Abstract: Comparisons of pp and \( p\bar{p} \) interactions at 205 GeV/c incident laboratory momentum are presented. Most features of the inelastic processes are remarkably similar.

Résumé: Des comparaisons d'interactions pp et \( p\bar{p} \) à un moment initial de 205 GeV/c sont présentées. Les caractéristiques des procédés inelastiques sont remarquablement semblables.

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I want to present here comparisons of some aspects of π⁻p and pp interactions at very high energy. The data on which these comparisons are made have already been published or presented at meetings and come principally from bubble-chamber exposures at NAL analysed by the ANL-NAL Collaboration¹ (pp at 205 GeV) and the NAL-LBL-UCB Collaboration² (π⁻p at 205 GeV). I must also particularly mention the work of F. Winkelmünn, from whose recent paper some of the figures to be presented are taken³.

As is well known, our present window onto high-energy processes has come almost exclusively from studies of pp collisions because (i) these are the only processes which can presently be studied at the ISR, and (ii) protons were the most readily available beam particles in the early operational stages of NAL. The ability to study different beam particles can add new dimensions to our understanding.

Table 1 shows some over-all cross-section comparisons between pp and π⁻p interactions at 205 GeV. The π⁻p total, elastic and inelastic cross-sections do not, within the uncertainties of ±0.5 mb, seem to change between 50 and 200 GeV/c.

<table>
<thead>
<tr>
<th></th>
<th>pp</th>
<th>π⁻p</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ(total)</td>
<td>39.0 ± 1.0 mb</td>
<td>24.0 ± 0.5 mb</td>
</tr>
<tr>
<td>σ(elastic)</td>
<td>6.9 ± 0.4 mb</td>
<td>3.0 ± 0.5 mb</td>
</tr>
<tr>
<td>σ(inelastic)</td>
<td>32.1 ± 1.1 mb</td>
<td>21.0 ± 0.5 mb</td>
</tr>
<tr>
<td>σ(elastic) /σ(total)</td>
<td>0.175</td>
<td>0.125</td>
</tr>
<tr>
<td>Elastic slope parameter</td>
<td>~ 11 GeV⁻²</td>
<td>~ 9 GeV⁻²</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Momentum (GeV/c)</th>
<th>⟨n⟩</th>
<th>f₂[⟨n(n - 2)/2⟩]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pp</td>
<td>π⁻p</td>
</tr>
<tr>
<td>50</td>
<td>5.32 ± 0.13</td>
<td>5.71 ± 0.13</td>
</tr>
<tr>
<td>100</td>
<td>6.32 ± 0.07</td>
<td>6.80 ± 0.14</td>
</tr>
<tr>
<td>200</td>
<td>7.68 ± 0.07</td>
<td>8.02 ± 0.12</td>
</tr>
</tbody>
</table>

Note: n ≡ charged multiplicity

f₂(n) ≡ ⟨n(n - 1)⟩ - ⟨n⟩²
Table 2 gives comparisons of pp and \( \pi p \) multiplicity parameters at 50, 100 and 200 GeV/c (where at 100 GeV/c, I have used \( \pi^+ p \) data, since \( \pi^- p \) results have not yet been reported)\(^4\). From inspection of the numbers in Table 2, one can conclude that:

i) The rate of change of mean multiplicity with \( \ln s \) is, within errors, just the same for \( \pi p \) and pp.

ii) The mean multiplicities are higher by a small but statistically significant amount for \( \pi p \) than for pp.

iii) The shapes of the multiplicity distributions, as represented by the parameter \( f_2 \) given in the table, are the same for \( \pi p \) and pp at the same incident energies.

I now want to turn to studies of the processes

\[
\begin{align*}
\text{(1a)} & \quad p + p \rightarrow p + X^+ \\
\text{(1b)} & \quad \pi^- + p \rightarrow p + X^- 
\end{align*}
\]

with incident momenta of 205 GeV/c. Identification of the outgoing protons is by bubble density, so that their laboratory momenta are restricted to be less than 1.4 GeV/c. The experimental data have been reported by Barish et al.\(^1\) [for process (1a)] and by Winkelmann et al.\(^2\) [for process (1b)], and comparisons between the two have been discussed by Winkelmann\(^3\).

Figure 1, taken from Ref. 3, shows a comparison of \( d\sigma / dM_X \), where \( M_X \) is the mass of the recoiling object \( X \) in reactions (1a), (1b), for pp and \( \pi^- p \) collisions, for various multiplicities. Several comments concerning this comparison are in order:

i) From an experimental viewpoint, the two-prong distributions pose a serious problem, namely separation of elastic from inelastic events in the lower part of the diffractive peak. Furthermore, the magnitude of this problem is energy dependent: it gets worse as the energy increases. The distributions in Fig. 1a certainly represent careful work by the groups involved, but the uncertainties are undoubtedly greater than what the statistics of the plots would suggest.

ii) Low-mass diffractive peaks are very strong for two- and four-prong events, fairly evident in six-prong events and small for higher multiplicities. These features are qualitatively similar for pp and \( \pi^- p \) interactions.

iii) Determinations of diffractive cross-sections from data such as those of Fig. 1 suffer from the evident difficulty of separation from non-diffractive background, particularly for high multiplicities.
In Table 3a, we show estimates of cross-sections for production of $X^+$ and $X^-$ in processes (1a), (1b) by diffractive dissociation of the incident beam particles. Non-diffractive background subtraction was roughly estimated and subtracted out\(^1\). In Table 3b we use factorization to estimate the cross-section for nucleon diffraction in the pion interactions and thus compare the total single-diffractive dissociation cross-sections in $\pi^- p$ and $p p$ collisions. It is interesting to note that for both $\pi^- p$ and $p p$ the two-prong and four-prong diffractive cross-sections are nearly equal to each other; and one might speculate that, at high energies, this equality may extend to higher multiplicities. This is what would be expected if the triple-pomeron coupling dominates diffractive dissociation.

Table 3a

<table>
<thead>
<tr>
<th>Single vertex diffractive cross-sections</th>
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<tbody>
<tr>
<td>$pp \rightarrow p + X^+$ $(\text{mb})$</td>
</tr>
<tr>
<td>Two-prong</td>
</tr>
<tr>
<td>Four-prong</td>
</tr>
<tr>
<td>Six-prong</td>
</tr>
<tr>
<td>Eight-prong</td>
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</table>

Table 3b

<table>
<thead>
<tr>
<th>Single diffraction cross-sections</th>
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</thead>
<tbody>
<tr>
<td>$pp \rightarrow [p + X^+] [X^+ + p]$ $(\text{mb})$</td>
</tr>
<tr>
<td>Two-prong</td>
</tr>
<tr>
<td>Four-prong</td>
</tr>
<tr>
<td>Six-prong</td>
</tr>
<tr>
<td>Eight-prong</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

It has been conventional to interpret high-energy multiplicity distributions in terms of so-called two-component models,

$$\sigma(n) = \sigma_D(n) + \sigma_{ND}(n),$$

(2)

where $\sigma(n)$, $\sigma_D(n)$, $\sigma_{ND}(n)$ are the total, diffractive and non-diffractive cross-sections for producing $n$ charged particles. Knowing $\sigma(n)$ directly and
\( \sigma_D(n) [\text{Table } 3] \), one can find \( \sigma_{ND}(n) \) by subtraction. The results at 200 GeV are that (i) \( \sigma_{ND}(n) \) is essentially identical for \( \pi^-p \) and \( pp \) and (ii) \( \sigma_{ND}(n) \) is extremely well-fitted by a Poisson distribution in \( (n - 2)/2 \) [this is the quantity \( n_- \) in \( pp \) analyses] with \( \langle n \rangle = 8.6 \). These pleasing features, which are shown in Fig. 2, certainly tend to support the two-component description.

We now briefly discuss the multiplicities of the objects \( X^+ \) and \( X^- \) in processes (1a) and (1b) as a function of their mass \( M_{X'} \). It has been pointed out\(^1,^2) \) that \( \langle n_{X^+} \rangle \) has nearly the same value at a given \( M_{X^+} \) as \( \langle n \rangle \) produced in a \( \pi p \) or \( pp \) collision has at \( s = M_{X^+}^2 \). However, just as \( (n - 2)/2 \) may be the more relevant variable in the \( \pi p \) or \( pp \) collisions, \( (n_{X^-} - 1)/2 \) might be expected to be the relevant multiplicity variable in the systems \( X^+ \) or \( X^- \).

Figure 3 shows \( \langle (n_{X^+} - 1)/2 \rangle \) versus \( M_{X^+}^2 \) for both processes (1a) and (1b) and compares these with the corresponding curves of \( \langle (n - 2)/2 \rangle \) versus \( s \) for \( \pi p \) and \( pp \) collisions. It is clear that with these multiplicity variables, the average multiplicities of the systems recoiling against the protons are always significantly higher than the over-all multiplicities, comparisons being made at \( M_{X^+}^2 = s \). This is true for both \( X^+ \) and \( X^- \), even though \( X^+ \) from process (1a) is a baryon state and \( X^- \) from process (1b) is a pure meson state.

Somewhat closer examination of the actual distributions of \( (n_{X^+} - 1)/2 \) and \( (n - 2)/2 \) suggests that these differences in average multiplicities may arise from two effects:

i) The diffractive piece (in the two-component model sense) of the \( (n_{X^+} - 1)/2 \) distribution appears to be much smaller, if present at all, than for the \( (n - 2)/2 \) distributions. This is illustrated by the fact that \( f_2 \) for the recoil multiplicities in Fig. 3 remains small rather than rising as for the over-all multiplicities.

ii) The non-diffractive piece of the recoil at a given \( M_{X^+}^2 \) has very roughly a similar multiplicity to the non-diffractive over-all system at \( s = 2M_{X^+}^2 \).

Obviously the \( X^\pm \) systems discussed here can be considered to be produced diffractively only in the mass region \( M_{X^\pm}^2 < 40 \text{ GeV}^2 \); hence we cannot be sure that the above observations, which cover a much larger \( M_{X^\pm}^2 \) range, apply specifically to such diffractively-produced systems (i.e. systems produced in pomeron-p or pomeron-\( \pi \) collisions). Experiments at higher incident energies will be required to resolve this interesting question.

I now want to turn to some remarks concerning the exclusive reactions \( pp \rightarrow ppn^+\pi^- \) and \( \pi^-p \rightarrow \pi^-p\pi^+\pi^- \). The identification of such reactions at energies of the order of a few GeV by kinematic fitting is very straightforward. At 200 GeV, however, the ability to separate background is
substantially reduced, at least in a bubble chamber of 75 cm diameter, and careful attention must be paid to the contributions of that background. Studies of these background contributions have been made, and are continuing, but the conclusion is that with appropriate cuts, samples of events consisting mainly of the $pp\pi\pi$ and $pp\pi^+\pi^-$ final states can be obtained with small and estimable background. The first useful remark is that the cross-sections for these states, namely $680 \pm 140 \mu b$ and $530 \pm 65 \mu b$ respectively, are not much lower than values measured at energies around 20 GeV and are higher than what would be expected from extrapolations of the form $\sigma \sim p^{-n}$ where $p$ is the incident momentum, as expected for diffractive mechanisms. Secondly, the dominant characteristic of these reactions is well illustrated in Fig. 4 which, for the $\pi^-\pi^+\pi^-$ final state, shows a two-dimensional histogram of the $\pi^-\pi^-\pi^+$ mass versus the smaller of the two possible $\pi^+\pi^-$ masses. It is striking that except for a few per cent of the events, all either exhibit a small $\pi^-\pi^-\pi^+$ mass (beam pion dissociation) or a small $\pi^+\pi^-$ mass (target proton dissociation), where "small" means $\lesssim 3.3$ GeV. Figure 5 shows a projection of the $\pi^-\pi^-\pi^+$ mass spectrum, which exhibits a rather clear $A_1$ peak followed by a tail which may include $A_2$ and higher states. It is clear in any case that even at high energy these higher states do not assume a dominant role in this particular reaction, presumably because they decay into systems of higher multiplicity than three pions. The cross-section in the $\pi^-\pi^+\pi^-$ mass range, of 800 to 1200 MeV, namely $160 \pm 40 \mu b$, differs very little from the measured value in the same mass range at 20 GeV of $190 \pm 30 \mu b$, again following the expectations from diffraction remarkably well. Finally, it is worth noting that factorization seems approximately satisfied in that

$$\sigma(pp + pp\pi\pi^-) = 2 \times \frac{\sigma(pp + pp\pi^+\pi^-)}{\sigma(pp + pp\pi^-\pi^+\pi^-)} \times \left[\sigma(\pi^-p + \pi^-p\pi^+)\right]_{\text{target diss.}}$$

where the factor 2 comes from the two-proton dissociation vertices and the last term in brackets is the target dissociation contribution to the $\pi^-p\pi^+\pi^-$ cross-section. The left-hand side is the measured value of $680 \pm 140 \mu b$ and the right-hand side comes out $800 \pm 160 \mu b$, giving reasonable agreement.
REFERENCES

   S. Barish et al., ANL/HEP 7361 (1974).

   G.S. Abrams et al., LBL-2112 (1973), Presented at the APS Division of
   Particles and Fields Meeting, Berkeley (1973).
   Some of the results given in these papers are presently being updated
   with more complete statistics and will undoubtedly be changed slightly.


5) The quoted cross-sections are taken from the papers of Derrick et al.
   and Abrams et al., listed in Refs. 1 and 2 above. More recent analy-
   sis of the π⁻p data may lead to a slight upward revision of that
   cross-section.
Fig. 1 Distributions in missing-mass squared, $M^2$, for $\pi^-p + p + X$ (dashed histograms) and $pp + p + X$ (solid histograms) for inelastic two-, four-, six-, eight- and $\geq$ ten-prong events.
Fig. 2 Non-diffractive multiplicity distributions for $\pi^-p$ and pp at 205 GeV. The solid curve is a Poisson in $(n - 2)/2$ with $(n) = 8.62$. 
Fig. 3 Values of $\langle (n_X - 1)/2 \rangle$ and $f_2[(n_X - 1)/2]$ as a function of $M^2_X$ for both $\pi p$ and $pp$ collisions.

Fig. 4 Plot of $M(\pi^-\pi^-\pi^+)$ versus the lower value of $M(\pi^-\pi^+p)$ in the $\pi^-\pi^-\pi^+p$ final state.
Fig. 5  \( M(\pi^-\pi^-\pi^+) \) spectra in 200 MeV and 50 MeV bins. The shaded events represent a more restrictively chosen sample in which the background is reduced relative to the signal.