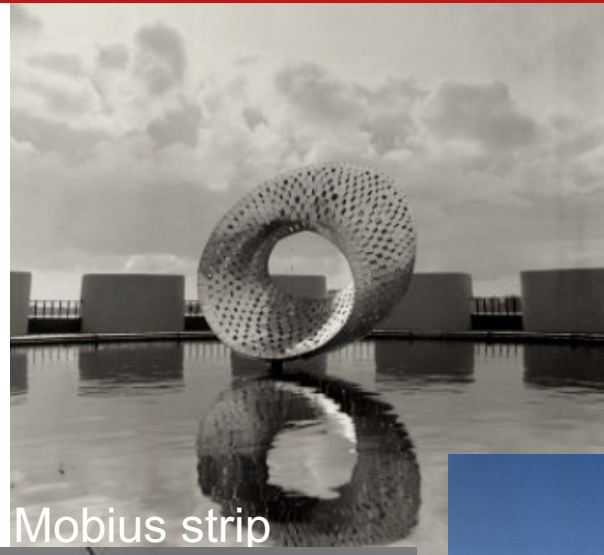




Broken symmetry



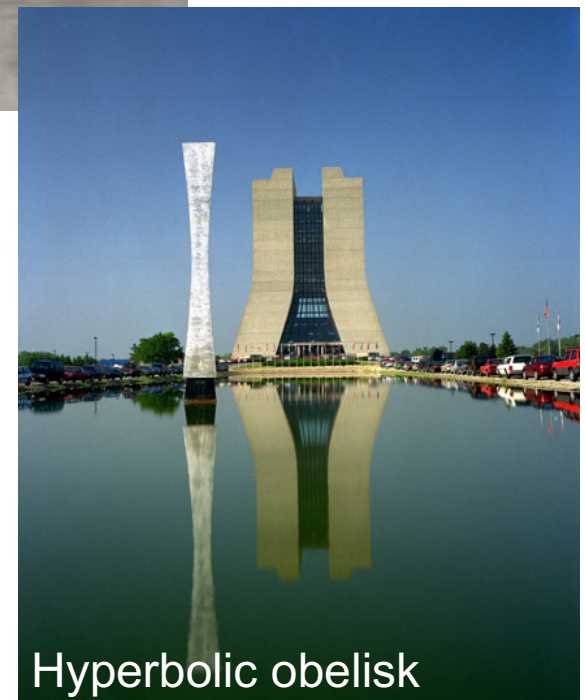
Mobius strip



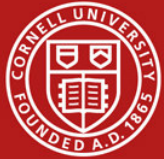
Tractricious



$\pi$  lines



Hyperbolic obelisk



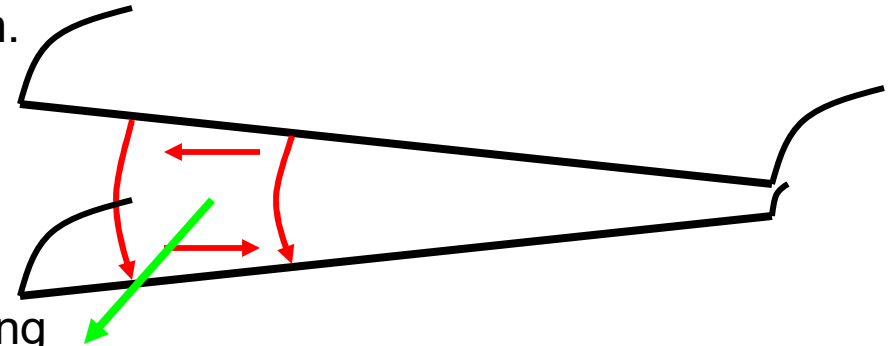
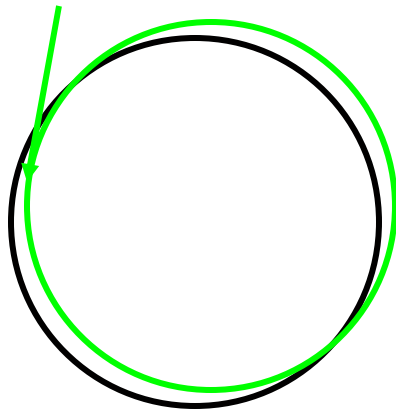
# Weak focusing Synchrotrons



CHESS & LEPP

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

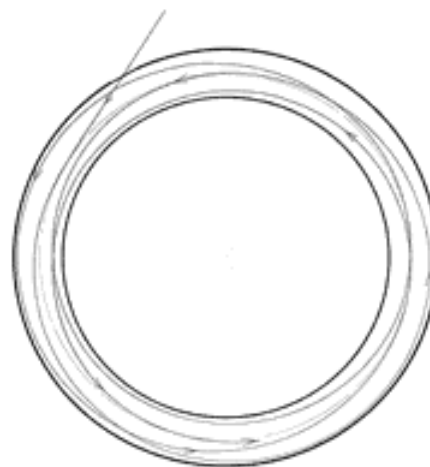
Natural ring focusing:



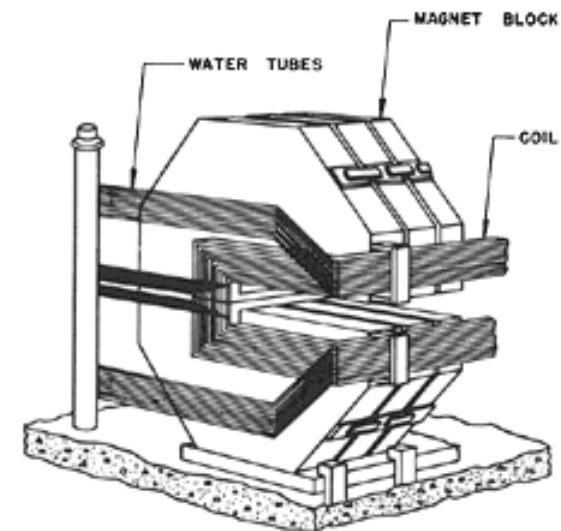
Vertical focusing  
+ Horizontal defocusing + ring focusing  
Focusing in both planes



The Cosmotron



Weak focusing accelerator





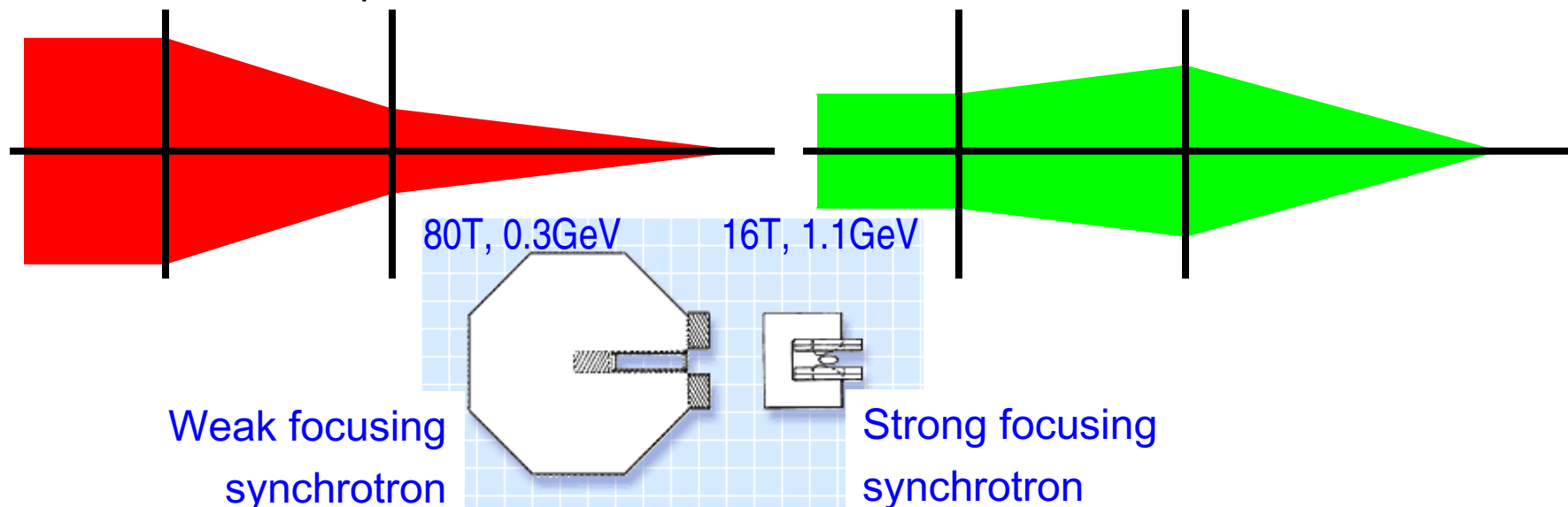
## Strong focusing Synchrotrons



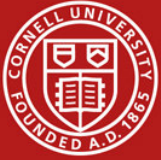
CHESS & LEPP

- 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



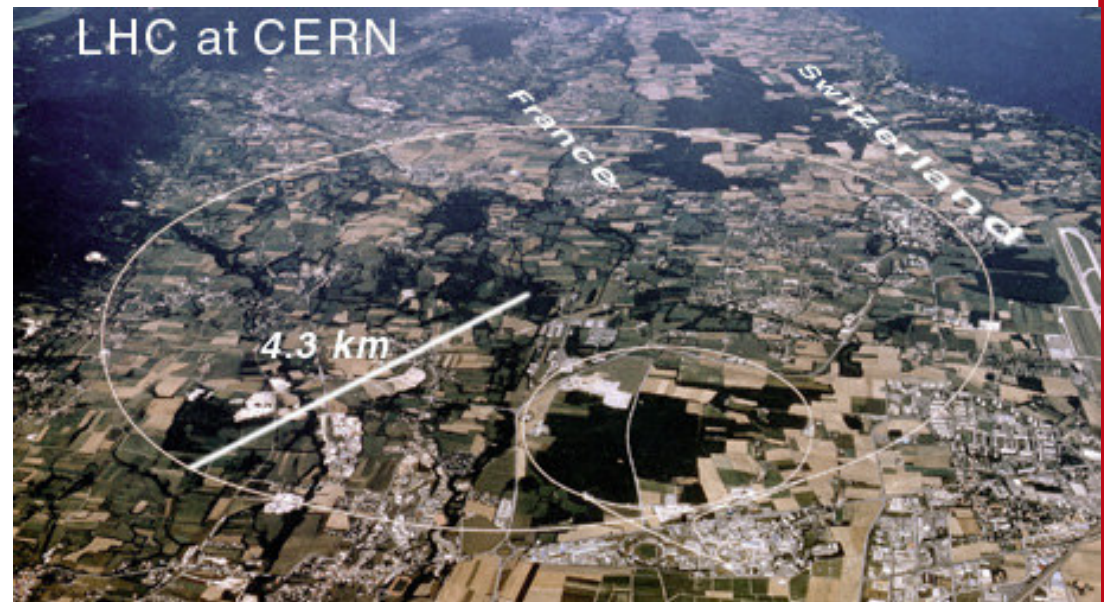
CHESS & LEPP

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

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

$$P_{\text{radiation}} = \frac{c}{6\pi\epsilon_0} N \frac{q^2}{\rho^2} \gamma^4 \quad \Downarrow$$

Energy needed to compensate  
 Radiation becomes too large



Electron beam with  $p = 0.1 \text{ TeV}/c$  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

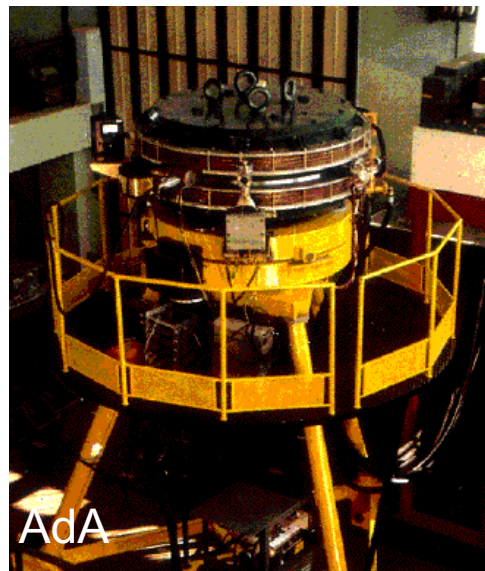
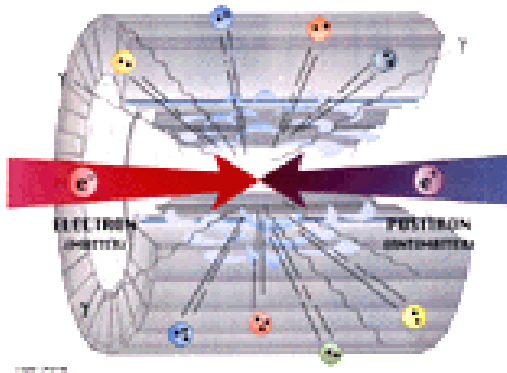


CHESS & LEPP

- 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



AdA



CESR

Drawback:

Less dense target

The beams therefore must be stored for a long time.

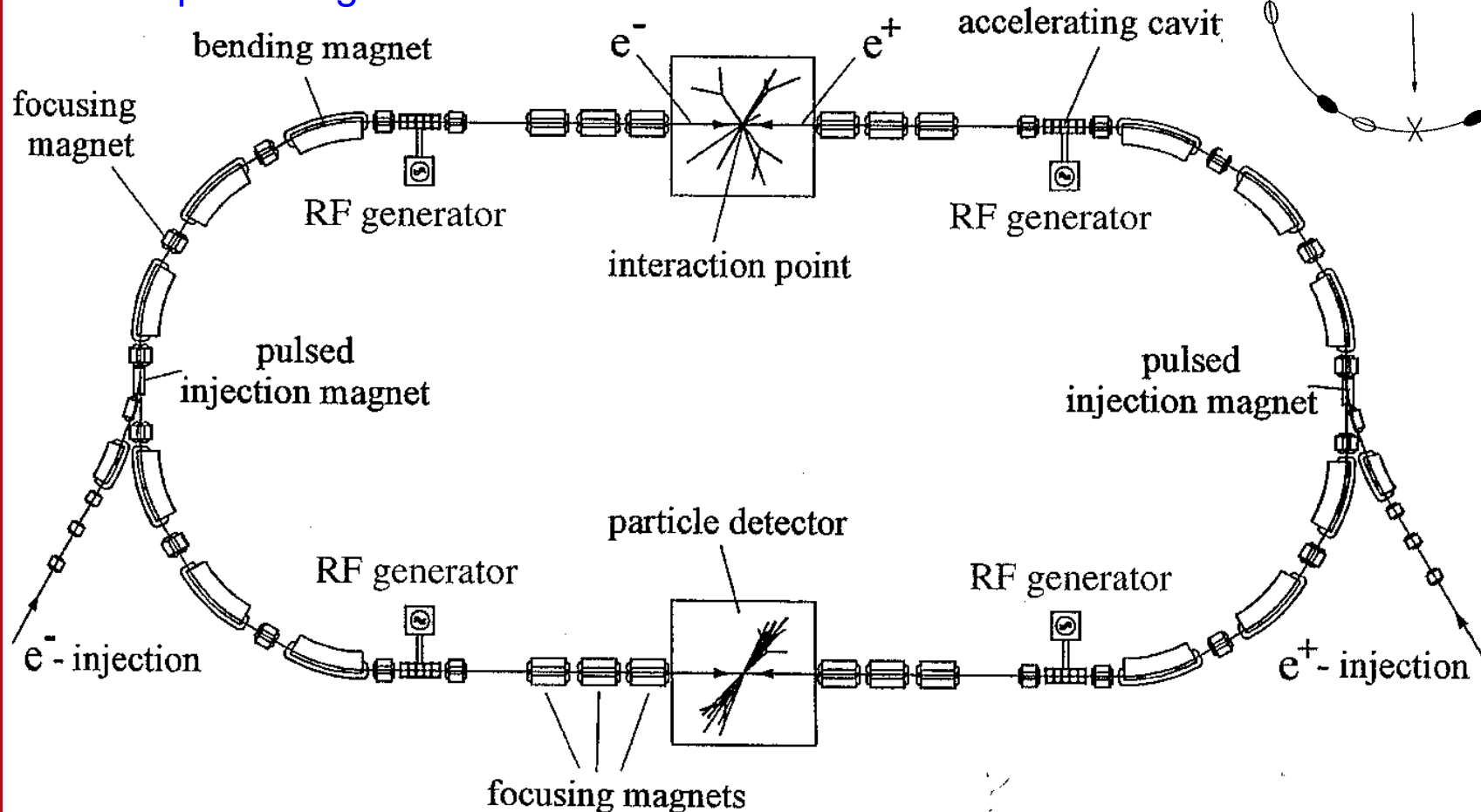


# Elements of a Collider



CHES & LEPP

- Saving one beam while injection another
- Avoiding collisions outside the detectors.
- Compensating the forces between  $e^+$  and  $e^-$  beams





## Storage Rings



CHESS & LEPP

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-protons 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 -



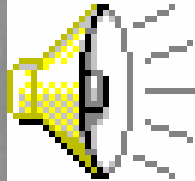
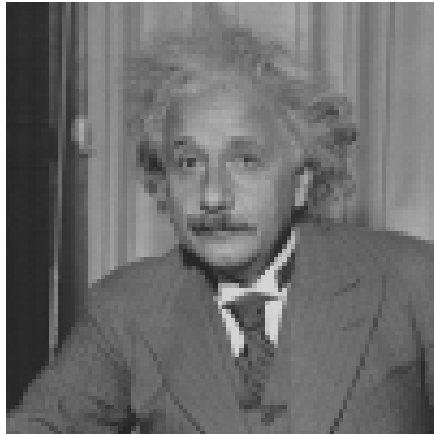
NP 1984  
Simon van der Meer  
Netherlands 1925 -







$$E = mc^2$$



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:

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

$$P^\mu \in \left\{ \frac{1}{c} E, p_x, p_y, p_z \right\}$$

$$\Phi^\mu \in \left\{ \frac{1}{c} \phi, A_x, A_y, A_z \right\}$$

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

$$K^\mu \in \left\{ \frac{1}{c} \omega, k_x, k_y, k_z \right\}$$

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

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



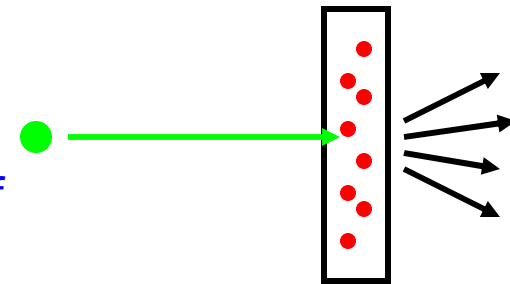
# Available Energy



CHESS & LEPP

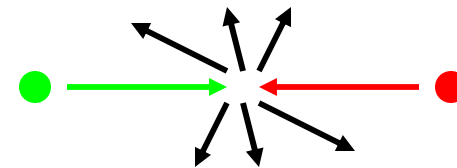
$$\begin{aligned}
 \frac{1}{c^2} E_{\text{cm}}^2 &= (P_1^\mu + P_2^\mu)_{\text{cm}} (P_{1\mu} + P_{2\mu})_{\text{cm}} \\
 &= (P_1^\mu + P_2^\mu)(P_{1\mu} + P_{2\mu}) \\
 &= \frac{1}{c^2} (E_1 + E_2)^2 - (p_{z1} - p_{z2})^2 \\
 &= 2\left(\frac{E_1 E_2}{c^2} + p_{z1} p_{z2}\right) + (m_{01} c)^2 + (m_{02} c)^2
 \end{aligned}$$

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



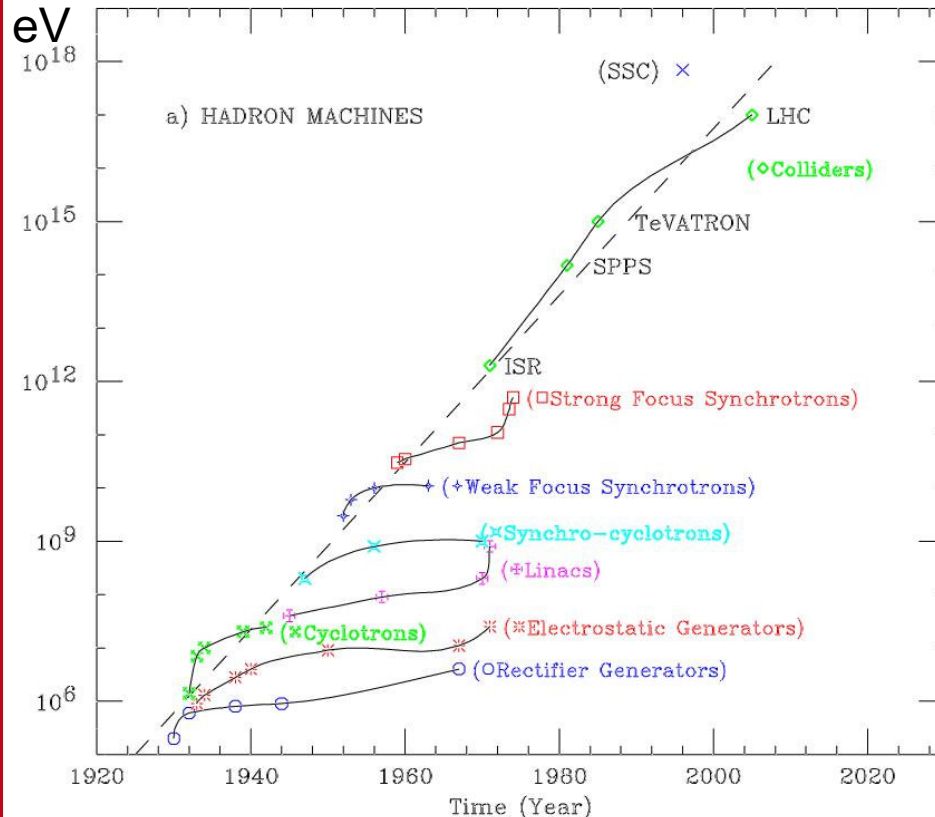
$$E_1 \gg m_{01} c^2; E_2 \gg m_{02} c^2 \Rightarrow E_{\text{cm}} = 2\sqrt{E_1 E_2}$$



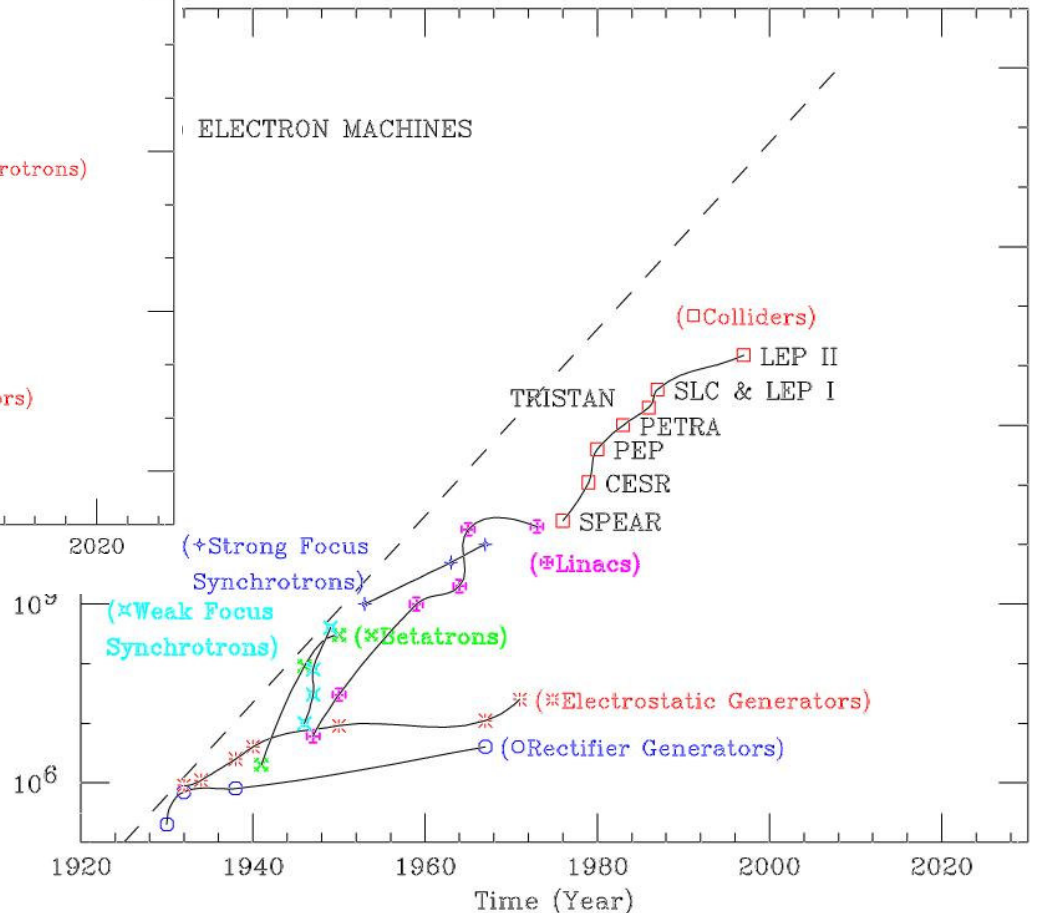
# The Livingston Chart



CHES & 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

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