Investigation of Muon Track Reconstruction Using Stacked Smartphone CMOS Sensors

The Mobile Muons
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1 Introduction

1.1 Abstract

When you think of a smartphone, you probably don't associate it with a particle detector. However, the CMOS sensors in smartphone cameras have pixels far smaller than those in typical particle trackers, that produce hits when particles pass through them. This experiment investigates whether multiple sensors can be stacked to reconstruct muon trajectories, providing a low-cost, high-resolution particle tracker.

1.2 Background

A study by physicists in the USA [1] tested whether smartphone cameras can detect cosmic ray muons by using scintillators as a trigger system. They found that the Galaxy S7 could detect muons with an 87% efficiency, and aimed to use a flat array of smartphones as a cosmic ray detector. Our experiment utilises predictable and frequent beam muons rather than cosmic rays, allowing us to measure efficiency far more accurately. Hit resolution can also be measured with a multi-layer detector configuration, where the use of muons is essential because they do not scatter unlike other particles.

1.3 Comparison to Existing Detectors

Spatial resolution describes the accuracy with which a detector measures the hit position. This precision depends on the number of pixels in a cluster but mainly the pixel size. If a particle can pass anywhere within a pixel, the uncertainty in the measured position can be approximated by:

$$\sigma_{\text{position}} = \frac{P}{\sqrt{12}} \quad (1)$$

Where (P) is the physical size of a pixel (pixel pitch), and σ represents the uncertainty in the measured hit position. Stacking multiple layers could achieve sub-micrometre precision which has not been demonstrated at such low cost. Pixel pitch and theoretical resolution is presented in Table 1.

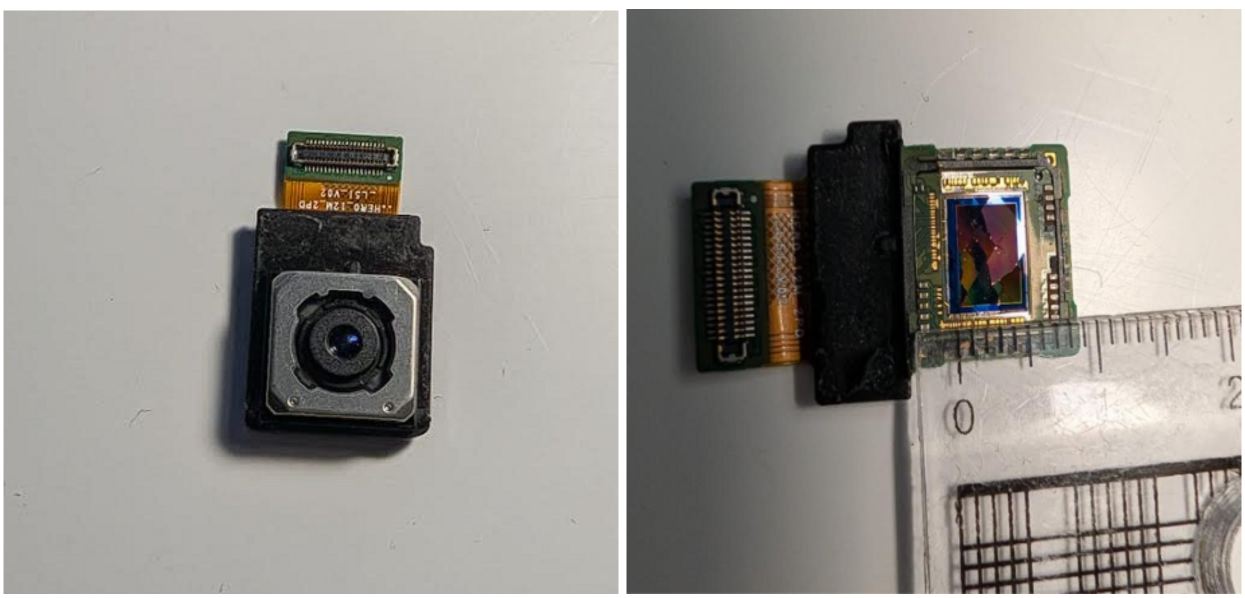
Detector	**Pixel Pitch (μm)**	**Theoretical (μm)**
Samsung Galaxy S7 CMOS Sensor	1.4	0.40
AEgIS Detector	2.1	0.60
sCMOS Detector	6.5	1.88
ALPIDE Monolithic Pixel Detector	27.0	7.80
ATLAS Pixel Detector	50.0	14.43
Timepix3 Pixel Detector	55.0	15.88

Table 1: Comparison of pixel pitch and theoretical spatial resolution of various detectors where the size of the pixel pitch changes the sensitivity of the detectors/sensor (note the pixel pitch (P) of the S7)

1.4 The CMOS Sensor

1.4.1 Dimensions

We disassembled a Galaxy S7 camera to access the CMOS sensor and verify its size, and although the sensor was damaged in the process, a photograph alongside a ruler still allows verification of its dimensions:

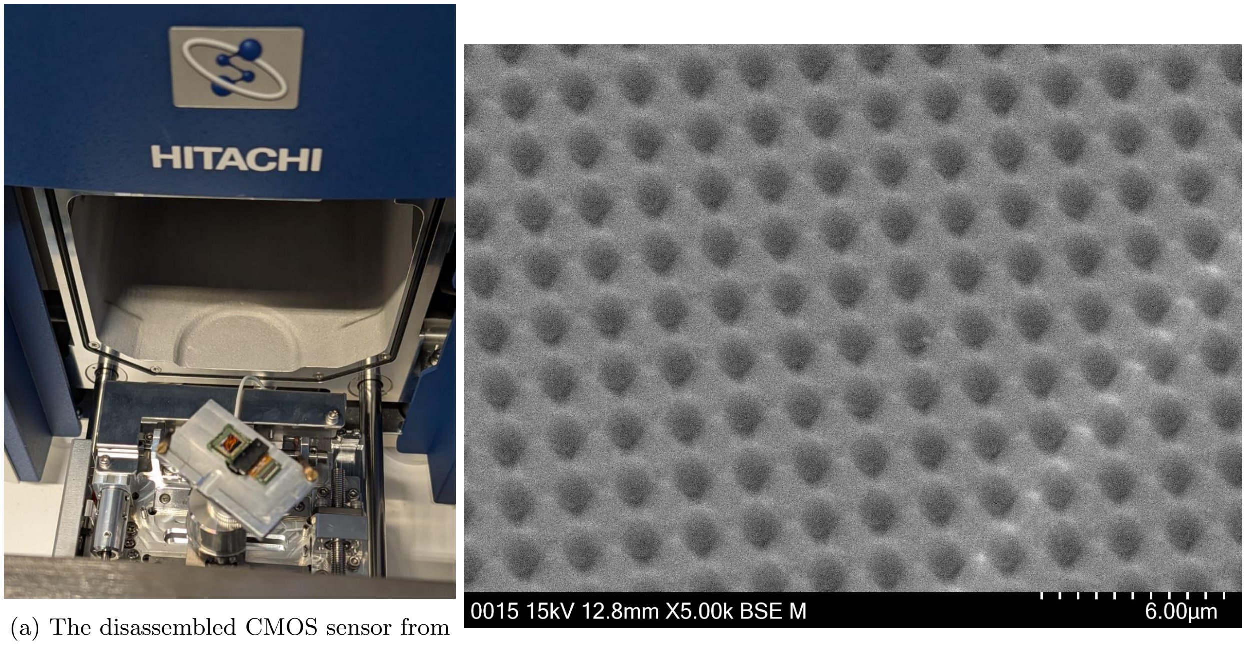


(a) Before Disassembly

(b) After Disassembly

Figure 1: The sensor has a 4:3 aspect ratio and measures approximately 0.56cm $\times$ 0.42cm. With a resolution of 4032 $\times$ 3024 pixels in total.

We also used the University of Liverpool's electron microscope to observe individual pixels:



(a) The disassembled CMOS sensor from a Galaxy S7 mounted on the stage of a Hitachi Electron Microscope prior to imaging.

(b) Electron microscope image of the CMOS pixel array from a Samsung Galaxy S7 sensor. Individual pixels are visible as repeating structures, 1 division is 1 µm, therfore pixel pitch is approximately 1.4 µm.

Figure 2: Imaging the CMOS sensor at 5000× magnification using the Hitatchi Electron Microscope

The CMOS sensor detects visible photons via the photoelectric effect, where particles deposit energy and ionise electrons in the silicon sensor. Electrons from the depleted region (with a depth of 30µm) move towards the positively charged photodiode pixels, inducing a current proportional to the energy deposited by the particle. In each pixel, charge-sensitive amplifiers convert charge inputs to potential differences, which then correspond to a certain intensity.

Muons are MIPs (Minimum Ionising Particles), meaning they are highly penetrating, and have a maximum momentum of 3 GeV/c [2] in the CERN relatively high-purity muon beam. Their energy deposition in short depletion regions ranges from 10-15keV. Unlike dedicated particle detectors, this sensor has a relatively low voltage leading to less electrons being collected and an overall efficiency decrease, explaining the 87% mentioned above. Confirming this value is essential to both our experiment and for comparable state-of-the-art studies such as DECO [3], and requires the high-statistics dataset available at CERN to do so.

2 Methodology

2.1 Equipment Diagram

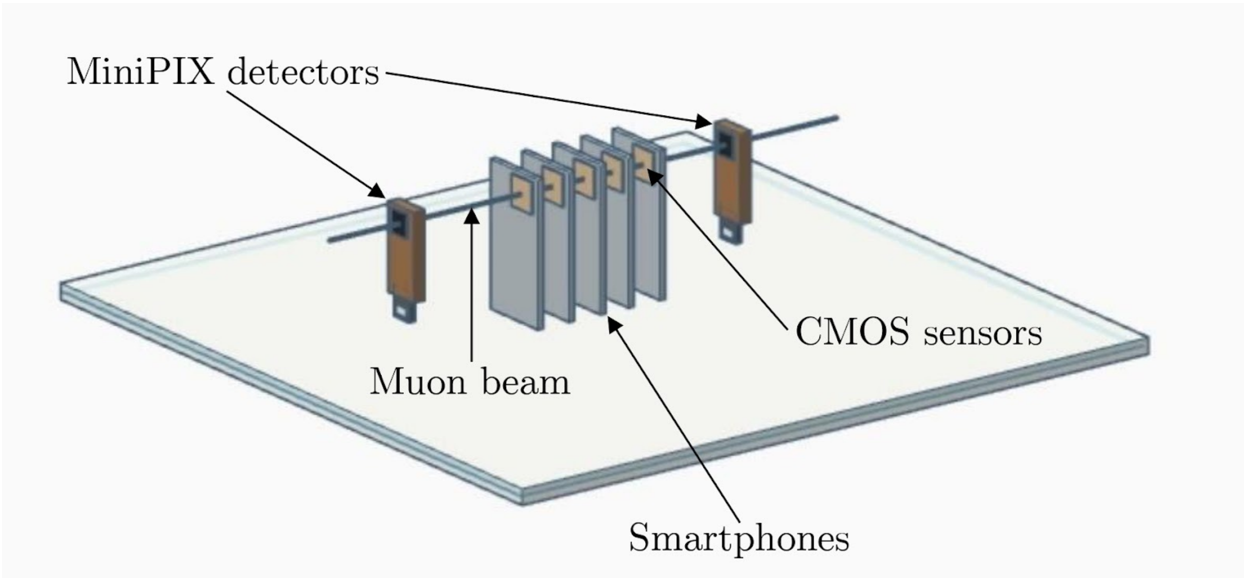
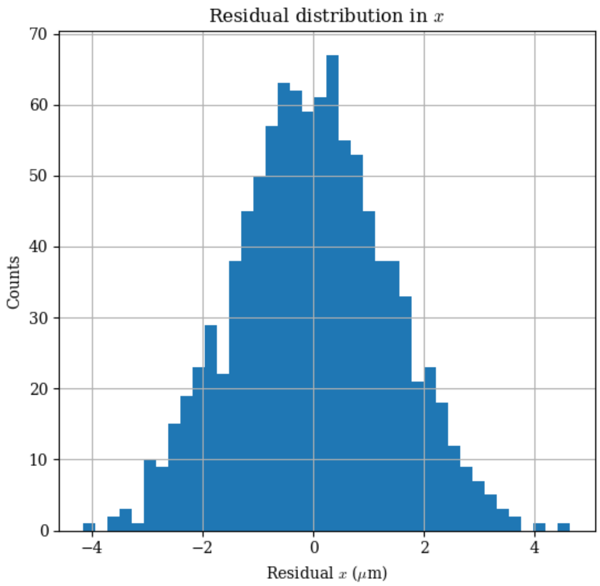


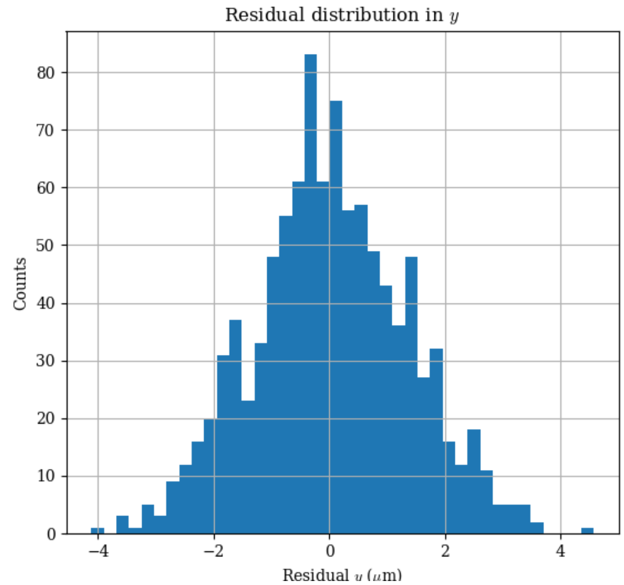
Figure 3: A 3D diagram depicting the experimental configuration and equipment in our experiment.

2.2 Experiment Description

The efficiency and resolution will be studied using a muon telescope consisting of the phones and MiniPIX detectors as a trigger system (Figure 3). The phones will be controlled from a computer via USB cables and a hub using ADB [4]. The telescope will then be placed into the high-purity muon beam. The occupancy will be controlled by the exposure time from $\frac{1}{24000}$s(minimum in Galaxy S7) to 0.4s (spill duration) and position of the telescope with respect to the beam axis.
To have an average of 4 tracking points for every muon, we calculated that with an 87% efficiency for each device, a minimum of 5 phones are needed. A 6th phone could be used for unbiased efficiency: $\epsilon = \frac{N_{\text{detected}}}{N_{\text{expected}}}$. The resolution will be measured as a standard deviation of the residual distribution (Figure 4). An alignment procedure has been tested as it will be crucial for the track reconstruction and negating systematic errors.
MiniPIX detectors, which will be borrowed from the University of Liverpool, provide additional tracking, as with 99% efficiency they give an almost guaranteed start and end point to our tracks. These points however will be lower resolution than the smartphones.



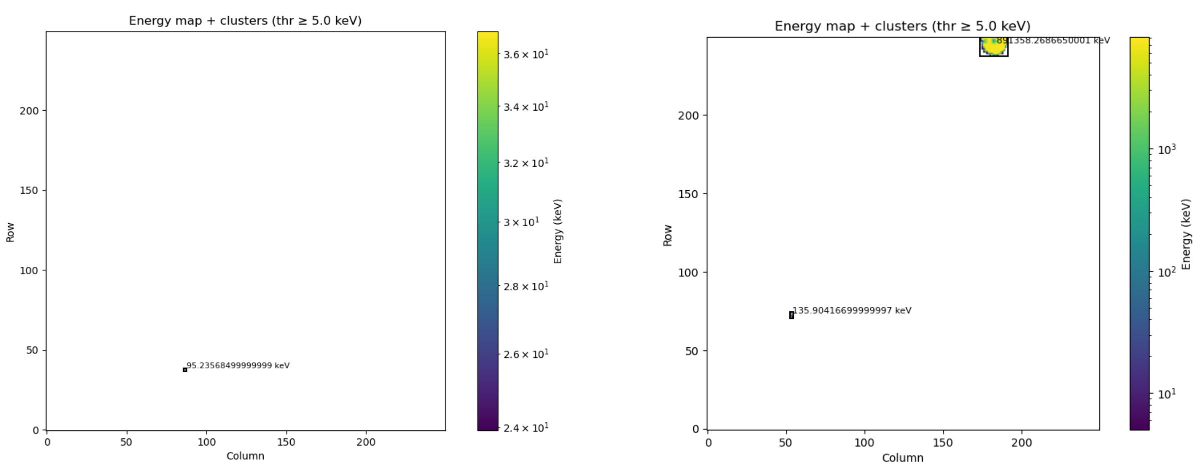
(a) x residuals after alignment — Translational misalignment of 10µm in x direction has been initially implemented



(b) y residuals after alignment — Translational misalignment of -5µm in y direction has been initially implemented

Figure 4: Residuals for 1000 simulated muons on a single plane, including a 5mrad rotation and Gaussian detector smearing (The simulation code has been produced with help from ChatGPT)

Figure 5: The setup we used to try and identify a cosmic muon that travelled perpendicular to the detectors



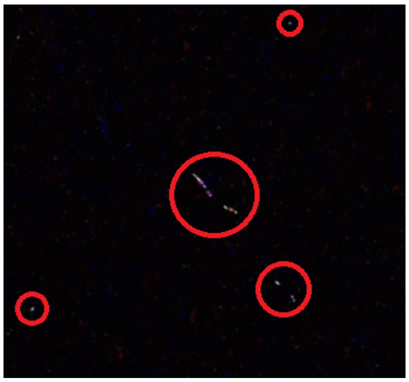
(a) Top MiniPix (frame 178, started Wed Mar 11 16:26:52.052377 2026, acquisition time 1s)

(b) Bottom MiniPix (frame 178, started Wed Mar 11 16:26:52.657000 2026, acquisition time 1s)

Figure 6: Using the setup in Figure 3, in 200s we were only able to identify this one cosmic muon, exemplifying the need to use a beamline. (Cluster reconstruction has been performed with a code prodcued by ChatGPT)

2.3 Smartphone Data Analysis

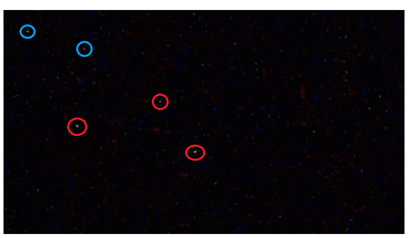
A 0.4s exposure was taken of normal background and another for when exposed to Cs-137 gamma emissions with a distancing of < 1cm from the source. The phone used was a Motorola G Play, and the ISO was set to 16,000. We then analysed the resulting recordings in Tracker [5] to look at individual frames. We noticed that in the recording involving Cs-137, the camera detected more gamma which appears as small bright spots (Figures 7, 8). We have shown that the sensor can detect gamma, and the same procedure can be used to detect muons.



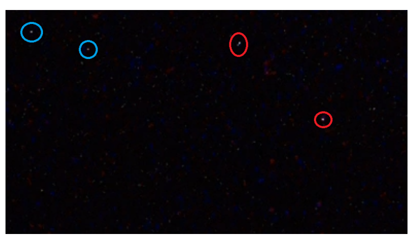
(a) Preliminary Experiment Frame 074 with Cs-137 Exposure (386 × 358 px)

(b) Preliminary Experiment Frame 086 Control (1343 × 656 px)

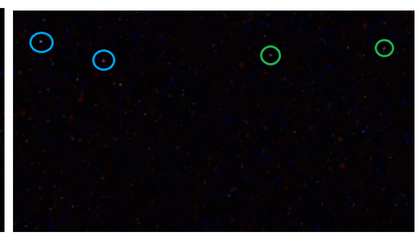
Figure 7: Red highlights the very likely detections of gamma and this shows that there is much less activity without a gamma source.



(a) Preliminary Experiment Frame 055 with Cs-137 Exposure (976 × 544 px)



(b) Preliminary Experiment Frame 056 with Cs-137 Exposure (976 × 544 px)



(c) Preliminary Experiment Frame 049 Control (887 × 489 px)

Figure 8: Red circles show likely gamma detections, blue for hotspots and green for very dim detections

Notice the two bright points circled in blue appearing on both the Cs-137 recording and the control, as well as being on multiple frames, and hence are suspected hotspots.

We then used frame by frame statistical analysis to identify hot pixels which we can later mask to avoid mistaking them for muons (Figure 9):

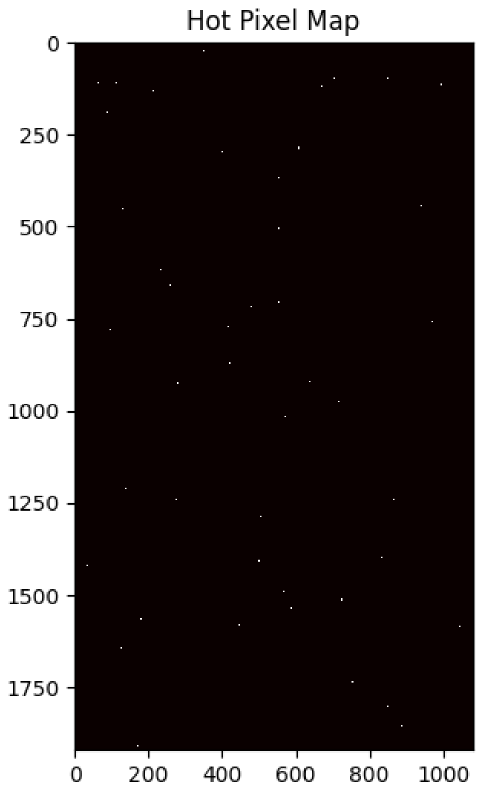


Figure 9: Hot pixel analysis of the preliminary control exposure - the minimum frequency threshold was to be present in 20% of frames and intensity had to be 7× the MAD (Median Absolute Deviation) plus the median. Here 690 hot pixels were identified out of the available 12 million.

3 Conclusion

While smartphones have already been demonstrated as capable particle detectors in previous experiments, we are proposing a new approach that systematically measures detection efficiency, spatial resolution and tracking capabilities within a single controlled setup. This is possible only with the relatively high-purity muon beam at CERN. Our preliminary measurements have demonstrated that the proposal is certainly feasible and would lead to publishable results, while also supporting similar cutting-edge research being done by groups like DECO [3] and AEGIS [6]. Additionally, the price of the Galaxy S7 is only £30, and so we hope to broaden the curiosity of like minds across the world with the setup's affordable accessibility, inspiring them to pursue their interest in particle physics just like us.

4 Outreach

We plan to bring the setup to our school and use it as a small-scale cosmic ray telescope, allowing us to share the excitement of viewing radiation interactions firsthand. Cosmic ray muons which would go through the entire stack are infrequent but having the setup which was tested and calibrated at CERN will make their detection possible. The data for each reconstructed track will be accessible online and projected onto a screen in real time, allowing multiple students to watch and interact with the data simultaneously. The tracks will have timestamps and can be used in a network of cosmic ray detectors, giving students in our school and beyond a chance to explore physics beyond the A-level syllabus. The stack could also be used to investigate changes in environmental radiation, for example, annual modulation or changes of the cosmic ray flux during solar storms, giving students a hands-on way to experience the effects of these real-world phenomena in a tangible way. We also plan to collaborate with DECO [3] and CRAYFIS [7] developers in the cosmic ray community projects, spreading awareness on the impact even students can make in the world of particle physics.

References

[1] Paper on the success of the study done in the USA - https://arxiv.org/pdf/2107.06332

[2] Beamline for Schools - https://beamlineforschools.cern/wp-content/uploads/2026/02/Beams_Detectors_BL4S_2026.pdf

[3] Paper on Deco - https://www.researchgate.net/publication/326810677_The_particle_detector_in_your_pocket_the_Distributed_Electronic_Cosmic-ray_Observatory

[4] Android Developers.— Android Debug Bridge (ADB) guide + software - https://developer.android.com/tools/adb

[5] Online open source physics software used for calculating relative change in displacement. https://opensourcephysics.github.io/tracker-online/

[6] AEGIS experiment - https://aegis.web.cern.ch/

[7] GitHub link to the open source software: https://github.com/ndguerra/FishStand

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