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Search for Higher Twists in meson resonance production in hadron interactions at $p_T \geq 2$ GeV/c

The WA77 Collaboration

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Abstract : We study the production of meson resonance at $p_T \geq 2$ GeV/c in π^- Be interactions at two beam energies (150 and 300 GeV/c). The motivation is to look for the higher twist (HT) production mechanism, expected to exist besides standard hadron production through the fragmentation process of scattered quarks and gluons, the so-called leading twist (LT) mechanism. We show that the ϕ , $\overline{K}^{*0}(892)$ and $K^{*0}(892)$ are found free from HT effects with a good accuracy, as expected from HT estimates and QCD sum rules. The magnitudes of the $f_2(1270)$ and ρ^0 mesons signals are found larger than expected from the standard Lund (LT) Monte Carlo and from informations provided by e^+e^- annihilation experiments. The possible connection of these excesses with HT physics is discussed. We also report the first evidence for the production of $f_0(975)$ mesons in hadronic experiments at large p_T .

1 Introduction

Since the discovery of jets at the ISR, all experiments studying high- p_T phenomena have given the feeling that QCD provides a suitable framework to understand particle physics at the parton level[1]. This theory has now been implemented in several physics simulation programs[2] together with a parton fragmentation scheme which describes (phenomenologically) the transition from quarks and gluons to hadrons. As it is highly dominated by non-perturbative effects, this last process is difficult to account for otherwise. The Lund string fragmentation model[3] (to which we shall refer in the following) provides a suitable parametrization of this non-perturbative transition and has been widely used to describe the production of hadrons in high energy e^+e^- annihilation or in hadron interactions at large p_T . The latest results in this field have been obtained in e^+e^- annihilation at the Υ energies by ARGUS[4, 5] and at the Z^0 mass by LEP collaborations[6, 7, 8, 9]. From these studies, it follows that the description of inclusive meson production is suitably reproduced by the Lund Monte Carlo, provided one proceeds to a tuning of some of its parameters : the strange to non-strange quark ratio s/u , the ratio of production rates of vector mesons to vector + pseudoscalar mesons $V/(V + PS)$, or the pseudoscalar mixing angle θ_{PS} .

The e^+e^- sector tests that leading order – α_s – predictions of the Standard Model convoluted with a parton fragmentation scheme are in agreement with experimental data. Correspondingly, in pure hadronic interactions, leading order – α_s^2 – predictions of QCD, as well as the next-to-leading order contributions – α_s^3 – illustrate the feature that the perturbative sector of high- p_T physics is suitably described by scaling expressions of the form :

$$p_T^4 \frac{d\sigma}{dp_T^2} = f\left(\frac{p_T}{\sqrt{s}}\right) \quad , \quad (1)$$

where s is the center-of-mass energy squared of the parton initial state. These contributions are generally referred to as leading twist (LT) contributions. Actually, because of initial and final state interactions and because of primordial transverse momentum effects, the observed dependence is p_T^{-8} rather than p_T^{-4} as it follows from QCD for production of mesons at large p_T ($\simeq 2$ to 10 GeV/c) ; it happens however that the Lund Monte Carlo accounts suitably for this effect as it has been illustrated in our ref.[10] for five vector meson resonances. Production of stable particles (π , K , η , p , $\bar{p}$) at high- p_T exhibits the same behaviour[11, 12, 13]. The relevance of the Lund Monte Carlo predictions has also been illustrated in details by our experiment[14] in the study of the inclusive yields of stable particles ($\pi^\pm$, $K^\pm$, p , $\bar{p}$) at $p_T \geq 1$ GeV/c, in the yields of oppositely charged particle pairs and in the flavor correlation within these pairs. In summary, several experiments have shown that the Lund Monte Carlo provides physical predictions in agreement with the measurements whenever LT predictions of QCD exist. It is therefore meaningful to look for departures from the Lund Monte Carlo predictions.

This remark is of relevance since QCD also predicts the existence of higher order corrections[15, 16, 17] which modify expression (1) to :

$$p_T^4 \frac{d\sigma}{dp_T^2} = f_0\left(\frac{p_T}{\sqrt{s}}\right) + \frac{R^2}{p_T^2} f_1\left(\frac{p_T}{\sqrt{s}}\right) \quad , \quad (2)$$

up to primordial transverse momentum effects which can be accounted for as when dealing with LT processes. These further terms, generally referred to as higher twists (HT), imply a scale breaking and therefore the occurrence of a parameter R which must have the dimension of a mass, in order to compensate the p_T^{-2} term in the additional contribution. In the case

of meson production this parameter is a meson decay constant. It comes together with the meson wave function which occurs when performing the convolution of the hard process with the recombination of a parton pair into a given meson through its wave function.

Higher twist (HT) contributions appear in several topics of particle physics (see ref.[18] for a review). However, the higher twist processes describing the prompt production of mesons :

$$parton + parton \rightarrow meson + parton$$

have a specific property with respect to most other HT processes : the non-perturbative structure involved in the hard process factors out into a numerical coefficient, while all kinematical (s, t, u) dependences of the cross sections are entirely determined by perturbative QCD calculations[16, 17]. Moreover, for all light flavor vector and pseudoscalar mesons (except for η and η'), this numerical factor can be estimated using existing results[19] obtained by means of QCD sum rule technics. With this respect, it should be noticed[18, 20] that most analyses of experimental data report effects which are 2 to 4 times larger than expectations from QCD, *i.e.* well above the theoretical uncertainties[19, 21]. This remark includes our preliminary publication[22] on prompt production of the ρ^0 meson at $p_T \geq 2$ GeV/c. This could indicate either strong violations of QCD numerical predictions for HT processes or that K-factor effects are larger in HT processes as compared to LT processes. This could also indicate that some sources of meson excesses (with respect to LT expectations) have not been fully accounted for. Therefore a detailed experimental study of the prompt production mechanism is needed in order to ascertain the existence of this enhancement with respect to HT expectations.

The motivation of the WA77 experiment was to search for the prompt production of meson resonances at large transverse momenta. Such a process is predicted to proceed via the higher twist (HT) QCD mechanism sketched in fig.(1a) in contrast to the bulk of high- p_T processes which are expected to proceed via leading twist (LT) parton hard scattering and fragmentation as sketched in fig.(1b).

The experimental method adopted stems from the observation that promptly produced mesons pick up the full momentum transfer carried by the exchange, while particles produced during the parton fragmentation pick up only a part of it, the rest being shared amongst the other fragmentation products.

The WA77 experiment has measured the yields of six meson resonances (ρ^0 , $f_2(1270)$, $f_0(975)$, $K^{*0}(892)$, $\overline{K}^{*0}(892)$, ϕ) produced at $p_T \geq 2$ GeV/c in π^- Be interactions at two beam energies (150 and 300 GeV/c). This allows to study the prompt production (HT) mechanism in the p_T region where it can significantly contribute (2 to 10 GeV/c). In the present study we compare resonance signals possibly affected by HT effects with resonance signals expected free from such effects. Having two beam energies is important for this purpose because ratios of some resonance yields ($\phi/\overline{K}^{*0}(892)$) are expected to be independent of the beam energy while the others (involving the $K^{*0}(892)$, $f_2(1270)$, ρ^0 mesons) are not ; this property affects mesons which do not share valence quarks with the incoming hadrons (nucleons, π^-). In our previous publication[22] we compared the magnitude of the ρ^0 signal to the magnitude of the background beneath. However, running our Lund Monte Carlo under various conditions has shown that the background structure is highly sensitive to the value of the parameter named[2] $V/(V + PS)$. This is the reason why we shall attempt, beside this method, another method not sensitive to the background yield and composition.

The outline of the paper is as follows. In section **2** we recall the main features of the prompt

production mechanism of mesons at large p_T ; we show how its magnitude for specific mesons is connected with results obtained using QCD sum rule methods. We also present the features of the Lund Monte Carlo that we have used to define the reference for leading twist (LT) physics. In section **3** we briefly recall the specific features of the WA77 experiment. The method used to perform the fits and get the resonance yields is the subject of section **4**. We discuss also here the $f_0(975)$ signal observed for the first time in hadronic interaction at large momentum transfer. Acceptance estimates and systematic errors are dealt with in section **5**. In section **6** we study the signals expected to be free from HT contributions (ϕ , $\bar{K}^{*0}(892)$, $K^{*0}(892)$) and then define physical references of the standard leading twist production mechanism (LT) ; these are the ϕ and $\bar{K}^{*0}(892)$ mesons. The search for HT signals in the production of $f_2(1270)$ and ρ^0 mesons is described in section **7**. Finally, we summarize our conclusions in section **8**.

2 Higher Twists and Leading Twists in Meson Production

An important property of HT contributions to meson production already noted is the factorization of the cross sections into their perturbative and non-perturbative parts at leading order¹. In this case, the meson wave function which describes the direct recombination of a parton pair into a meson factors out into a global scale factor. This property underlies the present study.

Denoting by x_1 and x_2 the fractions of the meson momentum carried by each quark ($x_1 + x_2 = 1$), and defining $\xi = x_1 - x_2$, the normalized wave function can be written $a_0\varphi(\xi)$, where² $a_0 = \sqrt{3}f_{PS}/3$ (for pseudoscalar mesons) or $a_0 = \sqrt{6}f_V/3$ (for vector mesons) and :

$$\int_{-1}^{+1} \varphi(\xi) d\xi = 1 \quad .$$

Then the scale factor R in rel. (2) can be written :

$$R = a_0 \int_{-1}^{+1} d\xi \frac{\varphi(\xi)}{1 + \xi} \quad . \quad (3)$$

The above expression can be rewritten in a more useful way :

$$R = a_0 \sum_{n=0}^{\infty} (-1)^n \langle \xi^n \rangle \quad , \quad (4)$$

where $\langle \xi^n \rangle$ denotes the n^{th} moment of the wave function :

$$\langle \xi^n \rangle = \int_{-1}^{+1} d\xi \xi^n \varphi(\xi) \quad , \quad (5)$$

which are computable using QCD sum rule methods[19] with an accuracy of the order of 20%. Therefore, using the results of QCD sum rules, we can evaluate with some accuracy the value of

¹In order to illustrate this peculiarity, let us notice for instance that the cross sections formulae intimately mix meson wave functions and (perturbative) hard process amplitudes in all annihilation processes of two photons into two mesons[23, 24].

²Some authors[19] prefer including the square root coefficient in the definition of the decay constant. Our choice corresponds to using $f_\pi = 93$ MeV and $f_\rho = 107$ MeV.

R associated with each meson for which estimates of the wave-function moments are available and thus compute the absolute magnitude of the corresponding HT cross section.

For the purpose of our prompt production studies, the cases which remain unconstrained by QCD are the η' , the $f_2(1270)$ and the $a_2^\pm(1320)$ mesons. This is unfortunate because of our large $f_2(1270)$ signal[25] on the one hand and, on the other hand, because a large η' HT signal[16, 26] can be expected in π^-N interactions, which could manifest itself through an important feed down in the ρ^0 meson yield. Promptly produced $a_2^\pm(1320)$ mesons also contribute to the observed ρ^0 meson yield through their decays into $\rho^0\pi^\pm$. However, the available information concerning meson wave functions[19] and cross-section calculations[16] allow already to expect that there is no measurable HT contribution to high- p_T production of ϕ , K^{*0} and $\overline{K}^{*0}$ mesons³ following from theoretical predictions[16]. This is subject to experimental tests (see section 6).

In order to perform a search for higher twist effects using the meson yields obtained at large p_T , a simulation program of high- p_T production of mesons through HT processes is needed. We have used a Lund-like Monte Carlo program[27] which includes in the PYTHIA program[2] all prompt production cross-sections for S - and P -wave light flavor mesons. All S -wave meson prompt productions have been activated ; among the P -wave meson production processes only tensor mesons have been activated because of the lack of information concerning decay constants and wave functions for 0^{++} and 1^{++} mesons.

The standard PYTHIA program[2] has been used in order to get the yields predicted from the usual LT processes. All Lund Monte Carlo parameters have been set to their default values except for s/u and the relative abundances of vector and tensor mesons. We have assumed the $V/(V + PS)$ parameter to be the same for strange and non-strange mesons⁴. For consistency, we have preferred tuning the s/u and $V/(V + PS)$ parameters using hadronic experiments which have a high- p_T trigger. Indeed, the WA77 trigger is designed to be sensitive to leading fragments. These two parameters have thus been tuned in order to reproduce the measurement of ϕ/π^- in proton nucleus interactions at 400 GeV/c of ref.[28]. Using $s/u = 0.32$ (default value 0.33) and $V/(V + PS) = 0.30$ (default value 0.50), we obtain for this ratio 0.44 ± 0.01 while the corresponding measurement is 0.42 ± 0.04 . These values also permit an estimate of the ratio $2\phi/(\rho^0 + \omega)$ in the experimental conditions of ref.[29] ; our Monte Carlo gives 0.084 ± 0.010 while the experimental measurement is 0.077 ± 0.046 . Our parameter values compare well with the recent estimates of ref.[5] obtained in e^+e^- annihilation.

Concerning the ratio T/V which governs the relative amount of tensor to vector mesons, and thus the LT value of f_2/ρ^0 , we have used 0.21. This value is in agreement with the recent result reported by the DELPHI collaboration[8] (0.22 ± 0.08) and former results in e^+e^- annihilations (see references in [8] and in [14]). Hadronic experiments tend to indicate larger values but consistent with our choice at the 1σ level[30, 31, 32, 33].

In the present study, our purpose is to look for HT contributions by comparing the observed meson yields with the ones expected from LT estimates. Therefore, we need a reliable calibration of the LT Lund Monte Carlo simulation. In this case, it is expected that all parameters

³One has actually to compare in table (13) from ref.[16] the meson production through fragmentation with the HT production cross-sections suitably weighted, *i.e.* by $0.10 \div 0.14$ for K^{*0} and $\overline{K}^{*0}$, by $0.14 \div 0.25$ for ϕ and $0.16 \div 0.24$ for (prompt) ρ^0 . The HT weights just quoted correspond to the QCD sum rule predictions[19] for c_1^2 , depending on the particular prompt meson and its helicity state.

⁴A recent analysis[5] indicates that this parameter is larger for strange mesons (0.335 ± 0.034) than for non-strange mesons (0.208 ± 0.041). We shall comment on this important property later on.

describing the parton hadronization have values in agreement with the corresponding values found in e^+e^- annihilation. In this respect, the most exhaustive study has been produced by ARGUS[5] for pseudoscalar and vector mesons. Referring to this collaboration, we can already remark that our Lund LT estimate for ρ^0 production could be overestimated by as large as 30%. This is of relevance when discussing a possible anomalous yield of ρ^0 connected with HT.

3 The WA77 Experiment and the Data Samples

The WA77 experiment has been performed at the CERN SPS using the OMEGA spectrometer and has collected data in π^- Be interactions at two beam energies (150 and 300 GeV/c). Details on the apparatus and the trigger have been given in several previous publications[14, 22, 34, 35]; we shall restrict ourselves to remind the main features.

The trigger system was designed in order to select events having three tracks at $p_T \geq 0.9$ GeV/c and CMS rapidities $-1 \leq Y_{cms} \leq +1$ coming from the interaction point. Accepted events consisted of a pair of oppositely charged particles produced opposite in azimuth to a third trigger track. The pair side of this trigger is suitable to study the production at large p_T of resonances decaying to two bodies (ρ^0 , $f_2(1270)$, ϕ , $K^{*0}(892)$, $\bar{K}^{*0}(892)$, $f_0(975)$). A further selection was done off-line by requiring the pair and the opposite particle transverse momenta to have an azimuthal angle greater than 90° . Other constraints were :

$$\begin{cases} p_T^{trig. part.} \geq 1 \text{ GeV/c} \\ p_T^{pair} \geq 2 \text{ GeV/c} \\ 3.23 - 0.5 \leq Y_{lab}^{pair} \leq 3.23 + 0.5 \end{cases} \quad (6)$$

The same setup has been used at both 300 and 150 GeV/c beam energies. Therefore the accepted laboratory rapidity window was both times centered at 3.23 which is the CMS π^-N rapidity at 300 GeV/c. After all selection criteria, it remains 219,099 events at 300 GeV/c and 256,475 events at 150 GeV/c.

4 Analysis of the Mass Spectra

The spectra to be fitted are the pair invariant mass spectra obtained by assuming the mass assignments $\pi^+\pi^-$, K^+K^- , $K^+\pi^-$ and π^+K^- . Previous studies of these spectra[10, 25] have shown structures corresponding to the ρ^0 , $f_2(1270)$, $S^*/f_0(975)$, ϕ , $K^{*0}(892)$ and $\bar{K}^{*0}(892)$ mesons.

Spectra obtained with the $\pi^+\pi^-$ mass assignment have been fitted separately using the same method and the physical input described in ref.[25]. This allows us to get the ρ^0 , $f_2(1270)$ and $f_0(975)$ resonance yields; the ϕ and $K^{*0} + \bar{K}^{*0}$ yields are obtained through their reflections in the $\pi^+\pi^-$ spectrum.

In order to look for the HT signal, it is however important to measure accurately the ϕ , and also the $K^{*0}(892)$ and $\bar{K}^{*0}(892)$ meson yields separately. For this purpose, we have performed a simultaneous fit of the K^+K^- , $K^+\pi^-$ and $K^-\pi^+$ spectra using the method and input described in ref.[10]. From here we have obtained the yields of K^{*0} , $\bar{K}^{*0}$ and ϕ mesons and the yields of ρ^0 and $f_2(1270)$ mesons through their reflections.

We have found that the yields of ϕ , ρ^0 and $f_2(1270)$ mesons obtained from these two independent sets of fits were consistent within 1 standard deviation⁵.

This procedure has been repeated for each beam energy. All numerical information concerning these fits are given in tables (1) and (2) (resp. χ^2/ndf and meson yields at both beam energies). The $\pi^+\pi^-$ spectra and fitting functions at both beam energies can be found in ref.[25] (see figures (2) and (4) there and notice especially the $f_0(975)$ signal which appears as a shoulder on the upper mass side of the ρ^0 distribution). The three other spectra and fits for the 300 GeV/c sample can be found in figure (1) from ref.[10].

The measured yield of $f_0(975)$ mesons is given in table (2) ; it represents a 2σ (300 GeV/c) or 3σ (150 GeV/c) effect. Its abundance relative to the ρ^0 yield is in agreement with the results obtained recently by ARGUS[4, 5] and DELPHI[8] in e^+e^- annihilation. To extract this signal, we have studied the effects of several parametrizations proposed by various collaborations (see in ref.[36] for references). The parametrization which allows the most appropriate description of our signal is that given by MARK II[37]. It is the first reported observation of the $f_0(975)$ meson in hadronic interactions at large p_T .

5 Acceptance Effects and Systematic Errors

In order to correct our yields for acceptance, we have done a simulation of our setup at 300 and 150 GeV/c. For acceptance estimates of the various observed meson resonances, we have assumed that the rapidity distribution is flat and extends by ± 0.5 unit beyond the central value ($Y_{pair}^{lab} = 3.23$). The p_T distribution has been assumed to be p_T^{-8} for all mesons except for the ϕ (p_T^{-10}) up to $p_T \simeq 5$ GeV. These p_T dependences have been determined by a direct study of meson resonance spectra in our experiment[10]. Uncertainties in the rapidity distribution of resonances have been studied in our refs. [10, 14, 25] and have been found to be negligible. The resonance mass distributions used for generating resonances are relativistic Breit–Wigner shapes.

We have neglected the MWPC inefficiencies as their effects are expected to cancel out in ratios of yields.

In order to study the effects of feed down we have computed acceptances for primary produced resonances and for the same resonances produced from higher resonance decays. This is mainly of concern for the ρ^0 meson which gets feed down contributions from η' decay to $\rho^0\gamma$ and, to a lesser extent, from $a_2^\pm(1320)$ decays to $\rho^0\pi^\pm$.

There are two possible sources of systematic errors in our yields. The first one is the above mentioned feed down effect due to $a_2^\pm(1320)$ decays ; it can be estimated by comparing with parent meson production. Indeed, one can assume that the relative yields for $a_2^+(1320) + a_2^-(1320)$, $a_2^0(1320)$ and $f_2(1270)$ on the one hand, and $\rho^+ + \rho^-$, ρ^0 and ω on the other hand are the same as predicted par the Lund Model⁶. Taking moreover into account the differential effects of geometrical acceptance, we find that the feed down correction in the ρ^0 yields due to $a_2^\pm$ decays is negligible ($\simeq 2\%$).

⁵The $f_0(975)$ signal is too small to be detected from its reflections and has not been introduced when fitting the K^+K^- , $K^+\pi^-$ and $K^-\pi^+$ spectra.

⁶Departures due to the mixing angles ($\simeq 35^\circ$ for vector mesons, $\simeq 26^\circ$ for tensor mesons) do not shadow significantly this symmetry.

The other source of systematic errors is the contamination of our π^- beam by K^- particles. This effect can be detected by studying the ϕ and $\overline{K}^{*0}(892)$ yields. These get negligible contributions from HT[16] ; since moreover they have no valence quarks in common with π^- , p and n , they are expected to be mainly produced during the string[3] fragmentation. However, if there is a significant amount of K^- in the beam, s -quarks become available at the valence level and make easier the production of these two mesons. In this case however, we expect a larger increase of the $\overline{K}^{*0}(892)$ yield than of the ϕ yield⁷. Therefore, any significant departure of the ratio of these two yields from Lund LT expectations could be considered as the signal of a kaon contamination in the beam. It will be shown in the next section that this source of systematic errors is also negligible.

Finally, most conclusions on LT and HT physics rely on a comparison with a reference. We have chosen the Lund (LT) model adapted to hadronic interactions under the form of the PYTHIA simulation[2]. Here we have used most parameters at their default values. Moreover all PYTHIA assumptions relative to the specific case of hadron-hadron interactions have been set to the default options (primordial k_T , hadron structure functions,...). This source of systematic errors has been limited at most by tuning the most important parameters (see section 2).

6 Tests of LT Physics : the ϕ , K^{*0} and $\overline{K}^{*0}$ Signals

As mentioned in section 2, the predicted values of R (see rels. (2), (4) and the moment values in ref.[19]) for the ϕ , $K^{*0}(892)$ and $\overline{K}^{*0}(892)$ mesons are such that the ratios⁸ :

$$S(M) = \frac{\sigma_{HT}(M)}{\sigma_{LT}(M)} \quad M = \phi, K^{*0}(892), \overline{K}^{*0}(892) \quad (7)$$

never exceed 1 to 3 % and are thus well below the sensitivity of our experiment which is typically 10 to 20% (see table (2)). Therefore our yields for these mesons can be safely considered as solely due to LT physics with a negligible HT contribution. A comparison of our results with Lund LT predictions is therefore meaningful. For this purpose, we give in table (3) the LT production cross sections of the three considered mesons together with their acceptance values.

In table (4), we give the ratios $\overline{K}^{*0}/K^{*0}$ and $\overline{K}^{*0}/\phi$ corrected for acceptance in our data samples and in the corresponding Lund LT samples. From here it appears that the measured ratio $\overline{K}^{*0}/\phi$ is in good agreement with the Lund LT prediction. Moreover, as this ratio is expected to be independent of the beam energy⁹, it is interesting to perform the average of the predictions and measurements at 150 and 300 GeV/c ; we thus obtain :

$$\left[\frac{\overline{K}^{*0}}{\phi} \right]_{LT} = 2.41 \pm 0.09 \quad , \quad \left[\frac{\overline{K}^{*0}}{\phi} \right]_{exp} = 2.29^{+0.26}_{-0.29} \quad . \quad (8)$$

This result is interesting since it does not exhibit any enhancement of $\overline{K}^{*0}$ with respect to ϕ , as it should be expected if our π^- beam were significantly contaminated by K^- particles.

⁷The expected increase of $\overline{K}^{*0}(892)$ meson yield can be expected about 3 times larger than the increase of the ϕ yield. Indeed, referring to the Lund Model the relative increase of these two yields is practically given by the inverse of the s/u parameter value.

⁸These ratios are nothing but the ratios of the second term to the first term in rel. (2) for the cross section of the corresponding meson.

⁹It essentially depends on Lund parameters describing the string fragmentation.

Secondly, in our Lund LT simulation, the ϕ signal has been calibrated using the accurate ϕ/π^- ratio given by ref.[28] ; then the agreement shown by rels. (8), means that our $\overline{K}^{*0}$ signal is correctly fitted using the procedure recalled in section 4.

The ratio $\overline{K}^{*0}/K^{*0}$ is given in table (4). It shows at both energies too large values than expectations ($\simeq 2\sigma$ in each case). As the ratio $\overline{K}^{*0}/\phi$ is correctly reproduced, this indicates that K^{*0} mesons are slightly less produced than expected from Lund LT estimates while $\overline{K}^{*0}$ mesons are produced at the expected level. Therefore, we can consider as satisfactory the agreement observed in our experiment between the measurements and the Lund LT Monte Carlo predictions for the $\overline{K}^{*0}$, K^{*0} and ϕ signals at the two beam energies.

We conclude that the Lund LT Monte Carlo successfully describes the relative yields for $\overline{K}^{*0}$, K^{*0} and ϕ mesons, where HT contributions were expected to be small[16].

7 Search for the HT Signal

In this section, we study the possible onset of the HT mechanism in the observed mesons yields using two different approaches. The first one (section 7.1) is the method we used in ref.[22] but extended to the case when two beam energies are available. The second method (sections 7.2–7.4) uses more detailed predictions for HT+LT processes in order to determine the HT contribution and compare with QCD predictions.

7.1 First Approach to HT

The characteristic features of high- p_T meson prompt production versus fragmentation mentioned in the Introduction were exploited both in the trigger and in the physics analysis of our first π^-N experiment at 300 GeV/c[22]. After having selected three high- p_T particles, *i.e.* a pair of oppositely charged particles produced opposite in azimuth to a third one, the quantity :

$$x_E = \frac{p_T^{opposite}}{p_T^{pair}} \quad (9)$$

was computed for each event. This quantity is expected to be smaller on average for the direct (HT) process than for the indirect (LT) one. The x_E dependences of the ρ^0 signal and of the non-resonant background underneath the ρ^0 were then used to estimate the contributions of the HT and LT processes. The experimental $\pi^+\pi^-$ mass spectra for two different x_E intervals were compared to the predictions of two Monte Carlo programs adapted to our conditions : the standard Lund program PYTHIA[2] based on LT parton scattering modelling the production of indirect ρ^0 mesons and of the non-resonating $\pi^+\pi^-$ background, and the TWISTER[2] program modelling the prompt production of ρ^0 via HT processes.

The two x_E regions we have chosen are $0 \leq x_E \leq 0.5$ and $0.5 \leq x_E \leq 1$. The former interval is expected to be enriched in promptly produced ρ^0 , while the latter interval is expected to be depleted in promptly produced ρ^0 .

The analysis of the 300 GeV/c data showed that the ratio of the ρ^0 signal to the background of uncorrelated $\pi^+\pi^-$ pairs had an x_E behaviour consistent with about one half of the observed ρ^0 signal being promptly produced[22]. As a test of such an hypothesis, the experiment was repeated at 150 GeV/c primary momentum since the fraction of the ρ^0 signal due to HT processes was expected to increase significantly when going from 300 to 150 GeV/c.

As mentioned in section 3, due to the different kinematical conditions, the accepted phase space region is slightly different at the two beam energies. In order to have good statistics in the same phase space window for both the 300 and 150 GeV/c data, a rapidity interval narrower than in ref.[22] was chosen, namely $0 \leq Y_{cms}^{pair} \leq 0.5$, while still requesting $p_T^{pair} \geq 2$ GeV/c.

Table 5 gives the ratio F_ρ of the signal to the sum of signal + non-resonant background measured at the two energies. Also given are the predictions at 150 GeV/c under two hypotheses : **i**/ that at 300 GeV/c ρ^0 mesons are produced about equally by HT (55%) and LT (45%) – LT+HT hypothesis – as suggested in ref.[22], **ii**/ that only LT processes are present – LT hypothesis –, the excess reported in ref.[22] being then not due to HT.

Clearly the experimental values at 150 GeV/c are in contradiction with a HT contribution as large as extrapolated from the results at 300 GeV/c. It should be noticed that, fully attributed to HT, the observed excess of ρ^0 mesons at 300 GeV/c corresponds to choosing $R = a_0$ (see rel. (4)), *i.e.* about 4 times the value expected using the prediction of the QCD sum rules for the wave function moments[19]. However, such a value corresponds to choosing the ρ^0 meson wave function as $(x_1 x_2)^\beta$ with $\beta = 1/4$ as proposed for the pion by Brosky and Lepage in ref.[21] to describe the pion form factor. A smaller contribution in agreement with QCD sum rules expectations[19] is however possible (see the following sections).

Another prediction of the model concerns the ϕ/ρ^0 ratio. As shown in the previous section, the ϕ mesons are not promptly produced in a significant way at both beam energies. As a consequence, in the LT+HT hypothesis ($\beta = 1/4$), we would expect the ϕ/ρ^0 ratio to decrease by a factor of 2 when going from 300 to 150 GeV/c ; in the LT hypothesis instead, this ratio should remain constant.

The experimental results, calculated in the same window as F_ρ , at 300 and 150 GeV/c are given in table 6. They indicate, if anything, an increase of the ratio ϕ/ρ in contradiction with the higher twist hypothesis extrapolated from the initial analysis at 300 GeV/c, assuming $\beta = 1/4$.

Therefore we exclude the existence of a strong HT contribution in the ρ production as it has been suggested by the 300 GeV/c data. However, a small HT contribution is not excluded (see next sections). The bulk of the contribution to the ρ signal interpreted first as an HT effect has to be attributed to some other effect unaccounted for in the Lund LT Monte Carlo PYTHIA.

7.2 Second Approach to HT

In the following, we study the behaviour of the $f_2(1270)$ and ρ^0 meson signals relative to ϕ and $\overline{K}^{*0}$ at the two beam energies in the full window defined by rels. (6). Our study of section 6 has indeed shown that the ϕ and $\overline{K}^{*0}$ mesons are reliable LT references in the search for HT in other meson productions. For a full study of HT effects in $f_2(1270)$ and ρ^0 high- p_T production, the available information from QCD sum rules is not sufficient[19] to estimate theoretically the magnitude of a possible HT signal. Indeed, the wave function dependent scale factor (see rel. (3)) for the $f_2(1270)$ is unknown ; our study of its polarization properties[38] indicates however that it is negligible. For the ρ^0 meson, a specific HT contribution is expected to be small as already mentioned in section 2. However a feed down of ρ^0 from HT η' decays has an unknown magnitude, as no information is available about the η' wave function ; there is some indication that it can be large[26].

Basically, this second approach to HT is a comparison of our experimental data with simulation samples. For this purpose, we have generated samples of LT and HT events using simulation programs [2, 27], followed them through the simulation of our setup, required the

trigger conditions and selected the events falling in the window defined by rels. (6). In this way, we can define the LT and HT cross sections for each meson (M) decaying to two bodies and accepted as the trigger pair (see section 3) in our setup¹⁰; these accepted cross sections are denoted $\sigma_{LT}(M)$ and $\sigma_{HT}(M)$ in the following. The values for $\sigma_{LT}(M)$ are given in table (3). They are absolute predictions and only depend on our tuning of the Lund Monte Carlo input parameters (see section 2). The numerical values for $\sigma_{HT}(M)$ are computed assuming an arbitrary value for the scale factor R (see rel. (2)). In this way, the observed production cross section $\sigma(M)$ for each meson M at each beam energy can be written :

$$\sigma(M) = \sigma_{LT}(M) + A_M \sigma_{HT}(M) \quad , \quad (10)$$

and the parameter A_M – which is independent of the beam energy – has to be fitted or fixed. In the case of ϕ and $\bar{K}^{*0}$, we choose $A_M = 0$ in order to drop out any HT contribution, in agreement with the results presented in section 6. When analyzing the $f_2(1270)$ meson production, the A_M parameter (which will be denoted A_f) is theoretically unknown and then has to be fitted.

In the case of the ρ^0 meson, we have to consider two possible sources for a HT contribution. One is the prompt ρ^0 production, the other is the prompt production of η' mesons which produces accepted ρ^0 through its $\rho^0\gamma$ decay mode. Therefore, in the case of ρ^0 meson production, the second term in the right-hand side of rel. (10) should be understood as :

$$A_\rho \sigma_{HT}(\rho^0) + A_{\eta'} \sigma_{HT}(\eta') \quad . \quad (11)$$

In this case, we shall fit both A parameters, keeping however in mind that the order of magnitude of A_ρ is known using QCD sum rule results[19] and rel. (4) above. A comparison with theory is possible here.

7.2.1 Analysis of the $f_2(1270)$ Signal

We denote by $\bar{\sigma}$ the cross section of each meson and by N the acceptance corrected meson yields. Using our simulation results and the meson yields obtained by fitting the experimental data, we define for each beam energy the quantity :

$$W_f = \frac{1}{a_\phi^2} \left[\frac{N_f}{N_\phi} - \frac{C_f \bar{\sigma}_{LT}(f_2) + A_f \bar{\sigma}_{HT}(f_2)}{\bar{\sigma}_{LT}(\phi)} \right]^2 + \frac{1}{a_{\bar{K}^{*0}}^2} \left[\frac{N_f}{N_{\bar{K}^{*0}}} - \frac{C_f \bar{\sigma}_{LT}(f_2) + A_f \bar{\sigma}_{HT}(f_2)}{\bar{\sigma}_{LT}(\bar{K}^{*0})} \right]^2 \quad (12)$$

In this expression, a_ϕ and $a_{\bar{K}^{*0}}$ are the errors on respectively N_f/N_ϕ and $N_f/N_{\bar{K}^{*0}}$. They are computed using the yields given in table (2). C_f and A_f are two parameters which can be either fixed or fitted : C_f can account for a (possible) rescaling of the Lund parameter T/V (see section 2) and A_f can account for a (possible) HT contribution.

We deduce physics information by minimizing the function :

$$\chi^2 = W_f(300\text{GeV}/c) + W_f(150\text{GeV}/c) \quad , \quad (13)$$

which depends on 4 measured quantities and 0, 1 or 2 free parameters (depending on the assumptions about C_f and A_f).

¹⁰Their acceptances are computed separately for corrections.

As a first attempt, we have computed expression (12) by fixing $C_f = 1$ and $A_f = 0$; this corresponds to assuming that there is no HT contribution to the $f_2(1270)$ cross section and that the T/V ratio we have chosen for our Lund LT Monte Carlo is exact. We get $\chi^2/dof = 96/4$.

As a second attempt, we have assumed $A_f = 0$ and left C_f free. In this case, we obtain $C_f = 3.33 \pm 0.24$ with $\chi^2/dof = 5.4/3$; this solution turns to assert that $T/V = 0.70 \pm 0.05$, in full contradiction with all existing results[8, 29, 30, 31, 32, 33] in e^+e^- annihilation and in hadronic experiments.

A third attempt has been done which is to fix $C_f = 1$ and leave A_f free. The result leads also to an unacceptable solution : the HT cross section is greater than the LT cross section by a factor $\simeq 4$ (300 GeV/c) or $\simeq 1.6$ (150 GeV/c). This result ($\chi^2/dof = 4.9/3$) implies that the coefficient R in rel. (4) is around 10 times larger than for any pseudoscalar or vector meson. This possibility seems unlikely for a P wave meson.

As a final attempt, we have left free both C_f and A_f . In this case, we obtain with $\chi^2/dof = 0.14/2$, $C_f = 4.21 \pm 1.84$ and $A_f = 2.20 \pm 0.55$. This corresponds to a corrected $T/V = 0.88 \pm 0.39$ and HT fractions of 0.23 ± 0.11 (300 GeV/c) and 0.10 ± 0.05 (150 GeV/c).

The first remark is that our experimental errors and the limited number of measurements generally provide large uncertainties in the final results. Moreover, we do not account for the uncertainties inherent in our Lund Monte Carlo programs. Nevertheless, the general trend of these results leads to the conclusion that T/V is sensitively larger than 0.20 as indicated by some hadronic experiments[31, 32]. Moreover, a small admixture of HT improves the understanding of the data but it is only a 2σ effect, without taking into account our main source of systematic errors (the Lund Monte Carlo physical assumptions). This result confirms our previous conclusion on HT effects in f_2 production following from its observed polarization properties[38].

7.2.2 Analysis of the ρ^0 Signal

The main aim of our experiment was to look for a possible HT contribution besides the standard LT contribution in the production of ρ^0 at large p_T . We have already seen in section 7.1 that a large HT component in this yield is unlikely. In this section we plan to amount more precisely the possible HT component. For the present study, we basically rely on the method used for the $f_2(1270)$ meson. Now we define :

$$Z_\rho = \frac{1}{b_\phi^2} \left[\frac{N_\rho}{N_\phi} - \frac{C_\rho \bar{\sigma}_{LT}(\rho) + A_\rho \bar{\sigma}_{HT}(\rho) + g A_{\eta'} \bar{\sigma}_{HT}(\eta')}{\bar{\sigma}_{LT}(\phi)} \right]^2 + \frac{1}{b_{\bar{K}^{*0}}^2} \left[\frac{N_\rho}{N_{\bar{K}^{*0}}} - \frac{C_\rho \bar{\sigma}_{LT}(\rho) + A_\rho \bar{\sigma}_{HT}(\rho) + g A_{\eta'} \bar{\sigma}_{HT}(\eta')}{\bar{\sigma}_{LT}(\bar{K}^{*0})} \right]^2 \quad (14)$$

All notations here have been already defined except for b_ϕ , $b_{\bar{K}^{*0}}$ and g ; C_ρ is a possible rescaling factor as C_f above. These b_i parameters are similar for the ρ^0 mesons yields to the a_i defined above for the $f_2(1270)$ yields. The origin of g is due to the fact that N_ρ , $\bar{\sigma}_{LT}(\rho)$ and $\bar{\sigma}_{HT}(\rho)$ are normalized to the acceptance of primarily produced ρ^0 (LT or HT), while $\bar{\sigma}_{HT}(\eta')$ has been normalized to the acceptance of the ρ meson produced in the decay of high- p_T η' (0.61% at 300 GeV/c and 0.53% at 150 GeV/c). In order that $A_{\eta'}$ keeps its physical meaning (see section 2), we have introduced g . This parameter is equal to 0.61/4.40 at 300 GeV/c and to 0.53/3.75 at 150 GeV/c.

The function which has been minimized in order to study the ρ^0 production is :

$$\chi^2 = Z_\rho(300\text{GeV}/c) + Z_\rho(150\text{GeV}/c) \quad . \quad (15)$$

Rel. (15) involves four measured ratios and can have up to three free parameters. We have analyzed several assumptions :

1 Assuming no HT (*i.e.* $A_\rho = A_{\eta'} = 0$), we have tried fixing $C_\rho = 1$. We obtain $\chi^2/dof = 12.3/4$ (15% probability). We have also tried to leave C_ρ free and got $C_\rho = 1.29 \pm 0.09$ with $\chi^2/dof = 2.7/3$ (44% probability). Therefore, assuming no HT contribution tends to increase the value $V/(V + PS)$ from 0.3 (see section 2) to about 0.4. This would contradict the result obtained by ARGUS[5] for continuum data at the Υ mass. One can conclude herefrom that our data are consistent with an excess of ρ^0 mesons, if one refers to the exhaustive study of ARGUS[5].

2 Assuming $C_\rho = 1$, we have left free A_ρ and $A_{\eta'}$. We get $A_\rho = 0.01^{+0.85}_{-0.01}$ and $A_{\eta'} = 5.22 \pm 1.69$ with $\chi^2/dof = 2.6/2$. This value for A_ρ is in agreement with what can be expected from QCD sum rules, therefore we can fix $A_\rho = 0.2$ as it can be expected using the QCD sum rule results. In this case we obtain $A_{\eta'} = 4.42 \pm 1.69$ with $\chi^2/dof = 2.8/3$. Moreover, one can always find solutions intermediate between ($C_\rho \simeq 1$, $A_{\eta'} \simeq 4.5$) and ($C_\rho \simeq 1.3$, $A_{\eta'} \simeq 0$) by choosing the value of C_ρ , each with $\chi^2 \simeq 2.8$.

To summarize, we observe an excess of ρ^0 mesons produced at large p_T . The magnitude of this excess is about 30% at both energies. The data are consistent with the predictions concerning prompt ρ^0 which mix QCD perturbative calculations and meson wave function estimates from QCD sum rules. Prompt ρ^0 cannot explain more than $\simeq 10\%$ of the observed excess. The remaining $\simeq 20\%$ excess can be explained by either increasing the $V/(V + PS)$ to a value close to 0.4 or by a contribution provided by HT η' decaying to $\rho^0\gamma$; intermediate solutions are all as likely.

In other words, the χ^2 defined by rel. (14) exhibits, as a function of C_ρ and $A_{\eta'}$, a valley and not an absolute minimum. The only way to reach a conclusion is to include extra information ; for instance, if one assumes $C_\rho = 1$ the ρ^0 excess can be explained by HT η' decays to $\rho\gamma$. Moreover, in this case, the wave function factor $c_1 = \sqrt{R/a_0}$ (see rel. (4)) is $c_1 = 2.10 \pm 0.4$, in agreement with the conclusion reached in ref.[26] ($1.2 \leq c_1 \leq 1.5$) when studying η' production at the ISR.

8 Conclusion

We have studied the production at $p_T \geq 2$ GeV/c of the ϕ , $K^{*0}(892)$, $\overline{K}^{*0}(892)$, $f_2(1270)$ and ρ^0 resonances in $\pi^- Be$ interactions using two data samples collected at two different beam energies (150 and 300 GeV/c). We find evidence for the production of the $f_0(975)$ meson at both energies at a level consistent with the results obtained in e^+e^- annihilations.

We have also found that the ϕ and $\overline{K}^{*0}(892)$ signals behave as expected from the Lund model : in these cases, our results are consistent with a production mechanism dominated by parton hard scattering followed by the parton fragmentation into hadrons. The study of the ratio $\overline{K}^{*0}(892)/K^{*0}(892)$ shows however a slight departure from expectations indicating that K^{*0} mesons could be less produced than predicted by the Lund (LT) Monte Carlo. This is a 2σ effect. No evidence for an excess is observed, in agreement with QCD predictions concerning HT effects for these three mesons.

Comparing the ρ^0 to the background beneath we do not find the strong HT signal which could be inferred from our data at 300 GeV/c alone.

Choosing as reference for leading twist physics the ϕ and $\overline{K}^{*0}(892)$ mesons, we have performed a search for the higher twist signal by studying the production of the $f_2(1270)$ and ρ^0 mesons at both beam energies. We observe in both cases an excess with respect to the results obtained in e^+e^- annihilation ; this motivated a further analysis in order to see whether these excesses can be attributed to the higher twist production mechanism or if rescaling leading twist parameters allows to explain the experimental data.

The study of $f_2(1270)$ production allows to conclude that the ratio HT/LT for this meson is non-zero only at the 2σ level. One concludes from this that the LT part of the $f_2(1270)$ production appears larger in hadronic interactions than in e^+e^- annihilations.

In the study of the ρ^0 meson, we have first illustrated that the prompt (or HT) production fraction is in agreement with QCD expectations and cannot explain the whole observed excess. If one relies on the ARGUS results in e^+e^- annihilation, the only way to explain the (largest) part of the observed excess is to invoke promptly produced η' with a magnitude consistent with former measurements from the CERN ISR.

Our main result is however that nothing in our data contradicts the HT estimates following from QCD sum rules predictions when they exist. This covers the production at large p_T of the ϕ , $\overline{K}^{*0}(892)$ and $K^{*0}(892)$ mesons ; for these mesons, no HT contribution is found as expected. A HT component in $f_2(1270)$ production is not statistically significant. Finally, for the ρ^0 meson, the observed excess is well explained by the feed down from HT η' and not by an abnormal ρ meson wave function.

Tables

Mass Assignment	300 GeV/c Sample	150 GeV/c Sample
$\pi^+\pi^-$	118/139	150/139
$K^+\pi^-$	144/92	121/92
π^+K^-	129/92	126/92
K^+K^-	107/98	69/98

Table 1 : Fits of the four mass assignments. First line displays the value of χ^2/dof for each sample. The next three lines display the value of $\chi^2/number\ of\ bins$ for each assignment ; as the number of parameters is small compared to the number of bins, this information gives a good hint of the statistical quality of the global fit (see ref.[10] for further explanations).

Meson	300 GeV/c		150 GeV/c	
	Acceptance	Raw Yield	Acceptance	Raw Yield
ρ^0	4.40	14374 ± 1380	3.75	18633 ± 1299
$f_2(1270)$	2.67	4881 ± 374	2.04	4634 ± 355
$S^*/f_0(975)$	2.36	320 ± 151	1.98	638 ± 223
$K^{*0}(892)$	3.98	3689 ± 352	3.27	4303 ± 649
$\overline{K}^{*0}(892)$	3.98	1963 ± 348	3.27	2462 ± 217
ϕ	6.80	1432^{+282}_{-162}	5.30	1748^{+201}_{-185}

Table 2 : Raw meson yields from the 300 GeV/c and 150 GeV/c sample. Acceptances (in percents) are computed from simulation (see text) and are given in percents.

Meson	300 GeV/c		150 GeV/c	
	Acceptance (percents)	Cross Section (nb)	Acceptance (percents)	Cross Section (nb)
$K^{*0}(892)$	3.98	6.79 ± 0.10	3.27	1.88 ± 0.03
$\overline{K}^{*0}(892)$	3.98	2.38 ± 0.06	3.27	0.57 ± 0.02
ϕ	6.80	1.69 ± 0.05	5.30	0.38 ± 0.01
$f_2(1270)$	2.67	1.29 ± 0.04	2.04	0.34 ± 0.01
ρ^0	4.40	10.78 ± 0.13	3.75	3.45 ± 0.04

Table 3 : LT accepted cross sections (in nanobarns) and acceptance values (in percents) for the two data samples.

Ratio	300 GeV/c		150 GeV/c	
	Simulation	Data	Simulation	Data
$\overline{K}^{*0}(892)/K^{*0}(892)$	0.35 ± 0.01	0.53 ± 0.11	0.29 ± 0.02	0.57 ± 0.10
$\overline{K}^{*0}(892)/\phi$	2.40 ± 0.12	$2.34^{+0.49}_{-0.62}$	2.43 ± 0.14	$2.28^{+0.31}_{-0.33}$

Table 4 : Ratios of acceptance corrected yields for the LT Lund generated sample and for the collected data at the two beam energies.

x_E Interval	300 GeV/c	150 GeV/c	
	Data	Prediction	Data
$0.5 \leq x_E \leq 1$	0.21 ± 0.02	0.34 ± 0.02 (LT+HT)	0.20 ± 0.03
		0.23 ± 0.02 (LT)	
$0 \leq x_E \leq 0.5$	0.27 ± 0.02	0.44 ± 0.02 (LT+HT)	0.23 ± 0.03
		0.23 ± 0.02 (LT)	

Table 5 : Ratio F_ρ of signal to signal plus background for the ρ^0 meson. The phase space window is defined in section 7.1

Ratio	300 GeV/c	150 GeV/c
ϕ/ρ	0.10 ± 0.02	0.14 ± 0.02

Table 6 : Ratio ϕ/ρ^0 in the phase space window defined in section 7.1.

Figure 1: (a) Example of a higher twist diagram for the direct production of a ρ^0 meson. (b) Example of a diagram for the indirect production of a ρ^0 meson in the reaction πN , via quark scattering and subsequent fragmentation.

References

- [1] W. Geist *et al.*, Phys. Rep. **197** (1990) 263.
- [2] H. Bengtsson and G. Ingelman, Comput. Phys. Comm. **34** (1985) 251 ;
“The Lund Monte Carlo Programs”, CERN long writeups W5035, W5045, W5046, W5047, W5048, nov. 1989.
- [3] B. Andersson *et al.*, Phys. Rep. **97** (1983) 31.
- [4] H. Albrecht *et al.*, Zeit. für Phys. **C58** (1993) 199;
Preprint DESY 93–084, july 1993.
- [5] H. Kapitza, in “Proceedings of the International Europhysics Conference on High Energy Physics”, Marseille, July 1993, J. Carr and M. Perrottet Eds, p.73, Editions Frontières, 1994.
- [6] D. Buskulic *et al.*, Phys. Lett. **B292** (1992) 210.
- [7] P.D. Acton *et al.*, Zeit. für Phys. **C56** (1992) 521.
- [8] P. Abreu *et al.*, Phys. Lett. **B298** (1993) 236.
- [9] Y. F. Wang, in “Proceedings of the International Europhysics Conference on High Energy Physics”, Marseille, July 1993, J. Carr and M. Perrottet Eds, p.79, Editions Frontières, 1994.
- [10] A. Bellogianni *et al.*, Zeit. für Phys. **C59** (1993) 35.
- [11] H.J. Frisch *et al.*, Phys. Rev. **D27** (1983) 1001.
- [12] C. De Marzo *et al.*, Phys. Rev. **D36** (1987) 16.
- [13] M. Aguilar–Benitez *et al.*, Zeit. für Phys. **C34** (1987) 419.
- [14] A. Bellogianni *et al.*, Zeit. für Phys. **C54** (1992) 535.
- [15] E.L. Berger *et al.*, Phys. Rev. **D23** (1981) 99.
- [16] M. Benayoun *et al.*, Nucl. Phys. **B282** (1987) 653.
- [17] M. Benayoun and M. Froissart, Nucl. Phys. **B315** (1989) 295.
- [18] “High p_T Physics and Higher Twists”, Nucl. Phys. **B** (Proc. Suppl.) **7B** (1989), 1.
- [19] V. L. Chernyak and A. R. Zhitnitsky, Phys. Rep. 112 (1984) 175.
- [20] M. Benayoun, “Experimental Results in Higher Twist Physics”, in Proceedings of the XXIIIrd Rencontre de Moriond, Les Arcs, March 1988, Editions Frontières, 1989, p. 341.
- [21] G. Lepage and S. Brodsky, Phys. Rev. **D22** (1980) 2157.
- [22] M. Benayoun *et al.*, Phys. Lett. **B183** (1987) 412.

- [23] S. Brodsky and G. Lepage, Phys. Rev. **D24** (1981) 1808.
- [24] M. Benayoun and V. L. Chernyak, Nucl. Phys. **B329** (1990) 285.
- [25] A. Bellogianni *et al.*, Zeit. für Phys. **C61** (1994) 371.
- [26] M. Benayoun *et al.*, Phys. Lett. **B192** (1987) 447.
- [27] K. Safarik, to be published.
- [28] C.W. Akerlof *et al.*, Phys. Rev. Lett. **39** (1977) 861.
- [29] K.J. Anderson *et al.*, Phys. Rev. Lett. **37** (1976) 799.
- [30] I.V. Chliapnikov *et al.*, Nucl. Phys. **B176** (1980) 303 ; Zeit. für Phys. **C12** (1982) 113.
- [31] N.M. Agababyan *et al.*, Zeit. für Phys. **C41** (1989) 539.
- [32] A. Breakstone *et al.*, Zeit. für Phys. **C43** (1989) 185.
- [33] M. Aguilar-Benitez *et al.*, Zeit. für Phys. **C50** (1991) 405.
- [34] W. Beusch *et al.*, Nucl. Instrum. Methods **A249** (1986) 591.
- [35] M.T. Trainor, “Direct meson production at $p_T \geq 2$. GeV/c in 300 GeV/c π^- Be interactions”, PhD thesis, University of Birmingham, March 1988 ;
R. Fini, “Produzione inclusiva di risonanze a medio-alto momento trasverso”, Tesi di Dottorato, Università degli studi di Bari, January 1990, National library of Rome and Florence.
- [36] Review of Particle Properties, K. Hikasa *et al.*, Phys. Rev. **D45** (1992) S1.
- [37] G. Gidal *et al.*, Phys. Lett. **107** (1981) 153.
- [38] A. Bellogianni *et al.*, Zeit. für Phys. **C64** (1994) 15.