The Next Linear Collider
and
the Origin of Electroweak Physics

Jim Brau, Univ. of Oregon

Science Seminar

University of Puget Sound

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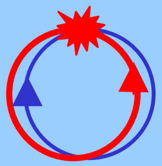
The Next Linear Collider
and the Origin of Electroweak Physics

- What is the Next Linear Collider?
- Electroweak Physics
  - Development
    - unification of E&M with beta decay (weak interaction)
  - Predictions
    - eg. M_W, M_Z, ...
  - Missing components
    - origin of symmetry breaking (Higgs Mechanism)
- The Hunt for the Higgs Boson
  - Limits from LEP2 and future accelerators
- Other investigations
  - supersymmetry, extra dimensions

Particle Accelerators

- In the search of the the most fundamental laws of physics, larger, and more energetic accelerators have been built in many parts of the world
- Most of these are circular machines, which allow the counter-rotating particles to travel around the accelerator over and over again and occasionally collide
  - preserving the current
  - increasing particle energy with each cycle

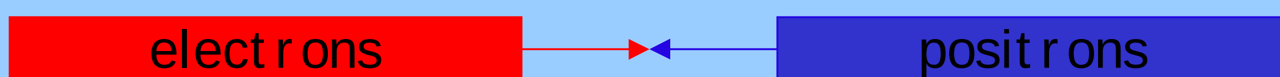


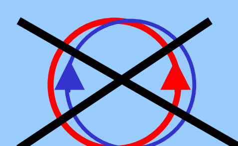
Linear Colliders

- Acceleration of electrons in a circular accelerator is plagued by Nature's resistance to acceleration
  - Synchrotron radiation
  - $\Delta E \sim (E^4/m^4\,R)$ per turn (lighter particles radiate strongly)
  - eg. LEP2 $\Delta E/E = 4$ GeV/100 GeV Power ~ 20 MW

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

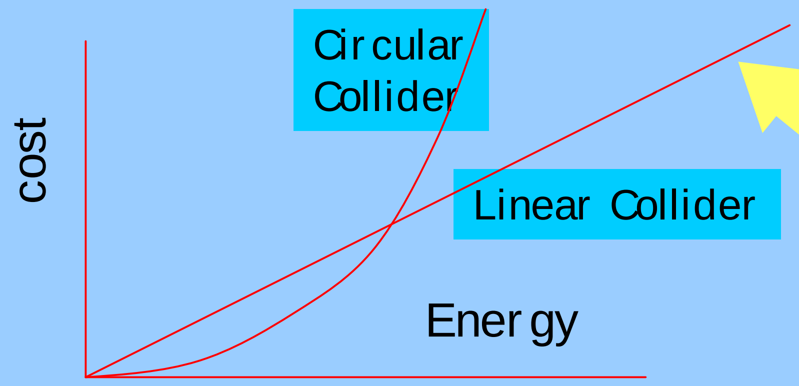
- For this reason, at very high energy it is preferable to accelerate electrons in a linear accelerator, rather than a circular accelerator





Linear Colliders

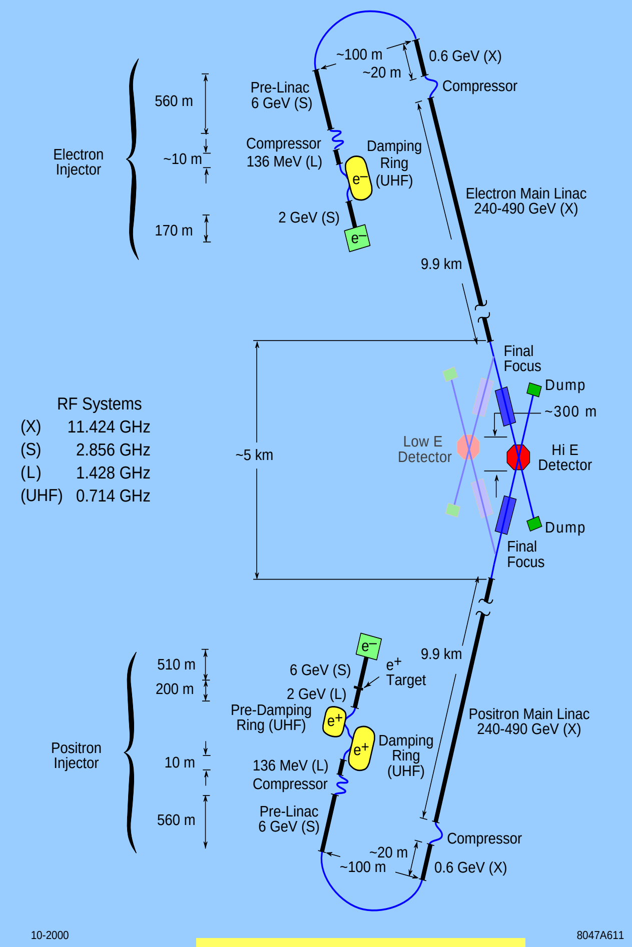
- Synchrotron radiation
  - $\Delta E \sim (E^4 / m^4 R)$
- Therefore
  - Cost (circular) $\sim a R + b \Delta E \sim a R + b (E^4 / m^4 R)$
    - Optimization $R \sim E^2 \Rightarrow$ Cost $\sim c E^2$
  - Cost (linear) $\sim a' L$, where $L \sim E$



- At high energy, linear collider is more cost effective

The Next Linear Collider

- A plan for a high-energy, high-luminosity, electron-positron collider (international project)
  - E_{cm} = 500 - 1000 GeV
  - Length ~25 km ~15 miles
- Physics Motivation for the NLC
  - Elucidate Electroweak Interaction
    - particular symmetry breaking
    - This includes
      - Higgs bosons
      - supersymmetric particles
      - extra dimensions
- Construction could begin around 2005-6 and operation around 2011-12



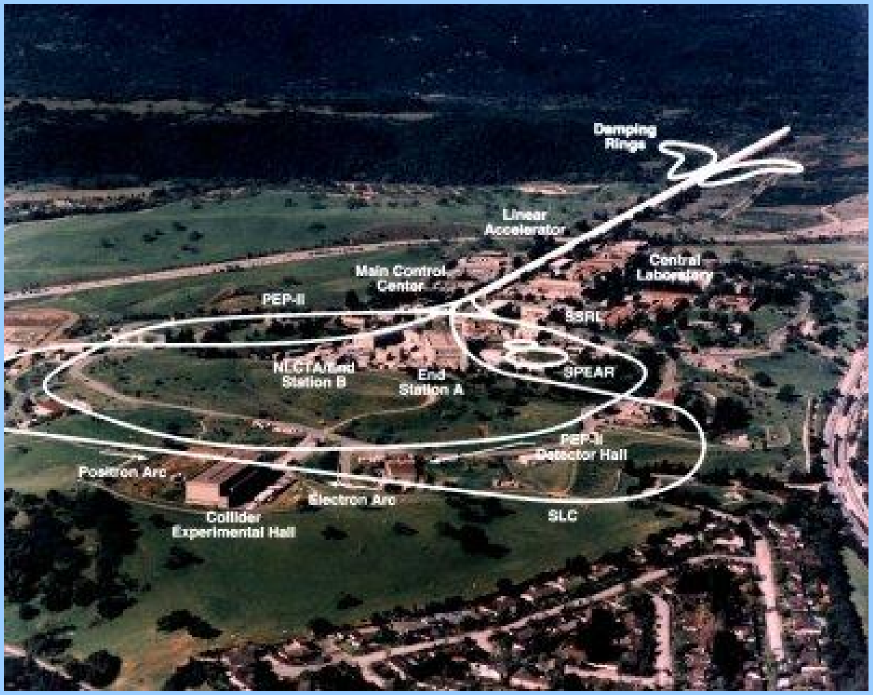
not to scale

The First Linear Collider

- This concept was demonstrated at SLAC (Stanford Linear Accelerator Center) in a linear collider prototype operating at ~91 GeV (the SLC)
  - Oregon collaborated

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

- Operated 1989-98
  - precision Z^0 measurements
  - established LC concepts



The Next Linear Collider

- DOE/NSF High Energy Physics Advisory Panel
  - Subpanel on Long Range Planning for U.S. High Energy Physics
  - A year long study was recently concluded with the release of the report of recommendations
  - A high-energy, high-luminosity electron-positron linear collider should be the <u>highest priority</u> of the US HEP community, preferably one sited in the US

The “next” Linear Collider

The next Linear Collider proposals include plans to deliver **a <u>few hundred</u>** <u>fb^{-1}</u> of integrated lum. per year

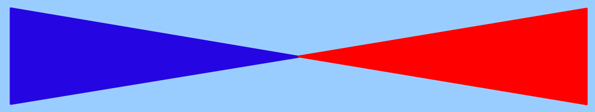
	TESLA	JLC-C	NLC/JLC-X *
	(DESY-Germany)	(Japan)	(SLAC/KEK-Japan)
$\mathcal{L}_{design}$ (10^{34})	$3.4 \rightarrow 5.8$	0.43	$2.2 \rightarrow 3.4$
E_{CM} (GeV)	$500 \rightarrow 800$	500	$500 \rightarrow 1000$
Eff. Gradient (MV/m)	$23.4 \rightarrow 35$	34	70
RF freq. (GHz)	1.3	5.7	11.4
Δt_{bunch} (ns)	$337 \rightarrow 176$	2.8	1.4
# bunch/train	$2820 \rightarrow 4886$	72	190
Beamstrahlung (%)	$3.2 \rightarrow 4.4$		$4.6 \rightarrow 8.8$

There will only be one in the world, but the technology choice remains to be made

* US and Japanese X-band R&D cooperation, but machine parameters may differ

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 Tesla

beam-beam induced bremsstrahlung - "beamstrahlung"

The “next” Linear Collider

<u>Standard Package:</u>

- $e^+ e^-$ Collisions
- Initially at 500 GeV
- Electron Polarization $\geq$ 80%

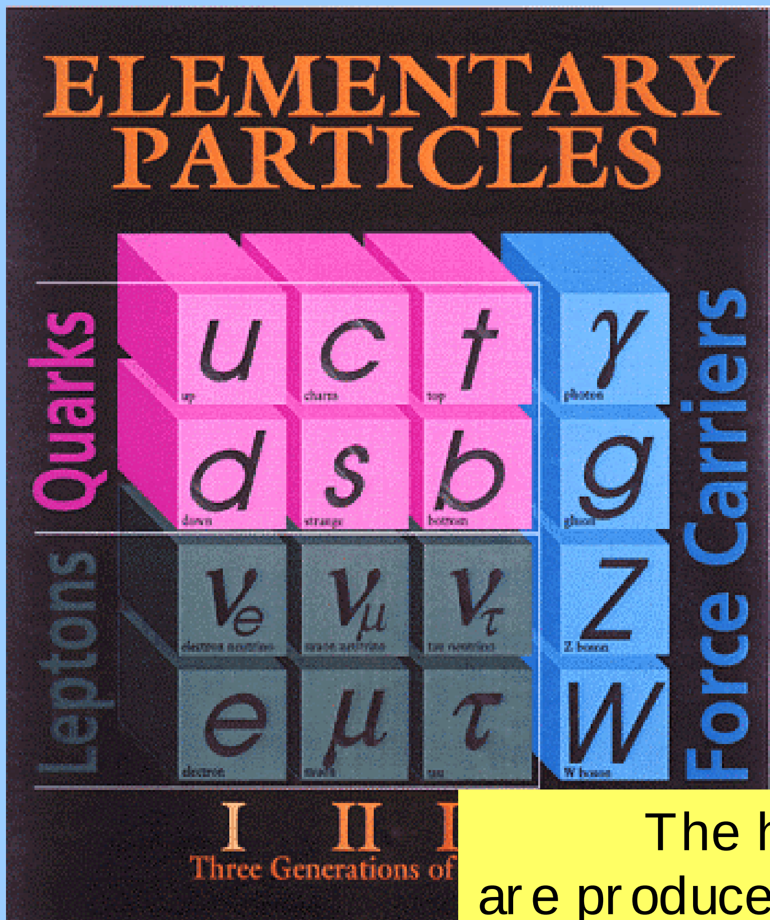
<u>Options:</u>

- Energy upgrades to ~ 1.0 - 1.5 TeV
- Positron Polarization (~ 40 - 60% ?)
- $\gamma\gamma$ Collisions
- $e^- e^-$ and $e^-\gamma$ Collisions
- Giga-Z (precision measurements)

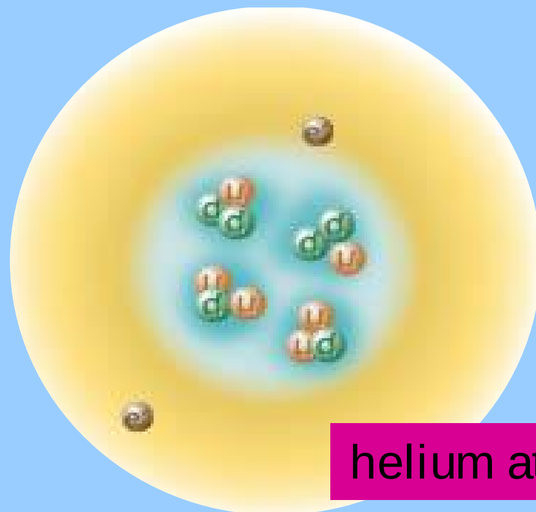
Past 30 years ⇒ Tremendous Progress in Particle Physics

- Standard Model
  - All ***known*** matter is made from three families (generations) of quarks and leptons which interact through the forces:
    - electroweak
      - unified electromagnetic and weak
    - strong
    - gravity

The Standard Model



Everyday matter is composed of the lightest quarks and leptons



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

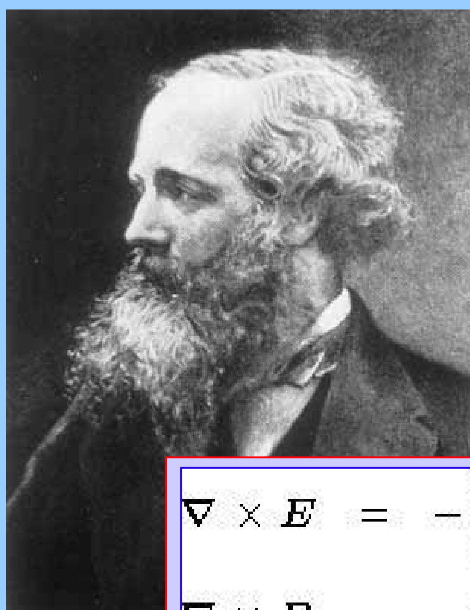
Electroweak Symmetry Breaking

- A primary goal of the Next Linear Collider is to elucidate the origin of Electroweak Symmetry Breaking
  - The weak nuclear force and the electromagnetic force have been unified into a single description SU(2) x $U(1)_Y$
  - Why is this symmetry hidden?

    (or why do the two forces appear so different?)
  - The answer to this 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

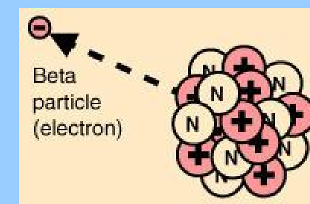
Electromagnetism and Radioactivity

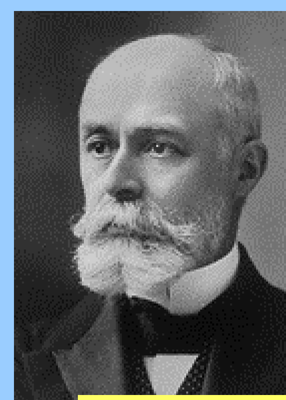
- Maxwell unified Electricity and Magnetism with his famous equations (1873)



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

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

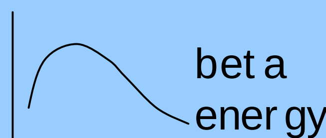




Could this new interaction (the weak force) be related to E&M?

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

A MODEL OF LEPTONS*

Steven Weinberg†

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

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
).

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sics Department,
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67)

a right-handed singlet

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

Enter Electroweak Unification

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

$$L = e J_\mu^{(em)} A_\mu$$

  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

$$L = g\mathbf{J}_\mu \cdot \mathbf{W}_\mu + g' J_\mu^Y B_\mu$$

$\tan\theta_W = g'/g$

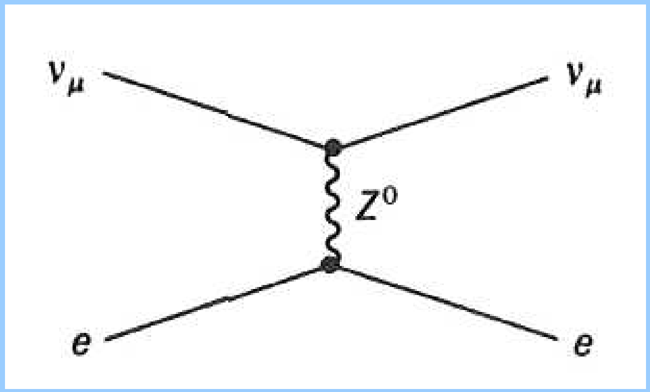
$\sin^2\theta_W = g'^2/(g'^2+g^2)$

$$W_\mu^{(3)} = \frac{gZ_\mu + g'A_\mu}{\sqrt{g^2+g'^2}} \qquad B_\mu = \frac{-g'Z_\mu + gA_\mu}{\sqrt{g^2+g'^2}} \rightarrow e J_\mu^{(em)} A_\mu$$

$e = g \sin\theta_W = g' \cos\theta_W$

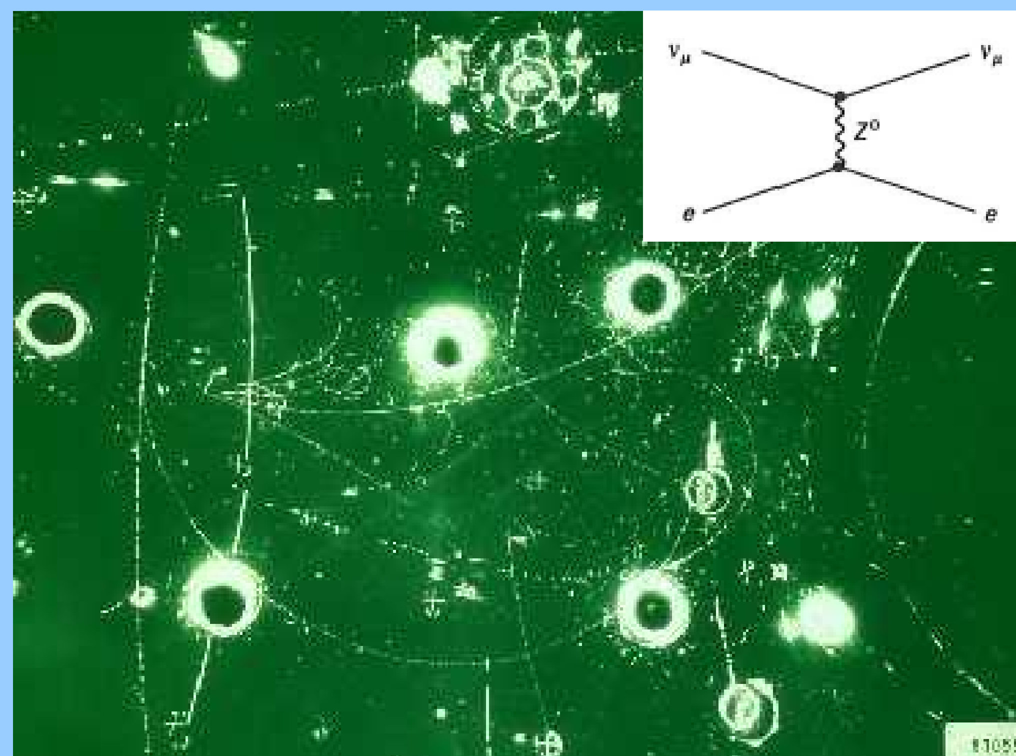
Electroweak Unification

- 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

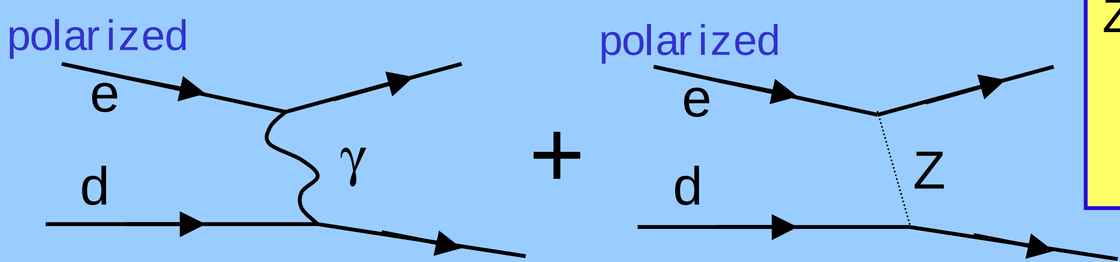


- Muon neutrino beam
- Electron recoil
- Nothing else

- Neutral Current Discovered

Confirmation of Neutral Currents

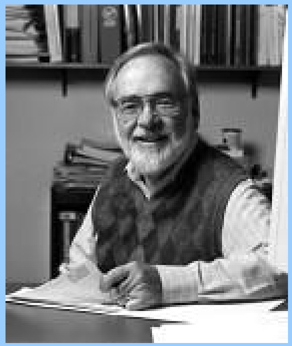
- Weinberg-Salam Model predicts there should be some parity violation in polarized electron scattering
  - The dominant exchange is the photon (L/R symmetric)
  - A small addition of the weak neutral current exchange leads to an expected asymmetry of $\sim 10^{-4}$ between the scattering of left and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

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

The W and Z Masses

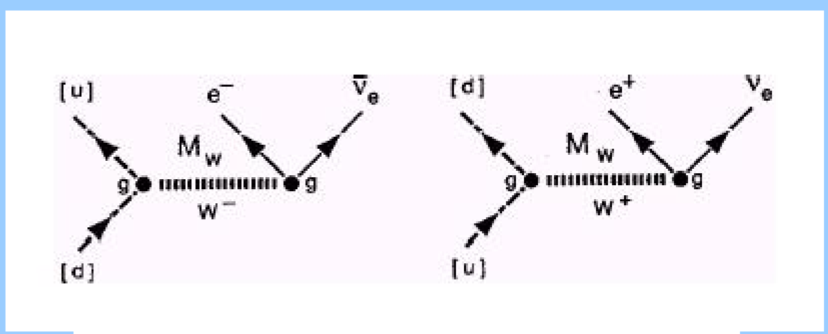
- Knowing $\sin^2\theta_W$ allows one to predict the W and Z boson masses in the Weinberg-Salam Model

$$M_{W^\pm} = \left(\frac{e^2\sqrt{2}}{8G\sin^2\theta_W}\right)^{1/2} = \frac{37.4}{\sin\theta_W}\ \text{GeV} \qquad \sim 80\ \text{GeV}/c^2$$

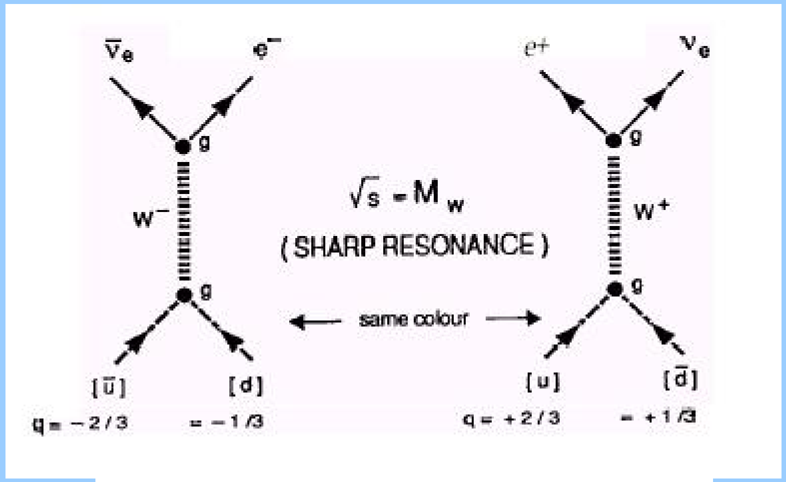
$$M_{Z^0} = \frac{M_{W^\pm}}{\cos\theta_W} = \frac{75}{\sin 2\theta_W}\ \text{GeV} \qquad \sim 90\ \text{GeV}/c^2$$

Discovery of the W and Z

- Motivated by these predictions, experiments at CERN were mounted to find the W and Z



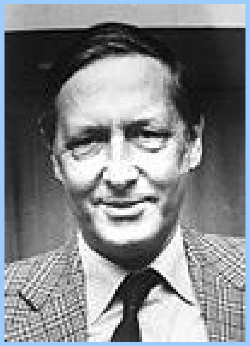
β^- decay β^+ decay



q anti-q annihilation to $W^{\pm}$

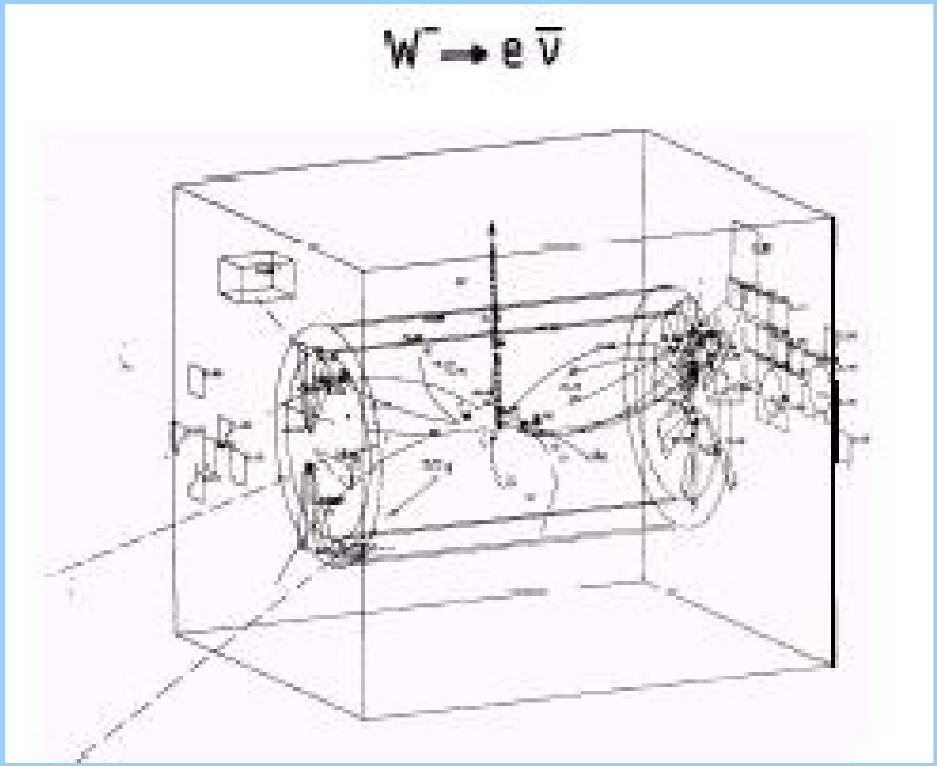
Discovery of the W and Z

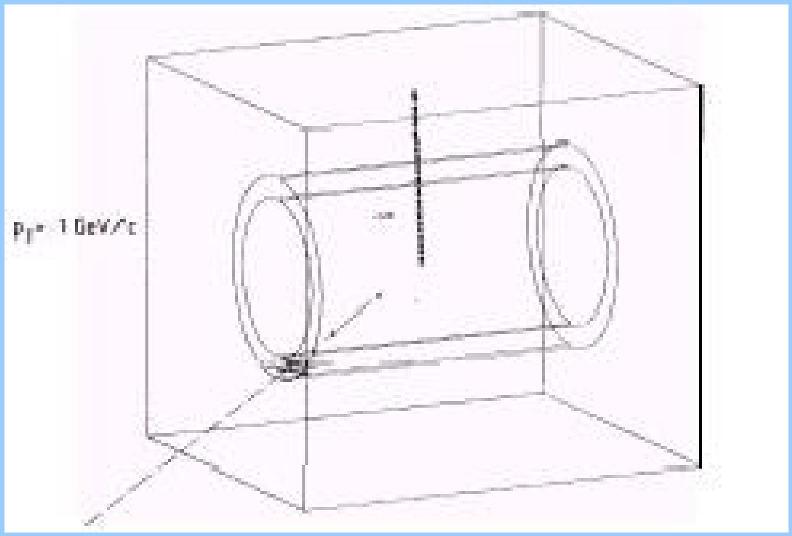
- 1981 - antiprotons were stored in the CERN SPS ring and brought into collision with protons



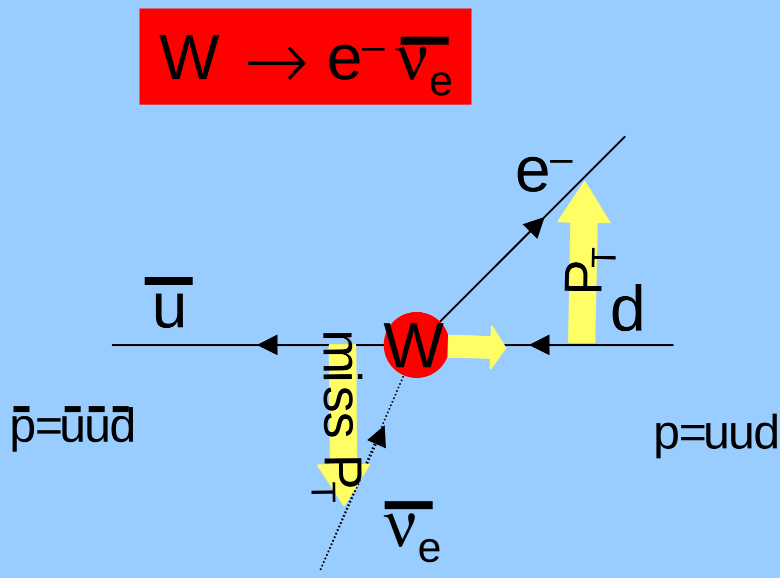
Discovery of the W and Z

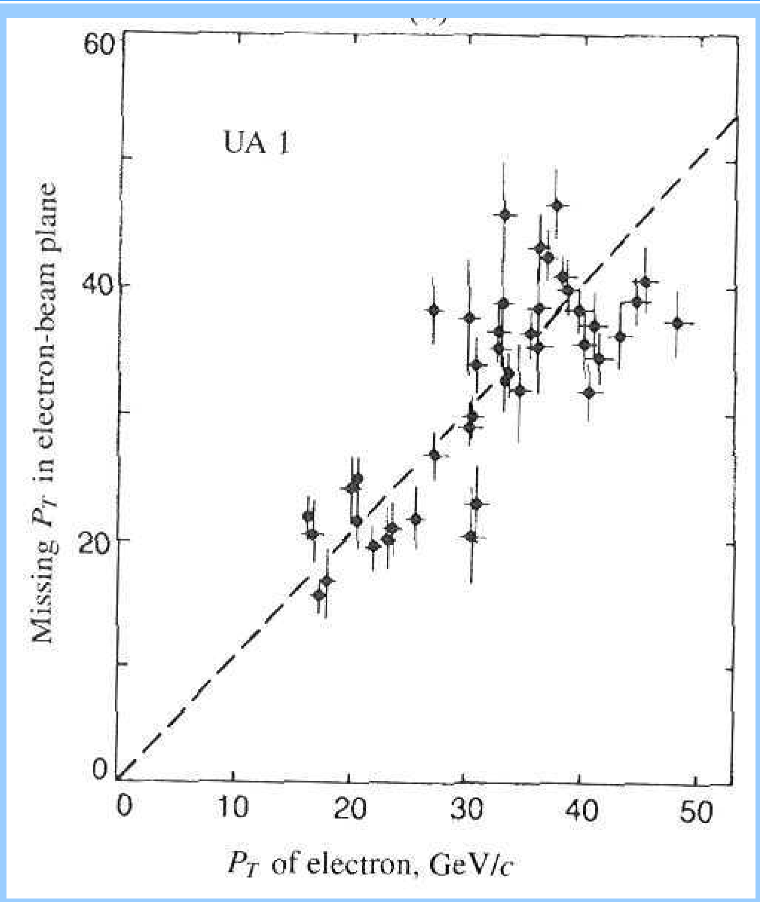
- 1981 UA1





Discovery of the W and Z





Discovery of the W and Z

- That was 20 years ago
- Since then:
  - precision studies at Z^0 Factories
    - LEP and SLC
  - precision W measurements at colliders
    - LEP2 and TeVatron

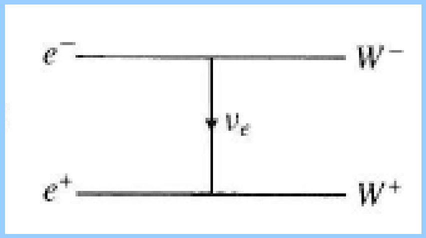
$M_Z = 91187.5 \pm 2.1$ MeV $\qquad$ $M_W = 80451 \pm 33$ MeV/c^2

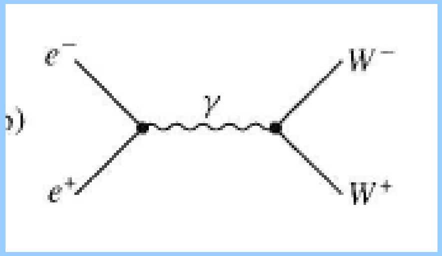
- These precise measurements (along with other precision measurements) test the Standard Model with keen sensitivity
  - eg. are all observables consistent with the same value of $\sin^2\theta_W$

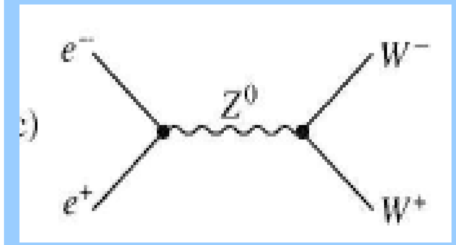
Electroweak Symmetry Breaking

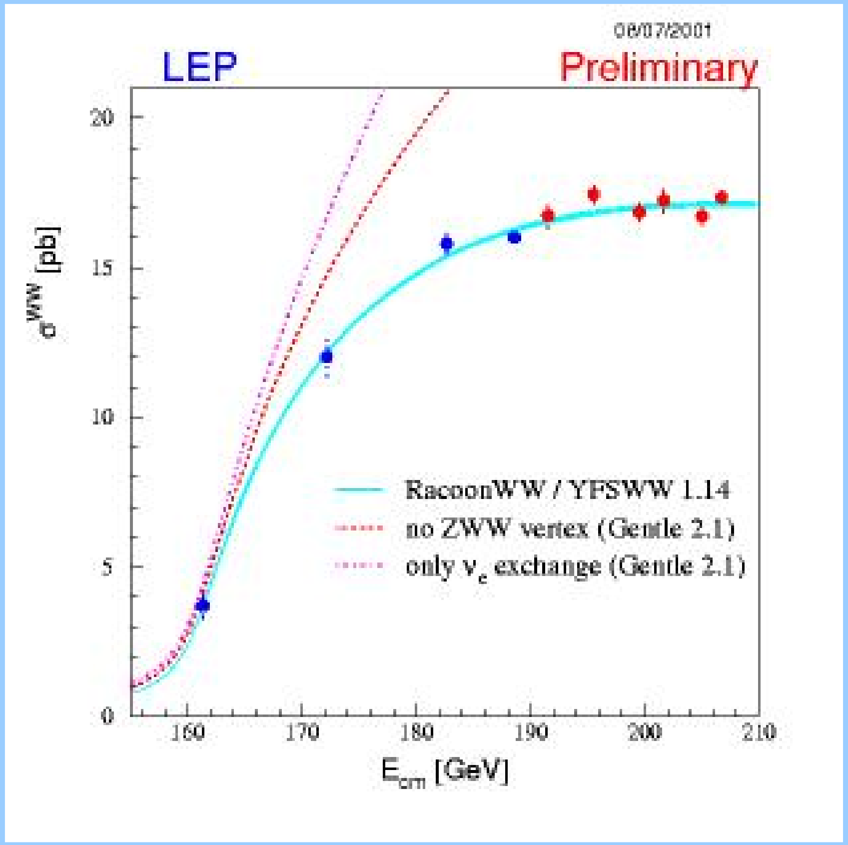
•Confirmation of the completeness of the Standard Model (LEP2)

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









The Higgs Boson

- Why is the underlying SU(2)xU(1) symmetry

$$L = g\mathbf{J}_\mu \cdot \mathbf{W}_\mu + g' J_\mu^Y B_\mu$$

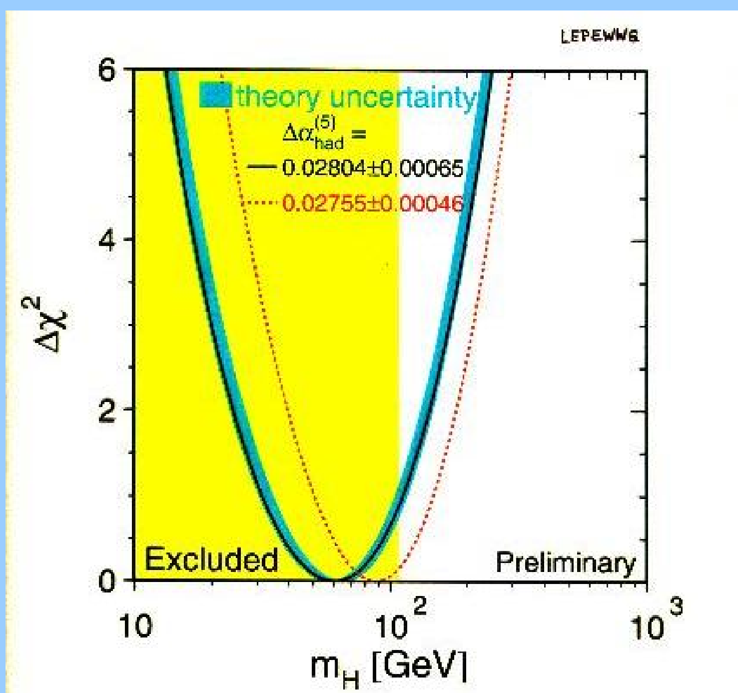
broken

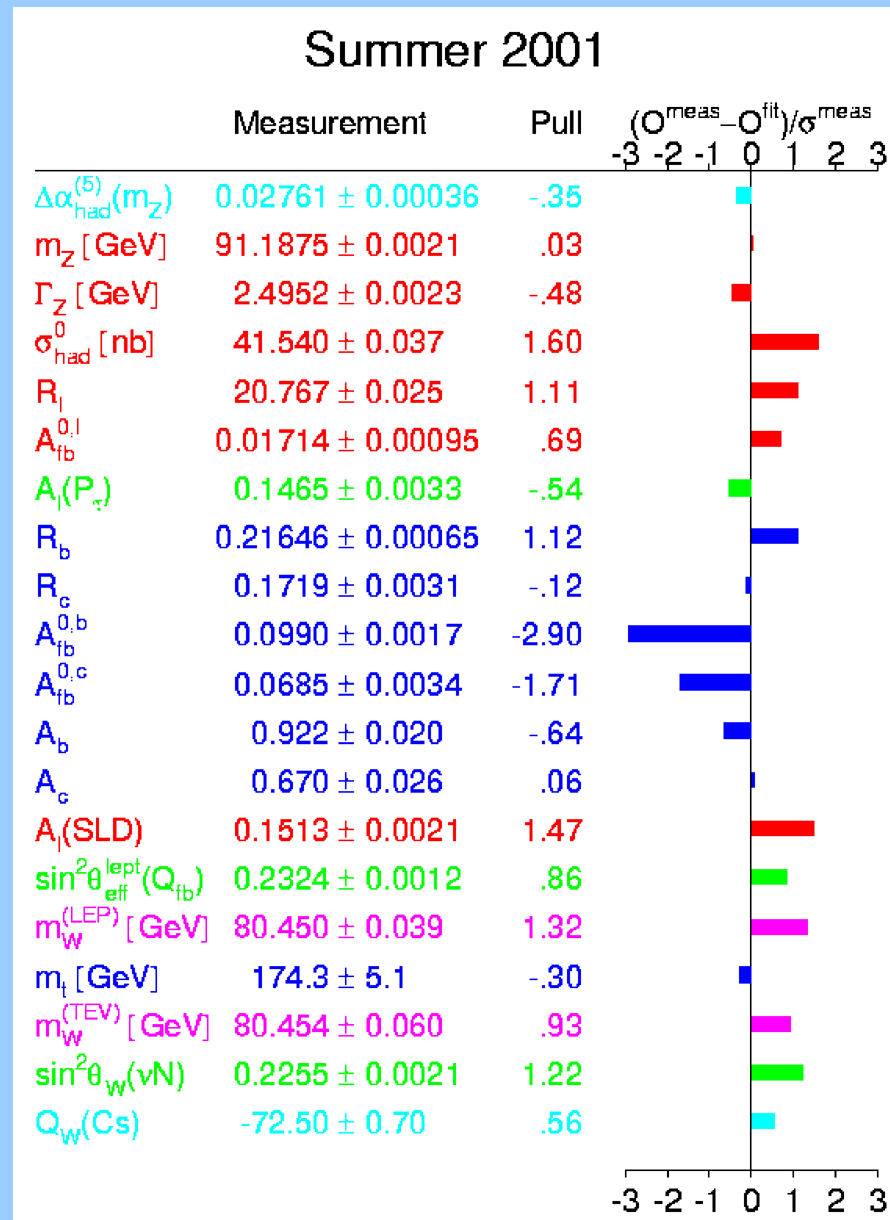
$$-\frac{g}{2\sqrt{2}}\sum_i \overline{\psi}_i\, \gamma^\mu\, (1-\gamma^5)(T^+\, W_\mu^+ + T^-\, W_\mu^-)\, \psi_i$$
$$-e\sum_i q_i\, \overline{\psi}_i\, \gamma^\mu\, \psi_i\, A_\mu$$
$$-\frac{g}{2\cos\theta_W}\sum_i \overline{\psi}_i\, \gamma^\mu (g_V^i - g_A^i \gamma^5)\, \psi_i\, Z_\mu\, .$$

- Theoretical conjecture is the Higgs Mechanism:
  a non-zero vacuum expectation value of a scalar field, gives mass to W and Z and leaves photon massless

Standard Model Fit

- $M_H = 88\ ^{+53}_{-35}$ GeV/ c^2

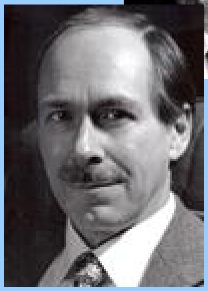




	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
$Q_W(Cs)$	-72.50 ± 0.70	.56

The Higgs Boson

- This field, like any field, has quanta, 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



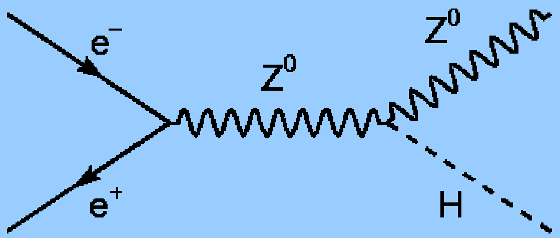
- This spontaneously broken local gauge theory is renormalizable - t'Hooft (1971)
- The Higgs boson properties
  - Mass < ~ 800 GeV/c^2 (unitarity arguments)
  - Strength of Higgs coupling increases with mass
    - fermions: $g_{ffh} = m_f / v$ $v = 246$ GeV
    - gauge boson: $g_{wwh} = 2\ m_Z^2 / v$

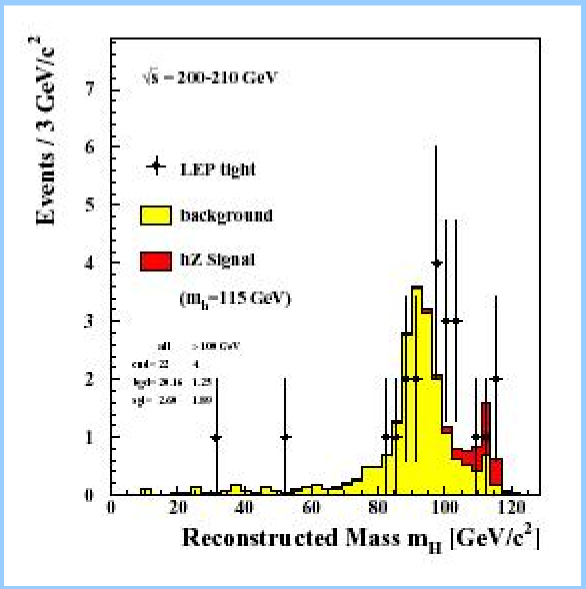
Particle Physics History of Anticipated Particles

Positron	1932 - Dirac theory of the electron
Neutrino	1955 - missing energy in beta decay
Pi meson	1947 - Yukawa's theory of strong interaction
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.)



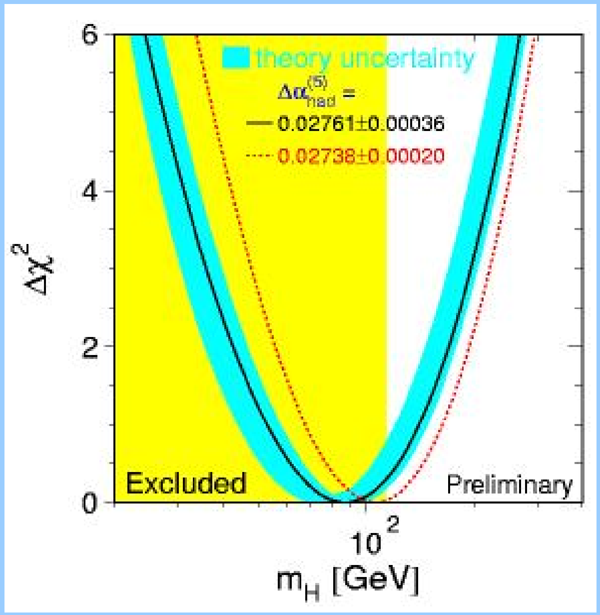


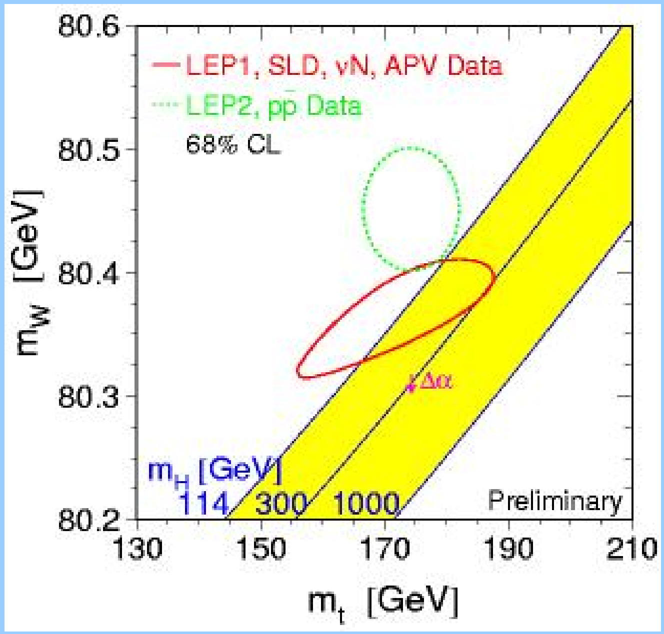
The Higgs Search Moves On

- Tevatron at Fermilab
  - Proton/anti-proton collisions at E_{cm}=2000 GeV
  - Now

- LHC at CERN
  - Proton/proton collisions at E_{cm}=14,000 GeV
  - Begins operation ~2007

Indications for a Light Standard Model-like Higgs





(SM) M_{higgs} < 195 GeV at 95% CL.
LEP2 limit M_{higgs} > 114.1 GeV.
Tevatron can discover up to 180 GeV

W mass (± 33 MeV)
and top mass (± 5 GeV)
agree with precision measures
and indicate low SM Higgs mass

LEP Higgs search – Maximum Likelihood for Higgs signal at m_H = 115.6 GeV with overall significance (4 experiments) ~ 2σ

Establishing Standard Model Higgs

precision studies of the Higgs boson will be required to understand Electroweak Symmetry Breaking; just finding the Higgs is of limited value

We expect the Higgs to be discovered at LHC (or Tevatron) and the measurement of its properties will begin at the LHC

We need to measure the full nature of the Higgs to understand EWSB

The 500 GeV (and beyond) Linear Collider is the tool needed to complete these *precision* studies

References:

TESLA Technical Design Report

Linear Collider Physics Resource Book for Snowmass 2001

(contain references to many studies)

Candidate Models for Electroweak Symmetry Breaking

Standard Model Higgs

excellent agreement with EW precision measurements

implies M_H <200 GeV (but theoretically ugly - h'archy prob.)

MSSM Higgs

expect M_h<~135 GeV

light Higgs boson (h) may be very "SM Higgs-like"

(de-coupling limit)

Non-exotic extended Higgs sector

eg. 2HDM

Strong Coupling Models

New strong interaction

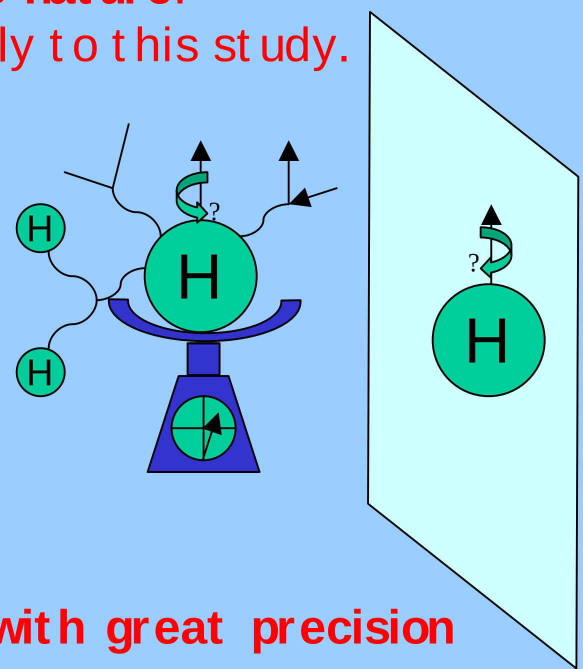
The NLC will provide critical data for all of these possibilities

The Higgs Physics Program of the Next Linear Collider

Electroweak precision measurements suggest there should be a relatively light Higgs boson:

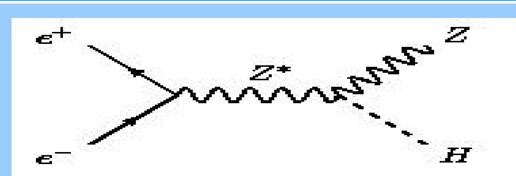
When we find it, we will want to study its nature.
The LC is capable of contributing significantly to this study.

Mass Measurement
Total width
Particle couplings
  vector bosons
  fermions (including top)
Spin-parity-charge conjugation
Self-coupling



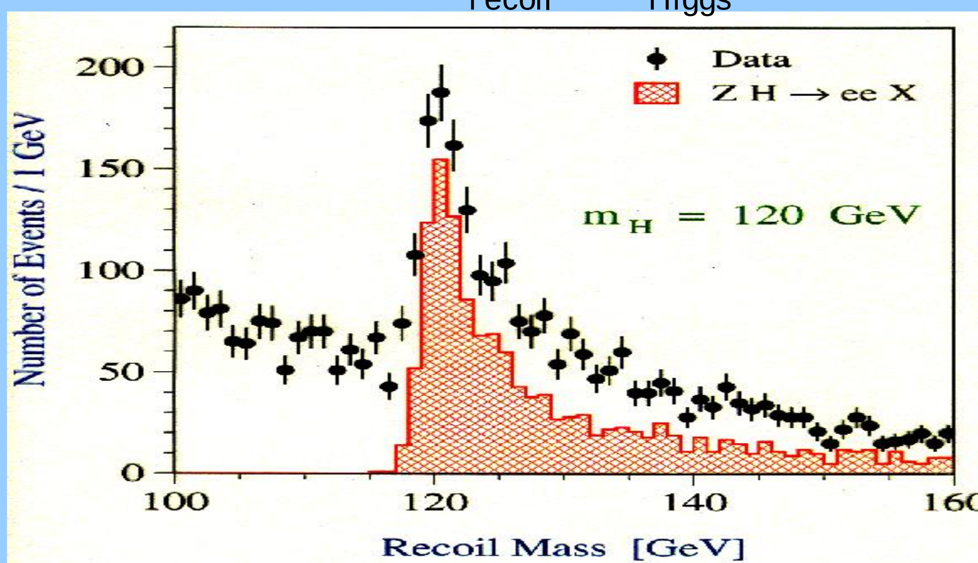
The Linear Collider could measure all this with great precision

Higgs Studies
- the Power of Simple Reactions



The LC can produce the Higgs recoiling from a Z, with known CM energy⇓, which provides a powerful channel for unbiassed tagging of Higgs events, allowing measurement of even invisible decays (⇓ - some beamstrahlung)

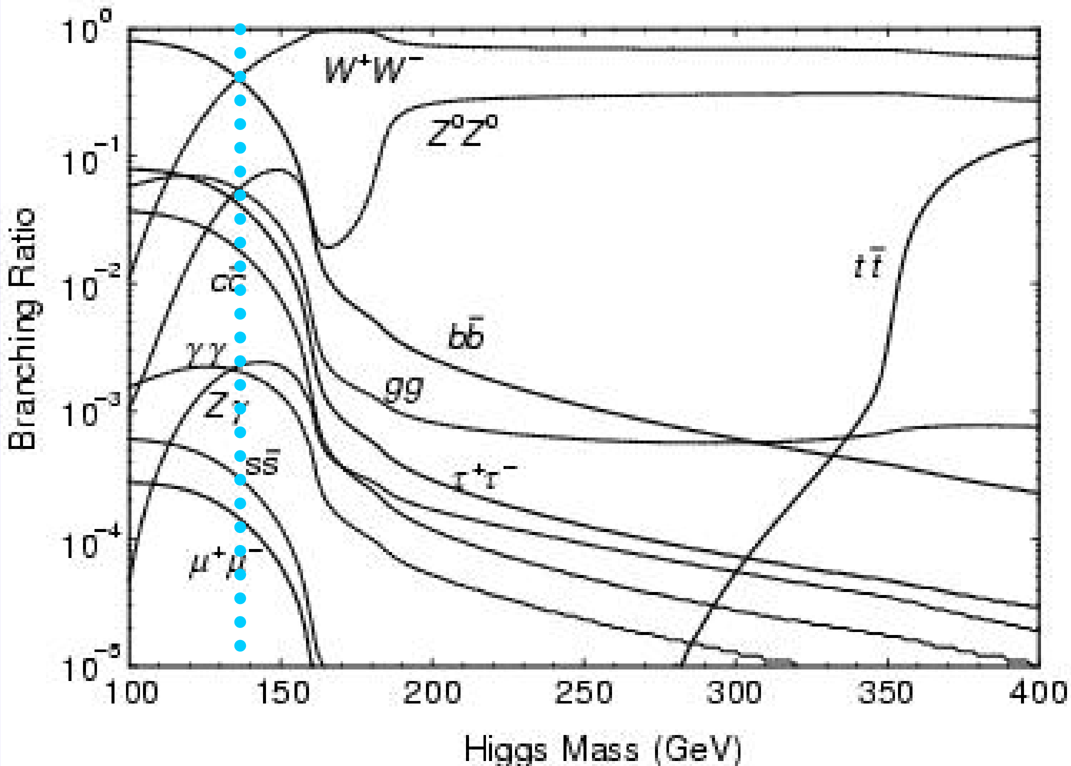
- Tag $Z \rightarrow l^+ l^-$
- Select $M_{recoil} = M_{Higgs}$



Invisible decays are included

500 fb^{-1} @ 500 GeV, TESLA TDR, Fig 2.1.4

Higgs Couplings - the Branching Ratios



bb	$\delta g_{Hbb} / g_{Hbb} \approx 2$ %
cc	$\delta g_{Hcc} / g_{Hcc} \approx 22.5$ %
$\tau^+\tau^-$	$\delta g_{H\tau\tau} / g_{H\tau\tau} \approx 5$ %
WW^*	$\delta g_{Hww} / g_{Hww} \approx 2$ %
ZZ	$\delta g_{HZZ} / g_{HZZ} \approx 6$ %
gg	$\delta g_{Hgg} / g_{Hgg} \approx 12.5$ %
$\gamma\gamma$	$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} \approx 10$ %

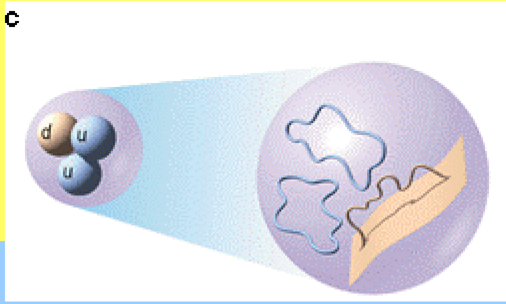
Measurement of BR's is powerful indicator of new physics

e.g. in MSSM, these differ from the SM in a characteristic way.

Higgs BR must agree with MSSM parameters from many other measurements.

String Theory

- Compelling theory of the fundamental structure of the elementary particles
- Each particle type is a vibrating string in 10 space-time dimensions (actually 11 - M-theory)
  - 11 dimensions include 4 familiar space-time dimensions, plus 7 additional, so far unseen, dimensions
- Unifies all forces, including gravity
- Theory is "well-behaved" at all energies
- Two dramatic predictions (caution, this is all still speculation, although many physicists are betting on something like this)
  - New spectrum of particles
    - supersymmetric particles
  - Extra dimensions



Supersymmetry

- all particles of Standard Model matched by super-partners
  - super-partners of fermions are bosons
  - super-partners of bosons are fermions
- inspired by

> Strongly broken symmetry
> Super-partners are very heavy

- high energy
  - well behaved theory at all energies
- could play role in solution to dark matter problem
  - photinos, or other light supersymmetric particles
- many new particles (detailed properties only at NLC)

Extra Dimensions

- string theory predicts these extra dimensions
- solves "hierarchy problem" ($M_{planck} > M_{EW}$) if extra dimensions are large
  - another way to state the "hierarchy problem" is
    "why is gravity so much weaker than the other forces?"
- large extra dimensions would be observable at NLC (see Physics Today, February 2002)

Large Extra Dimensions

- Some of the extra dimensions could be quite large
- The experimental limits on the size of extra dimensions are <u>not</u> very restrictive
  - to what distance has the $1/r^2$ force law been measured?
  - extra dimensions could be as large as 0.1 mm, for example
  - experimental work is underway now to look for such large extra dimensions

Large Extra Dimensions

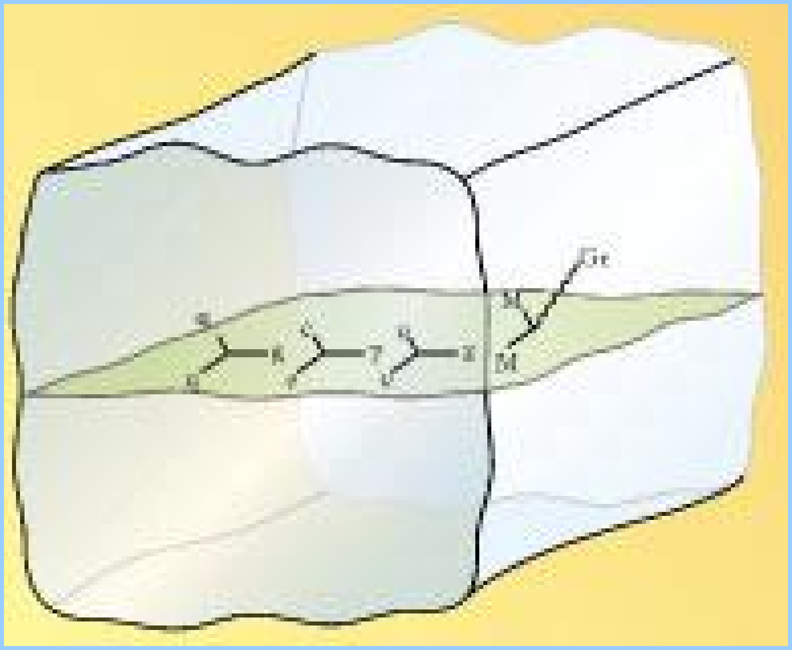
(see "Large Extra Dimensions: A New Arena for Particle Physics", Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

An exciting new idea explains the hierarchy problem

- In addition to the three infinite spatial dimensions we know about, it is assumed there are n new spatial dimensions of finite extent R.
- The space spanned by the new dimensions is called "the bulk."
- Particles of the standard model (quarks, leptons, and gauge bosons) all live in our familiar realm of three spatial dimensions, which forms a hypersurface, or "3-brane" within the bulk.
- The propagation of electroweak and strong forces is then confined to the 3-brane.
- Gravity is different:
  - Gravitons propagate in the full (3 + n)-dimensional space
  - this may be why gravity is so weak

Large Extra Dimensions

- Gravity is different:
  - Gravitons propagate in the full (3 + n)-dimensional space
- If there were only one large extra dimension, its size R would have to be of order 10^{10} km to account for the weakness of gravity.
- But two extra dimensions would be on the order of a millimeter in size.

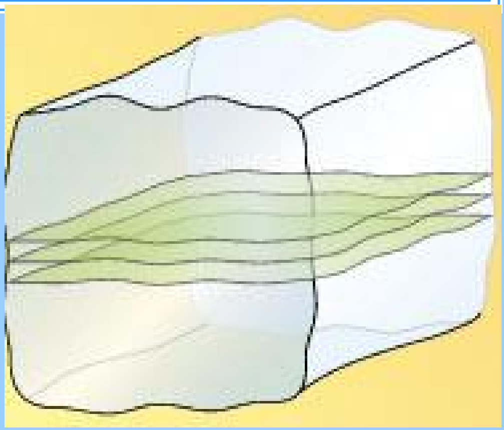


(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

- As the number of the new dimensions increases, their required size gets smaller.
  - For six equal extra dimensions, the size is only about 10^{-12} cm

Explaining the weakness of gravity

Large Extra Dimensions



- Others branes near our brane?
- The physics on those other branes
  - the particles and their forces

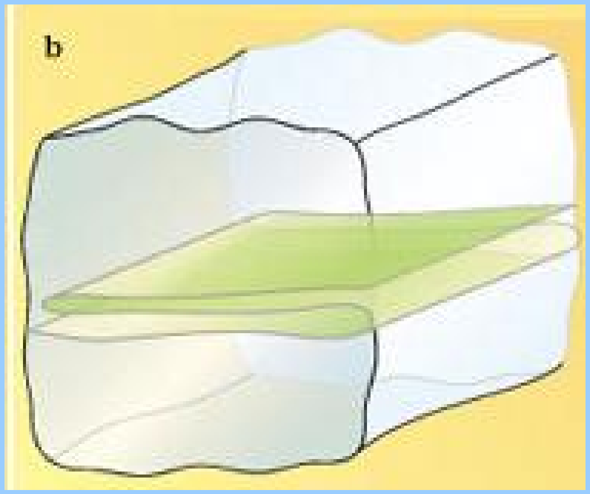
    may be different from ours.
- Nevertheless, their presence would influence physics on our brane.
  - That's because branes are sources for bulk fields, much as charges are sources for the electric field. The values of these bulk fields at the location of our brane may determine the parameters of our standard model
    - for example, the electron mass,
    - the Cabbibo angle,
    - and the electroweak-mixing angle.
  - Conversely, these parameters probe the location of those other branes in the bulk.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Large Extra Dimensions

- Folds of our own 3-brane.?

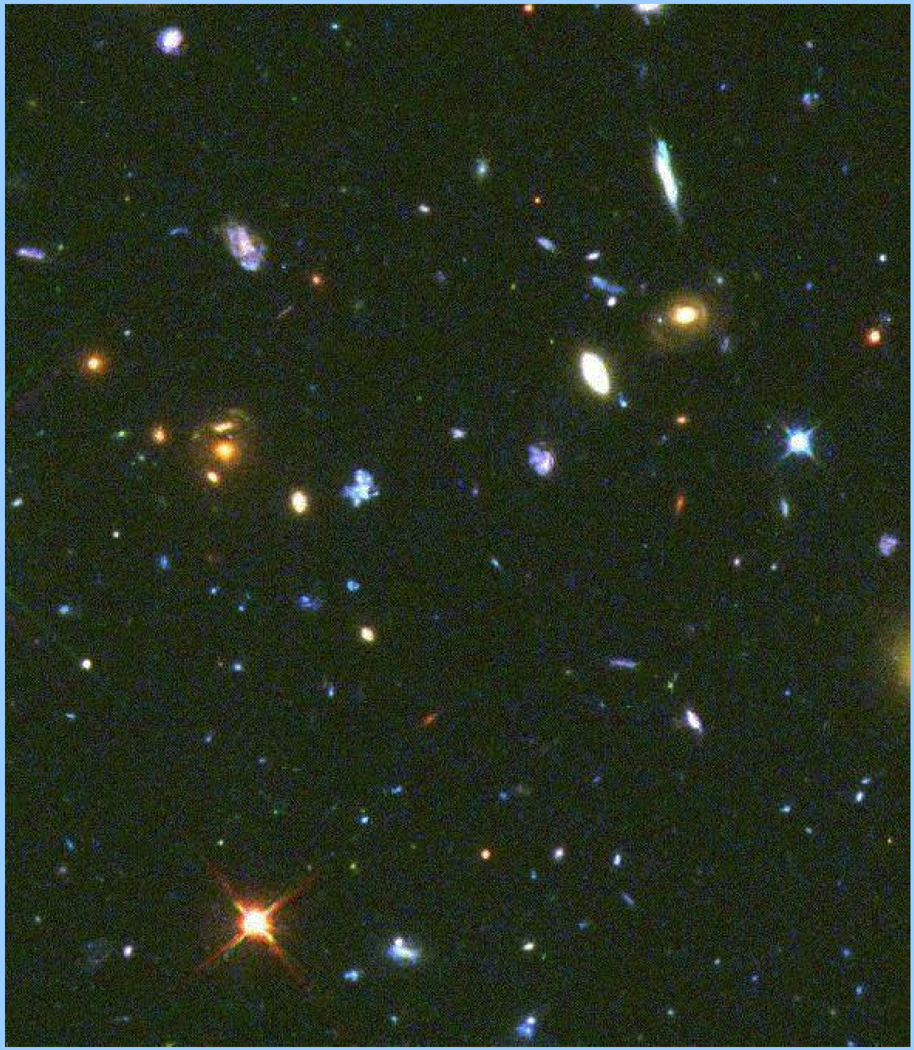
- It might be that the astrophysical and cosmological anomalies we attribute to "dark matter" are actually weak manifestations, across short intervals of the bulk, of ordinary matter in adjacent folds of our 3-brane.



(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Cosmic connections to Particle Physics

- Big Bang Theory
- Grand Unified Theory motivated inflation
- dark matter
- accelerating universe
- dark energy



The Large Hadron Collider (LHC)

- The LHC at CERN, colliding proton beams, will begin operation around 2007
- This "hadron-collider" is a discovery machine, as the history of discoveries show

discovery	facility of discovery	facility of study
charm	BNL + SPEAR	SPEAR at SLAC
tau	SPEAR	SPEAR at SLAC
bottom	Fermilab	Cornell
Z^0	SPPS	LEP and SLC

- The "electron-collider" (the NLC) will likely be needed to sort out the LHC discoveries

Adding Value to LHC measurements

The Linear Collider will add value to the LHC measurements ("enabling technology")

How this happens depends on the Physics:

- Add precision to the discoveries of LHC
  - eg. light higgs measurements
- Susy parameters may fall in the tan β / M_A wedge.
- Directly observed strong WW/ZZ resonances at LHC are understood from asymmetries at Linear Collider
- Analyze extra neutral gauge bosons
- Giga-Z constraints

Conclusion

The Linear Collider will be a powerful tool for studying the Higgs Mechanism and Electroweak Symmetry Breaking.

This physics follows a century of unraveling the theory of the electroweak interaction

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

Current status of Electroweak Precision measurements and the developments in particle theory strongly suggests that the physics at the LC will be rich

Construction could begin around 2005-6 and operation around 2011-12