1961: First storage ring for electrons and positrons (AdA) in Frascati for 250MeV

1972: SPEAR electron positron collider at 4GeV. Discovery of the J/Psi at 3.097GeV by Richter (SPEAR) and Ting (AGS) starts the November revolution and was essential for the quarkmodel and chromodynamics.

1979: 5GeV electron positron collider CESR (designed for 8GeV)

Advantage:
More center of mass energy

Drawback:
Less dense target
The beams therefore must be stored for a long time.
Ellements of a Collider

- Saving one beam while injection another
- Avoiding collisions outside the detectors.
- Compensating the forces between $e^+$ and $e^-$ beams
To avoid the loss of collision time during filling of a synchrotron, the beams in colliders must be stored for many millions of turns.

Challenges:
- Required vacuum of pressure below $10^{-7}$ Pa = $10^{-9}$ mbar, 3 orders of magnitude below that of other accelerators.
- Fields must be stable for a long time, often for hours.
- Field errors must be small, since their effect can add up over millions of turns.
- Even though a storage ring does not accelerate, it needs acceleration sections for phase focusing and to compensate energy loss due to the emission of radiation.
Further Development of Colliders

- 1981: Rubbia and van der Meer use stochastic cooling of anti-portons and discover $W^+, W^-$ and $Z$ vector bosons of the weak interaction
- 1987: Start of the superconducting TEVATRON at FNAL
- 1989: Start of the 27km long LEP electron positron collider
- 1990: Start of the first asymmetric collider, electron (27.5GeV) proton (920GeV) in HERA at DESY
- 1998: Start of asymmetric two ring electron positron colliders KEK-B / PEP-II
- Today: 27km, 7 TeV proton collider LHC being build at CERN

NP 1984
Carlo Rubbia
Italy 1934 -

NP 1984
Simon van der Meer
Netherlands 1925 -
Special Relativity

\[ E = mc^2 \]

Four-Vectors:
Quantities that transform according to
the Lorentz transformation when viewed
from a different inertial frame.

Examples:
\[ X^\mu \in \{ct, x, y, z\} \]
\[ P^\mu \in \\{\frac{1}{c}E, p_x, p_y, p_z\} \]
\[ \Phi^\mu \in \\{\frac{1}{c}\phi, A_x, A_y, A_z\} \]
\[ J^\mu \in \{c\rho, j_x, j_y, j_z\} \]
\[ K^\mu \in \\{\frac{1}{c}\omega, k_x, k_y, k_z\} \]

\[ X^\mu \in \{ct, x, y, z\} \quad \Rightarrow \quad X^\mu X_\mu = (ct)^2 - \vec{x}^2 = \text{const.} \]

\[ P^\mu \in \\{\frac{1}{c}E, p_x, p_y, p_z\} \quad \Rightarrow \quad P^\mu P_\mu = \left(\frac{E}{c}\right)^2 - \vec{p}^2 = (m_0c)^2 = \text{const.} \]
Available Energy

\[
\frac{1}{c^2} E_{\text{cm}}^2 = (P_1^\mu + P_2^\mu)_{\text{cm}} (P_1^\mu + P_2^\mu)_{\text{cm}} = (P_1^\mu + P_2^\mu)(P_1^\mu + P_2^\mu) = \frac{1}{c^2} (E_1 + E_2)^2 - (p_{z1} - p_{z2})^2 = 2 \left( \frac{E_1 E_2}{c^2} + p_{z1} p_{z2} \right) + (m_{01}c)^2 + (m_{02}c)^2
\]

Operation of synchrotrons: fixed target experiments where some energy is in the motion of the center of mass of the scattering products

\[E_1 \gg m_{01}c^2, m_{02}c^2; p_{z2} = 0; E_2 = m_{02}c^2 \Rightarrow E_{\text{cm}} = \sqrt{2E_1 m_{02}c^2}\]

Operation of colliders: the detector is in the center of mass system

\[E_1 \gg m_{01}c^2; E_2 \gg m_{02}c^2 \Rightarrow E_{\text{cm}} = 2\sqrt{E_1 E_2}\]
Energy that would be needed in a fixed target experiment versus the year of achievement:

\[ E_1 = \frac{E_{cm}^2}{2m_0c^2} \]
Example: Production of the pbar

1954: Operation of Bevatron, first proton synchrotron for 6.2 GeV, production of the anti-porton by Chamberlain and Segrè

\[ p + p \quad \mapsto \quad p + p + p + \bar{p} \]

\[ \frac{1}{c^2} E_{\text{cm}}^2 = 2 \left( \frac{E_1 E_2}{c^2} + p_{z_1} p_{z_2} \right) + (m_{01} c)^2 + (m_{02} c)^2 \]

\[ (4m_{p0} c)^2 < \frac{1}{c^2} E_{\text{cm}}^2 = 2 \frac{E_1 m_{p0}}{c^2} + (m_{p0} c)^2 + (m_{p0} c)^2 \]

\[ 7m_{p0} c^2 < E_1 \]

\[ K_1 = E_1 - m_0 c^2 > 6m_{p0} c^2 = 5.628 \text{ GeV} \]
Example: c-cbar states

1974: Observation of $c - \bar{c}$ resonances ($J/\Psi$) at $E_{cm} = 3095\text{MeV}$ at the $e^+/e^-$ collider SPEAR

$$\frac{1}{c^2} E_{cm}^2 = 2\left(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}\right) + (m_0 c)^2 + (m_0 c)^2$$

$$E_1 = E_2 \implies E_{cm}^2 = 4E^2$$

Energy per beam:

$$K = E - m_0 c = 1547\text{MeV}$$

Beam energy needed for an equivalent fixed target experiment:

$$\frac{E_{cm}^2}{c^2} = 2[Em + (mc)^2]$$

$$K = E - m_0 e c^2 = \frac{E_{cm}^2}{2m_0 e c^2} - 2m_0 e c^2 = 9.4\text{TeV}$$

NP 1976
Burton Richter
USA 1931

NP 1976
Samuel CC Ting
USA 1936