Invited talk, International Workshop on Electron Polarized Ion Collider, Bloomington, Indiana April 1999

Diffractive Dissociation of High Momentum Pions

Daniel Ashery

School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences Tel Aviv University, Israel

Abstract

The diffractive dissociation of 500 GeV/c $\pi^-$ into di-jets is described as a way to measure the momentum distribution of quarks in the pion. The measurements of the pion diffractive dissociation were carried out using data from Fermilab E791. Preliminary results show that the $|q\bar{q}\rangle$ Asymptotic wave function which was developed using perturbative QCD methods describes the data well for $Q^2 \sim 10 (\text{GeV}/c)^2$. At these values signals of color transparency are expected and, indeed, observed through the $A$-dependence of the yield of the diffractive di-jets.

1 Introduction

One of the most sensitive tests of QCD is measurement of the internal momentum distribution of quarks in hadrons. These distributions were calculated for the pion already about 20 years ago (section 2.1) through calculations of the light-cone wave functions. However, there were no direct experimental measurements. Measurements of observables which are related to these distributions, such as the pion electromagnetic form factors, turned out to be rather insensitive to the light-cone wave functions. The pion wave function is expanded in terms of Fock states:

$$\Psi = \alpha|q\bar{q}\rangle + \beta|q\bar{q}g\rangle + \gamma|q\bar{q}gg\rangle + \ldots$$

(1)

The first (valence) component will be dominant at large $Q^2$ as the other terms are suppressed by powers of $m^2/Q^2$.

2 The Pion Momentum Wave Function.

2.1 Theoretical predictions

Two functions have been proposed for the $|q\bar{q}\rangle$ configuration. The Asymptotic function was calculated [1, 2] using perturbative QCD methods and is thus expected to be correct for very large $Q^2$ ($Q^2 \rightarrow \infty$):

1Representing the E791 collaboration. Supported in part by the Israel Science Foundation and the US-Israel Binational Science Foundation.
\[ \phi_{as}(x) = \sqrt{3}x(1-x). \]  

(2)

\(x\) is the fraction of the longitudinal momentum of the pion carried by a quark in the infinite momentum frame (see Fig. 2). Using QCD sum rules Chernyak and Zhitnitsky [3] proposed a function that is expected to be correct for low \(Q^2\):

\[ \phi_{cz}(x) = 5\sqrt{3}x(1-x)(1-2x)^2. \]  

(3)

Figure 1: Two predictions of the wave functions of the pion. Asymptotic function: dashed line, and CZ function: solid line.

The wave functions are plotted in Fig. 1 and, as can be seen, there is big difference between the two. Measurements of the electromagnetic form factors of the pion were considered as the best way to study these wave functions. A comprehensive summary of the status of these measurements was recently published [4]. Measurements of the pion electric form factor suffer from two major drawbacks: measurements done by elastically scattered pions from atomic electrons measure directly the pion electric form factor but can be done only at very low \(Q^2\). The alternative method is measurements of \(p(e,e'\pi^+)n\) in the electron-pion quasi-free scattering kinematics. The relation between the form factor and the longitudinal cross section is model dependent as it includes the \(p \rightarrow n\pi^+\) matrix element. Finally, the form factor is related to the wave function through integral over the wave function and the scattering matrix element reducing the sensitivity to the wave function. Indeed, as shown in [4] the two wave functions can be made to agree with the experimental data. Similar situation exists for inelastic form factors, decay modes of heavy mesons etc. The problem is that comparisons with these observables are not sensitive to details of the wave function and thus cannot provide critical tests of the \(x\)-dependence of the functions. An open question is also what can be considered as high enough \(Q^2\) to qualify for perturbative QCD calculations and what is a low enough value to qualify for a treatment based on QCD sum rules. An experimental study that provides information about the momentum distribution of the \(|q\bar{q}\rangle\) in the pion will be described.

2.2 Pion Diffractive Dissociation and Momentum Wave Function.

The concept of an experiment that maps the pion momentum wave function is shown in Fig. 2. A high energy pion dissociates diffractively on a nuclear target
imparting no energy to the target so that it does not break up. This is a coherent process in which the quark and antiquark break apart and hadronize into two jets. If in this fragmentation process the quark momentum is transferred to the jet, measurement of the jet momentum gives the quark (and antiquark) momentum. Then:

\[ x_{\text{measured}} = \frac{p_{\text{jet}1}}{p_{\text{jet}1} + p_{\text{jet}2}} \]  

(4)

By varying \( k_t \) (Fig. 2) the measurement can map the \( x \) dependence for different \( |q\bar{q}| \) sizes.

The diffractive dissociation of high momentum pions into two jets can be described, like the inclusive Deep Inelastic Scattering (DIS) and exclusive vector meson production in DIS, by factoring the perturbative high momentum transfer process from the soft nonperturbative part [5]. This is described in Fig. 3.

This factorization allows the use of common parameters to describe the three processes. The Virtuality of the process is given by \( Q^2 \), the mass of the virtual photon, in inclusive and exclusive light vector meson DIS. In exclusive DIS production of heavy vector mesons this mass equals that of the produced meson (\( J/\psi \)). For diffractive dissociation into two jets the mass of the di-jets is playing this role. From simple kinematics and assuming that the masses of the jets are small compared with the mass of the di-jets, this can be shown to equal \( \frac{k_t^2}{x(1-x)} \). \( k_t \) is the transverse momentum of each jet.

Figure 2: Measurement of the quark momentum wave function of the pion by measuring longitudinal momentum of the two jets from diffractive dissociation.

Figure 3: Factorization of inclusive DIS, vector meson production and pion dissociation.
2.3 Fermilab E791 Experiment

Fermilab experiment E791 \cite{6} recorded $2 \times 10^{10}$ events from interactions of a 500 GeV/c $\pi^-$ beam with Carbon (C) and Platinum (Pt) targets. The trigger included a loose requirement on transverse energy deposited in the calorimeters. Precision vertex and tracking information was provided by 23 silicon microstrip detectors (6 upstream and 17 downstream of the targets), ten proportional wire-chamber planes, and 35 drift-chamber planes. Momentum was measured using two dipole magnets. Two multicell, threshold Čerenkov counters were used for $\pi$, $K$, and $p$ identification. Only 1/3 of the E791 data was used for the analysis presented here.

The data was analysed by selecting events in which 90% of the beam momentum was carried by charged particles. This reduced the effects of the unobserved neutral particles. The selected events were subjected to the JADE jet-finding algorithm \cite{7}. The algorithm uses a cut-off parameter ($m_{cut}$) that describes the mass of individual jets. Its value was determined from Monte Carlo simulations to optimize di-jet detection. The di-jet invariant mass was calculated assuming that all the particles were pions. Only two-jet events were selected for further analysis. To insure clean selection of events, a minimum $k_t$ of 1.5 GeV/c was required.

Diffractive di-jets were identified through the $e^{-b q_t^2}$ dependence of their yield ($q_t^2$ is the square of the transverse momentum transferred to the nucleus and $b$ is proportional to the r.m.s. radius squared of the nuclear target). Figure 4 shows the $q_t^2$ distributions of di-jet events from platinum (top) and carbon (bottom). The different slopes at low $q_t^2$ in the coherent region reflect the different nuclear radii. Events in this region come from diffractive dissociation of the pion with the nucleus retaining its characteristic shape and remaining intact.

2.4 Results

The basic assumption that the momentum carried by the dissociating $q\bar{q}$ is transferred to the di-jets, was examined by Monte Carlo (MC) simulation. Two samples
of MC with 6 GeV/c$^2$ mass di-jets were generated with different $x$ dependences at the quark level. One sample simulated the Asymptotic wave function and the other the Chernyak Zhitnitski function. The two samples were allowed to hadronize through the LUND PYTHIA-JETSET \cite{8} simulation and then passed through simulation of the experimental apparatus.

In Fig. 5 the initial distributions at the quark level are compared with the final distributions of the detected di-jets, including distortions in the hadronization process and influence due to experimental acceptance. As can be seen the qualitative features of the two distributions are retained.

For events in the coherent region described in the previous section the value of $x$ was computed from the measured longitudinal momentum of each jet (eq. \ref{eq:4}). The resulting $x$ distribution is shown in Fig. 6. Superimposed on the data is a fit to a combination of the two simulated final di-jet distributions of Fig. 5.

**Figure 5:** Monte Carlo simulations of the two wave functions at the quark level (left) and of the reconstructed distributions of di-jets as detected (right).

**Figure 6:** The preliminary $x$ distribution of the diffractive di-jets from the platinum target. The line is a fit to a wave function with about 90% asymptotic and 10% CZ. The CZ contribution is shown with a dashed line.
The preliminary result under the analysis conditions as described is that the data can be fitted well with ≥ 90% of the Asymptotic wave function and ≤ 10% of the CZ wave function. The requirement that \( k_t > 1.5 \text{ GeV/c} \) can be translated to \( Q^2 \sim 10 \text{ (GeV/c)^2} \) (section 2.2). This shows that for these \( Q^2 \) values the perturbative QCD approach that led to construction of the asymptotic wave function is reasonable.

3 Pion Diffractive Dissociation and Color Transparency

3.1 Theoretical Predictions

Diffractive dissociation of pions to di-jets with \( k_t > 1.5 \text{ GeV/c} \) \( (Q^2 \sim 10 \text{ (GeV/c)^2}) \) can be associated with a \(|q\bar{q}\rangle\) system with size \( <r>_{|q\bar{q}\rangle} \sim 1/Q \leq 0.1 \text{ fm} \). Such a small size configuration is expected to exhibit the effect of color transparency, namely a reduced interaction with the nuclear medium. The condition for observation of the effect is that the system does not expand while traversing the nucleus. The distance that the system passes before it decays and expands (the “Coherence Length”) is estimated by \( l_c \sim \frac{2p_{lab}}{M^2-m^2_{\pi}} \) where \( M \) is the di-jet mass. It is required that \( l_c > R_A \). In E791 \( 2p_{lab} = 1000 \text{ GeV/c} \). Using \( M \sim 6 \text{ GeV/c}^2 \) the result is \( l_c \sim 20 \text{ fm} \) which is larger than all nuclear radii.

Bertch et al. [9] proposed that when high momentum pions hit a nuclear target the small \(|q\bar{q}\rangle\) component will be filtered by the nucleus and materialize as diffractive di-jets. Frankfurt et al. [10] proposed that diffractive dissociation of pions to high \( k_t \) di-jets selects the small size \(|q\bar{q}\rangle\) Fock state with the size controlled by \( k_t \). They calculate the cross section for this diffractive dissociation of pions on nuclear targets with the striking result that for \( t = 0 \) and \( k_t > 1.5 \text{ GeV/c} \)

\[
\frac{d^4\sigma_A}{dx dM^2 q_t} = \frac{d^4\sigma_N}{dx dM^2 q_t} A^2 \quad (t = 0) \tag{5}
\]

Namely that the differential cross section at \( t = 0 \) is proportional to \( A^2 \) which is a very unusual dependence. The \( t \)-dependence for \( t \neq 0 \) is given by the nuclear form factor: \( |F_A(t)|^2 \sim e^{bt}, \quad b = \frac{<R^2>}{a} \).

3.2 Expected Diffractive Di-Jet A-dependence

Realistically, it is impossible to measure the cross section at \( t = 0 \) for two reasons: there is always a minimal \( t \) transferred to the target as a result of excitation of the pion to a heavy mass, and the statistical and systematic uncertainties near \( t \)
= 0 make it difficult to obtain precise results.

The minimal $t$ transfer can be estimated from simple kinematics. The result for a pion being excited from $m_\pi$ to the di-jet mass $M_{jets}$ is a longitudinal momentum transfer of:

$$ q_z = \frac{M_{jets}^2 - m_\pi^2 - 2E_1 \frac{t}{2MA} - t}{2p_1} \quad (6) $$

with $E_1$ the bombarding energy. The energy transferred to the nucleus is:

$$ q_0 = -\frac{t}{2MA}. \quad (7) $$

For a numerical estimate we use:

$$ -t < 1/b = \frac{3}{r^2 \text{ fm}^2} \quad \text{Carbon} \approx 2.0 \times 10^{-2} \ (\text{GeV/c})^2 \quad (8) $$

$$ \text{Platinum} \approx 4.3 \times 10^{-3} \ (\text{GeV/c})^2 $$

$t \times E_1/MA \approx 0.83 \ (\text{GeV/c})^2$ (carbon) and $0.011 \ (\text{GeV/c})^2$ (platinum), $m_\pi^2 = 0.02$

We can therefore neglect all the terms except for $M_{jets}^2$ and write

$$ q_z \approx \frac{M_{jets}^2}{2p_1} \quad (9) $$

The minimal longitudinal momentum-square transferred to the nucleus as a consequence of exciting the pion to $M_{jets}$ is $q_z^2 = -t_{min}$. With $M_{jets} \sim 6 \text{ GeV/c}^2$ we get:

$$ -t_{min} = q_z^2 \approx (\frac{M_{jets}^2}{2p_\pi})^2 \approx (\frac{36}{1000})^2 = 0.0013 \ (\text{GeV/c})^2. \quad (10) $$

While this value is small, it is not negligible compared with the $t$ values for Pt. In order to avoid this problem and to increase the precision of the measurement we integrate the data in the diffractive region. This modifies the expected $A$ dependence. We first write:

$$ \frac{d\sigma}{dt} = \sigma_N A^2 e^{bt} = \sigma_N A^2 e^{-b(q_0^2 + q_z^2 + q_t^2)} \quad (11) $$

with $q_t^2$ the transferred transverse-momentum squared. From the numerical estimates we see that $q_0^2$ can be neglected so that $t = t_{min} - q_t^2$ and $d\sigma/dt \rightarrow d\sigma/dq_t^2$.

Integration of the diffractive region (using $R = R_0 A^{1/3}$) yields:

$$ \int (d\sigma/dq_t^2) dq_t^2 = \sigma_N A^2 e^{bt_{min}} e^{-bq_t^2} \times (1/b) = \sigma_N A^2 e^{bt_{min}} e^{-bq_t^2} \times \frac{3}{R_0^2 A^{2/3}} \quad (12) $$
and the expected general $A$ dependence is: $\frac{d^2\sigma}{dxdM_T} \propto A^{4/3}$.

In the particular case of E791, using the numerical values of the nuclear radii of C and Pt:

$$\left(\frac{R_{Pt}}{R_C}\right)^2 = \left(\frac{5.27}{2.44}\right)^2 = 4.665 = \left(\frac{195}{12}\right)^x; \quad x = 0.55. \tag{13}$$

so that we will expect $\frac{d^2\sigma}{dxdM_T} \propto A^{1.45}$.

### 3.3 Analysis and Results

To obtain the $A$ dependence of the diffractive yield from the experimental results of Fig. 4 we must realize that these results are a combination of three elements: coherent nuclear diffraction, incoherent nuclear diffraction (interaction with individual nucleons) and smearing of both components by the experimental apparatus. In order to extract the coherent nuclear diffractive yield we simulate the coherent and incoherent $q_t^2$ distributions of the dissociation by assigning them the nuclear and the nucleon form factors, respectively. The simulated distributions are passed through the simulated experimental system so that the individual reconstructed distributions are obtained. At this stage a combination of the reconstructed distributions of the Pt nucleus and that of the nucleon is fitted to the data from the Pt target giving the ratio of coherent/incoherent yields and an overall normalization factor between the data and the simulation. The same is done for the C target. Results of these fits are shown in Fig. 7.

The final results are obtained by integrating over the diffractive regions (of Pt and C) in the generated MC multiplied by the total normalization factor between MC and data. The analysis was done separately in two $k_t$ ranges since, as predicted by [10] there can be some dependence of $\alpha$ in $\sigma \propto A^\alpha$ on $k_t$. The PRELIMINARY result, compared with those expected according to [10], labelled $\alpha$(CT) are:

| $k_t$ range | $\alpha$         | $\alpha$(CT) |
|-------------|------------------|--------------|
| $1.5 < k_t < 2.0$ | $1.61 \pm 0.08$ | $1.45$       |
| $2.0 < k_t$        | $1.65 \pm 0.09$ | $1.60$       |
which are close to the Color Transparency expectations.

Figure 7: $q_t^2$ distributions of di-jets for C and Pt targets. The lines are fits of the MC simulations to the data.

4 Summary

The following observations have been made:

- Diffractive dissociation of hadrons into di-jets can be used to study the hadron’s internal quark structure.

- The momentum wave function of the $|q\bar{q}\rangle$ in the pion is described well at $Q^2 \sim 10 \text{ (GeV/c)}^2$ ($k_t > 1.5 \text{ GeV/c}$) by the Asymptotic wave function.

- Using data from Pt and C targets and assuming $\sigma \propto A^\alpha$ the cross section for diffractive dissociation of pions to di-jets is found to be proportional to $\sim A^{1.61\pm0.08}$ for $1.5 < k_t < 2.0 \text{ GeV/c}$ and $\sim A^{1.65\pm0.09}$ for $2.0 \text{ GeV/c} < k_t$. These results are consistent with predictions based on the color transparency effect.

References

[1] S.J. Brodsky, G.P. Lepage, Phys. Rev. D22, 2157 (1980); S.J. Brodsky, G.P. LePage, Phys. Scripta 23, 945 (1981); S.J. Brodsky, Springer Tracts in Modern Physics 100, 81 (1982).
[2] A.V. Efremov, A.V. Radyushkin, Theor. Math. Phys. 42, 97 (1980).

[3] V.L. Chernyak and A.R. Zhitnitski, Phys. Rep. 112, 173 (1984).

[4] G. Sterman and P. Stoler, Ann. Rev. Nuc. Part. Sci. 43, 193 (1997).

[5] J.C. Collins, L.L. Frankfurt, and M. Strikman, Phys. Rev. D56, 2982 (1997).

[6] E. M. Aitala et al., Phys. Rev. Lett. 76, 364 (1996); E. M. Aitala et al., submitted to Eur. Phys. Journal, hep-ex/9809023 (September 1998).

[7] CDF collaboration, FERMILAB-Conf-90/248-E [E-741/CDF]; JADE collaboration, W. Bartel et al., Z. Phys. C33, 23 (1986)

[8] H.-U. Bengtsson and T. Sjöstrand Comp. Phys. Comm. 82, 74 (1994); T. Sjöstrand, PYTHIA 5.7 and JETSET 7.4 Physics and Manual, CERN-TH.7112/93, 1995.

[9] G. Bertsch, S.J. Brodsky, A.S. Goldhaber, J. Gunion, Phys. Rev. Lett. 47, 297 (1981)

[10] L.L. Frankfurt, G.A. Miller and M. Strikman, Phys. Lett. B304, 1 (1993)