American Physical Society
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Proton-Antiproton Colliders

Lyndon Evans/CERN
<table>
<thead>
<tr>
<th>Leptons</th>
<th>Mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>0.511</td>
</tr>
<tr>
<td>Muon</td>
<td>105.65</td>
</tr>
<tr>
<td>Tau</td>
<td>1777.05</td>
</tr>
<tr>
<td>Up</td>
<td>3.25</td>
</tr>
<tr>
<td>Down</td>
<td>6</td>
</tr>
<tr>
<td>Strange</td>
<td>115</td>
</tr>
<tr>
<td>Charm</td>
<td>1250</td>
</tr>
<tr>
<td>Bottom</td>
<td>4250</td>
</tr>
<tr>
<td>Top</td>
<td>173800</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Quarks</th>
<th>Mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion(charged)</td>
<td>139.57</td>
</tr>
<tr>
<td>Pion(neutral)</td>
<td>134.97</td>
</tr>
<tr>
<td>Proton</td>
<td>938.27</td>
</tr>
<tr>
<td>Neutron</td>
<td>939.56</td>
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</table>

<table>
<thead>
<tr>
<th>Hadrons</th>
<th>Mass (MeV)</th>
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<tbody>
<tr>
<td>Photon</td>
<td>80410</td>
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<tr>
<td>Gluon</td>
<td>91107</td>
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</table>

Higgs and super-symmetry? Or something else maybe

Behind the history plot is hidden the technological development required for each step.

Obs: you can notice different particle species used in the different colliders: electron-positrons and hadron colliders (either p-p as Tevatron, p-p as LHC).
CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV}, \quad L_{\text{int}} = 3.1 \text{ pb}^{-1} \]
In 1976, Rubbia, Kline and McIntyre proposed that the CERN SPS and the Fermilab Main Ring could be converted into proton-antiproton colliders to search for the W and Z bosons.

In order to achieve this, it was first necessary to develop the technology for the production, accumulation and cooling of intense antiproton beams.
Joseph Liouville (1809 – 1882)
Liouville’s theorem states that the phase space density of a particle beam cannot be changed under the action of conservative forces if the beam is considered to be a continuous medium.

Electron beams are naturally cooled by the emission of synchrotron radiation.

In the 1960’s, Budker proposed the cooling of protons by their interaction with a cold electron beam (non-conservative) Coulomb collisions.

In 1972 (from work done in 1968), Van der Meer discovered the principle of stochastic cooling, which makes use of the fact that the beam is not a continuous medium.
Electron Cooling
Electron Cooling

- Fast

- Most suited for low-β beams. Very effective for heavy ions and is used to cool the Pb ion beam for LHC. Until recently it was not possible to cool antiprotons produced at high energy.

- Effective at cooling beams that are already cool. Not good for cooling antiprotons directly from production target.
The Intersecting Storage Rings (1971-1984)

- First hadron storage rings
- First observation of Schottky noise
- First demonstration of stochastic cooling
FINAL NOTE

This work was done in 1968. The idea seemed too far-fetched at the time to justify publication. However, the fluctuations upon which the system is based were experimentally observed recently. Although it may still be unlikely that useful damping could be achieved in practice, it seems useful now to present at least some quantitative estimation of the effect.
\[ \bar{x} = \frac{\sigma_s}{\sqrt{N_s}} \quad \frac{1}{\tau} = \frac{W}{2N} \]

No mixing from pickup to kicker

Good mixing from kicker to pickup
In 1977 the (g-2) ring at CERN was converted into a machine on which stochastic cooling could be tested in detail.

In parallel, the theory of stochastic cooling was developed by Sacherer, Hereward, Van de Meer and Mohl.

In May 1978 ICE achieved cooling for the first time in all 3 dimensions

In June the ppbar project was submitted to CERN Council for approval.
Schottky scan after 1, 2 and 4 min.

Signal height proportional to the square root of density and width proportional to $\Delta p/p$. 
Fermilab was in the middle of the construction of the Doubler (now the Tevatron), the world’s first large superconducting machine.

In November 1978 it was decided that this would remain top priority and that colliding beams would be in the Tevatron and not the Main Ring.
The Antiproton Accumulator
The acceleration and storage of intense proton and antiproton colliding beams create many problems which have to be resolved in order to produce luminosity.

They include:

- Beam stability
- RF noise
- Intrabeam scattering
- Low-beta optics
- The beam-beam interaction.
Beam Separation and Lifetime

![Diagram of beam separation and lifetime](image)

- **Graph**: Shows separation switched on over time.
  - Less than 2 hours: Near the origin.
  - More than 100 hours: Further along the graph.

- **Diagram**: Illustrates the points of interest along the path.
Electrostatic Separator
Recycler Electron Cooling

- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV - 0.5 Amps
  - DC - 200μrad beam spread - 99% recirculation efficiency
Recycler Electron Cooling

- Electron cooling commissioning
  - Electron cooling was demonstrated in July 2005 two months ahead of schedule.
  - By the end of August 2005, electron cooling was being used on every Tevatron shot.

- Electron cooling goals
  - Can presently support final design goal of rapid transfers (30eV-Sec/2hrs)
  - Can presently reliably support stacks of $250 \times 10^{10}$ (FY06 design goal)
  - Have achieved 500 mA of electron beam which is the final design goal.

Electron beam current: 200 mA
Traces are 15 min apart

Lyn Evans
The Large Hadron Collider
The Large Hadron Collider

LHC DIPOLE: STANDARD CROSS-SECTION

ALIGNMENT TARGET
MAIN QUADROPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST
The developments leading to the successful conversion of the two high energy accelerators to proton - antiproton colliders has taken the art of manipulating and controlling particle beams to new heights and have made the most fundamental discoveries in the last quarter of the 20th century.

The lessons learned have been essential for the design of the LHC. However, due to the need for an increase of two orders magnitude in luminosity, the use of antiprotons is no longer an option. The final closure of the Tevatron collider will end an exciting and productive chapter in the development of accelerator technology.