pp vs $\bar{p}p$: From Intersecting Storage Rings to Superconducting Supercollider

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The difference between the pp and $\bar{p}p$ elastic $d\sigma/dt$'s found at the CERN intersecting storage rings and the behavior of the $\bar{p}p$ $d\sigma/dt$ at the CERN collider have profound implications for the high-energy behavior of hadron scattering amplitudes. The consequences are shown to be striking in the tetraelectronvolt region.

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All standard models of diffraction scattering,[1] including the recent study of Bourrely, Soffer, and Wu,[2] predict that the differential cross sections for pp and $\bar{p}p$ elastic scattering become indistinguishable by the middle of the energy range ($\sqrt{s} \approx 23.5$–62.5 GeV) of the CERN intersecting storage rings (ISR).

There is now convincing evidence from the ISR for a striking difference of shape between pp and $\bar{p}p$ differential cross sections up to the highest ISR energies.[3] Moreover, the remarkable behavior of $\bar{p}p$ at the CERN collider[4] ($\sqrt{s} = 546$ GeV) does not at all represent a smooth extrapolation of the ISR pp data to collider energies, whereas it does reflect the shape and structure seen in $\bar{p}p$ data at the ISR.

This difference of shape at the ISR energies proves unequivocally that the crossing-odd amplitude is playing an important role in an energy region where, according to conventional wisdom, it should long have been dead and buried.

Donnachie and Landshoff[5] have suggested that the persisting difference between pp and $\bar{p}p$ is due to three-gluon exchange, calculated in pertubative QCD. Their Regge plus three-gluon model fits the ISR data well but fails by an order of magnitude in the shoulder region at $\sqrt{s} = 546$ GeV.

Some years ago it was suggested that the crossing-odd amplitude F_- might remain important at very high energies. An elegant realization of this idea is to make F_-, like F_+, grow as fast with energy as it is permitted to by general asymptotic theorems, thus making the strong interactions "maximally strong."[6]

In the language of the complex J plane this corresponds to the following singularities: (i) for F_+ a triple pole at $J=1$ when $t=0$, associated with the Froissart-Martin bound[7] $\mathrm{Im}F_+ \sim s\ln^2 s$; (ii) for F_- a double pole at $J=1$ when $t=0$, associated with the odderon[8] behavior $\mathrm{Im}F_- \sim s\ln s$.

The t dependence permitted with such energy growth is nontrivial. For example, although the slope grows like $\ln^2 s$ *at* $t=0$, it can only at most grow like $\ln s$ for any fixed $t\neq 0$, *no matter how small.* Auberson, Kinoshita, and Martin (AKM)[9] have given a general representation for amplitudes $F(s,t)$ having Froissart growth. The representation holds equally well for amplitudes with definite crossing symmetry, and in particular for the odderon amplitude.

We have obtained the explicit forms in s and t of the amplitudes with Froissart and odderon behavior satisfying the AKM representation and corresponding to the simplest possible choice of J-plane singularities, namely (R_+ and R_- are constants),

$$f_+(J,t) = \frac{\beta_+(J,t)}{[(J-1)^2 + R_+^2(-t)]^{3/2}}, \tag{1}$$

$$f_-(J,t) = \frac{\beta_-(J,t)}{(J-1)^2 + R_-^2(-t)}, \tag{2}$$

which collapse to the required triple and double poles at $t=0$.

Assuming that the $\beta(J,t)$ are slowly varying in J and have simple exponential behavior in t, we use the Sommerfeld-Watson transform to arrive at the following forms for the Froissart (F) and odderon (O) parts of the amplitudes (note that $\bar{s}$ and $\bar{\tau}$ are complex variables):

$$\frac{1}{is}F_+^{(\mathrm{F})}(s,t) = F_1 \ln^2\bar{s}\, \frac{2J_1(R_+\bar{\tau})}{R_+\bar{\tau}} e^{b_1^+ t} + F_2 \ln\bar{s}\, J_0(R_+\bar{\tau}) e^{b_2^+ t} + F_3[J_0(R_+\bar{\tau}) - R_+\bar{\tau} J_1(R_+\bar{\tau})] e^{b_3^+ t}, \tag{3}$$

$$\frac{1}{s}F_-^{(O)}(s,t) = O_1 \frac{\sin(R_-\bar{\tau})}{R_-\bar{\tau}} e^{b_1^- t} + O_2 \ln\bar{s}\cos(R_-\bar{\tau}) e^{b_2^- t} + O_3 e^{b_3^- t}, \tag{4}$$

where J_n are Bessel functions, F_k, O_k, $b_k^{\pm}$ $(k=1,2,3)$ are constants,

$$\bar{s} \equiv \frac{s}{s_0} e^{-i\pi/2}, \quad \text{with} \quad s_0 = 1\ \text{GeV}^2, \tag{5}$$

and $\bar{\tau}$ is the crossing-symmetric version of the AKM scaling variable

$$\bar{\tau} \equiv \left(-\frac{t}{t_0}\right)^{1/2} \ln\bar{s}, \quad \text{with} \quad t_0 = 1\ \text{GeV}^2. \tag{6}$$

With the addition to these of the contributions of the standard Pomeron and Regge poles and their cuts we have achieved a remarkably good description[10] of all pp and $\bar{p}p$ data (σ_T, ρ, $d\sigma/dt$) in the range $\sqrt{s} = 7.6$ GeV ($p_L = 30$ GeV/c) to $\sqrt{s} = 546$ GeV, for $|t| \lesssim 2.5$ GeV^2. But our prime concern in this Letter is to display results for the high-energy region (ISR to collider) and to draw attention to the striking features that are expected in the tetraelectronvolt region.

In Fig. 1 we compare our results with the ISR data on pp and $\bar{p}p$. The agreement is satisfactory, even when we extrapolate to values of $t \simeq -5$ GeV^2.

It should be remembered that at much lower energies, where pp has only a shoulder, $\bar{p}p$ already shows a sharp dip. The pp dip begins to appear at $p_L \simeq 100$ GeV/c and we see in Fig. 1 how the $\bar{p}p$ dip gradually turns into a shoulder through the ISR region. This facet is seen reinforced in the $\bar{p}p$ data at $\sqrt{s} = 546$ GeV in Fig. 2, where the cross section at the shoulder is an order of magnitude larger than at the ISR.

We note also from Figs. 1 and 2 that beyond the dip-bump region the curves for pp and $\bar{p}p$ approach each other as the energy increases. The reason for this is surprising and amusing. It is the crossing-odd amplitude becoming dominant, resulting in $F_{pp} \simeq -F_{\bar{p}p}$ and thus almost equal $d\sigma/dt$'s in this t region. As an illustration we show the behavior of the amplitudes at $\sqrt{s} = 546$ GeV in Fig. 3.

There emerges an intriguing picture of pp vs $\bar{p}p$ in the tetraelectronvolt region. For very small t the $d\sigma/dt$'s are essentially equal because F_+ dominates and $F_{pp} \simeq F_{\bar{p}p}$. For $|t| \gtrsim 1.2$ GeV^2 we again have almost equal $d\sigma/dt$'s but now because F_- dominates, as explained above.

Finally, we note from Fig. 2 that the structure between these two regions of t becomes more and more complex with energy: (i) The dip in pp sharpens and moves towards smaller t roughly like $1/\ln^2 s$, while $\bar{p}p$ begins anew to develop a dip, which also moves inwards roughly like $1/\ln^2 s$. The fact that the movement

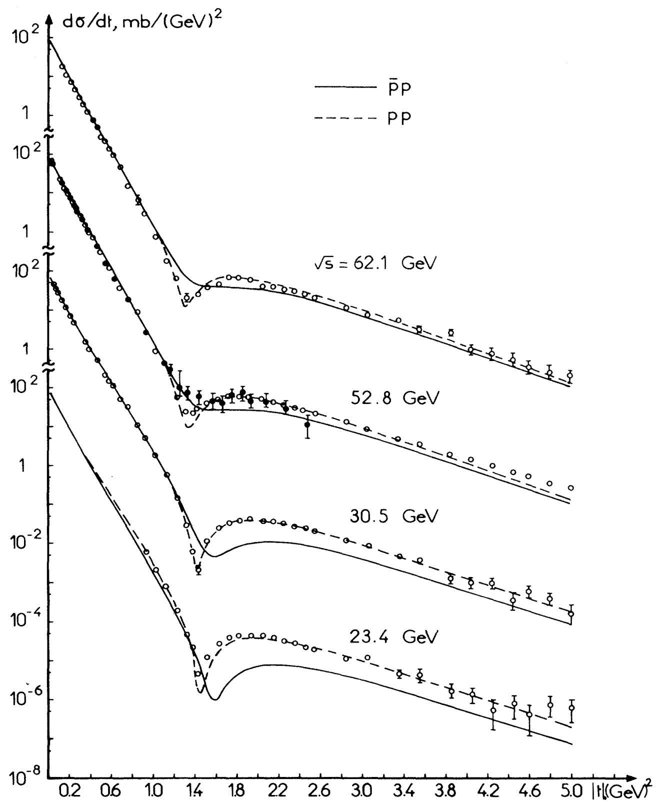

FIG. 1. Comparison between our results and the ISR data on pp and $\bar{p}p$ differential cross sections (Refs. 3 and 11).

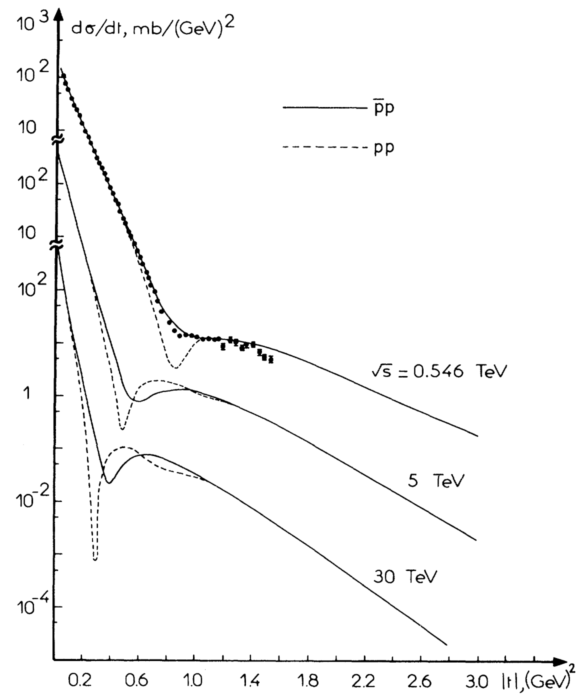

FIG. 2. Our predictions for the pp and $\bar{p}p$ differential cross sections in the tetraelectronvolt region. The recent UA4 experimental results at $\sqrt{s} = 0.546$ TeV (Refs. 4 and 12) are also shown.

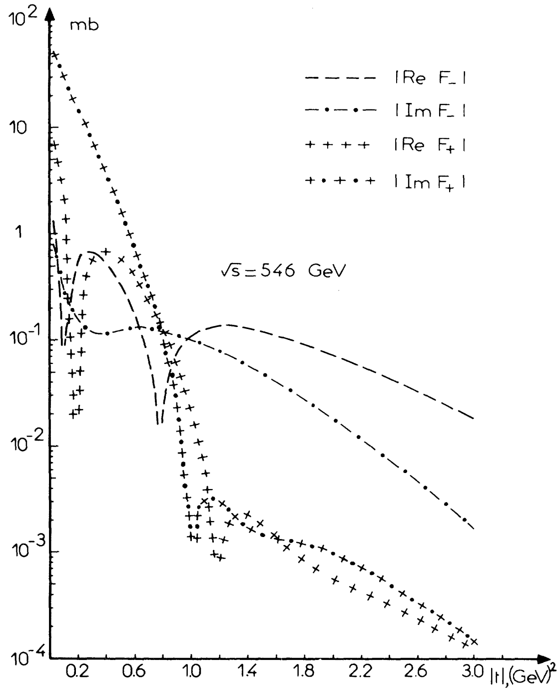

FIG. 3. The behavior of the real and imaginary parts of the crossing-even and crossing-odd amplitudes (all divided by s), defined by Eqs. (3)–(6), at $\sqrt{s} = 546$ GeV.

of the dip is not exactly $1/\ln^2 s$ indicates that the asymptotic regime is very remote, in agreement with the conclusions already drawn from an analysis of the forward data.[13] (ii) The difference between the two $d\sigma/dt$'s shows an increasing number of oscillations.

If our interpretation is correct, this phenomenon of activity in the dip region will persist for all energies.[14]

It would be fascinating to search for this behavior using *pp and* $\bar{p}p$ supercolliders.

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[1]T. T. Chou and C. N. Yang, Phys. Rev. D **19**, 3268 (1979), and Phys. Lett. **128B**, 457 (1983); H. Cheng and T. T. Wu, Phys. Rev. Lett. **24**, 1456 (1970); H. Cheng, J. K. Walker, and T. T. Wu, Phys. Lett. **44B**, 97 (1973).

[2]C. Bourrely, J. Soffer, and T. T. Wu, Nucl. Phys. **B247**, 15 (1984), and Phys. Rev. Lett. **54**, 757 (1985).

[3]A. Breakstone *et al.*, CERN Report No. CERN/EP 85-9, 1985 (to be published).

[4]M. Bozzo *et al.*, CERN Report No. CERN/EP 85-31, 1985 (to be published)

[5]A. Donnachie and P. V. Landshoff, Nucl. Phys. **B231**, 189 (1983), and private communications.

[6]L. Lukaszuk and B. Nicolescu, Nuovo Cimento Lett. **8**, 405 (1973).

[7]M. Froissart, Phys. Rev. **123**, 1053 (1961); A. Martin, Phys. Rev. **129**, 1432 (1963), and Nuovo Cimento **42A**, 930 (1966).

[8]P. Gauron, E. Leader, and B. Nicolescu, Phys. Rev. Lett. **52**, 1952 (1984); for a recent review of the odderon problem see B. Nicolescu, in *Proceedings of the Seventh European Symposium on Antiproton Interactions, Durham, United Kingdom, 1984,* edited by M. R. Pennington, Institute of Physics Conference Series No. 73 (Hilger, London, 1985) pp. 411–419.

[9]G. Auberson, T. Kinoshita, and A. Martin, Phys. D **3**, 3185 (1971).

[10]Details concerning numerical results and description of the data at lower energies will be presented elsewhere.

[11]G. Barbiellini *et al.*, Phys. Lett. **39B**, 663 (1972); A. Bohm *et al.*, Phys. Lett. **49B**, 491 (1974); N. Kwac *et al.*, Phys. Lett. **58B**, 233 (1975); H. de Kerret *et al.*, Phys. Lett. **68B**, 374 (1977); U. Amaldi *et al.*, Phys. Lett. **66B**, 390 (1977); L. Baksay *et al.*, Nucl. Phys. **B141**, 1 (1978); E. Nagy *et al.*, Nucl. Phys. **B150**, 221 (1979); A. Breakstone *et al.*, Nucl. Phys. **B248**, 253 (1984); S. Erhan *et al.*, Phys. Lett. **152B**, 131 (1985).

[12]M. Bozzo *et al.*, Phys. Lett. **147B**, 385 (1984).

[13]P. Gauron and B. Nicolescu, Phys. Lett. **143B**, 253 (1984).

[14]This does not contradict the theorem of H. Cornille and A. Martin, Phys. Lett. **40B**, 671 (1972), since there is still a region $|t| < \text{const}/\ln^2 s$ where the ratio $[d\sigma(\bar{p}p)/dt]/[d\sigma(pp)/dt] \rightarrow 1$ as $s \rightarrow \infty$.