Computation of the TEVATRON Luminosity Using Measured Machine Parameters

N. M. Gelfand *
Fermi National Accelerator Laboratory
P.O.Box 500
Batvia Il 60510

Abstract

In order to extract the cross section from a measured reaction rate an experimenter needs to know the incident flux. At a collider the flux is referred to as the luminosity $\mathcal{L}$. The luminosity can be determined in an experiment by measuring the rate of a reaction with a known cross section. This paper describes an alternative calculation of the luminosity based on measurements made on the stored beam in the TEVATRON. The measurements necessary for the calculation, which must be made on each of the p and $\bar{p}$ bunches, are the intensity and the transverse and longitudinal extent of each of the bunches.

Luminosity Calculation

In order to compute the luminosity of the TEVATRON it is necessary measure certain properties of the beam and to calculate the characteristics of the lattice.

We need to measure for each bunch, the following information :

- The transverse dimensions of the beam at the interaction point.
- The bunch length.
- The beam intensity.

Data on the properties of each of the 12 (6 p and 6 $\bar{p}$) bunches in the TEVATRON were collected during the last collider run and stored (along with the associated time and date) in a relational data base. The data needed for this analysis was retrieved from the data base.

The transverse dimensions of the beam at the interaction point are calculated from the bunch width, σ, as measured by the flying wires, and the computed values of the lattice functions β and the dispersion η at the locations of the flying wires and at the interaction point. [1] The particular lattice, *viz.* mini-β, fixed target *etc.* is determined from a knowledge of the current in the low β quadrupoles and the beam energy.

The bunch intensity and length are measured by the S(ampled) B (unch) D(isplay).

The following discussion is limited to measurements made with the TEVATRON energy at 900GeV (corresponding to a center of mass enrgy of 1.8 TeV), the mini-β lattice (β^* =0.5m), and with 6 p and 6 $\bar{p}$ bunches in the TEVATRON. The data are from store 1728 (11/6/88) to the end of the collider run, store 2284 on 5/31/89.

It must be recognized that there is very little redundancy in the measurements used in these calculations. Nor is there a good way of monitoring closely the performance of the devices used in the measurements or their calibrations. Thus care must be used when approaching the data and further we must look at the results of the calculations to identify bad or suspect data.

The one place where we do have redundancy is in the measurement of the longitudinal emittance ϵ_l. It can be calculated from the measurement of the bunch length made by the SBD (ϵ_l(SBD) and from the measurement of dp/p calculated from the flying wire data (ϵ_l(WIRE)). In Figure 1 is plotted ϵ_l(WIRE) vs ϵ_l(SBD) for protons and antiprotons. There are obviously anomalous data which are almost certainly due to bad data from the flying wires.

The results presented for the calculated luminosity include only those measurements that survived after a cut was imposed on the ratio ϵ_l(WIRE)/ϵ_l(SBD). This was done to insure that the WIRE data are consistent with the SBD measurements. A cut was also imposed on the ratio of ϵ_v/ϵ_h in an attempt to remove other bad measurements.

The effect of these cuts can be seen by comparing the data in Figure 1 and those in Figure 2.

Even after the cuts are applied to the data there are still problems. The longitudinal emittance as computed from the SBD data is, on the average, more than 20% larger than that computed from the WIRE measurements for the proton bunches and 10% larger for the anti-protons. While an error in the lattice functions at A17 and C48 could account for the difference between the SBD measurements and those based on the flying wires, the difference between protons and anti-protons suggests that part of the discrep-

*Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000.

[1] The lattice functions and γ_t have been calculated using TEVLAT and the MTF measurements of the high order multipoles for the dipoles and quadrupoles and the measured strengths of the quadrupoles.

0-7803-0135-8/91$01.00 ©IEEE

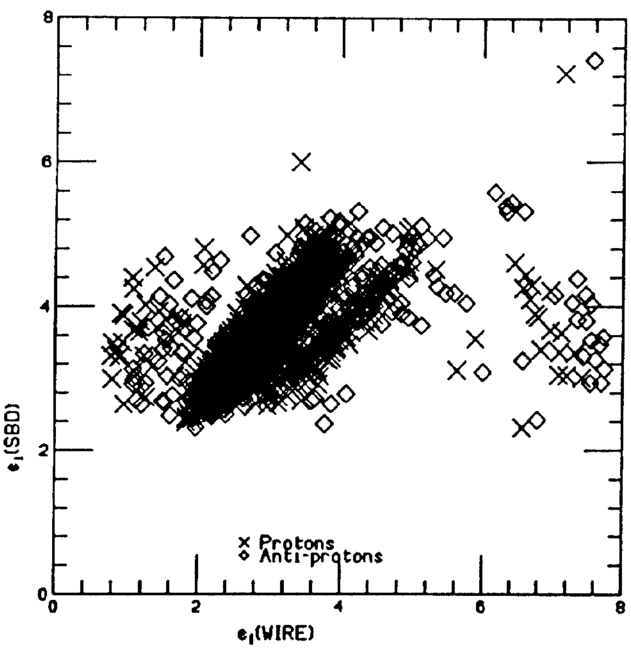

Figure 1: ϵ_l(WIRE) vs ϵ_l(SBD)

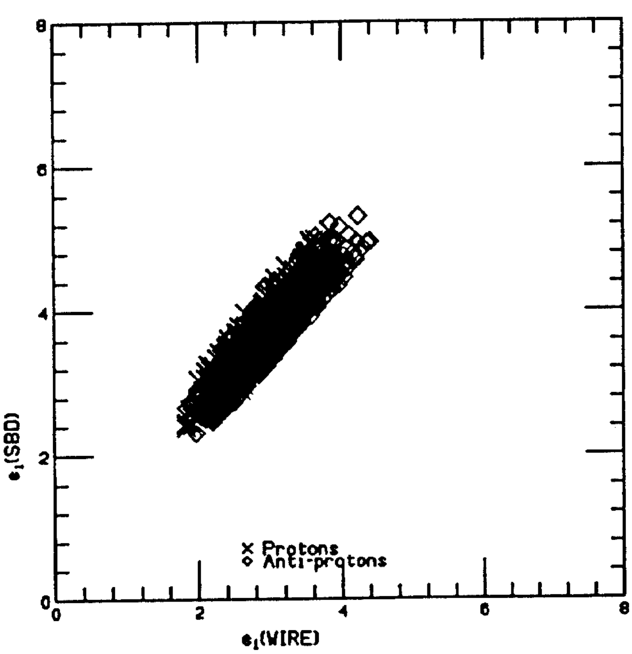

Figure 2: ϵ_l(WIRE) vs ϵ_l(SBD) - After cuts.

ancy could be due to an to an intensity dependent error (the protons and anti-protons have significantly different intensities) of the SBD determination of the bunch length σ_l.

Similarly ϵ_v is $\approx$ 10% larger than ϵ_h. Here there is no significant difference between the protons and the anti-protons. If there is no systematic error in the σ (which could arise due to problems with the detectors recording the particles scattered from the wires) from the flying wires then the difference could be due to an error in either or both of the β functions at C48.

Our inability to understand these inconsistencies in the data limit our ability to confidently measure the luminosity.

In order to calculate the luminosity $\mathcal{L}$ we require, in addition to the the beam properties, we need the values of the lattice functions β and α and the the values of the dispersion functions η and η' at the interaction point.

The calculations of $\mathcal{L}$ presented here makes use of the the transverse emittances calculated from the flying wires, the dp/p derived from the SBD data and incorporates an integration over the longitudinal extent of the beam.

Comparison With The Measured Luminosity

The calculated values for the luminosity can be compared with the value for the luminosity measured at CDF. [2] The comparison is shown in figure 3. It must be noted that no correction has been made to any of the measured quantities for possible miscalibrations. These data can be fit with a quadratic form viz.

$$\mathcal{L}_{cal} = a_0 + a_1 \times \mathcal{L}_{meas} + a_2 \times \mathcal{L}^2_{meas} \qquad (1)$$

The fit, shown as the line in figure 3, is good, the rms deviation of the fitted value from the calculated luminosity being $\approx \pm 0.02 \times 10^{30}/\ \mathrm{cm}^2\cdot$ sec. There is no strong dependence of the coefficients on the store number. The intercept of the fitted curve is ≈ 0. The coefficient of the linear term, 1.09$\pm$0.01, is significantly different from 1. There is also a significant negative quadratic coefficient in the fit. This result is that the value of $\mathcal{L}$ calculated from the measurements made on the TEVATRON are lower that those measured at CDF for values of the measured luminosity greater than $\approx 1.25 \times 10^{30}$ cm$^2\cdot$ sec.

Errors

Any meaningful calculation of the luminosity must include an estimate of the error. Table I contains a list of the quantities (Q) that go into the calculation of the luminosity, an estimate of their systematic and random uncertainties and their contribution to the uncertainty in the

[2] The measurement at CDF is based on an assumption of a cross section and is not a direct measurement of the luminosity.

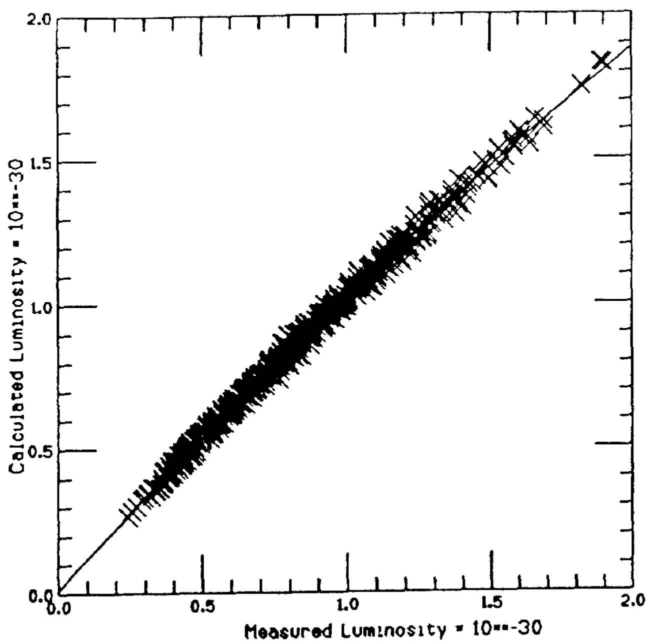

Figure 3: $\mathcal{L}_{measured}$ vs $\mathcal{L}_{calculated}$

luminosity. The resulting uncertainty from the measurement uncertainties is $\approx$ 1.3% while the uncertainty due to systematic uncertainties is $\approx$ 11.4%. The uncertainty due to the ascribed errors in measurement is quite comparable to the $\approx$ 2% spread seem in the comparison of the calculated luminosity and the measured luminosity (the error in the measured luminosity is $\approx$ 0.5%).

The factor that contributes most to the uncertainty in $\mathcal{L}$ is the calibration of the SBD measurements of the bunch intensities. Also contributing significantly to the error in the calculated luminosity are the uncertainty in the measured wire σ (particularly the vertical wire σ at C48 because of the relatively small value of β_y) and the uncertainties in the lattice functions at the wires and at B0. We also find that there is a significant contribution to the error on $\mathcal{L}$ from the measurements of the SBD of the bunch length and the calculated value of dp/p using the measured bunch length and the r.f. voltage (due to the systematic uncertainty in the voltage).

Conclusions

The calculation of the luminosity is in good agreement with the estimates coming from the CDF measurements. It is, however, clear that if we wish to improve the uncertainty with which we measure the luminosity it will be important to improve the calibration of the SBD in measuring the length and intensities of the bunches. A better determination of the lattice functions would also improve the accuracy of the calculation. This can be done by with more, and better, measurements of β, not only at the wire locations and the interaction points, but at enough other points to constrain the model used to calculate the lattice functions. The error could also be reduced if β at the vertical wire were larger. This might require having the vertical wire at a different location from the locations of the horizontal wires.

It is also important to calibrate, and periodically monitor the calibration, of the various devices whose output is needed to calculate the luminosity. This calibration should be done over the range of normal working conditions, including energy.

Acknowledgements

I wish to acknowledge many helpful conversations with Dr. David Finley in the course of this work.

Table I

Values used:
Energy 900 GeV
Bunch Intensities

$N_p = 52 \times 10^9$
$N_{\bar{p}} = 20 \times 10^9$

Normalized emittances

$\epsilon_h(p) = \epsilon_h(\bar{p})$ =20 mm-mr
$\epsilon_v(p) = \epsilon_v(\bar{p})$ =25 mm-mr
$\epsilon_v(p) = \epsilon_v(\bar{p})$ =3.5 eV-sec

Luminosity (1 bunch on 1 bunch)

$1.22 \times 10^{29}/\mathrm{cm}^2/\mathrm{sec}$

Contributions of Systematic Errors in Measured and Calculated Quantities to the Error in the Luminosity

Variable Q	Value	Systematic δQ	$\delta\mathcal{L}/\mathcal{L}$
Bunch Length	54.6 cm	5%	-2.9%
r.f. Voltage	1.2MV/turn	5%	-0.6%
β_h(C48)	164 m	5%	+1.8%
β_h(A17)	196 m	5%	-0.0%
β_v(C48)	69.9 m	5%	-2.5%
β_h(B0)	0.55 m	5%	-1.1%
β_v(B0)	0.53 m	5%	-1.5%
α_h(B0)	+0.124	5%	+0.0%
α_v(B0)	-0.049	5%	-0.0%
η(C48)	0.595 m	5%	+0.1%
η(A17)	6.95 m	5%	-0.0%
η(B0)	0.197 m	5%	-1.3%
η'(B0)	-0.145	10%	-0.0%
Intensity		5%	+10.2%

Contributions of Random Errors in Measured and Calculated Quantities to the Error in the Luminosity

Variable Q	Value	Random δQ	$\delta\mathcal{L}/\mathcal{L}$
Bunch Length	54.6 cm	1cm	-0.5%
HC48 Wire Sigma	0.759 mm	20μ	-1.0%
VC48 Wire Sigma	0.551 mm	20μ	-1.8%
HA17 Wire Sigma	1.32 mm	20μ	+0.1%
Intensity		1×10^9	+0.5%