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Central pseudoscalar production in pp scattering and the gluon contribution to the proton spin

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Abstract

Central pseudoscalar production in pp scattering is suppressed at small values of $Q_\perp$, where Q is defined as the difference between the momenta transferred from the two protons. Such a behaviour is expected if the production occurs through the fusion of two vectors. Photon exchange could provide the dominant contribution here, but we argue that an extension of the experiment could probe the gluon contribution to the proton spin.

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1 Introduction

The use of a glueball-$q\bar{q}$ filtering method has been recently advocated to study central hadron production in pp scattering [1]. At this occasion, it was noticed that, somewhat surprisingly, pseudoscalar production (and in general $q\bar{q}$ mesons production) was suppressed at small values of $Q_\perp$ [2], where Q is defined as the difference of the momenta transferred from the two protons.

We show in this note that such a behaviour is precisely expected if a pseudoscalar meson is produced through the fusion of two vector intermediaries. Furthermore, we argue that the dominant observed contribution in the exclusive channel $pp \to ppX$ could be due to two photon exchange, but that an extension of the experiment would test the gluon contribution to the proton spin.

In Sect. 2 we introduce the basic formulæ. In Sect. 3 we try to work a way around some important experimental cuts to provide suggestions for comparison to the data. In particular, we provide the $Q_\perp$ distribution at fixed $k_\perp$, k being the momentum of the resonance X. This allows for a comparison between π^0, η and $\eta\prime$ production and a test of the electromagnetic nature of the process. Finally, in Sect. 4 we advocate extending the study to non-exclusive channels $pp \to \tilde{p}\tilde{p}X$, where $\tilde{p}$ are jets corresponding to p fragmentation, to observe the QCD equivalent of the process. We then argue that a measurement of the production cross section at $Q_\perp = 0$ would provide a test of the gluon contribution to the proton spin.

2 The basic formulæ

The WA102 and NA12 experiments [2, 3] have examined in kinematical detail the reaction $pp \to ppX$ where X is a single resonance produced typically in the central region of the collision between a proton beam and an hydrogen target.

We will be more particularly interested in the case where X is a $J^P = 0^-$ state, notably π^0, η or $\eta\prime$. The interest of this experiment is that the kinematics are entirely determined (in fact overdetermined) since the momenta of all protons are known and the disintegration of X is entirely measured (e.g. in the $\gamma\gamma$ mode).

The production cross section is affected by two distinct mechanisms: *i)*

the emission of the intermediaries from the protons and *ii)* the fusion of those intermediaries into the resonance X.

The production of a pseudoscalar resonance through the fusion of two intermediaries in parity conserving interactions could arise from scalar-pseudoscalar (SP) or vector-axial (VA) fusion if no factor of momenta is allowed, or, vector-vector (VV) or axial-axial (AA) fusion if the momentum variables can be used [4, 5]. Since the first axial resonance is rather heavy, we restrict ourselves to low-lying states in SP or VV fusion.

In the case of SP fusion, the only pseudoscalar which could be involved in the π^0, η and $\eta\prime$ production is the particle itself, but we still need to find a low-lying scalar, possibly the "sigma" or a "pomeron" state. Moreover, due to the absence of any derivative coupling, the suppression of the production cross section at small $Q_\perp$ cannot be understood, and thus, it cannot be a leading contribution. This leaves VV fusion as the only alternative.

Vector-vector fusion is possible through the vector-vector-pseudoscalar (VVP) coupling

$$C_{VVP} = \epsilon_{\mu\nu\alpha\beta} q_1^\mu q_2^\nu \epsilon_1^\alpha \epsilon_2^\beta \ , \tag{1}$$

where q_1 and q_2 are the momenta of the exchanged vectors with polarizations ϵ_1 and ϵ_2 respectively. This coupling is well known from the anomalous decay $\pi^0 \to \gamma\gamma$. When evaluated in the X rest frame with $k = q_1 + q_2$ and $Q = q_1 - q_2$, it yields simply

$$C_{VVP} = -\frac{1}{2} m_X \vec{Q} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \ , \tag{2}$$

where clearly the difference $\vec{Q}$ between q_1 and q_2 3-momenta appears now as a factor and we thus expect a suppression at small $\vec{Q}$. But this is insufficient in itself to explain the suppression observed at small $Q_\perp = |\vec{Q}_\perp|$, where $\vec{Q}_\perp$ is defined as the vector component of $\vec{Q}$ transverse to the direction of the initial proton beam. However, as seen from (2), the polarizations of the vectors play an essential role. In particular, in the X rest of frame, $\vec{\epsilon}_1 \times \vec{\epsilon}_2$ must have components in the $\vec{Q}$ direction, which implies that both $\vec{\epsilon}_1$ and $\vec{\epsilon}_2$ must have components in the plane perpendicular to $\vec{Q}$, that is, the exchanged vectors must have transverse polarization (helicity $h = \pm 1$). In other terms, the production process will be proportional to the amount of intermediate vectors with $h = \pm 1$.

If we consider now the emission of a vector from a fermion, we observe that in the high-energy limit the vector only couples to $\bar{f}_L \gamma^\mu f_L$ and $\bar{f}_R \gamma^\mu f_R$,

that is, the helicity of the fermion cannot change. In the X rest frame, assumed to lie in the central region of the production, the colliding fermions cannot (unless they were backscattered, a situation contrary to the studied kinematical region) emit $h = \pm 1$ vectors in the forward directions, as this would violate angular momentum conservation.

We thus reach the conclusion that in the above-mentioned kinematical situation, the production of pseudoscalar mesons by two-vector fusion cannot happen if $\vec{Q}$ is purely longitudinal, but requires $\vec{Q}_\perp \neq \vec{0}$ [3].

It is easy to write down the differential cross section for the central production of pseudoscalar resonance X in the reaction $pp \to ppX$. Although it may seen daring to treat the p as a pointlike particle in the process considered, this approximation of the ppV (V any vector) coupling seems phenomenologically more reasonable than the use of a quark parton model when strictly exclusive processes are considered (where p fragmentation is not allowed for).

We use the following notations: $p_1 = (E; 0, 0, p)$ is the beam proton momentum, p_2 the target proton momentum, p_3 the momentum of the outgoing proton closest to the beam kinematical area and p_4 the momentum of the outgoing proton closest to the target kinematical area. The transferred momenta to the intermediate vectors are $q_1 = p_1 - p_3$ and $q_2 = p_2 - p_4$ respectively, and the momentum of the resonance X is then defined as $k = (W; \vec{k}_\perp, k_\parallel) = q_1 + q_2$ with $k^2 = m_X^2$ and $W = \sqrt{m_X^2 + k_\perp^2 + k_\parallel^2}$. We also define $Q = (\omega; \vec{Q}_\perp, Q_\parallel) = q_1 - q_2$ as the difference between the momenta transferred from the two protons.

The differential cross section reads

$$\frac{d\sigma}{dQ_\perp dk_\perp dk_\parallel d\varphi} = \frac{1}{(2\pi)^4} \frac{1}{128 W E p} \frac{k_\perp Q_\perp}{|(2p - Q_\parallel)(2E - W) - k_\parallel \omega|} \overline{|\mathcal{M}|^2} \,, \quad (3)$$

where we have choosen as integration variables: $Q_\perp = |\vec{Q}_\perp|$, $k_\perp = |\vec{k}_\perp|$, $k_\parallel$ and φ defined as the angle between the two transverse vectors $\vec{k}_\perp$ and $\vec{Q}_\perp$. The averaged square of the invariant matrix amplitude $\mathcal{M}$ at the lowest order

[3] There is still a loophole: $\vec{q}_1$ and $\vec{q}_2$ must have transverse components, but in a small area of phase space we could still have $\vec{Q}_\perp = (\vec{q}_1 - \vec{q}_2)_\perp = \vec{0}$. The explicit calculation below shows this is not significant.

in the vector exchange is expressed in terms of kinematical invariants as[4]

$$\begin{aligned}
\overline{|\mathcal{M}|^2} &= \frac{(e^2 g_{VVP})^2}{(t_1 - m_V^2)^2 (t_2 - m_V^2)^2} \{ \frac{t_1 t_2}{2} [(k\cdot Q)^2 - m_X^2 Q^2] \\
&+ t_1 [m^2((k\cdot Q)^2 - m_X^2 Q^2) + m_X^2 (p_2\cdot Q)^2 + Q^2 (p_2\cdot k)^2 \\
&\quad -2(p_2\cdot k)(p_2\cdot Q)(k\cdot Q)] \\
&+ t_2 [m^2((k\cdot Q)^2 - m_X^2 Q^2) + m_X^2 (p_1\cdot Q)^2 + Q^2 (p_1\cdot k)^2 \\
&\quad -2(p_1\cdot k)(p_1\cdot Q)(k\cdot Q)] \\
&+ 4 \left(\epsilon_{\mu\nu\alpha\beta} p_1^\mu p_2^\nu k^\alpha Q^\beta \right)^2 \} \ ,
\end{aligned} \tag{4}$$

where g_{VVP} stands for the coupling constant of the VVP interaction (e is the electric charge), $t_{1,2}$ are the square of the momentum transfer to each vector, m_V is the mass of the exchanged vector, m_X the resonance mass and m the proton mass. In order to write (3) in terms of the integration variables we have used the following substitutions: $(p_{1,2}\cdot k) = EW \mp pk_\parallel$, $(p_{1,2}\cdot Q) = E\omega \mp pQ_\parallel$, $(k\cdot Q) = W\omega - k_\parallel Q_\parallel - k_\perp Q_\perp \cos\varphi = -2pk_\parallel + 2E\omega$, $Q^2 = \omega^2 - Q_\perp^2 - Q_\parallel^2 = -m_X^2 + 4EW - 4pQ_\parallel$ and $t_{1,2} = q_{1,2}^2 = E(W \pm \omega) - p(Q_\parallel \pm k_\parallel)$.

Due to the smallness of t_1 and t_2 we have checked that independently of the mass of the vector exchanged, the dominant contribution of (4) to the cross section (3) comes from the term proportional to $1/(t_1 - m_V^2)^2 (t_2 - m_V^2)^2$. The differential cross section thus simplifies to

$$\begin{aligned}
\frac{d\sigma}{dQ_\perp dk_\perp dk_\parallel d\varphi} &\simeq \frac{1}{(2\pi)^4} \frac{1}{128 W E p} \frac{k_\perp Q_\perp}{|(2p - Q_\parallel)(2E - W) - k_\parallel \omega|} \\
&\times 16 (e^2 g_{VVP})^2 E^2 p^2 \frac{k_\perp^2 Q_\perp^2 \sin^2\varphi}{(t_1 - m_V^2)^2 (t_2 - m_V^2)^2} \ ,
\end{aligned} \tag{5}$$

where now one can clearly see the suppression of the cross section at small $Q_\perp$ (and indeed $\lim_{Q_\perp \to 0} d\sigma = 0$), as it is seen experimentally.

Once the expression for the differential cross section is presented, we may now enter into conjectures about the nature of the vectors exchanged. The simplest candidates for elementary particles are of course photon or gluon,

[4]Given the experimental condition, the diagram where the "fast" and "slow" protons are exchanged gives a negligible contribution, and it is not included in (4).

with the possible addition of the massive vectors ρ, ω and ϕ. Again, due to the smallness of t_1 and t_2, we have checked that the dominant contribution to the simplified cross section (5) comes from the exchange of massless vectors, so we neglect the possible contributions of massive vectors. Then, we are left with photons or gluons. However, in the present situation, gluon exchange seems not to be the dominant contribution, as it would lead to a large number of $\eta\prime$ and η and no π^0, while the opposite is observed experimentally. Most probably, the selection of isolated protons in the final state is too restrictive for gluon exchange to take place significantly. So then, we conclude that a pure photoproduction hypothesis may be the main contribution to the cross section.

Assuming the photoproduction mechanism as the main responsible of the pseudoscalar production, we would like to point out that any relevant information can be obtained here of the (t_1, t_2) behaviour of the $\gamma\gamma$-pseudoscalar from factor, a question highly discussed in the literature [6].

3 Working around the cuts

As we have seen in the previous section, photon-photon fusion could be the main mechanism responsible for the pseudoscalar production in the central region. One can see that this mechanism tends to favour low values of exchanged momenta. Thus, we observe that the cross section tends to peak sharply at small values of $Q_\perp \simeq k_\perp$ (through the photon denominators), even though it decreases to zero when $Q_\perp$ or $k_\perp \to 0$.

This behaviour is however difficult to observe experimentally, due to the presence of experimental set-up restrictions, leading to a loss of acceptance when the transverse momenta of the outgoing protons decreases. This seems to be specially sensitive for the "slow proton". As a result, although the theoretical cross section peaks for small non-zero values of $Q_\perp \simeq k_\perp$, this domain of parameter space is totally inadequate for a detailed comparison to experiment.

In practice, we suggest to work at fixed $k_\perp$ (for instance, at $k_\perp = 0.5$ GeV) in order to avoid the experimental restrictions, and explore the $Q_\perp$ dependence of the cross section. In that case, pseudoscalar production by photon-photon fusion (and in general by any vector-vector fusion) will be characterized by the vanishing of the cross section at small $Q_\perp$.

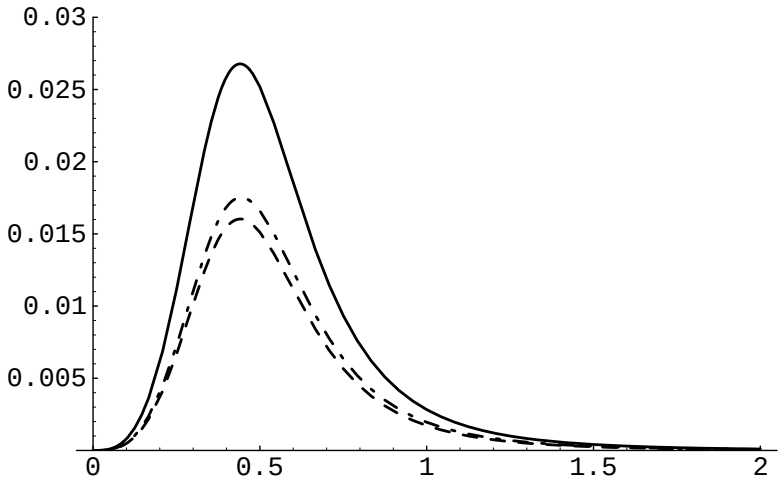

Figure 1: Differential cross section for $pp \to ppX$ ($d\sigma \times 10^{-6}$ (GeV^{-2})), as a function of $Q_\perp$ (GeV). We have fixed $k_\perp = 0.5$ GeV and $k_{||} = 0$, and this plot is given for $\varphi = 45°$. The curves describe $X = \pi^0$ (solid line), $X = \eta$ (dashed line) and $X = \eta\prime$ (dashed-dotted line).

We give as examples, curves[5] of the pseudoscalar production cross section of π^0, η and $\eta\prime$ as a function of $Q_\perp$ for two characteristic values of the angle φ between $\vec{k}_\perp$ and $\vec{Q}_\perp$. For $\varphi = 45°$ (or in fact, any value of the angle φ far away from 0° and 180°), both $q_{1\perp}$ and $q_{2\perp}$ are far from zero, and we do not expect acceptance restrictions. On the contrary, for $\varphi \simeq 10°$ (or in fact, any value of the angle φ close to 0° and 180°), the cross section turns out to be much larger, but we expect here acceptance limitations, since close to $Q_\perp = k_\perp$ we can have either $q_{1\perp} \approx 0$ or $q_{2\perp} \approx 0$.

While these curves are given as indicatives and seem to have some bearing to published data, a detailed comparison, which can only be made with an

[5]For simplicity, we have restricted ourselves to the case $k_{||} = 0$.

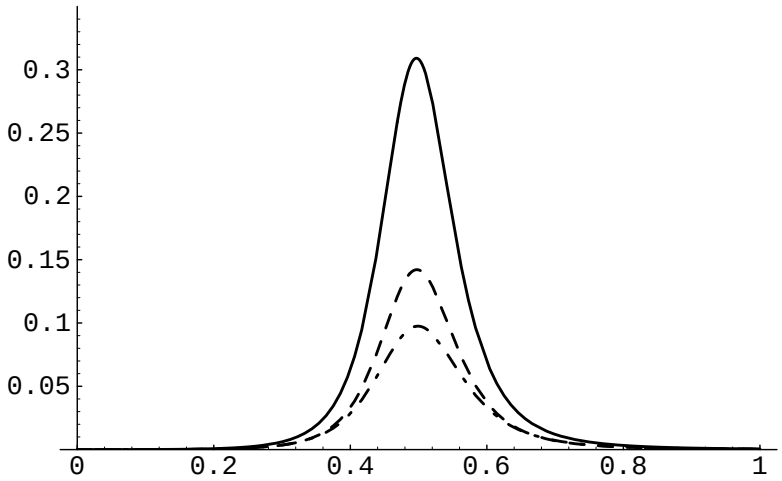

Figure 2: The same as Fig. 1 but for $\varphi = 10°$.

extensive simulation of the experimental detection, is clearly to be left to the experimental collaborations.

A work equivalent to the former can be done if instead of using $Q_\perp$ as the distribution variable for the curves one uses the azimutal angle ϕ (not to be confused with the angle φ introduced before) between the fast and slow proton that is related to $Q_\perp$ by $\cos\phi = \frac{Q_\perp^2 - k_\perp^2}{4 q_{1\perp} q_{2\perp}}$.

4 Extending the approach to gluons

In this final section, we would like to advocate for an extension of the present study to non-exclusive processes $pp \to \tilde{p}\tilde{p}X$, where $\tilde{p}$ are jets corresponding to p fragmentation, in order to observe the QCD equivalent of the production mechanism (gluon-gluon fusion).

In this case indeed, we must distinguish between gluons emitted from

the fermionic partons (and obeying the helicity constraints discussed at the beginning of the previous section) and "constituents" or "sea" gluons. The latter simply share part of the proton momentum and their helicity is in no way constrained. Helicity $h = \pm 1$ gluons can then be met even for $\vec{Q}_\perp = \vec{0}$, and in that case we would expect that the production distributions in $Q_\perp$ could be considerably affected.

In this possible extension of the experiments, the $\eta\prime$ and η now produced at small $Q_\perp$ are sensitive to the polarization of the individual gluons in the proton. Such polarization of the individual gluons is always present independently of the total polarization of the gluons in the proton, and is in itself not indicative of the fact that a significant proportion of the proton spin could be carried by the gluons. If such would be the case however, and a net polarization of the gluons exists, a similar experiment conducted with polarized beams or target would lead to a difference in the production rates of $\eta\prime$ and η at small $Q_\perp$, and provide a direct measurement of this polarization.

In summary, we have shown in this letter that the experimental evidence of the suppression at small $Q_\perp$ of the central pseudoscalar production in pp scattering can be explained if the production mechanism is through the fusion of two vectors, with photon exchange probably the dominant contribution. We also have proposed an extension of such experiments in order to observe the QCD equivalent of the process and to provide a test for the gluon contribution to the proton spin.

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