Measurement of Singly Polarized \( p\vec{N} \) Collisions at HERA

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Abstract

A summary is given on the physics potential of measuring singly polarized proton–nucleon collisions using a polarized internal target in the 820 GeV HERA proton beam. This summary is based upon talks given at the 2nd Meeting on Possible Measurements of Singly Polarized \( p\vec{p} \) and \( p\vec{n} \) Collisions at HERA, which was held at DESY Zeuthen from August 31 to September 2, 1995 as a follow-up to the Workshop on the Prospects of Spin Physics at HERA.

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1 Introduction

A series of meetings was started at PNPI Gatchina in July 1994 [1] to study the physics case for possible measurements of singly polarized proton-proton and proton-neutron collisions utilizing an internal polarized H/D target in the unpolarized 820 GeV HERA proton beam. Such a target offers unique features as polarization above 80%, no dilution, and a high density up to $10^{14}$ atoms/cm$^2$ [2]. Moreover, small systematic errors are expected when comparing data from protons and neutrons.

Measurements of single spin asymmetries were performed a few years ago by the E704 collaboration at Fermilab [3, 4]. Using an unpolarized Hydrogen target in an external 200 GeV polarized proton beam intriguingly large single transverse spin asymmetries $A_N$ were revealed in inclusive pion production [3]. At transverse momenta between 0.7 and 2 GeV/c $A_N$ exhibits a clear increase with $x_F$, as can be seen from fig. 1. Similar results had been obtained earlier at BNL [6] and IHEP [7] utilizing beam energies of 18 and 40 GeV, respectively.

In the framework of perturbative QCD inclusive asymmetries $A_N$ are supposed to vanish at twist-2 and significant non-zero asymmetries are usually associated with higher twist effects. However, the experimental asymmetries are much larger than those predicted by pQCD. To this end, the data seem to seriously question the validity of the presently accepted pQCD picture, at least the onset of its validity is not yet reached at the presently accessible transverse momenta.

Measuring single spin asymmetries at HERA with $\sqrt{s} \simeq 40$ GeV would open up the possibility to extend the reach in transverse momentum up to about 10 GeV/c depending on the inclusive final state chosen. This appears feasible in three real years of HERA running allowing for an integrated luminosity of about 240 pb$^{-1}$ [8]. Data taken in this unexplored kinematic region would yield very interesting input to further understand the transition region between non-perturbative and perturbative QCD and thus facilitate a deeper understanding of the QCD spin sector [9].

If such an experiment utilizing a polarized target in the HERA proton beam (tentative project name HERA–$\vec{N}$) should become feasible in a few years, the unpolarized beam would focus its initial physics scope to the measurement
of single spin asymmetries (‘phase I’). Once later polarized protons should become available, the same set-up would be readily available to measure various kinds of double spin asymmetries. These ‘phase II’ measurements would constitute an alternative –fixed target– approach to similar physics as it will be accessible to the STAR and PHENIX experiments at the low end of the RHIC energy scale ($\sqrt{s} \approx 50$ GeV) \cite{10}. The two most interesting spin physics items at this time will presumably still be the separate measurements of the polarized gluon and strange quark distributions. Their knowledge is badly needed to eventually resolve the long–standing problem of the nucleon spin decomposition.

The aim of this meeting was to present theoretical results obtained over the past 12 months on single spin asymmetries in various inclusive final states. Future directions of interest were subject of a lively discussion led by J. Soffer. A summary of this meeting, selected from the viewpoint of the feasibility to perform adequate measurements in phase I of HERA–$\vec{N}$, will be given in the subsequent chapters of this paper. Two contributions dealing with ‘phase II’ physics \cite{11, 12} will not be discussed here. The full text of all contributions can be found in a separate proceedings volume \cite{13}.

The 3rd meeting of the series is scheduled to be held at JINR Dubna in June 1996, its physics scope will be extended to cover both phase I and phase II of HERA–$\vec{N}$ physics.

## 2 Review Talks

In the invited introductory talk S. Nurushev \cite{14} discussed the variety of existing data on single spin asymmetries measured at beam energies above 10 GeV. In the detailed review on single spin measurements performed with the E704 experiment \cite{1} the unexpectedly large $A_N$ measured at average transverse momenta of about 1 GeV/c appears still as one of the most interesting pieces of data which calls for confirmation at higher energies.

An invited survey on measurements of single spin asymmetries at RHIC was presented by G. Ladinsky \cite{15}. At RHIC both beams will be polarized from the very beginning, hence double and single spin asymmetries will be acces-
sible at the same time. Data taking is envisaged to yield 800 inverse pb$^{-1}$ at $\sqrt{s} = 500$ GeV and 320 pb$^{-1}$ at $\sqrt{s} = 200$ GeV. At these energies and luminosities $W^\pm$ and $Z$ physics can be studied and parity violation in electroweak interactions can be used as a tool. In particular, the parity violating helicity asymmetry $A_{PV}^L$ allows to study the polarized antiquark distributions $\Delta \bar{u}$ and $\Delta \bar{d}$ with accuracies on the few percent level. Also, $A_L$ measurements in Drell–Yan pair production can be used to probe sea quark densities. The measurement of single transverse spin asymmetries in inclusive photon and pion production at RHIC might provide information on twist-3 parton distribution functions, although they are presently expected to be very small at the anticipated transverse momenta of several 10 GeV.

The today’s knowledge on the spectrum of single spin asymmetries potentially accessible at HERA was covered in two mini-review talks by G. Ladinsky [16] and O. Teryaev [17]. Most of the topics included there will be discussed in the following sections, although from an experimentalist’s point of view.

3 QCD Based Single Spin Asymmetries

Photon Asymmetries.
Quantitative estimates of single transverse spin asymmetries measured in inclusive direct photon production were discussed by A. Schäfer [18]. Sizeable asymmetries would indicate the existence of (leading) twist-3 effects and thus allow to study the almost virgin field of multi–parton correlations in the nucleon. In contrast to earlier predictions of J. Qiu and G. Sterman [19] suggesting an asymmetry of 10...20% more recent estimates of quark–gluon correlations by A. Schäfer et al. [20] indicate asymmetries of only a few percent when measuring with a proton target; the neutron target asymmetry is predicted to be several times larger.

Basing on the possible existence of a collective gluon field in the nucleon a direct relation was revealed some time ago [21] between these asymmetries and $d^{(2)}$, the twist-3 contribution to the second moment of the deep inelastic structure function $g_2$, and predictions for $d^{(2)}$ were calculated. Predictions
were obtained by other groups from QCD sum rules and Lattice calculations, however up to now there is no clear consensus between them [33].

On the other hand, recent preliminary data from E143 [23], although measured at rather small $Q^2$, indicate very small values for both $d^{(2)}_p$ and $d^{(2)}_d \simeq \frac{1}{2}(d^{(2)}_p + d^{(2)}_n)$. Moreover, within error bars no difference is seen yet between results from proton and neutron target, respectively. Hence more precise data on $g_2$ are required to be able to decide whether the measurement of single transverse spin asymmetries in inclusive photon production with HERA-$\vec{N}$ could be a useful tool to study the possible existence of a coherent gluon field in the nucleon.

The contribution to the same asymmetry basing upon 3-gluon correlations [24] instead of quark–gluon ones was calculated, as well [18]. The resulting hard scattering asymmetry increases with $\sqrt{s}$, however at HERA-$\vec{N}$ energies it does barely exceed the 1% level, as can be seen from fig. 2. It might therefore be very difficult to untangle this contribution.

**Jet Asymmetry.**

In a dedicated talk given at the main workshop O. Teryaev discussed twist-3 aspects in proton–nucleon single spin asymmetries [25]. He recalled that the contribution from 'gluonic poles', introduced by J. Qiu and G. Sterman and reconsidered by A. Schäfer et al., is now believed to be small (cf. previous section). However the 'fermionic poles', suggested even earlier by A. Efremov and O. Teryaev as a possible source of single spin asymmetries [26], might in fact yield the dominant contribution.

Based upon the hypothesis of 'fermionic poles' the short-distance part was already calculated in Born approximation for a number of quark–gluon subprocesses [27]. Some properties of the large distance partonic correlations were obtained by means of a simple model for the twist-3 part of $g_2$ that accomodates the sum rules derived in twist-3 QCD. It is compatible with existing data but smaller error bars are required to eventually decide on its validity.

In case of jet production the simple left/right cross section asymmetry (with respect to the normal to the scattering plane) is found to represent the asymmetries of quark and gluon production and claimed to be as clear a QCD
test as the direct photon asymmetry. Fragmentation is not involved at this level, hence no complicated detailed analysis of the jet structure is required. Whereas the short–range calculations support a jet asymmetry on the 10% level the long–range estimates based on the model of twist-3 $g_2$ and QCD sum rules indicate an asymmetry on the level of a few percent, only. The long–range part needs to be understood better before quantitative predictions including the $x_F$ dependence of the asymmetry can be given. Under HERA–$\vec{N}$ conditions the high jet cross section would allow for statistical errors on the permille level [16, 8]. Hence the experimental sensitivity will be dominated by the systematic error which has to be assessed carefully.

It was indicated that very similar theoretical arguments hold for a left/right single transverse spin asymmetry in dilepton production [25]. No quantitative predictions exist here either.

**Pion Asymmetries.**
Since the quark–gluon subprocesses contribute also to single spin asymmetries in pion production a possible dominance of ‘fermionic poles’ over ‘gluonic poles’ would lead to very interesting conclusions. For practically vanishing gluonic poles significant numerical differences are observed if instead of a gluon a quark in the transversely polarized nucleon is struck by the gluon of the unpolarized nucleon [25]; the asymmetry due to the gluon–quark contribution is obtained several times larger [28]. Even more importantly, this mechanism quite ‘naturally’ leads to a flavour dependence when explaining the pion asymmetries; the $\pi^+$ asymmetry is related to the correlation between gluon and $u$–quark, the $\pi^-$ asymmetry to the one between gluon and $d$–quark.

No quantitative predictions were presented yet, but the existence of mirror asymmetries for $A_{\pi^+}$ and $A_{\pi^-}$ can already be deduced rather easily.

**Dimuon Asymmetry.**
As for any inclusive final state, single helicity asymmetries vanish on the Born level for Drell–Yan production, as well. At order $\alpha_s$ a non–zero asymmetry can be constructed by the interference of tree diagrams with 1–loop diagrams, provided the dilepton pair has a non–vanishing transverse momentum. Hence both momenta of the pair have to be detected to access the asymmetry.
Following the initial paper of R. Carlitz and R. Willey [30], P. Nadolsky has calculated predictions for HERA–$\vec{N}$ conditions [31]. There the steeply falling cross section, suppressed by $\alpha_{em}$ as in case of inclusive direct photon production, requires to consider rather small dilepton masses $Q^2 \simeq 1.5 \text{(GeV/c)}^2$ and similar transverse momenta $Q^2_\perp$ at the same time to end up with a reasonable statistics. Special care had to be taken to alleviate several theoretical difficulties arising in this kinematic region. Still, as shown in fig.’s 3a and 3b for $Q^2 = 1.3$ and 2 (GeV/c)$^2$, even there the eventually achievable statistics is not sufficient to distinguish between $\Delta G = 0$ and $\Delta G = 2$; only very large values like $\Delta G = 5$ would lead to statistically significant effects. As a remaining possibility the ’dimuon + jet’ final state might have better sensitivity, since there the parton cross section needs not to be integrated over $x_{Bj}$. A corresponding study is in progress [32].

$J/\psi$ Asymmetry.
A novel way to possibly access the gluon contribution to the nucleon spin was discussed by O. Teryaev [29]. Inclusive helicity asymmetries are supposed to vanish on the Born level in singly polarized nucleon–nucleon collisions. Preliminary results from one-loop calculations were shown for $\sqrt{s} = 40 \text{ GeV}$. As can be seen from fig. 4a, a hard scattering asymmetry of a few percent is expected for not too large $J/\psi$ energies at $p_t^2 = 5 \text{(GeV/c)}^2$, which is about the lower limit of the expected HERA–$\vec{N}$ acceptance. The calculated cross section, shown in fig. 4b, appears high enough to realize statistical asymmetry errors on the permille level [3]. This might be sufficient since the only dilution in $J/\psi$ production comes from target polarization times average initial gluon polarization, which is anticipated to be of the order of 0.2 to 0.4. Certainly Monte Carlo studies and a careful assessment of the systematic errors are required to decide on the feasibility of this very interesting measurement.

$\Lambda$–Hyperon Asymmetry.
The measurement of inclusive $\Lambda^0$ production in singly polarized proton–nucleon scattering implies the possibility to determine the strange quark contribution to the nucleon spin, $\Delta s$. However, in the polarized target nucleon the hyperon can be produced from both a strange quark or a gluon at similar $x_{Bj}$. This makes it difficult to determine $\Delta s$ separately from the
gluon spin contribution, $\Delta G$.

In a talk by S. Manayenkov \[33\] it was outlined that indeed it is practically impossible to untangle both contributions from the analysis of kinematical variables. Another way to probe $\Delta s$ might be to measure the $\bar{N}$ polarization. Under HERA–$\bar{N}$ conditions it was found from Monte Carlo calculations that this polarization can be determined for transverse momenta up to 5 GeV/c. There are indications that the statistical accuracy will allow to distinguish between different strange quark polarizations.

## 4 Models with Orbital Angular Momentum

Trying to explain the non-zero transverse pion asymmetries measured by E704 some theoretical models are successful when assuming the existence of quark orbital momenta in the polarized nucleon. Two of them were discussed during the meeting.

**Current Quark Orbital Momentum in the Constituent Quark.**

In the constituent quark model approach of S. M. Troshin and N. E. Tyurin \[34\], presented by S. M. Troshin \[35\], the current quarks are assumed to perform an angular motion 'inside' the constituent quarks. The latter are believed to have a relatively slow motion within the whole nucleon. The origin of the current quark orbital angular momentum is explained by pairing correlations in analogy with an anisotropic generalization of the theory of superconductivity \[36\]. An axis of anisotropy is associated with the polarization vector of the valence quark, located at the origin of the constituent quark. A non-zero orbital momentum of the partons inside the constituent quark implies their existence of significant multiparton correlations, hence this picture is well suited to describe a hadron at moderate momentum transfers. At high momentum transfers the internal structure of a constituent quark is resolved and it is represented as a cluster of non–interacting current quarks.

**Pion Asymmetries.**

Compensation effects between valence and sea quark spins can lead to a $p_t$ dependent asymmetry for the inclusive meson which is formed by constituent quark recombination. The resulting single spin asymmetry shows a weak
energy dependence, significant values start at transverse momenta above 1 GeV/c \cite{34}. The predicted $A_N$ values can be seen from fig. 5a, where inclusive $\pi^0$ production at laboratory momenta of 200 GeV and 800 GeV is shown together with E704 data. Corresponding predictions for inclusive charged pion production are shown in fig. 5b.

$\phi$ Asymmetry.
Applying the same model to inclusive $\phi$ production \cite{37} the magnitude of the non-zero orbital momentum of rotating strange quark–anti-quark pairs is found proportional to the magnitude of the polarization of the constituent, i.e. the valence quark. The proportionality factor is just given by the relative amount of strange quarks within the constituent quark. At moderate $p_t \simeq 1$ GeV/c the asymmetric structure of the constituent quark is probed and leads to a single spin asymmetry predicted to be of the order of 1 to 5%.

Valence Quark Orbital Momentum in the Nucleon.
In the 'Berliner Model' of T. Meng and co-workers \cite{38}, presented by Z. Liang \cite{39}, the orbital angular momentum is assigned to the valence quarks directly. Since orbital momentum is not a good quantum number, orbital motion is involved for quarks even when being in the ground state. From the semi-classical wave function for a polarized nucleon it is deduced that the average number of valence quarks with a polarization parallel to the nucleon polarization is different from the number of those being polarized anti-parallel. Hence this relativistic quark model avoids from the very beginning the ‘deficiency’ of perturbative QCD of not being flavour sensitive.

Pion Asymmetries.
A significant part of mesons observed in the fragmentation region of the polarized nucleon are believed to be directly created from a valence quark and a sea anti-quark. The effective orbital motion attributed to the valence quark in conjunction with a significant (front) surface effect encountered by the unpolarized nucleon leads then, in the fragmentation region of the polarized nucleon, to significant single spin asymmetries whose magnitude increases with rising $x_F$. It has to be mentioned here that the existence of a surface effect of the necessary strength is not unanimously agreed upon. Still, there is fair agreement with the E704 inclusive pion data, as can be seen from fig. 6. The predictions are not sensitive to the type of the incoming unpolarized
nucleon and no asymmetry is expected in its fragmentation region.

**Drell–Yan and W/Z Production.**

Predictions of the same model, applied to calculate left-right asymmetries in singly polarized Drell-Yan pair and W/Z-boson production processes, were presented by C. Boros [40]. For Drell–Yan pairs produced by two nucleons the above described creation process leads to non-zero asymmetries not only in the fragmentation region of the polarized nucleon, but also in the region of small positive and negative $x_F$-values. As can be seen from fig. 7, given for 820 GeV incoming energy, the flavour sensitivity implied in the model leads to substantially different predictions for polarized protons, neutrons, or deuterons.

Additionally, predictions have been calculated for Drell–Yan pair production by pions as well as for W/Z-boson production in singly polarized (anti) nucleon–nucleon collisions. Strongly different asymmetries are predicted at $\sqrt{s} = 500$ GeV for $W^+$ vs. $W^-$ production which could be tested at RHIC or possibly at the Tevatron with a polarized proton beam.

### 5 Other Models

**Double J/ψ Production in the Colour Singlet Model.**

The production of J/ψ pairs was considered by S. Baranov and H. Jung [41] as a tool to probe the gluon polarization using the framework of the non–relativistic Colour Singlet Model [42]. Recently, T. Gehrmann reconsidered the case for HERA–N [43]. At $\sqrt{s} \simeq 40$ GeV gluon–gluon hard scattering dominates over quark–antiquark annihilation, hence the majority of double J/ψ events could be used to probe the gluon polarization. However, the cross section for $p_t^2 \geq 1$ (GeV/c)$^2$ amounts to about 5 pb, only. This is further diminished by a branching fraction of at most 12% in conjunction with an about 20% chance to reconstruct the helicity state of one of the two J/ψ’s. This results in a combined efficiency of about 2%, even without taking into account the experimental acceptance. Altogether this yields about 30 useful events expected during the three (assumed) years of HERA–N running, i.e. there is no realistic chance to access the gluon polarization through single
spin asymmetry measurements in double $J/\psi$ production.

**Instanton Mechanism of Single Spin Asymmetries.**
Non-perturbative interactions between quarks can be associated with the existence of instantons, i.e. vacuum fluctuations of gluon fields. N. Kochelev [11] obtained the instanton contribution to the quark distribution functions from the cross section for the instanton induced quark–nucleon interaction. The latter is found to be characterized by both a spin–flip and a strong flavour dependence, which makes it an especially interesting mechanism when considering flavour dependent effects in polarized scattering, like e.g. single spin asymmetries as seen for inclusive pions.

Whereas single spin asymmetries haven’t been considered quantitatively, yet, predictions were shown for the total quark contribution to the nucleon spin, $\Delta \Sigma$, and the polarized longitudinal structure function $g_1(x)$. The finite size of the instantons, described by a form factor, results in a strong $Q^2$–dependence of $\Delta \Sigma$. As can be seen from fig. 8, the violation of the Ellis–Jaffe sum rule appears in the instanton model at low photon virtualities below $2 (\text{GeV}/c)^2$, i.e. is clearly a non–perturbative effect. Similarly, the predictions for the polarized structure functions $g_1^p(x)$ and $g_1^n(x)$, shown in fig.’s 9a and 9b, exhibit instanton induced effects at lower values of $x_{Bj}$, only. These predictions can be clearly checked against the forthcoming precision data from the HERMES, E154, and E155 experiments.

**Diffractive High p_t 2–Jet Production.**
Another possibility to study the spin structure of QCD at large distances, i.e. the hadron wave function, may be given by the $p_t$–dependence of the single transverse spin asymmetry in diffractive $Q\bar{Q}$ production. In a perturbative calculation of the spin–dependent quark–pomeron vertex [12] additional contributions were identified which imply significant spin–flip terms. The latter were shown not to affect the standard pomeron contribution to the proton structure function.

Using this spin–dependent description the single spin asymmetry for diffractive light quark $Q\bar{Q}$ production was calculated at the pomeron–proton vertex and compared to the standard case [14]. Results obtained for $\sqrt{s} \simeq 40 \text{ GeV}$ at small pomeron fractional momentum ($x_p = 0.05$) and small momentum transfer ($|t| = 1 \text{ GeV}^2$) are shown in fig. 10. Additionally, the experimen-
tal sensitivity is shown by the projected error bars for HERA–$\vec{N}$ conditions without taking into account the acceptance of the spectrometer. As can be seen, the standard pomeron implies no $p_t$–dependence for the asymmetry, whereas by the spin–flip contributions a remarkable transverse momentum dependence is predicted which has a good chance to be confirmed after an integrated luminosity of 240 pb$^{-1}$ has been collected.

It is important to note that besides the two high $p_t$ jets it is necessary to detect the recoil hadron to guarantee the diffractive nature of the collision.

6 Conclusions

As it is well known, single spin asymmetries for inclusive final states are supposed to vanish in the framework of perturbative QCD when considering lowest order for helicity asymmetries and twist-2 in the case of transverse spin, respectively. Hence the intriguingly large single transverse spin asymmetries measured at BNL, IHEP, and by E704 for $0.5 \text{ GeV}^2 \leq p_t^2 \leq 4 \text{ GeV}^2$ are preferentially to be interpreted as higher twist effects. This hypothesis would be confirmed if an experiment accessing larger transverse momenta (like HERA–$\vec{N}$) should find these asymmetries decreasing with $p_t$, as predicted by pQCD. As a result the onset of pQCD would be defined more exactly and, more generally, the pQCD spin sector would be validated.

On the other hand, it is quite possible that the envisaged exploratory measurements with HERA–$\vec{N}$ (phase I) might reveal the persistence of large asymmetries at higher transverse momenta. There are indeed strong indications from several sides that higher twist effects might not vanish at all at rather large $p_t^2$, in strong contrast to pQCD expectations. Very recent theoretical results on the proton magnetic form factor, obtained from leading twist calculations [13], fall short by at least 50% when compared to the data from unpolarized exclusive reactions. The striking non–zero single spin asymmetry found more than 10 years ago at the AGS in 28 GeV/c proton–proton elastic scattering at $p_t^2 \simeq 6 \text{ GeV}^2$ [18] is at variance with pQCD since that time.

These and other disagreements between theory and experiment might imply that the simple twist-2 picture of perturbative QCD is not applicable, at
least to certain reactions. If this was true, the envisaged measurements with HERA–\vec{N} with their adequate reach in \( p_t \) would allow to shed completely new light onto the structure of Quantum Chromo Dynamics at small distances. It is not difficult to predict that in this case the theoretical interest to perform such an experiment would presumably be even higher.

In any case, new data about the \( p_t^2 \) dependence of single spin asymmetries in an hitherto unexplored region up to several tens of \( \text{GeV}^2 \) should allow for a considerable improvement in the understanding of the features of quark–gluon interactions. Especially, such data might turn out to be very useful to be confronted with then much further developed QCD lattice calculations.

In summary, the 2nd Meeting on Possible Measurements of Singly Polarized \( p\bar{p} \) and \( p\bar{n} \) Collisions at HERA has demonstrated a considerable improvement in understanding the physics potential of a possible HERA–\vec{N} experiment. Still, some more general and some additional specific components would make the physics program more sound. We need quantitative predictions for single transverse spin asymmetries based upon the proposed existence of 'fermionic poles'. Also, calculations from non–perturbative models, like e.g. the instanton model, might lead to very interesting and possibly unexpectedly large predictions on single spin asymmetries in the HERA–\vec{N} domain, i.e. for transverse momenta up to 10 GeV. A realistic way to access \( \Delta G \) via single spin asymmetries would be a very desirable extension of the physics scope. Generally speaking, more plausible and compelling theoretical ideas are most welcome to further increase the interest in such an experiment.

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References

[1] W.-D. Nowak, J. Soffer, Summary of the 1st Meeting on the Measurement of Singly Polarized Nucleon-nucleon Collisions at HERA, Gatchina, July 4-5, 1994 (unpublished)

[2] E. Steffens, K. Zapfe–Düren, Status of Internal Polarized Targets, these Proceedings

[3] A. Yokosawa, Proceedings of the XXI. International Symposium on Multiparticle Dynamics, Sept. 1991, Wuhan, China, p. 545

[4] S. B. Nurushev, Single Spin Measurements in the E704 Experiment, to appear in [13]

[5] D. L. Adams et al., Phys. Lett. B 264, 462 (1991)
D. L. Adams et al., Z. Phys. C56, 181 (1992)

[6] S. Saroff et al., Phys. Rev. Lett. 64, 995 (1990)

[7] V. D. Apokin et al., Phys. Lett. B 243, 461 (1990)

[8] W.-D. Nowak, AIP Conference Proceedings 343, High Energy Spin Physics, 11th International Symposium, Bloomington, Indiana, Sept. 1994, ed. by K. Heller and S. Smith, p. 412

[9] S. Brodsky, private communication

[10] RSC Collaboration, Proposal on Spin Physics using the RHIC Polarized Collider, August 1992
[11] R. D. Tangerman, P. J. Mulders, Twist-three Distributions and their appearance in the Doubly–polarized Drell–Yan Process, to appear in

[12] B. Pire, Probing the Polarized Gluon Content of the Proton through $\chi_2$ Hadroproduction, to appear in

[13] Proceedings of the 2nd Meeting on Possible Measurements of Singly Polarized $p\bar{p}$ and $p\bar{n}$ Collisions at HERA, Zeuthen, Aug.31–Sept.2, 1995, Desy Zeuthen Internal Report 95-05, ed. by H. Böttcher and W.–D. Nowak, in preparation

[14] S. B. Nurushev, Review of Single Spin Asymmetry Measurements at High Energy, to appear in

[15] G. Ladinsky, Measurements of Single Spin Asymmetries at RHIC, to appear in

[16] G. Ladinsky, Review of Single Spin Asymmetries I, talk at 2nd Meeting on Possible Measurements of Singly Polarized $p\bar{p}$ and $p\bar{n}$ Collisions at HERA, Zeuthen, Aug.31-Sept.2, 1995

[17] O. Teryaev, Review of Single Spin Asymmetries II, ibid.

[18] A. Schäfer, N. Hammon, Single Transverse Spin Asymmetries for Direct Photons, to appear in

[19] J. Qiu, G. Sterman, Phys. Rev. Lett. 67, 2264 (1991)

[20] A. Schäfer et al., Phys. Rev. D 47, R1 (1993)

[21] B. Ehrnsperger, A. Schäfer et al., Phys. Lett. B 321, 121 (1994)

[22] L. Mankiewicz, QCD Sum Rule Estimates of Higher Twist Corrections to the Bjorken Sum Rule, these Proceedings

[23] St. Rock, Future Spin Experiments at SLAC, these Proceedings

[24] X. Ji, Phys. Lett. B 289, 137 (1992)

[25] O. V. Teryaev, Twist-3 in Proton–Nucleon Single Spin Asymmetries, these Proceedings

14
[26] A. V. Efremov, O. V. Teryaev, *Phys. Lett. B* 150, 383 (1985)

[27] V. M. Korotkiyan, O. V. Teryaev, *Phys. Rev. D* 52, R1 (1995)

[28] A. V. Efremov, V. M. Korotkiyan, O. V. Teryaev, *Phys. Lett. B* 348, 577 (1995)

[29] D. Kazakov, O. Teryaev, A. Tkabladze, The Single Spin Asymmetry in Hadronic $J/\psi$ production, *to appear in* [13]

[30] R. D. Carlitz and R. S. Willey, *Phys. Rev. D* 45, 2323 (1992)

[31] P. M. Nadolsky, On the Study of Singly Polarized Lepton Pair Production at HERA, *to appear in* [13]

[32] P. M. Nadolsky, priv. comm.

[33] A. A. Jgoun, S. I. Manayenkov, M. G. Ryskin, Probing Spin–dependent Parton Distributions through Polarization Measurements in $p + \bar{p} \rightarrow \Lambda^0(\Lambda^0) + X$, *to appear in* [13]

[34] S. M. Troshin and N. E. Tyurin, *Phys. Rev. D* 52, 3862 (1995)

[35] S. Troshin, Single Spin Asymmetries in Inclusive Production, talk at 2nd Meeting on *Possible Measurements of Singly Polarized $p\bar{p}$ and $p\tilde{n}$ Collisions at HERA*, Zeuthen, Aug.31–Sept.2, 1995

[36] H. Fritzsch, *Phys. Lett. B* 256, 75 (1991)

[37] S. M. Troshin and N. E. Tyurin, Strangeness Content of Constituent Quarks and Asymmetries in Inclusive $\phi$–meson Production, *to appear in* [13]

[38] C. Boros, Z. Liang, and T. Meng, *Phys. Rev. Lett.* 70, 1751 (1993)

C. Boros, Z. Liang, and T. Meng, *Phys. Rev. D* 51, 4867 (1995)

[39] Z. Liang, Orbiting Valence Quarks and Single Spin Asymmetry in Inclusive Meson Production Processes, *to appear in* [13]

[40] C. Boros, Left-right Asymmetries in Drell-Yan Pair and $W/Z$-boson Production Processes, *to appear in* [13]
[41] S. P. Baranov and H. Jung, Z. Phys. C66, 647 (1995)

[42] B. Humpert, P. Mery, Z. Phys. C20, 83 (1983)
B. Humpert, P. Mery, Phys. Lett. B 124, 265 (1983)

[43] T. Gehrmann, Single Spin Asymmetries in J/ψ pair production, to appear in [13]

[44] N. I. Kochelev, Instanton Contribution to the Quark Distribution Functions, to appear in [13]

[45] S. V. Goloskokov, Phys. Lett. B 315, 459 (1993)

[46] S. V. Goloskokov, Study of Single Spin Asymmetry in Diffractive High \( p_t \) Jet Production, to appear in [13]

[47] J. Bolz et al., Z. Phys. C66, 267 (1995)

[48] P. R. Cameron et al., Phys. Rev. D 32, 3070 (1985)
Figure Captions

Fig. 1: Single transverse spin asymmetry $A_N$ in dependence on $x_F$, as measured by E704 for inclusive pion production at small and medium transverse momentum.

Fig. 2: Single transverse spin asymmetry vs. $x_F$, as predicted from twist–3 pQCD 3-gluon correlations for inclusive direct photon production at $\sqrt{s} = 30$ GeV.

Fig. 3: Single helicity asymmetry for Drell–Yan production vs. $Q^2$, as predicted from pQCD one–loop calculations for $Q^2 = 1.3$ (Gev/c)$^2$ (fig. 3a) and $Q^2 = 2$ (Gev/c)$^2$ (fig. 3b) at $\sqrt{s} = 40$ GeV.

Fig. 4: Single helicity asymmetry (fig. 4a) and cross section (fig. 4b) for $J/\psi$ production at $p_T = 5$ (GeV/c)$^2$, as predicted from twist–3 pQCD for $\sqrt{s} = 40$ GeV. Both are shown in dependence on the $J/\psi$ energy.

Fig. 5: Single transverse spin asymmetry for inclusive $\pi^0$ (fig. 5a) and $\pi^+$ production vs. $p_T$, as predicted by a constituent quark model for beam energies of 70, 200 and 800 GeV.

Fig. 6: Single transverse spin asymmetry vs. $x_F$ for inclusive pion production in scattering polarized (anti)protons on unpolarized protons at 200 GeV beam energy. The predictions shown are from the 'Berliner' model, data points are from E704.

Fig. 7: Same for dilepton production in scattering unpolarized protons on polarized protons, deuterons, and neutrons at 800 GeV beam energy.

Fig. 8: Prediction of the Instanton model for the total quark contribution to the proton spin as a function of $Q^2$.

Fig. 9: Instanton model predictions for the spin–dependent structure functions of the proton, $g_1^p(x)$ (fig. 9a) and of the neutron, $g_1^n(x)$ (fig. 9b).

Fig. 10: Single spin asymmetry vs. $p_T^2$, predicted in diffractive high $p_t$ 2–jet production in case of the existence of a spin–dependent quark–pomeron vertex.