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# DRAFT

## CMS CRAFT Performance Note

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### Performance of the CMS Cathode Strip Chambers with Cosmic Rays

The CSC DPG  
CERN

#### Abstract

The Cathode Strip Chambers (CSCs) constitute the primary muon tracking device in the CMS endcaps. Their performance has been evaluated using data taken during a long cosmic ray run in Fall 2008. Distributions of basic global quantities are well reproduced by the simulation. Noise levels are low according to measurement, and nearly all anode and cathode channels deliver data. Efficiencies have been measured and are very high, and the spatial resolution of the chambers has been studied and measured, with good results. Finally, a brief exploratory study of the potential timing capabilities of the CSCs has been completed.

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## 1 Introduction

The Cathode Strip Chambers (CSCs) comprise an essential component of the CMS muon detector, providing precise tracking and triggering of muons in the endcaps. Their performance is critical to many planned physics analyses based on muons. An early assessment of their performance is possible using data recorded during the Fall of 2008 as part of the *Cosmic Run At Four Tesla* (CRAFT) campaign. This paper summarizes the early results obtained from the analysis of those data.

The CRAFT campaign involved all installed subdetector systems, most of which were nearly fully operational, as described in other reports included in this volume. Close to 300 M cosmic ray muon triggers were recorded while the magnet was at full field (3.8 T). Of these, roughly a fifth originated from the CSCs.

The CSC subdetector is composed of rings of trapezoidal chambers mounted on eight disks - four in each endcap. The rings of chambers are designated by  $ME\pm S/R$ , where the  $\pm$  sign indicates the endcap,  $S$  indicates the disk (or "station"), and  $R$  is the ring number. A drawing of CMS highlighting the CSC subdetector is shown in Fig. 1. Each chamber contains six detecting layers each composed of an anode wire plane between two planar copper cathodes, one continuous, the other segmented in strips to provide coordinate readout [1]. The CSCs measure the  $\phi$  coordinates of muon tracks well, as the bending of the muon trajectories in the magnetic field returned through the iron disks is mainly about the  $\hat{s}$  direction, where  $\hat{s}$  is a unit vector in cylindrical coordinates pointing away from the beam line. The strips describe constant  $\phi$  values, and hence are trapezoidal in shape, like the chambers themselves. A high precision is achieved on the basis of the shape of the charge distribution on three consecutive strips; this allows an adequate measurement of the muon momentum as needed for triggering purposes. The anode wires provide a relatively approximate measure of the radial coordinate.

The readout of a CSC is triggered by the presence of Anode and Cathode Local Charged Track patterns, referred to as ALCT and CLCT, respectively. They are defined in the trigger logic [2, 3]. A correlated LCT is also defined and used in triggering the readout of the chamber. The final CSC muon trigger is generated by the CSC track finder and sent to the general muon trigger processor. For CRAFT, events were recorded with a very loose CSC trigger based on the logical "OR" of the trigger signals of all individual chambers. The rate of this loose trigger was about 60 Hz. The drift tube barrel muon detector also provided cosmic muon triggers at about four times this rate.

In the sections that follow, we present a selection of distributions characterizing the useful cosmic ray flux through the endcaps, an assessment of the CSC anode electronics, results on the measurement of efficiency and resolution, and some basic information about the timing capabilities of the CSCs. Most of these results are documented more fully in Ref. [4–7]. We begin with a brief account of the commissioning of the system and of the basics of offline reconstruction.

## 2 Commissioning the CSCs

The assembly of the CSCs included a comprehensive commissioning regimen to verify chamber performance during production [8]. This set of tests was performed again on each chamber upon arrival at CERN, and multiple times following installation on the endcap disks on the surface during 2005-7. In 2007, the disks were lowered into the CMS cavern at Point 5, and the full set of services and infrastructure became available early in 2008. At this time, a team

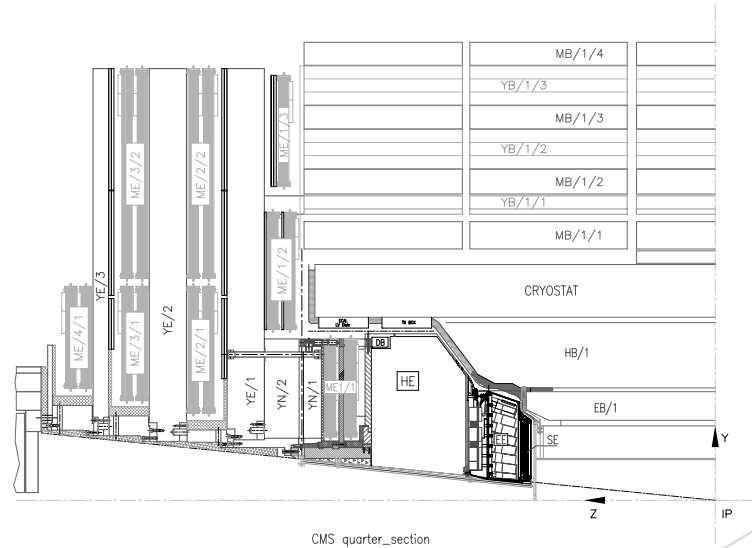


Figure 1: A cross-sectional view of the CMS detector, highlighting the CSCs.

45 of physicists and engineers expanded the scope of the commissioning program from checking  
 46 one chamber at a time to covering the entire set of 468 chambers as a subdetector system.

47 The commissioning effort included the following tasks: establishing inter-component commu-  
 48 nication, loading new versions of firmware to the electronics boards, turning on and configur-  
 49 ing all components in a robust way, and measuring the parameters necessary to ensure syn-  
 50 chronization of the system. An essential aspect of the commissioning effort was to diagnose  
 51 what components, including cables, had problems so that they could be fixed before the CMS  
 52 detector was closed. In addition, the development of a suite of software tools was essential to  
 53 bring the CSC system online - a system whose size requires procedures and rigor akin to an  
 54 assembly line. By the time of CRAFT, more than 96% of the readout channels were live. Fig 2  
 55 shows that hits could be reconstructed successfully in most of the chambers.

56 During CRAFT, the CSCs functioned well over a period of several weeks, and they were in-  
 57 cluded in the readout for about 80% of the CRAFT running period. The system was exposed  
 58 to a different set of issues which had not been encountered during the normal commissioning  
 59 period.

### 60 3 Local Muon Reconstruction

61 Raw data recorded from the detector are unpacked into integer-based objects called “digis.”  
 62 There are digi collections for the strip signals, the wire signals, and the local charged trigger  
 63 tracks (LCTs). The information stored in the digis is processed to produce a collection of objects  
 64 called “rechits” with measured  $x$  and  $y$  coordinates at a known  $z$  coordinate. These represent  
 65 the measurement of the intersection point between the track and a CSC layer. The rechits re-  
 66 constructed in a given chamber are used to form a straight-line segment, which is fit to provide  
 67 a measure of the muon trajectory in the chamber. Only one rechit is used from any given layer,

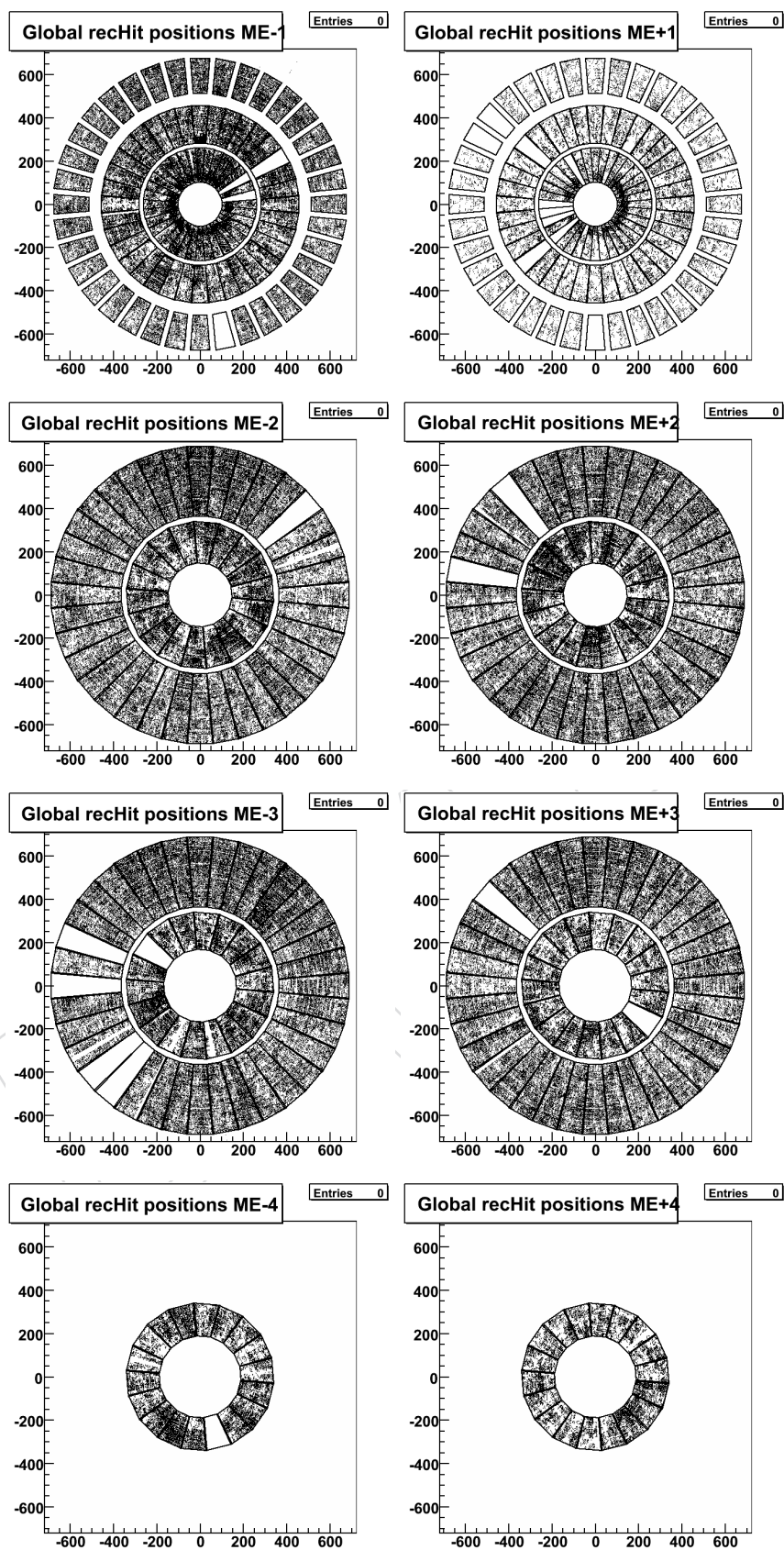


Figure 2: Distributions of rechits reconstructed from a portion of the CRAFT data. Nearly all of the chambers were fully operational. The less than 3% of chambers that did not provide data have been repaired since CRAFT.

68 and a minimum number of three rechits is required. The majority of segments have six rechits,  
69 while a modest fraction have fewer due to the impact of  $\delta$ -ray electrons and the boundaries  
70 of the chamber. These segments are used to seed the reconstruction of muon tracks based on  
71 muon chamber data only – these are called “stand-alone muons” [9]. Due to the very broad  
72 range of cosmic ray incident angles, only a small fraction of the stand-alone muons can be  
73 matched to reconstructed tracks in the Silicon tracker, especially those in the endcaps.

74 The alignment of the muon chambers and of the Si tracker is based on two complementary  
75 methods - the first uses lasers and specially placed sensors, while the other uses muon tracks.  
76 The first method provided basic information about the position of the endcap disks relative to  
77 the barrel, and this information was used in the reconstruction of the CRAFT data. Alignment  
78 of the muon endcap detectors with tracks is ongoing. For more details, see Ref. [10] in this  
79 volume.

80 The magnetic field map was verified by examining the deflection of selected muon tracks pass-  
81 ing through the disks and the Si tracker. It was shown to be accurate to 5% or better [11].

82 Simulated data sets were produced using the `CMSCGEN` Monte Carlo event generator, which is  
83 configured to reproduce the CRAFT data as closely as possible [12]. The simulated data, the  
84 reconstructed CRAFT data, and the results presented in this paper are based on official CMS  
85 reconstruction code releases dating from the Spring of 2009.

## 86 4 Basic Information from Cosmic Rays

87 Most cosmic rays above ground have an energy of at most a few GeV [13]. In the underground  
88 cavern at Point 5, the energy spectrum is shifted to somewhat higher values. Muons must have  
89 energies of at least a few GeV in order to pass through three consecutive CSC stations, since the  
90 iron disks between them are approximately  $34 X_0$  thick. Most reconstructed cosmic ray muons  
91 have only a few GeV, so multiple scattering in the iron yokes can displace the muon’s trajectory  
92 by several centimeters with respect to the ideal trajectory.

93 Most of the muons triggered in the endcaps are not useful because their trajectories are steeply  
94 inclined or pass through only an edge of one of the endcaps. Only a minute fraction of the  
95 recorded cosmic ray muons follow a useful path through the endcaps, and satisfy the nominal  
96 geometric requirements for the efficient triggering and readout of the CSCs, as explained in  
97 detail below.

98 In order to secure a sample of useful events, a skim of the primary data set selected events in  
99 which at least three chambers had hits, and in which at least two segments had been recon-  
100 structed. Events with very many rechits or segments were excluded, since they were likely  
101 contain muon-induced showers which would frustrate these performance studies. These rel-  
102 atively loose criteria reduced the data sample with CSC triggers by a factor of twenty, and  
103 enabled direct comparisons of the simulated data to the real CRAFT data.

104 Distributions of simple quantities such as the total number of rechits per event and the num-  
105 ber of segments per event are shown in Fig. 3. The requirement of three chambers with hits  
106 suppresses entries at the low end of these distributions.

107 Further information about the reconstructed segments is shown in Fig. 4. The first plot shows  
108 the number of hits on a segment, which must be at least three and cannot be more than six.  
109 Most segments have one rechit in every layer, and this is well reproduced by the simulation.  
110 The second and third plots show the inclinations of the segments, namely, the polar angle



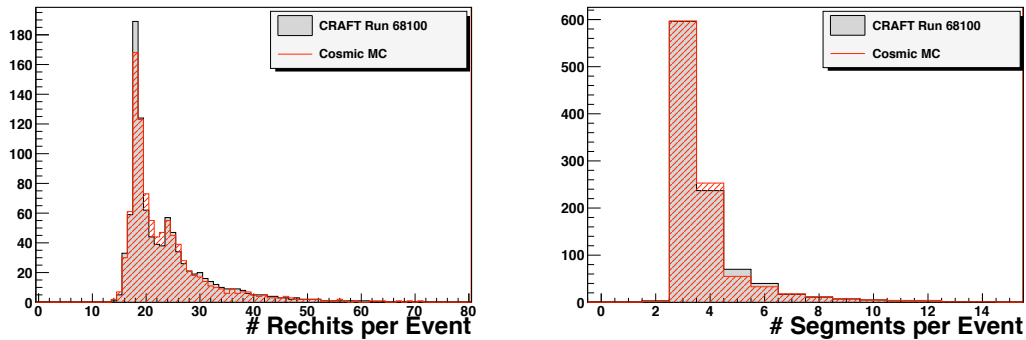


Figure 3: A comparison of the simulated events to the real CRAFT events for simple global quantities. *LEFT*: total number of rechits per event. *RIGHT*: total number of segments per event.

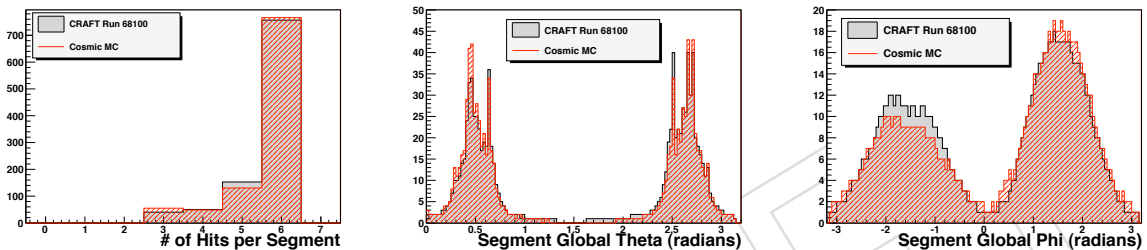


Figure 4: A comparison of the simulated events to the real CRAFT events for reconstructed segment quantities. *LEFT*: number of hits per segment. *MIDDLE*: global polar angle. The two endcaps are clearly visible (ME+ at  $\theta \sim 0.5$  and ME- at  $\theta \sim 2.7$ ). *RIGHT*: global azimuthal angle. The bump at  $\phi \sim 1.8$  corresponds to the upward vertical direction, and  $\phi \sim -1.8$ , to the downward.

111 (“global theta”) and the azimuthal angle (“global phi”). The vertical nature of the cosmic ray  
 112 flux is evident in these distributions, which are very well reproduced by the simulation.

113 Finally, basic distributions for stand-alone muons in the endcaps are presented in Fig. 5. The  
 114 first plot shows the distribution of the number of CSC rechits on the track. The distribution  
 115 of simulated events differs from the CRAFT distribution in part because the alignment of the  
 116 muon endcaps has not been completed. The second plot shows the distribution of polar angles  
 117 computed at the point on the stand-alone muon track closest to the center of the detector. The  
 118 agreement is very good.

## 119 5 Noise

120 An assessment of the fraction of nonfunctional and noisy channels must be made before any  
 121 discussion of efficiencies or resolution. Setting aside the few chambers that were turned off  
 122 due to problems with high voltage, low voltage, or a very small number of broken electronics  
 123 boards, the number of anode wire and cathode strip channels that failed to give data were  
 124 below 1% of the total. Given the six-layer redundancy of each chamber, and the redundancy of  
 125 the four disks in each endcap, the impact of these very few dead channels is negligible.

126 Noise can have two different deleterious effects, in principle: it can generate extra hits which

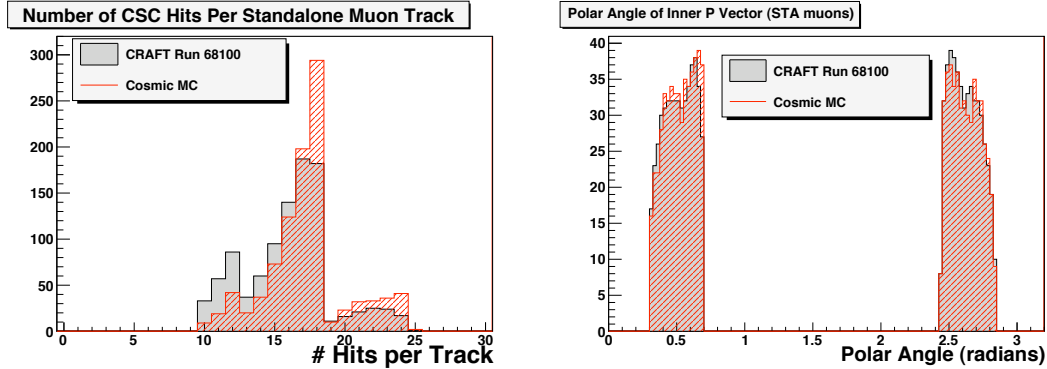


Figure 5: A comparison of the simulated events to the real CRAFT events for stand-alone muon tracks. *LEFT*: number of hits per track. *RIGHT*: global polar angle.

127 interfere with the reconstruction of muon tracks, and it can smear or distort the measurement  
 128 of the charge picked up on the strips, thereby smearing or distorting the calculated strip coordi-  
 129 nates. We have used the CRAFT data to make a basic assessment of the noise on both the  
 130 anode wire and cathode strip channels.

131 The first two time bins in a strip signal are reserved for an estimate of the *base line* and should  
 132 be free of signal. Prior to the beginning of CRAFT, the overall timing of the CSCs was adjusted  
 133 to ensure that this was the case. Consequently, the difference in the ADC values recorded for  
 134 the first two time bins,  $Q_1 - Q_0$ , should be zero, aside from any random fluctuations due to  
 135 electronics noise<sup>1</sup>. In order to be very sure that no signal contributed to  $Q_1$  and  $Q_0$ , strip  
 136 channels which had a sum of charges above base line of 13 ADC counts or more were omitted.

137 The rms of the distribution of  $\Delta_{01} \equiv Q_1 - Q_0$ ,  $\sigma_{01}$ , is taken to be a measure of noise, and was  
 138 obtained for all sets of 16 strip channels. Fig. 6 shows the distribution of all  $\sigma_{01}$  values.

139 The typical values are about 3 or slightly larger; there is little spread indicating excellent unifor-  
 140 mity. There are absolutely no large values, indicating no oscillating or otherwise noisy channels  
 141 at all.

142 Two peaks can be discerned in Fig. 6, corresponding to smaller and larger chambers. Fig. 7 dis-  
 143 plays some example distributions for  $\Delta_{01}$  showing that the rms is larger for the larger chambers  
 144 ( $ME \pm 2/2$  in the figure. The distributions are Gaussian with no tails or asymmetry.

145 The anode wire signals normally extend over one or two time bins. A noisy channel, however,  
 146 will rise above threshold in more time bins, so a useful quantity with which to identify noisy  
 147 channels is the number of time bins for which a given anode hit is *on*, denoted here by  $N_{\text{on}}$ .  
 148 The distribution of  $N_{\text{on}}$  for all anode channels in a particular chamber is shown in Fig. 8, on  
 149 a semi-log plot. A very small tail for  $N_{\text{on}} > 2$  can be seen. The number of noisy anode wire  
 150 channels is estimated to be less than 0.1%.

## 151 6 Efficiency

152 The goal of this study is to measure the absolute efficiency of each step in the reconstruction of  
 153 muons in the CSCs, from the generation of ALCs and CLCs through to segment reconstruc-  
 154 tion. By design, for good muons coming from the interaction point, all steps should be highly  
 155 efficient. The method described here uses two chambers to “tag” a muon that passes through

<sup>1</sup>Slow components in the noise on a channel will not be efficiently detected this way.



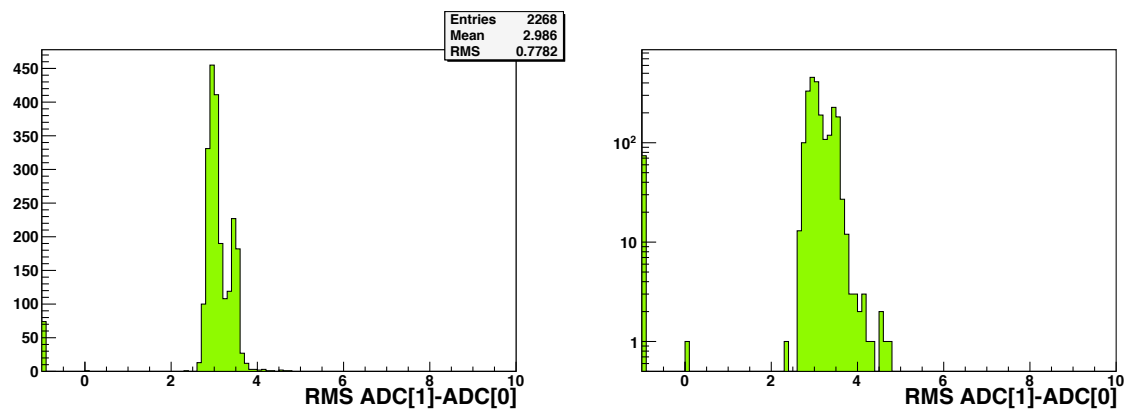


Figure 6: Distribution of all  $\sigma_{01}$  values, on a linear scale (left) and a log scale (right)

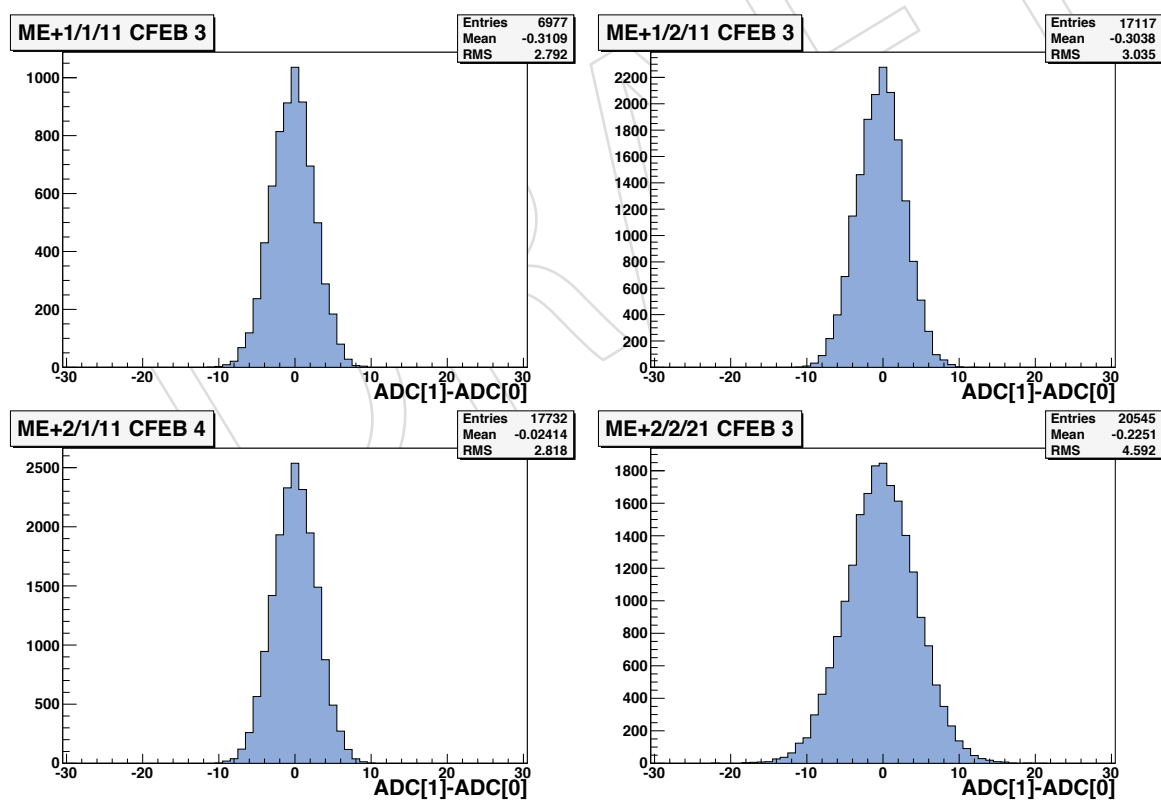


Figure 7: Four examples of  $\Delta_{01}$  distributions.

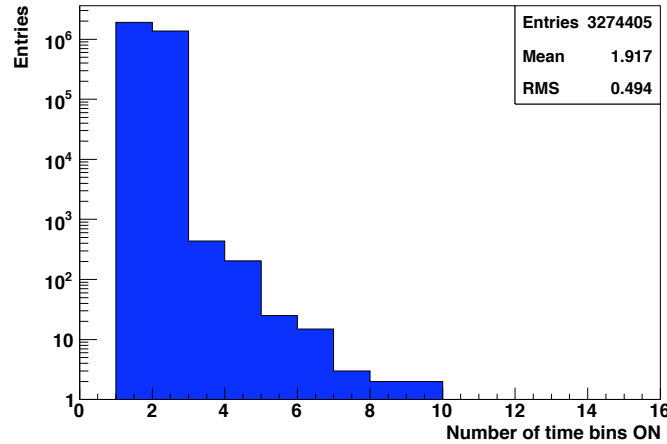


Figure 8: A semi-log plot of  $N_{\text{on}}$  for all anode wire channels in ME-2/1/9

156 a designated “probe” chamber. When computing the efficiency of each step, the same tagged  
 157 sample (i.e., the “denominator” in the efficiency calculation) is used for all steps.

158 For efficiency measurements, we need a well-defined muon track which is independent of the  
 159 measurements in the chamber under investigation. We use muon tracks reconstructed in sev-  
 160 eral CSCs without any information from the Si tracker – these are the “stand-alone” muons.  
 161 The number of useful stand-alone muons is adequate for the present purposes, thanks to the  
 162 redundancy of the muon endcap system. To minimize the impact of possible difficulties com-  
 163 ing from multiple scattering, energy loss, and tracking in a strong magnetic field, a chamber is  
 164 probed only if it lies between the endpoints of the track. Consequently, at least two indepen-  
 165 dent measurements of the muon track are needed, and only interpolation and not extrapolation  
 166 to the probe chamber is used. Some rings, namely  $\text{ME}\pm 1/1$ ,  $\text{ME}\pm 4/1$  and  $\text{ME}-3/2$  cannot be  
 167 covered by this study, although hits in the Resistive Plate Chambers (RPCs) allow coverage of  
 168  $\text{ME}+3/2$ .

169 A typical event selected for these efficiency measurements contains three or four CSCs con-  
 170 tributing to a good stand-alone muon track. Since the trigger efficiency is generally high (see  
 171 below), and a trigger from any one of these chambers sufficed to produce a trigger for read out  
 172 of CMS, we assume that any trigger bias in the results is negligible.

173 We place cuts on the predicted position of the muon in the probe chamber to avoid losses due  
 174 to insensitive regions at the periphery of the chamber and at the boundaries of the high voltage  
 175 segments. Fig. 9 shows distributions of the difference between the measured position of a  
 176 segment in the probe chamber and the predicted position, obtained by propagating the muon  
 177 track from another station to the probe chamber, taking the magnetic field, multiple scattering  
 178 and energy loss into account. In this figure, the local coordinate  $X$  runs parallel to the wires, and  
 179 is measured primarily by the strips, while  $Y$  runs perpendicular to the wires, and is measured  
 180 by the wire signals. According to these distributions, nearly all of the tracks fall within 10 cm  
 181 of the predicted position.

182 A set of stringent criteria is used to select “good” tracks for the denominator of all efficiency  
 183 calculations [5]. Only one stand-alone muon track is allowed in an endcap. This track has to  
 184 have at least a minimum number of hits, and to be reconstructed well, as indicated by the  $\chi^2$   
 185 and the relative error on the momentum. The momentum itself should be in a reasonable range,

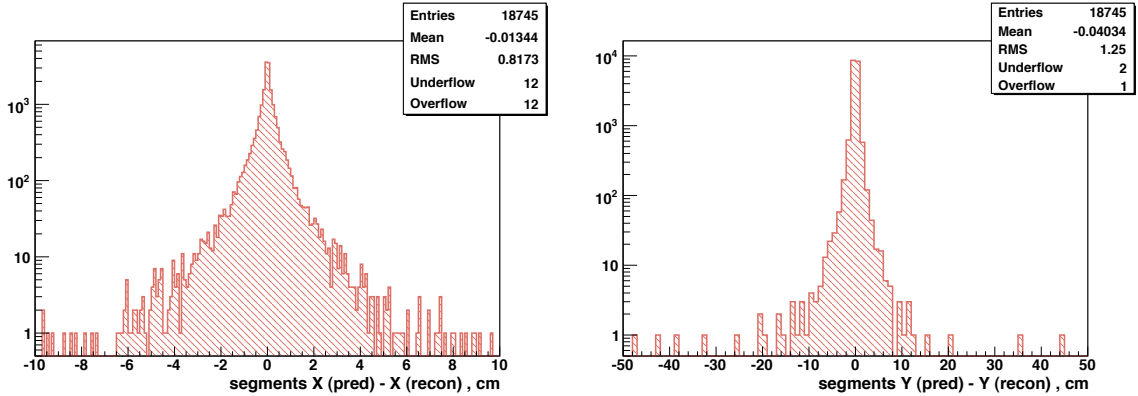


Figure 9: Differences between the predicted positions of a segment and the position of the reconstructed segment in the probe chamber.  $\Delta X$  is on the left, and  $\Delta Y$  is on the right, where  $X$  and  $Y$  are local coordinates.  $X$  is measured primarily by the strips, and  $Y$ , by the wires

186  $25 < p < 100$  GeV/ $c$ . A track satisfying these requirements is propagated to a designated ring  
 187 of CSC chambers to ascertain which chamber is the probe chamber. If the interpolated point  
 188 lies within 10 cm of the edges of the chamber or dead regions defined by high voltage segment  
 189 boundaries, then the chamber is skipped. The tracks which pass all of these criteria are the  
 190 “probe” tracks.

## 191 6.1 Results from CRAFT

192 The following sections report the details of the measurements and the values of the efficiency  
 193 for each step in the CSC local reconstruction.

### 194 6.1.1 LCT Efficiencies

195 The ALCT and CLCT efficiencies are measured independently. For a given chamber, the ALCT  
 196 and CLCT digis are unpacked to test for the presence of a valid ALCT or CLCT. If they are  
 197 present anywhere in the chamber, then the trial is a “success” and the chamber is “efficient” for  
 198 that event.

The ALCT wire patterns and the CLCT strip patterns were designed to be efficient only for muons originating from the interaction point [3]. The wire group width varies between 1.5 and 5 cm for different chambers. The distance between layers is 2.54 cm, except for the ME1/1 chambers, for which it is 2.2 cm. The range of track inclination ( $dy/dz$  in local coordinates) which should give efficient ALCT response is  $-0.69 < dy/dz < 0$  for smaller chambers, and  $-1.97 < dy/dz < 0$  for larger chambers. Similarly, for the CLCT response the range is  $|dx/dz| < 0.24$  for smaller, and 0.63 for larger chambers. For collision data, the muons will naturally have inclination angles within these ranges. Muons from cosmic rays, however, arrive at a wide variety of angles. To suppress the muons which are not likely to fire the ALCT and/or CLCT triggers, we apply cuts on the slopes of the muon tracks interpolated through the chamber:

$$-0.8 < \frac{dy}{dz} < -0.1 \quad \text{and} \quad \left| \frac{dx}{dz} \right| < 0.2. \quad (1)$$

199 One could adjust these ranges for the various rings of chambers, but the impact on the ef-  
 200 ficiency measurements is negligible. All the efficiencies measured with CRAFT data include  
 201 these requirements in the event selection.

202 The variation of the ALCT efficiency as a function of  $dy/dz$  is shown in Fig. 10 (left). For this

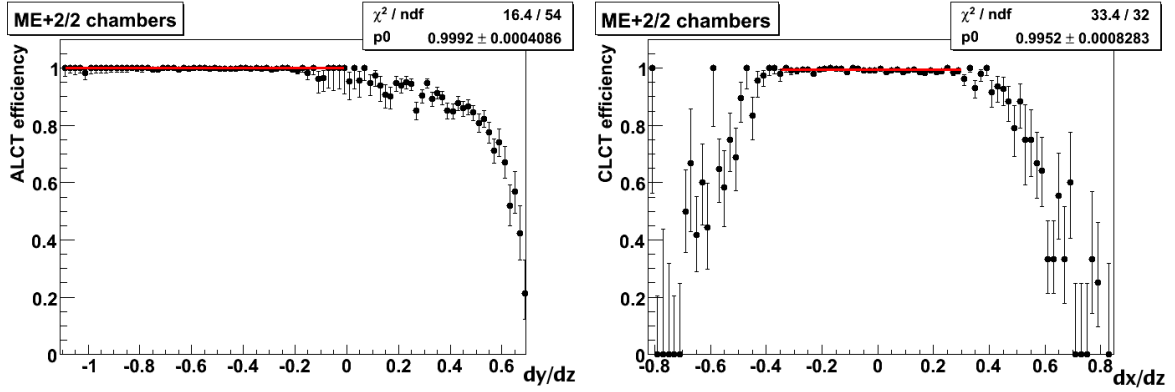


Figure 10: LEFT: ALCT efficiency as a function of the track inclination,  $dy/dz$  in local coordinates. RIGHT: CLCT efficiency as a function of the track inclination,  $dx/dz$  in local coordinates

203 figure, the cut on  $dy/dz$  was not applied, although the cut on  $dx/dz$  was applied. Similarly,  
 204 the variation of the CLCT efficiency as a function of  $dx/dz$  is shown in Fig. 10 (right), with  
 205 the cut on  $dx/dz$  relaxed, and the cut on  $dy/dz$  applied. The results shown in these plots are  
 206 based on data from chambers 5–13 in ring ME+2/2 which were known to be operating well.  
 207 In both figures, clear plateaus can be seen which were fit with level functions to ascertain the  
 208 efficiency. Very high values in excess of 0.999 are observed, confirming earlier results obtained  
 209 with cosmic rays [18].

### 210 6.1.2 Strip and Wire Group Efficiencies

211 In principle, the presence of an ALCT and CLCT should trigger the readout of the chamber,  
 212 and hence, signals on the wires and strips should be present in the raw data, or equivalently,  
 213 in the strip and wire digis. The efficiency for strip and wire digis are measured independently.  
 214 The probe is given by a good track passing through the given chamber.

The efficiencies of strips, wire groups and rechits are defined naturally per layer. If the layer measurements are independent, then the average efficiency per chamber would be

$$\bar{\epsilon} = \frac{\sum_i \epsilon_i}{L} = \frac{\sum_i n_i}{N \times L} \quad (2)$$

with an estimated uncertainty of

$$\Delta\bar{\epsilon} = \sqrt{\frac{\bar{\epsilon} \times (1 - \bar{\epsilon})}{L \times N}}, \quad (3)$$

215 where  $L = 6$  is the number of layers,  $\epsilon_i$  is the efficiency in layer  $i$  ( $i = 1, \dots, 6$ ),  $n_i$  is the number of  
 216 efficient cases (“successes”) for layer  $i$ , and  $N$  is the number of probe tracks. In principle, there  
 217 might be events with a simultaneous loss of information from all six layers, in which case Eq. 3  
 218 is incorrect. There is no evidence for any such correlated losses.

219 The average wire group and strip digi efficiencies are shown in Fig. 11. Typically, all six layers  
 220 are highly efficient, greater than 99.4%.

### 221 6.1.3 Rechit Efficiency

222 The efficiency for reconstructing a rechit is measured for each layer in a chamber. The chamber  
 223 is efficient if the rechits are found in a given layer - there is no requirement on the distance

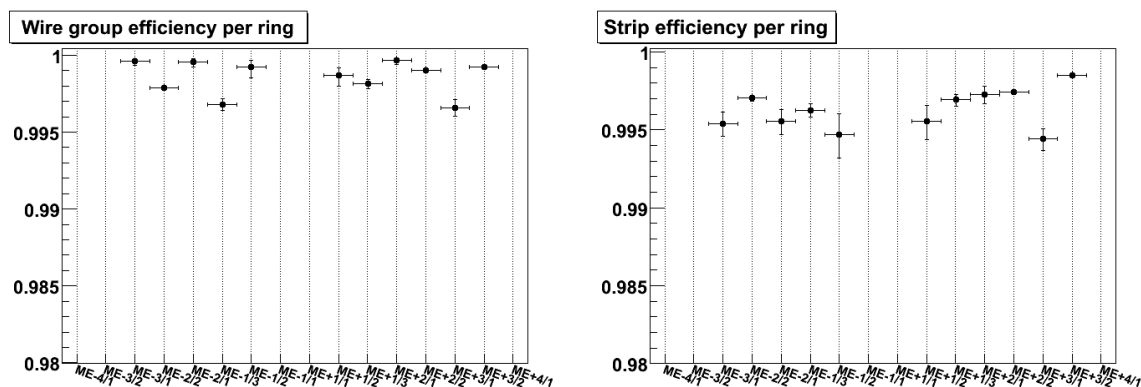


Figure 11: A summary of wire group (left) and strip (right) digi efficiencies, over all functioning chambers in a ring. Some rings are inaccessible in this study with CRAFT data.

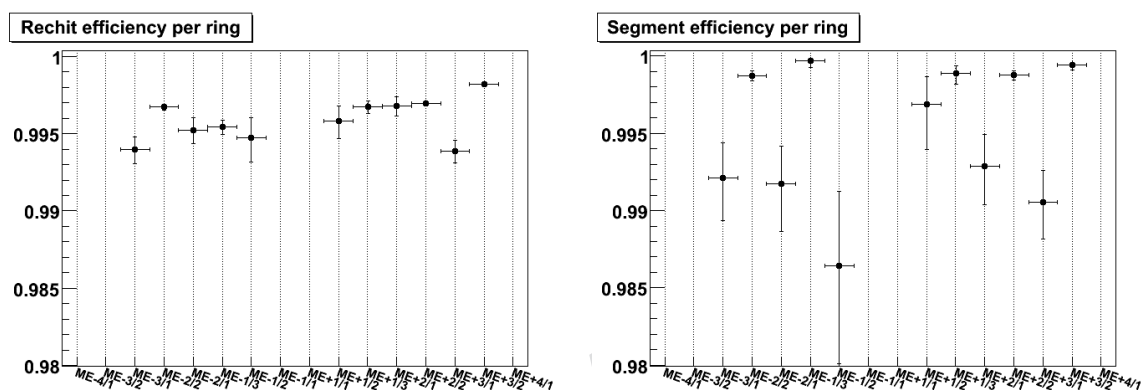


Figure 12: Summaries of rechit and segment efficiencies, analogous to Fig. 11

224 between the rechit and the interpolated point. Also, no quality requirements are placed on the  
 225 individual rechits as part of the measurement of rechit efficiency.

226 The rechit efficiency will be a convolution of the strip and wire group digi efficiencies. It might  
 227 also depend on some of the details of the rechit reconstruction algorithm, especially as regards  
 228 quality or other criteria applied to the strip and wire signals. The rechit efficiency for all the  
 229 CSC rings is shown in Fig. 12. The rechit reconstruction efficiency is above 99.3%.

#### 230 6.1.4 Segment Efficiency

231 It should be possible to build a segment if at least three good rechits are recorded along the  
 232 muon trajectory. The chamber is efficient if a segment has been reconstructed. No matching  
 233 criteria have been applied (cf. Fig. 9).

234 Ideally, the segment efficiency would be related in a simple and direct way to the rechit effi-  
 235 ciency. The segment reconstruction algorithm, however, also places requirements on the rechits  
 236 used to build segments. It does not find segments in chambers with very many hits, due to pro-  
 237 hibitive combinatorial problems – this will register as an inefficiency in the present study. The  
 238 segment efficiency for all the rings in the CSC system is shown in Fig.12. For cosmic rays, the  
 239 overall segment efficiency is above 99%.

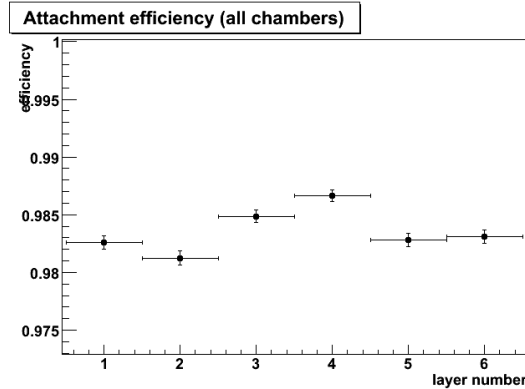


Figure 13: The attachment efficiency for each layer

Table 1: A summary of efficiencies for chambers in good operating condition

quantity	typical efficiency (%)
ALCT	> 99.9
CLCT	> 99.9
wire digis	> 99.5
strip digi	> 99.4
rechit	> 99.2
segment	> 98.5

### 240 6.1.5 Attachment Efficiency

241 The attachment efficiency is a characteristic of the segment finder. It is defined as the proba-  
 242 bility of the segment to use a rechit from a given layer if there are rechits in that layer. The  
 243 segment finder could reject some rechits if their quality were poor, or if they were producing  
 244 a bad fit, so one can anticipate a small inefficiency with respect to the efficiency for producing  
 245 rechits. What is important is that this inefficiency should be the same for all layers. Any signif-  
 246 icant variation with layer number would be a hint of a problem – for example, an unacceptable  
 247 dependence on the track angle. Fig. 13 shows that there is no bias in the CRAFT data.

248 Given the excellent efficiencies measured at all levels of the readout and reconstruction, an  
 249 estimate of the efficiency for reconstructing muons in collision data would be plausible. A  
 250 sample of simulated  $W \rightarrow \mu\nu$  decays was used to make such an estimate: for all chamber types,  
 251 the efficiency to reconstruct a segment is above 99%, if the muon passes through the chamber –  
 252 regardless of whether the muon goes through a good region or close to a high voltage boundary  
 253 or the periphery of the chamber. According to the same simulation, the efficiency to reconstruct  
 254 a stand-alone muon is above 95% in the  $\eta$  range covered by the CSCs.

255 In summary, all the basic efficiencies have been shown to be high, for chambers in good oper-  
 256 ating condition during CRAFT. See Table 1.

## 257 7 Resolution

258 The CRAFT data were used to study and measure the spatial resolution of the CSCs as they are  
 259 meant to be operated for early physics <sup>2</sup>. The purpose of this study is to demonstrate that all

<sup>2</sup>The current high voltage settings are intentionally lower than what was used for the test beam studies, in order to avoid aging the chambers unnecessarily during commissioning periods. This has a significant impact on the



260 working chambers perform as they should, before colliding beams commence. Excellent earlier  
261 studies of CSC spatial resolution can be found in Ref. [19, 20].

262 The following sections define what we mean by “resolution,” and how we measure it. We  
263 show the expected variations of the resolution as functions of charge, position within a strip,  
264 the width of the strip, and angle. Special studies have been carried out for  $ME\pm 1/1$  chambers,  
265 as their design differs somewhat in order to cope with the high magnetic field and difficult  
266 demands for resolution [17]. We report measured values of the resolution for all types of cham-  
267 bers, and then conclude.

## 268 7.1 Analysis

269 The reconstruction of muon trajectories and the measurement of the muon momentum de-  
270 pends critically on the spatial resolution of the chambers. The most important coordinate is  $\phi$ ,  
271 so these studies are concerned with the strip measurements only. An adequate measurement  
272 of  $R$  at a given  $z$  is given by the anode wires.

### 273 7.1.1 Methodology

274 The *resolution* is the typical measurement error. It is determined by the design parameters  
275 of the chamber (width of the cathode strip, distance to the anode wire plane, high voltage,  
276 anode wire radius and pitch, gas mixture, electronics noise and cross talk) as well as certain  
277 characteristics of each muon track (angle, position with respect to the center of the struck strip,  
278 and amount of charge collected), and of course the physics of multi-wire proportional cham-  
279 bers (electron diffusion, magnetic field influence) and the reconstruction (reduction of data and  
280 knowledge of misalignments). The distribution of hit residuals with respect to the muon tra-  
281 jectory can give a good measure of the resolution. A *residual* is the difference between the  
282 measured coordinate and the true or estimated true (i.e., predicted) coordinate.

283 For the purposes of the study, the coordinate of interest is the coordinate measured by the  
284 strips. In global coordinates, this would be  $R\phi$  as measured in centimeters, but most of the  
285 results presented here are couched in *strip coordinates*. The strip coordinate,  $s$ , is the  $R\phi$  co-  
286 ordinate relative to the center of the strip, divided by the strip width at the position of the hit.  
287 Modulo resolution effects, one has  $-0.5 \leq s \leq 0.5$ . Most of the plots here will show residuals  
288 distributions in strip coordinates. In order to obtain a resolution in physical units, we multiply  
289 by the mean width of a strip in the given chamber. A synopsis of relevant chamber parameters  
290 is given in Table 2.

The residuals distribution is not Gaussian, in general, so one must settle on a measure of the  
residuals distribution to be identified with the “resolution” of the given chamber. Usually we  
fit the distribution with a sum of two Gaussian functions, with zero mean, using the functional  
form:

$$f(x) \equiv \frac{A_1}{\sqrt{2\pi}\sigma_1} \exp\left(\frac{-x^2}{2\sigma_1^2}\right) + \frac{A_2}{\sqrt{2\pi}\sigma_2} \exp\left(\frac{-x^2}{2\sigma_2^2}\right) \quad (4)$$

where optimal values for the parameters  $\sigma_1$ ,  $\sigma_2$ ,  $A_1$  and  $A_2$  are obtained from the fit. We take  
the resolution to be:

$$\text{resolution : } \quad \bar{\sigma} = \sqrt{\frac{A_1\sigma_1^2 + A_2\sigma_2^2}{A_1 + A_2}}. \quad (5)$$

291 If one Gaussian suffices, then we take simply the  $\sigma$  parameter of the single Gaussian. We  
292 do not take the r.m.s. as the residual distributions often have long non-Gaussian tails which

Table 2: Selected relevant physical specifications of the cathode strip chambers. For more information, see Ref. [1]

ring	chambers per ring	strips per chamber	strip width (mm)	(mrad)
ME±1/1a	36	48	4.11 – 5.82	3.88
ME±1/1b	36	64	4.44 – 7.6	2.96
ME±1/2	36	80	6.6 – 10.4	2.33
ME±1/3	36	64	11.1 – 14.9	2.16
ME±2/1	18	80	6.8 – 15.6	4.65
ME±2/2	36	80	8.5 – 16.0	2.33
ME±3/1	18	80	7.8 – 15.6	4.65
ME±3/2	36	80	8.5 – 16.0	2.33
ME±4/1	18	80	8.6 – 15.6	4.65

293 inflate the r.m.s. - these tails are caused by  $\delta$ -ray electrons and fall outside a discussion of the  
 294 core resolution. The residuals distributions of the eight chamber types with fits to Eq. 4 are  
 295 given in Fig. 14.

As defined, the resolution  $\bar{\sigma}$  pertains to a hit in a *single layer*. The resolution of a chamber is more complicated, since it depends on the number of hits in the segment, the angle of the segment, the generally non-normal angle between wire groups and strips, and the fact that the strips are staggered layer-by-layer for all chambers except ME±1/1. We can take the special case of segments with six hits that are normal to the chamber and pass through the center. If the residuals distribution near the edge of a strip has Gaussian width  $\sigma_e$ , and near the center of a strip,  $\sigma_c$ , then to a good approximation, the resolution for the segment is

$$\text{segment : } \sigma_{\text{seg}} = \left( \frac{3}{\sigma_e^2} + \frac{3}{\sigma_c^2} \right)^{-1/2}. \quad (6)$$

296 We will use this expression to characterize the chamber resolution.

Another method for measuring the resolution does not rely on the residuals of a single layer, but rather on the value of  $\chi^2$  for the linear fit to all six hits. Let us define the *unweighted*  $\chi^2$  as follows:

$$\chi_0^2 \equiv \sum_{i=1}^6 (s_i - (a + bi))^2 \quad (7)$$

297 where  $a$  and  $b$  are free parameters, and the layer number  $i$  plays the role of the  $z$  coordinate.  
 298 Notice we have set all uncertainties to one. As a consequence,  $\langle \chi_0^2 \rangle = 4\sigma_0^2$ , where  $\sigma_0$  is the  
 299 effective uncertainty on  $s_i$ .

300 We do not have a good exterior measure of the position of the muon, so we have to use the  
 301 segment itself. Perhaps the cleanest procedure is to use five out of the six hits on a good seg-  
 302 ment to predict the position of the sixth. In practice, we fit the hits in layers 1, 2, 4, 5 and 6 to  
 303 a straight line to predict the “correct” position in layer 3, and then compare to the measured  
 304 position in layer 3. Monte Carlo studies show that the width of the residuals distribution is  
 305 inflated by about 10% due to the measurement error from the five-hit fit; this uncertainty is  
 306 larger for layers 1, 2, 5 or 6. We do not remove this 10% inflation for the results reported in this  
 307 note.

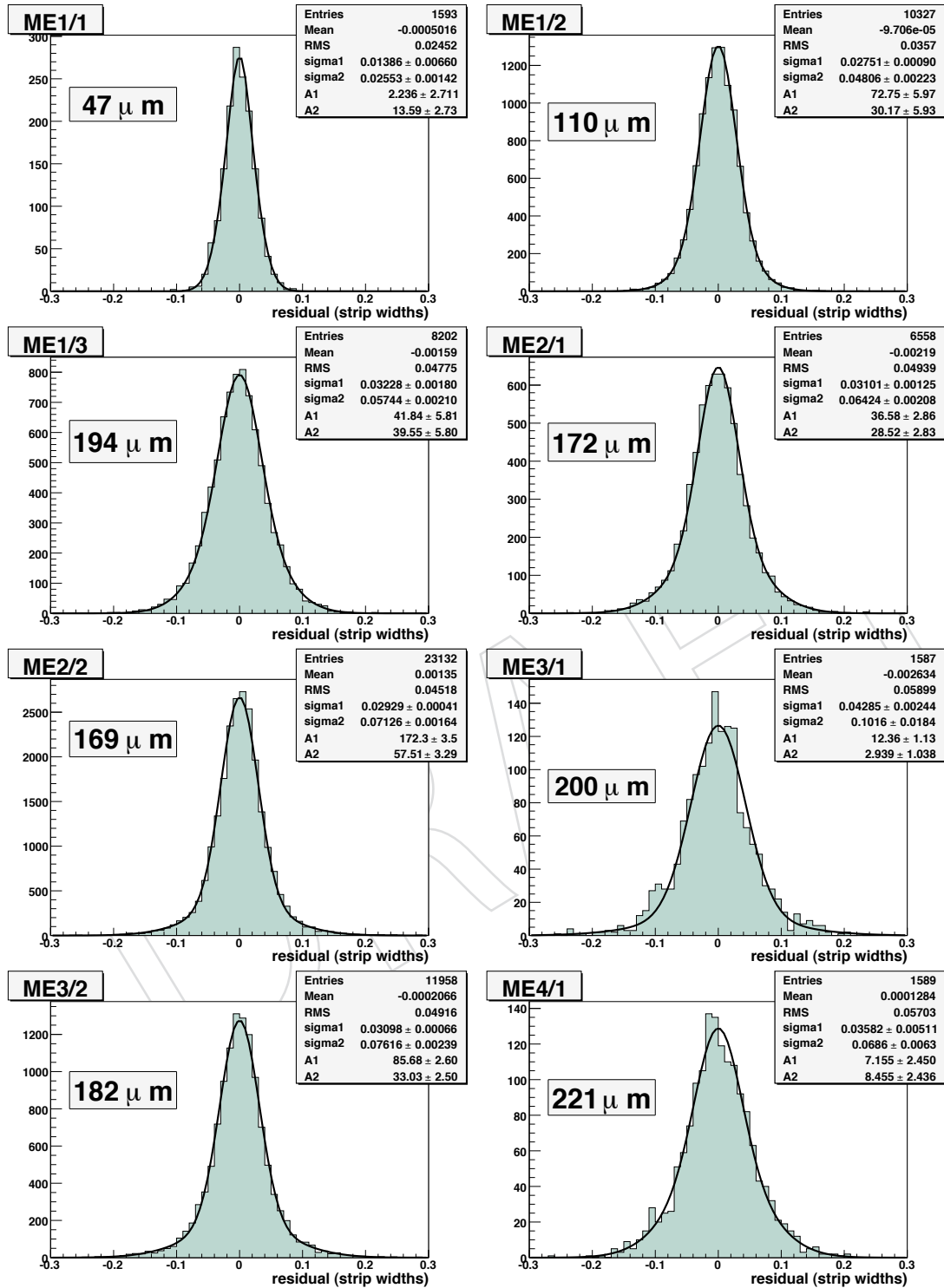


Figure 14: Distributions of residuals fit to the double-Gaussian function given in Eq. 4.

### 7.1.2 Expected Behavior

The resolution is known to vary with several quantities, including the charge recorded for that hit, the position within the strip, the physical width of the strip, the inclination of the track and the magnetic field, among others. This behavior can be understood qualitatively, given a model for the formation of signals on the strips.

Analytical calculations for the formation of signals in cathode strip chambers have been available for many years. Gatti described how charge was apportioned among the strips in 1979 [21]. His calculation was updated and extended by Mathieson and Gordon in 1984 [22].

A simple picture of the signal on three strips labels the charges  $Q_L$ ,  $Q_C$  and  $Q_R$ , where by definition the charge on the central strip is larger than that on the left and right side strips. The central strip extends across  $-0.5 < s < 0.5$ , and the left strip is at  $s = -1$  and the right, at  $s = +1$ . With the muon passing through the central strip slightly to the right of the center of the center strip ( $s > 0$ ),  $Q_R > Q_L$ , and of course  $Q_C > Q_R$ .

It is intuitively clear that the position of the muon relates to the relative difference  $Q_R - Q_L$ , and indeed the first approximation to this position is simply

$$s \approx \frac{1}{2} \frac{Q_R - Q_L}{Q_C - \min(Q_R, Q_L)}. \quad (8)$$

For a justification of this choice, see Ref. [19]. Other choices can be made - this is not critical for the present discussion.

The accuracy of the measurement of  $s$  depends on how well the difference  $Q_R - Q_L$  can be measured. For the CSCs, most of the charge appears on the central strip, unless the muon passes quite close to the edge of the strip. For the large chambers especially,  $Q_R$  and  $Q_L$  are only a few percent of  $Q_C$ , and in the worse cases are not much larger than the pedestal width. This width characterizes the electronics noise, so the central question is: are the observed charges  $Q_R$  and  $Q_L$  larger than or comparable to this noise?

If the total charge  $Q$  is large, then the impact of the noise will be reduced. This explains why the resolution improves as  $Q$  increases, so long as  $\delta$ -ray electrons are not interfering with the charge distribution. Explicit calculations show that the resolution should be proportional to  $1/Q$  [21, 22].

The charge on the right strip will increase as the muon trajectory approaches  $s = 0.5$ . In the limit that  $s \rightarrow 0.5$ ,  $Q_L$  does not matter, and the approximation in Eq. 8 becomes

$$s \approx \frac{1}{2} \frac{Q_R}{Q_C} \rightarrow \frac{1}{2}$$

since  $Q_R \rightarrow Q_C$  in this limit. In such a case, the electronics noise becomes relatively unimportant, since both  $Q_R$  and  $Q_C$  are substantial. In contradistinction, as the muon trajectory approaches  $s = 0$ , both  $Q_L$  and  $Q_R$  are minimal and therefore maximally impacted by electronics noise, making the difference  $Q_R - Q_L$  relatively difficult to measure. For these reasons, one expects the best resolution for muon trajectories close to the edge of the strip, and the worst resolution when they go through the center.

The spatial distribution of the charge depends on the separation between strips, for a fixed distance between the strip plane and the anode wire plane. If the physical width of the strip is large, then  $Q_L$  and  $Q_R$  will be small. Due to the impact of electronics noise, which tends to be larger when the strips are larger, the resolution is poorer in chambers with large strips than

343 in chambers with small strips. For this reason, the strips in the  $ME\pm 1/1$  chambers have been  
 344 made particularly small (cf. Table 2), since they play a key role in the momentum measurement  
 345 in the end caps [1].

346 Finally, a muon which passes through the anode plane at an oblique angle (with respect to the  
 347 strips) will produce a relatively broad distribution of charge across the gas gap, leading to a  
 348 smearing of the distribution of charges  $Q_L$  to  $Q_R$ , and a poorer resolution.

349 The above discussion is heuristic in nature; the actual calculation of coordinates and uncertain-  
 350 ties is based on the full Gatti function and on quantitative studies of the variation of resolution  
 351 with charge, position within a strip, and strip width. For a detailed technical discussion of  
 352 precise position measurement with cathode strip chambers, see, for example, Ref. [23].

### 353 7.1.3 Qualitative Results from CRAFT

354 Events were selected which contained a good segment from which residuals distributions for  
 355 layer 3 could be formed. A good segment was one which contained six rechits and  $\chi^2 < 200$   
 356 (unreduced). An event was selected if it contained at least one good segment. In order to retain  
 357 only clean events, any event with more than eight segments of any quality were rejected, as well  
 358 as events with more than fifty rechits. The event was also rejected if any chamber contained  
 359 more than four segments of any quality. About  $5 \times 10^4$  events were selected [6].

360 Further criteria were applied when filling residuals distributions, to ensure that the results were  
 361 based on the cleanest possible segments and hits:

- 362 1. the estimated errors on the six rechits have to be smaller than 0.2 strip widths. This  
 363 eliminates rechits based on a single strip or for which the cross-talk correction led to  
 364 negative values for  $Q_R$  and  $Q_L$ .
- 365 2. The sum of charges for three strips and three time slices for layer 3 could not be too small  
 366 or too large:  $250 < Q_{3 \times 3} < 1000$  ADC counts.
- 367 3. The segment inclination should correspond to tracks originating roughly from the inter-  
 368 action point:

$$-1 < \frac{dy}{dz} < -0.15 \quad \text{and} \quad \left| \frac{dx}{dz} \right| < 0.15 \quad (9)$$

367 where these are local coordinates:  $dy/dz$  is the angle with respect to the anode wires, and  
 368  $dx/dz$  is the angle with respect to the cathode strips.

- 369 4. The strip coordinates were fit to a straight line. The resulting  $\chi^2$  value were required to  
 370 be less than 9 for the 5-hit fit, and less than 50 for the 6-hit fit.

371 These cuts were relaxed singly when checking the impact of these criteria.

372 In the remainder of this section, we use the CRAFT data to demonstrate the expected behavior  
 373 as described in Section 7.1.2. No attempt was made to remove layer-by-layer misalignments,  
 374 as these are known to be small compared to the resolution.

375 The ‘‘charge’’ depends on several factors, including the gas composition, pressure, high volt-  
 376 age, amplifier gain, and of course the ionization of the gas by the muon. We denote by  $Q_{3 \times 3}$   
 377 the sum of the charges recorded in three time bins across three consecutive strips [19]. A dis-  
 378 tribution of  $Q_{3 \times 3}$  for the CRAFT data is shown in Fig. 15 (left). The distribution has a long tail,  
 379 similar to that expected from the Landau distribution.

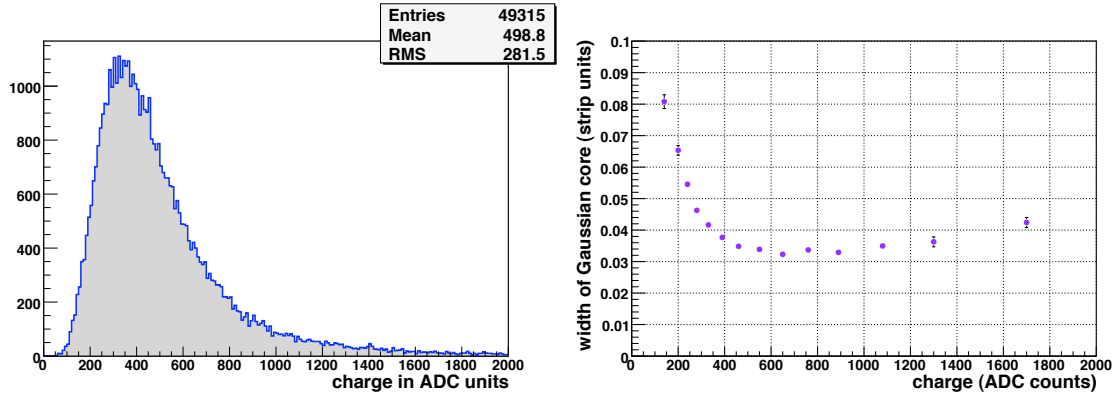


Figure 15: *Left*: Observed charge distribution,  $Q_{3\times 3}$ , in ADC counts. *Right*: Variation of the *per layer* resolution as a function of  $Q_{3\times 3}$ . This measurement was made using chambers in  $ME\pm 2/2$  and  $ME\pm 3/2$ ; other chambers give very similar results.

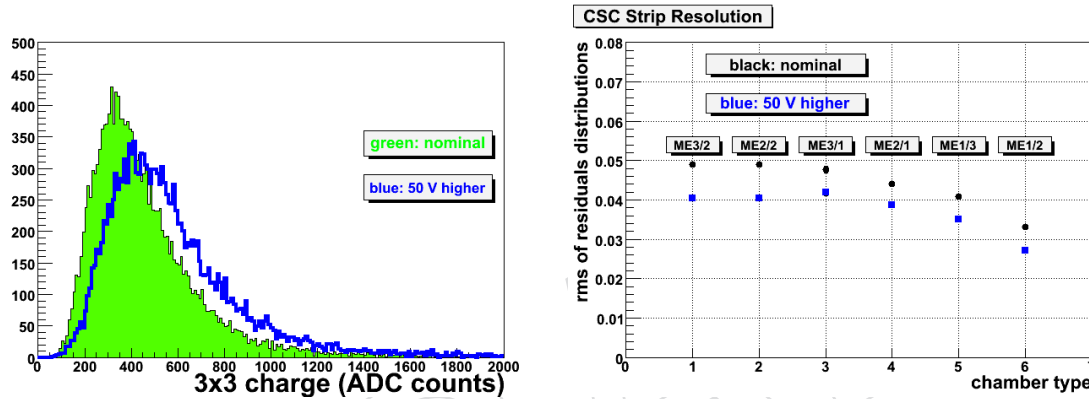


Figure 16: *Left*: Charge distributions for two consecutive runs. The solid histogram corresponds to the nominal setting, and the open histogram corresponds to an increase of 50 V. *Right*: Comparison of the resolution for the same two runs.

380 A summary of the variation of the resolution as a function of charge is given in Fig. 15 (right).  
 381 Chambers in rings  $ME\pm 2/2$  and  $ME\pm 3/2$  were selected for this plot, since they have the largest  
 382 number of events in CRAFT. The cuts on the  $\chi^2$  of the 2-dimensional strip fit were relaxed for  
 383 this study, so that the impact of  $\delta$ -ray electrons is evident at large angles. If the cuts are imposed,  
 384 then the rise for  $Q_{3\times 3} > 800$  ADC counts is eliminated.

385 Another demonstration of the sensitivity of the resolution to charge is provided by two runs  
 386 taken outside of the CRAFT exercise, in which the high voltage was raised by 50 V. Since the  
 387 number of events was modest, the event and segment selection was somewhat looser than  
 388 described above. The improvement in resolution is consistent with the expected  $1/Q$  behavior,  
 389 as demonstrated in Fig. 16.

390 The variation of the resolution with the position within a strip,  $s$ , is shown in Fig. 17. For the  
 391  $ME\pm 2/2$  chambers, the resolution in the center of the strip is worse by about a factor of two  
 392 than at the edge. This variation is weaker for chambers with thinner strips, such as  $ME\pm 1/2$   
 393 and  $ME\pm 1/1$ .

394 Most of the analysis presented here is done in terms of the normalized strip width,  $s$ . The  
 395 physical width of the strip matters, too. For broad strips, most of the charge is collected on the



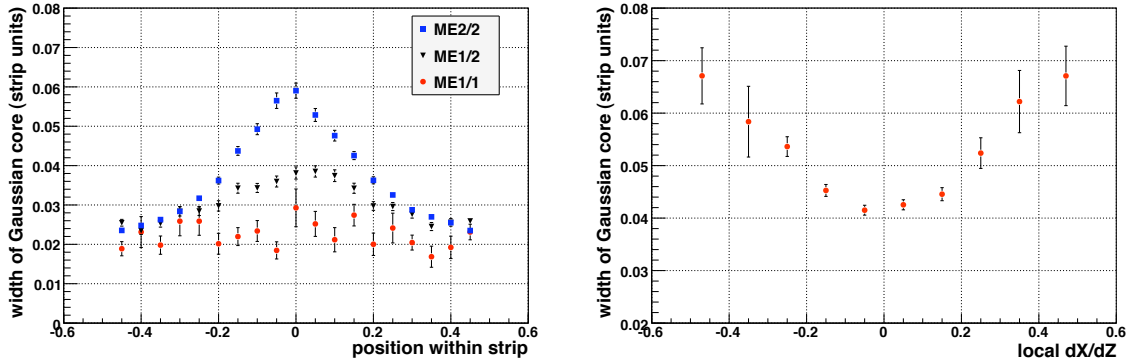


Figure 17: *Left:* Variation of the *per layer* resolution as a function of  $s$ , the position within the strip, for three different types of chambers. *Right:* Variation as a function of local  $dx/dz$ , which quantifies the segment inclination with respect to the strips. These measurements were done with the  $ME\pm 2/2$  chambers.

396 central strip, leaving a small amount for  $Q_L$  and  $Q_R$ , leading to a poorer resolution. For this  
 397 reason, the smaller chambers have a much better resolution than the larger chambers. Within  
 398 a chamber, there is a mild variation of the resolution along the strip, since the strip is narrower  
 399 at the narrow end of the chamber and wider at the broad end.

400 The results described above were derived for muon trajectories that were nearly perpendicular  
 401 to the strips. For low-momentum muons coming from the interaction point, however, more  
 402 oblique trajectories are possible. We have observed a clear variation of the resolution as a  
 403 function of  $dx/dz$  in chambers from ring  $ME\pm 2/2$ , see Fig. 17. For all other results reported in  
 404 this note, a tight cut on  $|dx/dz|$  has been applied (Eq. 9).

405 The estimated uncertainty is computed taking variations as a function of charge, position  
 406 within a strip, and strip width into account. Distributions of normalized residuals (“pull distri-  
 407 butions”) allow us to check those calculations. A summary of the pulls for all chamber types is  
 408 given in Table 3. Overall, the pulls are somewhat too wide, especially for the  $ME\pm 1/1$  cham-  
 409 bers. It will be possible to adjust the error estimates on the basis of the CRAFT data.

#### 410 7.1.4 Measurements of the Nominal Resolution

411 The results in the previous section demonstrate the expected qualitative behavior of the reso-  
 412 lution. In this section, we quantify the resolution of the CSCs, as measured with CRAFT data,  
 413 in order to verify that they are performing as designed.

414 Residuals distributions for chambers in each ring were fit to the sum of two Gaussian functions  
 415 (Eq. 4), and the resolution computed according to Eq. 5. These distributions are shown in  
 416 Fig. 14. Table 3 lists the *per layer* resolution obtained in this manner. The values given in  $\mu\text{m}$   
 417 are obtained by multiplying the resolution in strip widths by the average width of the strip (see  
 418 Table 2).

419 We formed distributions of  $\chi_0^2$  (Eq. 7) for each chamber type. We computed  $\sigma_0$  (which would be  
 420 in units of the strip width) and converted to an uncertainty in  $\mu\text{m}$  using the average physical  
 421 strip width. The results are listed in Table 3. These values agree very well with the values  
 422 obtained from the fit to two Gaussian functions.

423 The resolution of a chamber, given six good rechits, can be estimated on the basis of the *per*

Table 3: Resolution *per layer* for each chamber type, and the rms of the pull distributions

ring	resolution				pull r.m.s.
	<i>fit to two Gaussians</i>		<i>derived from <math>\chi_0^2</math></i>		
	strip widths	$\mu m$	strip widths	$\mu m$	
ME $\pm$ 1/1	0.024 $\pm$ 0.002	128	0.021	115	1.89 $\pm$ 0.06
ME $\pm$ 1/2	0.034 $\pm$ 0.001	285	0.036	300	1.34 $\pm$ 0.01
ME $\pm$ 1/3	0.044 $\pm$ 0.001	578	0.050	658	1.52 $\pm$ 0.01
ME $\pm$ 2/1	0.046 $\pm$ 0.001	510	0.054	600	1.28 $\pm$ 0.02
ME $\pm$ 2/2	0.040 $\pm$ 0.001	487	0.048	581	1.42 $\pm$ 0.01
ME $\pm$ 3/1	0.054 $\pm$ 0.002	633	0.064	751	1.26 $\pm$ 0.04
ME $\pm$ 3/2	0.044 $\pm$ 0.001	534	0.050	614	1.37 $\pm$ 0.02
ME $\pm$ 4/1	0.054 $\pm$ 0.004	648	0.064	766	1.17 $\pm$ 0.03

Table 4: Resolution *per chamber* for each chamber type

ring	resolution ( $\mu m$ )		
	design	<i>per layer</i> / $\sqrt{6}$	Eq. 6
ME $\pm$ 1/1	75	52	47
ME $\pm$ 1/2	75	116	110
ME $\pm$ 1/3	150	234	194
ME $\pm$ 2/1	150	208	172
ME $\pm$ 2/2	150	199	169
ME $\pm$ 3/1	150	258	200
ME $\pm$ 3/2	150	218	182
ME $\pm$ 4/1	150	264	221

424 *layer* resolution. One can simply take the numbers listed in Table 3 and divide by  $\sqrt{6}$ , or one  
425 can perform a slightly more refined analysis indicated by Eq. 6. The latter gives systematically  
426 lower values for the resolution than the former. Table 4 lists both sets of values, which can be  
427 compared to the design values [1]. Most the observed values are somewhat higher, except for  
428 the ME $\pm$ 1/1 chambers, which are significantly better than design. The fact that the high volt-  
429 age is set to a somewhat reduced value is the primary reason for the slightly worse resolution  
430 in the non-ME $\pm$ 1/1 chambers.

### 431 7.1.5 Special Studies of ME1/1

432 The ME $\pm$ 1/1 chambers play a special role. First, they prove the key measurements for the high-  
433 momentum muon tracks expected at high  $|\eta|$ . And second, they must operate in a very high  
434 magnetic field, which alters the drift of the electrons inside the gas layers. For these reasons,  
435 the gas gaps are smaller, the gas gain is higher, the strips are narrower, and the wires are tilted  
436 with respect to wires in the other chambers [17].

437 The drift of the electrons perpendicular to the anode wires depends sensitively on the magnetic  
438 field. Most of the CRAFT data were taken at full field, but some data were taken with zero field,  
439 and with some intermediate values. These data were analyzed to measure the resolution as a  
440 function of the magnetic field, with the results shown in Fig. 18. Clearly the resolution is best  
441 at full field, confirming the details of the initial design.

442 The radial extent of the ME $\pm$ 1/1b chambers was divided into four regions in order to check  
443 the resolution at different radii. Fig. 18 shows that the resolution is best near the beam line,

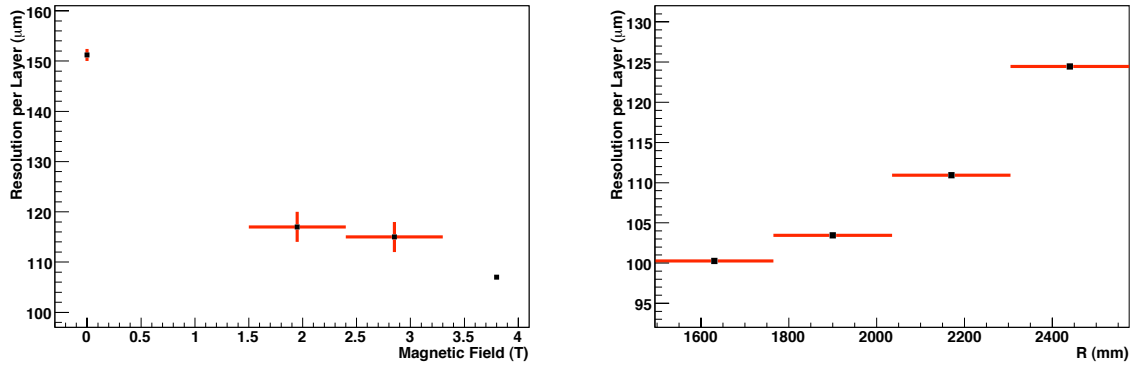


Figure 18: *LEFT*: Variation of the resolution in the  $ME\pm 1/1b$  chambers as a function of magnetic field in Tesla. *RIGHT*: Variation of the resolution as a function of the radius (distance from the beam line)

444 where it is most critical, and rises rapidly with radius. A further study of the resolution for  
 445 different azimuthal regions of the  $ME\pm 1/1b$  chambers shows a mild variation with the angle  
 446 of the anode wires, confirming the choices made in the design of these chambers.

## 447 8 Timing

The readout of the cathode strips provides enough information to reconstruct the pulse shape and infer the time of the signal. The output from the cathode strip front-end amplifier is sampled every 50 ns (2 BX) with the results stored in a switched capacitor array (SCA). The arrival of the pulse is arranged so that the first two time bins are free from signal, allowing a dynamical estimate of the signal base line. A good description of the pulse shape recorded in the SCA is given by a 5-pole semi-Gaussian:

$$S(t) \propto \left( \frac{t - T_S}{T_0} \right)^4 \exp \left( - \frac{(t - T_S)}{T_0} \right)$$

448 valid for  $t > T_S$ , the start time. Given the fixed exponent of the  $(t - T_S)$  term, the shape of the  
 449 pulse is determined by the decay constant  $T_0$ . The maximum occurs at  $t = T_S + 4T_0$ .

450 This pulse shape is very well established through studies with prototypes [20] as well as with  
 451 cosmic ray data. Cross-talk is approximately 10% of the signal, and should be taken into ac-  
 452 count in order to describe the pulse shape precisely.

453 We used the CRAFT data to make some simple tests of the timing capabilities of the CSCs. The  
 454 time of flight of a muon through a single chamber is quite small, essentially zero compared  
 455 to the 25 ns BX spacing. Fig. 19 shows the distribution of differences in measured times for  
 456 layers 6 and 1, in units of 50 ns time bins. The mean is consistent with zero, and the r.m.s. is  
 457 0.143 bins, which corresponds to 7.2 ns, or 5 ns per layer. Most segments have six rechits (cf.  
 458 Fig. 4), so a single segment should have a time resolution of about 2 ns. This compares well  
 459 with the transit time of a muon from the interaction point to the CSCs of roughly 30 ns, and of  
 460 the beam crossing time of 25 ns.

461 Improvements to the use of the strip timing information can be foreseen, based on a more  
 462 detailed analysis of the subtle effects of cross talk and noise correlations, as suggested by pilot  
 463 studies with test beam data [20].

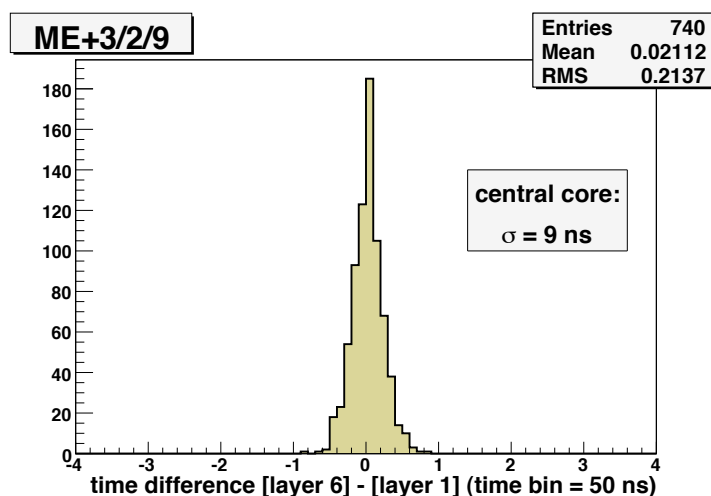


Figure 19: The difference in rechit times for layers 6 and 1 in chamber  $ME + 2/2/9$ . Units are 50 ns time bins. A fit of the central core to a Gaussian function gives a width of 9 ns.

464 It is hoped to use this timing capability for rejecting out-of-time hits and tagging the time of  
465 the muon independently of the trigger system.

## 466 9 Summary

467 An assessment of the performance of the CSCs has been completed using the large CRAFT data  
468 sample recorded in Fall 2008. More than 97% of the CSC muon detector system was in excel-  
469 lent working condition and participated in the bulk of this campaign. The agreement of basic  
470 global quantities between the real data and simulation is good. The fraction of channels which  
471 provided no signal, or were noisy, is very small, less than 1%. All of the essential efficiencies  
472 have been measured, ranging from the local charged tracks which trigger the chamber readout  
473 through the reconstruction of segments. These efficiencies are all very high. The position res-  
474 olution has been studied, with variations observed as a function of several relevant variables,  
475 such as the charge, position within a strip, high voltage, track inclination, and in the case of  
476 the  $ME \pm 1/1$  chambers, of the magnetic field, radius and wire tilt. The measured chamber res-  
477 olutions are not quite as good as design, due to an intentional reduction of the high voltage,  
478 except for the  $ME \pm 1/1$  chambers, which surpass the design criterion. Finally, the potential  
479 timing capabilities of the CSCs was briefly investigated.

480 The prospects for future studies are very good. The operating conditions of the CSC subsystem  
481 have been improved since the CRAFT data were taken, and one can anticipate that the CSC  
482 subsystem will function extremely well once the LHC delivers collisions to CMS.

## 483 References

- 484 [1] CMS Collaboration, *CMS – The Muon Project*, CERN/LHCC 97-32
- 485 [2] CMS Collaboration, “*CMS Physics Technical Design Report*”, CERN/LHCC 2006-001 (2006)
- 486 [3] J. Hauser et al., “*Experience with Trigger Electronics for the CSC System of CMS*”, Proceedings  
487 of the 10th Workshop on Electronics for LHC Experiments and Future Experiments (2004)

- 
- 488 [4] N. Terentiev, T. Ferguson and M. Ignatenko, *Performance of the CMS Endcap Muon Anode-*  
489 *Wire Front-end Electronics in the CRAFT 2008 Data*, CMS-NOTE, submitted
- 490 [5] S. Stoynev and M. Schmitt, *Efficiency Measurements in the CSC Muon Endcap System*, CMS-  
491 NOTE, in preparation
- 492 [6] I. Bloch et al., *Measurement of the CSC Spatial Resolution with Cosmic Ray Muons*, CMS-NOTE,  
493 in preparation
- 494 [7] V. Pereilygin et al., *ME1/1 CSC Spatial Resolution*, CMS NOTE, submitted.
- 495 [8] R. Breedon et al., *Post-Production Testing and Commissioning of the CMS End-cap Cathode Strip*  
496 *Chambers*, CMS-NOTE, in preparation
- 497 [9] CMS Collaboration, *Studies of CMS Muon Reconstruction Performance with Cosmic Rays*, in  
498 preparation
- 499 G. Abbiendi et al., *Muon Reconstruction in the CMS Detector*, CMS-AN/2008-097
- 500 [10] CMS Collaboration, ALIGNMENT PAPERS
- 501 [11] CMS Collaboration, MAGNETIC FIELD MAP PAPER
- 502 [12] P. Biallass, T. Hebbeker, K. Hoepfner, *Simulation of Cosmic Muons and Comparison with Data*  
503 *from the Cosmic Challenge using Drift Tube Chambers*, CMS NOTE-2007/024 (2007)
- 504 [13] W.-M. Yao et al., *Journal of Physics* **G33** 1 (2006)
- 505 [14] D. Acosta et al., *Large CMS Cathode Strip Chambers: Design and Performance*, *Nucl. Instrum.*  
506 *Meth.* **A453**, 182-187 (2000).
- 507 [15] CMS Collaboration, *The CMS Experiment at the CERN LHC*, *Journal of Instrumentation*  
508 (JINST) **3**, S08004 (2008).
- 509 [16] T. Ferguson, N. Terentiev, I. Vorobiev, N. Bondar, A. Golyash, and V. Sedov, *Anode Front-*  
510 *End Electronics for the Cathode Strip Chambers of the CMS Endcap Muon Detector*, *Nucl. In-*  
511 *strum. Methods Phys. Res.* **A539**, 386-406 (2005) [CMS-Note 2004/003]
- 512 [17] Yu V. Erchov et al., *Cathode Strip Chamber for CMS ME1/1 Endcap Muon Station*, *Physics of*  
513 *Paticles and Nuclei Letters*, Vol. 3, No. 3, (2006) 183.
- 514 [18] D. Acosta et al., *Measuring Muon Reconstruction Efficiency from Data*, CMS NOTE-2006/060  
515 (2006)
- 516 D. Acosta et al., *Efficiency of Finding Muon Track Trigger Primitives in CMS Cathode Strip Cham-*  
517 *bers*, *Nucl. Instrum. Meth.* **A592** (2008) 26 [CMS Note 2007/031]
- 518 [19] V. Barashko et al., *Fast Algorithm for Track Segment and Hit Reconstruction in the CMS Cathode*  
519 *Strip Chambers*, *Nucl. Instr. Meth.* **A589/3** (2008) 26 [CMS NOTE 2007/023]
- 520 [20] TESTBEAM STUDIES. *Please help specify these.*
- 521 [21] E. Gatti et al., *Optimum Geometry for Strip Cathodes or Grids in MWPC for Avalanche Local-*  
522 *ization Along the Anode Wires*, *Nucl. Instrum. Meth.* **163** (1979) 83

- 523 [22] E. Mathieson and J. Gordon, *Cathode Charge Distributions in Multiwire Chambers: I. Measure-*  
524 *ment and Theory*, Nucl. Instrum. Meth. **227** (1984) 267; *op. cit.*, II. *Approximate and Empirical*  
525 *Formulae*, Nucl. Instrum. Meth. **227** (1984) 277
- 526 [23] I. Golutvin et al., *Cathode Strip Chambers Data Analysis*, Proceedings of the  
527 Seventh International Conference on Advanced Technology and Particle Physics, Como,  
528 Italy, 15-19 October 2001

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