

Total Cross Section and Elastic Scattering from TEVATRON to LHC

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A review of measurements of the total cross section in $p\bar{p}$ collisions at the TEVATRON and an outlook on the expected performance for similar determinations at the LHC is given. The experimental method is based on the optical theorem to determine the total cross section independent of the machine luminosity. It consists of the extrapolation of the t -spectrum for elastic scattering to $t \rightarrow 0$ with a simultaneous measurement of the total inelastic rate.

1 Introduction

One of the most elementary observables at hadron colliders is the total cross section. Precise measurements at high energies have been pioneered at the SPS by the UA4 [1] collaboration. The method requires an instrumentation of the forward region far away from the interaction point but close enough to the beam to measure small-angle elastic scattering. At high energies the t -value for elastic $p\bar{p}$ and pp scattering can be obtained from a measurement of the scattering angle θ by $-t = (p \cdot \theta)^2$ with the beam momentum p . The scattering angle is reconstructed from the proton impacts in the forward tracking devices, usually located in movable beam pockets, the so-called Roman Pots. On the other side, simultaneously with the elastic measurement, the total inelastic rate must be determined, which requires an extended pseudorapidity η coverage. In this case the total cross section is given by

$$\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{dR_{\text{el}}/dt|_{t \rightarrow 0}}{R_{\text{in}} + R_{\text{el}}}, \quad \rho = \frac{\text{Re}(F_{\text{el}}(t))}{\text{Im}(F_{\text{el}}(t))} \Big|_{t \rightarrow 0},$$

independent of the machine luminosity. In this formula, $R_{\text{in(}(\text{el})}$ is the inelastic (elastic) rate, and the F are the corresponding amplitudes. In the following we shall review the measurements performed by the TEVATRON experiments and summarise the potential for the LHC experiments.

2 Measurements at the TEVATRON

2.1 E710

At the FNAL TEVATRON $p\bar{p}$ -accelerator the first total cross section measurement was done by the E710 experiment [2]-[4] at $\sqrt{s} = 1.8$ TeV. The E710 set-up was located around the E0 interaction point and was equipped with two Roman Pots at each side of E0 for the measurement of elastic protons. The Roman Pots were instrumented with wire chambers for the tracking and trigger scintillators. The locations of these detectors were in between 25 and 124 m from the interaction point. Under suitable beam conditions with high β^* optics and low emittance the detector could be moved close to the beam at a distance of a few millimetres. In this case the impact position $u = x, y$ is related to the scattering angle by $u \propto \sqrt{\beta^* \beta_{RP}} \theta$, where β is the betatron oscillation function resulting from the magnetic lattice. The measured t spectrum from E710 is shown in fig. 1. The t -spectrum exhibits an approximately exponential fall-off with

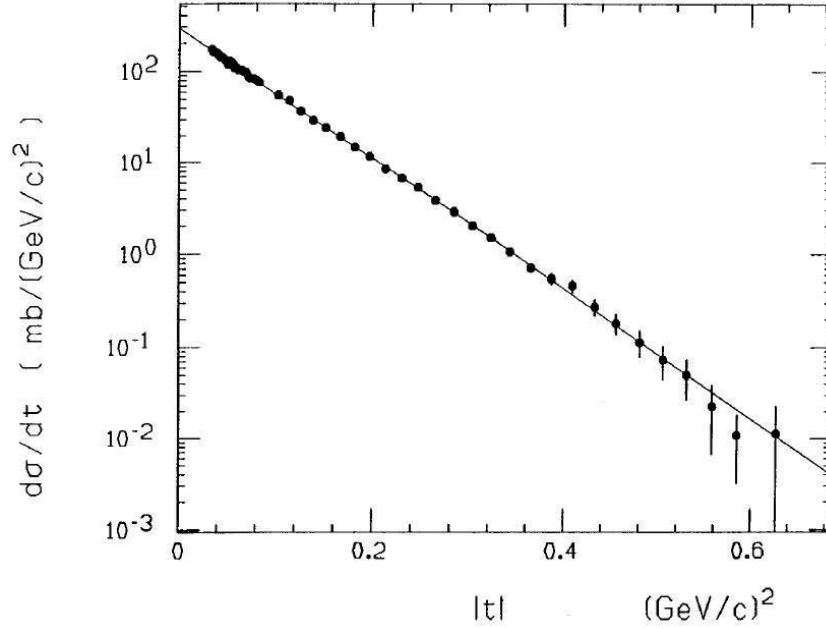


Figure 1: Elastic t spectrum at 1.8 TeV measured by E710 [2].

the nuclear slope B in the considered range. The elastic differential cross section is normally given by

$$\begin{aligned} \frac{d\sigma}{dt} &= \frac{1}{16\pi} |F_C(t) + F_N(t)|^2 ; \\ F_C(t) &= -8\pi\alpha\hbar c \frac{G^2(t)}{t} \exp(i\alpha\Phi(t)) ; \\ F_N(t) &= (\rho + i) \frac{\sigma_{\text{tot}}}{\hbar c} \exp\left(\frac{-Bt}{2}\right) , \end{aligned} \quad (1)$$

with the Coulomb and nuclear amplitudes F_C resp. F_N , the electric form factor of the proton $G^2(t)$ and the Coulomb phase $\Phi(t)$. The Coulomb contribution is rather small in the t -range covered by E710, thus only the nuclear component was used to fit the spectrum (line in fig. 1) in order to determine the optical point, which is defined by the value of the fit at $t = 0$.

The total inelastic rate was measured in E710 by the set-up depicted in fig. 2. It consisted of

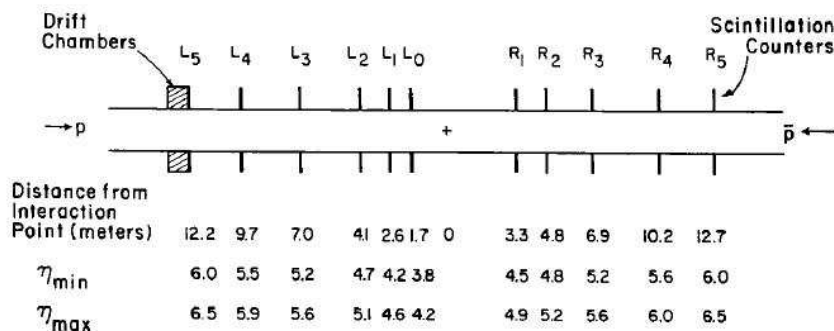


Figure 2: Inelastic detectors of E710.

various annular scintillator counters segmented in four quadrants along the beam line covering a pseudo-rapidity range from 3.8 to 6.5, supplemented by drift chambers for precision tracking. With a trigger coincidence between the left and right arm about 70% of the inelastic interactions are covered. Some events, in particular from single diffraction processes escaped the left-right detection and were recovered by a single-arm OR trigger condition. This trigger is dominated by background from beam-gas interactions or halo protons which was measured using non-colliding bunches in the machine and then subtracted. A small fraction of events could still not be detected because of the limited angular acceptance coverage. The acceptance corrections were also obtained from the data using the drift chamber extrapolation the rate as function of the cosine of the maximum detected angle to zero, following a method developed by UA4 [1]. The final results from E710 are summarised in Table 1.

Table 1: Results from TEVATRON experiments.

σ_{tot} [mb]	σ_{el} [mb]	$\sigma_{\text{tot}}/\sigma_{\text{el}}$	experiment
80.03 ± 2.24	19.70 ± 0.85	0.246 ± 0.004	CDF
71.42 ± 2.41	15.79 ± 0.87	0.220 ± 0.008	E811
72.8 ± 3.1	16.6 ± 1.6	0.230 ± 0.012	E710

2.2 CDF

The second experiment to perform measurements of elastic and total cross sections at the TEVATRON was CDF [5],[6]. The elastic spectrometer of CDF consisted of three Roman Pot stations on the \bar{p} -side and two on the p -side, each instrumented with wire chambers, silicon strip detectors and trigger scintillators. The acceptance for elastic scattering was obtained from a detailed beam transport simulation and is shown in fig. 3. The inelastic measurement

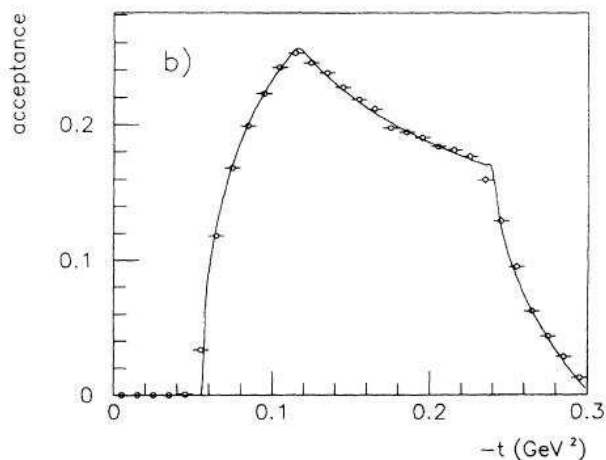


Figure 3: Acceptance of CDF for elastic scattering.

of CDF profited from the rich instrumentation around the interaction point; in particular the vertex TPC covering up to $|\eta| \leq 3.5$ allowed for a high-quality vertexing and enabled efficient background rejection. In the forward region a telescope of drift chambers from UA4 covering $3.8 \leq |\eta| \leq 5.5$ and a movable telescope enclosing completely the beam pipe when in beam position and covering then to $|\eta| \leq 7$ were installed. For the determination of the inelastic rate, in addition to the traditional left-right coincidence, a dedicated single-diffraction trigger consisting of a coincidence between the elastic spectrometer on one side detecting the diffractive proton and the opposite inelastic detectors tagging remnants of the diffractive dissociation was set up. Acceptance corrections for the limited angular coverage of the inelastic detectors and for losses of the diffractively scattered protons were obtained from detector and beam line simulations. The result from CDF, given in Table 1, is somewhat larger than the E710 result, both for the elastic and the total cross section. It should be noted that CDF has also provided a measurement [6] at 546 GeV, $\sigma_{\text{tot}} = 61.26 \pm 0.93$ mb, compatible with the UA4 result [1].

2.3 E811

Given the discrepancy between E710 and CDF, another experiment E811 [7] was built upgrading the E710 location. E811 used the same inelastic detectors as E710 but replaced the elastic detectors by a scintillating fibre tracked coupled to a CCD read-out yielding a spatial resolution of $20 \mu\text{m}$. The analysis technique was similar to the E710 method but E811 accumulated larger statistics, extended the t -range and improved the systematic uncertainties [8]. Their final result [9] confirms the first E710 measurement and differs from CDF by 2.6σ on the total and by 2.9σ on the elastic cross section. The total cross section measurements are shown in fig. 4 together with lower energy $p\bar{p}$ results.

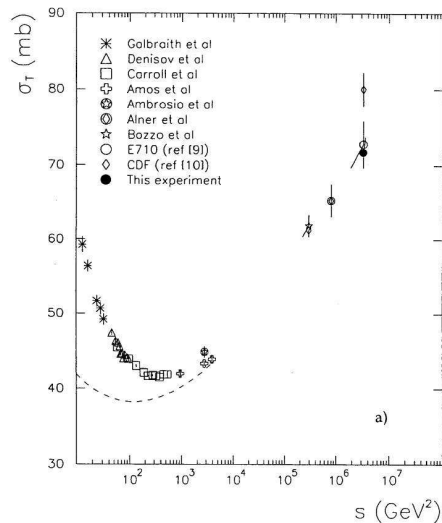


Figure 4: Summary of total cross section measurements at TEVATRON compared to lower energy data. *This experiment* is E811, taken from [8]

3 Prospect for measurements at LHC

3.1 TOTEM

At the LHC similar measurements are proposed by the TOTEM experiment [10],[11] and ATLAS [12] with its dedicated ALFA subsystem [13]. TOTEM shares the interaction point with CMS and has Roman Pot stations at 147 and 220 m distance, with both detection in the vertical and horizontal planes to cover elastic scattering and diffraction and to ease alignment. The elastic set-up is shown in fig. 5; each station houses silicon detectors for high-precision tracking and triggering. At each location two stations separated by a few meters allow for the determination of the local track slope. The detectors consist of 10 planes of silicon strips alternating in U- and V-Geometry, in a novel edgeless technology allowing to approach the beam as close as possible. The running scenario foresees a dedicated beam optics for the total cross section measurement with a β^* value of 1540 m, in which case a good t -acceptance between 0.002 and 1.5 GeV² is achieved. But also other configurations with smaller β^* are considered which opens up access to large t values up to 10 GeV² and to extended diffractive studies.

The inelastic detectors are shown in fig. 6. They consist of two tracking telescopes T1 and T2 in the pseudorapidity region $3.1 \leq |\eta| \leq 6.5$. T1 is of conical shape and inserted underneath the CMS flux return yoke at a distance between 7.5 and 10.5 m from the interaction point. Given the requirements on rate capabilities and radiation hardness, cathode strip chambers were selected as technology choice. The compact T2 telescope is installed in the forward shield of CMS in front of the CASTOR calorimeter at about 13.5 m from the interaction point. For T2 gaseous electron multiplier detectors were selected because of their excellent ageing performance. The telescopes will be used to trigger inelastic events with high efficiency and for the reconstruction of the primary vertex to discriminate against beam-gas and beam-halo background. In addition, integrated cross sections for hard and soft diffraction can be measured, also differentially in t

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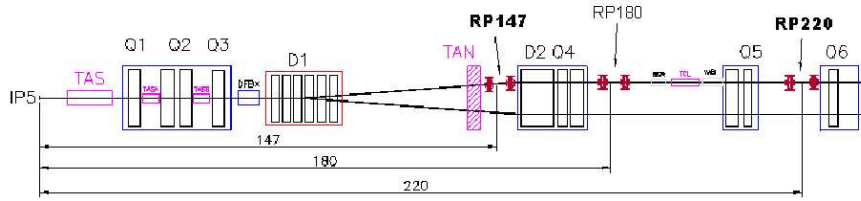


Figure 5: TOTEM elastic detectors.

and in the diffractive mass M_x .

The systematic uncertainties for the total cross section depend on the optics used. For the intermediate optics with $\beta^*=90$ m an uncertainty of 4% is anticipated, dominated by the uncertainty of the optical functions needed for the t -reconstruction, but for the high β^* optics the uncertainty may decrease to 1%.

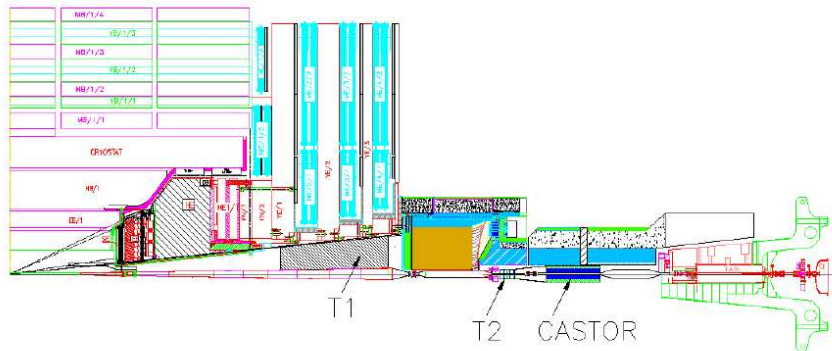


Figure 6: Inelastic detector T1 and T2 of TOTEM embedded in CMS components.

3.2 ATLAS ALFA

The primary focus of the ATLAS ALFA detector is on the absolute luminosity calibration for the different relative luminosity monitors of ATLAS and specifically the dedicated relative monitor LUCID. Therefore the detector is designed to run only for a short period and under special beam conditions at low luminosity, thereby relaxing the constraints on the radiation tolerance. The luminosity can be determined according to eq. 1 without using a measurement of the inelastic rate if the Coulomb-nuclear interference (CNI) region is covered. In this case the total cross section and the luminosity decouple because of the appearance of the Coulomb term. From a fit of the elastic t spectrum the luminosity, total cross section, B and ρ parameters can be determined simultaneously. An example of a fit to the t -spectrum reconstructed with ALFA is shown in fig. 7. This requires, however, that the CNI point where $|F_C| \approx |F_N|$, i.e. $t \approx 6.5 \cdot 10^{-4} \text{ GeV}^2$ is reached. It is therefore envisaged to use a very high β^* optics with 2600 m

at a low luminosity of about $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ with low emittance. In this case the detector can approach the beam as close as 1.5 mm (12σ) and the CNI point is covered.

The ALFA detector is located at 240 m from the ATLAS interaction point; at each location two vertical Roman Pot stations will be installed at a distance of 4 m from each other. The Roman Pots are instrumented with 10 planes of scintillating fibres, each double-sided plane carrying 64 U- and 64 V- fibres. The fibres have a good sensitivity also at the edge oriented to the beam, which is essential for a high acceptance at small t . The scintillation light is recorded by multi-anode photomultipliers. Since the detector is operated only for short periods it is foreseen to be removed after each period in order to prevent radiation damages during normal LHC operations. The scintillating fibre tracker is supplemented by plain scintillator tiles for triggering. The selected optics provides a parallel-to-point focusing in the vertical plane, and the accuracy of the t -scale depends crucially on an accurate vertical alignment. This is obtained by dedicated overlap detectors, which are made of horizontally aligned scintillating fibres housed in extrusions of the Roman Pots. When the Roman pots are in beam position the upper and lower overlap detector will measure the same halo tracks and the distance between the two pots can be determined with $\pm 10 \mu\text{m}$ precision.

The elastic trigger will consist of a left-right coincidence requesting a signal from an upper detector on one side and from a lower one on the other side in agreement with the back-to-back topology of elastic events, while coincidences of the same detector type can be used to measure the beam related background. Further background rejection can be achieved by using the local slope information from the two stations at each location. This enables a reconstruction of the transverse interaction vertex position through the beam transfer matrices.

The systematic uncertainties are dominated by the knowledge of the optical functions, the detector alignment and the background determination. According to simulation a total uncertainty of 3% is achievable, for a running time of about 100 hours at a luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$.

4 Conclusion

The long-standing tradition of total cross section measurements at hadron colliders from elastic scattering and the optical theorem has been successfully pursued at the TEVATRON with several measurements by CDF, E710 and E811 with an accuracy of about 3%. At the LHC the dedicated TOTEM experiment will continue along these lines and even more precise measurements of 1% accuracy are expected, which will also be measured by ATLAS experiment with their dedicated ALFA system.

5 Acknowledgments

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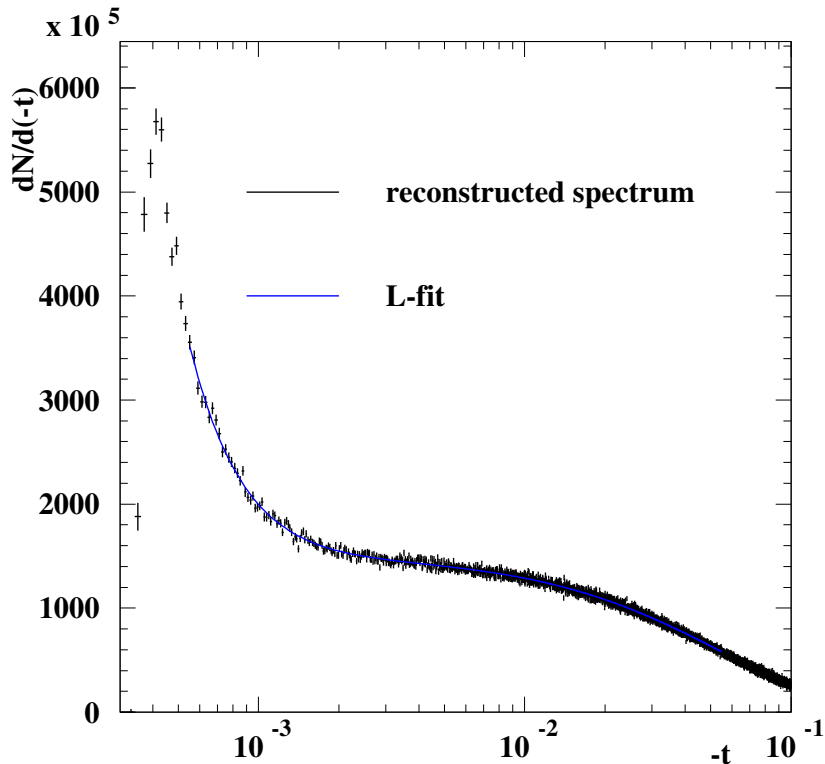


Figure 7: Simulated t -spectrum after reconstruction by the ATLAS ALFA detector compared to the fit yielding the absolute luminosity calibration.

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