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PRODUCTION OF CHARGED PIONS AT HIGH TRANSVERSE MOMENTUM
IN pp COLLISIONS AT $\sqrt{s} = 45$ and 62 GeV

Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration

A. Breakstone¹, C.D. Buchanan^{3(*)}, R. Campanini², H.B. Crawley¹,
G.M. Dallavalle², M.M. Deninno², K. Doroba⁶, D. Drijard³, F. Fabbri³,
A. Firestone¹, H.G. Fischer³, H. Frehse^{3(**)}, W. Geist³, G. Giacomelli²,
R. Gokieli⁶, M. Gorbics¹, P. Hanke⁵, M. Heiden³, W. Herr⁵,
P.G. Innocenti³, E.E. Kluge⁵, J.W. Lamsa¹, T. Lohse⁴, W.T. Meyer¹,
G. Mornacchi³, T. Nakada⁵, M. Panter^{4(***)}, A. Putzer⁵, K. Rauschnabel⁴,
F. Rimondi², R. Sosnowski⁶, J. Spahn^{3(*)}, M. Szczekowski^{4(***)},
O. Ullaland³, and D. Wegener⁴

- 1 Ames Laboratory and Physics Department, Iowa State University, Ames, USA
- 2 Istituto di Fisica dell'Università and INFN, Bologna, Italy
- 3 CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 4 Institut für Physik der Universität, Dortmund, Germany
- 5 Institut für Hochenergiephysik, Heidelberg, Germany
- 6 University and Institute of Nuclear Problems, Warsaw, Poland

ABSTRACT

We report on measurements of charged pion production cross sections at $\theta \approx 50^\circ$, $p_T \approx 3$ –11 GeV/c and $\sqrt{s} = 45$ GeV, taken with the Split Field Magnet Detector at the CERN Intersecting Storage Rings (ISR). Together with previous data at $\sqrt{s} = 62$ GeV, this allows the calculation of the power law dependence p_T^{-n} . Values of $n \approx 8$ are found at low $x_T = 2p_T/\sqrt{s}$ which drop to about 7 at $x_T \approx 0.3$. The measured values of π^+/π^- rise with x_T and approach ≈ 2 at $x_T \approx 0.3$. A first-order QCD calculation is reasonably consistent with the data.

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(*) Also at UCLA, Los Angeles, USA.

(**) Now at Brown, Boveri & Cie, Turgi, Switzerland

(***) Now at CERN, Geneva, Switzerland

1. INTRODUCTION

Production cross sections of high transverse momentum (p_T) particles in proton-proton collisions provide useful tests of hard scattering models. Comparisons with the expectations from QCD, which may be the fundamental theory underlying these interactions, are particularly important.

We have previously reported such measurements at $\sqrt{s} = 62$ GeV and at a c.m. polar angle $\theta \approx 50^\circ$ obtained with the Split Field Magnet (SFM) detector at the CERN-ISR [1]. In this letter we report similar results for $\pi^\pm$ production at $\sqrt{s} = 45$ GeV, and compare these data with data taken at higher energy. In the following letter [2] the inclusive ratios K^+/π^+ and K^-/π^- at $\sqrt{s} = 62$ GeV and 45 GeV are presented.

2. EXPERIMENT AND ANALYSIS

The experiment was performed with the SFM detector, a proportional-chamber spectrometer which momentum-analyzes charged particles over nearly 4π steradians solid angle [3]. Event triggers are provided by two telescopes at angles of $\sim 50^\circ$ relative to the beam direction, each with a threshold Cerenkov counter at atmospheric pressure, which was used to separate pions from kaons and protons above $p_T \approx 3$ GeV/c. Measurement of the inclusive pion spectra at $\sqrt{s} = 45$ GeV used techniques similar to those previously performed with the 62 GeV data [1]. Corrections included geometrical acceptances, nuclear absorption, track-finding inefficiency, Cerenkov inefficiencies for low p_T pions, removal of cosmic ray background, and momentum resolution.

The largest systematic uncertainties in the absolute cross sections arise from geometrical acceptances ($\approx \pm 10-15\%$) and luminosity monitoring ($\approx \pm 5\%$). In general, the experimental conditions (magnetic field, vertex position, geometrical alignment) are sufficiently different for the $\sqrt{s} = 45$ GeV and 62 GeV data that most of the uncertainties are compounded in any comparison. In addition, positive and negative particles travel through different chamber "road systems" and thus have uncorrelated uncertainties in geometrical acceptance.

3. PION CROSS SECTIONS

The corrected inclusive pion cross sections for $\sqrt{s} = 45$ and $\theta \approx 50^\circ$ are listed in table 1 and displayed in fig. 1. A comparison of these data with results previously reported at $\sqrt{s} = 62$ GeV [1] shows that in each case the data fall by nearly six orders of magnitude from $p_T \approx 3$ GeV/c to $p_T \approx 10$ GeV/c. Further, at a given p_T the cross section at $\sqrt{s} = 45$ GeV is always smaller than at 62 GeV and falls more rapidly with p_T . At each energy the cross section for π^- is smaller than for π^+ .

4. POWER LAW BEHAVIOUR

We assume for the invariant cross section a dependence

$$E d^3\sigma/dp^3 \propto p_T^{-n} f(x_T, \theta)$$

where $x_T = 2 p_T/\sqrt{s}$. In naive quark-quark scattering models n is expected to be about 4. However, it is known that scalebreaking effects in parton structure functions and fragmentation functions may raise n to a value of 5 to 6 [4]. Furthermore, intrinsic parton transverse momenta and higher twist diagrams [5] may raise the value of n even more at lower p_T .

Comparing the data at $\sqrt{s}_1 = 45$ and $\sqrt{s}_2 = 62$ GeV allows us to extract n as a function of x_T . In contrast to some other estimates of n we did not assume a functional dependence of $f(x_T, \theta)$ since one can equate the ratio of the measured cross sections at the same x_T to $(\sqrt{s}_2/\sqrt{s}_1)^n$. Fig. 2 shows the results for $n^+(\pi^+ \text{ data})$ and $n^-(\pi^- \text{ data})$. The errors shown are statistical only; in addition there is an overall systematic uncertainty ± 0.30 . Also shown in fig. 2 are the results for $n^0(\pi^0 \text{ data})$ of the CCOR and ABC groups [6]. In order to determine a possible x_T dependence of n , we average our points into a low x_T bin at 0.18 (0.16 to 0.21) and a high x_T bin at 0.26 (0.24 to 0.29). We find that:

$$\begin{aligned} n^+(0.18) &= 8.34 \pm 0.06, & n^+(0.26) &= 7.36 \pm 0.23 \\ n^-(0.18) &= 7.74 \pm 0.05, & n^-(0.26) &= 7.11 \pm 0.28, \end{aligned}$$

where the quoted errors are statistical only.

Including the relative systematic uncertainties, we find a drop in n^+ of 0.98 ± 0.31 and in n^- of 0.63 ± 0.35 from $x_T = 0.18$ to $x_T = 0.26$. Data from other experiments [6] indicate that n decreases with increasing x_T , and probably approaches 5 to 6 around $x_T \approx 0.4$.

5. π^+/π^- RATIO

The ratio π^+/π^- of inclusive π^+ and π^- cross sections is shown vs x_T in fig. 3. The results from ref. [6] at $\sqrt{s} = 27$ GeV and $\theta \approx 90^\circ$ are also included. The prediction from a QCD model (described in sect. 6) is given as well.

Our experimental results show a rise of the π^+/π^- ratio from 1.2 at $x_T \approx 0.13$ to 2.0 at $x_T \approx 0.3$. This rise agrees qualitatively with the expectations from the quark composition of the proton. For high p_T pions, we expect π^+ mesons to be produced mainly from scattered up quarks and π^- mesons to be produced mainly from down quarks. Thus at high x_T , we expect $\pi^+/\pi^- \approx 2$ which reflects the valence quark structure functions of the proton at Bjorken $x \approx 0.30 - 0.50$.

At lower x_T , we expect the π^+/π^- ratio to drop toward ≈ 1 , as the ratio should here reflect processes such as possible charge-symmetric contributions from scattered neutral partons (e.g. gluons). Other charge-symmetrizing effects include neutral vector meson decays and "rank reordering" [7] in which a scattered fragmenting valence quark is not contained in its fastest fragment, i.e. the measured pion.

6. COMPARISON WITH QCD CALCULATIONS

A first-order QCD Monte-Carlo calculation was performed which incorporates quark and gluon structure functions from the parametrization of ref. [8]. For the intrinsic transverse momentum k_T of the initial partons a phenomenological gaussian distribution for both components was used, with $\langle k_T \rangle = 850$ MeV. For the probability $P(q\bar{q})$ to extract a quark-antiquark pair from the vacuum or from a gluon, $P(u\bar{u}) = P(d\bar{d}) = 0.4$ and $P(s\bar{s}) = 0.2$ were chosen; equal probabilities for creating pseudoscalar and vector mesons are used [9]^(*). A more complete description of the calculation may be found in ref. [10].

(*) A non-scalebreaking exponent 1.5 instead of 1.0 [10] was used in the gluon fragmentation function. The results in [10] are insensitive to this change.

In figs 4(a) and 4(b) we compare the predictions of the model with our measured cross sections. At $\sqrt{s} = 62$ GeV the QCD predictions for both π^+ and π^- production vary from $\approx 50\%$ below the data at $p_T = 4$ GeV/c to $\approx 20\%$ above the data at the highest p_T points. At $\sqrt{s} = 45$ GeV for p_T above 5 GeV/c, the predictions for both charges average 40% below the data. At $p_T = 3$ GeV/c, the predictions are $\approx 60\%$ below the data.

The overall agreement, however, of our QCD calculations and the data in absolute magnitude and in slope is reasonable, especially at the higher values of $\sqrt{s}$ and p_T .

7. CONCLUSIONS

The measured pion production cross sections at $\sqrt{s} = 45$ and 62 GeV fall almost six orders of magnitude in the p_T range from 3 to 11 GeV/c, and exhibit an approximate power law behaviour. This is consistent with models of hard scattering sub-processes. Specifically, the inverse power law structure p_T^{-n} calculated from these data yield values of n of approximately 8 at low x_T and appear to fall by about one unit in n over our x_T range. This matches qualitatively the expectation that, at high x_T , n will fall to values of about 5 or 6 characteristic of parton-parton scattering models including scalebreaking effects.

The ratio of π^+/π^- production rises from ≈ 1 at low x_T to ≈ 2 at higher x_T , as expected qualitatively from the valence quark composition of the proton.

Cross sections calculated using a first-order QCD model agree reasonably well with the measured cross sections over more than 5 orders of magnitude.

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TABLE 1

Invariant cross sections for inclusive π^+ and π^- production at $\sqrt{s} = 45$ GeV and $\theta \approx 50^\circ$. Errors include p_T dependent relative systematic uncertainties. In addition there is an uncertainty on the normalisation of about $\pm 15\%$.

$$E \frac{d^3\sigma}{dp^3} \quad (\text{cm}^2 \text{ c}^3 \text{ GeV}^{-2})$$

p_T (GeV/c)	π^+	π^-
3.1	$(1.17 \pm 0.11) \times 10^{-31}$	$(8.32 \pm 1.33) \times 10^{-32}$
3.3	$(6.97 \pm 0.35) \times 10^{-32}$	$(4.79 \pm 0.48) \times 10^{-32}$
3.5	$(4.12 \pm 0.17) \times 10^{-32}$	$(2.66 \pm 0.11) \times 10^{-32}$
3.7	$(2.39 \pm 0.08) \times 10^{-32}$	$(1.48 \pm 0.05) \times 10^{-32}$
3.9	$(1.40 \pm 0.04) \times 10^{-32}$	$(8.44 \pm 0.23) \times 10^{-33}$
4.1	$(8.55 \pm 0.19) \times 10^{-33}$	$(4.97 \pm 0.11) \times 10^{-33}$
4.3	$(4.90 \pm 0.13) \times 10^{-33}$	$(2.96 \pm 0.08) \times 10^{-33}$
4.5	$(3.04 \pm 0.10) \times 10^{-33}$	$(1.74 \pm 0.06) \times 10^{-33}$
4.7	$(1.88 \pm 0.08) \times 10^{-33}$	$(1.00 \pm 0.04) \times 10^{-33}$
4.9	$(1.21 \pm 0.06) \times 10^{-33}$	$(6.78 \pm 0.35) \times 10^{-34}$
5.1	$(7.96 \pm 0.55) \times 10^{-34}$	$(4.46 \pm 0.34) \times 10^{-34}$
5.3	$(4.60 \pm 0.40) \times 10^{-34}$	$(2.72 \pm 0.25) \times 10^{-34}$
5.5	$(2.53 \pm 0.27) \times 10^{-34}$	$(1.12 \pm 0.16) \times 10^{-34}$
5.7	$(1.63 \pm 0.22) \times 10^{-34}$	$(1.01 \pm 0.14) \times 10^{-34}$
5.9	$(1.29 \pm 0.19) \times 10^{-34}$	$(7.10 \pm 1.16) \times 10^{-35}$
6.41	$(4.59 \pm 0.48) \times 10^{-35}$	$(2.22 \pm 0.27) \times 10^{-35}$
7.42	$(6.4 \pm 1.3) \times 10^{-36}$	$(3.0 \pm 0.9) \times 10^{-36}$
8.43	$(1.7 \pm 0.9) \times 10^{-36}$	$(2.6 \pm 2.6) \times 10^{-37}$
9.44	$(5.8 \pm 4.1) \times 10^{-37}$	

FIGURE CAPTIONS

- Fig. 1 The invariant cross section for inclusive π^+ and π^- production as a function of transverse momentum at $\sqrt{s} = 45$ GeV for $\theta \approx 50^\circ$.
- Fig. 2 The values of n from the $p_T^{-n} f(x_T, \theta)$ parametrization of the invariant cross section, plotted as a function of x_T . The π^0 results from the CCOR and the ABC groups at $\sqrt{s} = 31$ to 62 GeV are also shown [6].
- Fig. 3 The π^+/π^- production ratios vs x_T for $\sqrt{s} = 45$ and 62 GeV and $\theta \approx 50^\circ$. The CP results at $\sqrt{s} = 27$ GeV and $\theta \approx 90^\circ$ are also shown [6]. The cross hatched band displays the predictions from our QCD calculations.
- Fig. 4 Comparison of our QCD predictions with the data at $\sqrt{s} = 45$ and 62 GeV for pion production: (a) π^+ production at $\langle\theta\rangle = 49^\circ$, (b) π^- production at $\langle\theta\rangle = 53^\circ$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b