Charged Current Interactions at HERA
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Citation for published version (APA):

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Chapter 6

Muon Finder

6.1 Introduction

The charged current event sample is contaminated with overlapping events. These can either be due to cosmic ray or "halo" muons together with a normal e-p-interaction or beam-gas event.

Halo muons are muons created by interactions upstream of the detector, which traverse the detector from RCAL to FCAL at a large radius. These halo muons can produce large $R_y$ because they traverse the BCAL parallel to the scintillator plates. The pulse height registered can then be many factors larger than one would expect from a muon, due to the significantly increased sampling along the muon track.

Cosmic muons arrive predominantly from above and traverse the detector from top to bottom. These are in general no problem as the minimum ionizing energy deposit will not generate a large transverse momentum. There are exceptions to this though. A cosmic muon can enter FCAL or RCAL or to a lesser extent BCAL from above and again travel parallel to the scintillator plates, giving large apparent energy, and then in general as they are "off center" a large $R_y$. Another possibility for a cosmic muon to produce large $R_y$ is that the high energy muon produces a bremsstrahlung photon in the UCAL, before exiting the detector. Also events with multiple muon tracks form a significant background.

Figures 6.1 through 6.3 and figure 6.8 show examples of the different background categories mentioned above.

These events can not be detected by the algorithms employed so far, as these algorithms assume that the halo muon or cosmic is alone in the detector. When the halo or cosmic muons overlay a genuine e-p event the information from the underlying e-p-event masks the information of the muon and thus render the algorithms useless.

The muon finder (MUFFIN) described in this chapter attempts (and succeeds) to find these muons. The principle of the program is to search for a topology of calorimeter cells within normal events, which is consistent with a muon traversing the detector. The characteristic topology is a series of aligned cells (i.e. high energy muons traverse the detector in straight or almost straight lines). When a muon candidate is found the event is removed from the CC sample if by removing the muon candidate energy deposits the event no longer passes the CC selection cuts. The detector elements that are important in the muon finder are the muon chamber system (FMUON, BMUON and RMUON), the calorimeter (FCAL, BCAL and RCAL) and the central tracking system (CTD).

In current physics analyses visual scanning is an accepted method to remove this source of background. This method has several disadvantages though:
CHAPTER 6. MUON FINDER

Figure 6.1: Example of a cosmic muon traversing the ZEUS detector together with what appears to be a beam-gas event. On the left side the cells surrounding the FCAL beam pipe region are shown. On the right side the cosmic muon which traverses the BCAL can be seen. In the middle of the picture tracks stemming from the beam-gas event are drawn.

- The number of events a physicist can scan for an analysis is limited.
- Visual scanning has a high efficiency but the efficiency is not constant.
- It is difficult to estimate the efficiency and purity of the visual scan method.

The following will be a detailed description of the muon finder program.

6.2 The Muon Finder Algorithm

A traversing muon deposits energy in detector elements along its flight path. The pattern of hit detector elements is usually isolated from the overlap event because of the high granularity of the ZEUS detector and the low occupancy of most events. During visual scan the trained physicist identifies such a pattern easily because it usually forms a straight line. \(^1\)

\(^1\)It would sound like a good idea to use a specialized pattern finder program based on a neural net to identify a cosmic muon event. This however is very difficult because the net would be far too big - it would have to contain all ZEUS detector elements as entry neurons and would thus require a huge number of cosmic muon events to
MUFFIN tries to find all patterns of hit detector elements which form a straight line. It uses tracks from the muon detectors and calorimeter condensates (see section 6.3.1) to find these patterns. For each pattern a set of parameters is calculated and compared to the parameters describing a traversing muon. If MUFFIN were to use a brute force method and just calculate all combinations of tracks and condensates it would take too much time to evaluate an event. Instead MUFFIN uses several tricks to speed up the search for a candidate pattern:

- MUFFIN stops after a single traversing muon has been identified by the trigger conditions.
- MUFFIN temporarily removes all detector hits which belong to a traversing muon candidate from the event. Only if the remaining event fails the trigger conditions for the event (e.g. the CC $R_z$ cut), the candidate pattern is further evaluated. This algorithm is based on the assumption that the event consists of a background event that would normally not pass the trigger and a traversing muon which is responsible for the event passing the trigger.
- MUFFIN uses ray tracing algorithms to speed up the most time consuming part of the processing which is to find the cells which are hit by a muon trajectory. Upon initialization train. But then it would only be able to recognize single cosmic muon events, a detection of a cosmic muon overlapping with a beam-gas or true collision event would be extremely difficult.
MUFFIN creates 27 evenly distributed volumes “containers” (three in each coordinate direction) which contain the entire calorimeter. Each of these volumes contains again 27 volumes, “boxes”. Each of those boxes contains calorimeter cells. When MUFFIN tries to find the cells hit by a muon it first checks which “containers” are hit by the muon and then inside each hit container it checks which “boxes” are it. Only then will it check cell by cell.

In order to test whether a cell is hit MUFFIN has two radii available, the radius of the largest sphere around the cell center that is fully contained in the cell $r_{\text{inner}}$ and the radius of the smallest sphere around the cell center that contains the cell $r_{\text{outer}}$. By testing the distance of the cell center to the trajectory $d$ MUFFIN can determine quickly whether the trajectory hits the cell ($d \leq r_{\text{inner}}$) or not ($d > r_{\text{outer}}$). Only for the remaining cases ($r_{\text{inner}} < d \leq r_{\text{outer}}$) MUFFIN performs a precise geometric check testing whether the trajectory hits any of the cells surfaces.
6.3 Muon Finder Input Data

6.3.1 UCAL Cells

Energy Cuts

The muon finder uses only cells which are reconstructed by the standard ZEUS offline reconstruction program CCRECON. CCRECON applies energy cuts of 60, 100, 110 GeV for EMC, HAC1 and HAC2 cells respectively to reject noise (see \[36\]).

UCAL Geometry

For MUFFIN every calorimeter cell consists of several boxes which contain the uranium scintillator sandwiches. With this representation MUFFIN can calculate for a traversing particle the exact length of the trajectory within each cell.

Almost all cells in the HAC region consist of a single box, while the cells in the EMC region consist of three (FCAL) or two (BCAL, RCAL) boxes to take into account the HES gap. Only the HAC cells in BCAL towers 1 and 14 are constructed of two boxes to construct their volumes precisely.

UCAL Photomultiplier Time

The calorimeter data as stored by the reconstruction program contain the time reported by the digital cards. A time-of-flight correction has been applied to this time online so that the reported time is zero for a particle coming from a collision at the nominal interaction point. This is ideal for the trigger system because it can simply select good events by requiring the average event time to be close to zero.

A traversing muon however is obviously not coming from the nominal interaction point, so in order to allow a measurement of the velocity of the muon the correction is undone.

Whenever calculations involving the time measured in the calorimeter are performed MUFFIN uses the individual photomultiplier time as well as the energy reported by this photomultiplier to calculate an error on the time. For the error calculation it uses the same formula that is used inside the standard offline reconstruction program (see (3.1)).

UCAL Readout Holes

MUFFIN considers the calorimeter to consist only of the good cells in an event: If a muon traverses an inactive cell MUFFIN does not expect energy from this cell.

UCAL Photomultiplier Sparks

Standard analyses of ZEUS data usually remove all calorimeter cells with a large imbalance (see (5.1)) from the event data. MUFFIN instead keeps all those cells. The reason is that the probability for a coincidence of a spark and a background muon is very low. So if there is a cell with large imbalance this is more likely due to the muon than to a spark, for example because of a muon bremsstrahlung near the wave length shifter.
Figure 6.4: Schematic view of a muon traversing UCAL cells. From the cells with enough energy to pass the noise cuts CCRECON (on the left) constructs three condensates as shown by differently shaded boxes while CONDENSOR (on the right) only constructs a single condensate.

**UCAL Condensates**

A "condensate" is an object which contains calorimeter cells which are clustered together. The standard ZEUS UCAL reconstruction program CCRECON (see [36]) creates condensates of neighboring cells if they have a common surface.

MUFFIN uses a separate program "CONDENSOR" to construct condensates. Here cells are also neighbors if they touch each other on a common edge or corner (see figure 6.4).

In CONDENSOR the extreme towers of BCAL can also have neighbors in FCAL or RCAL. CONDENSOR knows of two different neighborship relations: Cells are neighbors when either their projections on the $X - Y$ plane overlap or if a straight line through $(X = 0, Y = 0, Z = 0)$ hits both cells. Unlike CCRECON CONDENSOR does not remove condensates with little energy. CONDENSOR also performs a 3-D line fit to the cell centers and uses this line to calculate shape parameters such as the "hit ratio" which is the ratio of the number of cells hit by the trajectory over the total number of cells. These parameters are used by the muon finder to speed up calculations.

### 6.3.2 Muon Chamber Tracks

Barrel and rear muon detector detector tracks are already used in the trigger system to reject some of the cosmic muon background events online. Still many of the cosmic or halo muon events contain tracks of the muon detectors and it turns out that all information coming from the muon detectors is very useful for MUFFIN.

MUFFIN uses full tracks from the FMUON, BMUON and RMUON detectors. A full track has valid information in all 3 coordinates.

MUFFIN also uses tracks for which only wire or strip readout is available. Wire or strip readout tracks are only available from BMUON and RMUON. For these tracks one of the coordinates
Figure 6.5: The figure shows schematically (in 2D) how MUFFIN combines two muon chamber tracks to one. A muon track consists of an offset and a direction vector, MUFFIN makes a combined muon track as track connecting the two offset vectors but checks if the angles $\alpha$ and $\beta$ are not too large.

MUFFIN tries to find combinations of two full muon tracks that are compatible with the combined track as shown in figure 6.5. It calculates a straight line between the two offset vectors of the tracks. This straight line is a better approximation of the muon trajectory than that of the individual muon tracks since the two offset vectors are known to much higher precision than the direction vectors. MUFFIN then removes combined muon tracks for which the angle between the combined track and the individual tracks' direction vector is too large (angles $\alpha$ and $\beta$ in figure 6.5 have to be less than 10°).

Combined Full and Wire Tracks

MUFFIN tries to find combinations of a full muon track with a wire readout track. The wire readout tracks are track segments for which one coordinate is unknown. If the track is found in the barrel region this unknown coordinate is $Z$, if the track is in the rear region the unknown coordinate is $X$. MUFFIN tests whether for both tracks the angle between the track and the combined track is smaller than 15°. This test is performed in the plane where the coordinates and the direction vectors are known, so either in the $X$-$Y$ plane for wire tracks from the barrel region or the $Y$-$Z$ plane for the rear region.

For the combined tracks the missing coordinate is estimated from the full track. Then MUFFIN performs a minimization (MINUIT) [37] using the calorimeter information. It maximizes
the sum of the track trajectories through all calorimeter cells that have energy. If the angle between the full track and the resulting trajectory is less than 0.2 rad and the track hits any calorimeter cells with energy, the combined track is kept.

Combined Wire Tracks

MUFFIN also tries to combine tracks for which only wire readout is available if these tracks are in the BMUON. For these tracks the $Z$ position is unknown. The method is the same as is used for combining full tracks as described in section 6.3.2 but only $2-D$ information is used. These combined wire tracks are not used to find muon candidates because of the missing coordinate. Instead for each muon candidate the minimum angle between the candidate trajectory and the $2-D$ combined muon track is calculated and used to identify muon candidates.

6.3.3 Inner Tracks

CTD Tracks

MUFFIN uses tracks from the central tracking detector which have been projected onto the UCAL inner surface. The tracks are used to help to separate the pattern of a true traversing muon from a genuine physics or beam gas event. MUFFIN requires the track momentum to be bigger than 1 GeV/c to select only straight tracks.

Vertex

MUFFIN uses the event vertex (either from the tracking detector, the C5 run average or nominal vertex) to determine $E_t$ and $R_t$. It also determines the distance of a muon trajectory from the vertex as one of the candidate parameters.

6.4 Muon Bremsstrahlung

6.4.1 Muon Bremsstrahlung Shower in UCAL

A high momentum muon can produce a bremsstrahlung shower in the UCAL. If the shower is not localized to the cell it occurred in but hits more cells it can pose a problem to the muon finder because the fitted trajectory does not pass through all cells. In figure 6.6 such a case is illustrated. MUFFIN identifies such a case by requiring that the energy in the shower center cell is bigger than 5 GeV and all the energy in all neighboring cells which are not hit by the fitted trajectory (cells “1”, “2” and “3”) is less than 10% of the energy in the shower center.

6.4.2 Muon Bremsstrahlung Shower in a UCAL Wave Length Shifter

A muon can produce a bremsstrahlung shower in or near the wave length shifter (WLS). Such a shower will not be localized to the cell it occurred in but also cause the photomultipliers of neighboring cells to record energy. Figure 6.7 illustrates this for two neighboring modules. Since the cells are neighboring and since MUFFIN is largely based on condensates these cells (the EMC cells in figure 6.7) which have not been traversed by the muon are part of the candidate. When MUFFIN tries to perform the trajectory fit these cells will reduce the hit ratio of the candidate and thus reduce the efficiency of the finder for such events.
One possibility to deal with this problem would be to perform a cut on the imbalance in a cell. This however would compromise the muon finder efficiency for muons which only traverse a few cells.

Instead MUFFIN uses CONDENSOR to find all cells which could have energy just because there was a shower that leaked into their WLS:

CONDENSOR first tries to identify the cell that contains the center of the shower. Such a cell has to have imbalance bigger than 0.1 and more than 5.0 GeV energy. The imbalance of the cell points to the side where the shower occurred. Due to the geometric structure of the UCAL only cells in front of the cell that contained the shower can be potential candidates for cells with energy due to a shower. Also cells in neighboring towers can be candidates, so MUFFIN scans the next 2 towers.

For this WLS shower topology CONDENSOR requires at least one cell on the other side of the WLS-gap to have a large imbalance of 0.5. Only then will it use a lower imbalance cut of 0.3 to find the other cells. Moreover CONDENSOR requires that for all candidate cells the channel that is not on the WLS-side recorded energy below the noise cut value. This value is the per-cell noise cut value (see section 6.3.1) divided by $\sqrt{2}$.

### 6.4.3 Muon Bremsstrahlung Showers leaking into the CTD

Events where the muon bremsstrahlung occurs just before the muon traverses the CTD or inside the CTD volume usually cause many tracks to be seen in the CTD. Moreover, because of the solenoidal field in ZEUS, particles will be bent away from their initial trajectory and cause a wide area of cells to be hit near the region where the muon leaves the inner volume. Figure 6.8 shows such an event. MUFFIN tries to identify the cells which have been hit by such particles by using the trajectory of the muon and the direction of the magnetic field to calculate the plane in which the particles’ trajectories are located. MUFFIN allows the vector pointing from the cell
Figure 6.7: Schematic view of two modules (A top, B bottom) and the WLS and different channels. If a muon showered in the location given by the hatched circle the EMC and HAC1 channels near the gap record energy (A.EMC.L, A.HAC1.L, B.EMC.R, B.HAC1.R) while the other channels do not record energy.

to the muon trajectory to deviate 15° from the normal to the magnetic field.

6.5 Program Initialization

During the initialization phase of MUFFIN some lookup tables are zeroed and all steering cards are processed. It is possible to create a template of the steering cards file with the current settings, as well as a LATEX [38] file which contains the steering cards in the default setting and which can be included in a document.

Most of the remaining initialization work is performed when the first event is read because MUFFIN needs to know the event date to select geometry and calibration data valid for that data taking period:

- read all geometry information
- calculate the calorimeter cell geometry
- read the neighborship relation lookup table
- calculate parameters for fast ray tracing through the calorimeter

Normally all this initialization is only performed a single time, but if MUFFIN is used on data stemming from periods with different geometry setup, MUFFIN can be instructed to redo the initialization for every run.
MUFFIN can perform additional tasks:

- calculate the neighborship relation lookup table.
- create CAR files with the neighborship relation lookup table.
- create a VRML file [39] with the neighborship relation lookup table for every cell type (so not for every cell, but for every neighborship type one file).
- check various geometric algorithms inside the CONDENSOR code.
- check for overlapping cell volumes (which would be a serious mistake in the geometry).
- create a template steering cards file with the current settings.

### 6.6 VRML File Output

MUFFIN can output the event data as VRML-1.0 files. VRML, "Virtual Reality Modeling Language" [39] is a file format which can be used to describe 3-D scenes which can then be looked
at with a VRML-browser. Such browsers are available as so called “plug-in” software for many popular WWW HTML browsers. MUFFIN can also add the candidate information to the data, thus allowing to view the results of the calculations in a graphical form and improve and debug the algorithms.

6.7 Muon Candidate Finders

For every event the following muon candidate finders are called one after the other in the sequence below until a muon is found:

1. Find candidates based on combined muon chamber tracks (see section 6.7.2)
2. Find candidates based on muon chamber tracks (see section 6.7.2)
3. Find candidates based on condensates only (see section 6.7.3)
4. Find halo muon candidates which occur very close to the beam pipe (see section 6.7.4)
5. Find candidates based on the condensate timing (see section 6.7.5)

A very important step to eliminate candidates is based on the following idea: The MUFFIN finder assumes that the reason why an event was taken by the trigger system is the overlapped muon. It assumes that, had the muon not been there, the event would have been rejected.

In the case of the CC sample the traversing muon has increased the $R_t$ of the event and so the event was triggered. This is an important property for a muon candidate and it is used to reduce the sample of possible candidates significantly: Giving a trigger condition such as $R_t > X \text{ GeV}$ MUFFIN temporarily removes all candidate cells and tests the condition. If the condition is not fulfilled anymore it means that the candidate might be a traversing muon. Should the condition still be fulfilled it means that the candidate is just a random combination of cells which happened to look like a traversing muon. This check is done at an early stage of the calculation in order to avoid unnecessary calculations.

6.7.1 Muon Energy Deposit Connected to FCAL Beampipe Energy Deposit

For most physics events and beam gas collisions particles hit the FCAL beam pipe region. The cells in this region usually form a single large condensate. If the traversing muon hits this condensate MUFFIN is unable to identify the muon because there are too many cells in the condensate which are not hit by the muon.

MUFFIN finds the muon in such events by removing successively rings of cells around the FCAL beam pipe hole and rerunning all of its algorithms.

6.7.2 Muon Track Based Finder

Both the finder that is based on combined muon tracks as well as the finder based on single muon tracks work in the same way: A muon candidate consists of all calorimeter condensates which are hit by the muon track. If a candidate is found all candidate parameters are calculated at highest precision. For the finder based on combined muon tracks the trajectory fit is not redone because the muon chamber tracks are the best estimate for the trajectory. For the finder based on single muon tracks the offset vector is not refitted but only the direction of the trajectory.
6.7. **MUON CANDIDATE FINDERS**

### 6.7.3 Condensate Based Finder

This finder is based on calorimeter condensates only. It uses several different algorithms to find the condensates of a candidate. The algorithms have in common that they begin with a "seed condensate" and then more condensates get added to the candidate. MUFFIN first tries to find a candidate with the first algorithm and all seeds, only then will it continue with the next algorithm.

#### Condensate Finder Seed

The finder selects calorimeter condensates as seeds which contain at least 2 cells. It will also avoid using a condensate that has too many cells from the FCAL beam pipe region: MUFFIN rejects condensates seeds that have more than 7 EMC, 2 HAC1, 2 HAC2 or more than 4 cells in total neighboring the beam pipe. The condensates are sorted into descending order according to their hit ratio. This way the condensates which have a track-like shape come first.

#### Add Condensates to the Candidate

The algorithms to add condensates use different methods:

1. **Maximize Number of Hit Cells**
   
   MUFFIN looks for the condensate which, if added to the seed, maximizes the number of cells hit by the trajectory fitted through the seed and the condensate. It then declares both condensates as the new seed and looks for the next condensate which maximizes the number of hit cells. MUFFIN only allows candidates for which the fitted trajectory hits all condensates.

2. **Maximize Number of Hit Cells Blown Up**
   
   This algorithm is just like the algorithm described above but the cell volumes are artificially increased by projecting the corners along the line connecting them with the cell center by a constant value. This improves the finders efficiency because during the candidate search only the quick linear regression line fit can be used which is not accurate enough.

3. **Maximize Occupancy**
   
   This algorithm is just like the one described above only that instead of adding the condensate which maximizes the number of cells hit this algorithm adds the condensate which maximizes the occupancy, i.e. the ratio of the number of cells of this candidate hit by the fitted trajectory over the number of cells of the calorimeter hit by the trajectory.

4. **Add Condensates with Minimum Hit Ratio**
   
   In this algorithm a condensate is added to a candidate if the hit ratio of the sum of condensate and candidate is bigger than 0.5. The hit ratio is the ratio between the number of cells of a candidate hit by the fitted trajectory over the total number of cells in the candidate.

#### Candidate Veto

Before the candidate is evaluated further it has to pass a number of veto conditions to prevent excessive, unnecessary calculations:
1. Candidate already calculated
The muon finder algorithm is made such that it is unavoidable that certain combinations of condensates are found several times. In this case a new candidate is vetoed to avoid duplication.

2. Candidate has too many cells
The muon finder rejects candidates with too many cells in order to avoid unnecessary calculations.

3. Candidate hit ratio is too low
Candidates with hit ratio less than 0.6 are rejected. The hit ratio is a measure for the shape of the candidate, a bad hit ratio suggests that it does not stem from a traversing particle.

4. Candidate occupancy is too low
Candidates with occupancy less than 0.15 (occupancy is the ratio of number of candidate cells hit by the trajectory over the total number of calorimeter cells hit by the trajectory) are rejected. This cut is not executed for candidates which have a long and narrow shape or which are parallel to the beam axis but far away from it and for which the velocity is near the speed of light.

5. Not all condensates hit by trajectory
Candidates for which not all condensates are hit by the fitted trajectory are rejected if the distance of the condensates which are not hit to the trajectory is smaller than 100 cm.

6. Event without candidate still passes trigger
MUFFIN tests whether the event, if the candidate cells were removed, would still pass the trigger condition. For a charged current event sample it would test whether the $P_T$ of the event is below the trigger cut of 9 GeV after the cells are removed. The candidate is rejected if the event still passes the trigger.

This test is not performed if MUFFIN has found the event likely to be a multiple muon shower: MUFFIN calls an event a muon shower candidate if one or more of the following conditions is true:

- There are parallel trajectories fitted to long and narrow condensates.
- There are parallel muon chamber tracks.
- There are more than 6 parallel two dimensional muon chamber tracks.

A candidate that fails any of the veto conditions is removed and will not appear on the output. (the NTUPLE).

Precise Calculation of Candidate Parameters
MUFFIN calculates the precise candidate parameters, the trajectory is fitted with a minimization fit (see section 6.8.4). If after this fit the trajectory hits another, not yet added condensate this condensate gets added to the candidate and all parameters are recalculated. Should the fitted trajectory not hit all of the condensates, the condensates which are not hit are removed and all parameters are recalculated.
Candidate Classification

MUFFIN calls a user-supplied routine to classify candidates. In this routine the candidates are compared to a set of parameters and it is determined if they indeed stem from a traversing muon. Should the classification be positive the candidate is removed from the event and processing ends. If the candidate is not positively identified it will be stored in the output for further study, but processing continues. Table 6.2 lists the muon classification cuts together with a description of the type of muon candidate found by the cut.

6.7.4 Beampipe Halomuon Finder

This muon finder is specialized on halo muons which are close to the beam pipe and hit both FCAL and RCAL. In principle the condensate based muon finder should find these halo muons too but for some cases the vetoing of candidates removes a beam pipe halo muon candidate.

This finder simply searches pairs of condensates, one in the FCAL ($Z > 200.0\text{cm. AND } p < 100.0\text{cm}$) and one in the RCAL ($Z < -100.0\text{cm. AND } p < 100.0\text{cm}$).

In this finder a candidate is vetoed if the event, when the candidate is removed, still passes the trigger conditions.

For each such pair MUFFIN calculates the candidate parameters precisely and then calls the user-supplied classification routine (see section 6.7.3) to positively identify the candidate.

6.7.5 Condensate Timing Based Finder

This muon finder looks for pairs of condensates which are far away from each other (distance of the condensate centers of more than 100 cm). It then calculates the velocity at which a particle would need to travel between the two condensates from the average condensate times. Then the candidate parameters are determined. If additional condensates are hit by the fitted trajectory they are added and the parameters are recalculated.

Candidates are vetoed if one of the following conditions is true:

1. The event would still pass the trigger if the candidate cells were removed.
2. The candidate contains a positron candidate (see section 6.7.6).

After calculating the muon candidate parameters at highest precision the user-supplied classification routine (see section 6.7.3) is called to positively identify the candidate.

6.7.6 Final State Positron vs. a Shower in EMC

Kernbremsstrahlung of a muon in the EMC section produces a high energy gamma which showers in the EMC. This can result in a shower very similar to that of a final state positron of a genuine positron-proton collision event.

In order to avoid misidentification MUFFIN tries to find a final state positron prior to execution if the $E - P_z$ value of the event is compatible with an NC event: If $E_{tot} - P_z > 35\text{ GeV}$ and $E_{tot} - P_z < 70\text{ GeV}$ then MUFFIN runs the SINISTRA positron finder [40]. If a positron has been found by that finder and if there is a condensate that contains nothing but those cells then this condensate is tagged. Should a muon candidate be found that contains this condensate the candidate will be tagged too, this tag can then be used in the muon classification (see section 6.7.3) to reject the candidate.
6.8 Trajectory Fits

MUFFIN returns information about the muon trajectory. It assumes this trajectory to be a straight line.

During candidate search a quick 3D line fit is necessary while for a final classification (see section 6.7.3) of a candidate a more precise fit is necessary.

6.8.1 Linear Regression Fit

Two consecutive linear regression fits to the coordinates of the cell centers are used to get a 3D line that follows the trajectory of the candidate.

First the coordinates are sorted according to the size of the candidate in the coordinate direction. The coordinate corresponding to the maximum size is used as the ordinate for the first fit, the second biggest is used as the abscissa. For the second fit the ordinate is the projection of the cell onto the line obtained with the first fit. The abscissa is the third unused variable.

The fit algorithms take care of special cases where a candidate has no size in one or two coordinate directions.

The fits are performed eight times with all possible combinations of the following algorithms:

1. Energy weighted: $w_x = w_y = w_z = E_{cell}$
2. Cell size weighted: $w_x = w_x/\text{size}_x; w_y = w_y/\text{size}_y; w_z = w_z/\text{size}_z$;
3. Correction of the cell position based on the cell imbalance: $c'_{new} = c_{old} + \text{WLS} \times \text{Imbalance}$ where WLS is the direction perpendicular to the WLS corresponding to positive cell energy imbalance.

Of those fitted lines the one with the best HitRatio is selected. To allow for problems with the fit accuracy the hit ratio is calculated using the blown up cell geometry.

6.8.2 Minimisation Fit

The straight line fits described above have a couple of disadvantages:

- There are candidate cell configurations which can hardly be fitted properly. This might decrease the Occupancy and thus make the identification more difficult.
- The treatment of cells that are close to a bremsstrahlung shower is not clear. A possibility would be to omit them for the fit, but then cases with only few cells hit become very difficult to detect. If those cells were always taken into account the linefit would sometimes produce incorrect results.

A more complex fit using MINUIT is used to make a precise fit of the muon trajectory.

If the entire calorimeter readout information was available offline one could calculate the probability for a muon to deposit a certain amount of energy in a cell. This could be used to define a function MINUIT has to minimize.

The data available to MUFFIN only contain zero-suppressed calorimeter information (see section 6.3.1). Also here bremsstrahlung showers pose a problem because the cell energy can be very high and consequently the probability for a muon to have caused such a signal very low.
The following function is minimised by modifying the trajectory parameters (offset and direction).

\[ F_{\text{MINUIT}} = 5918 - \sum_{\text{cell}_{\text{hit}}^{\text{sig}}} P_{\text{sig}} - \sum_{\text{cell}^{\text{sig}}} P_{\text{sig}} \]  

(6.1)

5918 is the number of cells in the UCAL. \( P_{\text{sig}} \) is the probability for a cell to have a signal for a given trajectory. \( P_{\text{sig}} \) is the probability for a cell not to have a signal for a given trajectory. These probabilities are calculated using the estimated energy loss of a muon in the UCAL material and the energy cut value of each cell (see also section 6.8.4 for a detailed description).

By splitting up the sums into sums of cells hit and not hit by the fitted trajectory one can write:

\[ F_{\text{MINUIT}} = 5918 - \sum_{\text{cell}_{\text{hit}}^{\text{sig}}} P_{\text{sig}} - \sum_{\text{cell}^{\text{hit}}^{\text{sig}}} P_{\text{sig}} - \sum_{\text{cell}_{\text{hit}}^{\text{sig}}} P_{\text{sig}} - \sum_{\text{cell}^{\text{hit}}^{\text{sig}}} P_{\text{sig}} \]  

(6.2)

The first sum is the number of cells that have not been hit. For those cells the probability for no signal \( P_{\text{hit}}^{\text{hit}} = 1.0 \) and the sum is simply the number of cells which have no signal and have not been hit: \( N_{\text{hit}}^{\text{hit}} \)

The fourth sum contains the cells which have not been hit, for those cells the probability for a signal \( P_{\text{sig}} = 0.0 \) so the term disappears.

So we have

\[ F_{\text{MINUIT}} = 5918 - N_{\text{hit}}^{\text{hit}} - \sum_{\text{cell}_{\text{hit}}^{\text{sig}}} P_{\text{sig}} - \sum_{\text{cell}^{\text{hit}}^{\text{sig}}} P_{\text{sig}} \]  

(6.3)

This can be simplified by writing:

\[ 5918 - N_{\text{hit}}^{\text{hit}} = \frac{N_{\text{hit}}^{\text{hit}} + N_{\text{hit}}^{\text{hit}}}{N_{\text{hit}}^{\text{hit}}} + N_{\text{hit}}^{\text{hit}} + \frac{N_{\text{hit}}^{\text{hit}} - N_{\text{hit}}^{\text{hit}}}{0} \]

And so the function to be minimized is:

\[ F_{\text{MINUIT}} = N_{\text{hit}}^{\text{hit}} + N_{\text{hit}}^{\text{hit}} - \sum_{\text{cell}_{\text{hit}}^{\text{sig}}} P_{\text{sig}} - \sum_{\text{cell}^{\text{hit}}^{\text{sig}}} P_{\text{sig}} \]  

(6.4)

The individual terms are:

- \( N_{\text{hit}}^{\text{hit}} \) The total number of cells hit by the fitted trajectory.
- \( N_{\text{hit}}^{\text{hit}} \) The number of cells of the candidate which have a signal but are not hit by the fitted trajectory.
- \( \sum_{\text{cell}_{\text{hit}}^{\text{sig}}} P_{\text{sig}} \) The sum of the probabilities for recording no signal for the cells which have no signal but are hit by the fitted trajectory.
- \( \sum_{\text{cell}^{\text{hit}}^{\text{sig}}} P_{\text{sig}} \) The sum of the probabilities for recording a signal for the cells which have a signal and are hit by the fitted trajectory.

The minimization function in (6.4) expresses the following ideas:
• It does not really matter if a muon hits a cell and does not cause a signal as long as it only traverses a small volume of that cell: In that case the total number of cells hit increases by 1.0 but at the same time the probability for not causing a signal in that cell is also close to 1.0.

• If a muon hits a cell with a signal it would be good to traverse so much volume that it is possible for the muon to cause a signal in the cell.

MINUIT modifies the line parameters direction and offset such that $F_{\text{MINUIT}}$ becomes minimal.

If a candidate cell (per definition with signal) is not hit by the trajectory $F_{\text{MINUIT}}$ increases by 1.0. There is however a reason why a cell might belong to a muon candidate but still not have been traversed by the muon: The reason for this is muon bremsstrahlung showers. Here a cell can have energy without being traversed by the muon. MINUIT will try to put the candidate trajectory through these cells too. Sometimes though this is geometrically impossible. MUFFIN tries to identify cells that have possibly only energy because there was a bremsstrahlung shower. It uses the algorithm described in section 6.4.1 and 6.4.2 to tag all cells that might have energy only because there was a bremsstrahlung shower. If such a cell is not hit by the trajectory fit to the cells $F_{\text{MINUIT}}$ is not increased by 1.0.

To get the start value for the track parameters MUFFIN chooses one of the following trajectory estimates depending on which estimate gives the best $HitRatio$:

• A muon chamber track.

• An inner track.

• The result of the linear regression line fit.

### 6.8.3 Candidate Velocity Fit

The calorimeter is capable of a very precise measurement of the time of the energy deposit with a resolution in the nanosecond range. Since the dimensions of the calorimeter are in orders of meters it is possible to use the time information to calculate the velocity of the traversing muon.

The candidate velocity is then calculated through a weighted linear regression fit using the position of each cell along the fitted line and the cell time. The cell time is in addition corrected for the distance of the cell center from the line. The weight is calculated using the prescription explained in [18].

Even though the velocity of a candidate seems like a good identification tool it should only be used with care: An event with a prompt muon and opposing it some very low energy deposit might result in a muon candidate with a velocity close to the speed of light because the low energy deposit might not contribute enough to the linear regression line fit.

Figure 6.9 shows a histogram of the velocity for all positively identified muon candidates, the histogram is restricted to $(v < 100\, \text{cm/ns})$ but only 19 of the 648 candidates have a velocity outside the shown region. The mean value of the distribution is at $34.2\, \text{cm/ns}$ which is very close to the speed of light indicating that indeed the observed signal stems from highly energetic particles traversing the detector.
6.8. TRAJECTORY FITS

Figure 6.9: The distribution of the absolute value of the velocity for the muon candidates found in the CC event sample. The mean value of the distribution is at 34.2 cm/ns which is very close to the speed of light indicating that indeed the observed signal stems from highly energetic particles traversing the detector.

6.8.4 The Probability for a Muon Signal in a Cell

The calorimeter segmentation into cells has been chosen such that a MIP particle like a muon deposits enough energy to be above noise cuts. This is true for muons that traverse the entire volume of a cell almost perpendicularly to the uranium plates of the cell, like prompt muons.

A muon that traverses only a part of the cell might not deposit enough energy and so the signal might be suppressed by the noise cuts.

The energy loss of a muon in the calorimeter follows a Landau distribution. This has been shown in many measurements of the calorimeter prototype modules as well as with halo muons in HERA.

In most of those tests though the muon traversed the calorimeter perpendicularly to the uranium plates.

It is possible to show this distribution also for muons traversing the detector at different angles. In figure 6.10 the opening angle between the muon trajectory and the direction perpendicular to the uranium plates (the sampling direction) is shown. This histogram contains data from muon candidates found in the charged current event sample.

Clearly three peaks can be identified. At 0, π/2 and π. They correspond to cells coming from halo muon events. For those events the cells in BCAL are penetrated from the side while for FCAL and RCAL the muon hits the cells in sampling direction.

In figure 6.10 the energy deposited in a cell is divided by the length of the muon trajectory through active material. Clearly two peaks can be identified. A cut on the angle under which the cell is traversed shows the reason for those two peaks. In figure 6.11 only cells with the muon hitting the cells almost perpendicularly is shown. The secondary peak has completely
Figure 6.10: For all cells of muon candidates found in the CC event sample, histogram (a) shows the angle between the muon direction and the sampling direction $\theta$ and histogram (b) shows the energy loss $dE/dX$ for these cells, two peaks are visible.

disappeared. In figure 6.11 only cells where the muon traverses from the side is shown. Here the secondary peak is very much enhanced.

The second peak stems from muons that only traverse scintillator material. The energy loss is smaller but more light is produced.

In figure 6.12 (a) cells with angles $0.1 < \theta < 1.56$ or $1.58 < \theta < 3.04$ are selected. In the same figure a Landau distribution is shown that has been fitted to the experimental data:

To fit a Landau distribution the following formula is used with $a$ and $b$ as free parameters:

$$L(dE/dX, a, b) = e^{-0.5(a(x-b)+e^{-(a(x-b))})}$$

The following parameterization results:

$$a = 270.0 \text{ cm/GeV}$$  
$$b = 0.15 \text{ GeV/cm}$$

This parameterization is used for the calculation of the probability to cause a signal. The reason is that MUFFIN has no problem detecting halo muons, muons in general if they run along a module. That is a very clear pattern. More difficult are muons that traverse the detector at other angles. And for those muons the ideal parameterization for the Landau distribution has to be found.

From the $dE/dX$ distribution it is possible to calculate the probability for a muon to deposit so much energy in a cell that the measured cell energy is bigger than the noise cut. For a known length $l$ of the muon trajectory in the cell and a cell cut $E_{\text{cut}}$ the probability is simply the integral of the Landau distribution from $E_{\text{cut}}/l$ to infinity:

\[ L(dE/dX, a, b) e^{-0.5(a(x-b)+e^{-(a(x-b))})} \]
Figure 6.11: For all cells of muon candidates found in the charged current event sample, histogram (a) shows $dE/dX$ for cells with $\theta$ small: $(\theta < 0.1$ or $\theta > 3.04)$. The peak at higher $dE/dX$ from figure 6.10 (b) has disappeared. Histogram (b) shows $dE/dX$ for cells with $\theta$ close to $\frac{\pi}{2}$: $(|\theta - 1.57| < 0.1)$. The peak at higher $dE/dX$ from figure 6.10 (b) is more pronounced.

Figure 6.12: $dE/dX$ for all cells of muon candidates found in the CC event sample for angles $0.1 < \theta < 1.56$ and $1.58 < \theta < 3.04$ together with the Landau distribution that has been fitted to the data (a), and the integral of the Landau distribution (b) which gives the probability for a signal in a cell with an energy cut $E_{\text{cut}}$ if the muon traverses $l$ material.
\[ P_{\text{sig}}(E_{\text{cut}}/l) = C \times \int_{E_{\text{cut}}/l}^{\infty} L(\rho) d\rho \]  

(6.8)

\( C \) is a normalization factor such that \( P(0.) = 1.0 \). The probability to measure an energy bigger than the \( E_{\text{cut}} \) is 1.0 if either the energy cut is zero or the amount of material traversed infinite.

The probability not to measure a signal is:

\[ P_{\text{sig}}(E_{\text{cut}}/l) = 1.0 - P(E_{\text{cut}}/l) \]  

(6.9)

The probability distribution for the parameterization chosen is shown in figure 6.12 (b): Clearly for a given energy cut \( E_{\text{cut}} \) a muon has to traverse a certain amount of UCAL material to deposit enough energy to cause a signal above the cut value. The more material is traversed, the higher the probability to cause a signal.

These results are used in the minimization line fit (see section 6.8.2).

### 6.9 Muon Candidate Parameters and Classification

Table 6.1 shows the parameters that are calculated for every muon candidate. These parameters are used by the candidate classification routine (see section 6.7.3). Some of the parameters are calculated when only a linear regression line fit (see section 6.8.1) is available some require that the MINUIT based minimization fit has been done (see section 6.8.2). Table 6.2 gives a list of the muon classification cuts used in the presented analysis. In total 90 different combinations of cuts are used.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Candidate number</td>
</tr>
<tr>
<td>( P_T(\mu) )</td>
<td>missing transverse momentum of the event calculated without the candidate cells ( P_T(\text{Event} - \text{Muon Candidate}) )</td>
</tr>
<tr>
<td>( E_t(\mu) )</td>
<td>transverse energy of the event calculated without the candidate cells ( E_t(\text{Event} - \text{Muon Candidate}) )</td>
</tr>
<tr>
<td>( E_{tot}(\mu) )</td>
<td>total energy of the event calculated without the candidate cells ( E_{tot}(\text{Event} - \text{Muon Candidate}) )</td>
</tr>
<tr>
<td>Step</td>
<td>Processing step at which this candidate was found.</td>
</tr>
<tr>
<td>Algo</td>
<td>Muon candidate finder algorithm that found this candidate, see 6.7 for a list of finders.</td>
</tr>
<tr>
<td>Type</td>
<td>Muon type. This value is set to the value specified in the muon trigger specification, see 6.7.3 for a list of types.</td>
</tr>
<tr>
<td>Quality</td>
<td>Muon quality. This value is set to the value specified in the muon trigger specification.</td>
</tr>
<tr>
<td>CalcLevel</td>
<td>Precision level of the calculations: 1: Parameters calculated based on linear regression linefit. 2: Parameters calculated based on a MINUIT minimisation linefit.</td>
</tr>
</tbody>
</table>

*continued on next page*
### Parameter Name | Description
--- | ---
$N_{CElCand}$ | Does this muon contain a possible NC electron?
$LineHitsAllCond$ | does the fitted line hit all the condensates?
$LineHitsOtherCond$ | does the fitted line hit other condensates?
$EventWouldBeKilled$ | would the event be removed if the data belonging to the candidate were removed?

$N_{Cond}$ | number of condensates in the candidate
$N_{Cells}$ | number of calorimeter cells in the candidate
$N_{Holes}$ | number of calorimeter readout dead cells
$N_{Hit}$ | number of candidate cells hit by fitted line ($N_{tot}^{hit}$).
$N_{CAL}$ | number of calorimeter cells hit by the fitted line.

$N_{Hit}/N_{Cells}$ | A hit ratio of 1.0 means that all candidate cells are hit by the line.

$R_{WLS}$ | $N_{Hit}/(N_{Cells} - N_{WLS})$.
$R_{S}$ | $N_{Hit}/(N_{Cells} - N_{Shower})$.
$R_{NB}$ | $N_{Hit}/(N_{Cells} - N_{NB})$.
$R_{B}$ | $N_{Hit}/(N_{Cells} - N_{B})$.
$R_{BS}$ | $N_{Hit}/(N_{Cells} - N_{Hit}^{BS} - N_{Shower})$.

$O$ | Occupancy $N_{Hit}/N_{CAL}$: An occupancy of 1.0 means that the candidate contains all calorimeter cells which have been hit by the line.

$L_x, L_y, L_z$ | Fitted line offset vector. It is in the centre of the candidate.
$L_{\theta}, L_{\phi}$ | Direction of the fitted line, in spherical coordinates.
$L_{p}$ | $\sqrt{L_{x}^2 + L_{y}^2}$

$d(l, Cand)$ | Candidate length. This is calculated by projecting all candidate cells onto the line and taking the difference between maximum and minimum projection.
$max(d(l, Cand))$ | Maximum distance of the centers of all candidate cells from the line.
$L_{CAL}$ | Difference between maximum and minimum projection of all hit calorimeter cells onto the line.
$d(l, CAL)$ | Average distance of the centers of all hit calorimeter cells to the line.
$max(d(l, CAL))$ | Maximum distance of the centers of all hit calorimeter cells to the line.
$d(l, BP)$ | Distance of the line to the beam line.
$d(l, Vtx)$ | Distance of the line to the event vertex.
l($l, InnerDet$) | Length of the trajectory through the inner detector volume which is approximated as a cylinder of 120 cm radius from $z = -140$ cm to $z = 210$ cm.
### Parameter Name | Description
--- | ---
STSlop | Slope of “candidate velocity fit”, should be close to $1/c$ for a traversing muon. $(1/STSlop)$ except for candidate finder based on condensate timing (6.7.5), here it contains the velocity based on the average time of the two condensates and their distance.

$V_{fit}$ | Number of candidate cells that are not hit but that are part of a bremsstrahlung shower (see 6.4.1).

$N_{WLS Cells}$ | Number of candidate cells that are not hit but that have one of the WLS hit by a bremsstrahlung shower (see 6.4.2).

$N_{Cells}$ | Number of candidate cells that are not hit but might have been hit by particles from a bremsstrahlung shower that were bent away from the muon trajectory by the magnetic field (see 6.4.3).

$N_{NB Cells}$ | Number of cells that are not hit but have at least one neighbor cell hit by the line.

$N_{MuTrk max}$ | Maximum number of candidate cells hit by any muon track.

$N_{MuTrk max-1}$ | Second biggest number of candidate cells hit by any muon track.

$r_{max}^{MuTrk}$ | Hit ratio for the best muon track.

$r_{max-1}^{MuTrk}$ | Hit ratio for the second best muon track.

$\Delta\alpha_{min}^{MuTrk}$ | Minimum angular difference between the direction of the fitted line and any muon track that hits any candidate cell.

$\Delta\alpha_{min}^{MuWire}$ | Minimum angular difference between the fitted line and any muon wire track, this value is calculated in the $2-D$ coordinate system which is given by the wire track orientation.

$\Delta\alpha_{min}^{MuStrip}$ | Minimum angular difference between the fitted line and any muon strip track, this value is calculated in the $2-D$ coordinate system which is given by the strip track orientation.

$\Delta d_{max}^{MuTrk}$ | Maximum number of cells hit by any inner track. The track is used as an arrow pointing from the inside of the detector to the outside.

$\Delta d_{max}^{MuStrip}$ | Second biggest number of cells hit by any inner track, the track has to point in the opposite direction to the one that hit the maximum number of cells.

$\Delta d_{min}^{MuWire}$ | Minimum distance of the fitted line to any muon wire track.

$\Delta d_{min}^{MuStrip}$ | Minimum distance of the fitted line to any muon strip track.
### MUON CANDIDATE PARAMETERS AND CLASSIFICATION

**Table 6.1:** List of the parameters calculated by MUFFIN for all muon candidates. The parameters are used by the muon identification algorithm to select muon candidates.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{InTrk}}^{\text{max}} )</td>
<td>hit ratio for the best inner track</td>
</tr>
<tr>
<td>( R_{\text{InTrk}}^{\text{max}-1} )</td>
<td>hit ratio for the second best inner track</td>
</tr>
<tr>
<td>( \Delta \alpha_{\text{InTrk}}^{\text{max}} )</td>
<td>maximum angular difference between the direction of the fitted line and any inner track that hits any candidate cell</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Muon types found using muon chamber tracks:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Muon with good occupancy and hit ratio</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R &gt; 0.9 )</td>
</tr>
<tr>
<td>2</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_{\text{WLS}} &gt; 0.9 )</td>
</tr>
<tr>
<td>3</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_S &gt; 0.9 )</td>
</tr>
<tr>
<td>4</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_{\text{ES}} &gt; 0.9 )</td>
</tr>
<tr>
<td>5</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_{\text{ES}} &gt; 0.9 )</td>
</tr>
<tr>
<td><strong>Muon candidate that traverses all of UCAL</strong></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R &gt; 0.7 \land 0 )</td>
</tr>
<tr>
<td>12</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_{\text{WLS}} &gt; 0.7 \land 0 )</td>
</tr>
<tr>
<td>13</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_S &gt; 0.7 \land 0 )</td>
</tr>
<tr>
<td>14</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_{\text{ES}} &gt; 0.7 \land 0 )</td>
</tr>
<tr>
<td>15</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land 0 &gt; 0.9 \land R_{\text{ES}} &gt; 0.7 \land 0 )</td>
</tr>
<tr>
<td><strong>Muon candidate hit by two muon tracks</strong></td>
<td></td>
</tr>
<tr>
<td>201</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land \text{Algo} = 2 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land N_{\text{MuTrk}}^{\text{max}-1} &gt; 0 \land \Delta \alpha_{\text{MuTrk}}^{\text{max}} &lt; 0.1 \land R_{\text{ES}} &gt; 0.5 \land 0 &gt; 0.7 )</td>
</tr>
<tr>
<td><strong>Muon candidate far away from beampipe and vertex</strong></td>
<td></td>
</tr>
<tr>
<td>301</td>
<td>( R_{\text{c}}(\mu) &lt; 9 \land \text{Algo} = 1 \land d(l, BP) &gt; 120 \land d(l, Vtx) &gt; 200 )</td>
</tr>
<tr>
<td><strong>Event only consists of muon</strong></td>
<td></td>
</tr>
<tr>
<td>302</td>
<td>( R_{\text{c}}(\mu) &lt; 1 \land E_{\text{tot}}(\mu) &lt; 5 \land 0 &gt; 0.85 \land R_{\text{ES}} &gt; 0.3 \land 0 \land V_{\text{fit}} &gt; 20 \land V_{\text{fit}} &lt; 50 \land \Delta \alpha_{\text{MuTrk}}^{\text{max}} &lt; 0.1 )</td>
</tr>
</tbody>
</table>

*continued on next page*
### Chapter 6. Muon Finder

**Type** | **Description, Cuts**
--- | ---
Muon candidate very far away from vertex

| 303 | \( R^V_l < 5 \land \mathcal{O} > 0.7 \land d(l, Vtx) > 350 \land \mathcal{R}_{WLS} > 0.3 \land N^\text{max}_{\text{MuTrk}} > 0 \land \Delta \alpha^\text{max}_{\text{MuTrk}} < 0.1 \) |

Muon candidate very far away from beampipe

| 304 | \( R^V_l < 2 \land \mathcal{O} = 1 \land V_{\text{fit}} > 20 \land V_{\text{fit}} < 40 \land d(l, BP) > 350 \land \mathcal{R}_{BP} > 0.2 \land \mathcal{R}_{NB} > 0.35 \land \Delta \alpha^\text{max}_{\text{MuTrk}} < 0.1 \) |

Muon candidates found by removing rings of cells around FCAL beampipe hole

| 901 | \( \text{Step} > 0 \land R^V_l < 1 \land \mathcal{R}_{NB} > 0.8 \land \mathcal{O} > 0.8 \land \left( l_{\text{Cand}} - L_{\text{CAL}} \right) > -20 \) |
| 902 | \( R^V_l < 1 \land V_{\text{fit}} > 20 \land V_{\text{fit}} < 40 \land \left( l_{\text{Cand}} - L_{\text{CAL}} \right) > -20 \land \text{Alg} = 1 \land \Delta \alpha^\text{max}_{\text{MuTrk}} < 0.1 \) |

**Muon types found using condensates only:**

Halo muon with or without showers

| 1001 | \( \mathcal{O} > 0.9 \land \mathcal{R} > 0.9 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1002 | \( \mathcal{O} > 0.9 \land \mathcal{R}_{WLS} > 0.9 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1003 | \( \mathcal{O} > 0.9 \land \mathcal{R}_{S} > 0.9 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1004 | \( \mathcal{O} > 0.9 \land \mathcal{R}_{NB} > 0.9 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1101 | \( \mathcal{O} > 0.8 \land \mathcal{R} > 0.8 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1102 | \( \mathcal{O} > 0.8 \land \mathcal{R}_{WLS} > 0.8 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1103 | \( \mathcal{O} > 0.8 \land \mathcal{R}_{S} > 0.8 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1104 | \( \mathcal{O} > 0.8 \land \mathcal{R}_{NB} > 0.8 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1201 | \( \mathcal{O} > 0.7 \land \mathcal{R} > 0.7 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1202 | \( \mathcal{O} > 0.7 \land \mathcal{R}_{WLS} > 0.7 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1203 | \( \mathcal{O} > 0.7 \land \mathcal{R}_{S} > 0.7 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |
| 1204 | \( \mathcal{O} > 0.7 \land \mathcal{R}_{NB} > 0.7 \land 0.15 < L_\theta < (\pi - 0.15) \land L_\rho > 110 \) |

Halo muon traversing BCAL EMC, many cells hit but occupancy bad

| 1301 | \( N^{\text{Hit}}_{\text{Cells}} > 20 \land L_\rho > 110 \land l_{\text{Cand}} > 50 \land 0.15 < L_\theta < (\pi - 0.15) \land \mathcal{R} > 0.65 \) |

Muon candidates hit by CTD tracks

| 1011 | \( \mathcal{O} > 0.9 \land \mathcal{R} > 0.9 \land N^\text{max}_{\text{InTrk}} > 0 \land \Delta \alpha^\text{max}_{\text{InTrk}} < 0.2 \) |
| 1012 | \( \mathcal{O} > 0.9 \land \mathcal{R}_{WLS} > 0.9 \land N^\text{max}_{\text{InTrk}} > 0 \land \Delta \alpha^\text{max}_{\text{InTrk}} < 0.2 \) |
| 1013 | \( \mathcal{O} > 0.9 \land \mathcal{R}_{S} > 0.9 \land N^\text{max}_{\text{InTrk}} > 0 \land \Delta \alpha^\text{max}_{\text{InTrk}} < 0.2 \) |

*continued on next page*
### 6.9. MUON CANDIDATE PARAMETERS AND CLASSIFICATION

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<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1014</td>
<td>$O &gt; 0.9 \land R_{NB} &gt; 0.9 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{InTrk}}^{\text{max}} &lt; 0.2$</td>
</tr>
<tr>
<td>1111</td>
<td>$O &gt; 0.8 \land R &gt; 0.8 \land N_{\text{InTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{InTrk}}^{\text{max}} &lt; 0.2$</td>
</tr>
<tr>
<td>1112</td>
<td>$O &gt; 0.8 \land R_{WLS} &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{InTrk}}^{\text{max}} &lt; 0.2$</td>
</tr>
<tr>
<td>1113</td>
<td>$O &gt; 0.8 \land R_{S} &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{InTrk}}^{\text{max}} &lt; 0.2$</td>
</tr>
<tr>
<td>1114</td>
<td>$O &gt; 0.8 \land R_{NB} &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{InTrk}}^{\text{max}} &lt; 0.2$</td>
</tr>
</tbody>
</table>

#### Muon candidates hit by 3 – 5 muon chamber tracks

<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1012</td>
<td>$O &gt; 0.9 \land R &gt; 0.9 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1022</td>
<td>$O &gt; 0.9 \land R_{WLS} &gt; 0.9 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1023</td>
<td>$O &gt; 0.9 \land R_{S} &gt; 0.9 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1024</td>
<td>$O &gt; 0.9 \land R_{NB} &gt; 0.9 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1121</td>
<td>$O &gt; 0.8 \land R &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1122</td>
<td>$O &gt; 0.8 \land R_{WLS} &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1123</td>
<td>$O &gt; 0.8 \land R_{S} &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
<tr>
<td>1124</td>
<td>$O &gt; 0.8 \land R_{NB} &gt; 0.8 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0$</td>
</tr>
</tbody>
</table>

#### Muon candidate hit by muon chamber tracks that does not traverse the Inner detector volume

<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1125</td>
<td>$O &gt; 0.7 \land R_{NB} &gt; 0.7 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{MuTrk}}^{\text{max}} &lt; 0.1 \land l(l, \text{InnerDet}) = 0$</td>
</tr>
</tbody>
</table>

#### Muon candidate hit by muon chamber tracks with velocity near $c$

<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1126</td>
<td>$O &gt; 0.75 \land R_{S} &gt; 0.75 \land N_{\text{MuTrk}}^{\text{max}} &gt; 0 \land \Delta \alpha_{\text{MuTrk}}^{\text{max}} &lt; 0.2 \land V_{fit} &gt; 0 \land V_{fit} &lt; 40$</td>
</tr>
</tbody>
</table>

#### Muon candidates hit by muon wire chamber 2 – 5 tracks

<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1031</td>
<td>$O &gt; 0.9 \land R &gt; 0.9 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 20$</td>
</tr>
<tr>
<td>1032</td>
<td>$O &gt; 0.9 \land R &gt; 0.9 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 0.2$</td>
</tr>
<tr>
<td>1033</td>
<td>$O &gt; 0.9 \land R_{WLS} &gt; 0.9 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 20$</td>
</tr>
<tr>
<td>1034</td>
<td>$O &gt; 0.9 \land R_{WLS} &gt; 0.9 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 0.2$</td>
</tr>
<tr>
<td>1035</td>
<td>$O &gt; 0.7 \land R_{WLS} &gt; 0.5 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 0.1 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 20$</td>
</tr>
<tr>
<td>1036</td>
<td>$O &gt; 0.9 \land R_{S} &gt; 0.9 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 0.1 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 20$</td>
</tr>
<tr>
<td>1037</td>
<td>$O &gt; 0.65 \land R &gt; 0.7 \land 0.15 &lt; L_{\theta} &lt; (\pi - 0.15) \land L_{\theta} &gt; 110 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 5 \land \Delta \alpha_{\text{MuWire}}^{\text{min}} &lt; 0.1$</td>
</tr>
</tbody>
</table>

#### Muon candidates that are not hit by an inner track

<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1041</td>
<td>$O &gt; 0.9 \land R &gt; 0.9 \land N_{\text{InTrk}}^{\text{max}} = 0$</td>
</tr>
<tr>
<td>1042</td>
<td>$O &gt; 0.9 \land R_{WLS} &gt; 0.9 \land N_{\text{InTrk}}^{\text{max}} = 0$</td>
</tr>
<tr>
<td>1141</td>
<td>$O &gt; 0.9 \land R &gt; 0.8 \land N_{\text{InTrk}}^{\text{max}} = 0$</td>
</tr>
<tr>
<td>1142</td>
<td>$O &gt; 0.9 \land R_{WLS} &gt; 0.8 \land N_{\text{InTrk}}^{\text{max}} = 0$</td>
</tr>
</tbody>
</table>

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### CHAPTER 6. MUON FINDER

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<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon candidates far away from vertex and beampipe</td>
<td>1501 $O &gt; 0.7 \land R_{WLS} &gt; 0.5 \land d(l, BP) &gt; 120$</td>
</tr>
<tr>
<td>Muon candidates with velocity near c</td>
<td>1501 $O &gt; 0.8 \land R_{WLS} &gt; 0.6 \land V_{fit} &lt; 50 \land O^V &lt; 0.7 \land d(l, BP) &gt; 120$</td>
</tr>
<tr>
<td>Muon candidates found by removing rings of cells around FCAL beampipe hole</td>
<td>1502 $R_{Vtx} &lt; 2 \land O &gt; 0.9 \land R_{BS} &gt; 0.6 \land V_{fit} &gt; 20 \land V_{fit} &lt; 60$</td>
</tr>
<tr>
<td>Event consists only of muons</td>
<td>1503 $R_{Vtx} &lt; 2 \land O &gt; 0.7 \land R_{BS} &gt; 0.7 \land V_{fit} &gt; 20 \land V_{fit} &lt; 60$</td>
</tr>
<tr>
<td>Halo muons close to the beampipe:</td>
<td>1504 $R_{Vtx} &lt; 2 \land O &gt; 0.8 \land R_{BS} &gt; 0.9 \land R &gt; 0.7 \land V_{fit} &gt; 20 \land V_{fit} &lt; 60$</td>
</tr>
</tbody>
</table>

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6.9. MUON CANDIDATE PARAMETERS AND CLASSIFICATION

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<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>( R_i(\mu) &lt; 9 \land O &gt; 0.9 \land R_{NB} &gt; 0.6 \land (L_\theta &lt; 0.1 \lor L_\theta &gt; (\pi - 0.1)) )</td>
</tr>
<tr>
<td>2012</td>
<td>( R_i(\mu) &lt; 9 \land O &gt; 0.8 \land R_{NB} &gt; 0.8 \land (L_\theta &lt; 0.1 \lor L_\theta &gt; (\pi - 0.1)) )</td>
</tr>
<tr>
<td>2013</td>
<td>( R_i(\mu) &lt; 1 \land E_{tot}(\mu) &lt; 5 \land O &gt; 0.8 \land R_S &gt; 0.3 \land (L_\theta &lt; 0.1 \lor L_\theta &gt; (\pi - 0.1)) )</td>
</tr>
<tr>
<td>2014</td>
<td>( R_i(\mu) &lt; 1 \land E_{tot}(\mu) &lt; 5 \land O &gt; 0.75 \land R_{\bar{S}}S &gt; 0.2 \land (L_\theta &lt; 0.1 \lor L_\theta &gt; (\pi - 0.1)) )</td>
</tr>
<tr>
<td>2015</td>
<td>( R_i(\mu) &lt; 1.5 \land O = 1 \land R_{\bar{S}}S = 1 \land (L_\theta &lt; 0.1 \lor L_\theta &gt; (\pi - 0.1)) \land V_{fit} &gt; 30 \land V_{fit} &lt; 36 )</td>
</tr>
</tbody>
</table>

Muons found by condensate timing based finder:

<table>
<thead>
<tr>
<th>Muons found by condensate timing based finder:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3001</td>
</tr>
<tr>
<td>3002</td>
</tr>
<tr>
<td>3003</td>
</tr>
<tr>
<td>3005</td>
</tr>
<tr>
<td>3006</td>
</tr>
<tr>
<td>3007</td>
</tr>
<tr>
<td>3008</td>
</tr>
</tbody>
</table>

Muon candidates found by removing rings of cells around FCAL beampipe hole

| 3901  | \( Step > 0 \land L_\theta < 0.1 \land R_i(\mu) < 1 \land V_{fit} > 20 \land V_{fit} < 40 \land O = 1 \land R_{\bar{S}}S > 0.3 \land N_{InTrk}^{max} > 0 \land \Delta \alpha_{InTrk}^{max} < 0.1 \) |

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<table>
<thead>
<tr>
<th>Type</th>
<th>Description, Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>3902</td>
<td>( \text{Step} &gt; 0 \land L_{\theta} &lt; 0.1 \land R_{v}(\mu) &lt; 1 \land V_{fit} &gt; 20 \land V_{fit} &lt; 40 \land \mathcal{O} = 1 \land R_{BS} &gt; 0.55 )</td>
</tr>
<tr>
<td>3903</td>
<td>( \text{Step} &gt; 0 \land R_{v}(\mu) &lt; 1 \land V_{fit} &gt; 20 \land V_{fit} &lt; 40 \land \mathcal{O} &gt; 0.95 \land R &gt; 0.8 \land R_{BS} = 1 )</td>
</tr>
</tbody>
</table>

Table 6.2: Cuts used to classify muon candidates.

6.10 Summary

Of the 693 candidate CC events 489 are rejected due to being identified as events with overlapping muons. Table 6.3 gives a breakdown of the number of events rejected by each of the muon finder algorithms.

<table>
<thead>
<tr>
<th>Muon Finder Algorithm</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon track based finder</td>
<td>241</td>
</tr>
<tr>
<td>Condensate based finder</td>
<td>195</td>
</tr>
<tr>
<td>Beam pipe halomuon finder</td>
<td>28</td>
</tr>
<tr>
<td>Condensate timing based finder</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 6.3: The table gives a breakdown of the number of events rejected by each of the muon finder algorithms.

Figure 6.9 shows the velocity distribution of all candidates while figure 6.13 shows the orientation of the fitted trajectory. The peaks in histogram (a) at very small and high azimuthal angles \( \theta \) stem from halo muons. The halo muon events have been removed from histogram (b) for the polar angle \( \phi \). Histogram (b) only has entries for \( \phi \) values between 0° and 180°. This is due to the fact that during the trajectory fits \( \phi \) is chosen such that the trajectory points upwards, away from earth. The velocity fitted to almost all of these candidates is negative, indicating that cosmics come from above.
Figure 6.13: Figure (a) shows the distribution of the polar angle $\theta$ for all identified muons. The peaks at low and high angles correspond to halo muons, these have been omitted in figure (b) which shows the distribution for the azimuthal angle $\phi$. Histogram (b) only shows $\phi$ values between $0^\circ$ and $180^\circ$. This is due to the fact that during the trajectory fits $\phi$ is chosen such that the trajectory points upwards, away from earth.