JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Simulation of proton-proton and proton-nuclei interactions in the frame of Monte-Carlo models

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ABSTRACT

The aim of this student work was a simulation of proton-proton and proton-nuclei interactions in Monte-Carlo models with visualisation of results. ROOT and GEANT4 packages for analysis and simulations have been used. Basic methods of ROOT for plotting and simple modeling, such as Random and PhaseSpace generators have been used. Geant4 was used for simulation of proton-proton interaction at vatious energies. We have compared our calculations in the frame of FTF and QGS generators in Geant4 with experimental data of NA61/SHINE collaboration on proton-carbon interactions at initial momenta 31 GeV/c and 120 GeV/c.

CONTENTS

INTRODUCTION

Monte Carlo simulations are widely used for modeling of various process based on random number generators. This is very important for high energy physics. A goal of present work was an understanding and consideration of the two most popular software packages for analysis and simulations in high energy physics – ROOT and Geant4. These packages allow one to model and analyse particle interactions, and compare calculation results with experimental or theoretical studies. ROOT v6.28.12-1 and GEANT4 v11.1.3-1 installed at HybriLIT cluster in Laboratory of Information Technologies of JINR, Dubna have been used.

1. Simpliest simulations in ROOT Framework

ROOT is an open-source data analysis framework applied in elementary particles physics, nuclear physics and other fields. ROOT enables scientific studies and visualization of large amounts of data. Nowadays, ROOT is a base framework used in science for storing and analysing big data obtained in experiments. ROOT provides the most basic tools for simulations: random number generators, phase space generator and others.

1.1. Random generators

There are generators Rannor(), Rndm() and others from TRandom class of ROOT. Rndm() method gives a random number uniformally distributed in interval $[0, 1]$. Rannor() generates two variables with Gaussian distribution with unit dispersion. This variables can be two components of transverse momentum (p_z) – p_x and p_y. In this case, p_z is giving by formula $p_z^2 = p_x^2 + p_y^2$. Calling Rannor() for 10 particles in cycle 100 000 times one can obtain 1 000 000 numbers that should be stored. For storing one can use ROOT TTree. Each call is called *event*. Corresponding script for ROOT for particles like protons, neutrons, mesons and kaons is given below:

```
#include "TFile.h"
#include "TTree.h"
#include "TBrowser.h"
#include "TH2.h"
#include "TRandom.h"

void tree_Prand() {
        TFile f("tree_Prand.root","recreate");
        TTree t1("t1","TTree");
        Float_t px, py, pz;
        Int_t id;
        const Int_t n = 10;
        Int_t id1[n]{2212,2112,211,-211,111,321,-321,311,421,-421};
        t1.Branch("id",&id,"id/I");
        t1.Branch("px",&px,"px/F");
        t1.Branch("py",&py,"py/F");
        t1.Branch("pz",&pz,"pz/F");

        for (Int_t k=0; k<n; k++) {
                for (Int_t i=0;i<10000;i++) {
                        gRandom->Rannor(px,py);
                        pz = sqrt(px*px + py*py);
                        t1.Fill();
                }
        }
        t1.Write();
}
```

Using this script, output one can create various histogramms as presented in Fig. 1.

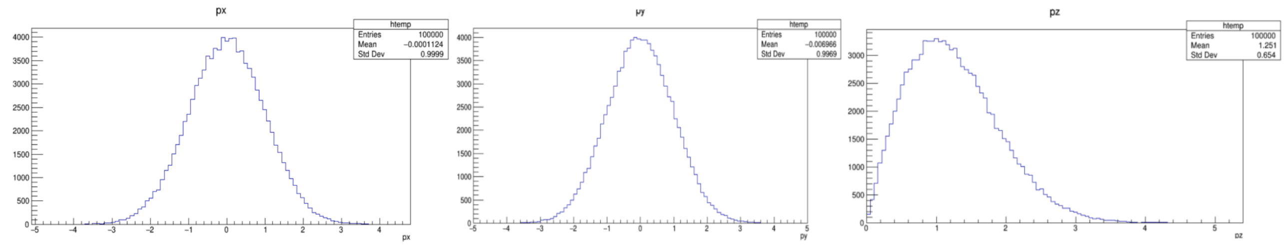

Figure 1: p_x, p_y and p_z distributions of all particles.

1.2. Phase space model

So-called "Phase space" is, in general, a multi-dimensional space in which all possible "states" of a dynamical system are represented. Each possible state corresponds to one unique point in the phase space. For systems of point-like objects, the phase space usually consists of all possible values of position and momentum variables of the object. For an uninteracting object, it is natural to assume that the points are uniformly distributed in the phase space. It is a model what was applied in multi particle physics many years ago. The phase space model in ROOT allows one to generate particle distributions in the center of mass system (CMS) or laboratory systems with target at rest (LAB) at defined topology of events. In ROOT it can be implemented as follows: a user has to create Lorentz vectors for incident particles, set their masses and use TGenPhaseSpace class for "decaying" of this particles, for simulation of production events with defined topology. SetDecay() function allows to choose the number and types of pruduced particles.

Using Phase Space model in ROOT, we have generated proton-proton interactions in CMS system with production of 2 protons and 2 π-mesons and also with production of 2 protons and 2 D_0-mesons. Before the generation, we have created a set of one-dimentional histogramms for particles distributions of momenta, rapidity, energy, transverse momentum and angle θ, and two-dimentional histogramms for momenta vs angle and momenta vs rapidity distributions. In Fig. 2, an exaple of two-dimensional histogramm is presented.

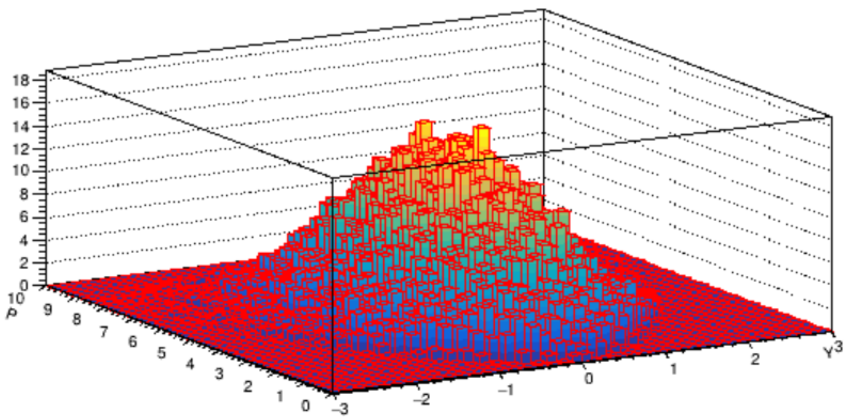

Figure 2: Full momentum - rapidity distribution for π-mesons in Phase Space model for $p + p \to p + p + \pi^+ + \pi^-$ reactions.

2. Modeling using Geant4 Toolkit

Geant4 is a comprehensive toolkit designed for simulation of particle penetration through matter. It provides a user with a wide array of features such as tracking, geometry, physics models and hits. It includes electromagnetic, hadronic, and optical processes, as well as a significant set of long-lived particles, materials and elements in order to covering an extensive range of physics processes. The Geant4 is applied in various fields, such as particle physics, nuclear physics, accelerator design, space engineering, and medical physics. The Geant4 uses advanced Monte Carlo methods for particles interaction with matter. The toolkit provides a wide range of models for simulations of particle interactions at various energies. In this work we simulated proton-nucleus (carbon 12) interactions using FTF (Fritioff) and QGS (Quark Gluon String) models.

2.1. Description of FTF and QGS models

The Fritiof model (FTF) is used in Geant4 for simulation of hadron-nucleus at momenta, $P_{\rm lab} > 3 - 4$ GeV/c, nucleus-nucleus at $P_{\rm lab} > 2 - 3$ GeV/c/nucleon, antibaryon-nucleus at all energies, and antinucleus-nucleus interactions. Upper limit of the FTF validity range is estimated to be 1000 GeV/c per hadron or nucleon.

The model assumes that one or two unstable objects (quark-gluon strings) are produced in elementary interactions. If only one object is created, the process is called diffraction dissociation. It is assumed also that the objects can interact with other nucleons in hadron-nucleus and nucleus-nucleus collisions, and can produce other objects. The number of produced objects in the non-diffractive interactions is proportional to the number of participating nucleons. Thus, multiplicities in the hadron-nucleus and nucleus-nucleus interactions are larger than those in elementary ones.

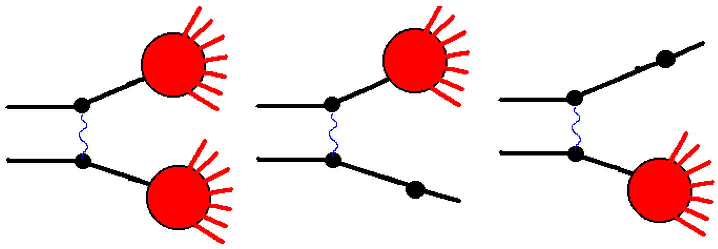

Figure 3: Non-diffractive and diffractive interactions considered in the Fritiof model

The Quark–Gluon String model (QGS) describes quite reasonably and in a theoretically consistent way many features of high energy production processes, including the inclusive spectra of different secondary hadrons, their multiplicities, etc., both in hadron-nucleon and hadron-nucleus collisions. High energy interactions are considered as taking place via the exchange of one or several pomerons, and all elastic and inelastic processes result from cutting through or between those exchanged pomerons. Pomeron is a composite object proposed to explain the behavior of particles in high-energy hadron collisions. Pomeron is a Reggeon with vacuum quantum numbers. The possibility of different numbers of pomerons to be exchanged introduces absorptive corrections to the cross sections which are in agreement with the experimental data on production of hadrons consisting of light quarks.

Both of these models are implemented in Geant4 toolkit as particle generators. There are various parameters, for example, the probabilities of the creation of strange quarks, etc in these generators. The parameters can be choosed or tuned using various experimental data.

2.2. FTF and QGS model's calculations

Recently, NA61/SHINE collaboration published experimental data on production of protons, π^+, π^-, K^+ and K^--mesons in $p+C$ interactions at initial momenta 120 GeV/c [1]. The authors of the paper compared their experimental data with prediction of the older version of Geant4-10.7. The aim of our works was to compare results of simulations in new Geant4 11.1.2 version with the experimental data.

Previous data on $p+C$ interaction at $P_{\rm lab} = 31$ GeV/c have been also considered and compared with experimental data of NA61/SHINE collaboration [2].

2.2.1. Results for 120 GeV/c $p + C$ interactions

The NA61/SHINE collaboration measured particle multiplicities in $p + C$ interaction at $P_{\rm lab} = 120$ GeV/c for various emission angle of particles. In Fig. 4, experimentral data for proton multiplicities are shown as a function of proton momenta. The collaboration compared the data with Geant4 predictions (see lines in Fig. 4). As seen, the FTF model describes the data sufficiently well. Calculations with QGS model are far away from measurements. In Fig. 5, our calculations with Geant4 11.1.1 are shown. As seen, now the QGS in Geant4 11.1.2 works much better than the QGS in Geant4 10.7 – at the lower angles there are no anomalous peaks at 55-60 GeV/c.

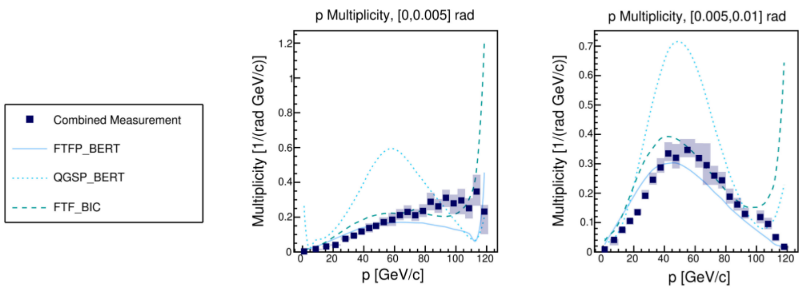

Figure 4: NA61/SHINE combined multiplicity measurements for protons.

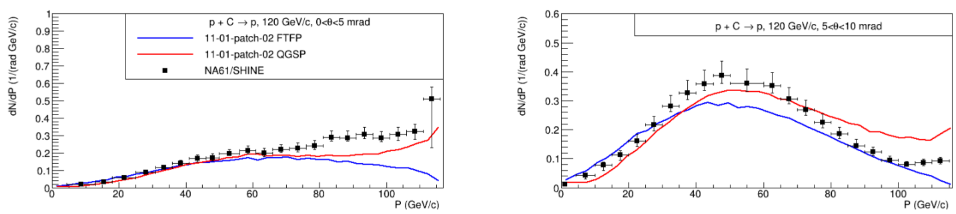

Figure 5: Geant4 11.1.2 FTF and QGS models calculations for protons.

In Fig. 6, the plots from the experimental paper for π^--mesons multiplicities are shown – together with model calculations, performed by the collaborators. In Fig. 7 our corresponding calculations are shown. It can be seen, that QGS model has been improved. It now works well at low θ. The same results we have for π^+-mesons.

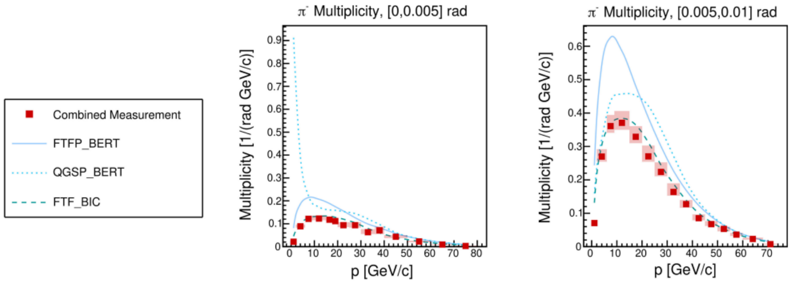

Figure 6: NA61/SHINE combined multiplicity measurements for π^--mesons.

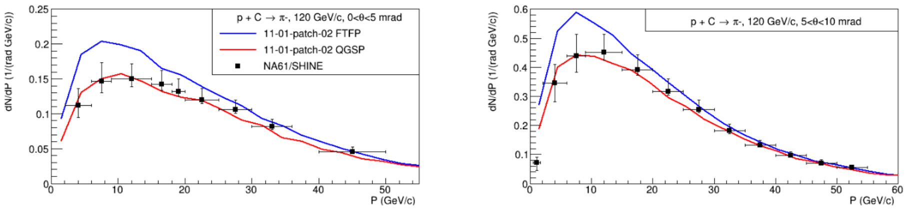

Figure 7: Geant4 1.11.2 FTF and QGS models calculations for π^--mesons.

In Fig. 8, one can see the plots from the experimental paper for K^+-mesons multiplicities, and in Fig. 9 our calculations, correspondingly. As seen, both models have been improved a lot. There are not anomalous peaks at low $P_{\rm lab}$, and both models describe the experimental data well, if we take into account large errors of the experimental measurements. The same results have been obtained for K^--mesons.

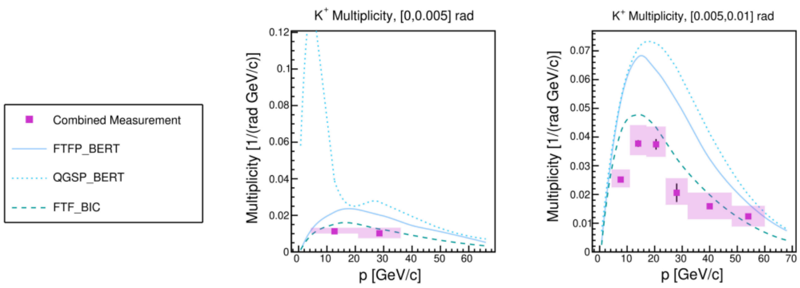

Figure 8: NA61/SHINE combined multiplicity measurements for $K+$-mesons.

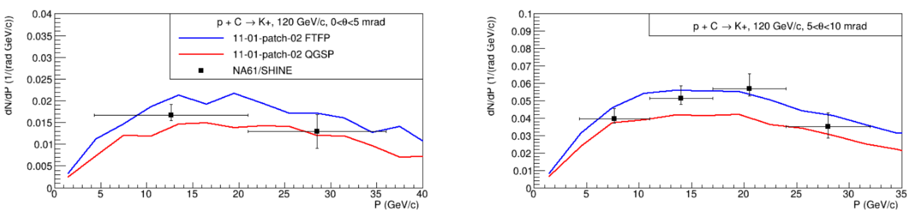

Figure 9: Geant4 11.1.2 FTF and QGS models calculations for K^+-mesons.

2.2.2. Results for 31 GeV/c $p + C$ interactions

Let us consider double differential cross section, $d^2\sigma/(dpd\theta)$, of produced particles in $p + C$ interaction at $P_{\rm lab} = 31$ GeV/c for various angles. In Fig. 10, our calculations for protons are shown with experimental data of NA61/SHINE collaboration. As seen, the QGS model describes experimental data better than the FTF model, especially at lower P.

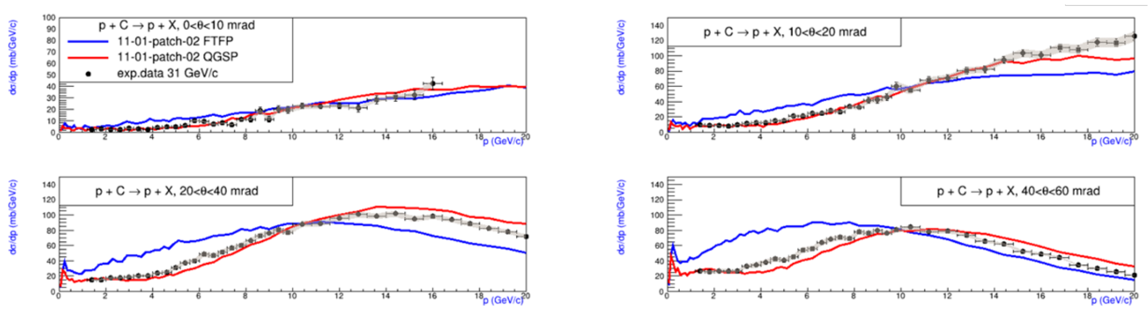

Figure 10: Geant4 11.1.2 models predictions for double differential cross sections of protons.

In Fig. 11, our calculations for momentum distributions of π^--mesons in a comparison with experimental data are shown. QGS model describes experimental data very well. FTF model has some problems at low momentum. The similar results have been obtained for π^+-mesons.

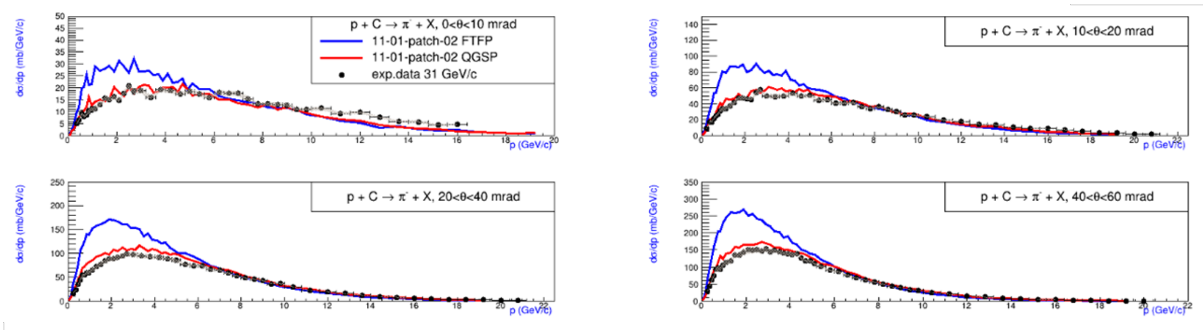

Figure 11: Geant4 11.1.2 models predictions for double differential cross sections of π^--mesons.

In Fig. 12, our calculations for momentum distribution of K^+-mesons and experimental data at various angles – 20, 40, 60 and 100 mrad are shown. As seen, both models predictions are close to each other. At low angles 20 and 40 mrad, models describe experimenta data quite well. At high angles 60 and 100 mrad, models underestimate the yield of K^+-mesons.

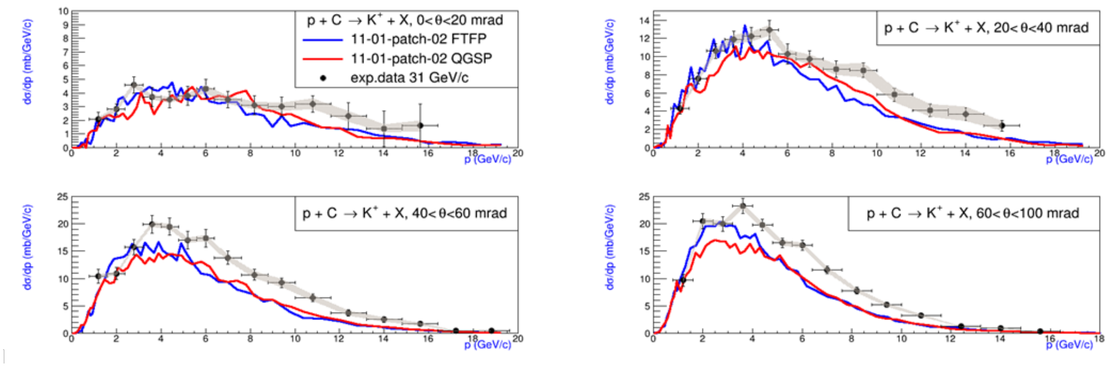

Figure 12: Geant4 11.1.2 models predictions for double differential cross sections of K^+-mesons.

Finally, in Fig. 13 our calculations for K^--mesons and experimental data are shown. The models reproduce the shape of experimental data, but not the absolute value. In general, the FTF model describes experimental data better than the QGS model.

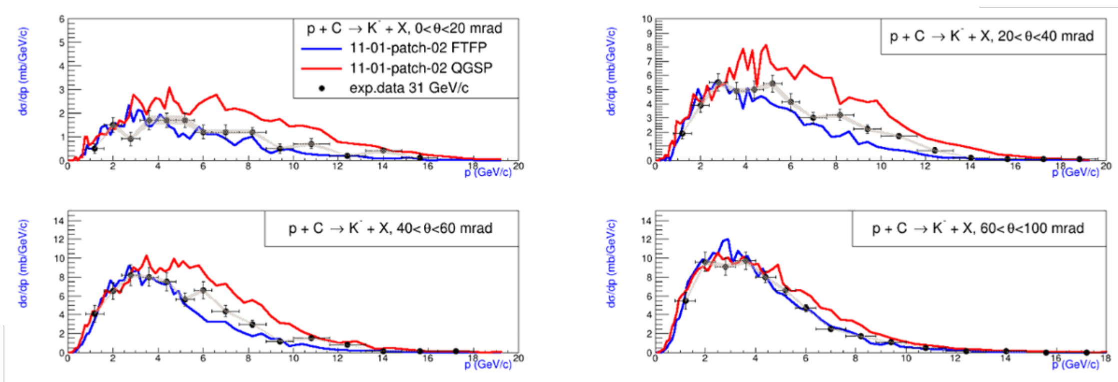

Figure 13: Geant4 11.1.2 models predictions for double differential cross sections of K^--mesons.

CONCLUSION

The basic classes of ROOT package for plotting and sumilation have been studied. Proton-proton interactions were simulated in uniform phase space value for final state of two protons and two π-mesons and also for final state of two protons and two D_0-mesons.

The FTF and the QGS models of Geant4 and their application for simulation of proton-nuleus interactions $p+C$ at 31 and 120 GeV/c have been investigated. We have compared our calculation results with that presented in experimental paper. The collaboration used the old version of Geant4-10.7. We found, that the QGS model has been significantly improved, especially at lower energies, but some additional changes are needed for description of proton production. The calculations show, that the FTF model works quite well at 120 GeV/c, but there is some problem at 31 GeV/c in the newest version of Geant4.

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