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HADRON SPIN PHYSICS

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Abstract. - A survey of results from recent (and some older) polarization experiments is presented, in order to give an update of present views on hadronic spin phenomena and to attempt an outlook on prospects for spin physics, based on current theoretical trends and experimental programs at high energy facilities.

1. Introduction

The invitation to contribute to this commemorative Conference is for me an honour and an opportunity to revisit a field, Spin Physics, which I have been cultivating intensely until few years ago (and still watching carefully its development and progress [1]). The main topics of this Conference:

- LHC Physics
- Dark Matter and Neutrino Physics
- Accelerator Physics
- Spin Physics with Polarized Beams and Targets

are propitious to a reflection on the situation of current subjects in particle physics, in specific circumstances when the physics community is poised to enter novel areas with the start-up of LHC.

This is particularly important for Spin Physics, which has witnessed a high degree of interest for what has become well known as the "Spin Crisis" [2] of the parton model (and maybe QCD): a puzzling shortfall in the composition of nucleon's spin by valence quarks [3]. This wide interest could however eventually fade away, unless the role of spin is recognized also in the basic processes and the new phenomena that are expected to become accessible in the high energy regime of future colliders.

2. A Recollection Prologue

Among her many other physics' interests, Engin Arik has been an important collaborator in SMC [4], the experiment at CERN that has continued and developed the studies on the nucleon spin structure, initiated in EMC [3] by Vernon Hughes; I had the privilege of being also a member of that highly successful collaboration.

This was not the only occasion when my scientific pathway bordered the research of Engin Arik, neither the first time she was engaged in polarization experiments...

In the period 1976 - 1979, at Westfield College (London), Engin Arik took part to a series of measurements of

- $\pi^+ p$ backward elastic differential cross-section and
- $\pi^+ p \to \Sigma^+ K^+$ differential cross-section and polarization

between 1.27 GeV/c and 2.50 GeV/c at Nimrod (Rutherford Lab), using the RMS (Rutherford Multiparticle Spectrometer) (Fig. 1), built around a large magnet, equipped with chambers to measure tracks in magnetic field and a large Cherenkov counter for particle discrimination [5].

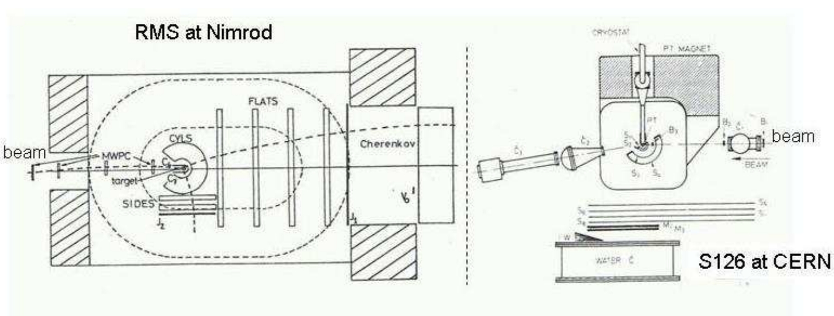

Figure 1: The experimental layouts of the RMS at Nimrod and of Exp. S126 at the CERN-PS, in the late 70's.

Almost at the same time, I was engaged on measurements of

- $\pi^\pm p$ backward elastic scattering and
- $\pi^+ p \to \Sigma^+ K^+$ and $\pi^- p \to \Sigma^- K^+$

differential cross-section and polarization at 3.50 GeV/c, with the CERN-Trieste collaboration [6]. This experiment was performed at CERN PS using a polarized proton target [7], in a special magnet, with a system of wire chambers (inside and outside the magnet gap for momentum reconstruction), triggered by scintillator and Cherenkov counters (Fig. 1).

At that time, these experiments were technically challenging and their results were important for the strong interaction models with Regge exchanges and the associated concepts of exchange degeneracy and duality [8].

The backward scattering cross section is small, decreasing rapidly with increasing energy and, in terms of Regge trajectories, it is mediated by baryon exchanges. In backward elastic scattering the large observed polarization requires contributions of at least 2 exchanges, having nucleon N, Δ quantum numbers.

In the associated production reactions, with high polarization (Fig. 2), the 2 exchanged trajectories should have strangeness (Λ and Σ).

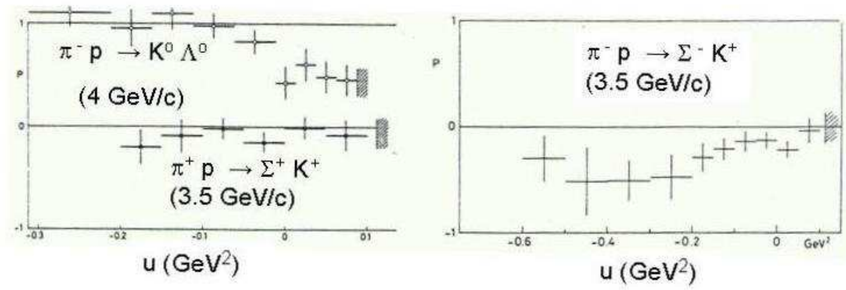

Figure 2: The $\pi^+ p \to \Sigma^+ K^+$ and $\pi^- p \to \Sigma^- K^+$ polarization at 3.5 GeV/c; for comparison $\pi^- p \to \Lambda^0 K^0$ data at 4.0 GeV/c are also shown.

From baryon spectroscopy and experiments of this type, the general properties of baryon Regge trajectories were obtained:

- Regge trajectories for mesons and Δ's have the same slope ($\alpha \approx 0.9\ GeV^{-2}$);
- Δ resonances with S=1/2 and S=3/2 are on the same Regge trajectory;
- N and Δ resonances with spin S=3/2 lie on a same Regge trajectory; S= 1/2 N's are shifted.

Similar, though more complex, relationships exist for strange baryon trajectories.

Degeneracy of (baryon) trajectories (EXD) is a characteristic property of dual models, with important dynamic consequences.

A connection of duality and string models has been assessed through the mathematical frame (Euler Beta function) of dual models established by G. Veneziano [9], and the physical representation, given by Y. Nambu [10], of nuclear forces as vibrating strings (with quarks at the ends). This string model included naturally the confinement of quarks in hadrons; furthermore such strings, in rotation, would have an angular momentum proportional to the squared energy of the string, thus following Regge behaviour (Fig. 3) ($J \approx \alpha M^2$) where α is the slope of the trajectory: $\alpha \approx 0.9\ GeV^{-2}$.

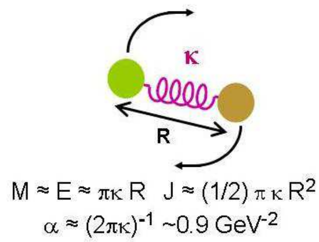

Figure 3: The string model of hadrons: quarks are held together by colour flux tubes, acting like strings; a rotating string shows a "Regge" behaviour.

Presently hadronic models should be embraced in the QCD framework: however Regge phenomenology and string-like behaviour may be associated with non-perturbative (confinement) aspects of QCD.

Meanwhile the concepts of duality and strings have acquired much further-reaching significance, than their original hadronic interpretation, in the context of supergravity [11].

3. Polarization Trends

Spin dependence is unavoidable in the gauge theories [12] that constitute the backbone of the Standard Model, giving distinct parity-violating (PV) asymmetries in weak processes and predicting substantial parity-conserving (PC) spin correlations in hadronic reactions [13].

These effects result from the role of chirality in gauge theories: at the level of spin-1/2 leptons and quarks, interacting by exchange of spin-1 carriers of gauge forces, the chirality of these fermions has distinct functions in the electro-weak and strong interactions: weak vector bosons couple preferentially with states of one definite chirality, producing parity violation; gluons interact equally but separately with left- and right-handed quarks, giving parity and helicity conservation in QCD.

Beyond the Standard Model, spin has been recognized as a sensitive probe for searches of new gauge bosons, supersymmetry and compositness [14]; for example rare PV events, that might pass unobserved in spin-averaged experiments, swamped with an overwhelming PC background from QCD, may be identified in spin dependent reactions or decays.

3.1 Lepton Colliders

In the projects for future lepton colliders, both a linear collider (e^+e^-), in any of the various versions proposed, as well as for the $\mu^+\mu^-$ collider envisaged more remotely, polarized beams are foreseen in the baseline design [15],[16].

Although the physics scenario at the time scale when such machines may be built and operated will be strongly influenced by earlier findings at LHC (or presently running colliders?), the role of polarization asymmetry measurements would remain important either for more detailed investigations of newly discovered particles or interactions, or as a tool for furthering such searches.

In particular a linear e^+e^- collider, with $\sqrt{s} \sim 500 GeV$ or higher and luminosity $L \sim 5 - 10 \times 10^{33} cm^{-2} s^{-1}$, unless unexpected effects occur during acceleration, could provide $P_{e^-} \sim 70 - 80\%$ (as in SLC), as emphasized in design reports [17] and justified in physics reviews [15]. Interesting schemes for polarized positrons exist also [18], if deemed necessary.

3.2 Hadron Colliders

At hadron machines the case for polarized protons is not established at the same level of consensus (despite serious theoretical work surveying the potential of spin physics at multi-TeV energies [19]). For example, in LHC emphasis goes to luminosity: even highest-flux polarized proton sources would be a limitation to the extreme intensities required for LHC.

There are however strong opportunities for spin measurements also at LHC [20] with unpolarized beams, which may be crucial in distinguishing major scenarios of TeV scale new physics. In particular, the spin of superpartners differ from their Standard Model counter parts by half integers: this property should be checked for any supersymmetric candidate found at LHC. The usual way of measuring the spin of a new particle involves studying its decay angular distribution about the polarization axis in its rest frame, reconstructed using the same decay products.

In most new physics scenarios of interest such a strategy is complicated by the existence, amongst the decay products, of undetectable massive particles. Direct and model independent ways of measuring spin using angular correlation among decay products of the new physics particles are needed, using Lorentz invariant combinations of momenta of the observable decay particles, which encode the spin information of intermediate particles in the decay chain.

Although polarization in the initial state is not indispensable for performing remarkable spin measurements (*eg* the well-known hyperon polarization results [21]), more detailed information becomes available with polarized beams and/or targets.

3.3 The RHIC Collider

In this respect, the RHIC collider at BNL emerges [22] as the leading facility for $p\,p$ spin physics, including studies of PC and PV processes up to $\sqrt{s} = 500$ GeV. With the acceleration, storage and interaction of the first polarized proton beams in a collider, hadron spin physics entered a new domain, previously reserved to electron machines. This achievement was made possible at BNL thanks to the infrastructure and mastery of polarized proton beams developed at AGS and a substantial contribution from RIKEN (Japan).

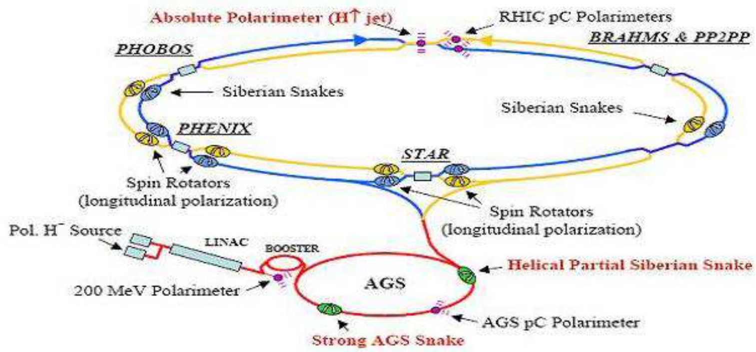

Figure 4: The RHIC accelerator complex at BNL; a full gear of spin handling tools is installed on the RHIC rings: siberian snakes, rotators, polarimeters, etc.

The RHIC collider (Fig. 4), filled with polarized protons ($P_B \approx 70\%$) and equipped with Siberian Snakes and Spin Rotators is designed [23] to provide collisions at top luminosity $L \approx 2 \times 10^{32}\, cm^{-2}\, s^{-1}$, in the range ($50 \leq \sqrt{s} \leq 500 GeV$). RHIC is carrying on a diversified program of spin physics with its major experiments (STAR, PHENIX and BRAHMS): some results will be discussed below.

Hands-on experience of polarized proton beams at RHIC, and sharper physics focus on momentous spin issues, might eventually enhance the interest for polarized beams also at other hadron machines (LHC?), despite the fact that acceleration and storage of polarized proton beams, involving siberian snakes' systems and fine tuning of the machine, might appear very cost- and labour-intensive.

Furthermore, spin effects would be accessible in the short-distance regime of large $\sqrt{s}$ and momentum transfer $p_T\,(Q^2)$ at high energy colliders with polarized beams, provided the interacting elementary particles (leptons and partons) carry some of the initial beam polarization into the collision processes at constituents' level. Leptons (e,μ) can be directly polarized, but partons (quarks and gluons) need to inherit a share of their parent beam hadron (*eg* proton) polarization, much the same way as their energy fraction x. This may be possible for leading (large-x) valence quarks, but not obvious for partons at small-x. As it appears now most plausible, a polarized nucleon structure, where the proton spin is carried only partially by valence quarks, and practically not shared with gluons, justifies the doubt that even an initially high p-beam polarization could be ineffective at partonic level, in particular at very high energies, where parton interactions at small-x become dominant. This is another reason why a complete solution of the "Spin Crisis" is important and urgent.

4. The Nucleon Spin Puzzle

About twenty years ago the study of spin phenomena evolved from measurements at intermediate energies (10 - 20 GeV/c) to much higher (100 - 200 GeV/c) ones, thus reaching the ability of probing the partonic structure of hadrons and its spin dependence.

At CERN the already successful European Muon Collaboration added a cryogenic ammonia target, containing polarized protons, to their apparatus, and started an experiment using their muon beam from in-flight decay of π and K, generated by SPS protons hitting a production target; these muons were naturally polarized longitudinally ($P_b \approx 70 - 80\%$) by parity violation in the decay. The 100 - 200 GeV/c muon beam was directed onto the polarized target, and the deep inelastic μ-p events were detected in the EMC spectrometer.

At the same time, a high energy polarized p/$\bar{p}$ beam was obtained at FNAL via the parity-nonconserving decay of $\Lambda/\bar{\Lambda}$ hyperons, produced by the extracted 800 GeV/c Tevatron primary proton beam on a beryllium production target [25]. The polarized beam ($P_b \approx 65\%$) was directed to a polarized proton target and a large variety of events produced in the polarized p-p interactions were measured in a large acceptance spectrometer. Results from this experiment (E704) on spin asymmetries in hadron production ($\pi^{\pm}, \pi^0, \gamma, \Lambda^0, etc.$), over a wide kinematic range in x and p_T, were obtained showing high relevance for hadronic interaction dynamics and spin composition. Some of these results were among the significant motivations that prompted the implementation of polarized protons in RHIC.

In 1988, the European Muon Collaboration (EMC) reported that most (i.e $\approx 90\%$) of the nucleon spin was not carried by its valence quarks and anti-quarks [3] and triggered large interest and an intense theoretical activity trying to explain this puzzling result [24]. The twenty following years have seen large progress in our knowledge of the distribution of spin within the proton. We now know that the "Spin Crisis"' is not as severe as once thought, but still not satisfactorily solved...

EMC was followed by the Spin Muon Collaboration (SMC) at CERN (confirming the "Spin Crisis"); the next generation of experiments (COMPASS at CERN and HERMES at HERA) were able to provide data an order of magnitude more precise in determining the integral of the polarized structure function $g_p^1(x, Q^2)$.

In parallel at SLAC (where polarized DIS experiments initiated the study of the nucleon spin structure in the 70's [26]!) a series of experiments (E142, E143) contributed both to investigations of the "Spin Crisis" and checks of the Bjorken sum rule [27].

These experiments have been followed by a new generation: E158, using the 48 GeV polarized electron beam at SLAC scattering off unpolarized electrons in a liquid hydrogen target, for a precision measurement of the purely leptonic weak neutral current coupling (now measured only at the Z^0 mass) at small $Q^2 \approx 0.03\,(GeV/c)^2$ in Moeller scattering [28].

4.1 New Lepton - Hadron Polarized DIS Experiments

The HERMES experiment [29] has been running since 1995, until the end of HERA operation in 2007. It used the 27.6 GeV longitudinally polarized e^+ beam ($P_B \approx 60\%$), stored in the HERA collider and a polarized gas storage cell containing H (D) and ^3He with areal densities of $7. \times 10^{13}$ (H) and 10^{15} nucleons/cm^2 (^3He). The target polarization P_T was typically 92% and 47% respectively. Events were detected in a spectrometer with a 1.3 Tm dipole magnet, including microstrip gas and drift chambers for track and momentum reconstruction. Positron-hadron separation was provided by a lead-glass calorimeter with preshower and TRD. A RICH counter, a muon system, a large angle calorimeter and a forward quadrupole spectrometer completed the apparatus with the purpose of extending the sensitivity of the experiment to charm channels and having access to the gluon share ΔG of the nucleon spin, through the process $\gamma^* \, g \to c\,\bar{c}$, with production of $D\,(\bar{D})$ mesons (open charm) or of J/ψ.

The COMPASS experiment [30] at CERN, started taking physics data in 2002, on the same muon beam (with various upgrades) previously used for EMC/SMC in order to extend their experimental program to a direct measurement of the gluon polarization through the same charm process considered by HERMES.

Also the whole EMC/SMC apparatus underwent a major rejuvenation program, with important additions such as large RICH counters for particle identification, electromagnetic and hadronic calorimeters and tracking detectors adapted to increased intensities with 2×10^8 μ/spill ($P_B \approx 80\%$) at 100 GeV/c, giving a nominal luminosity $L = 5 \times 10^{32}\, cm^{-2}\, s^{-1}$. The polarized target (2 cells 60 cm long, oppositely polarized) can contain either NH_3 or ^6LiD, for reactions on protons or deuterons, with polarizations of 85% and 50% respectively. The experiment also provided high statistics data on g_1, semi-inclusive muon scattering and the transversity polarized structure function h_1. Also production of hadron pairs ($\pi^+\pi^-$, K^+K^-,...) at $p_T \geq 1.5$ GeV/c was considered [31]; in this case the photon-gluon process is accompanied by leading-order and Compton scattering contributions, which have to be properly accounted for; the statistical accuracy however can be significantly improved.

4.2 New Results from HERMES and COMPASS

The latest analyses of Hermes [32] and COMPASS [33] yield respectively the following values for the summed contribution of quarks to the proton spin:

- $\Delta\Sigma = 0.330 \pm 0.011(thry) \pm 0.025(exp) \pm 0.028(evol)$
- $\Delta\Sigma = 0.33 \pm 0.03(stat) \pm 0.05(syst)$

This represents a very substantial increase in the fraction of the spin of the proton carried by its quarks and anti-quarks with respect to EMC, still not sufficient to consider the "Spin Crisis" solved ...

Polarized gluons, which in principle could contribute to the nucleon spin balance through the axial anomaly [34], in practice seem to play no significant role. This new

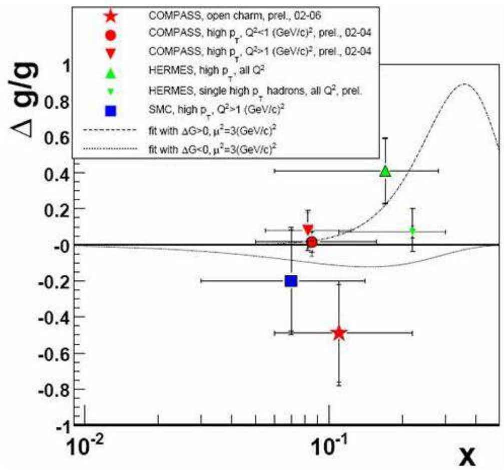

Figure 5: A compilation of results on $\Delta G/G$ from lepton-hadron experiments.

information comes from semi-inclusive measurements that look for high-p_T hadrons in a deep-inelastic event. Such direct measurements have been done at HERMES and COMPASS [35],with negligible gluon polarization results:

- $\Delta G/G = 0.071 \pm 0.034 \pm 0.011$ for HERMES

- $\Delta G/G = 0.06 \pm 0.031 \pm 0.006$ for COMPASS
  ($\Delta G/G = 0.016 \pm 0.058 \pm 0.055$; released 2006)
  ($\Delta G/G = -0.49 \pm 0.27 \pm 0.11$; from charm measurements D0+D*)

These results imply that constituent quarks account for only 1/3 of the nucleon spin and that ΔG is small and unlikely to solve the puzzle of the missing nucleon spin (Fig. 5). The challenge of the proton spin structure has changed goal but it is still with us.

For the record, a similar preliminary conclusion on a negligible gluon contribution to the nucleon spin composition, had been reached already in the early 90's by E704, from measurements of inclusive π^0 and multi-γ asymmetries in polarized p-p collisions [36] at the FNAL polarized p/$\bar{p}$ beam. These data, within substantial statistical uncertainty, were pointing to a value for $\Delta G/G$ compatible with zero (or slightly negative); this clue went practically unnoticed at a time when most of the predictions for $\Delta G/G$ were positive and large, and expectations were concentrating on charm production in lepton-nucleon polarized deep inelastic scattering ... However it re-emerged when the interest of using hadronic probes for measuring gluon properties was realized and was later exploited successfully at RHIC.

4.3 RHIC results on $\Delta G/G$

At RHIC both PHENIX [37] and STAR [38] have measured asymmetries in polarized p-p collisions (Fig. 6), in either jet or π^0 production. Preliminary analysis of the latest PHENIX data prefers a value of ΔG between -0.5 and zero. For STAR preliminary analysis yields a limit for ΔG below 0.3 (at 90% confidence level) and again consistent with zero. A value of $\Delta \text{G} \leq 0.3$ implies that through the axial anomaly the gluons may yield a correction of less than 5% to the quark spin content of the proton.

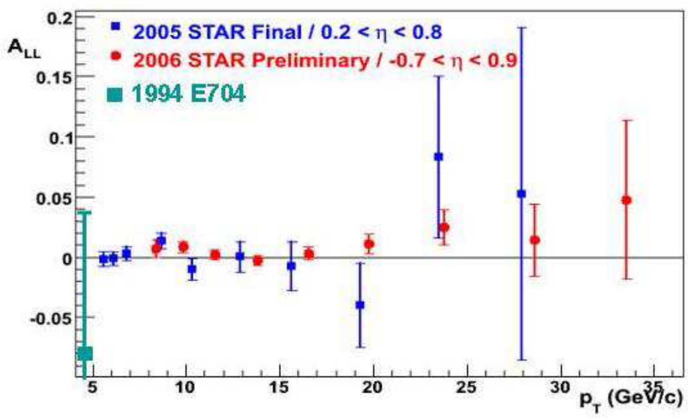

Figure 6: The longitudinal asymmetry A_{LL} from STAR, implying negligible gluon polarization; also shown the early result from E704 on π^0 and multi-γ production.

Better information on the contributions by all different nucleon constituents is obtained with new global fits to the DIS and to the RHIC data simultaneously [39]; from such challenging analysis it results again that both $s(\bar{s})$ quarks and gluons give insignificant contributions. An additional contribution is needed to build the full spin of the nucleon, and if it doesn't reside in s-quarks [40] it should come from orbital angular momenta; again experiments have to distinguish the amount of angular momentum carried by quarks or by gluons.

A recent approach [41] consists in considering the non-perturbative structure of the proton, and properly including in the evaluation of the amount of angular momentum carried by the proton's constituents some additional effects that were not fully accounted before, such as:

- the relativistic motion of the valence quarks,
- the one-gluon-exchange interaction,
- the pion cloud required by chiral symmetry.

This also implies [42] that the partons will acquire orbital angular momentum, that can be estimated, at least for the quarks, via a study of deeply virtual Compton scattering on protons. If this scheme turns out to be not only credible, as it looks like, but also effective, it would be another manifestation that non-perturbative confinement effects cannot be neglected for a realistic representation of hadronic phenomena.

5. Confinement Effects on Hadron Polarization

At hadronic level, confinement, essential attribute of strong interactions, still eluding a firm theoretical formulation, may be responsible for two apparently contrasting effects of diluting the polarization in hadronization of quarks, and of producing polarized quarks in hadron fragmentation.

The Lund model [43], for example, describes phenomenologically these non - perturbative processes by creation of $q - \bar{q}$ pairs in the break-up of color strings, and their subsequent recombination, to form the final hadrons.

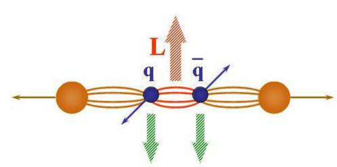

Figure 7: The break-up of an hadronic string, with production of a $q - \bar{q}$ pair.

Quarks of definite helicity from a primary interaction (for instance from weak bosons), recombining with quarks from these pairs, may produce baryons retaining only a fraction of the original quark polarization. It has been noticed that confining forces may lead, in the string break-up, to pairs with a finite $q - \bar{q}$ separation d (of typical hadron scale), and orbital angular momentum $L \approx d \times kT$, normal to the production plane: kT is the q ($\bar{q}$) transverse momentum, that should be balanced by the $q - \bar{q}$ spins pointing opposite to L, with a polarization which is eventually carried into the final hadron (Fig. 7).

Data on single-spin pion inclusive production with polarized $p\,\bar{p}$ beams from E-704 [44], show large asymmetry A_N (Fig. 8), with clear systematic patterns compatible with the simple string beak-up and (soft) recombination mechanisms described above. Other interpretations, involving harder partonic processes, or QCD twist-3 contributions have been proposed for these characteristic results [45], that recently have been reproduced also at RHIC, where the interaction regime should be more adequate to genuine QCD behaviour. These effects have been also studied in lepto-production SIDI processes [46].

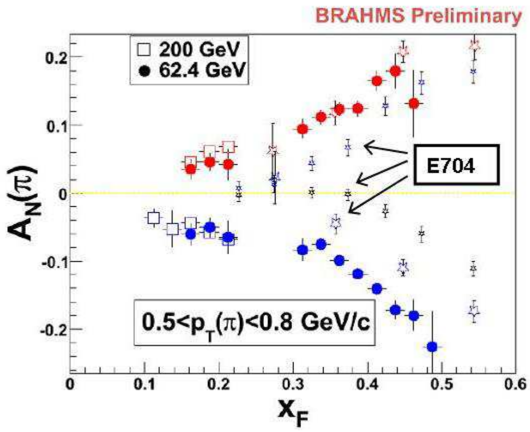

Figure 8: Spin asymmetry A_N in $pp \to \pi^{\pm,0}\ X$ with 200 GeV/c beams(E-704); new data from BRAHMS at RHIC shown for comparison.

5.1 Hyperon Polarization in Hadronic Production

The interplay of these various spin mechanisms, shows up in the inclusive hadronic production of hyperons [21], where substantial polarizations ($P_Y \approx 0.2$), transverse to the production plane, were measured for most hyperons Y, through their parity violating weak decays, and became popular, over the last two decades, as a paradigm of spin relevance to high energy hadron interactions.

The general pattern of strange baryon polarization (at $p_T \approx 0.7$ GeV/c and $x_F \approx 0.4$), is qualitatively in agreement with creation of polarized s-quarks in hadron fragmentation, and their recombination with (unpolarized) spectator quarks of the beam, to form (large x_F) polarized hyperons, according to their SU(6) wavefunctions; the Λ^0 polarization in $pp \to \Lambda^0\ X$, for instance, could be naively thought to be determined only by the s-quark (u, d quarks in spin-0 state) and therefore should be independent on the incident proton spin direction.

This basic picture however needs substantial refinements: with a 200 GeV/c polarized proton beam, E-704 found a significant spin transfer DNN (Fig. 9) in $pp \to \Lambda^0\ X$ [47]. The measured spin structure of nucleons is indeed more complex than their SU(6) wavefunctions; this should reflect in other baryons, in particular Λ^0. Hence u(d) quarks can carry a fraction of the proton spin to the Λ^0, contributing, together with the s-quark, to its final polarization. Other FNAL experiments (E-756, E-800) have obtained a sizable spin transfer to Ω^0- from a neutral hyperon beam containing transversally polarized Λ^0's and Ξ^0's, suggesting that spin-transfer may be a general feature of hyperon production.

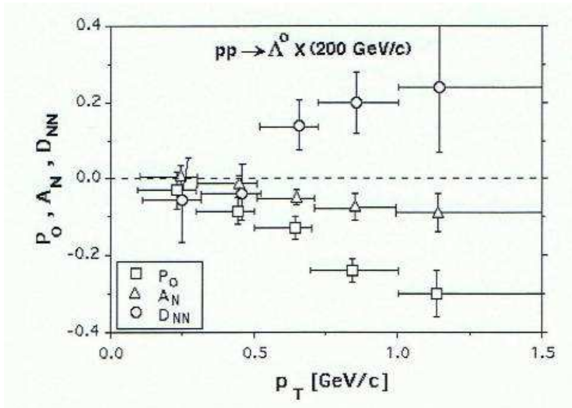

Figure 9: Spin parameters in $pp \rightarrow \Lambda^0\ X$ at 200 GeV/c (E-704).

5.2 Spin Effects in Heavy Flavor Production

Only a handful of spin measurements exist for heavy-flavor baryon hadroproduction; data on Λ_c^+ hadroproduction [48], have been used to deduce the Λ_c^+ polarization from analysis of the decay channel $\Lambda_c^+ \rightarrow p\ K^-\ \pi^+$. A large and negative Λ_c^+ polarization, ranging from -0.5 to -0.7, has been deduced, assuming realistic estimates for the 3-body decay parameter $\alpha\Lambda_c{}^(K)$. Under present large uncertainties, spin effects for charm baryons might be even larger than for hyperons. High statistics measurements of heavy-flavor baryons with (polarized) hadron and lepton beams could provide a new opportunity for spin studies at the quark level.

A special role may be reserved to production of top quarks at present and future colliders; because of their large mass, top quarks decay [typical chain $t \rightarrow b\ W^+$ ($\rightarrow l^+\ \nu$ or $u\ \bar{d}$)] very rapidly after production and the chirality of the top quark cannot be perturbed by hadronization. Spin effects at production should be directly visible in the angular correlations of top decay products giving the direction of its spin, for instance along the $\bar{p}$ beam direction in $p - \bar{p}$ annihilation (or along the spectator jet for $W - g$ fusion) in single top production [49].

6. Outlook

In the near future it appears that RHIC is taking the flagship role as hadron spin facility, developing its full potential with hadronic probes and reaching most of its ambitious goals (Tab.1):

- polarized pp production of Vector Bosons,
- prompt photon asymmetries (golden channel for $\Delta G/G$)
- hadron (jets) production asymmetries

Table 1: Summary of RHIC Experiments

Channel	Parton Process	Measurement
$pp \to W^+X$	$u\bar{d} \to W^+ \begin{smallmatrix} \nearrow e^+\nu \\ \searrow \mu^+\nu \end{smallmatrix}$	V-A Tests – – – – – – $\Delta u/u; \Delta\bar{d}/\bar{d}$
$pp \to W^-X$	$d\bar{u} \to W^- \begin{smallmatrix} \nearrow e^-\nu \\ \searrow \mu^-\nu \end{smallmatrix}$	V-A Tests – – – – – – $\Delta d/d; \Delta\bar{u}/\bar{u}$
$pp \to l^+l^-X$	$q\bar{q} \to \gamma^*, Z^0 \begin{smallmatrix} \nearrow e^+e^- \\ \searrow \mu^+\mu^- \end{smallmatrix}$	$\Delta q/q \times \Delta\bar{q}/\bar{q}$ $(A_{NN} \to h_1)$
$pp \to j(j)X$	*New Currents*; *Contact Terms*	W', Z'; Λ_C
$pp \to \gamma(j)X$	$q\,g \to \gamma\, q$	$\Delta G/G$
$pp \to j(j)X$	$g\,g \to q\,\bar{q}$	$\Delta G/G$
$pp \to c\bar{c}X$ (also $b\bar{b}$)	$g\,g \to c\bar{c}\,(b\bar{b})\ [\to \mu^+(\mu^-)]$	$\Delta G/G$

Nevertheless COMPASS will be a valid contender on many subjects, in particular on Generalized Parton Distributions (GPD), to tackle the orbital angular momentum contributions to the nucleon spin, and transversity. A distinctive feature of COMPASS is its ability of using both leptonic and hadronic probes, according to the needs (for instance in the studies on transversity, via hadronic production of dimuons, or on transverse single spin hadronic effects).

It is likely that *polarized* hadron probes (p $\bar{p}$) would add an extra bonus to this ambitious programme. An option similar to the FNAL E-704 beam line may be considered in the North Area of SPS [50]. In particular such a scheme is the only presently viable solution for a high energy polarized $\bar{p}$, fully proven and successfully used for experiments.

Despite vague claims on this controversial issue, today there is still no realistic alternative to obtain high energy $\bar{p}$ beams of sizable polarization and reasonable intensity. Perspective methods for enriching stored $\bar{p}$ beams in one spin component by selective absorption (Spin Filter [51]) or by Stern-Gerlach effect (Spin Splitter [52]) are limited for the moment to low energies, and suffer respectively from:

- lack of information on the (double) spin dependence of $p-\bar{p}$ cross-sections (Spin Filter),
- lack of proof-of-principle on a proton storage ring (Spin Splitter).

Until these crucial problems are not solved, the only realistic perspective for using polarized $\bar{p}$ beams concerns fixed target experiments on a secondary beam line from hyperon weak decay.

7. Conclusion

Few additional comments to summarize my personal views on Hadron Spin Physics status and perspectives:

- In this survey, much more experiments and projects would have deserved to be discussed or mentioned: even if I believe that RHIC and COMPASS will take the front stage of Spin Physics in the next few years, I am convinced that JLAB has greatly contributed and is going to play a strong role (particularly in the study of Generalized Parton Distributions [53]); some of the JLAB activities were part of another talk at this Conference. Other projects with emphasis on polarization (for instance FAIR and J-PARC) would deserve dedicated talks on their own...
- In 1998 [1] I was asked to outline "Future Spin Experiments and Projects" and I then focused on HERMES, COMPASS, RHIC, E158 and their promises: it is amazing to see today how much these groups, and the spin community as a whole, have been able to achieve in one decade!
- Therefore I am confident that in the coming years there will be further impressive progress, on the hadron spin structure, the confinement role, the helicity dependence in Standard Model and beyond. Spin physics has stepped into this century with a full gear of new tools; these are now perfectly functional, and ready to perceive and decipher the fingerprints of chiral structure in the world of elementary particles.

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