

The DØ Luminosity Monitor Operations and Performance

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Abstract

The D0 Luminosity Monitor (LM) plays a crucial role in D0 physics analyses by providing the normalization for many cross section measurements. The detector consists of two sets of 24 scintillator wedges read out with photomultiplier tubes. The detector is located in the forward regions surrounding the beam pipe, covering a pseudo-rapidity range of $2.7 < |\eta| < 4.4$. The LM is sensitive to a large fraction of the total inelastic cross section and measures the luminosity by counting the number of empty proton-antiproton bunch crossings, using Poisson statistics to extract the instantaneous luminosity. The techniques used to convert the measurements made by the LM into the assessed luminosity will be discussed, as well as the performance and operational details of the detector.

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1. Introduction

The D0 detector is one of two multiple purpose particle physics detectors on the Tevatron ring at Fermilab. The Tevatron collides bunches of protons and anti-protons at a center of mass energy of 1.96 TeV. The D0 detector uses a set of sub-detectors that surround the interaction point to collect information about particles created in the $p-\bar{p}$ collisions. The Silicon Microstrip Tracker (SMT) and the Central Fiber Tracker (CFT) comprise the tracking system which helps identify secondary vertices and measures the momentum of charged particles by the radius of their bend since the tracking system sits in a 2 T magnetic field. The next detector subsystem, moving away from the interaction point, is the Calorimeter which measures the total energy of electrons, photons, and hadrons. Muons penetrate the tracker, magnet, and calorimeter and are detected in the muon system, the outer-most subsystem of the D0 detector. Along with the three layers of scintillator and proportional drift tubes, the muon system uses a toroid magnet to provide a second measurement of the muon momentum. Details of the D0 detector can be found in Reference [1].

The Luminosity Monitor (LM) is located in the forward region between the SMT and the calorimeter. The LM consists of scintillating wedges with photomultiplier tube (PMT) readout. The LM has 48 scintillator and PMT channels split into two arrays, referred to as North and South, see Figure ???. The channels sit in the forward region of the detector at ± 140 cm from the nominal interaction point. The channels surround the beam pipe like a doughnut with the scintillator perpendicular to the beam direction covering a pseudo-rapidity range of $2.7 < |\eta| < 4.4$, where pseudo-rapidity, η , measures the angle of trajectory of a particle with the beam direction being $\theta = 0$, as given by Equation 1.

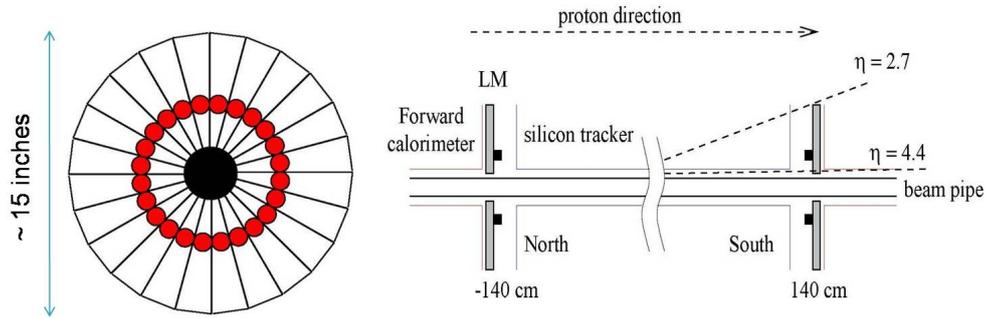


Fig. 1. A schematic showing the r-φ and r-z view of the luminosity monitor. The North and South arrays are shown with respect to beam direction, position, and pseudo-rapidity coverage [2].

$$\eta = -\ln(\tan(\theta/2)) \tag{1}$$

2. Luminosity Measurement

Luminosity is a measurement of the number of interactions during beam crossings for a given cross section. If N is the number of interaction per second, L is the luminosity, and σ is the cross section, then they are simply related by $N = L\sigma$. Note that the units of luminosity, also called instantaneous luminosity, are $\text{cm}^{-2} \text{s}^{-1}$. The peak luminosity observed at D0 is $421\text{E}30 \text{ cm}^{-2} \text{ s}^{-1}$. At this time the Tevatron has delivered over 11 fb^{-1} of integrated luminosity, and D0 has recorded over 10 fb^{-1} . The luminosity measurement is an important component to physics analyses. The luminosity at D0 is measured by a technique called “counting empties”, where “empty” is defined as a beam crossing in which no hit was recorded in the LM. For the purposes of the luminosity system, a hit requires firing at least one channel on both the north and south array with an in-time coincidence. By counting the number of hits and the number of crossings, the number of empties can be determined. The luminosity measurement is made using the number of empties and Poisson statistics as given in Equation 2.

$$P(0) = e^{-\sigma_{eff}L/v} * (2e^{(-\sigma_{ss}/2v)L} - e^{-\sigma_{ss}L/v}) \tag{2}$$

Here $P(0)$ is the probability of an empty crossing, L is the luminosity, and v is the crossing frequency for the beam bunches. The luminosity constant, σ_{eff} , is the effective cross section seen by the luminosity monitor, see Section 2.1. Particles that hit the LM come from inelastic collisions in the beam interaction. The luminosity constant is determined using the cross section for inelastic $p - \bar{p}$ collisions at the Tevatron energy and the acceptances of the luminosity monitor. The factor in parenthesis which depends on the single-sided cross section, σ_{ss} , is a correction for backgrounds which arise when two separate interactions, each of which fire only one side of the LM, overlap to fake a double-sided hit.

Beam in the Tevatron is separated into 36 bunches. The luminosity is measured separately for each bunch. Figure 2 shows that the bunches are distributed into 3 groups of 12 bunches, a train, separated by abort gaps. The luminosity system at D0 measures and monitors the beam halo as well as the luminosity. Halo comes from particles that travel with the beam but are outside the beam pipe. Halo is often created by particles from the beam interacting with material upstream of the collision point and causing a shower. Halo goes through one array of the LM in early but reaches the other array in-time. Thus it is very important to monitor the halo to make an accurate luminosity measurement as well as for the safety of other sub-detectors at D0. Halo is measured separately for the (anti-) proton beam which fire the (South) North array at approximately -9 ns , as diagramed in Figure 3.

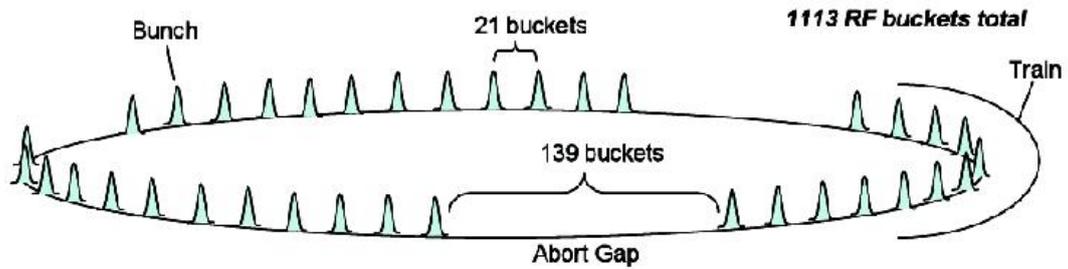


Fig. 2. The 36 bunches in the Tevatron are grouped into sets of 3 super-bunches separated by abort gaps [3].

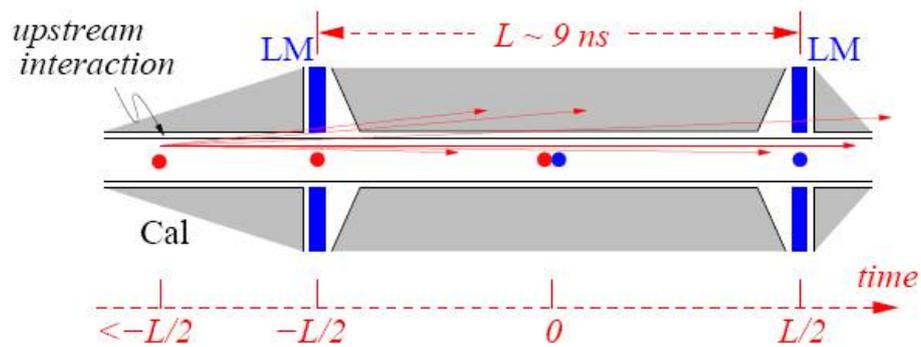


Fig. 3. A diagram showing the production of halo and interaction in the luminosity monitor.

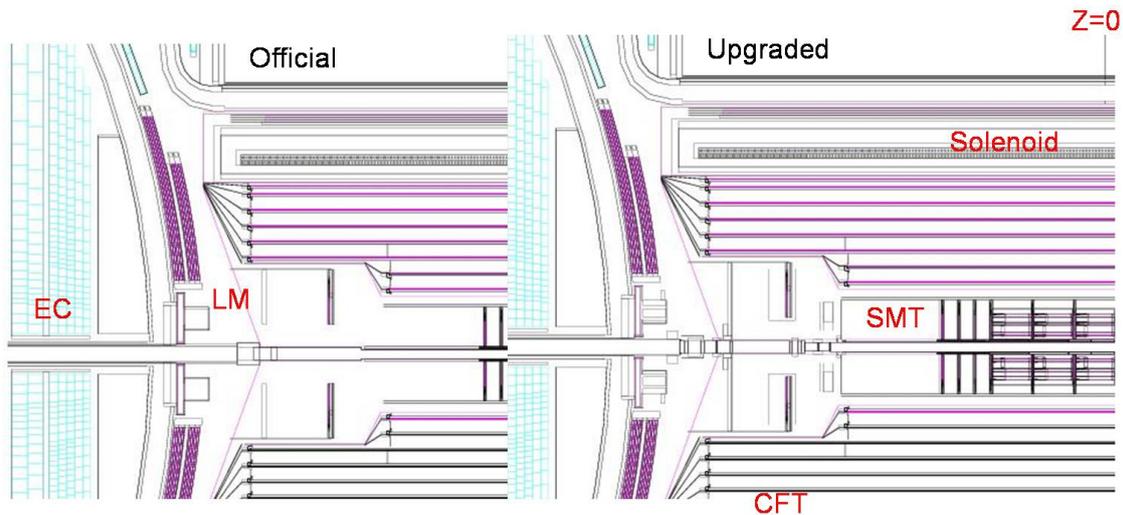


Fig. 4. A drawing of the inner D0 detector showing the changes to the MC model. The half slice starts at the $z=0$ interaction point on the right hand side and shows the tracking system (SMT, CFT, and solenoid), luminosity monitor (LM), and end cap calorimeter (EC). Note the material changes in the beam pipe, going horizontally through the center, and in the forward region.

2.1. Run IIB Luminosity Constant

At D0 the period after the March 2006 shutdown is referred to as Run IIB. During this shutdown, an additional silicon layer was added to the D0 detector. In order to add the detector layer, changes were also made to the beam pipe and support structure. A material change in the inner and forward region of the D0 detector changes the material in front of the LM which can affect the acceptances to the LM. While the effect to the luminosity constant was expected to be small, it was important to re-evaluate it for this period.

The re-evaluation of the Run IIB luminosity constant included taking new data sets, updating the Monte Carlo (MC) model, and improving the analysis technique, among other tasks. The result of this work is a significant improvement in the systematic uncertainty of the luminosity measurement. Results will be publically available and part of physics analysis soon.

The D0 experiment has constructed a detailed Monte Carlo (MC) model of the full detector based on the GEANT3 [4] software package. Updating the MC material model for RunIIB was critical for determining the new acceptances for the luminosity monitor. The additional layer of silicon became the most inner layer of the Silicon Microstrip Tracker. The change meant going to a smaller beam pipe in this region and the addition of bellows and flang connections. Carbon fiber support structures were changed to accommodate the new weight load. In order to get readout from the new sensors, an outer layer of silicon sensors in the forward region was removed. The preamplifier boards in the luminosity system were also upgraded in the 2006 shutdown. While the changes to the silicon sensors and some support structure were updated in the D0 Monte Carlo material model, details of the forward region were not added since the effect on physics analysis MC was negligible. However, the LM is particularly sensitive to the material in the forward region, so the material in the high η region was updated for the luminosity constant work. Figure 4 highlights the difference in the standard MC geometry and the upgraded geometry used for the constant analysis.

3. Luminosity Monitor (LM)

The luminosity monitor uses Saint-Gobain BC-408 scintillator. The scintillator is polyvinyltoluene (PVT) primarily doped with anthracene. The photomultiplier tubes are one inch, fine mesh tubes (Hamamatsu R7494) custom made for the system. The fine mesh allows the PMTs to work inside the magnetic field

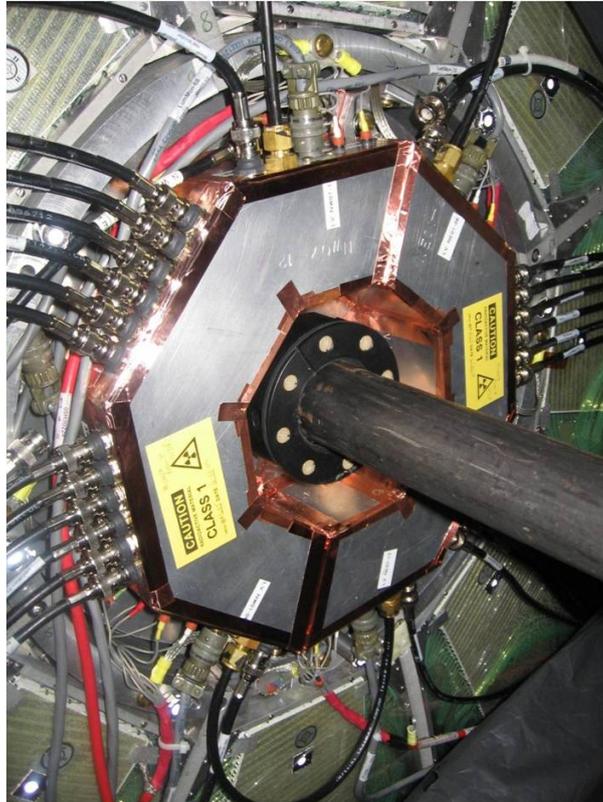


Fig. 5. Picture of the North LM taken during the Summer 2009 shutdown. This view is not possible during normal operations. The gold tape going diagonally across the LM highlights the separation between the enclosures. The brown pipe is the beam pipe.

of the solenoid, which has an approximate field strength of 1.25 T at the LM. The PMTs have a quartz window to help combat radiation damage. The 24 channels in each array are further separated into 2 enclosures visible in Figure 5. The enclosures allow the LM to be removed during long shutdowns for maintenance. For each channel the PMT signal is preamplified in a board in the LM. The signal is sent by cable to a readout system outside of the collision hall. A readout system based on NIM electronics is used to determine the beam halo. An improved system based on VME electronics has been used for all the luminosity measurements during the Run IIB period. The VME system uses an analog-to-digital converter (ADC) and a timing-to-digital converter (TDC) to determine the charge and timing separately for all channels. The NIM system relies on summing over many channels to determine charge and timing information. A diagram of the luminosity system electronics readout is shown in Figure 6. [2]

4. Luminosity Operations

Standard luminosity system operations includes calibrations, monitoring, maintenance, and dealing with challenges as they arise. The operations team has worked hard to keep the stability of the luminosity measurement with a $\pm 0.5\%$ during the Run IIB period.

4.1. Calibrations

Timing and pedestal calibrations are part of regular luminosity operations. The timing window for a hit to the D0 luminosity system is ± 6.4 ns relative to nominal. The window is set to separate halo interactions and hits from inelastic beam collisions. Figure 7 x gives an example of the timing distribution with halo

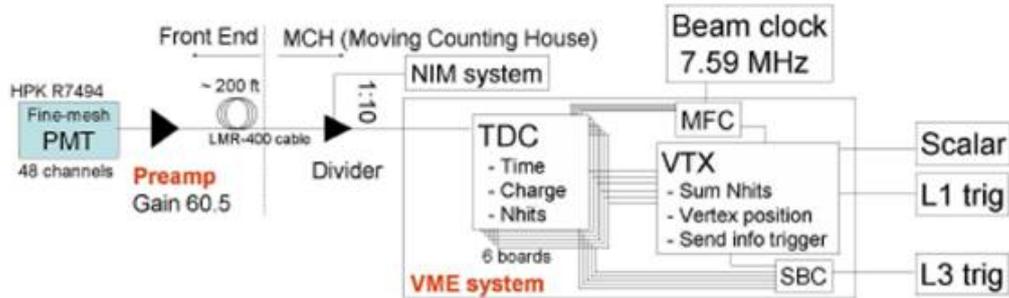


Fig. 6. This schematic shows the luminosity electronics readout system.

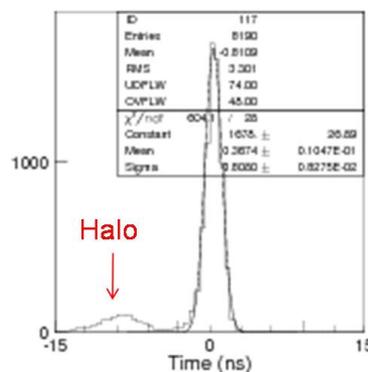


Fig. 7. Plot of the timing for a single channel during the halo removal process before the store. During this time, the luminosity voltage is set to 70% of the appropriate value. This data is not used for physics analysis, but is used to highlight the timing of a halo interaction.

hits highlighted. To ensure that good hits do not drift outside of the timing window, the timing calibration is adjusted to keep the mean time for each channel within approximately ± 1 ns of nominal, as shown in Figure 8. Monitoring of the mean time has been automated, and the value of 1 ns has been determined from operational experience to keep good hits in the timing window and halo interactions out. Timing drifts occur because the signal for collisions is sent from the Accelerator Division on cable which expands and contracts with temperature variations in the seasons. The change in cable length can be up to 2 ns. The pedestals for the luminosity system can also shift due to temperature variations. The goal is to keep the pedestal values in a ± 4 pC range, where 4 pC is equivalent to $33 \mu V$ at the preamplifier input. The output of pedestal checks before and after a calibration can be seen in Figure 9.

4.2. HV Updates

Correctly setting the high voltage (HV) value on the PMTs is vital to making an accurate luminosity measurement at D0. The HV values are set for each channel so that the gain produces an anode current of $18 \mu A$ at a luminosity of $300E30 \text{ cm}^{-2}\text{s}^{-1}$. As the system is bombarded by radiation from the beam, the scintillator is damaged and the light output reduced. To compensate for this damage, the HV setting on the PMT is periodically adjusted. In practice, the HV is raised approximately every 1 fb^{-1} of delivered luminosity. The operations group uses ADC versus luminosity plots for each channel and HV and Threshold Scans to determine when to raise the HV setting on the photomultiplier tubes. During a HV or Threshold Scan, the HV or threshold set point is varied during beam and the difference in the luminosity measurements

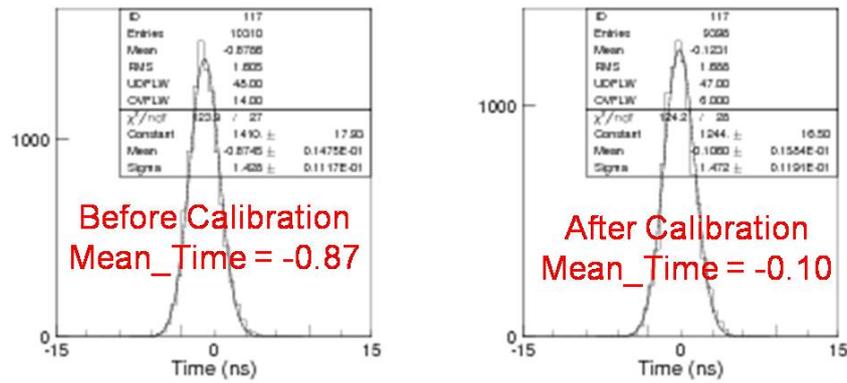


Fig. 8. A comparison of timing distributions before (left hand plot) and after (right hand plot) calibration. Before calibration the mean time is -0.87 ns and after calibration it is -0.10 ns.

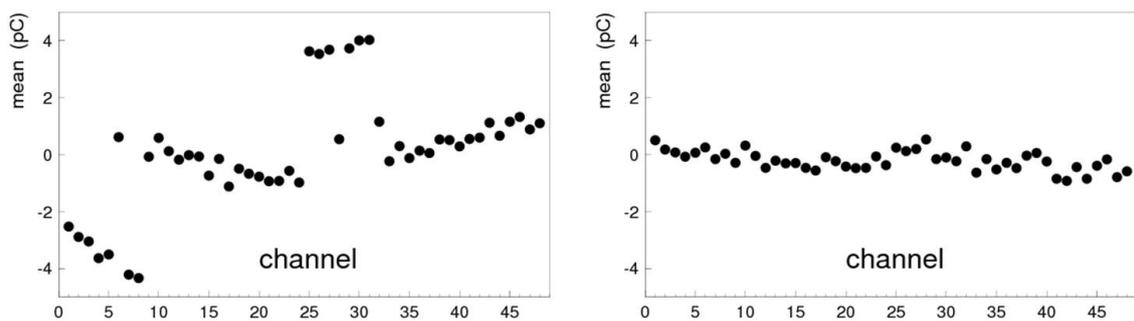


Fig. 9. Pedestal distributions before and after calibration.

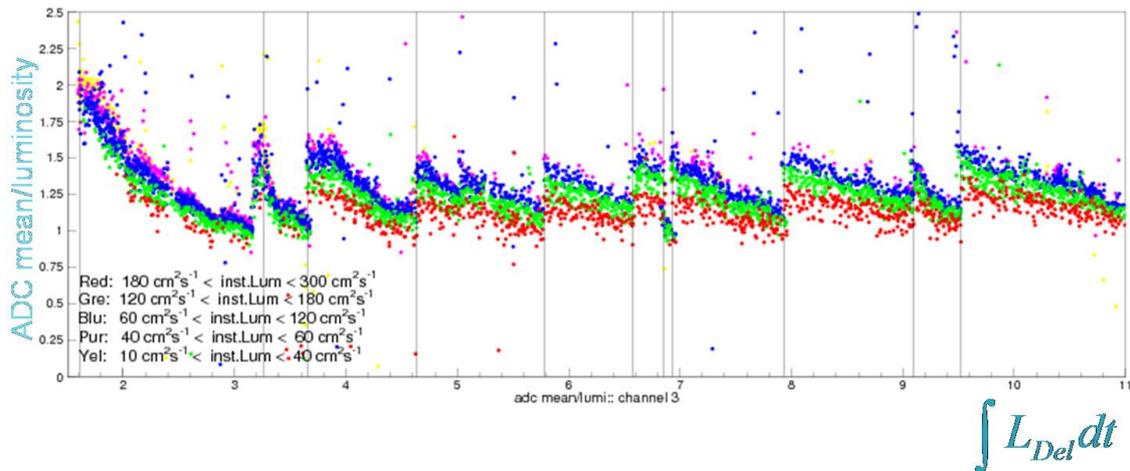


Fig. 10. Plot of the average charge normalized by instantaneous luminosity versus integrated delivered luminosity (fb^{-1}) for a single channel. Each dot represents a single run, or segment of data collected. While the vertical units are arbitrary, experience shows that keeping the gains above 1 provides a stable luminosity measurement.

is studied to check the operating conditions. The ADC versus luminosity plot, an example of which is shown in Figure 10, looks at the average charge normalized by instantaneous luminosity for a single channel. The drop in gain as a function of delivered luminosity is monitored to help determine when HV settings need to be changed and to see problems in individual channels. Raising the HV setting on the PMTs only works as long as the scintillator is not badly damaged. At that point, the scintillator needs to be changed.

4.3. Shutdowns

During long accelerator downtimes, one or more months, the operations group takes the opportunity to do maintenance on the luminosity monitor. The main task of these shutdowns is a full scintillator replacement. The scintillator was replaced in the Summer of 2006, 2007, 2009, and 2010. One of the major concerns with doing maintenance on the LM is getting the enclosures out safely. This is a worry because, as seen in Figure 5, the LM closely surrounds the beam pipe, which should not be touched. The 2010 shutdown was particularly interesting because it was the shortest shutdown in which a scintillator replacement was done. In addition, 14 of the 48 PMTs were replaced at this time due to aging concerns. For the 2010 shutdown, the LM was out for only 2 weeks to get all this work accomplished. Figure 11 is a picture comparing the radiation damaged scintillator replaced in 2009 with the new scintillator being put into the luminosity monitor. Note the yellow color near the tip of the wedge. This region is closest to the beam pipe. The scintillator in Figure 11 accumulated 3.6 fb^{-1} of delivered luminosity over a two year period. This is the most luminosity delivered to a batch of scintillator before replacement.

4.4. Challenges

Every detector comes with a new set of challenges to overcome as the running conditions continue to evolve and components age. One interesting issue the luminosity group has had to deal with recently is a double peak structure in the timing distributions of some channels at high luminosity, see Figure 12. This behavior is due to electronics saturation along the signal readout chain. While the behavior is undesired, it has not affected the luminosity measurement. Figure 12 shows the timing for good hits is still within the $\pm 6.4 \text{ ns}$ window. As an update to this talk, the saturation was tracked down to a component in the TDC boards. The issue is being monitored, but the boards will not be replaced before the end of running since the issue is not affecting the measured luminosity. The double peak structure was more noticeable as the Accelerator Division provided higher initial luminosity stores and the HV was increased, but the feature did not become a problem.



Fig. 11. Comparing new and old scintillator during the Summer 2009 shutdown. The bottom piece of scintillator was exposed to 3.6 fb^{-1} of delivered luminosity over a two year period. Note the yellow discoloration at the tip which was closest to the beam pipe.

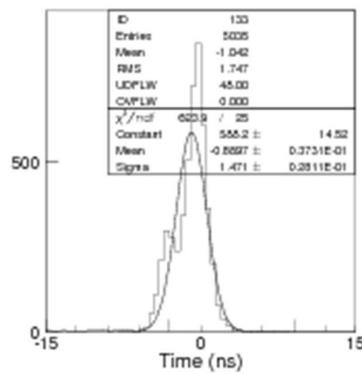


Fig. 12. The timing double peak in one channel at high luminosity. The right hand plot shows that the early timing hits are from saturation at large charge.

5. Conclusions

The D0 luminosity system is a very robust detector. Operations of the luminosity monitor is vital to the collection of good physics data at D0. Maintenance, monitoring, calibrations, and dealing with challenges as they arise keep the system running smoothly and keep the luminosity measurement within a $\pm 0.5\%$ stability range. Thanks to all who contribute to this effort!

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