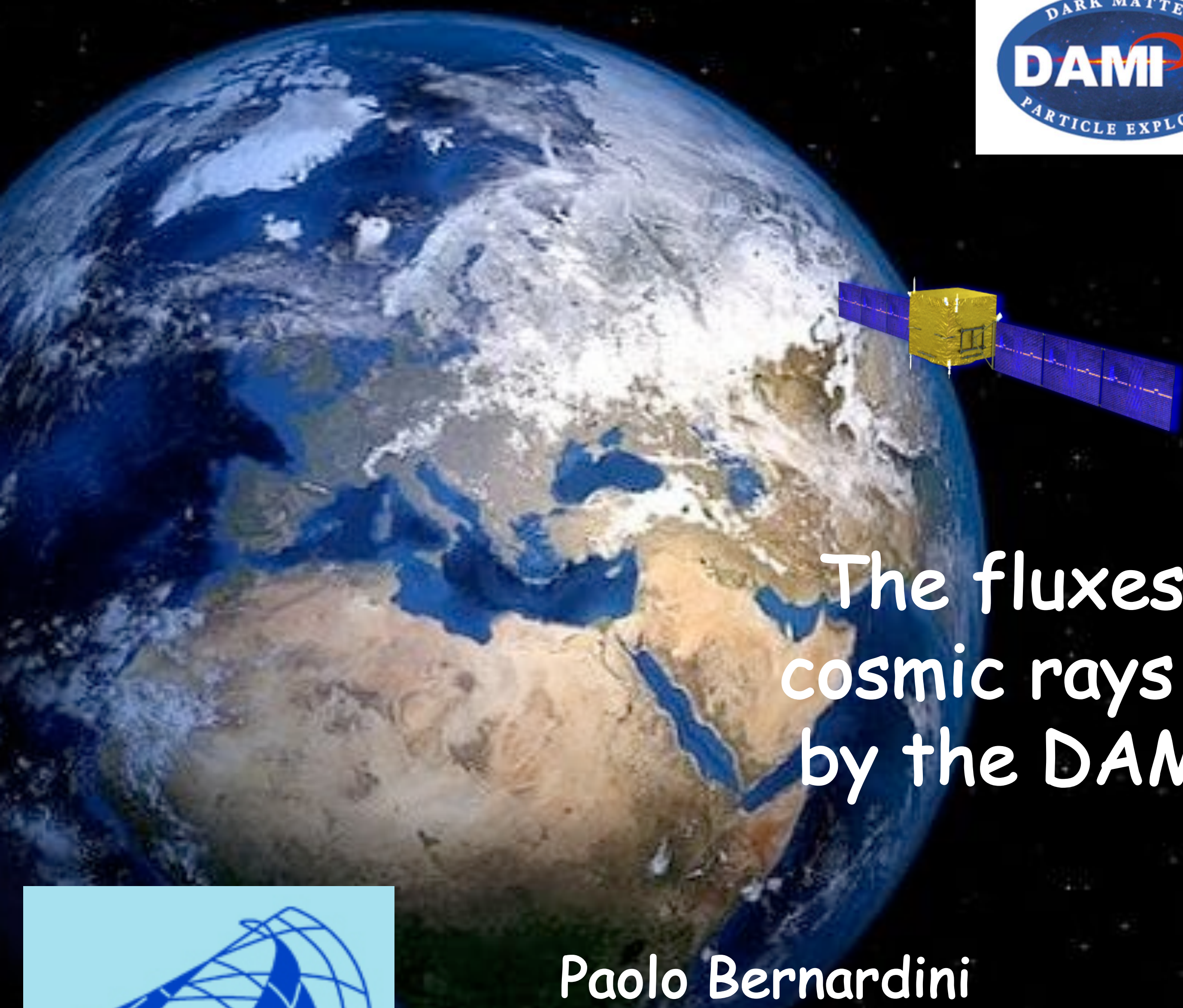


The fluxes of charged cosmic rays as measured by the DAMPE satellite

Paolo Bernardini
(on behalf of DAMPE Collaboration)
Università del Salento and INFN, Lecce, Italy

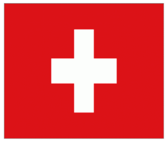
The collaboration

DArk Matter Particle Explorer

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

- 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

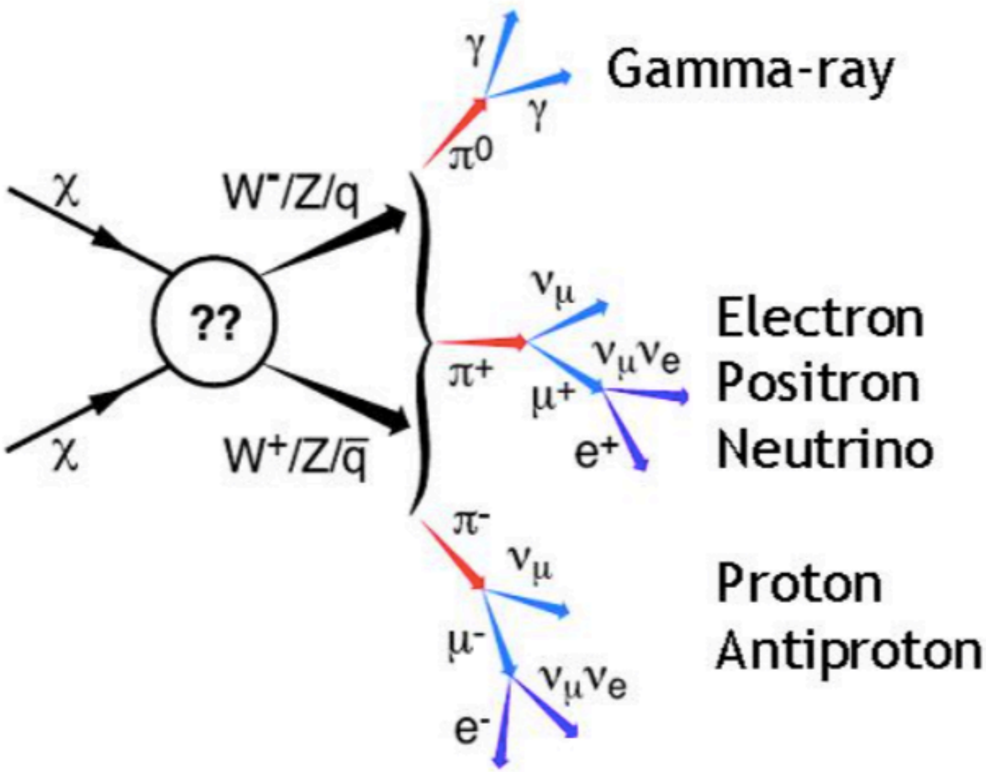
- SWITZERLAND
  - University of Geneva



Outline

- Scientific goals
- Detector & beam test
- On-orbit performances
- Charged cosmic rays
  - ✓ electron spectrum
  - ✓ light nuclei (p, He)
  - ✓ heavier nuclei
- Conclusions

The physics goals (I)



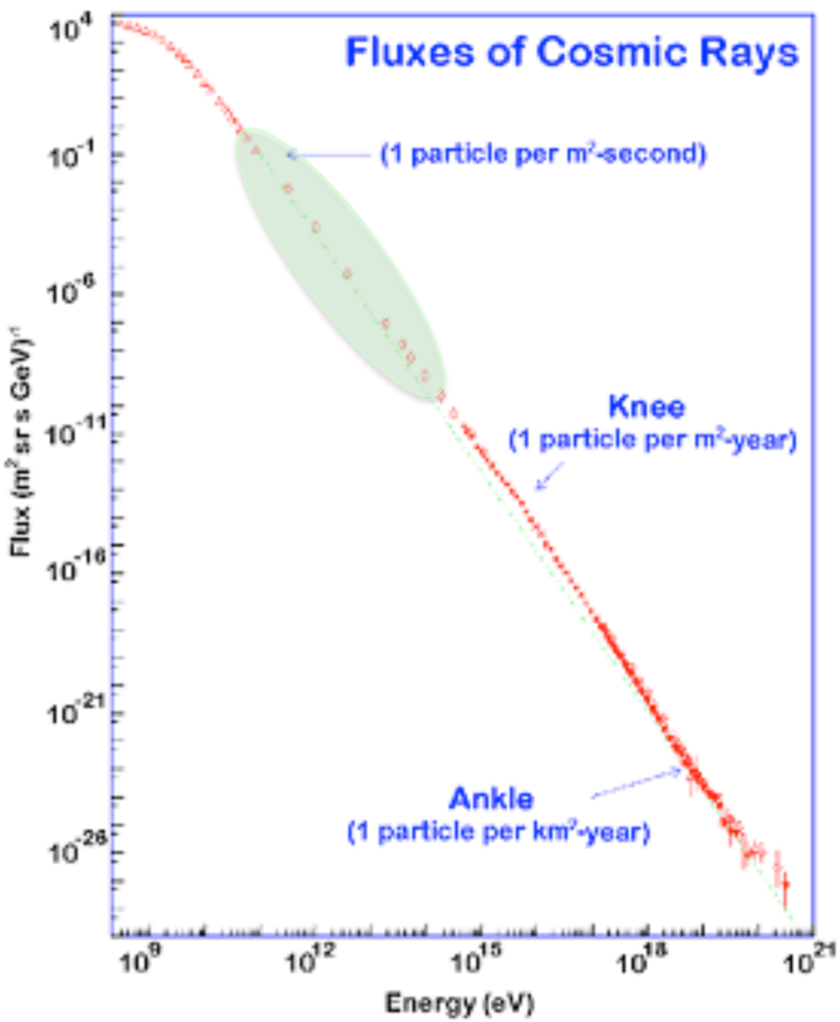
Possible indirect detection of Dark Matter in space

Long exposure and high energy resolution are required to observe such a possible signal

DAMPE has the features to search for Dark Matter signatures in cosmic charged and gamma rays

(electrons and photons detected in the range 25 GeV - 10 TeV)

The physics goals (II)



Does a simple power-law describe the CR spectrum before the knee ?

Canonical model of SN shock acceleration. Is it the proper one ?

Precise measurements for different components are essential for testing the CR models (sources & production, acceleration & diffusion, different populations …)

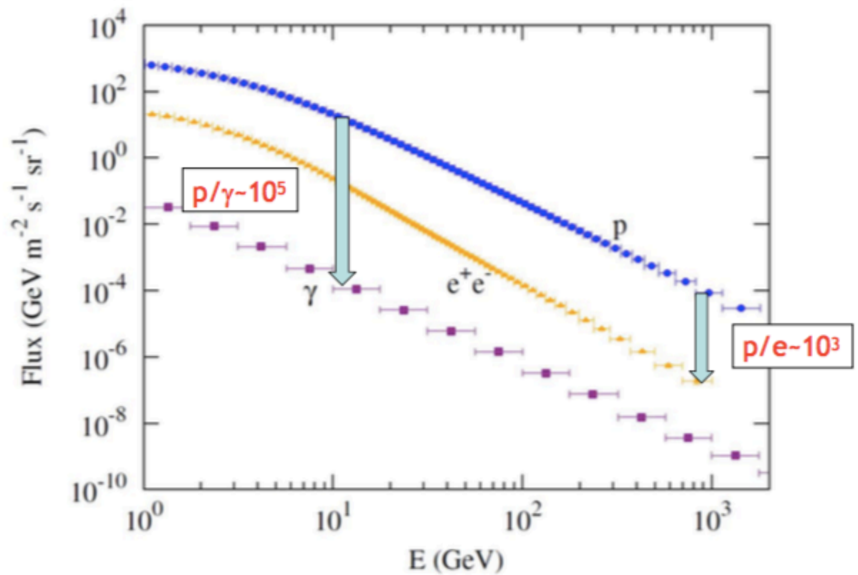
DAMPE goals:

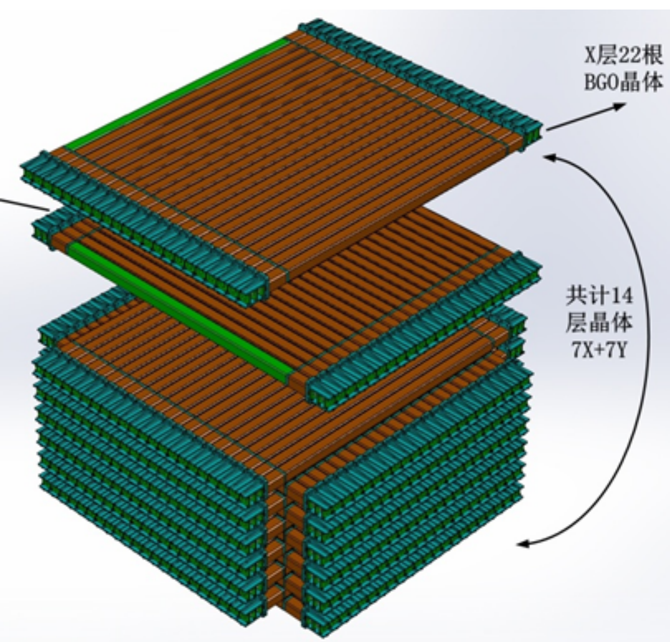
- investigate spectrum structures in the range 40 GeV – 200 TeV for different nuclei
- put a bridge between space and ground exp.s

Challenge detector features

Highly efficient particle-identification to remove proton background

1 electron / 10^3 protons
1 gamma / 10^5 protons



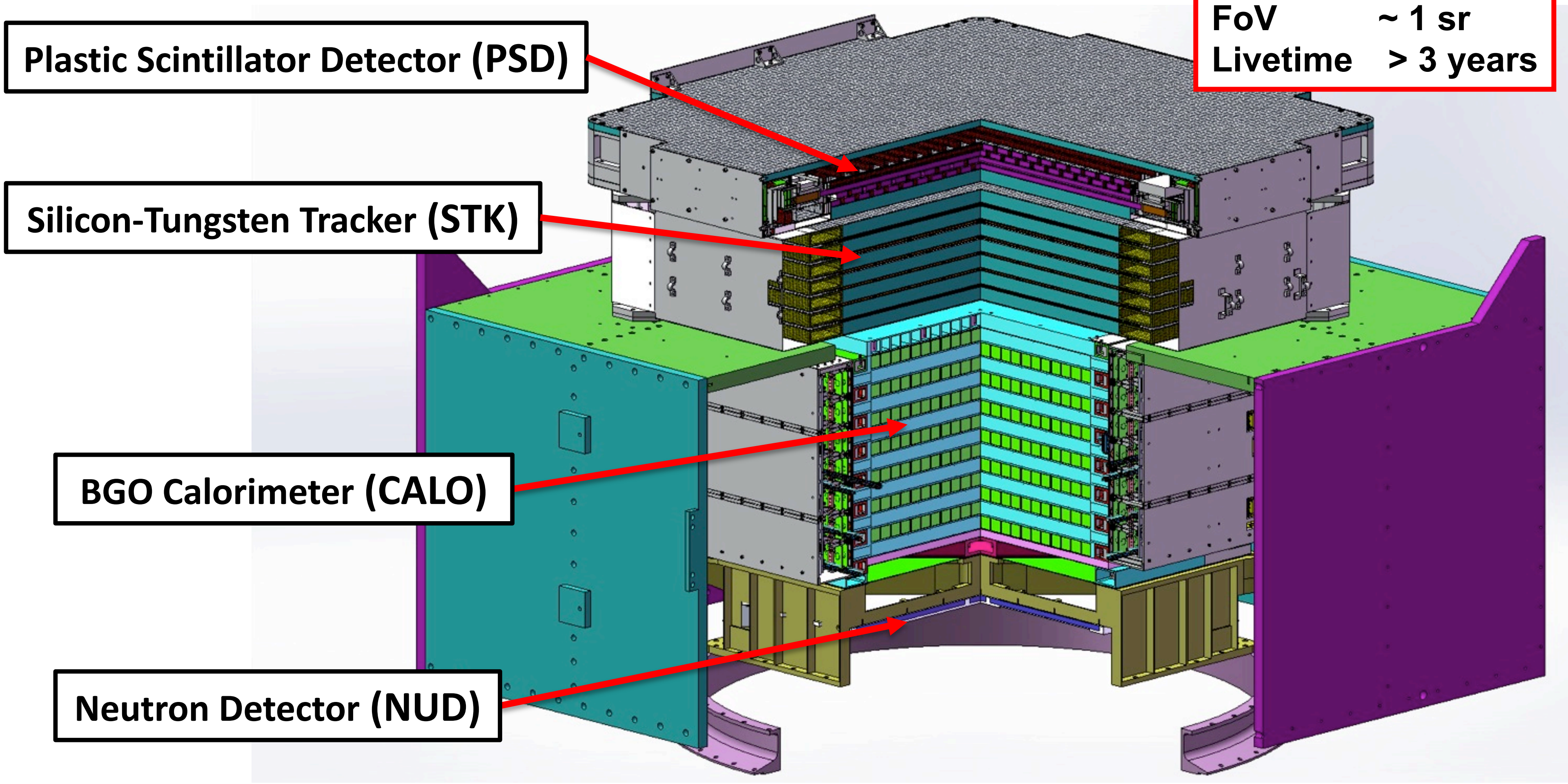


Detection of electrons and gamma-rays in the range GeV – tens TeV

Dynamical range of each calorimeter element must be MeV – TeV

The detector

Mass	1400 Kg
Power	~ 0.4 kW
FoV	~ 1 sr
Livetime	> 3 years



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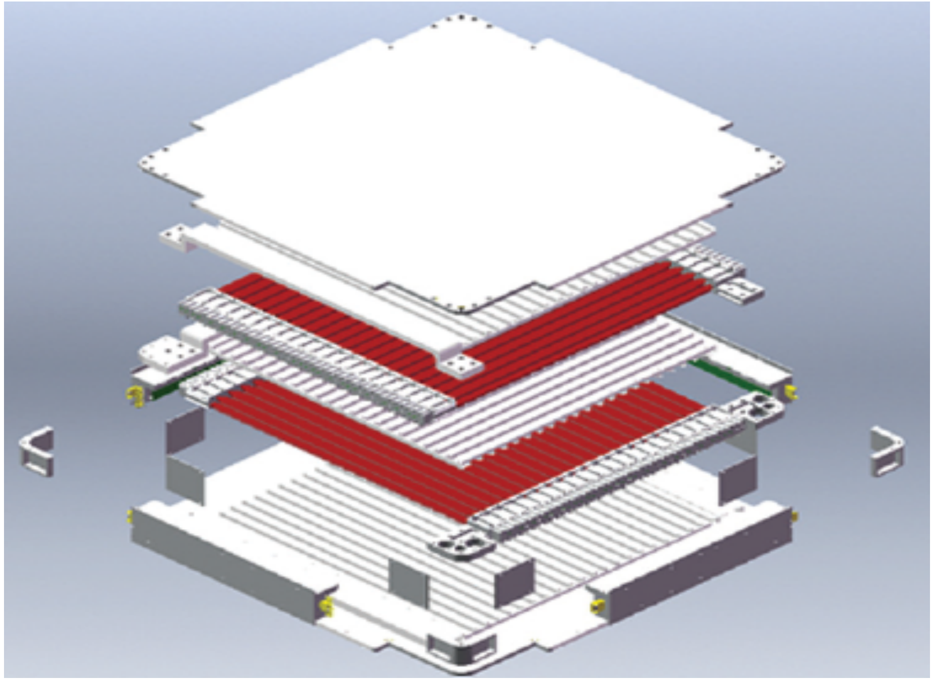
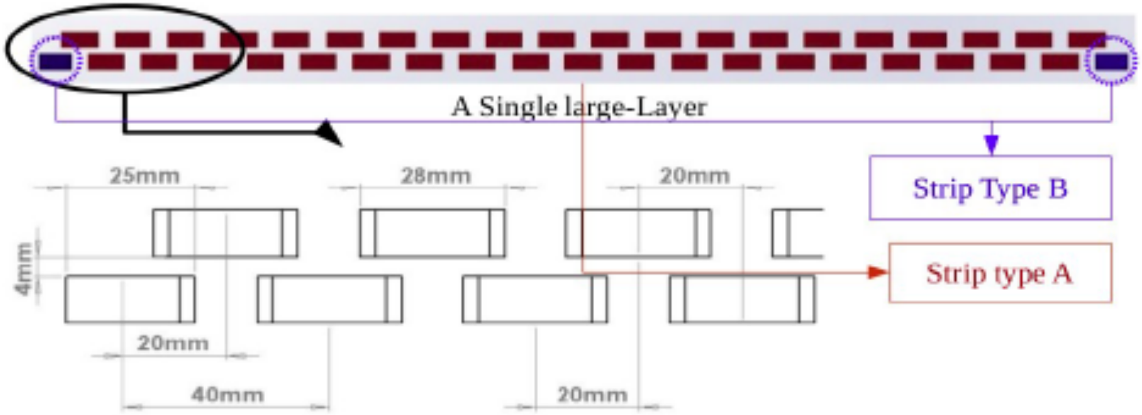
Plastic Scintillator Detector



- plastic scintillator strips ($2.8 \times 82 \times 1\ cm^3$)
- staggered by 1.2 cm in a layer
- 82 cm × 82 cm layers
- 2 layers (x and y views)

Position resolution < 2 cm
Single layer efficiency > 95%

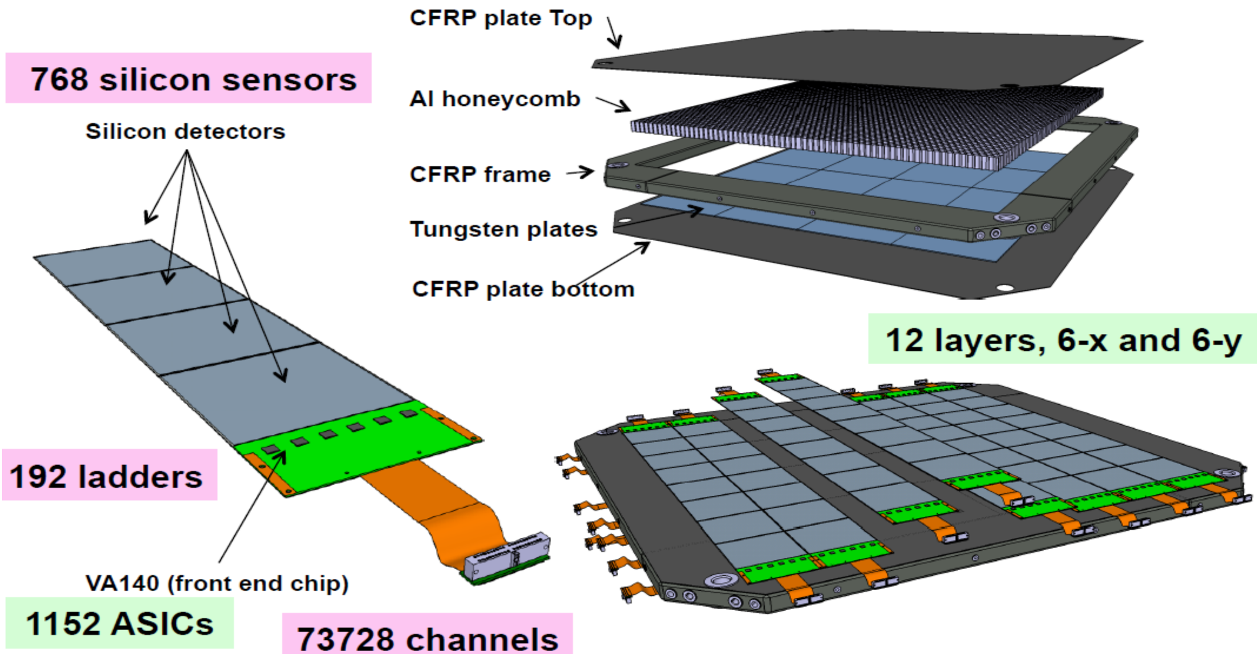


The Silicon TracKer

12 STK layers
(6 x-view, 6 y-view)

3 tungsten plates
as photon converter
in-between layer 1
and layer 4

Depth ~ 1 X_0



NIM A 831 (2016) 78

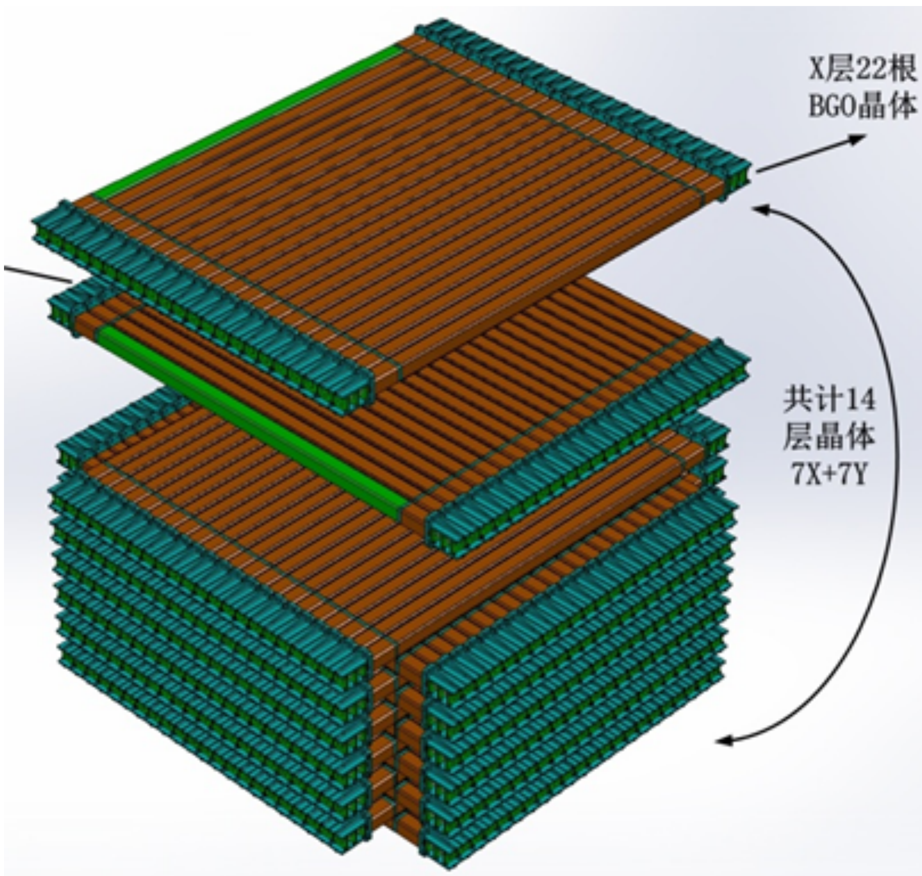
- 48 μm wide Si strips with 121 μm pitch
  - 768 strips = 1 Silicon Strip Detector (SSD)
    - 4 SSD = 1 ladder (380 mm × 95 mm × 0.32 mm)
      - 16 ladders = 1 layer (760 mm × 760 mm)

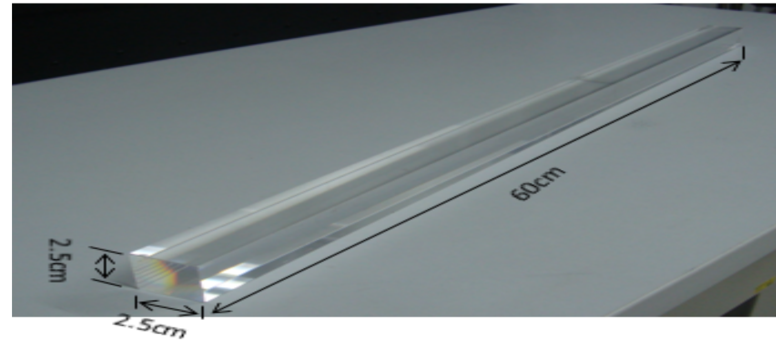
Analog Readout of each second strip (384 channels / ladder)

The BGO CALOrimeter

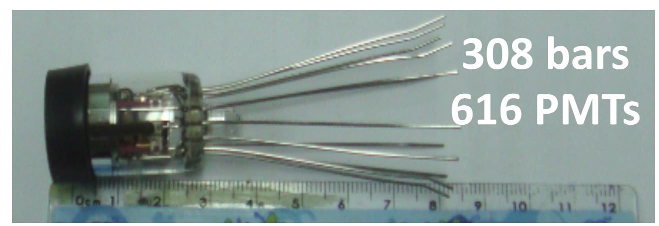
Hodoscopic stacking of 14 alternate orthogonal layers

Depth ~32 X_0





- BGO bar（2.5×2.5×60 cm^3）
- 22 BGO bars in each layer

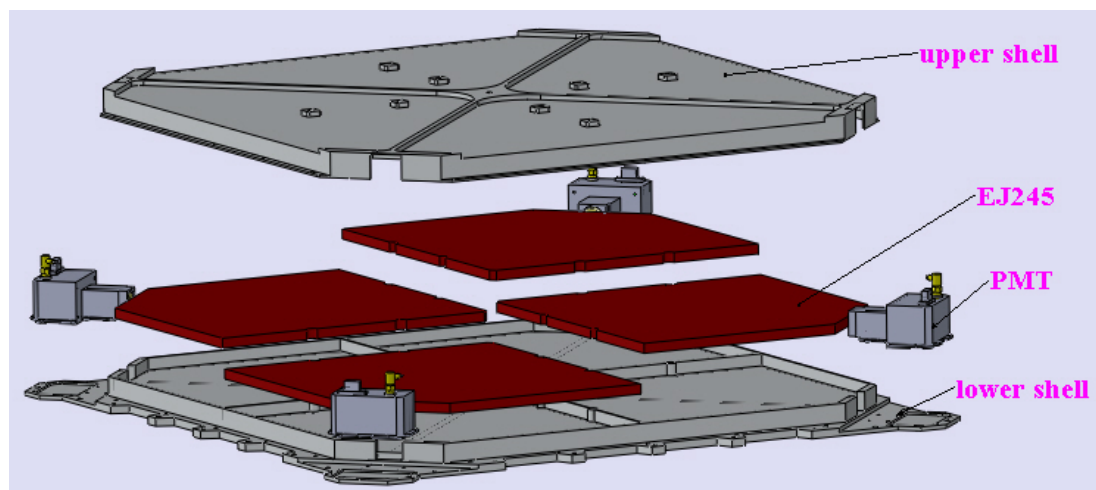


- PMTs coupled with each BGO crystal bar in two ends
- Front-end electronics on each side of the module

NeUtron Detector

4 large area boron-doped plastic scintillators (30 cm × 30 cm × 1 cm)

$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li + \gamma$$



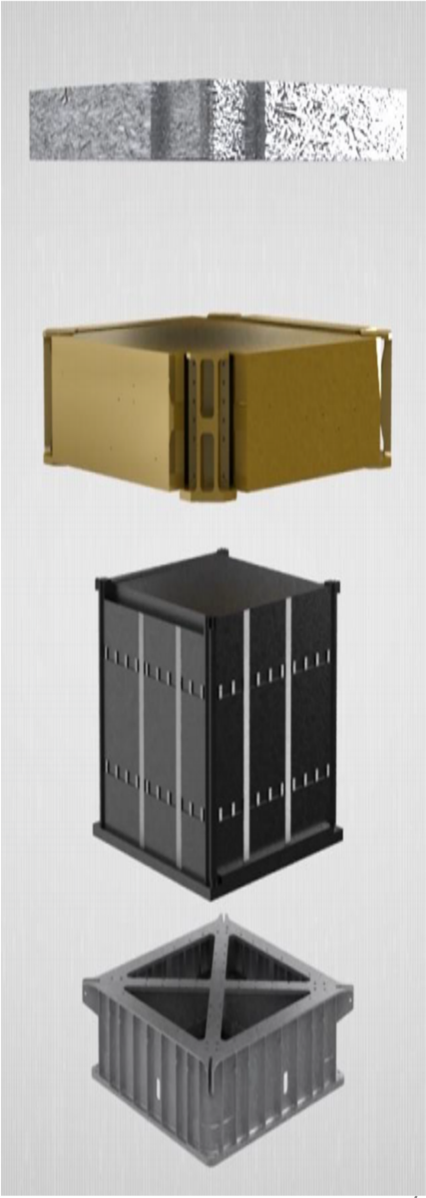
Summary of sub-detectors

PSD - Charge measurement ($Z \propto \sqrt{dE/dx}$)
- Z-range = 1-28, using two dynodes
- Veto for gammas

STK - Precise tracking
  - spatial resolution < 80 μm (incidence < 60°)
  - angular resolution ~ 0.2° (γ at 10 GeV)
- Tungsten converter for pair production
- Charge measurement ($Z \propto \sqrt{ADC}$)

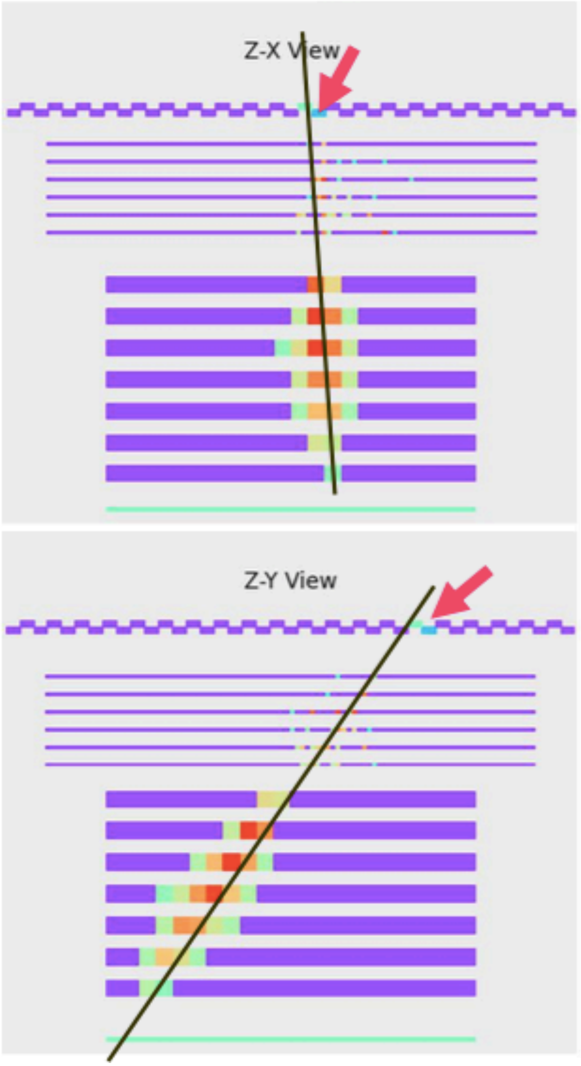
CALO – Thickness ~ 32 X_0
- Energy measurement using two dynodes
  - 5 GeV – 10 TeV for electrons and γ
  - 50 GeV – 200 TeV for nuclei
- Charge measurement for MIPs

NUD - Hadron rejection looking for delayed (~2 μs) coincidence of neutrons

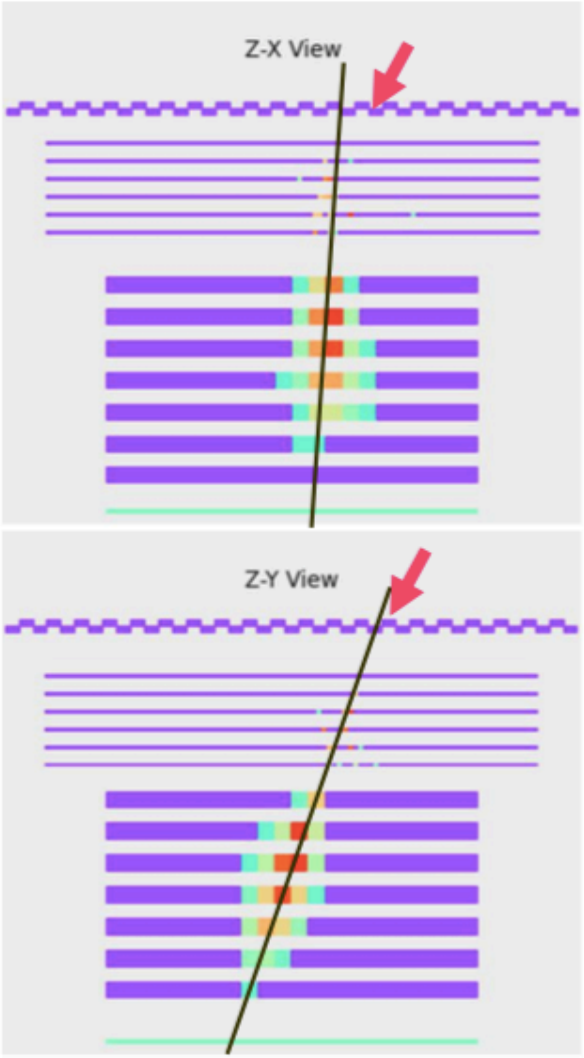


Topology of different events in DAMPE

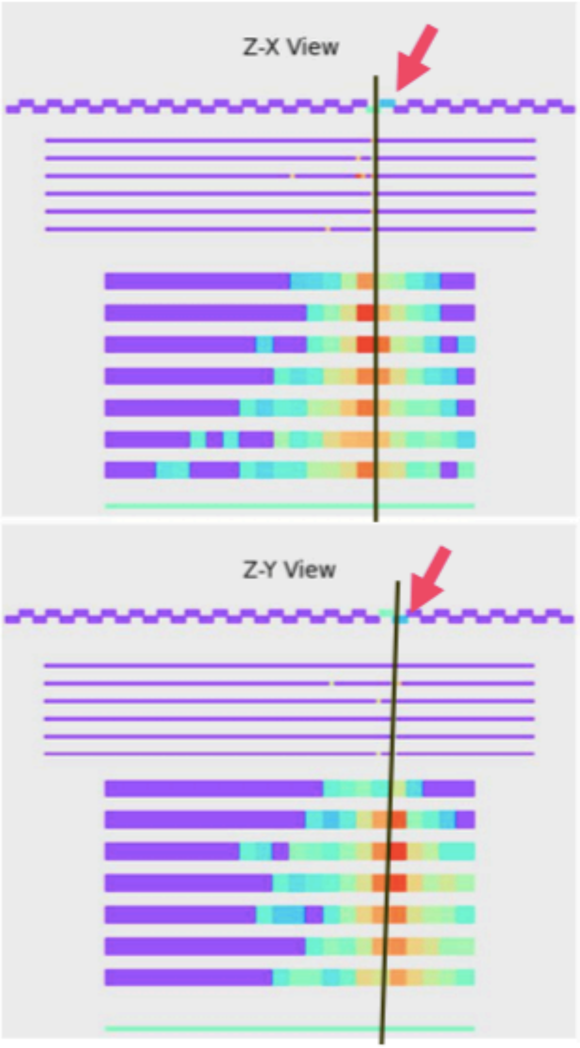
Electrons
(e.m. shower)



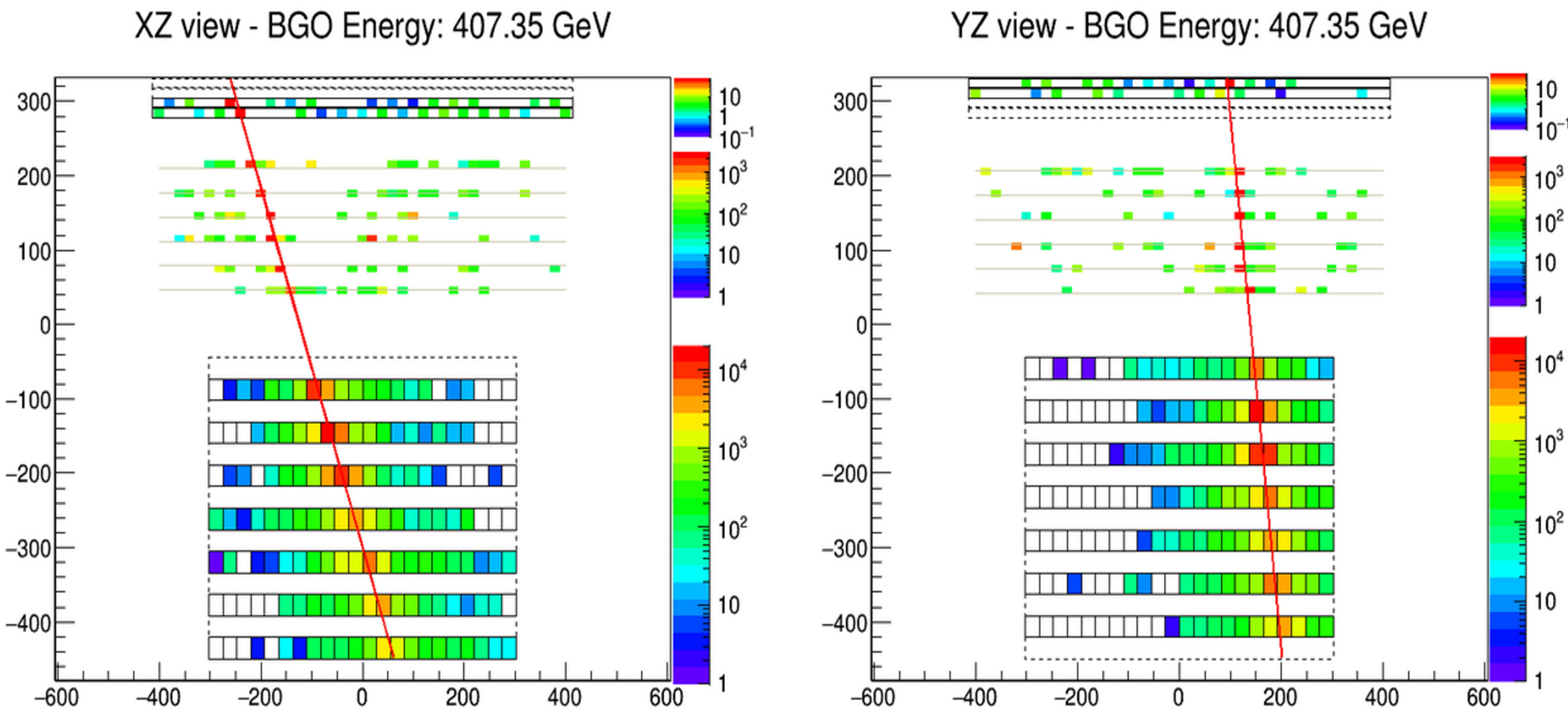
Gamma-rays
(no PSD signal, e.m. shower)



Protons & nuclei
(hadronic shower)



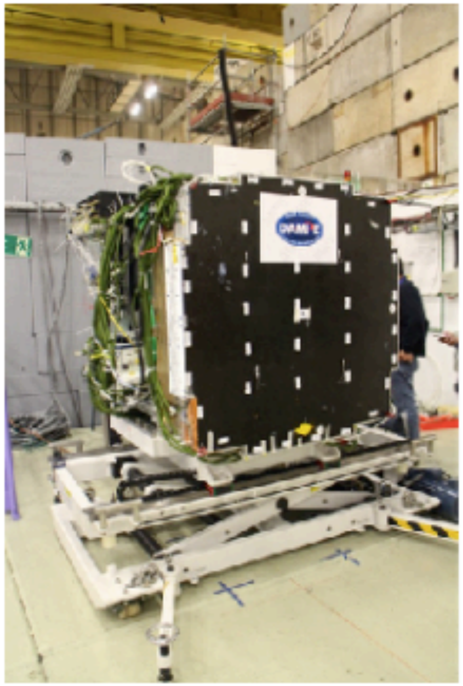
Display of a real CR event

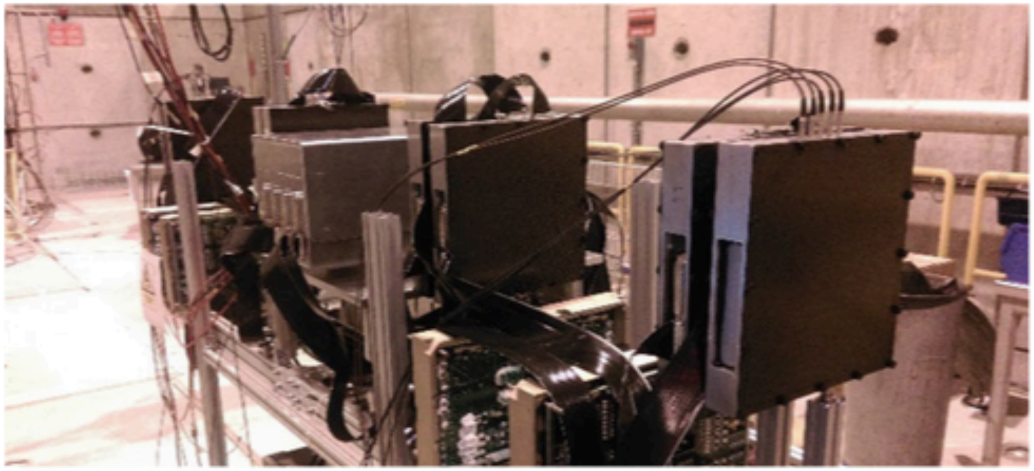


Beam test at CERN

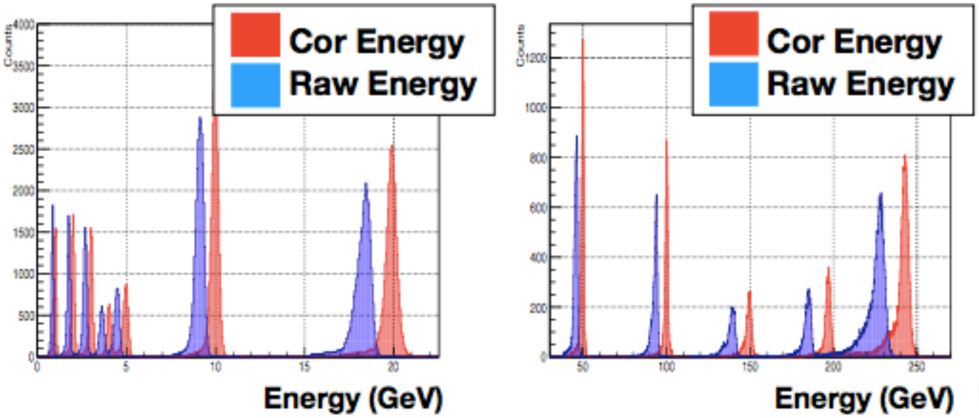
2014 - PS & SPS
- electrons
- protons
- pions
- gamma
- muons

2015 - SPS
- argon (and fragments)
- lead (and fragments)
- electrons
- protons
- pions
- gamma
- muons

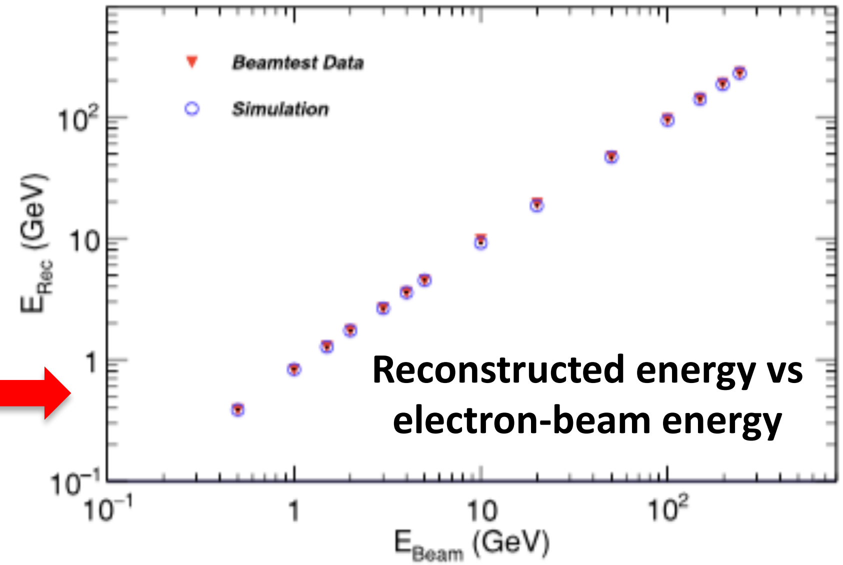




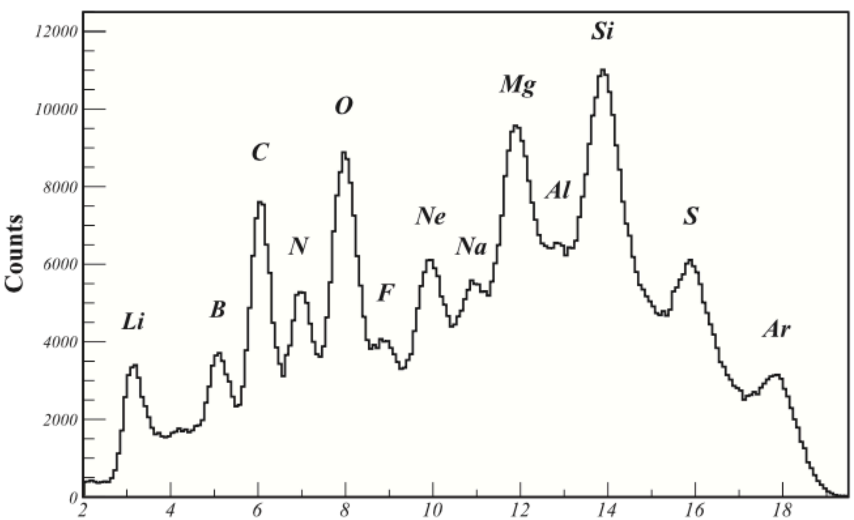
Some results of the beam test



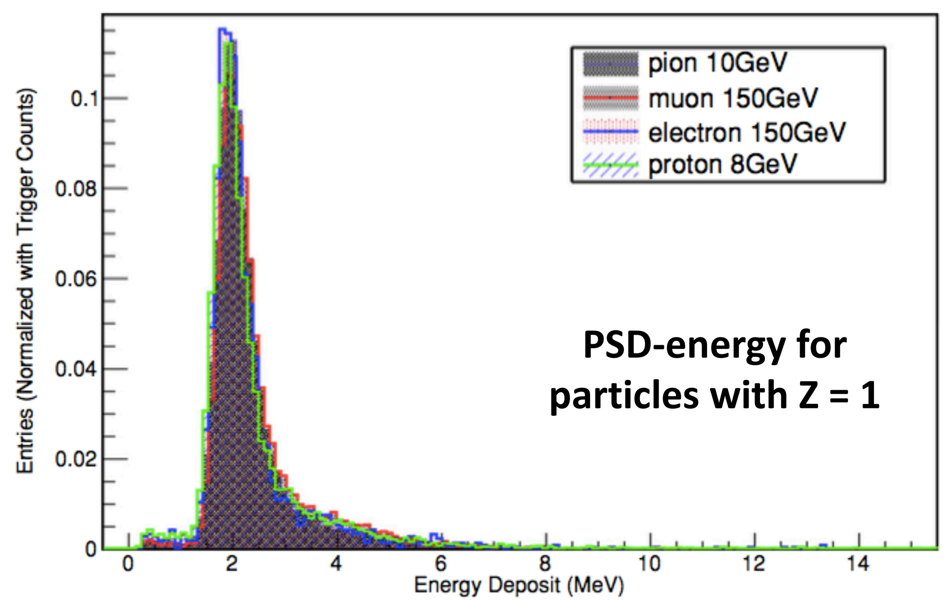
Electron BGO-energy before and after correction (resolution 0.8% for 100-GeV electrons)



Reconstructed energy vs electron-beam energy

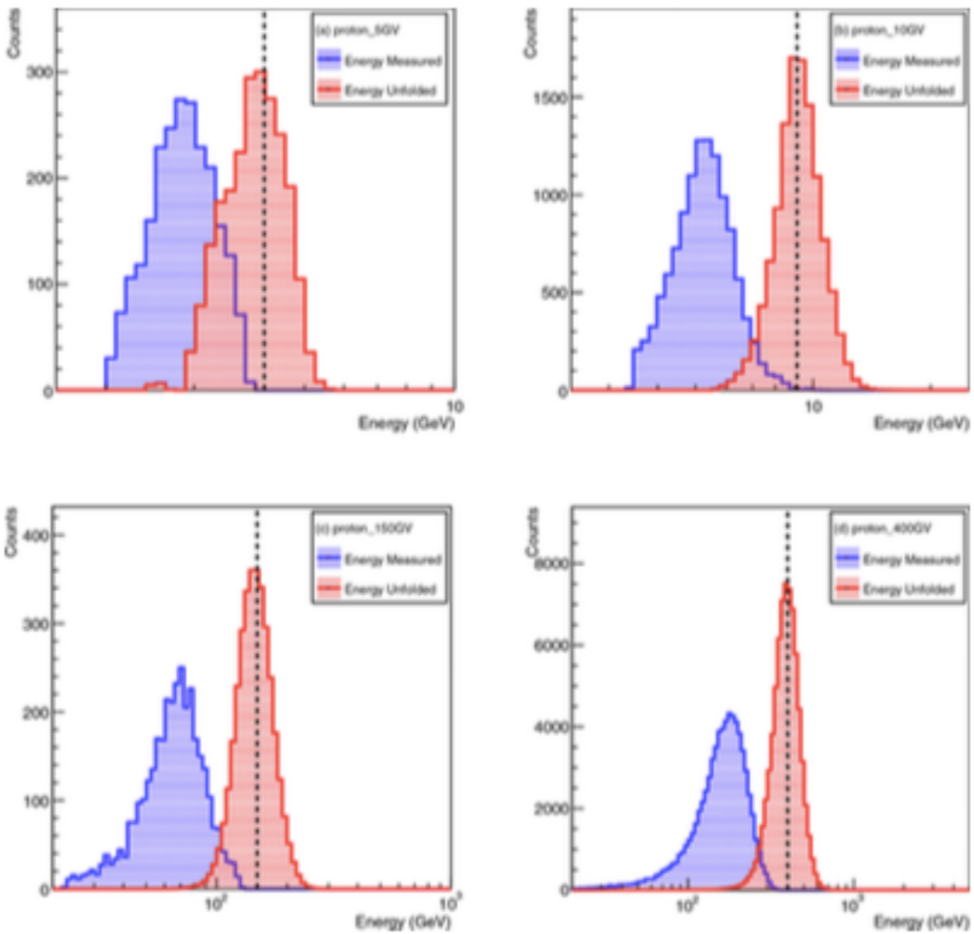


Argon-beam on PSD: Charge spectrum of fragments (Helium peak removed)

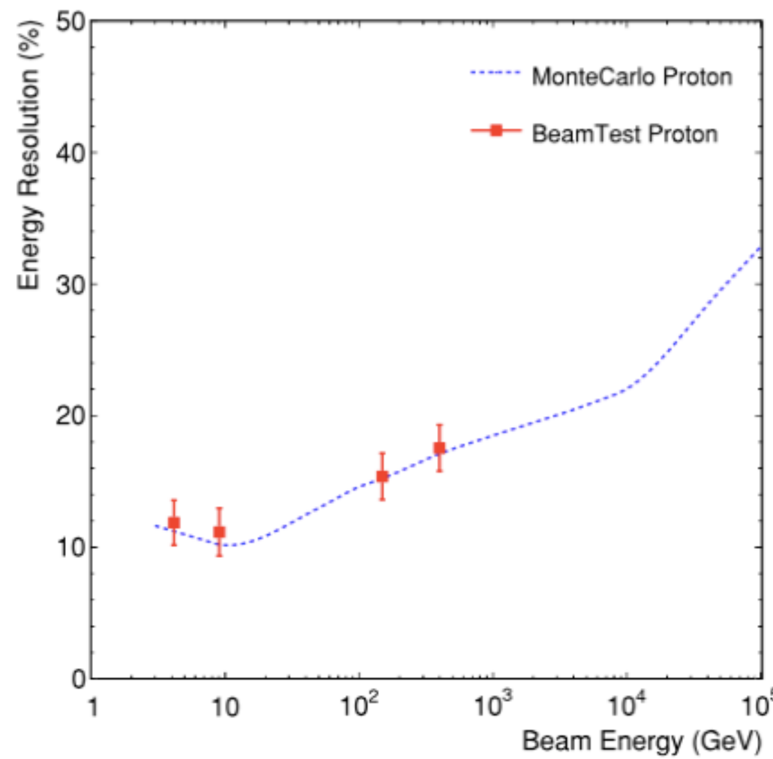


PSD-energy for particles with Z = 1

Other results of the beam test



BGO-deposited energy (blue) and unfolded ones (red) for different proton beams (5, 10, 150, 400 GeV/c)



Energy resolution for protons (simulation and beam-test data)

The launch: Dec 17th 2015, 0:12 UTC

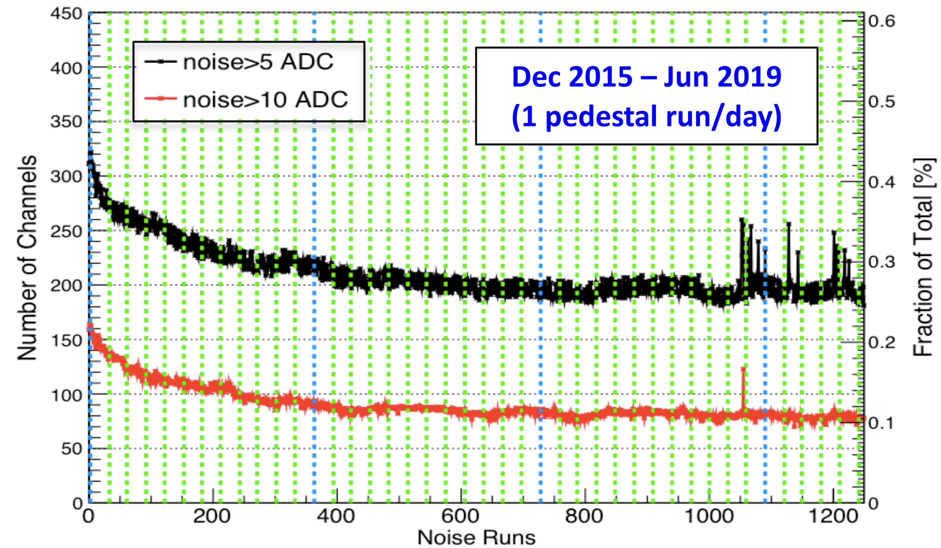
Jiuquan Satellite Launch Center
Gobi desert, China

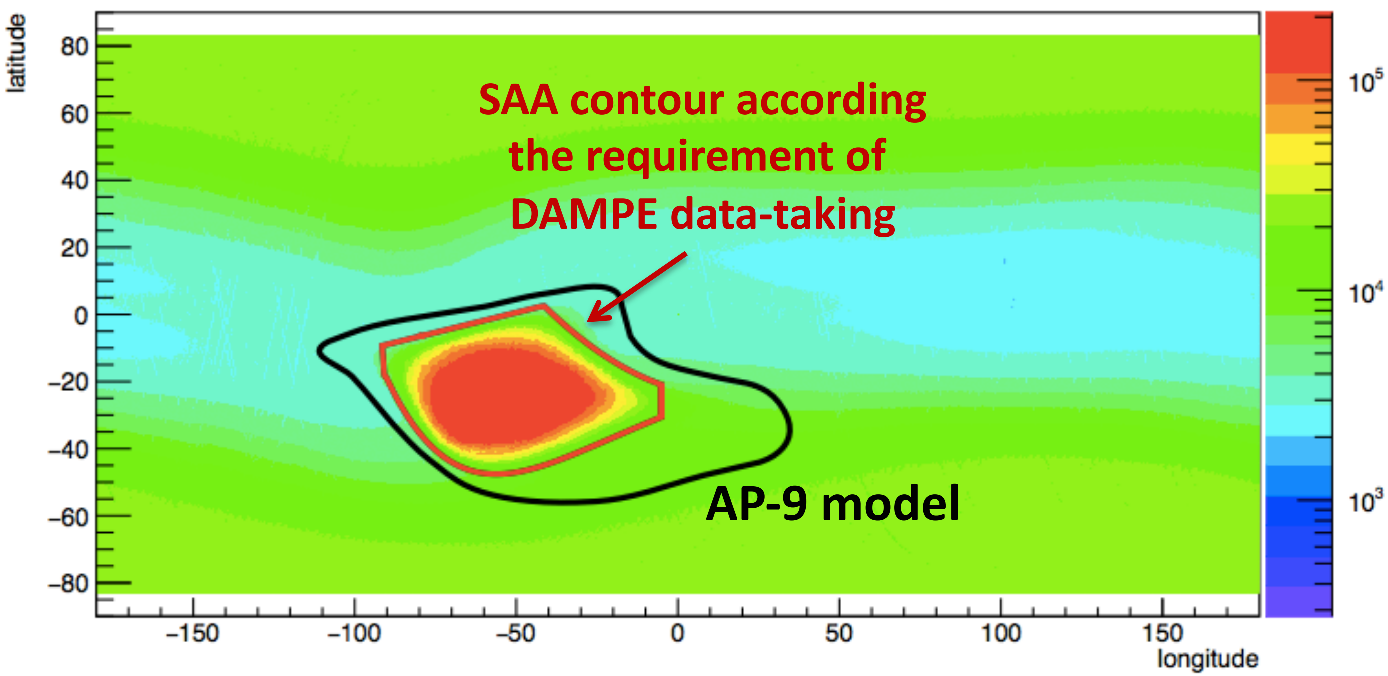
Orbit: Sun-syncronous
Altitude: 500 km
Period: 1.5 hours

Dec 24th, 2015: HV on

On-orbit performances (I)

The percentage of noisy STK-channels is very low (< 0.5 %) and decreases with time

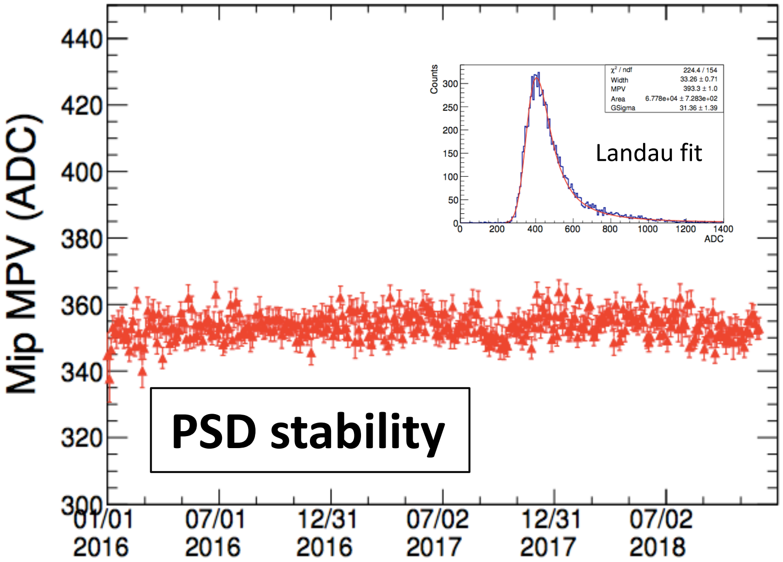


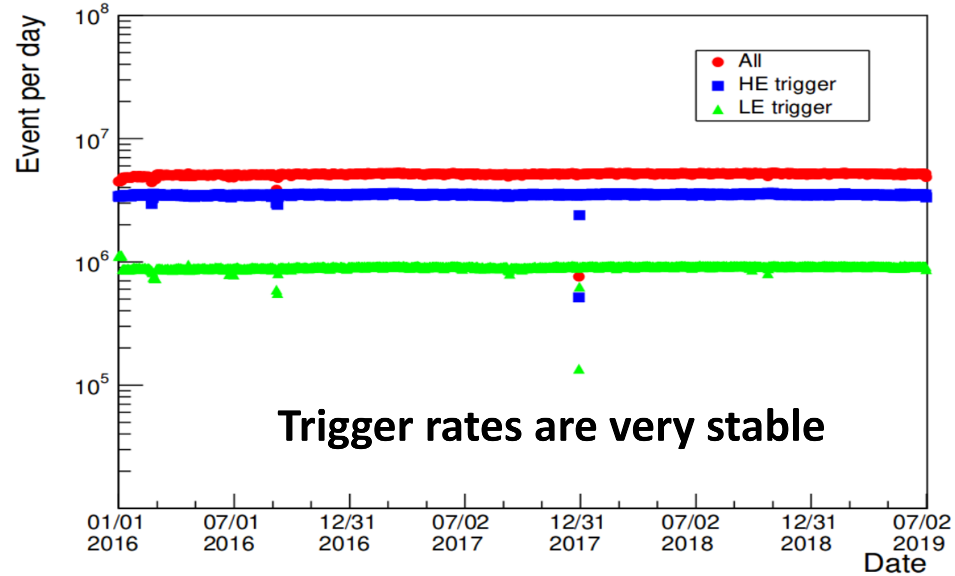


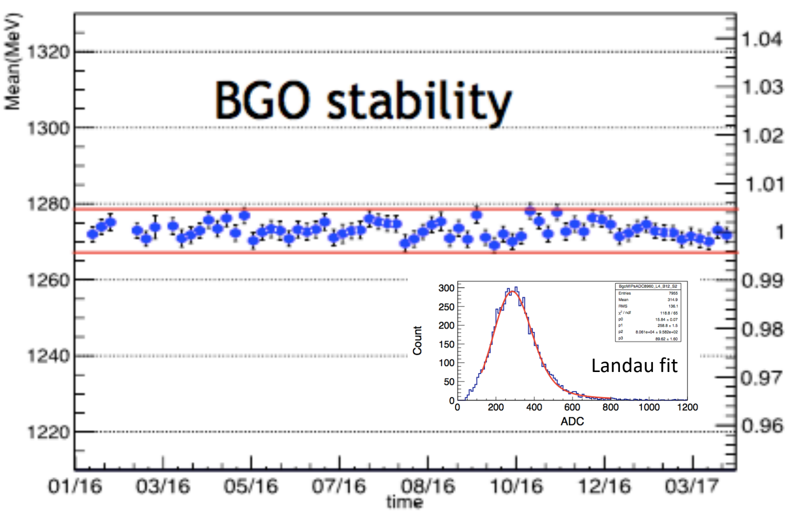
South Atlantic Anomaly (SAA)

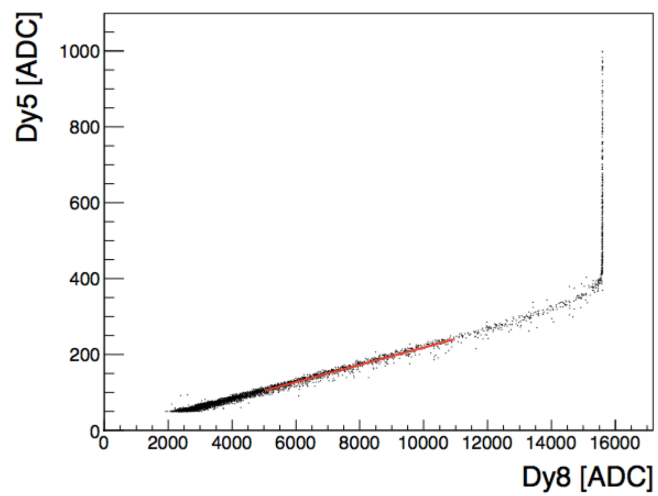
On-orbit performances (II)

Average trigger rate: ~ 50 Hz
100 GB/day on ground (about 5 M events)



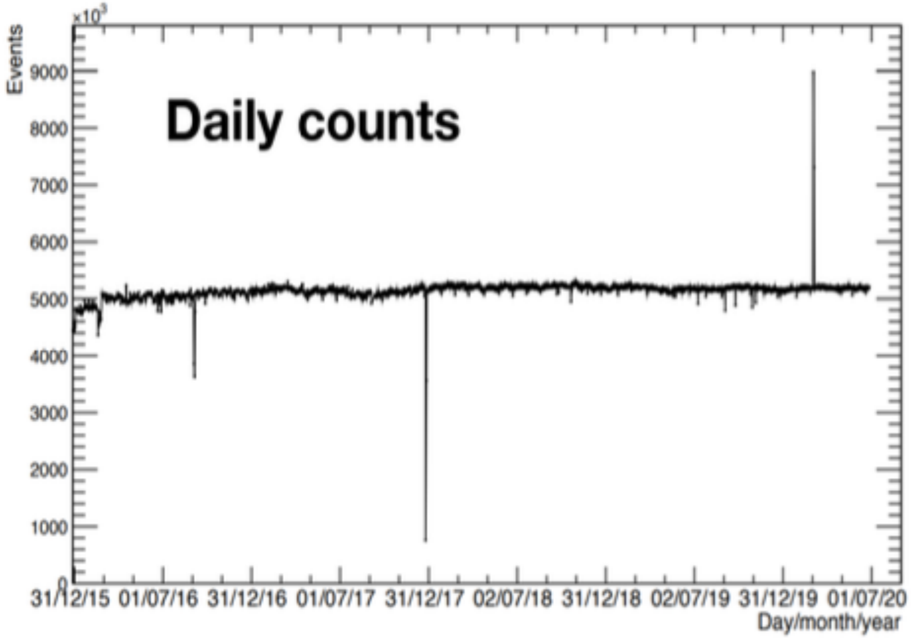






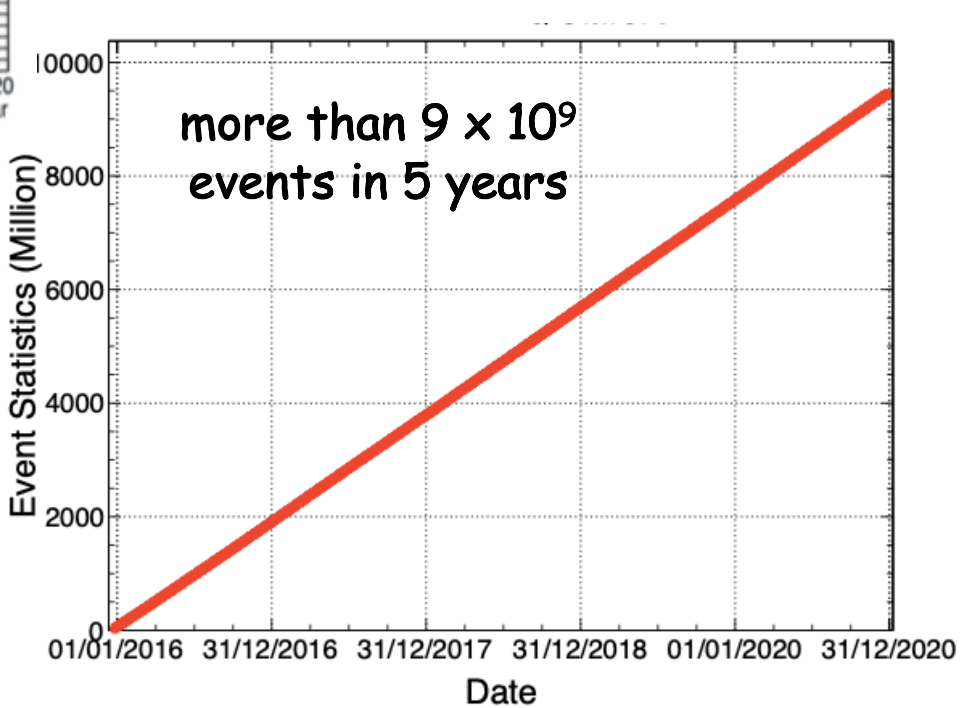
Two dynodes to cover a wide range

On-orbit performances (III)



Very stable data taking

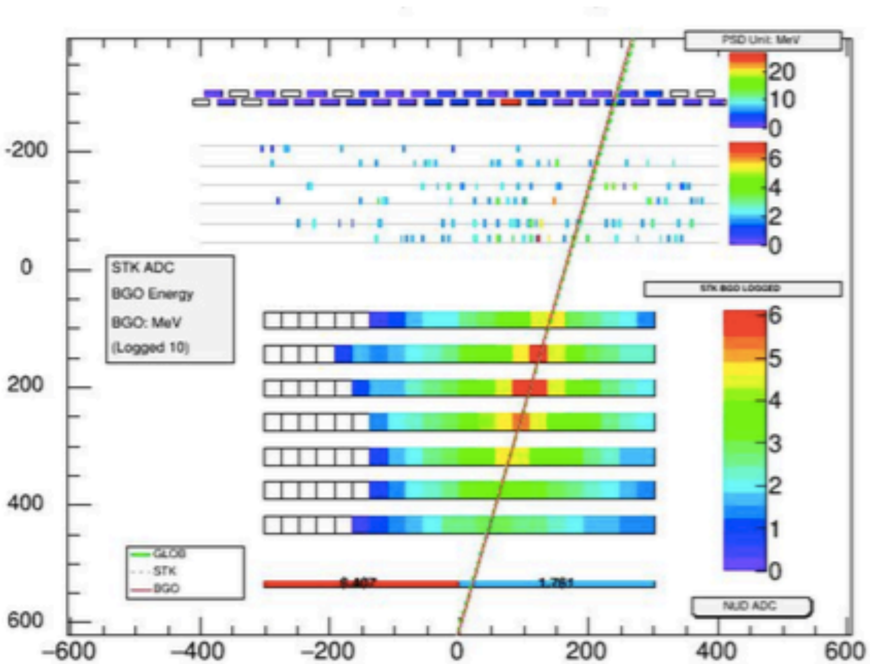
~ 5 x 10^6 events/day

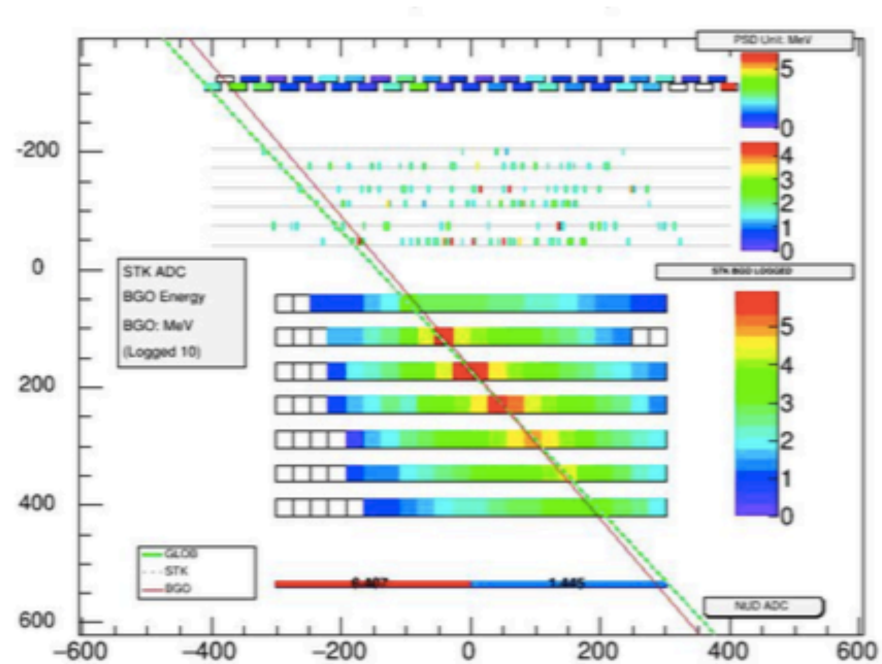


Electron+positron identification

Selected events with $Z_{PSD} = 1$

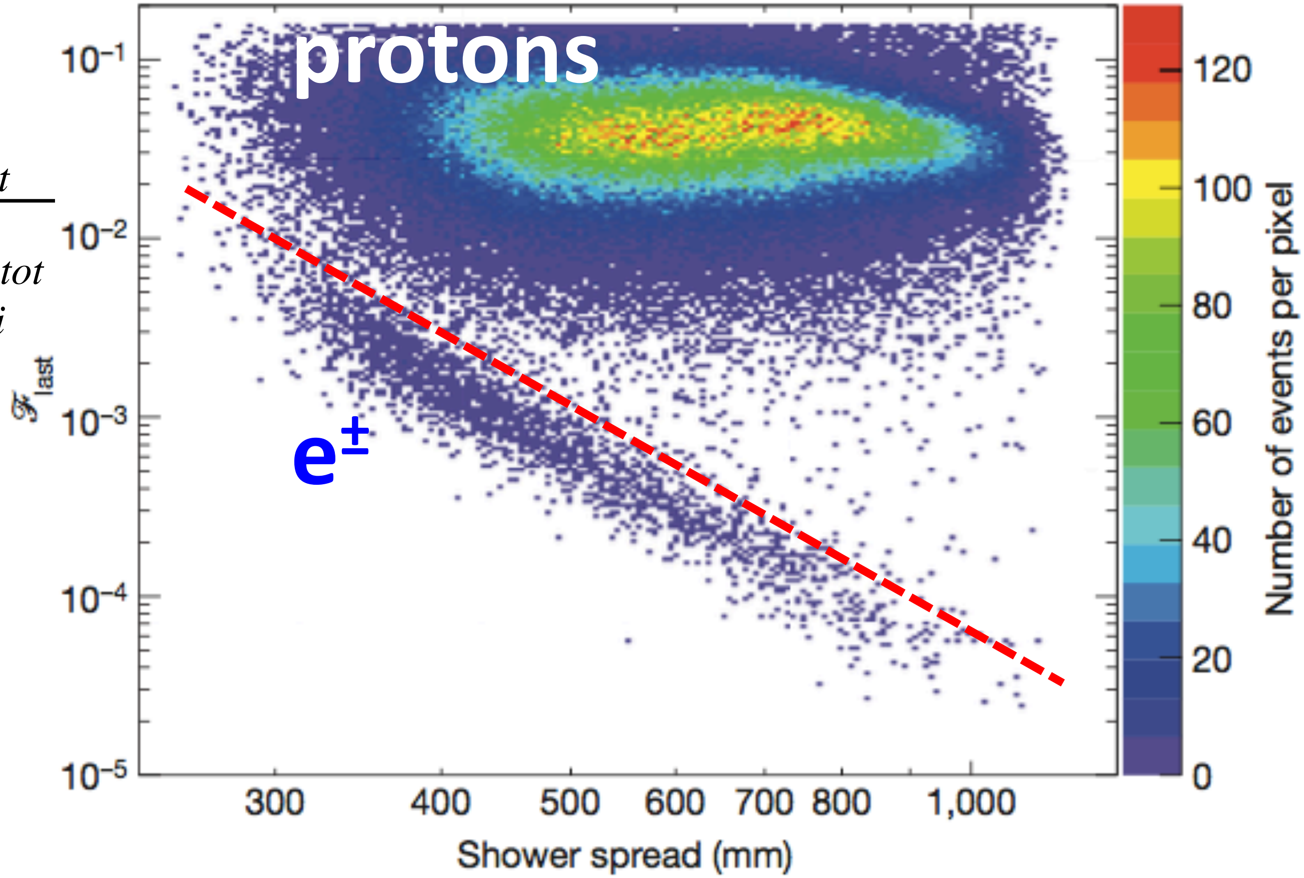
Exploiting the imaging CALO-features





BGO imaging to separate electrons and hadrons

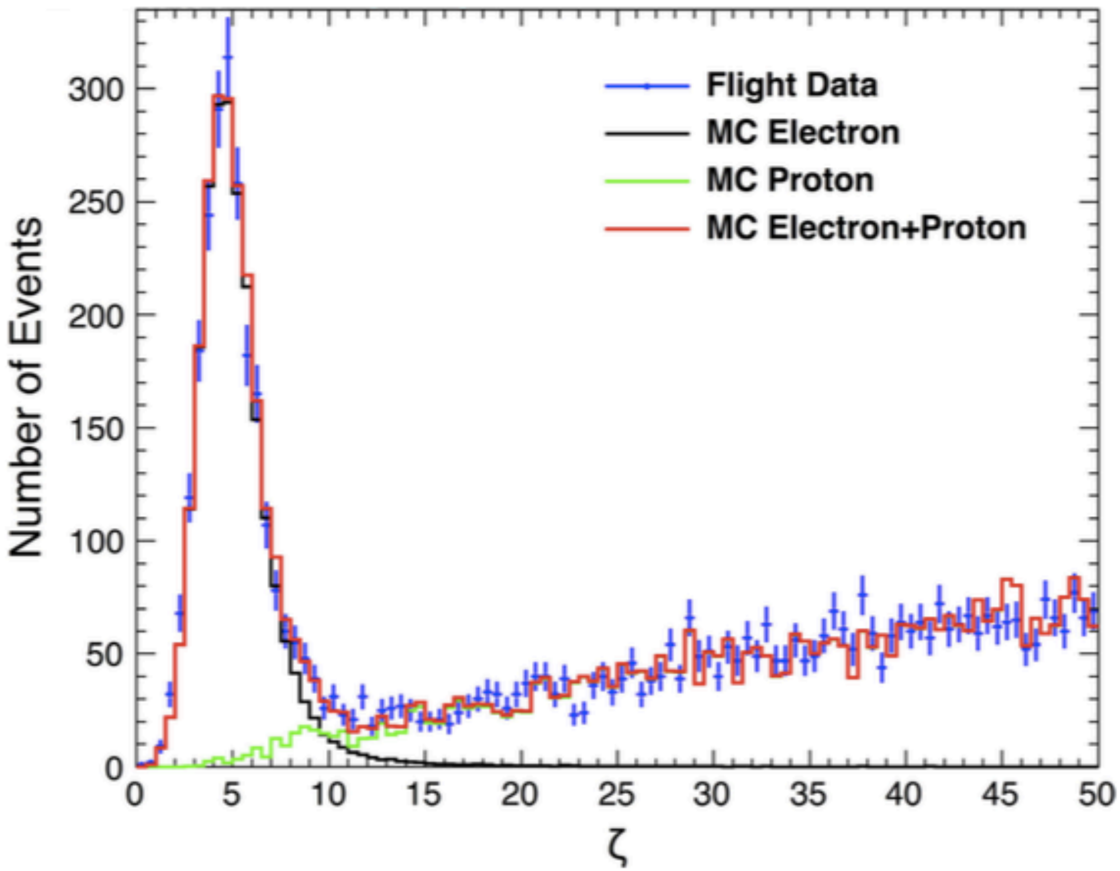
$$F_{last} = \frac{E_{last}^{tot}}{\sum_{i=1}^{14} E_i^{tot}}$$



$$spread = \sum_{i=1}^{14} RMS_i = \sum_{i=1}^{14} \sqrt{\frac{\sum (x_{ij} - x_{iC})^2 E_{ij}}{E_i^{tot}}}$$

nature
International journal of science
552 (2017)63-66

BGO imaging to separate electrons and hadrons



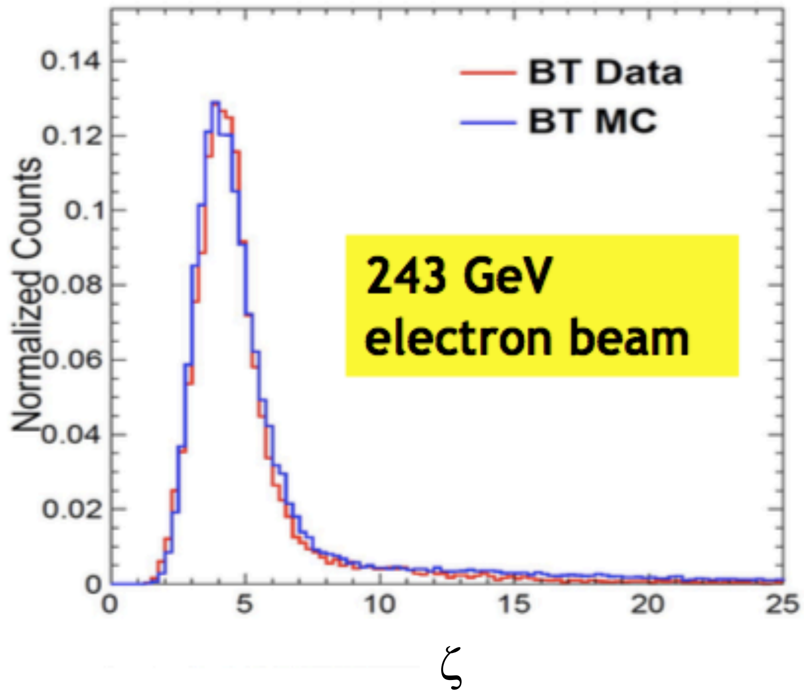
Electron and positron selection

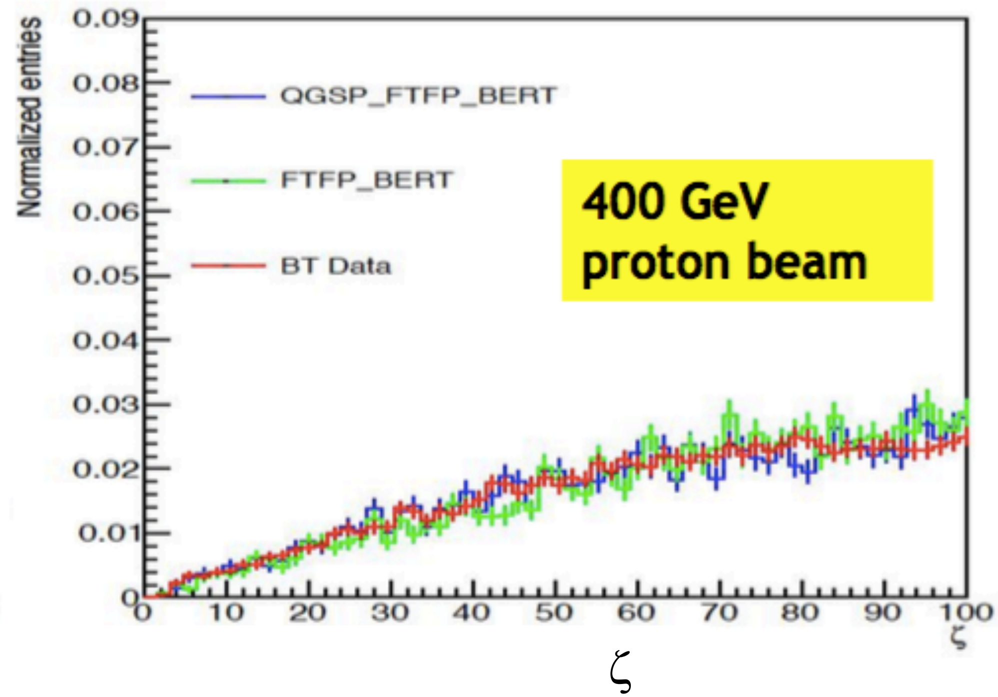
Estimate of proton pollution

$$\varsigma = F_{last} \frac{(spread / mm)^4}{8 \times 10^6} < 8.5$$

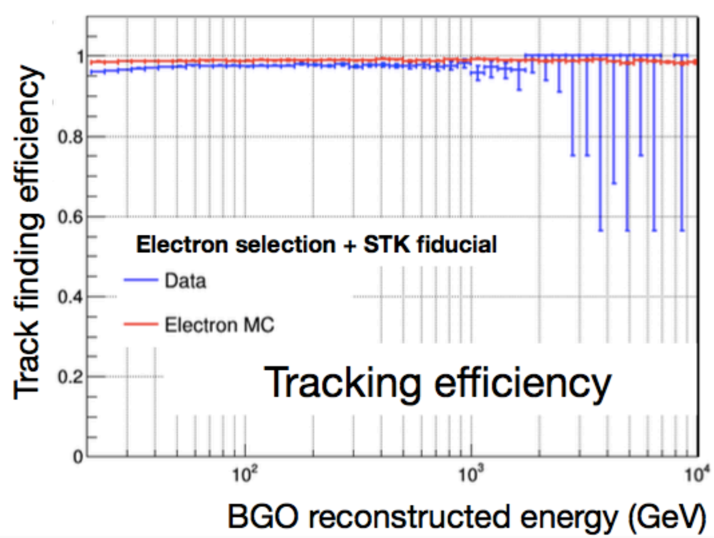
nature International journal of science
552 (2017)63-66

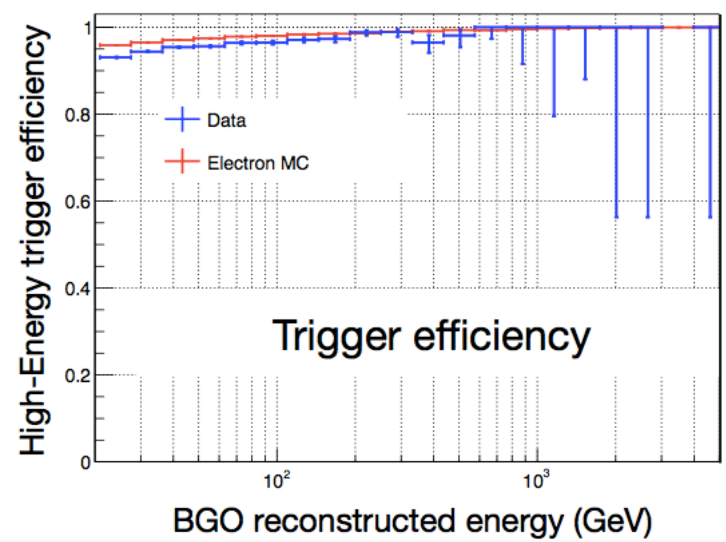
Validation of parameter ζ with beam-test data



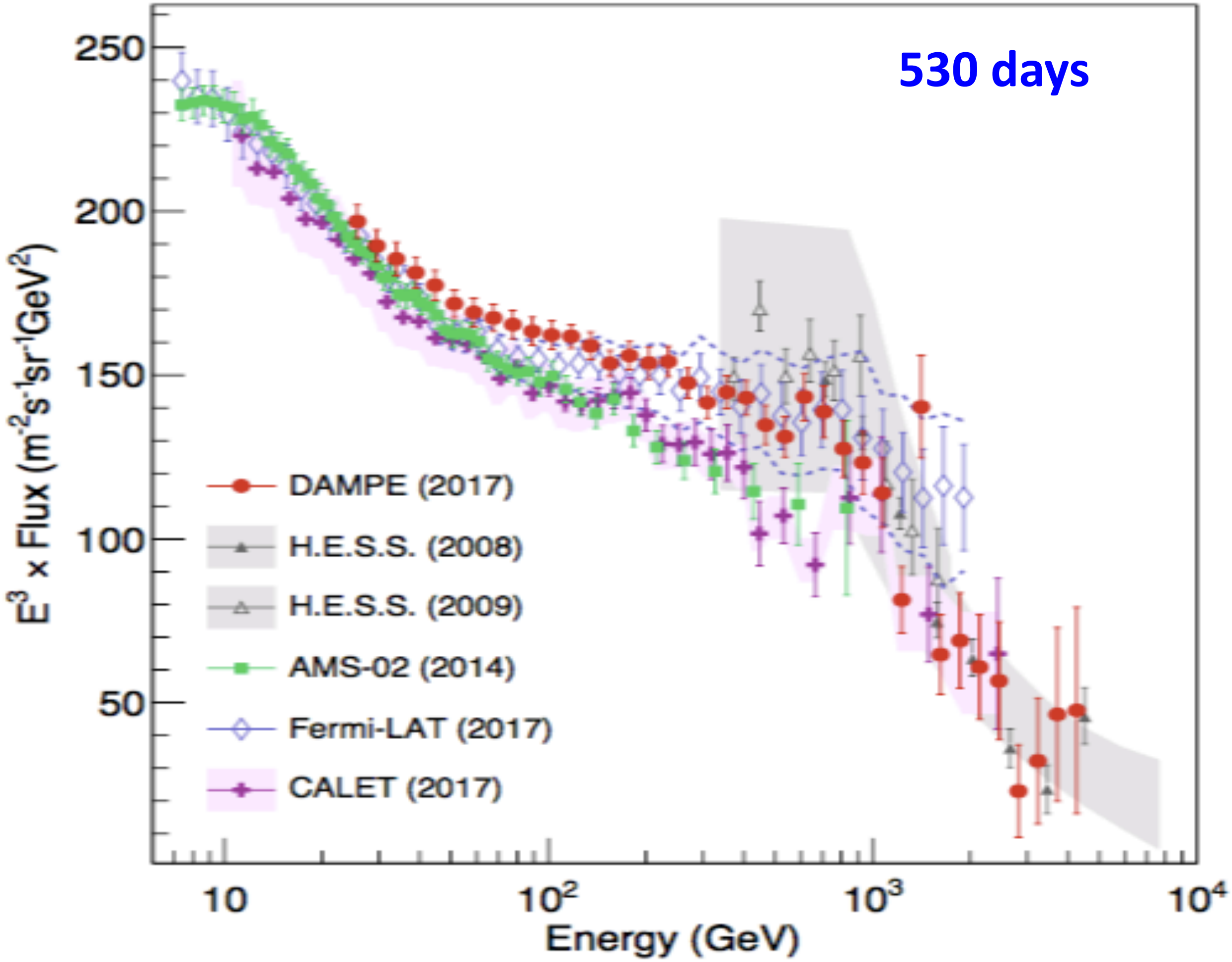


Tracking and trigger efficiencies agree with simulation





Electron+positron spectrum



nature
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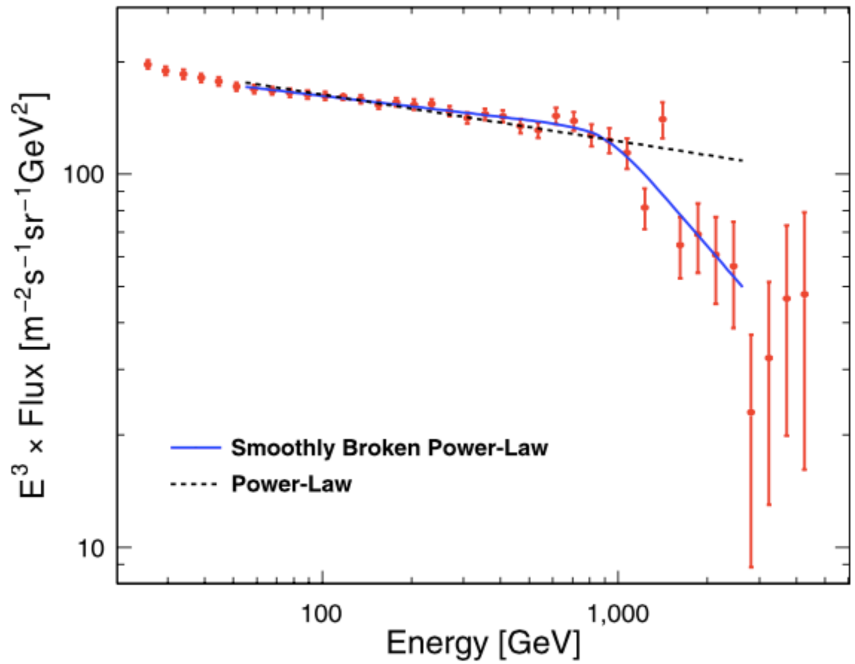
Energy range:
25 GeV – 4.6 TeV

Energy resolution <1.2%
for E > 100 GeV

Uncertainties mainly due to the statistics at high energy
Significant improvements are expected with more data-taking

Electron+positron spectrum



Smoothly Broken Power-Law is favorite (6.6 σ)

$$\Phi = \Phi_0 \left(E/100\ GeV\right)^{-\gamma_1}\left[1+\left(E/E_B\right)^{-(\gamma_1-\gamma_2)/\Delta}\right]^{-\Delta}$$

$\Delta = 0.1$
$\gamma_1 = 3.09 \pm 0.01$
$\gamma_2 = 3.92 \pm 0.20$
$E_B = (914 \pm 98)$ GeV

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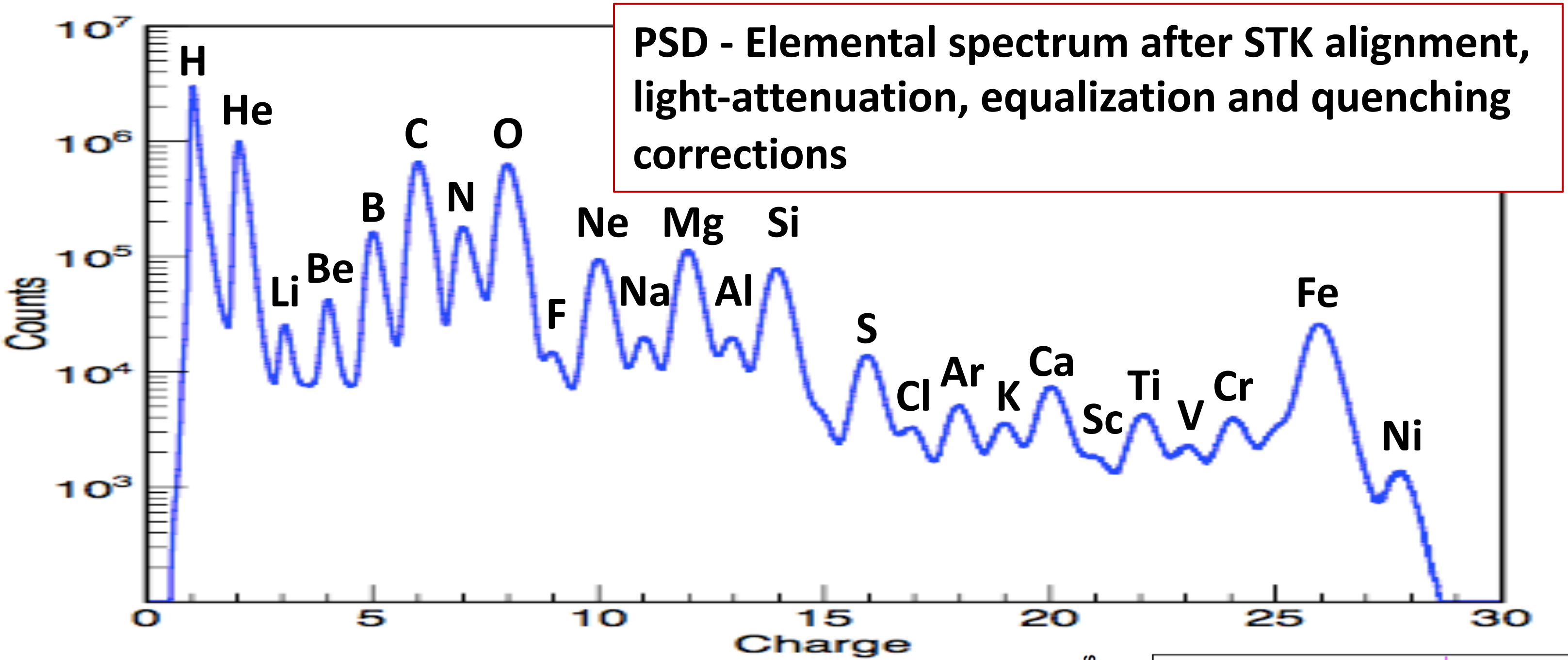
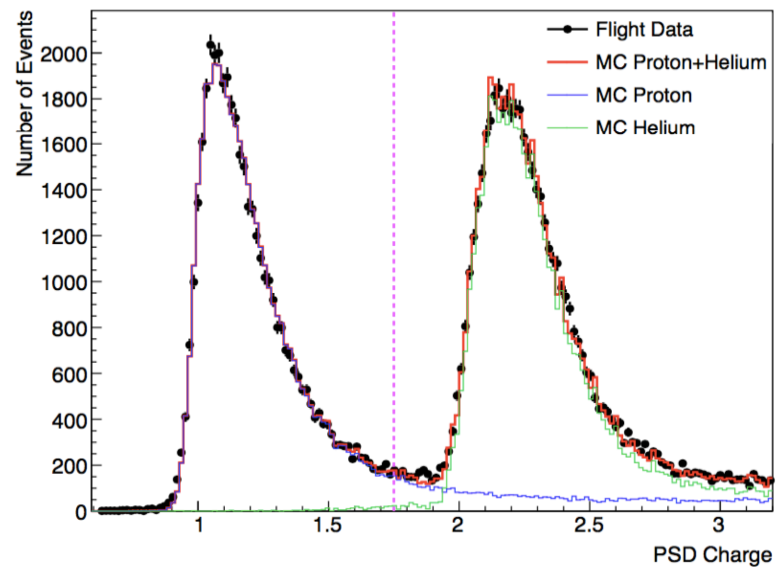
Nuclei (Z=1-26 and more)



Element	σ_Z
p	0.07
He	0.12
Li	0.14
Be	0.21
B	0.17
C	0.18
N	0.21
O	0.21

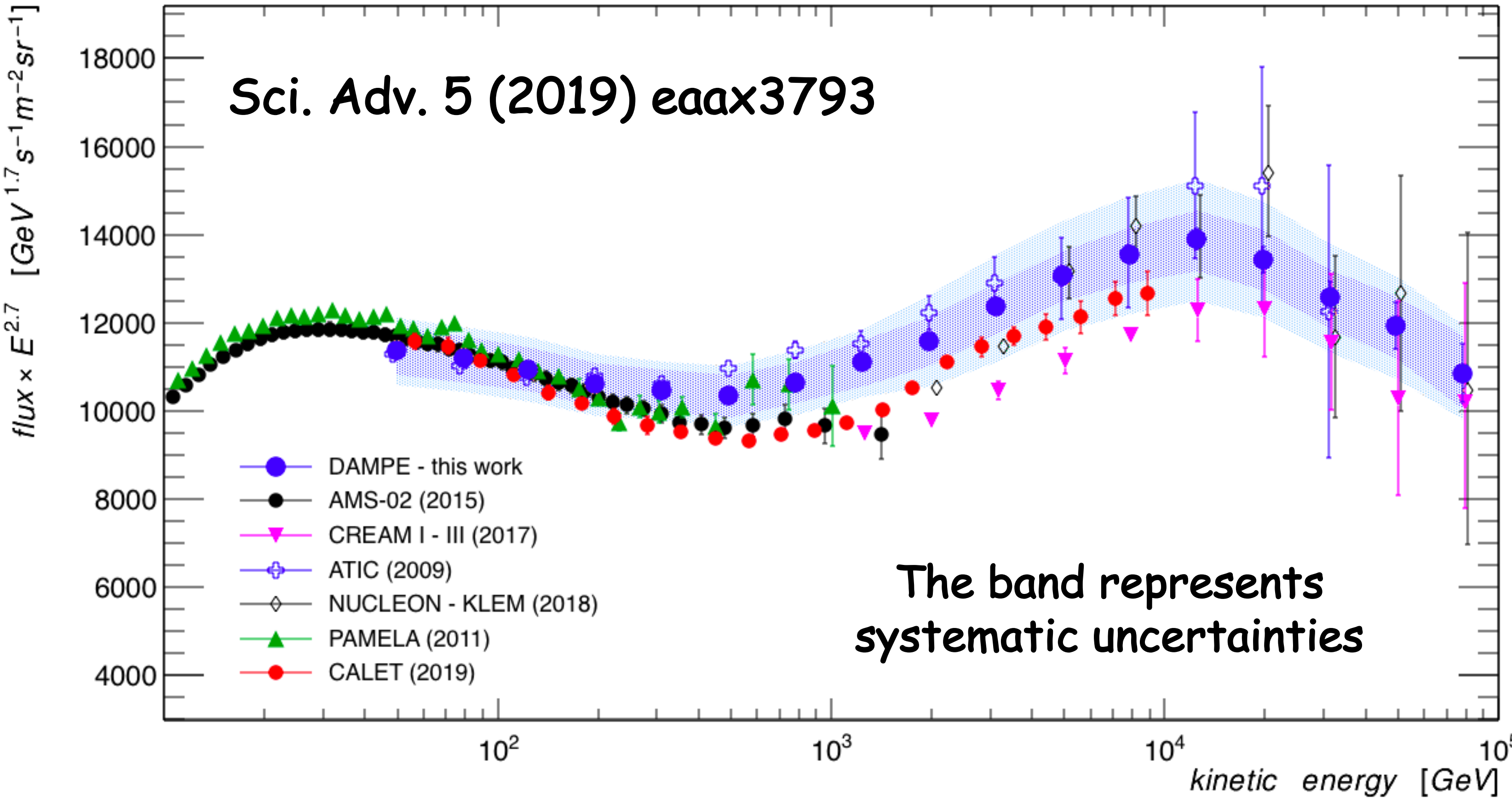
Template fit for protons and Helium



Proton flux (I)

30 months of data (Jan 2016 – Jun 2018)

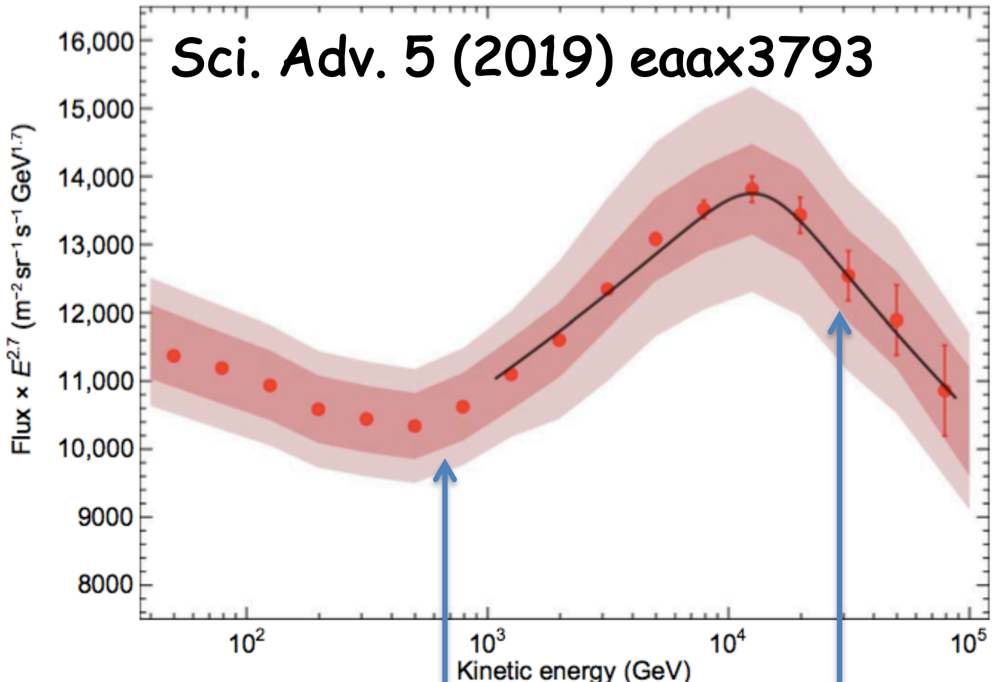
Spectral hardening followed by softening
(measured with unprecedented precision)



Proton flux (II)

Fit with Smoothly
Broken Power Law (s = 5)

$$\Phi(E) = \Phi_0 \left(\frac{E}{TeV}\right)^{-\gamma_1} \left[1 + \left(\frac{E}{E_B}\right)^s\right]^{-(\gamma_2-\gamma_1)/s}$$



100 GeV – 6.3 TeV **Hardening**
E_B = 480 GeV γ_1 = 2.772 γ_2 = 2.599

1 – 100 TeV **Softening (significance 4.7 σ)**
E_B = 13.6 TeV γ_1 = 2.60 γ_2 = 2.85

Helium flux (I)

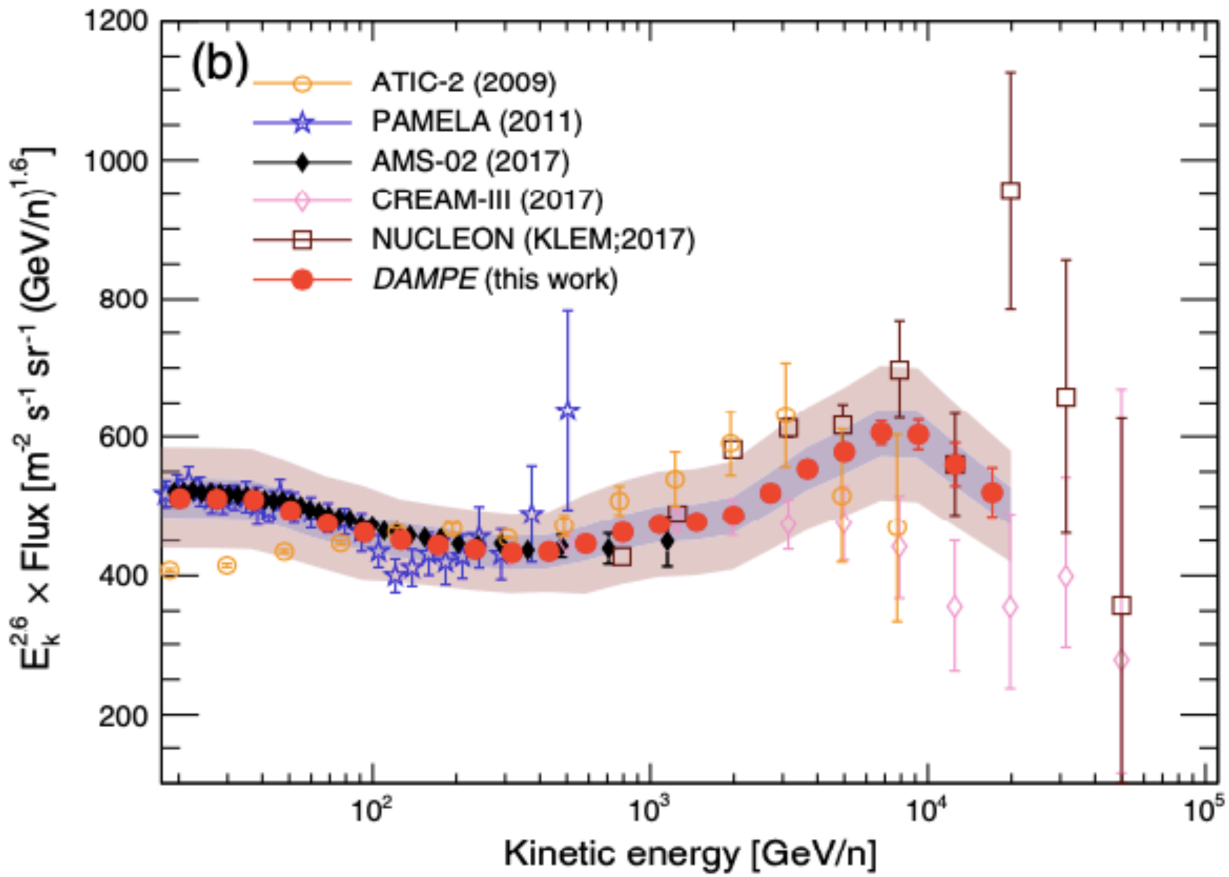
PRL 126 (2021) 201102

54 months of data
(Jan 2016 – Jun 2020)

Spectrum observed with unprecedented resolution

Measurement in the range 70 GeV – 80 TeV

The hardening is confirmed and a softening is visible

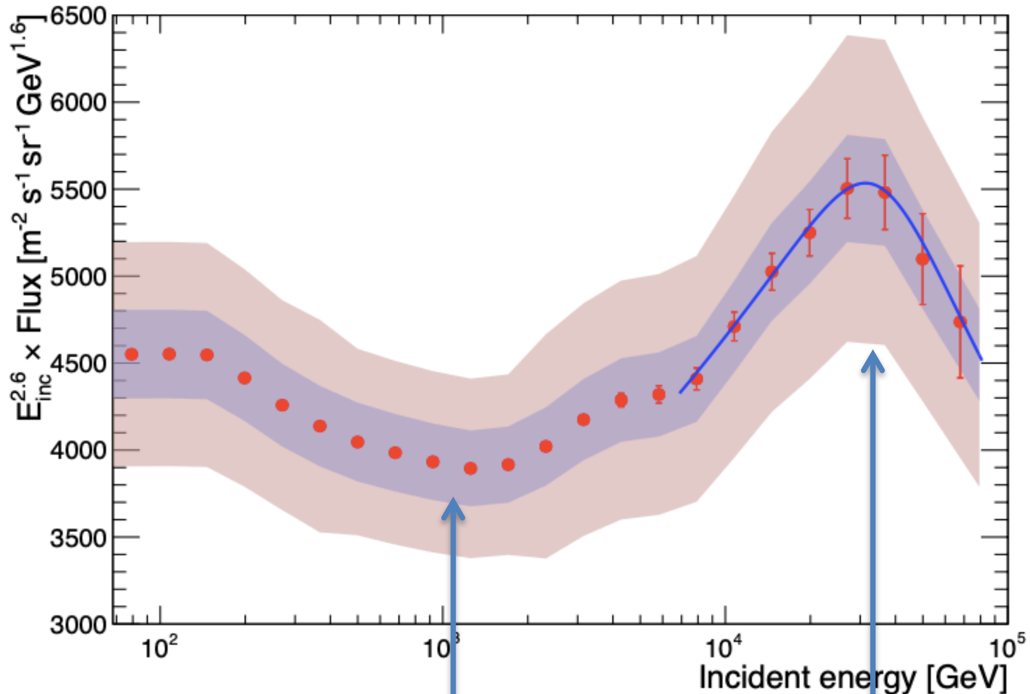


Helium flux (II)

Fit with Smoothly Broken Power Law

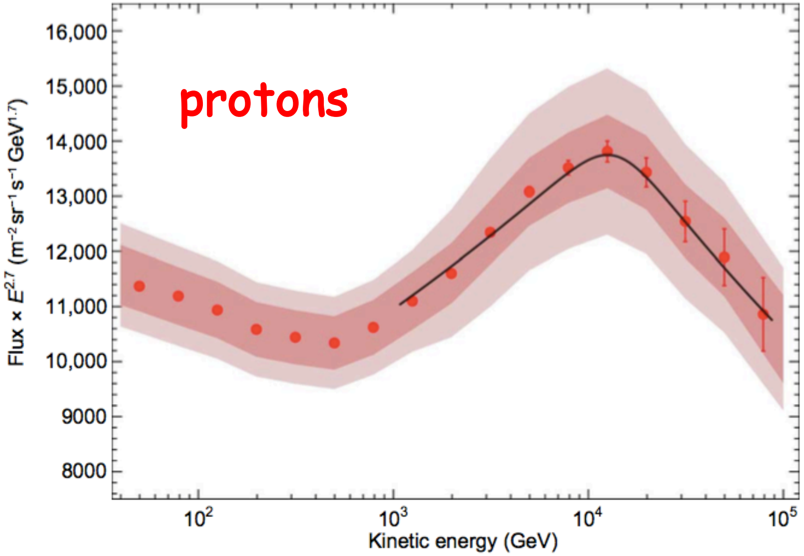
$$\Phi(E) = \Phi_0 \left(\frac{E}{TeV}\right)^{-\gamma_1} \left[1 + \left(\frac{E}{E_B}\right)^{s}\right]^{-(\gamma_2-\gamma_1)/s}$$

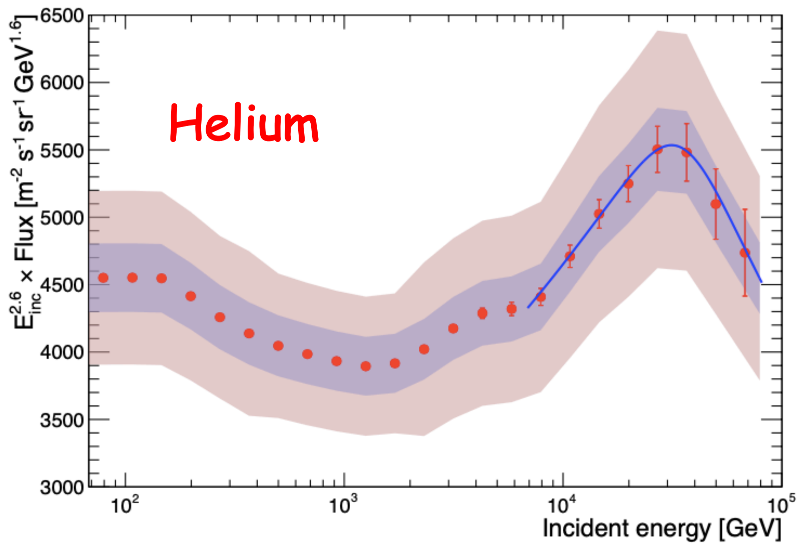
PRL 126 (2021) 201102



320 GeV – 5 TeV	Hardening	
E_B = 1.25 TeV	$\gamma_1 = 2.68$	$\gamma_2 = 2.5$

6.8 – 80 TeV	Softening (significance 4.3 σ)	
E_B = 34.4 TeV	$\gamma_1 = 2.41$	$\gamma_2 = 2.92$





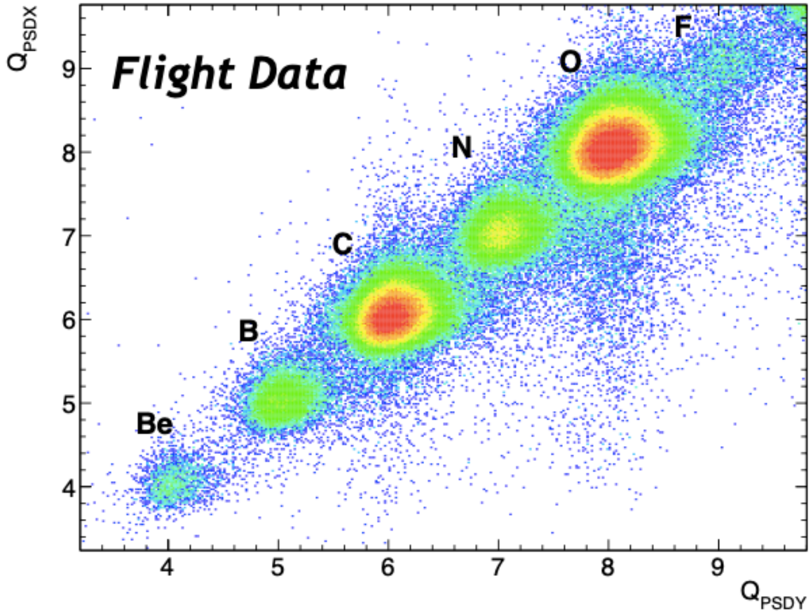
Clear structures (hardening + softening) have been detected in light CR spectra

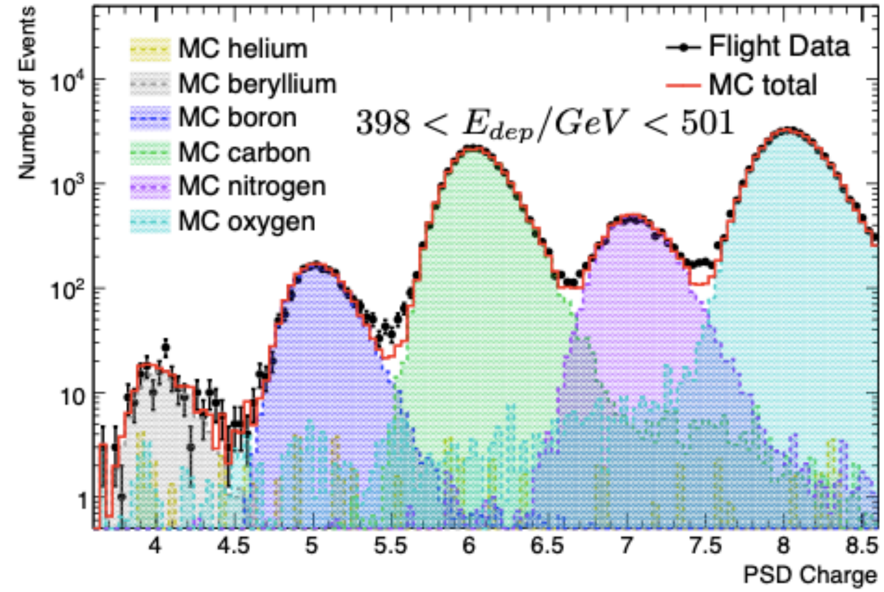
Spectra of cosmic protons and helium nuclei suggest that the softening energy depends on the particle charge

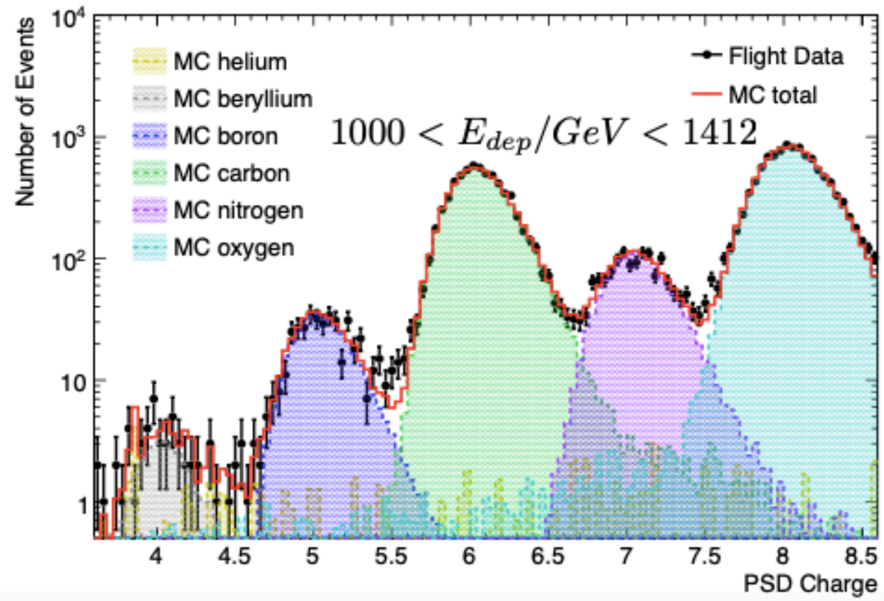
Anyway the current uncertainties do not allow to rule out a dependence on the mass

A combined analysis (p+He) confirms the measurements for proton and Helium

Heavier nuclei







Exploiting the DAMPE features heavier nuclei analyses are going on successfully

Measurements of other spectra are expected very soon

Summary

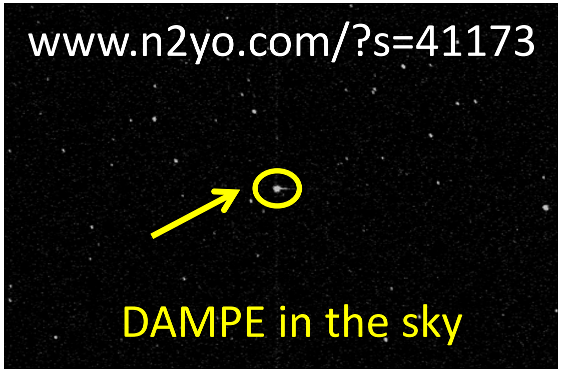
Satellite experiments push precise direct measurements closer to the CR spectral knee as a bridge towards the ground-based measurements

DAMPE is a very "deep" detector (~33 X_0). It works properly since its launch more than 5 years ago. We expect DAMPE will take data still for a long period

Positron + electron spectrum has been measured with high precision and low background in TeV energy range. A clear spectral break has been directly detected at ~ 1 TeV

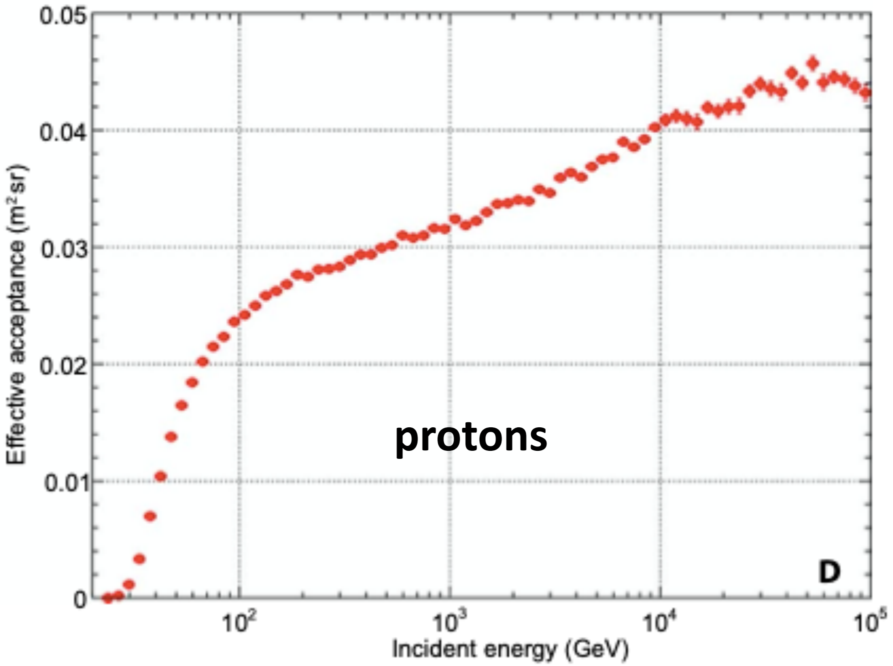
Clear structures (hardening + softening) have been detected in light CR spectra (proton up to 100 TeV and Helium up to 80 TeV)

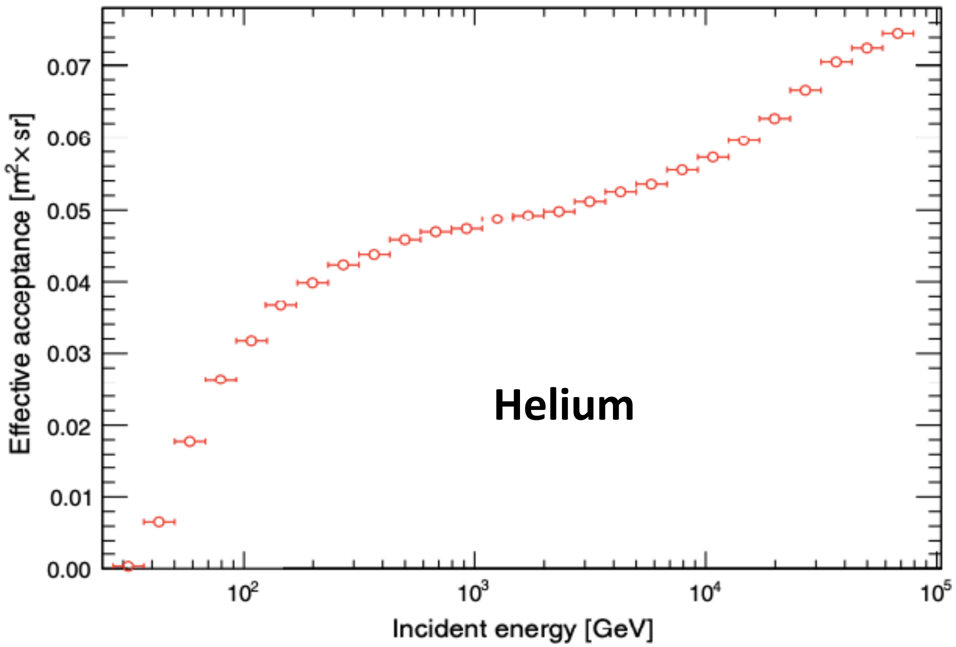
The simple power law does not fit these CR spectra



Backup slides

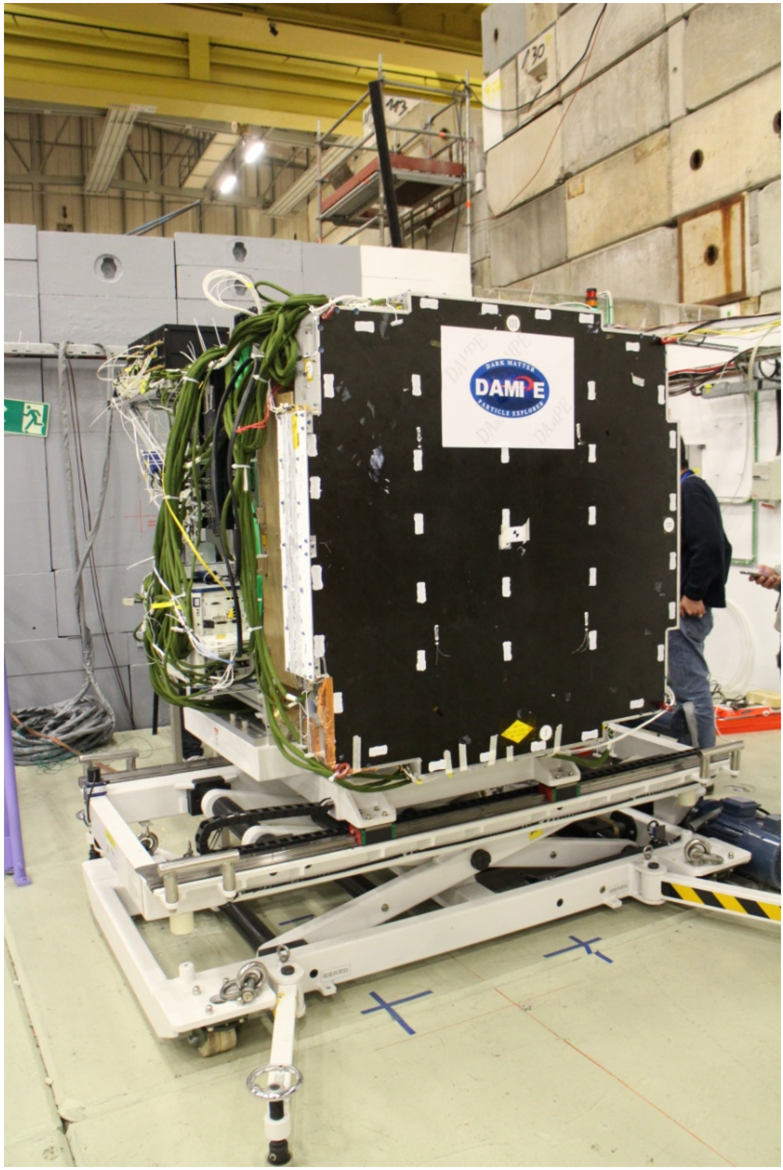
Acceptances





Test beam at CERN

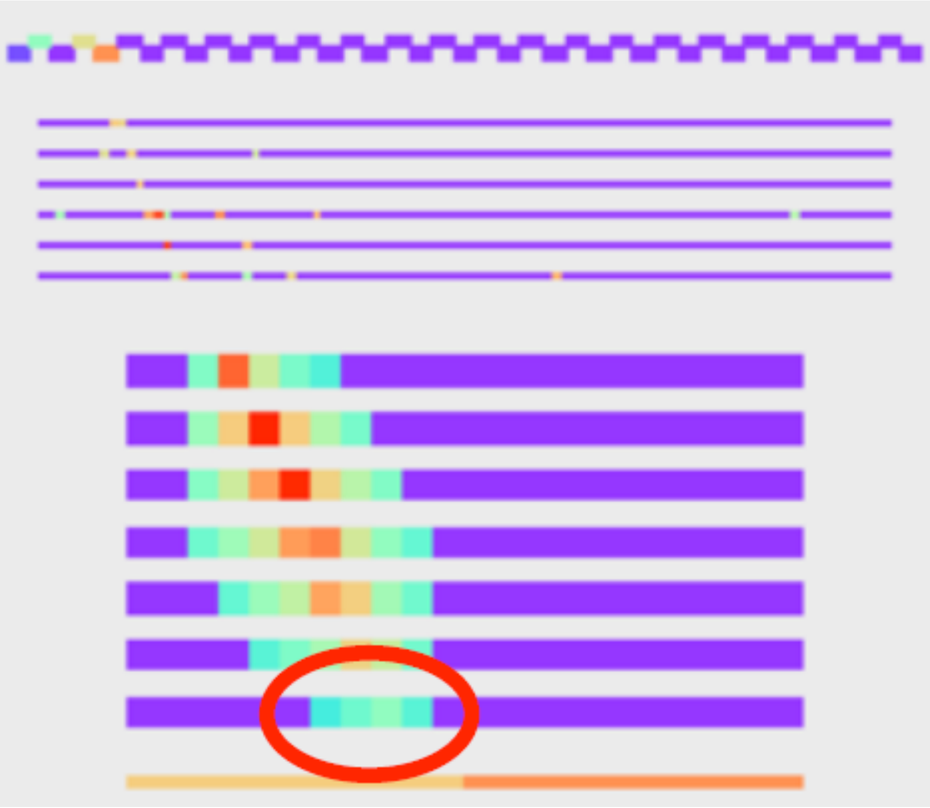
- 14 days@PS, October 29 – November 11, <u>2014</u>
  - e @ 0.5, 1, 2, 3, 4, 5 GeV/c
  - p @ 3. 5, 4, 5, 6, 8, 10 GeV/c
  - π @ 3, 10 GeV/c
  - γ @ 0.5-3 GeV/c
- 8 days@SPS, November 12 – 19, <u>2014</u>
  - e @ 5, 10, 20, 50, 100, 150, 200, 250 GeV/c
  - p @ 400 GeV/c (SPS primary beam)
  - γ @ 3-20 GeV/c
  - μ @ 150 GeV/c
- 17 days@SPS, March 16 – April 1 <u>2015</u>
  - Argon (and fragments): 30 – 40 – 75 A GeV/c
  - Protons: 30, 40 GeV/c
- 21 days@SPS, June 10 – July 1 <u>2015</u>
  - p @ 400 GeV/c
  - e @ 20, 100, 150 GeV/c
  - γ @ 50, 75, 150 GeV/c
  - μ @ 150 GeV/c
  - π+ @ 10, 20, 50, 100 GeV/c
- 6 days@SPS, November 20-25 <u>2015</u>
  - Pb (and fragments): 30 A GeV/c

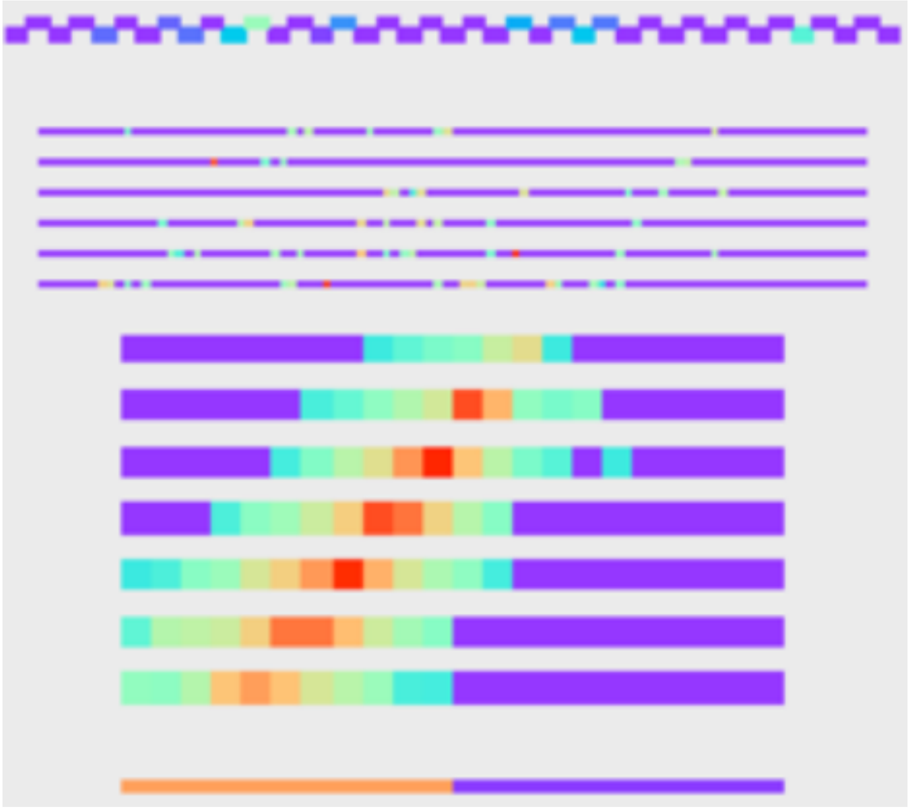


Electron+positron identification

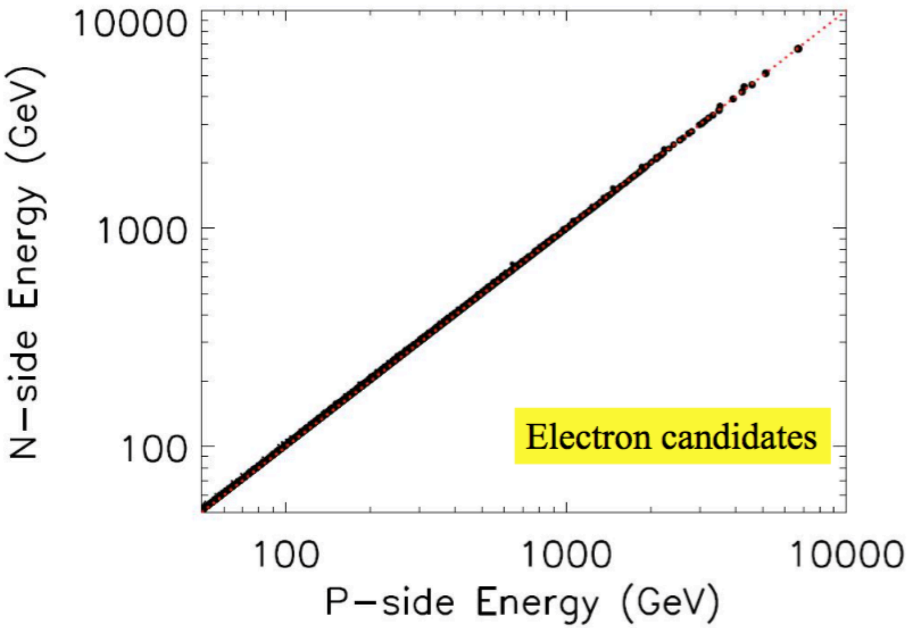
Selected events with $Z_{PSD} = 1$

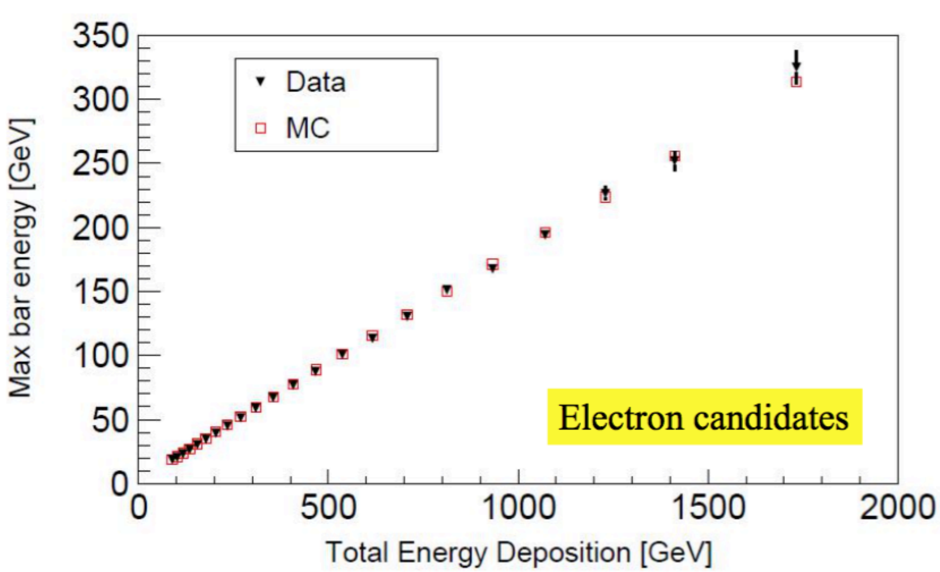
Exploiting the imaging CALO-features





Electron-like events
Energy measurement





Smootly broken power law

$$\Phi(E) = \Phi_0 \left(\frac{E}{TeV}\right)^{-\gamma_1} \left[1 + \left(\frac{E}{E_B}\right)^s\right]^{-(\gamma_2-\gamma_1)/s}$$

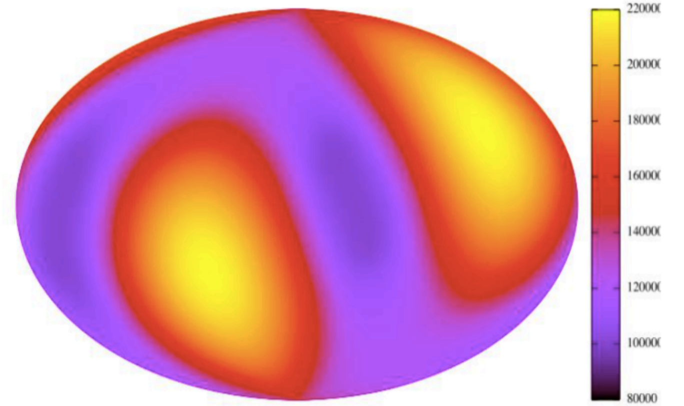
protons

$$\Phi = \Phi_0 \left(\frac{E}{100\ GeV}\right)^{-\gamma_1} \left[1 + \left(\frac{E}{E_B}\right)^{-(\gamma_1-\gamma_2)/\Delta}\right]^{-\Delta}$$

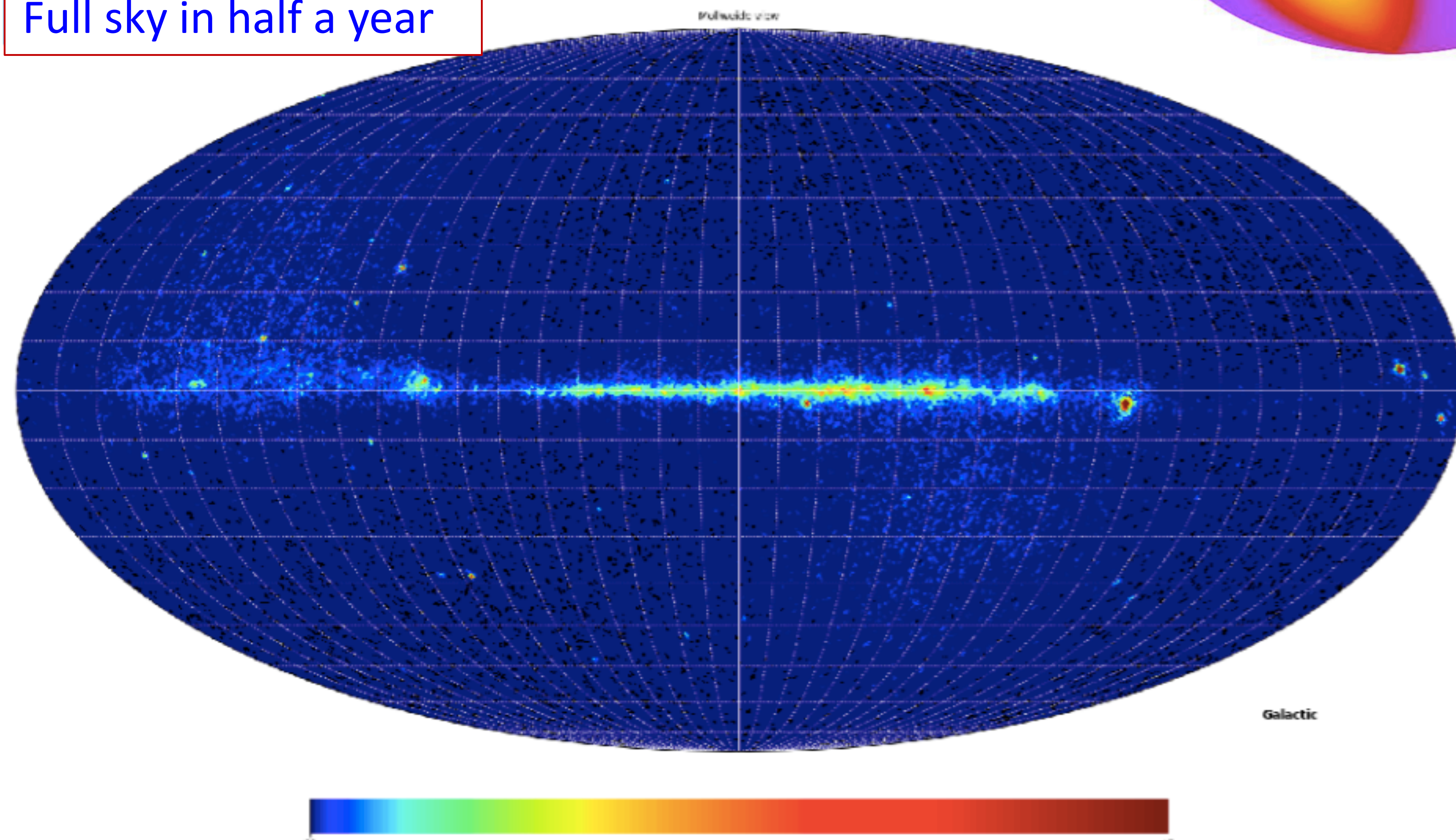
electrons

same function if $\Delta = \frac{\gamma_2 - \gamma_1}{s}$

Gamma sky



$\sigma_\theta \approx 0.2°$ @ 30 GeV
Full sky in half a year



Photon clustering

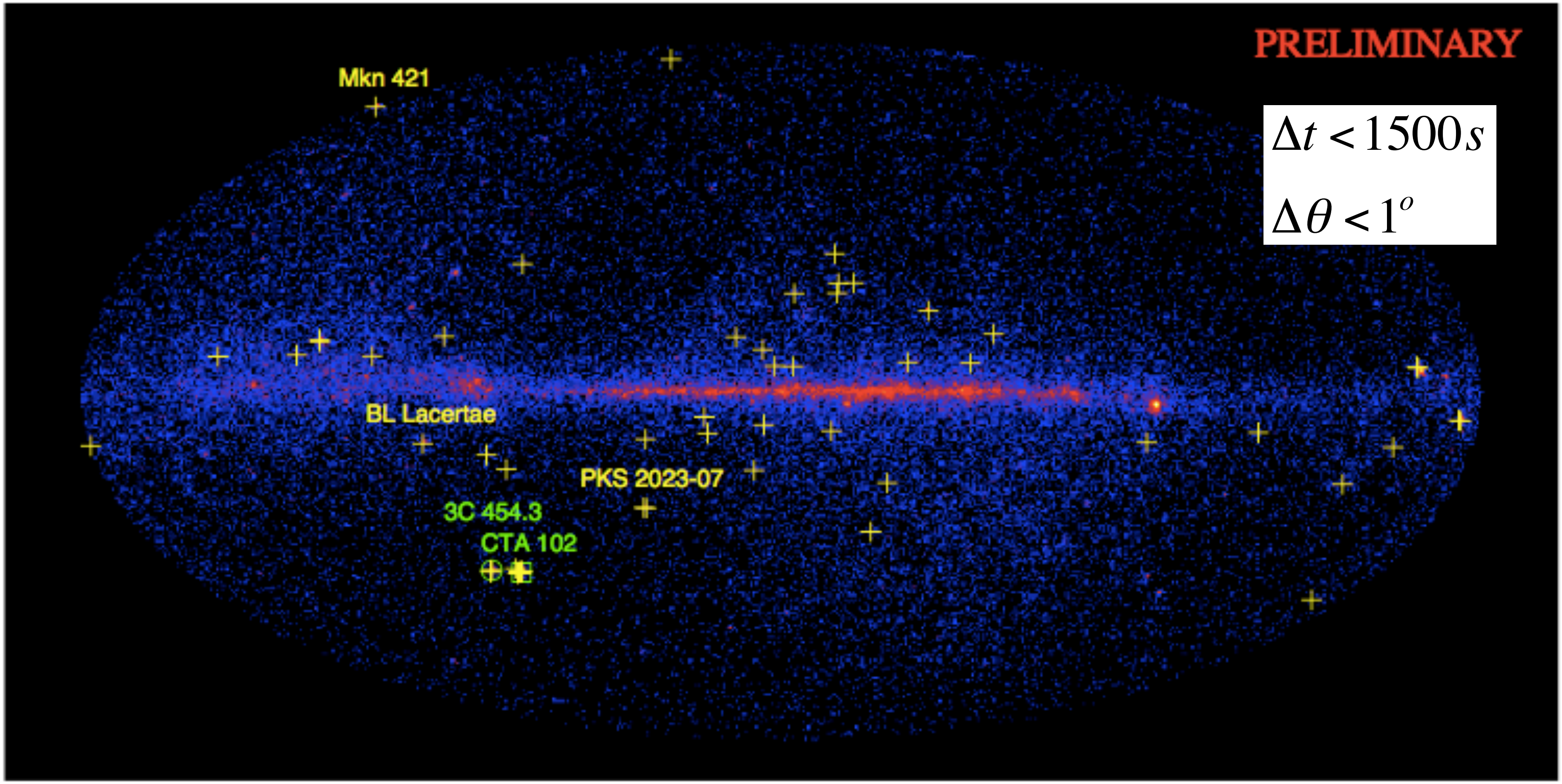
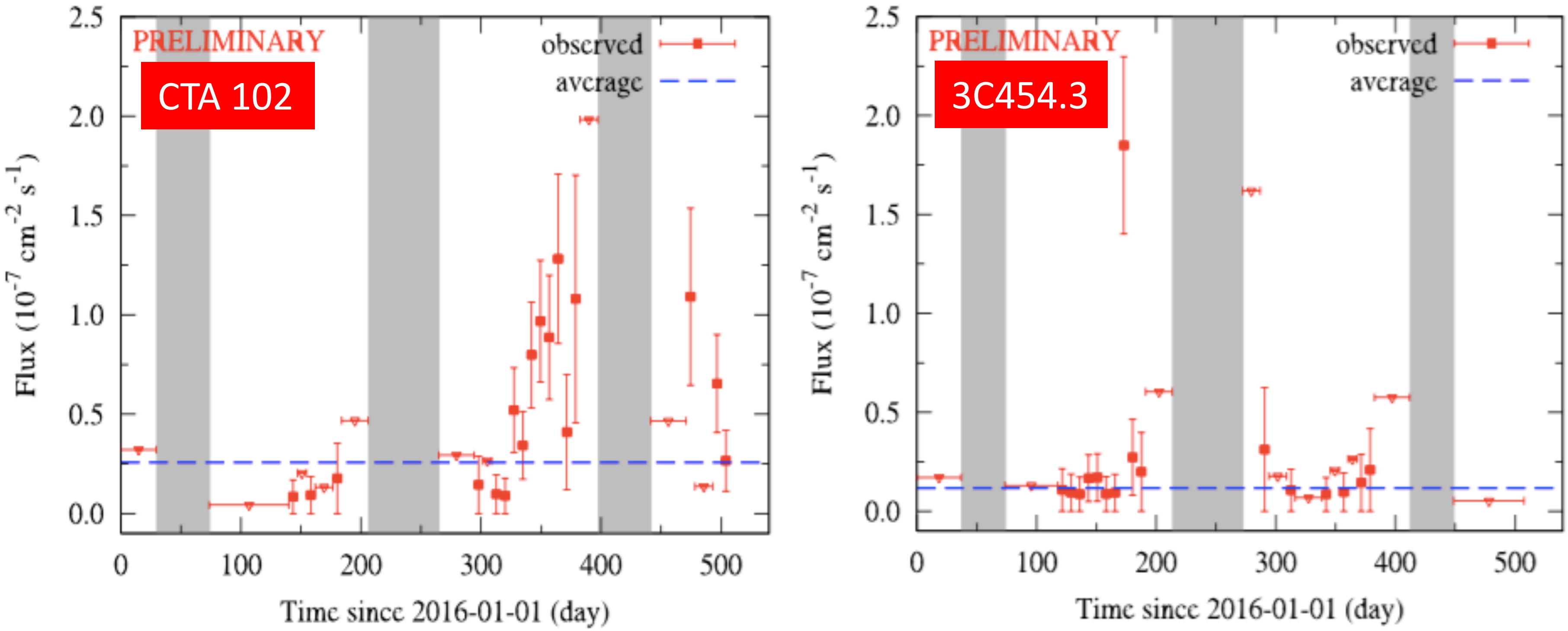


Figure 3: Skymap of DAMPE photon counts overlaid with the coordinates of photon clusterings. Crosses are for photon pairs, the circle is for the triple, and the box is for the quadruple.

Variable Gamma Sources

$E_\gamma > 2$ GeV

Search for variable source in bins of 3×10^{-4} sr
Weekly light curve for each angular bin

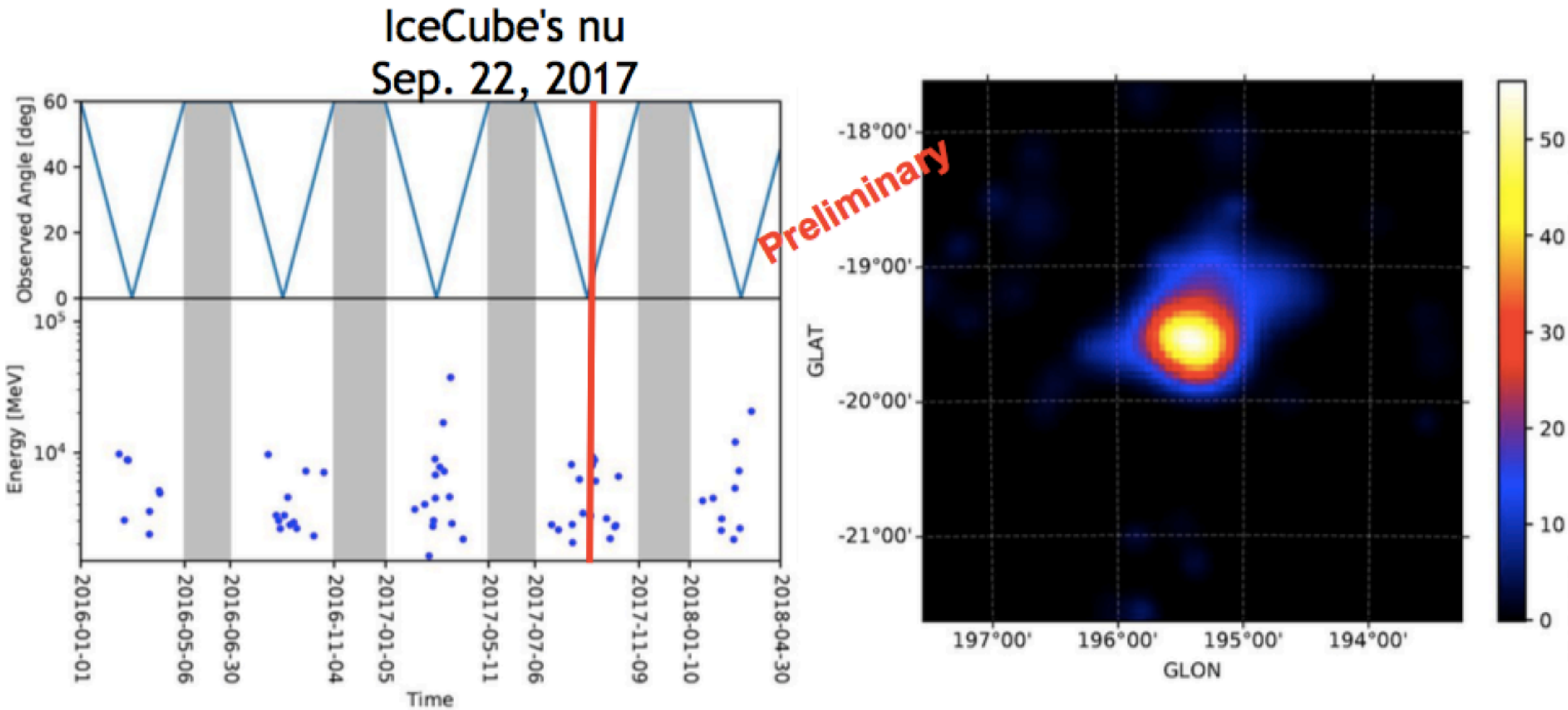


Flare in November-December 2016

Flare in June 2016

Results consistent with other observations (Agile, Fermi-LAT)

Observations of neutrino event candidate TXS 0506+056



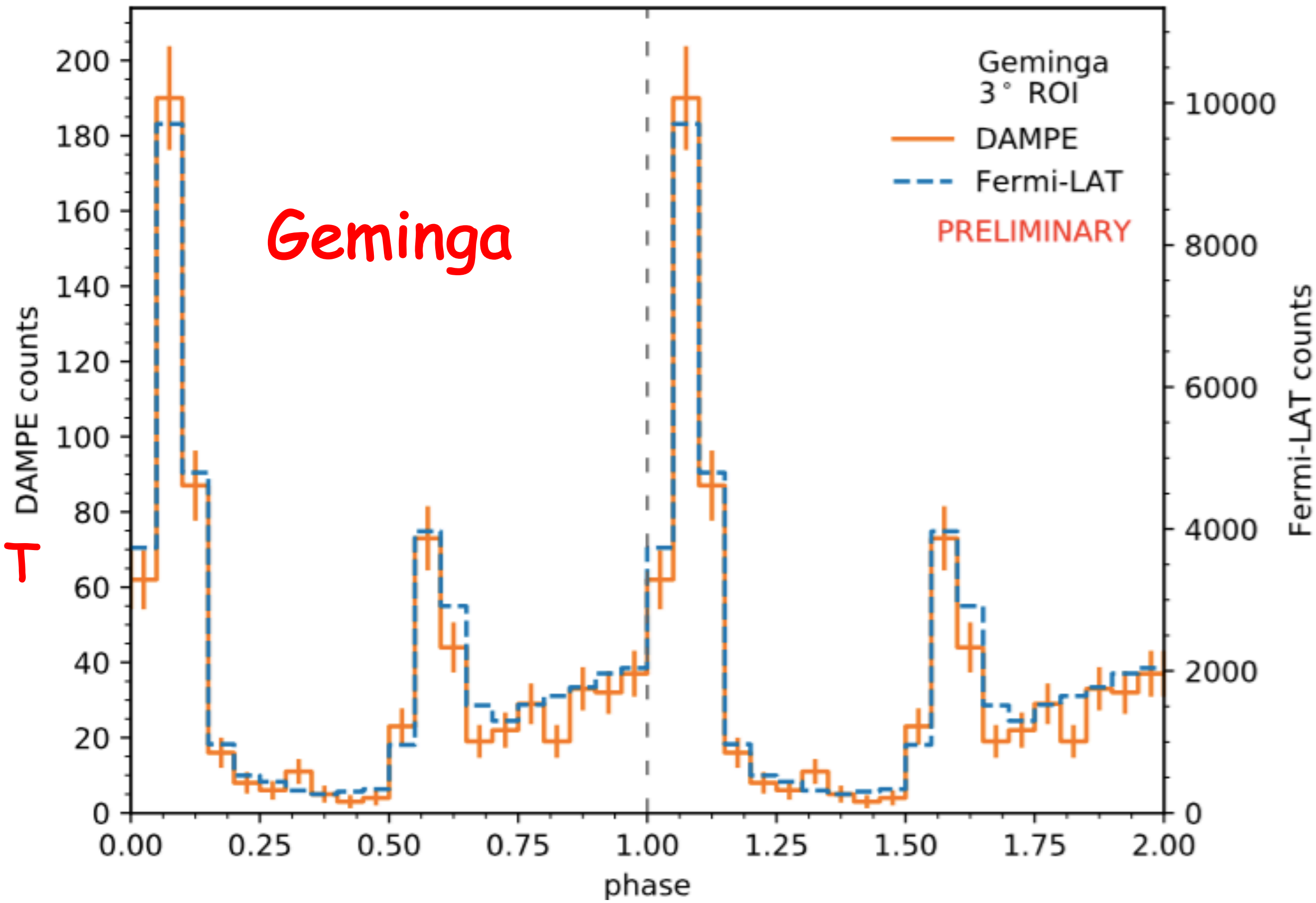
- DAMPE has detected the gamma-ray source TXS 0506+056 which is possibly associated with a neutrino event
- No clear variabilities are revealed due to limited statistics

Pulsar periodicity

1 < E_γ < 50 GeV

RoI 3°

Agreement with Egret and Fermi-LAT results



Detected periodical signal from other pulsars (Vela, PSR J0007+7303 …)