IDEAS FOR A HIGH LUMINOSITY MUON PHYSICS DETECTOR WITH COMPLETE PARTICLE IDENTIFICATION

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ABSTRACT

Modifications of the existing EMC-NA9 spectrometer at the SPS muon beam by using a Time Projection Chamber (TPC) as vertex-detector and Ring Image Cerenkov (RICH) counters allow at least a factor 5 increase in luminosity and provide complete hadron identification. The compactness of the new detectors gives space for future 4π coverage for neutral particle detection.

1. INTRODUCTION

The existing EMC spectrometer\(^1\) at the SPS muon beam (Fig. 1) was conceived in 1974\(^2\). It uses the then available best technology for particle identification (multicell gas Cerenkov counters, aerogel Cerenkov counter, time of flight hodoscopes) covering the kinematical range of produced particles as completely as possible. As vertex detector a streamer chamber with inserted target of 1 m length is in use. Neutral particle detection is possible within the forward kinematical range (pos \(x_p\)) with a lead-glass calorimeter. For the study of hadrons produced in deep inelastic muon scattering especially in quark or gluon jets one is aiming for higher luminosities with complete charged and neutral particle identification\(^3\).

On the basis of acceptance studies using Monte-Carlo events we discuss the possibility to achieve this aim by using very modern detection devices:
- a TPC as vertex detector and as particle identifier for momenta below \(\sim 1\) GeV;
- liquid and gas ring image Cerenkov counters for a complete identification of charged particles in the momentum range from 0.7 GeV/c to maximum momentum.

The compactness of RICH detectors gives space in the vertex part of the spectrometer for implantation of e.m. and/or hadron calorimetric devices. The expected performance concerning the possible luminosity, estimates of the influence of background events, cost and timescale estimations are discussed.

2. ACCEPTANCE STUDY

As input for acceptance studies a sample of MC events generated according to the Lund model\(^4\) within the kinematical limits for the scattered muon of \(4 < Q^2 < 200\) GeV/c\(^2\), \(15 < v < 260\) GeV, \(E > 25\) GeV, \(\theta_{\text{Lab}} > 0.5^\circ\), \(40 < W^2 < 400\) GeV\(^2\) and \(0 < v/E < 0.9\) was used. The EMC-NA9 standard running conditions of 280 GeV incoming positive muons, vertex magnet field + 1.5 Tesla, forward spectrometer magnet field -1.5 Tesla and the 1/2 degree trigger were applied.
Fig. 1  1981 set-up of the EMC-NA9 experiment with a streamer chamber (SC) vertex detector, multicell gas Čerenkov counters (C0, C1, C2), aerogel Čerenkov counter (CA), time of flight hodoscopes (F1,2,3,4) and lead glass array (LG).
As reference planes for the acceptance description the wire chamber planes behind the vertex magnet (PV2) and behind the forward spectrometer magnet (W3) are taken (see Fig. 1). To simplify the description two angles $\phi$ and $\theta$ as defined in Fig. 2 are used. They are given by connecting the impact point of a track on the reference plane with the centre of the target. Otherwise the EMC coordinate system is used:

- $x$: beam direction (pos. downstream)
- $y$: horizontal axis (pos. downstream left)
- $z$: vertical axis (pos. up).

![Diagram showing reference planes and angles $\phi$ and $\theta$.]

**Fig. 2** Definition of acceptance angles $\phi$ (horizontal) and $\theta$ (vertical)

The resulting hit pattern at the vertex exit and the forward spectrometer exit are shown in Figs. 3 and 4 respectively. The corresponding distributions of momenta as a function of the horizontal deflection $\phi$ and the vertical deflection $\theta$ are shown in Figs. 5 and 6 behind the vertex and Figs. 7 and 8 behind the forward spectrometer. The momentum cutoff at about 0.5 GeV behind the vertex magnet and about 3 GeV behind the forward spectrometer magnet is due to the magnetic field settings.

![Diagram showing hit patterns at PV2 and W3 magnet.]

**Fig. 3** Hit pattern of MC tracks at PV2 behind the vertex magnet.

**Fig. 4** Hit pattern of MC tracks at W3 behind the forward spectrometer magnet.
Fig. 5 Momenta of tracks as function of horizontal deflection $\phi$ downstream of the vertex spectrometer

Fig. 6 Momenta of tracks as function of vertical deflection $\theta$ downstream of the vertex spectrometer

Fig. 7 Momenta of tracks as function of horizontal deflection $\phi$ downstream of the forward spectrometer

Fig. 8 Momenta of tracks as function of vertical deflection $\theta$ downstream of the forward spectrometer
3. VERTEX MAGNETIC FIELD

The performance of a Time Projection Chamber (TPC) as vertex detector or as photon detector in a Ring Image Cerenkov counter (RICH) is crucially dependent on the absence of field components perpendicular to the electron drift direction which is given by \( \hat{\mathbf{v}}_{\text{dr}} \parallel \mathbf{E} \parallel \hat{\mathbf{B}}_z \). For example the Lorentz angle \( \alpha = \frac{|\mathbf{v}_{\text{dr}} \times \hat{\mathbf{B}}_z|}{|\mathbf{E}|} \) with standard values \( |\mathbf{v}_{\text{dr}}| = 5 \text{ cm/\mu sec} \), \( |\mathbf{E}| = 0.5 \text{ kV/cm} \) and assuming \( |\hat{\mathbf{B}}_z| = 0.01 \text{ Tesla} \) produces after a 40 cm drift an offset of 4 mm (= 10 mrad).

In principle for the TPC vertex detector it is always possible to correct for Lorentz drifts by using the field map of the vertex magnet. The same is true for \( \hat{\mathbf{B}}_z \) components out of the RICH-TPC plane. In the plane \( \hat{\mathbf{B}}_z \) components are destructive for electrons drifting near the TPC walls and therefore have to be avoided. The actual field configuration of the EMC vertex magnet is to a good approximation radially symmetric\(^5\). In Figs. 9,10,11 are shown respectively the main field component \( B_z \) along the beam (x coordinate), the \( \hat{B}_y \) component at \( y = 50 \text{ cm} \) as a function of \( x \) and the \( \hat{B}_x \) component measured along the beam. The position of the inner coil boundary is indicated (± 1 m from the centre) as well as the position of the target, the TPC and the liquid RICH counter. The residual \( B_x \), \( B_y \) components within the volume defined by the poles amounts to about 0.05 Tesla.

Possible magnet modifications to reduce \( B_x \) and \( B_y \) are under study\(^6\). These are:
- close the now open pole region by introducing iron plugs which can be shaped adequately. The possible maximum \( B_z \) field changes in this case from 1.5 Tesla to 2.3 Tesla;
- adding of compensating coils near the inner coil edges;
- widening of the magnet aperture but leaving the polepiece gap at 1 m distance.

Independent of the envisaged modifications we assume in the following no principal hindrance to the TPC vertex detector performance within the inner volume of the magnet. Nevertheless, the arrangement of RICH-TPC's inside the magnet has to be radially symmetric to avoid \( \hat{\mathbf{B}}_z \) components in the plane of the TPC.

4. THE TPC VERTEX DETECTOR

A high multiplicity event taken from NA9 streamer chamber hydrogen data is shown in Fig. 12 looking onto the bending plane (x-y plane). On average a multiplicity of 6 tracks outside the beam region was measured. Taking into account the event topology the TPC shape was chosen as shown in Fig. 13 and put inside the 2 m\( ^\circ \) pole region. The target of 1.5 m length and 7 cm\( ^\circ \) is inserted protruding 30 cm upstream and ending 40 cm before the end of the TPC cage to give enough tracking length also for tracks emerging from the target end. The beam region is decoupled from the TPC over the whole length by a pipe of 10 cm\( ^\circ \).
Fig. 9  $B_z$ component of the vertex magnet field along $x$ at $y=z=0$ cm

Fig. 10  $B_y$ component of the vertex magnet field along $x$ at $y=50$ cm and $z=0$ cm

Fig. 11  $B_x$ component of the vertex magnet field along $x$ at $y=z=0$ cm
Fig. 12  Streamer chamber event taken from NA9 - Data on Hydrogen

Fig. 13  TPC shape in the bending plane. The liquid RICH counter is arranged at the downstream end of the TPC
Fig. 14  Layout of the TPC field cage. The outer surface of the beam pipe is also covered with potential strips.

Fig. 15  Layout of the TPC end plate.
A possible layout of the TPC field cage with two boxes of 30 cm height and drift distance, each away from the -6kV central plane, is shown in Fig. 14.

The TPC end plate construction with pad rows of varying density in x and y (near the target) and adapted to the event topology is shown in Fig. 15. The sense wires at +3.7 kV having 4 mm pitch and separated by the field wires at +0.4 kV are spanned in y direction 4 mm above the pad rows at 0kV. A further 4 mm above the sense/field wire plane is built a 2 mm pitch gridwire plane (or mesh) at 0kV. A third wire plane with 2 mm pitch is spanned 8 mm above the gridwires. It is acting as trap for incoming electrons by application of +100/-100 volts pairwise which are switched to 0 volts during the event recording. A summary of the main TPC parameters is given in Table 1. The $\Delta p/p^2$ momentum resolution achievable with the proposed layout is comparable to the resolution of the existing streamer chamber:

- TPC resolution $\Delta p/p^2 = 0.5\%$ to 1\% per GeV/$c$\textsuperscript{7},
- streamer chamber resolution $\Delta p/p = (1+p)\%$\textsuperscript{1}

### Table 1

Main Vertex TPC Parameters

- height 2 x 300 mm
- length 1550 mm
- width 600/1450 mm conically shaped with 42.5° acceptance in the bending plane
- target 1500 mm long, 70 mm§ inserted in the TPC
- TPC field cage -6kV with beam pipe of 100 mm§
- sense wire spacing 4 mm
- 21 pad rows with 8 x 8 mm² pads (5 x 8 mm² near the beam)
- row distance varying from 100 mm to 40 mm
- pressure 1 atm, gas mixture 80% Argon, 20% methane
- gate wire plane in front of the grid wire plane to avoid production of ions if no trigger takes place
- resolution: in y $\sim 250$ μm, in z $\sim 1$ mm (with 2 to 5 cm drift per μsec and with a 60 nsec clock readout), in x defined by 4 mm sense wire pitch
- readout time $\sim 15$ μsec
- z coordinate loss near the end plates $\sim 10$ mm if the trigger is formed in 500 nsec
- two track separation $2 \times 2$ cm²
- $\Delta p/p^2 \sim 0.5\%$ proportional to $\sigma_B L^2 N$ with $L$ = track length and $N$ = number of pad crossings
5. PARTICLE IDENTIFICATION WITH THE VERTEX TPC

The mean track length of about 1 m within the TPC gives a mean number of 1 m/4 mm = 250 samples from the CCD or FADC electronics connected to the sensewires to provide a dE/dx measurement with an accuracy of about σ(dE/dx) = 5%.

The upper limits for identification with a 3σ separation are then 7):

\[ \frac{e}{\pi} < 8 \text{ GeV/c} \]
\[ \frac{\pi}{K} < 0.75 \text{ GeV/c} \text{ (and 4 to 10 GeV/c)} \]
\[ K/p < 1.3 \text{ GeV/c}. \]

The lower limits are determined by the 3.5 cm radius target size. At 90° track angle, protons of less than 230 MeV/c (pions of less than 60 MeV/c) are trapped within the target material.

6. THE VERTEX LIQUID RICH DETECTOR

Particles with momenta greater than \( \sim 750 \text{ MeV/c} \) are identified by a liquid RICH detector situated close to the downstream end of the TPC (Fig. 13) with a \( \phi \) acceptance of about ±42°. The radial arrangement takes into account the actual radially symmetric vertex magnet field and avoids \( B_T \) components in the RICH-TPC plane. Radial \( B_T \) components produce a Lorentz angle deviation which has to be corrected. The use of 1 cm C\(_6\) F\(_{14}\) (FC72) radiator and 14 cm photon driftspace from the quartz window to the 4 cm thick RICH-TPC gives an overall thickness of about 20 cm. A possible modular arrangement of RICH-TPC's as shown in Fig. 16 takes into account increasing particle density towards the beam region which itself is deadend out. The inner modules about the bending plane have 10 cm driftlength (\( \sim 2 \text{ usec read out time} \)), top and bottom modules have 2 x 15 cm drift length (\( \sim 3 \text{ usec} \)) with only one detection grid in the middle. The outer modules have 40 cm driftlength (\( \sim 8 \text{ usec} \)). The overlap with respect to the vertex-TPC size helps to detect the rings of \( \sim 25 \text{ cm}^2 \) also for tracks leaving the vertex-TPC at the edges. The expected identification limits are 8):

4σ-W/K - separation from 0.2 to 4.5 GeV/c,
4σ-K/P - separation from 0.7 to 8 GeV/c,

of which the lower limit is defined by detection of at least 3 photoelectrons.

Fig. 16  Layout of the photon detector modules of the vertex RICH
7. THE GAS RICH DETECTORS

One gas RICH detector filled with C₃H₈ (FC87) downstream of the vertex magnet with ψ-acceptance of ± 10° and one downstream of the forward spectrometer magnet filled with 50%/50% Neon/Argon mixture and of ψ-acceptance of ± 2.5° provide the identification of high momentum particles.

The TPC photon detector, modular shaped according to increasing particle density like in the case of the liquid RICH-TPC's, cover the detector entrance windows. The beam region is deadend out.

Parameters of the TPC-photon detectors are summarized in Table 2.

Table 2

Parameters of the RICH photon detector TPC's

| - depth 40 mm |
| - size variable as function of particle densities to adapt the total readout time (< 10 μsec) |
| - gas mixture methane, isobutane and TMAE |
| - detection grid 4 mm pitch |
| - with 60 nsec time digitisation the spacial resolution in the electron drift direction is ~ 1 mm |
| - quartz window towards the radiator volume |
| - gating grid in front of the OkV grid with ~ 1.5 mm pitch |
| - sensitive amplifiers (~ 0.1 μA) |

A spherically built mirror array of 2.5 m radius at 1.25 m distance behind the TPC's is used as focussing element in the vertex gas RICH detector. Similarly a mirror array of 10 m radius at 5 m distance is used behind the TPC's of the forward gas RICH detector. Assuming N₀ = 100 cm⁻¹ one expects about 40 photoelectrons per ring in the vertex gas RICH and about 22 photoelectrons in the forward gas RICH.

The identification limits are for the vertex gas RICH detector:

40-π/K - separation from 2.5 to 20 GeV/c,
40-K/P - separation from 9.5 to 35 GeV/c.

Assuming a dominant contribution to the error of the Cerenkov angle measurement from chromatic aberration and taking as dispersion for the Neon/Argon mixture the value Δφ = 0.12 * 10⁻⁶ the identification limits of the forward gas RICH are:
4σ-π/K - separation from 7.2 to 128 GeV/c,
4σ-K/P - separation from 25.5 to 270 GeV/c.

Lower limits are in each case fixed by the 3 photoelectron condition. The identification performance of all RICH detectors are summarized in Table 3. Fig. 17 shows the matching in momentum of identification in the vertex part of the proposed layout.

Table 3

<table>
<thead>
<tr>
<th>Identification parameters of RICH counters</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIQUID RICH C₆F₁₄ (FG72)</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Radiator length</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Nₑ in photo electrons</td>
</tr>
<tr>
<td>(β=1, N₀=100cm⁻¹)</td>
</tr>
<tr>
<td>Y threshold</td>
</tr>
<tr>
<td>4σ-π/k-separation</td>
</tr>
<tr>
<td>4σ-k/p-separation</td>
</tr>
<tr>
<td>dominant contrib. to resolution δθ</td>
</tr>
<tr>
<td>focussing type</td>
</tr>
</tbody>
</table>

Fig. 17 Match of identification of the vertex detector system
Fig. 18 Results of the background event study by Atkinson et al. (Ref. 10)

8. BACKGROUND EVENTS

An extensive study\(^\text{10}\) of the handling of background events in a gas RICH detector to be used in the CERN SPS OMEGA spectrometer was done by simulation of identification of MC event tracks. Size and kinematical conditions within that detector are very similar to the discussed vertex and forward gas RICH detectors. The study shows that the identification efficiency does not drop from nearly 100% for multiplicities of background tracks below about 40 within a sensitive time of the TPC photon detector of 3 \(\mu\)sec (Fig. 18). EMC data contain on the average one halo muon background track per 6 streamer chamber pictures taken with 1 \(\mu\)sec sensitive time each.

9. POSSIBLE LUMINOSITY

A comparison of the actual (1982) luminosity for data taking on hydrogen and the possible luminosity with the proposed spectrometer layout (Fig. 19) is done in Table 4. An increase of at least a factor 5 seems to be achievable.

10. COST AND TIMESCALE ESTIMATIONS

The electronics cost for the vertex-TPC detector with 21 pad rows x 130 pads on average per row gives 2730 pad channels. Plus 400 sense wire channels the total channel number for 2 TPC endplates is 6260. All channels equipped with CCD's or FADC's of channel price 300 SFR per channel give a total electronics cost of \(\sim 1.9\) MSF. The TPC mechanics cost scaled down from a LEP detector TPC is 0.5 MSF. So the total TPC cost sums up to \(\sim 2.5\) MSF.
Fig. 19  The new EMC experimental setup. For the description of non indicated parts, see Fig. 1 and Ref. 1
A cost estimate for the three RICH detectors also obtained by scaling down from LEP detector costs gives in total 1.5 MSF, so that the proposed layout seems realisable for about 4 MSF. No cost for any vertex magnet modification is included.

A timescale estimation is given by taking timescales for the corresponding LEP detector prototype construction which are proposed to be 2 to 3 years.

Table 4

Comparison of luminosity parameters for μ-p scattering

<table>
<thead>
<tr>
<th>parameter</th>
<th>1982</th>
<th>future</th>
</tr>
</thead>
<tbody>
<tr>
<td>- target</td>
<td>1 m Hydrogen</td>
<td>1.5 m Hydrogen</td>
</tr>
<tr>
<td>- trigger</td>
<td>1/2 degree</td>
<td>1/2 degree</td>
</tr>
<tr>
<td>- effective spill</td>
<td>1.6 sec</td>
<td>1.6 sec</td>
</tr>
<tr>
<td>- primary intensity</td>
<td>$55 \times 10^{11}$ ppp</td>
<td>$150 \times 10^{11}$ ppp</td>
</tr>
<tr>
<td>- deep inelastic events</td>
<td>$5 \times 10^{-7}$/muon</td>
<td>$7.5 \times 10^{-7}$/muon</td>
</tr>
<tr>
<td>- muon energy</td>
<td>280(400)GeV</td>
<td>320(450)GeV</td>
</tr>
<tr>
<td>- vertex detector dead time</td>
<td>100 msec/20%</td>
<td>$\sim 10$ msec/0%</td>
</tr>
<tr>
<td>- recorded events</td>
<td>3 to 4/pulse</td>
<td>21/pulse</td>
</tr>
<tr>
<td>- luminosity factor</td>
<td>1</td>
<td>5</td>
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<tr>
<td>- good events</td>
<td>10 to 20%</td>
<td>$\sim$ 20%</td>
</tr>
<tr>
<td>- analysis</td>
<td>SC picture analysis in 8 laboratories</td>
<td>filmless</td>
</tr>
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</table>
11. CONCLUSIONS

A high luminosity muon physics detector is feasible by using a TPC type vertex detector and RICH detectors for particle identification. The modification cost is about 10% of the cost of the existing apparatus and the construction time is about 2.5 years. The main advantages are:

- luminosity increase at least a factor 5,
- full range charged particle identification,
- very high identification granularity given by RICH detectors, (4 x 4 mm² in comparison to now 120 x 120 mm² at 3 m distance from the vertex) which allows identification of dense track topologies within jets,
- true 3 dimensional tracking in the vertex detector which provides nonambiguous track pattern recognition,
- filmless straightforward analysis of vertex detector data,
- lots of space for neutral detector devices in the proximity of the target to allow small size/low cost calorimetry over the full solid angle.

12. Acknowledgement

Thanks to V. Eckardt, H.E. Montgomery and T. Ypsilantis for discussions.

***

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