The proton-proton elastic scattering count rates from the ANKE Forward Detector: Systematic uncertainties

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1 Data processing

1.1 The data and the setup calibration

The data were collected during the June 2010 ANKE beam time at 8 beam energies 1.0, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6 and 2.8 GeV. The effective target density was measured with the Schottky device. For the final cross section determination, the following sets of runs were selected at each energy:

Energy	runs
1.0	18620–18622
1.6	18672, 18675, 18678, 18684, 18687
1.8	18653–18655
2.0	18668–18671
2.2	18707, 18708
2.4	18770–18774
2.6	18730, 18732, 18734, 18735
2.8	18784–18788

Schottky measurements were available for all the runs detailed above and these particular ones were selected on the basis of the target density stability. Only complete cycles were retained in the analysis in each run. The cycle start and stop times were defined from the data and fixed in a table. The same time limits were used for the Forward Detector (FD) data processing and for the target density determination. Due to a problem with (probably) the ramping of the COSY magnets, it was decided to cut off the first 60 seconds of the 270 seconds DAQ ON part of the cycle.

Triggers and dead time

The two triggers used were T2.1 = FdOr (any of the FD hodoscope walls fired), and T2.3 = STTOr (any of the STT second layers fired), both unprescaled. Due to the absolute normalisation used, the dead-time correction had to be applied. Since the STT system blocks its trigger IN count during the readout (but not the T2.1 IN), the common trigger IN rate could not be used to calculate the dead time. Instead, a separate scaler counting T2.1 IN triggers was employed. The dead-time correction factor $\mathrm{T_{out}/T_{in}}$ was typically equal to $0.2 - 0.4$, and increased by $1-2\%$ during the cycle. Due to the cutoff of the first minute of each cycle, the dead-time factors were evaluated only for the rest of the cycle.

Detector efficiency

The FD hodoscope counters were repaired before the beam time. The counter efficiency was studied in the data by analysing the amplitude as a function of the vertical hit coordinate for the selected *pp*-elastic events. No signs of the amplitude falling below the threshold was observed, except for the first (closest to the beam pipe) counters in each hodoscope wall, which were anyway not in the acceptance of MWPC3. Remembering that the trigger was fired by any of the walls, the hodoscope inefficiency was considered to be negligible.

The wire chamber efficiency was obtained in a form of 2D maps for each plane and each run. The MWPC 2,3 efficiency stayed high ($> 97\%$) during the beam time. For the drift chambers, it was found that at 1.0 GeV and partially at 1.8 GeV, the X planes had a reduced efficiency of $\sim 80\%$; this also depended strongly on the track distance to the wire. This made problematic the use of the integral calibration method and required the development of methods, involving fitting of the track residuals. Nevertheless, due to the combinatorial track search algorithm, the total correction for the MWPC efficiency stayed below 0.3% even for the worst runs.

Detector calibration

The setup parameters were adjusted in a geometry tuning procedure, with the use of the $pp \to pp$, $pp \to pn\pi^+$, $pp \to pp\pi^0$ and $pp \to d\pi^+$ reactions. For the last reaction, both ejectiles were detected in the FD and this gave a handle on the systematics of the transverse momentum reconstruction. The maximal residual value of the total transverse momentum corresponded to a 0.15° shift in the *pp* elastic scattering CM angle.

As was mentioned above, two drift chamber calibration methods were used. The first used the integral time spectrum and the second involved a description of the residuals of the tracks as a function of the drift time. The second method was applied iteratively, with the results of the previous iteration used to build the residuals on the next one, with the integral calibration being used as a first approximation. The procedure was stopped after two iterations.

The amplitudes of the hodoscope were also calibrated. This led to an effective proton/deuteron separation at 1.0 GeV, thus improving the background subtraction at this energy.

Track and momentum reconstruction

The initial analysis of the *pp* elastic angular distribution at 1.0 GeV showed point-to-point fluctuations that exceeded the statistical uncertainties. The main cause for this was a reduced DC efficiency. For this reason, different sets of wire chambers and planes were considered for the track reconstruction, and the spread of the results yielded the main contribution to the systematic uncertainty. These sets included: use of MWPC only, use of the complete DC, use of the inclined DC planes only, and of the X DC planes only. Although the momentum and angular resolution was quite different in these cases, the sets produced very similar results for the cross sections (with the maximal difference in the overall scale of 2%), but with different sizes of the point-to-point fluctuations.

Another factor reducing the fluctuations was the use of the kinematic fitting. These procedure also reduced the polar angle uncertainties down to $\sigma(\theta_{cm}) \sim 0.1^\circ$ for all plane combinations, as well as allowed a better control of the systematic uncertainty in θ_{cm}. It was used for the momentum reconstruction in the final analysis.

1.2 *pp* elastic count rates

Acceptance

The setup acceptance was defined from a GEANT simulation, followed by the same track and momentum reconstruction procedures that were applied to the data. Two kinds of acceptance cuts used: the equal $|\varphi| < 10^\circ$ cut for all polar angles and a cut on the track vertical coordinate on the D2 exit window, $|Y_{\text{track}}| < 10$ cm. The first cut produced a flat acceptance as a function of θ, rejecting more than half of the events. The number of events rejected by the second cut was nearly constant for different θ, but the acceptance changed by a factor of ~ 2. Comparison of the cross section results for the two cases gave us an estimate of the systematic uncertainty associated with the acceptance cuts. The ratio of the cross sections for the two cuts was calculated for each run. The deviations of these ratios from unity were distributed with a mean and RMS both equal 0.4%. The Y_{track} cut produced smaller point-to-point fluctuations and was adopted for the final analysis.

Background cuts and subtraction

Apart from the limitations on the track position on the D2 exit window, included in the acceptance calculation, the only background cut used was the one on the track vertical coordinate at the target position. The RMS of Y_{track} was defined at each energy and a 5 σ cut was applied.

The residual level of background was estimated from the missing-mass spectra in each angular bin. For this purpose, regions of pure background were selected on the left and right sides of the elastic peak and these parts of distribution were fitted in order to determine the number of background events under the peak. The peak region was not used in the fit and no assumptions about the shape of the peak were made.

At 1 GeV, the background estimation was preceded by the subtraction of a small $pp \to d\pi^+$ contribution, located on the left side of the elastic peak. This contribution was defined using energy loss cuts to select deuterons in the hodoscope and counting the number of events in the $pp \to d\pi^+$ peak in each angular bin, with the proton background subtracted. No energy loss cuts were applied to the total missing-mass spectrum from which the number of *pp* elastic events was finally determined.

The first approach was to describe the background by a straight line. At higher energies where, due to the resolution, the pion-production spectrum gets closer to the elastic peak, the front part of this spectrum was also included in the background estimation procedure as a smeared phase space distribution. The difference between the two descriptions did not exceed 0.5%, while the total background level under the peak was $1 - 2\%$.

2 Systematic uncertainties

The following sources of uncertainties were considered:

1. Shift of the reconstructed value of θ_{cm}:
   a) In the same way as in the A_y data analysis, the geometry fit shows the maximum residual shift of 0.15°. Taking into account the angular dependence of the count rate with the Y_{track} acceptance cut, this would translate into a 0.5% change in the cross section.
   b) Another way to check the angle reconstruction is to look at the cross section behaviour at the edges of the setup acceptance. By shifting the experimental rate distribution to optimise the edge points, it was found that the optimal shift value is in the $(-0.1°, 0°)$ range for all energies. This would correspond to $< 0.3\%$ change in the cross section.

2. Different track reconstruction methods used at 1.0 GeV (using PC, full DC, only DC X planes, only DC U planes, doing a kinematic fit or not, using different DC calibration methods, different acceptance cuts) provide cross section values that vary with an RMS of 0.95%.

3. Although the level of background in the M_x spectra is only in the $1-2\%$ range, it varies for different methods of describing the background. The maximal change observed here was 0.5%.

4. The cuts applied in the track reconstruction procedure are very mild and do not exceed 1% in total. Being very conservative, we can consider a 100% systematic uncertainty for this correction. This includes uncertainties connected with the MWPC efficiency (negligible in our case) as well as the one of the tracking algorithm ($> 99.5\%$).

In total, treating the maximal deviations listed above as RMS values, we obtain a 1.5% total systematic uncertainty.