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Violent collisions of spinning protons at Fermilab

A. D. Krisch
Spin Physics Center, University of Michigan - Ann Arbor, MI 48109-1040, USA

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Summary. — I will review the history of elastic scattering and polarized proton beams, and the unexpected and still unexplained large transverse spin effects found in high-energy proton-proton spin experiments at the ZGS, CERN, AGS, Fermilab and RHIC. Next, I will discuss possible experiments on violent elastic and inclusive collisions of polarized protons at Fermilab's new high-intensity Main Injector.

PACS 13.85.Dz – Elastic scattering.
PACS 13.85.Ni – Inclusive production with identified hadrons.
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PACS 29.27.Hj – Polarized beams.

I will first discuss the violent elastic collisions of unpolarized protons. Figure 1 shows the cross-section for proton-proton elastic scattering plotted against a scaled P_t^2 variable that was proposed in 1963 [1] and 1967 [2] following Serber's [3] optical model. This plot is from updates by Peter Hansen and me [4,5]. Notice that at small P_t^2 the cross-section drops off with a slope of $\sim 10\,(\mathrm{GeV}/c)^{-2}$. Fourier transforming this slope gives the size and shape of the proton-proton interaction in the diffraction peak; it is a Gaussian with a radius of about 1 fermi. The medium P_t^2 component, with a slope of about $3\,(\mathrm{GeV}/c)^{-2}$, disappears rapidly with increasing energy and has disappeared at TeV energies. There one sees a sharp destructive interference between the small-P_t^2 diffraction peak and the large-P_t^2 hard-scattering component. Since the diffraction peak is mostly *diffractive*, its amplitude must be mostly imaginary, which has been experimentally verified. Hence, the sharp destructive interference implies that the large-P_t^2 component is also mostly imaginary; thus, it is probably mostly *diffractive*. This large-P_t^2 component is probably the elastic *diffractive* scattering due to the *direct* interactions of the proton's constituents; its slope of $\sim 1.5\,(\mathrm{GeV}/c)^{-2}$ implies that these *direct* interactions occur within a Gaussian-shaped region of radius ~ 0.3 fermi. The possible $0.9\,(\mathrm{GeV}/c)^{-2}$ component could be confirmed using a high intensity 120–150 GeV polarized proton beam at Fermilab.

Since the medium-P_t^2 component disappears at high energy, it is probably the *direct elastic scattering* of the two protons. This view is supported by the experimental fact that proton-proton elastic scattering is the only exclusive process that still can be precisely measured at TeV energies. To understand this, note that *direct* elastic scattering and all

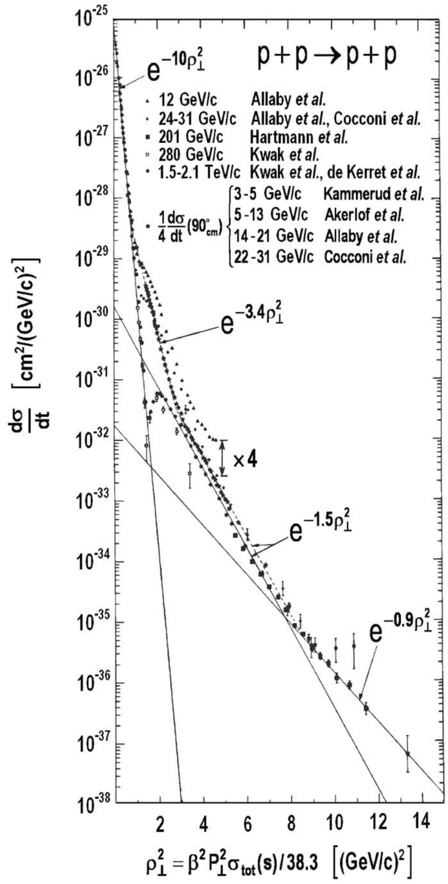

Fig. 1. – Proton-proton elastic cross-sections plotted *vs.* scaled P_t^2 variable [4, 5]. 12 GeV/c Allaby *et al.* data not corrected for 90°_{cm} particle identity.

other exclusive processes must compete with each other for the total p-p cross-section, which is less than 100 millibarns. At TeV energies, there are certainly more than 10^5 exclusive channels in this competition; thus, each channel has an average cross-section of less than 1 microbarn. Moreover, since the medium-P_t^2 elastic component does not interfere strongly with either the large-P_t^2 or small-P_t^2 components, its amplitude is probably real. Also note that the large-P_t^2 component intersects the cross-section axis at $\sim 10^{-5}$ below the small-P_t^2 *diffractive* component.

An earlier version of fig. 1 got me started in the spin business. In 1966, we measured p-p elastic scattering at the ZGS at exactly 90°_{cm} from 5 to 12 GeV [6]; the sharp slope-change, shown by the stars, was apparently the first direct evidence for constituents in the proton. Dividing these 90°_{cm} p-p elastic cross-sections by 4 (due to the protons' particle identity) made all then-existing proton-proton elastic data, above a few GeV, fit on a single curve [2]. During a 1968 visit to Ann Arbor, Prof. Serber informed me that, by dividing the 90°_{cm} points by 4, I had made an assumption about the ratio of the spin singlet and triplet p-p elastic scattering amplitudes. I was astounded and said that I knew nothing about spin and certainly had not measured the spin of either proton. He said

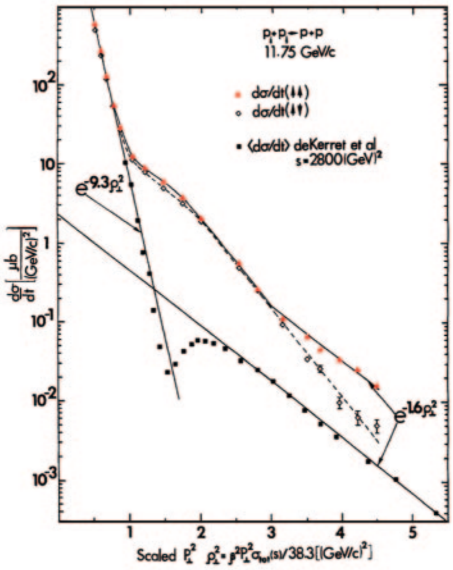

Fig. 2. – Proton-proton elastic cross-section near 12 GeV in pure initial spin states plotted *vs.* scaled P_t^2 [11].

with a smile that both statements might be true; nevertheless, my nice fit required this assumption. Prof. Serber, as usual, spoke quietly; however, as a student, I had learned that he was almost always right. Thus, I looked for proton-proton elastic scattering data, in the singlet or triplet spin states, above a few GeV. I found that none existed and decided to try to polarize the protons in the ZGS.

At the 1969 New York APS Meeting, I learned that EG&G was the representative for a new polarized proton ion source made by ANAC in New Zealand. I discussed this with my long-time colleague Larry Ratner, Bruce Cork, Argonne's Associate Director, and Robert Duffield, Argonne's Director. They apparently decided it was a good idea and hired me as a consultant at $100 per month. In 1973, after much hard work by many people, the ZGS accelerated the world's first high-energy polarized proton beam [7, 8].

The ZGS needed some hardware to overcome both intrinsic and imperfection depolarizing resonances. Fortunately, both types of resonances were fairly weak at the 12 GeV ZGS, which was the highest energy weak focusing accelerator ever built. All higher energy accelerators wisely use strong focusing [9], which unfortunately makes the intrinsic resonances much stronger. If we had first tried to accelerate polarized protons at a strong focusing accelerator, such as the AGS, we probably would have failed and abandoned the polarized proton beam business. Fortunately, it worked at the weak focusing ZGS [7, 8]. Its experiments [10] soon showed that the p-p total cross-section had significant spin dependence; this surprised many people, including me.

Figure 2 shows my favorite result [11] from the ZGS polarized proton beam. The 12 GeV proton-proton elastic cross-section in pure initial spin states is plotted against the scaled P_t^2-variable; in the diffraction peak the spin-parallel and spin-antiparallel cross-sections are essentially equal to each other and to the unpolarized CERN ISR data at $s = 2800\,\text{GeV}^2$; thus, in small-angle *diffractive* scattering, the protons in different spin states (and at different energies) all have about the same cross-section. The medium-

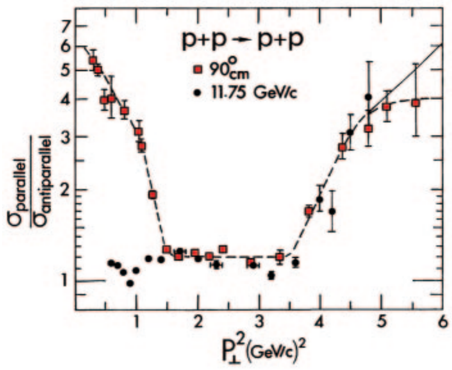

Fig. 3. – Spins-parallel: spins-antiparallel measured elastic cross-section ratio ($\sigma_{\uparrow\uparrow}/\sigma_{\uparrow\downarrow}$) plotted *vs.* P_t^2 [12].

P_t^2 component, which still exists near 12 GeV, has only a small spin dependence; recall that it has disappeared at 2800 GeV^2. However, the behavior of the large-P_t^2 hard-scattering component was a great surprise. When the protons' spins are parallel, they seem to have exactly the same behavior as the much higher energy unpolarized ISR data; however, when their spins are antiparallel their cross-section drops with the medium-P_t^2 component's steeper slope. When this data first appeared in 1977 and 1978, people were astounded; most had thought that spin effects would disappear at high energies. In the years following, many theoretical papers tried to explain this unexpected behavior; none were fully successful. The theory, which is now called QCD, has been unable to deal with this data; Glashow once called this experiment "... the thorn in the side of QCD". In his Blois 2005 talk, Brodsky called it "... one of the unsolved mysteries of Hadronic Physics".

I learned something important from questions during two 1978 seminars about this result. Two distinguished physicists, Prof. Weisskopf at CERN and then Prof. Bethe at Copenhagen a week later, asked the same question apparently independently. Each said that our big spin effect at large-P_t^2 was quite interesting; but at 12 GeV, the parallel-spins/antiparallel-spins ratio was only large near 90°_{cm}, where particle identity was important for p-p scattering. "Thus, how could one be sure that your large spin effect was due to hard-scattering at large-P_t^2, rather than particle identity near 90°_{cm}?" One would be foolish to ignore the comments of two such distinguished theorists; moreover, they were similar to Prof. Serber's comment 10 years earlier.

It seemed that their question could not be answered theoretically. Thus, we tried to answer it experimentally with a second ZGS experiment, which varied P_t^2 by holding the p-p scattering angle fixed at exactly 90°_{cm}, while varying the energy of the proton beam. This 90°_{cm} p-p elastic fixed-angle data [12] is plotted against P_t^2 in fig. 3, along with the fixed-energy data [11] of fig. 2. There are large differences at small P_t^2, where the 90°_{cm} data are at very low energy; however, above P_t^2 of about 1.5 (GeV/c)^2, the two sets of data fall right on top of each other. The points near $P_t^2 = 2.5\,(\text{GeV}/c)^2$, where the ratio is near 1, are just as much at 90°_{cm}, as the 5 (GeV/c)^2 point, where the ratio is 4. This data apparently convinced Profs. Bethe and Weisskopf that the large spin effect was not due to 90°_{cm} particle identity and was a large-P_t^2 hard-scattering effect.

I now turn to funding. In 1972 the AEC had agreed to shut down the ZGS in 1975 to get funding for PEP at SLAC. When the unique ZGS polarized beam started operating in 1973, the wisdom of this decision was questioned; AEC then set up a committee which extended ZGS operations through 1977. A second committee in 1976 extended operations of the ZGS polarized beam until September 30, 1979 [13]. Henry Bohm, the President of AUA, which operated Argonne, asked ERDA, which had replaced AEC, to set up a third committee to again extend ZGS running. However, OMB objected, so there was no third committee; nevertheless, his efforts had some benefit. When James Kane, of ERDA, responded negatively to Dr. Bohm, his justification was that it might now be possible to accelerate polarized protons in a strong focusing accelerator such as the AGS; moreover, Dr. Kane officially copied me on his letter.

We had started interacting with Ernest Courant and others at Brookhaven about polarizing the AGS, first at a 1977 Workshop in Ann Arbor [14]. Then at a 1978 Polarized AGS Workshop at Brookhaven [15], Brookhaven's Associate Director, Ronald Rau, asked me for a copy of Dr. Kane's letter. He used it to encourage William Wallenmeyer, the long-time Director of High Energy Physics at AEC, ERDA and DoE, to provide about $8 Million to Brookhaven, and about $2 Million split between Michigan, Argonne, Rice and Yale, for the challenging project of accelerating polarized protons in the strong-focusing AGS, and later in the 400 GeV ISABELLE collider. ISABELLE was canceled in 1983, but was later reborn as RHIC, which is now colliding 250 GeV polarized protons.

It was far more difficult to accelerate polarized protons in the strong focusing AGS than in the weak focusing ZGS. Strong focusing, which had been proposed by Courant, Livingston and Snyder [9], made possible all high energy circular accelerators by using alternating quadrupole magnetic fields to strongly focus the beam making it small both horizontally and vertically. Unfortunately, these strong quadrupole fields are very good at depolarizing protons. To accelerate polarized protons to 22 GeV at the AGS, we had to overcome 47 strong depolarizing resonances. This required: some very challenging hardware; significantly upgrading the AGS controls; and spending lots of beam- time individually overcoming the 47 depolarizing resonances. Michigan built 12 ferrite quadrupole magnets to overcome the 6 strong AGS intrinsic resonances by rapidly jumping the AGS's vertical betatron tune through each resonance. Brookhaven was building their 12 power supplies; but each power supply had to provide 1500 Amps at 15,000 Volts (~ 22 MW) during each quadrupole's 1.6 μs rise-time. Overcoming the many imperfection depolarizing resonances (occurring every 520 MeV) required programming the AGS's 96 small correction dipole magnets to form a horizontal B-field wave of 4 oscillations when the protons' energy passed through the $G\gamma = 4$ imperfection resonance. Then, about 20 ms later in the AGS cycle, when $G\gamma$ was 5, the 96 magnets had to form a horizontal B-field wave with 5 oscillations, etc. (The quantity γ is E/m, while the quantity $G = 1.79285$ is the proton's anomalous magnetic moment.)

After all this hardware was installed, an even larger problem was tuning the AGS. In 1988, when we accelerated polarized protons to 22 GeV, we needed 7 weeks of exclusive use of the AGS; this was difficult and expensive. Once a week, Nicholas Samios, Brookhaven's Director, visited the AGS Control Room to politely ask how long the tuning would continue and to note that it cost $1 Million a week. Moreover, it was soon clear that, except for Larry Ratner (then at Brookhaven) and me, no one could tune through these 47 resonances; thus, for some weeks, Larry and I worked 12-hour shifts 7-days each week. After 5 weeks Larry collapsed. While I was younger than Larry, it seemed unwise to try to work 24-hour shifts every day. Thus, I asked our Postdoc, Thomas Roser, who until then had worked mostly on polarized targets and scattering experiments, if he wanted to learn accelerator physics in a hands-on way for 12 hours every day. He learned well, and now chairs Brookhaven's Collider-Accelerator Department.

Another benefit of this difficult 7-week period [7, 16] was learning that our method of individually overcoming each resonance, which had worked so well at the ZGS [7, 9], might work at the AGS, but would be impossible at higher energy accelerators. This lesson helped to launch our Siberian snake programs at IUCF [7,17] and then SSC [18,19].

In the 1980's, a new proton collider, the SSC, was being planned; it was to have two 20 TeV proton rings each $\sim$ 80 km in circumference. Owen Chamberlain and Ernest Courant encouraged me to form a collaboration to insure that polarized protons would be possible in the SSC. We first organized a 1985 Workshop in Ann Arbor, along with Kent Terwilliger. This Workshop [18] concluded that it should be possible to accelerate and maintain the polarization of 20 TeV protons in the SSC, but only if the new Siberian snake concept of Derbenev and Kondratenko [20] really worked; otherwise, it would be totally impractical. Recall that it took 49 days to correct the 47 depolarizing resonances at the AGS, about one per day. Each 20 TeV SSC ring would have about 36,000 depolarizing resonances to correct. Moreover, these higher energy resonances would be much stronger and harder to correct; even at one per day, this would require about 100 years of 24/7 beam-tuning for each ring. The Workshop also concluded that one must prove experimentally that the *too-good-to-be-true* Siberian snakes really worked; otherwise, there would be no approval to install the 26 Siberian snakes needed in each SSC ring.

Indiana's IUCF was then building a new $\sim$ 200 MeV synchrotron Cooler Ring [7]. Some of us Workshop participants then collaborated with Robert Pollock and others at IUCF to build and test the world's first Siberian snake in the Cooler Ring. We brought experience with synchrotrons and high energy polarized beams, while the IUCF people brought experience with low energy polarized beams and the CE-01 detector, which was our polarimeter. In 1989, we demonstrated that a Siberian snake could easily overcome a strong imperfection depolarizing resonance [7, 17]. For 13 years we continued these experiments and learned many things about spin-manipulating polarized beams.

In 1990 our SPIN Collaboration submitted to SSC an Expression of Interest [19] a week before the deadline, which made it SSC EOI-001. It proposed to accelerate and store polarized protons at 20 TeV, and to study spin effects in 20 TeV p-p collisions. Ours was the first presentation to the SSC's PAC before a huge audience including newspaper reporters and TV cameras. Perhaps partly due to this publicity, we were soon *partly* approved by SSC Director Roy Schwitters. *Partly* means that 26 empty spaces for Siberian snakes were added to each SSC Ring; each was $\sim$ 20 m long, which added $\sim$ 500 m to each Ring. The SSC was canceled around 1993, after $\sim$ \$2.5 Billion was spent. Nevertheless, our detailed studies of the behavior and spin-manipulation of polarized protons at IUCF and then COSY helped in developing polarized beams around the world. Brookhaven now has 250 GeV polarized protons in each RHIC ring [7, 21].

Now we return to p-p data. After accelerating polarized protons to 22 GeV in the AGS [7, 16], we obtained some A_{nn} data [7, 22, 23] well above the ZGS's 12 GeV; but we never had enough *polarized-beam data-time* to get precise A_{nn} data at high-P_t^2. But, during tune-up runs for the A_{nn} experiment, we used the unpolarized AGS proton beam to test our polarized proton target (PPT) and double-arm magnetic spectrometer by measuring A_n in 28 GeV proton-proton elastic scattering; this data resulted in an interesting surprise. Despite QCD's inability to explain the large A_{nn} from the ZGS, QCD theorists had firmly predicted that the one-spin A_n must go to 0 at higher energies and higher P_t^2. But, as shown in fig. 4, A_n was instead quite large at P_t^2 of 5 to 6 $(\mathrm{GeV}/c)^2$. This led to more controversy [23]; some people said our A_n data was wrong. Thus, we started an experiment to measure A_n at high-P_t^2 with far better precision.

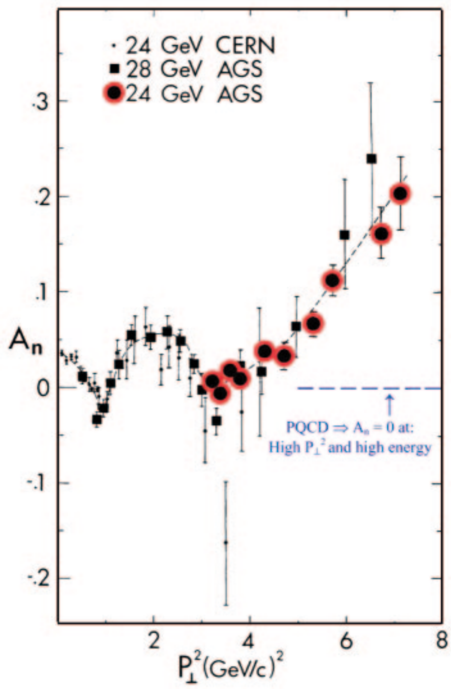

Fig. 4. – $A_n \equiv (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$ plotted *vs.* P_t^2 for p-p elastic scattering [25].

Our spectrometer worked well, but we could only use $\sim 0.1\%$ of the AGS beam to avoid heating our PPT and depolarizing it. Thus, we started building a new PPT [7, 24] that could operate with 20 times more beam intensity; this required ^{4}He evaporation cooling at 1 K, which has much more cooling power than our earlier ^{3}He evaporation PPT at 0.5 K. To maintain the same polarization ($\sim 60\%$) at 1 K required increasing the B-field from 2.5 to 5 Tesla. Thus, we ordered a 5 T superconducting magnet from Oxford Instruments, with a B-field uniformity of about 10^{-5} over the PPT's 3 cm diameter volume. We also bought Varian's first 20 W at 140 GHz microwave source. We were unsure what the polarization might be, but we were very lucky; it reached 96% [7, 24]. Moreover, the target polarization averaged 85% for a 3-month-long run with high-intensity AGS beam in early 1990.

As shown in fig. 4, this let us precisely measure A_n at even larger P_t^2. When these precise new data were published [25], some theorists seemed quite unhappy; they still believed the PQCD prediction that A_n must go to 0, but they now refused to state at what P_t^2 or energy this prediction would become valid. They also now said that PQCD might not work for elastic scattering, which they now considered less fundamental than inelastic scattering, where they said PQCD should work.

However, spin experiments had also started at Fermilab with no polarized beam or target. Figure 5 shows the 400 GeV inclusive hyperon polarization from the experiments during 1970s and 1980s, led by Pondrum, Devlin, Heller and Bunce [26]; it clearly shows a small polarization at small P_t and a larger polarization at larger P_t. Moreover, their data is consistent with 12 GeV data from the KEK PS and 2000 GeV data from the CERN ISR. These data do not support PQCD's prediction that inelastic spin effects disappear

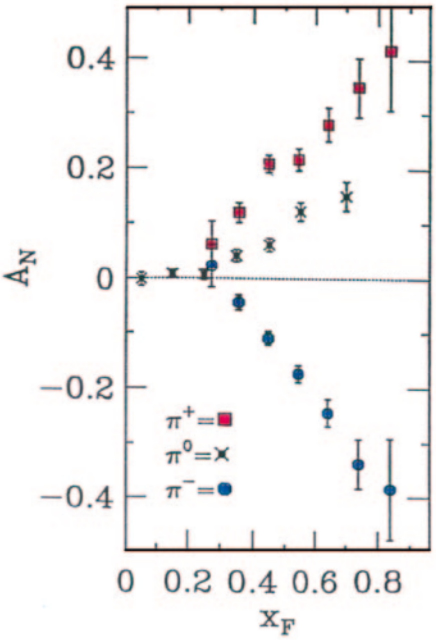

Fig. 5. – Inclusive Λ polarization plotted against P_t [26].

at high energy or high P_t^2. Another group at Fermilab, led by Yokosawa, developed a *secondary* polarized proton beam using the polarized protons from polarized hyperon decay. The beam's intensity was only $\sim 10^5$ per second, but its polarization was $\sim 50\%$ and its energy was ~ 200 GeV. They obtained some nice A_n data on inclusive π meson production [27], which are shown in fig. 6. The A_n values for π^+ and π^- mesons are both large but with opposite signs, while A_n for the π^0 data is $\sim 50\%$ smaller and is positive. These 200 GeV data do not support PQCD.

We tried to measure spin effects in very high energy p-p scattering at UNK, which IHEP-Protvino started building around 1986 [7]. Our main contribution to NEPTUN-A was a 12 Tesla at 0.16 K Ultra-cold Spin-polarized Jet [7]. UNK's circumference was 21 km with 3 rings: a 400 GeV warm ring and two 3 TeV superconducting rings; its injector was IHEP's existing 70 GeV accelerator, U-70 [7]. By 1998 the UNK tunnel and about 80% of its 2200 warm magnets were finished; and 70 GeV protons were transferred into its tunnel with 99% efficiency. However, progress became slower each year due to financial problems; in 1998 Russia's MINATOM placed UNK on long-term standby [7].

IHEP Director, A.A. Logunov, had earlier suggested moving our experiment to IHEP's existing 70 GeV U-70 accelerator. By March 2002 the resulting SPIN@U-70 Experiment on 70 GeV p-p elastic scattering at high P_t^2 was fully installed, except for our detectors and Polarized Proton Target (PPT) [7, 24]. However, just before our 4 tons of detectors, electronics and computers were to be shipped, the US Government suspended the US-Russian Peaceful Use of Atomic Energy Agreement started by President Eisenhower in 1953. Nevertheless, DoE asked us to send the shipment. When the shipment arrived at Moscow airport on March 11, 2002, it was impounded for 8 months and then returned to Michigan. This ended SPIN@U-70. However, we had our scheduled test run in April 2002

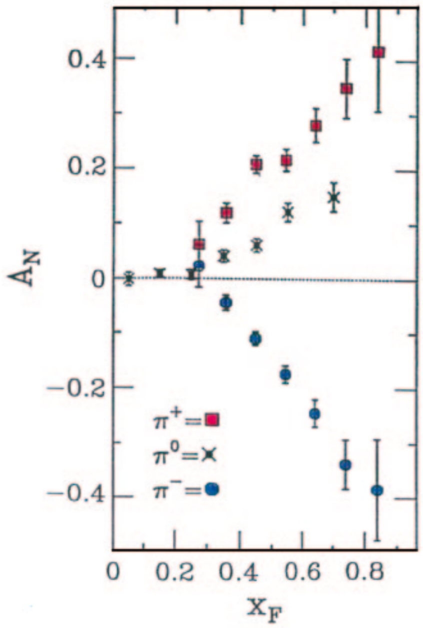

Fig. 6. – A_n in 200 GeV/c inclusive π-meson production *vs.* X_F [27].

by hastily borrowing IHEP equipment; its data showed that, with only part of the recoil spectrometer working, the elastic signal to background ratio was 80:1 [7].

To summarize, for the past 30 years PQCD-based calculations have continued to disagree with the ZGS 2-spin and AGS 1-spin elastic data, and the ZGS, AGS, Fermilab and now RHIC [28] inclusive data shown in fig. 7. To be specific:

- These large spin effects do not go to zero at high-energy or high-P_t, as was predicted.
- No QCD-based model can yet explain simultaneously all these large spin effects which instead seem to grow larger at high-P_t.

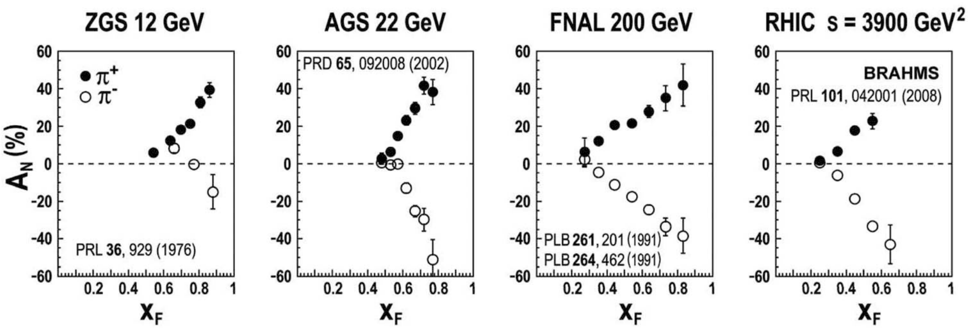

Fig. 7. – Inclusive pion asymmetry in proton-proton collisions [27].

Precise proton-proton elastic (along with inclusive) spin data on $d\sigma/dt$, A_{nn} and A_n from the high intensity Main Injector could probably provide the best guidance for the needed modifications to PQCD. This is because elastic scattering is the only exclusive process that one can precisely measure above 100 GeV, where its total cross section continues to be $\sim$ 25% of the σ_{TOT} of $\sim$ 100 milibarns. For details about Fermilab's possible high intensity polarized beam see refs. [7, 29].

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