

Analysis of TAx4 hybrid trigger and events

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Abstract

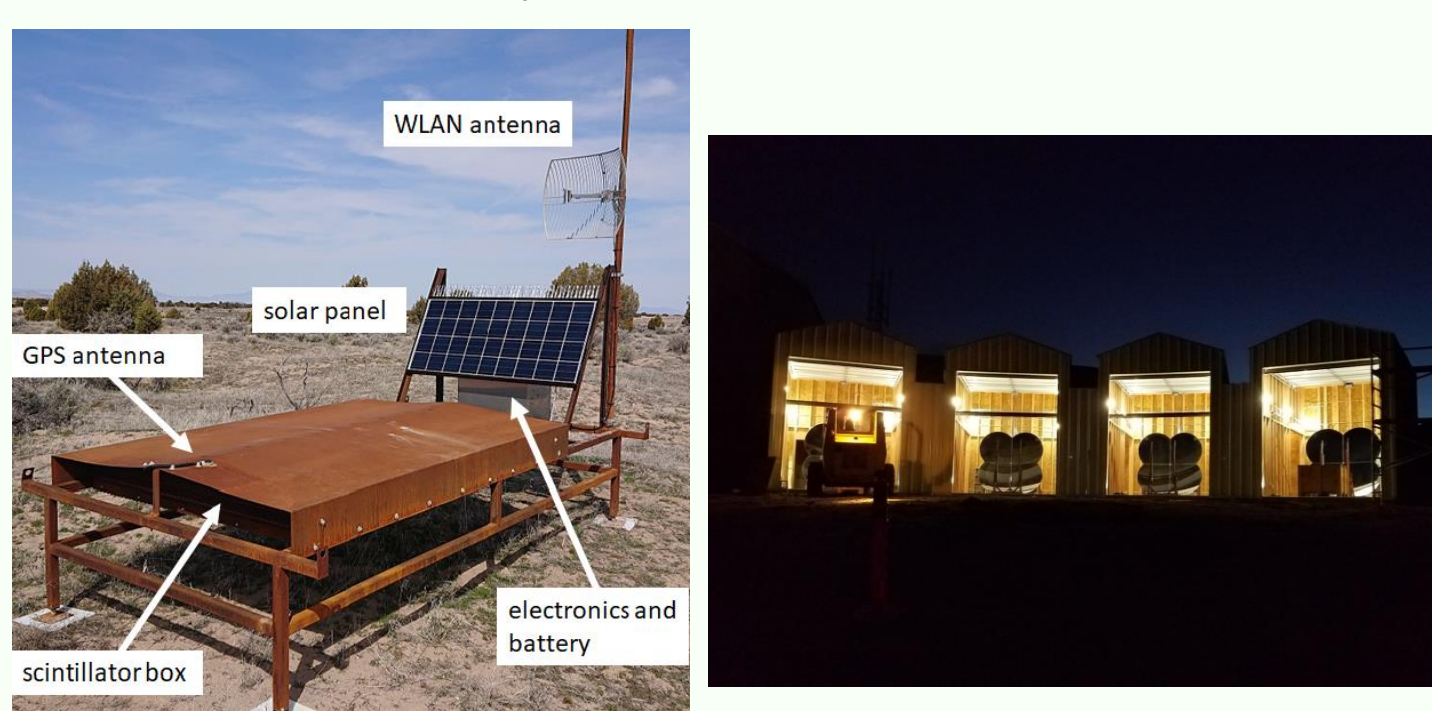
The Telescope Array is the largest ultra-high energy cosmic ray hybrid detector in the Northern hemisphere. While the TAx4 Surface Detector (TAx4 SD) has a duty cycle of $\sim 100\%$, it should be noted that the TAx4 Fluorescence Detector (TAx4 FD) observes the full longitudinal profile of the cosmic ray air showers and therefore is able to determine their energies more accurately than TAx4 SD. In addition, observing cosmic rays in hybrid mode ("hybrid events") has several advantages. Events seen in hybrid mode by the TAx4 FD and SD are used to establish the energy scale of the TAx4 SD. Moreover, the FD longitudinal profile is used to determine the mass composition of the primary cosmic ray particles, when the event geometries are well constrained by FD and SD measurements simultaneously. Despite large differences in the TAx4 SD/FD stand-alone performances, both detector types complement each other in measuring important physical quantities. Since August 2019, direction, energy, and X_{\max} can be obtained from reconstructing hybrid events. In this poster, preliminary analysis of TAx4 hybrid trigger and TAx4 hybrid events will be presented with focus on energy and X_{\max} observations.

1. TAx4 Detectors

TA found evidence for a cluster of arrival directions of cosmic rays with $E > 57$ EeV (hotspot). To confirm this hotspot including subsequent TA anisotropy results, we made a plan to quadruple the TA to accelerate the data collection speed.

So far we deployed 257 plastic scintillation detectors on a square grid with 2.08-km spacing for the TAx4 SD. The total area including the TA SD is approximately 2.5 times larger than the TA SD.

Two TAx4 FD stations were constructed, one with four telescopes at the Middle Drum (MD) site and the other with eight telescopes at the Black Rock (BR) site, to confirm the energy scale of cosmic-ray events measured with SD and increase the number of cosmic-ray events for accurate measurement of the depth of air shower maximum from longitudinal shower profile measured with FD (X_{\max}) related to mass composition utilizing hybrid events simultaneously observed with FD and SD. The TAx4 MD and BR FDs have been taking data regularly since June of 2018 and October of 2019, respectively.



(Left) a deployed TAx4 SD. (Right) the telescopes at the TAx4 MD site.

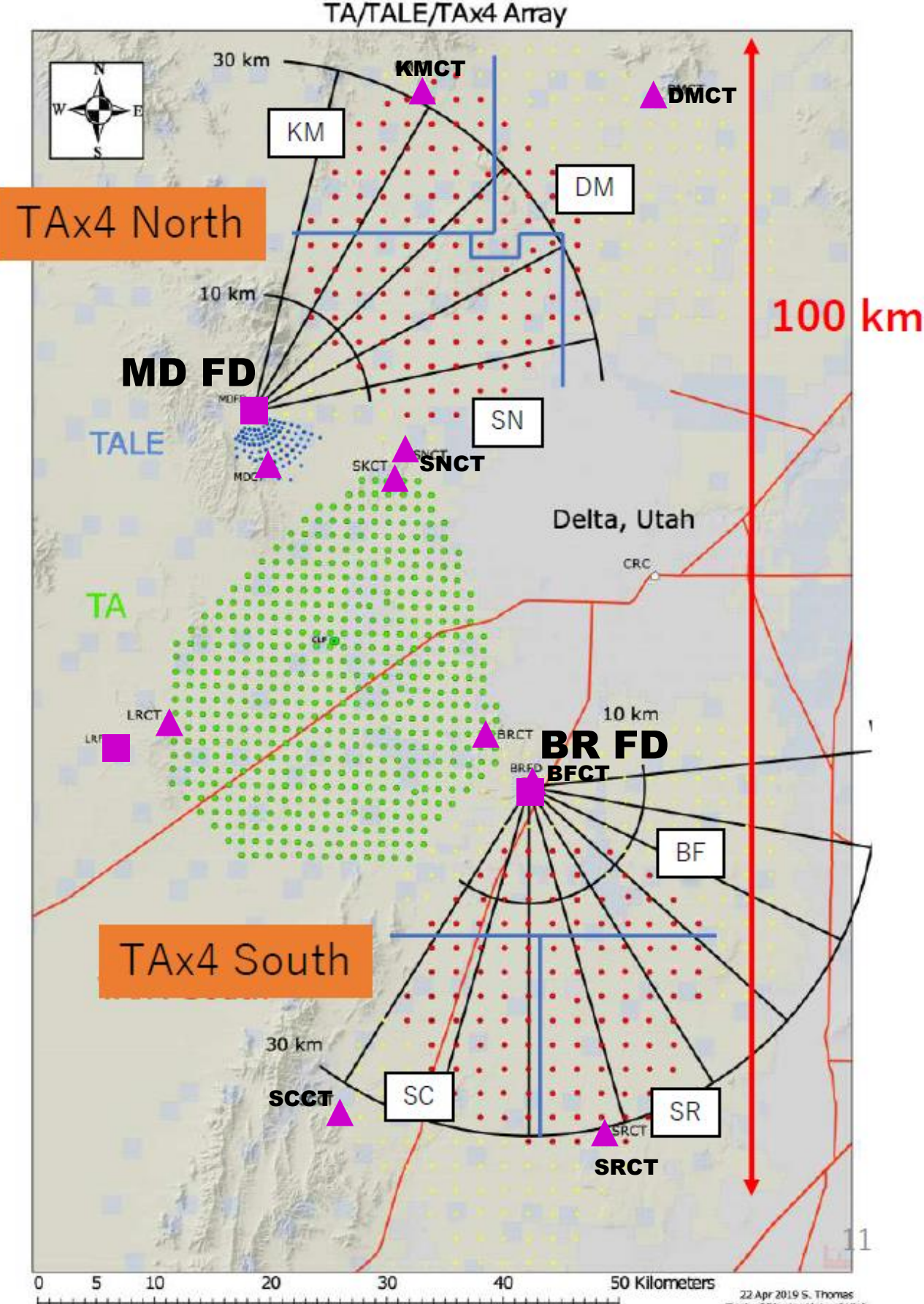


Fig.1 Layout of the TAx4 detector. Red circles denote deployed TAx4 SDs. Yellow dots denote planned TAx4 SDs. Purple triangles denote the communications towers (SNCT, KMCT, and DMCT in the northern lobe; BFCT, SCCT, and SRCT in the southern lobe for TAx4). The TAx4 SD array is divided into six sub-arrays (KM, DM, SN, BF, SC and SR). Blue lines show the boundaries of the TAx4 SD sub-arrays. Green circles denote the TA SDs. Blue circles denote the TALE SDs. Purple squares denote the fluorescence telescope stations (TA, TAx4 and TALE FDs at MD and TA and TAx4 FDs at BR).

2. Hybrid Trigger

When a primary ultra-high-energy cosmic ray (UHECR) enters the atmosphere, it generates an extensive air shower. The mass composition of UHECRs can be inferred from the measurement of X_{\max} . Composition of primary cosmic rays provides a strong constraint on models describing UHECR sources and hadron interaction models. UHECR composition can be measured directly up to about 10^{14} eV, but the composition around and above 10^{15} eV is indirectly measured using extensive air showers by the comparison with Monte Carlo (MC) simulation with hadron interaction models tuned by the data from particle accelerator experiments.

Current statistics of UHECRs above 10^{19} eV observed with TA is not enough to conclude the composition of real data comparing with MC simulation. Therefore the observation of UHECRs with the TAx4 FD is important to increase the statistics especially above 10^{19} eV.

Typical accuracy of the measurement of X_{\max} with monocular FD is ~ 60 g/cm². If the timing information of one SD near the core is used for the shower reconstruction mentioned in Section 3, the shower axis is determined better than the analysis using monocular FD only. The expected accuracy of the X_{\max} measurement is ~ 20 g/cm². Therefore, FD and SD hybrid analysis is very important for X_{\max} analysis. However, three adjacent SD hits are required to trigger showers with SD. The shower trigger efficiency for the TAx4 SD is about 30% at 10^{19} eV and lower for lower energies.

Therefore we installed hybrid trigger. The hybrid trigger is issued from FD when there is an FD trigger and sent to the communications towers to take SD signals with greater than 0.3 single-muon peak independent of SD shower trigger.

The latest hybrid trigger system was developed and used for the TA Low Energy Extension (TALE) detector that observes UHECR with energies from $\sim 10^{16}$ eV to $\sim 10^{19}$ eV. The average rate of hybrid trigger rate is about 50 mHz. We use the same system for TAx4. As a result, we obtained a hybrid trigger rate of about 5 mHz on average and about 15 mHz at maximum. The scheme of the flow of the hybrid trigger is shown in figure 2.

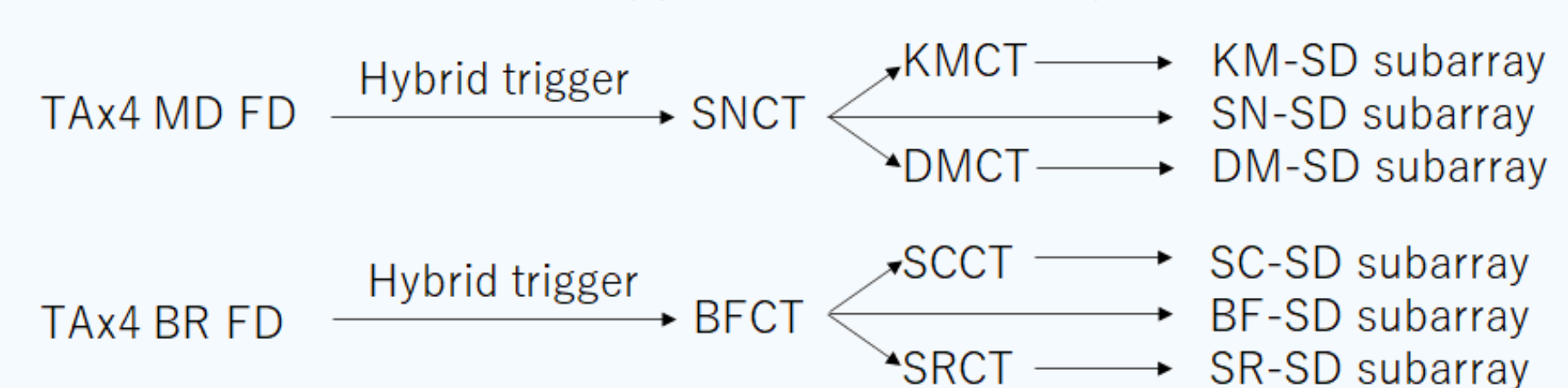


Fig. 2 Schematic diagram of the TAx4 hybrid trigger flow. The MD FD and the BR FD are the FD stations at the MD site and the BR site, respectively. The flows from the TAx4 MD FD and the TAx4 BR FD are the systems in the northern lobe and southern lobe, respectively. SNCT, KMCT, DMCT, BFCT, SCCT and SRCT are communications towers explained in figure 1 caption. The corresponding SD subarrays are described as SN-SD, KM-SD, DM-SD, BF-SD, SC-SD and SR-SD subarrays.

3. Reconstruction method

The events that are reconstructed in hybrid-trigger mode have their geometry determined by the following procedure. Firstly, the shower detector plane (SDP) is reconstructed from the pattern and pointing direction of the triggered photomultipliers (PMTs). Next Profile-Constraint Geometry Reconstruction that simultaneously fits the shower geometry and the shower profile. The shower geometry is calculated using the time versus angle fit that uses the pointing directions and timings of the PMTs. The expected timing of i -th PMT is described as

$$t_{exp,i} = t_{core} + \frac{1}{c} \frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{core}$$

For an event that has the timing information of one SD near the shower core, t_{core} is expressed as

$$t_{core} = t_{SD} + \frac{1}{c} (r_{core} - r_{SD}) \cos\psi$$

Once the shower geometry is determined, the profile of the air shower is fitted using the Gaisser-Hillas parametrization formula,

$$N(x) = N_{max} \left(\frac{x - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X_0}{\lambda}} \exp\left(-\frac{X_{max} - X_0}{\lambda}\right)$$

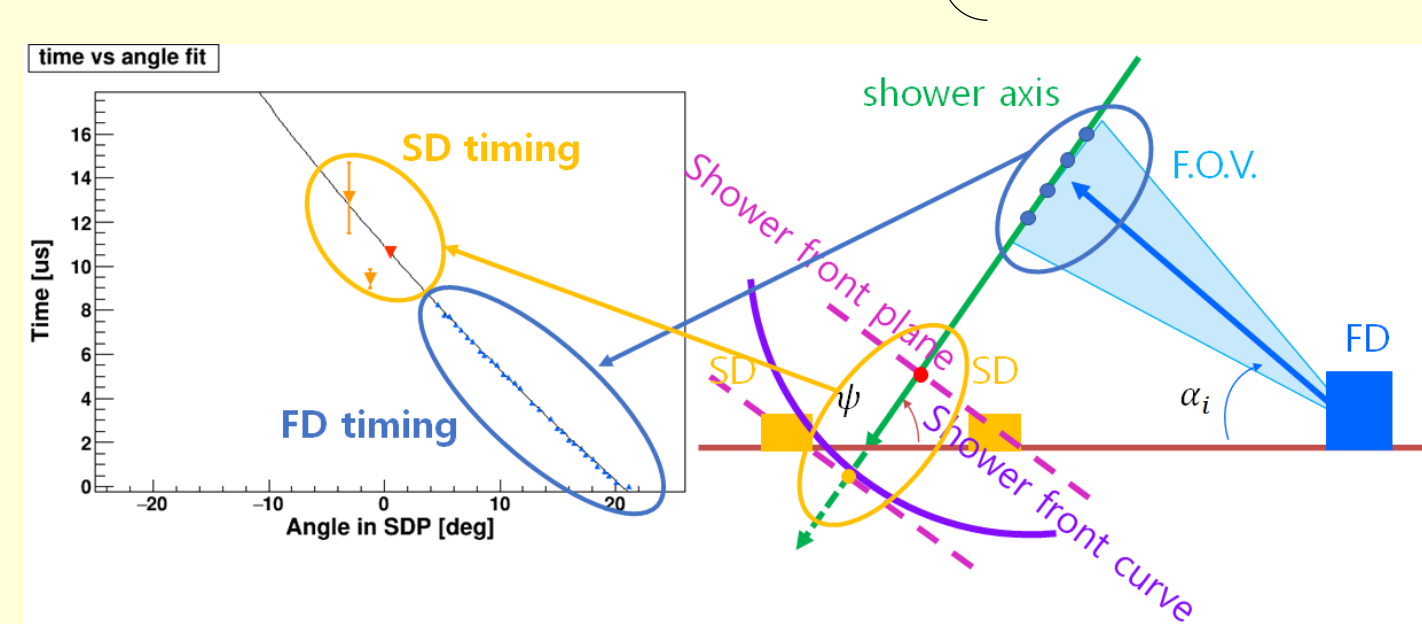


Fig. 3 Schematic of TAx4 hybrid reconstruction. Left) angle in SDP (Hybrid). Right) parameters used for reconstruction.

4. Data

TAx4 monocular FD and hybrid analyses are described in [1,2], and TAx4 SD analyses are described in [3,4]. The hybrid trigger system has been operating stably since June 2020. Fig.4 shows the On-time of hybrid-triggers to the northern and southern SD lobes.

To select good example events shown in Section 5, the following quality cuts are applied in the same way as the TA hybrid analysis:

- $0 < \psi < 55$ degrees
- $\chi^2/ndf < 6$
- $500 \text{ g/cm}^2 (X_{start}) < X_{max} < 1200 \text{ g/cm}^2 (X_{end})$

Here χ^2 is the χ^2 of the geometry fit, and ndf is the number of degrees of freedom.

- [1] M. Potts for this conference
- [2] R. Gonzalez for this conference
- [3] H. Jeong for this conference
- [4] K. Fujisue for this conference

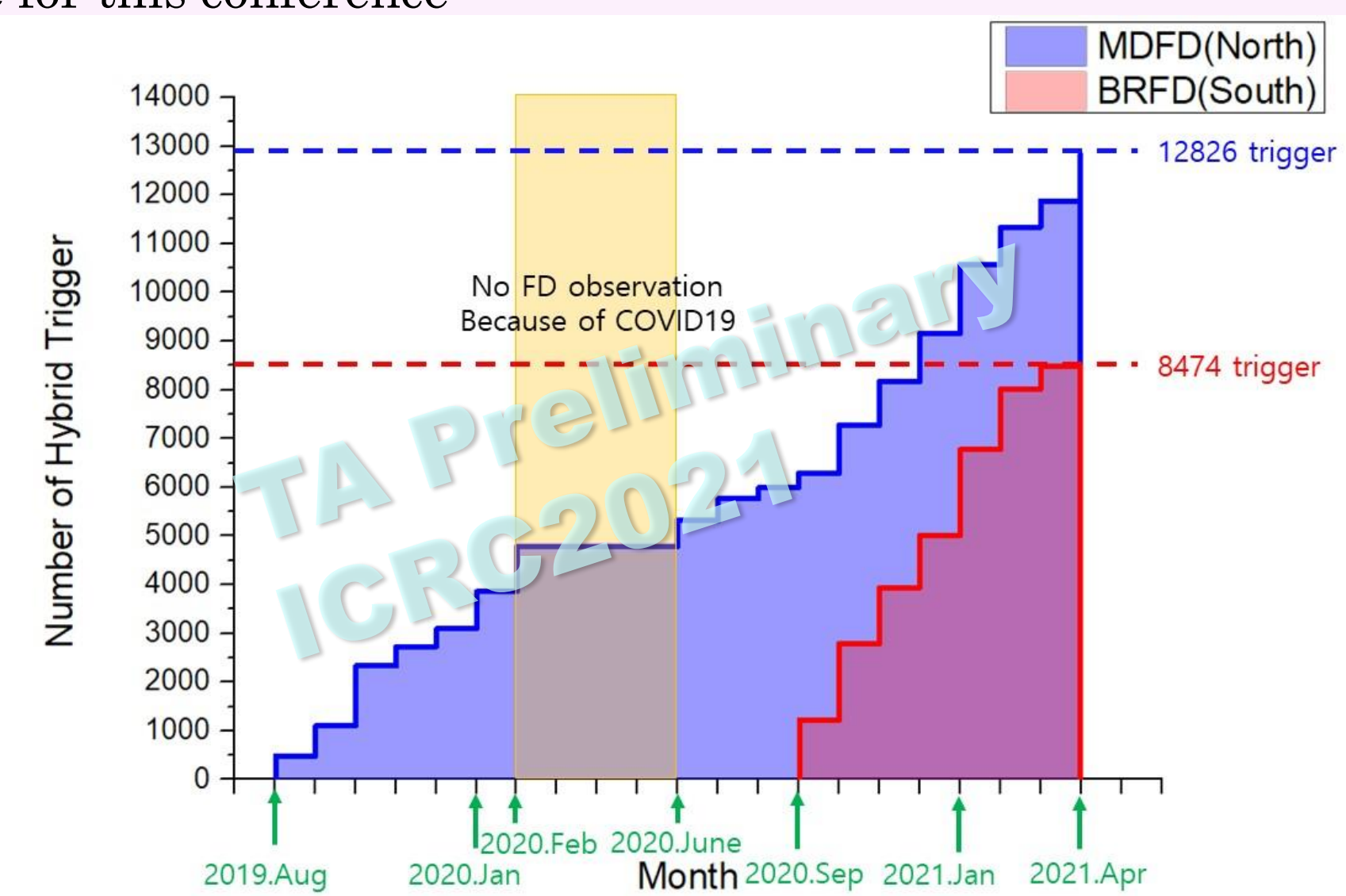


Fig. 4 Ontime of TAx4 hybrid triggers from the TAx4 MD FD to the TAx4 northern SD subarrays in magenta and from the TAx4 BR FD to the TAx4 southern SD subarrays in pink.

5. Results

Here examples of hybrid-trigger reconstruction for events with hybrid triggers in the northern lobe are shown. Figure 5 is the hybrid reconstruction fit result for a real event that was self-triggered by SD. Table 1 summarizes the reconstructed zenith angle, azimuth angle, core x, core y, energy and X_{\max} obtained by hybrid analysis. Figure 6 is the hybrid reconstruction fit result for a real event that was not self-triggered by SD. Table 2 summarizes the results by hybrid analysis. The detailed analysis of the real data is ongoing along with the study by MC simulation.

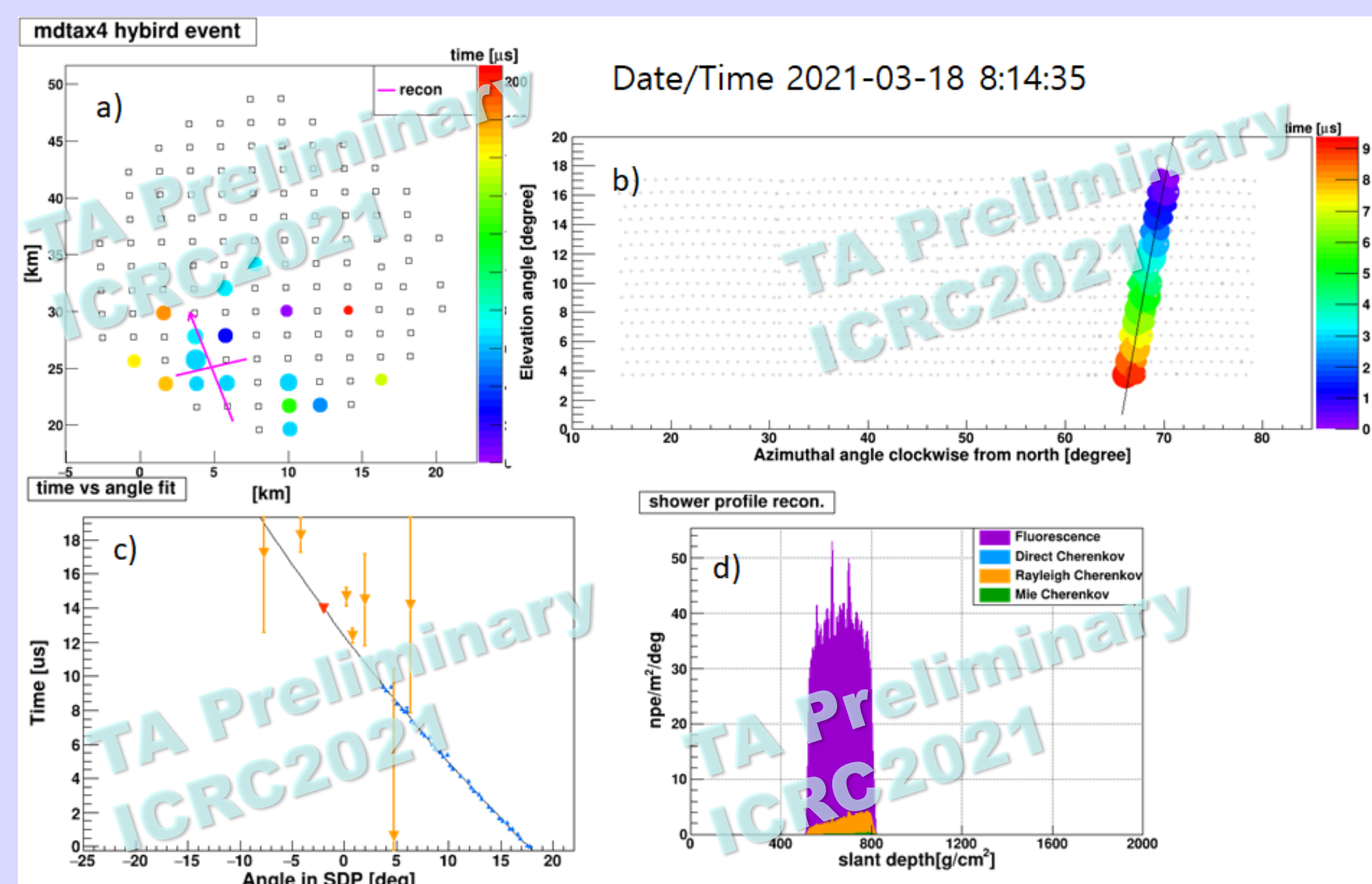


Fig.5 An event recorded at 2021/03/18 08:14:35.588009. (a) SD footprint with shower direction by magenta arrow and shower core position by the cross point. The labels for the x-axis and y-axis denote the position IDs in the west-to-east and the south-to-north directions, respectively. (b) FD display for zenith and azimuth angles. Blue triangles are FD data used for the fit. Inverse triangles are SD data: a red one is used for the fit and others (orange) are not used for the fit. (c) Time versus angle plot using hybrid reconstruction. (d) shower profile. The purple, blue, orange and green areas correspond to fluorescence, direct Cherenkov, Rayleigh Cherenkov and Mie Cherenkov components.

Analysis	zenith (deg)	azimuth (deg)	core x (km)	core y (km)	Log E	X_{\max} (g/cm ²)
Hybrid	14.6	163.1	4.803	25.112	19.22	763.2

Table 1: The result of hybrid reconstruction fit to an event that corresponds to figure 5 for zenith angle, azimuth angle, core x position, core y position, \log_{10} (energy) and X_{\max} .

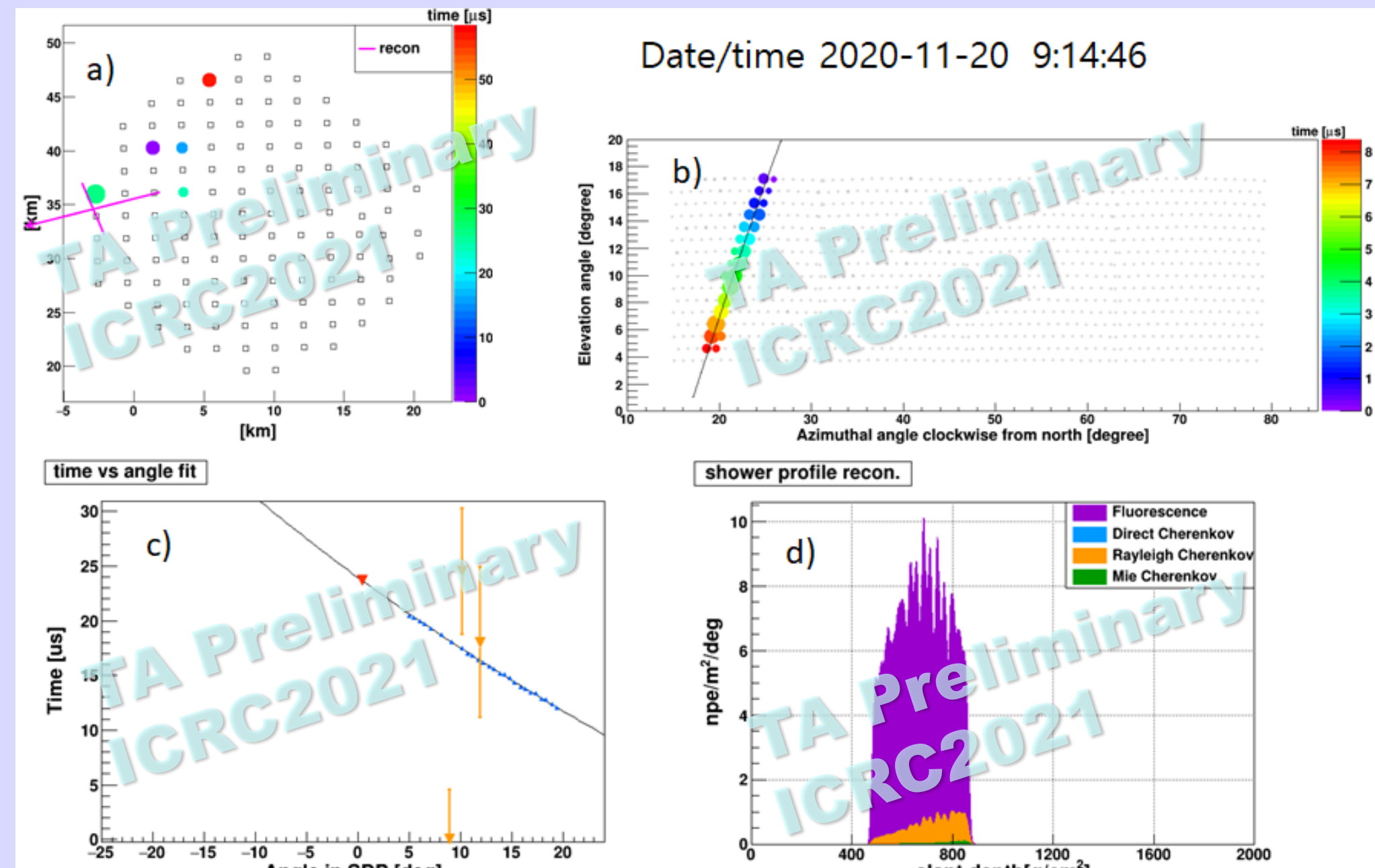


Fig.6 An event recorded at 2020/11/20 09:14:46.663632. (a) SD footprint with shower direction by magenta arrow and shower core position by the cross point. (b) FD display for zenith and azimuth angles. (c) Time versus angle plot using hybrid reconstruction. (d) shower profile.

Analysis	zenith (deg)	azimuth (deg)	core x (km)	core y (km)	Log E	X_{\max} (g/cm ²)
Hybrid	30.2	72.0	-2.914	34.567	18.73	743.3

Table 2: The result of hybrid reconstruction fit to an event that corresponds to figure 6.