講演番号：23aW2-9

CALETによる陽子、ヘリウム比の観測

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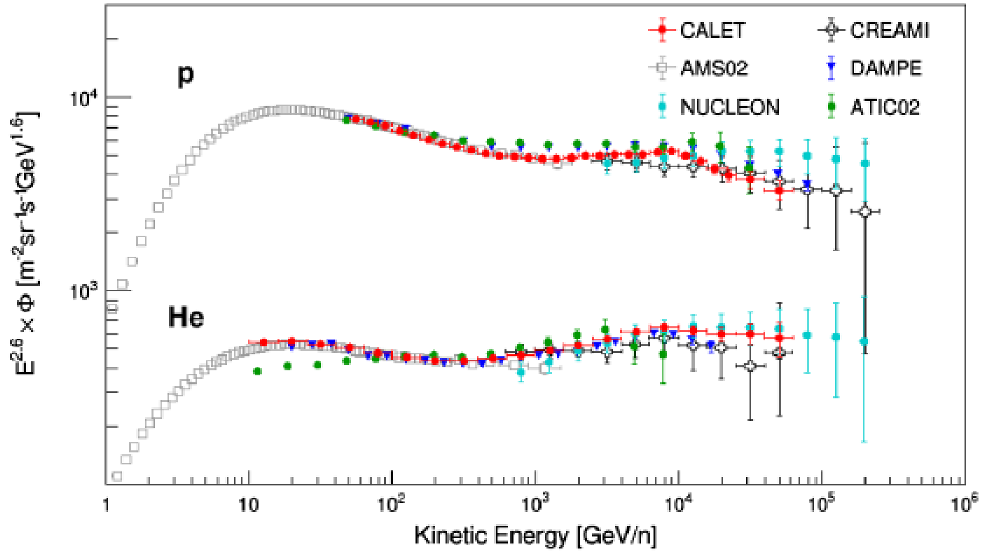
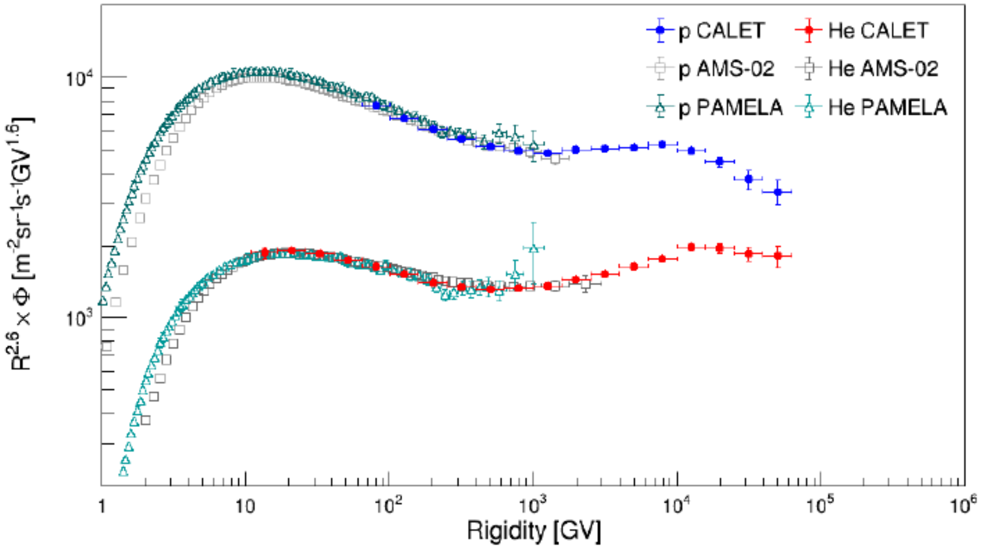
Motivation

- Proton and helium spectra and also proton/helium spectral ratio could help to understand the cosmic ray source, acceleration mechanism, and propagation.
- CALET published measurements of the proton flux (50 GeV < E < 60 TeV, PRL2022) and helium flux (40<E<250TeV, PRL2023) and confirmed a hardening and found softening.

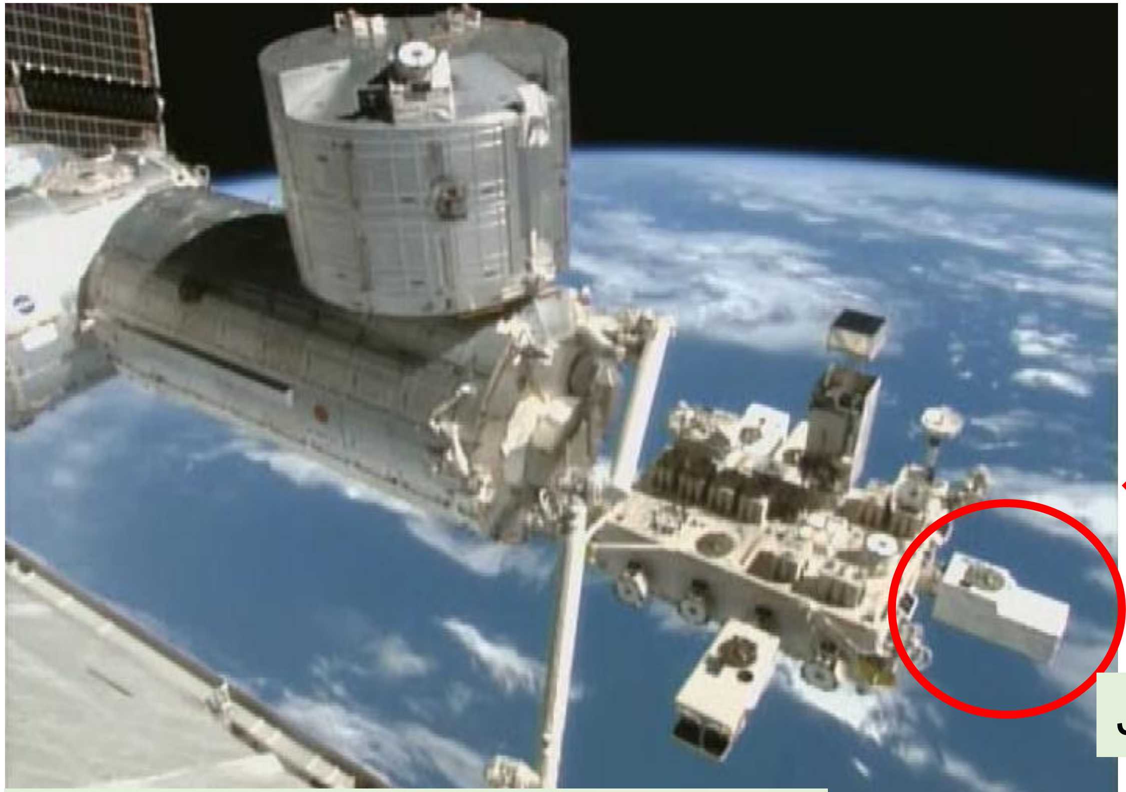
proton and helium flux at PRL2023



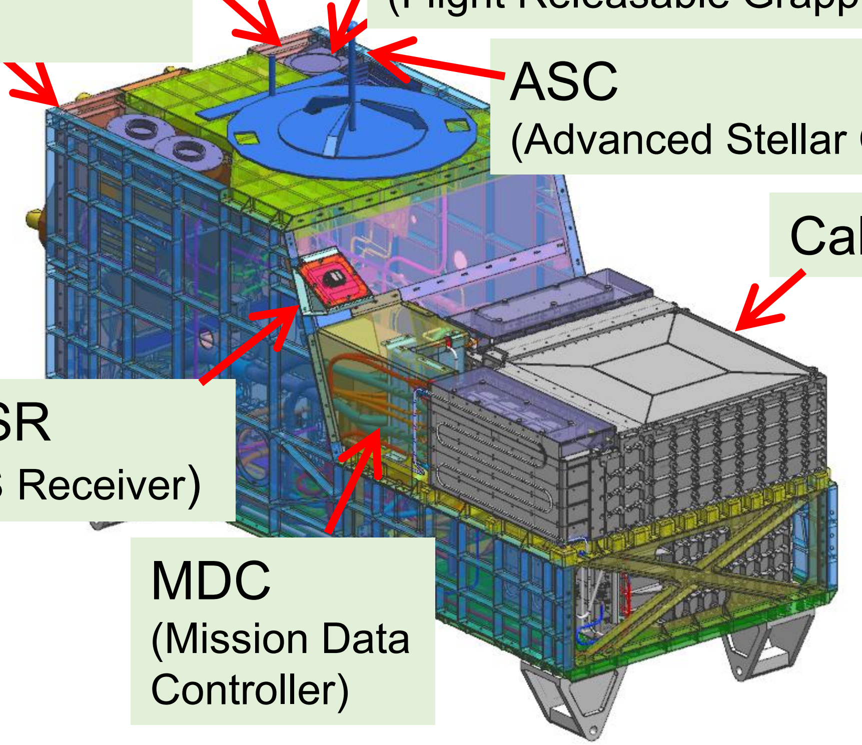


CALET Project

Aug. 2015: launched and installed on the ISS
Oct. 2015: scientific data taking began
Data taking is stably running up to now.
We plan to operate through the end of 2030.



International Space Station (ISS)



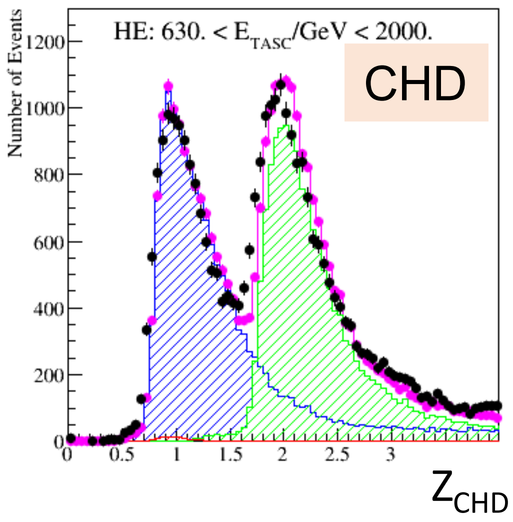
Mass	612.8kg
Power	507W (max)
Telemetry	600kbps (6.5GB/day)

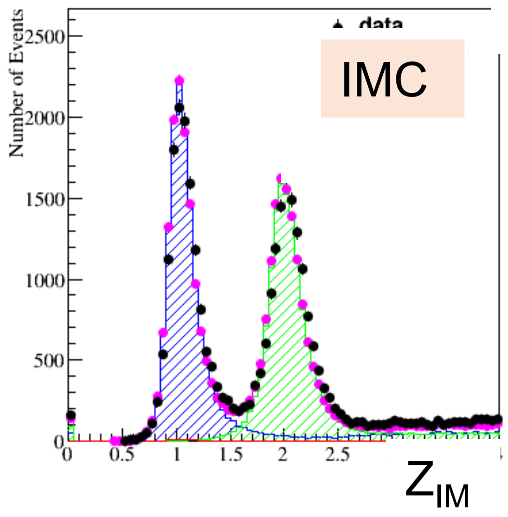
Proton Event Selection

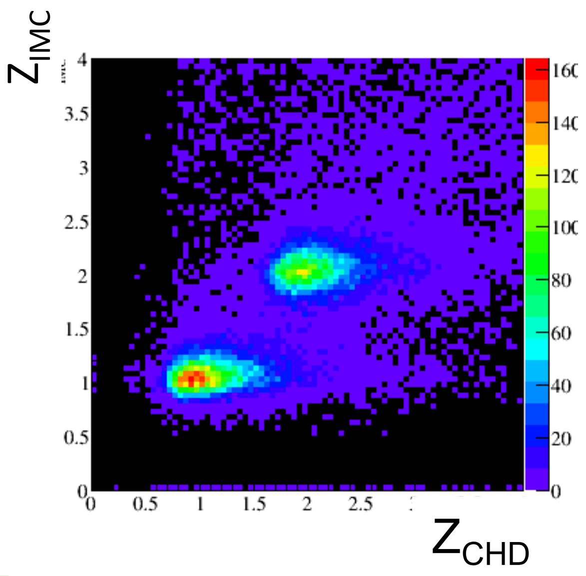
selection	Brief description
1. Event trigger	HE trigger in E>300GeV and LE trigger in E<300GeV are required.
2. Geometrical acceptance	Track going through the detector from the top to the bottom is selected.
3. Track quality cut	Reliability of Kalman Filter tracking in IMC is checked.
4. Electron rejection	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 events with mis-reconstructed tracks, we require events to have energy deposits at the top X/Y layer of TASC at positions consistent with the track as reconstructed in the 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.

Charge Identification in CHD and IMC

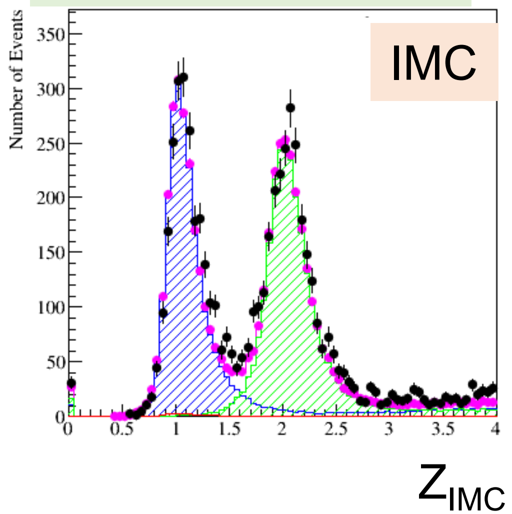
HE: 630<E<2000GeV



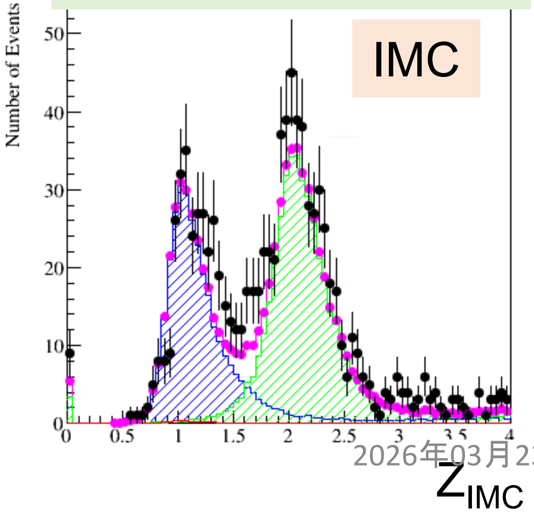




HE: 2<E<6.3TeV



HE: 6.3<E<20TeV

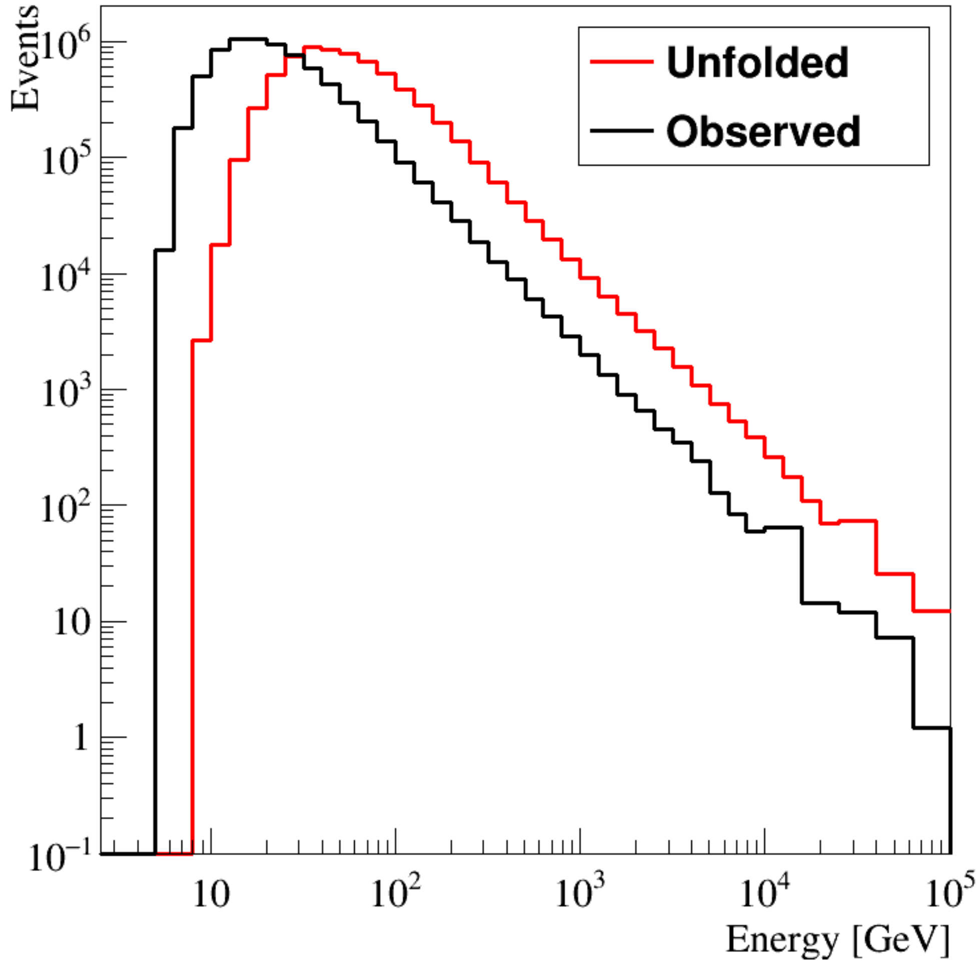


- Data
- MC all (EPICS)
- MC proton (EPICS)
- MC He (EPICS)
- MC electron (EPICS)

- 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).
- Although charge identification using the CHD alone doesn’t suffice for the higher energy region, identification including charge measurement in the IMC clearly separates p/He

Energy Unfolding (proton)

Observed/Unfolded energy spectrum

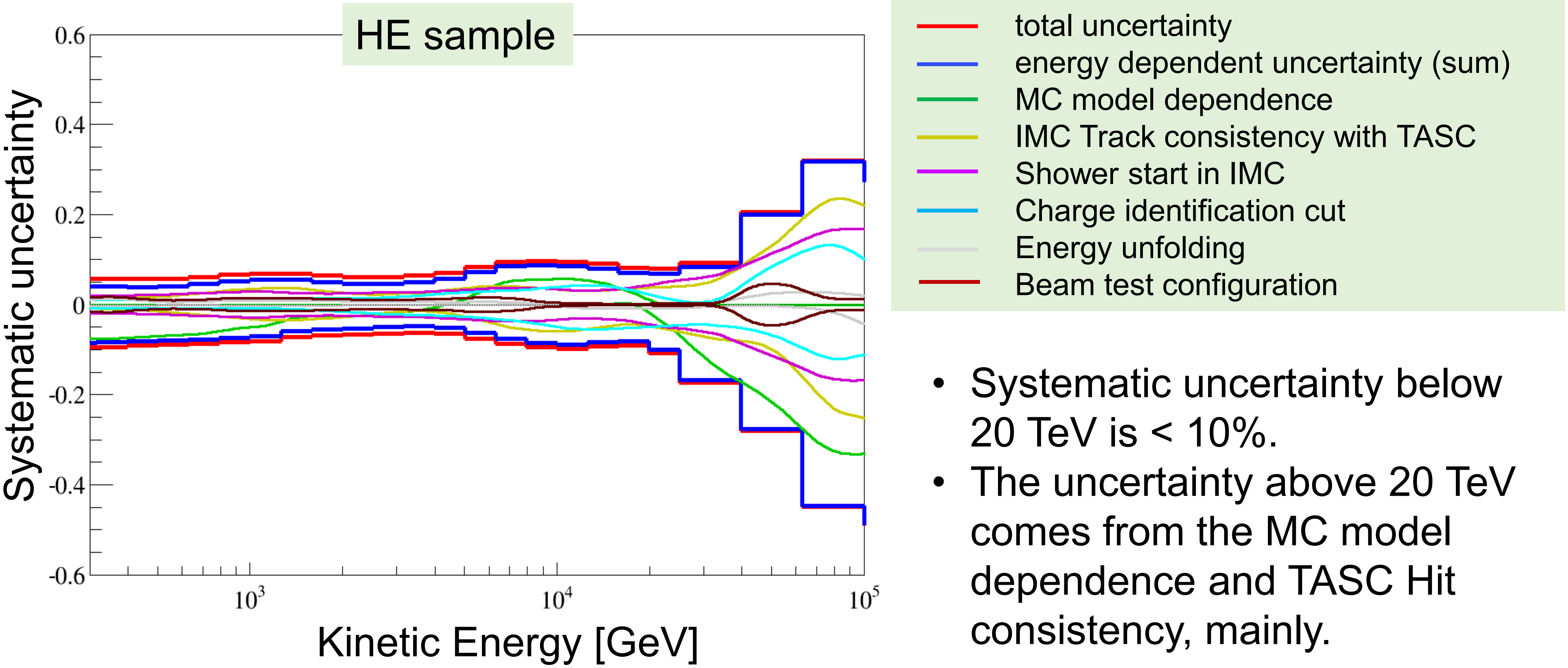


CALET's energy resolution for protons is 30-40%. Therefore, we apply Bayesian unfolding to calculate the flux.

1. Build response matrix between true and observed energy spectra using MC simulations.

2. Apply unfolding (RooUnfold) iteratively based on Bayes theorem with helium and electron background evaluation.

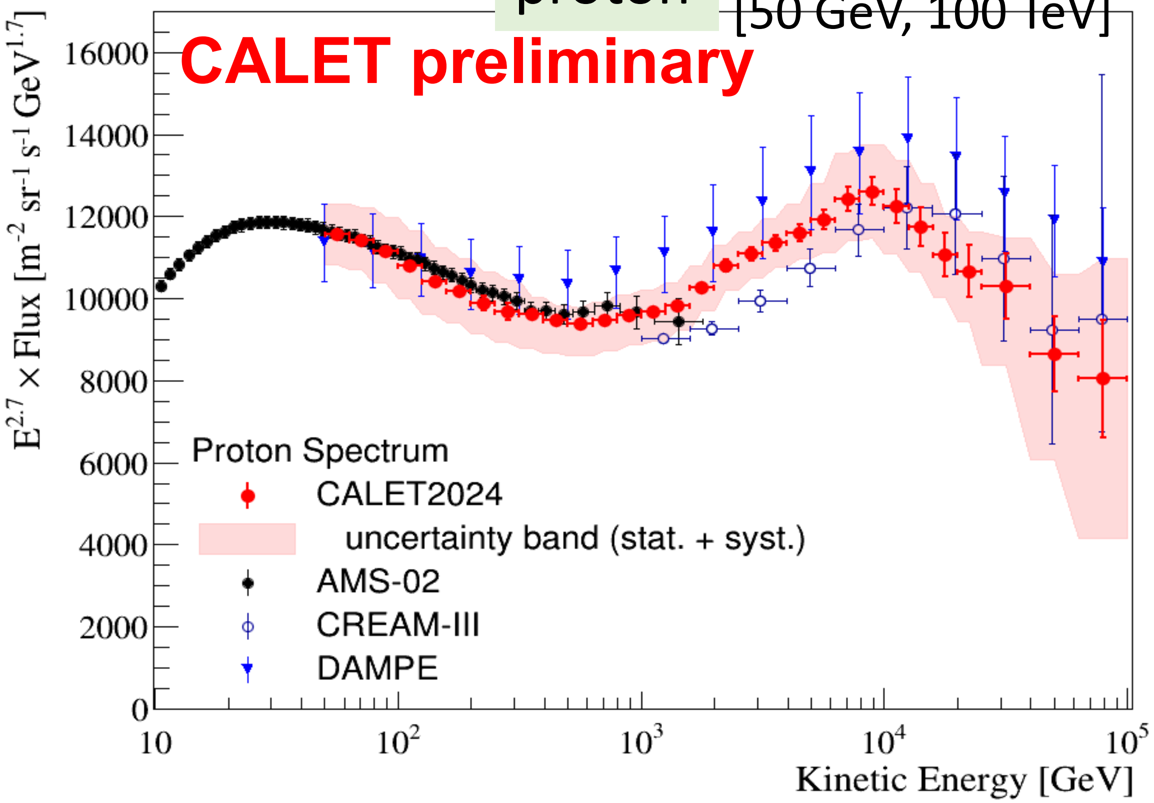
Systematic Uncertainty (proton)



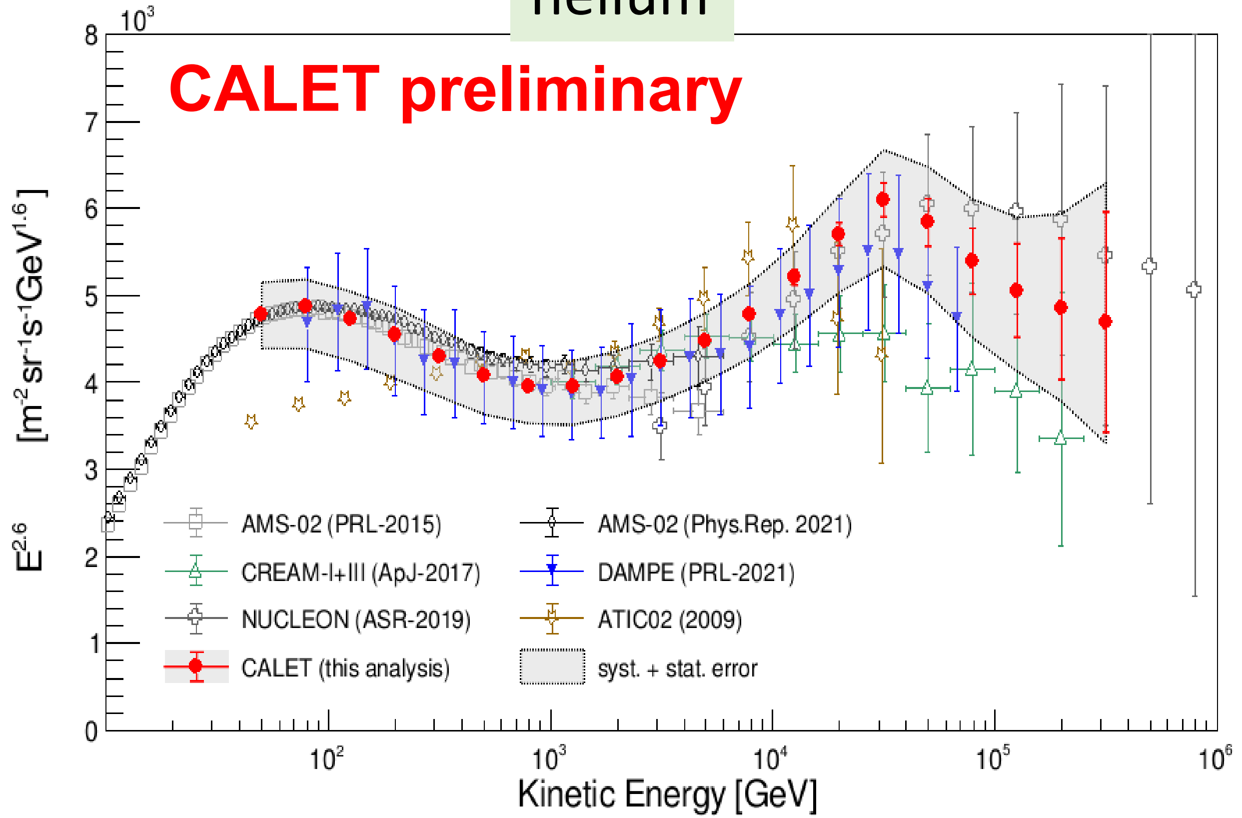
- Systematic uncertainty below 20 TeV is < 10%.
- The uncertainty above 20 TeV comes from the MC model dependence and TASC Hit consistency, mainly.

Proton and Helium Spectrum (kinetic energy)

proton [50 GeV, 100 TeV]



helium



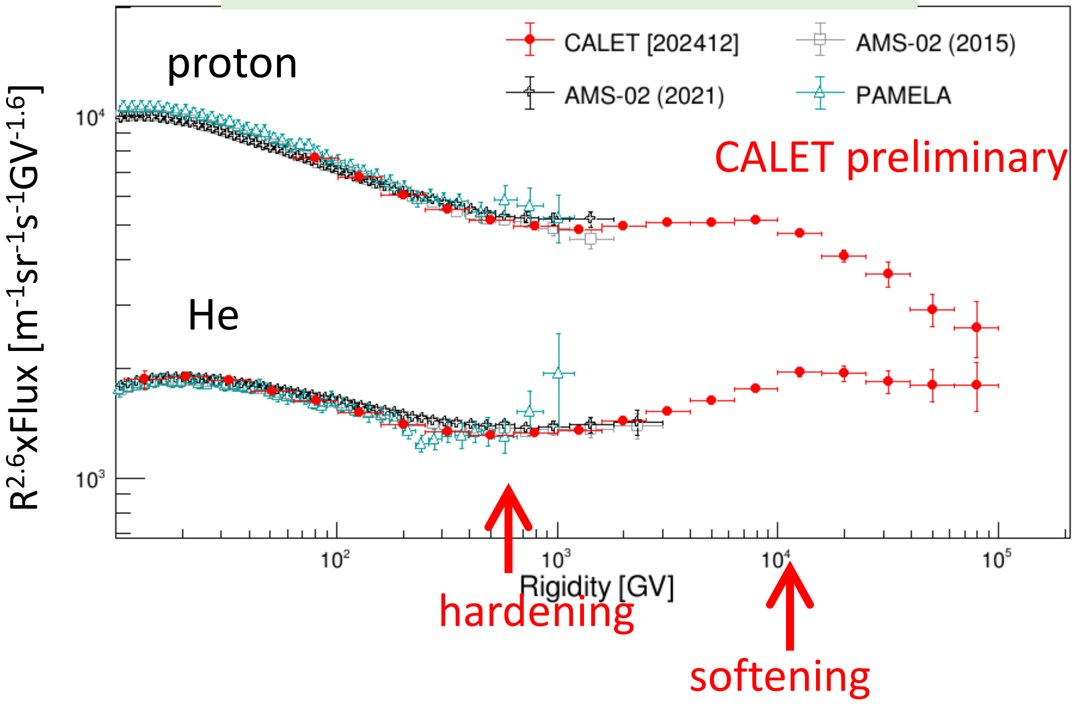
LE: same as PRL2022
HE: 2850 days of live time (Oct. 2015 – Dec. 2024)

Data: Oct. 2015 – Dec. 2024

Proton and helium have same spectral signature such as hardening and softening.

Proton/He ratio (rigidity) 1/2

p and He fluxes (rigidity)



If a simple leaky box model is assumed,

$$\frac{dN_p}{dR} \sim Q_{p\ source}(R)T_{res}(R)$$

$$\frac{dN_{He}}{dR} \sim Q_{He\ source}(R)T_{res}(R)$$

$$\rightarrow \frac{dN_p}{dR} / \frac{dN_{He}}{dR} \sim Q_{p\ source}(R)/Q_{He\ source}(R)$$

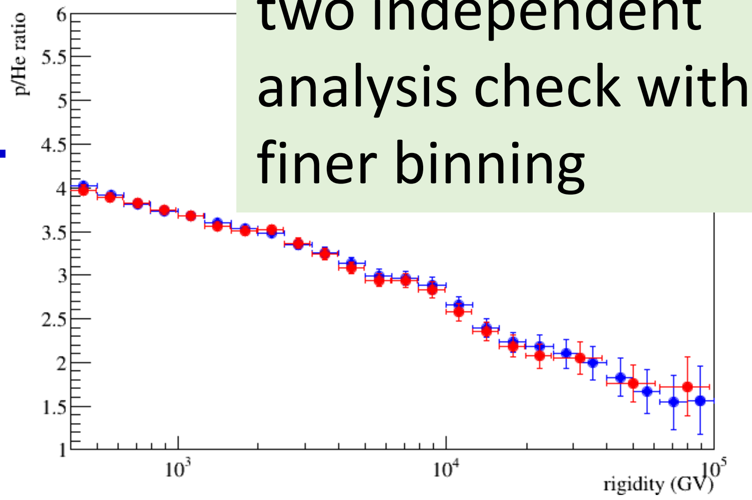
$N_{p/He}$: p/He density
R: rigidity
$Q_{source}(R)$: source
$T_{res}(R)$: residual time

p/He ratio would provide useful probes of CR sources.

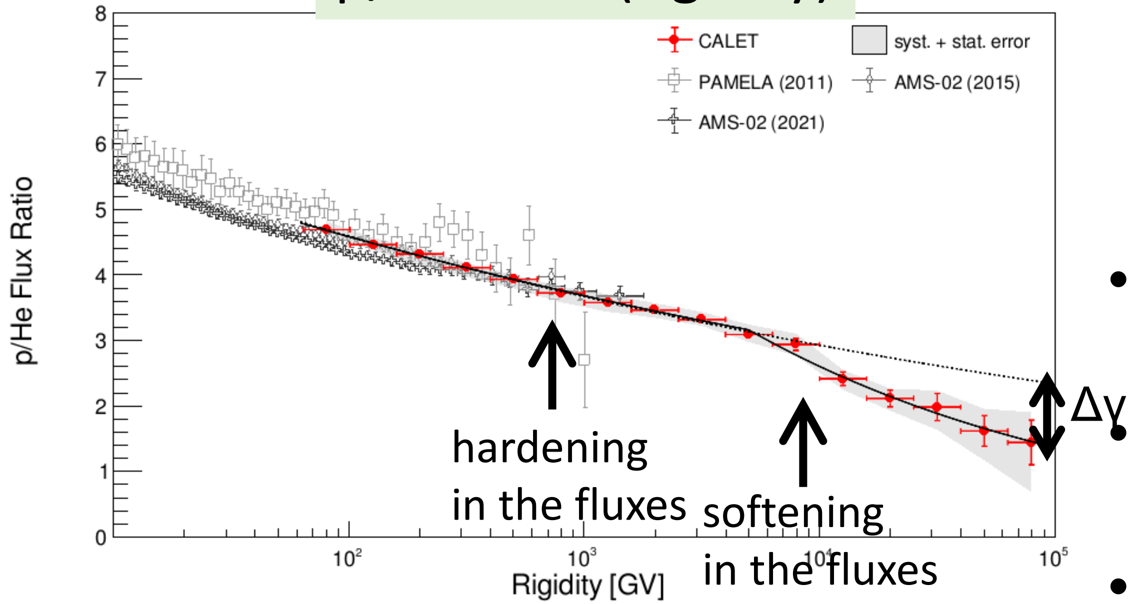
- Spectral hardening and softening in rigidity are consistent between proton and helium.

Proton/He ratio (rigidity) 2/2

two independent analysis check with finer binning



p/He ratio (rigidity)



- p/He ratio from tens GV to 10 TV is well described by SPL ($\Phi(R)$ =A $\times R^{\gamma}$, γ=-0.097±0.005).
- A spectral break is found around 10 TV, where both proton and helium spectra start softening.
- DPL is favored with a significance of 4.8σ compared to SPL from 60 GV to 100 TV.
- We performed two independent analyses and got the consistent result.

-> Different CR sources are needed to explain:
- the energy dependent (SPL up to 10 TV)
- the break around 10 TV

DPL: $$\Phi(R) = \begin{cases} C \times \left(\frac{R}{1GV}\right)^{\gamma} & (R < R_0) \\ C \times \left(\frac{R}{1GV}\right)^{\gamma} \times \left(\frac{R}{R_0}\right)^{\Delta\gamma} & (R > R_0) \end{cases}$$

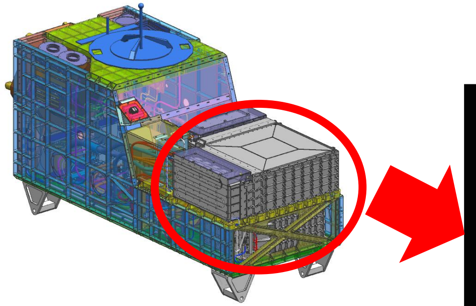
γ	-0.097±0.006
R_0	6.60±1.87 TV
Δγ	-0.23±0.08

Summary

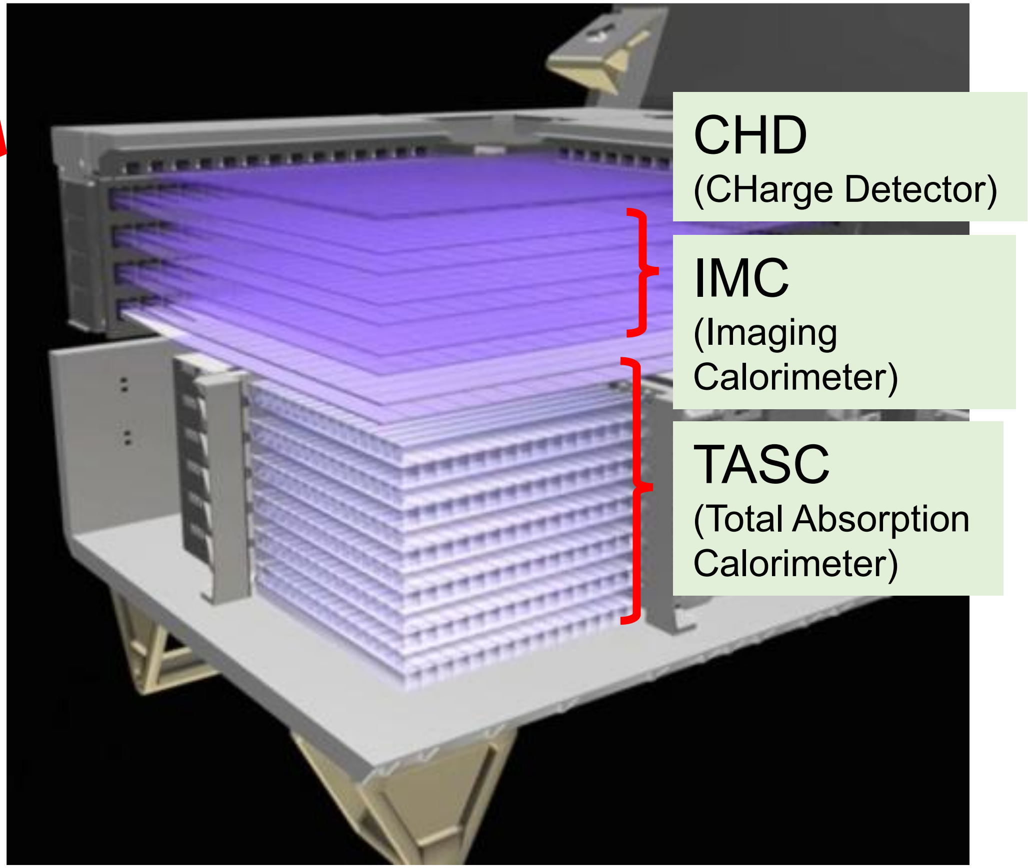
- CALET data taking is stably running without any serious problem more than 10 years.
- Proton and helium energy spectrum have a similar shape. Both have hardening and softening. Starting rigidity of spectral hardening are consistent between proton and helium.
- Proton/He ratio is not independent of rigidity. The ratio from tens GV to 10 TV is well described by SPL, while that from 60 GV to 100 TV is better described by DPL. Around the breaking rigidity (~10TV), spectral softening of both protons and helium starts in the same energy range. These results may indicate that different CR sources affect the proton and helium spectra.

Back up

CALET Detector

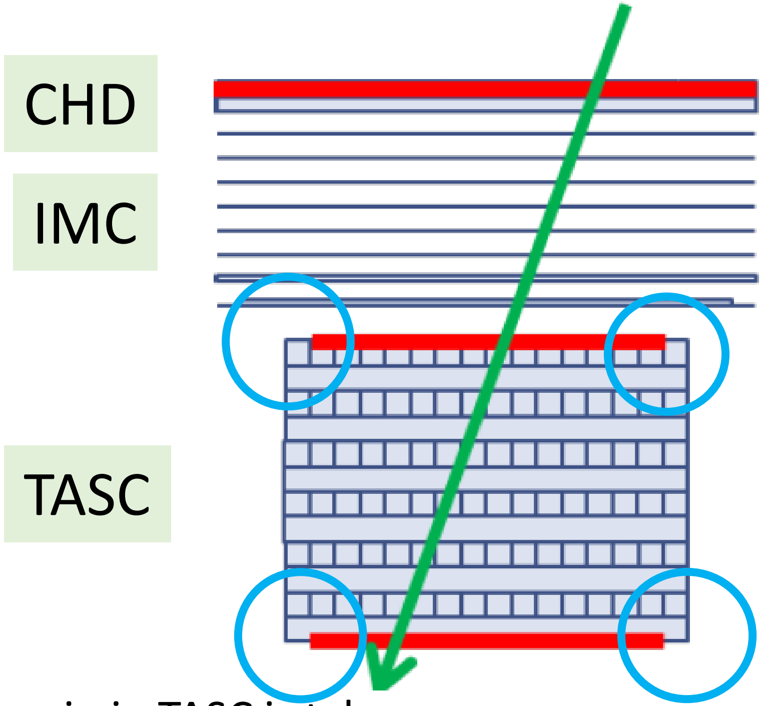


	Material/Sensor	Function
CHD	Plastic scintillator + PMT 28 paddles (=14x2layers(x,y)) (paddle size: 32x10x450mm)	Charge ID
IMC	Scifi./W + MAPMT (64anode) 7168 Scifi. (=448x16layers(x,y)) +7 W layers (Scifi. size: 1x1x448mm)	Tracking, Charge ID
TASC	PWO scintillator + APD/PD or PMT 192 logs (=16x12layers(x,y))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

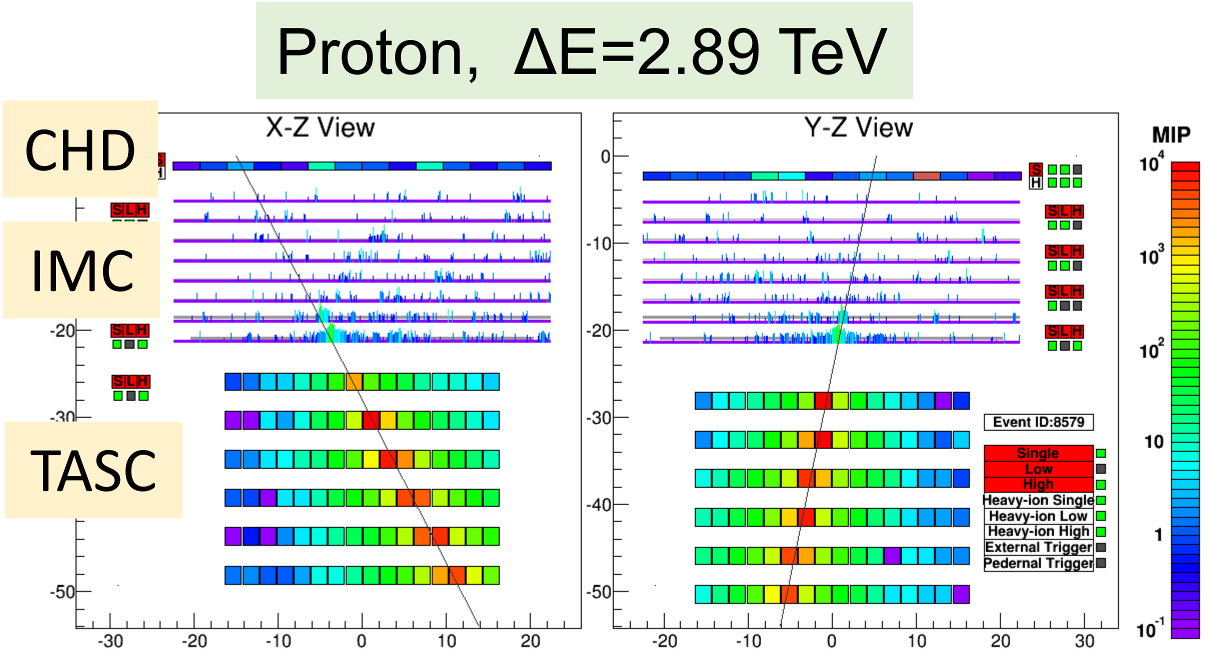


In total $30X_0$ thickness and 1.2λ,
($27X_0$ in TASC + $3X_0$ in IMC)

Geometrical acceptance and event example



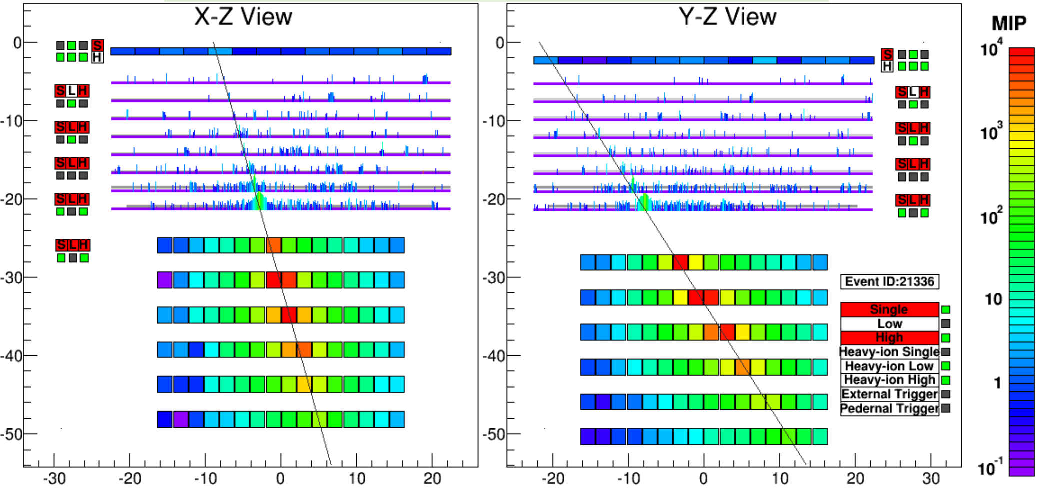
2cm margin in TASC is taken.



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

Event Examples

Electron, E=3.05 TeV

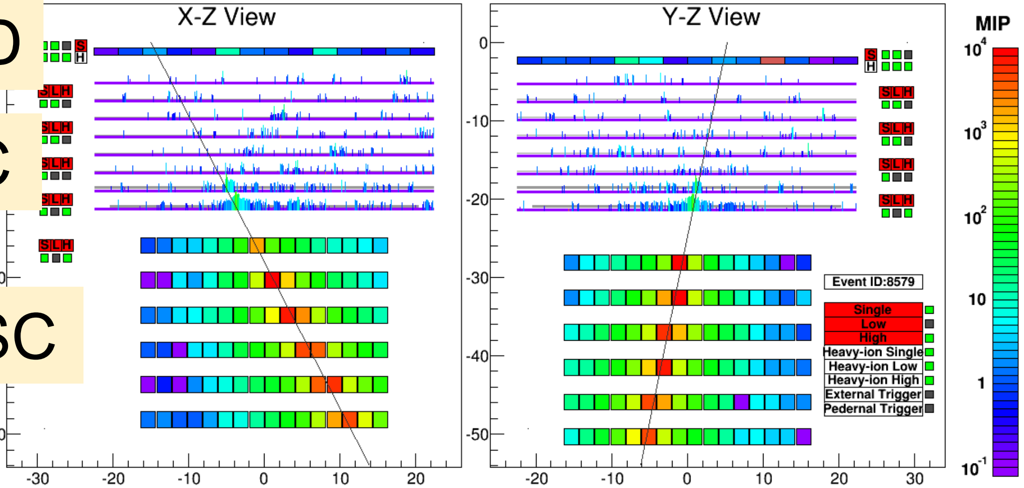


Proton, ΔE=2.89 TeV

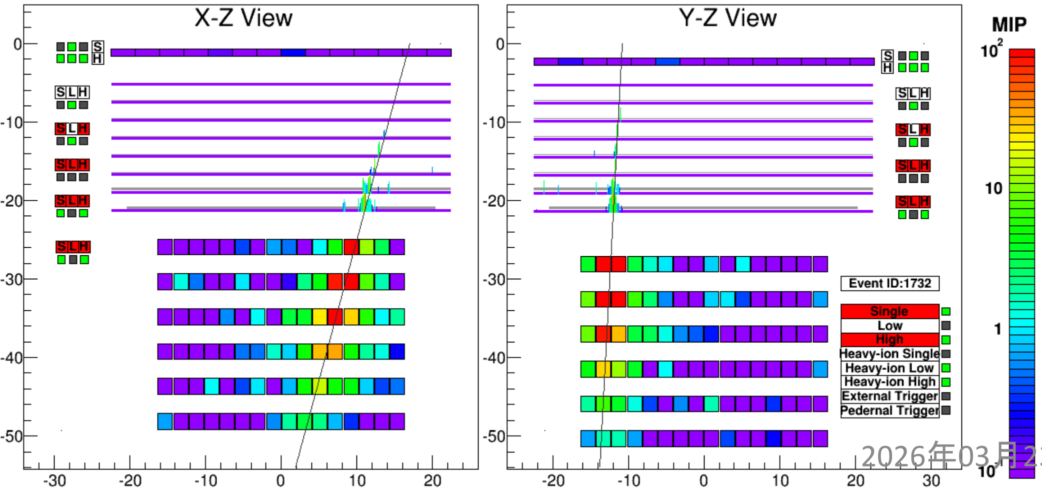
CHD

IMC

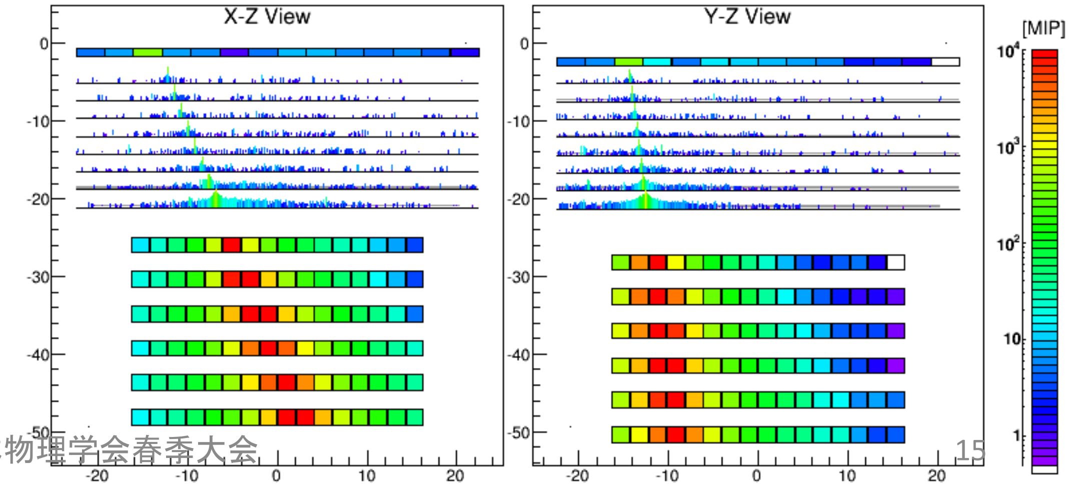
TASC



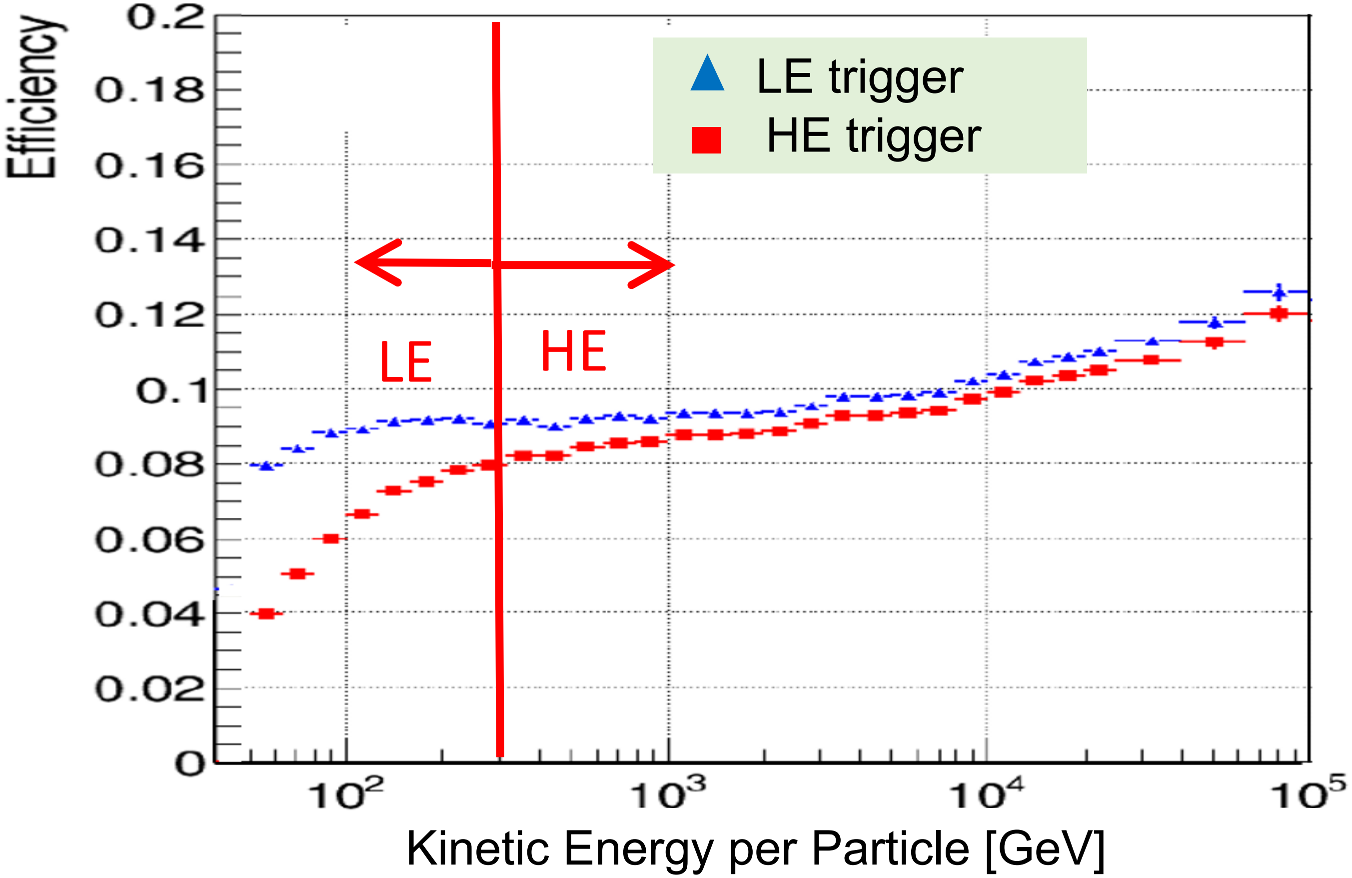
Gamma-ray, E=44.3 GeV

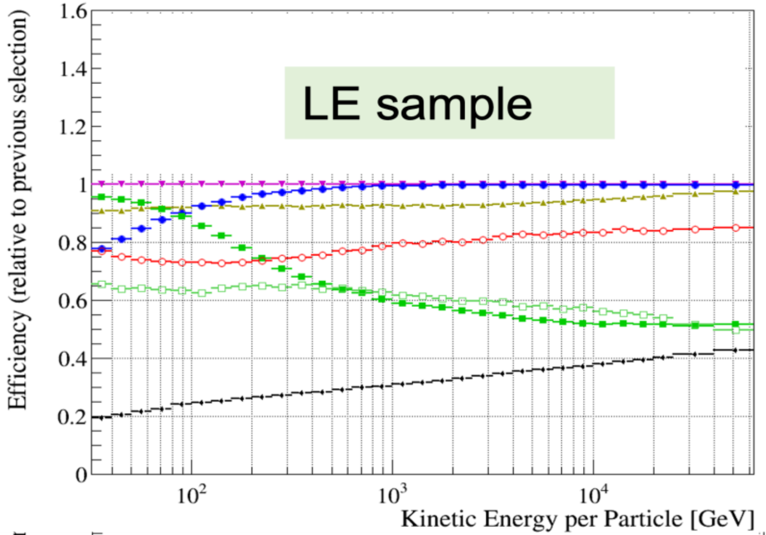


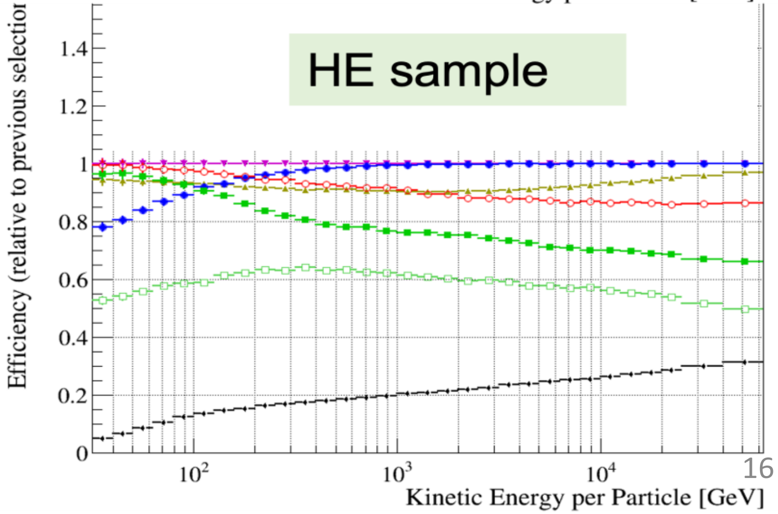
Fe, ΔE=9.3 TeV



Detection Efficiency (proton)



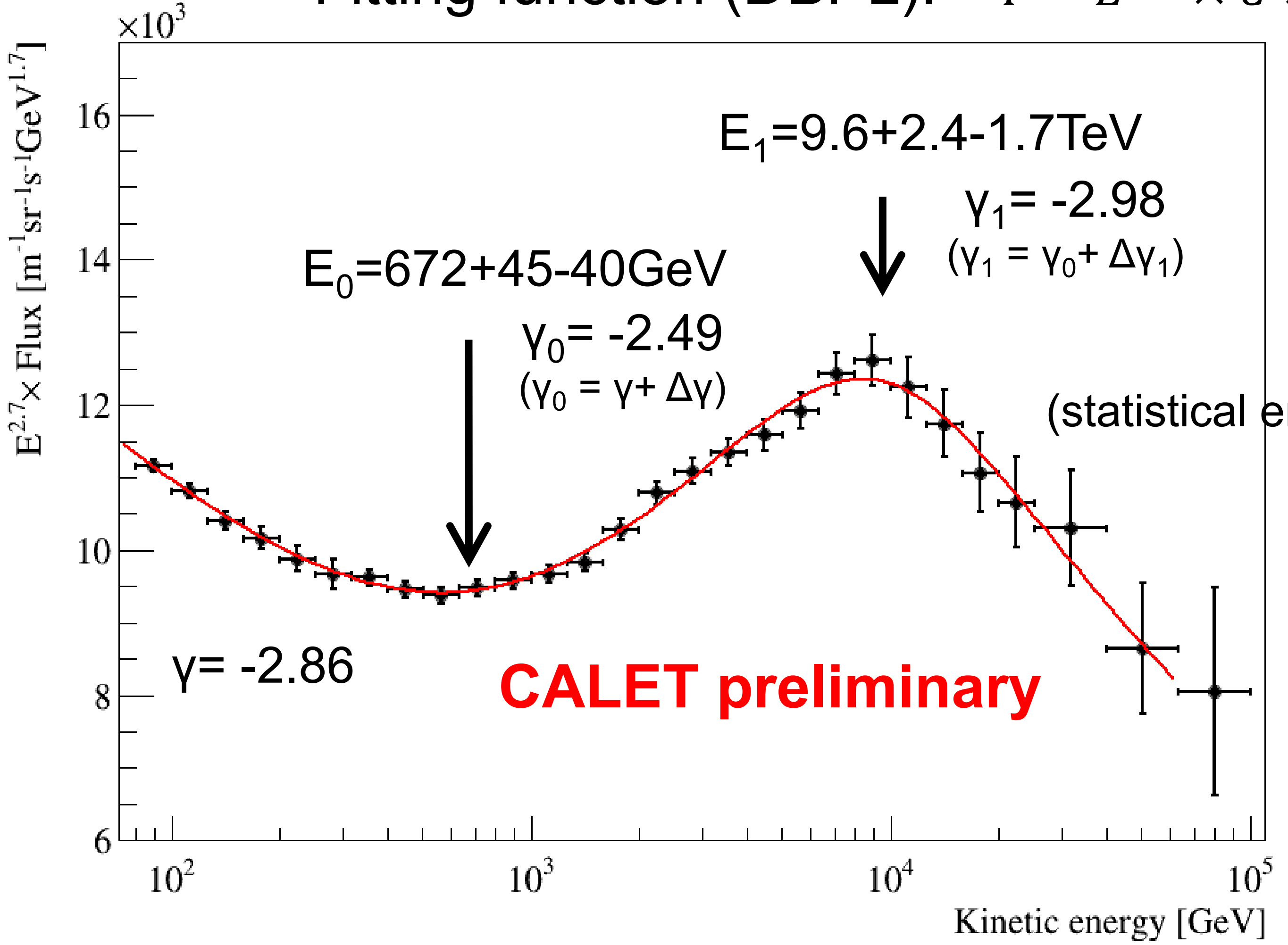




- In E>300GeV (E<300GeV), HE (LE) trigger is used. LE is used due to the high efficiency.
- Detection efficiency is 8-12% between 50 GeV and 100 TeV.

Proton Spectral Fit with Double Broken Power Law (DBPL)

Fitting function (DBPL): $\Phi = E^{2.7} \times C \times \underbrace{\left(\frac{E}{1GeV}\right)^{\gamma}}_{\text{Low energy}} \times \underbrace{\left(1 + \left(\frac{E}{E_0}\right)^{s}\right)^{\frac{\Delta\gamma}{s}}}_{\text{hardening}} \times \underbrace{\left(1 + \left(\frac{E}{E_1}\right)^{s_1}\right)^{\frac{\Delta\gamma_1}{s_1}}}_{\text{softening}}$



(statistical error only)

$\chi^2 = 6.8/20$

γ	-2.858+0.005-0.005
s	1.6±0.2
$\Delta\gamma$	$(3.7\pm0.1)\times10^{-1}$
E_0	$(6.72+0.45-0.40)\times10^{2}$
$\Delta\gamma_1$	$(-4.9+1.2-1.3)\times10^{-1}$
E_1	$(9.6+2.4-1.7)\times10^{3}$
s_1	2.7+3.5-0.5

The s_1 becomes smoother, but s_1 is larger than s.