Measurement of Inelastic Hadronic Cross Sections in Space with DAMPE

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The DAMPE experiment

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

Collaboration between:

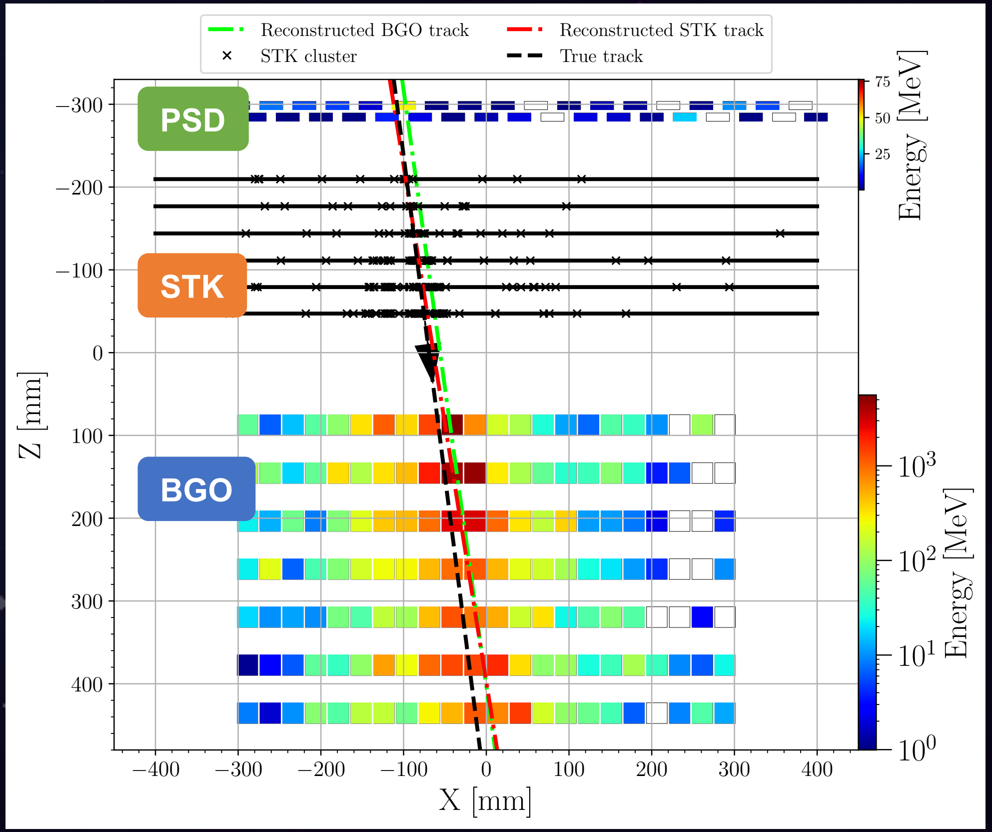
China
- Purple Mountain Observatory, CAS, Nanjing
- University of Science and Technology of China, Hefei
- Institute of High Energy Physics, CAS, Beijing
- Institute of Modern Physics, CAS, Lanzhou
- National Space Science Center, CAS, Beijing

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

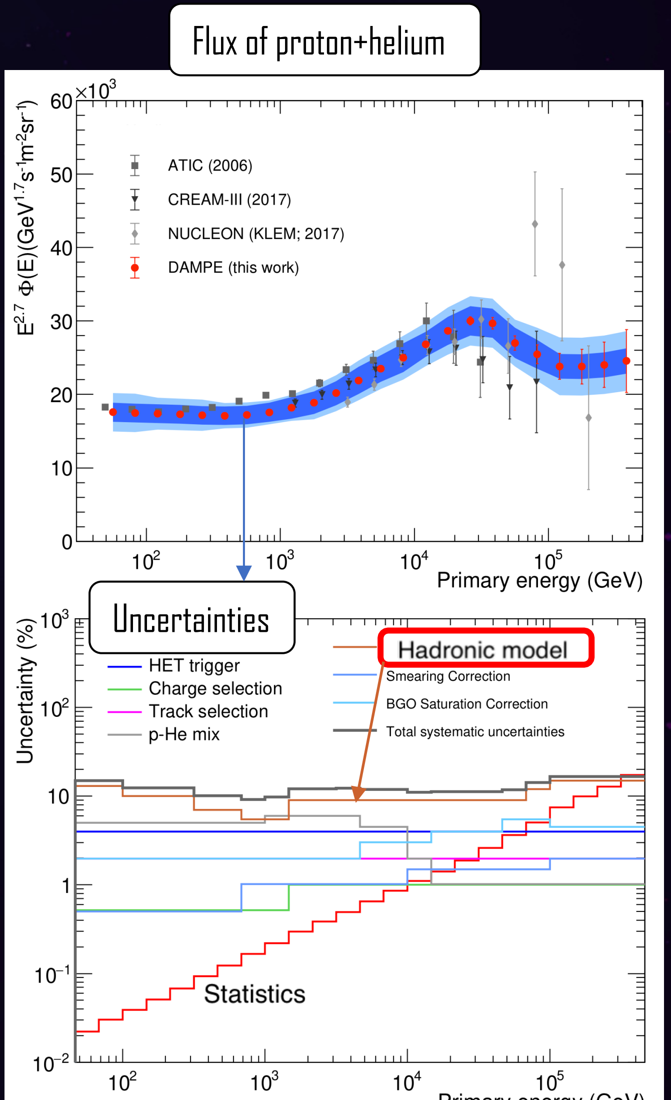
The DAMPE experiment

- Layered design with 4 sub-detectors:
  - Plastic scintillator detector (PSD)
    → Charge measurement primary CR
  - Silicon-Tungsten tracKer-converter (STK)
    → Measures track & charge primary CR
    → Converts photons into EM shower
  - Calorimeter (BGO)
    → Measures shower energy deposition
  - (NeUtron detector, NUD)
    → Differentiate EM from hadronic showers, not used in this work.

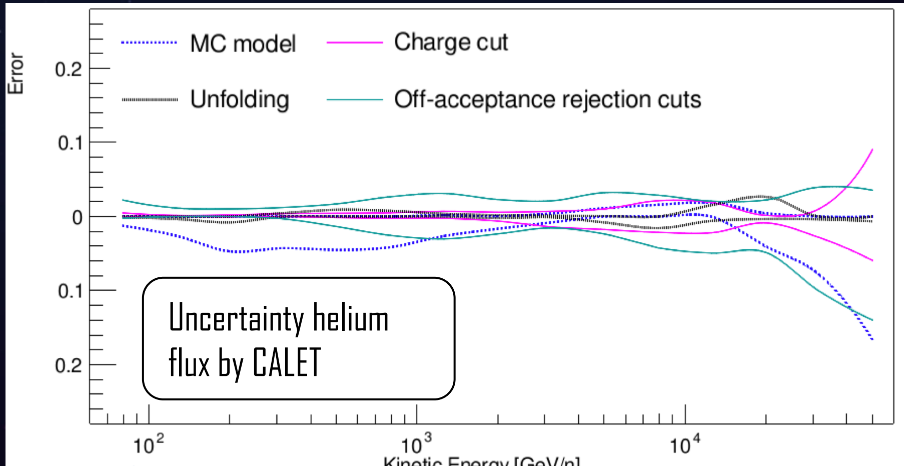


CR ion flux measurements

- Excellently equipped for the direct measurement of CR ions
  - Proton+helium flux up to 0.5 PeV
  - Also heavier ions (carbon, oxygen, etc.)
- Accuracy ion fluxes limited by hadronic model
- For DAMPE and other experiments equally so
- Cross sections unmeasured…



PRD: 10.48550/arXiv.2304.00137 (in print)

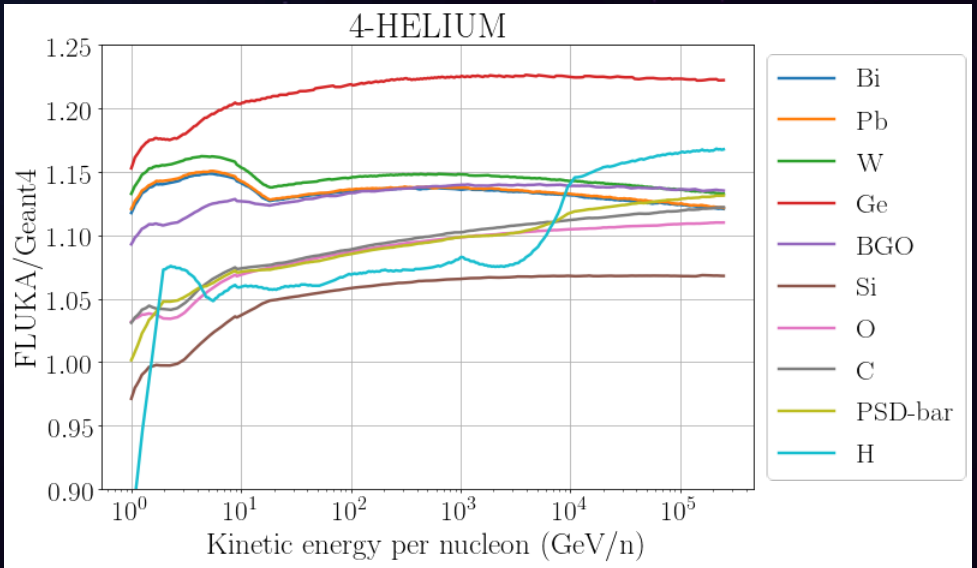


doi: 10.1103/PhysRevLett.130.171002

Inelastic hadronic cross sections

Experimental constraints:

- Protons → Can rely on measurements by colliders. For instance, LHC measurements:
  - Proton-Proton at $\sqrt{s} = 13$ TeV
    10.1016%2Fj.physletb.2016.06.027
    → $\gg$ PeV energy in fixed target equivalent
  - Proton-Lead at $\sqrt{s_{NN}} = 5$ TeV
    10.1007/JHEP07(2018)161

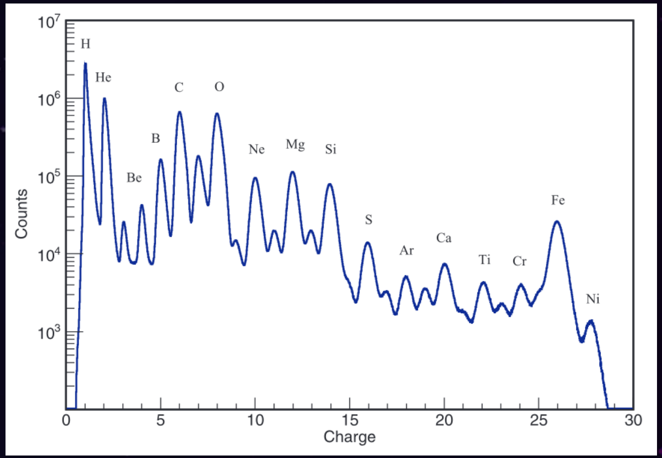


- Ions heavier than proton:
  - Measurements very limited, and usually sub-GeV
  - Rely on phenomenological model (e.g. Glauber or Gribov–Regge)
    10.1103/PhysRev.100.242
    10.1016/0550-3213(70)90511-0
    1968JETP...26..414G

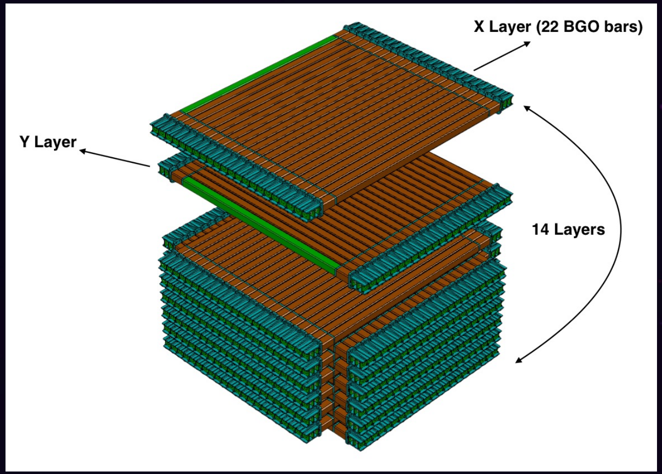
Cross sections with DAMPE

- Data:
  - Good statistics (88 months in this work)
  - Energy range: ~10 GeV up to few hundred TeV
  - CR ions from proton up to Nickel
- Measurement (this work):
  - Inelastic hadronic cross section
  - Proton and helium primary
  - $Bi_4Ge_3O_{12}$ target (calorimeter)

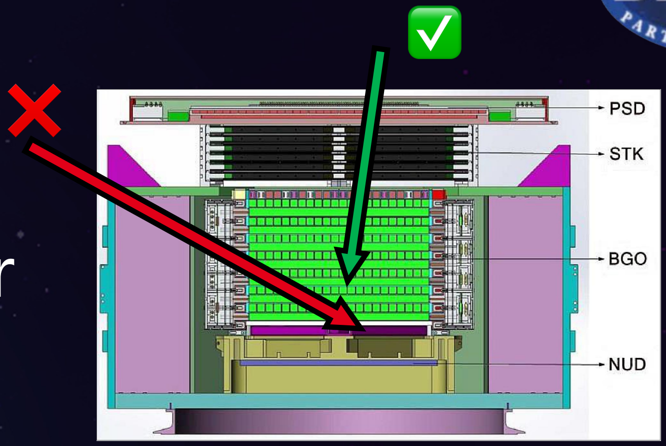
⇒ First step is to create proton (helium) sample



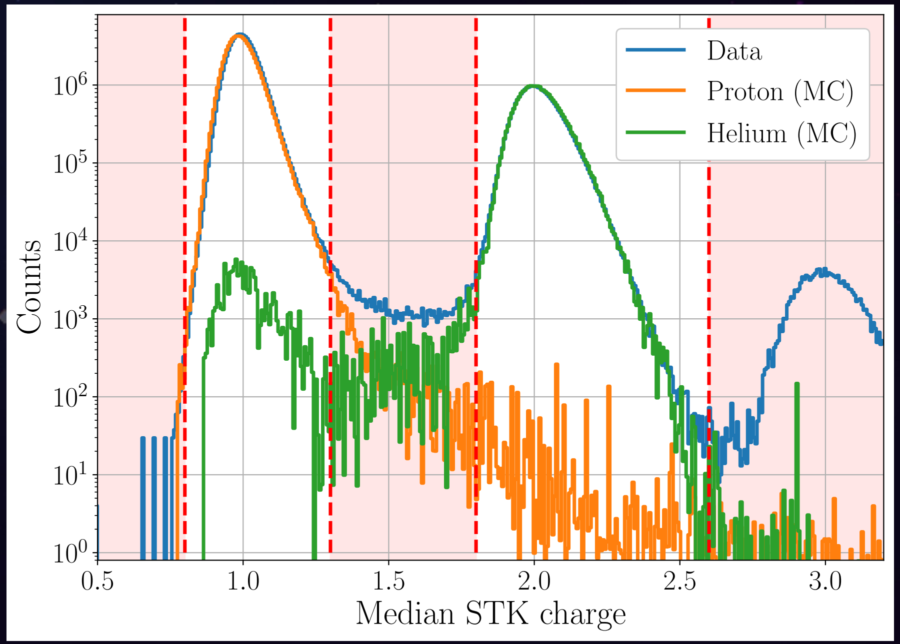
10.1134/S106377882113007X



Event selection



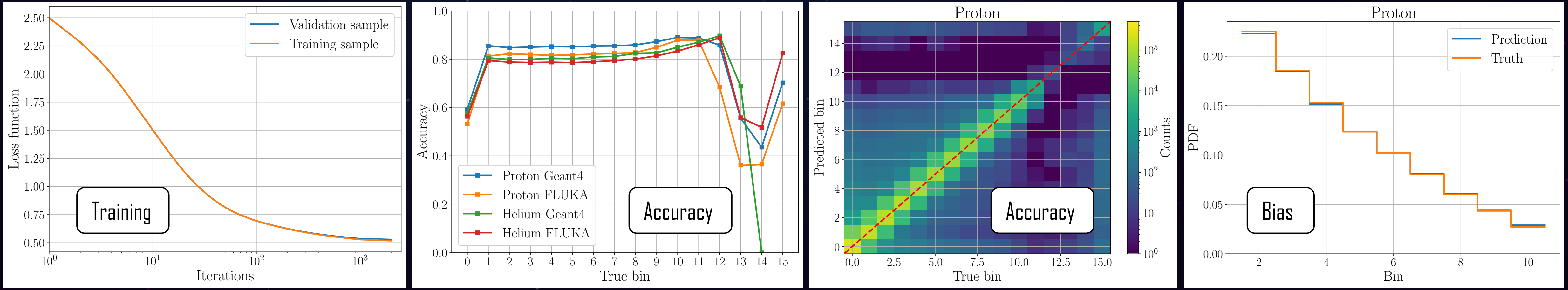
1. Trigger: Events with MIP energy or higher
2. Pre-cuts → contained events
   → using ML based track reconstruction
   10.1016/j.astropartphys.2022.102795
3. Select events that:
   1. Satisfy basic quality cuts
   2. Removal electron background
   3. Removal events interacting in PSD
   4. Fall in the proton or
      helium charge window



⇒ >80% signal efficiency for contained events, while background ≲0.2%

Cross section measurement

- Cross section ⟷ point of inelastic interaction
- Interaction depth classifier:
  - Gradient boosted decision tree (XGB)
  - 16 output classes:
    - Before calorimeter
    - One per layer (14x)
    - After calorimeter



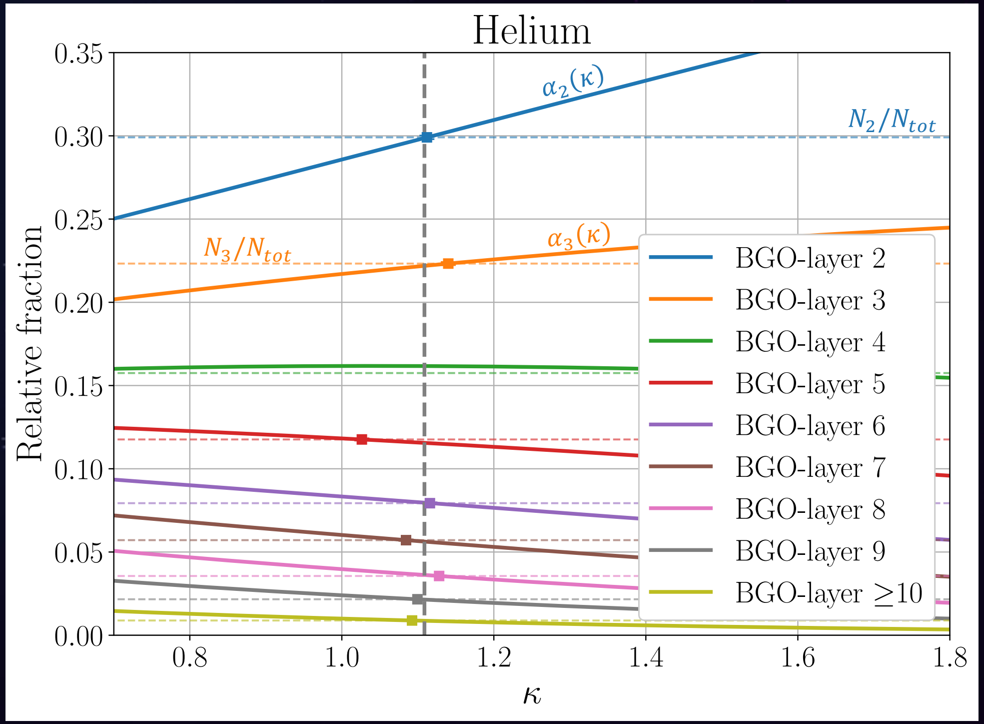
Cross section measurement

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

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

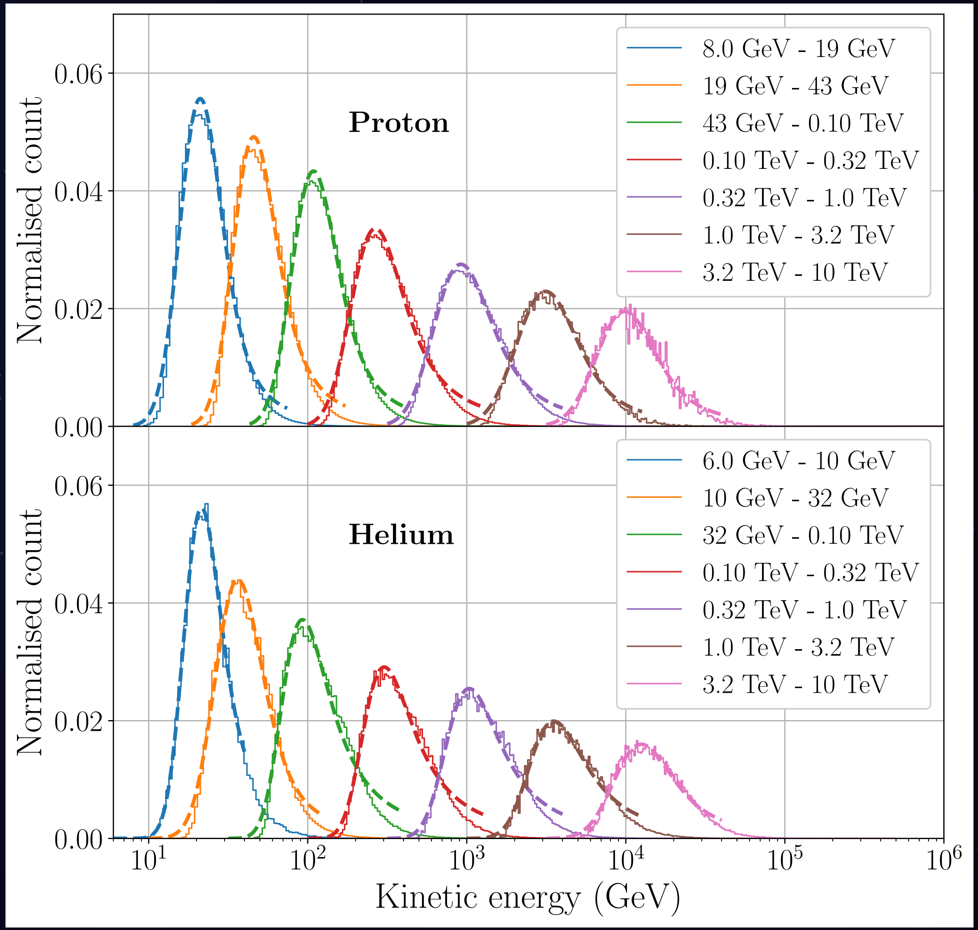
- Compare MC (α_i) to data $\left(\frac{N_i}{N_{tot}}\right)$:

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



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



Uncertainties

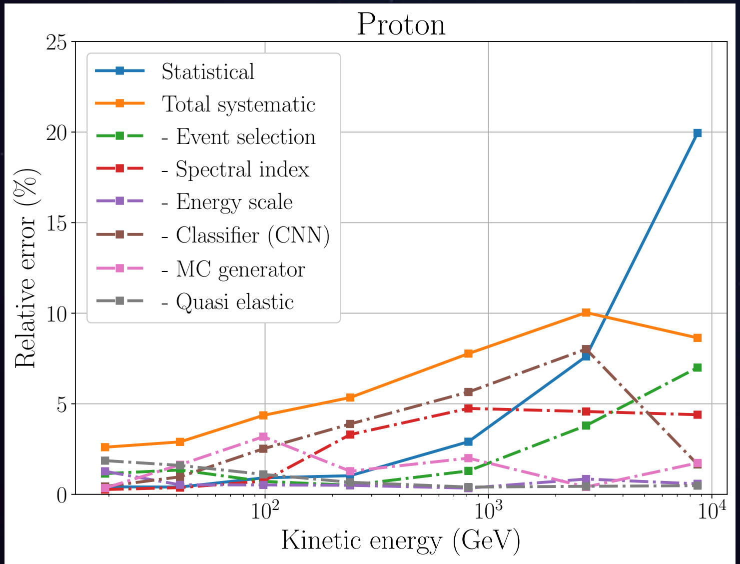
- Statistical uncertainty dominates in last bin
- Systematic uncertainty:

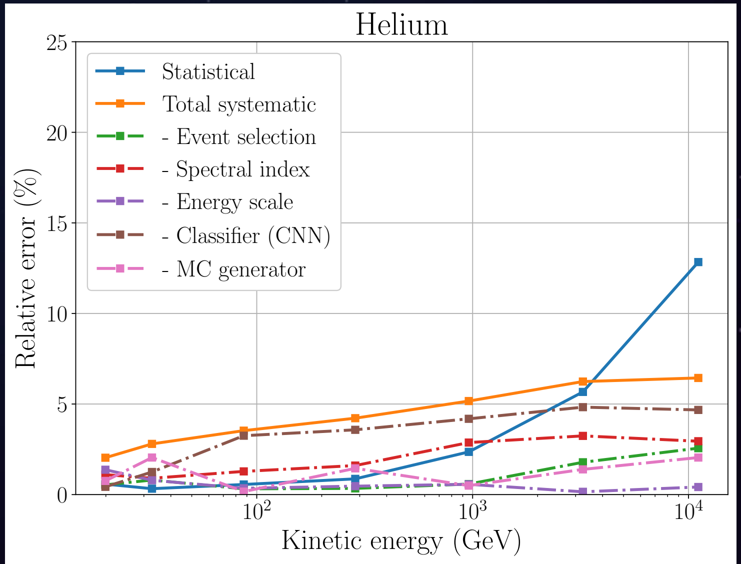
Largest

- Classifier
- Spectral index
- Event selection

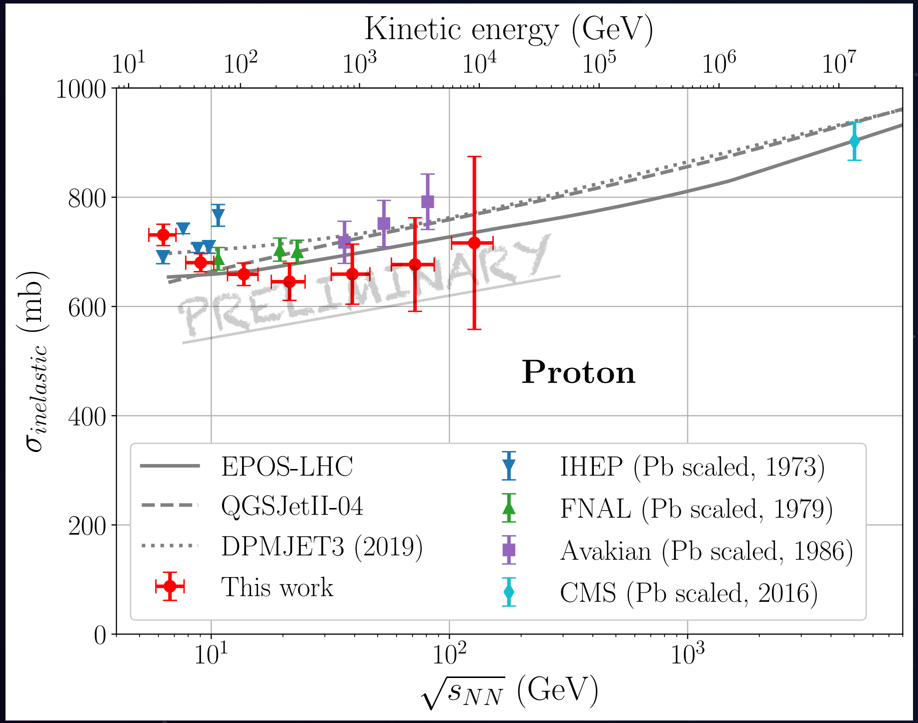
Smallest

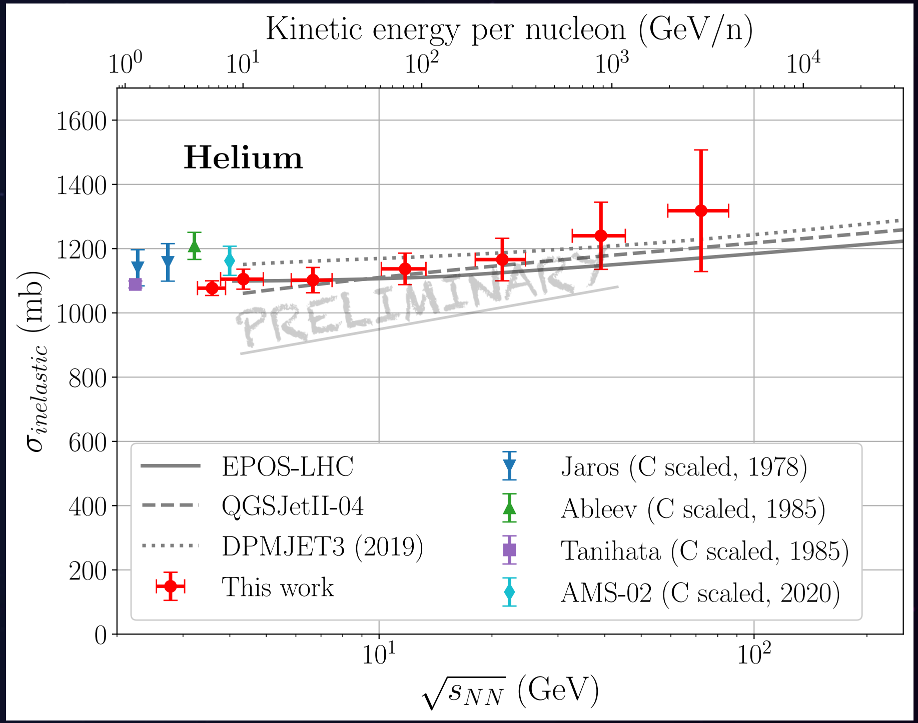
- Isotopes
- MC generator
- Energy scale





Results





PROTON:
Within error-band of measurements at same energy; but slightly lower normalization. Consistent with CMS.

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

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

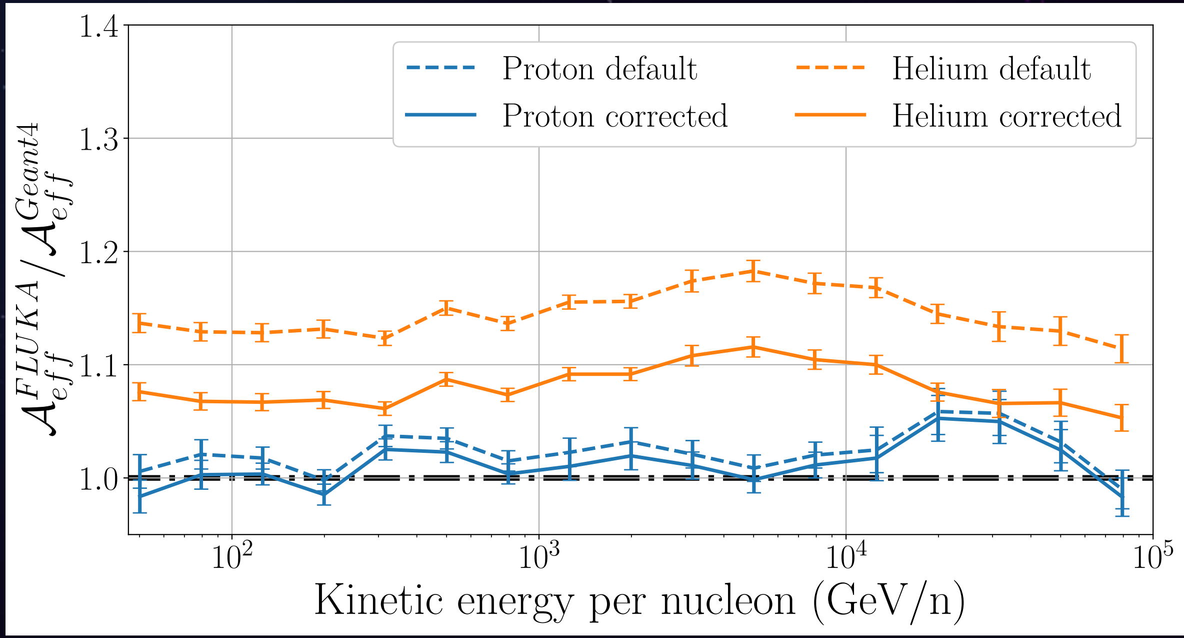
Effect on flux normalisation

- Effective detector acceptance depends on cross section:

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

- 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



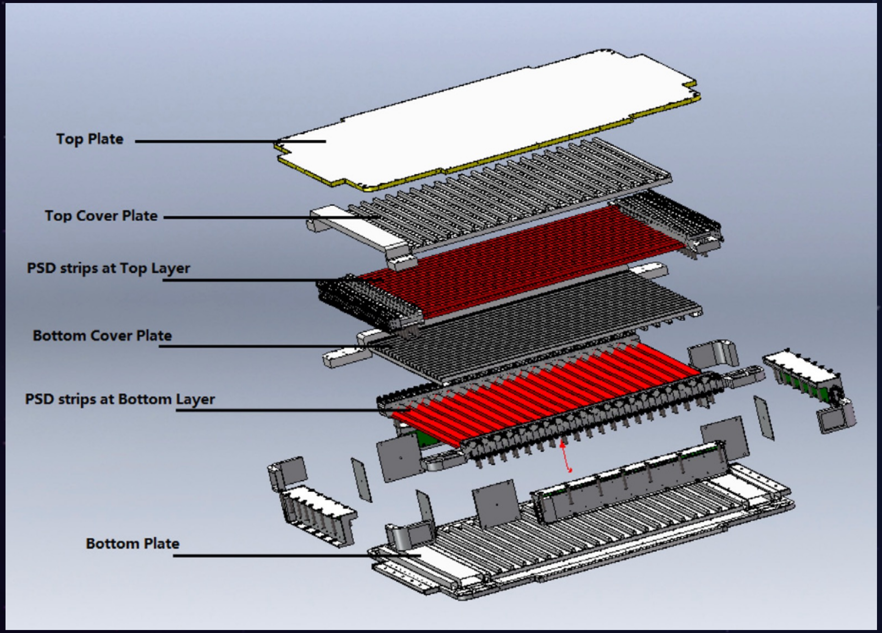
Conclusion & outlook

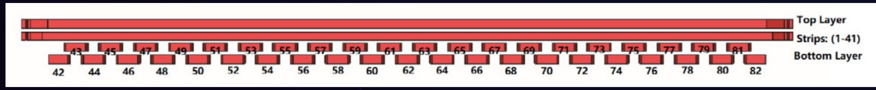
- Hadronic inelastic cross section is important systematic affecting CR ion-flux normalization
- Presented inelastic cross section measurement
  - $Bi_4Ge_3O_{12}$ target (calorimeter)
  - Proton: $18\ \mathrm{GeV}\ - 9\ \mathrm{TeV}$
  - Helium-4 (alpha): $5\ \mathrm{GeV/n}\ - 3\ \mathrm{TeV/n}$
    → First measurement at these energies!
- Outlook:
  - Near future: Analysis of carbon and oxygen
  - Future detectors such as HERD have the potential to extend measurements to much higher energies

Backup slides

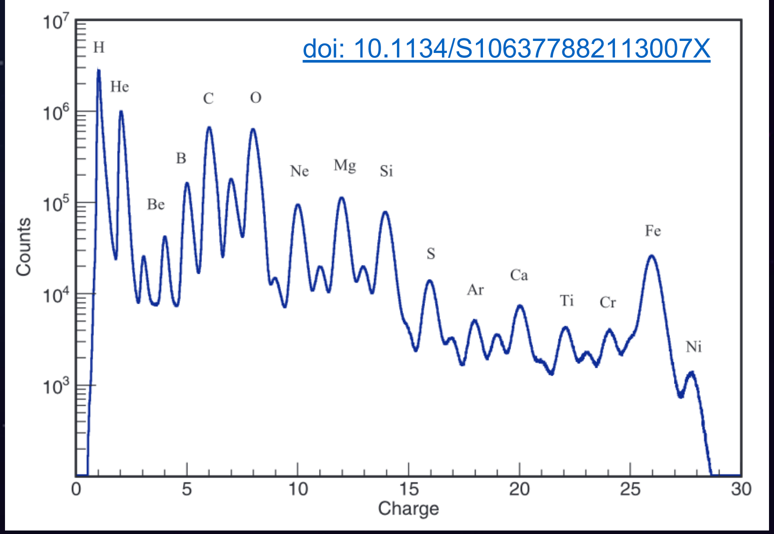
Detailed detector lay-out

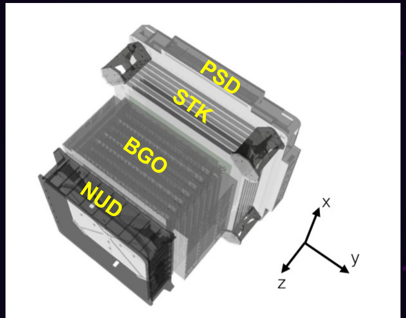
1. Plastic scintillator → identify absolute charge of particle





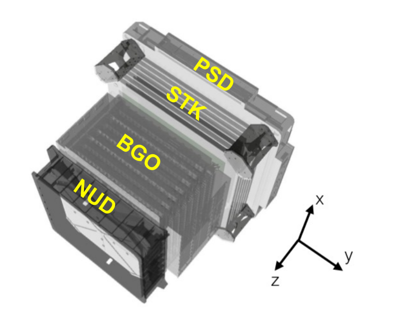
- 82 bars in 2 double layers
- Overall efficiency ≥ 0.9975
- Particles lose energy through ionisation energy losses: $dE/dx \propto Z^2$





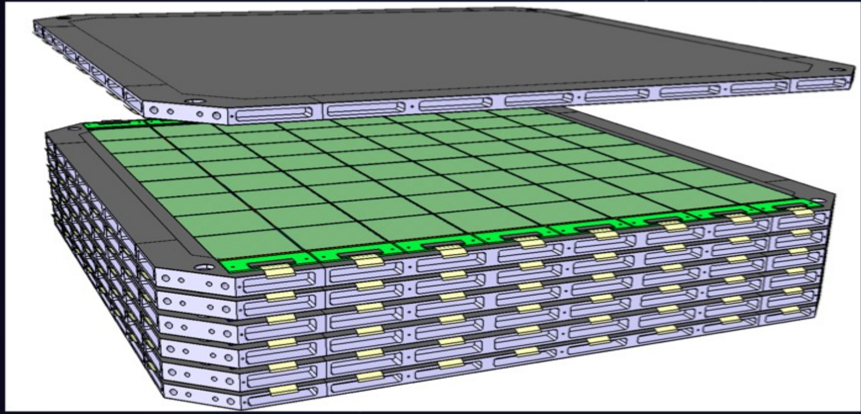
3D view of DAMPE (Geant4)

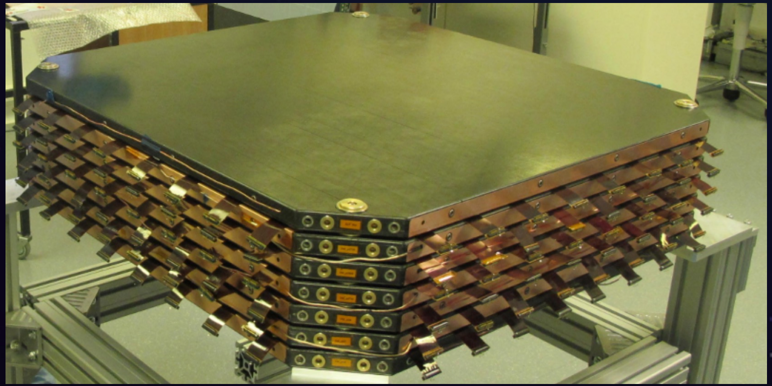
Detailed detector lay-out



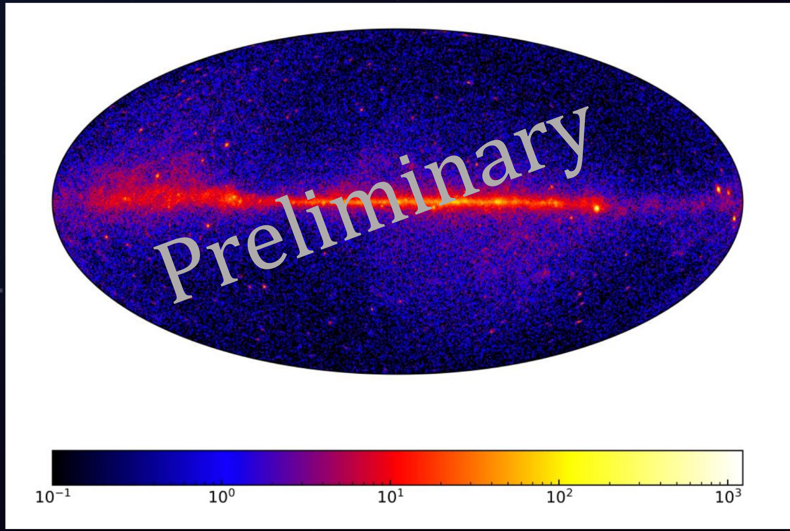
3D view of DAMPE (Geant4)

2. Tracker

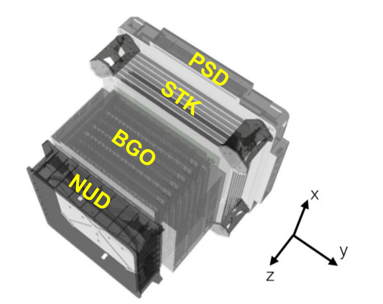




- 768 sensors of 768 strips each
- ~50 micron positional resolution
  → 0.1-1° pointing (electrons & photons)
- Also charge identification

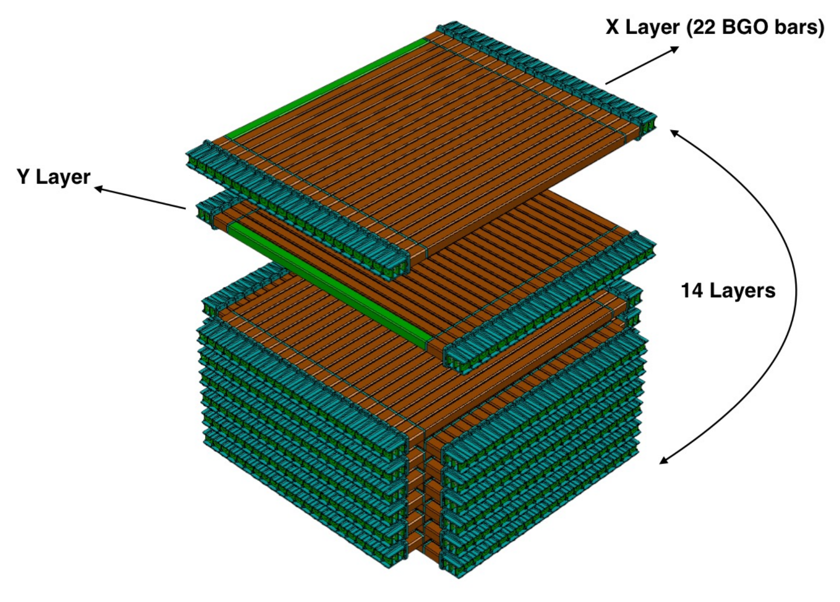


Detailed detector lay-out

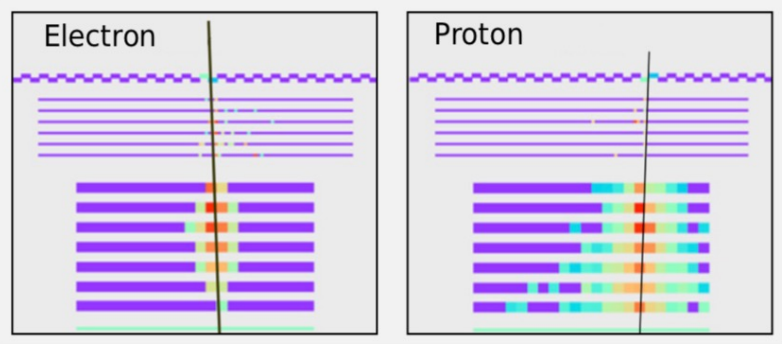


3D view of DAMPE (Geant4)

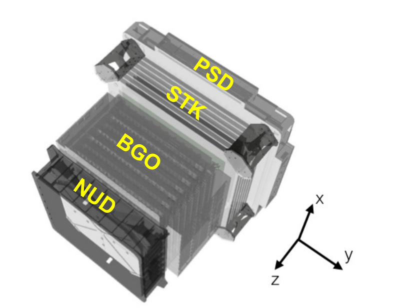
3. Calorimeter



- 308 bars spread over 14 layers
- Readout by PMT at each end of crystal
- $Bi_4Ge_3O_{12}$ material
- Energy resolution:
  - ~1% for electrons (shower contained)
  - ~40% for ions (shower not-contained)

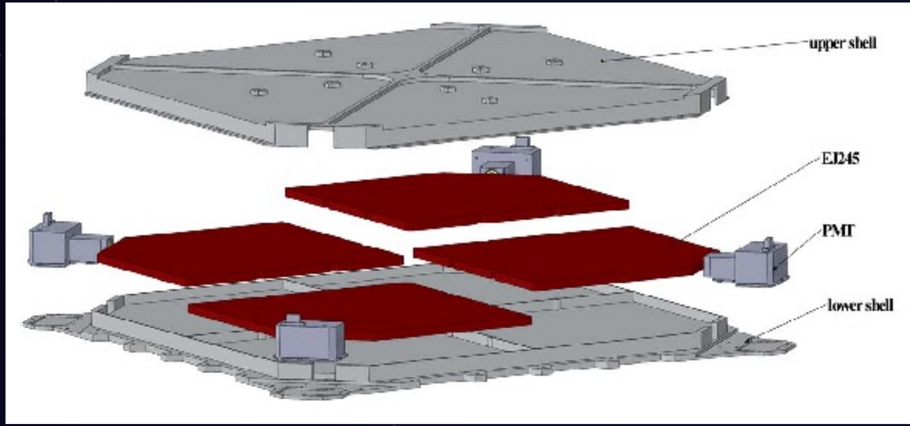


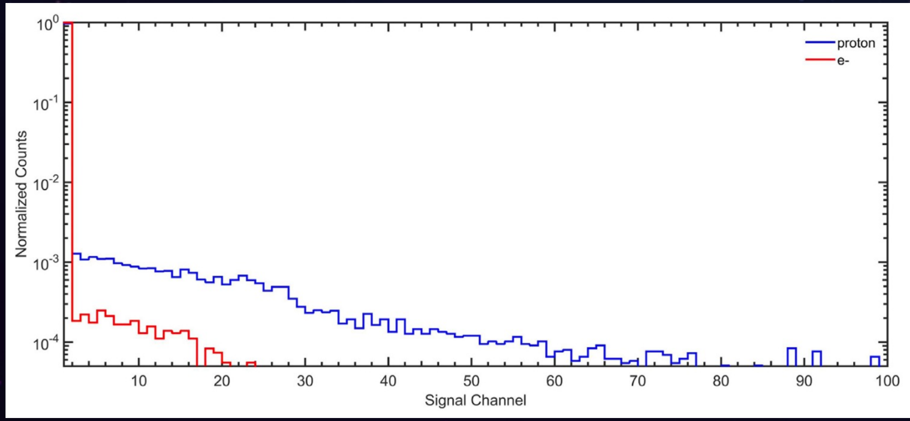
Detailed detector lay-out



3D view of DAMPE
(Geant4)

4. Neutron detector

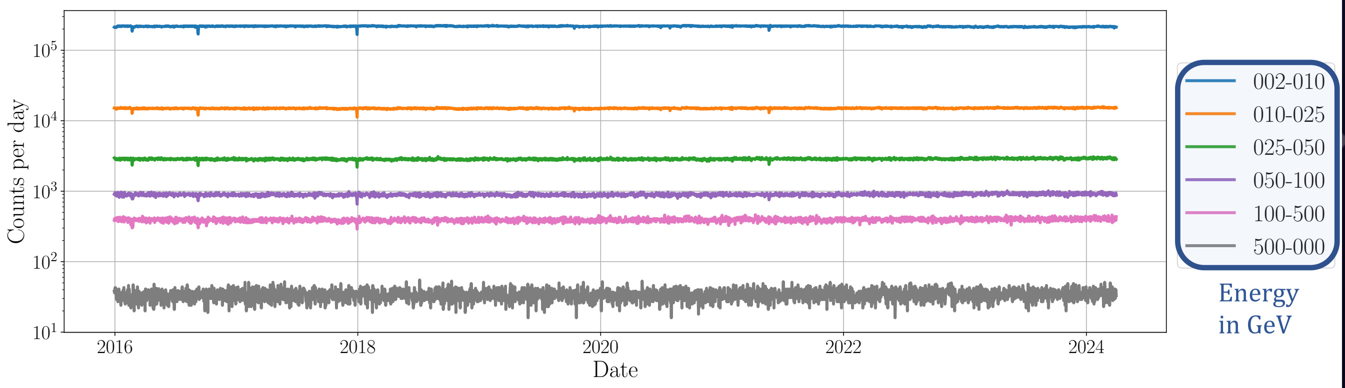


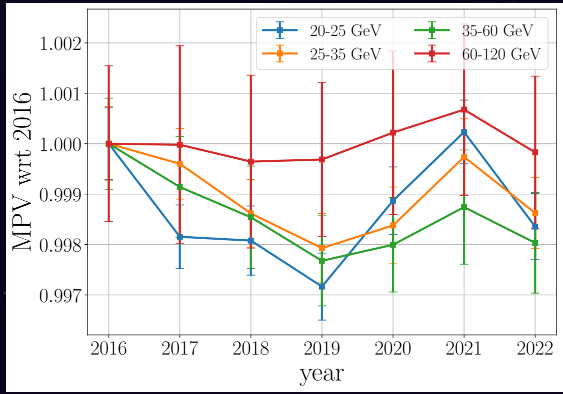


- 4 boron-doped plastic scintillators
- $B_{10} + n \rightarrow Li_7 + \alpha + \gamma$
- Hadronic showers produce ~10 times more neutrons than EM showers
- Provides additional discrimination power in electron analysis to reject dominant proton background

Detector calibration

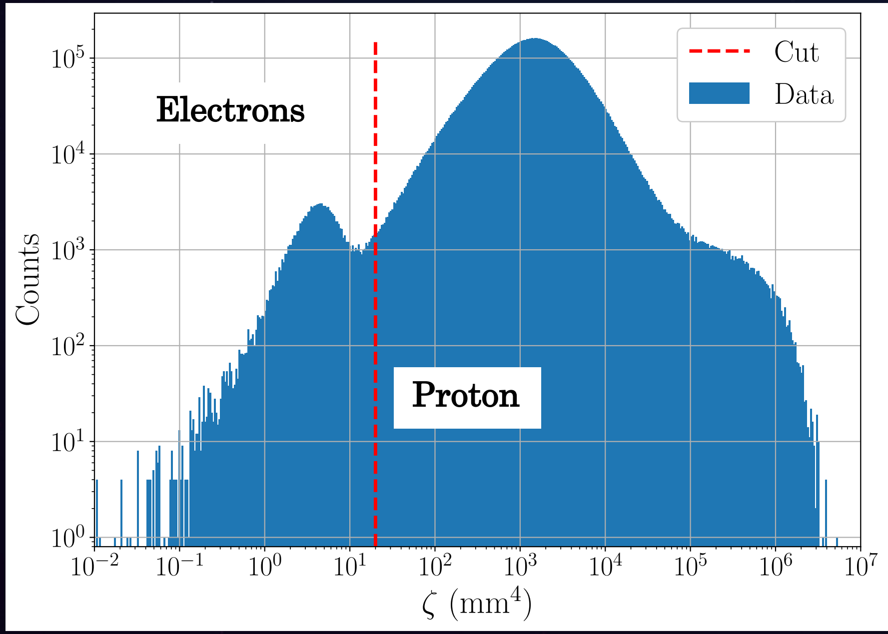
- DAMPE has been stably taking data for more than 8 years
- PMT gain, trigger thresholds, etc. are continually calibrated to ensure time-independent detector response
- Figure below shows per day rate of high-energy contained events





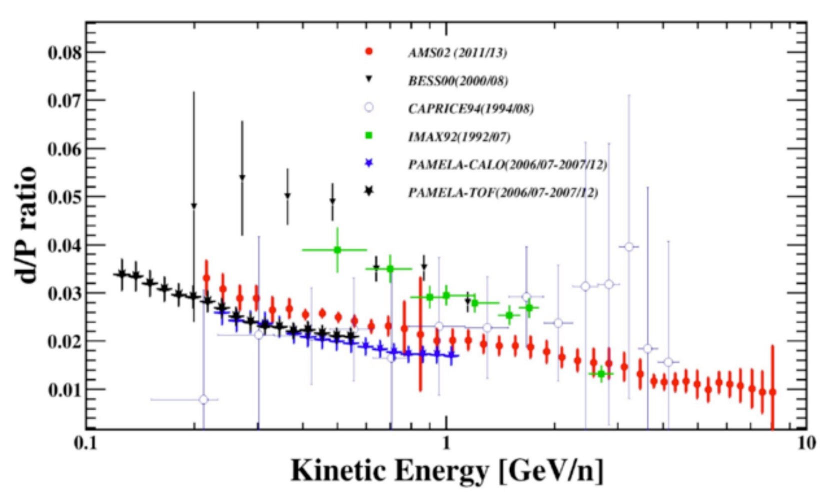
Event selection

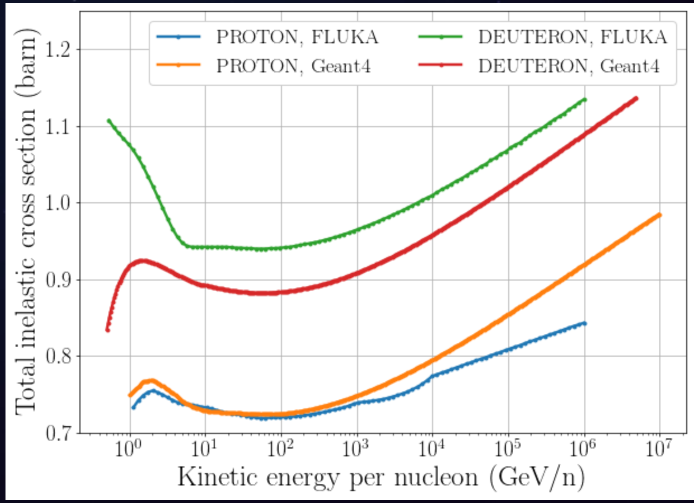
- Rejection of electrons (and positrons)
- XTRL variable has been developed
  (see doi: 10.1038/nature24475)



Deuteron contribution

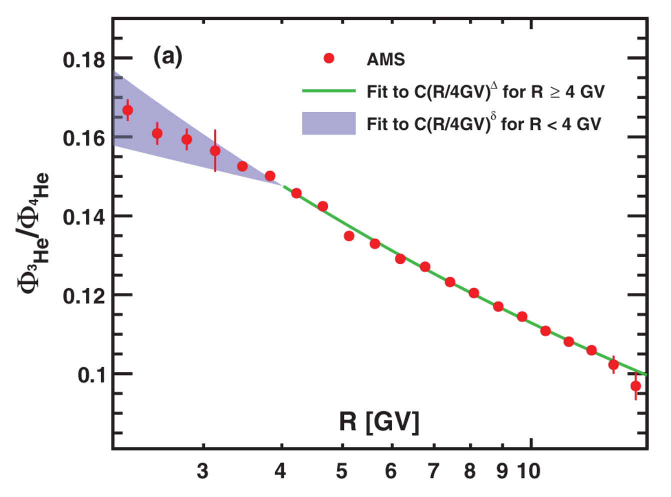
- DAMPE can measure charge but not mass
- No way to distinguish proton from deuteron
- Ratio $\Phi(^2H)/\Phi(^1H)$ has been measured by AMS doi.org/10.1016/j.nuclphysbps.2019.07.012
- Accounts for few percent of flux $\Rightarrow \leq 1.8\%$ effect on measurement

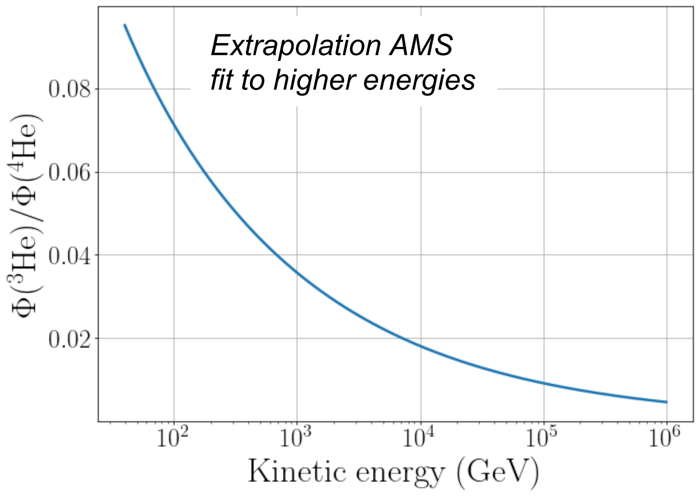


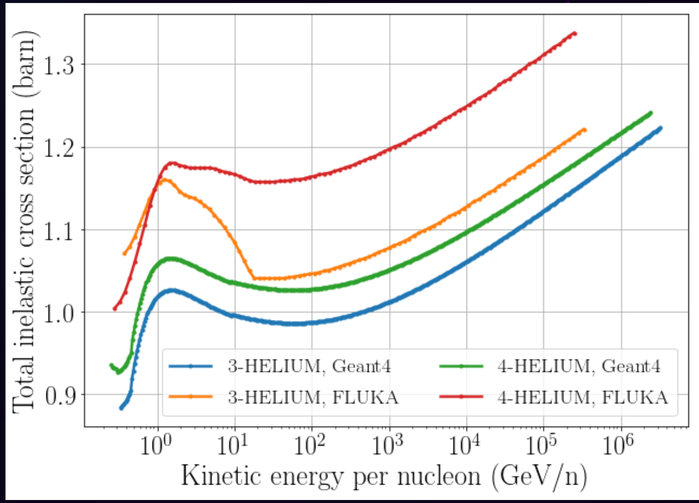


Helium-3 contribution

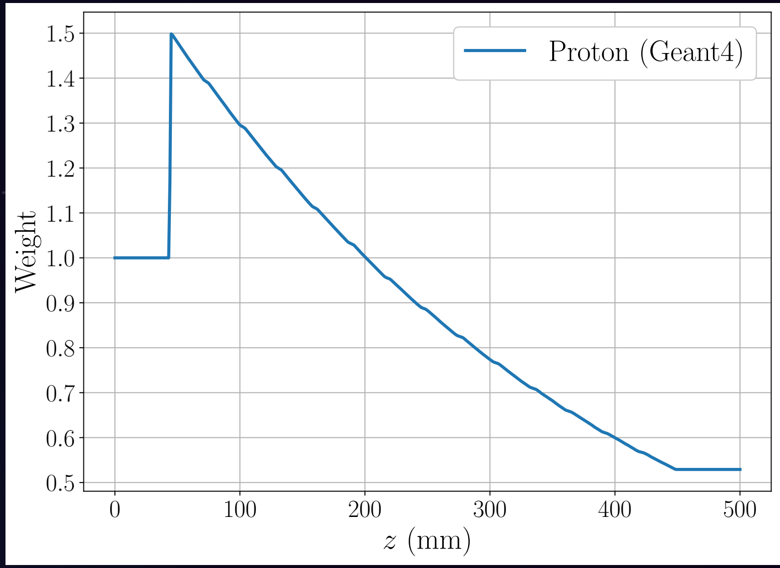
- DAMPE can measure charge but not mass
- No way to distinguish helium-3 from helium-4
- Ratio $\Phi(^3\text{He})/\Phi(^4\text{He})$ has been measured by AMS 10.1103/PhysRevLett.123.181102
- Accounts for few percent of flux $\Rightarrow \leq 1.2\%$ effect on measurement







Reweighting procedure



- Consider a fixed:
  - Particle type
  - Primary energy
  - Incident angle

- Use existing MC to parametrise the probability that such a particle interacts as a function of the depth (z) in the detector
- Rescale the CDF according to:

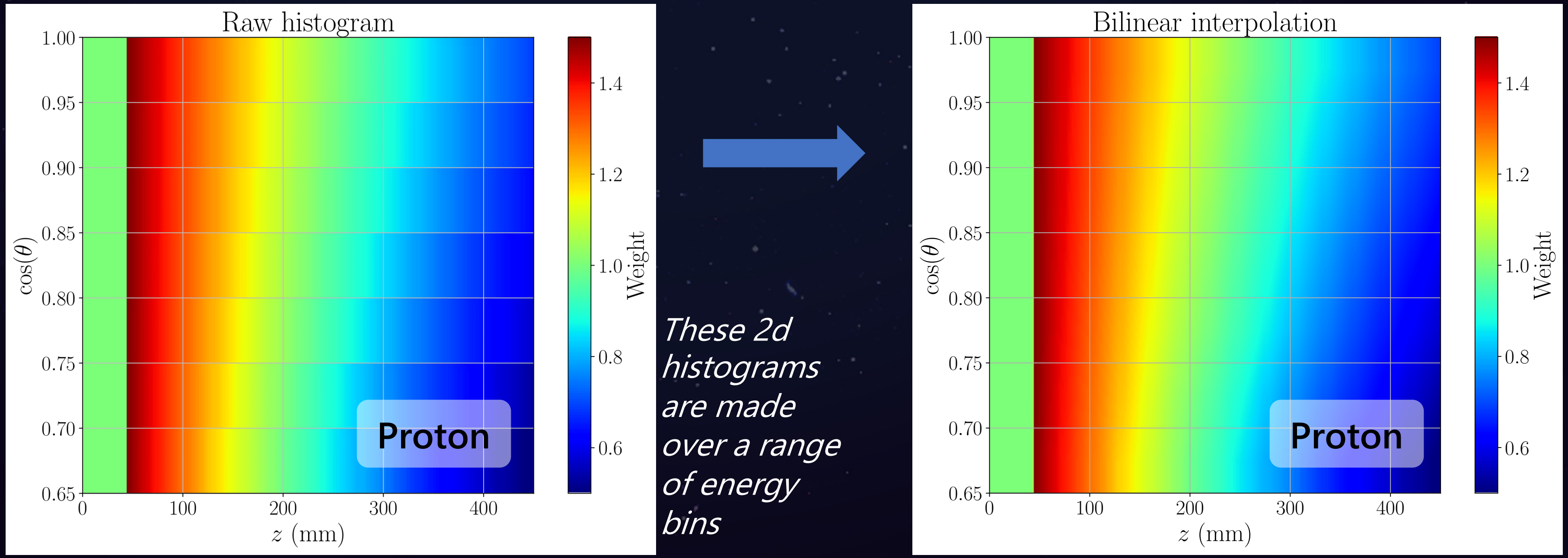
$$\mathrm{CDF}_{\mathrm{new}}(\mathrm{z}) \rightarrow 1 - (1 - \mathrm{CDF}(z))^{1+\alpha}$$

Here, α is the change in cross section, e.g. $\alpha = 0.5$ for a 50% increase as shown in the figure

- Ratio of PDFs tells us the weighting factor as function of z

Reweighting procedure

- Next step, determine weights over full parameter space (bin MC in primary energy ; incident angle ; z_{stop})
- To reweight a given event, do 3d interpolation (θ, E_p, z_{stop})



These 2d histograms are made over a range of energy bins

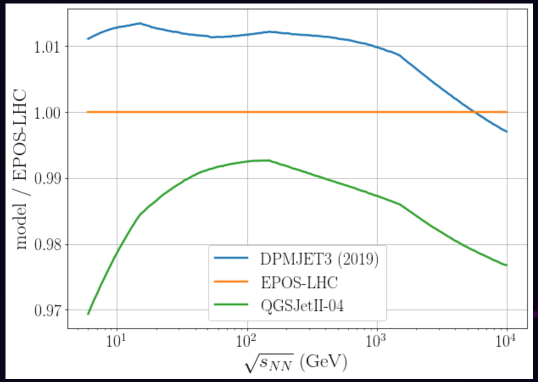
Comparison between target materials

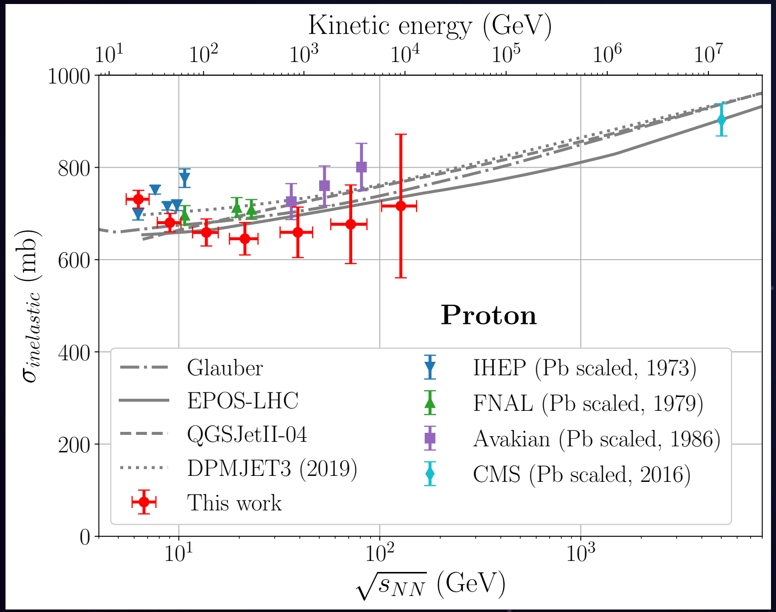
Our measurement is for a $Bi_4Ge_3O_{12}$ target

Measurements not for BGO are scaled: $\sigma^{model}_{target}/\sigma^{model}_{BGO}$

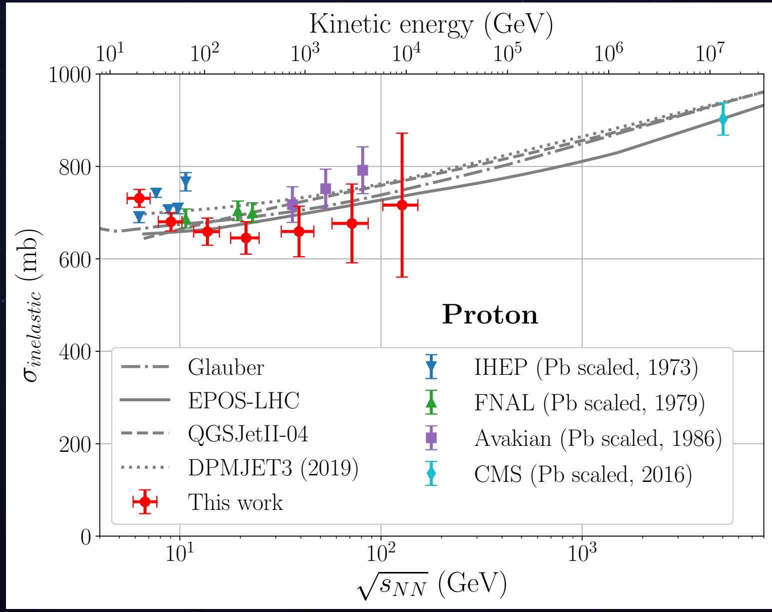
Three models considered: EPOS-LHC, QGSJetII-04, DPMJET3

→ 1-3% difference, no effect on interpretation result

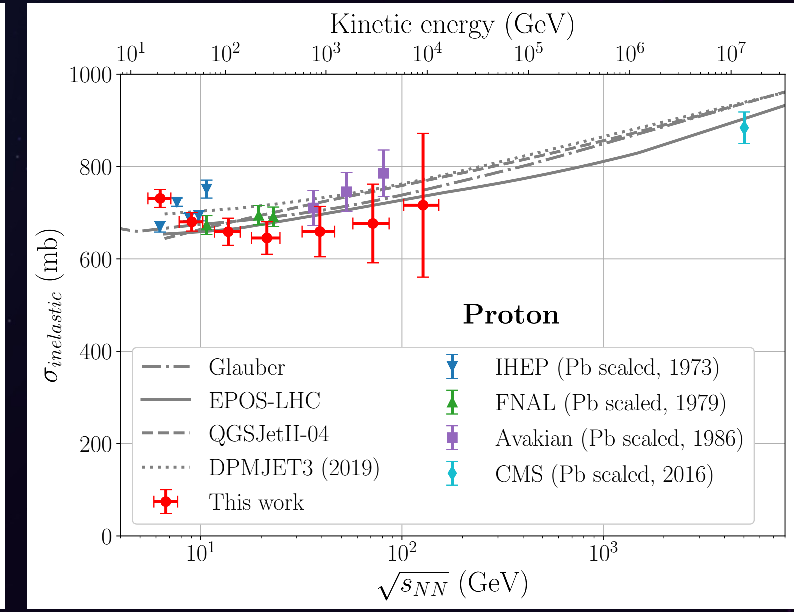




DPMJET3 based scaling



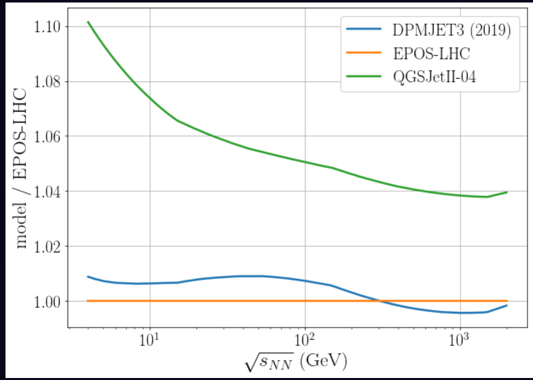
EPOS-LHC based scaling

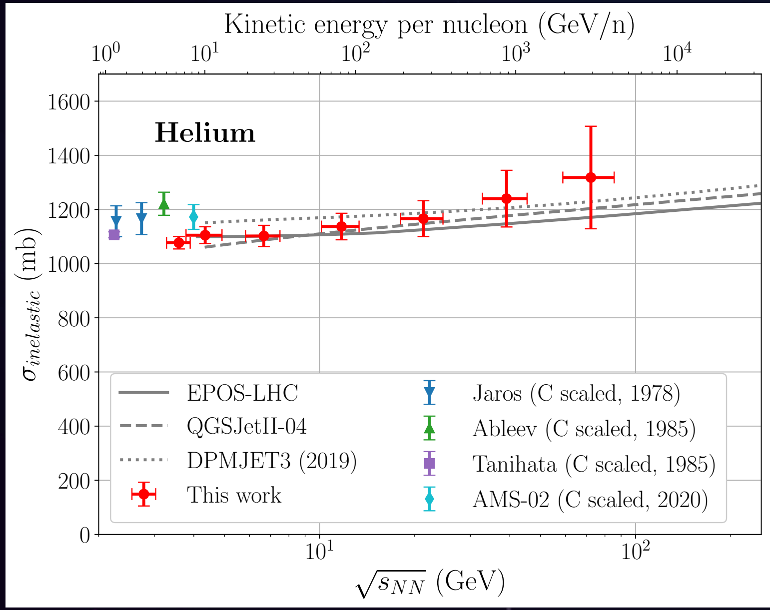


QGSJetII-04 based scaling

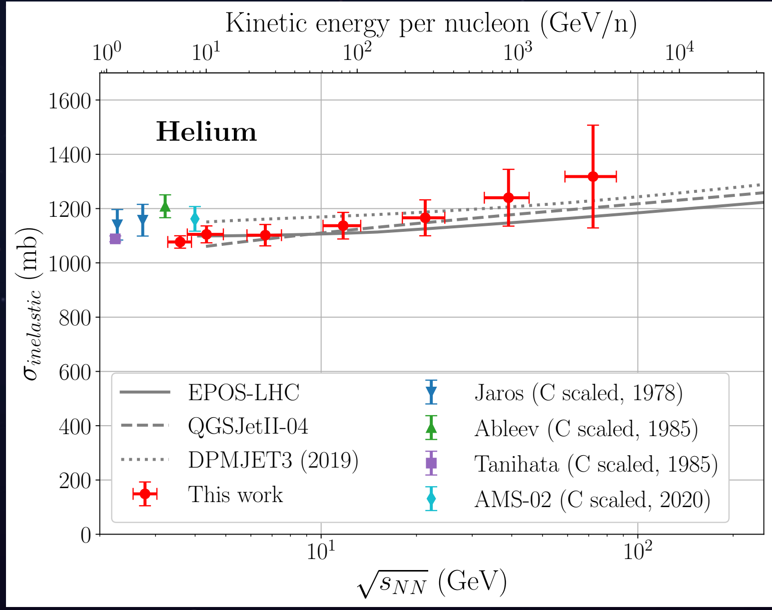
Comparison between target materials

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

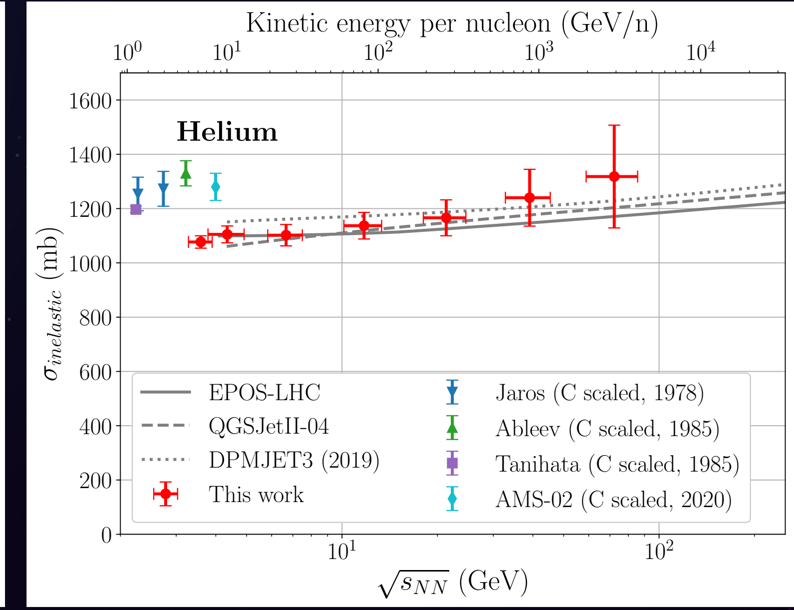




DPMJET3 based scaling



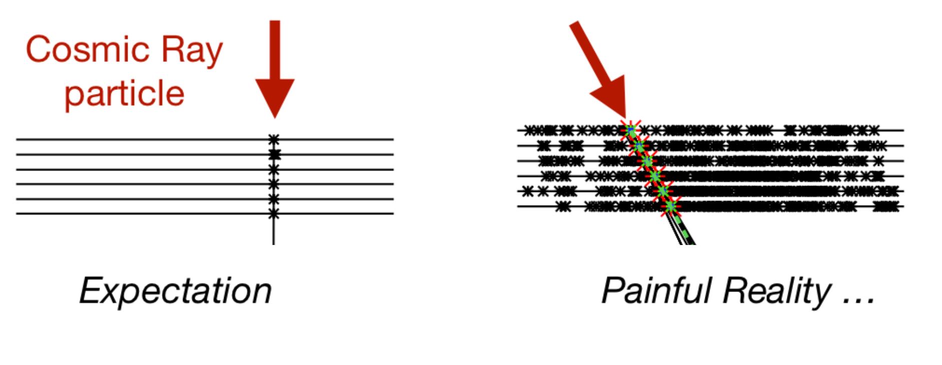
EPOS-LHC based scaling



QGSJetII-04 based scaling

Particle tracking

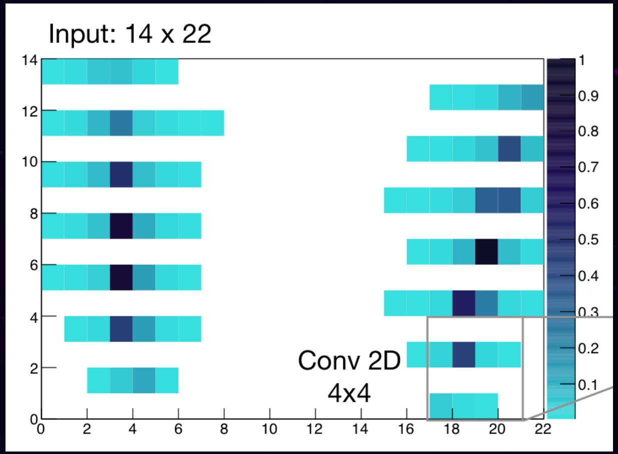
- Primary track drowns in a sea of secondaries
  - Pre-showering before the calorimeter
  - Back-splash from calorimeter
  - Majority of events affected
  - Gets worse at higher energies
- Not similar to LHC style tracking:
  - No magnetic field
  - Interaction point (axis) unknown
  - Way higher energies…
  - More passive material in/around tracker



⇒ Very challenging for conventional algorithms!

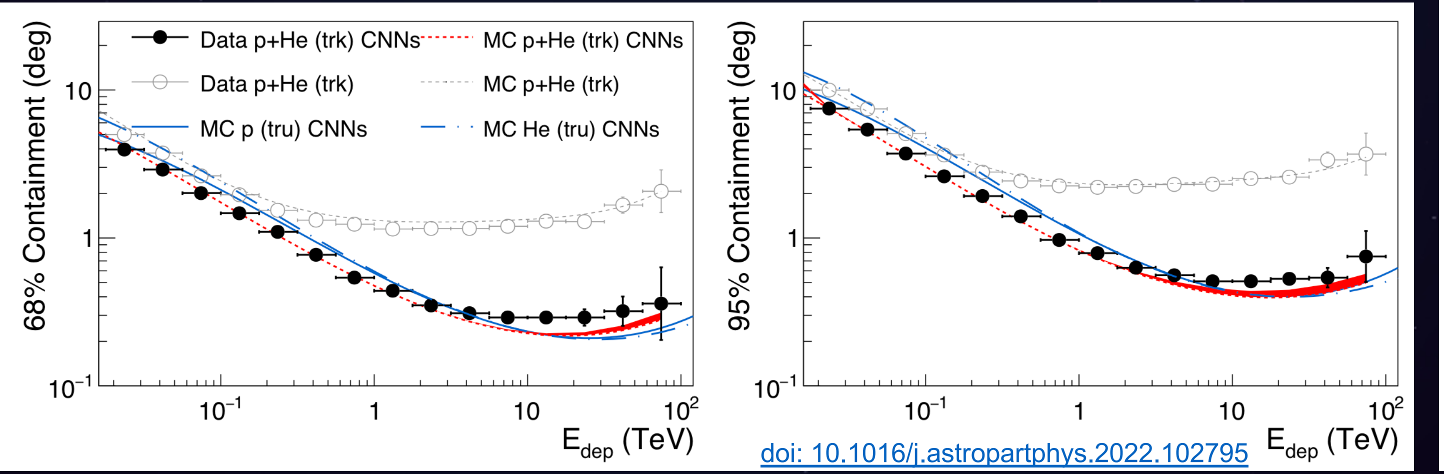
Particle tracking

- Area where ML shows huge potential for improvement!
- Two-step approach:
  - Initial prediction by calorimeter:
    - 14 layers of 22 bars → Image
    - Apply convolutional neural network
  - Refinement by tracker:
    - Using calo-prediction to identify region of interest (ROI)
    - Take Hough transform
      (works better than applying network on raw image)
    - Apply CNN convolutional neural network
  - Output 4 variables (fully characterising track)
    dir: $(v_x, v_y, 1)$; pos: $(x, y, 0)$

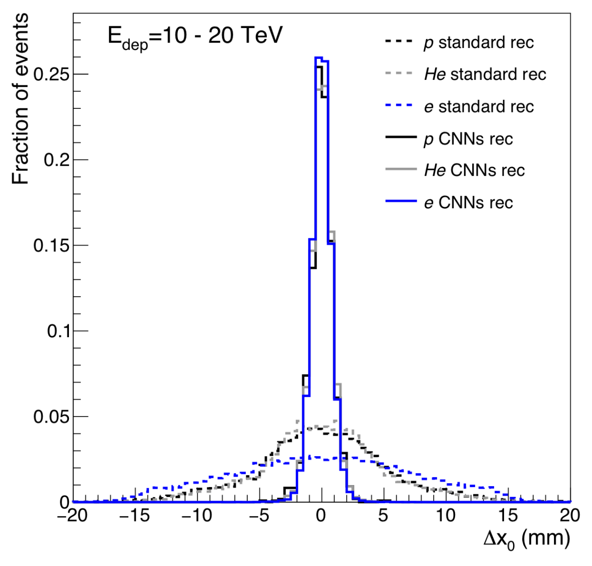


Particle tracking

- Developped CNNs outperform classical algorithms by order of magnitude at high energies!

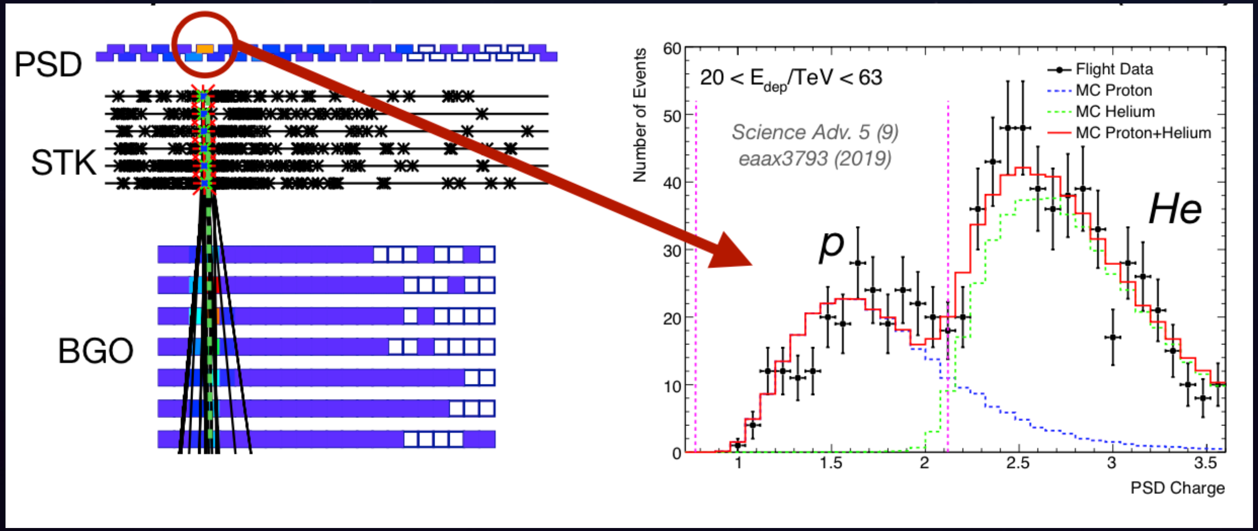


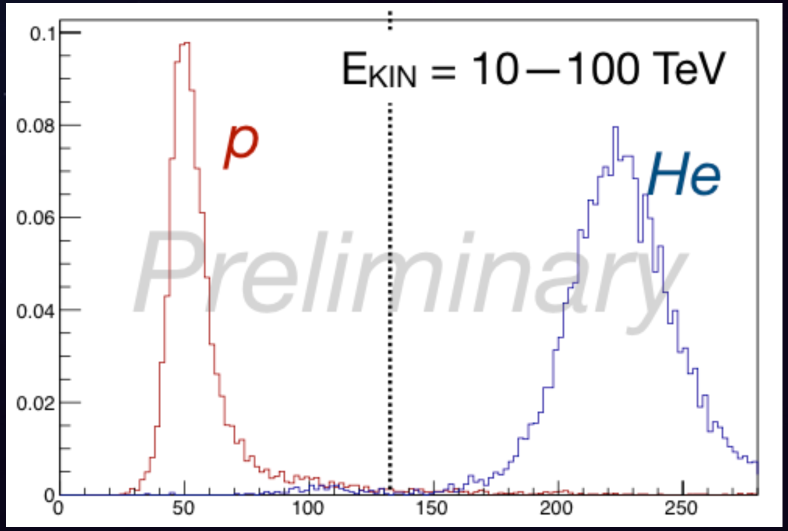
doi: 10.1016/j.astropartphys.2022.102795



Particle tracking

- At high-energies, the PSD gets overwhelmed
  → Very challenging to distinguish e.g. proton from helium
- With accurate tracking, the signal strength in the tracker can be used for particle identification → Much better separation power!

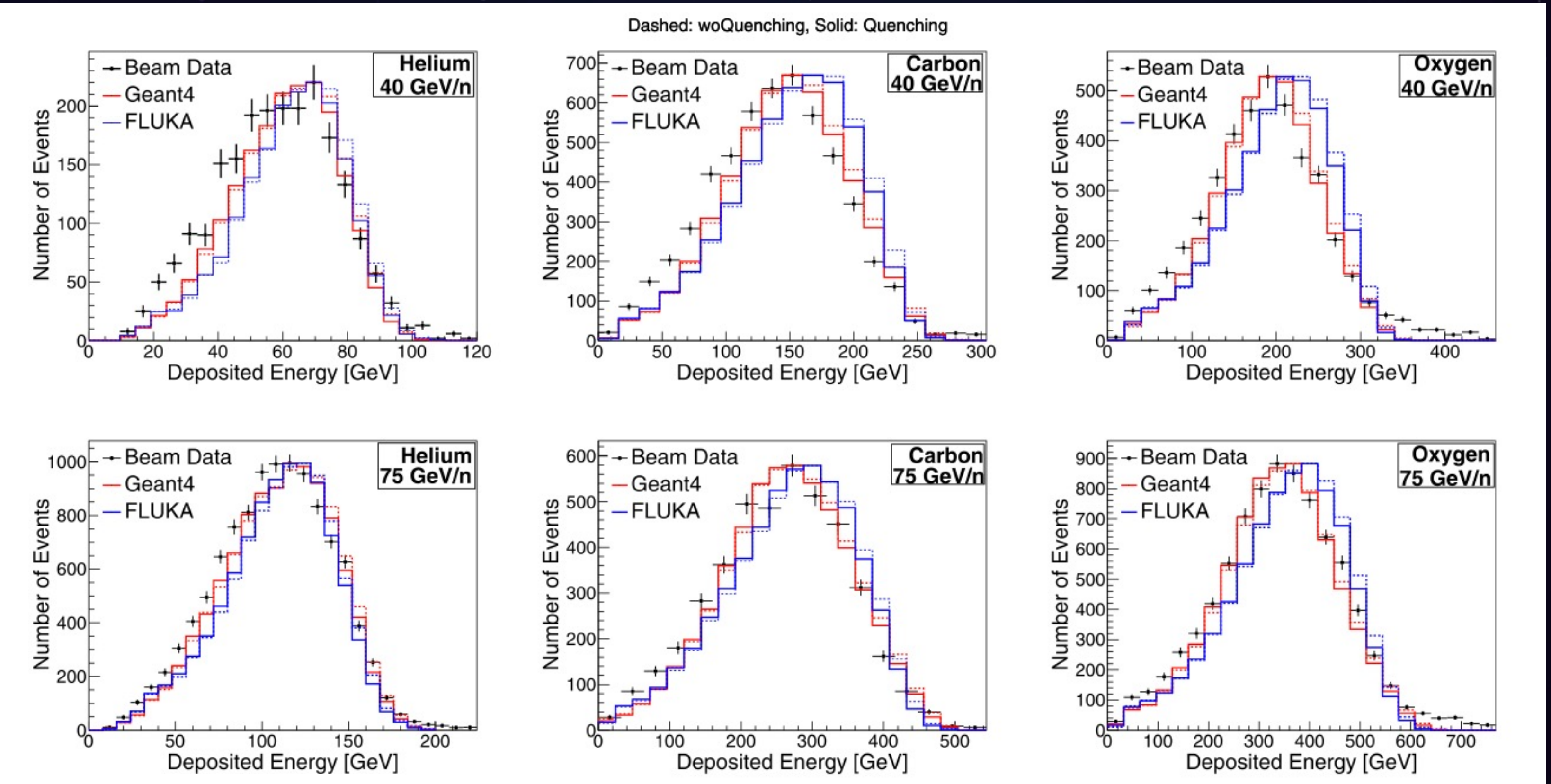




Simulation models

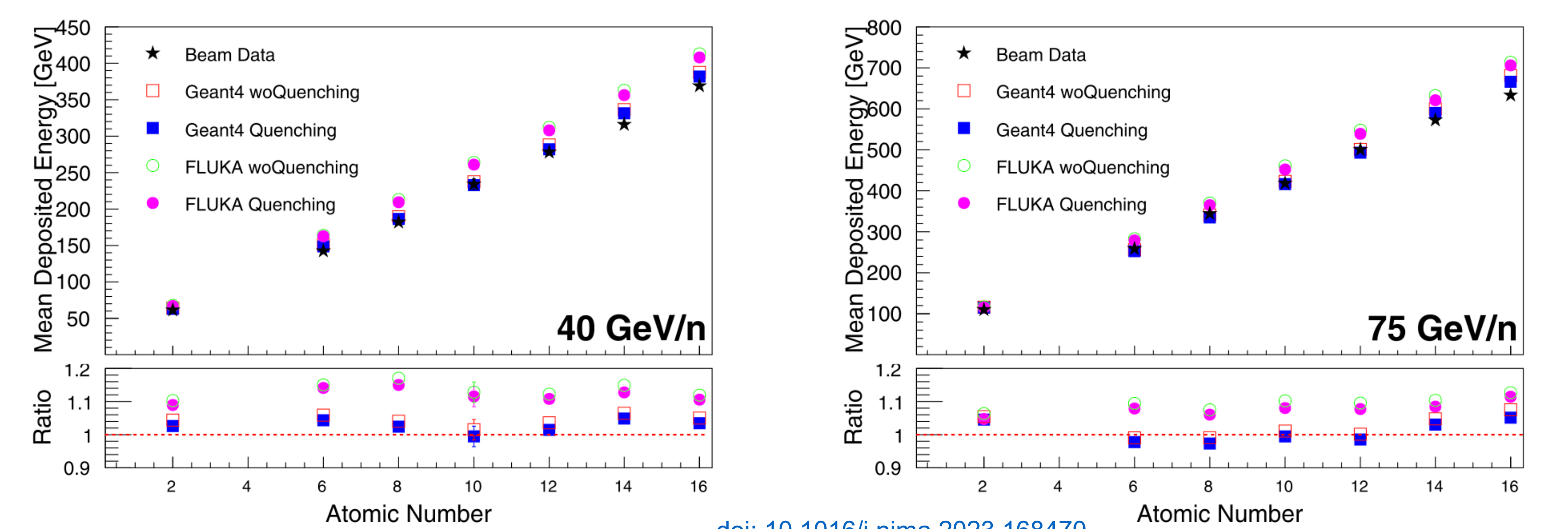
- Geant4 version 4.10.5
- FLUKA version 2011.2X.7
- Downgoing particle sampled in 'half-sphere' around detector
- Simulated energy spectrum per decade: $\frac{dN}{dE} \propto E^{-1}$
- Weighted to an $\Phi \propto E^{-2.65}$ spectrum

Geant4-FLUKA to data comparisons



doi: 10.1016/j.nima.2023.168470

Geant4-FLUKA to data comparisons



doi: 10.1016/j.nima.2023.168470