ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

CRD 17 Nuclear CR spectra: theory and observations

Conveners: Paolo Maestro, Brian Rauch, Eun-Suk Seo

Proton

Kazuyoshi Kobayashi / CALET

Gwangho Choi / ISS-CREAM

Eun-Suk Seo / ISS-CREAM

Helium

Paolo Brogi / CALET

Margherita di Santo / DAMPE

p+He

Francesca Alemanno / DAMPE

Carbon and oxygen

Paolo Maestro / CALET

Libo Wu / DAMPE

Sinchul Kang / ISS-CREAM

Scott Nutter / ISS-CREAM

Elemental range Ne-Si

Alberto Oliva / AMS

Cheng Zhang / AMS

Zhen Liu / AMS

Iron

Yao Chen / AMS

Francesco Stolzi / CALET

ZhiHiu Xu / DAMPE

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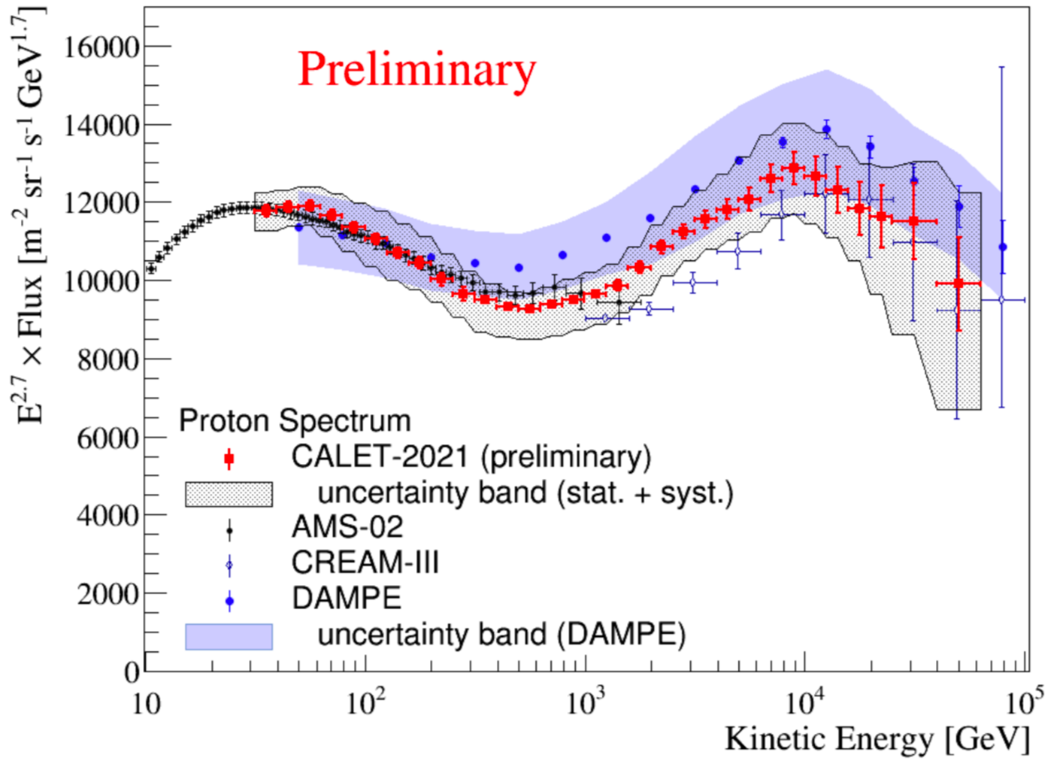
Proton and helium

CALET proton spectrum (30 GeV<E<60 TeV)

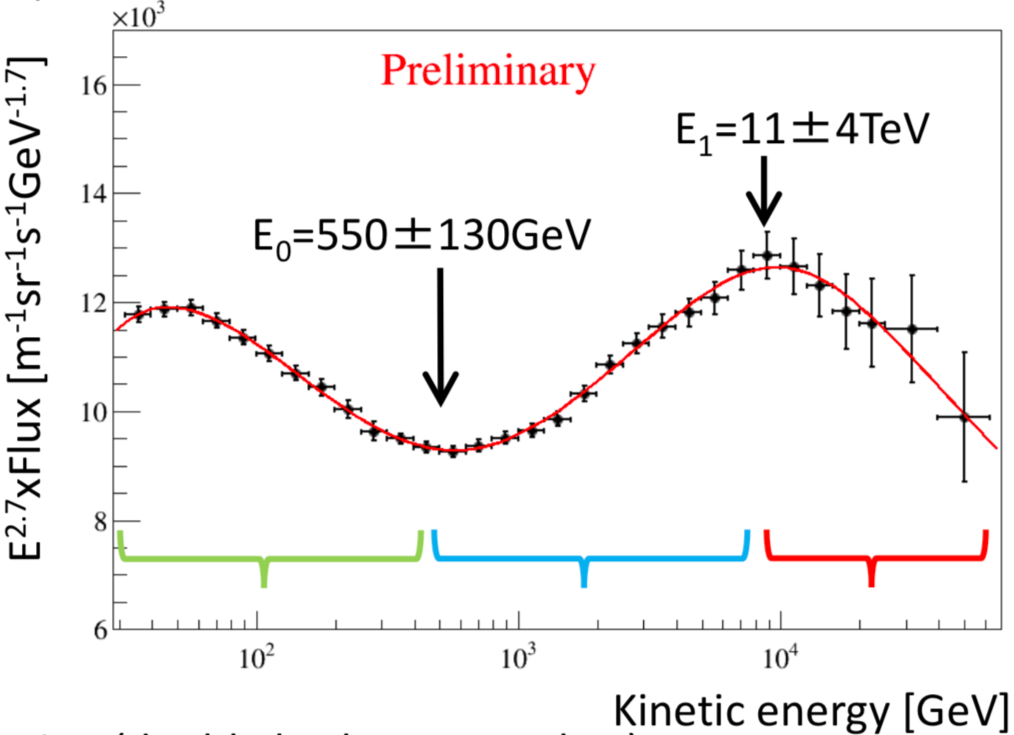


$$\Phi(E) = \frac{N(E)}{S\Omega T \Delta E \varepsilon(E)}$$

$\Phi(E)$: proton flux
$N(E)$: number of events in ΔE bin (after background subtraction)
$S\Omega$: geometrical acceptance ($510 cm^2 sr$)
T: livetime
ΔE: energy bin width
$\varepsilon(E)$: detection efficiency

- We confirm the spectral hardening around 500GeV reported in PRL2019.
- We also observe a spectral softening in E>10TeV.
- Two independent analyses with different efficiencies confirm the same result.

Spectral fit with Double Broken Power Law (statistical error only)



$\chi^2 = 2.9/22$

C	$(5.1\pm2.1)\times10^{-1}$
p_0	9.1 ± 26
P_1	-6.6 ± 470
γ	-2.9 ± 0.3
S	2.1 ± 2.0
Δγ	$(4.4\pm3.8)\times10^{-1}$
E_0	$(5.5\pm1.3)\times10^{2}$
$\Delta\gamma_1$	$(-4.4\pm3.0)\times10^{-1}$
E_1	$(1.1\pm0.4)\times10^{4}$

Fitting function (double broken power law):

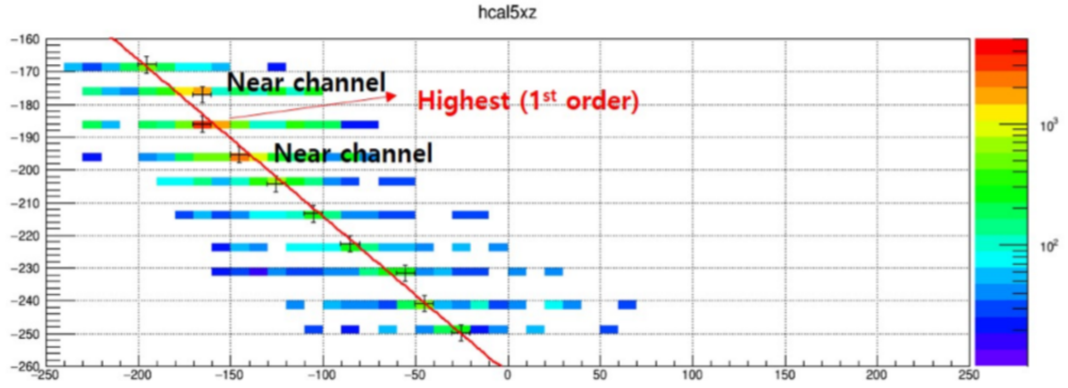
$$\Phi = E^{2.7} \times C \times \left(1 - \frac{p_0}{E} - \frac{p_1}{E^2}\right) \times \left(\frac{E}{45}\right)^{\gamma} \times \left(1 + \left(\frac{E}{E_0}\right)^{s}\right)^{\frac{\Delta\gamma}{s}} \times \left(1 + \left(\frac{E}{E_1}\right)^{s}\right)^{\frac{\Delta\gamma_1}{s}}$$

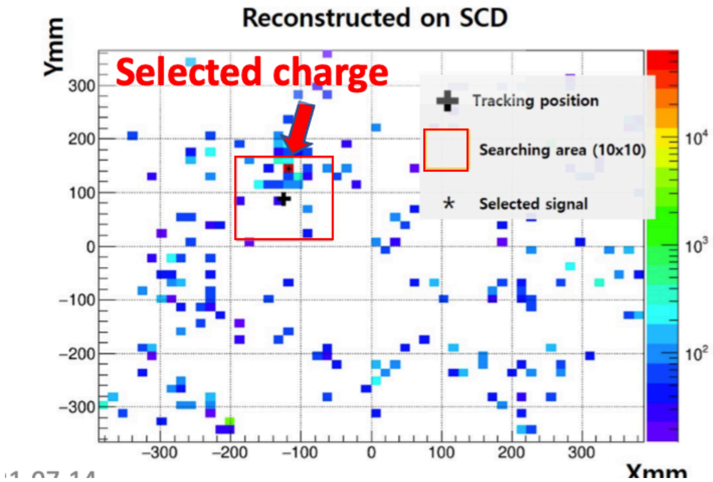
Low energy hardening softening

Gwangho Choi : “Analysis Result of the High-Energy Cosmic-Ray Proton Spectrum from the ISS-CREAM Experiment”

G.H. Choi on behalf of the ISS-CREAM collaboration ; chgwangho@skku.edu

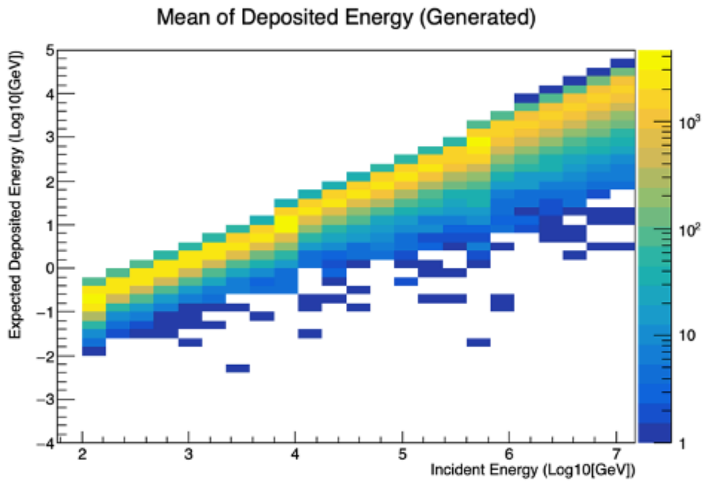
Tracking by CAL & charge determined by SCD





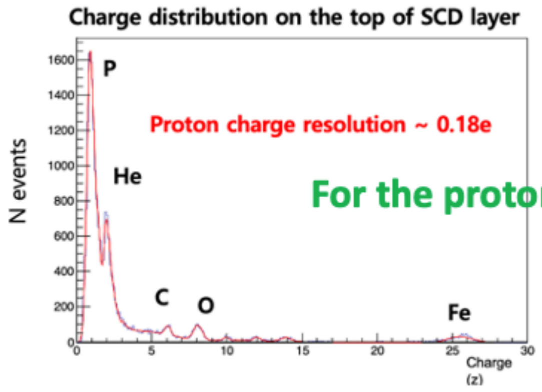
Spectral deconvolution

$$N_{inc,\,i} = \sum_j P_{i,j} N_{dep,\,j},$$



Correction for the small energy dependence of the energy resolution due to shower leakage

Charge distribution & Absolute flux for protons



For the protons range 0.7 ~ 1.7e

$$F = \frac{dN}{dE} \cdot \frac{(1-\delta)}{GF \cdot \varepsilon \cdot T}$$

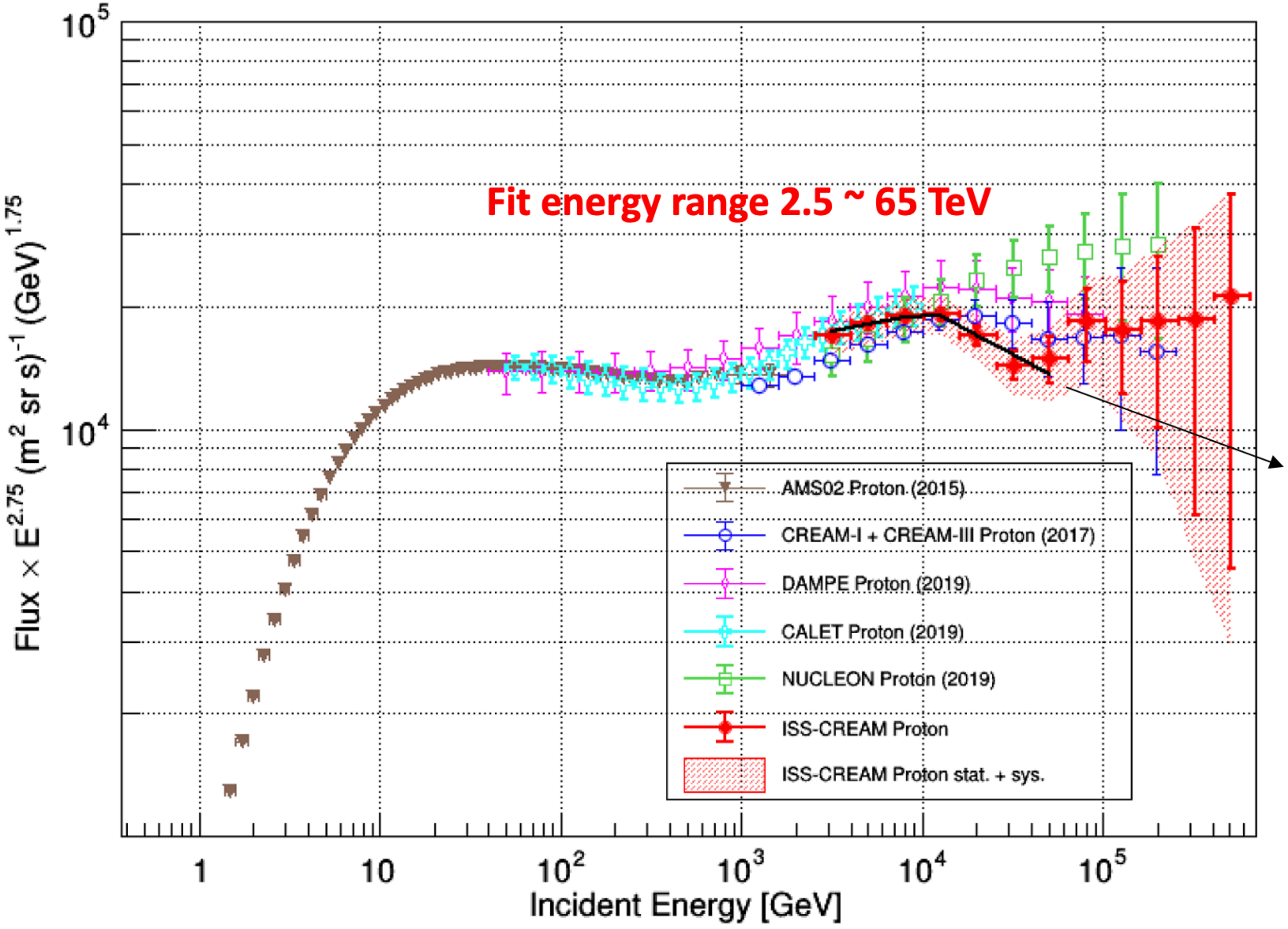
Absolute flux equation

ε : Efficiency
GF : Geometry factor
T : Live time
δ : Misidentified charge by backscattered particles

Gwangho Choi : "Analysis Result of the High-Energy Cosmic-Ray Proton Spectrum from the ISS-CREAM Experiment"

G.H. Choi on behalf of the ISS-CREAM collaboration ; chgwangho@skku.edu

Compilation of the proton spectrum



Measured around 2.5 ~ 655 TeV protons data

- Consistence result with the prior CREAM experiment within systematic errors.
- CREAM, DAMPE and NUCLEON observed spectral softens ~ 10 TeV.

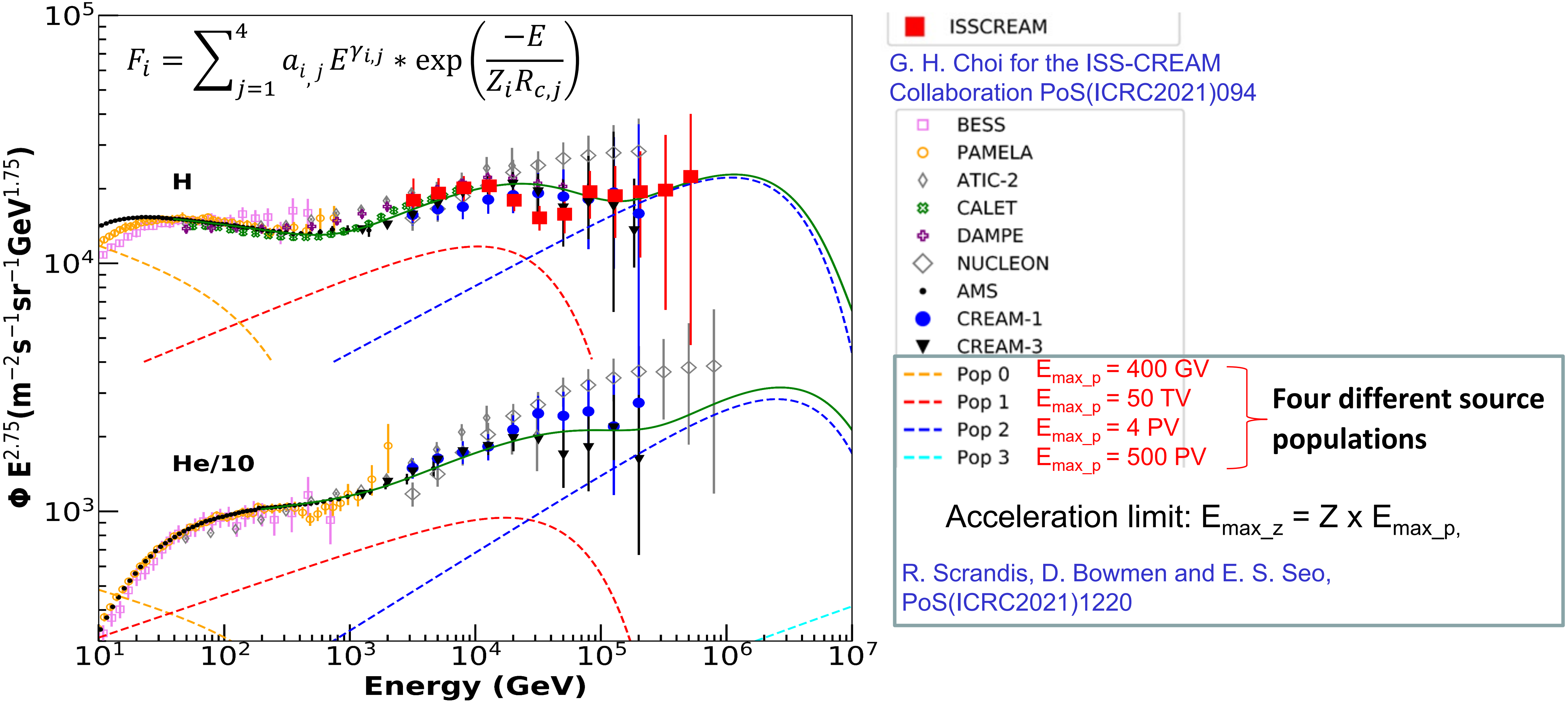
Spectral softening ~ 11.9 (± 5.2) TeV with significance 4.62 sigma

; 2.66 (± 0.03) with $\Delta\gamma$ = 0.33 (± 0.07)

$$\Phi(E) = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{\Delta\gamma}{\beta}}\right)^{-\beta} \quad (m^2\ sr\ s\ GeV)^{-1}$$

ISS-CREAM Proton Spectrum (2.5 – 655 TeV)

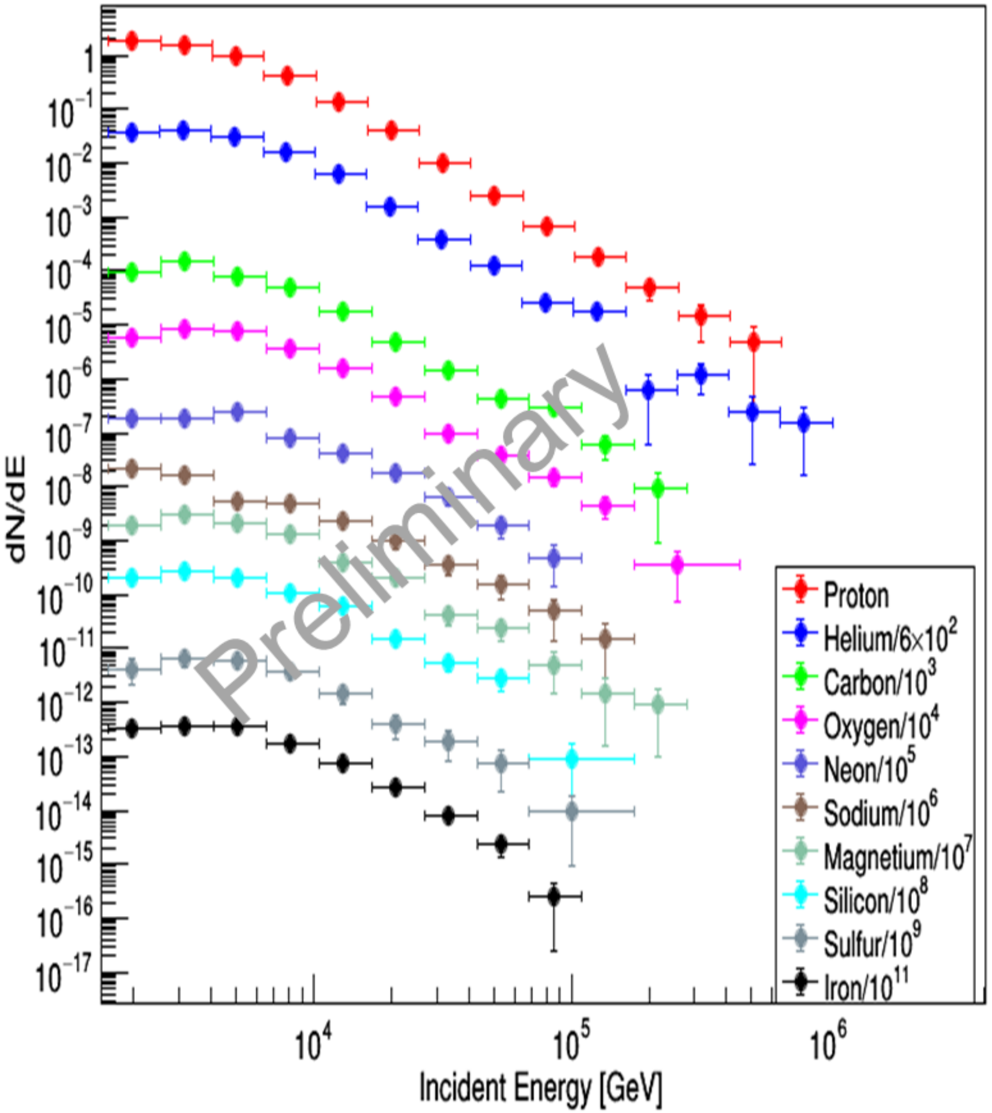
Eun-Suk Seo for the ISS-CREAM Collaboration, PoS(ICRC2021)095



Results from the ISS-CREAM experiment

Eun-Suk Seo for the ISS-CREAM Collaboration, PoS(ICRC2021)095

- The ISS-CREAM instrument successfully took high-energy cosmic-ray data for 539 days from 8/14/17 to 2/12/19.
- A proton spectrum is measured in the energy range 2.5 - 655 TeV.
  - A broken power law fit to 2.5 – 100 TeV data: $\gamma = 2.65 \pm 0.06$ and a break at ~9.94 ± 4.6 TeV with $\Delta\gamma = 0.26 \pm 0.1$.
  - At higher energies, the softening does not continue but the spectrum becomes harder again.
  - The deviation from a single power law near 10 TeV is consistent with the softening reported by CREAM-I &III, DAMPE, and NUCLEON, but ISS-CREAM extends measurements to higher energies than those prior measurements.
  - The spectral hardening at ~ 200 GV and softening ~ 10 TeV could indicate a transition from one type of source to another.
- Other nuclei analysis is in progress.



Helium Flux Measurement

Preliminary CALET results in the energy range from ~50 GeV to ~50 TeV.

UNIVERSITÀ DI SIENA 1240

Flux measurement:

$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

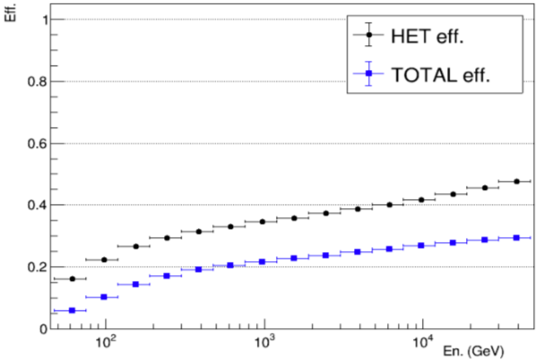
$N(E)$: events in unfolded energy bin

$S\Omega$: geometrical acceptance (510 cm^2sr)

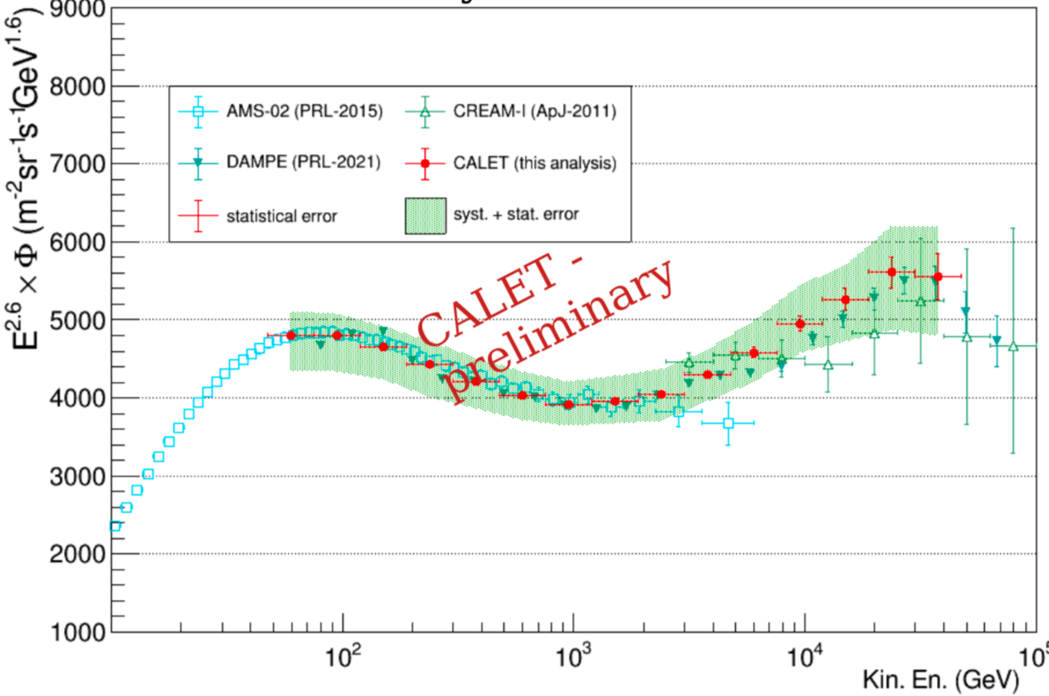
$\varepsilon(E)$: efficiency

T: live Time

ΔE: energy bin width

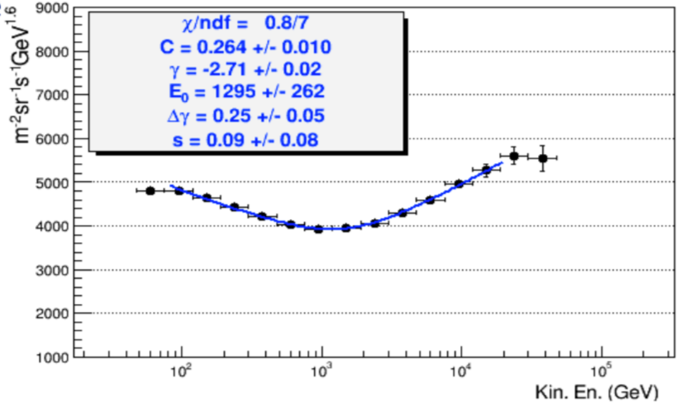


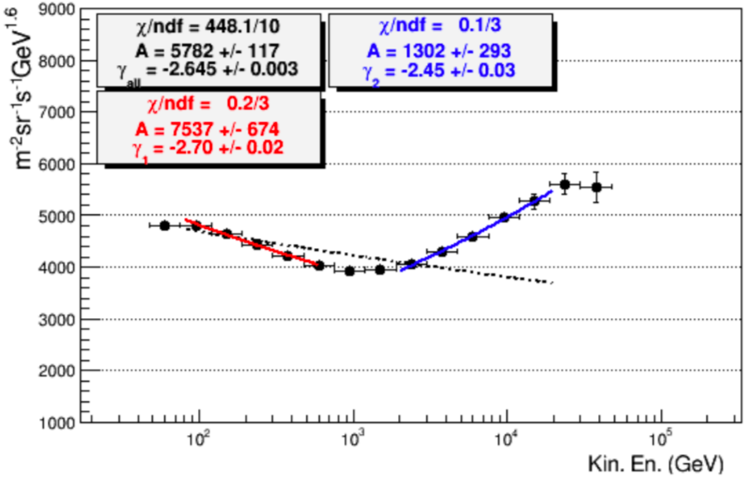
Preliminary Helium Flux x $E^{2.6}$



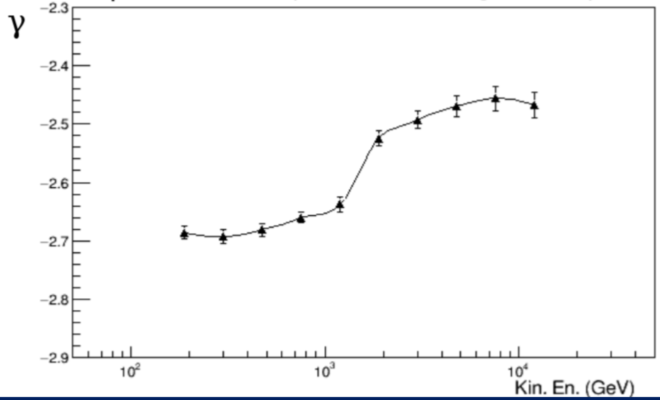
Spectral Behavior of Helium Flux

Preliminary results, only the statistical errors have been taken into account.



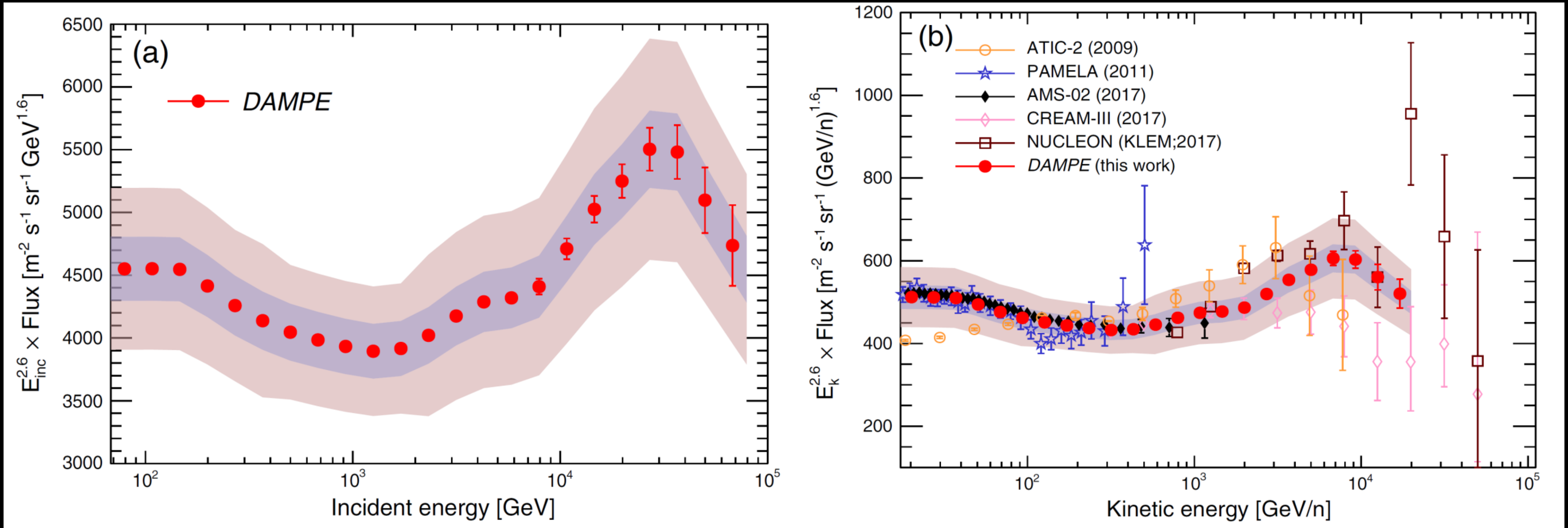


Spectral index (6 bins wide sliding windows)



- Sub-ranges of 80-600GeV, 2-20 TeV can be fitted with single power law function, but not the whole range.
- Progressive hardening up to the multi-TeV region was observed.
- "Smoothly broken power-law fit" gives power law index (γ), Δγ and break energy (E_0) consistent with the recent results from DAMPE.

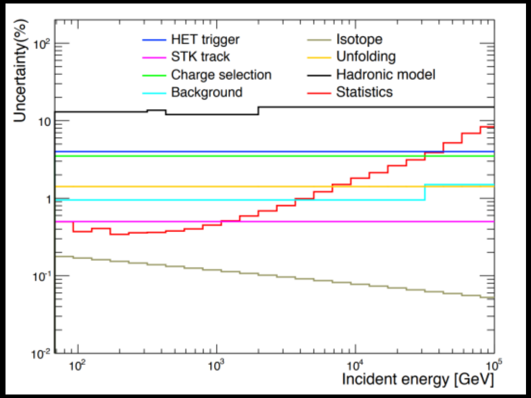
Helium energy spectrum



DATA SAMPLE:

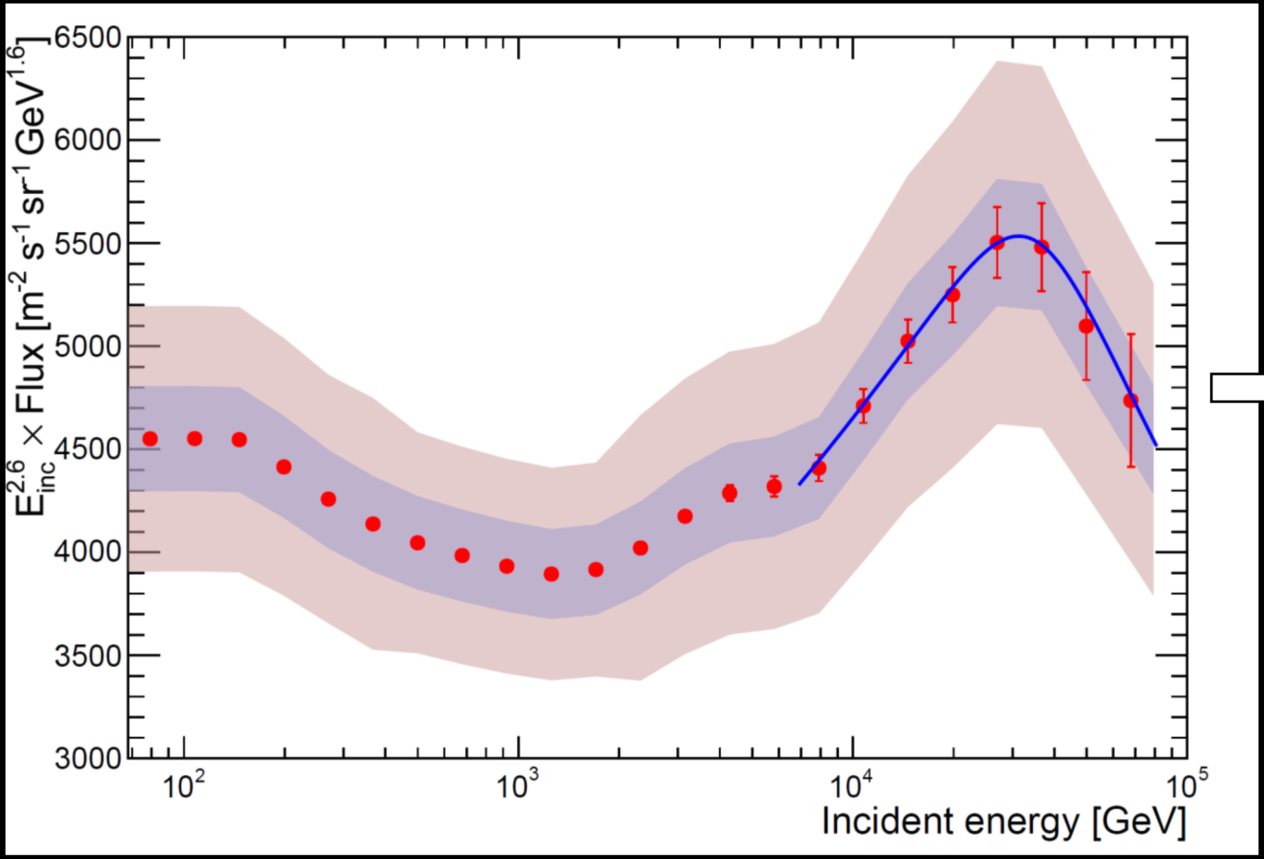
- 54 months of on-orbit data from January 1st, 2016 to June 30th 2020
- MC simulations with GEANT4 FTFP_BERT from 10GeV to 500TeV
- MC simulations with FLUKA 10GeV-500TeV

Error bars: statistical uncertainties
Inner dashed band: systematics due to the analysis σ_{ana}
Outer shaded band: $\sqrt{\sigma_{ana} + \sigma_{had}}$, σ_{had} obtained from the comparison with FLUKA MC simulations.



The DAMPE measurement of the helium energy spectrum confirms the observation of a spectral hardening at TeV-energies previously highlighted by other experiments and clearly shows an evidence of a spectral softening at tens of TeV.

Helium flux fit - Softening

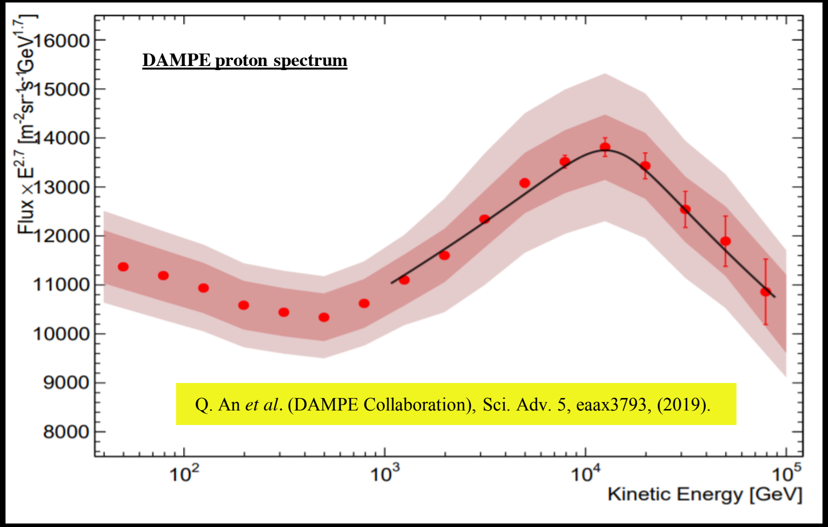


Fit of the softening structure with a Smoothly Broken Power-Law (SBPL) in the energy range [6.8 TeV - 80 TeV].

$$\Phi(E) = \Phi_0 \left(\frac{E}{\mathrm{TeV}}\right)^{\gamma} \left[1 + \left(\frac{E}{E_b}\right)^{s}\right]^{\Delta\gamma/\omega}$$

$$E_b = 34.4^{+6.7}_{-9.8}\ \mathrm{TeV}$$
$$\gamma = 2.41^{+0.02}_{-0.02}$$
$$\Delta\gamma = -0.51^{+0.18}_{-0.20}$$
$$s = 5.0\ (fixed)$$

Significance of the softening: $\sim 4.3\ \sigma$

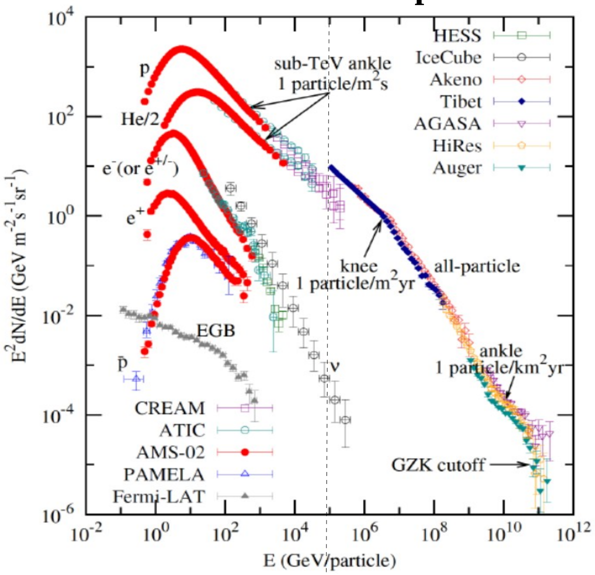


By comparing the implications of this result with the softening observed by DAMPE in the proton energy spectrum at ~13.6 TeV, it turns out a charge-dependent softening energy, even if a mass-dependence of the structure cannot be ruled out.

Measurement of the light component (p+He) energy spectrum with the DAMPE space mission

Francesca Alemanno (on behalf of the DAMPE collaboration) Indico-ID: 970

Measuring light elements in space (i.e. proton + helium spectrum) gives the **possibility to compare results between direct and indirect experiments**



Space-based experiments (direct measurements)

Ground-based experiments (indirect measurements)

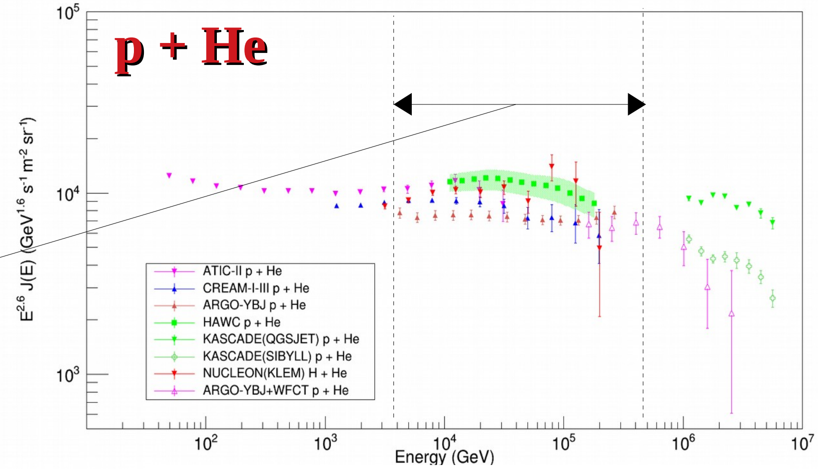
Motivations

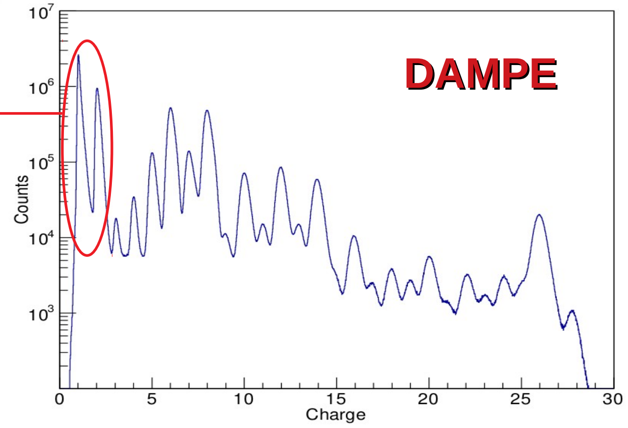
In this energy region direct and indirect spectra can be compared

Proton and Helium are well separated from other peaks

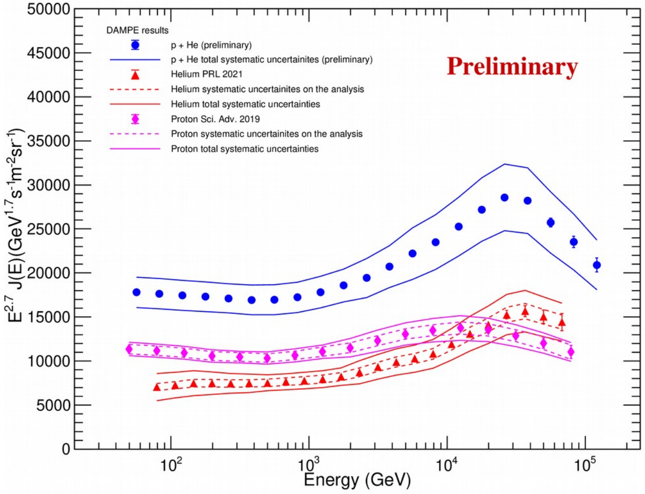
VERY LOW CONTAMINATION (less than 0.1 %)

Looser cuts
Possibility to go to higher energy

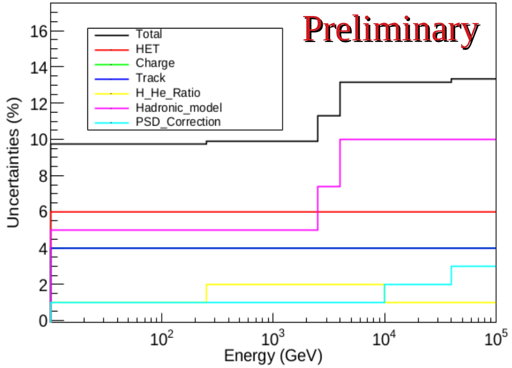




p+He spectrum with 60 months of data



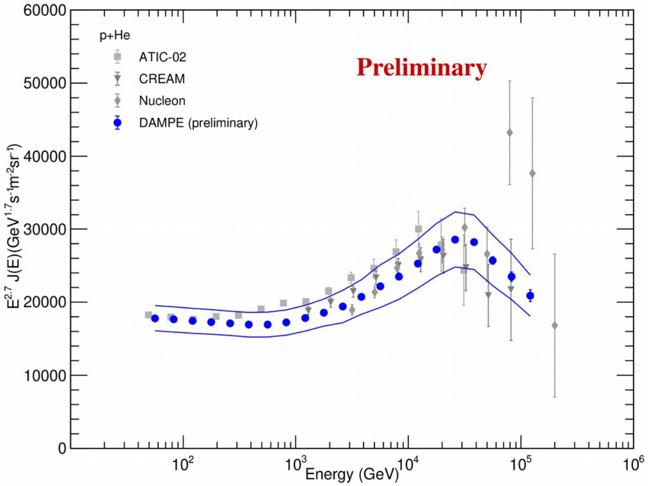
p+He systematic uncertainties



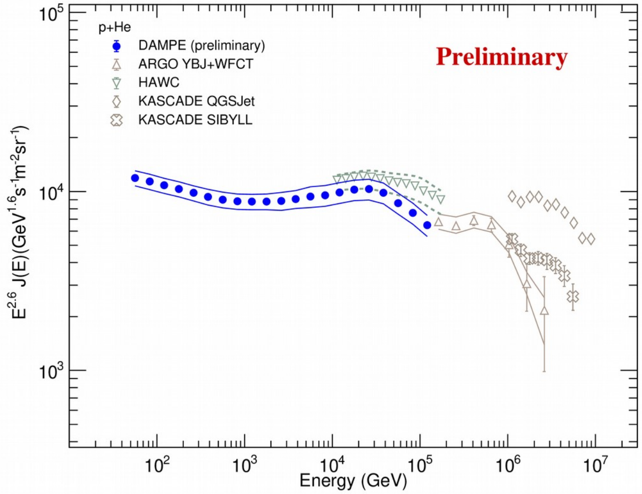
The p+He spectrum shows a spectral hardening at ~ 600 GeV and a softening at ~ 25 TeV

Good agreement with the sum of the two proton and helium independent analysis!

DIRECT MEASUREMENTS



INDIRECT MEASUREMENTS



- **The extension of the p+He spectrum to higher energy (~ 500 TeV) is ongoing**
- **The final evaluation of systematic uncertainties is in progress**

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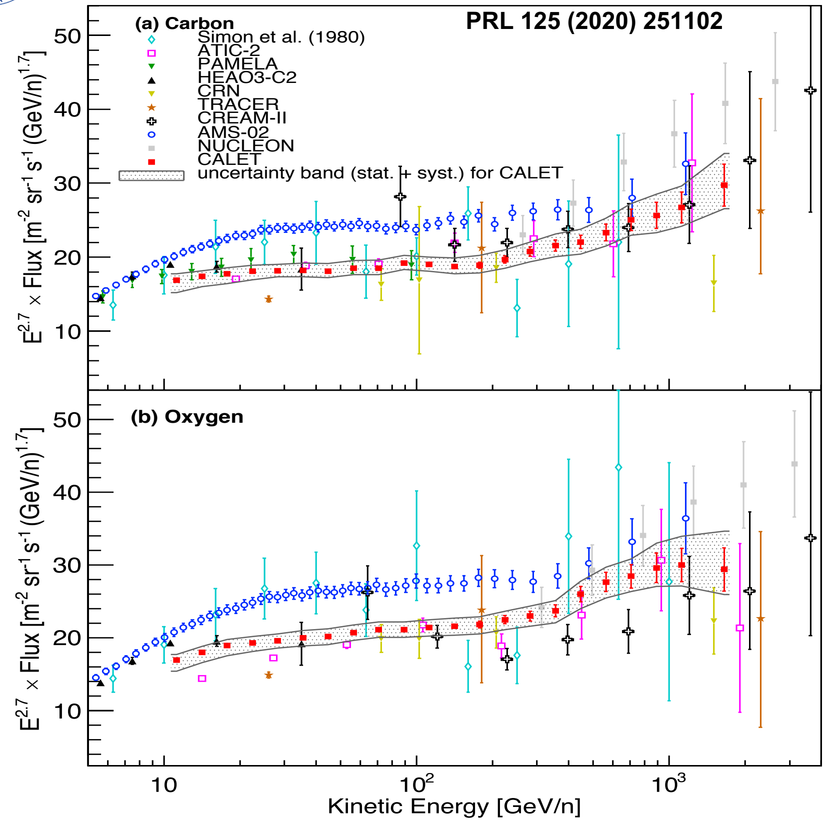
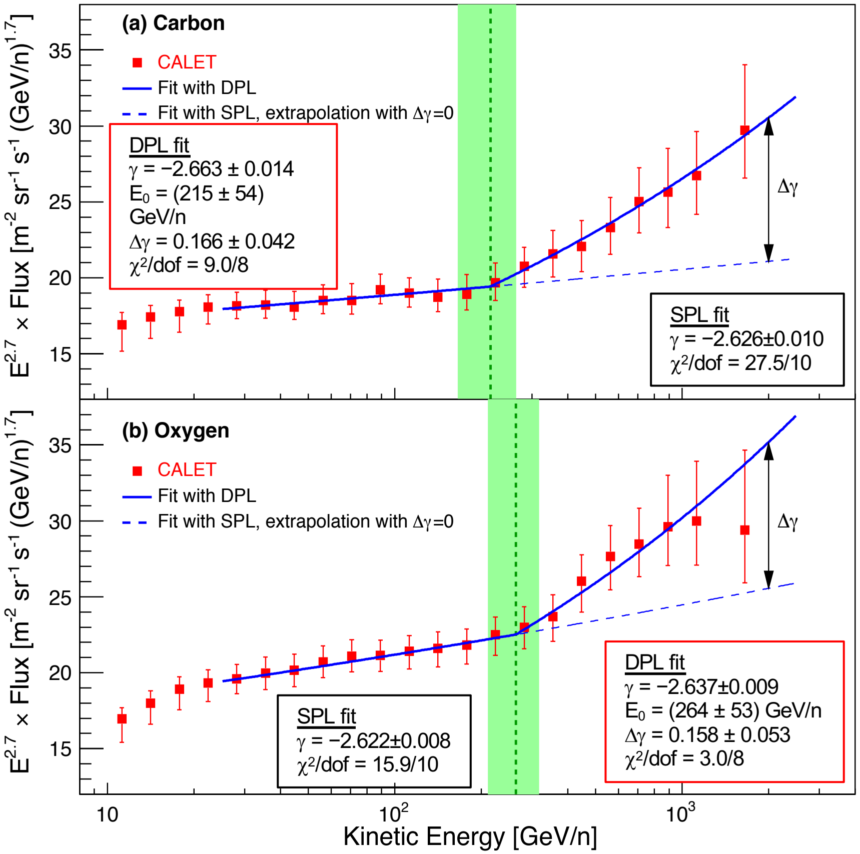
Carbon and oxygen

CALET measurement of C and O spectra from 10 GeV/n to 2.2 TeV/n



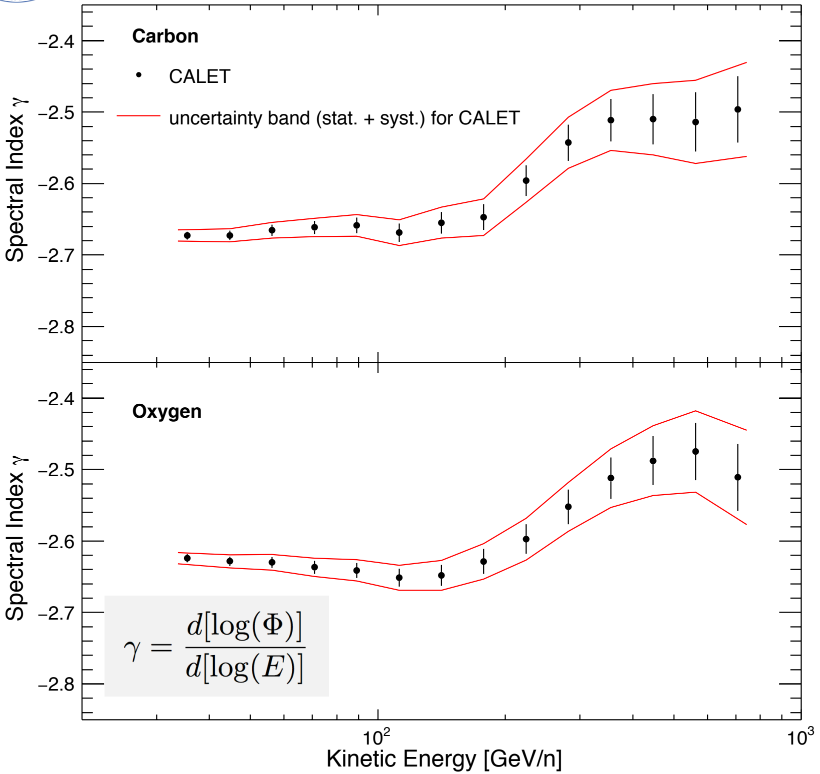


CALET spectra consistent with PAMELA and other experiments

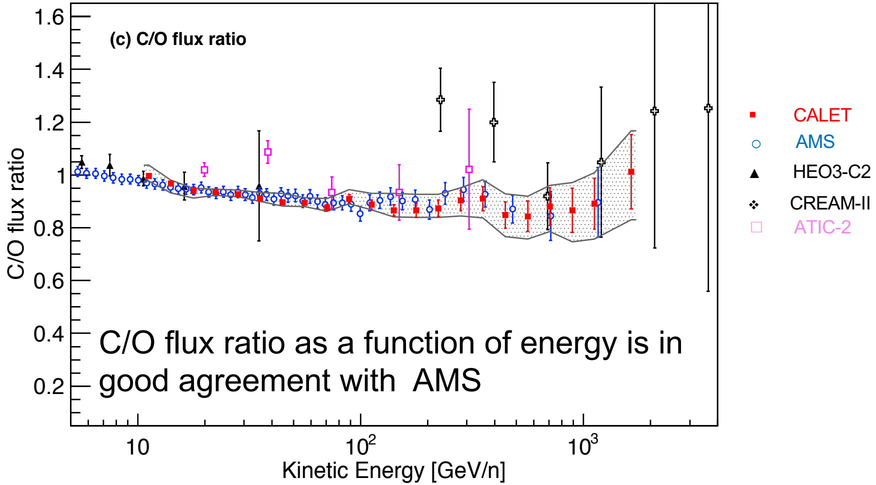
Spectral shape similar to AMS but lower normalization

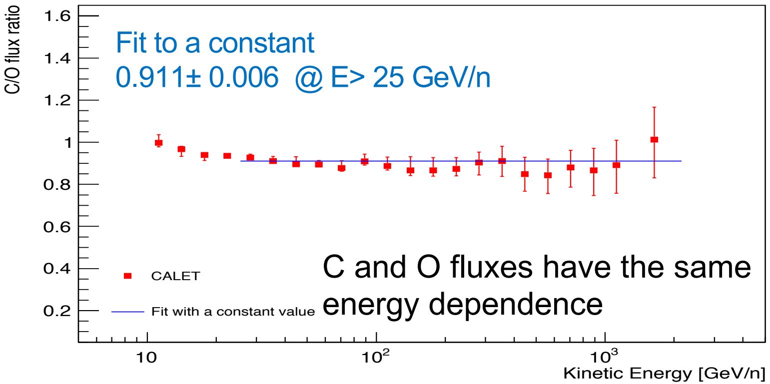
SPL hypothesis excluded at 3.9σ (3.2σ) level for C (O)

Energy dependence of the spectral index



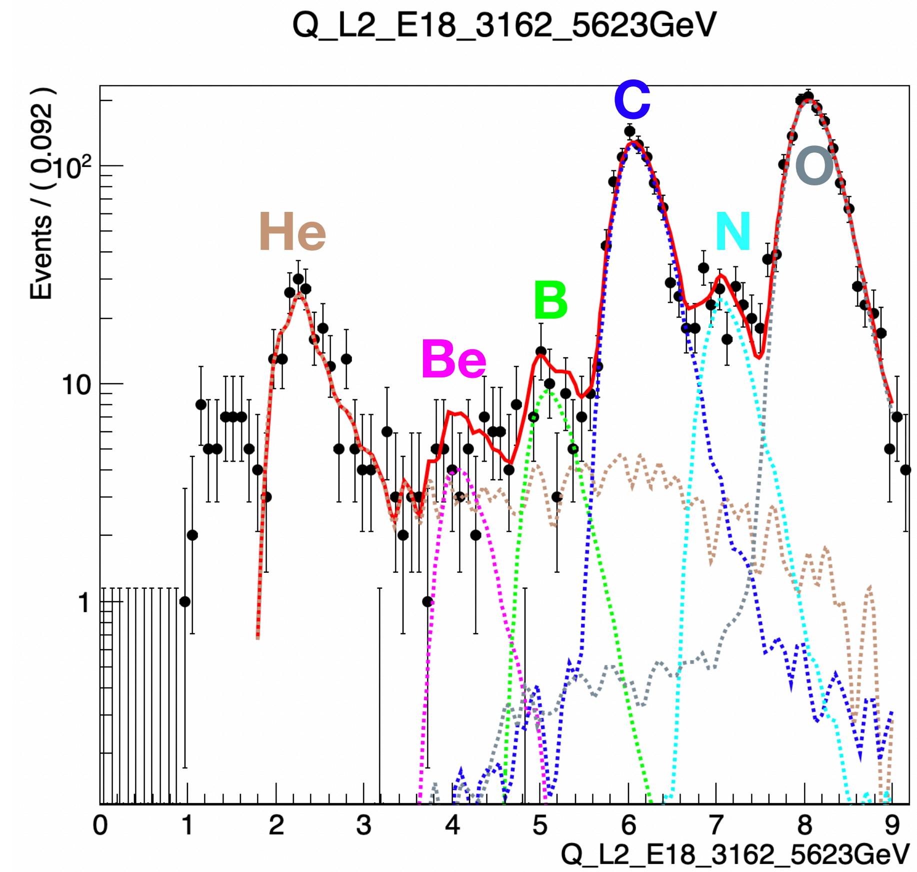
$$\gamma = \frac{d[\log(\Phi)]}{d[\log(E)]}$$

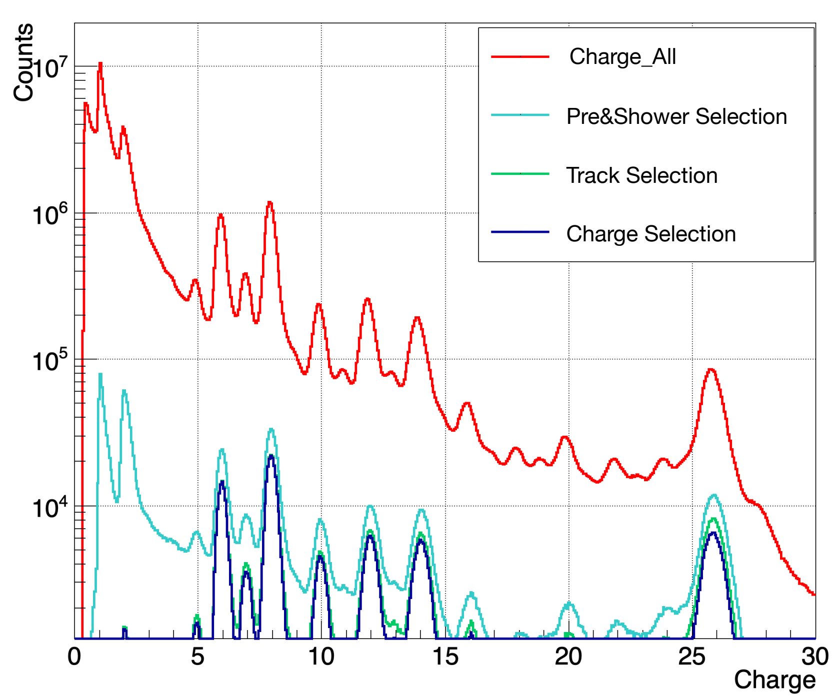


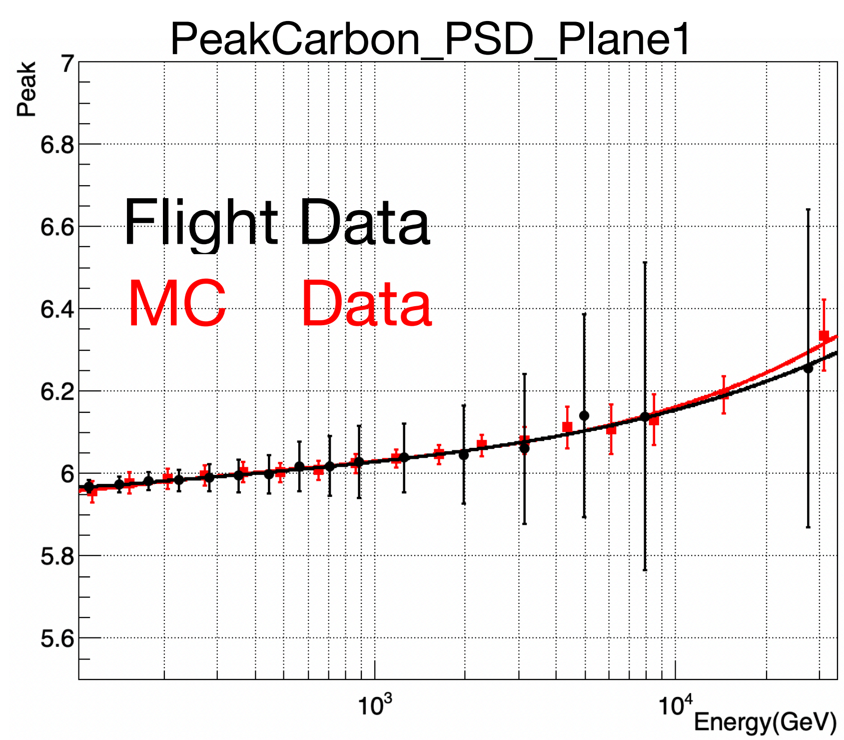


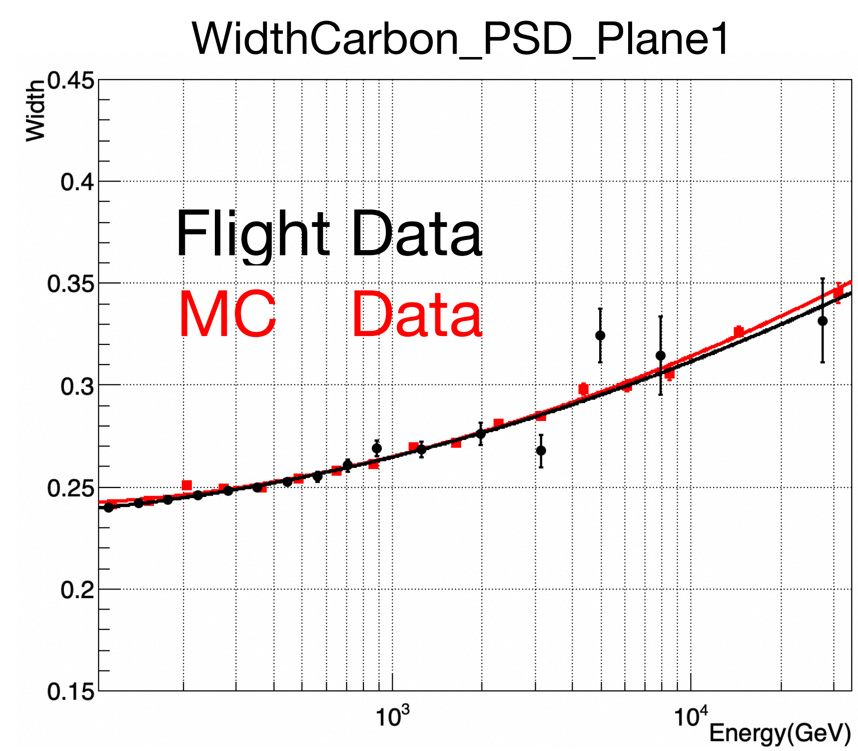
Carbon and oxygen fluxes harden in a similar way above a few hundred GeV/n

- **Not in SAA region**
- **BGO Energy > 100 GeV**
- **High Energy Trigger (G3)**
- **Track Selection**
- **Cross PSD & BGO**
- **PSD Charge Selection**

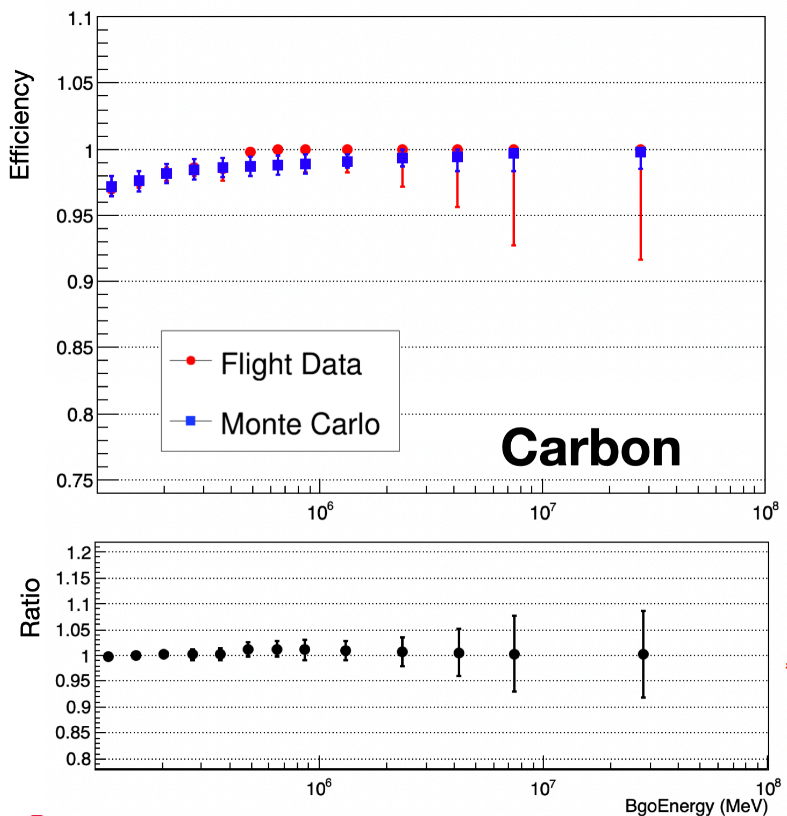




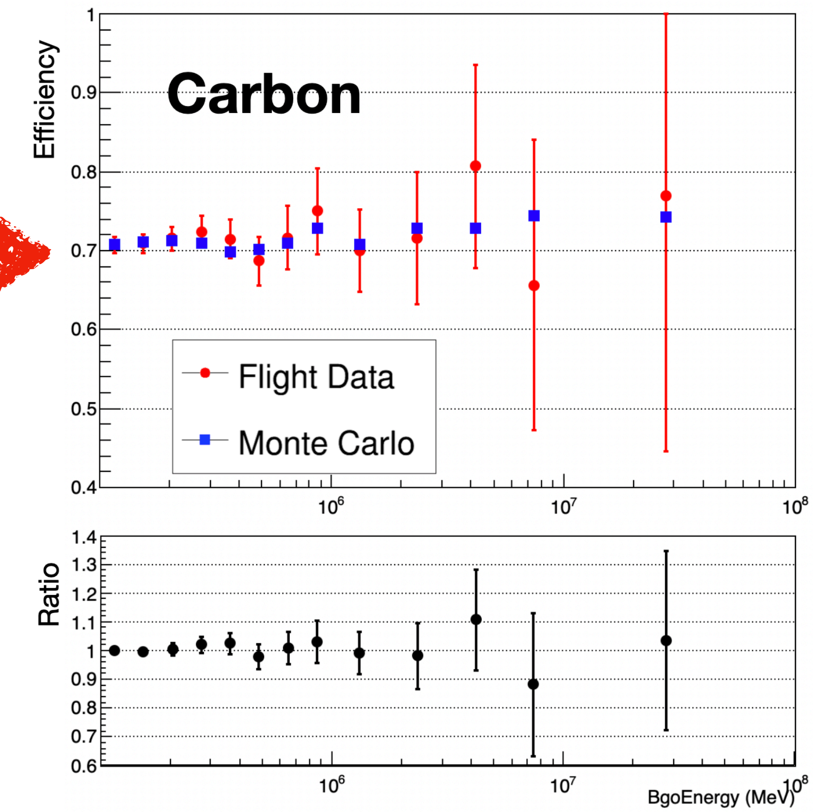




High Energy Trigger Efficiency



PSD Charge Efficiency



$$\varepsilon_{Charge_Y} = \frac{N_{y1}}{N_{y0\&Plane_x}}$$

$$\varepsilon_{trigger} = \frac{N_{G3\&G4}}{N_{G4}}$$

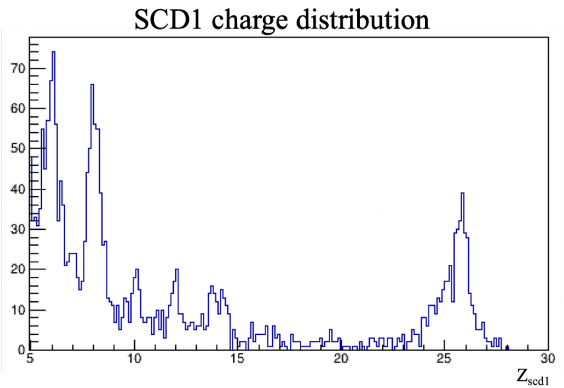
Summary:

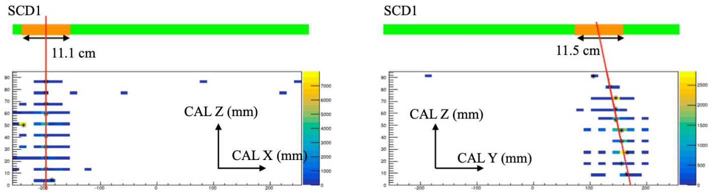
- DAMPE has been in smooth operation more than 5 years since its launch on Dec. 17th 2015.
- The selection criteria for carbon and oxygen analyses were presented.
- Efficiencies are being validated by Monte Carlo.
- **In the future**
  - More studies on systematics are necessary.
  - The quenching effect of BGO energy should be considered.

Cosmic-ray Heavy Nuclei Spectra Using the ISS-CREAM Instrument

Sinchul Kang for the ISS-CREAM collaboration (sinchul1216@gmail.com)

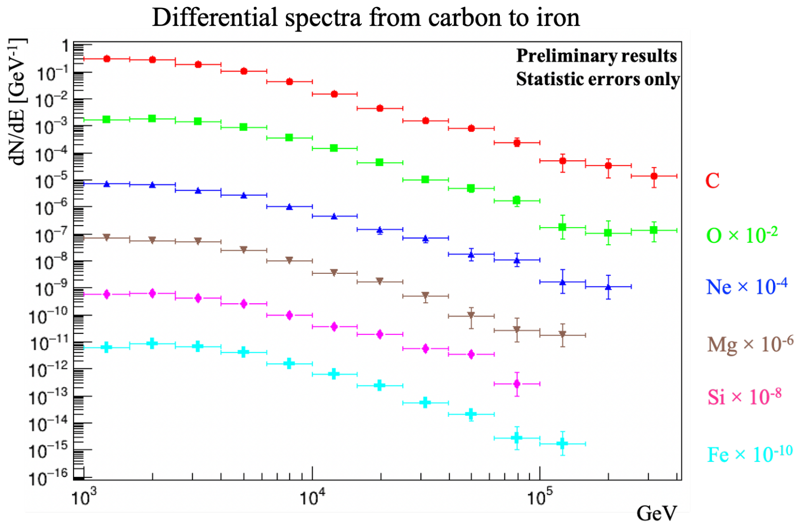
Charge Determination





- The SCD top layer (SCD1) is used for charge selection in this analysis.
- The charge distribution from carbon to iron are clearly separated in this presentation.
- The relative abundance SCD1 charge distribution has no physical significance as correction for interactions and propagation have not been applied.

Results

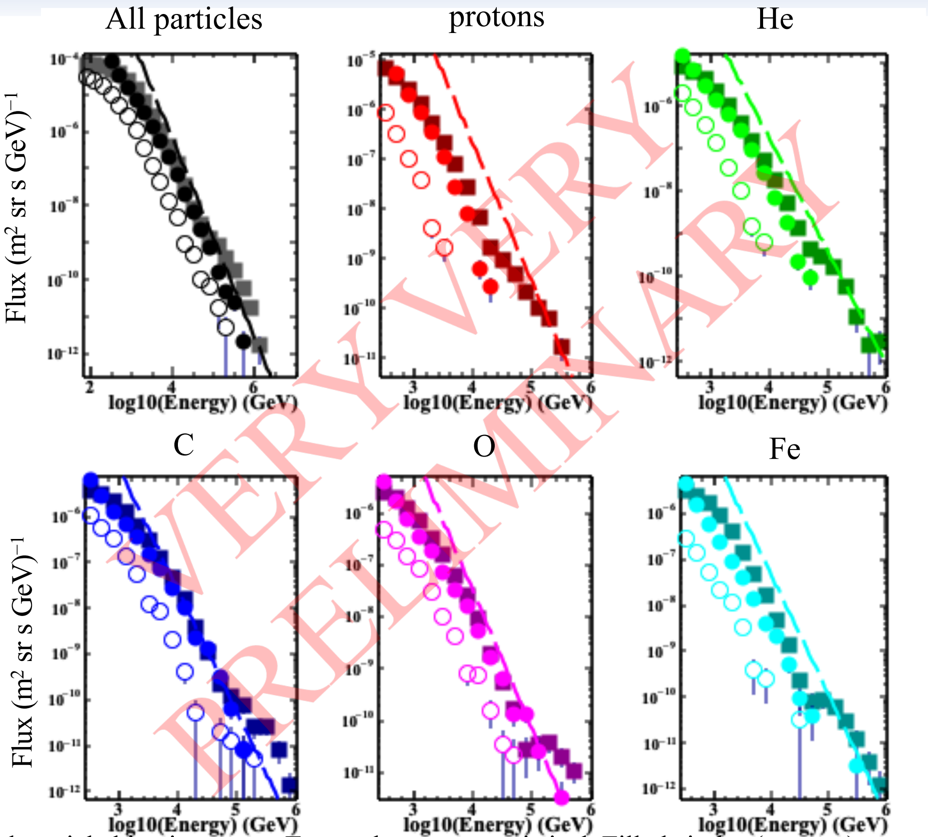


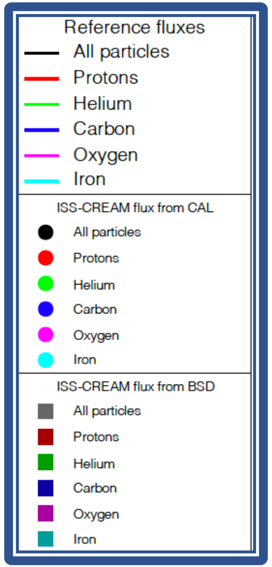
- This is a preliminary result of differential spectra from the ISS-CREAM experiment.
- The events of each element are determined from SCD1 charge distribution.
- The mean deposited energies in the calorimeter from incident energies for protons are used to determine incident energies in this presentation.
- All spectra show power-law like distributions.
- Correction for efficiencies aren't applied yet.
- The differential spectral will be corrected for geometry factor, live time and efficiencies to get the absolute fluxes.

ISS-CREAM: VERY Preliminary results

Scott Nutter
Poster 696
ICRC2021

- Flux vs particle total kinetic energy for selected charges using conservative x6 scaling of CAL energies.
  - BSD calibration suggested factor of 6-8 solves many problems
    - Better agreement between MC and on-orbit data
    - Reasonable fluxes/number of particle detections
      - Instrument threshold raised
    - Agreement between fluxes calculated with BSD and with CAL
- Future work:
  - Refine BSD calibration of CAL energy scale.
  - Refine proton selection cuts (tricky!).
  - Refine efficiency using on-orbit data compared to simulated data.
  - Estimate systematic errors.





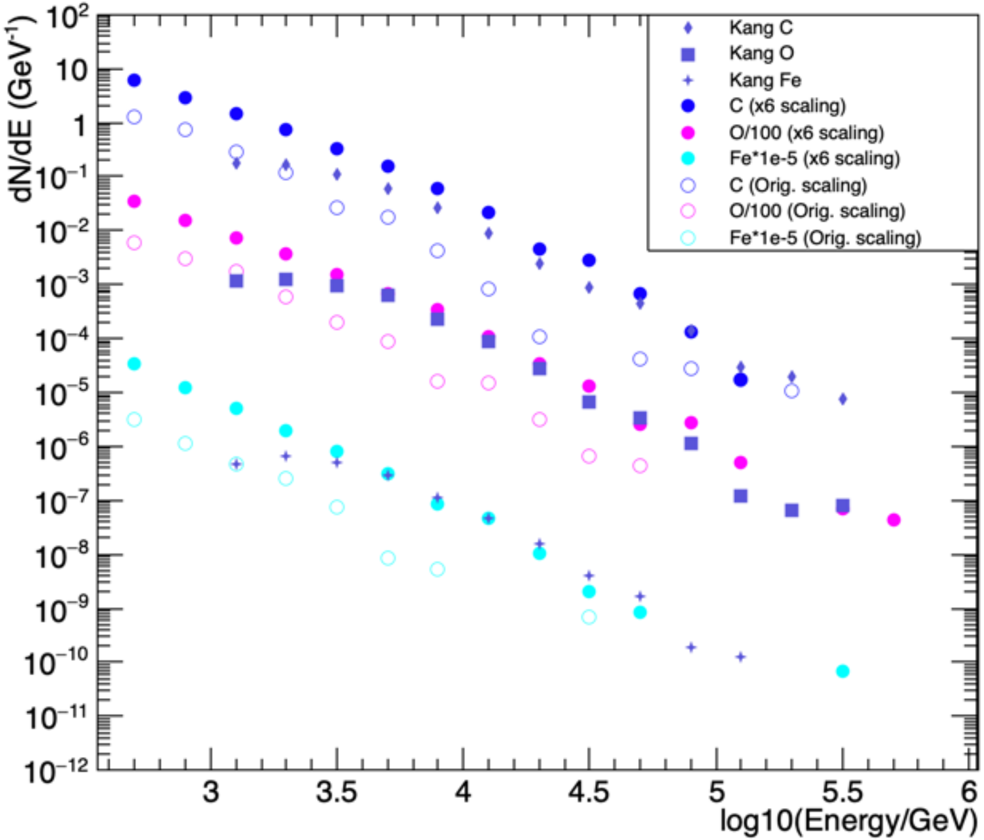
Flux vs total particle kinetic energy. Errors shown are statistical. Filled circles (squares) are reconstructed from the x6 scaled CAL (BSD) energy deposit. Open circles are the flux using the original CAL energy scaling as described in the proceedings. Dashed lines are reference fluxes from Wiebel-Sooth, Biermann, and Meyer, *Astron & Astrophys*, v.330, p.389-398 (1998).

Similar energy scale between analyses

Comparison of this analysis and S. Kang dN/dE for Carbon, Oxygen, and Fe

- Kang data scaled vertically for difference in live time.
- Energy reconstruction for protons gives similar results in two analyses

- Note: Vertical scaling applied to put all on one plot:
  - O x1.0e-2
  - Fe x1.0e-5



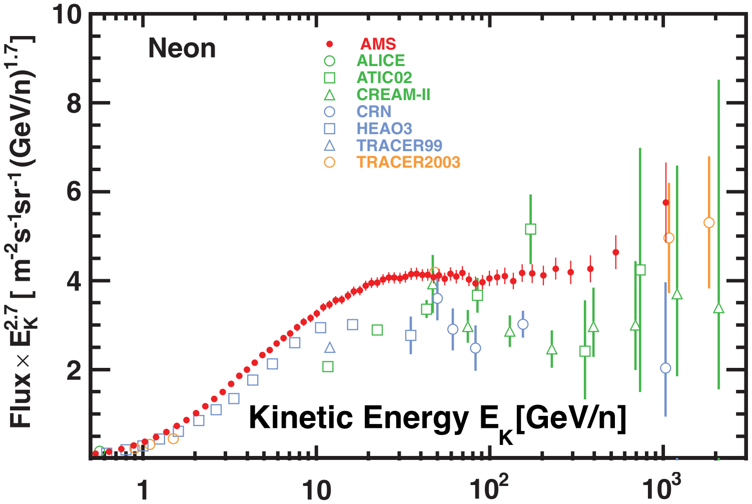
Nuclei with $10 \leq Z \leq 14$

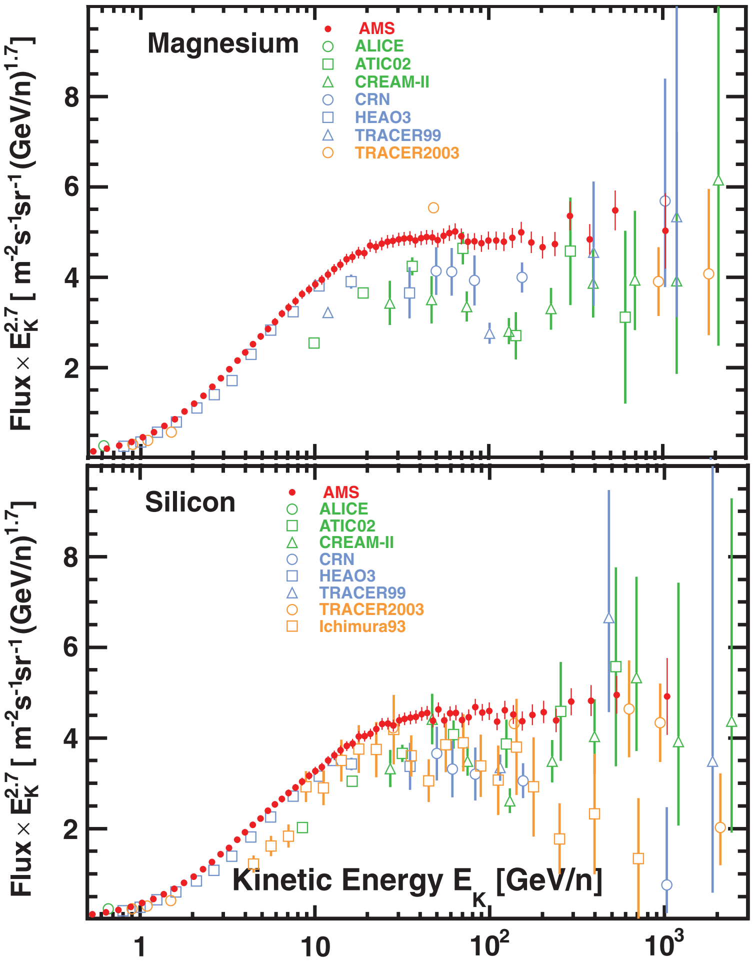
AMS Neon, Magnesium and Silicon CRs Fluxes

M. Aguilar *et al.*, PRL **124**, 21102 (2020)

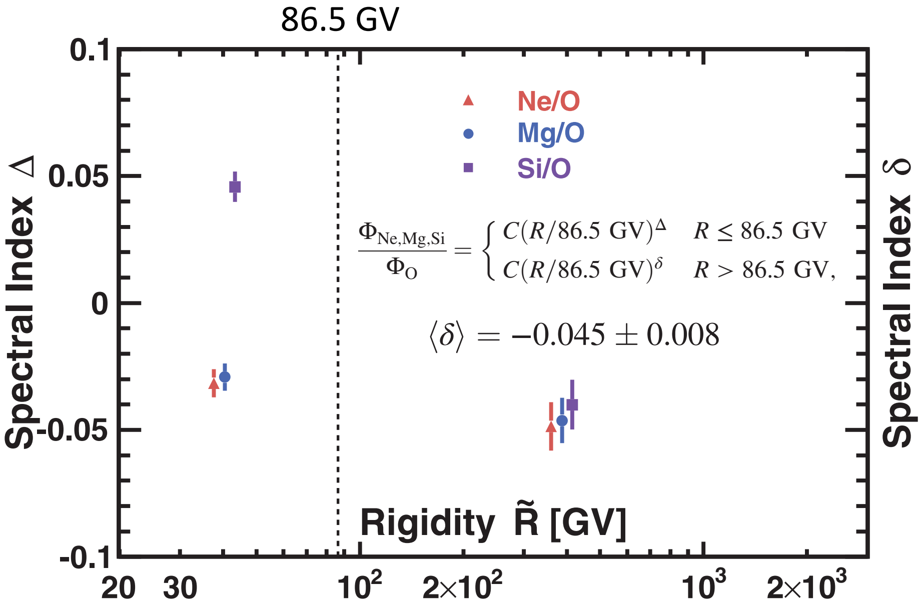
The publication has full description of analysis procedure and systematic error evaluation.

For comparison purposes our results are here converted from rigidity to kinetic energy per nucleon.

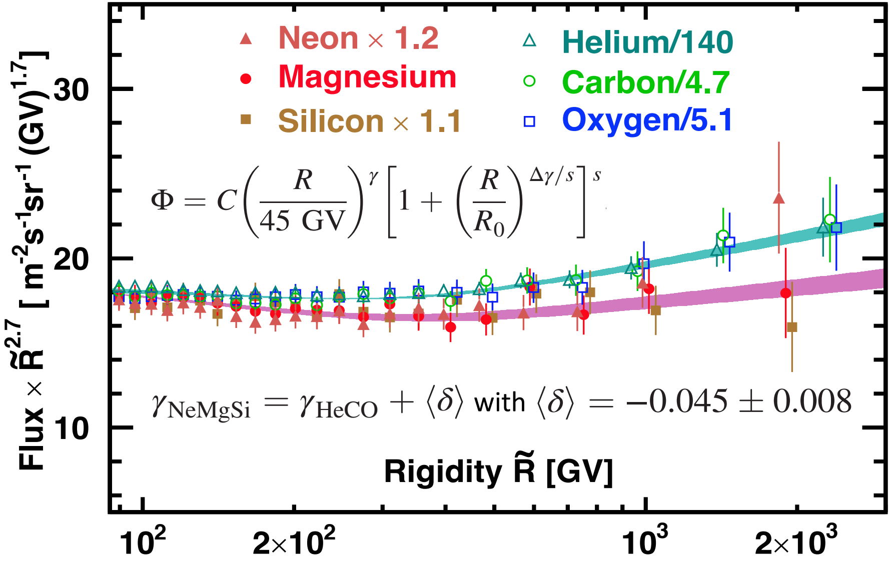




Properties of Primary Cosmic Rays with AMS



M. Aguilar *et al.*, PRL **124**, 21102 (2020)



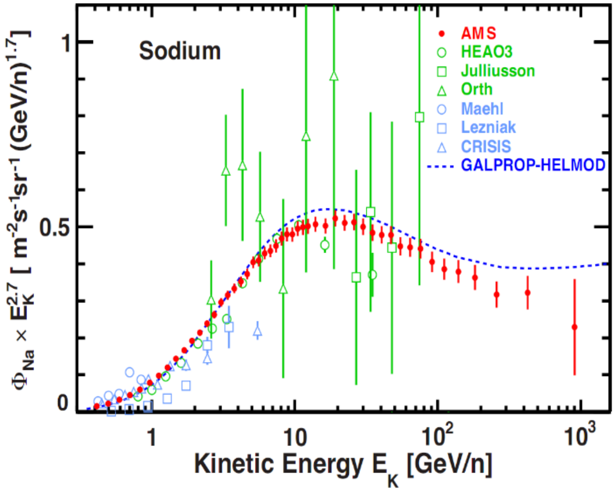
To examine the rigidity dependence difference between low-Z He, C and O and high-Z Ne, Mg and Si primaries the Ne/O, Mg/O, and Si/O flux ratios were studied. Their ratios differs by a power law by more than **5σ** above 86.5 GV showing that Ne, Mg and Si is a different class of primary CRs than He, C and O.

A. Oliva for the AMS Coll., Properties of Ne, Mg and Si Primaries in CRs Results from AMS, Indico-ID: 763, ICRC 2021.

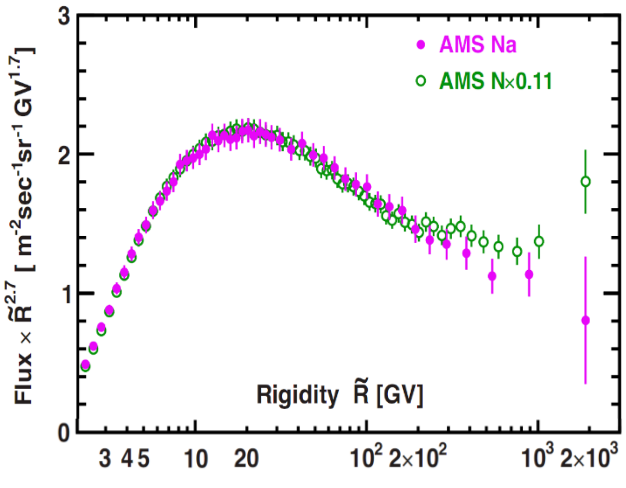
Cheng Zhang: AMS Sodium Flux Result (Indico-ID: 743) (1/2)

AMS Collaboration. Properties of a New Group of Cosmic Nuclei: Results from the Alpha Magnetic Spectrometer on Sodium, Aluminum, and Nitrogen

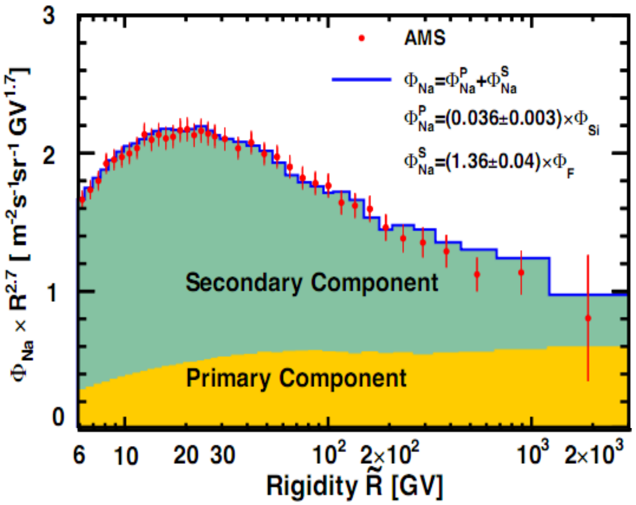
PHYSICAL REVIEW LETTERS 127, 021101 (2021), Published 7 July 2021



The AMS sodium flux as functions of E_K together with earlier measurements

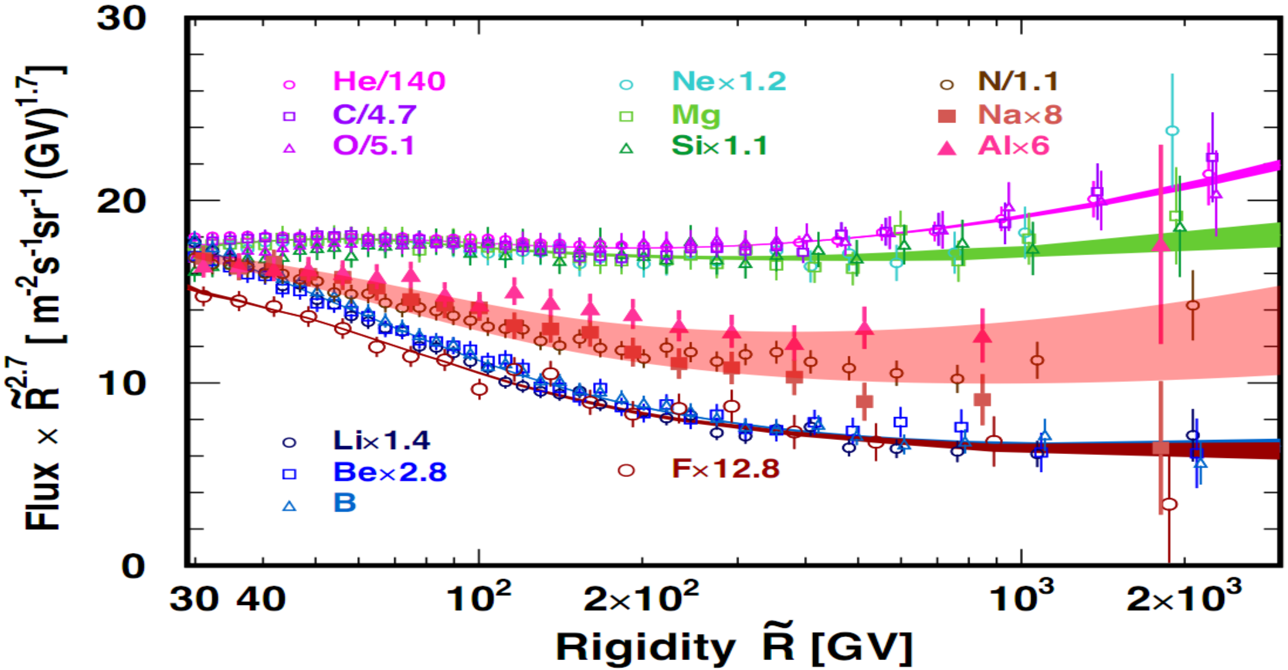


The AMS sodium flux together with the rescaled AMS nitrogen flux as function of rigidity



The AMS sodium flux Φ_{Na} fit to the weighted sum of the silicon flux Φ_{Si} and the fluorine flux Φ_F above 6 GV

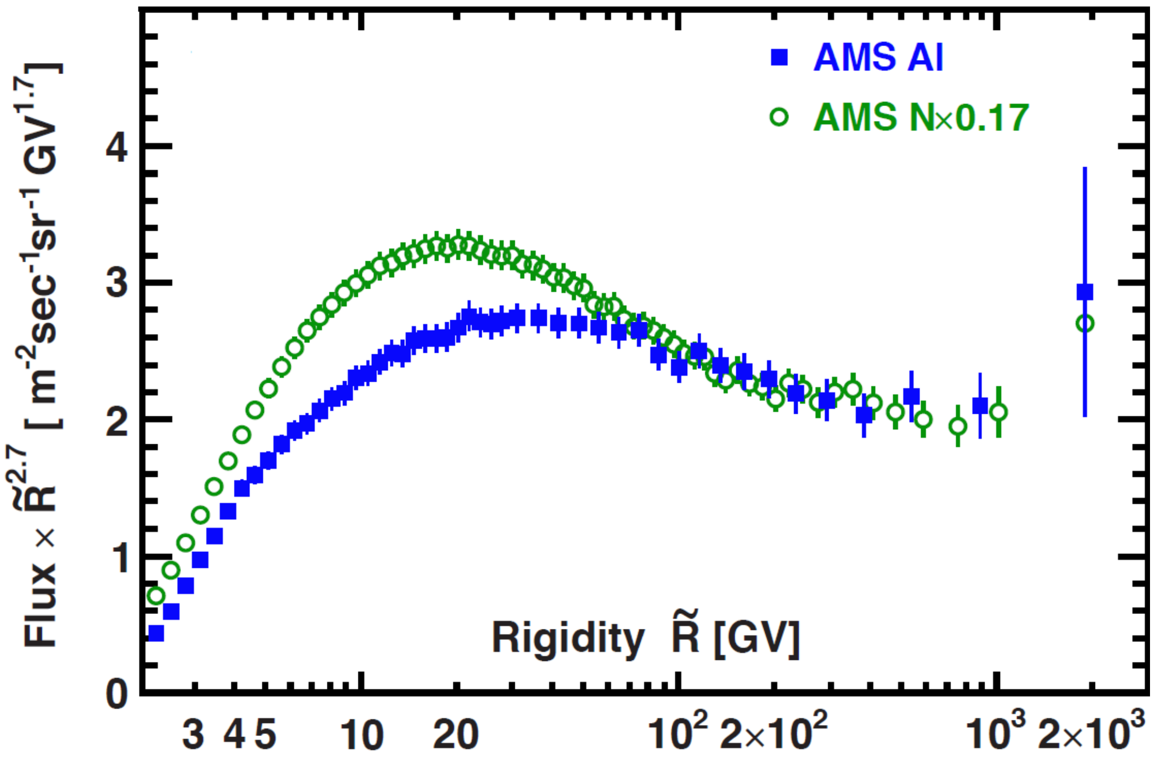
Cheng Zhang: AMS Sodium Flux Result (Indico-ID: 743) (2/2)



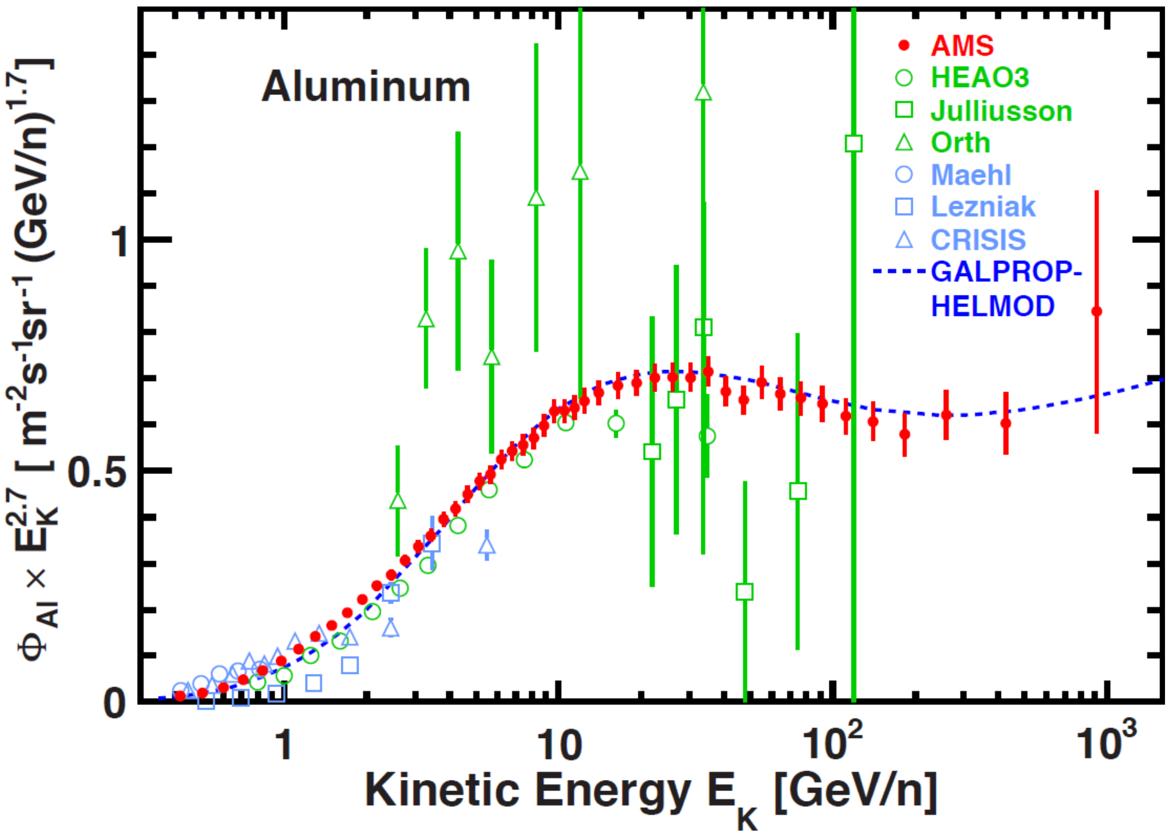
- Precision measurement of sodium (Na) cosmic ray flux from 2.15 GV to 3.0 TV based on 0.46 million AMS data (8.5 years) has been presented.
- Na and N belong to a distinct cosmic ray group and are the combinations of primary and secondary cosmic rays. The fraction of the primary component increases with rigidity for N and Na fluxes and becomes dominant at the highest rigidities.
- The Na/Si abundance ratio (0.036 ±0.003) at the source (primary component) is determined independent of cosmic ray propagation.

Properties of Cosmic Aluminum Nuclei: Results from the Alpha Magnetic Spectrometer

AMS aluminum flux together with the rescaled AMS nitrogen flux



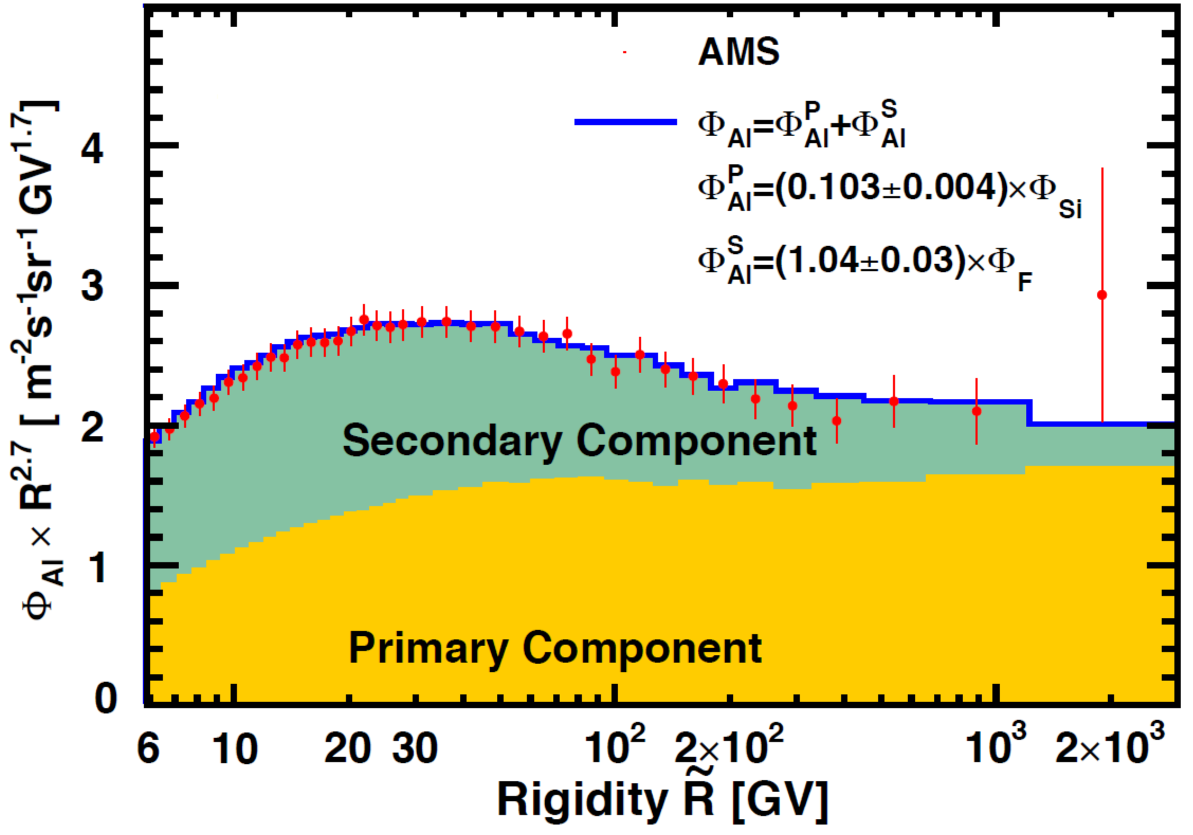
AMS aluminum flux compared with other experiments



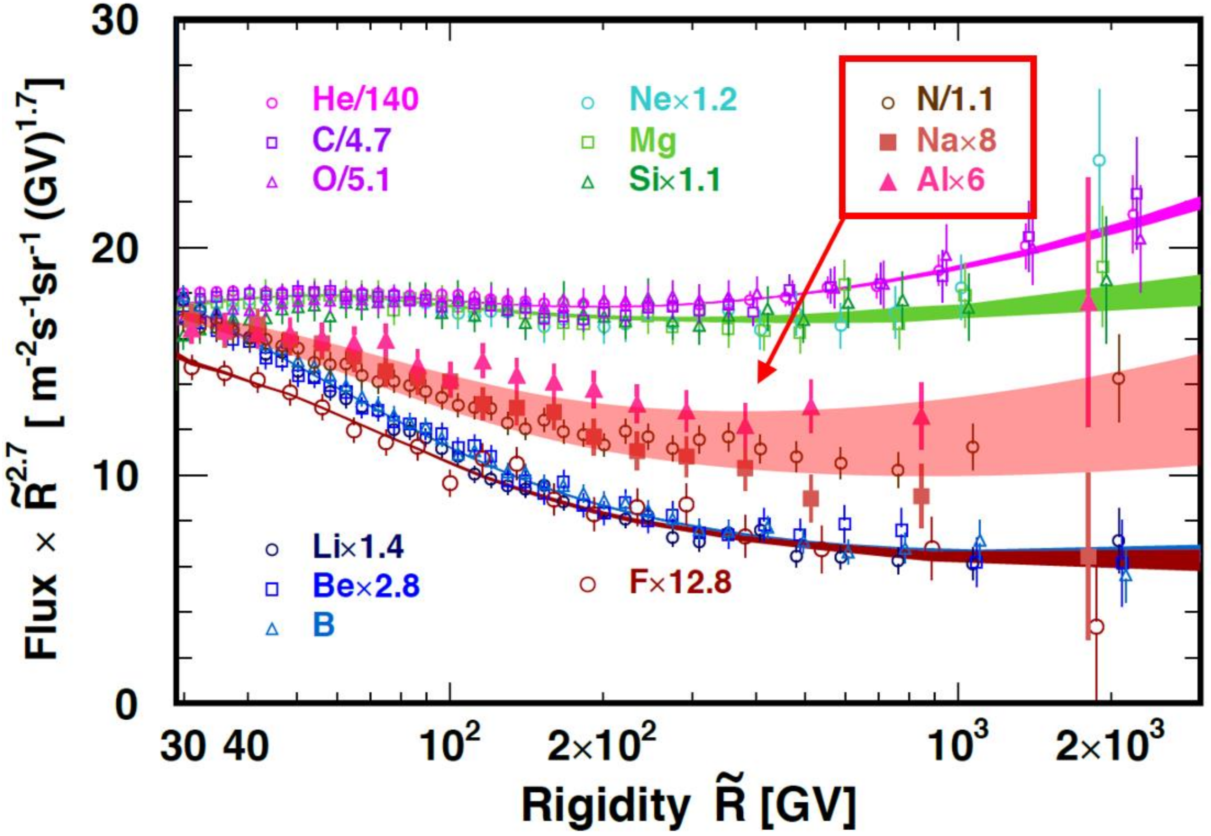
Zhen Liu, ICRC discussion session CRD 17, **indico-ID: 91896950007**

Properties of Cosmic Aluminum Nuclei: Results from the Alpha Magnetic Spectrometer

Property of aluminum flux



Cosmic nuclei fluxes measured by AMS from He (Z = 2) to Si (Z = 14)



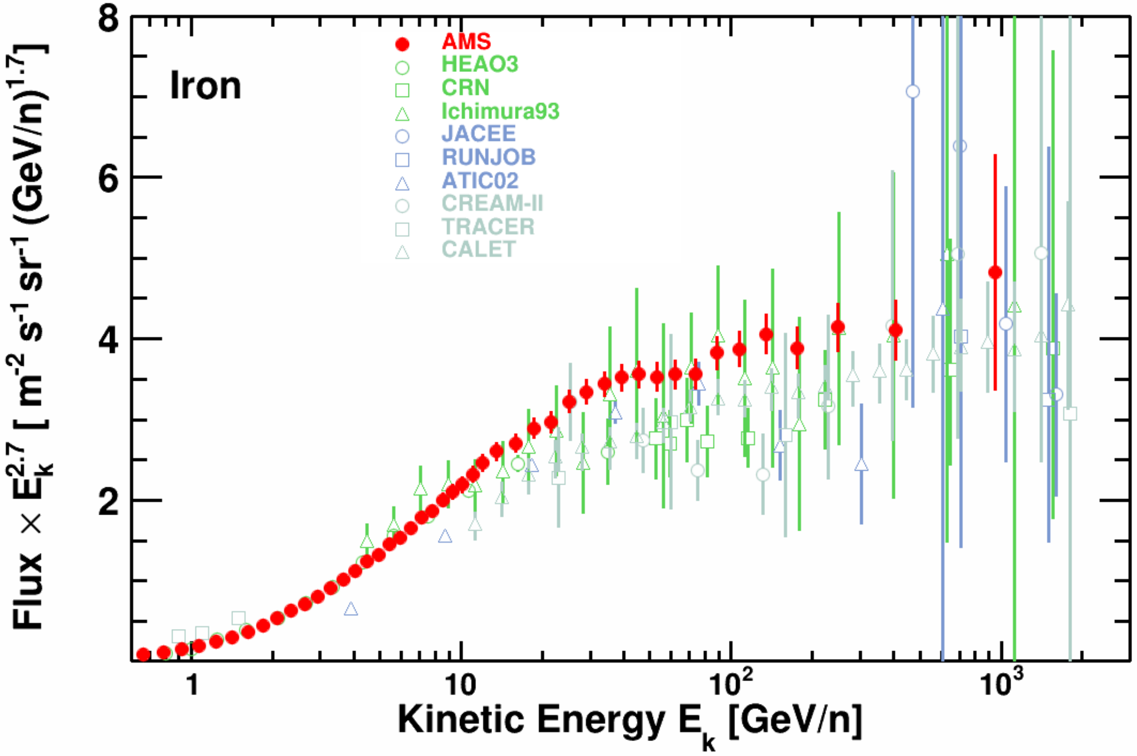
Zhen Liu, ICRC discussion session CRD 17, **indico-ID: 91896950007**

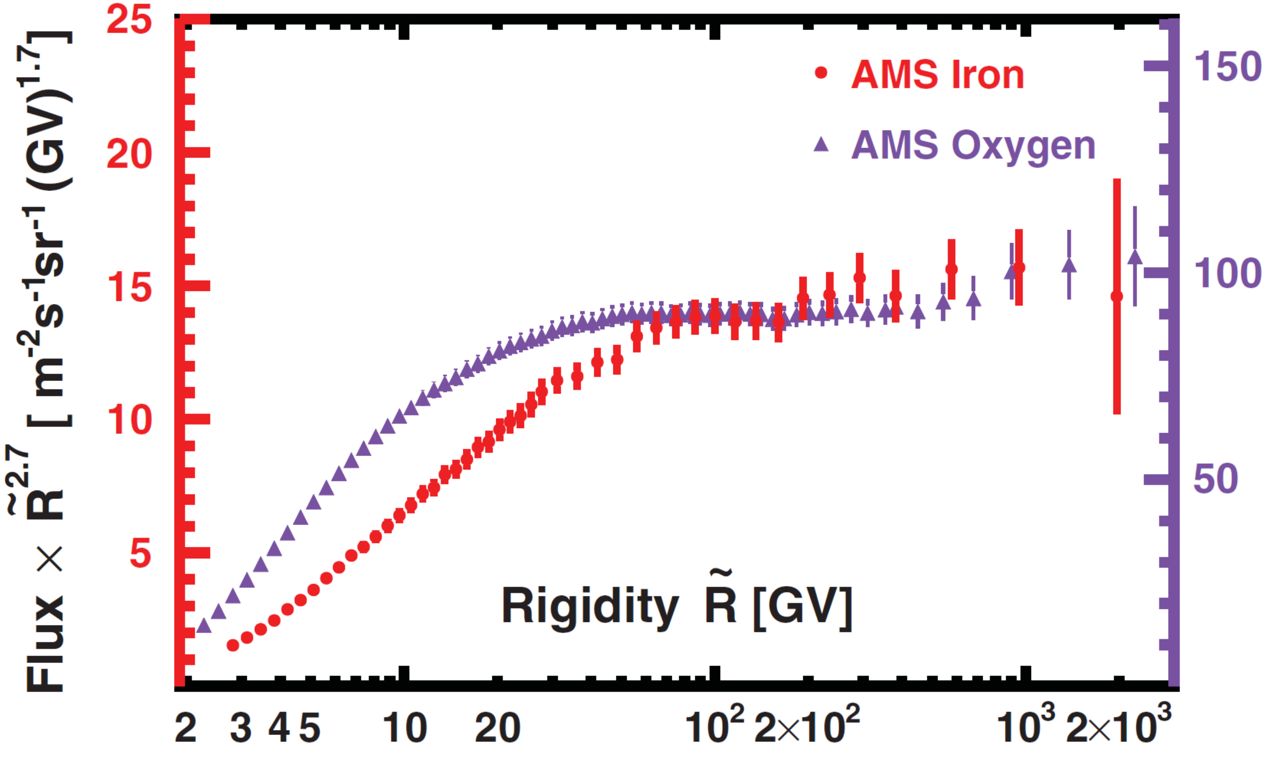
Iron

Properties of Iron Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer

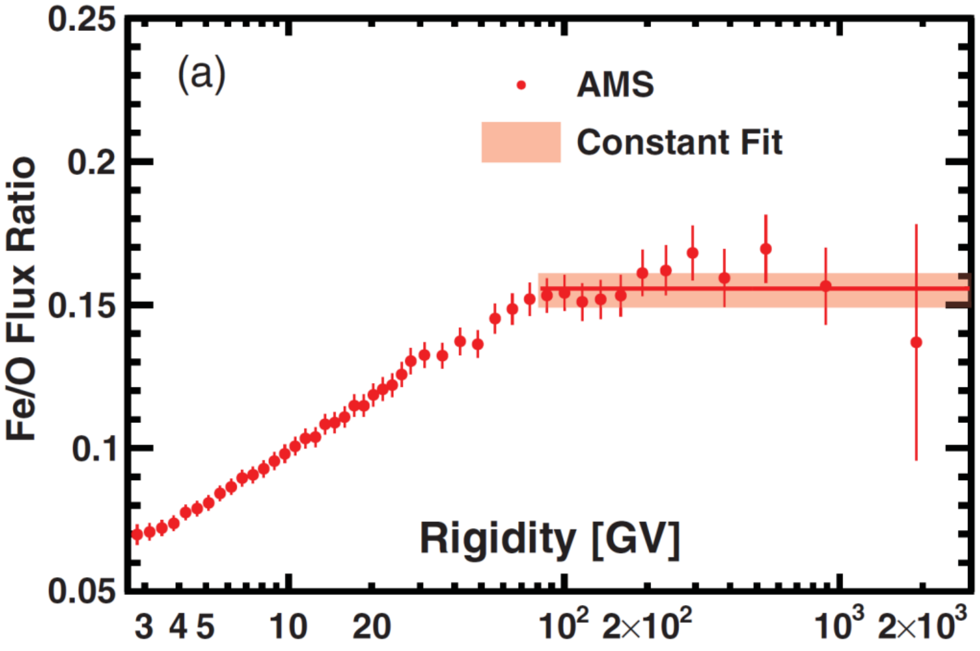
Yao Chen, indico-id: #1145

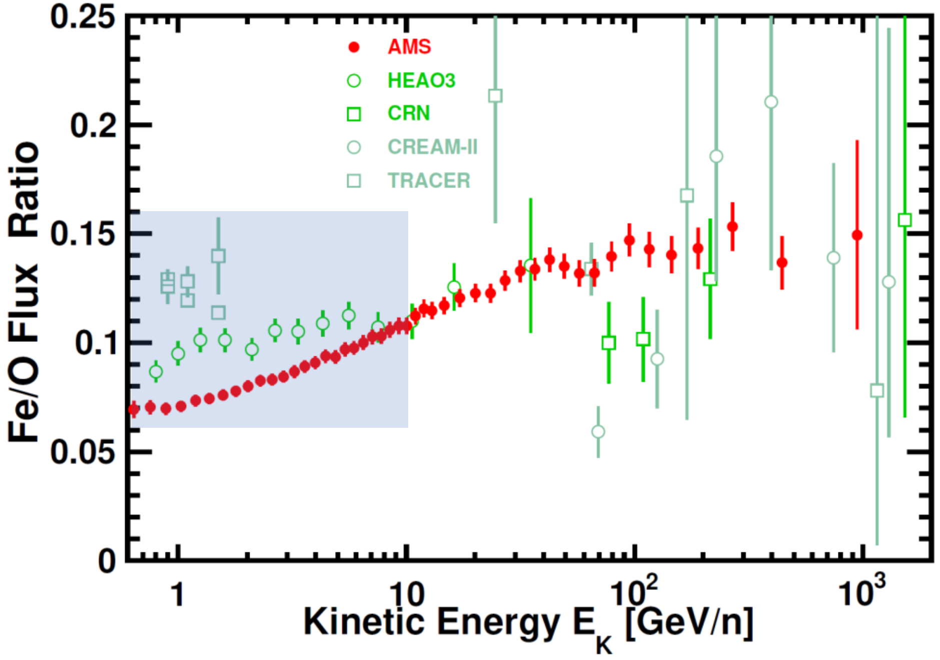
PHYSICAL REVIEW LETTERS **126,** 041104 (2021)

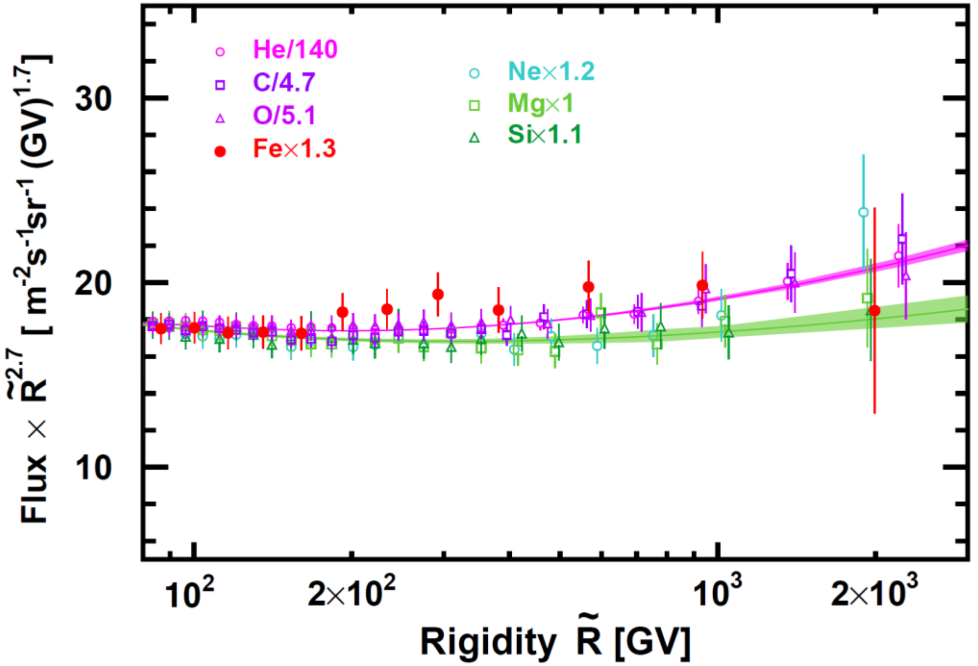




Iron spectrum **deviates from a single power law** and **hardening at high rigidity**.



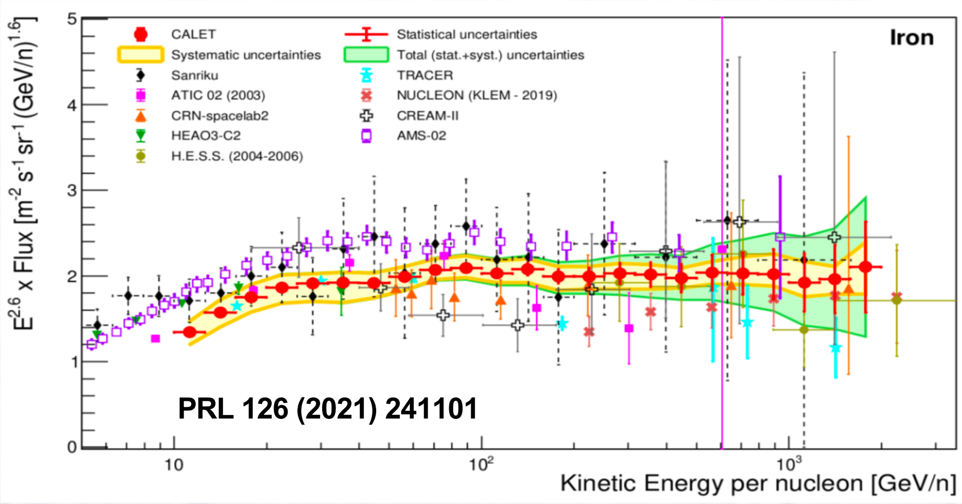


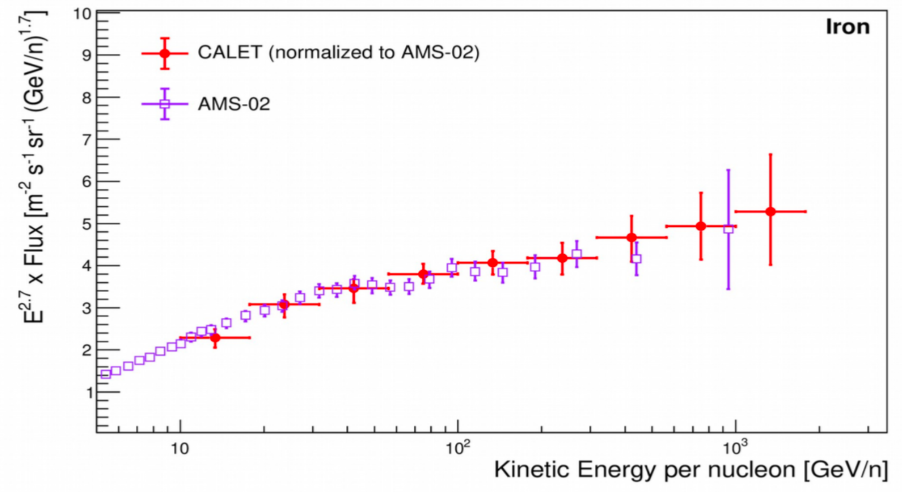


Unexpectedly, Fe and He, C, O (light nuclei) belong to the same class of primary cosmic rays, which are different from the Ne, Mg, Si

Iron flux normalization and spectral shape

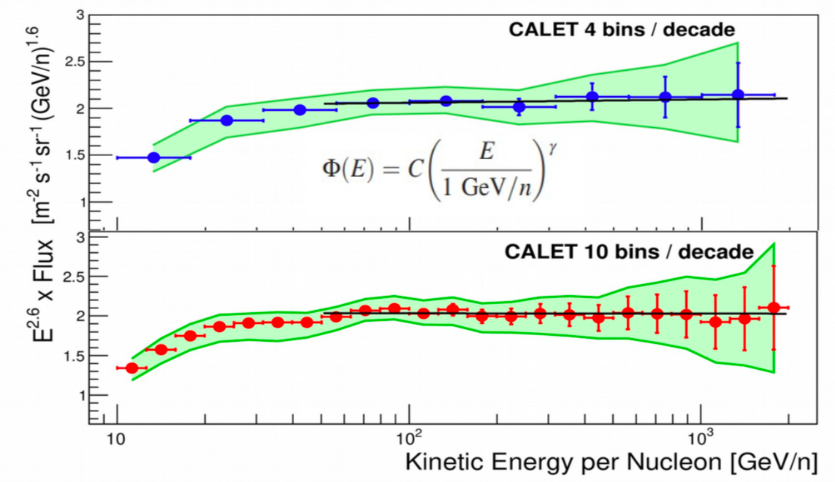
- CALET spectrum is consistent with ATIC 02 and TRACER at low energy
- CALET spectrum is consistent with CRN and HESS at high energy
- CALET and NUCLEON iron spectra have similar shape, but different normalization
- CALET and AMS-02 iron spectra have a very similar shape, but differ in the absolute normalization of the flux by ~20%





Spectral Index

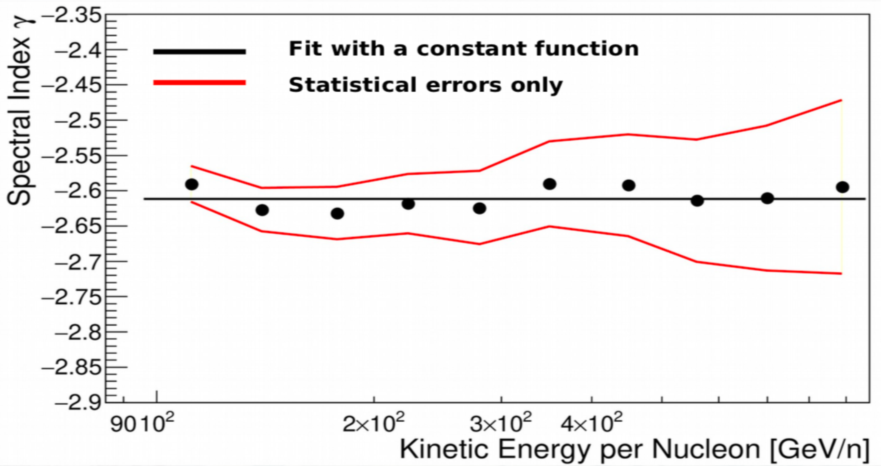
Fit from 50 GeV/n to 2.0 TeV/n, with a single power law function



- **10 bin/dec**: $\gamma = -2.60 \pm 0.02(\mathrm{stat}) \pm 0.02(\mathrm{sys})$, $\chi^2/\mathrm{DOF} = 4.2/14$;
- **4 bin/dec**: $\gamma = -2.59 \pm 0.02(\mathrm{stat}) \pm 0.04(\mathrm{sys})$

➔ **stable when larger energy bins are used**

Sliding window



- Spectral index γ determined for each bin by fitting the data using ±3 bins.
- $<\gamma> = -2.61 \pm 0.01$

The iron flux, above 50 GeV/n, is compatible within the errors with a single power law

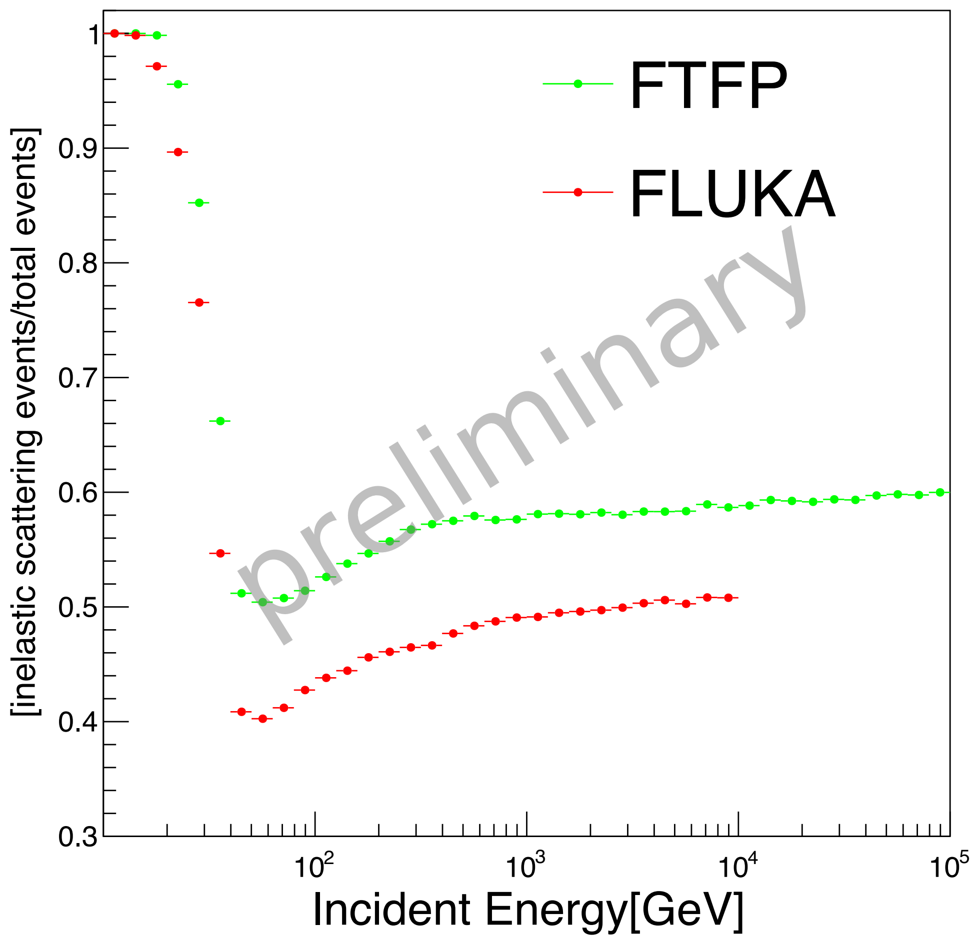
Fragmentation of iron

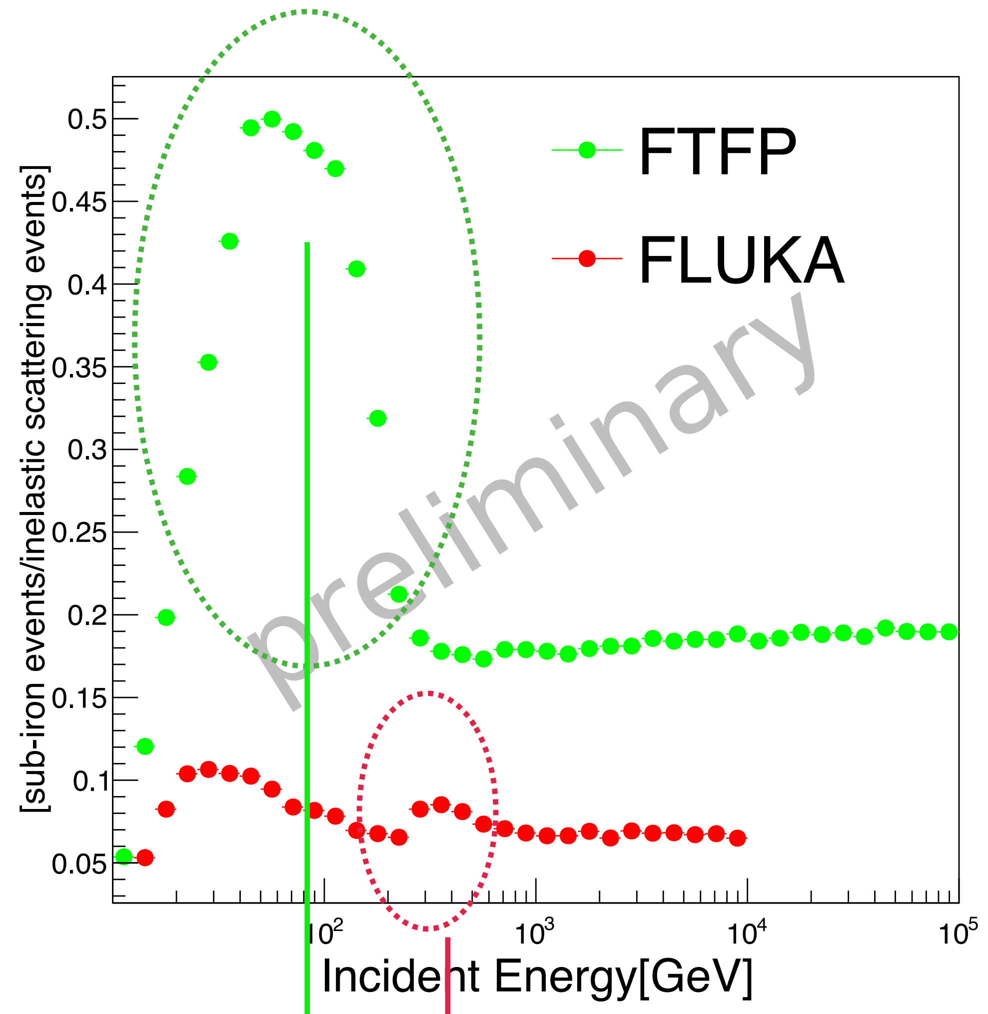
Name： ZhiHui Xu
indico_ID： 903

Proceeding URL: https://pos.sissa.it/395/115

Probability of total inelastic scattering (in PSD)

FTFP > FLUKA





Probability:

iron → sub-iron(Z=21-25)

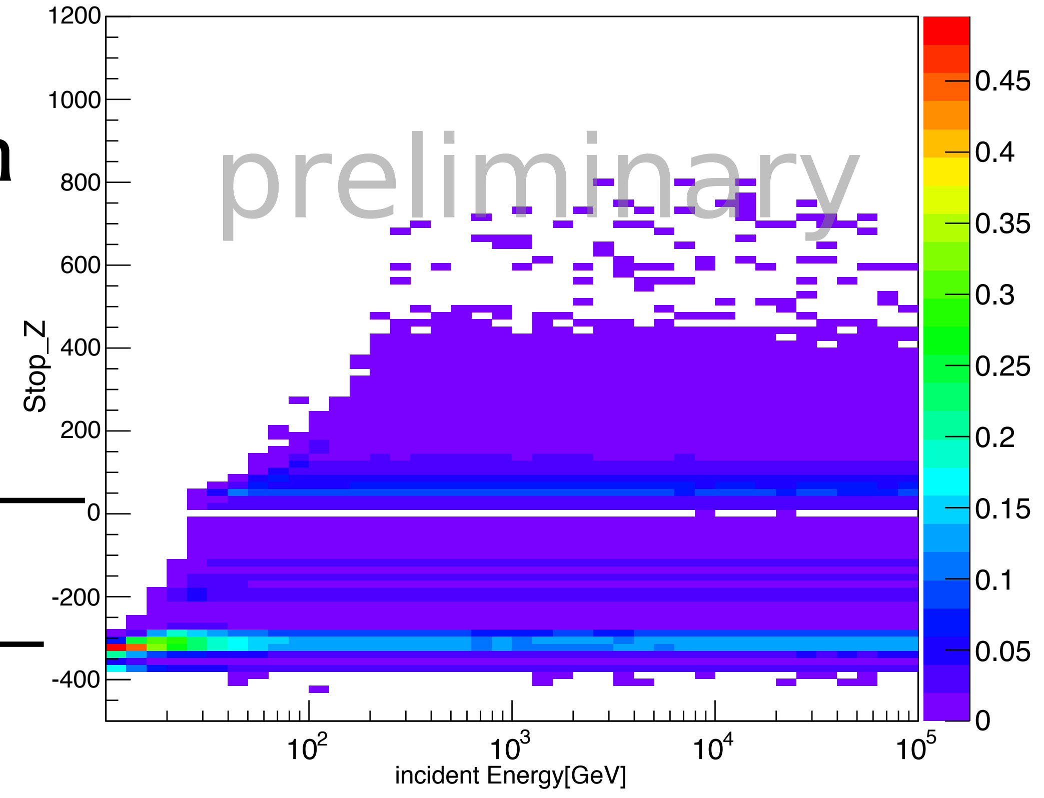
(in PSD)

FTFP has peak (20-200GeV)

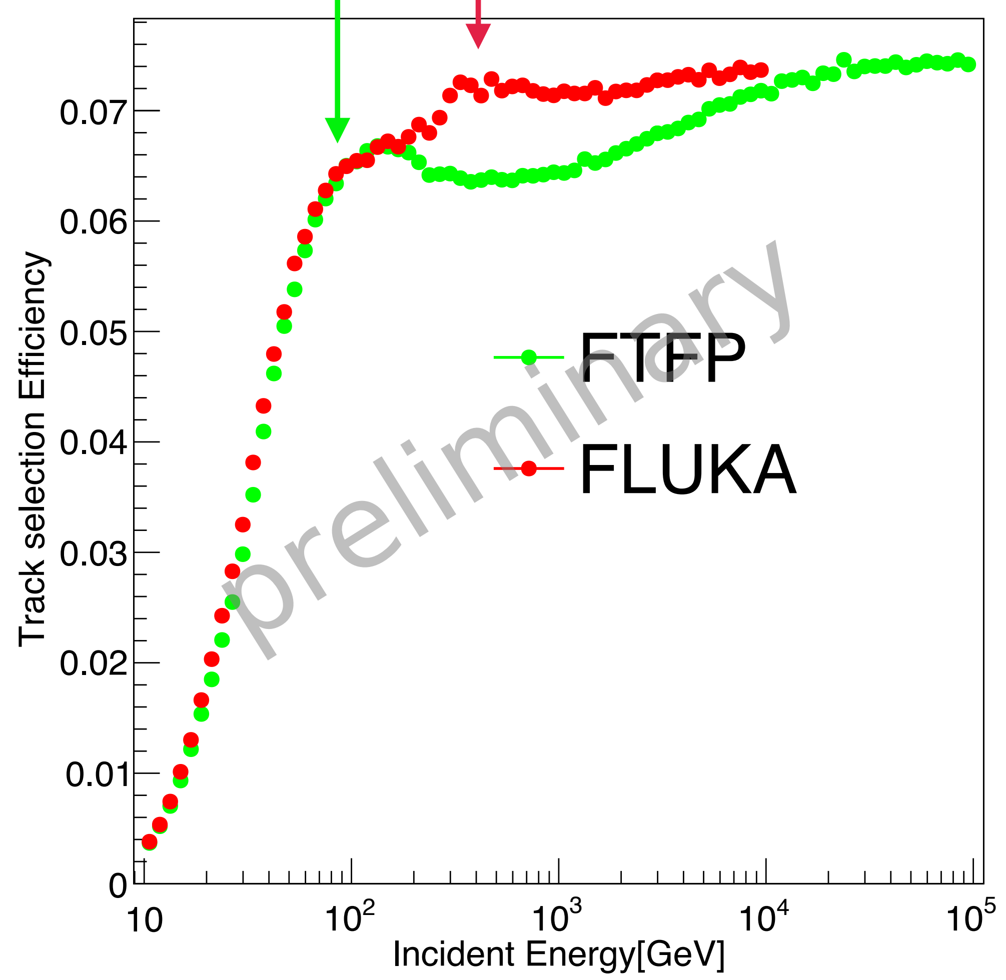
Iron Stop position in DAMPE

BGO

PSD



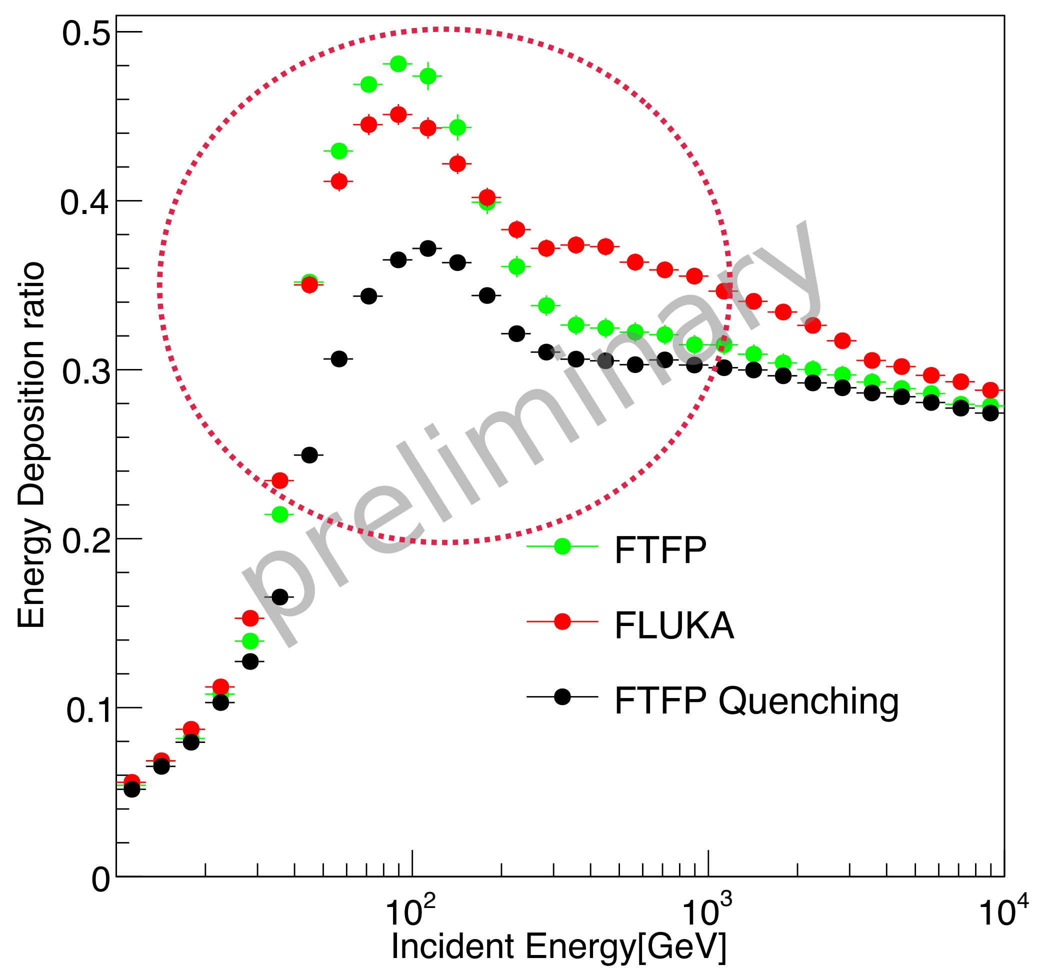
Low Energy: iron can not reach BGO



Track selection efficiency

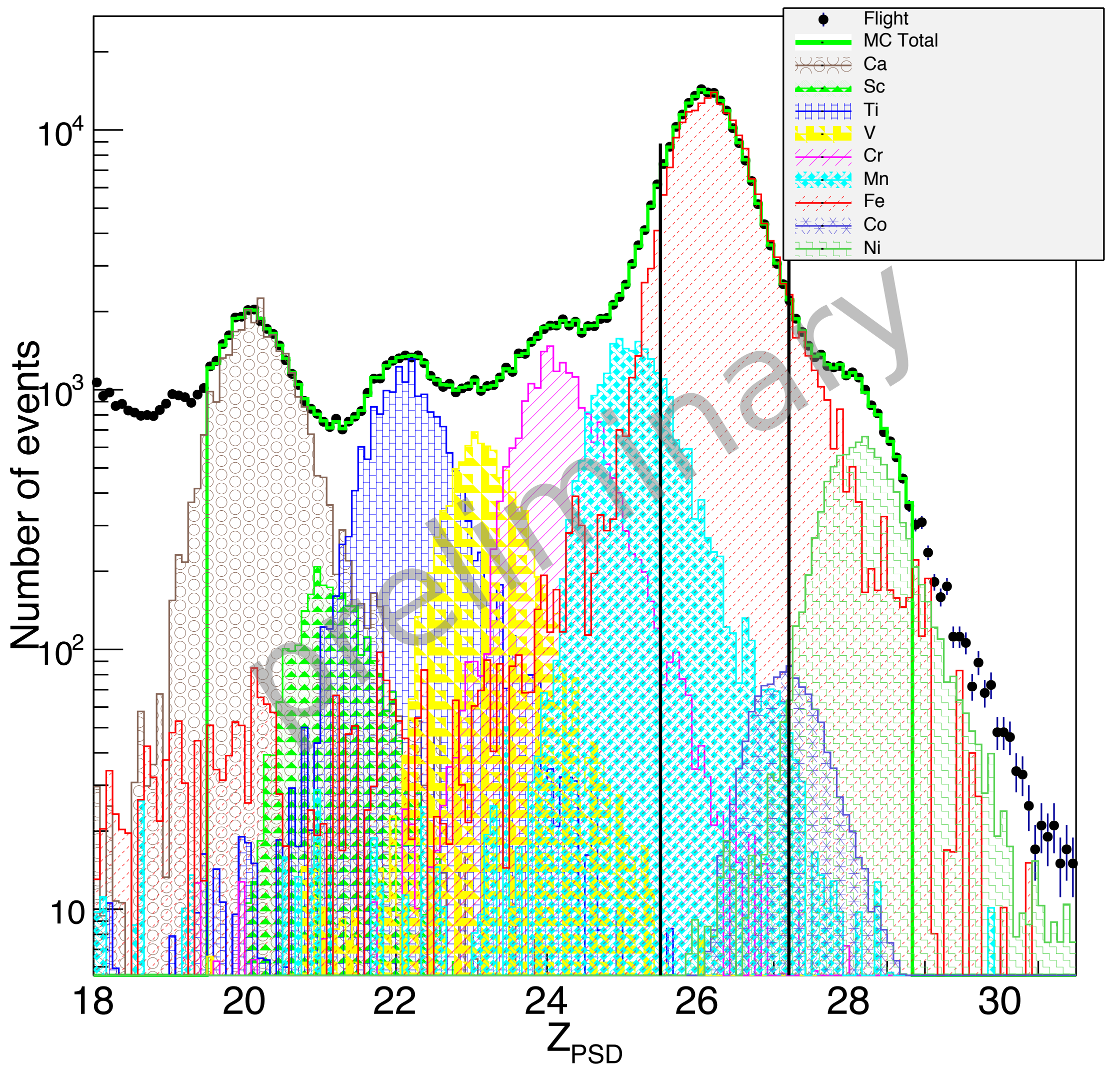
Fragmented to sub-iron has bigger probability to reconstruct track

Energy deposition



- Fragmentation affect the energy deposition and quenching effect.(sub-iron carry more energy to BGO)
- Low energy range (<80GeV): iron loss too much energy in PSD and STK

TempletFit



$$158 < E_{dep}/GeV < 200$$

$$25.5 < Z_{PSD} < 27.2$$

Summary

- Iron fragmentation channel affect the track reconstruction and energy deposition ratio(model dependent).
- DAMPE has accurate particle identification capability for Fe
- There are still a lot of detailed work to be done. In the future, we will give an iron spectrum up to few TeV/n and improve the precision at higher energies.