A Decade of Discovery Past

- Electroweak theory → law of nature \([Z, e^+e^-, \bar{p}p, \nu N, (g - 2)\mu, \ldots]\)
- Higgs-boson influence observed in the vacuum [EW experiments]
- Neutrino flavor oscillations: \(\nu_\mu \rightarrow \nu_\tau, \nu_e \rightarrow \nu_\mu/\nu_\tau [\nu_\odot, \nu_{\text{atm}}]\)
- Understanding QCD [heavy flavor, \(Z^0, \bar{p}p, \nu N, ep, \text{lattice}\)]
- Discovery of top quark [\(\bar{p}p\)]
- Direct CP violation in \(K \rightarrow \pi\pi\) decay [fixed-target]
- \(B\)-meson decays violate CP \([e^+e^- \rightarrow B\bar{B}]\)
- Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- Detection of \(\nu_\tau\) interactions [fixed-target]
- Quarks & leptons structureless at TeV scale [mainly colliders]
Our Picture of Matter (the revolution just past)

Pointlike \((r \leq 10^{-18} \text{ m})\) quarks and leptons

Interactions: \(SU(3)_c \otimes SU(2)_L \otimes U(1)_Y\) gauge symmetries
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The World’s Most Powerful Microscopes

Fermilab’s Tevatron Collider & Detectors

900-GeV protons: $c = 586 \text{ km/h}$
980-GeV protons: $c = 495 \text{ km/h}$

Improvement: $91 \text{ km/h}$!

Protons, antiprotons pass my window 45,000 times / second

...working toward $20 \times$ increase in luminosity

$\Rightarrow 10^7 \text{ collisions / second}$

CERN’s Large Hadron Collider, 7-TeV protons: $c = 10 \text{ km/h}$
CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $q\bar{q} \rightarrow \text{jet} + \text{jet}$
Gauge symmetry (group-theory structure) tested in
\[ e^+ e^- \rightarrow W^+ W^- \]
Gauge symmetry (group-theory structure) tested in

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

LEP PRELIMINARY

17/02/2005

$$\sigma_{WW} (pb)$$

$$\sqrt{s} (GeV)$$

YFSWW/RacoonWW

no ZWW vertex (Gentle)

only $\nu_e$ exchange (Gentle)
Gauge symmetry (group-theory structure) tested in

\[ e^+ e^- \rightarrow W^+ W^- \]
The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

\[ W_L^+ W_L^-, Z_L^0 Z_L^0, H H, H Z_L^0 \] satisfy s-wave unitarity,

Provided \[ M_H \leq \left( \frac{8\pi \sqrt{2}}{3G_F} \right)^{1/2} = 1 \text{ TeV} \]

- If bound is respected, perturbation theory is everywhere reliable
- If not, weak interactions among \( W^\pm, Z, H \) become strong on 1-TeV scale

*New phenomena are to be found around 1 TeV*
Precision Measurements Test the Theory ...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1875</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4957</td>
</tr>
<tr>
<td>$\sigma_0$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.477</td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>20.744</td>
</tr>
<tr>
<td>$A_{fb}^{0,l}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
</tr>
<tr>
<td>$A_l(P_{\tau})$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
<td>0.21586</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030</td>
<td>0.1722</td>
</tr>
<tr>
<td>$A_{fb}^{0,b}$</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
</tr>
<tr>
<td>$A_{fb}^{0,c}$</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
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<tr>
<td>$A_b$</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
</tr>
<tr>
<td>$A_l$(SLD)</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{fb})$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.398 ± 0.025</td>
<td>80.374</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.140 ± 0.060</td>
<td>2.091</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>170.9 ± 1.8</td>
<td>171.3</td>
</tr>
</tbody>
</table>

LEP EWWG
... and determine unknown parameters

\[ L \]  

\[ \left( 2494.6 \pm 2.7 \right) \text{ MeV} \]

\[ m_H = 60 - 1000 \text{ GeV} \]

\[ m_Z = 91186 \pm 2 \text{ MeV} \]

\[ s = 0.123 \pm 0.006 \]
Mass of the W Boson (preliminary)

$M_t = 171.4 \pm 2.1 \text{ GeV}$

linearly added to

$0.02758 \pm 0.00035$

had

Experiment

ALEPH 80.440 \pm 0.051
DELPHI 80.336 \pm 0.067
L3 80.270 \pm 0.055
OPAL 80.416 \pm 0.053

#2 / dof  =  49 / 41

LEP 80.376 \pm 0.033

… and determine unknown parameters
Revolution:

Understanding the Everyday

▷ Why are there atoms?
▷ Why chemistry?
▷ Why stable structures?
Imagine a world without a Higgs mechanism
If electroweak symmetry were not hidden ...

• Massless quarks and leptons
• QCD confines quarks into color-singlet hadrons

**Nucleon mass little changed**
• QCD breaks EW symmetry, gives tiny $W, Z$ masses; weak-isospin force doesn’t confine

• $p$ outweighs $n$: rapid $\beta$-decay
  ⇒ lightest nucleus is $n$ … no hydrogen atom

• Some light elements from BBN, but $\infty$ Bohr radius
• No atoms means no chemistry, no stable composite structures like liquids, solids, …

... character of the physical world
would be profoundly changed
Searching for the mechanism of electroweak symmetry breaking, we seek to understand why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and it is coming within the reach of particle physics.
The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV …

We do not know the nature of the new force.
The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV ...

We do not know the nature of the new force.
What is the nature of the mysterious new force that hides electroweak symmetry?

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions

Which path has Nature taken?
Essential step toward understanding the new force that shapes our world:
Find the Higgs boson and explore its properties.

• Is it there? How many?

• Verify quantum numbers (spin, parity, …)

• Does $H$ generate mass for gauge bosons and for fermions?

• How does $H$ interact with itself?

Finding the Higgs boson starts a new adventure!
Tevatron

Collider Run II Integrated Luminosity
What the LHC is not really for …

1. Find the Higgs boson, the Holy Grail of particle physics, the source of all mass in the Universe.

2. Celebrate.

3. Then particle physics will be over.

We are not ticking off items on a shopping list …

We are exploring a vast new terrain … and reaching the Fermi scale
Penumbra
Synthetic Spring
Neptune
Big Technology
I’m With You
Cooled
Faith (Yourself?)
Travel
Perpetual Symmetry

Produced By
Gareth Young
and Higgs Boson

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Revolution:
The Meaning of Identity

Varieties of matter

- What sets masses and mixings of quarks and leptons?
- What is $CP$ violation trying to tell us?
- Neutrino oscillations give us another take, might hold a key to the matter excess in the Universe.

All fermion masses and mixings mean new physics

- Will new kinds of matter help us to see the pattern?

What makes a top quark a top quark, an electron an electron, a neutrino a neutrino?
Flavor physics may be where we see, or diagnose, the break in the SM.

<table>
<thead>
<tr>
<th>Parameters of the Standard Model</th>
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<tbody>
<tr>
<td>3</td>
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<tr>
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<tr>
<td>3</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>26</td>
</tr>
</tbody>
</table>
The diagram represents the mass spectrum of fermions normalized to the weak scale. Different symbols are used to denote charged leptons (circles) and quarks (up triangles for up quarks, down triangles for down quarks). The logarithmic scale on the y-axis indicates the mass relative to the weak scale.
Quark family patterns: generations

Veltman: Higgs boson knows something we don’t know!
Neutrino family patterns (an example)
Neutrino Masses

\[ m_\nu \text{ (eV)} \]

\[ m_1 \text{ (eV)} \]

\[ m_h \]

\[ m_m \]
New Physics on the Fermi Scale?

If dark matter interacts weakly ...

... its likely mass is 0.1 to 1 TeV: *Fermi scale*
Many extensions to EW theory entail dark matter candidates

Supersymmetry is highly developed, has several important consequences:

✶ Predicts that Higgs field condenses, breaking EW symmetry, if top is heavy
✶ Predicts a light Higgs mass
✶ Predicts cosmological cold dark matter
✶ In a unified theory, explains the values of standard-model coupling constants
Revolution:
The Unity of Quarks & Leptons

▷ What do quarks and leptons have in common?
▷ Why are atoms so remarkably neutral?
▷ Which quarks go with which leptons?
▷ Quark-lepton extended family $\leadsto$ proton decay: SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y
▷ Unified theories $\leadsto$ coupling constant unification
▷ Rational fermion mass pattern at high energy? (Masses run, too)
Evolution of the strong coupling “constant”
\[
\log_{10} \left( \frac{E}{1 \text{ GeV}} \right)
\]
Gravity rejoin Particle Physics Rejoin
Natural to neglect gravity in particle physics

\[ G_{\text{Newton}} \text{ small} \iff M_{\text{Planck}} = \left( \frac{\hbar c}{G_{\text{Newton}}} \right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV large} \]

Estimate \[ B(K \to \pi G) \sim \left( \frac{M_K}{M_{\text{Planck}}} \right)^2 \sim 10^{-38} \]

But gravity is not always negligible …

**Higgs field contributes uniform vacuum energy density**

\[ \rho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \approx 10^{24} \text{ g cm}^{-3} \]

**Observed vacuum energy density** \[ \rho_{\text{vac}} \leq 10^{-46} \text{ GeV}^4 \]

Mismatch by 54 orders of magnitude
Evidence that vacuum energy is present ...

recasts old problem, gives us properties to measure

A chronic dull headache for thirty years …

Why is empty space so nearly massless?
How to separate EW, higher scales?

Does $M_H < 1$ TeV make sense?

The peril of quantum corrections – hierarchy problem

[Bar chart showing desired output, scalar loops, top-quark loops, gauge boson loops, tuned input, with values ranging from -2 to 2 on the y-axis, and 5 TeV indicated on the x-axis.]
How to separate EW, higher scales?

Traditional: change electroweak theory to understand why $M_H$, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model on the 1-TeV scale …

$\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$

composite Higgs boson

technicolor / topcolor

supersymmetry

…

Ask instead why gravity is so weak, why $M_{\text{Planck}} \gg$ electroweak scale
Revolution:

A New Conception of Spacetime

- Could there be more space dimensions than we have perceived?
- What is their size? Their shape?
- How do they influence the world?
- How can we map them?

*string theory needs 9 or 10*
Suppose at scale $R$ ... gravity propagates in $4+n$ dimensions

Gauss law: $G_N \sim M^{*-n-2} R^{-n}$  \( M^* \): gravity’s true scale

$M_{\text{Planck}}$ would be a mirage!
Gravity follows Newtonian force law down to $\lesssim 1$ mm

$$V(r) = - \int dr_1 \int dr_2 \frac{G_{\text{Newton}} \rho(r_1) \rho(r_2)}{r_{12}} \left[ 1 + \varepsilon_G \exp(-r_{12}/\lambda_G) \right]$$
Gravity follows Newtonian force law down to \( \leq 1 \) mm

\[
V(r) = - \int dr_1 \int dr_2 \frac{G_{\text{Newton}} \rho(r_1) \rho(r_2)}{r_{12}} \left[ 1 + \varepsilon_G \exp\left(-\frac{r_{12}}{\lambda_G}\right) \right]
\]
Connections ...
In a decade or two, we can hope to …

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in $B$ decays
Exploit rare decays ($K, D, \ldots$)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

... learn the right questions to ask
... and rewrite the textbooks!