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THE EXPERIMENTAL VIEW OF PARTICLES AND FORCES IN 1987: A PICTURE OUTLINE OF THE TALK*†

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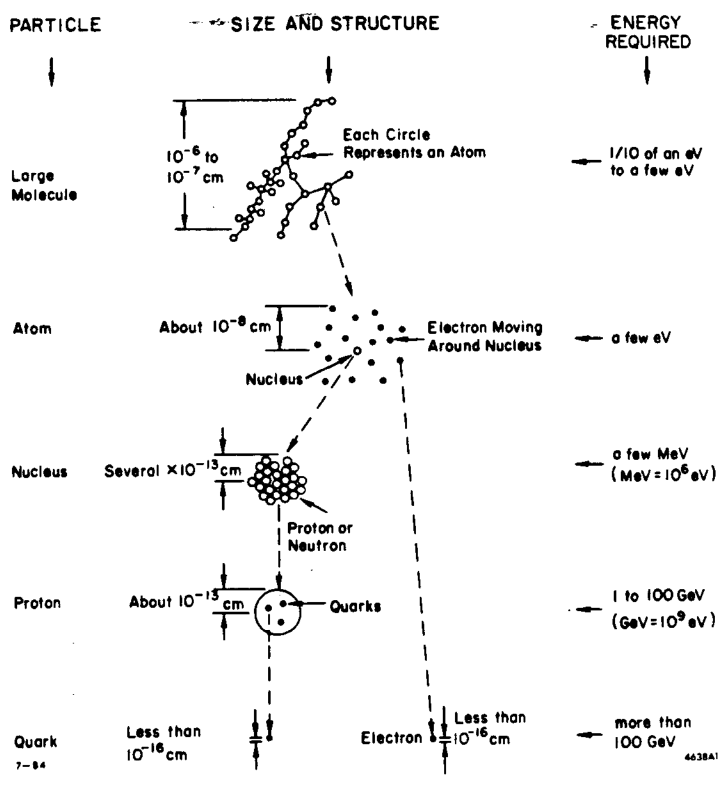


⋆ This work was supported in part by the Department of Energy, contract DE-AC03-76SF00515 (SLAC).

† Many of the figures in this talk were prepared by the author for Elementary-Particle Physics, Physics Through The 1990s (Nat. Acad. Press, Washington, D.C.,1986) Martin L. Perl and William T. Kirk, Ed. This book gives a full, introductory, account of the present state of elementary particle physics.

(Presented at the Annual Meeting of the American Association for the Advancement of Science, Chicago, Illinois, February 14-18, 1987)

CONTENTS

1. WHAT IS AN ELEMENTARY PARTICLE?

<u>Definition</u>: Not composed of other particles or parts.
No internal structure.

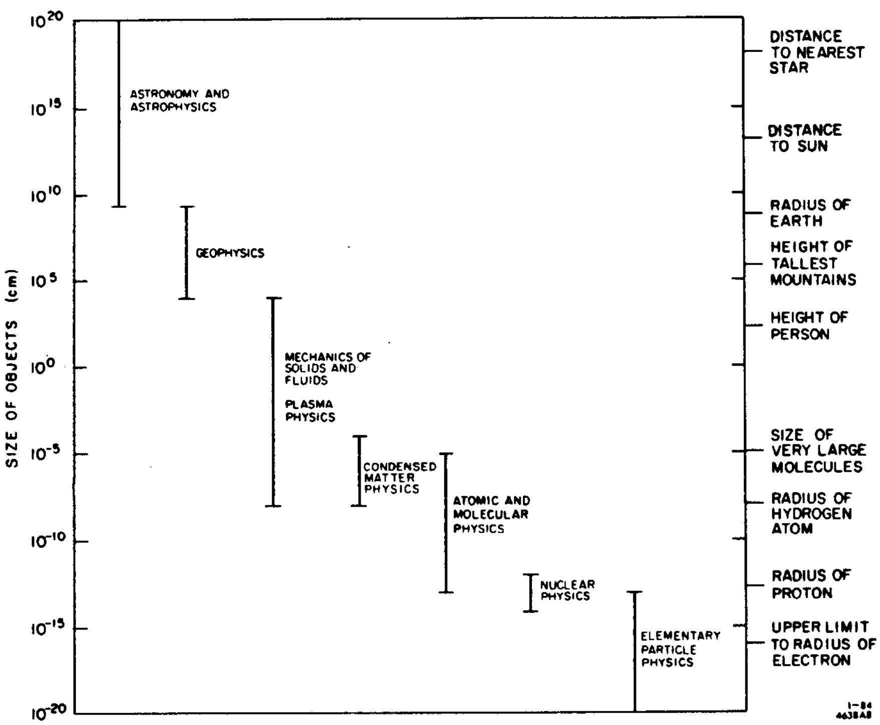
<u>Examples</u>: Elementary: electron, quark (see page 4).
Not elementary: atom, nucleus, proton, neutron.

<u>Size:</u> Smaller than 10^{-16} inches.

$10^{-16} = \frac{1}{10{,}000{,}000{,}000{,}000{,}000}$.

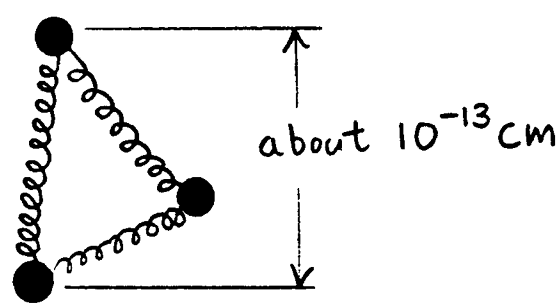
Perhaps zero size.

Elementary particle physics concerns the smallest things in nature.



Electron: All present experiments indicate that electron is elementary because no internal parts or structure can be found. There is no way to foretell if future, higher energy, experiments will confirm this conclusion.

Proton: Not elementary because experiments show it consists of three much smaller particles called quarks held together by the strong force. (In the picture below, the dots represent quarks and the springs represent the strong force).

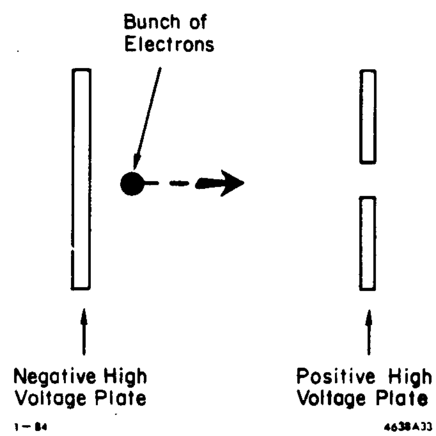


Quarks: Make up the proton and the neutron and many other sub-nuclear particles. All present experiments indicate that quarks are elementary. Five kinds of quarks have been found, called: up, down, strange, charm, and bottom.

2. HIGH ENERGY

Most experiments use particles with very large kinetic energies compared to their mass. Hence called high energy physics.

Required to	Convert energy into mass $E = MC^2$.
	Penetrate deeper into particles.
	High energy needed to investigate small distances by Heisenberg Uncertainty Principle $\Delta P \Delta X > \hbar$.
Units:	Electron-volt = eV = energy gained by 1 electron or 1 proton as it passes through 1 volt of electric field.
Accelerators:	Give electrons or protons high energy with strong electric fields.



1 MeV = 10^{+6} eV = 1 million electron-volts

1 GeV = 10^{+9} eV = 1 billion electron-volts

1 TeV = 10^{+12} eV = 1 trillion electron-volts

Electron mass is about 0.5 MeV

Proton mass is about 1 GeV

Heaviest known particle, the Z^0, has a mass of about 90 GeV

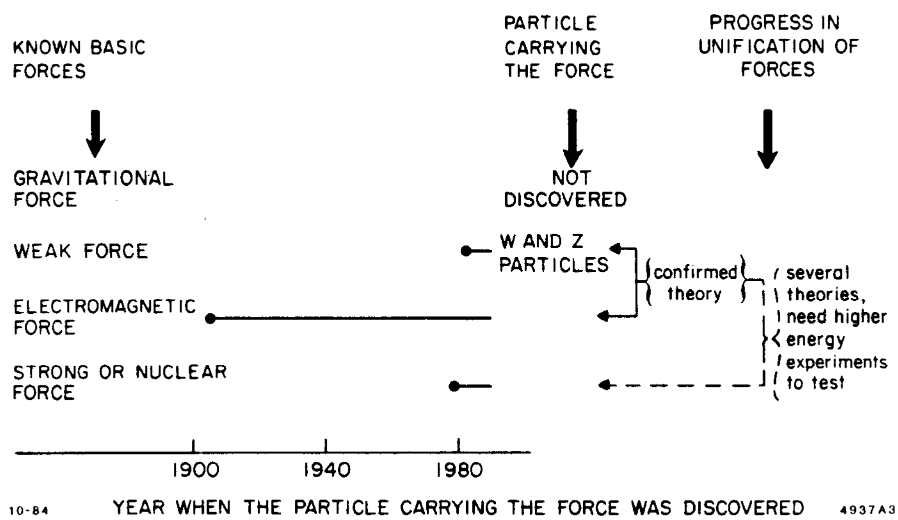
3. THE FUNDAMENTAL FORCES

Four fundamental forces known

From quantum mechanics expect each force carried by a particle

Weak and Electromagnetic have been unified in a single theory called Electroweak

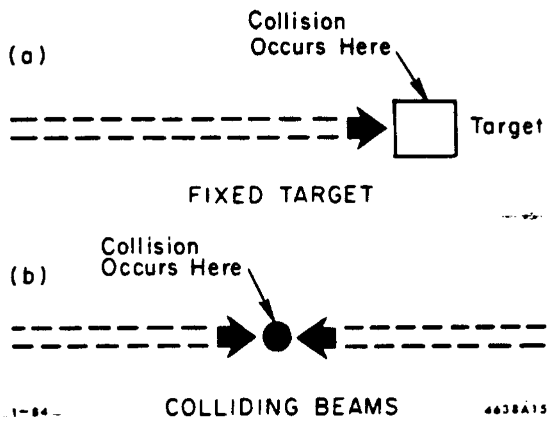
Type of Force	Gravitational	Weak	Electromagnetic	Strong or Nuclear
Behavior over distance	Extends to very large distances	Limited to less than about 10^{-16} cm	Extends to very large distances	Limited to less than about 10^{-13} cm
Strength relative to strong force at a nuclear distance	10^{-38}	10^{-13}	10^{-2}	1
Particle which carries the force	Not discovered	W^+, W^- and Z^0 Intermediate bosons	Photon	Gluon The gluon has been identified indirectly but it has not, and perhaps cannot, be isolated

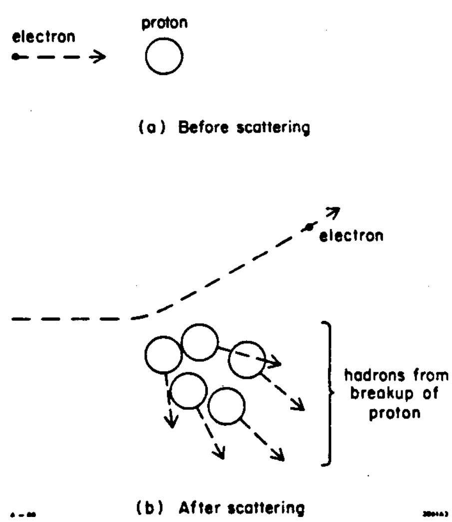


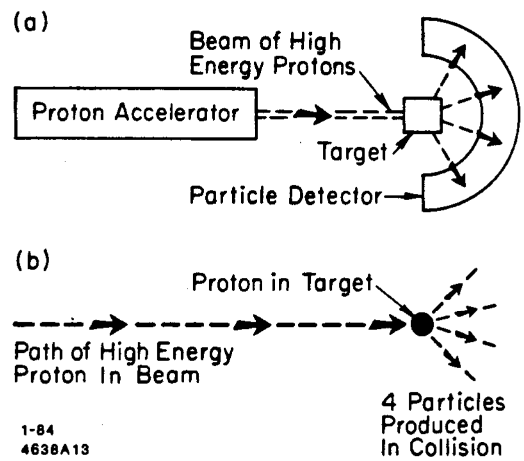
4. EXPERIMENTING WITH ELEMENTARY PARTICLES

Elementary particles are too small to disect or even to directly see. Most experiments use the collisions of high energy particles from accelerators to:

Measure the size, mass, and charge of particles.
Determine how particles interact with each other.
Study the forces between particles.
Look for new particles and forces.



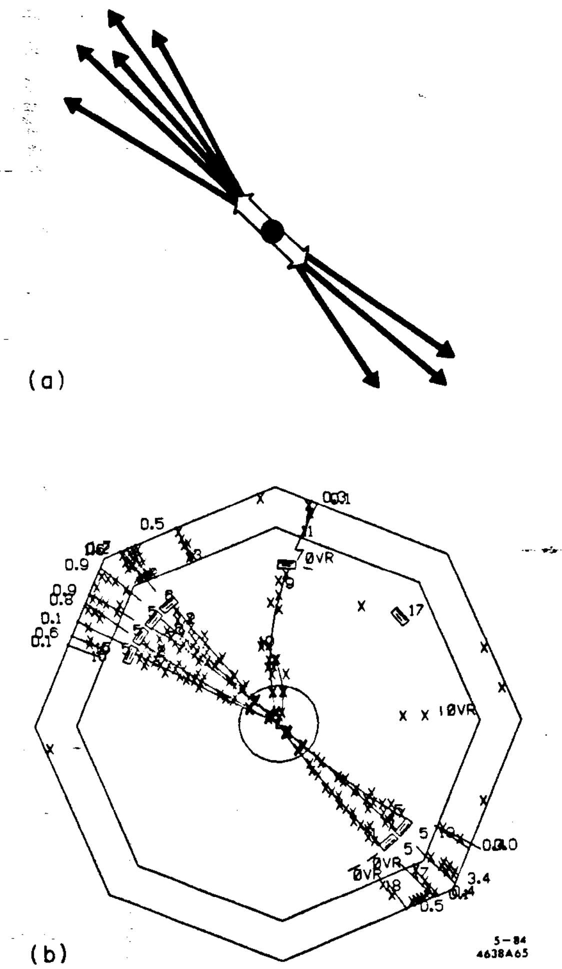




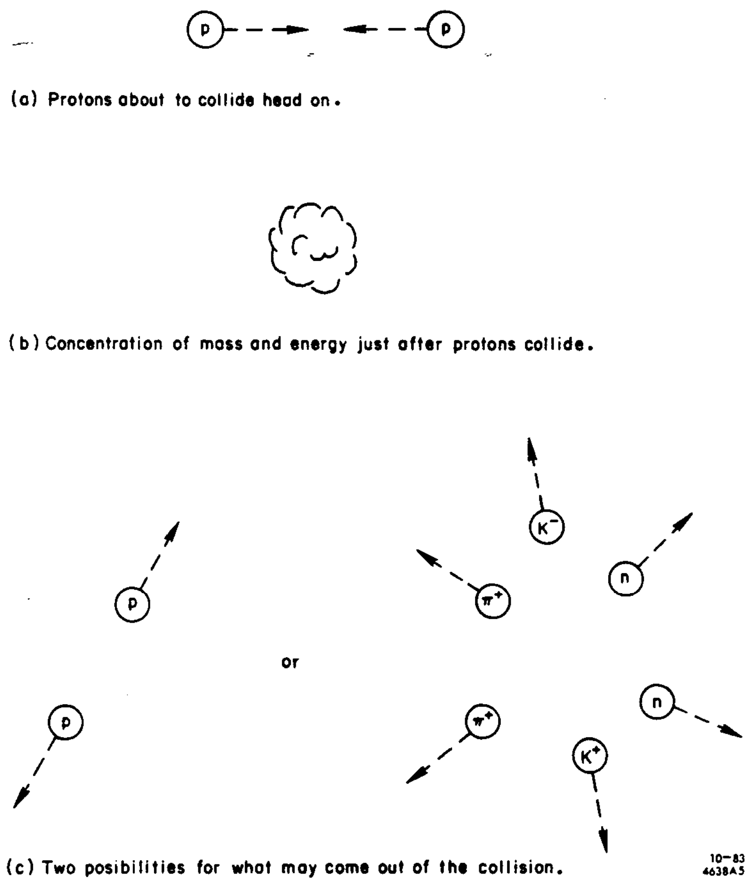
electron-proton collision

proton-proton collision

Fixed Target Experiments



electron-positron collision

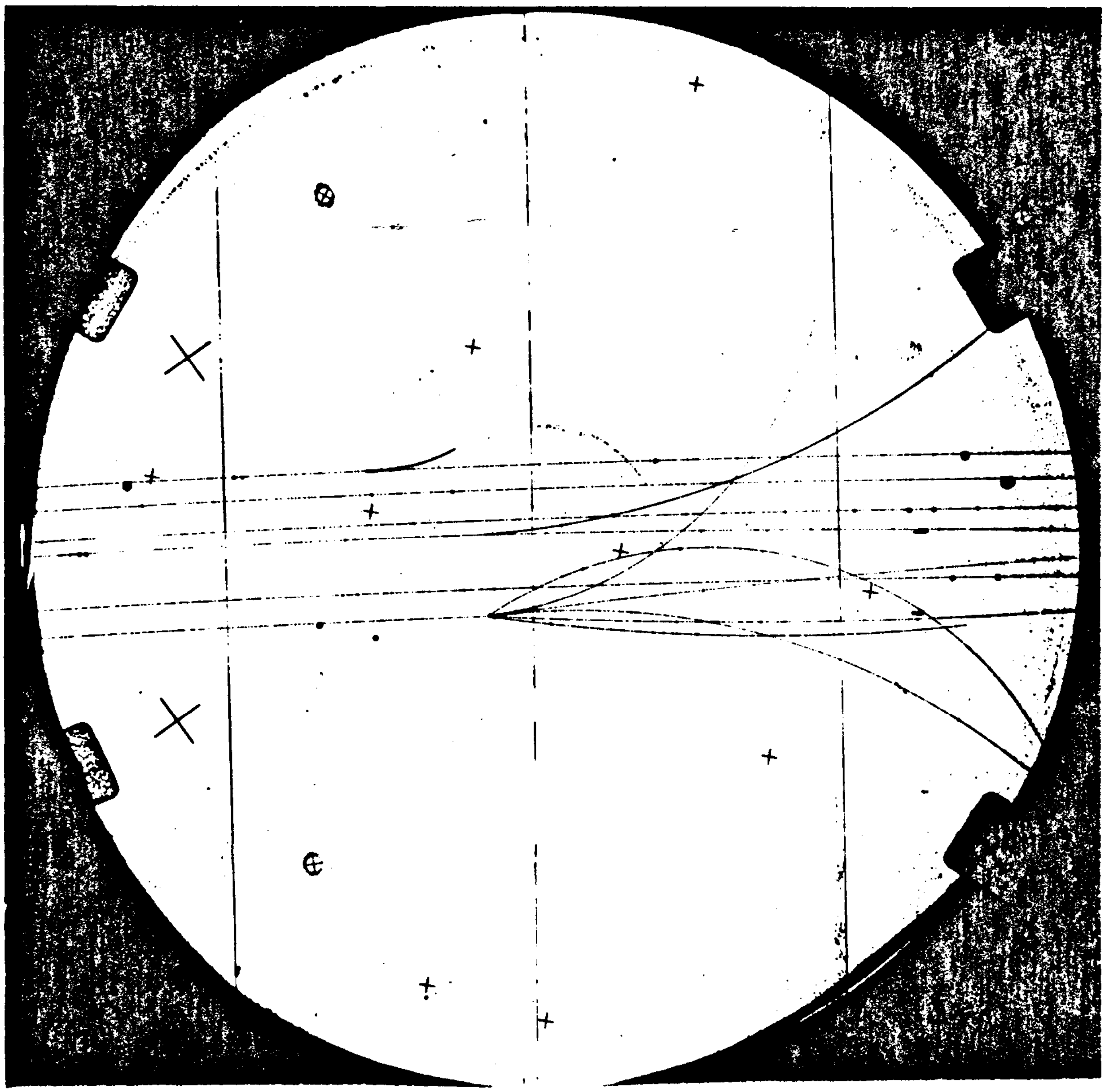


proton-proton collision

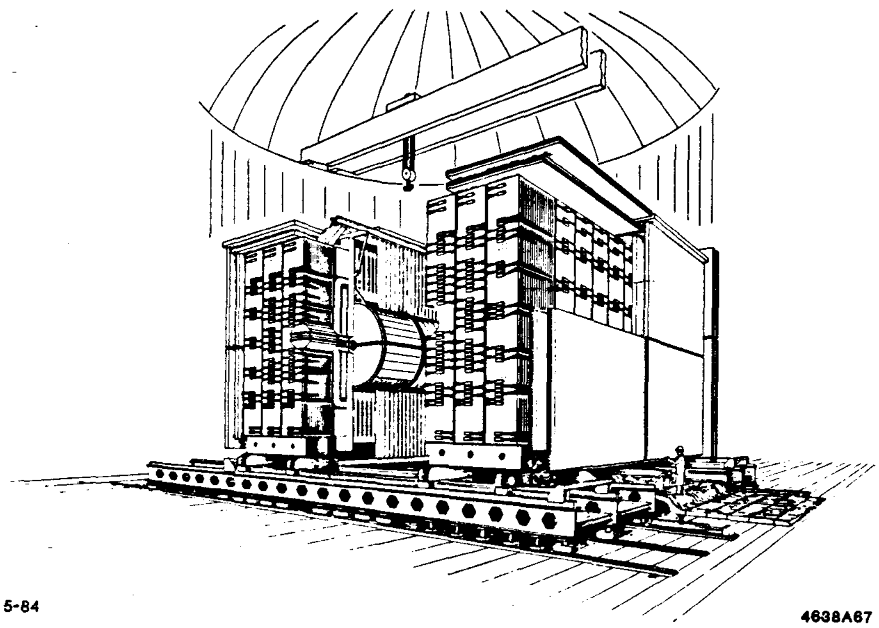
Colliding Beam Experiments

5. DETECTING ELEMENTARY PARTICLES

In a bubble chamber the paths of particles are detected by the trail of bubbles they leave as they pass through. Here six high energy pions entered the bubble chamber from the left, and more through it to the right. The lowest one collides with a proton in the chamber and makes six particles. The fourth one down also collides, making two particles.



Now most particle detectors find the paths of particles through electromagnetic and electronic devices, then use computers to construct a picture of the event.



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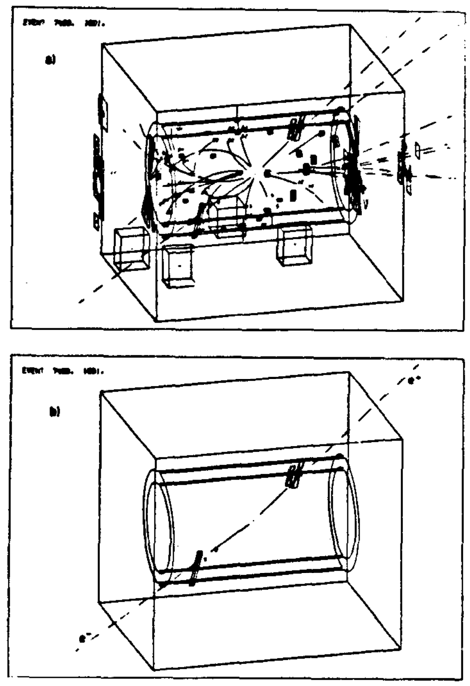
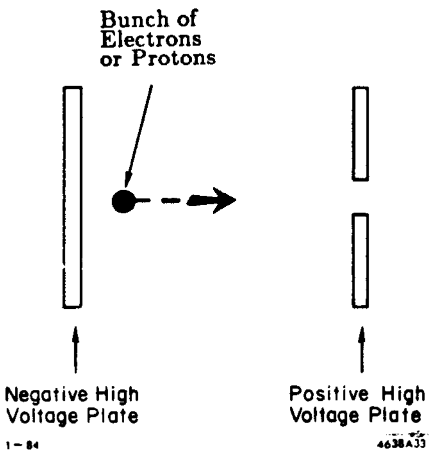
The UA1 detector at CERN. Note the enormous size of the detector compared to the person standing at its lower right side.



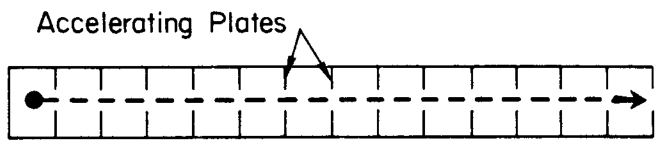
One of the Z^0 decay events from the UA1 detector.

A Large, Modern Particle Detector

6. ACCELERATORS

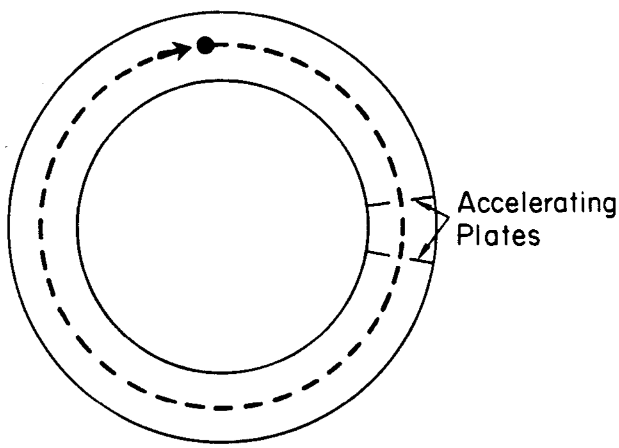


← Basic unit for accelerating particles



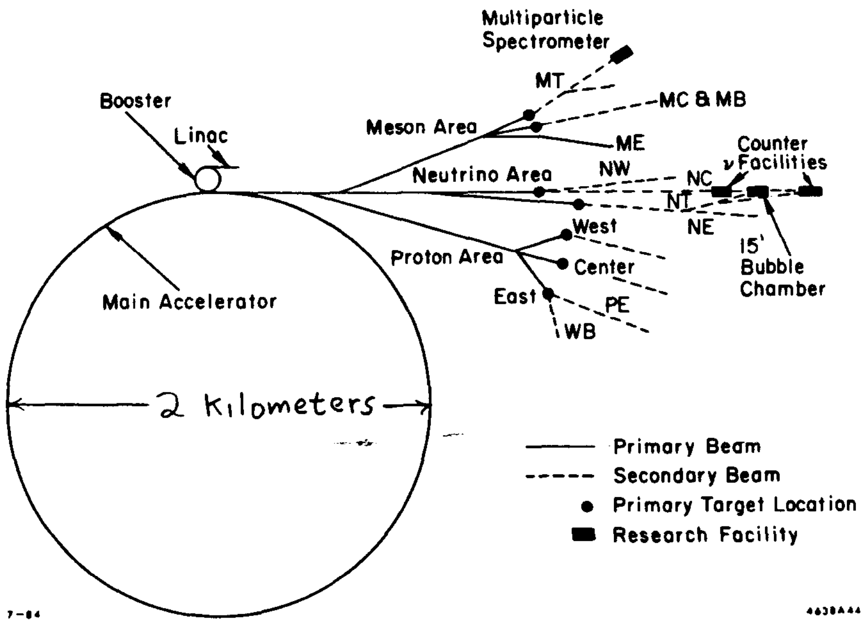
Linear Accelerator

To obtain high energy the particles must pass through an acceleration unit many times. In a linear accelerator many acceleration units are lined up. In a circular accelerator the particles pass through the same unit many times.

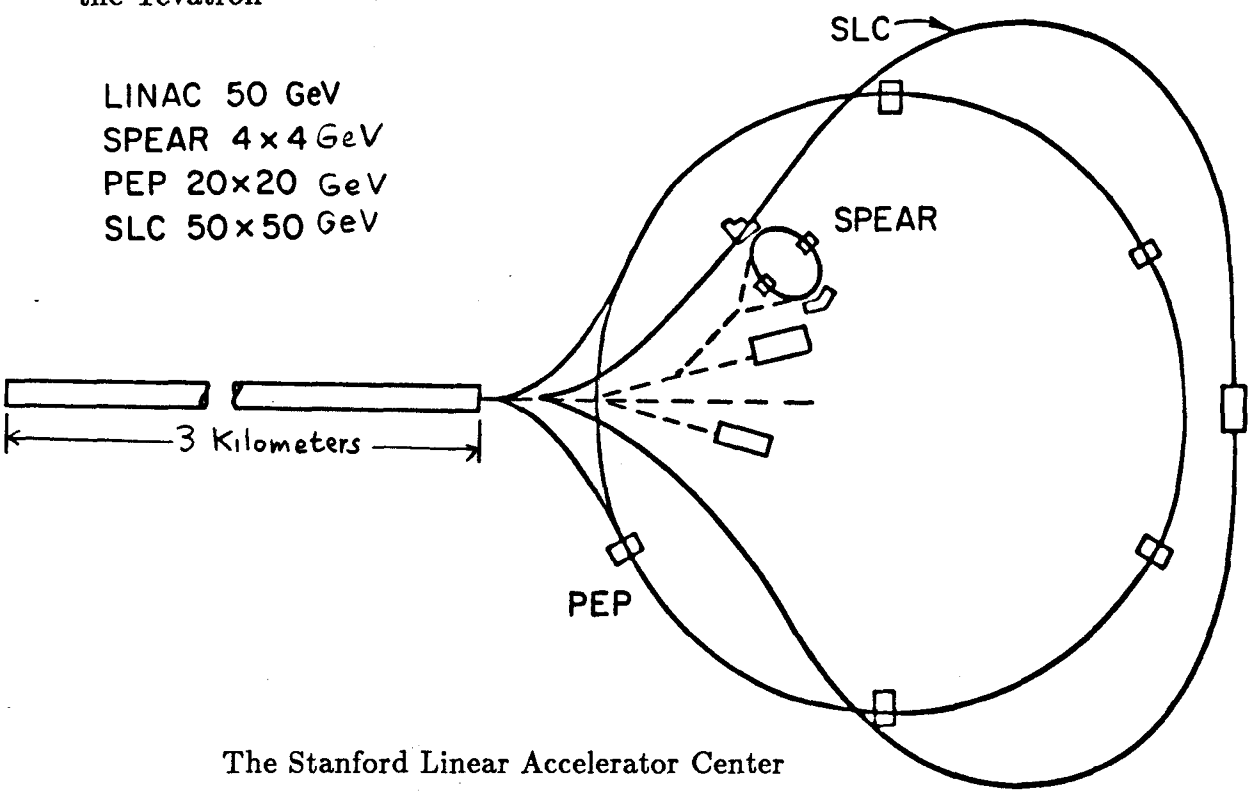


1-84 Circular Accelerator 4638A34

High energy accelerators are large and complex

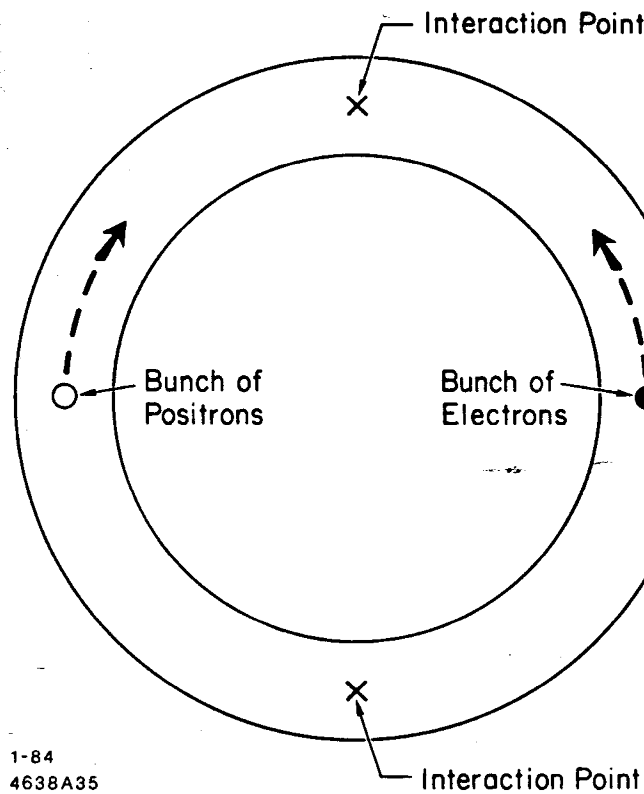


Fixed target facilities at the Fermilab proton accelerators, the Tevatron

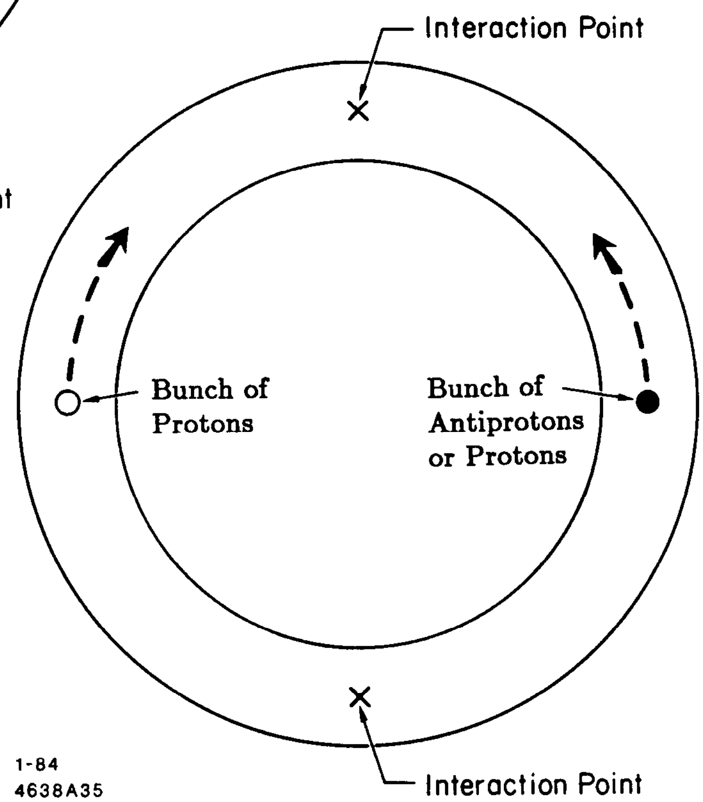


The Stanford Linear Accelerator Center

7. COLLIDERS



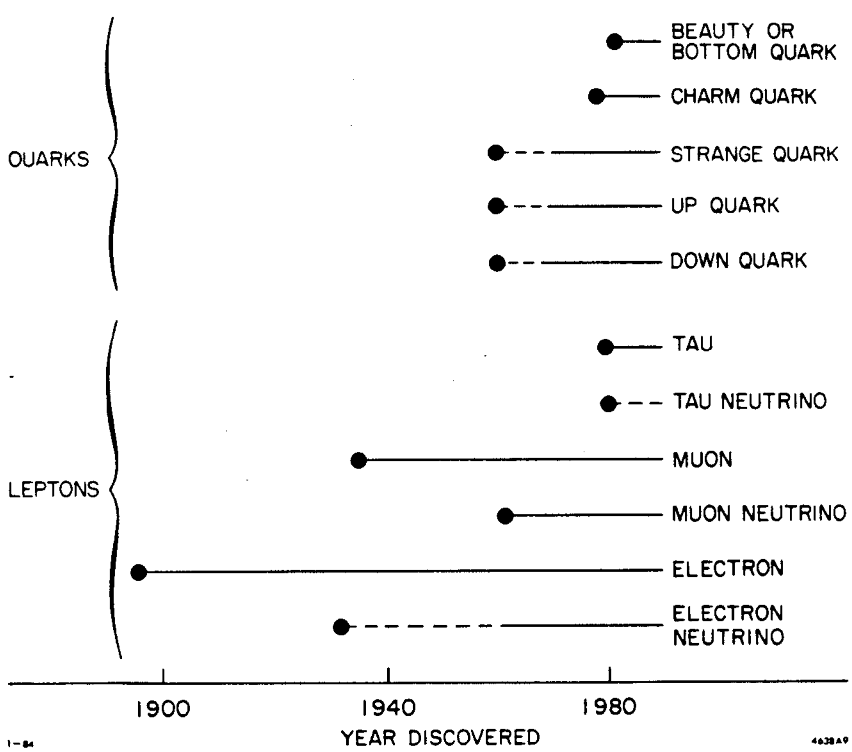
Electron-Positron Collider



Proton-Antiproton or Proton-Proton Collider

8. THE KNOWN ELEMENTARY PARTICLES: LEPTONS AND QUARKS

	Leptons	Quarks
Affected by electroweak force	Yes	Yes
Affected by gravity	Yes expected but not proven for all leptons	Yes
Affected by strong force	No	Yes
Can be isolated	Yes	Either no or very difficult
Combine together to make composite particles	No	Yes, form the hadrons
Electric charge in terms of electron charge	0, ±1	±2/3, ±1/3



THE KNOWN LEPTONS AND QUARKS: THE GENERATIONS

Generation	LEPTONS Particle	LEPTONS Charge	LEPTONS Mass	QUARKS Particle	QUARKS Charge	QUARKS Mass
1	electron (e)	–1	0.51 MeV	up (u)	+2/3	about 300 MeV
	electron neutrino (ν_e)	0	less than 40 eV	down (d)	–1/3	about 300 MeV
2	muon (μ)	–1	106 MeV	charm (c)	+2/3	about 1500 MeV
	muon neutrino (ν_μ)	0	less than .25 MeV	strange (s)	–1/3	about 1500 MeV
3	tau (τ)	–1	1784 MeV	†		
	tau neutrino* (ν_τ)	0	less than 70 MeV	bottom (b)	–1/3	about 5,000 MeV

*indirect evidence

†top (t) quark expected but not yet found.

Aside on Hadrons

Hadrons, such as protons, neutrons and pions, are subnuclear, but not elementary particles.

The meson family of hadrons, such as the pion, kaon and psi, are made up of one quark and one antiquark held together by the strong force.

The baryon family of hadrons, such as protons, neutrons and antiprotons, are made up of three quarks or three antiquarks held together by the strong force.

Some Hadrons

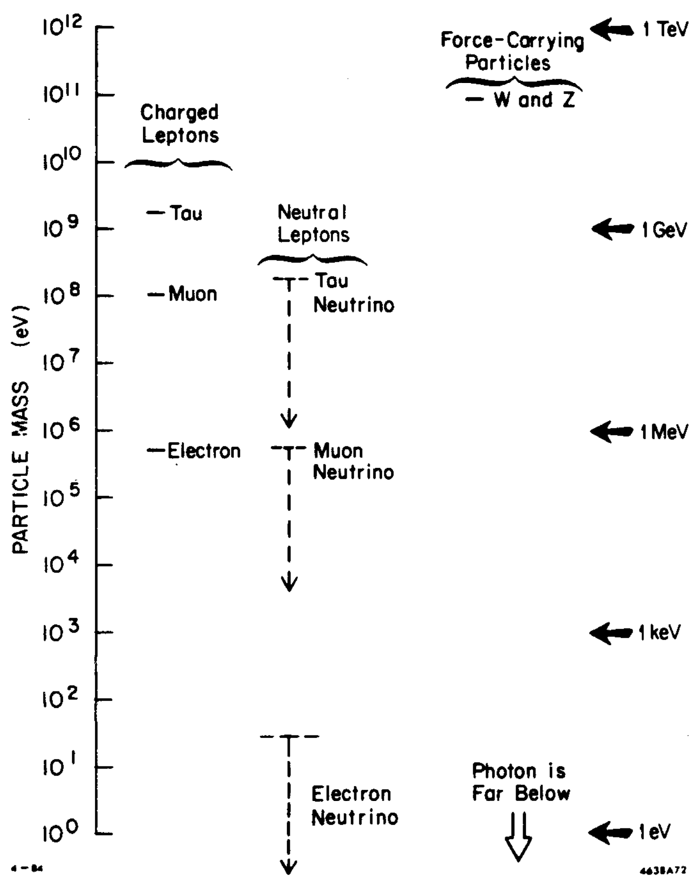
Name	Mass in GeV	Quarks in the hadrons
proton	0.938	2 up quarks plus 1 down quark
antiproton	0.938	2 anti-up quarks plus 1 anti-down quark
neutron	0.940	1 up quark plus 2 down quarks
positive pion	0.140	1 up quark plus 1 anti-down quark
positive kaon	0.494	1 up quark plus 1 anti-strange quark
psi or J	3.097	1 charm quark plus 1 anti-charm quark
upsilon	9.460	1 bottom quark plus 1 anti-bottom quark

9. THE KNOWN ELEMENTARY PARTICLES: FORCE-CARRYING PARTICLES

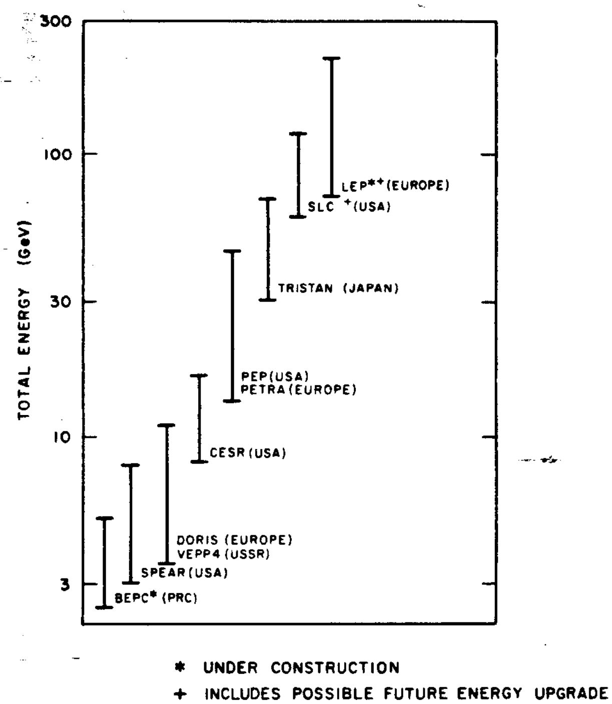
Force	Particle	Mass	Comment
Strong	Gluon	Indirectly measured to be close to 0	Existence proven indirectly but probably cannot isolated.
Electromagnetic	Photon	0	Has been isolated and studied for 80 years.
Weak	$W^{\pm}$	83 GeV	Recently discovered, isolated, and studied.
	Z^0	93 GeV	
Gravitational			Quantum mechanics predicts there should be a particle. Usually called graviton. But has not been discovered and there is no accepted quantum mechanical theory of gravitation.

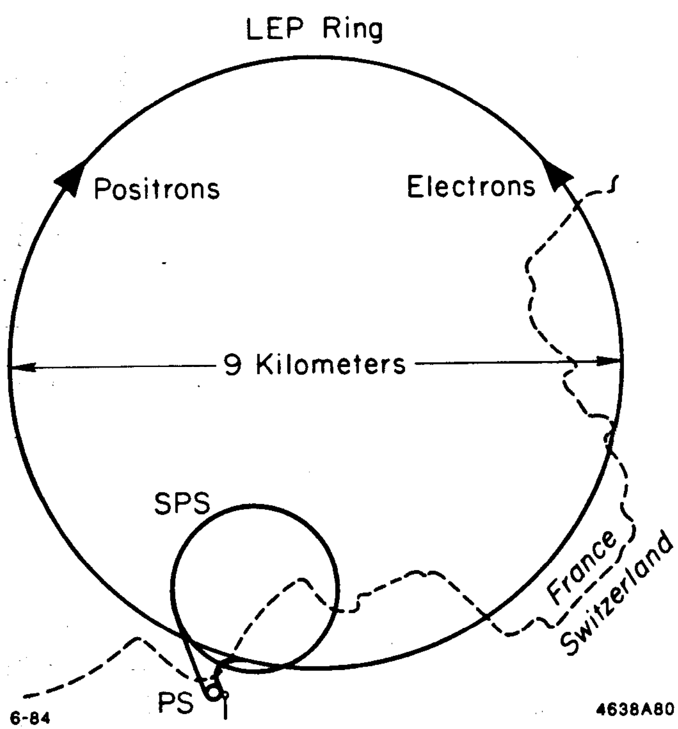
10. WHAT WE WANT TO KNOW

What is the origin of mass?
What sets the masses of the different particles?
Why are there quark and lepton generations?
Are there more than three quark or lepton generations?
Are the quarks and leptons truly elementary?
Can the strong and electroweak interactions be unified?
Are there undiscovered fundamental forces?
Are there undiscovered new types of elementary particles?

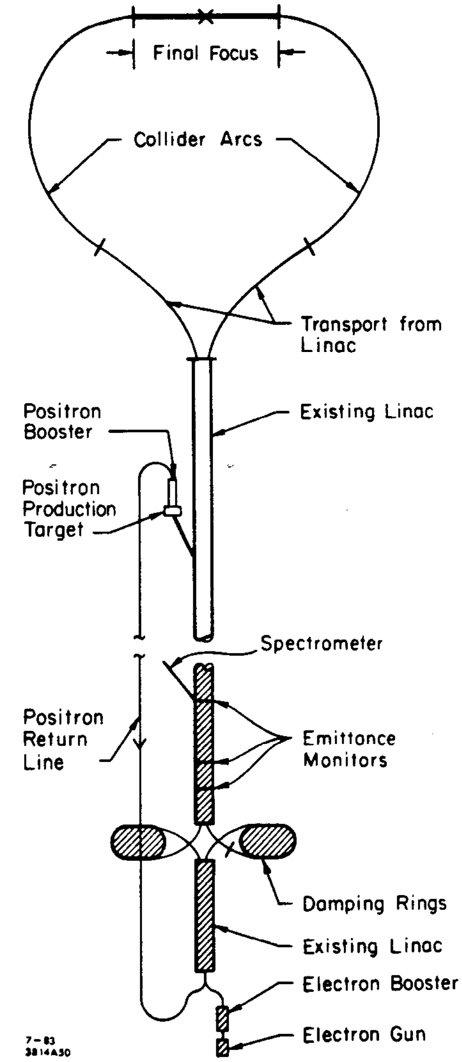


11. GOING TO HIGHER ENERGY: ELECTRON-POSITRON COLLIDERS



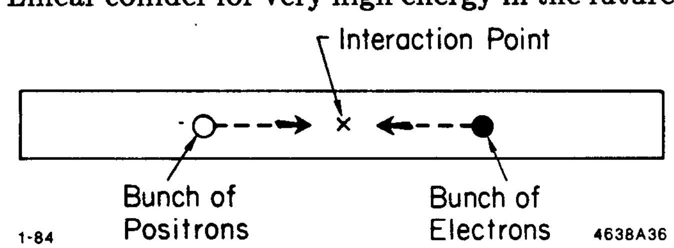


LEP (Circular Collider). Will be completed in 1989.

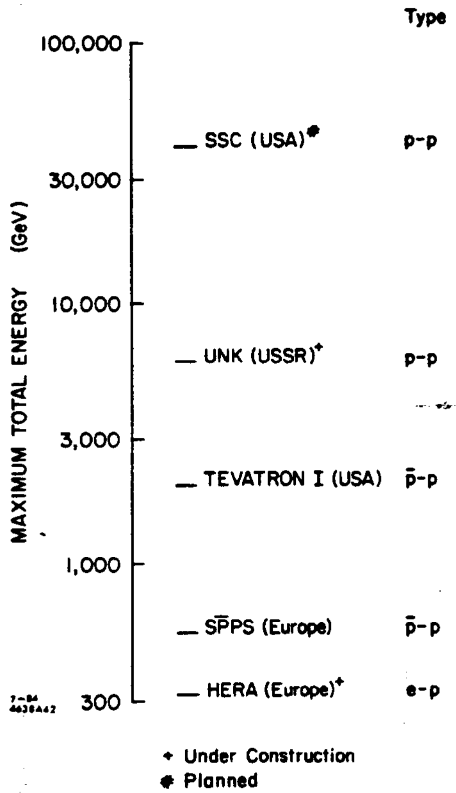


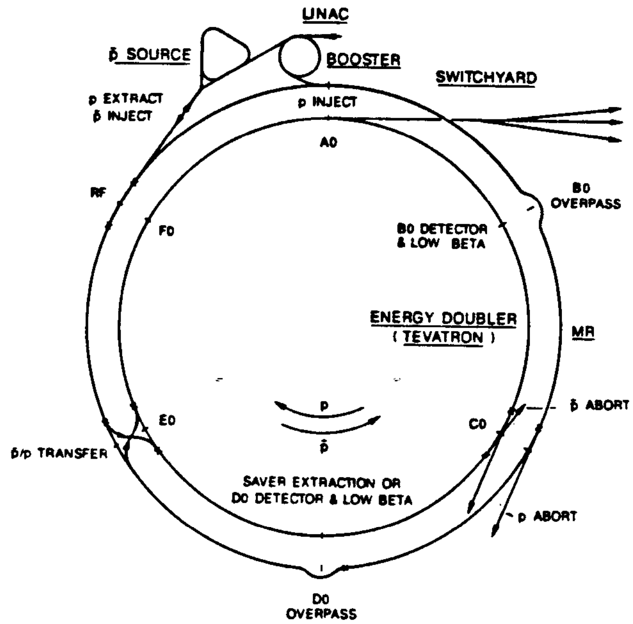
SLC (SLAC Linear Collider). Beginning operation.

Linear collider for very high energy in the future?

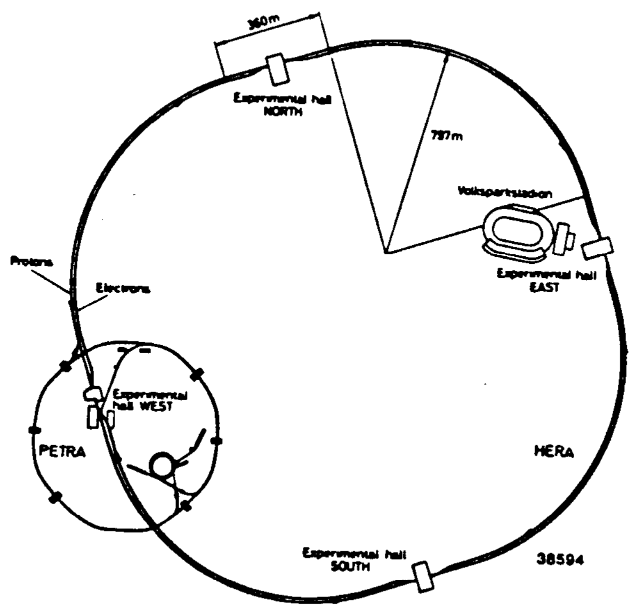


12. GOING TO HIGHER ENERGY: ANTIPROTON-PROTON, PROTON-PROTON, AND ELECTRON-PROTON COLLIDERS



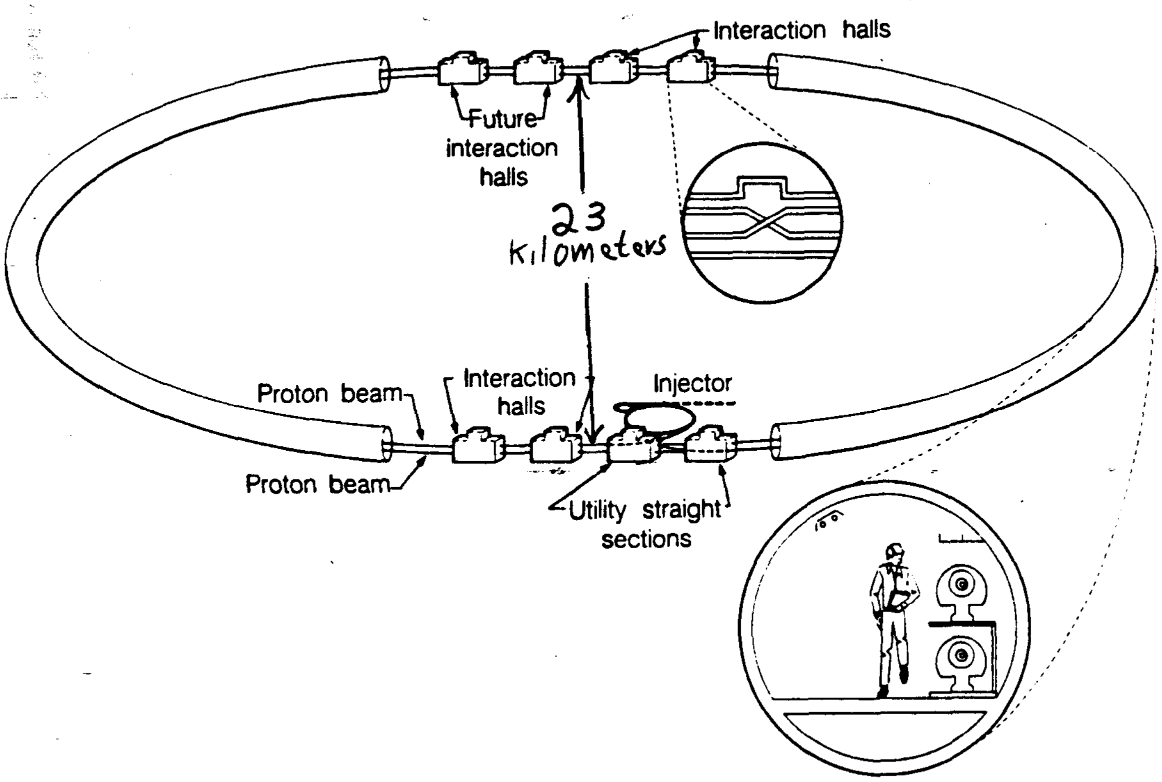


Tevatron proton-antiproton Collider. Beginning operation.

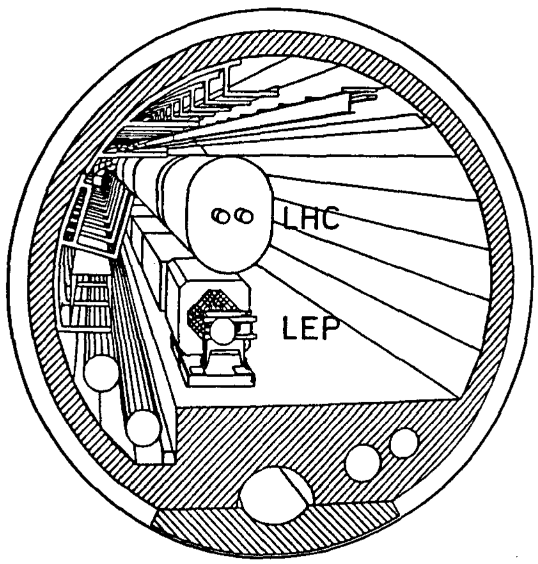


HERA electron-proton Collider. Under construction.

Proposed Very High Energy Proton-Proton Colliders



Proposed Superconducting Super Collider (SSC). 40 TeV energy.



Large Hadron Collider (LHC) being considered for LEP tunnel. About 18 TeV energy.