CR proton flux towards PeV energies with DAMPE

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(for the DAMPE collaboration)

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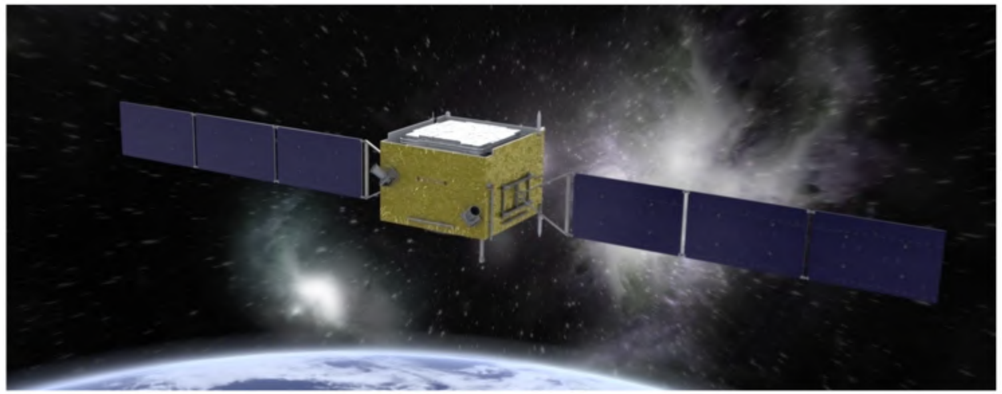
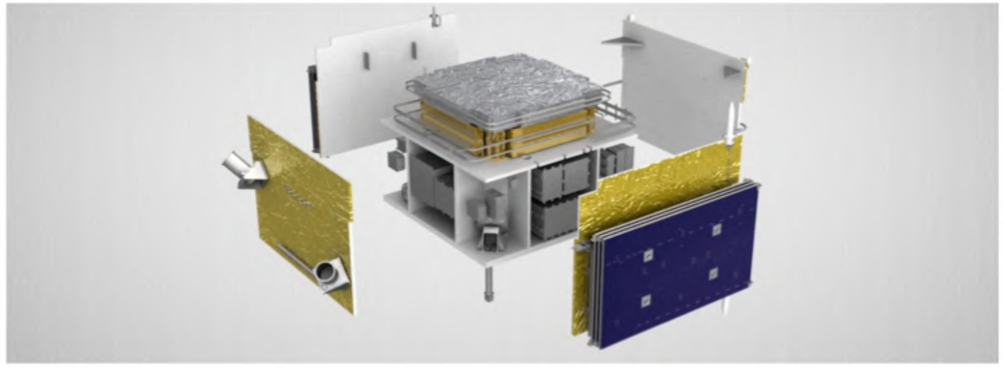
DArk Matter Particle Explorer (DAMPE)

- Launched in **Dec 2015**
- Orbit: sun-synchronous, **500 km**
- Period: **95 min**
- Payload: **1.4 Tonn**
- Power: ~ **400 W**
- Data: ~ **12 GByte / day**

Collaboration





DArk Matter Particle Explorer (DAMPE)

PSD

- Z identification up to *Ni* (Z=28)
- γ anti-coincidence signal

STK

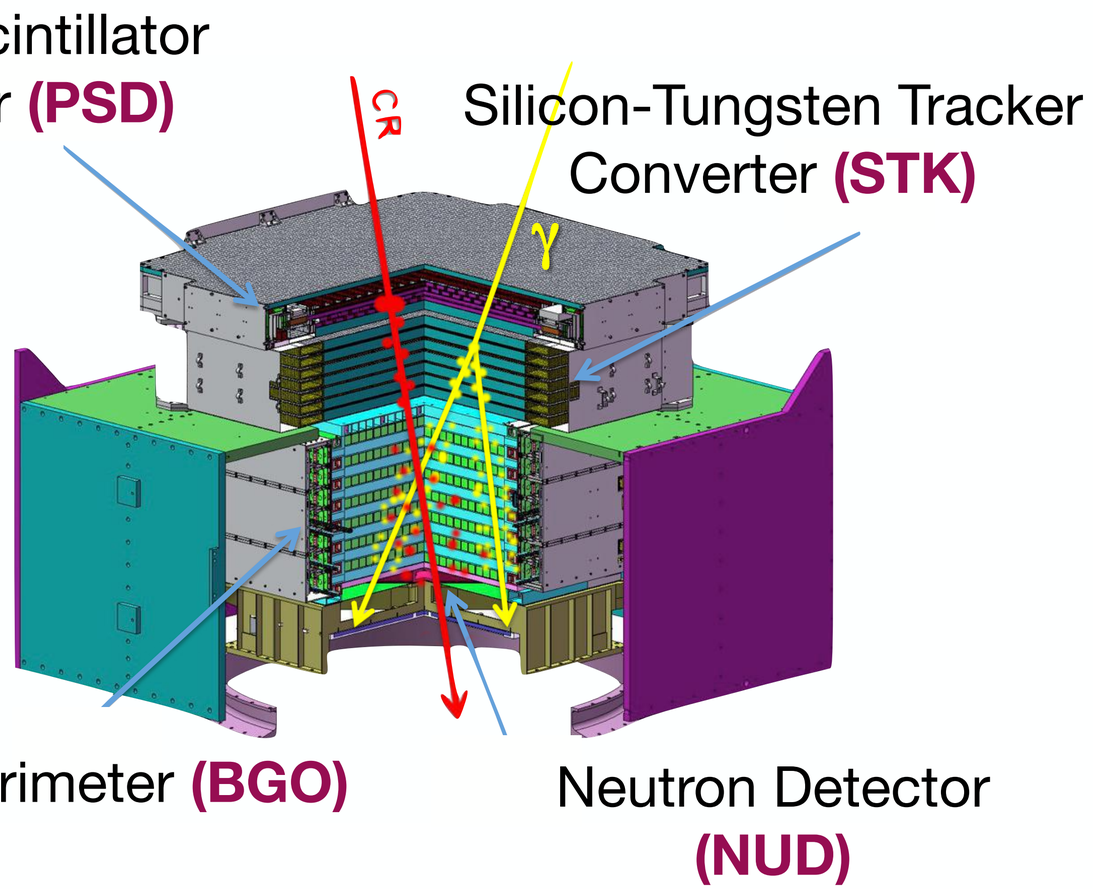
- Position solution ***~50 micron***
- γ angular resolution ***0.5°—0.1°*** (GeV— TeV)
- Absolute Charge (Z) identification

BGO

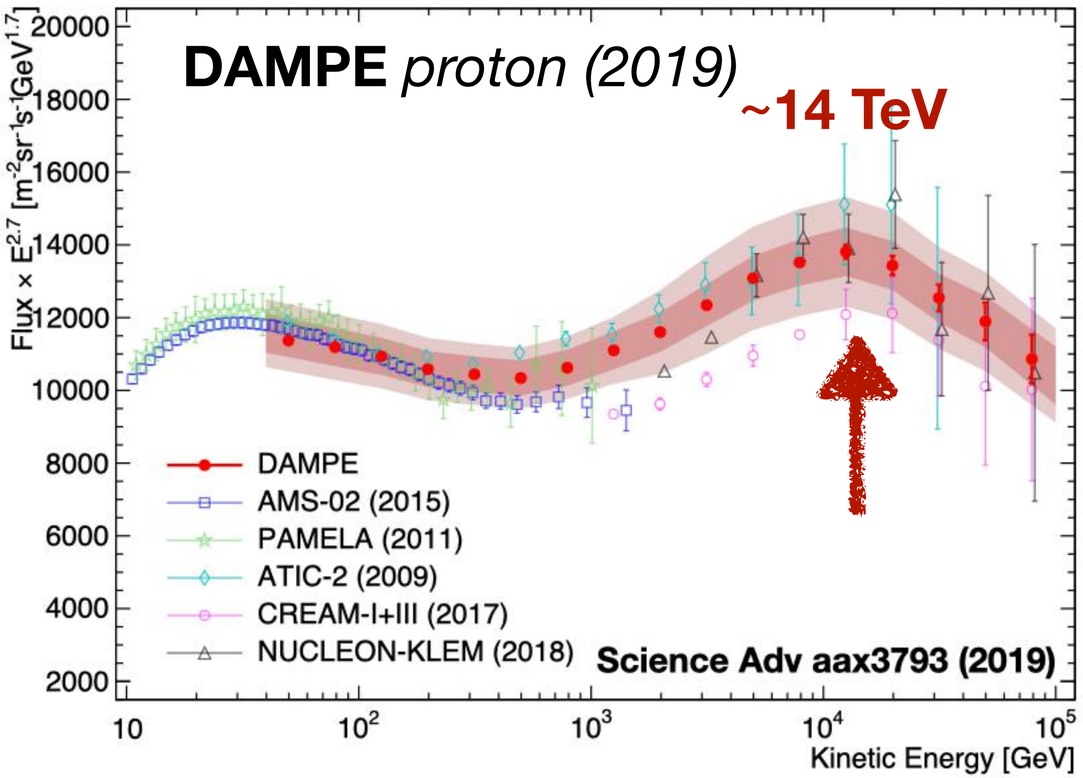
- 31 X_0 — thickest in space
- e/γ detection up to ***10 TeV***
- *p*/ions up to ***50 GeV — 500 TeV***

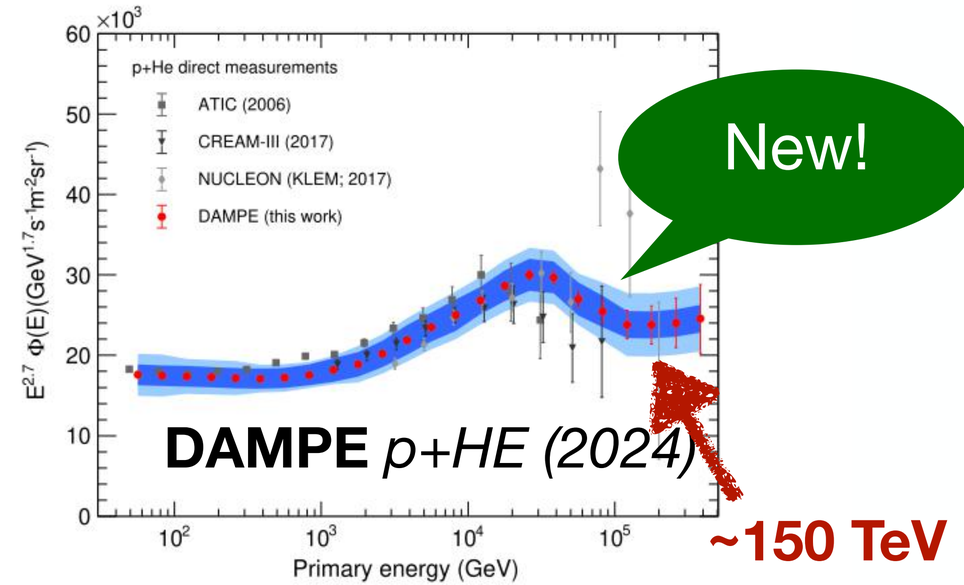
NUD

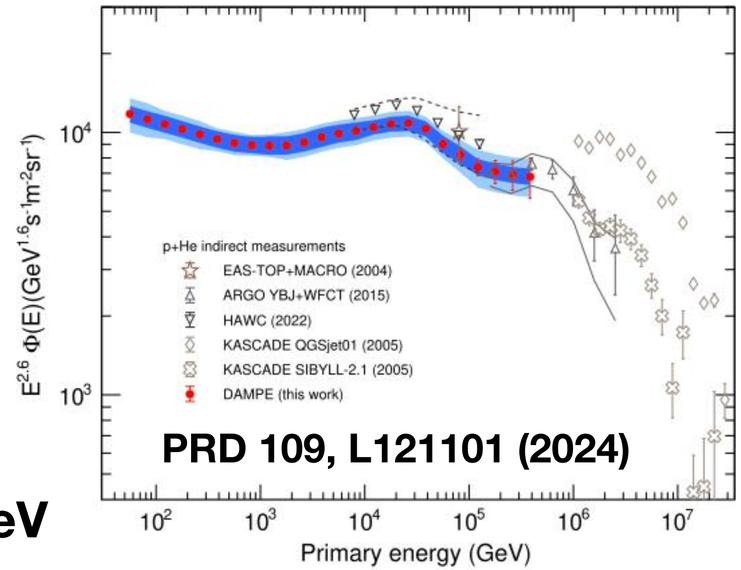
- Additional e/p rejection capability



Motivation







- Proton — most abundant CR and the only CR with Z=A
- Previous individual CR proton measurement reaching 100 TeV
  → limited by statistics and particle ID
- **p+He spectrum (2024) suggests a new hardening at ~ 150 TeV**

Challenge: track reconstruction

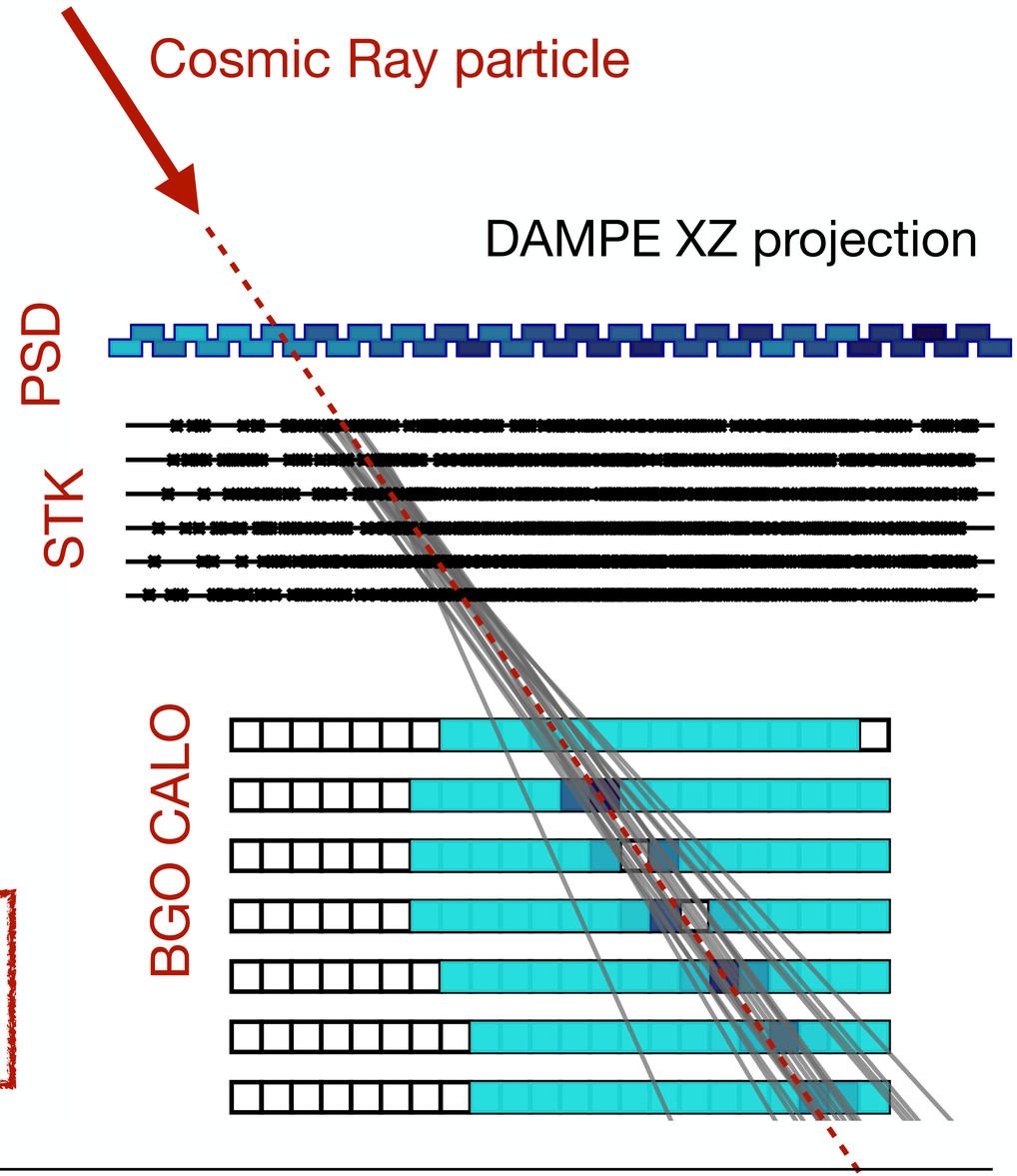
Conventional track reconstruction:

- Shower axis from CALO as a seed
- Kalman fitting
- Combinatorial track finding
- XZ and YZ fitted separately,
- … then combined in 3D tracks

Problems:

- Selection needed to find **the ONLY track**
- Efficiency drops at high hit multiplicity

At TeV— PeV hit multiplicity increases dramatically →
Track reconstruction & identification is a key challenge!

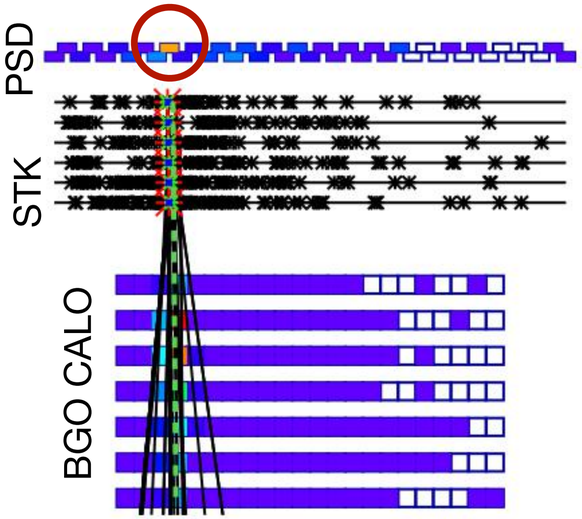


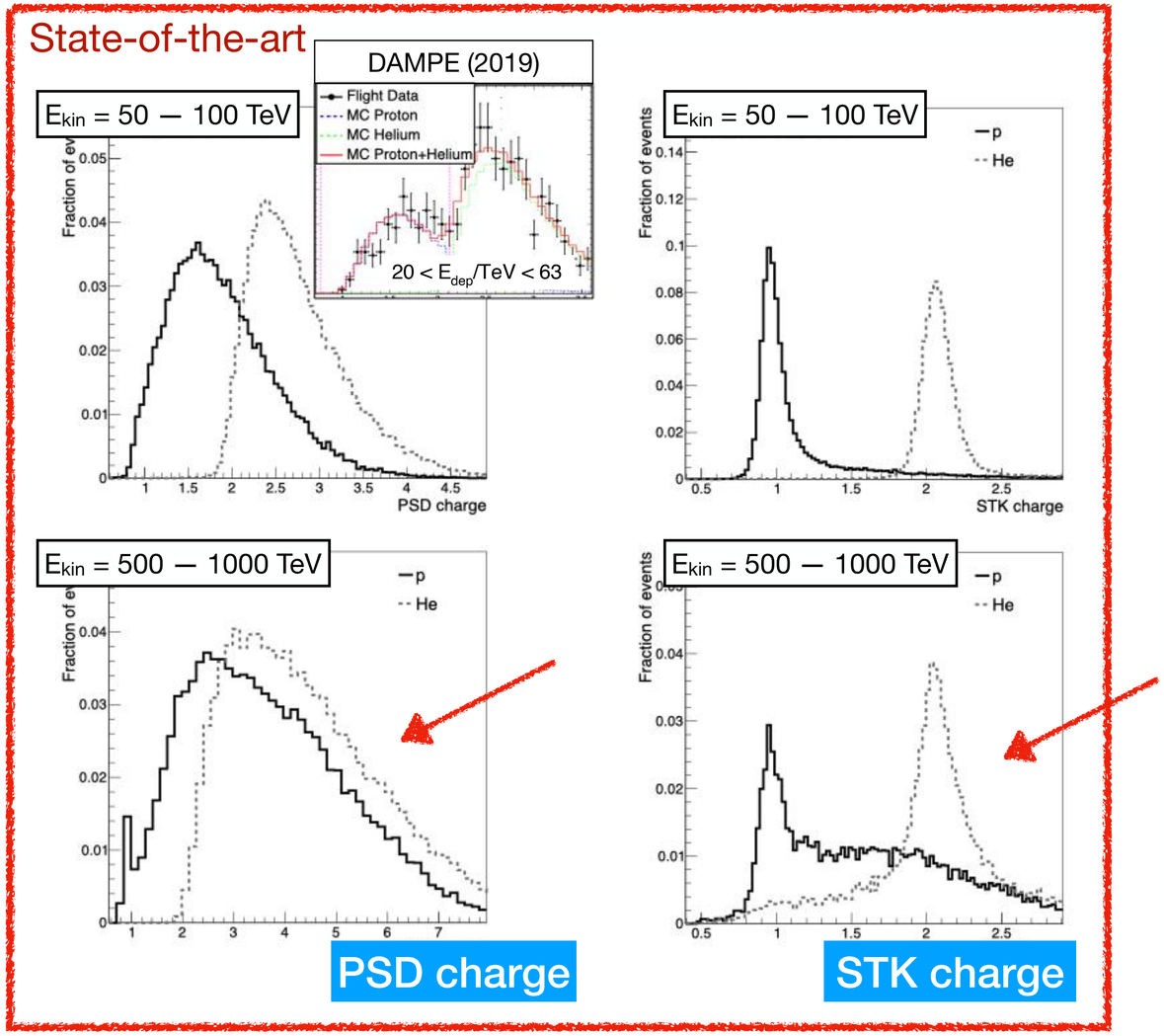
Challenge: charge identification

- Charge ID conventional done in PSD
- Track used as a pointer to PSD
- Tolerant to track mis-identification, however:

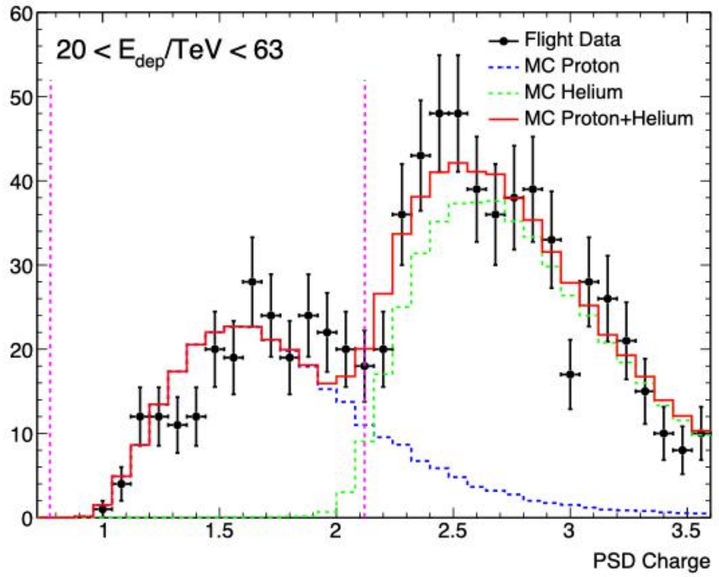
  ***p* and *He* peaks "washed out"**

  at high energies!

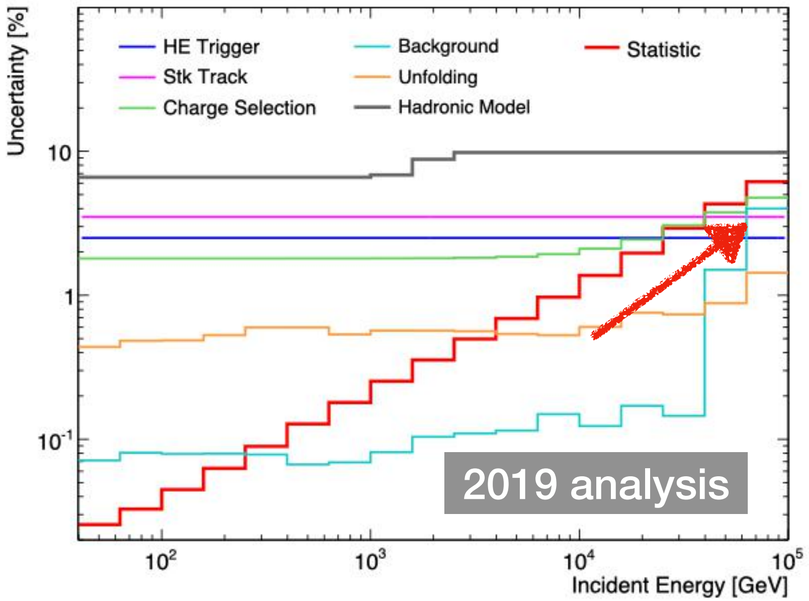




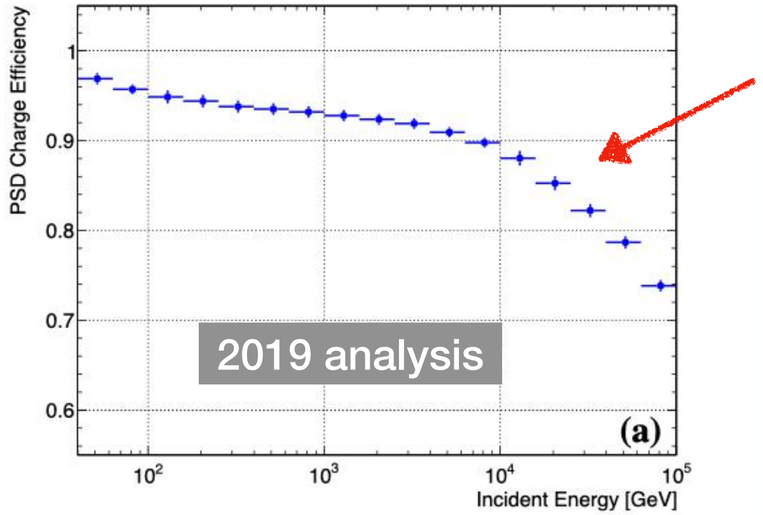
Challenge: tracking & charge ID



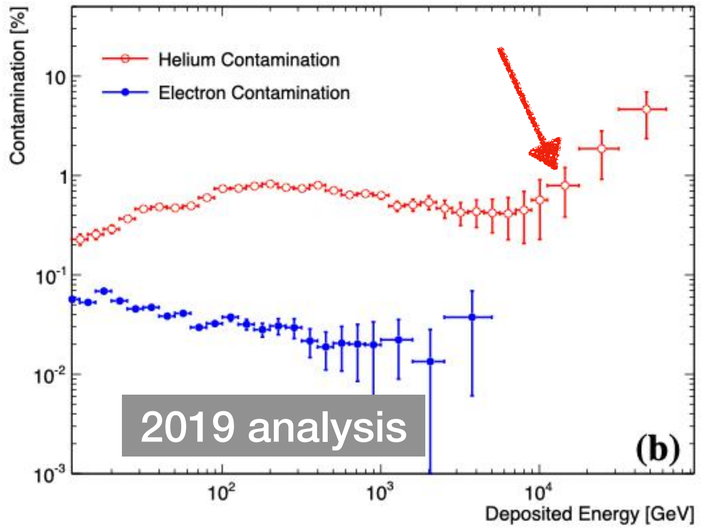
Statistical & Systematic errors



p charge selection efficiency



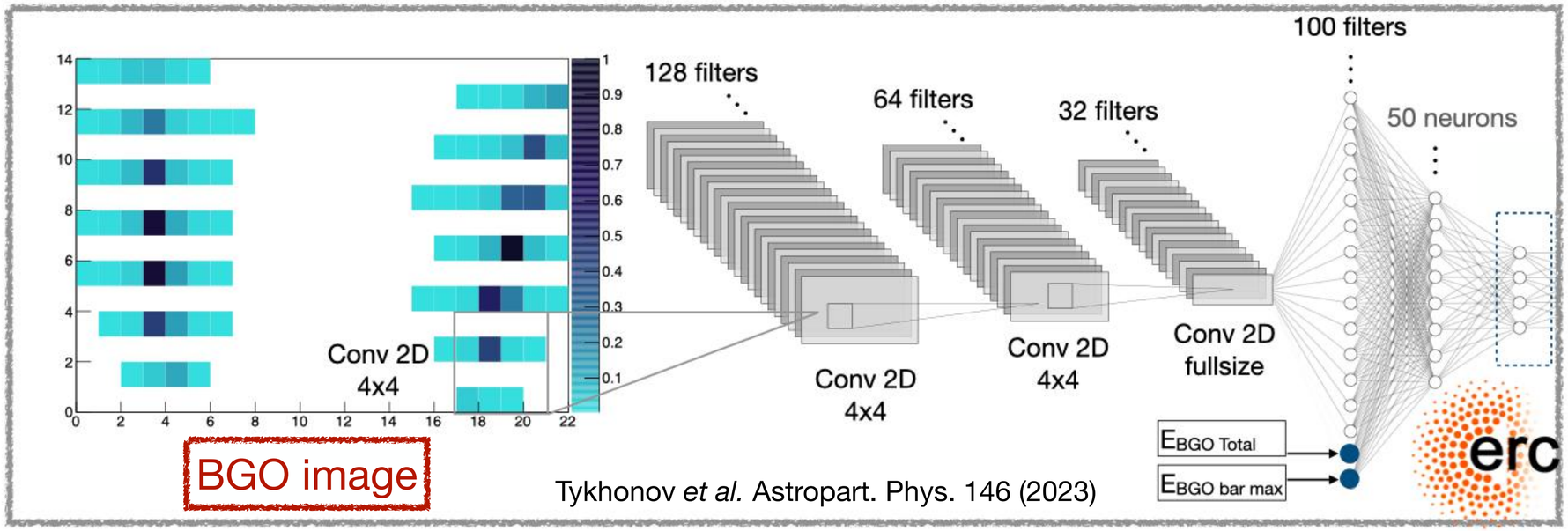
Background contamination



- Track reconstruction + proton charge identification + background contamination — dominating uncertainty at high energies!

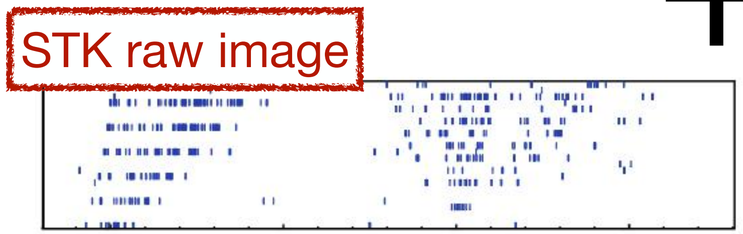
New tracking algorithm required for ~ PeV measurements!

New track reconstruction & ML



Tykhonov *et al.* Astropart. Phys. 146 (2023)

We employ **Convolutional Neural Networks (CNNs)** to boost the accuracy of track reconstruction & identification @ DAMPE



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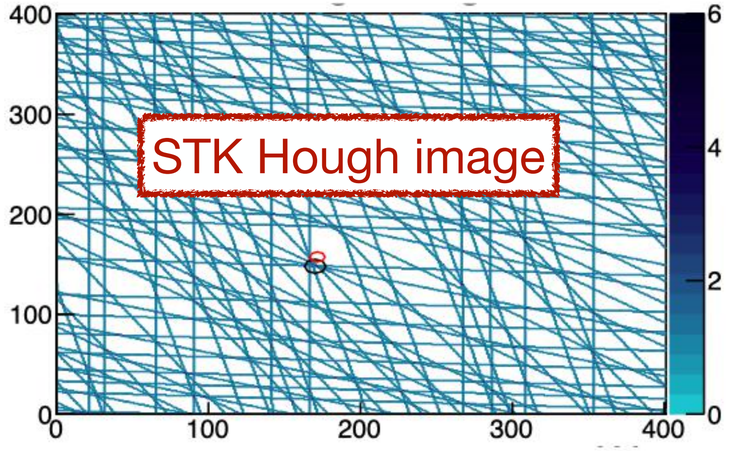
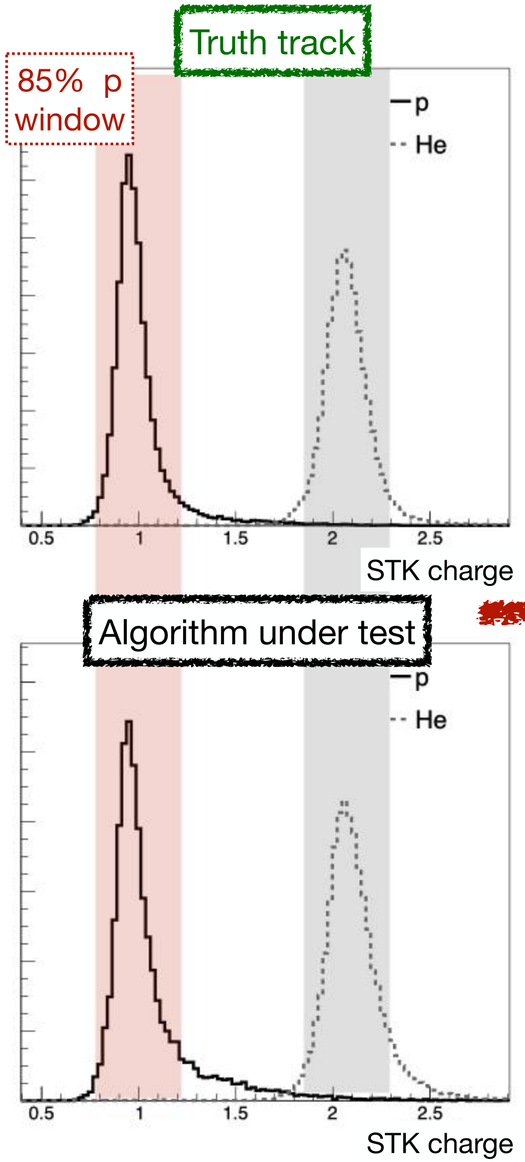
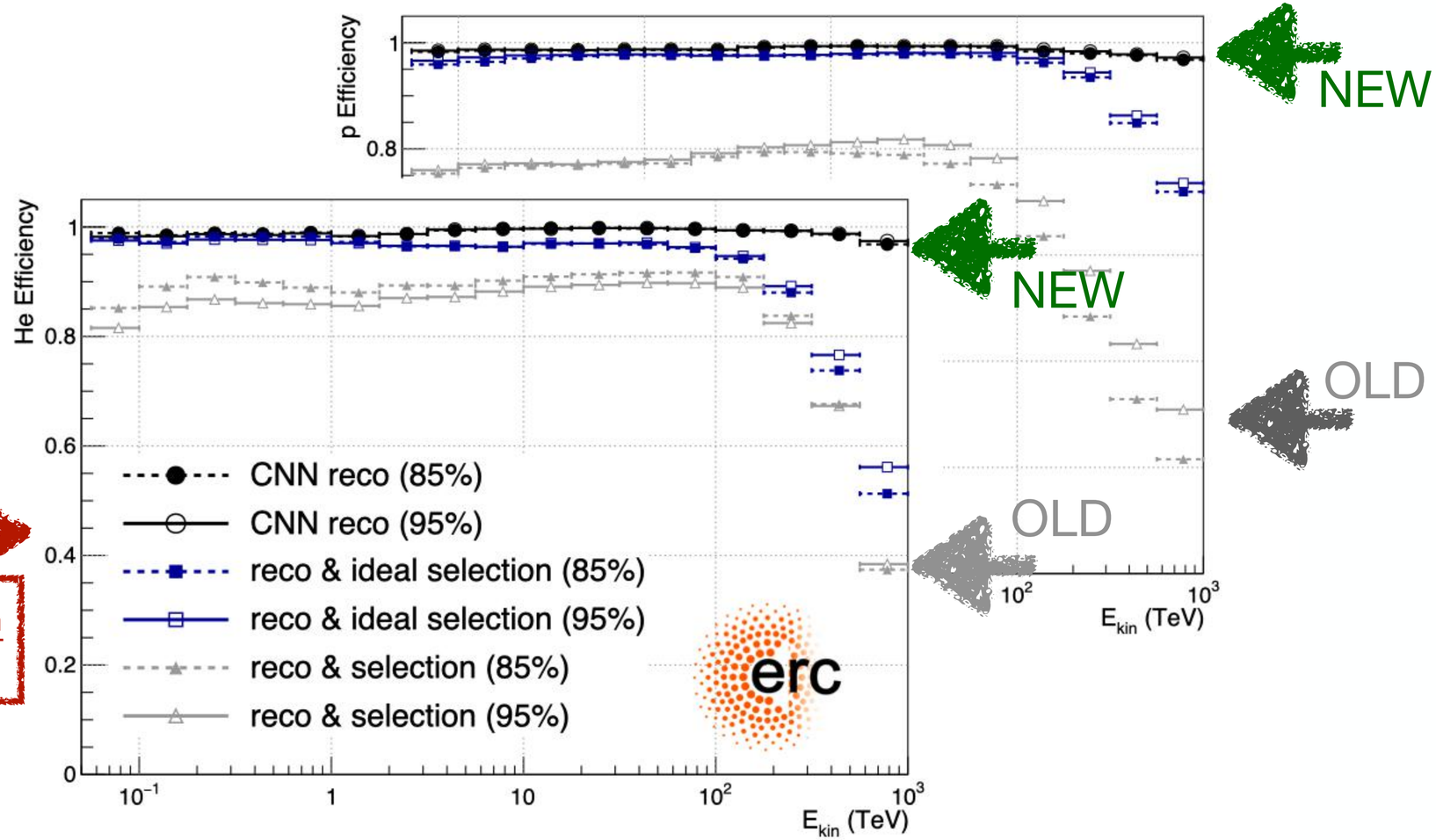


CALO & Tracker "images" used as input, regression type of problem — returns particle direction as an output (no track selection needed)

New track reconstruction & ML



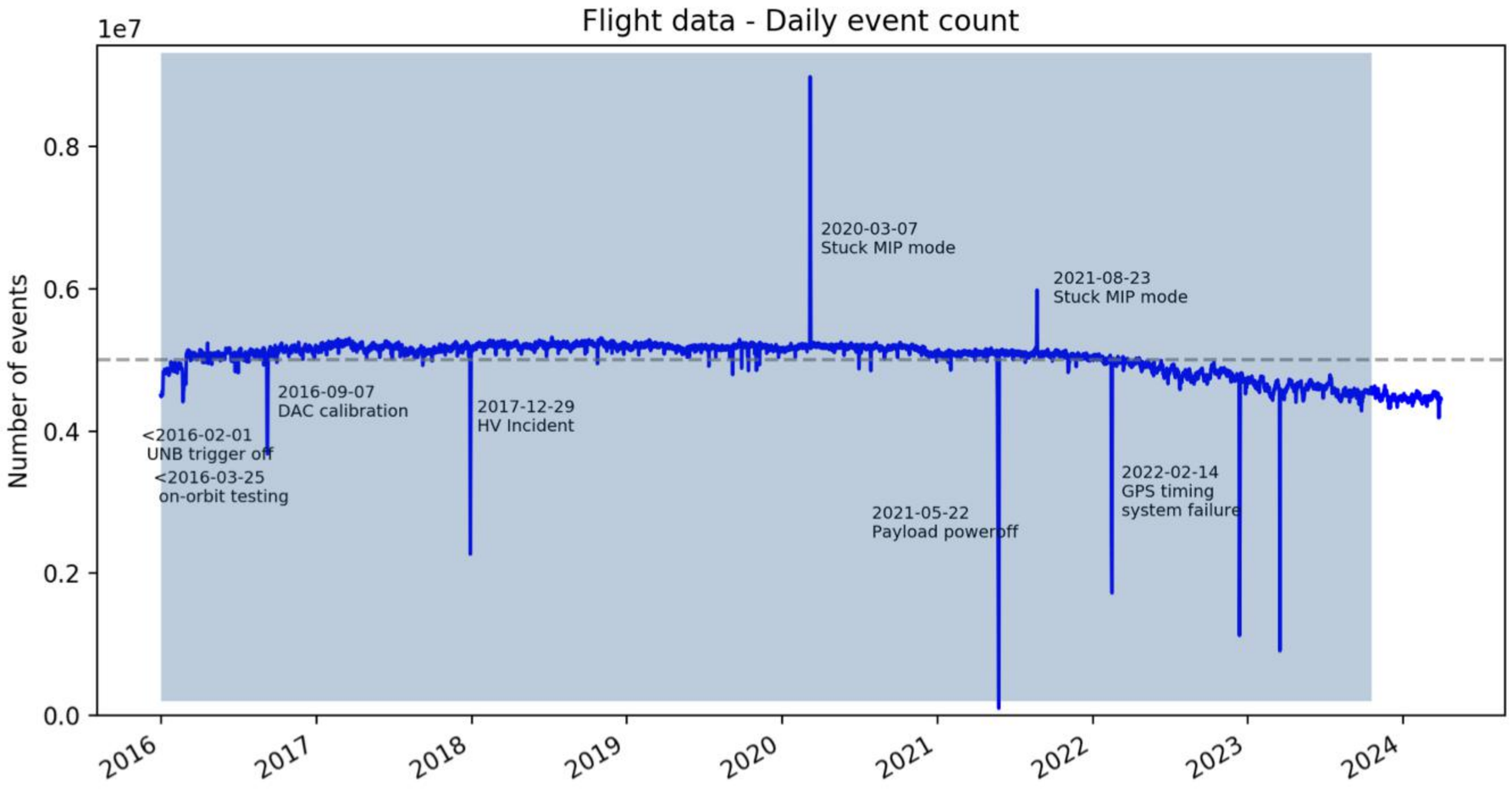
$$\text{Eff} = \frac{N_{\text{algorithm}}}{N_{\text{true}}}$$



Tykhonov *et al.* Astropart. Phys. 146 (2023)

CNN tracking efficiency = **98-99%** up to 500 TeV (> **96%** @ PeV)

Data

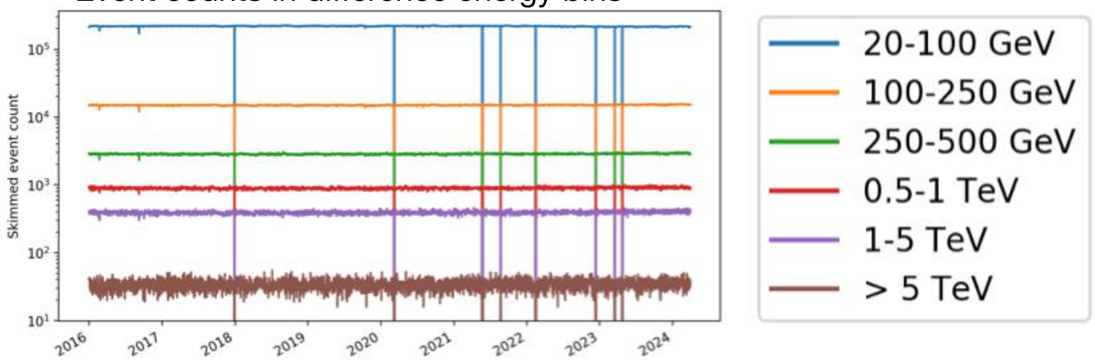


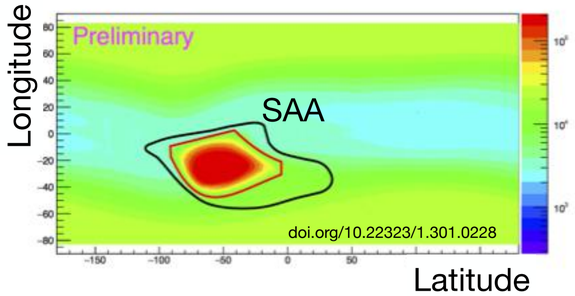
- **92 months of data**
- 14 billion events
- Livetime:
  183698199 seconds
  (76%)

Event selection

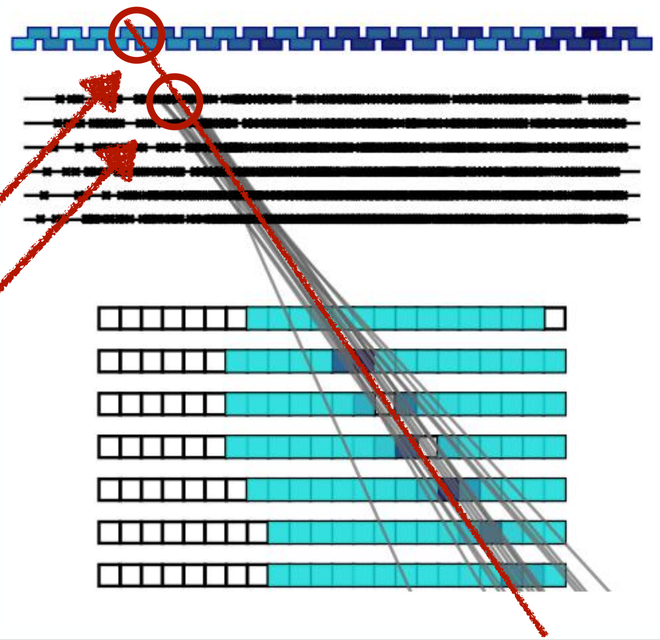
- **Pre-selection**:
  - Ensure well-reconstructed and fully-contained events in the detector
- **Selection**:
  - High-energy trigger
  - Deposited energy > 20 GeV
  - Removal of SAA region
  - Electron removal (ζ classifier)
  - ML track reconstruction

Event counts in difference energy bins



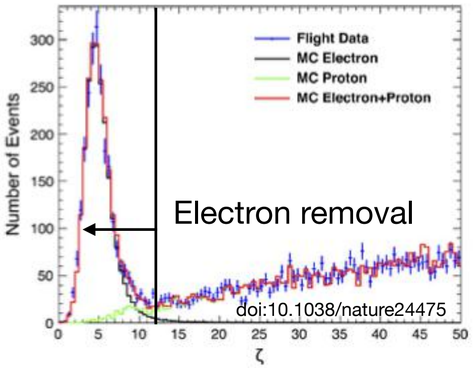


ML track

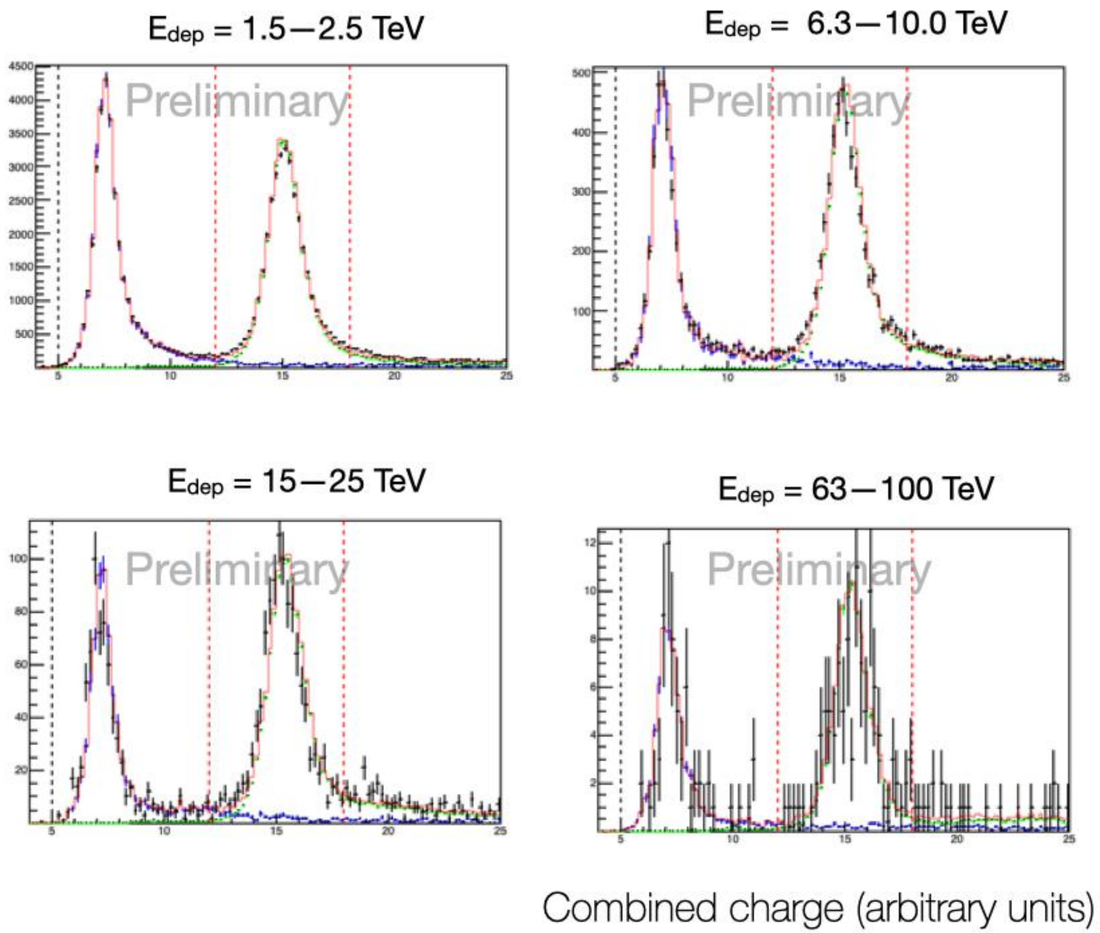


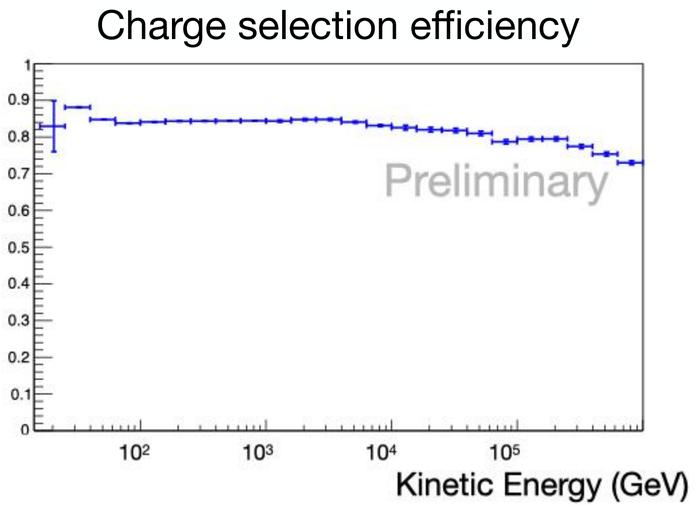
Combined charge selection =

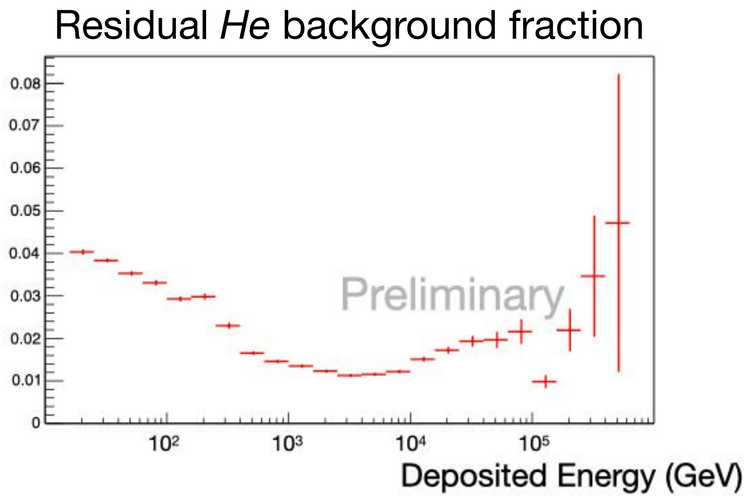
- PSD charge if CR interacts before STK
- STK charge if CR interacts after PSD



Charge selection

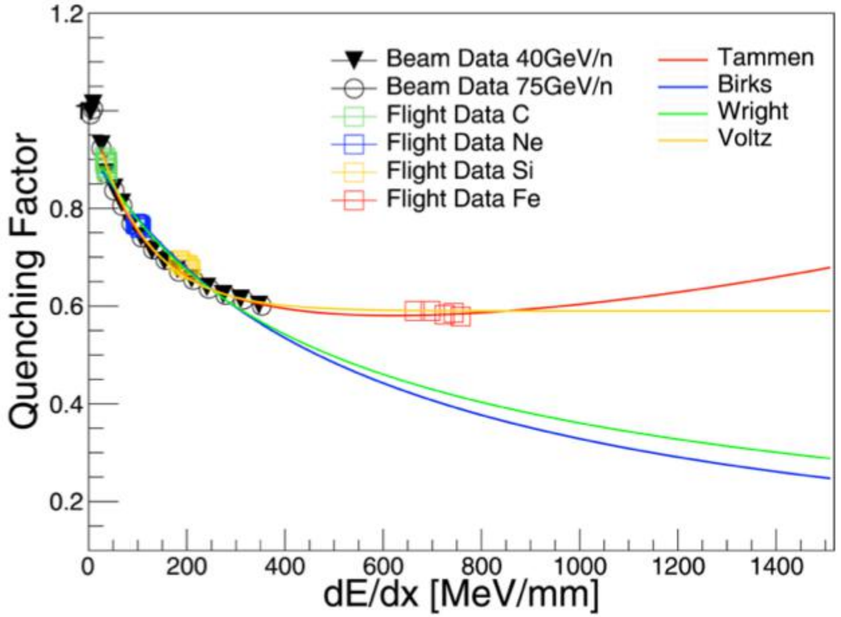






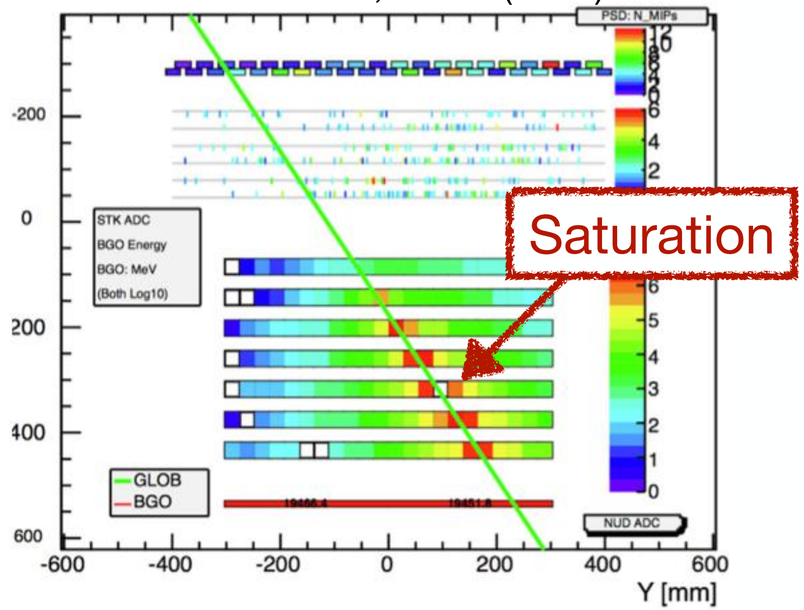
- He background below ~4% up to ~ 500 TeV
- Charge selection efficiency above 80% up to 100 ~TeV, 73% at ~PeV

BGO quenching and saturation corrections

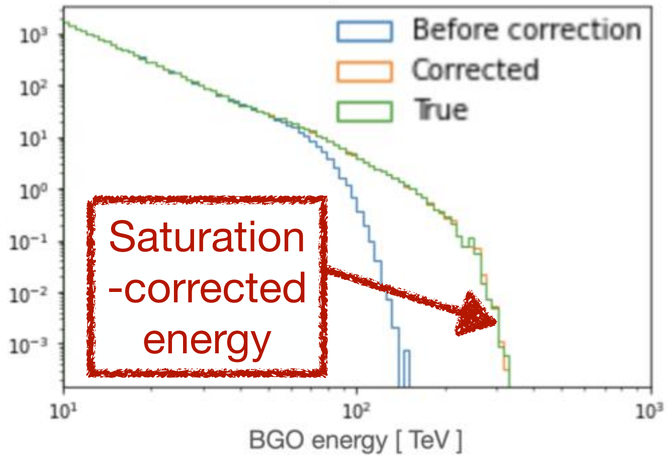


Y. Wei et al., Transactions on Nuclear Science, 67/6 (2020), Y.-F. Wei et al. NIM A 922 (2019), Z.-F. Chen et al. NIM A 1055 (2023)

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

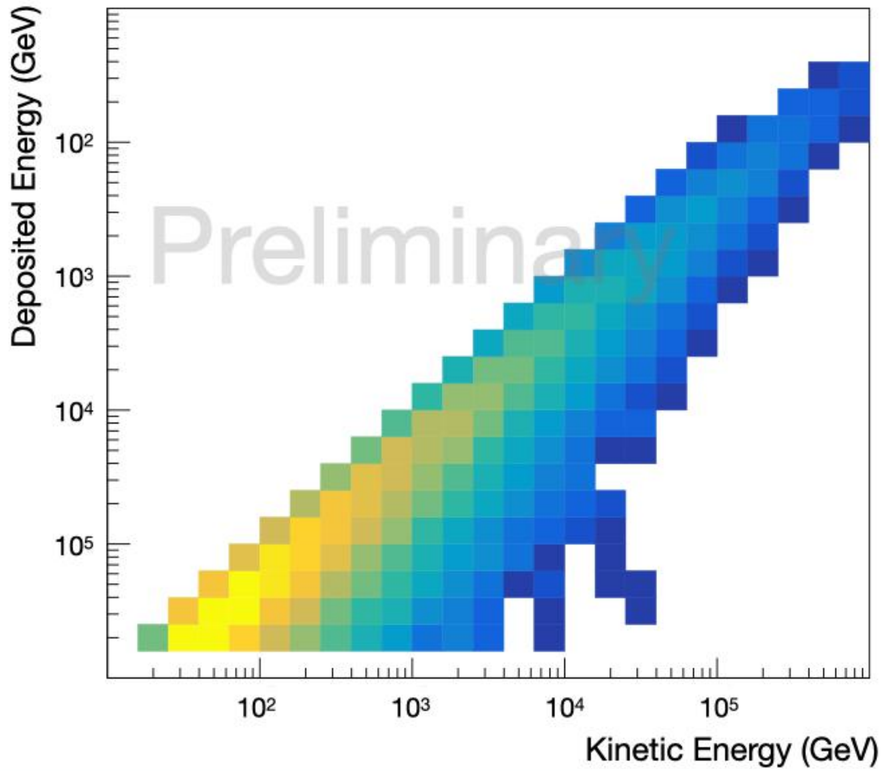
Saturation of BGO bars at ~100 TeV CR kinetic energy:

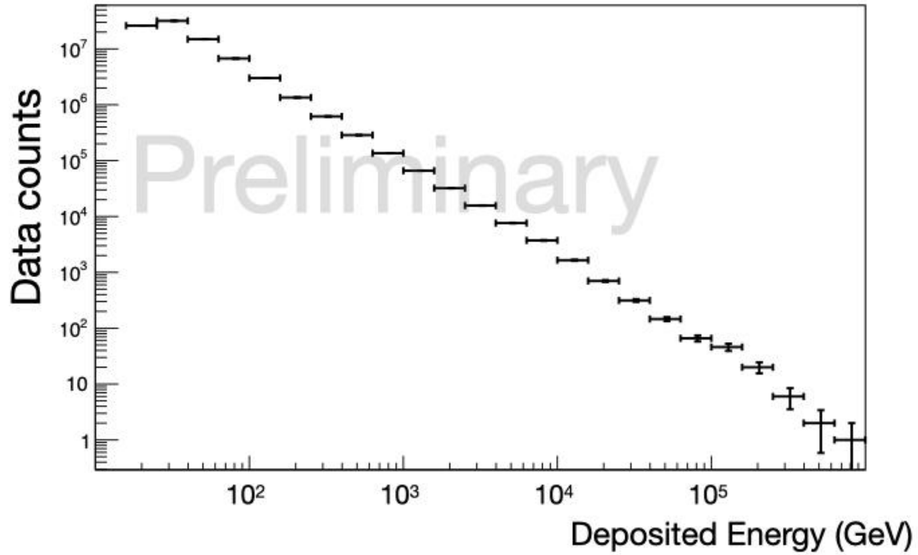
- corrections derived using analytical and ML methods

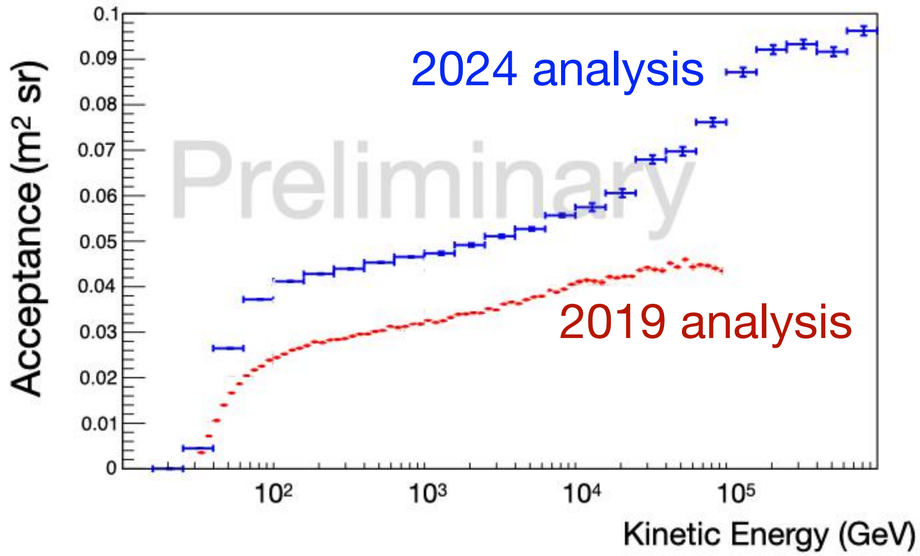
Event counts, energy unfolding

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

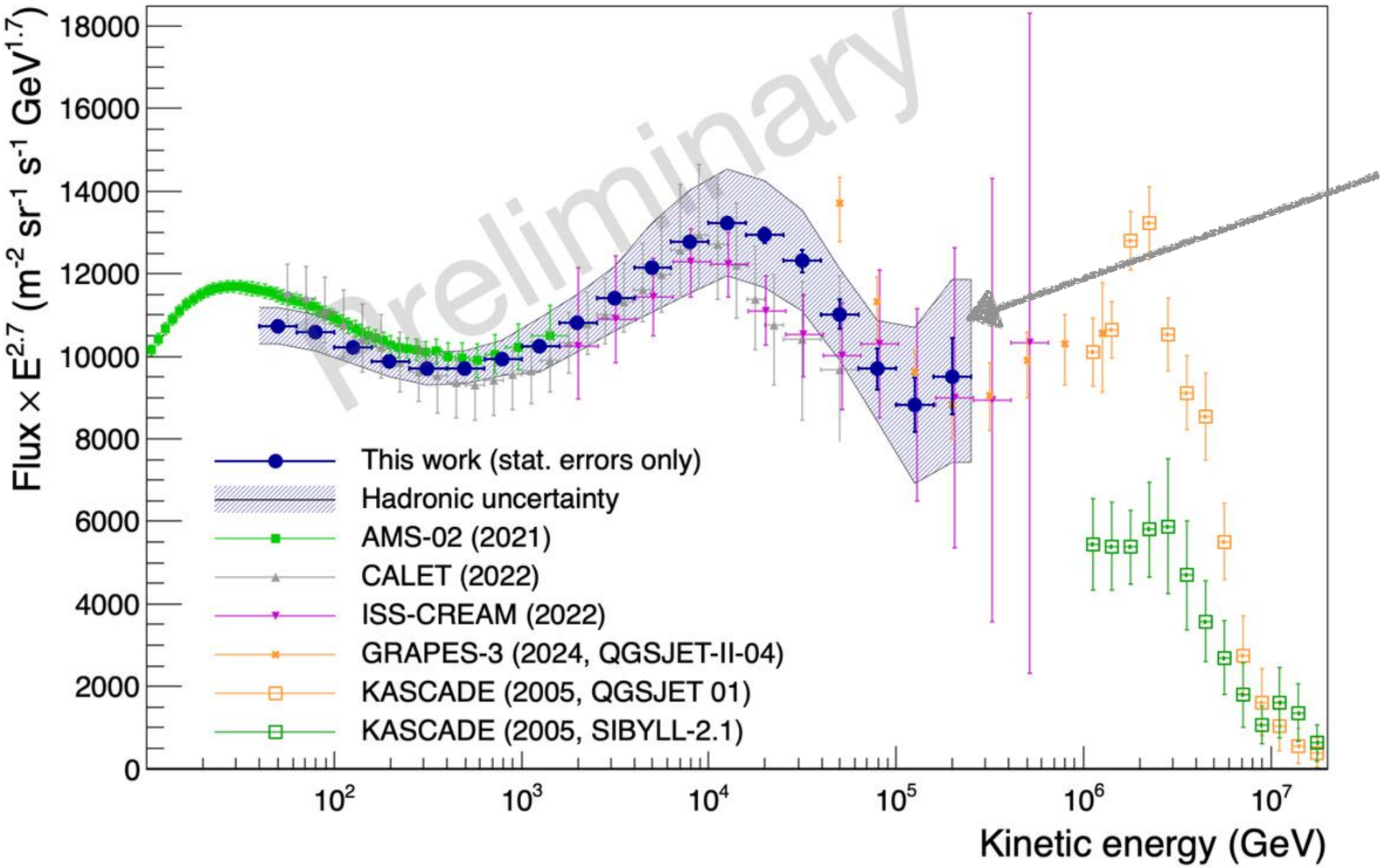
$$P(E_{\text{true},j}|E_{\text{meas},i}) = \frac{P(E_{\text{meas},i}|E_{\text{true},j})\ P(E_{\text{true},j})}{\sum_k P(E_{\text{meas},i}|E_{\text{true},k})\ P(E_{\text{true},k})}$$







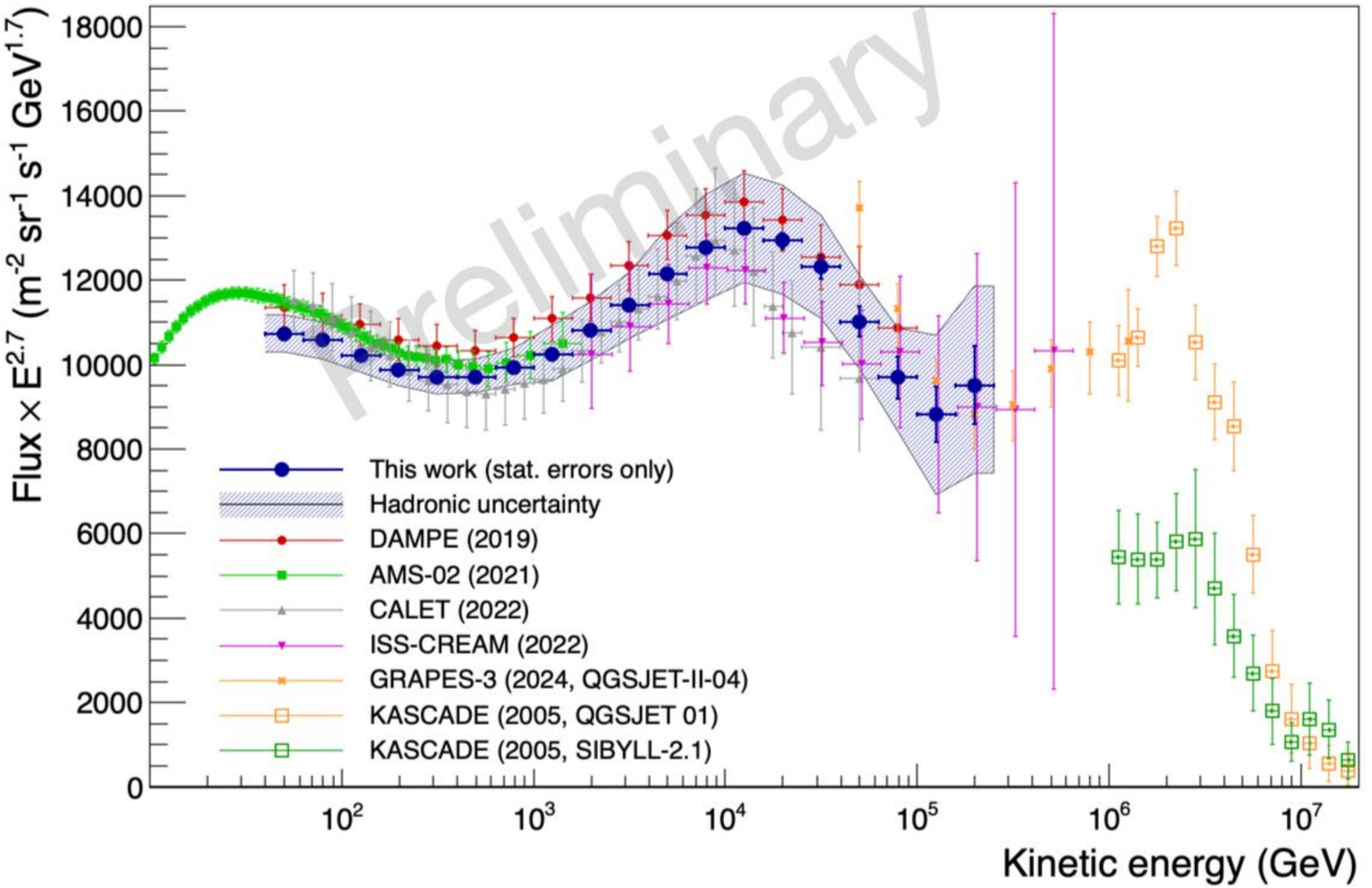
Flux



Hadronic errors:

- Estimated from Geant4 vs FLUKA comparison
- Mostly affect normalization
- Minor effect on flux shape

Flux



Good agreement with 2019 result within the analysis errors

Estimation of systematics in process, dominating factors: charge selection for PSD-interacting events, BGO saturation, quenching, …

Next steps: hadronic cross sections

Hadronic cross section affecting:

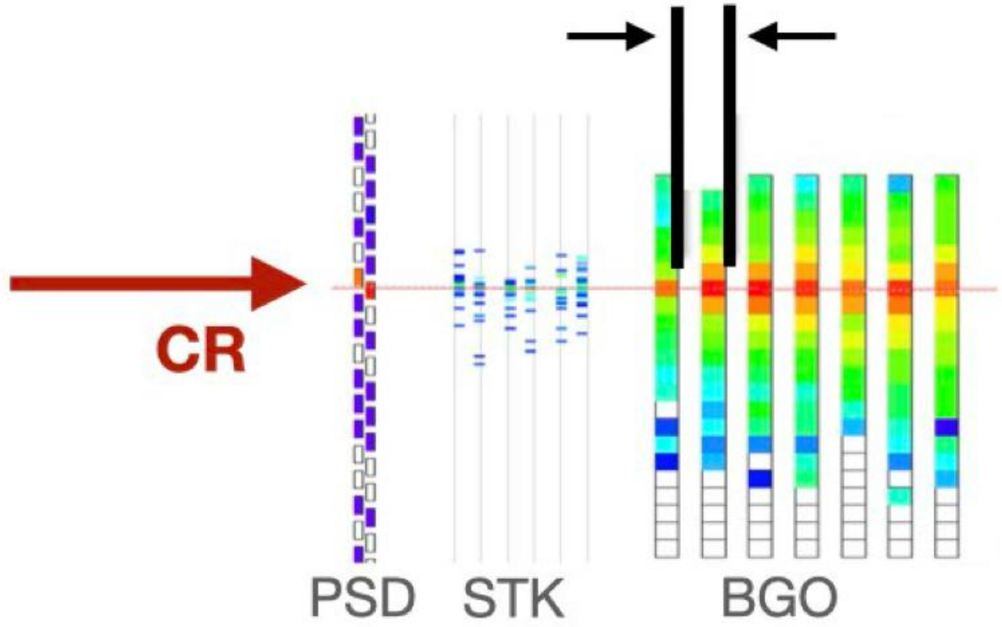
1) Acceptance

2) Energy response matrix

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

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

Good segmentation of BGO calorimeter and new AI tracking allows to use DAMPE for cross-section measurements:



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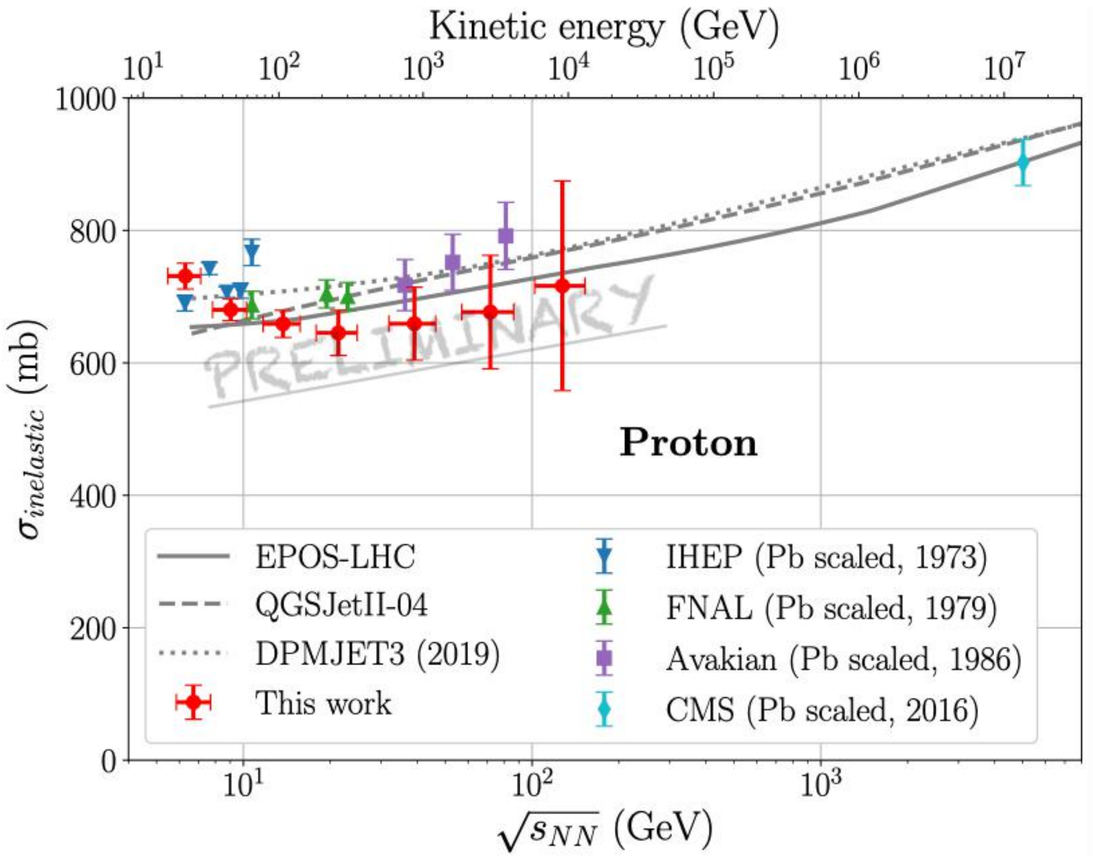
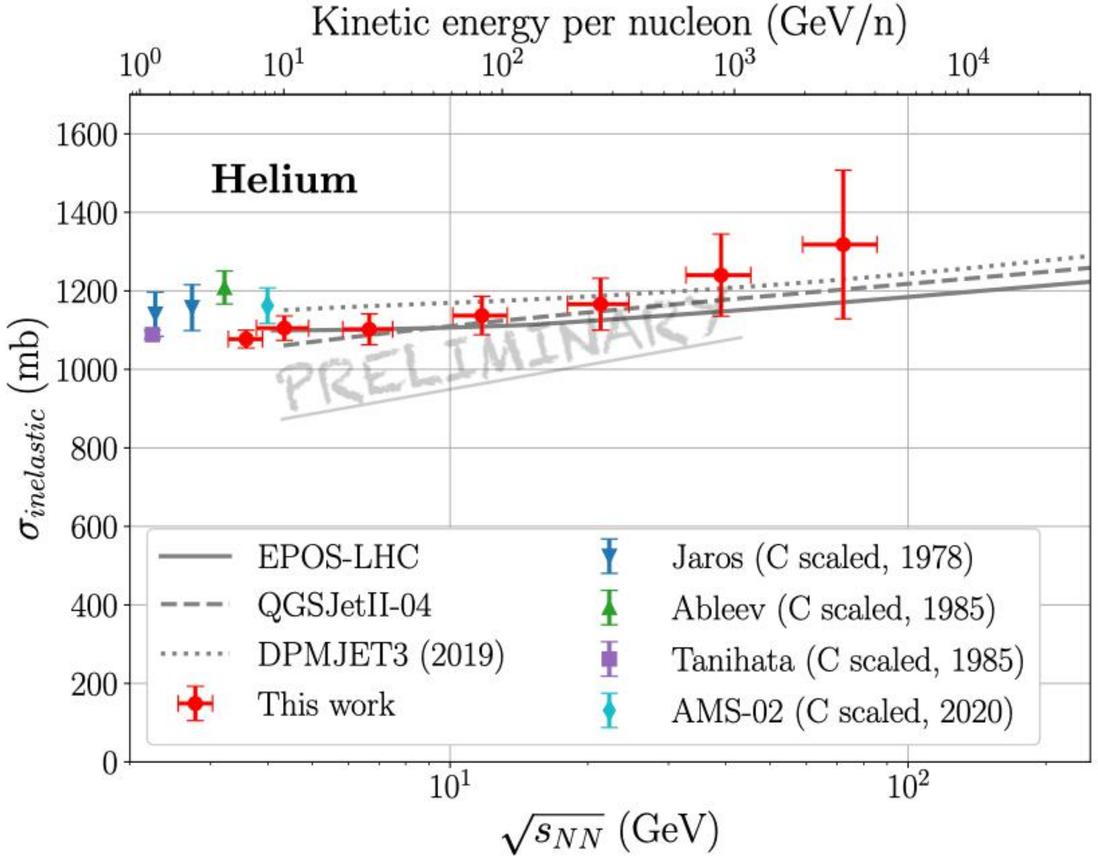
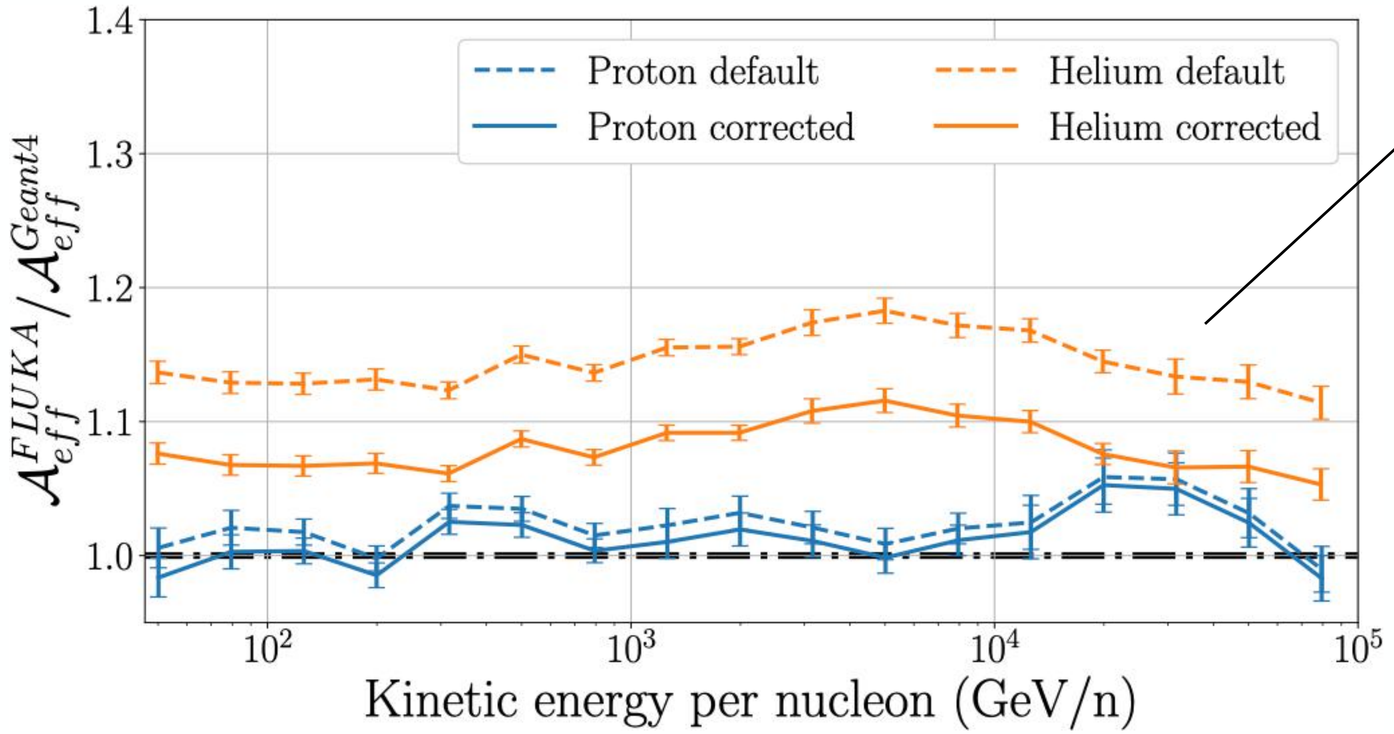




Paper coming soon …

Next steps: hadronic cross sections

Acceptance Geant4 vs FLUKA
(before and after correcting to the data):



Helium: 15% → 8 %
Proton: 2.3% → 1.2%

Dedicated work on hadronic measurements & corrections, see

XSCRC2024: Cross sections for Cosmic Rays @ CERN this October!

Conclusions

Motivation

- First publication of proton flux in 2019 (30 months data)
- Classical analysis limited to ~100 TeV by ~ particle ID
- Hints of new feature in combined p+He at ~150 TeV

New result

- 92 months of data
- Based on ML tracking
- Increased acceptance and improved particle ID
- Careful systematics study in process
- Dedicated work on hadronic measurements

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To be continued ….

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Thank You!