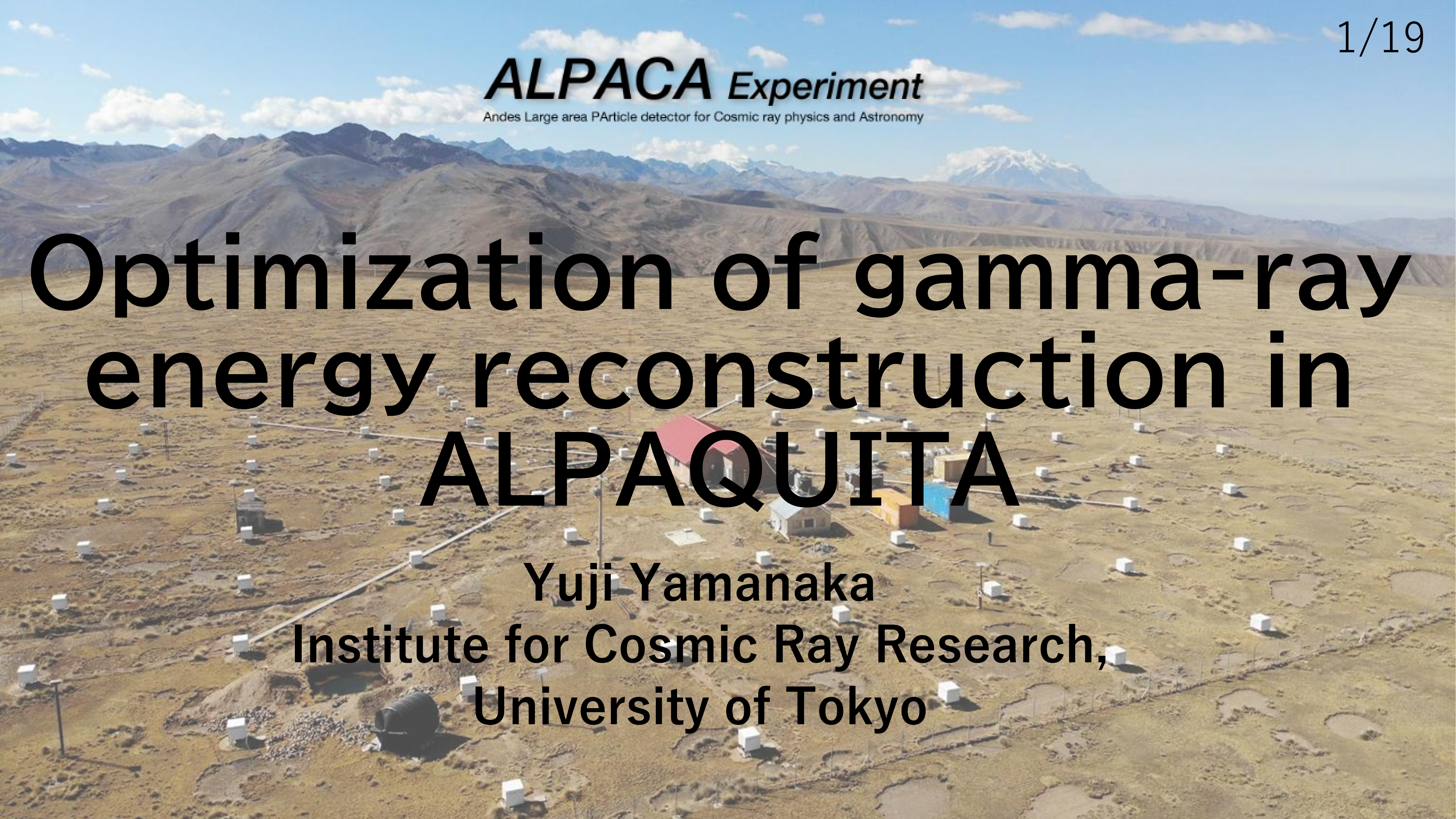


ALPACA Experiment

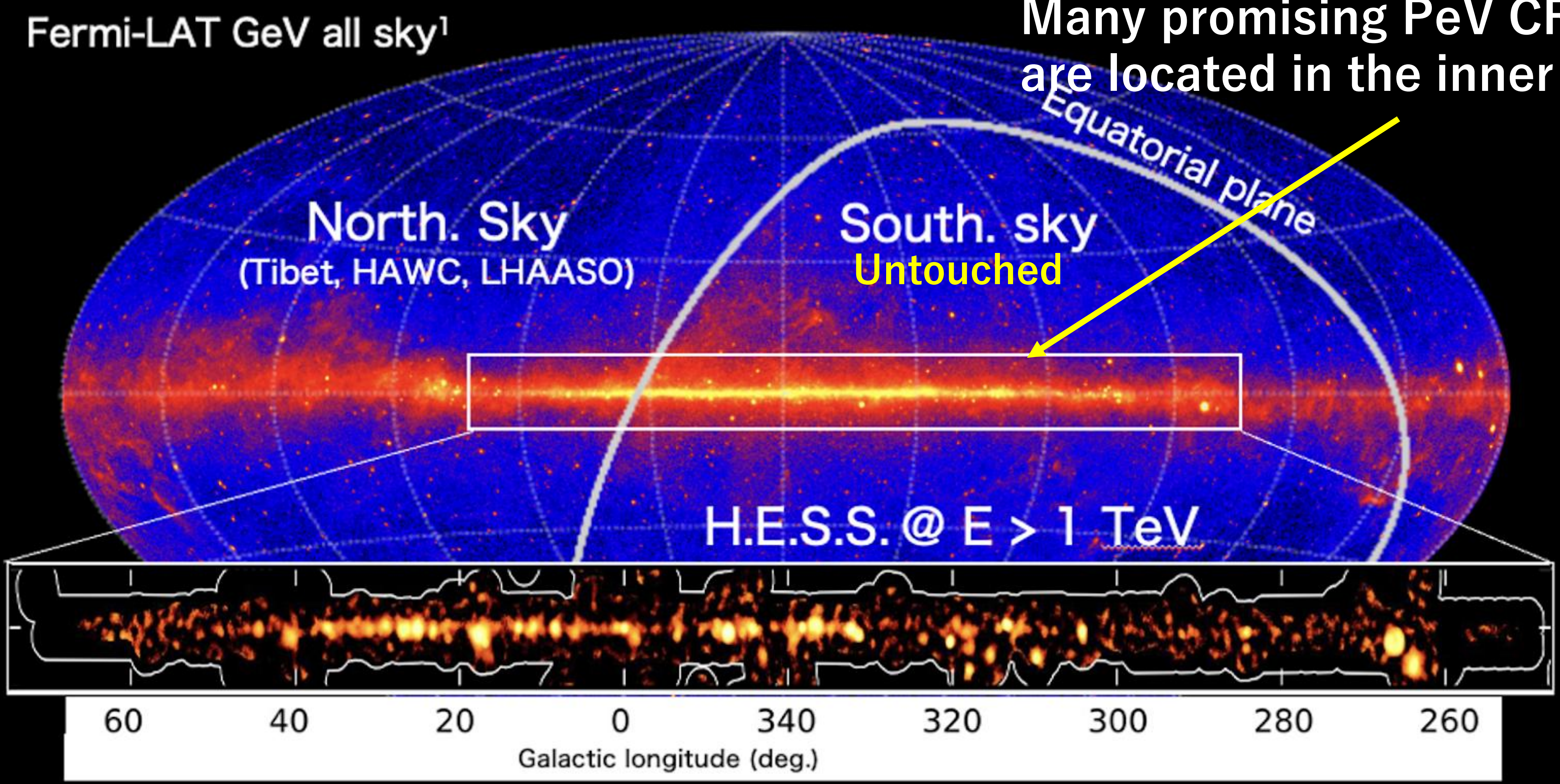
Andes Large area PArticle detector for Cosmic ray physics and Astronomy

Optimization of gamma-ray energy reconstruction in ALPAQUITA

Yuji Yamanaka
Institute for Cosmic Ray Research,
University of Tokyo

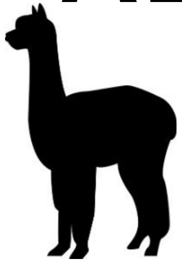
Southern Sky: A Promising Region for PeVatron Searches

Many promising PeV CR accelerators are located in the inner Galaxy.



Good energy resolution is essential for PeVatron searches.

ALPACA collaboration



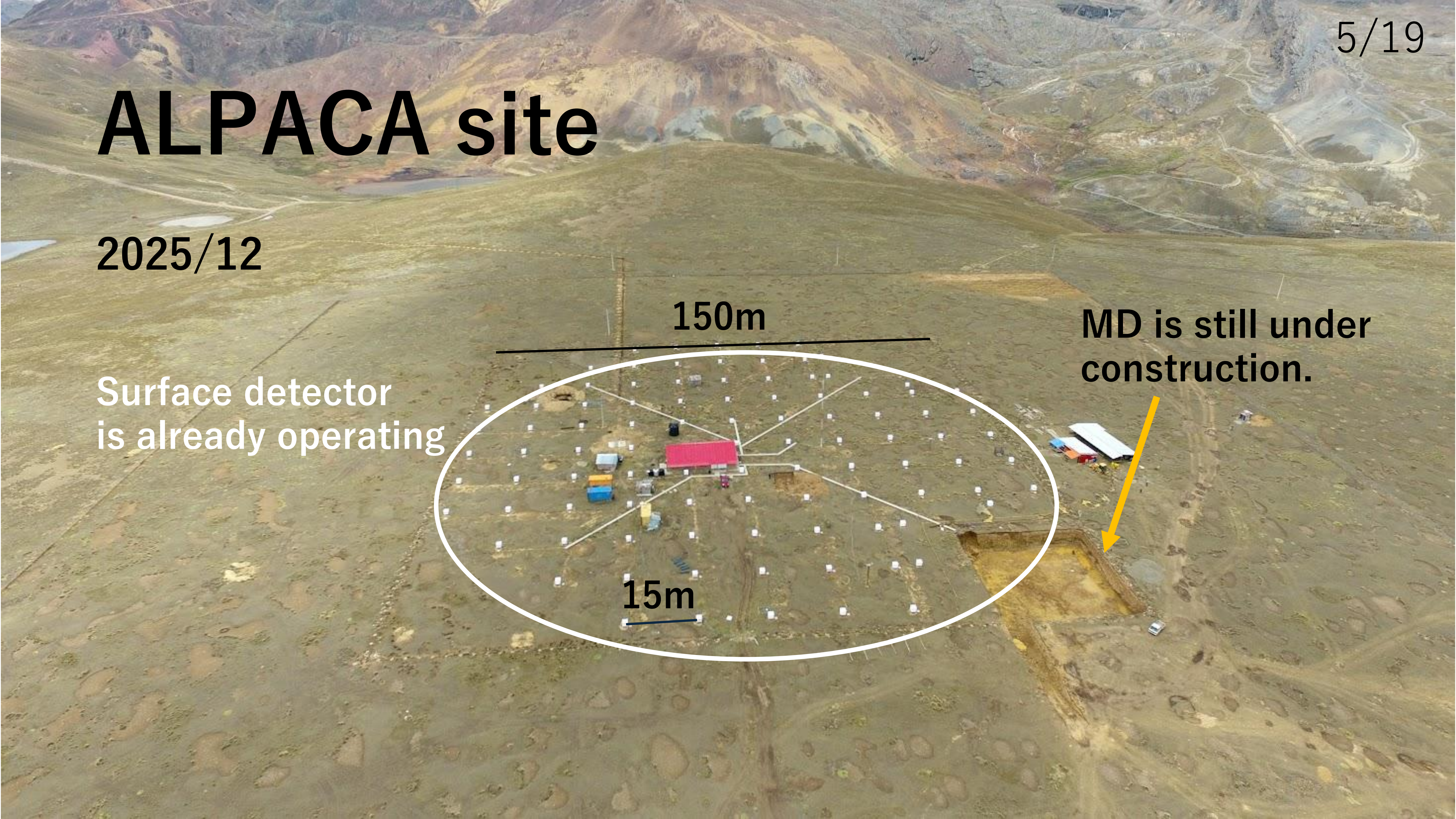
M. Anzorena[1], H. Asuke[1], E. de la Fuente[1,2,3], K. Fujita[4], R. Garcia[5], Y. Hayashi[6], K. Hibino[7], R. Higuchi[1], J. Hochido[8], N. Hotta[9], G. Imaizumi[1], A. Jimenez-Meza[3], Y. Katayose[8], C. Kato[10], S. Kato[11], T. Kawashima[12], K. Kawata[1], M. Kobayashi[8], S. Kobayashi[10], T. Koi[13], H. Kojima[14], P. Miranda[15], S. Mitsuishi[10], A. Mizuno[1], K. Munakata[10], Y. Nakamura[1], M. Nishizawa[16], S. Ogio[1], M. Ohishi[1], M. Ohnishi[1], A. Okumura[1], A. Oshima[13,17], M. Raljevic[15], H. Rivera[15], T. Saito[18], T. Sako[1], T. K. Sako[19], S. Shibata[14], A. Shiomi[20], M. Subieta[15], F. Sugimoto[1], N. Tajima[5], W. Takano[7], Y. Takeyama[8], M. Takita[1], N. Tamaki[1], Y. Tameda[4], H. Tanaka[19], K. Tanaka[21], Y. Terakado[8], R. Ticona[15], H. Tsuchiya[22], Y. Tsunesada[23,24], S. Udo[7], Y. Yamanaka[1], K. Yamazaki[13] and Y. Yokoe[1]

[1]ICRR, U. of Tokyo, [2]Dept. de Fís., CUCEI, Univ. de Guadalajara, [3]Doct. en Tecn. de la Info., CUCEA, Univ. de Guadalajara, [4]Fac. of Engn., Osaka Elec.-Comm. Univ., [5]RIKEN, [6]Dept. of Sci. and Tech., Shinshu Univ., [7]Fac. of Engn., Kanagawa Univ., [8]Fac. of Engn., Yokohama Natl. Univ., [9]Utsunomiya Univ., [10]Dept. of Phys., Shinshu Univ., [11]Dept. of Phys., Kyoto Univ., [12]NICT, [13]Coll. Engn., Chubu Univ., [14]Chubu Inn. Astro. Obs., Chubu Univ., [15]IIF, UMSA, [16]NII, [17]Grad. Sch. of Engn., Chubu Univ., [18]Tokyo Metro. Coll. of Ind. Tech., [19]Dept. of Info. and Elec., Nagano Pref. Inst. of Tech., [20]Coll. of Ind. Tech., Nihon Univ., [21]Hiroshima City Univ., [22]JAEA, [23]Grad. Sch. of Sci., Osaka Metro. Univ., [24]NYITEP, Osaka Metro. Univ.

The ALPACA site

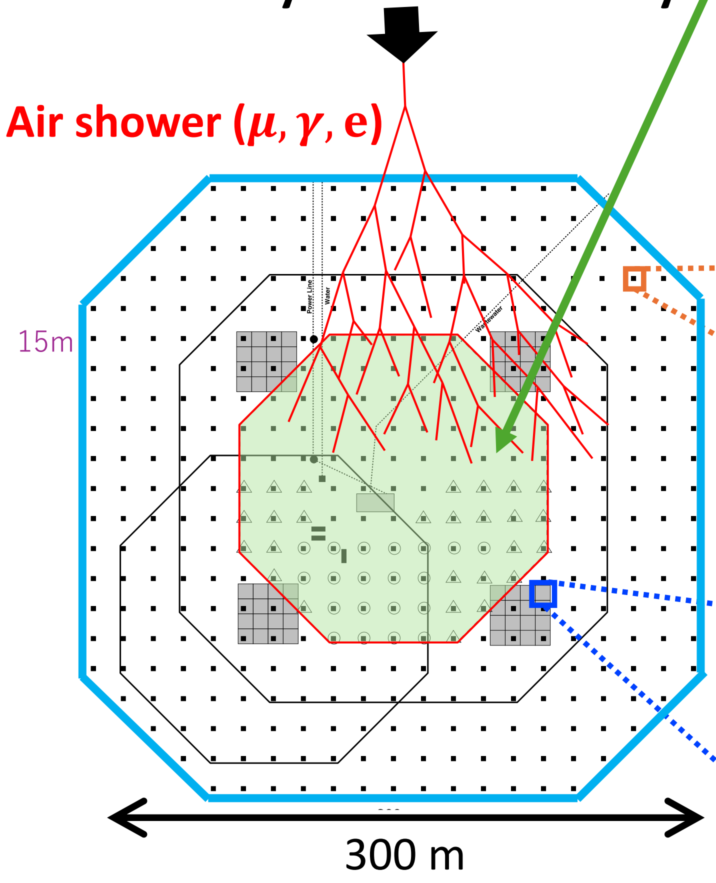
ALPACA site

2025/12

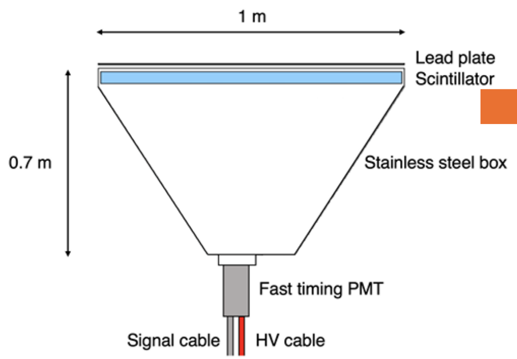


ALPAQUITA and Air-Shower Reconstruction

ALPACA : SDs ≃ 400 + 4 MDs area
ALPAQUITA(this study) :1/4-scale surface array of ALPACA
97 SDs / No MD /a prototype array

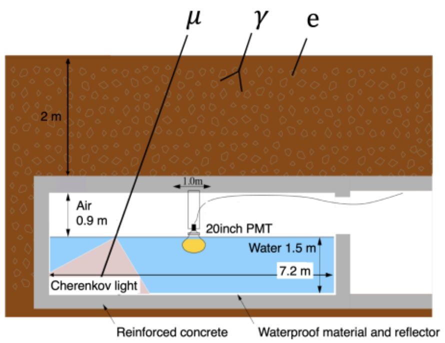


Surface air shower Detectors (SDs)



Measure secondary air-shower particles
① Particle density → Energy estimation
② Arrival time → Direction estimation

Underground Muon Detectors (MDs)



Muon counting → γ/CR separation

This study focuses on energy estimation using SD information.

Monte Carlo Setup for Energy Estimation

Gamma-ray energy reconstruction is studied using MC simulation
→ γ/CR separation is not included in this study.

Simulation
- CORSIKA 7.6400
- Geant4 10.04.p02
- Hadronic model: EPOS-LHC / FLUKA

MC conditions　10^8 gamma-ray events
- Primary: **gamma rays**
- Energy: **0.3 TeV – 10 PeV**
- Zenith angle: < **60°**
- Spectral index: **−2.0**
- Shower cores: **within 300 m from the array center**

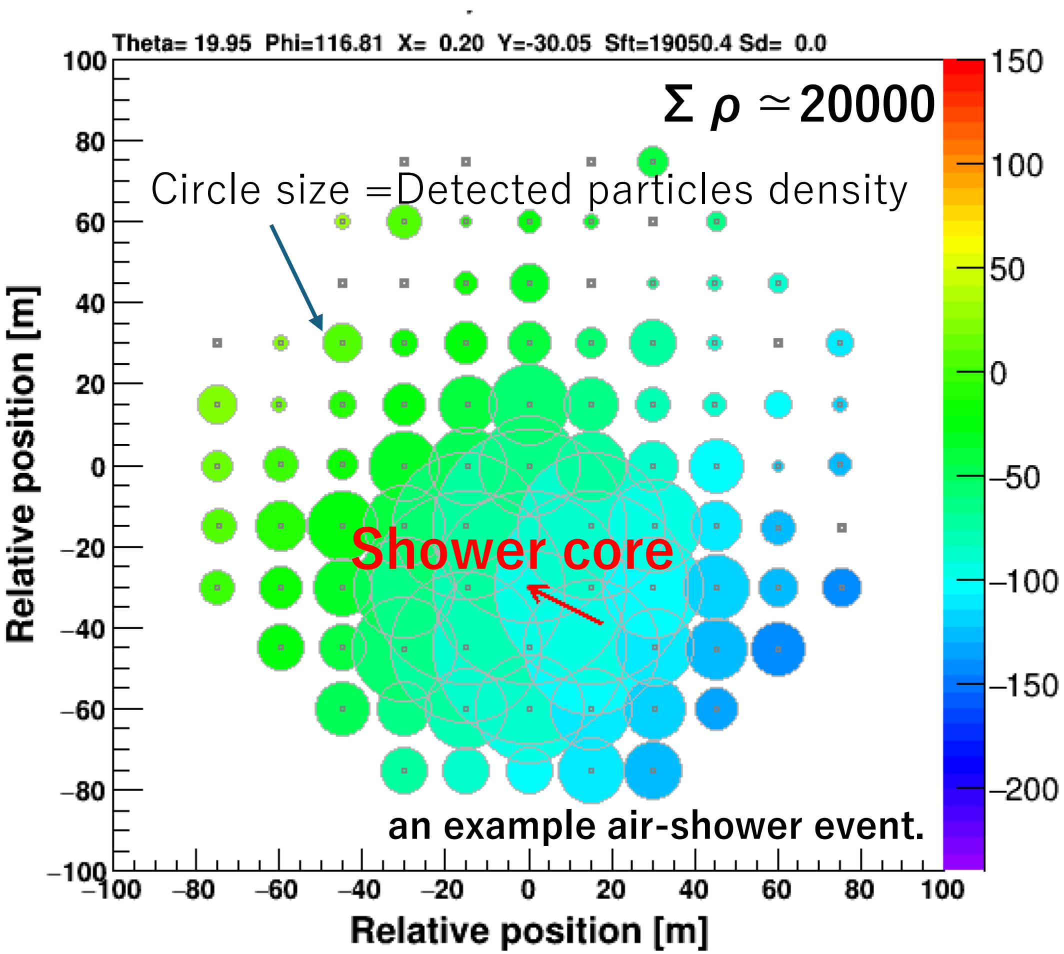
Simulation flow

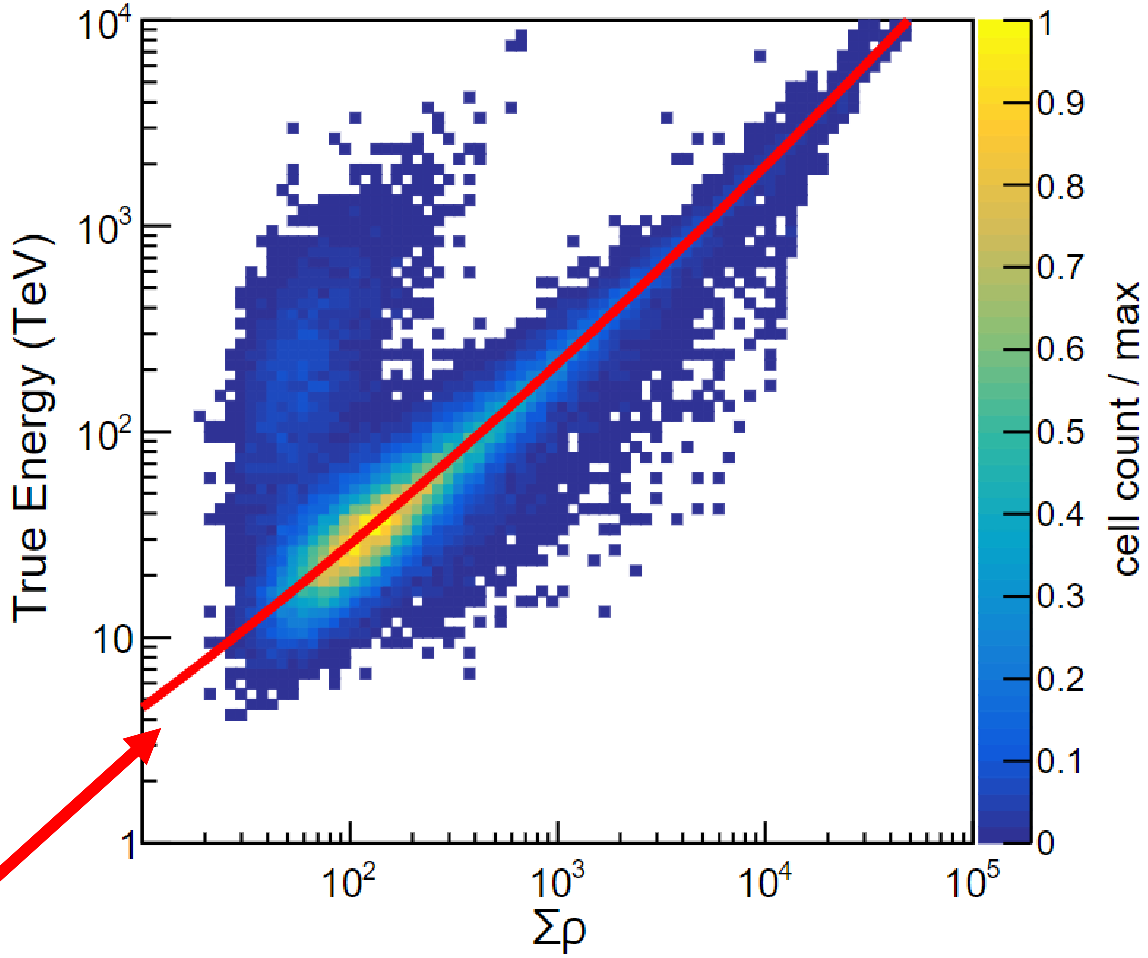
Generation of primary gamma rays & AS simulation with CORSIKA
↓
Detector response simulation with Geant4
↓
Event reconstruction/Energy estimation

Energy-estimation performance is evaluated by comparing estimated and true energies.

Energy Estimator 1: $\Sigma\rho$

$\Sigma\rho$:Total particle density measured by the surface detectors





larger $\Sigma\rho$ → higher Energy→ $\Sigma\rho$ can be used as an energy estimator

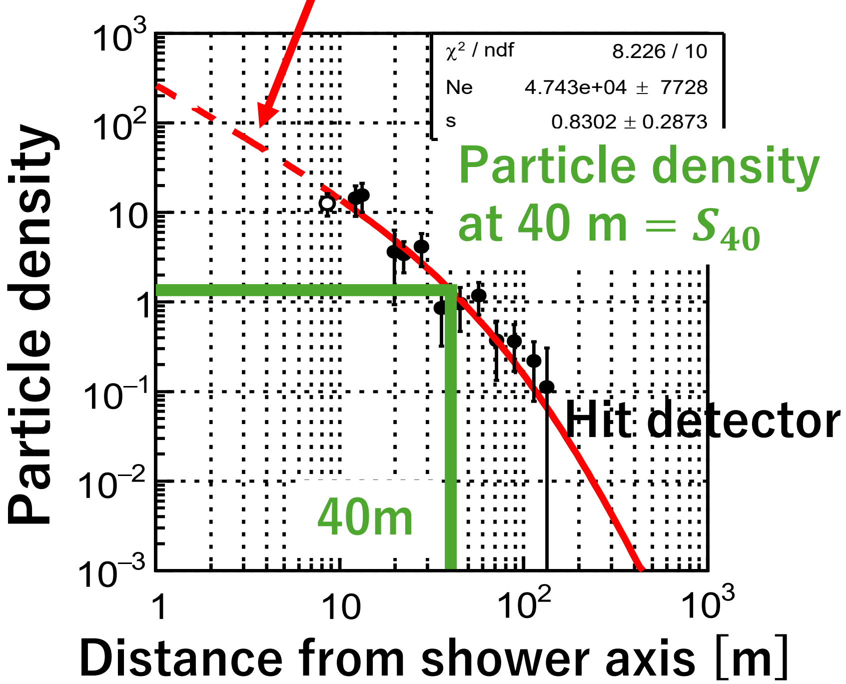
Energy Estimator 2: S_x

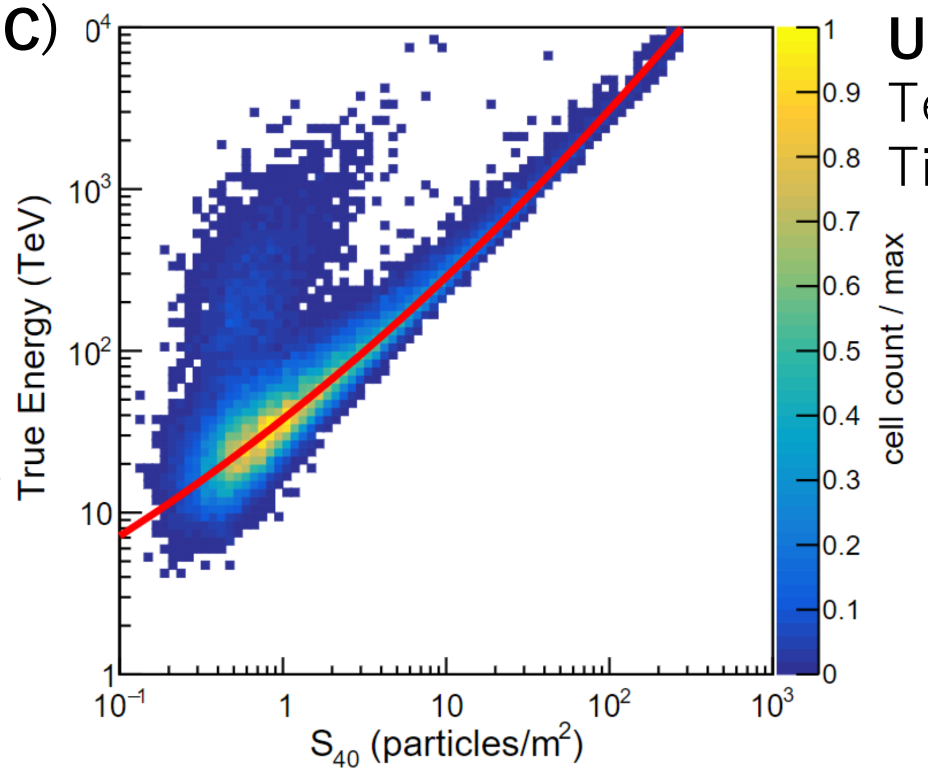
S_x : Particle density at x meters from the shower axis

$$\rho_{\mathrm{NKG}}(r) = \frac{N_{\mathrm{e}}}{r_{\mathrm{m}}^2} \frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\Gamma(4.5-2s)} \left(\frac{r}{r_{\mathrm{m}}}\right)^{s-2} \left(1+\frac{r}{r_{\mathrm{m}}}\right)^{s-4.5}$$

Fit the lateral distribution with the NKG function

Lateral particle distribution (1 MC)





Used in other AS experiments

Telescope Array : S_{800}

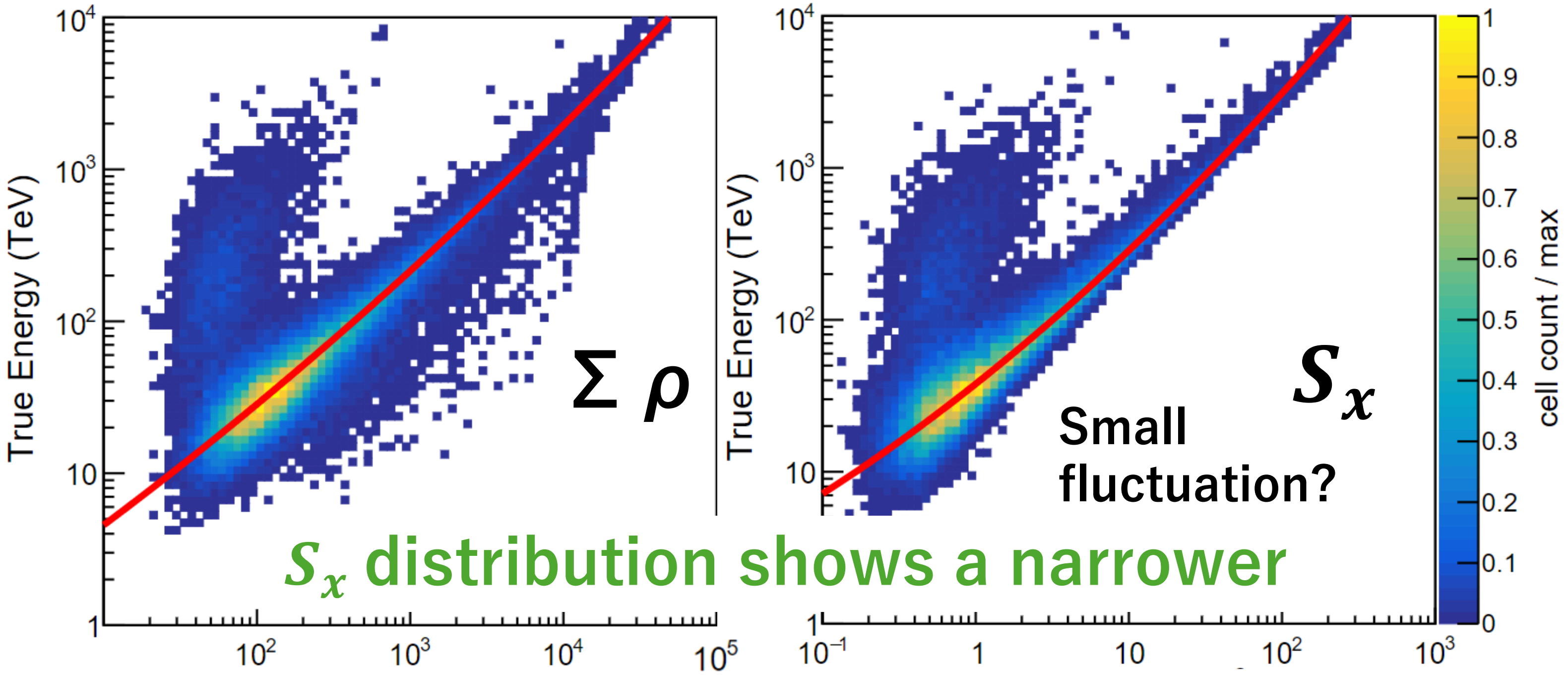
Tibet AS γ : S_{50}

The optimal distance depends on the array.

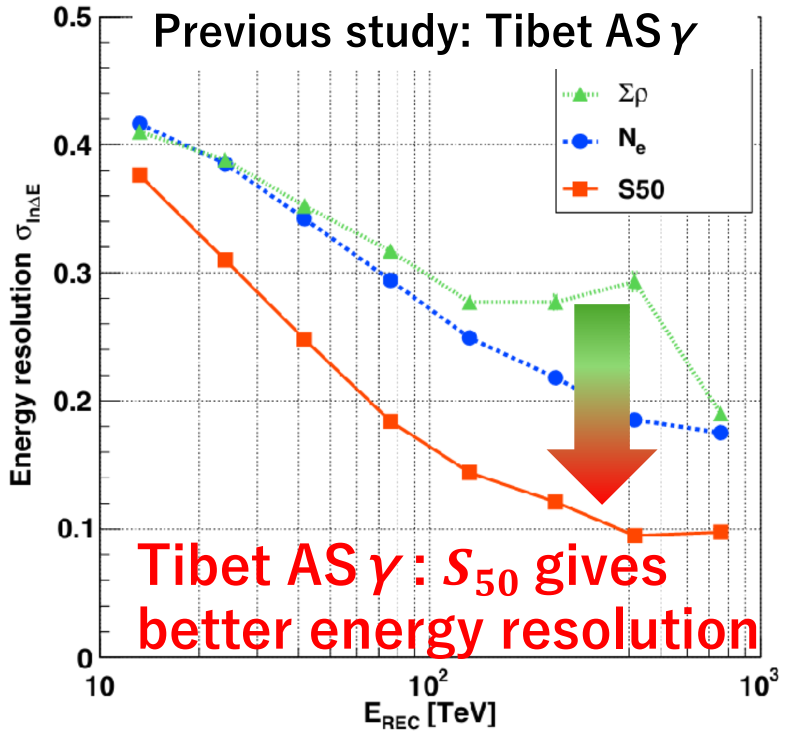
→ **Need to determine the optimal value of x for ALPAQUITA.**

Two Goals of This Study

1. Optimize the distance x for the S_x energy estimator for ALPAQUITA
→ which x is the best resolution for ALPAQUITA?
2. Compare the optimized S_x with conventional estimators
→ Can S_x improve the energy resolution?



Conventional estimator: $\Sigma\rho$ Candidate estimator: S_{40}



K. Kawata et al., Exp. Astron. 44, 1–9 (2017).

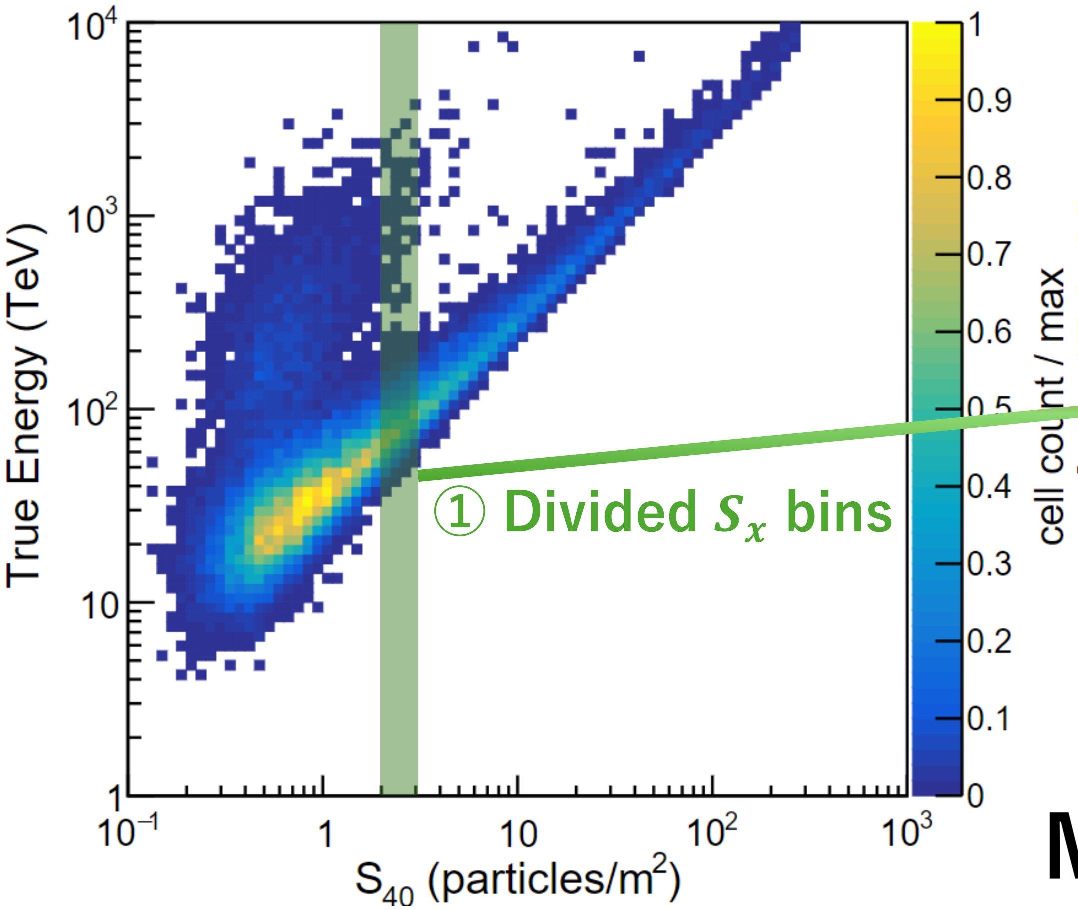
→Investigate whether an optimized S_x can also improve the energy resolution

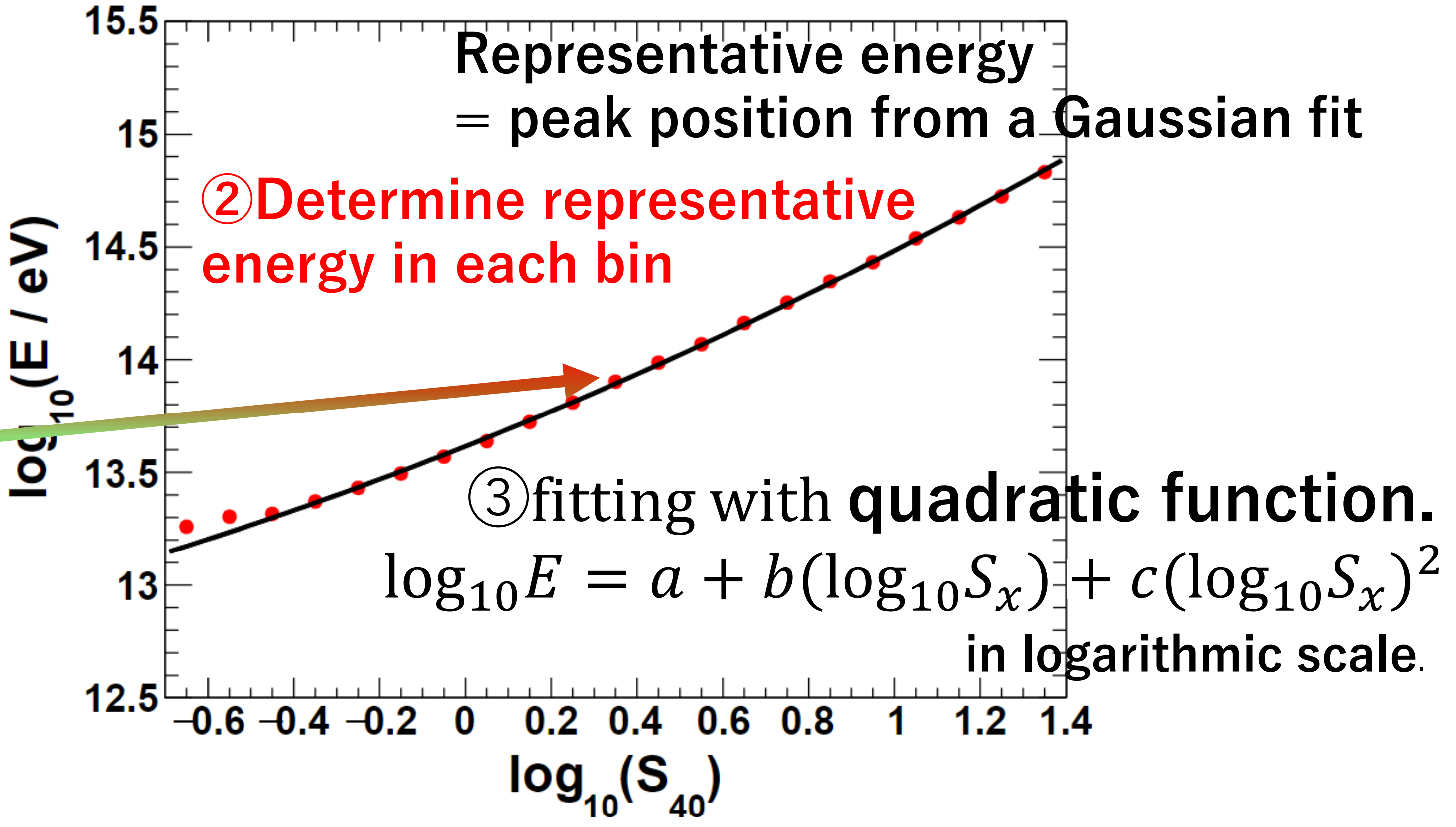
Zenith-independent Energy Estimation

1. Divide events into S_x bins
2. Determine representative **true energy** in each bin
3. Fit the representative points with a quadratic function

Previous ALPAQUITA studies used this method with $\Sigma\rho$.

S. Kato et al., Exp. Astron. 52, 85–107 (2021).

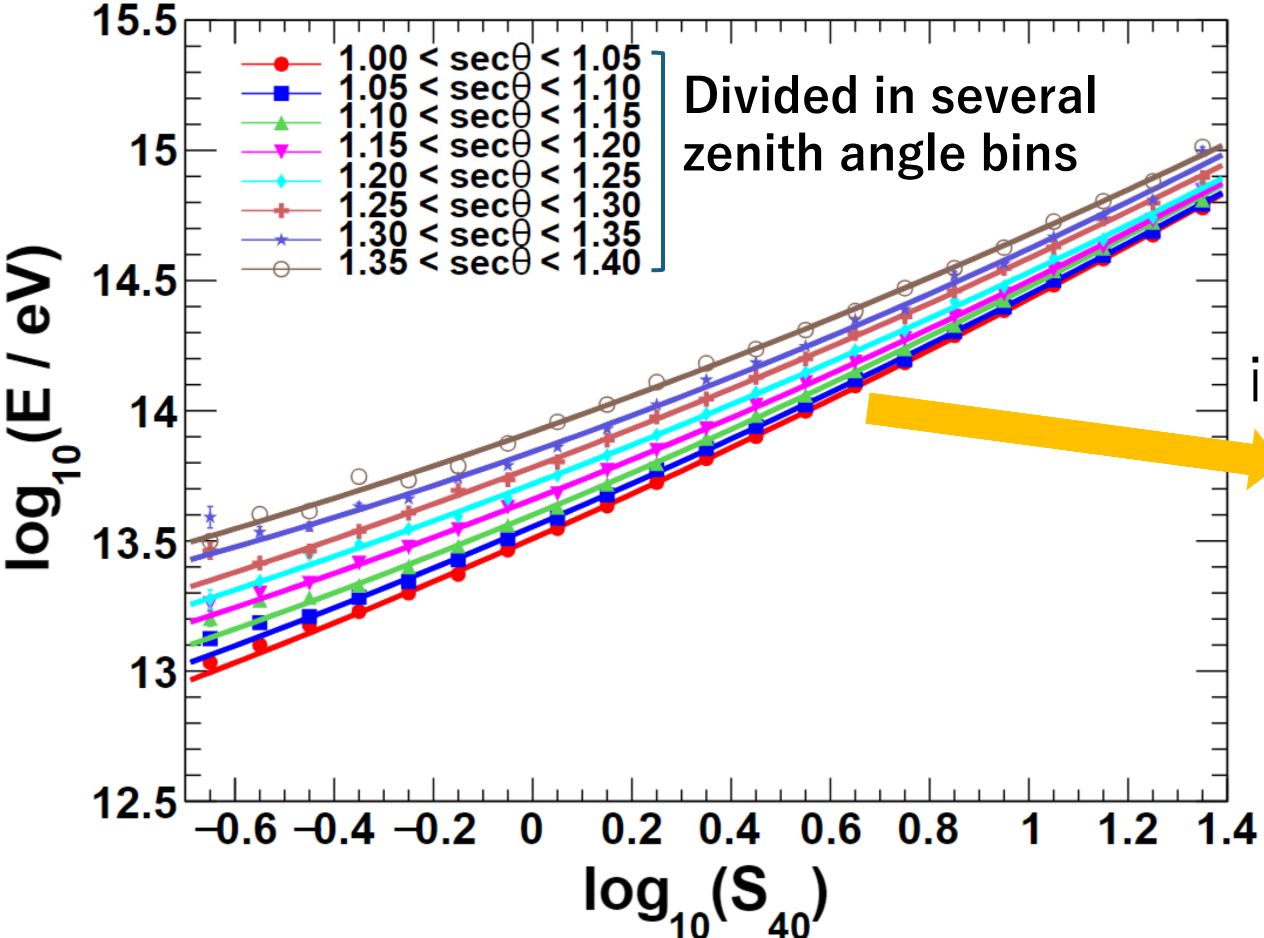




Measured S_x → Estimated energy

Zenith-dependent Energy Estimation

Shower development depends on the zenith angle.
→ Fit the S_x –energy relation in each $\sec\theta$ range.



a clear zenith angle dependence of the S_x and energy relation.

in each **$\sec\theta$ data** → each **fit function**

$$\log_{10}E = a_i + b_i(\log_{10}S_x) + c_i(\log_{10}S_x)^2$$

<u>Different zenith angles give different energy-estimation relations.</u>

Zenith-dependent Energy Estimation

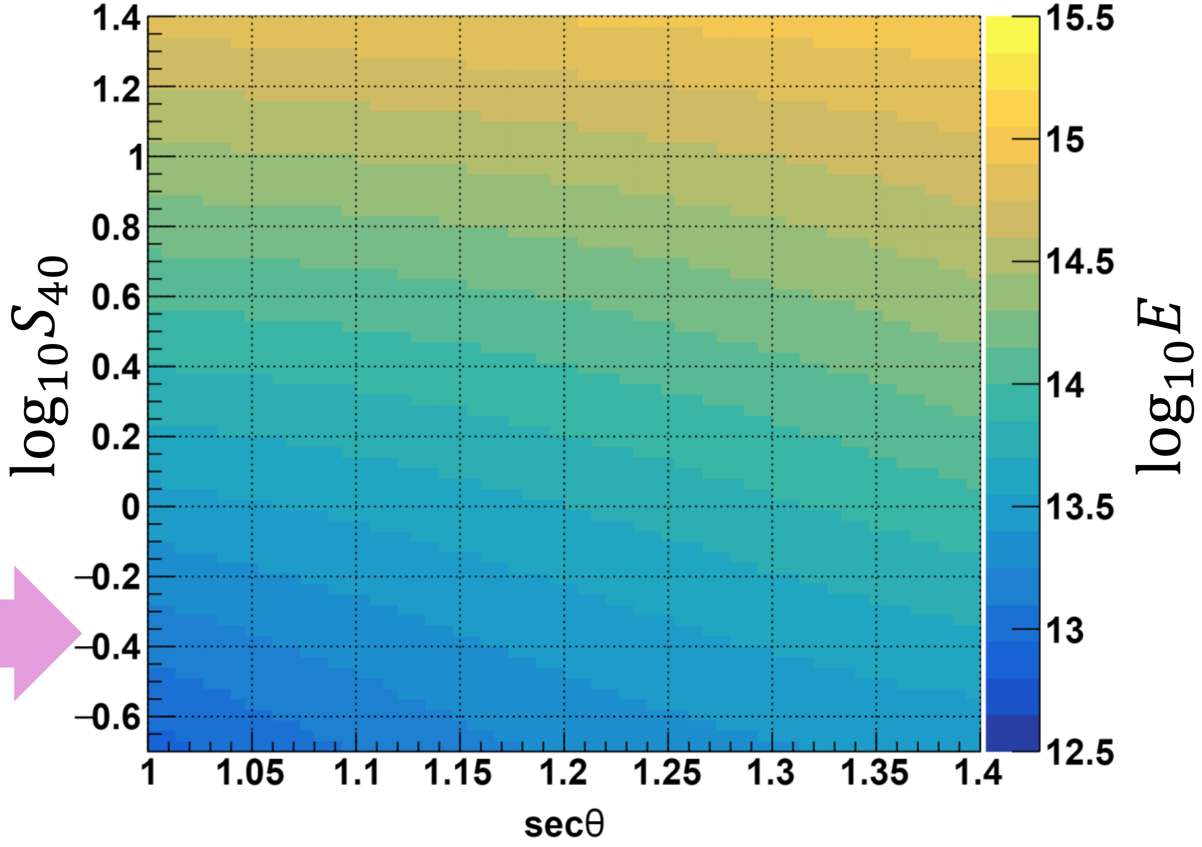
The discreate fit parameters a_i, b_i, and c_i depend on $\sec\theta$.

→ **Fitting these parameters as smooth functions of $\sec\theta$.**

$$a(\sec\theta) = \boxed{p0}\_a + \boxed{p1}\_a * \sec\theta + \boxed{p2}\_a * (\sec\theta)^2$$
$$b(\sec\theta) = \boxed{p0}\_b + \boxed{p1}\_b * \sec\theta + \boxed{p2}\_b * (\sec\theta)^2$$
$$c(\sec\theta) = \boxed{p0}\_c + \boxed{p1}\_c * \sec\theta + \boxed{p2}\_c * (\sec\theta)^2$$

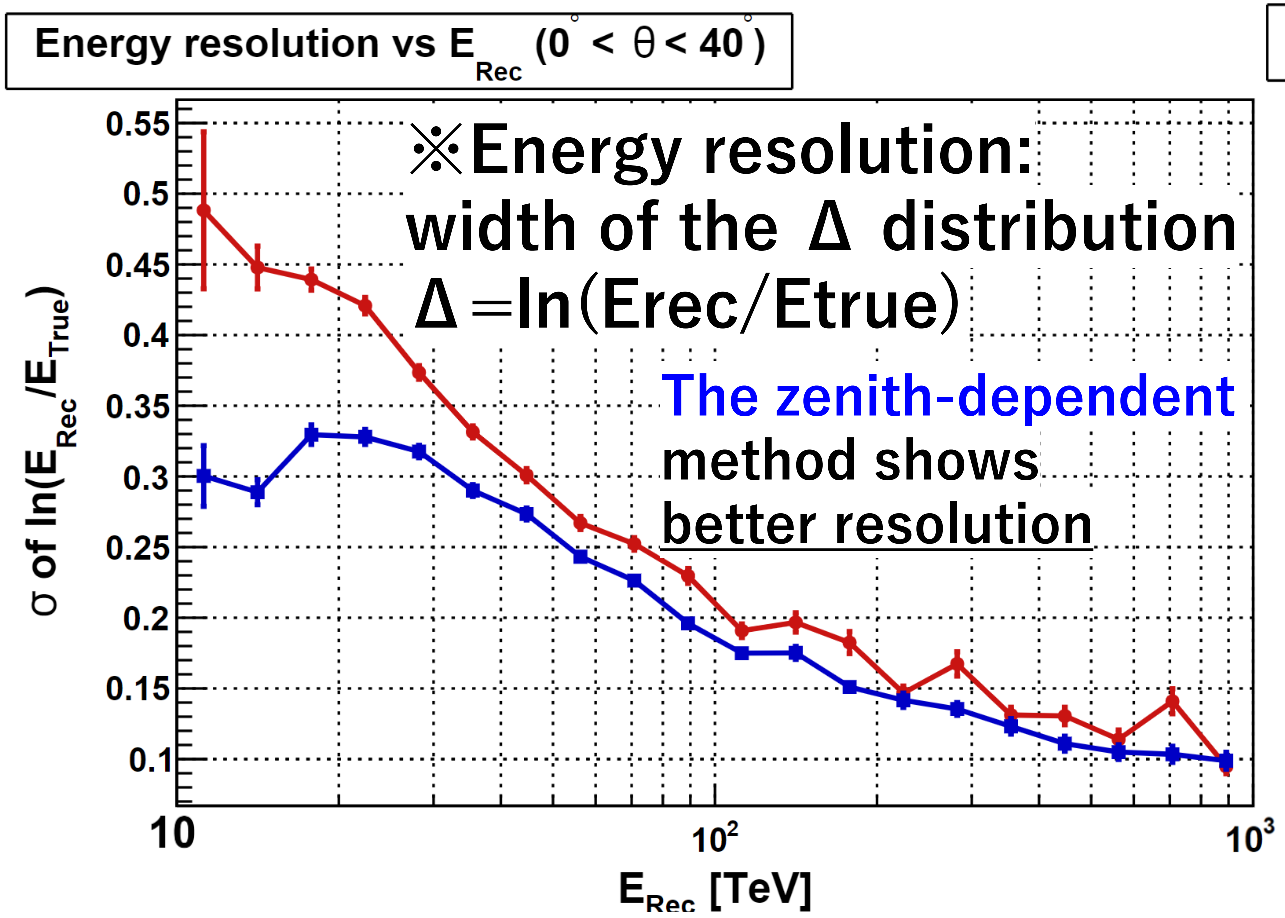
continuous conversion function

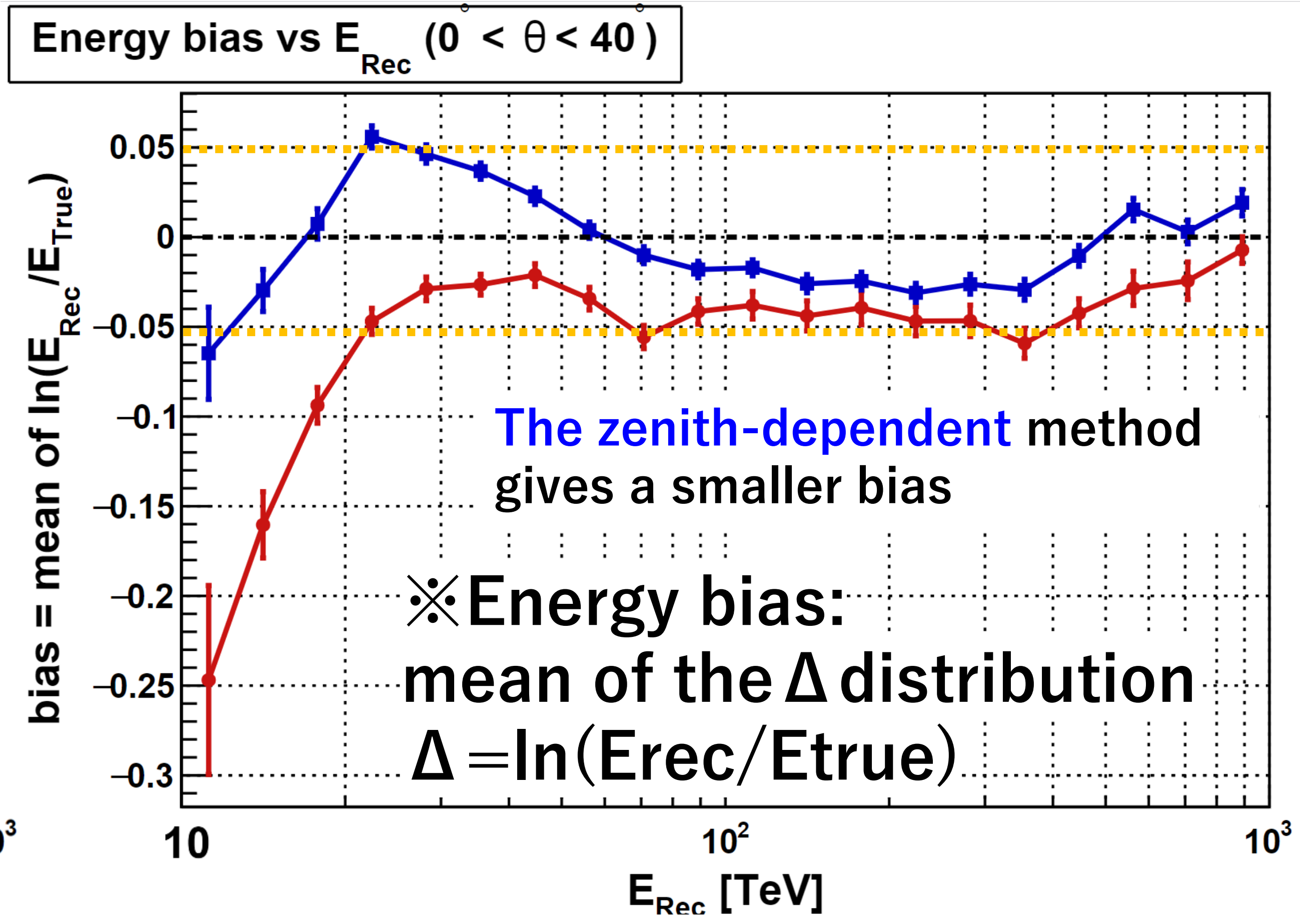
$$\log_{10}E = c(sec\theta) \times (\log_{10}S_x)^2 + b(sec\theta) \times (\log_{10}S_x) + a(sec\theta)$$



<u>Improved energy estimation using both S_x and zenith angle</u>

Zenith-Dependent vs Zenith-Independent method

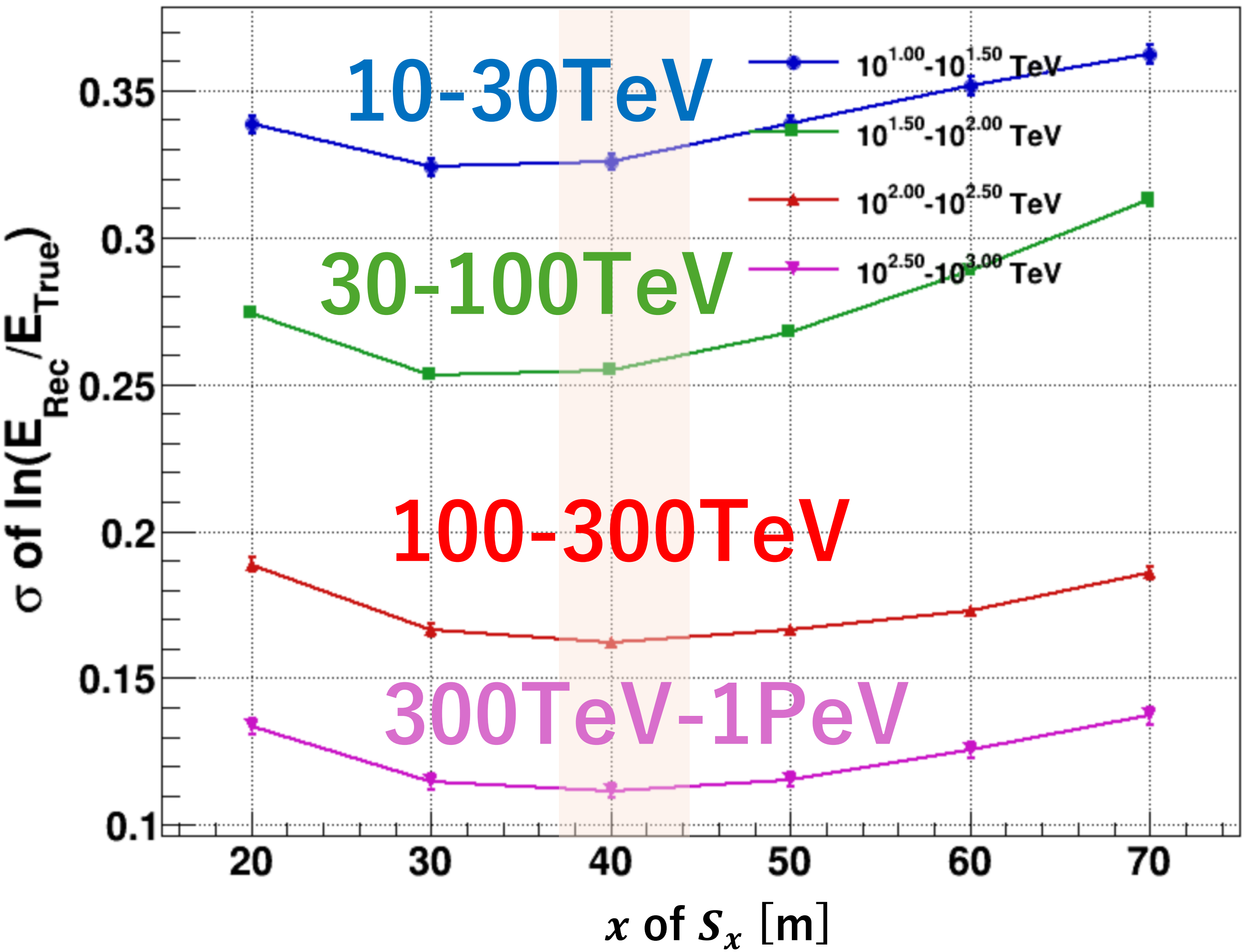




Zenith-dependent method gives **better performance**.

→ Zenith-dependent method is used in the following analysis.

Optimal Distance for S_x : 40 m

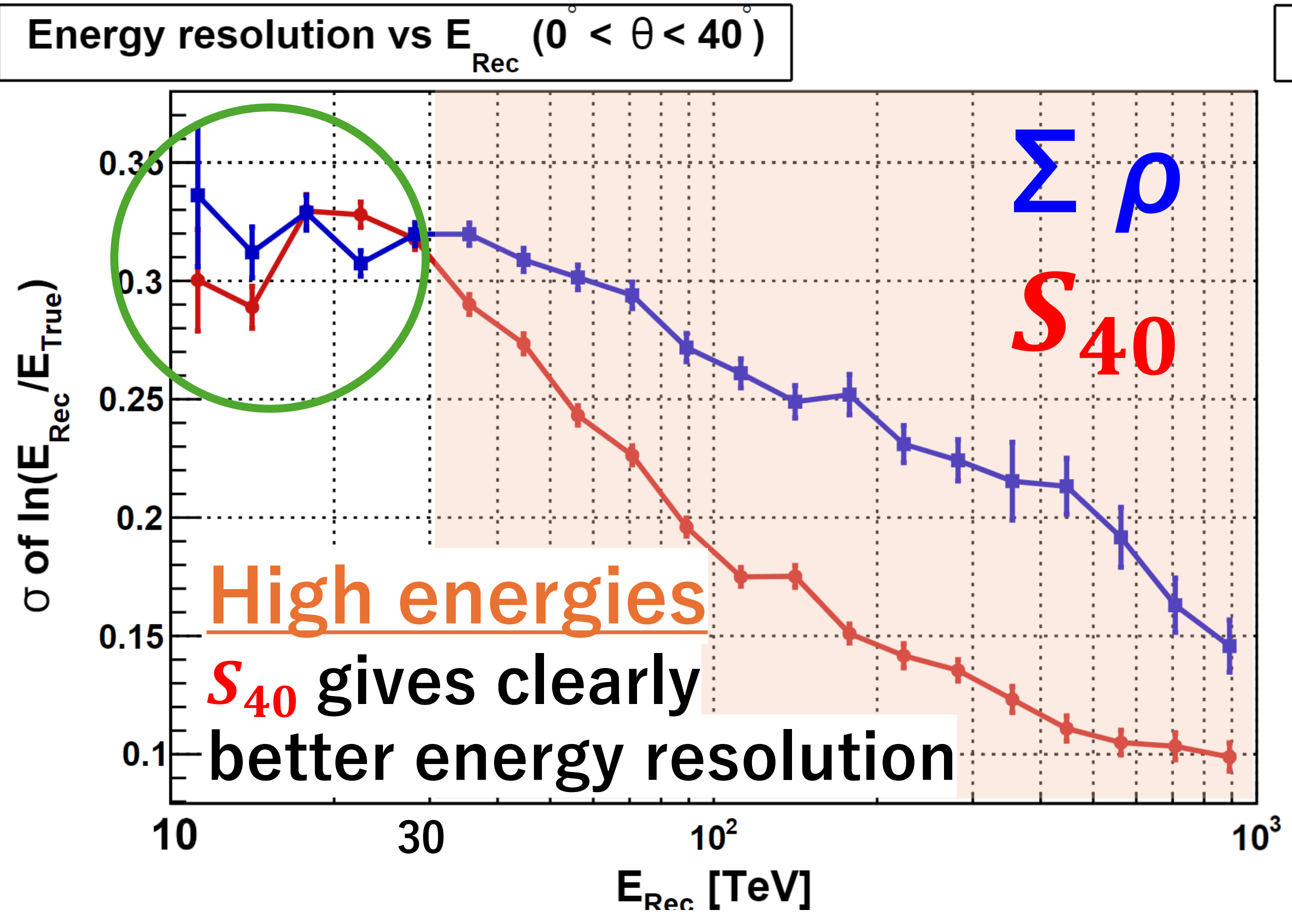


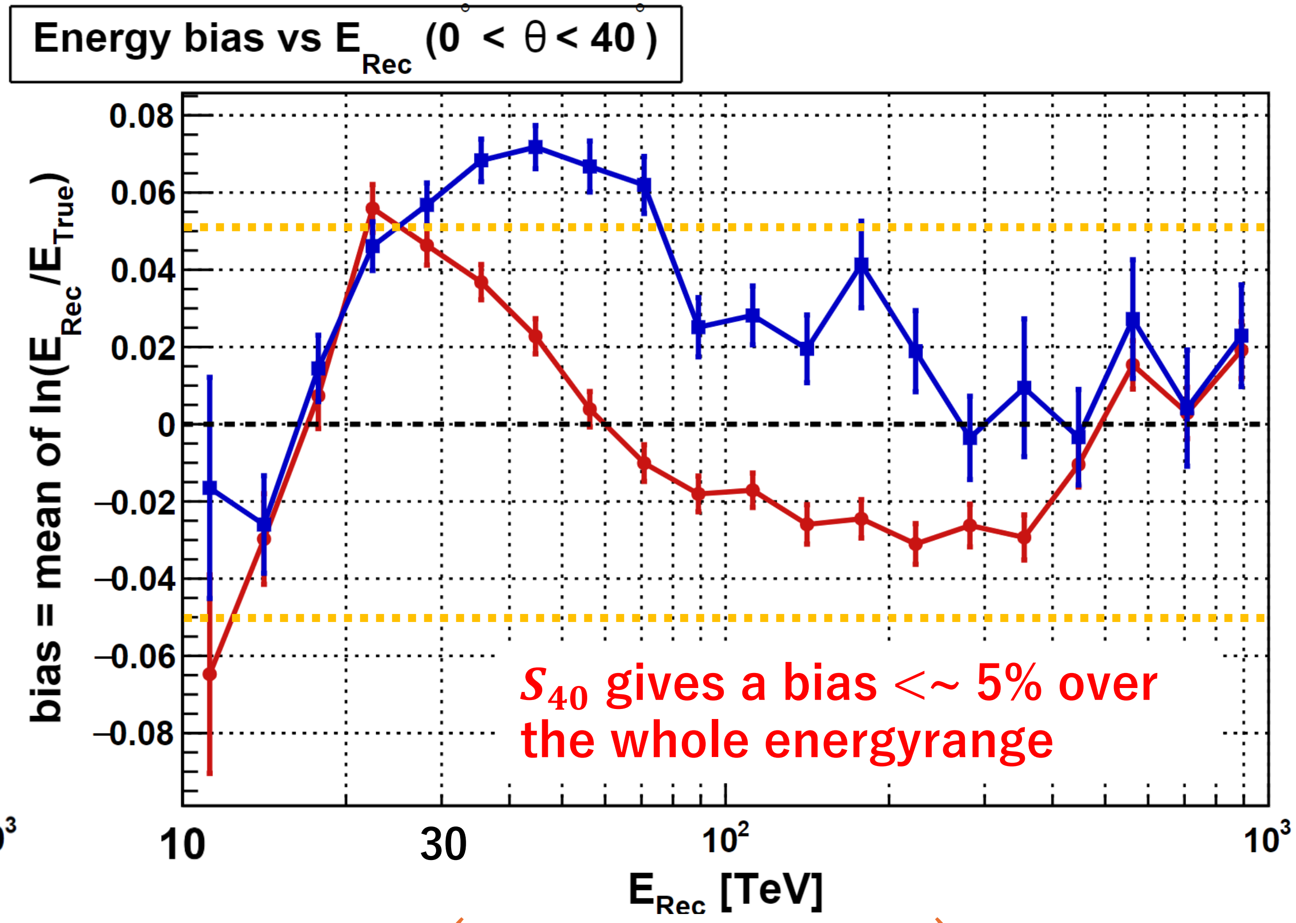
S_{30} and S_{40}:
gives best resolution

S_{40}: slightly better above 100 TeV
→ Select S_{40} for the following analysis

→compare the other estimators

Comparison the performance of S_{40} and $\Sigma\,\rho$





S_{40} gives better performance at high energies (above 30TeV).

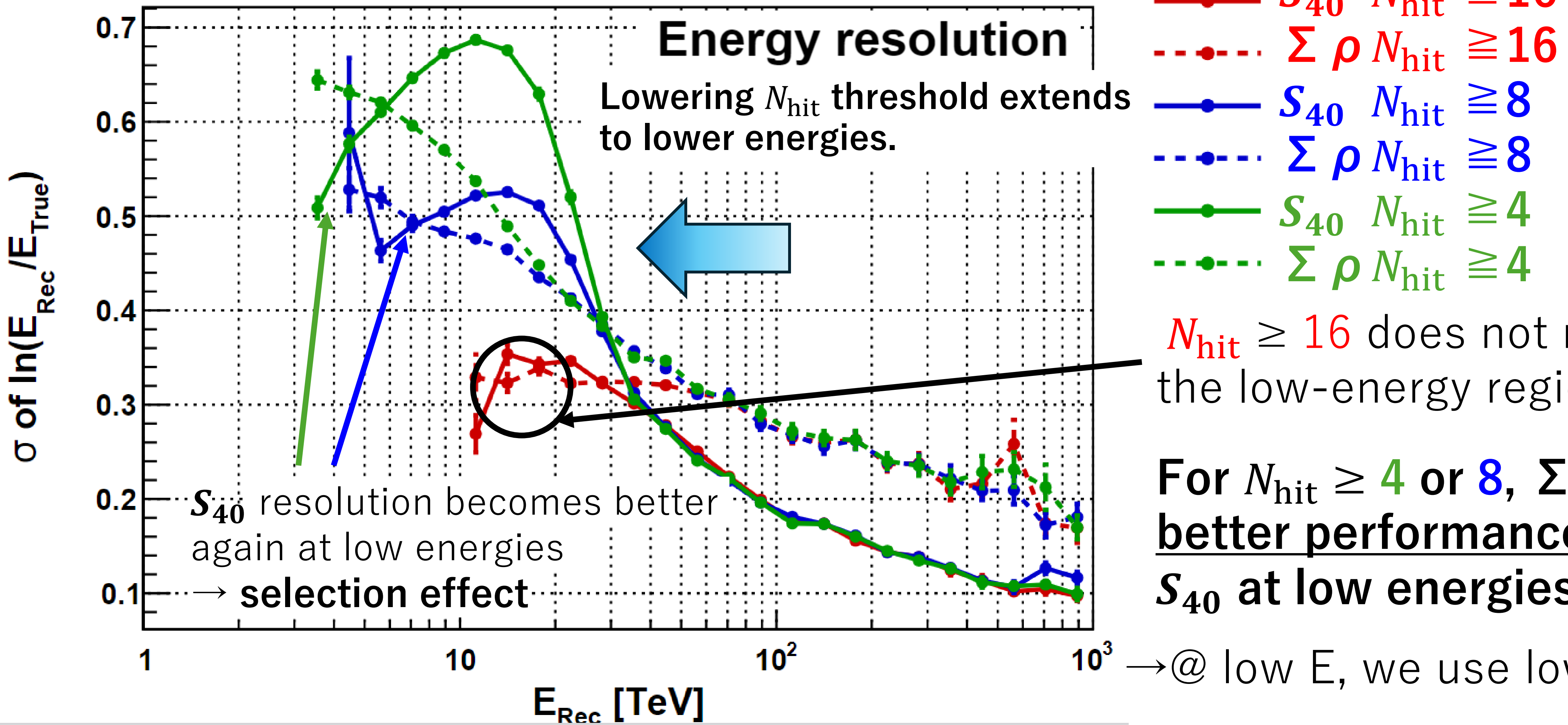
Low energy: the resolutions are **similar**

→ S_{40} requires **at least 16 hit detectors** (N_{hit}) for the lateral fit.

→ **What happens if the N_{hit} requirement is relaxed?**

Low-Energy Performance with N_{hit} Cuts

The lateral fit **requires at least 16 hit detectors**, limiting S_{40} at low energies.
→ We relax the N_{hit} requirement from **16 to 8 and 4.**

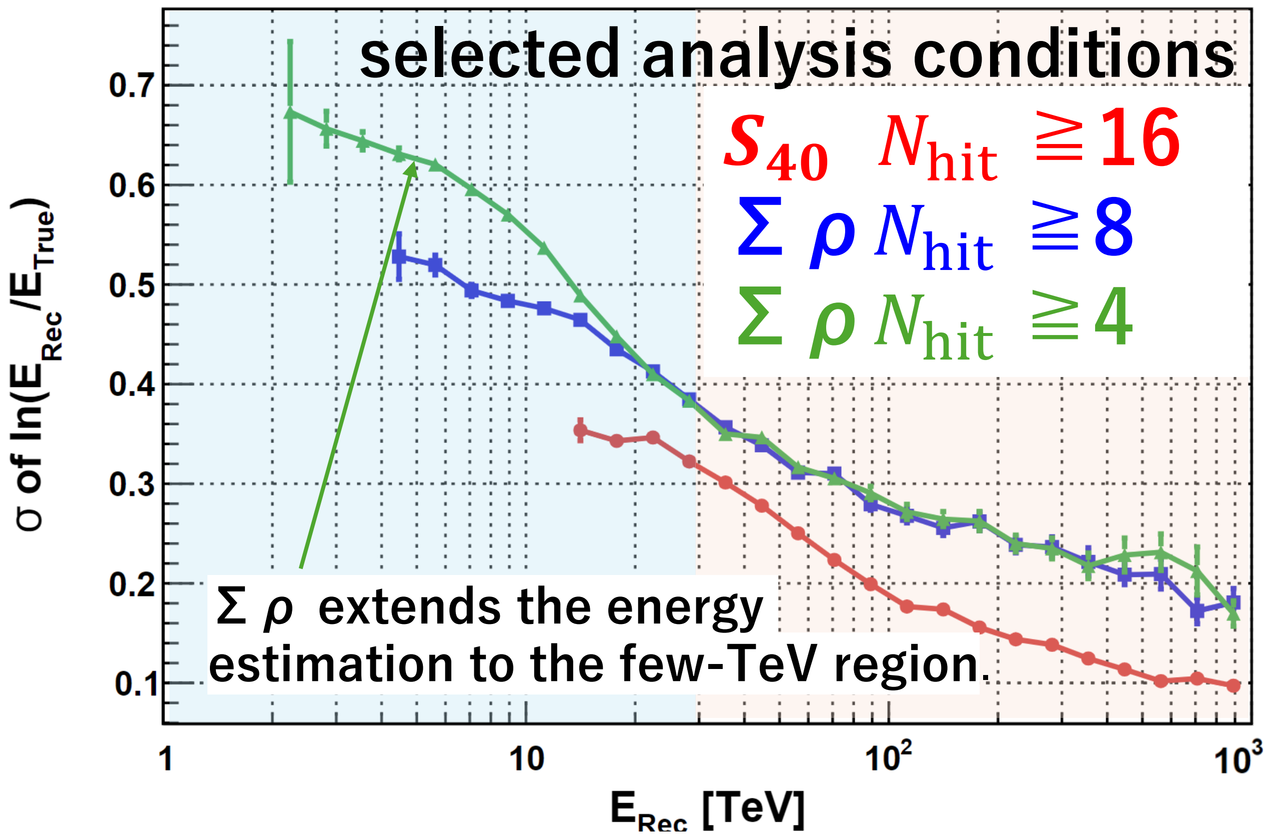


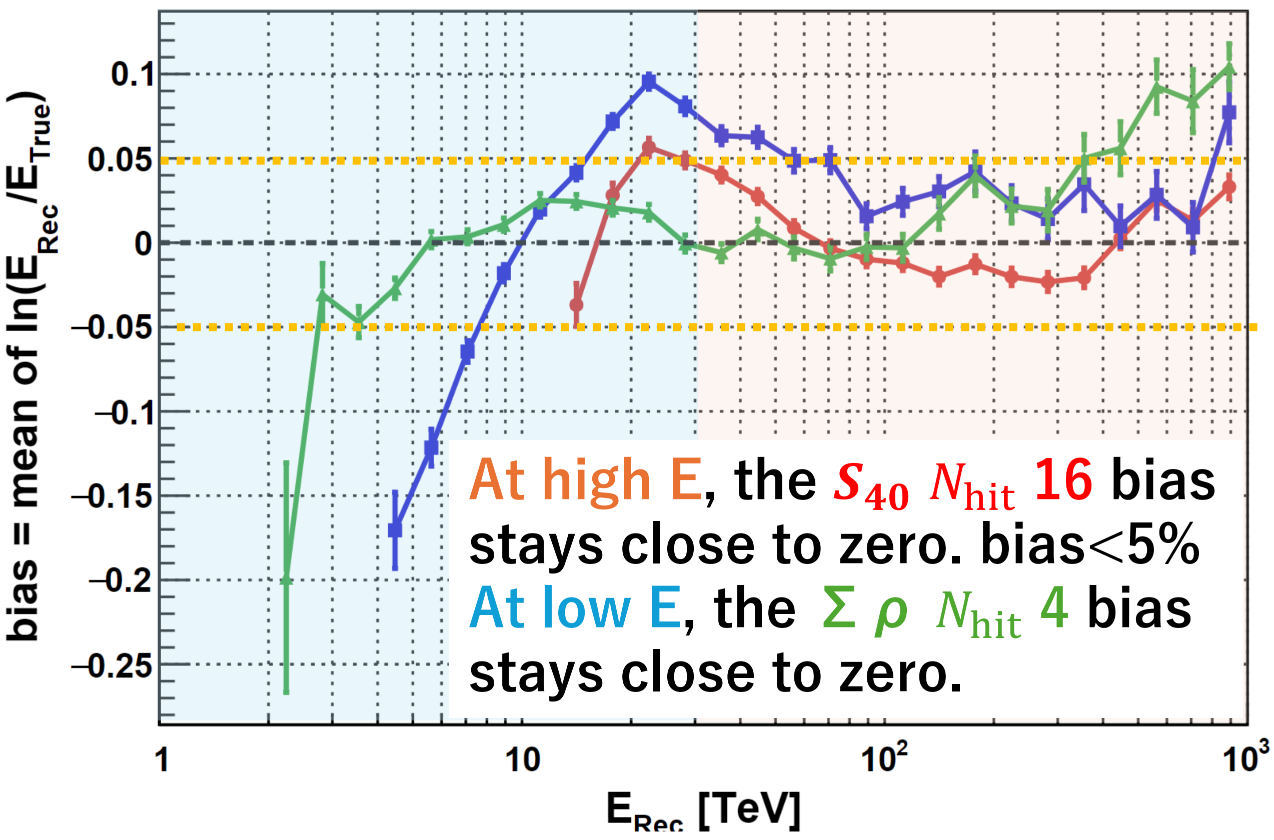
$N_{\mathrm{hit}} \geq 16$ does not reach the low-energy region.

For $N_{\mathrm{hit}} \geq 4$ or 8, $\Sigma\rho$ gives <u>better performance</u> than S_{40} at low energies.

→@ low E, we use low N_{hit} $\Sigma\rho$

Energy-Dependent Choice of Estimator





Based on the resolution, different conditions are adopted for low and high energies.

High Energy→ N_{hit} 16 S_{40}
Low Energy→ N_{hit} 4,8 $\Sigma\rho$

These conditions are used in the ALPAQUITA future analysis.

Summary

We performed an optimization of
the energy estimation for ALPAQUITA.

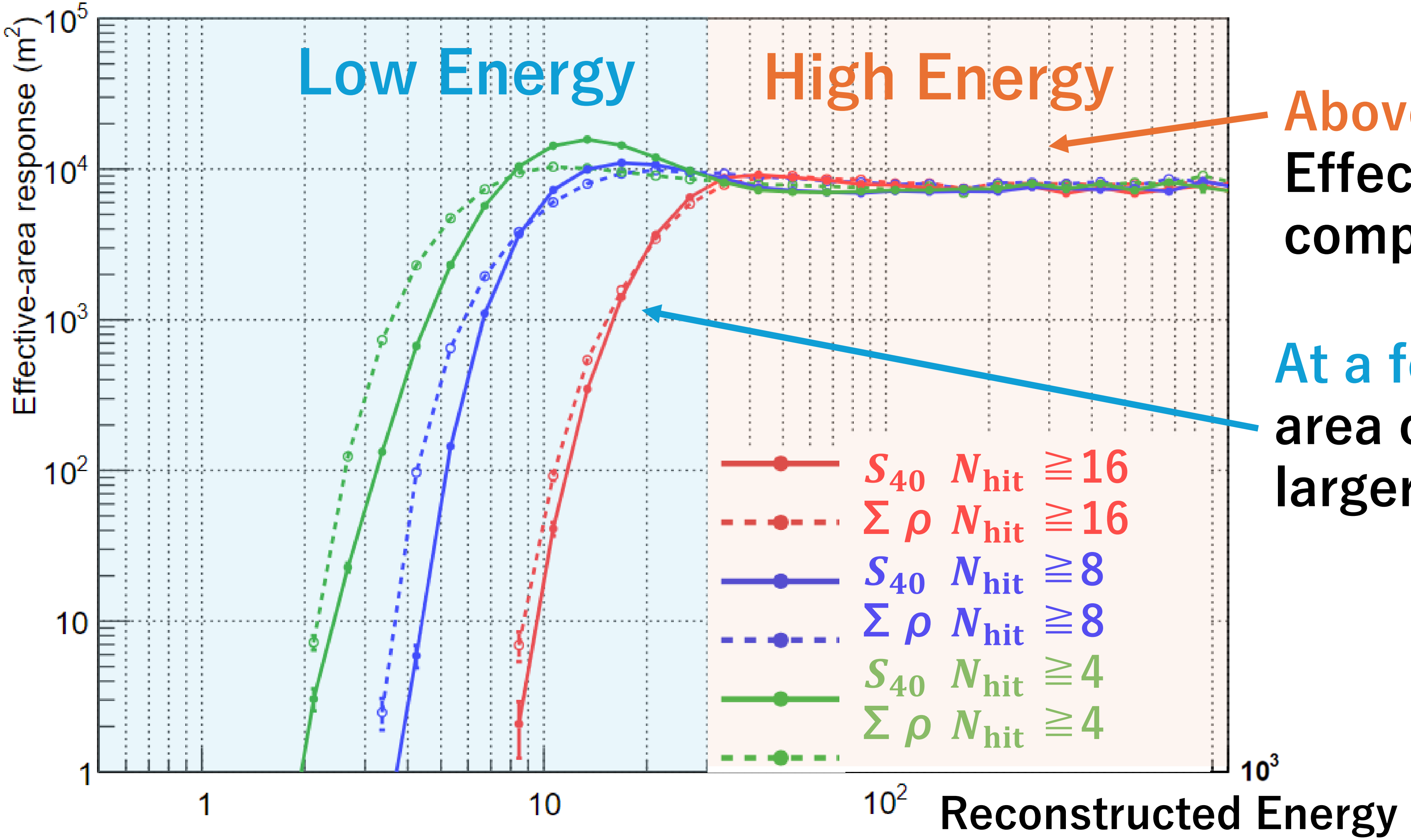
1. Zenith-angle-dependent S_x energy estimation was optimized for ALPAQUITA.
The shower lateral distribution and zenith angle are used together to estimate the primary energy.
2. S_{40} gives the best high-energy performance.
Among S_{20}–S_{70}, S_{40} gives the best overall resolution above ~ 10TeV.
Compared with the conventional Σρ method, the resolution is improved, with a small energy bias of about 5% or less at high energies.
3. Different estimators are used for high- and low-energy events.
S_{40} requires enough hit detectors for the lateral fit and is effective mainly above ~ 1TeV.At lower energies, Σρ with a lower $\mathrm{N_{hit}}$ threshold is adopted.

→ Energy reconstruction was established from a few TeV to the PeV region.

Back up

Aeff for the ALPAQUITA

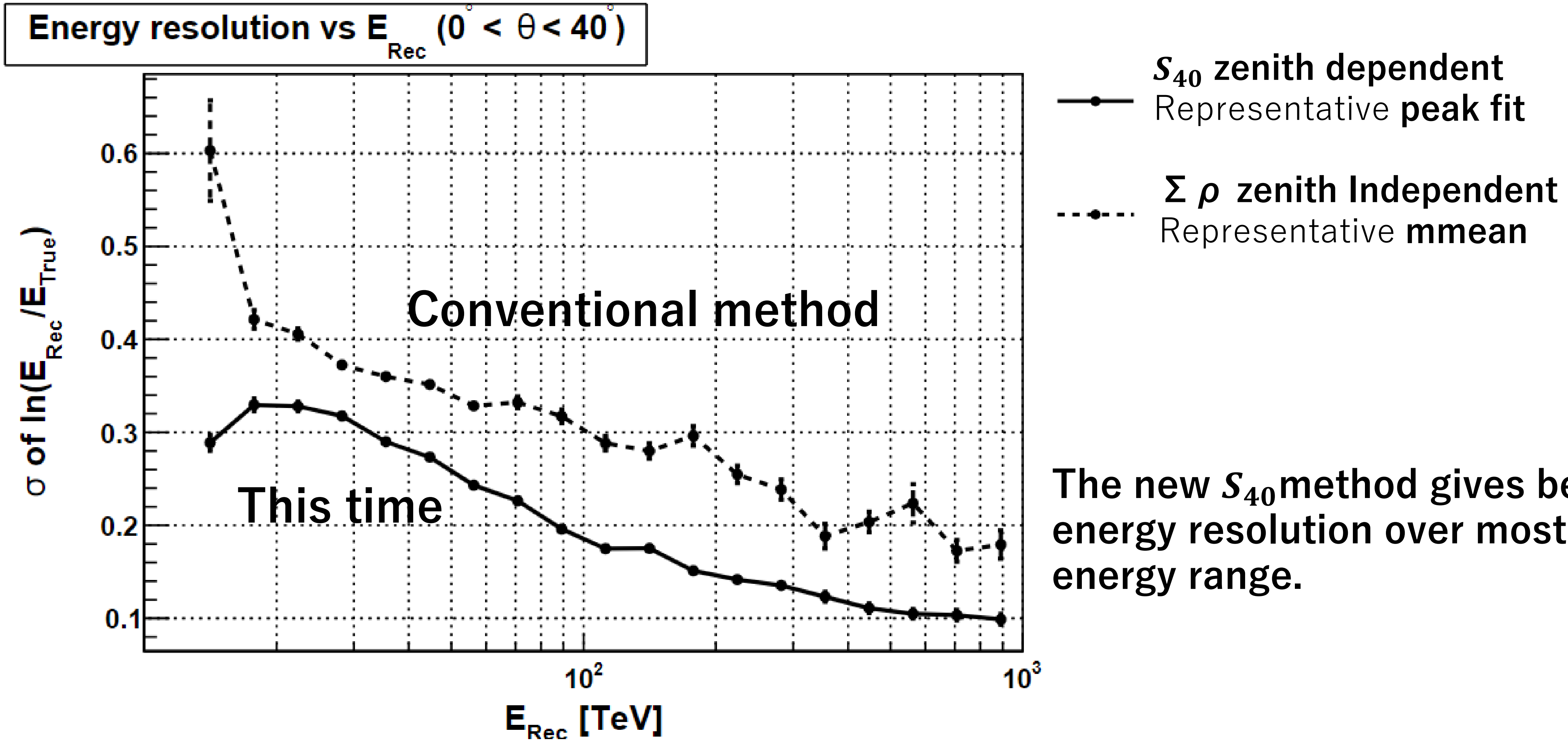
the effective area strongly depends on the N_{hit} requirement.



Above ~30 TeV
Effective areas become comparable.

At a few TeV, the effective area of $\Sigma\rho$ is several times larger than that of S_{40} .

Improvement over the conventional method

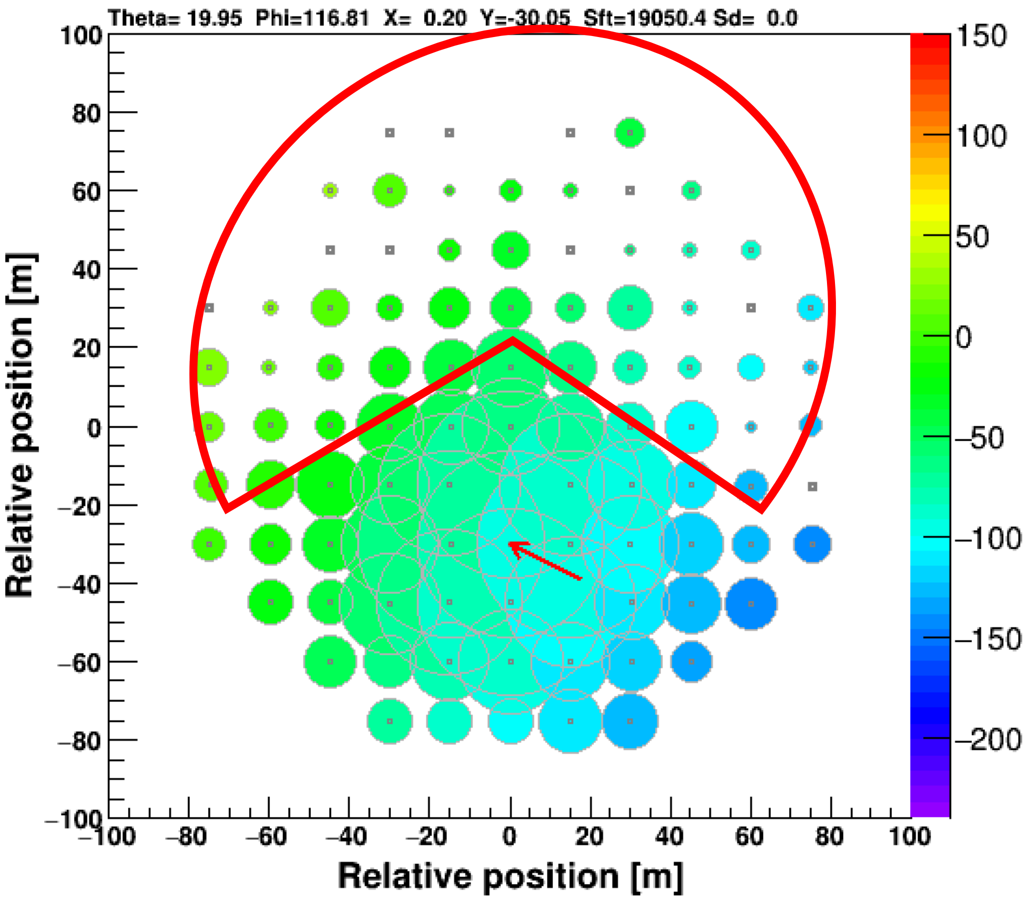


The new S_{40} method gives better energy resolution over most of the energy range.

Why does S_{40} outperform $\Sigma\rho$?

Particles falling outside the finite detector array are not measured, so their contribution is lost in $\Sigma\rho$.

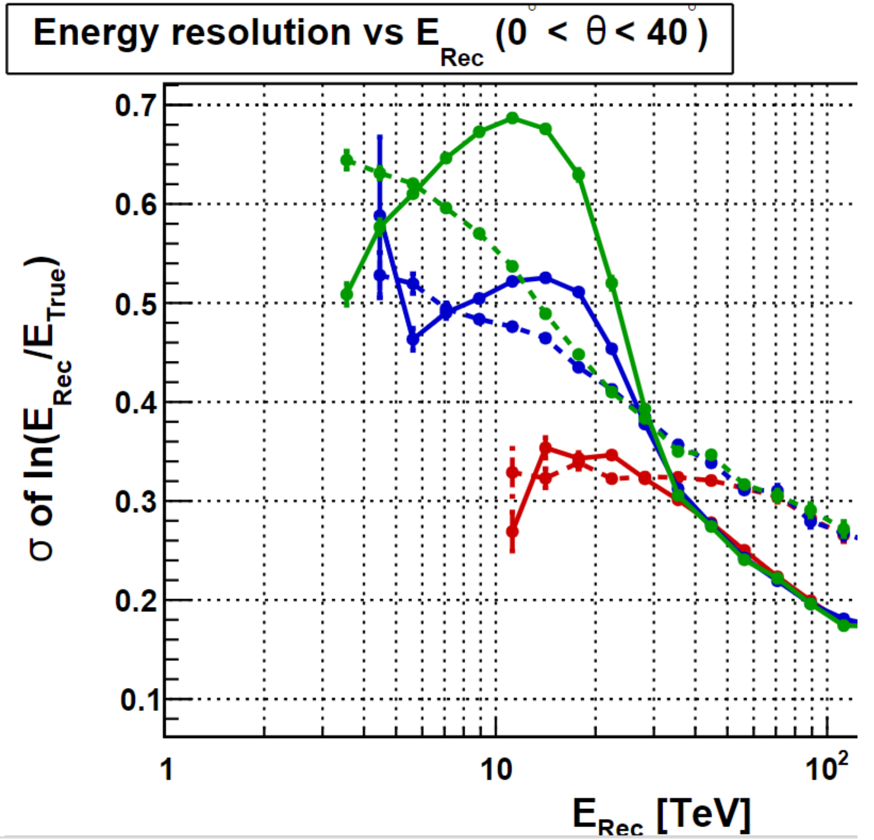
- For showers near the array edge, $\Sigma\rho$ misses particles falling outside the array and tends to underestimate the shower size.
- S_{40} is derived from a fitted lateral distribution, making it less sensitive to partial shower containment.



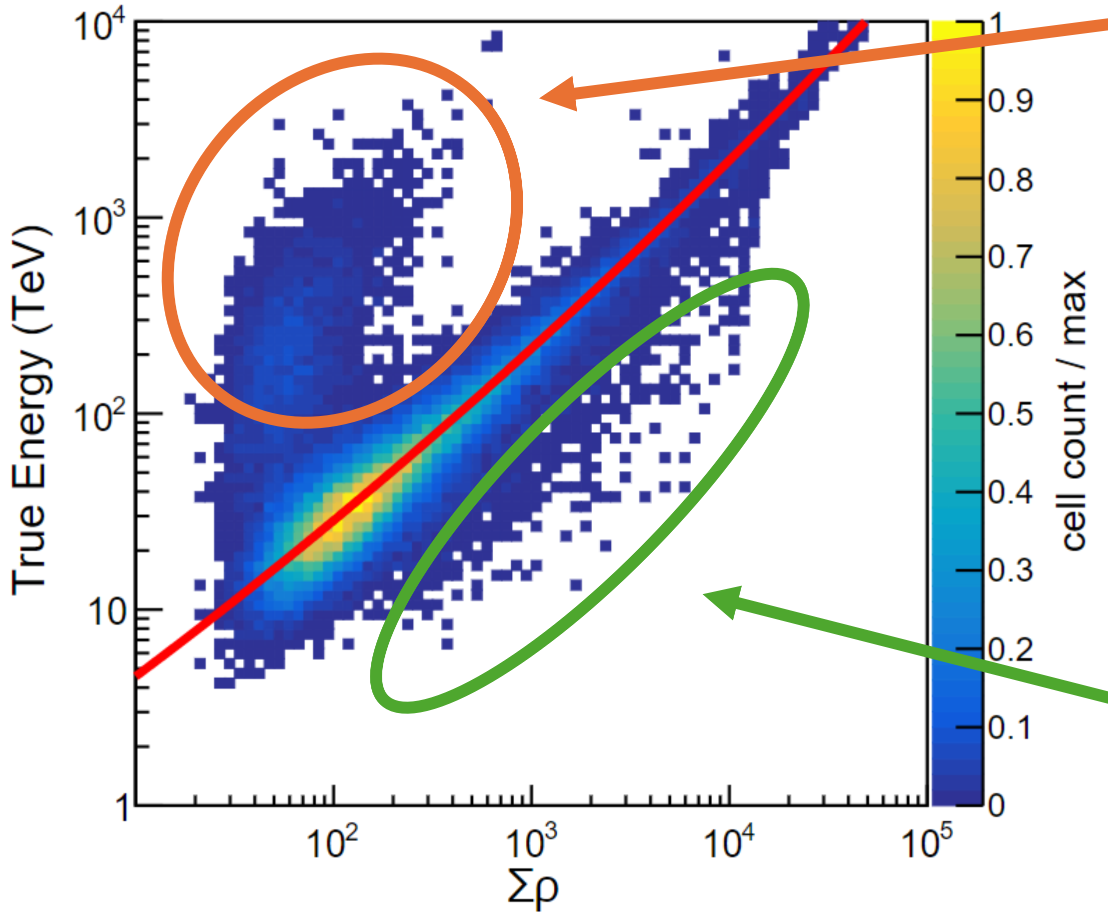
Possible origin of the low-energy recovery

- **At low energies, only a small fraction of events can reconstruct S_{40}.**
- **The selected events may be biased toward well-reconstructed showers.**

→ The apparent improvement is likely due to a selection effect, not an intrinsic improvement of S40



Abnormal Structures in the $\Sigma\rho$ Distribution



Mis-reconstructed shower-core position

High-energy showers with cores outside the array can be mis-reconstructed as having cores inside the array.
Only a small part of the shower is detected, making them appear similar to lower-energy showers.

Structure mainly seen for $\Sigma\rho$

$\Sigma\rho$ is directly affected by large signals from detectors close to the shower core.
Therefore, fluctuations in the core region can produce a large deviation in $\Sigma\rho$.
S40 is less sensitive to this effect because it is obtained from a lateral fit without directly using the innermost region around the shower core.

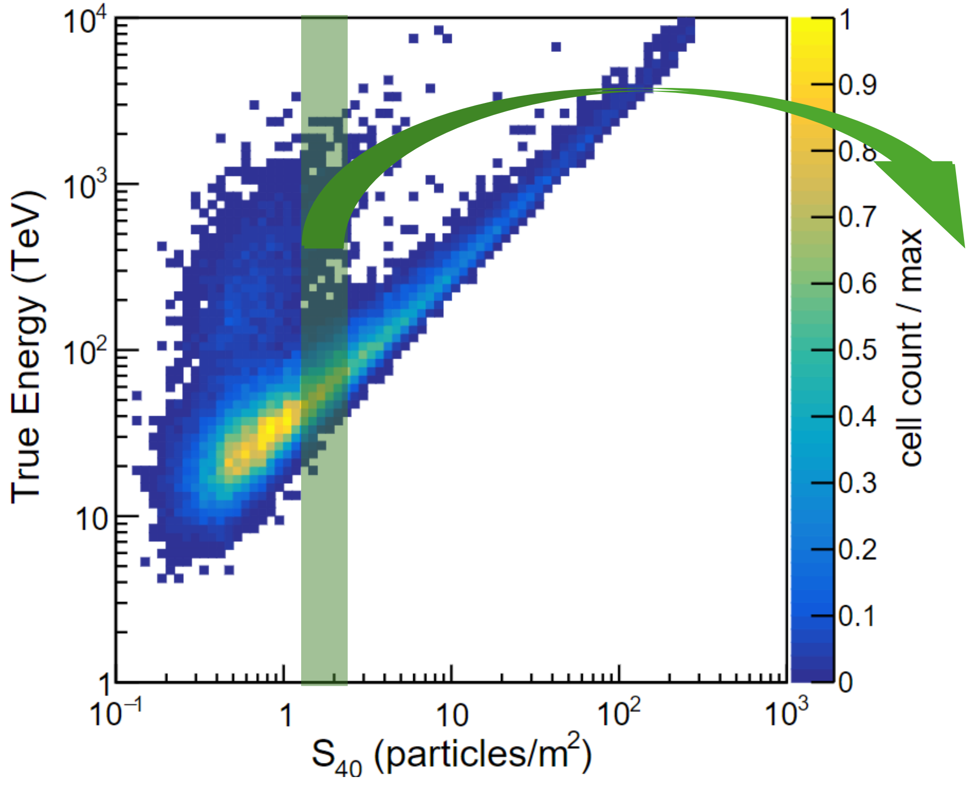
Procedure for Determining Representative Points

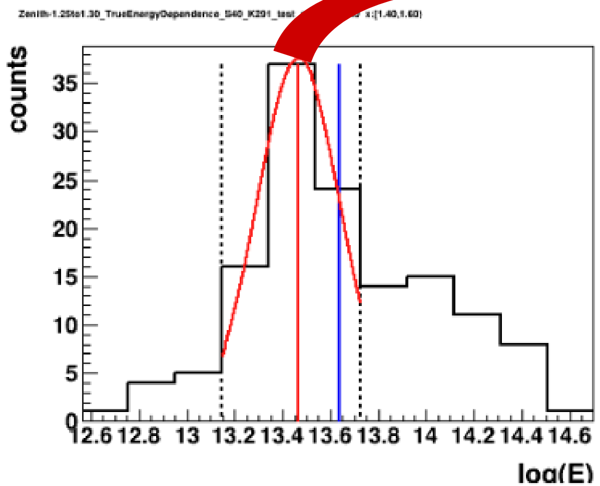
1. Binning of the scatter plot

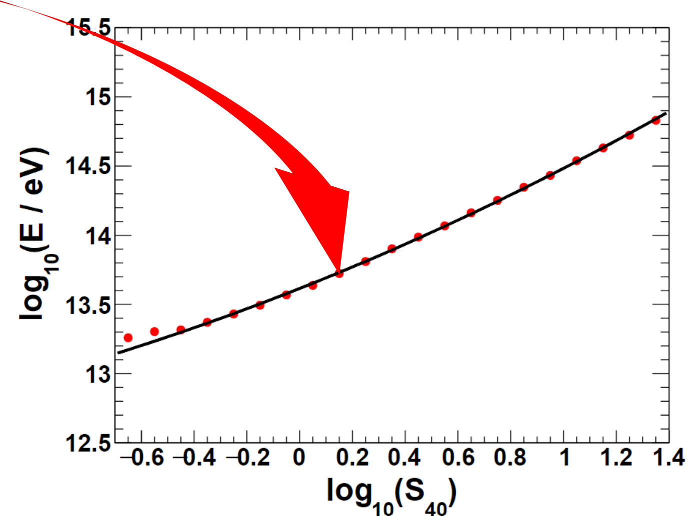
- Events are divided into bins of S_{40}.
- Each bin is required to contain at least 25 events.
- The bin center is used as the representative S_{40} value.

2. Peak fit in each projected distribution

- For each S_{40} bin, the true-energy distribution is projected.
- The distribution is binned uniformly in $\log(E)$.
- A Gaussian fit is performed around the peak.
- The fitted peak value is taken as the representative energy.

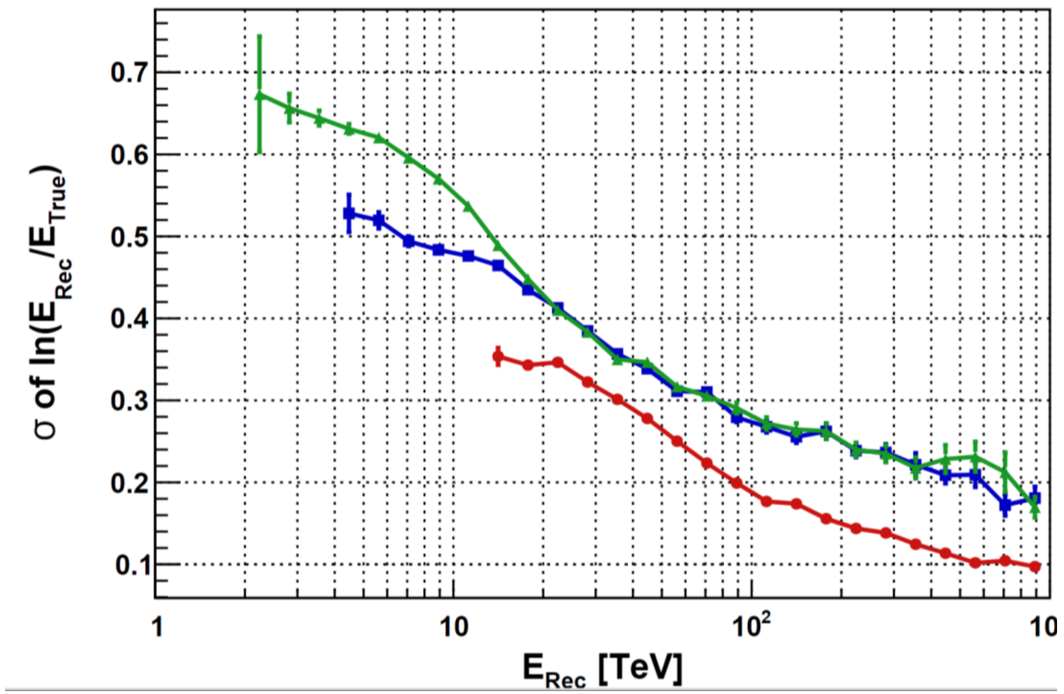






Energy Resolution Achieved in This Work

S40 provides the best resolution above several tens of TeV.
At 100 TeV, $\sigma_{\ln E} \approx 0.18$, corresponding approximately to an 18% fractional energy spread.



σ of lnE= σ [ln(Erec/Etrue)]

	3TeV	10TeV	30TeV	100TeV	300TeV
N_{hit} 4 $\Sigma\,\rho$	0.65	0.55	0.36	0.28	0.22
N_{hit} 8 $\Sigma\,\rho$	/	0.48	0.36	0.28	0.22
N_{hit} 16 S_{40}	/	/	0.32	0.18	0.13

Is the current performance sufficient?

- **This work achieves $\sigma_{\ln E} \approx 0.18$ at 100 TeV with S_{40}.**
  - This performance is already comparable to other major air-shower experiments.
  - Further improvement in energy resolution is still valuable.
  - However, at the $\sim 10\%$level, absolute energy-scale uncertainty also becomes important.
- **→ The current performance is meaningful, while further improvement should be considered together with energy-scale calibration.**

How Is Energy Reconstructed in Other Air-Shower Experiments?

A common approach is to use the shower signal at an optimal distance from the core. ALPAQUITA S_{40}, Tibet S_{50}, and KM2A $\rho_{50}$are based on the same general idea.

Experiment	Main energy estimator	Reconstruction
ALPAQUITA	S_{40}	Lateral fit → $\mathbf{S_{40}}$→ $E(S_{40},\theta)$
Tibet AS γ	S_{50}	Modified-NKG fit → $\mathbf{S_{50}}$→ zenith-**In**dependent energy
LHAASO-KM2A	ρ_{50}	ED lateral fit → $\boldsymbol{\rho_{50}}$→ zenith-dependent polynomial
HAWC	**Ground Parameter / NN**	Lateral signal at **~40 m** or neural network

Representative Energy Resolution around 100 TeV

The present ALPAQUITA performance is comparable to other major air-shower arrays at around 100 TeV.

Experiment / method	Reported metric	Representative resolution
This work — ALPAQUITA S_{40}	$\sigma[\ln(E_{rec}/E_{true})]$	$\approx$0.18 → $\approx$18%*
Tibet S_{50}MC	log-energy response width	$\approx$16%
LHAASO-KM2A	half-width of central 68%	$\approx$13%
HAWC NN	$\sigma_{\log_{10}}E$	$\approx$23–25% equivalent*
HAWC GP	$\sigma_{\log_{10}}E$	$\approx$30% equivalent*

Definitions and analysis conditions are not identical among experiments.

*Approximate fractional resolution using $\sigma_E/E \approx \sigma_{\ln E}$ for small fluctuations.

*HAWC values are approximate conversions from log-space resolution.

What Limits the Energy Resolution?

- **Energy resolution can be improved by optimizing the energy estimator and including shower-development information.**
  - Zenith-angle dependence reduces systematic shower-development effects.
  - Additional parameters such as shower age may further improve the estimation.
  - However, intrinsic shower-to-shower fluctuations remain.
  - These include fluctuations in the first interaction and subsequent shower development.
- **Therefore, the achievable resolution is ultimately limited by both shower fluctuations and reconstruction accuracy.**

What Is New in This Analysis?

- **New within ALPAQUITA**
  - First implementation of **zenith-angle-dependent S_x energy estimation**
  - Systematic optimization of the reference distance: S_{20}–S_{70} → S_{40}
  - Study of the **hit-detector requirement for the lateral fit**, including low-energy efficiency
  - Optimization of the estimator over a **wide energy range**
- **In the broader field**
  - The basic concept is **not new worldwide**
  - Similar approaches are already used in other air-shower experiments *e.g.* S_{50} *in LHAASO-KM2A,* S_{50} in Tibet As γ (not zenith)
  - **The key point of this work is to optimize the method specifically for ALPAQUITA**

Total E resolution &E bias