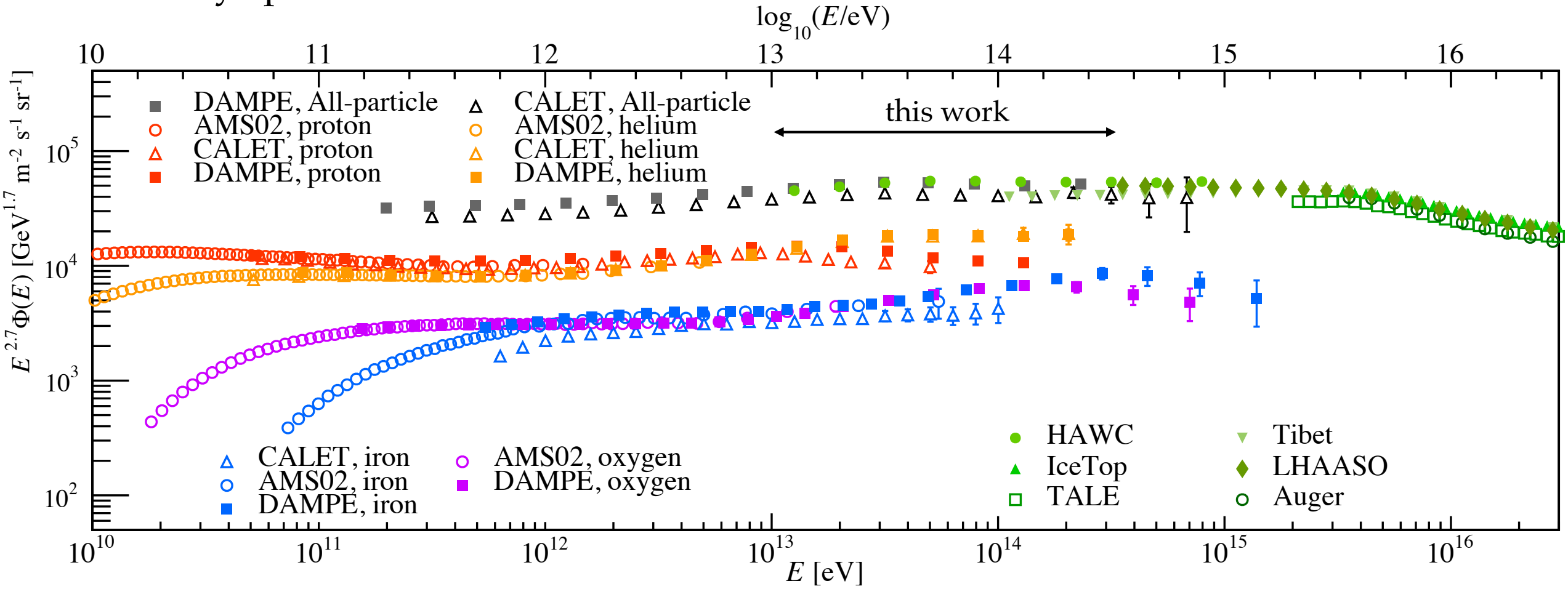
All-Particle Cosmic-Ray Spectrum in the 10-300 TeV Range with the ALPAQUITA Air-Shower Array

Sep. 03, 2026
Keitaro Fujita
Osaka Electro-Communication University
on behalf of the ALPACA Collaboration

TeV Particle Astrophysics
(TeVPA 2026)
Aug. 30 – Sep. 04, 2026
Tendo, Japan

Motivation

- Cosmic ray spectrum with direct/indirect measurements in GeV – TeV – PeV



- DAMPE / CALET reach ~1 PeV, HAWC down to 10 TeV
- We will present 10 TeV – 300 TeV spectrum measurement with ALPACA data

ALPACA experiment

Chacaltaya, Bolivia

(16° 23′ S, 68° 08′ W, 4,740 m a.s.l.)

Institute for Cosmic Ray Research, The University of Tokyo, Japan
M.Anzorena, H.Asuke, G.Imaizumi, K.Kawata, A.Mizuno, Y.Nakamura, S.Ogio, M.Ohishi, M.Ohnishi, F.Sugimoto, T.Sako, M.Takita, N.Tamaki, Y.Yamanaka, Y.Yokoe

Departamento de Física, CUCEI, Universidad de Guadalajara, Mexico
E.de la Fuente

Instituto de Investigaciones Físicas, Universidad Mayor de San Andres, Bolivia
P.Miranda, M.Raljevic, H.Rivera, M.Subieta, R.Ticona

RIKEN, Japan
R.Garcia, N.Tajima

Utsunomiya University, Japan
N.Hotta

Department of Science and Technology, Shinshu University, Japan
Y.Hayashi

Department of Physics, Shinshu University, Japan
C.Kato, S.Kobayashi, S.Mitsuishi, K.Munakata

Department of Physics, Kyoto University, Japan
S.Kato

Advanced ICT Research Institute, NICT, Japan
T.Kawashima

National Institute of Informatics, Japan
M.Nishizawa

Nuclear Science and Engineering Center, Japan Atomic Energy Agency, Japan
H.Tsuchiya

Faculty of Engineering, Kanagawa University, Japan
K.Hibino, W.Takano, S.Udo

Faculty of Engineering, Yokohama National University, Japan
J.Hochido, Y.Katayose, M.Kobayashi, Y.Takeyama, Y.Terakado

Faculty of Engineering, Osaka Electro-Communication University, Japan
K.Fujita, Y.Tameda

Tokyo Metropolitan College of Industrial Technology, Japan
T.Saito

Department of Information and Electronics, Nagano Prefectural Institute of Technology, Japan
T.K.Sako, H.Tanaka

College of Industrial Technology, Nihon University, Japan
A.Shiomi

College of Engineering, Chubu University, Japan
T.Koi, A.Oshima, K.Yamazaki

Graduate School of Engineering, Chubu University, Japan
A.Oshima

Chubu Innovative Astronomical Observatory, Chubu University, Japan
H.Kojima, S.Shibata

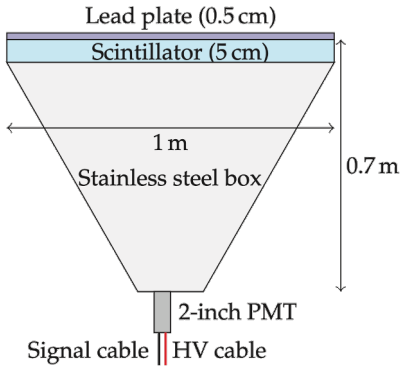
Hiroshima City University, Japan
K.Tanaka

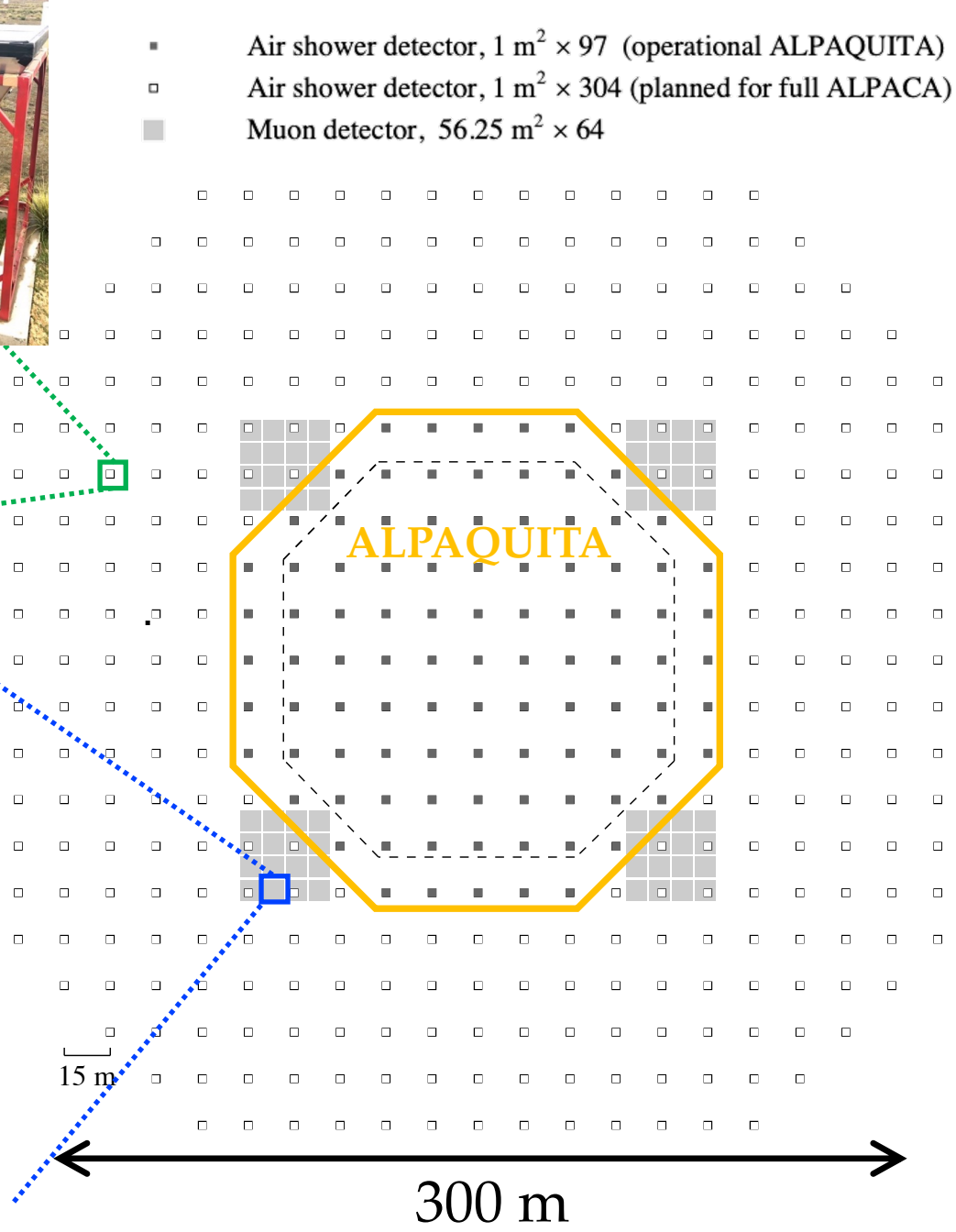
Graduate School of Science, Osaka Metropolitan University, Japan
Y.Tsunesada

ALPACA detectors

Surface Air Shower Array (Coverage: 83,000 m²)

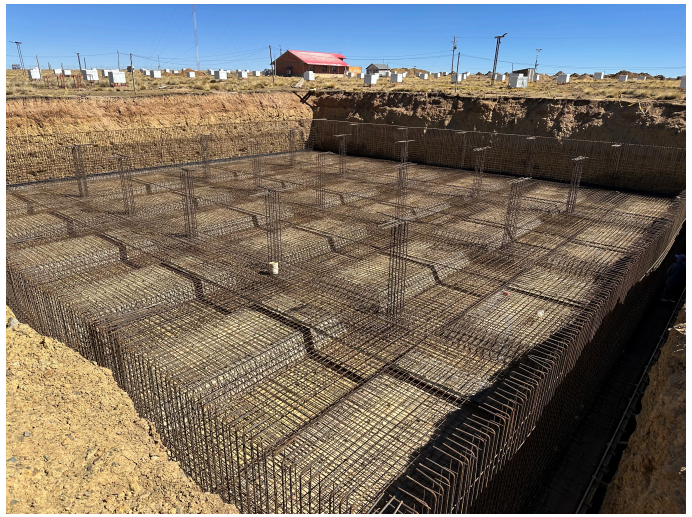
- 1 m² scintillation detector
  - × 401 counters
  - 5cm scintillatior
  - 5mm lead plate on the top
  - 15m spacing

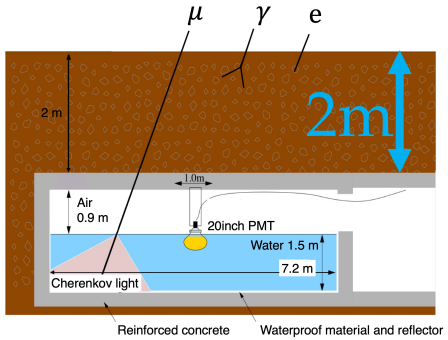




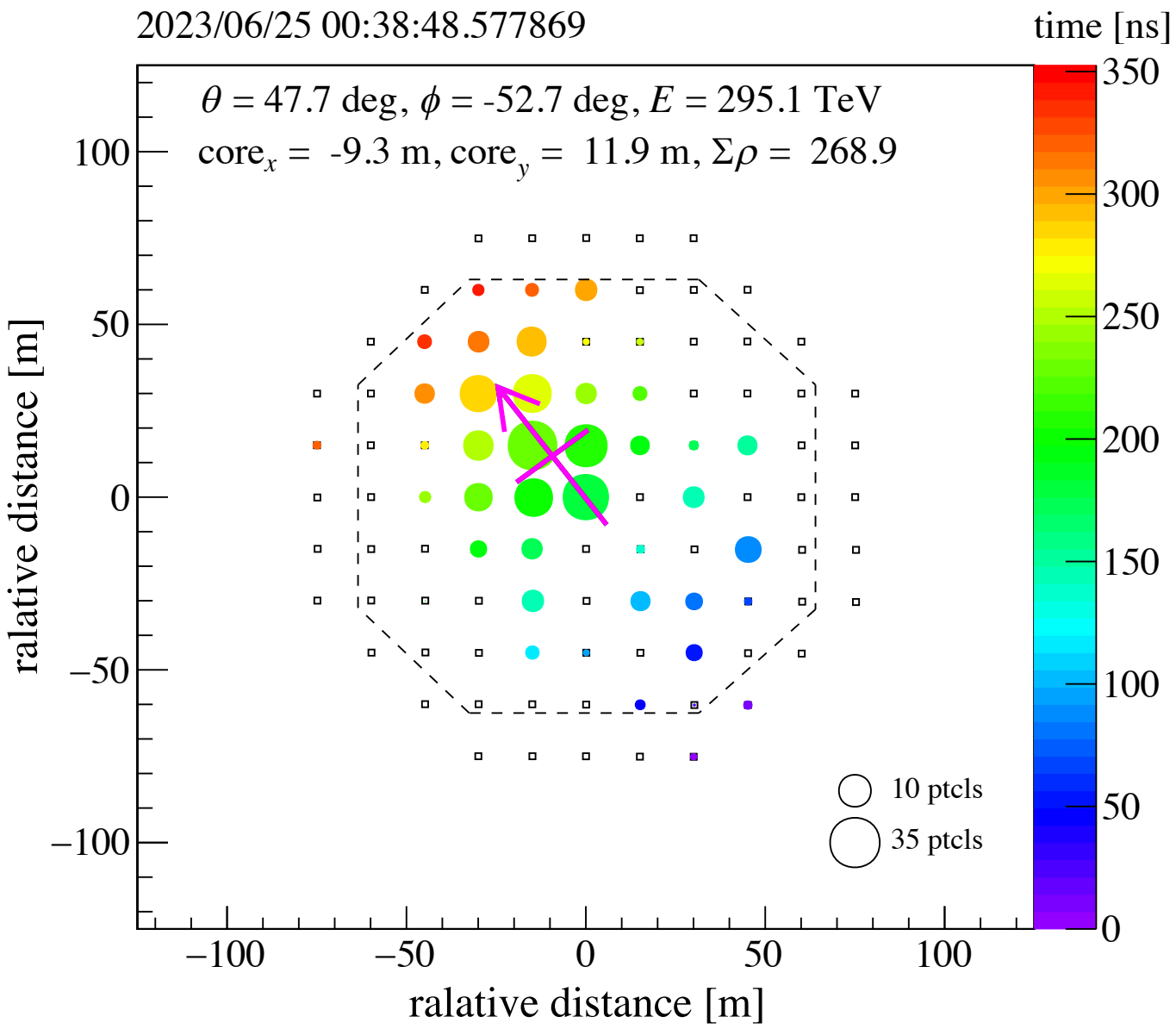
Underground Muon Detector Array (Total area: 3,600 m²)

- 56 m² / cells × 64 cells
- Provide good γ/h separation + composition sensitivity by # of μ in air-showers





ALPAQUITA air-shower array



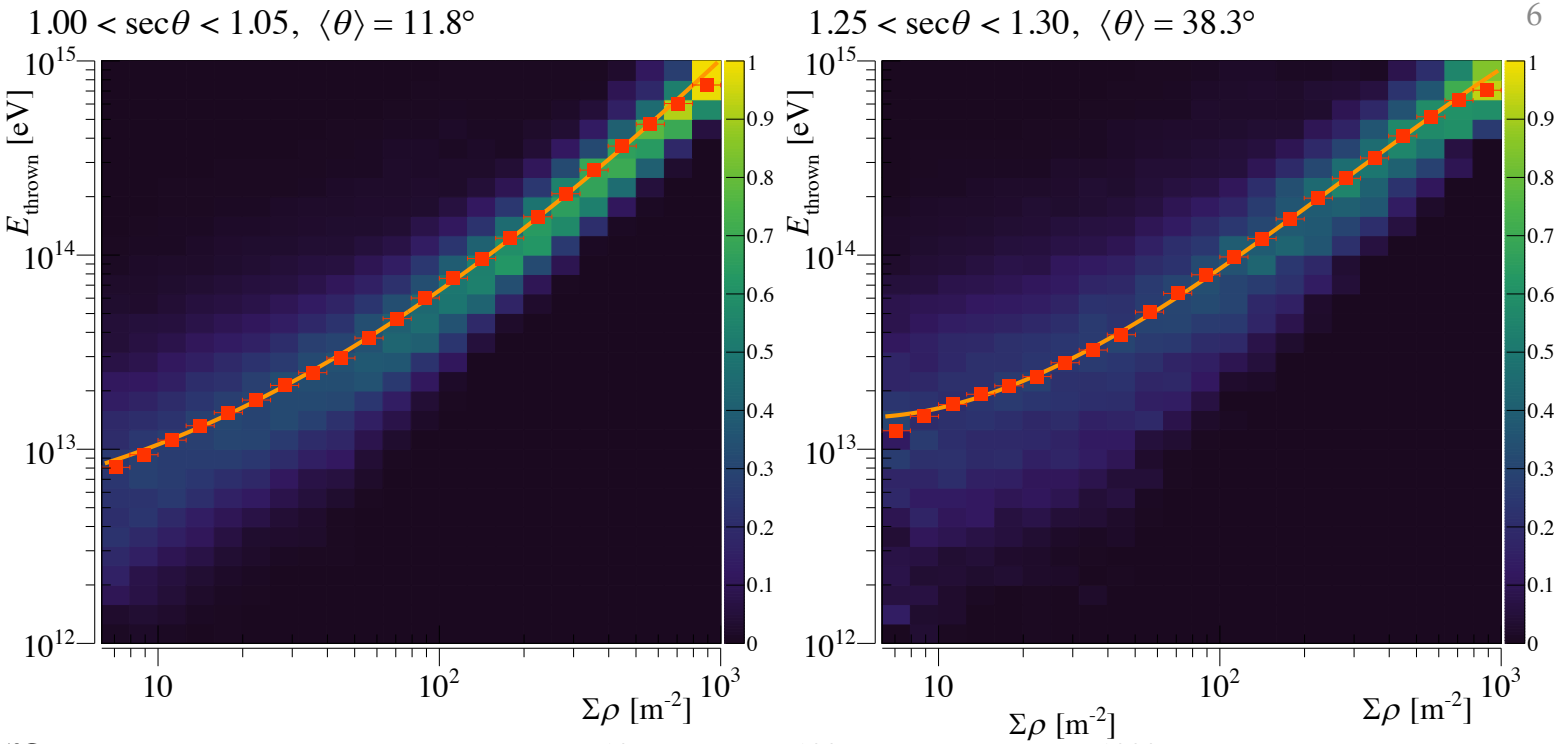
- ~1/4 size of full-ALPACA array
  - 97 scintillation detectors
  - Operating since 2023
- Sampling air-shower signals
  - Records hit timing and # of ptcls
- Core position

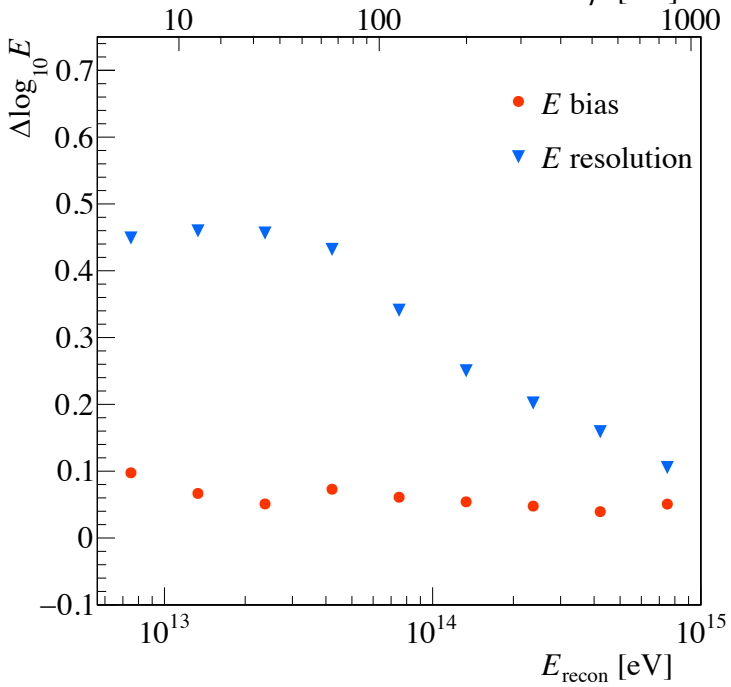
$$(x_c,\ y_c) = \left(\frac{\sum_i \rho_i{}^2 x_i}{\sum_i \rho_i{}^2},\ \frac{\sum_i \rho_i{}^2 y_i}{\sum_i \rho_i{}^2} \right)$$

- Arrival direction
  - Use relative timing differences
  - Assuming conical shower front
- Energy
  - function of $\Sigma\rho$ and θ (next page)

Energy estimation

- E estimator: $\Sigma\rho$
  - $\Sigma\rho$-E relation determined for each zenith-angle bin
  - Accounts for θ dependence of atmospheric attenuation
- Event selection
  - zenith angle < 40 deg
  - geom. fit $\chi < 1.0$
  - Above 1.25 ptcls with any 4 detectors
  - top 2/3 signals should be inside of inner area
  - $\log_{10}(\Sigma\rho\,/\,\mathrm{m}^2) < 2.8$
- Resolution
  - Arrival direction: ~1deg, $E > 10$ TeV
  - Core position: ~15m, $E > 10$ TeV
  - Energy: Right-Fig.

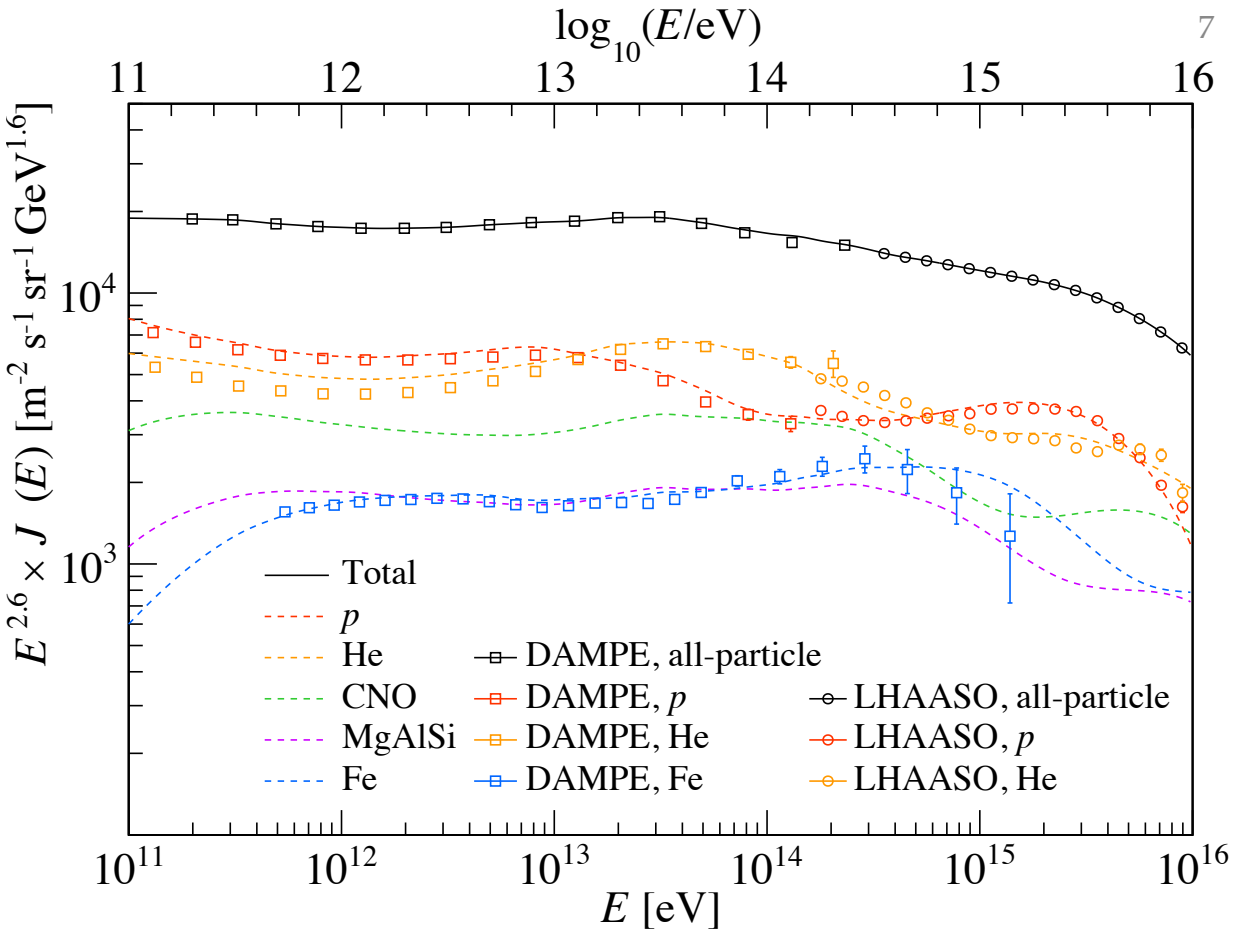




Datasets

- Observational data
  - 2023 Jun. - 2024 Apr., ~240 days
  - ~10^9 events used

- MC simulations
  - CORSIKA
  - Interaction model: EPOS-LHC + FLUKA
    - syst. study with QGSJet II-04 and Sibyll 2.3e
  - primary: *p* / He / N / Si / Fe
    - weighted to follow Right-Fig. CR flux model
  - *E* range: 300 GeV to 1 PeV
  - Zenith angle: 0 - 50 deg
  - Full detector simulation with GEANT4



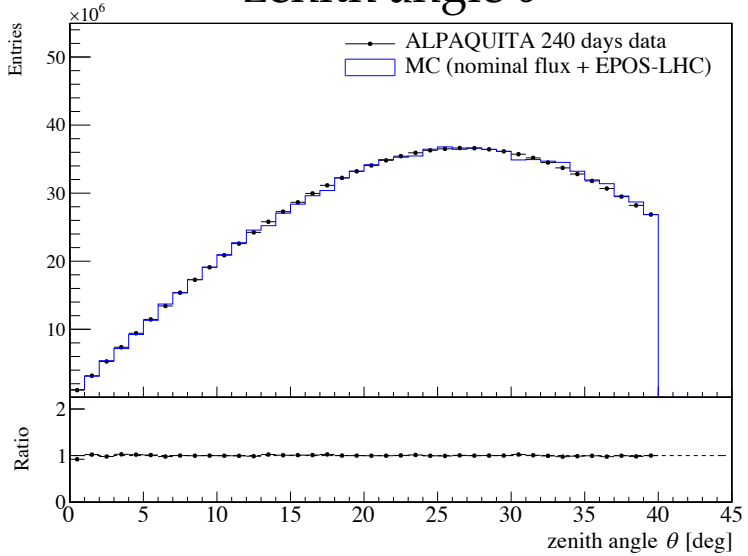
Nominal CR flux model derived from DAMPE and LHAASO data

LHAASO collaboration, Phys. Rev. Lett 132, 131002 (2024)
LHAASO collaboration, Phys. Rev. Lett 136, 121001 (2026)
DAMPE collaboration, Nature 653, 52 (2026)
DAMPE collaboration, PoS(ICRC2025)021

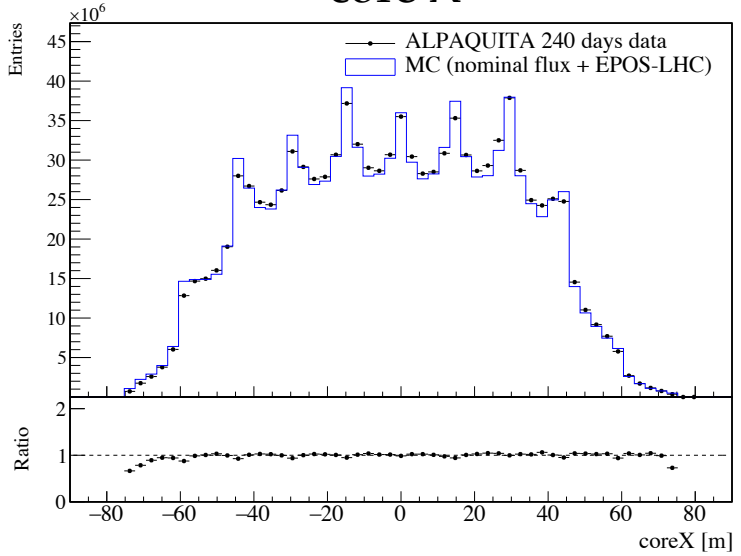
Data/MC comparisons

- Comparisons show reasonable agreement between observational data and MC

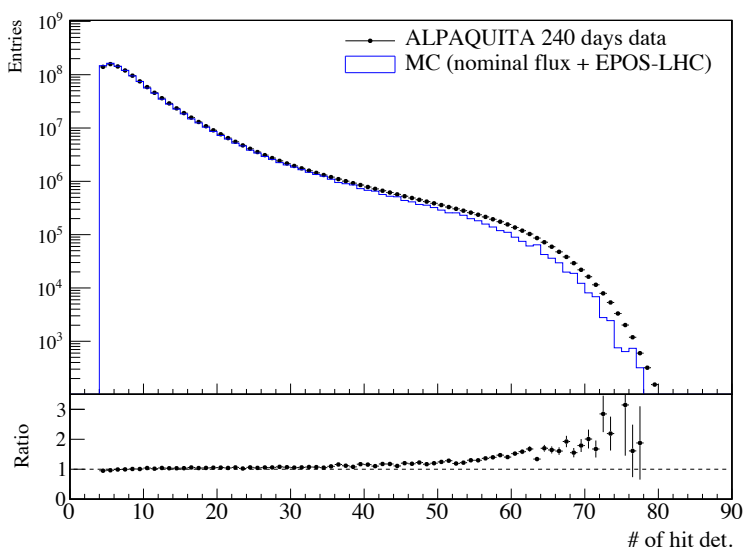
zenith angle θ



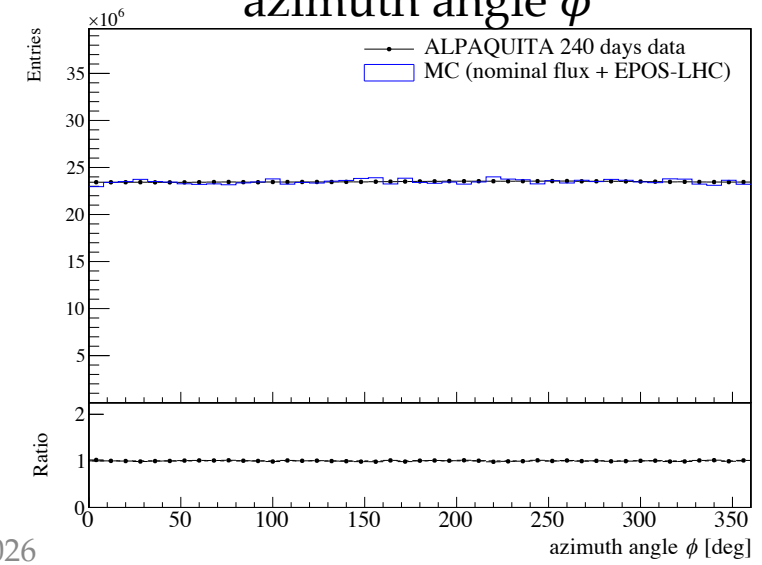
core X



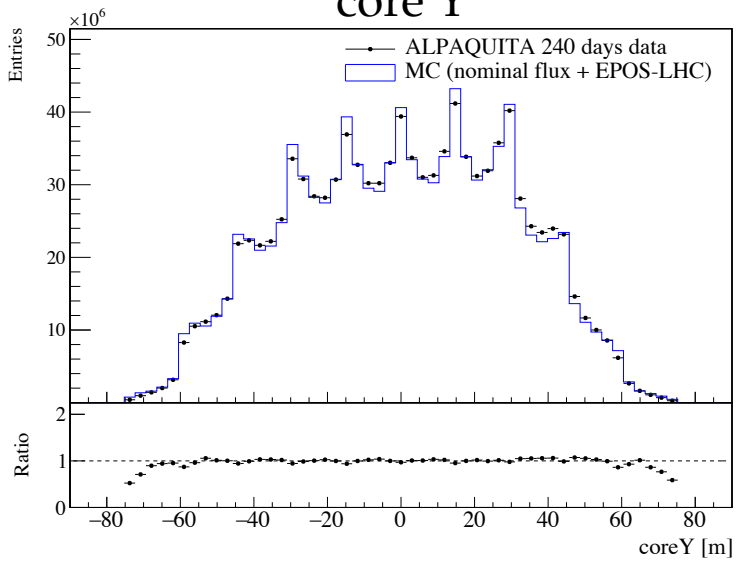
# of hit detector



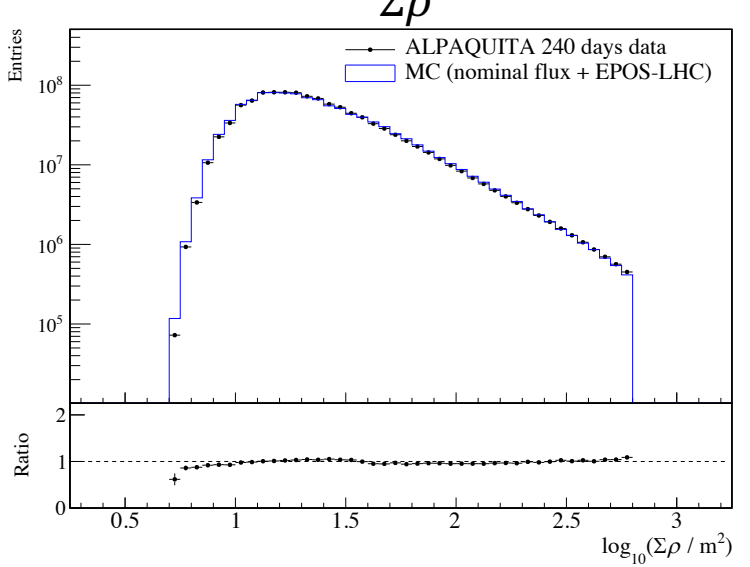
azimuth angle ϕ



core Y



$\Sigma\rho$



Spectrum measurement

- Energy spectrum:

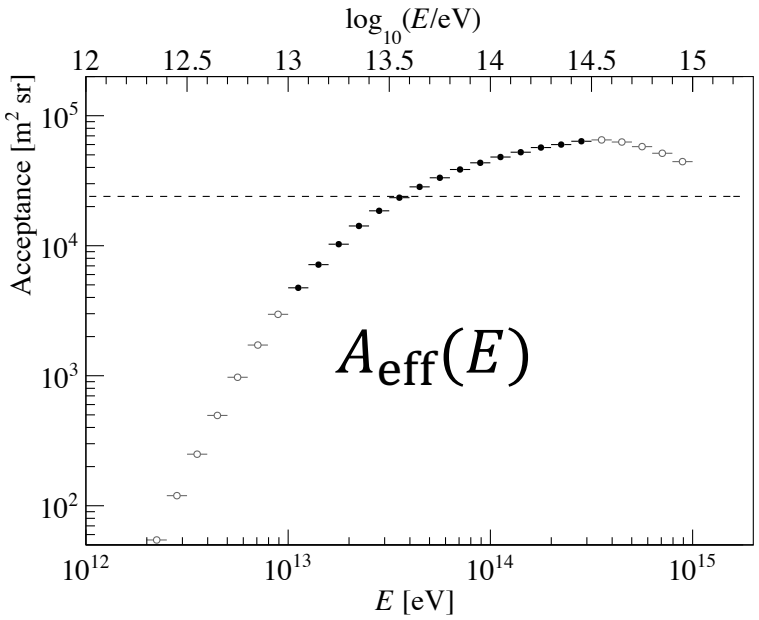
$$\Phi(E) = \frac{N(E)}{A_{\mathrm{eff}}(E)\, T\, \Delta E}$$

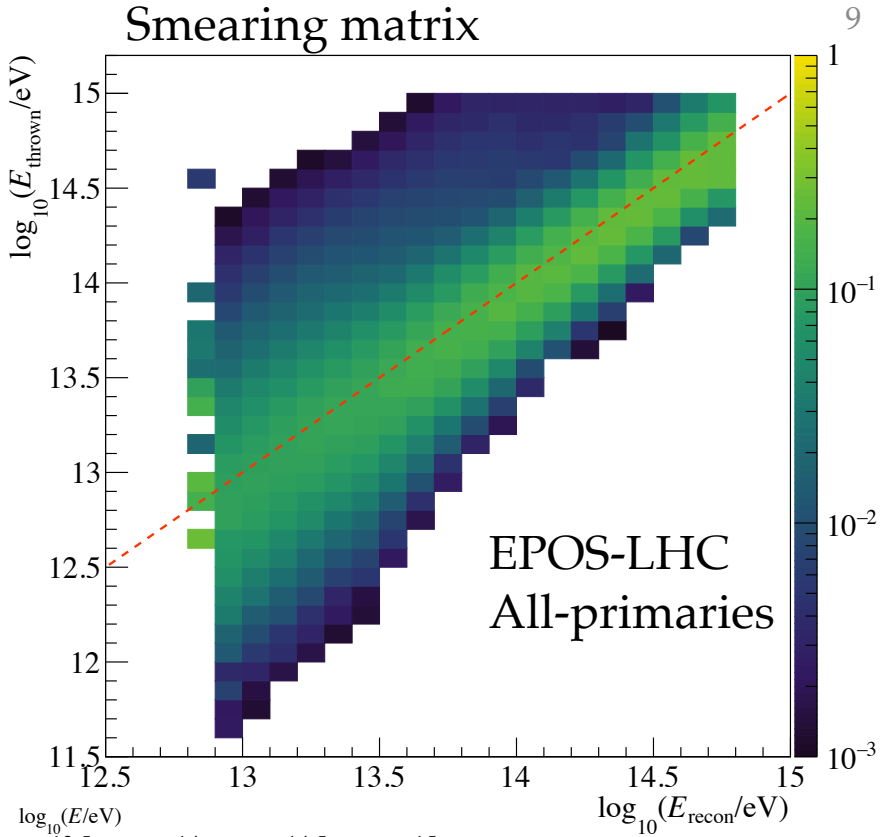
  - $N(E)$: unfolded distribution
  - $A_{\mathrm{eff}}(E)$: detector acceptance [m² sr]
  - T: observation time ~ 240days
  - ΔE: bin size of energy

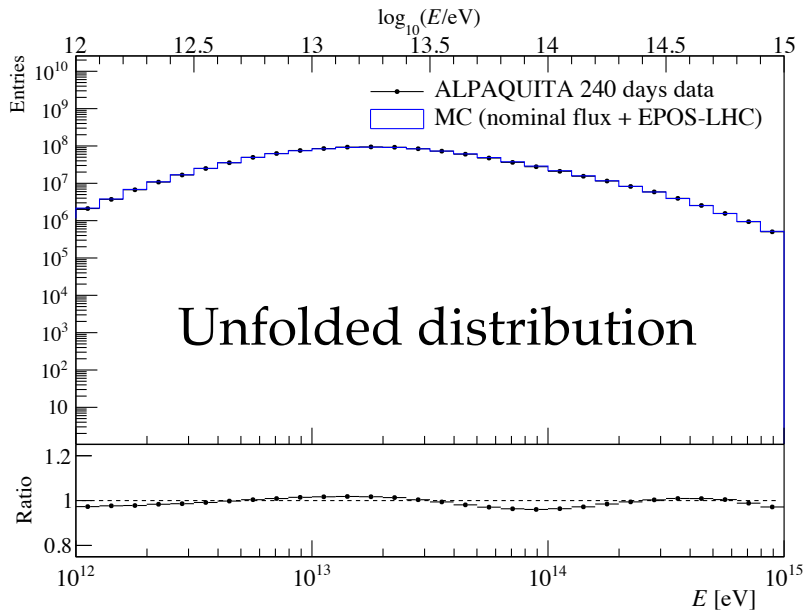
- Unfolding method

$$N(E) = \Sigma\, N(E_{\mathrm{recon}}) P(E|E_{\mathrm{recon}})$$

  - $N(E)$: unfolded energy distribution
  - $N(E_{\mathrm{recon}})$: raw energy distribution
  - $P(E|E_{\mathrm{recon}})$: smearing matrix
    - Use Bayes' unfolding method [D'Agostini, NIMA 362, (1995) 487]

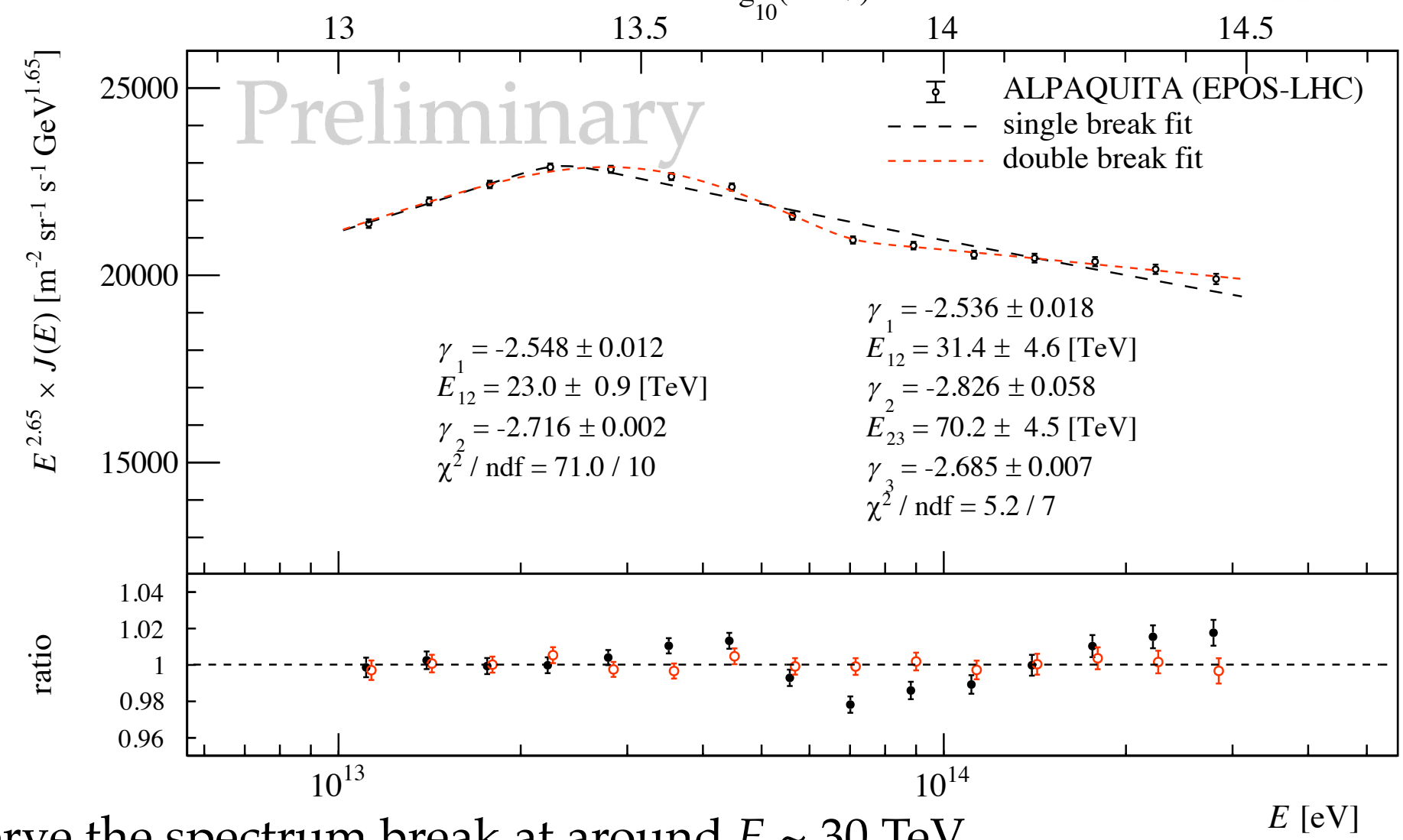






ALPAQUITA spectrum

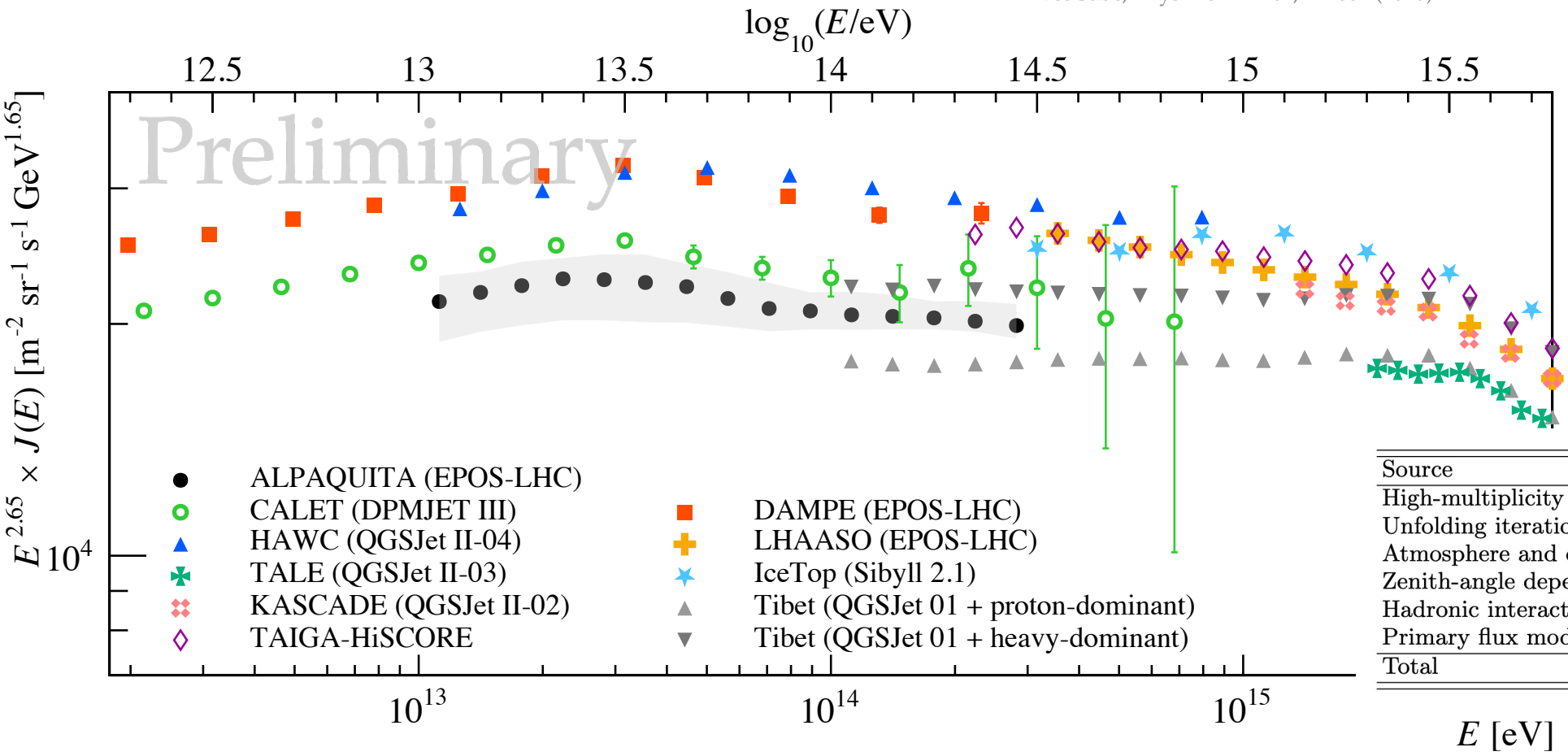
$$J(E) = J_0 \left(\frac{E}{E_0}\right)^{-\gamma_1} \prod_{i=1}^{1\text{ or }2} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}$$



- We observe the spectrum break at around $E \sim 30$ TeV
- In addition, our data favor a double-break fit

Spectrum comparison

LHAASO, Phys. Rev. Lett 132, 131002 (2024)
DAMPE, PoS(ICRC2025)021
CALET, PoS(ICRC2025)004
HAWC, Astropart. Phys., 167, 103077
IceCube, Phys. Rev. D 102, 122001 (2020)
Tibet, Astrophys. J. 678, 1165 (2008)
Telescope Array, ApJ. 865, 74 (2018)
KASCADE, Astropart. Phys. 47, 54 (2013)
TAIGA-HiSCORE, Bull. Russ. Acad. Sci. Phys. 89, 907 (2025)



Source	Maximum contribution
High-multiplicity events	$\leq 1.0\%$
Unfolding iterations	$\leq 1.0\%$
Atmosphere and detector response	$\leq 1.5\%$
Zenith-angle dependence	$\leq 2.5\%$
Hadronic interaction model	-4.5% to $+8.5\%$
Primary flux model	-11.0% to $+4.5\%$
Total	-12.3% to $+10.1\%$

- Spectral break around 30 TeV is consistent with the structure seen by CALET, DAMPE and HAWC

Conclusions

- ALPACA has been operating at Bolivia since 2023 with ALPAQUITA air-shower array
- We measured the all-particle cosmic-ray spectrum from 10 to 300 TeV with the ALPAQUITA air-shower array
- A clear spectral break is observed around 30 TeV, consistent with recent direct measurements
- The spectrum shows an additional structure around 70 TeV