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TIME OF FLIGHT MEASUREMENTS WITH HADRONIC SHOWERS

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Abstract

We present the results obtained from measurements of the arrival time of hadronic particles in a segmented scintillator-uranium calorimeter which was equipped with dedicated time of flight scintillator hodoscopes in depths of 0.75, 1.5, 2.25, 3.0 and 4.5 λ_{int} . Gaussian shaped time resolutions with $\sigma \approx 90$ ps were obtained with π^- beams of 30 GeV/c and 70 GeV/c momentum. We discuss to what extent non-gaussian tails can be removed while keeping a reasonably high efficiency.

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gain instabilities of each individual read-out channel with good accuracy. The fifth module is similarly constructed, except that it contains 30 layers of 3.2 mm thick DU plates and 5 mm thick scintillators.

To make room for the insertion of the TOF scintillator hodoscope layers, we have removed two planes of DU absorber and scintillator plates in the center of the first two calorimeter modules. Identical TOF hodoscopes (see next section) have also been placed in the 3 gaps between the first four modules. The arrangement of the TOF counter hodoscopes within the calorimeter is shown in figure 1.

The energy resolution of the calorimeter was not affected by these modifications: We observed the same sampling term, $\sigma/E \cong 35\%/\sqrt{E/\text{GeV}}$, as reported in refs. [8, 10].

2.2 Time-of-Flight scintillator hodoscopes

Fast Bicron 404 scintillator material was used for the construction of the 5 TOF hodoscope planes. Each plane was built from 8 identical scintillator bars, which are 3 cm wide, 1 cm thick, and 75 cm long. Bent acrylic light guides of matching crosssectional dimensions and a length of about 50 cm were glued to either end of each scintillator. Every scintillator bar with its attached light guides was individually wrapped in successive layers of white reflecting paper, aluminum foil, and opaque scotch tape. Five sets of eight scintillator bars were then assembled to form the 5 TOF planes, as shown in figure 1. The cracks between adjacent scintillators (due to the wrapping material) were about 1.4 mm. The completed TOF planes had a total width of about 25 cm. These TOF planes were

Figure 1: Arrangement of the TOF scintillator hodoscope inside the calorimeter.

inserted vertically into the calorimeter, leaving an ~ 17.5 cm wide area uncovered on each side. The lower ends of the scintillator bars were aligned flush with the bottom of the calorimeter, thus letting the scintillators extend 15 cm beyond its top (cf. fig. 1). This was done to steer a beam of minimum ionizing particles directly at individual TOF scintillators (bypassing the calorimeter) for calibration purposes. For the read-out of the scintillation light we used H1949 photomultiplier assemblies from Hamamatsu, each of which contains a 2" diameter photomultiplier of the type R1828 and includes voltage divider and magnetic shielding. No grease or glue was used for the coupling of the photomultipliers to the light guides.

2.3 Trigger and start counters

A beam telescope was placed about 3 m upstream of the calorimeter with the embedded TOF hodoscopes. Beam triggers were defined by the three-fold coincidence $B_1 \cdot B_2 \cdot S$, where B_1 and B_2 are scintillation counters of 1 cm thickness and with a transverse overlap of 3×7 cm², and S is the start counter [7] of dimensions $1 \times 1 \times 1$ cm³. For minimum ionizing particles, the start counter yields a timing resolution of $\sigma = 47$ ps for the mean time of the pulses from the two photomultipliers. Care was taken in the timing adjustments of the inputs to the trigger coincidence, $B_1 \cdot B_2 \cdot S$, to ensure that the timing of the output pulse was strictly correlated with the S input signal. The acceptance of a trigger coincidence was further subjected to an anti-coincidence with the signals from any of four veto counters, which were placed just downstream of the light guides of the B_1 , B_2 , and S counters. This was done to prevent beam-halo particles from triggering via the production of Čerenkov light in the light guides.

2.4 Electronics

Every photomultiplier base circuit provided a pair of equal analog signals. For each of the 80 TOF channels, one of these was connected to a LeCroy 4300B FERA ADC for recording the pulseheight. FERA ADC's provide 11 bits dynamic range. The other signals were fed into home made constant fraction discriminators [7]. The discriminator outputs were fed into LeCroy TFC 4303 time to charge converters, which were connected to another set of FERA ADC's. Every TFC/ADC pair acts like a time to digital converter (TDC), with a nominal conversion factor of 50 ps/count.

3 TEST BEAM MEASUREMENTS

The measurements were performed in the X1 beam line of the CERN SPS. The calorimeter with the embedded TOF hodoscopes was mounted on a moveable stand such that any arbitrary position on the surface of the calorimeter could be chosen as point of impact for the beam. The energy calibration of the calorimeter was done with a 30 GeV/c electron beam. Each of the 12 cells in all 5 calorimeter modules were calibrated individually.

For the time of flight measurements we used beams of negatively charged pions of 30 and 70 GeV/c momentum. All data described in the remainder of this paper were obtained with the beam pointing at the center of the calorimeter. Two different settings

of the discriminator thresholds in the TOF channels were used. Initially, the thresholds were set to 30 mV, corresponding to an energy deposition of ~ 0.5 mip. With this setting, and with the beam turned off, the counting rate of single TOF channels was of the order of 10^4 sec^{-1} due to uranium noise signals. To reduce the probability for random TDC stops due to uranium noise pulses, most data were taken with thresholds set to ~ 2 mip. With this higher setting the counting rate was reduced to about 10 sec^{-1} . In the following sections we will describe the results obtained using the low thresholds with a π^- beam of 70 GeV/c momentum, and those obtained with the high thresholds at beam momenta of 30 and 70 GeV/c. We refer to these data sets from here on as LOW70, HIGH70, and HIGH30, respectively.

The analysis of the data presented below has been restricted to hadronic showers which are fully contained in the calorimeter, by applying the following cuts on the total energy:

$$E_{tot} > 57 \text{ GeV} \quad \text{for the 70 GeV/c settings}$$

$$E_{tot} > 24 \text{ GeV} \quad \text{for the 30 GeV/c setting.}$$

These cuts suppress pions penetrating deeply into the calorimeter before undergoing a hadronic interaction. The arrival time of such pions, which deposit less energy in the calorimeter due to substantial longitudinal leakage, would not be well measured because of the lack of sufficient TOF hodoscope planes in the second half of the calorimeter. At the

Figure 2: Energy spectrum observed in the HIGH70 data set. The shaded area corresponds to the cut described in the text. The peak at low energies is due to the beam contamination with muons.

same time, these cuts effectively remove muon events. The pion beams were contaminated with 10.2% (1.8%) muons in the 70 (30) GeV/c settings. As an example, the observed energy spectrum and the cut applied for the case of the HIGH70 data set are illustrated in figure 2. A small electron contamination of 0.2% (2.6%) was removed with the help of shower profile variables as described in reference [8]. About 96% of all pions survive the above selection criteria.

4 DATA ANALYSIS AND RESULTS

4.1 Calibration of the TOF hodoscope counters

Several calibration steps were applied to all TOF channels. First, the raw pulseheight information, as measured by the ADC's, was converted to a common scale. The conversion factor between ADC counts and the most probable energy loss of minimum ionizing particles (mip) was measured channel by channel by sending the beam directly into the section of the TOF scintillators which extends 15 cm beyond the top of the calorimeter. The mip peak was typically found at ~ 25 ADC counts after pedestal subtraction. Assuming linearity of the ADC, the full 11 bit range therefore covers energy depositions up to about 80 mip.

For the timing channels, the following steps were carried out: TDC calibration, time-walk correction, and t_0 calibration. The TDC's, which have a nominal conversion factor of 50 ps/count, were calibrated with the help of a 100 MHz quartz oscillator, providing precise stop signals at intervals of $n \times 10$ ns, where $n = 1 \dots 16$. In the linear range between 200 and 1800 counts, deviations from the nominal conversion factor were found to be ≤ 1 ps/count. Appropriate cable delays were used for all stop signals to ensure that genuine coincidences with the start signal lie in the linear range between 500 and 700 TDC counts.

The time-walk effect refers to the systematic dependence of the observed TDC stop on the pulseheight of the analog signal. With the use of constant fraction discriminators, this effect is largely reduced, but corrections of the order of 200 ps are still necessary in the full dynamic range from 0 to 80 mip (cf. also ref. [7]). As an example, the time-walk effect of one channel is shown in figure 3. In order to correct for the time-walk effect, fits of the data as shown in the scatter plot in figure 3 to a truncated fourier series

$$TDC_{timewalk}(ADC) = \sum_{k=0}^{k_{max}} a_k \cos(\omega_k ADC)$$

have been performed. Here, a_k are free parameters and $\omega_k = 2\pi k / (ADC_{max} - ADC_{min})$, where ADC_{min} , ADC_{max} are the lower and upper end of the observed pulseheight distribution for a given channel. Good results were obtained with the value $k_{max} = 10$. Due to low statistics, $ADC_{max} - ADC_{min}$ was relatively small for the outer counters. In these cases a lower value of k_{max} was chosen to limit the highest occurring frequency ω_k .

The purpose of the t_0 calibration was to correct for different cable and electronic delays, such that the same time of flight for speed of light particles would be measured by all channels. This calibration was carried out independently for each of the three data sets, LOW70, HIGH70, and HIGH30. We first define t_0 as the location of the peak in the TDC distribution of each individual channel. Figure 4 shows these distributions for two

Figure 3: Time-walk effect using constant fraction discrimination of a central scintillator bar in the 2nd TOF plane. Data are from the LOW70 data set.

different channels and for all three data sets. One notes that the width of the peak for a scintillator at the edge of a TOF plane is significantly larger ($\sigma \approx 700$ to 800 ps) than that of a scintillator in the center ($\sigma \approx 260$ ps). For the outer scintillator, this geometrical effect reflects the wider distribution of path lengths on which prompt secondary particles travel from their point of creation to the scintillator. In our analysis, the arrival time of a beam particle in the calorimeter was defined by the time of the very first hit in the TOF hodoscopes (see section 4.3). The time resolution resulting from this definition was optimized in a second step by choosing improved t_0 values corresponding to the position of the rising edge in the TDC distributions.

4.2 The shower development

It is interesting to interpret the single-channel TDC distributions shown in fig. 4 in terms of the time development of hadronic showers in a uranium-scintillator sampling calorimeter. Extensive experimental [11] and Monte-Carlo [12] studies have established the time dependence and fractional contribution to the visible energy from all relevant processes. According to ref. [11], on average 50% (60%) of the visible energy are prompt at $20 \text{ GeV}/c^2$ ($100 \text{ GeV}/c^2$) incident π^- energy. This prompt energy is mostly due to the electromagnetic shower component induced by π^0 -decays. A delayed shower component comprising 43% (35%) of the signal is seen with an exponential decay time of ~ 9 ns. This energy originates primarily from protons recoiling in the scintillator after having been struck by a neutron released in the uranium absorber. The small remaining fraction

Figure 4: TDC distributions of a central (a), and an outer (b) counter in TOF plane 2. Occupancy = $\# \text{ entries in histogram} / \# \text{ events in data sample}$.

of the total visible energy is observed with time constants of 120 and 1160 ns, and is attributed to (n,γ) -capture reactions of ^{238}U .

Our TDC distributions shown in fig. 4 allow a detailed view of the shower as it develops during the first ~ 45 ns. One should keep in mind, however, that our TDC distributions do not represent energy deposition as a function of time, and thus detailed comparisons with the results of ref. [11] may not be appropriate. The prompt shower component is readily associated with the prominent peaks seen in fig. 4. A delayed shower component is seen as tails towards later TDC stops, which have an approximately exponential shape. The slopes of these tails are correlated with the pulseheights: Fitting a single exponential we find a decay constant of 6 ns for the case of the LOW70 data set, whereas the HIGH70 and HIGH30 data sets both yield time constants of 3.5 ns. For all

three data sets the observed time constants are independent of the position of the TOF scintillator within the calorimeter.

Comparing figures 4a and 4b, it looks as if scintillators at the edge of a TOF plane see the delayed shower component with larger probability. Delayed hits in central scintillators are, however, seen with reduced efficiency due to the large prompt shower component hitting these counters. To be more quantitative, we have listed in fig. 4 the occupancy of each channel shown. The values give the ratio of the number of events visible in a histogram to the total number of events in the corresponding data sample. When correcting for the drop in efficiency due to the large occupancy caused by the prompt shower component one finds roughly equal intensities of the delayed component in all scintillators of a given TOF plane. Thus the delayed shower component must be spread rather uniformly, in contrast to the prompt component (a similar conclusion was obtained in ref. [11]).

4.3 Time resolution and effectiveness of tail removal

After applying all the calibration steps described in section 4.1 we scan, for each event, all 40 TOF counters to find the earliest hit. The time of a hit is defined as the mean time obtained from the two photomultipliers viewing the same scintillator. The time of the first hit, t_{1st} , is taken to be the arrival time of the beam particle in the calorimeter. Other choices for characterizing the starting time of the shower, such as the mean time of the first few hits, have been considered, too. Such alternate variables may result in slightly better time resolutions, but in general show similar, or worse, non-gaussian tails in comparison to t_{1st} distributions. We are restricting the following discussion to the use of the t_{1st} variable only, because of its simplicity and ease of interpretation.

First hit distributions for all three data sets are shown in figure 5. The non-hatched histograms were obtained when only the energy leakage cut described in sect. 3 was applied. Common to all three distributions is the large peak in the center, and the exponential tail on the early side of the peak. The LOW70- t_{1st} distribution differs in two respects from those obtained with the high discriminator thresholds: First, there is a flat background at early times, due to random uranium noise pulses which sometimes cause a hit in the TOF counters before the arrival of the beam particle. Second, one observes essentially no tail towards delayed times. This latter fact implies that the probability of getting at least one hit from the prompt shower component is essentially 100 % in this data set¹⁾. In contrast, the HIGH70- and HIGH30- t_{1st} distributions show tails towards late times which account for approximately 0.1% and 1% of the events, respectively.

Both, the early and late tails in the t_{1st} distributions can be reduced substantially with appropriate cuts, as shown in fig. 5 by the hatched and cross-hatched distributions. In the following, we will first deal with the suppression of the late events, and later discuss the early tails.

Events with a delayed first hit are in general associated with a smaller number

¹⁾ Strictly speaking, this statement is only valid for about half of the statistics, since only 52.8% of the pions have their primary shower vertex within the first $0.75 \lambda_{int}$ of the calorimeter. The remaining 47.2% of the pions penetrate through the first TOF plane just as minimum ionizing particles (like muons), thereby giving rise to a “prompt” hit not originating from the shower.

Figure 5: t_{1st} distributions for the three data sets LOW70, HIGH70, and HIGH30. The cuts applied to suppress the tails are discussed in the text. The smooth curves show the result of gaussian fits to the cross-hatched histograms.

of hits in the TOF hodoscope than events with a prompt first hit. This can be seen in figure 6, which shows distributions of the number of hits for all events, and for events with a delayed first hit, respectively. Comparing the number of hits distribution of the LOW70 data to that of the HIGH70 data, one concludes that on average almost half of the hits are associated with pulseheights < 2 mip. In both high threshold data sets a few events were even lost because no hits at all were observed in the TOF hodoscopes. Events with a late first hit can be removed rather effectively by rejecting events associated with a small number of hits (cf. hatched histograms in fig. 5). However, a certain fraction of “good” events is then rejected, too. Figure 7 illustrates the trade-off between the degree of tail removal and the loss of detection efficiency. It is evident that, with the limited number of timing channels within the calorimeter, the degree of tail removal achievable in the case of the HIGH30 data set has to be balanced with the efficiency loss one can tolerate.

Figure 6: Distributions of the number of hits in the TOF hodoscope.
Open symbols correspond to events with $t_{1st} > 0.4$ ns.

Figure 7: Fraction of events with a delayed first hit versus loss in efficiency as a function of the minimum number of hits required (indicated by digits next to the data points).

The tail at early times remains unchanged when a minimum number of hits is required. One finds, however, that in almost all those events there is a second hit at the “correct” time. This can be seen in a scatter plot of the times of the first two hits, $t_{2\text{nd}}$ versus $t_{1\text{st}}$, as shown in fig. 8. It is tempting to think that one might just skip the first hit in those events, and associate the arrival time of the beam particle with the time of the second hit. But, unfortunately, it has proven to be impossible to devise an unbiased method for this purpose, which does not adversely affect the width of the peak or the tail remaining at late times. The only way to suppress the early tail is therefore to reject events with a large time difference $t_{2\text{nd}} - t_{1\text{st}}$. Distributions of this time difference are shown in figure 9. The cuts which were applied to arrive at the cross-hatched histograms in fig. 5 are also shown.

Table 1 summarizes the efficiencies of the cuts applied to suppress the tails, and gives the gaussian widths of the final $t_{1\text{st}}$ distributions.

	Low70	HIGH70	HIGH30
cut	$\times 10^3$ events	$\times 10^3$ events	$\times 10^3$ events
$E_{\text{tot}} > 24 \text{ GeV}$			314 (=100%)
$E_{\text{tot}} > 57 \text{ GeV}$	346 (=100%)	302 (=100%)	
# hits ≥ 5		285 (=94.4%)	225 (=71.6%)
$t_{2\text{nd}} - t_{1\text{st}} < 0.20 \text{ ns}$	327 (=94.4%)		
$t_{2\text{nd}} - t_{1\text{st}} < 0.25 \text{ ns}$		276 (=91.2%)	
$t_{2\text{nd}} - t_{1\text{st}} < 0.35 \text{ ns}$			222 (=70.5%)
σ of gaussian fit	$82 \pm 2 \text{ ps}$	$87 \pm 2 \text{ ps}$	$92 \pm 2 \text{ ps}$

Table 1: Number of events surviving the cuts applied in the analysis, and widths of the gaussian fits to the final $t_{1\text{st}}$ distributions. Errors of the gaussian widths are estimated from their dependence on the choice of cuts.

Figure 8: Scatter plot of t_{2nd} versus t_{1st} . The dashed line indicates the cut used to reject the early tail in the t_{1st} distribution.

Figure 9: Distributions of the time difference between the first and second hit. Full symbols: All events having at least 5 hits and surviving the energy leakage cut. Open symbols: Same as full symbols, but in addition rejecting events belonging to the early tail, $t_{1st} < -0.4$ ns. The smooth curves are drawn to guide the eye.

5 SUMMARY AND CONCLUSIONS

The goal of this study was to evaluate the feasibility of time of flight measurements of long-lived, neutral hadrons by measuring their arrival time in a calorimeter. We have reported the results obtained with negative pion beams impinging on a uranium-scintillator calorimeter, which was equipped with dedicated time of flight hodoscopes at depths of 0.75, 1.5, 2.25, 3.0 and 4.5 interaction lengths. For 70 GeV/c pions, we find that the probability of detecting at least one prompt hit in the TOF counters is essentially 100% when discriminator thresholds below 1 mip are used. With thresholds of 2 mip, this probability drops slightly below 100%, which becomes visible in the form of a non-gaussian tail towards late times. For 30 GeV/c pions and 2 mip thresholds, the probability of observing ≥ 1 prompt hit is about 99%.

Methods allowing to substantially reduce the non-gaussian tails have been presented in detail. Very small tails, far below 1% in relative intensity, are left in our final timing distributions. To avoid losses of detection efficiency at low energies one should however work with discriminator thresholds < 1 mip, and perhaps use more densely spaced timing layers.

Gaussian fits to the timing distributions yield widths of $\sigma = 82$ ps to $\sigma = 92$ ps, depending on the average number of prompt hits detected in the corresponding data set. We conclude that time of flight measurements of hadronic particles with a calorimeter are feasible, provided that timing channels are densely distributed within the calorimeter.

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