Physics 6213 Lecture 1

Overview of the Standard Model

Forces of the Standard Model

- Four forces known in nature—Strong, Weak, Electromagnetic, and Gravity;
  - Standard Model contains 22 free parameters;

4	coupling constants	4	mixing angles (CKM)
6	quark masses	6	lepton masses
1	Weinberg angle	1	Higgs mass

  - Gravity inconsistent with quantum mechanics—not renormalizable;
  - Electromagnetic and Weak interactions part of a single unified theory—the two force are mixed;
    * Amount of mixing given by Weinberg angle
  - In Quantum Field Theory fields (*forces*) are quantized—each force carried by gauge particle:
    * Electromagnetic force carried by massless neutral photon—generated by electric charge ($\alpha_{em} = 1/137$);
    * Strong force carried by eight massless gluons with net color (*strong*) charge—three possible color charges ($\alpha_s \approx 0.1$);
    * Weak force carried by massive $W^{\pm}$ and Z^0—carry net weak charge ($\alpha_w = 1/29$);

$$M_W = 80.41 \pm 0.10\,\mathrm{GeV} \quad M_Z = 91.187 \pm 0.007\,\mathrm{GeV}$$

Fermions of the Standard Model

- All matter particles are fermions;
- There are three generations of these fermions
  - Each generation has a charge 2/3 and −1/3 quark;
    - Quark see all forces—strong, weak, electromagnetic, and gravity.
  - Each generation also a neutral (*and massless*) plus charge −1
    - Leptons have no strong interactions

Charges and Masses

Quarks			Leptons		
Type	Charge	Mass	Type	Charge	Mass
u	$2/3$	1-5 MeV	ν_e	0	< 15 eV
d	$-1/3$	3-9 MeV	e^-	-1	.511 MeV
c	$2/3$	1.1-1.4 GeV	ν_μ	0	< 0.17 MeV
s	$-1/3$	60-170 MeV	μ^-	-1	106.7 MeV
t	$2/3$	173 GeV	ν_τ	0	< 18 MeV
b	$-1/3$	4.1-4.4 GeV	τ^-	-1	1777 MeV

Generation of Interactions

- Require equations to describe each field:
  - Spin 0 by the Klein-Gordon equation;
  - Fermions described by Dirac equation;
  - Photon by Maxwell's equations;
  - Other forces by equations similar to Maxwell;
- All forces (*interactions*) derived by requiring Lagrangian be invariant to unitary transformation;
  - Similar condition to gauge invariance in electromagnetism imposes on Dirac, Schrodinger, and Klein-Gordon equations;

$$\mathcal{L}[\psi] = \mathcal{L}[e^{i\vec{\alpha}\cdot\vec{\phi}(\mathbf{x})}\psi, A_i^\mu]$$

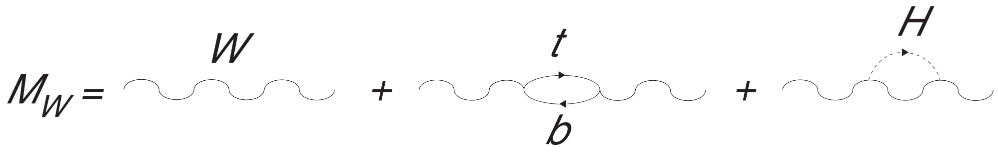
Generation of Masses

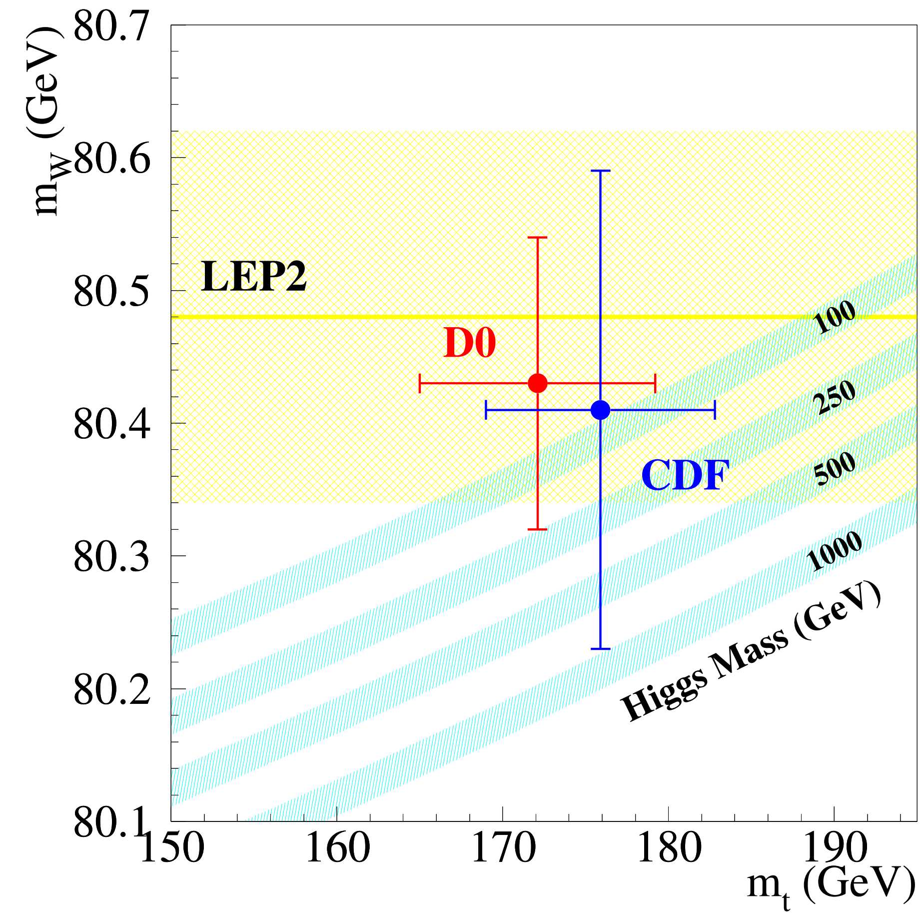
- Introduce a scalar field into $\mathcal{L}$
  - Parameters selected to give non-degenerate vacuum
- Minimum number of Higgs required to generate masses is one.
- Current mass estimate is 107^{+67}_{-45} GeV

Example of Quantum Effects

The Mass of the Higgs

- Due quantum fluctuations, mass of $W^{\pm}$ not that predicted by Standard Model Lagrangian;
  - Major corrections due to t-quark loops and H-boson loops;





Important Symmetries

- Gauge Symmetries—Charge Conservation
  - The various charges are conserved—electric, color, weak
- Lorentz Symmetries
  - Equations describing physics must be covariant
    - Must have same form in all frames
  - Physics described in terms of Lagrangian:
    - Lagrangian a Lorentz scalar—has same value in all frames
    - Hamiltonian (*Energy*) a component of a 4-vector—changes from frame to frame.
  - Discrete Symmetries—CPT
    - Quantum Field Theory requires the combined symmetry CPT be conserved;
    - Parity ($x \xrightarrow{P} -x$) not conserved by weak interaction;
    - Charge Conjugation ($q \xrightarrow{C} -q$) not conserved by weak interaction;
    - Time Reversal (equivalent to CP) ($t \xrightarrow{T} -t$) not conserved in weak interactions;

Review of Parity

- Spatial inversion—$\mathbf{x} \xrightarrow{P} -\mathbf{x}$
  - This implies $PY^{\ell}_{m}(\theta,\phi) = (-1)^{\ell} Y^{\ell}_{m}(\theta,\phi)$
- Parity of fermion opposite antifermion
  - By convention $P|f\rangle = +|f\rangle$ and $P|\bar{f}\rangle = -|\bar{f}\rangle$
  - Parity of other particles determined by wave-function

type	spin	parity	type	spin	parity
scalar	0	+1	pseudo-scalar	0	-1
vector	1	-1	pseudo-vector	1	+1

Review of Charge Conjugation

- Only neutral systems eigen-states of Charge Conjugation
  - Neutral means zero charge—electric, color, weak
  - Neutral also means zero baryon and lepton numbers
- Charge conjugation of gauge particles -1—photon, Z, and gluon
- Charge conjugation of opposite charged bosons
  - Inverts position of particles $\Rightarrow$ same as spatial portion of parity transformation
  - $C|\pi^+\pi^-\rangle = (-1)^\ell|\pi^-\pi^+\rangle$
- Charge conjugation of fermion antifermion pair
  - Equivalent to particle inversion
  - Spatial portion $(-1)^\ell$
  - Spin portion $(-1)^s$
  - Additional -1 from field theory
  - $C|f\bar{f}\rangle = (-1)^{\ell+s}|f\bar{f}\rangle$

Baryon and Lepton Number Conservation

- Number of baryons conserved by all interactions:
  - Quark flavor not conserved by weak interaction;
  - Best limit from lack of neutron anti-neutron oscillations;
  - Proton lifetime $>\approx 10^{31}$ years—also prohibited by lepton number violation
  - quarks have baryon number of $+1/3$
- Number leptons of each flavor conserved in all interactions;
  - Flavor not conserved if neutrinos have mass

The Quark Model

- Baryons—strongly interacting fermions
  - Composed of 3-quarks
  - Examples

$$p = uud \quad n = udd \quad \Lambda = uds \quad \Lambda_B = udb$$

- Mesons—strongly interacting bosons
  - Composed of quark plus antiquark
  - Examples

$$\pi^+ = u\bar{d} \quad \rho = u\bar{d} \quad K^+ = u\bar{s} \quad B^+ = u\bar{b}$$

  - States not allowed: $J^{PC} = 0^{--}$, 1^{-+}