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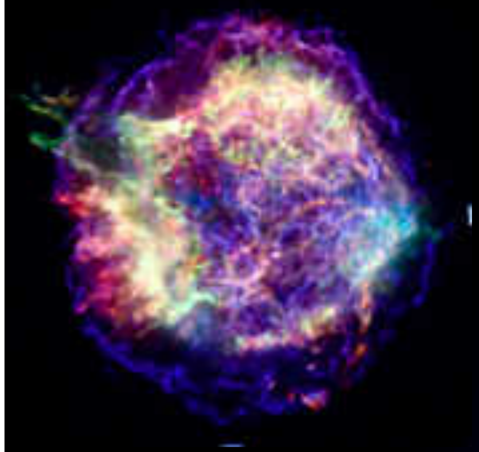
35th ICRC 12-20 July 2017, Busan, South Korea



Observation of Protons and Light Nuclei with CALET

Analysis and Preliminary Results

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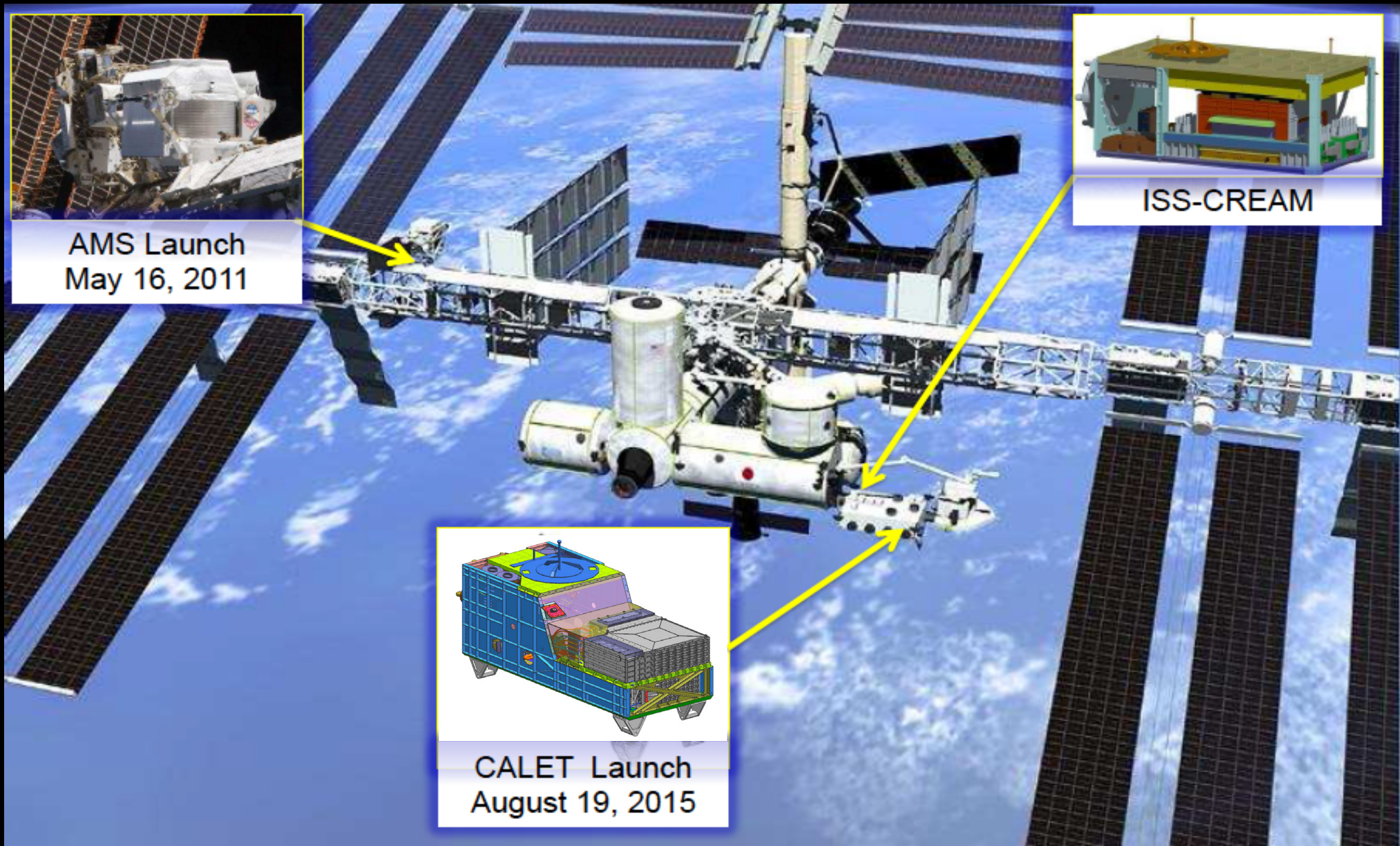
for the CALET Collaboration

ISS: a cosmic-ray observatory in Low Earth Orbit



Experiment	e^+ | e^- (present data)	$e^+ + e^-$ (Energy range)	CR nuclei (Energy range)	charge	Gamma-ray	Type	Launch
PAMELA	$e^+ < 300$ GeV $e^- < 625$ GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	$e^+ < 500$ GeV $e^- < 700$ GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014 Dec 26
CALET	-	1 GeV-20 TeV	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	2017
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	2017
GAMMA-400	-	1 GeV-20 TeV	1 TeV-3 PeV	1-26	20 MeV-1 TeV	SAT	~2023-25
HERD	-	10(s) – 10^4 GeV	up to PeV	TBD	10(s) – 10^4 GeV	CSS	~2022-25
HELIX	-	-	< 10 GeV/n	light isotopes	-	LDB	proposal
HNX	-	-	~ GeV/n	6-96	-	SAT	proposal
GAPS	-	-	< 1GeV/n	Anti-p, D	-	LDB	

Geometric Factor :

1040 cm^2sr for electron, proton

4000 cm^2sr for ultra-heavy nuclei

- **ΔE/E** :

  ~**2%** (>10 GeV) for e, gamma

  ~30-35 % for protons, nuclei

- **e/p separation** : ~10^{-5}
- **Charge resolution** : 0.15 - 0.3 e
- **Angular resolution** :

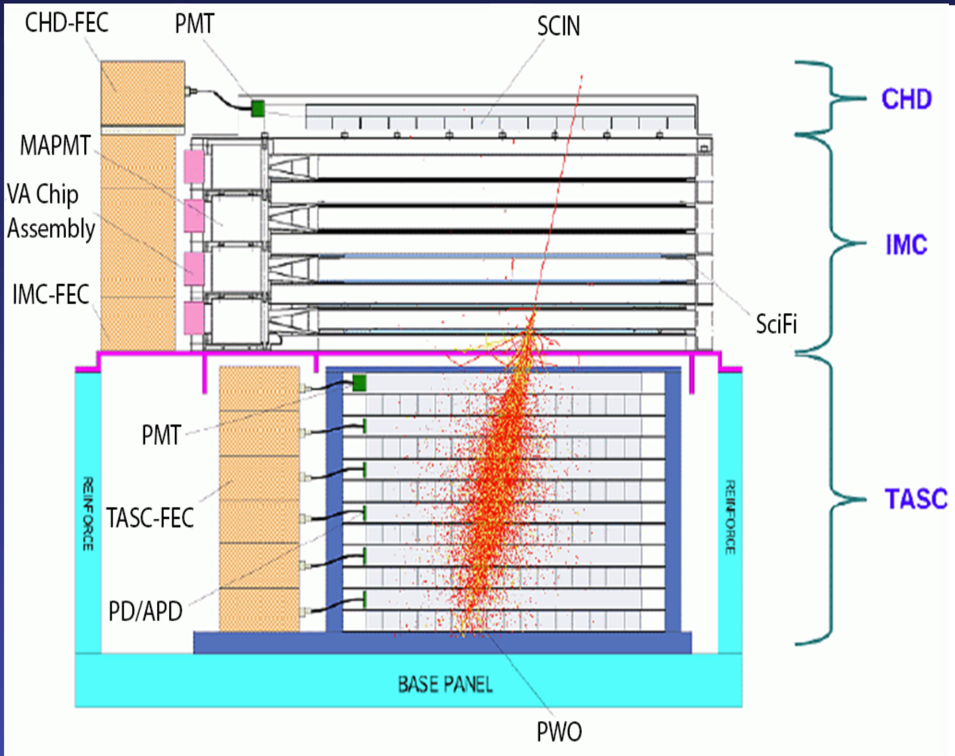
  0.2° for gamma-rays > ~50 GeV

CALET

CALorimetric **E**lectron **T**elescope

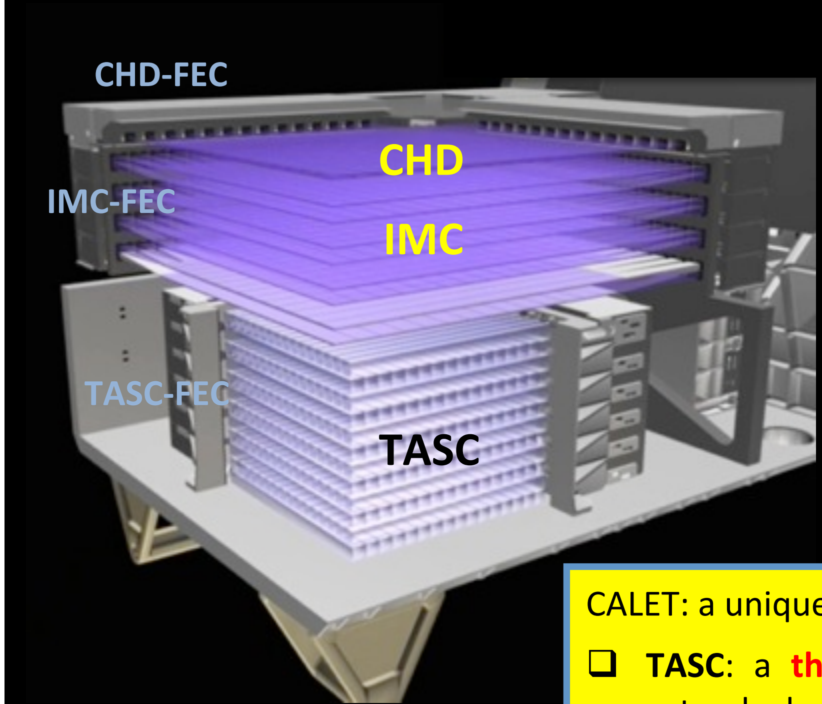
CALET main science goals

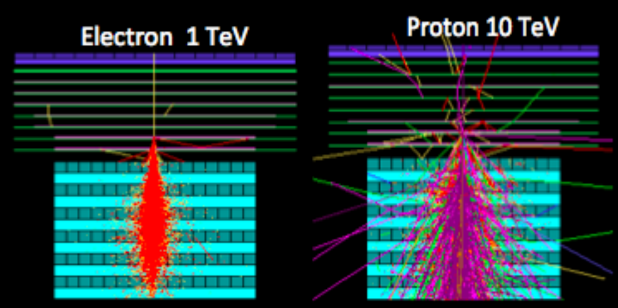
Science Objectives	Observation Targets
Nearby Cosmic-ray Sources	**Electron spectrum** in trans-TeV region
Dark Matter	Signatures in **electron/gamma** energy spectra in the 10 GeV – 10 TeV region
Origin and Acceleration of Cosmic Rays	**p-Fe** up to the multi-TeV region, Ultra Heavy Nuclei
Cosmic–Ray Propagation in the Galaxy	**B/C** ratio up to a few TeV /n
Solar Physics	**Electron flux** below 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays in 7 keV – 20 MeV



- **CHarge Detector (CHD)**
  (Charge Measurement Z=1-40)
- **Imaging Calorimeter (IMC)**
  (Particle ID, Direction)
  Total Thickness of Tungsten (W): $3\ X_0$, $0.1\ \lambda_I$
  Layer Number of Scifi Belts: 8 Layers × 2(X,Y)
- **Total Absorption Calorimeter (TASC)**
  (Energy Measurement, Particle ID)
  PWO 20mm x 20mm x 320mm
  Total Depth of PWO: $27\ X_0$ (24 cm), $1.2\ \lambda_I$

CALET instrument overview





HXM x2
7keV-1MeV

SGM x1
0.1-20MeV

CGBM

CALET
Gamma-ray
Burst
Monitor

- Standard Payload Size
- Mass: 612.8 kg
- Power: 507 W (Max)

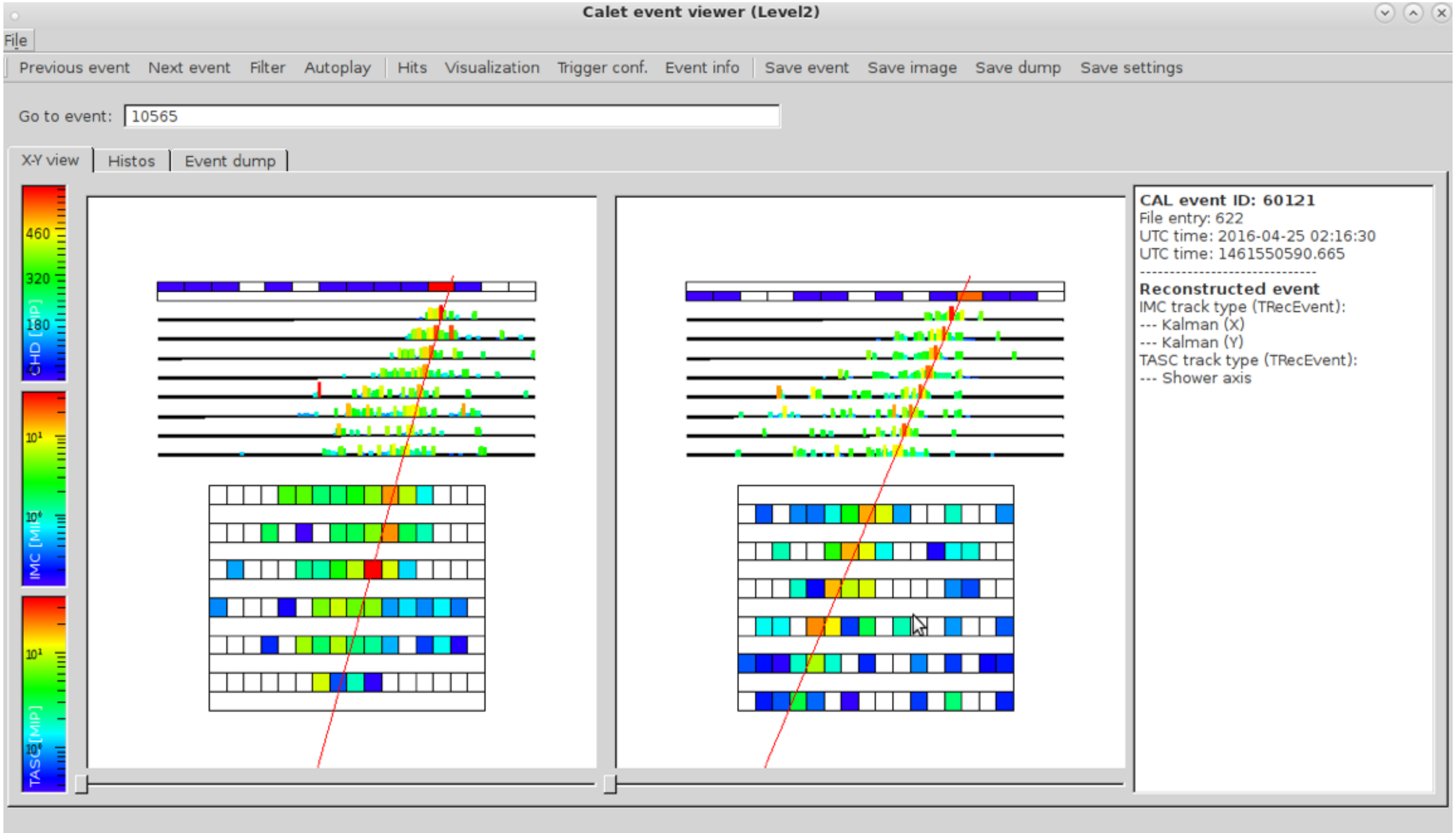
- Telemetry:
  - Medium rate: 600 kbps
  - Low rate: 50 kbps

CALET: a unique set of key instruments.

- **TASC**: a **thick, homogeneous calorimeter** allows to extend electron measurements into the TeV energy region with ~2% energy resolution.
- **IMC**: a **high granularity (1mm) imaging pre-shower with tracking capabilities** identifies the starting point of electromagnetic showers.
- TASC+IMC provide a **strong rejection power ～10^5** to separate electrons from the abundant protons.
- **CHD: a charge detector** combined with multiple dE/dx samples from IMC identifies individual elements.

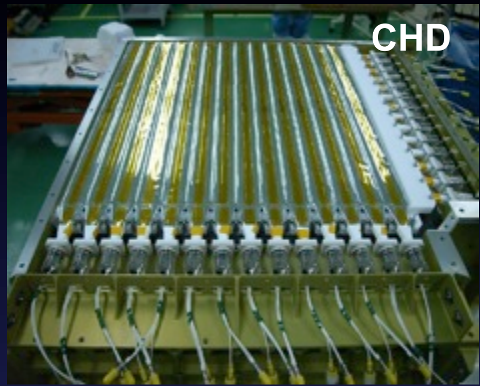
✧ CALET **tracking** takes advantage of the IMAGING capabilities of IMC thanks to its granularity of 1 mm with Sci-fibers **readout individually**.

Example: A multi-prong event due to an interaction of the primary particle in the CHD is very well imaged by the IMC.



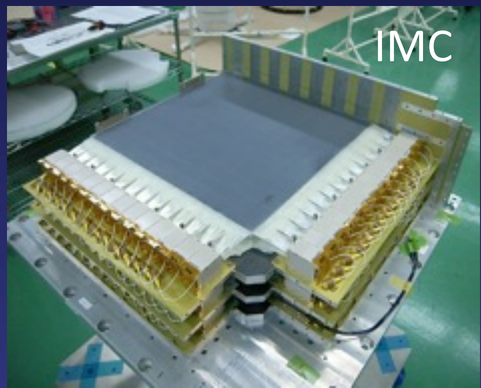
Charge Measurement: Dynamic Range

2 x 14 layers = 28

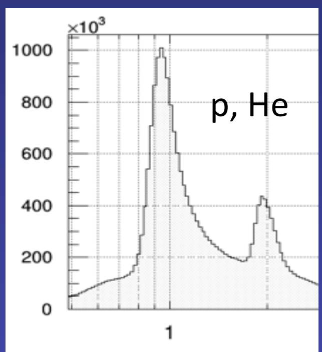


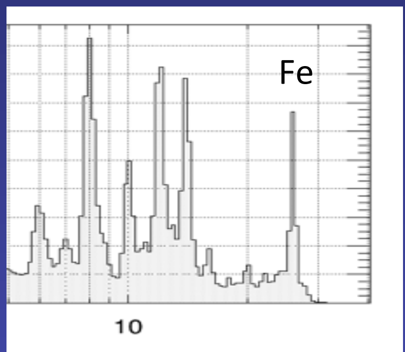
➡ PMT+ CSA

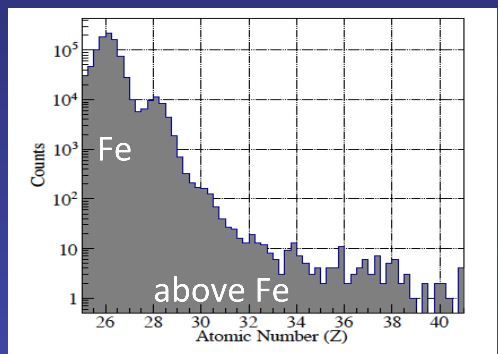
448 x 16 layers = 7168



➡ 64 -anode PMT(HPK) + ASIC

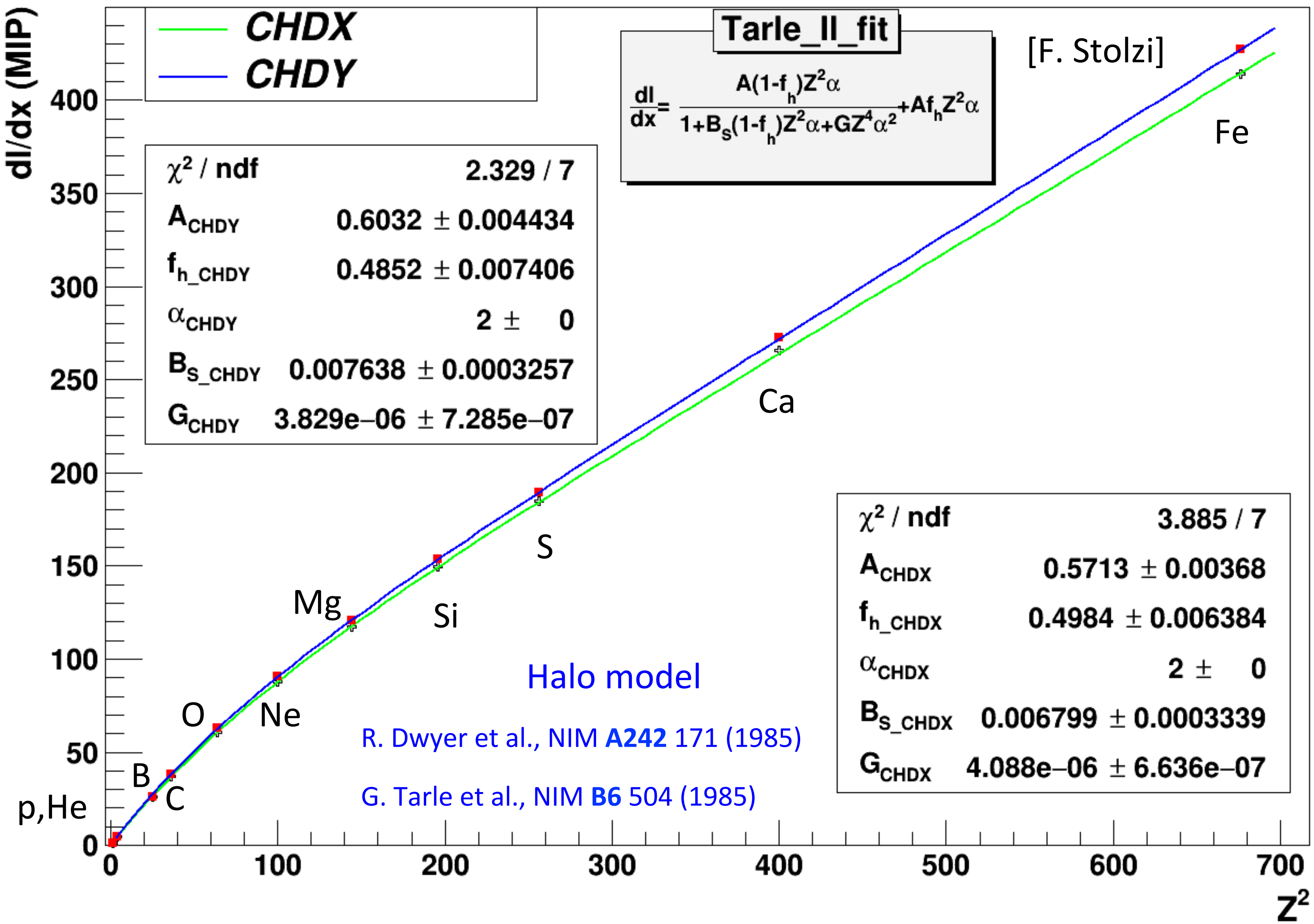




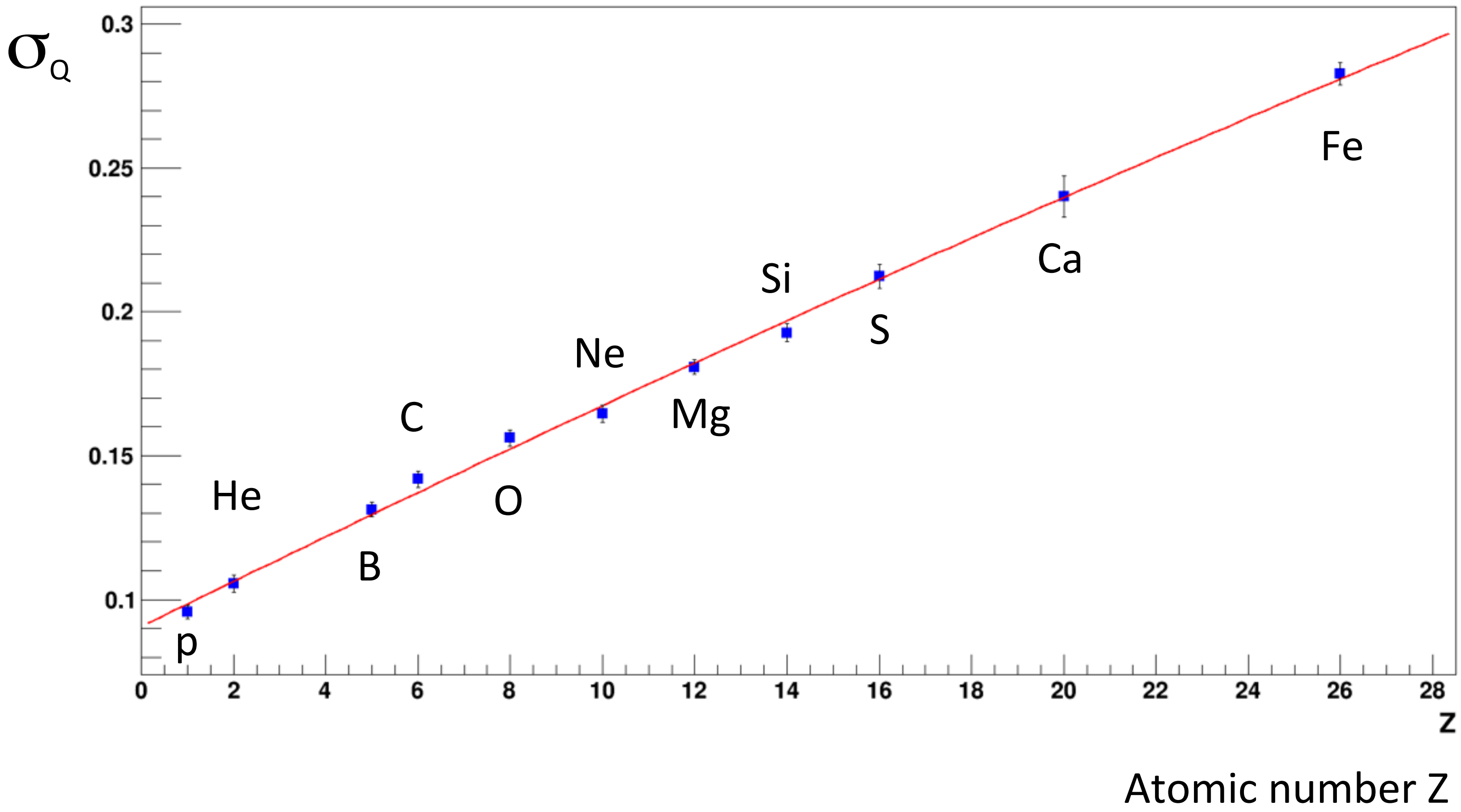


$1 \leq Z \leq 40$

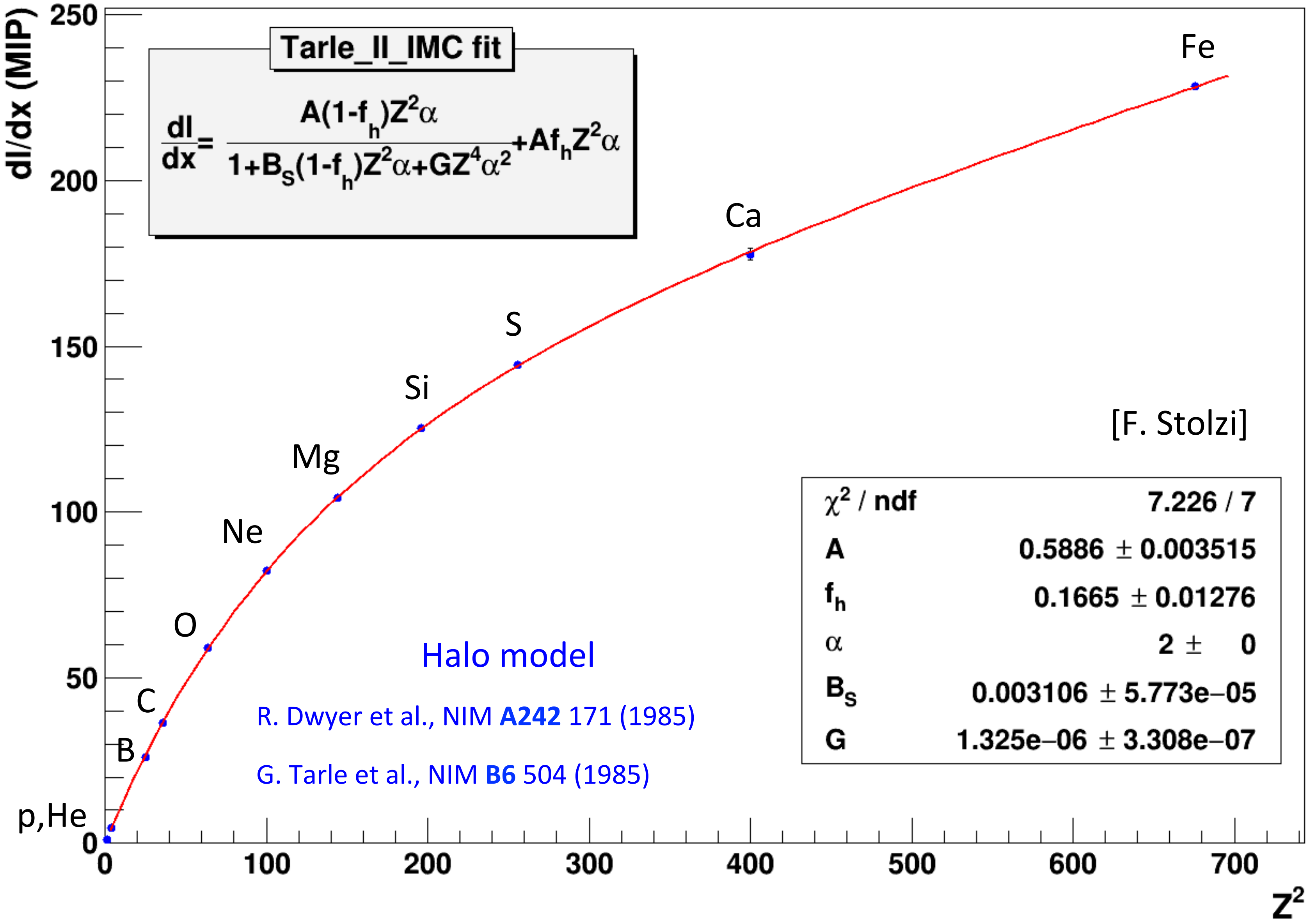
Fit of non-linear response of CHD layers vs Z^2



CHD charge resolution (2 layers combined) vs Z



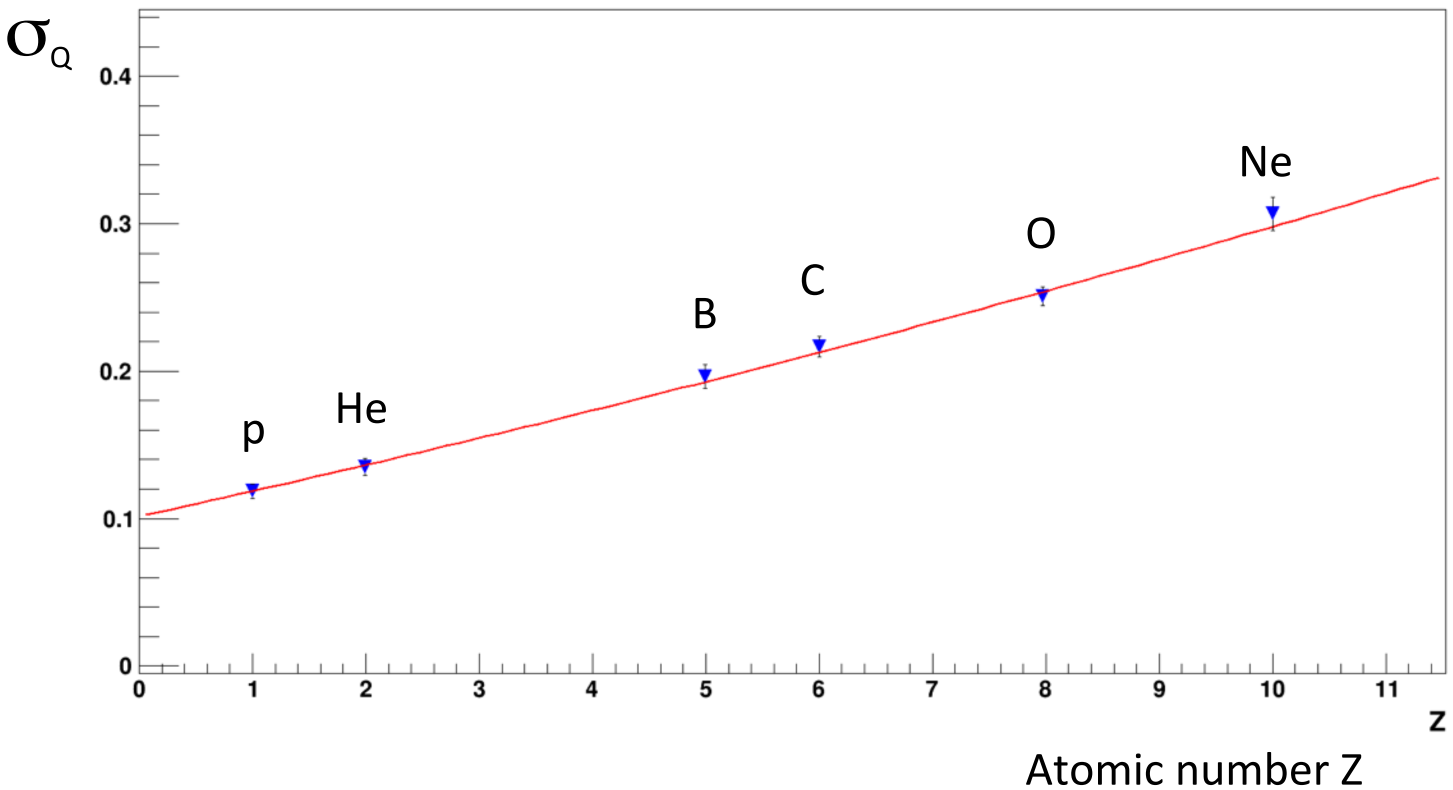
Fit of non-linear response of IMC fibers vs Z^2



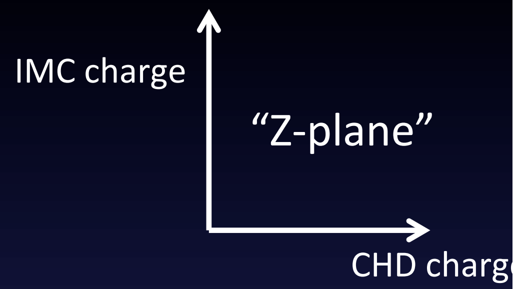
IMC charge resolution vs Z

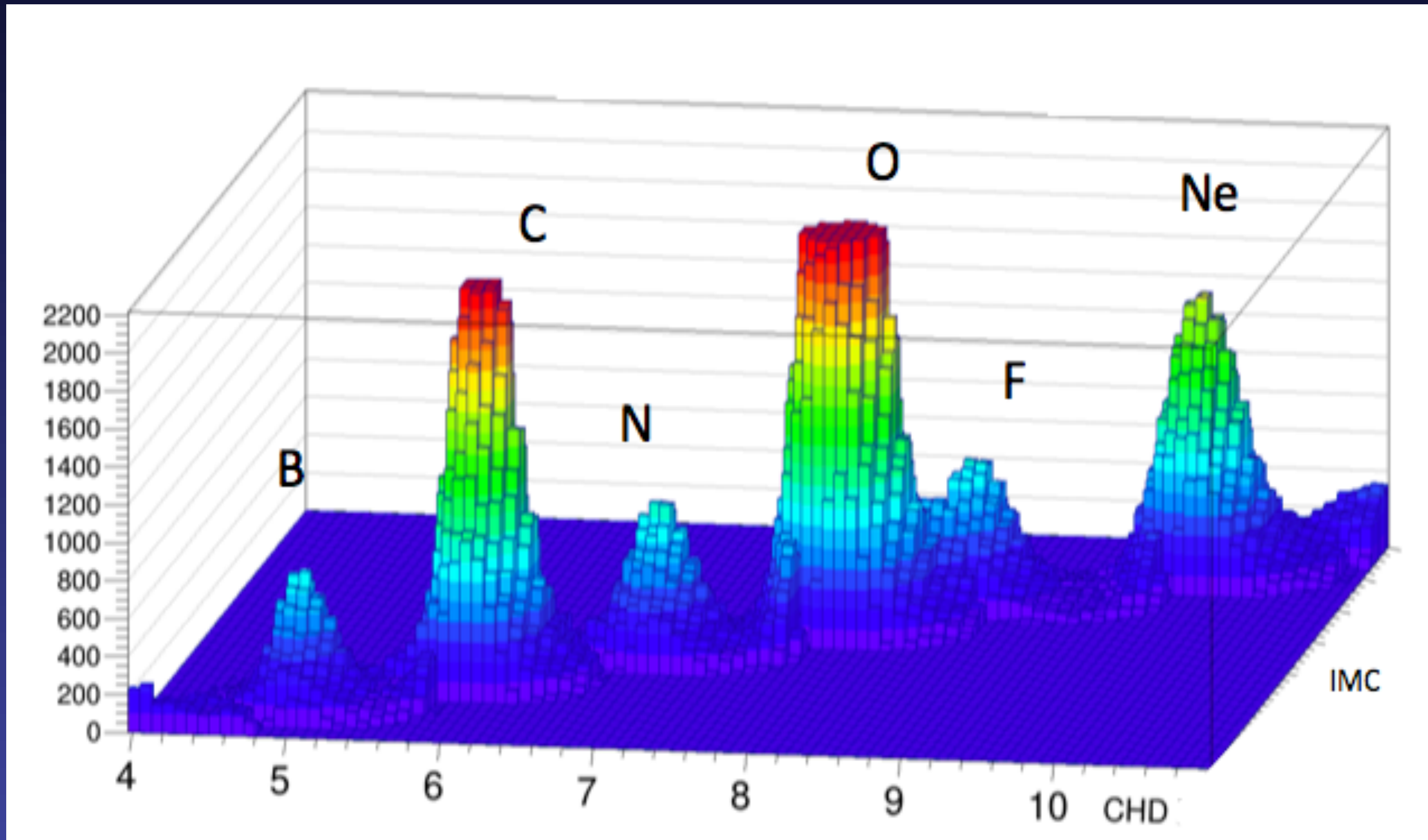
IMC single fibers have photoelectron yield/MIP about 1 order of magnitude lower than the CHD paddles, but due to **multiple dE/dx sampling** (up to 16 independent measurements) the charge resolution of IMC is adequate to identify light nuclei.

Example: B to C charge separation is **~ 7**σ with CHD and **~ 5**σ with IMC

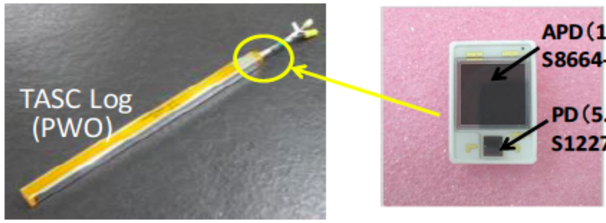


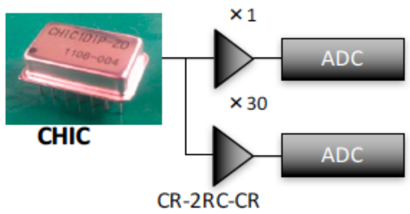
Example of combined CHD + IMC charge identification of light elements from boron to neon

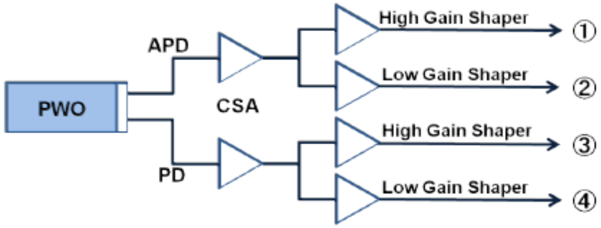




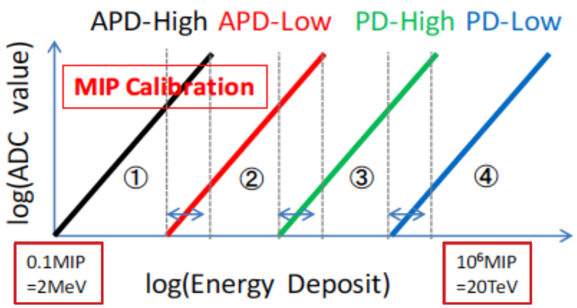
Energy Measurement: Dynamic Range & Calibrations



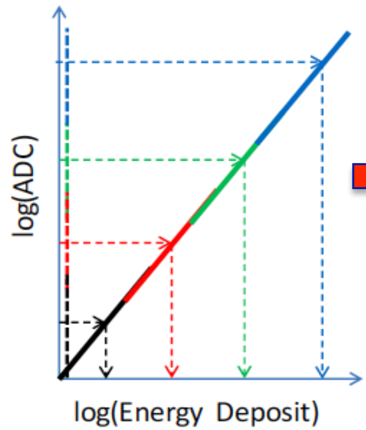


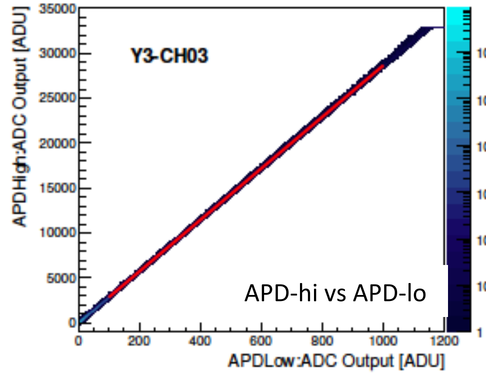


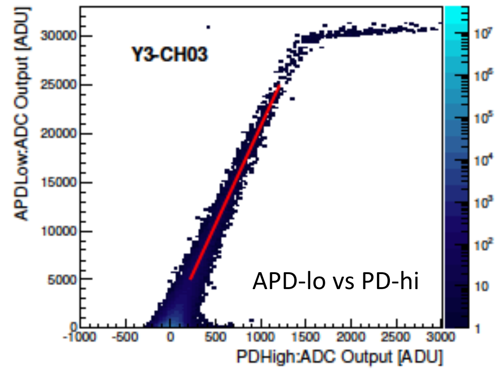
Gain Ratio Calibration

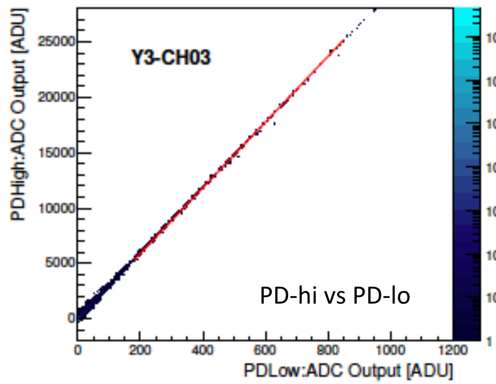


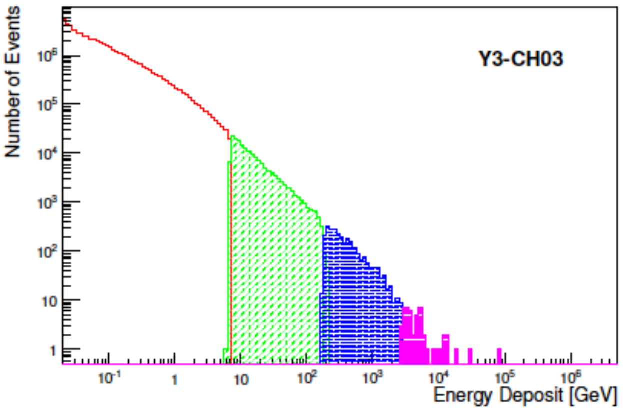
Calibrating full range (6 order of magnitude) is quite a challenge!











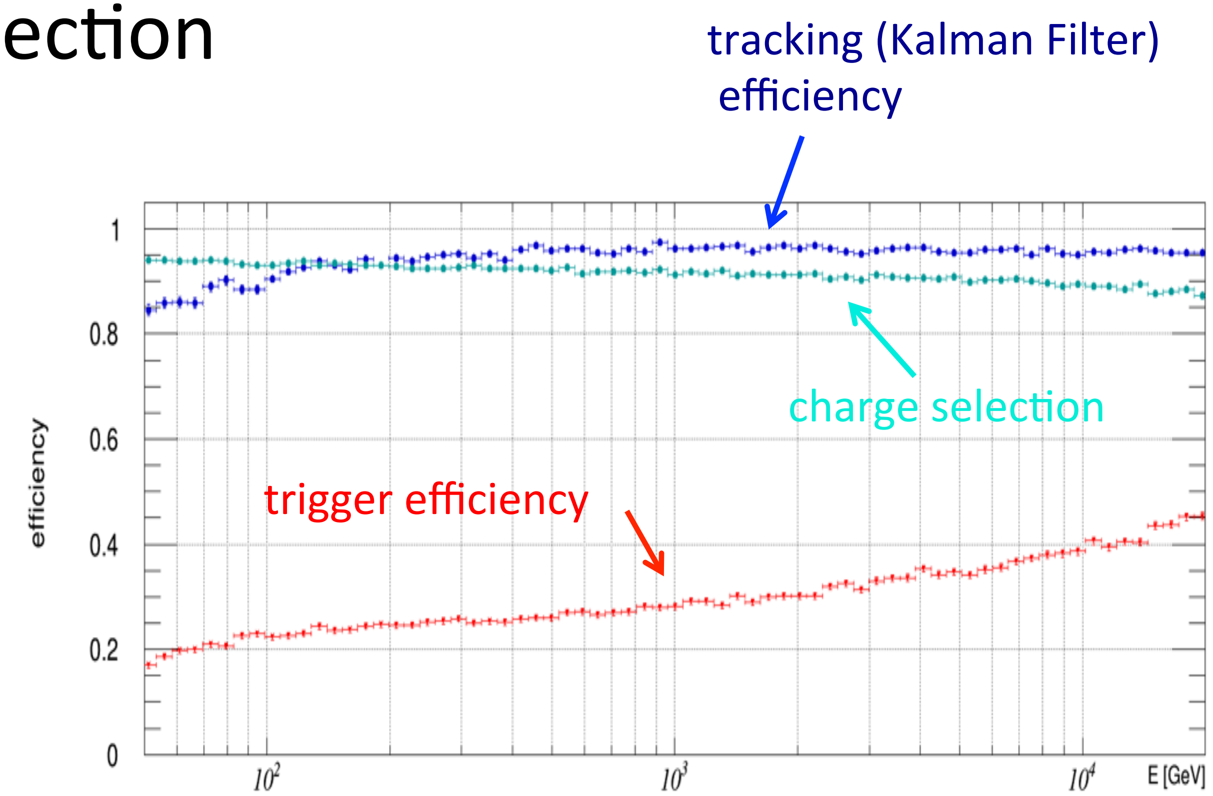
R. Miyata et al., this conference
Y. Komiya et al., this conference

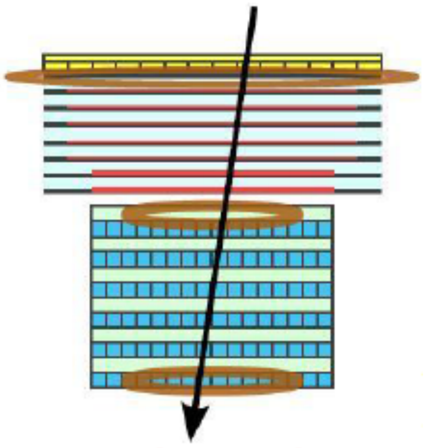
final stitching

Y. Asaoka et al., Astropart. Phys. 91 , 1 (2017)

Proton Event Selection

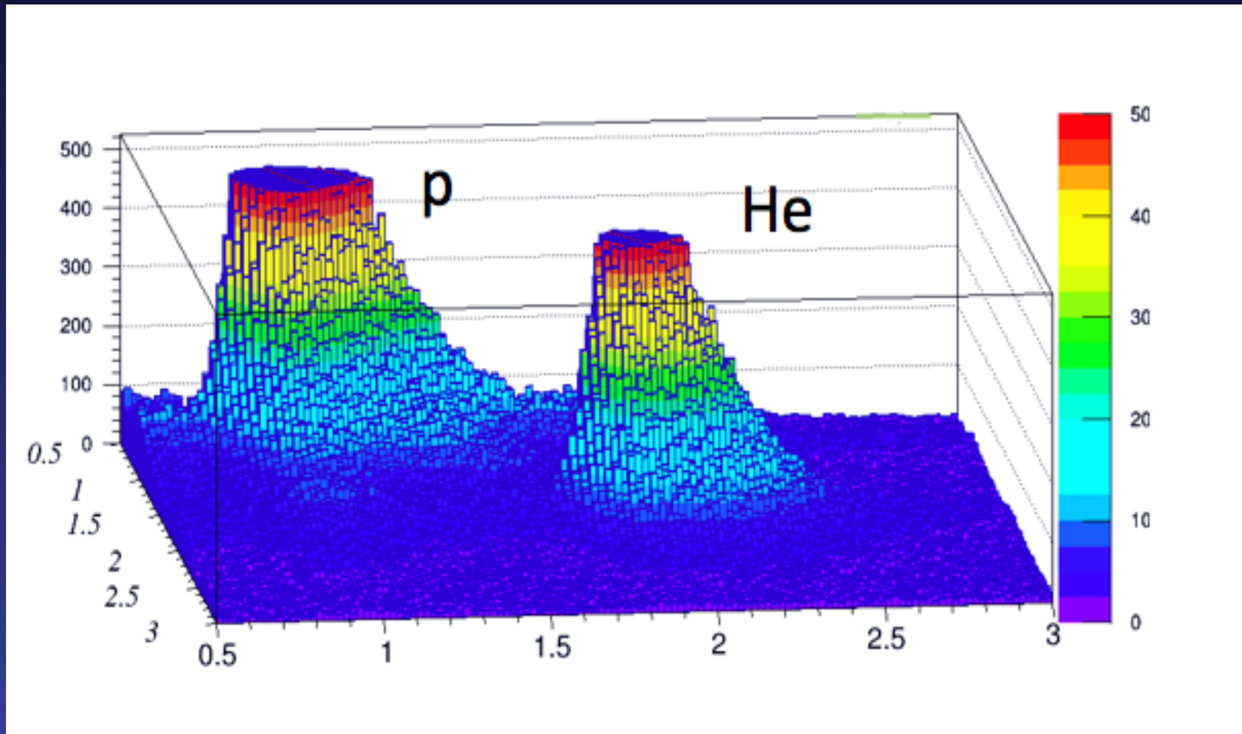
1. Acceptance-A selection
2. Good Tracking (KF)
3. High Energy Trigger (HET)
4. Charge selection Z = 1
5. Helium rejection cuts
6. Electron rejection cuts



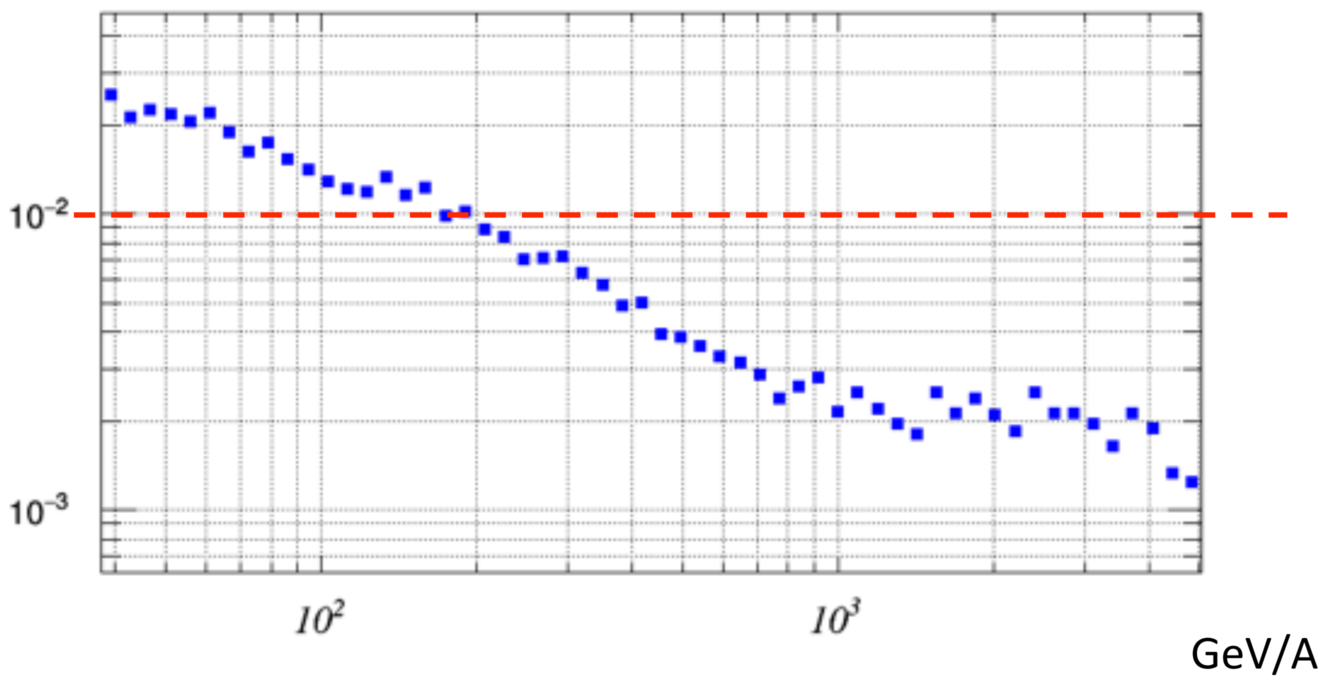


Fiducial Acceptance-A

Example of combined CHD + IMC charge identification of proton and helium



Residual He background after rejection of Z > 1 nuclei

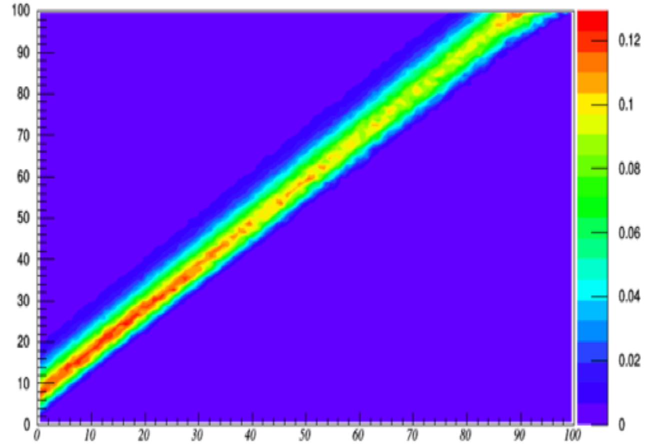


Energy unfolding

A standard procedure is to construct an *energy overlap matrix* A_{ij} **from MC data**:

- *matrix element* α_{ij} and *normalization factor* n_j are weighted with the *MC event weight* when the *"MC truth" energy* falling into bin i leads to a *reconstructed energy* in bin j

- the normalized matrix is defined as: $$A_{ij} \equiv \frac{\alpha_{ij}}{n_j}$$



We also define:

- ε_i = total *efficiency* in i-th bin

- β_j = *background* contamination in j-th bin

- M_j = number of events (weighted) *measured* in j-th bin (sum up to M_{tot} in energy range)

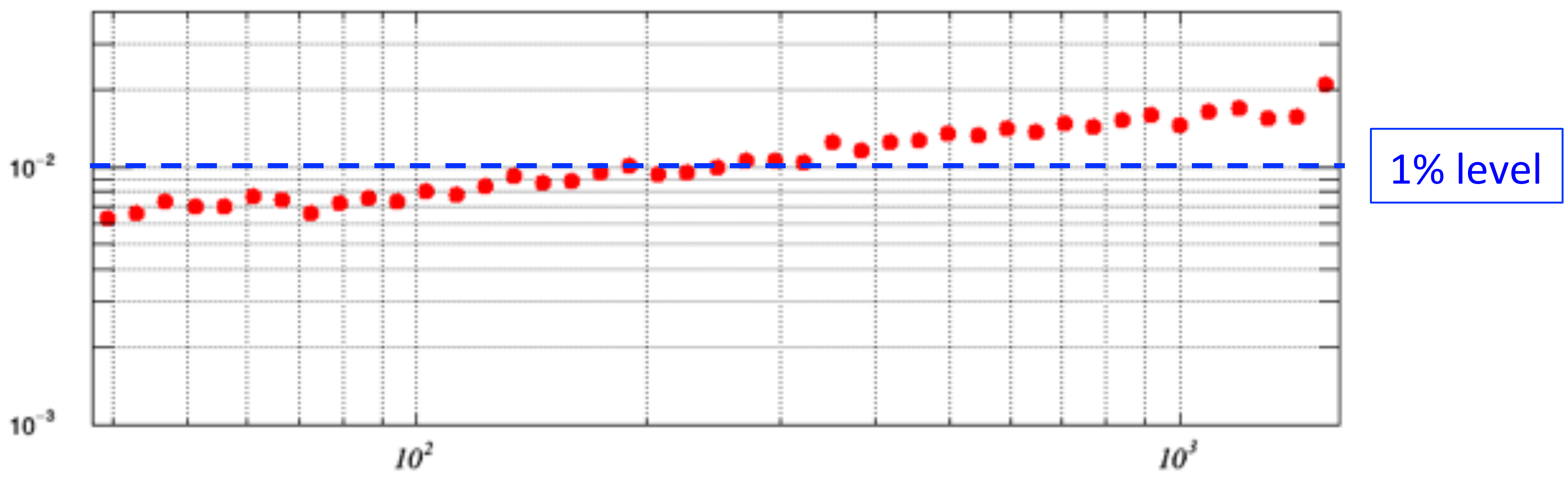
- N_i = energy unfolded number of events (weighted) in i-th bin

Then: $$N_i = \frac{1}{\epsilon_i} \sum_{j=1}^{n} A_{ij}(M_j - \beta_j M_{\text{tot}})$$

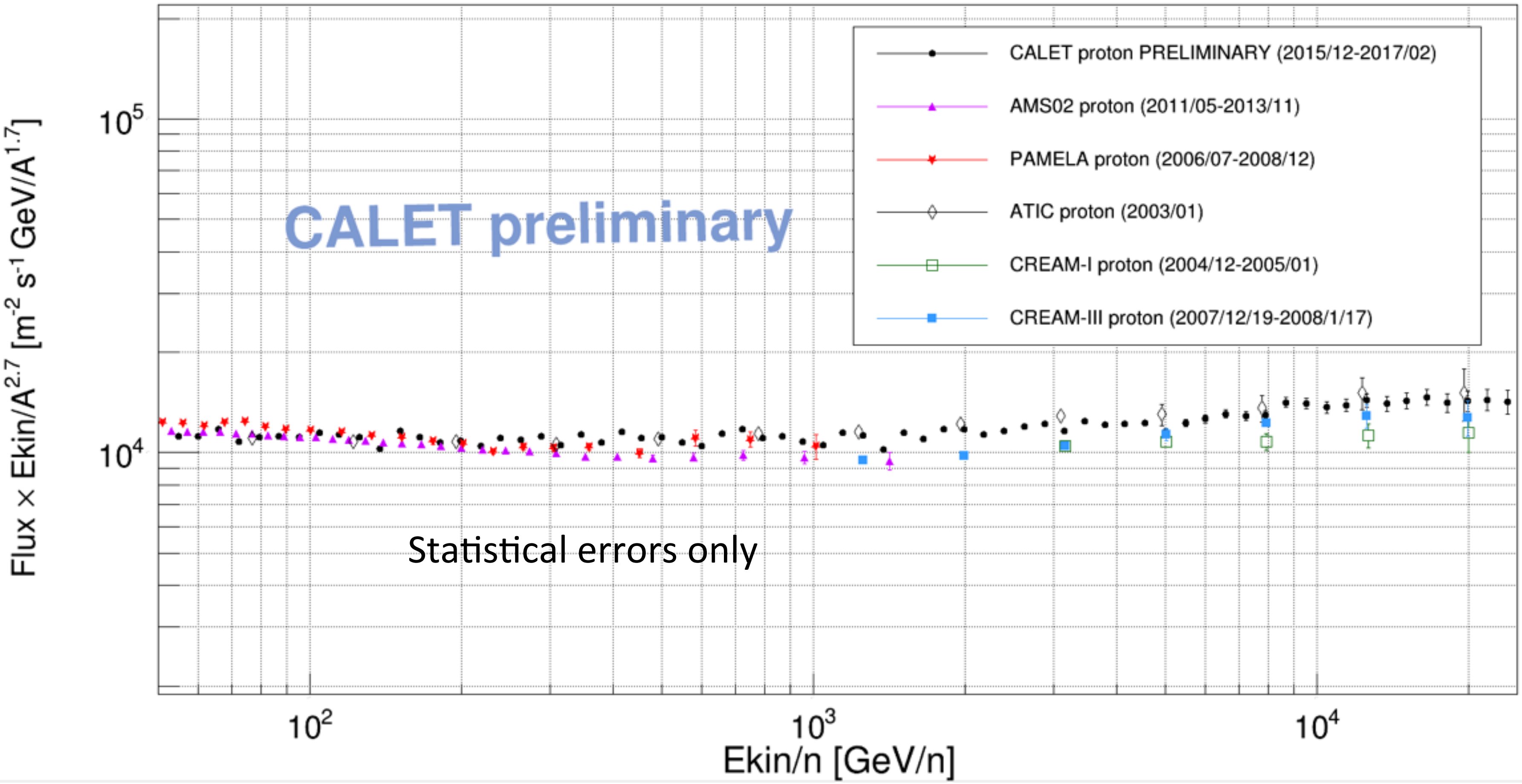
Residual electron contamination in proton sample

Preliminary analysis:

- Loose electron rejection cut: ratio of bottom TASC layer energy deposit / E_{TASC}
- Efficiency of the cut decreases with energy but contamination < 2%
- Electron background contamination can be further reduced by applying full e/p discrimination criteria.

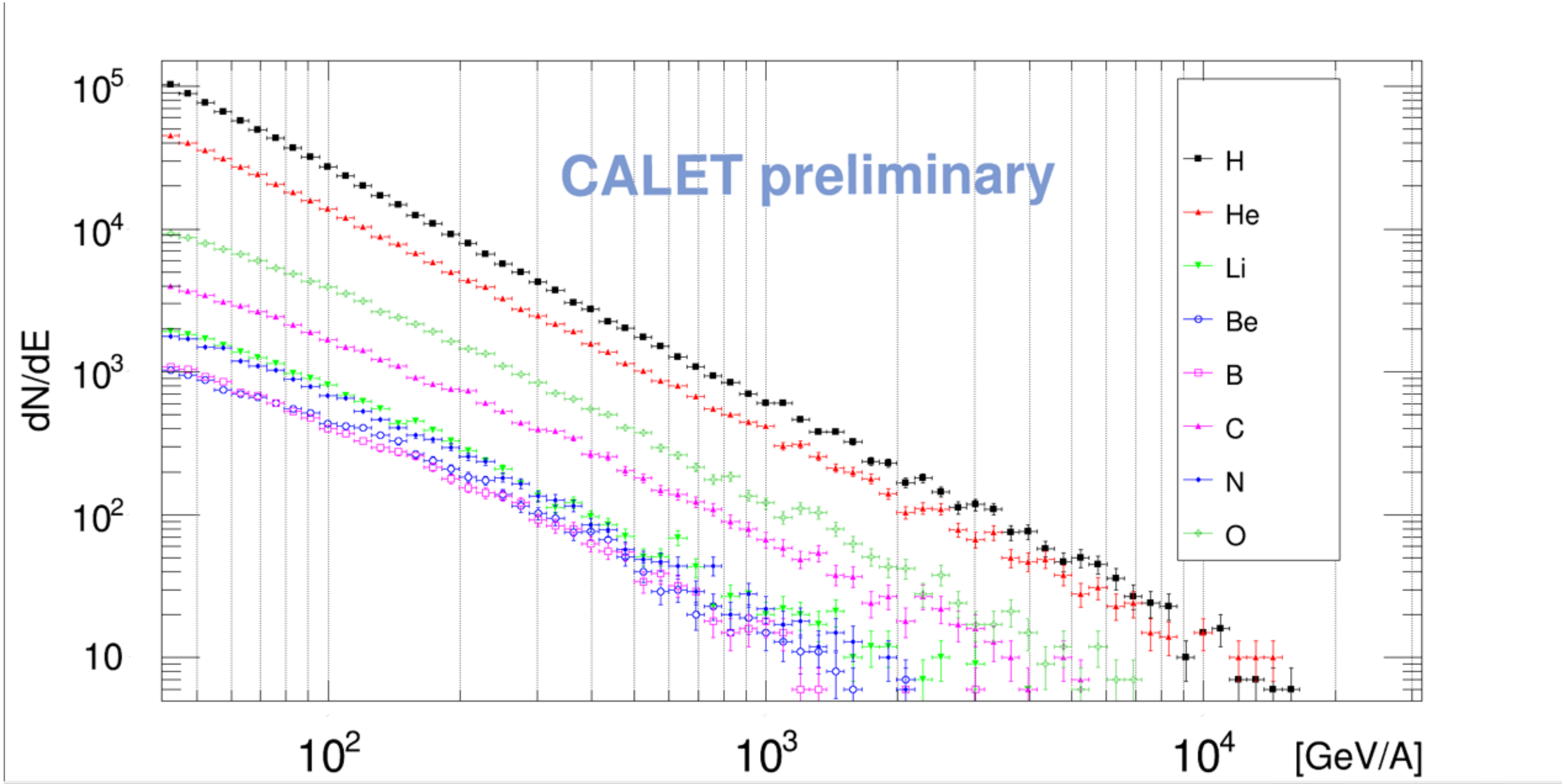


Preliminary proton flux $E^{2.7}$ from 50 GeV to 22 TeV



- 15 months of observation from December 1st , 2015 to February 28th, 2017
- subset of total acceptance: acceptance A (fiducial) with SΩ = 416 cm^2 sr
- Assessment of the systematic errors: IN PROGRESS

Preliminary dN/dE for light elements: proton to oxygen

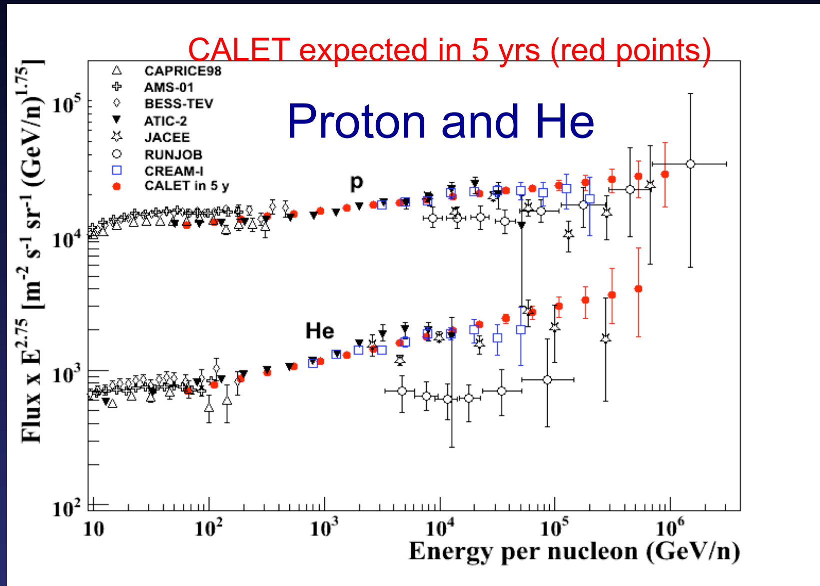


CALET is exploring the Multi-TeV region

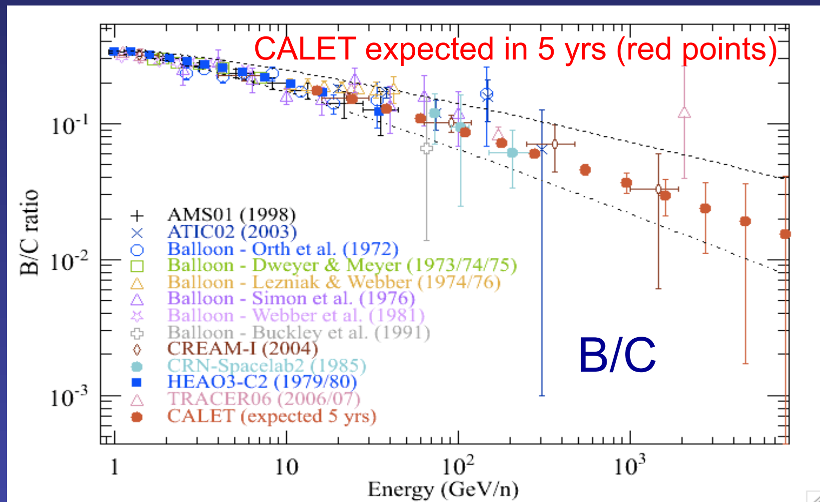
- elemental spectra & relative abundances,
- flux ratios (secondary-to-primary, primary-to-primary, secondary-to-secondary)

CALET Energy reach in 5 years:

- Proton spectrum to ≈ 900 TeV
- He spectrum to ≈ 400 TeV/n
- Spectra of C,O,Ne,Mg,Si to ≈ 20 TeV/n
- B/C ratio to ≈ 4 - 6 TeV/n
- Fe spectrum to ≈ 10 TeV/n



	λ_{INT}	X_0 (normal incidence)
CREAM	0.5 + 0.7	20
CALET	1.3	30
AMS-02	0.5	17
DAMPE	1.6	31



Conclusions

- CALET has been delivering science data from the ISS during the last 20 months
- Total observation time 627 days with live time fraction to total time close to 84%
- Instrument performance and stability are excellent
- Single elements have been identified thanks to redundant charge measurements
- A preliminary analysis of proton and light nuclei has been presented
- The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year observation period is likely to provide a wealth of new interesting results