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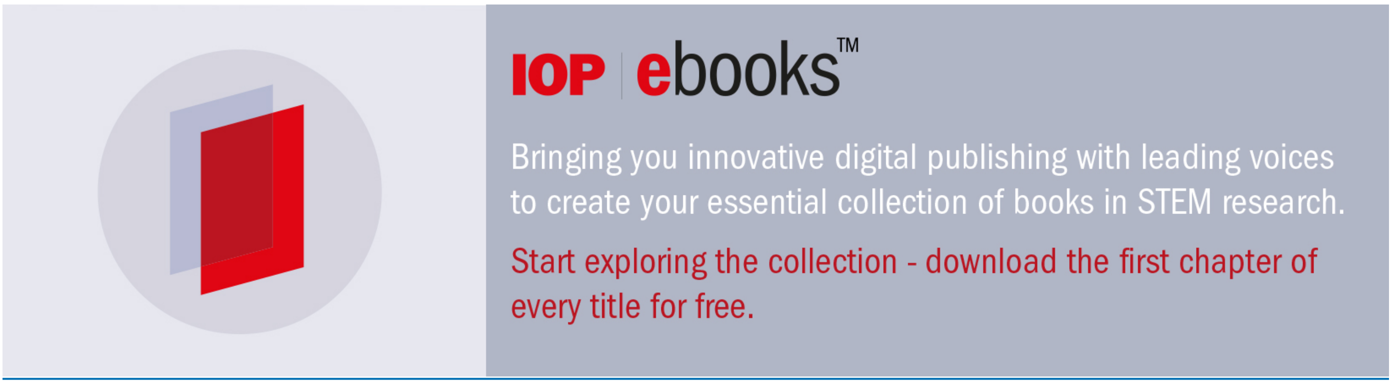
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Testing the validity of the Lorentz factor

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Abstract
The CERN Beamline for Schools Competition gives high school students the opportunity to perform an experiment of their design using the T9 facility. Our team, 'Relatively Special', was fortunate enough to be joint winners of this global event and travel to CERN for a unique adventure. This paper gives an account of our story including the application, preparation, experience and the overall effect which it has had on us. We also detail our proposed experiment (Proposal from Relatively Special and Video) which aimed to test the validity of the Lorentz factor with two methods: the time of flight (TOF) of various particles and the decay rate of pions at different momenta. Due to the high sensitivity required for the second method the results were inconclusive, therefore we report only on the results of the first method. We focus on the techniques we used, the setup of detectors, and how they function.

Introduction

One morning in 2015, a tweet from CERN began to stir excitement among students in our school, Colchester Royal Grammar School.

> "CERN is offering high-school students from around the world the chance to create and perform a scientific experiment on a CERN accelerator beamline [2]".

This seemed like an incredible opportunity, and 17 of us, aged 16–18, quickly formed a team to tackle the challenge. Meeting weekly, we worked together to write the 1000 word proposal and create the 1 min video needed to submit a complete application.

Our early meetings focussed on deciding which experiment to choose. Researching in small groups, we explored ideas ranging from matter-anti-matter symmetry to deep inelastic scattering. Each group regularly presented their findings to the team and through a democratic process we decided to investigate Special Relativity. After this, the team name 'Relatively Special' was quickly proposed and chosen.

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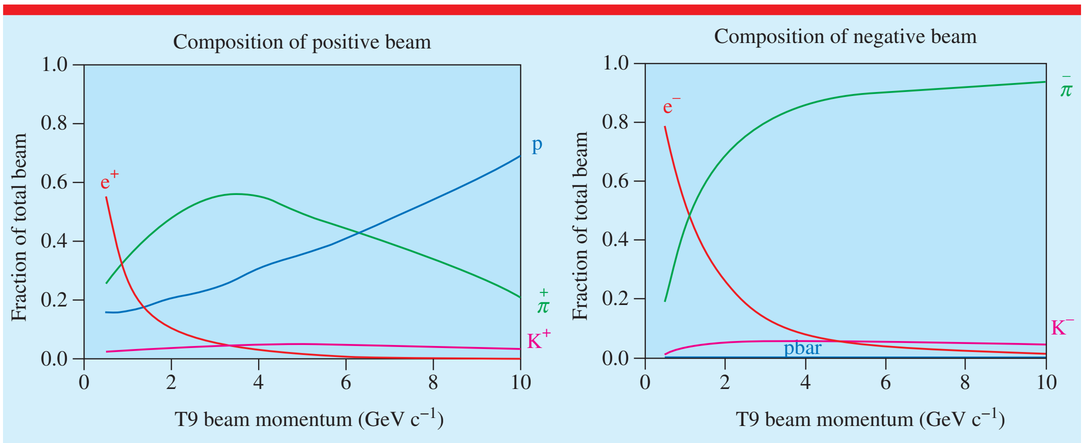

Figure 1. Composition of the beam in T9.

Our enthusiasm for the topic quickly inspired more research, and our teachers were a useful resource for discussing conceptual details. Another helpful resource was the CERN website, where we found specific information about the detectors and resources on offer. This helped us design our experimental method, which aimed to test the validity of the Lorentz factor with two methods: the time of flight (TOF) of various particles at different beam momenta and the changing decay rate of pions.

Having a variety of interests within the team was incredibly beneficial and led to valuable discussions at each step of our journey. This was especially true while writing our proposal, since we each investigated different aspects of the experiment and then shared our findings. This process helped us develop our ideas, which we eventually collaborated to form our final proposal.

For our 1 min video we decided to design, build, and film a Rube-Goldberg machine (an ingeniously and unnecessarily complicated series of devices which are linked together to produce a domino effect). We knew this was ambitious, however, we were excited to pursue such a unique idea. Our school was incredibly helpful by regularly rearranging classrooms to provide us workspace, and even teaching around our construction when this was not possible. They also equipped us with the tools and resources that we needed to build the machine. The members of our team had a diverse skill-base, which proved useful when milling custom MDF components and filming with a self-stabilising camera. We filmed the machine entirely in one-take and then submitted the video along with our research proposal to CERN [1].

In May of 2016 we discovered that we had won the Beamline for Schools competition, along with another team from Poland called ‘Pyramid hunters’. This was the exciting beginning to our journey.

Preparing for CERN

The wait between learning the amazing news and travelling to Geneva was livened by the communication with one of the support scientists. He updated us with the work which CERN had been doing to determine the feasibility of our experiment. We were informed that simulations had been carried out using the Geant4 software, which highlighted some of the limitations of the setup which had not been considered in our experimental proposal. Methods were discussed to overcome the problems while maintaining the general aim of the proposed experiment.

The initial proposal [6] detailed a plan to single out the pions of the beam and compare their theoretical velocity at varying beam momenta with their measured actual velocity (method 1). We also planned to compare this to a velocity obtained from measuring different decay rates due to time dilation (method 2). It was decided that it would be best to separate the two methods into different runs, due to a variety of reasons, including the fact that a positive beam was preferred for method 1 and a negative beam for

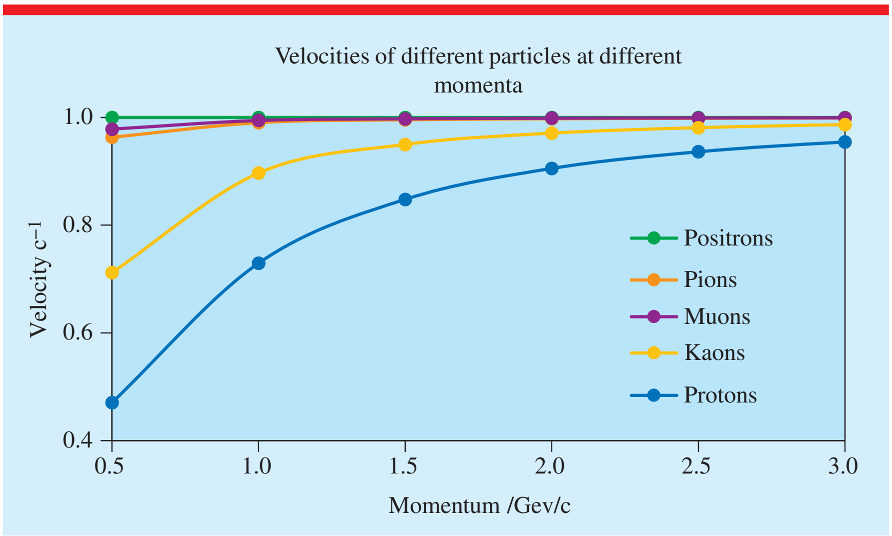

Figure 2. Velocity of the particles composing the T9 beam.

method 2. This was owing to the different beam compositions (figure 1).

Concerning method 1, as a result of the small mass of pions, muons and positrons, the range of their TOFs would be too little for the detectors to distinguish over the possible 0.5–10 GeV c^{-1} momentum span. This led us to consider these particles as one group so that we would obtain an increased count rate. On the other hand, the proton's mass is large enough so that it could be distinguished from the other particles, thus these were used as another TOF validation. We were also informed that new, more precise detectors, namely the MRPCs and smaller $1 \times 1\,\text{cm}^2$ scintillators, had been built which would be used in the setup.

Concerning method 2, alterations were made to the experimental method before our trip. However, due to the high sensitivity of measurement required, the results obtained at CERN were inconclusive.

T9 Beamline

The experimental area encompasses an area of 5 m by 12 m in which different detectors [3], outlined below, can be positioned. The beam entering the experimental area is composed of positive or negative particles. The positive beam contains protons, pions, kaons and positrons and the negative contains their respective antiparticles. Figure 1 shows estimations for the respective proportions of particles at each momentum. The beam momentum could be set between 0.5 and 10 GeV, delivering bursts of up to 10^6 particles in 0.4 s.

Method

The Lorentz factor, γ, describes the relativistic change in properties of an object that is moving with respect to an inertial frame at velocity, v. As particles travel close to the speed of light, c, in particle accelerators, the effects of special relativity become significant enough to measure. This includes the effect of mass increase.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1}$$

$$p = \gamma m_0 v. \tag{2}$$

Equation (2) describes the relativistic momentum, p, of a particle with rest mass, m_0.

From the previous two equations using the time, t, to travel a distance, d, in the inertial frame's perspective, equation (3) can be derived:

$$t = \frac{d\sqrt{m_0^2 c^2 + p^2}}{pc}. \tag{3}$$

Using the facility at CERN, a beam of a particles at a certain momentum could be defined, and the

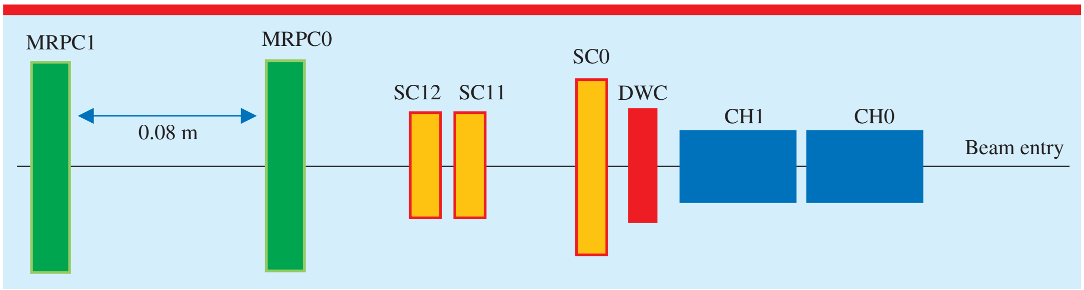

Figure 3. TOF first setup.

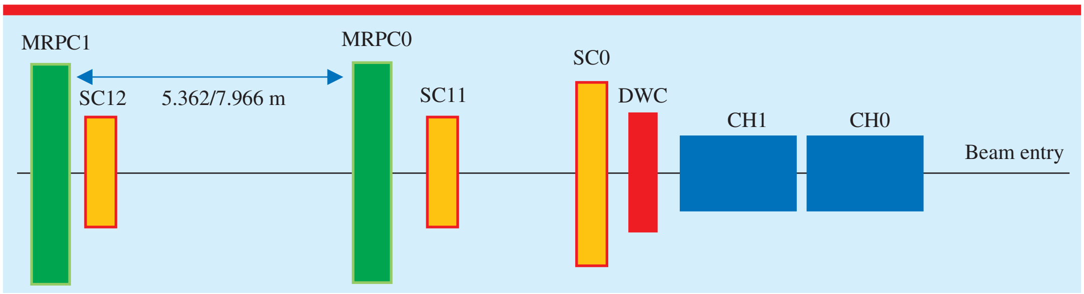

Figure 4. TOF second setup.

time it took for them to travel a known distance could be measured. These results could then be compared with the theoretical predictions given by equation (3) and seen in figure 2 for all particles of the beam.

Apparatus

The experimental set up is outlined in figures 3 and 4. This allowed us to record TOF of different particles within the beam.

Cherenkov Counters (CH0, 1)

Two Cherenkov detectors are part of the fixed detectors in T9. They can be tuned to discriminate between electrons, muons and pions by appropriately changing the pressure of the gas inside the detectors. The identification of heavier particles is not possible in T9 for technical reasons.

The speed of light in a medium is less than that in a vacuum, due to the interactions of photons with its particles. It is given by $c_m = \frac{c}{n}$, where n is the refractive index of the medium. A fast moving, charged particle can therefore pass through the medium with a greater velocity than that of the light, causing electromagnetic radiation to be emitted in a similar mechanism to that of a sonic boom. The radiation trails behind the charged particle, spreading outwards in the shape of a cone (figure 5). From equation (2), we can rearrange to find that $\frac{v}{c} = \frac{p}{\sqrt{p^2+m^2}}$ telling us that a heavier particle will have a smaller velocity for the

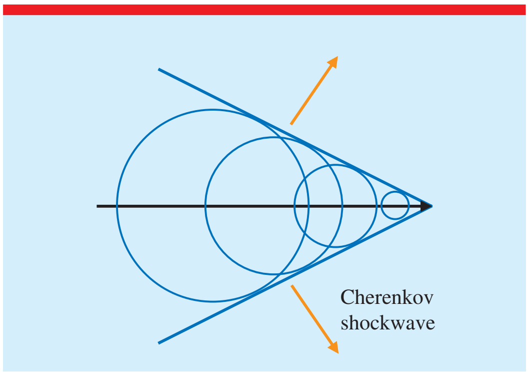

Figure 5. Diagram to show the formation of the Cherenkov shockwave.

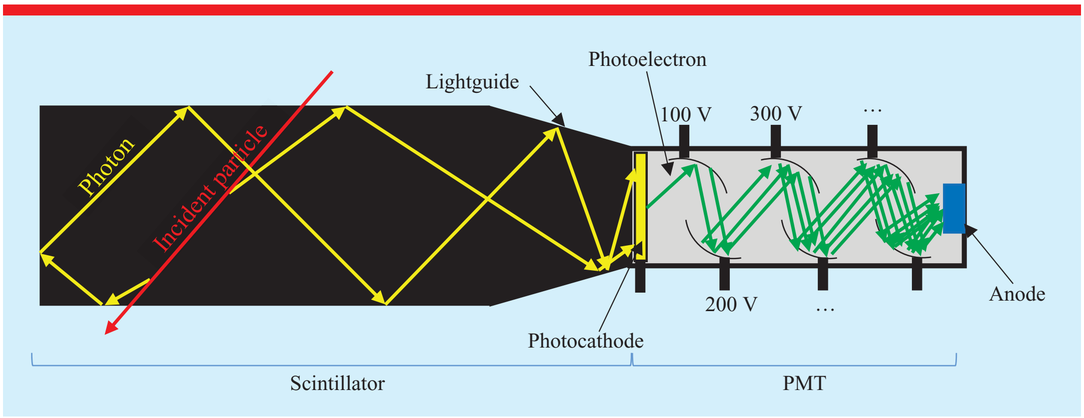

Figure 6. Diagram to show the structure of a scintillator detector.

same momentum, in the same medium. By tuning the pressure of the gas within the detector, we can control the value of n and therefore c_m in the medium allowing us to assign a mass to a particle detection and therefore determine its identity.

The Cherenkovs, filled with CO_2, were used to tag only the electrons so we could find an exact time of flight for each of the distances. While in use, they were monitored to ensure that constant pressure and temperature were maintained. Using these times, we worked out the effective lengths between the MRPCs allowing errors in measurements to be accounted for.

The combined efficiency of the Cherenkov detectors was around 50%, i.e. of the electrons that passed through, about half were tagged. The ones which were not tagged did not affect the experiment as they did not trigger a coincidence (see ‘Scintillators’).

Scintillators (SC0, 11, 12)

A scintillator (figure 6) detects the presence of an ionising particle. It is made of a luminescent material whose electrons absorb some of an ionizing particle’s energy and are excited into a higher energy state. They quickly fall back into their lower energy state and emit a photon in the process. The material is transparent to this photon so it can travel through the lightguide and into the photomultiplier tube (PMT). The PMT contains a photocathode which absorbs the photon and emits an electron by the photoelectric effect. A series of dynodes with increasing potentials are in turn struck by the electrons and emit more, amplifying the signal before they impinge on an anode to register a detection.

Beamline for Schools has many scintillators of various shapes and sizes. In addition, one scintillator is part of the fixed detectors in T9. Three scintillators were used to reduce the chance of a false signal. This was facilitated by NIM modules which were used to connect the detectors to ensure that a particle would only be registered if it passed through all three (and the two MRPCs)—an event known as a coincidence. Any background noise would be filtered out by the unlikely chance that a random signal would appear in all at the right times.

SC11 and SC12 were $1 \times 1\,\text{cm}^2$ which allowed a very narrow beam to be defined. Although using a narrow beam significantly reduced the rate, it facilitated the analysis of the data. It also meant that there was no need to consider the spread of the beam through the experimental area- as some particles would have travelled at an angle to the beam axis resulting in a greater distance travelled than others.

The scintillators themselves are made from a transparent, organic plastic and are quite cheap, however the main cost comes from the PMT, the lightguide, polishing, and manufacturing to precise dimensions. This gave a cost of around 2’500 euros for one of the scintillators used, resulting in an efficiency in detecting particles of about 90%.

Multi-gap resistive plate chamber (MRPC0, 1)

The multi-gap resistive plate chambers (MRPC) [4], shown in figure 7, are gaseous detectors

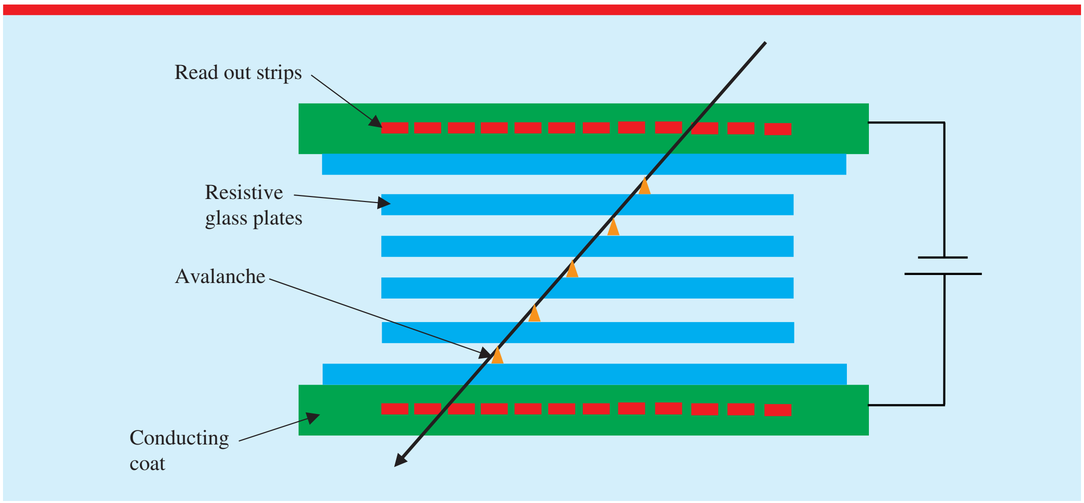

Figure 7. Diagram to show the structure of an MRPC.

which can provide very accurate time information for the passage of a particle, thus, they were used to measure TOF of the particles. The MRPCs used by Beamline for Schools consist of 6 equally spaced, electrically floating, resistive plates of resistivity $4.2 \times 10^{12} \Omega$ cm and thickness 280 μm. The gas gaps between plates are 220 μm in width and consist of a mixture of $C_2H_2F_4$ and SF_6 in a 95 : 5 ratio. The plates are enclosed by an anode and cathode with 12 readout strips on either side and a high voltage applied across.

An ionizing particle passes through the detector and ionises the gas. The electric field due to the voltage is strong enough so that the avalanche process begins instantaneously-where the charged, secondary particles build up and move in the electric field. We put in the resistive plates to stop the avalanches from becoming too large and causing sparks, this also means a greater electric field can be applied across the detector leading to faster signals and hence improved temporal resolution. The induced signal, to which the resistive glass plates are transparent, is caused by the movement of all the avalanches summed together and is picked up by the readout strips.

Due to the narrowness of the beam defined by the small 1×1 cm^2 scintillators, only one readout strip on each MRPC needed to be analysed as this is where the majority of events occurred. This meant that we could feed the two inputs into a single time-to-digital converter (TDC), which gave a 25 ps resolution (plus a little extra from electronics and cabling).

The materials used to make the MRPCs were cheap, the main cost comes from labour and the use of machinery. Including the cost of some electronics, the construction of three MRPCs totalled less than 10 000 euros. They have an efficiency of greater than 95%, and can reach a temporal resolution of better than 100 ps (this requires a more sophisticated level of data analysis which was not used in our experiment, meaning we obtained nearer 350 ps resolution).

Experimental procedure

5.362 m

Our first set up, figure 3, was with the MPRCs at a separation of 5.362 m. This distance was selected as it was far enough for the results to have a noticeable change in times as we increased momentum from 0.5 GeV c^{-1} to 2.5 GeV c^{-1} in 0.5 GeV c^{-1} intervals. Our lowest momentum was limited by the beam composition and the highest by the fact that at large momenta, the speeds of particles tend to that of light and become very close until our equipment could not distinguish them.

7.966 m

The next set up had the MRPCs 7.966 m apart which was the maximum possible distance we could achieve in the experimental area. We also moved SC12 so it was positioned just in front of MPRC1 so that the beam width was kept constant during the runs, seen in figure 4. Although this lowered the count rate, it increased accuracy of the data. Runs were taken from the range of 1 GeV c^{-1} to 3 GeV c^{-1} in 0.5 GeV c^{-1} intervals. The reading at 0.5 GeV c^{-1} was excluded as the proportion of protons was too low and included at 3 GeV c^{-1} because the greater distance meant distinguishing particles at higher velocities was possible.

Analysis

The time of arrival of the particles to each MRPC was calculated as the average time that was recorded by the cards on both sides of the strip that was hit. TOF was calculated by subtracting the time of arrival of the first MRPC from the time of arrival of the second.

TOF measurements, precise in a picosecond level, would require a careful alignment and positioning of the detectors, study of the timings of the electronic chain and the systematics of the experimental setup. Although we isolated the major parameters such as cable lengths and timing of the signals, it became evident that deeper study that exceeds the scope of the competition was required.

Therefore, a method was developed to allow us to factor in the systematics without the need to isolate and quantify them. Using runs with 1 GeV c^{-1}, electrons only, we measured their TOF for each of the two setups and calculated an effective length (L_{eff}) which would then be used to calculate the theoretically expected TOF for the rest of the particles. The effective lengths for the two distances are seen in table 1.

Results

The histograms obtained for each run mostly contained two distinct peaks, one for electrons, muons and pions and another for protons. The masses of the particles in the first peak are similar enough for their TOFs to all be very close over the momentum range (figure 8). For this reason, and the limited resolution of the equipment, this group of particles was treated as a single, mixed peak.

Dual Gaussian distributions were plotted as in figure 8. This enabled us to find the mean TOF and standard deviation at each momentum for the protons and mixed peaks. Error bars were placed at ±1 SD on each of our measured times as seen in figures 9 and 10.

The theoretically expected time of flight for all the particles for the two distances are seen in table 1 and our results are seen in figures 9 and 10.

Conclusion

The trend of the experimental values appears to match closely with the theoretical predications as shown in figures 9 and 10. We can therefore say that our results verify the relativistic effect of the Lorentz factor.

Experience

We were lucky enough to be awarded two weeks of research at CERN in Switzerland. We were trained in Nuclear, Electrical, and Cryogenic safety (which ended with a simulation evacuation of the LHC tunnels), as well as Cybersecurity. Next, we set up our own experiment in the T9 experimental area using a range of detectors and trigger logic. Members of the team took shifts operating the experiment using the Proton Synchrotron whilst others performed data-analysis. The execution of our experiment required us to have an in depth understanding of the experimental setup as well as the impact of background signals on the measurements.

We shared this unforgettable experience with the team of students from Poland. Setting-up and operating our experiments together quickly formed lasting friendships. These grew even stronger as we spent numerous late nights in the T9 experimental area collaborating and sharing stories. We remain in contact with students from the Polish team, and a few members of our team have since travelled to Poland to visit our new friends.

Experiencing a foreign culture and taking trips to France and Switzerland was also really enjoyable. We had the opportunity to learn about the history and future of CERN by visiting the synchrocyclotron display, antimatter factory, and even the ATLAS control centre. Other activities included learning C++ with a support scientist and also building a cloud chamber to detect ionizing particles. We tasted fondue, saw the Jet d’Eau in Geneva, and made memories that we will never forget. Our entire experience was incredible!

Table 1. Theoretically expected TOF for all the particles of the beam for the two distances.

Distance	7.966				
Momentum	TOF_positrons	TOF_muons	TOF_pions	TOF_kaons	TOF_protons
1.0	26553	26699	26812	29605	36407
1.5	26553	26618	26669	27951	31318
2.0	26553	26590	26618	27348	29329
2.5	26553	26577	26595	27065	28361
3.0	26553	26570	26582	26909	27821
Distance	5.362				
Momentum	TOF_positrons	TOF_muons	TOF_pions	TOF_kaons	TOF_protons
0.5	17873	18263	18561	25100	37997
1.0	17873	17972	18048	19927	24506
1.5	17873	17917	17951	18814	21080
2.0	17873	17898	17917	18408	19741
2.5	17873	17889	17901	18218	19090

Effect on us

For many of us, working in research was something we found particularly interesting and was a career path we had not previously considered. It was great to work with diverse teams of students and scientists and tackle a wide variety of new challenges. Whether that be designing the experiment's trigger logic or learning how to use the 'Root' software, we appreciated the opportunity to learn new skills and research at the same time.

During our time at CERN, we developed flexibility and resourcefulness, especially while preparing the setup in the T9 experimental area. Our team learned to adapt quickly to the demanding environment and we were always trying to propose solutions to fine tune the details of the ongoing activities. These skills have been beneficial for other projects since BL4S and will continue to benefit our future careers. This is something which every member of our team believes, even those following non-physics related career paths (e.g. Medicine). When we returned, we presented various talks to promote STEM activities in school as well as discuss our journey with Beamline for Schools. Our team also authored this research paper alongside scientists at CERN, building valuable data-analysis and research documentation skills.

The Beamline for Schools experience motivated us to continue pursuing new challenges. Since CERN, our team members have gone on to study at a range of universities, including Cambridge, Imperial College London, Bath, and even internationally at MIT and HKU.

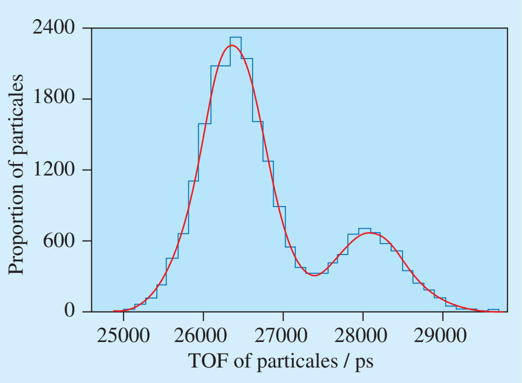

Figure 8. A characteristic TOF spectrum (2.5 GeV c^{-1}). The left peak corresponds to positrons, muons and pions and the right to protons. Kaons are too few to be identified.

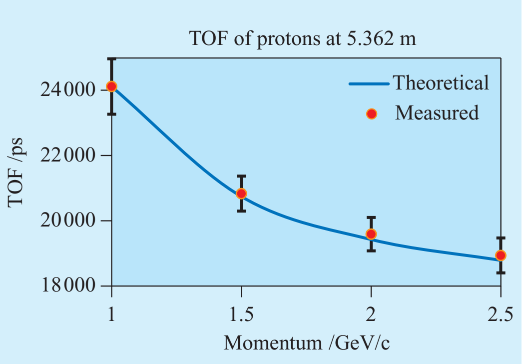

Figure 9. TOF of protons at 5.362 m. The blue line corresponds to the theoretically predicted values and the red dots to the measured ones.

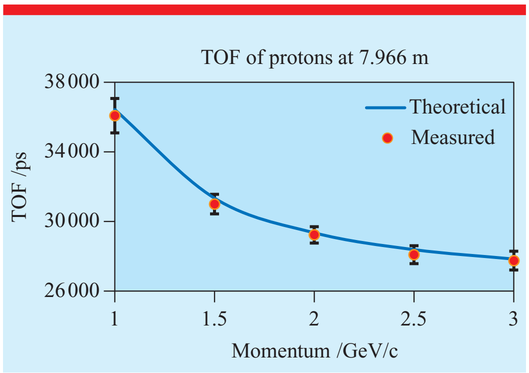

Figure 10. TOF of protons at 7.966 m. The blue line corresponds to the theoretically predicted values and the red dots to the measured ones.

Acknowledgments

We would like to thank CERN for providing us with a wholly educational and enjoyable experience [5] by making our experiment possible. We would also like to thank the organisers of the competition and the scientists who volunteered their time for us and without whom would have made this impossible: Mr Markus Joos, Dr Theodoros Vafeiadis, Dr Alexander Hristov, Dr Oskar Wyszynski, and many more.

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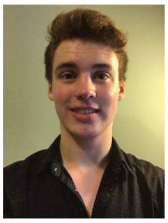
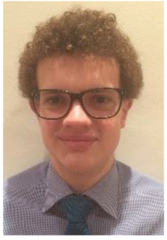
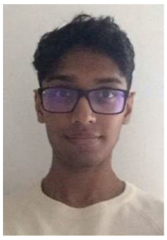


H Broomfield was a student at Colchester Royal Grammar School and is studying Mathematics with Physics at Cambridge University.

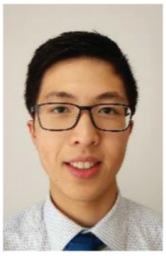


J Hirst was a student at Colchester Royal Grammar School and is going to study Mathematics at Cambridge University.



A Singh was a student at Colchester Royal Grammar School and is studying Mathematics at Imperial College London.

M Raven was a student at Colchester Royal Grammar School and is studying at Massachusetts Institute of Technology.



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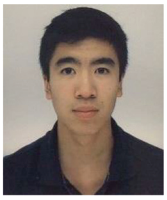
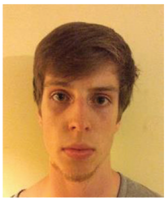


T Kwok was a student at Colchester Royal Grammar School and is studying Natural Sciences at Magdalene College Cambridge.

J Li was a student at Colchester Royal Grammar School and is currently studying Medicine at the University of Cambridge.

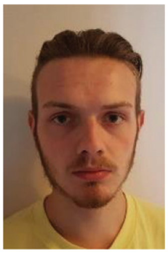
K Tsui was a student at Colchester Royal Grammar School and is studying Dentistry at the University of Hong Kong.

A Tsui was a student and a boarder at Colchester Royal Grammar School and is studying Medicine at Imperial College London.

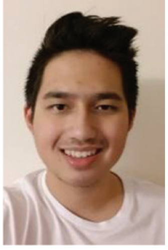


R Perkins, a past student of Colchester Royal Grammar School, is going to study Physics at Imperial College London.

H Mandelstam is a student at Colchester Royal Grammar School and has applied to study Physics at University.

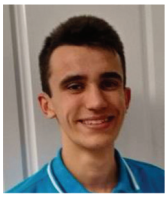


J Southwell was a student at Colchester Royal Grammar School and is studying Mechanical Engineering at Bath University.



D Khoo was a student at Colchester Royal Grammar School and is currently studying at the University of Bath and is working towards a degree in Mechanical Engineering.

J Martin-Halls was a student at Colchester Royal Grammar School and is currently working as a Consulting Engineer, intending to study Engineering at university.



D Townsend is a student at Colchester Royal Grammar School and has applied to study Mathematics at University.

H Watson is a student at Colchester Royal Grammar School. He intends to study Mathematics at university.