Chapter 2

The CHORUS experiment

The CHORUS experiment was built to detect $\nu_\mu \rightarrow \nu_\tau$ oscillation in an almost pure $\nu_\mu$ beam. The detector was designed with one specific process in mind: locating and identifying a $\tau$ particle from a charged-current $\nu_\tau$ interaction inside a large stack of nuclear emulsion plates. Emulsion is ideal for the detection of short-lived particles which is crucial to attain the design sensitivity for oscillation which requires the rejection of events due to $\nu_\mu$ interactions to be better than $1$ in $10^6$. The use of emulsion also permits detailed studies of events with similar length scales as $\tau$ decays, like charmed-particle production and decay.

The perfect detector does of course not exist and trade-offs between different detector choices need to be made. Sometimes a new technology allows improvements to be made while the detector is already running. One of those new technologies, a honeycomb tracker, was installed in the CHORUS experiment for the last one and a half years of data taking. Chapter 3 describes the development and performance of this detector.

This chapter explains the general layout and design of the CHORUS experiment. A detailed description of the full detector and its performance can be found in Ref. 156 and the details of several sub-detectors in Refs. 157–165. As Chapters 4 and 5 of this dissertation require a detailed understanding of the particularities of emulsion as a tracking detector, the emulsion target and the location and reconstruction of neutrino vertices inside it will be described in more detail.
2.1 Detection principle

The detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation is based on the identification of charged-current $\nu_\tau$ interactions in a $\nu_\mu$ beam which does not contain any $\nu_\tau$. Any $\tau$ particle produced in a charged-current interaction of a $\nu_\tau$ can therefore only be due to neutrino oscillation transforming a $\nu_\mu$ in a $\nu_\tau$. The experiment therefore requires a good detection efficiency of $\tau$ particles while rejecting all processes that might mimic this signal. The $\tau$ identification is complicated, however, by its short lifetime and the fact that its decay produces neutrinos which leave the detector undetected. Hence, an accurate determination of the invariant mass from the decay products is impossible. In the CHORUS experiment, the $\tau$ identification uses both the short lifetime and the missing momentum.

2.1.1 Tau identification in emulsion

In its proposal [166,167], the CHORUS experiment aims for the two easiest detectable $\tau$-decay topologies where a $\tau^-$ decays into a single charged particle (see Figure 2.1). The $\tau^-$ can decay into a $\mu^-$ via $\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu$ with a branching ratio of $\text{Br}(\tau \rightarrow \mu) = 17.4\%$ or into a single charged meson ($\pi^-$ or $K^-$) via $\tau^- \rightarrow \nu_\tau h^- n(\pi^0)$ with $\text{Br}(\tau \rightarrow h) = 49.5\%$. In both cases, the undetected neutrinos carry away part of the momentum and energy of the $\tau$ parent ($m_\tau = 1777\,\text{MeV}$). Therefore, the charged daughter particle has a different direction from its parent. In the experiment this is visible as a kink in the track made by the $\tau^-$ and its charged daughter. A kink angle of 50 mrad or more is measurable.

\[\langle d \rangle = \langle \gamma \rangle c \tau_{\tau} \approx 87 \langle E/m_t \rangle \mu\text{m}.\]

To detect the short flight path of any produced $\tau$ ($c \tau_{\tau} = 87\,\mu\text{m}$), a detector is needed with a very good resolution in 3-D. To get enough events, the target must also have a large mass because of the very small interaction cross-section of neutrinos. Nuclear emulsions are both excellent targets and detectors, because they give 3-D track detection at sub-micron scale and are relatively dense due to the high silver content ($\rho = 3.815\,\text{g/cm}^3$). The disadvantage of emulsion is that it does not provide any time information; it records all ionizing tracks passing through it in the period between pouring and development.
In early emulsion experiments, the exposure time was usually short and the quantity of emulsion small, allowing human operators to scan all of the emulsion for interesting events. In the CHORUS experiment, the exposure time of two years is exceptionally long and the emulsion volume an order of magnitude larger than ever before. For CHORUS, it was no longer possible to scan all of the 1540 kg of emulsion for interesting events. There have been two runs with each 770 kg of emulsion; one spanning the years 1994 and 1995; the other in 1996 and 1997. The chosen solution was to use electronic tracking detectors to indicate where to look in the emulsion for a particular event. This is known as a hybrid emulsion-electronic detector. As the emulsion can only be examined under a microscope after it has been developed, the electronic data are also needed to separate the events recorded during the two years of data taking.

The limit on $\nu_\mu \rightarrow \nu_\tau$ oscillation [168] at the time of the CHORUS proposal was such that a maximum of 35 charged-current $\nu_\tau$ interactions could be detected in a sample of $5 \cdot 10^5$ charged-current and $1.5 \cdot 10^5$ neutral-current $\nu_\mu$ interactions. The total number of events $(6.5 \cdot 10^5)$ exceeded the emulsion scanning capacity at that time by far. For the proposal, it was estimated that 40,000 events could be scanned, at maximum, during two years of analysis. Therefore additional detectors were needed for pre-selection of events with a higher probability of being due to a $\nu_\tau$ interaction. For this pre-selection and to suppress background from charm decays, two magnetic spectrometers and a calorimeter were placed downstream of the emulsion target. The spectrometers measure the momentum and charge of particles leaving the target and the calorimeter measures the total energy in an event. The calorimeter also serves as passive muon filter.

The pre-selection was based on kinematic variables and would select one track in an event that is most likely the daughter of a $\tau$ particle. Following only that track back in the emulsion lowers the scanning load. The detection of the kink is then done in a single pass through the emulsion, avoiding the need to follow all tracks downstream from the interaction vertex. The kinematical selection requires a high reconstruction efficiency and good resolution of the kinematic quantities. Any inefficiency or wrongly measured variable lowers the maximum sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillation. The kinematical cuts which were to be applied, are primarily based on the energy and momentum that is carried away by the neutrino(s) in the $\tau$ decay. In a neutrino charged-current interaction, the lepton’s transverse momentum $p_T$ balances the transverse momentum of the shower resulting from the nuclear breakup. In a $\nu_\tau$ interaction part of that momentum is carried away by the neutrino(s) from the $\tau$ decay. The direction of the missing transverse momentum is typically opposite to the hadron shower direction. Finally, the energy spectrum of the muon or meson from $\tau$ decay is different from that induced by $\nu_\mu$ events.

During the time the experiment was taking data and doing the analysis, automatic scanning microscopes have become much faster. The allowed scanning load has grown by more than a factor hundred. The increased scanning speed has made it possible to select all events with a reconstructed vertex inside the emulsion for scanning. Only the target trackers, located directly behind the emulsion (section 2.4), are used for this reconstruction, so any inefficiency due to wrong matching or identification in the downstream detectors is avoided. Only the muon spectrometer is used to preferentially select muon tracks for scanning. The vertex and possible decay topologies are reconstructed in the emulsion. This has the benefit that all tracks from the neutrino vertex can be checked for kinks. To increase the event location efficiency, an alternative track selection procedure has been applied. The selection of tracks for scanning is discussed in section 2.8, event
location and reconstruction in the emulsion in section 2.10. The data from the other detectors are used to measure momenta and identify particle type of event-related tracks reconstructed in the emulsion.

2.1.2 Background processes

There are at least 10,000 charged-current and 3,000 neutral-current $\nu_\mu$ interactions for every charged-current $\nu_\tau$ interaction. These numbers take into account a lower limit for oscillation at high $\Delta m^2$ of $4 \cdot 10^{-4}$, the difference in energy dependence of the neutrino cross-sections, and the energy spectrum of the neutrino beam. Multiplying this by the inverse of the branching ratio $\text{Br}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu) = 17.4\%$, the number of $\nu_\mu$ events per charged-current $\nu_\tau$ interaction becomes 75,000. Background events in the $\tau^- \to \mu^-$ channel should thus be suppressed by a factor $10^5$. For the $\tau^- \to h^-$ channel, the event has to be detected among the neutral-current interactions and those charged-current events where the primary muon is missed (about 10%). With $\text{Br}(\tau^- \to \nu_\tau h^- n(\pi^0)) = 49.5\%$, the $\tau^- \to h^-$ background should thus be suppressed by a factor of $10^4$. The probability to miss a primary $\mu^+$ is higher than that for a $\mu^-$. The probabilities to miss a primary $e^-$ or $e^+$ are even higher. As background suppression is partly based on identifying the primary lepton, it is important to keep the relative flux of $\nu_\mu$, $\nu_e$ and $\nu_\tau$ in the neutrino beam as low as possible.

There are three processes which are identical to or mimic a $\tau$ decay and therefore contribute to the background for the $\nu_\mu \to \nu_\tau$ oscillation search:

1. Charged-current interactions of $\nu_\tau$ contamination in the neutrino beam. The $\nu_\tau$'s originate from the decay of $D_s$ and $\tau^-$ created in proton interactions with the primary target.

2. Decay of negatively-charged mesons close to their production vertex. These events are only a background if either the primary lepton in a charged-current interaction remains undetected or in neutral-current interaction where there is no primary lepton.

3. Elastic scattering of a muon or hadron on a nucleus with no visible recoil in the emulsion, known as white kinks.

Point 1 is identical to the oscillation signal and is therefore an irreducible background. The ratio $\nu_\tau/\nu_\mu$ in the neutrino beam must therefore be as low as possible (see section 2.2). For points 2 and 3, the kink must be located first and the kink daughter identified. The efficiencies for kink detection in both real $\tau$ decays and these backgrounds are very similar, except for (small) differences in energy and momentum.

Regarding the background of point 2, the single-prong decays of $\pi^- \to \mu^-$ and $K^- \to \mu^- n(\pi^0)$ can be eliminated by requiring $p_T > 240\text{ MeV}/c$ with respect to the kink parent’s direction (see Table 2.1). As the decay $K^- \to \mu^- \overline{\nu}_\mu$ is close to this cut ($p_T, \text{max} = 236\text{ MeV}$), the measurement uncertainties lead to a probability of about 10% to exceed this cut. As the lifetime of a $K$ meson is much longer than that of a $\tau$ lepton, this background can be suppressed at the required level by restricting the flight length of the kink parent to be less than 3 mm. This background is only present in charged-current interactions where the primary lepton is not recognized, which leads to an additional reduction by a factor of about 10. For neutral-current interactions there is no primary
lepton, but the neutral-current cross-section is smaller than the charged-current cross-section and therefore this background is suppressed by the ratio of neutral-current to charged-current cross-sections.

The decay of the negative charmed meson, $D^-$, cannot be eliminated in this way, as it has similar flight length ($c\tau = 312\,\mu m$) and mass ($m_{D^\pm} = 1869\,\text{MeV}$) as the $\tau$ lepton. One of the contributions to this background is from neutral-current interactions where a $c\bar{c}$ quark pair is produced. As the cross-section for this process is relatively small and the associated charm quark (in a $D^+, D^0$, or charmed baryon) can also be detected in the emulsion, this background is low. The production cross-section for a single $c$-quark in charged-current interactions of anti-neutrinos is typically 20 times larger, but these are efficiently rejected by the detection of the primary positive lepton. However, the chance of not identifying the primary $\mu^+$ in a $\nu_\mu$ charged-current interaction is still about 15\%.

The fraction of $\nu_e$ in the beam is about a factor 10 smaller, but the probability for missing the primary $e^+$ is about 50\%. The contribution to the background from $\nu_e$ is therefore still about a third of that due to $\nu_\mu$.

The cross-section for the white-kink background (point 3) was mostly unknown. The cross-section is normally described as the mean free path $\lambda$ between white-kink scatters as function of $p_T$. To measure $\lambda$, two experiments have been done. One experiment was a test for a new neutrino-oscillation experiment [169], the other was dedicated to a measurement of the white-kink cross-section for pions [170].

In any case, the sensitivity of the emulsion (500 eV for rendering a grain developable) ensures that the probability of a scatter without visible recoil is very low. The energy transferred to the recoiling object depends on the $p_T$ of the kink and consequently on the kink angle and the parent’s momentum. The minimum kink angle of 50 mrad, the $p_T > 0.24\,\text{GeV}/c$ cut together with a minimum energy requirement for the daughter meson ensures that the energy transfer to the recoil is so large that the probability to miss it is sufficiently small. As the white-kink background is proportional to the total track length considered, the maximum decay length of 3 mm limits this background to an acceptable level in the $\tau^-\rightarrow h^-$ channel. For muons, high-angle scattering is less likely and therefore white kinks are not an important contribution to the background for the $\tau^-\rightarrow \mu^-$ channel.

### 2.2 Neutrino beam

The neutrino beam is generated by dumping the CERN super-proton-synchrotron (SPS) proton beam on a target. Most of the produced hadrons are $\pi^\pm$ and $K^\pm$ mesons which escape the thin rods of the target and can decay in flight. The decays of these secondary mesons generate the neutrino beam, consisting mostly of $\nu_\mu$, and $\bar{\nu}_\mu$ neutrinos and a lower flux of $\nu_e$ and $\bar{\nu}_e$ neutrinos. The flux of $\nu_\tau$ and $\bar{\nu}_\tau$ is almost negligible. Mainly muon neutrinos are produced, because of the preferential decays $\pi^+\rightarrow \mu^+\nu_\mu$ and $K^+\rightarrow \mu^+\nu_\mu$ (and their charge-conjugates). The decay to $e^+\nu_e$ ($e^-\bar{\nu}_e$ for $\pi^-$ and $\bar{K}^-$) is suppressed by a factor $(m_e/m_\mu)^2$ due to the parity violating nature of the weak interaction. The lepton in the two-body decay of the spin-zero mesons has to be produced with the wrong helicity which favours the decay to the heavier muon. The flux of $\nu_e$ and $\bar{\nu}_e$ comes from the decays $K^+\rightarrow e^+\nu_e\pi^0$ and its charge-conjugate which have a branching ratio of 4.82\% and $K^0_L\rightarrow \pi^-e^+\nu_e$ and its charge-conjugate which have a branching ratio of 38.81\%. The $\nu_\tau$ and $\bar{\nu}_\tau$ in the beam come from the decays of short-lived $D_s$ mesons.
However, the production cross-section for $D_s$ is much smaller than that for $\pi$ and $K$ mesons. The branching ratio for $D_s \to \tau \nu_\tau$ is quoted as $[6.4 \pm 1.5]\% \ [1]$. The energy spectra of the $\nu_\tau$ and $\tau_\tau$ in the beam have two contributions, as also the $\tau$ from the $D_s$ decay will quickly decay giving rise to a second $\tau$-neutrino.

Because of the relativistic energies of the secondaries, the decay products are boosted forward. At higher energies, the neutrino beam will be more focused and more energetic. At the same time, however, the decay length $\gamma_c \tau$ becomes longer. Consequently, a smaller fraction of the secondaries will decay in the available decay space. Therefore, one has to make a trade-off between energy and intensity of the neutrino beam. The kinematics of the two-body decay of the $\pi^+$ and $K^+$ to $\mu^+ \nu_\mu$ determine the energy spectrum of the neutrino beam. In the center of mass frame the muon and neutrino are emitted back-to-back and the available energy is balanced between the muon and the neutrino. In the lab frame, the momentum of the neutrino is therefore only dependent on the angle $\theta$ at which the neutrino is emitted with respect to the direction of the parent meson. The transverse momentum of the neutrino with respect to this axis is given by:

$$p_T = \frac{m_{\pi,K}^2 - m_\mu^2}{2m_{\pi,K}} \sin \theta ,$$

(2.1)

and the longitudinal momentum by

$$p_L = E \left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) \left(\frac{1}{2} + \frac{1}{2} \cos \theta \right) .$$

(2.2)

Because the kaon has more mass than the pion, the neutrino carries (on average) more of the total energy for kaon decays. Therefore, the higher-energy neutrinos in the beam are mainly due to $K$ decays. Table 2.1 gives a summary of the properties of the muon and the $\pi$ and $K$ mesons.

<table>
<thead>
<tr>
<th>mass</th>
<th>$\tau$</th>
<th>$\gamma_c \tau$</th>
<th>$\text{Br}(\to \mu \nu_\mu)$</th>
<th>$p_{T,\text{max}}$</th>
<th>$p_{L,\text{max}}$</th>
<th>$p_{\text{parent}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>105.7</td>
<td>2197.0</td>
<td>6233.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi$</td>
<td>139.6</td>
<td>26.0</td>
<td>55.9</td>
<td>99.99</td>
<td>30</td>
<td>0.427</td>
</tr>
<tr>
<td>$K$</td>
<td>493.7</td>
<td>12.4</td>
<td>7.52</td>
<td>63.43</td>
<td>236</td>
<td>0.944</td>
</tr>
</tbody>
</table>

Table 2.1: Properties of the muon and the $\pi$ and $K$ mesons. The last two columns give the maximum transverse and forward momentum transferred to the neutrino, calculated using equations (2.1) and (2.2).

For the CHORUS experiment, a hard neutrino spectrum is desired, because the charged-current cross-section for $\nu_\tau$ has a high energy threshold due to the $\tau$ mass and increases rapidly above this energy. As was explained in section 2.1.2, anti-neutrinos contribute to the experimental background and should be suppressed. Also the direct $\nu_\tau$ flux in the beam should be as low as possible. For the neutrino beam used by the CHORUS experiment, this irreducible background is calculated to be $4.1 \cdot 10^{-6}$ $\nu_\tau$ charged-current interaction per $\nu_\mu$ charged-current interaction $[171]$. For a total of $4 \cdot 10^{19}$ protons on target, this corresponds to 0.18 $\nu_\tau$ interactions.
Figure 2.2 gives a schematic overview of the components of the neutrino-beam. The setup is described in full detail in Ref. 172. The 450 GeV protons from the SPS accelerator are extracted in two ‘fast-slow’ extraction spills and dumped on the target. Each spill lasts about 6 ms; long enough to separate multiple interactions in the neutrino target; short enough to make pulsed operation of the focusing magnets possible. The target consists of eleven 3 mm thin beryllium rods separated by 9 cm. Each rod is 10 cm long. Using thin rods minimizes secondary interactions of the hadrons produced by the proton-beryllium collisions and therefore optimizes the neutrino flux and spectrum.

The number of anti-neutrinos is minimized by sweeping out the negatively charged hadrons by the magnetic fields of the horn and reflector. These are two specially shaped, single-winding, magnetic lenses which generate a pulsed toroidal field that focuses positively charged particles and defocuses negatively charged particles [173]. The focusing increases the energy-weighted beam flux by about a factor 5 and suppressed the unwanted anti-neutrino flux by a factor of 2. The tapered collimator matches the secondary particle beam to the horn aperture. The collimator in front of the reflector absorbs defocused negative mesons before they decay. The two helium tubes limit absorption and scattering of the mesons before they enter the 289 m long vacuum decay tunnel. The remaining protons and hadrons are absorbed in the first few meters of iron shielding at the end of the decay tunnel. The muons need more shielding and several sections of earth, concrete and iron shielding are in between the decay tunnel and the experimental area. The muon-flux is measured in three gaps in the first iron shield. These measurements are used to monitor the beam shape and intensity.

The large mass of the calorimeter (section 2.6.3) has been used to measure the beam flux as function of radius and energy. The results of these measurements are reported in Ref. 174 and chapter 4 of Ref. 175. In Ref. 175, the discrepancies with earlier reported values [172] for the horn and reflector efficiencies and the beam Monte-Carlo simulation is discussed (see also Ref. 176). An earlier measurement of the neutrino-flux from the interaction rate in the calorimeter is shown in Figure 2.3. A normal-distribution fit to the data shows that the neutrino-beam has a rms width of 0.7 m at the emulsion position in CHORUS. The estimated charged-current $\nu_\mu$ event rate in the emulsion target is $2.1 \times 10^{-14}$ events per proton on target.
2.3 Experimental setup overview

To point from the underground neutrino target to the experiments in the surface buildings, the neutrino beam has an upward slope of 42 mrad with respect to the horizontal. The coordinate system used in this dissertation is the one used in emulsion scanning where the $x$ and $y$ axis are in a vertical plane, with $x$ vertical. The $z$-axis points downstream and lies in the horizontal plane.

The position of the neutrino interaction is referred to as the primary vertex. The tracks coming from the vertex are Lorentz boosted forward with respect to the direction of the incoming neutrino. These tracks will lie within a cone which has an opening angle determined by the exchanged transverse momentum and the neutrino energy. All detector components (except the veto trigger plane) are therefore located downstream of the target and increase in size to cover the same solid angle. The components are installed vertically, but shifted upward with respect to each other to follow the beam slope. Figure 2.4 shows an overview of all the detector components and their layout.

The emulsion is mounted in a rigid frame which also houses the trackers, their layout is presented in section 2.4.4. Emulsion is prone to fading (see section 2.9.2) where the latent image of the particle tracks fades away in time. The speed of this effect increases with temperature. The fading can be limited by keeping the emulsion cold. Therefore, the whole target region is kept at $5 \pm 0.5^\circ C$ during its two years of exposure. The constant temperature also increases alignment accuracy by limiting thermal expansion. Therefore, the target region is located inside a large refrigerated volume, known as the coolbox. Inside the coolbox are the emulsion target, its associated electronic trackers, and the hadron spectrometer.

Just downstream of the coolbox was a gap of 21 cm where originally a set of streamer tubes was placed. These tubes were later replaced by a honeycomb tracker described in Chapter 3. Downstream of these trackers is the calorimeter, consisting of a 1 meter thick block of instrumented lead which absorbs almost all hadrons. Only muons with a momentum higher than 1.6 GeV/c pass through the calorimeter and enter the muon spectrometer. The hadron spectrometer, calorimeter and muon spectrometer are briefly discussed in section 2.6.
2.4 Emulsion target and electronic tracking detectors

To predict the position in the emulsion of tracks from a neutrino interaction, electronic tracking detectors are used. These detectors are placed directly downstream of the emulsion target. In this section, the design of the emulsion target and the tracking detectors is discussed. The guiding principle is to locate a neutrino interaction in the emulsion accurately and efficiently.

2.4.1 Emulsion target considerations

An emulsion target is made out of separate emulsion plates. An emulsion plate cannot be thicker than about 1 mm as the lenses used for scanning the emulsion have a working distance of about 1 mm. During development, the chemical reducing solution must be able to diffuse into the emulsion layer which also limits the thickness of the layers. The plates used in the CHORUS experiment have about 350 μm of emulsion deposited on two sides of a 90 μm thick plastic (tri-acetate-cellulose) base. These plates are known as the target plates. The emulsion target is made out of stacks of such emulsion plates. The plate size is 72 cm × 36 cm and is limited by the equipment needed to pour, dry, develop, and scan the plates.

Plate orientation

In a target, the emulsion plates can be put either perpendicular or longitudinal with respect to the beam direction, as shown in Figure 2.5a & c. The choice of orientation depends on how the emulsion scanned. One consideration is if events are reconstructed by a human operator or by an automatic scanning station. Another factor is how interesting events are located inside an emulsion stack. In the case of a hybrid detector like CHORUS, that means that track predictions need to be followed back to the vertex in the emulsion. As is indicated in Figure 2.5, the interesting tracks for CHORUS lie in a forward cone with respect to the beam direction.
Figure 2.5: Difference in image for emulsion plates oriented longitudinal (a,b) or perpendicular (c,d) to the incoming beam. The emulsion images in (b) and (d) show only $240 \times 240$ pixels of the $1024 \times 1024$ pixel full image. The contrast in the images has been enhanced to let the grains stand out more.

If the plates are oriented longitudinally, the interesting tracks have large angles $\theta_z$ with respect to an axis perpendicular to the plate ($z$-axis). In a single microscope view of a piece of emulsion — typically covering an area of $150 \mu m \times 150 \mu m$ — these large-angle tracks are easy to recognize for a human operator. These tracks have several grains visible within the depth of field of the microscope which lie on a straight line, as is indicated in Figure 2.5b. If the depth inside the emulsion which is in focus is moved, grains will appear at one end of this line and disappear on the other, giving the impression of a traveling particle. These tracks are therefore easy to follow by a human operator. Once the track leaves the border of the view, the plate has to be shifted under the objective. Automatic track finding for these tracks is also relatively easy, because multiple hits of the track are visible in each view. To follow the track in the emulsion, the automatic track-finding needs to be done online, because the track leaves the microscope view fairly quickly which requires shifting the emulsion plate.

If the plates are oriented perpendicular, the interesting tracks have small angles $\theta_z$. These tracks have typically only one grain per track visible inside the depth of field, as indicated by the arrows in Figure 2.5d. Visually, these tracks are identified by moving the depth in focus through the emulsion. The individual grains on a track will appear one after another. The position within the view of these grains will move slightly de-
pending on the track’s angle. The closer a track’s angle is to the z-axis, the smaller this movement and the more difficult it becomes for a human to spot the track in the background of randomly developed grains and the lines of the large-angle tracks. Using an automated scanning station, it is straightforward to take images at different depths inside the emulsion. One can then compute the correlation between grains at different depths and assign one grain per image to a particular track. Track finding can be done either online, for example in hardware, or offline from the analysis of a set of images.

For human scanning of an event in emulsion, it is easier if the plates are oriented longitudinally, because the tracks of interest lie in the plane of a microscope view. However, when a track crosses from one plate to another, it is difficult to locate the continuation of the track on the next plate because the alignment errors grow proportional with \( \tan \theta_z \).

Finding the prediction of a track requires a search at the outer edge of several emulsion plates; scanning through their full depth while looking for a track that matches in angle. Once the vertex is located, several plates need to be scanned at very different positions to reconstruct completely all the tracks from an event. Depending on a track’s angle, a significant part of the track is missed where the particle crosses the plastic base of the plates.

If the plates are placed perpendicular to the beam, like in Figure 2.5c, the tracks cross all plates downstream of the interaction vertex at relatively small angles \( \theta_z \). Following a track upstream from plate to plate is done by scanning the upstream plate starting at the position where the track exited the downstream plate. An electronic prediction can be found by looking for an angular match in one or more microscope views around the predicted position on the most downstream plate. In the perpendicular orientation, all predicted tracks for a stack of plates can be located first on the most downstream plate, before the scanning of all found tracks on the next upstream plate. This step is then repeated until all interaction vertices have been located. Just downstream of a vertex, all vertex tracks will be in the same microscope view and can be reconstructed using the set of images already taken when following the predicted track to the vertex. Once all interaction vertices are located, all event related tracks can be followed in a second pass through all plates, now going downstream.

As several thousand events were subject to scanning using automatic scanning stations, the choice for a perpendicular orientation of the plates in CHORUS is obvious. Many discoveries using emulsion have used longitudinal exposures though, as can be clearly seen in the events that led to the discovery of the pion [187, 188] of which Figure 2.6 shows an example [177].

**Stack thickness**

A stack of target plates, called a module, is vacuum packed to preserve its water contents and to mechanically fix the relative positions of the plates. The neutrino beam has a radius of about 1.4 m at the site of the detector (see Figure 2.3). Therefore, \( 2 \times 4 \) stacks of emulsion plates of \( 72 \text{ cm} \times 36 \text{ cm} \) are used to cover the beam cross-section. The eight modules are put in two rows of four modules with the long edge of the plates oriented vertically.

Given the density of emulsion, \( \rho = 3.815 \text{ g/cm}^3 \), the total stack thickness for 770 kg of emulsion would be 9.7 cm. With the radiation and interaction length of emulsion being \( X_0 \approx 29 \text{ mm} \) and \( \lambda \approx 35 \text{ cm} \), respectively, this thickness would represent roughly \( 3.4 X_0 \) and 0.3 \( \lambda \). Absorption and showering in such a thick stack would lower the efficiency.
of reconstructing primary-vertex tracks downstream of the stack. The track parameters measured behind the stack are smeared due to multiple scattering [1]. Although, this smearing is not so important for finding the track in the emulsion, it does affect the vertex reconstruction accuracy. Another important consideration is that with a stack of about 140 plates, the scanning load would be high, because on average half of the number of plates needs to be scanned to follow a track back to the interaction vertex. For these reasons, the set of emulsion plates is split into four separate stacks, each containing 36 plates. Electronic trackers are inserted between these stacks to accurately predict the position of the primary-vertex tracks for each stack separately. A particle from the primary vertex now crosses on average only 18 plates before its track parameters are measured. The multiple scattering in the downstream stacks can be taken into account in the track fit. The average number of plates that needs to be scanned to locate the vertex in this configuration is also only 18 plates, instead of 72.

2.4.2 Interfacing emulsion and electronic tracking detectors

The design parameters of the electronic tracking detectors are mainly determined by the need to accurately locate a single track in the emulsion. The matching between tracks found in the emulsion (subscript ‘e’) and tracks reconstructed by the electronic tracking detectors (subscript ‘p’) is based on the $\chi^2$ sum over four matching variables; the position and slope differences in $x$ and $y$:

$$\chi^2 = \frac{(x_e - x_p)^2}{\sigma_{xy}} + \frac{(y_e - y_p)^2}{\sigma_{xy}} + \frac{(\theta_x e - \theta_{x p})^2}{\sigma_{\theta}} + \frac{(\theta_y e - \theta_{y p})^2}{\sigma_{\theta}} .$$

The $\chi^2$ is mainly determined by the position resolution of the electronic tracking detectors and the angular resolution of the emulsion. If a 10% contamination of fake matches is allowed when scanning an area with sides of $3\sigma_{xy}$, then the matching should give less than 0.1 candidate for a random area of emulsion of this size averaged over the angular distribution of all tracks. The required resolutions are then determined by the track density in emulsion ($\rho_{\text{tracks}}$) and its angular distribution, i.e.:

$$\int_{3\sigma_{xy}} \rho_{\text{tracks}}(\theta_x, \theta_y) \, dx \, dy \, d\theta_x \, d\theta_y < 0.1 .$$
There are two ways to reach this goal: one, reduce the $3\sigma_{\chi^2}$ volume; two, lower $\rho_{\text{tracks}}$ in the emulsion. The latter can be achieved by reducing the exposure time. The slope resolution of emulsion is limited by distortion of the emulsion layers (section 2.9.2) to $\sigma_{\theta} \approx 15$ mrad for the target plates. A better slope resolution and a low track density can be achieved simultaneously by inserting special emulsion plates between the emulsion target and the electronic tracking detectors and exchanging them regularly. These plates are special in the sense that they use two 100 $\mu$m thick emulsion layers on a 800 $\mu$m thick plastic base. As distortion does not affect the position of a measured track at the emulsion–base interface ($\sigma \approx 0.5$ $\mu$m), the slope of the track can be measured over the base with an accuracy of better than 1 mrad. This type of plate is known as interface plates.

Three of these interface plates are inserted in each stack. One, called special sheet (SS), is packed with the target plates and changed every year. Two others are placed between the emulsion stack and the first tracker plane and are called changeable sheets (CS). The changeable sheets are exchanged depending on the number of integrated tracks (beam-muons, X7 muon beam, and cosmic rays). Due to the increase in scanning power and the lower X7 intensity, the number of changeable sheet periods has been reduced during the experiment from 7 periods in 1994, 3 in 1995, 2 in 1996, to just 1 in 1997.

2.4.3 Tracking detector

The efficiency, resolution and two-track separation of the tracking detectors are important parameters for a reliable and accurate track match with the emulsion. The position resolution should be better than 160 $\mu$m to limit the $3\sigma$ scanning area to 1 mm$^2$. The angular resolution should be comparable to that of the changeable sheets, i.e. 1\ldots 2 mrad. As the tracking detector is close to the interaction vertex, the spacing between tracks and therefore the required two-track resolution is of the order of a millimeter. To limit absorption and reinteraction of hadrons before they reach the hadron spectrometer, the tracking detectors should also not interpose too much material. In the design of the tracking detectors, two other considerations for detectors were not important in the CHORUS experiment. The maximum detection rate is not an issue as the average event rate is less than 0.7 events per spill. Secondly, the occupancy in the detectors is low as the average number of primary tracks in a neutrino interaction is only 4.1 [178].

A good compromise between these requirements and building cost has been achieved using scintillating fibers. Plastic scintillators have relatively low mass (for solid-state detectors), are fast and efficient, but offer limited resolution as they are normally built in strips of several millimeters thick and several centimeters wide. Better resolution can be achieved using thin fibers, but at the cost of detection efficiency. High detection efficiency and good resolution has been achieved by stacking several layers of thin scintillating fibers. The fibers are read out individually using a CCD camera. Because the diameter of the individual fibers is small (500 $\mu$m), a two-track separation at the level of about 1 mm is also achieved. The read-out of CCD cameras is normally slow with a read-out time of several milliseconds, but in CHORUS they can be used because the event rate is low. A similar optimization for low-rate and occupancy has been used several times in the experiment, for example in the honeycomb (section 3.4.1) and muon-spectrometer (section 2.6.4) drift-time measurements.
2.4.4 Target region experimental setup

Figure 2.7 shows the arrangement of the emulsion stacks and the electronic tracking detectors. The tracking detectors are referred to as the target trackers. The setup of the emulsion stacks and trackers consists of two identical sections, each containing two emulsion stacks and four tracking detectors. Each tracking detector consists of four rotated planes such that tracking of particles is possible in 3-d. The target trackers provide the missing time-resolution of the emulsion by uniquely matching a single track in the emulsion to a specific, electronically recorded, event. As discussed previously, good spatial and angular resolution and good two-track separation is crucial. The construction of the tracking planes is described below. The $3 \times 4$ tracking planes behind each pair of emulsion stacks provide the angular measurement and are sufficient to do stand-alone track reconstruction. The four planes between each pair of emulsion stacks are used to recover position accuracy for the upstream stack as the emulsion stack interposes about one radiation length of matter.

![Figure 2.7: Layout of two emulsion stacks and the associated target trackers. This setup is identical to the setup of the other two emulsion stacks in the experiment.](image)

The distance between the emulsion and the target trackers is a trade-off between two conflicting requirements, the two-track separation and the prediction accuracy. The changeable sheets, CS1 and CS2, are used to resolve this conflict by placing CS2 just 1 mm upstream of the first tracker plane. The CS1 plate is 14 mm further upstream and the actual emulsion stack another 38 mm. The two changeable sheets are mounted on a honeycomb panel which is traversed by 15 X-ray guns per emulsion module. A similar honeycomb panel with X-ray guns is placed between CS1 and the emulsion stack. The X-ray guns are brass cylinders with a $^{56}$Fe X-ray source inside. The X-rays create a 1 mm diameter black dot on the surface of the two emulsion plates. These dots are used to determine the alignment between the interface sheets and the target trackers.
A detailed description of the target trackers can be found in Ref. 157. The target tracker consists of modules which contain four planes each. Each module contains one pair of horizontally and vertically oriented planes \((XY)\) and one pair of rotated planes \((X\pm Y\pm)\). The rotation angle is \(8^\circ\) and alters sign for successive modules. Each tracker plane is composed of seven layers of 2.3 m long scintillating plastic fibers with a diameter of 500 \(\mu\)m. The far end of the fibers is coated with an aluminum mirror to increase the light-yield. The other end of the fibers is coupled to the camera. The light-output of a single fiber is too small to be detected directly by a CCD camera. Therefore, an opto-electronic image intensifier is inserted between the fibers and the camera. The image intensifier also demagnifies the image to match the fiber diameter to the CCD pixel size. The measured hit density is between 5 and 7 for a minimum-ionizing particle passing at 220 cm and 70 cm from the read-out end, respectively. The measured inefficiency of a plane is 0.2\%. The disadvantage of the image intensifiers is that they need to be shielded from magnetic fields (even the earth’s magnetic field) and therefore no magnetic (stray) fields are allowed in the target region.

The read-out of the CCD camera takes about 20 ms, but the CCD chip can store one image in a memory zone within 125 \(\mu\)s. Using the memory zone, two events can be buffered in the CCD during the 6 ms beam spill. The buffered events are read out during the time between the spills. Because of the limited buffer capacity of the camera, the image recording needs to be delayed to allow for the application of a trigger signal. The image intensifier contains a multi-channel plate that can be electronically gated to expose the CCD only for triggered events. A fluorescence phosphor with a long decay time in the first stage of the image intensifier is used to delay the image. If the trigger enables recording of the event, the CCD captures about 30\% of the light in a time window of 20 \(\mu\)s after the arrival of the scintillation light.

**Figure 2.8:** Position and angular resolution of the target tracker as measured by comparing scanning predictions to tracks found in the emulsion.
The track residual of a single target-tracker plane was measured to be around 180 \( \mu \text{m} \). The final resolution of the scanning predictions can be evaluated by comparing the predictions with the tracks found in the changeable sheet. The resulting distributions for muons, after alignment (section 4.6.3), are shown in Figure 2.8. The position resolution is \( \sigma_{xy} \approx 190 \mu \text{m} \) and the angular resolution \( \sigma_\theta \approx 2.3 \text{ mrad} \) after unfolding the 1 mrad emulsion resolution. Because of the asymmetric distribution of tracking planes around the emulsion stacks, these resolutions are different for each stack. The plots in Figure 2.8 are for the last stack which has the smallest amount of tracking planes behind it.

### 2.5 Trigger

The main purpose of the trigger system is to select primarily events due to neutrino interactions in the emulsion. For this, the emulsion target is surrounded by several scintillator planes, as shown in Figure 2.9. All planes are made out of two staggered planes of plastic scintillator strips. The trigger planes are coded as follows: E = emulsion, T = trigger, H = hodoscope, V = veto and A = anti-counter. Both the T and V plane provide accurate timing (\( \approx 1 \text{ ns} \)) by averaging the time of a detected hit on both sides of the scintillator strip (mean-time).

A coincidence of hits in the T and H planes indicates the presence of a charged particle that left the emulsion, while an anti-coincidence with the V-plane makes sure that no charged particle entered the emulsion. To avoid vetoing events due to back-scattered particles, the V-plane is put 2 m upstream of the emulsion. This gives a time difference of 13 ns between forward and backward going particles. The accurate timing of the V and T planes is used to distinguish between these two cases. Another important criterion in the trigger design is the high rate of beam related muons that must be efficiently vetoed which requires a high efficiency of the V-plane. In effect, the V-plane has an inefficiency of less than \( 1.5 \cdot 10^{-3} \).

As the mass of the material surrounding the target (metal supports, concrete & iron floors, shielding) is much larger than the target mass, many more interactions will take place around the target than in the target itself. The expected rate of neutrino interactions in the emulsion is about 0.34 events per spill at the maximum spill intensity.
of $1.5 \cdot 10^{13}$ protons on target. The number of events ($k$) per spill is then (ignoring dead time) given by the Poisson distribution $P(k; \mu = 0.34)$. The CCD read-out of the target trackers limits the maximum number of events that can be recorded per beam spill to two. If the trigger would fire only for events in the emulsion, the recording efficiency is given by:

$$\varepsilon = \frac{1}{\mu} \left( P(1; \mu) + 2 \sum_{k=2}^{\infty} P(k; \mu) \right),$$

which yields for $\mu = 0.34$: $\varepsilon = 98.4\%$. If, instead, the total triggered mass with respect to the emulsion mass is larger by a factor $f$, then the average event rate $\mu'$ is $f \times \mu$. The recording efficiency will decrease as the average number of triggered emulsion events is now given by:

$$\langle k \rangle = \frac{1}{f} P(1; \mu') + \frac{2}{f} \sum_{k=2}^{\infty} P(k; \mu').$$

The decrease in the recording efficiency $\varepsilon = \langle k \rangle / \mu$ for real emulsion events is shown in Figure 2.10 as a function of $f$. For a $T + H + \nabla$ trigger $f = 6$ and the recording efficiency has dropped to about 72%. Most of the additional triggers are due to cosmic rays and neutrino interactions in the iron floor, the frame and read-out equipment of the target trackers, and the concrete floor in front of the experiment. Requiring an additional coincidence in the E-plane (installed in the 2nd year of data taking) improves the selection of emulsion events. Putting the A-plane in anti-coincidence removes events from the concrete floor. Cosmic rays and events from the iron floor are suppressed by requiring a hit combination in T and H consistent with a particle track with $|\tan \theta| < 0.2$ with respect to the neutrino beam. The size of the V-plane is such that any incoming cosmic ray not hitting the V-plane crosses the emulsion at a larger angle than this. The final trigger rate for emulsion events corresponds to a total mass of 1700 kg ($f = 2.2$). For typical spill intensities of $1 \cdot 10^{13}$, the expected efficiency is then 96.7%, which is accounted for as dead time of the detector. The acceptance of the trigger to neutrino interactions in the emulsion target has been estimated to be 99%.

**Figure 2.10:** Relative recording efficiency as function of the ratio of the total trigger mass and the emulsion mass due to the two-event limit of the CCD read-out.
Several other triggers are made for the sub-detectors and other physics. The details of these triggers and the hardware and software implementation of the trigger logic are described in Ref. 159.

2.6 Downstream detectors

The detectors downstream of the target region are used for particle identification and for energy and momentum measurements. Originally foreseen to measure the kinematic variables for a pre-selection of $\tau$-decay candidates, in the final analysis they are mainly used to assign charge, momentum and energy to the tracks found in the emulsion.

2.6.1 Hadron spectrometer

The hadron spectrometer is placed directly behind the emulsion target and target trackers. It consists of three scintillating fiber trackers, called the diamond trackers, which are placed around a magnet. The purpose of this spectrometer is to measure the momenta of hadrons up to about 20 GeV/$c$. This spectrometer is also used to measure the momentum of muons of less than 2 GeV/$c$ that do not reach the muon spectrometer (section 2.6.4). The momenta of the hadrons must be known in order to suppress some of the background (section 2.1.2). All the components of this detector must be light to minimize multiple scattering and showering which would affect the momentum resolution and the energy measurement in the calorimeter located downstream. The spectrometer magnet must have a very low stray-field because of the image intensifiers used in the read-out of the both the target trackers and the tracking planes in the hadron spectrometer itself (image distortion). The depth must also not be too large in order to keep the lateral dimensions of the downstream detectors reasonable for the same solid angle.

A solution was found by using a superposition of toroidal magnetic fields. Toroidal fields have closed field lines and therefore the stray-field outside the windings is very weak. Another advantage of a toroidal field is that the B-field is perpendicular to the particle’s direction which gives the largest bending power. The main disadvantage of a standard toroidal magnet is that the material of the windings is in the particle’s path and that all the windings cross at the center of the magnet. A compromise was found by using very light aluminum windings (0.04 radiation length) and distributing the center windings. The center windings are spread out over six spokes of a hexagonal shaped magnet. The magnet, shown in Figure 2.11a, was specially designed for the CHORUS experiment and is described in more detail in Ref. 161. It has a depth of 0.75 m and consists of six equilateral triangular sections with 1.5 m wide sides. The field inside a triangle is homogeneous and the field lines are parallel to the triangle’s outer edge. The field in the triangles is homogeneous because the number of windings per unit length contributing to the field at any point is constant. The magnet is pulsed synchronously with the beam spills and has a field strength of 0.12 Tesla. The field is oriented such that negative particles are focused. The overall current running along the windings creates a single winding running once around the whole magnet which creates a solenoidal stray-field. This was compensated for by winding the feeding wires once in the opposite direction along the outer rim of the magnet.

The target trackers (section 2.4.4) give an accurate measurement upstream of the magnet. The same detection technique used for these trackers has been used for the tracking detectors around the magnet. Upstream of the magnet there is one tracking module (DT1) and downstream there are two (DT2, DT3). Each module consists of two
layers of three diamond-shaped paddles, with the second layer rotated by 60°, as shown in Figure 2.11b. Each paddle is made out of seven layers of scintillating fibers. Of the two paddles which cover a magnet triangle, one measures the coordinate parallel to the base of the triangle (perpendicular to the bending plane) and the other a coordinate rotated by 60°. In this configuration, the DT1 module upstream of the magnet provides an accurate measurement of the entry point of a track reconstructed in the target trackers. The two planes behind the magnet, DT2 and DT3, are oriented such that for each magnet triangle they provide two measurements in the bending plane and two coordinates rotated by respectively +60° and −60° with respect to the bending plane.

2.6.2 Streamer-tubes and honeycomb detector

The four measurements from DT2 and DT3 behind the magnet are not sufficient to perform stand-alone tracking. Four planes of streamer tubes, recovered from the CHARM II detector [179], were placed in the 21 cm gap between calorimeter and coolbox. These 1 cm by 1 cm streamer tubes give additional hits to aid the track finding. In 1995, at the beginning of the second year of data taking, two additional planes were added.

However, the streamer tubes had a limited resolution and small stereo angles (7°) between the planes. A new tracker which could be used for stand-alone 3-D track reconstruction was proposed to replace the streamer tube planes. This new tracker, the honeycomb tracker, was installed halfway the 1996 data-taking run. Its construction and read-out electronics are the subject of Chapter 3. The new honeycomb tracker turned out to be essential in determining the alignment of the diamond tracker paddles. This alignment was then applied to pre-honeycomb events to improve the momentum resolution of the hadron spectrometer for the data from 1995 and beginning of 1996.
2.6.3 Calorimeter

The energy measurement, originally needed for $\tau$-decay candidate pre-selection, is done using the calorimeter. The calorimeter in CHORUS requires tracking capabilities, because a muon which passes through the calorimeter and is detected in the muon spectrometer, must be connected to the corresponding track in the target trackers. For this, streamer tubes were recovered from the CHARM II experiment and interspersed between planes of calorimeter modules.

The energy resolution depends mainly on the ratio of active to passive material. The active material is used to measure a fraction of the total energy. The passive material is used for the development of the shower. Any energy deposited in the passive material is not measured, but is assumed to be proportional to the energy deposited in the active material. Due to pair production in electro-magnetic interactions of electrons and positrons, the deposited energy can vary with small spatial dimensions. To have an accurate measurement of the energy in an electro-magnetic shower requires, therefore, fine-grained sampling inside the passive material.

The calorimeter is constructed from bar-shaped modules made out of lead with plastic scintillator as active material. Each module has a separate read-out channel (one photomultiplier read out with an analogue-to-digital converter). The high-sampling rate is obtained by interspersing many small-diameter scintillating fibers inside the lead. All fibers from a single module are read out by a single photomultiplier tube. The ratio of lead and scintillator mass is chosen such that differences in shower development for electrons and hadrons are compensated in the total energy measurement [180]. The size of individual modules of the calorimeter is adapted to the need to measure the energy deposited by individual particles.

The calorimeter contains three sections. Each section consists of several planes of the lead–scintillator modules placed perpendicular to the beam direction. The planes are oriented alternatively horizontally and vertically. Electrons and positrons deposit most of their energy in the first section. This section consists of four planes constructed from 4 cm wide and 4 cm deep bars. The second section contains five planes with bars of 8 cm wide and 8 cm deep. In the final section, the electro-magnetic component of the shower is so much reduced that fine sampling is no longer necessary. The bars in this section are constructed with alternating layers of lead and scintillator strips. These bars are 10 cm wide and 10 cm thick.

In total, the calorimeter represents 5.2 hadronic interaction lengths and 144 radiation lengths. Showers of 5 GeV hadrons are fully contained in 99% of the cases. Additional information about the calorimeter and its performance can be found in Refs. 163, 164.

2.6.4 Muon spectrometer

The calorimeter acts as a muon filter because the muons are the most likely to pass through, having no hadronic interactions and much smaller radiation losses then electrons. The muon spectrometer, placed downstream of the calorimeter, measures the charge and momentum of muons. The magnetic field necessary to measure the momentum and charge is generated in iron disks. At maximum magnetization, the field reaches 1.7 Tesla inside the iron disks using an electric current of 700 A. The toroidal field in the disks is oriented such that negative muons are focused.
The muon spectrometer consists of seven tracking sections interleaved by six magnets. Each magnet is made from twenty iron disks with scintillator planes interspersed. The fast scintillator planes are used to measure the muon arrival time and are used in the trigger. They are also used to measure the energy of hadron showers leaving the calorimeter. In this way, the first few modules of the spectrometer work as a tail catcher for the calorimeter. The magnet modules were recovered from the CDHS experiment [181]. The tracking sections consist of wire chambers also recovered from CDHS [182] and streamer tubes recovered from CHARM II [179]. The layout of one section is shown in Figure 2.12a.

![Exploded drawing of a single section of the muon spectrometer](image)

Figure 2.12. Exploded drawing of a single section of the muon spectrometer (a). The resolution of the muon spectrometer as function of muon momentum is plotted in (b). For muons with $p_\mu < 7\text{ GeV}/c$ the momentum is determined by the range, indicated by the gray bar at 7%.

The wire chambers and streamer tubes are read out using time-to-digital converters (TDCs). As the occupancy in the spectrometer is low, the drift-time measurement in the wire-chamber is multiplexed with four wires connected to a single TDC channel. For the streamer-tube planes, each tube is read out digitally and $4 \times 8$ tubes are grouped together to a single TDC channel with 10 ns accuracy. The four groups of eight cells are time-multiplexed by delaying the signals of each group. To get a better drift-time measurement in the streamer tubes, all 352 tubes in a plane are also wired together to a single 1 ns resolution TDC channel.

The muon momentum is measured from the bending in the six magnet sections. The resolution $\Delta p_\mu/p_\mu$ as function of the momentum $p_\mu$ is shown in Figure 2.12b. The resolution is limited to about 12% due to multiple-Coulomb scattering inside the iron of the magnets. At momenta above 10\,GeV/$c$, the resolution of the tracking sections also contributes to the resolution. A better momentum measurement can be achieved for muons that stop inside the spectrometer from their range [183]. For stopping muons ($p_\mu < 7\text{ GeV}/c$), the momentum resolution is about 7%, indicated by the gray bar in Figure 2.12b.
2.7 Online monitoring

The hardware and software of the CHORUS data-acquisition system is extensively described in Ref. 160. Here, only the monitoring and visualization system is described. This system reads histograms created by online tasks and displays them on request of the user. A graphical user interface (GUI) was written using Tcl/Tk [184] and the TiX extension [185]. This interface has a connection with a C++ program that reads and displays histograms using the CERN library HIGZ.

TiX uses a kind of class for the widgets it adds to Tk. Using a similar desing, the GUI could be written in an object-oriented fashion, even in a scripting language like Tcl/Tk. A class concept was designed for Tcl scripts which makes it possible to define classes and methods in Tcl and to instantiate objects. These objects become Tcl commands that invoke the methods given to them. The Tcl interpreter made it possible to do this in plain Tcl code. Using these Tcl classes, common classes for displaying parts of the user interface can be reused.

The object-oriented C++ program contains a class hierarchy for all the different histogram types of the CHORUS histogram libraries and also encapsulates the CERN library HBOOK histograms. A bridge class for the HIGZ histogram plotting toolkit was created which reorganizes the page and histogram layout options of HIGZ. These page and histogram layout classes define all values, distances, and sizes of items (like headers, labels, axis values, etc.) in a consistent top-to-bottom and left-to-right order and automatically resize the histogram zones to fit everything in the window. Displaying histograms is then done by specifying a page-layout (containing title, legends, etc.) and histogram layout (containing labels, histogram header, etc.) to the abstract plot method in the histogram classes. The plot method can be called with different layout objects. Layout objects were defined, for example, to display histograms with all axis and values attached and to create a compact display of many histograms using the same scale and only one set of axis labels.

A tool was developed to map C++ classes to corresponding Tcl classes. This tool was used to make the histogram class hierarchy, layout classes, and HIGZ interface class directly available as Tcl classes and objects. Using these classes, all histogram manipulations, layout, and plotting could be done directly from a Tcl script. For example, the title of a HIGZ page or the axis label of a histogram become simple variables of a Tcl object and can be manipulated using standard Tcl commands. The final trick, necessary to create a fully interactive histogram monitoring task, was to capture the main HIGZ window inside a Tk window. This allows (Tk detected) mouse events on the HIGZ display to become active events. Having achieved that, it was then easy to read histograms and display them in all kinds of configurations from a Tcl/Tk script. Histograms of different runs can be added to look at averages, overlaid in a single plot to spot differences between runs, or automatically compared to a reference histogram. With a mouse-click, a histogram can be selected for individual display, its scale changed or bin values extracted, for example to locate the exact dead and hot channels in some detector.

Figure 2.13 shows the GUI for selecting a set of histograms and runs to display. The pull-down menus on top select between the main categories of histograms for all the sub-detectors and some derived values calculated online. The left-panel in the window shows a detailed layout of histogram sub-categories which can be selected using buttons, radio-buttons and active graphical elements. In the right panel all runs accessible from disk are shown. One or more runs, including (if present) the currently active run, can
Figure 2.13: The graphical user interface for online monitoring. This screen-shot shows the configuration used to select histograms for the muon counters in one of the beam-line pits. In this case, the left-side of the GUI selects between different counters in the muon pits, the right-side selects one or more run numbers to be displayed.

Figure 2.14: Histograms of honeycomb drift time distributions (see also Chapter 3) in the online-monitor main window. A left mouse click pops up a position sensitive menu with, for example, the ‘zoom’ submenu to manipulate the display options of one or more histograms. A separate ‘Bin Contents’ window at the bottom shows the contents of the bin the mouse cursor is over.
be selected in this window and then displayed, either added together or all overlaid in a single plot. These kind of options are enabled or disabled with the buttons in the middle column. Clicking on the ‘Select and Display’ button brings up the main window showing the histograms for the runs selected. The histograms shown can then be manipulated using the mouse as described above. A screen-shot of the displayed histograms and the mouse activated menu is given in Figure 2.14, in this case for honeycomb drift time histograms (see also Chapter 3).

2.8 Track reconstruction and scanning predictions

The offline analysis program (CHANT) is used to reconstruct events from the data [186]. One of its main tasks is to select one track for each event which should be followed down into the emulsion to locate the vertex. These tracks are referred to as the scanning predictions or scan-back track. The scanning predictions are selected from the tracks reconstructed in the target tracker (section 2.4.4). First a vertex position is calculated from the target-tracker tracks. If the vertex lies inside an emulsion stack within the uncertainty, a scanning prediction is generated from the tracks attached to the vertex.

The track finding starts with clustering the CCD images recorded by the target tracker. These clusters correspond to the center positions of track segments in the seven fiber layers. In the second step, all combinations of hits in each module of four planes are considered. Track segments inside a module should have a hit in at least three out of the four planes. The track segments from the four modules in a target section are then combined into tracks using a minimum spanning tree. Connected branches in this tree yield an initial estimate for a common vertex. If the event is located in the first two stacks, then the tracks in the upstream target section are combined with tracks and hits in the downstream section.

Each found track is fitted taking into account multiple scattering in the various materials between the hits. The track fit yields a $\chi^2$-probability $P(\chi^2)$. In this calculation, the hit resolution is assumed to be $\sigma = 180 \mu m$. Two effects cause the $P(\chi^2)$ distribution to deviate from the expected uniform distribution. First, the momentum of the track can be unknown. In this case, a momentum of 1 GeV/c is assumed. Depending on the real momentum of the particle, this can over or under estimate the multiple scattering contribution to the hit resolution. Therefore, a cut on $P(\chi^2)$ introduces a bias on momentum, selecting preferably high momentum tracks. Second, the hit-residual distribution has tails with a rms width of about 750 $\mu m$. These tails are probably due to cross-talk in the input window of the image intensifier or backscattering in the multi-channel plate. This leads to reconstructed tracks with very low $\chi^2$-probability. However, these tracks have been found in the emulsion.

A vertex is defined as the point of closest approach between tracks. If a vertex is reconstructed in one of the emulsion stacks, the event is marked for scanning. There can be several vertices in an event, in which case a quality value is assigned to each vertex. The quality value is defined such that it is highest for the vertex that is most likely the primary vertex. It takes into account the presence of a muon track, the number of tracks attached to the vertex and the vertex position (more upstream higher value).

The increase in scanning power has made it possible to remove the selection of the most likely $\tau$-decay daughter as the scanning prediction. Instead, the track most likely to be found in the emulsion is taken as prediction. If the event contains a vertex with a primary muon, the muon track is always chosen as prediction. Muons are identified independently
in the muon spectrometer (section 2.6.4). A matching is attempted between the target-tracker tracks and the spectrometer muon tracks in order to identify primary muons. If there is a muon in the spectrometer but no target-tracker track can be matched to it with good probability, the same selection procedure as for events without a muon is used. For these events, one track is selected from those attached to the primary vertex with the additional requirement that it has a fit probability $P(\chi^2) > 10\%$. Because of the non-uniformity of the $P(\chi^2)$ distribution, the $P(\chi^2)$ cut is lowered to $10^{-4}$ if no track in the event has an acceptable $P(\chi^2)$ value. In all cases where there are several candidate tracks, track isolation is used as a tie-breaker. The selected tracks are then refitted to give the impact point on the most downstream plate of the emulsion stack containing the vertex. Because of the distribution of emulsion and target-tracker planes, the various emulsion stacks show different reconstruction and event-location efficiencies.

2.9 Emulsion and scanning techniques

Nuclear emulsion has a rich history of scientific discoveries, starting in 1896 with the accidental discovery of radioactivity by Becquerel (see Figure 2.15). In 1947, Powell and his collaborators discovered the pion in emulsion plates exposed to cosmic rays [187,188]. This discovery was quickly followed by other discoveries of elementary particles with emulsion, for example, the charged kaons, the $\Lambda^0$ [189] and $\Xi^0$ [190], and the $\Sigma^+$ [191,192]. In hind-sight, also the $\Omega^-$ was first seen in emulsion [193]. Emulsion experiments also played a crucial role in elucidating the parity-violating decays of the charged kaons, the so-called $\tau-\theta$ puzzle [194–197]. The power of emulsion is maybe best illustrated by a rocket experiment in which a few postage-stamp sized emulsion pieces gave detailed information about the components and spectra of the earth’s Van Allen radiation belts [198]. For over a decade, emulsion remained one of the prime tools in experimental particle physics. After that, emulsion was largely replaced by bubble chambers and electronic detectors which eliminated the need for laborious manual scanning. Only for very few experiments did the benefit from emulsion’s unrivaled spatial resolution outweigh the drawbacks of manual scanning.

Figure 2.15: The original photographic emulsion plate which led to the discovery of radioactivity by Becquerel. The plate, wrapped in opaque paper, was left near uranium salts and became dark even though it was never exposed to light.

2.9.1 Hybrid experiments and automatic scanning

In the last three decades, the drawbacks of the manual scanning of emulsion have been remedied, largely due to two interrelated developments. First, the combination of nuclear emulsion with electronic detectors bridges the gap between the micrometer position resolution of emulsion and the nanosecond time resolution of electronic detectors. Such hybrid experiments offer the best of both worlds: real-time measurements in the electronic detectors and high-resolution track and vertex information in the emulsion. The idea of hybrid experiments has led to the revival of emulsion. Second, the development
of automatic scanning techniques opens up the possibility to analyze several hundred-thousand events within a reasonable amount of time.

With scanning predictions from hybrid experiments, only a minute fraction of the emulsion volume has to be inspected. In 1965 an experiment along those lines was performed using a neutrino beam at CERN and seven neutrino interactions were found [199, 200]. The first large-scale hybrid experiment was WA17 at CERN, exposing 31.5 \ell of emulsion in front of BEBC, the Big European Bubble Chamber. The WA17 experiment located 169 neutrino charged-current interactions, including eight candidates of a charmed-particle [201].

In the middle of the eighties, a breakthrough came with the development of the first semi-automatic scanning techniques. With the plates oriented perpendicular to the beam, the emulsion was used as a tracking device rather than as a visual display. These techniques were pioneered by the E531 experiment [202] at FNAL which exposed 58.6 \ell of emulsion to a neutrino beam. To evaluate the advantages and drawbacks of different scanning techniques, part of the emulsion was oriented parallel to the beam, part of it perpendicular. The E531 experiment can be considered the direct predecessor of CHORUS. With the continuing work of the Nagoya university in Japan, fully automatic scanning became possible in the beginning of the nineties [203]. Using these techniques, the E653 experiment at FNAL performed a study of hadronically produced heavy flavour states using a 71 \ell emulsion target, exposed to an 800 GeV proton beam and a 600 GeV pion beam [204]. In total, more than 50,000 interactions were located; the proton exposure yielded 146 identified charm events [205] and the pion exposure yielded nine beauty pairs [206]. A review of hybrid experiments, focusing in particular on neutrino experiments, is given in Ref. 207.

The development towards more massive emulsion targets in which a larger number of events could be located with the aid of automatic scanning have led to the CHORUS experiment. To this date, the 400 \ell of emulsion used in this experiment remains the largest emulsion target ever built. Also its two year exposure is exceptionally long. A detailed description of the pouring and processing facilities used for CHORUS can be found in [208]. In 2007, OPERA will start operating needing at least 12,000 \ell of emulsion.

The following quote from the beginning of Barkas’s first book on emulsion — considered as the standard texts on nuclear emulsion [209,210] — puts all of the above in perspective:

“Nevertheless it should be pointed out that emulsion has no great advantage when one is looking for a particle of predicted properties. It is of greatest use for discovering utterly new things, the anomalous behavior of which often can be recognized from a single event.”

A recent example of how telling even a single event may be is the observation by the CHORUS experiment of neutrino-induced diffractive production of $D^*_s \to D^+_s \gamma$, $D^+_s \to \tau^+ \nu_\tau$ and $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$, reported in Ref. 211.

In the following sections, the typical properties of emulsion will be discussed, followed by a description of the scanning microscopes and the automatic track finding hardware.

### 2.9.2 Emulsion characteristics

Probably the best short-description of emulsion as a particle detector is given by Barkas, to quote from Ref. 209:
“Silver-halide emulsion of the type used for registering the tracks of charged particles consists of about equal parts by volume of halide crystals, a few tenths of a micron in diameter, and a matrix material which is chiefly gelatin. An ionizing particle on encountering a crystal may render it developable. [...] With a microscope the paths of charged particles that penetrated the emulsion are visible as trails of minute silver grains. A true three-dimensional image is produced. The paths of particles, outlined by silver, literally exist in space.”

Latent image formation

Nuclear emulsions are made from a suspension of tiny silver-halide crystals, usually AgBr, with typical crystal sizes in the order of a few tenths of a micron. The composition of nuclear emulsion and the physical processes underlying the formation of the image and its development are largely identical to those for photographic emulsion. The chief differences are the larger thickness of the plates — up to several hundred μm as opposed to a few μm in the case of photographic film — and a higher density of crystals. Photons or a passing charged particle can excite electrons from the valence band to the conduction band, leaving behind positively charged holes. The electrons are free to move through the crystal and can get trapped at internal lattice defects or special surface sites formed by colloidal silver or silver-sulfide. There they reduce silver ions to neutral silver atoms which form little centers of so called photolytic silver, referred to as the latent image. During development, these silver specks, which can be as small as three silver atoms, serve as growth centers for larger silver crystals, referred to as grains.

Normal photographic emulsion is not sensitive enough to detect minimum ionizing particles. A through-going charged particle is not very efficient at rendering a crystal developable. A particle creates many electron-hole pairs in a crystal in a very short time which greatly enhances the recombination probability. Furthermore, photons from ionization have energies far above the excitation threshold of 2.5 eV for AgBr. Whereas about 30 eV, deposited by a few visible light photons, suffice to render a silver-halide crystal developable, a particle must deposit between 500 eV and 3 keV to achieve the same. Especially for small crystals, a relatively small fraction of the energy loss effectively contributes to the formation of the latent image. Addition of several inorganic (like sulfur or gold) or organic molecules (dyes) sensitizes the emulsion so that minimum-ionizing particles can be seen. The processes responsible for this are still not well understood and some ingredients are kept secret. Sensitization probably works by creating additional internal lattice defects or surface sites where silver specks can form easier and are stabilized. The sensitivity of emulsion is usually measured in the number of developable grains per 100 μm track length. The world record for minimum-ionizing particles is about 70 grains/100 μm, the CHORUS emulsion has about 30 grains/100 μm.

The binding potential for latent image specks, especially if they are composed of only a few atoms, is relatively shallow and, with time, the latent image of a particle track gradually fades when the silver atoms re-oxidize. This process, known as fading, is strongly temperature dependent and enhanced by the presence of oxidizers in the emulsion. Fading can therefore be reduced by lowering the temperature and deploying the emulsion in a protective atmosphere of nitrogen or in vacuum. Tests on the CHORUS emulsion showed that the rate of fading is negligible for an exposure of up to two years if the emulsion is kept at 5°C and vacuum packed. The CHORUS emulsion was monitored during its exposure using small samples developed at intervals, to check for fading and fog (explained below).
Gelatin matrix

The value of gelatin as the emulsion matrix stems from a unique combination of properties. It encapsulates the silver-halide crystals, allowing them to be dispersed and to produce a uniform distribution of crystals. The components of gelatin, mostly organic molecules containing sulfur compounds, are photographically sensitizing. The gelatin has an exceptional mechanical strength, but does not prevent the penetration of watery solutions needed for pouring and development. As gelatin binds strongly to silver and silver-halide crystals, it keeps both the undeveloped silver-halide crystals and the silver grains in place, even though the emulsion can swell by as much as a factor of ten during development. The cross-linked network of long molecules in the gelatin ensures that the crystals or grains return to their original position when the emulsion is dried, except for some distortions which are discussed below. Unfortunately, gelatin is strongly hygroscopic, causing it to swell with increasing humidity and to shrink when drying. Therefore, emulsion plates need to be kept in a controlled environment with stable humidity.

Development

The latent image is converted into a stable image in the development process. Development works by reducing the silver-halide crystals and depositing silver on the latent image specks. The silver-halide crystals that are not part of the latent image are dissociated into their respective ions which are evacuated from the emulsion in the fixing stage. The various procedures are similar to those used in photographic development, but the larger thickness of nuclear emulsion plates leads to greatly increased soaking times. The development process is based on a delicate balance between different reaction rates, the formation of metallic silver aided by the presence of latent image centers and reduction and dissolving of silver-halide.

Because of the immense number of crystals present and the differential nature of the development process, some random crystals will become developed as well, leading to a background of track unrelated grains, known as fog. Various effects lead to a higher fog density at the surface of the emulsion. During development, the surface layer of the emulsion will develop more rapidly than the bulk, causing a built up of fog at the surface. The surface could have been exposed to light, which does not penetrate more than a few micron in the undeveloped emulsion. The surface is also subject to mechanical abrasion. Both processes cause excessive development leading to black spots and streaks. These two processes are actually exploited to print patterns on the emulsion. Using light, reference points are printed on the emulsion with a carefully aligned mask placed on the undeveloped emulsion. The stack and plate numbers are written with a blunt, non-writing, pencil and they show up after development. To be able to scan a developed plate under a microscope, the dark surface layer is removed without removing also the reference marks.

Resolution, shrinkage and distortion

The power of emulsion is its ability to visualize the paths of particles in 3-D with high resolution. The silver spheres that are produced during development tend to be larger, by up to a factor of two, than the corresponding silver-halide crystals. This growth is largely uniform. The resolution is therefore determined by the crystal diameter in the undeveloped emulsion, which ranges from 0.05 μm to 0.5 μm. This resolution should not be taken at face value, because the intrinsic resolution is only meaningful to the extent
that measurements can be made in the same reference frame as where the emulsion has been exposed. Shrinkage as well as distortions will affect the practical resolution.

Shrinkage results from the removal of the undeveloped crystals during development. The silver-halide contents is about 50% in volume of the exposed emulsion whereas only a very tiny fraction contributes to the latent image. During development, the undeveloped silver-halide crystals are removed and therefore the thickness of the emulsion layer is much reduced after development. The lateral area is unaffected because it is determined by the size of the mechanical support plate. The shrinkage factor, defined as the emulsion thickness at the time of exposure divided by the thickness at the time of scanning, is typically about two. However, the shrinkage factor varies with the water content of the emulsion. Because of the hygroscopic nature of gelatin, the shrinkage may vary with the scanning conditions. For instance, during scanning the top surface is typically insulated by a thin layer of immersion oil whereas the bottom surface is kept under vacuum leading to dessication. As a consequence, the shrinkage factor may vary along the depth.

Although the gelatin network is exceptionally strong, it is also very flexible and thus free to distort. This actually happens when tension built up during pouring and drying is released during development. During processing, the emulsion swells in the development baths. These tensions can then relax, causing the emulsion to distort. Additional distortions appear because the emulsion tends to swell in all directions whereas the surface mounted on the plastic base is constrained to retain its dimensions. The fact that particle tracks in developed emulsion do not appear as straight lines is generally referred to as distortion, regardless of its origin.

**Figure 2.16**: Effects of distortion and shrinkage on one side of an emulsion plate. The mechanical support plate is located at the bottom (dashed area). With respect to the original track (dashed line), the distorted track has a parabolic shape (thick solid line).

The most common form of distortion results in a parabolic shape of tracks. This kind of distortion results from shearing stress in the emulsion layer which is proportional with the distance to the base. Because the emulsion is fixed at the base, the stress force there is zero. The release of a stress that increases linearly with the distance to the base leads to a displacement which is quadratical with the depth in the emulsion. Because the outer emulsion surface is not constrained, it will have more or less the same shear down to a certain depth. The net result is that the position at the support plate is unchanged, whereas the slope of the track at the outer surface is free of distortion. Figure 2.16 schematically represents the combined effect of shrinkage and this type of distortion. Because the base position is unaltered, accurate angular track information can be obtained from double-sided emulsion with a relatively thick base. This idea was first suggested in Ref. 212 and has been used for the interface sheets as discussed in section 2.4.2.
2.9.3 Scanning microscopes

The layout of a microscope for emulsion scanning is depicted in Figure 2.17. The microscope consists of a movable stage on which the emulsion plate is mounted, a high numerical-aperture but low power objective, and a light source. The stage movement is in the plane perpendicular to the optical axis. The stage is used to position a selected part of the emulsion precisely under the objective. The objective creates a magnified image of the emulsion with a limited field of view. The size of the view depends on the magnification and the size of the image sensor. It is typically around 150 μm. Because of the magnification, the depth of field is small (typically a few microns), meaning that only a thin slice of the emulsion is in focus. Moving the objective along the optical axis brings slices at different depths in focus. Normally, emulsion microscopes use trans-illumination where a condenser lens focuses the light through the emulsion. With this kind of illumination, the grains in the image show up as tiny dark dots on a more or less uniform light-gray background. These dots are the shadows of the corresponding silver spheres that lie within the depth of field. The gray background reflects the fact that gelatin and the plastic base are transparent in most of the optical spectrum and that the grains out of focus cast very dispersed shadows. As was shown in Figure 2.5, tracks parallel to the emulsion surface are seen within a field of view as an aligned set of dots. For tracks perpendicular to the surface, typically only one or two grains lie within the depth of field. Moving the focus up and down, subsequent grains appear one after another and one can picture the track in three dimensions.

![Figure 2.17: Schematic view of a microscope for emulsion scanning. The data flow between the various components involved in automated track finding is indicated by the arrows. A photograph of the real setup in the CERN scanning laboratory is shown in Figure 4.2.](image)

2.9.4 Automatic track recognition

Figure 2.17 also indicates the data-flow in the automatic scanning. In an automatic scanning station, the stage and objective movement is controlled by a computer, the human peering through the objective is replaced by a digital camera, and the images are processed by computers. To reconstruct tracks, a set of images at a fixed position...
A pattern recognition algorithm is applied to this tomographic image set to reconstruct the tracks. The results are usually stored in some kind of database. The Nagoya FKEN laboratory has developed hardware to perform the pattern recognition using FPGAs and processors. The original hardware was built specifically to look for a track at a given angle and was therefore called track-selector [203, 213]. The hardware takes a tomographic set of 16 images up to a depth of 100 μm in the emulsion. These images are preprocessed with a digital filter to enhance the contrast between grains and background and a threshold cut is applied to binarize the images. The track finding algorithm can be cursorily summarized as shifting and summing. First, each of the binarized images is shifted by the reverse of the displacement corresponding to the predicted direction. Then, the summed image is obtained by counting for each pixel the number of shifted images in which this pixel is above threshold. If a track is present, it will show up in the sum as a distinct peak above a flat background. The peak’s height reflects the average grain density. Because of uncertainties in the predicted track direction, the hardware repeats the shifting and summing for each point in a grid of angles that covers a given angular acceptance.

The track selector can also be used to look for all tracks in the emulsion within a certain (wide) slope range by simply trying out all shifts. For a view of 150 μm × 120 μm and slope acceptance of 400 mrad × 400 mrad, the early version of the track selector would take more than 30 seconds. The latest version used by CHORUS takes only 0.3 seconds. This increase in speed was achieved using a 120 Hz CCD camera and parallel processing hardware. The track-finding efficiency is found to be above 98% for track slopes less than 400 mrad [214].

2.10 Reconstructing tracks and vertices in emulsion

In this section, the way neutrino interactions are located and reconstructed in the emulsion is explained. The required plate-to-plate alignment for this is discussed first, followed by an explanation of the scan-back procedure. Finally, the reconstruction of the event, including secondary vertices, using the net-scan technique is described. The net-scan technique was originally developed for the DONUT experiment (see section 1.1.3) and then used for analysis of the CHORUS emulsion. More details about the vertex location and reconstruction in the emulsion can be found in Refs. 214–216.

2.10.1 Alignment

The scanning predictions must be located inside the emulsion which requires a precise alignment between the emulsion interface sheets and the target trackers, see section 2.4.4. The 1 mm diameter black dots left by the X-ray guns (section 2.4.4), shown in Figure 2.18, provide an initial alignment between the target trackers and the three interface plates. The position of the X-ray guns is known from a survey. The initial alignment is refined by scanning a set of about 200 well reconstructed predictions. For this initial set, single isolated muons with a slope of about 200 mrad are selected. The slope requirement is necessary for determining the longitudinal alignment. Because of the uncertainty of the initial alignment of about 0.5 mm, an emulsion area of 1.5 mm × 1.5 mm around each prediction is scanned. A new alignment can then be made by minimizing the distances between found tracks and their predictions. The parameters of the alignment are a
perpendicular and longitudinal shift of the interface sheet (either CS2 or CS1) and a $2 \times 2$ matrix representing rotations and linear deformations. This new alignment has a typical residual of about 300 $\mu$m. All predictions are then scanned using this alignment and a scanning area of 1 mm $\times$ 1 mm. The same procedure is applied to determine the alignment between the three interface sheets. For this inter-plate alignment, the typical uncertainty is about 150 $\mu$m. The scanning area is therefore reduced to 500 $\mu$m $\times$ 500 $\mu$m on the special sheet.

The emulsion target is made out of stacks of plates. Following tracks from plate to plate in a stack requires precise alignment between the plates. This alignment is different for the two years in an exposure because the stack has been repacked after the first year for changing the special sheet. Furthermore, the alignment has to take into account that the target plates are flexible and deform easily because of their very thin base (90 $\mu$m). This flexibility is illustrated in the photograph of Figure 2.18.

The special sheet contains two sets of reference points. The X-ray marks which connect it with CS1 and a set of printed reference points, called fiducials, which are also
printed on each target plate. The fiducials are a grid of 50 μm diameter dots and dots with a 200 μm diameter ring, spaced 19.5 mm apart. Before development, the mask with fiducials is aligned with each special and target sheet in one corner and along two axes, the sheet is flattened by vacuum and then exposed using a flash of light. Because of the flexibility of the target emulsion sheets, the accuracy of this alignment is about 1 mm.

To get a better alignment between the sheets, six to eight track maps are scanned on each sheet. A track map is an area of 3 mm × 3 mm centered in a square of 4 fiducials. The emulsion is then scanned to reconstruct all tracks within this area. Matching the extrapolated tracks between the maps, yields a shift of the fiducials between each plate. For each position on the plate, a local alignment is obtained from the shifts of the three nearest maps. This alignment has a typical uncertainty of about 20 μm.

Pattern recognition software on the scanning microscopes is used to locate the fiducials and to reconstruct their central position. The fiducials are often damaged such that parts of the ring or the dot is missing. Furthermore, the radii of the dot and ring vary with the light intensity and the applied gray-level cut. A picture of several fiducials with the reconstructed central position indicated by white markers is shown in Figure 2.19. The pattern-recognition algorithm uses an edge-detect filter followed by a minimum-spanning-tree to collect points belonging to the same edge. The central position is then determined from calculating circle solutions to maximally spaced sets of three points on the same edge. As can be seen from Figure 2.19, the algorithm is capable of locating the fiducial marks reliably, also when part of the fiducial is missing or when edges are connected by black streaks on the emulsion.

2.10.2 Interaction location by scan-back

Emulsion data taking for a single module starts with the search for all scanning predictions within an area of 1 mm² centered around each prediction on one or both of the changeable sheets. Emulsion tracks are selected as candidates to be followed further upstream on the basis of an improved alignment. This alignment is obtained by finding the best match of the full set of pairs consisting of a prediction and the track found in the emulsion. The process of following tracks upstream through the stack of emulsion plates is drawn schematically in Figure 2.20 and called scan-back. The introduction of the interface sheets helps in matching predictions to emulsion tracks and reduces the pick-up of accidental background because of their low track density. On the interface-sheets (CS and SS), the most selective parameter for candidate matching is the direction, because of the accurate base-slope measurement (section 2.4.2). However, this implies that four track segments must be found on the two interface-sheets, namely the upstream and downstream side of the CS and the SS.

The found tracks are followed upstream from one plate to the next, where the scanned area reduces as the position resolution from the measured emulsion tracks and the plate alignment improves. Within the stack of target plates, the scanning area is reduced to a square of 50 μm × 50 μm. Due to distortion, the direction resolution of the target plates is only approximately 10 mrad. The matching inside the stack of target plates is therefore dominated by the position resolution. After the precise alignment between candidates and predictions from the previous plate, the position resolution is about 5 to 10 μm. Within the candidate-selection area of typically 30 μm × 30 μm, there are usually no other (unrelated) candidates. In case a second candidate is found, both tracks are followed.
In the scan-back of the target plates, the images are taken in the 100 μm upstream surface of the plate. If the track is not found in this upstream layer, something must have happened inside that plate. The vertex plate is defined as the first (most downstream) of two consecutive plates where the scan-back track is not found. The requirement for two misses suppresses scanning inefficiencies quadratically. The event-location process is described in detail in Refs. 214, 215. The name ‘vertex plate’ only indicates that the scan-back track disappeared in that plate. The most likely reason is indeed that a neutrino interaction took place in that plate. However, the scan-back track could also have changed direction or originate from a secondary interaction in that plate.
Figure 2.20: Illustration of the scan-back procedure in which a track is followed upstream from plate to plate. Only the most upstream 100 μm thick layer of emulsion is scanned around the predicted position. Track candidates found in the emulsion are indicated with thick black boxes. The scan-back procedure stops when a predicted track is not found in two consecutive plates, indicated by the empty boxes and crosses. The first plate where the track was not found is considered the vertex plate. The predicted track either originates in this plate or changes direction inside it.

In the net-scan procedure (section 2.10.3), volumes in eight plates around the disappearance point of the track are scanned to find all event-related tracks. The light-gray areas indicate these volumes. Each volume is 1500 μm wide, 100 μm thick, and centered on the disappearance point of the scan-back track, corrected for the beam slope.
2.10.3 Vertex reconstruction with net-scan

Once the vertex plate is identified, a detailed analysis of the emulsion volume around the vertex position is made. In this procedure, known as net-scan, track segments within a given volume and with a given angular acceptance are reconstructed. The scanning is done on several consecutive plates around the vertex plate. In the CHORUS experiment, the net-scan volume spans eight emulsion plates, corresponding to a length of 6.3 mm along the beam direction. It is 1.5 mm wide in each transverse direction. The eight plates contain the vertex plate itself, the plate immediately upstream, and the six plates downstream of the vertex plate. As the track-selector hardware can only scan layers of 100 μm thickness, the upstream surfaces are scanned. The plate upstream of the vertex acts as a veto for passing through tracks. The six plates downstream of the vertex act as decay volume and are used to detect the tracks of the decay daughters. The scanning area on the vertex plate is centered on the extrapolated transverse position of the scan-back track. On the other plates, the area is shifted with the neutrino beam slope (42 mrad). The angular acceptance for tracking corresponds to a cone with a half-opening angle of 400 mrad.

The first step of the vertex reconstruction is the selection of only those segments belonging to the neutrino interaction out of the large number of track segments found. A coarse plate-to-plate alignment is determined by comparing the pattern of segments in a plate with the corresponding pattern in the next upstream plate. With this coarse alignment each segment found on one plate is extrapolated to the next plate where a matching segment is looked for within a cone of 20 mrad and an area of about 4 μm. The size of the matching area corresponds to 3σ of the alignment resolution. To recover scanning inefficiencies, if no track is found on the next plate, the matching is tried one plate further upstream. A second and more accurate inter-plate alignment is performed using tracks passing through the entire volume after the connection of all matched segments. These tracks are mainly coming from muons associated with the neutrino beam or charged-particle beams upstream of the experimental area. After this alignment, the distribution of the residual of the segment positions with respect to the fitted track has a RMS width of about 0.45 μm. At this stage, typically about 400 tracks remain in the volume. The majority of these are tracks of low-momentum particles (mainly Compton electrons and δ-rays) with momentum less than 100 MeV/c. These background tracks are rejected with a criterion based on the χ² of a straight-line fit to the track segments. The final step is the rejection of all tracks not originating from the scanning volume. After this filtering, the average number of tracks originating in the scan volume is about 40.

Figure 2.21 shows an example of net-scan data and the result of a simplified vertex search. It shows how a vertex can be located among all the track segments by simply requiring a small impact parameter. The real net-scan analysis is more sophisticated and also uses segments reconstructed on a single plate, for example a short-lived particle decaying in the next plate.
Figure 2.21: Example of a net-scan result. (a) Result of a net-scan on seven plates and 1 mm$^2$ showing more than 10,000 track segments. (b) Idem, but requiring at least three connected segments, yields 222 multi-segment tracks. (c) Vertex consisting of five tracks that cross each other within a 1 μm diameter volume. All scales in the figures are in micrometer, showing the excellent resolution of emulsion.