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CALETによる陽子のエネルギースペクトルの観測の最新結果

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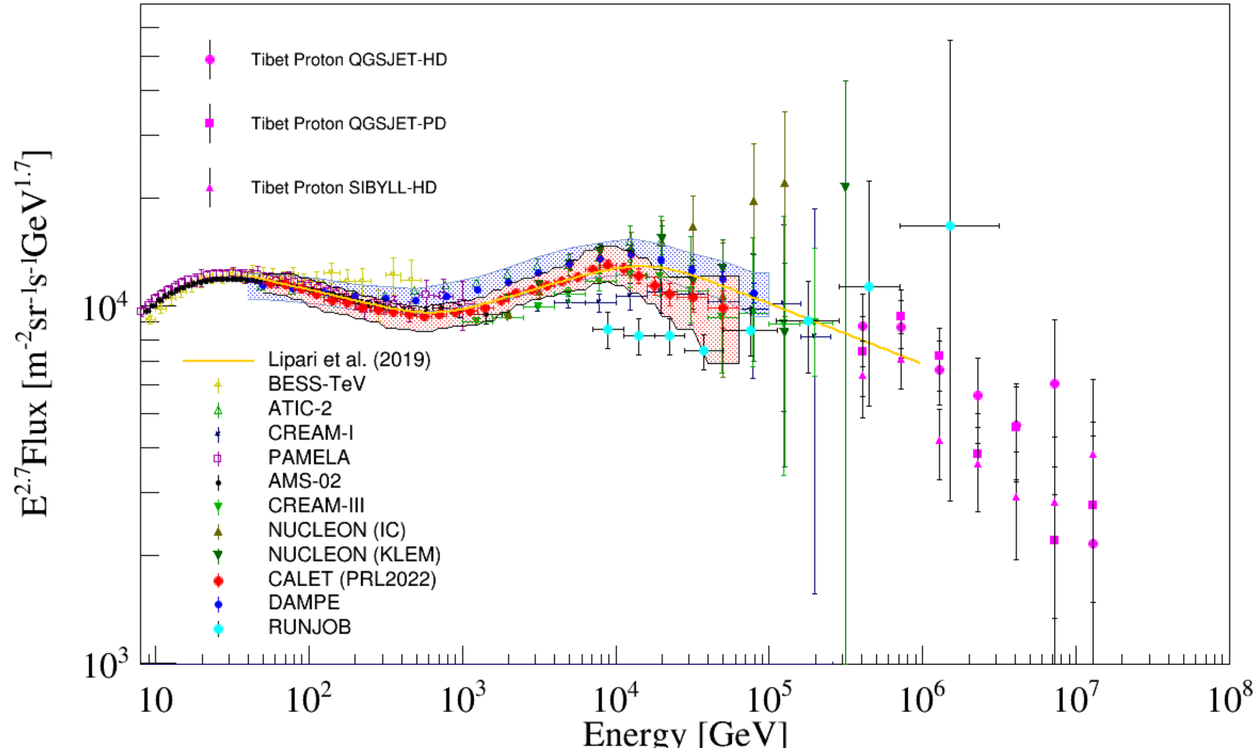
Motivation

- 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



- Due to the computer (HDD) trouble, we cannot present the latest result. I will present the situation of CALET proton flux measurement and the strategy of the analysis improvement and expected future result.

Overview of CALET Payload

CAL

- Charge Detector (CHD)
- Imaging Calorimeter (IMC)
- Total Absorption Calorimeter (TASC)

CGBM

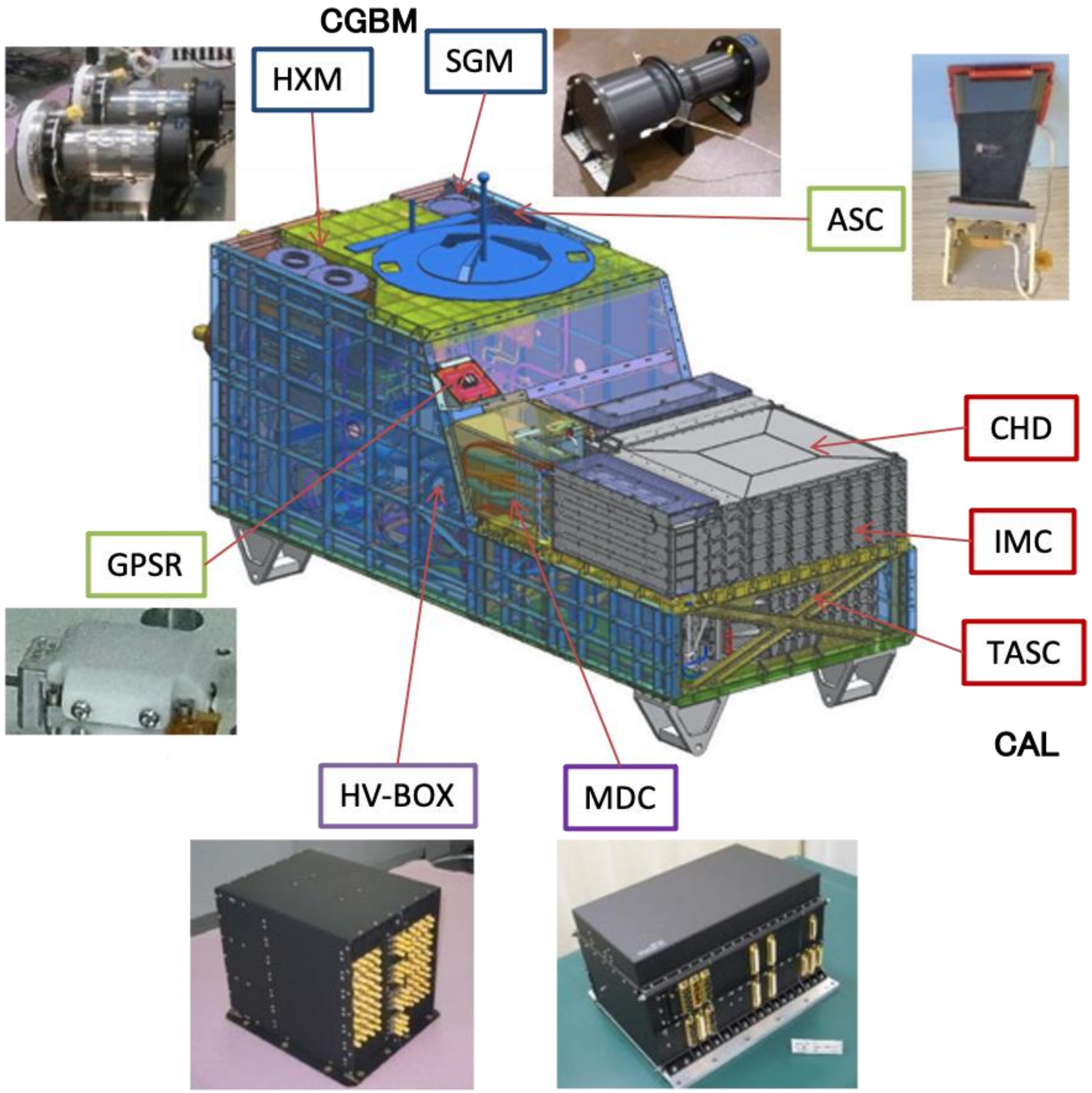
- Hard X-ray Monitor (HXM) x 2
  $LaBr_3$: 7keV～1MeV
- Soft γ-ray Monitor (SGM)
  BGO : 100keV～20MeV

Data Processing & Power Supply

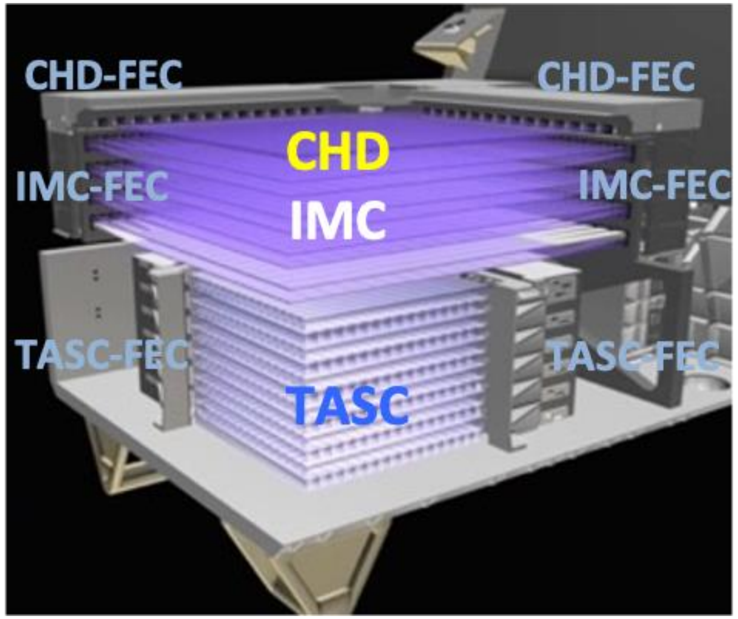
- Mission Data Controller (MDC)
  CPU, telemetry, power, trigger etc.
- HV-BOX (Italian contribution)
  HV supply (PMT:68ch, APD:22ch)

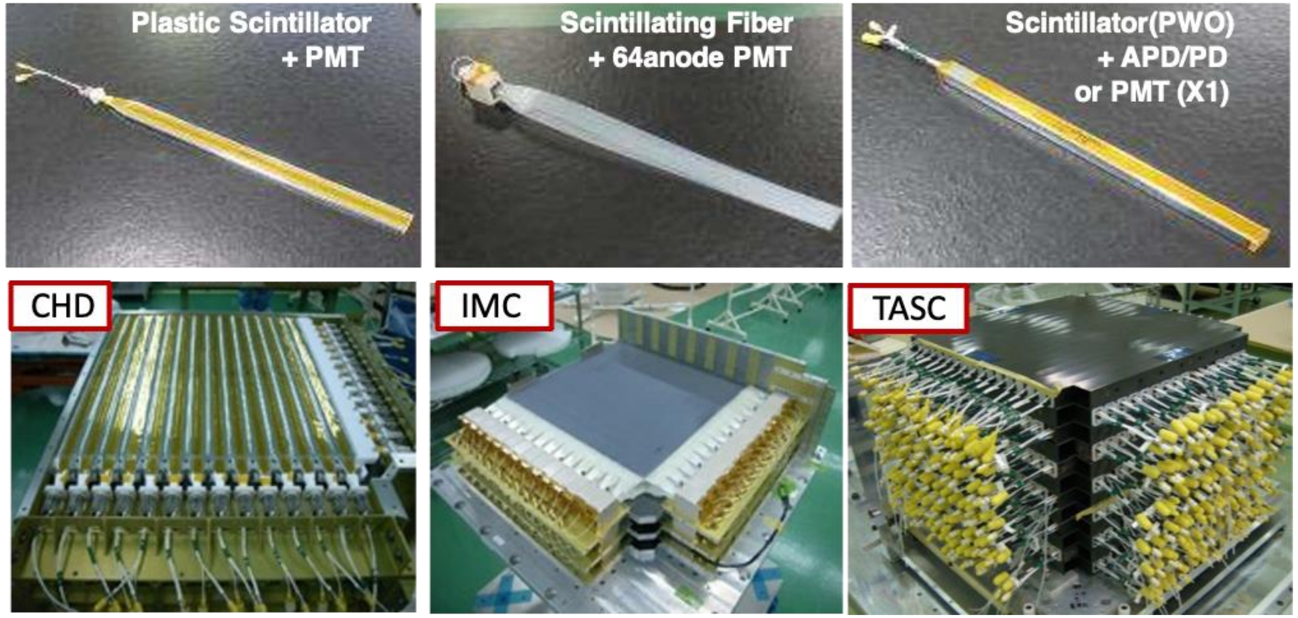
Support Sensors

- Advanced Stellar Compass (ASC)
  Directional measurement
- GPS Receiver (GPSR)
  Time stamp of triggered event (<1ms)



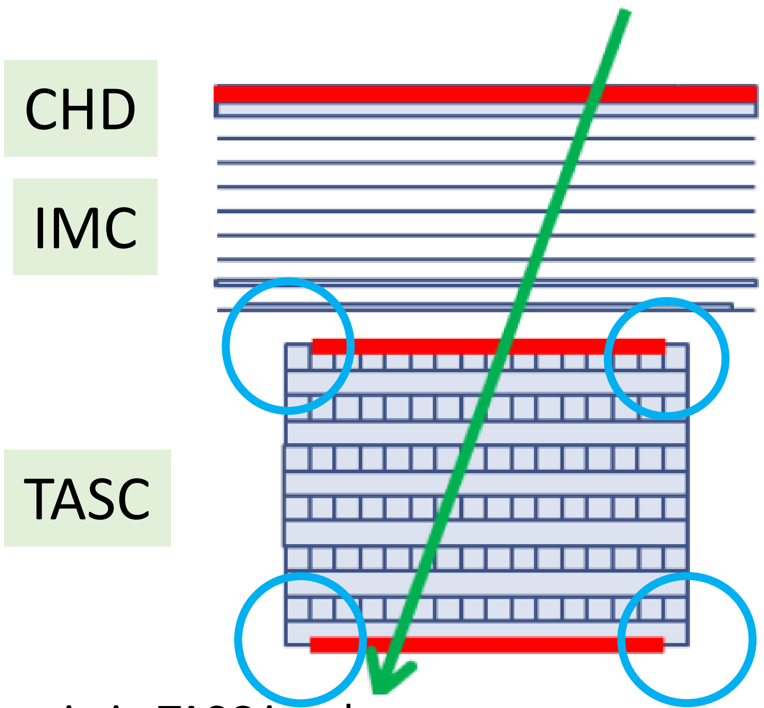
CALET Detector: Calorimeter



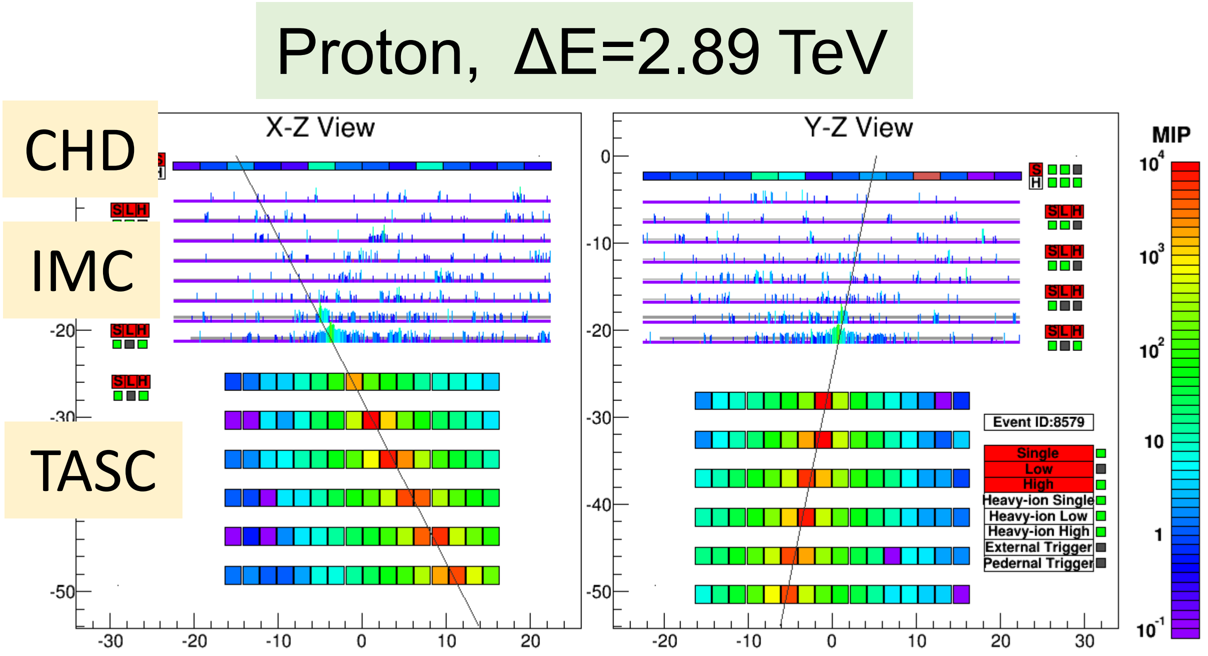


	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers (3X$_0$): 0.2X$_0$ x 5 + 1X$_0$ x2 Scifi size : 1 x 1 x 448 mm^3**	**16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm^3 Total Thickness : 27 X$_0$, ~1.2 λ_I**
Readout	**PMT+CSA**	**64-anode PMT + ASIC (VA32-HDR)**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**

Geometrical acceptance and event example



2cm margin in TASC is taken.

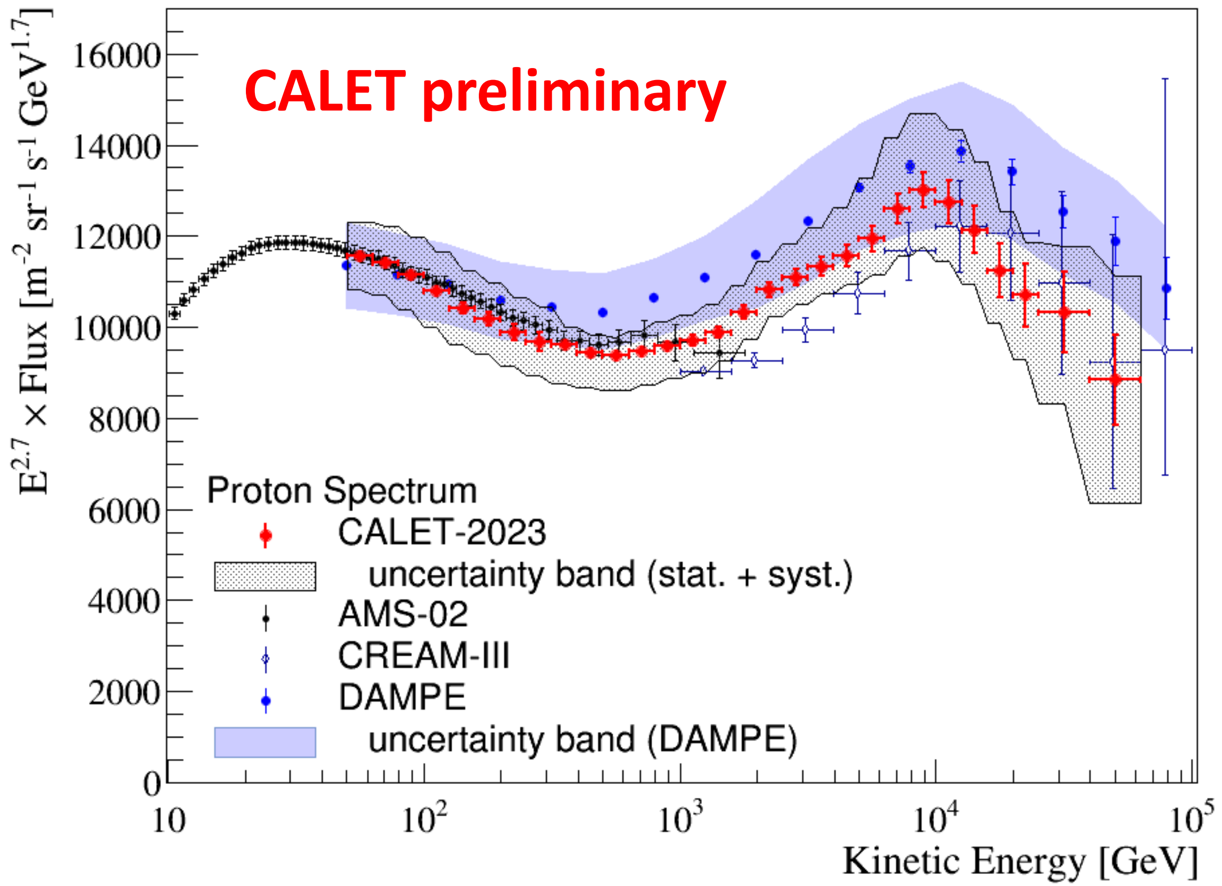


- The reconstructed track is required to cross the CHD and TASC from top to bottom.

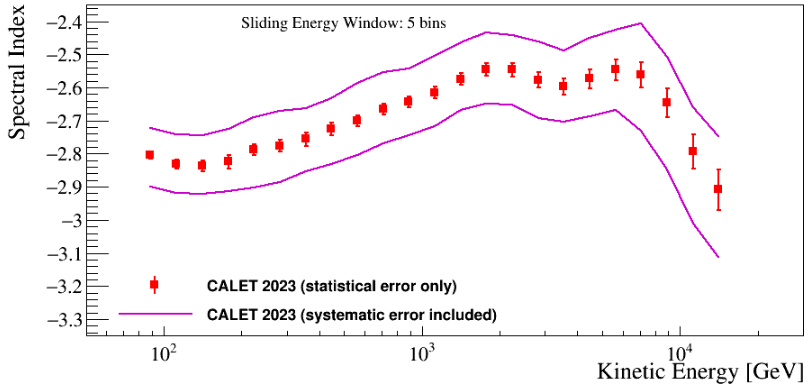
Proton spectrum (50GeV<E<60TeV)

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

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

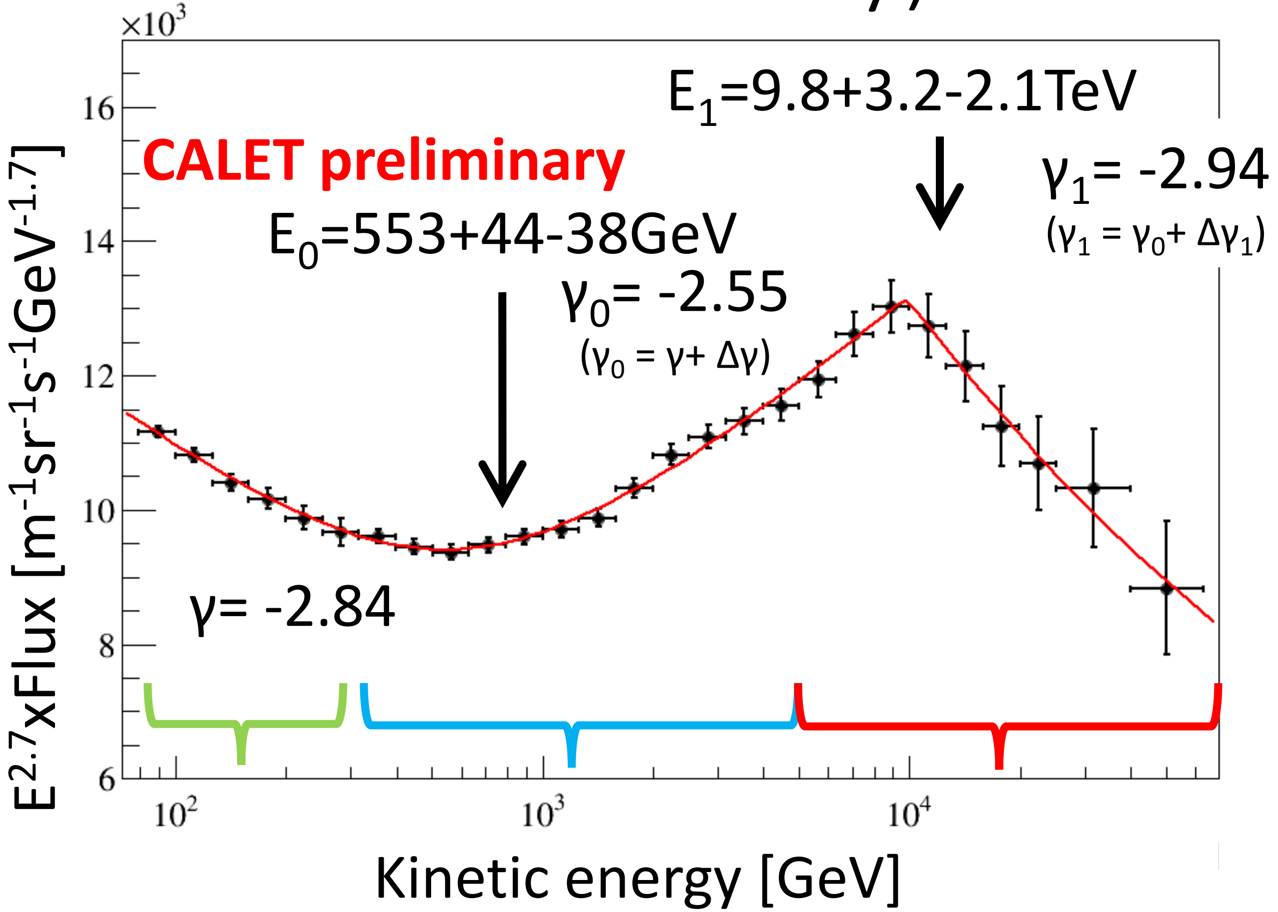


- Live time has increased by 21% from PRL2022.
- Sharp spectral softening starting at E~10TeV is getting clearer.



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

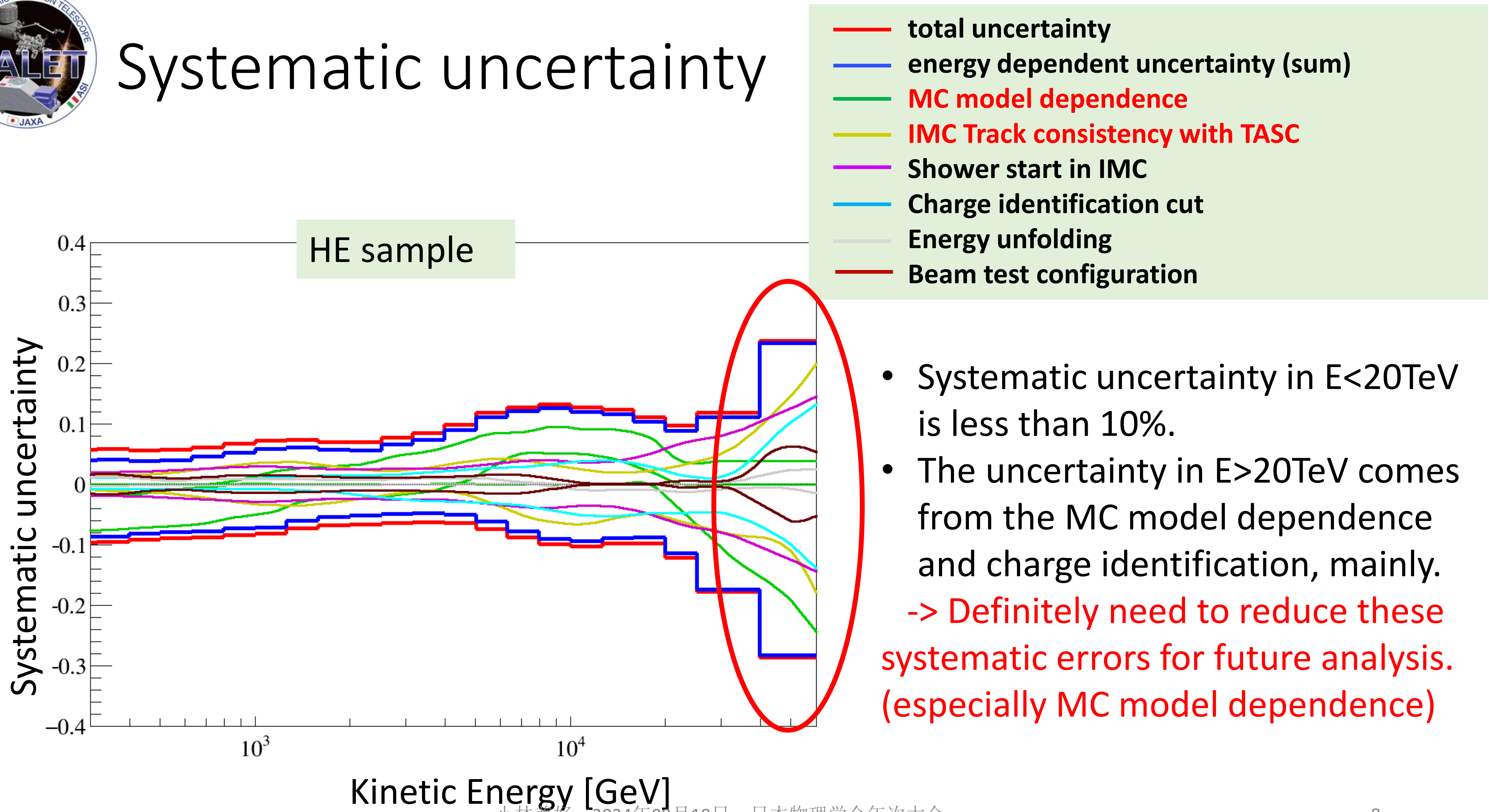
Softening is much sharper and the s_1 becomes higher with a large uncertainty.

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

Systematic uncertainty

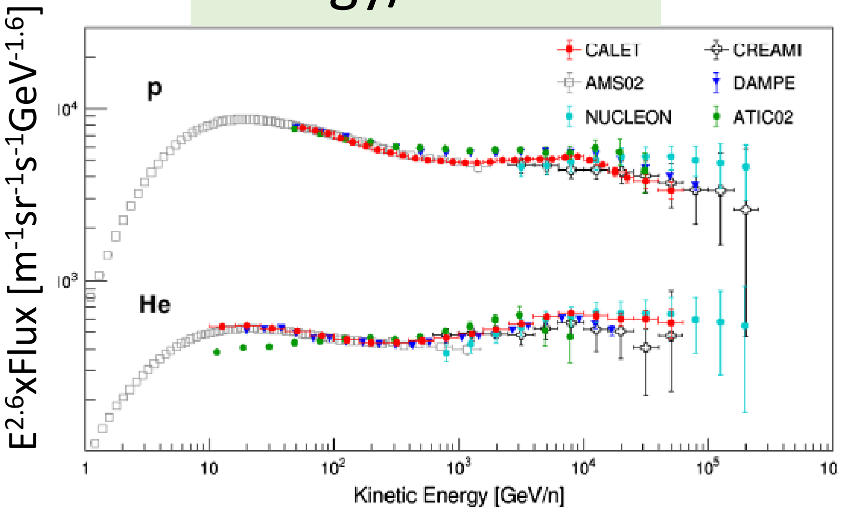


- Systematic uncertainty in E<20TeV is less than 10%.
- The uncertainty in E>20TeV comes from the MC model dependence and charge identification, mainly.

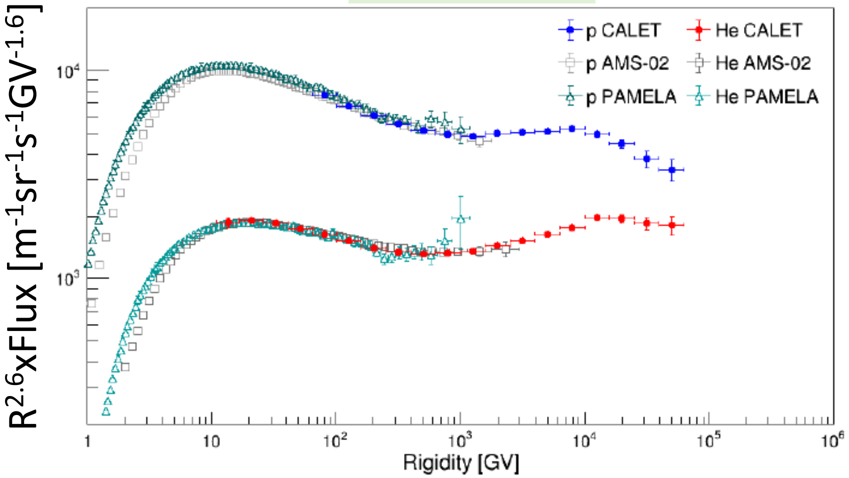
-> Definitely need to reduce these systematic errors for future analysis. (especially MC model dependence)

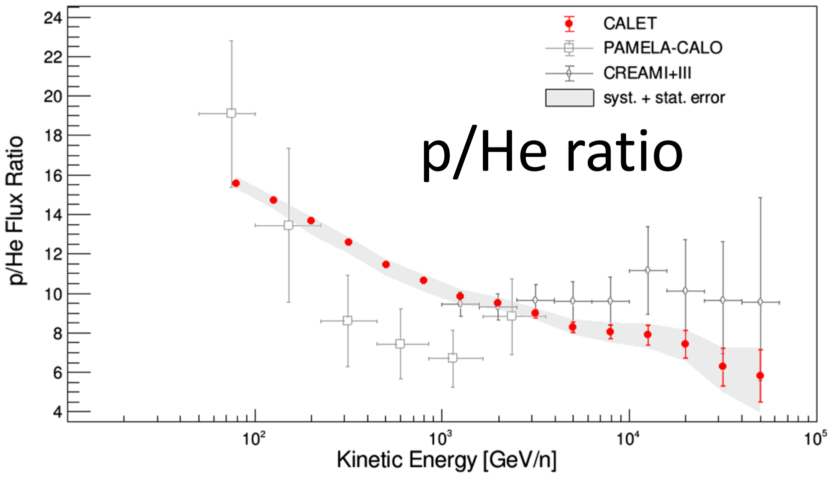
Proton/He ratio

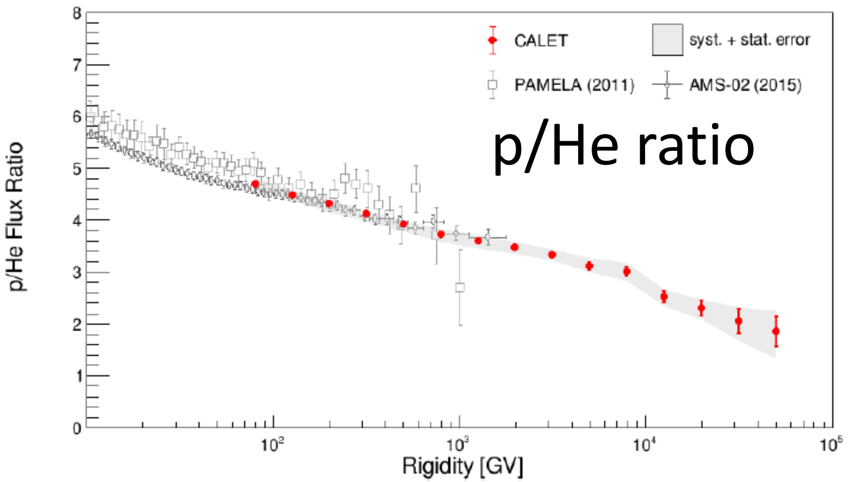
Energy/nucleon



rigidity



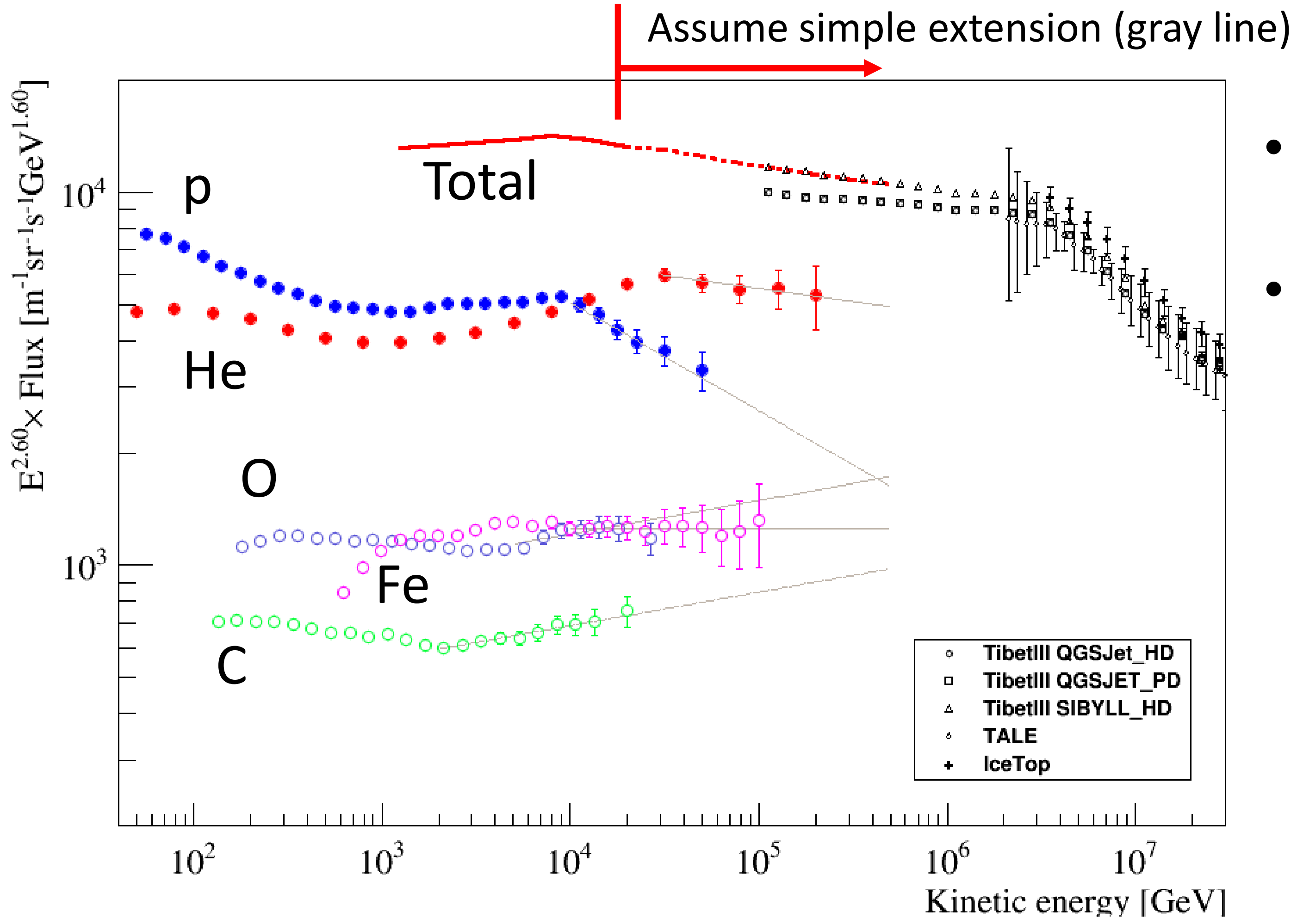




- Spectral hardening in rigidity are consistent between proton and helium.
- p/He ratio in 60GV/n<E<60TV/n is consistent to previous measurements.

	hardening (GeV)	softening (TeV)
Proton	584^{+61}_{-58}	$9.3^{+1.4}_{-1.1}$
Helium (E/Z)	$660^{+56}_{-46}{}^{+134}_{-62}$	$16.6^{+4.9}_{-3.1}{}^{+0.9}_{-1.3}$
Helium (E/n)	$330^{+28}_{-23}{}^{+67}_{-31}$	$8.3^{+2.3}_{-3.8}{}^{+0.5}_{-0.6}$

Total energy spectrum



- Helium is the dominant component at E>20TeV.
- We can directly compare to the Tibet ground observation if we extend the proton measurement.

What is expected in proton spectrum at 60-600TeV?

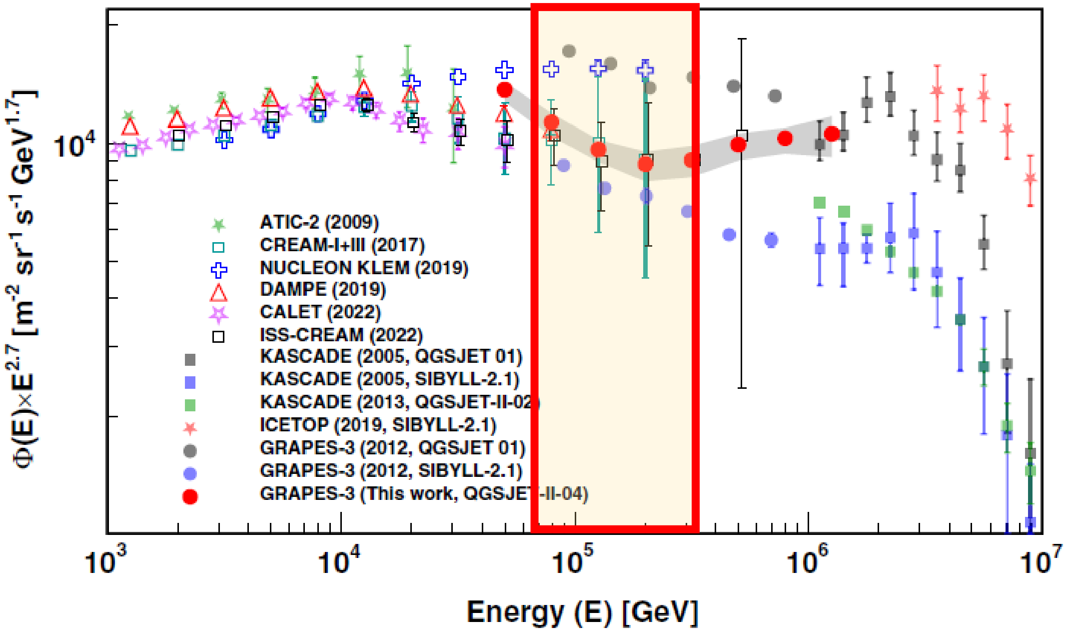
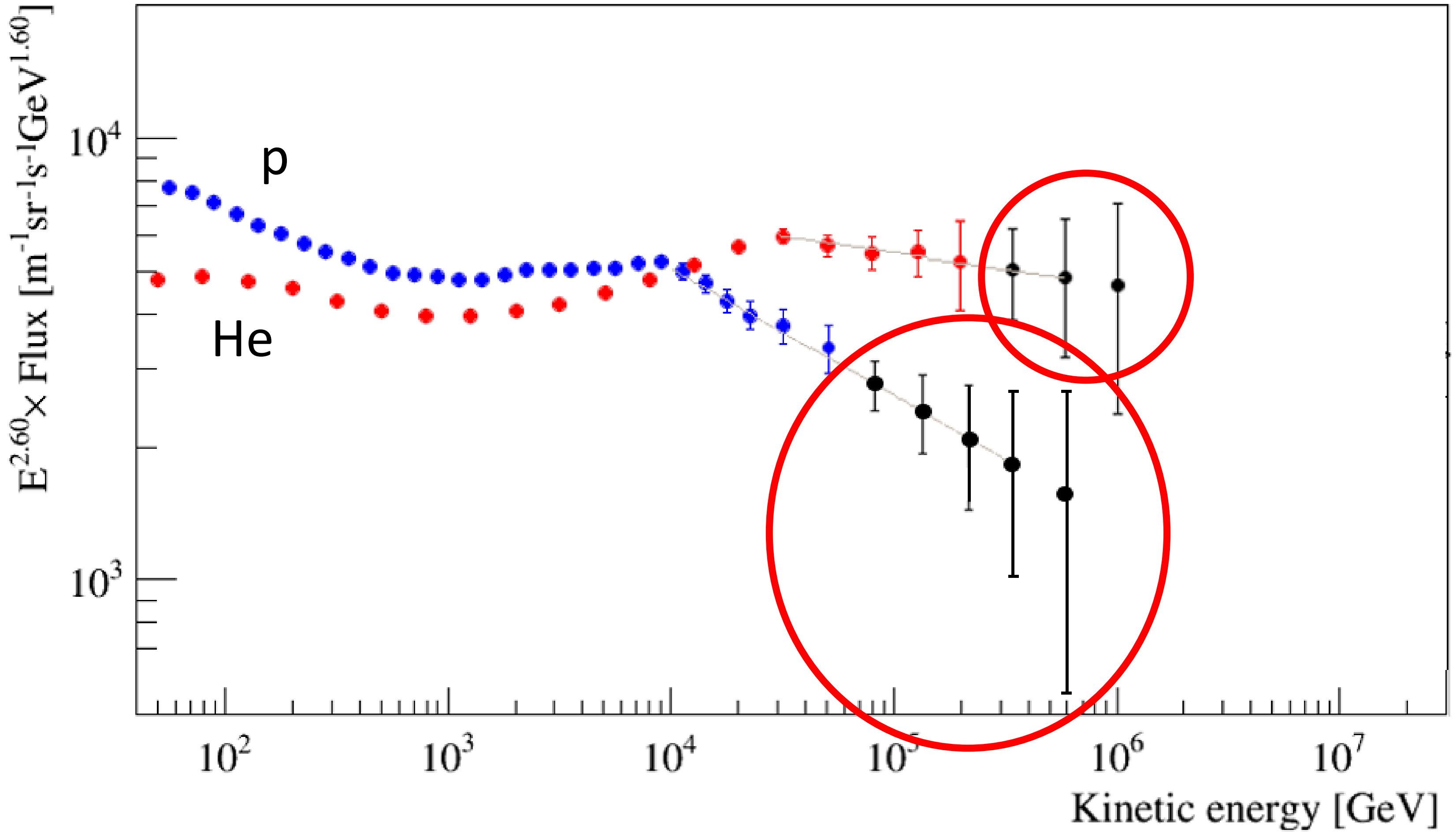


FIG. 4. Cosmic ray proton energy spectrum measured with the GRAPES-3 data (red circles) compared with results from direct and indirect observations (see text for references). The statistical error bars are smaller than the marker size and the gray band represents systematic uncertainty.

GRAPE3, PRL132, 051002 (2024)

GRAPE3 recently reported the proton spectral hardening at 166TeV. We may test the hardening.

Future prospect (-2030)



- Gray lines show the simple extension in high energy region.
- Black points (p/He) are the expected points in 2030 (only statistical error) using the gray line.

Summary

- CALET data taking is stably running without any serious problem more than 8 years.
- Due to the computer trouble, we haven’t update the proton analysis.
- More understanding of the simulation model, we could improve the systematic uncertainty and expand the energy region up to ~600TeV, where GRAPE3 indicates another hardening.

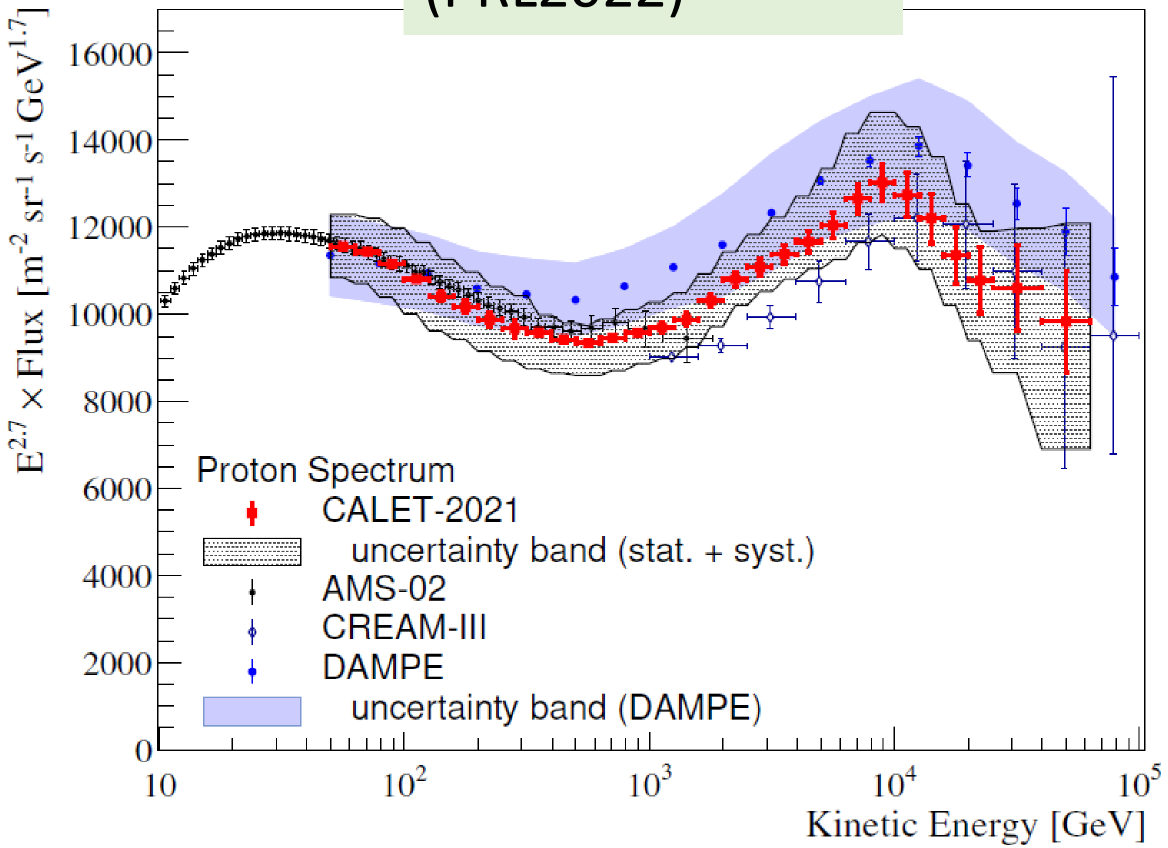
backup

Proton event selection

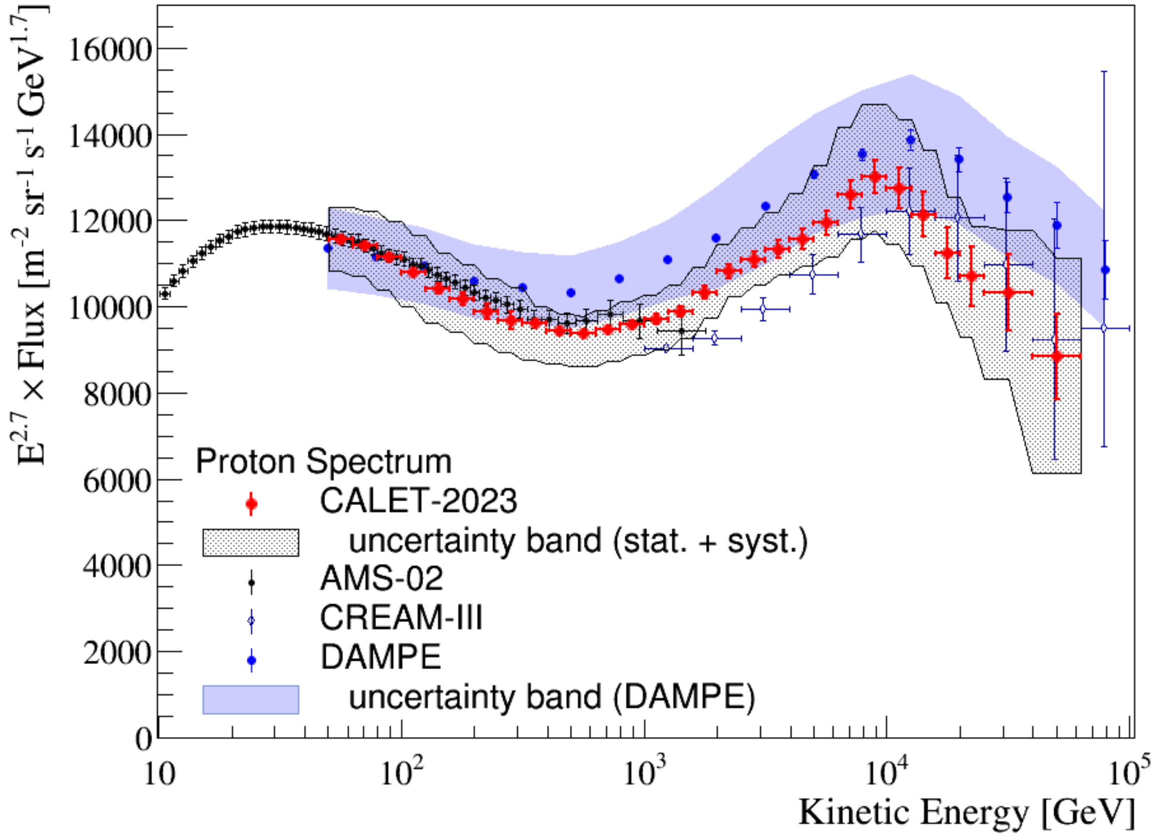
selection	Brief description
1. Event trigger	HE trigger in E>300GeV and LE trigger in E<300GeV.
2. Geometrical acceptance	Track going through the detector from the top to the bottom is selected.
3. Track quality cut	Reliability of Kalman Filter fitting in IMC is checked.
4. Electron rejection	Electron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

Proton spectrum comparison

201513-211231
(PRL2022)

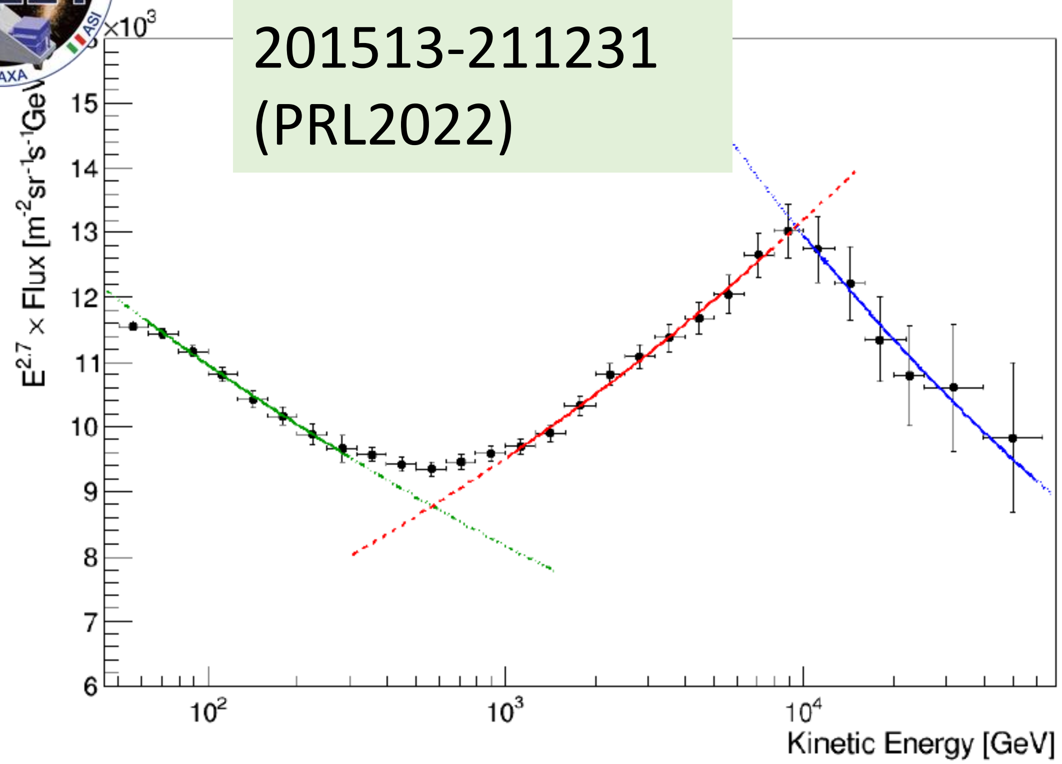


201513-230430



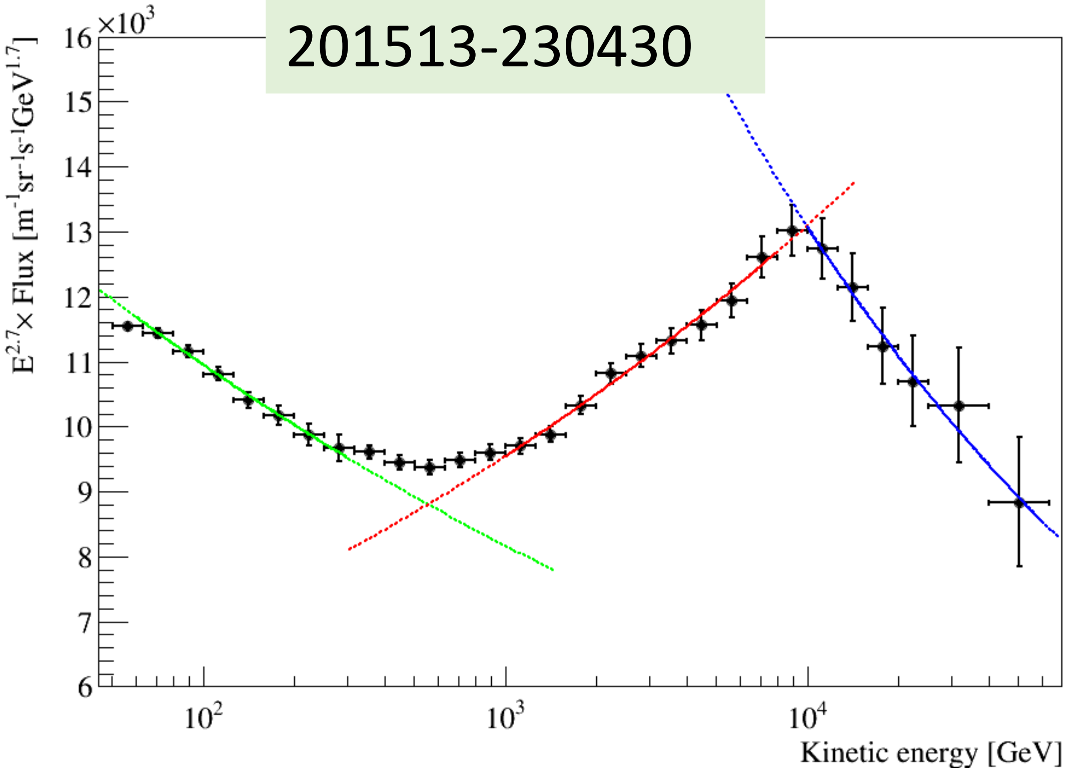
Single power law fit comparison

201513-211231
(PRL2022)



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

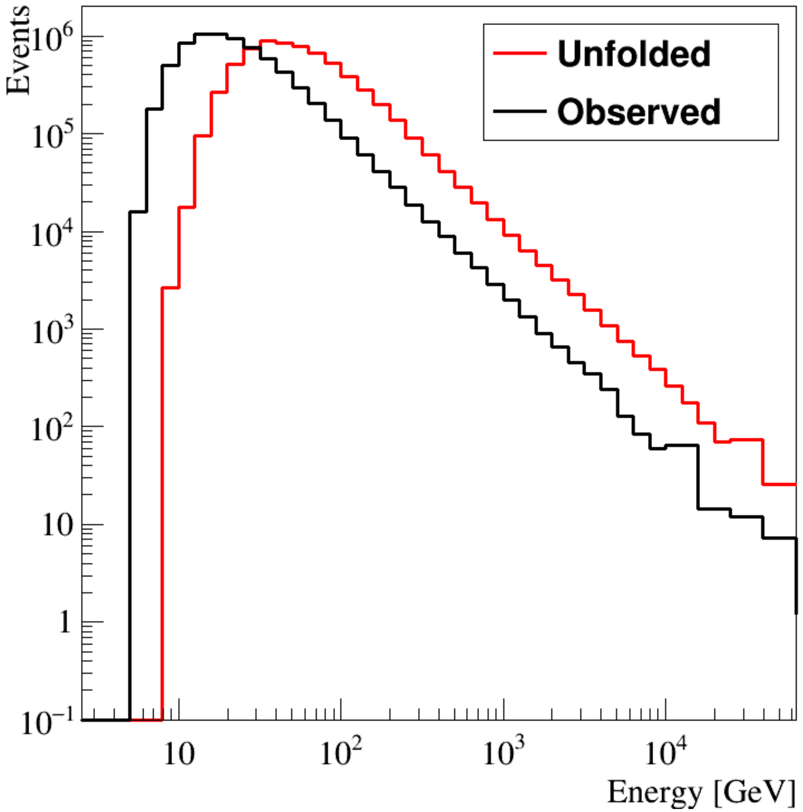
201513-230430



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

Energy unfolding

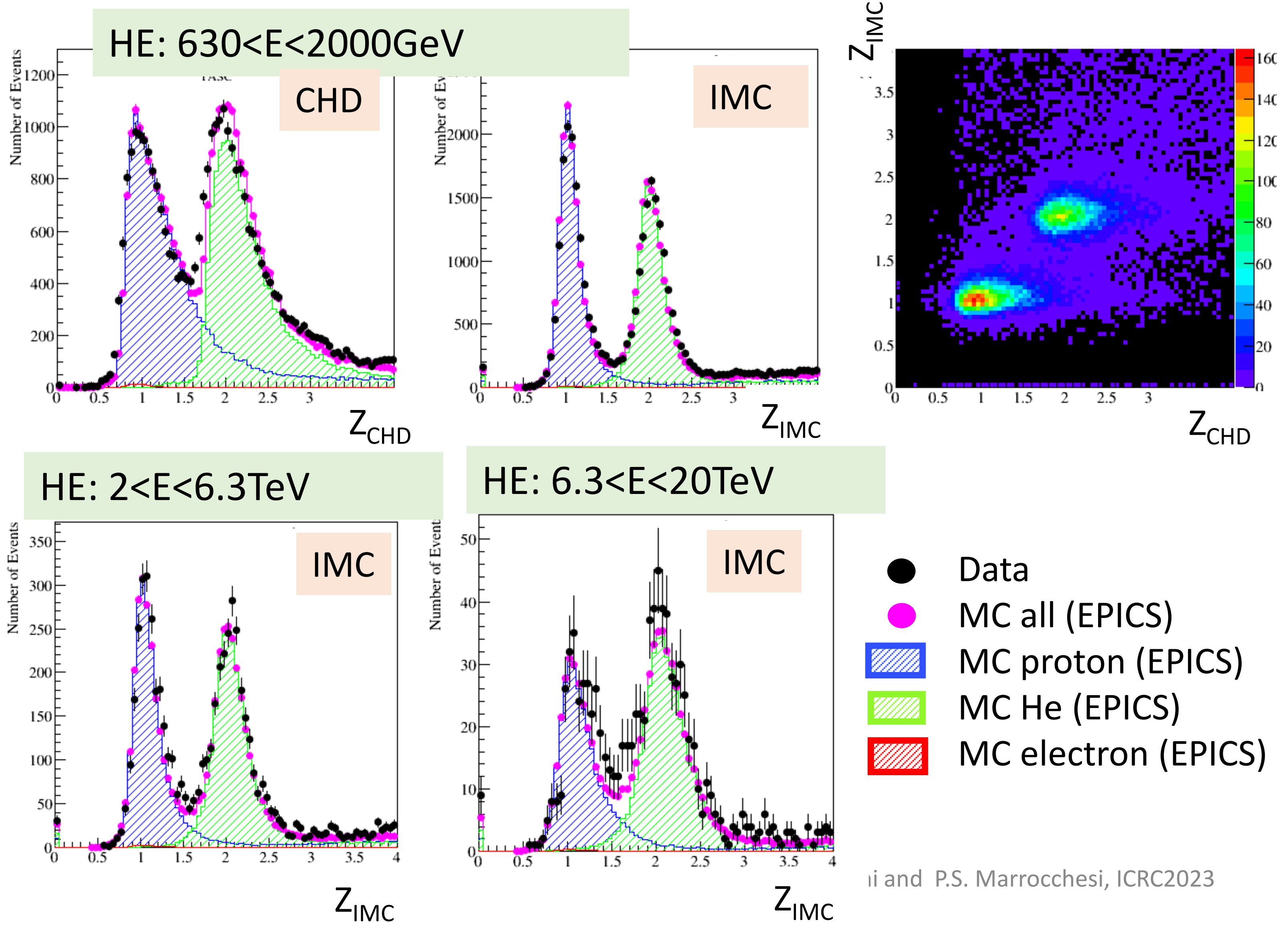
Observed/Unfolded energy spectrum



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.

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