Antiproton–proton colliders and Intermediate Bosons

Phase-space cooling makes p̄p colliders practical; CERN and Fermilab plan to use them to find and measure the properties of the Intermediate Vector Bosons.

David Cline and Carlo Rubbia

The development of particle accelerators in the 1920–30's was strongly influenced by the availability of intense sources of ions as well as the ability to shape magnetic fields and to produce high electric fields. Later, electron synchrotrons required intense electron sources. Still later the development of electron–positron colliding-beam machines required positron sources. At present CERN and Fermilab are developing intense sources of antiprotons and related beam-cooling techniques needed to make intense sources. We expect these antiproton sources to influence the development of future particle accelerators and storage rings just as profoundly as ion, electron and positron sources have in the past. One immediate use for the antiprotons is the creation of high-energy antiproton–proton colliders.

CERN is building an antiproton–proton collider that will have 270 GeV in each beam. This collider is scheduled to be operating in summer 1981. The Antiproton Accumulator at CERN (figure 1) cooled its first proton beam early last month. Fermilab plans to build an antiproton–proton collider that will have 1000 GeV in each beam. The energy available with these colliders is expected to be for the first time large enough to cross the threshold for creation of intermediate vector bosons, expected to have a mass in the range 80–90 GeV.

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The development of intense sources of antiprotons will undoubtedly provide for other experiments as well. One can search for bound states of baryons and antibaryons (baryonium). At CERN a storage ring—the Low-Energy Antiproton Ring—is being developed. This ring will use the intense source of antiprotons and provide for antiproton collisions with resting protons. Other areas of research may be affected; for example, it will be possible to accelerate antiprotons in a high-energy synchrotron to 400–1000 GeV, extract the beam and allow it to strike a target, as is routinely done for proton synchrotrons.

To estimate the rate of production of intermediate vector bosons, we must calculate the luminosity of an antiproton–proton collider. The luminosity is given by

$$L = \frac{N_{\bar{p}}(f\gamma)(\Delta\nu)_{\max}}{r_p\beta^*}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

where β^* is related to the size of the beams at the interaction point, $N_{\bar{p}}$ is the total number of antiprotons, $(\Delta\nu)_{\max}$ is the maximum tune shift due to beam–beam interaction, r_p is the classical proton radius and $f\gamma$ is the revolution frequency f, times the Lorentz factor for the beam. The rate of interactions is given by $L\sigma$ where σ is the cross section for the collision. The tune shift due to beam–beam interactions is given by

$$(\Delta\nu)_{\max} = \frac{r_p N_{\bar{p}}}{n_b\epsilon}$$

where n_b is the number of bunches in the machine and ϵ is the invariant emittance of the beam.

Table 1 compares the various values of these parameters for the antiproton–proton colliders under construction or being discussed. To obtain a high luminosity, the total number of antiprotons produced by the source must be greater than 10^{11}. The collection of such a large number of antiprotons poses an extremely difficult technical problem.

Consider the yield of antiprotons from a beam of high-energy protons striking a target:

$$\frac{N_{\bar{p}}}{N_p} = \frac{1}{\sigma_0}E\frac{d^3\sigma}{dp^3}(p\Delta p)\Delta\Omega(\epsilon_1)(\epsilon_2)$$

where ϵ_1 is the factor for absorption in the target, $\Delta\Omega$ the collection solid angle, ϵ_2 is the target efficiency, p the momentum of the proton beam and $Ed^3\sigma/dp^3$ the invariant production cross section.

The invariant antiproton production cross section has been measured at different incident energies (figure 2). Above 100 GeV the increase in cross section is small. The optimum yield occurs for antiprotons produced at rest in the center of mass of the collision. A reasonable estimated cross section is

$$E\frac{d^3\sigma}{dp^3} \sim 1\ \mathrm{mb/GeV}^2$$

and for the case of a feasible storage ring to collect the antiprotons with acceptance $\epsilon_x \sim \epsilon_y \sim 100$ mm-mr and momentum acceptance $\Delta p/p = \pm 2\%$, the ratio of antiprotons to protons interacting in the target

$$N_{\bar{p}}/N_p = 9\times10^{-6}$$

For $N_p = 4\times10^{12}$/sec at CERN or Fermilab, this gives 4×10^7 p̄/second and

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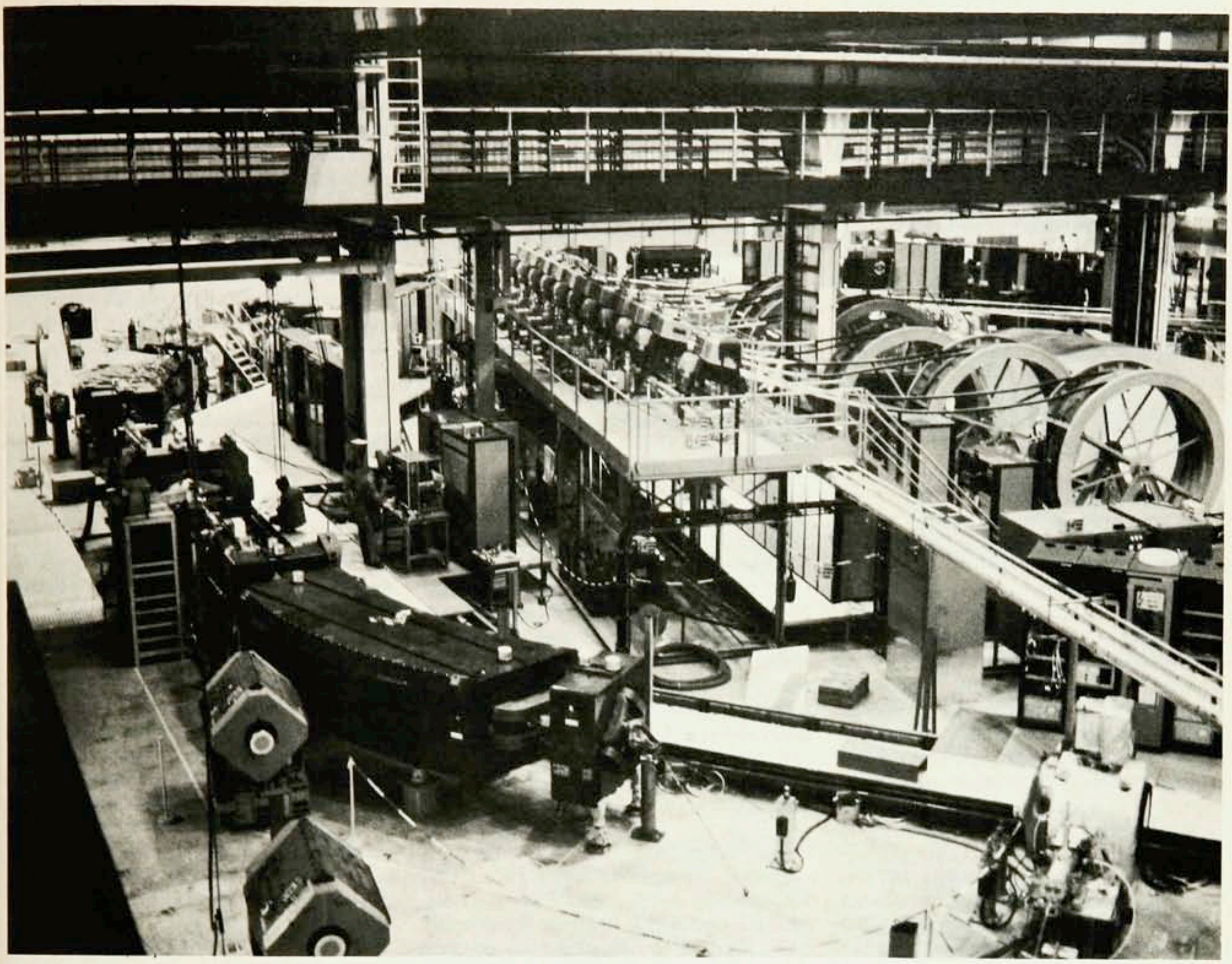


Antiproton Accumulator at CERN cooled its first proton beam early in July. After cooling, the antiprotons are accelerated, first to 26 GeV/c, then to 270 GeV/c. They then collide with a 270-GeV/c proton beam. Figure 1

greater than 5×10^{11} $\bar{p}$/day.

Thus the accumulation of large numbers of antiprotons is feasible provided a method of storing the large number of individual pulses is devised. Because high-energy protons are required, the number of locations at which intense sources of antiprotons can be produced is limited at present.

The accumulation of a large number of antiprotons requires phase-space compression because after a few injections of antiprotons, nearly any conceivable storage ring will have its phase space completely filled. In addition the transverse temperature $T_\perp$ must be reduced. The average transverse temperature of antiprotons produced by proton beams is

$$kT_\perp = \tfrac{1}{2}mv_\perp{}^2 + \frac{(\Delta p_\perp)^2}{2m_p}$$

$$\langle \Delta p_\perp \rangle \sim 300\ \mathrm{MeV}/c$$

and thus

$$T_\perp \simeq 5\times10^6\,\mathrm{eV}$$

The transverse temperature accepted by a high-energy storage ring is

$$T_\perp \simeq 1.2\times10^4\ \mathrm{eV}$$

Two phase-space cooling techniques to reduce the transverse temperature of a beam have been developed—electron cooling[1] and stochastic cooling.[2] The use of these techniques is fundamental to the collection of antiprotons.

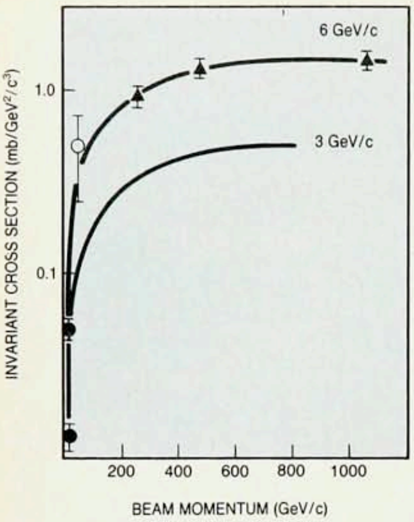
The general scheme for antiproton–proton colliders is to focus high-energy protons on a target; the antiprotons produced are then transported to a storage ring (cooling ring), which provides for cooling of the transverse and longitudinal temperatures of the $\bar{p}$ beams and also provides for storage of the accumulated antiprotons. Once greater than 10^{11} $\bar{p}$ are collected, they are accelerated and injected along with protons into a high-energy storage ring for antiproton–proton collisions.

Phase-space cooling

The beams of particles stored in accelerators are largely subject to Liouville's theorem because they are under the influence of conservative forces. Simply put, Liouville's theorem states: "Under the action of a force that can be derived from a Hamiltonian, the motion of a group of particles is such that the local density of the representative points in phase space remains everywhere constant." However, it is possible to introduce "non-Liouvillian" processes into a beam, and this is what is meant by "beam cooling." Table 2 lists the kinds of Liouvillian and non-Liouvillian forces that we know of. Stochastic cooling is not included in the table because it results from fluctuations.

The beam can be described by a temperature and entropy as well. When two beams are brought together the laws of thermodynamic events can be applied; this is the basic concept for electron cooling.

The suggestion of electron cooling came from Gersh I. Budker many years ago, and it is schematically shown[1] in figure 3. Suppose that a "hot" proton or antiproton beam circulates in a storage ring. The temperature is meant to be related to the average residual energy in the frame of reference of the ideal particle of the equilibrium orbit. Suppose that "cold"



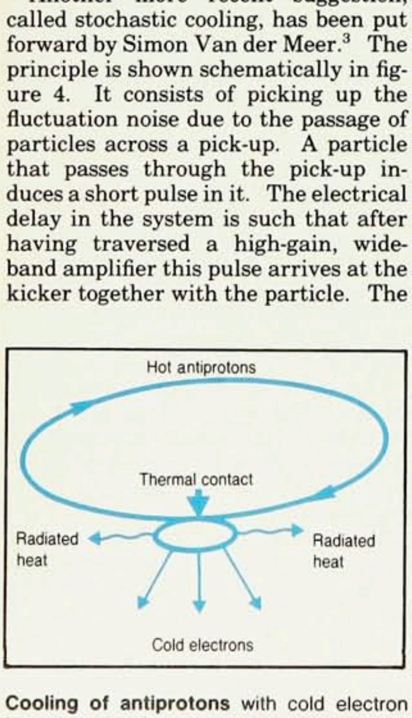
Antiproton production as a function of incident proton energy. Above 1000 GeV the increase in cross section is small. Figure 2

electrons are put in "thermal" contact with the protons. To ensure a thermal contact with no additional "friction," electrons must have the same average (vector) velocity as the heavy particles throughout the cooling section. This means $\langle v_e \rangle = \langle v_p \rangle$ or equivalently

$$\langle E_e \rangle = \frac{m_e}{m_p} \langle E_p \rangle \simeq \frac{1}{1830} \langle E_p \rangle$$

The "heat" is then removed by the electrons, which are either produced cold enough or radiate their acquired heat away by synchrotron radiation.[2]

Another more recent suggestion, called stochastic cooling, has been put forward by Simon Van der Meer.[3] The principle is shown schematically in figure 4. It consists of picking up the fluctuation noise due to the passage of particles across a pick-up. A particle that passes through the pick-up induces a short pulse in it. The electrical delay in the system is such that after having traversed a high-gain, wide-band amplifier this pulse arrives at the kicker together with the particle. The kicker is designed to correct for the deviation of the particle from the equilibrium orbit. At the same time, other particles also produce pulses. They are not infinitely narrow, due to the finite system bandwidth; so some of them will also influence the particle under consideration. The mean effect of this noise will be zero if the system does not transmit the dc component. It will, however, lead to an increase in the rms deviation of the beam. Because the pulse duration is quite short compared to the revolution time and because different particles have different revolution times, each particle will be influenced by a small and continuously changing factor contributed by the other particle. The quasi-random effect has been analyzed quantitatively, and it was found that the blow-up is similar to the one due to purely random kicks. That is, the mean square spread is proportional to time and to the square of the electronic gain. The proportionality factor depends on the amount by which particles overtake each other at each turn. Therefore, because the damping factor on the particle is linearly proportional to time and electronic gain, there is always a sufficiently low gain at which the "cooling" action overtakes the "heating" action due to random noise.



Cooling of antiprotons with cold electron beam occurs when electrons have the same average velocity as the antiprotons. The electrons remove the "heat." Figure 3

Electron cooling

Let us consider in more detail the idealized case of a massive particle (such as a proton or antiproton) slowing down due to the longitudinal component of the momentum transfer from collisions with electrons. We consider first the collision between an electron of initial velocity $\mathbf{v}_e$ and a particle of initial velocity $\mathbf{v}_p$. We shall also assume that $\mathbf{v}_e$ and $\mathbf{v}_p$ have the same order of magnitude and that they are both much smaller than c. Then in the center of mass of the collision, the particle ($m_p >> m_e$) is essentially at rest,

$$\mathbf{v}_{cm} = \frac{m_e \mathbf{v}_e + m_p \mathbf{v}_p}{m_e + m_p} \simeq \mathbf{v}_p$$

and we can describe the scattering as classic Rutherford scattering of the electron on a fixed potential.

We can easily evaluate the longitudinal momentum transfer to the particle per unit of time. After integrating over all momentum transfers and electron velocities, we get the final expression for the drag force **F**:

$$\mathbf{F} = \frac{2\pi e^4 L n_e}{m_e} \int d\mathbf{K}_e f(\mathbf{v}_e) \frac{\mathbf{v}_e - \mathbf{v}_p}{|\mathbf{v}_e - \mathbf{v}_p|^3}$$

where L, the Coulomb logarithm, $= \log q^2_{max}/q^2_{min} \simeq 20$; e, m_e are the charge and mass of the electron respectively and $f(\mathbf{v}_e)$ is the electron velocity distribution.

The simple two-component plasma relaxation picture is used to obtain some general guidelines for the case $|\mathbf{v}_p| >> |\mathbf{v}_e|$. There are both theoretical and experimental reasons to expect that this picture gives a reasonable description of at least the (initial) part of the process.

A simplified formula for the cooling time can be derived for the electron velocity distribution of a δ-function ($\mathbf{v}_p >> \mathbf{v}_e$), equivalent to the point-charge approximation of the electrostatic analog. The drag force becomes:

$$\mathbf{F} = -\frac{2\pi e^4 L n_e}{m_e} \frac{\mathbf{v}_p}{|\mathbf{v}_p|^3}$$

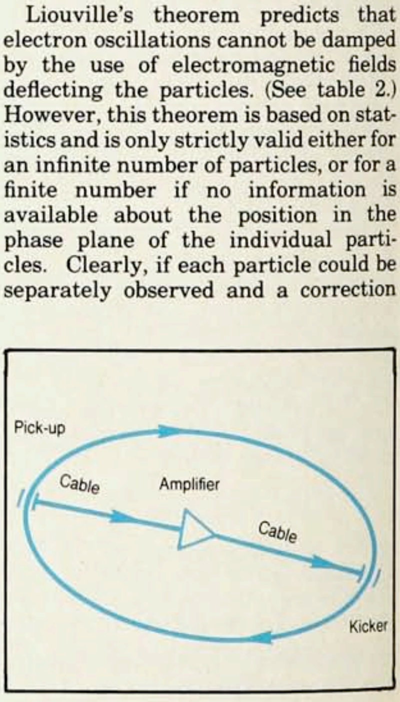
The formula for the cooling time τ in the laboratory frame is

$$\tau = \frac{1}{6\pi} \frac{e\beta\gamma^2}{r_p r_e j L \eta} \left[\frac{p^*}{m_p} \right]^3$$

where β,γ are the usual relativistic factors of the average electron speed; j is the electron current density; η is the fraction of the time the particle is traversing the electron beam and $\mathbf{p}^*$ is the effective initial particle momentum in the electron frame. For pure longitudinal cooling $p^* = \Delta p/\gamma$, where Δp is the deviation from the momentum of one of the equilibrium particles with the orbit. Note that the cooling time increases very rapidly with p^*; thus electron cooling is really only effective for low-energy antiprotons. (However at very high energy a special circumstance makes electron cooling effective again.[2])

Stochastic cooling

Liouville's theorem predicts that electron oscillations cannot be damped by the use of electromagnetic fields deflecting the particles. (See table 2.) However, this theorem is based on statistics and is only strictly valid either for an infinite number of particles, or for a finite number if no information is available about the position in the phase plane of the individual particles. Clearly, if each particle could be separately observed and a correction



Stochastic cooling. The kicker corrects for the deviation of a particle from the equilibrium orbit, and beam cooling occurs. Figure 4 applied to its orbit, the oscillations could be suppressed. It is well known that coherent betatron oscillations (where the beam behaves like a single particle) can be damped by means of pickup-deflector feedback systems. In the same way, the statistical fluctuations of the average beam position, caused by the finite number of particles, can be detected with pickup electrodes and a corresponding correction applied. In other words, the small fraction of the oscillations that happens to be coherent at any time due to the statistical fluctuations can be damped.

A special trick, the notch filter, has been invented at CERN to increase the damping of the beam considerably.[4] In the notch filter method, information regarding a particle's momentum is obtained through its relationship with its revolution frequency. A filter system in the pickup-kicker chain appropriately conditions signals to accelerate or decelerate particles toward a specific rotation frequency (that is, momentum). A useful filter element for this purpose is a shorted transmission line whose length corresponds to half the rotation period. Such an element exhibits "zeros" in its input impedance at all harmonics of the rotation frequency. The resultant transfer functions of such an element, when used in a voltage-divider configuration, appears as a series of notches, hence the term "notch filter."

Cooling measurements

Over the past few years beam cooling measurements have been made at Novosibirsk,[5] CERN[6,7] and Fermilab, and the theory of both stochastic and electron cooling has improved.[4,8] The pioneering Novosibirsk measurements demonstrated electron cooling for the first time. Recent measurements at CERN fully confirm the Novosibirsk results.[7] An electron cooling experiment is also being carried out at Fermilab,[9] where construction of a special cooling ring started in 1977. Recently both the momentum spread and transverse beam dimensions were stochastically cooled in this ring by a Lawrence Berkeley Lab group.

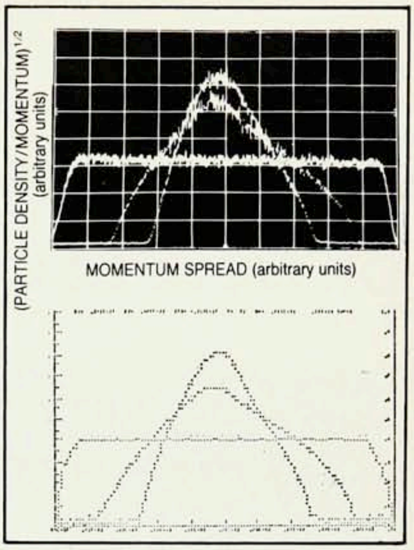
Very important cooling results have been obtained from the Initial Cooling Experiment ring at CERN,[7] which was specifically constructed to study both stochastic and electron cooling. The observed stochastic cooling of the beam momentum is compared with the theory of stochastic cooling in figure 5. The excellent agreement between theory and measurements gives confidence that the antiproton collection rings at CERN and Fermilab will work.

The characteristics of the phase-space cooling techniques are quite different and complementary. Stochastic cooling is relatively independent of the beam energy but less effective at high beam intensity. Also the cooling of transverse beam dimensions is expected to be very slow. Unlike stochastic cooling, electron cooling mainly is effective for low-energy beams, and the cooling time is relatively independent of the beam intensity. Transverse beam cooling is very fast and effective.

CERN and Fermilab colliders

The CERN antiproton–proton collider[10] (figure 6) now under construction accepts a fixed antiproton beam energy—3.5 GeV/c. These are produced with a momentum spread of 0.7×10^{-2} by 27 GeV/c protons from the Proton Synchrotron. The antiprotons are transferred to a very large aperture storage ring—the Antiproton Accumulator—cooled rapidly (a few seconds) in momentum space and slowly in transverse phase space by stochastic cooling. (The Antiproton Accumulator, which was just finished, only two years after it was approved, has properties very similar to those made in our 1976 proposal[11] to convert existing synchrotrons into colliders.) After $1\text{–}5 \times 10^{11}$ $\bar{p}$ are collected, they are transferred into the Proton Synchrotron, accelerated to 26 GeV/c, bunched and injected into the Super Proton Synchrotron. Meanwhile protons are injected into the SPS at 26 GeV/c. Both the proton beam and the antiproton beam are accelerated to 270 GeV/c each and then collide at Section F in the SPS, where a large experimental detector will be placed. Early in July the Antiproton Accumulator cooled its first proton beam, and by mid-July antiproton injection was expected.

The Fermilab antiproton–proton collider[12] (figure 7) uses two sequences: precooling to reduce the initial phase space and freezing to produce very cool beams for storage.[13] The Main Ring will accelerate 1.8×10^{13} protons to 80 GeV, extract and aim them at an antiproton production target. The antiprotons are then collected in a large-aperture Precooler ring, roughly the same size as the present Booster ring. The antiprotons, at 4.5 GeV with a transverse emittance of 4.8 mm-mrad in each plane and momentum spread of $\pm 2\%$, are stochastically momentum cooled by a factor of about a hundred in several seconds. This occurs in three or four steps; each time cooling is followed by some deceleration. Then the cooled beam is decelerated to 200 MeV,



Stochastic cooling of momentum as a function of time in the Initial Cooling Experiment at CERN. Experimental results (top) show square root of particle density in momentum space increases as the beam is cooled. Theoretical calculation (bottom) agrees well with the experiment. Figure 5

Table 1: Parameters for Three Antiproton–Proton Colliders

	γ	$f\gamma$	β^*(m)	Δ_{max}	L (cm^{-2} sec^{-1})	N_p
CERN SPS $\bar{p}p$ Collider	2.7×10^2	1.3×10^7	1.5	2×10^{-3}	10^{30}	6×10^{11}
Fermilab Tevatron $\bar{p}p$ Collider	10^3	5×10^7	1.5	2×10^{-3}	4×10^{30}	5×10^{11}
5–10 TeV $\bar{p}p$ Collider at CERN or Fermilab		10^8	2	5×10^{-3}	10^{32}	5×10^{12}

Table 2: Liouville's Theorem Applied to Particle Beams

Liouvillian	Non-Liouvillian
External fields	*Dissipative forces*
Time periodic	Synchrotron radiation
Constant magnetic or electric fields	*dE/dX* in thin foils
Long-range forces	*Single-particle collisions or decay*
Beam–beam interactions	H^- injection into accelerators
Space-charge effects	$\Lambda/\bar{\Lambda}$ decays
Plasma oscillations	Electron cooling

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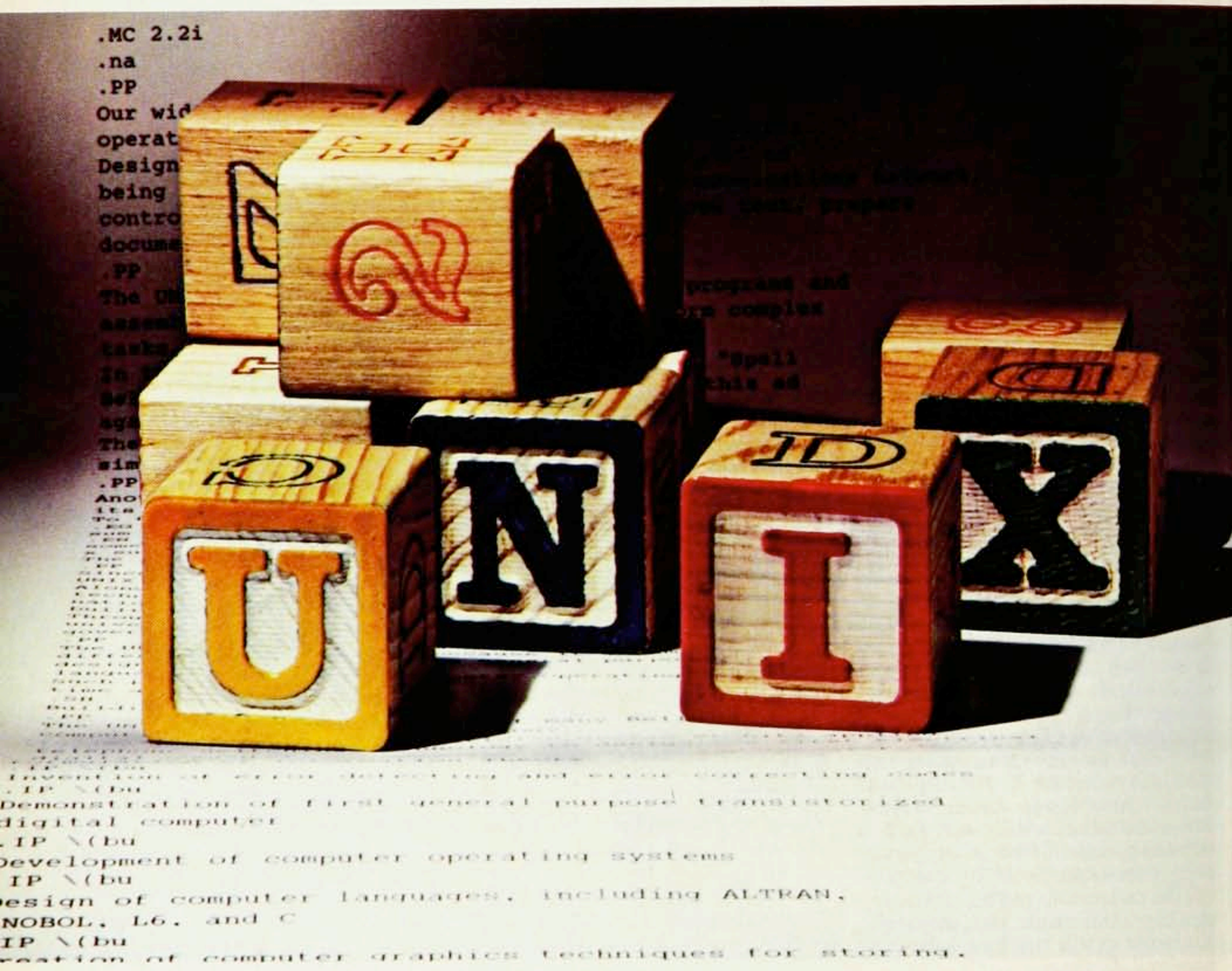

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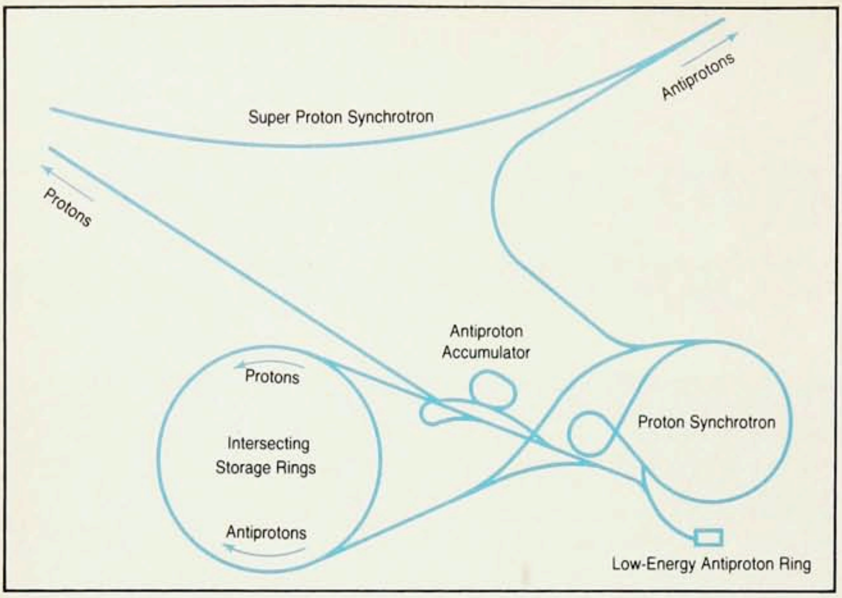


CERN p̄p collider. Antiprotons are cooled in the Antiproton Accumulator, collected, transferred to the Proton Synchrotron, accelerated to 26 GeV/*c*, bunched and sent to the Super Proton Synchrotron. Meanwhile 26-GeV protons are injected into the SPS at 26 GeV/*c*. Both beams are then accelerated to 270 GeV/*c* and allowed to collide. Figure 6

bunched and transferred to the Freezer. Here the antiprotons are cooled further while more antiprotons are added. When some 10^{11} antiprotons have been obtained, they will be transferred back to the Precooler, reaccelerated to 8 GeV and then injected into the Main Ring. After further acceleration, the antiprotons are transferred into the Superconducting Ring. Protons are accelerated in the conventional fashion in the Main Ring and transferred to the Superconducting Ring. Then both beams are simultaneously accelerated to collision energy.

The target station and Freezer are already under construction as part of the Fermilab R&D program. The $18-million (including contingencies and escalation) Precooler is being designed and is scheduled for completion in 1983. The Precooler is part of the Tevatron I package, which is in the DOE FY 1981 budget request. This package also includes the refrigeration and experimental areas needed for p̄p collisions at 1000 GeV on 1000 GeV.

The Fermilab research and development project is a collaboration of Argonne National Laboratory, Lawrence Berkeley Laboratory, Fermilab, Institute for Nuclear Physics at Novosibirsk, USSR and the University of Wisconsin.

Table 3 compares the parameters of the CERN and Fermilab schemes. Note that both machines are expected to reach a luminosity of 10^{30} cm^{-2}sec^{-1}. This appears to be adequate to carry out an exciting research program at CERN and Fermilab. However, considerable experience is likely to be required with these systems before the higher luminosity is reached.

Table 3: Properties of the CERN/Fermilab Schemes

	Fermilab	CERN
Energy (GeV)	1000	270
Number of protons (N_p)	1.2×10^{12}	6×10^{11}
Number of antiprotons ($N_{\bar{p}}$)	10^{11} (5 h)	6×10^{11} (24 h)
Number of bunches	12	6
Low beta at interaction $\beta^* = \sqrt{(\beta_x\beta_y m)}$	1.5	2.2
Proton emittance, horizontal (mrad)	$2.6\pi\times10^{-8}$	$3.5\pi\times10^{-8}$
Proton emittance, vertical (mrad)	$2.6\pi\times10^{-8}$	$3.5\pi\times10^{-8}$
Antiproton emittance, horizontal (mrad)	$1.0\pi\times10^{-8}$	$3.8\pi\times10^{-8}$
Antiproton emittance, vertical mrad)	$1.0\pi\times10^{-8}$	$1.9\pi\times10^{-8}$
Luminosity (cm^{-2} sec^{-1})	$>10^{30}$	10^{30}

Intermediate Vector Bosons

When the first p̄p machine operates it will be the beginning of the study of ultra high-energy interactions and very likely of the weak interaction at very high energy. Hideki Yukawa first predicted in the mid-1930's that the exchange of a massive object could be responsible for the weak force.[14] These particles have been named the Intermediate Vector Boson. The gauge theory of Sheldon Glashow, Steven Weinberg and Abdus Salam,[15] which received remarkable support with the discovery of weak neutral currents[16] at CERN and Fermilab in 1973, incorporated three intermediate bosons—W^+, W^- and Z^0— and provides predictions for the static and dynamic properties of these particles. It is crucial that these properties be measured by some technique. Table 4 gives a list of these properties, using the current experimental estimates of the Weinberg angle.

We now turn to the mechanism of producing such massive bosons in high-energy collisions. The intermediate vector boson particles decay by the channels

$$Z \rightarrow \text{lepton} + \text{antilepton}$$
$$Z \rightarrow \text{quark} + \text{antiquark}$$

Thus the inverse process, the fusion of $\bar{\ell}\ell$ or $\bar{q}q$, provides a reaction to produce the intermediate vector boson, and very high energy e^+e^- or quark–antiquark collisions can result in IVB production.[13,17,18] Antiproton–proton collisions involve copious quark–antiquark collisions and thus provide a mechanism for production of the IVB.

However, to study the complete properties of the IVB it is necessary to produce the IVB in reactions other than quark–antiquark fusion as well. Figure 8 shows the processes that we expect will be crucial to discover and measure the properties of these particles. The cross sections for these reactions have been calculated by several groups and are shown[17] in figure 9. These calculations illustrate that antiproton–proton colliders have several characteristic advantages in this regard. A p̄p collider with luminosity 10^{30}–10^{31} cm^{-2}sec^{-1} results in copious numbers of IVB per day. (See figure 7.) Two such properties, among others, are observable:

► $\bar{p}p \rightarrow W^{\pm} + \text{all}$. Measurement of the decay lepton with respect to the beam direction will show a forward–backward asymmetry.[18]

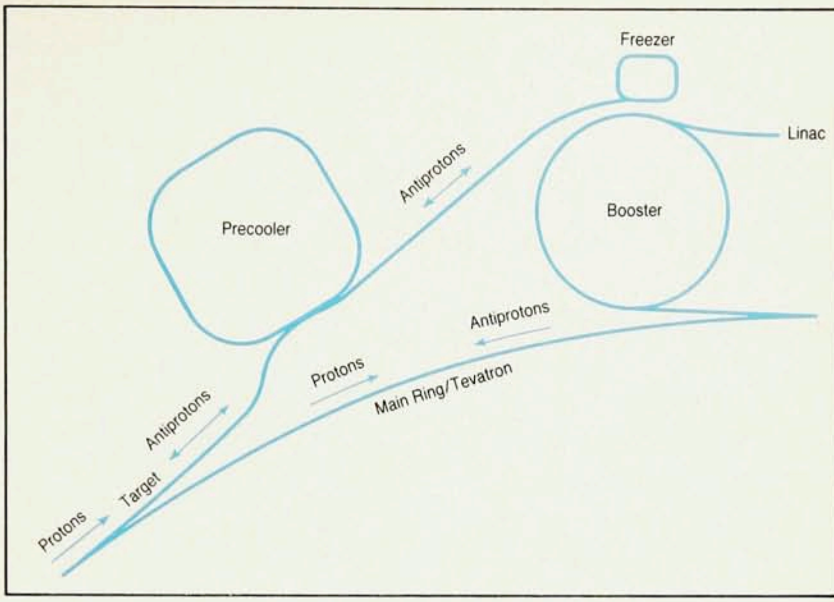
► $\bar{p}p \rightarrow W^{+} + \gamma + \text{all}$. Measurement of the photon angular distribution with respect to the $\bar{p}$ direction is sensitive to the anomalous magnetic moment of the W.[19]

Table 4 lists the other properties of the IVB that are to be measured. In nearly all cases it appears that these measurements are accessible to experimental techniques using the antiproton colliders being constructed at CERN and Fermilab. Note that the IVB pair production is predicted to rise. (See figure 7.)[20]

The Higgs Boson plays a crucial role in the gauge theory because it is necessary to eliminate several infinities. Unfortunately the mass and decay modes are not yet well defined.

The next generation of antiproton–proton collider should provide an even greater "source" of IVB's and thus allow more refined measurements of the properties of these particles. We believe that these machines are almost unique to the study of the IVB in much the same way as special rings have been built to study the $(g-2)$ of the electron and muon.

Special particle detectors covering nearly 4π solid angle are necessary to detect and study the properties of the IVB. Unfortunately we have no space to describe these detectors except to note that such detectors are in an advanced stage of construction at CERN. One such detector, the UA1 detector, is expected to be quite "universal" and well matched to "W/Z physics." It employs a large dipole magnetic field and complete particle tracking as well as electron and muon identification and momentum measurements.



Fermilab p̄p collider. Antiprotons at 4.5 GeV are stochastically cooled in the Precooler, decelerated to 200 MeV, bunched and sent to the Freezer, where they are further cooled. The antiproton beam is then sent back to the Precooler, reaccelerated to 8 GeV and sent to the Main Ring. After further acceleration, the beam goes to the Superconducting Ring. Meanwhile a proton beam is accelerated and transferred to the Superconducting Ring, where it collides with the antiproton beam. Figure 7

Future antiproton–proton colliders

The antiproton–proton colliders now under construction at CERN and Fermilab were first suggested to allow the discovery of the intermediate vector bosons and to study their properties.[11] In that case it was shown that a luminosity of roughly 10^{30} cm^{-2} sec^{-1} provides an adequate event rate, if suitable detectors are employed. This goal has been incorporated as a design criterion for the two machines being constructed. If higher energy p̄p colliders are to be constructed the design luminosity must be set by either physics goals or by the inherent limitations in the luminosity that can be achieved in such machines. This limitation may arise from beam–beam interaction or from the total intensity of the antiproton source.

Consider first the expected cross sections for high-energy pointlike reactions

$$\sigma^{w}_{pt} \simeq \frac{4\pi\alpha^2}{3Q^2} \simeq \frac{87}{s} \times 10^{-33}\ \text{cm}^2$$

for the electro-weak cross section where s is the center-of-mass energy squared for the collision and α the fine-structure constant. For strong interaction cross sections

$$\sigma^{s}_{pt} \simeq \left(\frac{\alpha_s}{\alpha}\right)^2 \left(\frac{87}{s}\right) \times 10^{-33}\ \text{cm}^2$$

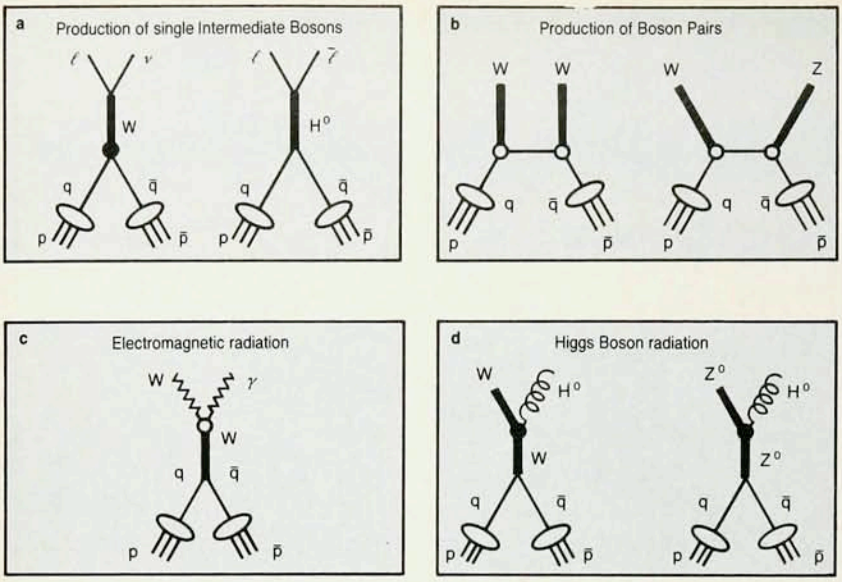
where α_s is the strong-interaction coupling constant and $(\alpha_s/\alpha)^2 >> 1$. The cross section falls rapidly with center-of-mass energy, and the luminosity of a p̄p machine required to produce one event per day for $\sqrt{s} = 10$ TeV is 10^{32} cm^{-2} sec^{-1}.

There is an obvious moral to all this—high-energy p̄p machines should provide for the production of W and Z with modest luminosity but may need high luminosity to reach into new areas of very high momentum transfer pointlike collisions, where new physics may be hiding.

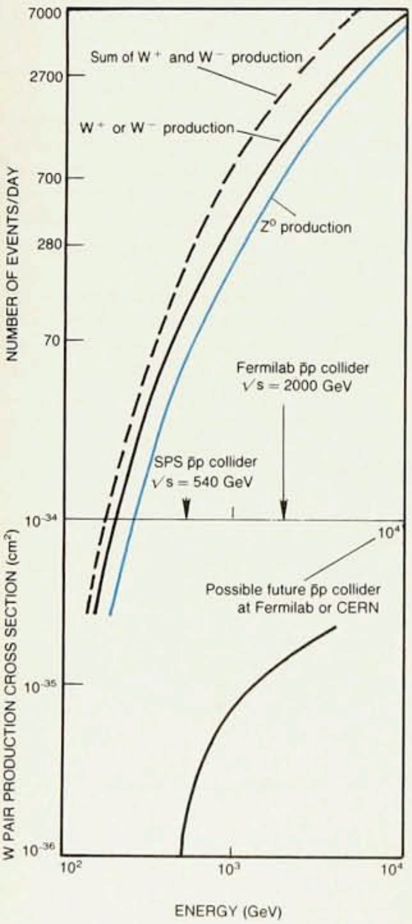
Table 1 gives a comparison of the luminosity of a machine at 5–10 TeV with that of the present generation of machines. Such machines could be

Table 4: Properties of Intermediate Bosons

Boson	Property	Prediction from SU(2)×U(1) theory	Technique to measure	Expected resolution
$W^\pm$	Mass	79.5 GeV	$W^\pm \to e^\pm + \nu_e$	~10%
	Width	2.6 GeV	$W \to \ell + \nu$ + missing $p_\perp$ measurement	~100%
	Anomalous magnetic moment, K	$K = +1$	$\bar{p}p \to W^\pm + \gamma$ + all	$\delta K/K$ ~ 20%
	WW coupling strength	Yang–Mills	$\bar{p}p \to W^+ + W^-$ + all	
	Principal decay modes	quark–antiquark and lepton pairs	$\bar{p}p \to W^\pm \to \ell + \nu$; $\searrow q + \bar{q}$	
	Higgs Boson coupling	Semi-strong coupling between W and H	$\bar{p}p \to W$ + Higgs Boson (H) + all	
Z^0	Mass	90 GeV	$Z^0 \to e^+e^-$ or $\mu^+\mu^-$	~5%
	Width	2.6 GeV	$Z^0 \to e^+e^-$	~50%
	WZ/ZZ coupling	Yang–Mills	$\bar{p}p \to W + Z$ + all; $Z + Z$ + all	
	Principal decay modes	lepton, antilepton quark, antiquark pairs	$Z \to \ell\bar{\ell}$, $\bar{b}b$, $\bar{t}t$	
	Rare decay modes	gluon pairs, neutrino pairs	$e^+e^- \to Z^0$ Factory	
	Higgs Boson coupling	Semi-strong coupling between Z and H	$\bar{p}p \to Z^0 + H^0$ + all; $e^+e^- \to Z^0 + H^0$	



Production and decay of Intermediate Vector Bosons. Properties measured are (a) mass, width and decay modes; (b) coupling constant, g_{WW}; (c) anomalous magnetic moment of Intermediate Bosons; (d) coupling constants, g_{WWH} and g_{ZZH}. Figure 8



Production of Intermediate Vector Bosons as a function of energy in p̄p colliders. The ordinate for the top curves is events/day; the ordinate for the bottom curve is cross section. Note that the cross section for W pair production is 3×10^{-37} cm^2 for the energy of the Isabelle pp collider. Figure 9

constructed in the latter half of the 1980's in the large tunnel being constructed at CERN for the LEP machine or at Fermilab as a new "site filling" ring. There are also plans in the USSR for a 3-TeV p̄p machine. However it is likely that a much more intense antiproton source will be required than for the present generation of p̄p colliders. Thus the present generation of antiproton sources should lead to more intense sources for the higher energy machines, in the same manner that the ion sources in the 1930's are now standard equipment at Fermilab and CERN but are correspondingly more intense. Low-energy antiproton facilities will likely also become of increasing interest and importance.[21]

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We would like to thank J. Adams, D. Berley, R. Billinge, G. Budker, N. Dikansky, F. Kreinan, P. McIntyre, F. Mills, D. Mohl, G. Petrucci, S. Van Der Meer and F. Sacherer, N. Skrinsky, L. Thorndahl and D. Young for many enlightening discussions about beam cooling and antiproton–proton colliders.

References

1. G. I. Budker, Atomnaya Energiya **22**, 346 (1967).
2. The feasibility of cooling high-energy beams using electrons is described in D. Cline, A. Garren, H. Herr, F. E. Mills, C. Rubbia, A. Ruggiero, D. Young, "High Energy Electron Cooling to Improve the Luminosity and Lifetime in Colliding Beam Machines." SLAC-PUB-2278, March 1979.
3. S. Van Der Meer, "Stochastic Cooling of Betatron Oscillations in the ISR," CERN-ISR, PO/72/31 (1972).
4. G. Carron, L. Thorndahl, "Stochastic Cooling of Momentum Spread by Filter Techniques," CERN Report 2RF/78-12 (1979); D Möhl, G. Petrucci, L. Thorndahl, S. Van Der Meer, CERN/PS/AA 79-23 (1979).
5. G. I. Budker *et al.*, "New Experimental Results of Electron Cooling," Preprint 76-32, Nucl. Phys. Inst., Novosibirsk. Presented to the All Union High-Energy Accelerator Conference, Moscow, October 1976. G. I. Budker *et al.*, Particle Accelerators **7**, 2044 (1976), G. I. Budker *et al.*, "Experimental Study of Electron Cooling," IYaF Preprint 76-33, Nucl. Phys. Inst., Novosibirsk (1976). (Translated by Brookhaven National Laboratory, BNL-TR-634.)
6. D. Möhl, "Stochastic Cooling," CERN Report PS/D7/78-75 (1978).
7. M. Bell *et al.*, "Electron Cooling Experiment at CERN," CERN EP/79-96, 3 Sept. 1979.
8. F. Sacherer, "Stochastic Cooling Theory," CERN Report IST/TH78-11.
9. "The Fermilab Electron Cooling Experiment," Fermilab report, August, 1978.
10. "The CERN p̄p Design Report," CERN/PS/AA 78-3 Report (1978).
11. C. Rubbia, P. McIntyre, D. Cline, "Producing Massive Neutral Intermediate Vector Bosons with Existing Accelerators," in Proceedings of the International Neutrino Conference Aachen, H. Faissner, H. Reithler, P. Zerwas (Eds.), 1976. D. Cline, P. McIntyre, F. Mills, C. Rubbia, Fermilab Internal Report TM-689 (1976).
12. "Tevatron Phase I Report," Fermilab Report (1979).
13. D. Cline *et al.*, Harvard/Wisconsin proposal to Fermilab 492 (1976).
14. H. Yukawa, Proc. Phys.-Math. Soc. Japan **17**, 48 (1935).
15. S. L. Glashow, Nucl. Phys. **22**, 579 (1961). S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967). A. Salam, in Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8), N. Svartholm, ed. (Almqvist and Wiksell, Stockholm, 1968), page 367.
16. F. J. Hasert *et al.*, Phys. Lett. **46B**, 121 (1973); **46B**, 138 (1973); Nucl. Phys **B73**, 1 (1974). A. Benvenuti *et al.*, Phys. Rev. Lett. **32**, 800 (1974); B. Aubert *et al.*, ibid., **32**, 1454 (1974); **32**, 1457 (1974).
17. C. Quigg, Rev. Mod. Phys. **49**, 297 (1977); L. B. Okun, M. B. Voloshin, Nucl. Phys. **B120**, 459 (1977); R. F. Peierls, T. L. Trueman, L.-L. Wang, Phys. Rev. **D16**, 1397 (1977).
18. F. Paige, "Updated Estimates of W Production in pp and p̄p Interactions," in Proceedings of the Topical Workshop on New Particles in Super High-Energy Collisions, Madison, Wisc., 1979.
19. K. O. Mikaelian, M. A. Samuel, Phys. Rev. Lett. **43**, 746 (1979).
20. R. W. Brown, K. O. Mikaelian, Phys. Rev. **B19**, 922 (1979).
21. U. Gastaldi, K. Kilian, G. Plass, "A Low Energy Antiproton Facility at CERN." CERN/PSCC/79-17.

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