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CALETによる陽子，ヘリウムの
エネルギースペクトルの観測の最新結果

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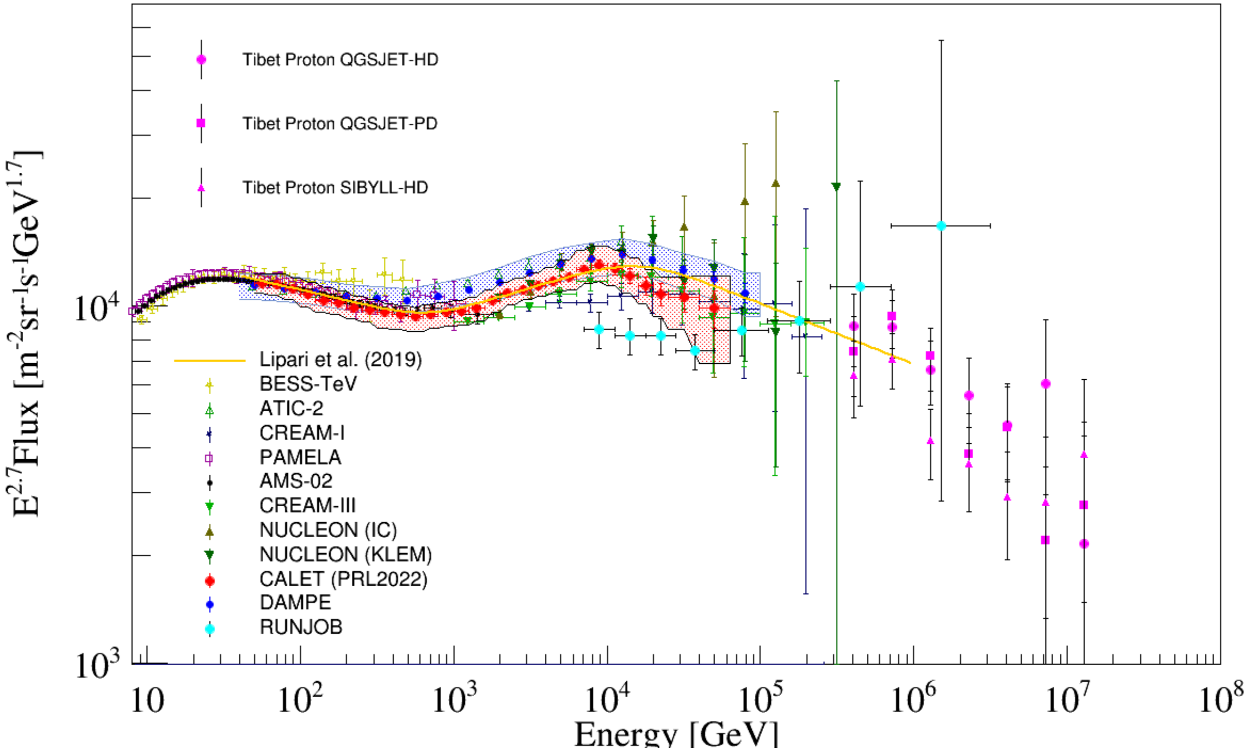
Motivation

- 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



- We present updated proton flux using data with increased statistics by 21% from PRL2022 and helium flux at 40GeV<E<200TeV newly published in PRL2023.

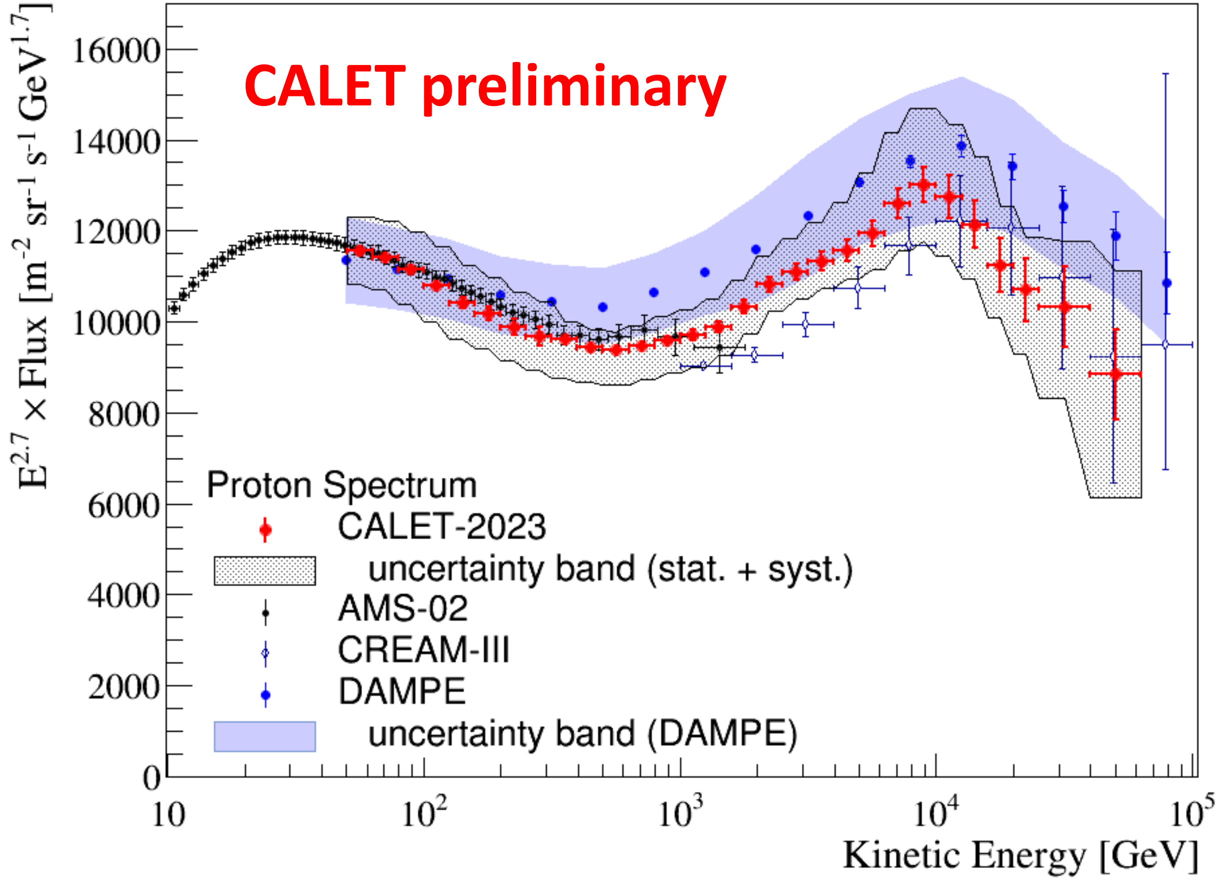
Proton event selection

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.

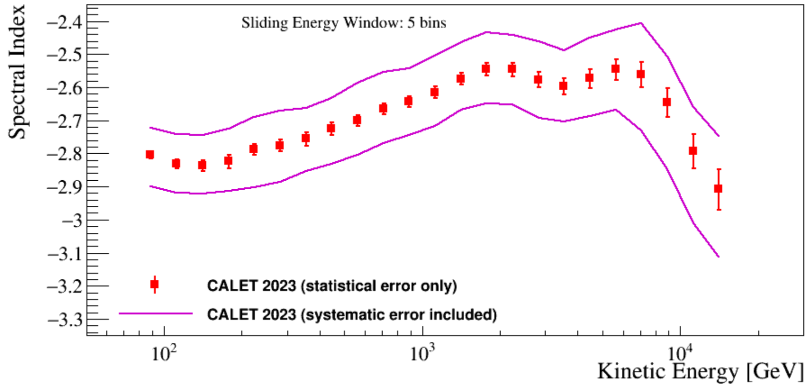
Proton spectrum (50GeV<E<60TeV)

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

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

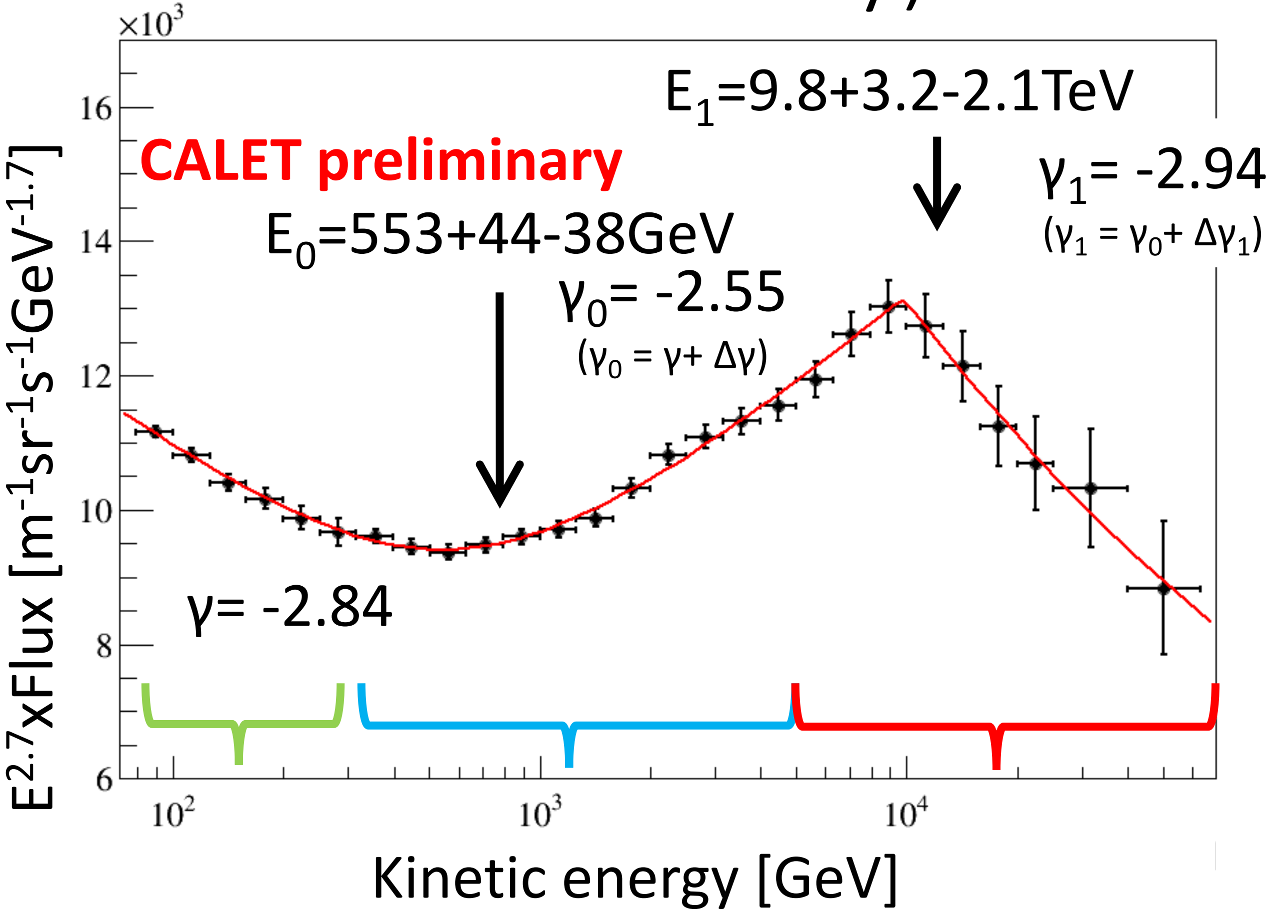


- Live time has increased by 21% from PRL2022.
- Sharp spectral softening starting at E~10TeV is getting clearer.



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
$\Delta\gamma$	$(2.9\pm0.1)\times10^{-1}$
E_0	$(5.53+0.44-0.38)\times10^{2}$
$\Delta\gamma_1$	$(-3.9+1.5-1.8)\times10^{-1}$
E_1	$(9.8+3.2-2.1)\times10^{3}$
s_1	~90

Fitting function (double broken power law):

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

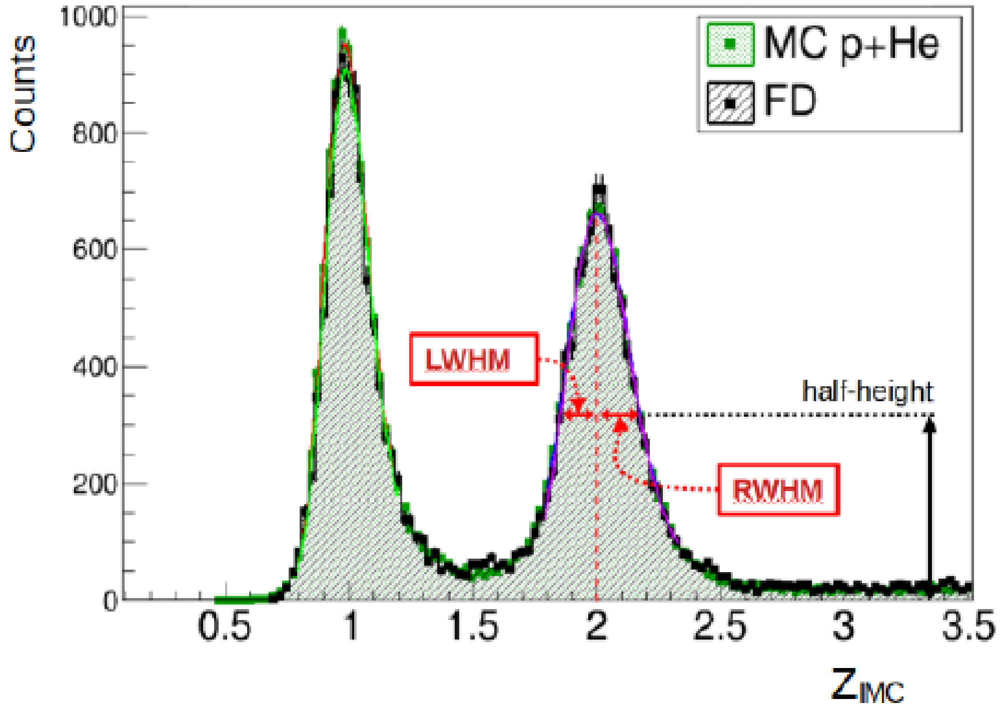
Low energy hardening softening

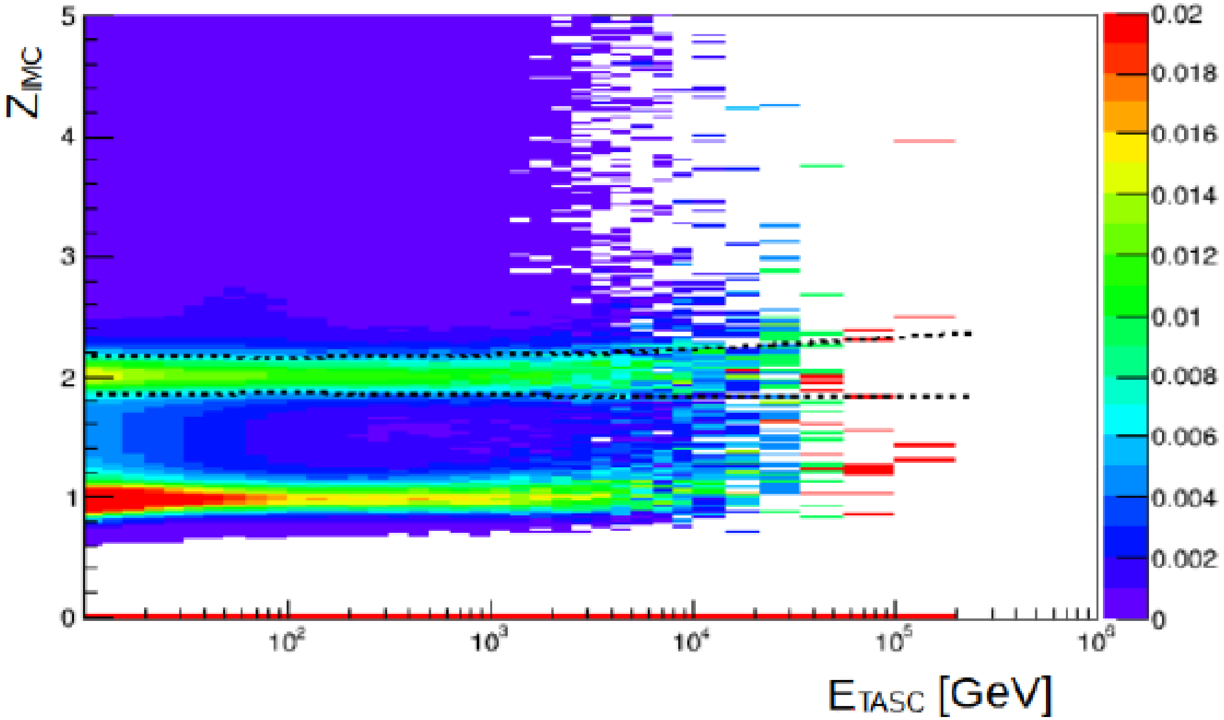
Softening is much sharper and the s_1 becomes higher with a large uncertainty.

Helium event selection

selection	Brief description
1. Event trigger	HE trigger
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. Charge identification in CHD and IMC (see later slide)	Charge identification using the energy deposit in CHD and IMC (before shower development starts) is performed to reject proton events, mainly.

Charge identification (Helium) in CHD and IMC

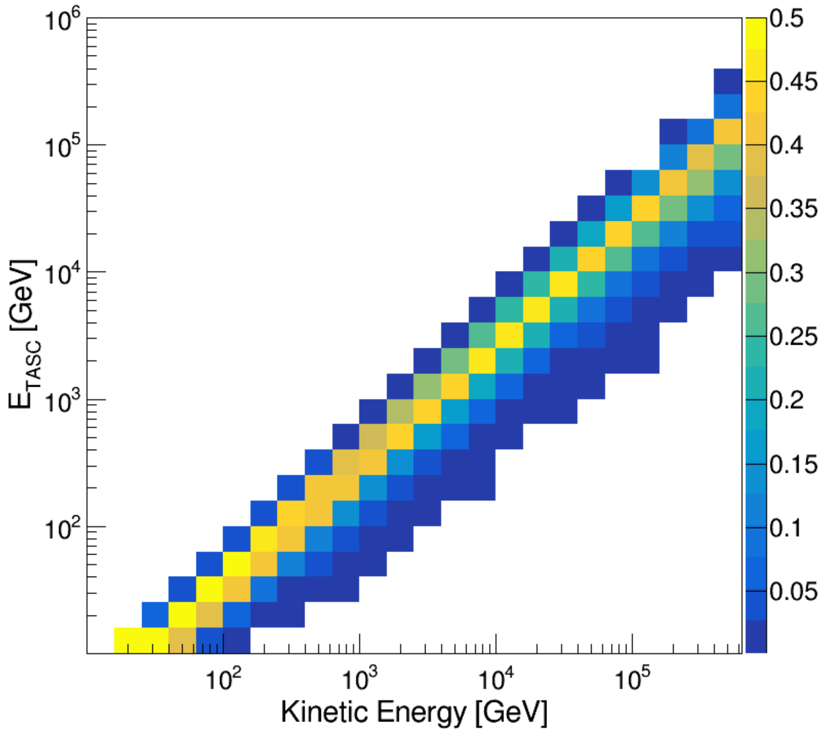




Events with 3xLWHM<Z_{IMC}<5xRWHM are selected.

Energy unfolding

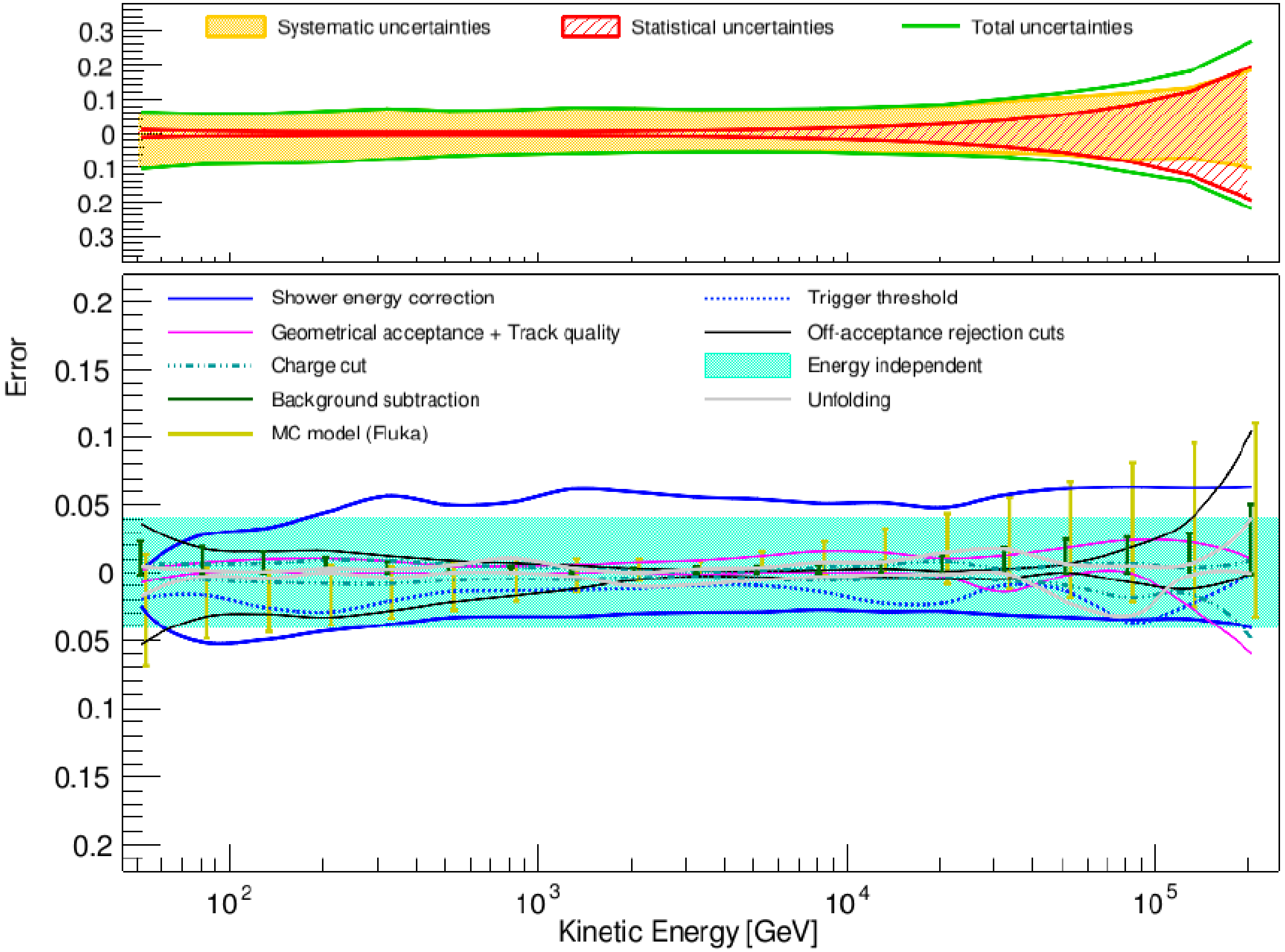
Observed/Unfolded energy spectrum



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

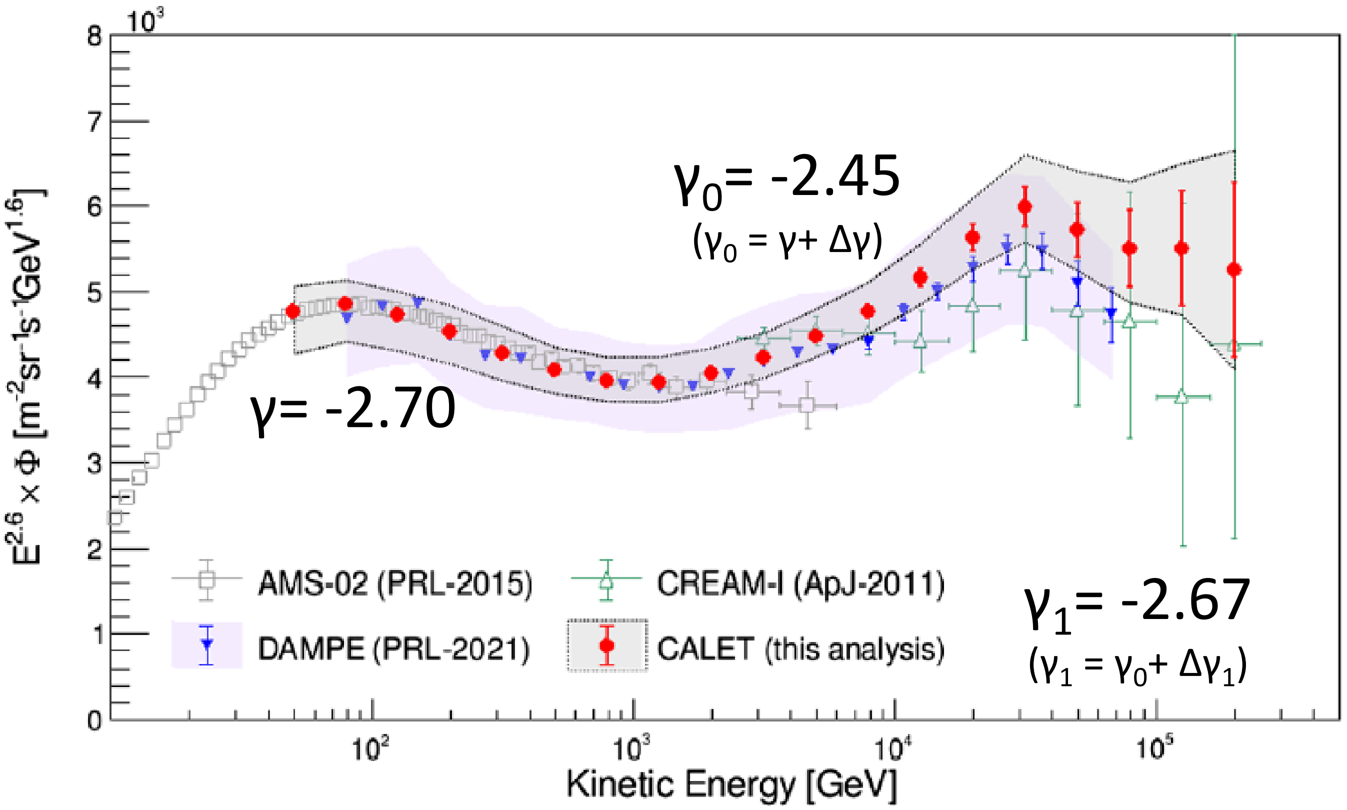
1. We build response matrix between true and observed energy spectrum using MC simulation.
2. We apply unfolding (RooUnfold) iteratively based on Bayes theorem with helium and electron background evaluation.

Systematic uncertainty (Helium)



- Systematic uncertainty in E<100TeV is less than 10%.
- The uncertainty in E>100TeV comes from the MC model dependence and off-acceptance rejection cuts, mainly.

Helium spectrum

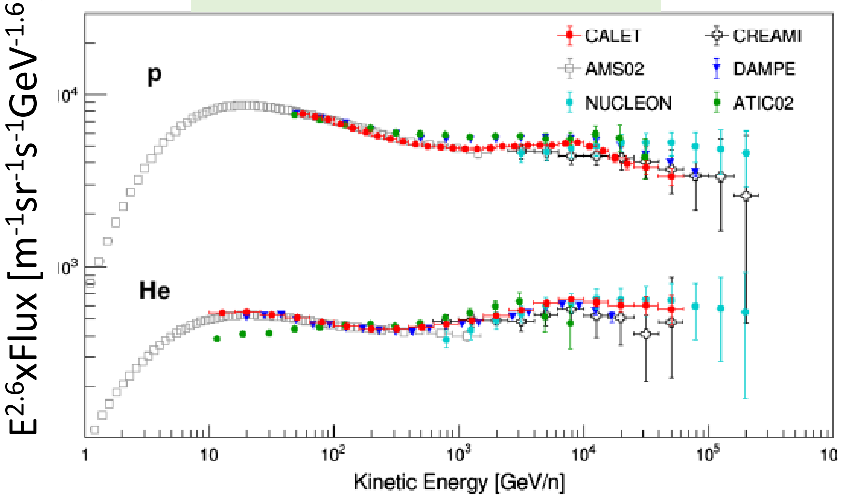


Kinetic energy [GeV/particle]

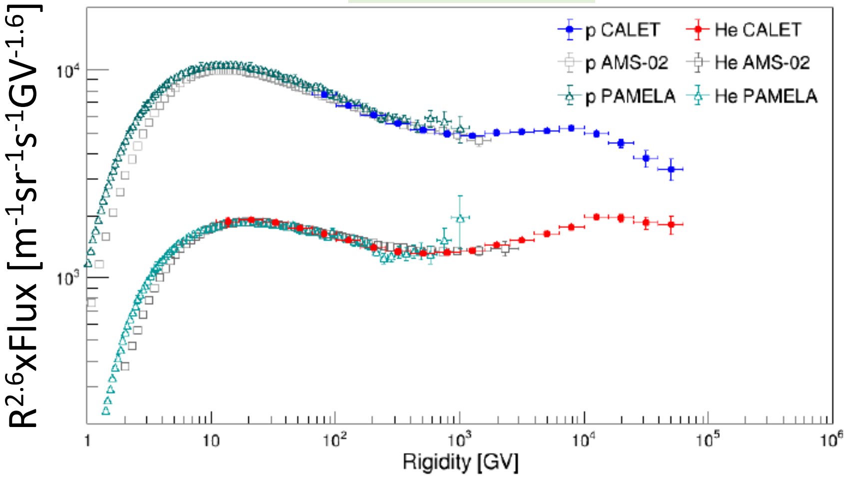
- We observe the spectral hardening starting at $E_0 = 1.319^{+0.113}_{-0.093}(stat)^{+0.267}_{-0.124}(sys)\text{TeV}$ This is consistent with DAMPE result (PRL 2021)
- We also observe spectral softening starting at $E_1 = 33.2^{+9.8}_{-6.2}(stat)^{+1.8}_{-2.3}(sys)\text{TeV}$

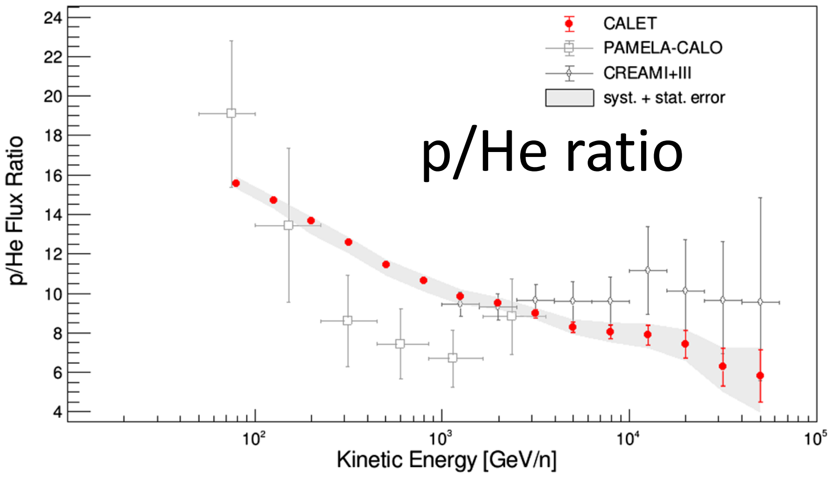
Proton/He ratio

Energy/nucleon

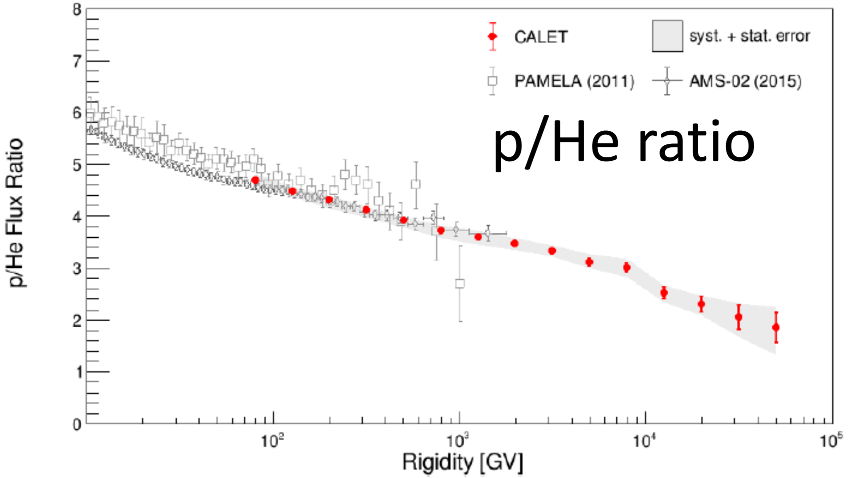


rigidity





p/He ratio



p/He ratio

- 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)	$330^{+28}_{-23}{}^{+67}_{-31}$	$8.3^{+2.3}_{-3.8}{}^{+0.5}_{-0.6}$

Summary

- CALET data taking is stably running without any serious problem more than 7 years. We have summarized the helium analysis.
- In proton spectrum, sharp spectral softening starting at E~10TeV is observed.
- In helium spectrum, both spectral hardening and softening are observed (PRL 130, 171002 (2023)).
- Helium energy spectrum have a similar shape to proton. The helium spectral hardening in rigidity is consistent to proton. p/He ratio in 60GV/n<E<60TV/n is consistent to previous measurements.