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Measurements of production and inelastic cross  
sections for  $p + C$ ,  $p + Be$ , and  $p + Al$  at  $60 \text{ GeV}/c$   
and  $p + C$  and  $p + Be$  at  $120 \text{ GeV}/c$

The NA61/SHINE Collaboration

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52 This paper presents measurements of production cross sections and inelastic cross sections for the following  
53 reactions:  $60\text{ GeV}/c$  protons with C, Be, Al targets and  $120\text{ GeV}/c$  protons with C and Be targets. The  
54 analysis was performed using the NA61/SHINE spectrometer at the CERN SPS. First measurements  
55 were obtained using protons at  $120\text{ GeV}/c$ , while the results for protons at  $60\text{ GeV}/c$  were compared with  
56 previously published measurements. These interaction cross section measurements are critical inputs for  
57 neutrino flux prediction in current and future accelerator-based long-baseline neutrino experiments.

# 58 1 Introduction

59 Long-baseline neutrino beams are typically initiated by high-energy protons that strike a long target,  
60 yielding hadrons that can decay to neutrinos or can reinteract in the target (carbon and beryllium being  
61 the most frequently used materials) or in the aluminum focussing horns, potentially producing additional  
62 neutrino-yielding hadrons. The NA61/SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) [1], which  
63 is a fixed-target experiment at the CERN Super Proton Synchrotron (SPS), has already been very successful  
64 at measuring the yields of secondary hadrons generated by protons at 31 GeV/c on carbon targets [2, 3, 4]  
65 for the T2K long-baseline neutrino oscillation experiment [5]. NA61/SHINE has recently completed  
66 data collection at higher energies to benefit other accelerator-based long-baseline neutrino experiments,  
67 particularly experiments that use the NuMI beamline or the future LBNF beamline at Fermilab. NuMI is  
68 initiated by 120 GeV/c protons on a carbon target, while LBNF will use 60-120 GeV/c protons on a carbon  
69 target.

70 NA61/SHINE has already measured integrated cross sections of pions and kaons to constrain predictions  
71 of the neutrino flux coming from reinteractions of pions and kaons [6]. This paper presents measurements  
72 of proton integrated cross sections to further improve neutrino flux predictions coming from the primary  
73 interactions in the neutrino beam targets or reinteractions of protons in the target and aluminum horns.

74 During the 2016 data collection, NA61/SHINE recorded interactions of protons on thin carbon, beryllium,  
75 and aluminum targets using beam momenta of 60 GeV/c and 120 GeV/c. Interactions were recorded with  
76 all three targets at 60 GeV/c, while interactions on thin carbon and beryllium targets were recorded at  
77 120 GeV/c.

78 The methodology to measure the inelastic cross section  $\sigma_{\text{inel}}$  and the production cross section  $\sigma_{\text{prod}}$  follows  
79 the same approach as the previous NA61/SHINE measurements [6]. The inelastic process is defined as  
80 the sum of all strong-interaction processes that result in the disintegration of the target nucleus (including  
81 quasi-elastic interactions). This is equivalent to the total cross section minus the coherent elastic cross  
82 section. The production process is defined as those in which new hadrons are produced. Using the coherent  
83 elastic cross section,  $\sigma_{\text{el}}$ , and the quasi-elastic cross section,  $\sigma_{\text{qe}}$ , one can define  $\sigma_{\text{inel}}$  and  $\sigma_{\text{prod}}$  as:

$$\sigma_{\text{inel}} = \sigma_{\text{total}} - \sigma_{\text{el}}, \quad (1)$$

$$\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}. \quad (2)$$

84 It is worth noting that not all measurements and experiments use the same terminology for these processes.  
85 For instance, the MINER $\nu$ A experiment [7] on the NuMI beamline uses the term “absorption” cross section  
86 for  $\sigma_{\text{inel}}$ , while previous measurements sometimes refer to either  $\sigma_{\text{prod}}$  or  $\sigma_{\text{inel}}$  with the term “absorption”  
87 cross section (for example, Carroll et al. [8] used  $\sigma_{\text{prod}}$  as the “absorption” cross section, while Denisov et  
88 al. [9] used  $\sigma_{\text{inel}}$  as the “absorption” cross section).

89 This paper is organized as follows: Section 2 describes the experimental setup. Section 3 describes the event  
90 selection. Section 4 describes the procedure for measuring integrated cross sections. Section 5 describes  
91 the corrections to the raw trigger probability. Section 6 discusses systematic uncertainties. The final results  
92 and discussion are presented in Sections 7.

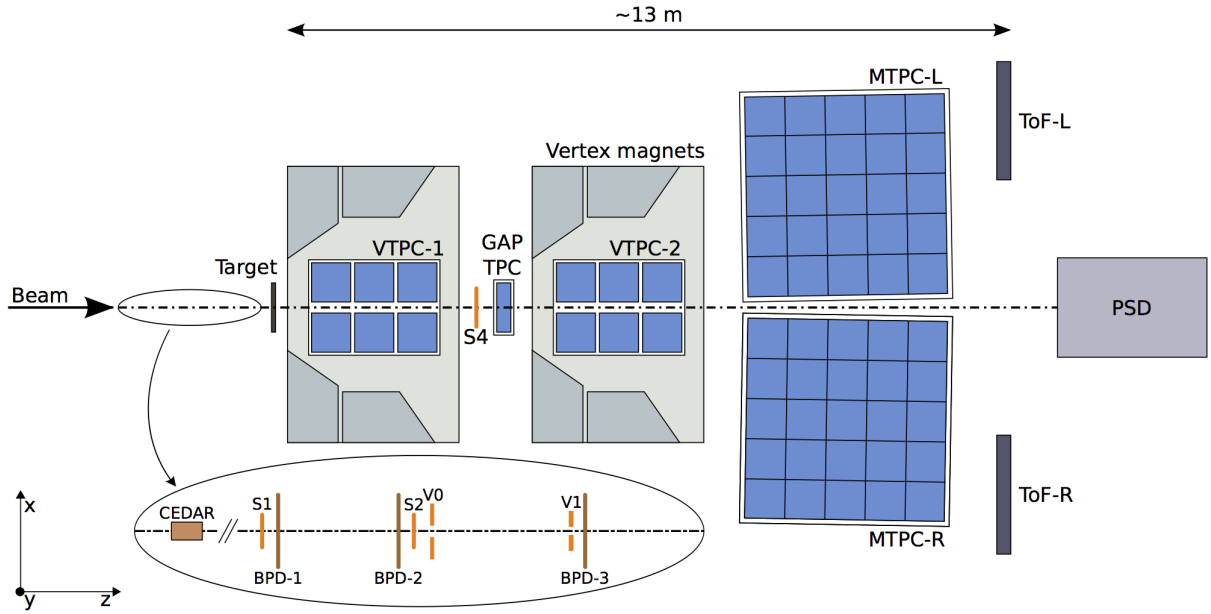


Figure 1: The schematic top-view layout of the NA61/SHINE experiment in the configuration used during the 2016 data-taking.

## 2 Experimental Setup

NA61/SHINE receives a secondary hadron beam from the 400 GeV/c SPS proton beam. Upstream of the NA61/SHINE detector, a magnet system is used to select the desired beam momentum between 13 GeV/c and 350 GeV/c.

The NA61/SHINE detector [1] is shown in Figure 1. It comprises two superconducting magnets, five Time Projection Chambers (TPCs), a Time of Flight (ToF) system, and a forward hadron calorimeter (the Projectile Spectator Detector, PSD). Two of the TPCs, Vertex TPC 1 (VTPC-1), and Vertex TPC 2 (VTPC-2), are contained within superconducting magnets, capable of generating a combined maximum bending power of 9 T·m. The most critical systems for integrated cross section measurements are the trigger system and the Beam Position Detectors (BPDs). The trigger system uses two scintillator counters (S1 and S2) to trigger on beam particles and two annular scintillation counters (V0 and V1) to veto divergent beam particles upstream of the target. The 1 cm radius S4 scintillator sits downstream of the target and is used to determine whether or not an interaction has occurred. A Cherenkov Differential Counter with Achromatic Ring Focus (CEDAR) [10, 11] selects beam particles of the desired species. For the 2016 data at 60 GeV/c (120 GeV/c), the beam was composed of approximately 22% (40%) protons.

Beam particles are selected by defining the beam trigger ( $T_{\text{beam}}$ ) as the coincidence of  $S1 \wedge S2 \wedge \overline{V0} \wedge \overline{V1} \wedge \text{CEDAR}$ . The interaction trigger ( $T_{\text{int}}$ ) is defined by the coincidence of  $T_{\text{beam}} \wedge S4$  to select beam particles which have interacted with the target. A correction factor for interactions that result in an S4 hit will be discussed in detail in Section 5.1. Three BPDs, which are proportional wire chambers, are located 30.39 m, 9.09 m, and 0.89 m upstream of the target and determine the trajectory of the incident beam particle to an accuracy of approximately 100  $\mu\text{m}$ .

The interactions of proton beams were measured on thin carbon, beryllium, and aluminum targets. Two

115 types of carbon targets were used: one composed of graphite of a density of  $\rho = 1.84 \text{ g/cm}^3$  with dimensions  
 116 of 25 mm (W) x 25 mm (H) x 20 mm (L) for 60 GeV/ $c$  proton beam, corresponding to roughly 4.2% of  
 117 a proton-nuclear interaction length, and one composed of graphite of a density of  $\rho = 1.80 \text{ g/cm}^3$  with  
 118 dimensions of 25 mm (W) x 25 mm (H) x 14.8 mm (L) for 120 GeV/ $c$  proton beam, corresponding to roughly  
 119 3.1% of a proton-nuclear interaction length. The beryllium target has a density of  $\rho = 1.85 \text{ g/cm}^3$  with  
 120 dimensions of 25 mm (W) x 25 mm (H) x 14.9 mm (L), corresponding to roughly 3.5% of a proton-nuclear  
 121 interaction length. The aluminum target has a density of  $\rho = 2.70 \text{ g/cm}^3$  with dimensions of 25 mm (W) x  
 122 25 mm (H) x 14.8 mm (L), corresponding to roughly 3.6% of a proton-nuclear interaction length.

### 123 3 Event Selection

124 Several cuts were applied to events to ensure the purity of the samples and to control the systematic effects  
 125 caused by beam divergence. First, the so-called WFA (Wave Form Analyzer) cut was used. The WFA  
 126 determines the timing of beam particles that pass through the S1 scintillator. If another beam particle passes  
 127 through the beam line close in time, it could cause a false trigger in the S4. In order to mitigate this effect,  
 128 a conservative cut of  $\pm 2 \mu\text{s}$  was applied, ensuring that only one particle is allowed to pass through the S1  
 129 in a  $4 \mu\text{s}$  time window.

130 Beam trajectory measurements are especially important for estimating the effects of beam divergence.  
 131 To understand these effects, tracks are fitted to the reconstructed BPD clusters, and these tracks are  
 132 extrapolated to the S4 location. The so-called ‘‘Good BPD’’ cut requires that the event includes a cluster in  
 133 the most-downstream BPD and that a track was successfully fit to the BPDs. Figure 2 shows examples of  
 134 the resulting BPD extrapolation to the S4. As seen in the left plot of Figure 2, a halo of beam particles can  
 135 miss the S4, mimicking the interaction trigger. To avoid such an effect and also to minimize the effect of  
 136 the S4 size and position uncertainties, which will be discussed in Section 6, a radial cut of 0.75 cm was  
 137 applied to the tracks extrapolated from the BPDs, as indicated in Figure 2. After the p + C 60 GeV/ $c$  data  
 138 collection, the S4 position was realigned for other measurements which can also be seen in Figure 2.

139 About two third of data was collected with target inserted and one third of data was collected with target  
 140 removed. The number of events remaining after the described selection cuts for target inserted and removed  
 141 are shown in Tables 1 - 3 for C, Be and Al, respectively.

p + C	60 GeV/ $c$		120 GeV/ $c$		
	Target	Inserted	Removed	Inserted	Removed
Total	254k	116k	393k	217k	
WFA	224k	102k	358k	196k	
Good BPD	215k	98k	257k	140k	
Radial cut	210k	95k	214k	117k	

Table 1: Number of selected events for p + C at 60 and 120 GeV/ $c$ .

### 142 4 Interaction Trigger Cross Sections

143 The probability of a beam particle interaction inside a thin target is proportional to the thickness,  $L$ , and the  
 144 number density of the target nuclei,  $n$ , in the thin target approximation. Thus, the interaction probability,

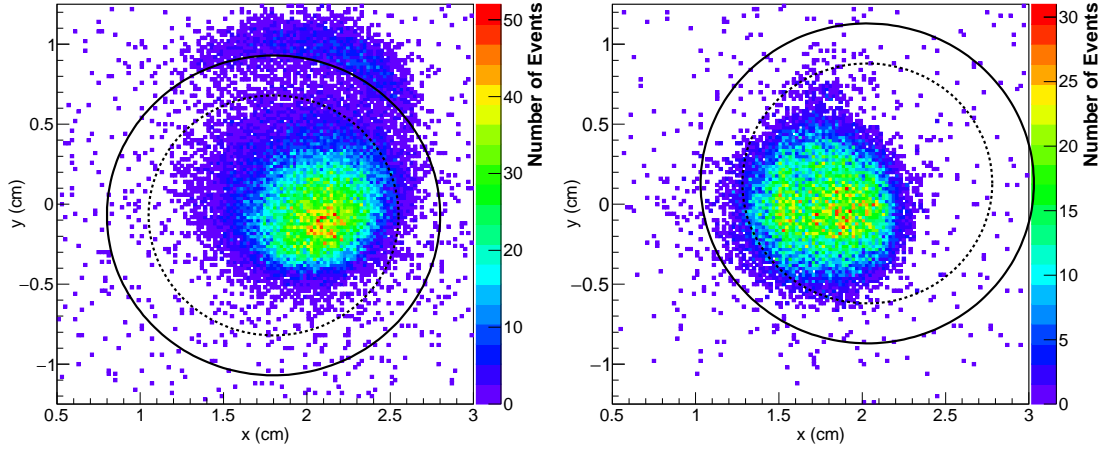


Figure 2: Positions of BPD tracks extrapolated to the S4 plane in Target Removed data runs from the p + C at 60 GeV/c (left) and p + Be at 120 GeV/c (right). The measured S4 position is shown as a black circle and the BPD radius cut is shown as a dotted black circle. Events are taken by the interaction trigger defined as  $T_{\text{int}}$  in Section 2.

p + Be	60 GeV/c		120 GeV/c	
	Target	Inserted	Removed	Inserted
Total	132k	64k	187k	112k
WFA	119k	58k	173k	103k
Good BPD	67k	33k	108k	64k
Radial cut	65k	31k	104k	62k

Table 2: Number of selected events for p + Be at 60 and 120 GeV/c.

p + Al	60 GeV/c	
	Target	Inserted
Total	208k	105k
WFA	188k	94k
Good BPD	117k	58k
Radial cut	113k	57k

Table 3: Number of selected events for p + Al at 60 GeV/c.

<sup>145</sup>  $P$ , can be defined in terms of the interaction cross section,  $\sigma$ :

$$P_{\text{int}} = \frac{\text{Number of events}}{\text{Number of beam particles}} = n \cdot L \cdot \sigma. \quad (3)$$

<sup>146</sup> The counts of beam and interaction triggers as described in Section 2 can be used to estimate the trigger  
<sup>147</sup> probability as follows:

$$P_{\text{Tint}} = \frac{N(T_{\text{beam}} \wedge T_{\text{int}})}{N(T_{\text{beam}})}, \quad (4)$$



148 where  $N(T_{beam})$  is the number of beam events passing the event selection cuts and  $N(T_{beam} \wedge T_{int})$  is the  
 149 number of selected beam events that also have an interaction trigger. In order to correct for events in which  
 150 the beam particle interacts outside of the target, such as interactions on beamline materials or air, data were  
 151 also recorded with the target removed from the beam. Table 4 summarizes the total trigger probabilities for  
 152 both the Target Inserted (I) and Removed (R) data.

153 Taking into account the trigger probabilities with the target inserted and removed,  $P_{Tint}^I$  and  $P_{Tint}^R$ , the  
 154 interaction probability  $P_{int}$  can be obtained as:

$$P_{int} = \frac{P_{Tint}^I - P_{Tint}^R}{1 - P_{Tint}^R}. \quad (5)$$

155 Using Equations 3 - 5, the trigger cross section,  $\sigma_{trig}$ , can be written as:

$$\sigma_{trig} = -\frac{m_A}{\rho L N_A} \ln(1 - P_{int}), \quad (6)$$

156 where  $N_A$ ,  $\rho$ , and  $m_A$  are Avogadro's number, the material density, and the atomic mass. The detailed  
 157 calculation is described in Ref. [6].

Interaction	$p$ (GeV/c)	$P_{Tint}^I$	$P_{Tint}^R$
p + C	60	$0.0516 \pm 0.0005$	$0.0047 \pm 0.0002$
p + Be	60	$0.0414 \pm 0.0008$	$0.0031 \pm 0.0003$
p + Al	60	$0.0431 \pm 0.0006$	$0.0034 \pm 0.0002$
p + C	120	$0.0320 \pm 0.0004$	$0.0024 \pm 0.0001$
p + Be	120	$0.0362 \pm 0.0006$	$0.0022 \pm 0.0002$

Table 4: Trigger probabilities in data. For each configuration, the observed probabilities for Target Inserted and Target Removed data are given.

## 158 5 Correction Factors

### 159 5.1 S4 trigger correction factors

160 The trigger cross section comprises interactions where the resulting particles miss the S4 scintillator counter.  
 161 But even when there has been an interaction in the target, there is a possibility that a forward-going particle  
 162 will strike the S4 counter. Moreover, not all elastically scattered beam particles strike the S4. Corrections  
 163 must be applied to account for these effects. From Equations 1 and 2, the trigger cross section can be  
 164 related to the production and inelastic cross sections with correction factors:

$$\sigma_{prod} = \frac{1}{f_{prod}} (\sigma_{trig} - \sigma_{qe} \cdot f_{qe} - \sigma_{el} \cdot f_{el}), \quad (7)$$

165 and

$$\sigma_{inel} = \frac{1}{f_{inel}} (\sigma_{trig} - \sigma_{el} \cdot f_{el}). \quad (8)$$

166 Here,  $f_{prod}$ ,  $f_{qe}$ , and  $f_{el}$  are the fractions of production, quasi-elastic, and elastic events that miss the S4  
 167 counter. These correction factors, as well as  $\sigma_{qe}$  and  $\sigma_{el}$ , are estimated from Monte Carlo simulations  
 168 (MC).

169 GEANT4 version 10.4.p03 [12, 13, 14] was used to estimate the MC correction factors. The QBBC physics  
 170 list was used to estimate correction factors relating to elastic events, while the FTFP\_BERT physics list was  
 171 used to estimate correction factors for other events. The resulting MC correction factors are summarized in  
 172 Table 5 (nominal).

Interaction	$p$ (GeV/c)	MC Correction Factors (nominal)						MC Correction Factors (systematic)					
		$\sigma_{el}$ (mb)	$f_{el}$	$\sigma_{qe}$ (mb)	$f_{qe}$	$f_{prod}$	$f_{inel}$	$\sigma_{el}$ (mb)	$f_{el}$	$\sigma_{qe}$ (mb)	$f_{qe}$	$f_{prod}$	$f_{inel}$
p + C	60	66.6	0.308	25.4	0.788	0.973	0.954	73.9	0.308	24.0	0.850	0.976	0.964
p + Be	60	47.7	0.319	22.4	0.782	0.972	0.951	54.5	0.318	21.0	0.879	0.978	0.968
p + Al	60	126.2	0.231	34.9	0.786	0.974	0.958	137.2	0.231	33.1	0.801	0.975	0.962
p + C	120	65.1	0.085	23.3	0.425	0.926	0.877	70.1	0.085	22.3	0.740	0.948	0.929
p + Be	120	48.9	0.072	21.2	0.409	0.925	0.871	52.8	0.071	20.1	0.804	0.957	0.942

Table 5: Correction factors to the nominal MC simulation for the elastic process, obtained with QBBC, and for other processes, obtained with FTFP\_BERT. The right hand side shows the same correction factors for a sample used to assess systematic uncertainties; these factors were obtained using FTFP\_BERT for the elastic process and FTF\_BIC for other processes. Model uncertainty treatment is further discussed in Section 6.3.

## 173 5.2 Beam purity

174 Kaons are the most probable source of contamination for proton beams. In the case of proton beams  
 175 at 60 GeV/c and 120 GeV/c, the CEDAR detector has enough power to discriminate protons from other  
 176 charged particles. The upper limit on kaon contamination was found to be smaller than 0.1% for the  
 177 120 GeV/c beam from pressure scans taken of the CEDAR detector and even lower for the 60 GeV/c beam.  
 178 It was concluded that the beam purity has a negligible impact on integrated cross section measurements  
 179 and no correction factor was applied.

## 180 6 Systematic Uncertainties

### 181 6.1 Target density

182 The uncertainty on the target density affects the calculation of the trigger cross section as shown in  
 183 Equation 6. The density uncertainty for each target was estimated by calculating the standard deviation of  
 184 the target densities determined from measurements of the mass and dimensions of the machined target  
 185 samples. (There were several machined samples fabricated for each target type.) This evaluation led to a  
 186 0.69% uncertainty on the density of carbon, 0.19% uncertainty on the density of beryllium, and a 0.29%  
 187 uncertainty on the density of aluminum, respectively.

### 188 6.2 S4 size and position

189 Another systematic uncertainty comes from the size and position of the S4 scintillator. The diameter of the  
 190 S4 has previously been found to have an uncertainty of  $\pm 0.40$  mm. The S4 position has been determined  
 191 using BPD tracks extrapolated to the S4 location. A conservative S4 position uncertainty of  $\pm 1.0$  mm in X  
 192 and Y coordinates is assigned. In order to propagate these uncertainties to  $\sigma_{inel}$  and  $\sigma_{prod}$ , two additional  
 193 MC simulation samples with the S4 diameter modified and four additional MC simulation samples with the  
 194 S4 position shifted were generated.

195 6.3 Model uncertainties

196 Physics model uncertainties on the S4 trigger correction factors were estimated for elastic and other processes  
 197 separately. GEANT4 version 10.4.p03 has two models for the elastic process: Barashenkov-Glauber-Gribov  
 198 and Chips. The former is available with the QBBC physics list, is used for the nominal correction, and is the  
 199 recommended model by GEANT4. The latter is available with other physics lists including FTFP\_BERT. In  
 200 order to estimate the model uncertainties associated with the elastic process, the S4 correction factors  $f_{el}$  and  
 201  $\sigma_{el}$  were recalculated with FTFP\_BERT physics list and are shown in Table 5 (systematic). Additionally,  
 202 validity of the model uncertainties on  $\sigma_{el}$  for p + C at 60 and 120 GeV/c have been evaluated with former  
 203  $\sigma_{el}$  measurements by Bellettini et al. at 21.5 GeV/c [15] and Schiz et al. at 70 GeV/c [16] and found to be  
 204 consistent within uncertainty.

205 The S4 correction factors  $f_{prod}$ ,  $f_{inel}$ , and  $f_{qe}$  as well as  $\sigma_{qe}$  were estimated using the FTFP\_BERT physics  
 206 list. In order to estimate the model uncertainties associated with these correction factors, the correction  
 207 factors were recalculated with three additional physics lists: QBBC, QGSP\_BERT and FTF\_BIC. Using  
 208 these additional correction factors, the model dependence of the integrated cross section measurements was  
 209 studied. As an example, obtained correction factors with FTF\_BIC are shown in Table 5 (systematic).

210 All systematic uncertainties discussed in this Section are summarized in Tables 6 and 7 for production and  
 211 inelastic cross section measurements.

Systematic uncertainties for $\sigma_{prod}$ (mb)							
Interaction	$p$			Total Syst.	Elastic	Other	Total Model
	(GeV/c)	Density	S4	Uncer.	Model	Model	Uncer.
p + C	60	$\pm 1.9$	$\pm 1.8$ $\pm 2.2$	$\pm 2.6$ $\pm 2.9$	$\pm 0.0$ $\pm 2.2$	$\pm 0.2$ $\pm 4.3$	$\pm 0.2$ $\pm 4.8$
p + Be	60	$\pm 0.4$	$\pm 1.0$ $\pm 1.4$	$\pm 1.1$ $\pm 1.5$	$\pm 0.0$ $\pm 2.2$	$\pm 0.0$ $\pm 4.7$	$\pm 0.0$ $\pm 5.2$
p + Al	60	$\pm 1.4$	$\pm 2.6$ $\pm 4.9$	$\pm 3.0$ $\pm 5.1$	$\pm 0.0$ $\pm 2.6$	$\pm 0.2$ $\pm 8.0$	$\pm 0.2$ $\pm 8.4$
p + C	120	$\pm 1.7$	$\pm 1.9$ $\pm 3.1$	$\pm 2.5$ $\pm 3.5$	$\pm 0.0$ $\pm 0.4$	$\pm 0.0$ $\pm 12.2$	$\pm 0.0$ $\pm 12.2$
p + Be	120	$\pm 0.4$	$\pm 1.7$ $\pm 1.8$	$\pm 1.7$ $\pm 1.8$	$\pm 0.0$ $\pm 0.2$	$\pm 0.1$ $\pm 14.3$	$\pm 0.1$ $\pm 14.3$

Table 6: Breakdown of systematic uncertainties for production cross section measurements with the NA61/SHINE data.

Systematic uncertainties for $\sigma_{inel}$ (mb)							
Interaction	$p$			Total Syst.	Elastic	Other	Total Model
	(GeV/c)	Density	S4	Uncer.	Model	Model	Uncer.
p + C	60	$\pm 1.9$	$\pm 1.7$ $\pm 2.2$	$\pm 2.5$ $\pm 2.9$	$\pm 0.0$ $\pm 2.3$	$\pm 0.0$ $\pm 4.2$	$\pm 0.0$ $\pm 4.8$
p + Be	60	$\pm 0.5$	$\pm 1.1$ $\pm 1.3$	$\pm 1.2$ $\pm 1.4$	$\pm 0.0$ $\pm 2.2$	$\pm 0.0$ $\pm 3.7$	$\pm 0.0$ $\pm 4.3$
p + Al	60	$\pm 1.4$	$\pm 2.7$ $\pm 4.9$	$\pm 3.0$ $\pm 5.1$	$\pm 0.0$ $\pm 2.6$	$\pm 0.0$ $\pm 6.5$	$\pm 0.0$ $\pm 7.0$
p + C	120	$\pm 1.8$	$\pm 2.0$ $\pm 3.2$	$\pm 2.7$ $\pm 3.7$	$\pm 0.0$ $\pm 0.4$	$\pm 0.0$ $\pm 14.1$	$\pm 0.0$ $\pm 14.1$
p + Be	120	$\pm 0.4$	$\pm 1.9$ $\pm 1.8$	$\pm 1.9$ $\pm 1.8$	$\pm 0.0$ $\pm 0.3$	$\pm 0.2$ $\pm 16.0$	$\pm 0.2$ $\pm 16.0$

Table 7: Breakdown of systematic uncertainties for inelastic cross section measurements with the NA61/SHINE data.

## 212 7 Results and Discussion

213 Several production cross sections have been measured in this analysis. Statistical, systematic, and physics  
 214 model uncertainties were estimated separately and are summarized in Table 8. For comparison, the  
 215 production cross sections predicted by the GEANT4 10.4.p03 FTFP\_BERT physics list are also shown  
 216 in Table 8. Production cross sections were measured to be higher than the predictions of GEANT4. The  
 217 p + C and p + Al at 60 GeV/c measurements are compared with the results by Carroll et al. [8] as shown in  
 218 Figure 3 (Left). The new NA61/SHINE results are consistent within errors with the previous measurements,  
 219 and our statistical and systematic uncertainties are smaller.

220 Several inelastic cross sections have also been determined in this analysis. Statistical, systematic, and  
 221 physics model uncertainties were estimated separately and are summarized in Table 9. For comparison,  
 222 the inelastic cross sections predicted by the GEANT4 10.4.p03 FTFP\_BERT physics list are also shown  
 223 in Table 9. Inelastic cross sections were measured to be higher than the predictions of GEANT4. The  
 224 measurements with 60 GeV/c protons are compared with the results by Denisov et al. [9] in Figure 3 (Right).  
 225 The measurements of p + C and p + Al at 60 GeV/c are found to be consistent within errors, while the  
 226 p + Be at 60 GeV/c inelastic cross section is found to be slightly lower by about one standard deviation.

227 For the proton beam at 120 GeV/c, large GEANT4 physics model dependencies were observed. This is  
 228 due to differences between the correction factors predicted by different physics list, and in particular from  
 229 FTF\_BIC, which has large differences from other physics lists. Differences in these values compared to the  
 230 nominal values in Table 5 cause large model uncertainties on non-elastic processes. One possible reason  
 231 is that the size and position of the S4 scintillator was not optimal for a 120 GeV/c beam. Furthermore,  
 232 future direct measurements of quasi-elastic processes will help to reduce model uncertainties, since the  
 233 measurements presented in this paper have achieved a few % level statistical and systematics uncertainties.

Interaction	$p$ (GeV/c)	Production cross section (mb)					$\sigma_{\text{prod}}^{\text{G4}}$
		$\sigma_{\text{prod}}$	$\Delta_{\text{stat}}$	$\Delta_{\text{syst}}$	$\Delta_{\text{model}}$	$\Delta_{\text{total}}$	
p + C	60	226.9	$\pm 3.1$	$\pm 2.6$ $\pm 2.9$	$\pm 0.2$ $\pm 4.8$	$\pm 4.1$ $\pm 6.4$	215.9
p + Be	60	185.3	$\pm 4.9$	$\pm 1.1$ $\pm 1.5$	$\pm 0.0$ $\pm 5.2$	$\pm 5.0$ $\pm 7.3$	179.1
p + Al	60	409.3	$\pm 7.8$	$\pm 3.0$ $\pm 5.1$	$\pm 0.2$ $\pm 8.4$	$\pm 8.4$ $\pm 12.5$	389.7
p + C	120	227.1	$\pm 3.4$	$\pm 2.5$ $\pm 3.5$	$\pm 0.0$ $\pm 12.2$	$\pm 4.2$ $\pm 13.1$	212.8
p + Be	120	190.8	$\pm 3.7$	$\pm 1.7$ $\pm 1.8$	$\pm 0.1$ $\pm 14.3$	$\pm 4.1$ $\pm 14.9$	183.1

Table 8: Production cross section measurements with the NA61/SHINE data. The central value as well as the statistical ( $\Delta_{\text{stat}}$ ), systematic ( $\Delta_{\text{syst}}$ ), and model ( $\Delta_{\text{model}}$ ) uncertainties are shown. The total uncertainty ( $\Delta_{\text{total}}$ ) is the sum of the statistical, systematic, and model uncertainties in quadrature. For comparison, GEANT4 predictions with the FTFP\_BERT physics list ( $\sigma_{\text{prod}}^{\text{G4}}$ ) are also shown.

## 234 8 Summary

235 In summary, production and inelastic cross sections of protons on carbon, beryllium, and aluminum targets  
 236 have been measured.

237 The production cross section with a proton beam at 120 GeV/c was measured for the first time with a  
 238 precision of about 6% (8%) for p + C (p + Be) including statistical, systematic, and model uncertainties.

Interaction	$p$ (GeV/c)	Inelastic cross section (mb)					$\sigma_{\text{inel}}^{\text{G4}}$
		$\sigma_{\text{inel}}$	$\Delta_{\text{stat}}$	$\Delta_{\text{syst}}$	$\Delta_{\text{model}}$	$\Delta_{\text{total}}$	
p + C	60	252.6	$\pm 3.2$	$\pm 2.5$ $\pm 2.9$	$\pm 0.0$ $\pm 4.8$	$\pm 4.1$ $\pm 6.5$	241.4
p + Be	60	207.8	$\pm 5.0$	$\pm 1.2$ $\pm 1.4$	$\pm 0.0$ $\pm 4.3$	$\pm 5.1$ $\pm 6.7$	201.6
p + Al	60	444.5	$\pm 7.9$	$\pm 3.0$ $\pm 5.1$	$\pm 0.0$ $\pm 7.0$	$\pm 8.5$ $\pm 11.7$	424.6
p + C	120	251.3	$\pm 3.6$	$\pm 2.7$ $\pm 3.7$	$\pm 0.0$ $\pm 14.1$	$\pm 4.5$ $\pm 15.0$	236.2
p + Be	120	212.5	$\pm 3.9$	$\pm 1.9$ $\pm 1.8$	$\pm 0.2$ $\pm 16.0$	$\pm 4.3$ $\pm 16.6$	204.3

Table 9: Inelastic cross section measurements with the NA61/SHINE data. The central value as well as the statistical ( $\Delta_{\text{stat}}$ ), systematic ( $\Delta_{\text{syst}}$ ), and model ( $\Delta_{\text{model}}$ ) uncertainties are shown. The total uncertainty ( $\Delta_{\text{total}}$ ) is the sum of the statistical, systematic, and model uncertainties in quadrature. For comparison, GEANT4 predictions with the FTFP\_BERT physics list ( $\sigma_{\text{inel}}^{\text{G4}}$ ) are also shown.

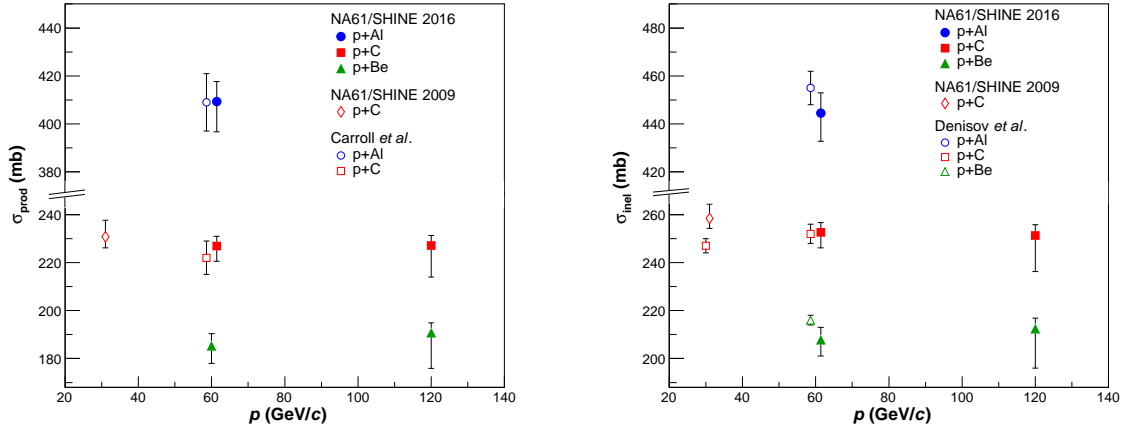


Figure 3: (Left) Summary of production cross section measurements. The results are compared to results by Carroll et al. [8]. (Right) Summary of inelastic cross section measurements. The results are compared to results by Denisov et al. [9].

239 At 60 GeV/c, the measured production cross sections are comparable to previous results for p + C and  
 240 p + Al, and the precision was improved to about 3%. The production cross section of p + Be at 60 GeV/c  
 241 was measured for the first time with a precision of about 4% including statistical, systematic, and model  
 242 uncertainties.

243 The inelastic cross section with a proton beam at 120 GeV/c was measured for the first time with a precision  
 244 of about 6% (8%) for p + C (p + Be) including statistical, systematic, and model uncertainties. For the  
 245 inelastic production cross section of the proton beam at 60 GeV/c, reasonable agreement with a previous  
 246 measurement was found.

247 The current uncertainties on NuMI and LBNF beam predictions have to extrapolate from data at lower or  
 248 higher energy than the actual beam energy. Thus, new measurements presented in this paper will improve  
 249 flux predictions by removing the necessity to extrapolate from different energies.

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