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The Hardware Muon Trigger Track Finder Processor in CMS - Specification and Method

A. Kluge, T. Wildschek

CERN, Geneva

Institute of High Energy Physics, Vienna

Abstract

The paper covers the specification and the applied track finder method of the hardware muon trigger track finder processor in the high energy experiment CMS at CERN. The processor is based on data from the drift tube muon chambers. The task of the processor is to identify muons and measure their transverse momentum p_t. Data of more than two hundred thousand drift cells are used to determine the location of muons and measure their transverse momentum.

INTRODUCTION

This note concentrates on specification and applied track finding method of the muon trigger track finder. A detailed description of the algorithm and a VHDL model representing the algorithm is presented in [1]. Prototype and final hardware implementation are covered in [2].

The muon detector fulfills three basic tasks: muon identification, trigger, and momentum measurement. The muon detector is placed behind the calorimeters and the magnet coil. It consists of four muon stations interleaved with the iron return yoke plates. A system of drift tubes (DT) [3] is applied in the barrel region, while cathode strip chambers (CSC) cover the forward region. In addition resistive plate chambers (RPC) cover the entire muon detector [4].

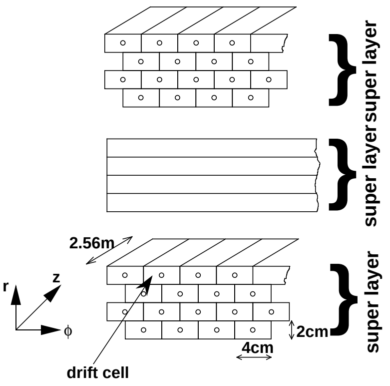

Fig. 1.: Three superlayers form a drift tube station.

The barrel part of the detector is divided in five wheels in z-direction and twelve 30° sectors, resulting in 60 (ηϕ) detector segments (see left part of fig. 2). Each sector comprises four measuring stations, MS1 to MS4. Every station contains one or two modules of drift tubes. The maximum drift time of the drift tube chambers is about 400 ns or 16 bx.

A drift tube cell has a cross section of 4 cm x 1.1 cm. A spatial resolution of about 200 µm is achieved. The total number of wires is about 200.000. Fig. 1. illustrates the arrangement of the drift tubes. A chamber consists of twelve layers of drift tubes arranged in three superlayers of four planes each. The tubes within a superlayer are staggered by half the width of a tube. The outer two superlayers (rϕ), whose wires are parallel to the z-axis, measure the ϕ-coordinate in the bending plane. The middle superlayer (rz) measures the z-coordinate along the beam line. However, in the present design this plane is not used in the track finder. The chambers are 2.56 m long and the width increases from 2 m in the inner station to 4 m in the outer station.

In the endcap regions the muon detector comprises four muon stations [4]. Muon stations are mounted vertically. Each muon station contains cathode strip chambers. Effort is being made to design a track finder system capable of processing data from both the drift tube system and the cathode strip chamber system. However, in this paper only the evaluation of the drift tube chamber data is discussed.

TRACK FINDER PROCESSOR ENVIRONMENT

The CMS muon trigger comprises three main components; the pattern comparator trigger (PACT) [4,5,6] based on resistive plate chambers (RPC), track finder processor (TF) based on drift tube chambers (DT) and possibly cathode strip chambers (CSC) and the global muon trigger. A detailed block diagram of the L1 trigger is shown in fig. 2.

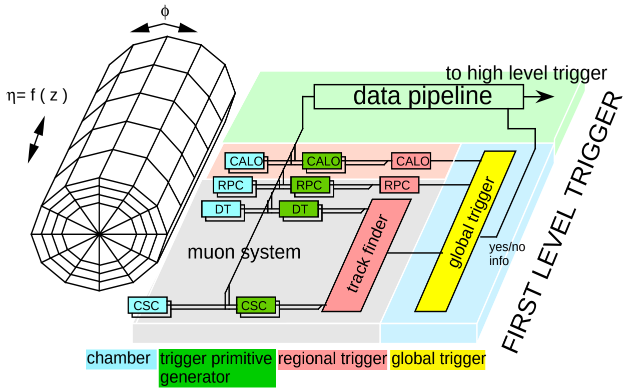

Fig. 2.: Block diagram of CMS first level trigger.

DT- and CSC-trigger primitive generators first process the information of the chamber locally. For the drift tubes up to two track segments (position and angle, see fig 3.a, b) per muon chamber are delivered. For the CSCs the number of trigger primitives per logical sector is still under discussion. Track segments from different stations are collected by the track finder.

The task of the track finder processor is to find muon tracks originating from the interaction point and to measure transverse momentum p_t and their location in ϕ and η.

The transverse momentum p_t is assigned. The track finder selects the four highest p_t muons in the detector and forwards them to the global muon trigger.

The DT-chamber system is divided into twelve ϕ-segments, five wheels in z-direction and four stations in r-direction (see left part of fig. 2). Thus the entire system comprises 12 x 5 x 4 = 240 chambers. Hence 480 track segments are delivered to the regional drift tube trigger, the track finder.

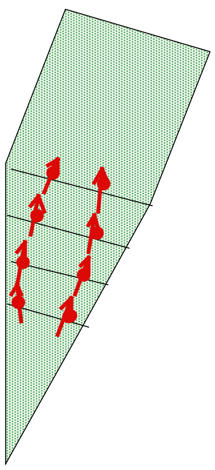

Fig. 3.a: Up to two track segments per chamber are given out.

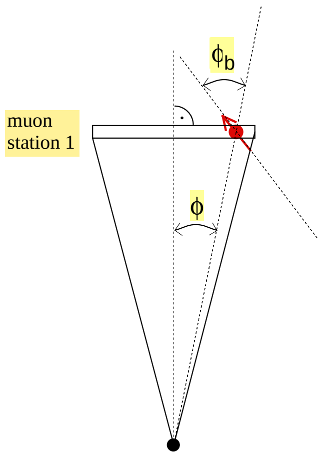

Fig. 3.b: A track segment consists of the spatial coordinate ϕ and the bend angle ϕ_b.

TRACK FINDER PROCESSOR OVERVIEW

In the following the main features of the track finder processors are listed and described shortly. The output quantities are:

- P_t-measurement

The resolution σ_{pt}/p_t of the transverse momentum measurement is a trade-off between technical feasibility and physics requirements. The transverse momentum p_t is derived from the curvature κ_c of the muon tracks. The resolution of κ_c is directly proportional to the resolution of the measured bend angle derived from the track segment coordinates [7,8]. The chamber can deliver a resolution of as low as 200 µm [4]. This accuracy cannot be used in the trigger level. A measurement resolution σ_{ts} of 0.3 mrad is provided for the track segment measurements by the drift tube trigger primitive generators. 0.3 mrad corresponds to approximately 1.25 mm in station one and two and 2.5 mm in station three and four. For further details refer to [9,10,11].

The p_t-range between 2.0 GeV/c and 140 GeV/c is divided into 25 p_t-classes (see table 1). The p_t-value is given out in a 5 bit number. A sixth bit indicates the charge of the particle.

- ϕ-measurement

The track finder processor partitions the total of twelve detector segments into 256 bins using an eight bit number. Hereby a ϕ-resolution of 1.4° or 25 mrad is provided.

p_t range	5 bit-p_t code	p_t range	5 bit-p_t code	p_t range	5 bit-p_t code	p_t range	5 bit-p_t code
nomuon	0	4.0-5.0	8	17-20	16	70-80	24
reserved	1	5.0-6.0	9	20-25	17	80-100	25
reserved	2	6.0-7.0	10	25-30	18	100-120	26
reserved	3	7.0-8.0	11	30-35	19	120-140	27
2.0-2.5	4	8.0-10.0	12	35-40	20	140-∞	28
2.5-3.0	5	10-12	13	40-50	21	reserved	29
3.0-3.5	6	12-14	14	50-60	22	reserved	30
3.5-4.0	7	14-17	15	60-70	23	reserved	31

Table 1: p_t-classes.

- η-measurement

The only information the η-coordinate can be derived from is the place where a particle crossed detector wheel boundaries. The η-value is given in a 2 bit code. A possible option to improve η-measurement is to include trigger primitives of the middle (rz) superlayers.

- Quality information

The processor outputs quality information which indicates the confidence that the found track is a real track and not a ghost track.

Important requirements of the system are:

- Dead time free

The first level trigger architecture requires a dead time free operation. That means that even in case of a positive level accept signal release the processor must stay operational for the subsequent events. The trigger system is capable of accepting data of each single event, with a data repetition rate of 40 MHz.

- Processing time - latency

It is important to keep the processing time of the track finder processor as low as possible, because during the time an event is evaluated in the level one trigger all corresponding detector data must be stored in the data pipeline. In CMS the number of detector channels is as high as 10^8. Most of them belong to the tracker. The tracker signals are analogue and are only converted into a digital number after a positive level one trigger accept signal. Thus the tracker data are going to be stored in analogue memories. Since they are expensive the storage depth of the CMS data pipeline has been limited to 128 steps. The level one trigger latency is dominated by transmission of signals from and to the detector and by signal propagation between processing units [12]. Thus only a smaller part is left over for the execution of the algorithms. Fig. 4 shows the latency distribution between the different system components. The first level trigger decision must be provided within 128 bunch crossings. A contingency must be foreseen (two bx in the present design). For the track finder processor 23 bunch crossings or 575 ns are reserved.

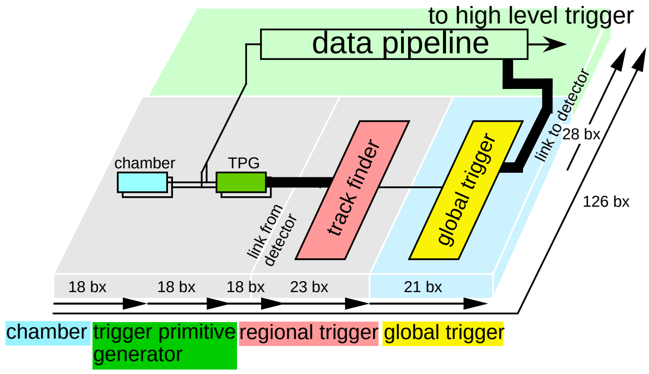

Fig. 4.: Latency of drift tube trigger components.

- Programmability

The trigger system is flexible enough to permit changes in the algorithm and changes in the detector geometry. In order to optimize the track finding and measurement algorithm simulations have to be employed. Obviously they are based on several assumptions. Simulation results may be refined in a later phase of optimization or at the time beam data will be available.

Another point is the detector geometry. Even if the designed chamber geometry is not going to be changed misalignment of the chambers must be accounted for. The trigger uses a resolution of 1.25 mm. However, it is impossible to install all chambers (of the dimensions 2.56 m x 2 m) within an accuracy of 1.25 mm with respect to each other. The chambers are installed within a coarser accuracy and a laser based alignment system provides information to the trigger electronics how much each chamber is displaced from the nominal position.

- Output segmentation

The trigger system must output the information about four muons with the highest p_t in the detector. The data output format is shown in table 3.

EVALUATION OF THE CMS TRACK FINDER PROCESSOR

The classical method in track finding hardware implementations is to search for predefined tracks or bit patterns. Predefined patterns are compared to the actual ones occurring (pattern comparison). Application of content addressable memories [13,14,15,16] is an obvious solution. However, it was shown that a pattern comparison method is not

track finder processor specifications
outputs the four highest p_t muons per detector: p_t, location, quality
p_t measurement range: 2.0 - ∞ GeV/c
ϕ-measurement: 25 mrad resolution
η-measurement: 0.04 - 0.4 resolution
dead time free
programmability: algorithm settings and chamber alignment
modular and flexible for use in the CSC and overlap region
processing time: < 21 bunch crossings or 525 ns.

Table 2: Track finder processor specifications.

output	number of bits
p_t + charge	5 + 1
ϕ	8
η	2
quality	2

Table 3: Output format.

applicable in the context of the track finder processor [17]. The low granularity of the detector and the high required p_t resolution combined with the high number of detector channels, the non-projective chamber geometry and high bending power of the detector does not allow to perform track finding and p_t assignment within the available calculation time using a pattern matching method. On one hand the number of patterns is far too high; on the other hand the resolution and complexity of the detector requires too much data to be processed at the same time.

A typical software approach, the track segment (or track element) method [17]- or extrapolation method was elaborated for the hardware implementation.

The basic principle is to attempt to match track segments caused by the same track together. This is done by extrapolating into the next station from a track segment using the spatial and angular measurement. The extrapolated hit coordinate is compared to the actually measured track segments. If the difference is found to be within a given threshold the extrapolation is considered successful and two track segments have been matched together to form a track segment pair.

While pattern matching methods, histogram methods or neural networks usually deliver the wanted track property directly, the extrapolation method requires three steps;

- extrapolation or pairwise matching of track segments

- assembling track segment pairs to full tracks
- assigning (or measuring) the track properties like transverse momentum and location.

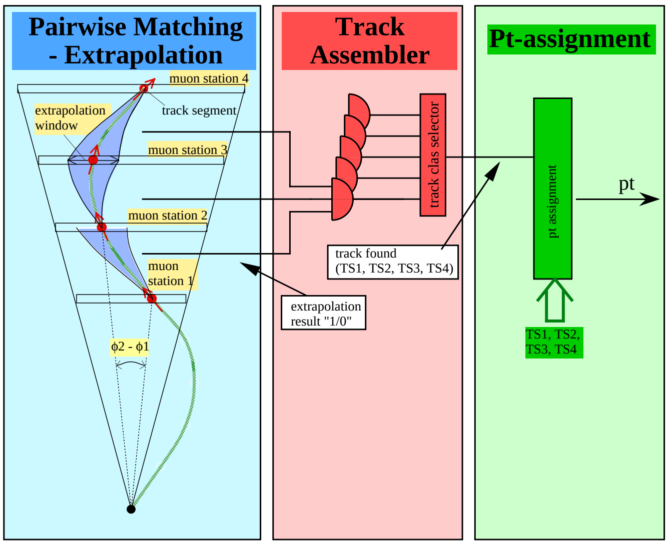

Fig. 5.: Principle of the track finder algorithm (3-Step scheme).

Fig. 5 illustrates the principle of the track finder algorithm. It is divided into three steps. In the first step track segments from different chambers are matched to track segment pairs by extrapolation. Later the track assembler links track segment pairs to form complete tracks and forwards the track segment data of the two highest ranking tracks to the assignment units where transverse momentum p_t and location of the tracks are determined.

After linking the track segment pairs to full tracks the information which track segments are involved is still available. Thus the track segment data can be used with the full resolution to assign the transverse momentum p_t.

All other previously mentioned methods (pattern match, histogram method, but also neural networking) work in a global or direct data processing way. The input data is directly set into relationship to the wanted features. While this would be an advantage in many applications, in this case it complicates the implementation. When performing a pattern match one looks for track segment combinations which belong to one track (track finding). For this task full measurement precision is not needed. However, after a pattern has been recognized the link to the original track segment data is not available anymore. Thus patterns must be formed by track segment data with full resolution so that each pattern allows directly the determination of the wanted features with high precision. Therefore the number of patterns is very high.

However, the extrapolation method splits the process of measuring the transverse momentum p_t into three steps. This approach allows for a flexible use of the resolution in each step according to the requirements. The extrapolation and track

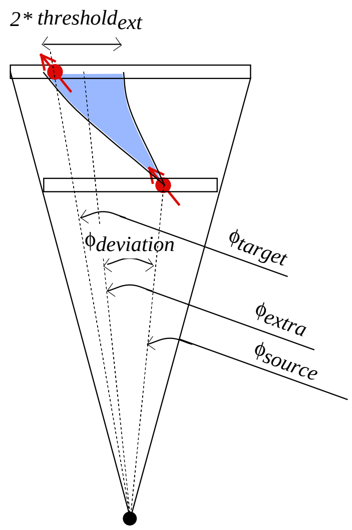

Fig. 6.: If a track segment is found to be within the extrapolation window given by ϕ_{extra} and $threshold_{ext}$, the extrapolation is considered successful.

assembly is performed with reduced resolution. As a consequence the hardware effort is smaller and the execution time shrinks. For assigning the transverse momentum p_t the full resolution of the track segment measurements is still available and used.

EXTRAPOLATION METHOD

The pairwise matching is based on the principle of extrapolation. Using the spatial coordinates ϕ_{source} and the angular measurement $\phi_{b,source}$ of the source track segment an extrapolated hit coordinate ϕ_{extra} in another chamber may be calculated. If a target track segment is found to be at the extrapolated coordinate within a certain extrapolation threshold $threshold_{ext}$ the match is considered successful (see fig. 6).

$$\phi_{extra} = \phi_{source} + \phi_{deviation}(\phi_{b,source}) \qquad \text{(Eqn. 1.)}$$

$$threshold_{ext} \geq |\phi_{extra} - \phi_{target}| \qquad \text{(Eqn. 2.)}$$

<u>Extrapolation feasibility</u>

Simulations have been conducted to prove the feasibility of the extrapolation between the stations [10]. Fig 7 shows the relation between the bend angle ϕ_b in the source station and the relative deviation of the particle track between target- and source-station $\phi_{deviation} = \phi_{target} - \phi_{source}$ for several station pairs. The graphs show unambiguous relationships proving the feasibility of extrapolation between these station pairs. The same condition can be found in all other station pairs except for those extrapolating from station three. Fig. 8 shows the situation when extrapolation is done from station three. No unambiguous relationship can be found. Moreover, for small bend angles no prediction can be done at all. This effect is caused by the zero crossing of the bend angle. However, since all other extrapolations are feasible these problems can be circumvented

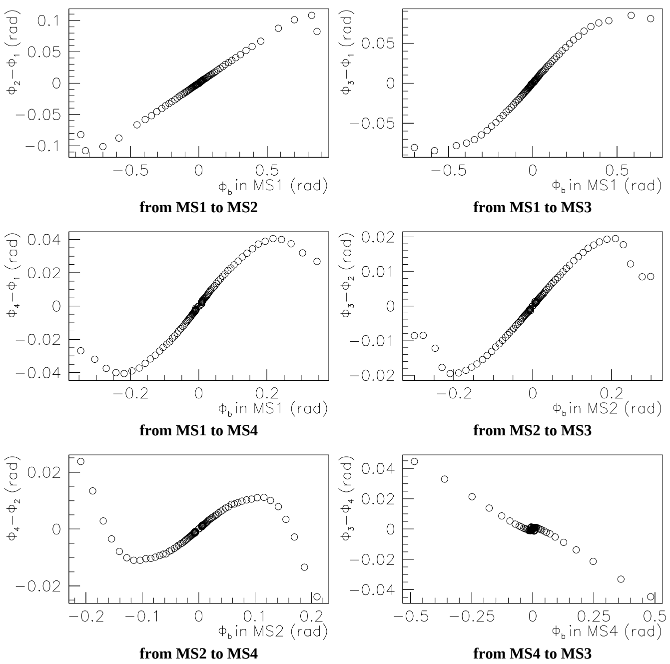

Fig. 7.: Relationship between bend angle measurement ϕ_b in the source station and deflection of a muon ϕ_{target}-ϕ_{source}.

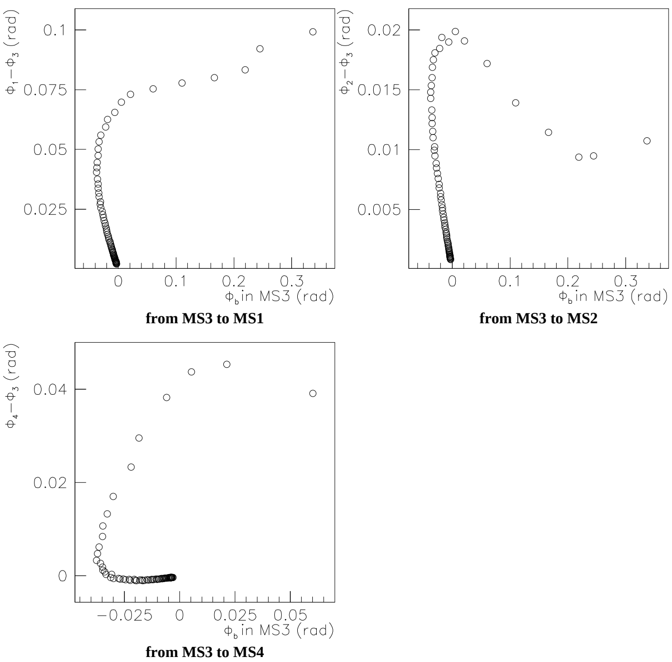

Fig. 8.: Relationship between bend angle ϕ_b in station three and deflection of the muon is unambiguous.

by extrapolating towards station three instead off station three (see left part of fig. 5).

Track segment assembling - Acceptance study

Once track segment pairs are found they are linked together to full tracks. Track segment pairs of different chamber pairs may be matched to each other if they have one track segment in common. This scheme is illustrated in fig. 9.

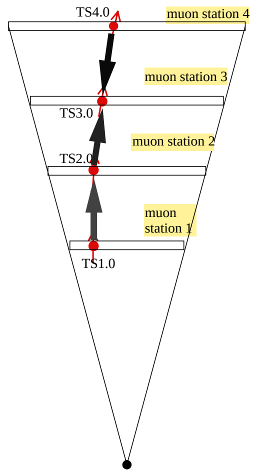

Fig. 9.: Matching track segment pairs are combined to a full track.

However, due to geometrical inefficiencies and chamber failures missing hits must be accounted for. Simulation studies for the acceptance of muons were conducted for tracks consisting of at least three out of four track segments and for at least two out of four track segments. Fig. 10 illustrates the results. When simulating the requirement of three out of four matching track segments only about 82% of all muon tracks are found. An acceptance of more than 95% is achieved when the requirements are loosened to two out of four matched track segments. Consequently the track finder accepts tracks consisting of only two matching track segments. As a consequence even a single track segment pair is already considered a valid track.

P_t - assignment

Transverse momentum measurement can be done in several ways once the track segments are matched to a full track [11,18].

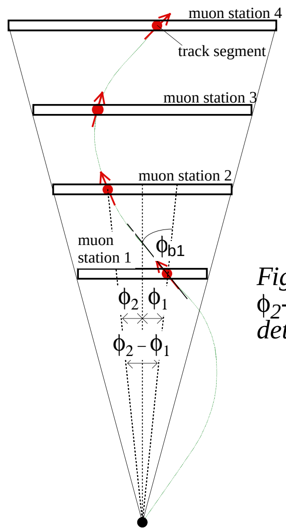

Fig. 11.: Using the deflection ϕ_2-ϕ_1 or the bending angle ϕ_b to determine p_t.

Acceptance Study

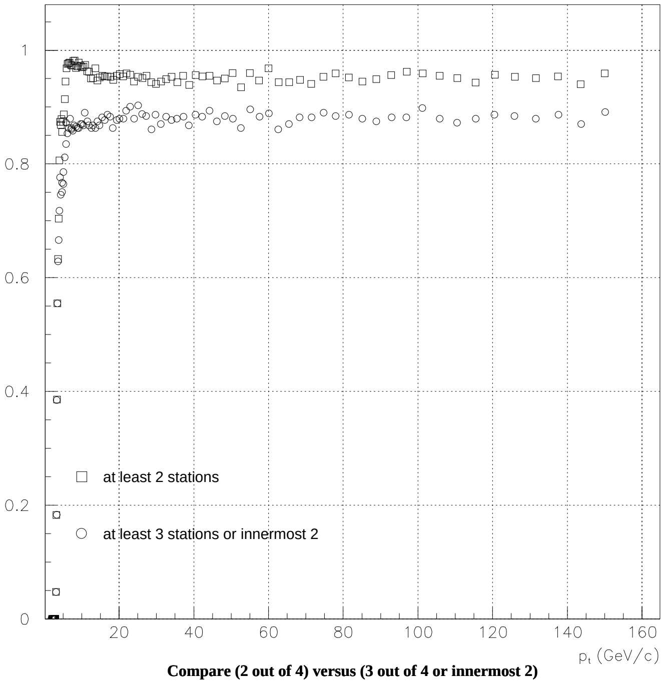

Fig. 10.: This plot compares two track finder requirements . Circles show the case where a track has to have at least three track segments or track segments in the two innermost stations. Squares require only two track segments for a valid track.

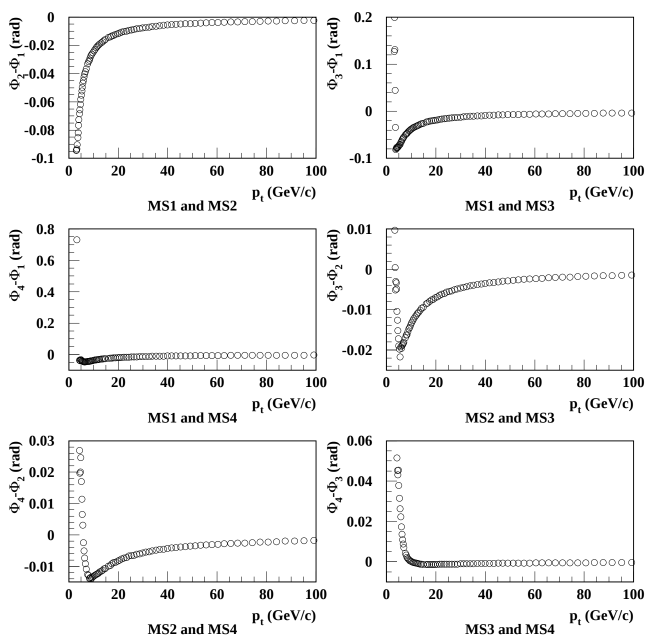

Fig. 12.: Difference of azimuthal hit coordinates ϕ_{ii}-ϕ_i (deflection of the muon between two stations) over transverse momentum p_t for several station pairs.

In order to assign transverese momentum p_t we use the track's bend angle. Two methods are available. One method uses the difference of positions in two distinct stations (see fig. 11). Two spatial coordinates are sufficient. Fig. 12 illustrates the relation between transverse momentum and afore mentioned difference. One expects the absolute value of the difference in bending angle to decrease with increasing p_t. However, due to the zero crossing of the bending in station three the absolute value of the difference of the angles first rises (except for ϕ_2-ϕ_1). An unambiguous relationship between difference of positions and transverse momentum p_t is shown for difference ϕ_2-ϕ_1. For other stations pairs this relationship is not unambigous. In such a case the bend angle measurement of a single track segment can be used to measure p_t. Fig. 13 shows the relation between transverse momentum p_t and bend angle ϕ_b measured in one station.

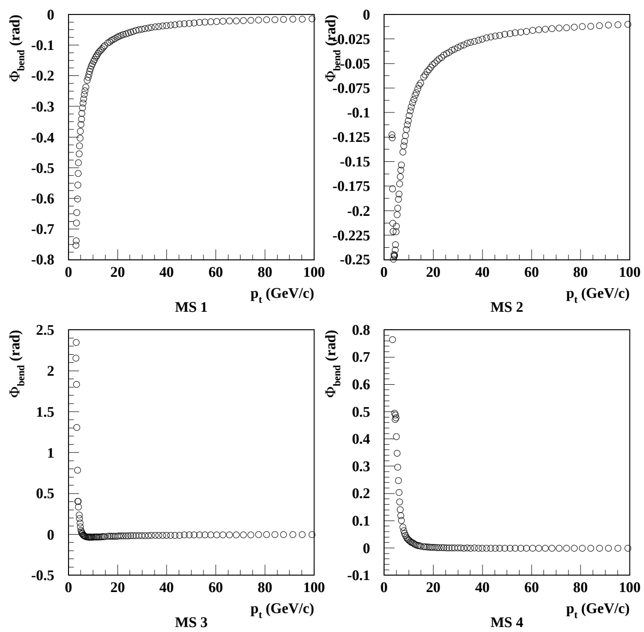

Fig. 13.: Bend angle in various stations for μ^+ over transverse momentum p_t.

The drift tube trigger primitive generator also delivers a quality information. This quality indicates how many layers and super layers of a chamber contributed to a track segment. It is also an indication of the measurement resolution of the track segments [3]. These quality bits are used to select the algorithm in order to provide the most accurate p_t-measurement.

The presented simulation results show that extrapolation, track assembling and p_t assignment are possible. The extrapolation scheme is a sophisticated method to find muon tracks and determine p_t.

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