EVIDENCE FOR PROMPT HIGH-$p_\perp$ η′-MESONS AT THE ISR

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ISR data on the ratios η/π^0, η'/π^0 and ω/π^0 at medium to high transverse momentum are examined in the context of prompt meson production through the higher twist mechanism in addition to the standard process of parton scattering and fragmentation. The η'/π^0 ratio in particular, can only be well understood by a sizeable prompt contribution in good agreement with the large η' cross section expected from higher twist calculations. Furthermore, by neglecting any glue component in the η′, a pseudoscalar mixing angle of $\approx -15°$ is preferred, slightly lower than some recent measurements.

Introduction. Although the possibility of prompt meson production through the so-called higher twist processes has been investigated theoretially since several years [1,2], it is only very recently that the first experimental evidence of such processes has been obtained [3,4]. A clear evidence for the inverse process, in which both valence partons of an incoming pion interacts coherently with the partons of the nucleon target, has also been reported [5].

Meson production through the prompt higher twist mechanism has generally been expected to have a much smaller cross section than that of the dominating process of parton scattering followed by fragmentation. Recent estimates [6] show, however, that this is not the case for some vector mesons as well as the η′ produced at medium to high $p_\perp$ in hadron–hadron scattering In particular, the detailed calculation in ref. [6], which takes mixing of neutral meson fully into account, has shown that the η′ production is of similar magnitude for these two kinds of mechanisms. More precisely, the ratio of inclusive cross sections of η′ to η production at $p_\perp > 2.5$ GeV/c, $R=\sigma(\eta')/\sigma(\eta)$, which for the fragmentation mechanism is expected to be close to unity, changes into $1.5 \lesssim R \lesssim 3$ if the higher twist processes occur at the expected level [6]; the bounds for R only reflect the uncertainties concerning a particular moment of the meson wave function $\Phi(x_1, x_2)$ entering the higher

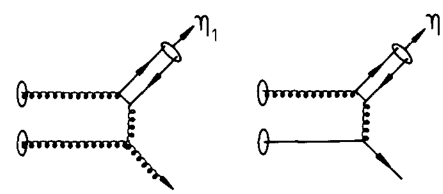

Fig. 1. Gluon–gluon fusion into an isosinglet q$\bar{\text{q}}$ pair giving the dominant contribution to the higher twist contribution of η′. (These diagrams are examples only, see figs. 2 and 3 in ref. [6] for the complete set.)

twist calculation. The favoured production of η′, compared to the other pseudoscalar mesons, is related to it being nearly a pure SU(3) isosinglet state which has a large overlap with the isosinglet q$\bar{\text{q}}$ state formed by the gluon–gluon fusion processes illustrated in fig. 1. Thus its production cross section depends essentially on $\cos^2\theta_{PS}$ whereas the η cross-section depends on $\sin^2\theta_{PS}$; where θ_{PS} is the singlet–octet mixing angle for pseudoscalar mesons, whose value is expected to be in the range $-23° \lesssim \theta_{PS} \lesssim -10°$ [7].

Production of η, η′ and ω at $p_\perp > 3$ GeV/c has been measured in pp collisions at the ISR [8,9] resulting in the conclusion that $\eta'/\eta \approx 1.71$ [#1]. This should be compared with the higher twist "post-diction" above and the approximate unit ratio expected from con-

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ventional fragmentation models like, e.g., the Lund model [10]. The possibility [11] for a gluon jet to hadronize preferentially into isoscalar particles could change this expectation, but we note that such a model is not compatible with experimental results on η and φ production in ϒ-decays whereas the Lund model does provide a good description [12]. The aim of this letter is thus to examine these data (reproduced in tables 1 and 2 [#2]) carefully with respect to their relevance as a possible signal for the occurrence of the higher twist interaction mechanism.

Monte Carlo method. Our analysis is based on a "Lund Monte Carlo", TWISTER [13], for high-$p_\perp$ particle production in hadronic interactions which includes all leading order (α_s^2) minimum twist (denoted MT in the following) $2\to2$ parton scattering processes followed by hadronization as described by the Lund string model [10,14] as well as all leading order (α_s^3) higher twist (denoted HT) prompt meson processes as given in ref. [6]. For the proton structure functions, which are folded with the parton level cross section in a well-known procedure, we use the parametrizations in ref. [15]. Although there are many parameters in the soft hadronization model [10], most of them are well determined by comparison with available data and we therefore use the current default values [14]. We note, however, that the probability to form a vector meson rather than a pseudoscalar from a $q\bar{q}$ pair, $\gamma=V/(V+PS)$, has some uncertainty which is of relevance to our analysis. Although using the default value, $\gamma_0=0.5$, we shall in the discussion below allow for a variation in accordance with the range of values (0.3–0.6) obtained experimentally [16]; the preferred value seems to be 0.3–0.4.

For the perturbative QCD calculation we use $\Lambda_{QCD}=300$ MeV and the momentum transfer scale $Q^2=q_\perp^2$, with $q_\perp$ the transverse momentum of the scattered partons, being aware that this choice is not unique [17] [#3]. This gives a mean value of the strong coupling constant $\alpha_s(Q^2)\approx0.3$ for $\langle Q^2\rangle\approx10$ GeV^2 relevant for the kinematic region defined below. We note that this makes perturbative calculations justified and is furthermore in agreement with the values of Λ_{QCD} and α_s usually obtained in phenomenological analyses.

Together with a primordial transverse momentum of the partons within the colliding hadrons, which accounts phenomenologically for non-perturbative effects and is described by a gaussian distribution with $\langle k_\perp^2\rangle=(0.8\ \mathrm{GeV}/c)^2$ [17], this provides a fair description of inclusive π^0 data [18] in the range $3<p_\perp<7$ GeV/c in pp scattering at $\sqrt{s}=63$ GeV. Our choice of π^0 production as a calibration process follows from the fact that it is largely dominated by the parton fragmentation mechanism compared to the prompt production one, $\sigma_{HT}/\sigma_{MT}\approx3\%$, and is therefore suitable to fix parameters independently from higher twist effects.

With these parameters we are left with a nearly constant K-factor, $K=\sigma_{exp}^{\pi^0}(p_\perp)/\sigma_{MT}^{\pi^0}(p_\perp)=2.75\pm0.15$, estimated from the data [18] in the above $p_\perp$-range. Strictly speaking, this K-factor also depends on the vector-to-peudoscalar ratio such that a change from the default value, γ_0, gives approximately [#4] the change $K\to K(1-\gamma_0)/(1-\gamma)=K/[2(1-\gamma)]$. A preferred lower value of $\gamma\approx0.4$ would thus give a reduced factor $K\approx2.3$ which is typical for phenomenological analyses in this $p_\perp$-range [17]. We note that by using the recently discussed optimized scale choices [19], which tends to give $Q^2\approx q_\perp^2/4$, the K-factor needed can be further reduced. Since these choices are only derived for some specific processes we have not, however, used such an alternative here.

As a further cross-check of the reliability of our Monte Carlo program we compare in fig. 2 the η/π^0 ratio as a function of $p_\perp$ with the available data in hadron collisions at FNAL [20] and ISR [21]. The small higher twist contribution is here neglected, but the more important dependence on the pseudoscalar mixing angle is shown. As also found in the model, this ratio depends very little on the energy and other conditions in the different experiments. For

[#2] The values and errors of the η/π^0 ratio have been read from fig. 3 in ref. [8] after magnification of this figure.

[#3] See ref. [17] for a recent review.

[#4] A change in the vector meson probability will affect the pseudoscalar production also in an indirect way through resonance decays, giving a more complicated behaviour. Furthermore, a significant variable change may have to be accompanied by a corresponding change in the hardness of the fragmentation function in order to bring the changed momentum spectrum due to more/fewer directly produced pions in agreement with data.

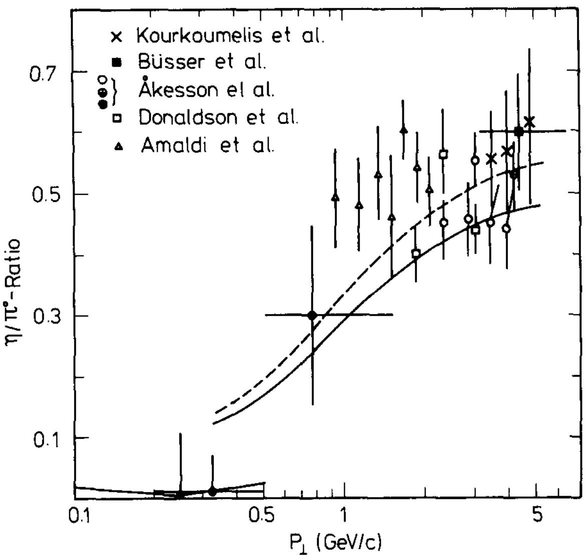

Fig. 2. Transverse momentum dependence of the η/π^0 ratio in hadron collisions at FNAL [20] and ISR [21] energies compared to the leading twist model calculation for two values of the pseudoscalar mixing angle; $\theta_{PS}=-11°$: solid curve, and $\theta_{PS}=-19°$: dashed curve.

$2 \lesssim p_\perp \lesssim 5$ GeV/c the model describes the data well and at lower $p_\perp$ a fair agreement is observed although our high-$p_\perp$ model is not expected to be reliable at very low $p_\perp$.

Method of analysis. The inclusive cross section for producing a given meson, M, with $p_\perp$ larger than some bound, e.g. $p_\perp > 3$ GeV/c, is given by the sum of the minimum and higher twist contributions

$$\sigma(\mathrm{M}) = 2K(1-\gamma)\sigma_{\mathrm{MT}}(\mathrm{M}) + c_1^2\sigma_{\mathrm{HT}}(\mathrm{M}) , \qquad (1)$$

$$\sigma(\mathrm{M}) = 2K\gamma\sigma_{\mathrm{MT}}(\mathrm{M}) + c_1^2\sigma_{\mathrm{HT}}(\mathrm{M}) , \qquad (2)$$

for M being a pseudoscalar and vector meson, respectively. The approximate [#4] dependence on the vector meson probability is indicated with the assumption that the σ_{MT}'s are calculated with the default value $\gamma_0 = 0.5$. The K-factor for the minimum twist case is explicitly taken into account and assumed to be the same for all mesons. The value of a similar K-factor for the higher twist case is not known and we therefore choose to absorb it in the parameter c_1^2. The higher twist cross section is expressed [6] such that this constant gives the explicit dependence on the prompt meson wave function through

$$c_1^2 = \int_0^1\int_0^1 \mathrm{d}x_1\,\mathrm{d}x_2\,\delta(1-x_1-x_2)\Phi(x_1,x_2)/x_1 , \qquad (3)$$

where x_1, x_2 are the longitudinal momentum fractions carried by the valence quarks inside the meson [#5].

We further assume that SU(3) nonet symmetry holds as far as the higher twist cross sections are concerned. This implies that c_1 has the same value for all pseudoscalar mesons and, separately, for all vector mesons. Thus, different c_1-values for the pseudoscalars and the vectors are possible although the present stage of phenomenological analysis does not seem to require such a complication and we shall therefore not make use of it below.

From the cross-sections for minimum and higher twist productions of π^0, η, η' and ω we can, neglecting $\sigma_{\mathrm{HT}}(\pi^0)$ relative to $\sigma_{\mathrm{MT}}(\pi^0)$ [#6], write for given intervals in the $p_\perp$ of the trigger meson

$$\left(\frac{\eta}{\pi^0}\right)_{\mathrm{th}} = \frac{\sigma_{\mathrm{MT}}(\eta)}{\sigma_{\mathrm{MT}}(\pi^0)} + \frac{c_1^2}{2(1-\gamma)K}\frac{\sigma_{\mathrm{HT}}(\eta)}{\sigma_{\mathrm{MT}}(\pi^0)} ,$$

$$\left(\frac{\eta'}{\pi^0}\right)_{\mathrm{th}} = \frac{\sigma_{\mathrm{MT}}(\eta')}{\sigma_{\mathrm{MT}}(\pi^0)} + \frac{c_1^2}{2(1-\gamma)K}\frac{\sigma_{\mathrm{HT}}(\eta')}{\sigma_{\mathrm{MT}}(\pi^0)} ,$$

$$\left(\frac{\omega}{\pi^0}\right)_{\mathrm{th}} = \frac{\gamma}{1-\gamma}\frac{\sigma_{\mathrm{MT}}(\omega)}{\sigma_{\mathrm{MT}}(\pi^0)} + \frac{c_1^2}{2(1-\gamma 0K}\frac{\sigma_{\mathrm{HT}}(\omega)}{\sigma_{\mathrm{MT}}(\pi^0)} . \qquad (4)$$

By comparison with the experimental data we can therefore obtain both $c_1^2/[2(1-\gamma)K]$ and $\gamma/(1-\gamma)$

[#5] Assuming $\Phi(x_1, x_2) \propto (x_1x_2)^\beta$ as suggested by Lepage and Brodsky [1], then $c_1 = (2\beta+1)/6\beta$. However, such an explicit dependence is not needed and we could as well consider c_1 as being a moment of $\Phi(x_1, x_2)$ to be estimated phenomenologically. The only property of Φ which plays an important role in our results is that $\Phi(x_1, x_2) = \Phi(x_2, x_1)$. Notice further that a $\sqrt{3}f_{\mathrm{PS}}$ or a $\sqrt{6}f_{\mathrm{V}}$ is dropped from Φ and absorbed (after squaring) in $\sigma_{\mathrm{HT}}(\mathrm{M})$ [6].

[#6] We recall that $\sigma_{\mathrm{HT}}(\pi^0)/\sigma_{\mathrm{MT}}(\pi^0) \approx 3\%$ and becomes even smaller when taking the K-factor into account since c_1 is surely of order unity; $\sigma_{\mathrm{HT}}(\pi^0)$ can thus be neglected compared to our statistical errors.

by a fitting procedure where the first factor is obtained from the η/π^0, η'/π^0 ratios and then used when determining the second factor from the ω/π^0 ratio. The theoretical errors that are given in the following results stem mainly from the limited Monte Carlo statistics of event generation in the minimum twist case.

Results. Since we are mainly concerned with the η, η' production we explicitly investigate the dependence on the SU(3) singlet–octet mixing angle, θ_{PS}, for pseudoscalar mesons. Theoretically, it is expected to be $\approx -10°$ based on quadratic mass formulae, whereas linear formulae would give $\approx -23°$ [7]. Experimental data on $\pi^- p \to \eta n$ and $\pi^- p \to \eta' n$ at $p_{lab} = 15$–40 GeV/c give $\theta_{PS} = (-18.2 \pm 1.4)°$ [22] and recent results on two-γ decays of π^0, η, η' give $(-19 \pm 1.8)°$ [23].

We thus generate Monte Carlo samples for $\theta_{PS} = -9.75°$, $-15.5°$, $-19.5°$ and interpolate linearly to obtain results at intermediate values; we have verified that this procedure gives reliable cross-section estimates. The quality of the model description is measured by

$$\chi^2 = \sum_{M=\eta,\eta'} \frac{[(M/\pi^0)_{th} - (M/\pi^0)_{exp}]^2}{\sigma^0[(M/\pi^0)_{th}] + \sigma^2[(M/\pi^0)_{exp}]}, \quad (5)$$

where the theoretical ratios are given by eq. (4). For each angle θ_{PS}, this is a χ^2 which for the pure minimum twist case has 6 degrees of freedom (the number of bins in $p_\perp$ to be fitted) whereas the inclusion of higher twist leads to 5 degrees of freedom due to the dependence on the extra parameter $\lambda = c_1^2/[2(1-\gamma)K]$.

The estimate of $\gamma/(1-\gamma)$ is obtained by minimizing a χ^2 similar to eq. (5), but with $M = \omega$, having one degree of freedom since λ is always fixed – to zero in the MT case and to the value that minimizes eq. (5) in the MT+HT case. Notice further that the ω production does not depend on θ_{PS}.

In both the pure MT case as well as the MT+HT case we get the same estimate of the vector meson parameter, $\gamma = 0.4$, which in turn gives $K \approx 2.3$. As discussed above this can be considered as a reasonable value of the K-factor needed in our problem.

All other relevant results are collected in tables 1 and 2, where the results of our calculations for both the pure MT and the MT+HT case are compared with the experimental data. The results are given for the two reference values of θ_{PS} $(-11°, -19°)$ and for the value which minimizes eq. (5). (The variation of the ω/π^0 ratio with θ_{PS} are purely statistical fluctuations from the Monte Carlo calculation.) As a general remark, valid for both the MT and MT+HT case, it is clear that $\theta_{PS} = -19°$ is too large in magnitude to give a correct value of η'/π^0 at $p_\perp > 3$ GeV/c. For $\theta_{PS} = -11°$, the results from MT alone do not provide a good desription of the η/π^0 and η'/π^0 ratios; by lowering the absolute value of θ_{PS} the η'/π^0 ratio can be reproduced, but only at the expense of a worse η/π^0 ratio. The inclusion of the higher twist process gives a much better agreement in this case $(\theta_{PS} = -11°)$ with the complete set of experimental data under study.

By minimizing eq. (5) with respect to θ_{PS} in the range $-10°$ to $-19°$ we find, for MT alone, the best agreement for $\theta_{PS} = -16.5°$. All ratios can then be well reproduced *except* η'/π^0 at $p_\perp > 3$ GeV/c. By including the higher twist processes, a comfortable agreement with *all* ratios can be obtained for $\theta_{PS} = -15°$. The corresponding χ^2-values are also given in tables 1, 2 and show that this last solution is indeed the best one.

For the minimum twist case, one should note that the increase of η'/π^0 with increasing $p_\perp$ (table 1) is in contrast to the opposite, decreasing tendency of the data. The inclusion of the higher twist process cures this problem (table 2) by adding an η' contribution mainly at lower $p_\perp$. Indeed, although the fundamental $p_\perp^{-6}$ dependence for HT and $p_\perp^{-4}$ for MT is changed by structure function effects and fragmentation, the basic ratio HT/MT$\propto p_\perp^{-2}$ holds as a rough approximation when neglecting the variations within the considered $p_\perp$ interval. The soft nature of the gluon distribution in the proton produces a faster decrease with $x_\perp = 2p_\perp/\sqrt{s}$ of the higher twist η' production since it is strongly dominated by gluon induced processes (fig. 1) at lower $p_\perp$.

Conclusions. From the discussion above it seems legitimate to conclude that the data in refs. [8,9], when taken as a whole, provide evidence for the existence of higher twist processes in high-$p_\perp$ η' production as predicted [6]. A value of the pseudoscalar mixing angle as large as $-19°$ is, however, disfavoured since agreement with all the data, in partic-

Table 1
Cross-section ratios for minimum twist case.

θ_{PS} (deg)	χ^2/DOF	η'/π^0 [%]		η/π^0 [%] in $p_\perp$ intervals [GeV/c]				ω/π^0 [%]	
		$p_\perp > 3.0$	$p_\perp > 6.0$	3.1–3.5	3.5–4.0	4.0–5.0	5.0–7.0	$p_\perp > 3.0$	$p_\perp > 6.0$
−11	11/6	60± 3	90± 6	48±3	53±5	53±6	53±4	65± 2	97± 4
−19	9.6/6	45± 2	62± 5	63±3	62±5	52±6	71±6	72± 3	94± 4
−16.5[a]	5.3/5	51± 2	72± 5	57±3	57±5	51±6	61±6	68± 2	95± 4
Data[b]		90±25	70±30	58±3	58±4	63±5	55±9	87±17	90±18

[a] Best value obtained through the minimization procedure discussed in the text.
[b] Experimental data from refs. [8,9].

Table 2
Cross-section ratios for minimum plus higher twist case.

θ_{PS} (deg)	χ^2/DOF	$\frac{c_1^2}{2(1-\gamma)K}$	η'/π^0 [%]		η/π^0 [%] in $p_\perp$ intervals [GeV/c]				ω/π^0 [%]	
			$p_\perp > 3.0$	$p_\perp > 6.0$	3.1–3.5	3.5–4.0	4.0–5.0	5.0–7.0	$p_\perp > 3.0$	$p_\perp > 6.0$
−11	5.6/5	0.84	109± 3	107± 6	52±3	57±5	56±6	56±4	78± 2	105± 4
−19	9.6/5	0.05	48± 2	63± 5	63±3	62±5	54±6	72±6	85± 2	103± 4
−15[a]	2.2/4	0.64	91± 3	92± 6	57±3	59±5	54±6	58±4	79± 2	104± 4
Data[b]			90±25	70±30	58±3	58±4	63±5	55±9	87±17	90±18

[a] Best value obtained through the minimization procedure discussed in the text.
[b] Experimental data from refs. [8,9].

ular the η'/π^0 ratio, is reached when $-16° \lesssim \theta_{PS} \lesssim -12°$. This implies an amount of higher twist contribution given by

$$0.52 \lesssim c_1^2/2(1-\gamma)K \lesssim 0.80\,, \qquad (6)$$

which means that

$$1.2 \lesssim c_1 \lesssim 1.5\,. \qquad (7)$$

This result is equivalent [6] to a power, β, of the meson wave function in the range $0.15 \lesssim \beta \lesssim 0.20$. It cannot be excluded that the range in eq. (7) is influenced by non-negligible higher order corrections to prompt meson production. If one, e.g., assumes a K-factor of ≈ 2, as in minimum twist processes, the "true" range of c_1 is lowered to

$$0.85 \lesssim (c_1)_{\text{true}} \lesssim 1\,, \qquad (8)$$

which would mean $0.25 \lesssim \beta \lesssim 0.32$; in agreement with ref. [4] but considerably lower than $\beta = 1$ as proposed in ref. [1].

More accurate data on medium to high transverse momentum ($2 < p_\perp < 6$ GeV/c) of η and η' mesons would, of course, allow more firm conclusions. In particular, multiparticle triggers of the kind used by the CERN WA77 collaboration [4] would enhance the higher twist contribution and decrease the ill-controlled effects of primordial transverse momentum in standard leading twist process [17,24].

A value for $|\theta_{PS}|$ higher than indicated by our best fit (15°), could possibly be compensated by a harder gluon distribution in the proton. Although this would increase higher twist production of both η and η' by the same factor, the larger η' cross section will give a more noticeable effect when added to the minimum twist contribution. Another way to circumvent this possible problem would be to include a gluon component in the η' [25], which would give additional higher twist production of η' through mixing with the 0^{-+} glueball production channel [6].

Finally we want to emphasize that the above results seem to be in good correspondence with the evidene for prompt ρ^0 production at $p_\perp > 2$ GeV/c in 300 GeV π^-N scattering [4] which was obtained based on the same kind of model calculations. Thus, taken together they constitute even stronger support for the occurrence of higher twist processes.

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