Measuring electronic latencies in MINOS with Auxiliary Detector

Son V. Cao
University of Texas at Austin
(on behalf of the MINOS collaboration)

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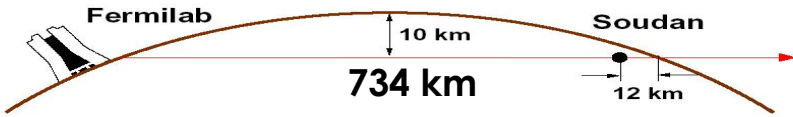
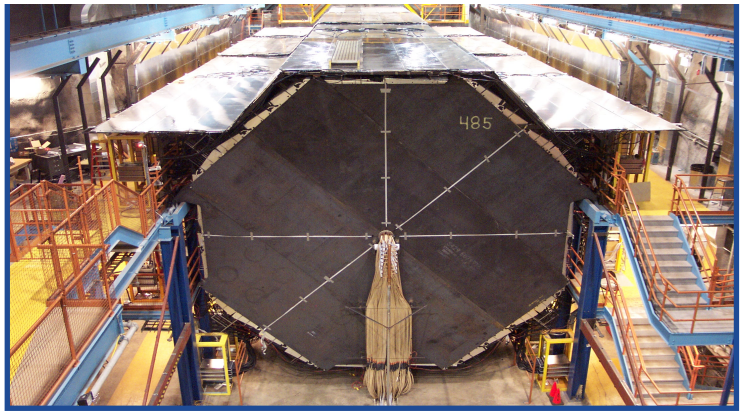
Main Injector Neutrino Oscillation Search (MINOS)

- ✓High intensity muon neutrino beam produced at Fermilab
- ✓ Two detectors: reduce systematic errors, magnetized to distinguish ν_μ and $\bar{\nu}_\mu$ interactions
- ✓ Near Detector to measure initial beam composition, predict no-oscillation spectrum at Far Detector
- ✓ Long baseline (734km) ⟶ Time of Flight (TOF) (1st measurement in 2007)

We revisit TOF with more statistics and refined understanding of system

Near det. 1.0 kton





Far det. 5.4 kton

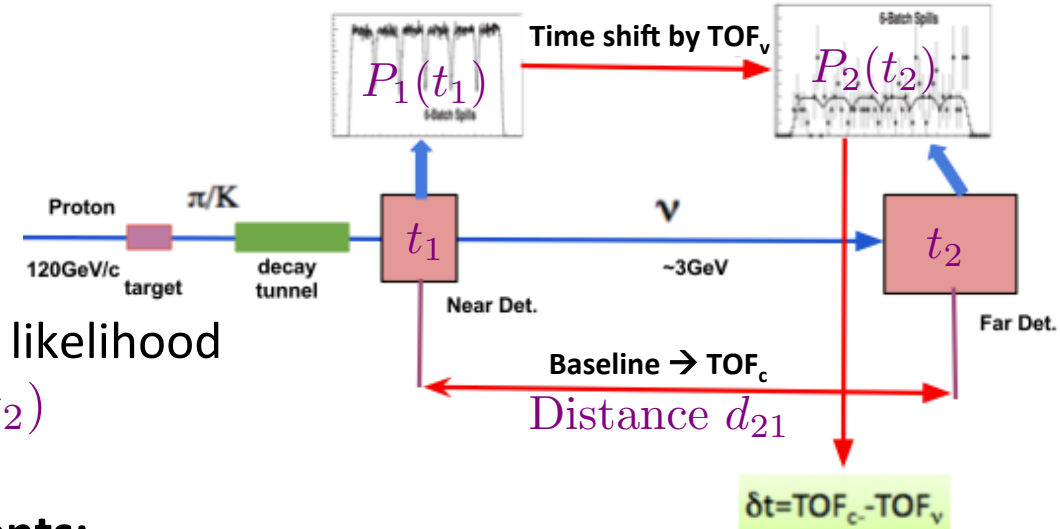
2. Time of Flight (TOF) principle

Basic principle:

$$v = \frac{d_{21}}{(t_2 - t_1)}$$

Real measurement:

Find δt_{21} to minimize the likelihood between $P_1(t_1)$ and $P_2(t_2)$



In 2007, used 473 FD events:

$$\delta t = -126 \pm 32(\text{stat.}) \pm 64(\text{syst.}) \text{ ns } (68\% \text{ C.L. })$$

$$(v/c - 1) = 5.1 \pm 2.9 \times 10^{-5} (68\% \text{ C.L.})$$

Source of latency	Uncertainty 2007
ND electronic latencies	32ns
FD electronic latencies	3ns
F/N detector relative latencies	9ns

Need to understand the timing system better!!!

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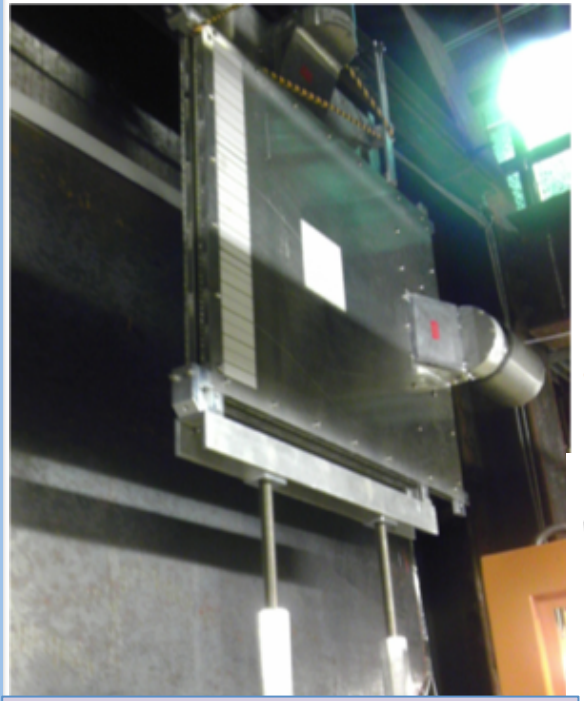
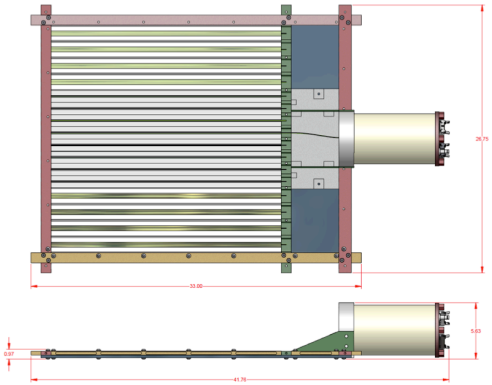
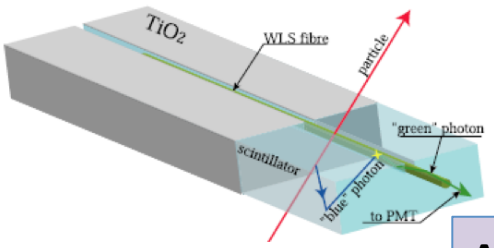
3. Auxiliary Detector (AD)

ν beam



Auxiliary Detector at the back end of Near Detector



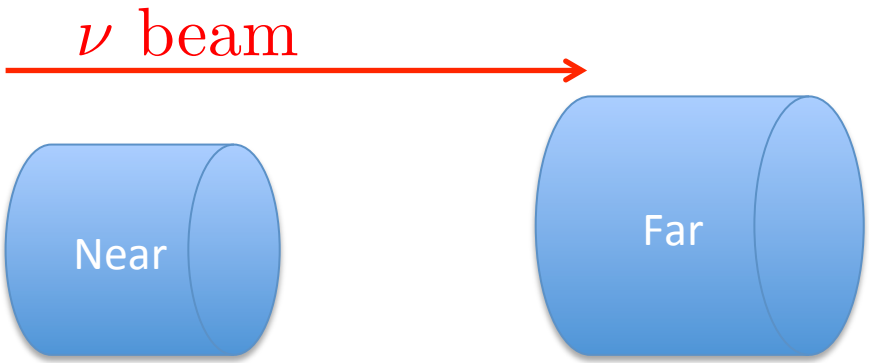


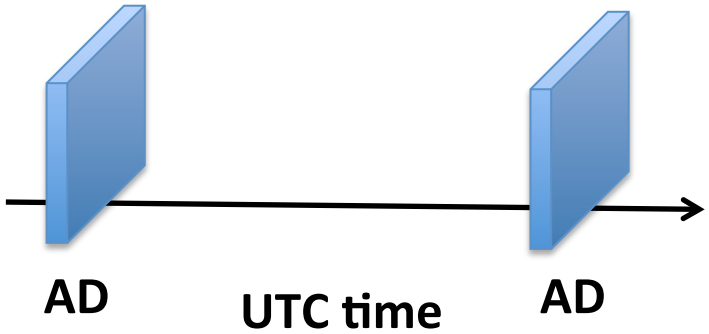
Auxiliary Detector in the middle of two Super-Modules at Far Detector

Auxiliary Detector timestamps muon, resultant particle of neutrino interaction, and matches with events recorded in real detector

3. AD setup: motivation

- ✓ Readout system has complicated latency, not easy to measure
- ✓ Two readout systems of MINOS detector are not the same
  ⟶ systematic error
- ✓ Using two identical readout systems, Auxiliary Detector (AD), can cancel out this error



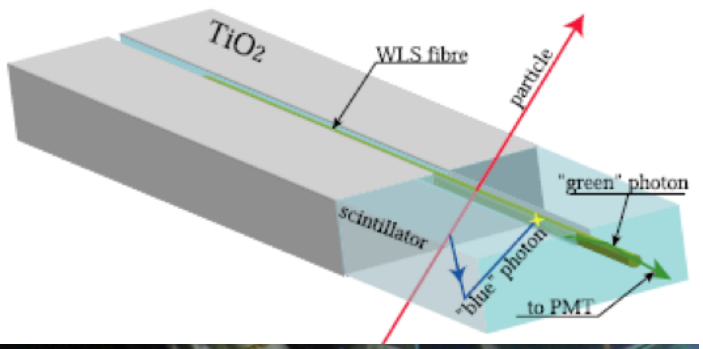


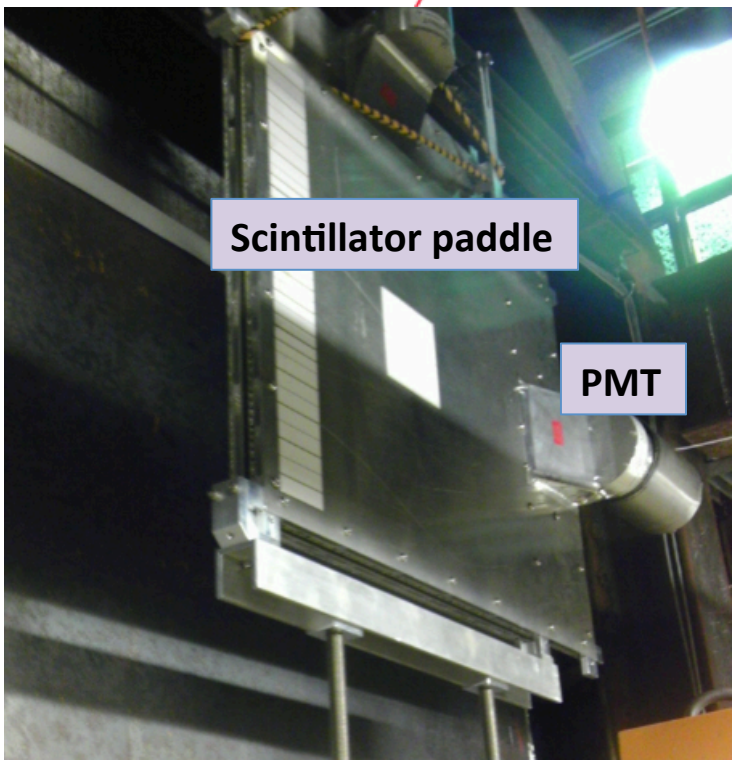
Goal: measure the latencies and mitigate the systematic error using a simple auxiliary system

3. AD setup: event timestamp

- ✓ Passage of muon produces blue scintillation light
- ✓ Wavelength-shifting fiber absorbs and shifts scintillation light
- ✓ Signals are multiplied by photomultiplier (PMT) and used as "STOP" signal
- ✓ Timestamp "STOP" signal with a "START" reference signal in each detector

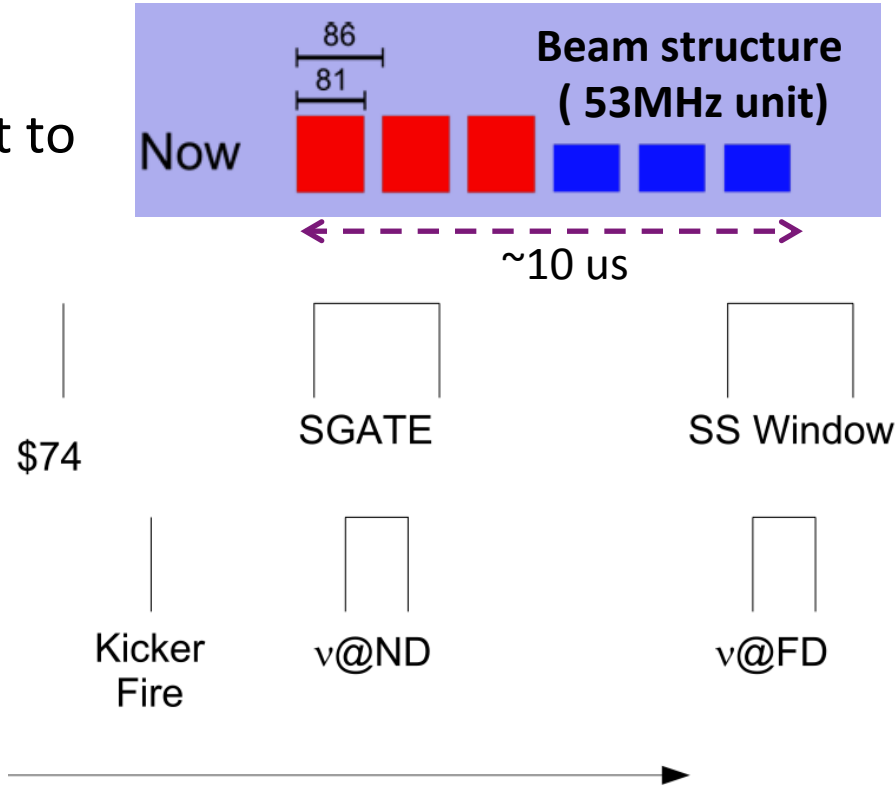
Relative electronic latency between ADs and real detectors is calculated by event matching





Timing system overview

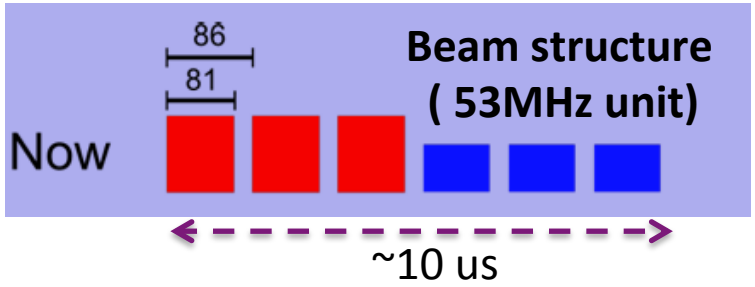
- ✓ Accelerator generates signal, named $74, tell kicker magnet to prepare extracting the proton beam
- ✓ Each spill lasts about 10us
- ✓ At ND, Front-End boards start window, labeled SGATE, to collect data
- ✓ At FD, another window, labeled SS Window, is opened to capture data at the time spill arrives

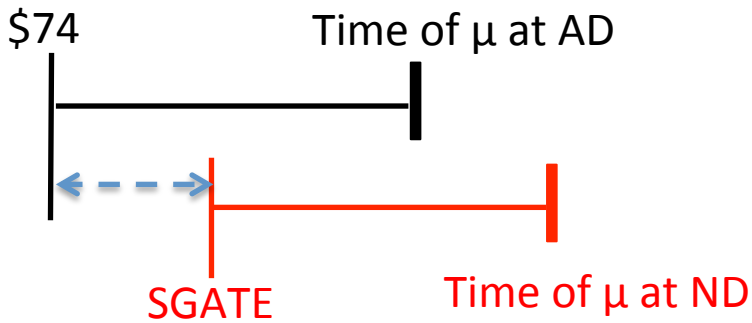


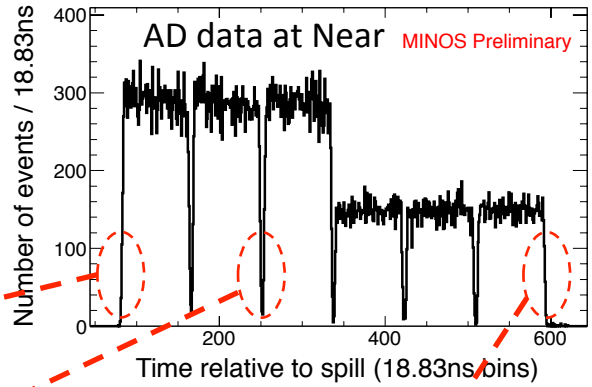
Timing diagram

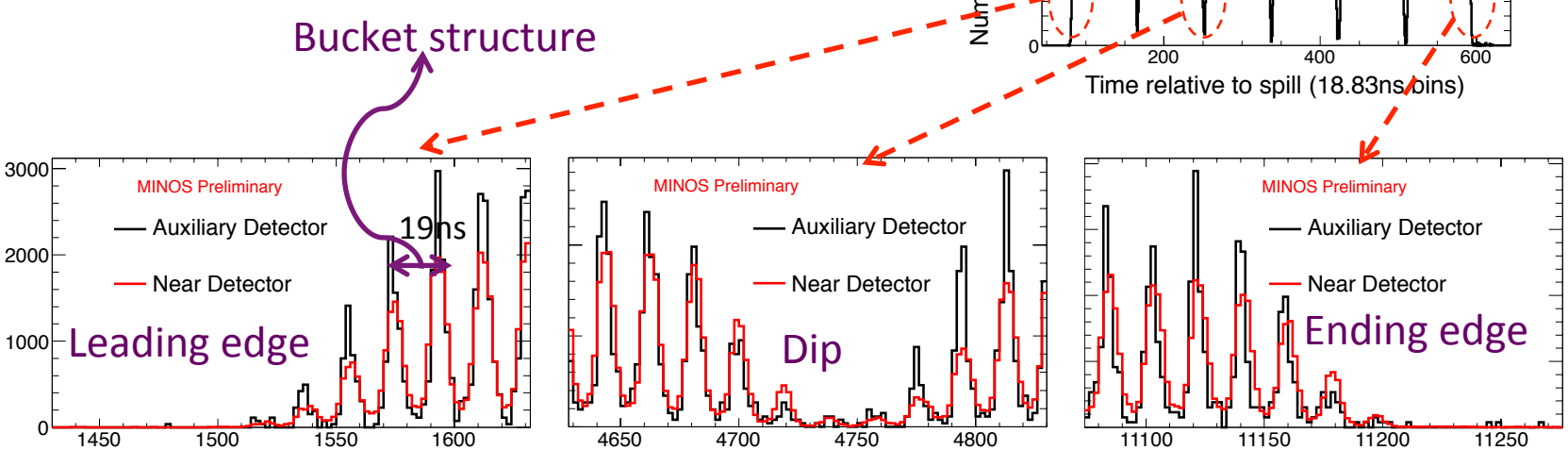
4. AD measurement at Near

Use $74 and SGATE as "START" signals respectively for Auxiliary and Near detectors





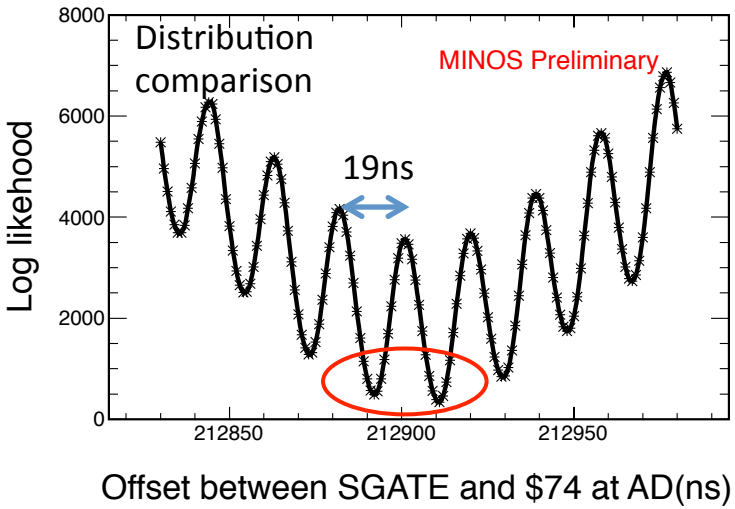


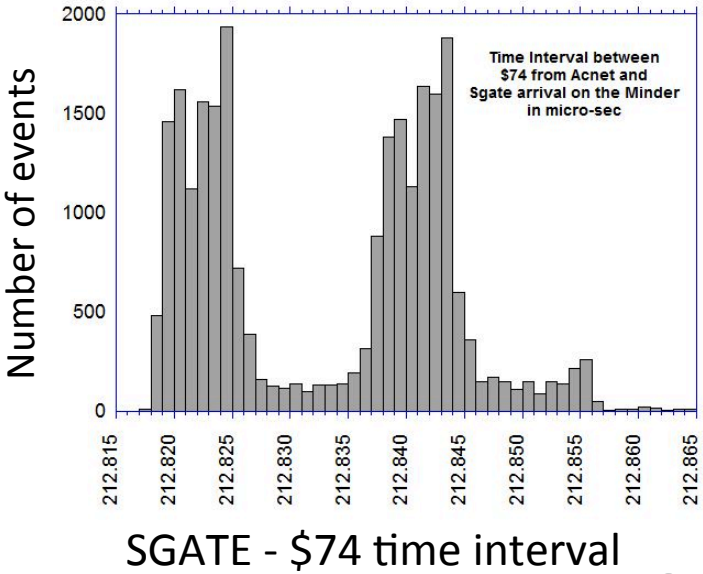


Matching between Auxiliary and Near Detector distribution

4. AD measurement at Near

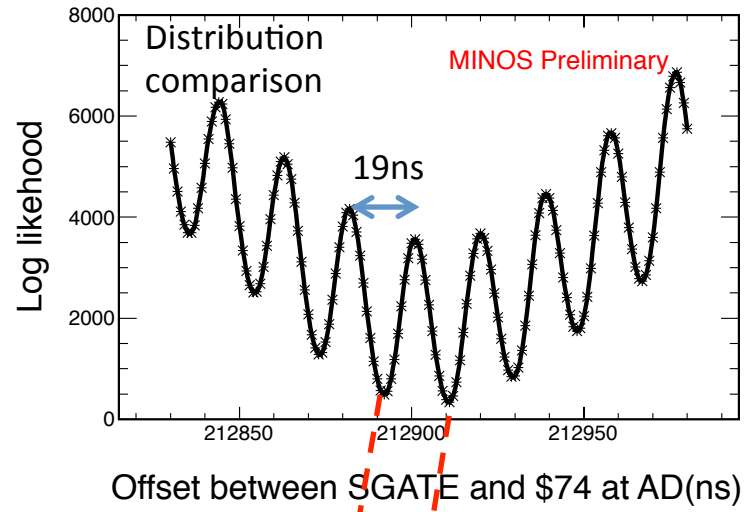
- ✓ Calculate likelihood of AD-ND distribution comparison as a function of SGATE-$74 "offset"
- ✓ Likelihood reflects very well the bucket structure but the true peak is not clear.
- ✓ SGATE-$74 time interval is not true offset. SGATE is programmably lined up with 53.1MHz clock tick.
- ✓ The direct measurement of SGATE-$74 time interval also shows two peaks separated by 19ns.

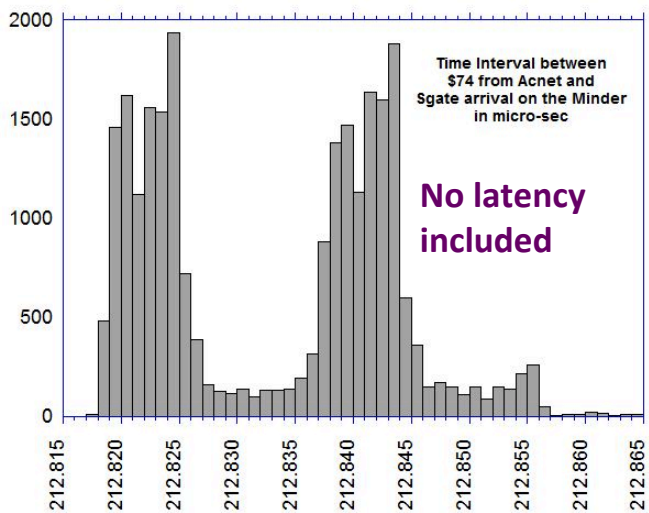


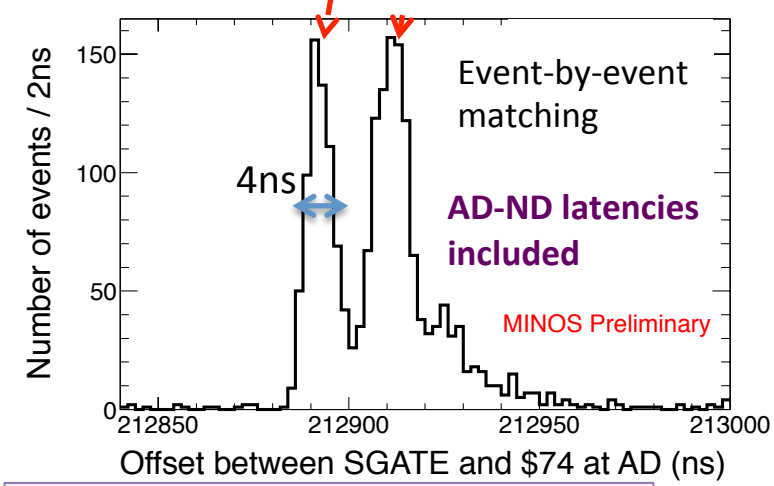


4. AD measurement at Near

- ✓ AD is synchronized to ND DAQ, permitted to match in event-by-event basis.
- ✓ These peaks agrees with those from distribution comparison
- ✓ "Offset" measured by AD includes the electronic latencies of AD and ND
- ✓ Calculate AD-ND electronic latency by comparing with time interval from direct measurement (mean of the peak is used)



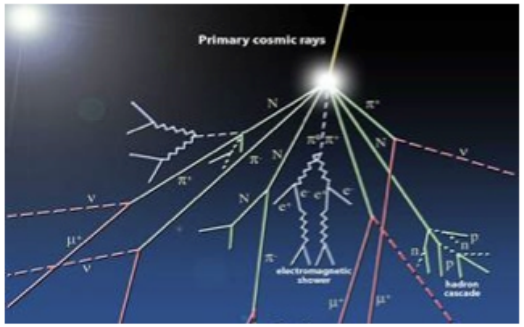


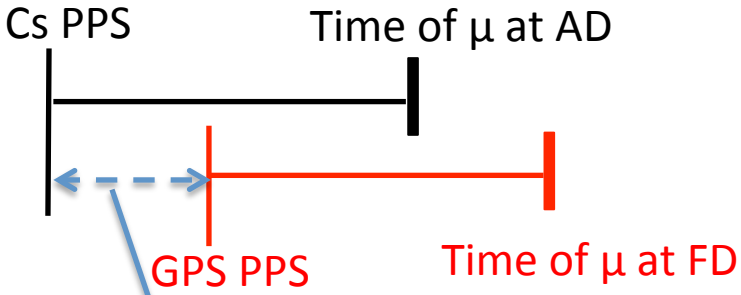


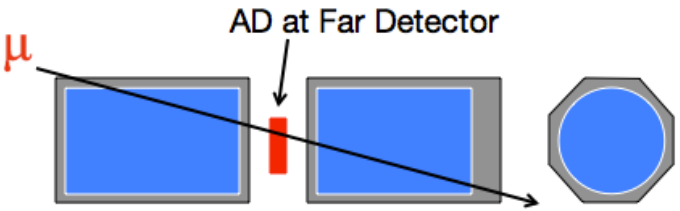
ND - AD latencies = 36 +/- 4ns

4. AD measurement at Far

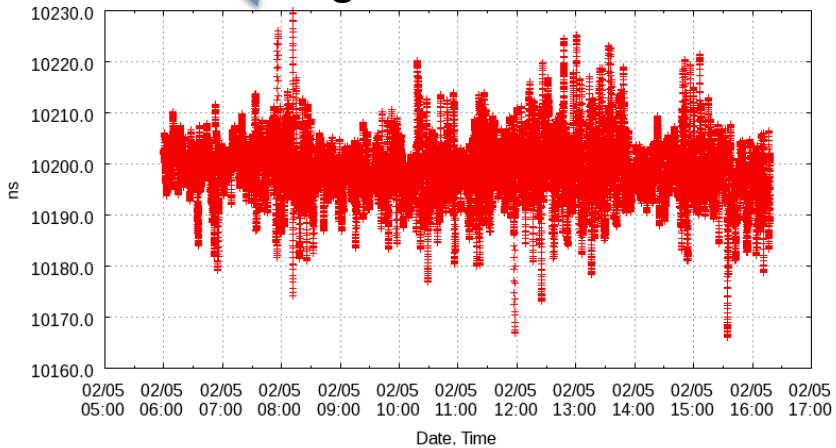
- ✓ Use cosmic ray events for matching
- ✓ Use PPS signals from Cs Clock and GPS as "START" signals respectively for Auxiliary and Far detectors

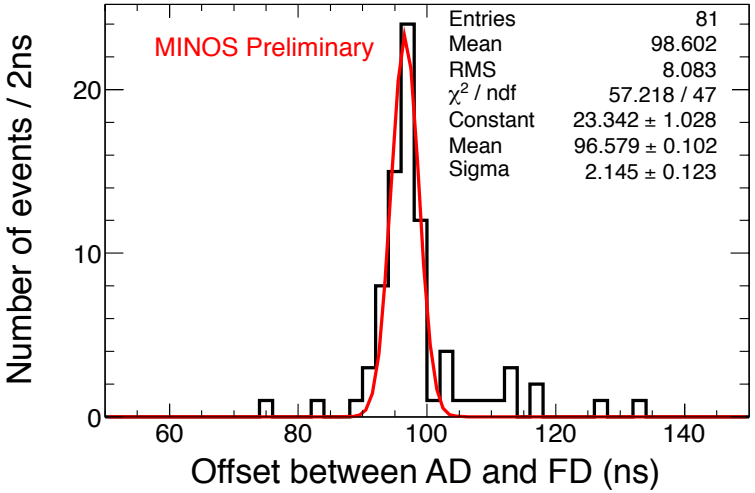






Monitored by Agilent 53230A





FD - AD latencies = 12 +/- 2ns

Summary

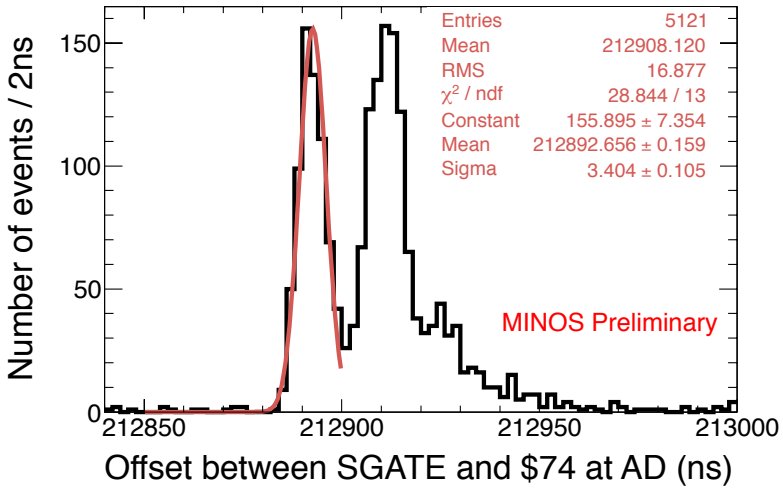
- ✓ The ADs are necessary for mitigating the electronic readout latencies
- ✓ The ADs has already installed and first results are used for TOF retrospective analysis in 2012

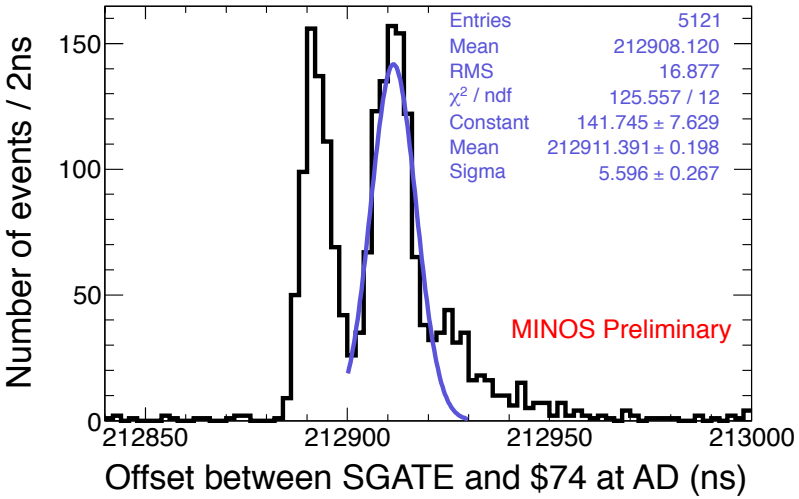
Full Spill approach: $TOF_v - TOF_c = -18 \pm 11$ (stat.) ± 29 (syst.) ns
Wrapped Spill approach: $TOF_v - TOF_c = -11 \pm 11$ (stat.) ± 29 (syst.) ns

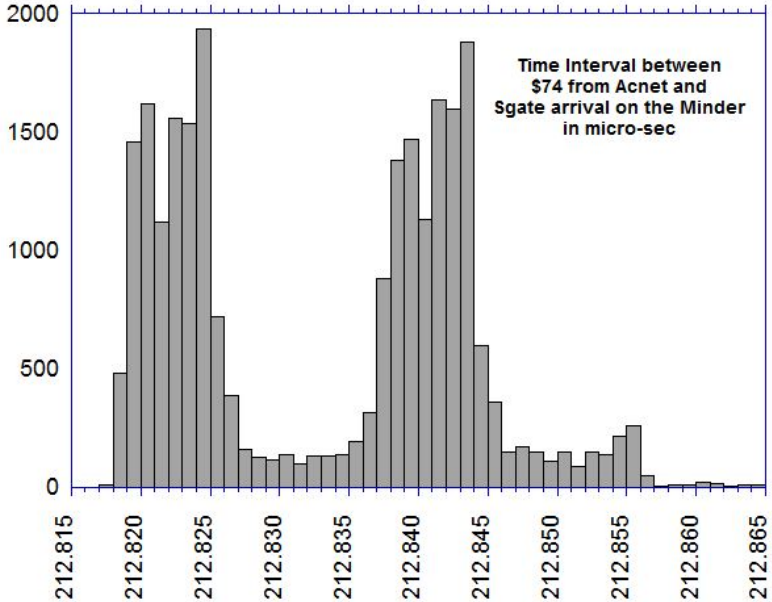
- ✓ The AD will be used in the next phase of Time Of Flight measurement

Source of latency	Uncertainty 2007	Uncertainty 2012
ND electronic latencies	32ns	4ns
FD electronic latencies	3ns	2ns
F/N detector relative latencies	9ns	1ns

Backup: Fit at peaks







Backup: Systematic revisit

MINOS overview
TOF principle
AD setup
Measurement
Summary

- (A) Resurvey the distance between two detectors
- (B,D) Re-estimate the length of cables
- (F) Better synchronization systems
- (C,E,G) Auxiliary detector to measure delays of readout system

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

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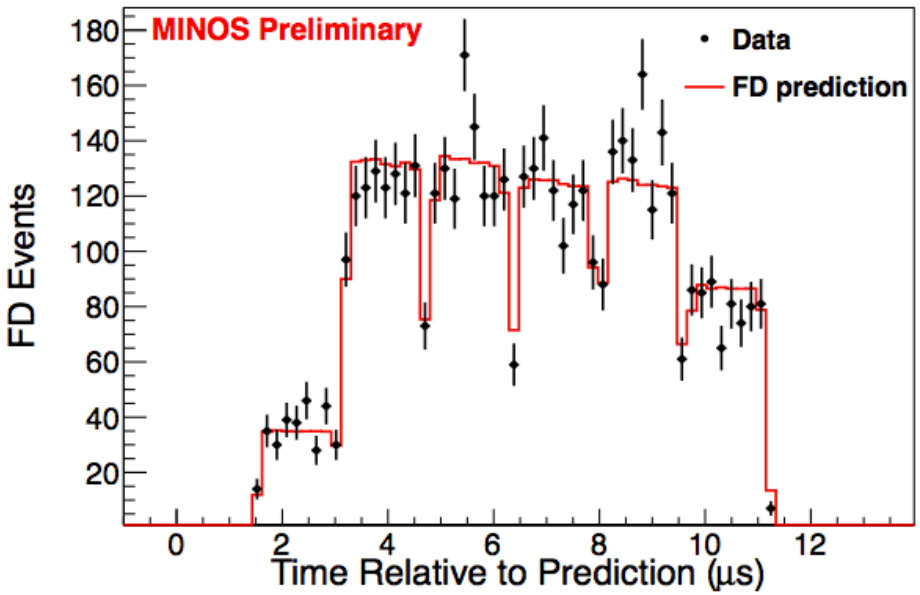
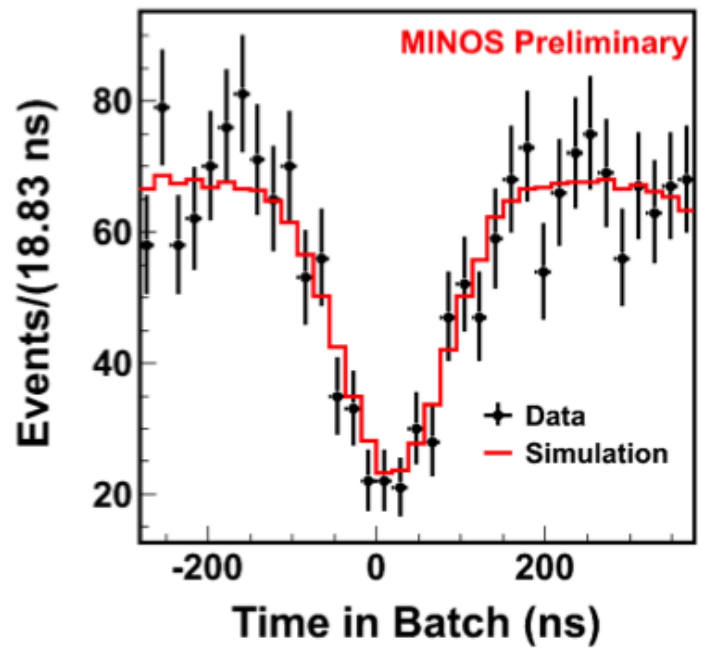
2007 Analysis	Phase I (6 months)	Phase II (9-12 months)	Phase III (2013 and on MINOS+ era)
	Re-analysis existing data, reduce dominant systematic errors	Hardware improvement	More hardware improvement , update beam energy
64 ns	18-33 ns	11-18 ns	2-7 ns

Backup: two TOF approaches

- NuMI neutrinos spill lasts about 10us
- Spill subdivided into 1.619 us batches (5 or 6 batches)
- 95ns gap between batches





Full Spill approach:

✓ ND event time within spill predicts FD timing distribution

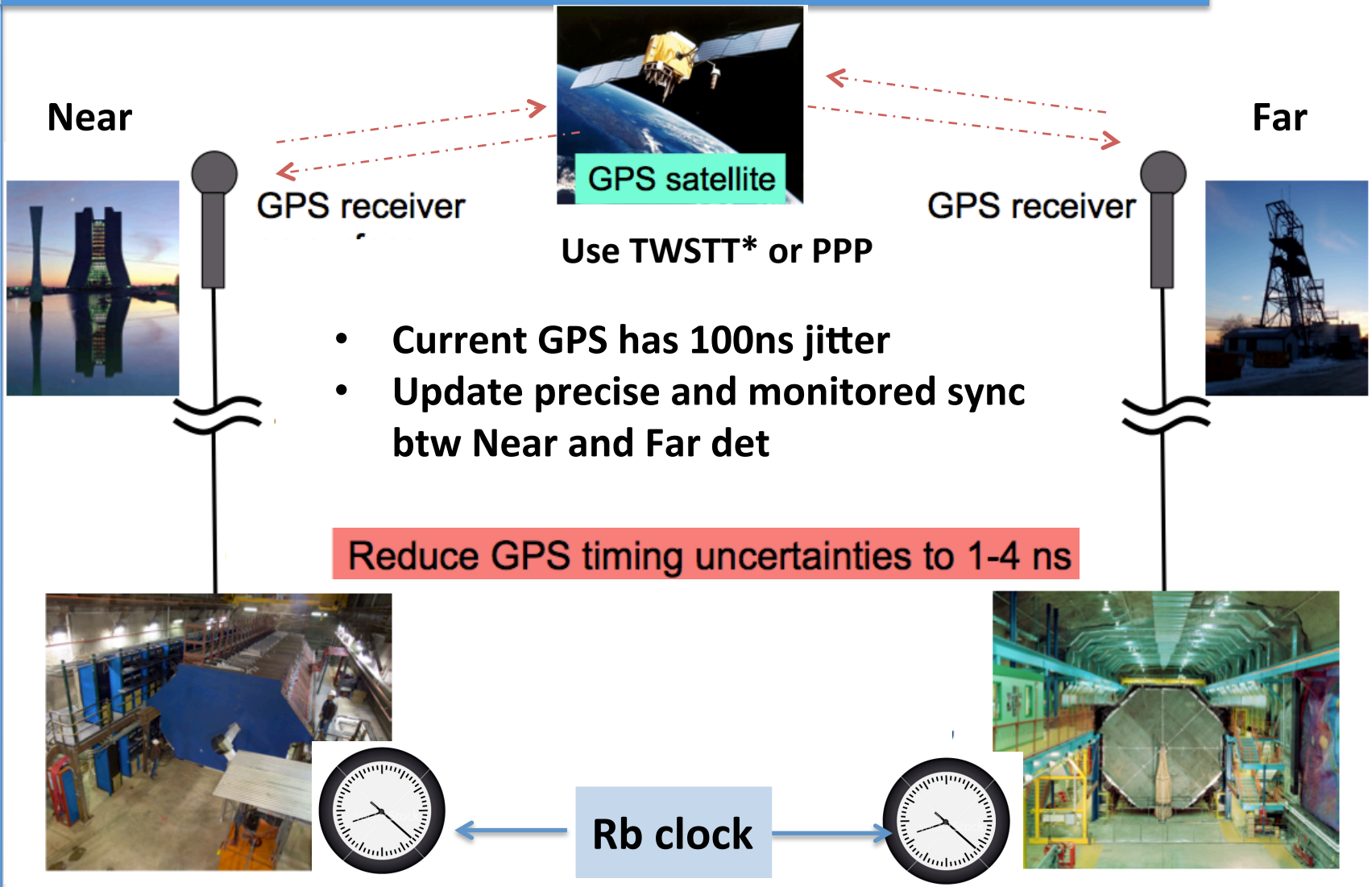
✓ Find best value of Time of Flight to match data

Wrapped Spill approach:

✓ Wrap events within batch in each detector

✓ Fit two gaps in two detector and subtract them

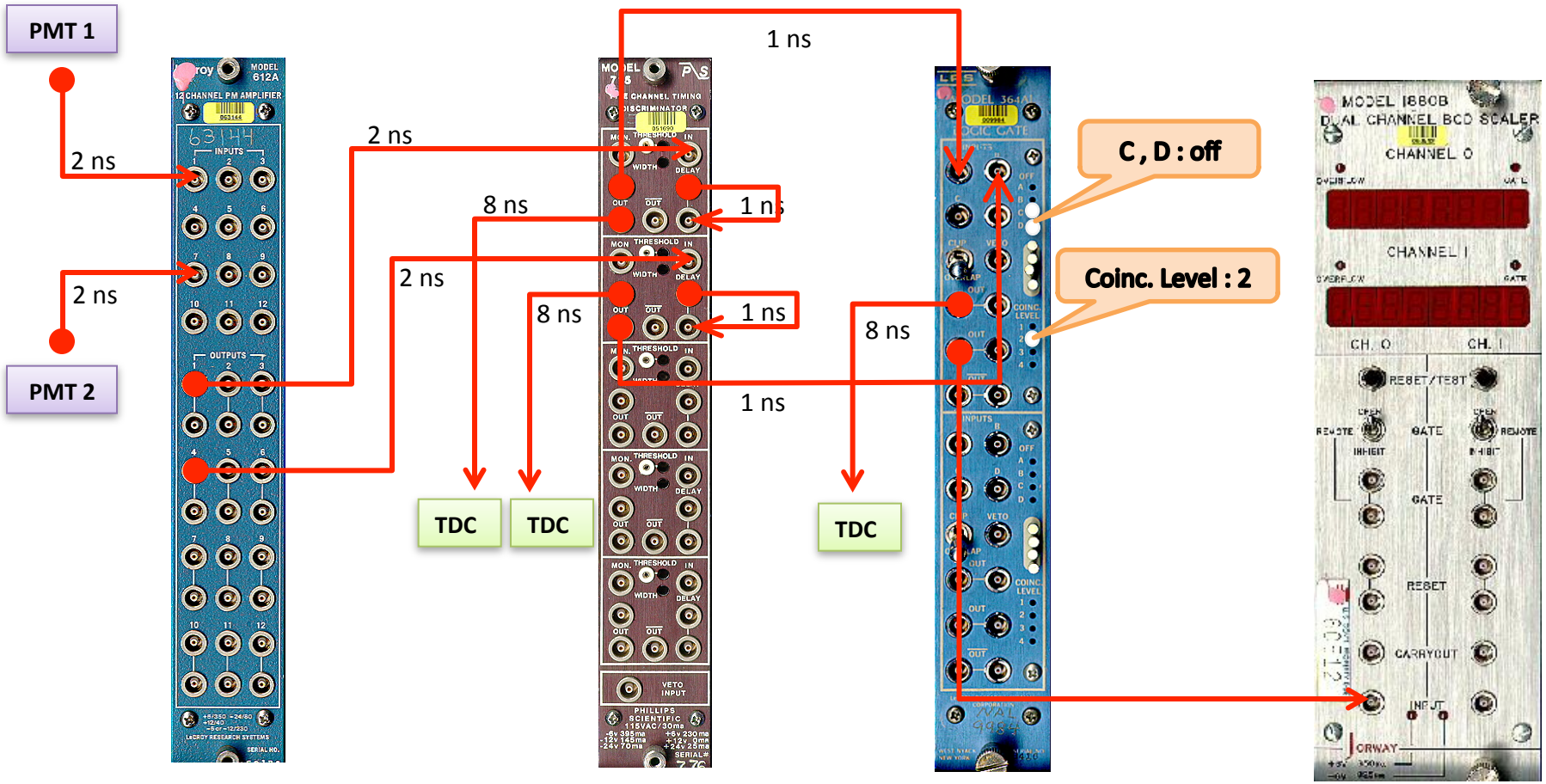
Backup: update timing system



- Current GPS has 100ns jitter
- Update precise and monitored sync btw Near and Far det

*TWSTT: Two-Way Satellite Time Transfer
PPS: Point Position System

From PMT to Amplifier to discriminator to Logic Unit



NIM Model 612A: 12-Channel Photomultiplier Amplifie

NIM 715: five-channel constant fraction timing discriminator

Model 364AL: Dual 4-Fold Majority Logic Units

Model 1880B: Dual Visual Scaler

Design slightly different