EUROPEAN LABORATORY FOR PARTICLE PHYSICS

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Revised data taking schedule with ion beams

By the NA61 Collaboration
http://na61.web.cern.ch

Abstract

This document presents the revised data taking schedule of NA61 with ion beams. The revision takes into account limitations due to the new LHC schedule as well as final results concerning the physics performance with secondary ion beams. It is proposed to take data with primary Ar and Xe beams in 2012 and 2014, respectively, and to test and use for physics a secondary ^{11}B beam from primary Pb beam fragmentation in 2010, 2011 and 2013.

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1   Introduction

In order to perform the measurements necessary to fulfill the NA61 physics program primary beams of protons as well as of C, Si, and In ions were requested in the NA61 proposal [1]. Data taking with proton/pion beams and the first run with sulphur beam were recommended by the SPSC in its session of June 27, 2007. Based on the I-LHC schedule at the time of the NA61 proposal submission (November 2006) data taking with ion beams was requested for 2009, 2010 and 2011 [2]. However, compatibility with the changing LHC and I-LHC schedules requires modifications of the original NA61 beam request.

The compatibility with the LHC and I-LHC schedules as of April 2008 required the first revision [3] of the original schedule. It was necessary to delay the start of the data taking with ion beams to 2011 as well as to use secondary ion beams produced by fragmentation of the primary Pb beam in 2011 and 2012. The use of primary ion beams was suggested for 2013.

This document presents the second revision of the data taking schedule which was recently discussed and agreed upon with representatives of the CERN Beams Department [4]. The tests of secondary ion beams are scheduled for 2010 and 2011. Runs with primary ion beams are now foreseen for 2012 and 2014. The secondary ion beam is planned to be used for physics in 2013 or even in 2011.

This document is organized as follows. The status of the 2007 data analysis as well as the 2009 run is briefly presented in Section 2. The NA61 running with primary ion beams is described in Section 3. The running with secondary ion beams is discussed in Section 4. Finally, the revised data taking schedule is presented in Section 5.

2   Status of the 2007 data analysis and 2009 run

The pilot data registered for the T2K physics program during the 2007 run are under analysis. Preliminary fully corrected spectra of π^- and π^+ mesons produced in inelastic p+C interactions at 31 GeV/c have been presented at several conferences [5, 6, 7, 8] in Summer 2009. As an example, the π^- spectra are shown in Fig. 1.

The goal of the 2009 data taking period scheduled from July 26 to November 16 is to register high statistics data for T2K (p+C and p+(T2K Replica Target) at 31 GeV/c) and cosmic-ray (π^-+C at 158 and 350 GeV/c) experiments as well as to perform an energy scan with p+p interactions (p+p at 10, 20, 30, 40, 80 and 158 GeV/c). The latter is part of the program aiming to search for the critical point of strongly interacting matter and study the properties of the onset of deconfinement.

The run started on July 26 with setting up the detector and commissioning of the ToF-F and trigger upgrades. The physics data taking continues since August 8. The data on p+C and p+(T2K Replica Target) interactions at 31 GeV/c as well as p+p interactions at 31 GeV/c are already registered. The run for p+p interactions at 20 GeV/c is in progress The up-to-date run history is presented in Fig. 2. The run will be finished on November 16.

After the TPC read-out upgrade the maximum number of events registered in a 10 seconds long spill went up from 80 to 800. The event rate during the physics data taking is lower (typically about 400 events per spill) due to the necessity to select the wanted beam particle type and the interaction probability limitations.
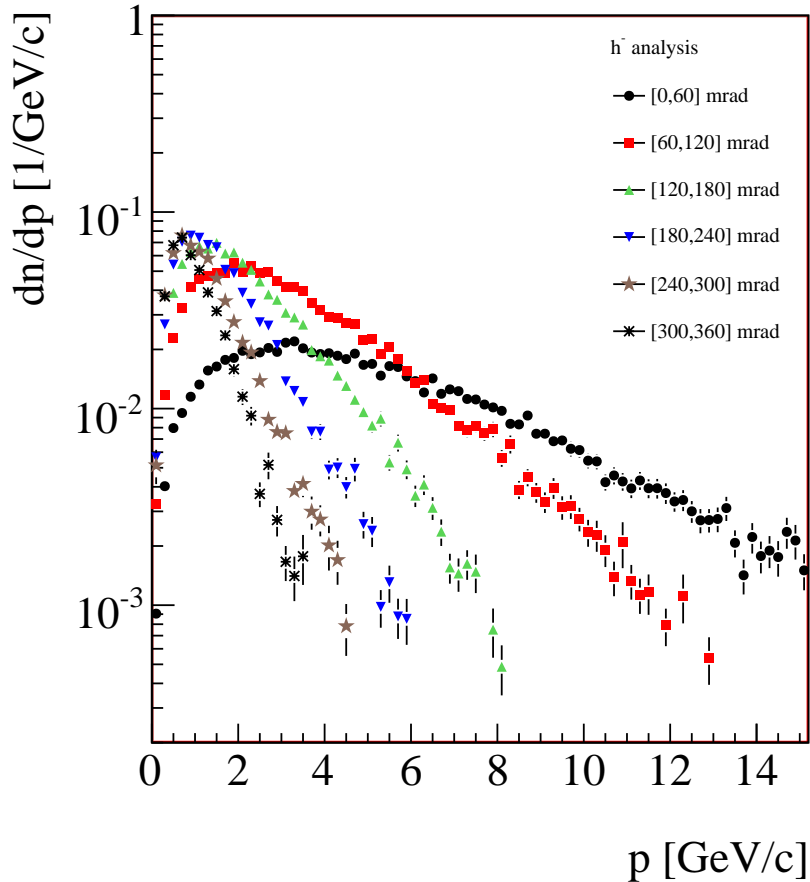
Figure 1: Laboratory momentum spectra of π^- mesons produced in inelastic p+C interactions at 31 GeV/c in six intervals of the polar angle.

3 NA61 running with primary ion beams

The maximum expected ion beam intensity in the CERN SPS is $\approx 1 \cdot 10^{11}$ charges/spill (in the ring). The machine would be hard to operate below $\approx 1 \cdot 10^9$ charges/spill (in the ring). These results in the minimum and maximum primary ion beam intensity at extraction as given in Table 1. Assuming a spill length of 10 sec the values are calculated for Ne, Ar, Xe and Pb ions which are the most suitable for the CERN ion source.

Typical beam intensity losses at extraction and during transport to the target are about 10%. The beam intensity at $10A$ GeV (the lowest energy, for the first time in the SPS) may be lower than in the case of higher energies ($20A$-$158A$ GeV) at which the SPS was already running in 1998-2002.

The maximum read-out rate of the upgraded NA61 detector is 80 Hz. In order to reach a read-out rate of about 40 Hz the trigger rate should be about 80 Hz. Assuming a target thickness corresponding to 1.5% inelastic interaction probability and an on-line centrality
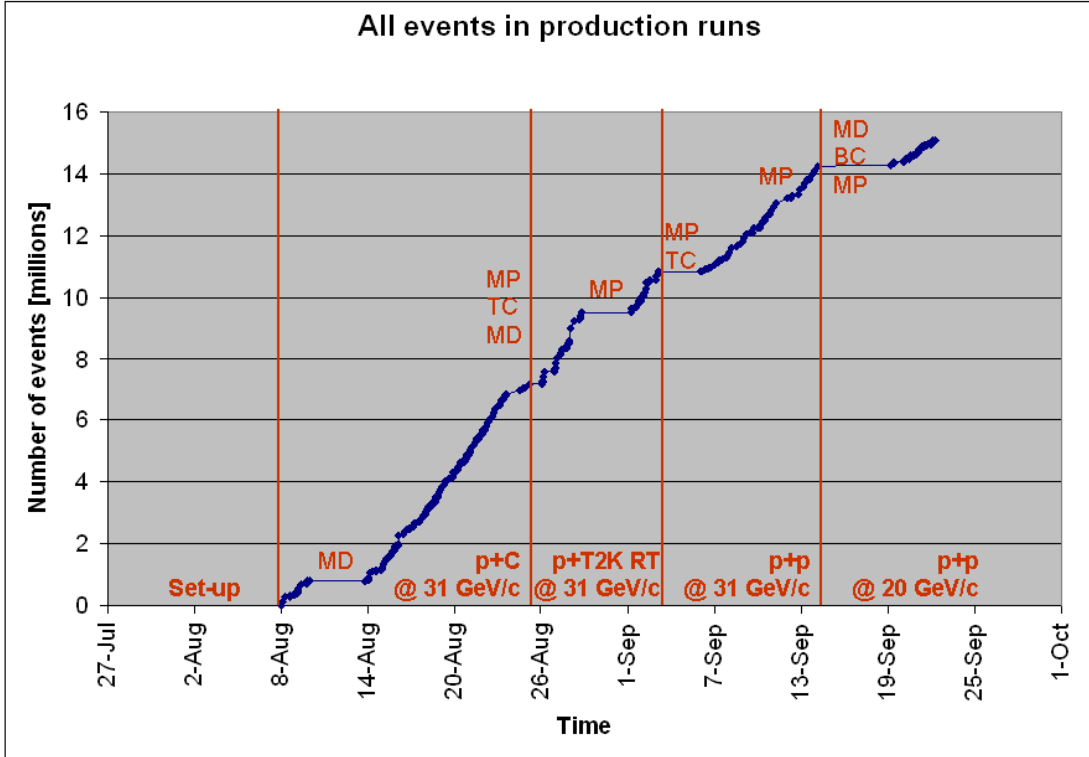
Figure 2: The number of events registered for physics in the 2009 NA61 run until September 22 as a function of time. The following abbreviations are used: MD - Machine Development, MP - Machine Problems, TC - Target Change.

selection of the 20% most central of all inelastic interactions one gets for the required ion beam intensity during the spill:

$$I(ions) \approx 3 \cdot 10^4 \text{ ions/sec} .$$

This intensity will lead to a typical separation in time between two ions of about 10 μsec.[1] This will not harm data taking because two interactions in the target can be well separated using the TPC information provided the time difference between them is larger than 5 μsec. In this case the tracks from both interactions are shifted along the drift direction by more than 5 cm, well above the resolution of the TPC measurements. The small ($< 1\%$) fraction events with close-in-time (< 5 μsec) pile-up interactions will be rejected using the Projectile Spectator Detector (PSD) information [3].

Thus the maximum ion beam SPS intensity is more than 10^3 times higher than the optimal intensity at the NA61 target and therefore even at the lowest untested energy of $10A$ GeV the

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[1]The exact number depends whether bunched or de-bunched beams will be used. Detailed studies [9] show that both are feasible.

ion	minimum intensity (ions/sec)	maximum intensity (ions/sec)
Ne	$\approx 1 \cdot 10^7$	$\approx 1 \cdot 10^9$
Ar	$\approx 5 \cdot 10^6$	$\approx 5 \cdot 10^8$
Xe	$\approx 2 \cdot 10^6$	$\approx 2 \cdot 10^8$
Pb	$\approx 1 \cdot 10^6$	$\approx 1 \cdot 10^8$

Table 1: The minimum and maximum ion beam intensities at the extraction from the SPS calculated for Ne, Ar, Xe and Pb ions assuming 10 sec spill duration.

optimal ion beam intensity should be reachable. The minimum SPS beam intensity can still be a factor of 10 too high which requires a reduction by this factor in the beam line.

Assuming a beam duty cycle of 25% and 60% overall data taking efficiency we expect about $0.5 \cdot 10^6$ events per data taking day for all reactions. This number should hold for all ions and energies.

4   NA61 running with secondary ion beams

This section discusses the performance of NA61 with secondary ion beams obtained using primary Pb beam and the H2 beam line modified to serve as a fragment separator. The proposed fragment separator and the associated simulation studies were introduced in Addendum-4 [3].

As in Addendum-4 [3] the following notation is used. All Pb fragments accepted and transported by the secondary ion beam line to the NA61 detector are denoted as *all-ions*. These consist of fragments with a range of charges and masses. The NA61 trigger selects ions with the desired charge Z (denoted as *t-ions*). These *t-ions* still consist of a fragment mixture with different nuclear mass numbers. Operating the beam line with suitable parameters ensures that ions with the wanted mass number A (denoted as *w-ions*) are the dominant component of *t-ions*. In the case of primary beam *t-ions* are equal to *w-ions* and *all-ions*.

For completeness the requirements concerning beam intensity and purity are repeated below. The maximum read-out rate of the upgraded NA61 detector is 80 Hz. In order to reach a read-out rate of about 40 Hz the trigger rate should be about 80 Hz. Assuming typical values for the target thickness corresponding to 1.5% inelastic interaction probability and an on-line centrality selection of the 20% most central of all inelastic interactions one gets for the necessary *t-ion* intensity during the spill:

$$I(t\text{-}ions) \geq 3 \cdot 10^4 \text{ ions/sec} .$$

This value together with the maximum intensity of the primary Pb ion beam ($1 \cdot 10^8$ ions/sec) yields the lower limit for the number of t-ions per primary Pb-ion of $3 \cdot 10^{-4}$.

The maximum beam particle flux (*all-ions*) is constrained by the time-resolution and maximum readout rate of the PSD and Z detectors [3]:

$$I(\text{all-ions}) \leq 2 \cdot 10^5 \text{ ions/sec} .$$

Thus, the fraction of *t-ions* in the *all-ion* beam should be larger than 15%.

The bias of the key physics measures caused by the contamination of *unwanted*-ions in the trigger selected *t-ions* is discussed in Appendix I. This bias is found to be small compared to the other sources of systematic errors when the ratio of *w-ions/t-ions* is larger than 0.3.

Table 2 presents results of a simulation performed for ^{11}B, ^{32}P and ^{111}Sn secondary ions at $10A$, $47A$ and $158A$ GeV from a primary Pb beam. Note that the configurations studied so far leave room for improvement especially at the lowest energy in which a reduced degrader thickness will lead to higher yields at the expense of a larger contamination of unwanted ions. For illustration distributions of the fragment mass number A for *t-ions* of ^{11}B(Z=5), ^{32}P(Z=15) and ^{111}Sn(Z=50) at $10A$ GeV and $158A$ GeV are shown in Fig. 3.

The obtained parameters of the secondary ion beams satisfy the criteria discussed above for ^{11}B and ^{32}P beams in the high energy domain ($> 40A$ GeV). However, for ^{111}Sn beam and/or in the low energy domain the ratio *t-ion/Pb-ion* is a factor of 2-3 lower than required. This implies that at the present level of experience and knowledge the event rate for these beams is expected to be 2-3 times lower than the maximum possible and the required beam time longer by the same factor.

It is obvious that such limitations do not apply to runs with primary ions, which are preferable also for other reasons, namely:

- the beam line to the experiment is simpler: no degrader is required, the quality (divergence) is much better and the Z-detector (still to be built) is not needed,

- the total intensity required to saturate data taking is up to 10 times lower, resulting in smaller pileup background and charge load in the TPCs.

In conclusion, it is possible to use secondary ion beams for the NA61 ion program, but data taking with primary beams is strongly preferred.

4.1 The fragment separator tests in 2010 and 2011

Based on the results of the simulation presented in this document and constrains due to the LHC schedule a 60-day data taking period with secondary ^{11}B beam is planned for 2013. As a step towards this run tests of the fragment separator are proposed to take place in 2010 and 2011.

During the 2010 preliminary test we plan to study production of ^{11}B and ^{32}P beams at $20A$ and $80A$ GeV. For each of the two energies the following steps will be performed:

ion	energy (A GeV)	$t\text{-}ion/Pb\text{-}ion$	$t\text{-}ion/all\text{-}ions$	$w\text{-}ion/t\text{-}ion$	$\sigma(prod)$ (mbarn)	degrader (cm)
^{11}B	158	$2.7 \cdot 10^{-3}$	0.15	1.0	111	5.6
^{32}P	158	$6 \cdot 10^{-4}$	0.14	0.58	15	5
^{111}Sn	158	$\mathbf{2 \cdot 10^{-4}}$	0.16	0.33	4.6	3
^{11}B	47	$7.9 \cdot 10^{-4}$	0.30	1.0	111	5.6
^{32}P	47	$3.5 \cdot 10^{-4}$	0.23	0.74	15	5
^{111}Sn	47	$\mathbf{3.0 \cdot 10^{-5}}$	0.28	0.40	4.6	5.6
^{11}B	10	$\mathbf{1.4 \cdot 10^{-4}}$	0.28	0.98	111	1.5
^{32}P	10	$\mathbf{8.0 \cdot 10^{-5}}$	0.25	0.65	15	1
^{111}Sn	10	$\mathbf{1.9 \cdot 10^{-4}}$	0.21	0.34	4.6	1

Table 2: Selected results on secondary ion beams (^{11}B, ^{32}P and ^{111}Sn at $10A$, $47A$ and $158A$ GeV) obtained from the simulation of the proposed NA61 fragment separator. The values which are below the corresponding lower limit are indicated in bold font.

- transport of the primary Pb beam to NA61 and measurements of its properties at the NA61 target,

- transformation of the H2 beam line into a fragment separator,

- study of the properties of secondary ^{11}B and ^{32}P beams by the NA61 detectors.

The test would require the preparation of the fragment separator which in particular includes a modification of the (primary) target station of the H2 beam line such that a fragmentation (carbon) target with the appropriate thickness is available as well as the insertion of the degrader
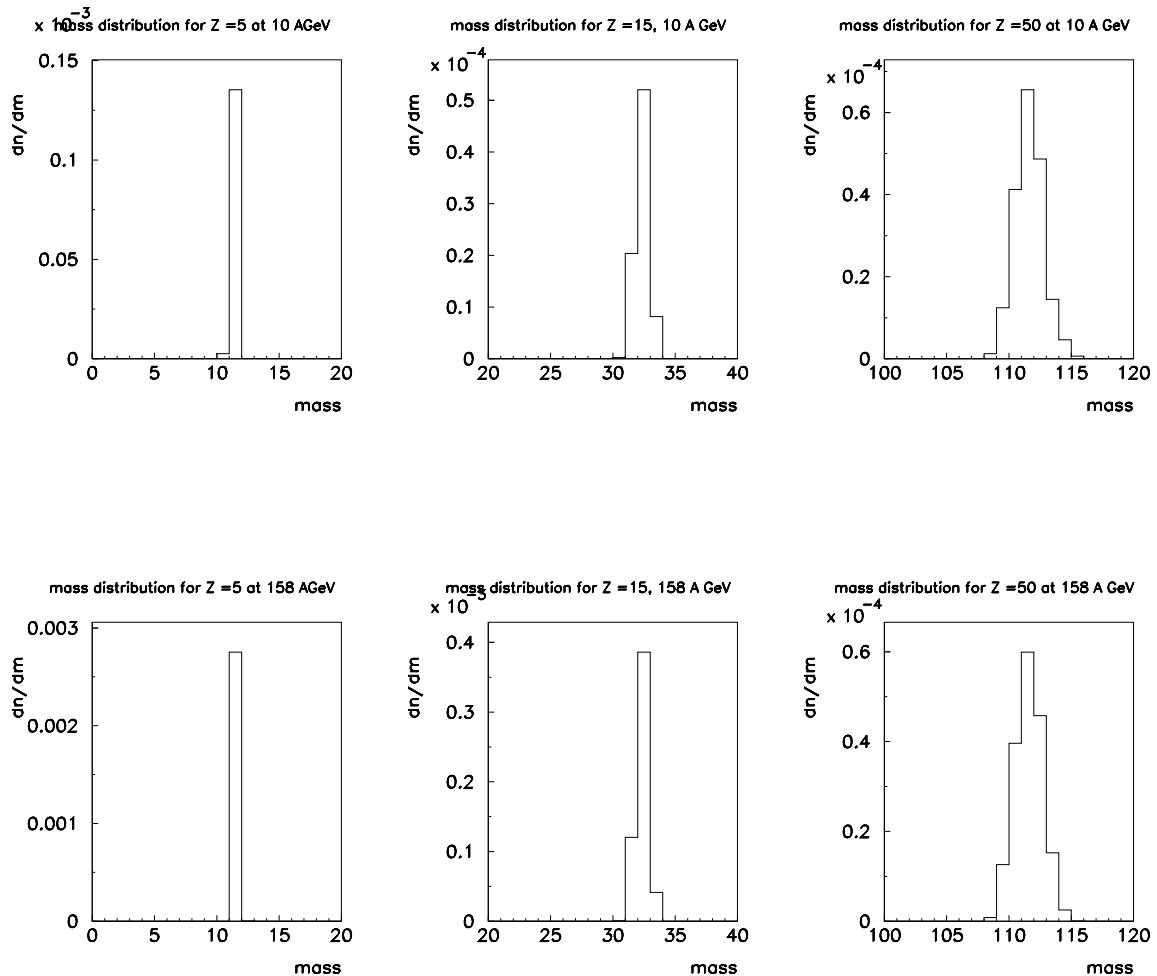
Figure 3: Distributions of the fragment mass number A for *t-ions* of ^{11}B(Z=5), ^{32}P(Z=15) and ^{111}Sn(Z=50) at $10A$ GeV (top) and $158A$ GeV (bottom).

(see Addendum-4 [3] for details). Furthermore, the NA61 Beam Position Detectors should be operational to perform measurements of the charge distribution of the secondary beam ions. The requested Pb beam time is 8 MDs.

During the final test in 2011 we plan to perform the fragment separator and the NA61 detector tests at all 6 energies ($10A$, $20A$, $30A$, $40A$, $80A$ and $158A$ GeV) selected for the physics runs. The detector test would be dedicated to commissioning and performance studies of the upgrades needed for the data taking with primary and secondary ion beams, namely: Projectile Spectator Detector, Z- and A-detectors as well as the He-beam pipe [3, 1]. The estimated test duration is about 20 days.

We propose to convert the 2011 final test into a physics run with secondary ^{11}B beam contingent on the success of the 2010 test and early completion of the NA61 upgrades. This

would require 60 days Pb beam time and would then replace the run planned for 2013 (see Table 3).

5   Revised data taking schedule

Taking into account the results of the studies presented in this document, as well as the limitations due to the new LHC schedule a revised data taking schedule is proposed as given in Table 3. It assumes running with primary ^{40}Ar and ^{129}Xe beams in 2012 and 2014, respectively. In 2013 a secondary ^{11}B beam produced by a primary Pb beam is presently foreseen to be used. The selection of projectile and target nuclei is discussed in Appendix II. Furthermore, the tests of the fragment separator with primary Pb beam are planned for 2010 and 2011. The test in 2011 can replace the 2013 run with the secondary ^{1}1B beam provided the 2010 test is successful and the NA61 upgrades are completed early.

Beam Primary	Beam Secondary	Target	Energy (*A* GeV)	Year	Duration days/MDs	Physics	Status
p			400				
	p	p	158	2010	77 d	High p$_T$	*recommended*
Pb			20,80				
	^{11}B	none	20,80	2010	10 MDs	FS test-1	*to be discussed*
p			400				
	p	Pb	158	2011	77 d	High p$_T$	*recommended*
Pb			10,20,30,40,80,158				
	^{11}B	C	10,20,30,40,80,158	2011	20 d	FS test-2	*to be discussed*
p			400				
	p	Pb	10,20,30,40,80,158	2012	6x8 d	CP,OD	*recommended*
Ar		Ca	10,20,30,40,80,158	2012	6x8 d	CP,OD	*recommended*
Pb			10,20,30,40,80,158				
	^{11}B	C	10,20,30,40,80,158	2013	6x10 d	CP,OD	*to be discussed*
Xe		La	10,20,30,40,80,158	2014	6x8 d	CP,OD	*to be discussed*

Table 3: The NA61/SHINE revised data taking plan. Runs with primary ion beams are planned for 2012 and 2014. A run with secondary ^{11}B beam is planned for 2013. The tests of the fragment separator (FS) and the NA61 upgrades are scheduled for 2010 and 2011. The following abbreviations are used for the physics goals of the data taking: CP - Critical Point, OD - Onset of Deconfinement, C-R - Cosmic Rays.

6 Appendix I: Physics performance in the presence of A-fluctuations

The proposed data taking plan assumes running in 2012 with a secondary beam of ^{11}B. As shown in Table 2 the fragment separator and the NA61 trigger will select almost pure ^{11}B ions (*w-ions/t-ions* ≈ 1). However, since we cannot exclude data taking with secondary ion beams heavier than ^{11}B a simulation study of the physics performance in the presence of unwanted isotopes (A-fluctuations) has been performed. The results are presented in this appendix.

In order to quantify a possible systematic bias of the physics results due to A-fluctuations interactions of a secondary P beam with a S target at $10A$, $47A$ and $158A$ GeV were studied as an example.

Collisions of ^{31}P+^{32}S, ^{32}P+^{32}S and ^{33}P+^{32}S at $10A$, $40A$ and $158A$ GeV were simulated with the UrQMD 2.3 [10] string-hadronic model. For each reaction central collisions were selected by the requirement that the number of projectile spectators is smaller than 5. Finally, the basic NA61 physics quantities were calculated at each collision energy by averaging over ^{31}P+^{32}S, ^{32}P+^{32}S and ^{33}P+^{32}S collisions at the corresponding energy. The averaging was performed using three different probability distributions of the nucleon number in the projectile nuclei, $P(A)$:

- $P(32) = 1$, which corresponds to the ideal case of a primary ion beam; this case is referred to as *pure* collisions,

- $P(A)$ resulting from the mocadi simulations of the secondary P beam at $47A$ GeV; this case is referred to as *mocadi* collisions,

- $P(31) = P(32) = P(33) = 1/3$, to quantify the effect for very large A-fluctuations; this case is referred to as *equal* collisions.

The corresponding $P(A)$ distributions are shown in Fig. 4.

In Figs. 5-9 the results for *pure*, *mocadi* and *equal* collisions at $10A$, $40A$ and $158A$ GeV are presented for basic observables relevant to the study of the properties of the onset of deconfinement and the search for the critical point [1].

6.1 Onset of Deconfinement

The main observables which will be measured for the study of properties of the onset of deconfinement are mean multiplicities of π^+ and K$^+$ mesons as well as the shape of their transverse momentum distributions [1, 11].

The mean multiplicities are plotted in Fig. 5 as a function of the variance of the A-distribution for *pure*, *mocadi* and *equal* collisions. For all studied reactions the change of the mean multiplicity with the variance is smaller than 1% and thus it is significantly smaller than the typical systematic error of about 5% [11] of the measured mean multiplicity due to other possible biases.

Transverse momentum probability distributions of π^+ and K$^+$ mesons are plotted in Figs. 6 and 7 (left panels) for *pure* collisions at the three studied energies. The ratio of the distributions for *mocadi* and *equal* collisions to the corresponding distributions for *pure* collisions is plotted

in the right panels of Figs. 6 and 7. In the region where the bulk of particles is produced ($p_T < 1$ GeV/c) the systematic differences, if any, are smaller than the statistical resolution of about 1%. This value is significantly smaller than the typical systematic uncertainty of about 5% of the transverse momentum spectra [11] measured by NA49.

6.2   Critical Point

The main quantities which will be measured in the search for the critical point are the scaled variance ω of the multiplicity distributions and the Φ_{p_T} measure of transverse momentum fluctuations of charged hadrons [1, 12, 13].

The scaled variance ω is plotted in Fig. 8 as a function of the variance of the A-distribution for *pure*, *mocadi* and *equal* collisions. In all cases the change of the scaled variance with the variance of the A-distribution is smaller than 1% and thus is significantly smaller than the typical systematic error of several % [12] due to other possible biases.

The Φ_{p_T} measure of transverse momentum fluctuations is plotted in Fig. 9 as a function of the variance of the A-distribution for *pure*, *mocadi* and *equal* collisions. In all cases the change of the Φ_{p_T} measure with the variance of the A-distribution is smaller than 0.5 MeV/c. Thus the change is smaller than the typical systematic error of 1 MeV/c [13] estimated by NA49.
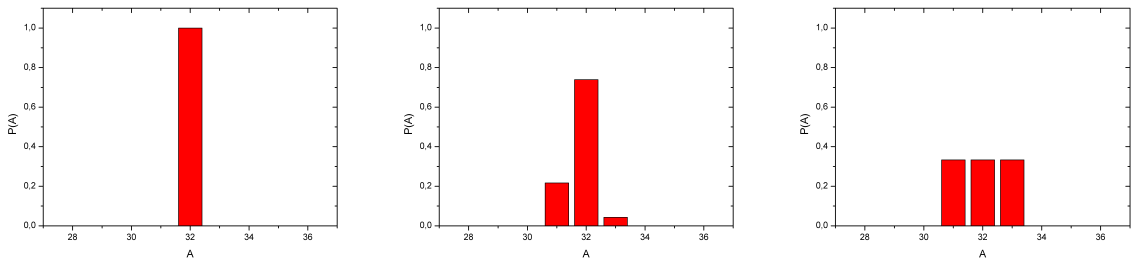
Figure 4:   Distributions of the number of nucleons of the triggered ^{A}P ions used for the simulation of the physics performance with secondary ion beams. Left: only wanted ions are present in the beam, middle: the distribution resulting from mocadi simulation, right: the extreme case P(31) = P(32) = P(33) = 1/3.

7   Appendix II: Beam and target nuclei

The NA61 scan in collision energy and size of the colliding nuclei requires collisions of medium ($A \approx 100$) and light ($A \approx 10$ and $A \approx 40$) mass nuclei [1]. NA49 results indicate that hadron production properties do not change significantly if the masses of the colliding nuclei change by $\pm 30\%$. In the NA61 proposal [1] ^{12}C+C, ^{28}Si+Si and ^{115}In+In collisions were suggested for the study. This selection was motivated by aiming for consistency with already existing data of the NA49 and NA60 collaborations.

In the revised data taking schedule presented in this document the study of ^{11}B+^{12}C, ^{40}Ar+^{40}Ca and ^{129}Xe+^{139}La collisions is suggested. This selection of projectile and target
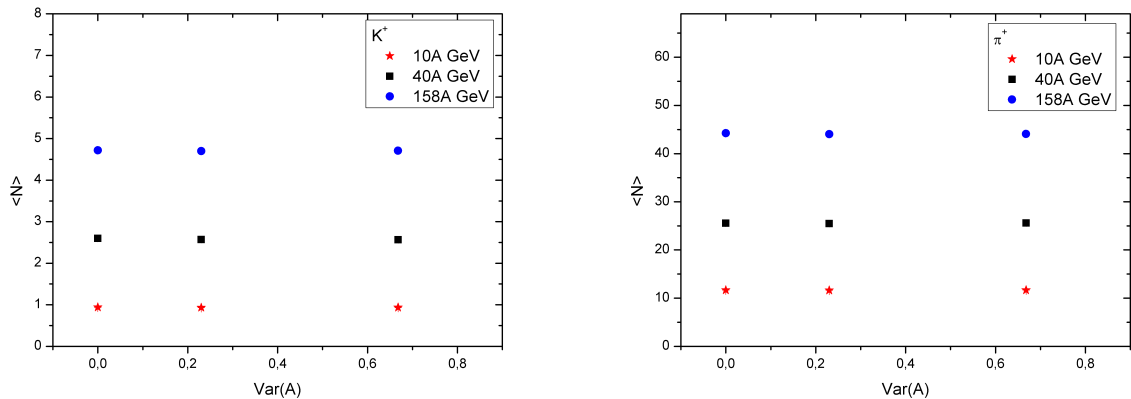
Figure 5: Left: The mean multiplicity of π^+-mesons in the forward hemisphere produced in central ^{A}P+^{32}S collisions at $10A$, $40A$ and $158A$ GeV as a function of the variance of the A distribution. Right: The mean multiplicity of K^+-mesons in the forward hemisphere produced in central ^{A}P+^{32}S collisions at $10A$, $40A$ and $158A$ GeV as a function of the variance of the A distribution.

nuclei obeys the limits imposed by the NA61 physics requirements.

The change of projectile nuclei is motivated by the intensity and purity requirements for the secondary ion beam with $A \approx 12$ and by the preference to use noble gases in the CERN ion source for the primary beams of Ar and Xe.

The targets were selected to be easily handled solids with nuclei somewhat heavier than the corresponding projectile nuclei. The difference of up to 10% between the number of nucleons in the projectile and target nuclei is not reflected in particle production properties for central collisions. This is because the NA61 selection of central collisions by the PSD measurement of the energy in the projectile spectators compensates the initial asymmetry.

This effect was studied for ^{11}B+^{12}C collisions at $40A$ GeV using the UrQMD 2.3 model [10]. As an example the ratio of the rapidity distributions in the forward and backward hemispheres for positively charged pions is shown in Fig. 10. The ratio is shown as a function of the rapidity distance from the c.m. rapidity ($y_{cm} = 2.22$ in the laboratory system) for the 20% most central collisions selected by the number of the projectile spectators ($N_S^{proj} < 4$). Systematic deviations from unity, if any, are smaller than 2%. Thus the influence of the small projectile-target nuclear mass asymmetry is largely compensated by the projectile-target asymmetry in the selection of central collisions.
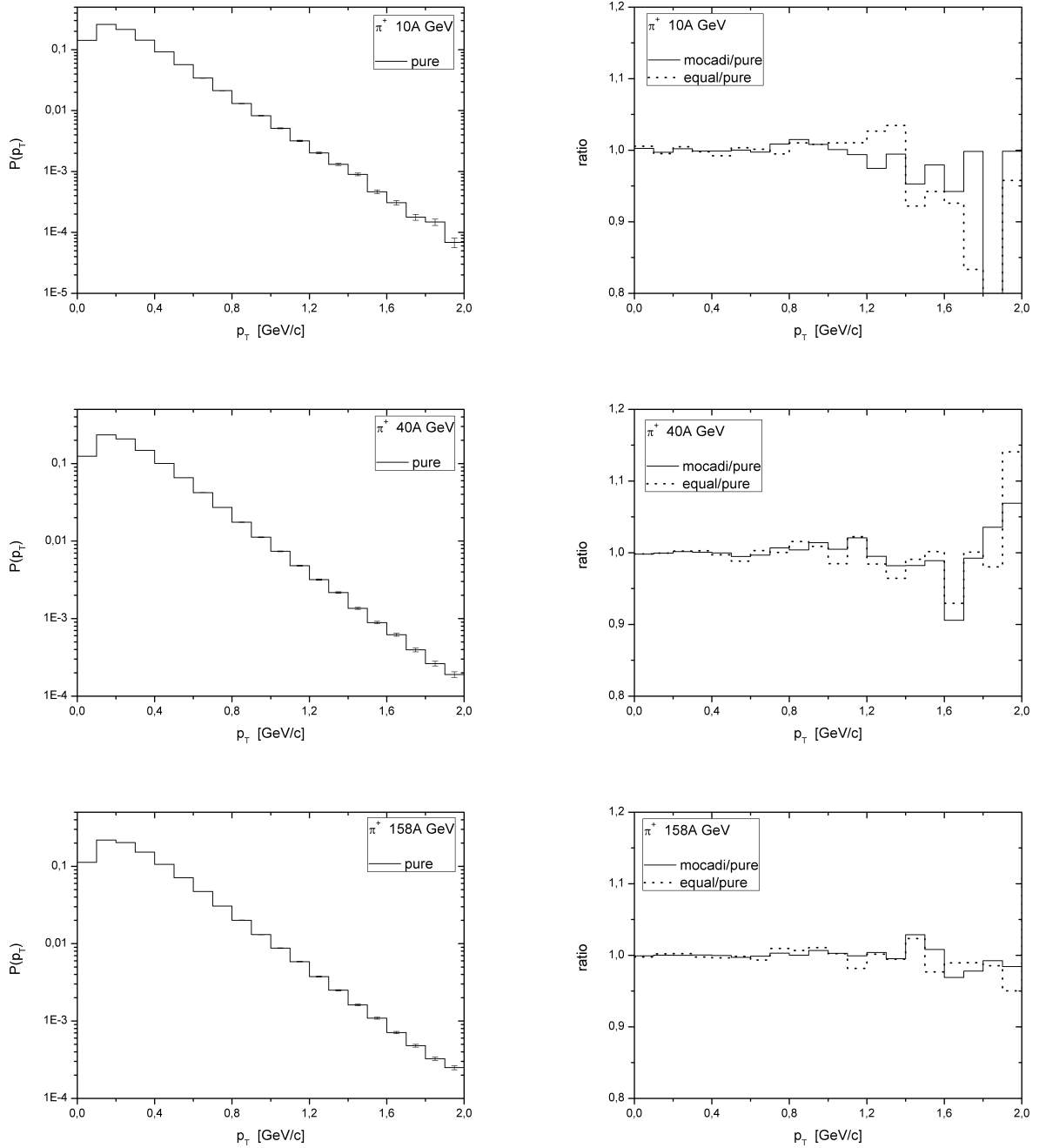
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Figure 6: Left: Transverse momentum spectra of π^+ mesons in the forward hemisphere produced in central ^{32}P+^{32}S collisions at $10A$ (top), $40A$ (middle) and $158A$ GeV (bottom). The spectra are normalized to unity. Right: The ratio of the p_T spectra from ^{A}P+^{32}S (mocadi,equal) and ^{32}P+^{32}S (pure,see left) central collisions at $10A$ (top), $40A$ (middle) and $158A$ GeV (bottom). For details see text.
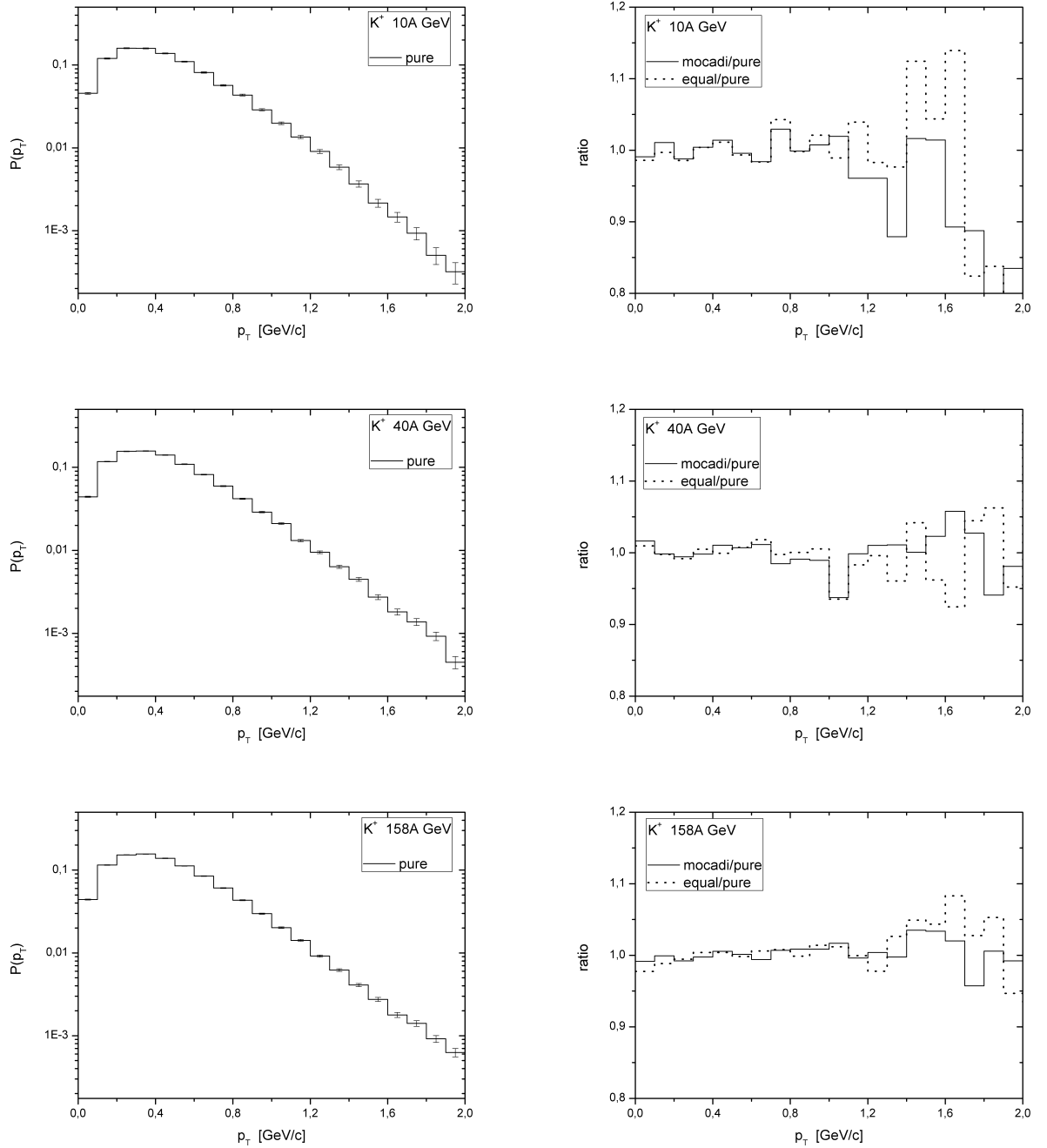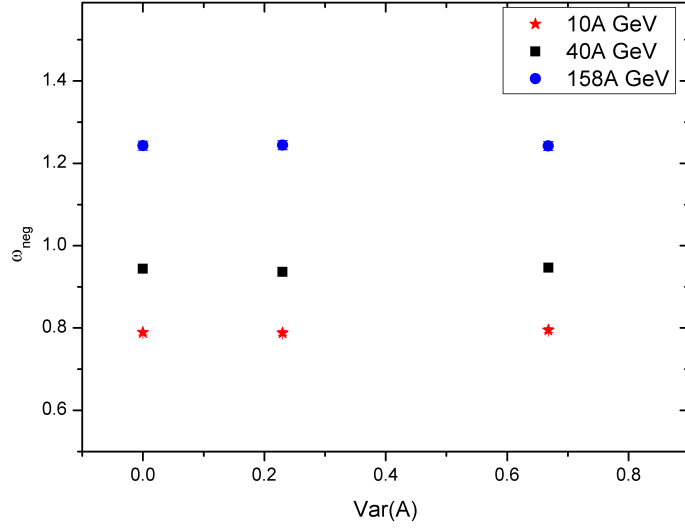
Figure 7: Left: Transverse momentum spectra of K^+ mesons in the forward hemisphere produced in central ^{32}P+^{32}S collisions at $10A$ (top), $40A$ (middle) and $158A$ GeV (bottom). The spectra are normalized to unity. Right: The ratio of the p_T spectra from ^{A}P+^{32}S (mocadi,equal) and ^{32}P+^{32}S (pure,see left) central collisions at $10A$ (top), $40A$ (middle) and $158A$ GeV (bottom). For details see text.

Figure 8: The scaled variance ω of the negatively charged hadron multiplicity distribution in central ^{A}P+^{32}S collisions at $10A$, $40A$ and $158A$ GeV as a function of the variance of the A distribution.
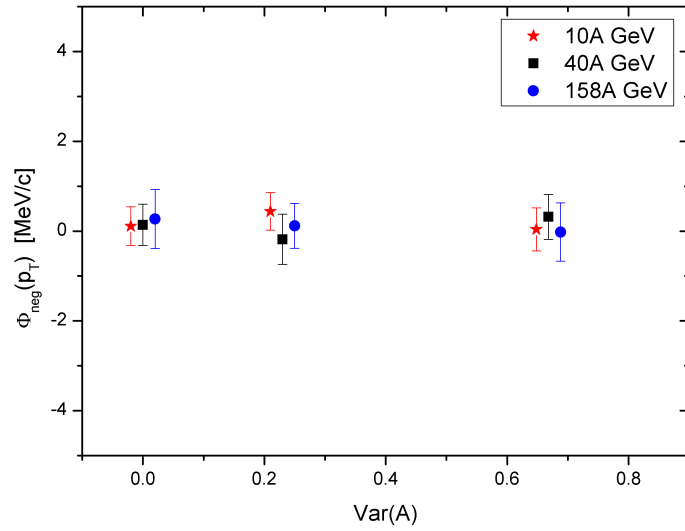

Figure 9: The ϕ_{p_T} measure of transverse momentum fluctuations for negatively charged hadrons produced in central ^{A}P+^{32}S collisions at $10A$, $40A$ and $158A$ GeV as a function of the variance of the A distribution.
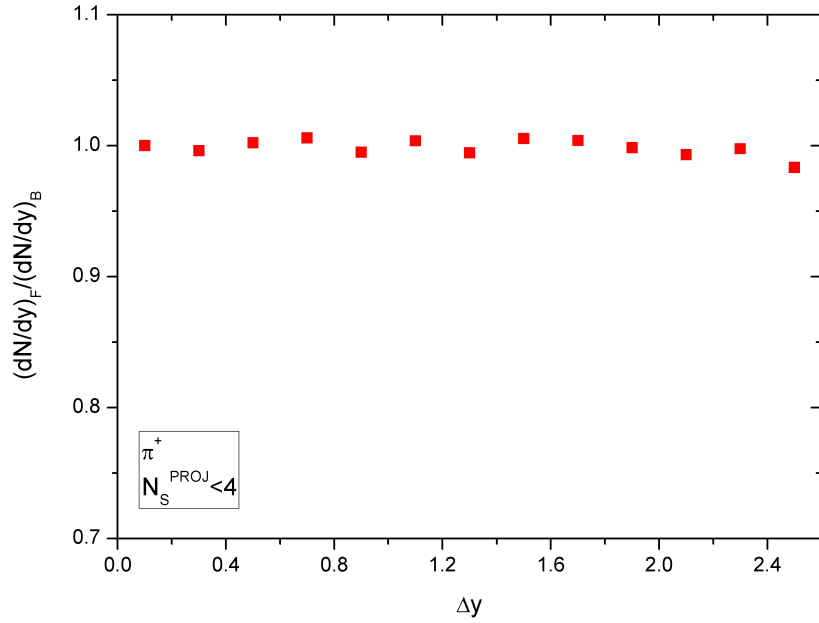
Figure 10: The ratio of the rapidity distributions in the forward and backward hemispheres for positively charged pions produced in 20% most central ^{11}B+C^{12} collisions at $40A$ GeV as a function of the distance to the c.m. rapidity ($y_{cm} = 2.22$ in the laboratory system).

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