NUCLEON-NUCLEON ELASTIC SCATTERING AT LARGE $P_{\perp}^2$ AND SPIN*

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This talk will review nucleon-nucleon elastic scattering at large $P_{\perp}^2$. For about 5 years this field was very quiet because of lack of new data. In the last year, this has changed rapidly and there is some very impressive new data. Many of us feel that this process probes most directly and most deeply into the inner structure of the nucleon. The high available energy and luminosity allows precise and direct measurements of

$$p + p \rightarrow p + p$$

over a cross section range of 10^{13} and an incident energy range of a few MeV to 2000 GeV. This enormous precision and range, coupled with the fundamental simplicity of the elastic scattering process, makes this data perhaps the most severe test of any theory of the dynamics of strong interactions. I feel that understanding the strong interactions of the nucleons that comprise our universe remains the central problem of high energy physics. Unfortunately it has not been an easy problem to solve.

During the past 30 years many experimental teams have labored to gather precise and extensive data on the processes:

$$p + p \rightarrow p + p$$
$$n + p \rightarrow n + p$$

Many brilliant and distinguished theorists have spent a major fraction of their lives trying to understand the

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data on this simple process. I believe that the only generally accepted truth that has emerged out of this effort is:

> In soft hadronic scatterings, which give the small-$P_\perp^2$ diffraction peak, nucleons behave as geometric objects with a size of about 1 fermi.

While this may not seem to be enormous progress, let me remind you that throughout the 1960's many theorists believed that, at the 1 fermi level, size was a totally meaningless concept and that the optical and geometric models proposed by Serber,[1] myself,[2] Van Hove,[3] Yang,[4] and others[5] were "Stone Age Physics". I believe the ISR and Fermilab elastic measurements make it clear that the idea of a nucleon having a hadronic size of 1 fermi is a meaningful and useful concept over an enormous energy range.

For many years the spin of the nucleon was considered an unfortunate complication, which hopefully would become unimportant at high energy. Perhaps this is because many of us had trouble understanding spinors as students of Quantum Mechanics. During the past 15 years this complication has become an area of high energy physics. The development of cryogenic polarized proton targets at Berkeley,[6] CERN[7] and Argonne[8] allowed detailed studies of the spin-orbit interaction in hadron-hadron scattering. These studies showed that some previously accepted dynamical theories of strong interactions could not meet the test of polarization experiments. The ZGS polarized proton beam used with a polarized target has allowed the first precise experiments on spin-spin forces in hadronic interactions. These spin-spin forces appear very large especially at large $P_\perp^2$ -- a totally new and unexpected result.

Now let me remind you that large-$P_\perp^2$ elastic scattering lets one probe very deeply into the proton. In fact, it is large $P_\perp^2$ and not high incident energy which lets one probe at very small distances. Notice that $P_\perp$ is canonically conjugate to the impact parameter b.

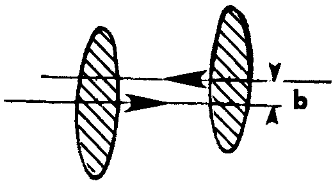

Fig. A. Two Lorentz contracted protons with a small impact parameter b about to collide.

Thus the very violent and probing "head-on" collisions at small b can only be precisely studied at large $P_\perp^2$. The Heisenberg uncertainty principle

$$bP_\perp = \hbar c = .197 \text{ GeV/c-fermi}$$

indicates that to clearly see an object of 1/20 fermi size requires a $P_\perp$ of 4 GeV/c or a $P_\perp^2$ of $16(\text{GeV/c})^2$. An elastic scattering event with $P_\perp = 4$ GeV/c has never been observed because of the small cross sections. We should look harder for such events to further our goal of discovering and studying the constituents of the proton which cause violent strong interactions, be they quarks, partons, cores, or whatever. I know of no direct way to study this problem except high-$P_\perp^2$ elastic or inelastic scattering.

PROTON PROTON ELASTIC SCATTERING DATA

I will first show in Fig. 1 a summary of p-p elastic scattering data up to 12 GeV compiled by the Indiana group.[9] The differential cross section, $d\sigma/dt$, is plotted against the conventional Mandlestam variable, -t, the square of the 4-momentum transfer. This plot shows several very interesting features of strong interactions. First notice that at all energies there is a very clear

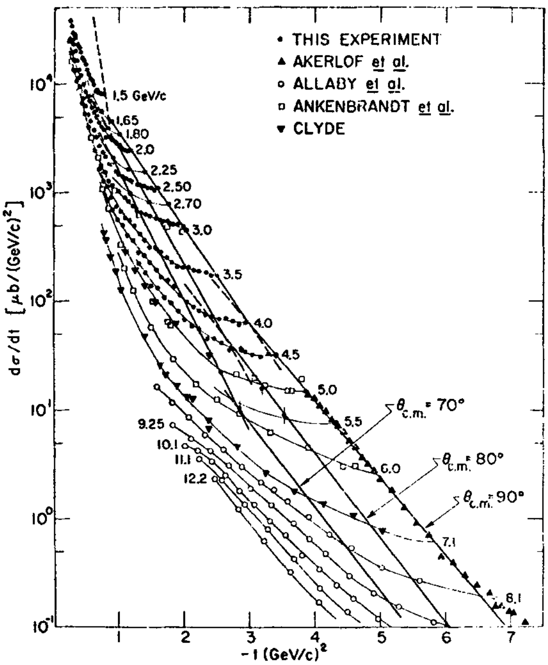

Fig. 1. Differential cross sections in p-p elastic scattering at fixed values of $\theta_{c.m.}$.

diffraction peak which drops like $e^{-b|t|}$. This is believed to be the diffraction or shadow scattering caused, through unitarity, by the many inelastic channels absorbing out part of the incident proton wave. The slope b of 6 to $9(\mathrm{GeV/c})^{-2}$ corresponds to the size of the "outside" of the proton which as we said before is about 1 fermi. The change of the slope with incident energy is the familiar "shrinkage" of the diffraction peak. This shrinkage indicates that either -t is not a good variable or the proton size grows with energy or both. At larger -t there is even more shrinkage. Thus dσ/dt is clearly not independent of incident energy when plotted against -t.

Also notice that at each energy dσ/dt becomes very flat near 90° in the c.m. This is because $-t = 2P^2(1-\cos\theta)$ changes by a great deal in going from 80° → 90°, while $P_\perp^2 = P^2 \sin^2\theta$ hardly changes at all. In fact, in the diffraction peak $-t$ and $P_\perp^2$ are essentially equal while at 90° $-t = 2P_\perp^2$. There are also some fixed angle contours drawn in the plot, which show the fixed angle energy dependence. Notice the 90° contour where the data is very precise. Clearly $d\sigma/dt$ (90°) drops very rapidly with energy, perhaps as e^{-s} or $e^{-\sqrt{s}}$ or perhaps as s^{-n}.

Let me next show in Fig. 2 a contribution to this meeting by the Argonne-Columbia-Minnesota group.[10] They studied π-p and p-p elastic scattering at fixed angle while varying the incident energy from 2-9 GeV in very fine steps. Notice that both cross sections drop off very rapidly with increasing s. Moreover $d\sigma/dt(\pi^-\text{-p})$ has much more structure than $d\sigma/dt$(p-p), perhaps because of the resonances in the π^--p system. The data are compared with the s^{-n} power law behavior predicted by the well-known constituent model of Blanckenbeckler, Brodsky, Farrar, and Gunion.[11] The data clearly does not

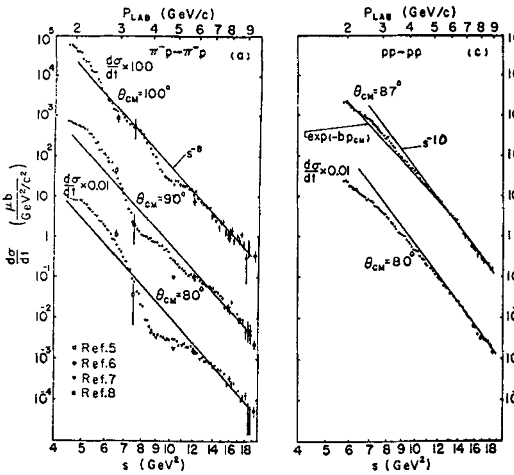

Fig. 2. The differential cross sections for π^--p and p-p elastic scattering at fixed cm angles are plotted against s.

agree well over this s-range, but the agreement is better at the higher s where the model was fit to earlier data.

Fig. 3 shows some very elegant ISR data on p-p elastic scattering from the CERN-Hamburg-Heidelberg-Annecy-Vienna group, at $s = 2800\ GeV^2$, which is equivalent to $P_{inc} = 1500$ GeV/c.[12] Notice the prominent diffraction peak, now with a slope of about $11(GeV/c)^{-2}$. This presumably still corresponds to the 1 fermi outer size of the proton. Next notice the dramatic deep dip

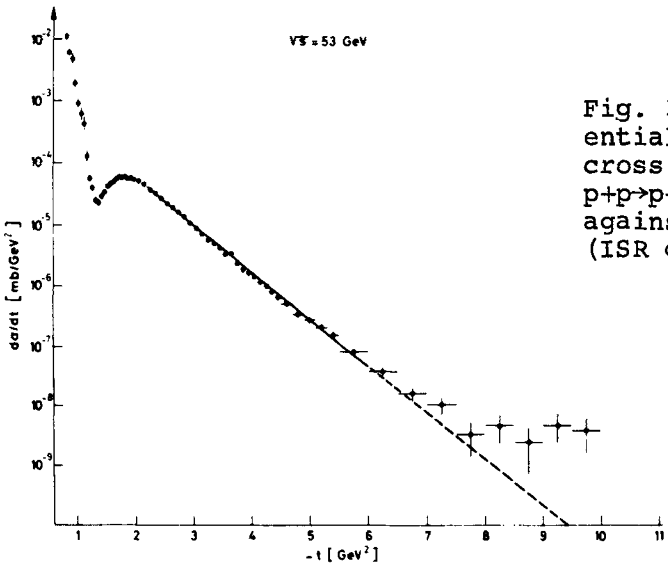

Fig. 3. Differential elastic cross section for p+p→p+p plotted against -t. (ISR data)

at $-t = 1.5(GeV/c)^2$. This was initially believed to be a diffraction minimum, as in a Bessel function diffraction pattern due to the scattering from a square well. However a diffraction pattern has a second minimum and a third minimum and so on. When this ISR data was extended to larger -t there was no 2nd or 3rd minimum. There was only a very elegant and smooth exponential which dropped for many decades exactly as $e^{-1.8|t|}$.

What causes this $e^{-1.8|t|}$ component in high-$P_{\perp}^{2}$ p-p elastic scattering? I believe it may be due to the direct scattering of the constituents of the proton. We do not know the exact nature of these constituents but the slope of $1.8(\mathrm{GeV}/c)^{-2}$ corresponds to a size of about 1/3 fermi. I feel that this hard elastic scattering component may measure the size of the constituents inside the nucleon.

In Fig. 4 we have some very nice new elastic data at 200 GeV/c submitted by the Cornell-McGill-Northeastern-Lebedev group.[13] Using the high luminosity of the Fermilab fixed-target accelerator they were able to extend the measurements of p-p elastic scattering to even larger $P_{\perp}^{2}$ than the ISR group. With their small errors and extended range it is quite clear that $d\sigma/dt$

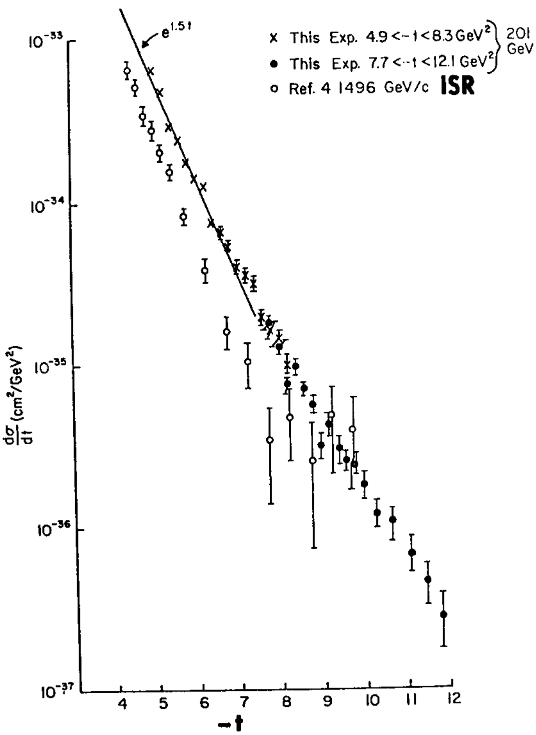

Fig. 4. Differential elastic cross section for p+p→p+p plotted against -t. (Fermilab and ISR data)

continues to drop rather smoothly out to $-t = 12(\mathrm{GeV}/c)^2$ and there is no 2^{nd} minimum. This group's plot compares their data to the 1500 GeV/c ISR data.[12] Two important features emerge from the comparison.

1. The elastic slope flattens somewhat at the largest -t; but not as much as suggested by the high -t ISR data with limited statistics.
2. The 200 GeV/c and 1500 GeV/c cross sections do not fall on top of each other when plotted against the variable -t.

I also have a very preliminary plot of the same groups' 400 GeV/c data. It lies nicely between the 200 GeV/c data and the ISR data and goes out to $-t = 14(\mathrm{GeV}/c)^2$. There is no minimum. The authors asked me not to include this preliminary data in the proceedings.

NEUTRON PROTON ELASTIC SCATTERING DATA

I will now discuss the second type of nucleon-nucleon elastic scattering

$$n + p \rightarrow n + p$$

Comparing this with p-p elastic scattering lets us study the isospin dependence of strong interactions.

There are two very nice new results on n-p elastic scattering, one from the ZGS[14] and one from Fermilab.[15] Both are from the same Michigan group. Figure 5 shows the ZGS data with quite complete angular distributions from 0° → 180° at incident momenta ranging from 5 → 12 GeV/c. The small -t diffraction peak is present at all energies and is very similar to the p-p diffraction peak in slope and in energy dependence. This indicates that the nucleon-nucleon strong interaction has a 1 fermi range in both isospin states. There is a break after the diffraction peak which results in the medium-$P_\perp^2$ $e^{-3|t|}$ component which is again quite similar to the p-p

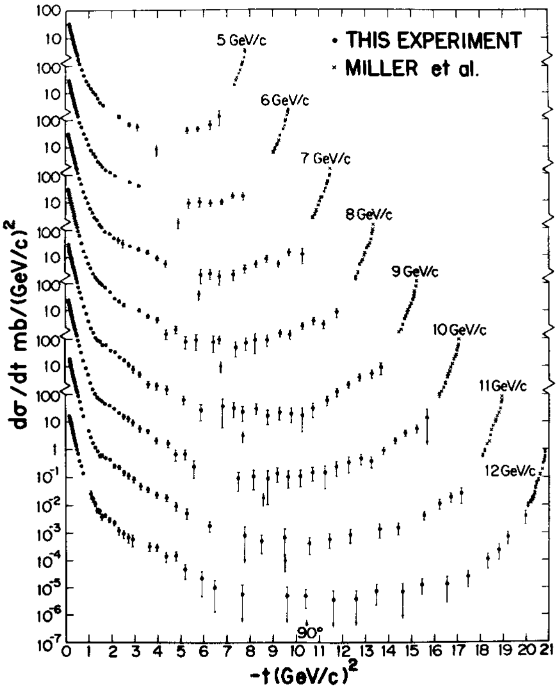

Fig. 5. The n-p elastic differential cross section is plotted against -t for data from 5 → 12 GeV/c.

case. The break clearly becomes sharper with increasing energy as in p-p.

A very important difference between p-p and n-p elastic scattering is that p-p involves identical particles. Thus in studying dσ/dt(p-p) beyond 90° you do not really go to larger -t, but just remeasure the mirror image of dσ/dt up to 90°. However in n-p -t really does increase beyond 90° up to $-t = 4P_{cm}^2$ at 180°. Thus for a given incident energy n-p scattering may probe the nucleon more deeply than p-p.

Notice that the data is actually rather flat for quite a large -t range after 90° until the sharp backward "charge exchange" peak is reached. This flatness in -t after 90° has never really been understood. Let me speculate that the flattening may occur because -t is not the correct variable for parameterizing hadronic scattering. Notice that beyond 90°, while -t is increasing $P_\perp^2$ is decreasing. Perhaps dσ/dt depends on some combination of -t and $P_\perp^2$ and the two effects are opposing each other. I have no "correct" variable to parameterize n-p scattering beyond 90°, but I propose that finding one is an important goal. Perhaps some of you could try to find it.

Next consider the 90° behavior of dσ/dt(n-p). Because the p-p system contains identical particles and the n-p system does not, you might expect some significant differences near 90°. Let us assume that the forward and backward amplitudes simply interfere constructively

$$d\sigma/dt(\theta) = |f(\theta) + f(\pi-\theta)|^2$$

and that charge exchange scattering is small which is true. The p-p and n-p cases are then as shown.

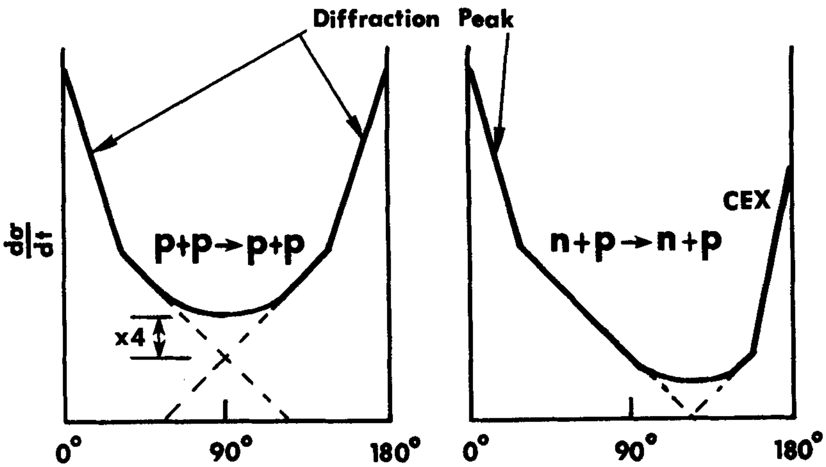

Fig. B. Comparison of 90° particle identity effect for p-p and n-p elastic scattering.

If $d\sigma/dt$(nucleon-nucleon)is isospin independent than at 90° the ratio

$$\frac{d\sigma/dt\,(n\text{-}p)}{d\sigma/dt\,(p\text{-}p)}$$

should be equal to about 1/4. The experimenters find that this ratio is about .3 over the 5 → 12 GeV/c range. This is an interesting result.

The next figure (Fig. 6) shows the new Fermilab n-p elastic data in the momentum range 100 to 370 GeV/c, which extends out to about $-t = 3.5(\text{GeV/c})^2$. Such precise measurements of $d\sigma/dt$(n-p) are quite impressive. Notice the sharp diffraction peak which is similar to the p-p diffraction peak even at these very high energies. A very important feature of the data is the clear development with increasing energy of a dip near

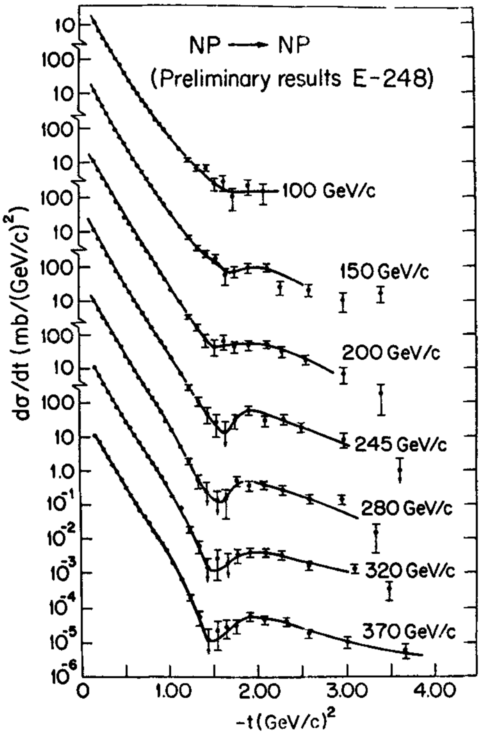

Fig. 6. The differential cross section for n-p elastic scattering from 100→ 370 GeV/c is plotted against -t.

$-t = 1.5(\mathrm{GeV}/c)^2$. Although the statistics obscure the exact depth of the dip, this n-p data is nevertheless the most precise study of the development of the dip. It is surprising that this development has been measured better in $d\sigma/dt$(n-p) than in $d\sigma/dt$(p-p).

MODELS FOR LARGE-$P_\perp^2$ ELASTIC SCATTERING

I will next discuss some theoretical contributions to this meeting. C.K. Chen has a model which assumes that large angle p-p elastic scattering is directly caused by quark-quark elastic scattering.[16] Figure 7 compares the calculations of his model with experimental values of $d\sigma/dt$(p-p) at fixed -t and at 90°. At small -t the agreement is poor, but at large -t and at 90° the agreement is fairly good. While I do not fully under-

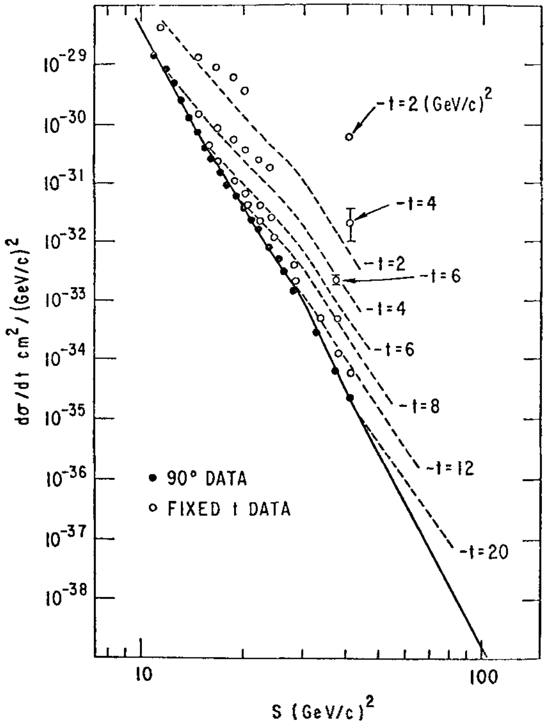

Fig. 7. The differential cross section for p-p elastic scattering at fixed -t and fixed angle is plotted against s. The predictions of the quark-quark model of Chen are shown.

stand the details of Chen's model I do think that large-$P_\perp^2$ nucleon-nucleon elastic scattering may indeed be caused by scattering of the internal constitutents.

Gerrity and Pagnamenta suggest that p-p elastic scattering at both small and large $P_\perp^2$ can be understood in terms of a two component Valence-Core model.[17] They assume the $e^{-10|t|}$ component is caused by the Valence quarks in the outer 1 fermi region of the proton, while the large -t component is due to scattering from a small core at the proton's center. This is reminiscent of my onion model. By fitting several parameters the authors obtain a fairly good fit to the ISR data as shown in Figure 8.

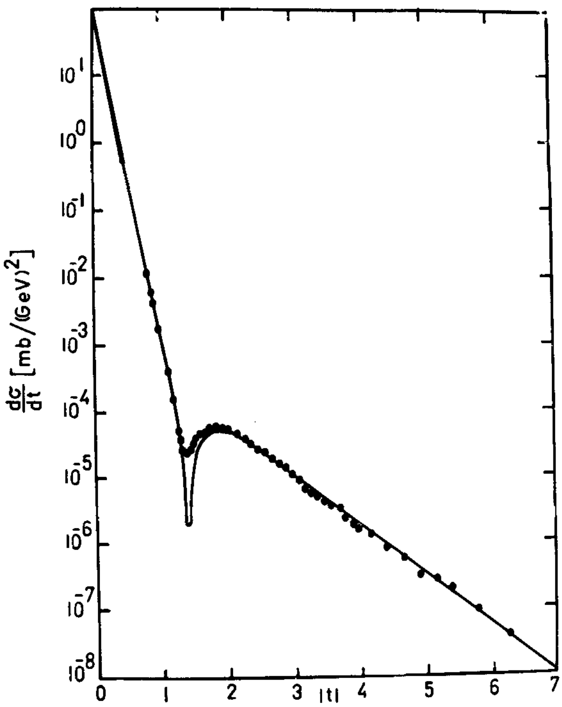

Fig. 8. Plot of $d\sigma/dt$ against -t for p-p elastic scattering for the ISR data. The Valence-Core model fit is shown.

C.N. Yang and T.T. Chou are just now updating their droplet model of 1967 [4] to deal with the ISR and Fermilab data. Let me remind you that the droplet model considers the large -t components of p-p elastic scattering to be the multiple scattering from very tiny and very numerous constituents of the proton. This model has many appealing features and I am looking forward to seeing their new results.

LORENTZ CONTRACTED GEOMETRIC MODEL

I will next remind you of a model I have been enthusiastically developing since 1963. It is called the Lorentz-Contracted Geometric Model and sometimes the Onion Model.[2,18] It assumes that protons behave as Gaussian-shaped clouds of hadronic scattering probability which are spherically symmetric except that they are Lorentz-contracted in the direction of motion. Each proton contains several concentric clouds with different sizes. Thus in some sense the model proton looks like an onion except that the clouds overlap.

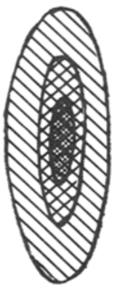

Fig. C. The Lorentz-contracted proton-proton interaction probability density with the 3 concentric regions.

The interaction probability is assumed to have the form

$$\varphi = \sum_i a_i'' e^{-\frac{1}{2}[x^2+y^2+z^2\gamma^2]/A_i'^2}$$

The elastic scattering amplitude which is defined to be exactly the Fourier transform of φ then depends only on the variable $\beta^2 P_\perp^2$, where $\beta = v_{cm}/c$.

$$\frac{d\sigma}{dt} = \left[\sum_i a_i' e^{-\frac{1}{2}A_i'^2 \beta^2 P_\perp^2} \right]^2$$

Since the growth in $\sigma_{tot}(s)$ is presumably caused by the growth in the proton size,

$$A_i'^2 = A_i^2 \sigma_{tot}(s)/38.3$$

and the elastic cross section has the form

$$\frac{d\sigma}{dt} = \left[\sum_i a_i e^{-\frac{1}{2}A_i^2 \beta^2 P_\perp^2 \sigma_{tot}(s)/38.3} \right]^2$$

Thus when $d\sigma/dt$ is plotted against the universal variable

$$\rho_\perp^2 = \beta^2 P_\perp^2 \frac{\sigma_{tot}(s)}{38.3} = \frac{tu}{s}\left(\frac{\sigma_{tot}(s)}{38.3}\right)$$

the plot should be totally independent of energy. Notice that the only assumption required for this striking result is that the probability density is spherically symmetric except for the Lorentz contraction.

$$r^2 \rightarrow x^2 + y^2 + z^2 \gamma^2$$

This parameterization seems to work at small $P_\perp^2$. Last year Peter Hansen and I compiled all p-p elastic diffraction peak data up to 2000 GeV/c and compared it with this prediction.[19] As shown in Figure 9 it totally removes all shrinkage. Thus from 3 → 2000 GeV/c, $d\sigma/dt$(p-p) seems to be a universal function of the variable $\rho_\perp^2$ in the diffraction peak.

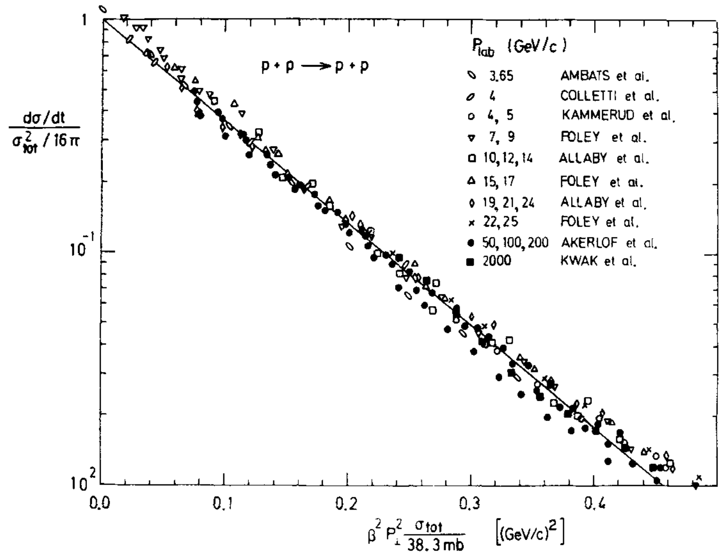

Fig. 9. Differential cross section for p-p elastic scattering from 3.65→2000 GeV/c is plotted against $\rho_\perp^2 = \beta^2 P_\perp^2 \sigma_{tot}/38.3$ in the diffraction peak.

However there are significant deviations in elastic scattering near $P_\perp^2$ of $2(GeV/c)^2$. This can be seen in the plot of dσ/dt(n-p) against $\rho_\perp^2$ taken from J. Stone's thesis[14] (Fig. 10). I have added n-p elastic data at 100 and 360 GeV/c.[15] Notice that in the diffraction peak dσ/dt(n-p) is clearly a universal function of $\rho_\perp^2$. However near the developing dip there is a serious deviation. I believe this is caused by a non-diffractive $e^{-3P_\perp^2}$ direct scattering component in nucleon-nucleon elastic scattering. At 5 or 10 GeV/c this component is dominant near $P_\perp^2 = 2(GeV/c)^2$ but disappears as 1/s due to competition from all the direct inelastic channels opening up as s increases. At about 200 GeV/c this $e^{-3P_\perp^2}$ component sinks below the dip. Thus the nucleon-nucleon cross section may have the general form

$$d\sigma/dt = \left[Ae^{-\frac{1}{2}10\rho_\perp^2} + \frac{B}{s}e^{-\frac{1}{2}3\rho_\perp^2} + Ce^{-\frac{1}{2}1.5\rho_\perp^2} \right]^2$$

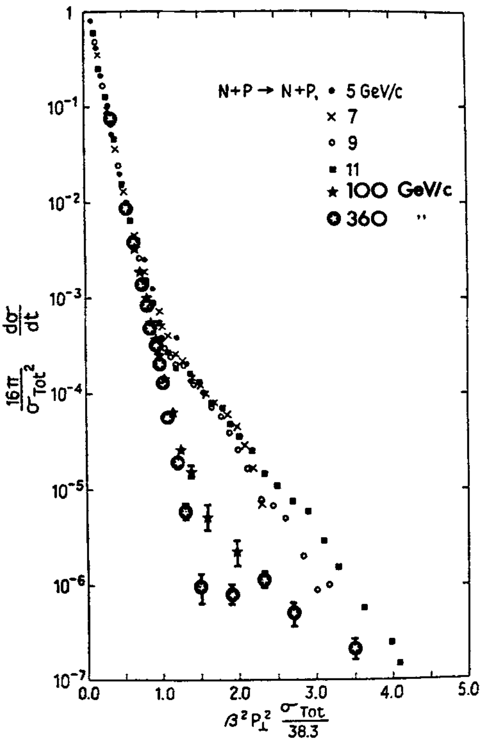

Fig. 10. Differential cross section for n-p elastic scattering is plotted against the variable $\rho_\perp^2 = \beta^2 P_\perp^2 \sigma_{tot}/38.3$ for data from 5→360 GeV/c.

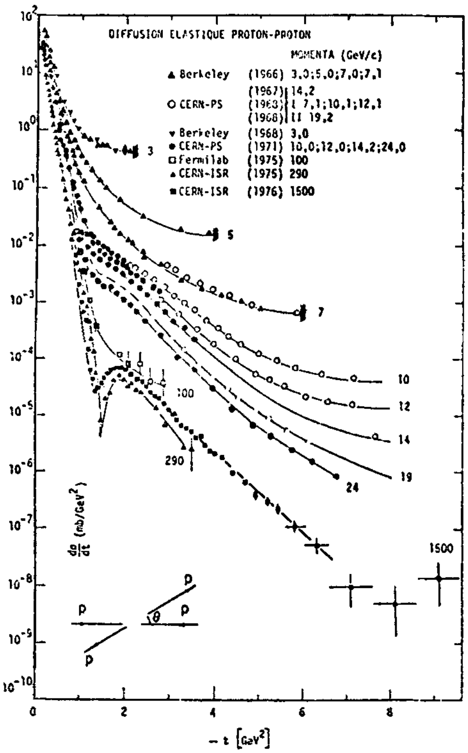

Fig. 11. Differential cross section for p-p elastic scattering is plotted against −t for data from 3→1500 GeV/c.

Before comparing this formula with data, let me show you Fig. 11, which is a conventional t-plot from a recent review by Giacomelli[20]. This nicely summarizes p-p elastic data from 3 to 1500 GeV/c. Notice that as the energy increases the diffraction peak extends over more and more decades as the medium -t component drops away and sinks below the dip. Notice also that the dip seems deeper at 290 GeV/c than at 1500 GeV/c. This interesting effect should be studied more closely. Note that the position of the dip decreases with increasing s in this conventional t-plot. Finally notice the enormous energy dependence in this plot. At $-t = 6(GeV/c)^2$ the cross section drops by a factor of 10,000 in going from 7 GeV/c to 1500 GeV/c.

In Fig. 12 I have plotted $d\sigma/dt$ against the variable $\rho_\perp^2$ for p-p elastic scattering from 3→2100 GeV/c. The data spans 13 decades.

Notice that I plotted, as stars, 1/4 of the measured value of $d\sigma/dt$ at 90°. This factor compensates for the constructive interference between the forward and backward scattering of the identical protons.

$$d\sigma/dt(90°) = [f(90°) + f(\pi-90°)] = 4|f(90°)|^2$$

This particle identity effect causes flattening near 90° which can clearly be seen in the 12 GeV/c data. The factor of 1/4 brings the 90° 12 GeV point back onto the universal curve. The large angle data at other energies from 3→30 GeV/c behave in a similar way. The particle identity factor clearly equals one well away from 90° but its behavior just below 90° depends on the spin dependence of $d\sigma/dt$(p-p) near 90° which we are just now starting to measure at the ZGS.

This graph clearly shows the deviation from a universal fit in the range $\rho_\perp^2 = 1\to3(GeV/c)^2$. I believe this is caused by the $e^{-3\rho_\perp^2}$ non-diffractive component decreasing with energy and finally sinking below the dip.

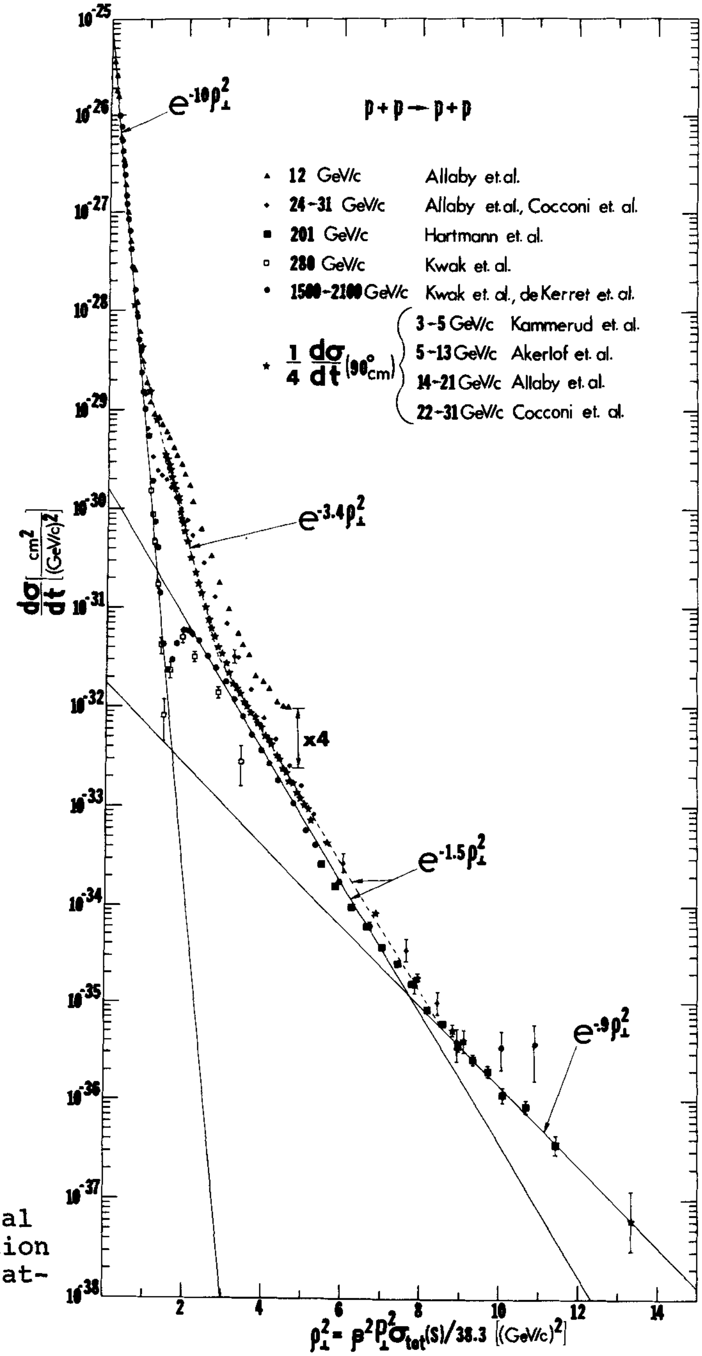

Fig. 12. Differential cross section for p-p scattering is plotted against $\rho_{\perp}^2$

Notice that the position of the dip is independent of energy in this $\rho_\perp^2$ plot.

At large $\rho_\perp^2$ and at small $\rho_\perp^2$ the fit is indeed universal. As we saw earlier, in the diffraction peak all data from 3 to 2000 GeV/c fit a universal function of this variable. At large $\rho_\perp^2$ all available data falls on a single universal curve within 30 or 40%. Notice that for the ISR and Fermilab data one is always very far from 90° so that there is no problem about the particle identity effect.

This plot clearly demonstrates several general features of p-p elastic scattering:

1. A complicated low energy medium-$\rho_\perp^2$ component which is probably non-diffractive and disappears by 200 GeV/c.
2. An energy-independent diffraction peak with a slope of $10(\mathrm{GeV/c})^{-2}$ which corresponds to the .9 fermi outer size of the proton.
3. An energy-independent large-$\rho_\perp^2$ component which may also be diffractive. Its slope of $1.5(\mathrm{GeV/c})^{-2}$ corresponds to a size of 1/3 fermi. This may be the size of whatever constituents the proton contains. This slope is similar to the $e^{-1.45\beta^2 P_\perp^2}$ obtained in my 1967 fit to large-$P_\perp^2$ lower energy data.
4. A dip which appears to be destructive interference between the two diffractive components.
5. An $e^{-.9\rho_\perp^2}$ component suggested by the new Fermilab[13] and ISR data[12] and one 1963 Brookhaven point.[21] While this component's existence is not totally established, its slope of $.9(\mathrm{GeV/c})^2$ corresponds to a size of

1/4 fermi. I will not speculate on what causes this component but it certainly looks interesting and should be studied further.

One can summarize the 5 points by writing the cross section as

$$\frac{d\sigma}{dt} = \left[iAe^{-\frac{1}{2}10\rho_\perp^2} + \frac{(B+ib)}{s} e^{-\frac{1}{2}3\rho_\perp^2} - iC\, e^{-\frac{1}{2}1.5\rho_\perp^2} + \ldots + \ldots \right]^2$$

SPIN AT LARGE $P_\perp^2$

Finally I will briefly discuss spin effects in nucleon-nucleon elastic scattering at large $P_\perp^2$.

For n-p elastic scattering the high-$P_\perp^2$ data is fairly limited but very interesting. The Argonne EMS group has studied spin effects in p-p and n-p elastic scattering at 2→6 GeV/c.[22] The spin of the incident polarized proton beam is normal to the scattering plane and may be either ↑ or ↓. The target is an unpolarized

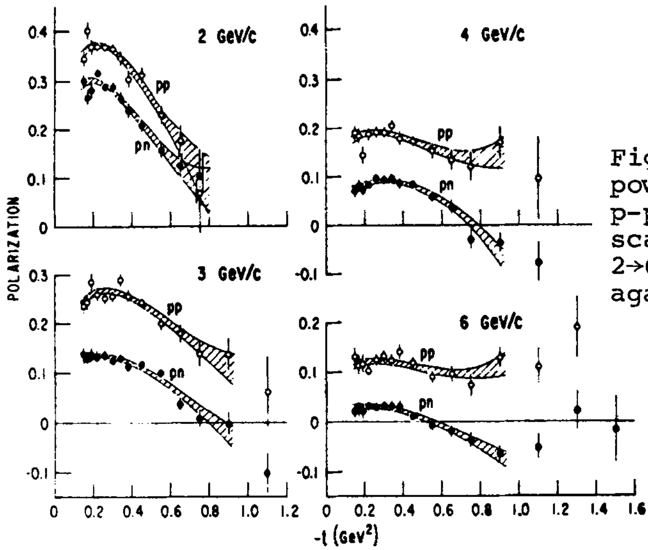

Fig. 13. Analyzing power for n-p and p-p elastic scattering at 2→6 GeV/c plotted against -t.

neutron or proton in deuterium. They measured the analyzing power which is

$$A = \frac{d\sigma/dt(\uparrow) - d\sigma/dt(\downarrow)}{d\sigma/dt(\uparrow) + d\sigma/dt(\downarrow)}$$

The plot of their data in Fig. 13 has several interesting features. Notice the variation with energy of the n-p analyzing power compared with the p-p. At 2 GeV/c A(n-p) has a shape similar to A(p-p) and is just slightly smaller. But at higher energy its nature changes and by 6 GeV/c A(n-p) is very different from A(p-p) which seems to decrease smoothly in the diffraction peak. Notice that A(n-p) is small at 6 GeV/c and changes sign at about $-t = 0.5(\text{GeV/c})^2$.

I will next show a contribution on new n-p elastic spin data at 3 GeV/c by the Argonne-Minnesota-Rice group[23] in Fig. 14. This extends to large -t and shows very interesting spin effects beyond 90°, where p-p scattering is impossible. Notice that A is very large and negative until one enters the sharp backward charge-

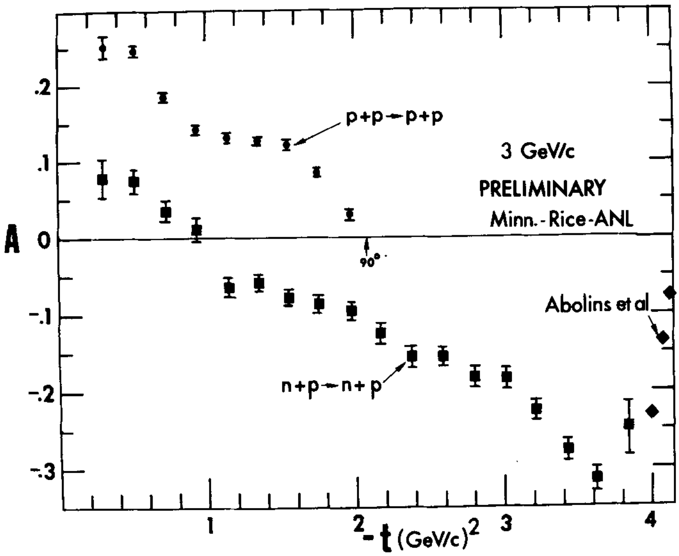

Fig. 14. Analyzing power for p-p and n-p elastic scattering at 3 GeV/c plotted against -t.

exchange peak.

The difference between the A(n-p) and A(p-p) is quite strange. Regge models predict that they should be the mirror images of each other like $A(\pi^+\text{-}p)$ and $A(\pi^-\text{-}p)$. Simple optical models suggest that A(n-p) and A(p-p) should be identical. The data disagree with both.

I believe that the geometric size of the nucleon is approximately the same for both p-p and n-p elastic scattering and their gross features such as the slope of the diffraction peak are similar. However there may also be a spin-orbit force caused by some direct process such as meson exchange which is quite different for p-p and n-p. This may be just the medium-$P_\perp^2$ component we discussed earlier.

Finally I will discuss my group's recent measurement of large-$P_\perp^2$ 11.75 GeV/c p-p elastic scattering in pure initial spin states.[24] By scattering a high intensity polarized proton beam from a polarized proton target we simultaneously measured A and A_{nn}.

The analyzing power, A, parameterizes the spin-orbit interaction in that it measures that part of $d\sigma/dt$ which depends on whether the spins are parallel or antiparallel to the orbital angular momenta.

$$A = \frac{d\sigma/dt(\uparrow\uparrow) - d\sigma/dt(\downarrow\downarrow)}{4\langle d\sigma/dt\rangle}$$

The spin-spin correlation parameter, A_{nn}, studies the spin-spin forces, for it measures the difference between the spin-parallel and spin-anti-parallel cross section.

$$A_{nn} = \frac{d\sigma/dt(\uparrow\uparrow) + d\sigma/dt(\downarrow\downarrow) - 2d\sigma/dt(\uparrow\downarrow)}{4\langle d\sigma/dt\rangle}$$

Our data is shown in Fig. 15. Notice first the

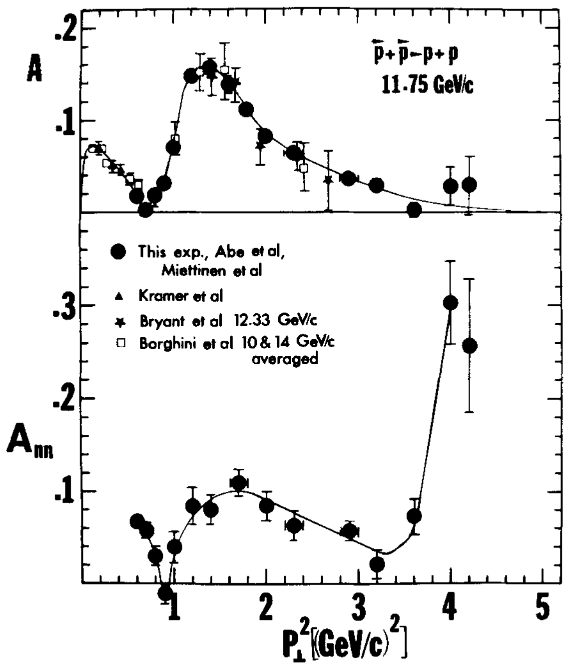

Fig. 15. Analyzing power, A, and spin-spin correlation parameter, A_{nn}, plotted against $P_\perp^2$ for p-p elastic scattering at 11.75 GeV/c.

behavior of A especially the smooth decrease at large $P_\perp^2$. At high energy the spin-orbit force does not appear to be very large in either the diffractive-type region at small $P_\perp^2$ or the one at large $P_\perp^2$. But it does seem very important in the medium-$P_\perp^2$ region, which may be evidence that this region is probably not diffractive.

The spin-spin interaction has much more dramatic structure. Notice especially the rapid rise in A_{nn} starting at $P_\perp^2 = 3.6(\text{GeV/c})^2$. A_{nn} reaches a value of 30% at $P_\perp^2 = 4(\text{GeV/c})^2$. This rapid rise occurs just at the start of the large-$P_\perp^2$ hard scattering component.

This can be seen even more clearly in Figure 16, where pure initial spin cross sections are plotted against $P_\perp^2$, giving an overall picture of spin effects in high energy p-p elastic scattering. The three different $d\sigma/dt)_{ij}$ are very close together in the diffraction peak.

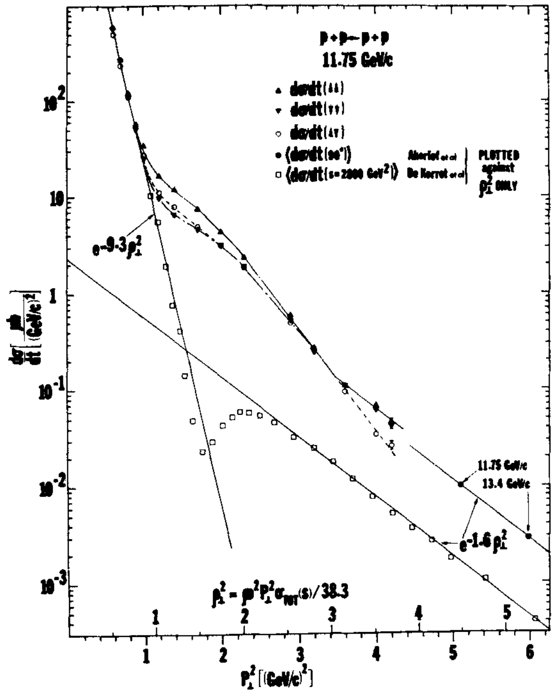

Fig. 16. Differential elastic cross section for p-p elastic scattering in pure initial spin states at 11.75 GeV/c is plotted against $\rho_\perp^2$. ISR "spin averaged" elastic cross sections are also plotted.

In the medium-$P_\perp^2$ non-diffractive region, just after the break, they move far apart and then back together again in a complicated way. In the large-$P_\perp^2$ region after the second break they split apart very rapidly until $d\sigma/dt)_{\uparrow\uparrow}$ becomes twice as large as $d\sigma/dt)_{\uparrow\downarrow}$.

The large A_{nn} may be associated with the break, in the sense of being caused by interference between the $\exp(-3\rho_\perp^2)$ component at medium $P_\perp^2$ and the $\exp(-1.6\rho_\perp^2)$ component at high $P_\perp^2$.

The large spin-spin interaction may instead be associated with the $\exp(-1.6\rho_\perp^2)$ region itself. Then the ratio $(d\sigma/dt)_{\uparrow\uparrow}/(d\sigma/dt)_{\uparrow\downarrow}$ might continue to grow with

$P_\perp^2$ or reach some constant value. Looking at the different slopes in Fig. 16 it is interesting to speculate on how much the parallel scattering might dominate the antiparallel at higher $P_\perp^2$. The maximum $P_\perp^2$ available at the ZGS polarized proton beam is indicated by the 90° points. It is also interesting to notice that $(d\sigma/dt)_{\uparrow\uparrow}$ is pure triplet scattering while $(d\sigma/dt)_{\uparrow\downarrow}$ is a mixture of singlet and triplet. Thus at large $P_\perp^2$ the triplet scattering dominates the singlet scattering by a very large factor, if singlet and triplet scattering are well defined at these high energies.

Notice in Fig. 16 that the $\exp(-1.6\,\rho_\perp^2)$ region at 11.75 GeV/c has essentially the same scaled slope as large-$P_\perp^2$ elastic scattering at s = 2800(GeV/c). Thus by measuring the spin-spin forces in 11.75 GeV/c high-$P_\perp^2$ $p+p \rightarrow p+p$ we may already be directly probing the inner structure of the nucleon in a spin-sensitive way. This probing may indicate whether the inner structure can be most easily understood in terms of spinning geometrical clouds or in terms of pointlike constituent quarks with spin. Our data indicate that the spin-parallel interaction dominates the anti-parallel interaction by a factor of 2 at $P_\perp^2 = 4.0(\mathrm{GeV/c})^2$, suggesting that the "hard" $\exp(-1.6\rho_\perp^2)$ component is dominated by the spin-parallel scattering.

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