Particles,
Mysteries,
and Linear Colliders

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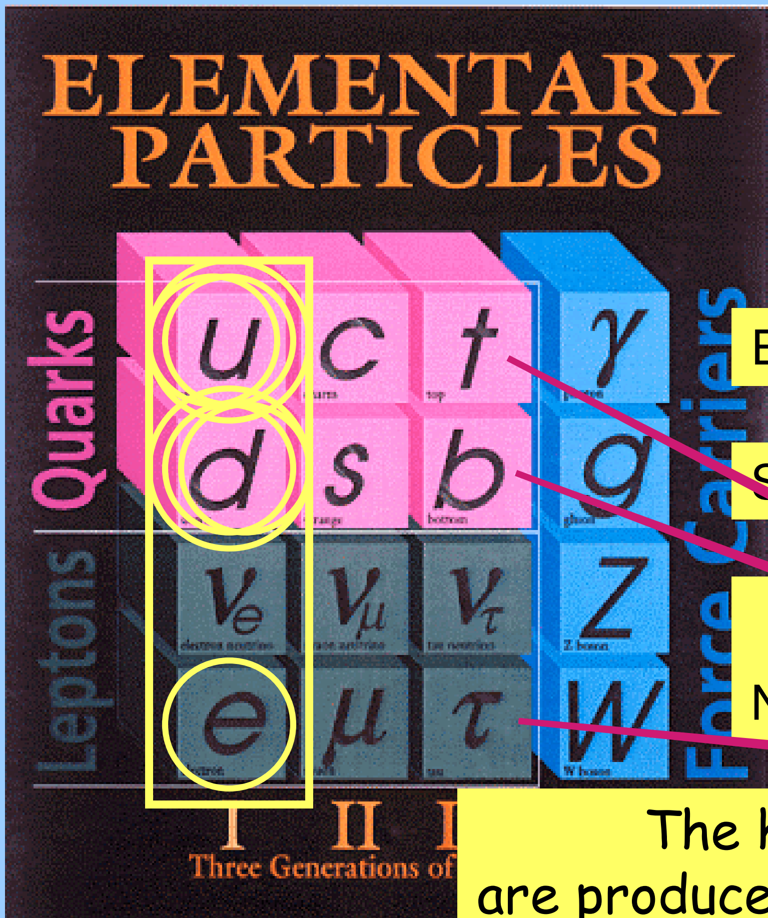
June 20, 2003

Particles and Forces



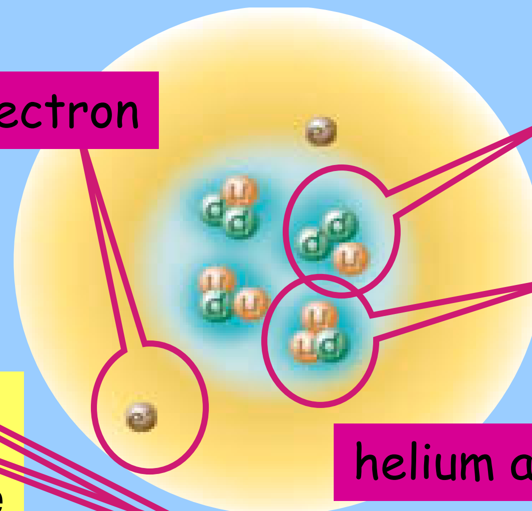
Electrom

Strong N

Weak

Nuclear Force

Everyday matter is composed of the lightest quarks and leptons



electron

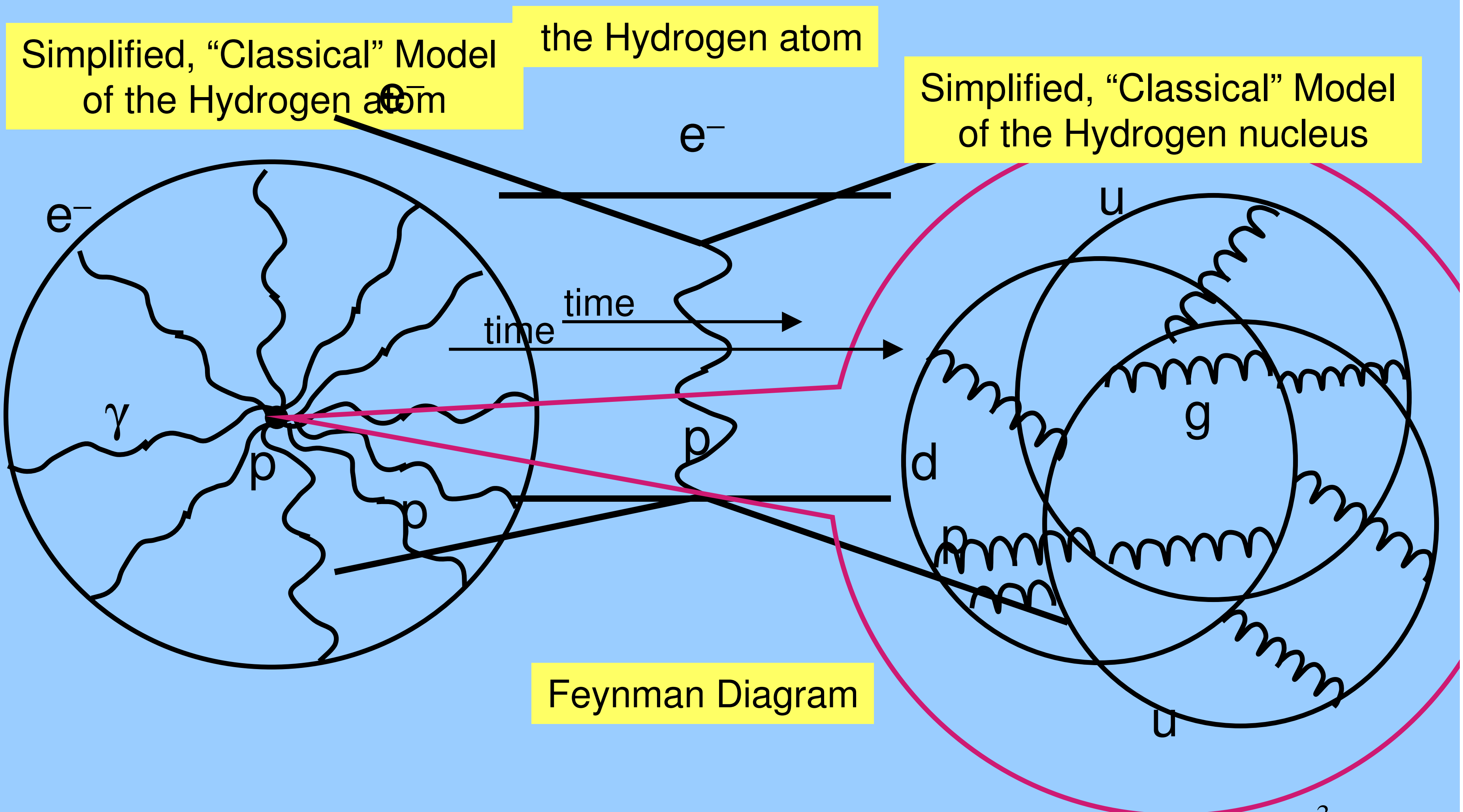
neutron

proton

helium atom

The heavier particles, such as t, b, and τ, are produced and studied at high energy accelerators, and were common in the early universe

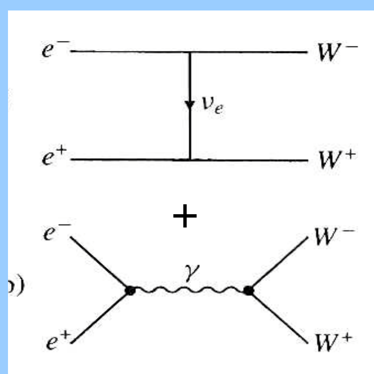
Particles and Forces

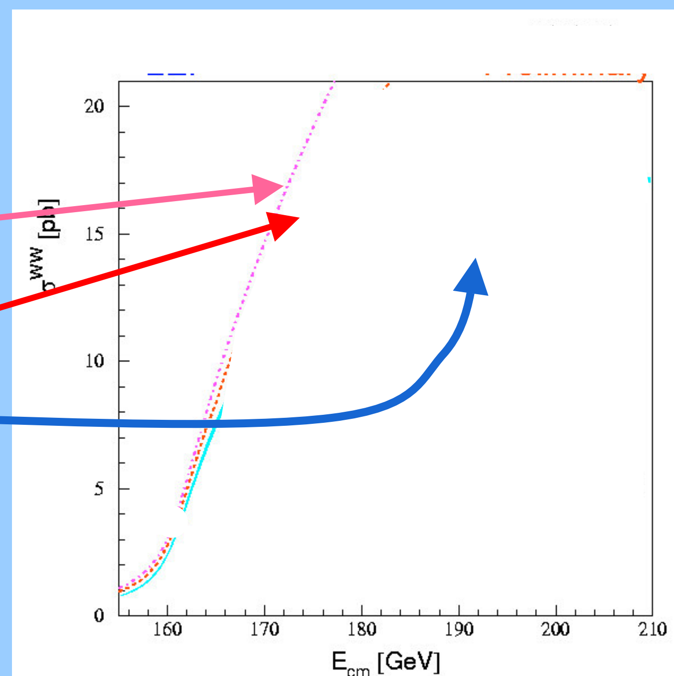


Particles

- Particle Physics left the 20th Century with a triumphant model of the fundamental particles and interactions - the Standard Model
  - quarks, leptons, gauge bosons mediating gauge interactions
  - thoroughly tested
  - no confirmed violations

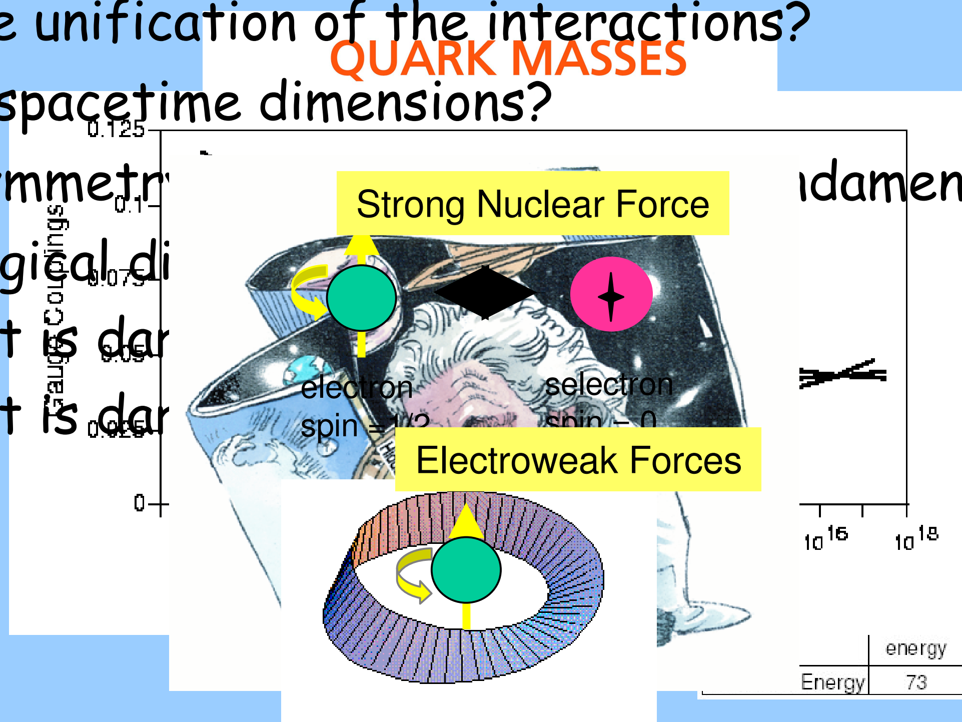
$e^+e^- \rightarrow W^+W^-$

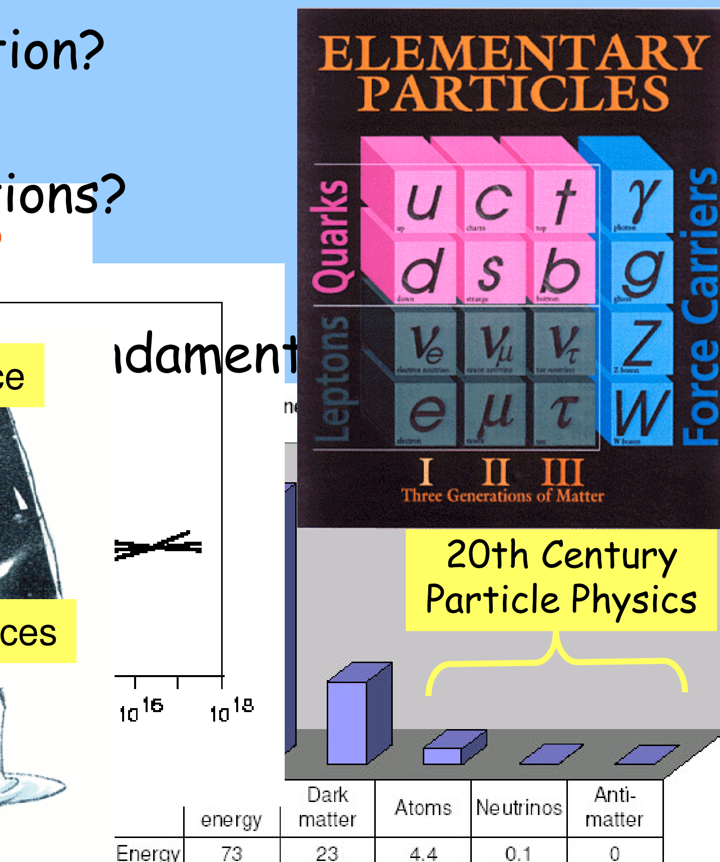




Mysteries

- We enter the 21st Century with mysteries of monumental significance in particle physics:
  - Physics behind Electroweak unification?
    - The top quark mass
  - Ultimate unification of the interactions?
  - Hidden spacetime dimensions?
  - Supersymmetr ıdament
  - Cosmological di
    - What is dar
    - What is dar



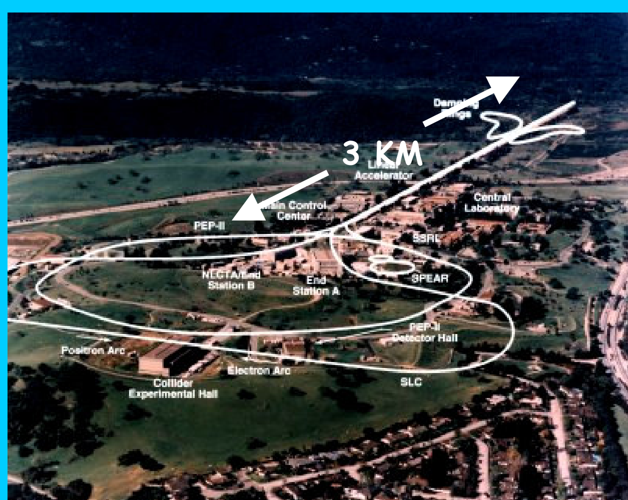


Linear Colliders

- The electron-positron Linear Collider is a critical tool in our probe of these secrets of Nature

The First Linear Collider

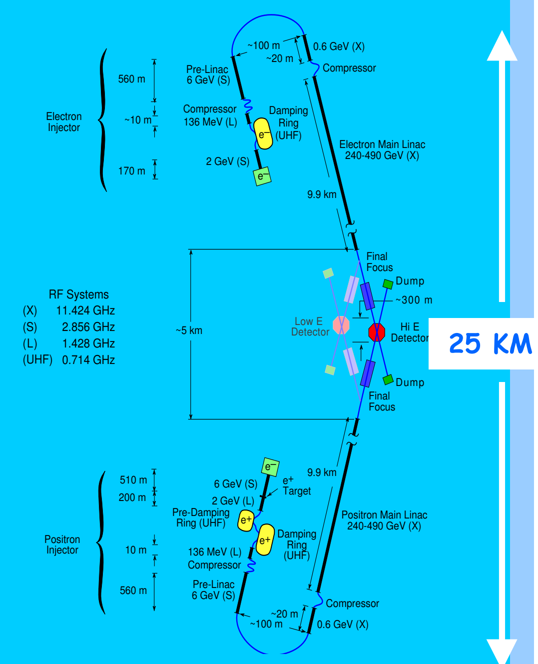
SLAC Linear Collider (SLC)
built on existing SLAC linac
Operated 1989-98



future Linear Collider

500 GeV
- 1 TeV
and beyond

could operate
by 2015



expanded horizontal scale

Electroweak Symmetry Breaking

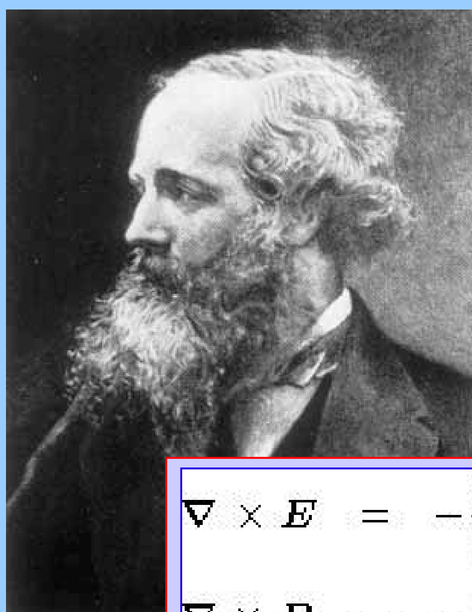
- One of the major mysteries in particle physics today is the origin of Electroweak Symmetry Breaking
  - Weak nuclear force and the electromagnetic force unified
    - $SU(2) \times U(1)_Y$ with massless gauge fields
  - Why is this symmetry hidden?
    - The physical bosons are not all massless
    - $M_\gamma = 0$ $M_W = 80.426 \pm 0.034$ GeV/c^2 $M_Z = 91.188 \pm 0.002$ GeV/c^2

GeV is the standard unit of energy in particle physics
Giga-electron Volt = 1,000,000,000 eV

  - The full understanding of this mystery appears to promise deep understanding of fundamental physics
    - the origin of mass
    - supersymmetry and possibly the origin of dark matter
    - additional unification (strong force, gravity) and possibly hidden space-time dimensions

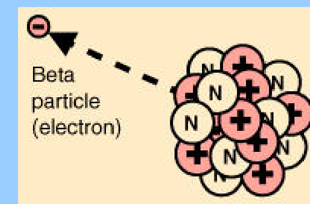
Electromagnetism and Radioactivity

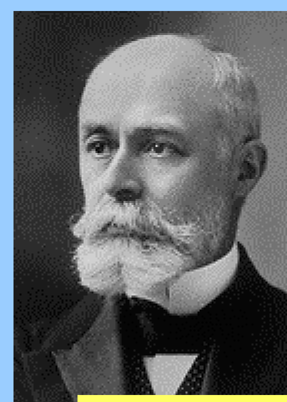
- Maxwell unified Electricity and Magnetism with his famous equations (1873)



$$\begin{aligned} \nabla \times \boldsymbol{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \boldsymbol{B} &= \mu_0 \mathbf{J} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} \\ \nabla \cdot \boldsymbol{E} &= \rho / \epsilon_0 \\ \nabla \cdot \boldsymbol{B} &= 0 \end{aligned}$$

- Matter spontaneously emits penetrating radiation
  - Becquerel uranium emissions in 1896
  - The Curies find radium emissions by 1898

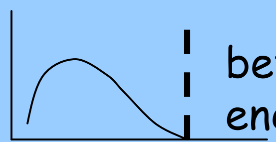




Could this new interaction (the weak force) be related to E&M?

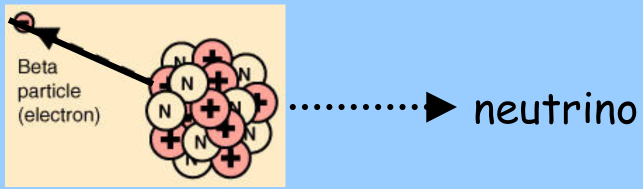
Advancing understanding of Beta Decay

- Pauli realizes there must be a neutral invisible particle accompanying the beta particle:
  - the neutrino

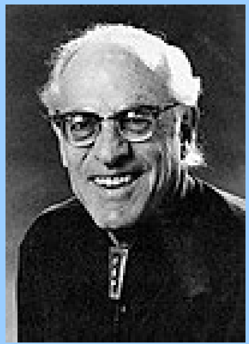


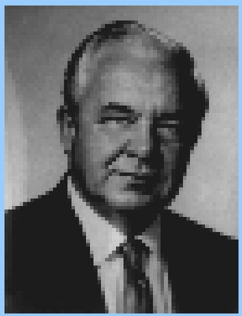
- Fermi develops a theory of beta decay (1934)

$$n \rightarrow p\, e^- \bar{\nu}_e$$



- 1955 - Neutrino discovered by Reines and Cowan - Savannah River Reactor, SC





Status of EM and Weak Theory in 1960

Quantum Electrodynamics (QED)

- Dirac introduced theory of electron - 1926
- Through the pioneering theoretical work of Feynman, Schwinger, Tomonga, and others, a theory of electrons and photons was worked out with precise predictive power
- example: magnetic dipole of the electron [(g-2)/2] $\mu = g \ (e\hbar/2mc) \ S$

- current values of electron (g-2)/2

theory: $0.5\ (\alpha/\pi) - 0.32848\ (\alpha/\pi)^2 + 1.19\ (\alpha/\pi)^3 + ..$

$= (115965230 \pm 10) \times 10^{-11}$

experiment $= (115965218.7 \pm 0.4) \times 10^{-11}$

Status of EM and Weak Theory in 1960

Weak Interaction Theory

- Fermi's 1934 pointlike, four-fermion interaction theory

$$M = G J^{\text{weak}}_{\text{baryon}} J^{\text{weak}}_{\text{lepton}} = G(\bar{\psi}_p O \psi_n)(\bar{\psi}_e O \psi_\nu)$$

V-A

$$W = \frac{2\pi}{\hbar} G^2 |M|^2 \frac{dN}{dE_0}$$

- Theory <u>fails at higher energy</u>, since rate increases with energy, and therefore will violate the "unitarity limit"
  - Speculation on <u>heavy mediating bosons</u> but no theoretical guidance on what to expect

The New Symmetry Emerges

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

ightly larger than that (0.23%) obtained from
minance model of Ref. 2. This seems to be
in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/$
lculated in Refs. 12 and 14.
Brown and P. Singer, Phys
).

A MODEL OF LEPTONS*

Steven Weinberg†

sics Department,
bridge, Massachusetts
67)

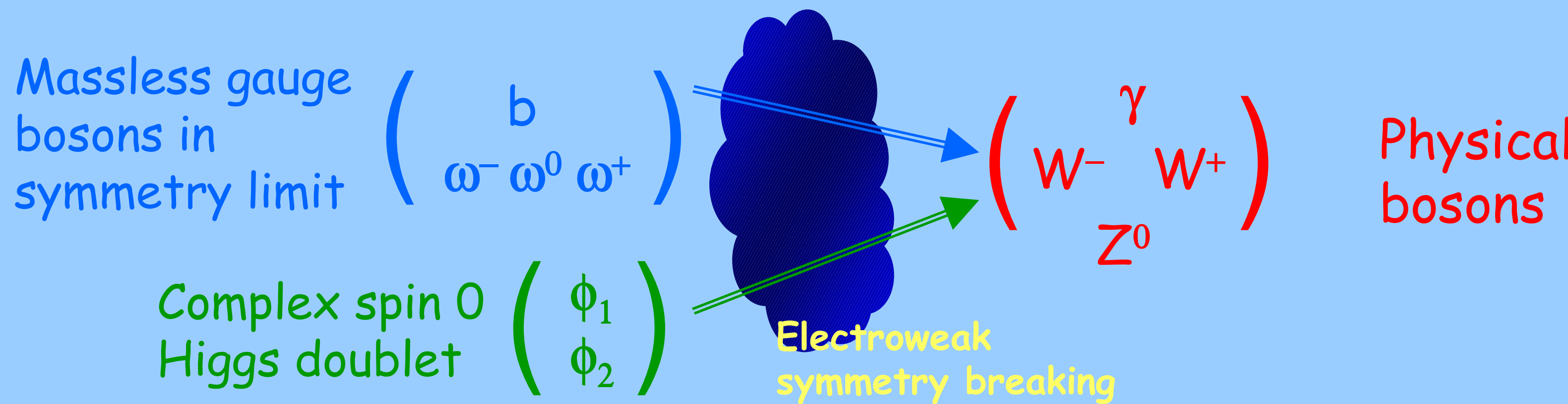
Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences

a right-handed singlet

$R=[\frac{1}{2}(1-\gamma_5)]e.$

Electroweak Unification

- The massless gauge fields are mixed by the Higgs mechanism into the massive gauge bosons



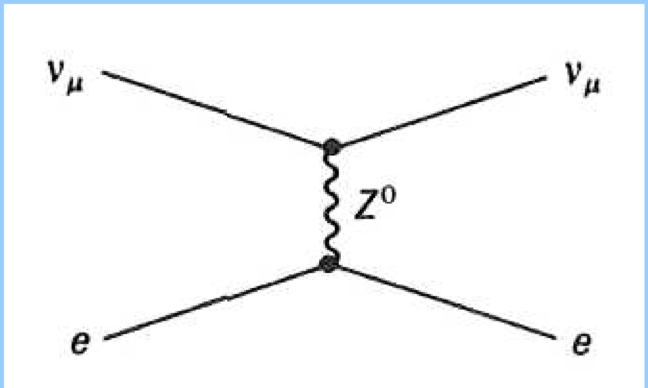
- Weinberg realized that the vector field responsible for the EM force
  - (the photon)

  and the vector fields responsible for the Weak force
  - (yet undiscovered W^+ and W^-)

  could be unified if another vector field, mediated by a heavy neutral boson (Z), were to exist
- This same notion occurred to Salam

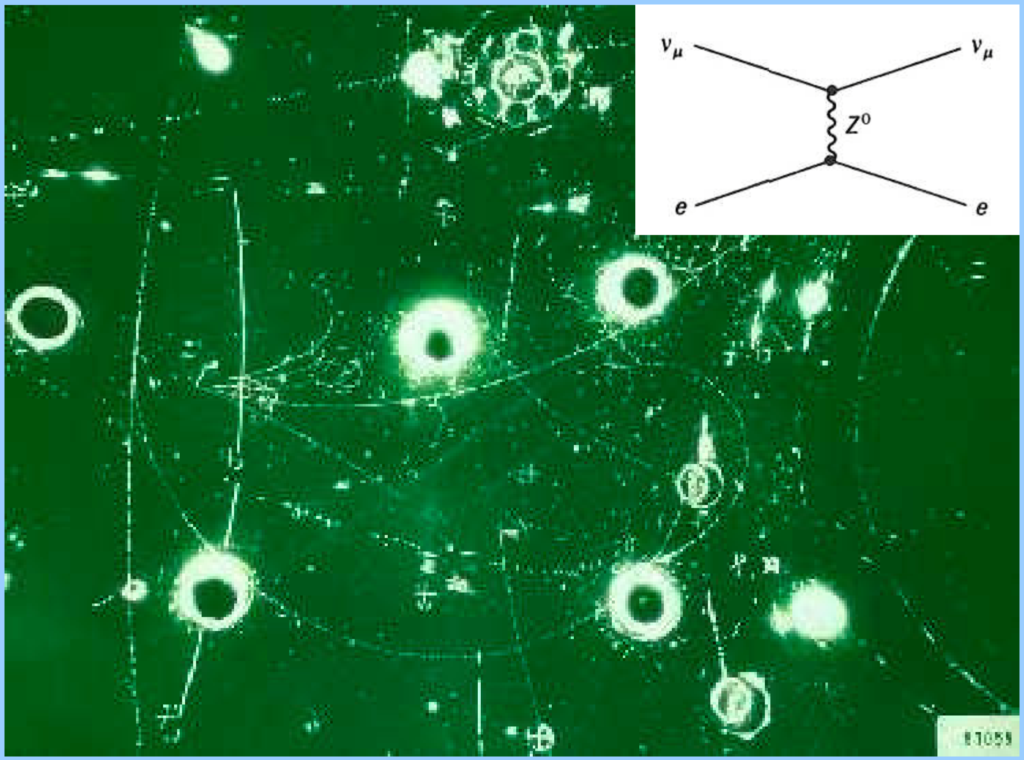
Electroweak Unification

- There remained a phenomenological problem:
  - where were the effects of the Z^0 ?
- These do not appear so clearly in Nature
  - they are small effects in the atomic electron energy level
- One has to look for them in high energy experiments



Neutral Currents Discovered!

- 1973 - giant bubble chamber Gargamelle at CERN
  - 12 cubic meters of heavy liquid

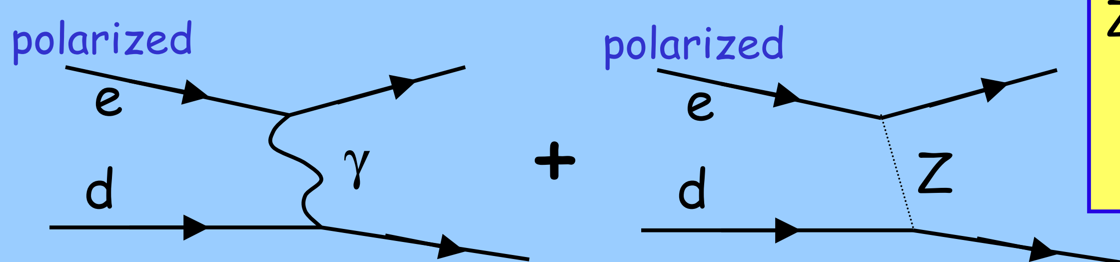


- Muon neutrino beam
- Electron recoil
- Nothing else

- Neutral Current Discovered

Confirmation of Neutral Currents

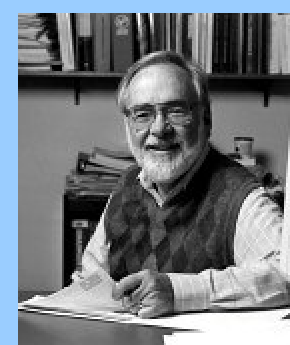
- Weinberg-Salam Model predicts there should be some parity violation in polarized electron scattering
  - The dominant exchange is the photon (L/R symmetric)
  - A small addition of the weak neutral current exchange leads to an expected asymmetry of ~ 10^{-4} between the scattering of left and right-handed electrons



Z exchange violates parity

$g_R \neq g_L$

An asymmetry of 10^{-4}



  - This was observed by Prescott et al. at SLAC in 1978, confirming the theory, and providing the first accurate measurement of the weak mixing angle

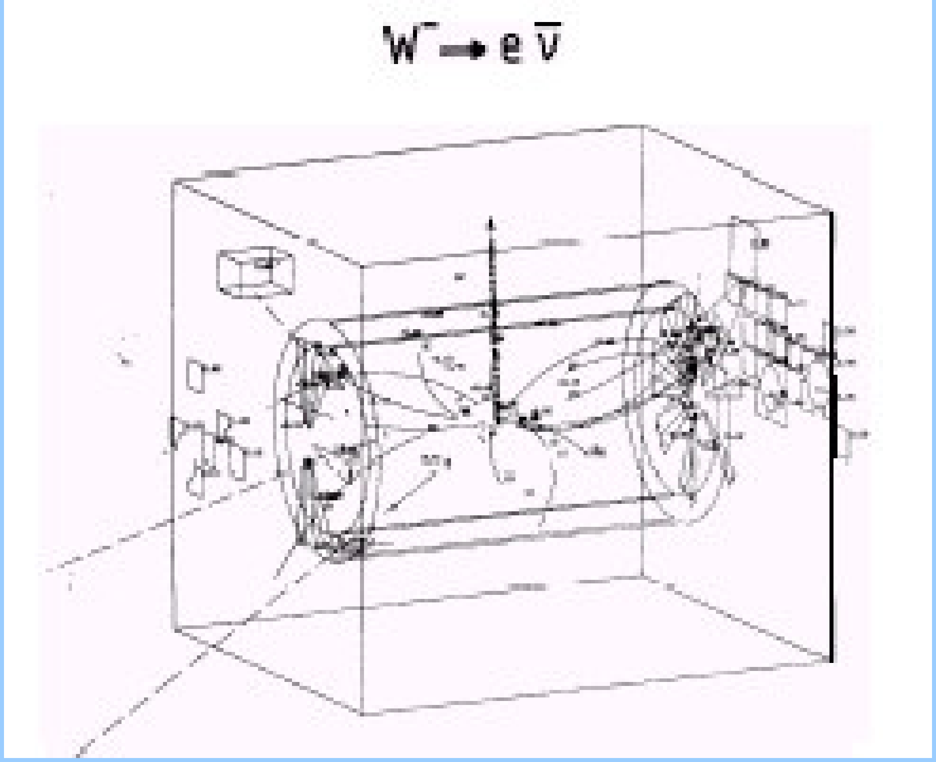
$$\sin^2\theta_W = 0.22 \pm 0.02$$

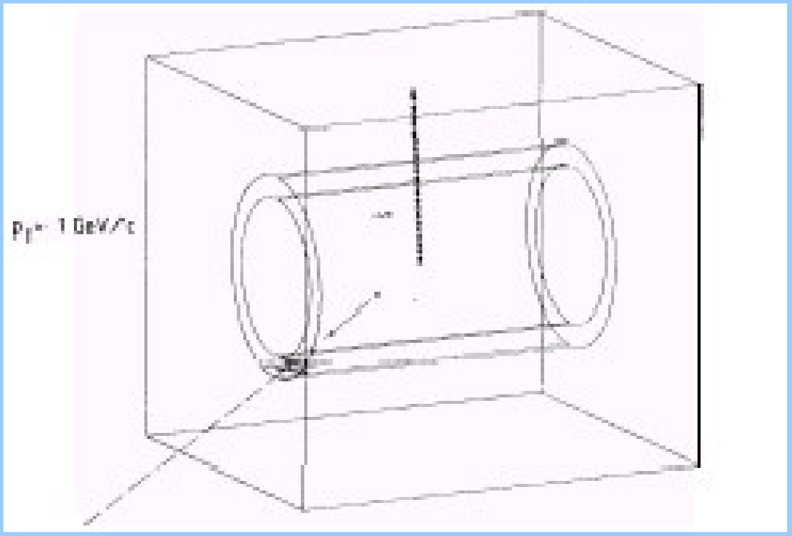
Discovery of the W and Z

- 1981 - antiprotons were stored in the CERN SPS ring and brought into collision with protons

Discovery of the W and Z

- 1981 UA1

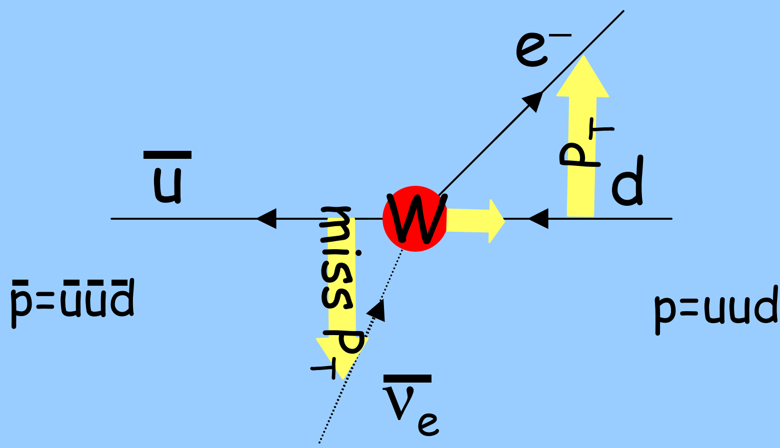


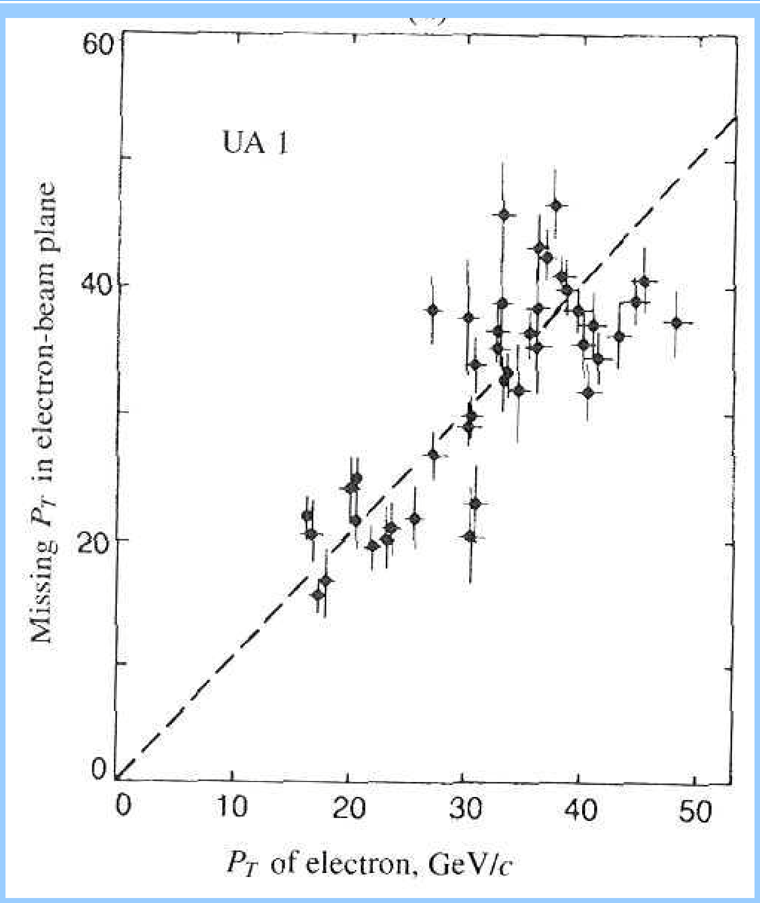


J. Brau, UO QuarkNet, June 20, 2003

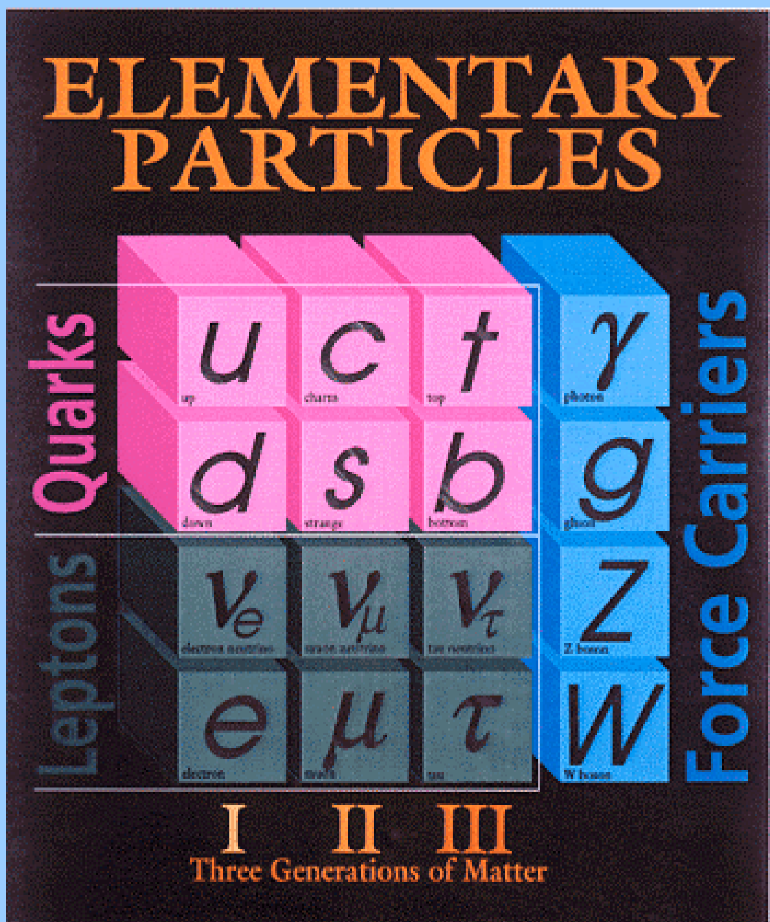
Discovery of the W and Z

$W \to e^- \overline{\nu}_e$





The Standard Model



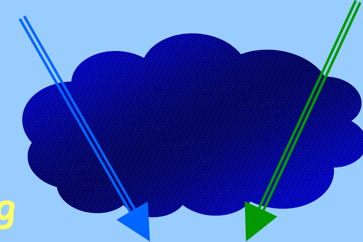
Massless gauge bosons in symmetry limit

$$\begin{pmatrix} b \\ \omega^{-}\ \omega^{0}\ \omega^{+} \end{pmatrix}$$

Complex spin 0 Higgs doublet

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

Electroweak symmetry breaking



$$\begin{pmatrix} & \gamma & \\ W^{-} & & W^{+} \\ & Z^{0} & \end{pmatrix}$$

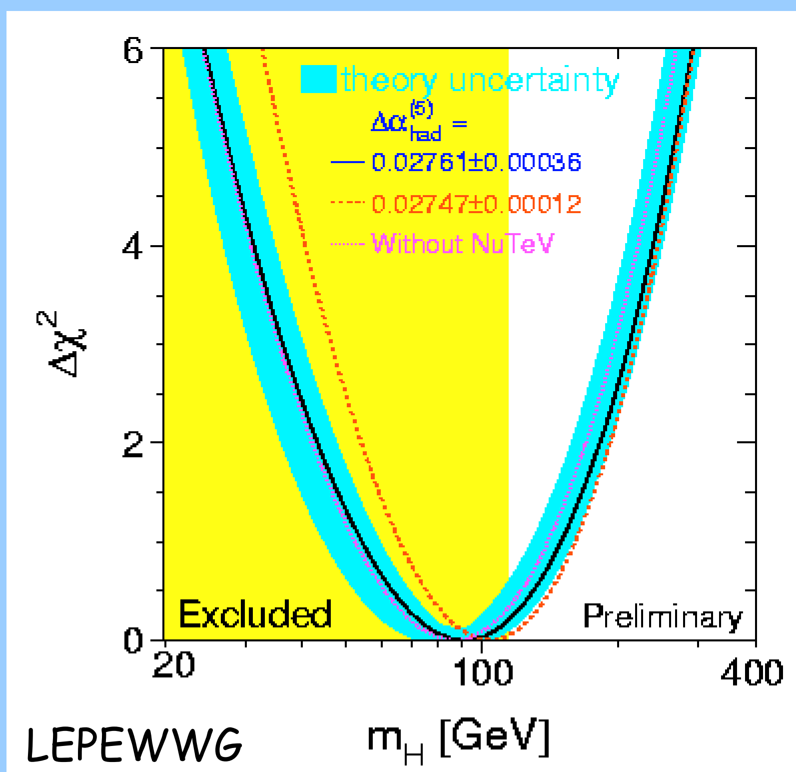
Physical bosons

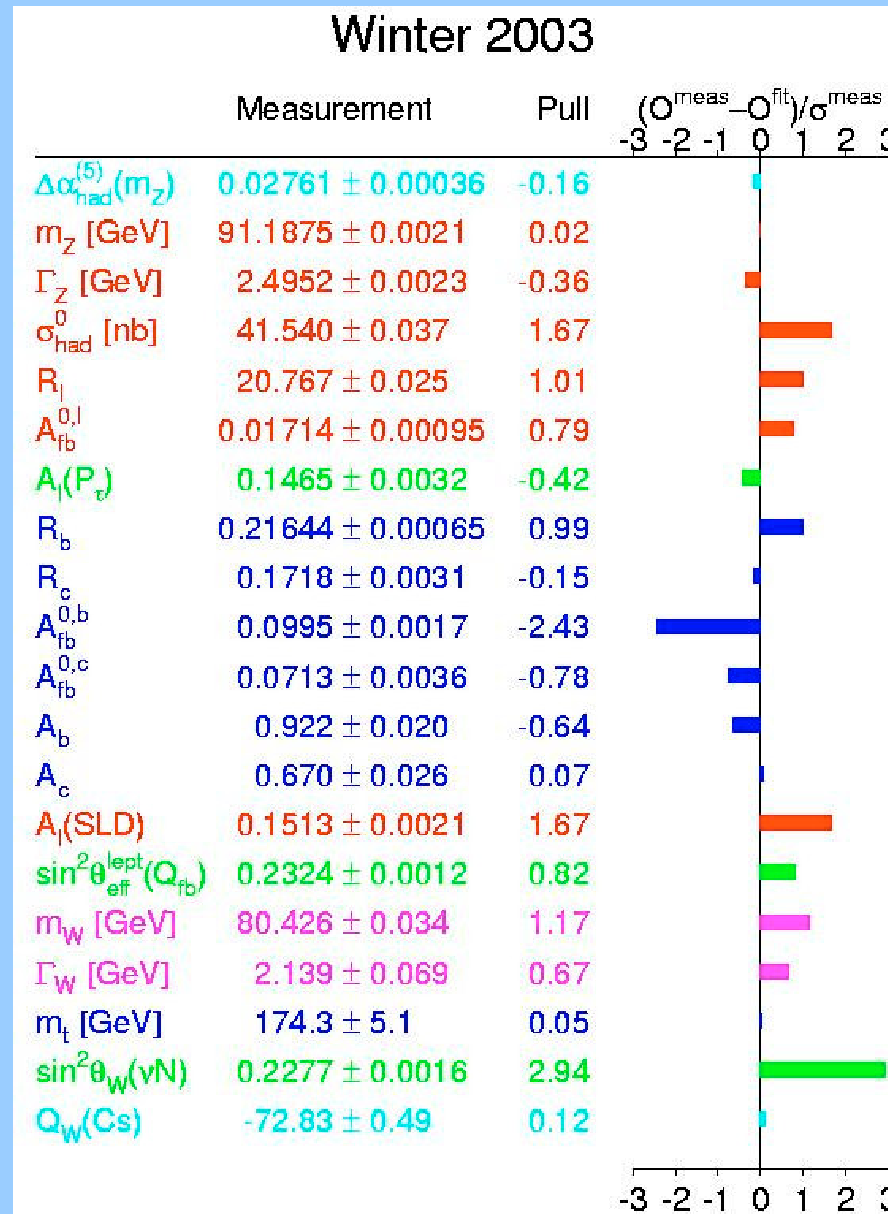
The Higgs Boson

- The quantum(a) of the Higgs Mechanism is(are) the Higgs Boson or Bosons
  - Minimal model - one complex doublet $\Rightarrow$ 4 fields
    - 3 "eaten" by W^+, W^-, Z to give mass
    - 1 left as physical Higgs
- This spontaneously broken local gauge theory is renormalizable - t'Hooft (1971)
- The Higgs boson properties
  - Mass < ~ 800 GeV/c^2 (unitarity arguments)
  - Strength of Higgs coupling increases with mass
    - fermions: $g_{ffh} = m_f / v$ $\quad$ $v = 246$ GeV
    - gauge boson: $g_{wwh} = 2\ m_Z^2/v$

Standard Model Fit

- $M_H = 91^{+58}_{-37}$ GeV/c^2



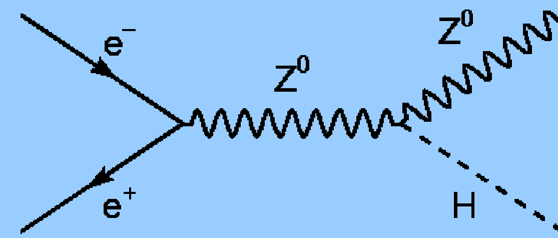


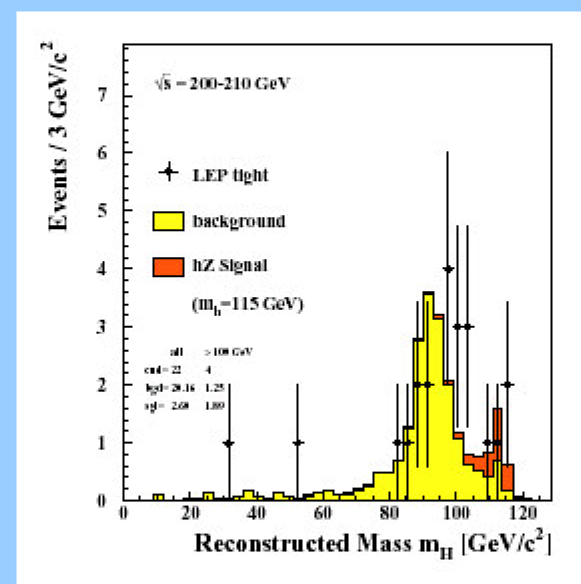
History of Anticipated Particles

Positron	1932 - Dirac theory of the electron
Pi meson	1947 - Yukawa's theory of strong interaction
Neutrino	1955 - missing energy in beta decay
Quark	1968 - patterns of observed particles
Charmed quark	1974 - absence of flavor changing neutral currents
Bottom quark	1977 - Kobayashi-Maskawa theory of CP violation
W boson	1983 - Weinberg-Salam electroweak theory
Z boson	1984 - " "
Top quark	1997 - Expected once Bottom was discovered Mass predicted by precision Z^0 measurements
Higgs boson	???? - Electroweak theory and experiments

The Search for the Higgs Boson

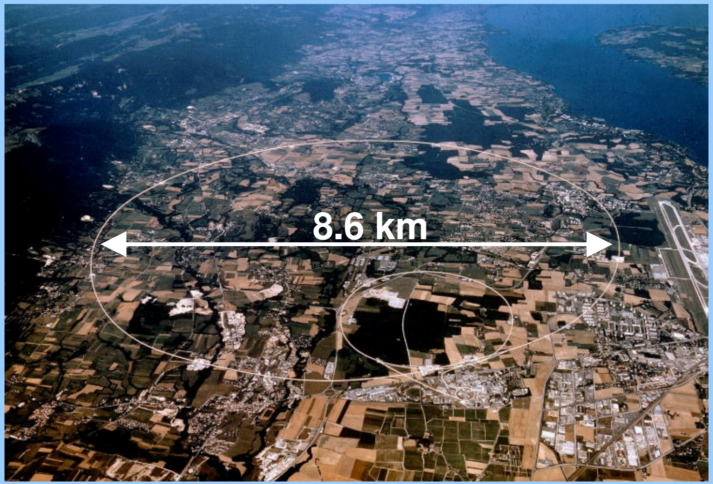
- LEP II (1996-2000)
  - $M_H > 114\ GeV/c^2$ (95% conf.)





The Search for the Higgs Boson

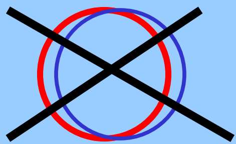
- Tevatron at Fermilab
  - Proton/anti-proton collisions at E_{cm}=2000 GeV
  - Collecting data now
    - discovery possible by ~2008?
- LHC at CERN
  - Proton/proton collisions at E_{cm}=14,000 GeV
  - Begins operation ~2007



The Next Linear Collider

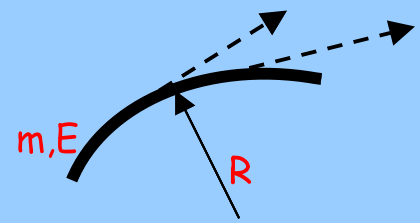
- Acceleration of electrons in a <u>circular</u> accelerator is plagued by Nature's resistance to acceleration
  - Synchrotron radiation
  - $\Delta E = 4\pi/3\ (e^2\beta^3\gamma^4 / \underline{R})$ per turn (recall $\gamma = E/m$, so $\Delta E \sim E^4/m^4$)
  - eg. LEP2 $\Delta E = 4$ GeV Power ~ 20 MW
- For … nergy it is preferable to acce… r accelerator, rather than…

positrons

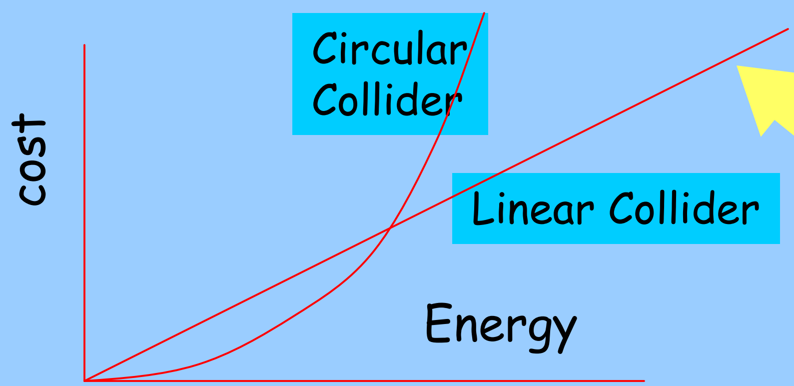


Cost Advantage of Linear Colliders

- Synchrotron radiation
  - $\Delta E \sim (E^4 / m^4 R)$



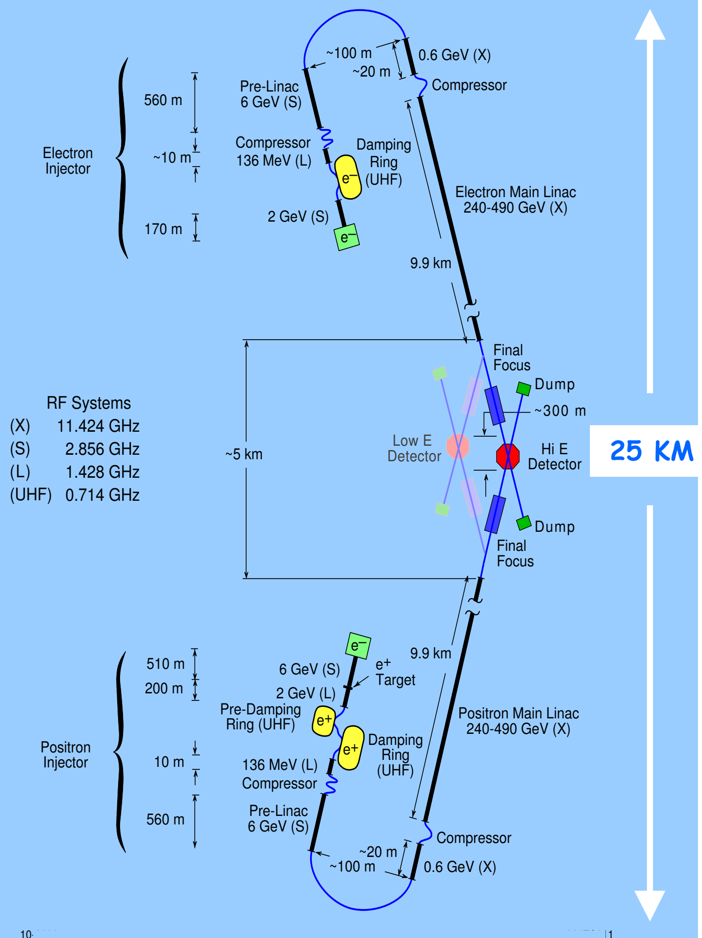
- Therefore
  - Cost (circular) $\sim a R + b \, \Delta E \quad \sim a R + b \, (E^4 / m^4 R)$
    - Optimization $R \sim E^2 \quad \Rightarrow$ Cost $\sim c \, E^2$
  - Cost (linear) $\sim a' L$, where $L \sim E$



At high energy, linear collider is more cost effective

The Linear Collider

- A plan for a high-energy, high-luminosity, electron-positron collider (international project)
  - E_{cm} = 500 - 1000 GeV
  - Length ~25 km
- Physics Motivation for the LC
  - Elucidate Electroweak Interaction
    - particular symmetry breaking
    - This includes
      - Higgs bosons
      - supersymmetric particles
      - extra dimensions
- Construction could begin around 2009 following intensive pre-construction R&D with operation beginning around 2015

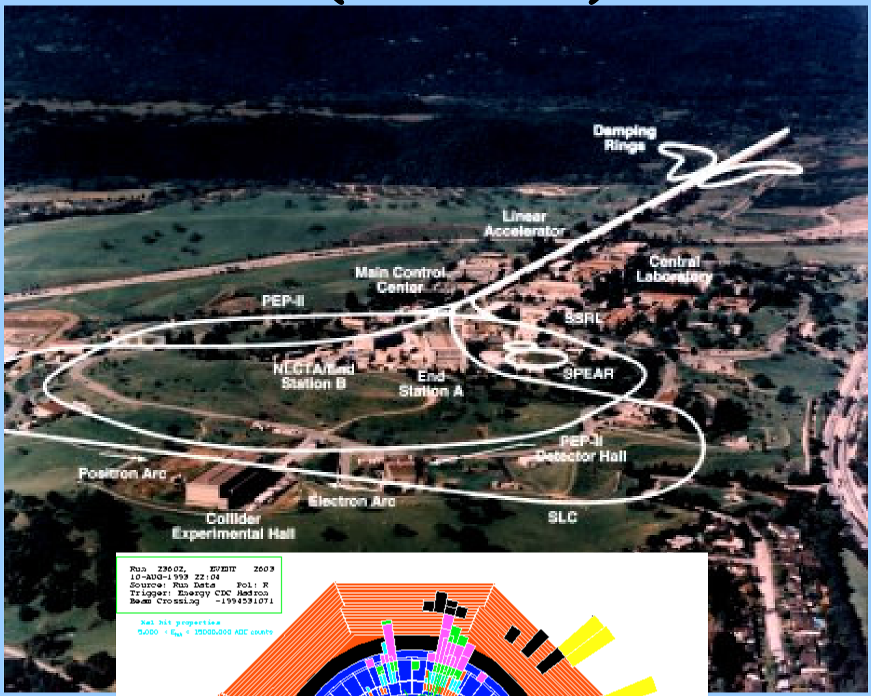


expanded horizontal scale

Warm X-band version

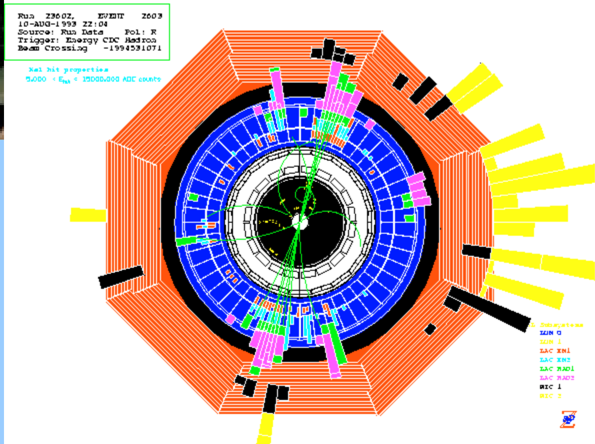
The First Linear Collider

- This concept was demonstrated at SLAC in a linear collider prototype operating at ~91 GeV (the SLC)



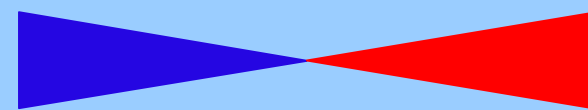
- SLC was built in the 80's within the existing SLAC linear accelerator

- Operated 1989-98
  - precision Z^0 measurements
    - $A_{LR} = 0.1513 \pm 0.0021$ (SLD) asymmetry in Z^0 production with L and R electrons
  - established Linear Collider concepts



NLC Engineering

- Power per beam
  - 6.6 MW cw (250 GW during pulse train of 266 nsec)
- Beam size at interaction
  - 245 nanometers x 3 nanometers



Stabilize

- Beam flux at interaction
  - 10^{12} MW/cm^2 cw (3 x 10^{13} GW/cm^2 during pulse train)
- Current density
  - 6.8 x 10^{12} A/m^2
- Induced magnetic field (beam-beam)
  - >1000 Tesl

beam-beam induced bremsstrahlung - "beamstrahlung"

Conclusion

The Linear Collider will be a powerful tool for studying Electroweak Symmetry Breaking and the Higgs Mechanism, as well as the other possible scenarios for TeV physics

Current status of Electroweak Precision measurements strongly suggests that the physics at the LC will be rich.

We can expect these studies to further our knowledge of fundamental physics in unanticipated ways