Development of a compact emulsion spectrometer for the identification of tau neutrinos and anti-tau neutrinos

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1.Introduction

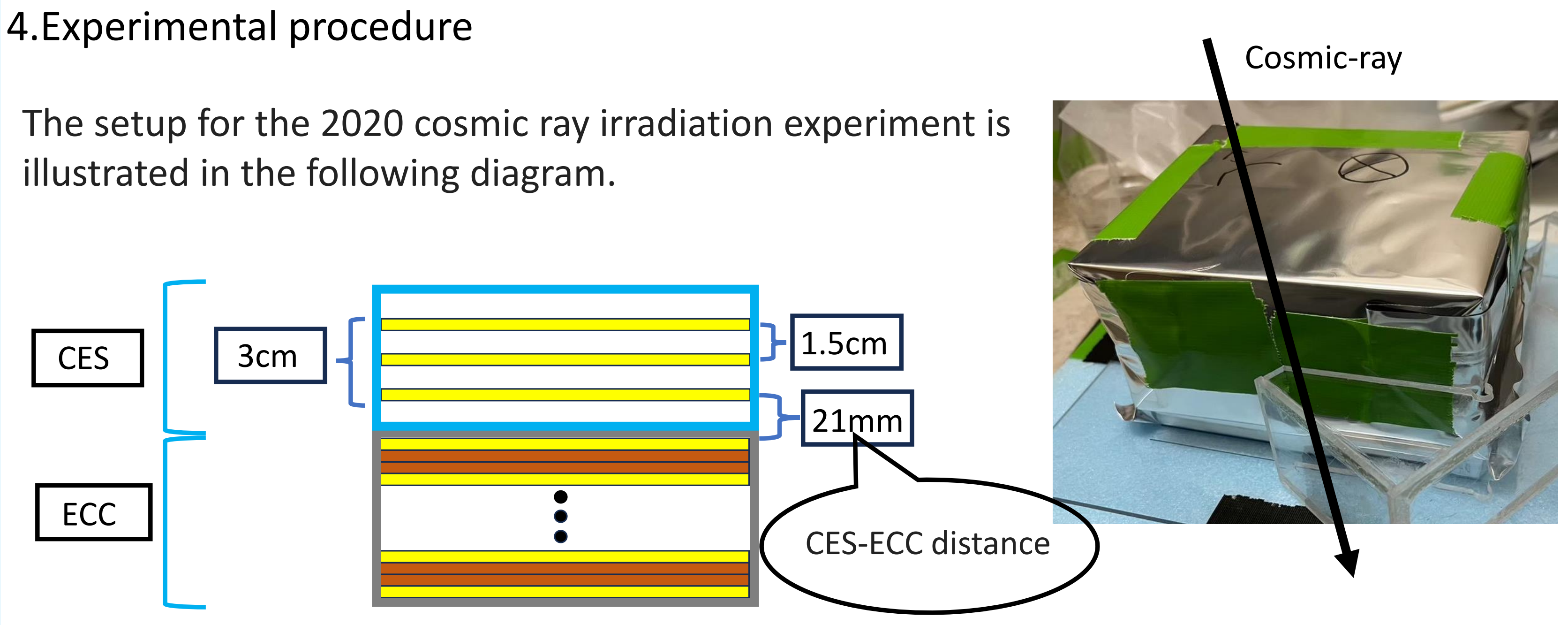
We are developing the Compact Emulsion Spectrometer (CES), a device capable of distinguishing between positive and negative tau neutrinos. The CES is a spectrometer that utilizes three glass-based nuclear emulsion plates, each 500µm thick, stacked with air gaps of 1.5cm between them within an electromagnetic field. By applying a magnetic field, the motion of charged particles passing through is bent, and this curvature, called as 'sagitta,' measured across the three plates, enables the determination of momentum. Sagitta is inversely proportional to momentum, necessitating a precise measurement of particle tracks with a precision of micrometers to achieve accurate momentum measurement, a requirement met by these nuclear emulsion plates. Additionally, the direction of bending due to the magnetic field varies based on the charge carried by daughter particles, enabling the determination of their charge. Performance evaluations were conducted through cosmic ray irradiation experiments in 2020 and 2022 without the application of a magnetic field.

2.Purpose

Neutrinos like $\nu_\mu$and ν_e, being easily generated and possessing high penetrative abilities, are particles with well-understood properties. However, τ neutrinos have a short lifespan, resulting in a limited detection count to date, which stands at 19 instances. Consequently, there's a lack of comprehensive understanding of their properties. We are developing a detection device specifically targeting ν_τ. CES, with its low mass and space-efficient design, enables experiments without reducing the mass while efficiently triggering reactions in neutrino experiments that require high mass targets. By measuring τ decay processes, we aim to verify lepton universality and investigate symmetry violations in the lepton sector. Hence, we are conducting performance verifications in preparation for operations.

4.Experimental procedure

The setup for the 2020 cosmic ray irradiation experiment is illustrated in the following diagram.



CES is positioned upstream while ECC is placed downstream. ECC consists of eight layers of emulsion plates, with 2mm-thick lead as a seven-layer stacked structure for the target layers. Here, cosmic rays are exposed for a duration of 24 hours. An analysis of momentum using multiple electromagnetic scatterings is conducted on the tracks of cosmic rays that have traversed all layers of the ECC. Subsequently, by linking the tracks of CES and ECC, momentum information is attributed to the tracks on the CES side. Selection and analysis of tracks that have passed through all layers of CES and ECC are performed. As the experiment is conducted without applying a magnetic field in the cosmic ray irradiation experiment, sagitta is set to 0. However, due to alignment precision, position measurement accuracy, momentum measurement precision, and the impact of multiple electromagnetic scatterings, the value of sagitta spreads from 0. Determining this spread of sagitta from 0 for each momentum and dividing the predicted sagitta at each momentum by the spread from sagitta allow for the measurement of charge identification precision.

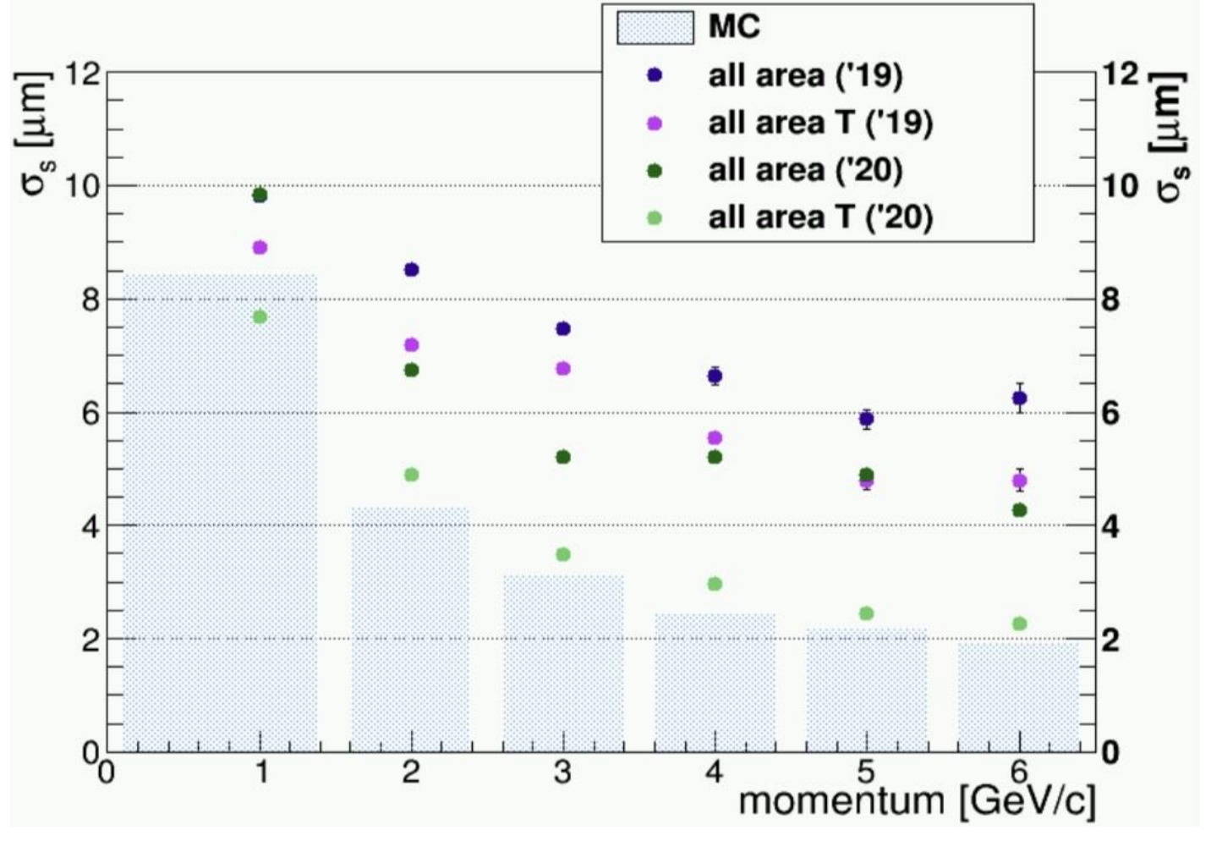
5.Results

We conducted an estimation of σ_s using Monte Carlo simulations as a reference.
With B=1.2T, L=0.03ｍ, we assumed a value for sagitta. As illustrated below, the charge identification accuracy is confirmed to be 3σ or higher even at 6GeV/c.

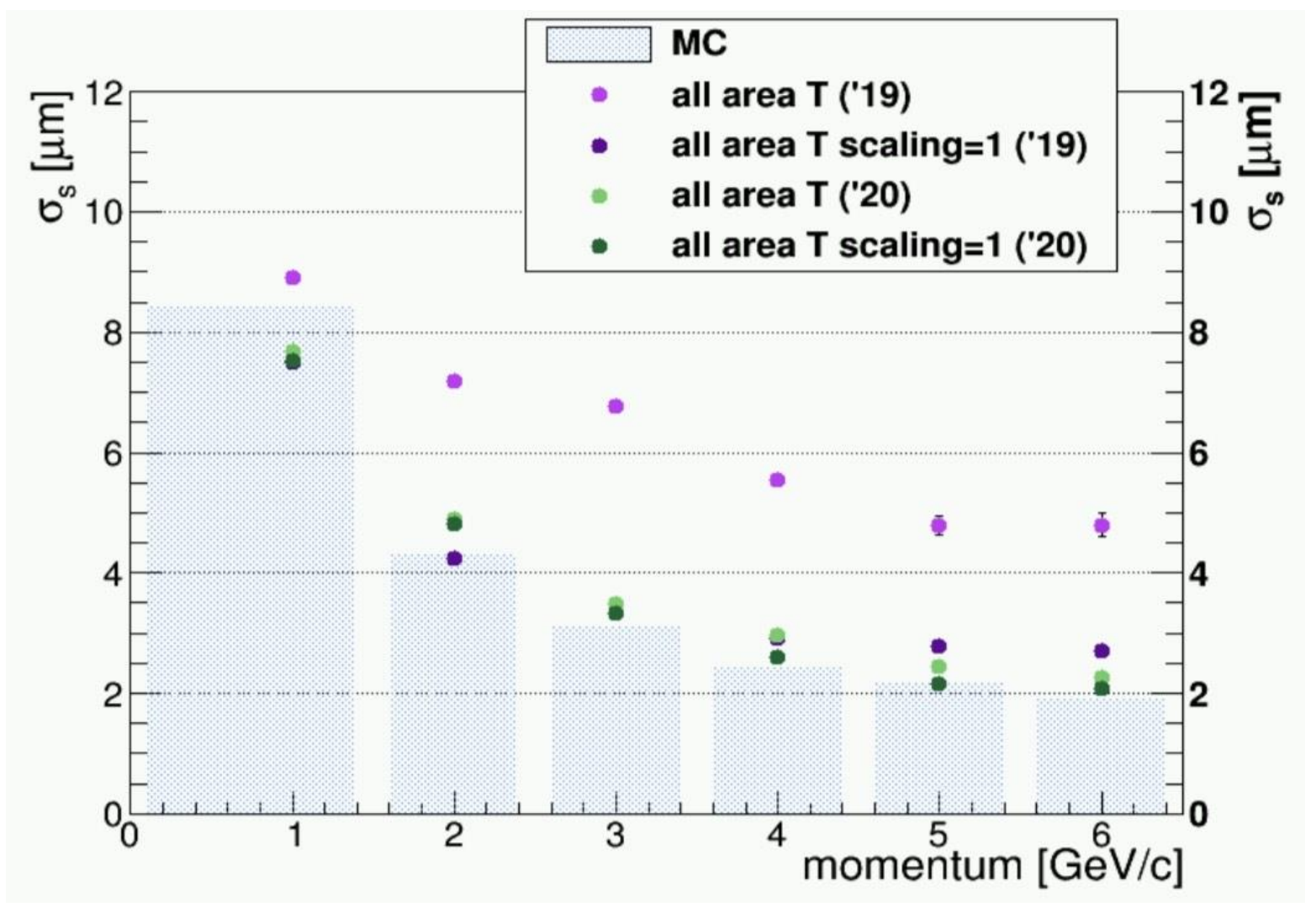
momentum(GeV/c)	sagitta(㎛)	σ_s（㎛）	the charge discrimination confidence level
1	40.51	8.41	4.8
2	20.26	4.31	4.7
3	13.51	3.13	4.3
4	10.13	2.44	4.1
5	8.1	2.16	3.8
6	6.75	1.9	3.6

The figure below summarizes the results of Monte Carlo simulations compared to actual values. In the left figure, there's a significant deviation from both the 2019 and 2020 simulation results. However, excluding the dependence on track angles, both cases exhibit values closer to the simulations (all area T). Furthermore, considering the potential misalignment of track reconstruction during CES track connections, adjustments were made to avoid adding scaling during affine transformation, leading to even closer proximity to simulation values,demonstrating its validity.

As a result, a charge identification confidence level of 2.5σ or higher was obtained within the momentum range up to 6GeV/c.



σ_s for each momentum before and after separating the LT axes.



σ_s for each momentum without scaling adjustments.

3.Principle

Due to the change in deflection caused by the charge of charged particles, it's possible to discern the charge of the pre-decay matter. Using the magnitude of the deflection (sagitta), it's also possible to measure momentum mechanically

$$s = \frac{0.3zBL^2}{8p}$$

(z: Charge, B: Magnetic field, L: Distance between the 1st and 3rd plates, p: Momentum)

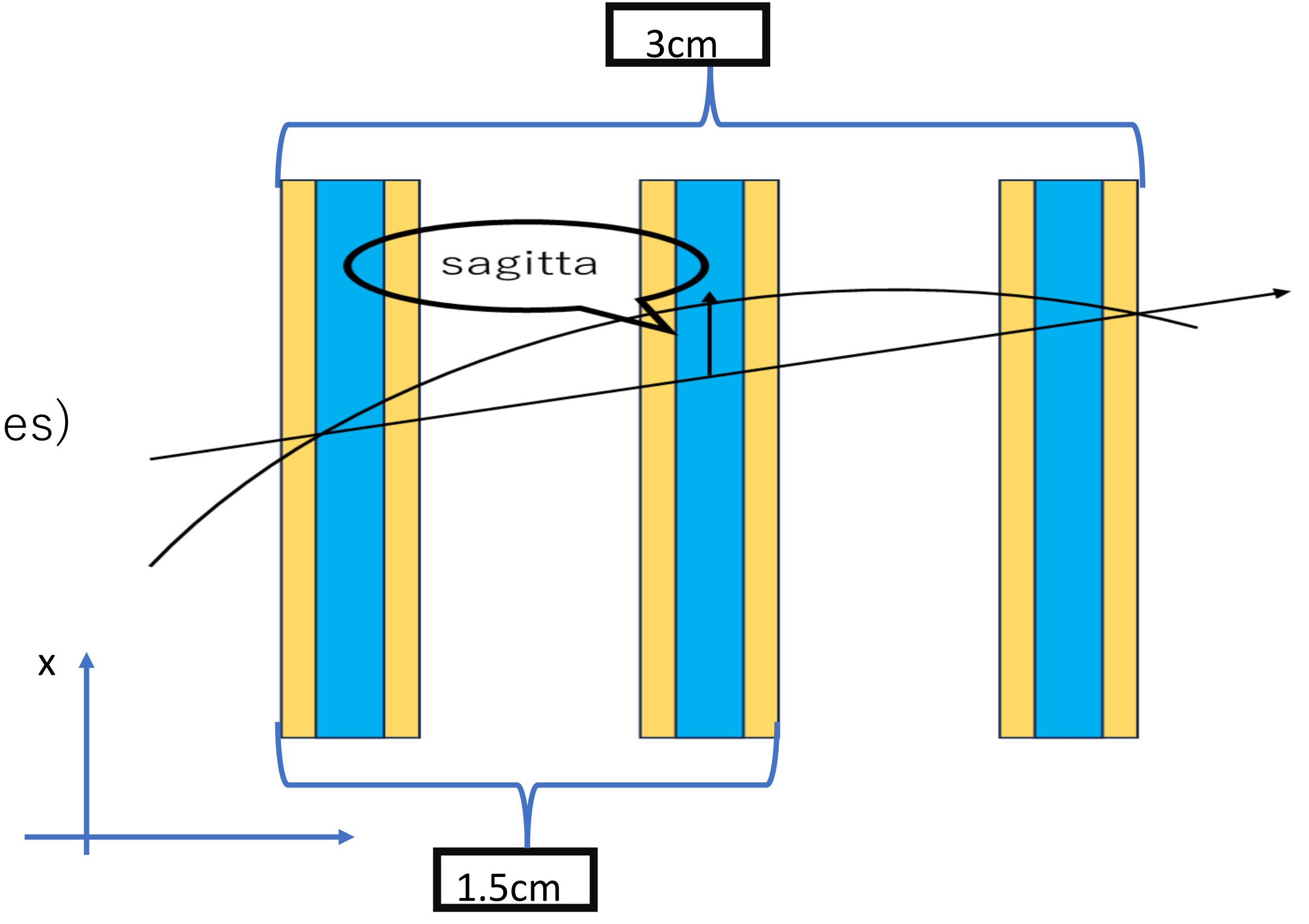
Using coodinates,

$$s = x_2 - \frac{x_1 + x_3}{2}$$

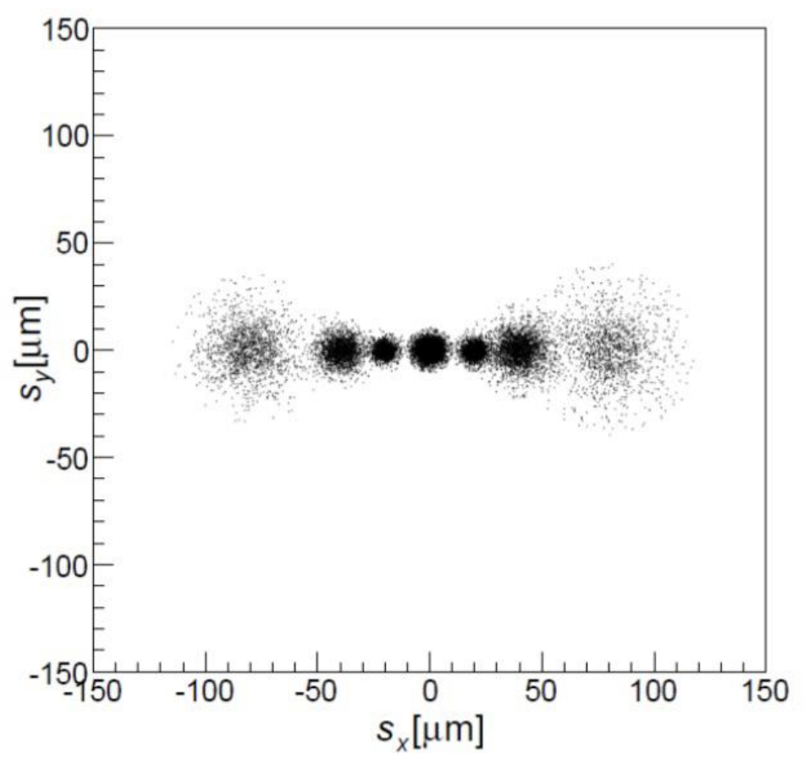
(x : Vertical coordinates)

So,sagitta is

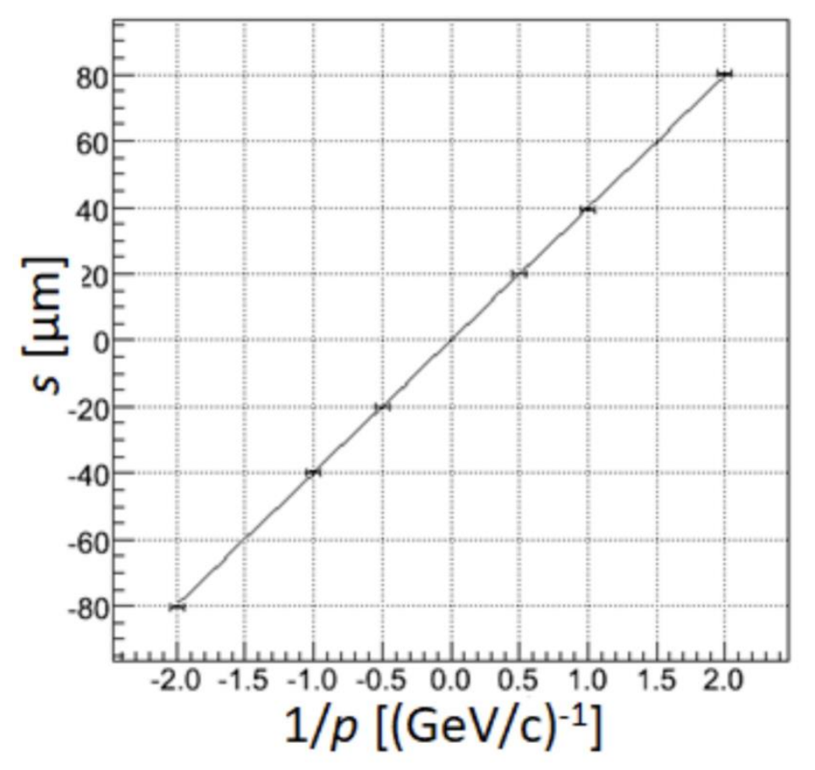
$$s \propto \frac{1}{p}$$



It is thereby understood that the momentum is inversely proportional to it. Therefore, by precisely measuring the position, the momentum can be deduced from the sagitta.
In 2005, as a validation of the principle, an experiment was conducted at the KEK PS Internal Target T1 beamline. A CES was placed in a 1T magnetic field, and π^± particles were vertically irradiated onto a 2×2cm central area of the emulsion plates. This aimed to verify the correlation between momentum and sagitta.



two-dimensional sagitta distribution



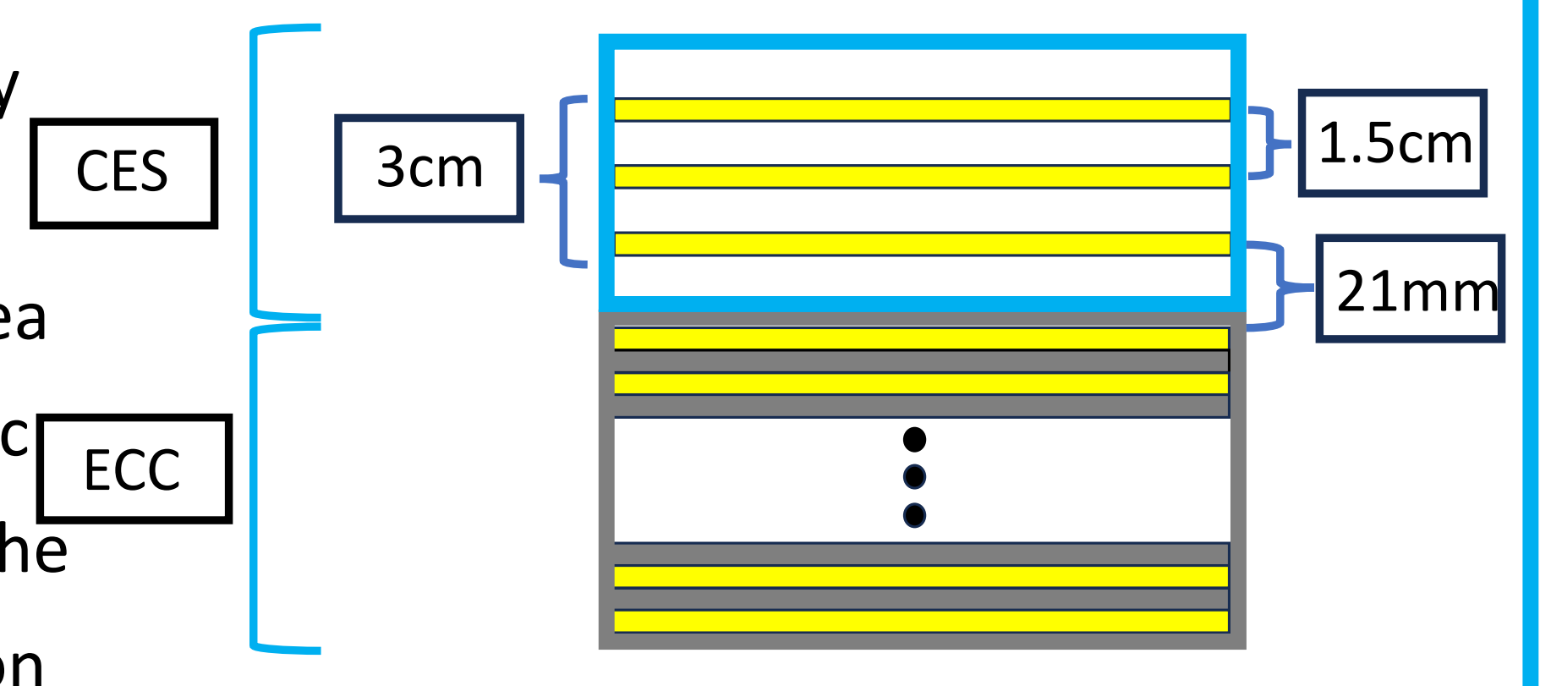
Sagitta and 1/p correlation

momentum(GeV/c)	-2.0	-1.0	-0.5	0.5	1.0	2.0
Ave(㎛)	-20.0	-39.5	80.4	80.6	40.2	19.9
RMS(㎛)	2.9	5.2	10.8	13.0	6.7	3.1
center value(㎛)	-20.0	-39.6	-80.4	80.4	40.0	19.9
σ(㎛)	2.9	5.1	10.6	12.6	6.2	3.1
expected Ave(㎛)	-19.9	-39.8	-79.6	79.6	39.8	19.9
expected RMS(㎛)	2.7	5.2	10.6	10.6	5.2	2.7

spread of sagitta per beam

From this experiment, a strong correlation between momentum and sagitta was confirmed.

6.Prospects



In the 2020 cosmic ray irradiation experiment, charge identification accuracy of more than 3.0σ was confirmed in the momentum region up to 6 GeV/c in an area of 70㎠. The purpose of the 2023 cosmic ray irradiation experiment was to obtain the reproducibility of the charge determination accuracy in the CES area and the reproducibility as an experiment. In addition, to improve the momentum measurement resolution by ECC, which cannot be removed in order to measure momentum by cosmic ray irradiation, we have replaced lead with tungsten, which has a higher density than lead of the same thickness, and 11 layers of emulsion plates to verify the charge discrimination accuracy in the cosmic ray irradiation experiment.