Abstract. The PANDA experiment, currently under construction at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, addresses 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 enables a high average interaction rate on the fixed target of $2 \times 10^7$ events/s. The PANDA experiment adopts 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 select many very rare physics processes simultaneously, an indiscriminate hardware trigger does not suffice. Instead, an online software-based data selection system will be used to achieve a data reduction of a factor up to 1000. This demands a highly advanced online analysis due to the high interaction rate which has to deal also with overlapping event data. Scalability and parallelization of the reconstruction algorithms are therefore a particular focus in the development process. An simulation framework called PandaRoot is used to develop and evaluate different reconstruction algorithms for event building, tracking and particle identification as well as to further optimize the detector performance. 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.
Figure 1. The PANDA spectrometer

full momentum range. Figure 1 shows the full PANDA detector consisting 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 can be operated to scatter the antiprotons with an interaction rate of up to $2 \times 10^7$ 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 programme of PANDA studied in diverse channels with cross sections varying by many order of magnitudes.

2. PandaRoot
PandaRoot [6] is the software framework for the PANDA experiment for full simulation, 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 with the I/O and 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 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]. For the transport of the particles through the detector material using Virtual Monte Carlo, Geant4 [14] and Geant3 [15] are available. 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 for the four momentum and position of the particles as well as particle selection and combination mechanisms are provided.
Event Generator
Physics Analysis
local: sub-detector response
global: track finding + fitting

Determine properties of particles in primary interaction
Extract signal from background
Fast Simulation
Full Simulation
Analysis

Figure 2. Left: Simulation stages within the framework PandaRoot. Right: Sketch of the online reconstruction and trigger system for the continuous, time based read out of the PANDA experiment.

3. Time based reconstruction
Due to using the continuous antiproton beam of the HESR with a high average Poisson distributed interaction rate of 20 MHz the signals of \( p\bar{p} \) annihilation events will overlap in time for slow subdetectors such as the Straw Tube Tracker [16]. In addition a common hardware trigger is not sophisticated enough to achieve the broad scientific program of the PANDA experiment, but every sub detector operates in a self triggering mode. Therefore, the data is marked with time stamps and streamed continuously to processing compute nodes. An 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. 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.

4. T0 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 the data pertinent to an \( p\bar{p} \) annihilation event. However the additional amount of wrongly matched 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 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 \( p\bar{p} \) annihilation will cluster in time within 4 ns. The first signal of a cluster is used as an estimate of the \( p\bar{p} \) 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.

In addition 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 an factor of 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 and calculate the expected time of creation for every single track using the reconstructed momentum and flight path information provided...
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 $pp$ annihilation. Right: The diagram visualize the ratio between MC events, correctly identified and missed events as well as triggered ghost events.

by the tracking system. The conformities of the track creation times for all reconstructed tracks and mass assumptions are rated using a $\chi^2$ 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 functional

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

summing over all tracks. The annihilation time $t_0$ is the free parameter to minimize the functional. $m_i$, $t_{i,0}$ and $\sigma_{TOF}$ 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 provide a first time-of-flight based particle hypothesis.

5. Conclusion
PandaRoot is the software framework for the PANDA experiment for full simulation, reconstruction and analysis. Various particle generators for different physics channels are integrated as well as different 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, event by event by 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 $\bar{p}p$ annihilation time and the event structure. With a fast algorithm based on the time-of-flight system of PANDA 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
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.

the online reconstruction. After passing the software trigger the full offline reconstruction chain will further enhance the reconstruction.

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