Dark Matter Particle Explorer (DAMPE)

Results after 8 years in Space

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on behalf of the DAMPE collaboration

Part I:

The Dark Matter Particle Explorer (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 $\sim 5 \times 10^6$ events per day
- Large effective area and deep calorimeter (32 radiation lengths)
  - Electrons / photons:
    5 GeV to 10 TeV ; acceptance $\sim 0.3\ \mathrm{m^2\ sr}$
  - 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

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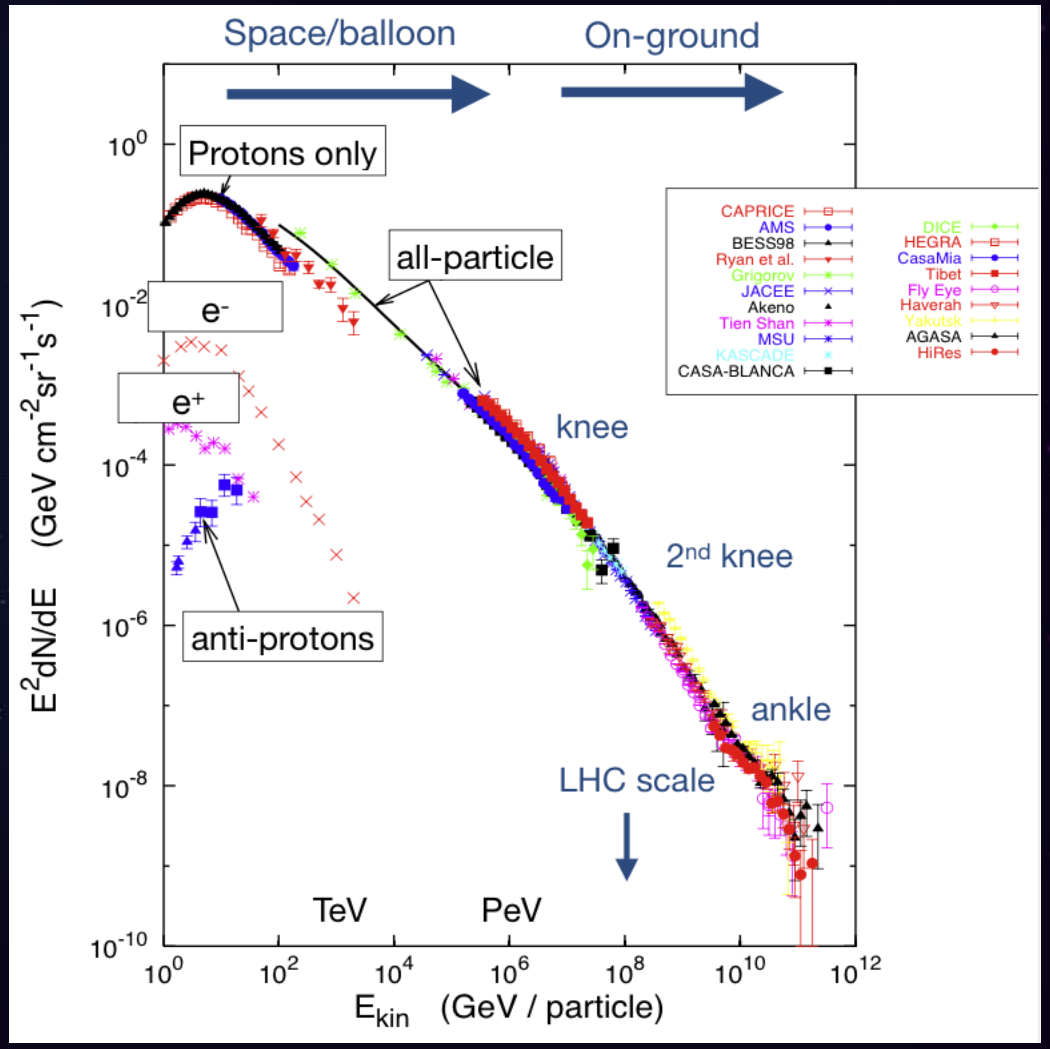
The cosmic-ray spectrum

- DAMPE trigger rate of 60 Hz from CRs
- Broken power law:
  - $dN/dE \sim E^{-2.7}$
  - Knee & 2nd knee:
    Maximal energy attainable by Galactic sources (for proton & iron)
  - Ankle: Extragalactic sources
- Particle content:
  - Mostly proton, heavy ions
  - Electrons, photons
  - Anti-matter: positron, anti-proton, …



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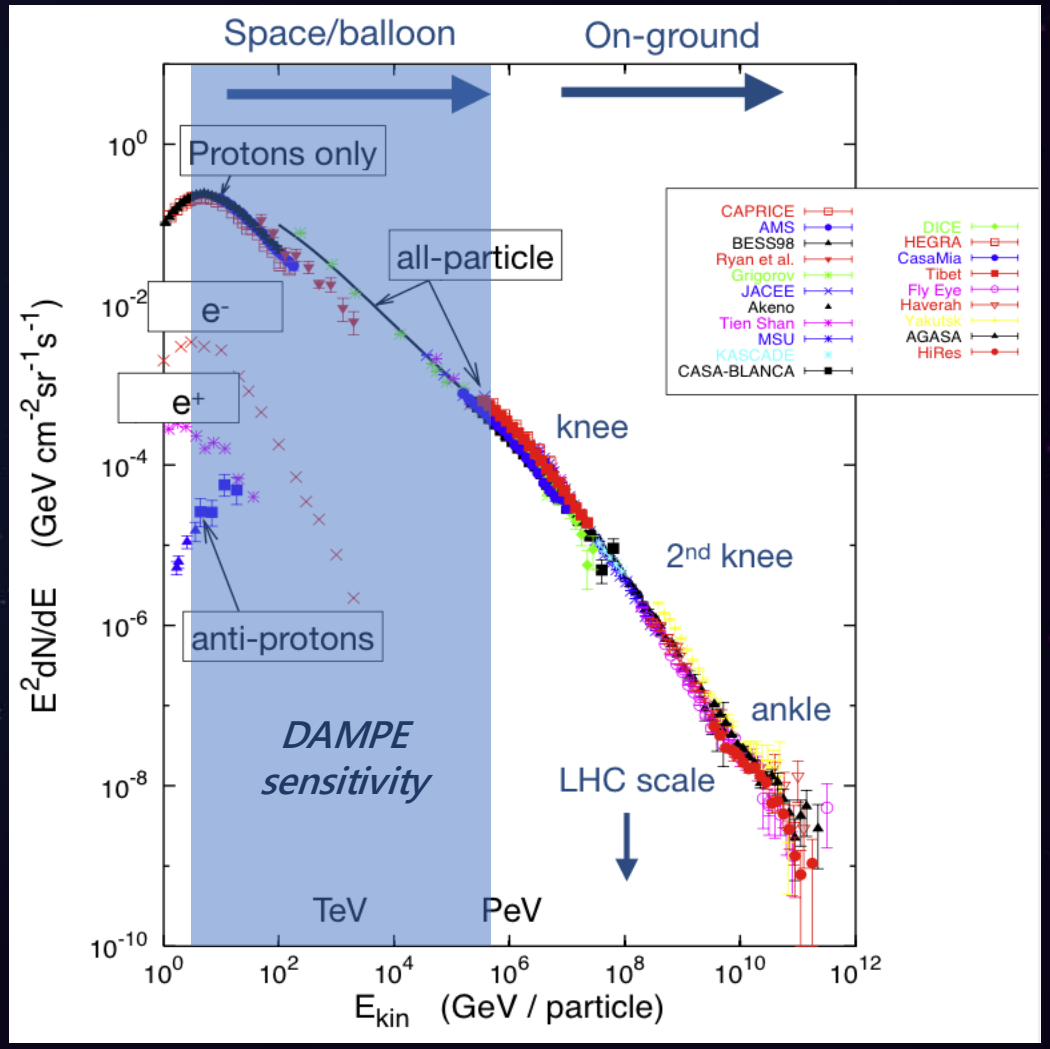


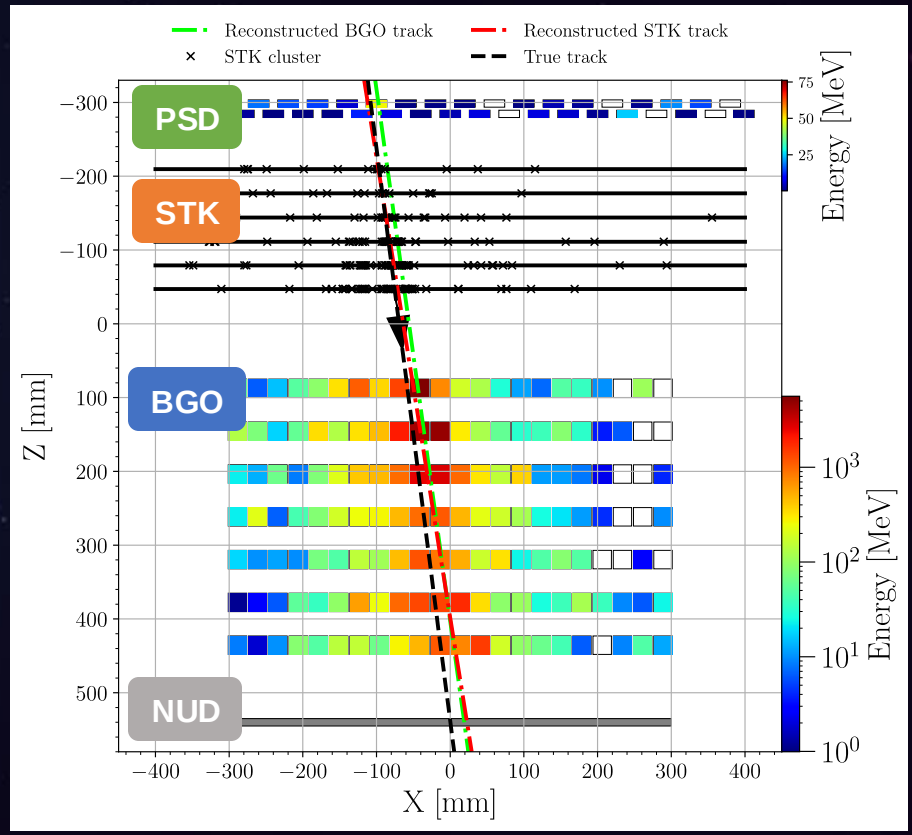
CR physics with satellite experiments

- Space-borne experiments sensitive up to PeV
  → Just below the knee → Supernova remnants
- Spectrum depends on:
  - Production at the source
  - Attenuation/spallation during propagation
- Currently challenges include explaining:
  - Extensive spectral features below PeV
  - PeV energies in the classic SNR paradigm
- Dark matter searches, gamma-ray astronomy, solar physics, particle physics, etc.

Crab N. in X-ray (seen by Chandra)

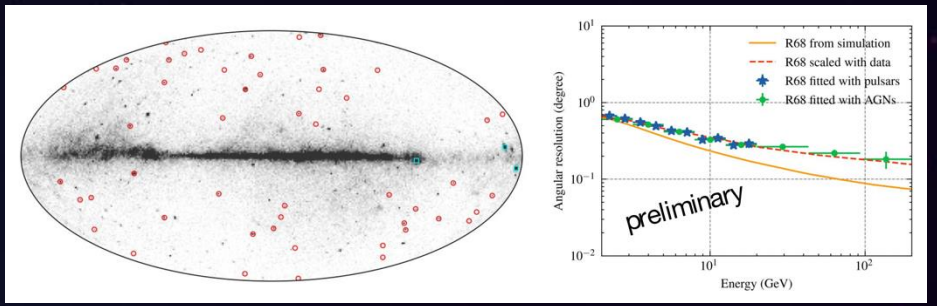
The DAMPE experiment

- 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

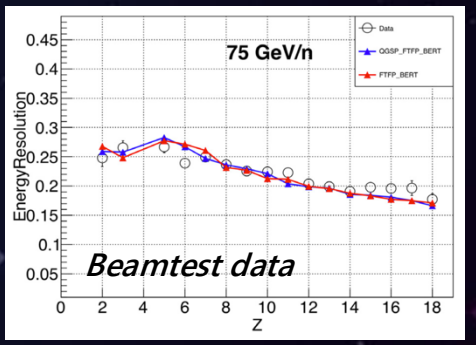


Calibration

- Angular (pointing):
  - Using photons from pulsars and AGN
  - Point-Spread Function (PSF) 0.3 deg @ 10 GeV
- Energy through beam tests:
  - At CERN PS & SPS
  - Electrons (protons): few GeV up to 250 (400) GeV
  - Ions: 40 GeV/n & 75 GeV/n
- Energy on orbit:
  - Using geomagnetic cut-off
  - Linearity BGO verified up to 2.5 TeV for electrons and 100 TeV for nuclei



doi: 10.22323/1.444.0670



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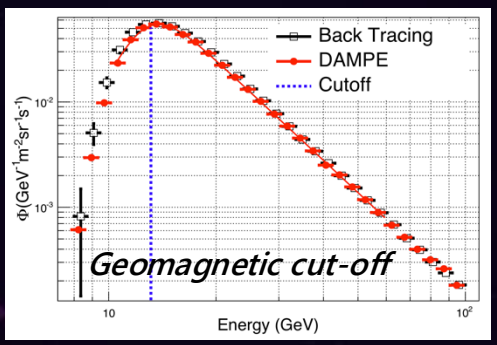
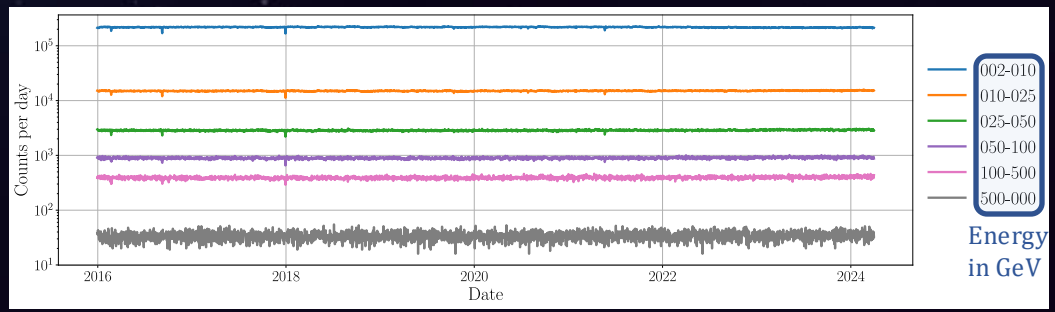


doi: 10.22323/1.301.0197



doi: 10.1134/S106377882113007X

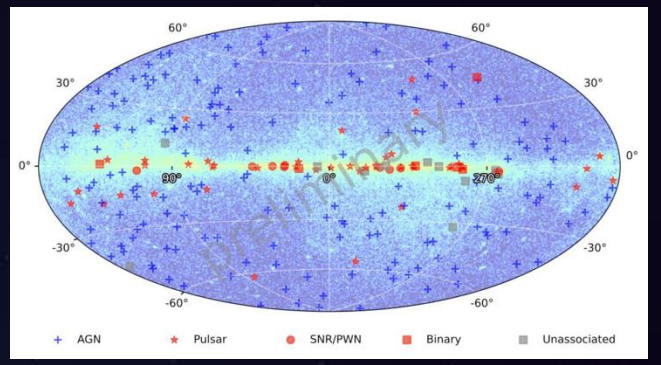
Part II:

Latest Results by DAMPE

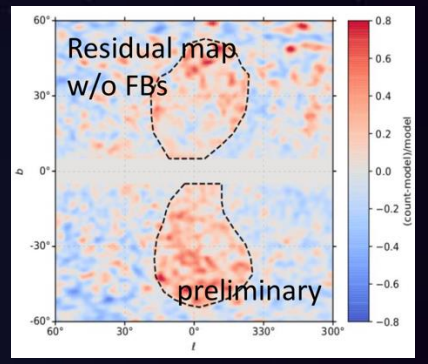
Results: Gamma-rays

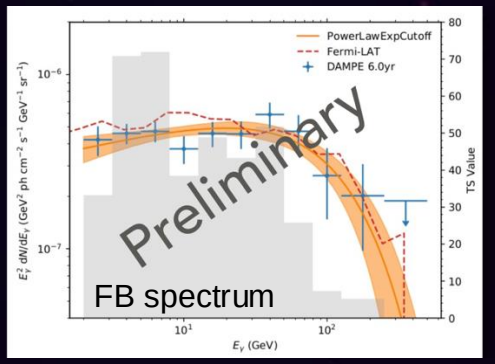
- >300 sources detected
- Measurement of Fermi bubbles
- Galactic center excess
- Online data release:
  - https://dampe.nssdc.ac.cn/dampe/dataquerys.php
  - http://dgdb.pmo.ac.cn/dampe/example.php
- Gamma-ray line searches:
  - Search for decaying dark matter
  - E_γ: $5 \rightarrow 450$ GeV
  - Strongest upper limits on DM decay lifetime below 100 GeV!

doi: 10.22323/1.444.0670



Source type	number
AGN	241
Pulsar	62
SNR/PWN	14
Binary	5
Global cluster	4
Unassociated	10
Total	336





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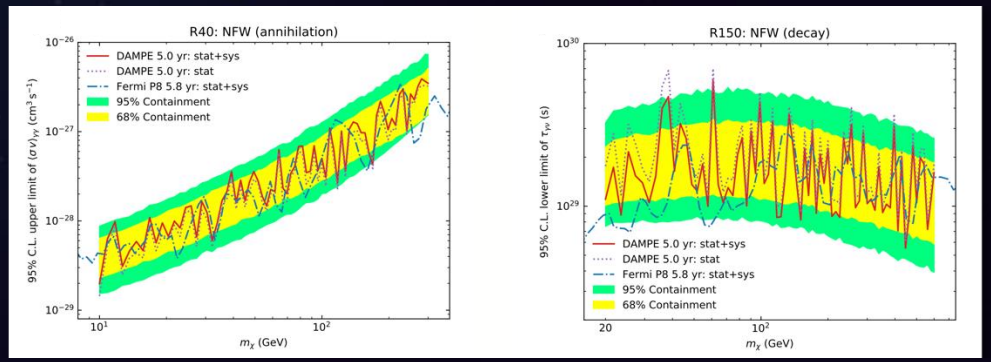
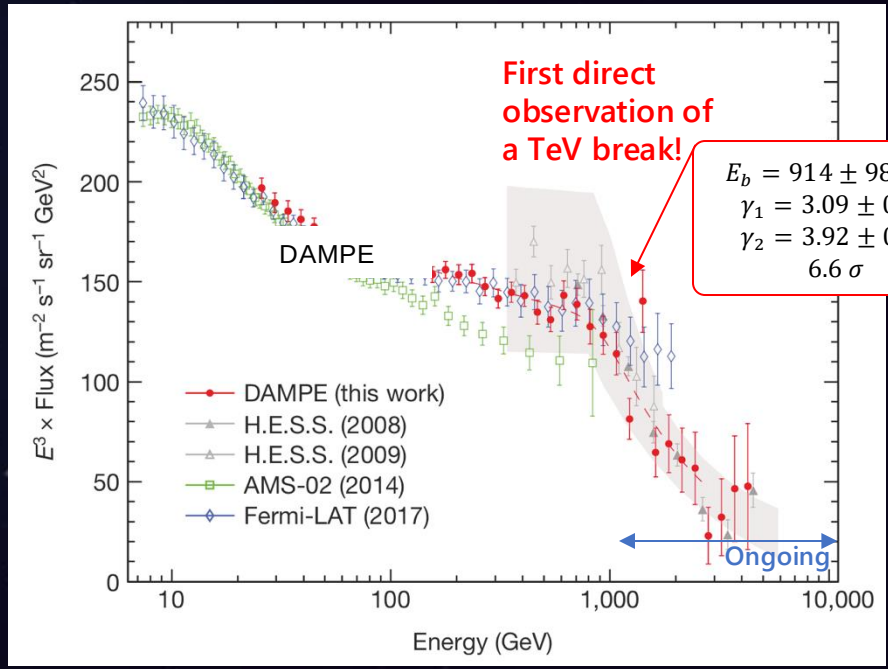


doi: 10.1016/j.scib.2021.12.015

Results: CR fluxes

- Electron/positron flux:
  - Hardening at ~50 GeV
  - **Break at 0.9 TeV**

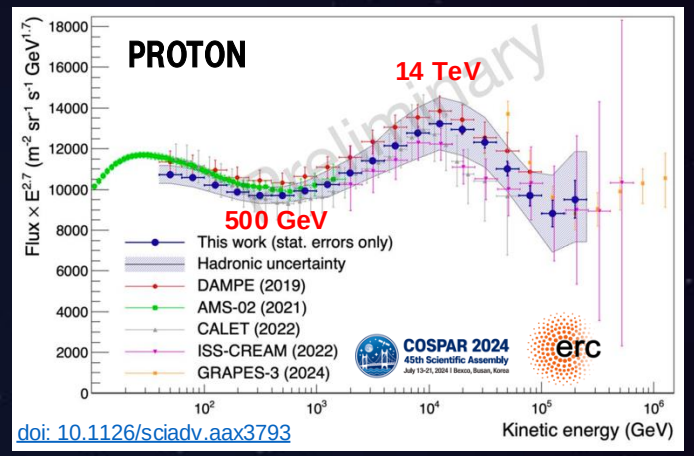
- Extending to 10 TeV:
  - 1: 20.000 signal-to-background ratio
  - New ML background rejection tools under development
  - CRE lose energy due synchrotron radiation → TeV sources within ~1 kpc



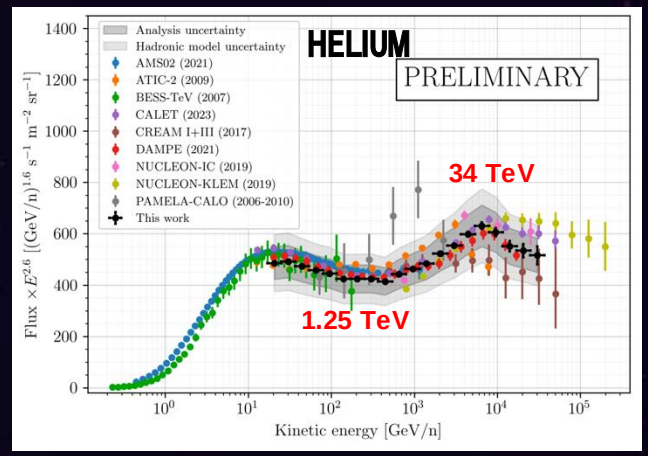
doi: 10.1038/nature24475

Results: CR fluxes

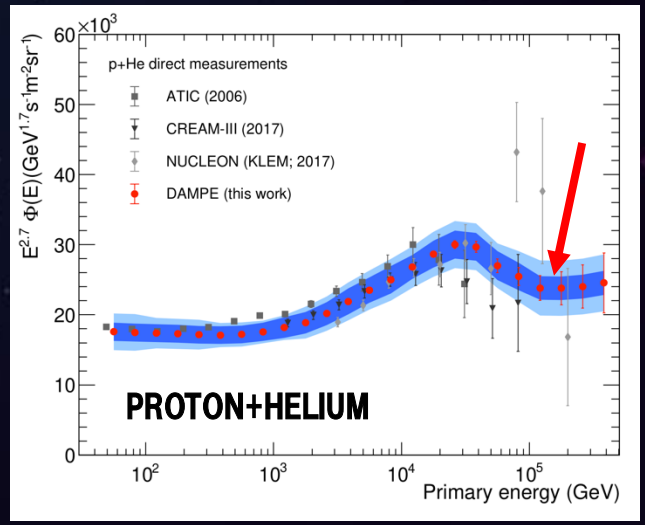
- Proton & Helium flux:
  - Direct measurements up to ~100 TeV
  - Z dependent features
- Proton + Helium:
  - Extends to 0.5 PeV
  - Hardening at ~150 TeV
  - Connect to ground-based experiments
- Interpretation:
  - No single power law for spectrum up to the knee
    → New class of sources?
    → Propagation effect?



doi: 10.1126/sciadv.aax3793



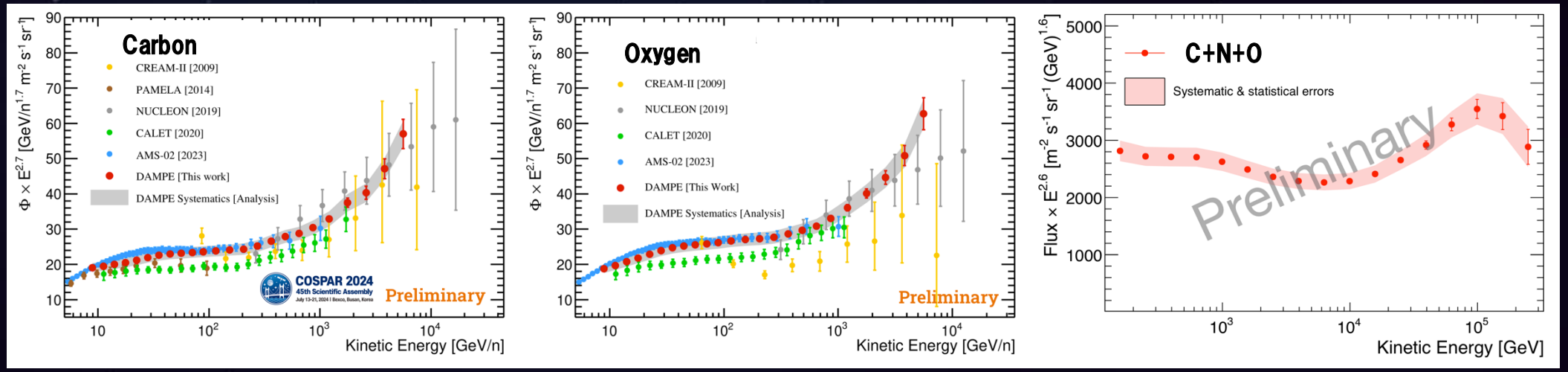
doi: 10.1103/PhysRevLett.126.201102
doi: 10.22323/1.444.0170



doi: 10.1103/PhysRevD.109.L121101

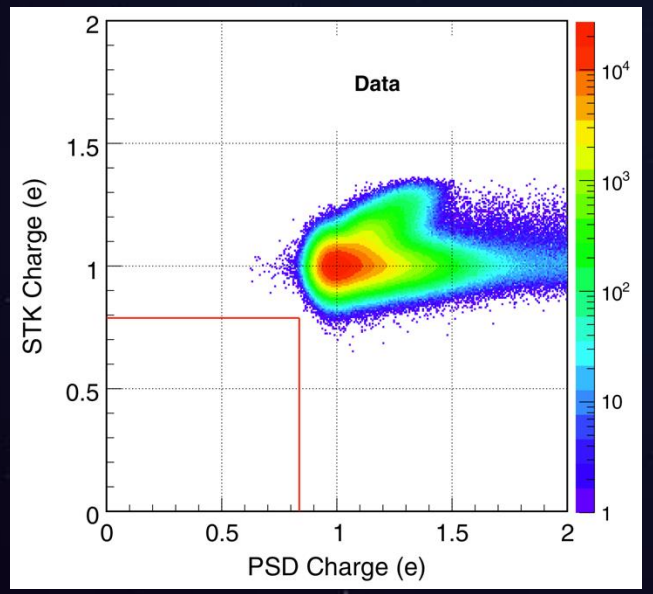
Results: CR fluxes

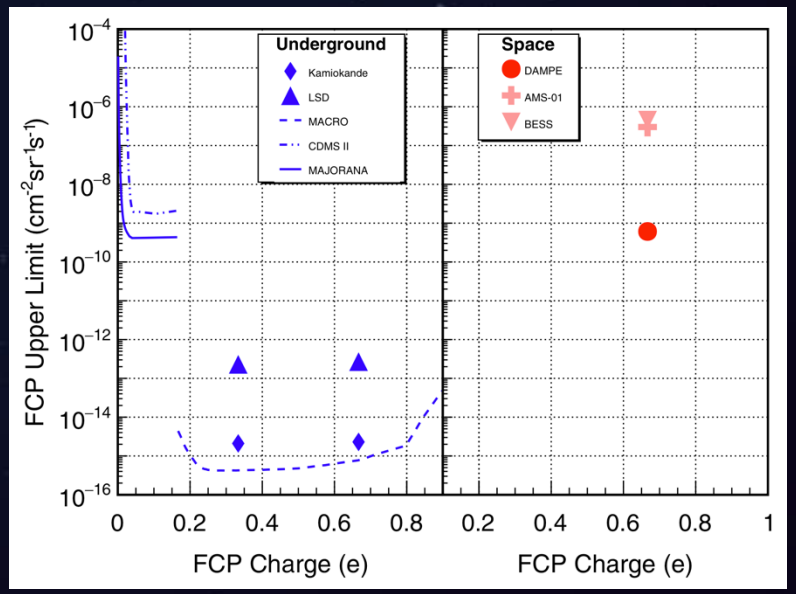
- Carbon, Nitrogen, and Oxygen:
  - CR primaries (like proton & helium)
  - **Confirmed spectral hardening @ several hundred GeV/n**
  - Also combined CNO analysis



Results: BSM searches

- Searches for Fractionally Charged Particles (FCPs):
  - Most stringent results in space for GeV fluxes! (ground-based experiments >100 GeV)

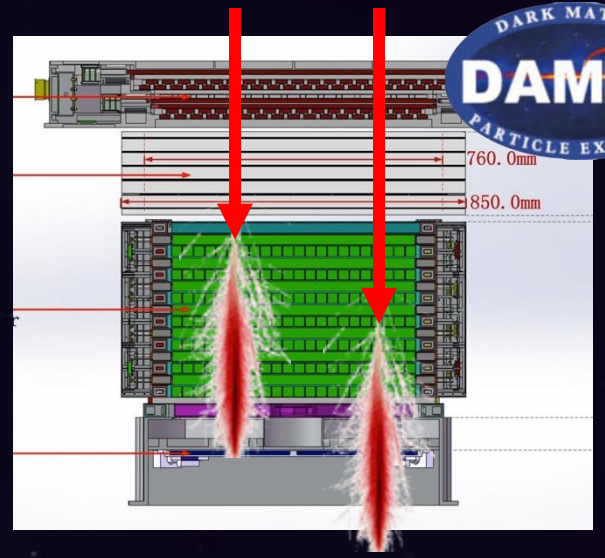


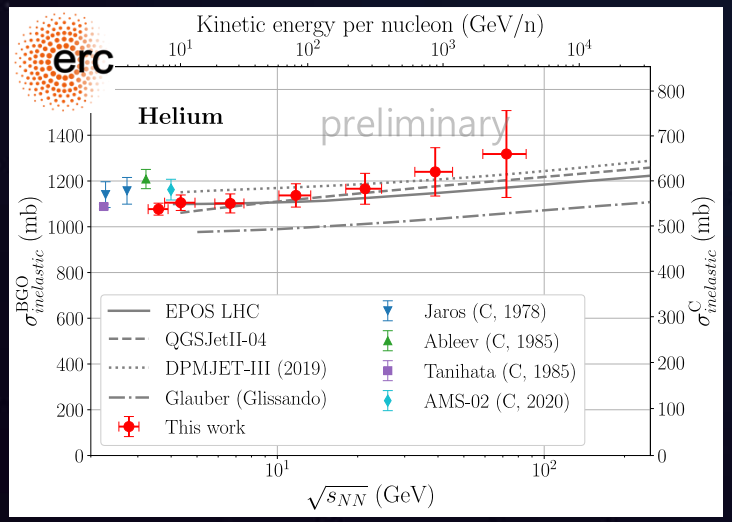


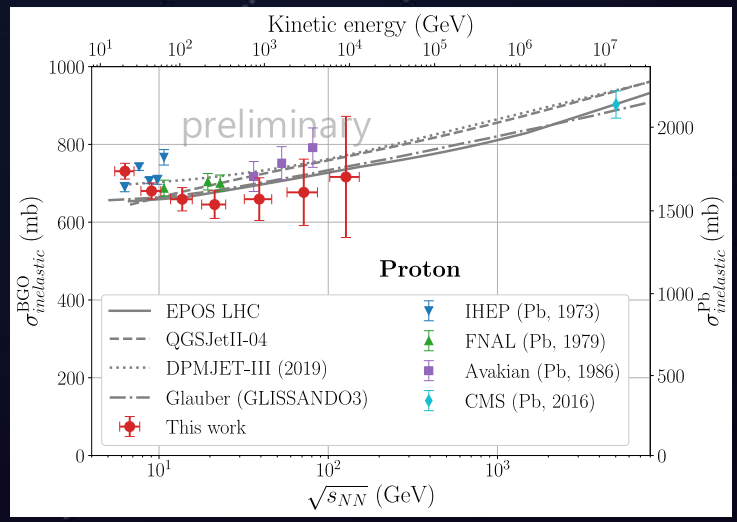
doi: 10.1103/PhysRevD.106.063026

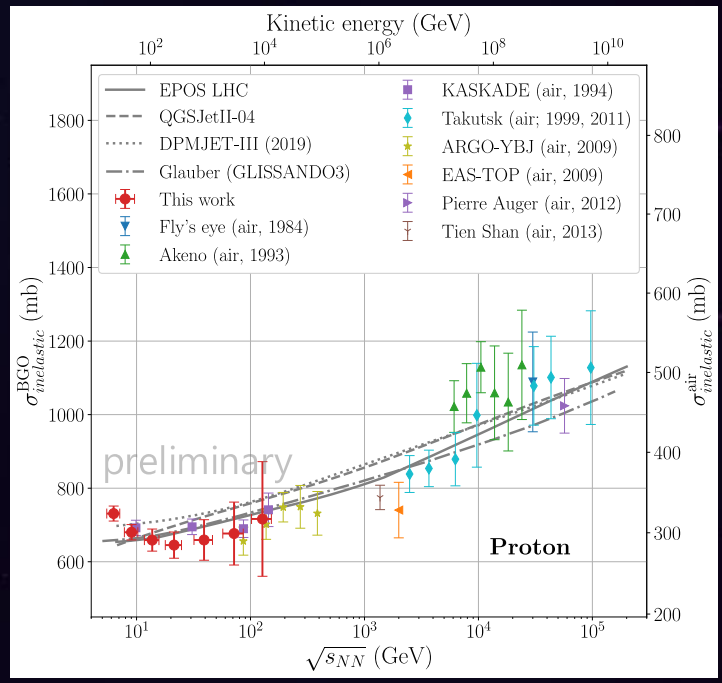
Results: Cross Sections

- Measure: inelastic hadronic cross section
- Proton & ^{4}He on $Bi_4Ge_3O_{16}$ → Improve hadronic models + CR flux!
- First measurement for ^{4}He nuclei at these energies!
- Extend measurement to carbon, oxygen, etc.



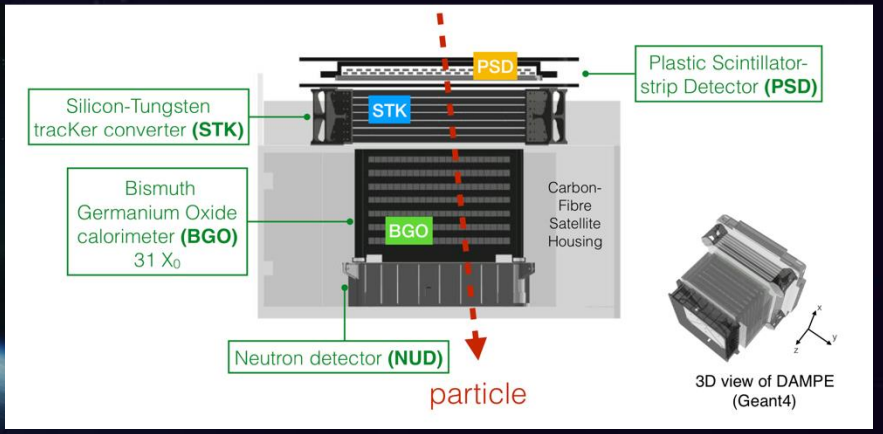






Paper submission in progress!

Conclusions



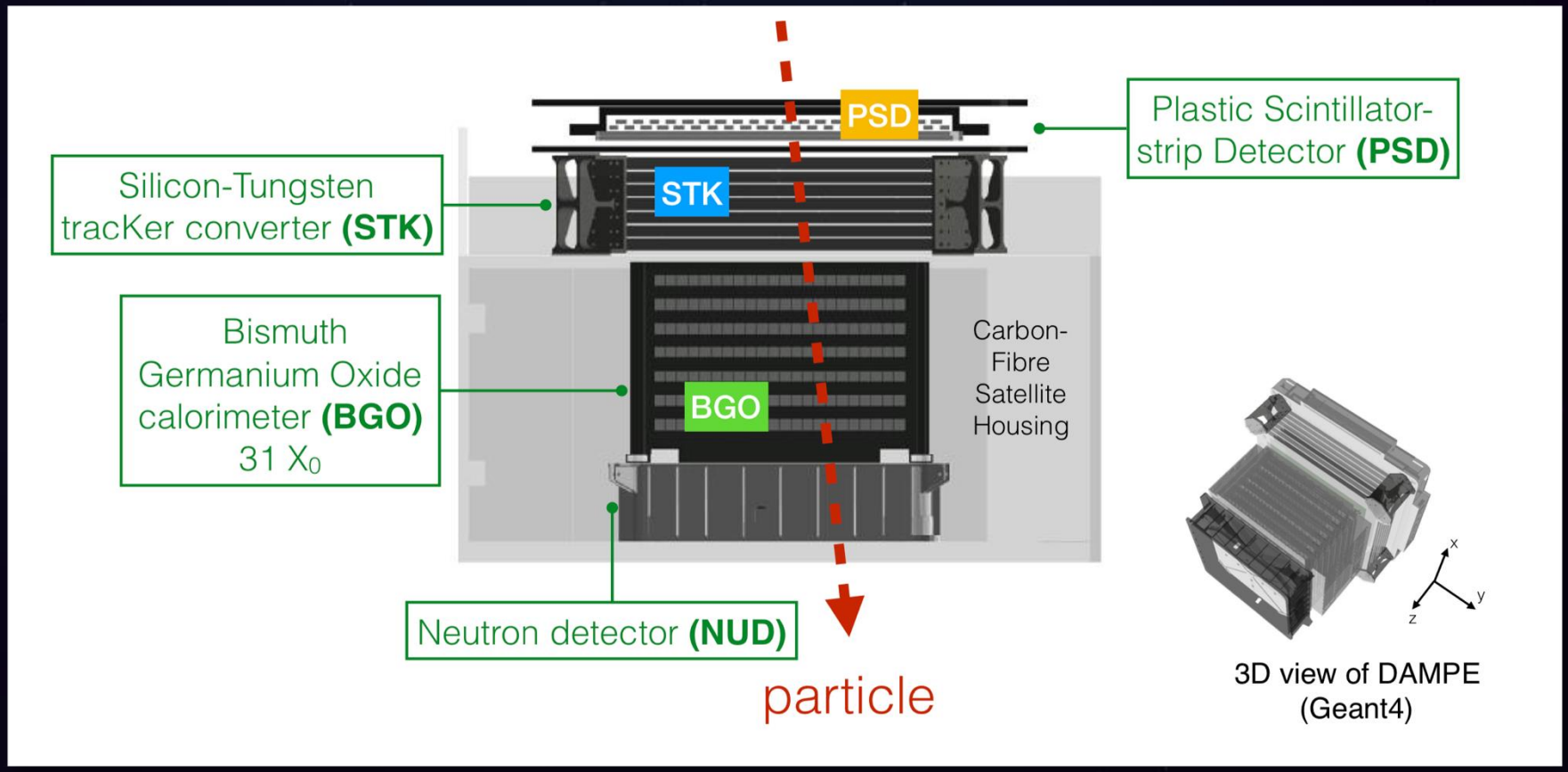
- DAMPE in stable operation since December 2015
- CR measurements from GeV - PeV
- Many interesting results:
  - CR fluxes: proton, He, B, C, O, Fe + secondary/primary flux ratios
  - Gamma-ray astronomy and DM searches
  - Particle physics: Cross sections & FCP
  - Heliospheric Physics: Forbush decrease ; CR anisotropy

Thank you for your attention!

Extra material

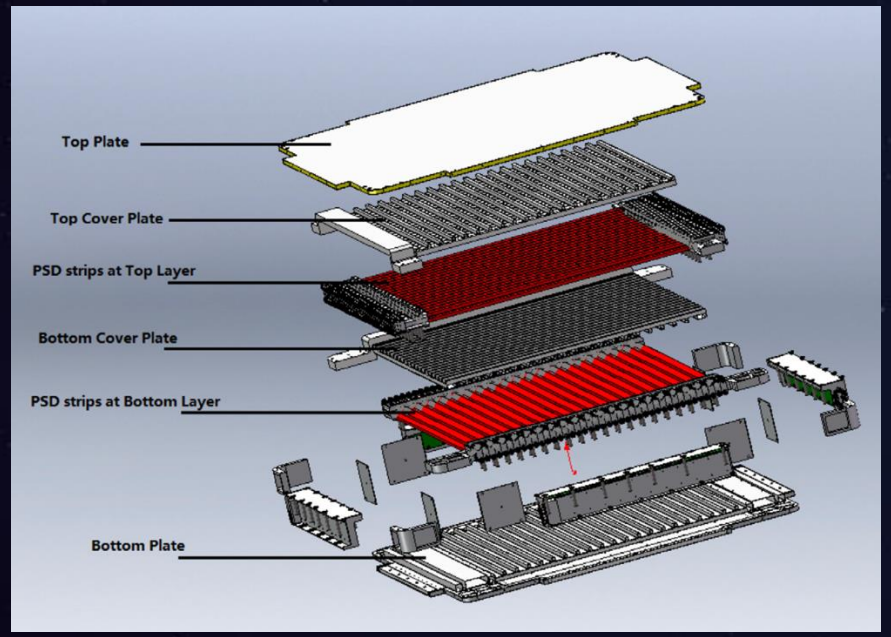
Detector lay-out

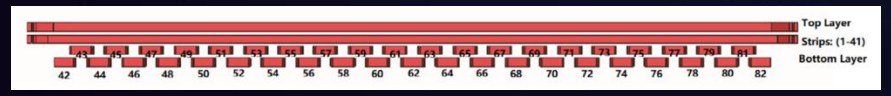
- Layered design with 4 sub-detector



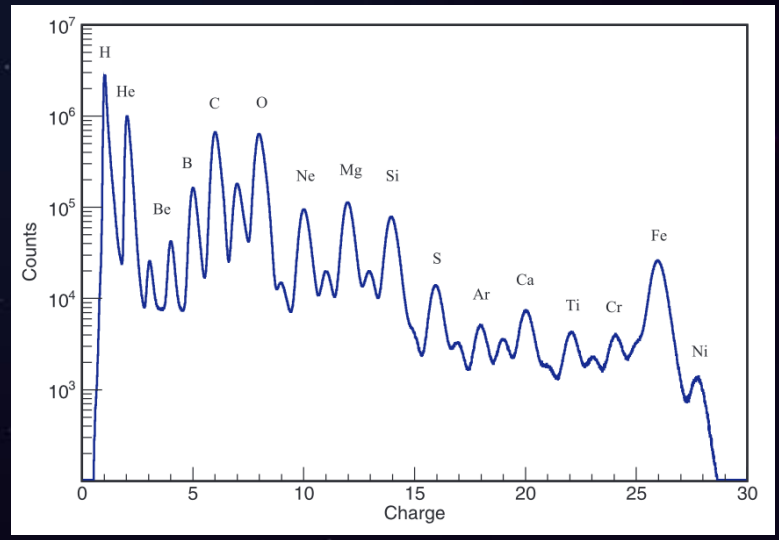
Detector lay-out

1. Plastic scintillator → identify absolute charge of particle





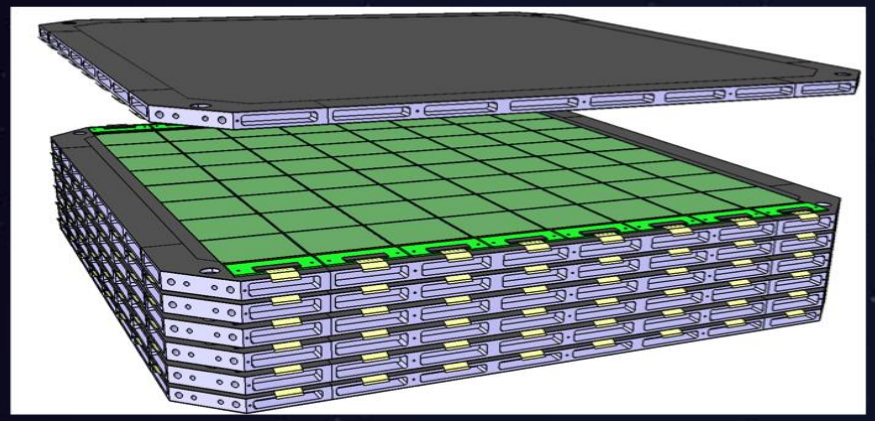
- 82 bars in 2 double layers
- Overall efficiency ≥ 0.9975
- Particles lose energy through ionisation: $dE/dx \propto Z^2$

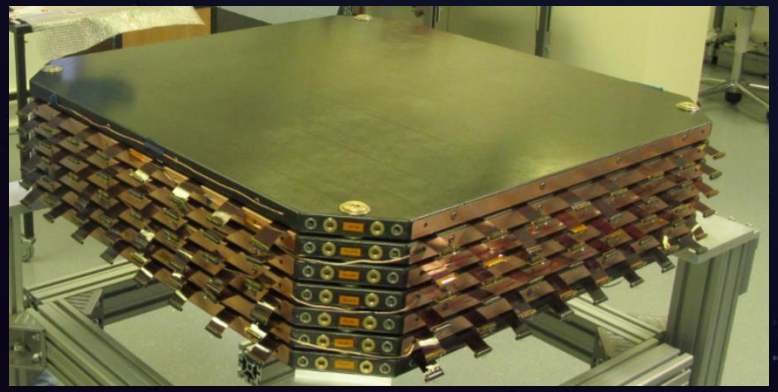


doi: 10.1134/S106377882113007X

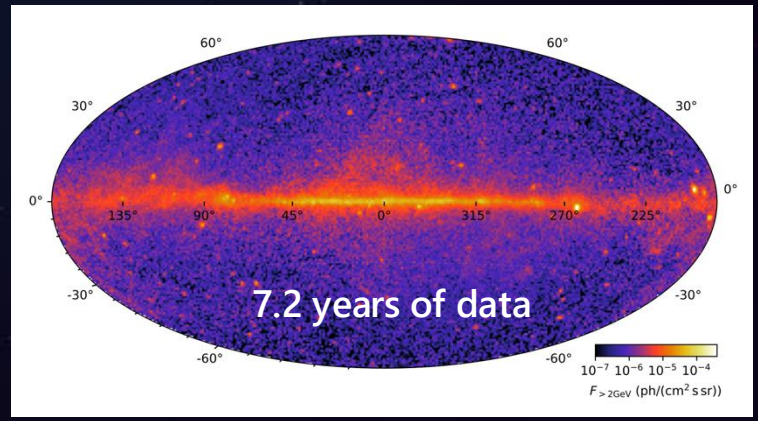
Detector lay-out

2. Silicon-Tungsten **Tracker** Converter





- 768 sensors of 768 strips each
- ~50 micron positional resolution
  → 0.1-1° pointing (electrons & photons)
- Tungsten layers for conversion $\gamma \rightarrow e^+e^-$
- Also charge identification



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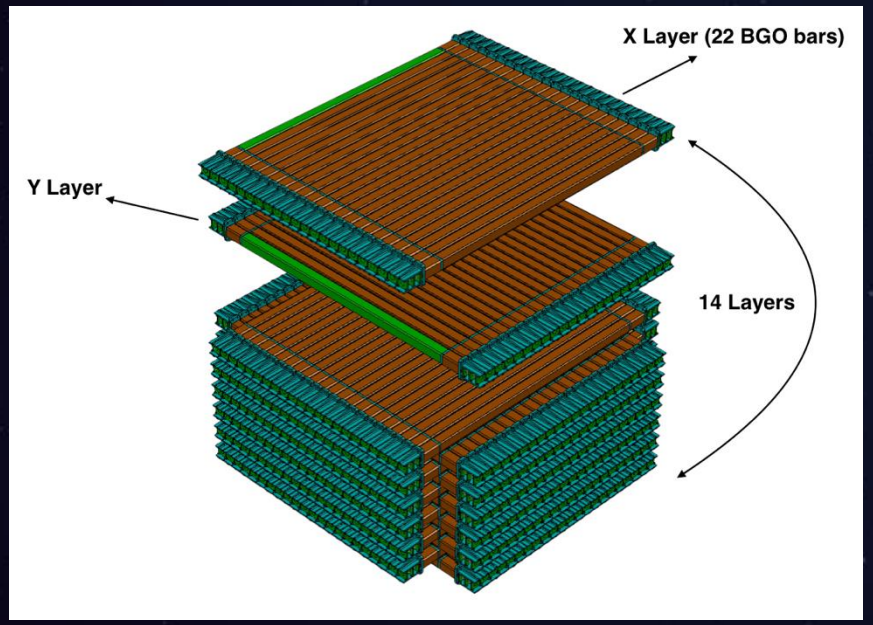
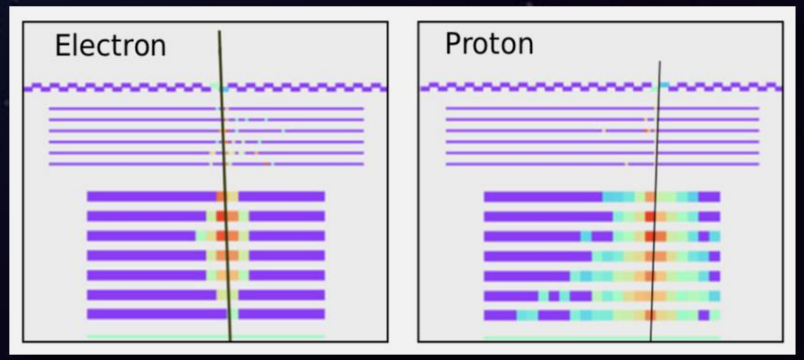
Detector lay-out

3. Calorimeter

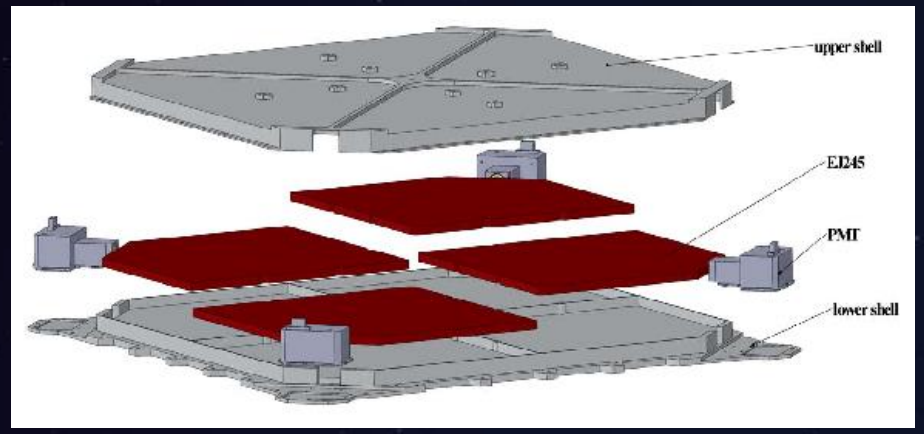


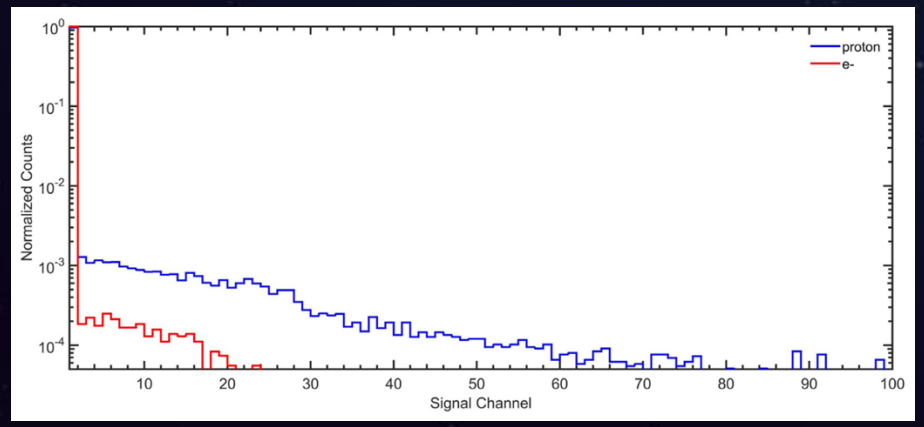
- 308 bars spread over 14 layers
- Readout by PMT at each end of crystal
- $Bi_4Ge_3O_{12}$ material (~1052 kg)
- Energy resolution:
  - ~1% for electrons (shower contained)
  - ~40% for ions (shower not-contained)



Detector lay-out

4. Neutron detector





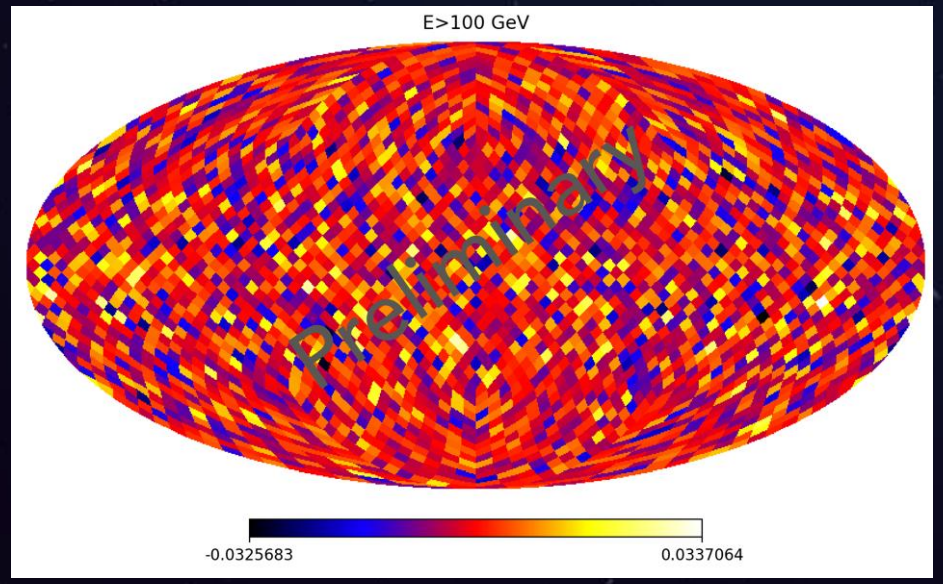
- 4 boron-doped plastic scintillators
- $B_{10} + n \rightarrow Li_7 + \alpha + \gamma$
- Hadronic showers produce ~10 times more neutrons than EM showers
- Provides additional discrimination in electron analyses to reject dominant proton background (at 1 TeV, proton background dominantes by $> 10^4$)

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 measured proton & helium spectra

Results: CR anisotropy

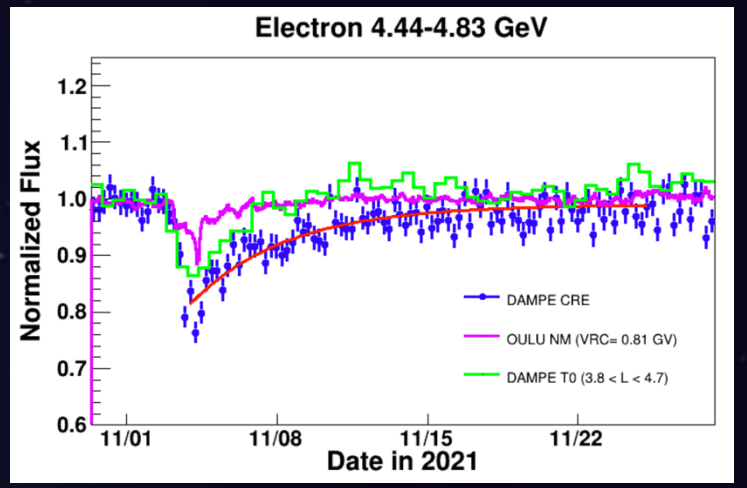
- Anisotropy not yet observed with space-based CR experiments
- Main sensitivity >100 GeV
- Upper limit on dipole: $\delta < 1.2 \times 10^{-3}$

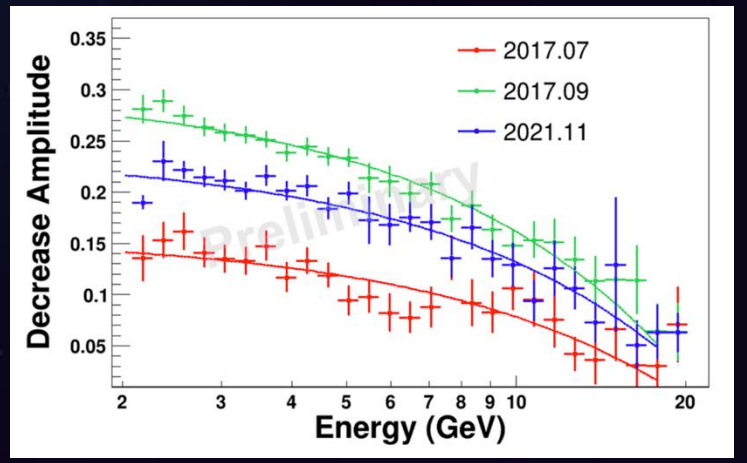


doi: 10.22323/1.395.0125

Results: Heliospheric Physics

- Polar orbit + large acceptance
  → precise measurement $\Phi_e(t)$
- Forbush Decrease (FD):
  - Coronal Mass Ejection (CME) followed by rapid decrease in CR intensity
  - New feature!
    Energy dependence of recovery time related to CME orientation

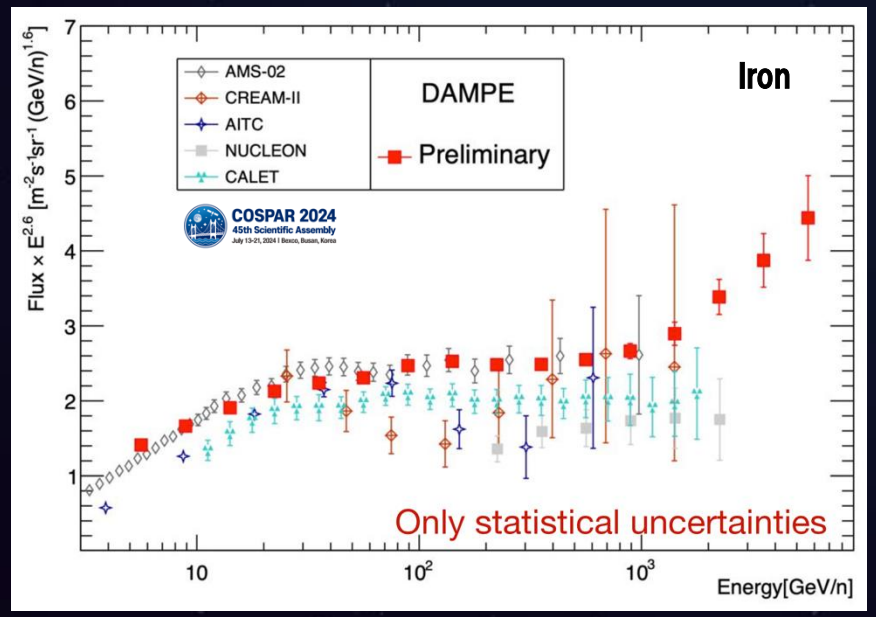


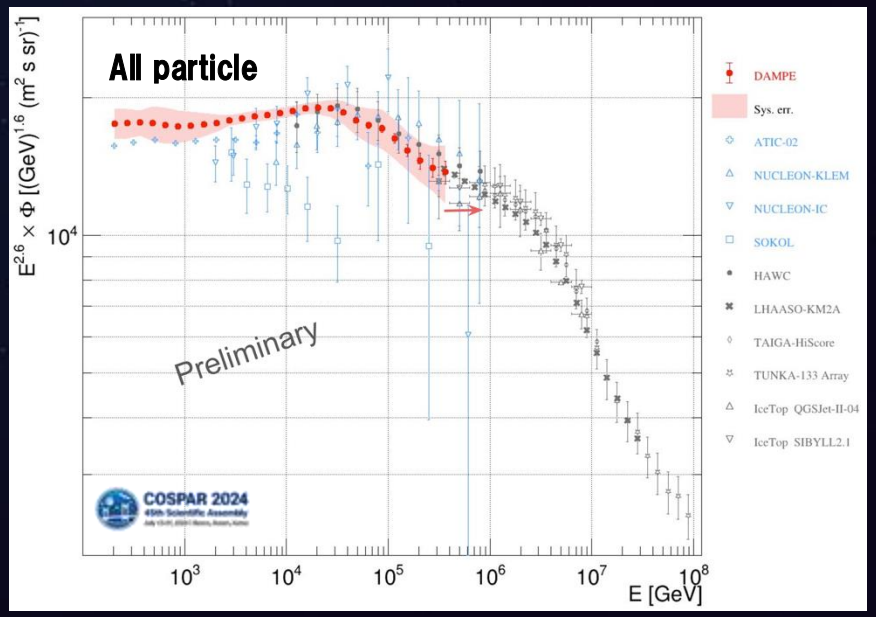


doi: 10.3847/2041-8213/ac2de6

Results: CR fluxes

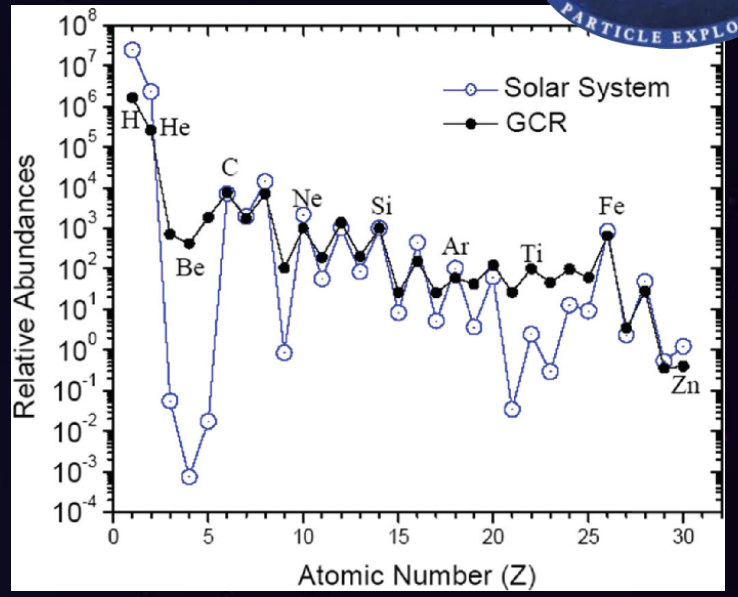
- Iron (primary):
  - Up to 10 TeV/n
  - Hardening around 1 TeV/n
- All particle spectrum:
  - Compare with indirect experiments
  - Extend measurement to ~0.8 PeV

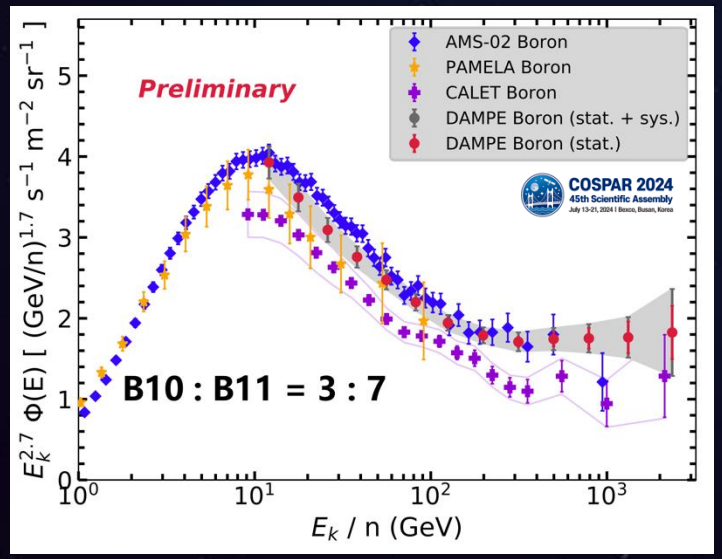


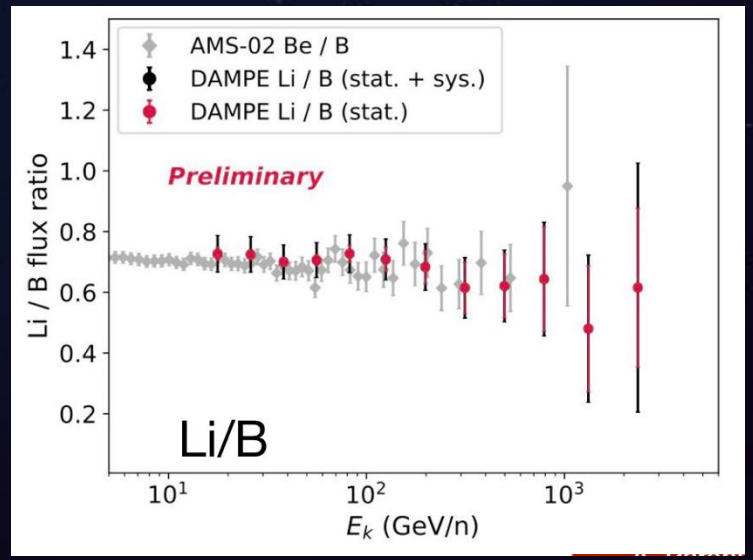


Results: CR fluxes

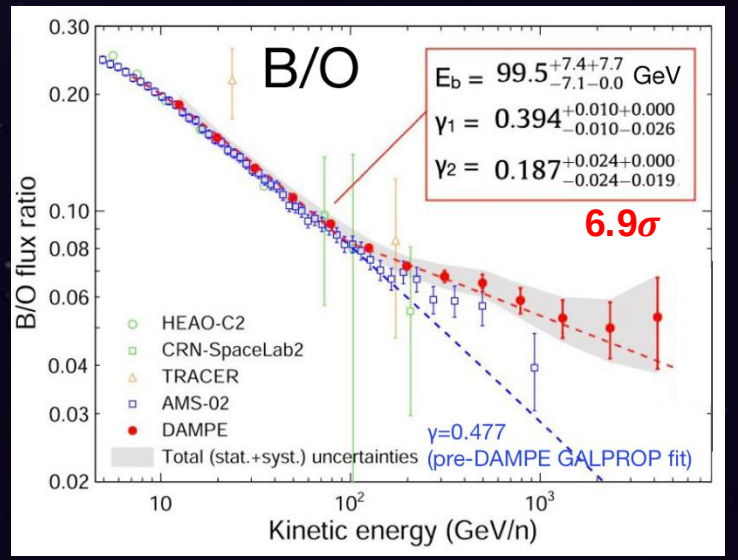
- Cosmic-ray secondaries:
  - Secondary/secondary ratio is constant
  - **Secondary/primary has break at ~100 GeV/n**
    → Change of CR diffusion coefficient?







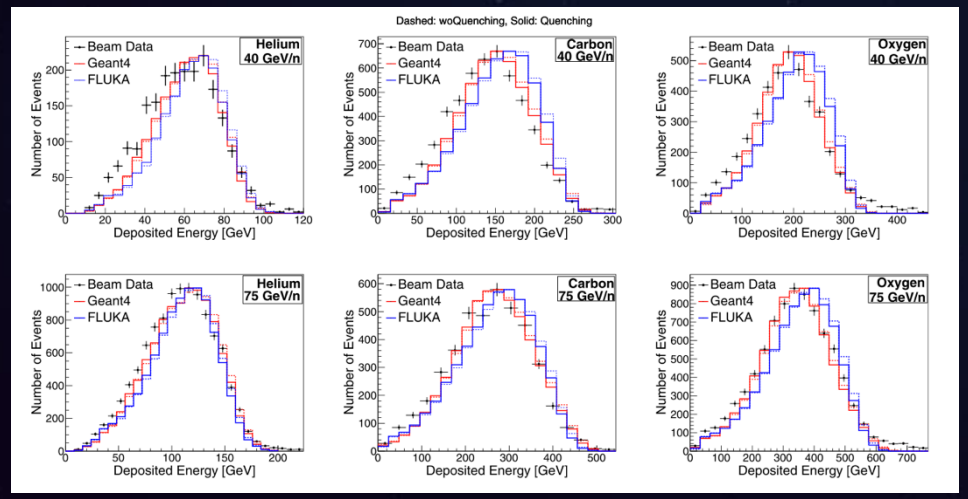
doi: 10.22323/1.444.0137

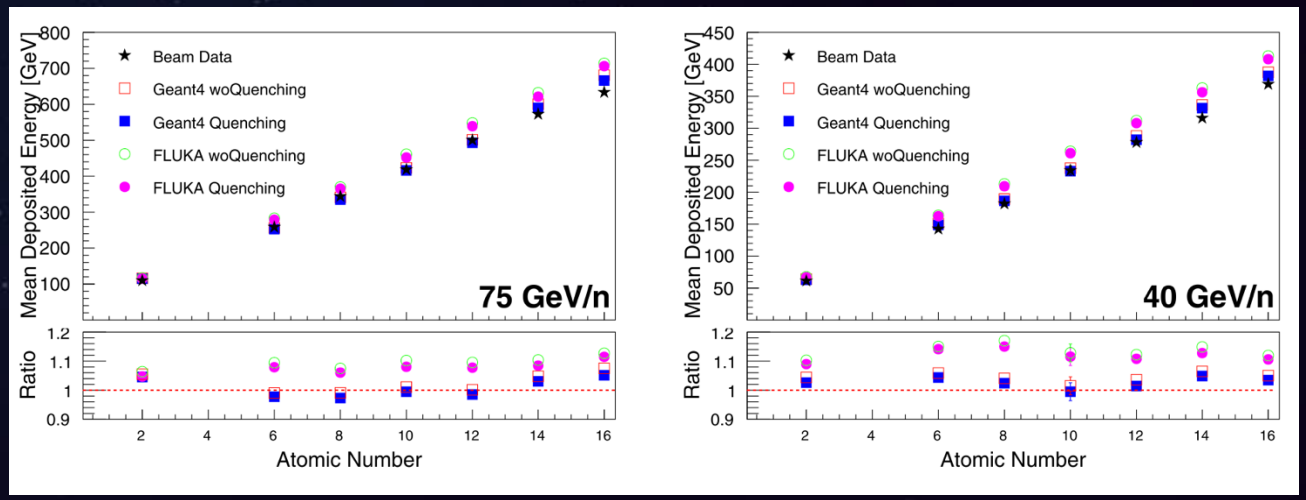


doi: 10.1016/j.scib.2022.10.002

Geant4-FLUKA to data comparisons

- Beam-tests at CERN-PS/SPS before launch
- Compare simulated vs measured deposited energy
- Geant4 generally better agrees with data than FLUKA





doi: 10.1016/j.nima.2023.168470

Geant4-FLUKA to data comparisons

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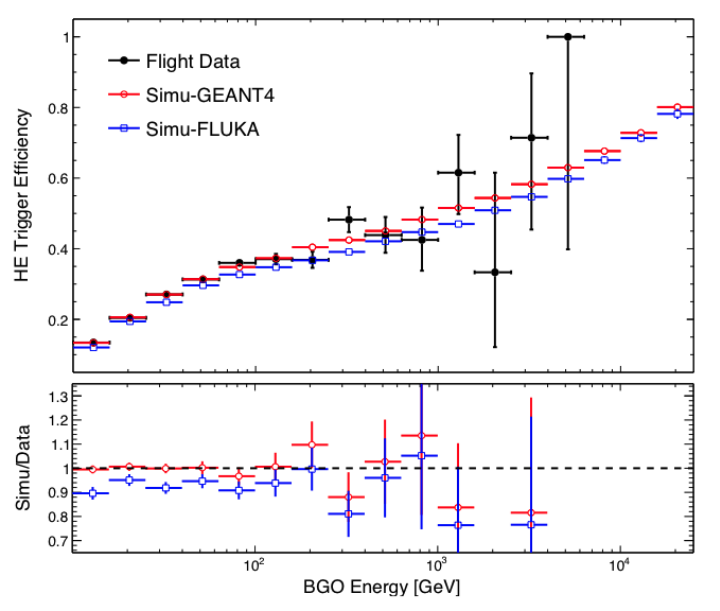
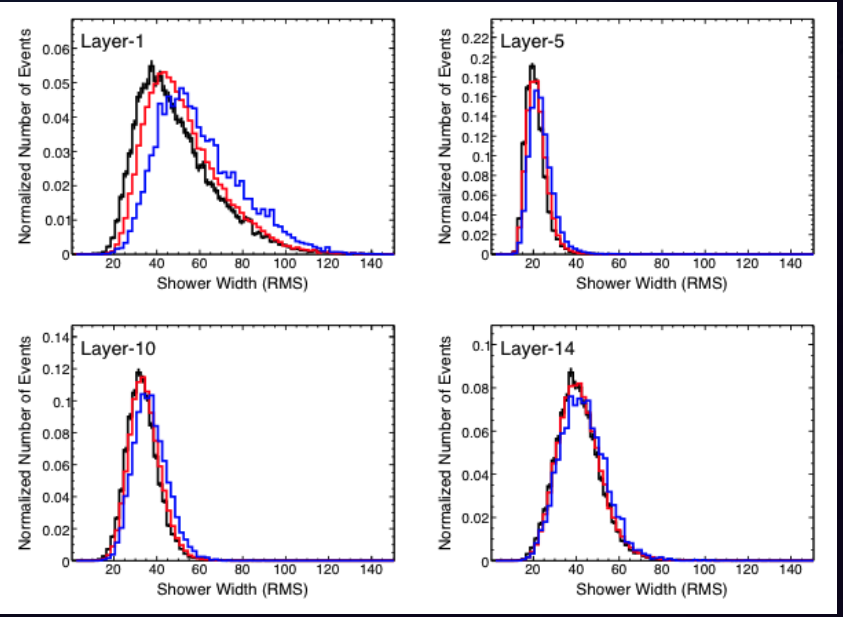
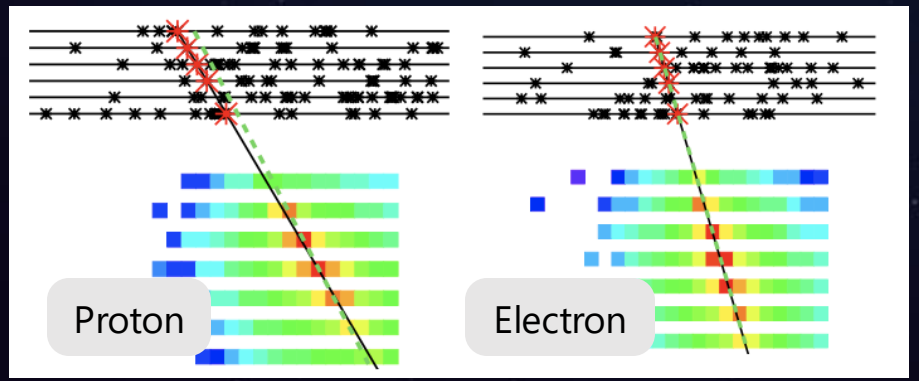




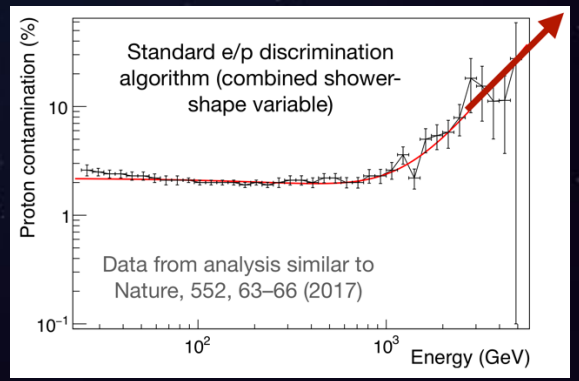
doi: 10.1088/0256-307X/37/11/119601

Electron – proton separation

- Low energy:
  - Proton showers are long and thick
  - Electron showers are thin and contained
- High energy (multi-TeV):
  - Some proton showers look almost like electrons
  - Background explodes using conventional algorithms

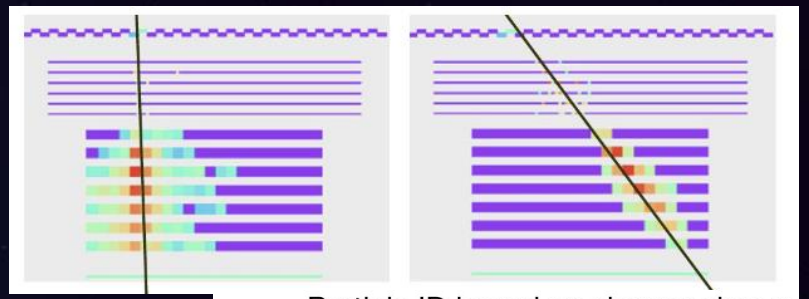


Events at 10 TeV

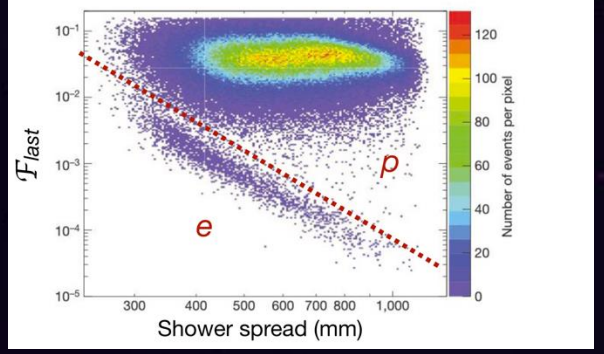


'low' energy events

Proton | Electron

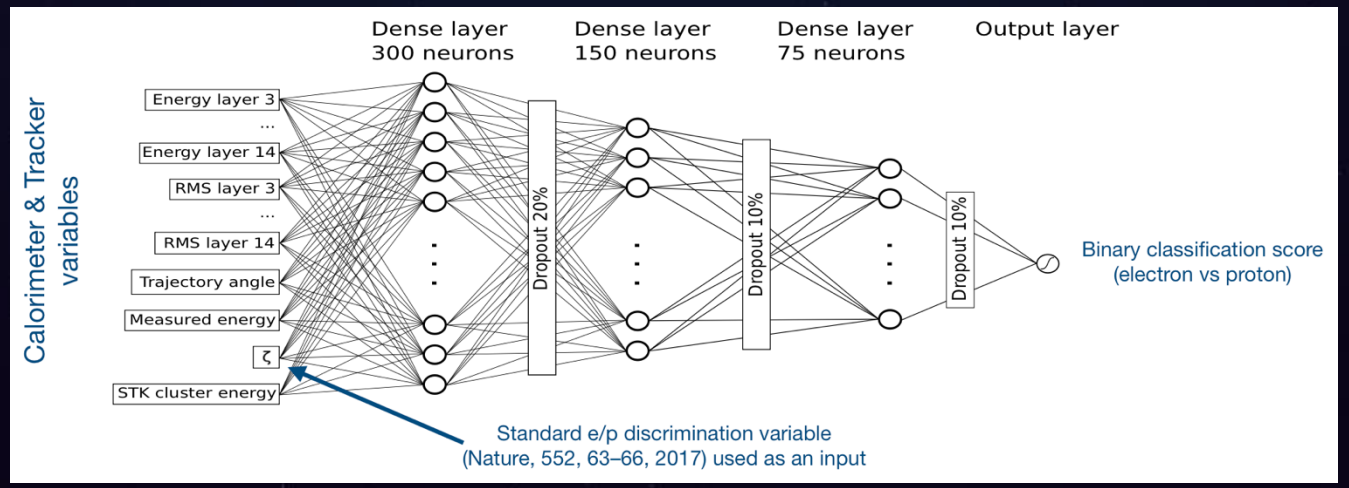


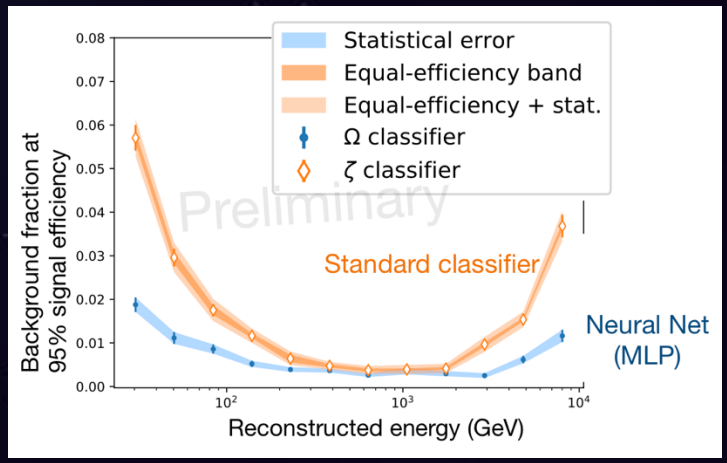
Particle ID based on shower-shape:



Electron – proton separation

- Similar approach to before was tested
  → Train CNN on image of tracker and calorimeter
- Alternative: 'Multi Layer Perceptron' (MLP) network
  - Deep learning network
  - Based on high-level variables





Similar performance to CNN,
but less requires less optimisation,
i.e. less sensitive to data-MC disagreement

doi: 10.1088/1748-0221/16/07/P07036