# Simulation and event reconstruction inside the PandaRoot framework

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**Abstract.** The PANDA detector will be located at the future GSI accelerator FAIR. Its primary objective is the investigation of strong interaction with anti-proton beams, in the range up to 15 GeV/c as momentum of the incoming anti-proton. The PANDA offline simulation framework is called "*PandaRoot*", as it is based upon the ROOT 5.14 package. It is characterized by a high versatility; it allows to perform simulation and analysis, to run different event generators (EvtGen, Pluto, UrQmd), different transport models (Geant3, Geant4, Fluka) with the same code, thus to compare the results simply by changing few macro lines without recompiling at all.
Moreover auto-configuration scripts allow installing the full framework easily in different Linux distributions and with different compilers (the framework was installed and tested in more than 10 Linux platforms) without further manipulation. The final data are in a tree format, easily accessible and readable through simple clicks on the root browsers.
The presentation will report on the actual status of the computing development inside the PandaRoot framework, in terms of detector implementation and event reconstruction.

## 1. Introduction

The Panda collaboration aims to conduct a sistematic study of the strong interaction in the charm sector, by means of anti-proton collisions with protons or nuclei, in the range up to 15 GeV/c as $\bar{p}$ momentum.
A large-scale detector, PANDA, is under development since some years and it will be installed at the future research facility FAIR. The planned setup consists on several sub-detectors which are composed by a very large amount of detecror modules of different kinds (tracking systems, calorimeters, pid detectors), thus the computing framework needs to have a very extensive code that can handle event generation, simulation and reconstruction, as well as physics analysis, in an easy and flexible way even to fulfill to the various physics goals of the experiment.
In 2006 the PANDA collaboration evaluated various computing frameworks used by several experiments, and decided to develop its computing framework as an extension of the FairRoot framework developed at GSI. The "*PandaRoot*" framework is based on ROOT [1] and Virtual Monte-Carlo [2], and its characteristics and the state-of-art of the implementation up to now will be discussed in this work.
After a general description of the PANDA experiment, the main concept of the framework will be explained in the following paragraphs, in terms of event generation, of detector implementation as well as reconstruction, with an example of full reconstruction of a neutral benchmark channel. Moreover it will be shown one of the possible studies that can be performed inside the framework

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within the Virtual Monte-Carlo, in order to compare the simulated response of the detectors by using Geant3 or Geant4 as transport model.

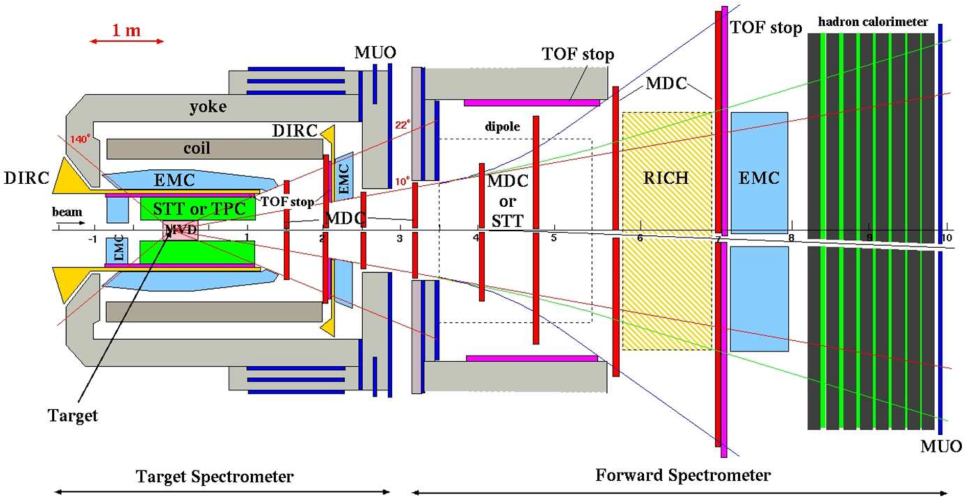


**Figure 1.** The PANDA spectrometer.

## 2. The PANDA experiment

PANDA (AntiProton Annihilations at Darmstadt) [3] is a fixed target multi-purpose detector that will be placed at the High-Energy Storage Ring (HESR) of the international FAIR facility (Darmstadt), that will be a sort of upgrade of the existing GSI laboratory. The detector is designed to take advantage of the extraordinary physics potential which will be available by using high intensity, phase space cooled antiproton beams.

The main goal of the experiment is to perform a very high resolution spectroscopy of charmonium state (open and hidden charm), resolution which cannot be achieved with the existing $e^+e^-$ machines and which can be reached only by means of $\bar{p}p$ annihilation processes; in this case even important considerations on the meson widths could be obtained. It will be also possible to study gluonic excitations and exotic states, such as glueballs, hybrids or molecular states, that are debated and searched since several years with indications but without clear evidence. Moreover with $\bar{p}A$ collisions the production of charm states inside the nuclear matter will be investigated, thus the behaviour of their properties when produced in-medium. The physics program foresees also many other topic, such as the production and studies of single and double hypernuclei, the study of the time-like form factor of the proton, unpolarised Drell-Yan processes, generalized parton distributions and CP-violating processes.

In order to cover this broad variety of physics processes, the PANDA detector has several challenges to face. Triggering on decaying charm particles requires precise micro-vertex tracking close to the target. An advanced particle identification system is mandatory, by means of charged particle tracking together with high-resolution electromagnetic calorimeters, Cherenkov detectors, time-of-flight walls and muon chambers. Moreover an almost full coverage of the solid angle is required; considering that PANDA is a fixed target experiment, this is fulfill by means of a detector region surrounding the target (target spectrometer - TS), with a solenoidal magnetic field, and a forward spectrometer (FS) with a dipole magnet. Fig. 1 shows a sketch of the spectrometer.

The complex detector arrangement has to assure the measurement of complete sets of parameters and signatures, with a robust and redundant physics reconstruction which is considered important in a high-luminosity environment.

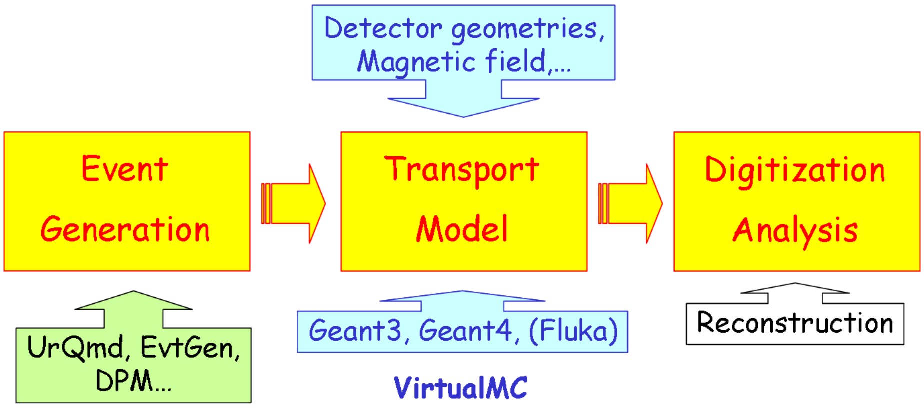


**Figure 2.** Scheme of the PandaRoot framework.

## 3. The PandaRoot framework

In preparation for this experiment, large-scale simulations need to be performed in the upcoming year for the design of the PANDA detector, to determine analysis strategies and for the interpretation of the physics results. In September 2006 the PANDA coordination board decided to pursuit the development of PANDA code inside the so called *"FairRoot"* framework, a GSI project to provide a common computing structure for all the experiments at the FAIR facility, such as PANDA, CBM [4] and the HADES upgrade [5].
*"PandaRoot"* is a framework for both simulation and analysis, and it is mainly based on the object oriented data analysis framework ROOT [1]. It features the concept of Virtual MonteCarlo [2], which allows to run different transport models such as Geant3, Geant4 and Fluka, with exactly the same code thus to compare results. At the moment PandaRoot is based on ROOT 5.14, VMC 2.0 and Geant4 8.2, but in a short time it is planned to upgrade to ROOT 5.16 and Geant4 9.0.
One of the ambitions of PandaRoot is that the code has to be easily installed and used by most of the collaboration: the user should be able to install the framework in his personal computer or laptop, without any restrictions on Linux distribution or C++ compiler, and to run analysis by himself. For this reason, through auto-configuration scripts the user can install the external packages (as ROOT and GEANT) and the PandaRoot code without caring about configurations, in an automatic way without additional manipulations. Moreover the framework is maintened under different compiler versions, and continuously checked. This is not so straightforward, in particular because of the differencies between the gcc compilers 3.X and 4.X; for this reason each day builds and test macros are executed in different machines placed at different institutes with different compilers, and all the results are sent to a centralized server that stores all these informations. In this way it is possible to find errors and warnings even connected to different compiler versions, thus to correct them in a short time. We plan to define even debug histograms per each detector and for the common code, in order to be sure that even the physics output is consistent between different machines.
The PandaRoot computation is divided into three main parts, as shown in Fig. 2, where the user can switch between different options without changes in the code and without recompiling,

just simply switching flags inside macros.
First the physics event generation occurs. The generators are provided as external packages because they are developed outside the collaboration: the user launches the physics simulation using the original event generator code. The event output file, in his original format, is used as input for the PandaRoot simulation; here several interpreters were developed, which translate the event output into a standard that can be read by the transport model part: the user has only to select the required interpreter and the name of the input file.
Then the generated particles are propagated inside the detectors, and their interactions with the spectrometer are computed by the transport model. At this stage the detector geometries and materials are defined, as well as a realistic magnetic field map. The user has the possibility, via the Virtual MonteCarlo, to switch between different transport models, such as Geant3 or Geant4, without changing a single line of code and without recompiling, just setting a flag in the simulation macro. In this way it is also possible to compare the results coming from the different models, to tune the cuts and to validate the physics implemented with a cross-check even with experimental data (in the next future it is foreseen even the usage of the Fluka [6] code).
Finally the simulation file is put as input for digitization and reconstruction, via tasks. The DST (Data Summary Tape) produced in this way can be used to finally perform the physics analysis; all the data in the output files are stored in a tree format, that can be easily browsed in ROOT with few clicks.

## 4. Event generators

In order to perform full simulations, the first step consists on generating the physics events of interest. In PandaRoot several event generators are implemented, in order to fulfill to the many physics goals of the experiment. The following is a list of what is present at the moment inside the code:

- Box generators: in order to perform study on efficiency and acceptance, or even to check the response of the code, particles can be generated with uniform distributions in a given range, such as momentum, angular variables, rapidity and so on. The box generator can be launched directly inside the simulation macro.
- EvtGen [7]: EvtGen is an event generator used by many collaborations, such as Belle, BaBar, CDF and other experiments. It allows to handle complex sequencial decay channels, such as several charmonium states decays, with different models or even setting angular distributions according to experimental results. The user can set the decay chain by himself and produce the event files that, through a suited interpreter, can be used as input for the simulation.
- Dual Parton Model [8]: The DPM generator allows to simulate string fragmentation and the decay of all the unstable hadrons by using the Dual Parton Model. In this way it is possible to generate background events to the main channels, evaluate detector occupancies and particle rates. The DPM generator is developed and maintened inside the PANDA collaboration, and the output is in a tree format that can be easily browsed and loaded into the simulation. Moreover it is also possible to switch the elastic and inelastic processes separately.
- UrQMD [9] [10]: The Ultra-relativistic Quantum Molecular Dynamic model is a microscopic model that can describe the phenomenology of hadronic interactions in nuclear collisions. The UrQMD generator is used to study $\bar{p}$A collisions; the output files are read by a suited interpreter and put into the simulation inside PandaRoot.

Moreover an interface to the Pluto [11] generator is also present. There are ongoing activities to enlarge the number of generators that can be handled by the framework, such as a Drell-Yan generator according to the model [12] [13], or models for Hypernuclei.

## 5. Detector Implementation

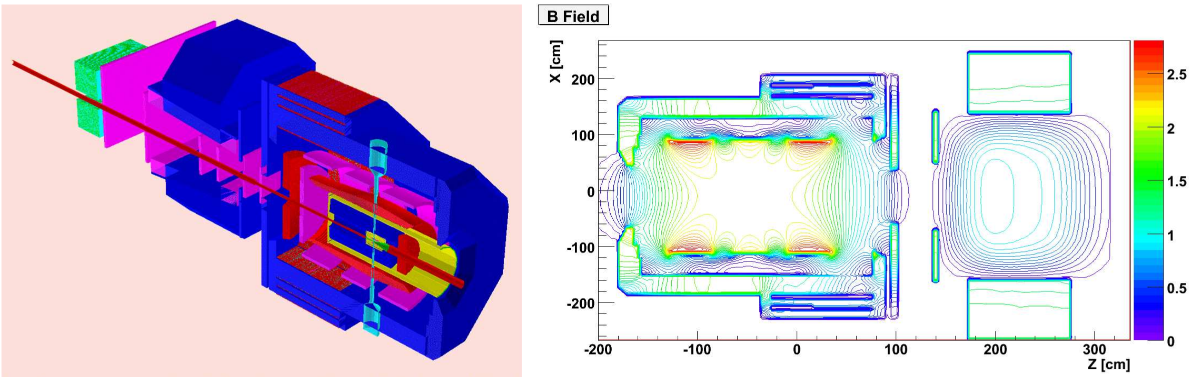


**Figure 3.** Detector implementation inside the PandaRoot framework. The left plot shows the PANDA detector coming from the ROOT geometry manager. On the right the implemented magnetic field map is shown, taken from TOSCA calculations.

After one year of development, the PANDA spectrometer geometry is almost fully implemented inside PandaRoot. The current state-of-art of each sub-module can be seen in Fig. 3 (left plot):

- Pipe: The beam-pipe as well as the target-pipe (for proton experiments a pellet or a cluster-jet target will be used) are implemented. The actual beam-pipe design corresponds to the *chicane* option.
- Magnet: The yoke of the solenoid and of the dipole magnets are implemented, as well as the coils. The implemented geometry of the solenoid yoke corresponds to the design with two lodgings for the muon detector planes (ver 0.1.7).
- MVD: The silicon Micro-Vertex detector is fully implemented; it consists on strips and pixels. In order to convert the CAD drawings to the PandaRoot geometry standard a converter was developed.
- Central tracker: There are two options at the moment for a gaseous drift chamber tracking detector: a Time Projection Chamber (TPC) or a Straw Tube (STT) detector (up to 10000 straw tubes are foreseen). Both the geometries are implemented, in particular several options for the STT, with parallel or skewed tubes, and with different geometry parameters.
- TOF: The time-of-flight of the TS is implemented, but still under development and optimization.
- DIRC: The Particle Identification system using the Detection of Internally Reflected Cherenkov (DIRC) light is implemented.
- EMC: Photon spectroscopy in the TS is performed by an electromagnetic calorimeter, which consists on a set of PWO crystals ($\sim$ 20000 crystals). The geometry is composed by a barrel surrounding the target, a forward and a backward end-cup.
- Muon: A muon detector is implemented, consisting of different planes placed before and inside the magnet iron yoke, in order to use the iron as absorber.
- DCH: The tracking at forward angles is performed by a set of drift chambers. Two of them are placed inside the TS, for the region between $10° < \theta < 20°$, while in the FS ($\theta < 10°$) a

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set of six planes is implemented, two before, two inside, two after the region of the dipole magnetic field.

- FSC: In the forward region a Shashlyk-type calorimeter is implemented, consisting on 378 layers of absorber and scintillators sandwiched together subsequently.

A realistic magnetic field is implemented (Fig. 3 right plot), with the values taken from TOSCA calculations. It consists on a solenoidal field in the TS and a dipole field in the FS. The region in between presents inhomogeneities that make tracking a real challenge there.

## 6. Reconstruction

### *6.1. Tracking*

A realistic tracking reconstruction is developed for both the two central tracker options (TPC and STT). Several pattern recognition algorithms are at the moment under study, to find the best solution for PANDA purposes. For the TPC a Conformal Mapping method is used [14]: the helix trajectories of the particles inside the field are transformated into straight lines via a conformal map. In this way the pattern recognition is much easier, and from the parameters of the lines it is possible to evaluate the helix ones.

For the STT detector the pattern recognition is based on a Hough Transformation algorithm [15]. In this way the signals in the hit straws belonging to the same recognized particle are fitted and the momentum can be calculated, as well as the other track parameters (see left plot of Fig. 5).

For the forward region a set of six drift chamber planes, two placed before, two inside and two after the dipole, is foreseen. At the moment realistic pattern recognition is performed via a Principal Component Analysis (which is already implemented inside ROOT). A fast momentum reconstruction is performed by using four planes of chambers, the one before and after the magnetic field: it is possible to parametrize the momentum in function of the trajectory deviation angle. With this algorithm the momentum resolution is $\sim 2\%$, and this value can be used as prefit for a Runge-Kutta method using all the six chambers or for a Kalman filter (see right plot of Fig. 5). The method does not require fit at all, it is very fast and it could be also implemented inside boards for an online event selection.

The next step is to construct a *global track*, thus to join all the informations from all the tracking detectors such as even MVD and the barrel drift chambers, in order to perform a real high resolution tracking. This is not straightforward, because of the field inhomogeneity between the solenoid and the forward spectrometer, where a simple extrapolation is not possible. For this reason a Kalman Filter [16] was implemented (the $''GENFIT''$ package) and it is running for TPC detector. As track follower, the GEANE [17] package is used. It allows to propagate the tracks from one detector plane into another, taking into account materials, and also to propagate the error matrices. It is currently implemented and used for STT tracking, but will eventually be used for all tracking detectors. One of the most important feature is that it is possible in this way to use the same geometry definition for both simulation and track following, without any need of detector models.

Actually the two packages (GENFIT and GEANE) are under strong development, and in a short time they will be merged in order to provide the high resolution global tracking that we plan to achieve.

### *6.2. Calorimetry*

The electromagnetic calorimetry is performed by two different kinds of detector. In the target spectrometer the calorimeter (EMC) consists on three sub-modules, the barrel around the target and two end-cups, composed by PWO crystals. In the forward spectrometer the calorimeter (FSC) has a Shashlyk design, so several layers of absorber (lead) and scintillators. The full digitization is implemented as well as the cluster reconstruction, which uses a common code

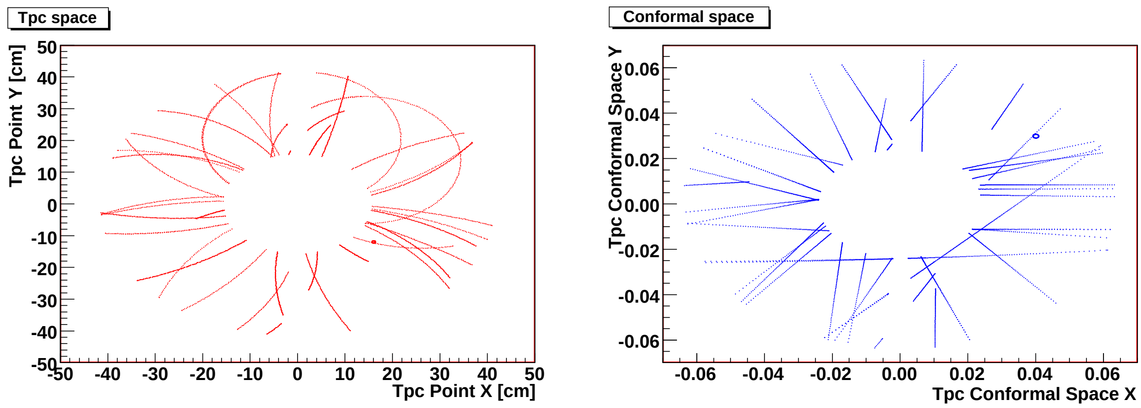



**Figure 4.** Example of recontruction in TPC. Charged particles travel inside the TPC following helix trajectories (the left plot shows their projection on the XY plane) due to the solenoidal field, that are transformed into straight lines by the conformal mapping (right plot). In this way the pattern recognition is simpler and the track parameters can be so calculated from the line ones.

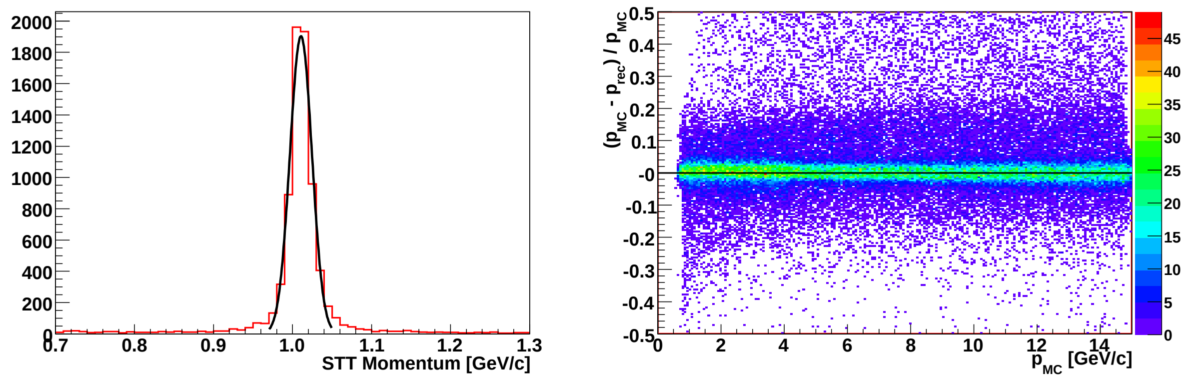



**Figure 5.** Reconstruction in STT and in the forward spectrometer. On the left plot recontructed momentum distribution in STT for muons at 1 GeV/c ($\sigma \sim 1.4\%$). On the right plot relative momentum resolution for tracking in the forward drift chambers ($\sigma \sim 2\%$ using the fast kick angle parametrization.)

for the two detectors; the EMC response is well tested while the FSC was implemented only recently and the energy response is still under testing.
In order to demonstrate the capability of the EMC code, in Fig. 6 it is shown the full reconstruction of the benchmark channel $\bar{p}p \rightarrow h_c \rightarrow \eta_c\gamma$, $\eta_c \rightarrow \pi^\circ\pi^\circ\gamma$, $\pi^\circ \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, with $\bar{p}$ @ 5.609 GeV/c ($M(h_c) = 3.526 GeV/c^2$). This channel is a challenge for neutral reconstruction, considering it has seven photons in the final state, but the plots demonstrate that the full reconstruction is possible.

### *6.3. PID*
The next step in the reconstruction will be to provide the information on particle identification. The implementation of PID detectors is still ongoing, soon it will be possible to merge their informations with the tracking, thus to construct an efficient way for particle selection on

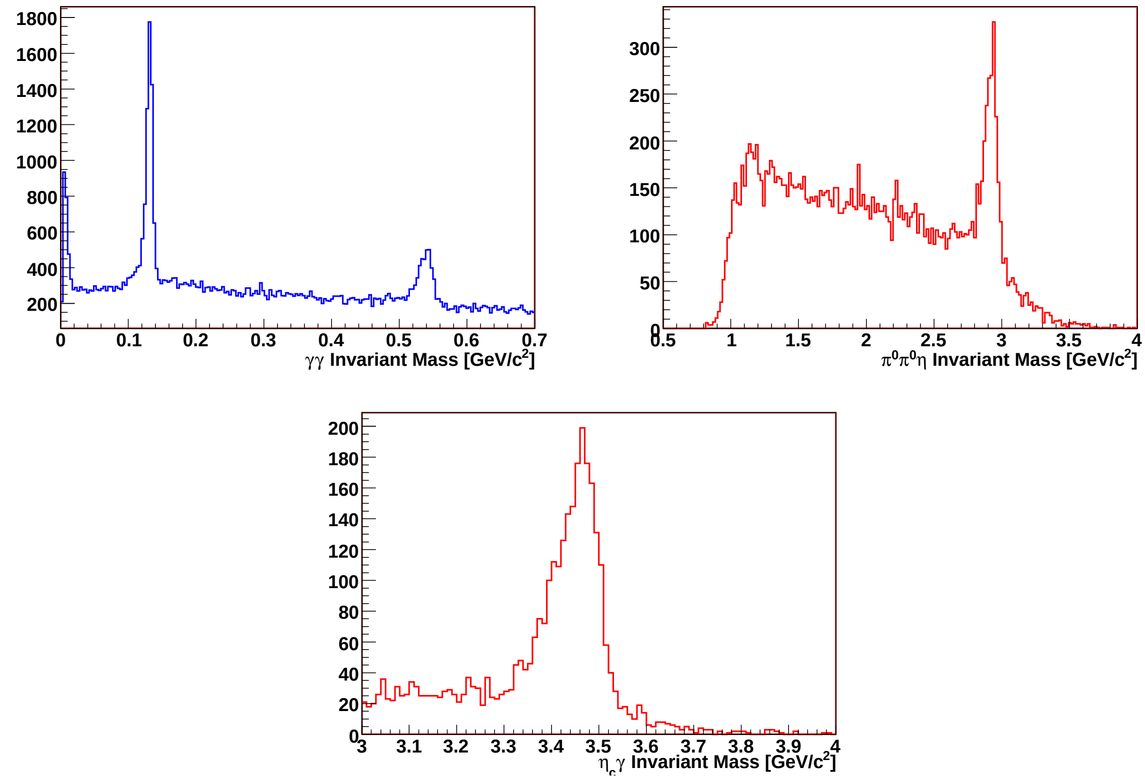



**Figure 6.** Example of recontruction a neutral $h_c$ decay into seven photons in the EMC (see text). The upper left plot shows the $2\gamma$ invariant mass distribution; two peaks are present, belonging to the $\pi^\circ$ and to the $\eta$ mesons. The upper right plot shows the invariant mass of $\pi^\circ\pi^\circ\eta$ combinations, and the $\eta_c$ is well evident. By combining the recontructed $\eta_c$ with the last $\gamma$, the lower plot demonstrates that the $h_c$ meson decaying into seven photons can be recontructed in this way.

probability density functions.
In each case a PID information is already available for several detectors, as shown in Fig. 7:

- The EMC can separate electrons from hadrons using $E/p$ plots (electrons lose almost all their energy inside the crystals), as well as shape parameters of the shower.
- In the DIRC it is already possible to reconstruct on the spherical mirror the arcs produced by pions, which generate Cherenkov light inside the DIRC rods; a pattern recognition algorithm is still under development, based on hough transformation, that will allow to separate pions from kaons.
- dE/dx informations can be provided by several detectors, such as TPC, STT and MVD, which will be used for particle identification at low momenta.

## 7. Transport model comparisons

One of the features of PandaRoot is the utilization of the Virtual MonteCarlo interface. This allows to use as transport model Geant3 or Geant4 with exactly the same detector code, indeed the same geometry definition and the same recontruction, without recompiling but just changing one flag in the simulation macro. In this way it is also possible to compare the results from

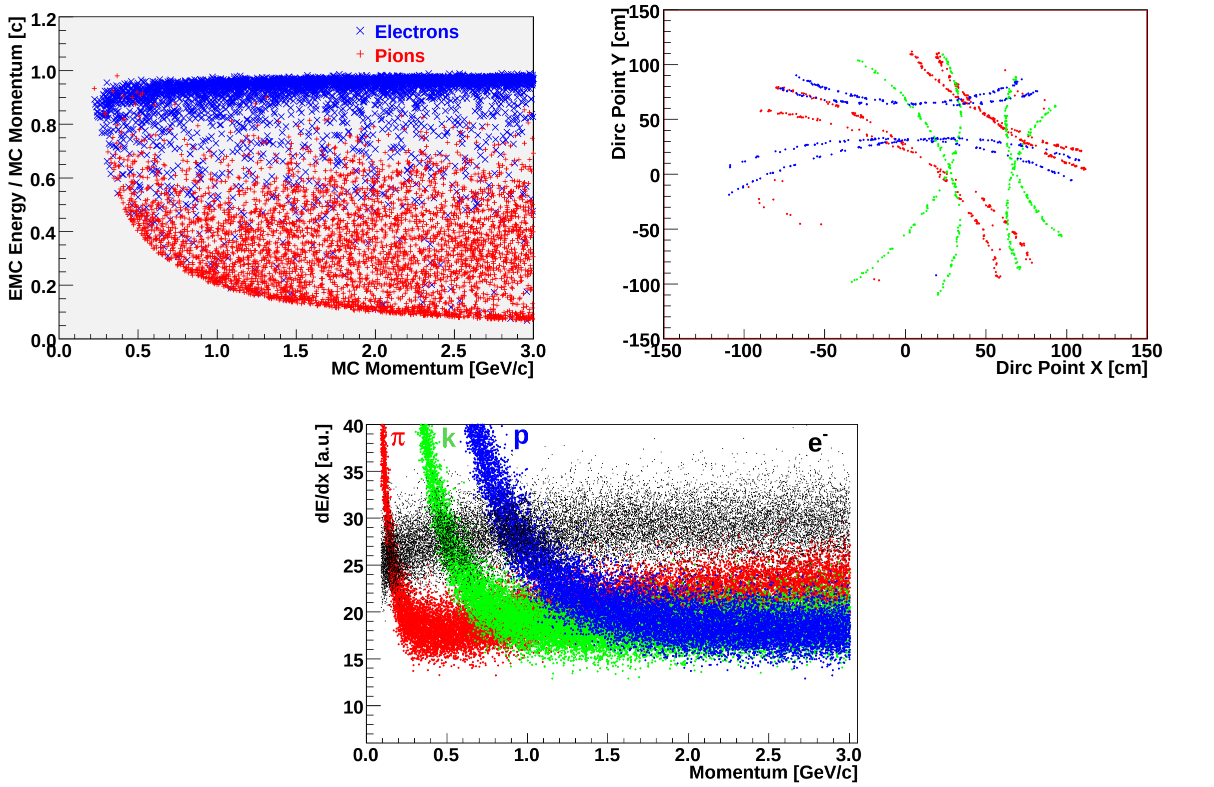
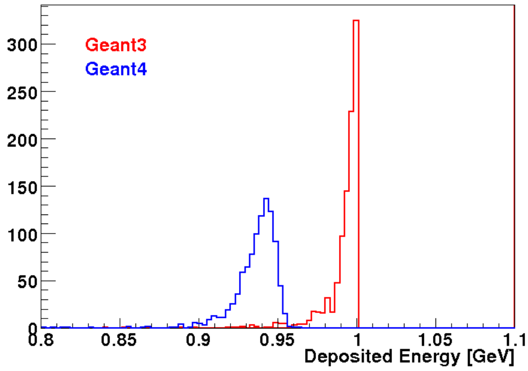



**Figure 7.** Example of particle identification on different detectors. Electron/pion separation in the EMC detector (upper left), signals of three pion events in the DIRC spherical mirror (upper right), dE/dx particle separation in STT (lower plot).

these two models with respect to experimental data, thus to validate physics lists and cuts.
One example of the comparison that can be performed is shown in Fig. 8. Version 9.0 of Geant4 was adopted, using the physics processes of G4EmStandardPhysics and G4EmExtraPhysics. Photons at 1 GeV were simulated by means of the uniform generator inside the acceptance region of the EMC barrel, and the total amount of energy deposited in the crystals, from MonteCarlo truth, is shown in the left plot.

It is possible to see that, while under Geant3 all the energy is deposited inside crystals, under Geant4 there is an energy leakage of few percent, probably due to escaping particles. The right plot shows the energy distributions after full digitization (including electronic noise and a 3MeV threshold cut per single crystal) and cluster reconstruction; in this case the peaks are smeared by the detector resolution, and are place at a bit lower energies due to the crystal energy threshold, but the difference in energy is still present and it plays a role for the energy calibration.
A good tuning of physics lists and cuts is required, and this will be done with direct comparison to experimental data coming from laboratory prototype detector tests. The Virtual MonteCarlo will allow to cross check the results with both the models, in order to perfom a proper validation of our simulation. In the next future the implementation of Fluka transport model is also foreseen.



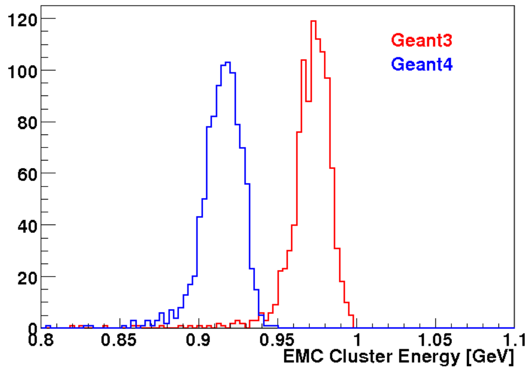




**Figure 8.** Comparison between results obtained with Geant3 and Geant4 in the EMC detector, with a preliminary physics list tuning. The left plot shows the total energy deposited in EMC for $\gamma$ at 1GeV, from MonteCarlo truth information, while the right plot shows the energy distribution of the reconstructed cluster, so after full digitization and reconstruction.

## 8. Conclusions

Since almost one year PandaRoot is the official framework for the PANDA full simulations. In this contribution a general overview of the framework was given, as well as the current state-of-art. The detector geometry implementation is almost complete, as well as the tracking and the reconstruction of neutral channels. Development activities are ongoing on the global tracking, in particular on the implementation of the GEANE package as track follower inside our Kalman filter (GENFIT). The next step will be to finalize tracking and to merge it with PID detectors, in order to be able to perform full recontruction even for charged channels.
Moreover the utilization of the Virtual MonteCarlo will allow a comparison between Geant3 and Geant4, and a proper validation of the physics lists used by direct comparison to experimental data from bench tests.

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