SLAC-PUB-4504
December 1987
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SPIN CORRELATIONS, QCD COLOR TRANSPARENCY, AND HEAVY QUARK THRESHOLDS IN PROTON-PROTON SCATTERING*

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ABSTRACT

The strikingly large spin-spin correlation A_{NN} observed in pp elastic scattering at $p_{lab} = 2.5\ GeV/c$ and $11.75\ GeV/c$ and the unexpected energy dependence of absorptive corrections to quasi-elastic proton-proton scattering in a nuclear target can be interpreted in terms of two $J = L = S = 1$, $B = 2$ resonance structures associated with the strange and charmed particle production thresholds, interfering with a perturbative QCD background. The results provide support for the "color transparency" phenomenon predicted in perturbative QCD away from resonances or heavy quark thresholds.

Submitted to *Physical Review Letters*

⋆ Work supported by the Department of Energy, contract DE–AC03–76SF00515.

One of the most serious challenges to quantum chromodynamics is the behavior of the spin-spin correlation asymmetry $A_{NN} = \frac{[d\sigma(\uparrow\uparrow)-d\sigma(\uparrow\downarrow)]}{[d\sigma(\uparrow\uparrow)+d\sigma(\uparrow\downarrow)]}$ measured in large momentum transfer pp elastic scattering.[1] At $p_{lab} = 11.75\ GeV/c$ and $\theta_{cm} = \pi/2$, A_{NN} rises to $\simeq 60\%$, corresponding to four times more probability for protons to scatter with their incident spins both normal to the scattering plane and parallel, rather than normal and opposite. Moreover, the data show a striking energy and angular dependence not expected from the slowly-changing perturbative QCD predictions.[2] The onset of this apparently new phenomenon[3] at $s \simeq 23\ GeV^2$ appears to signal new degrees of freedom or exotic components in the two-baryon system. In this letter we propose an explanation of (1) the observed spin correlations, (2) the deviations from fixed-angle scaling laws, and (3) the anomalous energy dependence of absorptive corrections to quasi-elastic pp scattering in nuclear targets,[4] in terms of a simple model based on two $J = L = S = 1$ broad resonances (or threshold enhancements) interfering with a perturbative QCD quark-interchange background amplitude. The structures in the $pp \to pp$ amplitude may be associated with the onset of strange and charmed thresholds. If this view is correct, large angle pp elastic scattering would have been virtually featureless for $p_{lab} \geq 5\ GeV/c$, had it not been for the onset of heavy flavor production. As a further illustration of the threshold effect, we also show the effect in A_{NN} due to a narrow $^3F_3$ pp resonance at $\sqrt{s} = 2.17\ GeV$ ($p_{lab} = 1.26\ GeV/c$) associated with the $p\Delta$ threshold.

The perturbative QCD analysis[5] of exclusive amplitudes assumes that large momentum transfer exclusive scattering reactions are controlled by short distance quark-gluon subprocesses, and that corrections from quark masses and intrinsic transverse momenta can be ignored. The main predictions are fixed-angle scaling laws[6] (with small corrections due to evolution of the distribution amplitudes, the running coupling constant, and pinch singularities), hadron-helicity conservation,[7] and a novel phenomenon described below called "color transparency."[8] The power-law scaling quark-counting predictions for form factors, two-body elastic hadron-hadron scattering,[9] and exclusive two-photon reactions[10] are generally consistent with experiment at transverse momenta beyond a few GeV. In leading order in $1/p_T$, only the lowest particle-number "valence" Fock state wavefunction with all the quarks within an impact distance $b_\perp \leq 1/p_T$ contributes to the high momentum transfer scattering amplitude in QCD. Such a Fock state component has a small color dipole moment and thus interacts only weakly with hadronic or nuclear matter[8]. This minimally interacting proton configuration can retain its small size as it propagates in the nucleus over a distance which grows with energy. Thus, unlike traditional Glauber theory, QCD predicts that large momentum transfer quasi-elastic reactions occurring in a nucleus suffer minimal initial and final state attenuation; i.e., one expects a volume rather than surface dependence in the nuclear number. This is the QCD "color transparency" prediction.

A test of color transparency in large momentum transfer quasi-elastic pp scattering at $\theta_{cm} \simeq \pi/2$ has recently been carried out at BNL using several nuclear targets (C, Al, Pb).[4] The attenuation at $p_{lab} = 10\ GeV/c$ in the various nuclear targets was observed to be in fact approximately half of that predicted by traditional Glauber theory. This appears to support the color transparency prediction. However at $p_{lab} = 12\ GeV/c$, normal attenuation was observed, in contradiction to the expectation from perturbative QCD that the transparency effect should become even more apparent! Our observation is that one can explain this surprising result if the scattering at $p_{lab} = 12\ GeV/c$ ($\sqrt{s} = 4.93\ GeV$), is dominated by an s-channel B=2 resonance (or resonance-like structure) with mass near 5 GeV, since unlike a hard scattering reaction, a resonance couples to the fully-interacting large-scale structure of the proton. If the resonance has spin $S = 1$, this can also explain the large spin correlation A_{NN} measured nearly at the same momentum, $p_{lab} = 11.75\ GeV/c$. Conversely, in the momentum range $p_{lab} = 5$ to $10\ GeV/c$ we predict that the perturbative hard-scattering amplitude is dominant at large angles. The experimental observation of diminished attenuation at $p_{lab} = 10\ GeV/c$ thus provides support for the QCD description of exclusive reactions and color transparency.

What could cause a resonance at $\sqrt{s} = 5\ GeV$, more than $3\ GeV$ beyond the pp threshold? We can think of several possibilities: (a) a multi-gluonic excitation such as $|qqqqqqggg\rangle$, (b) a "hidden color" color singlet $|qqqqqq\rangle$ excitation,[11] or (c) a "hidden flavor" $|qqqqqqQ\overline{Q}\rangle$ excitation, which is the most interesting possibility, since it is so predictive. As in QED, where final state interactions give large enhancement factors for attractive channels in which $Z\alpha/v_{rel}$ is large, one expects resonances or threshold enhancements in QCD in color-singlet channels at heavy quark production thresholds since all the produced quarks have similar velocities.[12] One thus can expect resonant behavior at $M^* = 2.55\ GeV$ and $M^* = 5.08\ GeV$, corresponding to the threshold values for open strangeness: $pp \to \Lambda K^+ p$, and open charm: $pp \to \Lambda_c D^0 p$, respectively. In any case, the structure at $5\ GeV$ is highly inelastic: we find that its branching ratio to the proton-proton channel is $B^{pp} \simeq 1.5\%$.

We now proceed to a description of the model. We have purposely attempted not to over-complicate the phenomenology; in particular, we have used the simplest Breit-Wigner parameterization of the resonances, and we have not attempted to optimize the parameters of the model to obtain a best fit. It is possible that what we identify as a single resonance is actually a cluster of resonances.

The background component of the model is the perturbative QCD amplitude. Although complete calculations are not yet available, many features of the QCD predictions are understood, including the approximate s^{-4} scaling of the $pp \to pp$ amplitude at fixed θ_{cm} and the dominance of those amplitudes that conserve hadron helicity[7]. Furthermore, recent data comparing different exclusive two-body scattering channels from BNL[9] show that quark interchange amplitudes[13] dominate quark annihilation or gluon exchange contributions. Assuming the usual symmetries, there are five independent pp helicity amplitudes: $\phi_1 = M(++,++)$, $\phi_2 = M(--,++)$, $\phi_3 = M(+-,+-)$, $\phi_4 = M(-+,+-)$, $\phi_5 = M(++,+-)$. The helicity amplitudes for quark interchange have a definite relationship.[2] For definiteness, we will assume the following form

$$\phi_1(PQCD) = 2\phi_3(PQCD) = -2\phi_4(PQCD)$$
$$= 4\pi C F(t)F(u)[\frac{t - m_d^2}{u - m_d^2} + (u \leftrightarrow t)]e^{i\delta} \ ,$$

The hadron helicity non-conserving amplitudes, $\phi_2(PQCD)$ and $\phi_5(PQCD)$ are zero. This form is consistent with the nominal power-law dependence predicted by perturbative QCD[5] and also gives a good representation of the angular distribution over a broad range of energies.[14] Here $F(t)$ is the helicity-conserving proton form factor, which for simplicity, we take as the standard dipole form, $F(t) = (1 - t/m_d^2)^{-2}$, with $m_d^2 = 0.71\ GeV^2$. As shown in reference 2, the PQCD-quark-interchange structure alone predicts $A_{NN} \simeq 1/3$, nearly independent of energy and angle.

Because of the rapid fixed-angle s^{-4} fall-off of the perturbative QCD amplitude, even a very weakly-coupled resonance can have a sizeable effect at large momentum transfer. The large empirical values for A_{NN} suggest a resonant $pp \to pp$ amplitude with $J = L = S = 1$ since this gives $A_{NN} = 1$ (in absence of background) and a smooth angular distribution. Because of the Pauli principle, an $S = 1$ di-proton resonances must have odd parity and thus odd orbital angular momentum. We parameterize the two non-zero helicity amplitudes for a $J = L = S = 1$ resonance in Breit-Wigner form:

$$\phi_3(resonance) = 12\pi \frac{\sqrt{s}}{p_{cm}} d^1_{1,1}(\theta_{cm}) \frac{\frac{1}{2}\Gamma^{pp}(s)}{M^* - E_{cm} - \frac{i}{2}\Gamma},$$

$$\phi_4(resonance) = -12\pi \frac{\sqrt{s}}{p_{cm}} d^1_{-1,1}(\theta_{cm}) \frac{\frac{1}{2}\Gamma^{pp}(s)}{M^* - E_{cm} - \frac{i}{2}\Gamma}.$$

(The $^3F_3$ resonance amplitudes have the same form with $d^3_{\pm 1,1}$ replacing $d^1_{\pm 1,1}$). Since we are far from threshold, threshold factors in the pp channel can be treated as constants. As in the case of a narrow resonance like the Z^0, we expect that the partial width into nucleon pairs is proportional to the square of the time-like proton form factor: $\Gamma^{pp}(s)/\Gamma = B^{pp}|F(s)|^2/|F(M^{*2})|^2$, corresponding to the formation of two protons at this invariant energy. The resonant amplitudes then die away by one inverse power of $(E_{cm} - M^*)$ relative to the dominant PQCD amplitudes. (In this sense, they are higher twist contributions relative to the leading twist perturbative QCD amplitudes). The model is thus very simple: each pp helicity amplitude ϕ_i is the coherent sum of PQCD plus resonance components: $\phi = \phi(PQCD) + \Sigma\phi(resonance)$. Because of pinch singularities and higher order corrections, the hard QCD amplitudes are expected to have a non-trivial phase;[15] we have thus allowed for a constant phase δ in $\phi(PQCD)$. Because of the absence of the ϕ_5 helicity-flip amplitude, the model predicts zero single spin asymmetry A_N. This is consistent with the large angle data at $p_{lab} = 11.75\ GeV/c$.[16]

At low transverse momentum, $p_T \leq 1.5\ GeV$, the power-law fall-off of $\phi(PQCD)$ in s disagrees with the more slowly falling large-angle data, and we have little guidance from basic theory. Our interest in this low energy region is to illustrate the effects of resonances and threshold effects on A_{NN}. In order to keep the model tractable, we have simply extended the background quark interchange and the resonance amplitudes at low energies using the same forms as above but replacing the dipole form factor by a phenomenological form $F(t) \propto e^{-\frac{1}{2}\beta\sqrt{|t|}}$. We have also included a kinematic factor of $\sqrt{s}/2p_{cm}$ in the background amplitude. The value $\beta = 0.85\ GeV^{-1}$ then gives a good fit to $d\sigma/dt$ at $\theta_{cm} = \pi/2$ for $p_{lab} \leq 5.5\ GeV/c$.[17] The normalizations are chosen to maintain continuity of the amplitudes.

The predictions of the model and comparison with experiment are shown in figures 1 and 2. The following parameters are chosen: $C = 2.9 \times 10^3$, $\delta = -1$ for the normalization and phase of $\phi(PQCD)$. The mass, width, and pp branching ratio for the three resonances are $M_d^* = 2.17\ GeV$, $\Gamma_d = 0.04\ GeV$, $B_d^{pp} = 1$; $M_s^* = 2.55\ GeV$, $\Gamma_s = 1.6\ GeV$, $B_s^{pp} = 0.65$; and $M_c^* = 5.08\ GeV$, $\Gamma_c = 1.0\ GeV$, $B_c^{pp} = 0.0155$; respectively. As shown in figs. 1(a) and 1(b), the deviations from the simple scaling predicted by the PQCD amplitudes are readily accounted for by the resonance structures. The cusp which appears in fig. 1(b) marks the change in regime below $p_{lab} = 5.5\ GeV/c$ where PQCD becomes inapplicable. It is interesting to note that in this energy region normal attenuation of quasi-elastic pp scattering is observed.[4] The angular distribution (normalized to the data at $\theta_{cm} = \pi/2$) is predicted to broaden relative to the steeper perturbative QCD form, when the resonance dominates. As shown in fig. 1(c) this is consistent with experiment, comparing data at $p_{lab} = 7.1$ and $12.1\ GeV/c$.

The most striking test of the model is its prediction for the spin correlation

A_{NN} shown in fig. 2(a). The rise of A_{NN} to $\simeq 60\%$ at $p_{lab} = 11.75\ GeV/c$ is correctly reproduced by the high energy J=1 resonance interfering with $\phi(PQCD)$. The narrow peak which appears in the data of fig. 2(a) corresponds to the onset of the $pp \to p\Delta(1232)$ channel which can be interpreted as a $uuuuddq\bar{q}$ resonant state. Because of spin-color statistics one expects in this case a higher orbital momentum state, such as a $pp\ ^3F_3$ resonance. The model is also consistent with the recent high energy data point for A_{NN} at $p_{lab} = 18.5\ GeV/c$ and $p_T^2 = 4.7\ GeV^2$ (see fig. 2(b)). The data show a dramatic decrease of A_{NN} to zero or negative values. This is explained in our model by the destructive interference effects above the resonance region. The same effect accounts for the depression of A_{NN} for $p_{lab} \approx 6\ GeV/c$ shown in fig. 2(a). The comparison of the angular dependence of A_{NN} with data at $p_{lab} = 11.75\ GeV/c$ is shown in fig. 2(c). The agreement with the data[18] for the longitudinal spin correlation A_{LL} at the same p_{lab} is somewhat worse.

Our goal is this paper has not been a global fit to all the pp elastic scattering data, but rather to show that many features can be naturally explained with only a few ingredients: a perturbative QCD background plus resonant amplitudes associated with rapid changes of the inelastic pp cross section. The model provides a good description of the s and t dependence of the differential cross section, including its "oscillatory" dependence[19] in s at fixed θ_{cm}, and the broadening of the angular distribution near the resonances. Most important, it gives a consistent explanation for the striking behavior of both the spin-spin correlations and the anomalous energy dependence of the attenuation of quasi-elastic pp scattering in nuclei. We predict that color transparency should reappear at higher energies ($p_{lab} \geq 16\ GeV/c$), and also at smaller angles ($\theta_{cm} \approx 60^o$) at $p_{lab} = 12\ GeV/c$ where the perturbative QCD amplitude dominates. If the J=1 resonance structures in A_{NN} are indeed associated with heavy quark degrees of freedom, then the model predicts inelastic pp cross sections of the order of 1 mb and 1 μb for the production of strange and charmed hadrons near their respective thresholds.[20] Thus a crucial test of the heavy quark hypothesis for explaining A_{NN}, rather than hidden color or gluonic excitations, is the observation of significant charm hadron production at $p_{lab} \geq 12\ GeV/c$. Other elastic reactions such as $\pi p \rightarrow \pi p$ should also display structures at the corresponding heavy quark thresholds.

We wish to thank S. Heppelmann, J. Martoff, A. Mueller, and J. Ralston for helpful conversations. G. de T. wishes to thank the Guggenheim Foundation for support.

FIGURE CAPTIONS

Fig. 1(a): Prediction (solid curve) for $d\sigma/dt(pp \to pp)$ at $\theta_{cm} = \pi/2$ compared with the data of Akerlof *et al.*[17] The dotted line is the background PQCD prediction. Fig. 1(b): Ratio of $d\sigma/dt(pp \to pp)$ at $\theta_{cm} = \pi/2$ to the PQCD prediction. The data[17] are from Akerlof *et al.* (open triangles), Allaby *et al.* (solid dots), and Cocconi *et al.* (open square). The cusp at $p_{lab} = 5.5\ GeV/c$ indicates the change of regime from PQCD. Fig. 1(c): The $pp \to pp$ angular distribution normalized at $\theta_{cm} = \pi/2$. The data are from the compilation given in Sivers, *et al.*, ref. 9. The solid and dotted lines are predictions for $p_{lab} = 12.1$ and $7.1\ GeV/c$, respectively, showing the broadening near resonance.

Fig. 2(a): A_{NN} as a function of p_{lab} at $\theta_{cm} = \pi/2$. The data[1] are from Crosbie *et al.* (solid dots), Lin *et al.* (open squares), and Bhatia *et al.* (open triangles). The peak at $p_{lab} = 1.26\ GeV/c$ corresponds to the $p\Delta$ threshold. The data are well reproduced by the interference of the broad resonant structures at the strange ($p_{lab} = 2.35$ GeV/c) and charm ($p_{lab} = 12.8$ GeV/c) thresholds, interfering with a PQCD background. The value of A_{NN} from PQCD alone is 1/3. Fig. 2(b): A_{NN} at fixed $p_T^2 = 4.7\ (GeV/c)^2$. The data point[1] at $p_{lab} = 18.5\ GeV/c$ is from Court *et al.* Fig. 2(c): A_{NN} as a function of transverse momentum. The data[1] are from Crabb *et al.* (open circles) and O'Fallon *et al.* (open squares). Diffractive contributions should be included for $p_T^2 \leq 3\ GeV^2$.

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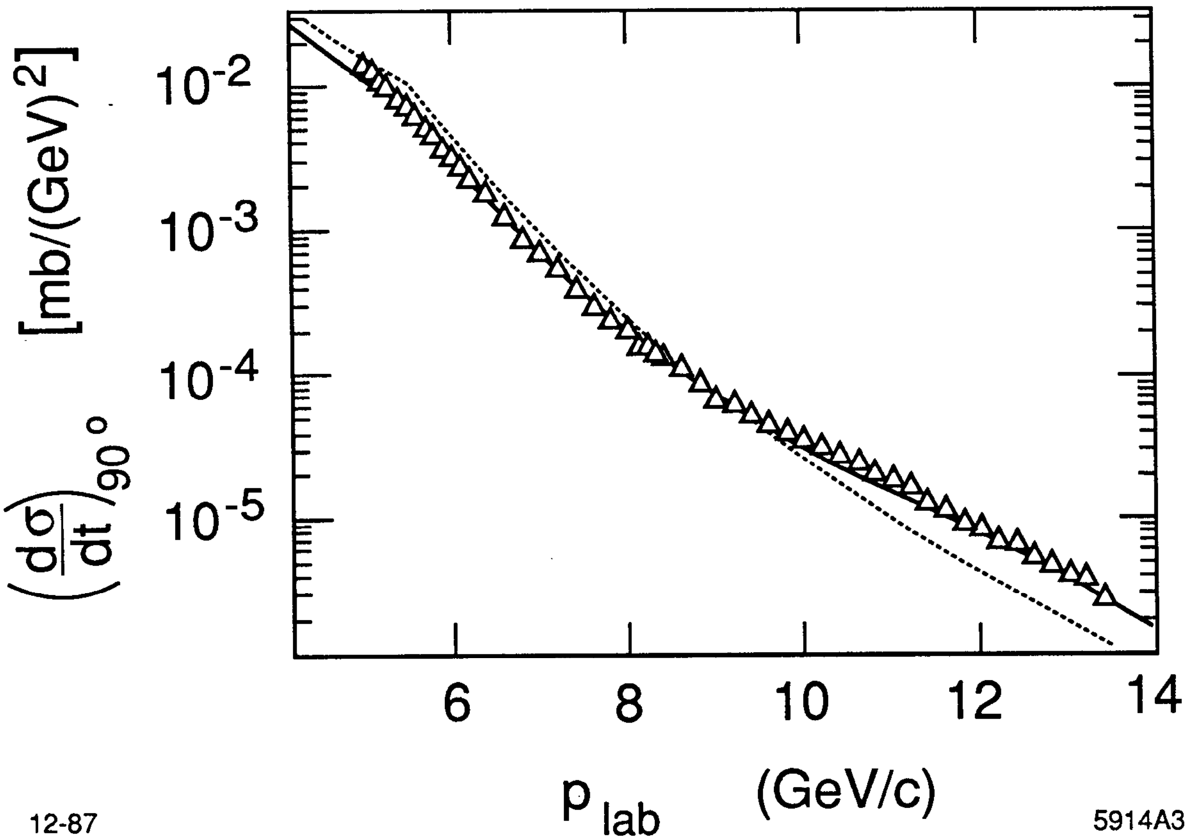
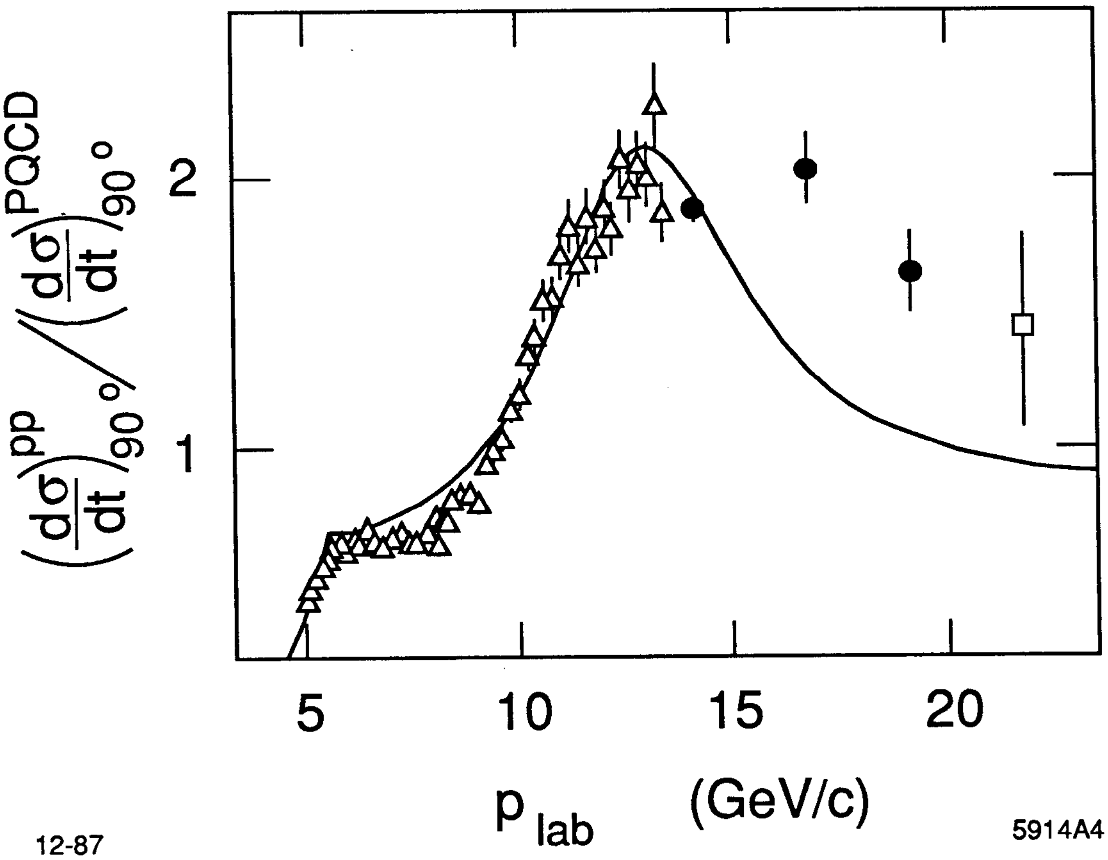


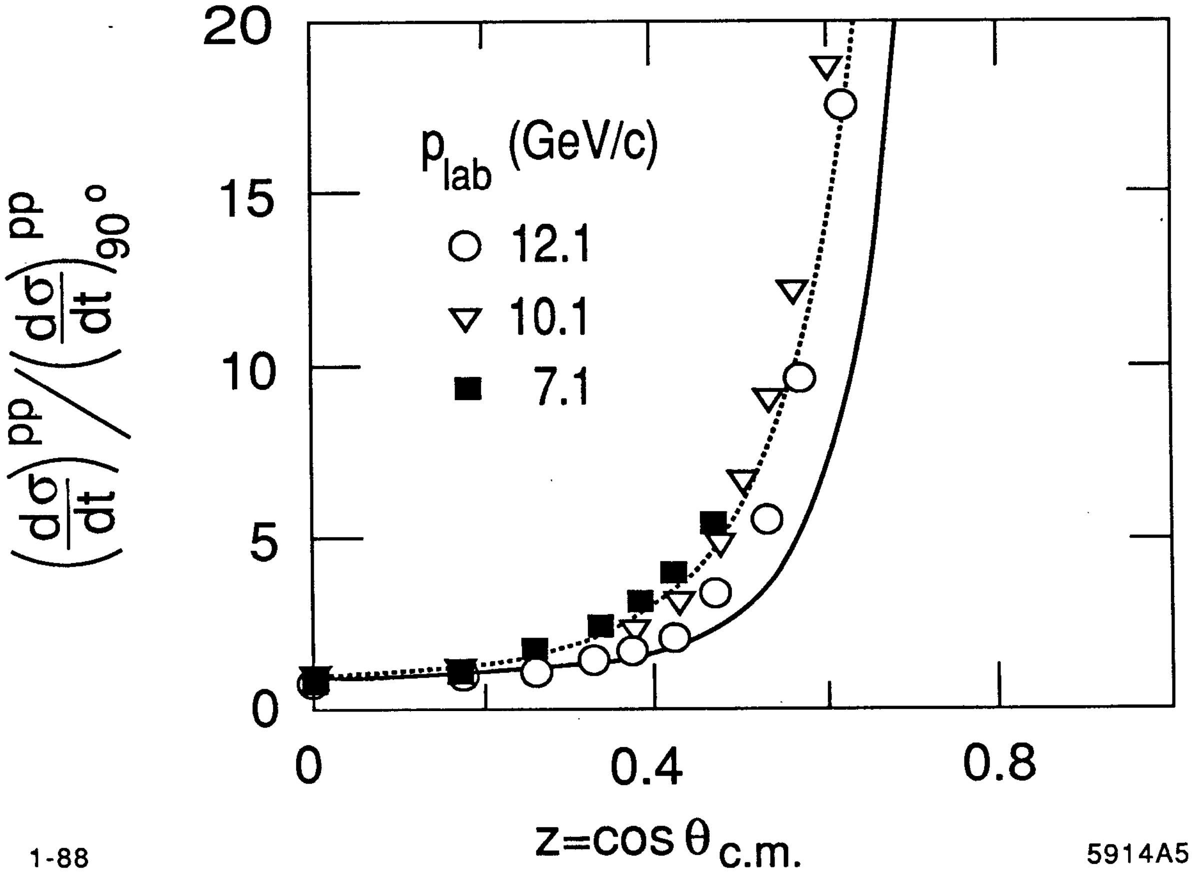
$\left(\frac{d\sigma}{dt}\right)_{90°}$ [mb/(GeV)^2]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
6
8
10
12
14
p_{lab} (GeV/c)
12-87
5914A3

Fig. 1a



$\left(\frac{d\sigma}{dt}\right)^{pp}_{90°} \Big/ \left(\frac{d\sigma}{dt}\right)^{PQCD}_{90°}$
2
1
5
10
15
20
p lab (GeV/c)
12-87
5914A4

Fig. 1b



20
15
10
5
0
0
0.4
0.8
p_{lab} (GeV/c)
12.1
10.1
7.1
$\left(\frac{d\sigma}{dt}\right)^{pp} \Big/ \left(\frac{d\sigma}{dt}\right)^{pp}_{90^\circ}$
z=cos θ c.m.
1-88
5914A5

Fig. 1c

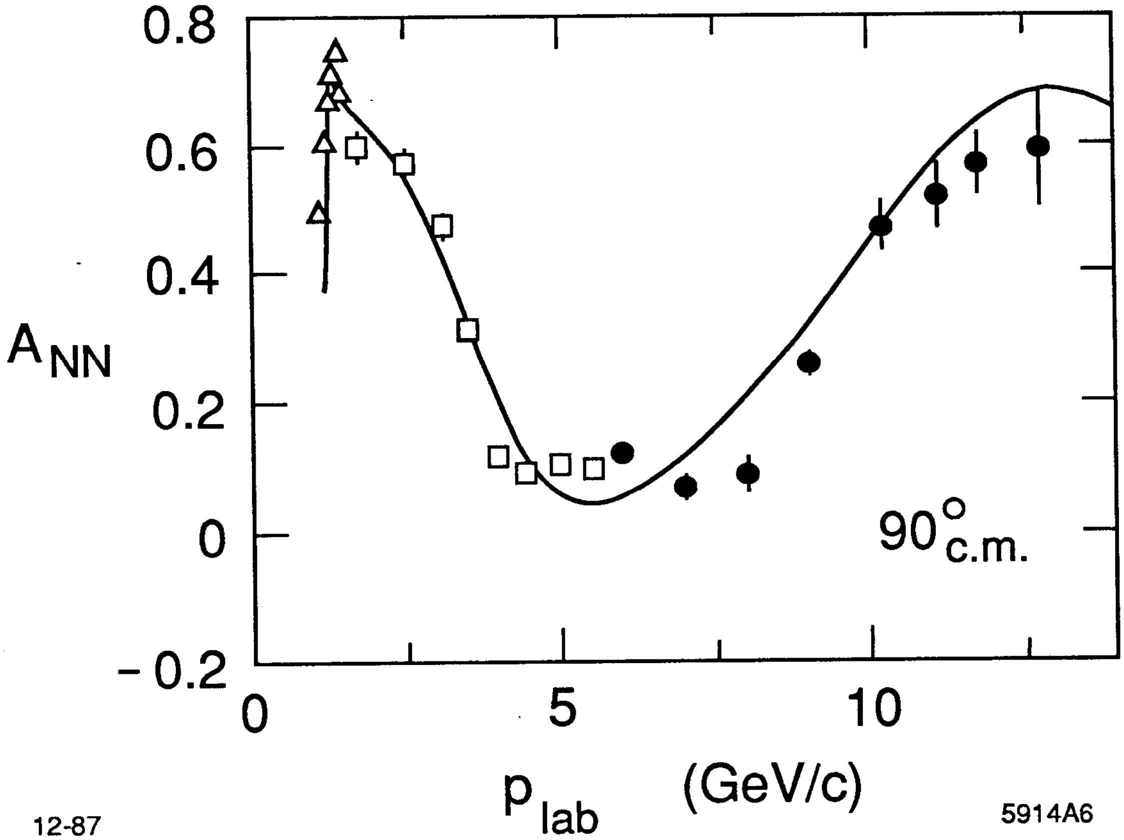


Fig. 2a

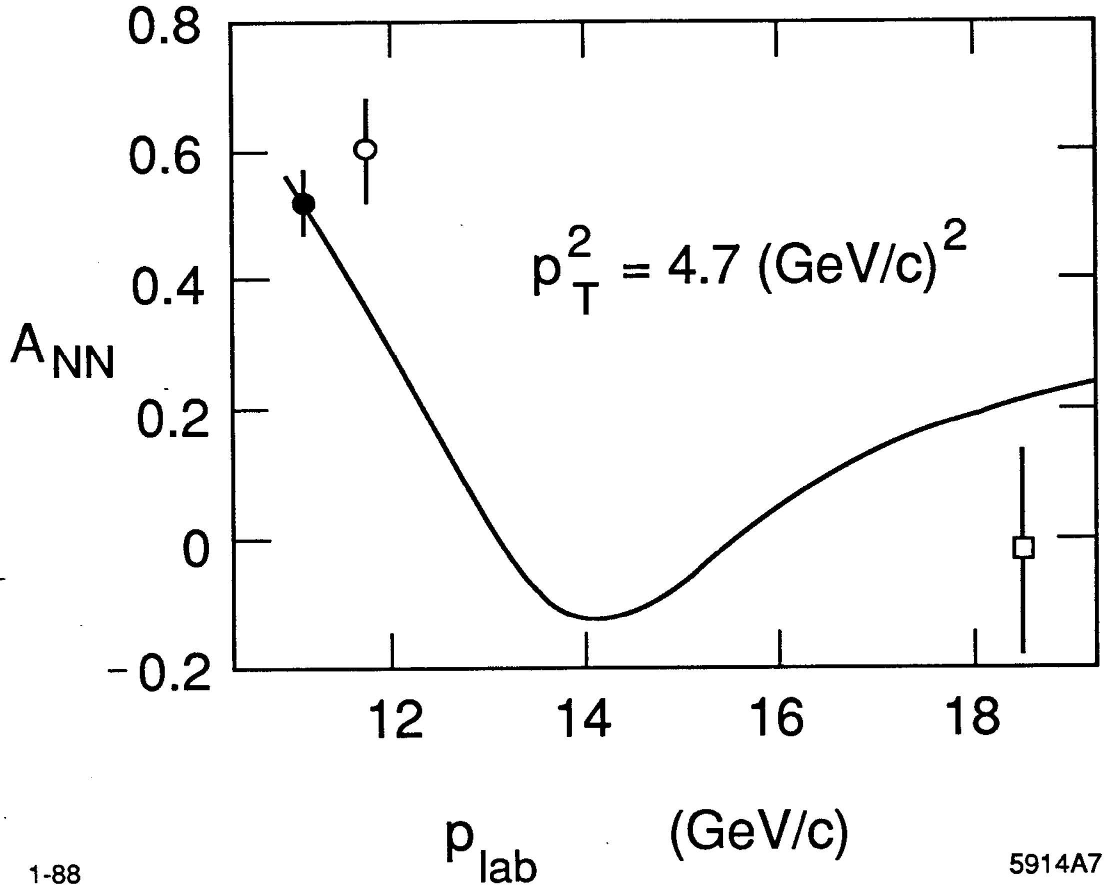


Fig. 2b

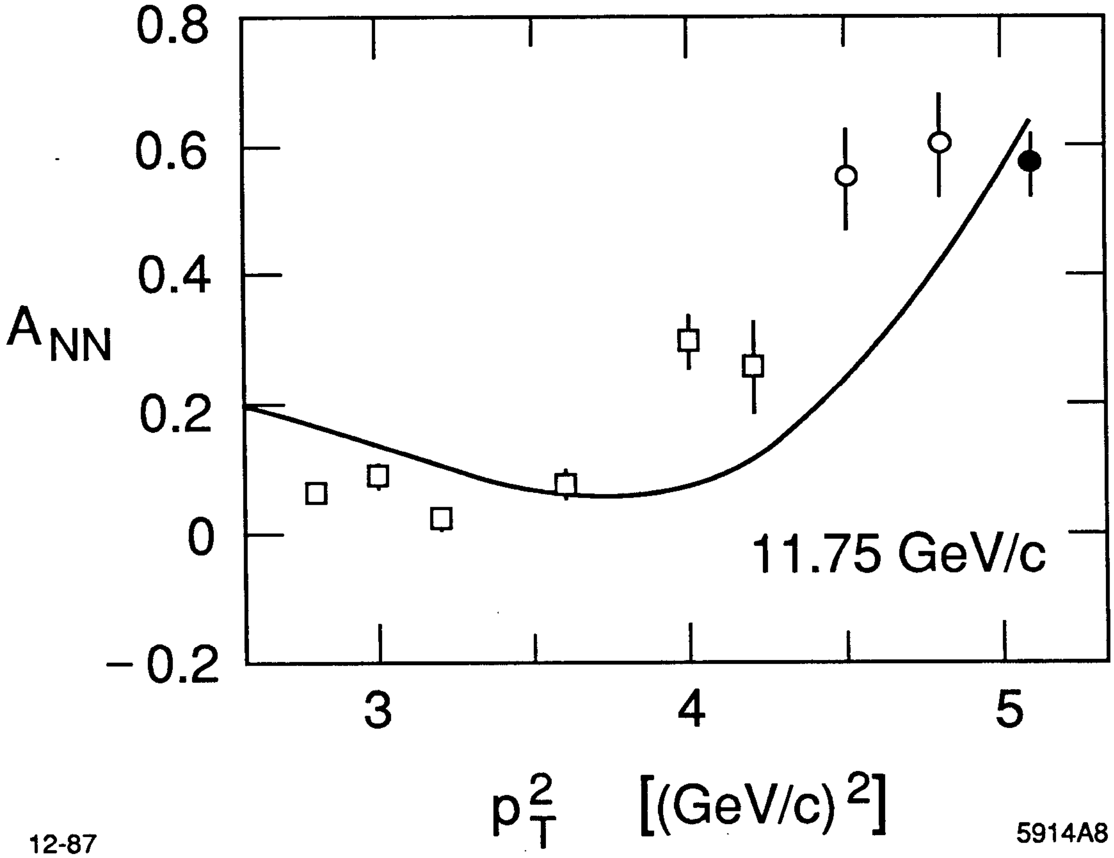


Fig. 2c