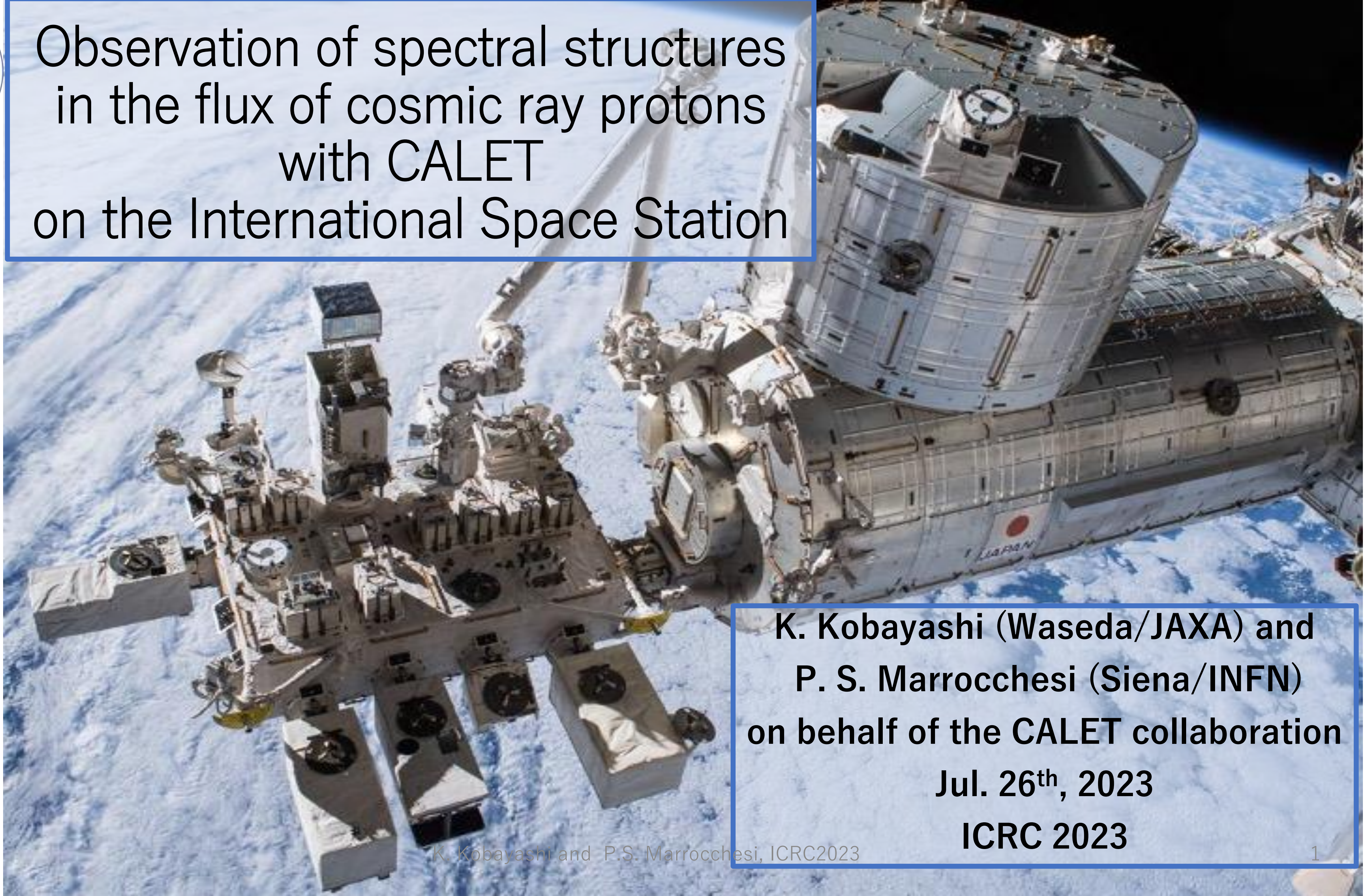
Observation of spectral structures in the flux of cosmic ray protons with CALET on the International Space Station



K. Kobayashi (Waseda/JAXA) and
P. S. Marrocchesi (Siena/INFN)
on behalf of the CALET collaboration

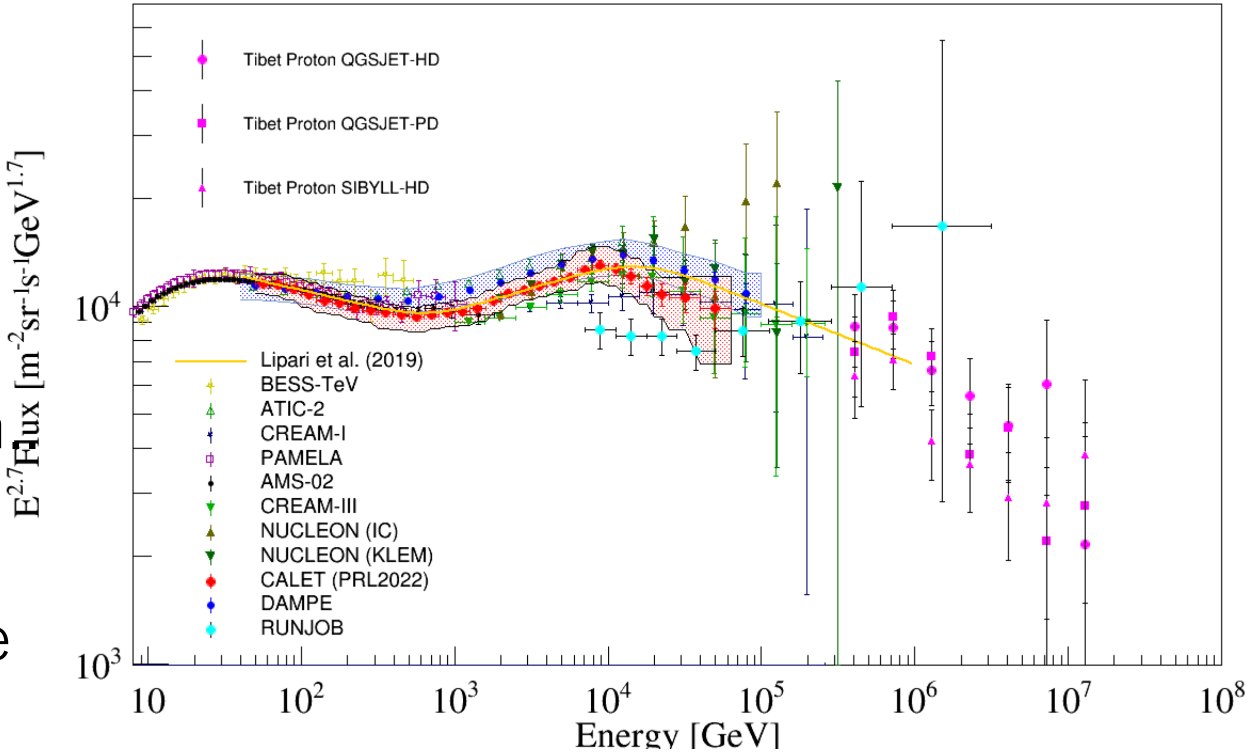
Jul. 26th, 2023

ICRC 2023

Motivation

- Recent observation of proton flux shows spectral hardening starting a few 100GeV and softening starting ~10TeV.
- Determination of these parameters could help to understand cosmic ray source, acceleration mechanism, and propagation.
- Direct flux measurement up to hundreds of TeV could provide normalization for the ground observation.

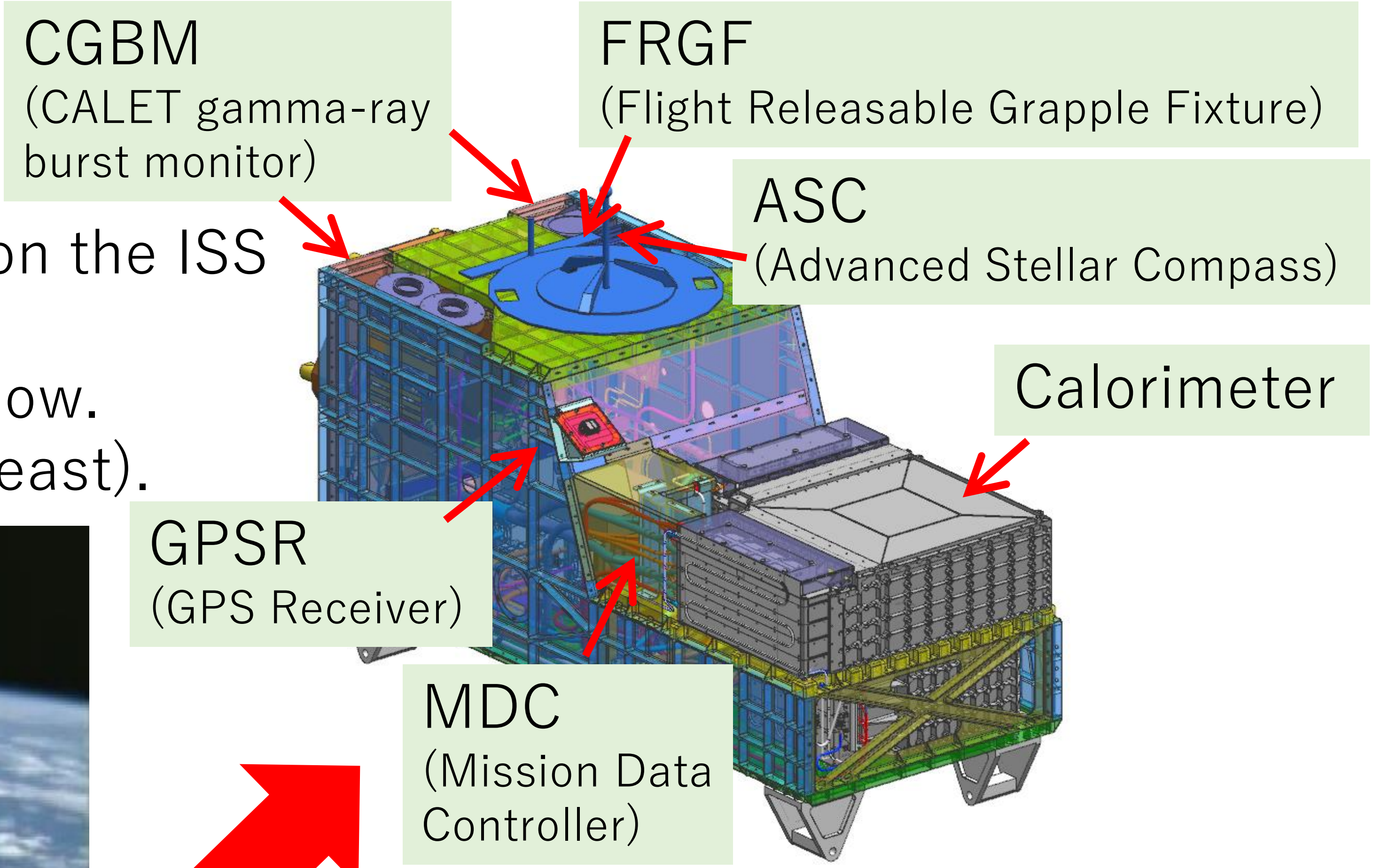
Proton flux in PRL2022 (red) compared to other direct and ground measurements



- CALET published a proton flux at 50GeV<E<60TeV in PRL2022 and confirmed hardening around 500 GeV and found softening around 10 TeV.
- We present updated result using data with increased statistics by 21% from PRL2022.

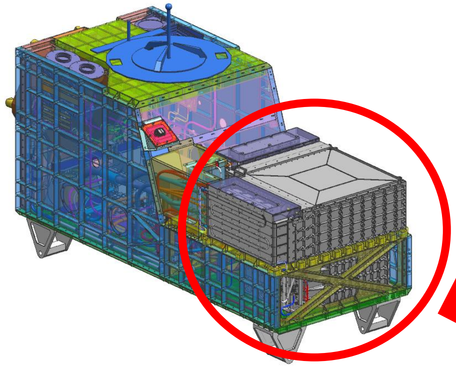
CALET project

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).

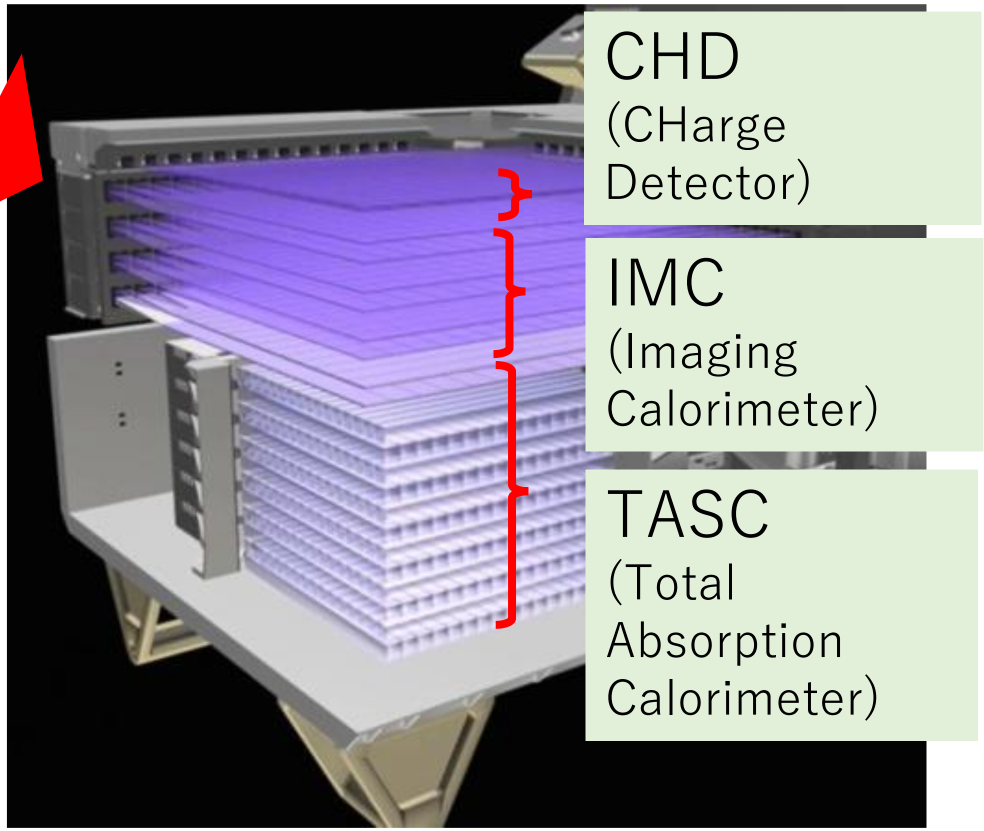


mass	612.8kg
power	507W (max)
telemetry	600kbps (6.5GB/day)

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



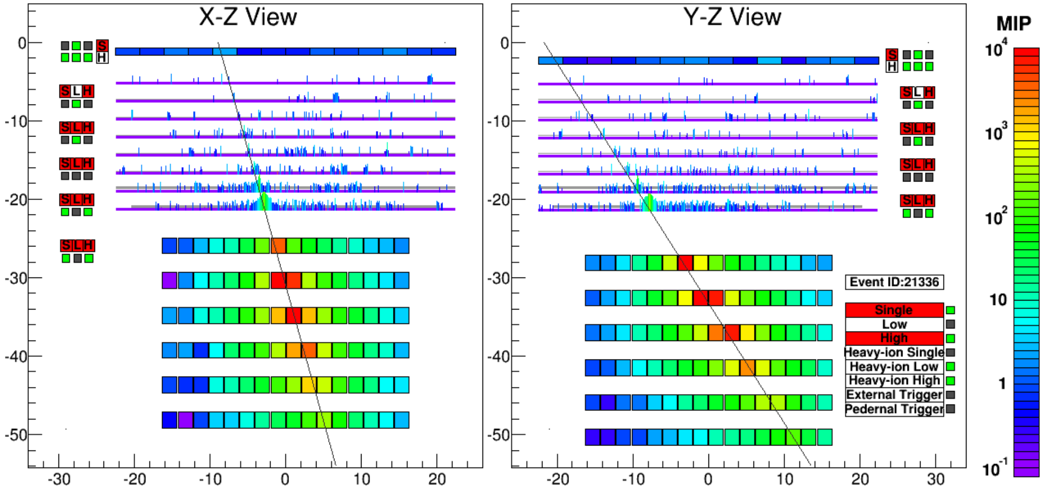
In total $30X_0$ thickness
(=1.2 λ ,
$27X_0$ in TASC + $3X_0$ in IMC)

Proton event selection

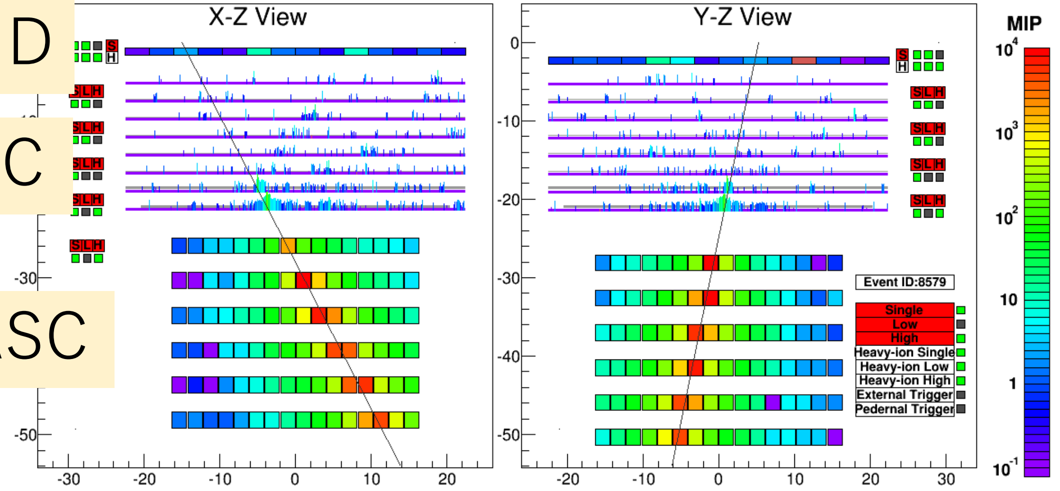
selection	Brief description
1. Event trigger	HE trigger in E>300GeV and LE trigger in E<300GeV.
2. Geometrical acceptance	Track going through the detector from the top to the bottom is selected.
3. Track quality cut	Reliability of Kalman Filter fitting in IMC is checked.
4. Electron rejection	Electron 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.

Event examples

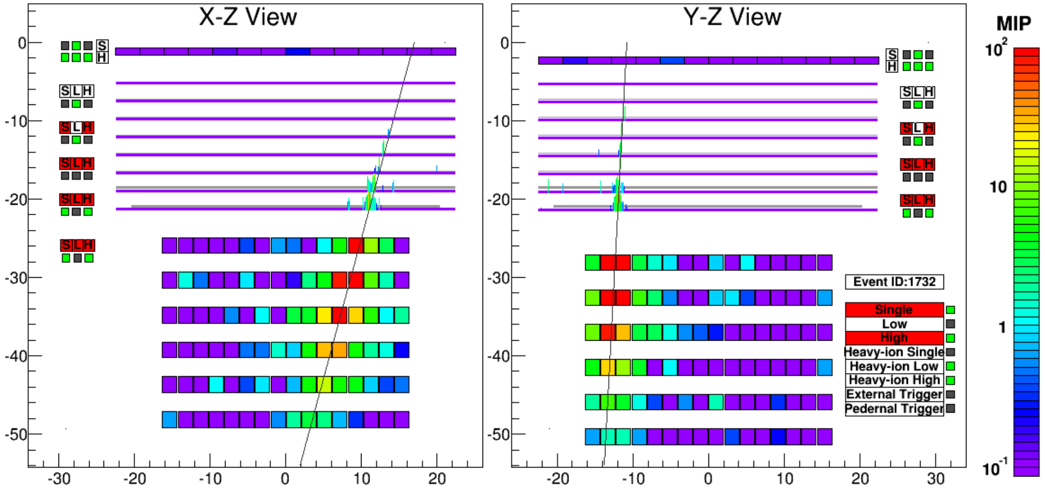
Electron, E=3.05 TeV



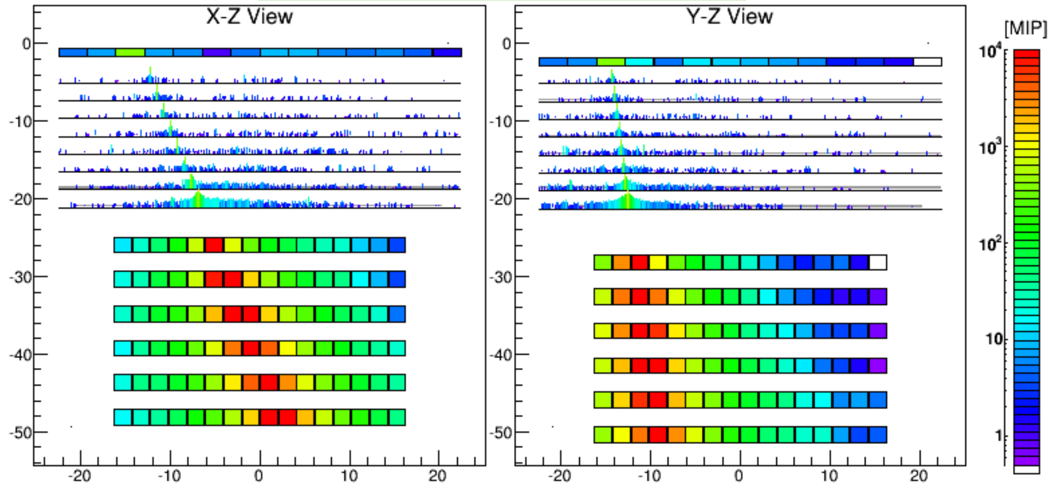
Proton, ΔE=2.89 TeV



Gamma-ray, E=44.3 GeV

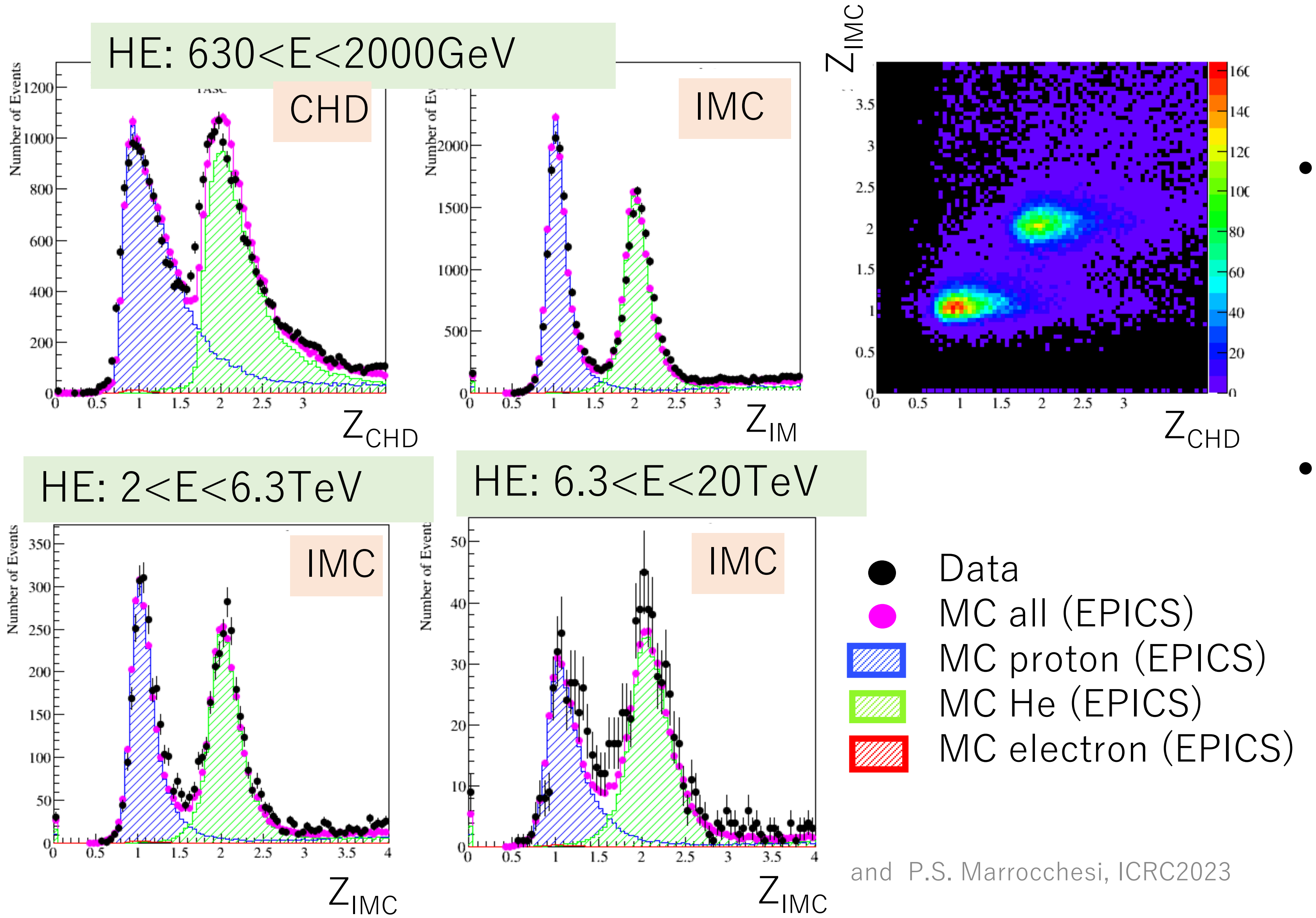


Fe, ΔE=9.3 TeV



and P.S. Marrocc

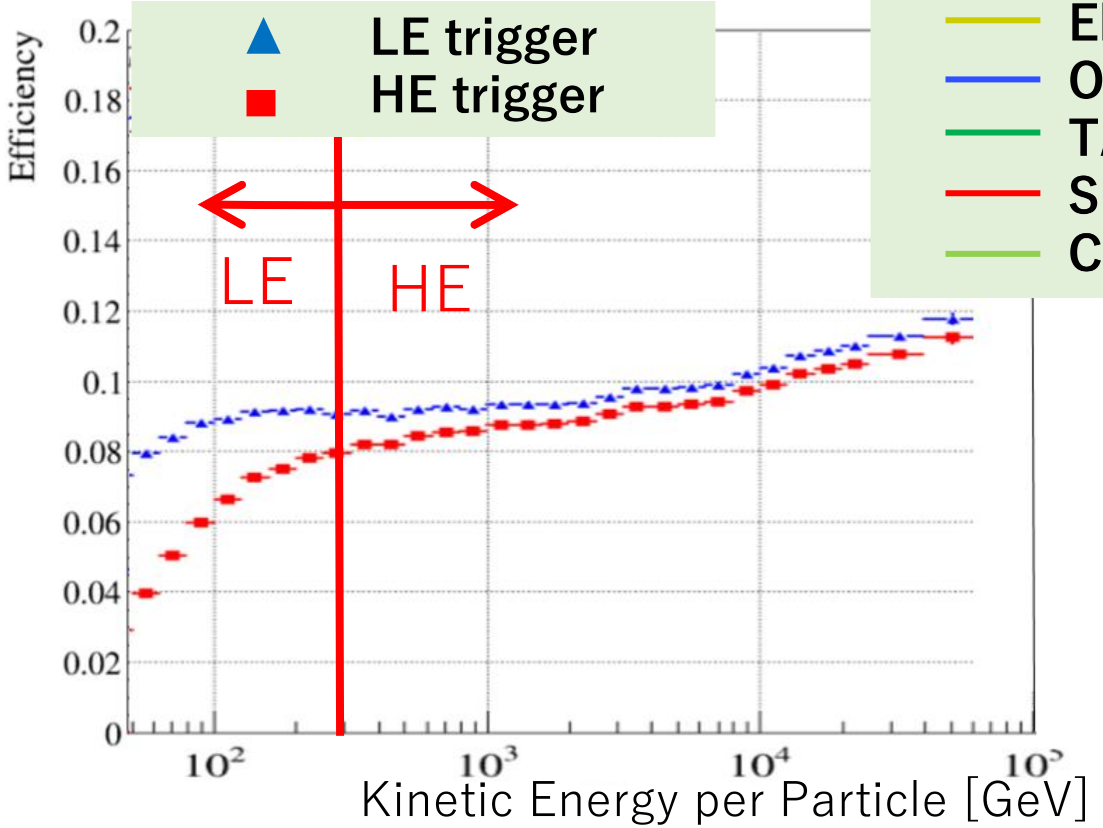
Charge identification in CHD and IMC

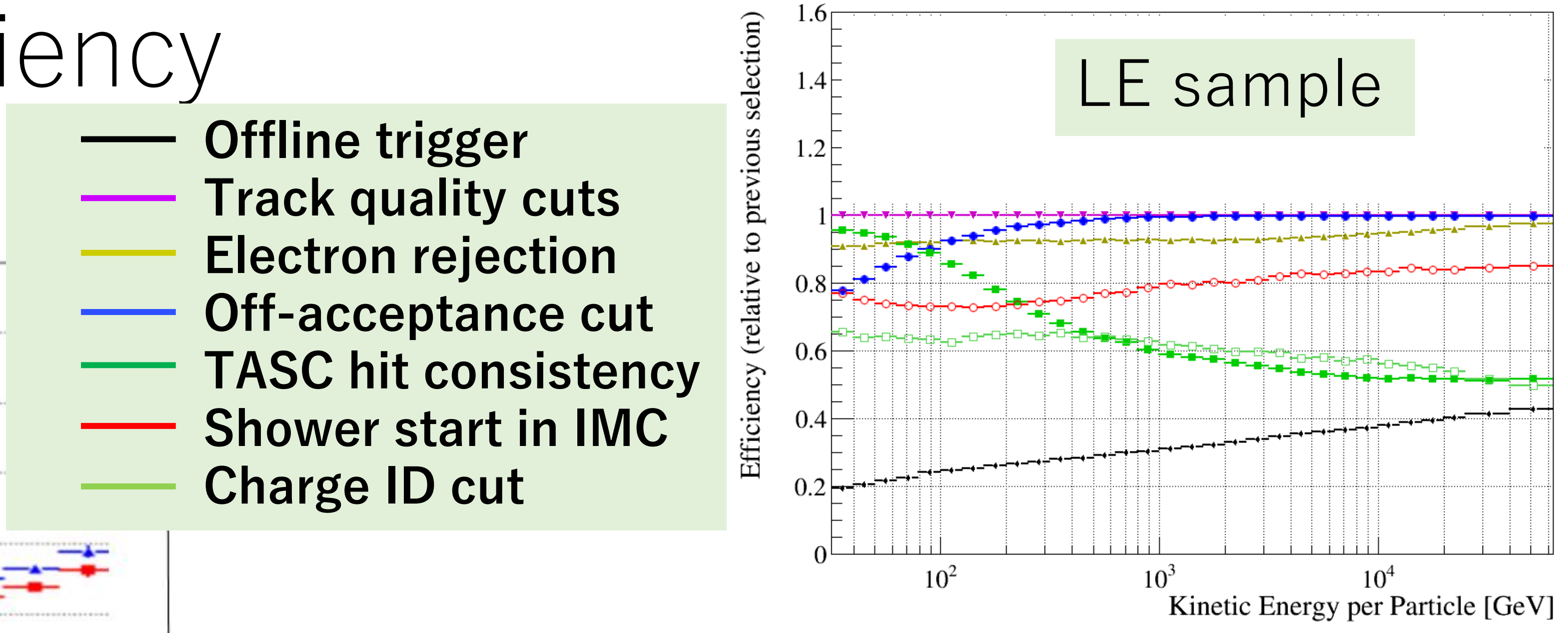


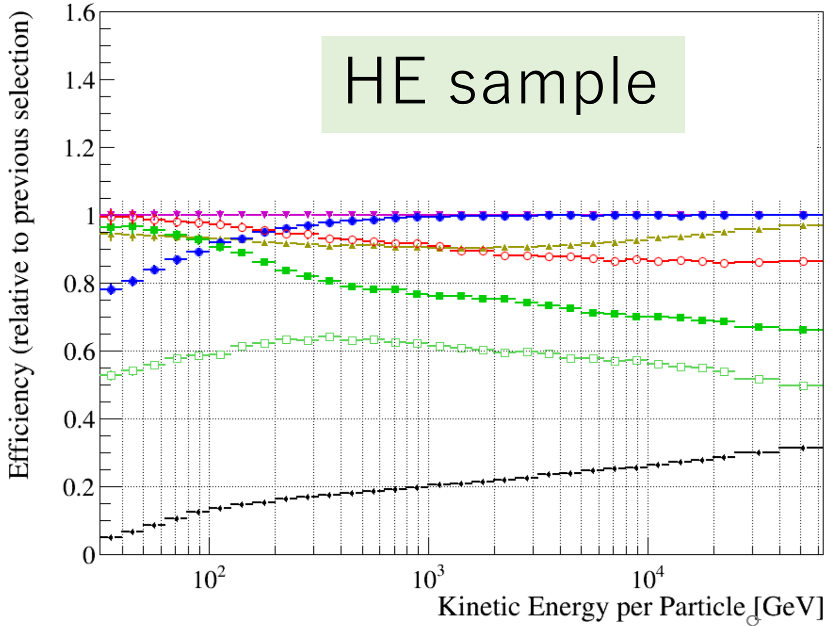
- Using the two charge identification parameters (Z_{CHD} and Z_{IMC}), proton and helium can be clearly separated.
- Total background contaminations are less than 13% in HE sample (630<E<2000GeV), respectively.
- Although charge identification using CHD doesn't work in higher energy region, identification using IMC works and p/He are clearly separated

and P.S. Marrocchesi, ICRC2023

Detection efficiency



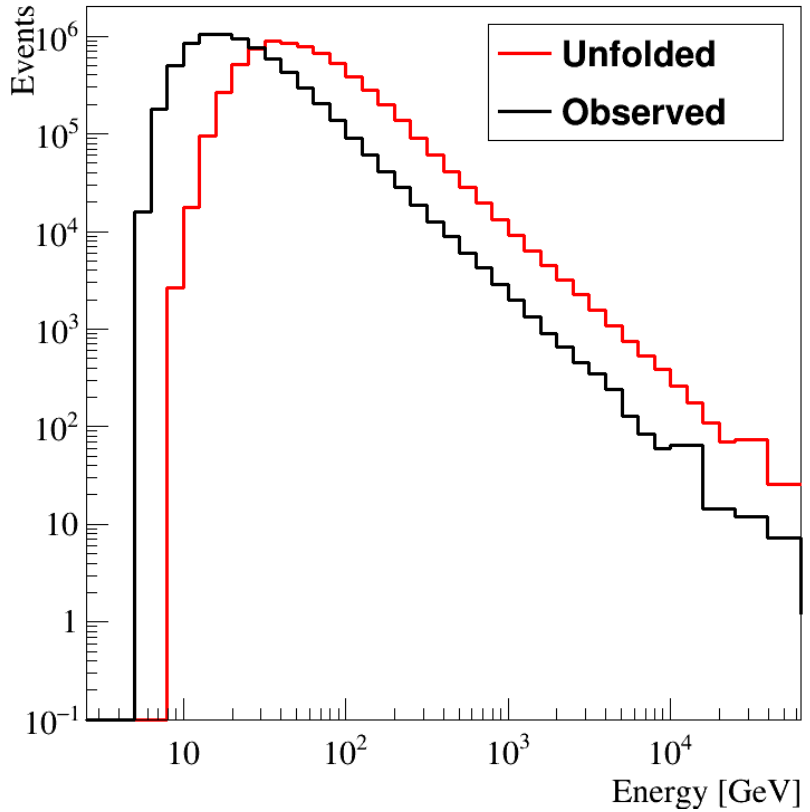




- In E>300GeV (E<300GeV), HE trigger (LE) is used. LE is used due to the high efficiency.
- Detection efficiency is 8-12% in 50GeV<E<60TeV.

Energy unfolding

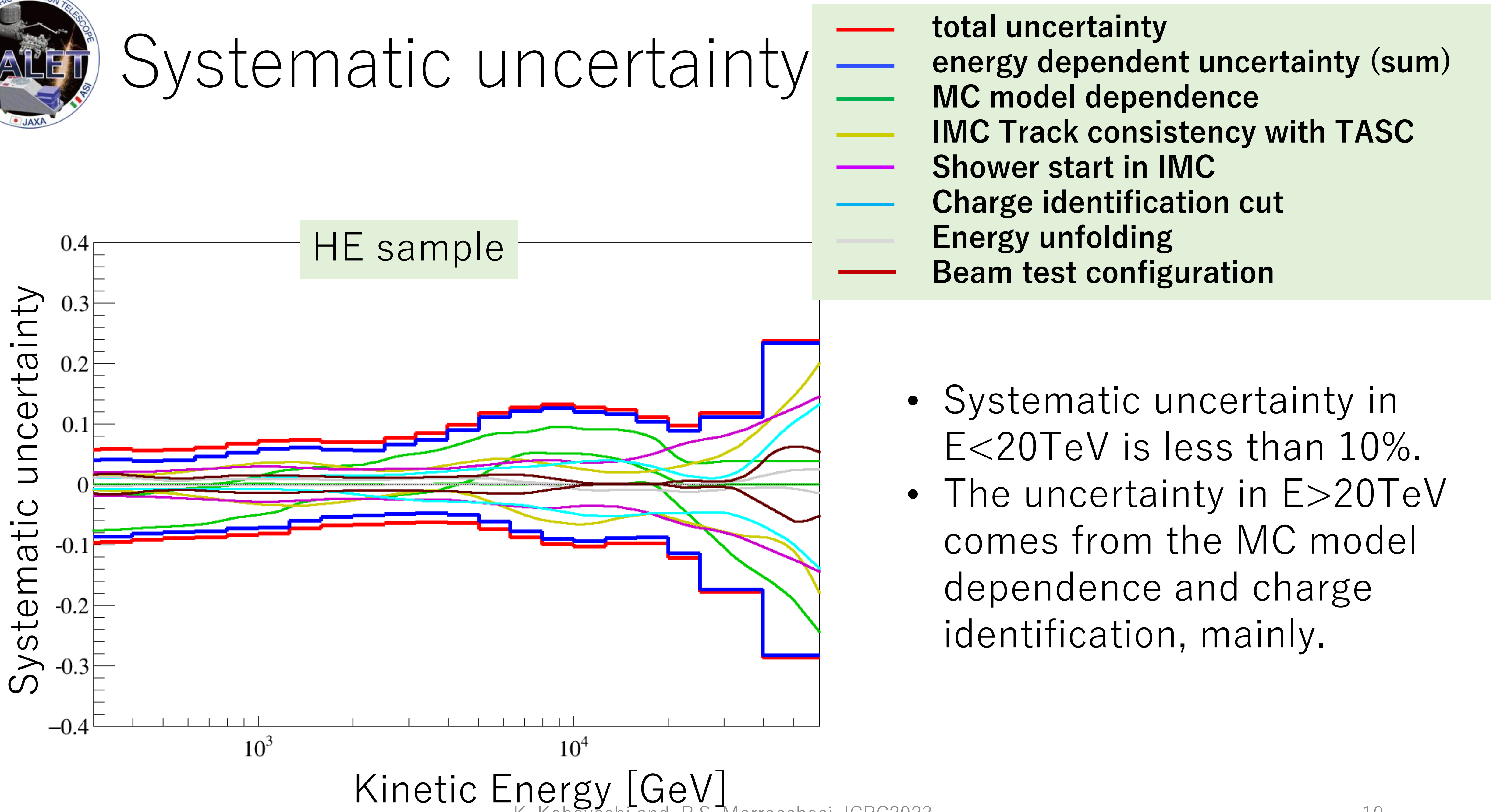
Observed/Unfolded energy spectrum



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.

Systematic uncertainty

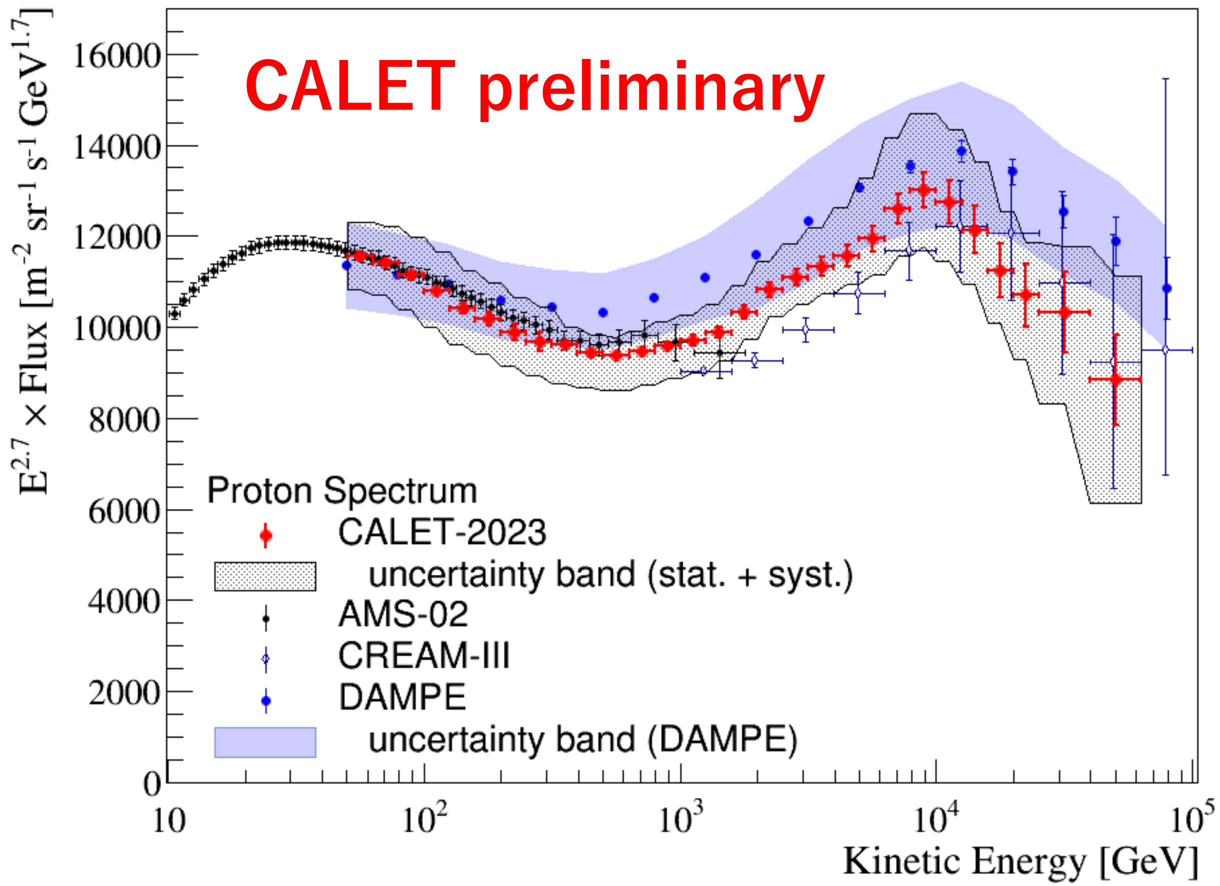


- Systematic uncertainty in E<20TeV is less than 10%.
- The uncertainty in E>20TeV comes from the MC model dependence and charge identification, mainly.

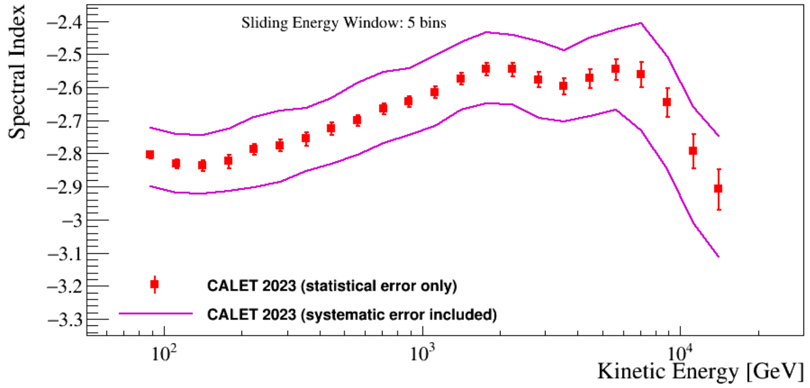
Proton spectrum (50GeV<E<60TeV)

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

$\Phi(E)$: proton flux
$N(E)$: number of events in ΔE bin (after background subtraction)
$S\Omega$: geometrical acceptance ($510\mathrm{cm}^2\mathrm{sr}$)
T: livetime
ΔE: energy bin width
$\varepsilon(E)$: detection efficiency

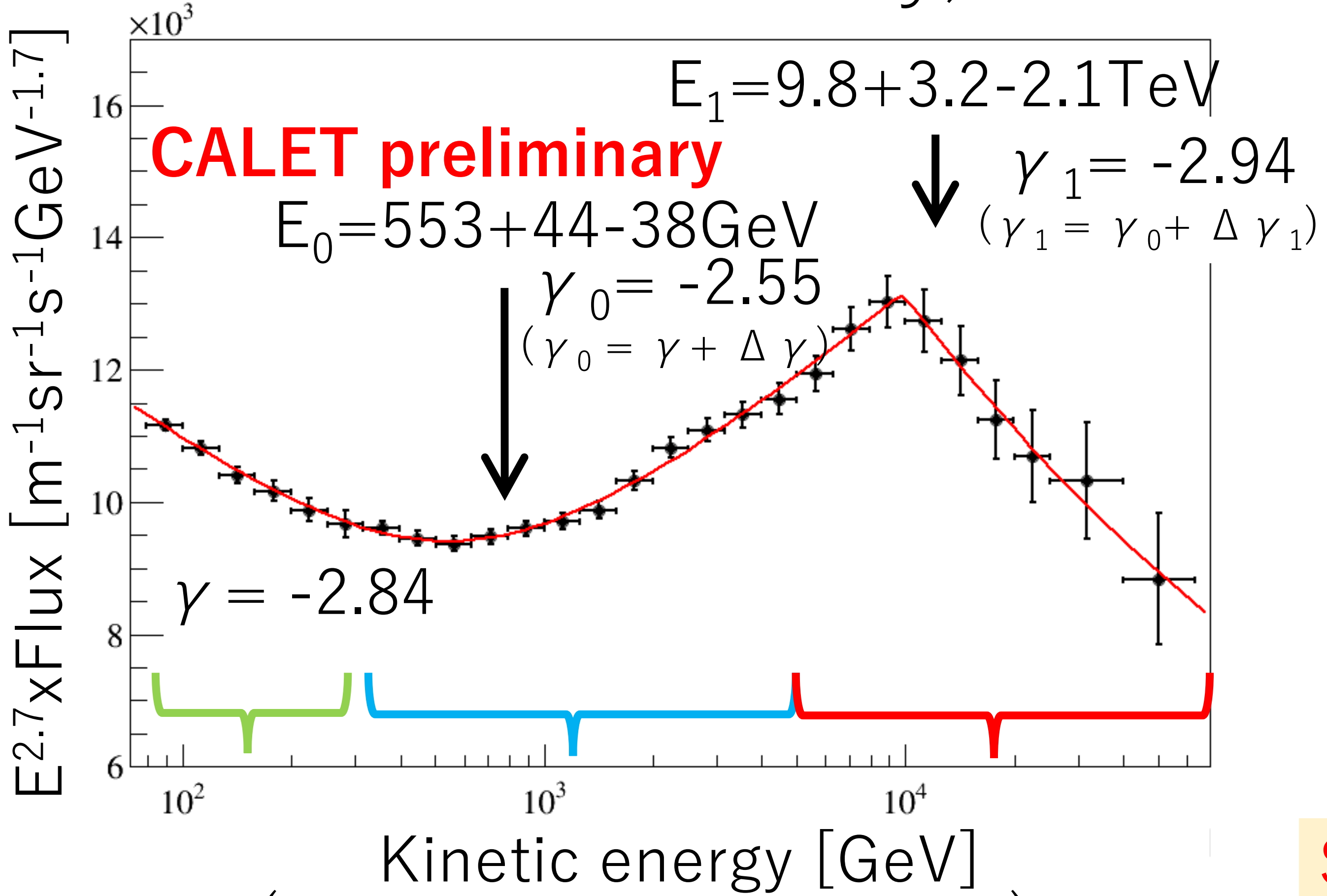


- Live time has increased by 21% from PRL2022.
- Sharp spectral softening starting at E~10TeV is getting clearer.



LE: same as PRL2019
HE: 1925 days of live time (Oct. 2015 – Apr. 2023)

Spectral fit with Double Broken Power Law (statistical error only)



$\chi^2 = 6.0/20$

γ	-2.843+0.005-0.005
s	2.1±0.4
$\Delta\gamma$	(2.9±0.1)x10^{-1}
E_0	(5.53+0.44-0.38)x10^2
$\Delta\gamma_1$	(-3.9+1.5-1.8)x10^{-1}
E_1	(9.8+3.2-2.1)x10^3
s_1	~90

Fitting function (double broken power law):

$$\Phi = E^{2.7} \times C \times \left(\frac{E}{1}\right)^{\gamma} \times \left(1 + \left(\frac{E}{E_0}\right)^{s}\right)^{\frac{\Delta\gamma}{s}} \times \left(1 + \left(\frac{E}{E_1}\right)^{s_1}\right)^{\frac{\Delta\gamma_1}{s_1}}$$

Low energy hardening softening

Softening is much sharper and the s_1 becomes higher with a large uncertainty.

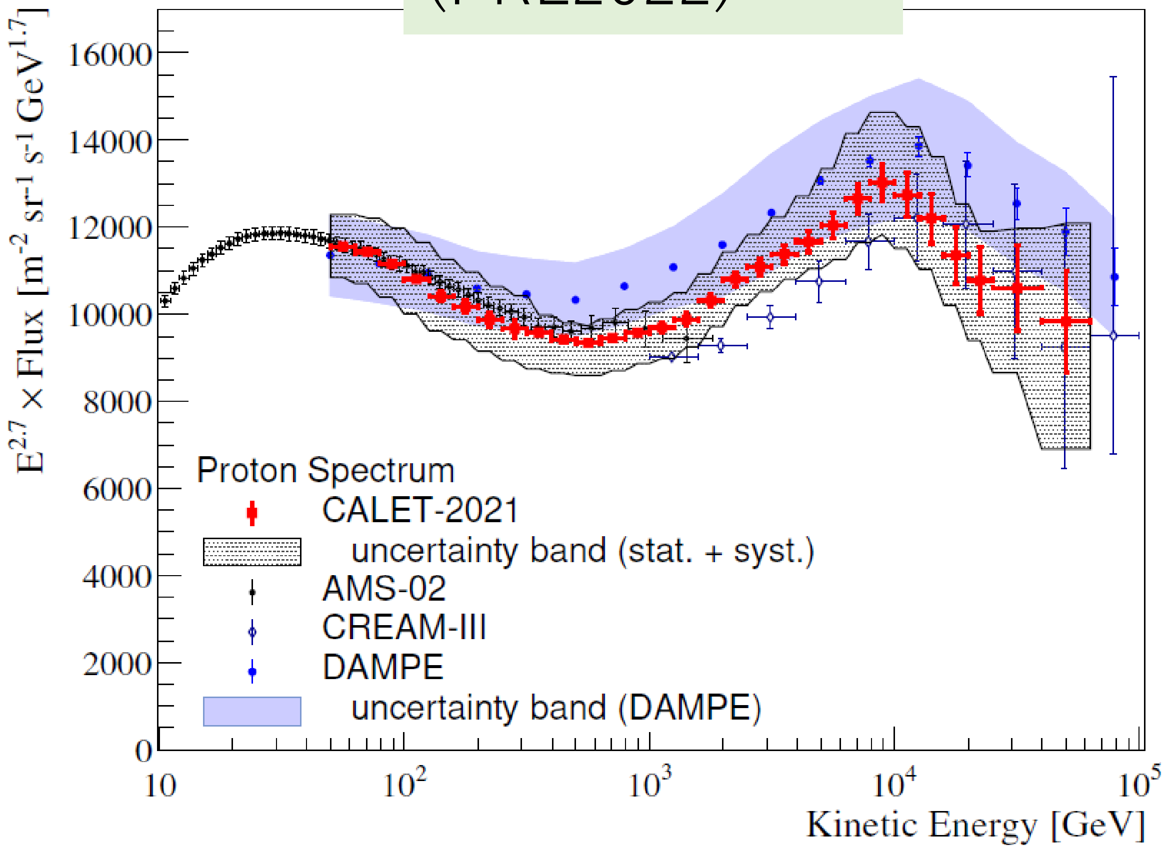
Summary

- CALET data taking is stably running without any serious problem more than 7.5 years.
- Last year our proton result have been published in PRL 129, 101102 (2022) and we have updated the analysis using data until Apr. 2023.
- We observed a sharp proton spectrum softening starting at 9.8+3.2-2.1TeV. The spectral index changes from -2.6 to -2.9.

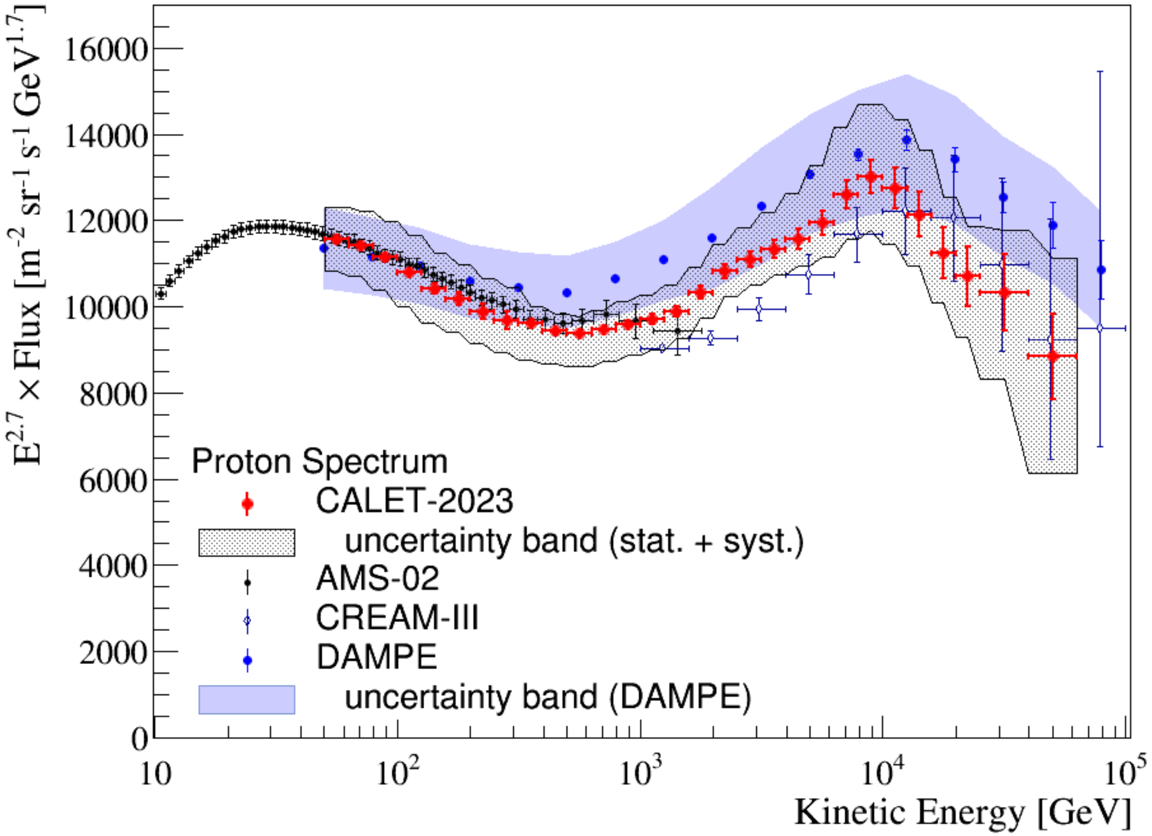
backup

Proton spectrum comparison

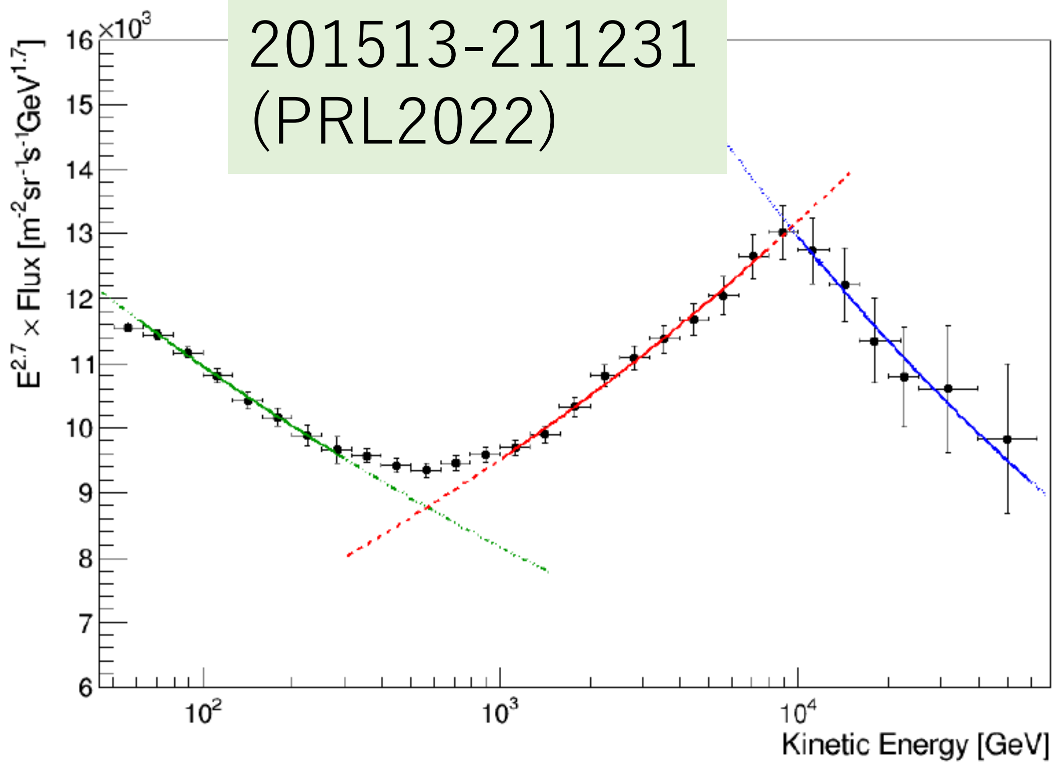
201513-211231
(PRL2022)

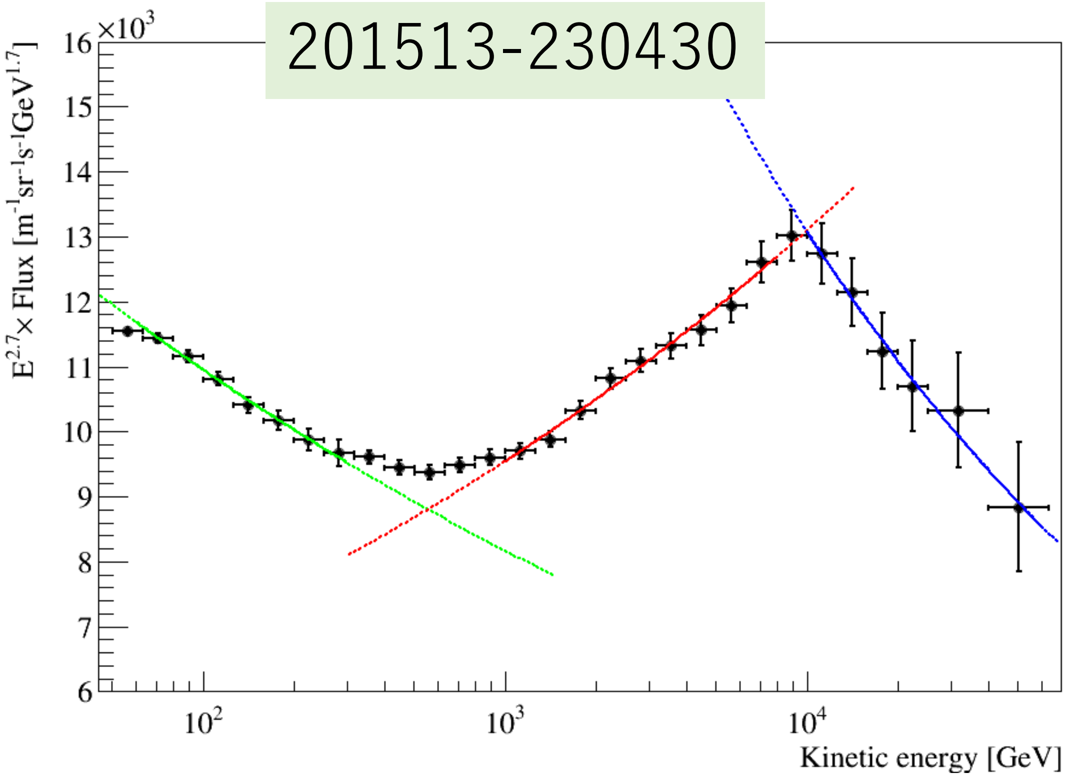


201513-230430



Single power law fit comparison





	gamma
60-300 GeV	-2.83±0.02
1-8 TeV	-2.56±0.01
10-60 TeV	-2.89±0.07

	gamma
60-300 GeV	-2.83±0.02
1-8 TeV	-2.56±0.01
10-60 TeV	-2.94±0.07