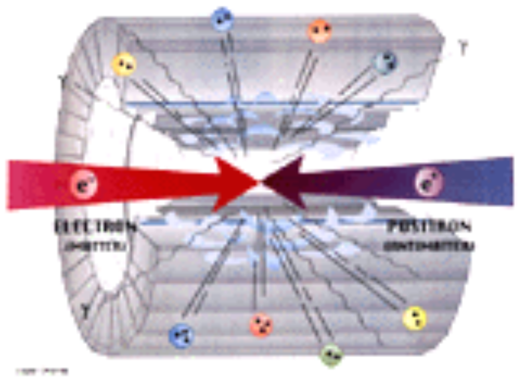
Colliding Beam Accelerators

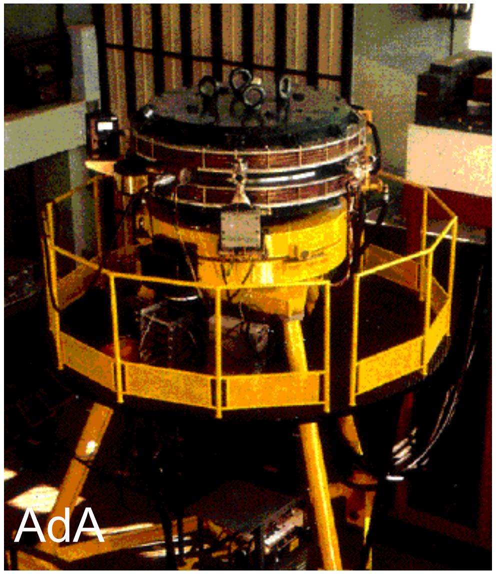
CHESS & LEPP

- 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





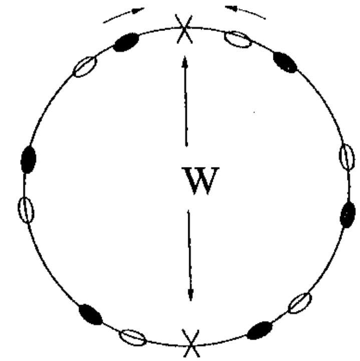
Drawback:

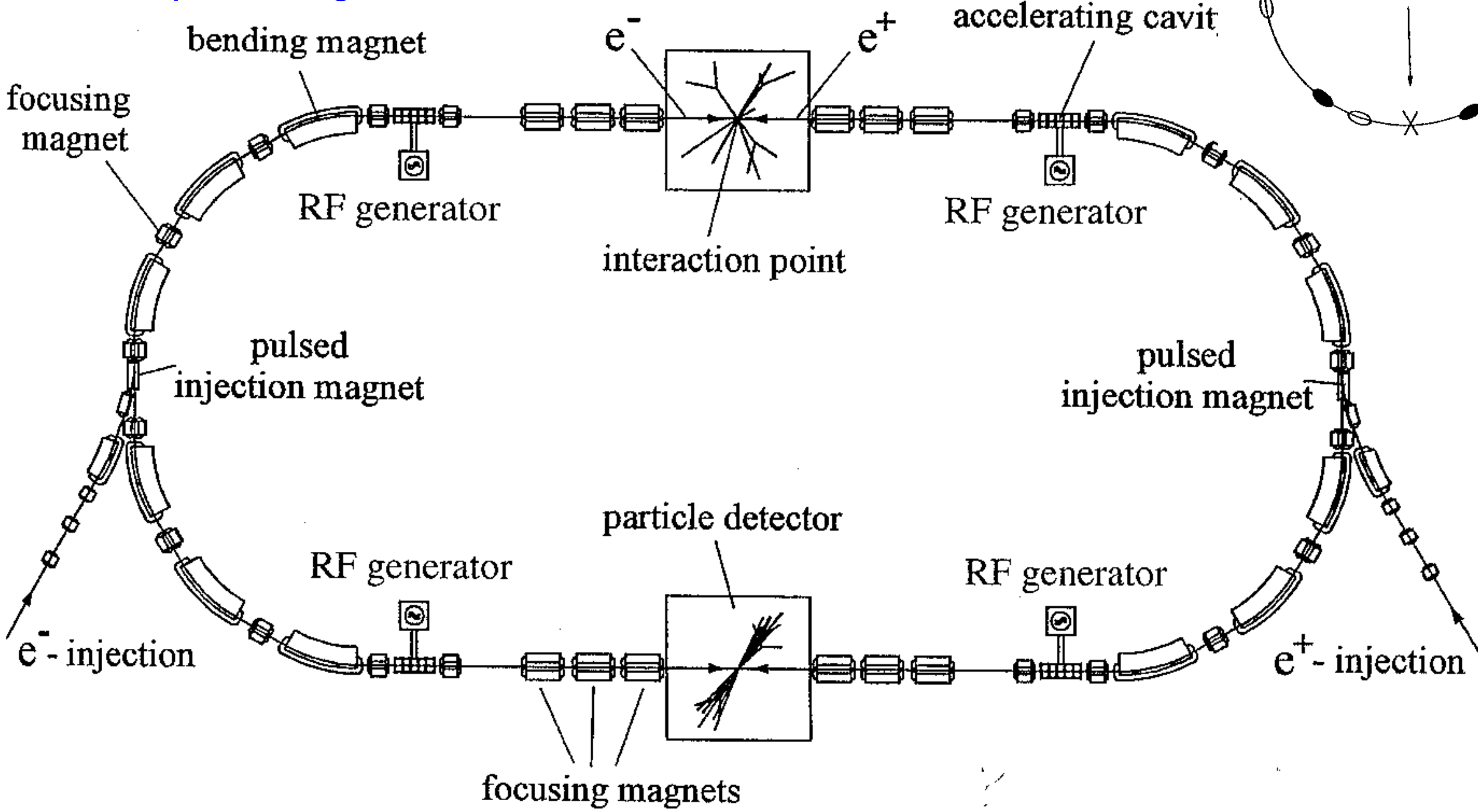
Less dense target

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





Storage Rings

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

CHESS & LEPP

- 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

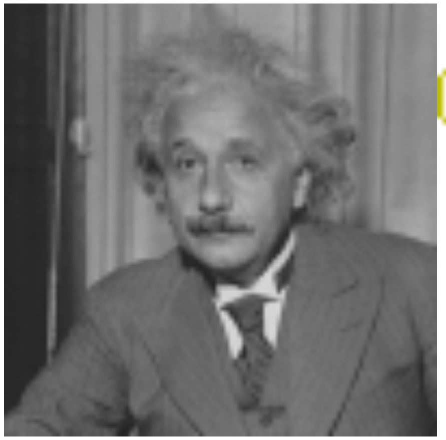
NP 1984
Carlo Rubbia
Italy 1934 -

NP 1984
Simon van der Meer
Netherlands 1925 -

Special Relativity

CHESS & LEPP

$$E = mc^2$$



Albert Einstein, 1879-1955
Nobel Prize, 1921
Time Magazine Man of the Century

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

Examples:

$$X^\mu \in \{ct, x, y, z\}$$

$$P^\mu \in \{\tfrac{1}{c}E, p_x, p_y, p_z\}$$

$$\Phi^\mu \in \{\tfrac{1}{c}\phi, A_x, A_y, A_z\}$$

$$J^\mu \in \{c\rho, j_x, j_y, j_z\}$$

$$K^\mu \in \{\tfrac{1}{c}\omega, k_x, k_y, k_z\}$$

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

$$P^\mu \in \{\tfrac{1}{c}E, p_x, p_y, p_z\} \Rightarrow \quad P^\mu P_\mu = \left(\frac{E}{c}\right)^2 - \vec{p}^2 = (m_0 c)^2 = \text{const.}$$

Available Energy

CHESS & LEPP

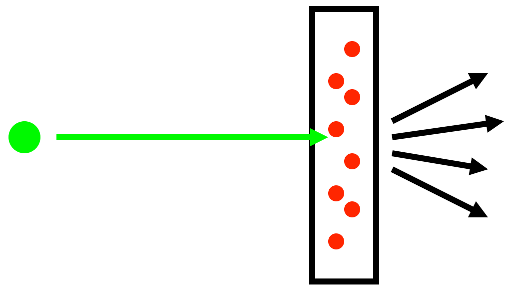
$$\frac{1}{c^2}E_{\rm cm}^2 = (P_1^\mu + P_2^\mu)_{\rm cm}(P_{1\mu} + P_{2\mu})_{\rm cm}$$

$$= (P_1^\mu + P_2^\mu)(P_{1\mu} + P_{2\mu})$$

$$= \frac{1}{c^2}(E_1 + E_2)^2 - (p_{z1} - p_{z2})^2$$

$$= 2(\frac{E_1E_2}{c^2} + p_{z1}p_{z2}) + (m_{01}c)^2 + (m_{02}c)^2$$

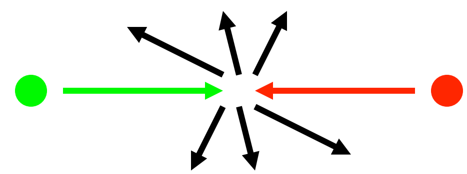
Operation of synchrotrons: fixed target experiments where some energy is in the motion of the center off mass of the scattering products



$$E_1 >> m_{01}c^2, m_{02}c^2; p_{z2} = 0; E_2 = m_{02}c^2 \quad \Rightarrow \quad E_{\rm cm} = \sqrt{2E_1m_{02}c^2}$$

Operation of colliders:

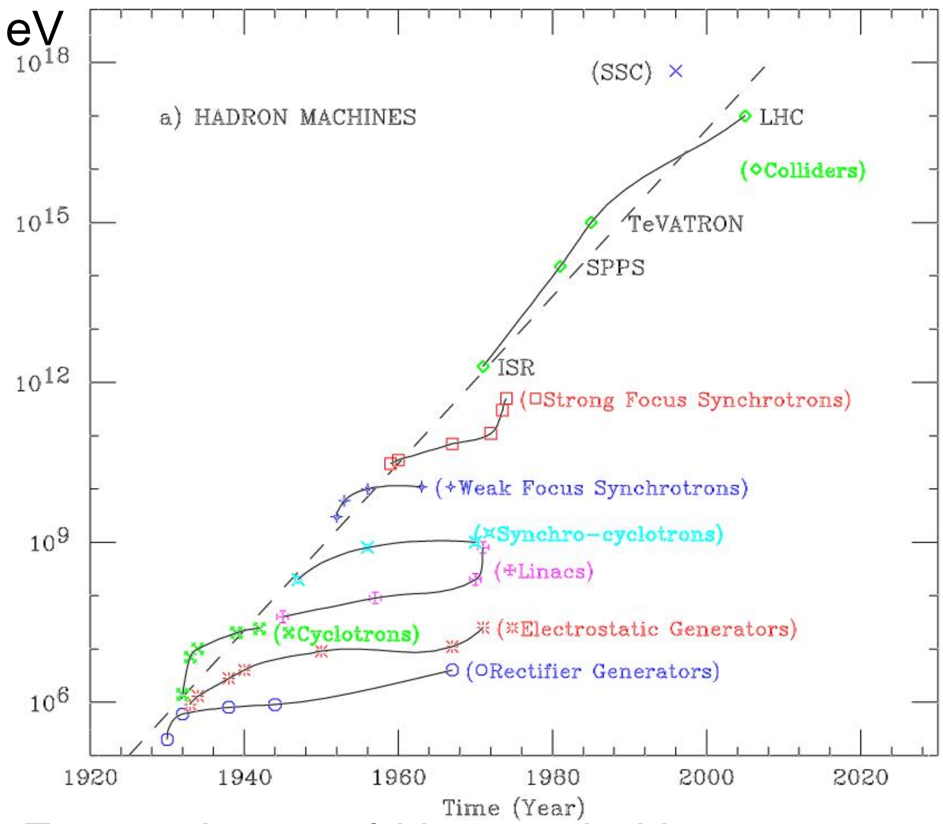
the detector is in the center of mass system



$$E_1 >> m_{01}c^2; E_2 >> m_{02}c^2 \quad \Rightarrow \quad E_{\rm cm} = 2\sqrt{E_1E_2}$$

The Livingston Chart

CHESS & LEPP

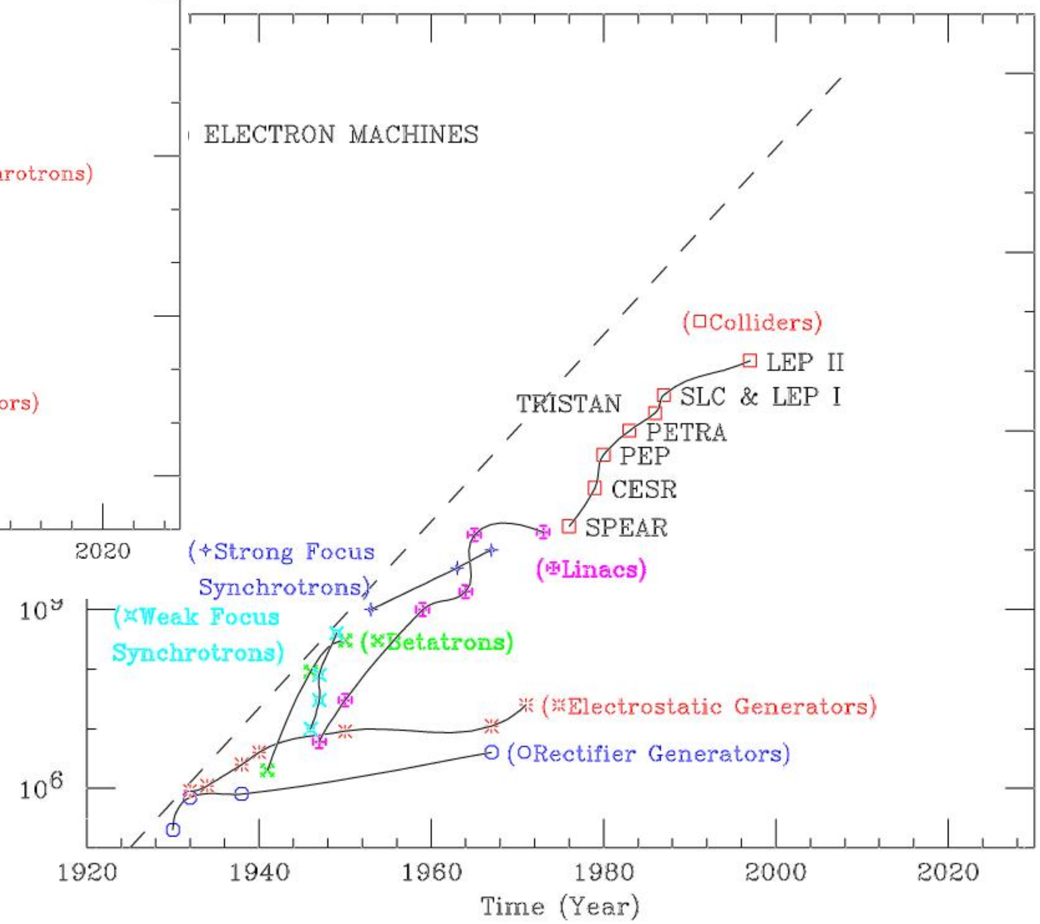


Comparison:

highest energy cosmic rays have a few 10^{20}eV

Energy that would be needed in a fixed target experiment versus the year of achievement

$$E_1 = \frac{E_{\mathrm{cm}}^2}{2m_{02}c^2}$$



Example: Production of the pbar

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

$$p + p \quad \mapsto \quad p + p + p + \bar{p}$$

$$\tfrac{1}{c^2} E_{\mathrm{cm}}^2 = 2(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}) + (m_{01} c)^2 + (m_{02} c)^2$$

$$(4 m_{p0} c)^2 < \tfrac{1}{c^2} E_{\mathrm{cm}}^2 = 2 \frac{E_1 m_{p0}}{c^2} + (m_{p0} c)^2 + (m_{p0} c)^2$$

$$7 m_{p0} c^2 < E_1$$

$$\underline{K_1} = E_1 - m_0 c^2 > 6 m_{p0} c^2 \underline{= 5.628\,\mathrm{GeV}}$$

NP 1959
Emilio Gino Segrè
Italy 1905 – USA 1989

NP 1959
Owen Chamberlain
USA 1920 - 2006

Example: c-cbar states

- 1974: Observation of $c-\bar{c}$ resonances (J/Ψ) at Ecm = 3095MeV at the e⁺/e⁻ collider SPEAR

$$\frac{1}{c^2}E_{\rm cm}^2 = 2(\frac{E_1E_2}{c^2}+p_{z1}p_{z2})+(m_{01}c)^2+(m_{02}c)^2$$

$$E_1 = E_2 \quad \Rightarrow \quad E_{\rm cm}^2 = 4E^2$$

Energy per beam: $K = E - m_0c = 1547\text{MeV}$

Beam energy needed for an equivalent fixed target experiment: $\frac{E_{cm}^2}{c^2} = 2[Em+(mc)^2]$

$$K = E - m_{0e}c^2 = \frac{E_{cm}^2}{2m_{0e}c^2} - 2m_{0e}c^2 = 9.4\text{TeV}$$

NP 1976
Burton Richter
USA 1931 -

NP 1976
Samuel CC Ting
USA 1936 -