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 $734,286.2 \pm 0.5$ m between the two MINOS detectors.

- Initial result after first year of data indicated neutrinos arrived at FD earlier than expected:
  \[126 \pm 32 \text{ (stat.)} \pm 64 \text{ (syst.) ns}^+\]

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

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**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.

<table>
<thead>
<tr>
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<th>2007</th>
<th>2012</th>
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<tbody>
<tr>
<td>GPS antenna to ND cable delay</td>
<td>1275 ± 29 ns</td>
<td>1309 ± 1 ns</td>
</tr>
<tr>
<td>GPS antenna to FD cable delay</td>
<td>5140 ± 46 ns</td>
<td>5098 ± 2 ns</td>
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- 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: $22 \pm 21$ 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:
  \[ 18 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.)} \text{ ns} \]
- In Wrapped Spill approach, neutrinos arrive earlier than expected by:
  \[ 11 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.)} \text{ ns} \]
- The two approaches give results consistent with one another
- The two results are consistent with neutrinos traveling at the speed of light