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STATUS AND FIRST RESULTS FROM
THE UA2 EXPERIMENT

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ABSTRACT

The UA2 detector was recently installed at the CERN SPS $\bar{p}p$ Collider. First data on $\bar{p}p$ collisions at an energy of $\sqrt{s} = 540$ GeV were recorded at the end of 1981. The first results reported here on inclusive neutral and charged particle production were obtained with a single arm spectrometer at 90° production angle.

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1. INTRODUCTION

The UA2 detector [1] was recently installed at the CERN Super Proton Synchrotron (SPS) $\bar{p}p$ Collider. The successful operation of the SPS $\bar{p}p$ Collider [2] allows the study of hadron interactions at a center of mass energy $\sqrt{s} = 540$ GeV, one order of magnitude higher than previously available. The data presented here were recorded with the UA2 detector during the first $\bar{p}p$ period, in November-December 1981.

The major objective of the UA2 experiment is to search for the weak intermediate vector bosons Z^0 and $W^\pm$ through their electronic decay modes :

$$\bar{p}p \rightarrow Z^0 + X \quad ; \quad Z^0 \rightarrow e^+e^- \quad (1)$$

$$\bar{p}p \rightarrow W^\pm + X \quad ; \quad W^\pm \rightarrow e^\pm \nu \quad (2)$$

From QCD calculations [3] the production cross sections for reactions (1) and (2) are predicted to be of the order of a few times 10^{-33} cm² at $\sqrt{s} = 540$ GeV. With three generations of quark and lepton doublets the branching fractions into electron channels are expected to be about 3% for (1) and 8% for (2) in the Glashow Weinberg Salam model of unified electroweak gauge theory [4]. In addition a strong forward-backward asymmetry for the $e^\pm$ from reaction (2) is expected in this model due to the V-A couplings of the $W^\pm$ to the quarks and leptons. The UA2 experiment accumulated data for a total integrated luminosity of only $\sim 10^{32}$ cm⁻² during the first $\bar{p}p$ period, which is not enough to observe reactions (1) and (2) at their expected rates.

In this talk we first give in Sect. 2 a description of the experimental apparatus and its performance. We then concentrate on the wedge detector, a single arm spectrometer situated around 90° production angle, used for the following measurements of inclusive particle production. The analysis and results for π^0 , η and single γ production over the transverse momentum range $1.5 < p_T < 4.5$ GeV/c are discussed in Sect. 3. Preliminary results on charged particle production are reported in Sect. 4. Finally, we present in Sect. 5 the results from a search for fractionally charged quarks.

2. EXPERIMENTAL APPARATUS

2.1 General overview

A plan view of the UA2 detector is shown in Fig. 1. At the center of the apparatus is the vertex detector which consists of a system of cylindrical proportional and drift chambers. It measures particle trajectories in a region without magnetic fields. In the central region the vertex detector is surrounded by highly segmented electromagnetic and hadronic calorimeters (central calorimeter) which cover ± 1 rapidity unit around 0. The forward and backward polar angular (θ) regions, of 20° to 37.5° and 142.5° to 160° , are each instrumented by twelve toroidal magnet sectors followed by drift chambers, multitube proportional chambers, and electromagnetic calorimeters. In the present stage of the experiment no central calorimeters are mounted over a 60° azimuthal (ϕ) region around the horizontal plane. Instead a large single arm spectrometer, called wedge detector, covers this solid angle. This detector is shown in Fig. 2.

Details of the UA2 detector have been described in Refs. [1] and [5]. In what follows we summarize the main components and the performance of each detector part.

2.2 Vertex detector

The cylindrical chambers of the vertex detector cover 2π radians in ϕ and from 20° to 160° in θ . The outer radius is about 35 cm. The chamber assembly consists of four multiwire proportional chambers (MWPC) with analog read-out on helicoidal cathode strips, two JADE type drift chambers [6] with six staggered sense wires per drift cell and read out including multihit and charge division electronics, and 24 scintillation counters arranged as a cylindrical hodoscope. A fifth MWPC is preceded by 1.5 radiation lengths of tungsten and is used for shower localization in front of the electromagnetic central calorimeter.

The vertex detector measures with high precision the coordinates of the interaction vertex and the directions of charged particles in the magnetic field-free central region. Typical resolutions (standard deviations) so far obtained for the vertex point determination are $\sigma \simeq 1.0$ to 1.3 mm transverse and $\sigma \simeq 1.1$ mm along the beams. The transverse resolution includes the natural beam size of the SPS $\bar{p}p$ Collider for different β conditions.

2.3 Forward-backward spectrometer

The polar angular regions of 20° to 37.5° and 142.5° to 160° are each equipped with a toroidal magnet. The coils define 12 forward and 12 backward azimuthal sectors covering 80% of 2π radians in ϕ . The average field integral along the particle trajectories is 0.38 Tm. Each spectrometer sector is instrumented with 9 drift chamber planes. Together with the vertex detector these chambers allow a measurement of the electron charge from reaction (2) up to 60 GeV/c transverse momentum.

The drift chambers are followed by a 1.4 radiation length thick iron-lead converter and four layers of multitube proportional chambers (MTPC) which define two coordinate axes at an angle of 77° between them. The purpose of these MTPC's is to localize electromagnetic showers. Resolutions of 5 mm (rms) have been obtained in each projection. Electromagnetic calorimeter sectors finally complete the forward-backward detectors. Each calorimeter sector is divided into ten cells covering 15° in ϕ and 3.5° in θ . The cells are lead-scintillator sandwiches. They are segmented in depth into two compartments (24 and 6 radiation lengths), to achieve good electron-hadron separation. The light of each compartment is collected by two photomultipliers (PM) via BBQ doped wavelength-shifting light guides [7]. The calibration procedure is described in the next section. The energy resolution for electrons measured in test beams is $\sigma_E/E = 0.15/\sqrt{E}$ (E in GeV).

2.4 Central calorimeter

The central calorimeter consists of electromagnetic lead-scintillator and hadronic iron-scintillator sandwich counters which cover polar angles from 40° to 140° and the full azimuthal range. Within its spherical shape the calorimeter is segmented into 240 cells. The cells have a so-called tower structure pointing to the interaction vertex. Each cell covers 15° in azimuthal and 10° in polar angle. The cells are segmented longitudinally into a 17 radiation lengths thick electromagnetic calorimeter followed by the two hadronic compartments of two absorption lengths each. The light of each compartment is collected by two BBQ-doped light guide plates [7] on opposite sides of the towers; the dead space between adjacent cells is minimized. In addition the last three

scintillator plates of the second hadronic compartment are also viewed by a BBQ rod placed in a hole in the center of the cell. Its signal can be used to indicate hadronic showers not fully contained in the calorimeter.

Details on the performance of the central calorimeter have been reported in Ref. [8]. The energy resolution for electrons has been measured to be $\sigma_E/E = 0.14/\sqrt{E}$ whereas the resolution for hadrons has been determined to be $\sigma_E/E \simeq 0.60/\sqrt{E}$ (E in GeV) ; the latter is energy dependent because of the increase in shower leakage at high energies.

Considerable importance has been given to the energy calibration of the calorimeters, in particular for the electromagnetic compartments. The mass resolution at $m_{Z^0} = 90 \text{ GeV}/c^2$ from reaction (1) is expected to be about $\sigma_m/m = 0.015$ using the energy resolution given above. It is therefore an experimental challenge to attempt to maintain the systematic calibration uncertainty within this limit. All calorimeters, including the forward-backward modules, have been calibrated in a CERN PS beam using $10 \text{ GeV}/c$ electrons for the electromagnetic compartments and $10 \text{ GeV}/c$ muons for the hadronic compartments using the response for minimum ionizing particles (MIP). The calibration has since been tracked with several methods. A Xe light flasher system on each module is used to send blue light via optical fibers to each PM channel and to light monitor devices (vacuum photo diodes and especially monitored PM's) for normalization. The response of the electromagnetic compartments is also evaluated regularly by a direct-current measurement on each PM, when a Co^{60} radioactive source is accurately placed in front of each calorimeter cell. This measurement is used for long-time corrections (periods larger than one month). Finally, the response to MIP is used as a cross-check. Overall drifts of the calorimeter response of the order of -5% per year have been observed. Using calorimeter modules identical to those used in the experiment we have measured, in a SPS test beam, that the described system is able to maintain the calibration to within $\pm 1\%$ per year with a PM to PM spread of $\sigma < 2\%$.

The calorimeters are also used to trigger the data acquisition for reactions (1) and (2), and for other $\bar{p}p$ interactions having large transverse energy flow. In addition to conventional sums over all electromagnetic or hadronic transverse energy in the calorimeters there is also

fast analog electronics for finding all 2×2 - cell electromagnetic clusters above an adjustable energy threshold. This triggering scheme has been described in Ref. [9].

2.5 Wedge detector

The wedge detector is a single-arm large-angle magnetic spectrometer (Fig. 2) in the horizontal plane covering 28° in ϕ and 68° in θ (± 0.7 units in rapidity) symmetrically around $\theta = 90^\circ$ with respect to the colliding beams. The magnet occupies the space of four central calorimeter modules that have been removed for that purpose. The calorimeter is used as a return yoke. The field integral is about 1 Tm. The charged particle trajectories are measured before the magnet with the vertex detector, and after in a set of 12 large drift chamber planes [10]. The momentum resolution so far obtained is $\sigma_p/p \simeq 0.02 p$ (p in GeV/c). These chambers are followed by a scintillator-iron-scintillator sandwich. Both scintillator hodoscopes consist of 28 vertical counters. Each counter of the front hodoscope is equipped with two PM's, for time of flight measurements (TOF). The counters after the 2 cm thick iron plate act as a pre-shower counter for the lead-glass wall, which completes the spectrometer. As shown in Fig. 3, the wall contains 2 arrays of lead glass blocks, each having a cross-section of $15 \times 15 \text{ cm}^2$, and a depth of 14.5 radiation lengths. The two arrays are separated by 30 cm in about the middle where a dE/dx counter has been installed. The energy resolution of the lead-glass wall has been measured to be $\sigma_E/E = (11.6 + 32.5/E)^{1/2} \%$ (E in GeV). Each block has been calibrated using 10 GeV electrons, and is monitored with a Xe light flasher system. The calibration remained stable to within $\pm 2\%$ during the $\bar{p}p$ running period.

The dE/dx counter mentioned above is used to search for fractionally charged particles (quarks). As shown in Fig. 4, it consists of 5 scintillator plates. Each plate is 4 cm thick and is viewed by two 5" PM's whose light guides are covered by additional scintillators used as veto counters. This dE/dx counter has also been calibrated at the CERN PS and its response to MIP has been studied as a function of the impact point.

2.6 Luminosity and trigger counters

Two scintillator arrays, with a total of 24 counters, surround the beam pipe at ± 10.3 m from the interaction point. These counter arrays cover 1.1 units of rapidity around $y = \pm 4.7$. A coincidence with a signal from each side is required in the trigger, for the data presented in this talk, to suppress backgrounds from non beam-beam collisions. The same counters are used to evaluate the integrated luminosity for the cross section normalization..

The total integrated luminosity for which we present results is $75 \mu\text{b}^{-1}$, calculated under the assumption that the non-diffractive $\bar{p}p$ cross section at $\sqrt{s} = 540$ GeV is 38 mb (see Ref. [11] for more details). The systematic error in the luminosity measurement has been estimated to be $\pm 17\%$.

3. INCLUSIVE π^0 , η AND γ PRODUCTION

Inclusive neutral particle production resulting in final-state photons has been studied [11] with the wedge detector using a trigger that requires the summed electromagnetic transverse energy in the lead-glass wall to exceed 1.1 GeV. For each such event the pattern of the energy deposition in the lead-glass has been reduced to clusters defined as adjacent cells having energies above 100 MeV. The halo contribution from surrounding cells is added to the cluster energy. The minimum spatial cluster separation is about 25 cm. We have corrected the energy for those photons which converted in the iron plate. This correction is proportional to the pulse height measured in the back hodoscope and amounts to 30 MeV per equivalent MIP.

The charged track to cluster correlation has been studied. We have only retained clusters as photon candidates if there is no charged particle trajectory passing within 12 cm of the cluster center.

3.1 Inclusive π^0 production

A sample of resolved $\pi^0 \rightarrow \gamma\gamma$ candidates has been obtained from events with at least two clusters each having an energy larger than 200 MeV. The invariant mass distribution for π^0 candidates with a transverse momentum p_T larger than 1.4 GeV/c is shown in Fig. 5, where

a clear π^0 peak is visible. The p_T cut ensures full trigger efficiency.

The solid line in Fig. 5 is the result of a Monte Carlo simulation including the measured lead-glass energy resolution and the finite shower size for photons. The lead-glass energy scale was adjusted by 4% to get agreement with the data. The uncertainty in the extrapolation from the calibration with 10 GeV electrons to photons in the one GeV range is of the same order. We therefore assign a systematic error of $\pm 4\%$ to the measured lead-glass energies (p_T scale).

The dashed line in Fig. 5 indicates the background, coming mainly from wrong photon pairings. This background has been calculated by interpolation from both sides of the π^0 peak, for each p_T bin, and amounts to typically 25%. In addition to the background subtraction the following corrections have been applied to the p_T (π^0) data with their relative contributions given in parenthesis : accidental charged track-cluster overlaps ($2 \pm 1\%$), photon conversions in the beam pipe or vertex detector (9%), overlaps with additional neutral clusters ($10 \pm 3\%$), and smearing effects due to the finite energy resolution (typically 8%).

The acceptance has been calculated from a Monte Carlo simulation. It is limited at low p_T by the solid angle to detect both photons and at high p_T by the spatial resolution of the detector. The acceptance reaches a maximum of 2% of 4π at $p_T = 2.7$ GeV/c.

The invariant cross section $E d^3\sigma/dp^3$, for inclusive π^0 production at 90° production angle and for transverse momenta between 1.5 and 4.5 GeV/c, is shown in Fig. 6 and listed in Table 1. The errors include the statistical uncertainty and the uncertainty from the background subtraction, which are added in quadrature. Additional systematic errors are $\pm 17\%$ in the normalization and $\pm 4\%$ in the p_T scale. It must be recalled that we have required in the trigger a signal from the small angle counters (Sect. 2.6). The measured production cross section corresponds to $\bar{p}p \rightarrow \pi^0 + X$ only if there is no correlation between a π^0 at about 90° production angle and particles triggering the small angle counters in non-diffractive collisions. This seems to be a very plausible assumption for the $p_T(\pi^0)$ range considered in this measurement.

The solid line in Fig. 6 describes the inclusive production cross-section for pp collisions at $\sqrt{s} = 53$ GeV [12]. Preliminary data from $\bar{p}p$ collisions at the ISR indicate the same behaviour [13]. The dashed line

in Fig. 6 corresponds to the extrapolation of the ISR results to $\sqrt{s} = 540$ GeV according to a $p_T^{-n} (1-x_T)^m$ parametrization with $x_T = 2p_T/\sqrt{s}$, $n = 8$, and $m = 9$ [12]. However, this comparison may be invalid because the present experiment probes much lower values of x_T than the measurements at the ISR over the same p_T region. A fit of the form $p_T^{-n_{\text{eff}}}$ to the measured invariant cross section yields $n_{\text{eff}} = 5.7 \pm 0.2$.

3.2 Inclusive η production

The $\gamma\text{-}\gamma$ mass distribution of Fig. 5 shows no evidence for an η signal. An enhancement at the η mass, shown in the insert of Fig. 5, has been obtained with stricter selection criteria than for the π^0 analysis. In addition to the previously described cuts we have retained only photon clusters below 3 GeV formed by at most two lead-glass cells. Events with more than 3 lead-glass clusters have been rejected. Furthermore, $\gamma\text{-}\gamma$ masses have been considered only if the energy asymmetry of the two clusters ($|E_1 - E_2|/(E_1 + E_2)$) is less than 0.4. These additional cuts reduce the acceptance by about a factor 3.

The observed enhancement in the η mass region corresponds to 53 ± 15 events above background. This is consistent with the expected 48 events obtained from a Monte Carlo simulation. In this calculation we have assumed a constant η/π^0 ratio of 0.55 as measured at the ISR [14] over the p_T range of this experiment.

3.3 Inclusive single γ production

Only photon clusters extending over at most two lead-glass cells have been accepted for the following analysis. Clusters of three or more cells are suspected to have a small contamination of neutral hadrons (mainly antineutrons). The purity of the photon clusters has been studied from the probability ρ that no conversion has occurred in the iron plate ($\rho = 0.44 \pm 0.01$ for γ from reconstructed $\pi^0 \rightarrow \gamma\gamma$).

In order to isolate a single γ contribution we have compared the transverse momentum distribution of these restricted photon clusters with the prediction of a Monte Carlo simulation. In this calculation we have used our measured inclusive π^0 cross section as an input. In addition we have assumed a p_T - independent η/π^0 ratio of 0.55 (see Sect. 3.2).

The p_T dependence of the observed photon spectrum is well predicted by the calculation. For p_T between 1.5 and 3.0 GeV/c there is a raw excess of 24 ± 58 photons, from a total of 1300 detected photons. After correcting for a possible non-linearity of the lead-glass energy response, and for the estimated contamination of neutral hadrons, we obtain a deficit of 46 ± 90 photons. This measurement restricts the inclusive ratio γ/π^0 to less than 7.5% at 95% confidence level for the p_T range 1.5 to 3 GeV/c at 90° production angle.

4. INCLUSIVE CHARGED PARTICLE PRODUCTION

Inclusive charged particle production can be studied from the data accumulated in the magnetic spectrometer of the wedge detector. Charged tracks have triggered the data acquisition by giving a coincidence signal of corresponding counters in the front and back hodoscopes. The analysis of these data is still in progress and the preliminary results presented here are obtained from a very small fraction of the total triggers.

The momentum of a particle has been evaluated from a matching through the magnetic field of the track segment measured in the wedge drift chambers with the interaction point determined by the vertex detector. The TOF information has been used to remove protons and antiprotons from the data sample by rejecting events with $m^2 > 0.5 \text{ GeV}^2$ (m = mass of the particle). The m^2 distribution from TOF and momentum measurements is shown in Fig. 7. The TOF measurement has, at the present stage of the analysis, a resolution of $\sigma = 500 \text{ ps}$. This includes the uncertainty in the exact occurrence of the interaction time (σ of about 300 ps) with respect to the induced signal from the arrival of the p bunch.

A preliminary p_T distribution of inclusive charged particles (pions and kaons) at 90° production angle is shown in Fig. 8.

5. SEARCH FOR FRACTIONALLY CHARGED PARTICLES

The dE/dx counter installed in the wedge detector at 90° with respect to the colliding beams has been used to search for fractionally charged particles (free quarks). The trigger for such events requires

a signal from at least 3 out of 5 counter plates above a pulse height threshold of 5% of a MIP. In addition at least one of the two overlapping counters of the front hodoscope had to register a pulse height above 3% of a MIP. About 15000 triggers were recorded over the entire $\bar{p}p$ running period.

Normalized pulse heights (in units of MIP) have been used in the analysis in order to get 5 dE/dx measurements I_1 to I_5 . Corrections have been applied for the impact point position by using the ratio of PM response at each end of the counter. Events with $I_1 = 0$, $I_5 = 0$, or $I_2 = I_3 = I_4 = 0$, have been rejected. The most probable energy loss has then been determined according to $I_0 = \sqrt[3]{I_1 I_2 I_3}$ (or $I_0 = \sqrt{I_1 I_2}$) where the I_i are the three (two) smallest non-zero pulse heights. The events for which the dE/dx measurements from the different counter plates are not consistent with a single Landau distribution have been discarded. Also, the pulse height in the front hodoscope counter has been required to agree with the measurement from the dE/dx counter and the veto counters covering the light guides of the dE/dx detector have been used to reject background events with small pulse heights due to the Cherenkov radiation of particles passing through the plastic light guides.

Further selection criteria have been applied to reject background events due to particles passing nearby the dE/dx counter or traversing it only partially. No energy deposition must be present in either one of the two adjacent lead-glass columns, if there is a reconstructed track present its extrapolation must cross all five dE/dx counter plates, for events with $I_0 > 0.5$ MIP at least 6 out of 12 drift chamber planes must have a hit in front of the counter, and the pulse height in the overlapping counters of the back hodoscope must be < 1.5 MIP. No candidate for a fractionally charged quark has been observed in the surviving data sample for which the distribution of the most probable energy loss I_0 is shown in Fig. 9.

The determination of an upper limit on quark production depends on the assumptions for the quark mass and momentum spectrum of the produced quarks. We have assumed that the quarks are produced with the same p_T spectrum as pions (i.e. a mean p_T of 400 MeV/c). The efficiency for detecting charge $|Q| = 1$ particles into the solid angle of the dE/dx counter has been evaluated to be 0.48 ± 0.02 for the above selection criteria.

The result of the search for fractionally charged quarks is summarized in Table 2 where 90% confidence level upper limits are listed for the ratio of light quark to $|Q| = 1$ particle production at 90° . These limits rapidly become worse with increasing quark mass.

6. CONCLUSIONS

The UA2 detector has been operated successfully during the first running period of the CERN SPS $\bar{p}p$ Collider. Inclusive particle production at 90° production angle has been investigated. We have reported the first measurement of inclusive π^0 production from $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV over the transverse momentum range from 1.5 to 4.5 GeV/c. The invariant π^0 cross section is larger than that measured at $\sqrt{s} = 53$ GeV. An η signal has been observed which is consistent with $\eta/\pi^0 = 0.55$, as measured at the ISR over the same p_T range. No evidence for single photon production has been found in the p_T range from 1.5 to 3 GeV/c at a level of $\gamma/\pi^0 < 7.5\%$ (at 95% C.L.). The study of identified charged particle production is in progress. No candidate for a fractionally charged free quark has been found. This implies, for light quarks, 90% C.L. upper limits on the ratio of quark to charge-one particle production of a few times 10^{-4} .

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TABLE 1

Invariant π^0 production cross-section in $p\bar{p}$ collisions at
 $\sqrt{s} = 540 \text{ GeV}$, $\theta \simeq 90^\circ$.

Transverse momentum (GeV/c)	Invariant cross-section ($\mu\text{b GeV}^{-2} \text{c}^3$)
1.51	217 ± 41
1.61	158 ± 29
1.72	108 ± 21
1.82	106 ± 14
1.92	68.4 ± 10.2
2.03	35.8 ± 8.7
2.18	31.0 ± 5.3
2.39	21.5 ± 3.0
2.60	12.3 ± 2.5
2.81	8.16 ± 1.36
3.02	5.30 ± 1.11
3.37	2.29 ± 0.44
3.89	1.02 ± 0.30
4.42	0.44 ± 0.20
Global additional uncertainties	
- on transverse momentum $\pm 4\%$	
- on cross-section $\pm 17\%$	

TABLE 2

Upper limits, at a 90% confidence level, for the ratio of quark over charge $|Q| = 1$ particle production at 90° .

quark mass	$ Q = 1/3$	$ Q = 2/3$
0	2.2×10^{-4}	2.2×10^{-4}
m_π	2.5×10^{-4}	2.5×10^{-4}
$2 m_\pi$	2.8×10^{-4}	3.0×10^{-4}
$1 \text{ GeV}/c^2$	4.5×10^{-4}	8.4×10^{-4}

Figure captions

Fig. 1 : Plan view of the UA2 detector.

Fig. 2 : Side view of central part of the UA2 detector showing the single arm large angle spectrometer (wedge detector).

Fig. 3 : Exploded view of the wedge detector.

Fig. 4 : Side view of the dE/dx counter implemented in the wedge detector.

Fig. 5 : Invariant mass distribution of the two-photons sample (full dots). The distribution in the insert around the η mass is for stricter cuts (see text). The result of the Monte Carlo simulation (solid lines) has been added to a hand-drawn background (dashed lines).

Fig. 6 : The measured invariant cross-section for $p\bar{p} \rightarrow \pi^0 + \dots$ (full dots) at $\sqrt{s} = 540$ GeV is compared to that for $pp \rightarrow \pi^0 + \dots$ at $\sqrt{s} = 53$ GeV (solid line). The pp data are from Ref [12] ; in the lower p_T range the mean of π^+ and π^- cross-sections has been used. The dashed line is an extrapolation of the data of Ref [12] to Collider energy using the form $p_T^{-n} (1-x_T)^9$.

Fig. 7 : Squared mass distribution for charged particles obtained from momentum and TOF measurements.

Fig. 8 : Preliminary $\frac{1}{p_T} \frac{dN}{dp_T}$ distribution for charged pions and kaons as a function of p_T .

Fig. 9 : Most probable energy loss distribution for charged particle in the dE/dx counter in units of minimum ionizing particle pulse heights.

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

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Fig. 6

Fig. 7

Fig. 8

Fig. 9