COSPAR 2022
44th SCIENTIFIC ASSEMBLY
16-24 July 2022, Athens, Greece
aMUSEd by the Athenian URANIA

New direct measurements of cosmic-ray iron and nickel with CALET on the International Space Station

Caterina Checchia# (University of Siena),
Francesco Stolzi (University of Siena),
Yosui Akaike (Waseda University),

on behalf of the CALET collaboration

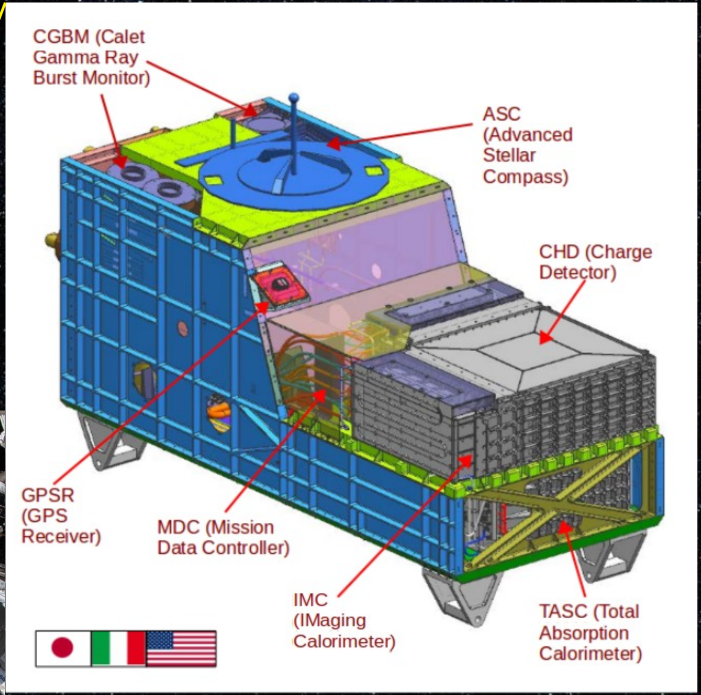
speaker

CALET PAYLOAD

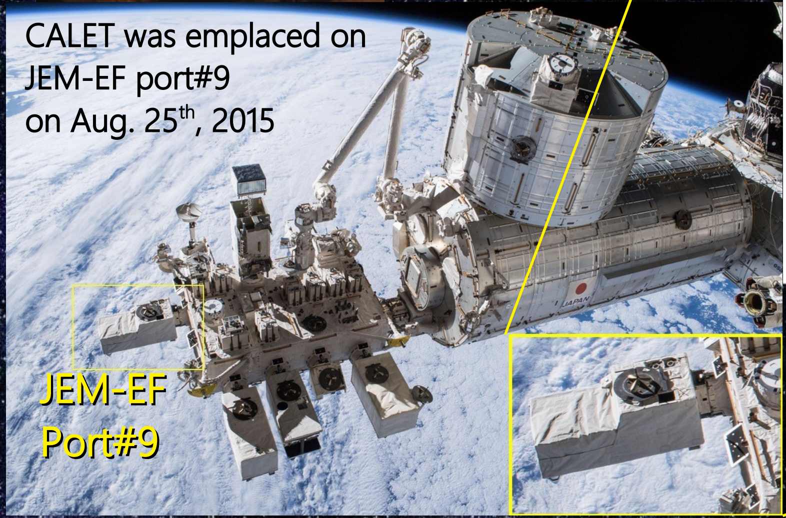
CALET launch on Aug. 19th, 2015 on Japanese H2-B rocket

JEM Standard Payload

- Mass: 612.8 kg
- Size: 1850 mm (L) x 800 mm (W) x 1000 mm (H)
- Power Consumption: 507 W (max)
- Telemetry: Medium (Low) 600 (50) kbps (6.5 GB/day)



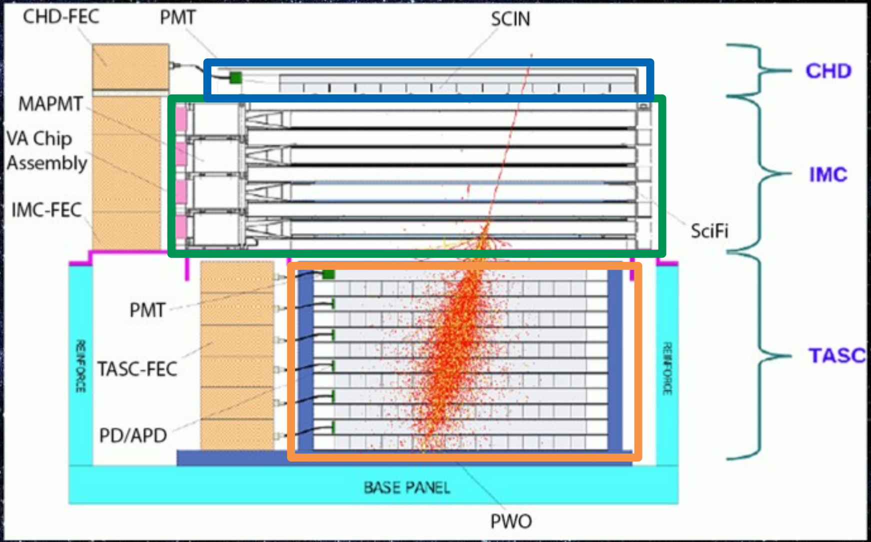
CALET was emplaced on JEM-EF port#9 on Aug. 25th, 2015

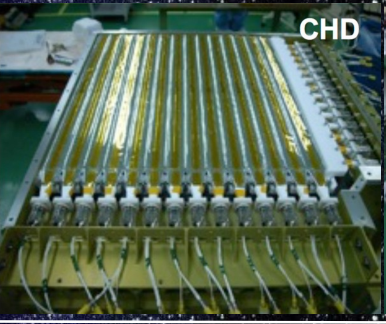


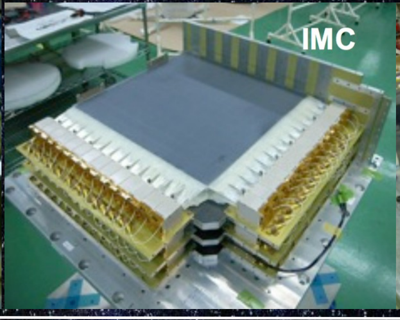
CALET started scientific observations on Oct. 13th, 2015
More than 3.4 billion events collected so far.

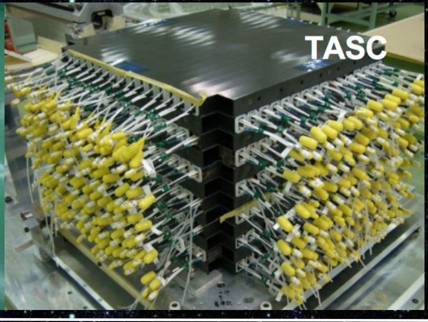
THE CALET INSTRUMENT

A 30 radiation length deep calorimeter designed to detect electrons and gammas up to 20 TeV and cosmic rays up to 1 PeV









CHD: Charge Detector

- 14x2 plastic scintillator paddles
- Single element charge ID from *p* to *Fe* and above (Z = 40)
- Charge resolution: 0.15 *e (C)*, 0.35 *e (Fe)*

IMC: Imaging Calorimeter

- SciFi belts (8x2x448, 1mm^2) + Tungsten plates (7 layers: $3X_0 = 0.2\ X_0 \times 5 + 1.0\ X_0 \times 2$)
- Track reconstruction and particle ID (up to Z = 14), shower imaging
- Angular resolution: ~ 0.1°, Spatial resolution on top CHD: ~200 μm

TASC: Total absorption calorimeter

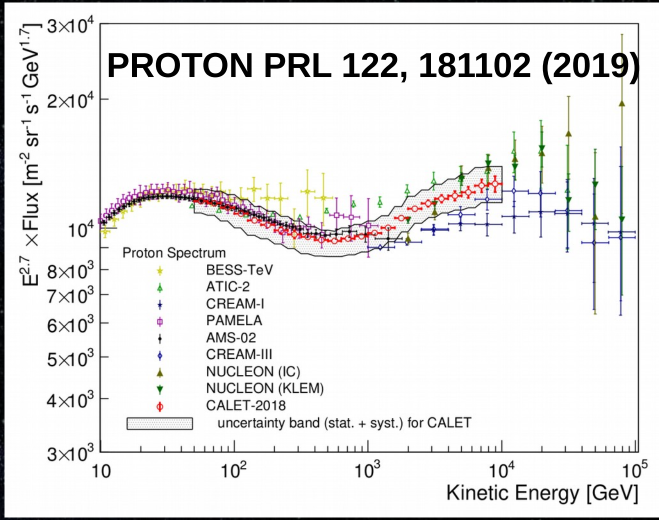
- 16 x 12 PWO logs: 27 X_0 (for e^-), 1.2 λ_I (for *p*)
- Energy measurement
- Energy resolution: ~ 2% for e^- γ (>10 GeV), ~30-35% for *p* and nuclei

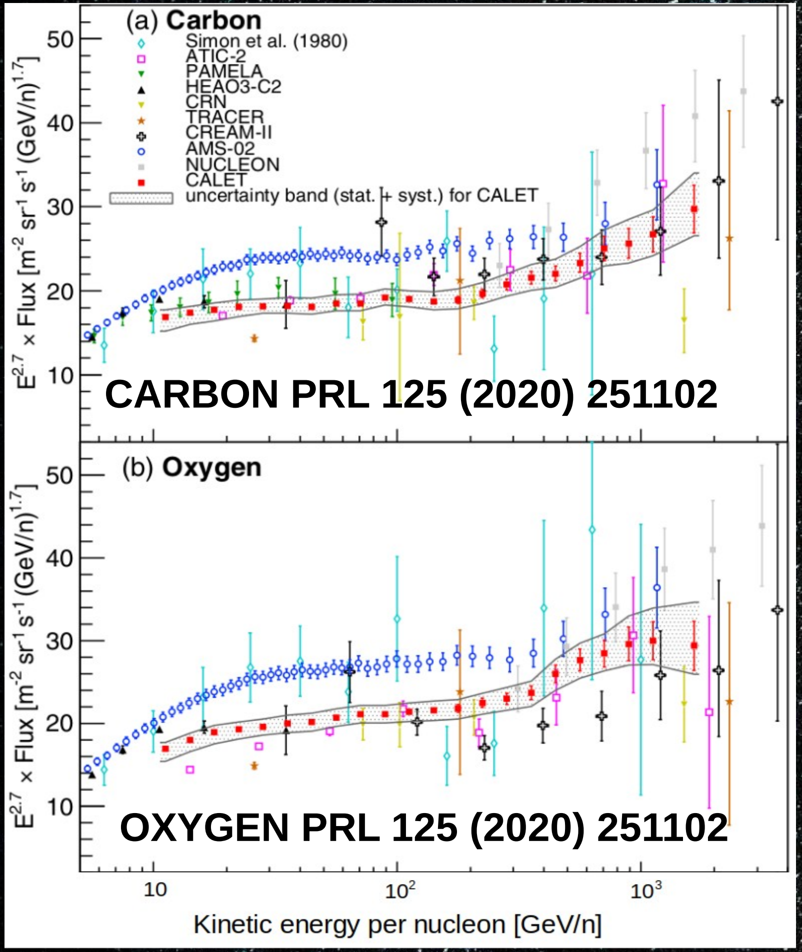
NUCLEI OBSERVATION WITH CALET

One of main Objectives:
precise measurement of the transition region for each nuclear species and extension to TeV energy → Spectral hardening

Wide dynamic range (1-10^6 MIP)
Large thickness (30 X_0 , ~1.3 λ_I)
Excellent charge ID (~ 0.1 *e*)

CALET can cover the whole energy range previously investigated in separate subranges by magnetic spectrometers and calorimeters.



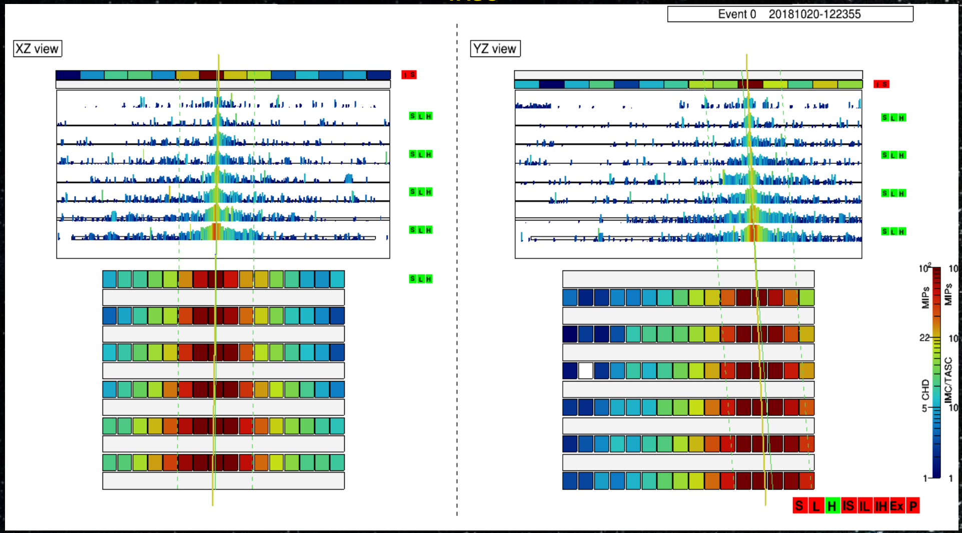


Energy spectra of proton, C and O indicate the spectral hardening at a few 100 GeV/n. What about havier nuclei?

ANALYSIS PROCEDURE

- MC simulation of the apparatus based on EPICS (w/DPMJET-III)
  - FLUKA as additional simulation for Iron
  - GEANT4 as additional simulation for Nickel
- Energy measurement: reconstruction of primary energy through beam test calibration
- Charge reconstruction by measuring the ionization deposits in the CHD

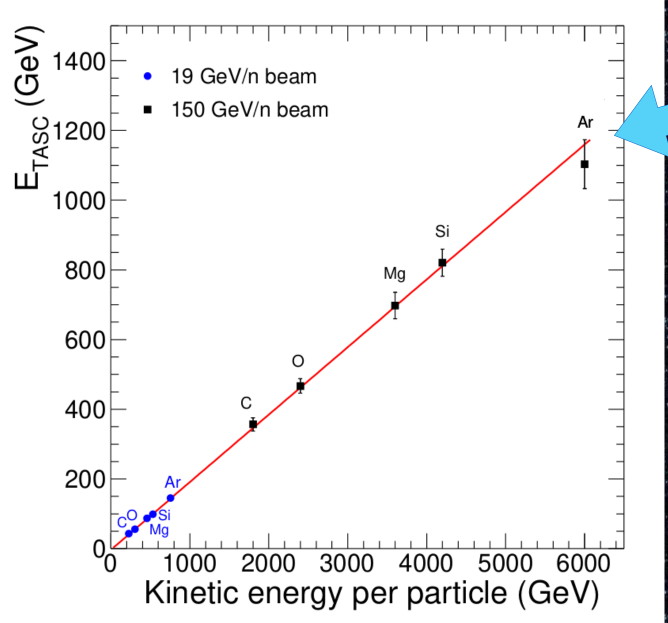
4 TeV (E_{TASC}) Iron Candidate



Event selection:

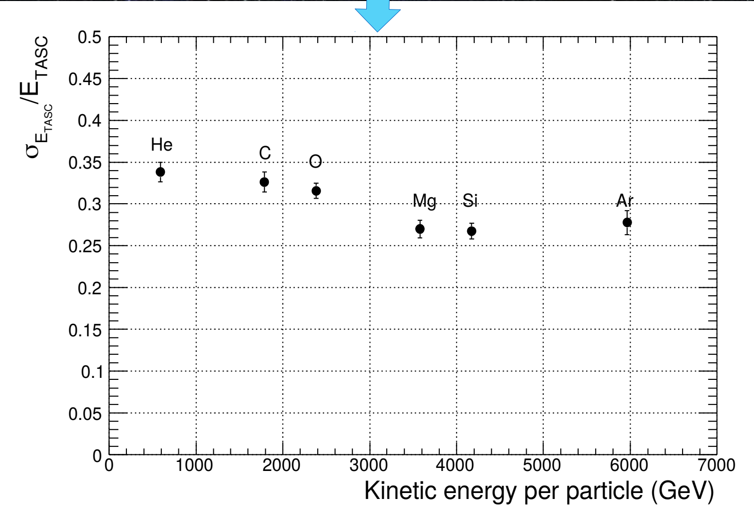
1) High energy shower trigger
2) Shower event selection: selects interacting particles
3) IMC reconstructed track
4) Acceptance Cut:
   - Iron: Events crossing the detector from top of CHD to bottom of TASC within 2 cm from the edge
   - Nickel: looser condition to enhance statistics, no condition on the TASC bottom layer
5) Charge consistency Cut: removes charge-changing particles in the upper part of the detector
6) Charge selection:
   - Iron: Ellipse centered in $Z = 26$
   - Nickel: Ellipse centered in $Z = 28$

ENERGY MEASUREMENT: CALIBRATION OF THE ENERGY SCALE



Beam Test Calibration (CERN-SPS in 2015):

- ✔ MC energy tuning with beams of accelerated ion fragments (A/Z = 2) of 150 GeV/c/n.
- ✔ Good linearity up to maximum available beam energy (~ 6 TeV)
- ✔ Fraction of particle energy released in TASC is ~ 20%
- ✔ Energy resolution 30-35%



Correction:

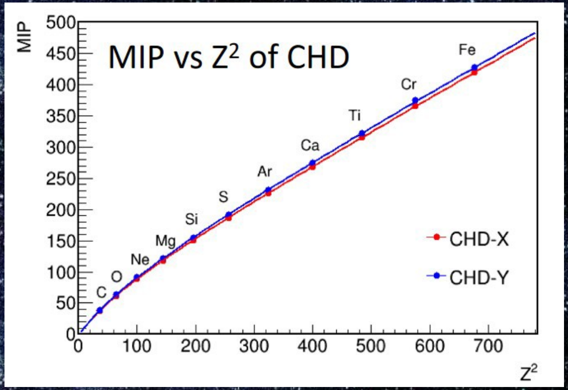
➔ 6.7% for E_{TASC} < 45 GeV;

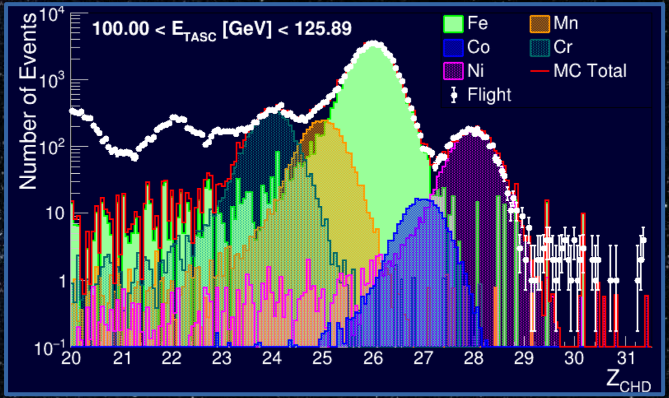
➔ 3.5% for $E_{TASC} \geq$ 350 GeV;

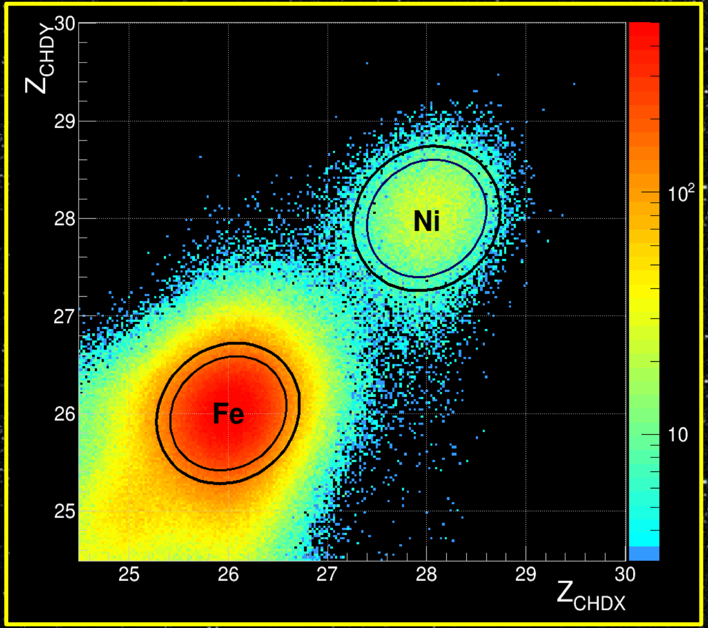
➔ linear interpolation for $45 \leq E_{TASC} <$ 350 GeV

CHARGE IDENTIFICATION

The charge Z is reconstructed by measuring the ionization deposits in the CHD.





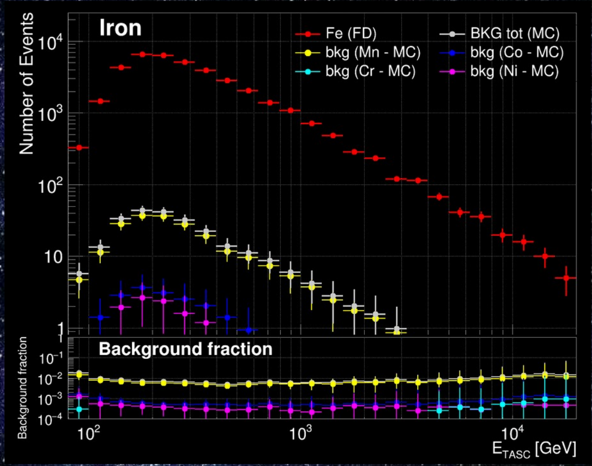


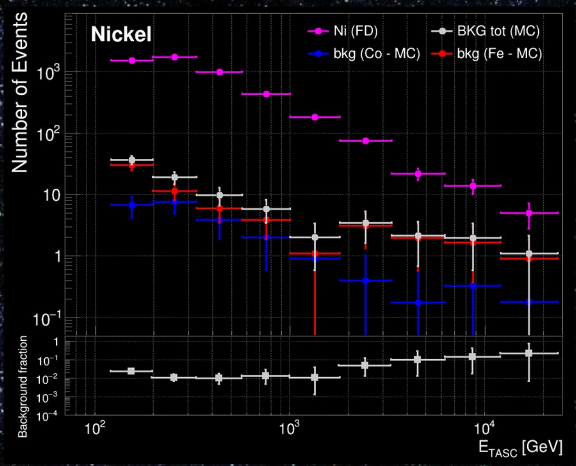
Non linear response to Z^2 due to the quenching effect in the scintillators is corrected using a "halo" model.

- ✔ In order to remove background events interacting in CHD a Charge Consistency Cut is applied: $|Z_{CHDX}-Z_{CHDY}|<1.5$
- ✔ Charge resolution σ_Z for iron (nickel) is 0.35 e (0.39 e).

Iron (nickel) events are selected within an ellipse centered at $Z = 26$ (28), with 1.25 σ_x (1.4 σ_x) and 1.25 σ_y (1.4 σ_y) wide semiaxes for Z_{CHDX} and Z_{CHDY}, respectively, and rotated clockwise by 45°

BACKGROUND ESTIMATION AND UNFOLDING





Background estimation:

- The number of contaminating events is estimated by MC simulation
- The total contamination is subtracted from the selected sample before doing the unfolding: few percent for iron, up to 10% for nickel

$$N(E) = U(N_{obs} - N_{bg})$$

- N_{obs}: observed events in each bin of E_{TASC}
- N_{bg}: contaminating events in each bin of E_{TASC}
- U: unfolding operator

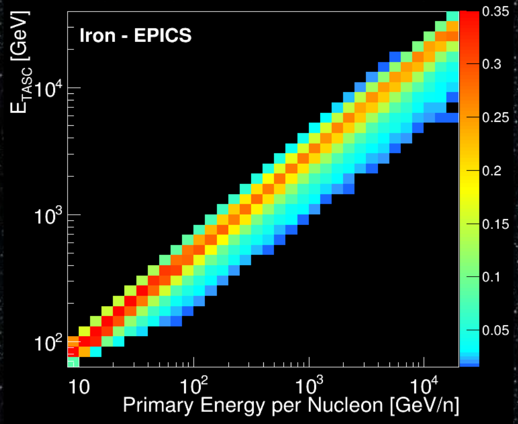
Energy unfolding:

applied to correct for bin-to-bin migration effect and obtain the primary energy spectrum.

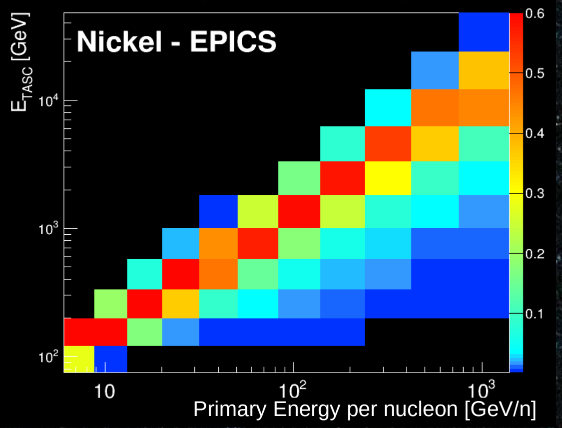
The smearing matrix is computed using Epics MC. The unfolding is performed by an iterative method based on the Bayes theorem.

The color scale indicates the probability, for a candidate with a given primary energy, of depositing energy in different intervals of E_{TASC}

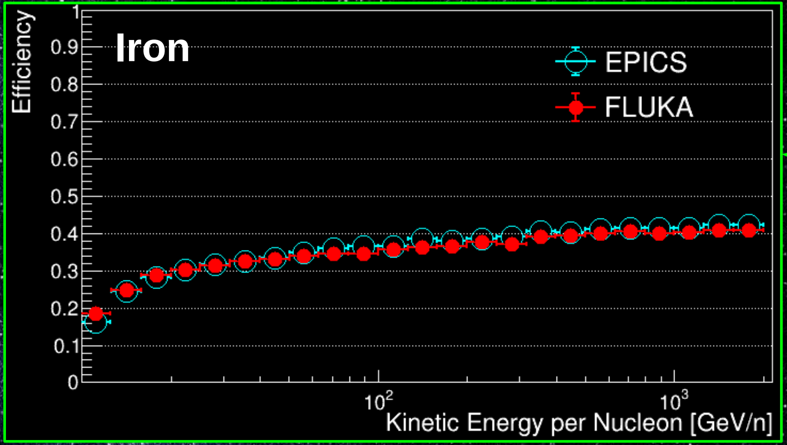
Smearing matrix for iron

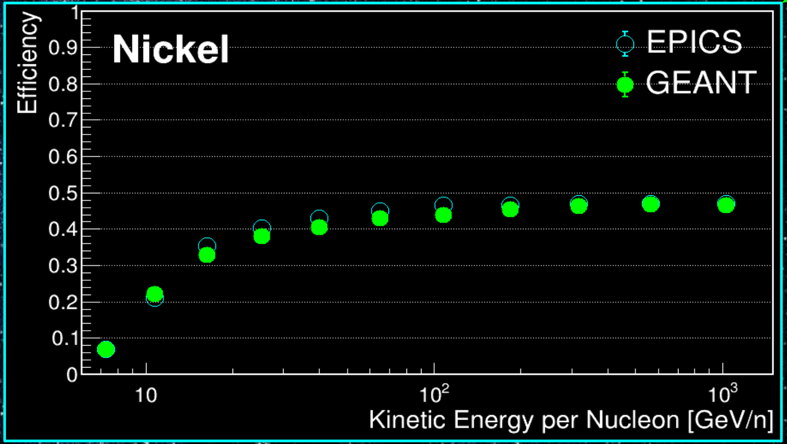


Smearing matrix for nickel



THE FLUX MEASUREMENT





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

Number of events in the unfolded bin

Bin width ΔE of reconstructed primary energy

Geometrical factor:

Iron: ~ 416 cm^2 sr

Nickel: ~510 cm^2 sr

Total Livetime:

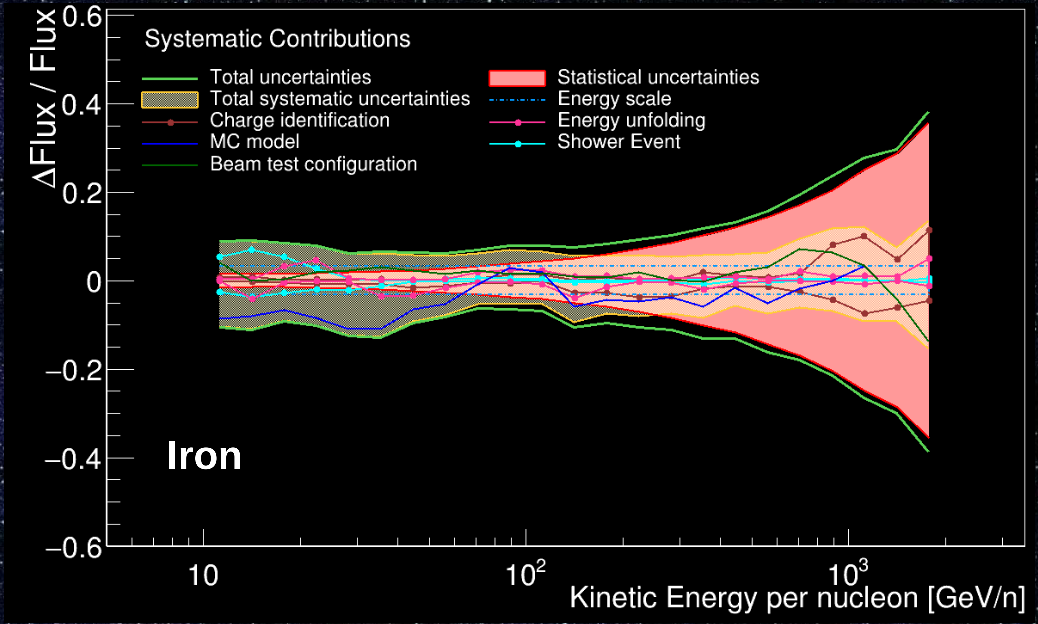
Iron:

- 1613 days from Jan 2016 to May 2020
- Live Time: 3.3 x 10^4 hrs → 85.8% obs time

Nickel:

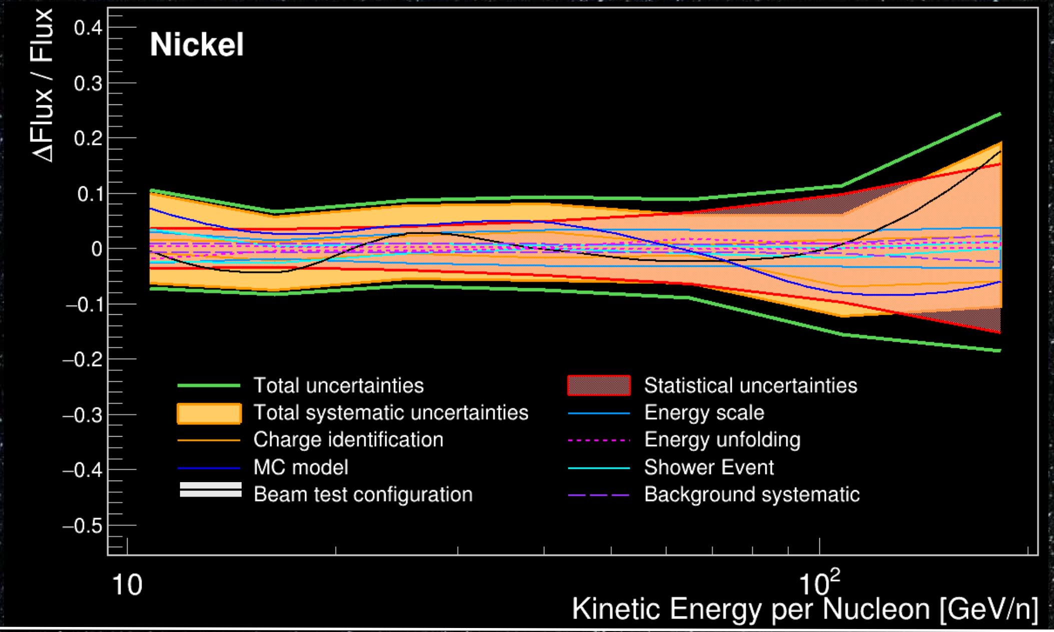
- 2038 days from Nov 2015 to May 2021
- Live Time: 4.1 x 10^4 hrs → 86% osb time

THE SYSTEMATIC UNCERTAINTIES



Energy Dependent:

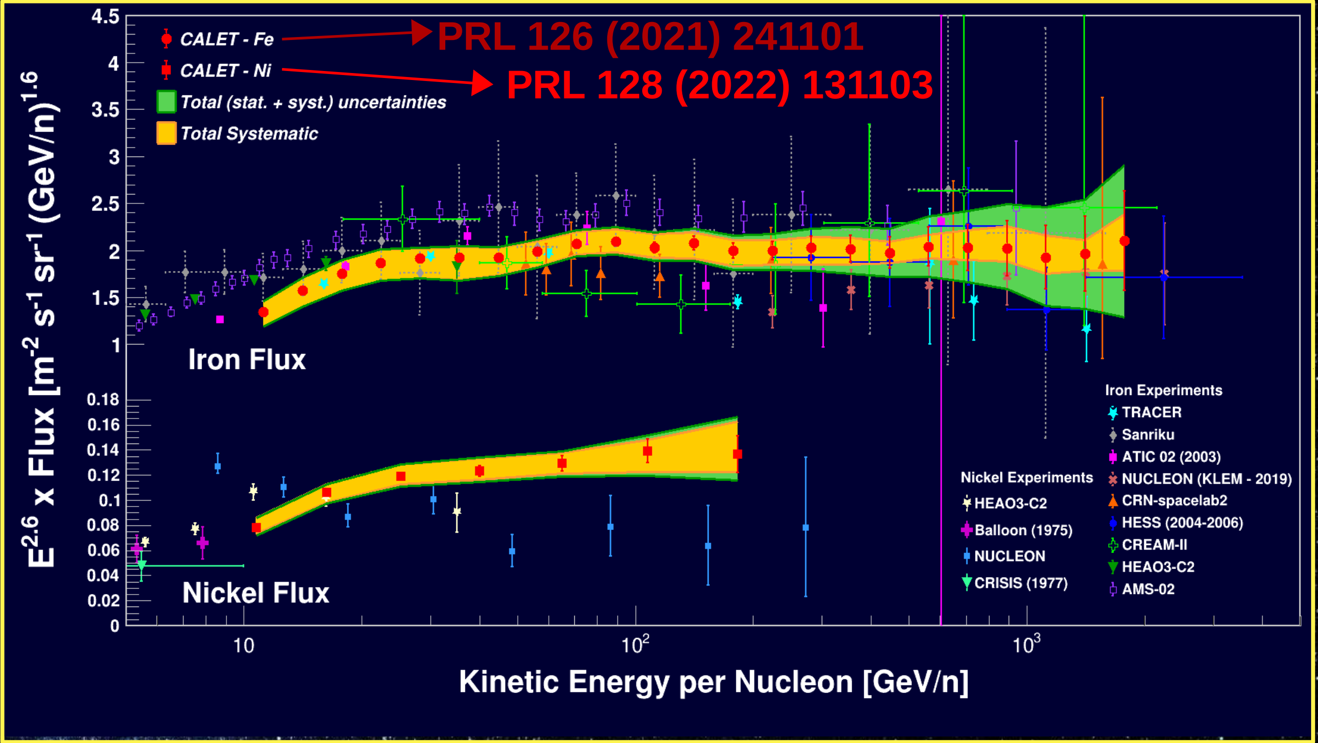
- Charge identification
- Energy scale correction
- Beam Test configuration
- MC model
- Shower Event
- Unfolding

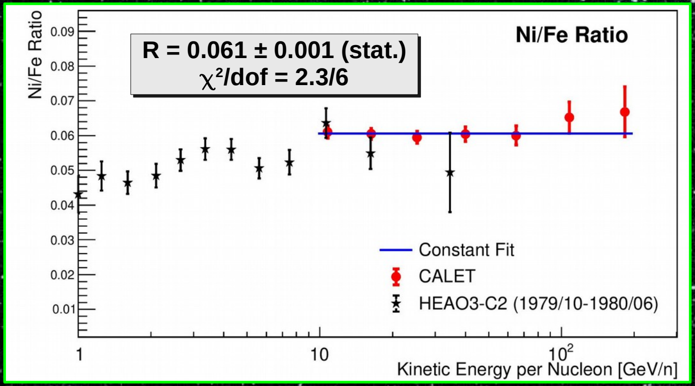


Energy Independent:

- Live Time (3.4%)
- Long Term stability (2.0-2.7%)
- Geometrical factor (1.6%)
- Isotopes composition (nickel only): 2.2%

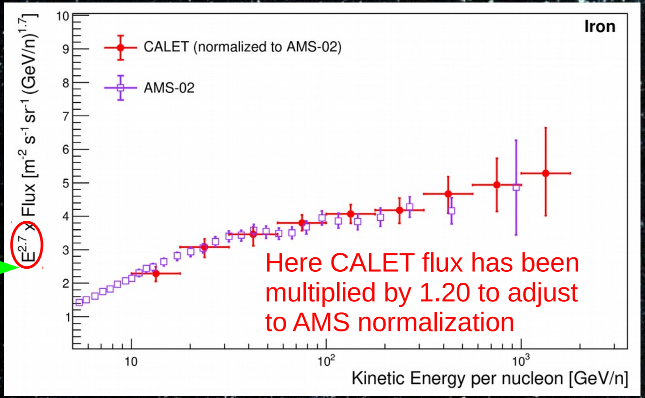
Fe and Ni energy spectra





<u>Nickel to Iron ratio:</u>

- Extented result up to 240 GeV/n

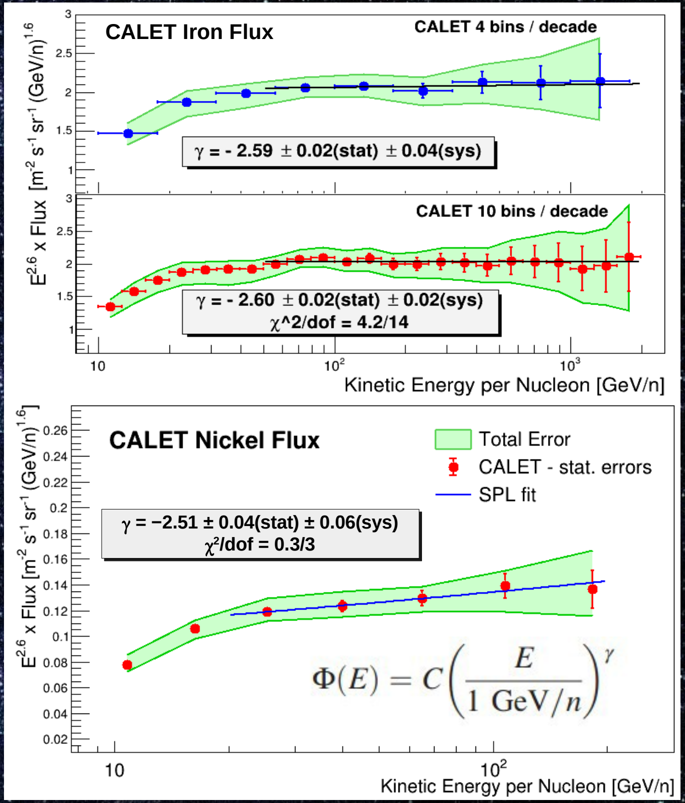


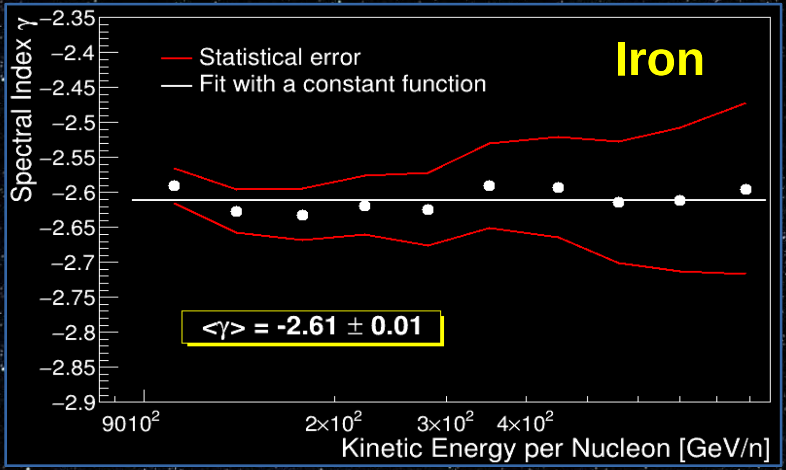
<u>Iron</u>: Good agreement between CALET and ATIC, Tracer, HESS and CRN

Normalization in tension with AMS-02

<u>Nickel</u>: similar normalization with respect to HEAO3-C2 and NUCLEON, though different spectral shape

SPECTRAL INDEX





To study the energy dependence of the spectral index in a model independent way, the spectral index is calculated by a fit of

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

in energy windows centered in each bin and including the neighbor ± 3 bins.

Fitting intervals:
Iron: 50 GeV/n - 2 TeV/n
Nickel: 20 GeV/n - 240 GeV/n

Iron and Nickel fluxes are compatible within the errors with a single power law above 50 GeV/n and 20 GeV/n, respectively.

CONCLUSIONS

- CALET measured iron and nickel fluxes between 10 GeV/n and 2 TeV/n and 8.8 GeV/n and 240 GeV/n respectively, with significantly better precision than most of the existing measurements.

- Above 50 GeV/n (for iron) and 20 GeV/n (for nickel), the spectra are compatible with a single power law with a spectral index of -2.60 ± 0.03 (for iron) and -2.51 ± 0.07 (for nickel).

- The flat behavior of the nickel to iron ratio indicates that the spectral shapes of Fe and Ni are the same within the experimental accuracy, suggesting also that Fe and Ni have a similar acceleration and propagation behavior, as expected from the small difference in atomic number and weight between Fe and Ni nuclei.

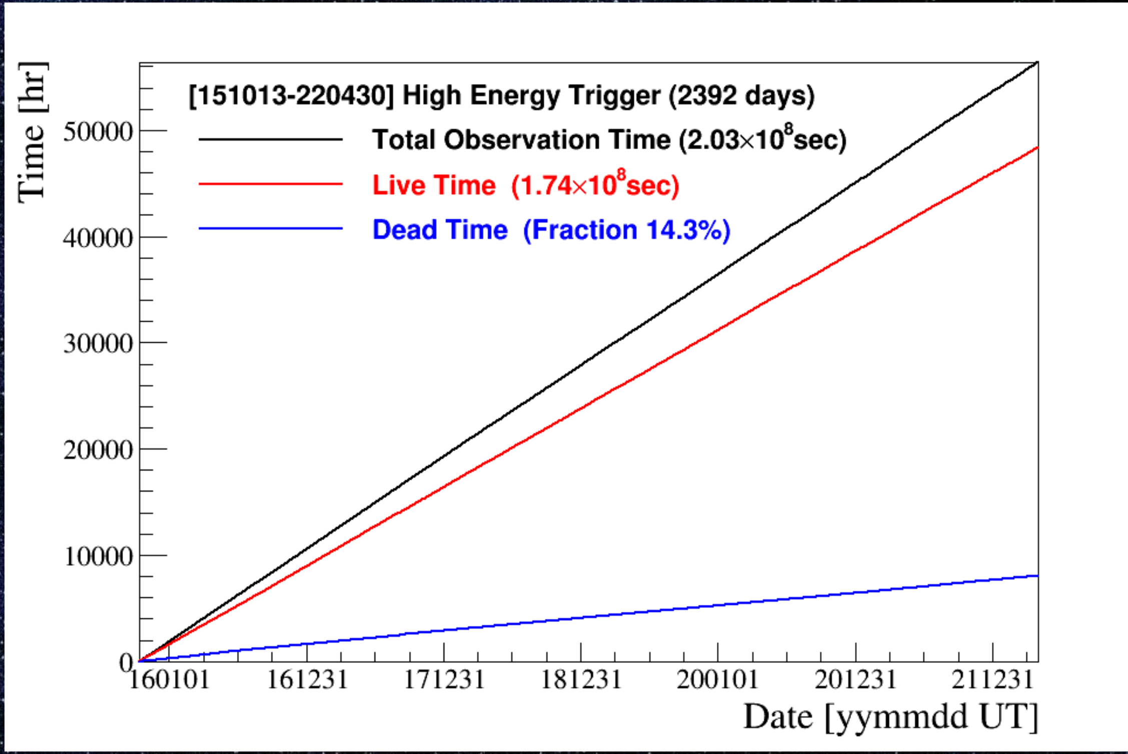
- The uncertainties given by our present statistics and large systematics do not allow us to draw a significant conclusion on a possible deviation from a single power law.

Thank you!

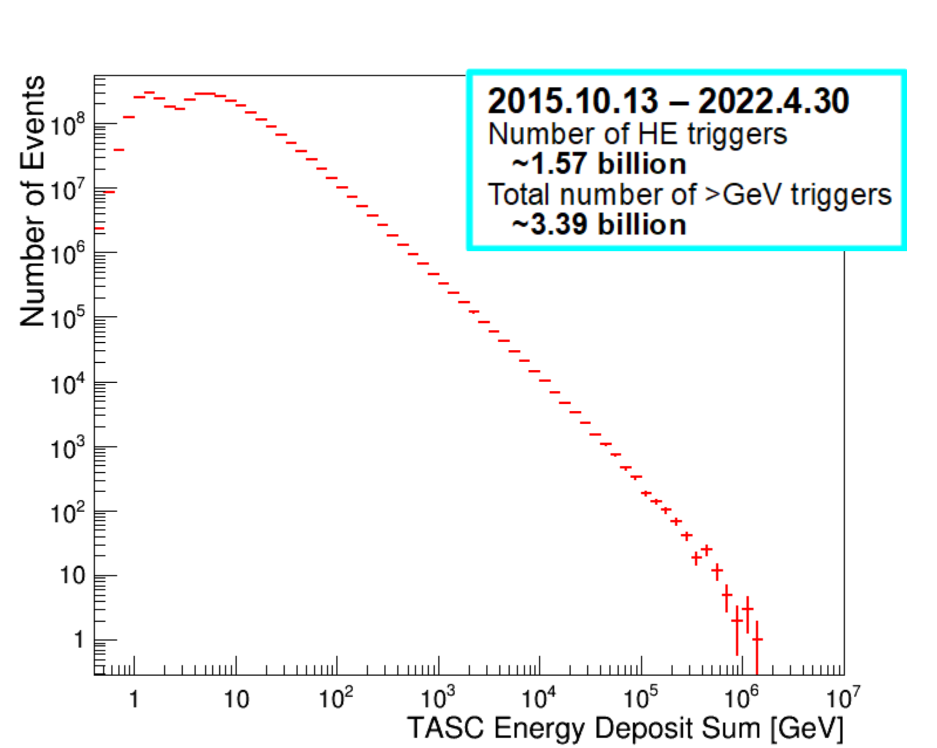
BACKUP

OBSERVATIONS WITH HIGH ENERGY TRIGGER

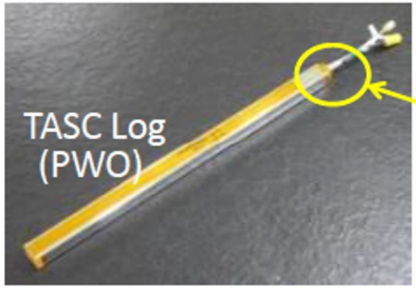
Accumulated observation

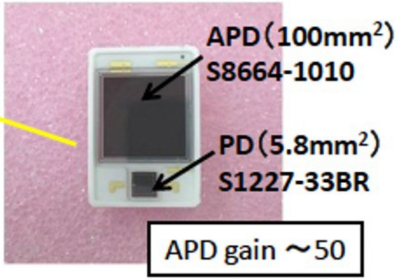


Distribution of deposit energies in TASC

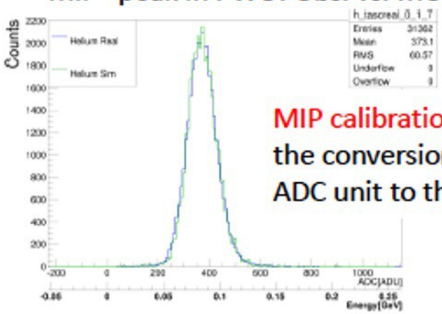


ENERGY MEASUREMENT IN A WIDE DYNAMIC RANGE (1-10^6 MIPS)

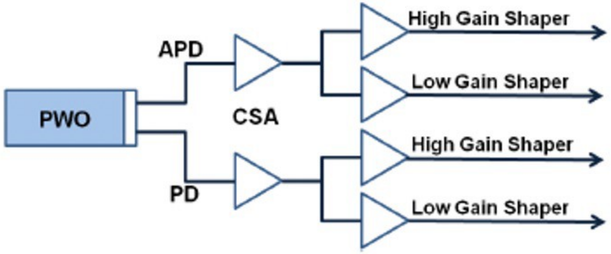




“MIP” peak in PWO: Obs. vs. MC



MIP calibration determines the conversion factor from ADC unit to the energy



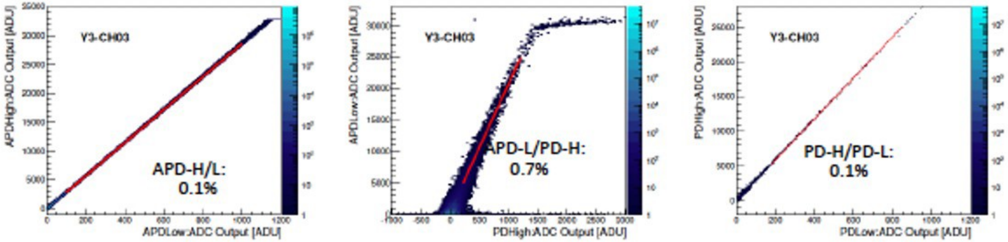
The whole dynamic range was calibrated by UV laser irradiation on ground :

1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

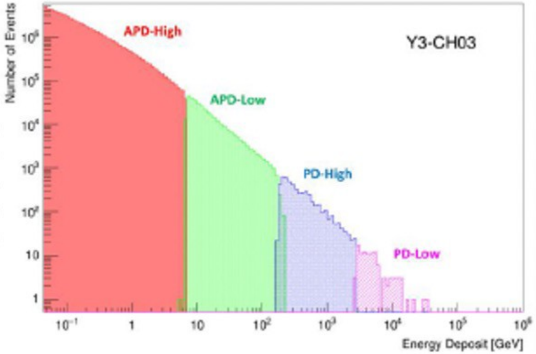
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.

APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%

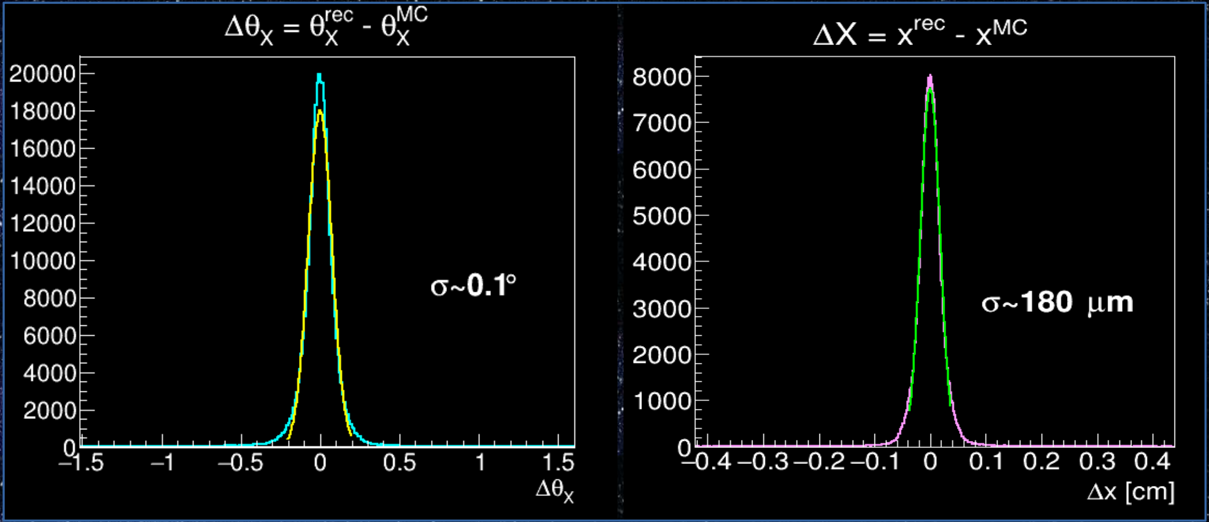


Example of energy distribution in one PWO log



TRACKING PERFORMANCE

Tracking:
based on a combinatorial Kalman Filter that exploits the fine granularity of IMC to reconstruct tracks with high precision



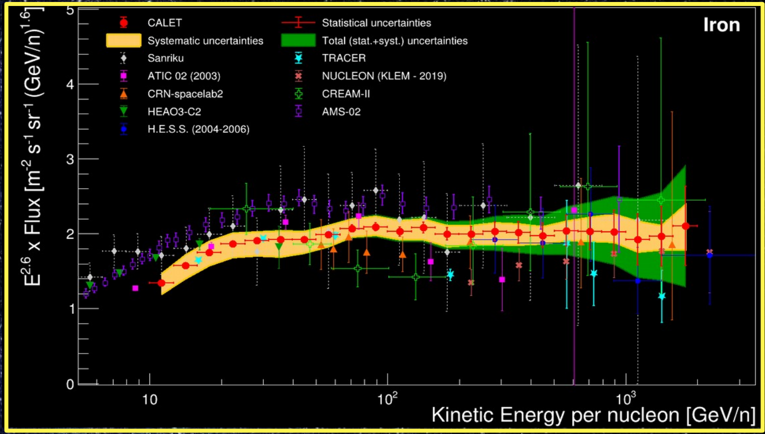
Tracking provides:

- Cosmic ray arrival direction
- Geometrical acceptance
- CHD paddles and IMC fibers crossed by the track (for charge ID)

Iron/Nickel performance:

- Angular resolution: ~0.1°
- Spatial resolution on top CHD: ~180 μm

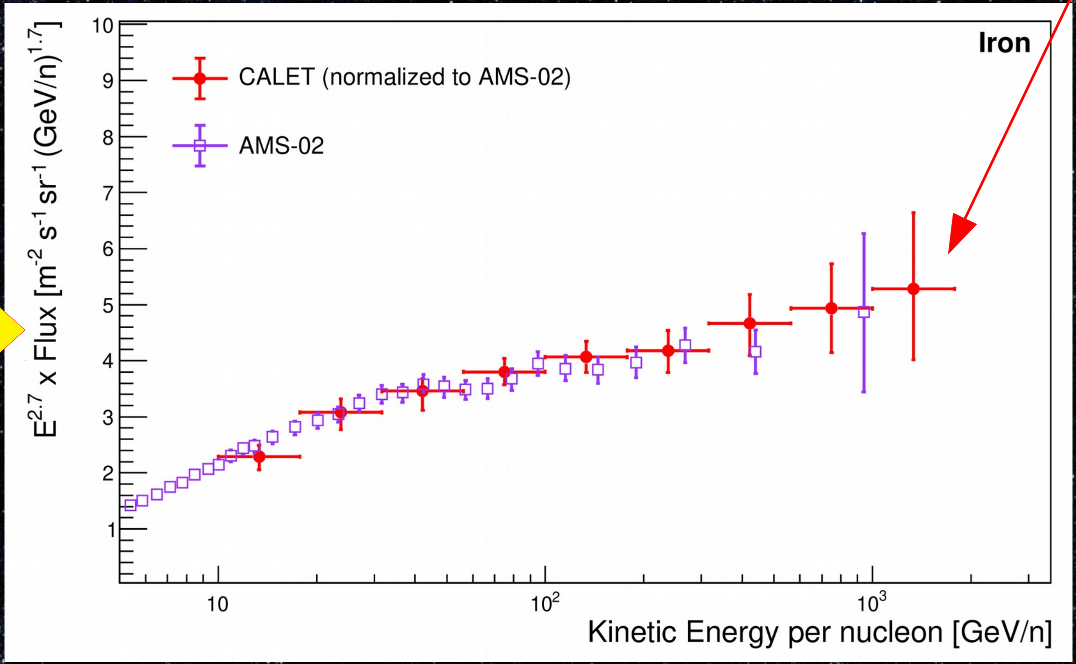
A COMMENT ON NORMALIZATION AND SPECTRAL SHAPE



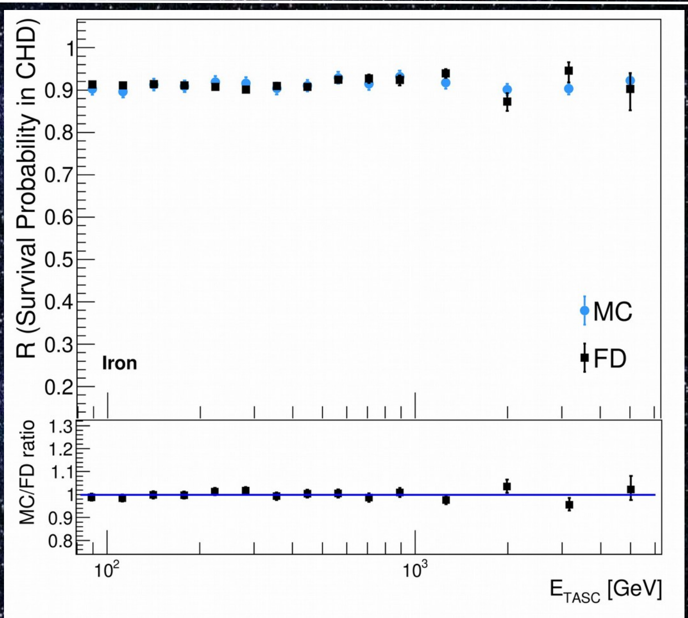
- Good agreement between CALET and ATIC, Tracer, HESS and CRN
- Different normalization with respect to NUCLEON and AMS.

Here CALET flux has been multiplied by 1.20 to adjust to AMS normalization

Also, the spectrum has been multiplied by $E^{2.7}$

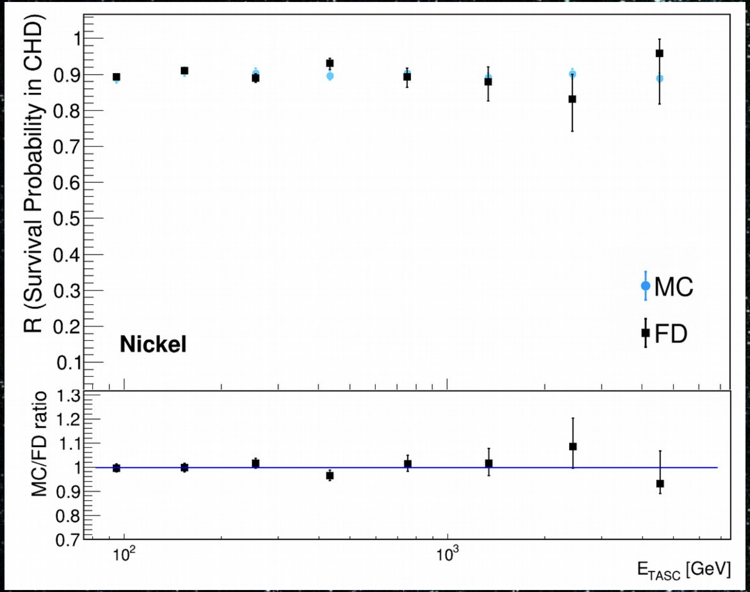


INTERACTIONS IN THE INSTRUMENT



$$R = (Z_{CHDX} \& Z_{CHDY})/Z_{CHDX}$$

Good consistency between MC and FD



Amount of material above the CHD: 2 mm thick Al cover (~2.2% X_0 and 5×10^{-3} λ_I)

Total loss (~10%) of interacting iron events taken into account in the total efficiency.