講演番号：17aEL104-3

CALETによる陽子、ヘリウム エネルギースペクトルの観測の最新結果

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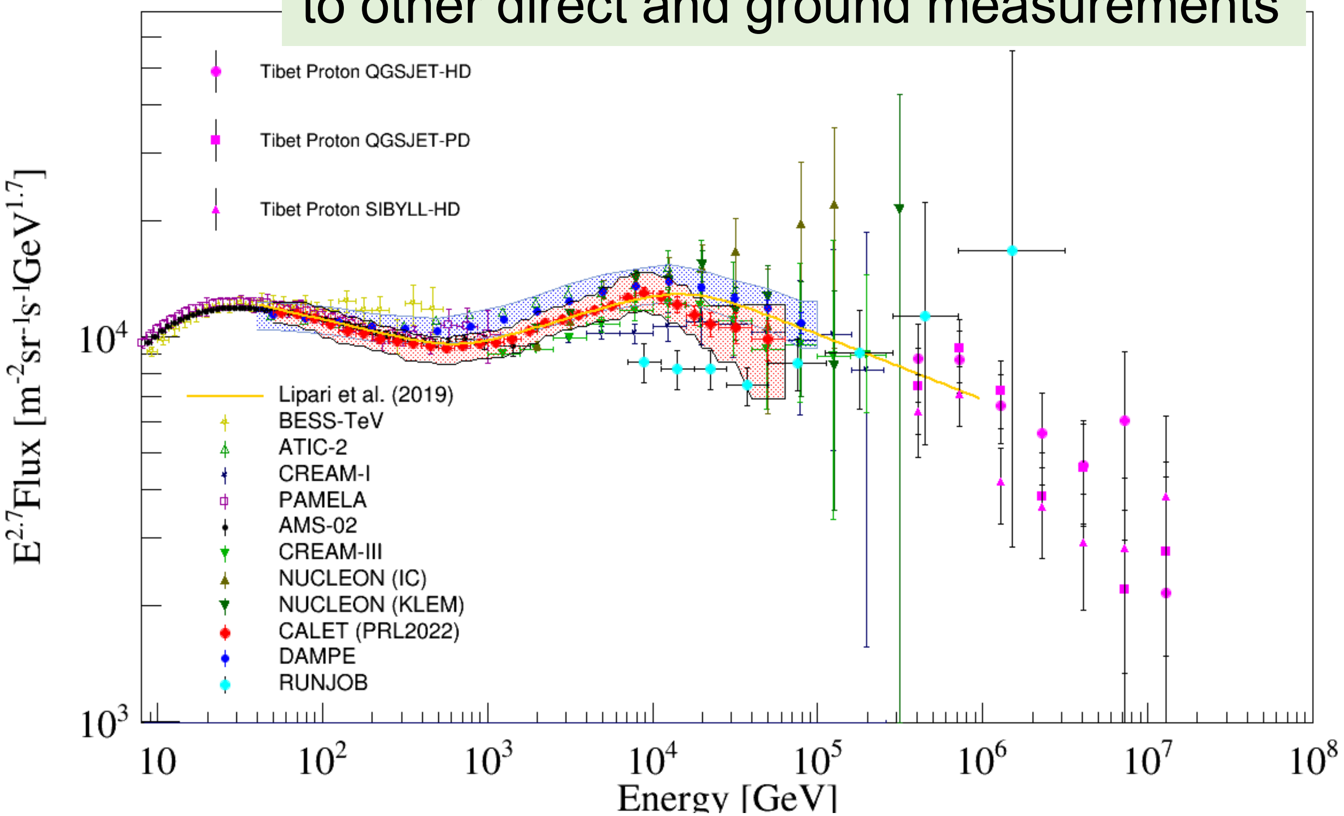
Motivation

- Characterizing proton/nuclei spectral features could help to understand the cosmic ray source, acceleration mechanism, and propagation.
- Direct measurement of the flux up to 100's TeV energies could provide normalization for ground-based observations.

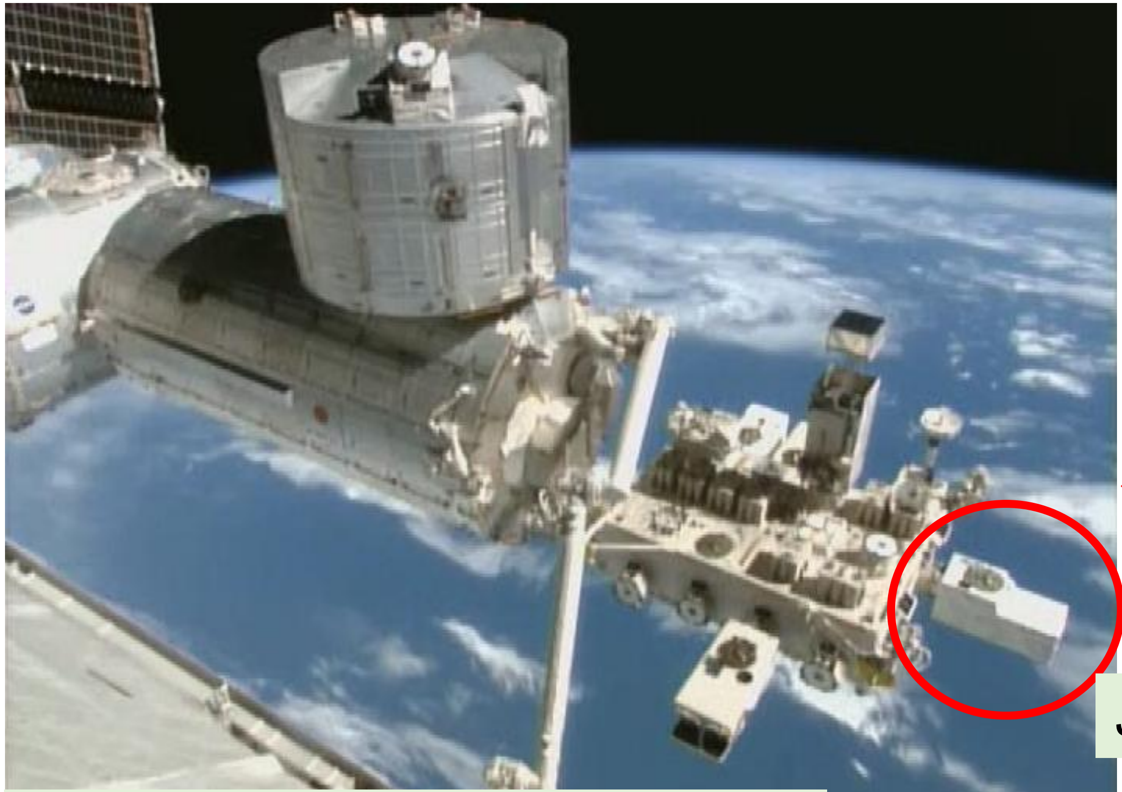
Proton flux in PRL2022 (red) compared to other direct and ground measurements



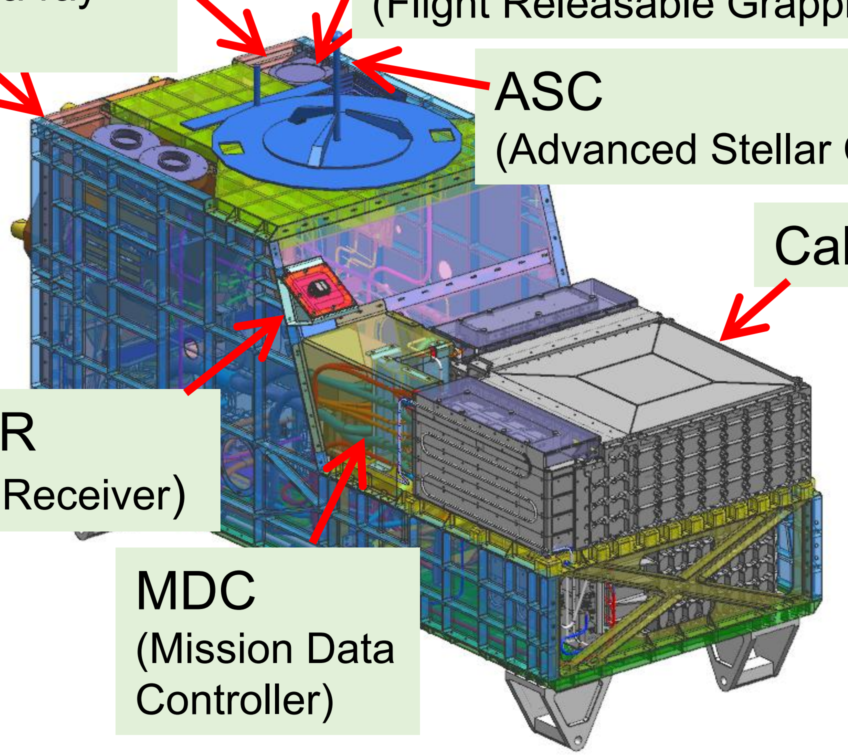
- CALET published measurements of the proton flux (50 GeV < E < 60 TeV, PRL2022) and helium flux (40<E<250TeV, PRL2023) and confirmed a hardening and found softening.
- Here we present an extended measurement up to 100 TeV in proton and 400 TeV in helium using data until the end of 2024.

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)



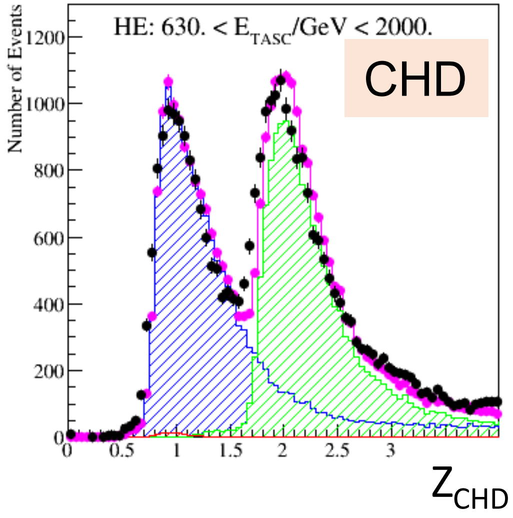
Mass	612.8kg
Power	507W (max)
Telemetry	600kbps (6.5GB/day)

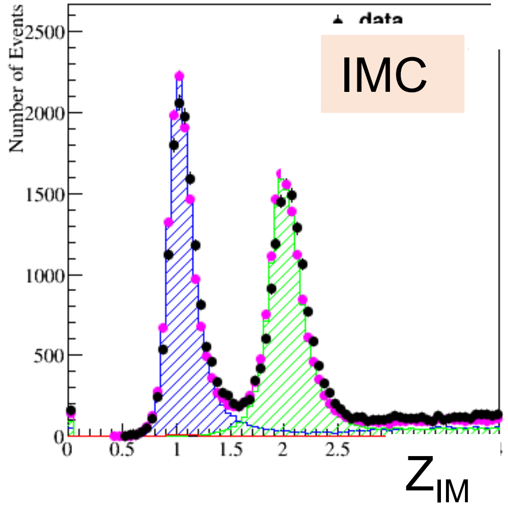
Proton Event Selection

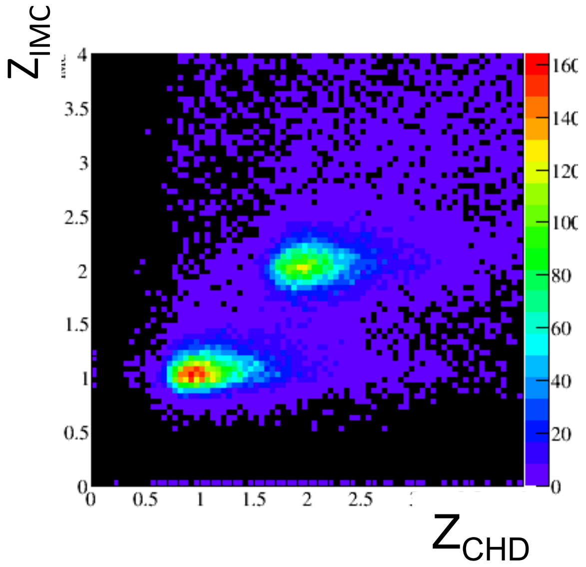
selection	Brief description
1. Event trigger	HE trigger in E>300GeV and LE trigger in E<300GeV are required.
2. Geometrical acceptance	Track going through the detector from the top to the bottom is selected.
3. Track quality cut	Reliability of Kalman Filter tracking in IMC is checked.
4. Electron rejection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

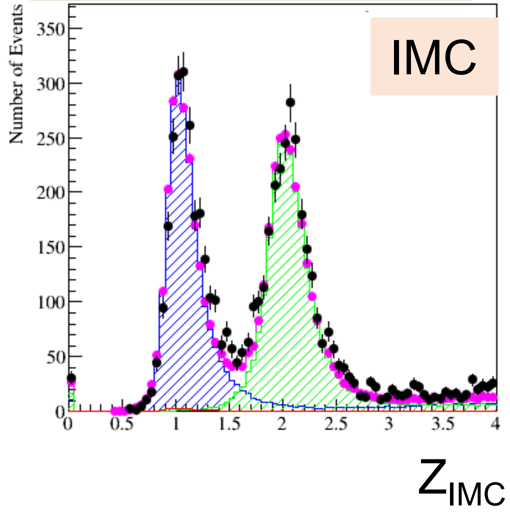
HE: 630<E<2000GeV



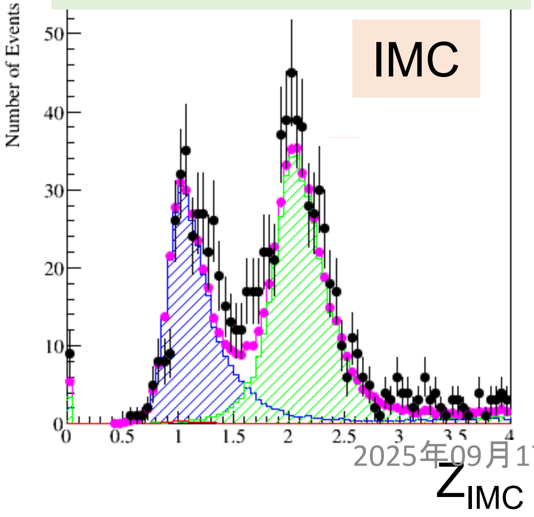




HE: 2<E<6.3TeV



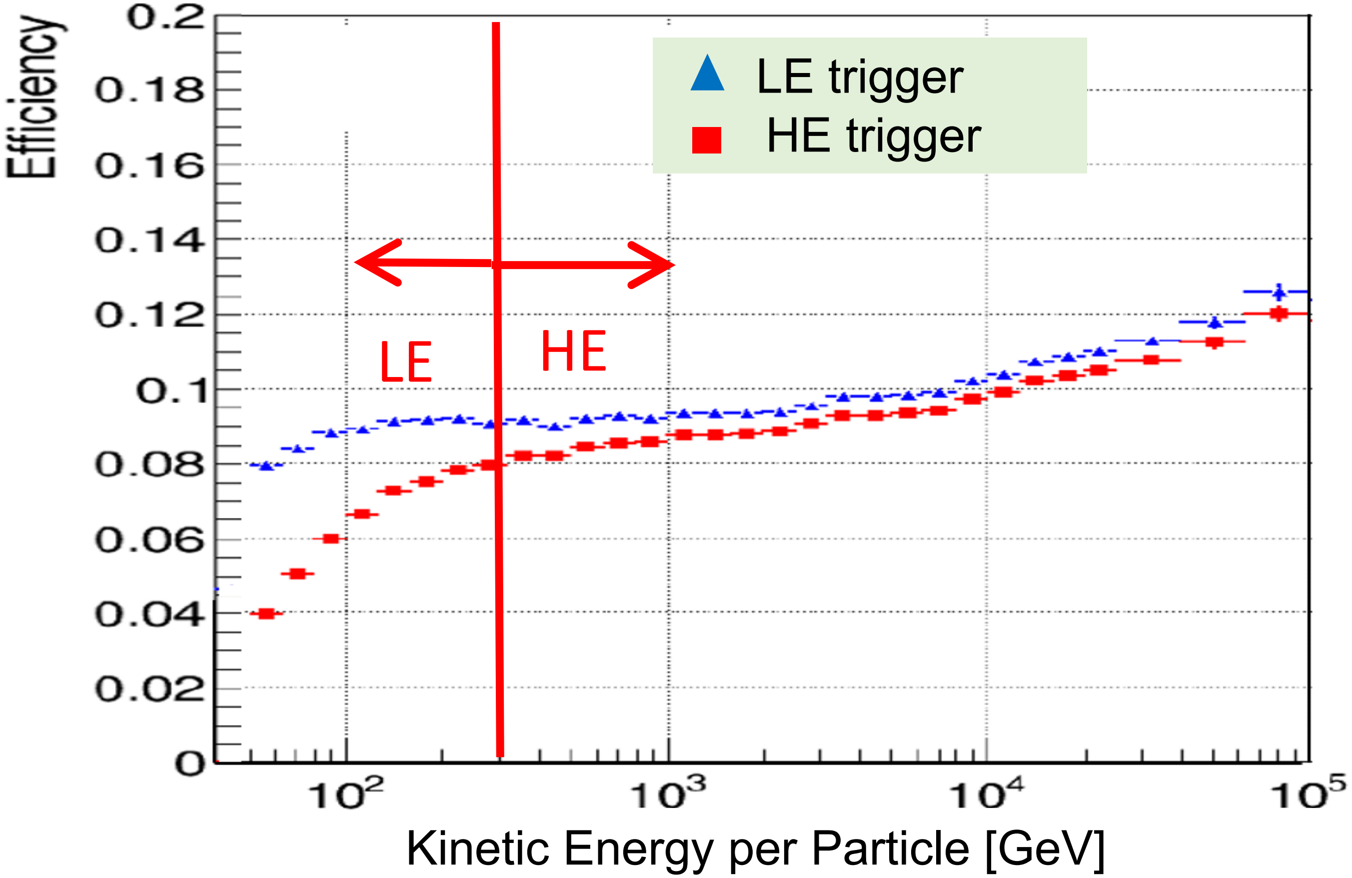
HE: 6.3<E<20TeV

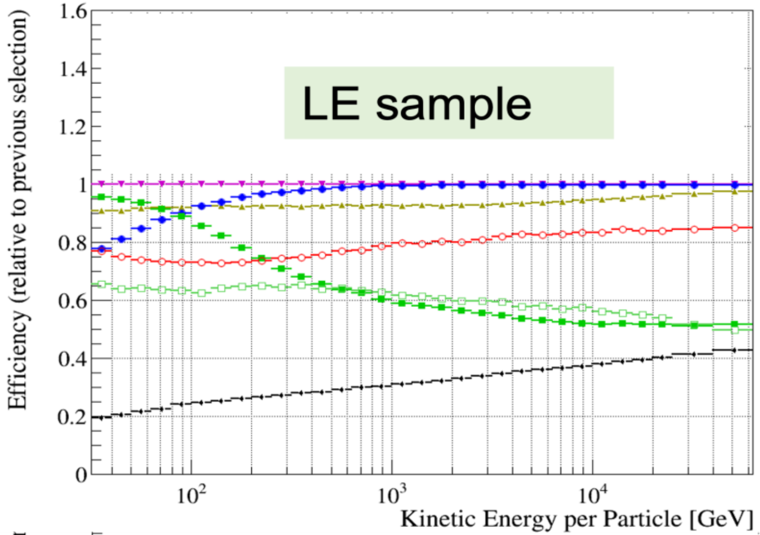


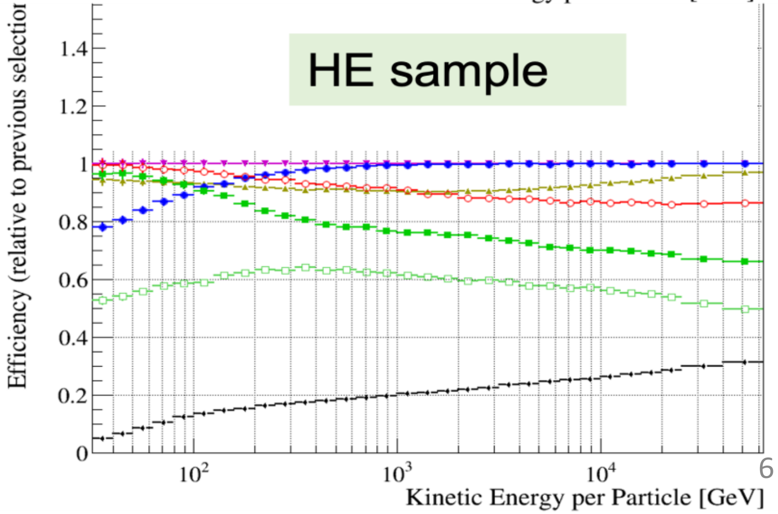
- Data
- MC all (EPICS)
- MC proton (EPICS)
- MC He (EPICS)
- MC electron (EPICS)

- 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

Detection Efficiency (proton)



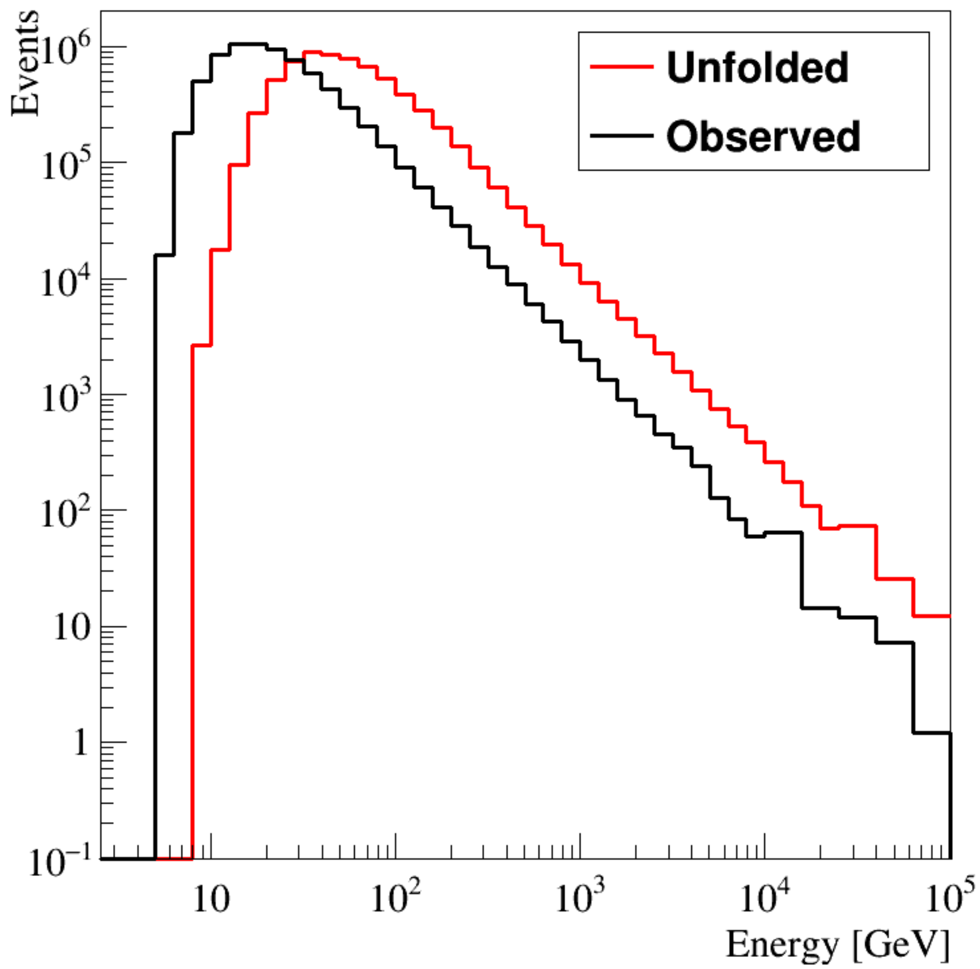




- In E>300GeV (E<300GeV), HE (LE) trigger is used. LE is used due to the high efficiency.
- Detection efficiency is 8-12% between 50 GeV and 100 TeV.

Energy Unfolding (proton)

Observed/Unfolded energy spectrum

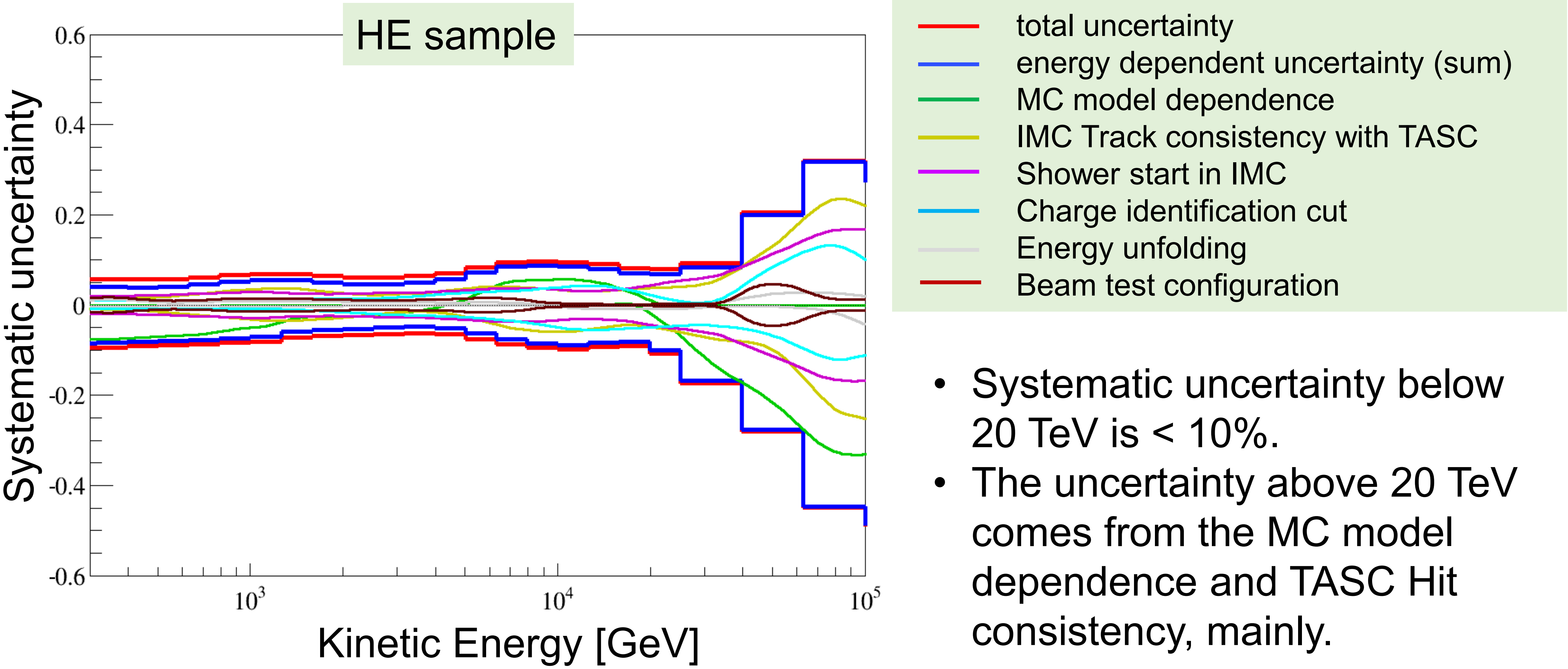


CALET’s energy resolution for protons is 30-40%. Therefore, we apply Bayesian unfolding to calculate the flux.

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

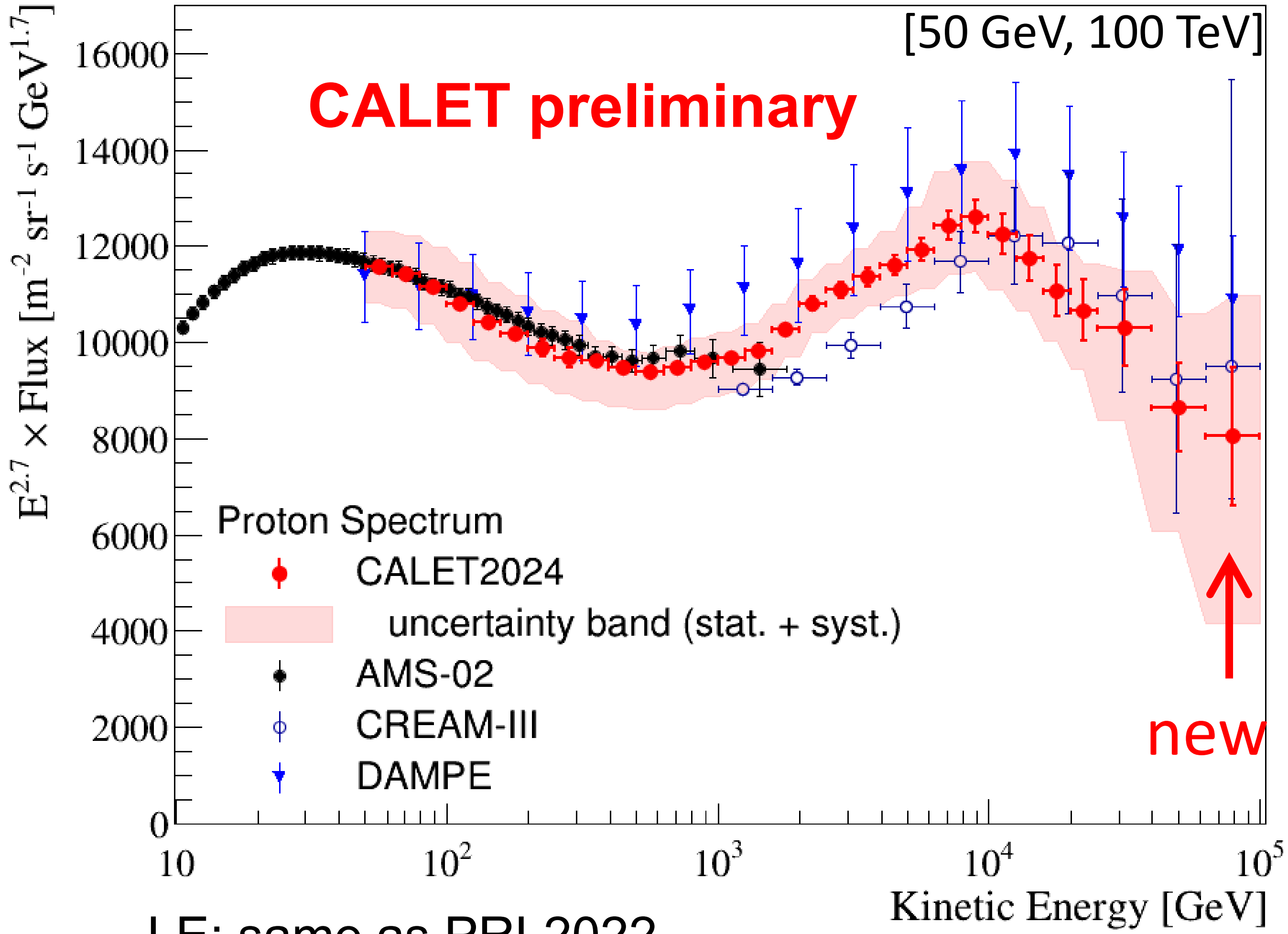
2. Apply unfolding (RooUnfold) iteratively based on Bayes theorem with helium and electron background evaluation.

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 Spectrum (50TeV<E<100TeV)



LE: same as PRL2022

HE: 2850 days of live time (Oct. 2015 – Dec. 2024)

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

$\Phi(E)$: proton flux

$N(E)$: number of events in ΔE bin (after background subtraction)

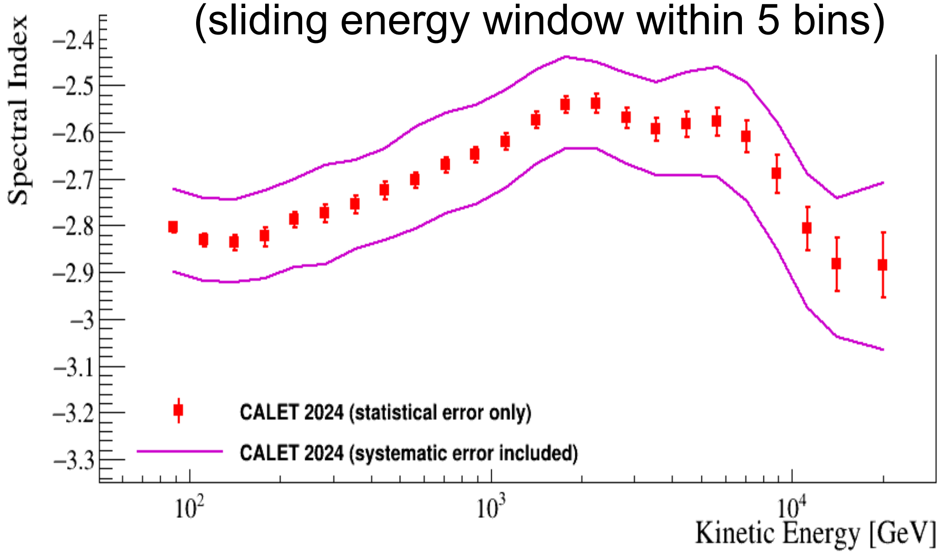
$S\Omega$: geometrical acceptance (510cm^{2}sr)

T: livetime

ΔE: energy bin width

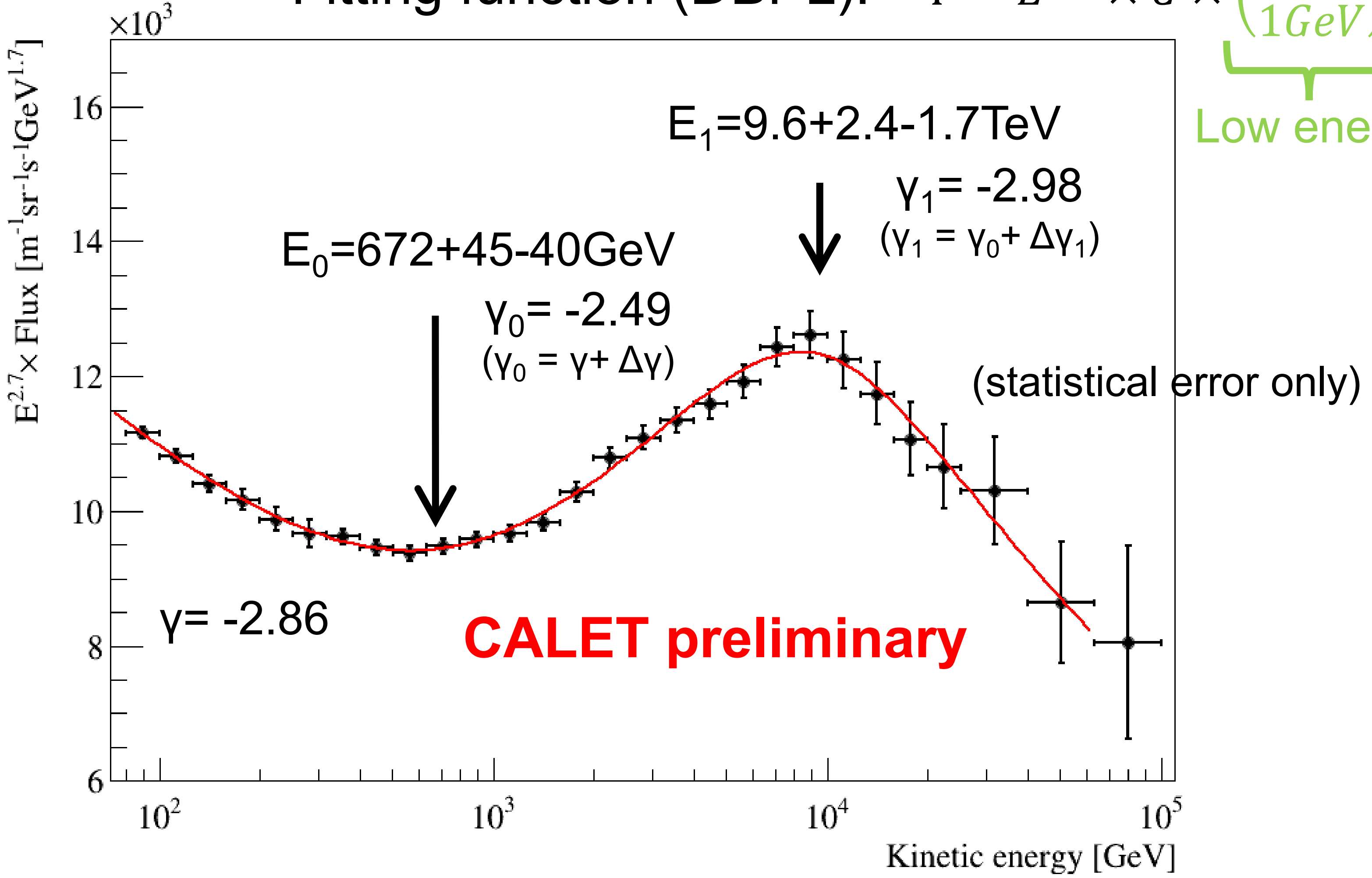
$\varepsilon(E)$: detection efficiency

Energy dependence of spectral index
(sliding energy window within 5 bins)



Proton Spectral Fit with Double Broken Power Law (DBPL)

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



$\chi^2 = 6.8/20$

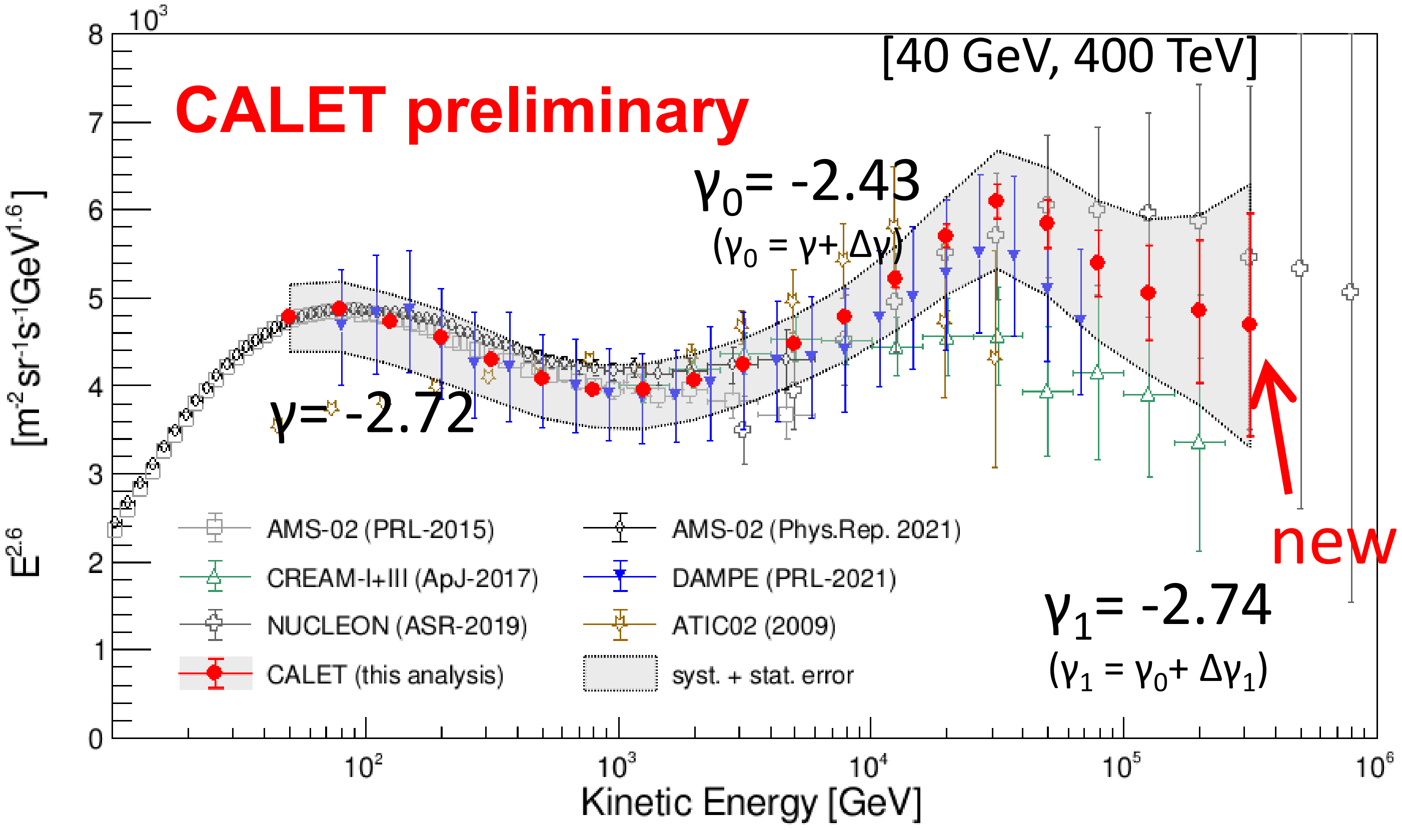
γ	-2.858+0.005-0.005
s	1.6±0.2
Δγ	(3.7±0.1)x10^{-1}
E_0	(6.72+0.45-0.40)x10^{2}
$\Delta\gamma_1$	(-4.9+1.2-1.3)x10^{-1}
E_1	(9.6+2.4-1.7)x10^{3}
s_1	2.7+3.5-0.5

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

Helium Energy Spectrum

PRL 130, 171002 (2023)
ICRC2025 update

Data: Oct. 2015 – Sep. 2020



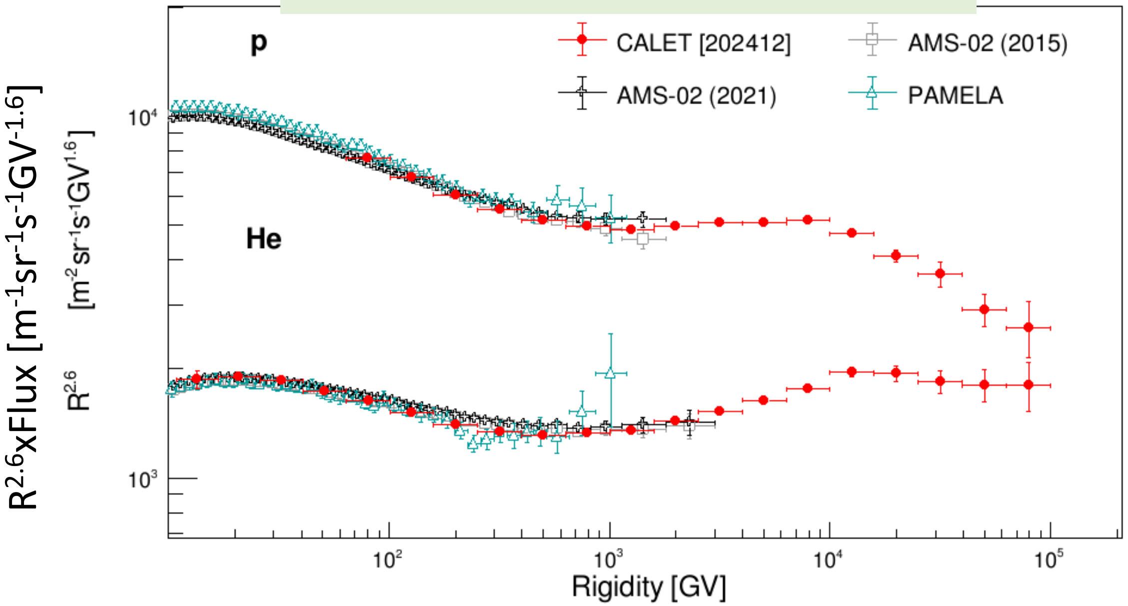
$$\Phi'(E) = C \times \left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma} \times \left[1 + \left(\frac{E}{E_0}\right)^{s}\right]^{\frac{\Delta\gamma}{s}} \times \left[1 + \left(\frac{E}{E_1}\right)^{s_1}\right]^{\frac{\Delta\gamma_1}{s_1}}$$

- We observe the spectral hardening starting at
  $$E_0 = 1.276^{+0.111}_{-0.094}(stat)^{+0.250}_{-0.198}(sys)\mathrm{TeV}$$
  This is consistent with DAMPE result (PRL 2021).
- We also observe spectral softening starting at
  $$E_1 = 34.6^{+7.2}_{-5.5}(stat)^{+1.6}_{-6.1}(sys)\mathrm{TeV}$$

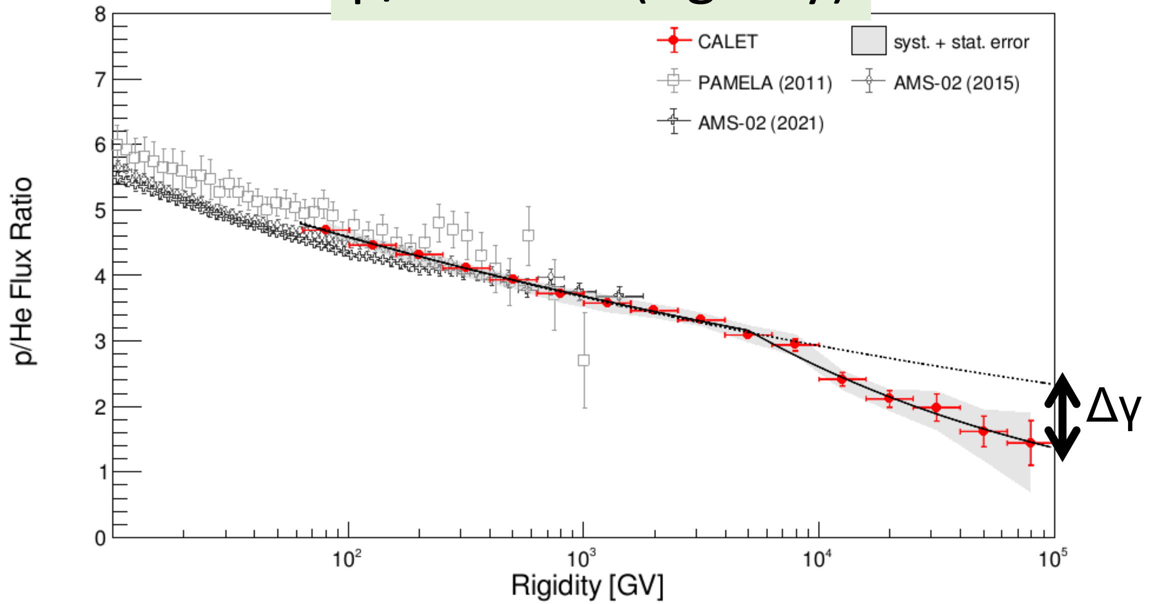
γ	-2.72±0.01±0.03
s	2.0±0.4+1.8-1.0
$\Delta\gamma$	(2.9+0.3-0.2+0.7-0.4)x10^{-1}
E_0	(1.28+0.11-0.94+0.25-0.20)x10^{3}
$\Delta\gamma_1$	(-3.1+0.7-0.9+0.6-0.8)x10^{-1}
E_1	(3.46+0.72-0.55+0.17-0.61)x10^{4}
s_1	114+83-109+194-103

Proton/He ratio

p and He fluxes (rigidity)



p/He ratio (rigidity)



- Spectral hardening and softening in rigidity are consistent between proton and helium.
- 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).
- DPL is favored with a significance of 4.8σ compared to SPL from 60 GV to 100 TV.

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

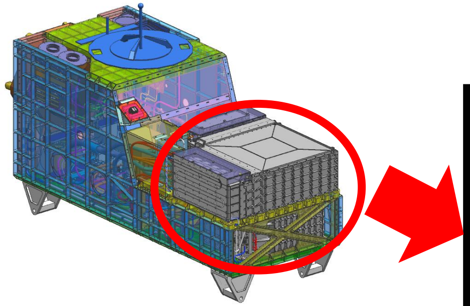
γ	-0.097±0.006
R_0	6.60±1.87 TV
Δγ	-0.23±0.08

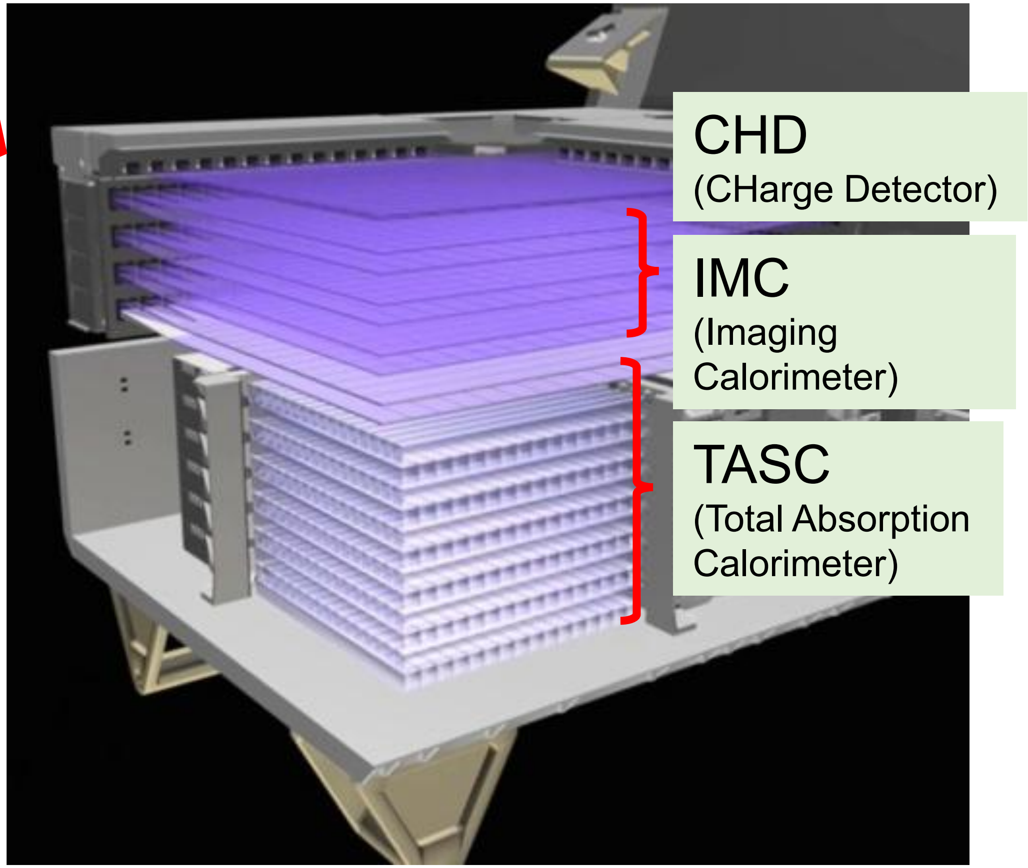
Summary

- proton
  - We have extended the proton measurement up to 100 TeV using data acquired through the end of 2024. Live time has increased by 50% from PRL2022.
  - We observed a proton spectral hardening above 672+45-40 GeV and a sharp proton spectral softening starting at 9.6+2.4-1.7TeV. The spectral index changes from -2.6 to -2.9 approximately.
- helium
  - We have extended the helium measurement up to 400 TeV using data acquired through the end of 2024. Live time has increased by 40% from PRL2023.
  - We observed a helium spectral hardening above 1.28 TeV and a sharp helium spectral softening starting at 34.6 TeV.
- p/He ratio
  - Spectral hardening in rigidity are consistent between proton and helium.
  - p/He ratio from tens GV to 10 TV is well described by SPL and that from 60 GV to 100 TV is favored by DPL.

Back up

CALET Detector

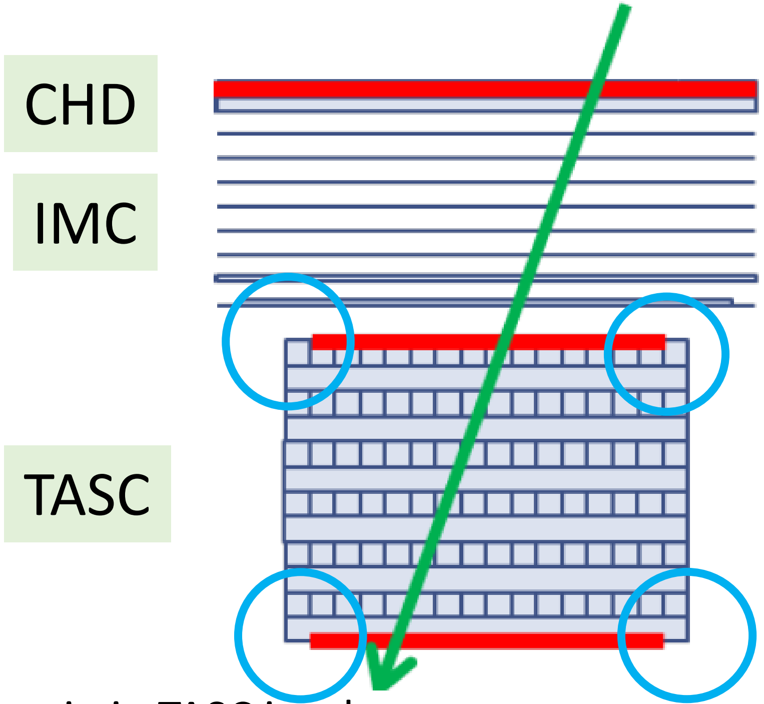




	Material/Sensor	Function
CHD	Plastic scintillator + PMT 28 paddles (=14x2layers(x,y)) (paddle size: 32x10x450mm)	Charge ID
IMC	Scifi./W + MAPMT (64anode) 7168 Scifi. (=448x16layers(x,y)) +7 W layers (Scifi. size: 1x1x448mm)	Tracking, Charge ID
TASC	PWO scintillator + APD/PD or PMT 192 logs (=16x12layers(x,y))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

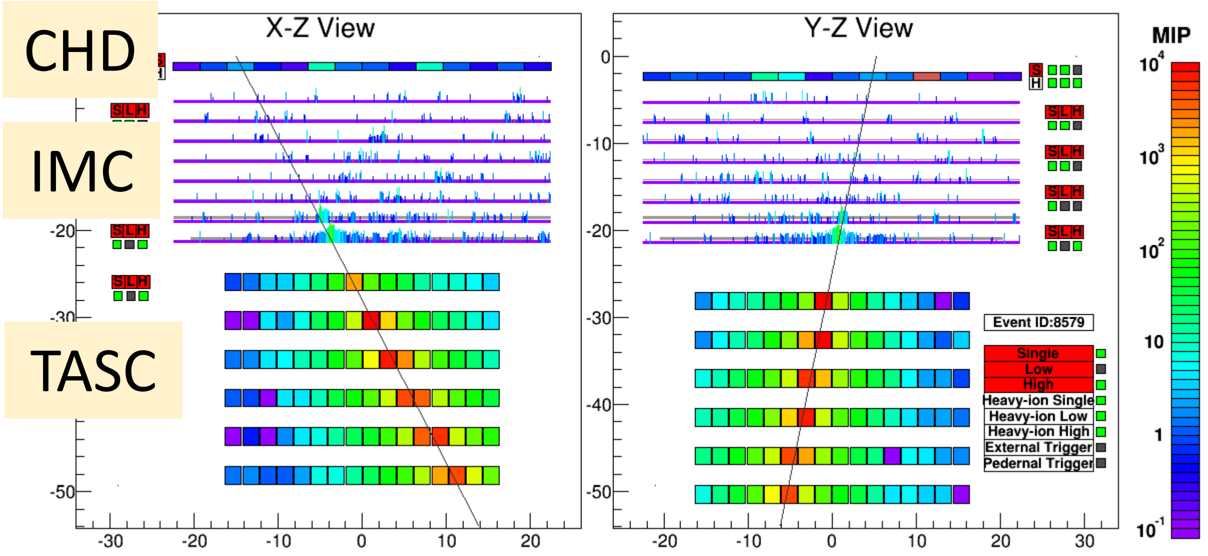
In total $30X_0$ thickness and 1.2λ,
($27X_0$ in TASC + $3X_0$ in IMC)

Geometrical acceptance and event example



2cm margin in TASC is taken.

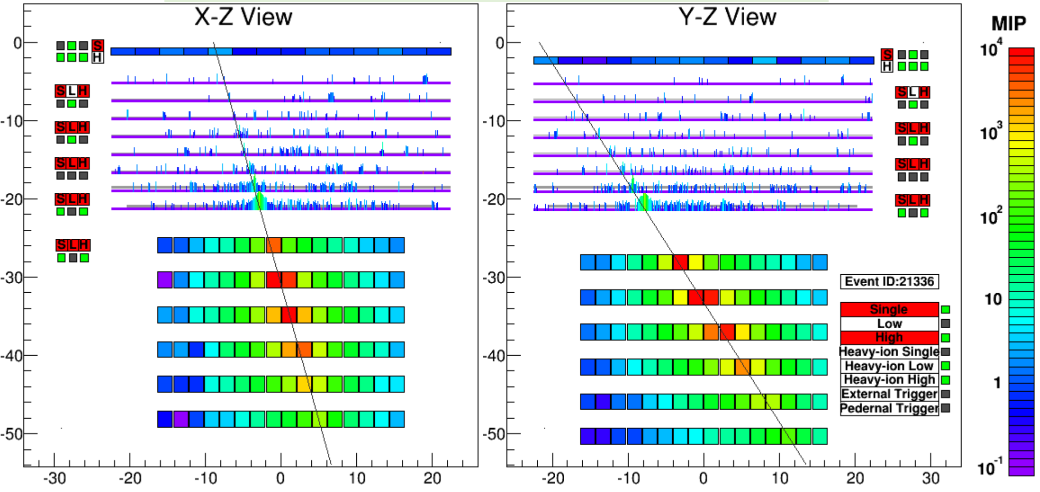
Proton, ΔE=2.89 TeV



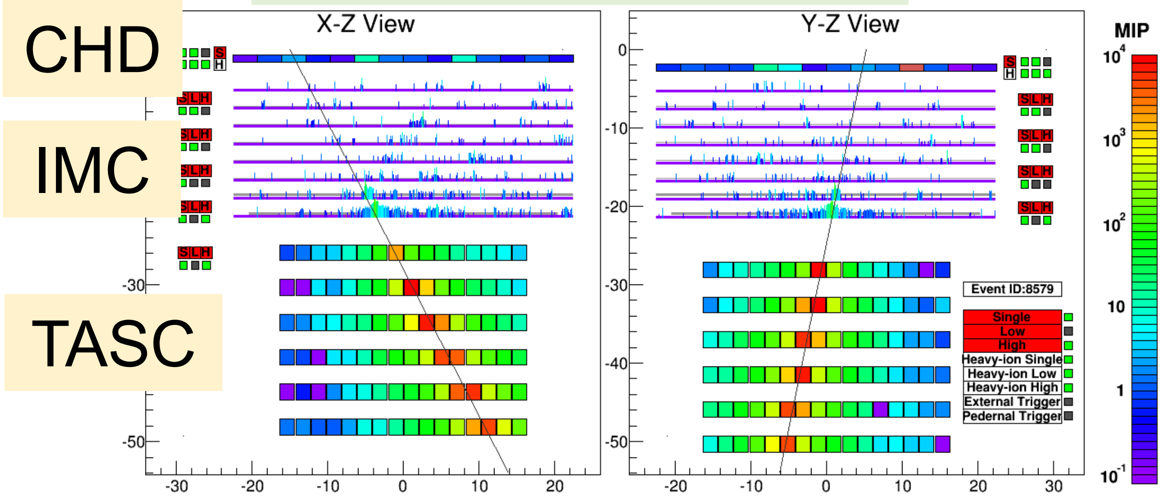
- The reconstructed track is required to cross the CHD and TASC from top to bottom.

Event Examples

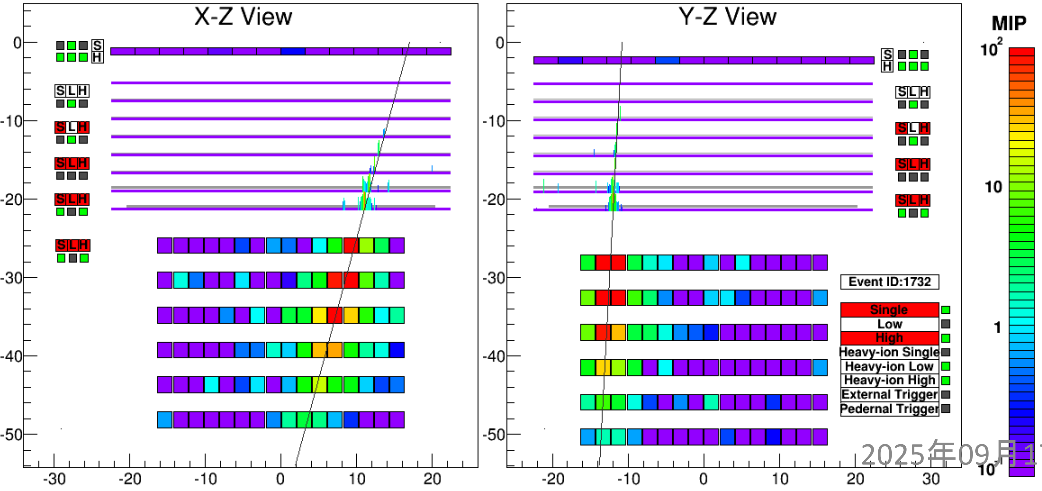
Electron, E=3.05 TeV



Proton, ΔE=2.89 TeV



Gamma-ray, E=44.3 GeV



Fe, ΔE=9.3 TeV