Extended measurement of the proton spectrum with CALET on the International Space Station

Jul. 14th, 2021

K. Kobayashi (Waseda/JAXA) and P. S. Marrocchesi (Siena/INFN)

on behalf of the CALET collaboration

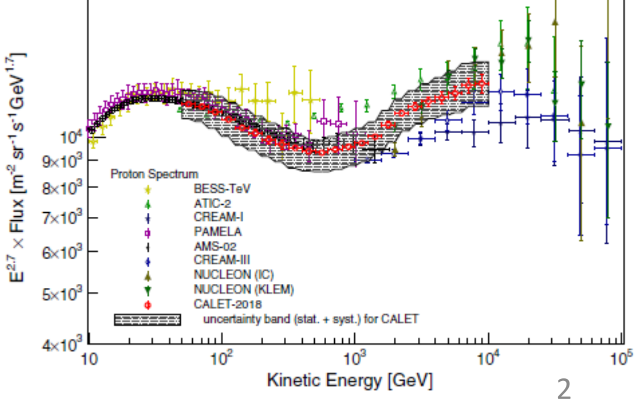
ICRC2021

CALET scientific motivation

Motivation	CALET Observation target
CR origin and acceleration	Electron (1GeV – 20TeV) Proton to Fe (10GeV – 1000TeV) Ultra Heavy ions (26<Z<=40) (>600MeV/n) Gamma-rays (1GeV – 10TeV)
CR propagation in the galaxy	B/C ratio, subFe/Fe ratio (<~TeV/n)
Nearby CR sources	Electron (100GeV – 20TeV)
Dark matter	Electron (100GeV – 20TeV)
Solar physics	Electron/proton (<10GeV)
Gamma-ray transient	Gamma-rays/X-rays (7keV – 20MeV)

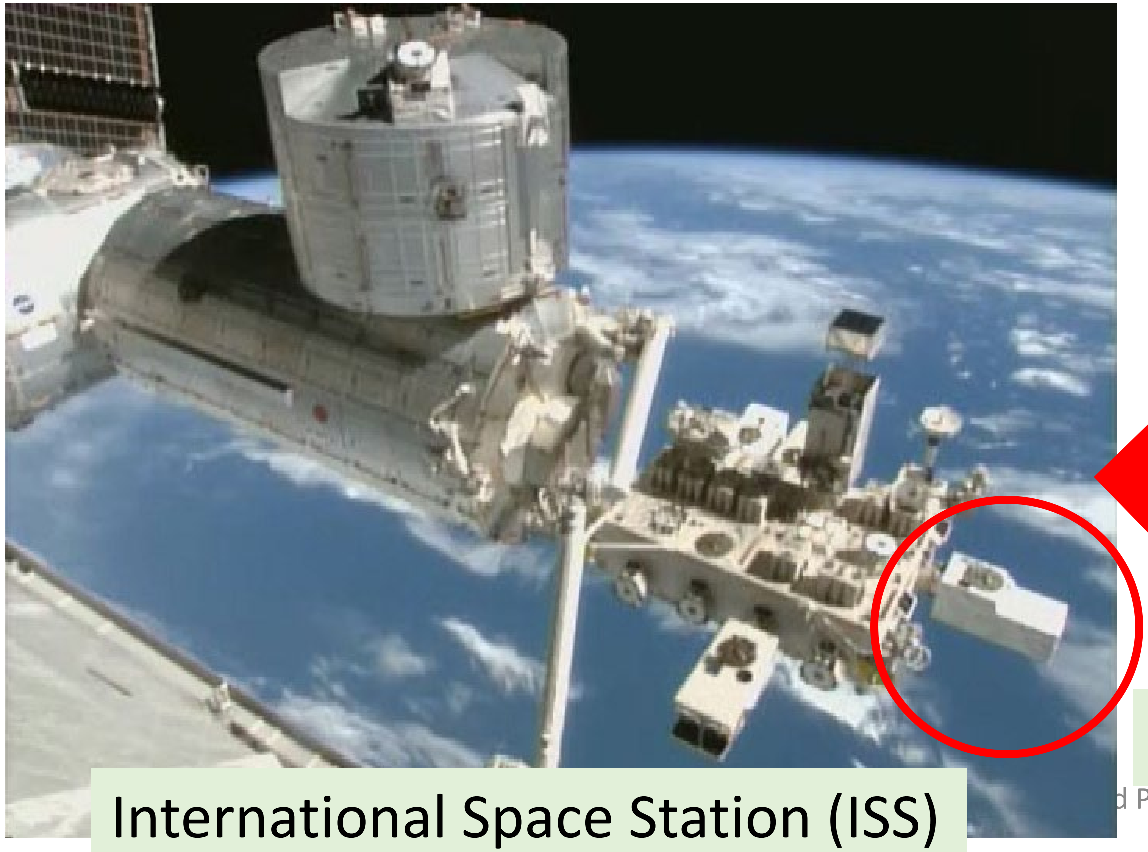
- We reported CALET proton flux in PRL122, 181102 (2019).
- In this talk, we use 2 more years of data since PRL paper, and also analyze the higher energy region up to 60TeV.

Proton flux in PRL2019

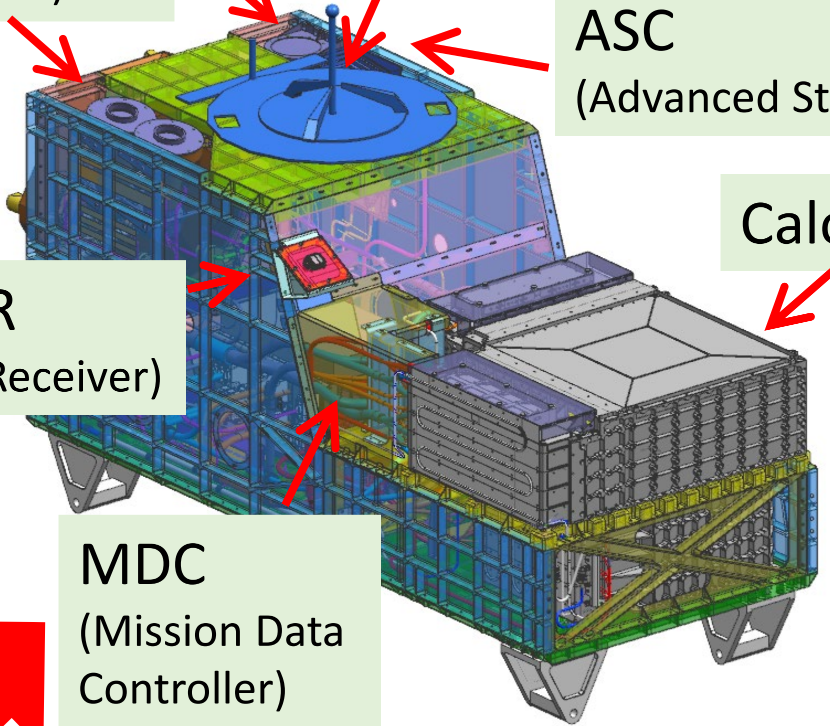


CALET project

Aug. 2015: launched and emplaced on the ISS
Oct. 2015: start data taking
Data taking is stably running up to now.
We plan to take data until 2024 (at least).

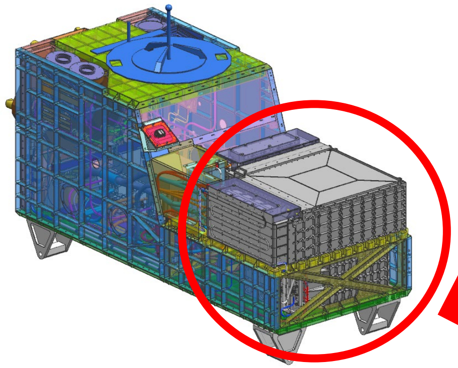


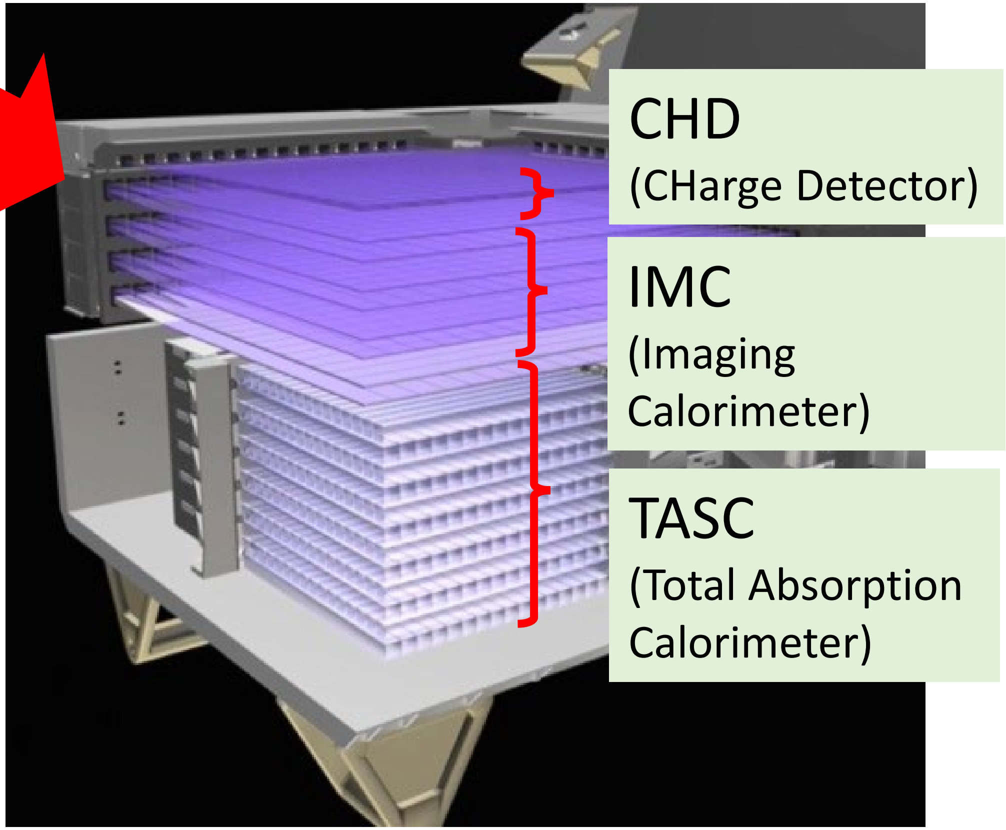
International Space Station (ISS)



mass	612.8kg
power	507W (max)
telemetry	600kbps (6.5GB/day)

CALET detector





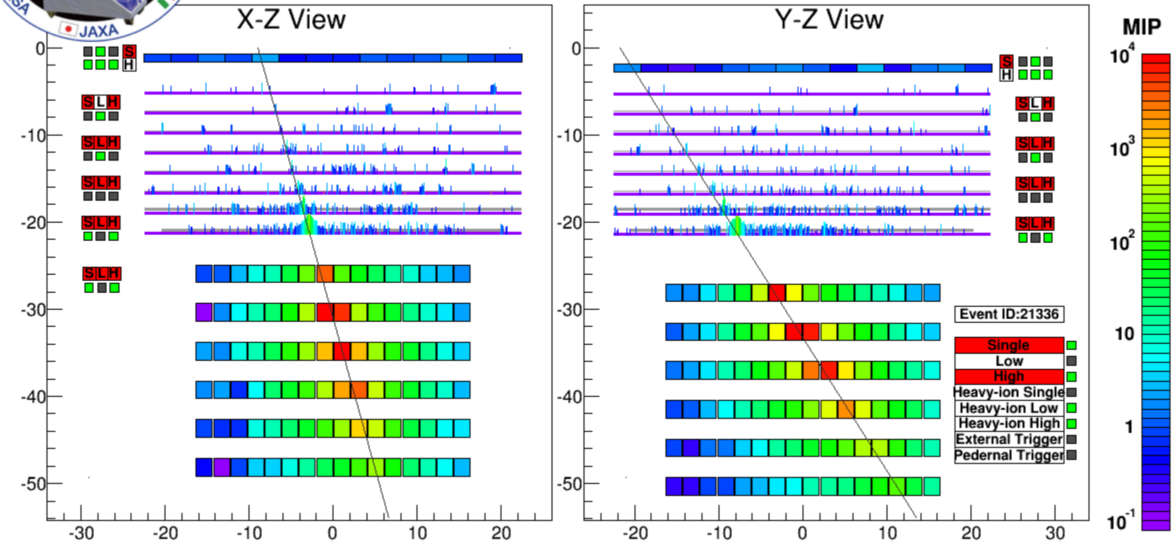
	Material/sensor	Purpose
CHD	Plastic scintillator + PMT 28 paddles (=14x2layers(x,y)) (paddle size: 32x10x450mm)	Charge ID
IMC	Scifi./W + MAPMT (64anode) 7168 Scifi. (=448x16layers(x,y)) +7 W layers (Scifi. size: 1x1x448mm)	Tracking, charge ID
TASC	PWO scintillator + APD/PD or PMT 192 logs (=16x12layers(x,y)) (Log size: 19x20x326mm)	Energy

In total $30X_0$ thickness
(=1.2λ, $27X_0$ in TASC + $3X_0$ in IMC)

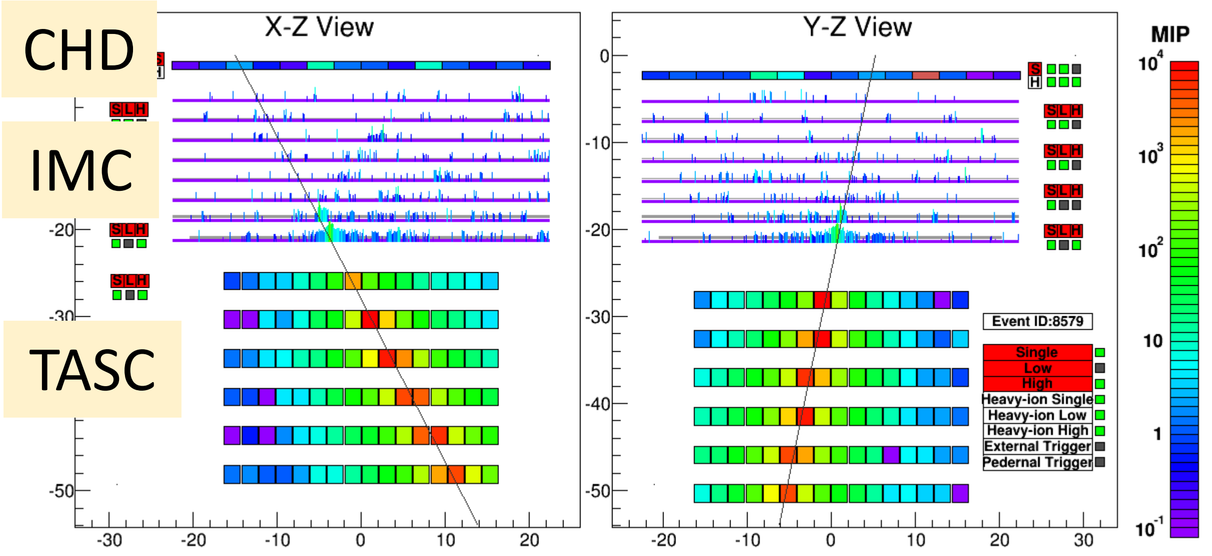
We report the analysis using data from Oct. 2015 to Sep. 2020.

Event examples

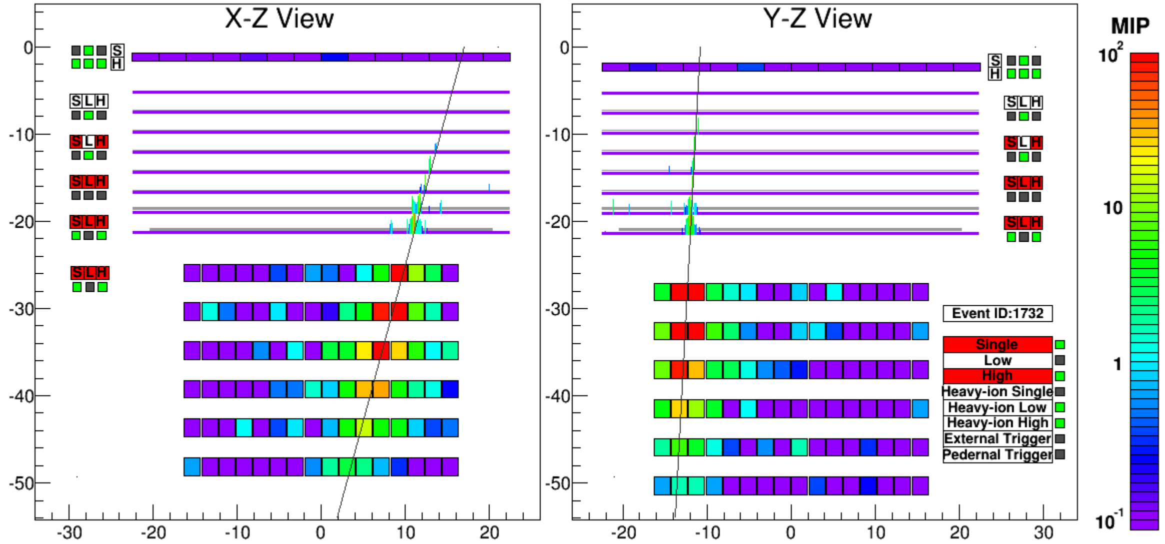
Electron, E=3.05 TeV



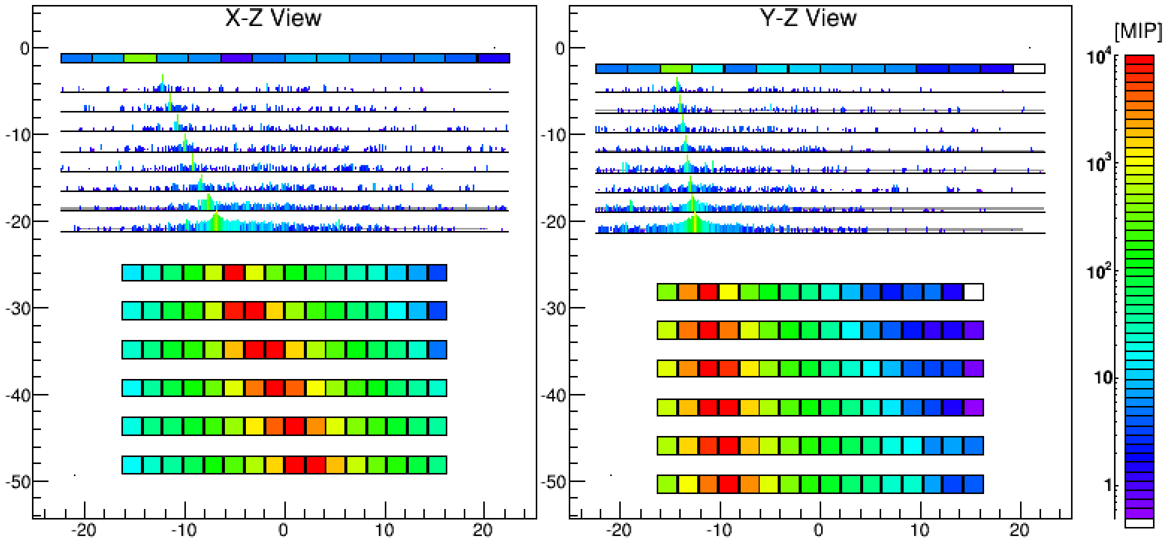
Proton, ΔE=2.89 TeV



Gamma-ray, E=44.3 GeV



Fe, ΔE=9.3 TeV

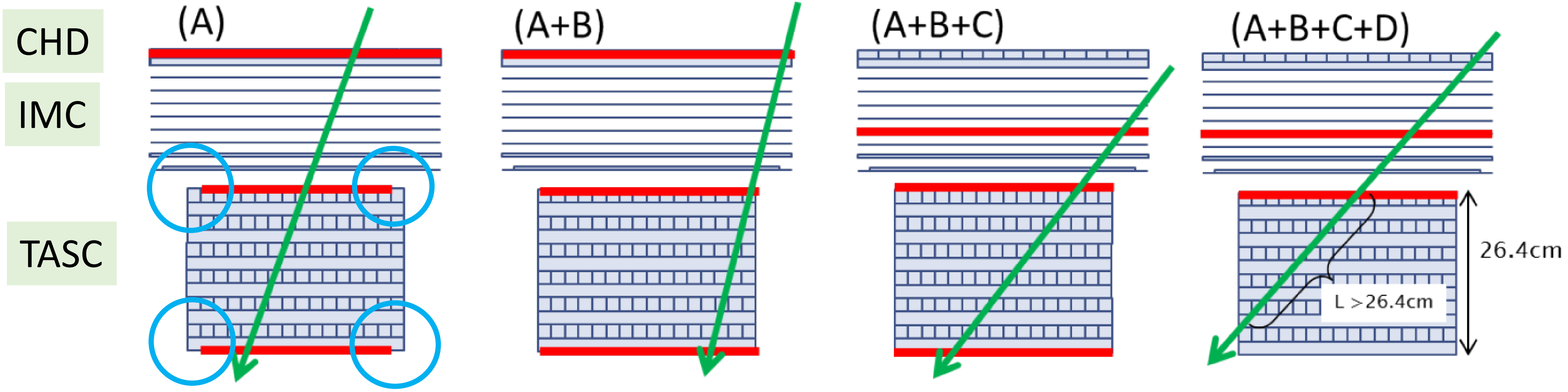


Proton event selection

selection	Brief description
1. Event trigger	HE trigger in E>300GeV and LE trigger in E<300GeV.
2. Geometrical acceptance	Track going through the detector from the top to the bottom is selected.
3. Track quality cut	Reliability of Kalman Filter fitting in IMC is checked.
4. Electron rejection	Electron events are rejected using the energy deposit within one Moliere radius along the track.
5. Off-acceptance cut	Residual events crossing the detector from the sides are rejected.
6. TASC hit consistency	In order to reject the events with mis-reconstructed track, we reject the events which doesn’t have consistent energy deposit at the top X/Y layer of TASC where the track is expected to go through from the track reconstruction in IMC.
7. Shower start in IMC	Shower development starting in IMC is required.
8. Charge identification in CHD and IMC	Charge identification using the energy deposit in CHD and IMC (before shower development starts) is performed to reject helium events, mainly.

In the following pages, selections 2, 5, 6, and 8 are explained.

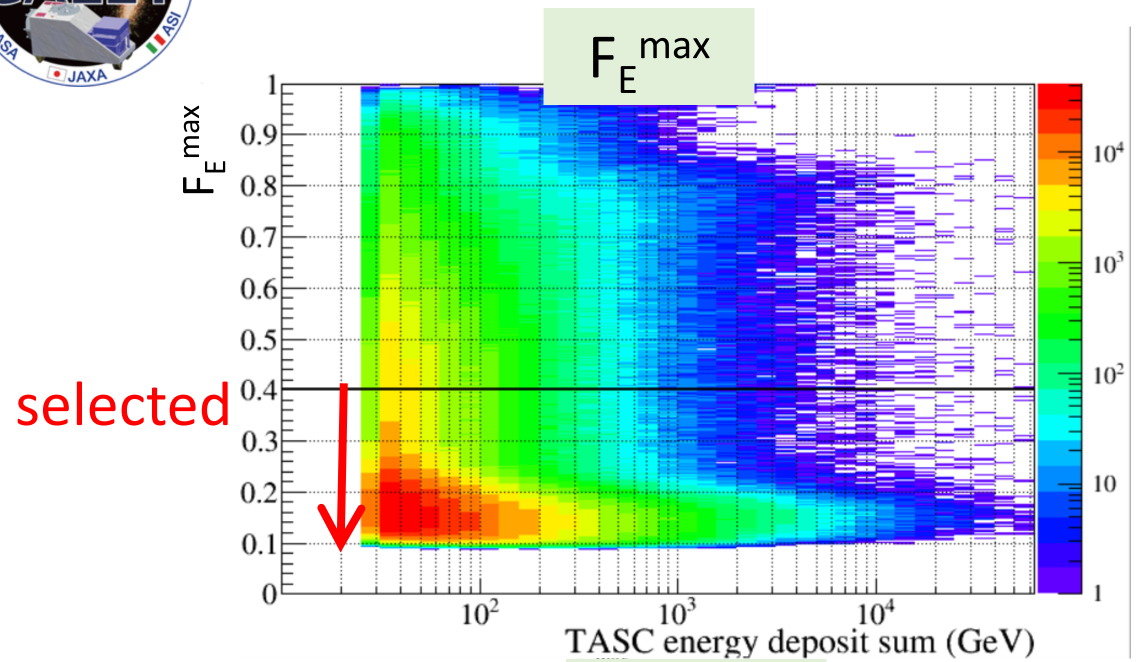
Geometrical acceptance

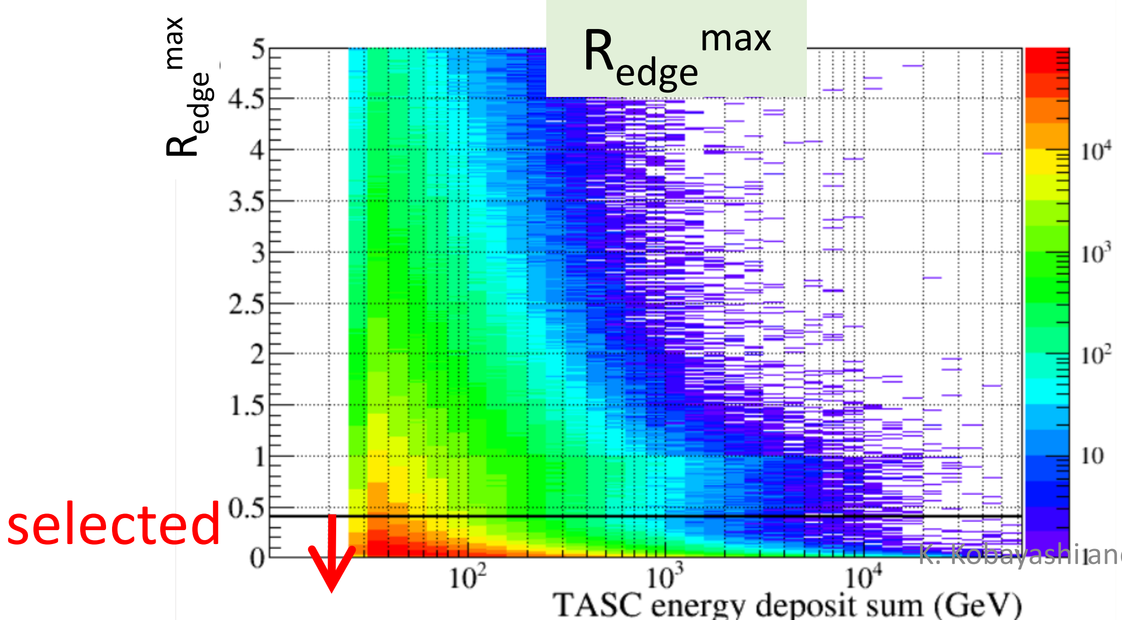


2cm margin in TASC is taken.

- In this proton analysis, we use the events with acceptance A: The reconstructed track is required to cross the CHD and TASC from top to bottom.
- Geometrical factor for acceptance A is ~510cm^{2}sr.

Side event rejection: Off-acceptance cut

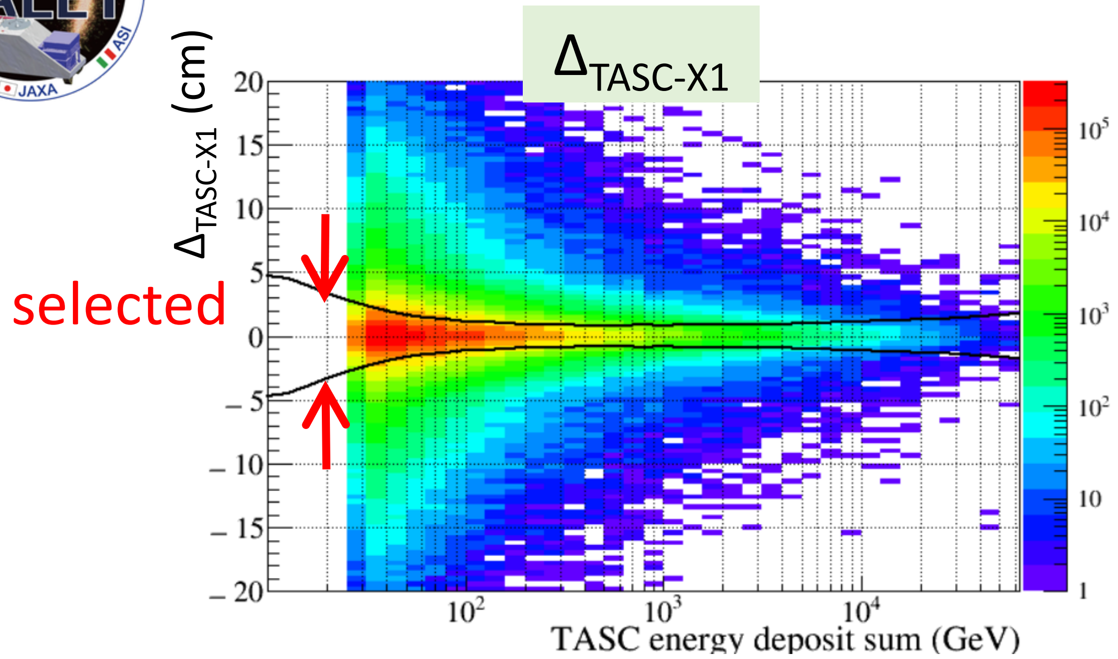


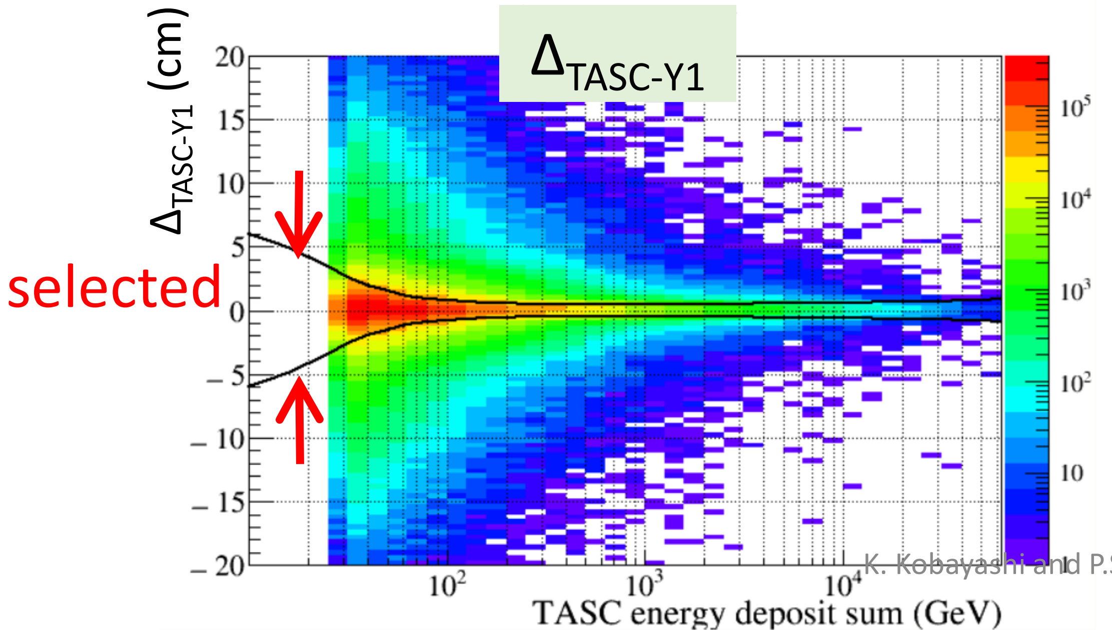


In order to reject the events coming from the side of the detector, the following selections are applied.

1. Maximum fractional energy deposit in TASC layer (F_E^{max}) should be less than 0.4.
2. Maximum energy deposit ratio (R_{edge}^{max}, edge channel to maximum channel in TASC) should be less than 0.4.

Mis-reconstructed event rejection: TASC hit consistency

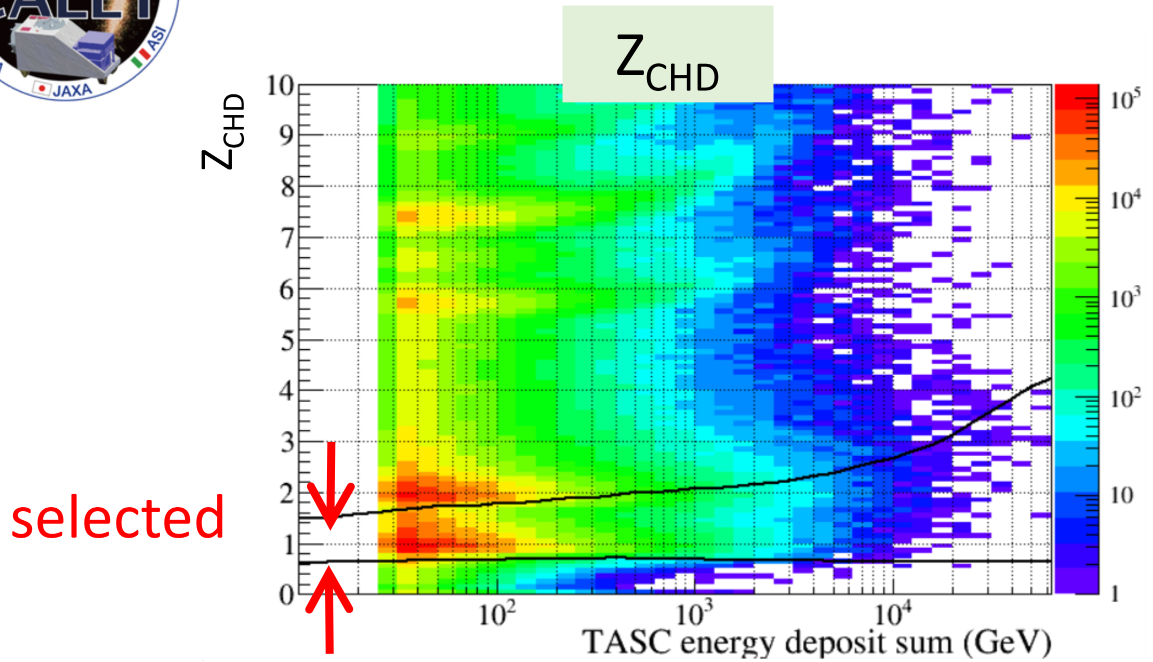


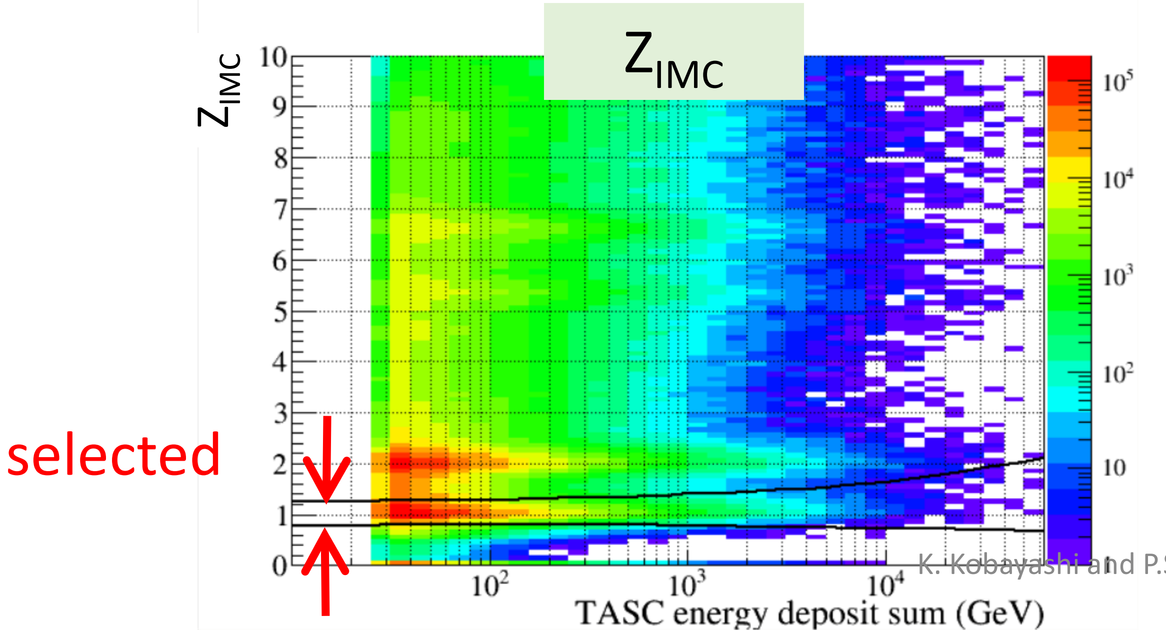


In order to remove residual mis-reconstructed events, track reconstructed in IMC is checked using TASC energy deposit.

1. The difference between center of gravity of energy deposit in TASC-X1/Y1 and point where the reconstructed track in IMC impinges on TASC-X1/Y1 ($\Delta_{TASC-X1}$, $\Delta_{TASC-Y1}$) is calculated. (TASC-X1/Y1 is the top layer in TASC)
2. Then we select the events whose absolute difference is within the black lines in the left figures to keep 95% efficiency.

Charge identification in CHD and IMC (1/2)





- Charges (Z_{CHD} and Z_{IMC}) are determined by the following formula in CHD and IMC, respectively:

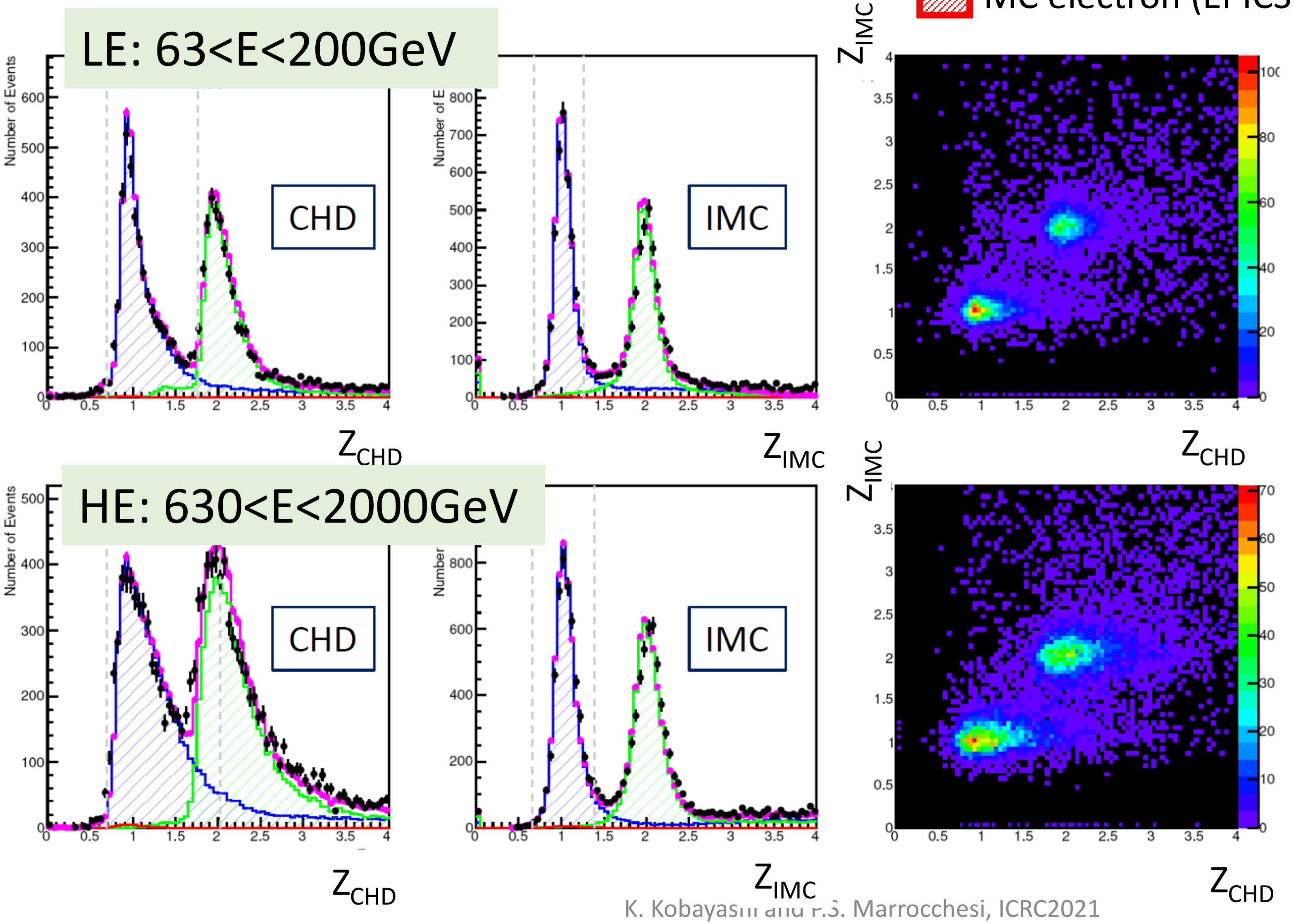
  $$Z = a(E)\sqrt{Q}^{b(E)}$$

  $a(E), b(E)$: energy dependent parameter

  Q: energy deposit in MIP

- We select the events that both Z_{CHD} and Z_{IMC} are within black lines in the left figures. These lines are determined to keep the efficiency 98% for lower Z side and 95% for higher Z side.

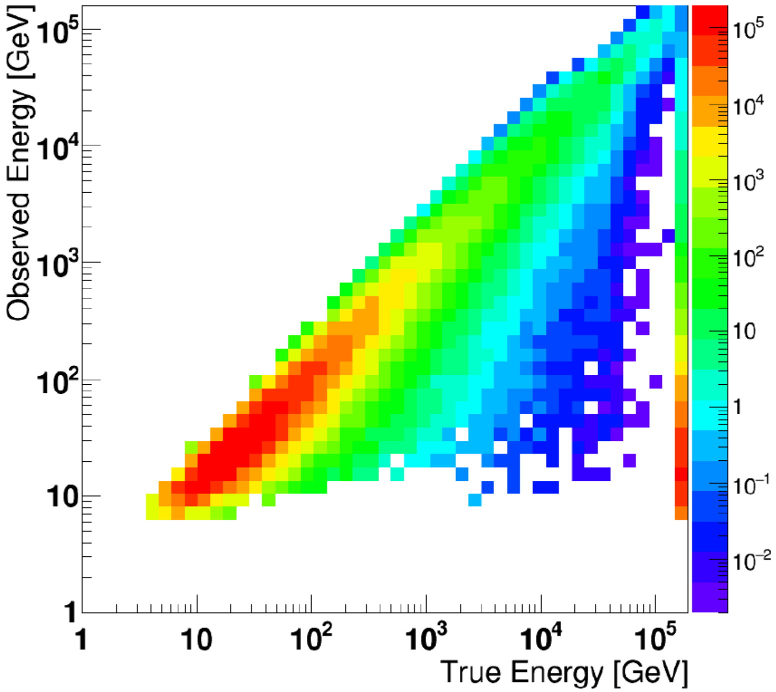
Charge identification in CHD and IMC (2/2)



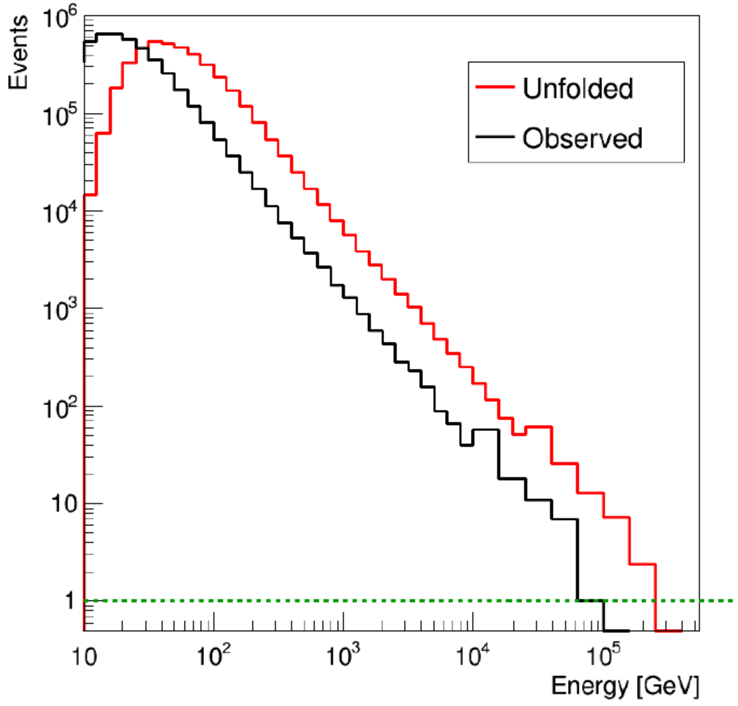
- Using the two charge identification parameters (Z_{CHD} and Z_{IMC}), proton and helium can be clearly separated.
- Total background contaminations are less than 8% in LE sample (63<E<200GeV) and less than 13% in HE sample (630<E<2000GeV), respectively.

Energy unfolding

Response matrix



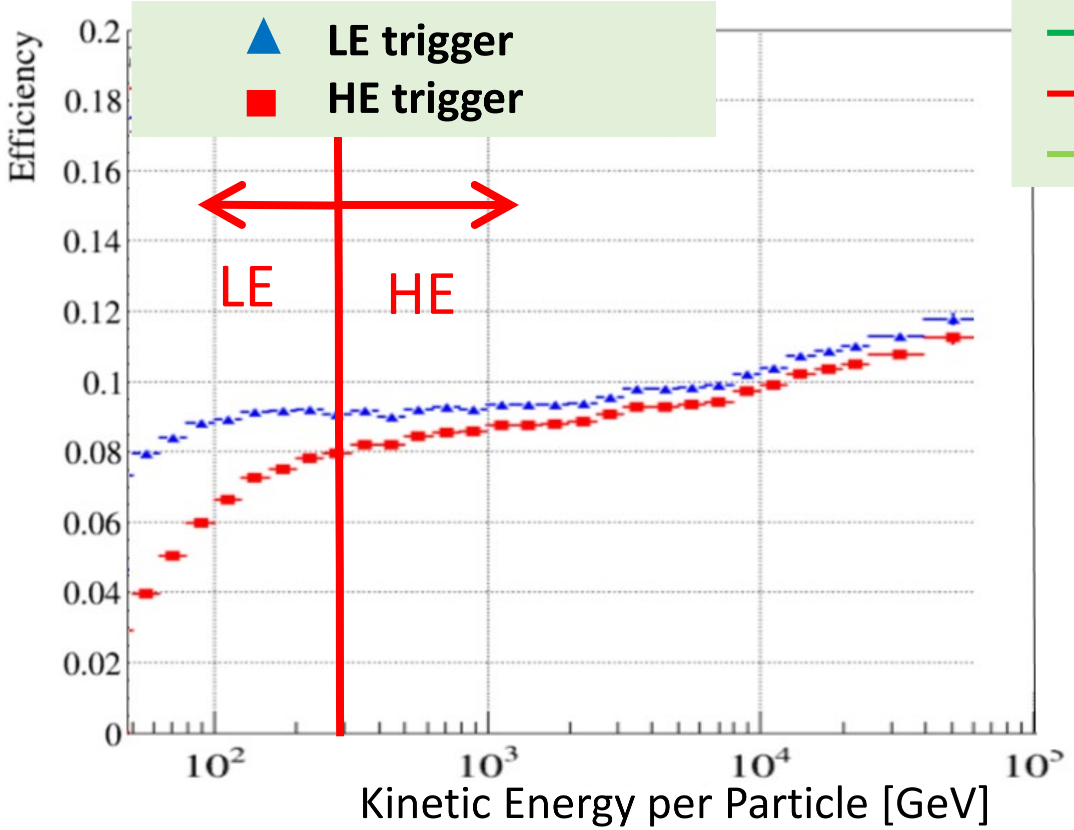
Observed/Unfolded energy spectrum

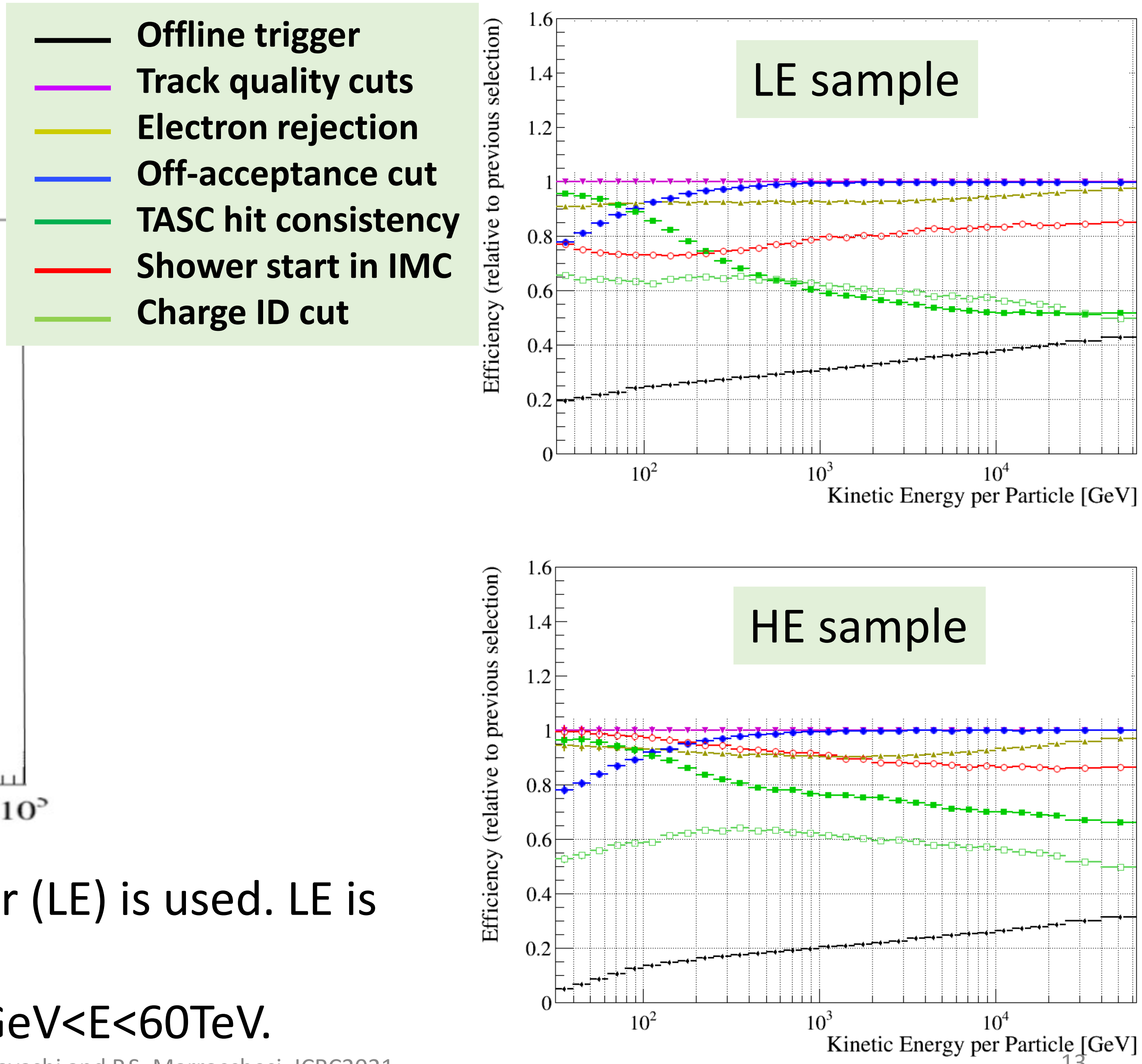


The energy resolution of proton is 30-40%. Therefore, we apply Bayes unfolding to reconstruct energy.

1. We build response matrix between true and observed energy spectrum using MC simulation.
2. We apply unfolding (RooUnfold) iteratively based on Bayes theorem with helium and electron background evaluation.

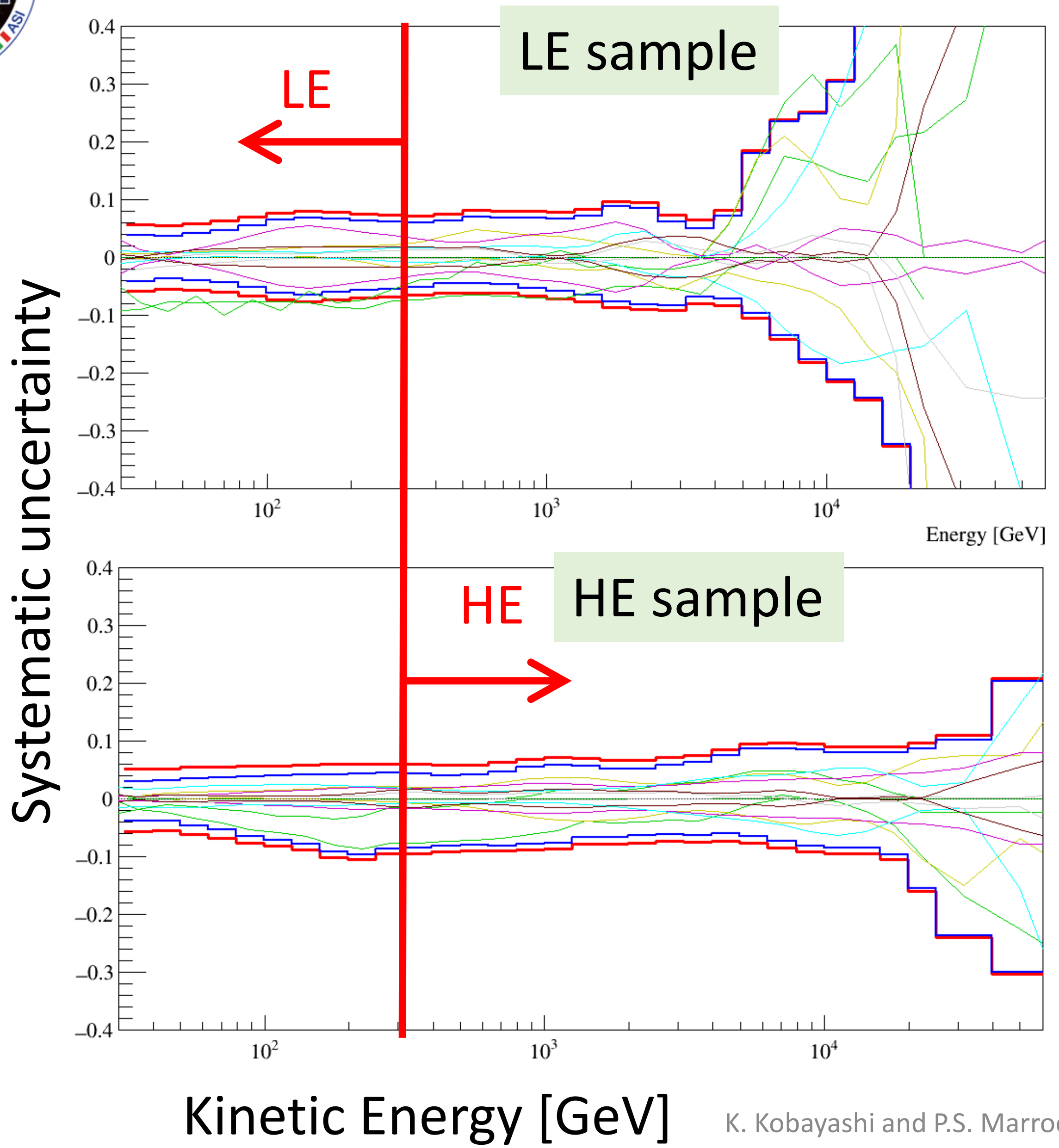
Detection efficiency





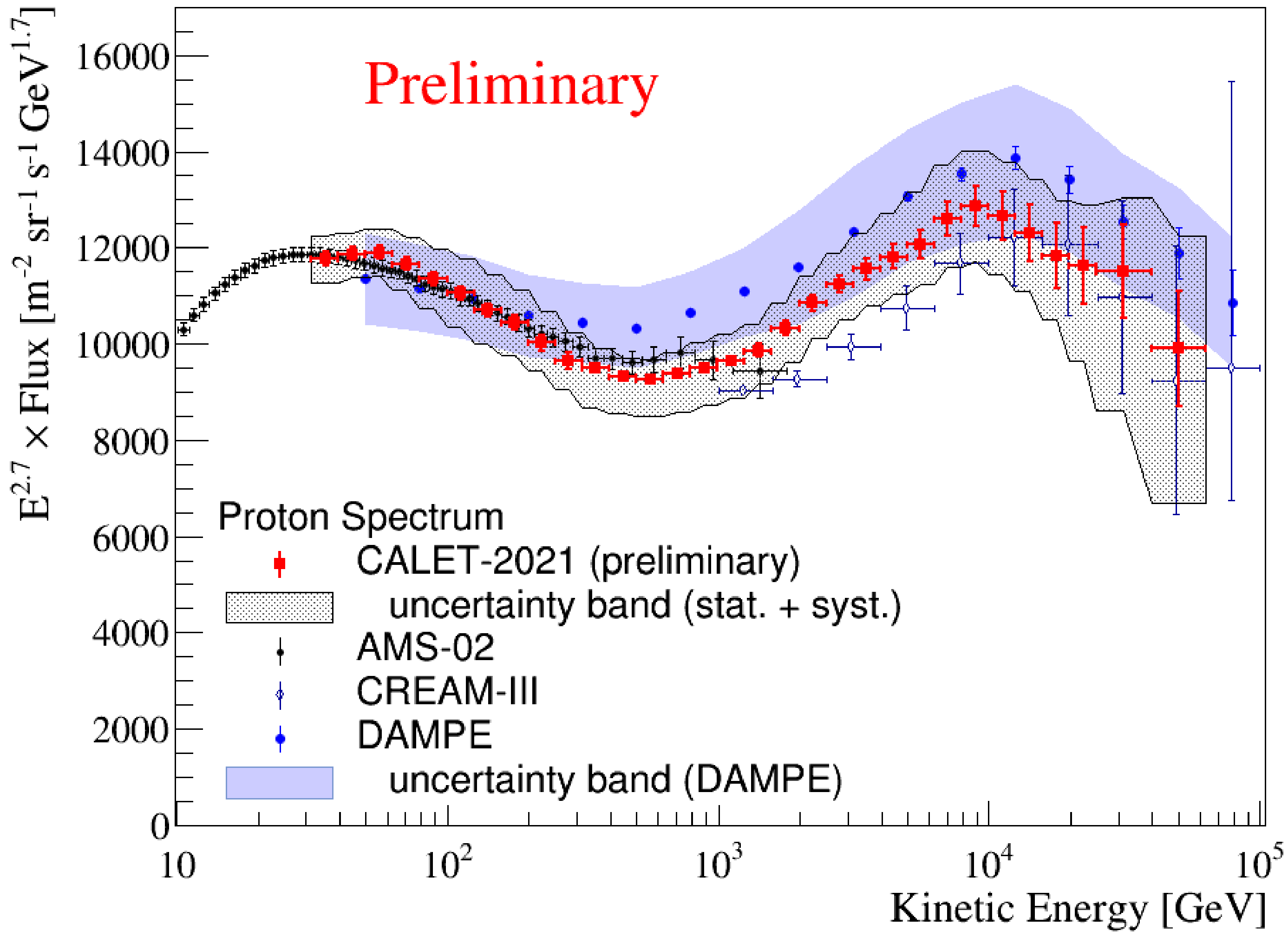
- In E>300GeV (E<300GeV), HE trigger (LE) is used. LE is used due to the high efficiency.
- Detection efficiency is 8-12% in 50GeV<E<60TeV.

Systematic uncertainty



- Systematic uncertainty in E<20TeV is less than 10%.
- The uncertainty in E>20TeV comes from the MC model dependence and charge identification, mainly.

Proton spectrum (30GeV<E<60TeV)

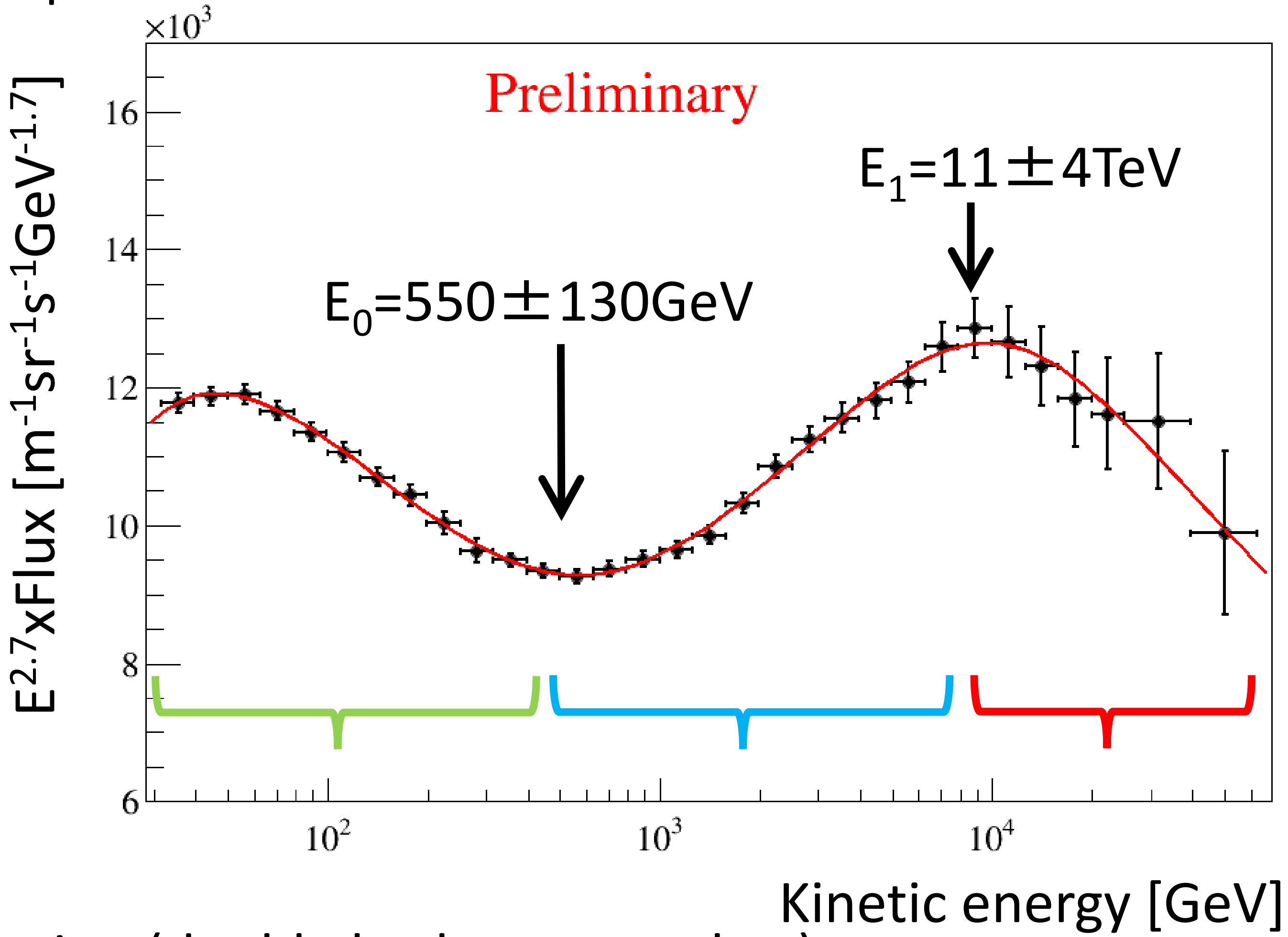


$$\Phi(E) = \frac{N(E)}{S\Omega T \Delta E \varepsilon(E)}$$

$\Phi(E)$: 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±2.1)x10^{-1}
p_0	9.1±26
P_1	-6.6±470
γ	-2.9±0.3
S	2.1±2.0
Δγ	(4.4±3.8)x10^{-1}
E_0	(5.5±1.3)x10^2
$\Delta\gamma_1$	(-4.4±3.0)x10^{-1}
E_1	(1.1±0.4)x10^4

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

Summary

- CALET data taking is stably running without any serious problem more than 5 years.
- We confirm the proton spectrum hardening around 500GeV with higher statistics.
- We expanded the energy region to 60TeV and observed a proton spectrum softening above 10TeV.
- An extension of CALET on-orbit operations to the end of 2024 was officially accepted. We plan to continue with stable scientific observations to accumulate more statistics in very high energy region.