Electroweak Theory
and Higgs Physics

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A Decade of Discovery Past . . .

▷ Electroweak theory → law of nature

▷ Higgs-boson influence observed in the vacuum

▷ Neutrino flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$

▷ Understanding QCD

▷ Discovery of top quark

▷ Direct $\mathcal{CP}$ violation in $K \rightarrow \pi\pi$

▷ $B$-meson decays violate $\mathcal{CP}$

▷ Flat universe dominated by dark matter, energy

▷ Detection of $\nu_\tau$ interactions

▷ Quarks & leptons structureless at TeV scale
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: \( \nu_\mu \rightarrow \nu_\tau, \)
  \( \nu_e \rightarrow \nu_\mu/\nu_\tau \) \([\nu_\odot, \nu_{\text{atm}}, \text{reactors}]\)

- Understanding QCD
  [heavy flavor, \( Z^0, \bar{p}p, \nu N, ep, \text{ions, lattice} \)]

- Discovery of top quark \([\bar{p}p]\)

- Direct \( CP \) violation in \( K \rightarrow \pi\pi \) \([\text{fixed-target}]\)

- \( B \)-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 \([\text{fixed-target}]\)

- Quarks & leptons structureless at TeV scale
  [mainly colliders]
Goal: Understanding the Everyday

▶ Why are there atoms?
▶ Why chemistry?
▶ Why stable structures?
▶ What makes life possible?
Goal: Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why stable structures?
- What makes life possible?

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?
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.
Tevatron Collider is running now, breaking new ground in sensitivity
Tevatron Collider in a Nutshell

980-GeV protons, antiprotons

\((2\pi \text{ km})\)

frequency of revolution \(\approx 45\,000 \text{ s}^{-1}\)

392 ns between crossings

\((36 \otimes 36 \text{ bunches})\)

collision rate \(= \mathcal{L} \cdot \sigma_{\text{inelastic}} \approx 10^7 \text{ s}^{-1}\)

c \approx 10^9 \text{ km/h}; \quad v_p \approx c - 495 \text{ km/h}\)

Record \(\mathcal{L}_{\text{init}} = 1.64 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}\)

[CERN ISR: \(pp, 1.4\)]

Maximum \(\bar{p}\) at Low \(\beta\): \(1.661 \times 10^{12}\)
The LHC will operate *soon*, breaking new ground in energy and sensitivity.
LHC in a nutshell

7-TeV protons on protons (27 km);

\[ v_p \approx c - 10 \text{ km/h} \]

Novel two-in-one dipoles (\( \approx 9 \text{ teslas} \))

Startup: \( 43 \otimes 43 \rightarrow 156 \otimes 156 \) bunches, \( \mathcal{L} \approx 6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \)

Early: 936 bunches,
\[ \mathcal{L} \gtrsim 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \ [75 \text{ ns}] \]

Next phase: 2808 bunches,
\[ \mathcal{L} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \]
25 ns bunch spacing

Eventual: \( \mathcal{L} \gtrsim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \): 100 fb\(^{-1}\)/year
Tentative Outline . . .

▷ Preliminaries

   Current state of particle physics

   A few words about QCD

   Sources of mass

▷ Antecedents of the electroweak theory

   What led to EW theory

   What EW theory needs to explain

▷ Some consequences of the Fermi theory

   $\mu$ decay

   $\nu_e$ scattering
Outline

- \( SU(2)_L \otimes U(1)_Y \) theory
  - Gauge theories
  - Spontaneous symmetry breaking
  - Consequences: \( W^\pm, Z^0/NC, H, m_f \)?
  - Measuring \( \sin^2 \theta_W \) in \( \nu e \) scattering
  - GIM / CKM

- Phenomena at tree level and beyond
  - \( Z^0 \) pole
  - \( W \) mass and width
  - Atomic parity violation
  - Vacuum energy problem
The Higgs boson and the 1-TeV scale
   Why the Higgs boson must exist
   Higgs properties, constraints
   How well can we anticipate $M_H$?
   Higgs searches

The problems of mass

The EW scale and beyond
   Hierarchy problem
   Why is the EW scale so small?
   Why is the Planck scale so large?

Outlook
General References

▸ C. Quigg, “Nature’s Greatest Puzzles,”
  hep-ph/0502070

▸ C. Quigg, “The Electroweak Theory,”
  hep-ph/0204104 (TASI 2000 Lectures)

▸ C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*

▸ I. J. R. Aitchison & A. J. G. Hey, *Gauge Theories in Particle Physics*

▸ R. N. Cahn & G. Goldhaber, *Experimental Foundations of Particle Physics*


▸ F. Teubert, “Electroweak Physics,” ICHEP04


*Problem sets: [http://lutece.fnal.gov/TASI/default.html](http://lutece.fnal.gov/TASI/default.html)*
Our picture of matter

Pointlike constituents ($r < 10^{-18}$ m)

$$
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L
\begin{pmatrix}
  c \\
  s
\end{pmatrix}_L
\begin{pmatrix}
  t \\
  b
\end{pmatrix}_L
$$

$$
\begin{pmatrix}
  \nu_e \\
  e^-
\end{pmatrix}_L
\begin{pmatrix}
  \nu_\mu \\
  \mu^-
\end{pmatrix}_L
\begin{pmatrix}
  \nu_\tau \\
  \tau^-
\end{pmatrix}_L
$$

Few fundamental forces, derived from gauge symmetries

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

Electroweak symmetry breaking

Higgs mechanism?
Elementarity
▶ Are quarks and leptons structureless?

Symmetry
▶ Electroweak symmetry breaking and the 1-TeV scale
▶ Origin of gauge symmetries
▶ Meaning of discrete symmetries

Unity
▶ Coupling constant unification
▶ Unification of quarks and leptons
  (neutrality of atoms ⇒ new forces!);
  of constituents and force particles
▶ Incorporation of gravity

Identity
▶ Fermion masses and mixings; CP violation; $\nu$ oscillations
▶ What makes an electron an $e$ and a top quark a $t$?

Topography
▶ What is the fabric of space and time?
  ... the origin of space and time?
CDF dijet event ($\sqrt{s} = 1.96$ TeV):

$$E_T = 1.364 \text{ TeV}$$

$$q\bar{q} \rightarrow \text{jet} + \text{jet}$$
Elementarity

If the Lagrangian has the form $\pm \frac{g^2}{2\Lambda^2} \bar{\psi}_L \gamma_\mu \psi_L \bar{\psi}_L \gamma_\mu \psi_L$ (with $g^2/4\pi$ set equal to 1), then we define $\Lambda \equiv \Lambda^{\pm}_{LL}$. For the full definitions and for other forms, see the Note in the Listings on Searches for Quark and Lepton Compositeness in the full Review and the original literature.

$\Lambda^{++}_{LL}(eeee) > 8.3$ TeV, CL = 95%
$\Lambda^{--}_{LL}(eeee) > 10.3$ TeV, CL = 95%
$\Lambda^{++}_{LL}(ee\mu\mu) > 8.5$ TeV, CL = 95%
$\Lambda^{--}_{LL}(ee\mu\mu) > 6.3$ TeV, CL = 95%
$\Lambda^{++}_{LL}(ee\tau\tau) > 5.4$ TeV, CL = 95%
$\Lambda^{--}_{LL}(ee\tau\tau) > 6.5$ TeV, CL = 95%
$\Lambda^{++}_{LL}(\ell\ell\ell\ell) > 9.0$ TeV, CL = 95%
$\Lambda^{--}_{LL}(\ell\ell\ell\ell) > 7.8$ TeV, CL = 95%
$\Lambda^{++}_{LL}(e\ell\ell\ell) > 23.3$ TeV, CL = 95%
$\Lambda^{--}_{LL}(e\ell\ell\ell) > 12.5$ TeV, CL = 95%
$\Lambda^{++}_{LL}(e\ell\ell\ell) > 11.1$ TeV, CL = 95%
$\Lambda^{--}_{LL}(e\ell\ell\ell) > 26.4$ TeV, CL = 95%
$\Lambda^{++}_{LL}(e\ell\ell\ell) > 1.0$ TeV, CL = 95%
$\Lambda^{--}_{LL}(e\ell\ell\ell) > 2.1$ TeV, CL = 95%
$\Lambda^{++}_{LL}(e\ell\ell\ell) > 5.6$ TeV, CL = 95%
$\Lambda^{--}_{LL}(e\ell\ell\ell) > 4.9$ TeV, CL = 95%
$\Lambda^{++}_{LL}(\ell\nu\ell\nu) > 2.9$ TeV, CL = 95%
$\Lambda^{--}_{LL}(\ell\nu\ell\nu) > 4.2$ TeV, CL = 95%
$\Lambda^{++}_{LL}(e\nu\ell\nu) > 3.10$ TeV, CL = 90%
$\Lambda^{--}_{LL}(e\nu\ell\nu) > 2.81$ TeV, CL = 95%
$\Lambda^{++}_{LL}(q\ell\ell\ell) > 2.7$ TeV, CL = 95%
$\Lambda^{--}_{LL}(q\ell\ell\ell) > 2.4$ TeV, CL = 95%
$\Lambda^{++}_{LL}(\nu\nu\ell\nu) > 5.0$ TeV, CL = 95%
$\Lambda^{--}_{LL}(\nu\nu\ell\nu) > 5.4$ TeV, CL = 95%
Two views of Symmetry

1. *Indistinguishability*

   One object transformed into another

   Familiar (and useful!) from

   Global Symmetries: isospin, $SU(3)_f$, ...  

   Spacetime Symmetries

   Gauge Symmetries

   "EQUIVALENCE"

   Idealize more perfect worlds, the better to understand our diverse, changing world

   Unbroken unified theory: perfect world of equivalent forces, interchangeable massless particles ... *Perfectly boring?*

   **Symmetry ⇔ Disorder**
A Perfect World
Two views of Symmetry

2. *Unobservable*

Goodness of a symmetry means something cannot be measured

e.g., vanishing asymmetry

<table>
<thead>
<tr>
<th>Unobservable</th>
<th>Transformation</th>
<th>Conserved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute position</td>
<td>$\vec{r} \rightarrow \vec{r} + \vec{\Delta}$</td>
<td>$\vec{p}$</td>
</tr>
<tr>
<td>Absolute time</td>
<td>$t \rightarrow t + \delta$</td>
<td>$E$</td>
</tr>
<tr>
<td>Absolute orientation</td>
<td>$\hat{r} \rightarrow \hat{r}'$</td>
<td>$\hat{L}$</td>
</tr>
<tr>
<td>Absolute velocity</td>
<td>$\vec{v} \rightarrow \vec{v} + \vec{w}$</td>
<td></td>
</tr>
<tr>
<td>Absolute right</td>
<td>$\vec{r} \rightarrow -\vec{r}$</td>
<td>$P$</td>
</tr>
<tr>
<td>Absolute future</td>
<td>$t \rightarrow -t$</td>
<td>$T$</td>
</tr>
<tr>
<td>Absolute charge</td>
<td>$Q \rightarrow -Q$</td>
<td>$C$</td>
</tr>
<tr>
<td>Absolute phase</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Unity
QCD is part of the standard model

... a remarkably simple, successful, and rich theory

Wilczek, hep-ph/9907340

▷ Perturbative QCD

- Exists, thanks to asymptotic freedom
- Describes many phenomena in quantitative detail:
  ▷ $Q^2$-evolution of structure functions
  ▷ Jet production in $\bar{p}p$ collisions
  ▷ Many decays, event shapes, ...
- We can measure the running of $\alpha_s$
  (engineering value for unification)

▷ Nonperturbative (lattice) QCD

- Predicts the hadron spectrum
- Gives our best information on quark masses, etc.

$F_2(x, Q^2)$ in $\nu\text{Fe}$ interactions (NuTeV)

The graph shows the $F_2(x, Q^2)$ distribution in $\nu\text{Fe}$ interactions for various values of $x$, ranging from $x=0.015$ to $x=0.75$. The data is compared with fits from different experiments:

- NuTeV
- CCFR
- CDHSW
- NuTeV fit

The graph includes data points with error bars for different values of $Q^2$ (in units of GeV/c$^2$) and x. The data is presented in a log-log scale, with $F_2$ on the y-axis and $Q^2$ on the x-axis.

The graph also includes labels for different values of $x$, such as $x=0.015$, $x=0.045$, $x=0.080$, $x=0.125$, $x=0.175$, $x=0.225$, $x=0.275$, $x=0.35$, $x=0.45$, $x=0.55$, and $x=0.65$. The data points are color-coded for different experiments.

The graph is labeled with hep-ex/0509010.
\[ F_2(x, Q^2) \text{ in } \ell N \text{ interactions (ZEUS)} \]

ZEUS

\[ F^\text{em}_2 \text{ - log}_{10}(x) \]

\[ Q^2(\text{GeV}^2) \]

ZEUS, hep-ex/0208023.
Inclusive jet cross section at $\sqrt{s} = 1.96$ TeV (CDF-II)

CDF Run II Preliminary

NLO pQCD EKS CTEQ 6.1M, ($\mu = p_T^{jet}/2$)  
Midpoint $R_{cone} = 0.7$, $f_{merge} = 0.75$, $R_{sep} = 1.3$  
$0.1<|y|<0.7$  
$\int L = 385$ pb$^{-1}$

$\frac{d^2\sigma}{dydp_T}$ [nb/(GeV/c)]

- Total systematic uncertainty
- Data corrected to parton level
- NLO pQCD
Running $\alpha_s(Q)$

Comprehensive survey: W. de Boer, hep-ex/0407021
Quenched hadron spectrum

(No dynamical fermions)

2 + 1 dynamical flavors: A. Ukawa, Beijing QCD 2005,

http://www.phy.pku.edu.cn/~qcd/transparency/20-plen-m/Ukawa.pdf
The Origins of Mass

(masses of nuclei “understood”)

$p, [\pi], \rho$ understood: QCD

*confinement energy* is the source

“Mass without mass”


We understand the visible mass of the Universe

... without the Higgs mechanism

$W, Z$ electroweak symmetry breaking

\[
M_W^2 = \frac{1}{2} g^2 v^2 = \pi \alpha / G_F \sqrt{2} \sin^2 \theta_W
\]

\[
M_Z^2 = M_W^2 / \cos^2 \theta_W
\]

$q, \ell^{\mp}$ EWSB + Yukawa couplings

$\nu_\ell$ EWSB + Yukawa couplings; new physics?

All fermion masses $\Leftrightarrow$ physics beyond standard model

$H$ ?? fifth force ??