence: 25 mm
- 3 bins are considered: [25,26] ; [26,27] ; [27,28]
- Final result by averaging

Proton-helium: Uncertainties

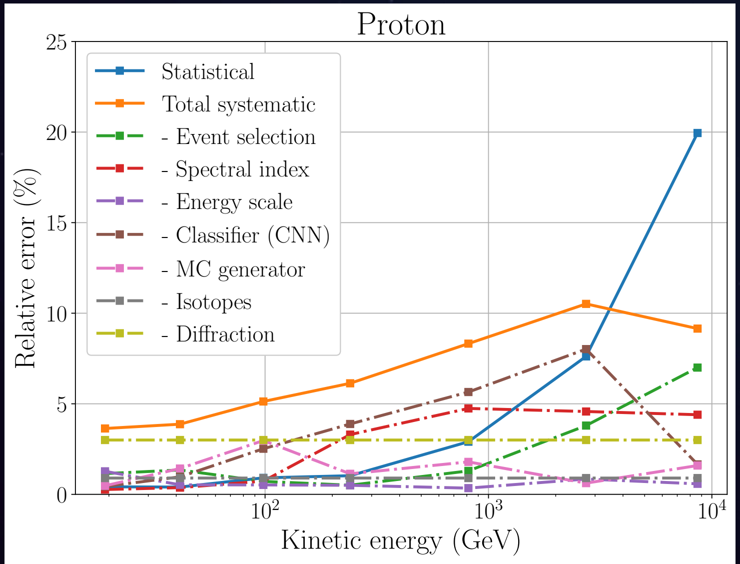
- Statistical uncertainty dominates in last bin
- Systematic uncertainty:

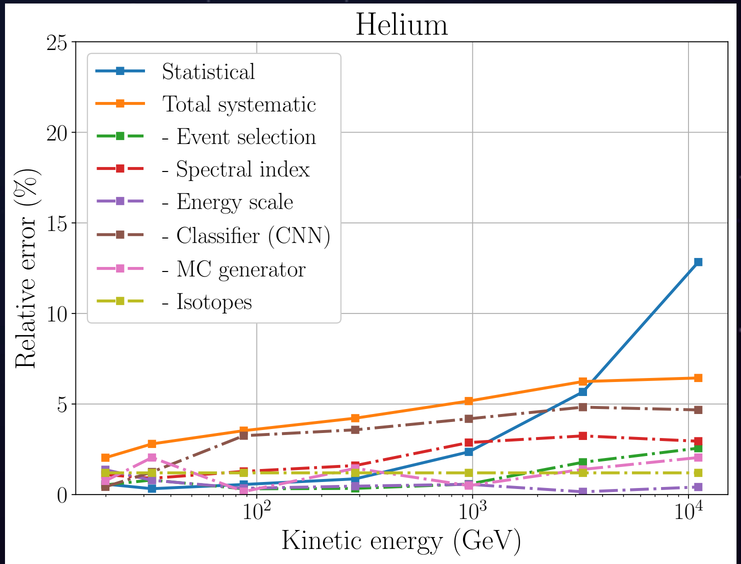
Largest

- Classifier
- Spectral index
- Event selection

Smallest

- Isotopes
- MC generator
- Energy scale





Carbon-Oxygen: Uncertainties

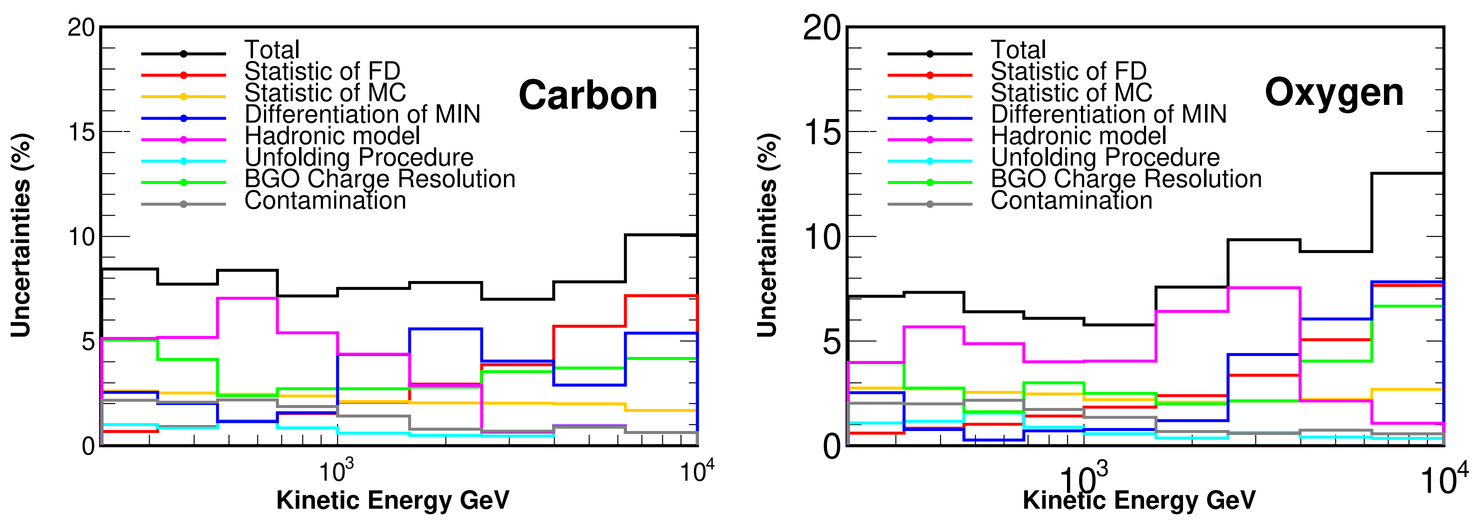
- Statistical uncertainty dominates in last bin
- Systematic uncertainty:

Largest

- Charge selection
- ID interaction
- Hadronic model

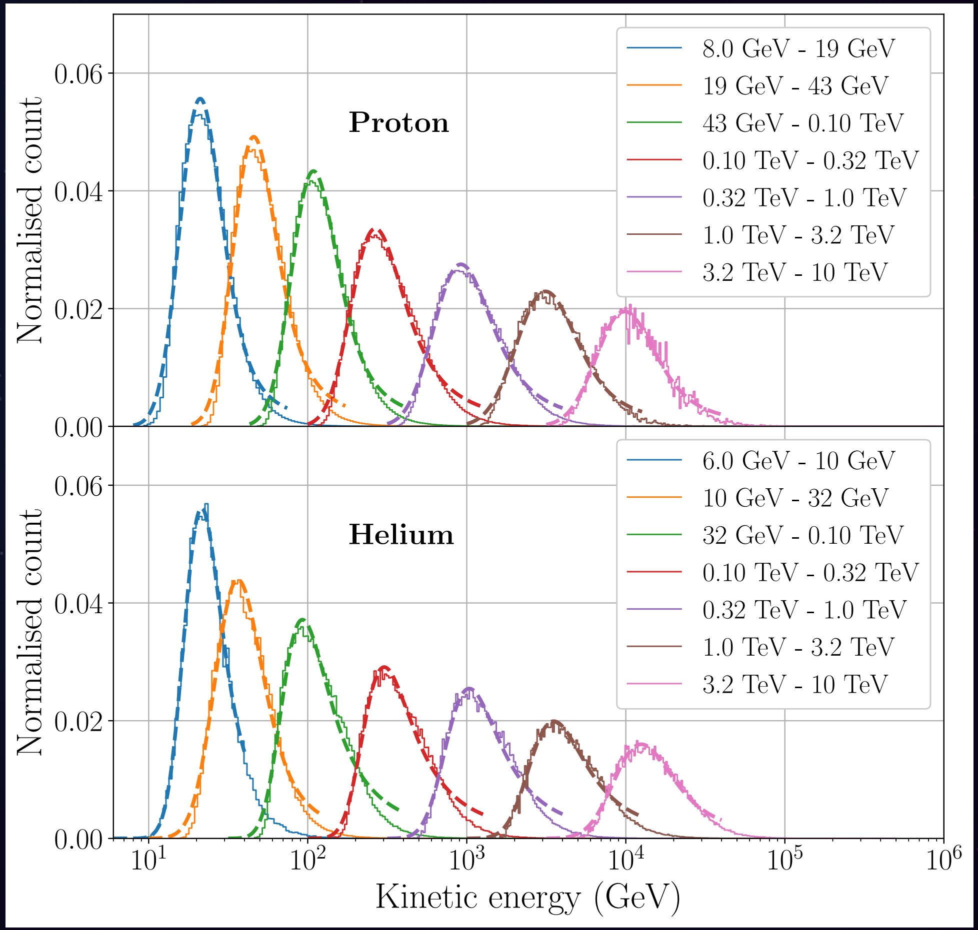
Smallest

- Background
- Unfolding
- Energy scale



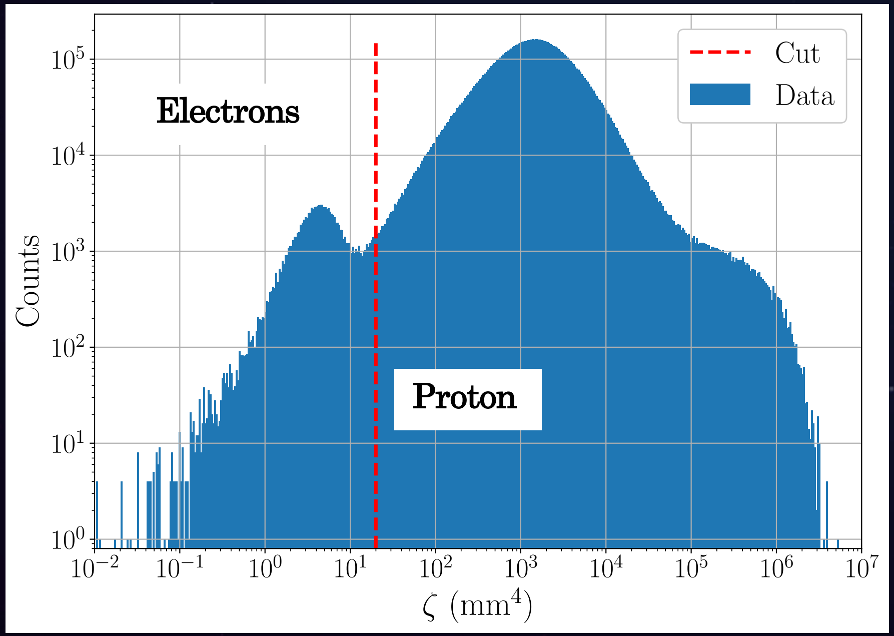
Proton-helium: Energy dependence

- Cross section measured as function of kinetic energy per nucl.
  - Bin events in total energy deposited in calorimeter
  - Determine corresponding kinetic energies from MC
  - Fit Landau+Gaussian
    → peak: reference value
    → width: uncertainty



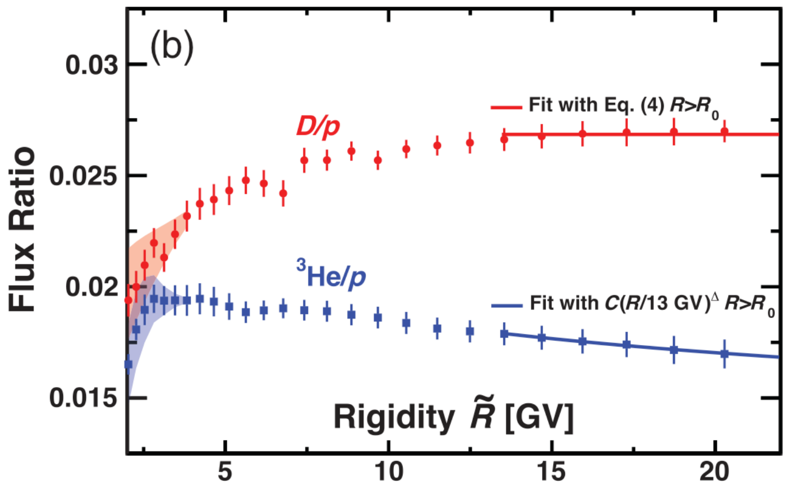
Proton-helium: Lepton rejection

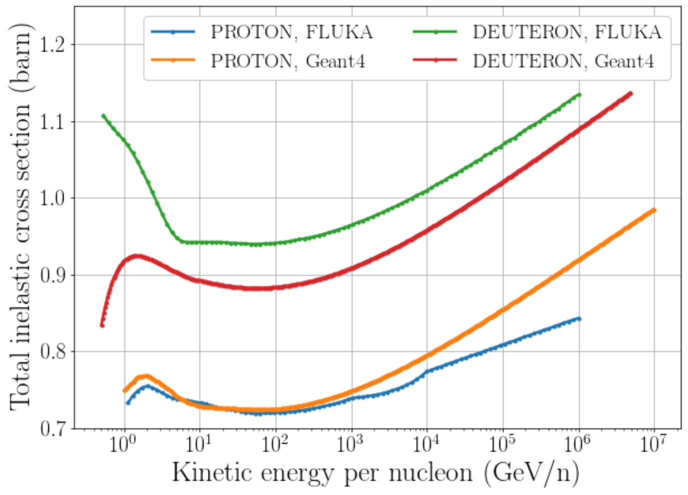
- Rejection of electrons (and positrons)
- XTRL variable has been developed
  (see doi: 10.1038/nature24475)



Deuteron contribution

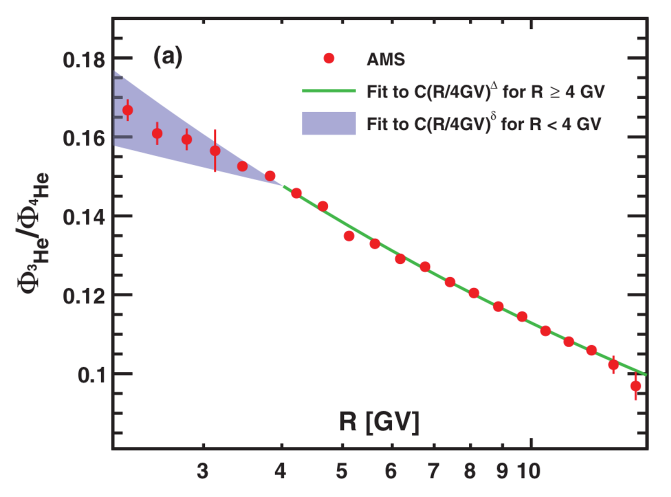
- DAMPE can measure charge but not mass
- No way to distinguish proton from deuteron
- Ratio $\Phi(^2\mathrm{H})/\Phi(^1\mathrm{H})$ has been measured by AMS [doi: 10.1103/PhysRevLett.132.261001]
- Accounts for few percent of flux $\Rightarrow \lesssim 0.9\%$ effect on measurement

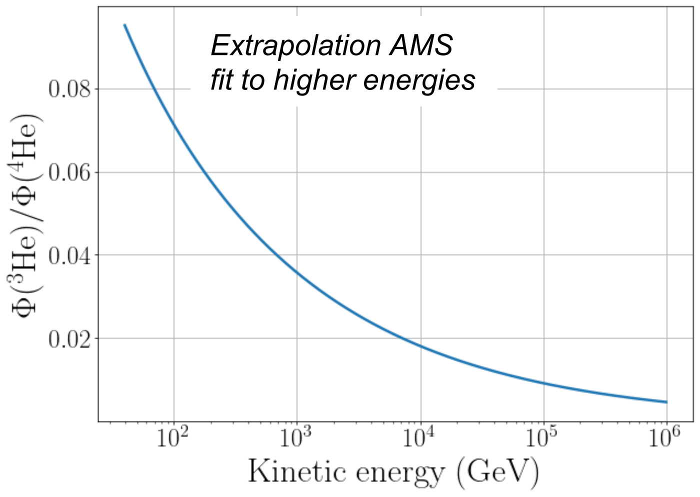


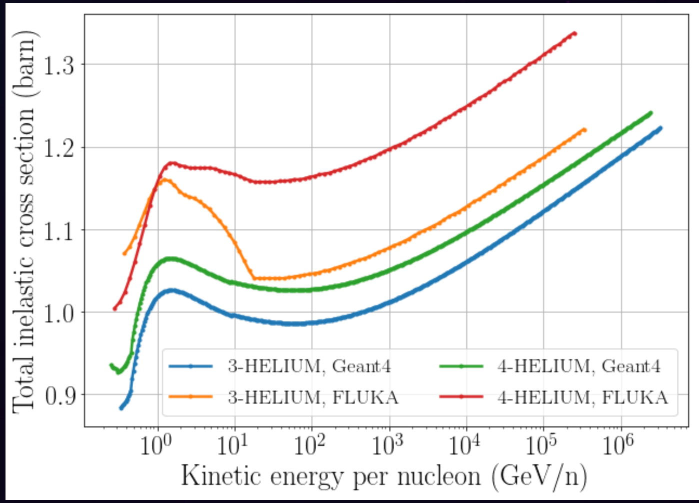


Helium-3 contribution

- DAMPE can measure charge but not mass
- No way to distinguish helium-3 from helium-4
- Ratio $\Phi(^3\mathrm{He})/\Phi(^4\mathrm{He})$ has been measured by AMS 10.1103/PhysRevLett.123.181102
- Accounts for few percent of flux $\Rightarrow \leq 1.2\%$ effect on measurement

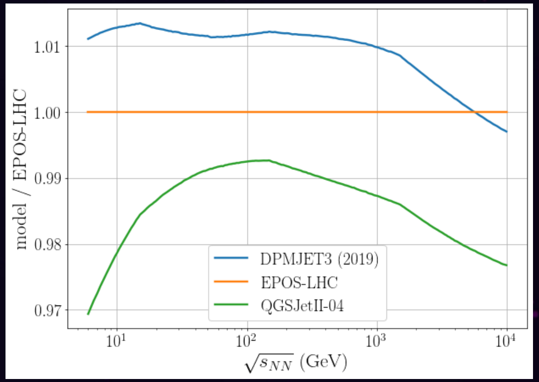


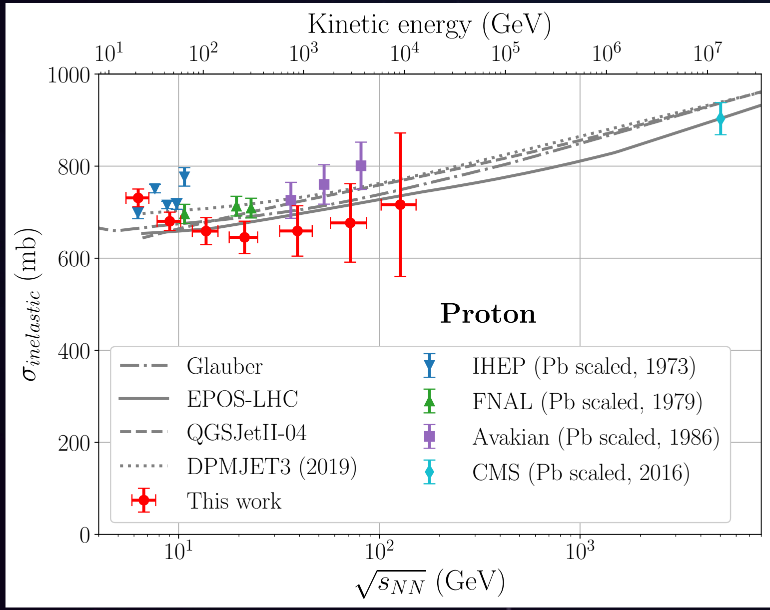




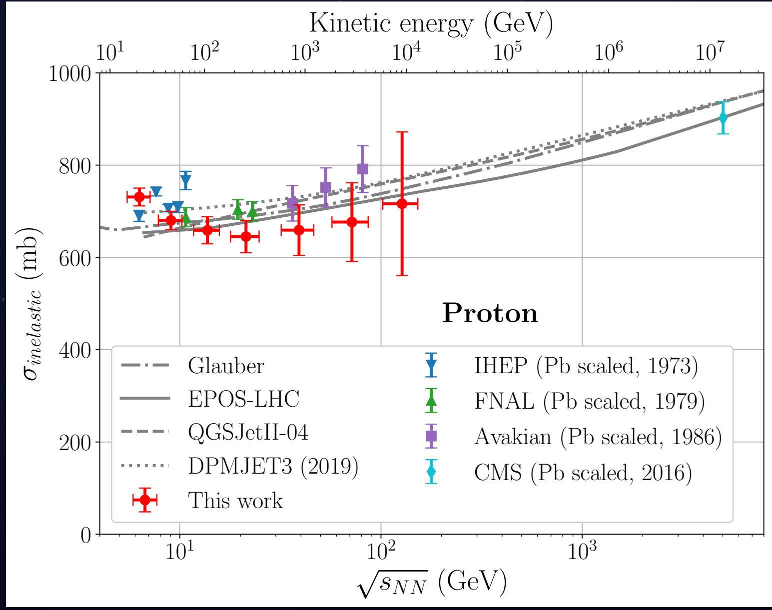
Proton: Other target materials

Our measurement is for a $Bi_4Ge_3O_{12}$ target
Measurements not for BGO are scaled: $\sigma^{model}_{target}/\sigma^{model}_{BGO}$
Three models considered: EPOS-LHC, QGSJetII-04, DPMJET3
→ 1-3% difference, no effect on interpretation result

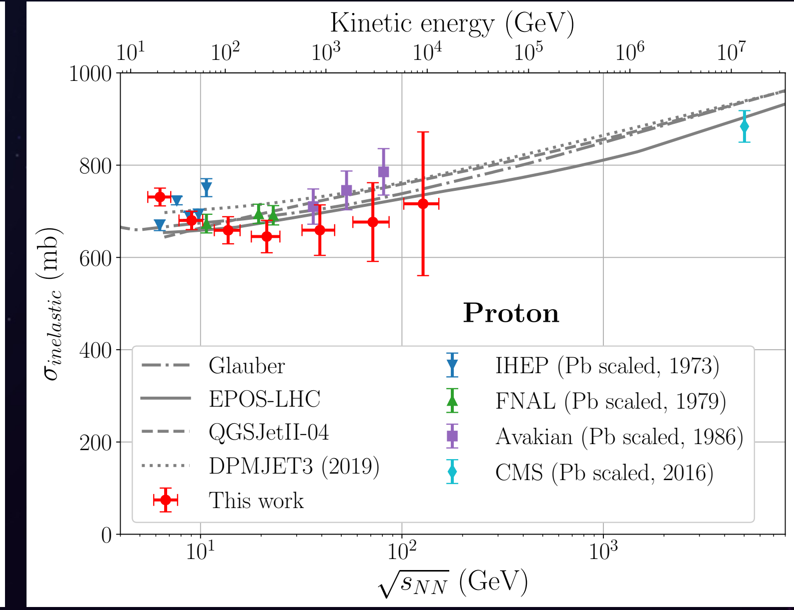




DPMJET3 based scaling

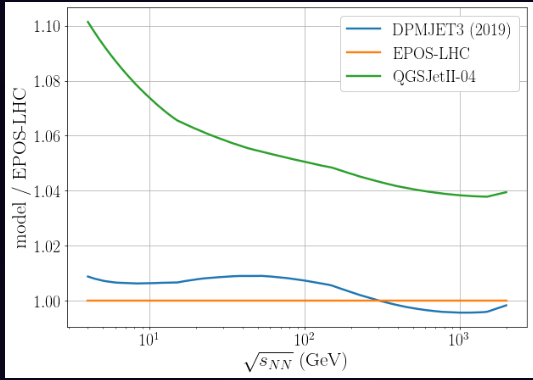


EPOS-LHC based scaling



QGSJetII-04 based scaling

Helium: Other target materials



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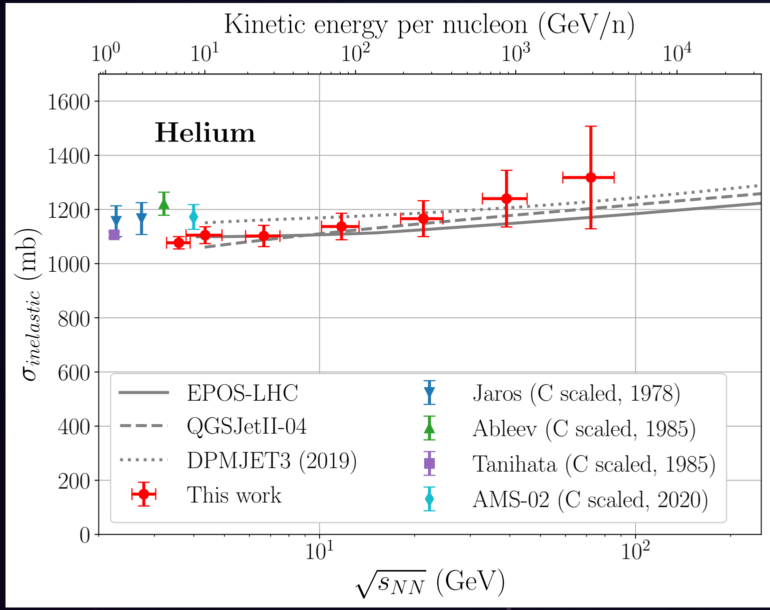
→ DPMJET3 & EPOS-LHC very close, QGSJetII-04 higher



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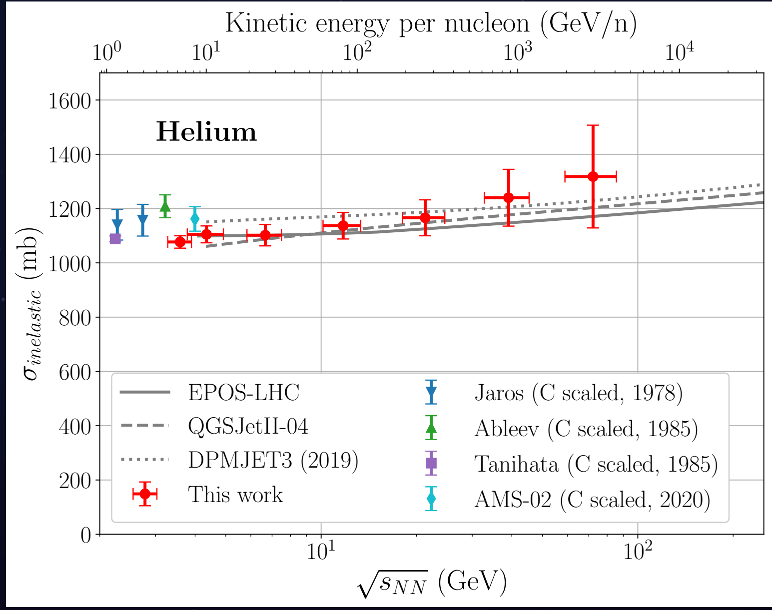
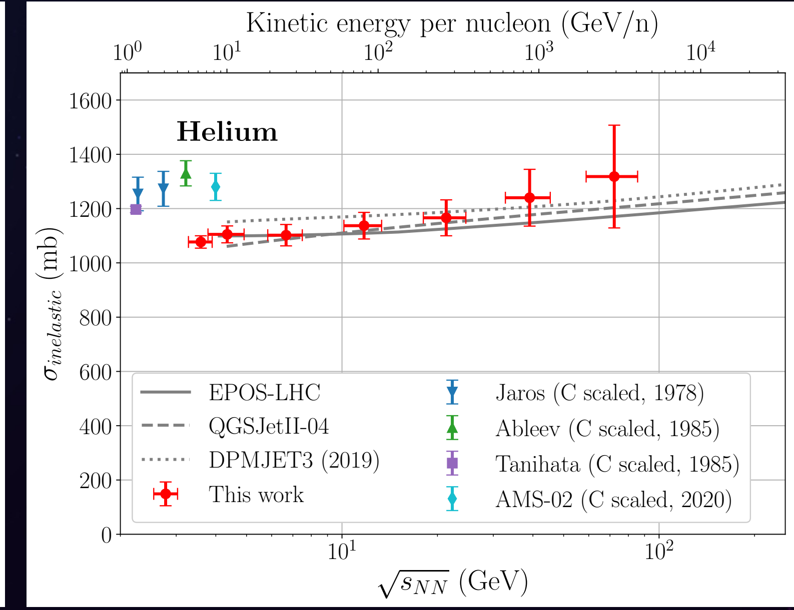


EPOS-LHC based scaling



QGSJetII-04 based scaling