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Report from the NA61/SHINE experiment at the CERN SPS

By the NA61/SHINE Collaboration

http://na61.web.cern.ch

Abstract

The physics program of the NA61/SHINE (SHINE ≡ SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS consists of three subjects. In the first stage of data taking (2007-2008) the measurements of hadron production in hadron-nucleus interactions needed for neutrino (T2K) and cosmic-ray (Pierre Auger and KASCADE) experiments will be performed. In the second stage (2008-2010) hadron production in proton-proton and proton-nucleus interactions needed as a reference data for better understanding of nucleus-nucleus reactions will be studied. In the third stage (2010-2012) hadron production will be measured in nucleus-nucleus collisions, with the aim to identify the properties of the onset of deconfinement and find evidence for the critical point of strongly interacting matter.

The experiment was approved at CERN in June 2007. The first pilot run was performed during October 2007. We report here first results from this run.

The NA61/SHINE Collaboration

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1 Introduction

The physics program of the NA61/SHINE (SHINE $\equiv$ SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS [1, 2, 3] consists of three subjects. In the first stage of data taking (2007-2008) the measurements of hadron production in hadron-nucleus interactions needed for neutrino (T2K) and cosmic-ray (Pierre Auger and KASCADE) experiments will be performed. In the second stage (2008-2010) hadron production in proton-proton and proton-nucleus interactions needed as a reference data for better understanding of nucleus-nucleus reactions will be studied. In the third stage (2010-2012) hadron production will be measured in nucleus-nucleus collisions, with the aim to identify the properties of the onset of deconfinement and find evidence for the critical point of strongly interacting matter.

The experiment was approved at CERN in June 2007. The first pilot run was performed during October 2007. The aims of this run were [2]:

- to set up and test the NA61/SHINE apparatus and the detector prototypes,
- to take pilot physics data on interactions of 31 GeV/c protons on a thin carbon and the T2K replica targets.

This documents presents a brief report from the 2007 run. The NA61/SHINE detector and prototypes prepared for the 2007 run are described in Section 2. The run history and first results are given in Sections 3 and 4, respectively.

2 The NA61/SHINE set-up and detector prototypes

2.1 The NA61/SHINE detector

The NA61/SHINE experiment is a large acceptance hadron spectrometer at the CERN-SPS for the study of the hadronic final states produced by collisions of various beam particles (π, p, C, S and In) with a variety of fixed targets at the SPS energies. The layout of the NA61/SHINE set-up is shown in Fig. 1. The main components of the current detector were constructed and used by the NA49 experiment [4]. The main tracking devices are four large volume Time Projection Chambers (TPCs), see Fig. 1, which are capable of detecting up to 70% of all charged particles created in the reactions studied. Two of them, the vertex TPCs (VTPC-1 and VTPC-2), are located in the magnetic field of two super-conducting dipole magnets (maximum bending power of 9 Tm) and two others (MTPC-L and MTPC-R) are positioned downstream of the magnets symmetrically with respect to the beam line. One additional small TPC, the so-called gap TPC (GTPC), is installed on the beam axis between the vertex TPCs. The NA61/SHINE TPCs allow precise measurements of particle momenta p with a resolution of $\sigma(p)/p^2 \cong (0.3 - 7) \times 10^{-4}$ (GeV/c)$^{-1}$. The setup is supplemented by two time of flight detector arrays (ToF-L/R) with a time measurement resolution of $\sigma_{tof} \approx 60$ ps.

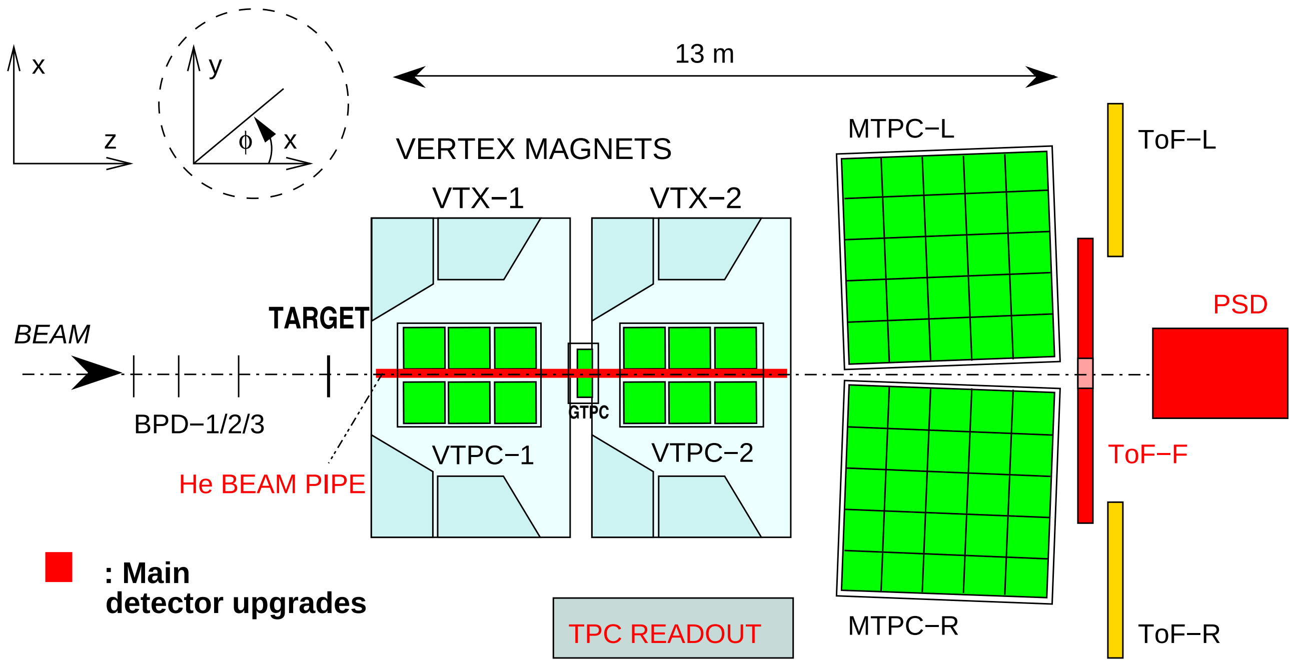

Figure 1: The layout of the NA61/SHINE set-up (not to scale) with the basic upgrades indicated in red.

For the 2007 run a new forward time of flight detector (ToF-F) was constructed in order to extend the acceptance of the NA61/SHINE set-up for pion and kaon identification as required for the T2K measurements. The ToF-F detector consists of 64 scintillator bars, oriented vertically, and read out on both sides with Hamamatsu R1828 photo-multipliers. The size of each scintillator bar is $120 \times 10 \times 2.5$ cm^3. The expected resolution of the new ToF-F wall is ≤ 120 ps. This resolution provides a 5 σ π/K separation at 3 GeV/c. The ToF-F wall is installed downstream of the MTPC-L and MTPC-R (see Fig. 1), closing the gap between the ToF-R and ToF-L walls. The installation phase and the installed modules of the ToF-F are shown in Fig. 2.

Furthermore, numerous small modifications and upgrades of the NA61/SHINE facility were performed before the 2007 run. They include:

- speed-up of the ToF-L/R readout,
- modification of the DAQ system to allow writing data on disk,
- refurbishing of the Beam Position Detectors (BPD-1/2/3 in Fig. 1),
- preparation of the targets and target holders and
- preparation and installation of the new beam counters for a new trigger logic.

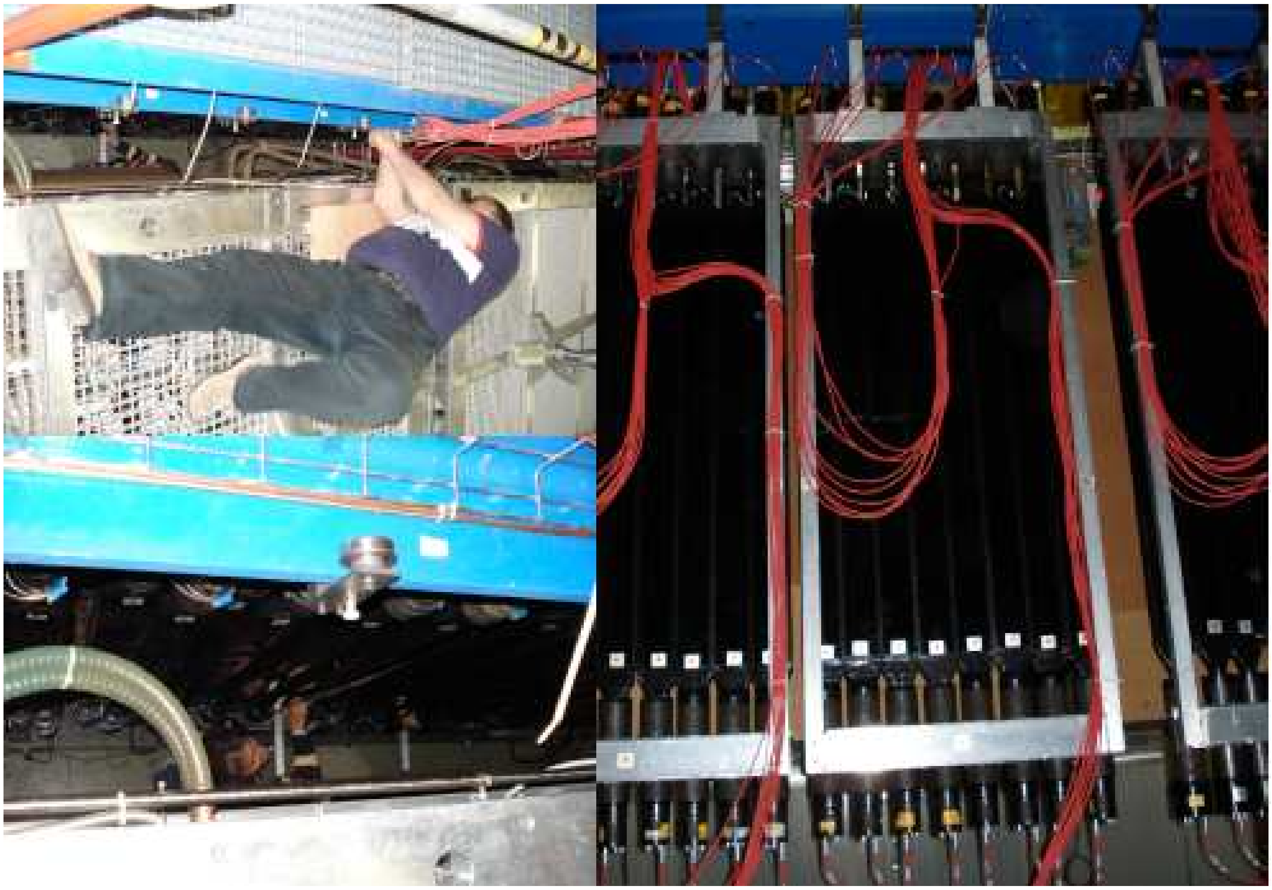

Figure 2: The installation (left) and the installed modules (right) of the ToF-F detector constructed for the 2007 run.

Two carbon (isotropic graphite) targets were used during the 2007 run:

- a 2 cm-long target (about 4% of a nuclear interaction length, λ_I) with density $\rho = 1.84$ g/cm^3, the so-called thin target,
- a 90 cm long cylinder of 2.6 cm diameter (about 1.9 λ_I), the so-called T2K replica target with density $\rho = 1.83$ g/cm^3, see Fig. 3.

The center of the targets was positioned about 80 cm upstream from the VTPC-1 entrance window.
Proton beam particles are identified and selected by means of CEDAR-West and threshold Cerenkov counters as well as several scintillation counters. The trajectory of beam particles is precisely measured by the BPDs. These detectors consist of pairs of proportional chambers and are positioned along the beam line.

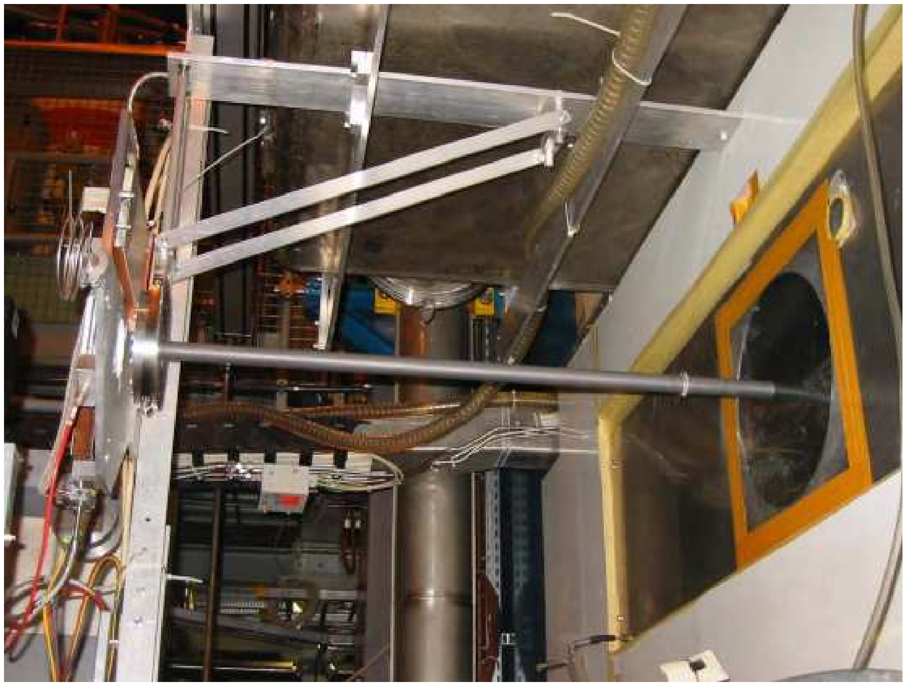

Figure 3: The T2K replica target installed in the NA61/SHINE set-up in front of the VTX-1 magnet.

Interactions in the target were selected by an anti-coincidence of the incoming beam particle with a small scintillation counter (S4) placed on the beam axis between the two vertex magnets.

2.2 The detector prototypes

Two detector prototypes were constructed for and tested during the 2007 run, namely:

- the super-module of the Projectile Spectator Detector (PSD) and
- the "FE Tester" needed for the development of the new TPC readout electronics.

2.2.1 The PSD super-module

In time for the first ion run the Projectile Spectator Detector will be constructed and placed downstream of the ToF-F detector. It will be a fully compensating modular lead-scintillator calorimeter with WLS-fibers and avalanche micro-pixel photo-diode (AMPD) readout. In the study of event-by-event fluctuations the PSD will be used to select samples of events with minimal variation of the number of nucleons participating in the collision and the PSD will be included in the trigger for on-line selection of collision centrality.

Figure 4: The PSD super-module positioned in the NA61/SHINE experiment downstream of the MTPC hut.

To study the energy resolution of the PSD prototype a new 3×3 array (super-module) of PSD modules has been constructed. A single PSD module is divided longitudinally into 10 sections with individual readout of each section by 3×3 mm^2 AMPDs produced by Dubna-Micron. Each section consists of 6 lead/scintillator layers of 10×10 cm^2 area with a thickness of about 0.6 λ_I. All 10 sections (60 lead/scintillator sandwiches) are loaded into a steel box with 0.5 mm thick walls. The sandwiches are tied by steel tape of the same thickness. The WLS-fibers coming from each scintillator tile are routed in a 2 mm air gap at the top side of the module. Every WLS-fiber is covered by a thin black pipe for light isolation and mechanical protection. The light from the 6 WLS-fibers from one section is collected by one optical connector viewed by an AMPD. The electrical signals from the 10 AMPDs of each module are fed to the amplifiers through short 10-15 cm coaxial cables.

The 9 PSD modules were assembled in a 3×3 module array which was placed in the final position of the PSD detector, downstream of the MTPC hut on a movable support structure (see Fig. 4) and was exposed to beams of muons and hadrons. The results of this test run will be shown in Section 4.

2.2.2 The "FE Tester"

The upgrade of the TPC read-out electronics is under construction and should be ready for the 2008 run. In the NA49 readout scheme the front end cards were read out in serial mode. The new front-end card readout electronics will perform parallel readout with expected data rate of about 85 Hz. This will increase the number of events that can be recorded per spill by a factor

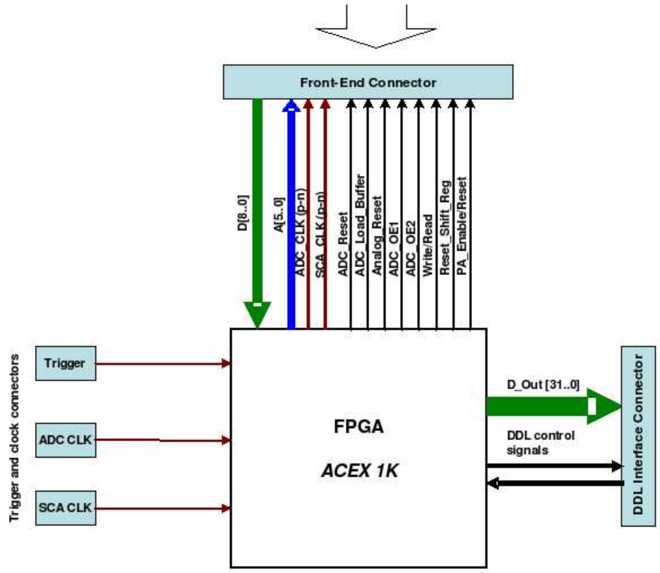

Figure 5: The layout of the front-end read out board ("FE Tester") used for the test purposes during the 2007 run.

of about 10. The upgrade requires production of new mother boards and concentrator cards as well as use of the Detector Data Links developed for the ALICE experiment at the CERN LHC.

A large amount of re-engineering work on the present TPC readout system (i.e. understanding the operation of the front-end (FE) and motherboards) had to be done. For testing and measurement purposes a dedicated FE readout board, "FE Tester", was developed. It reads out 3 FE cards on a single flat cable and has test points to access all FE interface signals. The data are transmitted to and stored on a server PC through a DDL link with the same DDL protocol as will be used in the new readout electronics. A simple graphical interface program has been written for visualization of data read out from the FE cards. The "FE Tester" diagram is shown in Fig. 5.

3 The 2007 run

The 2007 NA61/SHINE pilot run started on September 27 and ended on October 29. During this period the following studies were performed:

- September 27 - October 3:
  test of the PSD super-module with beams of muons at 75 GeV/c and hadrons at 20, 30, 40, 80 and 158 GeV/c;

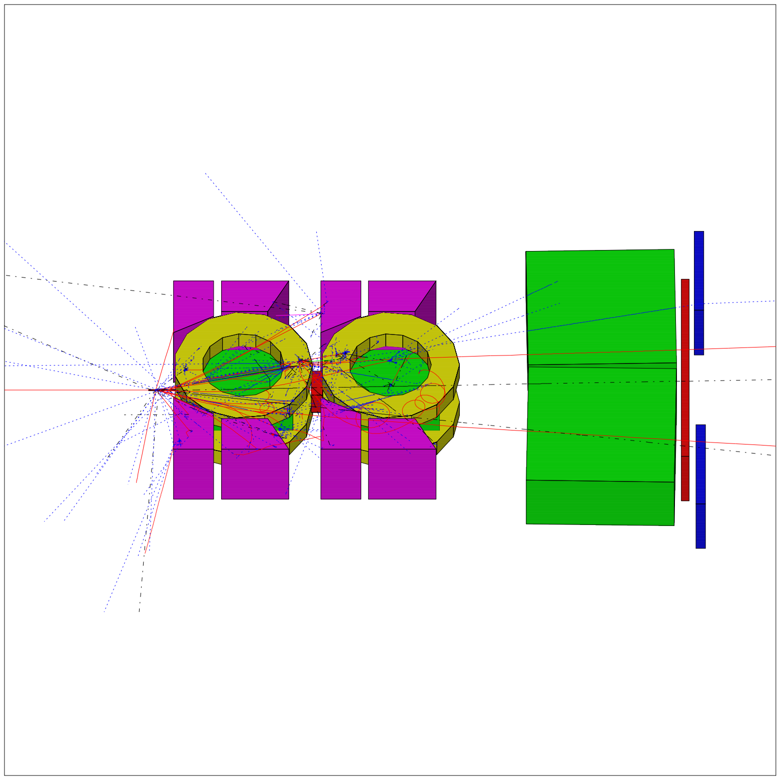

Figure 6: An example of a simulated p+C interaction (31 GeV/c incoming proton on the T2K replica target) in the full NA61/SHINE detector.

- September 27 - October 12:
  installation, test and tuning of the beam and trigger counters with beams of hadrons at 75 GeV/c and 30.9 GeV/c; optimization of the proton beam at 30.9 GeV/c;
- October 13 - October 24:
  pilot data taking with 30.9 GeV/c protons on the thin graphite target;
- October 25 - October 29:
  pilot data taking with 30.9 GeV/c protons on the T2K replica graphite target;
- October 25 - October 29:
  TPC readout tests with the "FE Tester".

In total about $1.5{\times}10^6$ events were registered. This includes 490k events with the thin target, 230k events with the T2K replica target and 80k events without target (empty target events).

The NA61/SHINE software has been set up and tested on the 2007 data. Both reconstruction and simulation chains have been heavily used for the on-line and off-line quality control as well as for the acceptance studies. An example of a simulated p+C interaction (31 GeV/c incoming proton on the T2K replica target) in the full NA61/SHINE detector is shown in Fig. 6. The data taken during the 2007 run are currenly being analyzed to perform detector calibration and to obtain first physics results.

Parallel to the run a workshop took place with lectures and discussions covering a broad range of subjects related to NA61/SHINE, i.e. from safety during shifts to cosmic-ray physics [5].

4 The first results from the 2007 run

4.1 The PSD super-module test

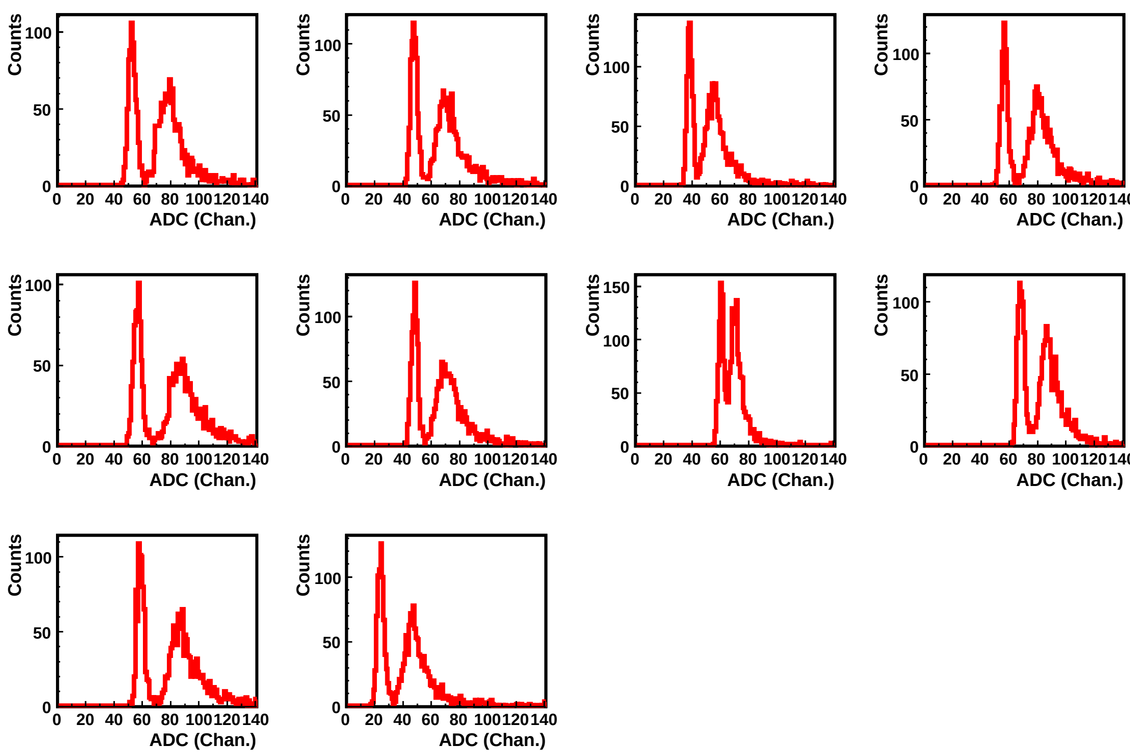

Figure 7: The response of the 10 subsequent longitudinal sections of the first module of the PSD prototype to the muon beam at 75 GeV/c. The muon peaks (second peak to the right of the pedestal peak) were used to determine the calibration coefficients.

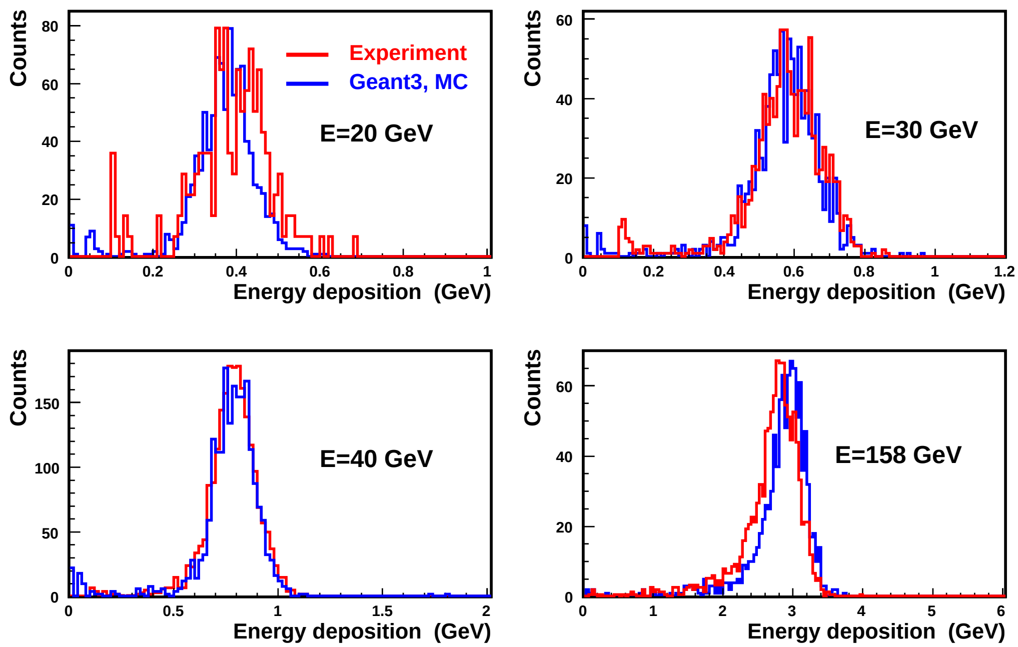

Figure 8: The measured (red) and simulated (blue) energy spectra for hadron beams at 20, 30, 40 and 158 GeV/c.

The main goal of the PSD super-module test performed in 2007 was to determine the energy resolution of the detector prototype.

The test started with calibration runs using the muon beam at 75 GeV/c. The muon energy calibration of each longitudinal section in the calorimeter is possible thanks to the large light yield of the scintillator tiles together with the AMPD's ability to detect low intensity signals. Peaks at 5 MeV from muon energy loss in 6 scintillator tiles are nicely separated from the pedestals, see Fig. 7. In order to obtain a full set of calibration coefficients the muon beam scan was performed for all 9 modules.

After the calibration runs the central module of the prototype was irradiated by hadron beams of 20, 30, 40, 80 and 158 GeV/c. The calibrated energy deposition summed over all 9 modules for hadron beams at all energies are shown in Fig. 8 together with the simulation results. The experimental and simulation spectra are in rather good agreement.

Fig. 9 presents the energy dependence of the measured energy resolution. A fit to the experimental points yields a stochastic term of about 55% and a constant term of about 3.7%. The calorimeter prototype with 30×30 cm^2 front size is too small to contain the entire hadron shower and non-negligible lateral shower leakage is expected. MC simulation confirms that about 16% of the hadron shower escapes from the PSD super-module. The effect of shower leakage on the energy resolution was included as a third term in addition to the stochastic and

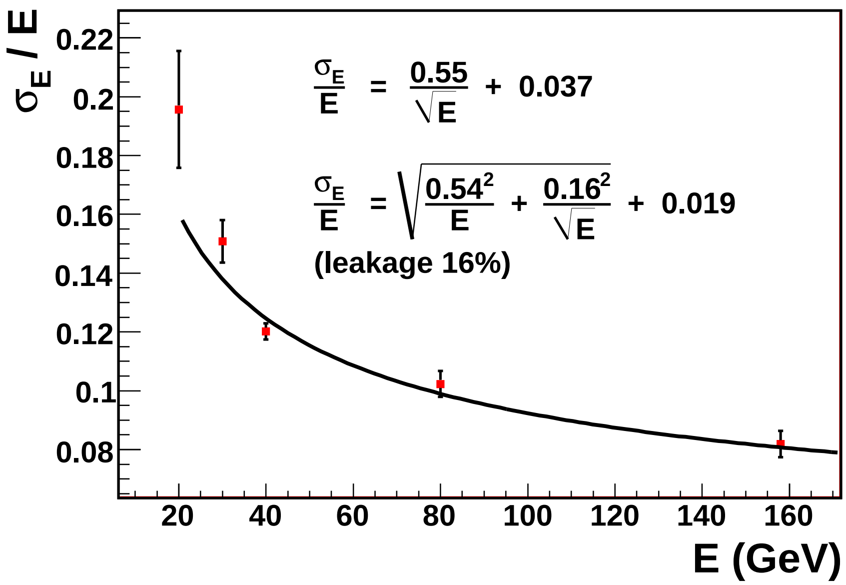

Figure 9: The dependence of the energy resolution of the PSD super-module on beam energy. The curves corresponding to the fits with two and three term formula overlap on this plot.

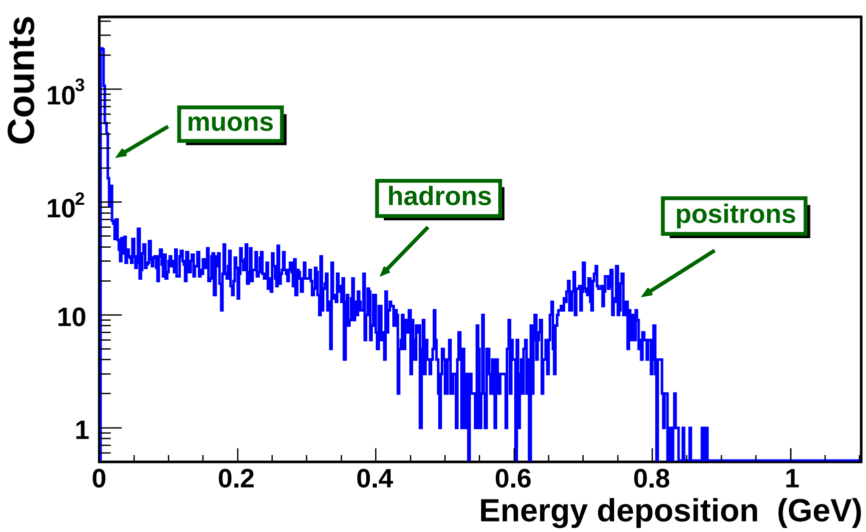

Figure 10: The energy deposition of the 30 GeV/c mixed hadron and positron beam measured in the first section of the PSD super-module.

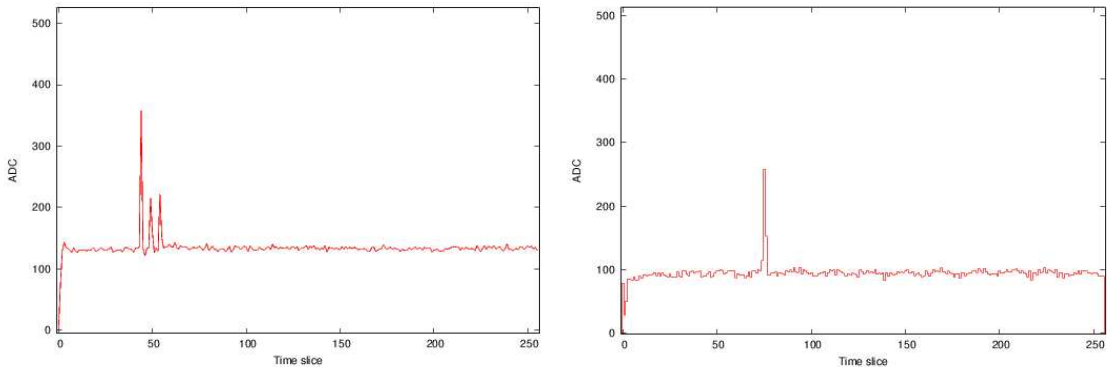

Figure 11: The pulser (left) and track (right) signals measured by the "FE Tester".

constant terms in the parameterization of the resolution. The fit of the experimental points with the three term formula results in a stochastic term of 53.5% and a constant term of 1.9% using a fixed leakage term of 16%. The non-negligible constant term in the energy resolution indicates the absence of full compensation in the calorimeter. Note, that this constant term has no significant influence on the precision of reconstruction of the number of spectators. This is because the relative energy resolution for N specatator nucleons is smaller by a factor of $1/\sqrt{N}$ than the corresponding resolution for a single spectator nucleon. Fig. 10 presents the spectrum of deposited energies in the first section of the super-module for a mixed beam of hadrons and positrons at 30 GeV/c. As can be seen from this figure, positrons lost almost their full energy in the first section, while hadrons left only part of their initial energy. Thus, an analysis of the longitudinal shower profile allows an identification and rejection of electromagnetically interacting particles.

4.2 The "FE Tester"

The "FE Tester" was connected to three consecutive front-end cards in one of the MTPC-L sectors. The signals generated by the pulser and by real tracks were recorded and later analyzed off-line. Two examples are shown in Fig. 11. The recorded track signals were matched and compared to the signals recorded by the current NA61/SHINE DAQ. The parameters of the clusters obtained via the "FE Tester" are similar to those of clusters recorded by the NA61/SHINE DAQ.

4.3 The pilot data for T2K

The major part of the 2007 run was devoted to recording pilot data for the T2K and cosmic-ray experiments. Particles produced in interactions of the 31 GeV/c proton beam on thin and T2K replica carbon targets were registered using the NA61/SHINE apparatus. The data were taken

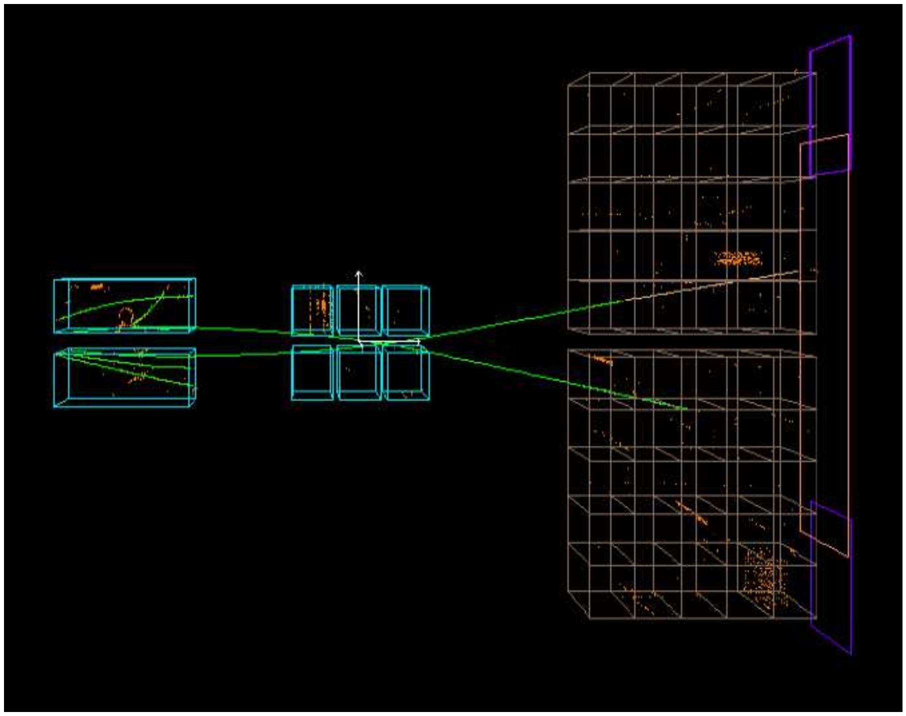

Figure 12: The "top view" display of a typical p+C interaction at 31 GeV/c registered by NA61/SHINE in the 2007 run.

with a magnetic field of total bending power of ≈1 Tm. In addition to the data production runs, numerous test and calibration runs were also performed. They will allow to determine corrections and to evaluate systematic errors on the final results. The following several examples illustrate the data quality. They were produced using the actual NA61/SHINE reconstruction software with preliminary calibration parameters.

The "top view" display of the NA61/SHINE TPCs with tracks from a typical p+C interaction at 31 GeV/c is shown in Fig. 12. The low track multiplicity leads to a very low space density of tracks and consequently to almost 100% track reconstruction efficiency.

The operation parameters of the TPCs (the Ar/CO_2 ratios, the drift voltages, the high voltages of the readout chambers) were tuned to reproduce the drift velocities and cluster properties established by NA49 as optimal. Figs. 13 and 14 show the distributions of the number of pad and time bins constituting the charge clusters created by the tracks passing the MTPC-L in order to demonstrate the high quality of the taken data.

In order to perform an independent test of the beam properties the magnetic field was increased to its maximum value which deflected beam particles into the MTPC-L and VTPC-2 detectors. The distribution of the reconstructed beam momentum is given in Fig. 15. Its mean value agrees within the beam line systematic error of about 130 MeV/c with the nominal set

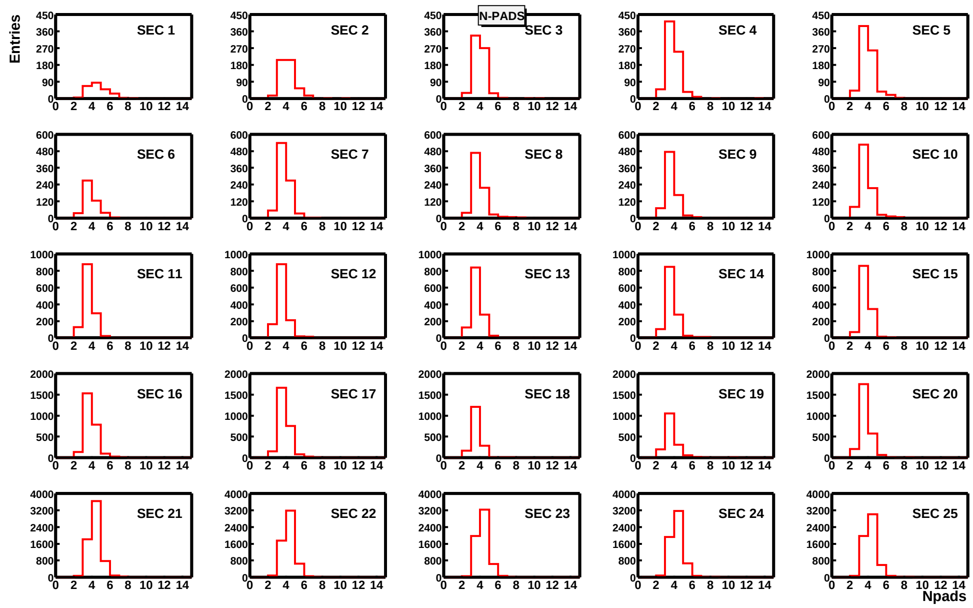

Figure 13: The distributions of the number of pads constituting the charge clusters created by the tracks passing the MTPC-L.

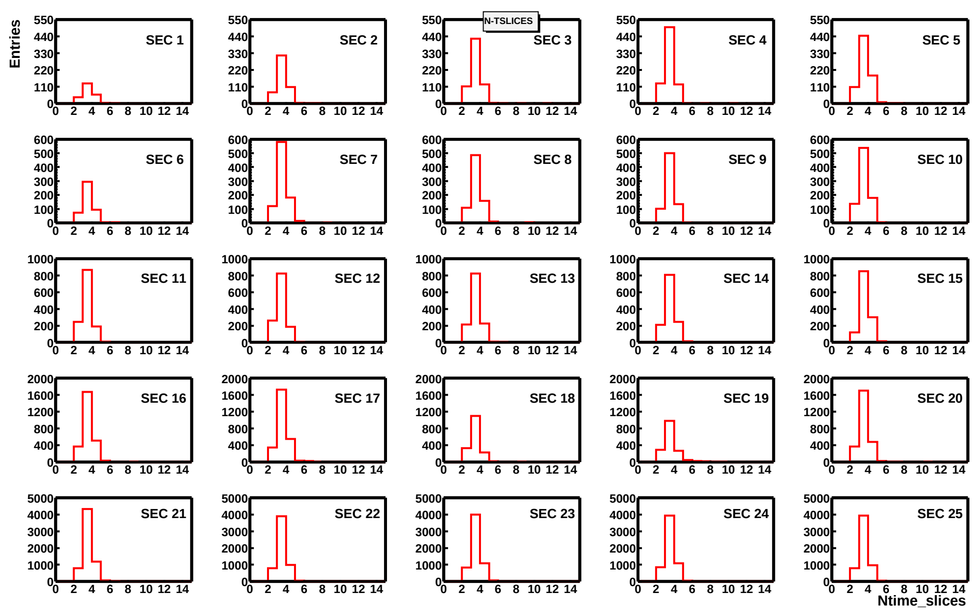

Figure 14: The distributions of the number of time bins constituting the charge clusters created by the tracks passing the MTPC-L.

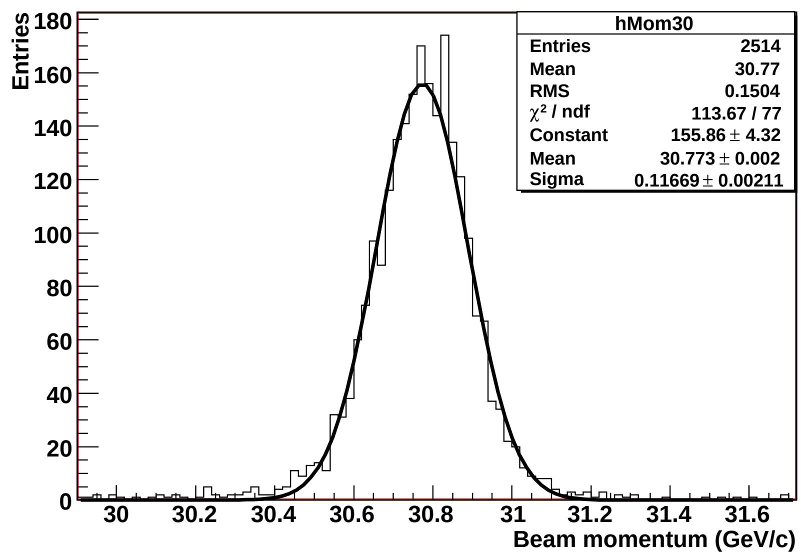

Figure 15: The distribution of the proton beam momentum measured by the NA61/SHINE TPCs in a special run during the 2007 data taking.

value of 30.92 GeV/c. The beam profile in the target plane as measured by the BPDs is shown in Fig. 16.

Fig. 17 shows invariant mass peaks due to K^0_S and Λ decays obtained after reconstruction of the V^0 topology and fitting of the momenta at the decay point. The measured positions of these peaks relative to the well-known PDG values are used for the precise calibration of the magnetic field.

Finally, Fig. 18 shows the preliminary results from the new ToF-F detector: the mass squared calculated from the time measured in the ToF-F after a preliminary calibration. Contributions from pions, kaons and protons are clearly visible.

5 Summary

The main goals of the 2007 NA61/SHINE run were reached, namely:

- the NA61/SHINE apparatus (including the new ToF-F system) was run successfully and detector prototypes were installed and tested,
- pilot physics data on interactions of 31 GeV/c protons on thin and T2K replica carbon targets were registered.

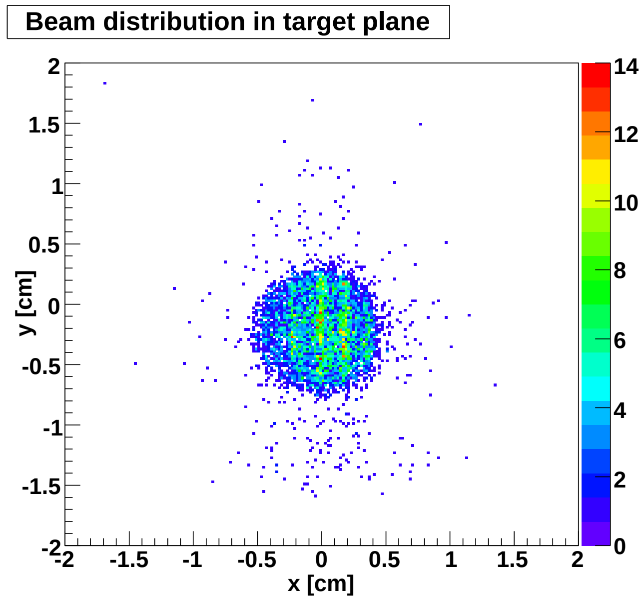

Figure 16: The beam profile in the target plane as measured by the BPDs.

The test results are being analyzed, but already now it is clear that they were very useful and will lead to important improvements of the planned detector upgrades.

The pilot data taken for T2K are of a quality similar to that of NA49. Precise calibration work is being carried out. First pre-production has been performed on the full set of 2007 physics data. The corresponding DSTs are currently being analyzed. Preliminary physics results are expected to be ready by Summer 2008.

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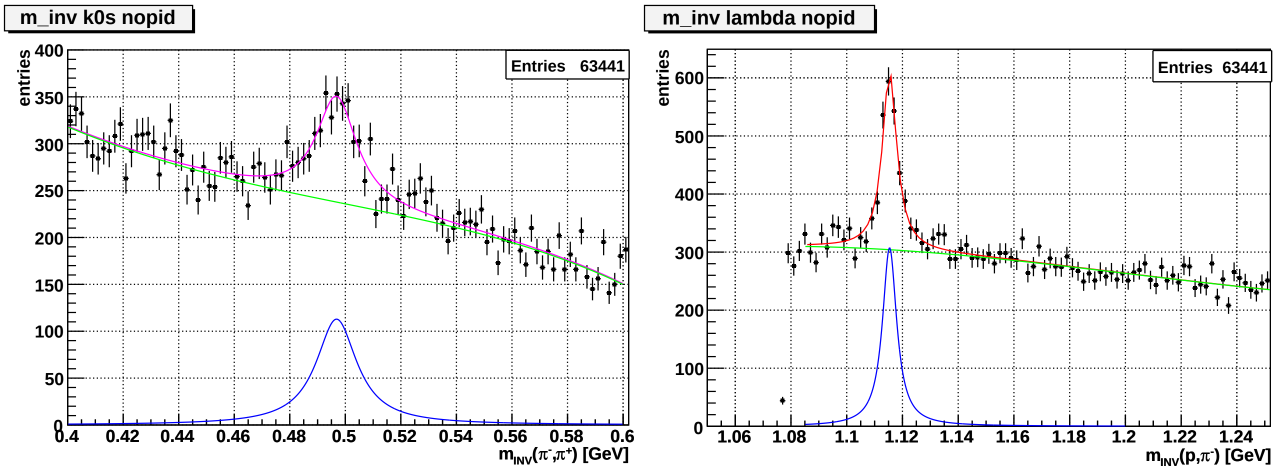

Figure 17: The invariant mass distributions for reconstructed V^0-vertices with clear peaks due to K_S^0 (left) and Λ (right) decays.

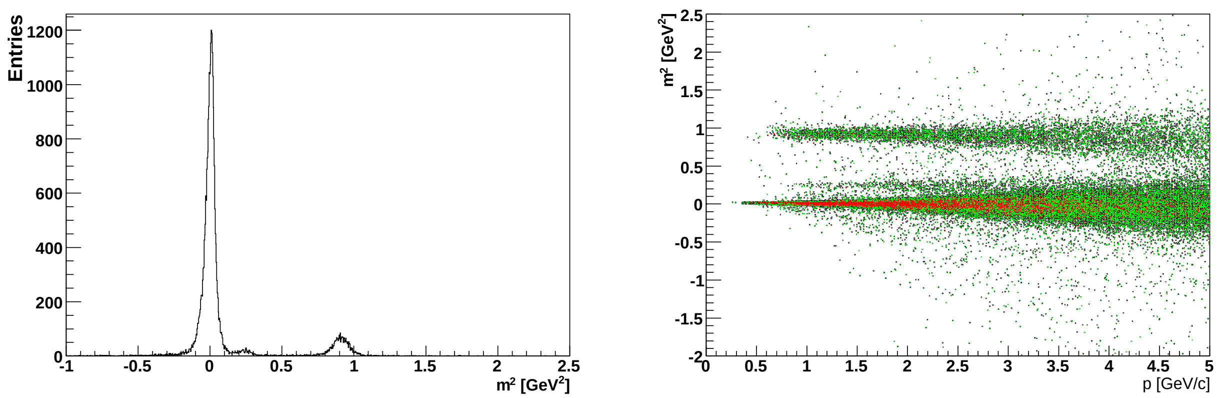

Figure 18: The mass squared calculated from the time measured in the ToF-F after a preliminary calibration (left). The mass squared as a function of momentum (right). Contributions from pions, kaons and protons are clearly visible.

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