The parallel-plate geometry of our prototype is not practical for large surface calorimeters. However, one can build such calorimeters out of high pressure gas tubes. Our group has designed and is now constructing a prototype tube calorimeter. The speed of high pressure gas calorimeters, combined with their unity gain and inherent radiation hardness, makes them a very attractive candidate for detectors at the new high energy, high luminosity colliders (SSC, LHC), and especially for the forward region of these detectors.

Acknowledgments
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6. Conclusions
A high pressure gas calorimeter has been constructed and tested in the pressure range of 20 to 100 atm. It proved easy to operate and its response was very stable over the run period. The collected signal saturates at the comfortable electric field of 500 V/mm and scales linearly with incident beam energy between 16 and 125 GeV. The pressure dependence of the collected charge and the energy resolution agrees well with EGS4 predictions, proving that the behaviour of this type of calorimeter is well understood. The electron collection time is 95%Ar + 5%CH4 at 100 atm is 20 ns/mm, which yields a signal duration comparable to that from scintillator-based calorimeters.

References

North-Holland

A hodoscope made of resistive plate chambers to identify muons in a fixed targeted hadroproduction experiment


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We have built a large area hodoscope to identify muons from semileptonic decays of beauty particles produced in the WA92 experiment at the CERN Super Proton-Synchrotron. The hodoscope is made of resistive electrode chambers read out with strips of 3 cm pitch. The hodoscope has a fast response with a time resolution of 5 ns and a space resolution of 1 cm. A fast trigger processor selects straight tracks pointing to the interaction vertex in a fixed processing time of 90 ns.

1. Introduction
High energy hadron interactions are a copious source of heavy quarks but, at the energy of SPS and FNAL fixed target experiments, the signal-to-noise ratio is rather unfavourable: of the order of 10^{-3} for charm and 10^{-6} for beauty. Though production of charm particles has been studied over the past decade in several fixed target experiments, the results on hadroproduction of beauty particles are still rather scarce. In order to fight the unfavourable signal-to-noise ratio experiments must exploit the features of beauty particle decays at trigger level. A trigger that is highly selective for the bulk of inelastic collisions while keeping a large acceptance for the beauty signal can exploit the following signatures:

i) the dominant decay cascade beauty → charm → stable hadrons originates several secondary vertices;

ii) the branching ratio for semileptonic decays is large;

iii) the decay of a large mass particle produces secondaries emitted with large transverse momenta.

The WA92 experiment at the Ω spectrometer of the CERN Super-Proton-Synchrotron, SPS, [1] aims to exploit the above three signatures. The heart of the experiment is a high precision silicon microstrip detector, the decay detector [2], placed behind a thin target. The task of the decay detector is to visualize the cascade decays that occur inside the detector itself. A second larger silicon microstrip tracker, the vertex detector [3], is used to reconstruct the interaction vertex and to trigger on tracks that originate in secondary vertices and are characterized by a large impact parameter at the primary vertex. Since the processing time of the vertex detector trigger is 10-20 μs, a prompt selective trigger is needed to reduce the dead time of the experiment. This prompt trigger exploits the above-mentioned signatures i) and iii).

The trigger on charged particles emitted at large transverse momenta in the central region of rapidity is done with two scintillator hodoscopes shaped in the characteristic butterfly configuration [4] to reject low momentum particles deflected in the magnetic field of the spectrometer. Semileptonic decays into muons are selected by a large acceptance hodoscope, placed behind an ion absorber, that triggers on penetrating particles pointing to the target. The design of the muon trigger hodoscope is described in the next sections.

2. The muon trigger hodoscope
The general lay-out of the WA92 experiment is shown in fig. 1. The muon trigger hodoscope consists of two detector planes placed behind two iron absorbers of 2.0 and 1.2 m thickness respectively. The core of the first absorber is made of disks of tungsten.
over several square metres. Each hodoscope plane is made of three detector planes, two equipped with horizontal read-out strips to measure the vertical coordinate, z-chambers, and one with vertical read-out strips, y-chamber. The four z-chambers are used to reconstruct the muon track in the non-bending plane. A fast processor is used to verify whether the track hits are collinear with the target. The two y-chambers are added to improve the association with the tracks measured in the spectrometer.

Each detector plane is made of six chambers of dimensions $1 \times 2 \text{ m}^2$ slightly staggered in the y direction to avoid dead regions. A perspective view of one hodoscope plane is shown in Fig. 2. The two z-chambers and the y-chamber that form a sextant of the plane are grouped together in a single module and the six modules are hung on a rigid support frame for the installation in the experiment.

Fig. 3 shows the longitudinal and transverse momentum spectrum of muons that originate in semileptonic decays of beauty particles and of background muons, both obtained using the PYTHIA event generator [6].

These muons are traced through the magnetic field, the electromagnetic calorimeter and the iron

**Fig. 1. Layout of the WA92 experiment.**

**Fig. 2. View of one hodoscope plane.**

where the 350 GeV/c $\pi^-$ beam is dumped. This dump is 1.98 m long, $\sim 21 \lambda$, and the dinks have increasing radii to cover a cone of 25 mrad semi-aperture centred on the beam line.

The thickness of the first absorber ($= 12 \lambda$) is chosen to filter out most of the hadrons produced in the target, while keeping the multiple Coulomb scattering of high energy muons at a low level to allow association of tracks measured in the hodoscope with those measured in the spectrometer. The probability for a hadron of 50 GeV/c momentum to punch through the first absorber is $\sim 0.04$. After the first absorber the average displacement of muons that originate in semileptonic decays of beauty particles is $\sim 1.7 \text{ cm}$, i.e. an angle of $\sim 1.2 \text{ mrad}$ when the track reconstructed in the hodoscope is projected to the target. The deviation due to multiple Coulomb scattering defines the requirement for the segmentation of the hodoscope.

The presence of the second absorber ensures that only muons are able to reach the second plane of the hodoscope ($= 20 \lambda$ in total). There are two background components: the muons that originate in decays in flight of pions and kaons and the muons that originate in hadron showers initiated in the electromagnetic calorimeter ($= 14 \lambda$). This second component has a softer momentum spectrum and a wider angular distribution; it can be strongly reduced by requiring the collinearity with the target.
Table 1 summarizes the acceptance for both the signal and the background for the muon trigger used alone or in coincidence with other trigger requirements.

3. The resistive plate chambers

The resistive plate chambers [5] are gaseous detectors that combine a good time resolution (few nanoseconds) with a good space resolution (few millimetres). Ionization of the gas in a strong uniform electric field causes a discharge between the resistive electrodes that is quickly quenched by the local extinction of the electric field. The charge induced on external read-out electrodes produces very fast and large pulses. The read-out electrodes can be shaped in various configurations according to the segmentation required by particular applications.

The RPC of the muon trigger hodoscope are made with two parallel plates of phenolic polymer, bakelite, of 1 × 2 m² surface and 2 mm thickness. The plates have a volume resistivity \( \rho = 1 \, \text{GΩ·m} \) and a dielectric constant \( \varepsilon = 30 \, \text{pF/m} \). The sensitive gas volume is a 2 mm gap between the two plates. To keep the plates at a fixed distance over the whole surface, disks of polyvinyl chloride, PVC, are glued on the plates. These disks are 12 mm in diameter and there are 200 disks at a distance of 100 mm from one another. The gas gap is closed at the edges with a PVC frame to ensure gas tightness and small pipes let the gas in and out close to the four corners.

The outer surface of the resistive plates is coated with a graphite solution with a surface resistivity of about 0.2 MΩ·cm. The two graphite electrodes, transparent to the fast component of the discharge pulse, are connected to the high voltage power supply to produce the electric field. A 300 μm foil of PVC is glued on the graphite surface to provide isolation of the high voltage electrodes. The inner surface of the resistive plates is coated with lined oil to ensure a very smooth surface and prevent local discontinuities of the electric field that would produce noise or discharges.

The read-out electrode is segmented into thin aluminum strips of 29 mm width and 31 mm pitch. The strip plane is separated from the outer ground shield with a foam plate and each strip behaves, respect to ground, as a transmission line. Each strip is terminated on its characteristic impedance of 50 Ω on either end and one side is connected to the front-end electronics. The propagation time along the transmission line is about 3 ns/m and there is no observable attenuation of the pulses from the induction point to the end of the strip. A cross-section of the chamber is shown in fig. 4.

**Table 1**

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Acceptance for beauty events [%]</th>
<th>Acceptance for background events [%]</th>
<th>Enrichment factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 μ</td>
<td>1.79 ± 0.2</td>
<td>1.9 ± 0.2</td>
<td>94 ± 1.2</td>
</tr>
<tr>
<td>2 μ</td>
<td>1.8 ± 0.4</td>
<td>0.03 ± 0.008</td>
<td>50 ± 15</td>
</tr>
<tr>
<td>1 μ × 1 HI-P</td>
<td>13.4 ± 1.3</td>
<td>0.4 ± 0.06</td>
<td>30 ± 5</td>
</tr>
<tr>
<td>1 μ × 2 HI-P</td>
<td>6.7 ± 0.8</td>
<td>0.002 ± 0.011</td>
<td>82 ± 15</td>
</tr>
</tbody>
</table>
Studies done in the laboratory on a prototype have shown that, when the chamber is efficient, the charge collected on the strips is typically 50% of the pulse amplitude, which is about 0.3 V with a risetime of about 5 ns and a decay time of about 20 ns. Due to the local extinction of the electric field after the discharge, the chamber is insensitive for a time of the order of \( \tau = 3 \times 10^{-7} \) s over an area of about 0.1 cm². Measurements of the efficiency as a function of the particle flux during the extraction of the SPS beam [9] have shown that the reduction in efficiency is smaller than 1% for fluxes of 10 Hz/cm². This is the flux expected in the region of the hodoscope closer to the beam axis that is most illuminated by the beam halo and leakage from the beam dump.

The \( z \)-chambers are equipped with 32 read-out strips 2 m long, while the \( y \)-chambers are equipped with 64 read-out strips 1 m long. The printed board with the front-end electronics are connected directly to the end of the read-out strips. Each printed board contains 16 channels. A scheme of the front-end circuit is shown in fig. 5. An input transistor is connected to a TTL gate that acts as a discriminator with an adjustable threshold, typically set at about 60 mV. The gate output is formed in time with a monostable whose output is sent to a line driver. The time formation is 50 ns to ensure a small probability of accidental coincidences of the muon halo traversing the hodoscope with the interaction trigger. The line drivers provide differential TTL outputs to send the signal over long cables to the counting room of the experiment. The outputs of the discriminators are fed together to provide a FAST OR signal from the 16 channels.

The chambers are filled with a gas mixture of 55% argon, 42% n-butane, and 3% Freon. With this mixture, they reach the efficiency plateau at an electric field of about 35 kV/cm. Fig. 6 shows the efficiency as a function of the applied voltage for some of the chambers. The efficiency is measured by the ratio of the rate of the fourfold coincidence to that of the threefold coincidence made with the FAST OR signals from chambers of the same sextant when illuminated by the muon halo. All chambers reach a plateau efficiency of about 97%. A small loss in efficiency is due to the dead area taken by the spacers (\( \approx 15\% \)). The chambers in the same sextant are staggered by about 3 cm in order not to overlap the spacers, thus the real efficiency is slightly higher than that measured by the fourfold to three-fold coincidence ratio.

The FAST OR signals from all \( z \)-chambers form a prompt muon trigger that is used, in coincidence with the interaction trigger, to send a fast strobe signal to hold the data from the silicon microstrips of the vertex detector. This pretrigger is done by a fast ECL logic circuit located close to the hodoscope that forms a coincidence of three out of the four \( z \)-planes of the hodoscope. The efficiency of the "3/4" pretrigger is higher than 96%. The pretrigger delay is due to the formation time of the streamer (\( \approx 10 \) ns), the rise time and the propagation time of the signal and the response time of the front-end electronics (\( \approx 20 \) ns), the delay of the "3/4" logic (\( \approx 10 \) ns) and the delays of the cables. The time jitter is a few nanoseconds. Fig. 7 shows the distribution of the time difference between the FAST OR signals of two chambers in the same sextant. The r.m.s. width of the distribution is 4.5 ns mainly due to the spread in time of the response of the electronics components of the different channels.

4. Trigger and read-out

The muon trigger processor [10] selects tracks pointing to the target in the nonbending plane. The input to the processor are the signals from the 768 strips of the \( z \)-chambers. Since the hodoscope is symmetric with respect to the central horizontal plane, there are two identical processors working in parallel. First all signals from the strips with the same value of the \( z \)-coordinate in the same hodoscope plane are OR-ed together in the OR-modules. This results in 64 OR-ed signals sent to each processor. Then the 64 OR-ed signals are loaded in two 32-bit input registers of the processor when strobed by a selectable combination of external signals. Each processor works with two 32-bit words representing the hits pattern on the first and the second plane of the hodoscope. Fig. 8 shows the logic scheme of the muon trigger.

To associate the hit pattern to the interaction vertex, the processor defines roads with programmable width and inclination. These roads are mapped onto a 32 x 32 matrix made of 16 fast programmable logic devices, PLD [7], with 12 as typical propagation time. The response is available after a fixed processing time of 90 ns. The hits on the first hodoscope plane that belong to patterns accepted by the trigger logic are loaded in a third 32-bit register of the processor that is read out together with the two input registers. The data of this register are also available on the front panel for use in a second level decision.

* Signetics Plus 173D.
CLEAR command to the registers and sends out a READ command to strobe the VME modules that read the information from the individual strips. The CLEAR command can be either generated internally or received from a higher level decision. The control register selects the external signal used to enable the processor, LOAD command, and defines the trigger configuration loaded in the PLDs. The three data registers, the control register and a status register are all accessible by the VME bus for read/write operations and for debugging of the circuit.

The information from all 1536 strips is read out in 16 VME modules. Each module has 96 differential line receivers and three 32-bit latches where the hits are recorded when strobed by the READ command from the processor. The muon trigger processors and the read-out modules follow the VME 32-bit bus protocol.

The OR modules, the two trigger processors and the 16 read-out modules are housed in two VME crates linked to the data acquisition system via two VME intelligent controller interfaces, VIC 47. A VME fast intelligent controller, VIC 48, resident in one of the local system crates of the 0 data acquisition system, transfers the 72 data words of 32-bit in about 40 μs.

5. Operation in the experiment

The design of the muon trigger hodoscope aimed at simplicity and reliability. The whole detector was constructed in a few months and tested and installed in a few weeks. After installation in the experimental site it performed according to the design figures. Moreover, compared with a hodoscope made with scintillator counters or wire chambers of similar dimensions and performances, it is much less expensive. The only drawback, when compared with the more popular scintillator hodoscope, is the need for careful control of the supplies of gas and high voltage. The flow rate of the individual components of the gas mixture and the setting and currents from the individual high voltage supply lines were continuously monitored with a CAMAC interface driven by a Macintosh computer.

The WA92 experiment took data during three weeks in summer 1991. During most of the data taking period the beam intensity was on average 1.2 MHz and the hodoscope rate, due to the halo of muons accompanying the pion beam, was 25 kHz. In these conditions, the interaction trigger rate was 30 kHz and the muon trigger rate 700 Hz providing a reduction factor of 45 very close to the design figure of table 1.

A preliminary analysis of the data collected confirms that the operation of the trigger hodoscope was quite satisfactory. Fig. 10 shows the correlation of the hits recorded in the first and second plane of the hodoscope for events selected by the muon trigger processor. The processor was operated with roads three strips wide: every strip of the second plane was in coincidence with three strips of the first plane.

A simple algorithm was used to check the tracking performance of the hodoscope. First adjacent hit strips were merged together to form a cluster, then clusters on different detector planes were linked to define tracks. The average number of strips per cluster was 1.3. A track was accepted when a cluster was found in the second plane within 2.2 strips from the line joining the target and the cluster in the first plane. The average number of reconstructed tracks per event was about 96/5. Fig. 11 shows the distribution of the residuals from a weighted fit of the clusters in the z projection. The r.m.s. width of the distribution is 1.7 cm on the first plane and 2.7 cm on the second. Taking into account the effect of the multiple Coulomb scattering in the absorbers, folded with the expected momentum distribution of background muons, these widths are consistent with a chamber resolution of 1 cm [9].

The wire chambers of the 11 spectrometer are mainly oriented to measure the coordinate in the bending plane, while the vertex detector measures the coordinate in the nonbending plane. To check the association of the tracks measured in the hodoscope, we refer to the vertex detector located 14 m upstream and to a wire chamber plane located in the magnet at 5.1 m from the target. In order to eliminate the vertex detector tracks produced by low momentum particles, we require that a hit is found in this wire chamber within 2 cm from the extrapolation of a vertex detector track. Fig. 12a shows the angular difference in the nonbending plane, Δφ, between the tracks reconstructed in the muon trigger hodoscope and those measured in the vertex detector in the same event and in different events (dashed histogram). Fig. 12b shows the same distribution for the combination with the best angular matching. A clear correlation is visible. The width of the distribution, σ = 2.4 mrad, is consistent with the detectors resolution, the effect of multiple Coulomb scattering and the kinematics of the decays in flight of pions and kaons produced in the target.

6. Conclusions

We have described the design and the performance of the fast tracking trigger hodoscope built to identify muons in the WA92 experiment at the CERN SPS.

The hodoscope is made of six detector planes placed behind iron absorbers that filter most of the hadrons. Each plane covers a surface of $13 \text{ m}^2$ and is segmented in strips of 3 cm pitch. The hodoscope is built with 26 RPC of $2 \text{ m}^2$ surface each. RPC are robust, easy to build and operate, reliable and inexpensive compared with other detectors. This is the first time RPC have been used in an experiment at CERN and they have proven to operate with good efficiency and with good space and time resolution.

The hodoscope has worked in the experiment with an average efficiency higher than 99%. The time resolution is about 5 ns and the space resolution obtained by fitting tracks and unfolding the effect of multiple Coulomb scattering is about 1 cm.

The RPC strips are read-out by a fast processor that selects tracks collinear with the interaction vertex in a fixed time of 90 ns. During the first run of the WA92 experiment, only the muon trigger was used. This trigger provided a reduction factor of the interaction trigger rate of about 45, very close to the design figure.

With the measured efficiency and the expected acceptance...
tance for detecting muons from semileptonic decays of beauty particles, the muon trigger in coincidence with the interaction trigger should provide an enrichment factor for beauty events of around ten.

Acknowledgements

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References


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The conceptual design of a large solenoid is described. It is optimized for precision muon spectroscopy for experiments at future hadron colliders, providing polar-angle coverage from 60° to 170°/74°. The design uses mass-produced industrial components with the aim of reducing construction costs.

1. Introduction

At the future hadron colliders (the Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC)) most physics topics will require the identification and momentum measurement of leptons. The identification of electrons, using transition radiation or "preshower" techniques, inevitably requires "tracking", which has to function at luminosities near $L = 10^{34}$ cm$^{-2}$ s$^{-1}$. The momentum measurement of electrons may, however, benefit from the potentially excellent resolution of calorimeters. Muons, on the other hand, when identified as penetrating charged particles beyond a calorimeter, are practically inert to the associated particle flux and event topology. This ease of identification is counterbalanced, to some extent, by the difficulty of achieving "good" momentum resolution for the range of interesting momenta of $\sim 10$ GeV/c to $\sim 2$ TeV/c. This challenge of good muon spectroscopy can be addressed in several ways. Iron toroids, magnetized to $\sim 1.8$ T, provide a robust method without tacking to the utmost the requirements of tracking methods [1]. The achievable momentum resolution is multiple scattering limited up to very high momenta (typically 500 GeV/c) and is given by $\sigma_p = 0.48\sqrt{1/\beta}$ [G. F. M.]. Alternatively, tracking in air fields, as pioneered by the L3 Collaboration [2] offers the attractive possibility of high-precision momentum analysis over a wide range of muon momenta. Superconductive magnet systems have also been considered [3,4]. In this note, we report on work on the "shaped solenoid" carried out within the framework of the "CERN LHC Magnet Study Group" [4]. This group had the task of analysing a number of potential muon spectroscopy magnets, which could be used in LHC experiments. The study concentrated on the evaluation of the engineering feasibility of such magnets. In section 2, we briefly mention the origins of this concept, discuss the basic design parameters and indicate the possible momentum resolution [5]. Section 3 provides an account of the engineering solution developed which allowed a rather reliable cost estimate to be made. In section 4 we give a brief discussion on the possible muon tracking system and the integration of other experimental apparatus.

2. The shaped solenoidal magnet

The following specifications were the starting point for the design study:

- **Rapidity coverage**: $|\eta| \leq 2.5$
- **Integral ($\mathcal{L}$)** for tracking: $-10$ [m$^{-2}$]

Here $\eta$ denotes the pseudorapidity of the muons, related to their polar angle $\theta$ through the relation $\eta = \ln \tan \frac{\theta}{2}$. The concept discussed here already has a long history. Approximately 15 years ago, the "open axial field magnet" was constructed for the axial field spectrometers at the CERN intersecting storage rings [6] and extrapolated to several novel magnet configurations for