Measurement of the ^{7}Be + ^{9}Be cross section at beam momenta of 13A, 20A and 30A GeV/c

Messung des ^{7}Be + ^{9}Be Wirkungsquerschnitts bei Strahlimpulsen von 13A, 20A and 30A GeV/c

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by

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Contents

Introduction

The NA61/SHINE experiment located at the SPS at CERN covers many purposes in various fields. It is a fixed target experiment, which operates with different targets and beams. In 2012 and 2013 data was taken at different beam momenta with a ^{7}Be beam and a ^{9}Be target. Within this Bachelor work the data of NA61/SHINE was analyzed and the first results on the ^{7}Be + ^{9}Be cross section at beam momenta of $13A$, $20A$ and $30A$ GeV/c are presented.

In chapter 1 a definition of the cross section is given and its approximation for the case of nucleus-nucleus collisions using the geometrical model is defined and calculated. The NA61/SHINE experiment and its detectors are described in chapter 2.

The procedure which is used for the evaluation of the cross section and the interaction probability is presented and explained in chapter 3. It also includes information about the analyzed runs and the used event cuts. Further the interaction probability is calculated for all data sets with the standard cuts.

The influence of the variation of different cuts on the interaction probability is studied in chapter 4. Also in this analysis the systematic error is estimated and presented. In chapter 5 the values of the cross section are shown for all analyzed data and compared with the results at $1.45A$ GeV/c.

1. Cross section

1.1. Definition of the Cross Section

The cross section σ is one the most important characteristics for the description and interpretation of interactions in scattering experiments. It allows to calculate the probability of a reaction between projectile and target particles. The dimension of the cross section is an area.

In the limit of a low density of scattering centers the cross section can be calculated as

$$\sigma = \frac{\text{number of reactions per unit of time}}{\text{number of beam particles per unit of time} \times \text{number of scattering centers per unit of area}} \tag{1.1}$$

The total cross section is the sum of the elastic and the inelastic cross section

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel.} \tag{1.2}$$

The cross section depends on the properties of the interaction between projectile and target particles and thus on their types and the collision energy [1, 10].

1.2. Approximation of the Cross Section

In nucleus-nucleus collisions the inelastic cross section is often calculated using the geometrical model. The resulting geometric cross section σ_g is calculated considering only the geometric shapes of the participating particles. In many cases this is a good approximation. If the 2-dimensional projections of target and projectile nuclei overlap, there is a collision:

$$\sigma_g(p,t) = \pi \left[R(p) + R(t)\right]^2 \tag{1.3}$$

where $R(p)$ denotes the projectile radius and $R(t)$ the target radius. The nuclear radii can be approximated using this relation:

$$R = 1.21 \cdot A^{1/3} fm \tag{1.4}$$

where A is the mass number of the nucleus.

For a ^{7}Be beam and a ^{9}Be target this approximation results in the nuclear radii R(p) = R(^{7}Be) = 2.31 fm and R(t) = R(^{9}Be) = 2.52 fm and a cross section of σ_g(^{7}Be + ^{9}Be) = 733 mb.

In a transmission experiment with a large-acceptance spectrometer the interaction cross sections σ for several Li and Be isotopes on Be, C and Al targets have been measured at a kinetic energy of 790 MeV per nucleon corresponding to a beam momentum of 1.45 GeV/c per nucleon. In this experiment the cross section for ^{7}Be + ^{9}Be collisions was evaluated as 682 ± 6 mb. The interaction cross section here is defined as the reaction cross section for the change of proton and/or neutron number in the incident nucleus [13]. A similar definition (disappearance of the ^{7}Be beam particle) is also used for the measurements presented in this work.

2. The NA61/SHINE Experiment

This chapter gives an overview of the NA61/SHINE experiment. The main physics goals and the detectors are described, while the focus is on the beam detectors, as they will be important for the following analysis.

2.1. The NA61/SHINE Experiment at CERN

The NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a multi-purpose fixed target experiment located in the North Area of CERN at the Super Proton Synchrotron (SPS) (see Fig. 2.1). The NA61/SHINE experiment is used to study hadron production in hadron-nucleus and nucleus-nucleus collisions. The physics goals include the search for the critical point of strongly interacting matter and a detailed study of the onset of deconfinement. Also precise hadron production reference measurements for neutrino (T2K) and cosmic-ray (Pierre Auger Observatory, KASCADE-Grande and KASCADE) experiments are made. The charged beam particles are transported from the SPS to the NA61 experiment by the H2 beam line [4, 8].

The NA61/SHINE experiment is the successor of the NA49 experiment. The main detector components were inherited from the NA49 experiment and upgraded and some additional detectors were added [12].

The detector is a large acceptance hadron spectrometer consisting of a set of six Time Projection Chambers (TPCs) and Time-of-Flight detectors (ToF) used for momentum measurements and identification of charged particles. The Projectile Spectator Detector (PSD) is a high resolution forward calorimeter which measures the energy flow around the beam direction and so determines the number of nucleons which participated in a reaction. A set of beam detectors is used to identify beam particles and to measure their trajectories [4, 8].

The first physics data with ion beams were recorded in 2011 with secondary ^{7}Be beams.

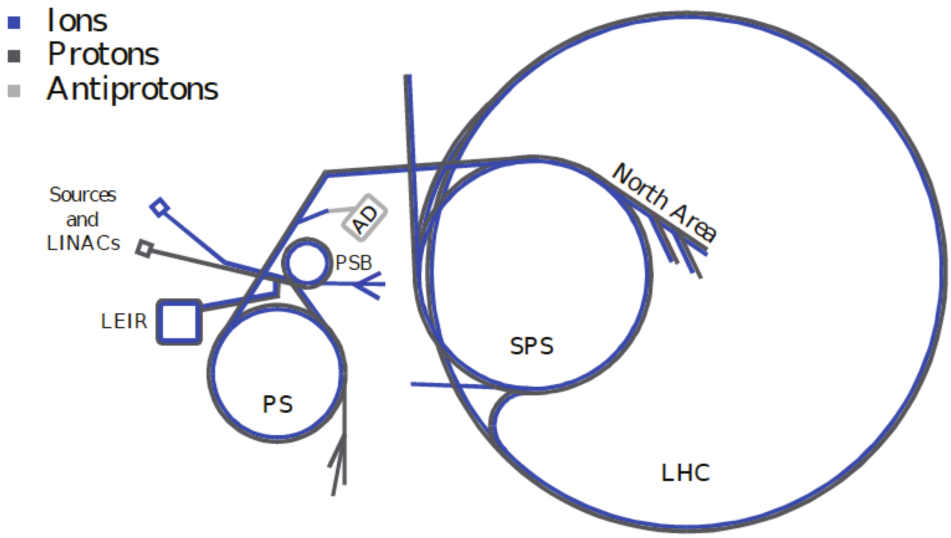


Figure 2.1.: The CERN accelerators. The NA61/SHINE experiment is located at the North Area and gets its beam from the SPS (Super Proton Synchrotron).

2.2. Production of the ^{7}Be beam

Since primary ion beams will become available only in 2014, a fragment beam was used during the runs from 2011 till 2013. A primary sample of isotopically pure ^{208}Pb is ionized and accelerated to energies between 13 and 160 GeV/c per nucleon in several pre-accelerators and the SPS. From there a beam of up to several 10^8 lead ions per spill is extracted into the H2 beam line, where it hits a primary Beryllium target. When the Pb beam passes through this 180 mm long fragmentation target a mix of nuclear fragments is produced by collisions with Be nuclei. The whole configuration is built in a way that the fraction of the created ^{7}Be to other ions is maximized.

2.3. Beam detectors and trigger settings

The beam detectors are sketched in Fig. 2.2. They consist of a set of scintillation counters, Cerenkov counters and beam position detectors (BPDs). In order to minimize interactions upstream of the target, the total detector material in the beam line is reduced to a minimum.

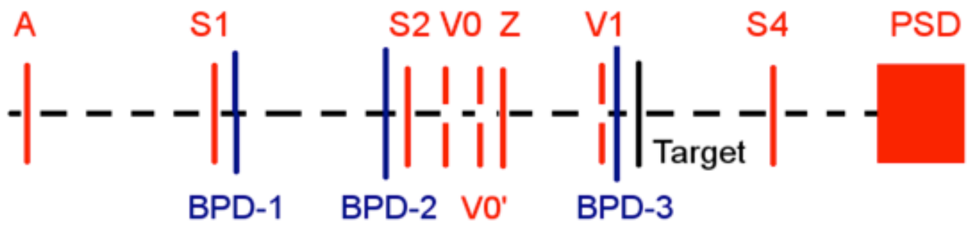


Figure 2.2.: The beam detectors

Detector	Size [cm] (x y z or ø z)	Z position [m]
A	1.5 x 15 x 0.5	-720.0
S1	6 x 6 x 0.5 (rotated about 45 degrees in the xy plane)	-618.2
S2	ø= 2.6 x 0.2	-390.8
V0	ø= 8 x 1 with hole ø = 1	-390.5
Z	14 x 4 x 0.25	-390.2
V1	10 x 10 x 1 with hole ø = 1	-383.1
S4	ø= 2 x 1	-378.5
V0'	30 x 30 x 1 with hole ø = 4	= V0 + 15 cm

Table 2.1.: Positions and sizes of the beam detectors

2.3.1. Beam counters

The set of beam counters consists of five scintillator counters: S1, S2, S4 and two veto counters V0 and V1. The S1 counter (0.5 cm thick and located at position z = -618.2 m) is also used for the time of flight measurement. Four photo-multipliers are directly coupled to the scintillator in order to determine a precise reference time. S2 is 0.2 cm thick and positioned at z = -390.8 m. The veto counters are used to reduce the background from upstream interactions. They both have a hole with 1 cm diameter. The first veto counter V0 (z = -390.5 m) was used for the 2012 run. It was replaced in 2013 by the V1 counter (z = -383.1 m) which is located closer to the target and also placed in vacuum. In the following analysis will become clear that this highly improved the beam particle selection. The S4 beam counter (1 cm thick and with 2 cm diameter) is located downstream of the target at z = -378.5 m. The signal in the S4 counter is used in order to determine if there was an interaction in the target [12, 8].

In scintillation counters the atoms of certain transparent materials are excited by ionized particles. This causes emission of scintillation light, which is detected by photo multipliers. In the NA61/SHINE experiment organic plastic scintillators are used. This allows a very short scintillation decay time of approximately 1 ns. In organic scintillators special molecules are added to the detector material. The atoms of these molecules are excited by passing particles and cause UV radiation when falling back to the ground state. For the conversion of UV light into blue light fluorescent materials are needed. These so-called wavelength shifters are added to the detector material as well. The blue light is then captured by photo multipliers and converted into electrical signals [8, 9].

2.3.2. Beam Position Detectors

Three proportional chambers, the Beam Position Detectors (BPDs), measure the transverse position of the beam particles before the target. The BPDs consist of many thin parallel wires spanned in a flat volume filled with gas and a cathode plane which is divided into thin strips. The wires are on positive high voltage and work as independent detectors. When charged particles pass the gas in the detector, they ionize the gas atoms along their track. This ionization releases electrons, which drift towards the anode wire. Since the electrical field near the thin wires is very strong, the electrons gain high enough kinetic energies to produce new ion-electron-pairs. A chain of such processes triggers an avalanche of charge [9, 10]. This induces a voltage pulse in the cathode strips, whose arrival time and amplitude can be measured. The position of the passing particle results from the known position of the cathode strip. In order to achieve a 2-dimensional measurement, two layers of proportional chambers with orthogonal cathode strips are used. The BPDs used in the NA61/SHINE experiment are filled with an Ar/CO_2 85/15 gas mixture and have an active area of 48 x 48 mm^2 each [8].

BPD-1 and BPD-2 are situated between the scintillation counters S1 and S2. BPD-3 is located directly before the target.

2.3.3. Z-detector

During the Beryllium runs a Quartz Cherenkov Detector was used in order to determine the charge of incoming beam particles. The signal in the detector is proportional to Z^2 where Z is the charge of the particle. The Z-detector consists of a 160 x 40 x 2.5 mm quartz plate, which is coupled with two photo-multipliers at both sides of the plate. In order to optimize the light transition optical grease is inserted between the quartz plate and the photo-multipliers. The Quartz Detector has a threshold momentum of about 0.88 GeV/c per nucleon [8].

Cherenkov detectors are using the effect, that a high momentum particle can be faster inside a dielectric than the phase velocity of light in this medium. The excited atoms emit light which builds a wave front with a constant angle to the particle trajectory. This phenomenon is called Cherenkov radiation.

The angle θ of the Cherenkov light depends on the speed of the incoming particle:

$$cos(\theta) = \frac{1}{n\beta} \tag{2.1}$$

where n is the refractive index and β the ratio of the particle velocity to the speed of light. From the measurement of the Cherenkov angle, the velocity of a particle can be determined directly. Cherenkov counters can also be used in order to distinguish between two relativistic particles with the same momentum but different masses [9].

2.3.4. Trigger settings

There are four different trigger settings: T1, T2, T3 and T4 as defined in Tab. 2.2. The T1 trigger selects beam particles with additional identification of beryllium particles in the Z-detector. The T2 trigger also selects Be beam particles, but additionally determines, if there was an interaction by demanding that the S4 counter and PSD are not triggered. T3 selects beam particles without identifying the type of particle. The T4 trigger first determines beam particles without identification. Additionally the T4 trigger demands that S4 is not triggered. The difference between the 13A GeV 2012 run and the other runs is that V0 was replaced by V1 in order to optimize the beam selection.

	13A GeV (2012)	13A GeV (2013), 20A GeV, 30A GeV
T1	$S1 \times S2 \times \bar{V}0 \times Z(Be)$	$S1 \times S2 \times \bar{V}1 \times Z(Be)$
T2	$S1 \times S2 \times \bar{V}0 \times Z(Be) \times \bar{S}4 \times P\bar{S}D$	$S1 \times S2 \times \bar{V}1 \times Z(Be) \times \bar{S}4 \times P\bar{S}D$
T3	$S1 \times S2 \times \bar{V}0$	$S1 \times S2 \times \bar{V}1$
T4	$S1 \times S2 \times \bar{V}0 \times \bar{S}4$	$S1 \times S2 \times \bar{V}1 \times \bar{S}4$

Table 2.2.: Trigger settings [11]

2.4. Electronic data taking and reconstruction to SHOE-Files

The measurements from the detectors are recorded by the data acquisition computer and subsequently written event for event to the CASTOR (CERN Advanced STORage manager) data archive (see [3] for more information about CASTOR). This raw data is then converted by the NA61 reconstruction software into SHOE (SHINE Offline Event) files. For this Bachelor thesis a C++ program was written, which reads the SHOE files, extracts the relevant values and fills them into histograms. The macro can be found in appendix A. The histograms are edited with the CERN data analysis framework ROOT (see [5] for more information about ROOT).

3. Data analysis

3.1. Evaluation of the Trigger Cross Sections

The interaction probability P_{int} determines the inclusive trigger cross section σ_{trig} according to the formula

$$\sigma_{trig} \equiv \frac{1}{n} \frac{N_{trig}}{N_{beam}} \tag{3.1}$$

where N_{trig} is the number of triggered events coming from the target, N_{beam} the number of incoming beam particles and

$$n = \rho L N_A / A \tag{3.2}$$

Here ρ is the target density, N_A the Avogadro constant, L the target length and A the target's atomic number [12].

Distortions in the trigger cross section due to

- interactions outside of the beryllium target
- exponential beam attenuation in the target

have to be corrected and will be included in the cross section calculation in the following.

Since interactions outside of the target can also cause triggered events, the interaction probability in the target (P_{int}) should be used instead of the percentage of triggered events for calculating σ_{trig}:

$$\sigma_{trig} = \frac{1}{\rho L N_A / A} P_{int} \tag{3.3}$$

The exponential beam attenuation in the target can be corrected by using an effective target length L_{eff} instead of the real target length L:

$$\sigma_{trig} = \frac{1}{\rho L_{eff} N_A / A} P_{int} \tag{3.4}$$

where

$$L_{eff} = \lambda_{abs}(1 - e^{-L/\lambda_{abs}}) \tag{3.5}$$

with absorption length

$$\lambda_{abs} = \frac{A}{\rho N_A \sigma_{trig}} \tag{3.6}$$

The trigger cross section is then evaluated in an iterative procedure:

$$\sigma_{trig,i} = \frac{P_{int} \cdot \sigma_{trig,i-1}}{1 - exp(-L\rho N_A \sigma_{trig,i-1}/A)} \tag{3.7}$$

The cross section of ^{7}Be + ^{9}Be can be expected to be related to the p + p cross section. According to [2] the inelastic cross section for p + p collisions slightly decreases at beam momenta between 1.45A and 30A GeV/c. So it can be expected that the ^{7}Be + ^{9}Be cross section also slightly decreases in this region.

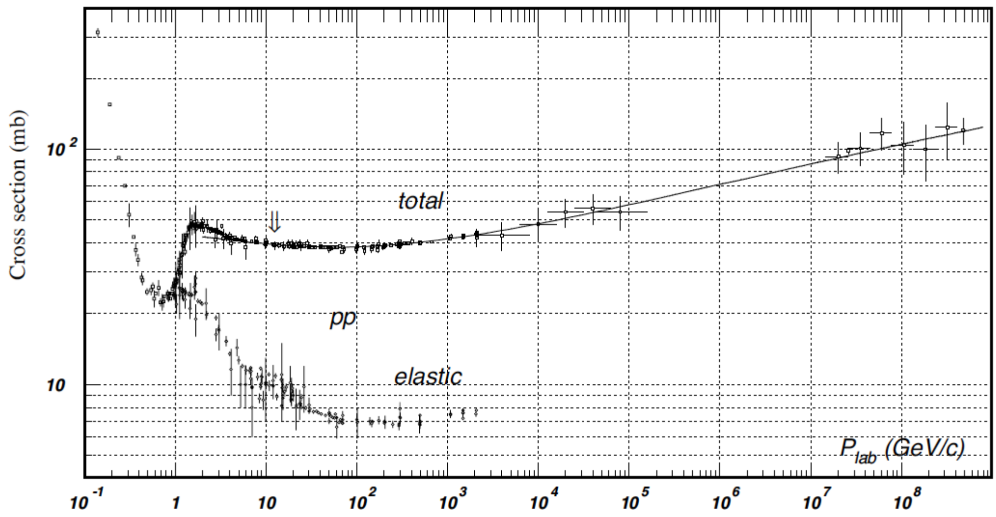


Figure 3.1.: Total and elastic cross sections for p+p collisions as a function of laboratory beam momentum [2].

3.2. Evaluation Procedure of the Interaction Probability

The calculation of the interaction probability is based on the signals obtained from the S4 counter. The S4 counter is a scintillation counter located after the target in the beam line of the experiment (see chapter 2.3). Its signal is proportional to Z^2, where Z is the charge of the incoming particle. In figure 3.2 the spectrum of the S4 counter with T1 trigger is shown for the 13A GeV/c run in 2012. The T1 trigger is selecting beryllium beam particles (see chapter 2.3 for a more detailled description of the trigger settings). The high peak on the right side of the spectrum is caused by Be particles. If there was an interaction before the S4 counter, the signal will be lower than the signal of a Be beam particle, as the charge of the produced particle is always lower than Z(Be). The spectrum above the Be area can be caused by the high pulse-height tail of the counter or additional off-time particles.

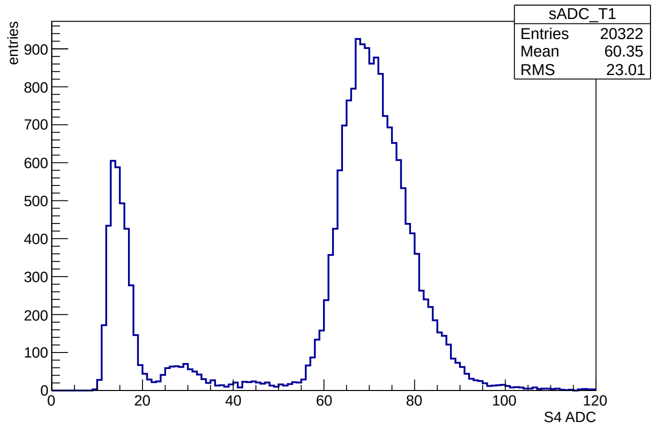


Figure 3.2.: S4 spectrum with T1 trigger for the 13A GeV run in 2012

In order to seperate particles which interacted from particles which did not interact, a cut is made at the beginning of the Be peak: the spectrum on the left side of the cut is caused by interactions (no Be particles), the spectrum on the right side of the cut mostly by beam particles which did not interact (Be particles).

The probability that a beam particle interacts can now be defined as the number of Be beam particles which cause a signal below the S4 cut divided by the total number of Be beam particles:

$$P_{I/R} = \frac{\text{number of events in S4 spectrum with trigger T1 and S4(no Be)}}{\text{number of events in S4 spectrum with trigger T1}} \tag{3.8}$$

where P_I (P_R) is the interaction probability in the target inserted (removed) configuration.

In order to include the fact that interactions take place also outside of the target,

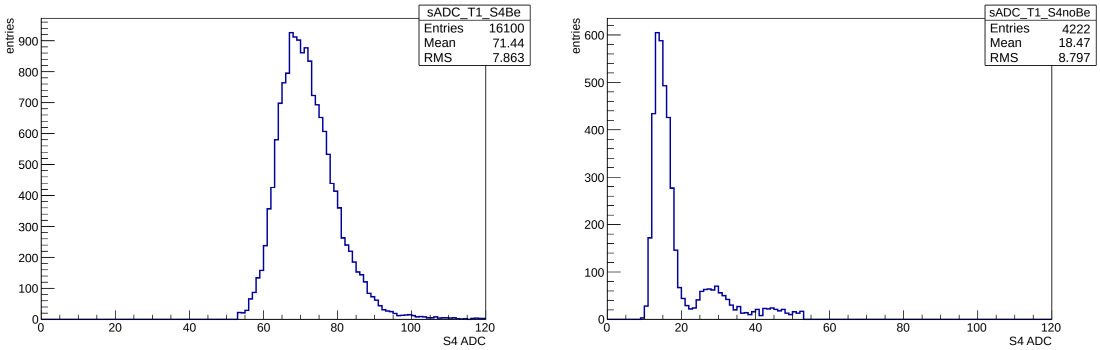


Figure 3.3.: S4 cut: on the left side is shown the part of the spectrum caused by not interacting beam particles, on the right side the part of the spectrum caused by interactions.

the interaction probability of the target removed configuration must be subtracted. But assuming $P_{int} = P_I - P_R$ would be an over-correction of P_I by neglecting the fact that the beam intensity decreases because of interactions in the target.

Beam particles can be lost downstream of the target because of interactions in the material between the target and the S4 counter, because they miss the S4 counter or because they produce a signal below the S4 cut. They can also be lost due to interactions inside the target or upstream of the target. The corresponding probabilities are defined as

P_u – probability to lose a particle upstream of the target

P_t – probability to lose a particle inside the target

P_d – probability to lose a particle downstream of the target

The particles contributing to the "no Be" part of the spectrum in the target inserted configuration can now be described as

$$N_u = B_u \cdot P_u = \text{number of particles lost upstream of the target}$$
$$N_t = B_t \cdot P_t = \text{number of particles lost due to interactions inside the target}$$
$$N_d = B_d \cdot P_d = \text{number of particles lost downstream of the target}$$

where B_u is the initial number of beam particles, B_t the number of particles hitting the upstream face of the target and B_d the number of particles hitting the downstream face of the target. This leads to

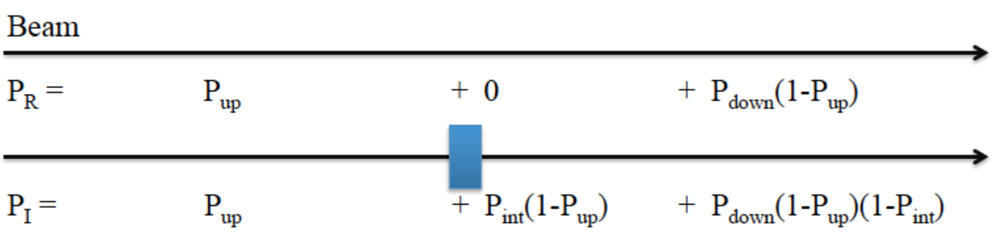
$$\begin{aligned} B_t &= B_u - N_u = B_u(1 - P_u) \\ B_d &= B_t - N_t = B_t(1 - P_t) = B_u(1 - P_u)(1 - P_t) \end{aligned} \tag{3.9}$$

The total number of lost beam particles in the target inserted configuration is now given by

$$\begin{aligned} N_I = N_u + N_t + N_d = B_u \cdot P_u + B_t \cdot P_t + B_d \cdot P_d = \\ B_u \cdot (P_u + (1 - P_u)P_t + (1 - P_u)(1 - P_t)P_d) \end{aligned} \tag{3.10}$$

and the interaction probability can be calculated using

$$P_I = \frac{N_I}{B_u} = P_u + (1 - P_u)P_t + (1 - P_u)(1 - P_t)P_d \tag{3.11}$$



For the target removed configuration the same formulas can be used, but as there is no target, $P_t = 0$.

$$P_R = \frac{N_R}{B_u} = P_u + (1 - P_u)P_d \tag{3.12}$$

Now it becomes apparent that the subtraction of P_R

$$P_{I-R} \equiv P_I - P_R = P_t(1 - P_u - P_d - P_u P_d) = P_t(1 - P_R) \tag{3.13}$$

is only a good approximation for the interaction probability in the target if $P_t P_R << P_t$. But especially for high S4 cuts this is not valid as P_R increases because more particles hit S4 below the cut. Rewriting the equation for P_{I-R} gives

$$P_{int} \equiv P_t = \frac{P_{I-R}}{1 - P_R} \approx P_{I-R}(1 + P_R) = P_I - (1 - P_{I-R})P_R \tag{3.14}$$

As calculations of P_I and P_R resulted in $P_{I-R} \approx 0.1$, the following approximation will be used in the cross section analysis:

$$P_{int} \approx P_I - 0.9P_R \tag{3.15}$$

Comparing equations 3.11 and 3.12 to equation 3.8 shows that N_I (N_R) is the number of events in S4 spectrum with trigger T1 and S4(no Be) in the target inserted (removed) configuration ($\equiv N_{int}$) and B_u is determined by the number of events in S4 spectrum with trigger T1 ($\equiv N_{beam}$).

If the S4 cut is too low, some of the interactions are not included in the "no Be" part of the spectrum and the calculated interaction probability is lower than in reality. Increasing the S4 cut to very high values on the other hand should not change the calculated interaction probability.

The propagation of uncertainties Δ of the measurements is given by

$$\Delta P_{I/R} = \sqrt{\left(\frac{\partial P_{I/R}}{\partial N_{int}}\Delta N_{int}\right)^2 + \left(\frac{\partial P_{I/R}}{\partial N_{beam}}\Delta N_{beam}\right)^2} = \frac{\partial P_{I/R}}{\partial N_{int}}\sqrt{N_{int}} = \frac{\sqrt{N_{int}}}{N_{beam}} \tag{3.16}$$

and

$$\Delta P_{int} = \sqrt{\left(\frac{\partial P_{int}}{\partial P_I}\Delta P_I\right)^2 + \left(\frac{\partial P_{int}}{\partial P_R}\Delta P_R\right)^2} = \sqrt{(\Delta P_I)^2 + (0.9\Delta P_R)^2} \tag{3.17}$$

3.3. Interaction Probabilities with Standard Beam Selection

The analysis contains runs with beam momenta of 13A, 20A and 30A GeV/c. For 13A GeV/c two different sets of data were taken. The first one was taken in 2012, the second one in 2013. The main difference is the replacement of the V0 counter by the V1 counter in 2013. As will be described in section 4.2 this highly improved the event selection by choosing only well focused beam particles. A ^{9}Be target with an area of 2 x 2 cm perpendicular to the beam direction and a length of 1.2 cm along the beam direction was used [11]. During the 30A GeV/c runs data was taken additionally with a thinner target of 0.3 cm. A list of the analized runs with run numbers can be found in appendix B.

Standard S4 cuts were defined at the beginning of the Be peak and in the area where the interaction probability is approximately stable with respect to a variation of the S4 cut. As the Be peak is not at the same position for the different runs, a different standard S4 cut was determined for each run. The trigger interaction probability is slightly decreasing for higher energies. For the 0.3 cm target the interaction probability is about one quarter of the 1.2 cm target probability, as would be expected, because the target length is one quarter of the standard target length.

In table 3.1 the positions of the standard S4 cuts and the interaction probabilities are listed for the different runs.

run	standard S4 cut	P_{int}
13A GeV/c (2012)	52	9.854 ± 0.425 %
13A GeV/c (2013)	70	9.731 ± 0.412 %
20A GeV/c	90	9.647 ± 0.317 %
30A GeV/c	82	9.298 ± 0.205 %
30A GeV/c (0.3 cm target)	82	2.452 ± 0.171 %

Table 3.1.: S4 ADC positions and trigger interaction probabilities at the standard S4 cuts for the different runs

4. Estimation of systematic uncertainties

The stability of the interaction probability and accordingly the inelastic cross section was studied under different cuts on several beam detectors. This chapter is giving a description of these cuts and their influence on the interaction probability.

4.1. Variation of the S4 Cut

As described in chapter 3.2 the signal in the S4 counter was used in this analysis in order to determine whether a beam particle interacted.

In figure 4.1 the S4 spectrum with T1 trigger (= Be beam particles, see chapter 2.3.4) is shown for target inserted (upper plot) and target removed data (center plot). The high peak on the right side is caused by Be beam particles which did not interact and can be seen clearly in both plots. The maximum is located at a S4 ADC value of about 92. The part of the spectrum below the Be peak contains ions with lower charge than Be and is caused by interactions before the S4 counter. As the number of interactions is significantly reduced by removing the target, there are a lot less entries in the target removed plot. At about 25 there is another clear peak, which is a result of the pedestal and has a small side peak on the right at about 29. A small peak can be seen also at about 42.

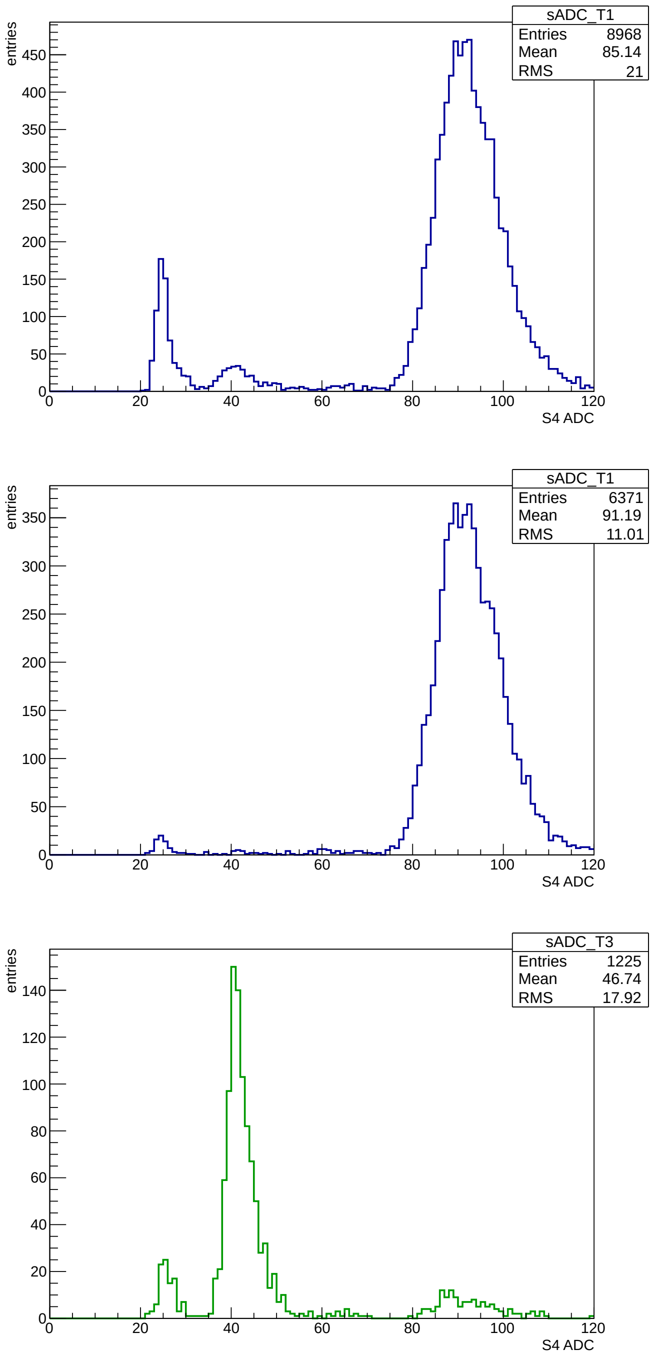


Figure 4.1.: The top histogram shows the S4 spectrum with T1 trigger for the target inserted configuration, the middle histogram for the target removed configuration. The bottom histogram displays the S4 spectrum with T3 trigger for the target inserted configuration. All data from the 13*A* GeV/c run in 2013.

If the pedestal is subtracted, the peaks are located at 0, 4, 17 and 67. As the signal in the S4 counter is proportional to Z^2, the position of the peak allows to conclude by which particle was produced.

$$4/67 \approx 1/16 = 1^2/4^2 = Z(H)^2/Z(Be)^2 \text{ and}$$
$$17/67 \approx 1/4 = 4/16 = 2^2/4^2 = Z(He)^2/Z(Be)^2$$

This suggests that the peak on the left is caused by the pedestal an hydrogen isotopes and the small peak in the middle by helium nuclei.

The green histogram at the bottom of figure 4.1 displays the S4 spectrum with T3 trigger (= beam particles without selection of Be). Here the second peak from the left is dominant, which means that the beam mainly consists of helium nuclei. This is a result of the fact that instead of primary ions a fragment beam was used. During the process of fragmentation many kinds of particles are created and although the fraction of the produced ^{7}Be nuclei is maximized, there are still other particles in the beam.

The S4 cut defining the "interaction" part of the spectrum on the left and the "no interaction" part of the spectrum on the right was now varied from values much below the beginning of the Be peak to about the maximum of the Be peak. The signal in the S4 counter was not stable and so the spectrum is shifted between the runs (see figure 4.2), different ranges were used for the S4 cut for the different runs. Another difference between the spectra can be noticed in the left peak. It is much lower for the $20A$ and $30A$ GeV/c runs, because the contribution of the pedestal was reduced.

In order to calculate the interaction probability inside the target, the interaction probabilities are first estimated seperately for target inserted and target removed data. The interaction probability is then determined using $P_{int} = P_I - 0.9 \cdot P_R$ as described in detail in chapter 3.2.

As can be seen clearly in figure 4.3, the background was reduced significantly after the $13A$ GeV/c data taking in 2012, and hence the interaction probability for target removed data is much lower for the other runs.

In figure 4.4 the interaction probability is plotted with statistical errors for the different runs and energies. As expected, for low S4 cuts the target interaction probability decreases for all runs, because some of the interactions are not counted as interactions. In the middle the probability stays approximately on one level. For high cuts the interaction probability is relatively stable for the $13A$ GeV/c run in

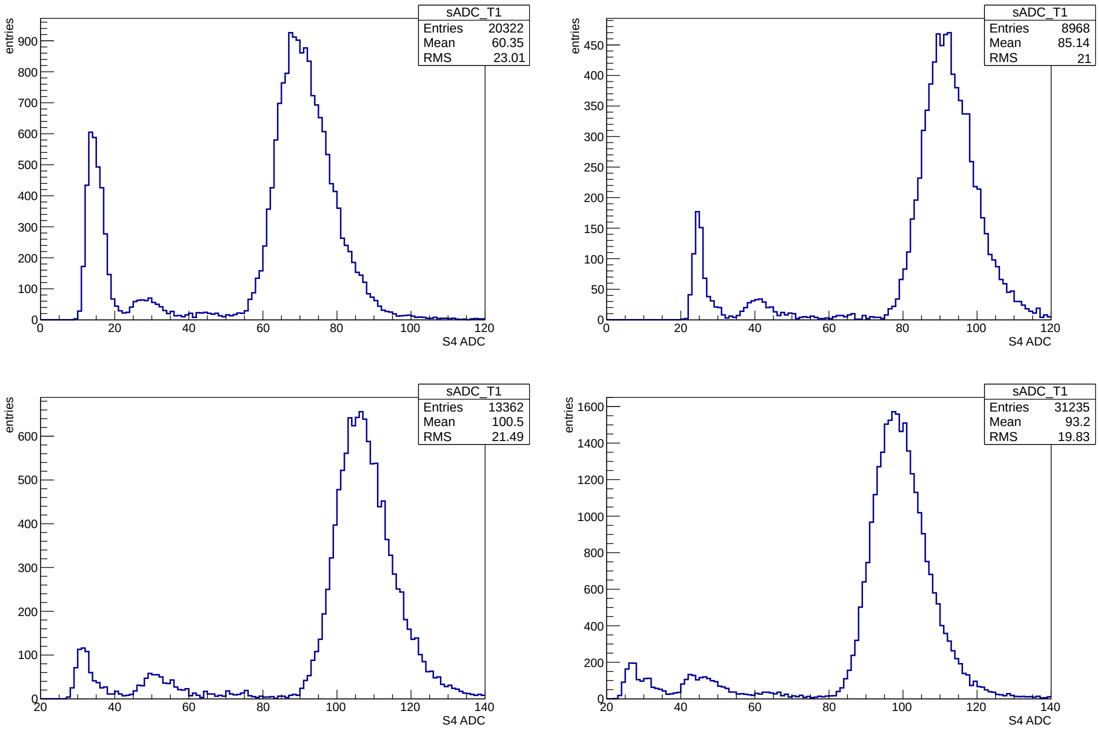


Figure 4.2.: S4 ADC spectrum for the different runs:
Top left: data from 13A GeV/c in 2012
Top right: data from 13A GeV/c in 2013
Bottom left: data from 20A GeV/c
Bottom right: data from 30A GeV/c

2013 and for the 20A GeV/c run, but with a tendency to go up. The probability for 13A GeV/c 2012 data first increases and then decreases for values above a very small plateau in the middle. For the 30A GeV/c data the interaction probability decreases for high S4 cuts.

If the signal in the S4 counter were stable, the interaction probability should not change when increasing the S4 cut. In order to determine if the instability of the S4 signal was responsible for the changing interaction probability, the Be part of the S4 spectrum was plotted for target inserted data and target removed data on top of each other. Figure 4.5 shows this plot for the 30A GeV/c run. Although the spectra are almost identical, the peak for target inserted data is located a bit more to the left. So for high S4 cuts the subtracted value is too high and the interaction probability goes down. This confirms the assumption that an unstable S4 signal is the reason for the change of the target interaction probability for high S4 cuts.

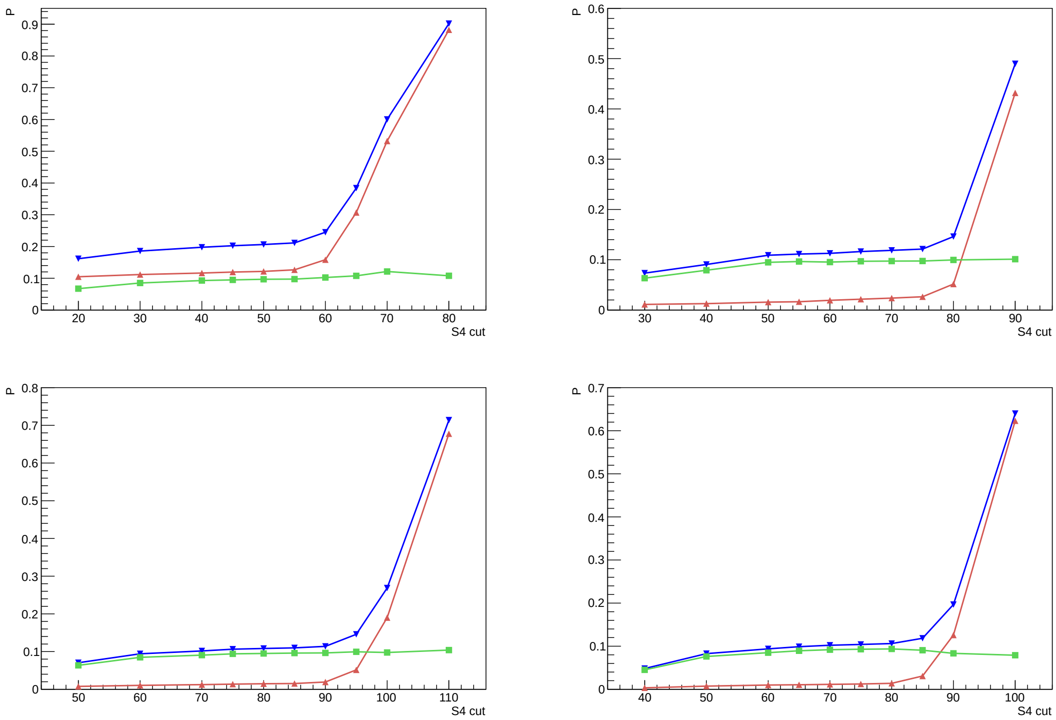


Figure 4.3.: Interaction probability for target inserted data (blue downward triangles), for target removed data (orange upward triangles) and target interaction probability (green squares).
Top - left: 13A GeV/c 2012, right: 13A GeV/c in 2013
Bottom - left: 20A GeV/c, right: 30A GeV/c

For the 30A GeV/c data with the thinner target the same S4 cuts were used as for the standard target. As the target is thinner than the target used during the other runs the interaction probability is lower. The interaction probability is quite stable between 60 and 85 and increases rapidly at higher values (see figure 4.6). The sensitivity of P_{int} with respect to reasonable S4 cut values can be seen from table 4.4.

4.2. Variation of the BPD Cut

Three BPDs (= Beam Position Detectors, see chapter 2.3.2) measure the x and y position of passing particles. In the experiment's coordinate system the z direction is parallel to the beam direction and x and y directions are perpendicular to the beam.

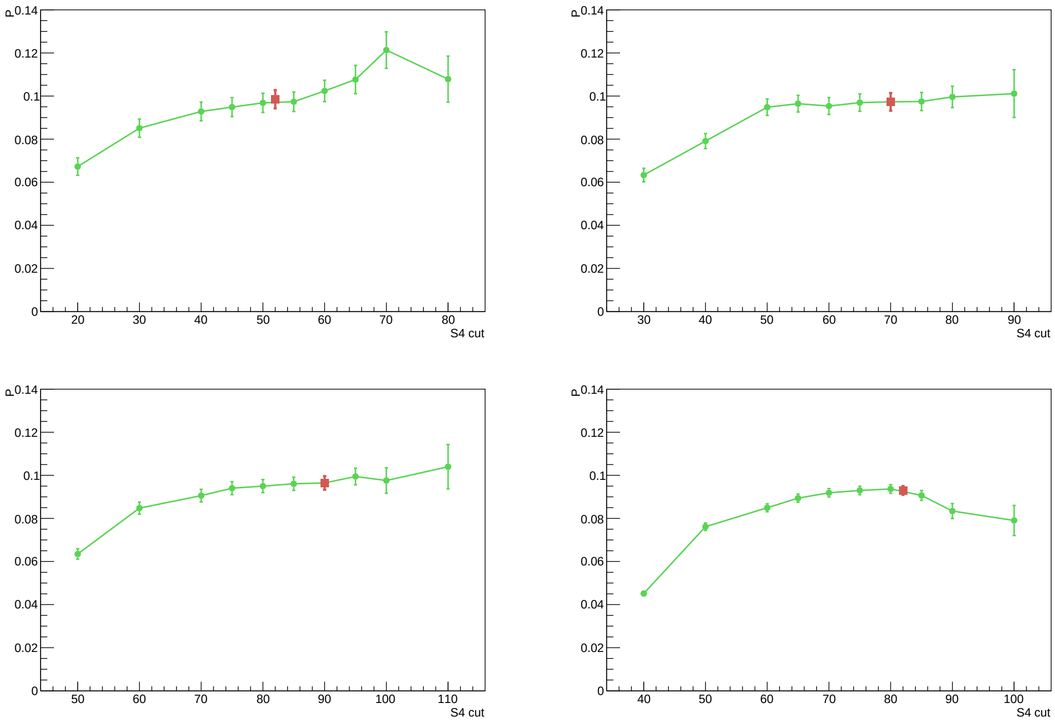


Figure 4.4.: Target interaction probability with statistical error (dots, in green) and standard S4 cut (squares, in red).
Top - left: 13A GeV/c in 2012, right: 13A GeV/c in 2013
Bottom - left: 20A GeV/c, right: 30A GeV/c

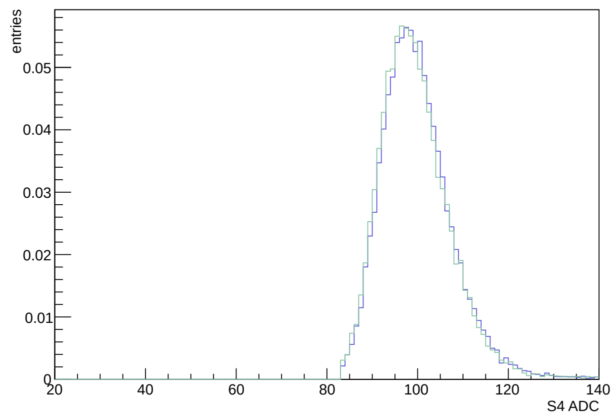


Figure 4.5.: Be part of the S4 spectrum for the 30A GeV/c run: in green for target inserted data, in blue for target removed data.

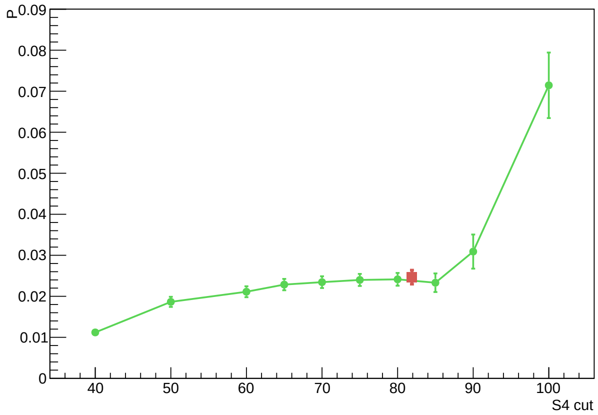


Figure 4.6.: Interaction probability for 30A GeV/c runs with a 0.3 cm target. Standard S4 cut (squares, in red).

In figure 4.7 the positions of the incoming particles in the BPD-3 are plotted for the different runs. Events with T1 trigger are selected, in order to only get Be beam particles. If the beam is not very well focused, some of the beam particles miss the S4 counter although they did not interact. So they are wrongly counted as interactions, which leads to a higher interaction probability for both target inserted and removed data. In the plot for 13A GeV/c data from 2012 the beam particles are distributed over a much bigger area than for the other runs. The reason for the improvement in 2013 is the replacement of the V0 detector by the V1 detector, which was located much closer to the target and placed in vacuum.

In order to reduce the background, a circular cut was applied on the BPD-3 distribution offline. Instead of using events from the whole distribution, just a circular area with radii between 0.2 and 0.4 cm (13A GeV/c 2012) or 0.1 and 0.3 cm (20A and 30A GeV/c) was used for the analysis. Since the beam was already well focused for almost all runs, the analysis with BPD-3 cut was made only for one run per energy. For the same reason the cut for the 20A and 30A GeV/c runs is stricter than for the 13A GeV/c run. The results of this analysis are shown in table 4.1.

The BPD-3 cut reduces the background significantly for the 13A GeV/c run in 2012: The interaction probability for the target removed configuration is reduced about 88 % from 12.635 ± 0.298 % to 1.565 ± 0.140 %. At the same time the interaction probability decreases a bit. For the other runs the influence of the BPD-3 cut is much smaller. The background is reduced approx. 14 % and the interaction probability slightly changes (max. 1 %). As the difference is very small and

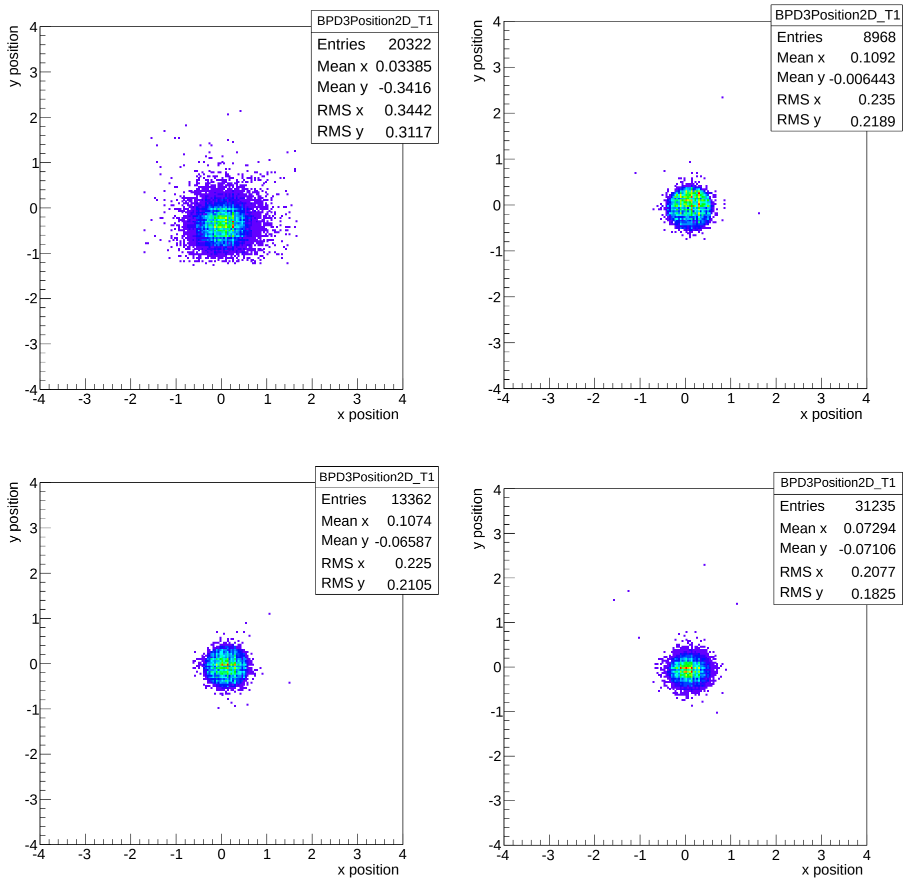


Figure 4.7.: Position in the BPD-3, events with T1 trigger:
Top - left: 13A GeV/c 2012, right: 13A GeV/c 2013
Bottom - left: 20A GeV/c, right: 30A GeV

the probability changes in both directions, no systematic change of the interaction probability can be concluded from the analysis of the BPD-3 cut.

	S4 cut	BPD-3 cut	P_I in %	P_R in %	P_{int} in %
13A GeV/c	52	-	21.225 ± 0.303	12.635 ± 0.298	9.854 ± 0.425
2012		r=0.4cm	13.738 ± 0.283	4.226 ± 0.199	9.935 ± 0.346
		r=0.3cm	12.126 ± 0.279	2.527 ± 0.162	9.852 ± 0.323
		r=0.2cm	11.068 ± 0.294	1.565 ± 0.140	9.660 ± 0.326
20A GeV/c	90	-	11.383 ± 0.292	1.929 ± 0.122	9.647 ± 0.317
		r=0.3cm	11.288 ± 0.293	1.875 ± 0.122	9.600 ± 0.317
		r=0.2cm	11.245 ± 0.309	1.822 ± 0.127	9.605 ± 0.334
		r=0.1cm	11.228 ± 0.380	1.633 ± 0.147	9.758 ± 0.408
30A GeV/c	82	-	10.796 ± 0.186	1.664 ± 0.087	9.298 ± 0.205
		r=0.3cm	10.807 ± 0.187	1.652 ± 0.087	9.320 ± 0.206
		r=0.2cm	10.738 ± 0.193	1.604 ± 0.089	9.294 ± 0.212
		r=0.1cm	10.591 ± 0.222	1.449 ± 0.098	9.287 ± 0.243

Table 4.1.: Influence of the BPD cut on the interaction probability.

4.3. Variation of the Z Cut

The Z detector was used in order to differentiate between Be beam particles and other beam particles. The signal in the detector is proportional to Z^2, where Z is the charge of the incoming particle. A more detailled description of the Z detector can be found in chapter 2.3.3.

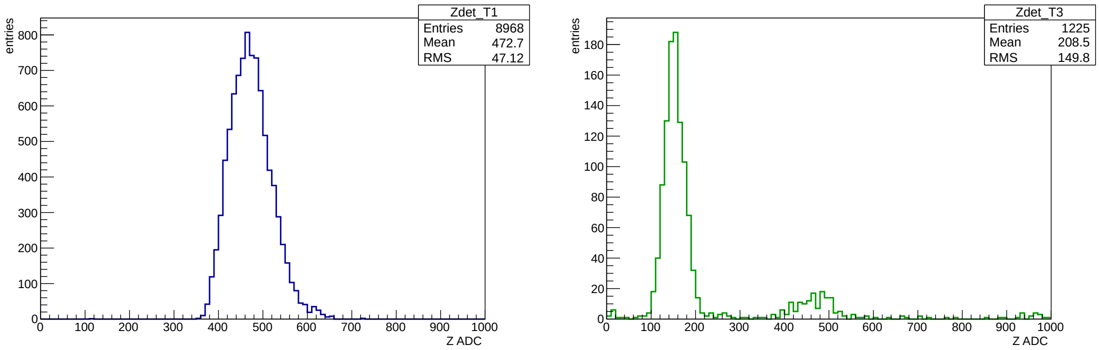


Figure 4.8.: Spectrum in the Z detector for the 13A GeV/c run in 2013. On the left the spectrum is shown for events with T1 trigger, on the right for events with T3 trigger.

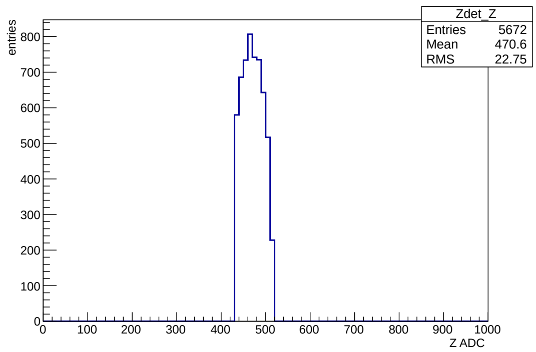


Figure 4.9.: Spectrum in the Z detector for the 13A GeV/c run in 2013 with Z cut from 430 till 515.

Looking at the histogram with T1 trigger in figure 4.8 (left), a clear peak caused by Be beam particles can be seen in the spectrum at an ADC value of about 460. Outside this peak the signal is 0. In the histogram with T3 trigger in figure 4.8 (right) there is a high peak due to He particles at the left side and a small Be peak in the middle.

The Z cut was varied to select an even smaller range of the Z spectrum than the T1 trigger. On the left and right side of the peak more restrictive cuts were made and only the middle part of the spectrum was examined (see figure 4.9). As the signal in the Z detector was shifted as well between the runs, different Z cuts were selected for each run.

	S4 cut	Z cut	P_I in %	P_R in %	P_{int} in %
13A GeV/c	52	-	21.225 ± 0.303	12.635 ± 0.298	9.854 ± 0.425
2012		300/425	20.473 ± 0.329	11.849 ± 0.319	9.809 ± 0.458
		320/405	20.424 ± 0.360	11.703 ± 0.346	9.891 ± 0.499
		340/385	20.469 ± 0.459	11.464 ± 0.439	10.151 ± 0.635
13A GeV/c	70	-	11.864 ± 0.364	2.370 ± 0.193	9.731 ± 0.412
2013		410/535	11.412 ± 0.393	2.213 ± 0.206	9.420 ± 0.444
		430/515	11.477 ± 0.450	2.080 ± 0.227	9.605 ± 0.504
		450/595	11.128 ± 0.582	1.893 ± 0.285	9.424 ± 0.648
20A GeV/c	90	-	11.383 ± 0.292	1.929 ± 0.122	9.647 ± 0.317
		430/580	11.115 ± 0.311	1.734 ± 0.125	9.554 ± 0.335
		450/560	11.281 ± 0.342	1.705 ± 0.136	9.746 ± 0.369
		470/540	11.267 ± 0.408	1.665 ± 0.162	9.768 ± 0.439
30A GeV/c	82	-	10.796 ± 0.186	1.664 ± 0.087	9.298 ± 0.205
		400/540	10.696 ± 0.198	1.644 ± 0.092	9.217 ± 0.219
		420/520	10.675 ± 0.218	1.661 ± 0.102	9.180 ± 0.241
		440/500	10.490 ± 0.267	1.465 ± 0.118	9.171 ± 0.292
30A GeV/c	82	-	4.377 ± 0.133	2.139 ± 0.107	2.452 ± 0.171
0.3 cm		400/540	4.225 ± 0.141	2.051 ± 0.113	2.379 ± 0.180
		420/520	4.253 ± 0.156	2.079 ± 0.126	2.382 ± 0.201
		440/500	4.285 ± 0.192	2.102 ± 0.201	2.393 ± 0.276

Table 4.2.: Influence of the Z cut on the interaction probability.

The interaction probabilites for the different Z cuts are shown in figure 4.2. The strictest Z cut reduces the background approx. 13 %. The trigger interaction probability changes about 1 - 3 %. For some runs it increases, for others it decreases with stricter Z cuts. Thus no systematic effect is observed.

4.4. Variation of the WFA Cut

A waveform analyzer (WFA) for the S1 scintillation counter measures the time at which particles pass through the detector in a time window of ± 25 μs around the triggering particle. In figure 4.10 histograms of these times, the beam time structure, is plotted for the different runs.

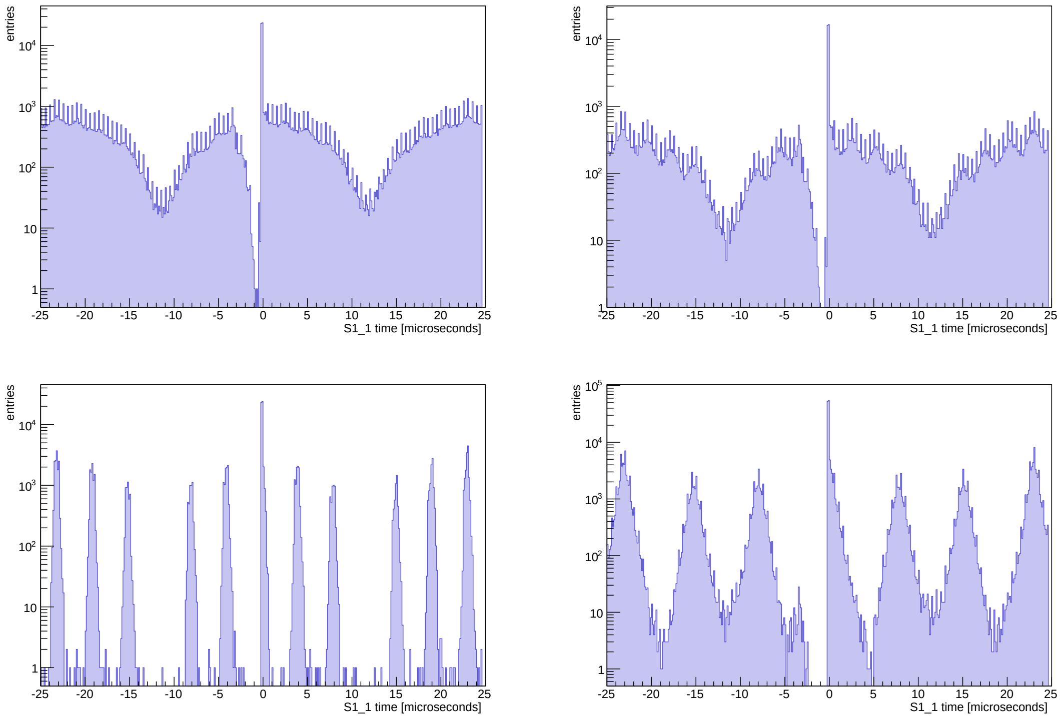


Figure 4.10.: Beam time structure for the different runs.
Top - left: 13A GeV/c 2012, right: 13A GeV/c 2013
Bottom - left: 20A GeV/c, right: 30A GeV/c

The intention of the WFA cut is to reduce possible effects due to off-time particles. Events are only included in the analysis, if there is only one beam particle within a certain time window. The studied time windows are 1, 2 and 5 μs.

The results of the WFA cut analysis are shown in table 4.3. The WFA cut shows no significant influence on the contribution of the background. The trigger interaction probability changes about max. 3 % and in both directions, thus indicating no systematic effects.

	S4 cut	WFA cut	P_I in %	P_R in %	P_{int} in %
13A GeV/c	52	-	20.776 ± 0.320	12.279 ± 0.312	9.725 ± 0.447
2012		1 μs	20.633 ± 0.337	12.228 ± 0.328	9.628 ± 0.470
		2 μs	20.730 ± 0.344	12.222 ± 0.344	9.730 ± 0.494
		5 μs	20.848 ± 0.392	12.065 ± 0.392	9.990 ± 0.570
13A GeV/c	70	-	11.864 ± 0.364	2.370 ± 0.193	9.731 ± 0.309
2013		1 μs	11.947 ± 0.381	2.369 ± 0.202	9.814 ± 0.432
		2 μs	11.974 ± 0.393	2.295 ± 0.206	9.909 ± 0.444
		5 μs	12.045 ± 0.449	2.380 ± 0.240	9.903 ± 0.509
20A GeV/c	90	-	11.383 ± 0.292	1.929 ± 0.122	9.647 ± 0.317
		1 μs	11.451 ± 0.302	1.861 ± 0.125	9.776 ± 0.327
		2 μs	11.444 ± 0.302	1.861 ± 0.125	9.769 ± 0.327
		5 μs	11.416 ± 0.361	1.716 ± 0.144	9.872 ± 0.388
30A GeV/c	82	-	10.796 ± 0.186	1.664 ± 0.087	9.298 ± 0.205
		1 μs	10.709 ± 0.200	1.635 ± 0.092	9.237 ± 0.220
		2 μs	10.747 ± 0.202	1.652 ± 0.092	9.261 ± 0.222
		5 μs	10.735 ± 0.202	1.655 ± 0.093	9.246 ± 0.223
30A GeV/c	82	-	4.377 ± 0.133	2.139 ± 0.107	2.452 ± 0.171
0.3 cm target		1 μs	4.305 ± 0.142	2.127 ± 0.116	2.391 ± 0.184
		2 μs	4.297 ± 0.143	2.132 ± 0.118	2.378 ± 0.185
		5 μs	4.289 ± 0.144	2.136 ± 0.118	2.367 ± 0.186

Table 4.3.: Influence of the WFA cut on the interaction probability.

4.5. Assignment of systematic error

For the systematic error due to the S4 cut two S4 cuts are selected. The first one (S4 min) is located at the left side of the region, where the trigger interaction probability is relatively stable in respect to small changes of the S4 cut, but also not too far from the beginning of the Be peak. The other S4 cut (S4 max) is located at the right end of the plateau. For the BPD-3, Z and WFA cuts in each case the results for the strictest cut were compared with those of the standard cuts. The maximum deviation of the interaction probability for the changed cut values was taken as the systematic error (see table 4.5).

13A GeV/c 2012	S4 cut = 52	S4 cut = 45	S4 cut = 65	BPD3 cut, r=0.2cm	Z cut = 340 / 385	WFA cut = 5 μs
P_I in %	21.225 ± 0.303	20.244 ± 0.316	38.392 ± 0.435	11.068 ± 0.294	20.469 ± 0.459	20.848 ± 0.392
P_R in %	12.635 ± 0.298	11.953 ± 0.308	30.697 ± 0.494	1.565 ± 0.140	11.464 ± 0.439	12.065 ± 0.392
P_{int} in %	9.854 ± 0.425	9.486 ± 0.441	10.765 ± 0.658	9.660 ± 0.326	10.151 ± 0.635	9.990 ± 0.570
13A GeV/c 2013	S4 cut = 70	S4 cut = 60	S4 cut = 80	BPD3 cut	Z cut = 450 / 495	WFA cut = 5 μs
P_I in %	11.864 ± 0.364	11.273 ± 0.355	14.608 ± 0.404	-	11.128 ± 0.582	12.045 ± 0.449
P_R in %	2.370 ± 0.193	1.931 ± 0.174	5.164 ± 0.285	-	1.893 ± 0.285	2.380 ± 0.240
P_{int} in %	9.731 ± 0.412	9.536 ± 0.395	9.960 ± 0.494	-	9.424 ± 0.648	9.903 ± 0.509
20A GeV/c	S4 cut = 90	S4 cut = 75	S4 cut = 95	BPD3 cut, r=0.1cm	Z cut = 470 / 540	WFA cut = 5 μs
P_I in %	11.383 ± 0.292	10.635 ± 0.282	14.579 ± 0.330	11.228 ± 0.380	11.267 ± 0.408	11.416 ± 0.361
P_R in %	1.929 ± 0.122	1.369 ± 0.103	5.149 ± 0.200	1.633 ± 0.147	1.665 ± 0.162	1.716 ± 0.144
P_{int} in %	9.647 ± 0.317	9.403 ± 0.300	9.945 ± 0.386	9.758 ± 0.408	9.768 ± 0.439	9.872 ± 0.388
30A GeV/c	S4 cut = 82	S4 cut = 70	S4 cut = 80	BPD3 cut, r=0.1cm	Z cut = 440 / 500	WFA cut = 5 μs
P_I in %	10.796 ± 0.186	10.219 ± 0.181	10.613 ± 0.184	10.591 ± 0.222	10.490 ± 0.267	10.735 ± 0.202
P_R in %	1.664 ± 0.087	1.146 ± 0.072	1.385 ± 0.079	1.449 ± 0.098	1.465 ± 0.118	1.655 ± 0.093
P_{int} in %	9.298 ± 0.205	9.188 ± 0.195	9.367 ± 0.201	9.287 ± 0.243	9.171 ± 0.292	9.246 ± 0.223
30A GeV/c 0.3 cm target	S4 cut = 82	S4 cut = 70	S4 cut = 80	BPD3 cut	Z cut = 440 / 500	WFA cut = 5 μs
P_I in %	4.377 ± 0.133	3.450 ± 0.118	6.544 ± 0.163	-	4.285 ± 0.192	4.289 ± 0.144
P_R in %	2.139 ± 0.107	1.228 ± 0.081	4.680 ± 0.158	-	2.102 ± 0.201	2.136 ± 0.118
P_{int} in %	2.452 ± 0.171	2.345 ± 0.143	2.331 ± 0.227	-	2.393 ± 0.276	2.367 ± 0.186

Table 4.4.: Interaction probabilities for the different runs and cuts: the standard S4 cut, S4 cut at the beginning of the plateau but not too far from the beginning of the Be peak, the S4 cut at the right edge of the plateau and the strictest BPD-3, Z and WFA cuts.

Statistical error

	13A GeV/c 2012	13A GeV/c 2013	20A GeV/c	30A GeV/c	30A GeV/c, 0.3 cm
P_{int} in %	9.854 ± 0.425	9.731 ± 0.412	9.647 ± 0.317	9.298 ± 0.205	2.452 ± 0.171

Systematic error (all values in %)

Cut	13A GeV/c 2012	13A GeV/c 2013	20A GeV/c	30A GeV/c	30A GeV/c, 0.3 cm
–	9.854	9.731	9.647	9.298	2.452
S4 min	9.486 (–0.368)	9.536 (–0.195)	9.403 (–0.244)	9.188 (–0.110)	2.345 (–0.107)
S4 max	10.765 (+0.911)	9.960 (+0.229)	9.945 (+0.298)	9.367 (+0.069)	2.331 (–0.121)
BPD-3	9.660 (–0.194)	–	9.758 (+0.111)	9.287 (–0.011)	–
Z	10.151 (+0.297)	9.424 (–0.307)	9.768 (+0.121)	9.171 (–0.127)	2.393 (–0.059)
WFA	9.990 (+0.136)	9.903 (+0.172)	9.872 (+0.225)	9.246 (–0.052)	2.367 (–0.085)
P_{int}	9.854	9.731	9.647	9.298	2.452
with syst.	– 0.368	– 0.307	– 0.244	– 0.127	– 0.121
error	+ 0.911	+ 0.229	+ 0.298	+ 0.069	+ 0

Table 4.5.: Results for interaction probability P_{int} with statistical and systematic errors.

5. Results

5.1. Calculation of the Cross Section

The cross section is first calculated using

$$\sigma_{trig} = \frac{1}{\rho L N_A / A} P_{int} \tag{5.1}$$

and then corrected for the exponential beam attenuation in the target by an iterative procedure:

$$\sigma_{trig,i} = \frac{P_{int} \cdot \sigma_{trig,i-1}}{1 - exp(-L\rho N_A \sigma_{trig,i-1}/A)} \tag{5.2}$$

For more information about the cross section calculaton see chapter 3.1. For the calculation of the iteration I created a small C++ program. The value for the cross section converges very fast, so that after approximately 6 steps the difference between two steps was already less than 10^{-5} mb.

Although the approximation $P_{int} = P_I - 0.9 \cdot P_R$ was sufficient in order to determine the systematic error and the standard S4 cuts, a better approximation for the interaction probability was favored for the calculation of the cross section and for this reason a different equation for P_{int} was used. The interaction probability inside the target was calculated as (see eq. 3.14)

$$P_{int} = (P_I - P_R)(1 + P_R) \tag{5.3}$$

with a statistical error of

$$\Delta P_{int} = \sqrt{\left(\frac{\partial P_{int}}{\partial P_I}\Delta P_I\right)^2 + \left(\frac{\partial P_{int}}{\partial P_R}\Delta P_R\right)^2} = \sqrt{(1+P_R)^2(\Delta P_I)^2 + (1 - P_I + 2P_R)^2(\Delta P_R)^2} \tag{5.4}$$

$\Delta\sigma_{trig}$ for the statistical error is estimated by inserting the maximum and minimum values for P_{int} and calculating the difference between these values and the original values for the inelastic cross section σ_{trig}, the effective target length L_{eff} and the absorption length λ_{abs}. For the calculation of the systematic error in addition to the systematic uncertainties of P_{int} the maximum and minimum values for the target length were used.

The values for the target length L, density ρ and atomic number A are as follows:

L [cm]	1.2 ± 0.03 (0.3 ± 0.03)
ρ [g/cm^3]	1.848
A[g/mol]	9.012182

5.2. Final Cross Section Results

In table 5.1 the results of the inelastic ^{7}Be + ^{9}Be cross section measurement are shown. First the interaction probability with statistical and systematic errors, then the zeroth approximation of the cross section, followed by the results for the absorption length, the effective length and the cross section after the first iteration and after the iteration process converges.

In figure 5.1 the cross section is plotted for beam momenta of 1.45A GeV/c (data from [13]), 13A GeV/c, 20A GeV/c and 30A GeV/c. As the background for the 13A GeV/c run in 2012 and with this the systematic error was high, only data from 2013 was used for this plot. Further the 30A GeV/c runs with the 0.3 cm target were neglected. Here the high relative error of the target length leads to a high systematic error. The value for the cross section slightly decreases (about 56 mb) in the region between 1.45A and 30A GeV/c, as it was already expected (see chapter 3.1).

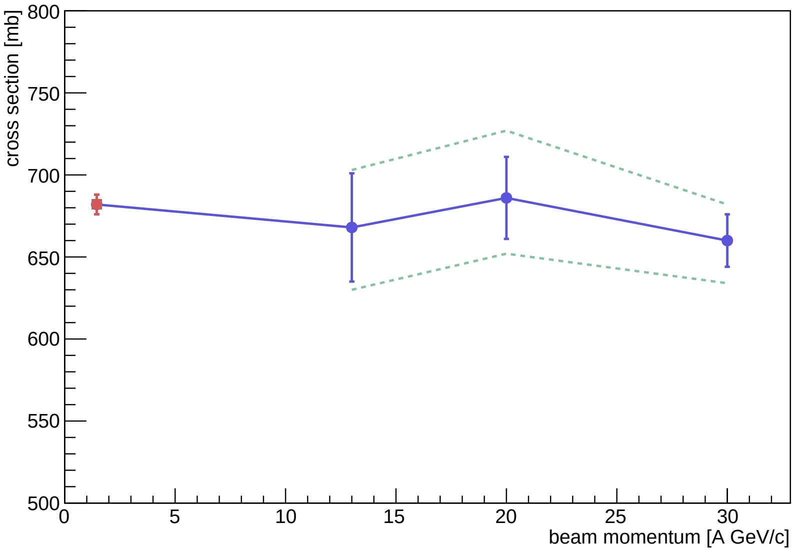


Figure 5.1.: Inelastic cross section of ^{7}Be + ^{9}Be measured by NA61/SHINE (this work) with statistical errors (dots, in blue) and systematic errors (dashed lines, in turquoise) as a function of beam momentum per nucleon. Point at 1.45A GeV/c taken from Ref. [13] (square, in red).

	13A GeV/c 2012	13A GeV/c 2013	20A GeV/c	30A GeV/c	30A GeV/c, 0.3 cm
P_{int} [%]	0.0968	0.0940	0.0964	0.0928	0.02286
stat. err.	±0.0055	±0.0044	±0.0033	±0.0021	±0.00179
syst. err.	–0.0037 +0.0091	–0.0031 +0.0023	–0.0024 +0.0030	–0.0013 +0.0007	–0.00121 +0
σ_{trig} [mb]	655	636	653	628	619
stat. err.	±38	±30	±23	±15	±49
syst. err	–49 +80	–36 +33	–32 +37	–24 +21	–86 +69
$\lambda_{abs,1}$ [cm]	12.4	12.8	12.5	12.9	13.1
stat. err.	±0.7	±0.6	±0.4	±0.3	–1.0 +1.1
syst. err.	–1.4 +0.8	–0.6 +0.8	–0.7 +0.6	–0.4 +0.5	–1.3 +2.1
$L_{eff,1}$ [cm]	1.144	1.145	1.144	1.146	0.297
stat. err.	±0.003	±0.003	±0.002	±0.001	±0.001
syst. err.	–0.0034 +0.0030	–0.0030 +0.0031	–0.0030 +0.0030	–0.0029 +0.0029	–0.0030 +0.0029
$\sigma_{trig,1}$ [mb]	688	667	685	658	626
stat. err.	±41	±33	±25	±16	±50
syst. err.	–44 +87	–39 +34	–34 +40	–25 +22	–87 +70
$\lambda_{abs,\infty}$ [cm]	11.8	12.2	11.8	12.3	13.0
stat. err.	±0.7	±0.6	±0.4	±0.3	±0.9
syst. err.	–1.3 +0.8	–0.6 +0.8	–0.7 +0.6	–0.4 +0.5	–1.3 +2.1
$L_{eff,\infty}$ [cm]	1.141	1.143	1.141	1.143	0.297
stat. err.	±0.003	±0.003	±0.002	±0.003	±0.001
syst. err.	–0.034 +0.031	–0.030 +0.030	–0.030 +0.030	–0.029 +0.030	–0.030 +0.029
$\sigma_{trig,\infty}$ [mb]	689	668	686	660	626
stat. err.	±42	±33	±25	±16	±50
syst. err.	–43 +88	–38 +35	–34 +41	–26 +22	–87 +70

Table 5.1.: Target interaction probability, cross section, effective target length and absorption length.

Outlook

In 2011 data was taken also at beam momenta of $40A$, $80A$ and $150A$ GeV/c. For this data a cross section analysis will be made using the PSD (Projectile Spectator Detector, a high resolution forward calorimeter located downstream of the S4 scintillator in the beam line) instead of the S4 counter, as the S4 detector was not used at these beam momenta.

Also for $13A$, $20A$ and $30A$ GeV/c the cross section will be analyzed with the PSD and the results will be compared to the results of the analysis with the S4 detector. This analysis is important in order to be able to compare the results for lower beam momenta with the $40A$, $80A$ and $150A$ GeV/c runs, as here only the PSD can be used for the cross section analysis.

The results from the cross section analysis can help defining parameters of models. In particular in the NA61 experiment the GLISSANDO (= Glauber Initial-State Simulation AND mOre. . .) model is used. GLISSANDO is a Monte-Carlo generator based on the Glauber model (see [6]).

Further a publication with the ^{7}Be +^{9}Be cross section measurements for different beam momenta is planned. For this reason the analysis made for this Bachelor thesis will be repeated with higher statistics.

Acknowledgements

At this point I want to thank Marek Gazdzicki for the opportunity to write my Bachelor thesis at the NA61/SHINE experiment. Thank you for valuable discussions and suggestions.

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A. Macro

```
#include <evt/Event.h>
#include <evt/RecEvent.h>
#include <evt/rec/RecEventConst.h>
#include <utl/ShineUnits.h>
#include <io/EventFile.h>

#include <TH1D.h>
#include <TH2D.h>
#include <TFile.h>
#include <TF1.h>

#include <iostream>
#include <iomanip>
#include <fstream>
#include <math.h>

using namespace std;
using namespace io;
using namespace utl;
using namespace evt;
using namespace evt::rec;

/* ——————————————————————————————————————————

   read and analyze a bunch of SHOE files given
   in a file list as input

   —————————————————————————————————————————— */
```

```
int
main(int argc, char* argv[])
{
  if (argc != 2) {
    cerr << "usage: " << argv[0] << " <file list>" << endl;
    return 1;
  }

  // open list of files to process
  cout << " reading file names from " << argv[1] << endl;
  ifstream fileList(argv[1]);

  if (!fileList.good() || !fileList.is_open()) {
    cerr << " Error, cannot read file list " << argv[1] <<
      endl;
    return 1;
  }


  // set everything off for reading ...
  std::vector<std::string> offBranches;
  offBranches.push_back("eventTree.fEvent.fRecEvent.*");
  offBranches.push_back("eventTree.fEvent.fRawEvent.*");
  // ... only a few things are needed here
  std::vector<std::string> onBranches;
  onBranches.push_back("eventTree.fEvent.fRecEvent.fBeam");
  onBranches.push_back("eventTree.fEvent.fRawEvent.fBeam");
  onBranches.push_back("eventTree.fEvent.fRecEvent.fPSD");


  // output files
  TFile outFile("bebe.root", "RECREATE");
```

```
ofstream outAll;
ofstream outS4;
ofstream outS4_BPD;
ofstream outZ;
ofstream outWFA;
ofstream outBPD;

outAll.open ("bebe.txt");
outS4.open ("S4.txt");
outS4_BPD.open ("S4_BPD.txt");
outZ.open ("Z.txt");
outWFA.open ("WFA.txt");
outBPD.open ("BPD.txt");


// PSD
const double minEnergy = 0;
const double maxEnergy = 200; // GeV
const unsigned int nEnergyBins = 200;

// BPD
const double minBPD = -4;
const double maxBPD = 4;
const unsigned int nBPDBins = 200;

// Z
const double minZ = 0;
const double maxZ = 1000;
const unsigned int nZBins = 100;
int nr_ev_Z = 0;

// WFA
const double minWFA = -25;
const double maxWFA = 25;
const unsigned int nWFABins = 400;
```

```
  Float_t WFACut_1 = 1;
  Float_t WFACut_2 = 2;
  Float_t WFACut_3 = 5;

  // 13 AGeV

  // ADC 13 AGeV
  const double minADC = 0;
  const double maxADC = 120;
  const unsigned int nADCBins = 120;

  // BPD 13 AGeV

  Float_t BPDCut1 = 0.4;
  Float_t BPDCut2 = 0.3;
  Float_t BPDCut3 = 0.2;

/*
  // 2012

  // S4 2012
  Float_t gS4Cut = 52.;
  // Float_t gS4CutMax = 93.;

  Float_t gS4Cut_1 = 20.;
  Float_t gS4Cut_2 = 30.;
  Float_t gS4Cut_3 = 40.;
  Float_t gS4Cut_4 = 45.;
  Float_t gS4Cut_5 = 50.;
  Float_t gS4Cut_6 = 55.;
  Float_t gS4Cut_7 = 60.;
  Float_t gS4Cut_8 = 65.;
  Float_t gS4Cut_9 = 70.;
  Float_t gS4Cut_10 = 80.;
```

```
  // Z cut 2012
  Float_t ZCutMin_1 = 300;
  Float_t ZCutMax_1 = 425;
  Float_t ZCutMin_2 = 320;
  Float_t ZCutMax_2 = 405;
  Float_t ZCutMin_3 = 340;
  Float_t ZCutMax_3 = 385;
*/

  // 2013

  // S4 2013
  Float_t gS4Cut = 70.;

  Float_t gS4Cut_1 = 30.;
  Float_t gS4Cut_2 = 40.;
  Float_t gS4Cut_3 = 50.;
  Float_t gS4Cut_4 = 55.;
  Float_t gS4Cut_5 = 60.;
  Float_t gS4Cut_6 = 65.;
  Float_t gS4Cut_7 = 70.;
  Float_t gS4Cut_8 = 75.;
  Float_t gS4Cut_9 = 80.;
  Float_t gS4Cut_10 = 90.;

  // Z Cut 2013
  Float_t ZCutMin_1 = 410;
  Float_t ZCutMax_1 = 535;
  Float_t ZCutMin_2 = 430;
  Float_t ZCutMax_2 = 515;
  Float_t ZCutMin_3 = 450;
  Float_t ZCutMax_3 = 495;
```

```
  /* 20 AGeV

  // ADC 20 AGeV
  const double minADC = 20;
  const double maxADC = 140;
  const unsigned int nADCBins = 120;

  // BPD cut 20 AGeV
  Float_t BPDCut1 = 0.3;
  Float_t BPDCut2 = 0.2;
  Float_t BPDCut3 = 0.1;

  // S4 20 AGeV
  Float_t gS4Cut = 90.;

  Float_t gS4Cut_1 = 50.;
  Float_t gS4Cut_2 = 60.;
  Float_t gS4Cut_3 = 70.;
  Float_t gS4Cut_4 = 75.;
  Float_t gS4Cut_5 = 80.;
  Float_t gS4Cut_6 = 85.;
  Float_t gS4Cut_7 = 90.;
  Float_t gS4Cut_8 = 95.;
  Float_t gS4Cut_9 = 100.;
  Float_t gS4Cut_10 = 110.;

  // Z cut 20 AGeV
  Float_t ZCutMin_1 = 430;
  Float_t ZCutMax_1 = 580;
  Float_t ZCutMin_2 = 450;
  Float_t ZCutMax_2 = 560;
  Float_t ZCutMin_3 = 470;
  Float_t ZCutMax_3 = 540;
*/
/*
```

```
  // 30 AGeV

  // ADC 30 AGeV
  const double minADC = 20;
  const double maxADC = 140;
  const unsigned int nADCBins = 120;

  // BPD cut 30 AGeV
  Float_t BPDCut1 = 0.3;
  Float_t BPDCut2 = 0.2;
  Float_t BPDCut3 = 0.1;

  // S4 30 AGeV
  Float_t gS4Cut = 82.;

  Float_t gS4Cut_1 = 40.;
  Float_t gS4Cut_2 = 50.;
  Float_t gS4Cut_3 = 60.;
  Float_t gS4Cut_4 = 65.;
  Float_t gS4Cut_5 = 70.;
  Float_t gS4Cut_6 = 75.;
  Float_t gS4Cut_7 = 80.;
  Float_t gS4Cut_8 = 85.;
  Float_t gS4Cut_9 = 90.;
  Float_t gS4Cut_10 = 100.;

  // Z cut 30 AGeV
  Float_t ZCutMin_1 = 400;
  Float_t ZCutMax_1 = 540;
  Float_t ZCutMin_2 = 420;
  Float_t ZCutMax_2 = 520;
  Float_t ZCutMin_3 = 440;
  Float_t ZCutMax_3 = 500;
*/
```

```
// PSD histograms

TH1D* psdEnergyHist = new TH1D("psdEnergy", ";E_{PSD}
    [GeV]; entries", nEnergyBins, minEnergy, maxEnergy);

TH1D* psdEnergy_T1Hist = new TH1D("psdEnergy_T1",
    ";E_{PSD} [GeV]; entries", nEnergyBins, minEnergy,
    maxEnergy);

TH1D* psdEnergy_T1noS4Hist = new TH1D("psdEnergy_T1noS4",
    ";E_{PSD} [GeV]; entries", nEnergyBins, minEnergy,
    maxEnergy);

TH1D* psdEnergy_T1normHist = new TH1D("psdEnergy_T1norm",
    ";E_{PSD} [GeV]; entries", nEnergyBins, minEnergy,
    maxEnergy);

TH1D* psdEnergy_T1noS4normHist = new
    TH1D("psdEnergy_T1noS4norm", ";E_{PSD} [GeV];
    entries", nEnergyBins, minEnergy, maxEnergy);

TH1D* psdEnergy_T2Hist = new TH1D("psdEnergy_T2",
    ";E_{PSD} [GeV]; entries", nEnergyBins, minEnergy,
    maxEnergy);


// sADC histograms

TH1D* sADCHist = new TH1D("sADC", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_T1Hist = new TH1D("sADC_T1", ";S4 ADC;
    entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4Be_T1Hist = new TH1D("sADC_T1_S4Be", ";S4
```

```
   ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1Hist = new TH1D("sADC_T1_S4noBe",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_T3Hist = new TH1D("sADC_T3", ";S4 ADC;
    entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_1Hist =              // S4 cuts
    new TH1D("sADC_T1_S4noBe01", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_2Hist = new TH1D("sADC_T1_S4noBe02",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_3Hist = new TH1D("sADC_T1_S4noBe03",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_4Hist = new TH1D("sADC_T1_S4noBe04",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_5Hist = new TH1D("sADC_T1_S4noBe05",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_6Hist = new TH1D("sADC_T1_S4noBe06",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_7Hist = new TH1D("sADC_T1_S4noBe07",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_8Hist = new TH1D("sADC_T1_S4noBe08",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_9Hist = new TH1D("sADC_T1_S4noBe09",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);
```

```
TH1D* sADC_S4noBe_T1_10Hist = new
    TH1D("sADC_T1_S4noBe10", ";S4 ADC; entries", nADCBins,
    minADC, maxADC);


TH1D* sADC_BPD_T1Hist =     // S4 cuts with BPD cut
    new TH1D("sADC_BPD_T1", ";S4 ADC; entries", nADCBins,
    minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_1Hist = new
    TH1D("sADC_BPD_T1_S4noBe01", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_2Hist = new
    TH1D("sADC_BPD_T1_S4noBe02", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_3Hist = new
    TH1D("sADC_BPD_T1_S4noBe03", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_4Hist = new
    TH1D("sADC_BPD_T1_S4noBe04", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_5Hist = new
    TH1D("sADC_BPD_T1_S4noBe05", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_6Hist = new
    TH1D("sADC_BPD_T1_S4noBe06", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_7Hist = new
```

```
    TH1D("sADC_BPD_T1_S4noBe07", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_8Hist = new
    TH1D("sADC_BPD_T1_S4noBe08", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_9Hist = new
    TH1D("sADC_BPD_T1_S4noBe09", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_BPD_S4noBe_T1_10Hist = new
    TH1D("sADC_BPD_T1_S4noBe10", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

// with Z Cut
TH1D* sADC_Z1Hist = new TH1D("sADC_Z1",    // Z cut 1
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_T1_Z1Hist = new TH1D("sADC_T1_Z1", ";S4 ADC;
    entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4Be_T1_Z1Hist = new TH1D("sADC_T1_S4Be_Z1",
    ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_Z1Hist = new
    TH1D("sADC_T1_S4noBe_Z1", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_T3_Z1Hist = new TH1D("sADC_T3_Z1", ";S4 ADC;
    entries", nADCBins, minADC, maxADC);

TH1D* sADC_T1_Z2Hist = new TH1D("sADC_T1_Z2", // Z cut 2
    ";S4 ADC; entries", nADCBins, minADC, maxADC);
```

```
TH1D* sADC_S4noBe_T1_Z2Hist = new
   TH1D("sADC_T1_S4noBe_Z2", ";S4 ADC; entries",
   nADCBins, minADC, maxADC);

TH1D* sADC_T1_Z3Hist = new TH1D("sADC_T1_Z3", // Z cut 3
   ";S4 ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_Z3Hist = new
   TH1D("sADC_T1_S4noBe_Z3", ";S4 ADC; entries",
   nADCBins, minADC, maxADC);


TH1D* sADC_T1_BPD1Hist =      // with BPD circular cut
   new TH1D("sADC_T1_BPD1", ";S4 ADC; entries",
   nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_BPD1Hist = new
   TH1D("sADC_T1_S4noBe_BPD1", ";S4 ADC; entries",
   nADCBins, minADC, maxADC);

TH1D* sADC_T1_BPD2Hist = new TH1D("sADC_T1_BPD2", ";S4
   ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_BPD2Hist = new
   TH1D("sADC_T1_S4noBe_BPD2", ";S4 ADC; entries",
   nADCBins, minADC, maxADC);

TH1D* sADC_T1_BPD3Hist = new TH1D("sADC_T1_BPD3", ";S4
   ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_BPD3Hist = new
   TH1D("sADC_T1_S4noBe_BPD3", ";S4 ADC; entries",
   nADCBins, minADC, maxADC);
```

```
TH1D* sADC_T1_WFA1Hist =     // with WFA Cut
    new TH1D("sADC_T1_WFA1", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_WFA1Hist = new
    TH1D("sADC_T1_S4noBe_WFA1", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_T1_WFA2Hist = new TH1D("sADC_T1_WFA2", ";S4
    ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_WFA2Hist = new
    TH1D("sADC_T1_S4noBe_WFA2", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);

TH1D* sADC_T1_WFA3Hist = new TH1D("sADC_T1_WFA3", ";S4
    ADC; entries", nADCBins, minADC, maxADC);

TH1D* sADC_S4noBe_T1_WFA3Hist = new
    TH1D("sADC_T1_S4noBe_WFA3", ";S4 ADC; entries",
    nADCBins, minADC, maxADC);


// PSD vs sADC histogram
TH2D* psdEnergyVsADCHist = new TH2D("psdEnergyVsADC",
    ";S4 ADC; E [GeV]", nADCBins, minADC, maxADC,
    nEnergyBins, minEnergy, maxEnergy);

// 2D BPD histograms

TH2D* BPD1Position2DHist = new TH2D("BPD1Position2D",
    ";x position ; y position", nBPDBins, minBPD, maxBPD,
    nBPDBins, minBPD, maxBPD);

TH2D* BPD2Position2DHist = new TH2D("BPD2Position2D",
```

```
    ";x position ; y position", nBPDBins, minBPD, maxBPD,
    nBPDBins, minBPD, maxBPD);

TH2D* BPD3Position2DHist = new TH2D("BPD3Position2D",
    ";x position ; y position", nBPDBins, minBPD, maxBPD,
    nBPDBins, minBPD, maxBPD);

TH2D* BPD1Position2D_T1Hist = new
   TH2D("BPD1Position2D_T1", ";x position ; y position",
   nBPDBins, minBPD, maxBPD, nBPDBins, minBPD, maxBPD);

TH2D* BPD2Position2D_T1Hist = new
   TH2D("BPD2Position2D_T1", ";x position ; y position",
   nBPDBins, minBPD, maxBPD, nBPDBins, minBPD, maxBPD);

TH2D* BPD3Position2D_T1Hist = new
   TH2D("BPD3Position2D_T1", ";x position ; y position",
   nBPDBins, minBPD, maxBPD, nBPDBins, minBPD, maxBPD);

TH2D* BPD1Position2D_S4Be_T1Hist = new
   TH2D("BPD1Position2D_S4Be_T1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
   maxBPD);

TH2D* BPD2Position2D_S4Be_T1Hist = new
   TH2D("BPD2Position2D_S4Be_T1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
   maxBPD);

TH2D* BPD3Position2D_S4Be_T1Hist = new
   TH2D("BPD3Position2D_S4Be_T1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
   maxBPD);

TH2D* BPD1Position2D_S4noBe_T1Hist = new
```

```
    TH2D("BPD1Position2D_S4noBe_T1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

TH2D* BPD2Position2D_S4noBe_T1Hist = new
    TH2D("BPD2Position2D_S4noBe_T1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

TH2D* BPD3Position2D_S4noBe_T1Hist = new
    TH2D("BPD3Position2D_S4noBe_T1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

// with BPD circular cut
TH2D* BPD3Position2D_Cut_T1_1Hist =
    new TH2D("BPD3Position2D_Cut_T1_1", ";x position ; y
        position",
    nBPDBins, minBPD, maxBPD, nBPDBins, minBPD, maxBPD);

TH2D* BPD3Position2D_Cut_S4Be_T1_1Hist = new
    TH2D("BPD3Position2D_Cut_S4Be_T1_1", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

TH2D* BPD3Position2D_Cut_S4noBe_T1_1Hist = new
    TH2D("BPD3Position2D_Cut_S4noBe_T1_1", ";x position ;
    y position", nBPDBins, minBPD, maxBPD, nBPDBins,
    minBPD, maxBPD);

TH2D* BPD3Position2D_Cut_T1_2Hist = new
    TH2D("BPD3Position2D_Cut_T1_2", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);
```

```
TH2D* BPD3Position2D_Cut_S4Be_T1_2Hist = new
    TH2D("BPD3Position2D_Cut_S4Be_T1_2", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

TH2D* BPD3Position2D_Cut_S4noBe_T1_2Hist = new
    TH2D("BPD3Position2D_Cut_S4noBe_T1_2", ";x position ;
    y position", nBPDBins, minBPD, maxBPD, nBPDBins,
    minBPD, maxBPD);

TH2D* BPD3Position2D_Cut_T1_3Hist = new
    TH2D("BPD3Position2D_Cut_T1_3", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

TH2D* BPD3Position2D_Cut_S4Be_T1_3Hist = new
    TH2D("BPD3Position2D_Cut_S4Be_T1_3", ";x position ; y
    position", nBPDBins, minBPD, maxBPD, nBPDBins, minBPD,
    maxBPD);

TH2D* BPD3Position2D_Cut_S4noBe_T1_3Hist = new
    TH2D("BPD3Position2D_Cut_S4noBe_T1_3", ";x position ;
    y position", nBPDBins, minBPD, maxBPD, nBPDBins,
    minBPD, maxBPD);


// Z detector histograms
TH1D* ZdetHist = new TH1D("Zdet", ";Z ADC ;entries",
    nZBins, minZ, maxZ);

TH1D* Zdet_T1Hist = new TH1D("Zdet_T1", ";Z ADC
    ;entries", nZBins, minZ, maxZ);

TH1D* Zdet_T3Hist = new TH1D("Zdet_T3", ";Z ADC
    ;entries", nZBins, minZ, maxZ);
```

```
TH1D* Zdet_ZHist = new TH1D("Zdet_Z", ";Z ADC ;entries",
   nZBins, minZ, maxZ);

TH1D* Zdet_noZHist = new TH1D("Zdet_noZ", ";Z ADC
   ;entries", nZBins, minZ, maxZ);

/* TH1D* Zdet_delHist = new TH1D("Zdet_del", ";Z ADC
   ;entries", nZBins, minZ, maxZ);

TH2D* Zdet_corHist = new TH2D("Zdet_cor", ";sum ;del",
   nZBins, minZ, maxZ, nZBins, minZ, maxZ);

TH1D* Zdet_divHist = new TH1D("Zdet_div", ";Z ADC
   ;entries", nZBins, minZ, maxZ); */


// WFA histograms
TH1D* WFAHist = new TH1D("WFA", ";S1_1 time
   [microseconds] ;entries", nWFABins, minWFA, maxWFA);


// --- loop over file list
while (true) {
  string fileName;
  fileList >> fileName;
  if (!fileList.good())
    break;

  cout << " --> processing " << fileName << endl;

  EventFile eventFile(fileName, eRead,
     Verbosity::eSilent, offBranches, onBranches);

  // loop over events
```

```
Event event;
while (eventFile.Read(event) == eSuccess) {

  // good BPD?
  const int beamStatus =
     event.GetRecEvent().GetBeam().GetStatus();
  if (beamStatus &
     (BeamConst::eNotFitted|BeamConst::eBadBPD3))
    continue;

  // 6 good clusters in the BPD?
  if (beamStatus != 0) continue;

  // --- triggers
  using namespace det::TriggerConst;
  const raw::Trigger& trigger =
     event.GetRawEvent().GetBeam().GetTrigger();
  // const rec::Trigger& rtrigger =
     event.GetRecEvent().GetBeam().GetTrigger();
  const bool isT1 = trigger.IsTrigger(eT1, ePrescaled);
  const bool isT2 = trigger.IsTrigger(eT2, ePrescaled);
  const bool isT3 = trigger.IsTrigger(eT3, ePrescaled);
  const bool isS4 = trigger.IsTrigger(eS4, eAll);
  const unsigned int s4ADC = trigger.GetADC(eS4);

  // PSD energy
  const double psdEnergy =
     event.GetRecEvent().GetPSD().GetEnergy();

  psdEnergyHist->Fill(psdEnergy/GeV);
  if (isT1) {    // T1 trigger
    psdEnergy_T1Hist->Fill(psdEnergy/GeV);
    psdEnergy_T1normHist->Fill(psdEnergy/GeV);
  }
  if (isT1 && !isS4) { // T1 & S4bar
```

```
  psdEnergy_T1noS4Hist->Fill(psdEnergy/GeV);
  psdEnergy_T1noS4normHist->Fill(psdEnergy/GeV);
}

if (isT2) { psdEnergy_T2Hist->Fill(psdEnergy/GeV); }

// S4 counter
sADCHist->Fill(s4ADC);
if(isT1) {           // T1 trigger
  sADC_T1Hist->Fill(s4ADC);
  if (s4ADC>gS4Cut) sADC_S4Be_T1Hist->Fill(s4ADC);
         // S4(Be)
  if (s4ADC<=gS4Cut) sADC_S4noBe_T1Hist->Fill(s4ADC);
        // S4(noBe)
  if (s4ADC<=gS4Cut_1)
     sADC_S4noBe_T1_1Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_2)
     sADC_S4noBe_T1_2Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_3)
     sADC_S4noBe_T1_3Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_4)
     sADC_S4noBe_T1_4Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_5)
     sADC_S4noBe_T1_5Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_6)
     sADC_S4noBe_T1_6Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_7)
     sADC_S4noBe_T1_7Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_8)
     sADC_S4noBe_T1_8Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_9)
     sADC_S4noBe_T1_9Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_10)
     sADC_S4noBe_T1_10Hist->Fill(s4ADC);
}
```

```
if(isT3) {
  sADC_T3Hist->Fill(s4ADC);
}


// WFA
if (trigger.HasTimeStructure
   (det::TimeStructureConst::eWFA,
   det::TriggerConst::eS1_1)) {
  const vector<double>& BeamTimes =
     trigger.GetTimeStructure
     (det::TimeStructureConst::eWFA,
     det::TriggerConst::eS1_1);

  // WFA cut: allow no other particle within 2
     microseconds
  size_t nBeamParticles1 = 0;
  for (size_t i = 0; i < BeamTimes.size(); ++i) {
    WFAHist->Fill(BeamTimes[i]/1000);
    if (fabs(BeamTimes[i]) < WFACut_1*micro*second)
       ++nBeamParticles1;
  }
  if (isT1 && (nBeamParticles1 == 1)) {
                              // T1 trigger & WFA Cut
    sADC_T1_WFA1Hist->Fill(s4ADC);
    if (s4ADC <= gS4Cut)
       sADC_S4noBe_T1_WFA1Hist->Fill(s4ADC);
                  // S4(noBe)
  }

  size_t nBeamParticles2 = 0;
  for (size_t i = 0; i < BeamTimes.size(); ++i) {
    if (fabs(BeamTimes[i]) < WFACut_2*micro*second)
       ++nBeamParticles2;
```

```
    }
    if (isT1 && (nBeamParticles2 == 1)) {
      sADC_T1_WFA2Hist->Fill(s4ADC);
      if (s4ADC <= gS4Cut)
        sADC_S4noBe_T1_WFA2Hist->Fill(s4ADC);
    }

    size_t nBeamParticles3 = 0;
    for (size_t i = 0; i < BeamTimes.size(); ++i) {
      if (fabs(BeamTimes[i]) < WFACut_3*micro*second)
        ++nBeamParticles3;
    }
    if (isT1 && (nBeamParticles3 == 1)) {
      sADC_T1_WFA3Hist->Fill(s4ADC);
      if (s4ADC <= gS4Cut)
        sADC_S4noBe_T1_WFA3Hist->Fill(s4ADC);
    }
  }

psdEnergyVsADCHist->Fill(s4ADC, psdEnergy/GeV);

// BPD position
const double x1 = event.GetRecEvent().GetBeam().
    GetBPDPlane(det::BPDConst::eBPD1x).GetPosition();
const double y1 = event.GetRecEvent().GetBeam().
    GetBPDPlane(det::BPDConst::eBPD1y).GetPosition();
BPD1Position2DHist->Fill(x1, y1);

const double x2 = event.GetRecEvent().GetBeam().
    GetBPDPlane(det::BPDConst::eBPD2x).GetPosition();
const double y2 = event.GetRecEvent().GetBeam().
    GetBPDPlane(det::BPDConst::eBPD2y).GetPosition();
BPD2Position2DHist->Fill(x2, y2);

const double x3 = event.GetRecEvent().GetBeam().
```

```
    GetBPDPlane(det::BPDConst::eBPD3x).GetPosition();
const double y3 = event.GetRecEvent().GetBeam().
    GetBPDPlane(det::BPDConst::eBPD3y).GetPosition();
BPD3Position2DHist->Fill(x3, y3);

if (isT1) {    // T1 trigger
  BPD1Position2D_T1Hist->Fill(x1, y1);
  BPD2Position2D_T1Hist->Fill(x2, y2);
  BPD3Position2D_T1Hist->Fill(x3, y3);

  if (s4ADC>gS4Cut /*&& s4ADC<gS4CutMax*/) {
                // S4(Be)
    BPD1Position2D_S4Be_T1Hist->Fill(x1, y1);
    BPD2Position2D_S4Be_T1Hist->Fill(x2, y2);
    BPD3Position2D_S4Be_T1Hist->Fill(x3, y3);
  }
  else {        // S4(noBe)
    BPD1Position2D_S4noBe_T1Hist->Fill(x1, y1);
    BPD2Position2D_S4noBe_T1Hist->Fill(x2, y2);
    BPD3Position2D_S4noBe_T1Hist->Fill(x3, y3);
  }
}

// if (pow(x3-0.1, 2) + pow(y3+0.4, 2) <= BPDCut1) {
          // BPD circular cut 13AGeV
if (pow(x3-0.08, 2) + pow(y3, 2) <= BPDCut1) {
              // BPD circular cut 20AGeV
  if (isT1) {    // T1 trigger
    BPD3Position2D_Cut_T1_1Hist->Fill(x3, y3);
    sADC_T1_BPD1Hist->Fill(s4ADC);
    if (s4ADC>gS4Cut) {   // S4(Be)
      BPD3Position2D_Cut_S4Be_T1_1Hist->Fill(x3, y3);
    }
    else {
      BPD3Position2D_Cut_S4noBe_T1_1Hist->Fill(x3,
```

```
            y3);
          sADC_S4noBe_T1_BPD1Hist->Fill(s4ADC);
        }
      }
    }

    // if (pow(x3-0.1, 2)+pow(y3+0.4, 2) <= BPDCut2) {
    if (pow(x3-0.08, 2) + pow(y3, 2) <= BPDCut2) {
      if (isT1) {
        BPD3Position2D_Cut_T1_2Hist->Fill(x3, y3);
        sADC_T1_BPD2Hist->Fill(s4ADC);
        if (s4ADC>gS4Cut) {
          BPD3Position2D_Cut_S4Be_T1_2Hist->Fill(x3, y3);
        }
        else {
          BPD3Position2D_Cut_S4noBe_T1_2Hist->Fill(x3,
            y3);
          sADC_S4noBe_T1_BPD2Hist->Fill(s4ADC);
        }
      }
    }

    // if (pow(x3-0.1, 2)+pow(y3+0.4, 2) <= BPDCut3) {
    if (pow(x3-0.08, 2) + pow(y3, 2) <= BPDCut3) {
      if (isT1) {
        BPD3Position2D_Cut_T1_3Hist->Fill(x3, y3);
        sADC_T1_BPD3Hist->Fill(s4ADC);
        if (s4ADC>gS4Cut) {
          BPD3Position2D_Cut_S4Be_T1_3Hist->Fill(x3, y3);
        }
        else {
          BPD3Position2D_Cut_S4noBe_T1_3Hist->Fill(x3,
            y3);
          sADC_S4noBe_T1_BPD3Hist->Fill(s4ADC);
        }
```

```
  }
}

// S4 counter with BPD cut
// if(isT1 && (pow(x3-0.1, 2) + pow(y3+0.4, 2) <=
   BPDCut3)) {   // T1 trigger && BPD cut 13 GeV
if(isT1 && (pow(x3-0.08, 2) + pow(y3, 2) <= 0.2)) {
            // T1 trigger && BPD cut 20 GeV
  sADC_BPD_T1Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_1)
     sADC_BPD_S4noBe_T1_1Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_2)
     sADC_BPD_S4noBe_T1_2Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_3)
     sADC_BPD_S4noBe_T1_3Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_4)
     sADC_BPD_S4noBe_T1_4Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_5)
     sADC_BPD_S4noBe_T1_5Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_6)
     sADC_BPD_S4noBe_T1_6Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_7)
     sADC_BPD_S4noBe_T1_7Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_8)
     sADC_BPD_S4noBe_T1_8Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_9)
     sADC_BPD_S4noBe_T1_9Hist->Fill(s4ADC);
  if (s4ADC<=gS4Cut_10)
     sADC_BPD_S4noBe_T1_10Hist->Fill(s4ADC);
}

// Z detector
nr_ev_Z++;
double sum =
   trigger.GetADC(det::TriggerConst::eZdet_sum);
```

```
// double del =
   trigger.GetADC(det::TriggerConst::eZdet_sum_del);
ZdetHist->Fill(sum);
/* Zdet_delHist->Fill(del);
Zdet_corHist->Fill(sum, del);
sum = sum/del;
Zdet_divHist->Fill(sum); */
if (isT1) { Zdet_T1Hist->Fill(sum); }
if (isT3) { Zdet_T3Hist->Fill(sum); }

if ((sum > ZCutMin_1) && (sum < ZCutMax_1))  {
   // Z Cut 1
  sADC_Z1Hist->Fill(s4ADC);
  if(isT1) {
     // T1 trigger
    sADC_T1_Z1Hist->Fill(s4ADC);
    if (s4ADC > gS4Cut)
       sADC_S4Be_T1_Z1Hist->Fill(s4ADC);   // S4(Be)
    else sADC_S4noBe_T1_Z1Hist->Fill(s4ADC);
                        // S4(noBe)
  }
  if(isT3) {
    sADC_T3_Z1Hist->Fill(s4ADC);
  }
}

if ((sum > ZCutMin_2) && (sum < ZCutMax_2))  {
   // Z cut 2
  if(isT1) {
    sADC_T1_Z2Hist->Fill(s4ADC);
    Zdet_ZHist->Fill(sum);
    if (s4ADC <= gS4Cut)
       sADC_S4noBe_T1_Z2Hist->Fill(s4ADC);
  }
  else Zdet_noZHist->Fill(sum);
```

```
    }

    if ((sum > ZCutMin_3) && (sum < ZCutMax_3))  {
      // Z cut 3
      if(isT1) {
        sADC_T1_Z3Hist->Fill(s4ADC);
        if (s4ADC <= gS4Cut)
          sADC_S4noBe_T1_Z3Hist->Fill(s4ADC);
      }
    }
  }
}

// Normalization histograms psdEnergy
TF1 *fNorm = new TF1("fNorm", "1", -100000, 100000);
Double_t entT1 = psdEnergy_T1Hist->GetEntries();
psdEnergy_T1normHist->Divide(fNorm, entT1);
psdEnergy_T1noS4normHist->Divide(fNorm, entT1);

// get entries of S4 histograms
Double_t entS4 = sADCHist->GetEntries();
Double_t entS4_T1 = sADC_T1Hist->GetEntries();
Double_t entS4_S4Be_T1 = sADC_S4Be_T1Hist->GetEntries();
Double_t entS4_S4noBe_T1 =
   sADC_S4noBe_T1Hist->GetEntries();
Double_t entS4_S4noBe_T1_1 =
   sADC_S4noBe_T1_1Hist->GetEntries();
Double_t entS4_S4noBe_T1_2 =
   sADC_S4noBe_T1_2Hist->GetEntries();
Double_t entS4_S4noBe_T1_3 =
   sADC_S4noBe_T1_3Hist->GetEntries();
Double_t entS4_S4noBe_T1_4 =
   sADC_S4noBe_T1_4Hist->GetEntries();
Double_t entS4_S4noBe_T1_5 =
   sADC_S4noBe_T1_5Hist->GetEntries();
```

```
Double_t entS4_S4noBe_T1_6 =
   sADC_S4noBe_T1_6Hist->GetEntries();
Double_t entS4_S4noBe_T1_7 =
   sADC_S4noBe_T1_7Hist->GetEntries();
Double_t entS4_S4noBe_T1_8 =
   sADC_S4noBe_T1_8Hist->GetEntries();
Double_t entS4_S4noBe_T1_9 =
   sADC_S4noBe_T1_9Hist->GetEntries();
Double_t entS4_S4noBe_T1_10 =
   sADC_S4noBe_T1_10Hist->GetEntries();

Double_t entS4_BPD_T1 = sADC_BPD_T1Hist->GetEntries();
   // S4 cuts with BPD cut
Double_t entS4_BPD_S4noBe_T1_1 =
   sADC_BPD_S4noBe_T1_1Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_2 =
   sADC_BPD_S4noBe_T1_2Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_3 =
   sADC_BPD_S4noBe_T1_3Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_4 =
   sADC_BPD_S4noBe_T1_4Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_5 =
   sADC_BPD_S4noBe_T1_5Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_6 =
   sADC_BPD_S4noBe_T1_6Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_7 =
   sADC_BPD_S4noBe_T1_7Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_8 =
   sADC_BPD_S4noBe_T1_8Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_9 =
   sADC_BPD_S4noBe_T1_9Hist->GetEntries();
Double_t entS4_BPD_S4noBe_T1_10 =
   sADC_BPD_S4noBe_T1_10Hist->GetEntries();

Double_t entS4_Z1 = sADC_Z1Hist->GetEntries();   // Z Cut
```

```
Double_t entS4_T1_Z1 = sADC_T1_Z1Hist->GetEntries();
Double_t entS4_S4Be_T1_Z1 =
   sADC_S4Be_T1_Z1Hist->GetEntries();
Double_t entS4_S4noBe_T1_Z1 =
   sADC_S4noBe_T1_Z1Hist->GetEntries();
Double_t entS4_T1_Z2 = sADC_T1_Z2Hist->GetEntries();
Double_t entS4_S4noBe_T1_Z2 =
   sADC_S4noBe_T1_Z2Hist->GetEntries();
Double_t entS4_T1_Z3 = sADC_T1_Z3Hist->GetEntries();
Double_t entS4_S4noBe_T1_Z3 =
   sADC_S4noBe_T1_Z3Hist->GetEntries();

Double_t entS4_T1_BPD1 = sADC_T1_BPD1Hist->GetEntries();
      // BPD Cut
Double_t entS4_S4noBe_T1_BPD1 =
   sADC_S4noBe_T1_BPD1Hist->GetEntries();
Double_t entS4_T1_BPD2 = sADC_T1_BPD2Hist->GetEntries();
Double_t entS4_S4noBe_T1_BPD2 =
   sADC_S4noBe_T1_BPD2Hist->GetEntries();
Double_t entS4_T1_BPD3 = sADC_T1_BPD3Hist->GetEntries();
Double_t entS4_S4noBe_T1_BPD3 =
   sADC_S4noBe_T1_BPD3Hist->GetEntries();

Double_t entS4_T1_WFA1 = sADC_T1_WFA1Hist->GetEntries();
      // WFA Cut
Double_t entS4_S4noBe_T1_WFA1 =
   sADC_S4noBe_T1_WFA1Hist->GetEntries();
Double_t entS4_T1_WFA2 = sADC_T1_WFA2Hist->GetEntries();
Double_t entS4_S4noBe_T1_WFA2 =
   sADC_S4noBe_T1_WFA2Hist->GetEntries();
Double_t entS4_T1_WFA3 = sADC_T1_WFA3Hist->GetEntries();
Double_t entS4_S4noBe_T1_WFA3 =
   sADC_S4noBe_T1_WFA3Hist->GetEntries();

// write in output text file
```

```
outAll << "Interaction probability for S4 cut at " <<
   gS4Cut << endl << endl;

outAll << "Number of events in S4 spectrum: " << entS4 <<
   endl;
outAll << "Number of events in S4 spectrum with trigger
   T1: " << entS4_T1 << endl;
outAll << "Number of events in S4 spectrum with trigger
   T1 and S4(Be): " << entS4_S4Be_T1 << endl;
outAll << "Number of events in S4 spectrum with trigger
   T1 and S4(noBe): " << entS4_S4noBe_T1 << endl << endl;

outAll << "P = S4(noBe)/T1 = " << entS4_S4noBe_T1 << "/"
   << entS4_T1 << " = " << entS4_S4noBe_T1/entS4_T1 <<
   endl;
outAll << "deltaP = sqrt(S4(noBe))/T1 = sqrt(" <<
   entS4_S4noBe_T1 << ")/" << entS4_T1 << " = " <<
   sqrt(entS4_S4noBe_T1)/entS4_T1 << endl << endl;

outAll << "*** S4 cut     T1&S4(noBe)     P       deltaP
   ***" << endl;    // S4 cuts

outAll << gS4Cut_1 << " " << entS4_S4noBe_T1_1 << " " <<
   entS4_S4noBe_T1_1/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_1)/entS4_T1 << endl;
outAll << gS4Cut_2 << " " << entS4_S4noBe_T1_2 << " " <<
   entS4_S4noBe_T1_2/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_2)/entS4_T1 << endl;
outAll << gS4Cut_3 << " " << entS4_S4noBe_T1_3 << " " <<
   entS4_S4noBe_T1_3/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_3)/entS4_T1 << endl;
outAll << gS4Cut_4 << " " << entS4_S4noBe_T1_4 << " " <<
   entS4_S4noBe_T1_4/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_4)/entS4_T1 << endl;
outAll << gS4Cut_5 << " " << entS4_S4noBe_T1_5 << " " <<
```

```
   entS4_S4noBe_T1_5/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_5)/entS4_T1 << endl;
outAll << gS4Cut_6 << " " << entS4_S4noBe_T1_6 << " " <<
   entS4_S4noBe_T1_6/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_6)/entS4_T1 << endl;
outAll << gS4Cut_7 << " " << entS4_S4noBe_T1_7 << " " <<
   entS4_S4noBe_T1_7/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_7)/entS4_T1 << endl;
outAll << gS4Cut_8 << " " << entS4_S4noBe_T1_8 << " " <<
   entS4_S4noBe_T1_8/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_8)/entS4_T1 << endl;
outAll << gS4Cut_9 << " " << entS4_S4noBe_T1_9 << " " <<
   entS4_S4noBe_T1_9/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_9)/entS4_T1 << endl;
outAll << gS4Cut_10 << " " << entS4_S4noBe_T1_10 << " "
   << entS4_S4noBe_T1_10/entS4_T1 << " " <<
   sqrt(entS4_S4noBe_T1_10)/entS4_T1 << endl << endl;

outAll << "*** S4 cuts & BPD cut ***" << endl;
outAll << "*** S4 cut     T1&S4(noBe)     P        deltaP
   ***" << endl;    // S4 cuts with BPD cut

outAll << "T1: " << entS4_BPD_T1 << endl;
outAll << gS4Cut_1 << " " << entS4_BPD_S4noBe_T1_1 << " "
   << entS4_BPD_S4noBe_T1_1/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_1)/entS4_BPD_T1 << endl;
outAll << gS4Cut_2 << " " << entS4_BPD_S4noBe_T1_2 << " "
   << entS4_BPD_S4noBe_T1_2/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_2)/entS4_BPD_T1 << endl;
outAll << gS4Cut_3 << " " << entS4_BPD_S4noBe_T1_3 << " "
   << entS4_BPD_S4noBe_T1_3/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_3)/entS4_BPD_T1 << endl;
outAll << gS4Cut_4 << " " << entS4_BPD_S4noBe_T1_4 << " "
   << entS4_BPD_S4noBe_T1_4/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_4)/entS4_BPD_T1 << endl;
```

```
outAll << gS4Cut_5 << " " << entS4_BPD_S4noBe_T1_5 << " "
   << entS4_BPD_S4noBe_T1_5/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_5)/entS4_BPD_T1 << endl;
outAll << gS4Cut_6 << " " << entS4_BPD_S4noBe_T1_6 << " "
   << entS4_BPD_S4noBe_T1_6/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_6)/entS4_BPD_T1 << endl;
outAll << gS4Cut_7 << " " << entS4_BPD_S4noBe_T1_7 << " "
   << entS4_BPD_S4noBe_T1_7/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_7)/entS4_BPD_T1 << endl;
outAll << gS4Cut_8 << " " << entS4_BPD_S4noBe_T1_8 << " "
   << entS4_BPD_S4noBe_T1_8/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_8)/entS4_BPD_T1 << endl;
outAll << gS4Cut_9 << " " << entS4_BPD_S4noBe_T1_9 << " "
   << entS4_BPD_S4noBe_T1_9/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_9)/entS4_BPD_T1 << endl;
outAll << gS4Cut_10 << " " << entS4_BPD_S4noBe_T1_10 << "
   " << entS4_BPD_S4noBe_T1_10/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_10)/entS4_BPD_T1 << endl <<
   endl;

// Z cut
outAll << "*** Z Cut from " << ZCutMin_1 << " to " <<
   ZCutMax_1 << " ***" << endl;

outAll << "S4: " << entS4_Z1 << "  T1: " << entS4_T1_Z1
   << "  T1&S4(Be): " << entS4_S4Be_T1_Z1 << "
   T1&S4(noBe): " << entS4_S4noBe_T1_Z1 << endl;
outAll << "P = " << entS4_S4noBe_T1_Z1/entS4_T1_Z1 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_Z1))/(entS4_T1_Z1) << endl <<
   endl;

outAll << "*** Z Cut from " << ZCutMin_2 << " to " <<
   ZCutMax_2 << " ***" << endl;
```

```
outAll << "T1: " << entS4_T1_Z2 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_Z2  << endl;
outAll << "P = " << entS4_S4noBe_T1_Z2/entS4_T1_Z2 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_Z2))/(entS4_T1_Z2) << endl <<
   endl;

outAll << "*** Z Cut from " << ZCutMin_3 << " to " <<
   ZCutMax_3 << " ***" << endl;
outAll << "T1: " << entS4_T1_Z3 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_Z3  << endl;
outAll << "P = " << entS4_S4noBe_T1_Z3/entS4_T1_Z3 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_Z3))/(entS4_T1_Z3) << endl <<
   endl;

outAll << "*** BPD Cut at " << BPDCut1 << " ***" << endl;
   // BPD Cut
outAll << "T1: " << entS4_T1_BPD1 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_BPD1  << endl;
outAll << "P = " << entS4_S4noBe_T1_BPD1/entS4_T1_BPD1 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_BPD1))/(entS4_T1_BPD1) << endl
   << endl;

outAll << "*** BPD Cut at " << BPDCut2 << " ***" << endl;
outAll << "T1: " << entS4_T1_BPD2 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_BPD2  << endl;
outAll << "P = " << entS4_S4noBe_T1_BPD2/entS4_T1_BPD2 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_BPD2))/(entS4_T1_BPD2) << endl
```

```
   << endl;

outAll << "*** BPD Cut at " << BPDCut3 << " ***" << endl;
outAll << "T1: " << entS4_T1_BPD3 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_BPD3  << endl;
outAll << "P = " << entS4_S4noBe_T1_BPD3/entS4_T1_BPD3 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_BPD3))/(entS4_T1_BPD3) << endl
   << endl;

outAll << "*** WFA Cut at "  << WFACut_1 << " ***" <<
   endl;  // WFA Cut
outAll << "T1: " << entS4_T1_WFA1 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_WFA1 << endl;
outAll << "P = " << entS4_S4noBe_T1_WFA1/entS4_T1_WFA1 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_WFA1))/(entS4_T1_WFA1) << endl
   << endl;

outAll << "*** WFA Cut at "  << WFACut_2 << " ***" <<
   endl;
outAll << "T1: " << entS4_T1_WFA2 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_WFA2 << endl;
outAll << "P = " << entS4_S4noBe_T1_WFA2/entS4_T1_WFA2 <<
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_WFA2))/(entS4_T1_WFA2) << endl
   << endl;

outAll << "*** WFA Cut at " << WFACut_3 << " ***" << endl;
outAll << "T1: " << entS4_T1_WFA3 << "  T1&S4(noBe): " <<
   entS4_S4noBe_T1_WFA3 << endl;
outAll << "P = " << entS4_S4noBe_T1_WFA3/entS4_T1_WFA3 <<
```

```
   endl;
outAll << "deltaP = " <<
   (sqrt(entS4_S4noBe_T1_WFA3))/(entS4_T1_WFA3) << endl
   << endl;

outS4 << gS4Cut_1 << " " << entS4_S4noBe_T1_1/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_1)/entS4_T1 << endl;
outS4 << gS4Cut_2 << " " << entS4_S4noBe_T1_2/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_2)/entS4_T1 << endl;
outS4 << gS4Cut_3 << " " << entS4_S4noBe_T1_3/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_3)/entS4_T1 << endl;
outS4 << gS4Cut_4 << " " << entS4_S4noBe_T1_4/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_4)/entS4_T1 << endl;
outS4 << gS4Cut_5 << " " << entS4_S4noBe_T1_5/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_5)/entS4_T1 << endl;
outS4 << gS4Cut_6 << " " << entS4_S4noBe_T1_6/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_6)/entS4_T1 << endl;
outS4 << gS4Cut_7 << " " << entS4_S4noBe_T1_7/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_7)/entS4_T1 << endl;
outS4 << gS4Cut_8 << " " << entS4_S4noBe_T1_8/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_8)/entS4_T1 << endl;
outS4 << gS4Cut_9 << " " << entS4_S4noBe_T1_9/entS4_T1 <<
   " " << sqrt(entS4_S4noBe_T1_9)/entS4_T1 << endl;
outS4 << gS4Cut_10 << " " << entS4_S4noBe_T1_10/entS4_T1
   << " " << sqrt(entS4_S4noBe_T1_10)/entS4_T1 << endl;

outS4_BPD << gS4Cut_1 << " " <<
   entS4_BPD_S4noBe_T1_1/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_1)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_2 << " " <<
   entS4_BPD_S4noBe_T1_2/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_2)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_3 << " " <<
   entS4_BPD_S4noBe_T1_3/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_3)/entS4_BPD_T1 << endl;
```

```
outS4_BPD << gS4Cut_4 << " " <<
   entS4_BPD_S4noBe_T1_4/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_4)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_5 << " " <<
   entS4_BPD_S4noBe_T1_5/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_5)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_6 << " " <<
   entS4_BPD_S4noBe_T1_6/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_6)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_7 << " " <<
   entS4_BPD_S4noBe_T1_7/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_7)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_8 << " " <<
   entS4_BPD_S4noBe_T1_8/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_8)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_9 << " " <<
   entS4_BPD_S4noBe_T1_9/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_9)/entS4_BPD_T1 << endl;
outS4_BPD << gS4Cut_10 << " " <<
   entS4_BPD_S4noBe_T1_10/entS4_BPD_T1 << " " <<
   sqrt(entS4_BPD_S4noBe_T1_10)/entS4_BPD_T1 << endl;

outZ << ZCutMin_1 << " " << ZCutMax_1 << " " <<
   entS4_T1_Z1 << " " << entS4_S4noBe_T1_Z1/entS4_T1_Z1
   << " " << (sqrt(entS4_S4noBe_T1_Z1))/(entS4_T1_Z1) <<
   endl;
outZ << ZCutMin_2 << " " << ZCutMax_2 << " " <<
   entS4_T1_Z2 << " " << entS4_S4noBe_T1_Z2/entS4_T1_Z2
   << " " << (sqrt(entS4_S4noBe_T1_Z2))/(entS4_T1_Z2) <<
   endl;
outZ << ZCutMin_3 << " " << ZCutMax_3 << " " <<
   entS4_T1_Z3 << " " << entS4_S4noBe_T1_Z3/entS4_T1_Z3
   << " " << (sqrt(entS4_S4noBe_T1_Z3))/(entS4_T1_Z3) <<
   endl;
```

```
  outWFA << WFACut_1 << " " << entS4_T1_WFA1 << " " <<
      entS4_S4noBe_T1_WFA1/entS4_T1_WFA1 << " " <<
      (sqrt(entS4_S4noBe_T1_WFA1))/(entS4_T1_WFA1) << endl;
  outWFA << WFACut_2 << " " << entS4_T1_WFA2 << " " <<
      entS4_S4noBe_T1_WFA2/entS4_T1_WFA2 << " " <<
      (sqrt(entS4_S4noBe_T1_WFA2))/(entS4_T1_WFA2) << endl;
  outWFA << WFACut_3 << " " << entS4_T1_WFA3 << " " <<
      entS4_S4noBe_T1_WFA3/entS4_T1_WFA3 << " " <<
      (sqrt(entS4_S4noBe_T1_WFA3))/(entS4_T1_WFA3) << endl;

  outBPD << BPDCut1 << " " << entS4_T1_BPD1 << " " <<
      entS4_S4noBe_T1_BPD1/entS4_T1_BPD1 << " " <<
      (sqrt(entS4_S4noBe_T1_BPD1))/(entS4_T1_BPD1) << endl;
  outBPD << BPDCut2 << " " << entS4_T1_BPD2 << " " <<
      entS4_S4noBe_T1_BPD2/entS4_T1_BPD2 << " " <<
      (sqrt(entS4_S4noBe_T1_BPD2))/(entS4_T1_BPD2) << endl;
  outBPD << BPDCut3 << " " << entS4_T1_BPD3 << " " <<
      entS4_S4noBe_T1_BPD3/entS4_T1_BPD3 << " " <<
      (sqrt(entS4_S4noBe_T1_BPD3))/(entS4_T1_BPD3) << endl;

  outAll.close();
  outS4.close();
  outS4_BPD.close();
  outZ.close();
  outWFA.close();
  outBPD.close();

  cout << "File names from " << argv[1]  << ", S4 Cut at "
     << gS4Cut << endl;

  outFile.Write();
  outFile.Close();

  return 0;
}
```

B. List of analyzed runs

13A GeV/c (2012)
Target inserted: runs 17111, 17298
Target removed: runs 17120, 17285

13A GeV/c (2013)
Target inserted: runs 18120, 18143
Target removed: runs 18119, 18006

20A GeV/c
Target inserted: runs 17586, 17546
Target removed: runs 17576, 17533

30A GeV/c
Target inserted: runs 17858, 17834
Target removed: runs 17833, 17808

30A GeV/c (0.3 cm target)
Target inserted: runs 17939, 17909
Target removed: runs 17937, 17920

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List of Figures

Selbstständigkeitserklärung

Hiermit versichere ich, dass ich diese Bachelorarbeit zum Thema "Bestimmung des ^{7}Be + ^{9}Be Wirkungsquerschnittes bei Strahlenergien von 13A, 20A und 30A GeV" selbstständig verfasst habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt, sowie Zitate kenntlich gemacht.
Mir ist bekannt, dass Zuwiderhandlung auch nachträglich zur Aberkennung des Abschlusses führen kann.

München, August 19, 2013	
Ort, Datum	Unterschrift