PHYSICS OF POLARIZED pp COLLISIONS

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ABSTRACT

I will summarize the physics that can be investigated with polarized pp collisions. It is technically feasible to use the RHIC collider for accelerating highly polarized protons to a center-of-mass energy of about 400 GeV, with high luminosity. Such collisions can be used to probe the spin-dependence of hard collisions and of partons in a hadron, including the gluons. There are interesting twist 3 phenomena that are likely to be significant in view of the large transverse spin asymmetries at lower energies; this will have important implications for the spin structure of the proton wave function. Recent theoretical developments include the possibility of probing the spin of transversely polarized quarks via asymmetries in the jets they make.

1. Introduction

It has been realized that it is possible to accelerate polarized protons in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, at a modest incremental cost. This opens up to reality a whole area of QCD physics. Therefore a collaboration has been formed—the RHIC Spin Collaboration (RSC) to promote this kind of physics.

The polarized RHIC would have proton beams of up to 250 GeV of energy, with 70% polarization and a luminosity of around $10^{32}$ cm$^{-2}$sec$^{-1}$, and we would propose running in polarized mode for 1 month a year. This would clearly allow hard scattering physics to be done with polarization under conditions comparable to those at proton-antiproton colliders.

The technical development that has allowed this is known as the Siberian snake. This is a spin rotator that does not affect the beam optics and can be used to cancel most of the depolarizing resonances. Previously acceleration of polarized protons to high energy was a tour-de-force, even at the modest energy of 20 GeV at the Brookhaven AGS. Snakes would make this easy. Tests of the snake concept have been made at low energy at the Indiana cyclotron, while tests at higher energy are underway at the AGS this year. (The AGS will serve as the injector for RHIC).

Compared to previous experiments, RHIC would have high energy, luminosity and undiluted high polarization, with easy spin reversal. Hence it will allow us to

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do high quality short-distance QCD physics with polarization effects. Among other things, this will give a good probe of the spin structure of the proton wave function, which in turn will provide a much needed window onto chiral symmetry and its breaking.

2. Polarized Hard Scattering in QCD

QCD predicts that suitable cross sections are a convolution of parton densities (and fragmentation functions, if needed) and of short-distance parton cross sections. Such cross sections include jet production, the Drell-Yan process, heavy flavor production, direct photon production at large transverse momentum.

In collisions of longitudinally polarized beams, there is an asymmetry of the cross section when one of the beam helicities is reversed. Schematically the asymmetry in the cross section is of the form

\[ \Delta_{LL} \sigma = \Delta_{LL} \hat{\sigma} \times \Delta \text{pdf}_1 \times \Delta \text{pdf}_2. \]  

(1)

Here \( \Delta_{LL} \hat{\sigma} \) is the corresponding helicity asymmetry in the short-distance cross section, and \( \Delta \text{pdf} \) is the helicity asymmetry of the number density of partons in initial hadron \( i \). In this formula, there is an implicit sum over parton types and an integral over the parton kinematics. This formula is valid up to corrections that are suppressed by a power law of the large scale. (These are the higher twist terms.)

A similar formula can be written when both beams are transversely polarized. But in many cases the numerical values of the asymmetries are expected to be small.

When one of the beams is transversely polarized and the other is unpolarized, QCD typically predicts that the spin asymmetry is twist 3, i.e., \( O(1/Q) \), as a consequence of helicity conservation at the elementary vertices of the theory. This prediction contrasts with the notoriously large measured asymmetries in single pion production. A devil’s advocate would argue that “Helicity conservation is violated whenever it has been directly measured.” This statement has a certain element of validity, even though there is much quantitative evidence for the correctness of the QCD interaction vertices, and hence for helicity conservation.

3. Measurements of Helicity Parton Distributions

One just has to look at other presentations at this conference to realize the importance of measuring the helicity asymmetry of the parton densities in the proton. Knowing the polarization of the sea quarks and antiquarks and of the gluon gives important information on the spin and chiral structure of the proton.

Since neutrino scattering on a polarized target is impractical, one can look to hadron-hadron scattering to provide much of the information on flavor separated distributions. One can look to all the standard processes: Drell-Yan (both to muon pair and to W and Z) provides a direct measurement of antiquark distributions, direct photon, heavy flavor, and jet production probe the quark, antiquark and gluon densities in various combinations. Jet production is particularly useful because of its high rate. In the unpolarized case, jet production is usually regarded as a cross section predicted with the aid of other measurements. In the polarized case, it can be used to probe the gluon density.
4. Transverse Polarization at Leading Twist; Fragmentation

The distributions of transversely polarized quarks in a transversely polarized proton are perfectly good twist-2 observables and there is an interesting range of cross sections sensitive to them. But many spin asymmetries that they give are likely to be small. The transverse spin distributions differ from the helicity distributions because of relativistic effects in the proton wave function, and are therefore of great interest.

It has recently been realized (or rediscovered!) that one should investigate spin-dependent asymmetries in jet fragmentation. These give twist-2 observables in collisions with only one incoming beam being polarized transversely. The usual theorem about single-spin observables being higher twist is overcome by using a spin sensitive observable in the final-state—an azimuthal distribution of the leading pion or of the leading two pions, for example. Another leading twist observable that has been discussed is the polarization of a Λ baryon at high transverse momentum.

Such measurements have the disadvantage of measuring the transverse spin distributions only in conjunction with the spin dependence of fragmentation. This is also an advantage, since the transverse-spin-dependence of fragmentation is a completely virgin subject and depends on chiral symmetry breaking in a situation dominated by dynamic (as opposed to static) processes.

5. Twist-3

There has been much theoretical work on twist-3 effects. In appropriate observables, these are the leading twist terms. These observables include all the simplest spin asymmetries in a collision of transversely polarized hadron with an unpolarized hadron.

Measurements of such quantities would provide much information about the spin structure of the proton, but are likely to be much harder to interpret than twist 2 measurements. Once one goes beyond the tree graph level for the Wilson coefficients, the number of operators involved is enormous as compared to the twist-2 case.

6. Outlook

The is much interesting QCD physics to be done at a polarized proton-proton collider. This could be done at RHIC at a modest incremental cost. Both longitudinal spin and transverse spin are of interest.

Because of this and because of the past, present and future measurements of polarized deep inelastic scattering, there has been a resurgence of theoretical interest.

Work needs to be done to decide on optimal detector configurations etc.

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