read out by standard MINOS Hamamatsu M16 multi-anode photomultipliers. The coincidence of the two planes was timed with respect to a detector timing signal with a Brilliant Instrument BI200 time interval analyzer. Both detectors were operated at the Near Detector, then one was transported to the Far Detector. Measuring the relative time of muon tracks in the MINOS detector and auxiliary detector allowed the determination of the relative latency of the Near and Far detectors with 1 ns accuracy.

5.2. Old timing system quirks

Using the upgraded timing equipment, MINOS was able to determine a number of unexpected quirks in the event timing. Absolute time, in the old system, was derived from a Truetime XL-AK GPS timing receiver. This receiver has a random offset with respect to GPS time that appears stable over time, but changes each time it is power cycled. This behaviour, under test conditions, is shown in figure 1. Our measurements indicate that we expect this GPS offset to have an RMS of about 60 ns (see figure 2.)

Over the 8 years of MINOS running, one or other GPS receiver was power-cycled on 29 occasions. Each period between power cycles was considered an independent measurement of the neutrino time of flight, with a random offset as described above. Considering only periods that contain at least 100 events at the far detector, in order to have a reasonable quality of fit, the data are divided into 19 datasets.

Figure 1: Offset between old GPS timing receiver and a good cesium atomic clock. Step changes occur when the GPS receiver is power-cycled. Power cycles occurred automatically on the hour for most of the day. Offset from zero here is arbitrary.

5.3. Two analysis methods

The data were analyzed in two different ways. The first method, known as the "full spill approach" closely

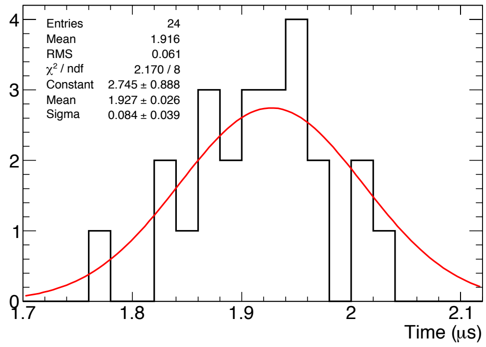

Figure 2: Distribution of offsets of old GPS timing receiver with respect to GPS time. Offset from zero here is arbitrary.

follows the 2007 analysis [12]. The data at the near detector is used to form a high statistics prediction for the time distribution at the FD, and an unbinned maximum likelihood fit is performed to determine the time offset.

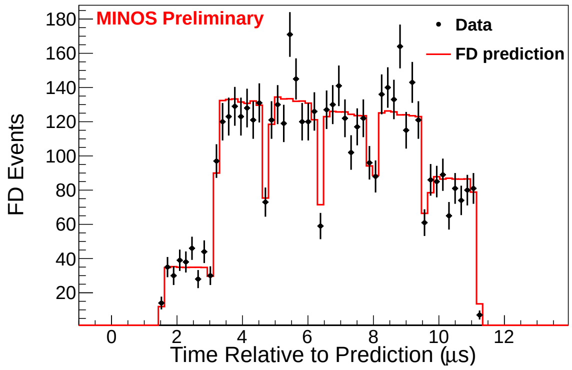

Figure 3: Fit to the far detector dataset in the "full spill" method.

The second method is known as the "wrapped batch" method. Exploiting the fact that the beam from the Main Injector is structured in six "Booster batches", each consisting of 81 consecutive 53 MHz RF bunches, separated by typically a five bunch ($\sim$ 100 ns) gap, the data from each batch are overlaid to obtain a higher precision measurement of the location in time of the gap between batches.

The data from the ND and FD are fit separately to determine the location of the gap, then the fit results subtracted to obtain a measurement of the time of flight. This method is illustrated in figure 4.

The results from these two methods, for the 19 time periods between GPS power cycles, are shown in figure 5. One observes good agreement for both methods

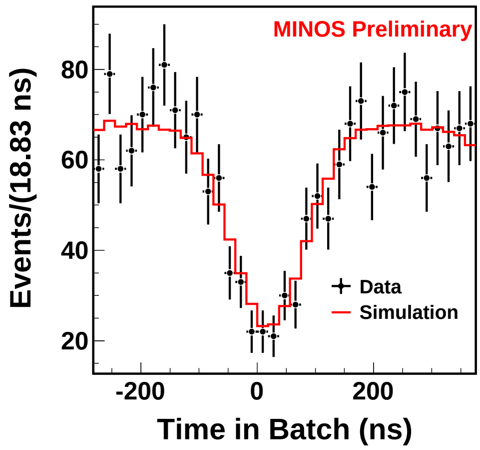

Figure 4: Fit to the far detector dataset in the "wrapped batch" method.

for all datasets. Combining the results produces a measurement of the discrepancy of the time of flight with respect to the speed of light of

$$\delta = -18 \pm 11\,(\text{stat}) \pm 29\,(\text{syst.})\,\text{ns} \quad (2)$$

for the full spill method, and

$$\delta = -11 \pm 11\,(\text{stat}) \pm 29\,(\text{syst.})\,\text{ns} \quad (3)$$

for the wrapped batch method.

The systematic error is dominated by the 21 ns uncertainty on the relative internal delay of the GPS receivers at the ND and FD. In principle, one could measure this rather better with some dedicated time and effort, but in practice the new, modern GPS system will render the idiosyncrasies of the old system of mere historical interest.

Combining these leads to a measurement of the fractional difference between the neutrino velocity and the speed of light

$$\left(\frac{v}{c} - 1\right) = 0.6 \pm 1.3 \times 10^{-5}\,(68\%\text{C.L.}) \quad (4)$$

6. Conclusions

MINOS has updated its 2007 analysis with a factor of eight more data and a better understanding of the systematic errors, and finds no evidence for superluminal neutrinos. MINOS has installed an updated timing system, and with two months of data from spring 2012, expects to measure the neutrino time of flight with a small

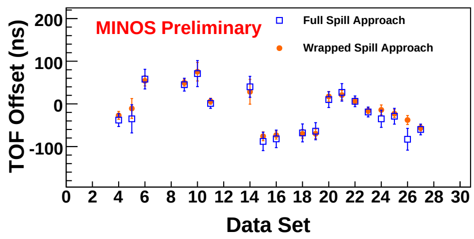

Figure 5: Measured time of flight with respect to the speed of light for the different run periods

statistical error, and with a systematic uncertainty of between 2 and 5 ns, corresponding to a velocity measurement approaching one part in a million. Results from this experiment are expected in late 2012.

T2K is in the process of installing a broadly similar system, and could be expected to achieve similar accuracy on the time of flight, and in view of the shorter baseline an uncertainty of more like three parts in a million. It will be in a position to begin to take data in the spring of 2013.

As reported elsewhere at this meeting, OPERA has located and corrected errors in their timing system, and all CNGS experiments now report neutrino velocities consistent with that of light.

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