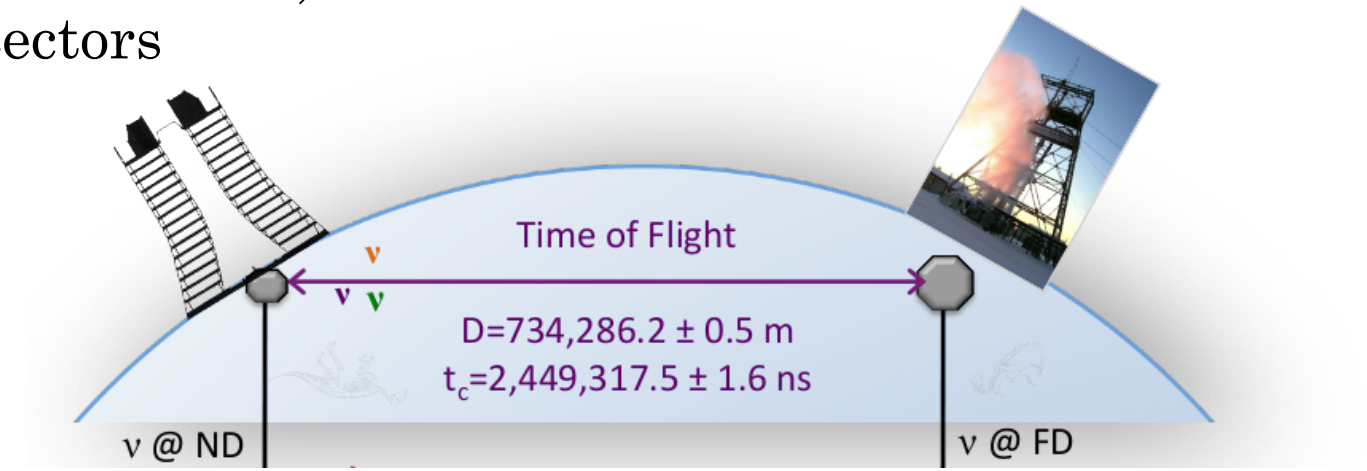
MEASURING THE SPEED OF NEUTRINOS WITH MINOS

June, 2012

Measuring neutrino time of flight

- Measure the time it takes for NuMI neutrinos to travel the 734,286.2 ± 0.5 m between the two MINOS detectors



- Initial result after first year of data indicated neutrinos arrived at FD earlier than expected:

126 ±32 (stat.) ± 64 (syst.) ns†

- We revisit this analysis with a factor of 8 more events and a refined systematic error analysis

†Phys. Rev. D76 (2007) 072005

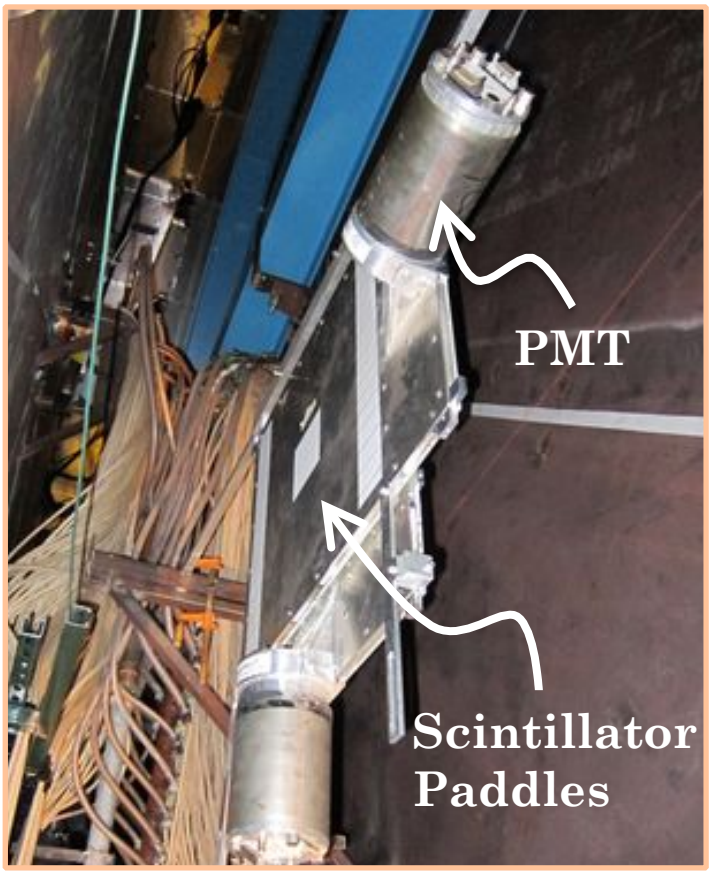
Major Systematic Uncertainties

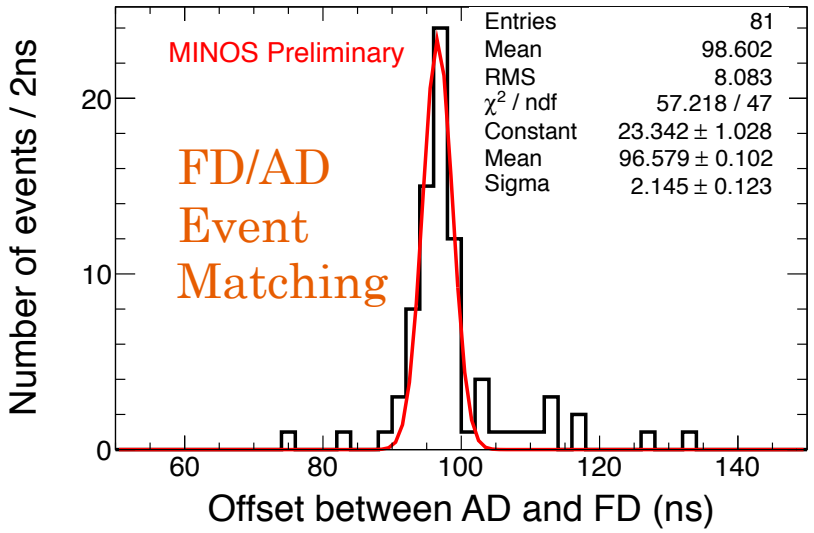
- Arrival times as recorded at each detector must be corrected for (sizeable) cable delays and electronics latencies
- Dominant systematics in first analysis largely mitigated by new, precision measurements of delays

	2007	2012
GPS antenna to ND cable delay	1275 ± 29 ns	1309 ± 1 ns
GPS antenna to FD cable delay	5140 ± 46 ns	5098 ± 2 ns

- Relative ND/FD electronics latencies determined using a special purpose Auxiliary Detector
- Total systematic from cable delay/electronic latency: 4 ns

The Auxiliary Detectors (AD)

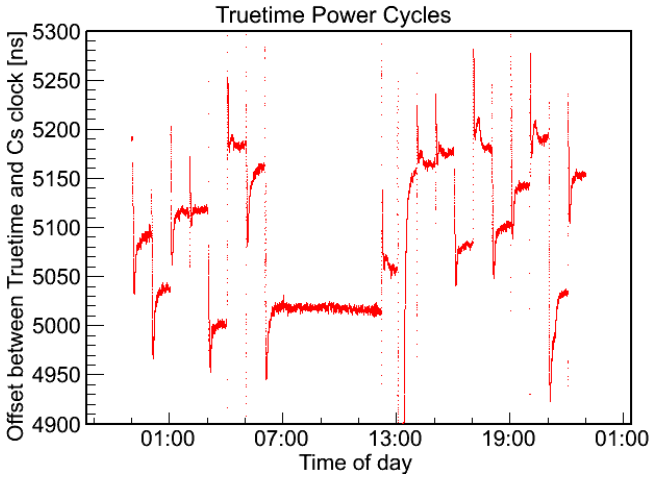


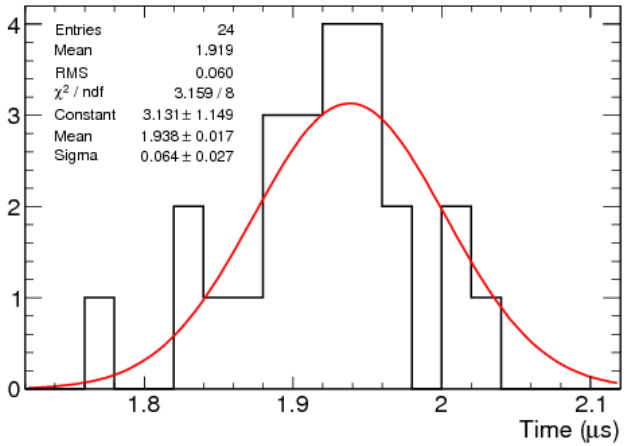


- Scintillator paddles with PMTs
- Two independent readouts
  - CAMAC TDC
  - Brilliant Instruments TDC
- Match muons in MINOS detectors with muons crossing AD
- Difference in matched event times recorded in each device measures latency in neutrino detector relative to AD latency
- Compare Near to Far Detector latencies, AD latency cancels
- Relative latency measured to 1 ns precision

TIMING SYSTEM STABILITY

- Recent measurements of the MINOS GPS receivers against cesium clocks reveal GPS time discontinuities after power cycles





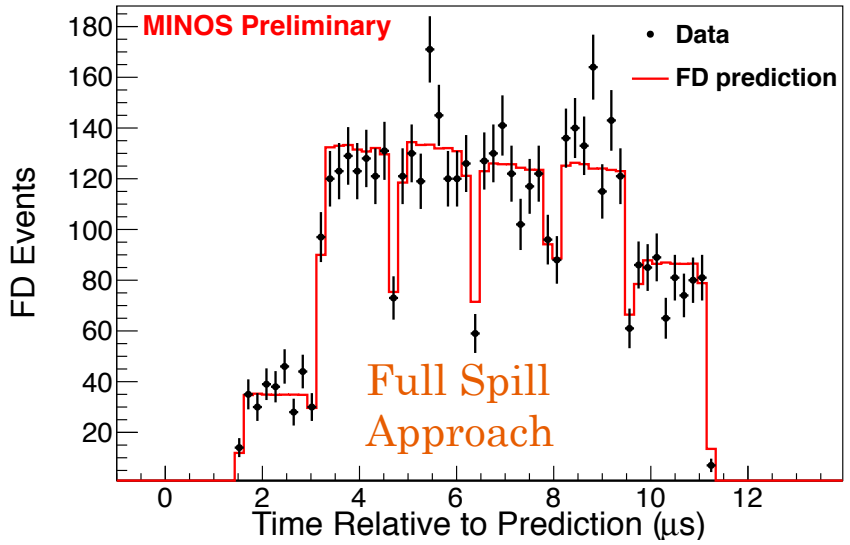
- Measured 60 ns jitter within manufacturer spec
- Neutrino arrival times recorded over past 7 years includes these random jumps
  - stable between power cycles
  - average over many power cycles cancels the effect of this random jitter

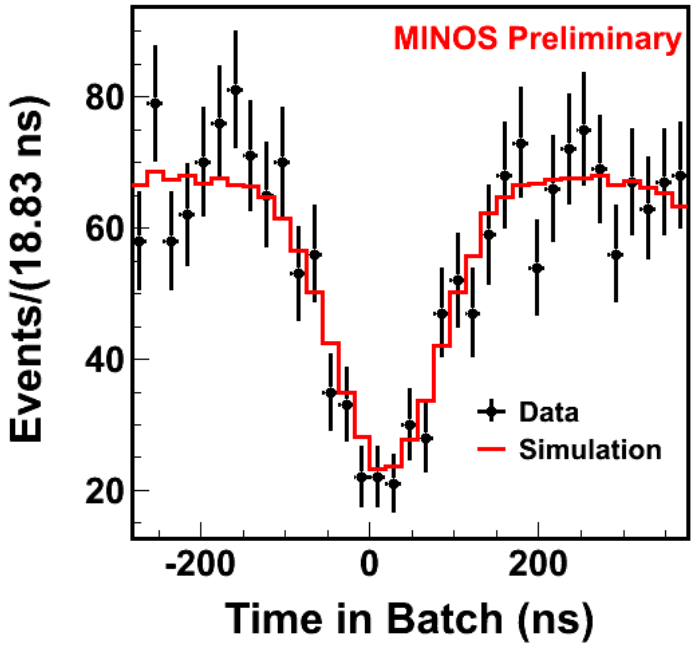
Additional Systematic Uncertainties

- Calibrating ND/FD GPS receiver offsets
  - Traveling TWSTT capable GPS receiver visited FNAL and Soudan
  - TWSTT (Two Way Satellite Time Transfer)
  - Two receivers exchange timing synchronization information via the satellite
  - Comparison of ND and FD GPS time to traveling receiver reveals mean time offset between ND and FD: 22 ± 21 ns
- ND Spill trigger delay
  - Delay between beam extraction signal and issue of ND beam trigger is bimodal
  - Incur systematic uncertainty of 19 ns

The Analyses

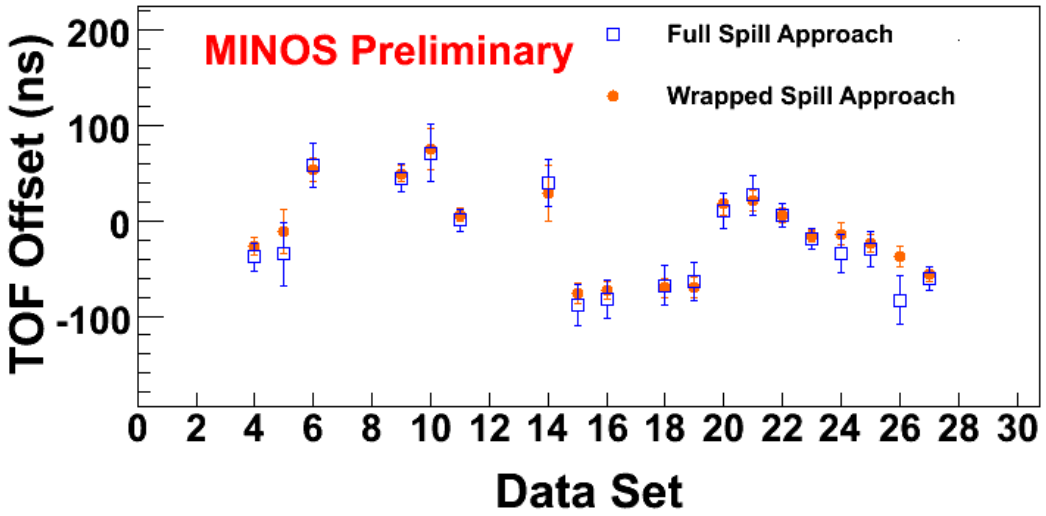
- NuMI neutrinos span a 10 us spill
  - spill subdivided into 1.619 us batches
  - 95 ns gap between batches
- Full spill approach
  - Use event time within spill distribution in ND to predict FD distribution
  - Vary time of flight to match prediction to data
- Wrapped Spill approach
  - Measure event time within batch
  - Find time of the gap between batches in each detector
  - Subtract gap times to find time of flight





Comparing the Approaches

- Divide data set into subsets between timing system power cycles



- Two approaches give consistent results in each time period
- Individual results change with power cycles
- Average over individual results for final TOF result
- Error on mean taken as the statistical error on the result

RESULTS

- In Full Spill approach, neutrinos arrive earlier than expected by:

$$18 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.) ns}$$

- In Wrapped Spill approach, neutrinos arrive earlier than expected by:

$$11 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.) ns}$$

- The two approaches give results consistent with one another
- The two results are consistent with neutrinos traveling at the speed of light