Optimization of the ALPAQUITA surface array performance

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Abstract

We optimize the performance of the ALPAQUITA surface air shower array including angular resolution and energy resolution. The angular resolution is defined as the 50% containment radius and is 0.2° in the 100 TeV range for gamma rays. It will help us detect source extension in the highest γ-ray energy range. Also, for the same gamma rays, the energy resolution is $\simeq 20\,\%$ (preliminary), which leads to making accurate flux points.

What is ALPAQUITA ?

ALPAQUITA is the prototype array of the ALPACA experiment which aims at southern very-high-energy γ-ray astronomy from 10 TeV to 1 PeV and cosmic ray physics from 10 TeV to 10 PeV. ALPAQUITA consists of a surface air shower array (AS array) and an underground water Cherenkov muon detector. In the ALPAQUITA phase, we will start observing TeV γ-ray sources before ALPACA.

ALPAQUITA AS array

The AS array consists of 97 plastic scintillation detectors each of which has an area of $1\,\mathrm{m}^2$. These detectors are located with $15\,\mathrm{m}$ spacing and cover $18{,}450\,\mathrm{m}^2$. Using the AS array, we observe extensive air showers and reconstruct incoming directions and energies of primary particles.

Incoming direction reconstruction

To reconstruct an incoming direction, first, we reconstruct the core position of a shower event as follows;

$$\left(\frac{\sum_i \rho_i^p x_i}{\sum_i \rho_i^p}, \frac{\sum_i \rho_i^p y_i}{\sum_i \rho_i^p}\right), \qquad (1)$$

where ρ_i is the number density of particle recorded with the i-th detector and x_i and y_i are the coordinates of the detector. An index p should be optimized so that the angular resolution holds the best performance.

Next, we assume the shower front to be in a conical shape that has a slope $b\,(\mathrm{ns/m})$ and modify the particle detection timing t_i of i-th the scintillation detector as follows;

$$t_i' = t_i - b\,r_i, \qquad (2)$$

where r_i is the distance between the i-th detector and the shower axis. Then, we calculate a directional cosine $\boldsymbol{l}$ that minimizes χ called *residual error* and defined as follows;

$$\chi^2 = \sum_i w_i\big(\boldsymbol{l}\cdot\boldsymbol{x}_i + c(t_i' - t_0)\big)^2, \quad \left(w_i = \frac{\rho_i^q}{\sum_j \rho_j^q}\right) \qquad (3)$$

where $\boldsymbol{x}_i = (x_i, y_i)$, t_0 is the hit timing averaged over all the detectors, and an index q is the quantity that should be optimized. After iterating the procedure (2) and (3) several times, we obtain the incoming direction of a primary particle as $\boldsymbol{l}$.

In a word, **we have three parameters that should be optimized; p in (1), b in (2), and q in (3)**.

Energy reconstruction

To reconstruct the energy, we fit the lateral particle density distribution of recorded shower events with NKG function (K. Kamata and J. Nishimura, Prog. Theor. Phys., 1958; K. Greisen, Ann. Rev. Nucl. Part. Sci, 1960; K. Kawata et al., Exp Astron, 2017) expressed as

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

where N_e is the total number of electrons contained in a shower, s is the age of the shower, and $r_\mathrm{m} = 125\,\mathrm{m}$ is Molière length at the ALPAQUITA site. **In this research, we use $\rho_{\mathrm{NKG}}(r)$ as an energy estimator and r should be optimized so that the energy resolution becomes optimal**. The aforementioned optimization procedure is now ongoing.

Results

Figure 1 shows the core position resolution (50% containment radius) for gamma-ray induced air showers for several values of p. The horizontal axis $\sum\rho$ indicates the total number density of particles recorded with the AS array per shower event. We note the corresponding energy ranges in the horizontal axis. Since we are interested in γ rays beyond 100 TeV, we choose $\boldsymbol{p = 1.5}$ as the optimal index. We also confirm that ~10% worsening of core position resolution does not affect the resultant angular resolution in the low $\sum\rho$ range.

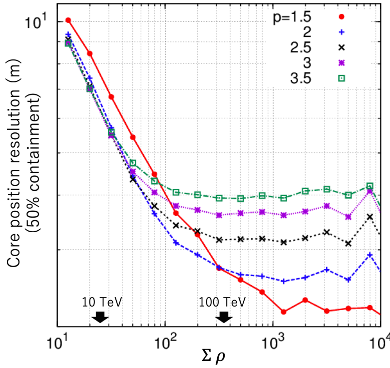

Fig.1 Optimization of p.

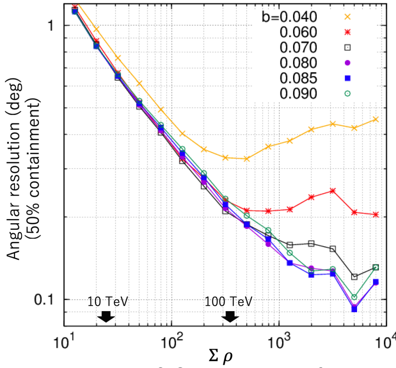

Fig.2 Optimization of b.

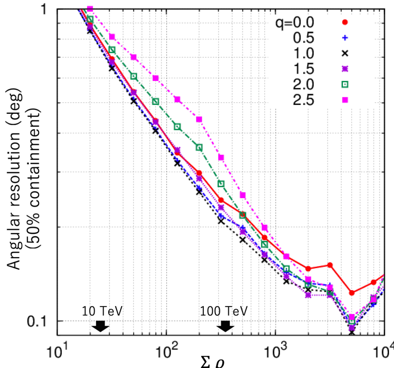

Fig.3 Optimization of q.

Figure 2 shows the angular resolution (50% containment radius) for gamma rays for several values of slope b. From this result, we determine the optimal b as a function of $\sum\rho$;

$$\boldsymbol{b\,(\mathrm{ns/m}) = 0.015\log_{10}(\Sigma\rho) + 0.035.} \qquad \boldsymbol{(0.07 \le b \le 0.085)}$$

After determining b, we search for the best value of q and find $\boldsymbol{q = 1}$ over the whole $\sum\rho$ range (Fig.3). We can see that **ALPAQUITA achieves the angular resolution of $0.2°$ for γ rays in the 100TeV range**.

Figure 4 shows a reconstructed energy map in the $(\sec\theta,\ \log_{10}\rho_{\mathrm{NKG}})$ plane. $\rho_{\mathrm{NKG}}(r = 30\,\mathrm{m})$ is used as an example. With this estimator, the energy resolution is estimated as ~20 % for γ rays in the 100 TeV range. Note that this value is still preliminary and requires further research.

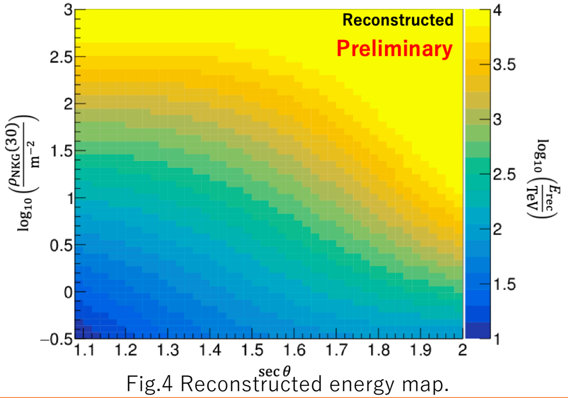

Fig.4 Reconstructed energy map.

Conclusion

We optimize three parameters that are used in the determination of γ rays' incoming directions. As a result, ALPAQUITA achieves the angular resolution of 0.2° for γ rays in the 100 TeV range. For the energy reconstruction, the results are still in preparation and will be presented shortly.