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ДОКЛАДЫ РАППОРТЕРОВ RAPPORTEURS' REVIEWS

E-1802

INTERACTIONS OF PIONS AND NUCLEONS ABOVE 1 GEV/C

Rapporteur S. J. Lindenbaum

Secretaries: V. A. Nikitin
E. G. Bubelev
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This publication is of a preliminary character. To facilitate the rapid appearance of Reports, they are printed in the form as presented by Rapporteurs.

It was somewhat more than a decade ago when the first high energy accelerator experiments in this field began.

At that time Fermi and many others believed that the statistical theory would explain high energy phenomena beyond a high enough energy. At that time a few BeV was considered high enough.

Accelerator experiments soon demonstrated that a few BeV was not high enough because the basic nucleon-nucleon and pion-nucleon cross sections were still showing structure and energy variations effects, and more important the elastic pion-nucleon and inelastic nucleon-nucleon and pion-nucleon production interactions were dominated by the formation of the $T = J = 3/2$ isobar, In fact an isobar model rather than a statistical model was successful in explaining the observations. Later it was shown that higher mass nucleon isobars and pion isobars were also important. Professor Nikitin will review the subject of Pion Resonances and Baryon isobars and discuss their properties and therefore I shall only comment on those subjects to the extent necessary to explain the pion-nucleon inelastic interactions discussed from general points of view.

The cosmic ray investigations also later found that at much higher energies multi-center models or fireball models were required to explain the data. Some authors now even invoke what are essentially combinations of isobar and fireball models.

The first asymptotic theorem was given to us some years ago by Pomeranchuk. The Pomeranchuk theorem essentially predicted that on the basis of the forward dispersion relations and some minor restrictions*) that at high energies

$$\sigma_{total}^{(\alpha+\beta)} = \sigma_{total}^{(\bar{\alpha}+\beta)}$$

where $\bar{\alpha}$ is the antiparticle of α. Pomeranchuk and many others felt that $\gtrsim$ 10 BeV was high enough energy for this theorem. However, experiments at accelerators again demonstrated this was not the case.

The Regge pole theory was in a sense an attempt to bridge the gap between where we are and the asymptotic region. That is to say it tried to assume that we were on the outskirts of the asymptotic region following a calculable simply predictable route so that we could extrapolate to the asymptotic region. Regge-Pomeranchuk pole models such as the three pole (p.p' and ω) were successful in explaining the total cross sections data. However, the failure of these and other simple and convincing versions of the Regge pole theory to explain the elastic scattering results has left us uncertain as to how far we are from the asymptotic region. Many of the experiments presented in this session bear on this problem. Professor Feinberg in his paper of the theoretical material presented will of course make many specific comments on this point. I of course intend to review the experimental data from a general point of view but will point out relevant characteristics which bear on this question.

For reviews of the situation as it was viewed a year ago the reader is referred to the Proceedings of the International Conference on Nuclear Structure at Stanford, July, 1963 and

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*) The restrictions were minimized by some later work such as Weinberg's.

the Proceedings of the Sienna Conference (Sept. 1963).

Total Cross Sections

We have had a REPORT by Kycia on 6-22 GeV/c total cross sections of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ incident on p and d.

They used scintillation and Čerenkov counter techniques and in general have smaller errors than previous experiments with which they agree well within errors. A summary of cross section curves is given in Fig. 1a. The glauber screening corrections were used to obtain particle neutron cross section. The main points to notice are:

The experimental results obtained for π^{+} + p total cross sections agree well with previous data within errors. The difference of $\sigma(\pi^{-}+p) - \sigma(\pi^{+}+p)$ between 10 and 20 BeV/c is apparently decreasing gradually with increasing energy. The p + p data also agree reasonably with other experiments but with the increased precision a slow (~ 3%) decrease is observed.

One must await a detailed fit analysis to check these questions quantitatively since the curves shown are not fits to the data.

The n + p cross section deduced from σ(p + d) and σ(p + p) appears to approach the p + p cross section at high energies but as the authors point out the errors are too large to decide this point. The K^{+} + p cross section is still found to be flat, with the K^{-} + p cross section falling with energy,

The $\bar{p}p$ and $\bar{p}n$ cross sections are the same within the accuracy of the measurement.

All particle - anti-particle cross section on a nucleon target appear to be decreasing slowly or are flat within errors above 6GeV/c.

The more accurate values will be useful for dispersion relations calculations and general asymptotic behaviour questions. Also presented (1) were more accurate surveys of the 2-6 GeV/c $\pi^{\pm}+p$ total cross sections, the results of which are shown on fig. 1b $\pi^{\pm}+p$ (T= 3/2 state) and fig. 1c (T= 1/2 state). These data exhibit for T = 3/2 a local maximum at a lab momentum of 3.77 BeV/c (corresponding to a total cms energy of 2.83 BeV and for T = 1/2 a local maximum at 3.24 BeV/c (corresponding to a total c.m.s. energy 2.65 BeV). Since there are **peaks narrow enough to be compatible with isobar formation the authors** suggest attributing these effects to new baryon isobars.

They do not see evidence for the Alvarez photo pion peaks but conclude the T = 1/2 peak might be the charge exchange peak observe by Wohlig but slightly shifted due to the differences in observation method.

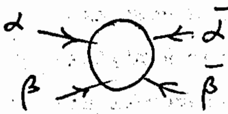
Small Angle Elastic Scattering

In the past there have been a number of experimental small **angle** scattering results which gave various degrees of supporting evidence for a real part of the scattering amplitude in p + p scattering in the neighbourhood of $\gtrsim$ 6-10 GeV/c. However these experiments suffered from various degrees of uncertainities both in the data and the analysis.

At this conference we have had several reports on small angle p + p scattering of much improved precision and also small angle $\pi^{\pm}$ + p scattering. These observations were made at low enough /t/ to observe interference effects of the real part of the nucleon amplitude with Coulomb amplitude.

Since the existence as well as the value and the error limits of the real part of the scattering amplitude deduced from an experiment are critically dependent on the theoretical actions made in the analysis and the assumptions made in the evaluations of the experimental errors I will consider both these points in some detail.

The Feynman diagram for elastic scattering is:



$$s \equiv (p_\alpha + p_\beta)^2 \equiv (E_{cm\ total})^2$$

$$t \equiv (p_\alpha + p_{\bar\alpha})^2 \equiv \text{four momentum transfer squared.}$$

If α and β are both spinless we have the well known result that there is one complex invariant amplitude A (s,t) which describes the elastic scattering. If α is spinless but β has spin 1/2 for example π-p scattering there are two complex invariant amplitudes,**onethe** nonspin flip and the **othera** spin flip amplitude.

Hence $$A(s,t) = A_{nf}(s,t) + A_{sf}(s,t)$$

But $A_{sf}(s,t)$ must be of the form $\vec{\sigma}\cdot\vec{n}$ where $\vec{n}$ is the normal to the scattering plane and hence

$$A_{sf}(s,t) \rightarrow 0 \qquad \text{as} \quad |t| \rightarrow 0$$

In the region where the interference of the real amplitude with the Coulomb amplitude is important

$$\vec{\sigma}\cdot\vec{n} < 10^{-2}$$

Hence we can safely neglect this spin flip amplitude unless by some completely non understood process its coefficient is anomalously large. Therefore in the case of small angle p + p scattering a one complex amplitude treatment of the data corresponds to the assumption of the no spin dependence. This assumption can certainly not as far as I know **at** present be demonstrated to be correct, even though it seems intuitively to be probable. On the other hand **a** complex amplitude treatment of π-p in each charge state is well justified to the extent that $< 10^{-2}$ (the $\vec{\sigma}\cdot\vec{n}$ factor in the spin flip amplitude) is small compared to 1.

of course, if there should be an anomalously large spin flip amplitude this would of course again cause trouble but this possibility seems remote.

It both α and β have spin 1/2 (p + p scattering) the situation is quite complex. As is well known there are five complex nucleon-nucleon scattering amplitudes possible after applying invariance with respect to rotation, parity, time reversal and allowing charge symmetry*).

Therefore for p + p $A(s,t) = A_1(s,t) + A_3(s,t) +$ + /2 terms of form $\vec{\sigma}\cdot\vec{n}$ + 1 term of form $\vec{\sigma}_1\cdot\vec{\sigma}_2$ / where A_1 is the singlet ordinary amplitude and A_3 is the triple ordinary amplitude. As $t \to 0$ the $\vec{\sigma}\cdot\vec{n}$ terms $\to 0$ but the $\vec{\sigma}_1\cdot\vec{\sigma}_2$ term remains finite. Hence in p + p scattering even at very small angles when $t \to 0$ three complex amplitudes remain a singlet, a triplet and a spin flip amplitude.

In addition to the nucleon amplitude we must take account of the Coulomb amplitude.

The one photon exchange amplitude is an excellent approximation for the small angle region**) and we can for small t write it in the form

$$f_c = \frac{\pm F}{|t|} \qquad \begin{cases} - \text{ sign for } p + p \text{ repulsion} \\ + \text{ sign for } \bar{p} + p \text{ attraction} \end{cases}$$

where F is the product of the point charge constant and the effective form factor. This problem of the form factor is more complicated than just using the e-p results since we now have

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*) This problem has been treated by Wolfenstein, Phys. Rev. 96, 165 (1954) and Phys. Rev. 94, 1077 (1955). For a recent view see Collision Theory by Goldberger and Watson (Wiley, 1964).

**) In particular I want to thank Dr. Yennie for a discussion of this.

for example in p + p two extended bodies and so have the product of two form factors*) which can be evaluated if one neglects possible polarisation effects which in this approximation appears reasonable.

In the case of πp this problem is more complicated since the pion form factor is not known. I would guess that it is likely to correspond to the same or a smaller radius than the proton form factor. Fortunately the form factor effects are small at small /t/ where the interference of nuclear and Coulomb amplitudes is important.

I have made estimates of these effects which indicate that neglect of them in a preliminary analysis should effect the deduced values of α reported at this Conference by $\lesssim 5$ - 10%. In combining the effects of the Coulomb and nuclear amplitudes one must take account of the relative phase introduced between them by the distribution of the wave function by the long range Coulomb interaction. This problem was solved by Bethe**) some time ago and we use his method. Therefore **if the** spin dependence **is assumed the complex nuclear scattering amplitude prediction** for $d\sigma/dt$ including the Coulomb interaction is

$$\frac{d\sigma}{dt} = \left| \frac{\mp F}{|t|} e^{2i\delta} + A_{N\,real} + i\,A_{N\,im} \right|^2 \qquad (1)$$

where δ is the relative phase shift introduced between the nuclear and Coulomb amplitudes and was shown by Bethe to be given by

$$\delta = \frac{e^2}{\hbar v} \ln \frac{1{,}06}{ka} \quad ; \quad a \simeq 1 \text{ fermi} \qquad (2)$$

For the /t/ region reported generally $\delta \lesssim 0.02$.

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*) Yao calculated this effect for us for p + p scattering.

**) Bethe, Ann. der Physik 3, 190 (1958).

Let us make the assumptions that the ratio α of the real to imaginary amplitude is a constant independent of /t/.

$$\alpha = \frac{A_{N\,real}}{A_{N\,im}}$$

The sign of α is negative if the real part of the scattering amplitude has the same sign as the Coulomb amplitude for p + p (i.e. repulsive) and α has a positive sign if the real part of the scattering amplitude has the same sign as the Coulomb amplitude in $\bar{\pi}$ + p (i.e. attractive). Then

$$\frac{d\sigma}{dt} = \frac{F^2}{|t|^2} \mp \frac{2F}{|t|} A_{N\,im}\left[\alpha \cos 2\delta \pm \sin 2\delta\right] + \left[1+\alpha^2\right] A^2_{N\,im} \quad (3)$$

The first term in brackets represents the interference between the real parts of the nuclear and Coulomb amplitudes and the second term represents the interference of the effective imaginary parts due to the phase difference introduced.The second term will stand generally for the values of α reported at this Conference (α~0.25). And the /t/ range investigated have an effect of $\lesssim$10% on the α value and hence to first order the two terms in the brackets can for preliminary analysis be lumped together into one equivalent interference and in fact the effect of the second term to first order could be absorbed in a slight change in the constant outside the bracket which could be denoted by F'.

For a preliminary analysis of the results presented at this Conference one neglected form factor effects and the second term in in the bracket in the equivalent fit what is permissible provided these effects could be approximately taken into account at least in the error estimates.

From previous experiments at higher /t/ and those reported at the Conference one can show that

$$\frac{d\sigma}{dt} = e^{a + bt + ct^2}$$

represents a good

parametric representations of the data.

At $/t/ \lesssim 0.05$ where the real amplitude effects are observed using the values deduced at higher /t/. We find $ct^2 \ll b/t/$ and can be neglected. One should also note there is no evidence for a ct^2 term in the small angle data. Therefore it is reasonable from the characteristics of the experiments to assume

$$/A_{min}/^2 = e^{a+bt}$$

for $/t/ \ll 0.05$ and this form follows from many models previously considered, such as A gaussian potential the optical model etc., and in fact more reasonable models would generally give a result consistent with this form.

Therefore to a good approximation*) for low $/t/ \lesssim 0.05$ and no spin dependence

$$\frac{d\sigma}{dt} \simeq \frac{F^2}{|t|^2} \mp \frac{2F'\alpha}{|t|} e^{\frac{a}{2}+\frac{b}{2}t} + (1+\alpha^2) e^{a+bt} \qquad (4)$$

a is determined from the total cross section by the optical theorem and $F' \approx F = F_0 \equiv$ (the value corresponding to a point charge).

Therefore we have a 2 parameter equation.

If one were to allow a different /t/ dependence to the triplet singlet ordinary amplitudes and assume no real part of either we would obtain the following partially spin-dependent equation for small angle p + p scattering:

$$\frac{d\sigma}{dt} = \frac{F^2}{|t|^2} + \left[\frac{3}{4} A^2_{3\,Im} + \frac{1}{4} A^2_{1\,Im} \right]$$

where $A_3^2 = e^{a_3+b_3t}$

$A_1^2 = e^{a_1+b_1t}$

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*) α must finally be corrected for form factor and interference effects and errors should reflect these effects.

with the relation from the optical theorem:

$$\sigma_{total}(p+p) = \frac{3}{4} e^{\frac{a_3}{2}} + \frac{1}{4} e^{\frac{a_1}{2}}$$

Hence it is a three parameter equation.

The next figure 2 **presents** the results of Kirillova et al obtained with an emulsion technique observing the recoil protons from an internal **polyethelene** target at the Dubna synchrophasotron. They have fit their data with the no spin dependence case and find a good fit with $\alpha = -0.17 \pm 0.07$ at 2.8 GeV/c ranging to $\alpha = -0.25 \pm 0.07$ at 10.9 GeV/c. The errors are Gaussian which include monitoring and optical point errors treated as Gaussian errors. The solid line in the plot is essentially a best fit to eq. (4). The next figure 3 gives the p + p results of Foley et al. A **counter hodoscope and on-line computer technique were used in an** external beam with hydrogen target. The errors shown contain all relative systematic as well as statistical errors. The $\alpha = 0$ solid **curve is the** prediction of the eq. (4) (the no spin dependence prediction), using the nucleon exponential slope (b) obtained in the actual fit. The dotted line is the $\alpha = 0$ curve with b varied for best fit which gives a χ^2 for this $\alpha = 0$ fit corresponding to greater than ten standard deviation and hence is entirely unacceptable. The constructive nature of the interference is clear. The best fit values of α obtained at 7.9, 10 and 12.1 GeV/c are

$$\alpha_{p+p} = (-0.253 \pm 0.02)^{+0.088}_{-0.088}$$

$$\alpha_{p+p} = -(0.26 \pm 0.02)^{+0.09}_{-0.09}$$

$$\alpha_{p+p} = (-0.254 \pm 0.02)^{+0.10}_{-0.12} \quad \text{respectively}$$

where the second error outside the **parentheses** represents the excursion of the fit from its mean point as each uncertain parameter is forced over its range of systematic uncertainty. Each point in the range of uncertainty of an error is assumed to be the precise value of the parameter and the fit is forced to go through it. The maximum of all such possible excursions is then taken as a limit error. These error limits will be reduced as the analysis is refined and completed.

The next figure 4 shows the pp results of Taylor et al who used chamber techniques with an external hydrogen target. They essentially analysed their data under similar but somewhat simplified assumptions and looked for the interference term in a linear plot. The probability of no interference was obtained to be 1%. The value of α implied is $\simeq -0.32 \pm 0.07$ (Gaussian). The next figure 5 shows the 19,3 GeV/c p + p results of Diddens et al who used a sonic chamber techniques and external hydrogen target. The two curves shown are essentially the prediction of the no spin dependence case for no real amplitude and also the calculated prediction (not a fit) for a real amplitude which is 0.3 times the imaginary amplitude assuming a nuclear slope of b = 10. The latter appears to fit the data well. One should remember that although the pp data in all those small angle experiments fits a real amplitude in one complex amplitude analysis it does not demonstrate that there is indeed a real amplitude, since it is my opinion that allowing a different triplet and singlet /t/ (four momentum transfer squared) dependence would explain all the data even though one has not even made use of the additional non vanishing spin flip amplitude which introduces more ambiguity.

In fact we found that our data (Foley et al) is completely compatible with such an analysis giving a much steeper singlet slope for a solution.

$\pi^{\pm} + p$ Small Angle Scattering

The next slide Fig. 6 shows our results (Foley et al) obtained with counter hodoscopes for $\pi^- + p$ small angle scattering which clearly exhibit a destructive interference of about the same magnitude as the constructive interference in p + p. Since the sign of the Coulomb potential has changed from that in the p + p case, the real amplitude again has a negative sign (i.e. repulsive). This observation clearly eliminates almost any conceivable instrumental error as being responsible for the observed effects. The results for α at 7.96, 9.89, and 11.88 BeV/c are $(-0.21 \pm 0.04)^{+0.13}_{-0.14}$, $(-0.23 \pm 0.04)^{+0.13}_{-0.14}$ and $(-0.27 \pm 0.08)^{+0.13}_{-0.14}$.

The next figure 7 shows the results obtained for π^+ + p at 10 BeV/c. And again we observe constructive interference of the same order and sign (i.e. repulsive) $\alpha = (-0.33 \pm 0.025)^{+0.11}_{-0.11}$.

Let us at this point remember that in π + p scattering there is only one non vanishing complex amplitude as $t \to 0$.

Hence unless one admits **wild** behaviour of the imaginary amplitude at very small /t/ to simulate the interference effect **we have a reasonable** near proof of a real amplitude.

Although it is difficult to conceive of such a large and strange effect occurring to the imaginary amplitude at such large distances (~ 2 - 7 fermis); in order to make sure I asked Goldberger the other day and he thought this possibility should not be considered seriously. Therefore, I think that we can safely dismiss it.

The next Figure 8 shows a compilation of the values of α deduced from the various reported results assuming no spin dependence.

The Kirillova et al errors are obtained by treating all errors including systematic errors as gaussian, the smaller errors being statistical only and the larger ones including systematic errors are also to be considered as Gaussian errors. In the Foley et al data errors the small errors flags are error fit estimates including all sources of relative systematic error and are gaussian. However, the wavy like upper and lower limit errors are maximum definite limits obtained by forcing the fit to pass precisely through the range of systematic error within their uncertainty limits and then taking the maximum and the minimum excursions of the value of α obtained as a measure of the limit error. Therefore these severe maximum error band limits have no statistical fluctuations since these are characterised by a small gaussian error for possible fluctuation outside the limit. Therefore these limit errors provide a severe and critical test of the reality of the conclusion. These limit estimates will be reduced considerdbly as final calibrations and small corrections to the data are finally processed.

Taylor points out that his error is a preliminary estimate of a gaussian error implied by analysis of a linear plot of the interference term. Diddens's experimental result was just obtained and they did not obtain least square fit for α or a fit estimate for the error. Diddens personal estimates that the error is 20% of the result.

It is clear that in the 8-12 BeV/c region there is good agreement between all the data within errors. It appears that α may be of the same order of magnitude (15-30%) of the imaginary amplitude and negative and may not be decreasing with increasing energy. However, α may still have a sizable energy variation since the analysis of the 19.3 GeV/c data of Diddens et al have not been completed. Furthermore in comparing different experiments there is, of course, the possibilities of a sizable systematic shift between them. Of course, as stated previously, spin dependence without a real amplitude explain our results and could probably explain all the rest if taken into account. One should remember here that in

πp the spin flip amplitude goes to zero as $/t/\to 0$ and therefore as discussed previously the no spin dependence equation is justified. Hence we have a near proof of real amplitude effects for πp . The lower part of Fig. 8 shows the values of α deduced for 8-12 GeV/c $\pi^- p$ and 10 GeV/c $\pi^+ p$. As one can see α has the same sign and order of magnitude as determined for p + p. Since the effect obtained in p + p is very similar the most likely explanation is that the p + p effect is not due to spin dependence but to a real amplitude, however we cannot demonstrate at present.

An important question that occurs to one immediately is how **these measurements** agree with the forward dispersion relations prediction for the real amplitude.

In the next figure (9) I have made such a comparison. In the upper half is a calculation by Levintov the shade d area being the limits of error in the calculations. He normalized to a questionable value of α at 20 GeV/c based on a poor experimental result. He used a double **subtraction** dispersion relation to remove sensitivity to the asymptotic behaviour but loses the sign of α Although there appears to be good agreement now, if the upper energy calibration which is very poorly determined became substantially higher there may be some difficulty accomodating the experimental mean value.Of course/the approximations in the non-physical region as well as the errors in the data are looked at carefully, we can of course for now conclud e that the predictions and results are in agreement. On the next figure (10) is shown a one subtraction dispersion relation calculat ion by Soding which retains the sign of α.

The Soding and Levintov (   ) calculations agree indicating that Soding's assumption about the asymptotic behaviour is probably right. Of course the p + p dispersion relation predictions are not to be trusted too well because of the well known large uncertainty due to the extensive unphysical region.

The next figure (11) shows a comparison of the α values of πp with calculations of the real part of the scattering amplitude by Barashenkov. He used only one subtraction but has informed me privately that he also tried two and obtained about the same result. The $\bar{\pi} p$ dispersion relation calculations do not have a contribution from the unphysical region and therefore rppresent a much more critical test of the dispersion relations. I think that we can be satisfied that there is no disagreement outside of errors between the data and the dispersion relations. As a matter of fact with these new measurements, accurately done over the available energy region we will be able for the first time to seriously check the high energy behaviour of the dispersion relations which are still the cornerstone of our quantum field theory. With enough subtractions they are not to^ sensitive to the higher energies and we can if they agree well with the data in this form use the single subtracted form to learn about asymptotic behaviour, by adjusting the asymptotic behaviour to fit the data.

As a matter of fact real amplitude measurements in elastic scattering experiments may well provide us with a new approach to studying asymptotic behaviour.

Of course more accurate dispersion relation calculations using the best data and coupled with a critical analysis of their error limit is required.

Polarization

There are two polarization measurements reported in p + p. The first is by Kanavets, Levintov and Morozov who measured polarization at $/t/ \approx 0.3$ GeV/c^2 at **proton** energies of 4.9 GeV and 8.5 GeV shown in the next figure 12. They found that the polarization drops rapidly with increasing energy and is consistent with zero at 8 BeV/c. A series of polarization measurements using a polarized target were reported by Steiner et al some of the results of which are also shown in the next figure 13. At approximately the maximum polarization P is given as a function of energy, we see, that the polarization also drops rapidly but is still $\gtrsim 0.1$ at 6 GeV and may even be levelling off.

The next figure 14 shows the angular distribution of the polarization as a function of energy which has a broad maximum.

The appreciable values of the polarization at 6 GeV/c should perhaps make us worry of assuming no spin dependence in the p + p scattering.

Charge Exchange

We have had a number of reports on charge exchange scattering.

n-p Charge Exchange

Manning et al have obtained results at 8.15 GeV/c n-p charge exchange and the results are shown in Fig. 15 together with those of the previous data at 2.85 BeV (   ) normalized so that both experiments are compared at the same momentum transfer. It is clear that they find the same narrow peak corresponding to a radius $\sim$ 2 fermi whereas as is well known the pp radius corresponds to $\sim$ 1 fermi.

Pion-Nucleon Charge Exchange

We also had results on pion nucleon charge-exchange which is getting some experimental attention lately. Wahling et al have obtained small angle results at 6 and 10 BeV/c in

$$\pi^- + p \rightarrow \pi^0 + n$$

in the forward direction using a spark chamber set-up.

Their results plotted (fig.16) as $\frac{d\sigma}{dt}$ vs $-t$ are characterized by a flat-topped appearance at $/t/ \lesssim 0.1$. Followed by a typical average pion-nucleon slope from $/t/ \approx 0.2$ to 0.4. Followed by what may possibly be a minimum at $/t/ \approx 0.55$ followed by a sudden transition to more are less flat background 1.5% of the peak value thereafter till $/t/ \approx 1.4$. The 6.0 GeV/c data tend to show a generally similar shape behaviour but the statistics are much poorer and hence this is inconclusive.

In another report from the Falk-Vairant group (fig.17) on $\pi^- + p \to \pi^0 + n$ also using spark chamber techniques they find at 5.9 GeV/c and 10 GeV/c generally similar behaviour but with better statistic points in the flat top region clearly demonstrating a rounding off the top of the curve for $/t/ \lesssim 0.15$. They also show the sudden transitionsto a flat region beyond $/t/ \gtrsim 0.5$ of $\approx$ 1% of the peak value, but their data points stop at $/t/ \approx 0.8$.

The flat rounded top region implies that the charge exchange interaction does not extend as strongly to large distances as the $\pi^{\pm} + p$ interaction.

Since the charge exchange amplitude depends on the difference of the two pion scattering amplitudes, small differences in the behaviour of $\pi^+ + p$ and $\pi^- + p$ scattering will have large effects in charge exchange, so a different behaviour is understandable.

The charge exchange cross section would of course be sensitive to the behaviour of the real amplitude as well as imaginary.

Therefore charge exchange is a complicated phenomenon.

The observed cross sections appear to considerably exceed the calculated values for the imaginary amplitude contribution and hence imply sizeable real parts.

Inelastic Interactions

It is well known by now that nucleon-nucleon inelastic interactions are generally dominated by isobar production. At this conference we find better evidence than previously available that this is also the case for nucleon-antinucleon interactions. For example, Goldschmidt-Clermont reported a hydrogen bubble chamber study of the anti-proton proton single pion production at 4.0 GeV/c.

These authors find that the T = 3/2 and T = 1 /2 resonance form factors previously deduced for O.P.E.M. (one pion exchange model) did not explain the p+p data since the T = 1/2 form factor had to be modified by this group so as to drop more rapidly with increasing energy (see fig.18) in order to explain their data. However the cross-section **versus** energy curves still do not fit the data. As the theoretical curves still show too rapid a rise with energy just above threshold, it appears to the speaker that the O.P.E.M. is likely to simple a view of the inelastic interactions. In Fig.19 the results of **Alichanov et al on the backward** elastic scattering cross section of π^- on neutron are given. The experiment was done over 1.2 - 4.5 GeV/c incident pion momentum region. The dependence of cross section $\frac{d\sigma}{d\omega}$ (mean value in $150^\circ \div 180^\circ$ c.m.s.) on the energy (on $S = E^2$) was measured. The experiment was performed by the bubble and spark chambers technique. The data show how the cross section fall, when the energy increases.

A report by Morrisson on the Aache-Berlin-CERN collaboration showed that 8 GeV/c (and also 4 BeV/c) $\pi^+ + p$ elastic and two prong

interactions exhibited considerable backward scattering. (fig.20).
The striking backward peak is based on few events however the authors feel that they satisfy all elastic scattering criteria. These authors also found striking evidence for isobar production in peripheral interactions for example the peripheral nature at the reaction

$$\pi^{+}+p \rightarrow N^{*++}+\rho^{0}$$

is shown in fig.21.

In studing 607 events of $\pi^{+}+p \rightarrow p+\pi^{+}+\pi^{+}+\pi^{-}$ they find about half of the events are one of the following

$$\pi^{+}+p \rightarrow N^{*++}+\rho^{0}$$

$$\pi^{+}+p \rightarrow N^{*++}+f^{0}$$

The apparent three body reaction

$$\pi^{+}+p \rightarrow N^{*++}+\pi^{+}+\pi^{-} \quad (\text{No } \rho^{0}, \text{ no } f^{0})$$

$$\pi^{+}+p \rightarrow p+\pi^{+}+\rho^{0} \quad (\text{No } N^{*}, \text{ no } N^{++}) \text{ production}$$

also occur frequently.

A study of $\bar{p}+p$ annihilation interactions at 5.7 GeV/c in the Saclay H_2 bubble chamber was made by Bockman et al. They also find O.P.E.M. gave too large values for the total cross section with the Ferrari-Selleri form factor used previously. The agreement is improved if one restricts oneself to low momentum transfers. This is the same sort of effect observed by Goldschmidt-Clermont.

Bartke et al studied the analysis of eight and ten prong stars which result from $\pi^- p$ interaction in hydrogen at 10 GeV/c incident momentum.

It was priviously shown by Borodin et al that the six prong interactions still showed features suggesting a peripheral character of the interaction.

The eight and ten prong stars represent the highest multiplicities obtained at 10 GeV, having cross sections of 0.50 mb and 0.04 mb respectively (2.3% and 0.2% of the total inelastic cross section).

In about 50% of the cases the proton track if there was one was identified.

Only slight assymetries were noted in the various angular distributions and high momentum transfer to the baryon seems quite frequent and the authors concluded that these general characteristics fit those one would expect for central rather than peripheral collisions.

The exact meaning of this must be carefully analysed before drawing a conclusion.

However I would like to mention that professor Feinberg will discuss this subject in his talk.

<u>Larger /t/ elastic scattering p + p</u>

Goldschmidt-Clermont reported on 4.0 GeV/c p+p interactions in the 81 cm Saclay hydrogen bubble chamber.

The next slide (fig.22a) compares this and other p + p and $\tilde{p}$ + p data. One should note the higher experimental slope of $\tilde{p}$+p compared to p + p and the lower values of the high /t/ cross-section by about an order of magnitude or more.

The slide 22b also shows collections of various optical model radii and clearly indicates the decrease of the $\tilde{p}$ + p radius and growth of p + p radius with increasing energy.

The next slide 23 shows the $\tilde{p}$ + p data obtained with counter hodoscopes and gives the one pole Regge-trajectory equivalent fit which shows considerable evidence for expansion (i.e. antishrinkage). If one added the lower energy data the effect would be significant. Hence, this trend continues from the lower energies to 16 BeV/c.

p + p

The next slide 24 shows the α (t) for p + p obtained after extension of the results beyond 25 BeV/c.

It is clear that there is some evidence for a possible reduction of shrinkage above 15 BeV/c but this is not conclusive in view of the error. Giacomelli reported the CERN spark chamber experimental study of p + p and π^- + p elastic scattering at 8, 12 and 18 GeV/c which find results for α /t/ in agreement within error with our results.

The next slide 25 shows the results obtained for p + p by Baker et al in the high /t/ region. It is clear that the shrinking effect becomes very large as /t/ increases.

Orear has observed (next slide 26a) that if the scattering amplitude is assumed of the form $e^{-\frac{a}{2}p_\perp}$ then $\frac{d\sigma}{d\omega} = \frac{A}{s}e^{-ap_\perp}$ is a good fit to the data.

He also finds that if one plots (fig.26b) the p + p $\rightarrow \pi^+ + d$ process the highest energy points also lie on a line with the same slope

It is not at all yet obvious to me what the significance of this is and whether it would hold for other elastic scattering reactions especially $\pi + p$ and $\tilde{p} + p$ which do not shrink since this substitution of $p_\perp$ for /t/ is in a direction to correct for shrinkage effects.

Yang has tried to attribute this effect to the probability of the two protons sticking together in a high transverse momentum collision and thereby concludes that $e - p$ scattering should drop as the square root of $\sqrt{\frac{d\sigma}{d\omega}}$ where square were of is a proper variable for e + p and he says Wilson told him this is consistent with the electromagnetic data.

An extension of the $\pi^- + p$ differential scattering ($0.2 \lesssim /t/ \lesssim 1.0$ BeV/c ^{2}) to beyond 25 BeV/c incident momentum shows no evident shrinkage.

At the end of the Stanford conference Dr. Salam pronounced Regge Poles dead and I haven't seen any evidence since of their recovery or for explaining elastic scattering processes in any convincing scheme without on excessive number of arbitrary parameters.

Seber has observed that if you use the scaling low $t' = \left(\frac{d\sigma}{dt}\right)_{t=0} t$ (i.e. rescale approximately proportional to σ_{tot}), then two $\tilde{p} + p$ and p + p (i.e. incident baryons) elastic scattering cross-sections are charachterized by similar values of the parameters while the $K^{\pm} + p$ and $\pi^{\pm} - p$ cross-sections (i.e. incident bosons) are also characterized by a different set of similar parameters within errors.

This is somewhat related to an observation I had made during the Stanford conference namely that the incident pions and kaons had average parameters which are about the same and lower than those obtained for incident protons and antiprotons which are again close together.

Peierls and Cottinghorn have used an impact parameter expansion applied to Van Hove's model in which elastic scattering is assumed to be pure imaginary shadow scattering corresponding to absorption into the multi-particle inelastic channels.

This model gives an essentially parameter, free fit to the π + p data with the addition of a slowly varying real part reproduces the behaviour of p + p data. In view of the evidence presented at this conference this and a lot of other calculations which assumed no real part in either π + p or p + p will have to be reconsidered.

Oehme has recently considered[x)] the analysis of the elastic scattering data presented at the Stanford Conference within the framework of dispersion theory and found inconsistencies.

Pomeranchuk and Gribov have tried to explain the experimental results by considering the Mandelstam cuts generated by one, two, three etc. Pomeranchukon's and find no real success.

Vernov et al reported the dependence of cross-sections of the inelastic interaction of nucleons with light nuclei upon the incident energy. Fig.27 shows their compilation of the results of various authors for these cross-sections as a function of energy. At the highest energy upper and lowes limits are reported for C and N nucleai.

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x) Oehme -High Energy Scattering and Dispersion Theory.

The study of inelastic interactions at high energies 10^{11}-10^{12} has recently partially became well understood in terms of a two centre fireball model.

The basic point which allows analysis of the experimental data relatively independent of the actual energy of the primary is the validity to a good approximation at these energies of the relation ship $\log tg\, \theta_{\mathcal{L}} \approx \log tg \frac{\theta_c}{2} - \log \gamma_c^{*}$.

It turns out that if the secondary particles are plotted versus logtan θ and a center of isotropic emission exists it will appear as an approximately gaussian distribution in the coordinate logtan θ (see Fig.28)

Therefore the angular distribution predicted by a multi center model should have the shape arising from the superposition of gaussian contributions the log γ_c^{**} term tends to shift the location of the center of the distribution to the left as the γ_c^{*} of the center or fireball increases.

Previous cosmic ray emulsion evidence and the work of Dobrotin and Slavatinksy using a cloud chamber combined with an ionization calorimeter has shown that at several hundred (300) BeV two fireballs occur about of half the time only.

However, beyond 1000 BeV and certainly beyond 10.000 BeV it appears that the fireball production is mostly double.

Gierula et al reported at the conference results from a new method for observing practically monochromatic energy interaction.

A heavy charged primary (i.e. Z = 15) if followed in a large

γ_c^{*} = Lorents factor of moving center in c.m.s. system

(80 liter emulsion stack flown at 106.000 feet). This heavy charged primary has 1.4 x 10^{12} ev per nucleon. Its interaction in the stack will therefore have a sharp upper edge in the energy per nucleon. Fig.28 shows the log tg θ_L plot for the events lumped in various classes.

The small angle group of particles has been identified in the upper part of the fig. as nucleons by its composition (charged to neutral ratio ~ 1), by a pronounced angular separation from other tracks and from the general consistency of the energy dissipation in the whole family of interactions.

The angle corresponding to 90° in the c.m.s. of nucleon-nucleon collisions is marked by a thick line along the figure. This well defined beam of about 30 nucleons produces the sample of 19 interactions which is nearly monochromatic

and clearly shows a strong bimodality of the angular distribution. The fact that the (left) forward cone is at the more or less the same location testifies to the near monochromaticity of the primaries.

The results support the fireball model well. Other characteristics deduced are $\langle K \rangle$ = (average inelasticity) 0.5. Average transverse momentum $\langle P_{\perp} \rangle \approx 0.4$ GeV/c and in any case not greater than 1 GeV/c. Average momentum transfer $\Delta \approx 0.5$ GeV/c.

The general characteristics of the nucleon-nucleus collisions strongly support the idea of a cascade generated by individual nucleon-nucleon collisions.

The large varieties of shapes and the average multiplicities per incident nucleon as illustrated in the table are two features of this type.

T a b l e

Target	Nucleus-Nucleus collisions	Nucleon-Nucleon collisions
HCNO ($N_h \leq 5$)	8.16 ± 1.7	11.5 ± 3.3
AgBR ($N_h \geq 5$)	17.1 ± 1.6	17.0 ± 5.2

I would like to now talk about the work of B. Peters and Yoshpal which I believe is an essential bridge allowing & common understanding of the phenomena in the artificial accelerator energy region (up to 30 BeV) and the higher energy cosmic ray region.

After the success of the isobar model in explaining the inelastic interactions of nucleon+nucleon and pion-nucleon interaction in the cosmotron energy region in 1957, Peters reasoned that there was no reason for these phenomena not to exist at cosmic ray energies ($\gtrsim$ 100 GeV).

The fireball model which was introduced in 1958 suggested that the majority of secondary particles are emitted nearly isotropically at low energies from a cloud which is approximately at rest in the centre of mass system of the colliding nucleus. Cosmic ray evidence indicates that the colliding nucleons themselves do not form part of this fireball; their energy is high in the C-system even after collision. This can be deduced for the propagation of nucleons through the atmosphere. In the majority of encounters a nucleon emerges which contains a large fraction of the incident energy.

However, Peters and Pal find evidence that in a considerable fraction of collisions a small number of pions is generated with energies which are high in the rest system of the fireball and low in the rest system of one of the baryons and whose creation can be described as being the result of the excitation of a baryon isobar. This is in accordance with the energy distribution among particles energies from high energy collisions. They conclude from an analysis that: 1) the ratio $\frac{\mu^{+}}{\mu^{-}} \approx \frac{5}{4}$ which is constant ever considerable energy range is explainable if the excess is due to a subgroup which receive, an abnormally high energy proportional to that of the incident nucleon (i.e. on isobar excitation and pion decay of the incident nucleon). The $\frac{K^{+}}{K^{-}}$ ratio 20 for stopping kaons in emulsion. The observation corresponds in the mirror system of nucleon-nucleon collisions to kaons which receive more than 25% of the primary energy which would be normal and easy to explain if a kaon arises from the de-excitation of a forward isobar so their model has two parts. A slow non-relativestic fireball or two moving slowly in C-system of the original n-n. The number of pions increases with energy but not much increase for their energy per particles in c.m. system. So they have lab. energies of the order of the square of the primary energy.

Even if the isobar pions represent a few percent of all pions produced, due to their high energy and kinematic reasons the secondary cosmic rays observed in the atmosphere at the surface of the earth or below ground represent a reasonably pure sample of the decay products of nucleon isobaric states and their progeny.

The production of particle studied at the CERN PS it has been observed by Dekkers et al and Damyorn Honsen that the preduction of particles is dominated in p + p collisions by baryon isobar production.

The fireballs of course are the analogue of the pion isobars or resonances at the accelerator energies but are not necessary resonant structures.

Hence in conclusion it appears clear that from several hundred MeV to the highest energies observed multicenter models 2 - 4 or perhaps even more are necessary to explain the data.

References cannot be included in this preliminary draft due to lack of time. The final version will contain them.

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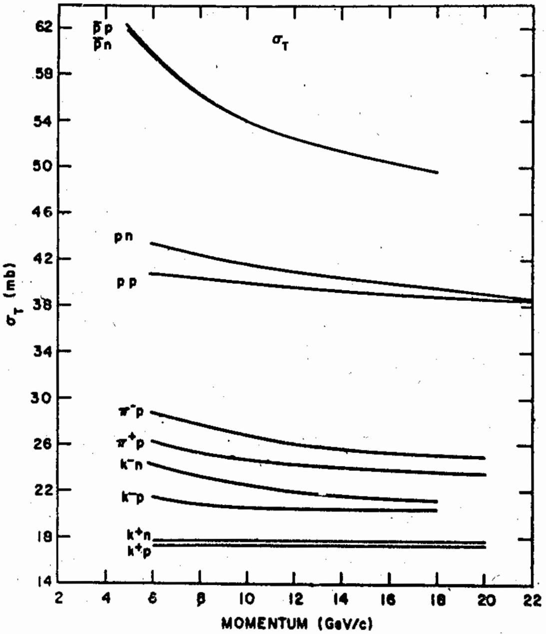


Fig.(1a) Total cross-section as a function of energy Kycia et al.

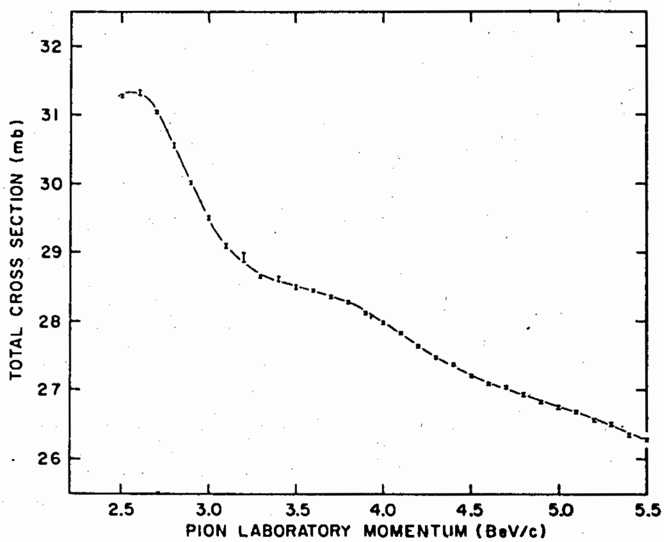


Fig.(1b) The $\pi^+ + p$ (T = 3/2) total cross-section ≈ 2 = 6 GeV/c.

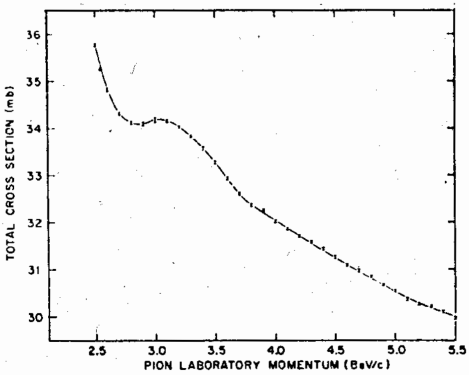


Fig.(1c) The T = 1/2 pion proton cross-section.

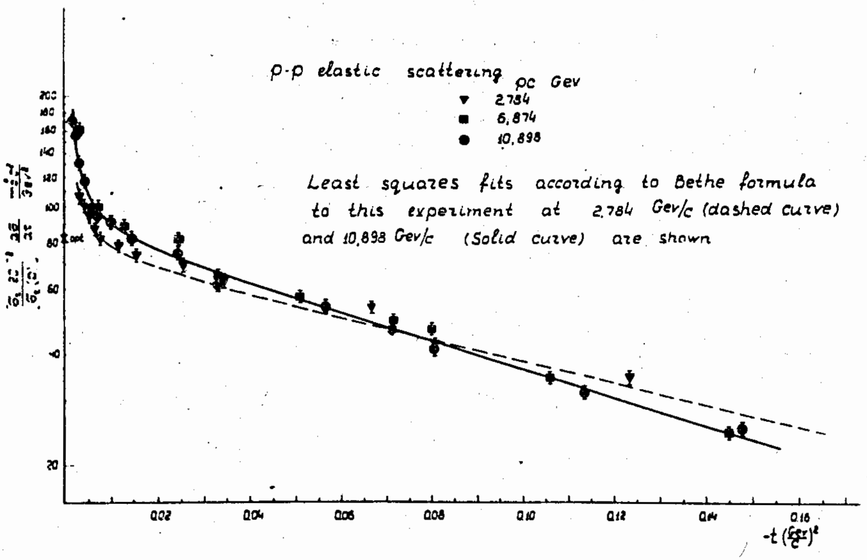


Fig. 2. p + p small angle scattering results of Kirillova et al. The solid curves shown are essentially a fit to the no spin dependence of one complex amplitude.

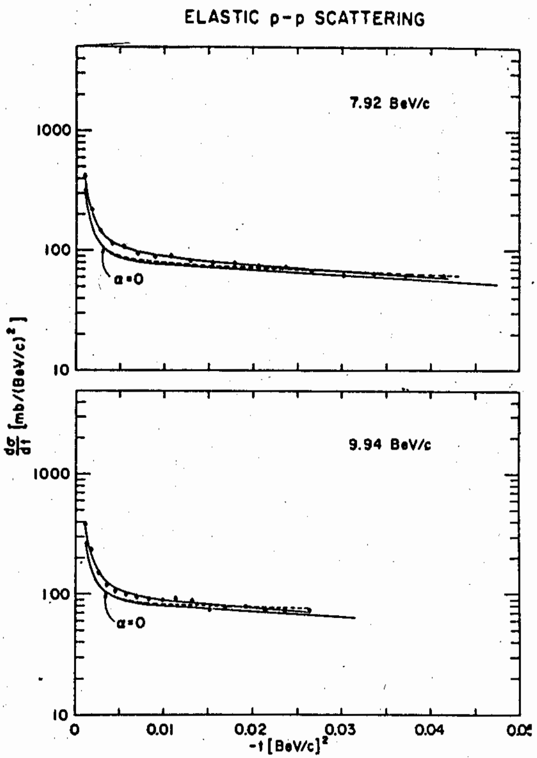


Fig. 3. The 7.96 and 9.89 BeV/c small angle scattering results of Fuley et al. Similar results obtained at 12.14 BeV/c are not shown.

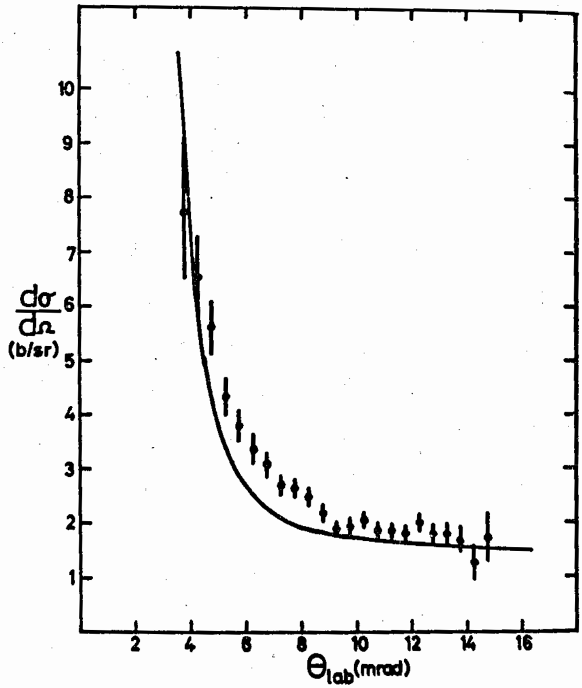


Fig. 4. The small angle scattering results of Taylor et al.

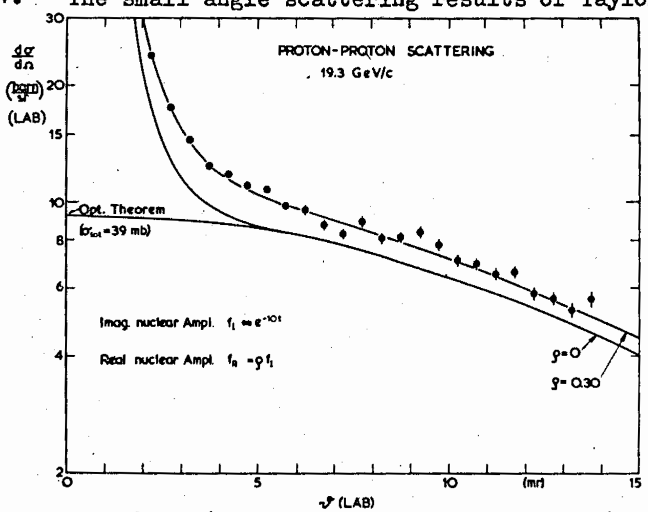


Fig. 5. The 19.3 BeV/c p + p small angle scattering results of Diddens et al.

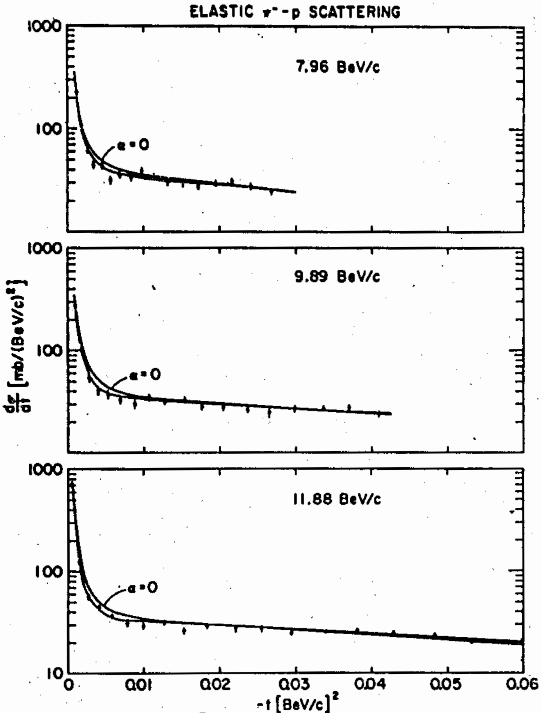


Fig. 6. 8–12 GeV/c $\pi^- + p$ small angle scattering results of Foley et al.

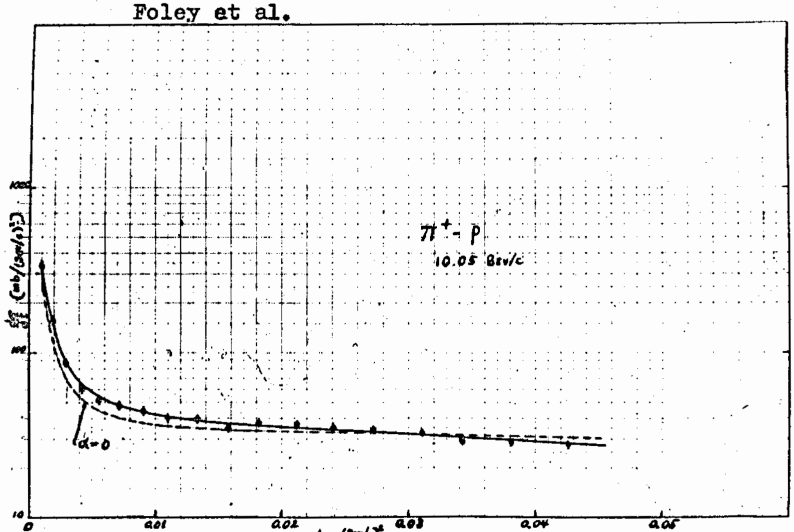


Fig. 7. 10 GeV/c $\pi^+ + p$ small angle scattering results of Foley et al.

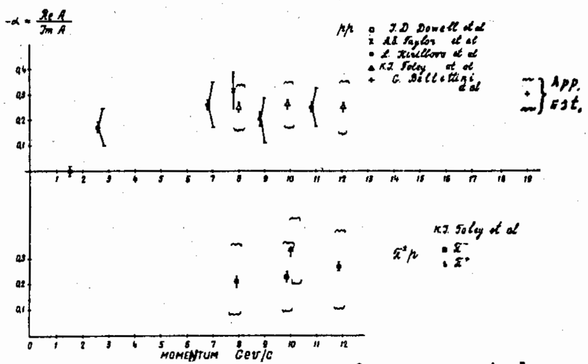


Fig.8. A compilations of the various reported results for

$$-\alpha = \frac{\text{Re Amplitude}}{\text{Imag. Amplitude}}$$

see text for discussion of the errors.

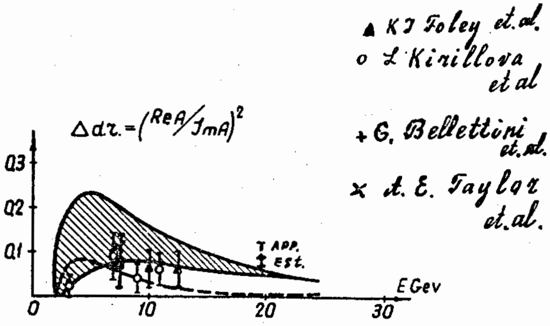
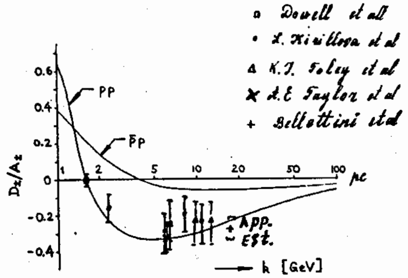


Fig. 9. A comparison of the p + p results for α with Levintov's et al dispersion relations calculations. All errors are Gaussion except Foley et al which show limit errors, about four times the **corresponding** Gaussian errors.



Ratio of real to imaginary part of the spin-independent pp and $\bar{p}p$ forward scattering amplitude, as a function of the lab momentum k of the incident (anti-)proton.

Fig. 10. (Soding caption on figure)

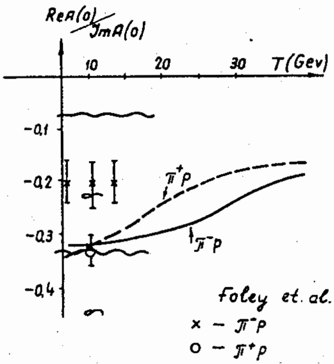


Fig. 11. Comparison of the $\pi^{\pm}$ - p results with one subtraction dispersion relation prediction by Barashenkov. See text for discussion of results.

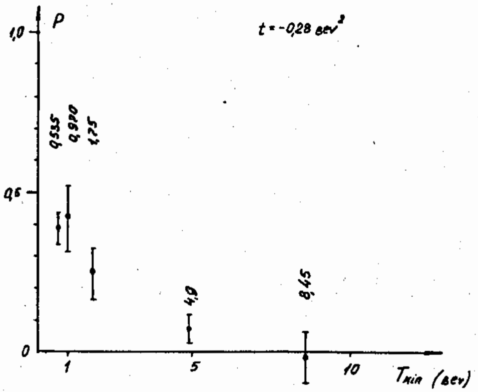


Fig. 12. The polarization near the maximum as a function of energy, Kanavets et al.

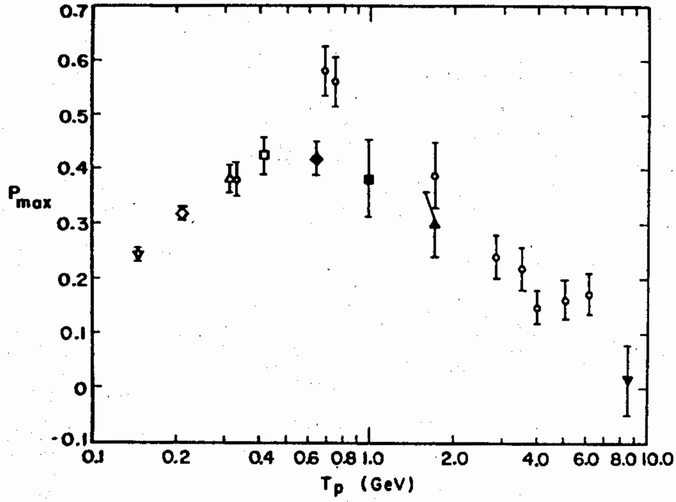
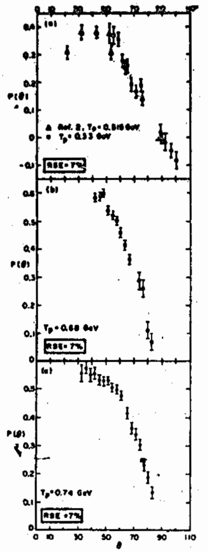
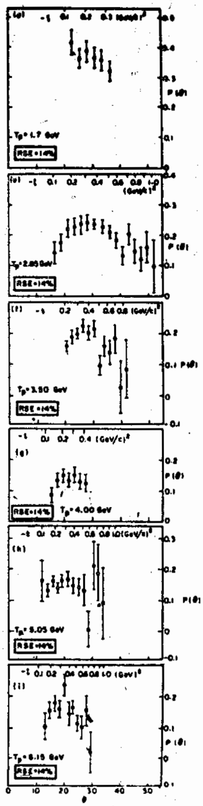


Fig. 13. The maximum polarization as a function of energy reported by Steiner et al.





Polarization as a function of center-of-mass angle θ and four momentum transfer squared (-t) for various beam energies T_p. RSE means relative systematic error. (a) Δ, Data from Ref. 2; O, data from this experiment.

Fig. 14. Angular distribution of polarization (Steiner et al and others).

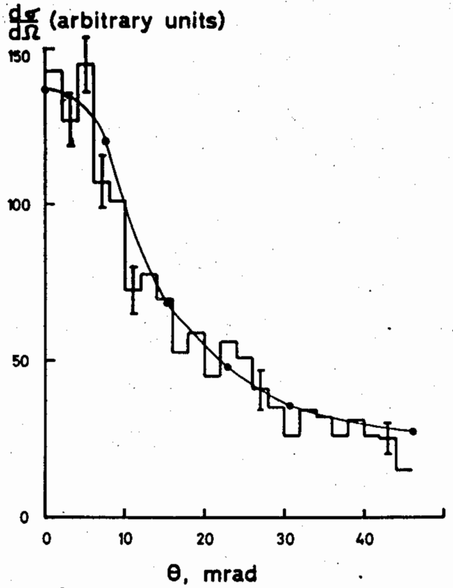


Fig. 15. n – p charge exchange-Monning et al at 8.15 GeV/c compared to 2.85 GeV data. Normalized so that both are composed at the same momentum transfer.

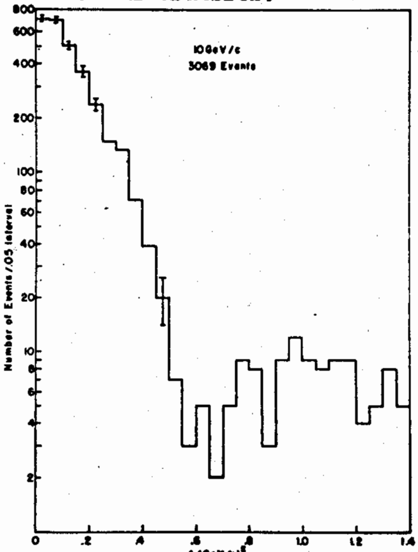


Fig. 16. $\pi^- + p \rightarrow \pi^0 + n$ – Wahlig et al – 10 GeV/c.

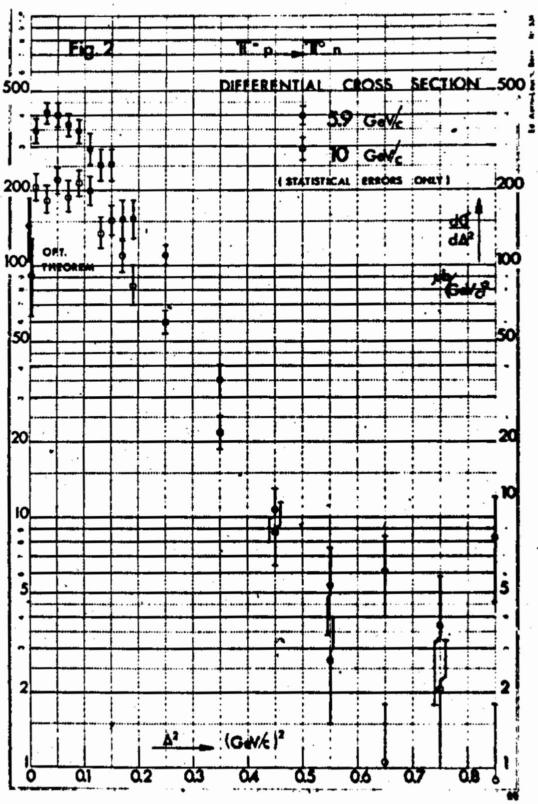


Fig. 17. $\pi^- + p \to \pi^0 + n$ - Falk-Voriant et al - 6 and 10 GeV/c.

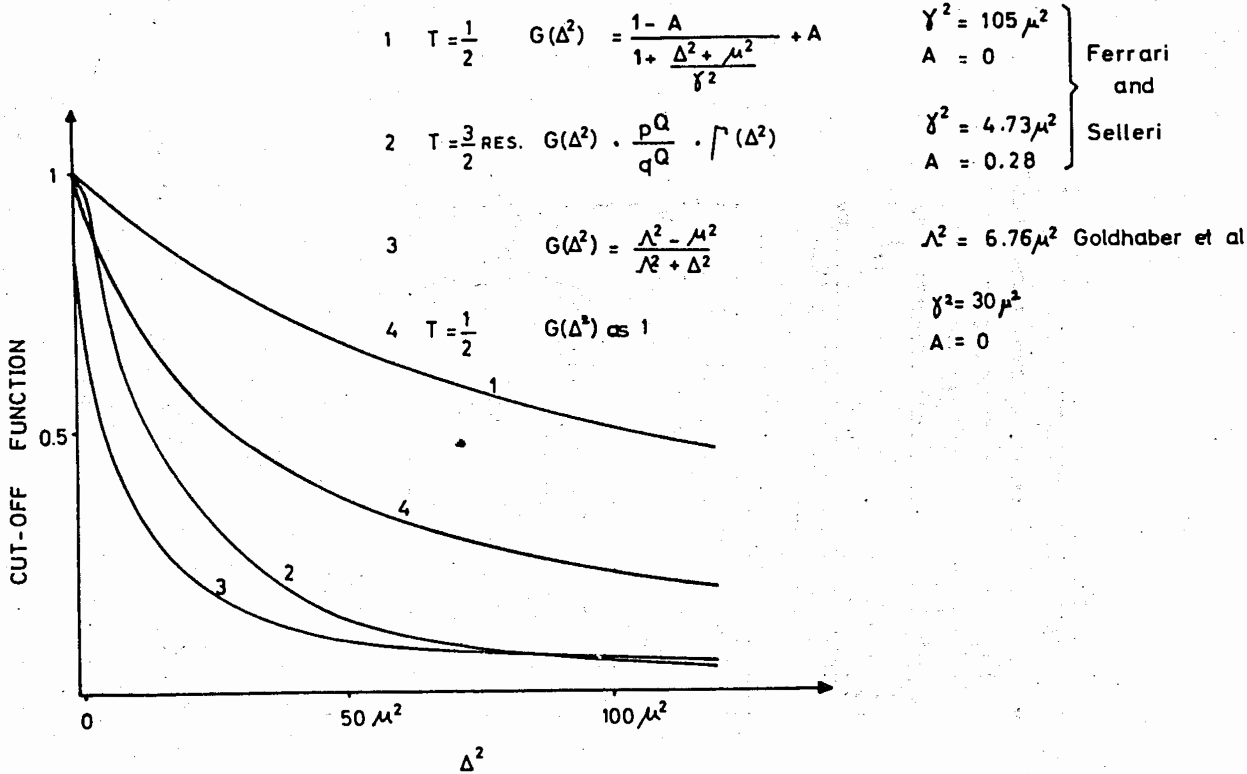


Fig. 18. O.P.E.M. Form Factors from Goldschmidt-Clermont report showing necessary modification of form factor to explain $\bar{p} - p$ single pion production.

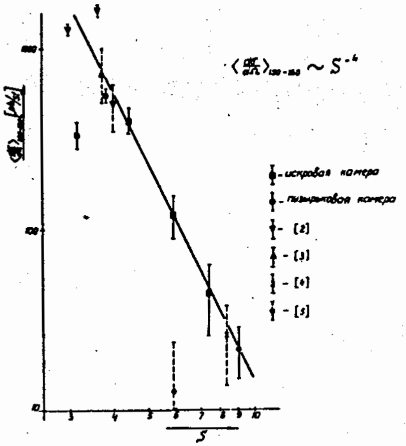


Fig. 19. π^- + n backward scattering

by Alikhanov et al.

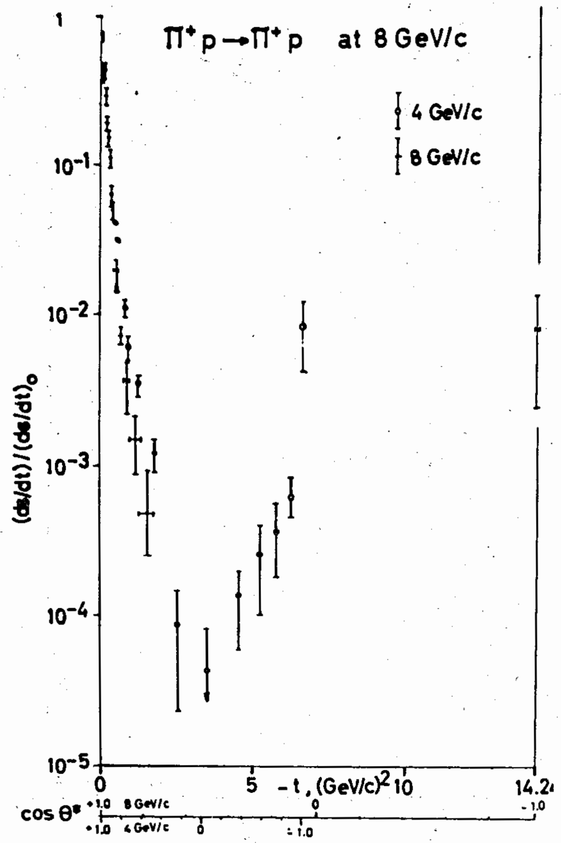


Fig. 20. π^+ + p El. Scattering at 8.0 GeV/c.

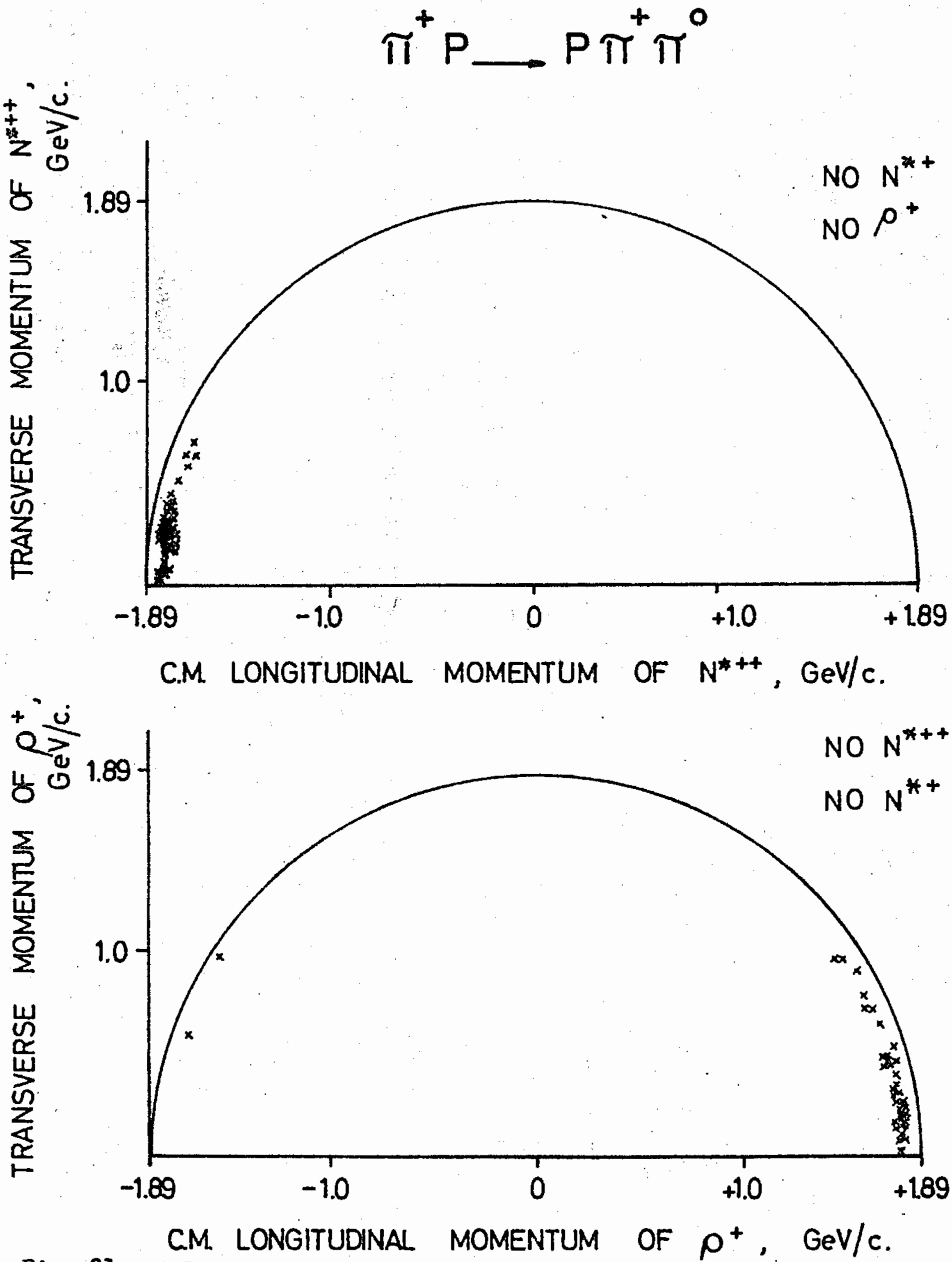
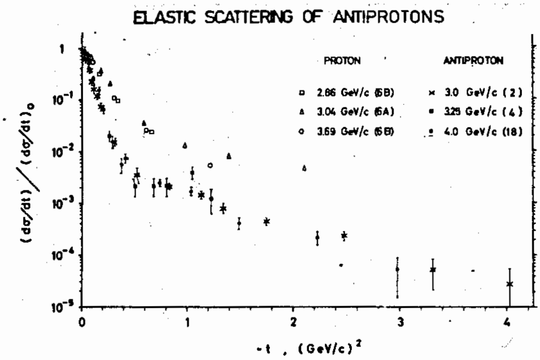
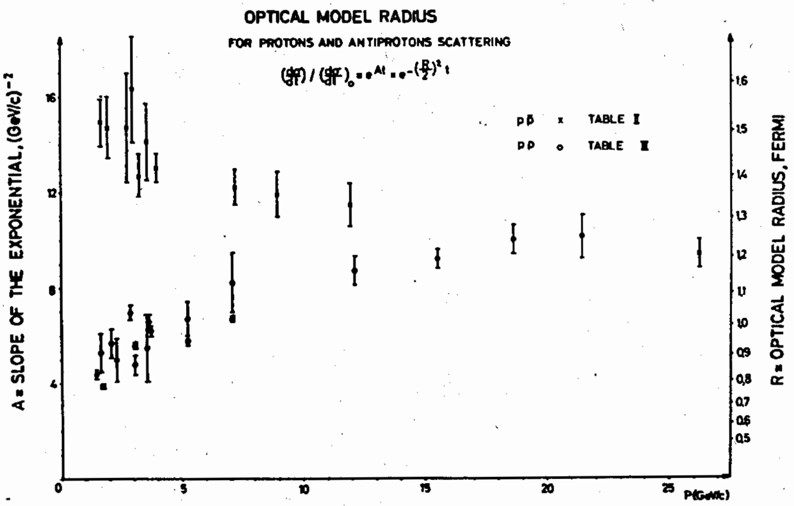


Fig. 21. A Peyrou Plot by Morrisson et al illustrating peripheral N^{*++} isobar production.



a)



b)

Fig. 22. Comparison of $\bar{p} + p$ and $p + p$ scattering.

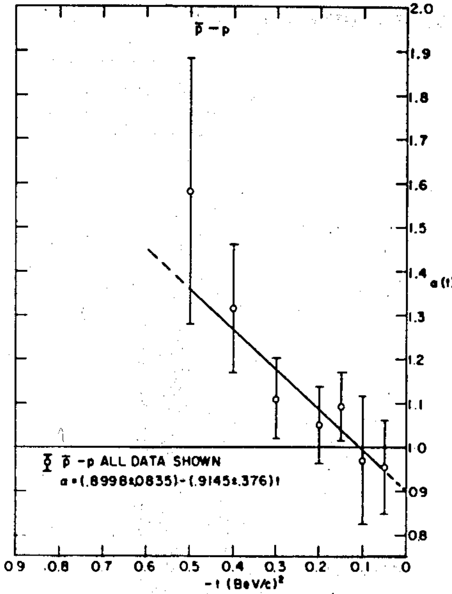


Fig. 23. α(t) vs − t for $\bar{p}$ + p. Foley et al.

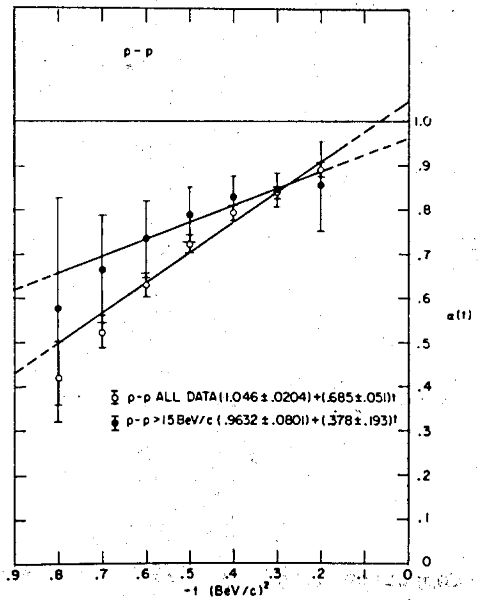
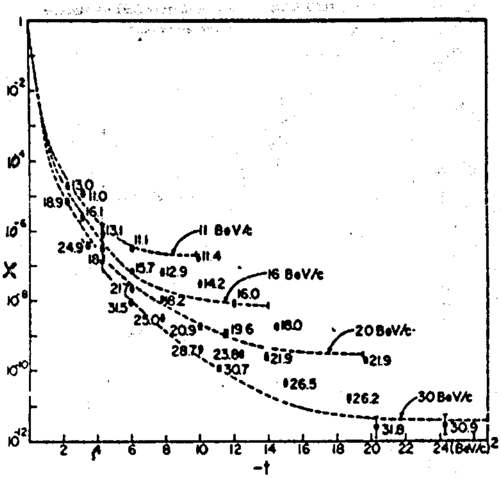


Fig. 24. α(t) for p + p. Foley et al.



Elastic differential cross section normalized to the forward scattering cross section, as a function of the squared four-momentum transfer $-t$. The 11 cross sections of this experiment are indicated by squares and the 18 cross sections of reference 1 by circles. Dashed lines describe the behavior of X at fixed beam momenta of 11, 16, 20, and 30 BeV/c; each line ends at t_{max} which corresponds to $\theta_{c.m.} = 90°$.

Fig. 25. High /t/ p + p scattering Baker et al.

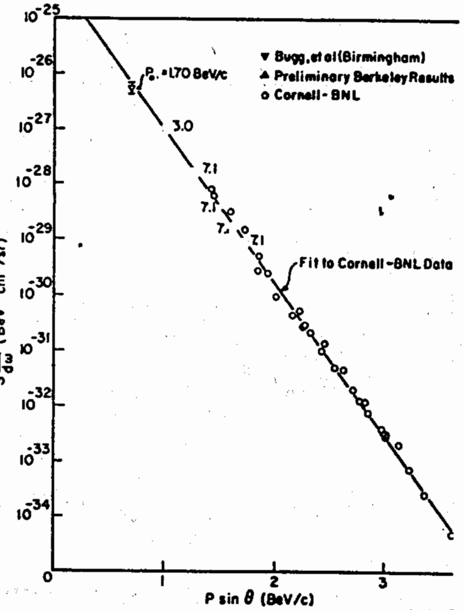


Fig. 26.(a) Orear's fit to the p + p high /t/ data

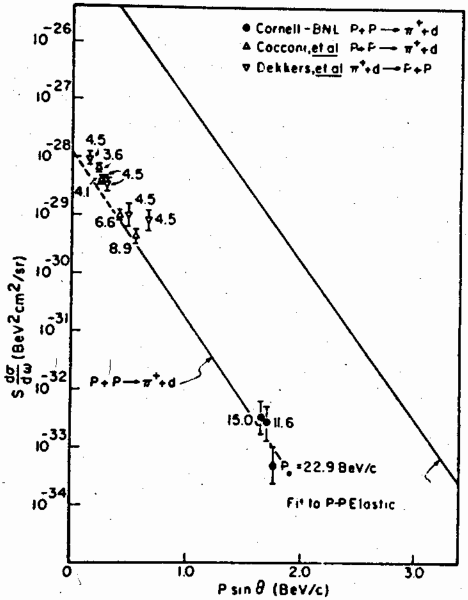


Fig. 26.(b) A similar fit to the p + p → π^+ + D data.

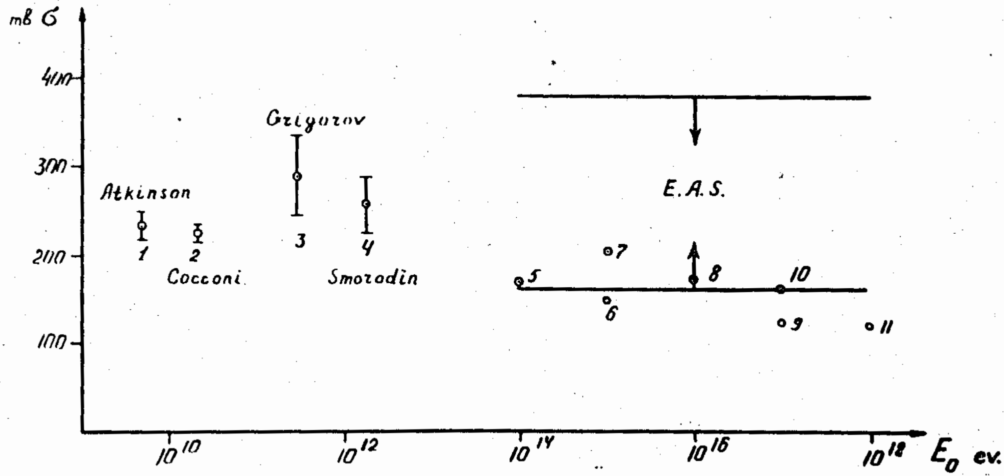


Fig. 27. The dependence of the cross -section of light nuclei on energy. Vernov et al.

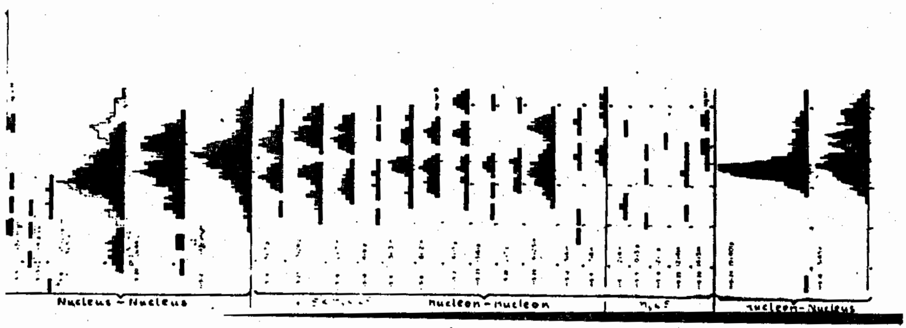


Fig. 28. The log. Tg.θ Plot (Gierula et al).