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Luminosity measurements at hadron colliders

Vaia Papadimitriou *

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA

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ABSTRACT

In this paper, we discuss luminosity measurements at Tevatron and HERA, as well as plans for luminosity measurements at LHC. We discuss luminosity measurements using the luminosity detectors of the experiments as well as measurements by the machine. We address uncertainties of the measurements, challenges and lessons learned.

1. Introduction

Luminosity measurements are an absolutely necessary component of any experimental beam colliding program since they provide the frequency of the interactions and the needed normalization for the physics process under study (Standard Model and beyond the Standard Model physics processes, new physics, etc.). Luminosity measurements also allow for the monitoring of the performance of the accelerator and for the implementation of beam parameter adjustments as needed for optimized performance.

We will discuss below luminosity measurements by the CDF and D0 experiments on the Tevatron side and by the H1 and ZEUS experiments on the HERA side. We will review the techniques used and discuss the uncertainties of the measurements. We will also discuss the challenges that were faced and the lessons learned. On the LHC side we will discuss the plans for luminosity measurements by the machine as well as by the experiments. In this case, we will focus on the high-luminosity regions of ATLAS and CMS. We will discuss again techniques, expected uncertainties and challenges to be faced.

2. Luminosity measurements at the Tevatron

The Tevatron, a proton–antiproton collider, has delivered $110\,\mathrm{pb}^{-1}$ per experiment to the CDF and D0 experiments in Run I (1992–1996) at a center of mass energy of 1.8 TeV and with a spacing of $3.5\,\mu\mathrm{s}$ between collisions. It has in addition delivered $3.85\,\mathrm{fb}^{-1}$ per experiment between July 2001 and March 2008 (Run II) at a center of mass energy of 1.96 TeV and with a spacing of 396 ns between collisions. Thirty-six proton bunches are colliding with 36 antiproton bunches in Run II, with a typical number of protons per bunch, $\sim 2.5\times 10^{11}$, and a typical number of antiprotons per bunch, $\sim 7\times 10^{10}$. On March 17, 2008 there was an initial luminosity record set of $3.15\times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Between March 24 and March 30, 2008 the accelerator complex delivered a record of $48\,\mathrm{pb}^{-1}$ for a single week. The Tevatron is expected to deliver 5.8–$6.7\,\mathrm{fb}^{-1}$ per experiment by the end of fiscal year 2009 and, if it runs longer, 7.3–$8.8\,\mathrm{fb}^{-1}$ by the end of fiscal year 2010.

Absolute luminosity measurements by the machine based on measurements of beam parameters like emittances, intensities, beam lattice, etc. have uncertainties of the order of 15–20%. The Tevatron luminosity measurements are basically based on the real-time, relative luminosity measurements performed by the CDF and D0 experiments, which are then normalized to a relatively well-known and copious process, in this case the inclusive, inelastic proton–antiproton cross-section. The instantaneous luminosity $\mathscr{L}$ is estimated by using Eq. (1), where μ is the average number of interactions per beam crossing, f_{BC} is the frequency of bunch crossings and σ_{in} is the inelastic cross-section. The average number of interactions can be estimated either by measuring the probability of zero interactions ($P_0(\mu)=\mathrm{e}^{-\mu}$ for a detector of 100% acceptance) or directly, by counting particles or hits or time clusters in the detector. The CDF and D0 collaborations have agreed to use a common proton–antiproton inelastic cross-section for luminosity normalization in Run II. This common cross-section has been derived [1] on the basis of averaging the inelastic cross-sections measured by the Fermilab CDF and E811 experiments at 1.8 TeV and extrapolating the cross-section at 1.96 TeV:

$$\mu f_{\mathrm{BC}} = \sigma_{\mathrm{in}}\mathscr{L} \tag{1}$$

In addition, one can cross-calibrate the luminosity measurements with rarer, cleaner and better understood processes like the decay $W\to l\nu$.

* Tel.: +1 630 840 8207; fax: +1 630 840 4552.
E-mail address: vaia@fnal.gov

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Both experiments have used scintillating counters to measure the luminosity during Run I. For Run II, where the instantaneous luminosity is substantially higher, CDF opted for a Cherenkov counter system, while D0 for a scintillating counter system of better granularity than Run I.

The CDF Cherenkov counter system [2] consists of 48 counters per side arranged in 3 layers with 16 counters each, covering the pseudorapidity region $3.7 \leqslant |\eta| \leqslant 4.7$. The counters are filled with isobutene and are read by Hamamatsu R5800QCC photomultipliers (PMTs) with a quartz window. The Cherenkov counter system allows for good separation between primaries and secondaries, good amplitude resolution (~18% from photostatistics, light collection and PMT collection), good timing resolution and, in addition, it is radiation hard. Full simulation with PYTHIA agrees well with the data for the amplitude distribution in the Cherenkov counters. In Fig. 1 is displayed the amplitude distribution in the data for one Cherenkov counter after an isolation requirement of <20 photoelectrons in the surrounding counters. The single particle peak (SPP) is clear. Fig. 2 shows how the average number of particles (total amplitude over the amplitude of the SPP) or hits (counters with amplitude above a certain threshold) varies as a function of the average number of proton–antiproton interactions and compares the data with the Monte Carlo simulation. The data and the simulation compare very well. At the highest luminosities the particle-counting algorithm is more linear. As a reference, note that μ approximately equal to 6 corresponds to $\mathscr{L}$ approximately equal to $2 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The CDF luminosity measurement is based as a default on measuring the probability of zero interactions and uses measuring hits and particles as a cross-check. CDF has evaluated that the luminosity measurement using the probability of zero interactions is reliable up to about $3.6 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The current CDF luminosity measurement uncertainty is 5.8%. The leading contribution is from normalizing to the proton–antiproton inelastic cross-section (4%). The next two most important contributions are due to simulating the material in the detector (3%) and the relative contribution from non-diffractive and diffractive processes in the Monte Carlo generator (2%). CDF is cross-checking their absolute luminosity measurements by comparing with the inclusive W and Z boson cross-section measurements and the comparison is very satisfactory. The yield of J/Ψ's and W's through the $J/\Psi \to \mu\mu$ and $W \to l\nu$ decays as a function of instantaneous luminosity serves as an additional

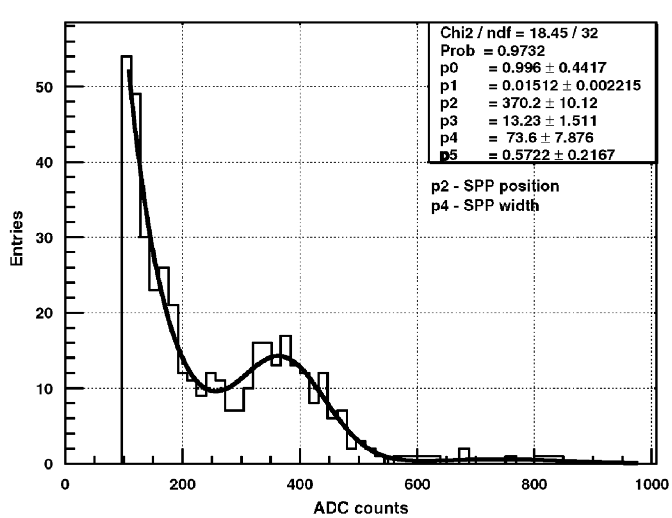

Fig. 1. Amplitude distribution for a single Cherenkov counter at CDF. The solid line represents a fit to the data.

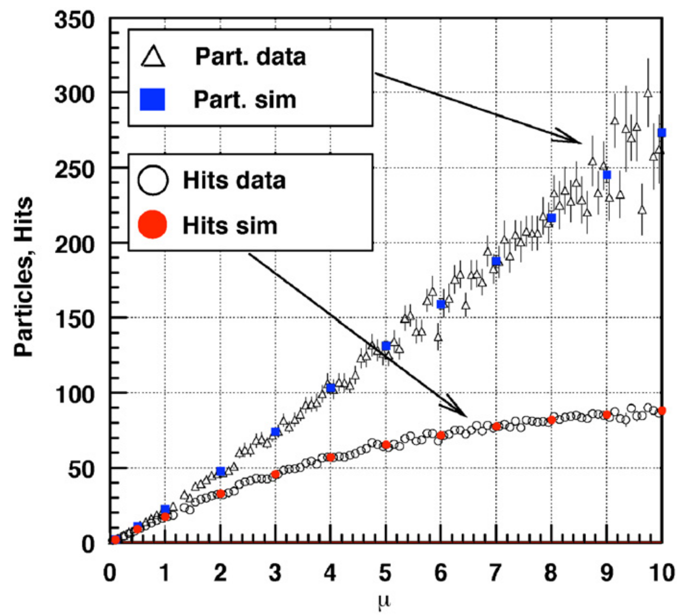

Fig. 2. Data vs. Monte Carlo simulation comparison of the average number of particles or hits vs. the average number of proton–antiproton interactions at CDF.

check of the stability of the luminosity measurements. The aging rate of the PMTs is ~35% per fb^{-1} and is being addressed by high voltage and PMT gain adjustments or with replacements as needed.

The D0 Run II luminosity system [3] consists of two forward scintillator arrays covering the pseudorapidity region $2.7 \leqslant |\eta| \leqslant 4.4$. There are 24 wedges per array, each read out with a fine-mesh PMT. Inelastic collisions are being identified by using the coincidence of in-time hits in the two arrays. Since October 2005, the luminosity readout electronics changed from NIM to custom VME [4]. The D0 luminosity measurement is based on measuring the probability of zero interactions. The current D0 luminosity measurement uncertainty is 6.1%. The leading contribution is from normalizing to the proton–antiproton inelastic cross-section (4%). The next two most important contributions are due to the determination of the non-diffractive fraction (~4%) and the long-term stability (~2.8%). Fig. 3 shows the data vs. Monte Carlo simulation comparison of counter multiplicity (above a threshold) assuming the final, non-diffractive fraction of 0.687 ± 0.044. D0 uses the yield of forward muons as a function of time and instantaneous luminosity as an additional check of the stability of the luminosity measurements (within ~1% during the past couple of years). The radiation damage to the scintillator is being addressed by annealing and replacement as needed.

The CDF/D0 ratio of instantaneous luminosities is being checked continuously and is being compared with the expected ratio on the basis of beam parameters. The goal is to keep this ratio within a couple of percent around 1. Significantly larger deviations observed a few times so far have led to thorough investigation on both the machine and experiment sides and resulted in either machine parameter adjustments or improvements in the techniques used by the experiments to measure the luminosity [4].

Some of the lessons learned so far from the luminosity measurements at the Tevatron are that: the method of counting zero interactions works well for the current Tevatron luminosities; fine granularity detectors are needed for high instantaneous luminosities (Run I vs. Run II); in situ calibration of the detector is very important; detector stability is crucial; a good simulation of