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Title: g-2 full muon simulation

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Description:

A full simulation of the g-2 ring in GEANT4 within the art software framework has been written, tested and validated. Through a series of mock data challenges large data sets have been centrally produced, using the SAM data handling system, and are being used experiment wide to develop analyses ready for real data taking starting next year.

Abstract:

This report details the contents of the full g-2 ring simulation which has been used to produce large centralised datasets of events for use in detector reconstruction and analysis. The full simulation code has been released and events have been generated with two different types of gun applicable to different studies. This document runs through the requirements on the code, the verification and the production and mentions the analyses that the data is currently being used for.

Introduction:

A full simulation of muons in the g-2 ring is important for developing reconstruction and analysis code which can then be used on the data produced by the experiment when it starts running next year. It is crucial that the simulation has an accurate representation of the detectors and material that the particles will see in the ring and that it produces data in the same format as that coming from the experiment such that the exact same analysis code can be run on both.

The simulation code has been used to produce large samples of events which are being used for development of different algorithms and analyses. This data was produced with the motivation of developing a lost muon analysis, hit reconstruction in the trackers and cluster reconstruction in the calorimeters. The lost muon analysis aims to establish a high-fidelity lost-muon signal in the presence of expected background from ordinary muon decay, which can be tested using the simulated events. The lost muon distribution as a function of time can then be produced as a function of the quadrupole scraping algorithm and kicker field amplitude. For the trackers the events will be used to develop robust track reconstruction algorithms in the trackers. The loop with then be closed by using algorithms to reconstruct the injected muon beam distribution. Lastly the events can be used for cluster finding and pile-up identification algorithms in the calorimeters.

This report will outline the contents of the simulation, describe the validation that was run before the event production started and detail the current status of the analyses that are being carried out on the data.

The g-2 simulation code:

In order for the simulation to produce useful data it must have an accurate representation of the magnetic field, the material in the ring and the detectors. Currently the simulation code contains the best representation of the magnetic field in both the storage and fringe region from an opera simulation, which matches well to the field measurements that have been made in the ring. The magnetic field can be easily updated as more accurate measurements of the magnetic field are made if this is necessary. The main geometry of the ring has been imported into GEANT4 using CAD models for the vacuum chambers, ports, internal plates, standoffs and rails. It is crucial to get the dimensions and material correct such that the distribution of secondaries and energies of the positrons reaching the detectors is a true representation. The tracking detectors have been inserted in to the correct positions in the ring and produce hits from primaries and secondaries in the same format as will be received in the data, along with the truth information that comes only from the simulation. The calorimeters are also accurately described and produce pulses with appropriate statistical smearing and proper energy sharing among crystals. This has been developed based on data taken at the SLAC test beam earlier this year. In addition the fibre harps, which can be used to measure the beam distribution destructively, have been added to the simulation with the option to either have them in the beam or not.

A couple of different muon guns have been produced for different purposes. Both the gas guns that are being used contain the fast rotation, coherent betatron oscillations and spin orientation. The muon gas gun correctly simulates the muon decay points and tracks the positrons from that point along with the secondary particles produced. The injection gun tracks the muons around the ring from the point of injection, along with the decays and the resulting positrons and all secondary particles. The muon gas gun is much quicker due to not having to track the muons and this has been used to produce most of the events and can be used to develop reconstruction algorithms for the detectors and for many of the analyses. A smaller set of events is produced with the injection gun and these are used for lost muon and beam injection studies which are not possible with the gas gun.

For the beam injection studies the inflector geometry has been updated and the IBMS detectors added. The kicker field has also been added to the simulation with the correct time and amplitude variation during injection. Lastly the quad scraping has also been included in the simulation.

Validation of the simulation:

A verification package has been written for the simulation which makes basic plots of the muon distributions and hits in the detectors. This is used to check that everything is running as expected and can be used to check for any variations between different version of the simulation code. A document has been written detailing the plots produced and how to run the code (gm2-docdb 4075).

The code produces plots of the hits in the different detector systems in the ring coordinates as a basic check that hits are appearing evenly in all detectors. There are also plots of the muon beam distribution, the muon decay times and the positron decay angles to ensure that the gas gun is performing as expected. There are also plots for the calorimeters and trackers. For the calorimeters the hits in the crystals and the corresponding deposited energies are plotted for all calorimeters and each one individually. These hits are also divided up into different particle types. For the trackers the positions of the hits are plotted for the trackers as a whole and for the individual modules that make up a tracker station. Some example plots can be seen in Figure 1 - the distribution of hits in the calorimeters and trackers in the global frame and the muon decay position in the beam coordinates. The full set of plots can be seen in the verification document.

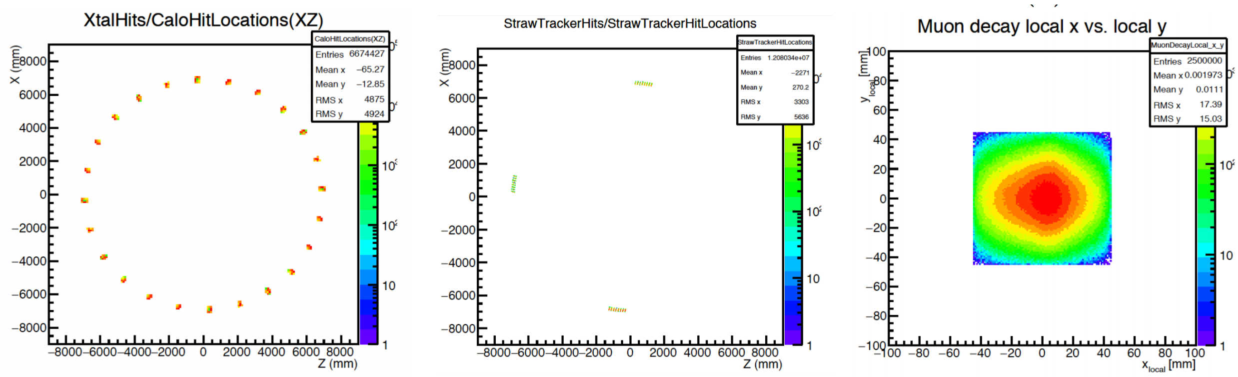

Figure 1. Some example plots from the verification package showing (from left to right) the distribution of hits in the calorimeters in the global frame, the distribution of hits in the trackers in the global frame and the muon beam profile at the decay point in the beam frame.

There is also a statistical package for comparing the distributions produced from two different samples. This outputs comparison plots between the two as well as chi-squared and p-values for the differences in the distributions to easily see if there are any significant differences that cannot be attributed to statistics alone. This has proved useful as the code was developing.

In addition to this paraview has proved a powerful tool for checking the geometries in the simulation. It is a display which imports the GEANT4 geometries and allows you to view the objects, zooming in and moving them around. An example of this is shown in Figure 2. Paraview also allows you to add in tracks on top of the detector geometries from the simulation so you can have a closer look at individual events. This is particularly useful when trying to understand any strange things you see and also for viewing reconstructed tracks and positions compared to the true trajectories.

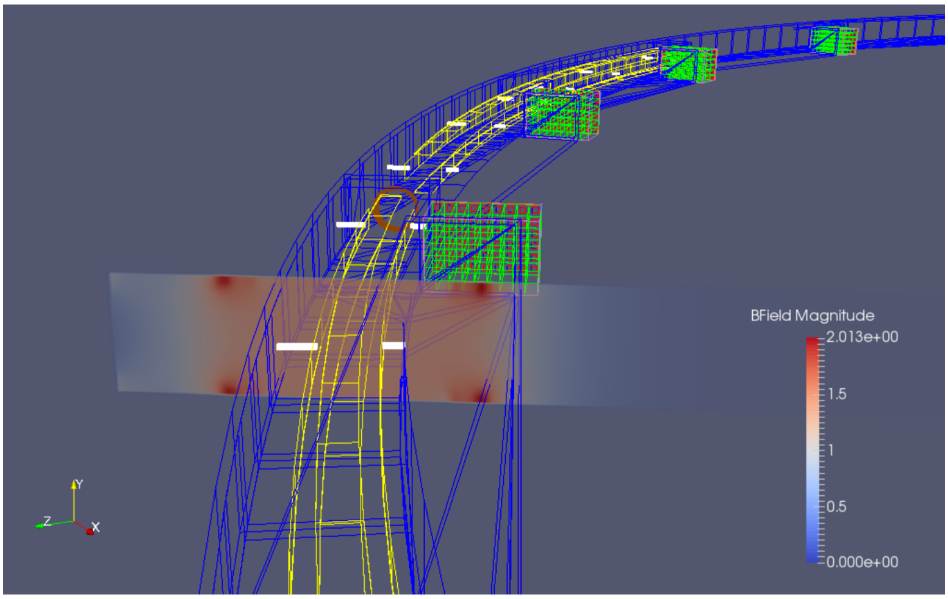

Figure 2. An example of the paraview event display showing part of the ring with the storage region, the calorimeters and the magnetic field.

Data Production:

The simulated events that are currently being used for analysis have been run on the Fermilab grid. The production process has been streamlined with simple job submission scripts. These scripts write the data out using the SAM (Sequential Access via Metadata) data handling system. The files are organised in SAM datasets which can then be accessed by name or by using a metadata query to run over all files satisfying a certain condition.

There is also a website on which the jobs can be monitored as they are running. An example of this is shown in Figure 3.

Figure 3. An example of the website used for monitoring jobs as they run on the Fermigrid

Data Analysis:

Currently analysis of the events produced from the simulation is ongoing in all the areas that were mentioned in the introduction. It is outside the scope of this document to describe all these aspects in detail but it is worth mentioning a brief outline to demonstrate the uses of the data. The first thing that was done with the data was to produce basic plots of hit position and time distributions. These distributions mainly looked as expected but were interesting for learning about the type of events that occur and the distributions of the primary and secondary hits.

The lost muon analysis in currently in the early stages but so far the energy distribution of lost muons entering the calorimeter and the probably that they go on to hit further calorimeters has been investigated using simulation. A plot of the time differences between hits in two and three calorimeters in shown in Figure 4 as an example. The lost muons are also being investigated for use in the alignment of the trackers as these form straight tracks passing though many of the tracker modules.

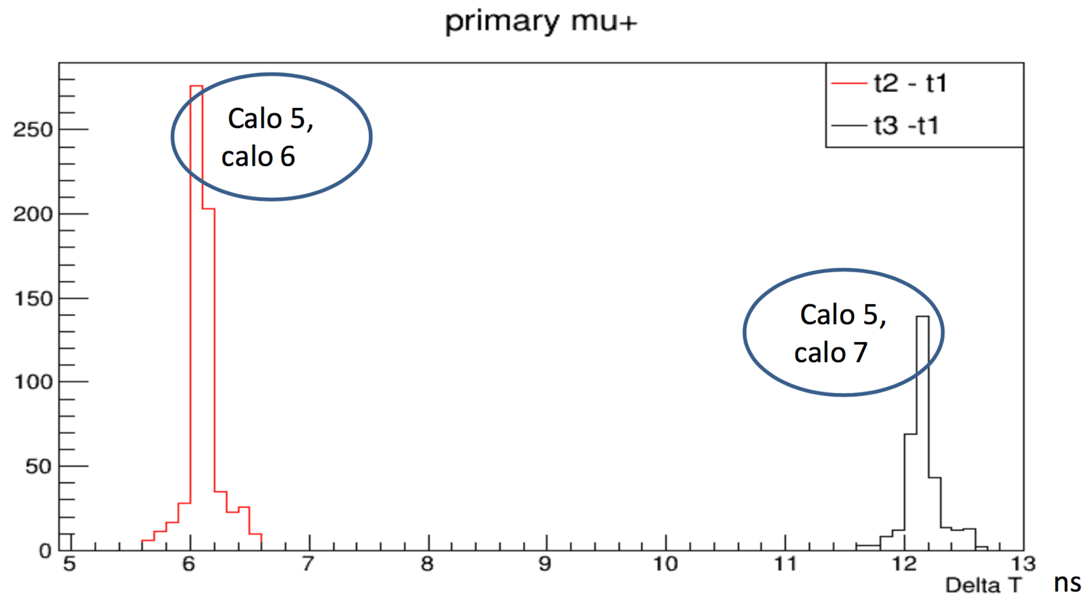

Figure 4. The time difference between hits from lost muons in subsequent calorimeters around the ring

The tracking algorithms are being developed and currently there is one tracking algorithm available with an extrapolation back to the muon beam distribution. It has been demonstrated that tracks can be reconstructed and the code is now being stress tested and optimised to give the best performance and best reconstruction of the muon beam. Figure 5 shows the first results from the tracking algorithm showing the difference between the true and reconstructed track positions

The calorimeter reconstruction is also now in an advanced state. There is code in place to go from simulated or real hits, form islands and fit the pulses. These pulses are then corrected for gain and energy calibrations to form crystal hits. The data is also being using to develop the T-method and Q-method analyses for extracting the spin precession frequency. An example of the pulse fitting is shown in Figure 6.

In addition to the analyses that have been mentioned there are also additional studies going on with the data. These include looking at the contributions from secondary particles, measuring a potential muon electric dipole moment and analyses involving the fibre harps to mention a few. All these analyses are ongoing and will continue to improve and develop over the coming months.

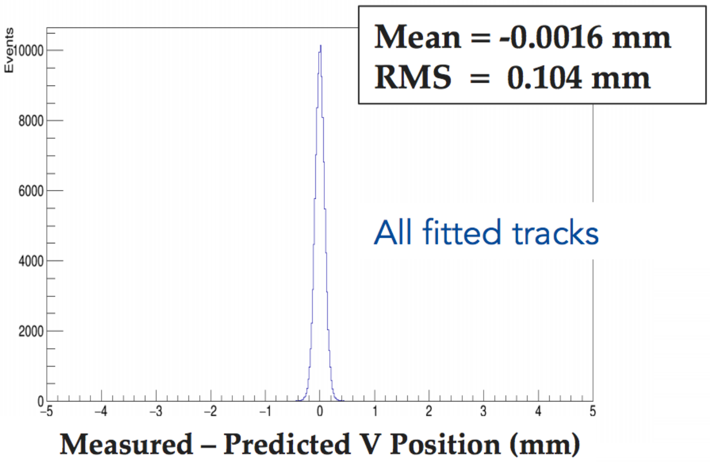

Figure 5. The difference between the tracks formed from the hits in the tracking detectors and the true position

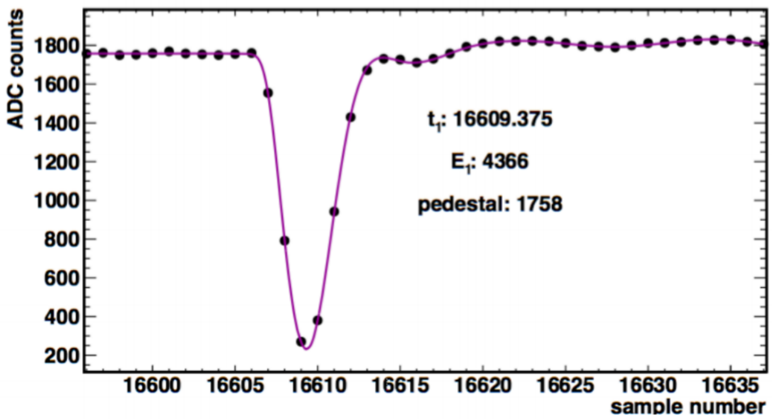

Figure 6. An example of a fitted pulse from a calorimeter crystal, forming part of the calorimeter reconstruction process.

Summary:

The g-2 simulation code is in a complete state and has been used to produce large datasets which are currently being used for analysis. The simulation includes all the material in the ring as well as the detectors and has two possible muon guns which are used for different purposes. The data that has been produced is being used to develop reconstruction techniques and analyses in advance of data taking starting next year.