Polarized Parton Densities and Processes

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Abstract. The main goals of 'spin physics' are recalled, and some theoretical and phenomenological aspects of longitudinally polarized deep inelastic scattering and other hard processes are reviewed. The spin dependent parton densities of protons and photons and polarized fragmentation functions are introduced, and the relevant theoretical framework in next-to-leading order QCD is briefly summarized. Technical complications typical for spin dependent calculations beyond the leading order of QCD, like a consistent γ_5 prescription, are sketched, and some recent results for jet and heavy quark production are discussed. Special emphasis is put on conceivable measurements at a future polarized upgrade of the HERA collider which is currently under consideration.

1 Introduction

One of the most fundamental properties of elementary particles is their spin. However, the vast majority of past and present experiments at high energy e^+e^-, ep, and pp colliders are performed with unpolarized beams thus neither exploiting the advantages of polarization, which were demonstrated, e.g., by the SLD experiment at SLAC, nor revealing any information on the spin dependence of fundamental interactions. Unlike lepton beams it is an extremely challenging task to maintain the polarization of protons throughout the acceleration to high energies, which explains the lack of polarized ep or pp collider experiments in the past. To circumvent this problem, a series of fixed target experiments with longitudinally polarized lepton beams scattered off, e.g., proton targets have been performed at comparatively low energies over the past few years [1].

Aiming at polarized deep inelastic scattering (DIS) these experiments have been used to extract first information about the spin dependent parton densities

$$\Delta f^H(x,Q^2) \equiv f_+^{H+}(x,Q^2) - f_-^{H+}(x,Q^2) \ , \tag{1}$$

where f_+^{H+} (f_-^{H+}) denotes the density of a parton f with helicity '+' ('−') in a hadron H with helicity '+'. It is important to notice that the Δf^H contain information *different* from that included in the more familiar unpolarized distributions f^H [defined by taking the sum on the r.h.s. of (1)], and their measurement is indispensable for a *complete* understanding of the partonic structure of hadrons. However, due to the lack of any experimental information apart from DIS and the limited kinematical coverage in x and Q^2 of the available measurements [1], our knowledge of the Δf is still rather rudimentary compared to the abundance of results on f.

Much experimental progress and, hopefully, exciting new results have to be expected in the next couple of years. Most importantly measurements of, for instance, jet, prompt photon, and W-boson production rates at the recently completed first polarized pp collider RHIC will vastly reduce our ignorance of the Δf. Ongoing efforts in the fixed target sector by HERMES [2] and (soon) by COMPASS [3] to study, in particular, semi-inclusive DIS and charm production, respectively, will contribute to a more complete picture of polarized parton densities as well. Here we will mainly focus on the prospects of a conceivable future polarized upgrade of the HERA ep collider [4], which is currently under scrutiny, and highlight on some important measurements uniquely possible at an ep collider.

Having pinned down the polarized parton densities (1) one can study one of the most fundamental aspects of polarization: the question of how the spin S_z of non-pointlike objects like nucleons is composed of the spin of their constituents, the quarks and gluons, and their orbital angular momentum $L_z^{q,g}$. The total contribution of quarks and gluons to S_z is determined by the first moments of (1), $\Delta f(Q^2) \equiv \int_0^1 \Delta f(x,Q^2)dx$, and S_z can be written as

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta g(Q^2) + L_z^q(Q^2) + L_z^g(Q^2) \;\; , \tag{2}$$

where $\Delta\Sigma \equiv \sum_q (\Delta q + \Delta\bar{q})$ and Q denotes the 'resolution scale' at which the nucleon is probed. The so far unmeasured angular momentum contribution $L_z^{q,g}$ has attracted considerable theoretical interest recently, and it was suggested [5] that deeply virtual Compton scattering $\gamma^*(Q^2)p \to \gamma p'$ in the limit of vanishing momentum transfer $t = (p-p')^2$ *may* provide first direct information on $L_z^{q,g}$, however this subject is beyond the scope of this talk.

The definition of polarized parton densities (1) also holds true for the hadronic content of *photons*, Δf^γ, and can be easily extended to the time-like case, i.e., spin dependent fragmentation functions, ΔD_f, as well. Both densities have been measured in the unpolarized case, and their Q^2 evolution provides an important test of perturbative QCD. Needless to stress again that a measurement of Δf^γ and ΔD_f is required for a complete understanding of space- and time-like distributions. So far Δf^γ is completely unmeasured, and almost nothing is known experimentally about spin dependent fragmentation. It is argued below that a polarized HERA would be also an ideal place to learn more about these densities.

Our contribution is organized as follows: First we review the spin dependent proton structure and shall give an example of a recent QCD analysis of polarized DIS data [6]. Then the framework is extended to the case of Δf^γ and ΔD_f, and theoretical models for these densities are introduced. Next we turn to polarized processes and briefly sketch the basic technical framework and complications due to the appearance of γ_5. Finally we discuss the main results of two recently finished NLO calculations: jet [7,8] and heavy flavor production [9]. It should be noted that we have to omit several interesting topics such as L_z, transverse polarization and transversity distributions, single spin processes, etc. Some recent results and references can be found, e.g., in [10].

2 Polarized Proton Structure and DIS

Longitudinally polarized DIS can be described by introducing a structure function g_1, in analogy to F_2 and F_L in the helicity-averaged case. The NLO expression for g_1 reads (suppressing the obvious x and Q^2 dependence)

$$g_1 = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \left[(\Delta q + \Delta\bar{q}) \otimes \left(1 + \frac{\alpha_s}{2\pi} \Delta C_q\right) + \frac{\alpha_s}{2\pi} \Delta g \otimes \Delta C_g \right] , \qquad (3)$$

where $\Delta C_{q,g}$ are the spin dependent Wilson coefficients, and the symbol $\otimes$ denotes the usual convolution in x space. From (3) it is obvious that the available inclusive DIS data [1] can reveal only information on $\Delta q + \Delta\bar{q}$, but neither on Δq *and* $\Delta\bar{q}$ nor on Δg, which enters (3) only as an $\mathcal{O}(\alpha_s)$ correction. Thus all QCD analyses [11,12,6] have to impose certain *assumptions* about the flavor decomposition in order to be able to estimate other hard processes for upcoming experiments like RHIC. Alternatively one can stick, of course, to a comprehensive analysis of quantities accessible in polarized DIS [13,14].

The Δf obey the standard DGLAP Q^2 evolution equations – with all unpolarized quantities such as splitting functions replaced by their spin dependent counterparts (given in [15,16]) – which are readily solved analytically in Mellin n moment space. A subtlety arises in NLO in the non-singlet (NS) sector [17]. The independent NS combinations $q_- = q - \bar{q}$ and $q_+ \sim q - q'$ evolve in the unpolarized and the polarized case with the same but interchanged kernels, i.e., $P_\pm = \Delta P_\mp$. This simply reflects the fact that in the unpolarized case the first moment of q_-, the number of valence quarks, is conserved with Q^2, whereas in the polarized case $\Delta q_+(Q^2)$ refers to a conserved NS axial vector current. The Δf are constrained by the unpolarized densities via the positivity condition

$$\left|\Delta f(x,Q^2)\right| \leq f(x,Q^2) \, , \qquad (4)$$

which is exploited in most of the QCD analyses. Of course, the bound (4) is strictly valid only in LO and is subject to NLO corrections [18] because the Δf become unphysical, scheme dependent objects in NLO. However the corrections are not very pronounced, in particular at large x [18], the only region where (4) imposes some restrictions in practice and hence (4) can be used also in NLO.

Figure 1 shows the result of a recent NLO QCD analysis [6] of all presently available data [1]. The fit is performed directly to the measured spin asymmetry

$$A_1(x,Q^2) \simeq \frac{g_1(x,Q^2)}{F_2(x,Q^2)/[2x(1+R(x,Q^2))]}, \qquad (5)$$

where $R = F_L/2xF_1$, rather than to the extracted structure function g_1 itself. Eq. (5) is related to the polarized-to-unpolarized cross section ratio $\Delta\sigma/\sigma$, and experimental uncertainties like the absolute normalization conveniently drop out.

As mentioned above, each QCD fit has to rely on several assumptions. The shown GRSV analysis [6] is characterized by the choice of a low starting scale for the evolution, $Q_0 \approx 0.6\,\mathrm{GeV}$, the $\overline{\mathrm{MS}}$ scheme, and a simple but flexible ansatz

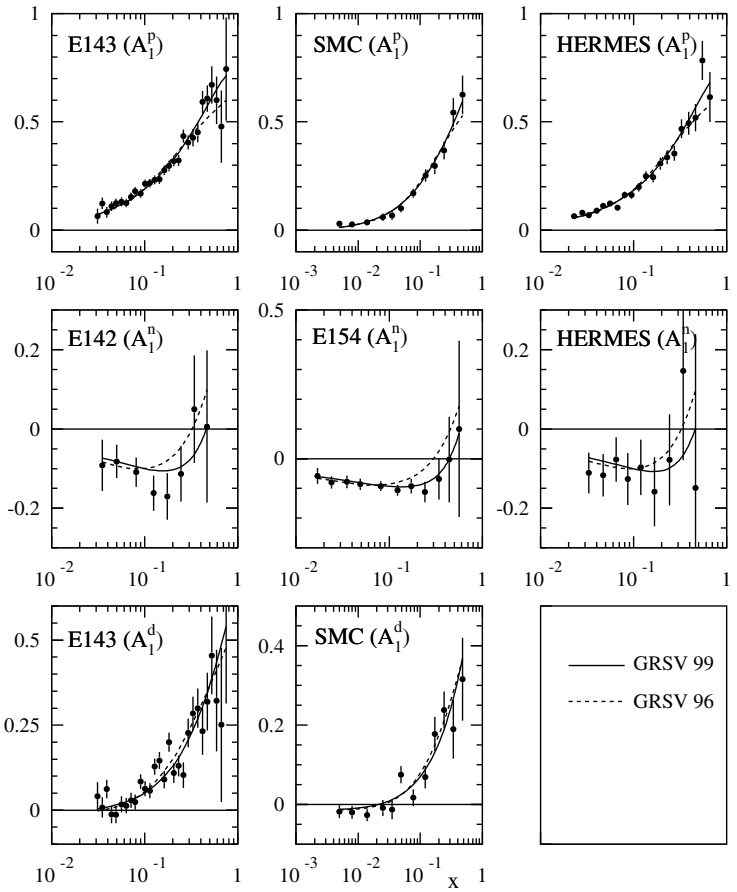

Fig. 1. Comparison of an updated NLO QCD analysis [6] in the GRSV framework [11] with available data sets [1] (the E155 data are not shown, but included in the fit). Also shown are the original GRSV results [11] based on older and fewer data sets.

for the polarized densities $\Delta f(x,Q_0^2) = N_f x^{\alpha_f}(1-x)^{\beta_f} f(x,Q_0^2)$, *assuming* that $\Delta\bar{q} = \Delta\bar{u} = \Delta\bar{d}$ and $\Delta s = \Delta\bar{s} = \lambda\Delta\bar{q}$. For the unpolarized reference distributions f the updated GRV densities [19] have been used, which also fixes the choice of Q_0 (and $\alpha_s(M_z^2) = 0.114$). The remaining free parameters are determined by the fit after exploiting constraints for the first moments of the NS combinations Δq_+ (F and D values) and by *choosing* $\lambda = 1$, i.e., a $SU(3)_f$ symmetric sea.

The individual parton densities Δf resulting from the fit in Fig. 1 are shown in Fig. 2. To demonstrate that, in particular, the gluon density is hardly constrained at all by present data, two other fits based on additional *ad hoc* constraints on Δg are shown in Fig. 2. The '$\Delta g = 0$' fit starts from a vanishing gluon input, and the 'static Δg' is chosen in such a way that its first moment becomes roughly independent of Q^2. Both gluons give also excellent fits to the available

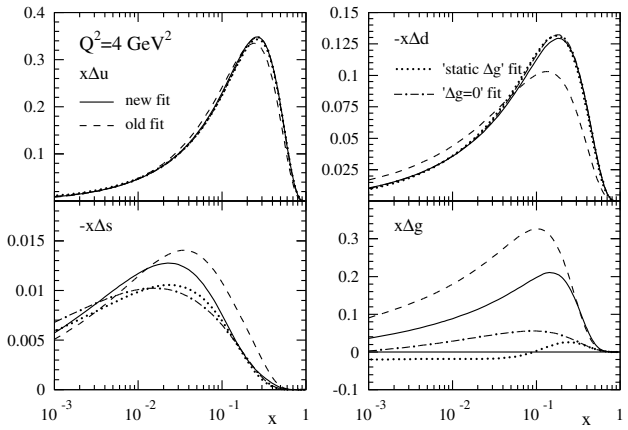

Fig. 2. The polarized NLO $\overline{\rm MS}$ densities at $Q^2 = 4\,{\rm GeV}^2$ as obtained in the new [6] and old [11] GRSV analyses. Also shown are the distributions obtained in two other fits employing additional constraints on Δg (see text).

data and do not affect the results for u and d. In fact one can obtain fits without changing χ^2 by more than one unit for an even wider range of gluon inputs. This uncertainty in Δg is compatible with the findings of other recent analyses such as [14]. In addition, similarly agreeable fits are obtained, e.g., for the choice $\lambda = 1/2$ as well as by using an independent x shape for Δs, reflecting the above mentioned uncertainty in the flavor separation. The range of results for the Δf obtained by the various QCD analyses [6,11–14] gives a rough measure of the theoretical uncertainties due to different assumptions used for the fits.

It is interesting to observe that for the 'best fit' gluon in the GRSV framework [6,11] the spin of the nucleon (2) is dominantly carried by quarks and gluons at the low bound-state like input scale Q_0, and only during the Q^2 evolution a large negative $L_z^g(Q^2)$ is being built up in order to compensate for the strong rise of $\Delta g(Q^2)$, see Fig. 5 in [20]. However, no definite conclusions can be reached yet because for the 'static Δg' the situation is completely different, and S_z is entirely of angular momentum origin for *all* values of Q^2, contrary to what is intuitively expected. In addition, direct measurements of $L_z^{q,g}$ are completely missing.

Inevitably the large uncertainty in Δg implies that the small x behaviour of g_1 is completely uncertain and not reliably predictable as is illustrated in Fig. 3. This translates also into a sizeable theoretical error for the $x \to 0$ extrapolation when calculating first moments of g_1, which play an important role in spin physics since they are related to predictions such as the Bjorken sum rule [21]. The situation is similar to our ignorance of the small x behaviour of F_2 in the pre-HERA era and can be resolved only experimentally. Needless to say that a polarized variant of HERA would be of ultimate help here. In addition, the high Q^2 region would be accessible for the first time at HERA. Here electroweak effects become increasingly important and new structure functions, which probe different combinations of parton densities, enter.

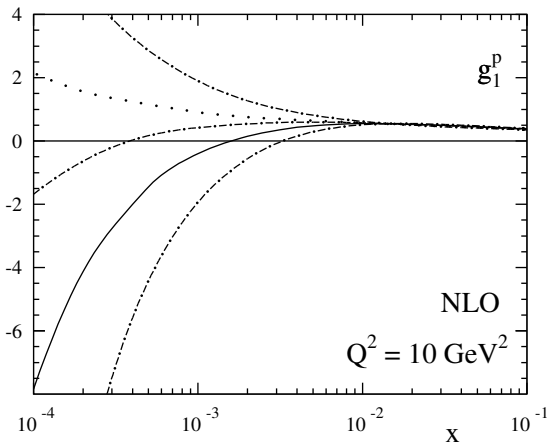

Fig. 3. Predictions for the small x behaviour of g_1 by extrapolating from the measured region $x > 0.01$ to smaller x values for different assumptions about Δg. The solid line is the result obtained using the 'best fit' Δg of [6] as shown in Fig. 2.

3 Polarized Photon Structure and Fragmentation

The complete NLO QCD framework for the Q^2 evolution of Δf^γ and the calculation of the polarized photon structure function g_1^γ, which would be accessible in $e\gamma$ DIS at a future polarized linear collider [22], was recently provided in [23]. Unlike the proton densities the Δf^γ obey an *inhomogeneous* evolution equation schematically given by

$$\frac{d\Delta q_i^\gamma}{d\ln Q^2} = \Delta k_i + (\Delta P_i \otimes \Delta q_i^\gamma) \quad , \tag{6}$$

where q_i^γ stands for the flavor NS quark combinations or the singlet (S) vector $\Delta \boldsymbol{q}_S^\gamma \equiv \binom{\Delta\Sigma^\gamma}{\Delta g^\gamma}$, and Δk_i denotes the photon-to-parton splitting functions. Again, solutions of (6), which can be decomposed into a 'pointlike' (inhomogeneous) and a 'hadronic' (homogeneous) part, $\Delta q_i^\gamma = \Delta q_{i,PL}^\gamma + \Delta q_{i,had}^\gamma$, can be given analytically for n moments (cf. [24]). It should be noted that perturbative instabilities for g_1^γ in the $\overline{\mathrm{MS}}$ scheme due to the $x \to 1$ behaviour of the photonic coefficient function ΔC_γ [23] can be avoided, as in the unpolarized case [24], by absorbing ΔC_γ into the definition of the quark densities [23] (DIS_γ scheme).

At present the Δf^γ are unmeasured, and one has to fully rely on theoretical models. The only guidance is provided by the positivity constraint analogous to Eq. (4). The 'current conservation' (CC) condition [25], which demands a vanishing first moment of g_1^γ and is automatically fulfilled for the pointlike part [23], is not very useful without any data since it can be implemented at x values smaller than the one is interested in, say, at $x < 0.005$. To obtain a realistic estimate for the theoretical uncertainties in Δf^γ coming from the unknown hadronic input, one can consider two very different models [26,23] by either saturating

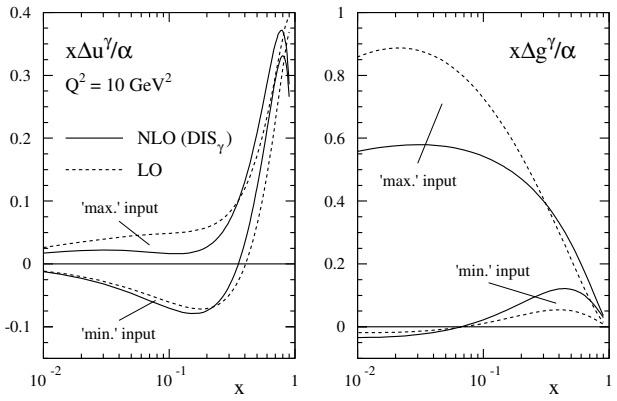

Fig. 4. $x\Delta u^\gamma/\alpha$ and $x\Delta g^\gamma/\alpha$ evolved to $Q^2 = 10\,\mathrm{GeV}^2$ in LO and NLO (DIS_γ) using the two extreme models explained in the text.

the positivity bound (4) at $Q_0 \simeq 0.6\,\mathrm{GeV}$ ('maximal scenario') with the phenomenologically successful unpolarized GRV photon densities [27] or by using a vanishing input ('minimal scenario'). The resulting Δf^γ for both scenarios are shown in Fig. 4 and will be applied below to estimate the prospects of measuring Δf^γ in photoproduction processes at a polarized HERA in the future.

Studies of *spin transfer reactions* could provide further invaluable insight into the field of spin physics. A non-vanishing twist-2 spin transfer asymmetry requires the measurement of the polarization of one outgoing particle, in addition to having a polarized beam or target, and is sensitive to spin dependent *fragmentation*. Λ baryons are particularly suited for such studies due to the self-analyzing properties of their dominant weak decay, which were successfully exploited at LEP [28] to reconstruct the Λ spin. In [29] a first attempt was made to extract the spin dependent Λ fragmentation functions, ΔD_f^Λ, by analyzing these data [28], which, however, turned out to be insufficient. Rather different, physically conceivable scenarios appear to describe the data equally well, and for the 'unfavoured' sea quark and gluon fragmentation functions one has to fully rely on mere assumptions. Clearly, further measurements are required to test the models proposed in [29], and, again, HERA can play an important role here.

The time-like (TL) ΔD_f^Λ are defined in a similar way as their space-like (SL) counterparts in Eq.(1) via

$$\Delta D_f^\Lambda(z,Q^2) \equiv D_{f_+}^{\Lambda_+}(z,Q^2) - D_{f_+}^{\Lambda_-}(z,Q^2) \quad , \tag{7}$$

where, e.g., $D_{f_+}^{\Lambda_+}(z,Q^2)$ is the probability for finding a Λ baryon with positive helicity in a parton f with positive helicity at a mass scale Q, carrying a fraction z of the parent parton's momentum. The Q^2 evolution of (7) is similar to the SL case, and it should be recalled only that the off-diagonal entries in the singlet evolution matrices $\Delta\hat{P}^{(SL,TL)}$ interchange their role when going from the SL to the TL case, see, e.g., [30,31].

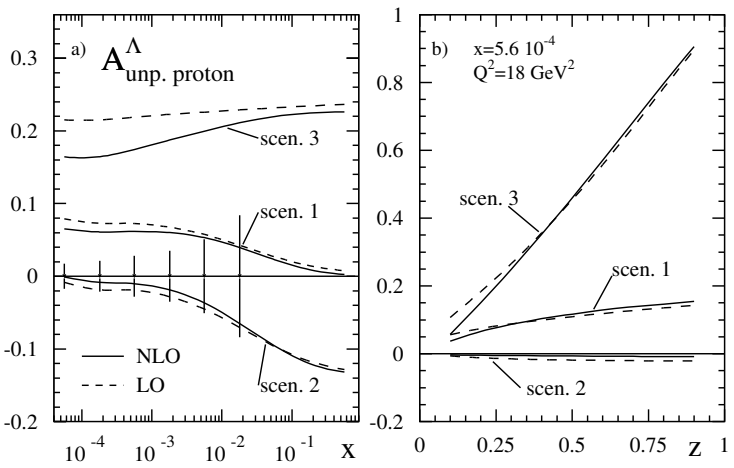

Fig. 5. The semi-inclusive DIS asymmetry A^{Λ} for unpolarized protons and polarized Λ's and leptons for the three distinct scenarios of ΔD_f^{Λ} of [29]. In **a)** the expected statistical errors for such a measurement at HERA are shown, assuming a luminosity of $500\,\text{pb}^{-1}$, a lepton beam polarization of 70%, and a Λ detection efficiency of 0.1.

As a manifestation of the so-called Gribov-Lipatov relation [32] the SL and TL splitting functions are equal in LO. Furthermore they are related by analytic continuation (ACR) of the SL splitting functions (Drell-Levy-Yan relation [33]), which can be schematically expressed as ($z < 1$)

$$\Delta P_{ij}^{(TL)}(z) = z\mathcal{AC}\left[\Delta P_{ji}^{(SL)}(x = \frac{1}{z})\right], \tag{8}$$

where the operation $\mathcal{AC}$ analytically continues any function to $x \to 1/z > 1$ and correctly adjusts the color factor and the sign [31]. The breakdown of the ACR beyond the LO in the $\overline{\text{MS}}$ scheme can be understood in terms of a corresponding breakdown for the $n = 4-2\varepsilon$ dimensional LO splitting functions and can be easily accounted for by a simple factorization scheme transformation [31]. Alternatively, the ACR breaking can be calculated, of course, graph-by-graph [31] in the light-cone gauge method [34], which is of course much more cumbersome.

LO and NLO predictions for the semi-inclusive spin asymmetry A^{Λ} for the production of polarized Λ's in DIS of *unpolarized protons* off polarized leptons [29] is shown in Fig. 5 for three different conceivable models of the ΔD_f^{Λ} mentioned above (see [29] for details). Such types of spin measurements, which would help to pin down the ΔD_f^{Λ} more precisely, can be performed at HERA immediately after the spin rotators in front of H1 and ZEUS have been installed even *without* having a polarized proton beam. Similar studies can be done in the photoproduction case where an integrated luminosity of only about $100\,\text{pb}^{-1}$ would be sufficient [35]. Helicity transfer reactions can be also examined in pp collisions at RHIC [36].

4 Polarized Processes

4.1 Some General Remarks, γ_5, and All That

To calculate longitudinally polarized cross sections one has to project onto the two independent helicity configurations of the incoming polarized partons (for simplicity we ignore here helicity transfer processes where the formalism applies in a similar way). This is achieved by using the standard relations (see, e.g., [37])

$$\epsilon_\mu(k,\lambda)\,\epsilon^*_\nu(k,\lambda) = \frac{1}{2}\left[-g_{\mu\nu} + i\lambda\epsilon_{\mu\nu\rho\sigma}\frac{k^\rho p^\sigma}{k\cdot p}\right] \tag{9}$$

for incoming bosons with momentum k and helicity λ, and where p denotes the momentum of the other incoming particle, and

$$u(k,h)\bar{u}(k,h) = \frac{1}{2}\,\not{k}(1-h\gamma_5) \tag{10}$$

for incoming massless quarks with momentum k and helicity h. Using (9) and (10) one can calculate the cross sections for unpolarized *and* polarized beams *simultaneously* by taking the sum or the difference of the two helicity dependent squared matrix elements

$$\text{unpolarized}: \quad \overline{|M|}^2 = \frac{1}{2}\left[|M|^2(++) + |M|^2(+-)\right] \tag{11}$$

$$\text{polarized}: \quad \Delta|M|^2 = \frac{1}{2}\left[|M|^2(++) - |M|^2(+-)\right] \tag{12}$$

where $|M|^2(h_1,h_2)$ denotes the squared matrix element for any of the contributing subprocesses for definite helicities h_1 and h_2 of the incoming particles. The possibility to recover well-known unpolarized results 'for free' is usually regarded as a first important check on the correctness of the spin dependent results.

As usual the presence of IR, UV, and collinear singularities demands some consistent method to make them manifest. For this purpose one usually works in the well-established framework of n dimensional regularization (DREG), which immediately leads to complications in the polarized case since both γ_5 and the totally antisymmetric tensor $\epsilon_{\mu\nu\rho\sigma}$ in (9) and (10) are genuine *four* dimensional and have no straightforward continuation to $n \neq 4$ dimensions[1]. Since the use of a naive anticommuting γ_5 in n dimensions is known to lead to algebraic inconsistencies [42], one usually chooses to work in the HVBM scheme [43], which was shown to be internally consistent in n dimensions, and its peculiarities will be briefly reviewed below. Alternatively one can stick to an anticommuting γ_5 by abandoning the cyclicity of trace [44]. In this scheme a 'reading point'

[1] Sometimes a variant of DREG, dimensional *reduction* [38] (DRED), is preferred. Here the Dirac algebra is performed in *four* rather than n dimensions. However, extra counterterms have to be introduced to match the UV sectors of DREG and DRED [39,40]. Once this is done DREG and DRED are simply related by a factorization scheme transformation [40,41,16].

has to be defined from where *all* Dirac traces of a given process have to be started which can be a quite cumbersome procedure. Another prescription was suggested to handle traces with one γ_5 [45] by utilizing $\gamma_\mu\gamma_5 = i/(3!)\epsilon_{\mu\nu\rho\sigma}\gamma^\nu\gamma^\rho\gamma^\sigma$ and contracting the resulting Levi-Civita tensors in n dimensions. This avoids $(n-4)$ dimensional scalar productions which show up in the HVBM scheme but results in more complicated trace calculations. Needless to say that in the end all consistent prescriptions should give the same result when used appropriately.

In the HVBM scheme [43] the four dimensional definition for γ_5 is maintained, and the ϵ-tensor is regarded as a genuinely four dimensional object. In this way the n dimensional space is splitted up into a four and a $(n-4)$ dimensional subspace, and $(n-4)$ dimensional scalar products ('*hat momenta*') can show up in $|M|^2\,(h_1,h_2)$ apart from their usual n dimensional counterparts (i.e., Mandelstam variables). For single inclusive jet or heavy quark production, e.g., one can choose a convenient frame where all non-vanishing $(n-4)$ dimensional scalar products can be expressed by a single hat momenta combination $\hat{p}^2$. These terms deserve special attention when performing the $2 \to 3$ phase space integrations since the $(n-4)$ dimensional subspace cannot be integrated out trivially as in any unpolarized calculation. However, the modified phase space can be conveniently written as $\mathrm{dPS}_3 = \mathrm{dPS}_{3,\mathrm{unp}} \times \mathcal{I}(\hat{p}^2)$ such that it reduces to the well-known 'unpolarized' phase space formula $\mathrm{dPS}_{3,\mathrm{unp}}$ for the vast majority of terms in the matrix element which do not depend on $\hat{p}^2$; see [46,9] for details.

The remaining calculation is then standard and proceeds in the same way as for any unpolarized cross section with one further crucial exception concerning the factorization of mass singularities. It was observed [16] that the LO polarized splitting function in $n = 4-2\varepsilon$ dimensions in the HVBM prescription, $\Delta P_{qq}^{(0),n}$, is no longer equal to its unpolarized counterpart, i.e., it violates helicity conservation, $\Delta P_{qq}^{(0),n}(x) - P_{qq}^{(0),n}(x) = 4C_F\varepsilon(1-x)$. This unwanted property has to be accounted for by an additional factorization scheme transformation whenever a pole $\sim \Delta P_{qq}^{(0)} 1/\varepsilon$ has to be subtracted [16]. When talking about the $\overline{\mathrm{MS}}$ scheme in the polarized case in connection with the HVBM prescription, it is always understood that this additional transformation is already done.

4.2 Some Recent Results: Jets, Heavy Quarks

Let us finally focus on some recent phenomenological results. The complete NLO QCD corrections for jet production in polarized pp [7] and ep [8] collisions have become available recently in form of MC codes which allow to study all relevant differential jet distributions. The photoproduction of jets at a polarized HERA is known to be an excellent tool to extract first information on the photonic densities Δf^γ by experimentally enriching that part of the cross section that stems from 'resolved' photons [47]. In case of single inclusive jet production this can be achieved by looking into the direction of positive jet rapidities (proton direction), and this feature was shown to be maintained also at NLO [8]. In addition, an improved dependence of the cross section on the factorization and

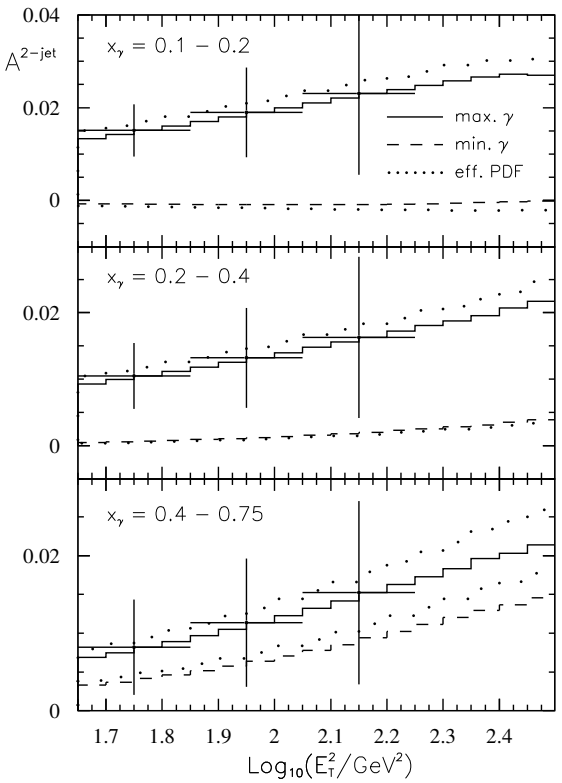

Fig. 6. Predictions for $A^{2-\mathrm{jet}}$ for different bins in x_γ using the two scenarios for Δf^γ as described in the text and the LO GRSV distributions [11] for Δf^p. Also shown are the results using the effective parton density approximation and the expected statistical errors assuming a luminosity of 200 pb^{-1} and 70% beam polarizations.

renormalization scales, μ_f and μ_r, respectively, was found, and the LO jet spin asymmetries in [47] receive only moderate NLO corrections [8].

Similar studies of *di*-jet production have the advantage that the kinematics of the underlying hard subprocess can be fully reconstructed and the momentum fraction x_γ of the photon can be determined on an experimental basis. In this way it becomes possible to experimentally suppress the 'direct' photon contribution by introducing some suitable cut $x_\gamma \leq 0.75$ [48], or by scanning different bins in x_γ. Very encouraging results were found in [49], and it was shown that the LO QCD parton level calculations nicely agree with 'real' jet production processes including initial and final state QCD radiation as well as non-perturbative effects such as hadronization, as modeled using the spin dependent `SPHINX` MC [50].

Figure 6 shows the experimentally relevant di-jet spin asymmetry $A^{2-\mathrm{jet}} \equiv d\Delta\sigma/d\sigma$ in LO for three different bins in x_γ [51], using similar cuts as in a corresponding unpolarized measurement [52]. $A^{2-\mathrm{jet}}$ in NLO QCD has not been studied yet, but again only moderate corrections should be expected. Since it would be a very involved task to unfold the Δf^γ from such a measurement of

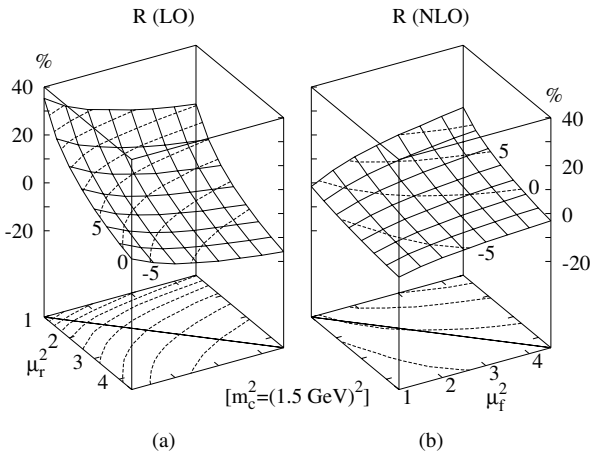

Fig. 7. $R = [\Delta\sigma^c_{\gamma p}(\mu_r^2,\mu_f^2) - \Delta\sigma^c_{\gamma p}(\mu_r^2=\mu_f^2=2.5m_c^2)]/\Delta\sigma^c_{\gamma p}(\mu_r^2=\mu_f^2=2.5m_c^2)$ in LO **(a)** and NLO **(b)** in percent for $\sqrt{S} = 10\,\mathrm{GeV}$. μ_f and μ_r are in units of the charm quark mass $m_c = 1.5\,\mathrm{GeV}$. The contour lines are in steps of 5% and for convenience a line corresponding to the usual choice $\mu_f = \mu_r$ is shown at the base of the plots.

$A^{2-\mathrm{jet}}$ due to the wealth of contributing subprocesses and combinations of parton densities, the result of the so-called 'effective parton density approximation' is also shown in Fig. 6. This handy but still accurate approximation which is based on an old idea [53], allows to straightforwardly extract a specific 'effective' combination of the Δf^γ given by [51] $\Delta f^\gamma_{\mathrm{eff}} \equiv \sum_q [\Delta q^\gamma + \Delta\bar{q}^\gamma] + \frac{11}{4}\Delta g^\gamma$, once the corresponding combination $\Delta f^p_{\mathrm{eff}}$ for proton densities is precisely known from, e.g., jet production in DIS at a polarized HERA [4] or from RHIC.

Finally, the calculation of the NLO QCD corrections to the polarized photoproduction of heavy quarks has been finished recently as well [9], and NLO results for the charm contribution g_1^{charm} to the DIS structure function g_1 [54] and for the hadroproduction of heavy quarks [55] will become available very soon. Heavy flavor production is dominated by gluon initiated fusion processes and hence highly sensitive to the so far poorly known Δg. Unfortunately at HERA neither g_1^{charm} nor the photoproduction of charm give sizeable enough contributions to be of any use in determining Δg. In the case of photoproduction of charm the prospects are much better for the upcoming fixed target experiment COMPASS at CERN [3]. The NLO corrections in this case appear to be sizeable but well under control, and, most importantly, the theoretical uncertainties due variations of the scale μ_f and μ_r are greatly reduced when going to the NLO of QCD [9] as is illustrated in Fig. 7.

Certainly the next couple of years will produce many new experimental results in the field of spin physics. In particular first data from the RHIC pp collider, but also results from HERMES and COMPASS, will considerably improve our knowledge of the spin structure of nucleons. But only a future polarized ep and a linear e^+e^- collider can ultimately resolve issues like the small x behaviour of g_1, the structure of polarized photons, and spin dependent fragmentation.

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