Trigger Studies for the OPERA HPT (Hamburg Precision Tracker)

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The following report presents a brief overview of my work as a summer student within the Neutrino Physics Group from the Hamburg University. I describe the task which I was given for the period of my summer school practice. I also give a realistic account of my small-step evolution towards the fulfillment of my task and towards obtaining concrete results. The final results are explained and commented within the framework of the OPERA experiment. Last but not least, a personal overview of the whole DESY summer school experience is presented in the last paragraph of my report.

1 Introduction: Theoretical aspects regarding the neutrino oscillations

The phenomenon of neutrino oscillation could be regarded as evidence of the existence of physics beyond the Standard Model (SM). In the following paragraph I will briefly overview the physics of neutrino oscillations and also the experimental facts which lead to the proposal and confirmation of this phenomenon.

In the 1960's it was already a known fact that the Sun is a natural fusion reactor. It was also known that electron neutrinos are emitted copiously as a result of the nuclear processes which take place in the Sun. In this context, Ray Davis' and John Bahcall's **Homestake** experiment had the ambitious task to measure the flux of solar neutrinos in order to verify whether the fusion reaction of hydrogen nuclei is indeed responsible for the Sun's glow.

John Bahcall calculated a specific rate of solar neutrino events while Ray Davis' main focus was the experimental set-up. The Homestake detector consisted of 380.000 liters of C_2Cl_4 (perchloroethylene, a wide-spread liquid used in dry-cleaning) and was situated 1500 m underground, in the shaft of the Homestake mines from South Dakota, USA. The perchloroethylene would offer approximately 2×10^{30} atoms of ^{37}Cl as a target for the incoming solar neutrinos. The experiment was designed to observe the following interaction:

$$\nu_e +^{37} Cl \longrightarrow^{37} Ar + e^- \tag{1}$$

When published, in 1968, the Homestake experiment's results seemed completely puzzling. It appeared that roughly only one third of the predicted number of electron neutrinos was observed. This unexpected outcome lead to the so called "*solar neutrino problem*". Other solar neutrinos experiments like Kamiokande in Japan, GALLEX in Italy and SAGE in Russia were reporting discrepancies between the predicted and the observed solar neutrino flux as well.

The solution to the solar neutrino problem was provided in 2001 by the Sudbury Neutrino Observatory from Ontario, Canada. The SNO detector was a huge container filled with 1000 tons of heavy water (D_2O) placed in the Sudbury mine. It was sensitive not only to electron neutrinos but it could also distinguish between muon and tau neutrinos. Thus, after counting the neutrino events regardless of their flavour it was discovered that the number of events was in good concordance with the predicted values, calculated based on the fusion reactions considered to take place in the Sun. The explanation of this outcome would be the fact that the neutrinos (originally emitted as ν_e) change their flavour while travelling the distance from the Sun to the

Earth. Bruno Pontecorvo had already predicted the oscillating behaviour of the neutrinos in the 1960's and the results from the SNO seemed to confirm his theory.

The principle of the phenomenon is that when a neutrino is emitted with a certain flavour it changes its flavour after a certain time turning into one of the other two possible flavours. This is a quantum effect based on the fact that the flavour eigenstate of a neutrino is in fact a superposition of mass eigenstates and, reciprocally, the mass eigenstate of a neutrino is a superposition of flavour eigenstates:

$$\begin{aligned} |\nu_\alpha\rangle &= \sum_i U^*_{\alpha i} \nu_i \qquad (2) \\ |\nu_i\rangle &= \sum_\alpha U_{\alpha i} \nu_\alpha \end{aligned}$$

where $|\nu_\alpha\rangle$ is the flavour eigenstate, $|\nu_i\rangle$ is the mass eigenstate and $U^*_{\alpha i}$ is the element of the electro-weak mixing matrix.

It is important to note that the phenomenon of neutrino oscillations requires that the neutrinos are not massless. If they were massless then we could not distinguish between the mass and flavour eigenstates. However, it is assumed within the Standard Model that the neutrinos should have a mass equal to zero. In this context, the fact that recent solar, atmospheric and reactor neutrino experiments have confirmed the observation of neutrino oscillations means that the Standard Model needs to be extended in order to accomodate the new physics of neutrinos with mass different than zero.

2 The OPERA Experiment

2.1 Goal and physics motivation

The neutrino oscillation hypothesis is, according to the present day knowledge, a proven fact. However, some aspects of the phenomenon have not been observed experimentally. Previous experiments like CHOOZ and Palo Verde ruled out the $\nu_\mu \leftrightarrow \nu_e$ as a candidate for the most plausible flavor change channel of the atmospheric ν_μ. Thus the present experimental evidence (K2K and MINOS) indicates that the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation is the channel to look for. However the appearance of the tau neutrino flavour from an initial muon neutrino still needs to be experimentally proven.

This is precisely the main goal of the OPERA experiment. In this experiment a ν_μ beam from CERN is sent towards the detector at Gran Sasso in Italy. The OPERA detector has the challenging task of observing the

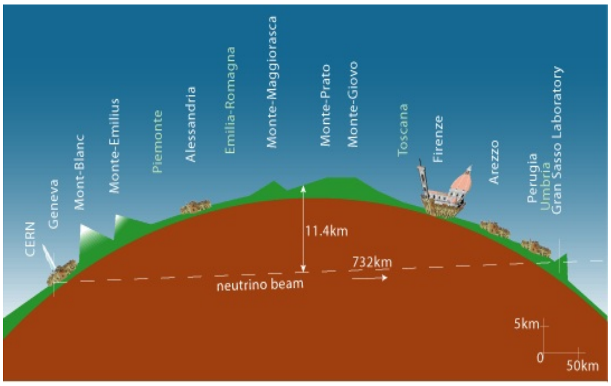
$\nu_\mu \leftrightarrow \nu_\tau$ oscillations by means of direct detection of the extremely short lived ($c\tau_{lifetime}$=87.11 μm) τ lepton produced in the ν_τ CC interactions within the target. A secondary task is to keep searching for the $\nu_\mu \leftrightarrow \nu_e$ channel which could be observed if the mixing angle θ_{13} is close to the CHOOZ limit.

The expected number of ν_τ CC events is approximately 10 for a run time of the OPERA experiment of 5 years. The experiment started running in the summer of 2008. The physics outcome of the five-year run is of great importance as it can confirm (or add a question mark to) the neutrino oscillation scenario and also give a closer limit for the Δm^2.

2.2 Experimental setup

➥ *The Gran Sasso Setup*

In order to achieve its ambitious goal, the OPERA experiment makes use of the CNGS ν_μ beam sent from CERN which travels a length of L=732 km before reaching the detector situated underground at Gran Sasso, in Italy, as shown in the left panel of Figure 1. The beam is optimized for the study of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillations: it has a mean energy of 17 GeV and suffers contaminations with $\overline{\nu_\mu}$ and $\overline{\nu_e}$ smaller than 2% while the contamination with ν_τ is negligible.



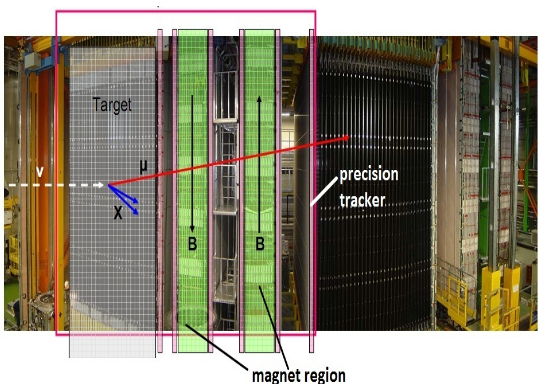


Figure 1: The OPERA experiment location and setup

The detection of the ν_τ is made by direct measurment of the τ lepton track as well as by observing the τ decay products (eq. 3) from the previous reaction.

$$\nu_\tau + N \longrightarrow \tau^- + X$$

$$
\begin{aligned}
\tau^- &\longrightarrow \mu^- + \overline{\nu_\mu} + \nu_\tau \ (18\%) \\
\tau^- &\longrightarrow e^- + \overline{\nu_e} + \nu_\tau \ (18\%) \\
\tau^- &\longrightarrow \pi^-(n\pi^0) + \nu_\tau \ (48\%) \\
\tau^- &\longrightarrow \pi^- + \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau \ (15\%)
\end{aligned} \tag{3}
$$

For this purpose, the OPERA detector was designed as a hybrid detector (right panel in Figure 1) which consists of two identical Super Modules (SM). Each one of the SM is composed of 103 168 target lead/emulsion bricks (the ECC technique) divided into 31 planes; two scinitillator planes are inter-placed between each pair of two target planes. These scintillator planes act like triggers and also help in locating the brick which has suffered a hit. The bricks are designed as sandwiches of 56 layers of lead with a thickness of 1 mm, interleaved with 44 μm thick emulsion layers on both sides of a 205 μm thick plastic base. Once a brick got hit it can be located and taken out for analysis. Further downstream there is a muon spectrometer consisting of two bending magnets interleaved with layers of the Precision Tracker drift-tubes ensembles. The muon spectrometer has the task of determining the resulting muons' charge and momentum and to eliminate charmed events' background.

➥ *The Hamburg Setup*

In order to calibrate and improve the precision tracker (PT) of the muon spectrometer, a smaller scale PT has been built in Hamburg by the Institute for Experimental Physics of the University of Hamburg. This is the so called "Small Test Setup" (STS) which is the main focus of my work performed in the OPERA group.

The STS is built up of aluminium drift tubes arranged in four units placed on top of each other. Each unit is made up of four layers of twelve drift tubes per layer. The drift tubes have an outer diameter of 38 mm, a wall thickness of 0.85 mm. The length of the drift tubes is 1 m. A gold-plated tungsten wire of 45 μm diameter is stretched in the center of each tube. The aluminium external wall acts as an cathode and the centered wire acts as an anode. As a drift gas, a mixture of Ar and CO_2 in the ratio 80/20 is used at a pressure of approximately 1000 mbar.Plastic scintillators act as a trigger.

The working principle of the drift tubes is quite straightforward. When a particle crosses the drift tube it ionizes the gas contained in the tube. Since there is a high voltage applied to the anode wire, the ionized pairs will travel either to the cathode or to the anode, according to the sign of their charge. The lighter electrons will travel faster to the anode. If there is a strong electric field near the near the anode wire, then the phenomenon of avalanche multiplication will take place (Fig. 2). This avalanche gives a signal on the anode wire which is preamplified and discriminated before reaching the TDC.

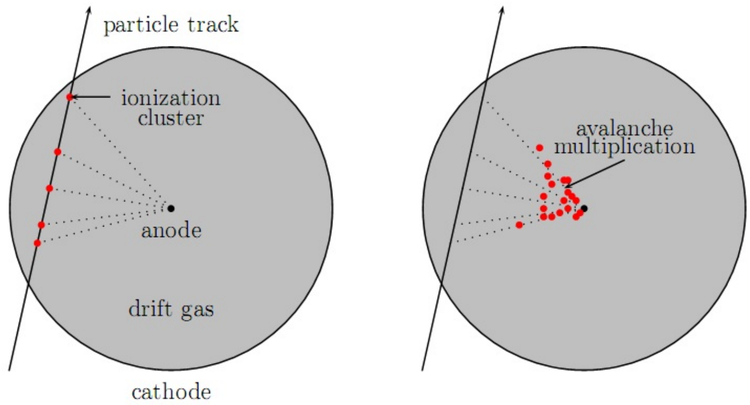


Figure 2: Principle of drift tubes

The main goal of the PT is to offer the necessary data in order for us to be able to reconstruct the track of a passing particle (muons, in our particular case). The necessary data refers to the accurate drift time, i.e the time necessary for the electrons to travel the distance from the particle's ionization track to the anode wire. Knowing the drift velocity and the drift time we can calculate a drift distance and thus by computing the drift distance for every single tube that got hit in the event we may reconstruct the particle's track. For a track reconstruction in two consecutive planes at least four hits are required.

- The data acquisition, i.e. the recording of the drift times, can be described as follows.
  We consider a single event:

- Step 1: a particle (muon) passes the detector, thus it almost instantaneously hits both the scintillators (which act as triggers) and the drift tubes(Fig. 3)

- Step 2: once the scintillators get hit at t=0 they send a delayed stop signal to the TDCs (Time to Digital Converter) which have the purpose of measuring the drift times. This step corresponds to the red arrow in Fig. 4. It is essential to note that the time counting must be regarded similar to the time counting of a stopwatch. This means that after the TDCs get the "START" signal from the wires they automatically stop from counting at a fixed time (Δt⟶ blue arrow in Fig. 4). In this sense we can intuitively say that the TDCs act as stopwatches in our case.

- Step 3: the drift tube in which the particle has passed closest to the anode wire (thus the time necessary for the electrons to travel from the particle ionization track to the anode wire is shortest) gives the first "START COUNTING " signal to the TDCs. This step is analogous for the other drift tubes which send their "START COUNTING" signal to the TDC one by one in ascending order of the distance between the particle track and the anode wire. It makes sense that the further away from the wire the particle crossed the tube, the larger the time the electrons need to hit the anode wire.

- Step 4: once the Δt has elapsed, all counting processes cease immediately. The data, i.e. the elapsed drift times of our event have been recorded: t1 for the drift tube which sent the first signal, t2 for the second tube, etc.

Thus, since the time counting functions as a stopwatch process, it is straightforward to say that t1>t2>t3>t4 because the TDC has recorded the largest number of counts for the drift tube which sent the first count signal, a smaller amount of counts for the second drift tube, etc. It is essential to note that:

$$t_{Drift} = \Delta t - t_{TDC} \tag{4}$$

Once the drift times have been recorded we can make use of the so called "time to distance" relation to determine the distance from the anode wire to the track. This leads us to an unsigned quantity: a radius of a circle around the anode wire. We cannot obtain information regarding on which side the particle has passed the wire from the drift times. This inconvenient is overcome however in the track reconstruction algorithm.

- The track reconstruction algorithm

The first step is to set a coordinate system (Fig. 5). Each reconstructed track is characterized by the angle (ϕ) and by the initial position with respect to the origin of the coordinate system (p). For the fit, the only information that we can obtain from the recorded drift times is the drift circles around the hit wires there are many possibilities to reconstruct the track (which is obviously tangent to the drift circles), as shown in Fig. 6. Naturally only one of the reconstructed tracks corresponds to the real track of the particle.

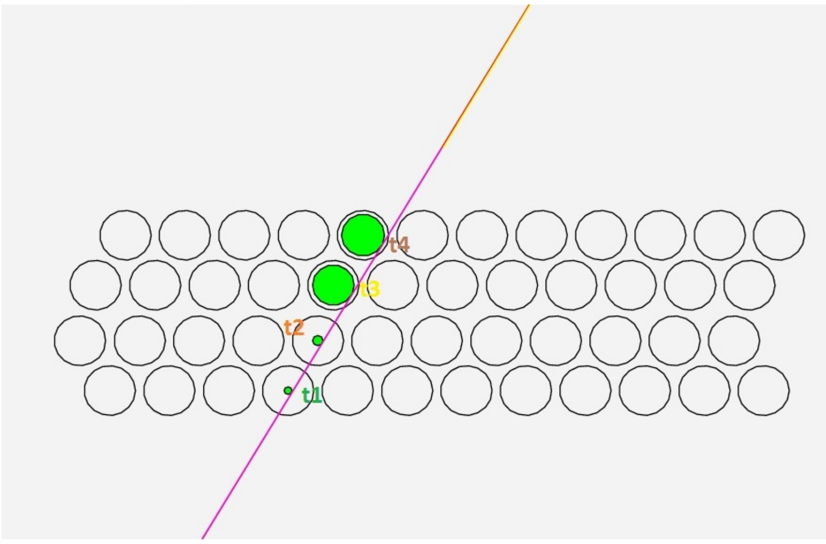


Figure 3: Particle track

Figure 4: Stopwatch diagram

In order to determine how close to the real track the reconstructed track is the following calculation must be performed:

$$\chi^2 = \sum_{i=1}^{N} \frac{1}{\sigma_i^2}(d_{m,i} - d_{t,i})^2 \tag{5}$$

where $d_{m,i}$ is the drift distance calculated from the drift time while $d_{t,i}$ is the distance from the anode to the reconstructed track. The track for which the χ^2 is minimum is the best and closest to the real track. In this sense, the χ^2 is a measure of how accurate the reconstructed track fits to the original, real track.

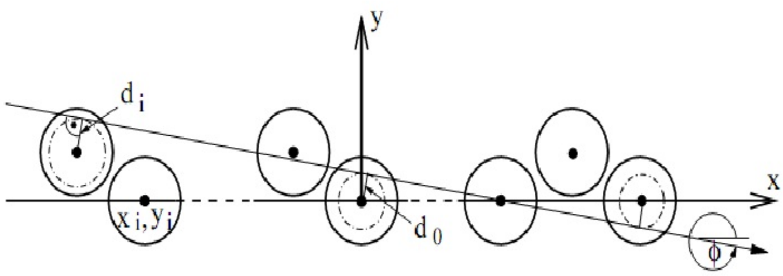


Figure 5: Particle track

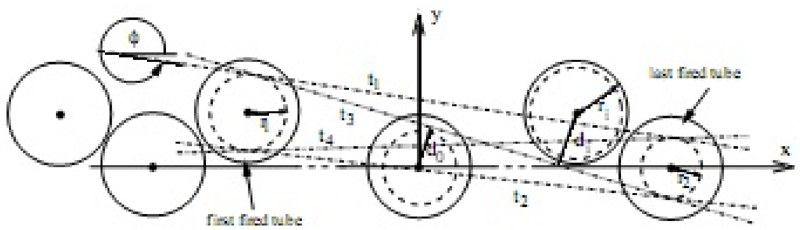


Figure 6: Possible track reconstructions

3 Task

My task for the duration of the Summer Student Program was focused on the Precision Tracker and mainly the track reconstruction procedure. Since the accurate determination of the drift times is extremely important for the track reconstruction it is very useful to try to eliminate the sources of errors as much as possible. It is easy to see that one important source of errors is the trigger device itself. This lead to the idea of studying whether the data acquisition process in a triggerless mode would be useful as an improvement for a prospect upgrade of the OPERA detector. Simulating triggerless data and comparing the quality of the track reconstructed from the triggerless data to the quality of the track reconstructed with the original (trigger included) data was my task.

3.1 Task fulfilment

➥ *Simulating the triggerless data*

The principle underlying my method of simulating the triggerless data is based on the characteristics of the data acquisition process. It is accurate to consider that the time offset pictured in blue in Fig. 4 corresponds to the drift time of the tube which sent the first count signal to the TDC.

I was provided with a set of real data for which the preset ΔT was known (ΔT=2355 in of TDC counts). Thus the algorithm for obtaining triggerless data from the original set is rather straightforward. In the beginning, the time offset (i.e. the drift time of the first signaling tube) is calculated for each event. This time offset is regarded as the connection of the data to the trigger. The next step is to add the calculated time offset to each TDC measured time for each event. This addition of the time offset is pictured in Fig. 7. In this manner the elimination of the trigger could be approximated.

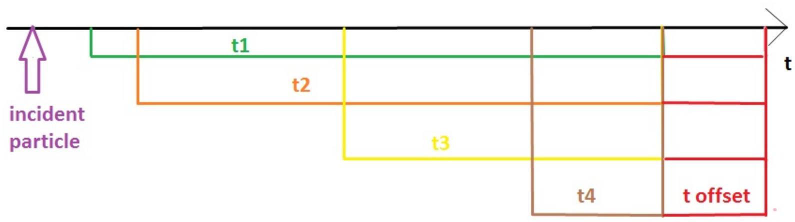


Figure 7: Stopwatch diagram of triggerless data

Following the calculation of the new TDC values, the track reconstruction algorithm (code) was repeatedly applied to each event trying different time offsets in steps of 10 TDC counts. The track parameters and the time offsets for which the best fit (minumum χ^2) was obtained were saved.

➥ *Comparison with the original data*

In the attempt to check whether working in a triggerless mode would make any sense at all the track reconstruction using the simulated triggerless data must be compared with the track reconstruction performed using the original data. For this purpose the following algorithm was elaborated: we search for the time offset (drift time) for which the triggerless data obtained a minimum χ^2 in the track reconstruction. Obviously, this means that if, hypothetically, the data acquisition worked in the triggerless mode, a real track could be found using the triggerless data. The important aspect is to verify whether this triggerless time offset for which χ^2 is minimum is similar or at least close to the original time offset; then this could prove that it would make sense and even be succesful to use triggerless data. Each triggerless TDC value in each and every event is analyzed.

It can be seen from Fig. 7 that the real time offset is always smaller than the triggerless t4. Therefore, the t4 (the smallest TDC value) was chosen as the proper range to search for the time offset. This range was scanned with a step of 10 TDC counts. For each step the track reconstruction procedure was executed and the χ^2 was calculated (as well as the other track parameters, of course) with the purpose of finding the time offset corresponding to the minimum χ^2.

4 Results

As it was already mentioned in the previous paragraph, an important checkpoint in determining whether it makes sense to use triggerless data or not is the difference between the triggerless time offset which corresponds to a minimum χ^2 and the real time offset. This difference is plotted in Fig. 8.

It can be observed that most of the events count as zero for the time offset difference. The plot shows that using triggerless events turns out to be accurate in approximately 80% of the cases. For this plot, as well as for the following, a number of 100 000 events were used. The code used to obtain this data analysis could be improved. In that case perhaps the percentage would increase in favor of the triggerless events.

The angle, ϕ is one of the two parameters which characterizes the track. Thus it would be relevant to compare the angle of the reconstructed track for which the triggerless data were used to the angle of the reconstructed track for which the original data were used. The difference between the two angles is shown here in Fig. 9.

The plot of the difference between the triggerless angle and the real angle shows that, indeed, reconstructing the track with the triggerless data could be possible.

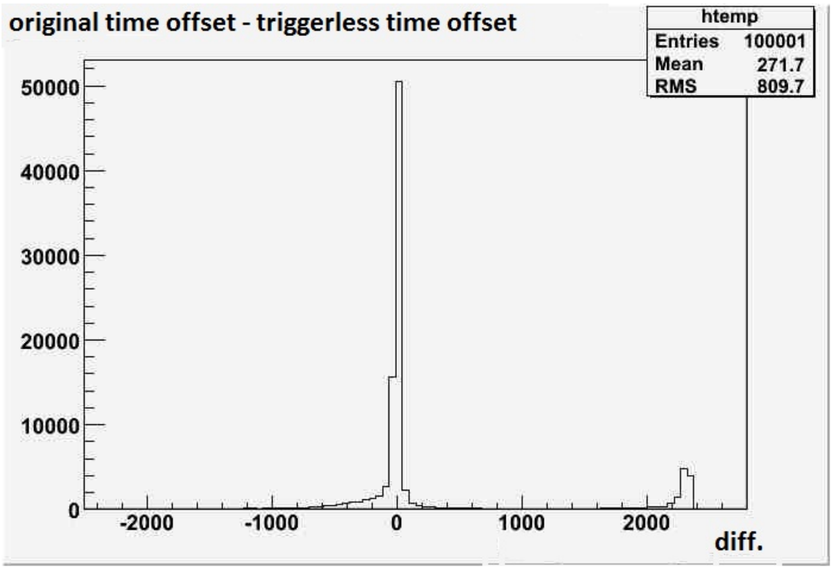


Figure 8: Time offset difference

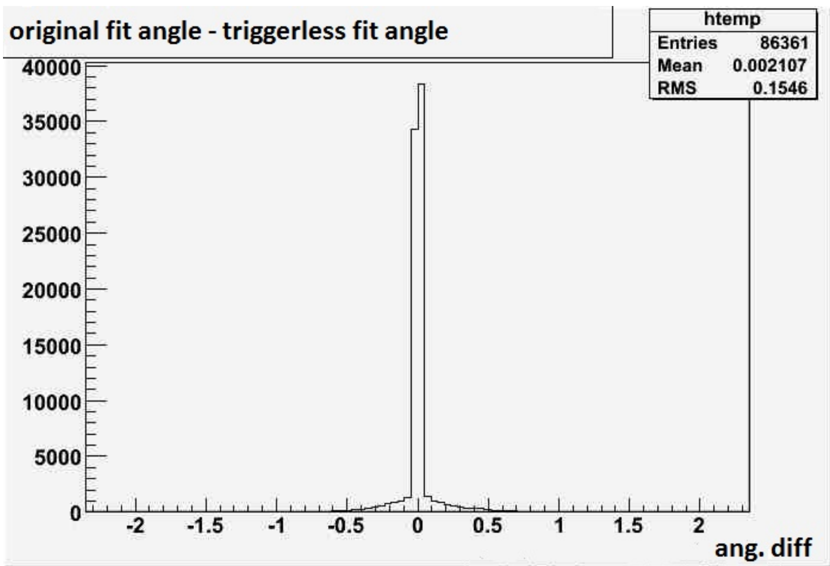


Figure 9: Angle difference

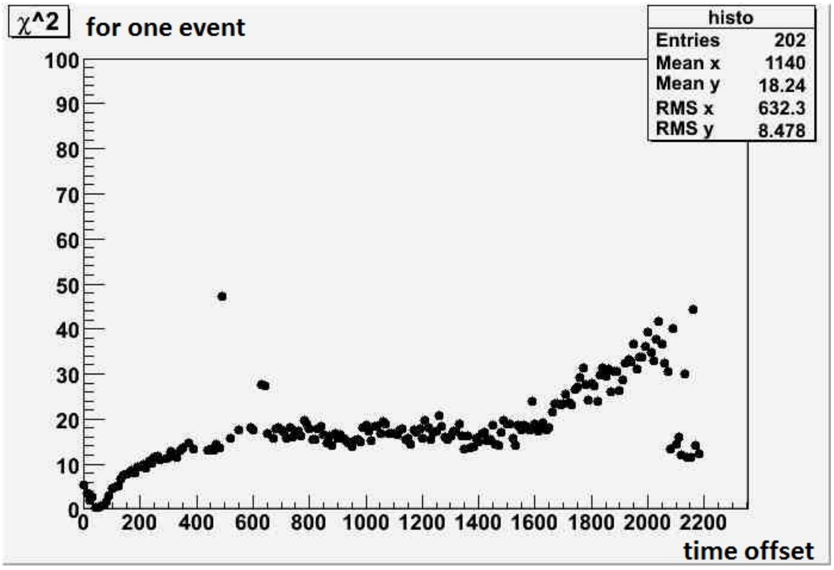


Figure 10: Angle difference

For Fig. 10, one random triggerless event was chosen. For this event the χ^2 was plotted versus the time offset, in bins of 10 (the size of the scanning step). The plot does show a minimum and the time offset corresponding to that particular minimum is indeed close to the original one: the original time offset was 54 TDC counts while the determined time offset from the triggerless data was 40 TDC counts.

5 Conclusions

➥ *Regarding my task*

The work I was able to perform during my Summer Student Program within the OPERA group is just the tip of the iceberg as far as the triggerless studies are concerned. However, I believe that the results which I have obtained show, at least, that it makes sense to take into consideration data acquisition processes for the triggerless mode. The code which I have written to obtain these results could be improved first of all by chosing a smaller step in scanning the time offset for the triggerles time offset corresponding to the minimum χ^2. Including the time offset in the actual fit routine would also be a great improvement. This, as well as other improvements are all future prospects for the study of triggerelss events.

➥ *Regarding my professional and personal experience*

I have enjoyed the experience of the DESY Summer Student Program a lot. On a professional level I learned a lot about the physics topics which DESY has/is/will be focusing on. I also learned a great deal about programming in C++ and about using ROOT in my data analysis.

On a personal level I enjoyed meeting people from various countries with various interests and exchanging ideas and opinions with them. Even more, since I am interested in pursuing a career in particle physics, I feel that having learned what the daily work and the daily life in a research group are like was very useful for me.

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I would like to thank the DESY Summer Student Program organizers for giving me the opportunity to enjoy such an intense learning experience. I learned a lot not just from a professional point of view but also from a personal point of view.

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