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Measurements of the elastic, inelastic and total pp cross sections with the ATLAS, CMS and TOTEM detectors

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Abstract.
The elastic ($\sigma_{\rm el}$), inelastic ($\sigma_{\rm inel}$), and total ($\sigma_{\rm tot}$) cross sections are related through the differential elastic cross section using the optical theorem. ATLAS and TOTEM have used forward detectors to measure the elastic scattering at $\sqrt{s}$ = 8 TeV. The results for the total cross section are $\sigma^{\rm TOTEM}_{\rm tot,\,8\,TeV} = 101.7 \pm 2.9$ mb and $\sigma^{\rm ATLAS}_{\rm tot,\,8\,TeV} = 96.07 \pm 0.92$ mb and for the inelastic cross section $\sigma^{\rm TOTEM}_{\rm inel,\,8\,TeV} = 74.7 \pm 1.7$ mb and $\sigma^{\rm ATLAS}_{\rm inel,\,8\,TeV} = 71.73 \pm 0.71$ mb. Alternatively, the inelastic cross section can be measured in a fiducial region and extrapolated to full phase-space using theoretical models. The results from ATLAS and CMS at $\sqrt{s}$ = 13 TeV are $\sigma^{\rm CMS}_{\rm inel,\,13\,TeV} = 71.3 \pm 3.5$ mb and $\sigma^{\rm ATLAS}_{\rm inel,\,13\,TeV} = 79.3 \pm 2.9$ mb.

1 Introduction

The elastic ($\sigma_{\rm el}$), inelastic ($\sigma_{\rm inel}$) and total ($\sigma_{\rm tot}$) pp cross sections are fundamental quantities which cannot be calculated with perturbative QCD since processes with low momentum transfer are involved. Therefore, measurements of the cross sections provide a probe of the models used to describe the non-perturbative regime of QCD.

The optical theorem gives a relation between $\sigma_{\rm tot}$ and $\sigma_{\rm el}$:

$$\sigma^2_{\rm tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \frac{{\rm d}\sigma_{\rm el}}{{\rm d}t}\Big|_{t=0} , \qquad \rho = \frac{{\rm Re}\,[F_{\rm el}(t)]}{{\rm Im}\,[F_{\rm el}(t)]} ,$$

where t is the four-momentum transfer. Therefore, a measurement of the differential cross section down to small angles gives not only the elastic cross section by integration, but also the total cross section from which the inelastic cross section can be deduced.

This paper is divided in two parts. The first part describes the measurement of $\sigma_{\rm el}$, $\sigma_{\rm inel}$ and $\sigma_{\rm tot}$ at $\sqrt{s}$ = 8 TeV from the differential elastic cross section with the forward detectors TOTEM and the ATLAS-ALFA subdetector. The second part describes the measurement of $\sigma_{\rm inel}$ at $\sqrt{s}$ = 13 TeV using the central detectors ATLAS and CMS in a fiducial region followed by extrapolation to full phase-space.

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2 Elastic, inelastic and total cross section at $\sqrt{s} = 8$ TeV

The elastic, inelastic and total cross sections are determined by ATLAS [1] and TOTEM [2–4] by measuring the differential elastic cross section as a function of the four-momentum transfer t. The four-momentum transfer can be calculated from the beam momentum of the LHC and the scattering angle of the protons. The smaller the values of t that can be measured, the smaller the extrapolation uncertainty on σ_{tot}. Therefore, both TOTEM and the ALFA subdetector of ATLAS use tracking detectors about 230 meters from the interaction point (IP) and inside Roman Pots in order to go as close as 1 mm from the beam center. There are two stations on each side of the IP allowing both a position and a local angle measurement. From the knowledge of the settings for the LHC magnet between the IP and the detectors, the scattering angle can be inferred. In addition, TOTEM has two tracking telescopes close to the IP used to measure the inelastic rate, thereby allowing a luminosity independent use of the optical theorem. The inelastic rate measurement is similar to the ATLAS and CMS approach in section 3.

The data are taken in special LHC runs with low pile-up below 0.1 and high β^* collision optics since, the minimum accessible t-value is inversely proportional to β^*. Both ATLAS and TOTEM have published results with $\beta^* = 90$ m and TOTEM also with $\beta^* = 1$ km.

The elastic events are selected when a track is reconstructed in all four stations. Furthermore, due to the back-to-back signature of an elastic event, the tracks are required to fulfill certain correlation criteria between inner-outer station and left-right side of the IP. The correlations are smeared by detector resolution and beam divergence and the boundaries are determined by simulation. The background contribution comes from beam halo protons and protons from diffractive processes that occur by happenstance. The background is determined from data by events where the two protons have an identical reconstructed vertical scattering angle. It is assumed that this will happen just as often as the real background with opposite signs. The background level is for both ATLAS and TOTEM below 0.12%. Also the track reconstruction inefficiency is data driven by determining the number of elastic events with a track in less than four stations. The t-resolution is influenced by detector resolution and beam divergence. The relative t-resolution is determined by MC to be better than 10 % and data is corrected by unfolding. The acceptance correction is also determined by simulation.

The differential elastic cross section is a superposition of the strong interaction amplitude and the Coulomb amplitude. Adding in quadrature gives

$$\frac{\mathrm{d}\sigma_{\text{el}}}{\mathrm{d}t} \propto \frac{G^4(t)}{|t|^2} + \sigma_{\text{tot}}^2(1+\rho^2)\cdot\exp(-B|t|) - \frac{\sigma_{\text{tot}}G^2(t)}{|t|}\left[\sin(\phi(t)) + \rho\cos(\phi(t))\right]\cdot\exp\left(\frac{-\mathrm{B}|t|}{2}\right),$$

where G is the proton form factor, B is the nuclear slope assuming a purely exponential fall off and ϕ is the phase between between the Coulomb and nuclear interaction. The first term in the equation is the Coulomb part, the second is the nuclear part, and the third is the interference term. Figure 1 shows a simulation of the contributions from the three terms in the differential elastic cross section.

The unfolded differential cross section is fitted with σ_{tot} and B as free parameters. A lower bound on the fit range is determined by requiring a certain acceptance level in the detectors. An upper bound is set to ensure that the exponential decay is a valid approximation. At $\beta^* = 90$ m, the lower bound is about $|t| \sim 0.01$ GeV^{-2}, hence the sensitivity to the interference and Coulomb terms is absent and ρ must be taken from global model extrapolations. At $\beta^* = 1$ km (only TOTEM), the lower bound is $|t| = 6\cdot 10^{-4}$ GeV^{-2} which also allows a measurement of ρ.

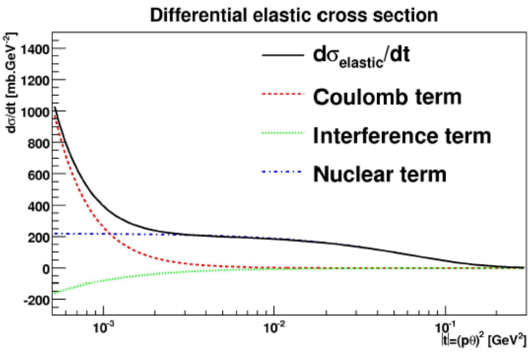

Figure 1. Simulation of the differential elastic cross section with $\sigma_{\text{tot}} = 100$ mb, $B = 18$ GeV^{-2} and $\rho = 0.13$.

2.1 Results

The results are shown in Table 1. The difference in σ_{tot} between ATLAS and TOTEM at $\beta^* = 90$ m corresponds to 1.9σ. Figure 2 shows the results along with measurements at other center-of-mass energies and a fit to data. The increase of the cross sections with energy has already been observed at lower $\sqrt{s}$ and is still evident at $\sqrt{s} = 8$ TeV.

Table 1. Results for the elastic, inelastic and total pp cross sections at $\sqrt{s} = 8$ TeV using elastic scattering and the optical theorem.

	ATLAS ($\beta^* = 90$ m)	TOTEM ($\beta^* = 90$ m)	TOTEM ($\beta^* = 1$ km)
σ_{tot}	96.07 ± 0.92	101.7 ± 2.9	102.9 ± 2.3
σ_{el}	24.33 ± 0.39	27.1 ± 1.4	-
σ_{inel}	71.73 ± 0.71	74.7 ± 1.7	-

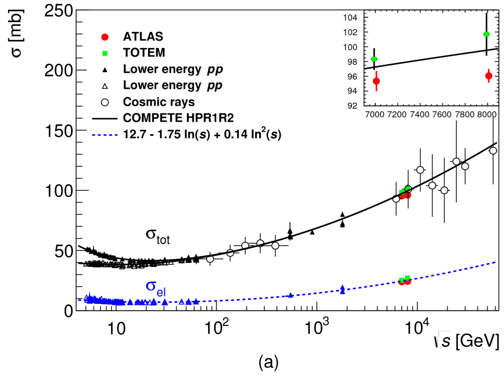

Figure 2. The total and elastic cross sections as a function of center-of-mass energy. The fit has not been updated with the ATLAS $\sqrt{s} = 8$ TeV result.

The assumption of a purely exponential decay of the elastic nuclear amplitude was investigated by TOTEM. Figure 3 shows the differential elastic cross section with respect to a reference function using a pure exponential. Only the t-dependent systematic uncertainties, i.e. without normalization, are important for this measurement. The purely exponential form is excluded by TOTEM by more than 7σ. ATLAS had t-dependent uncertainties that were too great to perform a similar test. The beam energy is the dominating contribution, and whereas TOTEM used a 0.1% uncertainty, ATLAS used a

0.65% uncertainty. Instead, ATLAS observed the effect of different B-parametrizations and measured the RMS value of σ_{tot} to be 0.28 mb.

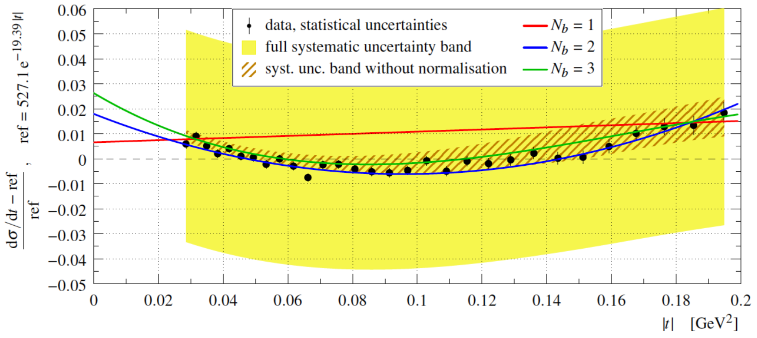

Figure 3. Differential elastic cross section relative to a reference exponential. The colored lines are fits to data where a polynomial of order N_b is used for the nuclear slope.

From the $\beta^* = 1$ km data, TOTEM was able to measure the ρ-parameter to be:

$$\rho = 0.12 \pm 0.03 \ ,$$

which is compatible with a model extrapolation from lower energies giving $\rho = 0.140 \pm 0.007$.

3 Inelastic cross section at $\sqrt{s} = 13$ TeV

The strategy for determining the inelastic cross section at $\sqrt{s} = 13$ TeV used by ATLAS [5] and CMS [6] is to measure the inelastic cross section in a fiducial region and then use theoretical models to extrapolate to the full phase-space. The fiducial inelastic cross section is determined from the number of observed collisions corrected for background, pile-up, detector efficiencies and luminosity.

3.1 Experimental setup

ATLAS uses thin plastic scintillation counters called the minimum-bias trigger scintillators (MBTS). They are placed at $z = \pm 3.6$ m on both sides of the IP and have a pseudo-rapidity coverage of $2.07 < |\eta| < 3.86$. CMS uses the hadron forward calorimeters (HF) and the CASTOR calorimeter, which cover $3.0 < |\eta| < 5.2$ and $-6.6 < \eta < -5.2$, respectively. The HFs are built from iron absorbers and quartz fiber for read out. CASTOR has tungsten for absorption and quartz plates for read out. Data was taken in special LHC runs with low pile-up (< 0.5) in order to minimize the effect of multiple collisions.

3.2 Results

The results for the fiducial inelastic cross section for CMS are:

$$\sigma_{\text{inel}}^{\text{fid,HF}} = 65.8 \pm 0.8(\text{exp.}) \pm 1.8(\text{lum.}) \text{ mb} \ ,$$
$$\sigma_{\text{inel}}^{\text{fid,HF+CASTOR}} = 66.9 \pm 0.4(\text{exp.}) \pm 2.0(\text{lum.}) \text{ mb} \ .$$

For ATLAS, the result is:

$$\sigma_{\text{inel}}^{\text{fid}} = 68.1 \pm 0.6(\text{exp.}) \pm 1.3(\text{lum.}) \text{ mb} \ .$$

Since the fiducial region in ATLAS and in CMS using only HF is the same, the ATLAS $\sigma_{\text{inel}}^{\text{fid}}$ and the CMS $\sigma_{\text{inel}}^{\text{fid,HF}}$ are directly comparable and they agree to within less than one standard deviation.

For each model, an extrapolation factor from fiducial to full phase-space can be found. CMS extrapolates the HF+CASTOR fiducial result using the average of the extrapolation factor for all their models as the nominal value and then taking the maximum difference between the models for systematics. The result is:

$$\sigma_{\text{inel}}^{\text{CMS}} = 71.3 \pm 0.5(\text{exp.}) \pm 2.1(\text{lum.}) \pm 2.7(\text{ext.}) \text{ mb} .$$

ATLAS tunes the theoretical models before using them for the extrapolation of the fiducial cross section to full phase-space. The fraction of the inelastic cross section coming from diffractive processes, f_D, differs between the theoretical models. However, it is related to the fraction of events with hits in ATLAS on only one side of the IP, R_{SS}, since such events are dominated by single diffractive processes. Figure 4 shows the measured value of R_{SS} and the functional dependence on f_D for the different models from which the amount that f_D needs to be tuned is deduced. After the models have been tuned using f_D, the predicted hit multiplicity in the MBTS for the different models are compared to data. Only the Pythia8 DL and Pythia8 MBR models give a reasonable description of the data, hence only these are used by ATLAS in the extrapolation. ATLAS constrains the model dependence

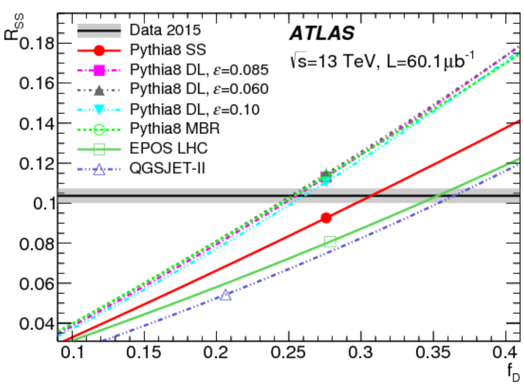

Figure 4. The relation between the ratio of single-sided events (R_{SS}) and the fraction of diffractive processes in inelastic scattering (f_D) for different models. The default value of f_D in each model is shown with a marker.

in the extrapolation using a previous and precise measurement of σ_{inel} at $\sqrt{s} = 7$ TeV done with the ALFA subdetector [7] using the same strategy as described in Section 2. The full phase-space inelastic cross section is calculated as

$$\sigma_{\text{inel, 13 TeV}} = \sigma_{\text{inel, 13 TeV}}^{\text{fid}} + (\sigma_{\text{inel, 7 TeV}}^{\text{ALFA}} - \sigma_{\text{inel, 7 TeV}}^{\text{fid}}) \times \frac{\sigma_{\text{inel, 13 TeV}}^{\text{MC, fid}}}{\sigma_{\text{inel, 7 TeV}}^{\text{MC, fid}}}$$

with Pythia8 DL as the nominal model and Pythia8 MBR used as a systematic uncertainty. The result is:

$$\sigma_{\text{inel}}^{\text{ATLAS}} = 79.3 \pm 0.6(\text{exp.}) \pm 1.3(\text{lum.}) \pm 2.5(\text{ext.}) \text{ mb} .$$

The results are summarized in Figure 5 and compared to the models used by CMS. Both CMS and the first ATLAS result tend to be lower than expected from the model predictions for both the fiducial and the full phase-space inelastic cross sections. An update of the ATLAS result shows better agreement with the model expectations.

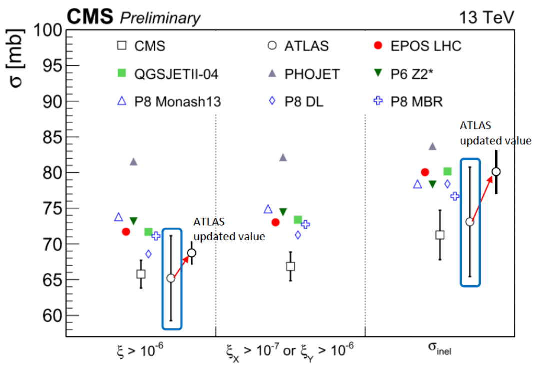

Figure 5. The inelastic cross section in different phase space regions compared to the models used by CMS.

4 Conclusion

The elastic, inelastic and total cross sections at $\sqrt{s}$ = 8 TeV have been measured by ATLAS and TOTEM using the differential elastic cross section. The total cross section is observed to increase with center-of-mass energy. TOTEM has excluded a purely exponential decay of the nuclear elastic amplitude by more than 7σ. Furthermore, they have measured $\rho = 0.12 \pm 0.03$, which is in good agreement with a model extrapolation from lower energies.

The inelastic cross section at $\sqrt{s}$ = 13 TeV has been measured by ATLAS and CMS. Theoretical models were used to extrapolate the fiducial cross section to full phase-space. For several models, ATLAS has observed deviations from data in the fraction of diffractive processes and in hit multiplicities in the detector. The predicted cross section agrees well with the ATLAS measurement, whereas the CMS value is lower than anticipated. By comparison of the ATLAS and CMS $\sqrt{s}$ = 13 TeV results wrt. the ATLAS and TOTEM $\sqrt{s}$ = 8 TeV results, one can observe that there has been an increase in the inelastic cross section wrt. $\sqrt{s}$ in the case of ATLAS, but not in the case of CMS.

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