Vector Meson Production at a Polarized HERA Collider

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Abstract

A successful interpretation of the cross sections for elastic and inelastic vector meson production can be made if one assumes the underlying dynamics to be governed by hard partonic subprocesses. Extending these partonic approaches to longitudinally polarized electron-proton collisions, we estimate the expected production asymmetries at the HERA collider. The anticipated statistical errors on these asymmetries mostly turn out to be larger than the asymmetries themselves, such that an experimental observation of these asymmetries at HERA looks not feasible.

1 Introduction

Vector mesons produced in lepton-nucleon collisions can be identified relatively easy from their decay signatures (e.g. $\rho \to \pi^+\pi^-$ or $J/\psi \to \mu^+\mu^-$). They are therefore among the most commonly studied final state observables in lepton-nucleon scattering experiments (e.g. [1, 2]). Depending on the virtuality of the incoming photon, one distinguishes the photoproduction ($Q^2 \approx 0$) and leptoproduction ($Q^2 \gg \Lambda^2_{\rm QCD}$) of vector mesons. The photoproduction cross sections are usually larger than the leptoproduction cross sections, which show a steep fall–off with increasing Q^2. Moreover, one has to distinguish between elastic (diffractive) and inelastic production of vector mesons. The identification of the elastic events in the experimental measurement can be made by tagging on a large rapidity gap around the outgoing proton direction or by requiring the vector meson to have the same energy as the incoming photon.

Both elastic and inelastic cross sections can be modeled in approaches based on a partonic interpretation of the underlying subprocess. The elastic production of vector mesons can be interpreted to be due to perturbative two gluon exchange with a $q\bar{q}$ pair in the photon wave function, which subsequently forms the vector meson [3, 4]. This model and its predictions for elastic polarization asymmetries will be presented in Section 2 and numerical predictions for HERA are contained in Section 3. The color singlet model [5] for inelastic heavy vector meson production assumes this process to be dominated by photon-gluon fusion, yielding a $q\bar{q}$ final state which transforms into a color singlet state by the emission of one hard gluon. Implications of this model for polarization asymmetries will be discussed in Section 4. For both elastic and inelastic production, we estimate the expected statistical errors of a measurement at a polarized HERA collider with an integrated luminosity of 1000 pb^{-1}, based on the measured unpolarized cross sections.

2 Two gluon exchange model for elastic vector meson production

The final state configuration of diffractive electron-proton interactions, containing an only minimally deflected proton, requires these processes to be mediated by the exchange of a color singlet configuration between proton and virtual photon. The simplest purely perturbative model for this color singlet exchange is given by two gluons, which are emitted simultaneously from the incoming proton. This perturbative two gluon exchange is the basis of a model [3, 4] which yields a successful description of the unpolarized elastic J/ψ and ρ production cross sections.

The leading logarithmic contribution to diffractive vector meson production in this model comes from the Feynman graphs shown in Fig.1. The upper quark loop describes the transition of the initial photon into a quark–antiquark pair which then forms the vector meson V. The vector meson wave function is included into the vertex $q\bar{q} \to V$.

In the Born approximation (neglecting the dashed lines in Fig.1) the amplitude of the interaction of the $q\bar{q}$ pair with the target proton is given by the two gluon exchange. We consider the region of small $x = (Q^2 + M_V^2)/W^2 \ll 1$ and large scale $Q^2 + M_V^2 \gg \Lambda^2$. The last is needed to justify the perturbative QCD approach.

To find the leading logarithmic approximation (LLA), which resums all terms of the form $\alpha_s^n \cdot \ln^n[(Q^2 + M_V^2)/\Lambda^2]$, one has to consider the ladder type diagrams which include the dashed lines shown in Fig.1. This is done by the replacement of the lower part of the diagram by the gluon structure function $G(x, q^2)$ which describes the probability to find an appropriate t-channel gluon in a proton. Therefore one finds for the unpolarized amplitude $\mathcal{A} \propto G(x, q^2)$. Extending this calculation to the spin dependent part of the amplitude, one finds $\Delta\mathcal{A} \propto x\Delta G$ [6, 7].

From the formal point of view, the amplitudes $\mathcal{A}$ and $\Delta\mathcal{A}$ are proportional to the off-diagonal distributions $G(x, x')$ (or $\Delta G(x, x')$) but when the difference $\delta x = x - x' \ll 1$ is small these off-diagonal distribution are rather close [8] ($\pm 10 \ldots 20\%$) to the diagonal ones, i.e. to the conventional structure functions $G(x)$ and $\Delta G(x)$.

The asymmetry for the J/ψ photo(lepto)production was calculated in [6] in the leading order

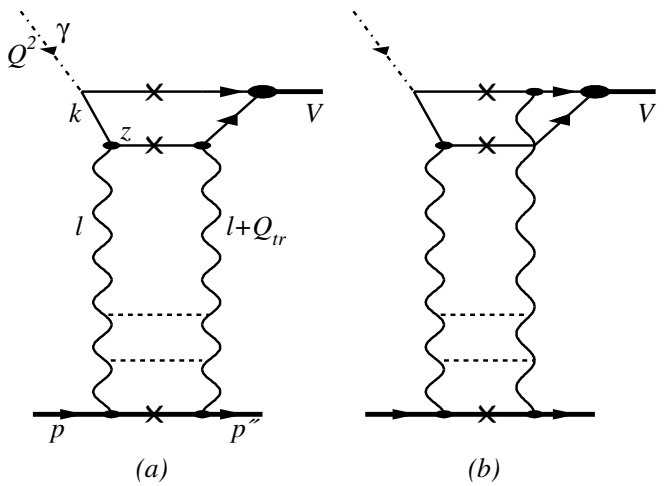

Figure 1: Diffractive open $q\bar{q}$ production in high energy $\gamma^* p$ collisions via the two gluon exchange.

(LO) LLA using the non-relativistic J/ψ wave function. It was found to be

$$A^{\gamma^* p \to J/\psi p} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = \frac{2\Delta G \cdot G}{G^2 + \Delta G^2} \simeq \frac{2\Delta G}{G} , \tag{1}$$

where the factor 2 arises from the fact that the unpolarized cross section is proportional to the gluon density squared while the polarized cross section comes from the interference term of spin-dependent and spin-independent amplitudes.

While the large charm quark mass justified the use of a non-relativistic wave function for the J/ψ, this is clearly inappropriate to ρ production. A consistent calculation would require the incorporation of the (unknown) relativistic wave function of the ρ-meson. To overcome this problem the hadron-parton duality hypothesis was used. The idea is as follows. Let us consider the amplitude of the open $q\bar{q}$ leptoproduction, project it on the state with the spin $J^{PC} = 1^{--}$ (isospin $I^G = 1^+$) and average over a mass interval $\Delta M_{q\bar{q}}$ (typically ~ 1 GeV^2) in the region of ρ mass. In this domain the more complicated partonic states ($q\bar{q} + g$, $q\bar{q} + 2g$, $q\bar{q} + q\bar{q}, ...$) are suppressed, while on the hadronic side the 2π states are known to dominate. Thus for low M^2 we mainly have $\gamma^* \to q\bar{q} \to 2\pi \to \rho$ or in other words

$$\sigma(\gamma^* p \to \rho p) \simeq \sum_{q=u,d} \int_{M_a^2}^{M_b^2} \frac{\sigma(\gamma^* p \to (q\bar{q})' p)}{dM^2} dM^2 \tag{2}$$

where the limits M_a^2 and M_b^2 are chosen so that they appropriately embrace the ρ-meson mass region and $(q\bar{q})'$ means the projection of the $q\bar{q}$ system onto the $J^{PC} = 1^{--}$, $I^G = 1^+$ state.

In ref. [9] it was demonstrated that based on this hadron-parton duality one can describe the diffractive ρ-meson electroproduction on the unpolarized target rather well in the framework of perturbative QCD, for both longitudinal and transverse ρ polarization. Thus we use the hadron-parton duality for the polarized cross sections as well.

It turns out that in the relativistic ρ system the asymmetry is washed out by the "Fermi motion" of the light quarks in the ρ-meson wave function. So the analyzing power becomes 4 times smaller [7]. Including the projection on the ρ quantum numbers, the asymmetry reads

$$A^{\gamma^* p \to \rho p} \simeq \frac{\gamma(G)\Delta G}{2\gamma(\Delta G) G} , \tag{3}$$

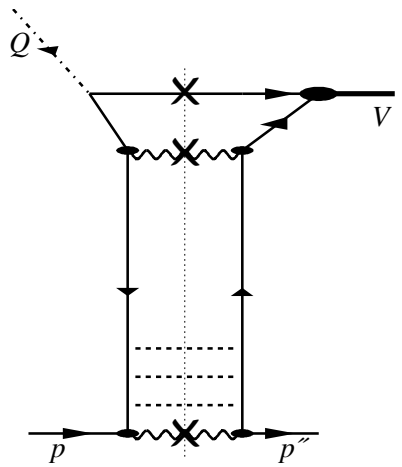

Figure 2: Diffractive open $q\bar{q}$ production in high energy $\gamma^* p$ collisions via the quark exchange.

where $\gamma(G, \Delta G)$ are the anomalous dimensions of the unpolarized and polarized gluon distributions in the small x region. Besides this the spin dependent light quark distributions also contribute to the ρ asymmetry (see Fig.2).

This approach can be extended a variety of other diffractive processes, including e.g. vector meson production with diffractive target dissociation. A brief overview is given in [10].

3 Asymmetries in elastic ρ leptoproduction and J/ψ photoproduction at HERA

Using the formulae for asymmetries in elastic vector meson production discussed above, it is possible to produce quantitative estimates for these asymmetries at HERA. Given that the polarized gluon distribution $\Delta G(x, Q^2)$ is only loosely constrained from present data, these estimates can only give an idea of the expected magnitude of the asymmetries, without attempting to make precise predictions. To illustrate this uncertainty, we use different parameterizations of the (leading order) polarized gluon distribution, GS(A–C) [11] and GRSVs [12], which were obtained from fits to polarized deep inelastic scattering data. These are consistently used in combination with the unpolarized (leading order) gluon distribution of [13].

All asymmetries defined above are valid for the ideal case of the collision of a polarized photon with a polarized proton. In electron-proton scattering experiments, only part of the electron polarization is transferred to the photon. This photon depolarization is described by the ratio of polarized to unpolarized electron-to-photon splitting functions

$$D(y) = \frac{1-(1-y)^2}{1+(1-y)^2} \; . \tag{4}$$

The effect of the photon depolarization is illustrated in Fig. 3, comparing the photon-proton and electron-proton asymmetries for J/ψ photoproduction at HERA. In particular at low values of $W_{\gamma p}$, corresponding to low y, the asymmetry is lowered by several orders of magnitude. The resulting observable J/ψ photoproduction asymmetry in electron-proton collisions never exceeds

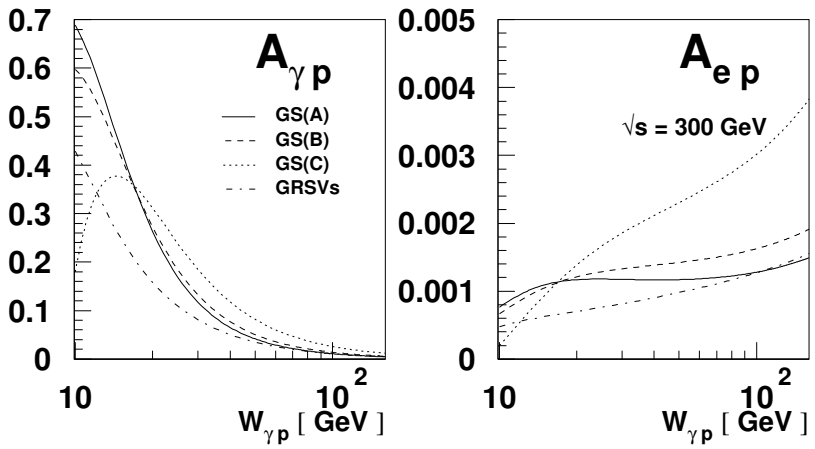

Figure 3: Asymmetries in elastic J/ψ photoproduction: photon-proton asymmetry (left) and electron-proton asymmetry at HERA (right).

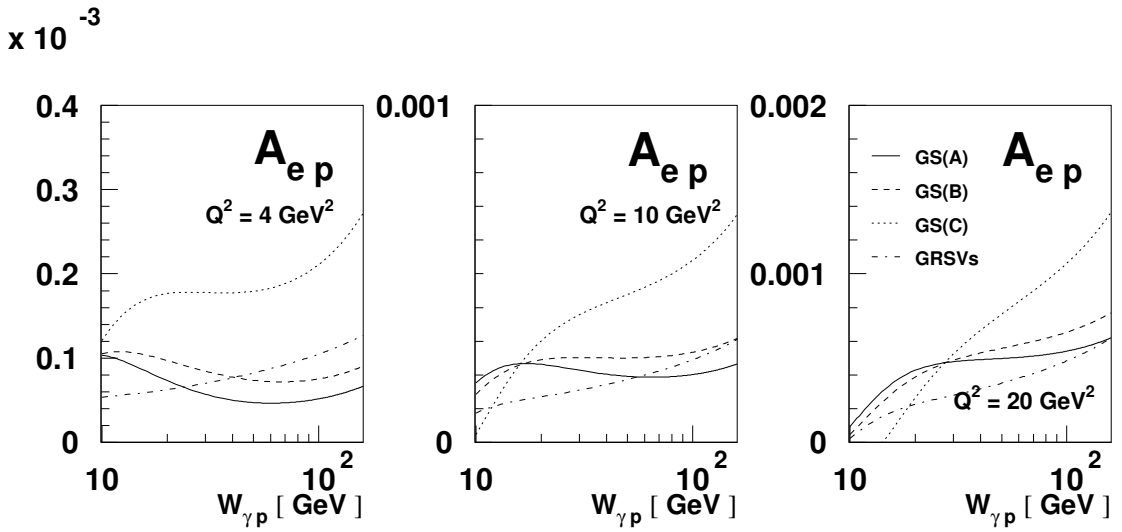

Figure 4: Asymmetries in elastic ρ leptoproduction for different Q^2.

0.004. Based on the experimental measurement of the unpolarized elastic J/ψ photoproduction cross section [2], it is possible to estimate the expected statistical accuracy of such a measurement. For an integrated luminosity of 1000 pb^{-1}, product of beam polarizations $P_p \cdot P_e = 0.5$ and reconstruction efficiency $\epsilon_{J/\psi} = 0.12$, we find that it would be possible to obtain four data-points in the region of $W_{\gamma p} = 40 \ldots 140$ GeV, each with a statistical error of ± 0.005 on the asymmetry. This estimate illustrates that the elastic J/ψ photoproduction asymmetry is unlikely to be observable at the HERA collider. We have moreover checked that no significant improvement is made for this measurement if the HERA centre-of-mass energy is lowered to $\sqrt{s} = 180$ GeV.

Finally, the electron-proton asymmetry for elastic Υ photoproduction is found to be about one order of magnitude larger than for the J/ψ. Since the unpolarized elastic Υ photoproduction cross section is not accurately known at present, it is however difficult to provide a sensible error estimate for this asymmetry.

An estimate of the asymmetry in elastic ρ meson electroproduction, based on the formulae of [7] is shown in Fig. 4. Since we are only interested in an order-of-magnitude determination of this asymmetry, two approximations have been made. As suggested in [7], we have used fixed anomalous dimensions for the small x behaviour of the parton distributions. The integration over the momentum fractions carried by quark and antiquark is simplified by using the saddle point method.

All parameterizations of $\Delta G(x, Q^2)$ yield electron-proton asymmetries of the order of 0.0001 at $Q^2 = 4$ GeV^2, which rise by about one order of magnitude if Q^2 is increased to 20 GeV^2. It is found that the contribution from the polarized quark sea (cf. Fig. 2) amounts maximally 10% to the total asymmetry. Based on the unpolarized measurement of [1], we have again estimated the anticipated errors on this asymmetry, using the same parameters as above, but $\epsilon_\rho = 1$. With two bins in the interval $W_{\gamma p} = 40 \ldots 140$ GeV, the estimated error on each point would be ± 0.01 for $Q^2 = 10$ GeV^2 and ± 0.015 for $Q^2 = 20$ GeV^2, which is about one order of magnitude larger than the expected asymmetry. Thus the ρ meson leptoproduction asymmetry is clearly not measurable at the HERA collider.

4 Asymmetries in inelastic heavy vector meson photoproduction at HERA

In the framework of the color singlet model, the inelastic photoproduction of a heavy vector meson is described as the perturbative production of a color singlet $q\bar{q}$ pair with the quantum numbers of the quarkonium state [5]. The formation of a meson from the quark pair is a non-perturbative process. Its probability reduces to a single parameter related to the meson wave function at the origin $|\Psi(0)|^2$, which is thought to be known for J/ψ and Υ families from the leptonic decay widths $\Gamma(V \to l^+l^-)$. This model yields a satisfactory description [14] of recent experimental data [1], once next-to-leading order corrections [15] to partonic subprocess and meson wave function are included.

An application of the color singlet model to vector meson production in polarized photon–hadron collisions has been proposed in ref. [16]. The next-to-leading order corrections are presently unknown in the polarized case, one should however expect that they partially cancel in the polarization asymmetry, the ratio of polarized and unpolarized cross sections. In particular, the leading order asymmetry is insensitive to the choice of the renormalization scale μ used in the strong coupling constant $\alpha_s(\mu)$, while polarized and unpolarized cross sections scale like $\alpha_s^2(\mu)$.

In addition to the color singlet production the so-called color octet mechanism [17] is also widely discussed in the literature. This model considers the production of a $q\bar{q}$ pair in a color octet state, i.e. with "wrong" quantum numbers. Then, after a (serial) soft gluon emission this pair is assumed to convert into real meson. The probabilities for the color octet transitions are not calculable within the theory and are in fact free model parameters. Their values have been estimated in ref. [18] from a fit to Tevatron data on J/ψ hadroproduction. However, the applicability of the color octet model to HERA conditions is doubtful. Given the transition probabilities (i.e. the color octet matrix elements) as estimated in the original paper [18], the color octet model predictions seem to disagree with the experimental results for ep collisions [19]. Several solutions to this disagreement have been proposed, the situation is however still inconclusive. Since the color singlet model alone yields already a good description [14] of the unpolarized data at HERA, we shall restrict us to this model and consistently neglect possible color octet contributions.

The analyzing power of the partonic subprocess $\gamma+g \to J/\psi+g$ is rather large, but a substantial suppression is induced by the ratio of polarized to unpolarized gluon densities $\Delta G(x)/G(x)$ and the photon depolarization factor $D(y)$, eq. (4). In the region $p_t < 2.5$ GeV (where the cross section is high) the visible polarization asymmetry for J/ψ photoproduction at HERA conditions does not exceed 0.002, while its average value stays at $A \simeq 0.0007$ (see fig. 5). Here we have assumed that no other cuts than the inelasticity requirement $z = E_{J/\psi}/E_\gamma < 0.9$ are applied. The anticipated statistical errors (± 0.002 for the same parameters as in the previous section but only a single bin covering the whole 30 GeV $< W_{\gamma p} <$ 150 GeV range at HERA, cf. [1]) on a measurement of this asymmetry exceed the value of this asymmetry by almost one order of magnitude.

The kinematical selection of large-x, large-y region may give access to highly polarized gluons and photons, but only at the price of practically vanishing partonic cross section. For example, the condition $x > 0.03$, $y > 0.2$ would lead to $D(y)\,\Delta G(x)/G(x) \gtrsim 0.04$, but implies $\hat{\sigma}(\gamma + g \to J/\psi + g)$ falling by three orders of magnitude. The increase in the observable asymmetry is therefore more than compensated by the strongly decreasing event statistics. Finally, the replacement of the J/ψ meson by a Υ meson enhances the asymmetry by approximately one

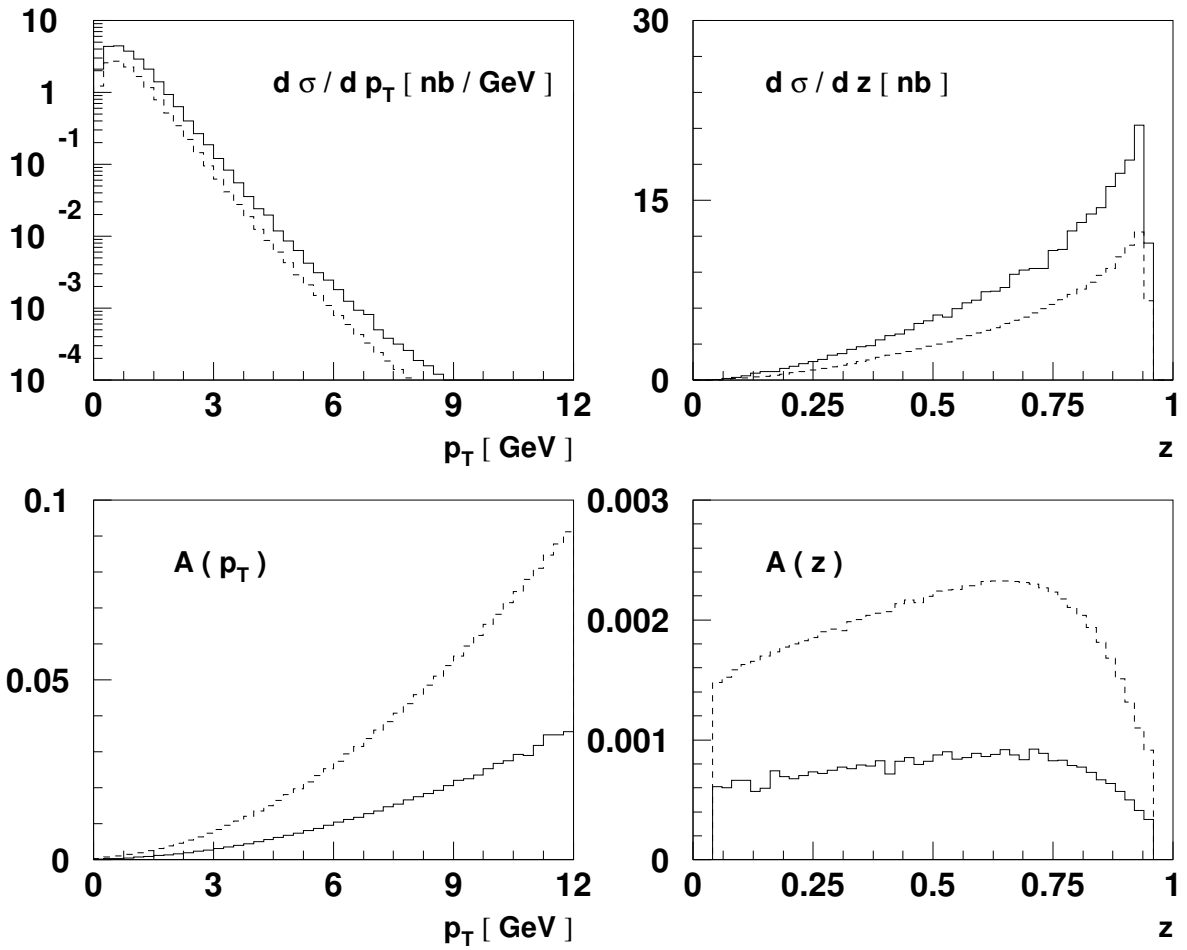

Figure 5: Production cross sections and polarization asymmetries in inelastic J/ψ photoproduction at HERA, $\sqrt{s} = 300$ GeV (solid histogram) and 190 GeV (dashed histogram). Cross sections and asymmetries are plotted as function of the J/ψ transverse momentum p_T (left) and of the photon energy fraction z carried by the J/ψ (right). The unpolarized parton distribution functions are taken from GRV [13], the polarized ones from GS, set (A) [11].

order of magnitude (i.e. from $5 \cdot 10^{-4}$ to $5 \cdot 10^{-3}$) but also yields a production rate which is lowered by a factor of 500 ($\sigma_\Upsilon \simeq 20$ pb versus $\sigma_{J/\psi} \simeq 10$ nb at $\sqrt{s} = 300$ GeV). The situation does not significantly improve if HERA is operated at $\sqrt{s} = 180$ GeV. In this context, the measurement of the polarization asymmetries in inelastic heavy vector meson production at HERA collider seems infeasible.

5 Conclusions

In this report we have investigated the asymmetries in the production of vector mesons in polarized electron-proton collisions at HERA. Our estimates are based on the extension of perturbative models for unpolarized elastic and inelastic production of vector mesons to the polarized case. Numerical studies of elastic and inelastic J/ψ photoproduction and elastic ρ electroproduction have shown that the prospects for a measurement of asymmetries in vector meson production

are rather poor, since the magnitude of the expected asymmetries is usually similar or smaller than the expected statistical errors on the measurement. The lowering of the HERA proton beam energy would lead to an enhancement of all vector meson production asymmetries, this enhancement is however not sufficient to make these asymmetries experimentally accessible.

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