Fast Simulations for the PANDA Experiment at FAIR

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Abstract. As one of the primary experiments to be located at the new Facility for Antiproton and Ion Research the PANDA experiment aims for high quality hadron spectroscopy from antiproton proton collisions. The versatile and comprehensive projected physics program requires an elaborate detector design. For optimization and tuning of the individual detector components a reliable simulation is mandatory, which allows to investigate different design options as well as estimate acceptance and efficiency of various physics benchmark channels. A realistic simulation based on full transport software often needs a lot of computing time. Therefore, a fast simulation providing effective parametrization of detector acceptance and resolution was implemented.

1. Introduction
The projected detector for the PANDA experiment will be a very complex machine consisting of a large number of different subdetectors like various tracking detectors, electromagnetic calorimeters, Cherenkov detectors, a vertex detector, etc. and is as a special characteristic equipped with two different magnets, a solenoid and a dipole, which makes global tracking a bit more challenging [1]. The simulation of such a system is a very demanding task in terms of computing power as well as man-power, since in this early stage of the experiment the detector design is not completely fixed and a number of different options for the realization of various subsystems have to be taken into account. On the other hand, particularly in this stage of the experiment a huge number of events have to be simulated in order to settle the detector design and do feasibility studies for specific physics cases.

For a rare reaction like \( \bar{p}p \rightarrow \eta_c \rightarrow K^0_S K^\pm \pi^\mp \) with a total cross section of \( \approx 10 \pm 3 \text{ nb} \), when aiming for a number of 10000 reconstructed signals in the peak of the invariant mass spectrum with a reconstruction efficiency of the order of 10\%, 100k of signal events have to be simulated. The cross sections of possible background channels like the non resonant \( \bar{p}p \rightarrow K^0_S K^\pm \pi^\mp \) [2] and channels with the same charged multiplicity like \( \bar{p}p \rightarrow K^+ K^- \pi^+ \pi^- \) [3] and \( \bar{p}p \rightarrow \pi^+ \pi^- \pi^+ \pi^- \) [4] easily add up to \( \approx 700 \mu\text{b} \), which is a factor 70000 higher than the signal cross section. Thus in the order of \( 10^9 - 10^{10} \) background events have to be simulated to get a realistic estimate of the background. In order to provide this number on a reasonable time scale for the detailed simulation, a lot of computing power will be required on one hand, on the other hand either the detector layout is settled at this point or the simulation has to be performed for different design options, which will put even more load on computing resources.
2. Realistic Simulation
Simulations of a complex detector system can be separated into well defined steps. These are

1. **Event Generation.** Simulation of the interaction of probe and target, resulting in a list of particles, represented in form of 4-vectors and production vertices.

2. **Particle Transport.** Transport code like Geant4 [5] simulates the interactions of the particles from step 1 with materials of the detector and produces so-called *hits*, which contain the position of the interaction and further information like e.g. the energy loss of the particle etc.

3. **Digitization.** Modeling of the expected signals from the front-end-electronics based on the hit information.

4. **Reconstruction.** Tracks are reconstructed based on the simulated detector response from step 3, resulting again in a list of 4-vectors with reconstructed initial vertices.

5. **Analysis.** The resulting list of particle candidates represents the basis for detailed physics analysis.

In particular step (2) is very time consuming and steps (3) and (4) might take much time as well depending on the complexity of the underlying detector geometry. For high statistics background studies $10^9$ or more events are needed as described above. The simulation of this huge number might evolve to an unfeasible task on middle-term time scales.

3. Fast Simulation
3.1. Technique
To overcome the problem portrayed above, the concept for the fast simulation is to replace the stages (2)-(4) by just one, which is based on parametrizations of detector responses like resolutions for track parameters, information about the particle type and spatial acceptance. This approach is motivated by the fact, that the uncertainties of most of these quantities have more or less Gaussian shape, or at least can be modeled analytically.

The complete detector setup is compiled from a set of previously defined subdetectors, where a subdetector representation in detail is given by

1. Angular acceptance in terms of limits for the angles $\theta$ and $\phi$, in projection from the interaction point.

2. Resolution functions for the quantities, which can be measured with a specific detector component, e.g. angular resolution for tracking devices and calorimeters, momentum for vertexer and trackers, energy resolution for electromagnetic calorimeters for $\gamma$’s and $e^\pm$, etc.

As a simple example, the e.-m. calorimeters energy resolution model currently is give by the function

$$ \frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{\sqrt{E}}} $$

There are of course much more sophisticated resolution models implemented, e.g. the momentum resolution for the Straw Tube Tracker (STT) [6]. As an alternative to deriving the appropriate resolution model from theoretical considerations it also can be directly parametrized from the results of the full simulation, when a particular subdetector is already available.

Figure 1 shows an example plot of the momentum smearing for simulated single particle events. Plotted is the difference of the generated and the smeared absolute value of the momentum of the particles vs. the polar angle $\theta$. In addition the angular coverages of different subdetectors are marked, with STT = Straw Tube Tracker, MDC = Mini Drift Chambers, TS = Target Spectrometer, Fw = Forward direction. As expected, the overall
resolution is better in polar angle regions, where more detectors provide measurements of the momentum.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{momentum_smeared.png}
\caption{Example plot for the momentum smearing for single track events. (Acronyms: see text.)}
\end{figure}

(3) Contribution to particle identification (PID). This can be \(dE/dx\) information from the central tracker and the vertexer, Cherenkov angle \(\theta_C\) measured by the RICH detectors or time measurement by the TOF devices. The information is provided as a set of likelihood values for the different particle hypotheses.

All these information are compiled as the total response for that particle. For each stable particle (\(e^\pm, \mu^\pm, \pi^\pm, K^\pm, p, \bar{p}, n, \bar{n}, \gamma, K^0_L\)) of the Monte Carlo truth list coming from the event generator, the following steps are accomplished

1. Acceptance check - which particle hits which particular detector?
2. Collect responses for detectors, which were hit, i.e. store the resolution information \(\sigma_i\) for every detector \(i\), which is able to measure properties of particles of the current type, e.g. a momentum resolution is provided by a tracking device for charged particles.
3. Modify the generated particle’s 4-vector and vertex based on the summarized detector responses. In case that no detector gave a response, remove the particle from the list.

The total resolution \(\sigma_t\) for a particular quantity computes to

\[\sigma_t = \left( \sum_i \frac{1}{\sigma_i^2} \right)^{-1/2}\]

where index \(i\) reflects the contributing detector components. The generated candidate is altered in that way, that a randomly chosen value from a Gaussian distribution with \(\sigma = \sigma_t\) centered around zero is added to the original value. This procedure informally is referred to as ‘smearing’.

The total PID likelihoods are taken as the products

\[L_j = \prod_i L_{ij}\]
for each particle hypothesis $j$ and detectors $i$. The single likelihood values reflect the probabilities for a specific candidate being of a particular type. These resulting likelihood values are stored for every candidate and can be accessed later in the analysis stage.

(4) Store the modified particle to a list for further analysis (step 5 from last chapter).

This method to transform the generated particles into a list of track candidates is very effective in terms of speed performance.

3.2. Secondary particles

One major difference between the full transport method and the effective approach described above is the handling and existence of secondary particles. Very prominent is the appearance of so called split offs in the electromagnetic calorimeter due to interactions of hadrons and leptons with the scintillating material. These interactions can fake electromagnetic showers which might be considered as true neutral candidates by the reconstruction algorithm. Also possible is backscattering of charged secondary particles into the active tracking volume which then will be reconstructed as charged particle candidates coming from the interaction region. Both sources can lead to a significant higher combinatorial background.

To overcome this discrepancy the Fast Simulation generates electromagnetic as well as hadronic split offs and adds them to the above described particle list prepared for analysis. Therefore the properties of the split offs created by the transport code of the full simulation have been parametrized and used as probability density functions for generation. The basic information for this purpose is, which kind of particle causes how many split offs, what energies do they have and what are their directions relative to the incident particle. These distributions are determined by running the full simulation for isotropic distributed single track events with momenta between 0 GeV/c and 6 GeV/c. For the different particle types ($e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$) the observed shapes are fitted with appropriate (empirical) models. Figure 2 shows the results for 100k single $K^\pm$ events as an example. Models are the sum of an exponential and a Gaussian in (a), the sum of two exponentials in (b) and the sum of two gaussians in cases (c) and (d). The models sufficiently describe the underlying distributions for the present purpose. Correlations of higher order like dependence of the model parameters from momentum or direction of the incident particle are neglected for the time being. Also possible variations in distributions due to more coincident charged tracks in the detector like in realistic events are not taken into account.

At this point it should be mentioned that neither the reconstruction algorithm in the realistic simulation is completely optimized nor is the detector setup and geometry in a final state. Therefore the absolute numbers and shapes in the shown plots are not necessarily representative for final properties of the PANDA detector or reconstruction results.

3.3. Implementation

There are different options to implement such a simplified simulation, since it in principle is completely independent from other software like transport software or analysis tools. One could think of a stand-alone implementation, which indeed was the chosen way for the first simulation software implemented for the PANDA experiment. The solution favored here is to incorporate the procedure introduced above into the framework, which also hosts the full simulation.

For the time being, the BaBar-like framework [7] is chosen, which is a very mature and elaborate one and features a lot of tools due to it’s long development and maintenance time. There is a very easy-to-use interface to several event generators like EvtGen [8] or UrQMD [9]. The perhaps most powerful feature is given by the analysis tool set Beta, which provides control structures for handling candidate lists and composites and furthermore gives access to powerful fitting routines.
Figure 2. Example for the parametrizations of the multiplicity and properties of hadronic split offs in the electromagnetic calorimeter induced by charged kaons. (a) Frequency of the multiplicity of neutral split offs. (b) Momentum distribution of split offs. (c) Angular deviation in $\phi$ from incident particle. (d) Angular deviation in $\theta$ from incident particle.

Since the PANDA–Collaboration decided to change the software due to practical reasons to the so called PandaRoot–framework [10] which is developed in a common effort with the CBM-experiment [11] also hosted at FAIR, the whole functionality of the Fast Simulation will be migrated to this software on a short term scale, when analysis tool sets are available.

The most important reason for choosing the implementation inside this software environment, which might on the first glimpse look like an overhead is, that there is a consistent interface between the data side an the analysis side. Thus there is from the analyst’s point of view no difference between analyzing real data, full simulated Monte Carlo events or events coming from the fast simulation. This makes it very easy to compare results from various sources.

3.4. Performance

In order to get information about the relative speed of the full featured simulation and the fast simulation, both were tested on a standard batch PC of the GSI cluster. It shall be noted, that the full simulation is based on Geant4.7.1 with the physics list accommodated and optimized for the BaBar experiment since the execution speed of the transport code can considerably depend on both. The test channel which was used was the benchmark channel reaction $\bar{p}p \rightarrow D_{s}^{\pm}D_{s}^{\mp}(2317)^{\mp} \rightarrow D_{s}^{\pm}D_{s}^{\mp} \pi^{0}$ with the subdecays $D_{s}^{\pm} \rightarrow \phi(1020)\pi^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$ and $\pi^{0} \rightarrow \gamma\gamma$. This channel has eight final state particles and thus demands quite some
computing power.

With this configuration it turns out that the fast simulation is about a factor \(10^2 - 10^3\) faster than the full featured simulation. This speed measurement reflects the overall speed ratio, including event generation an analysis. Due to that overhead this number is to a certain extend framework limited and therefore a lower limit of the actual speed gain. Of course the enhancement will not be completely independent of the simulated channel.

With this performance one will have access to much higher event numbers demanded for background estimation than with the full simulation. Additionally another factor in speed probably can be achieved by prefiltering techniques.

4. Quality test

Even more important than the pure speed of this simulation approach is the quality of the results after the analysis and its consistency with measured and realistic simulated data. Since the former is not available one has to satisfy with the latter one. Therefore as an example the results of the analysis of the above mentioned benchmark channel for both simulation scenarios are presented in this writeup. For this purpose 10k of signal events for the channel have been simulated in the given decay tree and fully reconstructed in the analysis part of the sequence. Only very loose selection criteria like broad mass windows around the resonances and requirements for the perpendicular momentum \(p_t\) of some of the candidates have been applied, which should not be discussed in detail here, but certainly exactly the same selection criteria have been applied for both simulation methods. The resulting histograms have not been relatively scaled in any way and therefore can be considered for absolute comparison.

The channel itself by the way is of particular interest since it is possible to obtain the widths of some the recently found \(D_{s J}\) resonances [12, 13, 14] by performing an energy scan over the threshold for their production together with a conventional recoiling \(D_s^\pm\) meson.

Figure 3 shows distributions of the invariant masses of some of the reconstructed intermediate particles of the considered decay tree for the full realistic simulation (solid line) and the fast simulation (shaded) as well as the number of neutral candidates per event. The latter distribution (a) shows quite nice that the split off parametrization and creation seems to work appropriately without taking into account the candidate multiplicity. This is also reflected in plot (b) where the invariant mass of the \(\pi^0\) candidates is shown. There is a slight difference in signal efficiency and resolution, but the background levels of both methods perfectly match. The shift of the \(\pi^0\) signal peak arises from an imperfect energy calibration of the electromagnetic calorimeter in the detailed simulation and thus does not affect the conclusions presented here. Considering the invariant masses of resonances decaying to charged final states like the \(D_s^\pm\) in (c) and the \(\phi(1020)\) in (d), the background also agree well. Slight inconsistencies in the signal shapes are present as well.

Although some tuning still is necessary the overall consistency is acceptable. One should not forget that the development of the full simulation is still in progress and therefore continuous adaption will be mandatory anyway.

5. Conclusion

It was shown that a fast simulation for the PANDA experiment was implemented, which achieved a speed up of a factor \(\approx 100-1000\) compared with the full featured simulation with an accuracy good enough to investigate physical questions. The performance in terms of consistency with the realistic simulation still needs tuning at this development stage.

Projected goal is to optimize and validate the parametrization of the detector response based on the realistic simulation in order to provide more reliable results from the fast simulation and make it a powerful tool for further physics and design studies for PANDA.
Figure 3. Comparison of the analysis results of the full (solid line) and fast (shaded) simulation for the benchmark channel. Shown is the number of neutral candidates per event (a) and the invariant masses of some intermediate particles of the investigated decay tree, the $\pi^0$ (b), $D_s^-$ (c) and $\phi(1020)$ (d).

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