SPIN MEASUREMENTS IN HADRONIC HIGH MOMENTUM TRANSFER SCATTERING*

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ABSTRACT

The results of recent experiments investigating spin effects in hadronic high momentum transfer scattering are reviewed. There is evidence for very large spin dependences at high momentum transfer in measurements involving both the polarization of a single particle and the polarizations of two particles.

INTRODUCTION

I will review recent spin measurements in hadronic reactions, concentrating on the higher momentum transfer range, with $P_{\perp} \geq 1$ GeV/c .[1] Momentum transfers of ~1 GeV/c are not exactly high but for some reactions are the highest that are available.

One general characteristic of high momentum transfer hadronic processes is the low cross sections, cross sections which fall continuously with increasing momentum transfer. A complete spin amplitude analysis of a particular reaction requires the measurement of final state as well as initial state polarizations. This final state polarization determination usually involves a rescattering, decreasing the event rate by a factor of 100 below the unrescattered processes. With present polarized beam and targets, carrying out the necessarily large set of initial and final state polarization measurements is only feasible at modest momentum transfers in a straightforward reaction such as p-p scattering. However, at higher momentum transfers the low rates preclude such a set of measurements and a complete spin amplitude analysis. So, we do what we can. What we can measure are spin effects involving a single particle and, with a polarized proton beam and target, two particles, enabling us to determine p-p cross sections in pure initial spin states.

Single particle spin effects in the high momentum transfer region have been investigated in a wide variety

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of hadronic reactions. They have been studied in inclusive processes, as in the production of polarized Λ° and protons using unpolarized proton beams, or, using polarized beams or targets, to create asymmetries in reaction products such as pions. They have been studied to modest momentum transfers in the exclusive process $p_\uparrow + p \to \Delta^{++} + n$ and to substantial momentum transfer in elastic p-n scattering. The p-$p_\uparrow$ elastic scattering process is of course the most intensively studied with single particle asymmetry measurements now up to 300 GeV/c beam momentum. The 12 GeV/c polarized proton beam at the ZGS has made possible the investigation of two particle p-p spin effects, with measurements now to $P_\perp^2 = 5\ (\mathrm{GeV/c})^2$.

SPIN PARAMETERS

I will now discuss the spin parameters which are measured in the various reactions. Fig. 1 shows a portion of the spin parameter convention agreed on at the Ann Arbor Polarization Workshop in the fall of 1977.[2] It should be noted that there are historical differences from this convention - and certainly no unanimous agreement to use it - so in this talk there will be considerable switching of notation. In the laboratory $\vec{N}$ is normal to the scattering plane, $\vec{L}$ along the beam, and $\vec{S} = \vec{N} \times \vec{L}$ in the scattering plane. Small letters denote the directions in the CM; they are similarly defined. For the two-spin beam-target processes considered today, the lab and CM directions are identical.

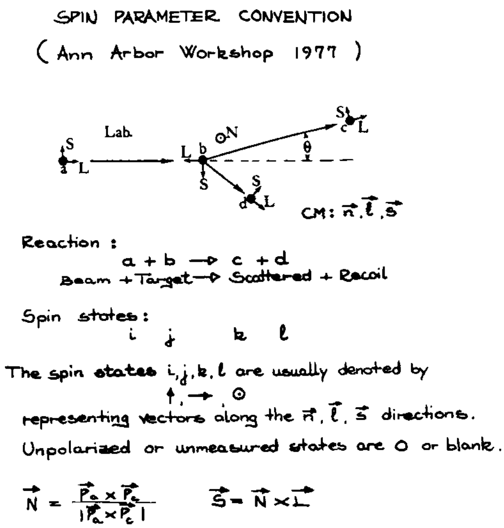

Fig. 1. Spin parameter convention. See Ref. 2.

Fig. 2 shows the type of experiments we will consider and the Wolfenstein spin parameters which are determined (again, using the Ann Arbor Convention). For one polarized particle, beam or target or one of the

EXPERIMENTS

I Asymmetries with one polarized particle

REACTION	DETERMINE WOLFENSTEIN PARAMETERS $(i,j;k,\ell)$
Inclusives:	
$p + \text{nucleus} \rightarrow \Lambda_\uparrow + X$	$P = (0,0;n,0)$
$p_\uparrow + X$	$P = (0,0;n,0)$
$\left.\begin{matrix} p_\uparrow + p \\ p + p_\uparrow \end{matrix}\right\} \rightarrow \binom{p}{\pi} + X$	$A = (n,0;0,0)$ $A = (0,n;0,0)$
Exclusives:	
$p_\uparrow + p \rightarrow \Delta^{++} + n$	$A = (n,0;0,0)$
Elastics:	
$\left.\begin{matrix} p_\uparrow + n \\ n + p_\uparrow \end{matrix}\right\} \rightarrow p + n$	$A = (n,0;0,0)$ $A = (0,n;0,0)$
$\pi + p_\uparrow \rightarrow \pi + p$	$A = (0,n;0,0)$
$\left.\begin{matrix} p_\uparrow + p \\ p + p_\uparrow \end{matrix}\right\} \rightarrow p + p$	$A = (n,0;0,0)$ $A = (0,n;0,0)$
$p + p \rightarrow p_\uparrow + p$	$P = A = (0,0;n,0)$

II Correlations with two polarized particles

$p_\uparrow + p_\uparrow \rightarrow p + p$	$A_{nn}(C_{nn}) = (n,n;0,0)$
$p_\rightarrow + p_\rightarrow \rightarrow p + p$	$A_{\ell\ell}(C_{\ell\ell}) = (\ell,\ell;0,0)$
$p_\odot + p_\rightarrow \rightarrow p + p$	$A_{s\ell}(C_{s\ell}) = (s,\ell;0,0)$

Measure as

$$A = \frac{1}{P_{B(T)}} \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \qquad A_{nn} = \frac{1}{P_B P_T} \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

Fig. 2

reaction products, the measurement is always of an asymmetry - for example to determine the asymmetry parameter for vertical polarization, A=(n,0,0,0), one measures the difference between the number of events with up and down beam polarization divided by the sum. Since the beam polarization is never 100% one must divide by it to get the pure state asymmetry. Equivalently, from rotational invariance, one could measure the number of left scatters minus right scatters over the sum and divide by the beam polarization. To determine a polarization parameter, as for the $\Lambda°$, P=(0,0,n,0), one measures the asymmetry in the $\Lambda°$ decay and divides by the known $\Lambda°$ asymmetry parameter. These asymmetry and polarization parameters are perhaps easiest to visualize as the possible measure of a spin-orbit coupling, in analogy with atomic and nuclear physics.

For two polarized particles one measures correlations - determines the dependence of the event rate on the product of the two particles' polarizations. So A_{nn} is the difference between the event rate with parallel and antiparallel polarizations divided by the sum, the result then divided by the product of the beam and target polarizations. A_{nn} is then a measure of the correlation of the particle spins - possibly due to a direct spin-spin interaction. Fig. 3 shows the p-p two-spin differential cross section for $\vec{n}$ polarization in terms of the Wolfenstein parameters A and A_{nn}, the beam and target polarizations and

p-p TWO-SPIN CROSS SECTION RELATIONS
(given for $\vec{n}$-polarization)

$$\frac{d\sigma}{dt} = \left\langle \frac{d\sigma}{dt} \right\rangle \left[1 + (P_B + P_T)A + P_B P_T A_{nn} \right]$$

Pure state cross sections:

$$\left.\frac{d\sigma}{dt}\right)_{\uparrow\uparrow} = \left.\frac{d\sigma}{dt}\right)_{\uparrow\uparrow \rightarrow 00} = \left\langle \frac{d\sigma}{dt} \right\rangle \left[1 + 2A + A_{nn} \right]$$

$$\left.\frac{d\sigma}{dt}\right)_{\downarrow\downarrow} = \left.\frac{d\sigma}{dt}\right)_{\downarrow\downarrow \rightarrow 00} = \left\langle \frac{d\sigma}{dt} \right\rangle \left[1 - 2A + A_{nn} \right]$$

$$\left.\frac{d\sigma}{dt}\right)_{\uparrow\downarrow} = \left.\frac{d\sigma}{dt}\right)_{\downarrow\uparrow} = \left\langle \frac{d\sigma}{dt} \right\rangle \left[1 - A_{nn} \right]$$

Fig. 3

the spin averaged cross section. This equation is equivalent to the previous relations for A and A_{nn}.[3] Also shown are the pure spin state parallel and anti-parallel cross sections directly obtained from the above relation. It will be of use later to note that since A = 0 at 90° CM in pp scattering, because of particle identity and rotational invariance, the spin-up and spin-down parallel cross sections become equal there.

SPIN EFFECTS WITH ONE POLARIZED PARTICLE INCLUSIVE REACTIONS

I will now discuss experiments involving one polarized particle, the measurement of a single asymmetry, and will begin with inclusive experiments. I will first consider reactions in which the incident beam is unpolarized and the polarization of a scattered particle is measured. One of the most exciting experiments showing high momentum transfer spin effects is that of the collaboration involving Michigan-Rutgers-Wisconsin and others, whose recent results were presented at this conference by Heller.[4] This group was the first to demonstrate the existence of large spin effects at very high energies - at 300 GeV at Fermilab.[5] They had observed the polarization of the inclusively produced $\Lambda°$ to increase with momentum transfer to over 20% at a $P_\perp \sim 1.6$ GeV/c. Very strikingly, their results were consistent with the same $P_\perp$ dependence seen at 24 GeV - implying an energy independent process. Their present experiment extends the energy to 400 GeV and $P_\perp \sim 2.1$ GeV/c. Their new data and the previous 300 GeV data are shown in Fig. 4. It is evident that the 400 GeV data tracks the 300 GeV - with a possible flattening at the higher $P_\perp$. One should

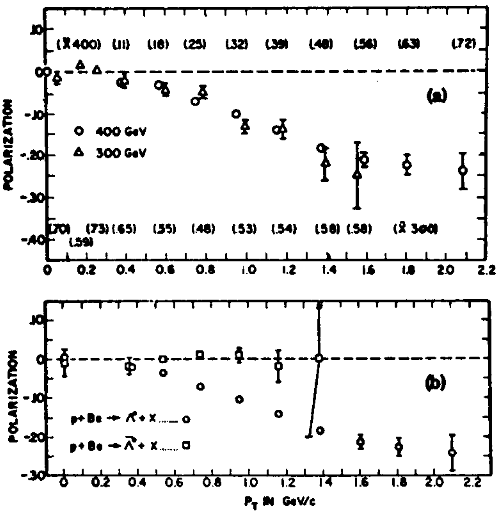

Fig. 4. (a) $\Lambda°$ polarization as a function of P_T. The number in parentheses is the average value of $\bar{x}$ for that point. (b) $\Lambda°$ and $\bar{\Lambda}°$ polarizations. The polarization is defined as positive along $\vec{n} = (\vec{k}_p x \vec{k}_\lambda)/|\vec{k}_p x \vec{k}_\lambda|$. From Ref. 4.

note that the observed Λ° may be partially from Σ° decay, with a consequent dilution of the measured polarization. The initially produced Λ° may have a considerably larger polarization. They also measured $\bar{\Lambda}^\circ$ polarization - consistent with zero, as indicated on the figure. Their conference presentation also showed evidence for a significant Ξ° polarization, ~10%. In addition they looked for an indication of proton polarization through a two step process producing Λ° but saw none. Why such strong Λ° polarization, but nothing for $\bar{\Lambda}^\circ$? A possibly pertinent difference is that Λ° are leading particles, carrying the valence quarks, the $\bar{\Lambda}^\circ$ are not. Wicklund commented that perhaps the mechanism might be a low energy resonance production process. In the theory panel presentation, Kane said that in a reasonable QCD model, at high $P_\perp$ and energy, the Λ° polarization should disappear. The group intends to test this next year at a $P_\perp$ of ~6 GeV/c.

The lack of proton polarization in a high transverse momentum inclusive process was also observed (at the 10% level) in a recent Brookhaven experiment, Carroll et al.[6], with 28 GeV/c protons on platinum. They measured the polarization of 7 GeV/c scattered protons at a $P_\perp$ =1.46GeV/c. Since this corresponds to nearly 90° in the cms the p-p process would not be expected to give an asymmetry, but there is no such restriction on p-n scattering.

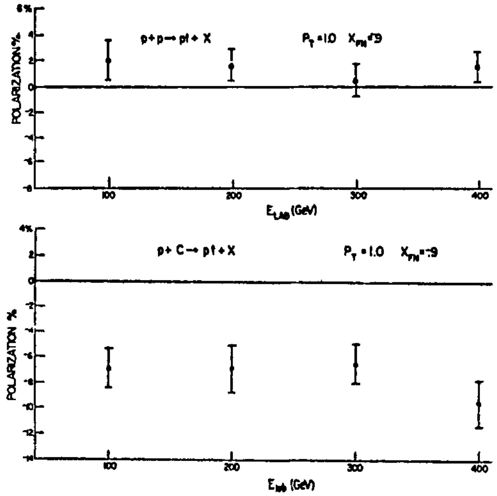

Fig. 5. Polarization of inclusively produced protons as a function of proton beam energy. Top curve: Hydrogen jet target; bottom: Carbon target. From Ref. 7.

Another experiment investigating the polarization of inclusively produced protons was carried out at Fermilab by the Indiana University group: their results were presented at the Tokyo Conference, Baranko et al.[7], and at this conference by Polvado. This group uses a carbon scattering polarimeter to analyze the polarization of the recoil proton. Their primary targets were an internal hydrogen gas jet and a rotating carbon target. Some of their results are shown in Fig. 5. Looking at large x at a $P_\perp$=1 GeV/c on hydrogen they see only a 2% level proton polarization. On carbon they observe -8% polarization -- they attribute the difference to rescattering of the recoil proton by the carbon nuclei in the target, creating a proton polarization going into their polarimeter much larger than that from the primary reaction.

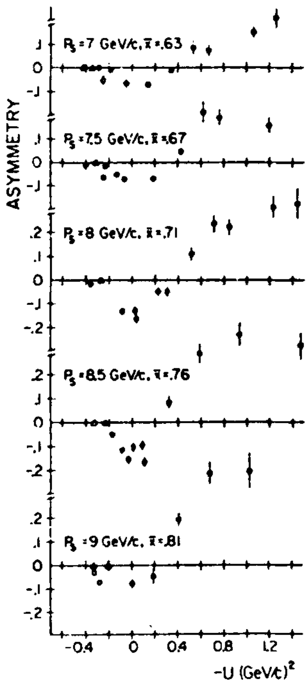

Figure 6. Asymmetry for inclusive π^+ production in $p_\uparrow p$ collisions at 11.8 GeV/c (solid circles) and 6 GeV/c (open circles). P_S is the scattered momentum at 11.8 GeV/c. From Ref. 8.

A second type of inclusive experiment involves the production of asymmetries in inclusively produced pions or protons with the use of a polarized beam or target. Some earlier work on inclusive pion production using the ZGS polarized proton beam was by an Argonne, Minnesota, Rice collaboration, Klem et al.[3]. Some of their results are shown in Fig. 6. They saw a large asymmetry in π^+ production at their largest momentum transfer. They interpreted their large x (forward production) results in terms of a baryon-exchange model and concluded they were essentially looking at backward π-p scattering.

A CERN, Oxford, Orsay collaboration, Dick et al.[9], was the first to use a polarized proton target to study asymmetries in inclusive reactions. Their original work was on inclusive $\pi^\pm$ production in $\pi^\pm p$ scattering at 8 GeV/c, giving evidence for mirror symmetry. In more recent work, Aschman et al.[10], they used 7.9 GeV/c protons from Nimrod at Rutherford Lab to study asymmetries in inclusive proton and pion production in $pp_\uparrow$ scattering. Some of their results are shown in Fig. 7. The proton and π^+ asymmetries are non-zero, at the ~5% level, with the π^+ asymmetry possibly large at their highest $P_\perp$.

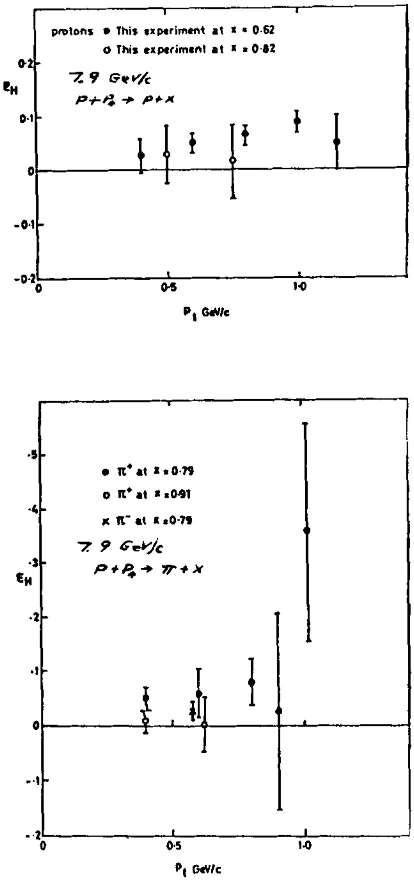

Fig. 7. Asymmetries in inclusive proton and pion production in 7.9 GeV/c pp$_\uparrow$ collisions, Ref. 10.

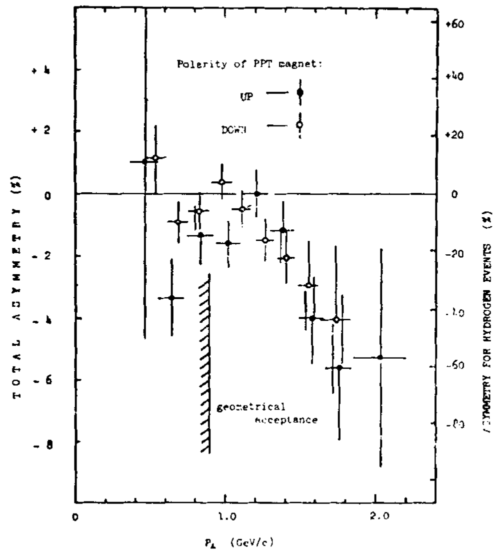

Fig. 8. Asymmetry in inclusive π° (2γ) production in 24 GeV/c pp$_\uparrow$ collisions, central region, x $\simeq$ 0. Left scale, raw measured asymmetry; right, hydrogen asymmetry after estimating the target dilution. Preliminary results, Ref. 11.

The group also studied inclusive π° (2γ) production at 24 GeV/c at CERN. Their very preliminary results were presented at Tokyo, Antille et al.[11], and at this conference by M. Fidecaro and are shown in Fig. 8. The raw asymmetry is indicated on the left hand scale. This asymmetry is of course strongly diluted by the non-polarized material in their target. They estimated the dilution factor from previous experiments to obtain a measure of the pure proton asymmetry, shown using the right hand scale, obtaining a dramatic -60% at $P_\perp$~2 GeV/c.

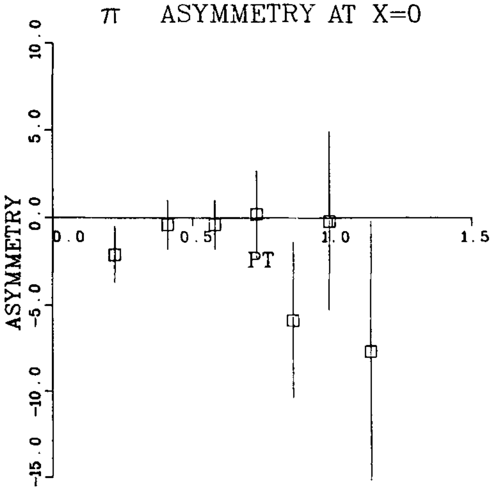

Fig. 9. Inclusive π^- asymmetry as a function of momentum transfer, 12 GeV/c $p_\uparrow p$ collisions, $x \cong 0$ region.

This is very exciting, the largest inclusive asymmetry seen at high $P_\perp$, if it holds up when they complete their analysis.

The asymmetry in inclusive produced π^- at $x = 0$ has been studied at 6 and 12 GeV/c here at the ZGS by an Argonne-Indiana collaboration. Some preliminary results presented at this conference by Gray are shown in Fig. 9. They are mostly at low momentum transfer and the asymmetry is small, at the few percent level. They hope to use their final data to test QCD calculations.

EXCLUSIVE, QUASI ELASTIC REACTION

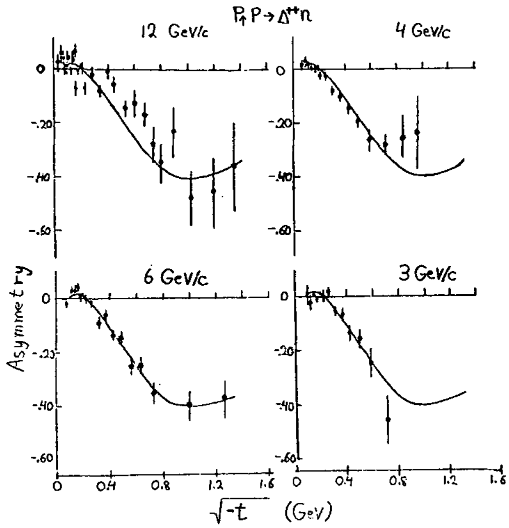

Fig. 10. Asymmetry in $p_\uparrow p \to \Delta^{++}$+n. 12 GeV/c data are preliminary. Ref. 12.

I will now switch to a quasielastic experiment carried out by the Argonne Effective Mass Spectrometer (EMS) group, Wicklund et al.[12] They studied the reaction $p_\uparrow p \to \Delta^{++} + n$, 3 to 12 GeV/c, but only to modest momentum transfer. Their measured asymmetries are shown in Fig. 10. The 12 GeV/c results are preliminary and based on 20% of their data sample. The hand drawn curve is common to all energies. The asymmetries are large and consistent with energy independence. The group compares their results with a quark-vector meson production with qualitative agreement.

ELASTIC SCATTERING

A comparison of the asymmetries in $p_{\uparrow}n$ and $p_{\uparrow}p$ elastic scattering was first done at at the ZGS at low momentum transfer in the 2-6 GeV/c range by the Argonne EMS group, Diebold et al.[13] This type of comparison has been extended to much higher momentum transfers in a ZGS experiment by the Minnesota group, Marshak et al.[14] presented at Tokyo. They have data at 2, 3, and 6 GeV/c - on the latter run covering practically the full angular range. Fig. 11 shows their 6 GeV/c data. I have shrunk their p-p plot to align the t scales. 90° CM corresponds to $|t| = 4.8$, and $P_{\perp}^2 = 2.4 (GeV/c)^2$. It is clear that the $p_{\uparrow}n$ asymmetry is completely unlike the $p_{\uparrow}p$ past the $|t| = 1.5 (GeV/c)^2$ region, going dramatically negative to -.3 at 90° CM and going further negative in the backward hemisphere. These appear to be the highest elastic symmetries observed at high transverse momentum.

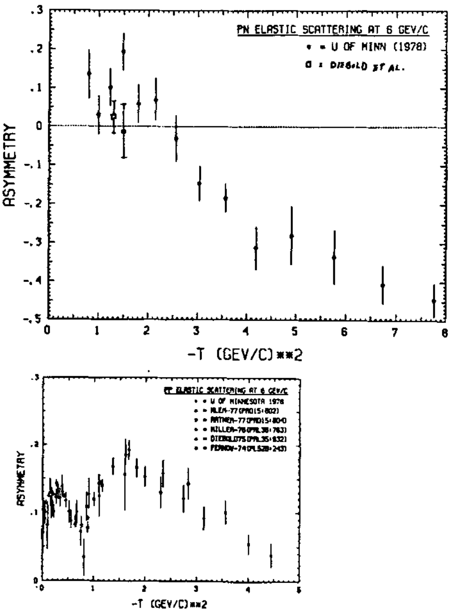

Fig. 11. Asymmetry in $p_{\uparrow}n$ and $p_{\uparrow}p$ elastic scattering at 6 GeV/c. Ref. 14

Turning now to the higher energies, asymmetry measurements at substantial transverse momenta were made in a recent experiment by the CERN-Oxford-Annecy collaboration, Crabb et al.[15], $pp_{\uparrow}$ elastic scattering at 24 GeV/c. Their results are shown in Fig. 12. Their data for $|t| < .9$ were published earlier.[15] The pp asymmetry parameter generally appears to hold in the few percent range, with evidence for a significant negative value, -(10→15%) or so at $|t| \sim 3.5 (GeV/c)^2$.

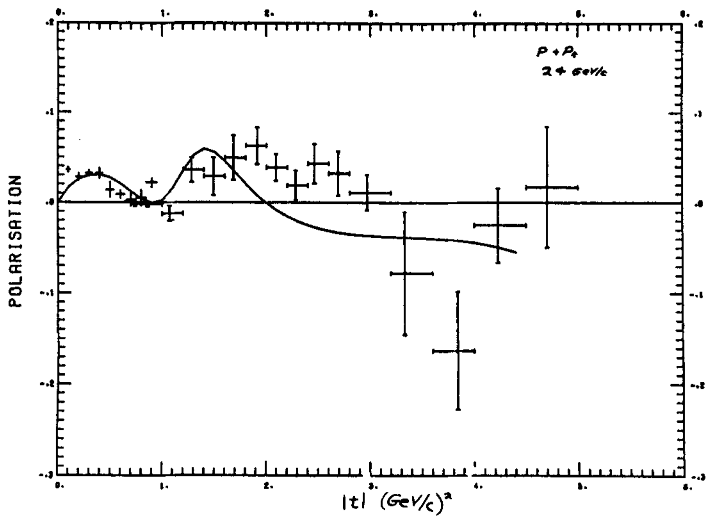

Fig. 12. Asymmetry parameter in 24 GeV/c pp↑ elastic scattering. Ref. 15.

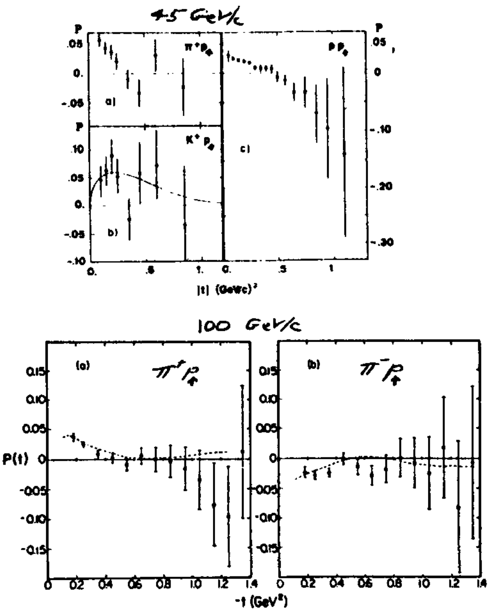

Fig. 13. Elastic scattering asymmetry parameters. Top, 45 GeV/c, Ref. 16. Bottom, 100 GeV/c, Ref. 17

At even higher energies the momentum transfer range becomes more limited and the error bars quite large at the experimenter's maximum t values. The top of Fig. 13 shows the results of the earlier 45 GeV/c experiment of Gaidot et al.[16] done at Serpukhov. The error bars are large but there is an indication that the asymmetry parameter has become larger in the $|t| = 1(\mathrm{GeV/c})^2$ range than at 24 GeV/c. The 100 GeV/c elastic $\pi^{\pm}p$ asymmetry parameter data shown on the bottom of Fig. 13 were obtained at Fermilab by the large scale collaboration, Auer et al.[17], and presented

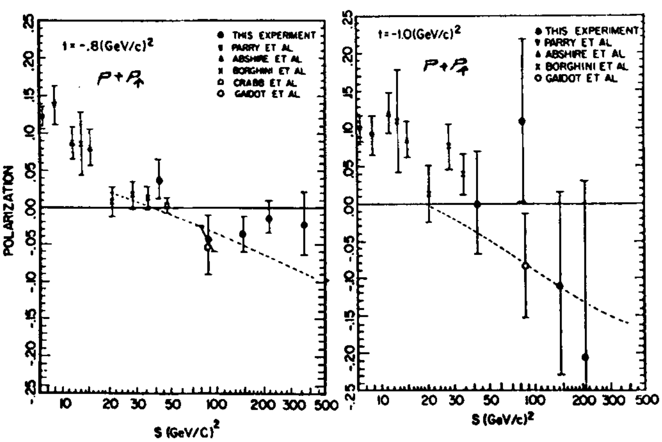

Fig. 14. Polarization parameter in pp elastic scattering as a function of S. Ref. 18. Dashed curve, Pumplin-Kane model, Ref. 19.

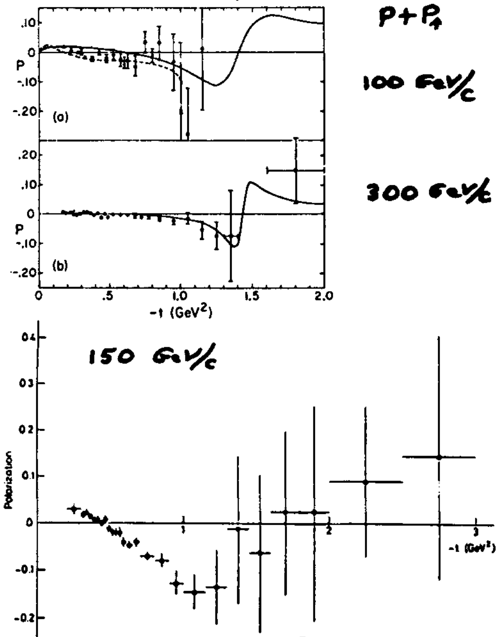

Fig. 15. Asymmetry parameter in $pp_{\uparrow}$ elastic scattering. Top, Ref. 20; theoretical curve, updated Kane-Seidl model, Ref. 21; bottom, Ref. 22.

here by Jonkheere. The asymmetry parameter values appear to be low, under 10%, in the $|t| \sim 1.2 (GeV/c)^2$ range, but possibly larger than the few percent level seen at lower t.

The Indiana University group, Corcoran et al.[18], used their scattering polarimeter to analyze the polarization of the recoil proton, determining the polarization parameter in pp elastic scattering over the range 20 to 200 GeV/c at Fermilab. Their results are shown in Fig. 14. Their maximum t value is $1 (GeV/c)^2$ but their range of energies along with other data does permit a look at the s dependence of the reaction. The asymmetry parameter appears to be down at the -15% level at the higher energies at $|t| = 1 (GeV/c)^2$.

Along with the $\pi^{\pm}p$ data, Jonkheere also discussed the results for $pp_{\uparrow}$ scattering at 100 and 300 GeV/c, Snyder et al.[20]. Their data are shown on the top of Fig. 15. Apparently the scale on the published 300 GeV/c plot needs to be multiplied by two. Below are the results of the 150 GeV/c $pp_{\uparrow}$ experiment done by the CERN collaboration, presented here by M. Fidècaro.[22] Again, I have attempted to align the t axes for comparison. Both the 150 and 300 GeV/c experiments have measured values of A in the -15% range at $|t| \sim 1.2$ GeV/c$)^2$; at larger t values the tendency of both sets of data is toward positive polarization.

SPIN EFFECTS WITH TWO POLARIZED PARTICLES

Now I would like to discuss some experiments involving two polarized particles. In these experiments both the asymmetry parameter and the spin-spin correlation parameter are simultaneously measured. The experiments are $p_{\uparrow}p_{\uparrow}$ elastic scattering, using the ZGS polarized beam and a polarized target.

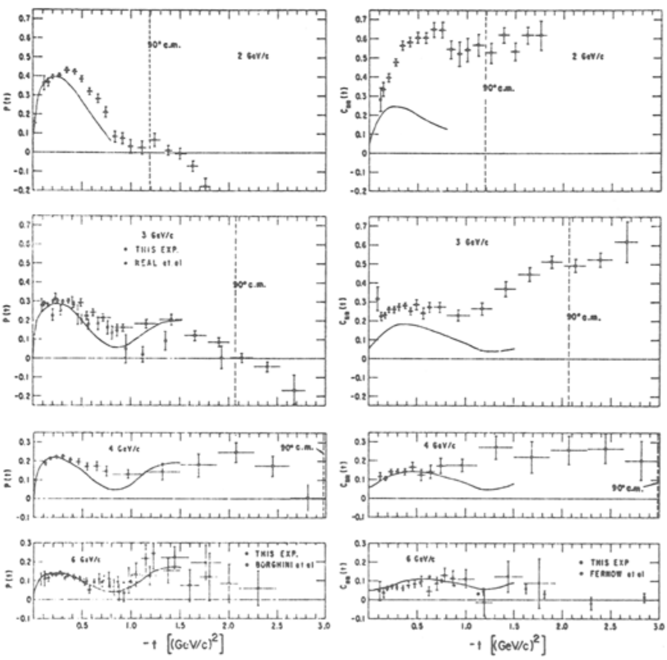

Fig. 16. A and C_{NN}, $p_{\uparrow}p_{\uparrow}$ elastic scattering 2 to 6 GeV/c. Ref. 23.

The first is a comprehensive experiment by the Northwestern-Argonne collaboration, Miller et al.[23], to measure A and C_{NN} (A_{NN} in the Ann Arbor Convention), the asymmetry and correlation parameters for beam and target polarizations normal to the scattering plane. Their measurements were at 2, 3, 4 and 6 GeV/c, with a maximum value of $|t| = 2.8(GeV/c)^2$ at nearly 90° CM at 4 GeV/c. Their results are shown in Fig. 16, along with data from other experiments. Let me concentrate on the correlation parameter, C_{NN}. At 2 and 3 GeV/c the values of C_{NN} rise to .6 and .5, the 90° CM value near the maximum. At 4 GeV/c the maximum value of C_{NN} has dropped off to ~.25 and at 6 GeV/c it is down to ~.1, quite a rapid fall off.

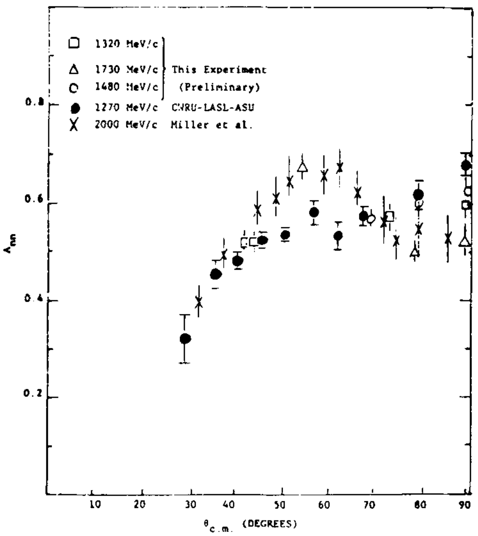

Fig. 17. A_{nn} in $p_\uparrow p_\uparrow$ elastic scattering in the range 1.3-2.0 GeV/c. Preliminary data.

A Rice University group has very preliminary data on A_{nn} also in the 1 to 3 GeV/c range which was presented at this conference by Mulera. A representative plot relating some of their results to other experiments is shown in Fig. 17. They are in agreement with the large value of $A_{nn} = .6$ at wide angles.

The Northwestern-Argonne group has used a solenoid and beam magnet system to rotate the beam polarization vector into the longitudinal ($\vec{L}$) and transverse ($\vec{S}$) directions in the scattering plane. The magnet for their polarized proton target is constructed to allow the target polarizations also to be longitudinal and transverse as well as normal to the scattering plane. Therefore they can measure the entire set of initial state correlation parameters. With this setup they carried out and previously reported a 6 GeV/c experiment, Auer et al.[24], the first high statistics measurement of C_{SS}. They found this parameter went almost linearly down from zero to -.2 at $1.2(GeV/c)^2$. In a very recent

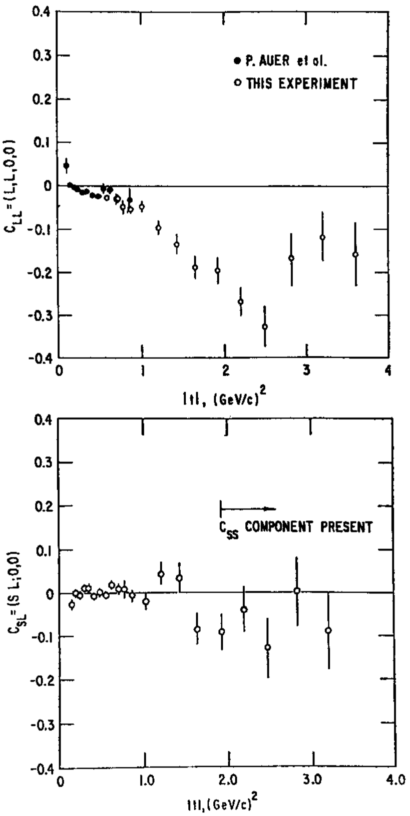

Fig. 18. C_{LL} and C_{SS} in 6 GeV/c pp elastic scattering. Preliminary data. Ref. 25.

experiment also at 6 GeV/c presented at Tokyo[25] they have measured C_{LL} and C_{SL} to $|t| = 3.5(\text{GeV/c})^2$. Their preliminary data are shown in Fig. 18. The C_{LL} plot contains a small admixture of C_{SL}, seen below. The values of C_{LL} are large at large $|t|$, going to -.3 at $|t| = 2.5(\text{GeV/c})^2$, larger than the 6 GeV/c values of C_{NN} which were in the .1 range. Notice that the increase in C_{LL} appears to begin at $|t|$ of ~ 1 $(\text{GeV/c})^2$, where the elastic differential cross section curve has changed from the steep fall-off of the diffraction region.

The past two years our group, a collaboration of Argonne, Michigan, and others, also has been working here at the ZGS investigating two-spin effects in elastic p-p scattering. We have studied the momentum transfer dependence at 11.75 GeV/c and the energy dependence at 90° CM, with beam momenta from 1.5 to 11.75 GeV/c. In our experiment the beam and target spins are oriented perpendicular to the horizontal scattering plane, in the $\vec{n}$ direction, the polarization of the scattered and recoil particles are unmeasured. We determine the Wolfenstein parameters A and A_{nn} and the associated parallel and antiparallel pure spin state cross sections discussed at the start of the talk.

During this two year period of running the average extracted polarized beam intensity at our target has increased from 2.5 10^9 per pulse to just over 10^{10} per pulse. With this increase in intensity we have been able to extend our measurements out to 90° CM at 11.75

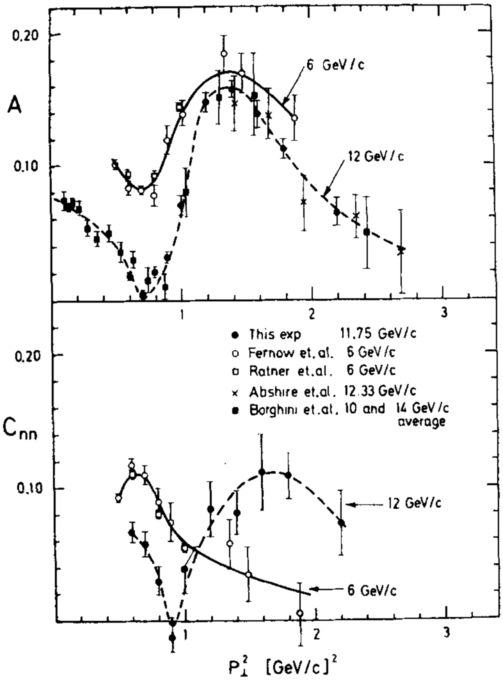

Fig. 19. A and C_{nn} $p_{\uparrow}p_{\uparrow}$ elastic scattering at 6 and 12 GeV/c. Ref. 26.

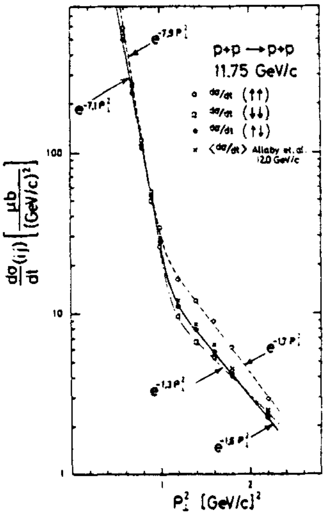

Fig. 20. Differential cross sections in pure initial spin states, $p_{\uparrow}p_{\uparrow}$ elastic scattering at 11.75 GeV/c. Ref. 26; cross section normalization, Ref. 27.

GeV/c. Our 1976 data, Abe et al.[26], is presented in the form of A and C_{nn} (A_{nn}) in Fig. 19, along with the results of other groups and our earlier 6 GeV/c runs. Of interest here is the well known sharp dip in A at $P_{\perp}^2$ = .8 GeV/c^2 at 11.75 GeV/c and the substantial increase in the 1-2(GeV/c)^2 $P_{\perp}^2$ region. At 11.75 GeV/c A_{nn} also looks remarkably similar to A. These results are reflected in the two-spin cross sections as seen in Fig. 20. The spin average cross sections are from Allaby et al.[27] As we noted in the previous Fig. 19, A and A_{nn} both went to nearly zero around $P_{\perp}^2$= .8 and this corresponds to the equality of the pure spin state cross sections at that $P_{\perp}^2$; the subsequent rise of A and A_{nn} is associated with the observed substantial cross section difference. It is of obvious interest that the spin difference becomes sizeable just after the end of the diffraction peak region - where the spin averaged differential cross section slope has decreased about a factor of five, a phenomenon similar to that we noted in the C_{LL} data of the Northwestern-Argonne collaboration. Our early 1977

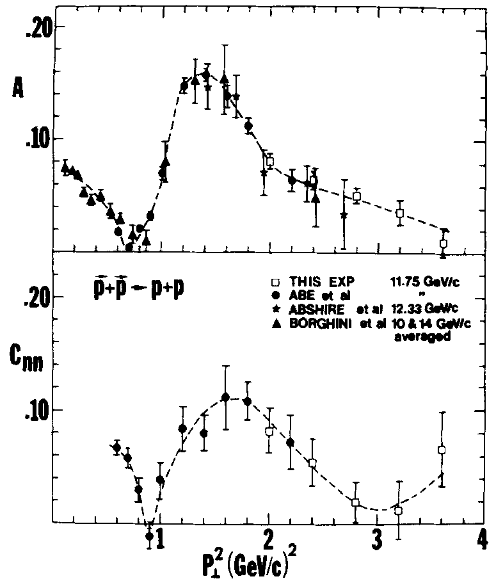

Fig. 21. A and C_{nn}, 11.75 GeV/c $p_\uparrow p_\uparrow$ elastic scattering to $P_\perp^2$ = 3.6(GeV/c)^2. Ref. 28.

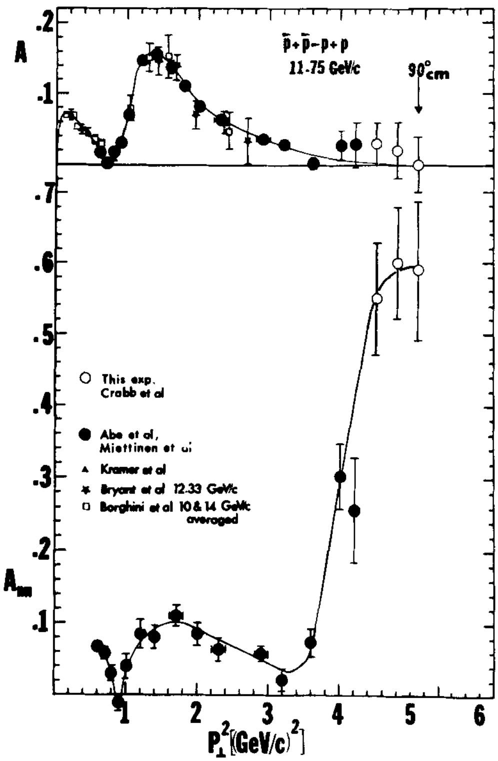

Fig. 22. Ref. 29,30.

data increased our $P_\perp^2$ range from 2 to 3.6 (GeV/c)^2.[28] The A and A_{nn} behavior is shown in Fig. 21. Both parameters have decreased smoothly. The dotted curve through A_{nn} "to guide the eye", drawn with a dip and rise at $P_\perp^2$ = 3.6(GeV/c)^2, was obviously pure hope - a flat "guide" curve would have been equally reasonable.

Fig. 22 shows our later 1977 A and A_{nn} results,[29] which went out to $P_\perp^2$ = 4.2(GeV/c)^2, and our most recent results to 90° CM, $P_\perp^2$ = 5.09(GeV/c)^2.[30] The hint of a rise of A_{nn} at $P_\perp^2$ = 3.6(GeV/c)^2 in the previous run has turned into a dramatic upturn with A_{nn} going to .6 - how lucky can a group be? A is consistent with zero, necessary for identical particle scattering at 90° CM. Since A is small the spin parallel up and down cross sections are essentially equal. We will call their average the spin parallel cross section. We have plotted the ratio of this average parallel cross section to the antiparallel cross section on a log scale in Fig. 23. This ratio reaches a factor of four in the 90° CM region. Clearly we will need better statistics at this

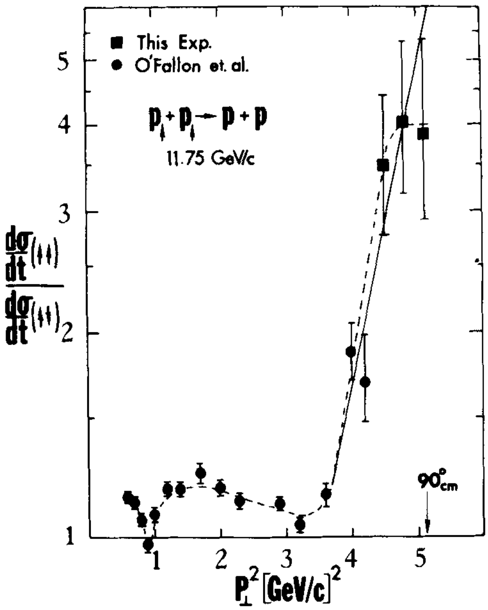

Fig. 23. The ratio of the cross sections in spin parallel to antiparallel initial spin states, $(1+A_{nn})/(1-A_{nn})$, Ref. 30.

energy or, hopefully, some running at a larger energy to test for a continuing increase or a flattening out. It is also obvious that a very exciting experiment would be the high momentum transfer measurement of the longitudinal and transverse spin parallel and antiparallel cross sections - the parameters $A_{\ell\ell}$ and A_{ss}; the Northwestern-Argonne group hopes to carry this out.

In Fig. 24 our spin parallel and antiparallel cross sections and the ISR data of DeKerret et al.[31] are plotted against a scaled momentum transfer scaled parameter, $\rho_\perp^2$, involving a Lorentz contraction factor and total cross section ratios, that Krisch[32] has suggested to attempt to superpose the differential cross sections over a wide range of energies. At 11.75 GeV/c it differs little from $P_\perp^2$. On this plot the antiparallel cross section appears to be falling as $e^{-2.6\rho_\perp^2}$ with no apparent change in slope from the intermediate 1 - 3 GeV/c^2 $\rho_\perp^2$ region. The spin parallel cross section is falling less rapidly, consistent with the same $e^{-1.6\rho_\perp^2}$ dependence of the ISR results in this range of momentum transfer. The interesting speculation is that if the antiparallel cross section continues to fade away high momentum transfer p-p scattering may end up occuring only in spin parallel states.

As mentioned earlier, we have also been studying the energy dependence of the elastic p-p spin-spin interaction at 90° CM, at the maximum $P_\perp^2$ for a given energy. Our data are from two runs, the first with beam momenta between 1.5 and 5.5 GeV/c [33] and the second up to 11.75 GeV/c.

As indicated before, A at 90° CM should be zero and our data are typically consistent with this within the errors of a percent or so.

Our 90° CM values of A_{nn} are presented in Fig. 25, along with those of Miller et al.[23] discussed earlier and some new Los Alamos results at low momentum, presented at the conference by Willard. The large value of A_{nn} at low momenta and the sharp drop which occurs at a laboratory momentum of ~3.5GeV/c ($P_\perp^2 \sim 1.25(\text{GeV/c})^2$ were clearly evident from the earlier Miller et al. data. We add an improvement in statistics and show evidence for a flattening out at the $A_{nn} \sim .1$ value above $P_{LAB} \sim 4$ GeV/c. A_{nn} increases sharply at a laboratory momentum of 9 GeV/c which corresponds to $P_\perp^2$ of $3.8(\text{GeV/C})^2$, close to the $P_\perp^2$ where we observed A_{nn} increasing abruptly at 11.75 GeV/c; the first sign of a rise there was at $P_\perp^2 = 3.6(\text{GeV/c})^2$. So at these close-by energies at least, the rapid increase of the spin parallel cross section over the anti-parallel is occuring at

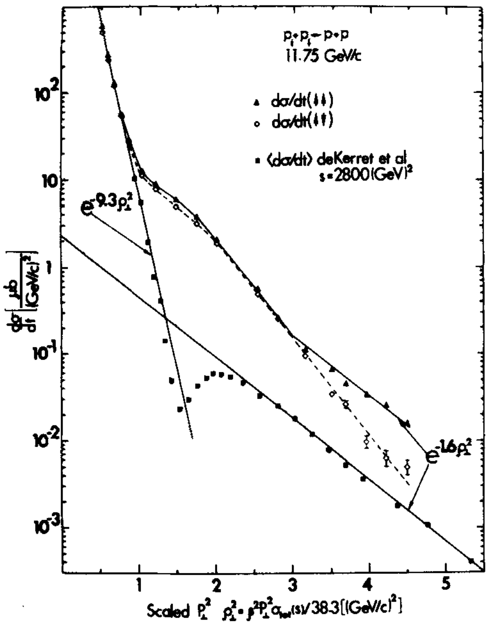

Fig. 24. Differential cross section for parallel and antiparallel initial spin states at 11.75 GeV/c. Also shown is spin-averaged ISR data, Ref. 31. The momentum transfer squared variable $\rho_\perp^2$ is discussed in Ref. 32.

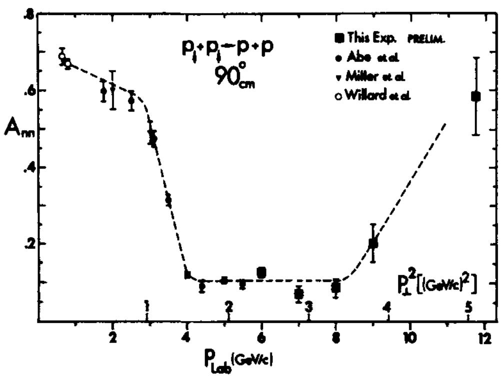

Fig. 25. A_{nn} at 90° CM as a function of $P_\perp^2$ and P_{LAB}.

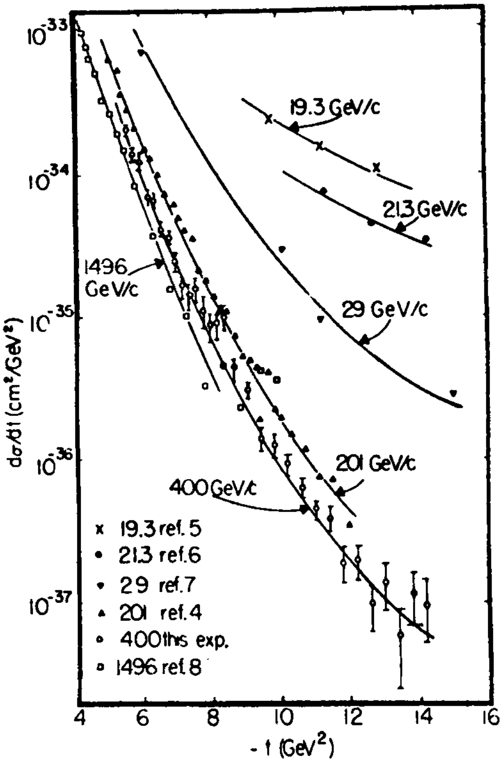

Fig. 26. Differential cross section for pp elastic scattering. Plot from Ref. 34.

similar transverse momenta. Perhaps this behavior might continue to higher energies.

To put the data in some perspective, I have to note that our momentum transfer range is small compared to the p-p spin-averaged data at higher energy. The recent results of the McGill, Northeastern, Cornell collaboration, Conetti et al.[34], at Fermilab along with the ISR and lower energy data are shown in Fig. 26. At our $P_\perp^2 \sim 5$ GeV/c^2 we are at the left edge of this graph. It is evident that in terms of t ($\sim P_\perp^2$ at high energies) the high momentum transfer differential cross sections have not reached an asymptotic value, and it would be a bit foolhardy to predict the spin dependences we see here will continue and that the parallel cross sections will dominate at higher energy and momentum transfers. But it is clear from the one and two spin experiments that there are dramatic spin dependences at high transverse momentum and continued investigation of these phenomena should produce further exciting results.

I would like to thank the authors who have kindly provided me with their data before publication. I also wish to acknowledge the work of the other members of our group in getting our recent data available for this conference. I want to thank Dr. Peter Hansen for his aid with some of the figures and for his helpful comments.

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