



# DEVELOPMENT OF THE DOUBLE CASCADE RECONSTRUCTION TECHNIQUE IN THE BAIKAL-GVD NEUTRINO TELESCOPE

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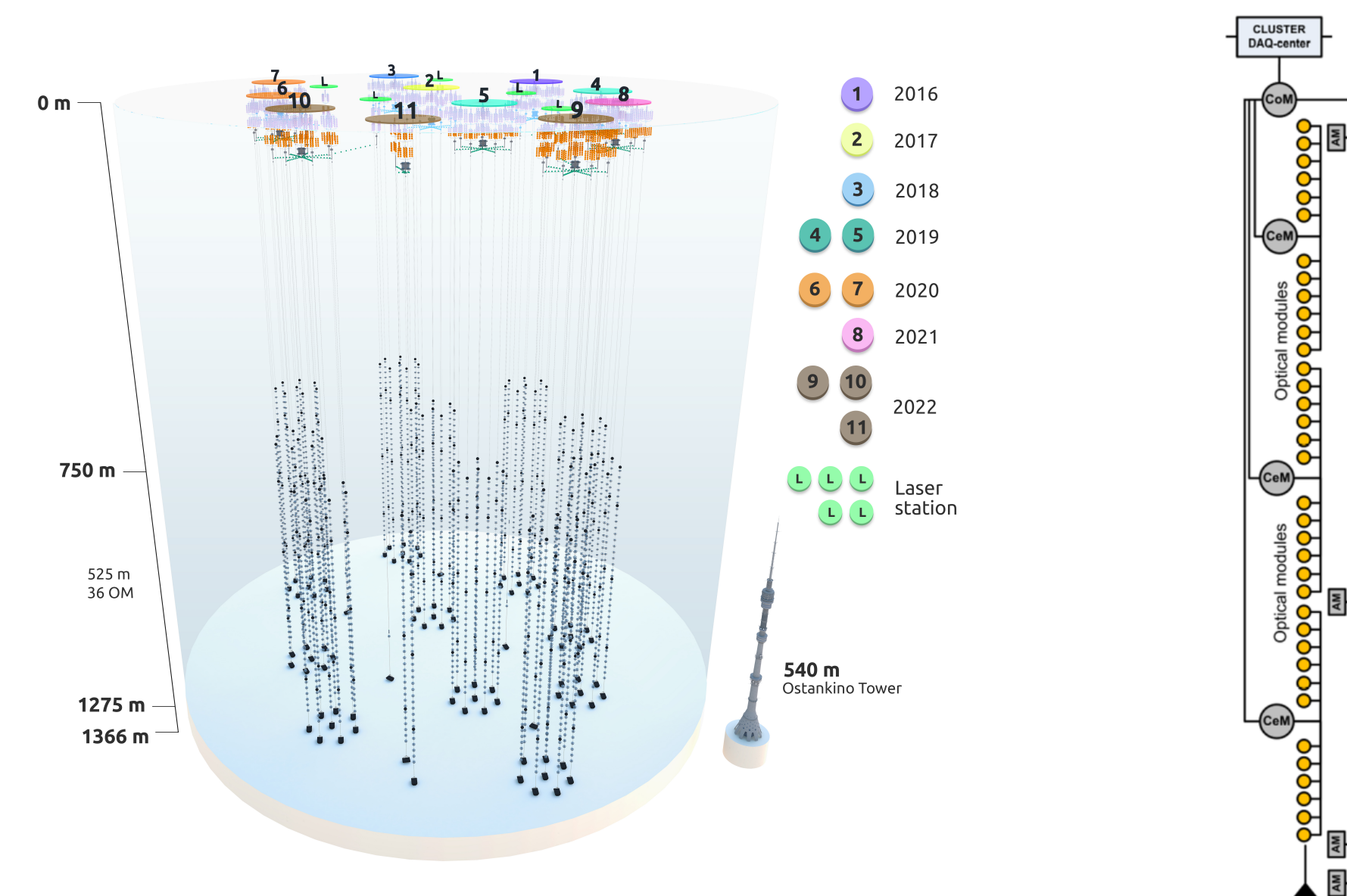


BAIKAL-GVD

## NEUTRINO TELESCOPE BAIKAL-GVD

The Baikal Gigaton Volume Detector (Baikal-GVD) [1] is a neutrino telescope installed in the deepest fresh-water lake in the world - Lake Baikal. The main goal of this telescope is to observe astrophysical neutrinos via detecting the Cherenkov radiation of the secondary charged particles originating in the interactions of neutrinos. It is a three dimensional array of photomultiplier tubes installed approximately 3 - 4 km from shore, at the depths of  $\sim 750$  - 1275 m.

The basic independently working unit of the Baikal-GVD is called cluster. The cluster consists of 8 vertical strings, on every string there are 36 Optical Modules (OM). In 2022, 10 clusters are installed resulting in 2880 OM deployed.



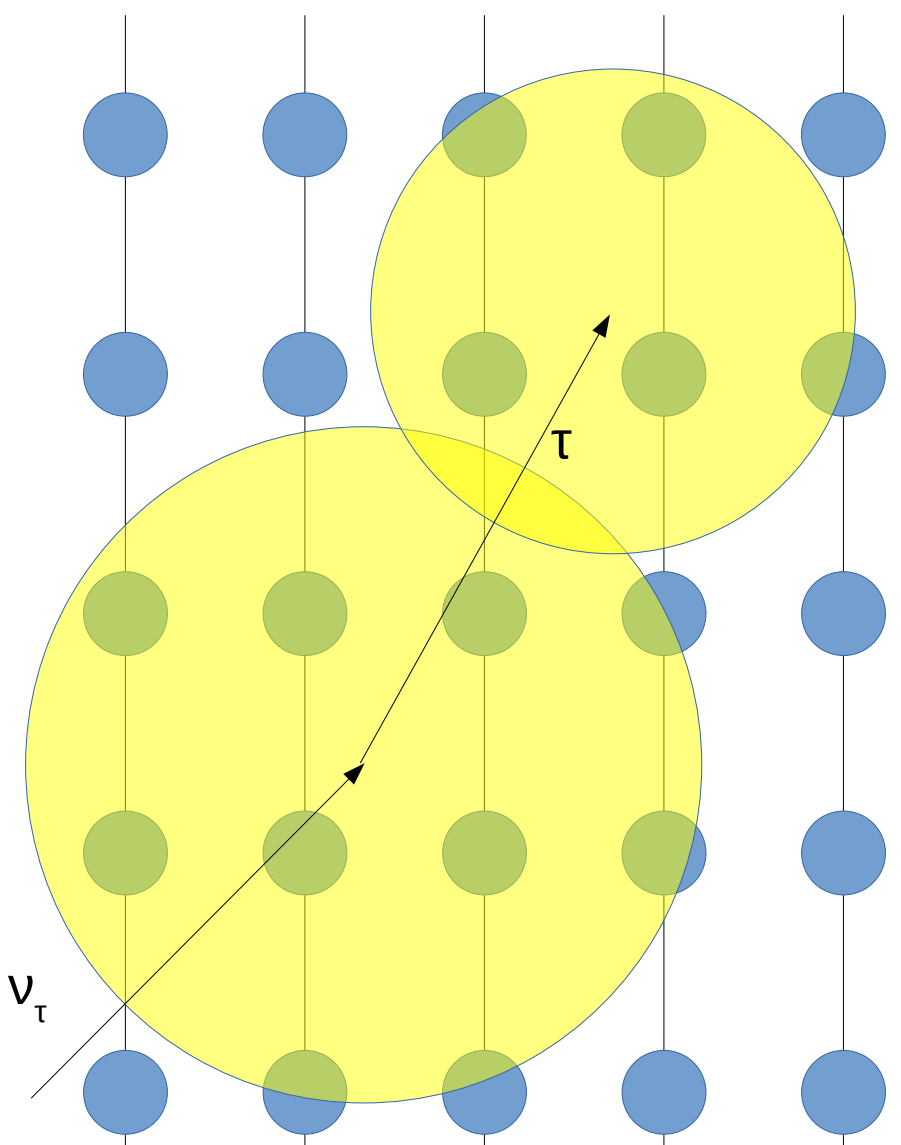
The main component of the OM is a photomultiplier tube with hemispherical photocathode enclosed in pressure-resistant glass sphere with a diameter of 42 cm. In OM, there is also a controller, a two channel amplifier, two LEDs for time and charge calibrations, and a high-voltage supply.

## TAU NEUTRINO INTERACTION

One of the methods for astrophysical neutrino detection is an observation of high-energy  $\nu_\tau$ , because the rate of  $\nu_\tau$  produced in the atmosphere is almost negligible [2].

In general, there are two types of signatures of charged current  $\nu_\tau$  interaction according to  $\tau$  decay mode:

- decay to muon  $\rightarrow$  single cascade signature, branching ratio  $\sim 17\%$
- decay to electron/hadrons  $\rightarrow$  double cascade signature, branching ratio  $\sim 83\%$



## DOUBLE CASCADE RECONSTRUCTION ALGORITHM

### 1. Hit selection

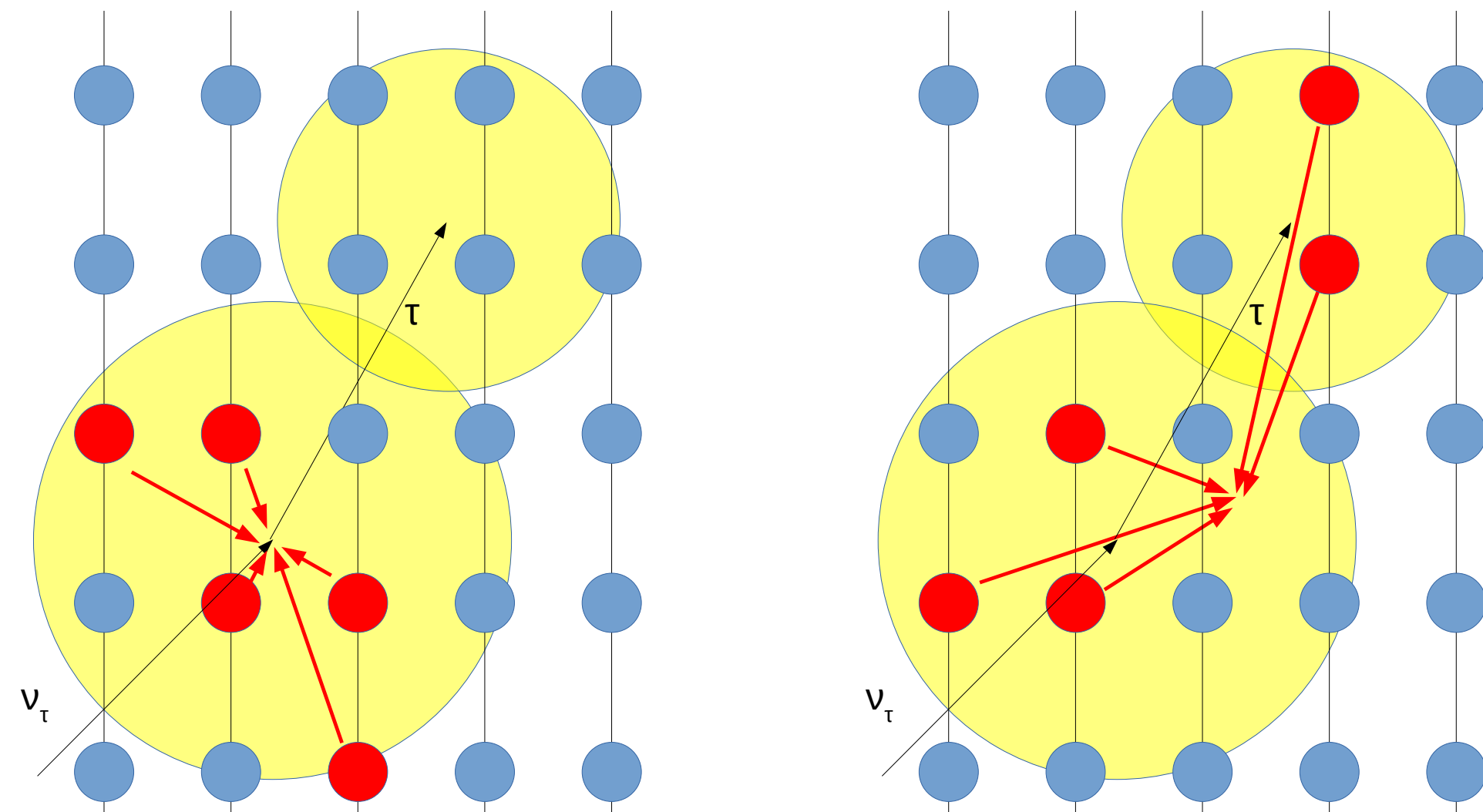
The first step in the single cluster double cascade reconstruction algorithm is to separate signal and noise pulses. The signal pulses are selected according to the causality criterion:

$$|T^{ref} - T_i^{meas}| < d_i/v + \delta t.$$

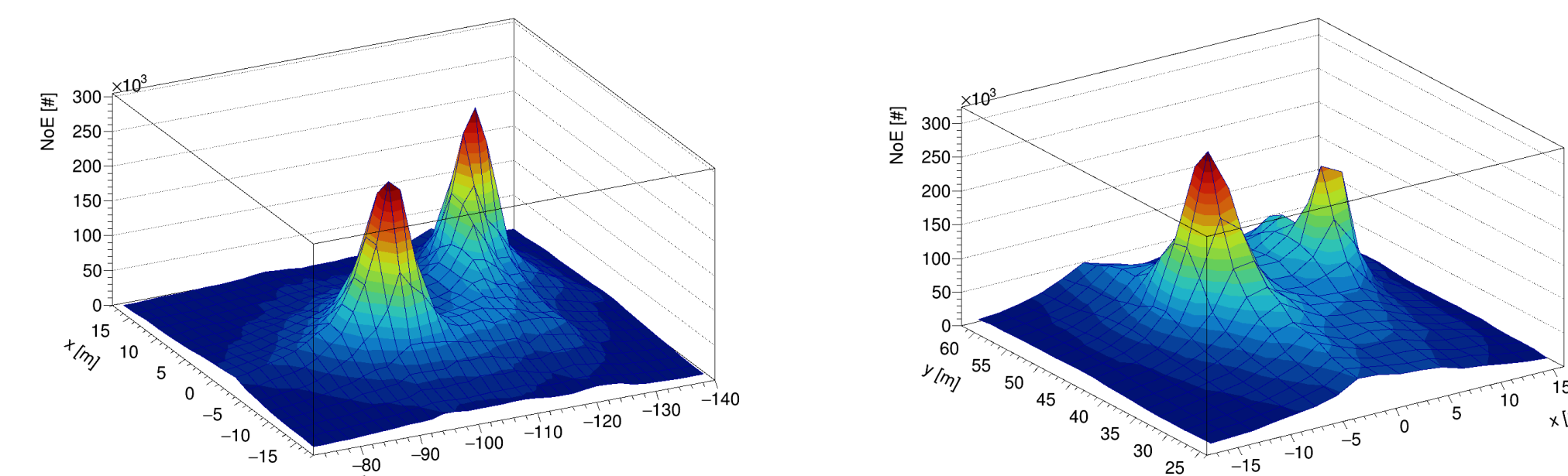
The efficiency of signal pulse selection is  $\sim 80\%$ . Hit purity after the causality filter is  $\sim 99\%$ .

### 2. Hit sorting

The second step is to divide signal pulses into two subsets that correspond to the two cascades. Firstly, a set of five pulses is selected. They are used for estimation of cascade position and time. If they correspond to one cascade only, position and time are estimated accurately.



If positions and times of the cascades are estimated from all possible sets of five pulses, two peaks corresponding to the positions and times of the two cascades should be created.



Accurate estimation of position and time of cascade allows effective selection of pulses corresponding to particular cascade. By selecting hits corresponding to the

## BACKGROUND ESTIMATION

type of MC	NoE [ $\text{y}^{-1} \text{ cluster}^{-1}$ ]	NoE <sub>DCreco</sub> [ $\text{y}^{-1} \text{ cluster}^{-1}$ ]	efficiency [%]
$\nu_\tau$ astrophysical (DC-like)*	$4.05 \cdot 10^{-2}$	$1.67 \cdot 10^{-2}$	41.3
atmospheric $\mu$ bundles	$5.38 \cdot 10^8$	38.1	$7.09 \cdot 10^{-6}$
$\nu_e$ atmospheric	9.34	$1.42 \cdot 10^{-3}$	$1.52 \cdot 10^{-2}$
$\nu_\mu$ atmospheric	87.4	$1.31 \cdot 10^{-2}$	$1.50 \cdot 10^{-2}$
$\nu_e$ astrophysical	1.71	$3.82 \cdot 10^{-2}$	2.24
$\nu_\mu$ astrophysical	$9.86 \cdot 10^{-1}$	$1.23 \cdot 10^{-2}$	1.25

\* signal MC

two estimated cascade vertices, two subsets of hits are chosen.

### 3. Position and time reconstruction

In the next step, the positions and times of cascades are estimated by minimizing of  $\chi^2$  distribution:

$$\chi^2 = \frac{1}{N_{hit1} + N_{hit2} - 7} \left( \sum_{i=0}^{N_{hit1}} \frac{(T_{1i}^{meas} - T_{1i}^{exp}(\vec{R}_1, T_1))^2}{\sigma_t^2} + \sum_{i=0}^{N_{hit2}} \frac{(T_{2i}^{meas} - T_{2i}^{exp}(\vec{R}_2, T_2))^2}{\sigma_t^2} \right).$$

Since the direction of double cascade event is defined as a vector connecting vertices of the two cascades, it is also reconstructed in this step.

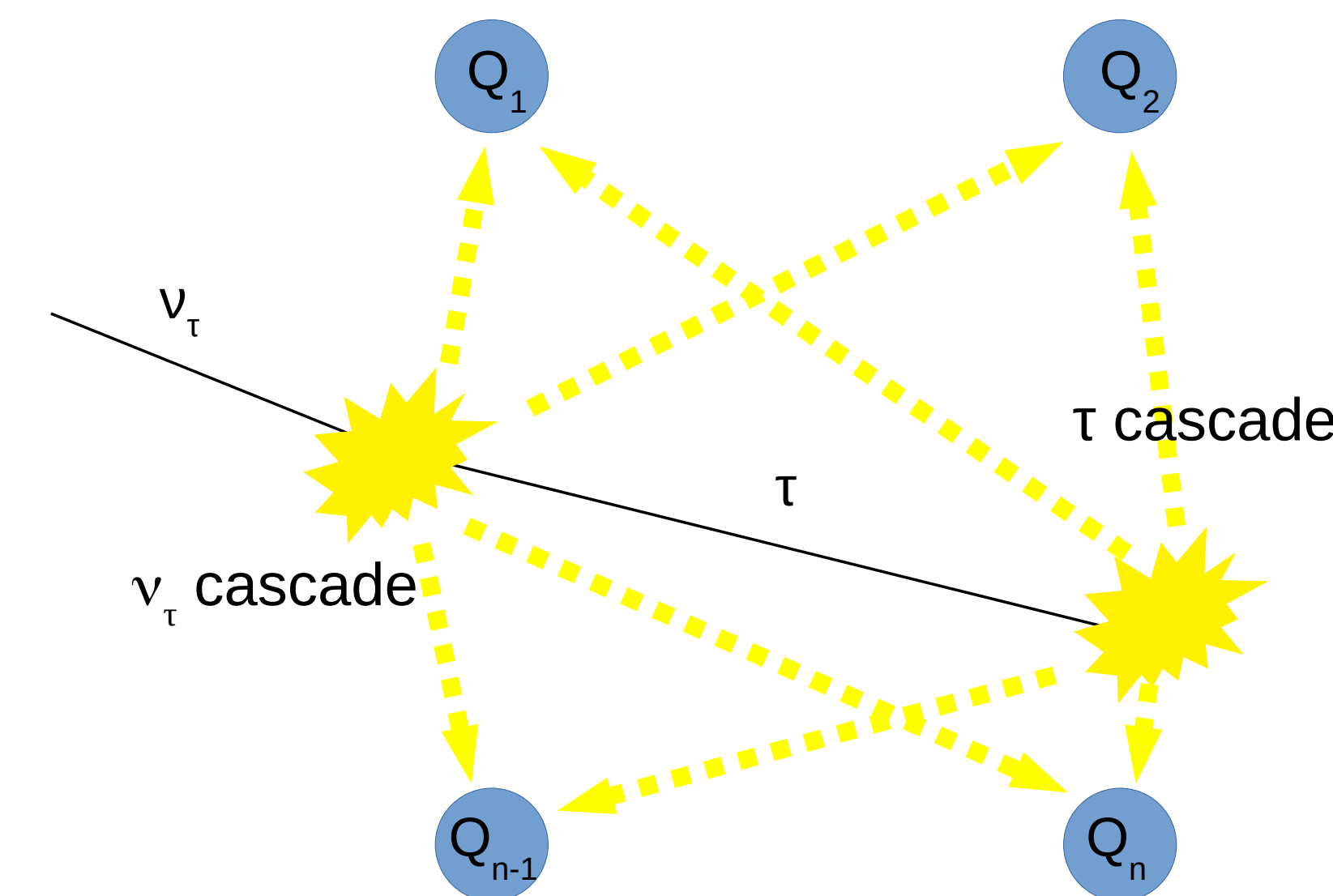
### 4. Energy reconstruction

Energies of cascades are determined by minimizing of likelihood function:

$$L = - \sum_{i=0}^{hitOM} \log(P_i(q_i | Q_i)) - \sum_{i=0}^{unhitOM} \log(P_i(q_i = 0 | Q_i)).$$

where  $P_i$  is the Poisson probability of detecting charge  $q_i$  on  $i^{th}$  OM, while detection of charge  $Q_i$  is expected. Charge expected on  $i^{th}$  OM is calculated as a sum of the charges from both cascades:

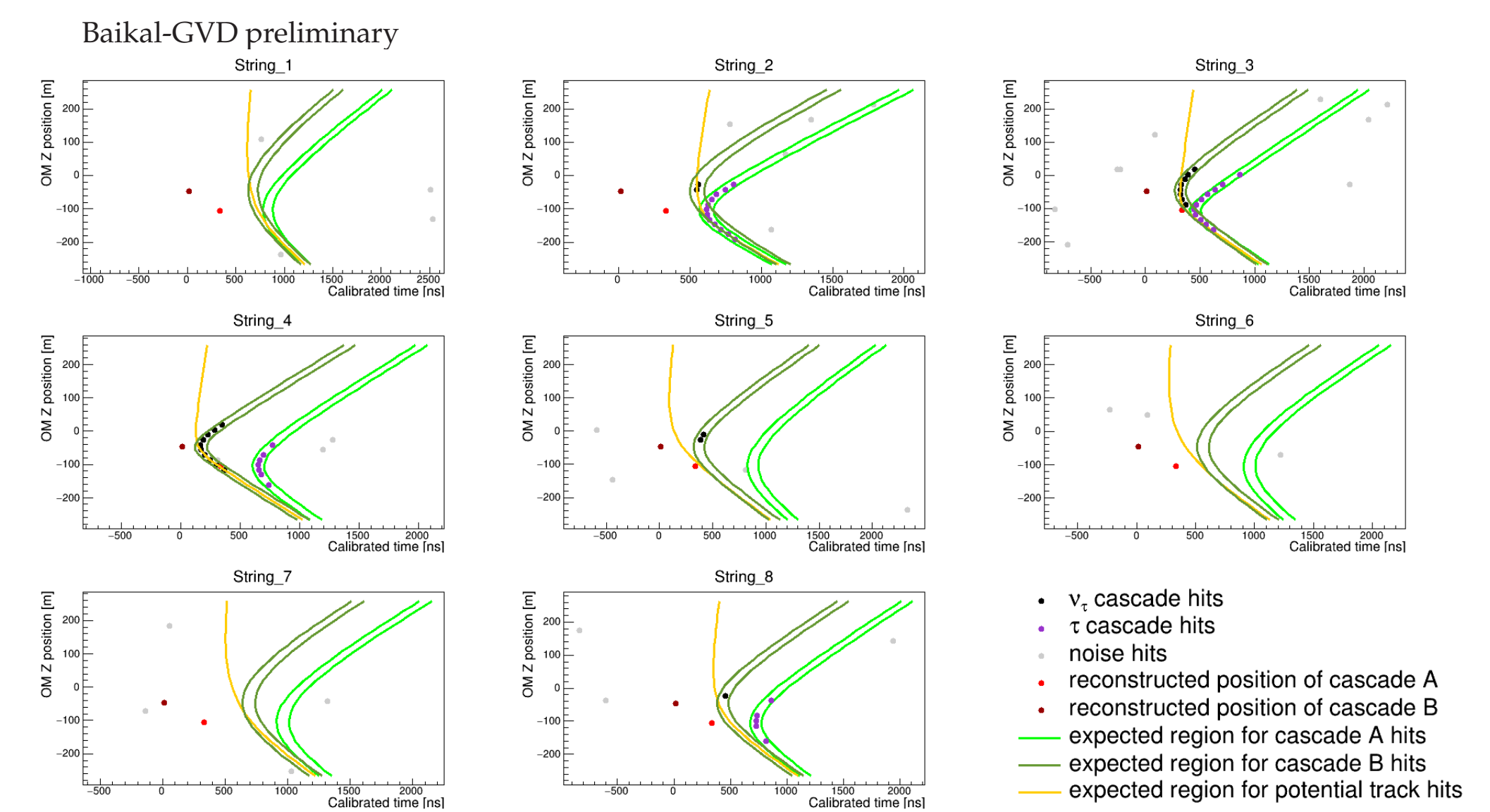
$$Q_i = Q(r_{1i}, t_{1i}, \theta, \phi, E_1) + Q(r_{2i}, t_{2i}, \theta, \phi, E_2).$$



## ALGORITHM PRECISION

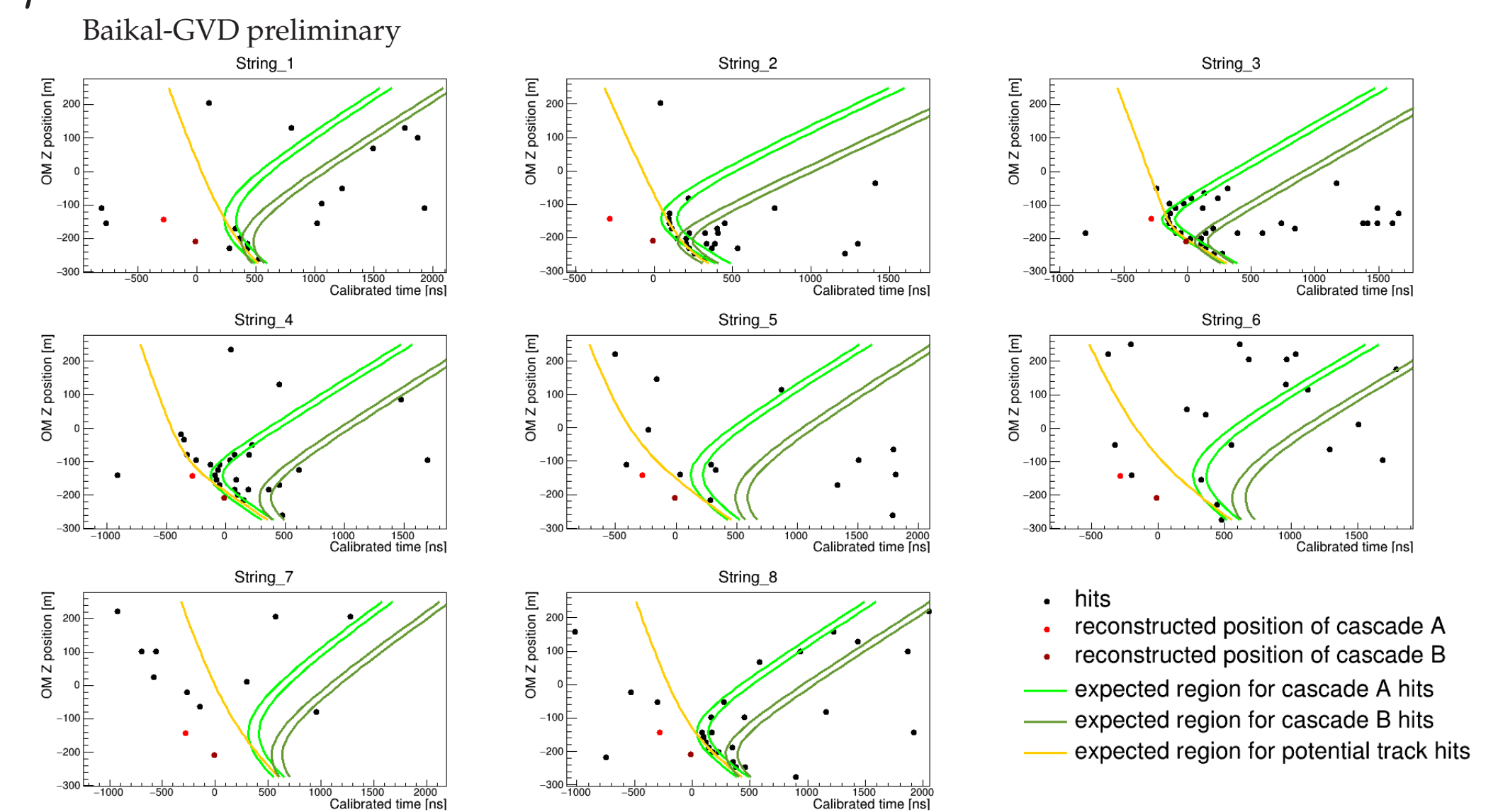
DC parameter	reco mismatch	
	mean	median
position cascade A [m]	3.09	2.27
position cascade B [m]	5.03	2.46
distance between vertices [m]	2.83	0.75
direction [deg]	9.96	2.67
E <sub>recoA</sub> /E <sub>MC</sub>	1.21	-
E <sub>recoB</sub> /E <sub>MC</sub>	1.40	-

## VISUALIZATION MC $\nu_\tau$ EVENT



## VISUALIZATION DATA EVENT

Illustration of potential double cascade event identified in experimental data. Hits located in track expected region (string 4) imply that it is most likely an atmospheric  $\mu$  bundle event.



## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] <https://baikalgvd.jinr.ru/>
- [2] A. Palladino et al., The importance of observing astrophysical tau neutrinos. J. Cosmol. Astropart. P. 8 (2018).

## CONTACT

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