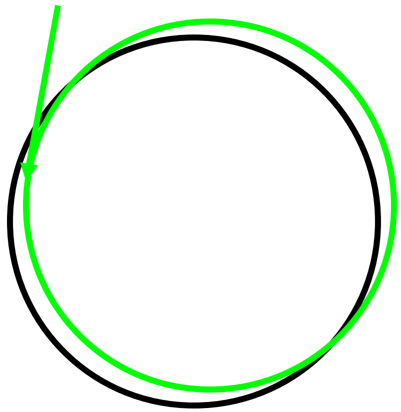
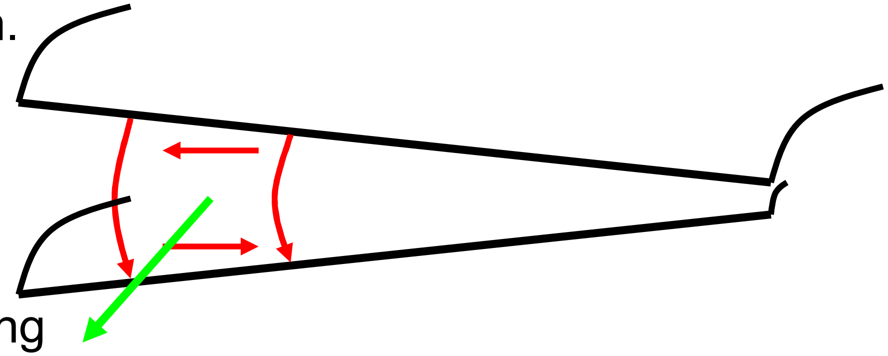
Weak focusing Synchrotrons

- 1952: Operation of the Cosmotron, 3.3 GeV proton synchrotron at Brookhaven: Beam pipe height: 15cm.

Natural ring focusing:



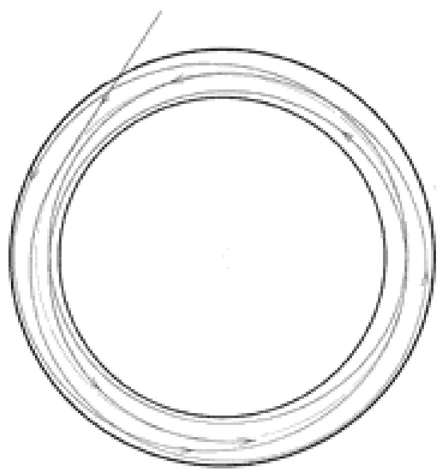


Vertical focusing

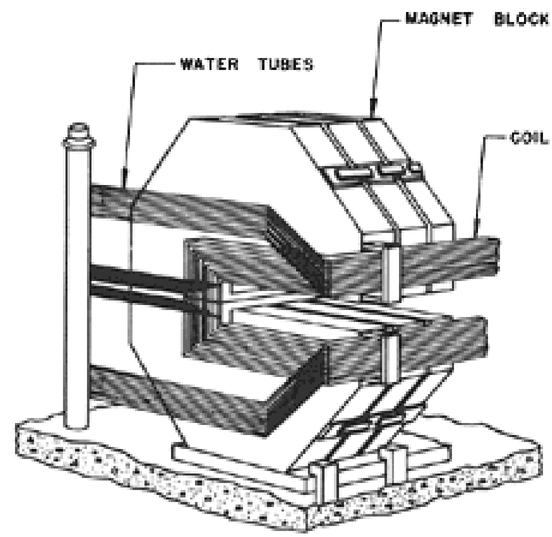
+ Horizontal defocusing + ring focusing

Focusing in both planes

The Cosmotron



Weak focusing accelerator

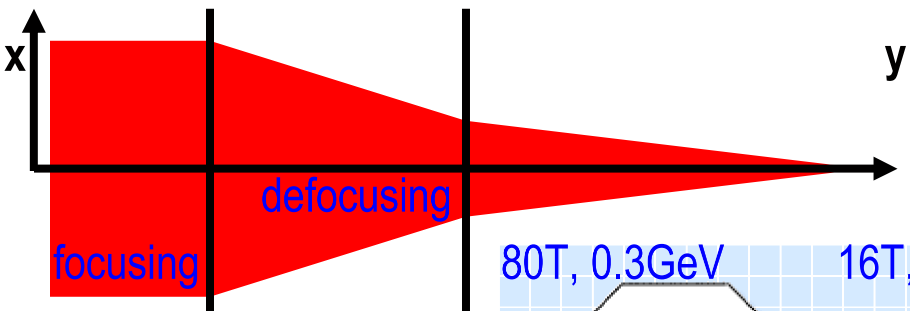


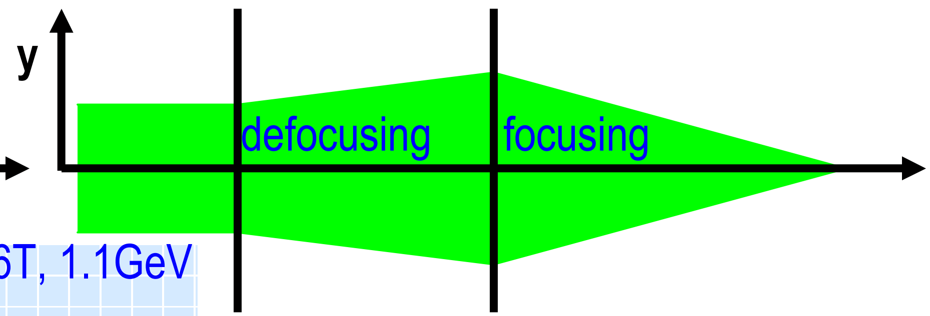
Strong focusing Synchrotrons

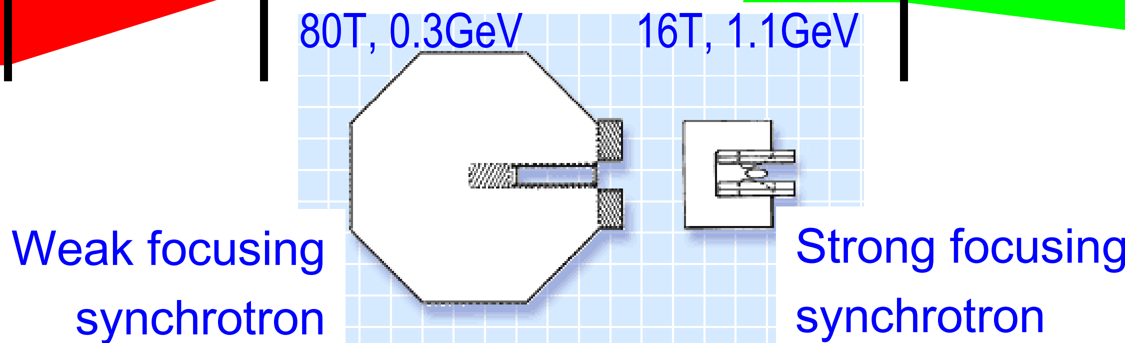
CHESS & LEPP

- 1952: Courant, Livingston, Snyder publish about strong focusing
- 1954: Wilson et al. build first synchrotron with strong focusing for 1.1MeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1959: CERN builds the PS for 28GeV after proposing a 5GeV weak focusing accelerator for the same cost (still in use)

Transverse fields defocus in one plane if they focus in the other plane.
But two successive elements, one focusing the other defocusing, can focus in both planes:







- Today: only strong focusing is used. Due to bad field quality at lower field excitations the injection energy is 20-500MeV from a linac or a microtron.

Limits of Synchrotrons

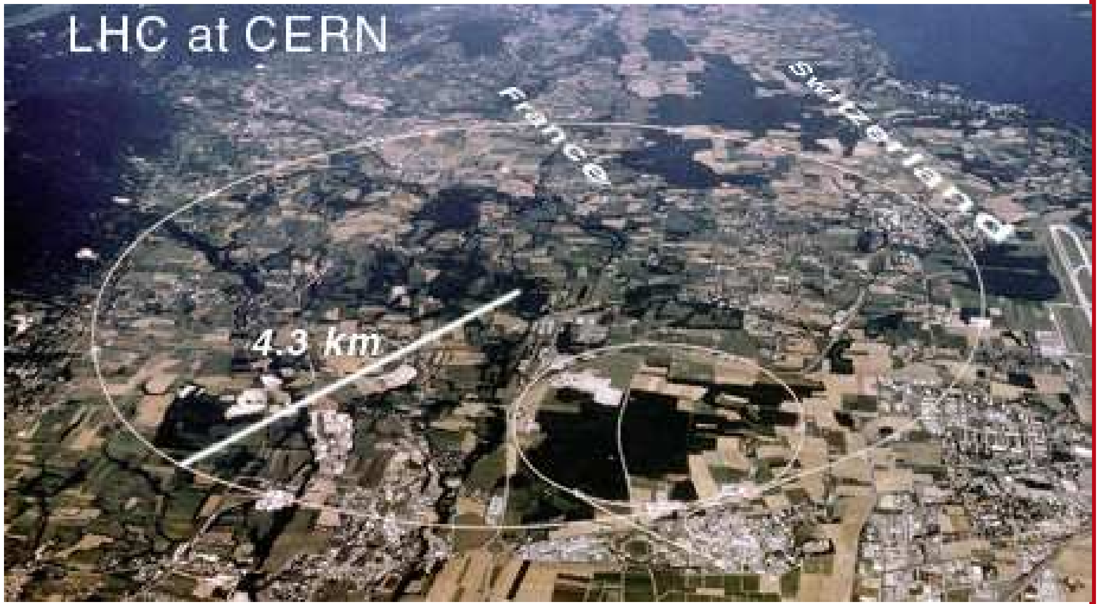
CHESS & LEPP

$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \text{The rings become too long}$$

Protons with p = 20 TeV/c , B = 6.8 T would require a 87 km SSC tunnel
Protons with p = 7 TeV/c , B = 8.4 T require CERN's 27 km LHC tunnel

$$P_{\text{radiation}} = \tfrac{c}{6\pi\varepsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

Energy needed to compensate
Radiation becomes too large



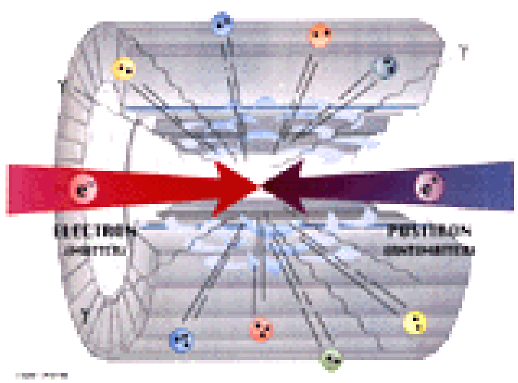
Electron beam with p = 0.1 TeV/c in CERN's 27 km LEP tunnel radiated 20 MW
Each electron lost about 4GeV per turn, requiring many RF accelerating sections.

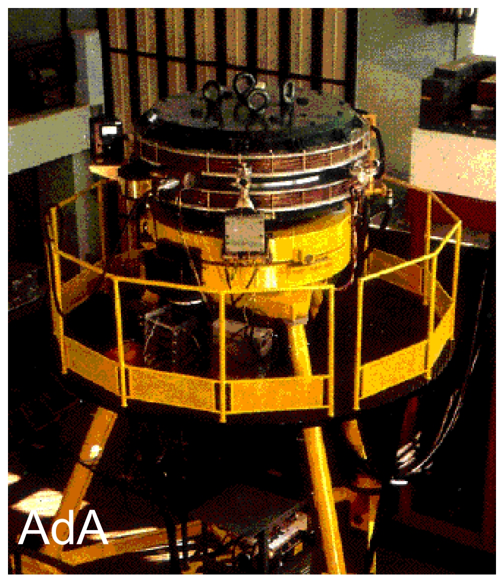
Colliding Beam Accelerators

- 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





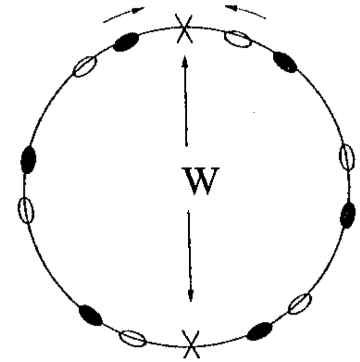
Drawback:

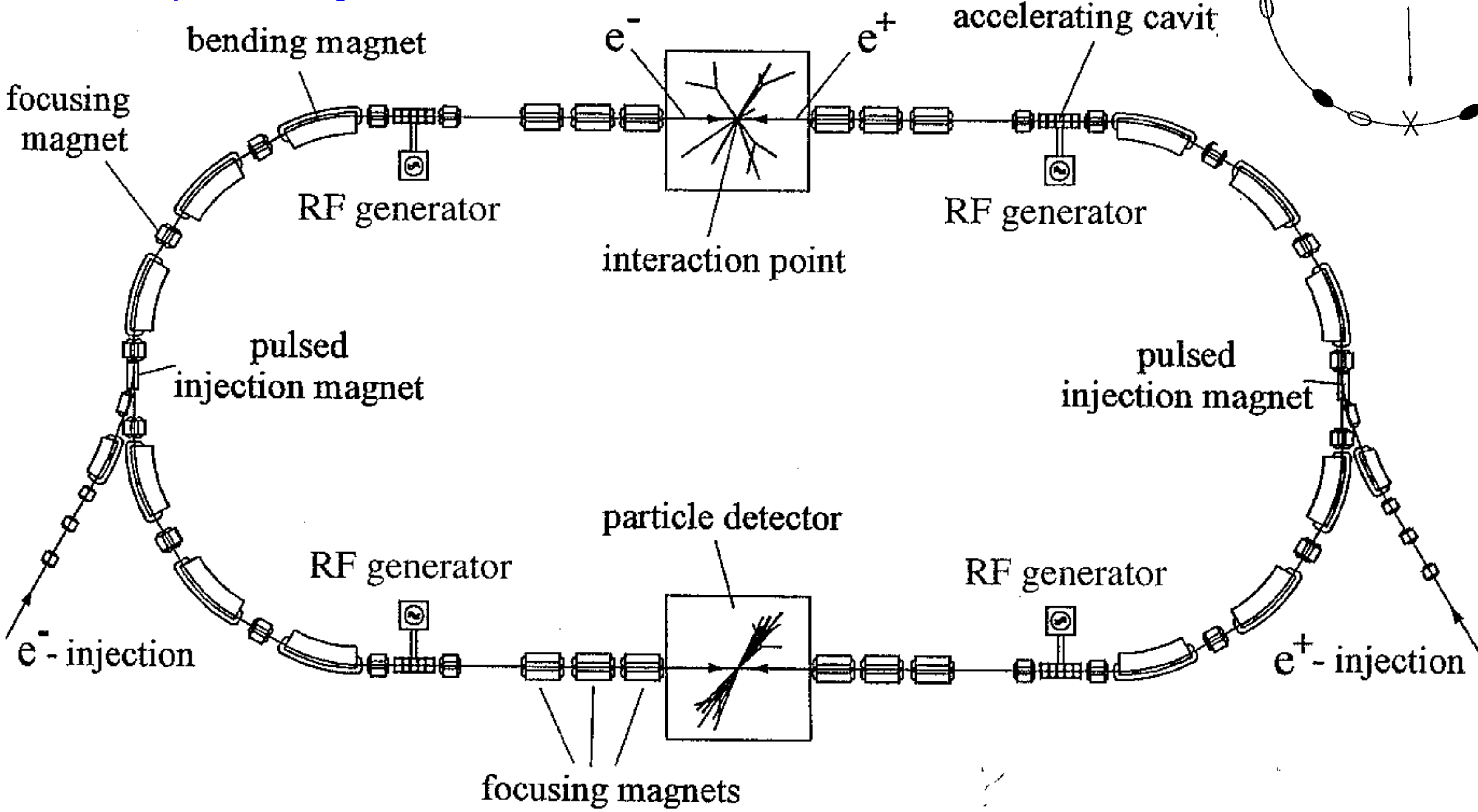
Less dense target

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

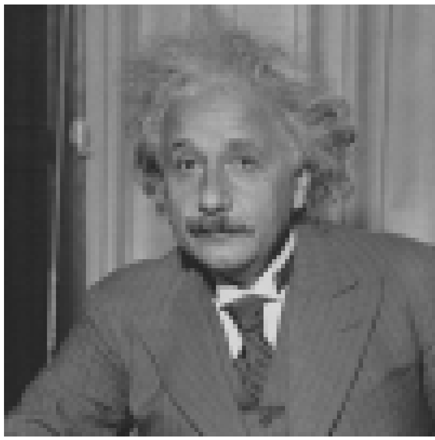
- 1981: Rubbia and van der Meer use stochastic cooling of anti-portons and discover W+,W- and Z vector bosons of the weak interaction
- 1987: Start of the superconducting TEVATRON at FNAL
- 1989: Start of the 27km long LEP electron positron collider
- 1990: Start of the first asymmetric collider, electron (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

$$E = mc^2$$



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:

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

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

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

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

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

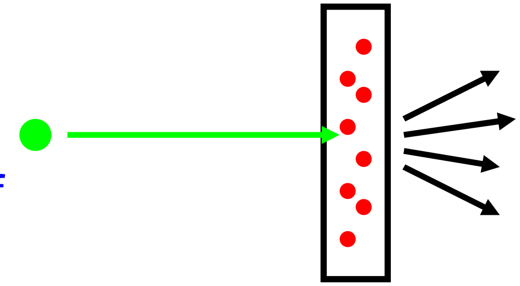
$$X^{\mu} \in \{ct, x, y, z\} \quad \Rightarrow \quad X^{\mu}X_{\mu} = (ct)^2 - \vec{x}^2 = \text{const.}$$

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

Available Energy

CHESS & LEPP

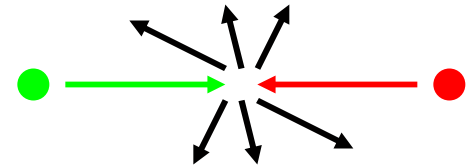
Operation of synchrotrons: fixed target experiments where some energy is in the motion of the center off mass of the scattering products



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

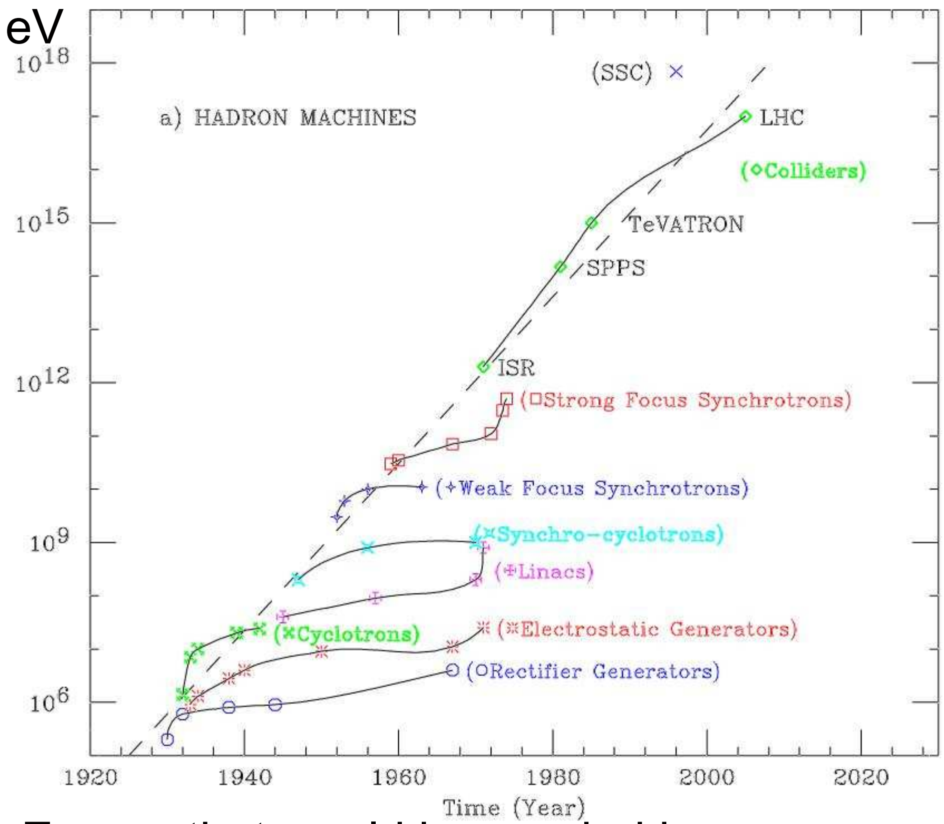
Operation of colliders:

the detector is in the center of mass system



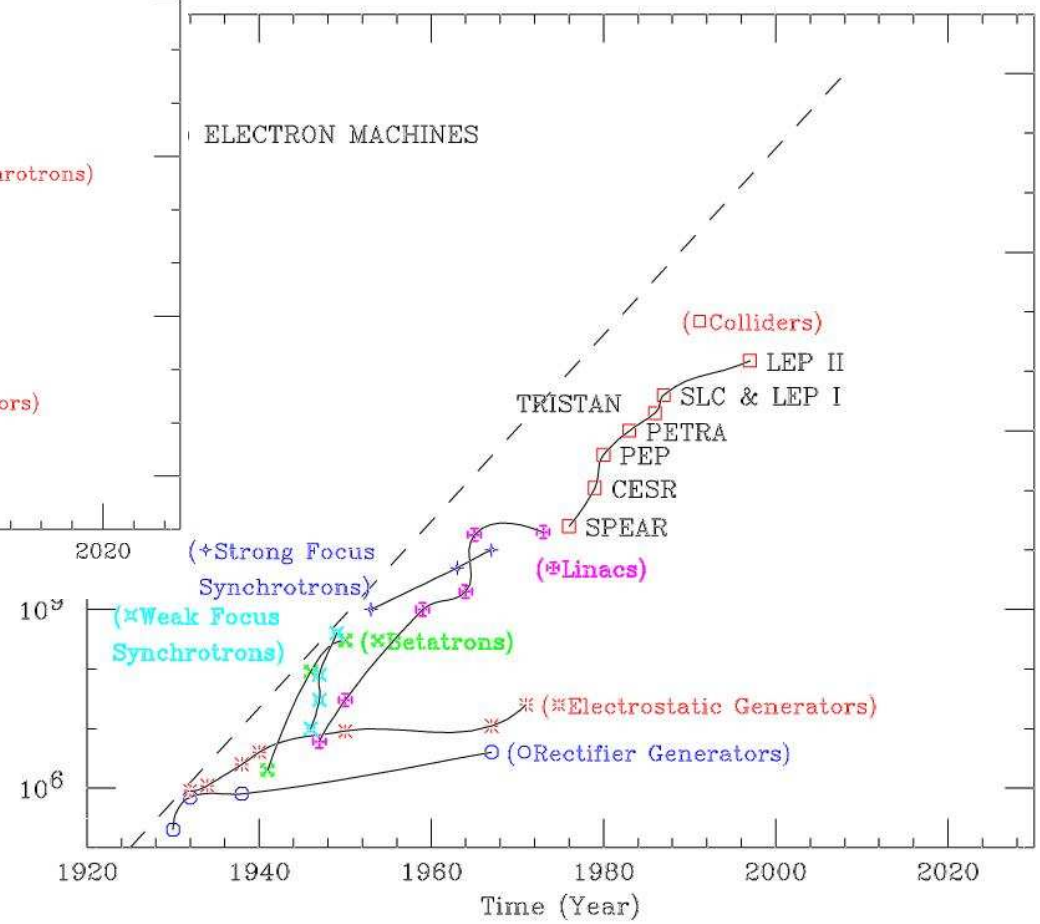
$$E_1 >> m_{01}c^2; E_2 >> m_{02}c^2 \quad \Rightarrow \quad E_{\mathrm{cm}} = 2\sqrt{E_1 E_2}$$

The Livingston Chart



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

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

Example: c-cbar states

CHESS & LEPP

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

$$E_1 = E_2 \quad \Rightarrow \quad E_{\mathrm{cm}} = 2E$$

Energy per beam: $K = E - m_0 c = 1547\mathrm{MeV}$

Beam energy needed for an equivalent fixed target experiment: $E_{\mathrm{cm}} = \sqrt{2Emc^2}$

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

NP 1976
Burton Richter
USA 1931 -

NP 1976
Samuel CC Ting
USA 1936 -

Rings for Synchrotron Radiation

CHESS & LEPP

- 1947: First detection of synchrotron light at General Electrics.
- 1952: First accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1968: TANTALUS, first dedicated storage ring for synchrotron radiation

Dale Corson
Cornell's 8th president
USA 1914 –

3 Generations of Light Sources

CHESS & LEPP

- 1st Genergation (1970s): Many HEP rings are parasitically used for X-ray production
- 2nd Generation (1980s): Many dedicated X-ray sources (light sources)
- 3rd Generation (1990s): Several rings with dedicated radiation devices (wigglers and undulators)
- Today (4th Generation): Construction of Free Electron Lasers (FELs) driven by LINACs