Study of collective flow effect at the NICA beam energy range with HSD model approach

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August 2015

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Abstract

The NICA (Nuclotron-based Ion Collider fAcility) is a project at JINR Dubna aimed to study the properties of hot and dense baryonic matter in the wide energy range. The main goal of this work was to perform the flow analysis of Au+Au events, generated within the HSD model for different energies taken from the NICA beam energy range. The resulting flow coefficients v_1 (directed flow) and v_2 (elliptic flow) were compared with the published results of the STAR Collaboration.

1 Collective flow

The appearance of the transverse, azimuthally asymmetric flow is one of the key observations in the physics of relativistic heavy-ions. The interaction region after averaging over many events has an almond-shaped form. The averaged spatial initial asymmetry of participants in the collision is symmetric with respect to reaction plane. The reaction plane is defined as a plane containing axis of the beam and vector of the impact parameter. Real profiles of the considered collisions are not smooth and the axises of symmetry in an individual event are tilted due to fluctuations. The geometry fluctuations in disposition of the participants lead to fluctuations of plane of symmetry of the participants of the reaction from one event to another giving large spatial eccentricities, which due to a gradient of pressure are transformed into elliptical flow for particles in the final state. Thus, the system is extended along the minor axis mainly [1].

The azimuthal momentum distribution of the produced particles is an important tool for studying of hot and dense nuclear matter created in the heavy ion collisions. The magnitudes of different collective flow effects are typically characterized by the Fourier coefficients,

$$v_n = \langle \cos\left(n[\phi - \Psi_{RP}]\right)\rangle \quad (n = 1, 2, ...), \tag{1}$$

where ϕ represents the azimuthal emission angle of a hadron and Ψ_{RP} is the azimuth of the reaction plane.

Directed flow refers to a collective sideward deflection of particles and is characterized by the first-order harmonic $v_1(y)$ of the Fourier expansion of the particle azimuthal angular distribution with respect to the reaction plane. The second harmonic coefficient v_2 of the expansion is called elliptic flow. The shape of the rapidity dependence $v_1(y)$ is of special interest because the directed flow in mid-rapidity region could be modified by the collective expansion and reveals a signature of a phase transition from normal nuclear matter to a quark-gluon plasma (QGP) [2].

For a given rapidity v_1 at a transverse momentum p_T can be evaluated according to the formula (2):

$$v_1(p_T) = \langle\cos(\phi - \phi_{RP})\rangle = \left\langle \frac{P_x}{P_T} \right\rangle, \tag{2}$$

where $P_T = \sqrt{P_x^2 + P_y^2}$ and $\langle ... \rangle$ denotes average over the azimuthal distribution of particles with the transverse momentum p_T.

Elliptic flow is one of the earliest observations at RHIC. It can be considered as a function of centrality, pseudorapidity η and transverse momentum p_T. It is associated with collision non-centrality (spatial eccentricity of the reaction zone) and re-scattering of partons. Elliptic shape of the overlap region leads to a difference in pressure in different directions, and, therefore, to a non-zero value v_2. Thus, v_2 is sensitive to evolution of the system at very early times. Depending on P_T it can be expressed by the formula (3).

$$v_2(p_T) = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle \tag{3}$$

2 NICA project

In JINR (Dubna) a scientific program applied to study of nuclear matter in hot and dense state is considered to be one of the priorities. It includes construction of accelerator complex called NICA aimed to investigate heavy ion collisions in a wide range of nuclear masses and collision energies $\sqrt{s_{NN}} = 4 \div 11 GeV$. It is important to note that the expected rate of data taking in the collider is $7 \cdot 10^3/s$ with an average of about 1500 multiplicity of charged particles in central gold-gold collisions at the highest energy of the accelerator.

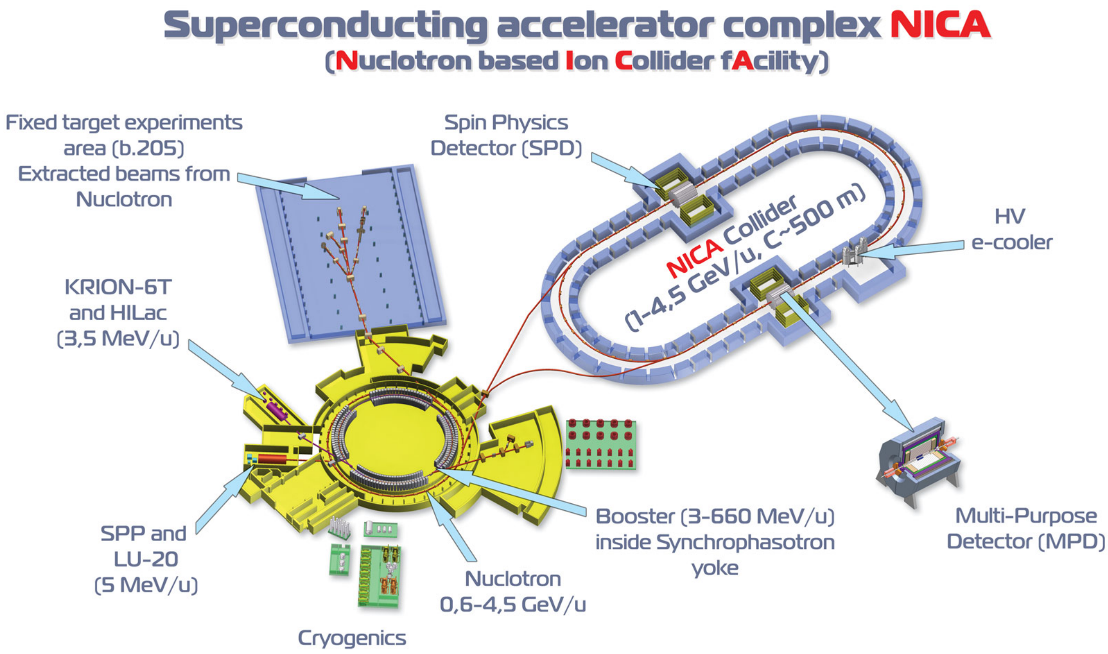


Figure 1. The view of the NICA facility at JINR, Dubna.

One of the facilities considered to be constructed at the NICA complex is a MultiPurpose Detector (MPD) (see Fig.2) aimed to study properties of hot and dense nuclear matter and search for some effects related to deconfinement and / or chiral symmetry restoration.

Applying to the MPD, a framework (MPDRoot) [3] used for different detector simulations was developed. It was done on basis of the widely used in high energy physics FairRoot software platform.

3 HSD model

During the practice I have studied the Hadron String Dynamics transport model HSD, which is used to describe proton-nucleus and nucleus-nucleus collisions of heavy ions. The HSD model includes creation of massive quarks via hadronic string decay – above the critical energy density $\sim 0.5\frac{GeV}{fm^3}$ - and quark fusion forming a hadron in the hadronization process. With some caution, the latter process can be considered as a simulation of a crossover transition because the underlying equation of state (EoS) in PHSD is a crossover. HSD is also a kind of hadron-string model. However, being based on the off-shell generalized transport equations arising from the Kadanov-Bame approach, quasiparticles in HSD model take into account modification of their properties in the nuclear medium, which is very important for the observed particles.

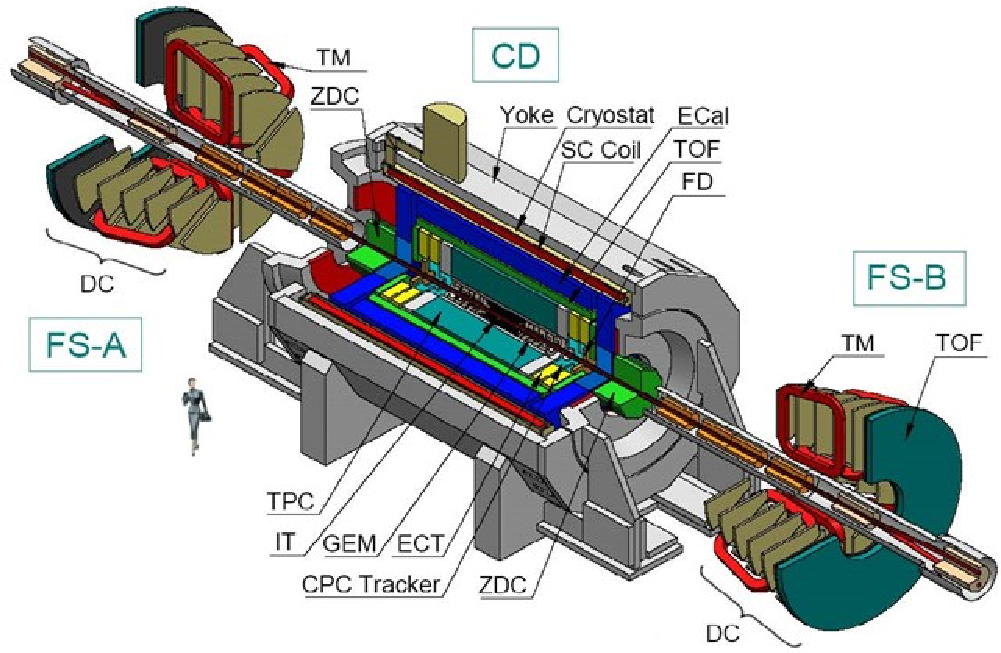


Figure 2. MPD (Multi Purpose Detector)

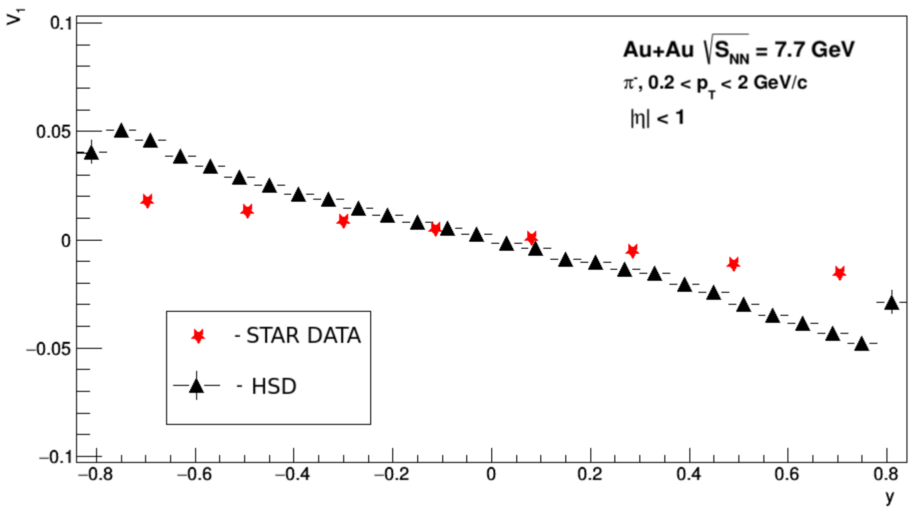
4 Comparison with the STAR results

During the summer school I have learned a formalism of the flow analysis. This allow me to perform a simple physical analysis of events generated using the HSD model for Au+Au collisions at $\sqrt{S_{NN}} = 7.7$ GeV and $\sqrt{S_{NN}} = 11.5$ GeV and compare them with published results from the STAR collaboration. Fig. 3, 4 show the comparison for rapidity dependence of directed flow for charged pions and protons from 10 - 40% central Au+Au collisions. One can conclude that the HSD model can reproduce the general trends of directed flow only, observed by the STAR collaboration [4].

The comparison with elliptic flow data, $v2$, as a function of the transverse momentum, pT, from 0 - 80% central Au+Au collisions is presented in Fig.5. The model also shows not good results for low energy range.

To perform the mentioned analysis I have developed a software that simplifies usage of the HSD model. The output data are written to ROOT tree, but not in a text document (see Appendix 1). It is necessary to speed up file processing and simplifies their further use. Also this root data container can be used in other software, since it is universal. The created root container contains different global characteristics of the simulated event (impact parameter, multiplicity) and characteristics related to tracks in the event (momentum projections, charge of particle, coordinate information, indication whether a given particle is spectator or not and so on).

Also, I have written a patch to the MPDRoot software giving an opportunity to perform different simulations passing data from the created root container (omitting text format) directly (see Appendix 2).



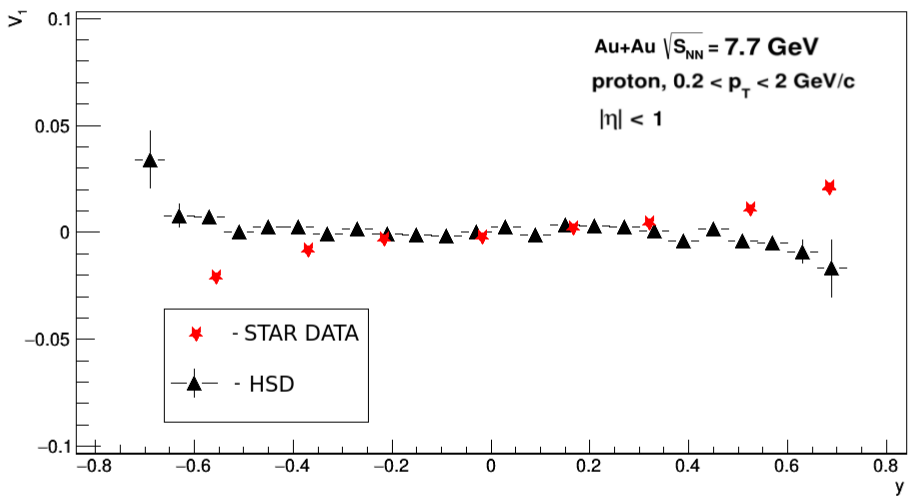


Figure 3. Directed flow $v1$ for protons and π-mesons Au+Au collision at collision energies $\sqrt{S_{NN}} =$ 7.7 GeV derived from the HSD. The experimental data are from the STAR collaboration. The following cuts were applied: $|\eta| \leq 1$, centrality is 10-40%, the experimental acceptance $0.2 \leq P_T$ ≤ 2 GeV/c is taken into account for all hadrons.

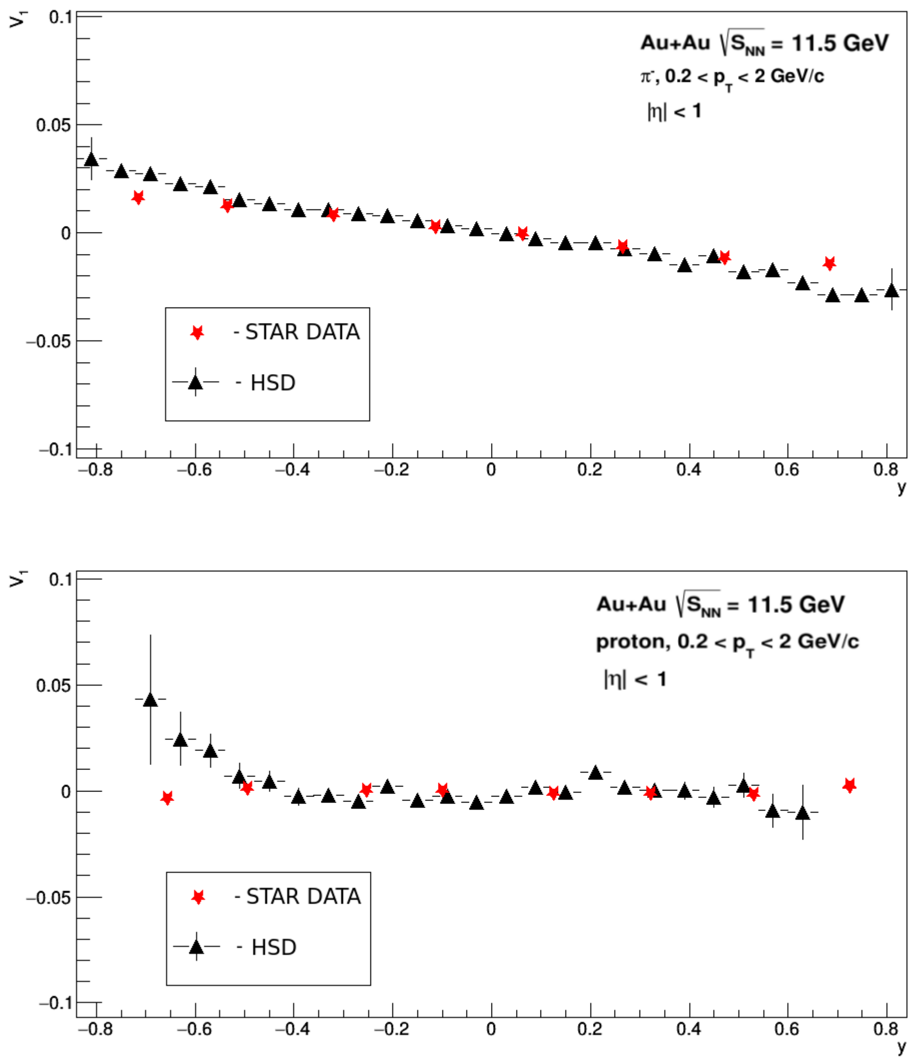


Figure 4. Directed flow $v1$ for protons and π-mesons Au+Au collision at collision energies $\sqrt{S_{NN}} =$ 11 GeV derived from the HSD. The experimental data are from the STAR collaboration. The following cuts were applied: $|\eta| \leq 1$, centrality is 10-40%, the experimental acceptance $0.2 \leq P_T$ ≤ 2 GeV/c is taken into account for all hadrons.

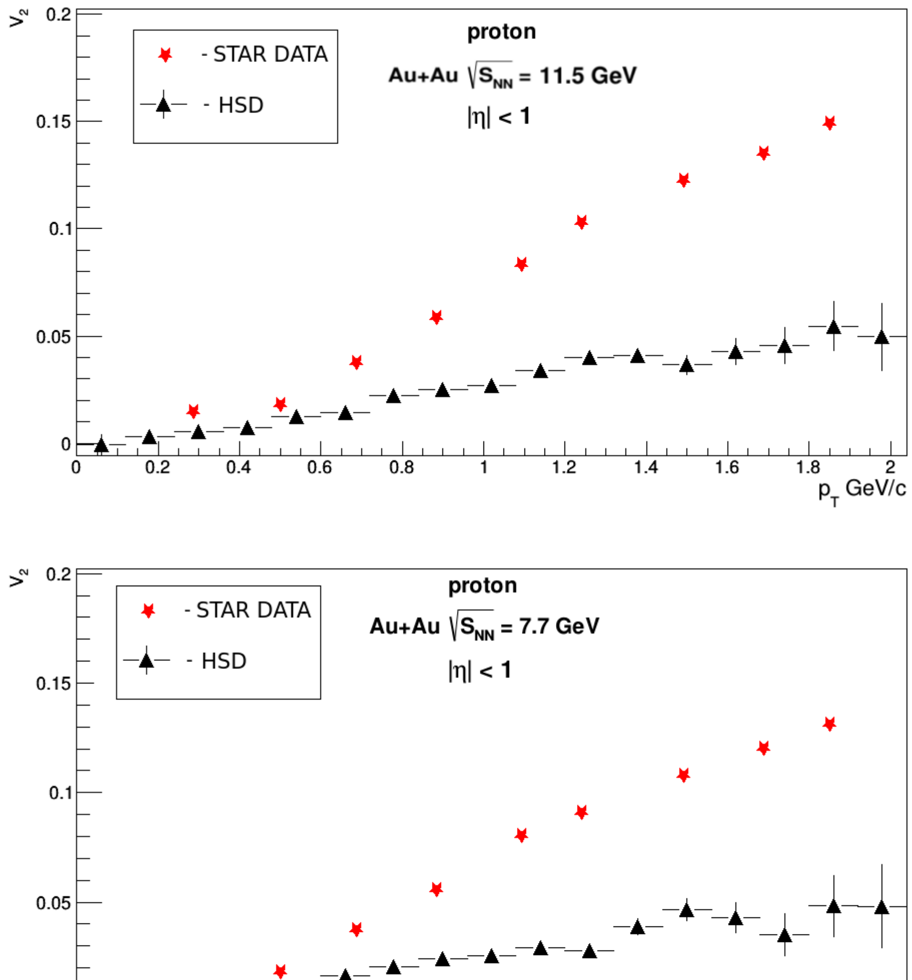


Figure 5. Elliptic flow $v2$ as a function of the transverse momentum P_T for protons from 0-80% central Au+Au collision for energies $\sqrt{S_{NN}} = 11.5GeV$ and $\sqrt{S_{NN}} = 7.7$ GeV.

Appendix 1

```
void fromphsd() {

ifstream file("phsd.dat");
  if (!file) {
    cout<<"file don't open"<<endl;
   return;
  }
  Float_t  b, px1, py1, pz1, E1, x1, y1, z1, tfz1;
  Int_t nt, ch1, j1, ptg1;
  TFile* f = new TFile("modeltree3.root", "recreate");
  TTree* t1 = new TTree("t1", "Simple Tree");
  vector <Int_t> *ptg = NULL;
  vector <Int_t> *ch = NULL;
  vector <Float_t> *px = NULL;
  vector <Float_t> *py = NULL;
  vector <Float_t> *pz = NULL;
  vector <Float_t> *E = NULL;
  vector <Int_t> *j = NULL;
  t1->Branch("nt", &nt);
  t1->Branch("b", &b);
  t1->Branch("ptg", &ptg);
  t1->Branch("ch", &ch);
  t1->Branch("px", &px);
  t1->Branch("py", &py);
  t1->Branch("pz", &pz);
  t1->Branch("E", &E);
  t1->Branch("j", &j);
  Float_t buf;
  while (!file.eof()) {
    ptg->clear();
    ch->clear();
    px->clear();
    py->clear();
    pz->clear();
    E->clear();
    j->clear();
    file >> nt >> buf >> buf >> b >> buf;
    for(Int_t knt = 0; knt < nt; knt++) {
      file >> ptg1 >> ch1 >> px1 >> py1 >> pz1 >> E1 >> j1;
      ptg->push_back(ptg1);
      ch->push_back(ch1);
      px->push_back(px1);
      py->push_back(py1);
      pz->push_back(pz1);
      E->push_back(E1);
      j->push_back(j1);
      }
```

```
     t1->Fill();
    nEv++;
  }
  t1->Write();
  f->Close();
  file.close();
}
```

Appendix 2

```
void MpdPHSDGenerator::ReadRootEvent(FairPrimaryGenerator* primGen) {
    fDstTree->GetEntry(fEventNumber);
    if (fisRP) {fPsiRP=frandom->Uniform(2.0*TMath::Pi()); }
    FairMCEventHeader *eventHeader = primGen->GetEvent();
    if (eventHeader && (!eventHeader->IsSet()))
      {
         eventHeader->SetB(fb);
         eventHeader->MarkSet(kTRUE);
         MpdMCEventHeader *extraEventHeader = dynamic_cast<MpdMCEventHeader*> (eventHeader)
         if (extraEventHeader)
           {
              extraEventHeader->SetPhi(fPsiRP);
           }
       }
     /* read tracks */
     for(Int_t i = 0; i < fntr; i++)
       {
         Int_t ipdg; Float_t px,py,pz;
         /* read track */
         px = Px->at(i);
         py = Py->at(i);
         pz = Pz->at(i);
         ipdg = pdg->at(i);

         if (ipdg==0) {printf("-W- MpdPHSDGenerator: particle with pdg=0\n"); continue; }

         // this decays will be improved in the next versions of PHSD
         if (ipdg==+413)  ipdg=+421;  // D*+     -> D0
         if (ipdg==-413)  ipdg=-421;  // D*-     -> D0_bar
         if (ipdg==+423)  ipdg=+421;  // D*0     -> D0
         if (ipdg==-423)  ipdg=-421;  // D*0_bar -> D0_bar
         if (ipdg==+4214) ipdg=+4122; // Sigma*_c+  -> Lambda_c+
         if (ipdg==-4214) ipdg=-4122; // Sigma*_c-  -> Lambda_c-
         if (ipdg==+4114) ipdg=+4122; // Sigma*_c0  -> Lambda_c+
         if (ipdg==-4114) ipdg=-4122; // Sigma*_c0  -> Lambda_c-
         if (ipdg==+4224) ipdg=+4122; // Sigma*_c++ -> Lambda_c+
         if (ipdg==-4224) ipdg=-4122; // Sigma*_c-- -> Lambda_c-
         if (fPsiRP!=0.)
            {
             Double_t cosPsi = TMath::Cos(fPsiRP);
```

```
             Double_t sinPsi = TMath::Sin(fPsiRP);
              Double_t px1=px*cosPsi-py*sinPsi;
              Double_t py1=px*sinPsi+py*cosPsi;
              px=px1; py=py1;
            }

         primGen->AddTrack(ipdg, px, py, pz, 0., 0., 0.);
         fEventNumber++;
       }
}
```

References

[1] Jean-Yves Ollitrault, C.E. Saclay, Flow systematics from SIS to SPS energies, arXiv:nucl-ex/9802005v1.

[2] V. P. Konchakovski, W. Cassing, Yu. B. Ivanov, Toneev V. D., Directed flow in relativistic heavy-ion collisions within the PHSD transport approach and 3FD hydrodynamical model, Journal of Physics: Conference Series, 612(2015), 012055.

[3] Official site of the project: `http://mpd.jinr.ru`

[4] V. P. Konchakovski, W. Cassing, Yu. B. Ivanov, V. D. Toneev, Examination of the directed flow puzzle in heavy-ion collisions, arXiv:1404.2765.