Event Reconstruction and Simulation in PandaRoot for the $\overline{\text{P}}$ANDA Experiment

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Abstract. The $\overline{\text{P}}$ANDA experiment, which is currently under construction at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, will address fundamental questions in hadron and nuclear physics via interactions of antiprotons with nuclei. It will be installed at the High Energy Storage Ring (HESR), which will provide an antiproton beam with a momentum range of 1.5 - 15 GeV/c and a high average interaction rate on the fixed target of 2×10^7 events/s. The $\overline{\text{P}}$ANDA experiment will adopt a continuous data acquisition and the expected data rate transmitted to a high-bandwidth computing network will be in the order of 200 GB/s. However, in order to be able to select many different and rare physics processes, an indiscriminate hardware trigger would not suffice. Instead, an online software-based data selection system will be used to select only relevant data and thereby reduce the data rate by a factor of up to 1000. Due to the high interaction rate a highly advanced online analysis must be developed to deal also with overlapping events. Scalability and parallelization of the reconstruction algorithms are therefore a particular focus in the development process. A simulation framework called PandaRoot is used to further optimize the detector performance and develop and evaluate different reconstruction algorithms for event building, tracking and particle identification. An overview about PandaRoot and the requirements on the event reconstruction algorithms is presented and algorithms for the event time reconstruction currently under development are discussed.

1. The $\overline{\text{P}}$ANDA experiment

The $\overline{\text{P}}$ANDA experiment (Anti**p**roton **An**nihilation at **Da**rmstadt) [1] will be one of the major experiments of the future international **F**acility for **A**ntiproton and **I**on **R**esearch [2][3] (FAIR), currently under construction at Darmstadt, Germany. The high-quality antiproton beam with a momentum range from 1.5 GeV/c to 15 GeV/c is provided by HESR (**H**igh **E**nergy **S**torage **R**ing) [4]. The accelerator can be operated in two complementary modes. The high luminosity mode with an average luminosity of up to $L = 2 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$ uses stochastic cooling with a momentum resolution of $\Delta p/p < 10^{-4}$. The high resolution mode with $\Delta p/p < 4 \times 10^{-5}$ is achieved by using additional electron cooling and can be operated up to a momentum of $p = 8.9\,\text{GeV/c}$. The scientific program [5] includes charmonium and open-charm spectroscopy, searches and investigations of exotic states, e.g. multi quark states, hybrids and glueballs, the study of modifications of hadrons in nuclear matter, hyperon physics and γ-ray spectroscopy of hypernuclei. To measure and study the $\bar{\text{p}}\text{p}$ reactions comprehensively, a simultaneous measurement of all produced leptons, hadrons as well as photons is required. Therefor the $\overline{\text{P}}$ANDA experiment covers the full solid angle and is capable of measuring the energy and

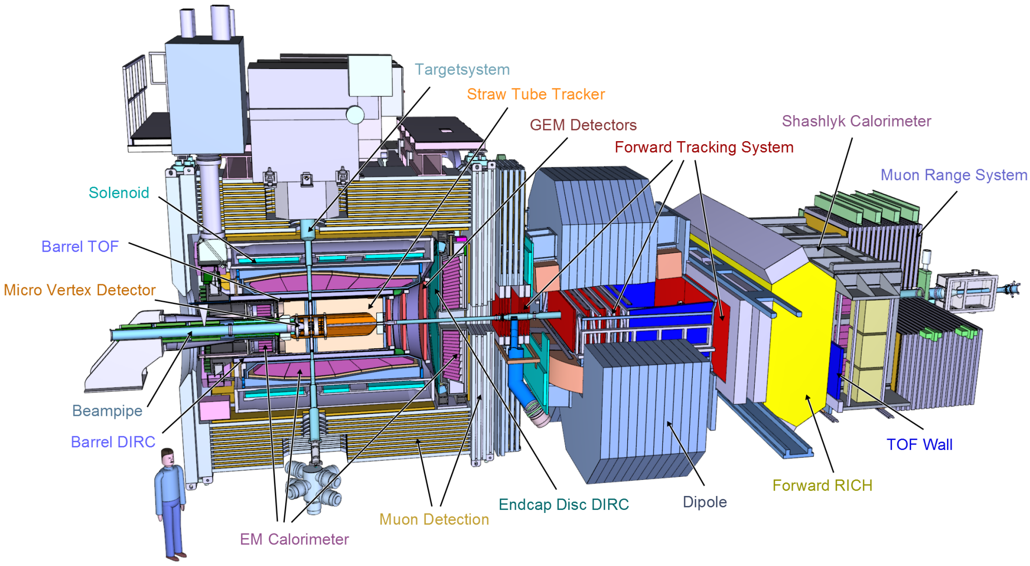

Figure 1. The $\overline{\text{P}}$ANDA spectrometer

momentum of all reaction products as well as being able to identify all particle types over the full momentum range. Figure 1 shows the full $\overline{\text{P}}$ANDA detector which consists of the Target Spectrometer covering the interaction point and the Forward Spectrometer with a maximum angular acceptance of 10 degrees horizontally and 5 degrees vertically in beam direction. A cluster-jet or pellet target system can be operated to scatter the antiprotons with an interaction rate of up to 2×10^7 Hz. The experiment will perform a trigger-less continuous read out, with raw data rates of about 200 GB/s, to provide the necessary flexibility for the complex physics program of $\overline{\text{P}}$ANDA, which will study a diverse range of channels with cross sections varying by many order of magnitudes.

2. PandaRoot

PandaRoot [6] is the software framework for the $\overline{\text{P}}$ANDA experiment which covers full simulations, reconstruction and analysis. It is based on the FairRoot [7] framework which is a project to provide a common computing structure for the future FAIR experiments. FairRoot handles the basic features, such as the interfaces with simulation, tasks, parameter database and the I/O. It is built on ROOT [8] and Virtual Monte Carlo [9]. PandaRoot is supported by various C++ compilers and several Linux distributions as well as macOS. Detector specific geometry, reconstruction and particle identification code is developed within PandaRoot and can be run in the respective stages as shown in the left part of figure 2. In the simulation stage specific initial state particle distributions, physics channels and antiproton-proton background reactions are produced. Therefore, several complementary event generators can be called, e.g. EvtGen [10], DPM [11], UrQMD [12] and Pythia [13]. Particle transport through the detector material is simulated with Virtual Monte Carlo, Geant4 [14] and Geant3 [15]. In the following digitization stage the generated MC data is processed to simulate the realistic response of the subdetectors. In the reconstruction stage information provided by the tracking detectors are combined to reconstruct charged tracks and propagate these to the outer subdetectors. Finally probability density functions (p.d.f.) are computed for every track based on different detectors and various particle identification (PID) concepts. These are combined to receive a global identification probability using Bayes theorem [6]. For the following analysis stage various fitting algorithms

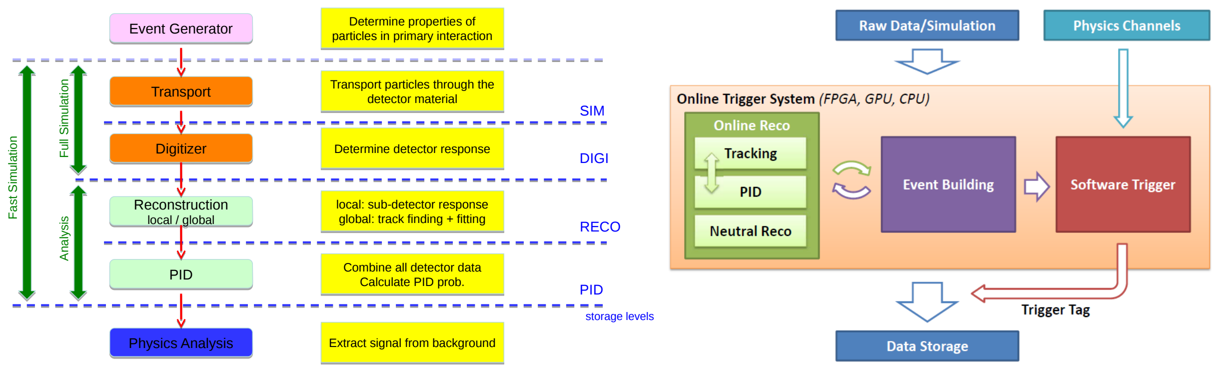

Figure 2. Left: Simulation stages within the framework PandaRoot. Right: Outline of the online reconstruction and trigger system for the continuous, time based read out of $\overline{\mathrm{P}}$ANDA

for the four momentum and position of the particles as well as particle selection and combination mechanisms are provided.

3. Time based reconstruction

The beam from the HESR is Poission distributed, with a high average interaction rate of 20 MHz. Due to this, the $\bar{p}p$ annihilation events will overlap in time for slow subdetectors such as the Straw Tube Tracker [16]. Furthermore the $\overline{\mathrm{P}}$ANDA detector will not use a hardware trigger since it would not be sophisticated enough to achieve the broad scientific program of the $\overline{\mathrm{P}}$ANDA experiment. Instead every sub detector will operate in a self triggering mode. Therefore, the data of every sub system is marked with time stamps and streamed continuously to processing compute nodes. The data are processed directly before storage by the so called online reconstruction. This advanced online event sorting, reconstruction, and software filter is necessary to reduce the raw data rate of about 200 GB/s by a factor of up to 1000 before storage and fully replaces a common hardware trigger. The available operation time for this process will depend on the buffer memory and processing power, and is still under evaluation. The right-hand schematic in figure 2 shows an outline of the planned execution. In an iterative process the event wise sorting, called event building, followed by a fast track reconstruction and PID will be done. The obtained information will be used to enhance the event building and tracking further to a level where the software filter can decide whether to discard or store the respective data. A full and, in terms of computing power, expensive so called offline reconstruction and analysis is only performed at a later stage on the stored data and can be redone with different algorithms if necessary.

4. T_0 reconstruction

A rough sorting of the detector signals, in so called event packages, can be done as an initial step of the online reconstruction, without tracking and PID information. These event packages must contain all data pertinent to a $\bar{p}p$ annihilation event. However, the number of mismatched signals must be reduced to a minimum. Various algorithms exploiting different sub detectors for this first stage are tested currently within the collaboration. One suitable detector to support such algorithms is the Barrel-TOF due to its good time resolution which is below 75 ps [17][18][19]. The left part of figure 3 illustrates the basic algorithm. The received time stamps from the detector are corrected according to the detection position assuming straight line propagation of the particles from the interaction point with the speed of light. Time stamps of signals coming from the same $\bar{p}p$ annihilation will cluster in time to within 4 ns. The first signal of a cluster is

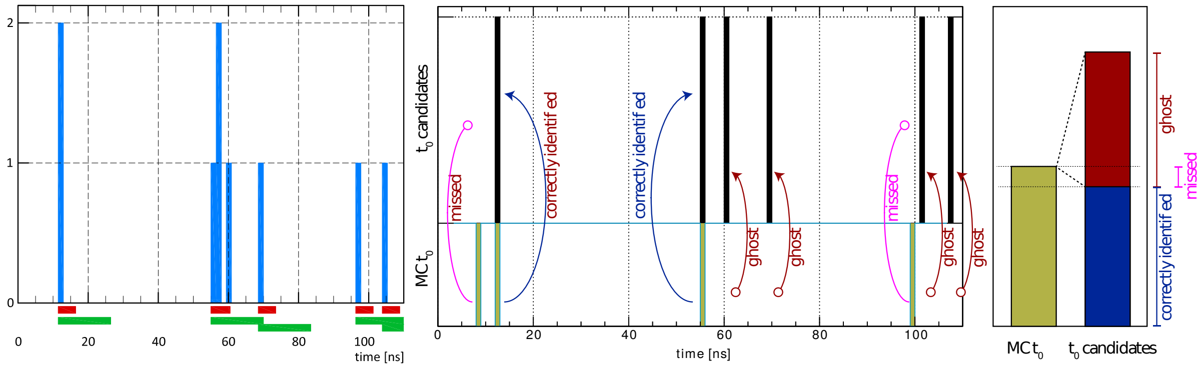

Figure 3. Left: basic principle of a Barrel TOF based event sorting algorithm. Every time stamp (blue) can potentially be the trigger for an event candidate. After a trigger has been accepted, there is a dead-time of 4 ns (red) where no other trigger is accepted. All timestamps after an accepted trigger and within a window of 15 ns are assumed to belong to a single event (green). These event time windows potentially overlap to ensure the completeness of the data. Center: Results for an average event rate of 20 MHz. The black lines indicate the triggered event times, the green lines the MC true values of the $\bar{p}p$ annihilation. Right: The diagram visualize the ratio between MC events, correctly identified and missed events as well as triggered ghost events.

used as an estimate of the $\bar{p}p$ annihilation time (t_0). The right part of figure 3 summarizes the simulation results for an average interaction rate of 20 MHz. 93% of the MC events are identified within 4 ns and the resolution of the estimated t_0 for these is about 0.55 ns. Additionally ghost events are triggered by signals from late arriving secondary particles with a rate of about 0.66 per MC event. First tests showed that crosschecking a potential trigger signal with signals of other sub detectors suppresses the ghost rate below 0.3.

After the first track reconstruction a relative time-of-flight algorithm improves the t_0 resolution and provides time-of-flight based PID information[20]. The basic principle is to iterate through all possible mass configurations (i.e. e, μ, π, K, p) and calculate the expected time of creation for every single track using the reconstructed momentum and flight path information provided by the tracking system. The conformities of the track creation times for all reconstructed tracks and mass assumptions are rated using a χ^2 probability weight based on the comparison of the measured time-of-flight and the calculated expected time-of-flight of the tracks. This task can be reduced to the minimization of the function

$$\chi^2_{(m_1,\ldots,m_N)} = \sum_{i=1}^{N} \frac{(t_{i,0} - t_0)^2}{\sigma^2_{TOF}} \quad (1)$$

which is summing over all tracks. The annihilation time t_0 is the free parameter to minimize the function. m_i, $t_{i,0}$ and $\sigma_{i,TOF}$ are the mass assumption, calculated track creation time and the time of flight resolution for track i. Figure 4 summarizes the basic principle and the results for simulated events with more than 2 reconstructed charged tracks detected in the Barrel TOF. The presented algorithm enhances the event time resolution to a value of $\sigma = 0.12$ ns and provides a first time-of-flight based particle hypothesis.

5. Conclusion

PandaRoot is the $\overline{\text{P}}$ANDA software framework for full simulation, reconstruction and analysis. Various particle generators for different physics channels are integrated as well as different

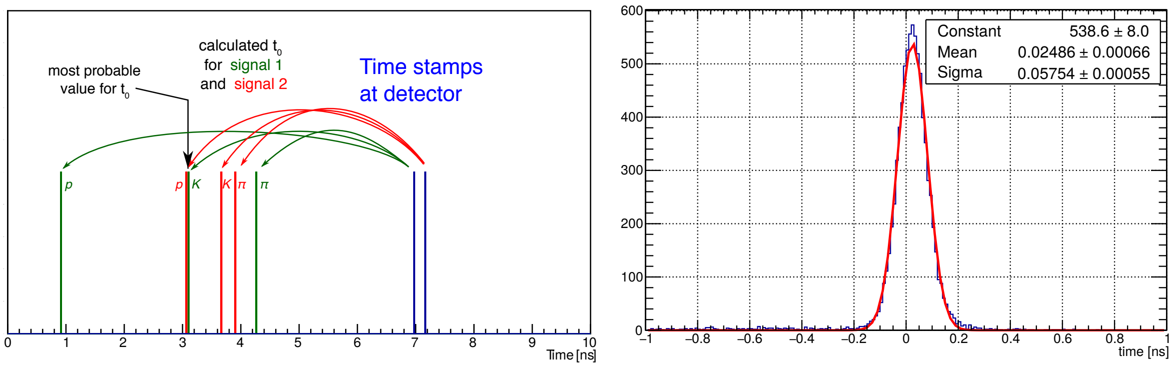

Figure 4. Left: For the detected signals in the Barrel TOF(blue) the corresponding possible track creation times according to a certain mass assumption are calculated (green and red). The combination providing the best conformity is equivalent to the most probable mass configuration. Right: The resulting t_0 distribution for events with more than 2 detected charged tracks shows a time resolution below $\sigma = 60\ ps$.

transport engines to simulate a realistic detector response. The event based simulation is in an advanced state and further improvements of tracking and PID algorithms are in development.

A strong effort is put into the time based simulation of the trigger-less data acquisition system. The continuous data stream must be sorted and reconstructed online on an event-by-event basis. This is done with an iterative and flexible algorithm before a sophisticated decision on discarding or storing the data is done. Currently algorithms are under development to reconstruct the $\bar{\mathrm{p}}\mathrm{p}$ annihilation time and the event structure. With a fast algorithm based on the time-of-flight system of $\overline{\mathrm{P}}$ANDA a first event building is achieved with a t_0 resolution of $\sigma = 0.55$ ns. This value is improved using more advanced relative time-of-flight algorithms to the order of $\sigma = 0.12$ ns to support the online reconstruction. After passing the software trigger the full offline reconstruction chain will further enhance the reconstruction.

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