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Laser & Cosmic-Ray Calibration of the CLAS TOF System

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1 INTRODUCTION

The CLAS Time-of-Flight (TOF) measurement system consists of 342 scintillator counters. The counters are located at approximately 5 m from the target and cover a large fraction of the 4 π solid angle. In order to distinguish Kaons from pions, time resolution $\sigma \leq 180$ ps is required. The overall time resolution depends on the intrinsic resolution of each counter and the accuracy with which time-walk corrections and calibration constants can be determined. Here we determine the combined effect of the intrinsic resolution including the time-walk corrections obtained with laser calibrations.
This note reports on the studies aimed at determining and measuring these three contributions. We begin by describing the calibration constants that are required for the TOF system and then the procedure we followed for measuring them for one plane of the forward-angle CLAS TOF counters.

2 BACKGROUND

We begin with the raw data buffer as described in [1]. The data for the TOF scintillators are recorded in the SC banks, with each sector specified by the bank number NR, which runs from 1 to 6. The contents of the data bank represents all information available for each scintillation counter:

ID T^L A^L T^R A^R , where ID = 1,2,...48

The index ID specifies the scintillator number in each sector [1]. The raw time recorded by the LeCroy 1872A FASTBUS TDC is denoted by T and the LeCroy 1881M ADC raw pulse height information is denoted by A. The units of these data are counts, nominally corresponding to 50 ps for the TDCs and 50 fC for the ADCs. The supercripts L and R refer to left and right photomultiplier tube signals respectively. However, for simplicity the superscripts will often be omitted when the discussion applies equally to either photomultiplier.

[1]The last 18 scintillators at large angles in each sector are electronically summed in pairs to produce nine channels of electronics, thus reducing the actual number of channels per sector from 57 to 48.

The constants required for each scintillator are stored in the SC calibration bank, having the following (preliminary) structure:

ID	c_0^L	c_0^R	c_1^L	c_1^R	c_2^L	c_2^R	w_1^L	w_1^R	w_2^L	w_2^R	w_3^L	w_3^R
	P^L	P^R	M_o^L	M_o^R	λ^L	λ^R	v_{eff}^L	v_{eff}^R	...			

The TDC calibration is determined with c_0 , c_1 and c_2 . Time walk correction constants are w_1 , w_2 and w_3 , and P is the ADC pedestal. The constant M_o corresponds to the pulse of a minimum-ionizing particle (MIP) traversing the center of the scintillator. In the sections below the constants are defined more precisely by function. The attenuation lengths λ and effective propagation in the scintillator v_{eff} will be addressed in a later document.

2.1 Offsets

The relative time offsets from PMT to PMT, and scintillator to scintillator is perhaps the most difficult constant to determine for the entire system. As transit times in the PMT, cable lengths, transit times through the electronics vary from channel to channel, the absolute comparison of times is determined in several steps. The final offset is given by the sum of several terms which include the initial TDC calibration constant ($c_0{}^{TDC}$), relative time between right and left PMTs ($c_0{}^{LR}$), relative time between adjacent scintillators ($c_0{}^{LR}$) and other terms not relevant for this study. It should be understood that the final constant c_0 will be given by

$$c_0 \quad = \quad c_0{}^{TDC} + c_0{}^{LR} + c_0{}^{btb} + ... \tag{1}$$

where each term relates a relative transit time through the data or calibration path.

2.2 TDC Calibration

To convert the raw TDC data to time units (ns) we use a quadratic fit, although measurements of the TDCs indicate that linear fits are comparable representations of the data (fig. 1):

$$t \quad = \quad c_0{}^{TDC} + c_1\, T + c_2\, T^2 \tag{2}$$

2.3 ADC Calibration

The pulse height must be corrected for the pedestal values. To convert to energy deposition, they must be normalized to a standard such as the pulse height of a normally incident minimum-ionizing particle M_o at the center of the scintillator:

$$a \quad = \quad \frac{(A - P\ )}{M_o} \tag{3}$$

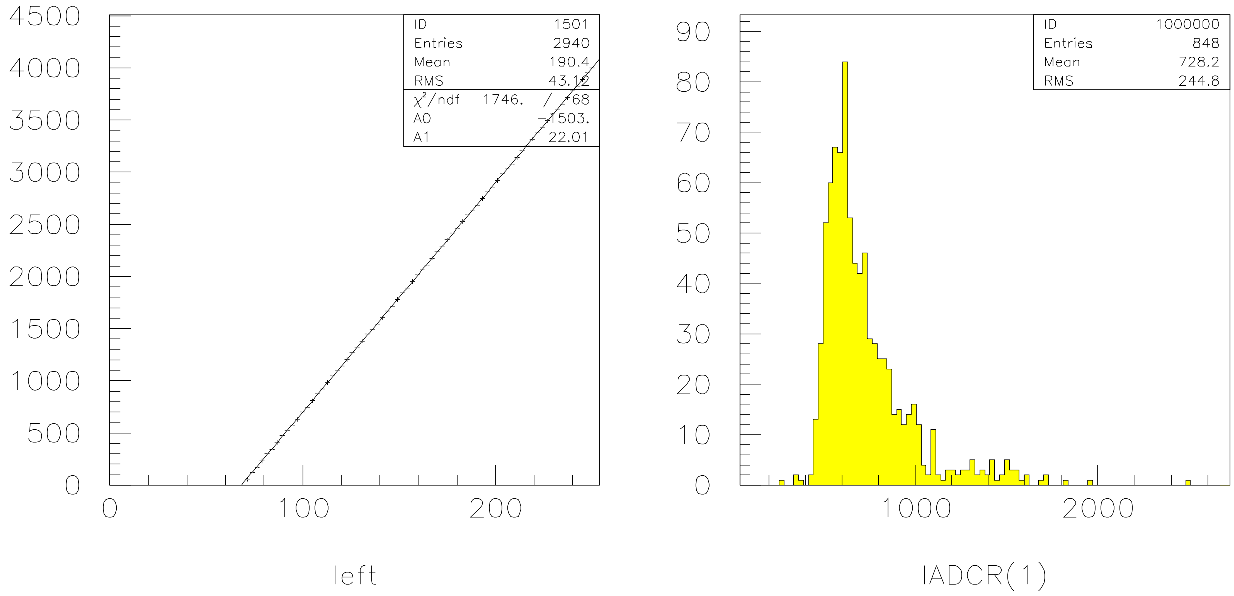

Figure 1: a) Linear fits for the conversion of TDC counts to time in ns. b) Pulse height spectra of a PMT for particles traversing the reference counters.

2.4 Time-Walk Corrections

The measured times correspond to leading-edge LeCroy 2313 discriminator pulses. To correct for time-walk we perform software corrections of the form

$$\mathrm{t}_w = t + f_w(A \rightarrow \infty) - \mathrm{f}_w(A) \tag{4}$$

The function $\mathrm{f}_w(A)$ should be a monotonically decreasing function of A, since the measured time is late for a pulse with finite rise time. This parametrization has the desirable limit that t and t_w are equal for large pulses. Note that the correction is a function of the unnormalized ADC value A, since time walk is a function of the actual pulse size, not the amount of energy deposited in the scintillator. Initial fits to data indicate that the following form for the correction function $\mathrm{f}_w(A)$ is robust and adequately describes the data for the forward-angle TOF scintillators:

$$\mathrm{f}_w(A) = \mathrm{w}_1 + \frac{\mathrm{w}_2}{(A - \mathrm{P}\ )^{\mathrm{w}_3}} \tag{5}$$

We note that the value of the fitted parameters depends on the discriminator threshold, which was fixed at 15 mV during this study.

3 INSTRUMENTAL PROCEDURE

3.1 Method

We adopted the following series of procedures to achieve our purpose:

- ADC Pedestal determination.
- Gain-Balancing and -Matching of the scintillator bars.
- Determination of the time-walk correction functions.
- Measurement of the bars time and position intrinsic resolutions.
- Determination of left-right offset constants.
- Determination of the bar-to-bar offset constants.

We describe in the following the tools and material we used.

3.2 The scintillators counters

The forward-angle TOF counters under study are made of Bicron BC-408 scintillator. They are 5.08 cm thick, 15 cm wide. They vary from 32 cm to 360 cm in length. Glued to them are light guides on both ends. EMI Electron Tubes 9954A PMTs collect the light.

3.3 Data acquisition

The signals from the PMTs are discriminated through LeCroy 2313 modules. The typical threshold value used throughout this study is 15 mV. We use Lecroy 1872A FASTBUS TDC and Lecroy 1881A FASTBUS ADC modules for the analog-to-digital conversions. ADC and TDC values are then read, stored in BOS/CODA format, transmitted through Ethernet and written to disk. An on-line software trigger [?] allows the selection of events before writing to disk. For example, we often require a specific number of hits (2, 3 or 4 hits according to the study) to keep the event. The number of hits corresponds to the number of scintillators in the data bank. Events are stored in an Hbook Ntuple format and the data analysis is carried out with PAW. All the read-out hardware will be part of the final CLAS data acquisition system.

3.4 Trigger considerations

We used two types of data sets: laser and cosmics.

3.4.1 Laser data

A laser calibration system was used to determine the scintillator time and position resolution and time-walk corrections. The nitrogen laser generates light at 337.1 nm which is transported to the center of each scintillator via UV-transmitting optical fibers. The UV light excites the scintillator and generates signals which are very similar to those produced by minimum-ionizing tracks. Before entering the fiber, the light is split and 10% illuminates a laser diode, which is used as a stable trigger signal for these data. After the

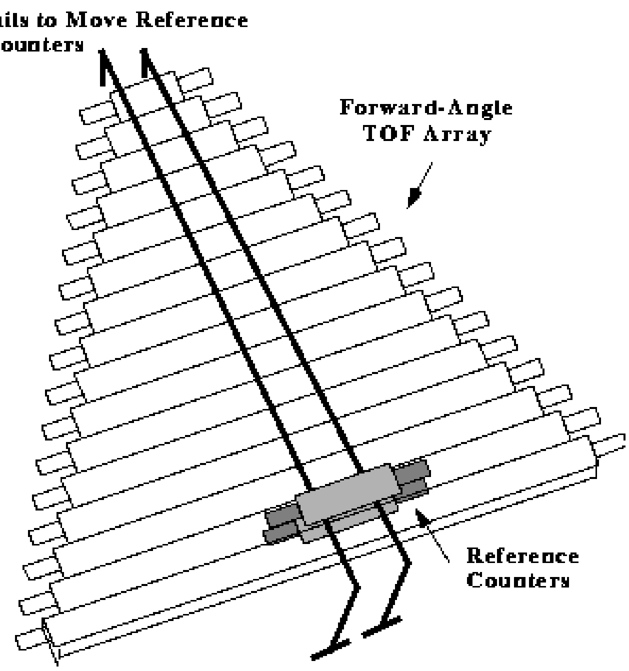

Figure 2: Schematic drawing of test array for cosmic-ray tests.

split, a neutral density filter is used to vary the intensity of light sent to each scintillator. The laser system is extensively described in Reference [2].

3.4.2 Cosmic-ray data

In order to determine the time response to particles we use cosmic-rays. An accurate and independent reference time for the these studies is obtained using two small scintillator counters. These counters are 5 cm thick, and 10×20 cm^2. They are mounted $\approx$ 12 cm one above the other on two rails which are $\approx$ 5 cm above the studied scintillator plane. Henceforth, we shall refer to these scintillators as "reference counters". They are used for triggering, and also in software to determine an accurate reference time. The arrangement allows us to position the two counters above each single bar, one at a time, and require cosmic-rays traversing the reference counters and the counter under test. Fig. 2 shows the actual setup. We define at this point:

$$\mathrm{T}_{ref} = \frac{1}{2}\left(\frac{\mathrm{T}^{L}_{1\ ref} + \mathrm{T}^{R}_{1\ ref}}{2} + \frac{\mathrm{T}^{L}_{2\ ref} + \mathrm{T}^{R}_{2\ ref}}{2}\right) \tag{6}$$

$$\tag{7}$$

We used two such counters to optimize the time resolution. Averaging the time of the two counters increases the resolution of the reference time by $1/\sqrt{2}$, restricts the hit location of the cosmics and minimizes the accidentals due to showers. The TDC and ADC values of the reference counters are read along with the data of the fixed tested counters. This allows us in software to compute T_{ref} which determines the incident particle time with much higher accuracy than the hardware trigger coincidence. To eliminate the dependence on the poorly defined trigger times, the quantities we extract from the measurements will always involve differences of TDC times (e.g. T^L -T^R , T(ID)-T(ID+1), T(ID)-T_{ref} , and so on).

In general, we will use the laser system when studying the characteristics of a single bar (its resolution, left-to-right offset constants, and so on.) Times between different scintillators must be studied with cosmics, as every laser fiber is different and might for example have a different length.

4 ADC PEDESTALS

Prior to any study, we have to determine the pedestal values of the ADCs. During a special run, in which the ADC data is not sparsified, we randomly trigger approximately 5000 events while our whole system is hooked up. During normal data taking, data is sparsified and the pedestal is subtracted before writing to disk.

5 GAIN-BALANCING AND -MATCHING

5.1 Gain-Balancing

The purpose of gain-balancing is to adjust the high voltages of the right and left PMTs of a single bar so that a MIP hitting the bar at its center produces the same pulse height at both PMTs. Due to the variations in the PMTs and the light collection, one expects different high voltage settings for each PMT. This is a necessary procedure because each counter must contribute equally to the trigger (for a common threshold discriminator level) and so that they all span the same ADC dynamic range.
To achieve this, we take cosmic-ray data by triggering on the counters under test (self-trigger). The reference counters are not used as no time study is involved. By adjusting the $log\frac{A^L}{A^R}$ to zero, we equalize the gain in right and left photomultipliers.

5.2 Gain-matching

The gain-matching procedure consists in adjusting the PMT high voltages so that MIPs produce a peak in channel 600 for every bar. The value is chosen from two considerations: the dynamic range of the ADC is 8000 and we expect a range of 8 which sets the upper limit. Also, we want to be above the low channels where time-walk corrections (see next section) are more important. This is done by adjusting the ADC geometric mean $\sqrt{A^L \times A^R}$ of right and left PMTs.

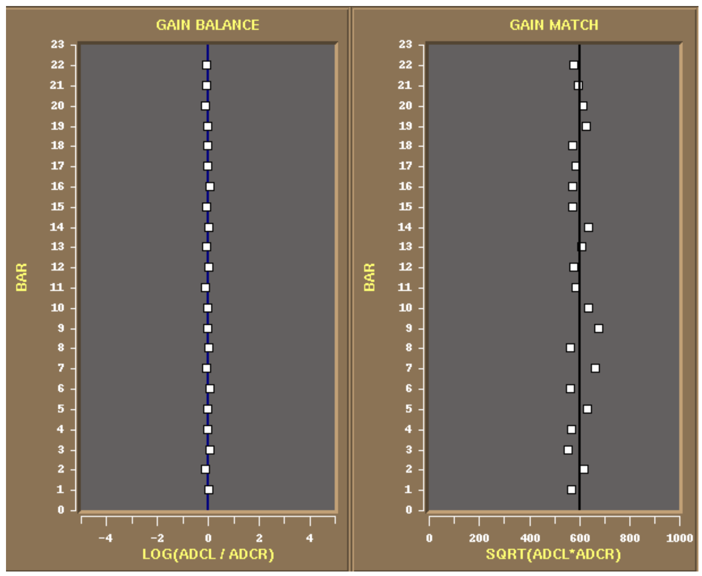

Figure 3: On-line graphical display of the gain-balancing and matching procedure.

All this procedure is done automatically through a TCL/EPICS interface which can remotely update and change the high voltage values. The gain varies as a large power of the high voltage (e.g. V^{10}). Fig. 3 shows that we achieved this to about 10%, which is adequate for our purpose.

6 TIME-WALK CORRECTION

Time-walk is the change in the output time of the discriminator due to varying input pulse heights. For example, large pulses cross the threshold earlier than small pulses. As we shall see below, there can be differences up to 4 ns (typical PMT pulse rise time) between a small and a large pulse.

To measure the time-walk corrections, we used the laser system. Each optic fiber delivers a light pulse into the center of the bar. Through a filter system, we vary the amount of light to be delivered to the bar and measure the corresponding TDC time. Using PAW, we then fitted the ADC vs TDC dependence with the function in Eq. 1. This function was chosen because it adequately represented the data over the region of interest (150 and 3000 counts) and was robust during the fitting procedure. The time-walk correction is a function of the actual pulse height, i.e. ADC value, and not the normalized energy lost in the scintillator.

Fig. 4 shows an example of the data and the corresponding fitted function (eq.(5)) for bar 19 & 20. The fitted parameters were obtained for the ADC range between 150 and 3000 counts. Fig. 5 shows a plot of the fitted parameters for each of the scintillators.

From now on, all the data we will use and mention will be time-walk corrected.

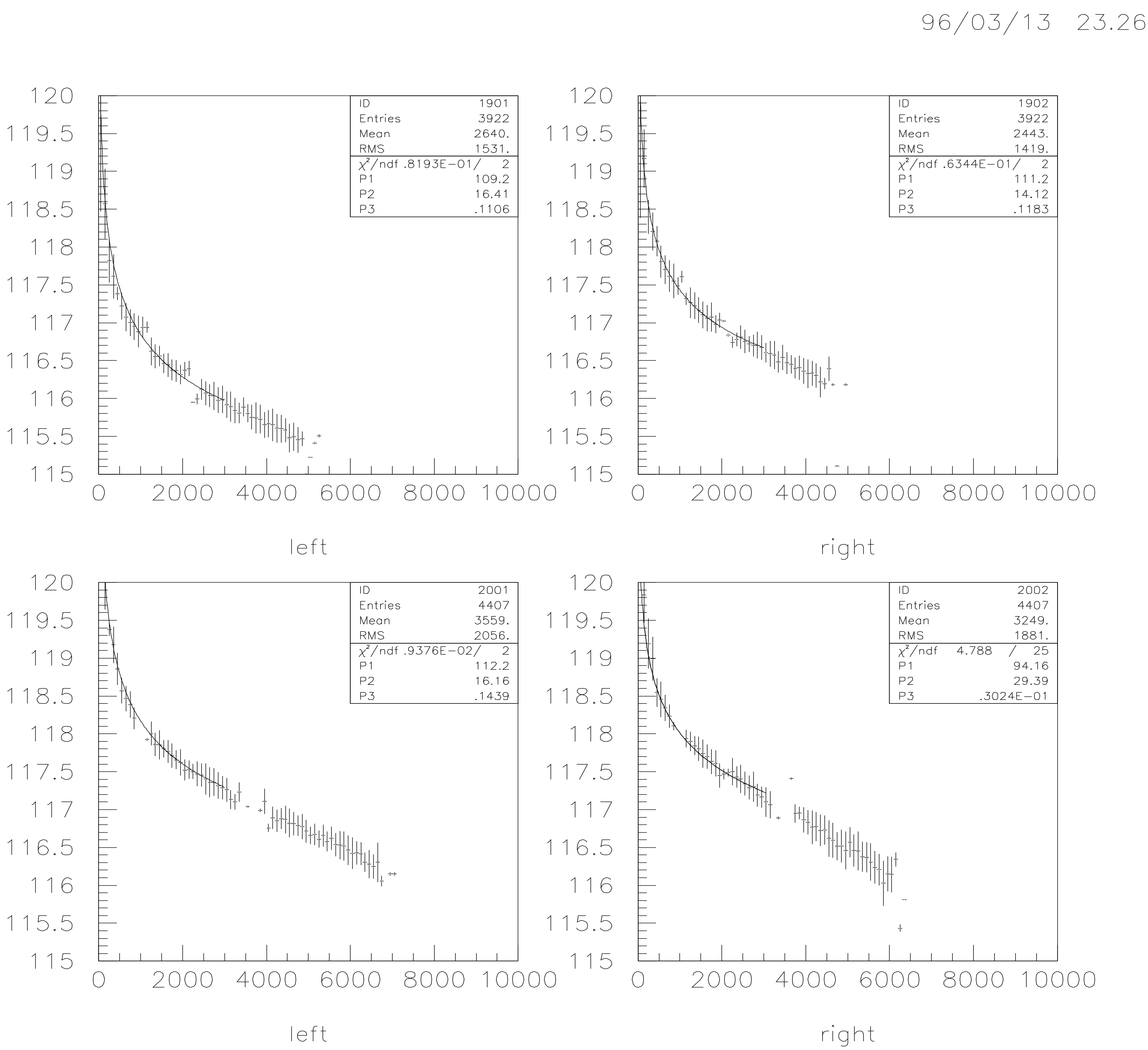

Figure 4: Typical examples of the dependence of the TDC times (ns) vs. the pulse height (ADC counts) for scintillators 19 & 20 (left & right PMTs). The line shows the fitted time-walk function of eq.(5).

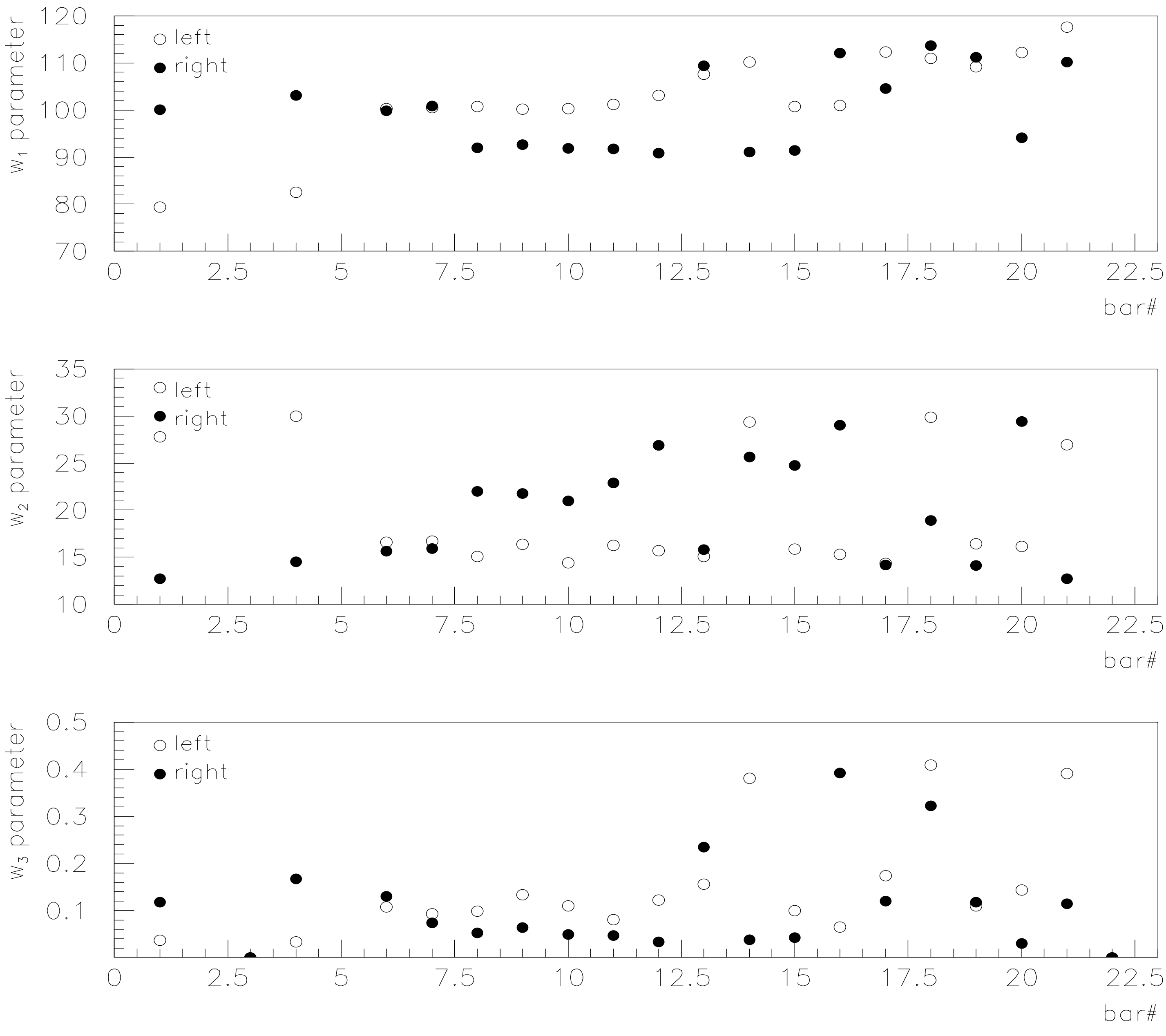

Figure 5: Fitted parameters for the time-walk correction, w_1 , w_2 , w_3 for all scintillators.

7 RESOLUTION

7.1 Time resolution

A measure of time resolution of each counter is given by $\sigma(\frac{T^L + T^R}{2})$. We have two ways to determine this resolution. The first one is to use the laser data and just plot the distribution of $\frac{1}{2}(T^L + T^R)$. We note that this is the only quantity of interest which depends directly on the trigger time, which should be very stable for the laser. The second one is to use cosmic ray data with the reference counters trigger and plot $\frac{T^L + T^R}{2}$ - T_{ref}. Here, it is necessary to use the reference counters to provide a good start time. Secondly, it selects vertical tracks, thereby minimizing the effects of geometry to the resolution. The measured widths contain a small ($\sim$ 10%) contribution due to the reference counters.
Fig. 6 shows examples of the measured resolutions with laser and cosmics and the effect of the successive corrections. Fig. 7 and columns 4, 5 & 6 of table 1 sum up the results for all the bars.

7.2 Position resolution

The intrinsic position resolution is given by $v_{eff} \times \sigma(T^L - T^R)$ for each bar. This is not so crucial for charged particles as the drift chambers and or calorimeter should give much better resolution. However, this is the only way to determine the position of neutral particles at large angles.

8 OFFSET CONSTANTS

Here, our concern is to make sure that when a particle hits the middle of any scintillator, we get the same TDC time on the left and right of every bar. This involves the determination of two sets of constants: The relative left-to-right timing for each scintillator and time from one scintillator to the next. It is necessary to determine these constants with an uncertainty less than the bar intrinsic resolution.

8.1 Left-Right timing

These constants are determined by measuring the centroid of the T^L - T^R distribution. The most straight-forward method to get these constants is to use the laser data which makes sure that the light source is at the center of the scintillator. Second column of Table 2 shows the values of these constants for every bar.

8.2 Bar-to-bar timing

As mentioned above, the laser procedure is not appropriate for this kind of study (comparison from bar to bar). We will therefore rely on cosmic ray data. The most straight-forward procedure is to use the reference counters as the trigger and place them above the center

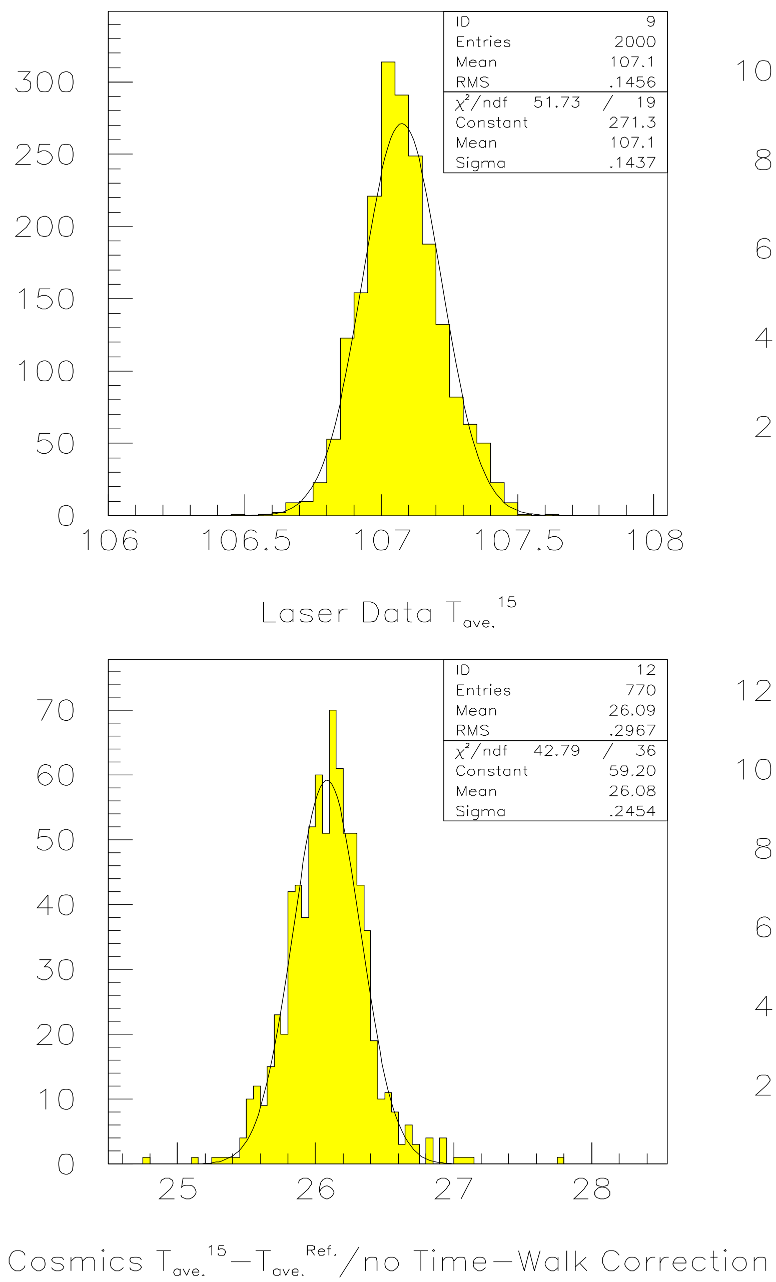

Figure 6: a) Time resolution as determined by laser data. b) Time resolution as determined by cosmic-ray data. c) Time resolution as determined by cosmic-ray data without time-walk corrections. d) Time resolution of reference counters.

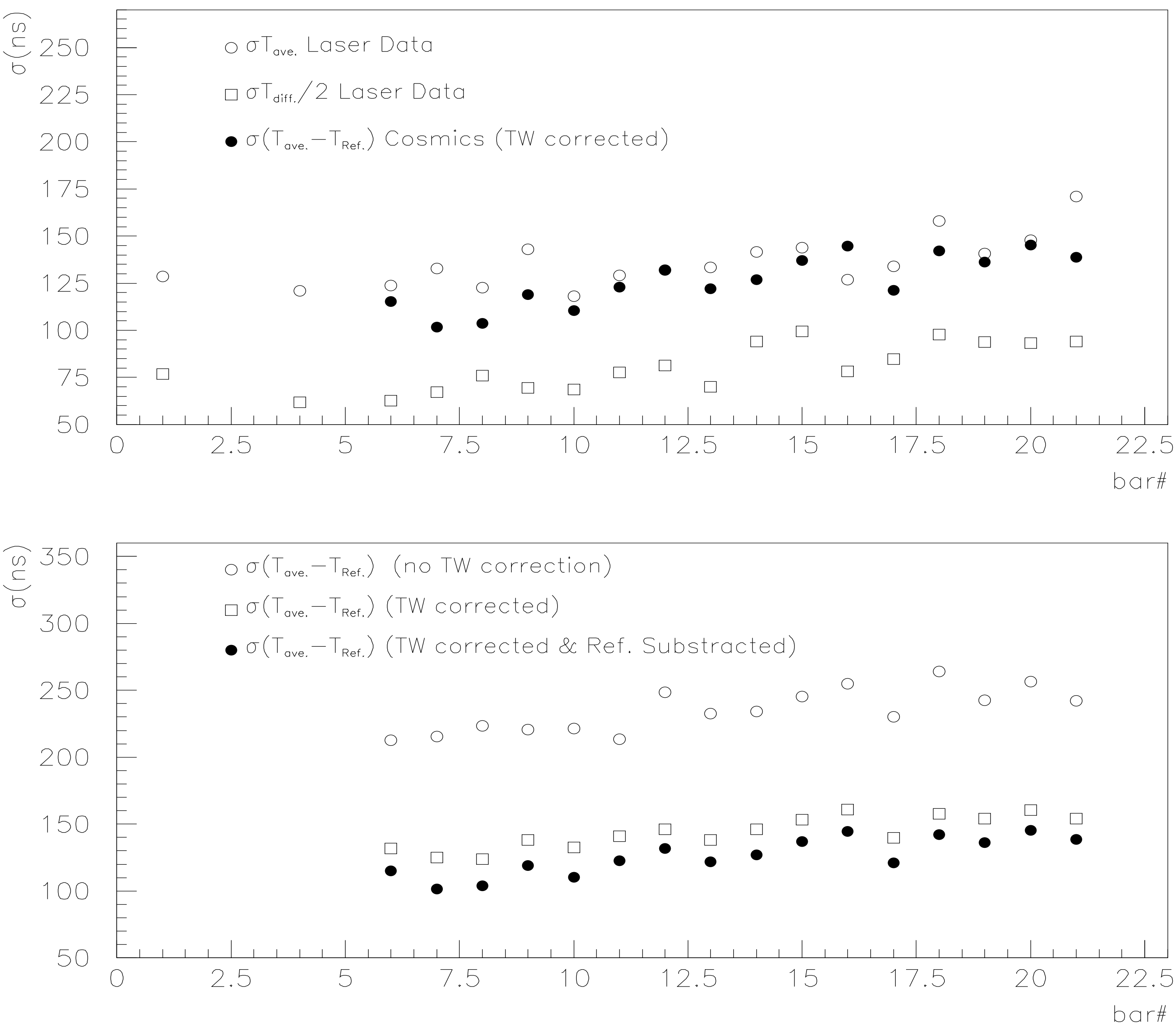

Figure 7: a) Comparison of time resolution as determined by laser data (Sum & difference) and cosmic-ray data for all bars. b) Effect of the time-walk correction and reference time jitter to the cosmic-ray determined time resolution for all bars.

	Laser data		*Cosmic ray data*		
bar#	$\sigma(\frac{T^L+T^R}{2})$	$\frac{1}{2}\sigma(T^L - T^R)$	$\sigma(\frac{T^L+T^R}{2} - T_{ref})$	$\sigma(\frac{T^L+T^R}{2} - T_{ref})$	$\sigma(\frac{T^L+T^R}{2} - T_{ref})$
	TW corr.		*no TW corr.*	*TW corr.*	*TW+ref. corr.*
6	123.755	62.647	212.777	131.942	115.221
7	132.709	67.150	215.350	124.919	101.656
8	122.692	75.946	223.351	123.723	103.727
9	142.927	69.590	220.535	138.298	118.975
10	118.197	68.584	221.220	132.443	110.397
11	129.150	77.581	213.353	140.792	122.769
12	131.902	81.462	248.377	145.956	131.817
13	133.266	69.898	232.728	138.166	121.959
14	141.490	94.124	234.032	145.961	127.001
15	143.727	99.482	245.434	153.447	137.035
16	126.877	78.105	255.015	160.669	144.640
17	133.927	84.596	230.290	139.816	121.185
18	157.945	97.700	263.997	157.738	142.109
19	140.616	93.695	242.573	154.141	136.058
20	147.877	93.184	256.280	160.407	145.328
21	170.911	94.007	242.065	154.252	138.620

Table 1: We tabulate in col. 2 & 3 the time resolutions from the laser data as calculated by the sum and the difference of right and left PMTs. Col. 4 & 5 show the cosmic-ray determined time resolutions without time-walk correction and with time-walk correction respectively. Col. 6 shows the cosmic-ray determined time resolution with time-walk correction and with the reference counters' contribution subtracted.

bar#	c_0 ^{RL}	bar#1/bar#2	c_0 ^{btb}	
6	-1.771	6/7	-2.644	-2.588
7	1.316	7/8	3.724	3.685
8	-1.415	8/9	1.280	1.143
9	-.381	9/10	-1.216	-1.055
10	-.474	10/11	-.892	-.882
11	-2.402	11/12	-1.414	-1.348
12	2.115	12/13	-1.673	-1.670
13	.123	13/14	1.612	1.622
14	-1.995	14/15	2.423	2.538
15	.919	15/16	-3.064	-3.045
16	3.623	16/17	-.998	-.918
17	-6.073	17/18	-.619	-.610
18	3.019	18/19	-.496	-.379
19	.902	19/20	-.833	-.759
20	-.075	20/21	.278	.291
21	-3.930			

Table 2: We tabulate the relative time offsets between left and right PMTs (col. 2) and the bar-to-bar offsets by two methods (col. 4 & 5).

of each bar. The time relative to the reference counters is measured $\frac{T^L+T^R}{2}$ - T_{ref}, thereby determining the time of each counter relative to each other.
However, the use the reference counters in Hall B will be cumbersome, due to space constraints, we check that it is possible to determine these constants by self-triggering the scintillators. This method involves the selection of cosmics which cross two adjacent bars, so that the quantity $\frac{T^L+T^R}{2}$ (id)-$\frac{T^L+T^R}{2}$ (id+1) yields the offset constant. To test this method, we started by keeping the reference counter trigger but requiring 4 hits in the software trigger, i.e. 2 for the reference counters and 2 for the bars under test (a priori adjacent, except for accidentals). The purpose of this preliminary step is to get precise a measurement with the geometric restriction of the reference counters and allowing both methods to be used on the same data set.
Secondly, we removed the reference counters and used the "self-triggering" procedure. The main consequence is then the increase of the ratio of accidentals (showers) to signal (single cosmics).

Fig. 8 shows an example of the results of the two methods for bar 12 and 13. We compare in tab. 2 the values provided by the two methods and conclude that we will be able to determine the bar-to-bar offset constants in Hall B by self-triggering the TOF scintillators.

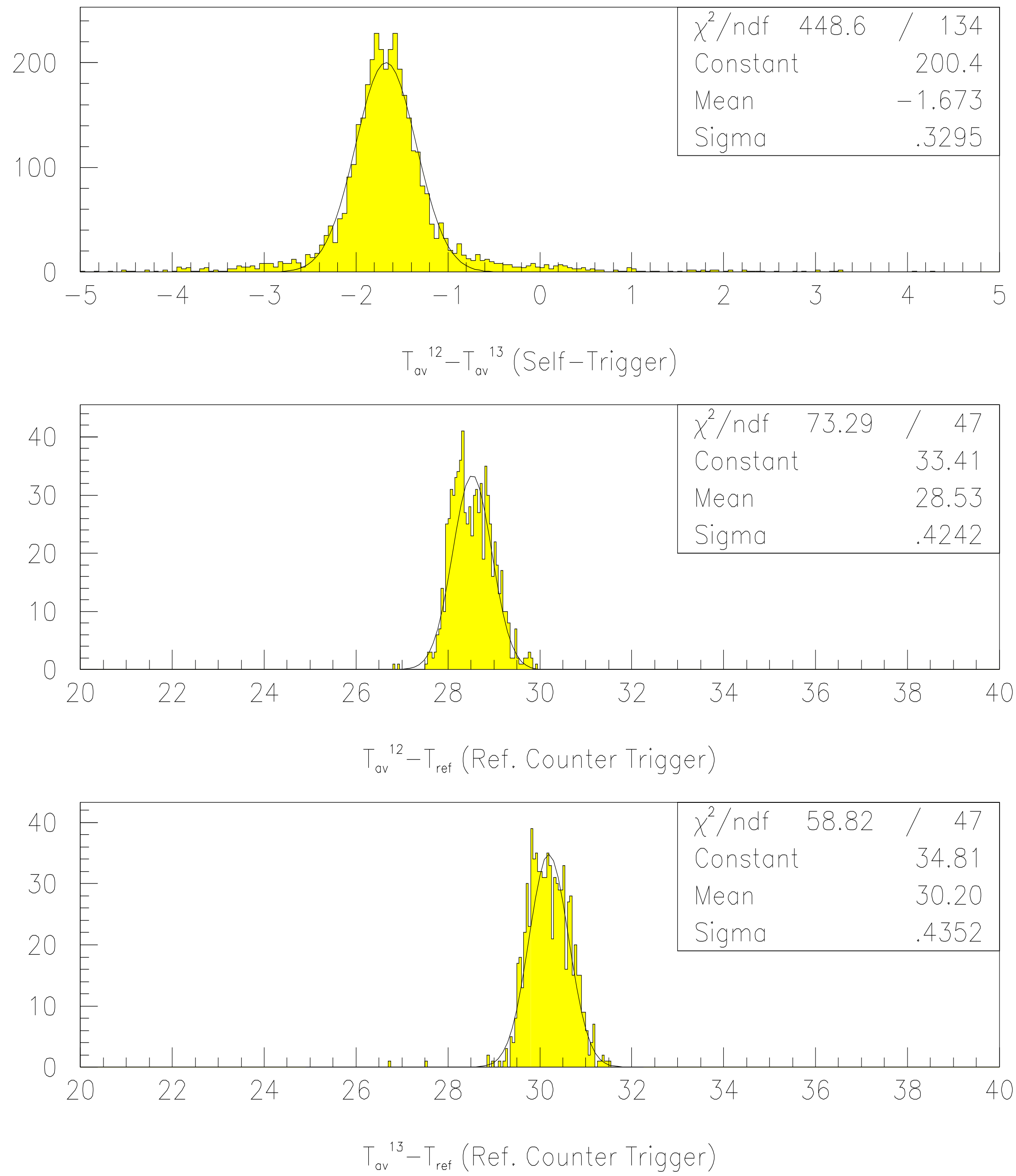

Figure 8: Comparison of the two methods for extracting the relative time from bar to bar. a) Offset constant obtained by the self-trigger method. b) Relative time between counter 12 and reference counter. b) Relative time between counter 13 and reference counter. The difference between b) and c) also determines the bar-to-bar offset constant $c_0{}^{btb}$.

9 SUMMARY

We have performed systematic studies of the calibration and resolution of the forward-angle TOF scintillators with a laser pulser system and cosmic rays. These tests are expected to be representative of data taken with CLAS, as final components of the hardware and software were used. The hardware includes the use of leading-edge discriminators, which require time-walk corrections to be made before final resolution can be achieved. For the first time here we have systematically studied software corrections to the measured time. The time-walk corrections were determined over a dynamic range of 1:20, which is approximately what is expected for real data. To extend the dynamic range the parametrization must be studied in more detail. All other time related constants were also determined allowing us to achieve a realistic calibration for the system.

We have measured the time resolution by various methods using both laser calibrations and cosmic-rays. All measurements show that the system achieves a resolution of less than 180 ps for all scintillators. However, the time resolution measured using the difference of right and left PMTs is about half that measured by using the laser sum and cosmic-rays. This discrepancy is not completely understood at present.

The relative time from scintillator to scintillator has been studied in detail using an external set of reference counters and self-triggering on the TOF scintillators themselves. We conclude that cosmic-rays hitting two adjacent scintillators we can be used as a good starting point for determining these constants. Constants determined in this manner agree within about 100 ps with the external reference method. Final determination of the relative times must be made with beam and particles of known mass originating at the target, but an initial set of constants determined with cosmic-rays will be invaluable.

References

[1] D. Cords *et.al.*, "CLAS Event Format with BOS," CLAS-NOTE-94-012, October 1, 1994.

[2] Chris Taggart, "Developmental Testing of a Laser Calibration System for the CLAS TOF Scintillation Counters," CLAS-NOTE 95-010, June 29, 1995.