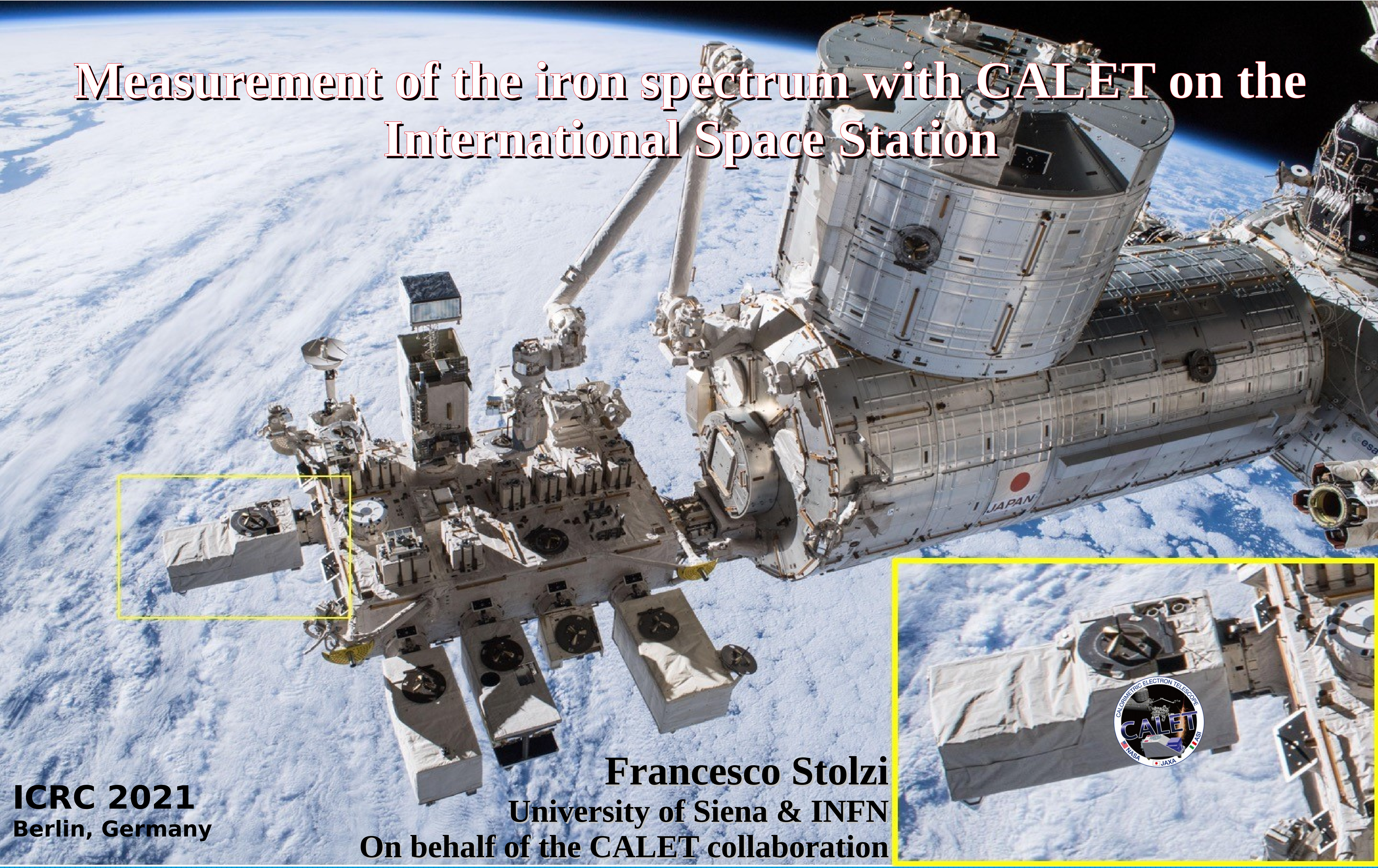
Measurement of the iron spectrum with CALET on the International Space Station



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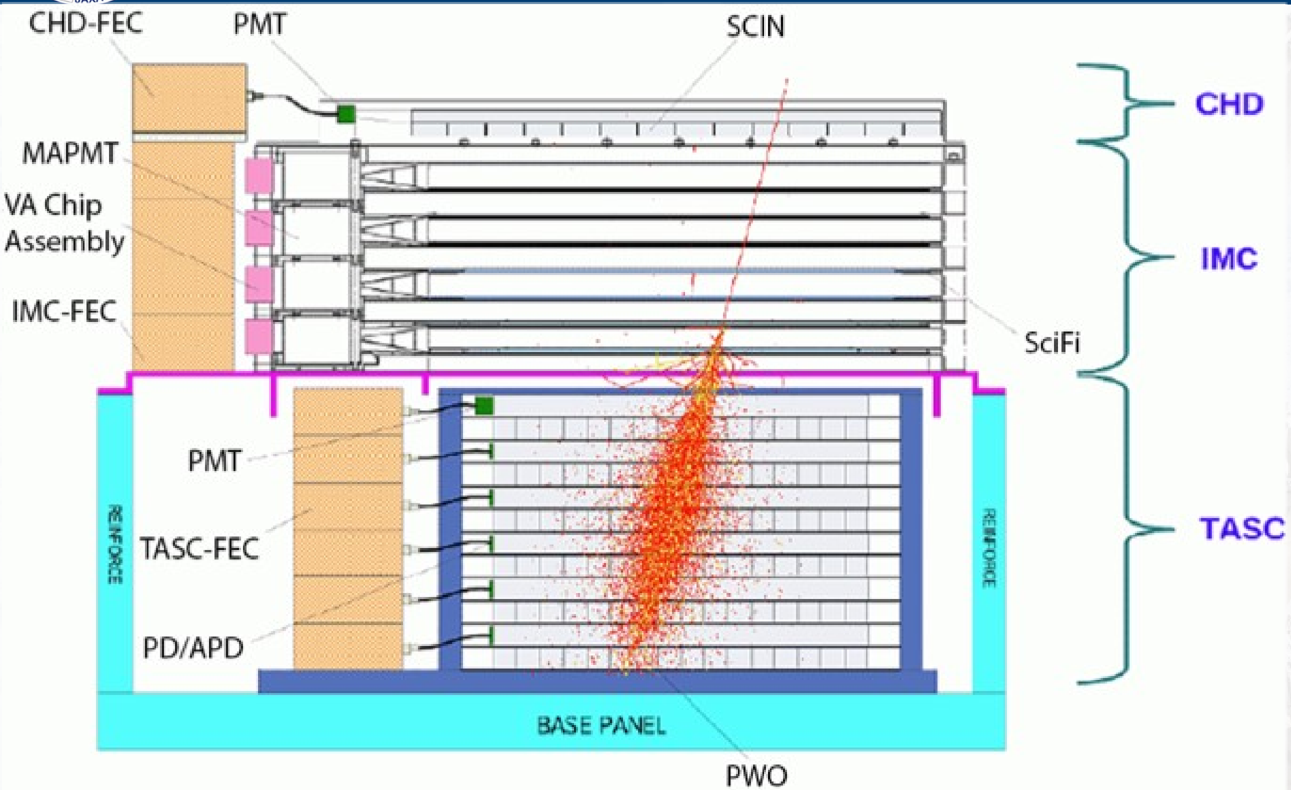
On behalf of the CALET collaboration

ICRC 2021
Berlin, Germany

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 ($1 \le Z \le 40$) $\Delta Z/Z$ = 0.15 for C, 0.35 for Fe	*Particle ID*, Tracking ΔX at CHD = 300µm	Energy, *Dynamic range ; 1 –10^6 MIP (1GeV –1PeV)*
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: 1mm^2 x 448 mm	16 PWO *logs* x 12 layers (X,Y) Total thickness: **27 X_0 , 1.2 λ_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)

Analysis procedure for iron

- Calibrated data from January 2016 to May 2020
- Monte Carlo (MC) simulations based on the EPICS

(1) High Energy Trigger (HET)

✔ Live time $T = 3.3 \times 10^4\ h$, 85.8% total observation time.

(2) Shower event selection

✔ Select interacting particles.

(3) Tracking with IMC

✔ Identify the impact point and the particle's direction.

(4) 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 and of the bottom TASC layer by at least 2 cm ($S\Omega \sim 416\ cm^2\ sr$).

(5) Charge consistency with CHD

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

(6) Charge selection with CHD

✔ Iron candidates are identified by an ellipse centered at $Z = 26$.

(7) Background extimation

(8) Energy measurements and unfolding

(9) Systematics errors

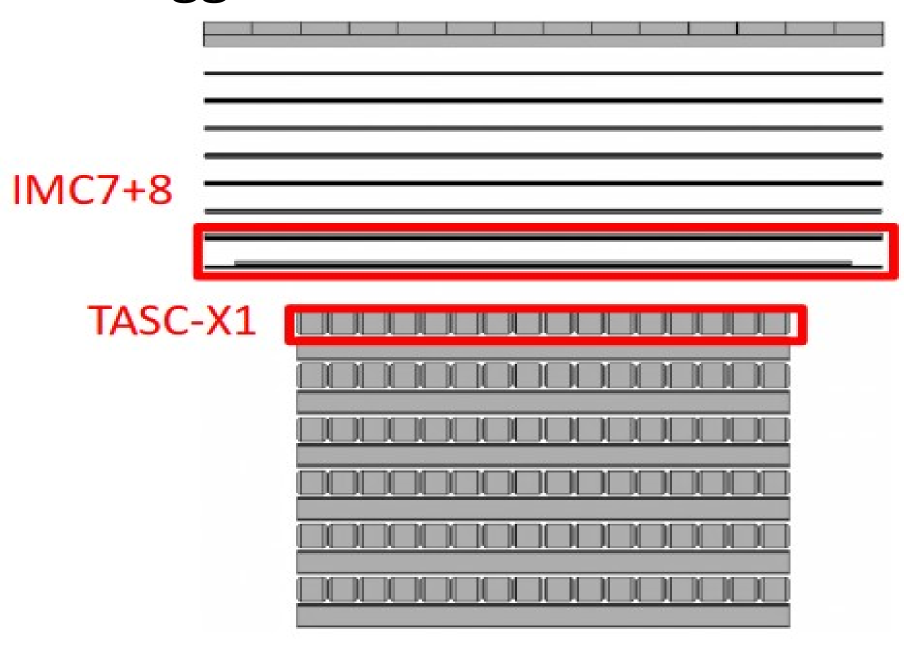
(10) Flux measurement

(1) (2) HET and Shower selection

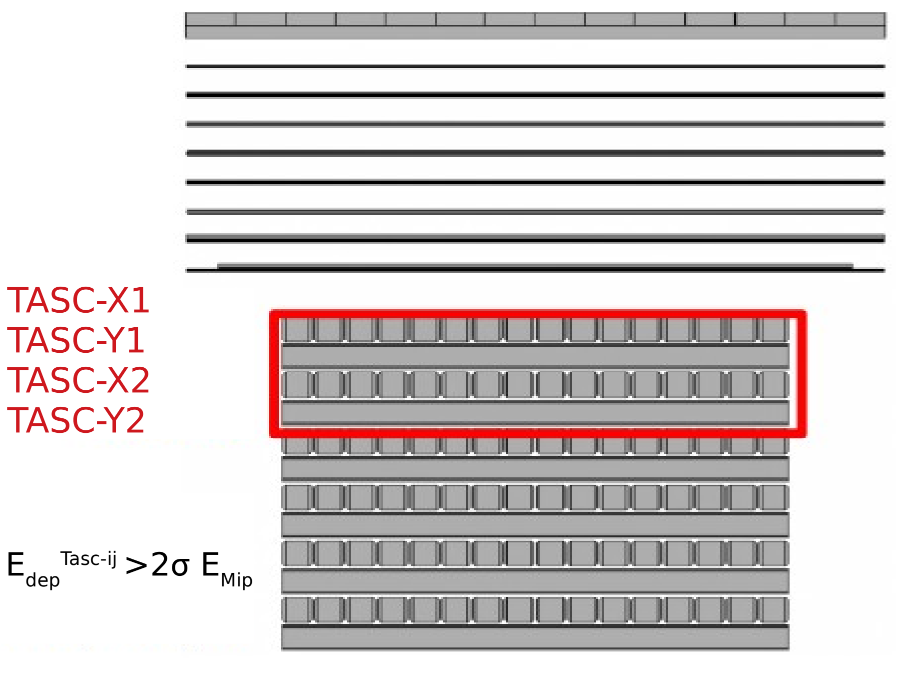
- For light nuclei (Z<10), only events interacting in the detector are triggered.
- For heavy nuclei, the HET threshold is far below the signal amplitude expected from a particle at minimum ionization (MIP) and the trigger efficiency is close to 100%.

➔ 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



(3) (4) Tracking with IMC

Tracking algorithm based on a combinatorial Kalman filter

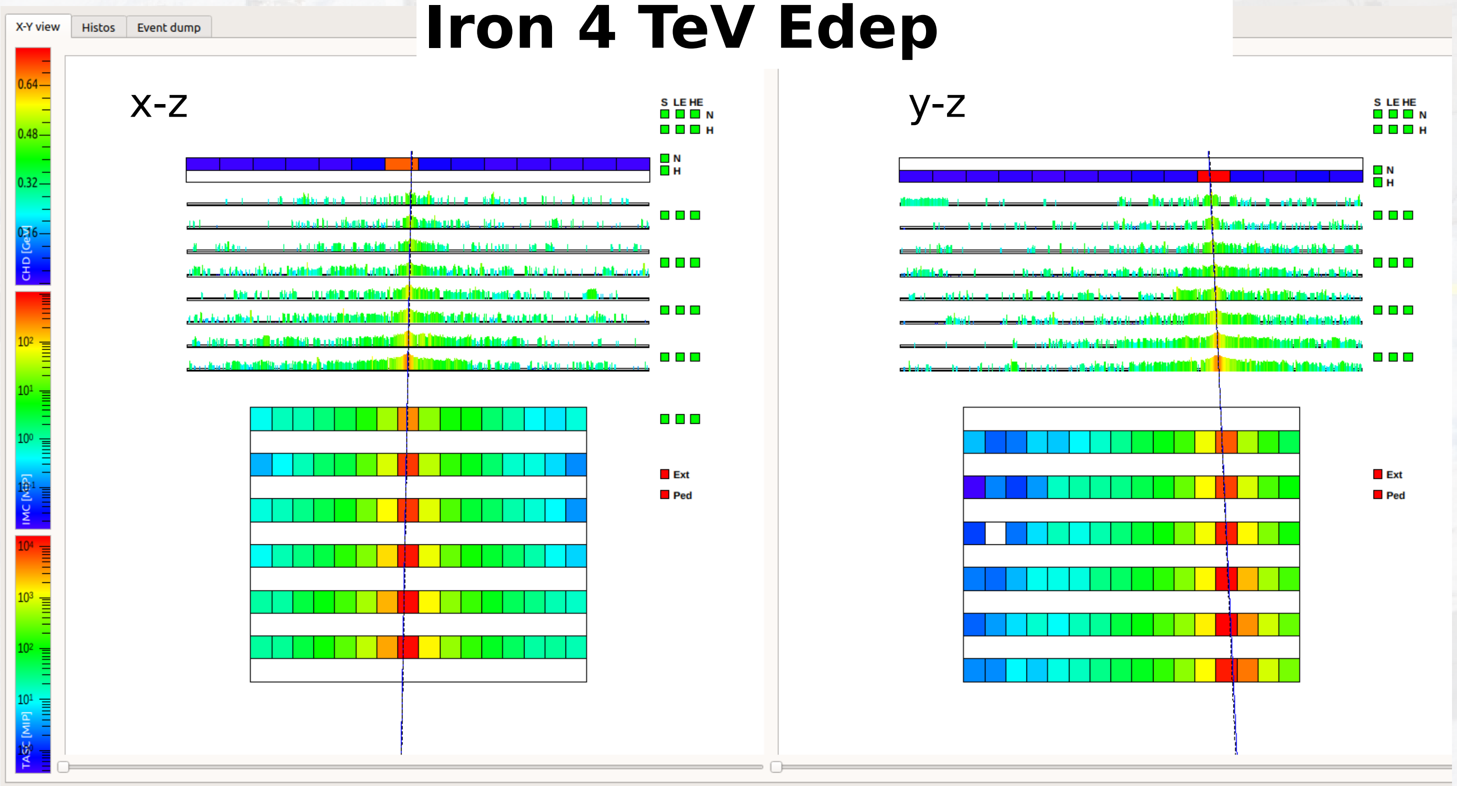
Tracking is used to:

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

Tracking performance for iron:

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

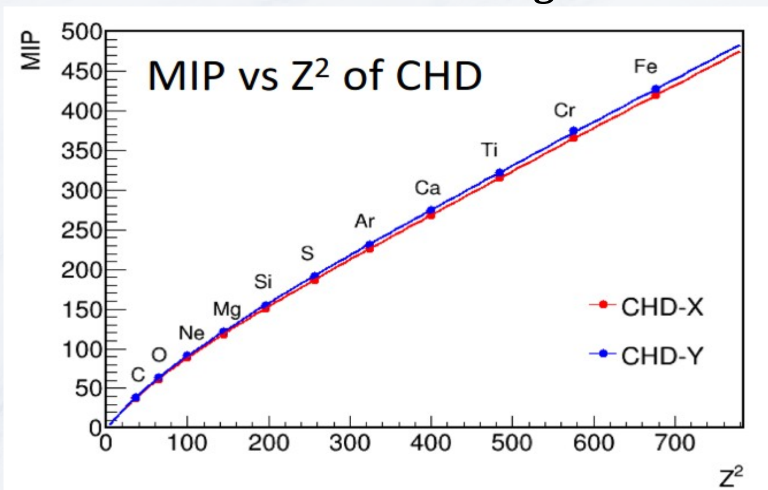
Iron 4 TeV Edep



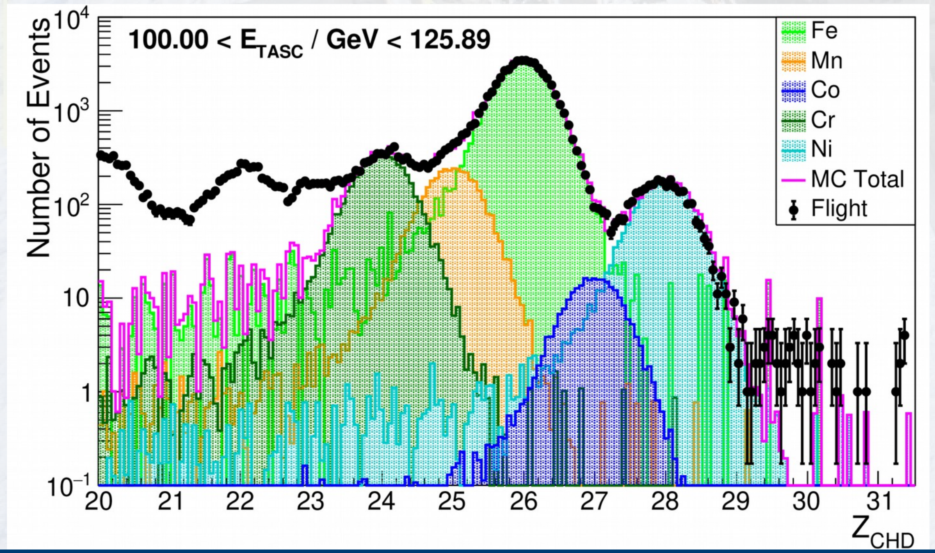
(5) (6) Charge identification

Charge Z reconstructed by measuring the ionization deposits in the CHD.

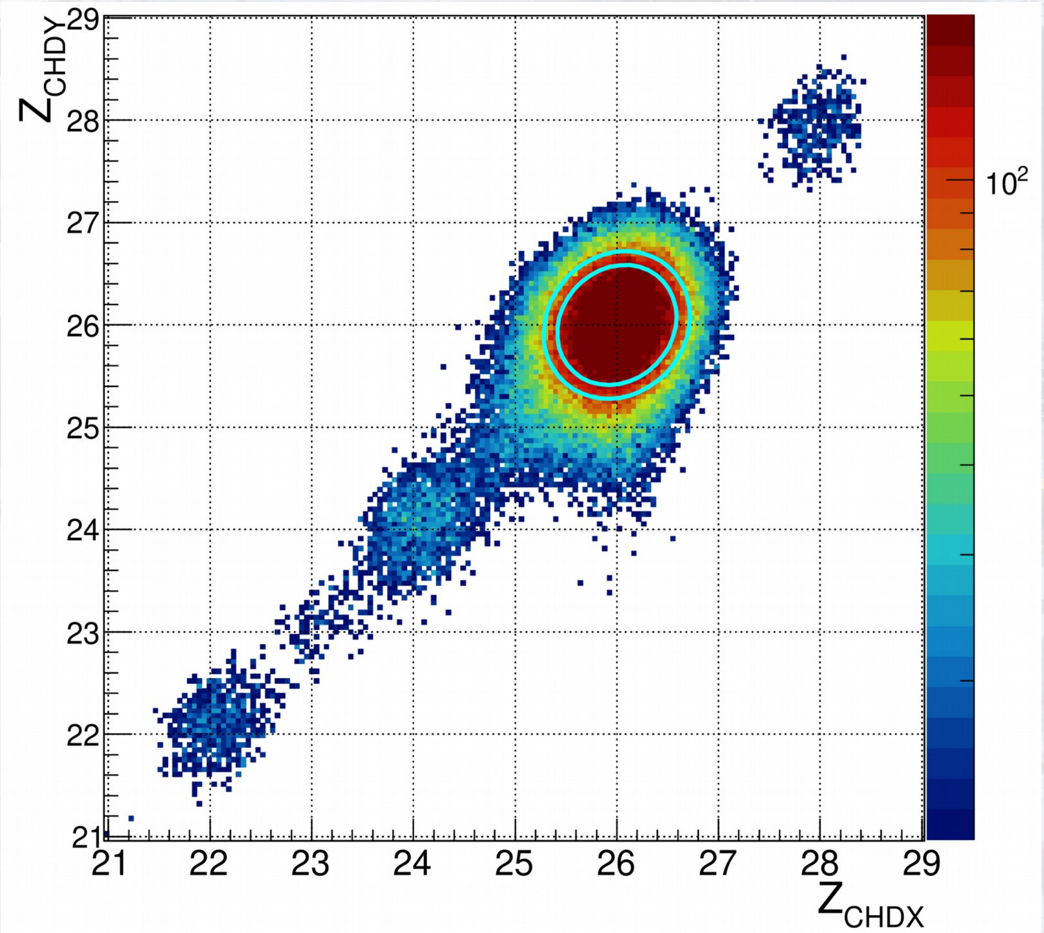
- Non linear response to Z^2 due to the quenching effect in the scintillators is corrected using a “halo” model.

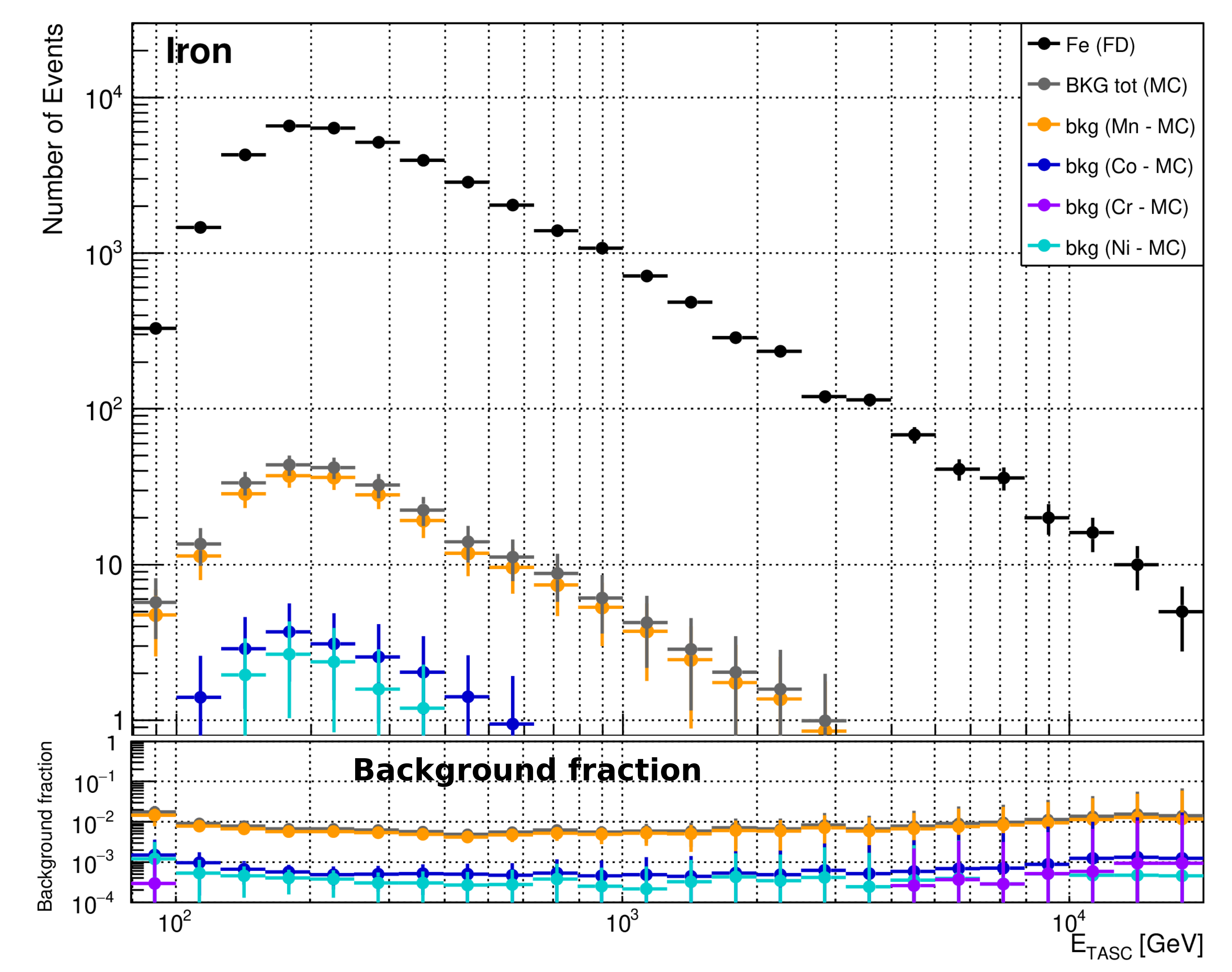


- In order to remove background events interacting in CHD the Charge Consistency Cut is applied: $|Z_{CHDX}-Z_{CHDY}|<1.5$
- Charge resolution σ_Z for iron 0.35 *e*.



- Iron events are selected within an ellipse centered at Z = 26, with $1.25\sigma_x$ and $1.25\sigma_y$ wide semiaxes for Z_{CHDX} and Z_{CHDY} , respectively, and rotated clockwise by 45°





- **dN/dEdep distributions for Fe, Mn, Co, Cr, Ni.**
- **Background contamination from different nuclear species misidentified as Fe are estimated by Monte Carlo simulation.**
- **Total background is few percent in all energy bins**

(8) Energy Scale

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.

- **Correction factors are:**
  - 6.7% for $E_{TASC} < 45$ GeV
  - 3.5% for $E_{TASC} \geq 350$ GeV;
  - linear interpolation for $45 \leq E_{TASC} < 350$ GeV

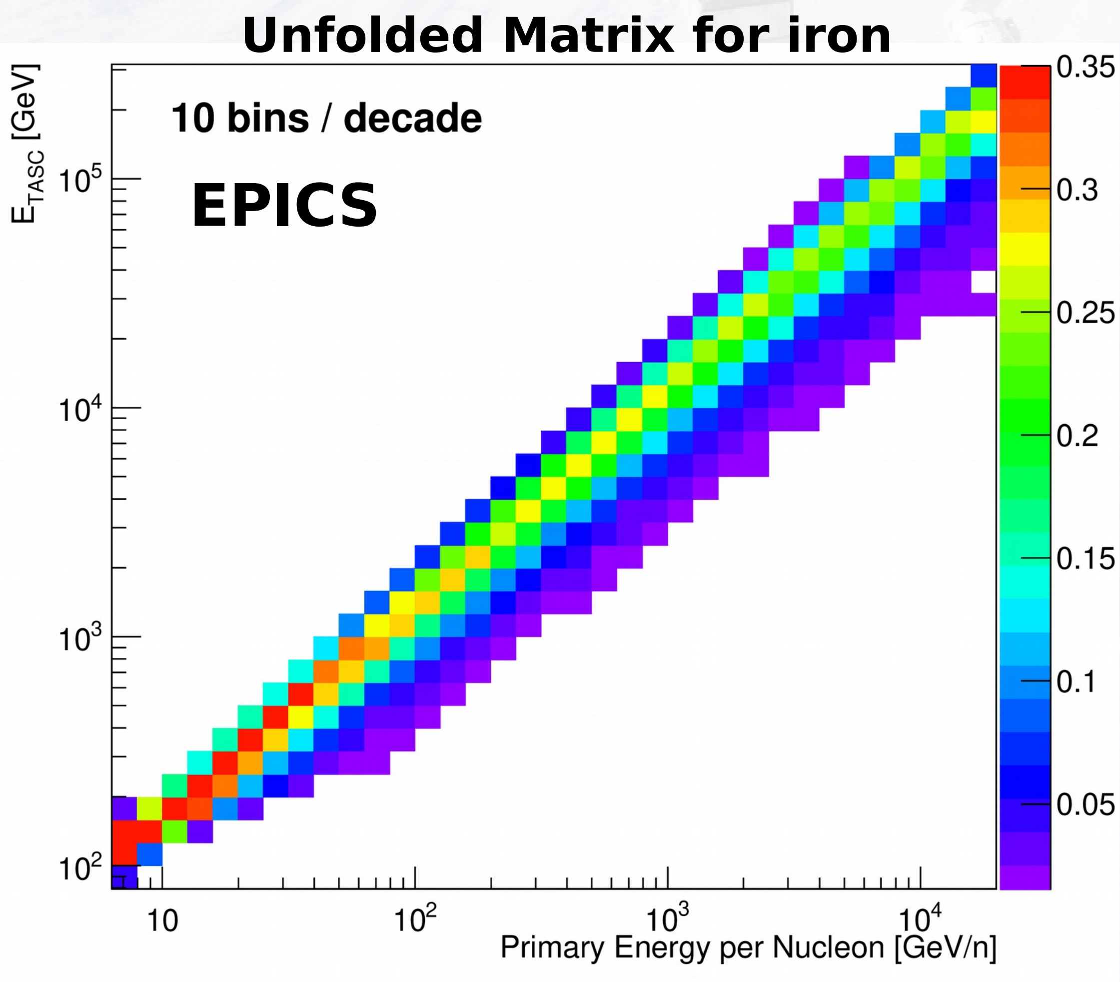
- **Good linearity up to maximum available beam energy (~6TeV) between the observed TASC energy and the primary energy.**

- **Energy resolution around 30%.**

(8) Energy Unfolding

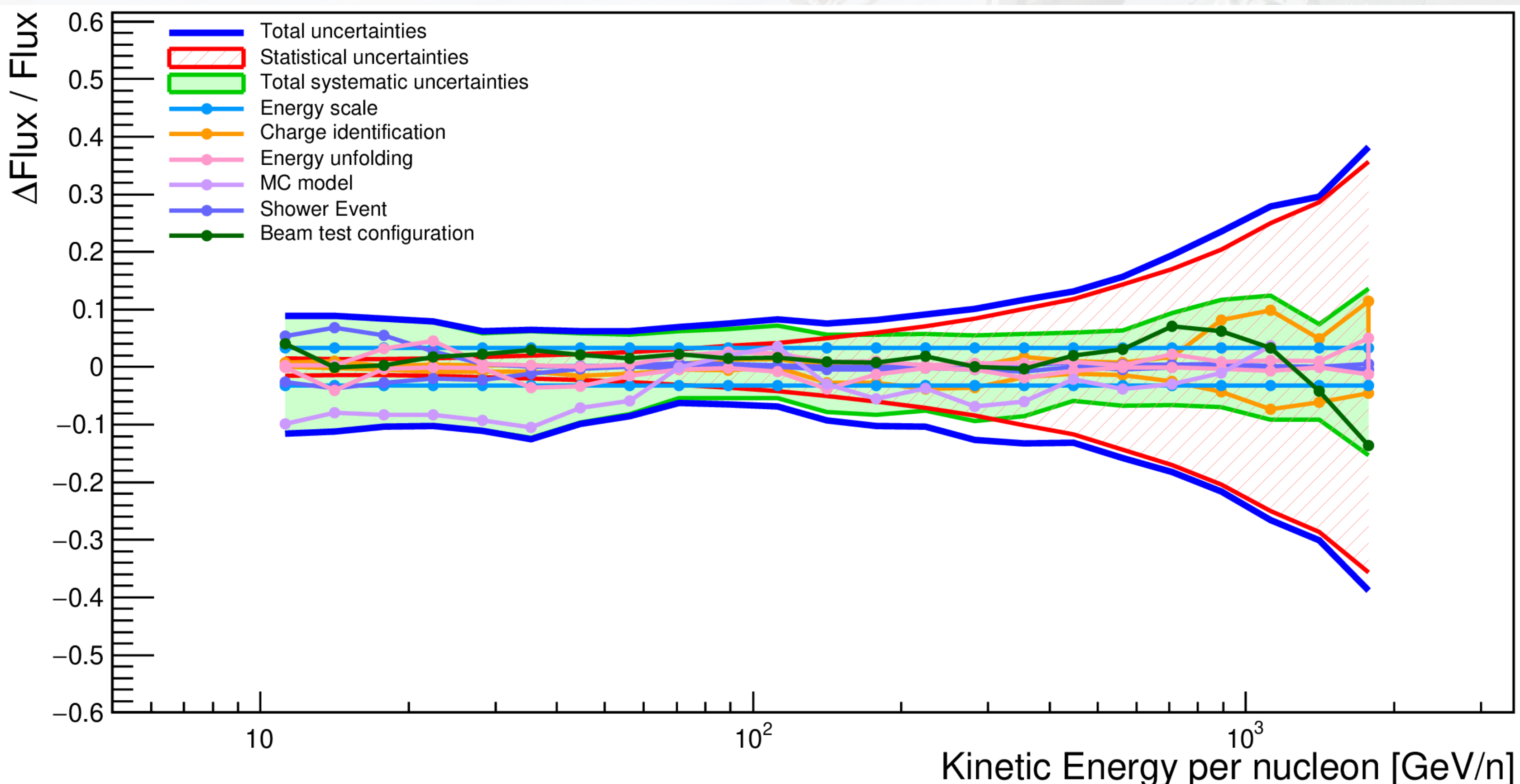
- **Relatively limited calorimetric energy resolution for hadrons (of the order of∼30%)**

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



- Two MC codes, EPICS and FLUKA are used to estimate the energy response ("smearing") matrix, applying the same selection cuts as in the FD analysis.
- The color scale is associated to the probability that iron candidates in a given bin of particle kinetic energy cover different intervals of E_{TASC}

(9) Systematic Errors



Systematic	Variation	Flux variation
Charge identification	Semiaxes of ellipse up to ± 15%	Few % below 600 GeV/n 10% @ 1 TeV
Energy Scale Correction	± 2% according to Beam Test	Rigid shift + 3.3%, -3.2%
Unfolding procedure	response matrix, varying spectral index from -2.9 to -2.2	Few %
MC Model	Energy responce matrix with FLUKA	Up to 10% below 40 GeV/n, few % in the 100 GeV region, less 5% up to 1 TeV
Shower event	Different shape cut	5% below 30 GeV/n, 1% above
Beam test configuration	Beam test model configuration	Few %

Energy-independent systematic uncertainties affecting the flux normalization include:

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

(10) Flux measurement

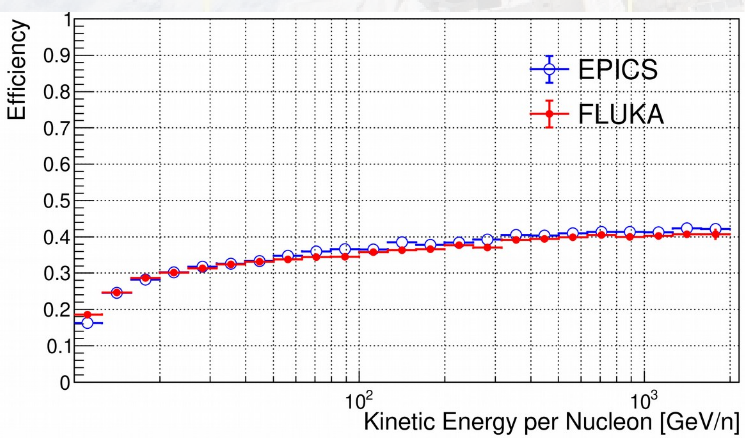
$$\Phi(E) = \frac{N(E)}{\Delta E \varepsilon(E) S\Omega T}$$

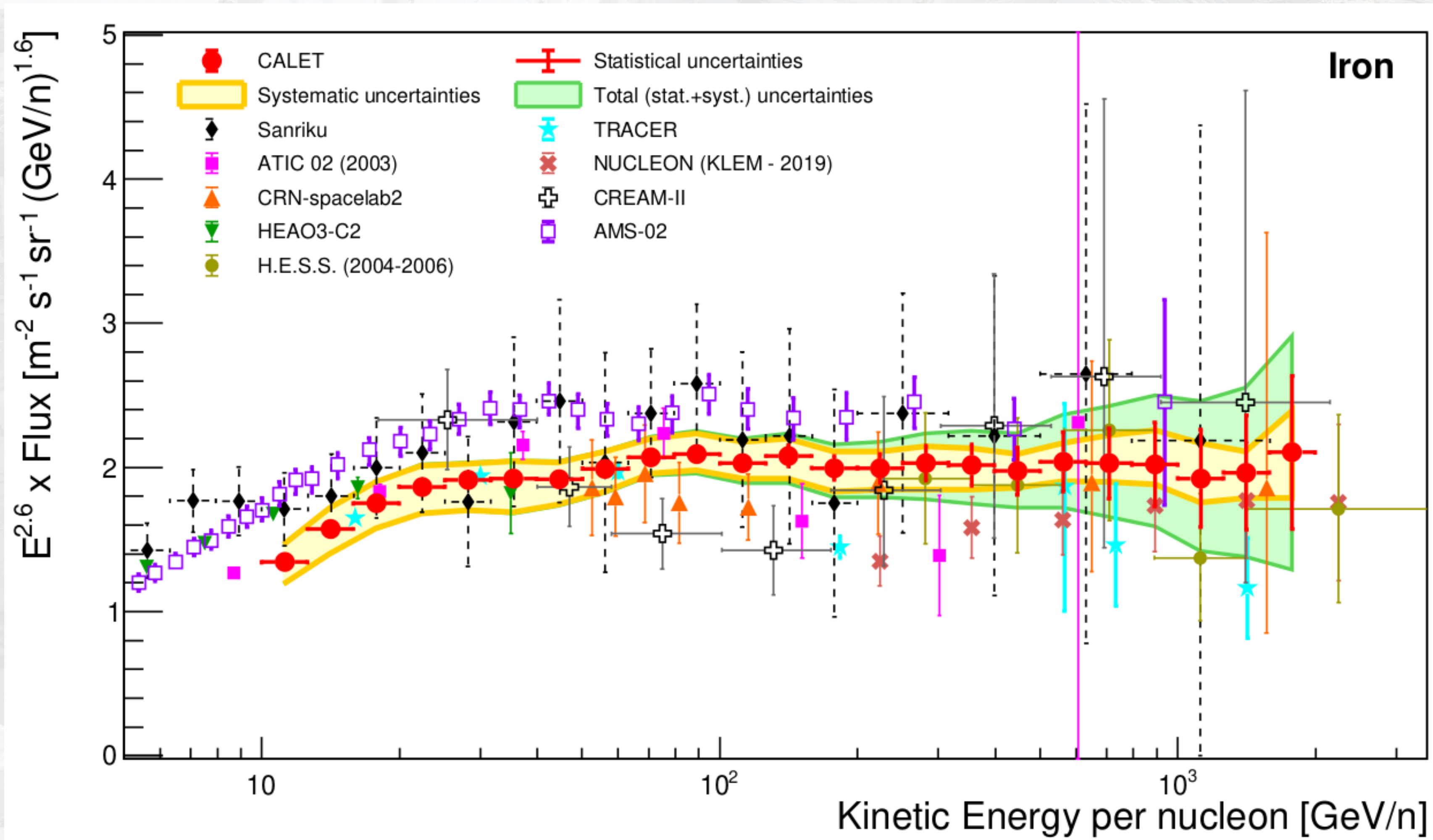
CALET Iron Flux with multiplicative factor $E^{2.6}$

O. Adriani et al. *Phys. Rev. Lett.* **126** (2021) 241101

- **N(E) : bin counts of the unfolded energy distribution**
- **ΔE : energy bin width**
- **SΩ : geometrical acceptance**

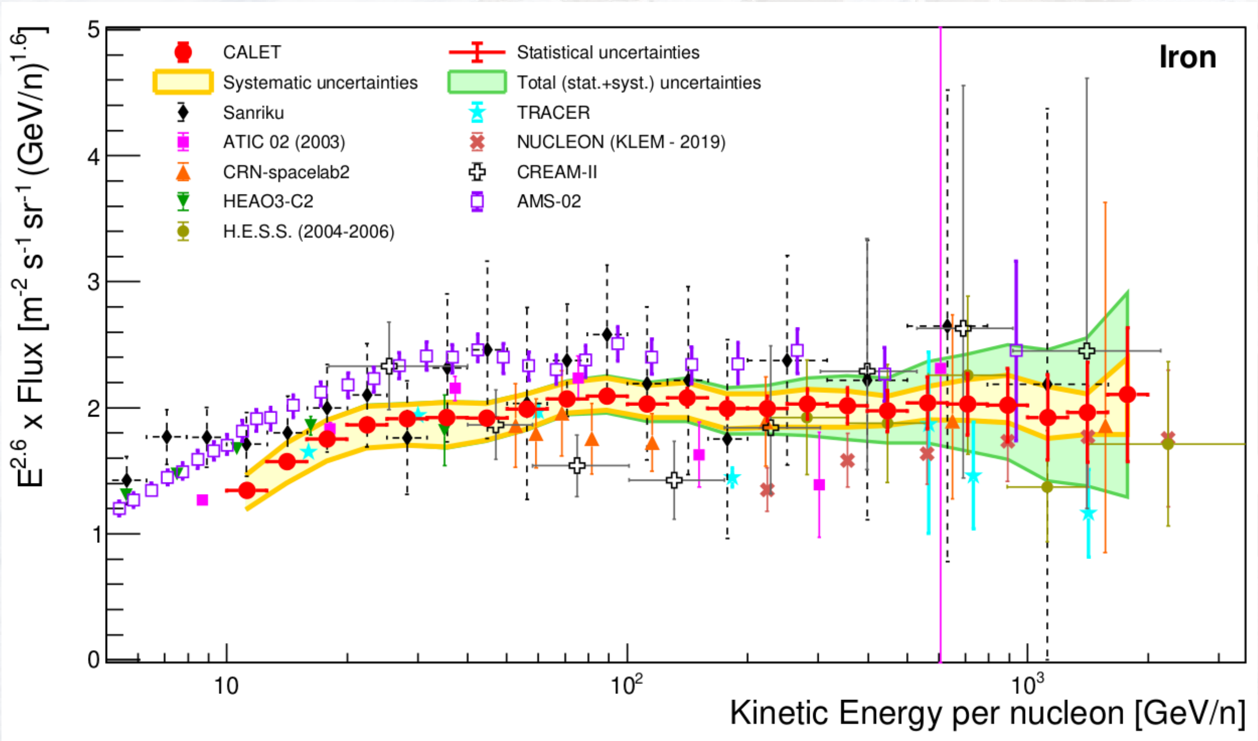
  SΩ ~ 416 cm^2 sr
- **T : live time 3.3 x 10^4 h**
- **ε(E) total selection efficiency**

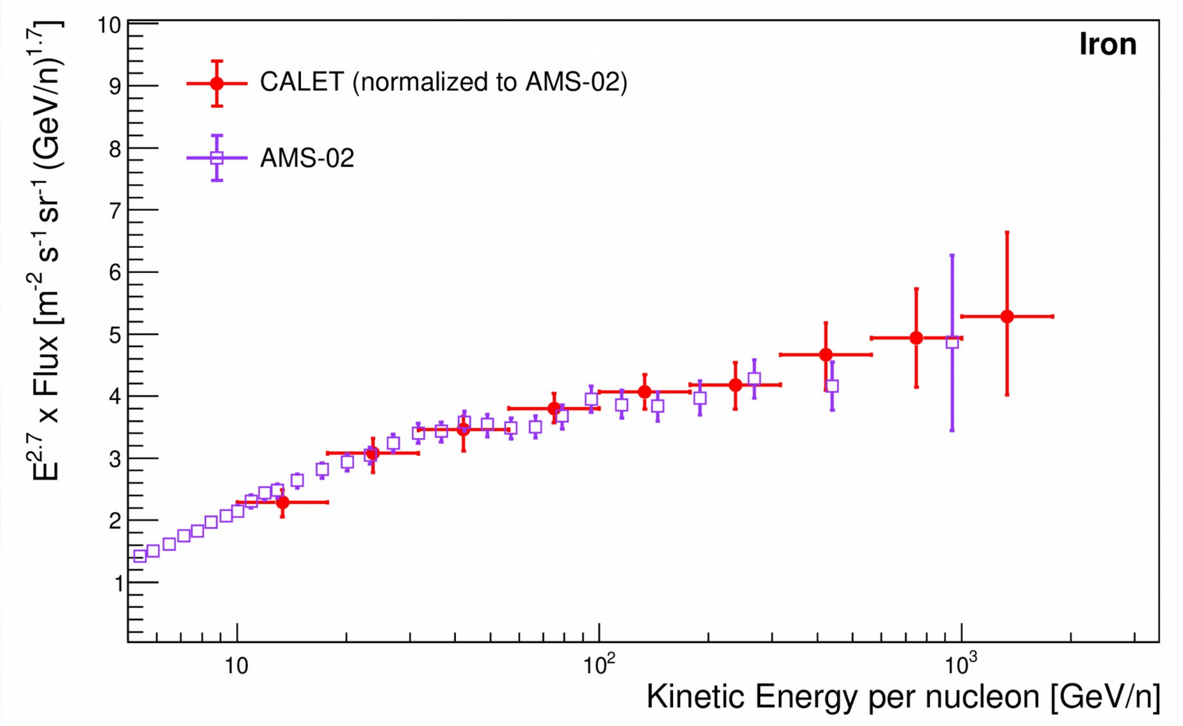




Iron flux normalization and spectral shape

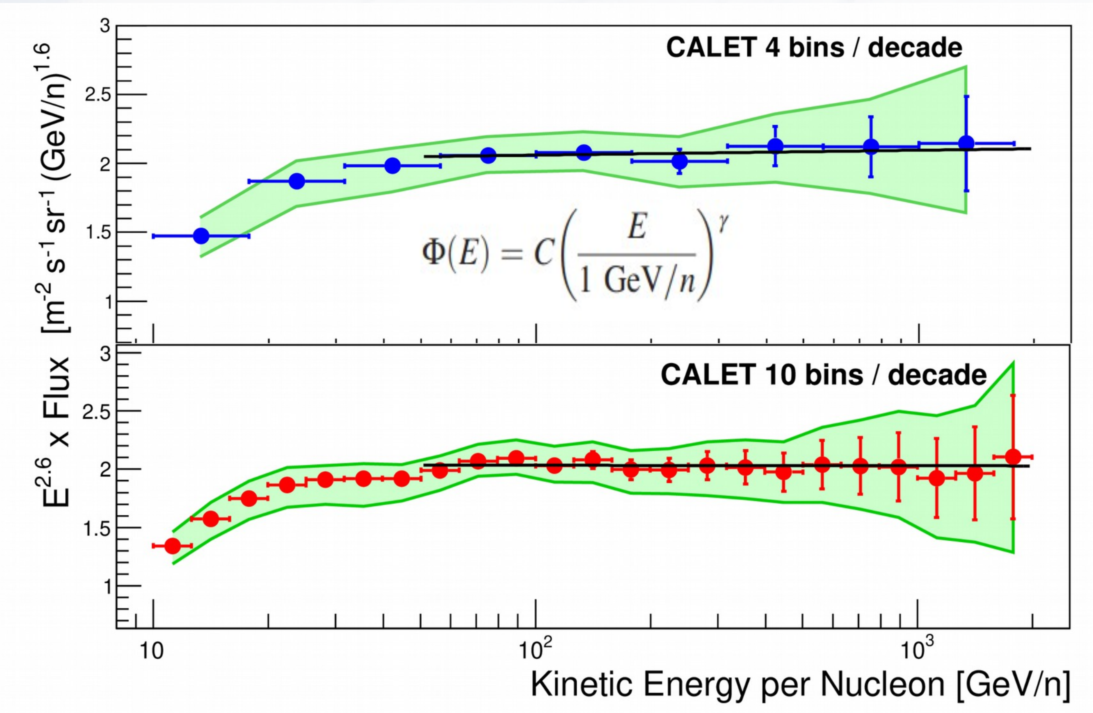
- CALET spectrum is consistent with ATIC 02 and TRACER at low energy
- CALET spectrum is consistent with CRN and HESS at high energy
- CALET and NUCLEON iron spectra have similar shape, but different normalization
- CALET and AMS-02 iron spectra have a very similar shape, but differ in the absolute normalization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



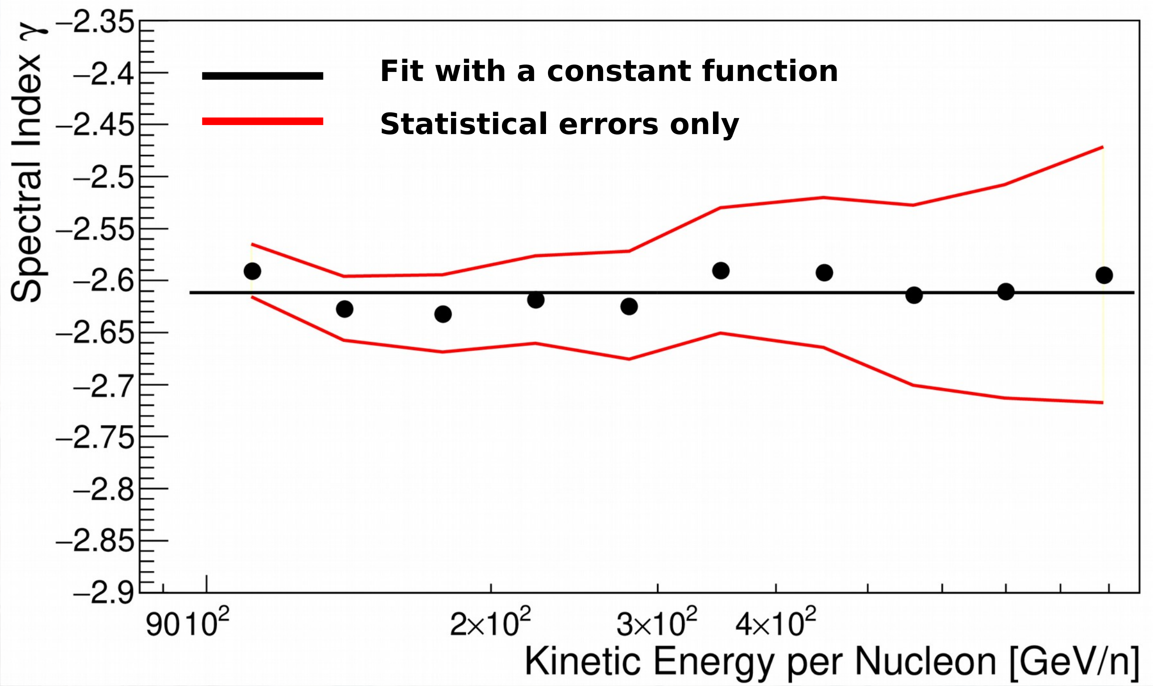


Spectral Index

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



Sliding window



- **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**

- 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

Conclusions

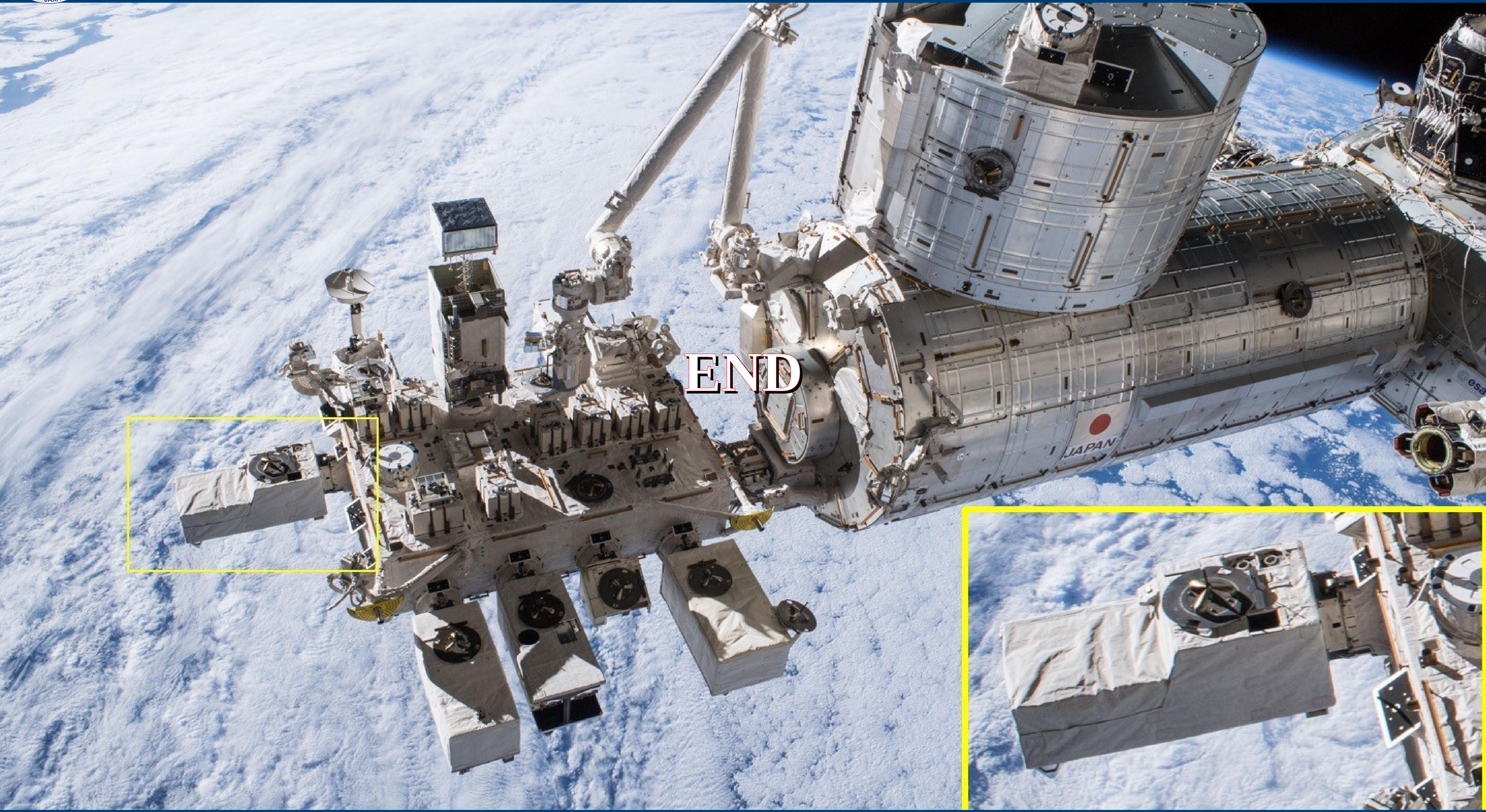
- The measurement of the energy spectrum of iron with CALET from 10 GeV/n to 2.0 TeV/n was performed with a significantly better precision than most of the existing measurements.

- Data turn out to be consistent with most of the previous measurements within the uncertainty error band, both in spectral shape and normalization. CALET and AMS-02 iron spectra have a very similar shape, but differ in the absolute normalization of the flux by ∼20%.

- Below 50 GeV/n the iron spectral shape is similar to the one observed for primaries lighter than iron.

- Above 50 GeV/n the iron spectrum is consistent with the hypothesis of a SPL spectrum up to 2 TeV/n with a spectral index value $\gamma = -2.60 \pm 0.03$.

- The uncertainties due to the statistic and large systematics errors do not allow significant conclusion on a possible deviation from a single power law.


END
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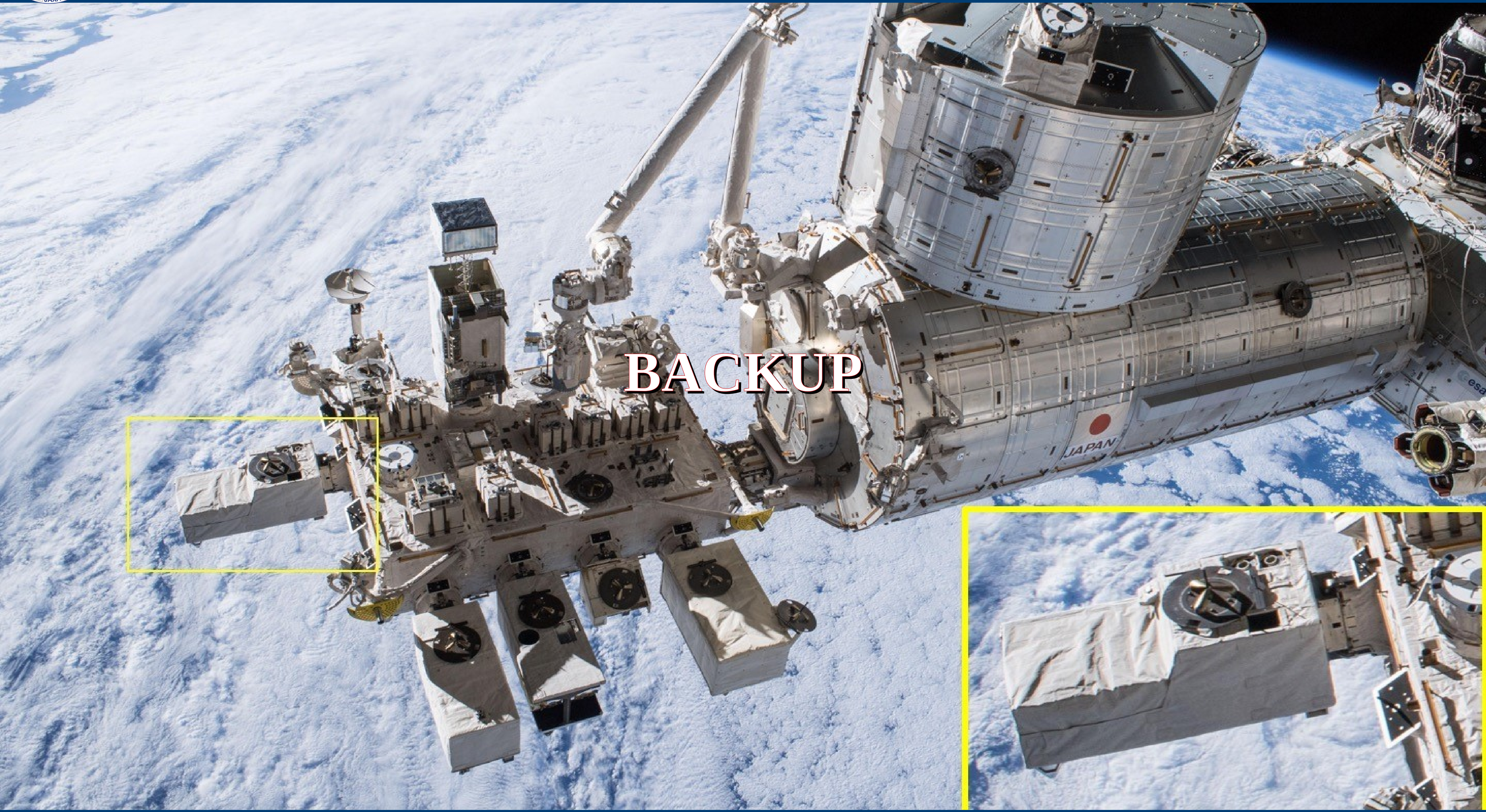
BACKUP
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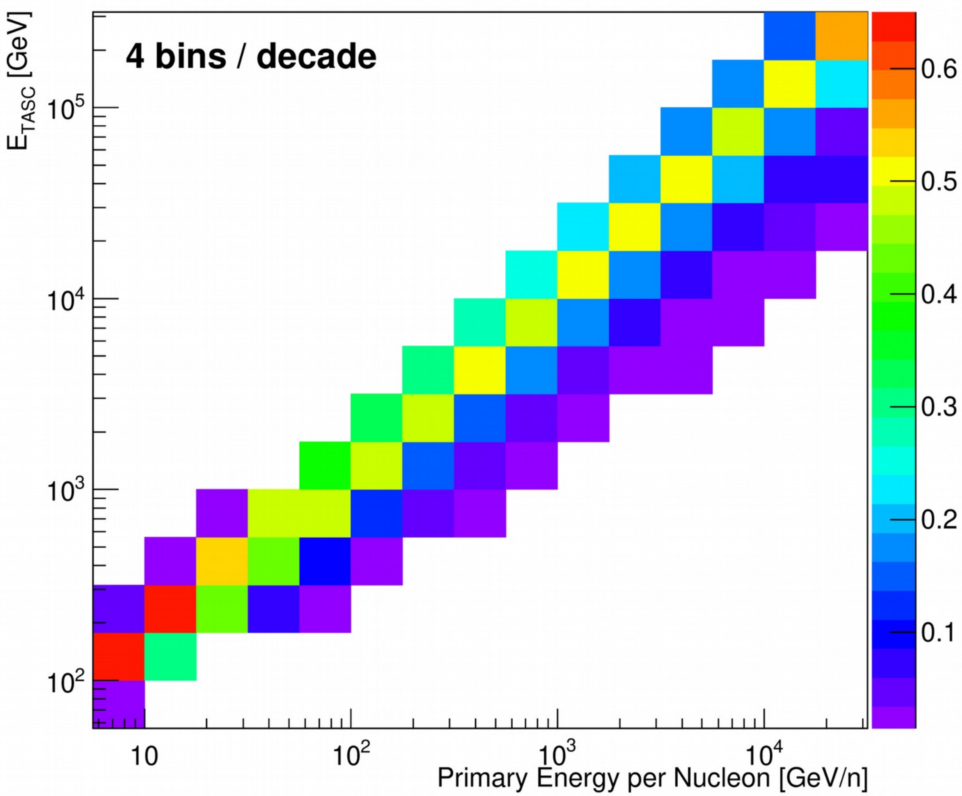
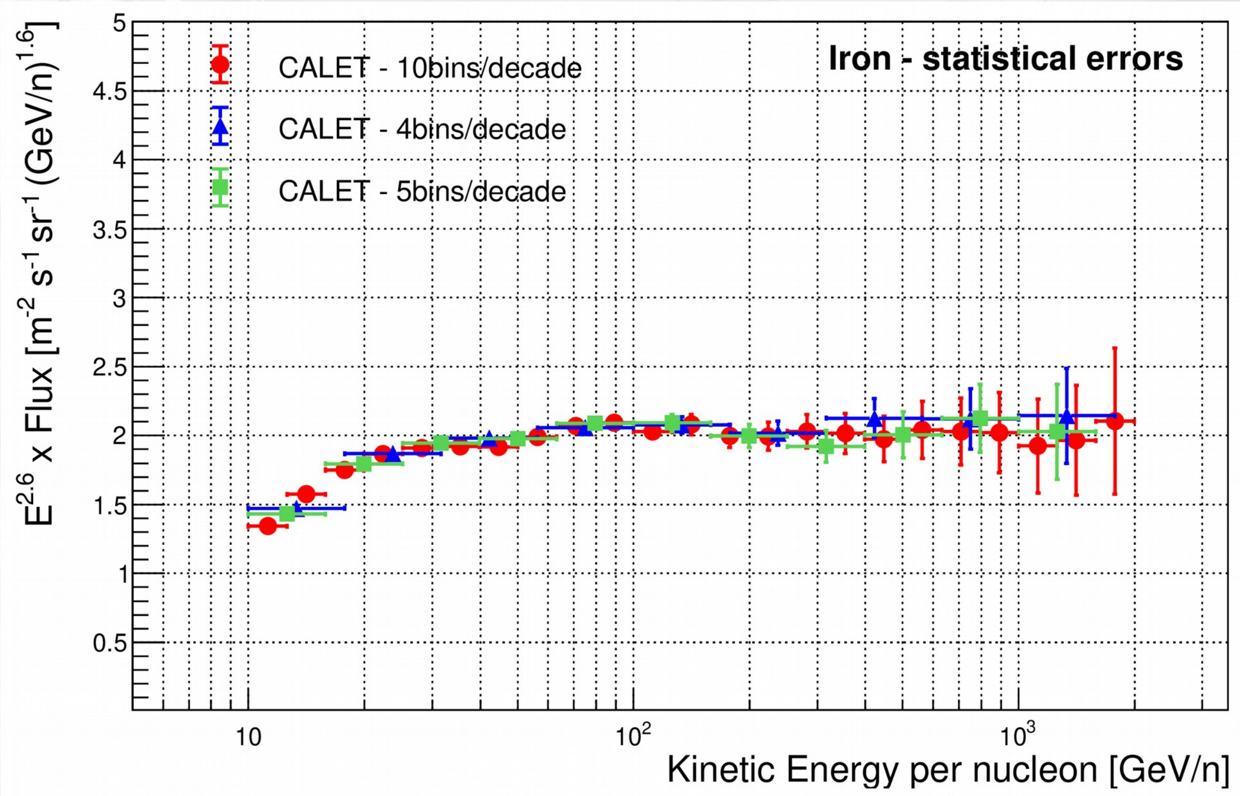
Bin Size

Three different binning schemes (4, 5, 10 equal log-bins /decade) have been applied for the correlation matrix used for the unfolding.

➔ Within the errors, no statistically significant difference was found among the three fluxes

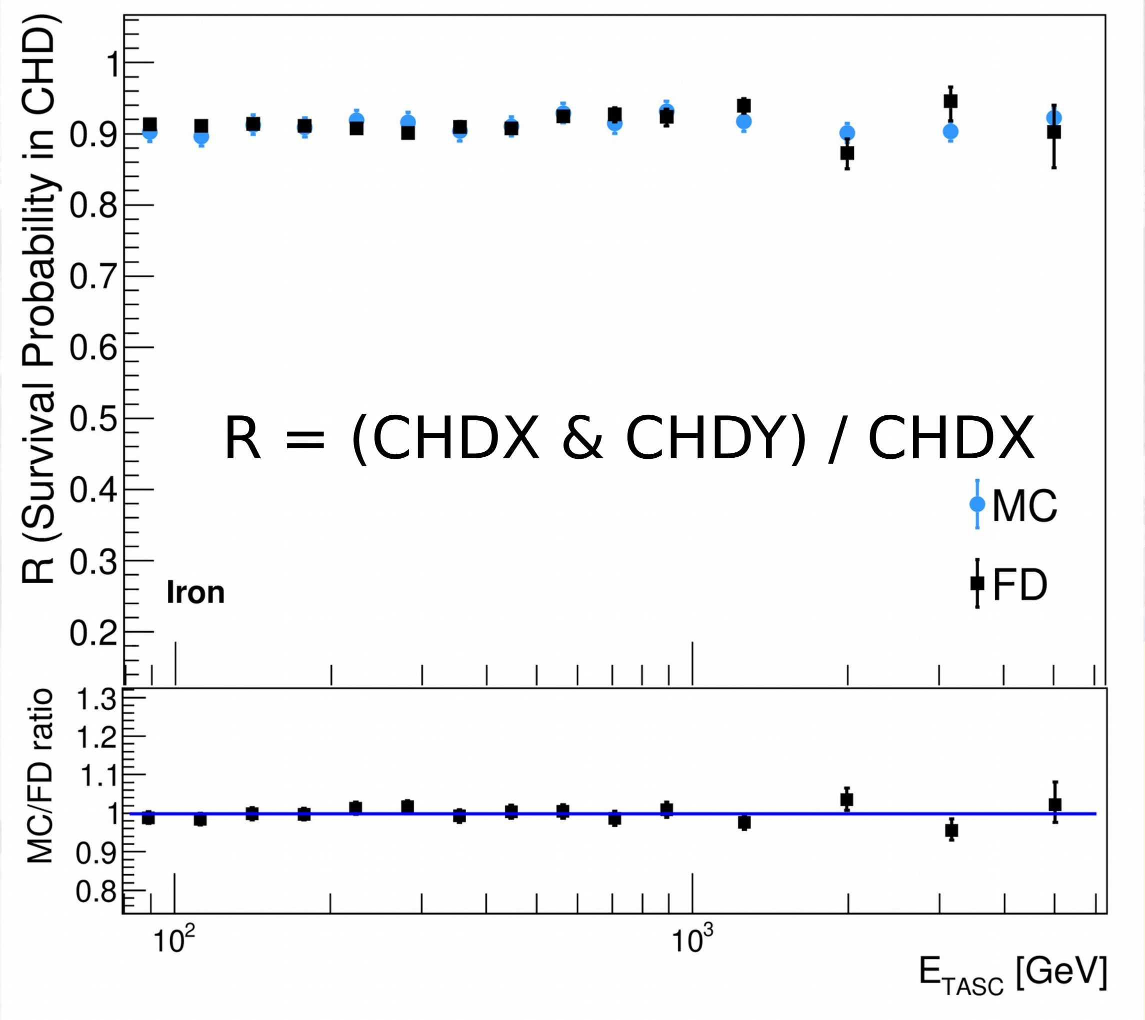




Interactions in the instrument

Amount of material above the CHD: 2 mm thick Al cover (~ 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 (~ 10%) of interacting iron events taken into account in the total efficiency.