Electroweak Physics

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Electroweak Physics

• SU(2)_L X U(1)_Y Gauge Interactions
• QED & weak interactions: properties of W^±, Z^0 bosons and particle couplings to them
  - Emphasis on Q^2 << M_Z^2
• Connections to High Energy Physics
  - What lies beyond the electroweak scale?
  - Are forces unified at a high energy scale?
  - Can we interpret new physics at colliders?
• Applications to Nuclear Physics
  - tests of low energy QCD
  - Electroweak probe more versatile than just the electromagnetic probe
Some Remarks

• Student background and preparation varies
  - Some of you would have had nuclear or particle physics but not all of you
  - Basic knowledge of modern physics assumed

• As postdoctoral researchers, you will learn to cope with “imperfect” knowledge
  - Qualitative rather than quantitative understanding
  - You won’t follow everything, but if you are totally lost, you should stop me with a question

• I hope to communicate the “big” picture
Overview of Lectures

I. Introduction to Electroweak Physics: Emphasis on Colliders
II. Current Status of Electroweak Physics and Role of “Low” Energy
III. Electroweak Physics at Low $Q^2$
IV. Weak Neutral Current Interactions
V. Anatomy of Parity-Violating Electron Scattering Experiments
Fundamental Interactions

**Gravity and Electromagnetic**

- Infinite range

**Strong and Weak**

- 10^{-15} meter

<table>
<thead>
<tr>
<th>Carried By</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graviton (not yet observed)</td>
<td>$W^+ W^- Z^0$</td>
<td>Photon</td>
<td>Gluon</td>
</tr>
<tr>
<td>Acts on</td>
<td>Quarks and Leptons</td>
<td>Quarks and Charged Leptons and $W^+ W^-$</td>
<td>Quarks and Gluons</td>
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</tbody>
</table>

- Radioactivity
- Electricity & Magnetism
- Nuclei & Nucleons

Weak decay of $^{60}$Co Nucleus

$^{60}$Ni → $^{60}$Co + $e^-$

Weak decay of $^{60}$Co Nucleus

$^{60}$Ni → $^{60}$Co + $e^-$

$\bar{p} \rightarrow \bar{p}$, $\bar{L} \rightarrow \bar{L}$, $\bar{s} \rightarrow \bar{s}$

**Parity Nonconservation**

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Electroweak Physics: Lecture I
Quantum Electrodynamics

Free fermions fields are solutions to the Dirac equation

\[ (i \gamma_\mu \partial^\mu - m) \psi = 0 \]

Corresponding Lagrangian: \( \mathcal{L} \sim \bar{\psi} (i \gamma_\mu \partial^\mu - m) \psi \)

Local gauge invariance: interaction with photon field:

\[-J_\mu A^\mu \]

Conserved electromagnetic current

\[ J^\mu = q \bar{\psi} \gamma^\mu \psi \quad 4\text{-vector} \]

Feynman Rules: emission and absorption of virtual photons by fermion electromagnetic current

Feynman Diagram \( \rightarrow \) Matrix Element \( \rightarrow \) Fermi’s Golden Rule

Cross-section \( \leftarrow \) Transition probability
**e-µ scattering**

Differential Cross Section

\[
\frac{d\sigma}{d\Omega} = \frac{4\alpha^2 E'^2}{q^4} \cos^2 \frac{\vartheta}{2}
\]

Muon pair production in e+e- annihilation

\[
\mathcal{M} \sim -\frac{g_e^2}{(p_1 + p_2)^2} \left[ \bar{u}(3) \gamma_\mu \nu(4) \right] \left[ \bar{\nu}(2) \gamma^\mu u(1) \right]
\]

\[ s = (p_1 + p_2)^2: \text{square of the C.O.M. energy} \]

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} (1 + \cos^2 \theta)
\]

\[ g_e = \sqrt{4\pi\alpha} \]

Multiply by 0.389 GeV²-mbarn  \[ \text{Total } \sigma \text{ in barn (10}^{-24} \text{ cm}^2) \]

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Weak Interactions

\[ \mathcal{M} \sim -\frac{G_F}{\sqrt{2}} \left[ \bar{u}(Co)\gamma_\mu (1 - \gamma^5)u(Ni) \right] \left[ \bar{u}(e)\gamma^\mu (1 - \gamma^5)v(\bar{\nu}) \right] \]

4-Fermi Contact interaction with parity violation

For massless particles:

\[ \gamma^5 u = (\vec{p} \cdot \vec{\Sigma}) u \]
\[ \vec{\Sigma} \equiv \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix} \]
\[ \vec{p} \cdot \vec{\Sigma} \equiv h \]

helicity operator

\[ \Sigma u = +u \rightarrow \left( 1 - \gamma^5 \right) \frac{u}{2} = 0 \]
\[ \Sigma u = -u \rightarrow \left( 1 - \gamma^5 \right) \frac{u}{2} = u \]

\[ P_L \equiv \frac{(1 - \gamma^5)}{2} \quad P_R \equiv \frac{(1 + \gamma^5)}{2} \]

Left- and right-handed projections

\[ P_{L,R} u \equiv u_{L,R} \]

\[ P_i P_j = \delta_{ij} P_j \quad \sum_i P_i = I \]

V X A gives rise to pseudo-scalars

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Handedness

Important: Chirality ≠ Helicity if m≠0!

Helicity operator commutes with free-particle Hamiltonian

Conserved but not Lorentz invariant!

(Can race past a massive particle and observe it spinning the other way)

Chirality operator not conserved, but Lorentz invariant!

Freely propagating left-chiral projection will develop a right-chiral component
Charge and Handedness

Electric charge determines strength of electric force
Electrons and protons have same charge magnitude: same strength

Neutrinos are “charge neutral”: do not feel the electric force

Weak charge determines strength of weak force
Left-handed particles (Right-handed antiparticles) have weak charge

$^{60}\text{Co}$ $^{60}\text{Ni}$

Right-handed particles (left-handed antiparticles) are “weak charge neutral”

$^{60}\text{Co}$ $^{60}\text{Ni}$

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µ Decay

\[ \mathcal{M} \sim -\frac{G_F}{\sqrt{2}} \left[ \bar{u}(v_\mu)\gamma_\mu (1-\gamma^5)u(\mu) \right] \left[ \bar{u}(e)\gamma^\mu (1-\gamma^5)v(\bar{v}_e) \right] \]

Each decay mode provides a partial width using Fermi’s Golden Rule

 Lifetime \[ \tau = \frac{1}{\sum_i \Gamma_i} \]

 Partial width has units of energy \[ \Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi} \]

 Muon lifetime in vacuum: 2.2 µs

Gedanken Experiments: The luxury of being a theorist

Consider \[ \bar{v}_e + e^- \rightarrow \bar{v}_\mu + \mu^- \]

Can use same \( \mathcal{M} \)

 Conversion factor: 197 MeV·fm

For \( E \sim 1 \text{ TeV} \), probability > 1!

More particles going out than coming in

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Electroweak Physics: Lecture I
**Massive Vector Bosons: W±**

\[
\begin{align*}
\mu^- &\rightarrow \nu_\mu + \bar{\nu}_e + e^- \\
\bar{\nu}_e &\rightarrow e^- + \nu_\mu \\
\mu^- &\rightarrow \bar{\nu}_e + e^- \\
\bar{\nu}_e &\rightarrow \nu_\mu + \mu^-
\end{align*}
\]

\[
G_F = \frac{g_W^2}{\sqrt{2} M_W^2}
\]

Mass of the W between 10 and 100 GeV

**Real W production**

\[
u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu_e
\]

**Fixed target:** \( M_{new}^2 \sim 2ME \)

**Collider:** \( M_{new}^2 \sim 4E^2 \)

Very short lifetime \quad \leftrightarrow \quad \text{Large width}

\[
p(E) = \frac{\frac{1}{2\pi} \frac{1}{(E-m_W)^2 + (\Gamma/2)^2}}{A + B \rightarrow W^+ \rightarrow C + D}
\]

\[
\sigma_{\text{peak}} \approx \frac{4\pi}{3m_W^2} \frac{\Gamma_{AB}}{\Gamma_{tot}} \frac{\Gamma_{CD}}{\Gamma_{tot}}
\]

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Electroweak Physics: Lecture I
Collider Physics

\[ \frac{\Gamma_{AB}}{\Gamma_{\text{tot}}} \] 

Relative probability of \( A+B \) decay w.r.t. total probability: Branching Ratio

Count possibilities:

\[ e^+ \nu_e, \mu^+ \nu_\mu, \tau^+ \nu_\tau, u \bar{d}, c \bar{s} \]

Few nbarn

Need ppbar collider with luminosity \( \mathcal{L} \sim 10^{27}/\text{cm}^2/\text{s} \)

\[ N \sim \mathcal{L} \sigma T = 10^{27} \times 10^{-9} \times 10^{-24} \times 10^7 \]

Few events!

Challenge: QCD background: 40 mbarn!

- \( e^+e^- \) or p-pbar or p-p
- "hermetic" detector
- Collision at heart of detector
- Engineering and technological challenges

W signal: highly energetic lepton with energy imbalance
The Z Boson and Unification

More gedanken experiments

\[ e^+ \nu_e \rightarrow W^+ \gamma \]

Electron-positron collisions

\[ e^+ e^- \rightarrow W^+ W^- \]

Unitarity violation forces important constraints

- Need \( WW\gamma \) vertex: same charge as electron!
- Need a new, neutral massive weak boson: the \( Z^0 \)
- One free parameter: \( \theta_W \), the weak mixing angle

Scattering of longitudinal vector bosons (\( m=0 \))

- \( eeZ \) couplings depend on \( \sin^2 \theta_W \)

\[
\frac{m_W}{m_Z} = \cos \theta_W
\]
W and Z Charges

- Left-handed particles in isodoublets
- Right-handed particles iso-singlets
- No right-handed neutrino

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<thead>
<tr>
<th></th>
<th>Left-</th>
<th>Right-</th>
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<tbody>
<tr>
<td>$\gamma$ Charge</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
</tr>
<tr>
<td>W Charge</td>
<td>$T = \pm \frac{1}{2}$</td>
<td>$T = 0$</td>
</tr>
<tr>
<td>Z Charge</td>
<td>$T - q \sin^2 \theta_W$</td>
<td>$-q \sin^2 \theta_W$</td>
</tr>
</tbody>
</table>

- Ws have no couplings to right-handed particles
- Zs couple to both: introduce $g_L$ and $g_R$

Also use $g_V$ and $g_A$:

\[
g_V = g_L + g_R \quad \quad \quad \quad g_A = g_L - g_R
\]

Vector and Axial-vector couplings

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Electroweak Physics: Lecture I
R and the Heavy Quarks

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} (1 + \cos^2 \theta)
\]

\[
R = \frac{e^+e^- \rightarrow \overline{q}q}{e^+e^- \rightarrow \mu^+\mu^-} = \sum_i Q_i^2
\]

3 colors for each quark!

Figure 8.3  \( R \) is plotted against electron energy (in GeV). (Source: F. Halzen and A. D. Martin, Quarks and Leptons (New York: Wiley, copyright © 1984, p. 229. Reprinted by permission of John Wiley & Sons, Inc.)

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The Z Resonance

e^+ e^- \rightarrow Z^0 \rightarrow l^+ l^- , q\bar{q} \quad \text{Count possibilities:} \quad 6(e^+ e^-) + 6(u\bar{u}) + 9(d\bar{d})

\Gamma_{ff} \propto g_L^2 + g_R^2

\sigma_{Z\rightarrow \text{hadrons}} \approx \frac{12\pi}{m_Z^2} (0.033 \times 0.7)

40 nbarn! 200 times larger than QED

\sigma(E) = \frac{\Gamma_{ee} \Gamma_{ff}}{(E - m_Z)^2 + (\Gamma / 2)^2}

Can measure total width without identifying all final states!

B.R.(leptons): 3.3% each, B.R.(quarks): 70%

N_\nu = 2.9840 \pm 0.0082
Summary

• Introduction to electromagnetic and weak interactions
• Motivation for Electroweak Unification
• Tests of Electroweak theory at colliders
• Introduced nomenclature for electroweak studies
• Continue precision studies of electroweak theory next time