Results of the Heavy Cosmic-Ray Analysis with CALET on the International Space Station

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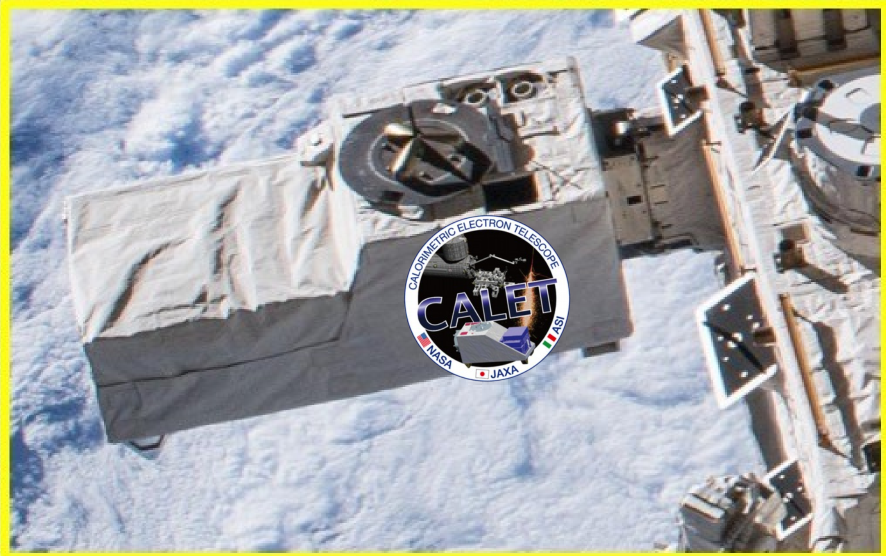
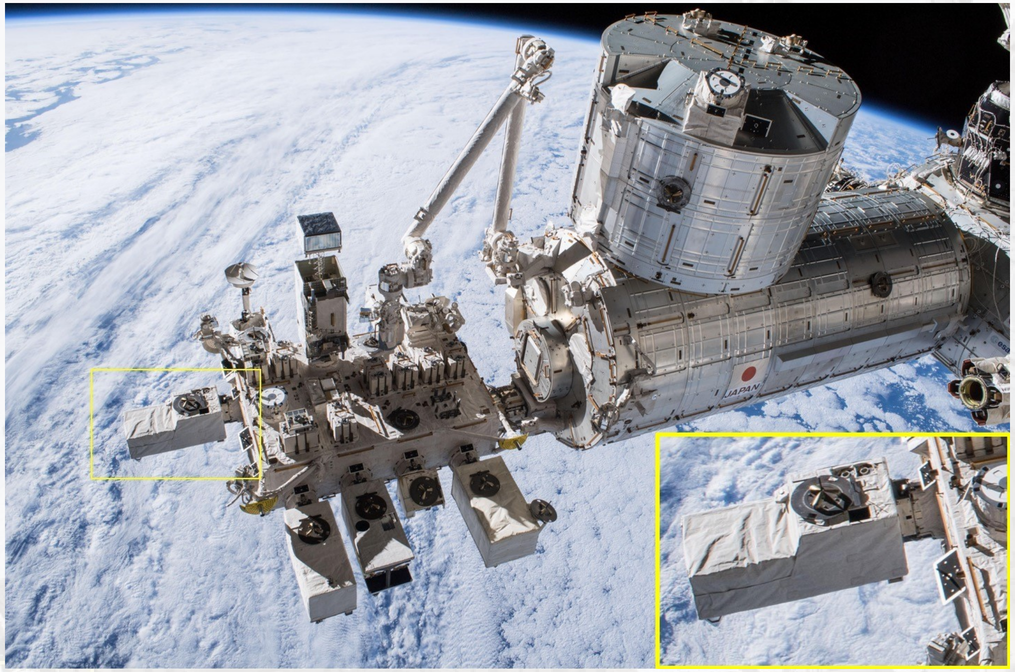
On behalf of the CALET collaboration

Vulcano workshop
2024
Ischia, Italy

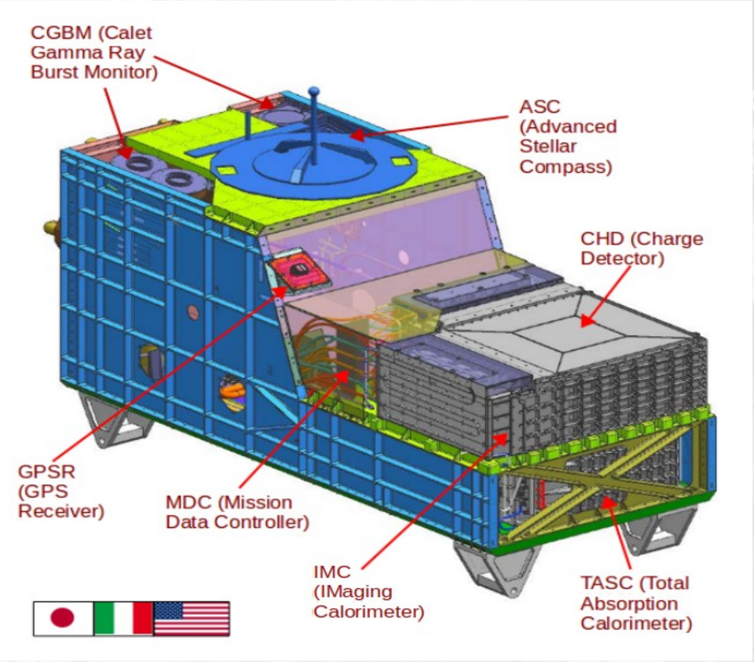


CALET PAYLOAD

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



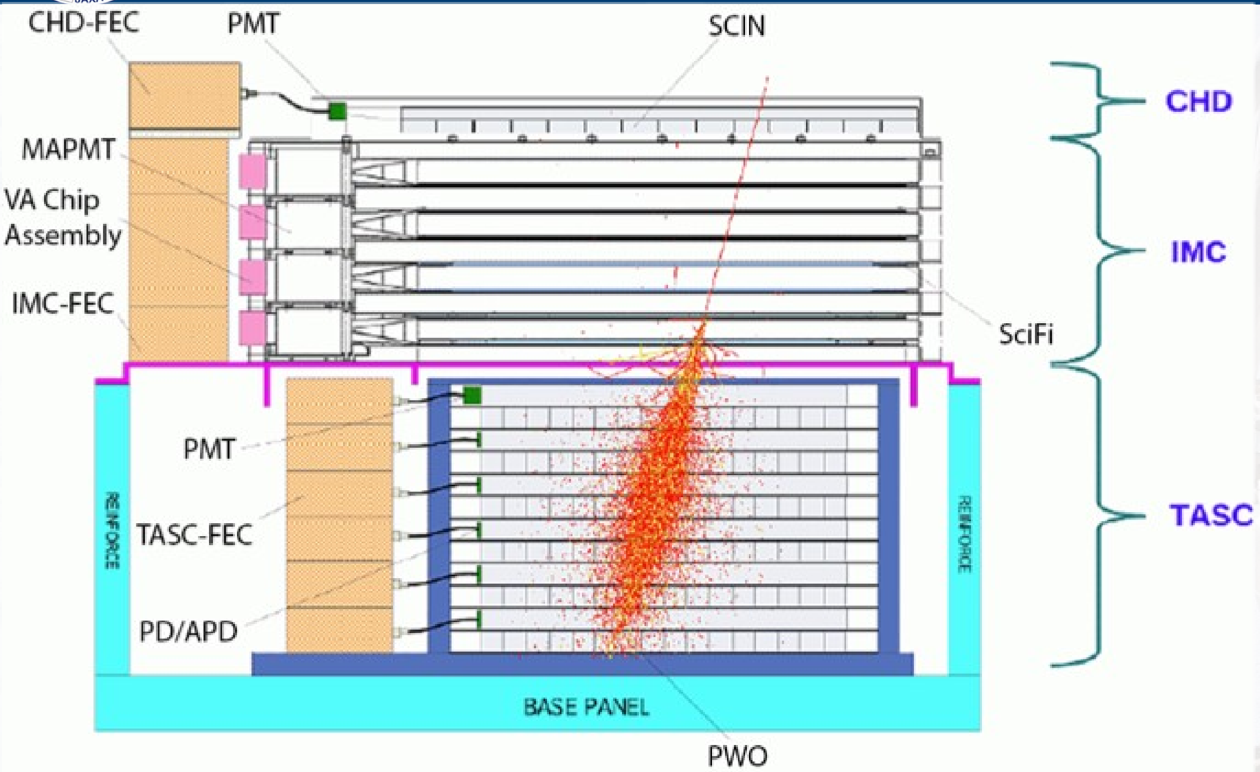
CALET was emplaced on Japanese Experiment Module – Exposed Facility (JEM-EF) port#9 on Aug. 25th, 2015



JEM Standard Payload
Mass: 612.8 kg
Size: 1850 mm (L) x 800 mm (W) x 1000 mm (H)
Power Consumption: 507 W (max)

CALET started scientific observations on Oct. 13Th, 2015. More than 4.5 billion events collected so far.

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)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimiter)
Measure	Charge $(1 \leq Z \leq 40)$ $\Delta Z/Z = 0.15$ for C, 0.35 for Fe	*Particle ID*, Tracking ΔX at CHD = 300 μm	Energy, *Dynamic range: 1 –10^6 MIP (1 GeV –1 PeV)*
Geometry/ Material	Plastic Scintillator 14 paddles x 2 layers (X,Y) Paddle size: 32 mm x 10 mm x 450 mm	Scintillating fibers 448 x 16 (X,Y) 7 W layers, total thickness: $3\ X_0$ Scifi Size: 1 mm^2 x 448 mm	16 PWO *logs* x 12 layers (X,Y) Total thickness: $27\ X_0$, $1.2\ \lambda_I$ Log size: 19 mm x 20 mm x 326 mm
Readout	PMT + CSA	64-anode MAPMT + ASIC	APD/PD + CSA PMT + CSA (for trigger)

IRON AND NICKEL ANALYSIS PROCEDURE

Data sample

- ✔ From November 2015 to December 2022, 2618 *d*, live time $T = 5.3 \times 10^4$ *h*, ~86% total obs. time.
- ✔ Iron (nickel) statistic increased by 1.6 (1.3) times with respect to our previous publications.
- ✔ MC simulations based on EPICS 9.21 w/ DPMJET-III.
- ✔ Preliminary iron analysis also based on GEANT4 10.5 w/ FTFP_BERT.
- ✔ Iron: improvement of charge calibration, extension of acceptance and of charge selection.

(1) Shower event selection and High Energy Trigger (HET)

Select interacting particles.

(2) Tracking with IMC

Identify the impact point and the particle's direction.

(3) Acceptance cut

Events crossing the whole detector from the top of the CHD to the TASC bottom layer and clear from the edges of TASCX1 by at least 2 cm ($S\Omega \sim 510$ cm^2 sr).

(4) Charge consistency with CHD

Remove particles undergoing a charge-changing interaction in the upper part of the instrument.

(5) Charge selection with CHD

Iron (nickel) candidates are identified by an ellipse centered at $Z = 26$ (28).

(6) Background estimation

(7) Energy unfolding

(8) Systematic errors

(9) Flux measurement

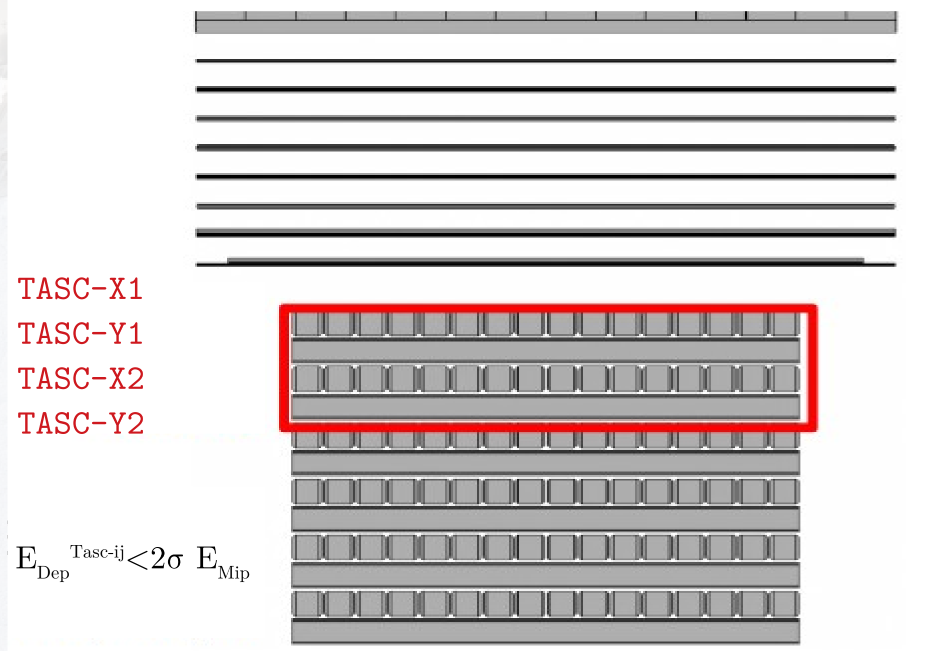
(1) HET and Shower selection

- For light nuclei (Z<10), only events interacting in the detector are triggered.
- For heavy nuclei, the HET threshold is far below the signal amplitude expected from a particle at minimum ionization (MIP) and the trigger efficiency is close to 100%.

→ in order to select interacting particles, a deposit larger than 2 sigmas of the MIP peak is required in at least one of the first four layers of the TASC.

HE Trigger

Shower Event selection for Fe, Ni



(2) (3) Tracking with IMC

Tracking algorithm based on a combinatorial Kalman filter

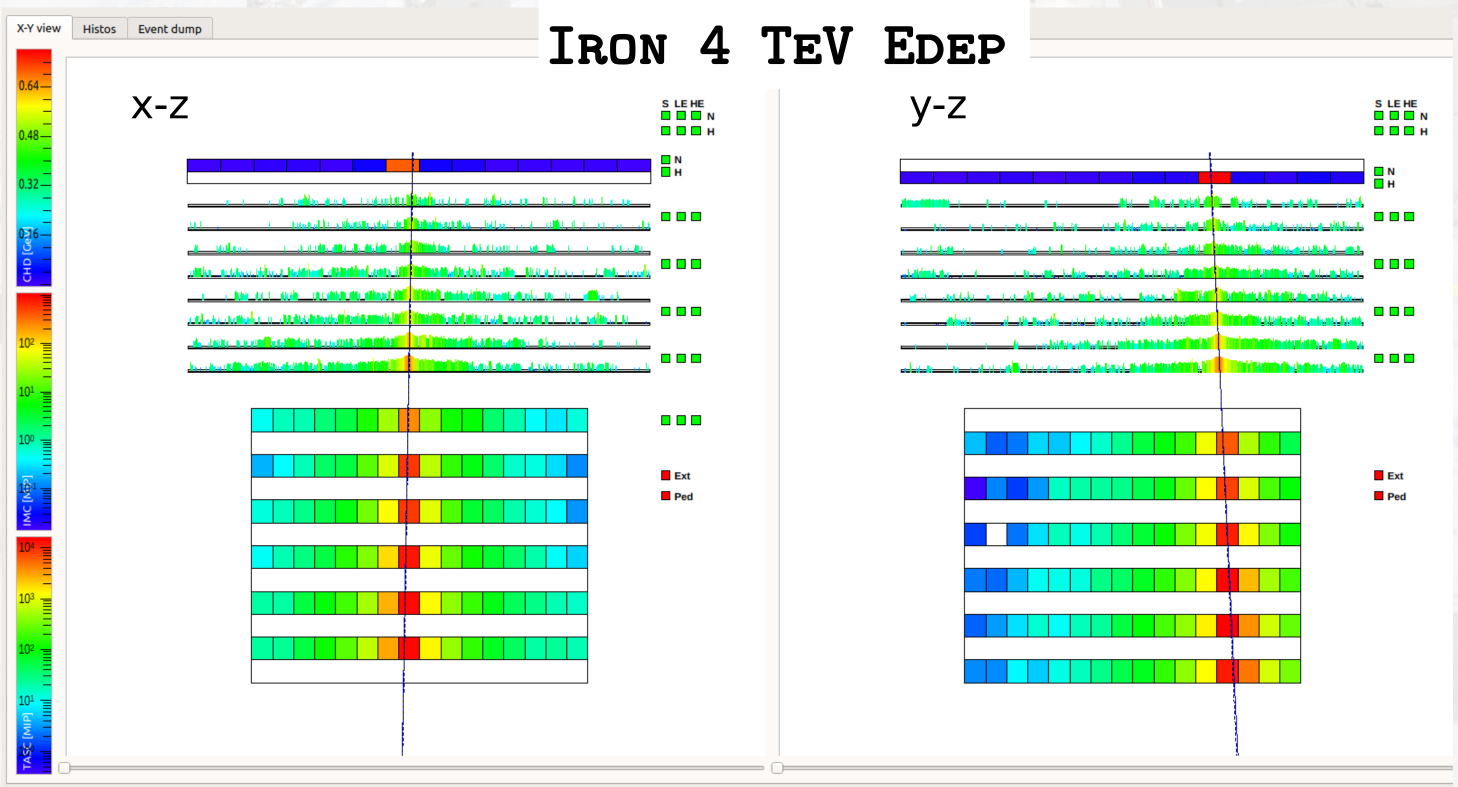
Tracking is used to:

- Determine cosmic ray (CR) arrival direction;
- Define geometrical acceptance;
- Identify CHD paddles and IMC scintillating fibers crossed by CR particle

Tracking performance for iron and nickel:

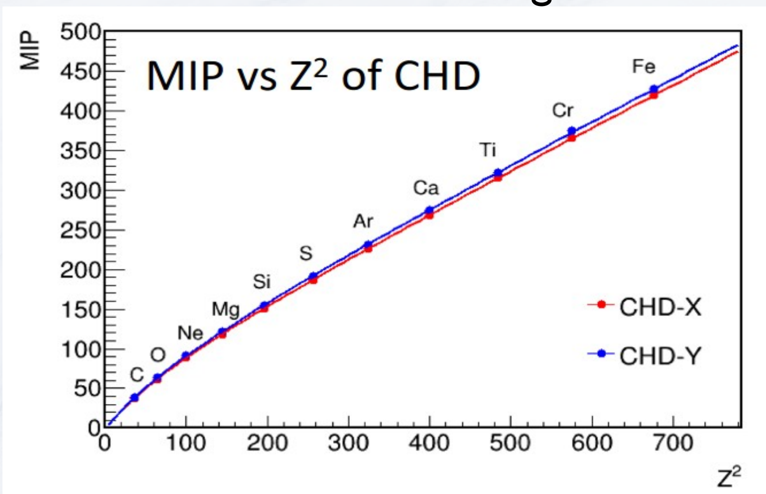
- angular resolution : ~0.08°
- spatial resolution for the impact point on the CHD: ~180 μm.

Iron 4 TeV Edep

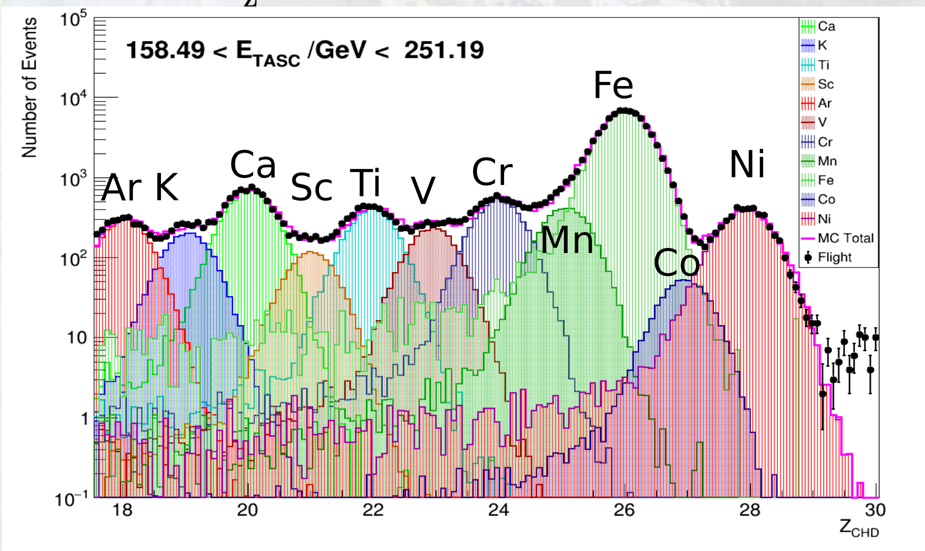


Charge Z reconstructed by measuring the ionization deposits in the CHD

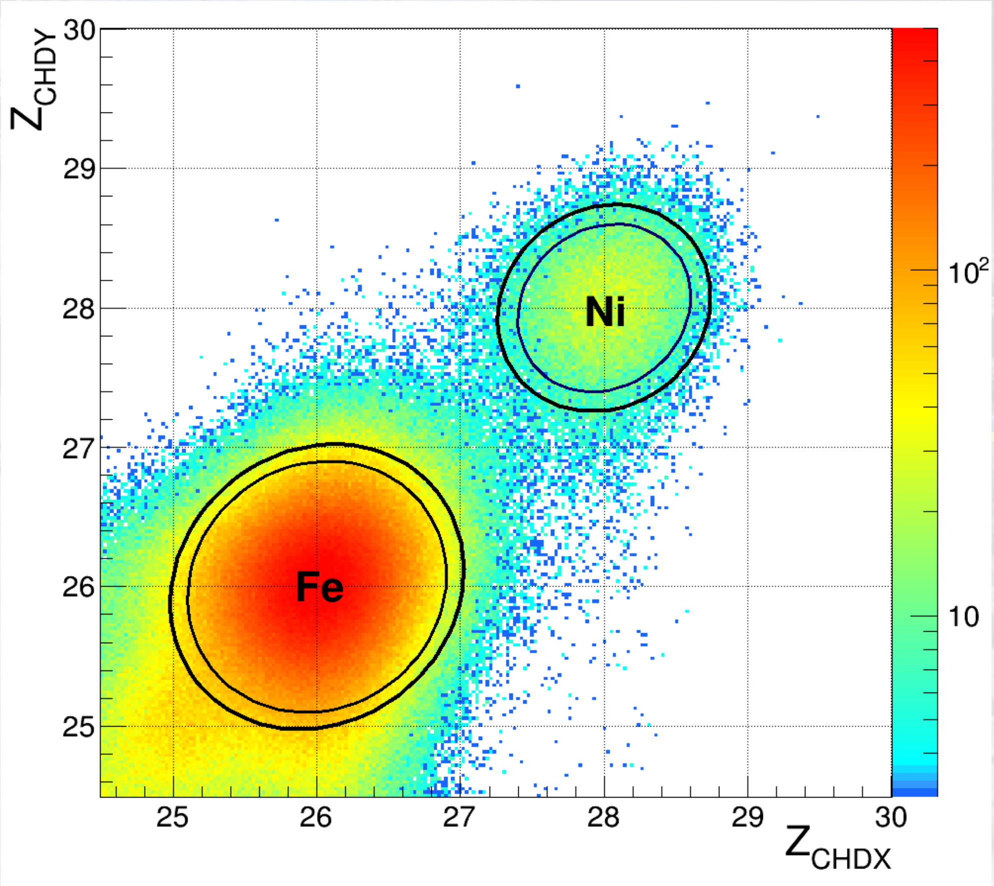
- Non linear response to Z^2 due to the quenching effect in the scintillators is corrected using a "halo" model.



- 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 are $0.35\ e$ and $0.39\ e$ for Fe and Ni respectively.

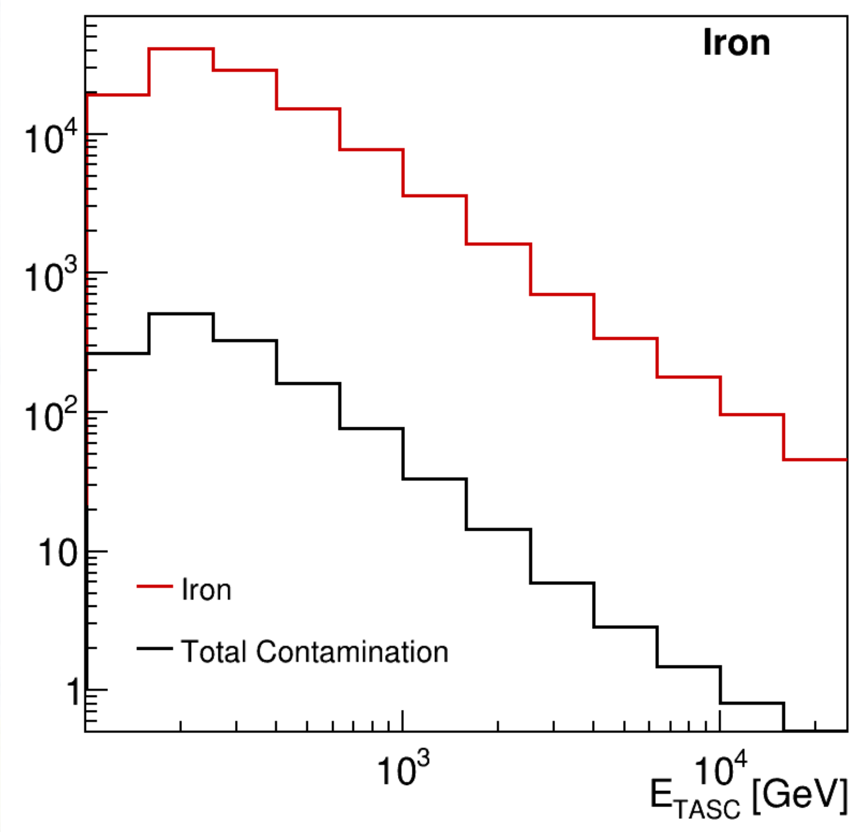


- Iron (nickel) events are selected within an ellipse centered at Z = 26 (28), with $2\sigma_x$ ($1.4\sigma_x$) and $2\sigma_y$ ($1.4\sigma_y$) wide semiaxes for Z_{CHDX} and Z_{CHDY}, respectively, and rotated clockwise by 45°

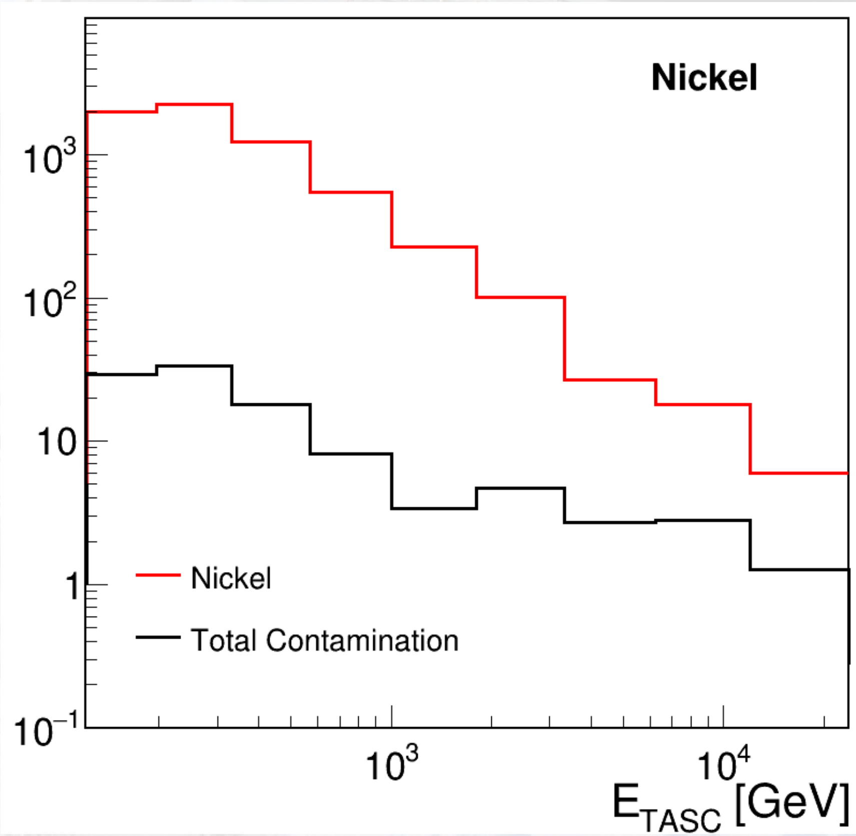


(6) Fe dN/dEdep and background estimate

dN/dEdep distributions for Fe and contamination by Mn, Co, Cr and Ni, after Fe selection



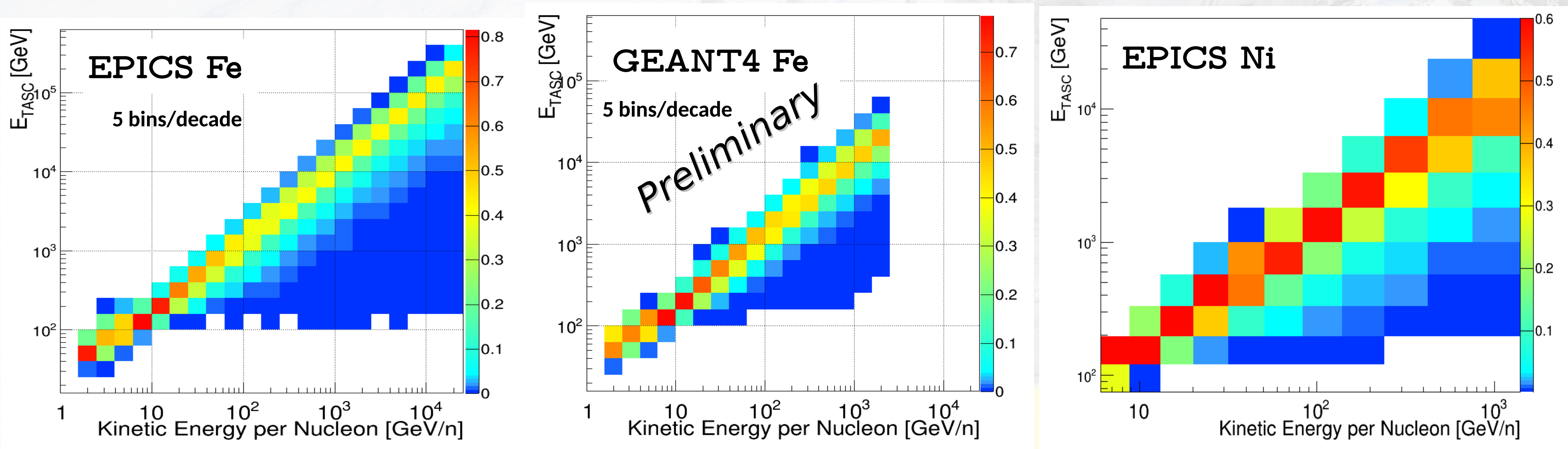
dN/dEdep distributions for Ni and contamination by Co, Fe after Ni selection



Background contamination from different nuclear species misidentified as Fe (Ni) are estimated by Monte Carlo simulation.

- Iron: total background is few percent in all energy bins.
- Nickel: ~ 1% between 10^2 and 10^3 GeV, up to 10% at 10^4 GeV

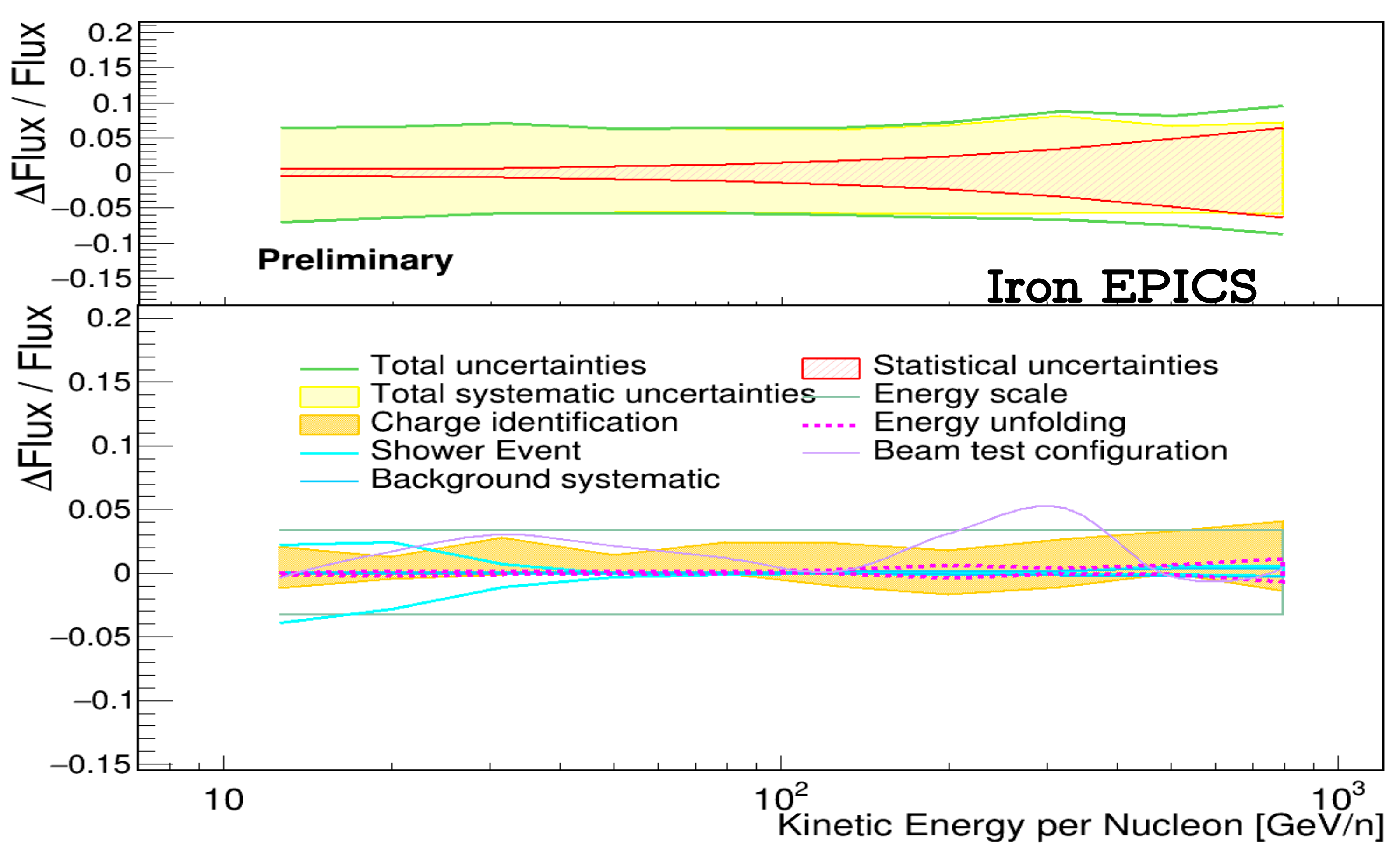
- Energy unfolding is applied to correct for bin-to-bin migration effect and obtain the primary energy spectrum



- In the figures the color scale is associated to the probability that iron (nickel) candidates in a given bin of kinetic energy cover different intervals of E_{TASC}

- EPICS and GEANT4 are used to estimate the energy response ("smearing") matrix, applying the same selection cuts as in the FD analysis

(8) Systematic Errors: Iron



Energy-independent systematic uncertainties include

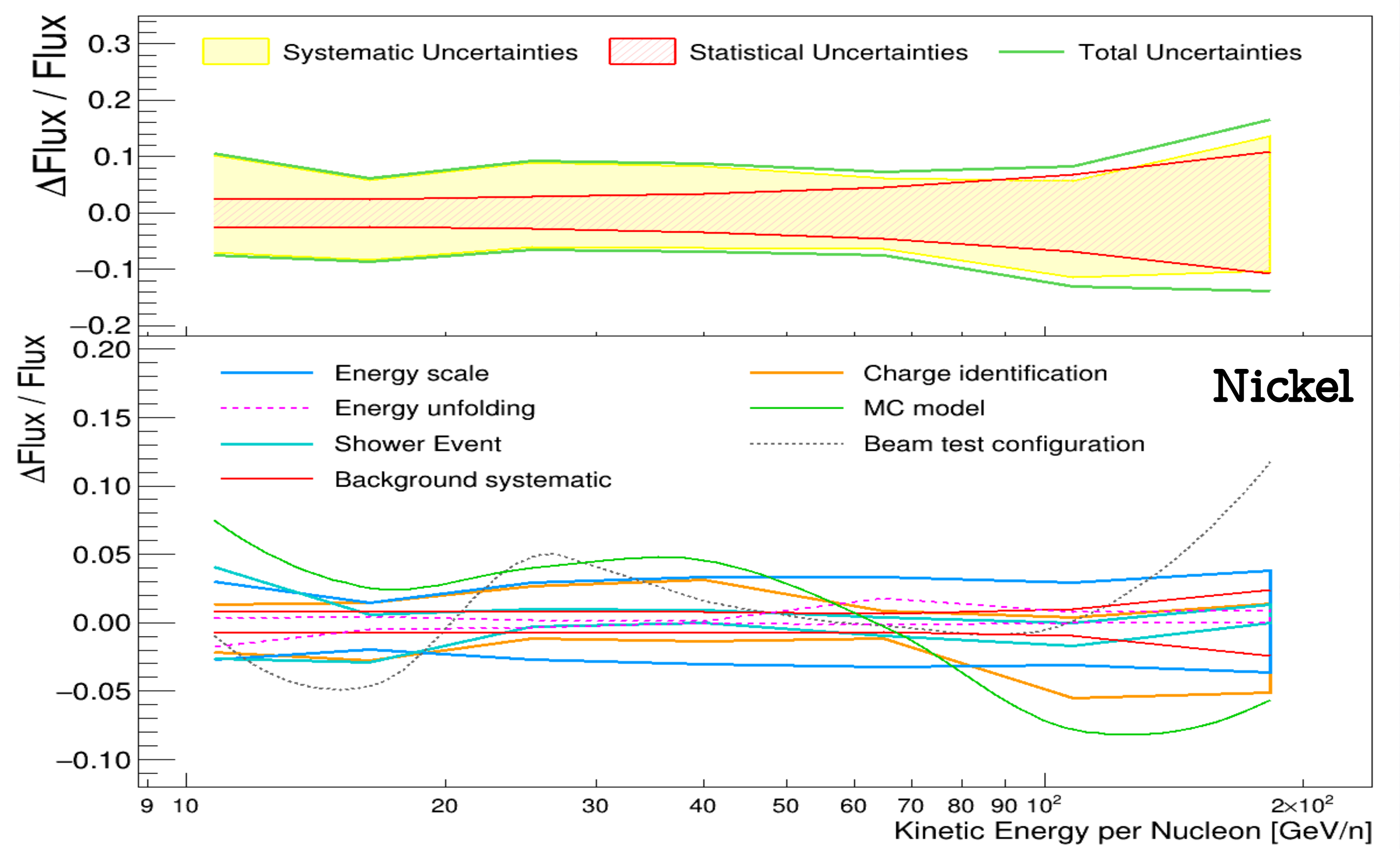
- live time (3.4%)
- long-term stability (< 2%)
- geometrical factor (~1.6%)

Energy-dependent systematic uncertainties include

- Charge identification
- Shower event
- Beam test configuration
- Unfolding procedure

Systematic uncertantines are well contained within ±10%

(8) Systematic Errors: Nickel



Energy-independent systematic uncertainties include

- live time (3.4%)
- long-term stability (< 3%)
- geometrical factor (~1.6%)
- Isotope composition (~2.2%)

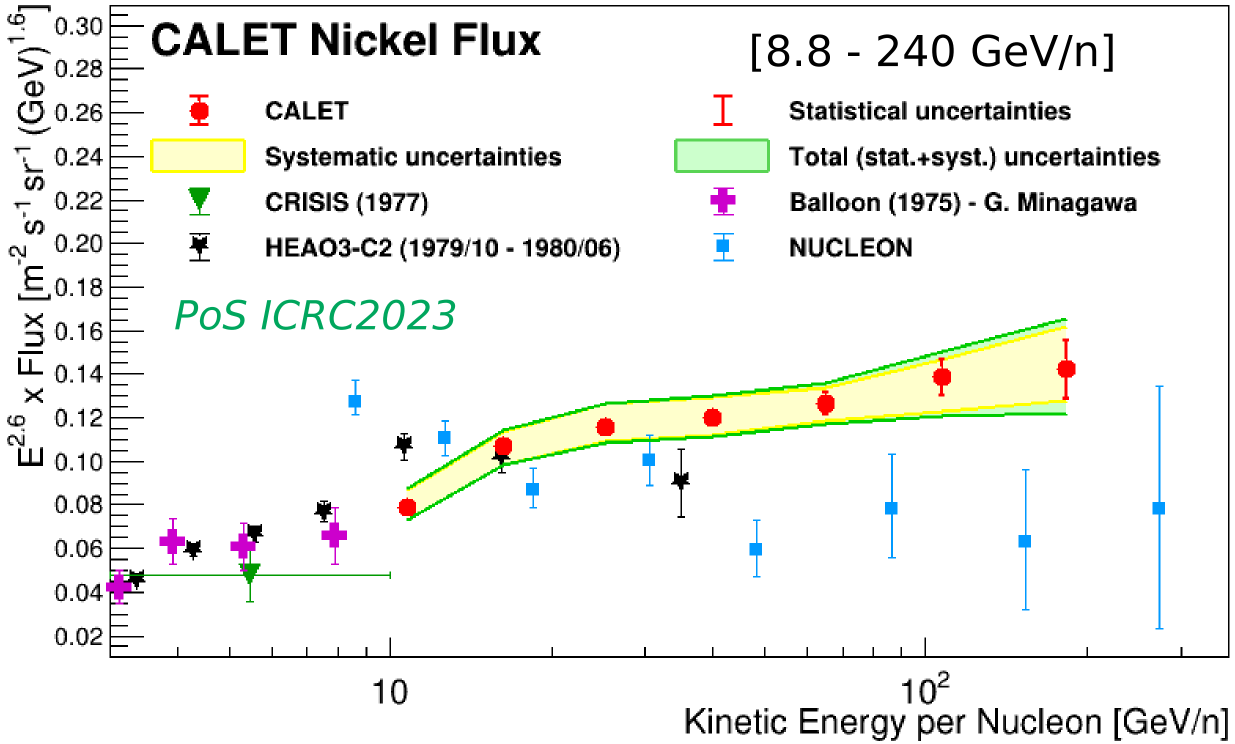
Energy-dependent systematic uncertainties include

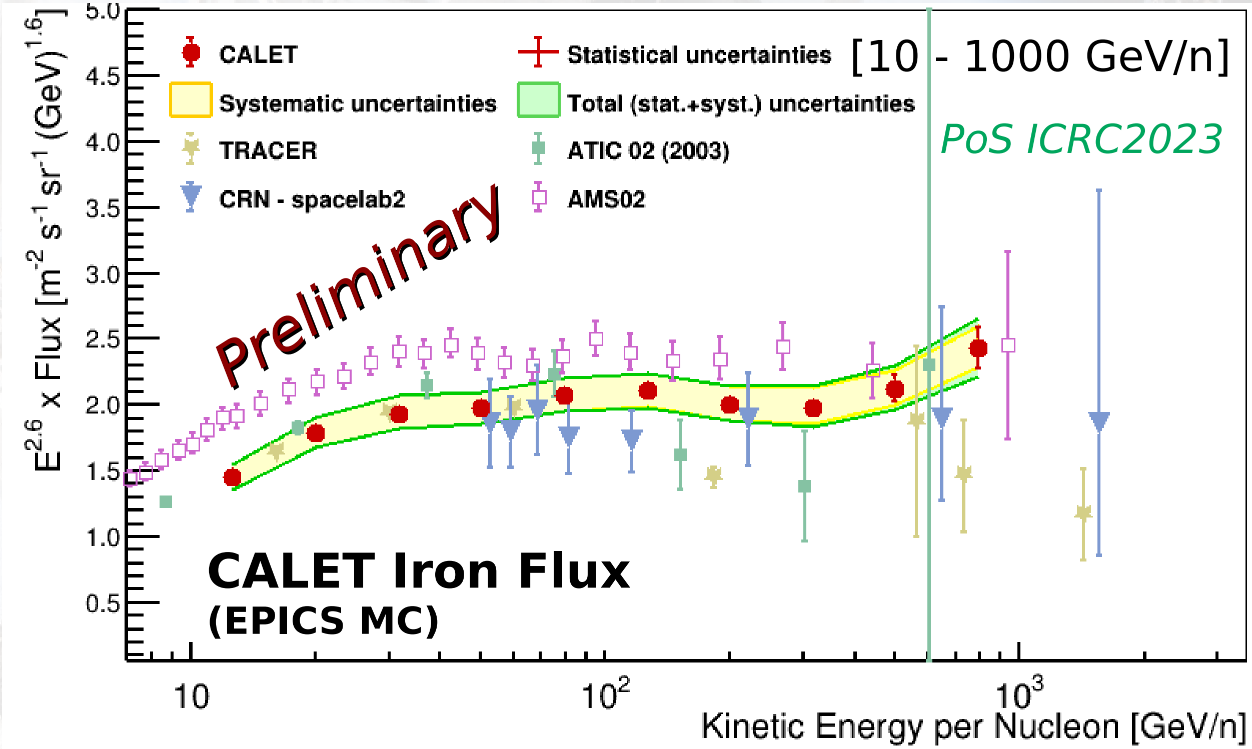
- Charge identification
- Shower event
- Beam test configuration
- Unfolding procedure
- MC model (GEANT4)

Systematic uncertantines are contained within ±10%

(9) Flux measurement

CALET Iron and Nickel Flux with multiplicative factor $E^{2.6}$



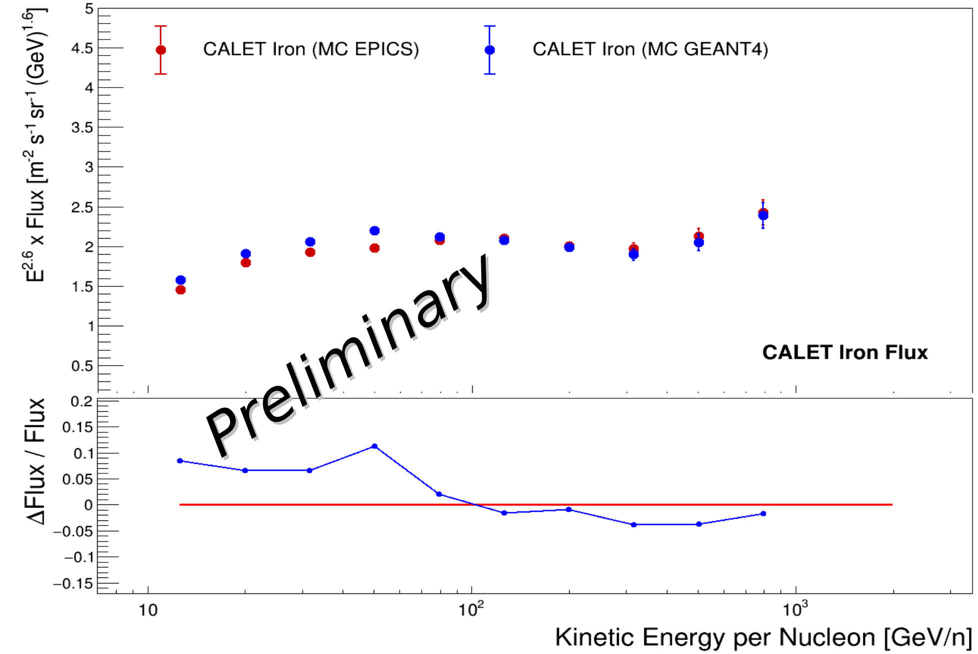


$$\Phi(E) = \frac{N(E)}{\Delta E \varepsilon(E) S\Omega T}$$

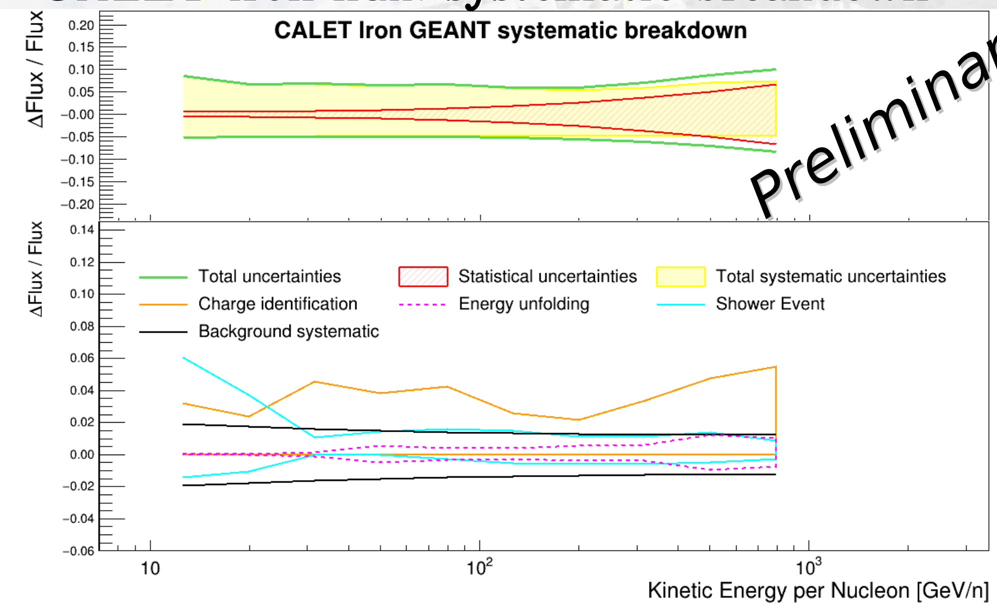
- N(E): bin counts of the unfolded energy distribution
- ΔE: energy bin width
- SΩ: geometrical acceptance
- T: live time
- ε(E): total selection efficiency

(9) Iron Flux measurement using GEANT4

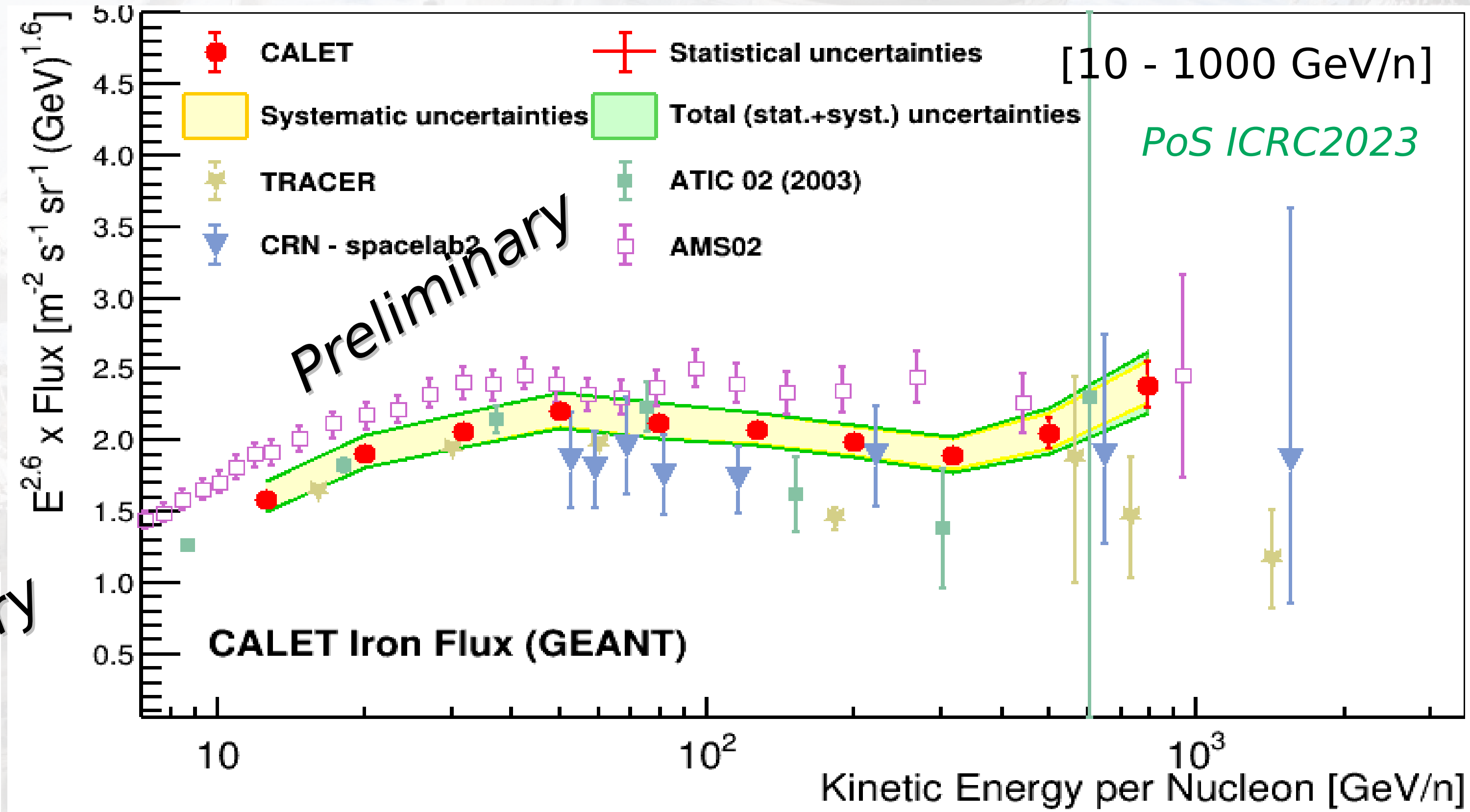
CALET iron flux: GEANT vs EPICS



CALET iron flux: systematic breakdown

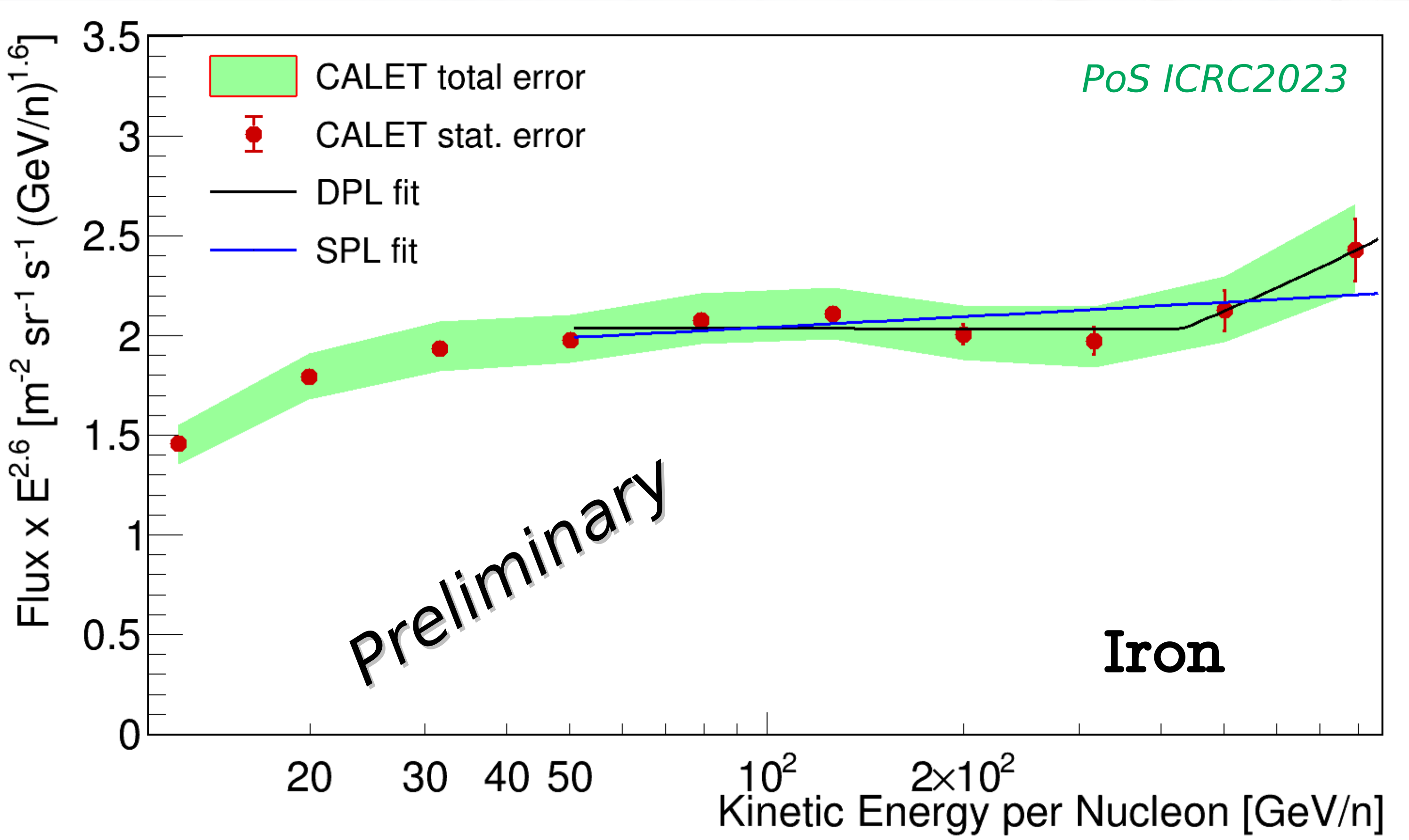


CALET GEANT Iron Flux with multiplicative factor $E^{2.6}$



Iron Spectral Index

Fit from 50 to 1000 GeV/n, with a single power law function (SPL) and double power law (DPL)



SPL Fit

$$\Phi(E) = C\left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma}$$

- $\gamma = -2.56 \pm 0.01(\mathrm{stat}) \pm 0.03(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 2.7/5$

DPL Fit

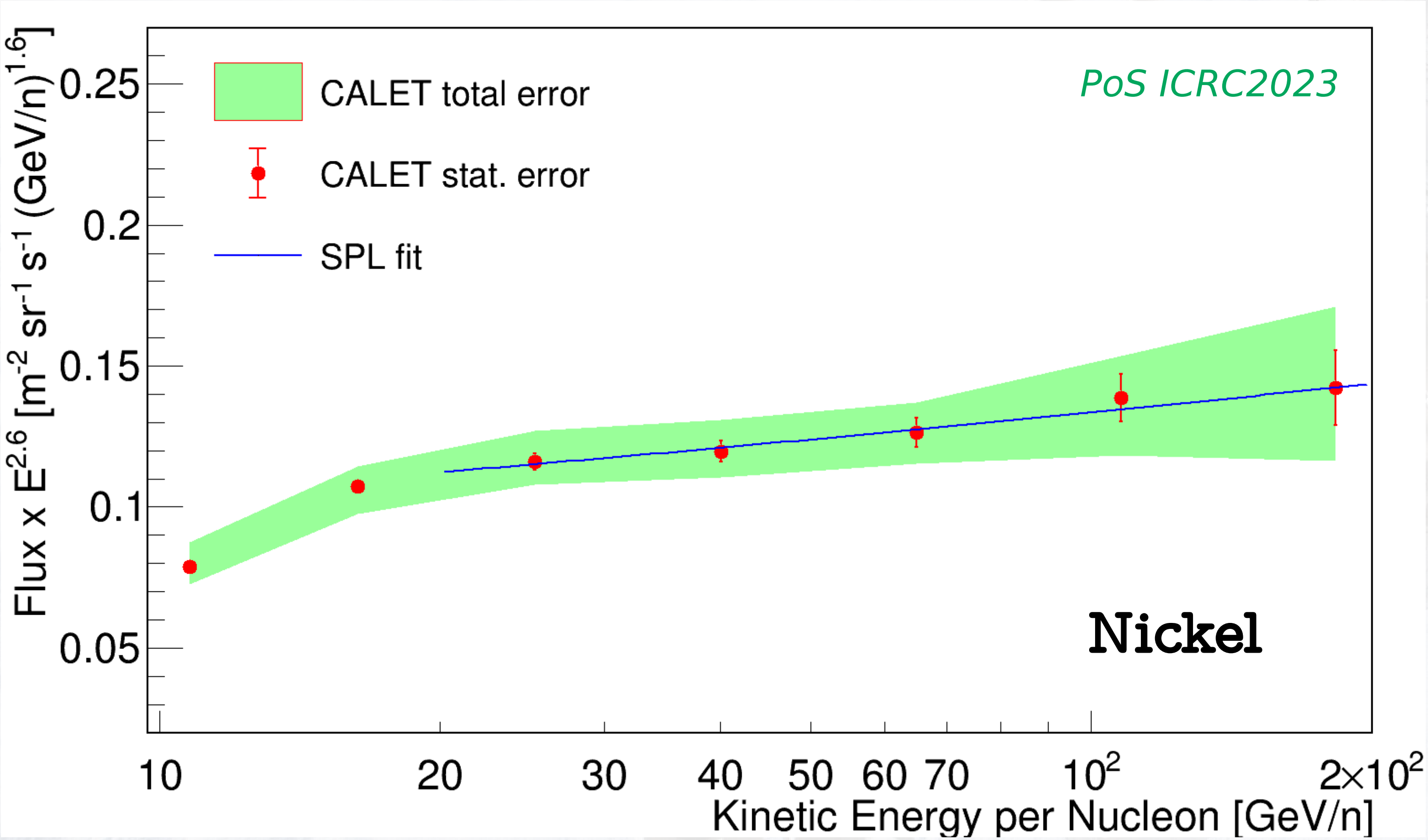
$$\Phi(E) = \begin{cases} c\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \leq E_0 \\ c\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

- $\gamma = -2.60 \pm 0.01(\mathrm{stat}) \pm 0.08(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 0.8/3$
- $\Delta\gamma = 0.29 \pm 0.27$
- $E_0 = (428 \pm 314)$ Gev/n

The significance of the fit with the DPL in the studied energy range is not sufficient to exclude the possibility of a single power law.

Nickel Spectral Index

Fit from 20 to 240 GeV/n, with a SPL



SPL Fit

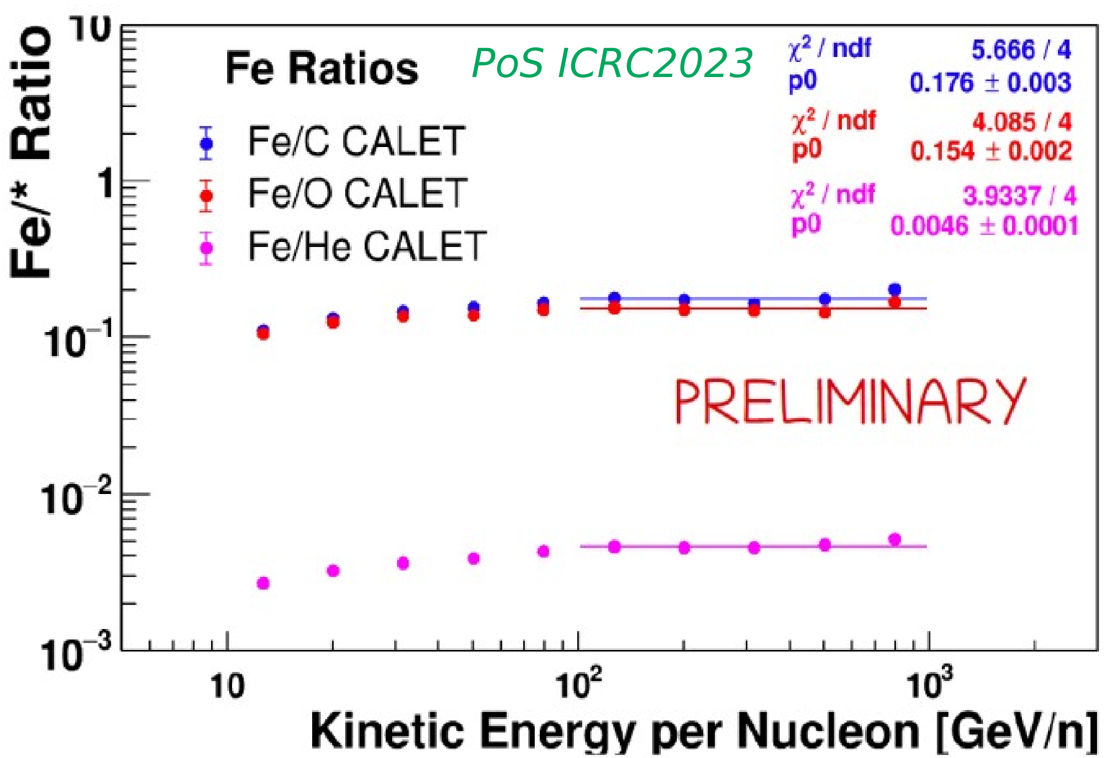
$$\Phi(E) = C\left(\frac{E}{1\ \text{GeV}}\right)^{\gamma}$$

- $\gamma = -2.49 \pm 0.03(\text{stat}) \pm 0.07(\text{sys})$
- $\chi^2/\text{DOF} = 0.1/3$

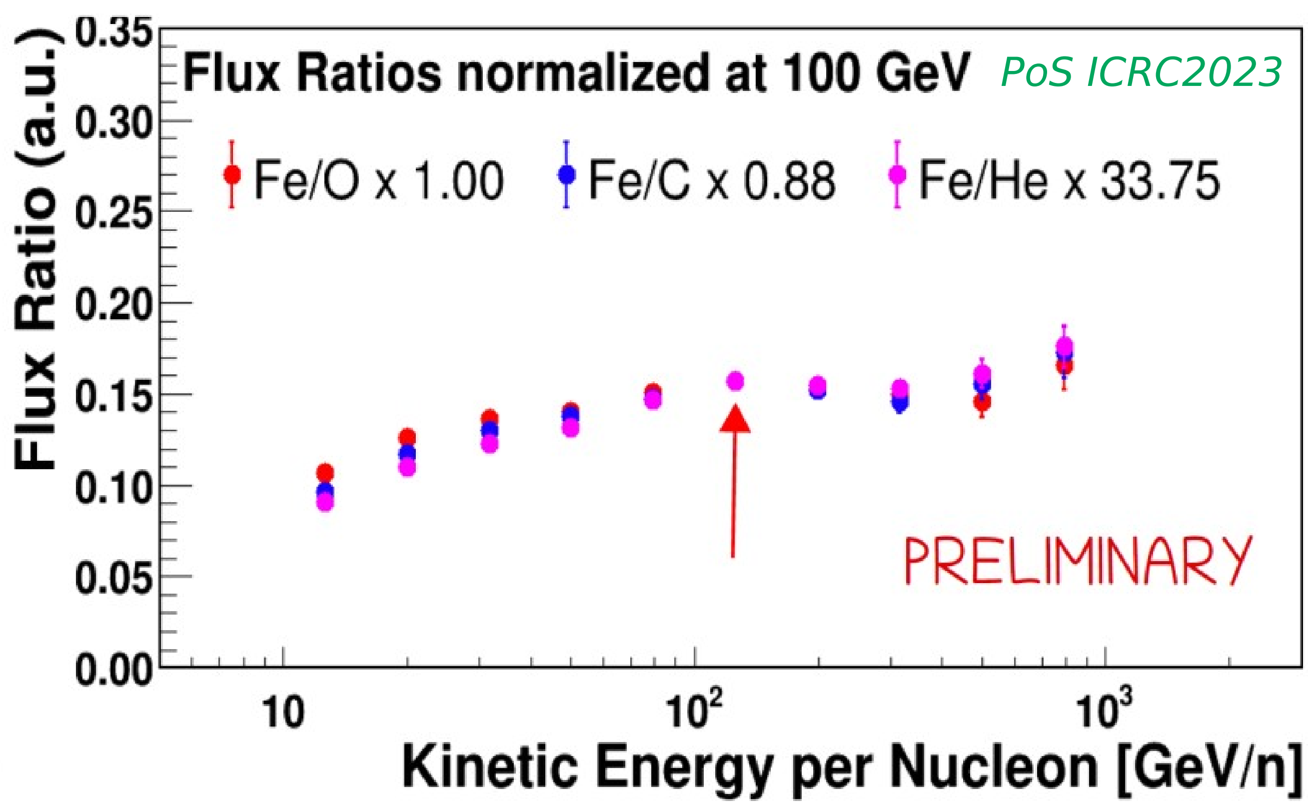
From 20 to 240 GeV/n the nickel flux is consistent with the hypothesis of an SPL spectrum

Iron to Primary Elements Flux ratio

Fe ratios to He, C and O



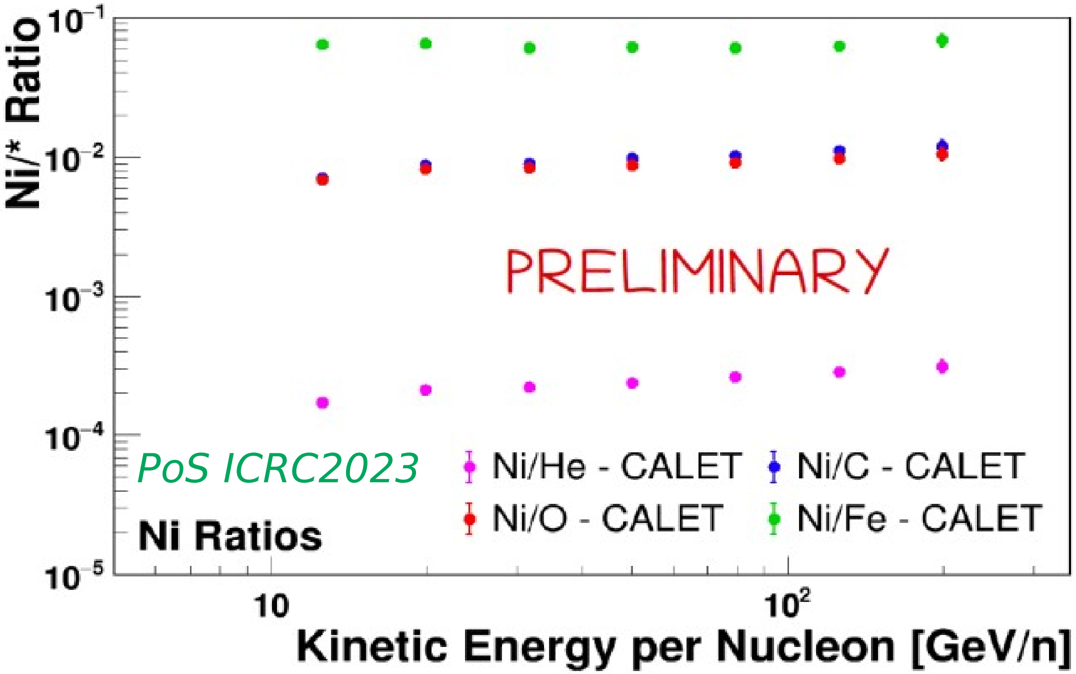
Fe ratios to He, C and O normalized at 100 GeV/n



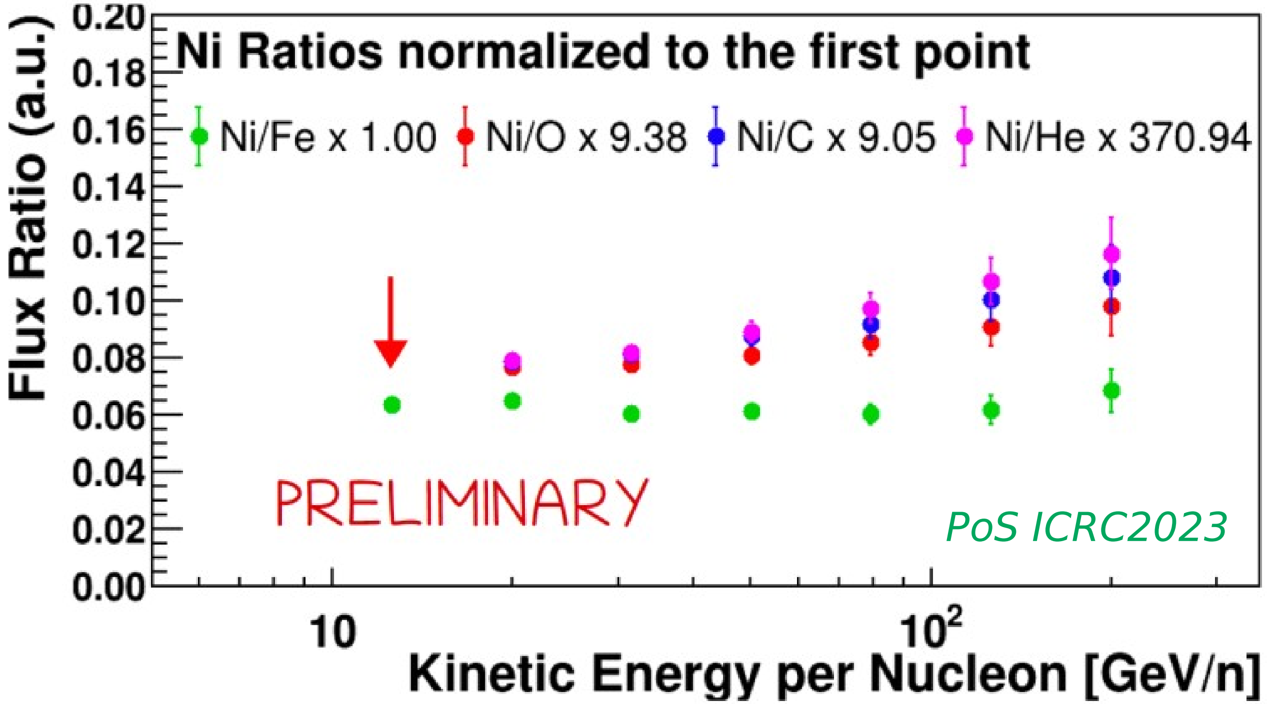
Fe/O, Fe/C and Fe/He are compatible with a constant above 100 GeV/n within errors.
⇨ Fe, O, C follow similar propagation

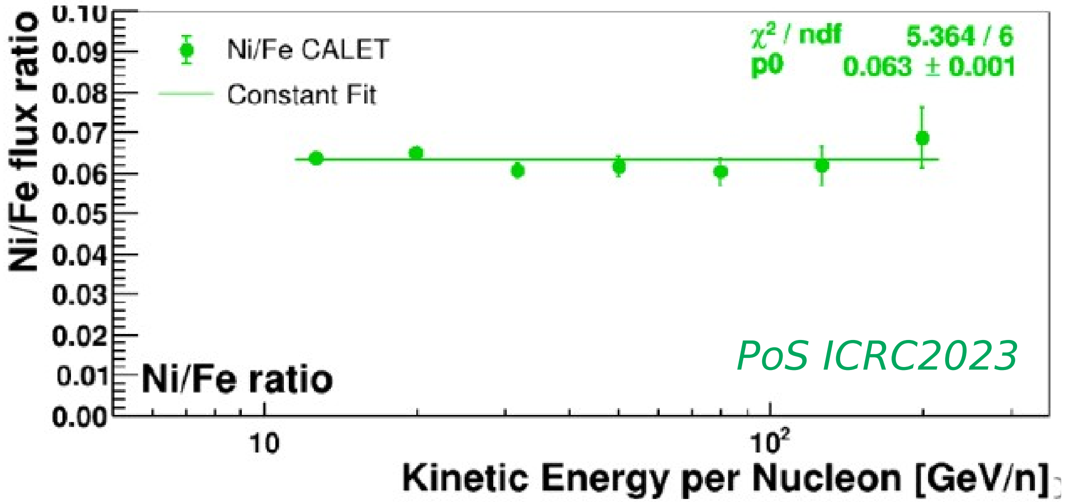
Nickel to Primary Elements Flux ratio

Ni ratios to He, C, O and Fe



Ni ratios normalized at around 10 GeV/n





- The Ni/Fe flux ratio is constant in all the energy range thus Ni and Fe have very similar behavior.
- The present energy range of nickel flux does not allow to fit the Ni/* ratios with a constant above 100 GeV/n.
- At low energy the Ni/O, Ni/C, Ni/He flux ratio show an increasing trend also visible in Fe/* ratios.

Conclusions

- The CR iron and nickel spectra were measured by CALET using 86 months of data collected on board the ISS, increasing the statistics with respect to our previous publications by 1.6 and 1.3 times, respectively (*Phys. Rev. Lett.* **126** (2021) 241101, *Phys. Rev. Lett.* ***128*** *(2022) 131103)*.

- The measurement of the iron energy spectrum was updated up to 1000 GeV/n, improving calibrations and extending charge selection and acceptance to 510 $cm^2\ sr$.

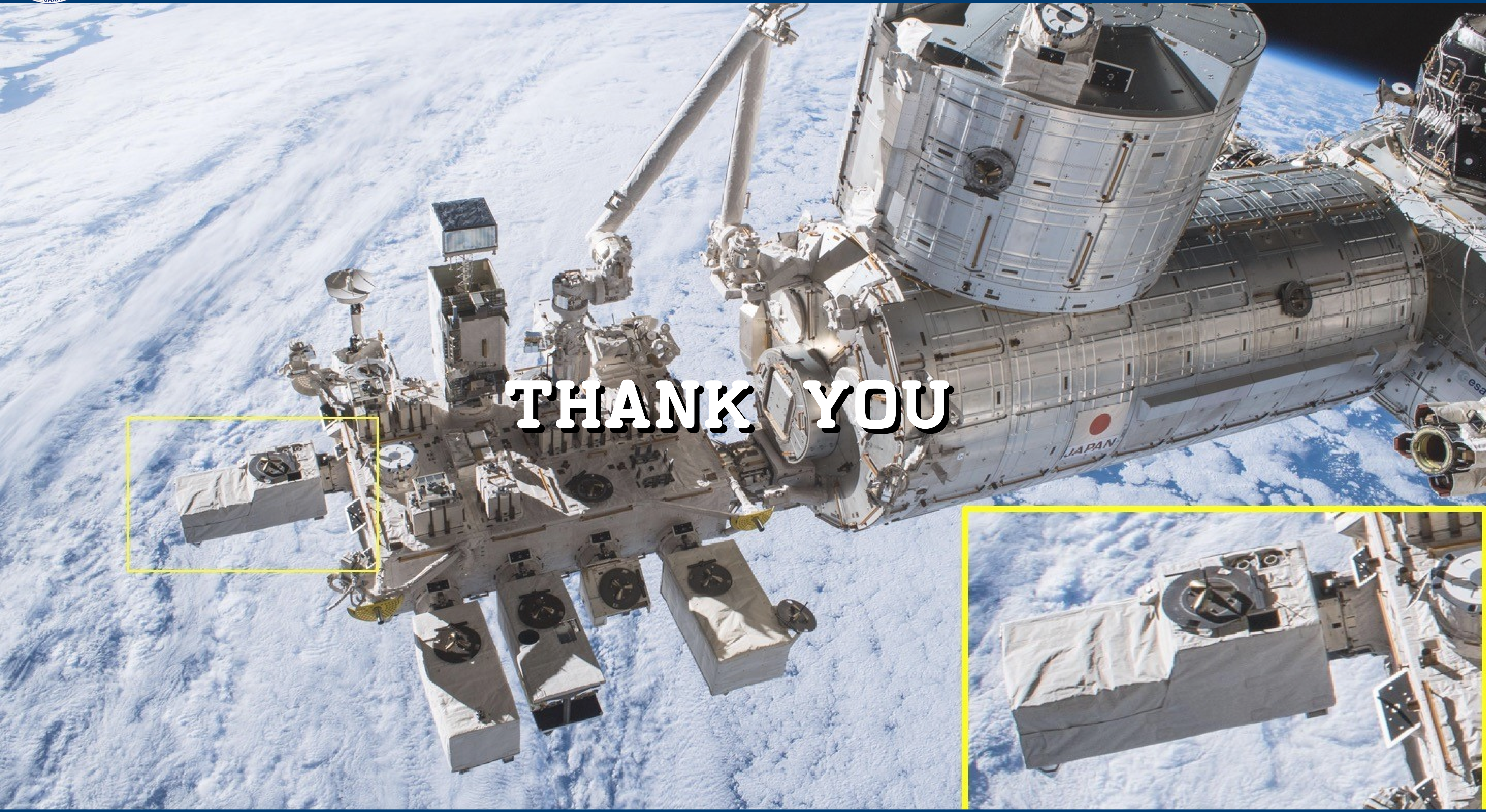
- A preliminary measurement of the iron energy spectrum was performed also using GEANT4 instead of EPICS: the two fluxes differ up to 10% below 100 GeV/n, while above they are in pretty good agreement.

- The preliminary fit with a DPL performed on the iron spectrum up to 1000 GeV/n do not allow to draw a significant conclusion on a possible hardening.

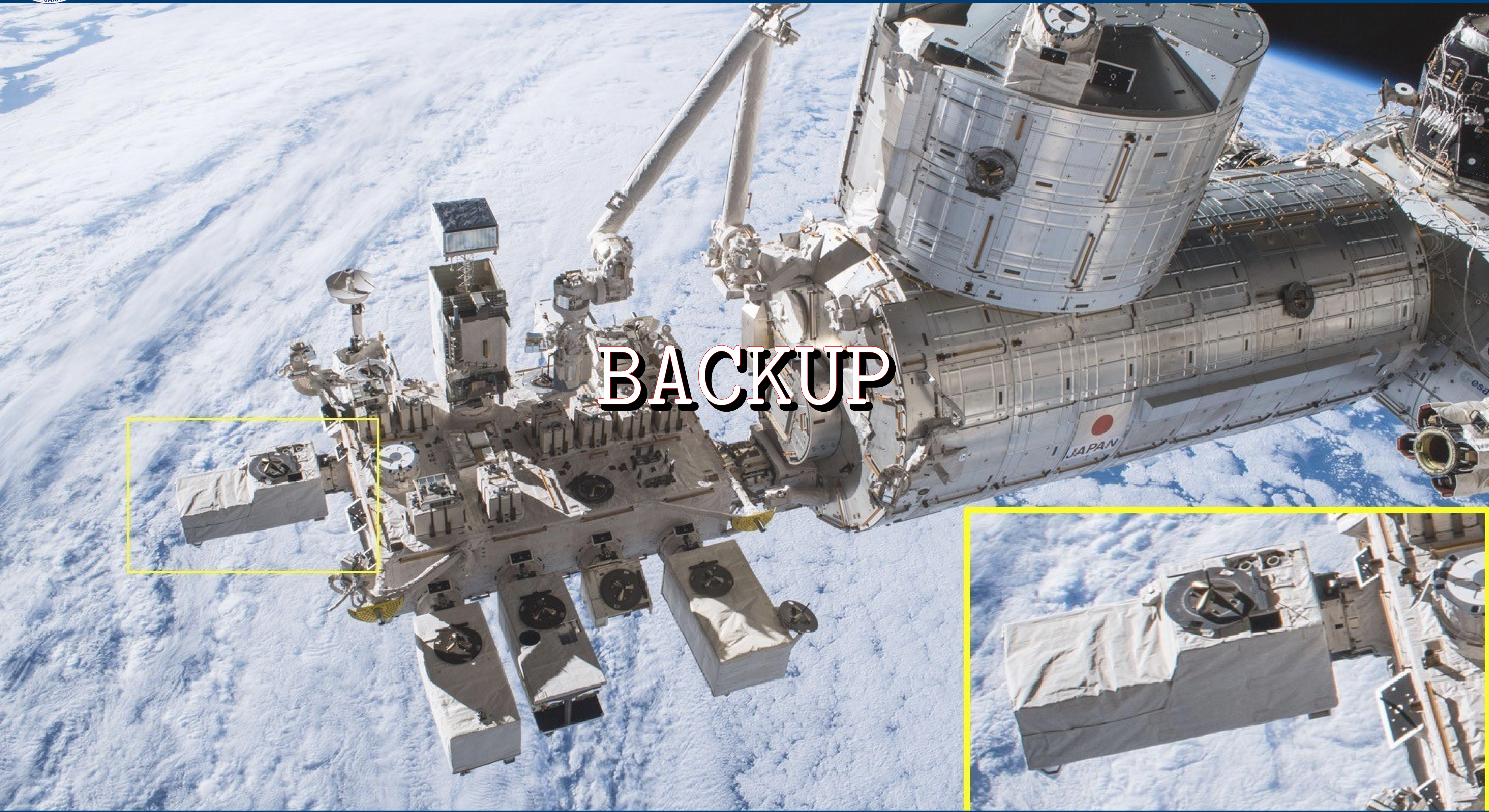
- Above 20 GeV/n the nickel spectrum is consistent with the hypothesis of a SPL spectrum up to 240 GeV/n with a spectral index value $\gamma = -2.49 \pm 0.08$.

- The flat behavior of the nickel to iron ratio suggests that the spectral shapes of Fe and Ni are the same within the experimental accuracy. This suggests a similar acceleration and propagation behavior.

THANK YOU



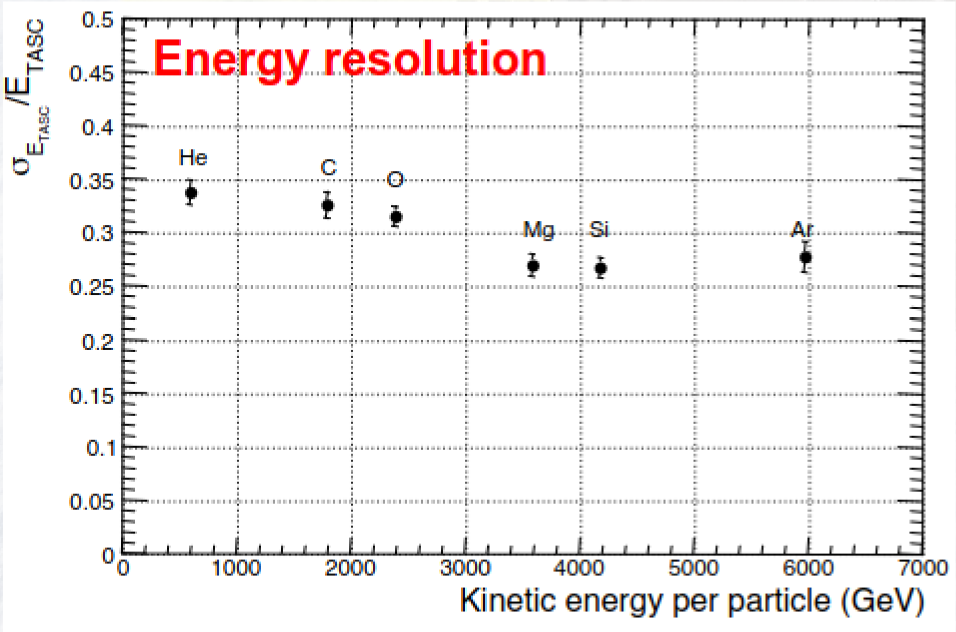
BACKUP

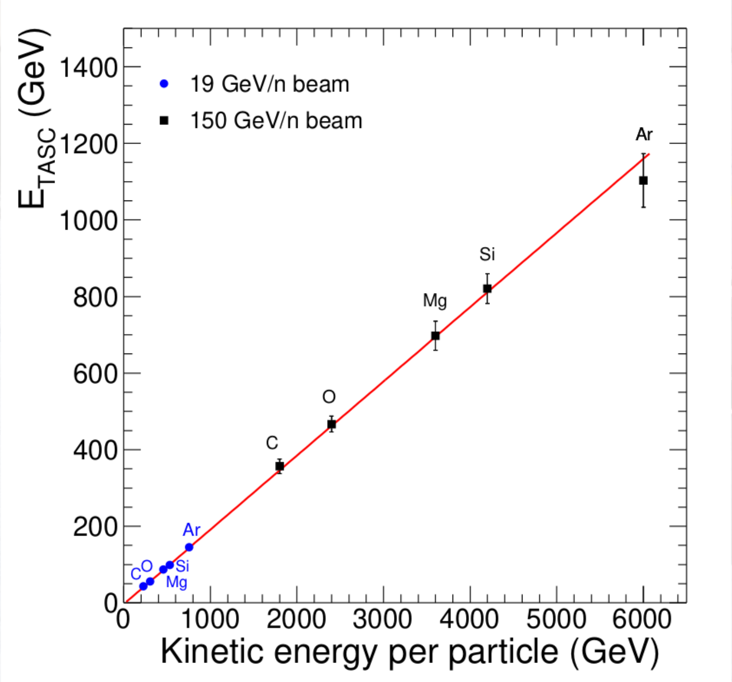


Beam Test Calibration

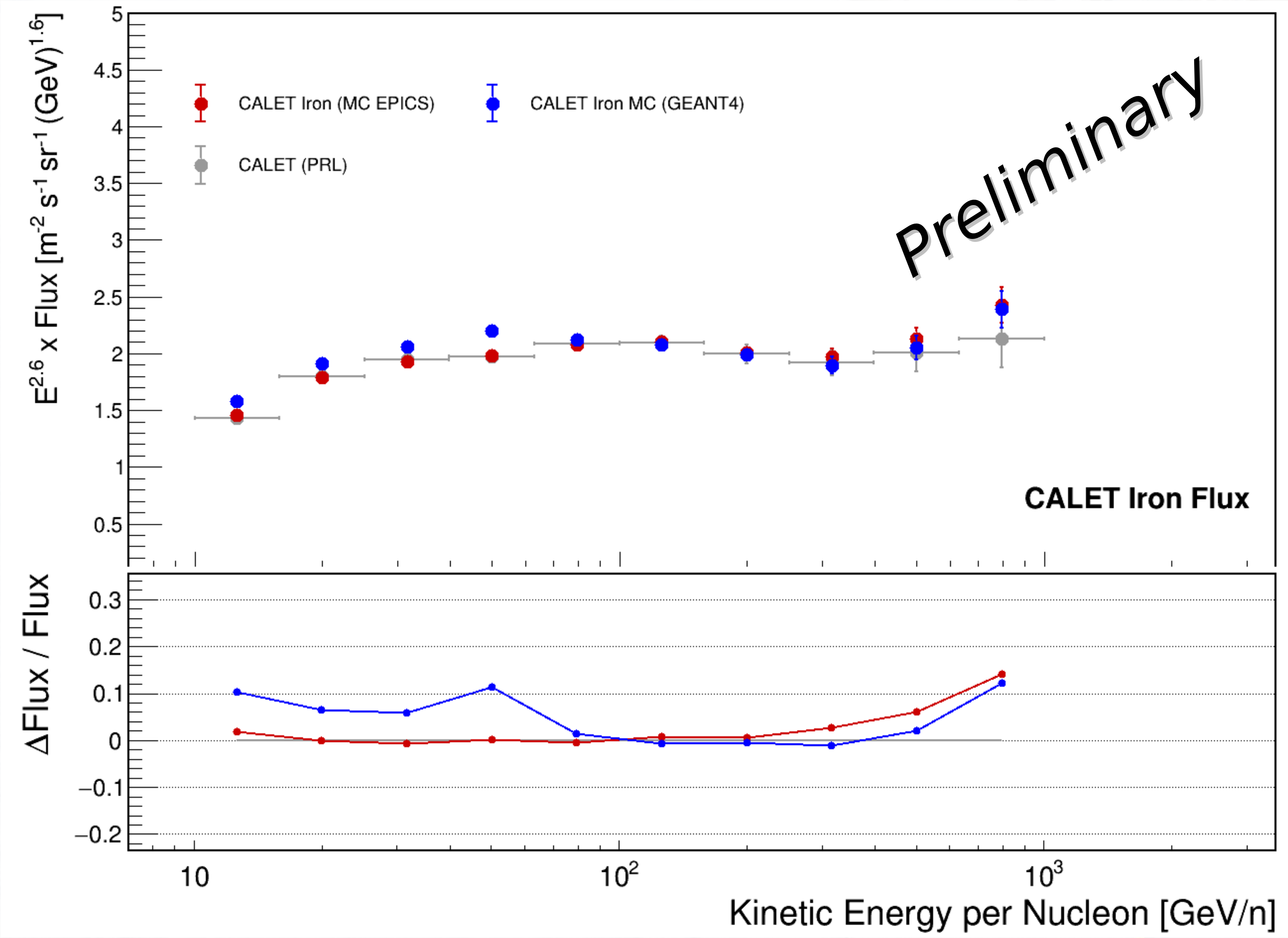
The energy response of the TASC derived from the MC simulations was tuned using the results of a beam test carried out at the CERN-SPS in 2015 with beams of accelerated ion fragments of 150 GeV/c/n.

- Good linearity up to maximum available beam energy (~6 TeV) between the observed TASC energy and the primary energy.
- Fraction of particle energy released in TASC is ~20%.
- Energy resolution around 30%.
- The energy response derived from MC simulations was tuned using the beam test results.





Iron Flux measurement: PRL comparison

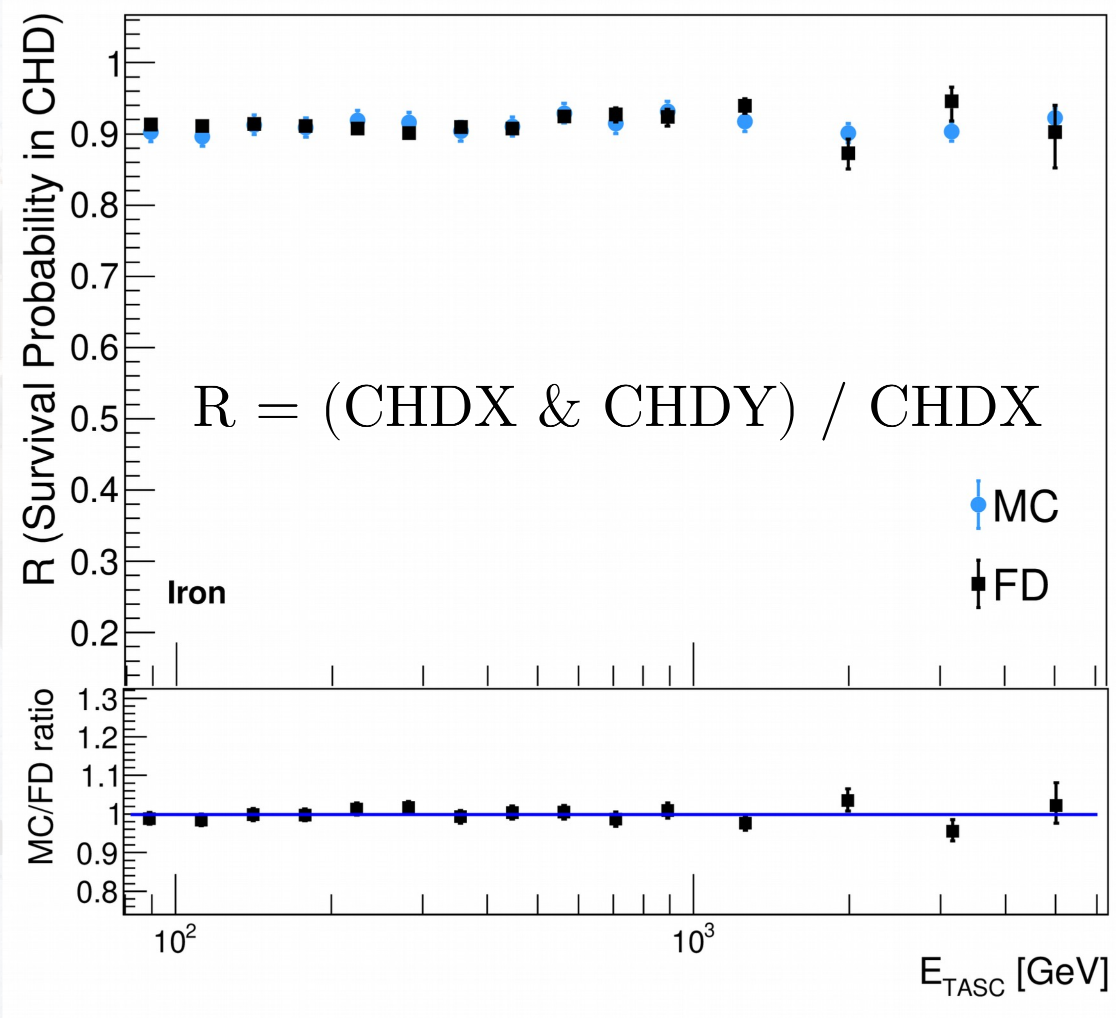


Difference with respect to the PRL *Phys. Rev. Lett.* **126** (2021) 241101

Interactions in the instrument

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

- the fraction of iron candidates tagged by both CHD layers among those detected by the top charge detector, was evaluated for MC and FD data.



- good level of consistency between the MC and flight data, within the errors.

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