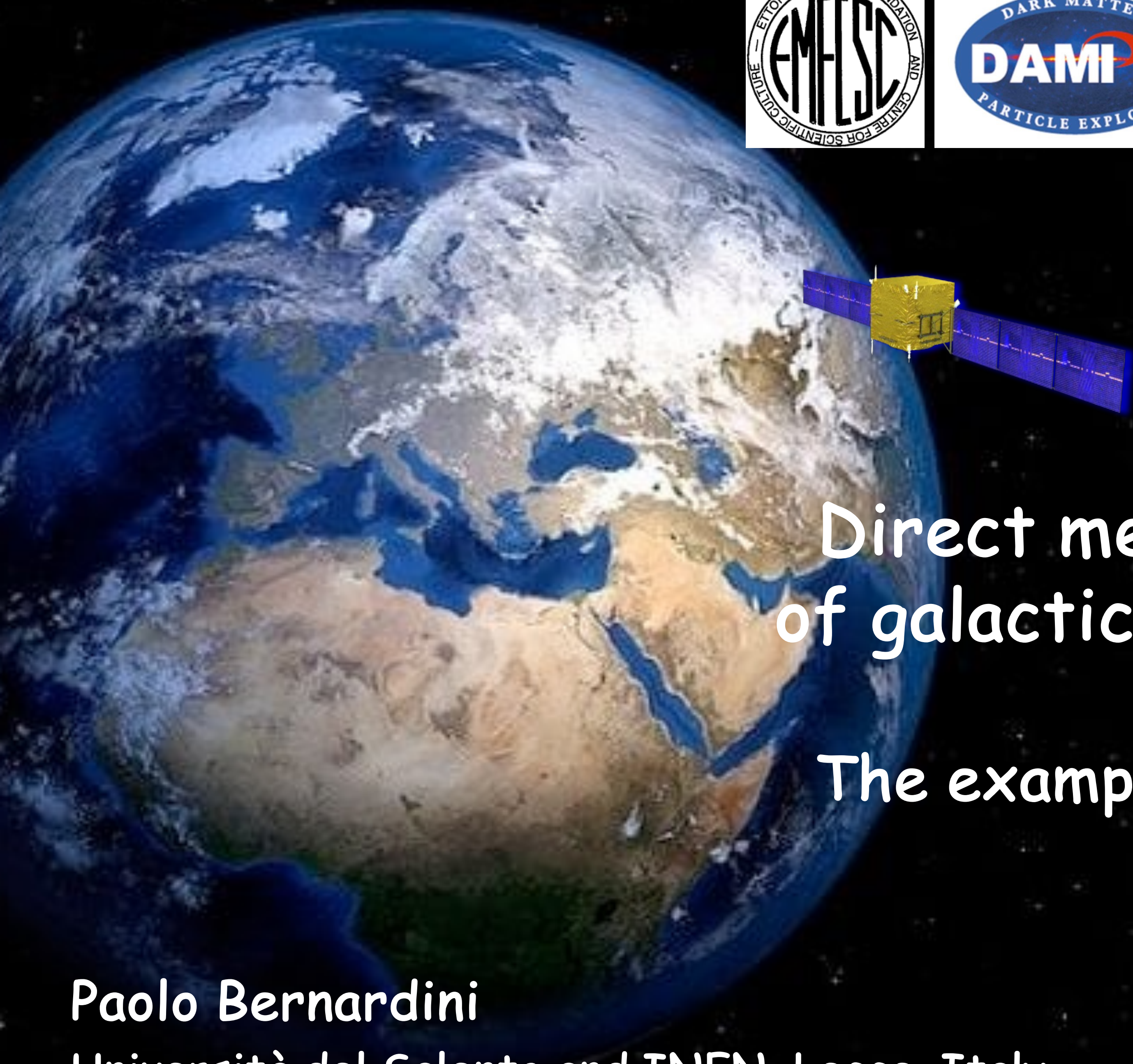
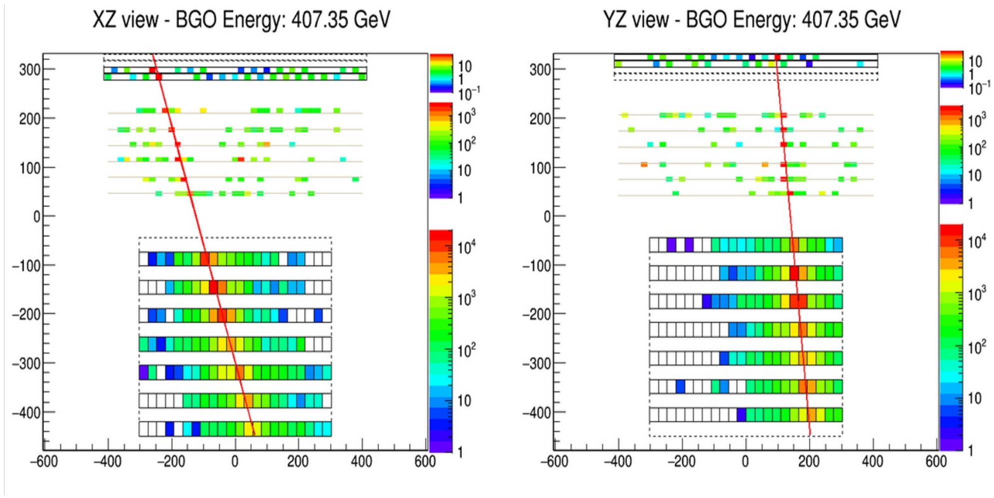


Lesson 2

Direct measurement of galactic cosmic rays

The example of DAMPE

Paolo Bernardini
Università del Salento and INFN, Lecce, Italy



To do:

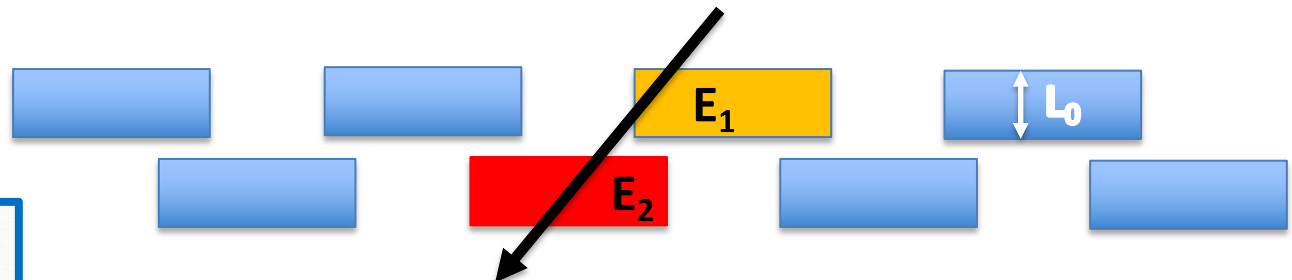
- Reconstruct the track in STK and BGO
- Distinguish the primary charge (Z)
- Select a “clean” sample of events
- Estimate event energy (E_{BGO} -> $E_{Primary}$)
- Measure the live time (Δt)
- Estimate effective acceptance by means of simulation
- Validate simulation by comparison with data

PSD - Charge measurement

Bethe-Bloch formula for energy loss
by ionization and atomic excitation

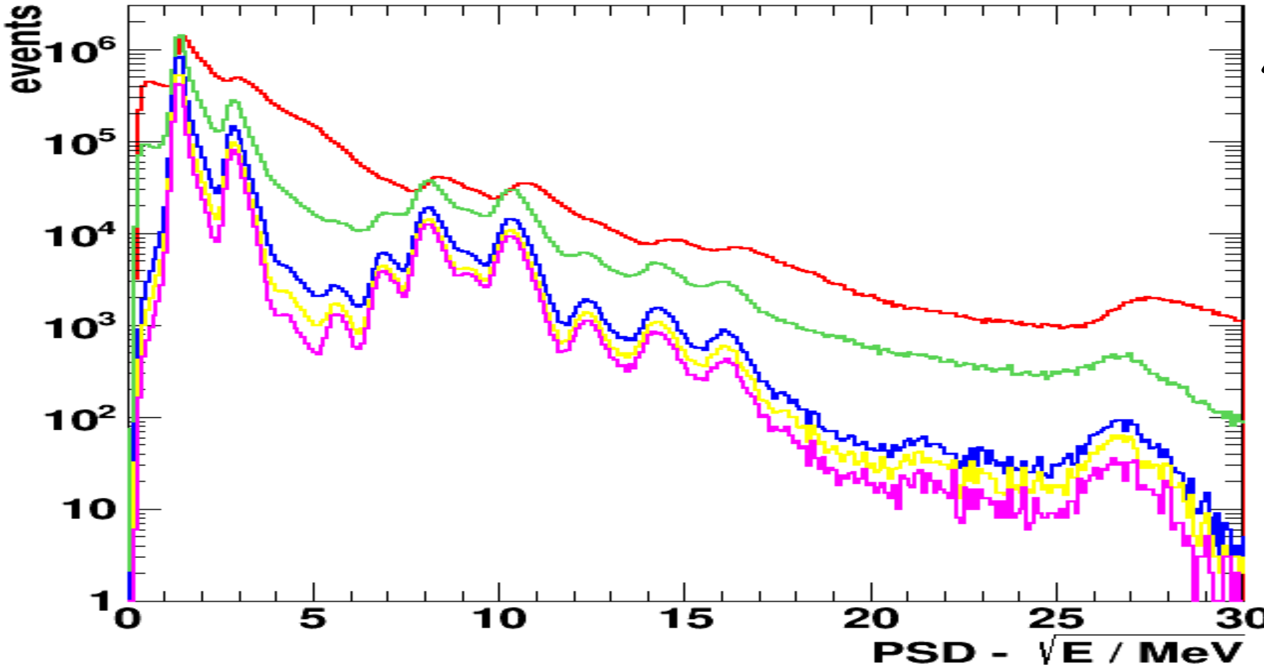
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\mathrm{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

$$Z \propto \sqrt{\frac{E_1 + E_2}{L_1 + L_2} L_0}$$



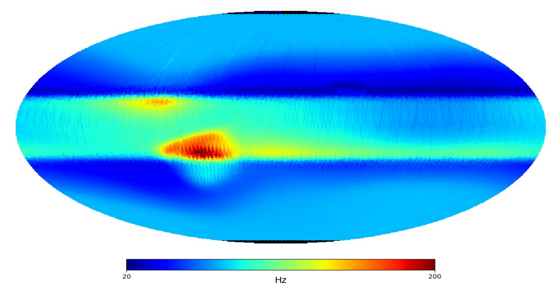
L_0	path in PSD for a vertical trajectory
L_1	path in the 1st intercepted PSD bar
L_2	path in the 2nd intercepted PSD bar

Z-measurement depends on the quality of the track reconstruction



An example of analysis cuts to get a "clean" sample

Applied to real and simulated data



Preselection:

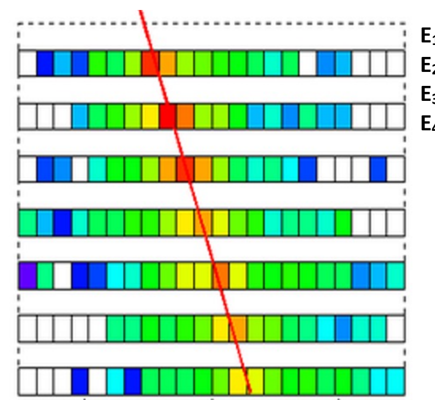
E_{BGO} > 20 GeV High Energy Trigger No events from SAA

Quality of STK track: χ^2/dof < 35 maximum signal

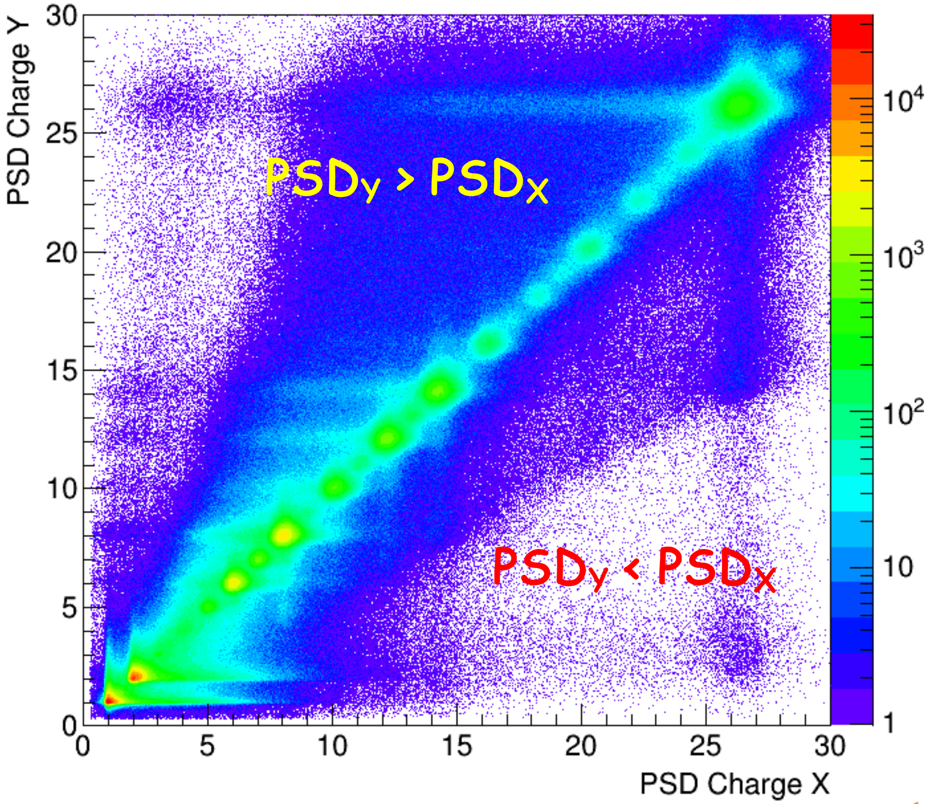
BGO - STK tracks agreement

BGO signal: $E_{MAX} < 0.35\ E_{TOT}$ $E_1 + E_2 < E_3 + E_4$

Minor analysis cuts



Double measurement of Z (1st and 2nd pair of PSD layers)

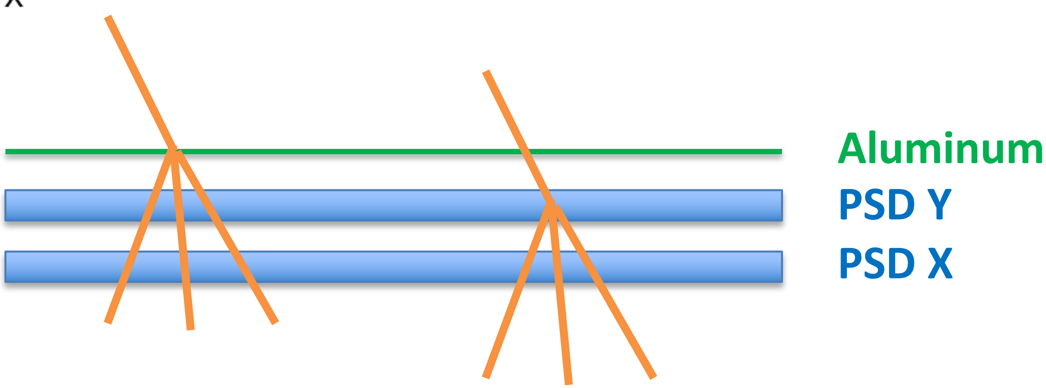


Coherent signals

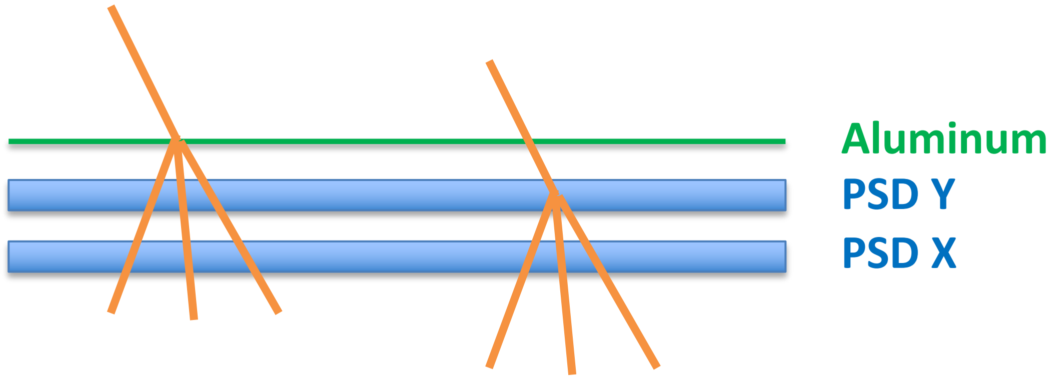
- PSDy ~ PSDx (bisector)

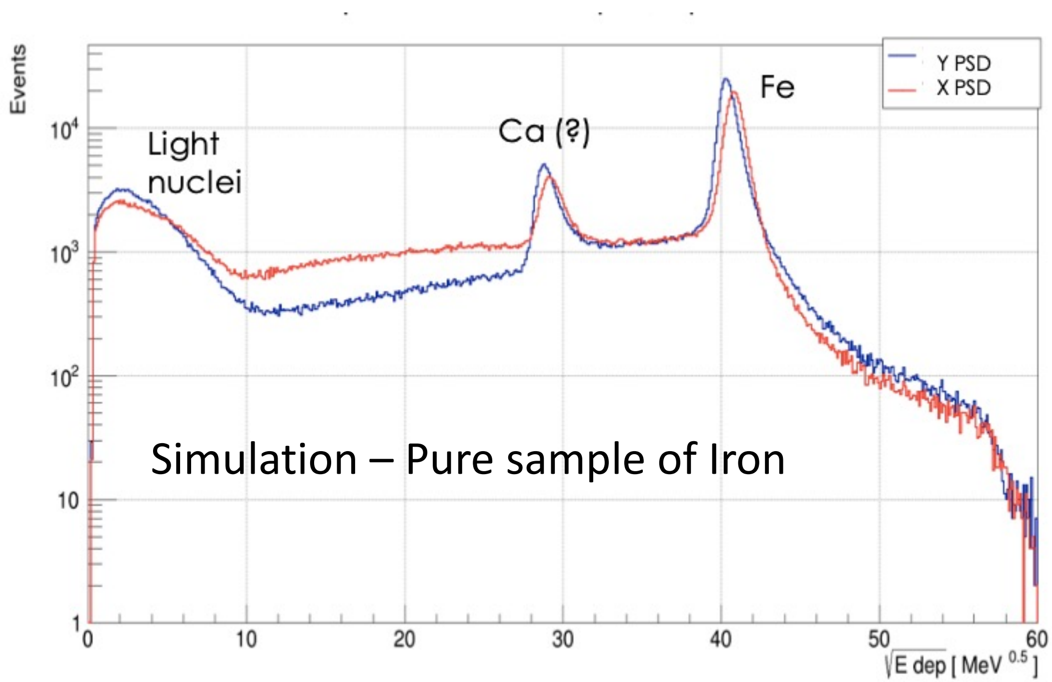
Anomalies

- PSDy > PSDx fragmentation
- PSDy < PSDx more particles on same x-bar



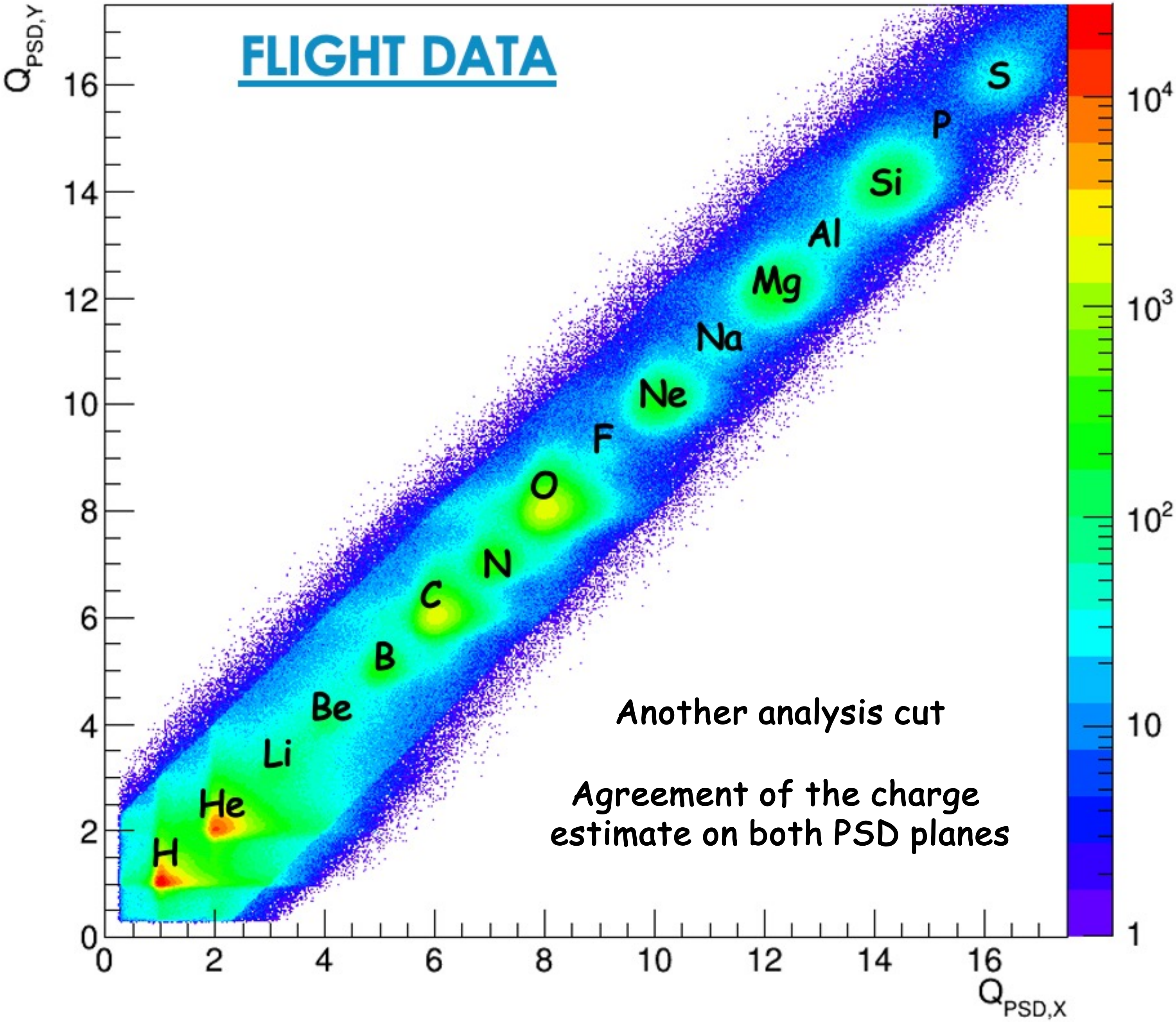
Check on fragmentation





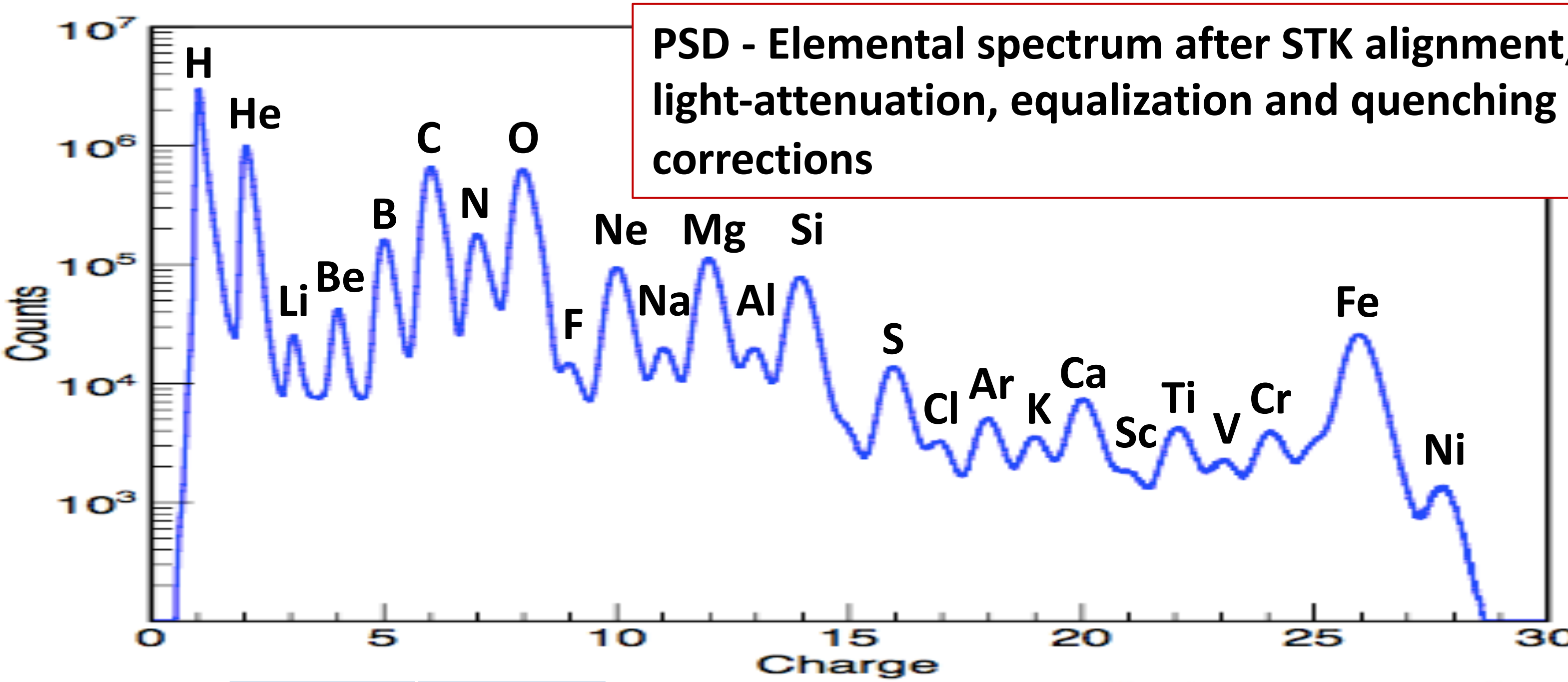
The hadron interaction in PSD or STK is a problem

Analysis is optimized for interaction in the BGO


FLIGHT DATA
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Another analysis cut
Agreement of the charge estimate on both PSD planes
Q_PSD,Y
Q_PSD,X

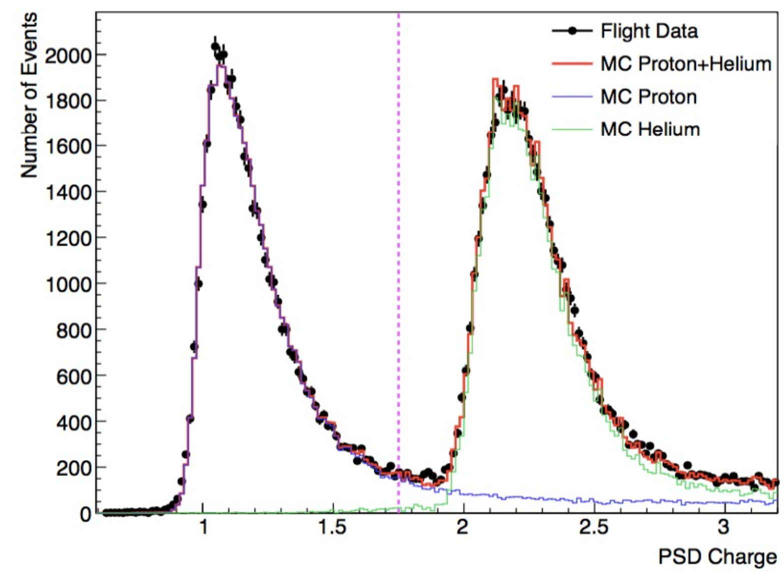
Nuclei (Z=1-26 and more)

PSD - Elemental spectrum after STK alignment, light-attenuation, equalization and quenching corrections

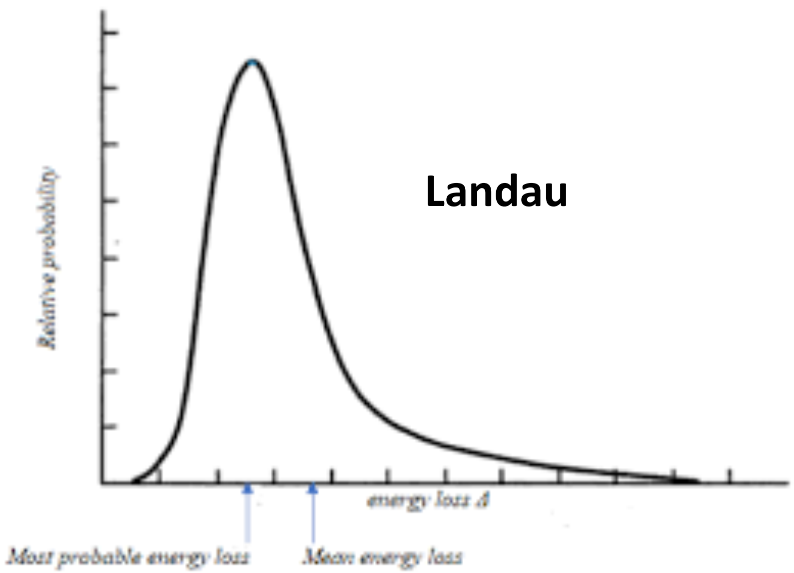


Element	σ_Z
p	0.07
He	0.12
Li	0.14
Be	0.21
B	0.17
C	0.18
N	0.21
O	0.21

Template fit for protons and Helium



Energy loss in a thin layer of matter



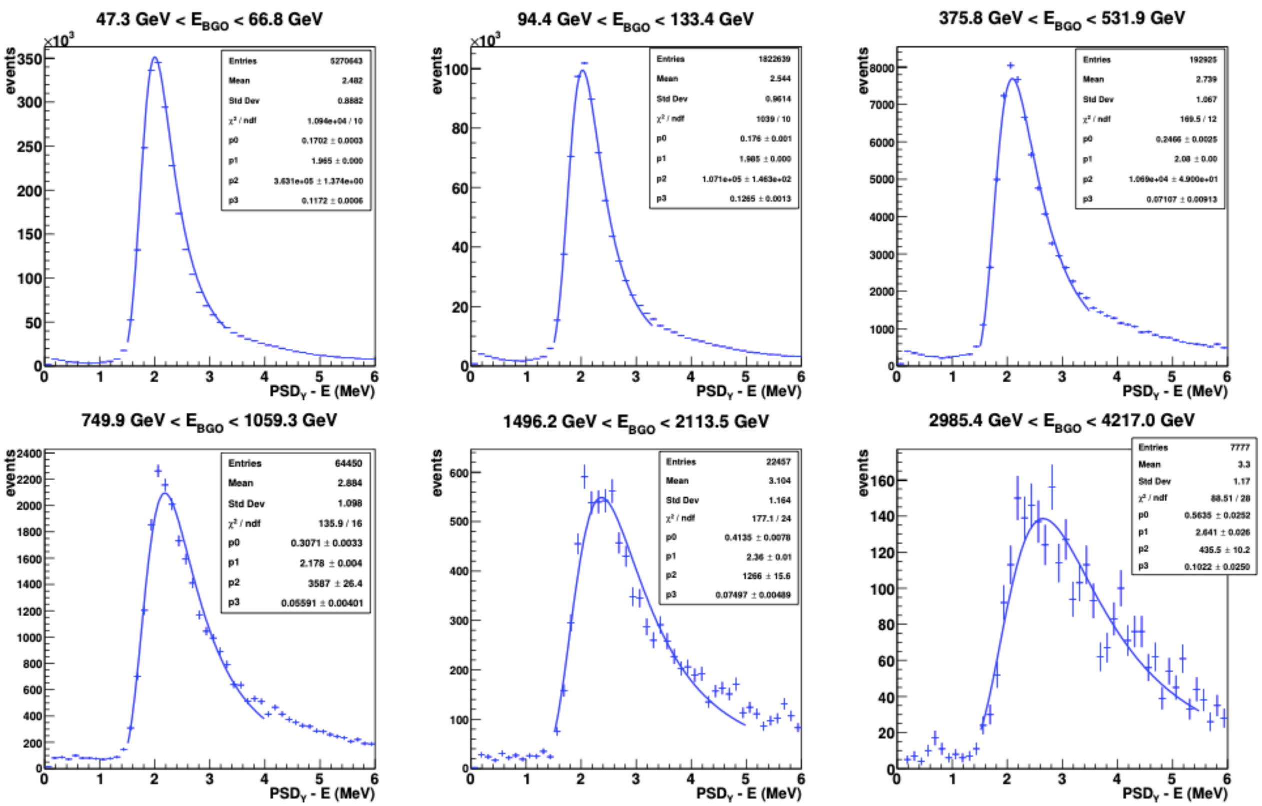
Landau

Measurement uncertainty

Gaussian

Langaus curve

Charge selection (protons as an example)



Landau + Gauss (langaus) fit of the PSD p-signal for different E_{BGO} ranges

Fit parameters

MPV (Most Probable Value)

σ_{Landau}

σ_{Gauss}

must be used to select the Z signal in real and simulated samples

Charge selection

$$MPV - 3\sqrt{\sigma_{Lan}^2 + \sigma_{Gaus}^2} < E_{PSD} < MPV + 4\sqrt{\sigma_{Lan}^2 + \sigma_{Gaus}^2}$$

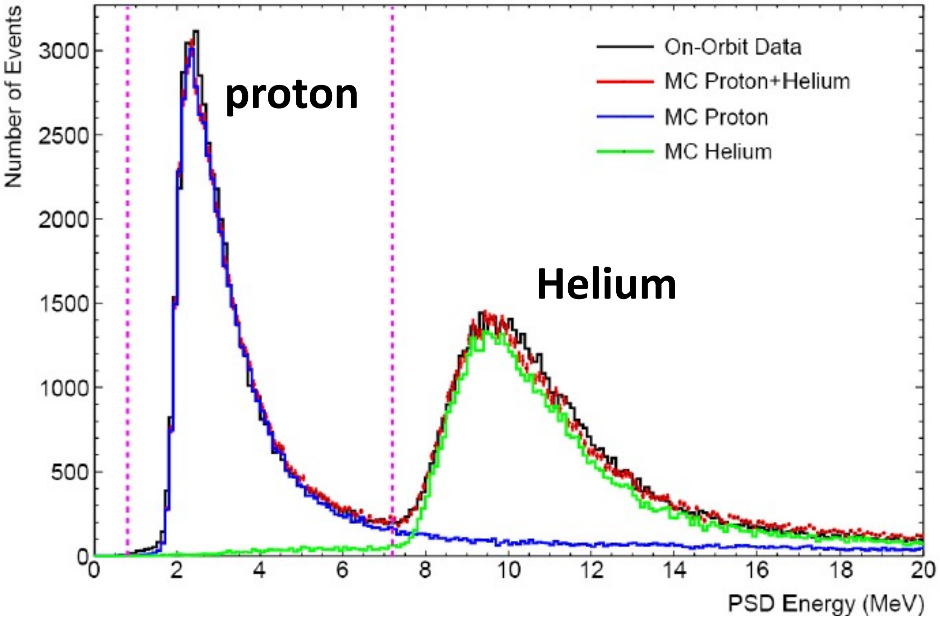
Same selection for real data and simulated ones

Parameters (MPV, σ_{Landau} , σ_{Gauss}) are functions on E_{BGO}

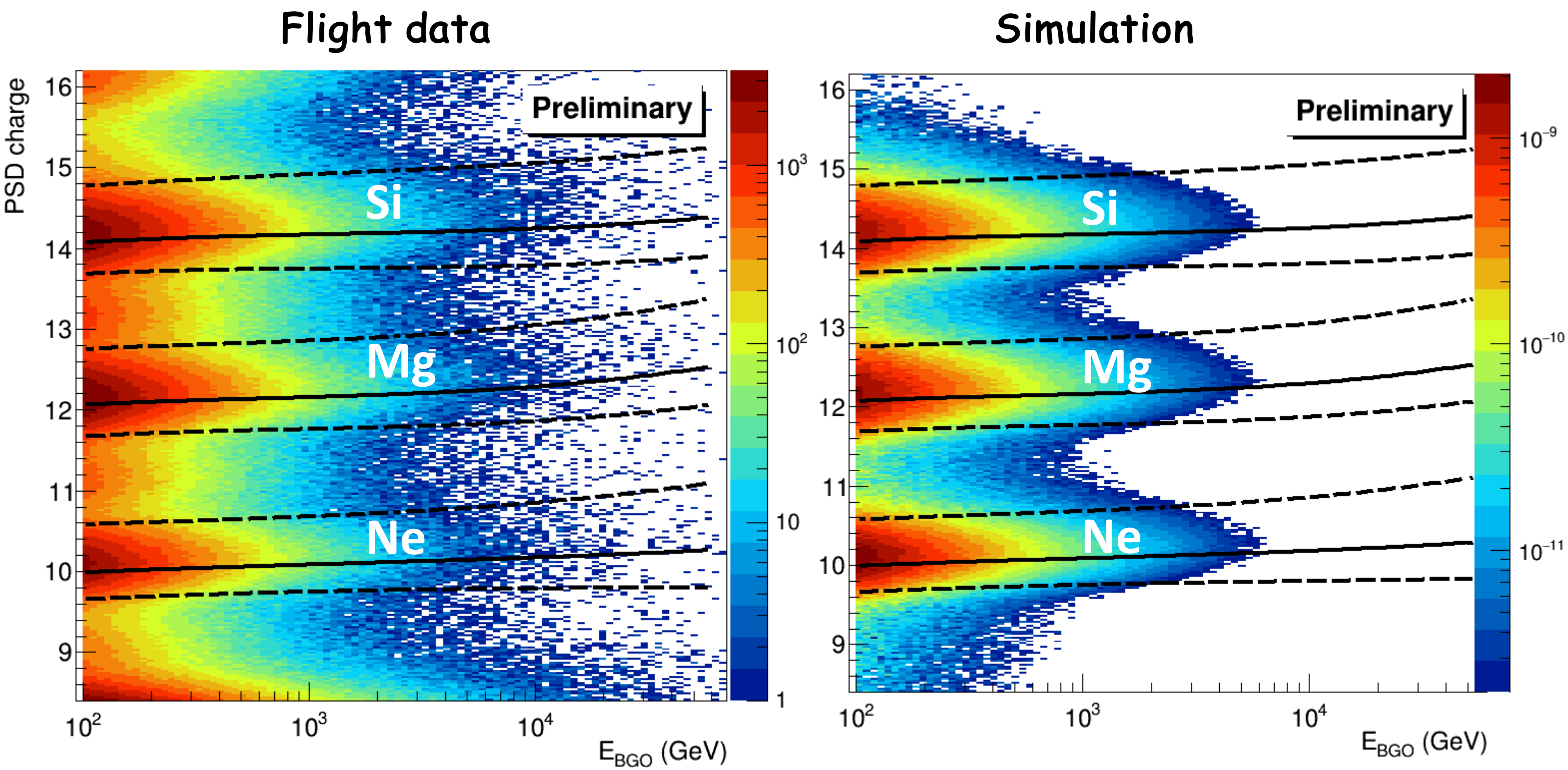
Background estimate

Template fit for protons and Helium

The background can be subtracted or taken into account as systematical error

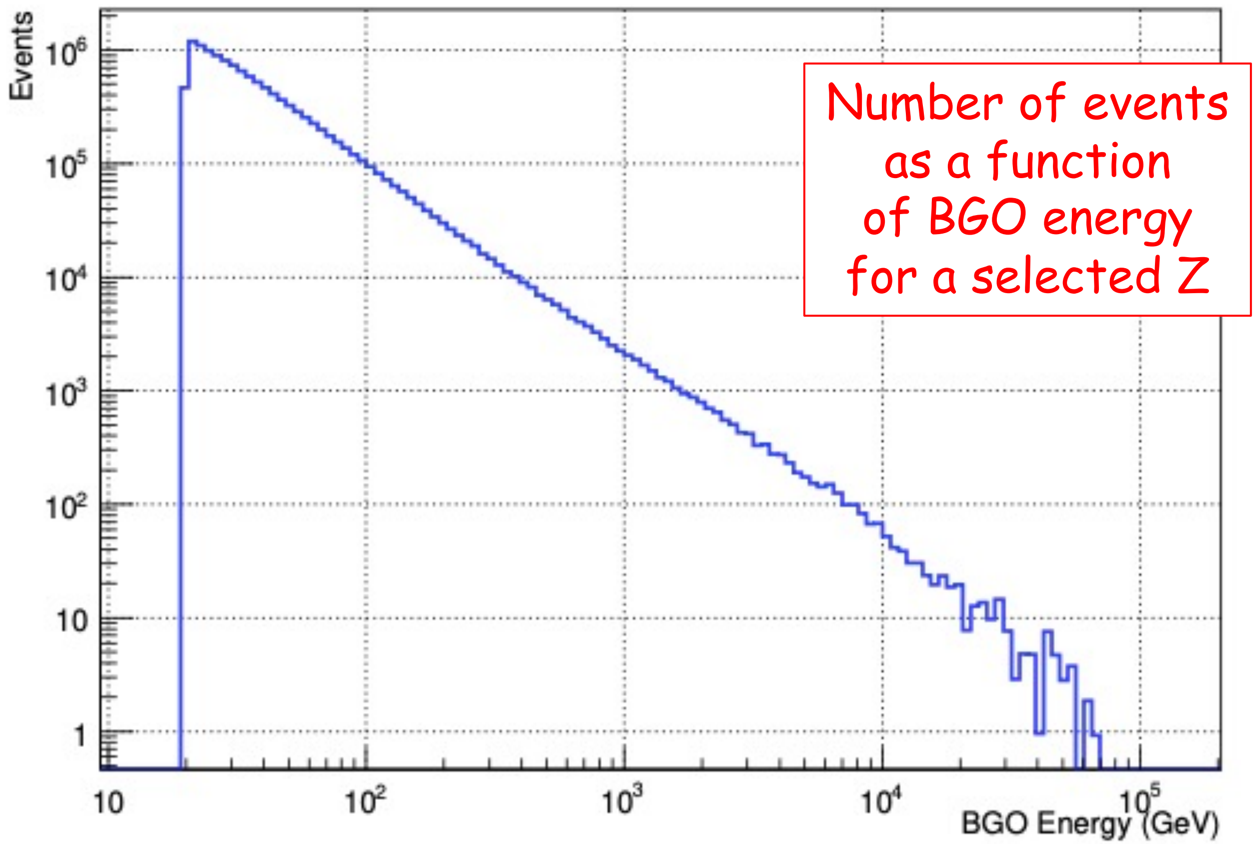


Charge selection vs BGO energy



In these plots: PSD energy → PSD charge

Unfolding procedure (I)

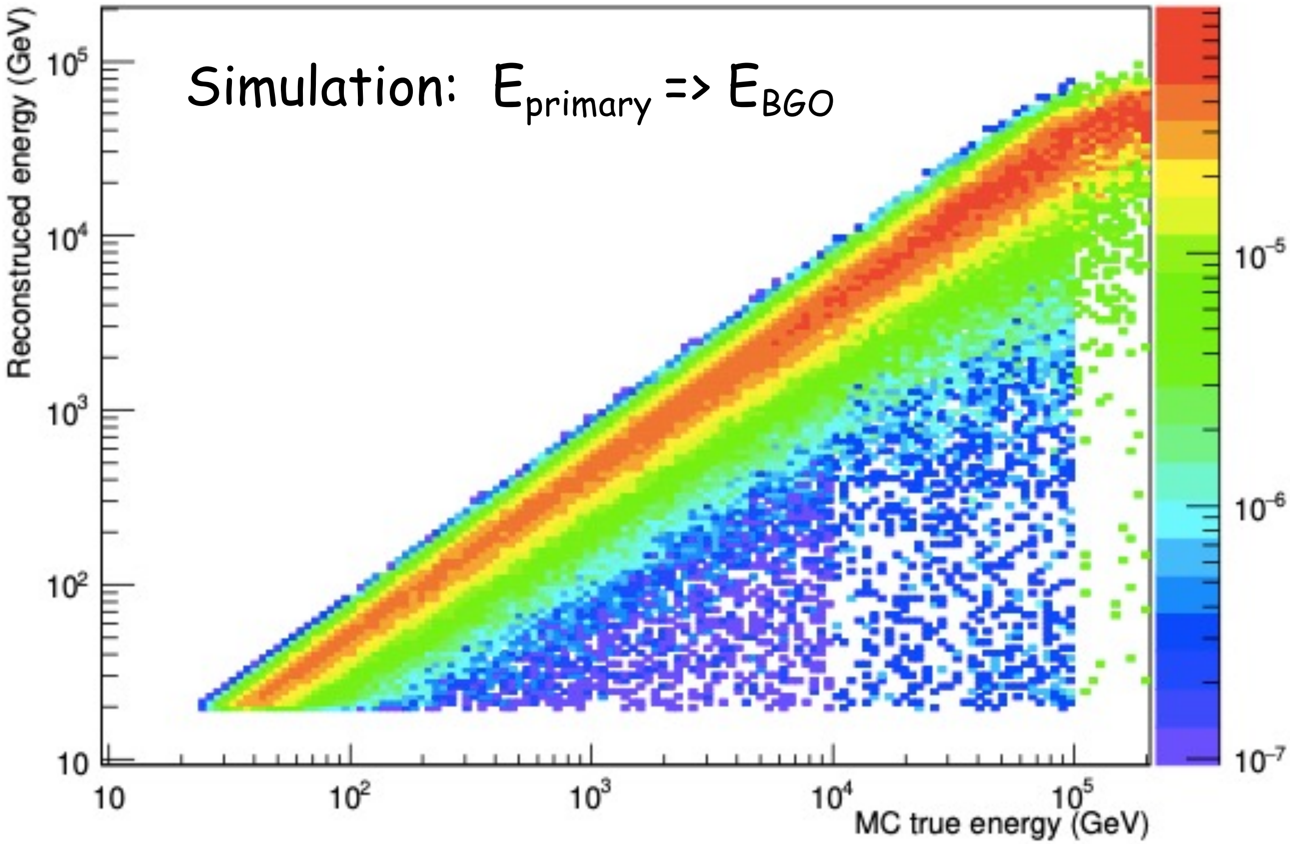


$N(E_{BGO}) \neq N(E_{RC})$

We need the number of events
as a function of primary energy

Unfolding procedure (II)

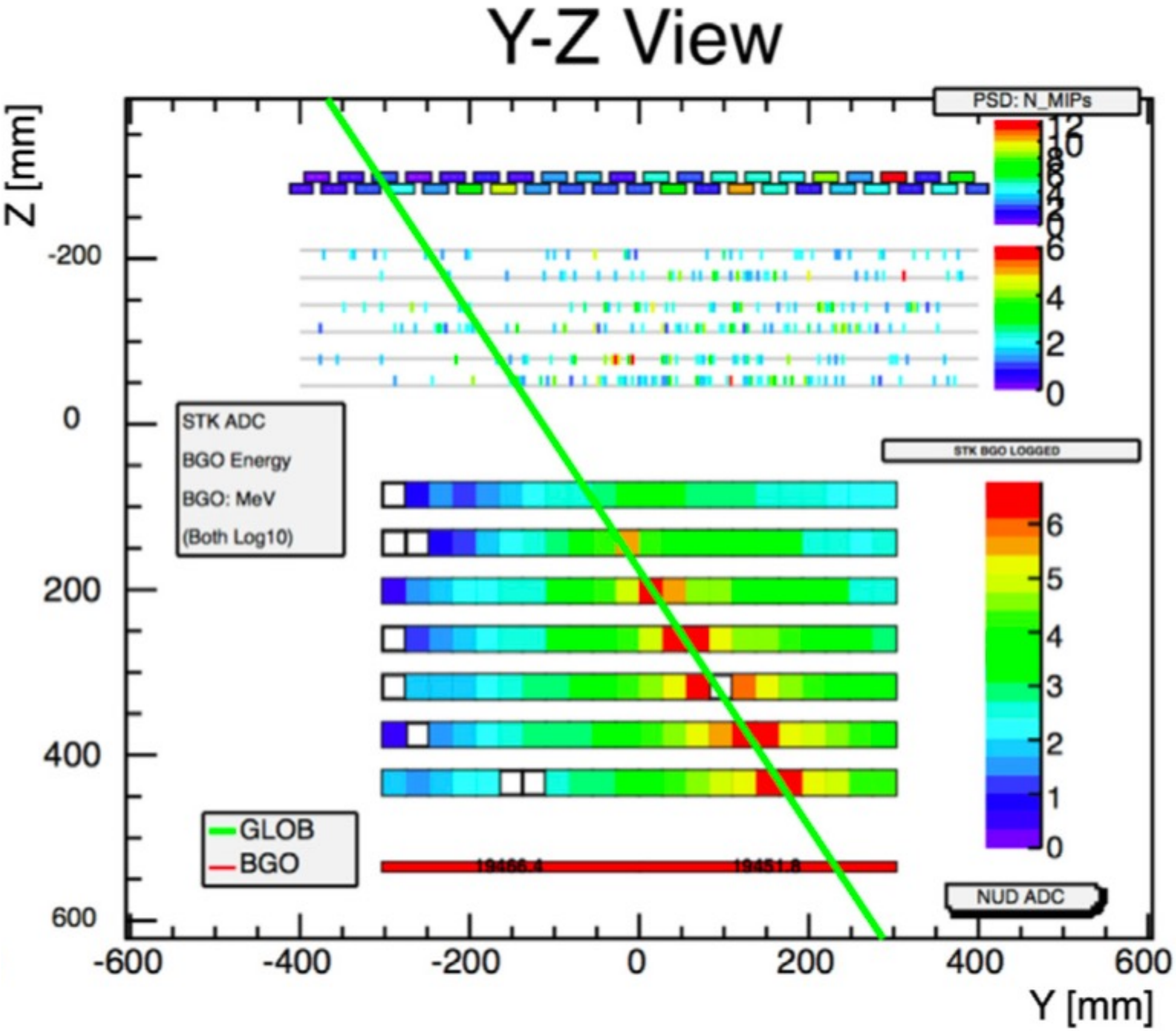
What energy in the calorimeter assuming the primary energy ?



By means of the **unfolding** matrix E_{BGO} => $E_{primary}$

(estimate on statistical basis)

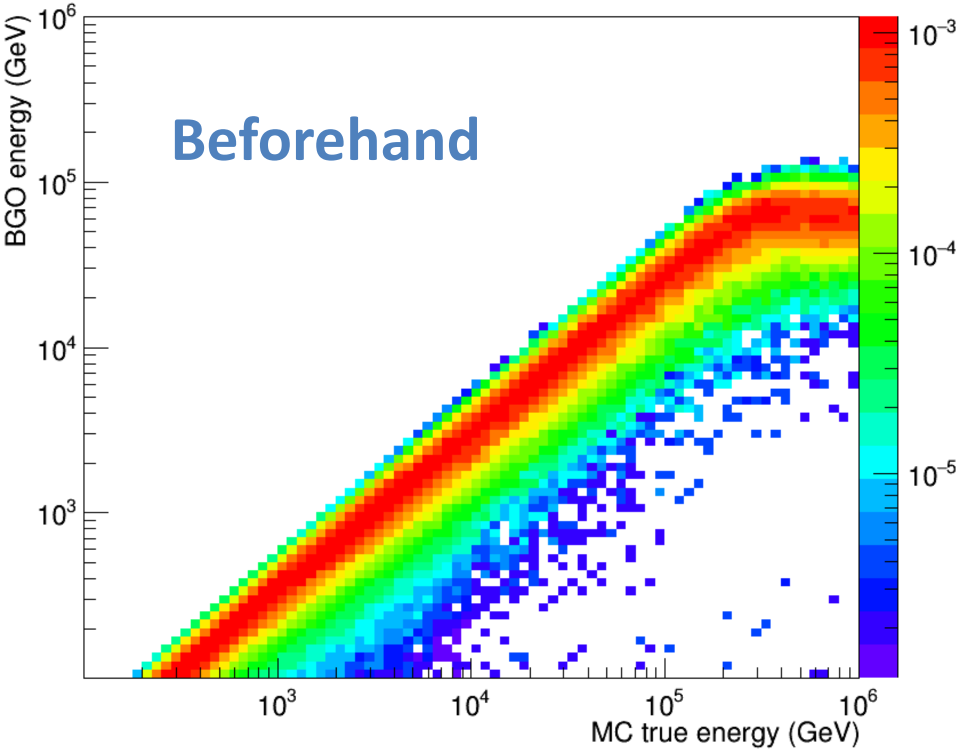
BGO saturation - white box close to red boxes

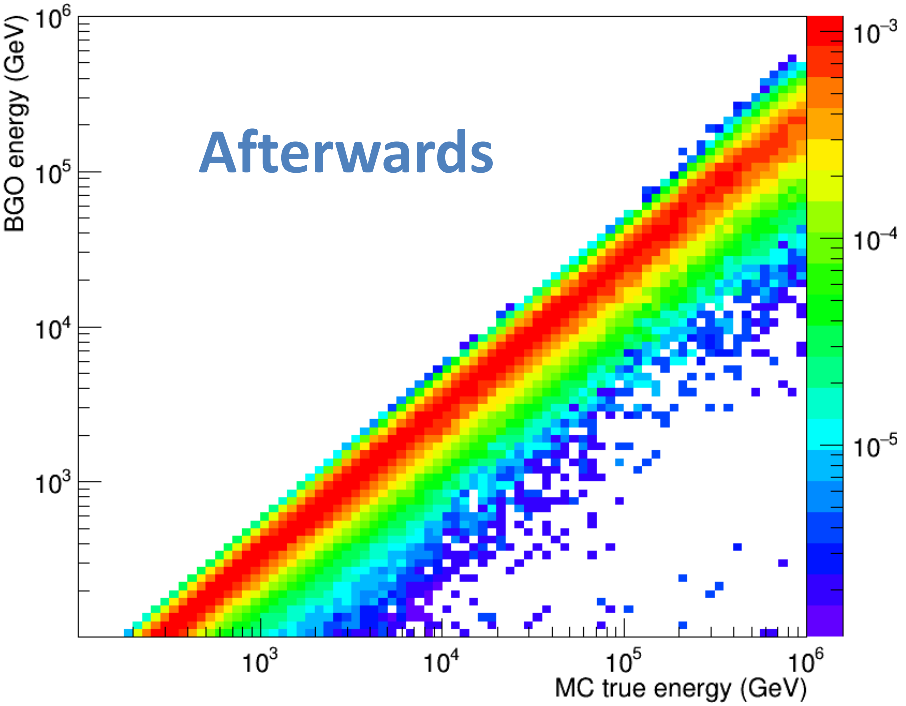


Correction by means of simulation

Effect of the saturation correction on the unfolding matrix

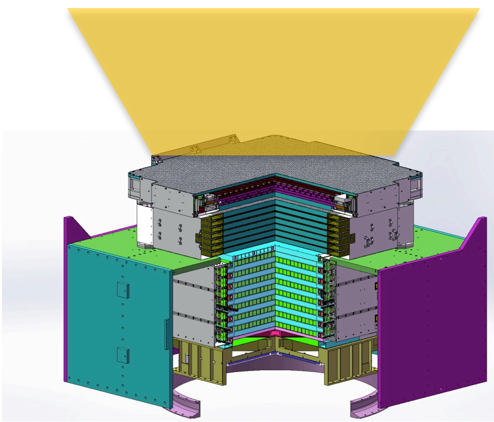
- Mg example -

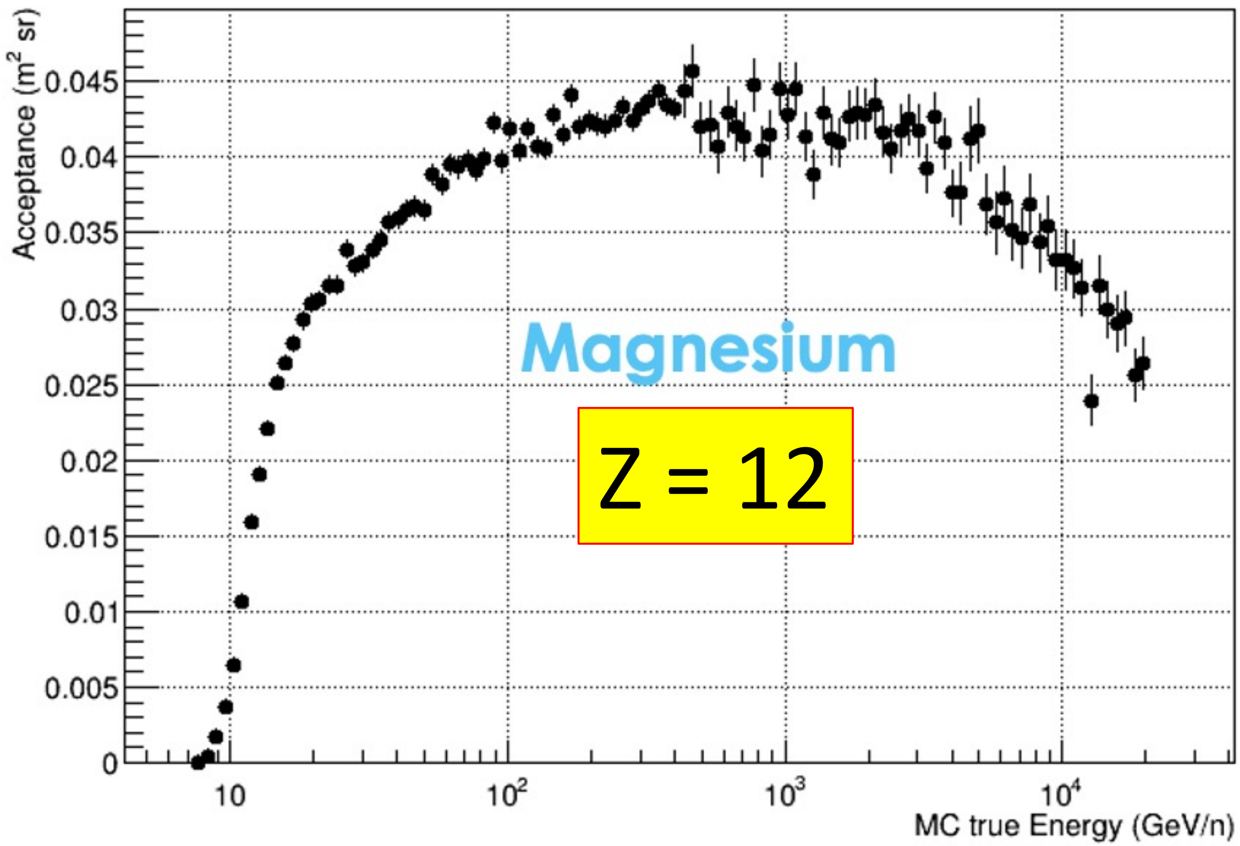




Estimate of acceptance

A_{GEOM} = area x solid angle [m^2 sr]





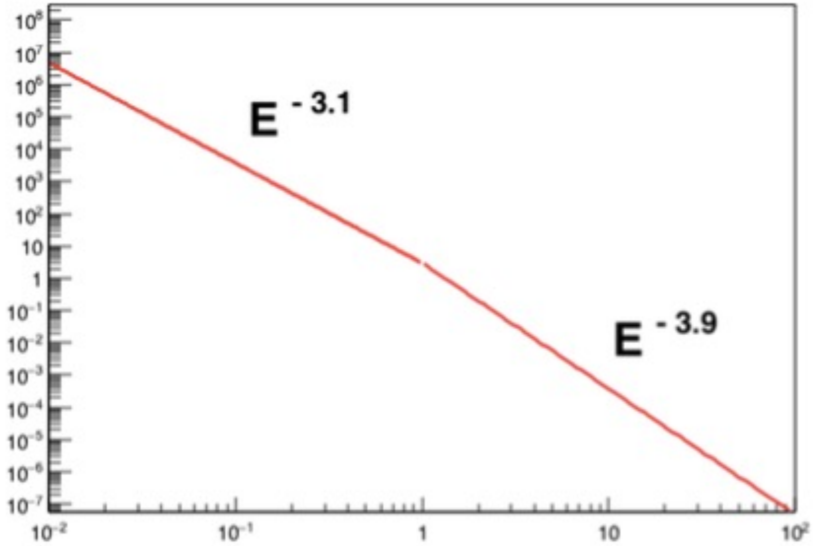
$$A_{EFF} = \varepsilon \, A_{GEOM} = (N_{surv} \, / \, N_{simu}) \, A_{GEOM}$$

Measurement of CR fluxes
Protons (Z=1), Helium (Z=2) and so on

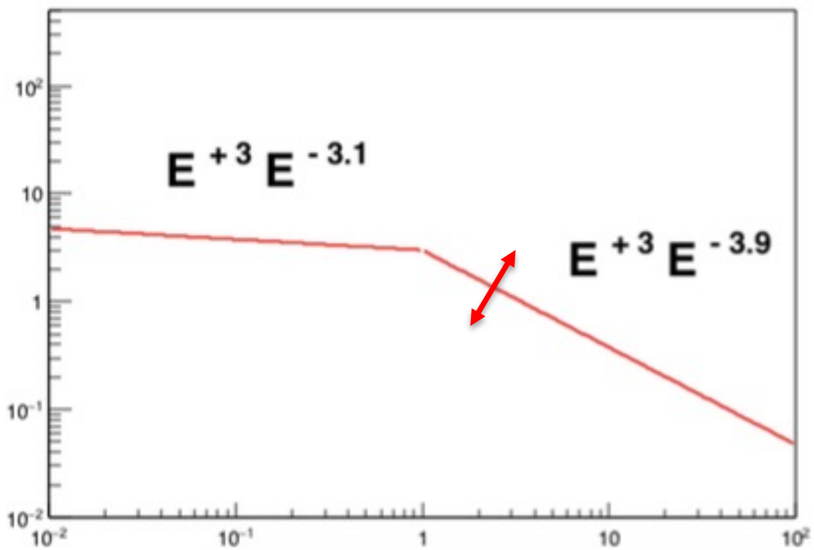
$$\Phi_Z(E) = \frac{N_Z(E)}{A_{EFF}\,\Delta E\,\Delta t}$$

$\Phi_Z(E)$	differential flux for the Z element
$N_Z(E)$	number of observed Z events in the energy range
A_{EFF}	effective acceptance, that is selection efficiency (ε) times geometrical acceptance (A_{GEOM})
ΔE	width of the energy bin
Δt	total live time

Power law



The change of the spectral index is not so evident



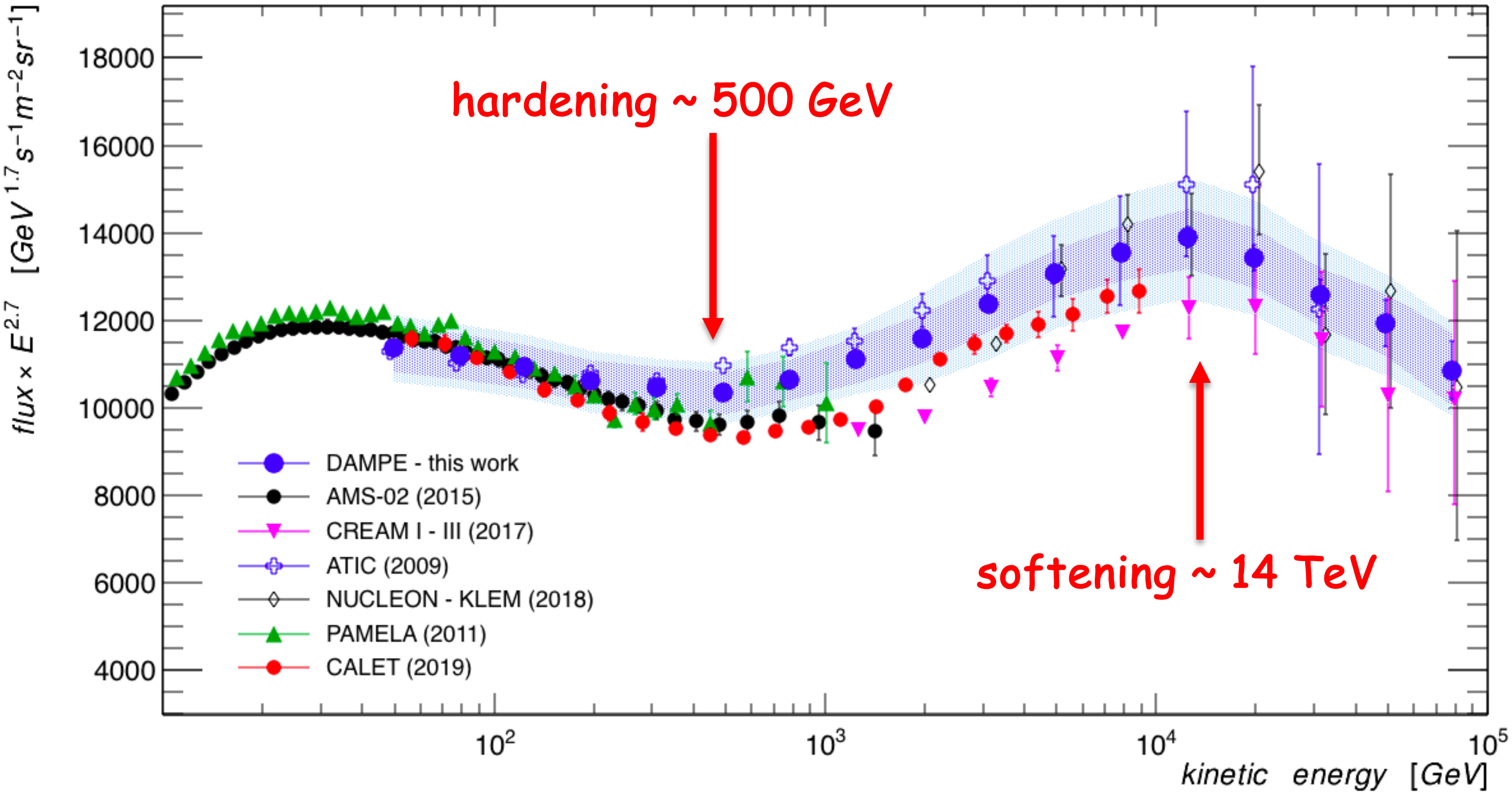
The change of the spectral index is made evident by the factor E^{+3}

Energy-correction affects both the axes

Proton spectrum (I)

30 months of data (Jan 2016 – Jun 2018)

Spectral hardening followed by softening
(measured with unprecedented precision)

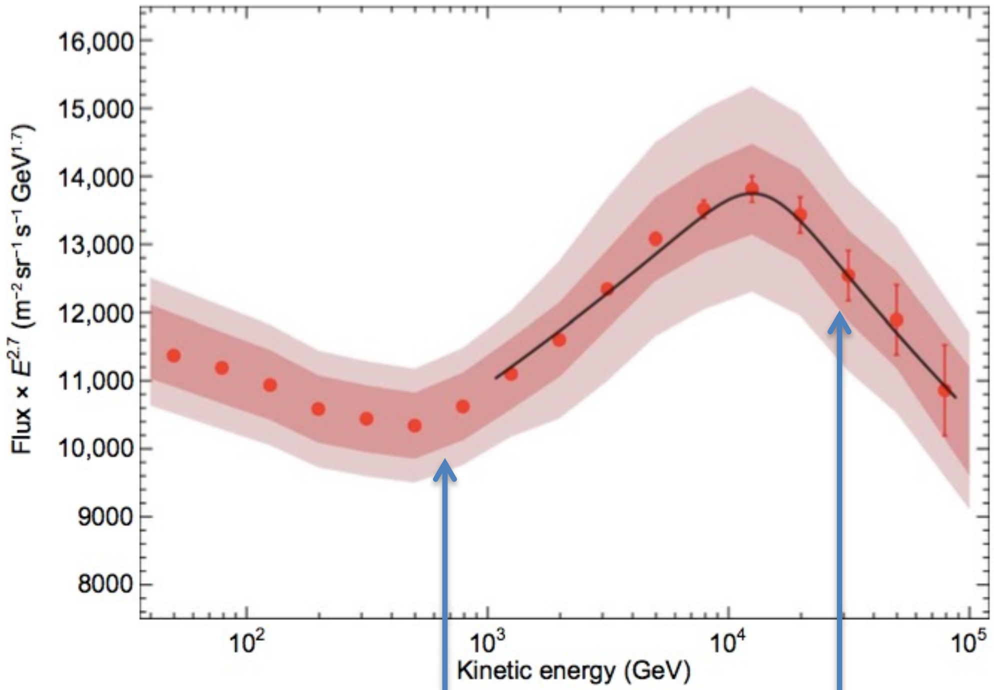


Sci. Adv. 2019; 5:eaax3793

Proton spectrum (II)

Fit with a Smootly
Broken Power Law (s = 5)

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



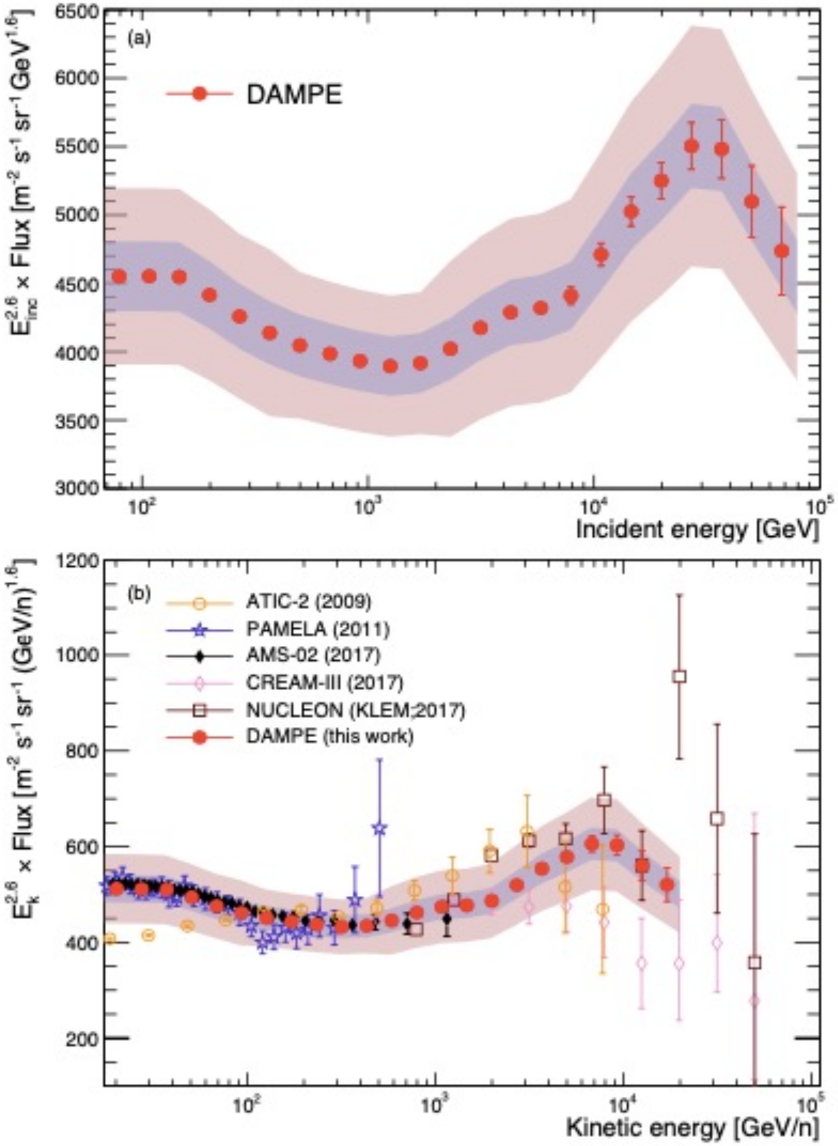
100 GeV – 6.3 TeV **Hardening**

E_B = 480 GeV γ_1 = 2.772 γ_2 = 2.599

1 – 100 TeV **Softening**

E_B = 13.6 TeV γ_1 = 2.60 γ_2 = 2.85

Helium spectrum



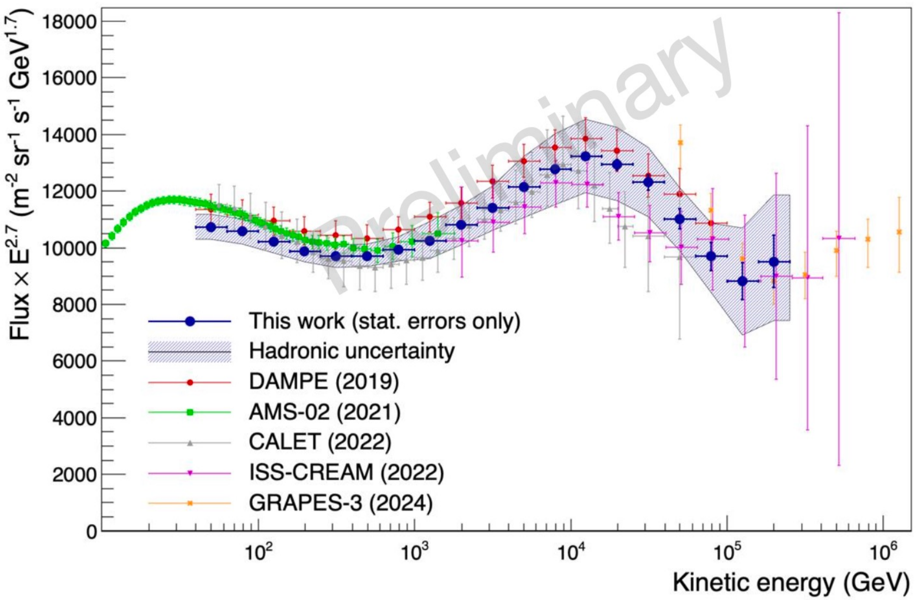
Physical Review Letters 126 (2021) 201102

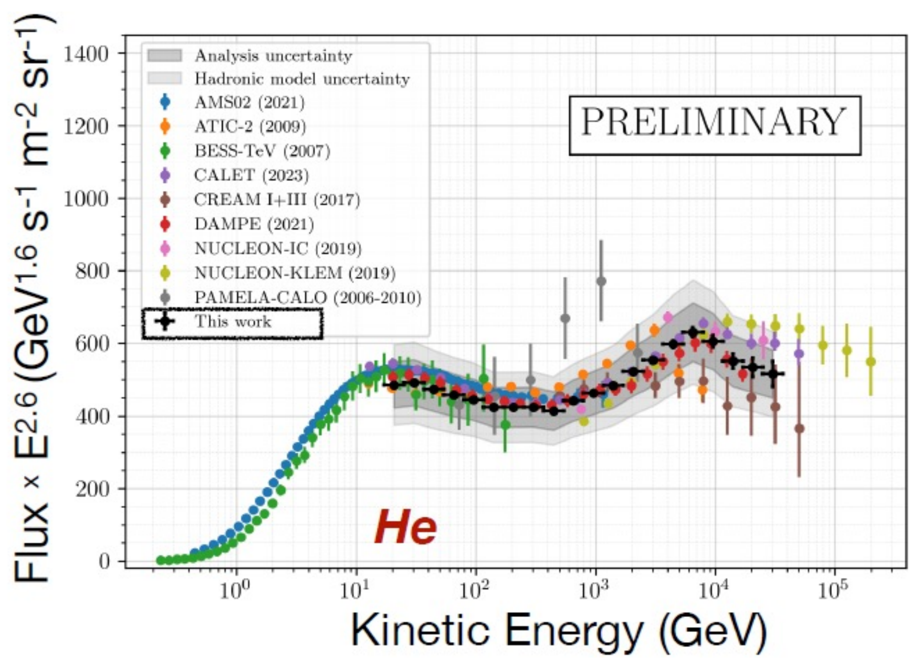
Hardening at ~ 1.2 TeV

First clear evidence of a softening at ~ 34 TeV

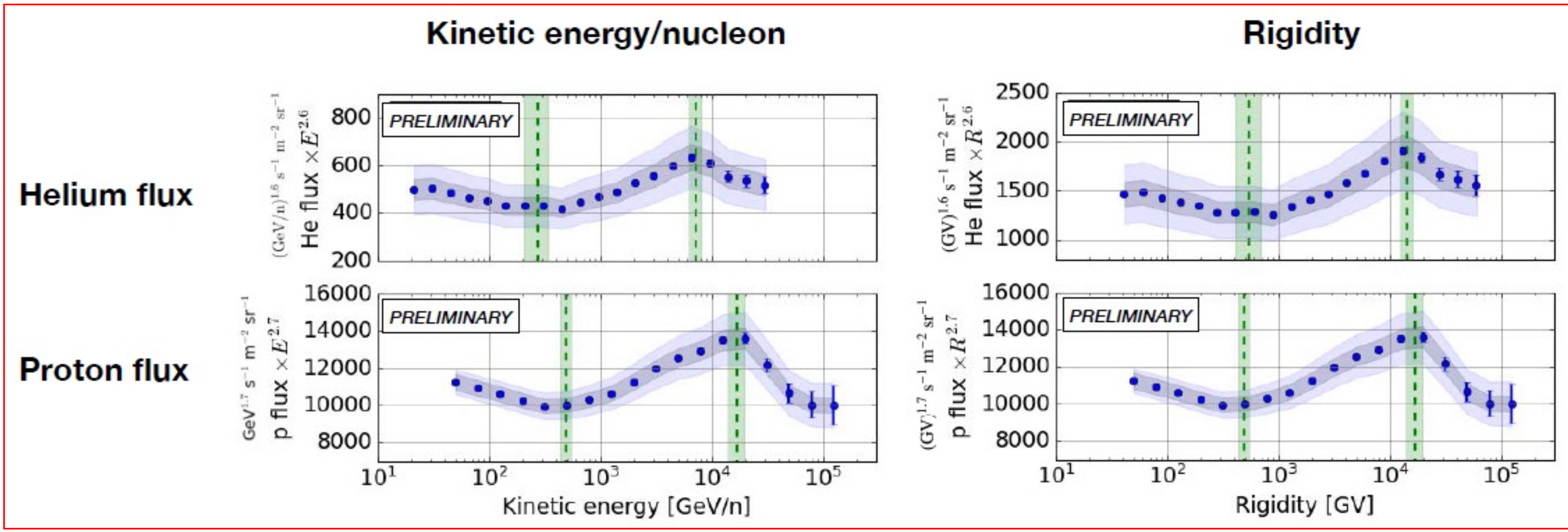
Z-dependent hardening and softening energies are suggested

Proton and He spectra: updates
- Neural Network tracking -



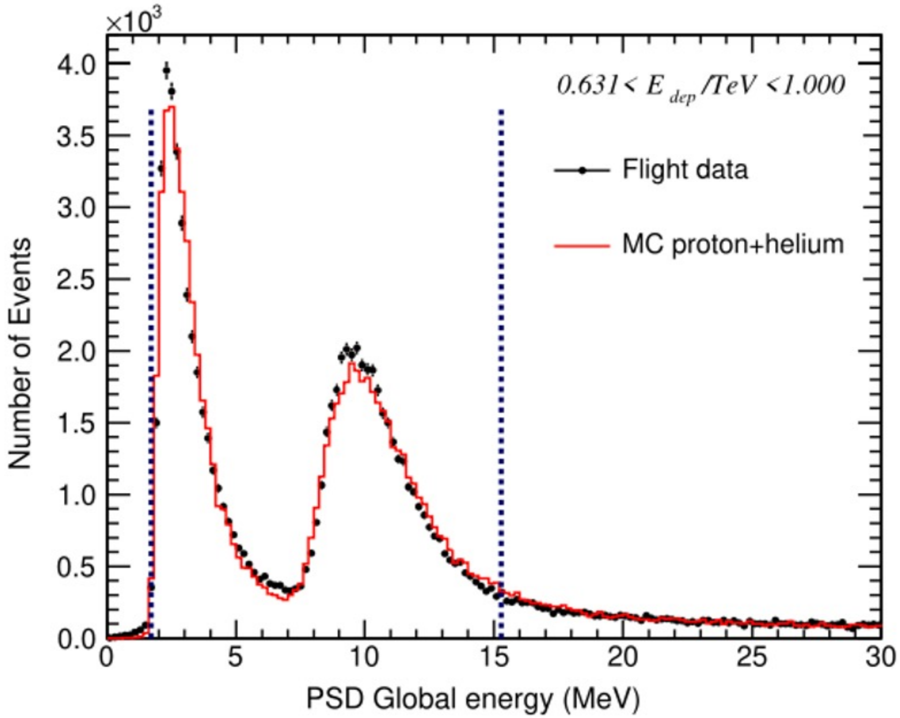


Hardening/softening energies

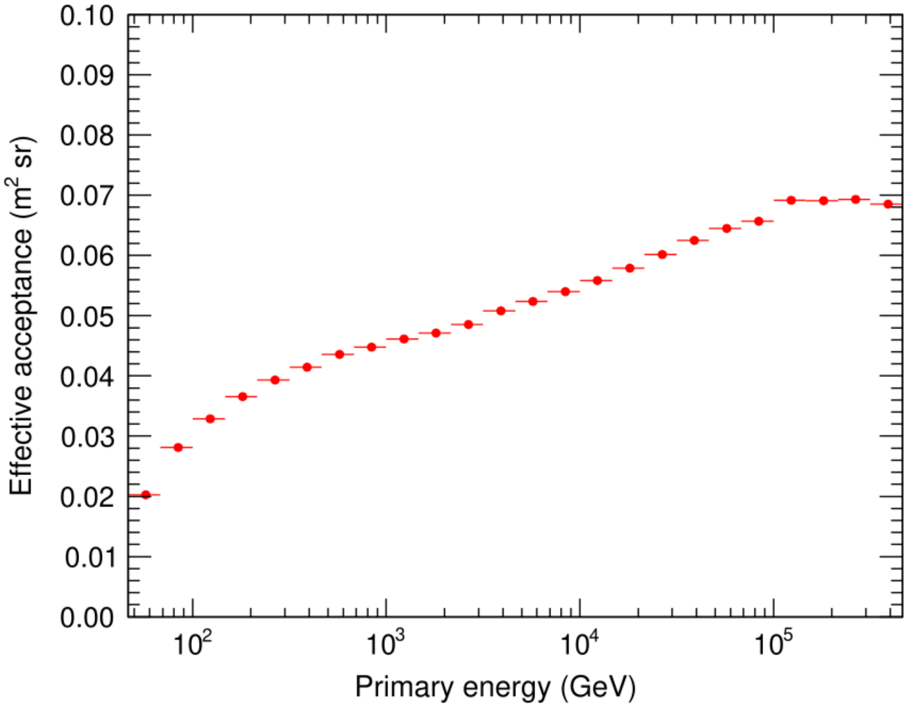


A rigidity dependence of hardening (500 GV) and softening (15 TV) is favoured by data

Protons + Helium – Bridge between space and ground measurements

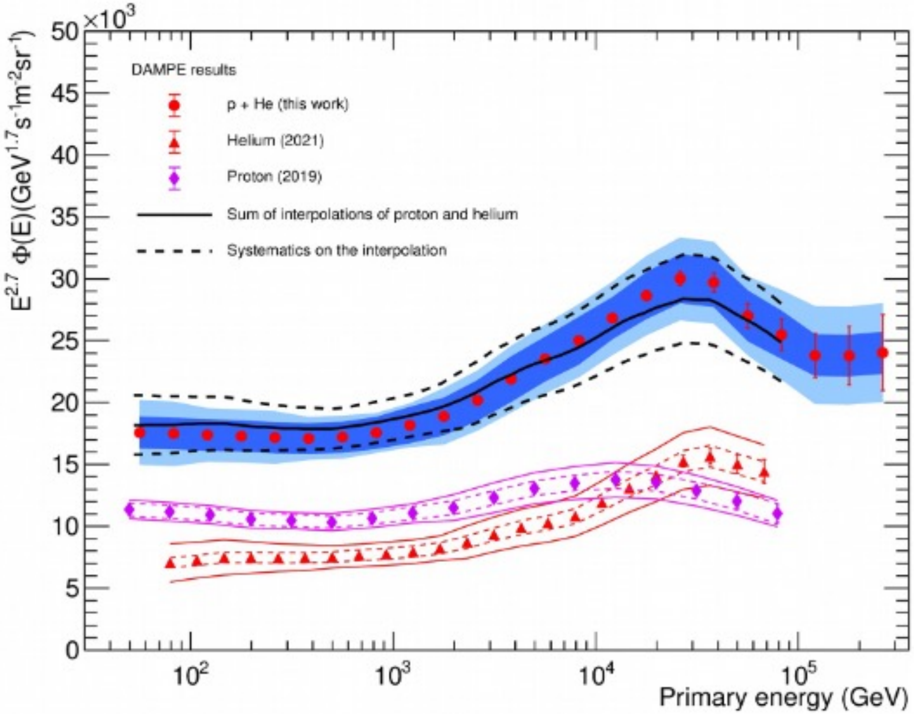


PRD 109 (2024) L121101

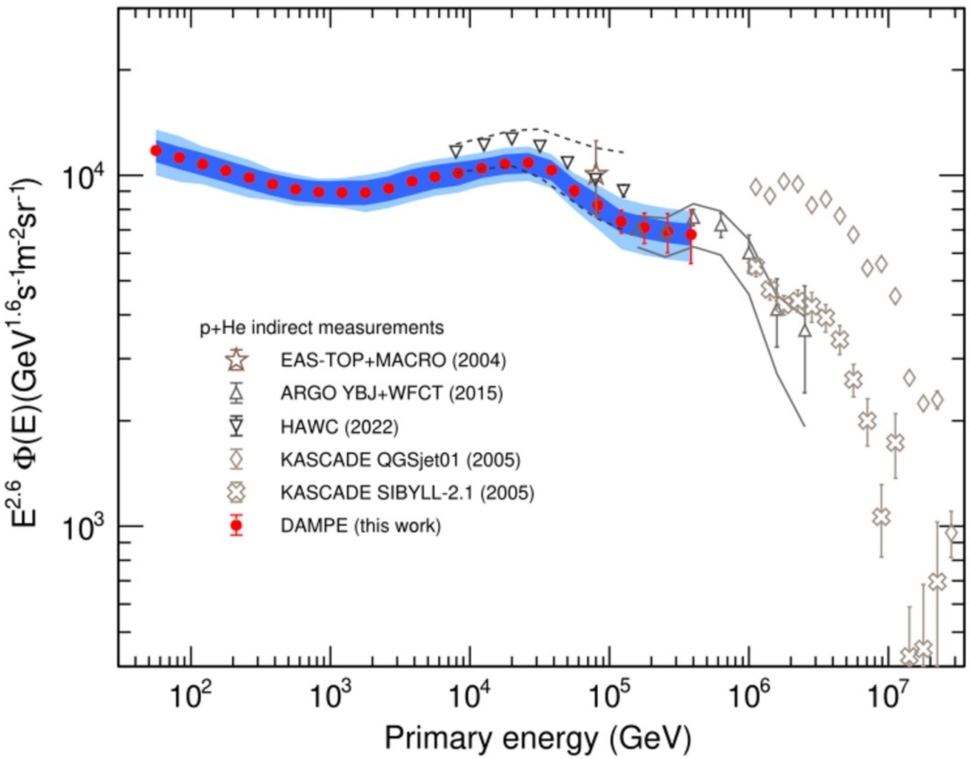


- *Higher effective acceptance*
- *Lower systematics*
- *Measurents at higher energies*

Protons + Helium – Bridge between space and ground measurements



PRD 109 (2024) L121101

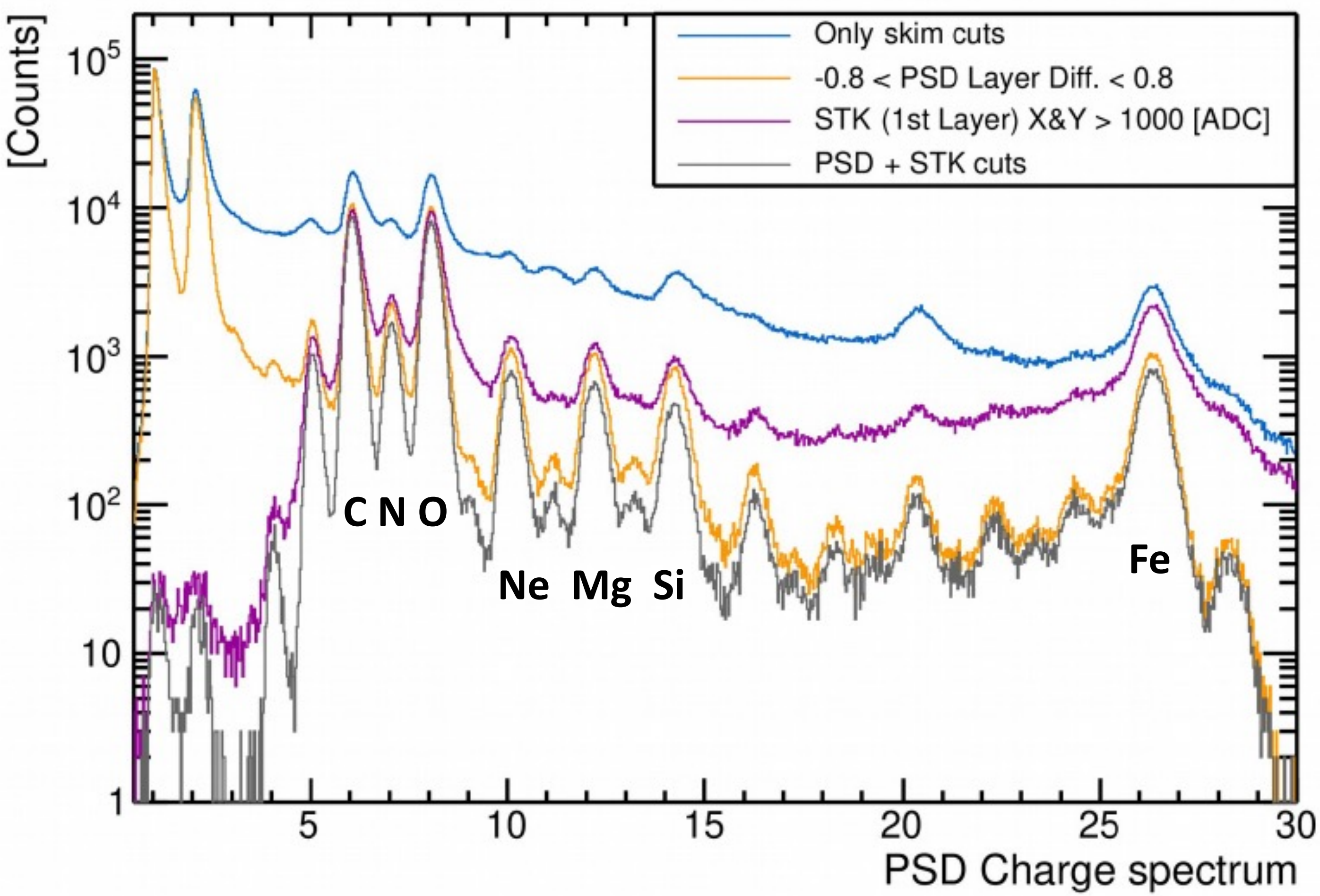


Softening confirmed at 15 TV

Hint of a following hardening

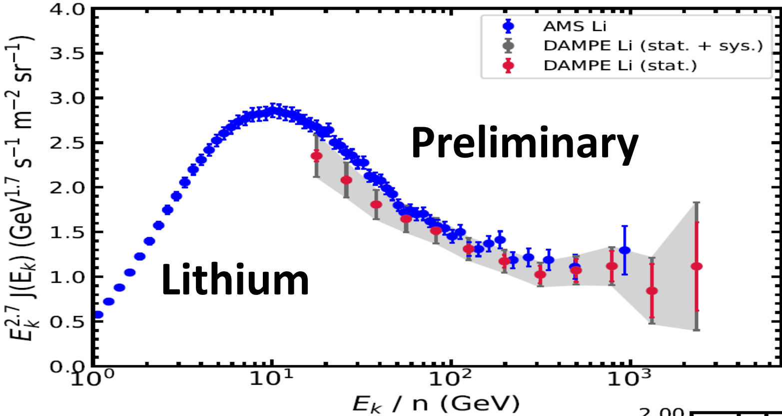
Bridge with ground experiment

Many independent analyses from Li up to Fe

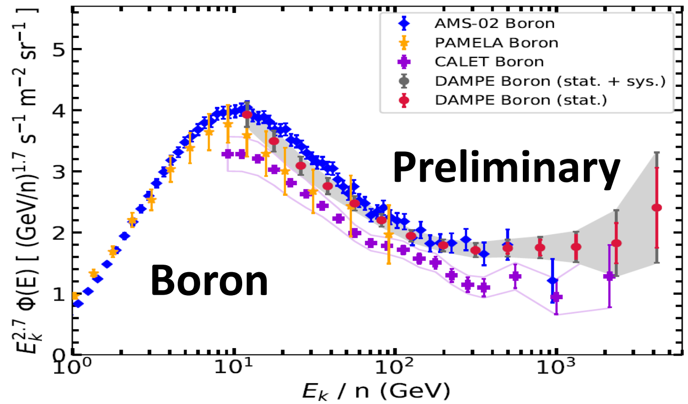


Just an example

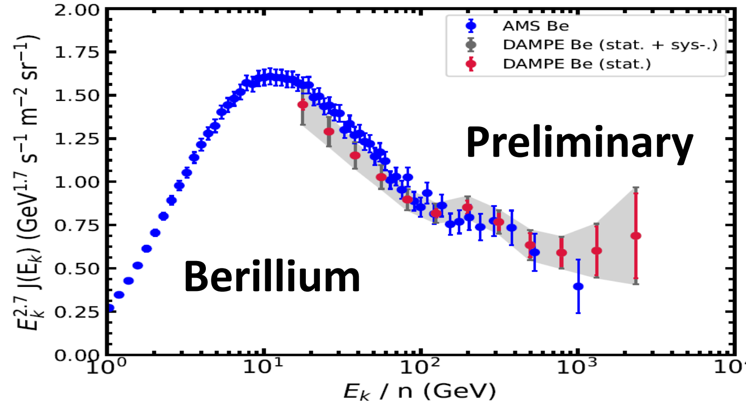
Elemental spectrum optimized for the CNO group



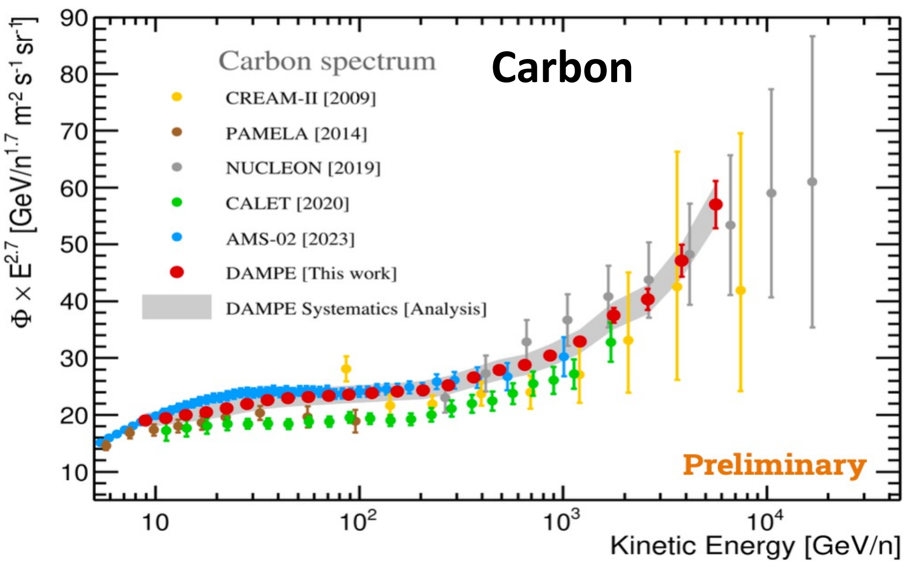
AMS Li
DAMPE Li (stat. + sys.)
DAMPE Li (stat.)
Preliminary
Lithium
$E_k^{2.7}$ J(E_k) (GeV$^{1.7}$ s^{-1} m^{-2} sr^{-1})
E_k / n (GeV)



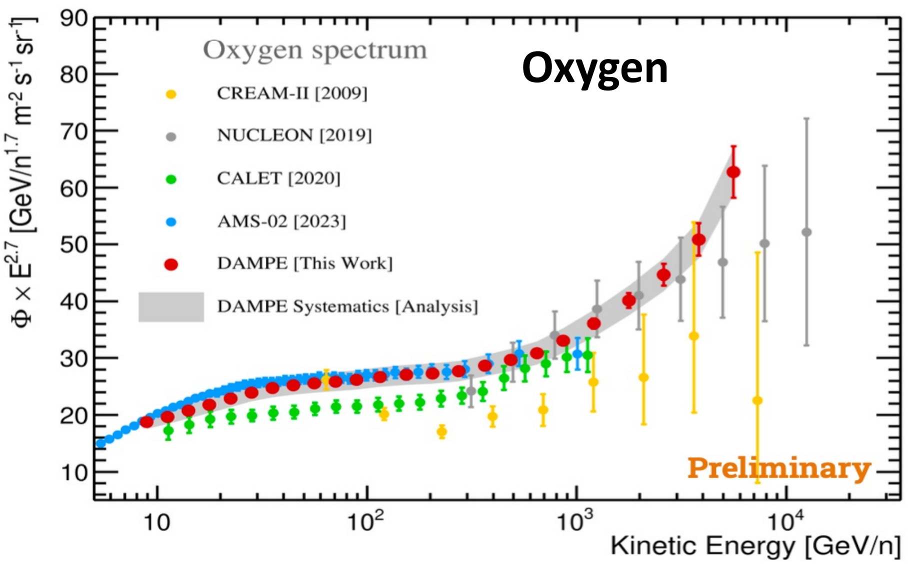
AMS-02 Boron
PAMELA Boron
CALET Boron
DAMPE Boron (stat. + sys.)
DAMPE Boron (stat.)
Preliminary
Boron
$E_k^{2.7}$ Φ(E) [(GeV/n)$^{1.7}$ s^{-1} m^{-2} sr^{-1}]
E_k / n (GeV)



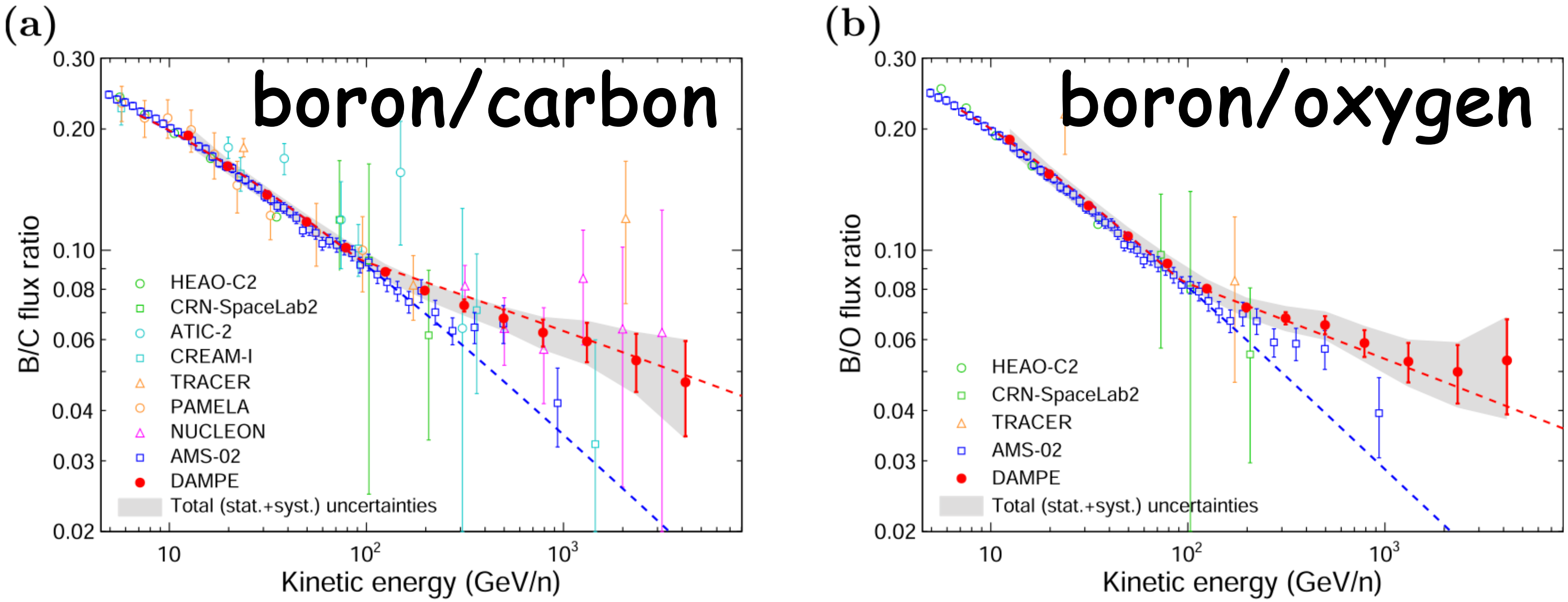
AMS Be
DAMPE Be (stat. + sys-.)
DAMPE Be (stat.)
Preliminary
Berillium
$E_k^{2.7}$ J(E_k) (GeV$^{1.7}$ s^{-1} m^{-2} sr^{-1})
E_k / n (GeV)



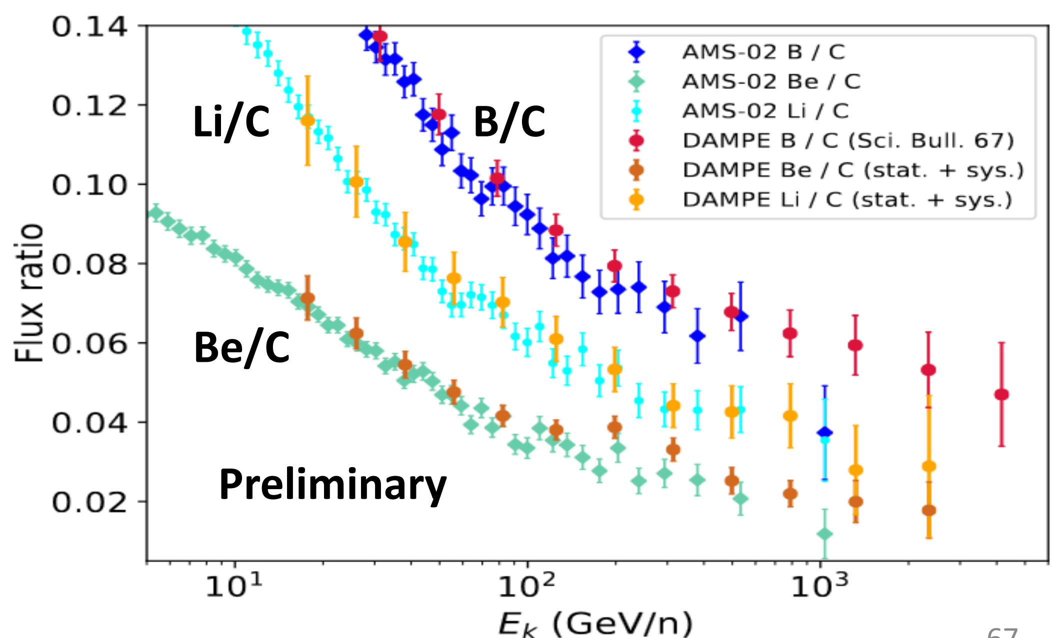
Carbon spectrum
Carbon
CREAM-II [2009]
PAMELA [2014]
NUCLEON [2019]
CALET [2020]
AMS-02 [2023]
DAMPE [This work]
DAMPE Systematics [Analysis]
Preliminary
Φ × E$^{2.7}$ [GeV/n$^{1.7}$ m^2 s^{-1} sr^{-1}]
Kinetic Energy [GeV/n]



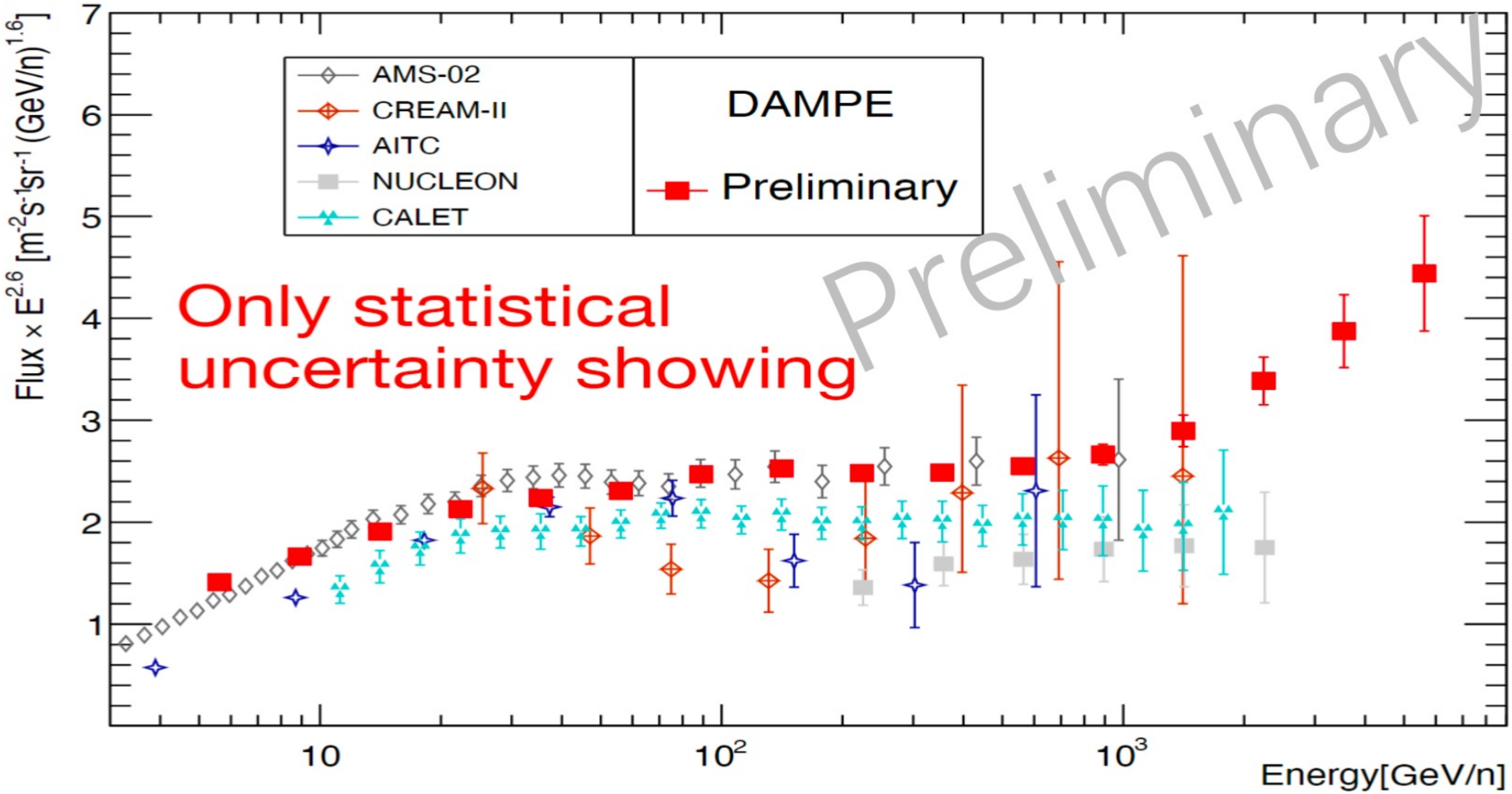
Oxygen spectrum
Oxygen
CREAM-II [2009]
NUCLEON [2019]
CALET [2020]
AMS-02 [2023]
DAMPE [This Work]
DAMPE Systematics [Analysis]
Preliminary
Φ × E$^{2.7}$ [GeV/n$^{1.7}$ m^2 s^{-1} sr^{-1}]
Kinetic Energy [GeV/n]



Measurements devoted to investigate the CR propagation in the galaxy



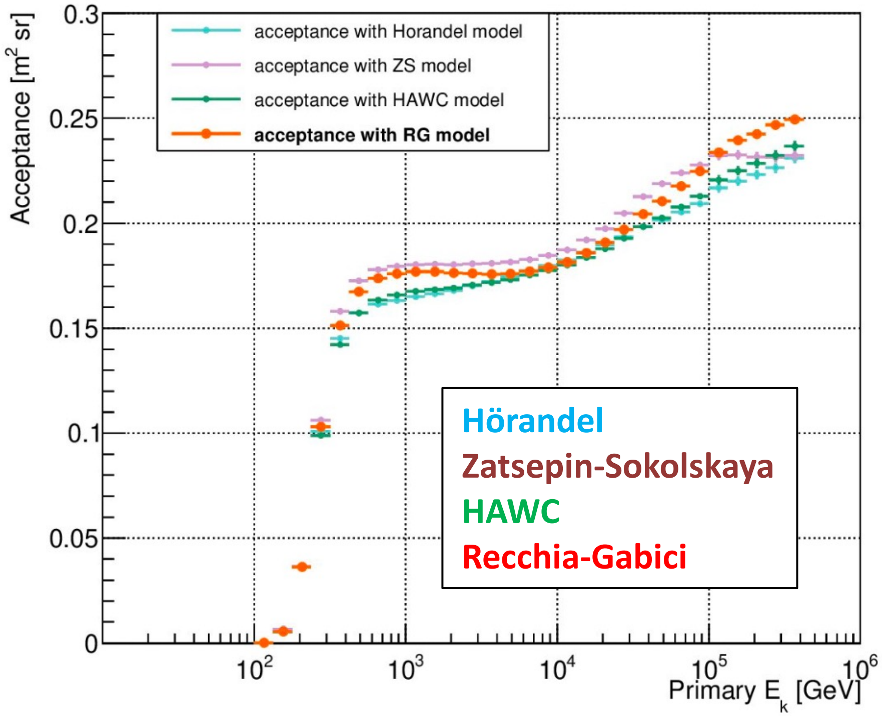
Iron spectrum



All-particle spectrum

Weighted mean acceptance

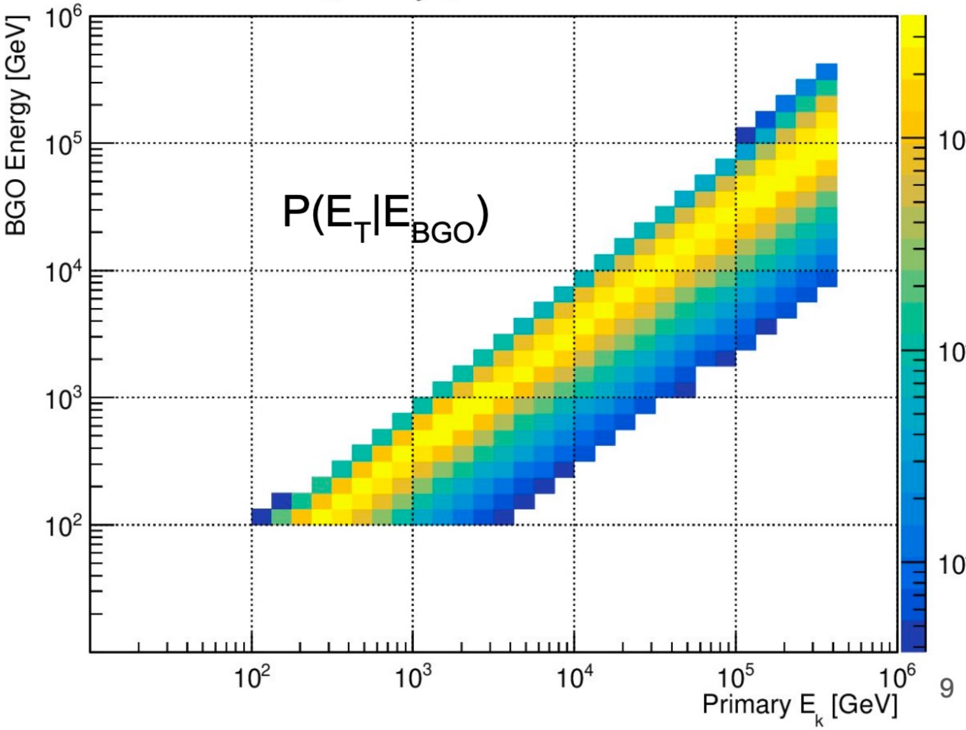
$$A_i = \sum_{el} w^{el} \; G^{el}_{gen} \; \frac{N^{el}_{sel}(E^i_T)}{N^{el}_{gen}(E^i_T)}$$



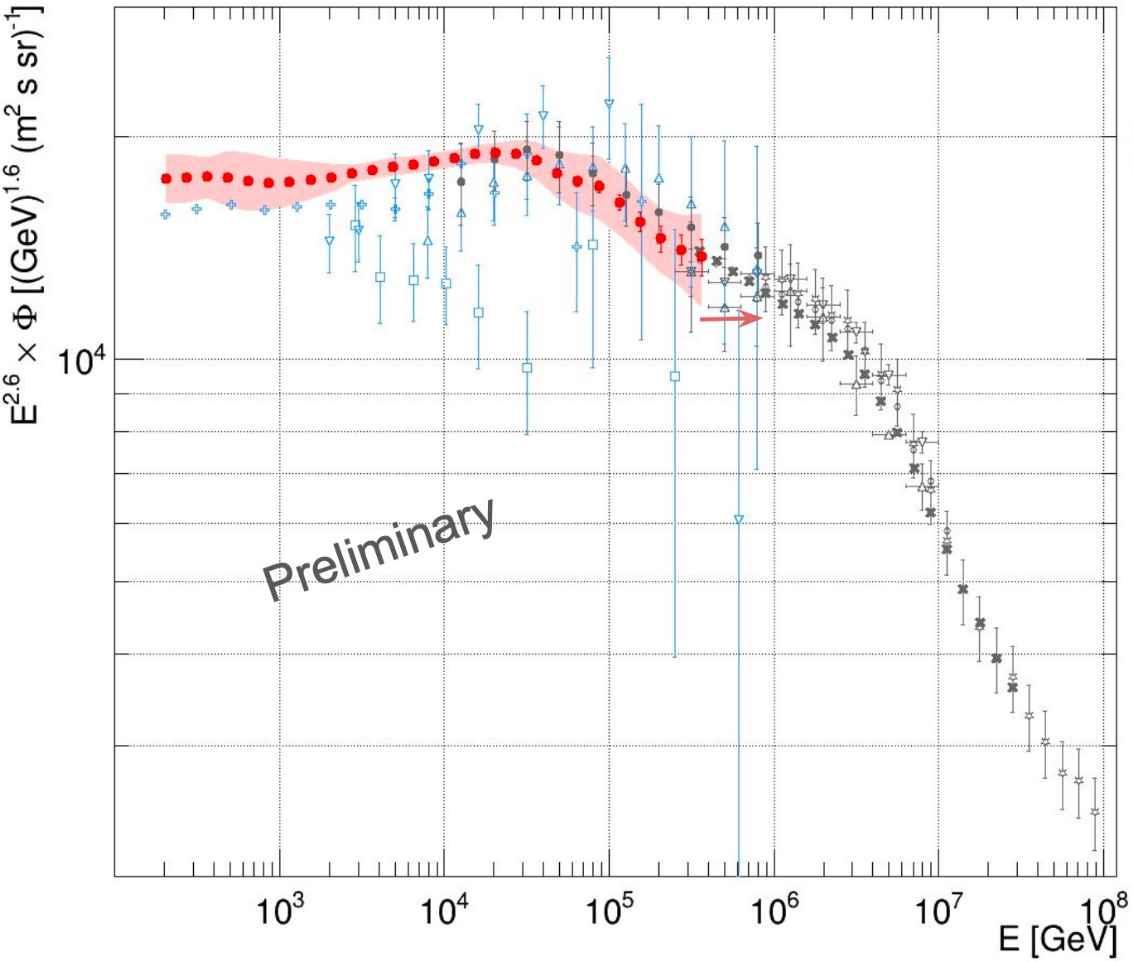
Weighted mean response matrix

for the unfolding: iterative Bayesian procedure is adopted to reconstruct the primary energy of the events

$$N_i = \sum_{el} w^{el} \sum_{j=1}^{n} P^{el}(E^i_T | E^j_{BGO}) \; N^{el}(E^j_{BGO})$$



All-particle spectrum



- Differential flux:

$$\Phi_i = \frac{N_i}{\Delta T \times A_i \times \Delta E_i}$$

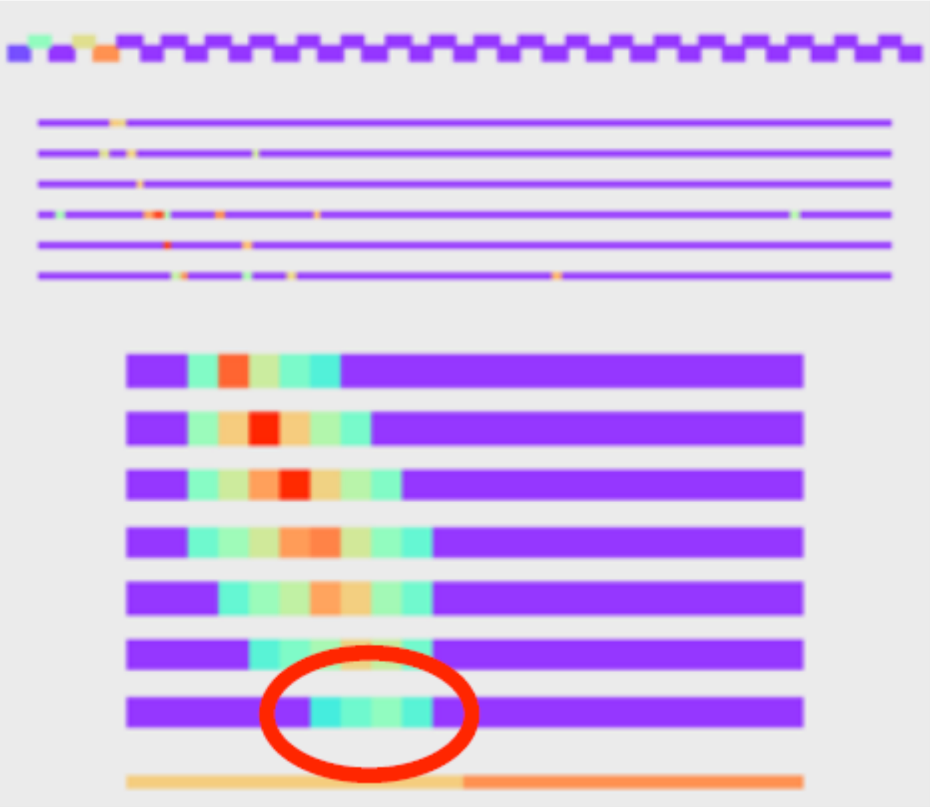
- Evaluated systematics
  - Unfolding
  - Composition model
- Contribution from hadronic model is under evaluation
- In agreement with indirect experiments results
- Structure at tens TeV (convolution of the softening of different nuclei?)
- Work in progress to extend the measurement up to 0.7/0.8 PeV

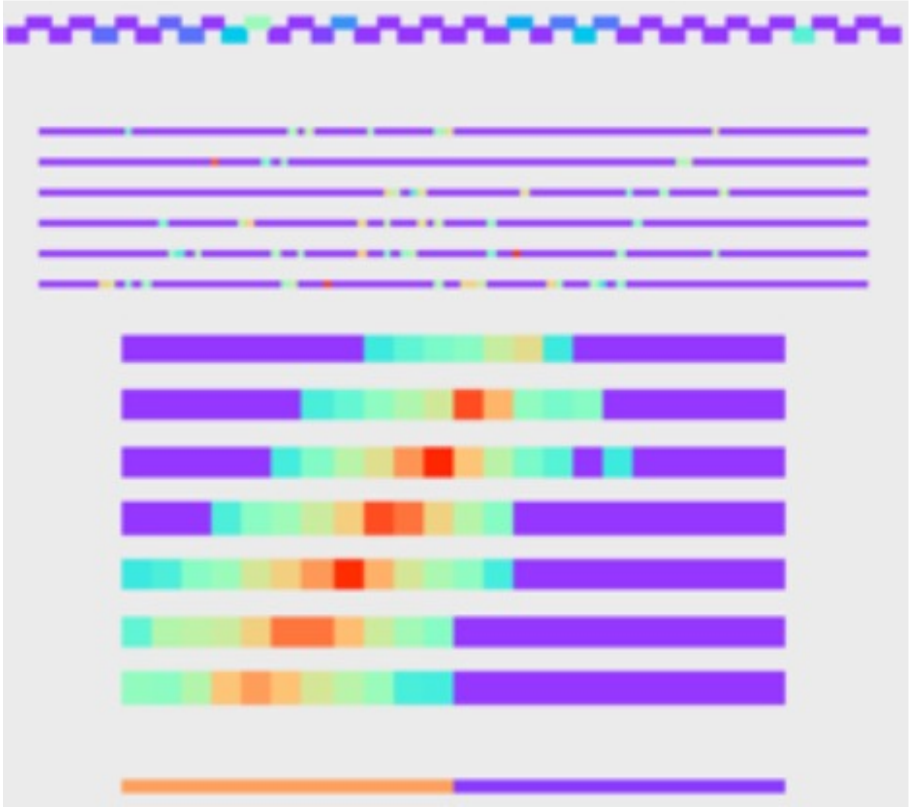
11

Electron+positron identification (I)

Selected events with Z_{PSD} = 1

Exploiting the imaging CALO-features

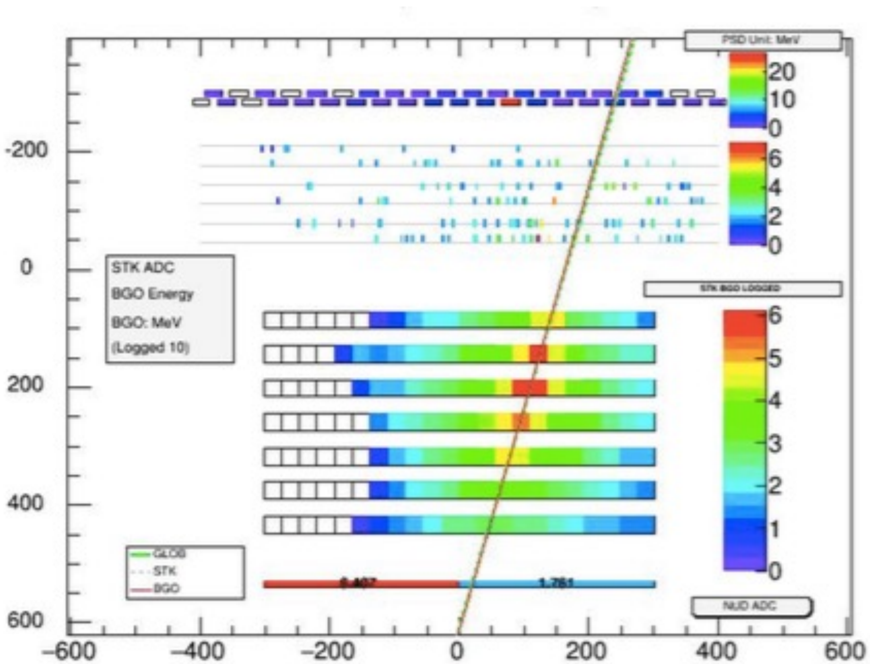


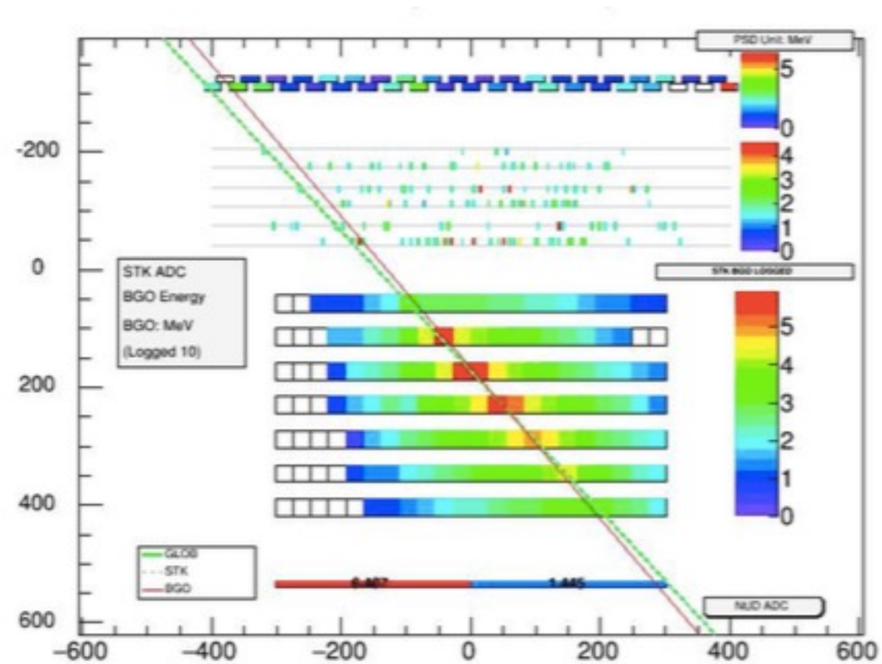


Electron+positron identification (II)

Selected events with $Z_{PSD} = 1$

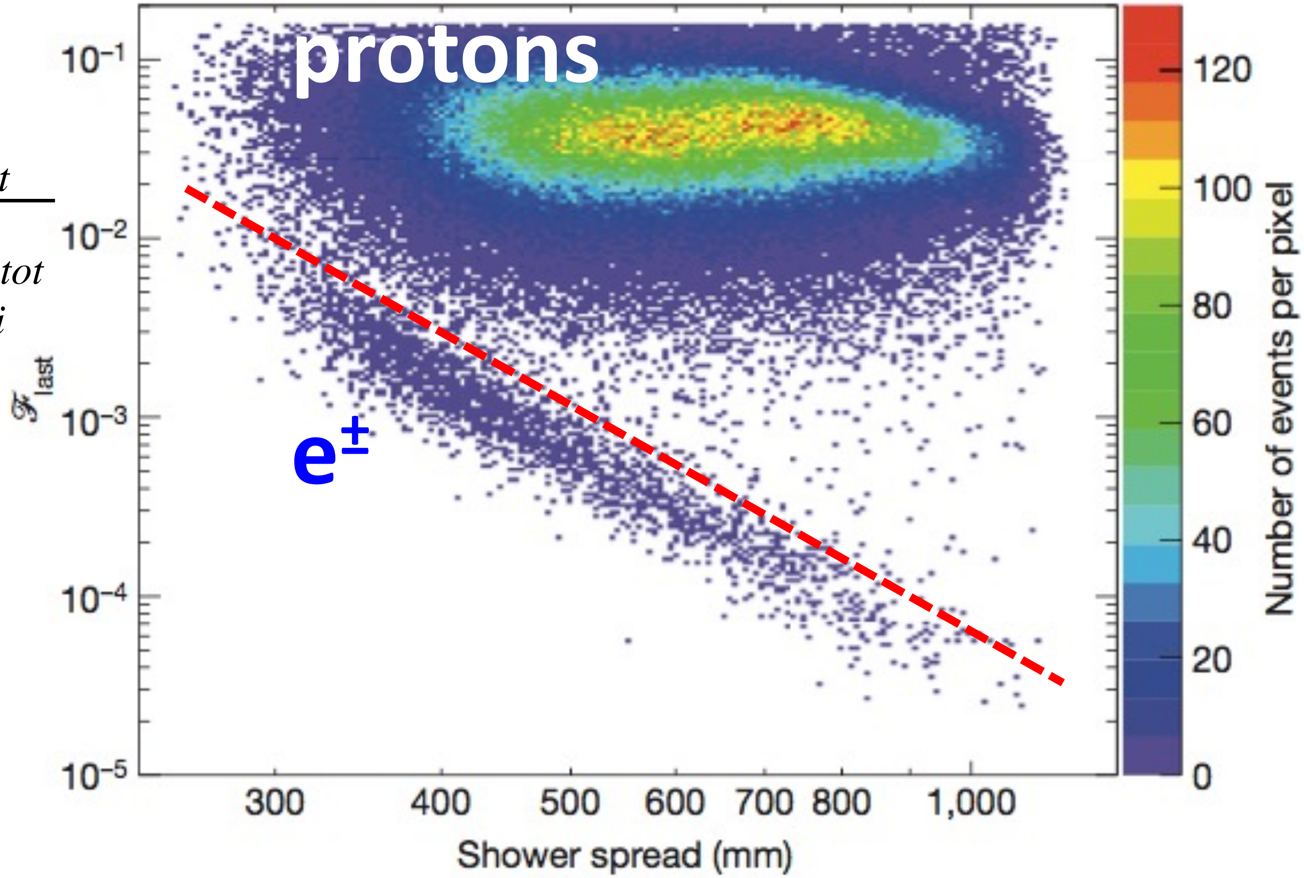
Exploiting the imaging CALO-features





BGO imaging to separate electrons and hadrons (I)

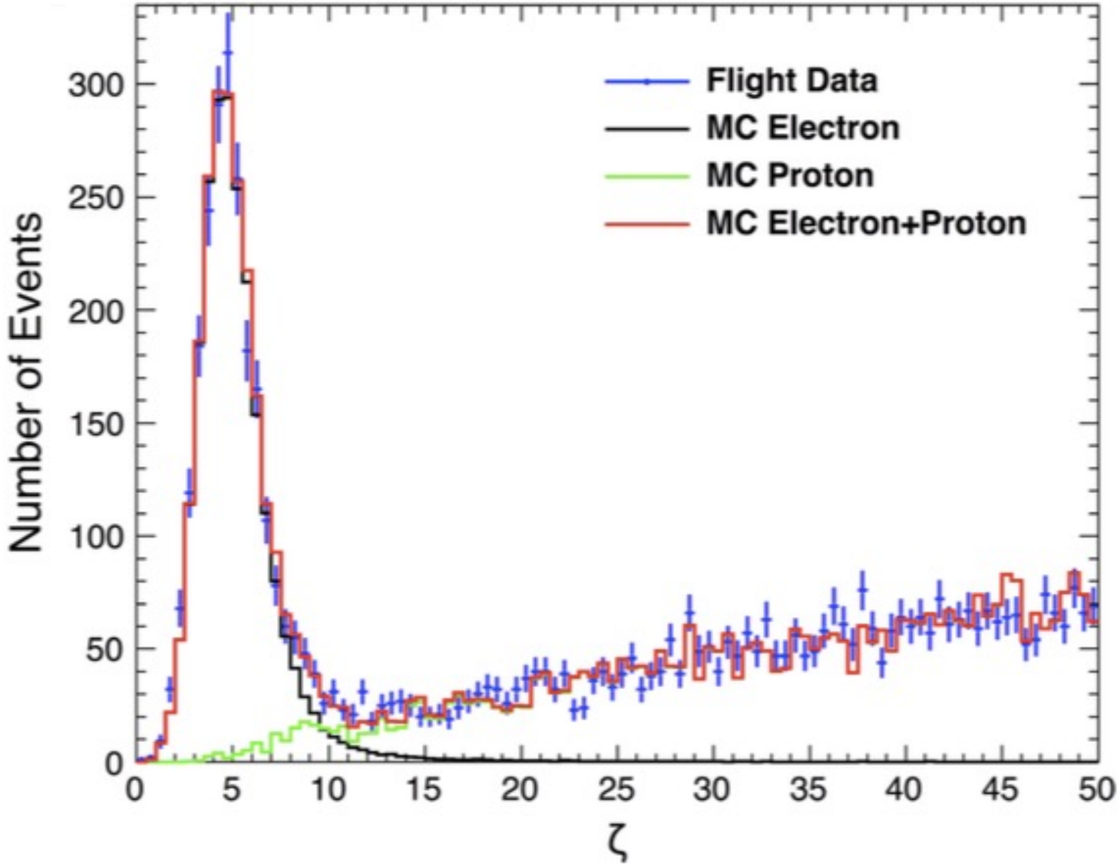
$$F_{last} = \frac{E_{last}^{tot}}{\sum_{i=1}^{14} E_i^{tot}}$$



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

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

BGO imaging to separate electrons and hadrons (II)



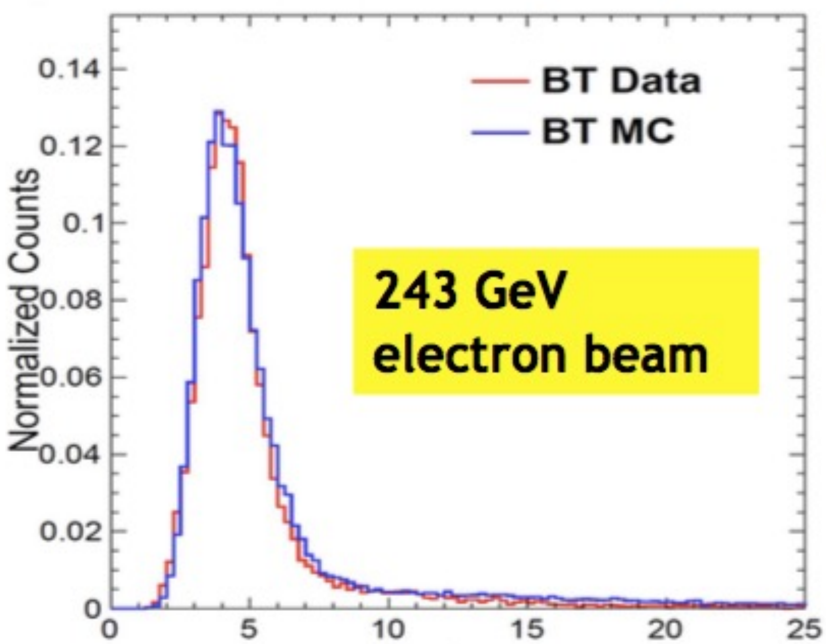
Electron and positron selection

Estimate of proton pollution

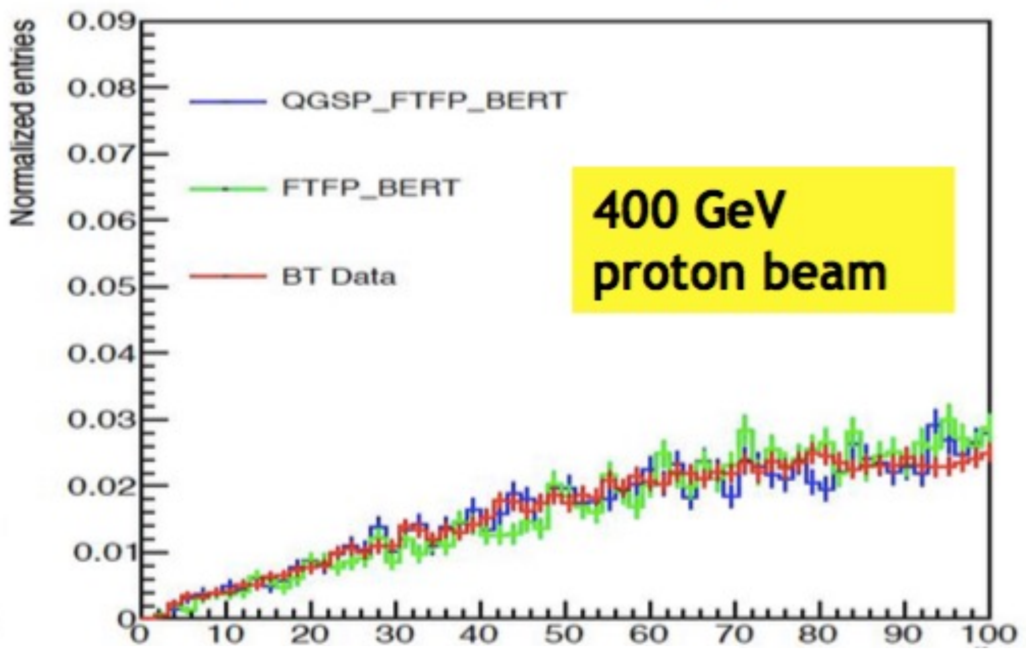
$$\varsigma = F_{last} \frac{(spread / mm)^4}{8 \times 10^6} < 8.5$$

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

Validation of parameter ζ with beam-test data

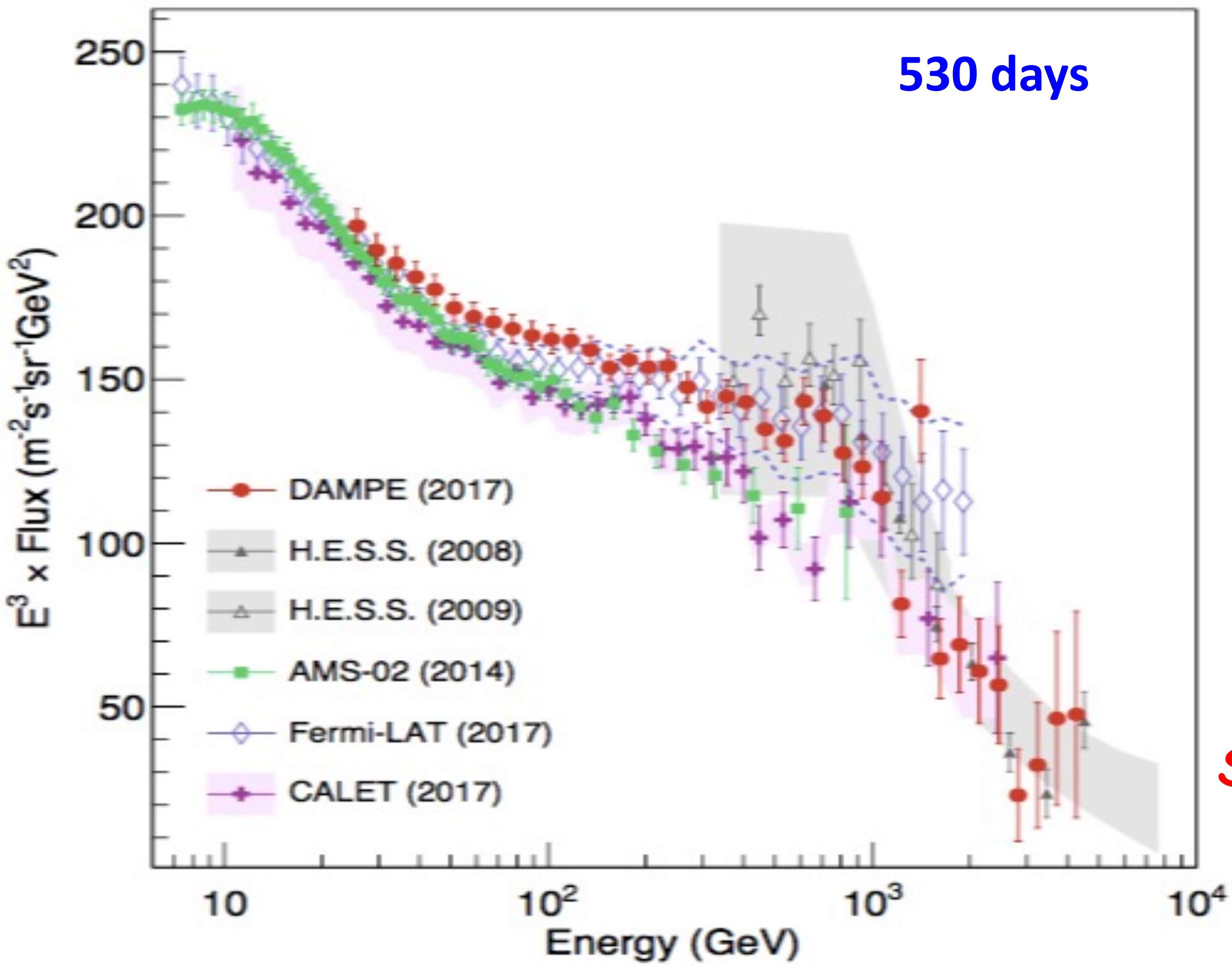


ζ



ζ

Electron+positron spectrum



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

Energy range:
25 GeV – 4.6 TeV

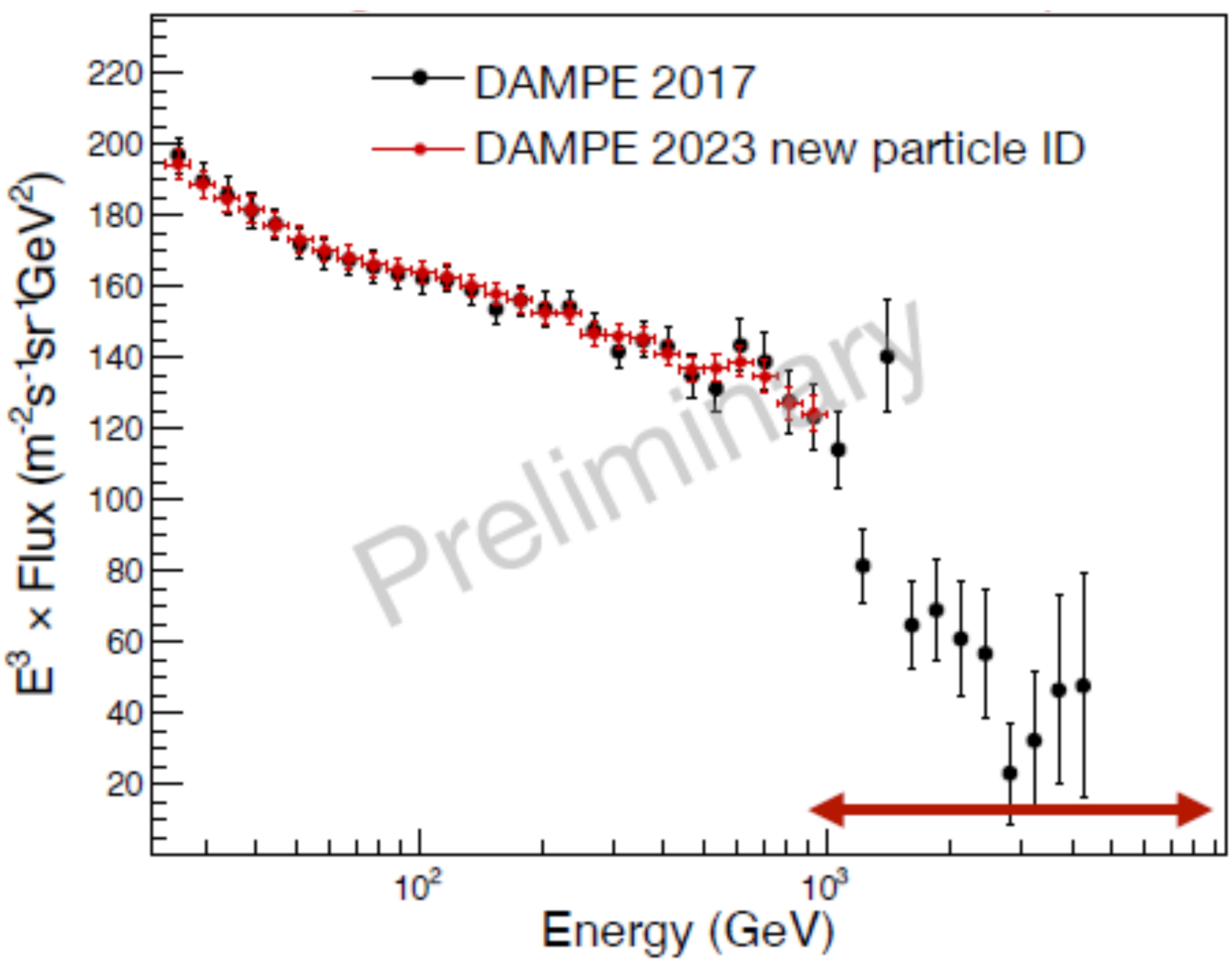
Energy resolution <1.2%
for E > 100 GeV

Spectral break ~ 1 TeV

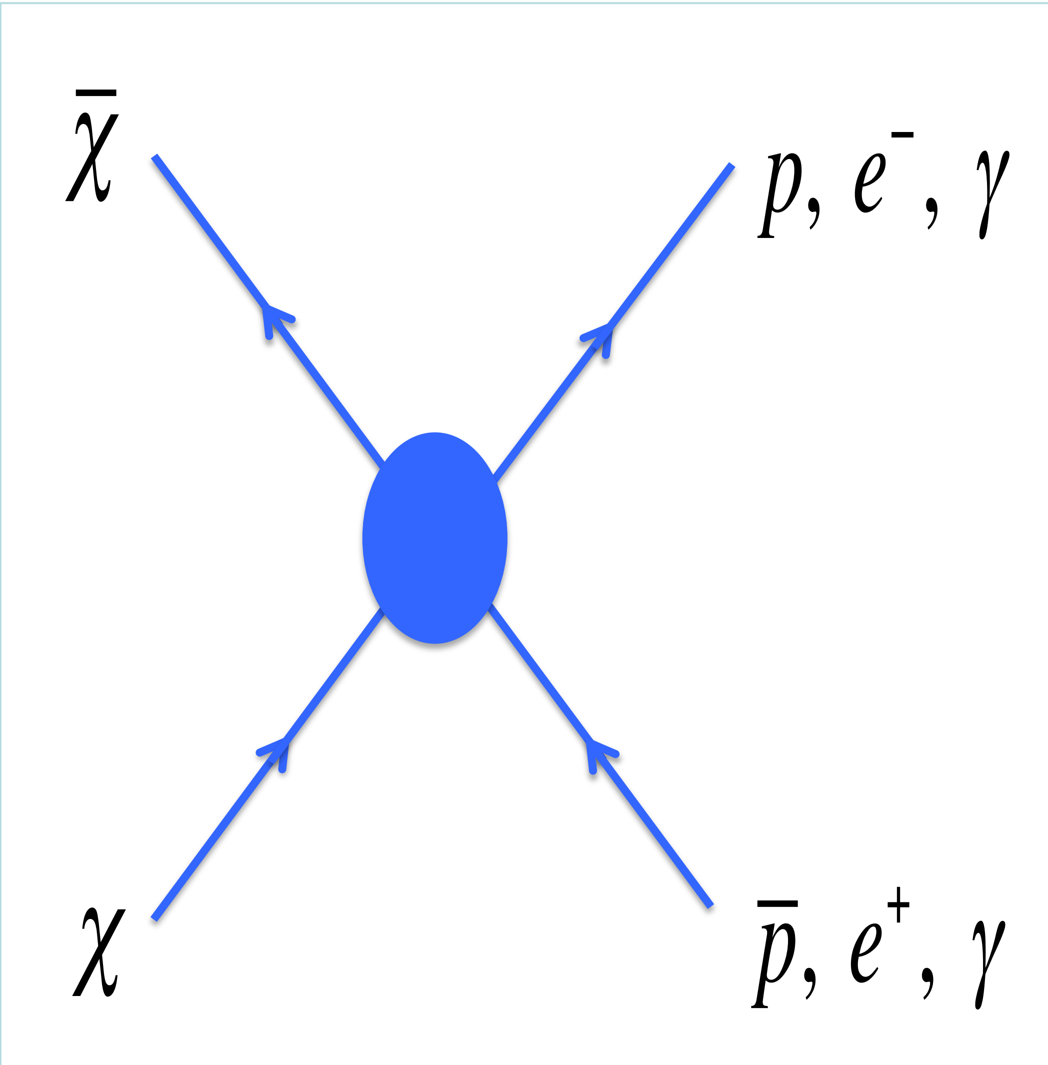
Uncertainties mainly due to the statistics at high energy

New analysis with Neural Network is ongoing

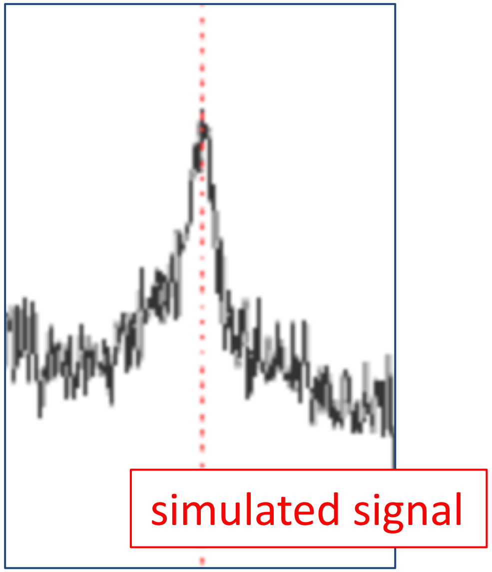
Excellent agreement with standard particle ID



Possible indirect detection of Dark Matter in space



γ line as possible signal ?



Looking for dark matter lines in photon spectrum

Science Bulletin 67 (2022) 679

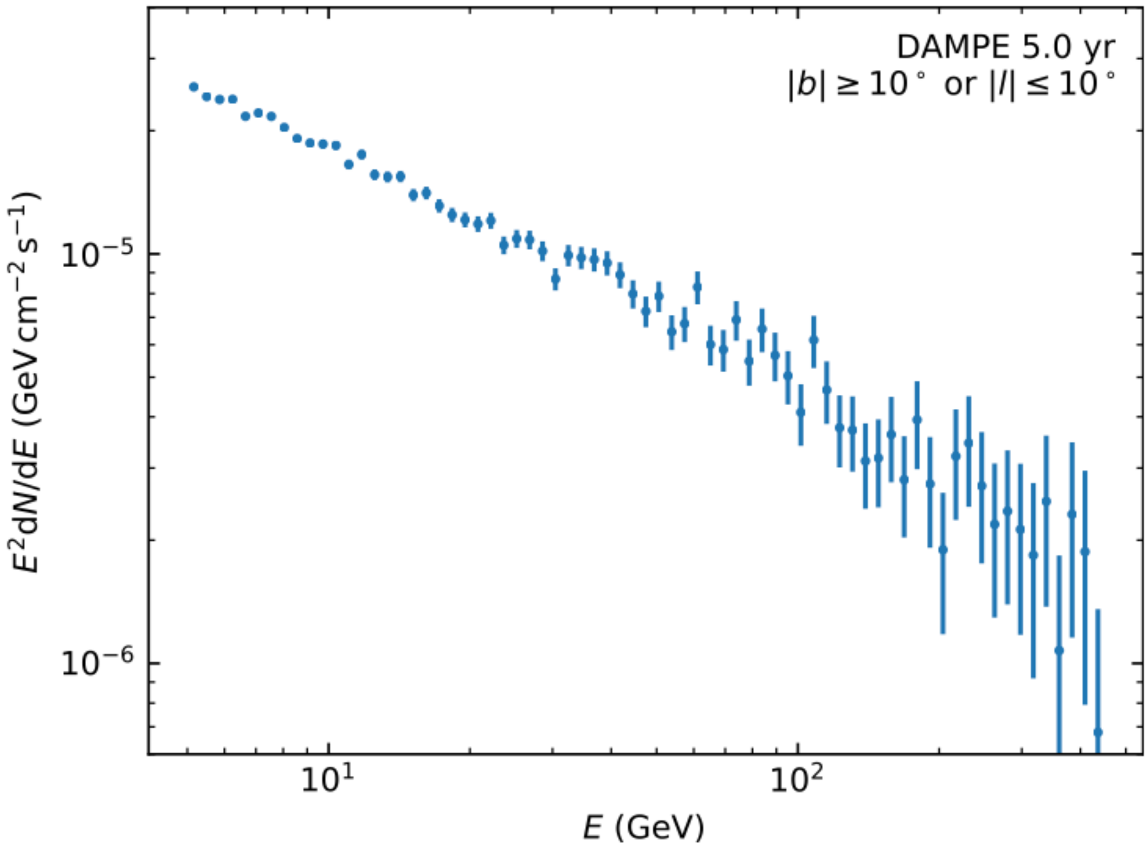


Fig. 1. (Color online) The average SED of the LineSearch and BgoOnly photons from the region with Galactic plane removed.

No visible lines up to now

Summary

DAMPE is "very deep" (~32 X_0) detector in orbit. It works properly since its launch more than 8 years ago. We expect DAMPE will continue to take data for some more years

Long exposure and high energy resolution are the unique tools to find a dark matter signal in the cosmic ray flux (if it exists)

Main DAMPE scientific results

- Evidence for a break at ~1 TeV in the all-electron spectrum
- Clear structures (hardening + softening) have been detected in the proton and Helium spectra
- Z-dependence for hardening and softening is suggested
- Measurement of p+He and all-particle are a bridge toward ground exp.s
- New spectral measurements are in progress (Li, Be, B … Fe)

Backup slides

CALET ratios