

Development of software for femtoscopic analysis in CbmROOT Framework.

Facility for Antiproton and Ion Research in Europe and
GSI Helmholtzzentrum für Schwerionenforschung

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Abstract

CBM (Condensed Baryonic Matter) is one of the experiments to be conducted at the FAIR (Facility for Antiproton and Ion Research) complex. The CBM experiment is dedicated to study the properties of matter at extremely high temperature and density. CbmROOT is a software created for data simulation and analysis in CBM. NicaFemto was created to perform femtoscopic analyses in all experiments that use the FairROOT framework (like CBM), however its main goal was the creation of software for analysis of data collected by MPD (Multi Purpose Detector) at NICA.

This document describes the development of the software for femtoscopic analysis in CbmROOT. First chapters describe the CBM experiment, the software used by CBM collaboration and correlation femtосcopy. The next chapter describes NicaFemto. This package was used as a base for creation of a new part of CbmROOT dedicated to correlation femtосcopy. Another chapter describes the process of software development, also results of analyses made with new software are presented here.

Declaration

I hereby declare that the project entitled "**Development of software for femtoscopic analysis in CbmROOT Framework**" is my own work and that I have correctly acknowledged the work of others.

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Chapter 1

The CBM experiment

CBM (Condensed Baryonic Matter) is one of the experiments that will be conducted at FAIR (Facility for Antiproton and Ion Research). The main goal of the CBM is exploration of the QCD phase diagram in the region of the high baryon density[3].

The QCD matter diagram can be explored by study heavy-ion collisions. By performing collisions of two heavy ions we can compress and heat up matter, possibly creating a new form of matter like Quark-Gluon Plasma (fig. 1.1). By variation of the collision energy it is possible to explore different areas of the QCD Phase Diagram.

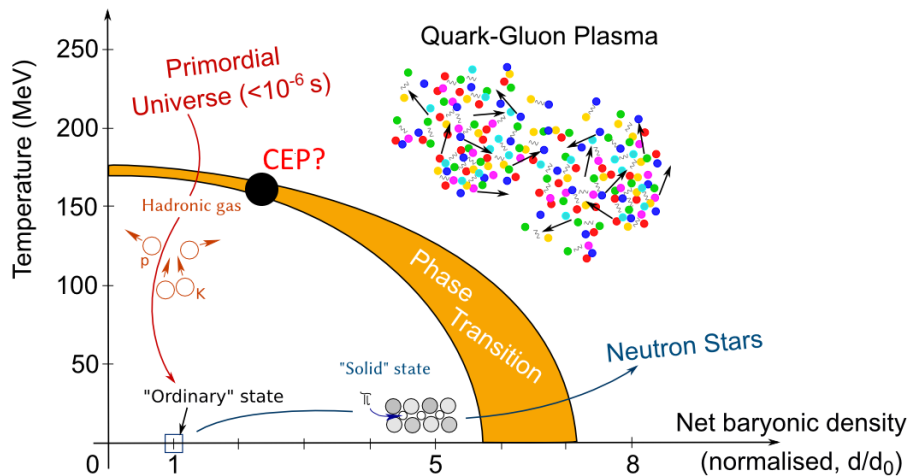


Figure 1.1: QCD phase diagram [1].

A heavy ion collision is a quite complicated process; the final products are particles. There are many ways to study the properties of matter created

during the collisions by studying the properties of the produced particles. Most important (in case of CBM) are:

- study of collective behavior of matter created during the collisions (by study of the anisotropy in the emission of particles)
- measurements of strange matter production
- observation of event-by-event fluctuations
- measurements of dilepton pairs properties
- measurements of production of charm quarks

CBM was designed to study collisions of heavy ions at energies up to $\sqrt{s_{NN}} = 4.9 \text{ GeV}$ (for $Z=N$ nuclei with beam from the SIS-100 synchrotron). Because some of the interesting observables are very rare, CBM will be able to register events with rates up to 10 MHz. The detector is made of many subdetectors (fig. 1.2):

- MVD (Micro Vertex Detector): this detector provides very high spatial resolution required for reconstruction of short-living particles
- STS (Silicon Tracking System): detector based of double-sided micro-strip sensors arranged in eight stations. STS will be the main detector for tracking of the particles
- TOF (Time of Flight Detector): thanks to TOF it's possible to measure the velocity of the particles. Together with information about the momentum (from other detectors), TOF makes possible to identify the particles.
- RICH (Ring Imaging Cherenkov) is a detector that detects Cherenkov radiation. With RICH it will be possible to identify electrons.
- TRD (Transition Radiation Detector) detector that will be used for particle tracking and identification based on the measurements of energy loss.
- MuCh (Muon Chamger) detector used for measurements of muons.
- ECAL (Electro Magnetic Callorimeter) for measurements of photons.
- PSD (Projectivle Spectator Detector) for event characterization.

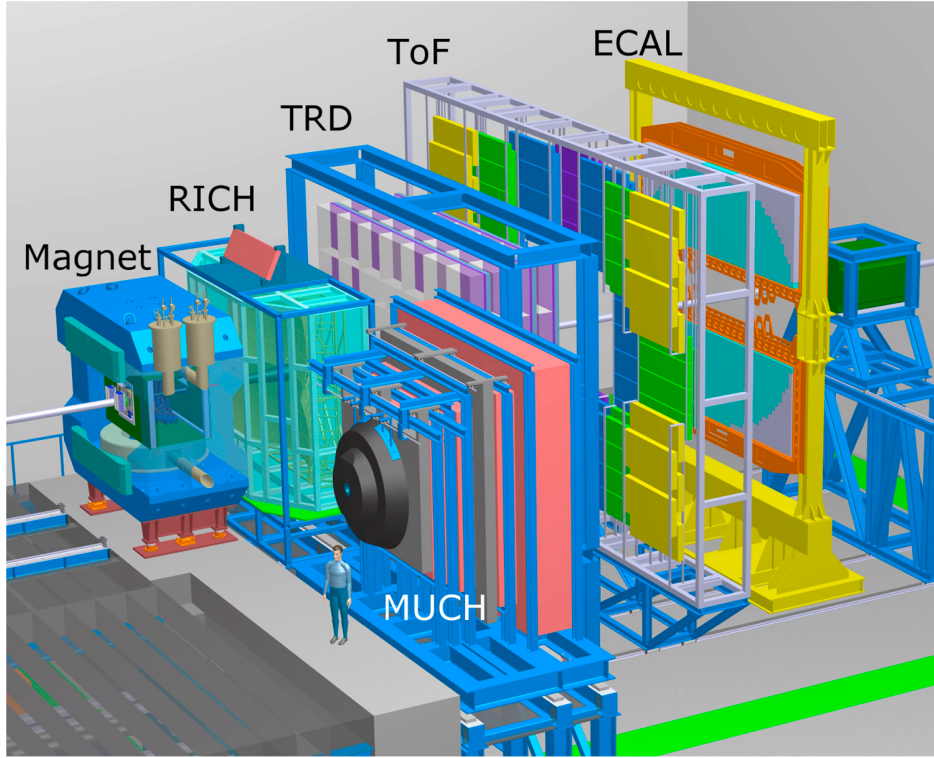


Figure 1.2: The structure of the CBM detector [2].

One of the important part of CBM is the dipole magnet. The presence of a magnetic field allows measurements of momentum and charge of the particles. Depending on the measurement type, different detectors will be used. The list of configurations currently available in framework for simulation for SIS-100 is presented in Tab. 1.1.

	hadron	electron	muon (J/ψ and LMVM)
MVD	+	+	
STS	+	+	+
MUCH			+
RICH		+	
TRD	+	+	+
TOF	+	+	+
PSD	+	+	

Table 1.1: CBM detector setups available in CbmROOT. LMVM - Low-Mass Vector Mesons.

Chapter 2

Correlation femtoscopy

The correlation femtoscopy is also called femtometry or HBT measurements (for pairs of identical particles). It uses correlations between particles to measure the size of the source that emits them [4].

- quantum statistic - if there are two identical particles, their wave functions must be symmetrical (for bosons) or anti-symmetrical (fermions). This effect (HBT effect) modifies the probability of emission/detection of two particles.
- final state interactions - if two particles interact, the probability of detection of such pair is also modified, e.g. the probability of registration of a pair of $\pi^+\pi^-$ with small relative momenta is increased due to coulomb attraction, whereas for same-charged particles it is decreased.

The correlation femtoscopy bases on correlation functions defined by:

$$C(q) = \frac{N(q)}{D(q)} \quad (2.1)$$

where $q = p_1 - p_2$. $N(q)$ - is the numerator of the correlation function (distribution of correlated pairs), and $D(q)$ is the denominator (distribution of uncorrelated pairs). The denominator (in most cases) is obtained by the so called mixing procedure, where both particles in a pair come from different events.

The correlation function can be used for measurements of the source size. Due to femtoscopic correlations, the measured correlation function is a kind of a transformation of the source emission function $S(r)$. In case of a source with a $S(r) \approx \frac{1}{r^2} e^{-\frac{r^2}{2R^2}}$ and non-interacting bosons with spin 0, the correlation function can be expressed as:

$$C(q) = 1 + \lambda e^{-q^2 R^2} \quad (2.2)$$

where R is the so-called “femtoscopic radius” and λ is the fraction of correlated pairs. Example correlation function is presented in Fig. 2.1.

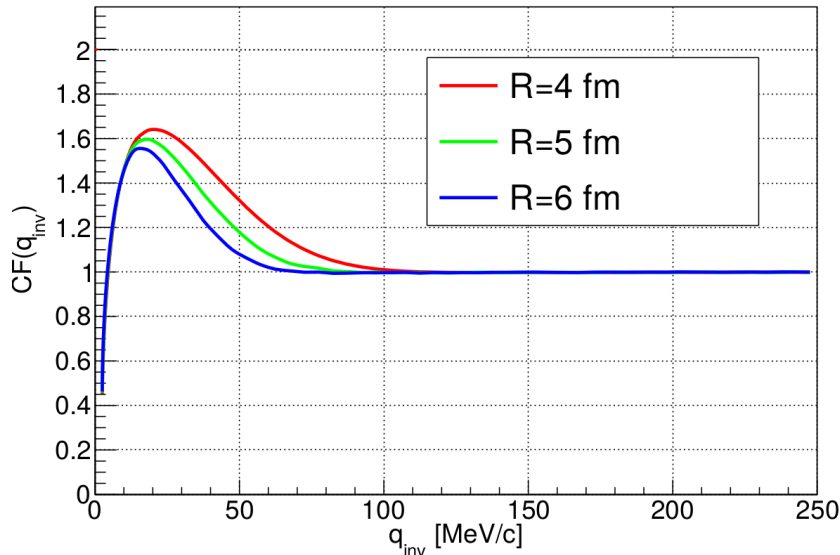


Figure 2.1: Correlation function for $\pi^+\pi^+$ pairs. It was generated with a Gaussian distribution of the source density. It can be noticed that a wider peak corresponds to a smaller source. For this function, the shape is defined by two effects - quantum statistics (see eq. 2.2) and coulomb repulsion (responsible for the decrease of the CF value when $q \rightarrow 0$).

This method is the only one currently known technique for measurements of the source size. The typical size of the measured source is a few femtometers.

There are two significant differences between correlation functions (CF) obtained from models and data. Models do not take into account femtoscopic effects - therefore such functions are flat (if non-femtoscopic effects can be neglected and femtoscopic effects are switched-off in the analysis). The correlation function measured in experiments is modified by detector effects like:

- particle misidentification
- limited momentum resolution
- two-track effects:

- track splitting - reconstruction one real track as a pair of tracks; this effect increases the value of the correlation function
- track merging - the reconstruction of a pair of tracks as a single particle; this effect decreases the value of CF

Because the CF is sensitive to those effects it can be used to study them. A non-flat shape of CF (without correlations taken into account) suggests problems with tracking.

Chapter 3

Software in the CBM experiment

3.1 CbmROOT framework

The software of CBM is called CbmROOT. CbmROOT bases on two packages:

- FairSoft - a group of scripts that install and configure many packages like ROOT or Geant. Geant is used for simulation of particles propagation in matter. ROOT is a framework used for many things like storing data in special format (called ROOT trees), visualization of data etc.
- FairROOT - a group of libraries that allows to use all FairSoft elements together, e. g. in FairROOT it is possible to use Geant3 for transport of particles and ROOT for storing the results of such simulation.

The main goal of the development of FairSoft and FairRoot is the creation of a uniform framework that can be used in future high-energy physics experiments. Today FairRoot is used in many experiments like CBM, MPD, BM@N or PANDA.

CbmROOT is based on FairROOT and contains many elements, the most important are responsible for:

- description of subdetectors
- simulation of detector response
- reconstruction of the tracks
- analysis of data

The main goal of this work was adding the option of performing HBT analysis in CbmROOT.

3.2 CMake package

CbmROOT is written in C++. Therefore it must be compiled. Small projects use makefiles. A makefile is a file that contains directives to build a project. Makefiles are easy to use for small projects. Using makefiles in CbmROOT is problematic because it is a huge project, compiled on many different operating systems. Therefore CbmROOT uses CMake. This is a tool responsible for creation of makefiles. Thanks to CMake the installation and development of CbmROOT is simple.

3.3 Simulation with CbmROOT

There are three macros used for simulation of data, which were used in this project:

- `run_transport.C` - this macro takes data from an event generator and simulates propagation of particles through the matter of the detector
- `run_digi.C` - this macro simulates the response of the detectors by using information from the file produced by `run_transport.C`
- `run_reco_event.C` - reconstructs events from data produced by `run_digi.C`

CBM can simulate data in two modes: “event by event” and “timeslice” mode. In mode “event by event” each event is simulated and reconstructed separately. In the “timeslice” mode many events (registered in a time window called “timeslice”) are reconstructed together. Due to high collision rates all events in CBM will be recorded (and reconstructed) in “timeslice” mode. Unfortunately algorithms for “timeslice” reconstruction are not ready yet. Therefore data for analyses in this work were simulated by using the “event by event” mode.

In this work 2.5 millions of central gold-gold collisions at $p_{beam} = 10 \text{ GeV}/u$ were simulated with the “sis100 electron” setup. This data were used for testing the implementation of the code. The same data were also used for femtosopic analysis.

Chapter 4

NicaFemto

4.1 History of the development of NicaFemto

The major part of software for HBT analysis looks almost the same in all experiments. A lot of classes in NicaFemto were inspired by code used in the STAR and the ALICE experiments. NicaFemto was originally designed as an “universal framework for femtoscopic analysis”; however the main goal of this project was the creation of software for analysis in MPD experiment (Multi Purpose Detector that will be part of NICA - Nuclotron-based Ion Collider fAcility. This framework was created by the author of this document.

In fact, the original NicaFemto was made of two parts:

- “core” called NicaFemto. This is a stand-alone project that contains algorithms for processing data, analysis of the correlation function etc.
- “interface” called nica_mpd. This is part of MpdROOT (framework used by the MPD collaboration). It contains interfaces for reading and selection of data collected (simulated) in MPD. This interface supports also data in Unigen format.

4.2 NicaFemto features

NicaFemto currently provides:

- a system of data selection (cuts)
- the option of processing any type of data (requires interface)
- a data monitoring system (cut monitors)

- calculation of one- and three-dimensional correlation functions for pairs of identical and nonidentical particles
- tools for fitting correlation functions obtained in the analysis
- a system of reports in form of HTML pages
- a simplified version of code for analysis of flow, spectra and fluctuations
- a system of warnings during merging of non-compatible files

Only the two first features depend on experiment. Therefore, the implementation of NicaFemto inside CbmROOT is much simpler than the creation of the new framework.

4.3 Usage of NicaFemto

NicaFemto is usually used as a task. The user has to create, configure and add such tasks to FairRunAna (class that manages all analyses in a given macro). There are few classes in this framework that represents tasks, the most important are:

- NicaFemtoBasicAna - manages almost all HBT analyses
- NicaFemtoFreezoutAna - calculates the source emission function from MC data
- NicaEventAna - class that represents event-by-event analysis
- NicaTrackAna - class that represents analysis focused on tracks
- NicaTwoTrackAna - class that represents analysis with loop over pairs of particles

The last three classes can be used as template for customized analysis. For example NicaFemtoBasicAna uses NicaTwoTrackAna as base class.

A very important part of the framework are cuts. Any cut in NicaFemto can have the following “properties”:

- fast/non-fast. A fast cut is created when the user adds a cut with the option “fast”. Fast cuts immediately reject objects from analysis (given objects are no longer processed by other cuts or cut monitors). Those cuts can speed up the analysis, but cannot be monitored.

- imaginary/real cuts - they check the “real” or “imaginary” part of the data, which works only with “complex” format. Those cuts can be created by adding a “normal” cut with “re” or ”im” option.
- collection ID: cuts with the same collection-ID are threaded as a single cut

An example of a adding cut and the cut monitor is shown in Alg. 1. In this function, analysis uses complex data. Therefore for verification of the vertex position, a “real” cut must be used. Because we would like to monitor this cut, it cannot be fast. The cut monitor is created by setting the name of the cut(s) and the number of parameter(s) for monitoring.

Algorithm 1 Example of adding event cut with monitor for monitoring “real” part of data.

```

1 void SetEventCuts(NicaEventAna *ana){
2     NicaEventVertexCut *vx = new NicaEventVertexCut();
3     NicaCutMonitorXY *mon = new NicaCutMonitorXY(vx->
        CutName("re"), vx->Rt(), vx->CutName("re"), vx->Z());
4     mon->SetXaxis(100, 0, 0.5);
5     mon->SetYaxis(100, -.1, .1);
6     ana->Add(vx, "re");
7     ana->Add(mon);
8 }

```

Chapter 5

NicaFemto in CbmROOT

5.1 Changes in NicaFemto

NicaFemto was designed as “experiment-independent”. However, during developing the code for HBT analysis it was necessary to make some changes.

The policy for the installation of packages in MpdROOT and CbmROOT is different. In MPD framework, NicaFemto was installed after the installation of MpdROOT, by a special bash script. NicaFemto in fact was a subdirectory added to MpdROOT. In CbmROOT this is not allowed - external code must be a “stand-alone” package that can be built by the framework. Therefore the first step was to rewrite the CMake files in NicaFemto. New version of this code can be installed in MpdROOT (as subdirectory), in CbmROOT (as external package) and as stand-alone code.

The source code of NicaFemto has also been changed, e. g. support of arrays with tracks is now better, the number of warnings during compilation of NicaFemto was significantly reduced. All those changes are now in the “main” version of NicaFemto.

This new version of NicaFemto is now a part of CbmROOT. However it is only a part of the code needed to perform femtosopic analysis in CBM. The next chapters describe another part of the required code - the new elements of CbmROOT.

5.2 Interfaces

The implementation of a single format requires the creation of four classes that base on:

- NicaEventInterface - this class stores events in original format, is responsible for reading data from file, can be optionally used for modifying original data
- NicaTrackInterface - stores track in the original format
- NicaEvent - class that stores event information. This is the class used in data processing. Event classes are used instead of “event interfaces” due to following reasons:
 - performance (do not use virtual functions)
 - memory consumption
 - simplification of code
 - flexibility (new methods/functions/members can be added without modification of the original data structure)
- NicaTrack - class that stores track information

The format can be specified by calling “NicaEventAna::SetFormat(X)”, where X is the event class that represents a given format e. g. NicaCbmGlobalEvent. Formats already implemented for CBM are:

- NicaCbmGlobalEvent - stores basic information about events and global tracks
- NicaCbmEvent - like NicaCbmGlobalEvent but also stores information about “subtracks” (like CbmStsTrack)
- NicaCbmMatchedEvent - like NicaCbmEvent but contains also pointer to MC data. This format is not used directly.
- NicaCbmMCEvent - carries information about MC tracks
- NicaCbmGlobalMCEvent - “complex format”; the real part of such event corresponds to NicaCbmMatchedEvent, the “imaginary” part corresponds to the NicaCbmMCEvent format.
- NicaUnigenEvent - for processing data in Unigen format (requires NicaUnigenSource instead of FairFileSource)

Implemented (but not tested) formats are:

- NicaCbmEventHits - stores the same information as NicaCbmEvents and hits
- NicaCbmGlobalMCEventHits - works like NicaCbmGlobalMCEvent but “the real part” is NicaCbmEventHits

5.3 Data selection

Cuts are responsible for data selection. Some cuts are part of the NicaFemto package (like the cut on transverse momentum). Other cuts cannot be part of NicaFemto because they depend on CbmROOT. The most important cuts created for CBM are:

- Track cuts
 - CbmTofTrackCuts - selects tracks by β_{TOF} and m_{TOF}^2
 - CbmTofMassCut - selects tracks by m_{TOF}
 - CbmTofM2Cut - selects tracks by m_{TOF}^2 . The user can specify the accepted mass as a function of the particle momentum.
 - CbmStsTrackHitsCut - selects tracks by number of hits in STS, MVD and sum of hits in STS and MVD
 - CbmStsStationsCut - rejects global track without STS track
 - CbmStsFarDetectorHit - rejects tracks without at least one hit in TRD or TOF
 - CbmHasTofTrackCut - rejects global tracks without TOF hit
- Pair cuts:
 - CbmStsPairAverageDistance - checks average distance between two tracks in all STS stations
 - CbmStsPairEntryDistance - checks distance between two tracks in the first STS station
 - CbmStsPairExitDistance - checks distance between two tracks in the last STS station

Pair cuts take into account the event position (all STS stations are shifted by the event position, which is needed for mixing procedure). The position of tracks in these cuts is calculated by using a track propagator.

5.4 Code tests

NicaFemto was tested many times during development of the code for MPD. Therefore tests of code for femtoscopic analysis were focused on testing the new parts of the code like cut algorithms and interfaces for data reading. A typical test was a comparison of results produced with two codes: one was using the framework for femtoscopic analysis, the second one was a simple macro.

Chapter 6

Analysis of simulated data

6.1 Momentum resolution

The first analysis was dedicated to the study momentum resolution. In case of HBT analysis, the correlation function is smeared due to non-perfect momentum reconstruction. This can be partially corrected, but larger corrections usually mean larger systematic uncertainties

The momentum resolution was studied as a function of number of hits in the detector. The main tracking detector in CBM is STS; therefore the resolution was studied as a function of hits in STS. As it was expected (fig. 6.1) - tracks with more hits in STS are reconstructed more precisely.

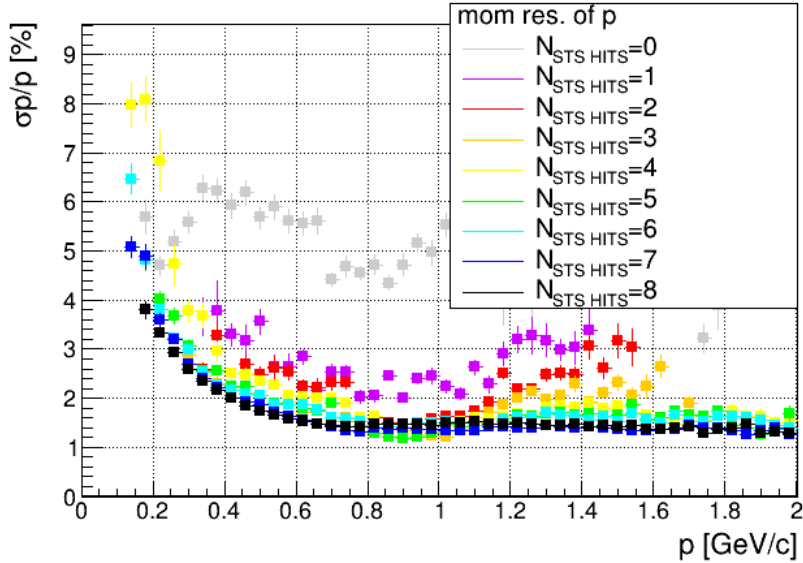


Figure 6.1: Momentum resolution of global tracks as a function of hit number in STS.

6.2 Primary/secondary particles

The particles created in the collisions can be divided in two groups:

- primary particles produced directly in the collisions
- secondary particles produced from unstable primary particles (or interactions in the detector materials)

Some unstable particles live long enough to decay far away from the collision position. In such case it is possible to distinguish between them and the rest of the particles. In most of the experiments, DCA cut is used.

DCA (Distance of Closest Approach) is the minimal distance between the collision position ($\vec{V} = (V_x, V_y, V_z)$) and the trajectory of particle. Unfortunately there is no simple way to calculate this value in (the current) version of CbmROOT. Therefore it was chosen to use the “approximated DCA”. The “aDCA” is a distance between the event position and the trajectory of particle in the plane defined by $z = V_z$.

The distribution of the ‘aDCA’ for primary and secondary particles is shown in Fig. 6.2

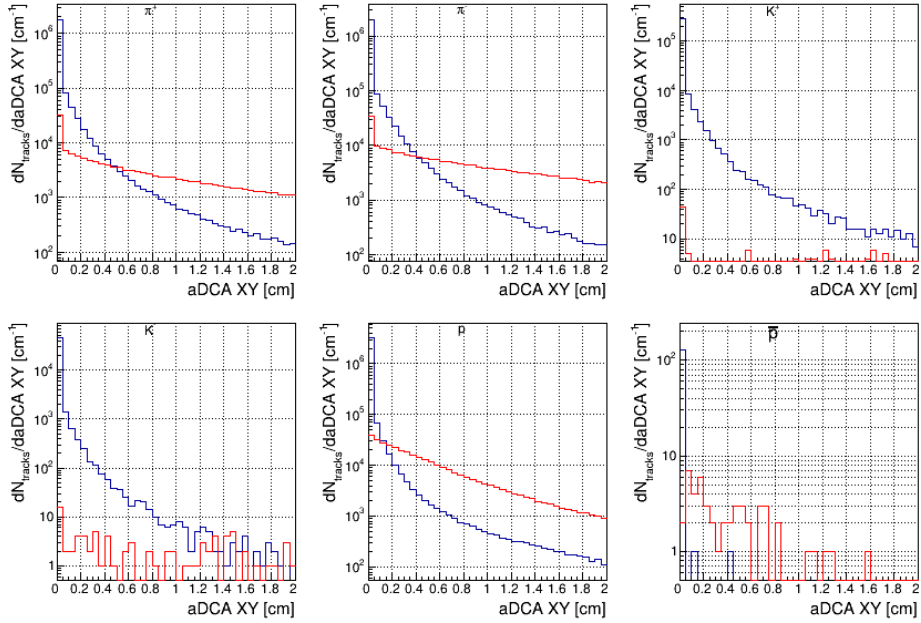


Figure 6.2: Distribution of “aDCA” for secondary (red) and primary (blue) particles.

6.3 Particle identification

Particle identification (PID) is done by using TOF measurements. In CBM the measured mass is not stored directly. The mass of a particle can be obtained from:

$$m^2 = \frac{p^2}{\beta^2 - 1} \quad (6.1)$$

Where β is the velocity of the particle. With mass, momentum and charge it is possible to identify the particle. The first point of the analysis was looking at the purity of particles with $N_{STS} \geq 6$ and $p_T > 0.2$. The purity is a ratio of the number of correctly identified particles to the total number of accepted particles. The fraction of particles without any PID cuts is shown in Fig. 6.3. It can be noticed that production of K^- and \bar{p} is so small, that no TOF information is needed to get a very pure sample of π^- , at least up to $p = 6\text{GeV}$.

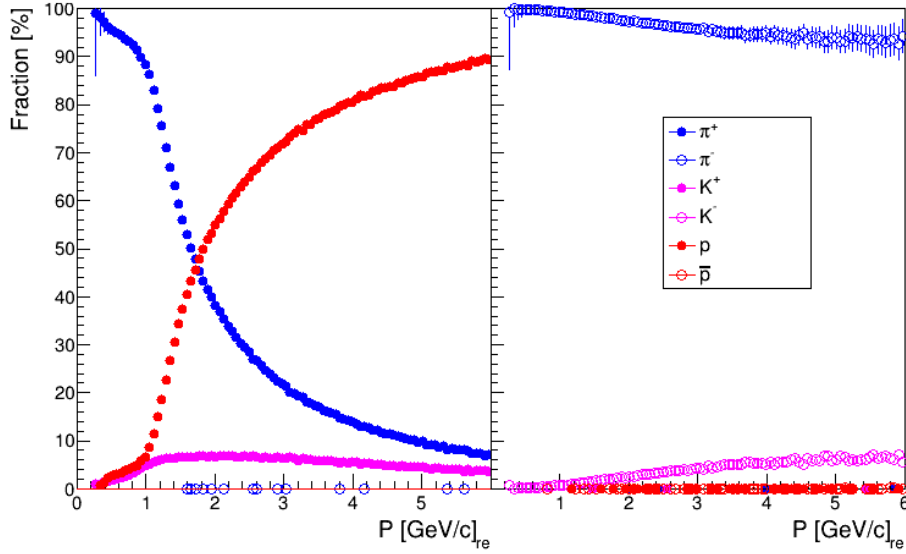


Figure 6.3: Purity of positively (left) and negatively (right) charged particles.

6.4 Analysis, two-particle cuts

The femtoscopic analysis was focused on $\pi^+\pi^+$ correlations. Such particles were chosen because they are easy to detect and numerous. Therefore, the following criteria were applied:

- $p > 100 \text{ MeV}/c$
- $0 < m_{TOF}^2 < 50 \text{ MeV}/c^2$
- $N_{STS \text{ hits}} \geq 6$
- $aDCA_{XY} \leq 2 \text{ mm}$

The results of the analysis are shown in Fig. 6.4. The correlation function was generated without any femtoscopic effects; however a large peak is visible at $q_{inv} < 20 \text{ MeV}/c$. Usually such effect is observed when splitting occurs. However, after removing pairs with the same MC parent (Fig. 6.5) there is still peak. Removing non-pions (Fig. 6.6) removes peak. The conclusion is that the peak is related to imperfect PID, however now a new effect appears - “the merging”

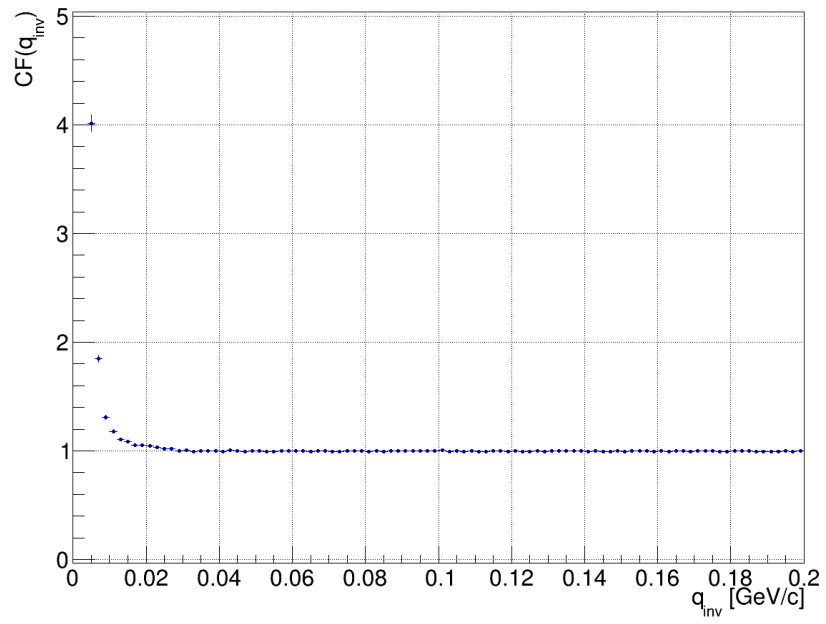


Figure 6.4: Correlation function without any two-particle cuts.

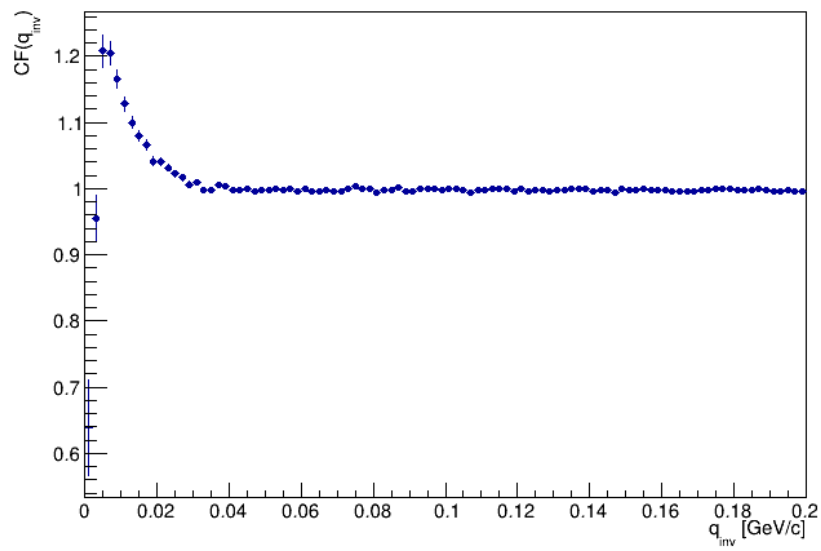


Figure 6.5: Correlation function with anti-splitting cut.

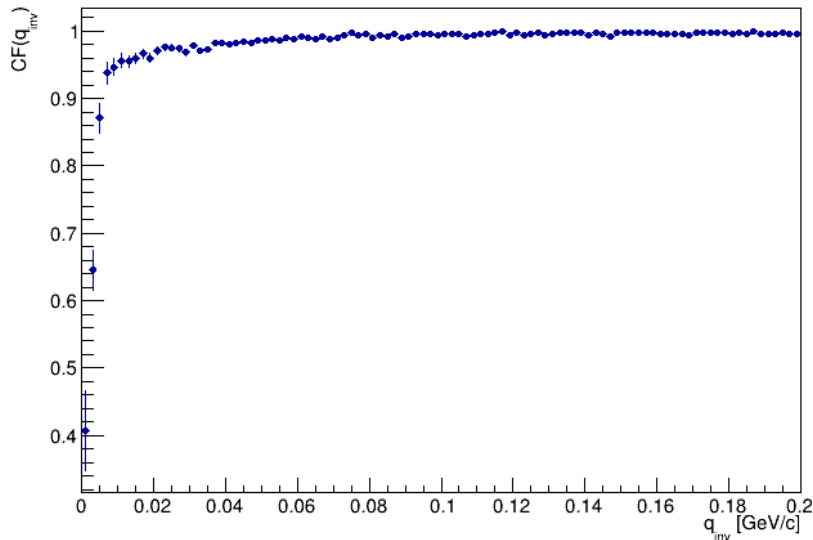


Figure 6.6: Correlation function after rejecting all non-pions.

Those simple analyses show that in CBM both two-track effects are present - splitting and merging. Also particle purity seems to affect the shape of the CF. Those three effects need a further study.

In this analysis splitting was removed by applying a cut on the MC-parent. This is of course impossible in experimental data. In collider experiments like ALICE and STAR splitting is removed by looking at the distribution of hits in layers of the detector. It is an open question if such procedure can be used in CBM - STS has only 8 stations whereas STAR and ALICE have more than 40 layers/rows of TPC pads [5, 6].

Merging is removed by removing tracks that fly very close. In fig. 6.7 it can be seen that merging is present at least for tracks with $STS\Delta X_{Entry} < 2mm$. Further studies of this effect require more data.

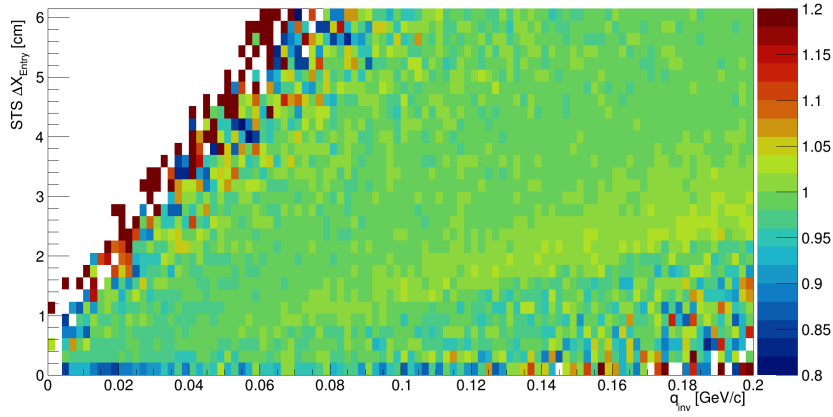


Figure 6.7: Correlation function after rejecting all non-pions and splitted pairs as a function of the separation between two tracks in the first station of STS.

Two-particle cuts require well-known information about the trajectory of the particle. Such information can be used to calculate hit positions (without the need to read hits from data) or distances between tracks. In collider experiments the trajectory is easy to calculate (it's a helix). The calculation of the trajectory in CBM is much more complicated due to the presence of inhomogeneous magnetic field.

A part of stay at GSI was dedicated to study classes for calculation of the particle's propagation in CBM detector. Those studies will be useful also for groups of physicist not related to femtosopic analysis. They will be reported in CBM Computing Note in the near future.

Chapter 7

Summary and future plans

Software for femtosopic analysis that base on NicaFemto was implemented as a part of CbmROOT framework. This was possible before creating the OCT19 version of CbmROOT. Therefore this is the first official release of CbmROOT that has code for femtosopic analysis. Now it is possible to calculate correlation functions with CBM data and MC data (in Unigen format). Analysis of simulated data shown that two-track effects require further studies. Currently the priority is testing the performance of different track propagators (classes used for calculation of track trajectory in CBM). The propagators are key classes for two-particle cuts. Such studies will be also useful for other groups. The result of this study is planned to be one of the CBM Computing Notes. Another plan for the future is to study the capabilities of the femtosopic measurements in CBM experiment.

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