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

FINAL REPORT ON THE START PROGRAMME

High p_T physics at Nuclotron facility

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Abstract

The internship report describes the study of the invariant mass spectra of proton-proton collision products at energies in the center of mass system of 4 GeV and 6 GeV. Two types of reactions were studied:

- exclusive reactions $p + p \to p + p + \pi^0 + \pi^0$ and $p + p \to p + p + \pi^+ + \pi^-$, when each particle in the final state has $|\bar{p}_T| > 0.5\ GeV$ and the angle relative to the collision axis in c.m.s. is greater than 45 and less than 135 degrees;
- all other reactions in which 2 or more particles satisfy the above conditions.

For these two types of reactions, distributions for invariant masses of pairs $pp, p\pi\ and\ \pi\pi$ were constructed. With extra conditions for pairs: 1 variant - $160^{\circ} \leq \varphi \leq 200^{\circ}$, $0.8 \leq |\bar{p}_T^1|/|\bar{p}_T^2| \leq 1.2$, where φ - angle between of transverse momenta in pair, p_T^i – transverse momenta of particle number i; 2 variant - $|\bar{p}_T^1 + \bar{p}_T^2| \leq 0.2\ GeV/c$.

Distributions for invariant masses of pairs were constructed. The Monte-Carlo FTF-8 generator natively integrated into Geant4 is used to simulate events. The obtained distributions confirmed the absence of contributions from the hard-scattering subprocesses of quarks and diquarks - q+q, q+qq, qq+qq.

In addition to searching for hard-scattering signals of quarks and diquarks, it was necessary to learn how to work in the Geant4 framework. As an example, the interaction of a proton beam with a hydrogen-liquid target was modeled. Secondary particles were recorded by scintillation counters.

Contents

1. Introduction

Opportunity to get proof of diquark existence was offered in [1]. The idea is to analyze exclusive reaction $p + p \rightarrow p + p + \pi^0 + \pi^0$ and $p + p \rightarrow p + p + \pi^+ + \pi^-$. Find $pp, p\pi$ and $\pi\pi$ pairs which satisfy with conditions (1):

1. High transverse momenta $p_T > 0{,}5\ GeV/c$ of each particle in pair.
2. $\bar{p}_T$ of both particles ought to be opposite in direction and approximately equal.

In reactions with high $\bar{p}_T$ can dominate subprocesses with q+q, q+qq and qq+qq scatterings. The idea is to build spectrum of invariant mass for pairs $pp, p\pi$ and $\pi\pi$ which can be directly connected with subprocesses $qq + qq,\ qq + q$ and $q + q$ accordingly.

2. pp reaction analysis

For simulation was chosen FTF-8 generator due to its native integration in Geant4. In future it will be much easier to make full simulation in Geant4.

2.1 Description of files and algorithms

There were created 2 files of pp collisions. The first file was generated with $\sqrt{S_{NN}} = 6\ GeV$ and 10 million events, the second one with $\sqrt{S_{NN}} = 4\ GeV$ and 100 million events. Also, to select pairs interesting for analysis there were developed two algorithms. The first one used to select pairs by these parameters:

1. $|\bar{p}_T| \geq 0{,}5\ GeV/c$
2. $160^{\circ} \leq \varphi \leq 200^{\circ}$
3. $0.8 \leq |\bar{p}_T^1|/|\bar{p}_T^2| \leq 1.2$,

where φ - angle between vectors of transverse momenta in pair, p_t^i – transverse momenta of particle number i. The second algorithm selected pairs by these parameters:

1. $|\bar{p}_T| \geq 0,5\ GeV/c$
2. $|\bar{p}_T^1 + \bar{p}_T^2| \leq 0.2\ GeV/c$

2.2 Invariant mass spectrum of inclusive reaction analysis

Possible invariant masses for q+q, qq+q and qq+qq which connects with pairs $pp, p\pi\ and\ \pi\pi$ for energy of pp interactions at 4 GeV and 6 GeV are presented in tab. 2.2.1.

Tab.2.2.1

Invariant mass of scattering type / energy of pp collision	$\sqrt{S_{NN}} = 4{,}000\ GeV$	$\sqrt{S_{NN}} = 6{,}000\ GeV$
$\sqrt{S_{q+q}}\ , GeV$	1,333	2,000
$\sqrt{S_{qq+q}}\ , GeV$	1,911	2,843
$\sqrt{S_{qq+qq}}\ , GeV$	2,667	4,000

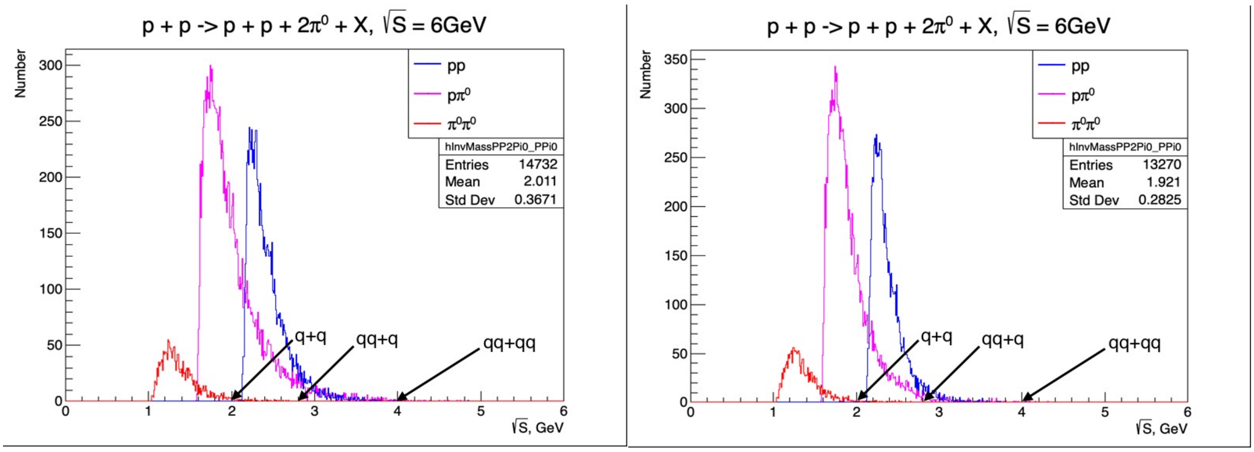

Fig. 2.2.1 Invariant mass of pairs in inclusive selection of events *($\sqrt{S} = 6\ GeV$); Left picture – first algorithm, Right picture – second algorithm.*

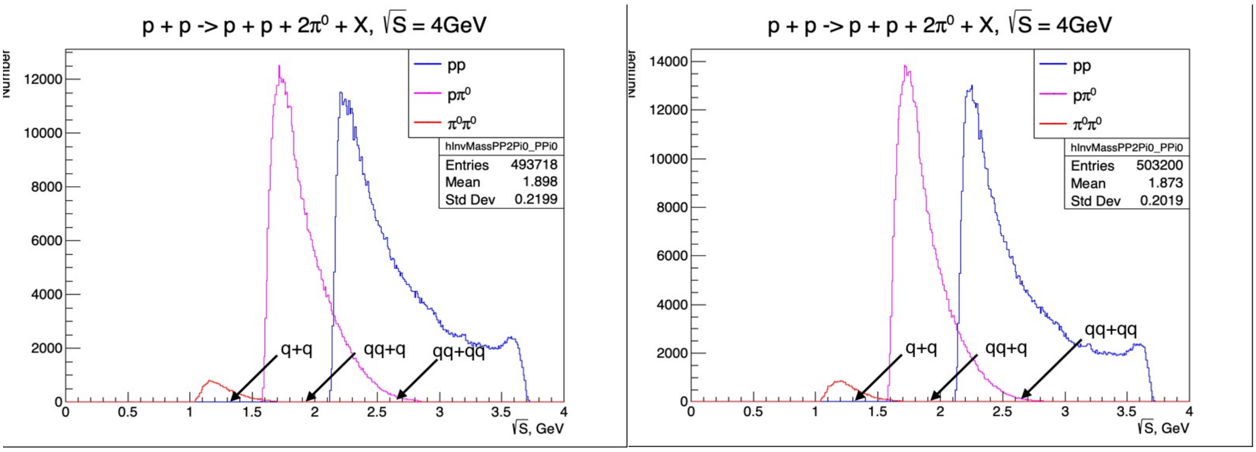

Fig. 2.2.2 Invariant mass of pairs in inclusive selection of events *($\sqrt{S} = 4\ GeV$); Left picture – first algorithm, Right picture – second algorithm.*

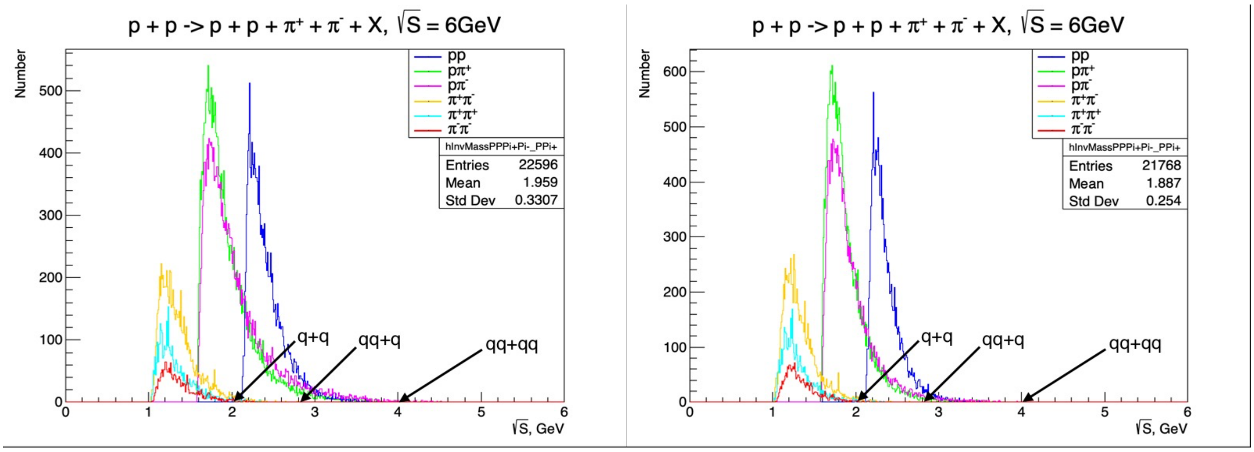

Fig. 2.2.3 Invariant mass of pairs in inclusive selection of events *($\sqrt{S} = 6\ GeV$); Left picture – first algorithm, Right picture – second algorithm.*

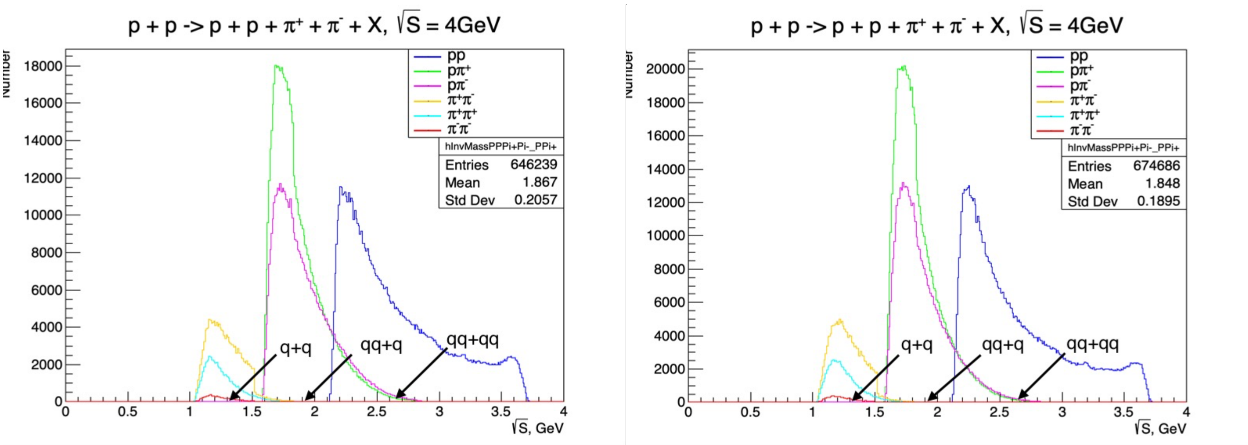

Fig. 2.2.4 Invariant mass of pairs in inclusive selection of events *($\sqrt{S} = 4\ GeV$); Left picture – first algorithm, Right picture – second algorithm.*

From figures 2.2.1, 2.2.2, 2.2.3 and 2.2.4 we can see that invariant masses region for q+q, qq+q and qq+qq are in tails of distributions. That means there are no contribution of quark-diquark subprocesses. But for energy $\sqrt{S_{NN}} = 4\ GeV$ we need more hard cut conditions. From these figures we see, that there are no differences between these 1st and 2nd selection algorithms. Execution time is presented in table 2.2.2. Time difference between algorithms in file with $\sqrt{S_{NN}} = 6\ GeV$ is small, but for $\sqrt{S_{NN}} = 4\ GeV$ bigger.

Table 2.2.2

Type of algorithm	File	Real-time, seconds	CPU-time, seconds
1st	$\sqrt{S_{NN}} = 6\ GeV$	3,28	3,11
2nd	$\sqrt{S_{NN}} = 6\ GeV$	2,13	2,05

1st	$\sqrt{S_{NN}} = 4\ GeV$	320,95	288,15
2nd	$\sqrt{S_{NN}} = 4\ GeV$	282,52	253,96

2.3 Invariant mass spectrum of exclusive reaction analysis

The result of analysis for exclusive reaction of invariant mass spectrum is presented below.

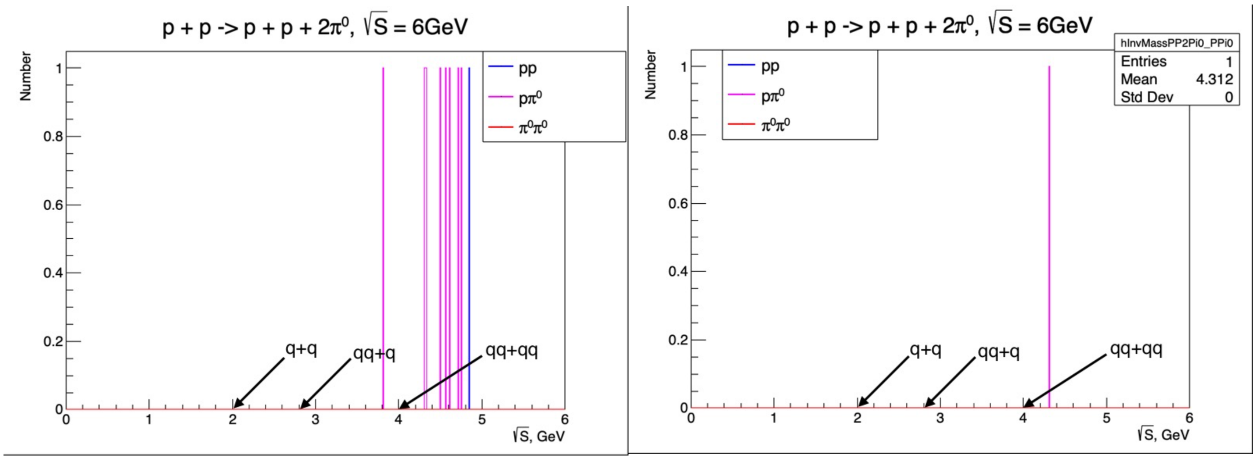

Fig. 2.3.1 Invariant mass of pairs in exclusive p + p -> p + p + $\pi^0 + \pi^0$ *reaction* ($\sqrt{S} = 6\ GeV$)*; Left picture – first algorithm, Right picture – second algorithm.*

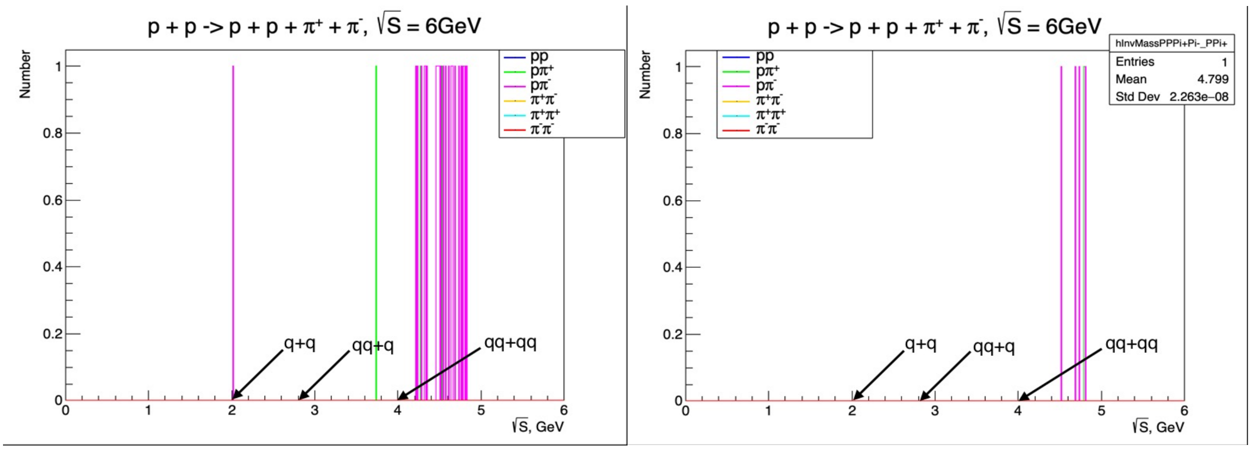

Fig. 2.3.2 Invariant mass of pairs in exclusive p + p -> p + p + $\pi^+ + \pi^-$ *reaction* ($\sqrt{S} = 6\ GeV$)*; Left picture – first algorithm, Right picture – second algorithm.*

Figures 2.3.1 and 2.3.2 show, that for both methods of pair selection there is not enough statistics in $\sqrt{S_{NN}} = 6\ GeV$ file. Such situation is a result of rarity of selected pairs, so 10 million generated events are not enough to provide this analysis.

Another situation with file with $\sqrt{S_{NN}} = 6\ GeV$, where 100 million events created.

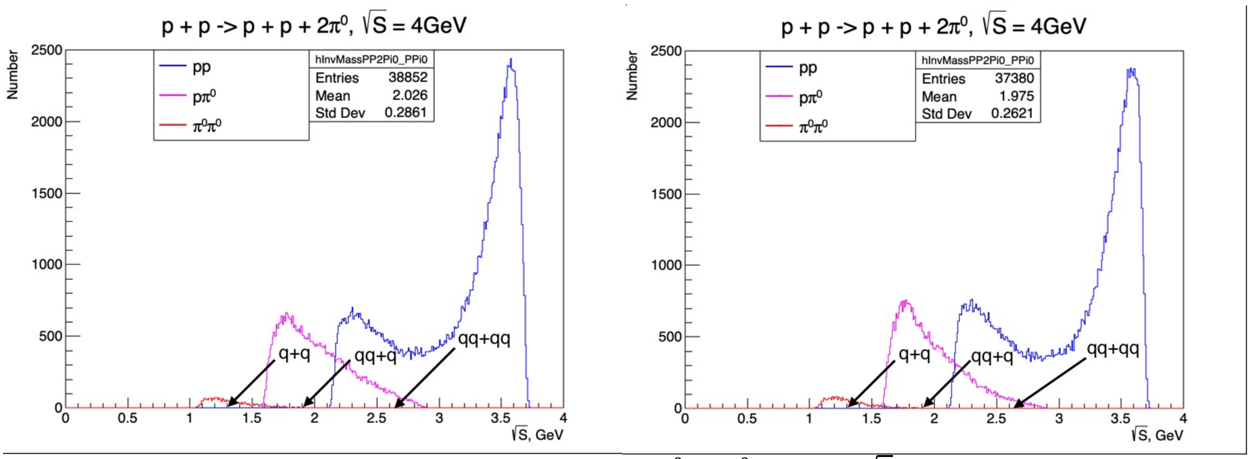

Fig. 2.3.3 Invariant mass of pairs in exclusive p + p -> p + p + $\pi^0 + \pi^0$ *reaction* ($\sqrt{S} = 4\ GeV$)*; Left picture – first algorithm, Right picture – second algorithm.*

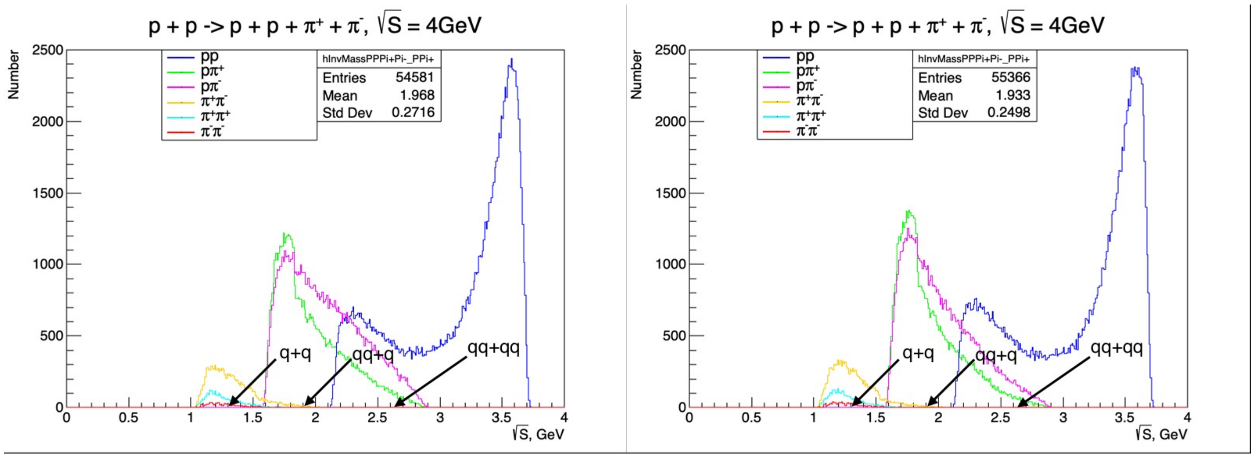

Fig. 2.3.3 Invariant mass of pairs in exclusive p + p -> p + p + $\pi^+ + \pi^-$ *reaction* ($\sqrt{S} = 4\ GeV$)*; Left picture – first algorithm, Right picture – second algorithm.*

Still distributions don't show any peaks at interested energy region. From figures 2.2.1, 2.2.2, 2.2.3 and 2.2.4 we can see that invariant masses region for q+q, qq+q and qq+qq are in tails of distributions. That means there are no contribution of quark-diquark subprocesses. But for energy $\sqrt{S_{NN}} = 4\ GeV$ we need more hard cut conditions. There is no difference in forms of spectrum build by 1st and 2nd algorithms, but distinctions in execution time imperceptible (Table 2.3.1).

Table 2.3.1

Type of algorithm	File	Real-time, seconds	CPU-time, seconds
1st	$\sqrt{S_{NN}} = 4\ GeV$	206,86	238,53

2nd	$\sqrt{S_{NN}} = 4\ GeV$	203,92	235,71

3. Geant4 examples study

3.1 Geant4 project structure

The following files are required for Geant4 to work: main.cc, CMakeLists.txt (every required file in Table 3.1.1). As well as classes: **ActionInitialization** is a class inherited from G4VUserActionInitialization. Its task is to initialize some event or Monte-Carlo particle step in the program. DetectorConstruction is a class inherited from G4VUserDetectorConstruction. He is responsible for creating physical volumes where physical phenomena are simulated. **PhysicsList** is a class inherited from **G4VModularPhysicsList**. Its purpose is to identify particles and physical phenomena that will be taken into account in the simulation. The integral components of the Geant4 project are also Action classes: **runAction**, **eventAction**, **SteppingAction**, **TrackingAction** – for managing the steps of Monte-Carlo simulation and data collection.

RunAction is a class that controls a separate startup. A trigger is a series of events that are modeled with unchanging conditions (for example, detector geometry, physical processes, primary particles). The following methods are provided in the **RunAction** class:

• **BeginOfRunAction** is called at the start of startup. Variables are initialized in the method to accumulate data, and files are opened for writing.

• EndOfRunAction is called at the end of startup. The method analyzes the collected data, outputs the results, closes files, frees up memory, and unloads the processor.

RunAction is necessary for calculating mathematical expectations of physical quantities, variances (other statistical quantities), and organizing multithreaded calculations.

EventAction manages individual events. An event is a single interaction of a primary particle (or several) with a detector, which can generate secondary particles. EventAction provides two methods:

• **BeginOfEventAction** is called at the beginning of the event. Allows you to reset variables related to an event and prepare to collect data for the next event.

• **EndOfEventAction** is called at the end of the event. Performs a preliminary analysis of the event data (for example, calculating the total energy release), making decisions about saving the event.

SteppingAction is a class that controls the steps of Monte-Carlo simulation. In one step M-C, the state of the wave function of the particle changes. **SteppingAction** has one main method:

• **UserSteppingAction** is called at each step of each particle. This allows the user to access detailed information about the motion of the particle and its interactions at each step of M-K.

SteppingAction is necessary to collect information about the trajectory of a particle, its energy, register particles that have entered the SensitiveDetector, and calculate the energy lost by the particle at each step.

Table 3.1.1

File name	Purpose	Directory
CMakeLists.txt	The main configuration file of the CMake build system	/
main.cc	The application entry point contains the main() function	/
MyDetectorConstruction.hh	The header file for the detector geometry construction class	include/

MyDetectorConstruction.cc	Implementation of methods for constructing detector geometry	src/
MyPhysicsList.hh	The header file for the physical process definition class	include/
MyPhysicsList.cc	Implementation of methods for determining physical processes	src/
MyPrimaryGeneratorAction.hh	The header file for the primary particle generation class	include/
MyPrimaryGeneratorAction.cc	Implementation of primary particle generation methods	src/
MyActionInitialization.hh	Header file for initializing actions	include/
MyActionInitialization.cc	Implementation of action initialization methods	src/
MyRunAction.hh	Header file for startup-level actions	include/
MyRunAction.cc	Implementing actions at the startup level	src/
MySensitiveDetector.hh	The header file for the custom sensor/detector class	include/
MySensitiveDetector.cc	Implementation of the methods of the custom sensor class	src/

3.2 Example: gamma radiation detector

Using Geant4 was created model of simple iodide scintillator placed in air volume. On figure 3.2.1 by red color demonstrated lead plate, by yellow sodium iodide sensor and by green line gamma. In the origin of coordinates was generated γ with energy 1 MeV. Application shown 2 two possible situations: when γ was absorbed by detector or when γ felt Compton scattering and flew through whole sensor.

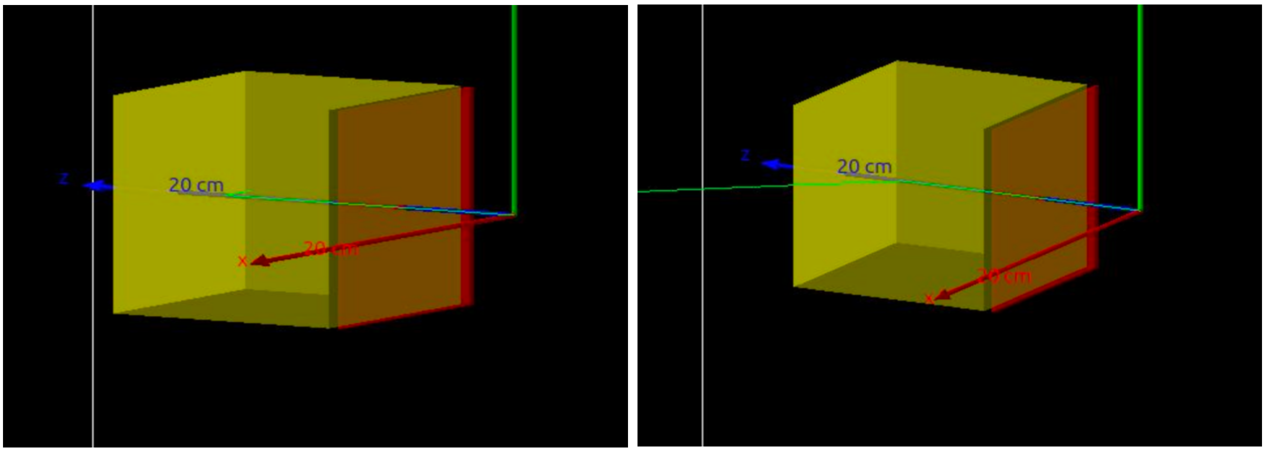

Fig. 3.2.1 Process of interaction gamma with scintillator. Left picture – absorption, right – scattering.

4. Geometry of experiment on fixed target

One more reaction, which could be analyzed for investigation of quark-diquark subprocesses, is exclusive reaction $p + p \rightarrow n + n + \pi^+ + \pi^+$. Experimental setup in Geant4 project includes generator of accelerated protons up to energy 7.598 GeV (energy in system of mass center will be 4 GeV), in origin of coordinates placed fixed target with liquid hydrogen and ideal spherical sensitive detector. Target looks like cylinder with length 30 cm and radius 5 cm. Detector is a sphere with inner radius 40 cm and outer radius 100 cm. This Geat4 project will help get angular distribution of neutrons and understand where neutron calorimeters need to be placed.

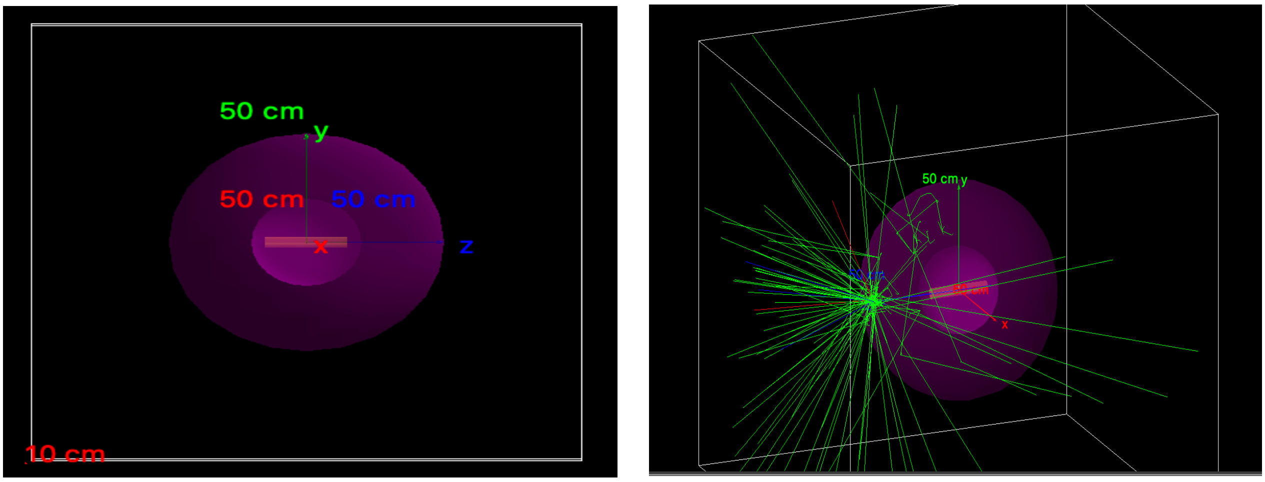

Fig. 4.1.1 Setup of Geant4 project. Yellow – target, violet – detector. Left picture – side view, right – visualization of pp collision run.

Conclusion

The internship report describes the study of the invariant mass spectra of proton-proton collision products at energies in the center of mass system of 4 GeV and 6 GeV. Two types of reactions were studied:

- exclusive reactions $p + p \rightarrow p + p + \pi^0 + \pi^0$ and $p + p \rightarrow p + p + \pi^+ + \pi^-$, when each particle in the final state has $|\bar{p}_T| > 0.5\ GeV$ and the angle relative to the collision axis in c.m.s. is greater than 45 and less than 135 degrees;
- all other reactions in which 2 or more particles satisfy the above conditions.

For these two types of reactions, distributions for invariant masses of pairs $pp, p\pi\ and\ \pi\pi$ were constructed. With extra conditions for pairs: 1 variant - $160^\circ \leq \varphi \leq 200^\circ$, $0.8 \leq |\bar{p}_T^1|/|\bar{p}_T^2| \leq 1.2$, where φ - angle between of transverse momenta in pair, p_T^i – transverse momenta of particle number i; 2 variant - $|\bar{p}_T^1 + \bar{p}_T^2| \leq 0.2\ GeV/c$.

Distributions for invariant masses of pairs were constructed. The Monte-Carlo FTF-8 generator natively integrated into Geant4 is used to simulate events. There are no contributions from the harsh scattering processes of the constituent quarks in this generator. The obtained distributions confirmed the absence of contributions from the hard-scattering subprocesses of quarks and diquarks - q+q, q+qq, qq+qq. Invariant masses region for q+q, qq+q and qq+qq are in tails of distributions. Analysis of inclusive reaction at $\sqrt{S_{NN}} = 6\ GeV$ with 10 million events is unavailable due to poor statistics. For $\sqrt{S_{NN}} = 4\ GeV$ we need more harsh selection conditions in a way to minimize background events. Execution time difference is neglectable at low amount on data. On bigger data volume difference becomes significant.

In addition to searching for hard-scattering signals of quarks and diquarks, it was necessary to learn how to work in the Geant4 framework. As an example, the interaction of a proton beam with a hydrogen-liquid target was modeled. Secondary particles were recorded by scintillation counters.

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