Particle Physics

A Brief Historical Review & Its Prospects

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IPM, Tehran

Dec 2009, Johannesburg

Plan of The Talk

- Past: A historical Review on Particle physics Since 1890's

  Introduction to
  - Particles & their Properties
  - Concepts used in Particle physics

- Present: The Standard Model (SM) & Open questions within the SM.

- Future: Experiments & Observations set up to explore the SM & Beyond.

Disclaimer: This talk is only intended to provide an overview on the field of particle physics & is in no way giving a detailed & complete picture.

Review of the past

I) From 1890's to 1930's

II) From mid 1930's to 1977

III) From '77 to 2008

(I) Important Events:

- 1894: J. J. Thompson discovered electron.
- 1896: H. Becquerel observed β-decay.
- Turn of century: Planck, $\hbar$ & photons.
- 1909: Millikan measured e/m of electron.
- 1918: E. Ratherford discovered proton & established existence of Nuclei.
- 1922: Stern-Gerlach observed Spin of electron.
- 1920's: Bohr Atom & Quantum Mechanics
- 1928: Dirac proposed "anti-electron" Positron.

- 1930: W. Pauli proposed "neutrino" in β-decay.
  (The name was coined by Fermi in 1931)

- 1932: J. Chadwick discovered neutron.

- 1932: C. Anderson discovered positron.

- 1934: E. Fermi proposed his model of β-decay.
  Fermi also introduced the fermi statistics.

- 1910 – ....: Atomic spectroscopy showed that
  - excited atoms emit electromagnetic radiation which is a signature of that atom.
  - emitted photons have energies 1eV – 100 keV.

  usually lower & higher energies have sourced other than atomic radiations.

SUMMARY of Period (I)

- All matter are made out of elementary particles.
  (Elementary does not necessarily mean Structure-less)

- Particles are specified by
  - their mass & Spin
  - the interactions they take part in.

- Elementary particles can be stable or decay with a given life-time; e.g.

$$n \rightarrow P^{+} + e^{-} + \bar{\nu}_e \quad (\beta\text{-decay})$$

- Three fundamental forces were distinguished:
  - Gravity (since Newton),
  - Electromagnetism (since Maxwel),
  - Weak Nuclear force (responsible for β-decay).

- **Electron e:**

  $m_e = 0.511 \ MeV/c^2 \quad (9.1 \times 10^{-31} kg)$

  Spin $1/2$

- electric charge $-1e$; Lightest charged Particle.

- Takes part in Weak Interactions

- Theoretically Stable; $\tau > 4.6 \times 10^{26}$ years

  Age of Universe $\sim 10^{10}$ years.

- Magnetic dipole : $\mu_m = 1.00115965218 59 \, \mu_B$

  $$\mu_B = \frac{e\hbar}{2m_e}$$

- Electric Dipole: $d_e = (0.07 \pm 0.07) \times 10^{-26}$ e.cm

electron electric dipole moments is still an open question in both theoretical & experimental particle physics.

- Proton p:

  $m_p = 938.2$ MeV

  Spin $1/2$

  - electric charge +1
  - Takes part in electromagnetic, weak & strong interactions.
  - lighest Nuleon; (almost stable within SM).

    life time $> 1.9 \times 10^{29}$ years

  Its stability poses a challenge to Grand Unified Theories (GUT's).

- Magnetic dipole:

  $$\mu_p = 2.792847351 \, \mu_N \qquad \mu_N = \frac{e\hbar}{2m_p}$$

Electric dipole:

$$d_p < 0.54 \times 10^{-23} \, e\,cm.$$

- ## Neutron n:

$$M_n = 939.5 \text{ MeV} \quad (M_n > M_p + m_e)$$

Spin $\frac{1}{2}$

- Electrically neutral but has magnetic dipole

$$\mu_n = -1.9130427 \pm 0.000,0005 \; \mu_N$$

- Takes part in strong, weak & electromagnetic interactions.
- life time = 885.7 ± 0.8 sec (for free neutron)

- Electric Dipole:

$$d_n < 0.63 \times 10^{-25} \text{ e.cm}$$

is still among important open questions in particle physics.

- Neutrino ν:

mass : ? But we know $m_\nu \neq 0$

& $m_\nu \sim 10^{-1} - 10^{-3}$ eV

Spin 1/2

- Only take part in Weak Interactions

- Theoretically Stable.

A lot is yet to be learned about Neutrinos...

- Photon: γ

Theoretically mass less, charge less & stable:

$m_\gamma < 1 \times 10^{-18}$ eV ; $q_\gamma < 5 \times 10^{-30}$ e

Spin 1, Boson & Carrier of electromagnetic force.

Period (II) : 1935 – 1977

Golden age of Strong & weak Interactions

Main Events

- 1935: Yukawa proposed Short range Strong force making the nuclei stable. He proposed Mesons (Pions) which exchange Strong force.

  Range of Yukawa force is inverse of Pion mass $m_\pi \sim 100$ MeV.

- 1936: Discovery of "heavy electrons", later called Muon. (At first were mistaken for Yukawa's Mesons.)

- 1947: Discovery of Pions in balloon experiments with cosmic rays.

- 1947: Discovery of K-mesons, Kaons in Cosmic ray experiments.

- 1948: Accelerator physics era begins....
  At Berkeley Nat'l LAB (LBNL)
  Pions were discovered.

- 1953: K-mesons discovered in Brook-Haven.
  & In '55 confirmed at LBNL.

- 1955: Chamblin & Serge discovered anti-proton
  at LBNL.

- 1956: Indirect observation of ν_e in Nuclear
  interactions.

- 1961: Gell Mann & Nishijima proposed the
  Quark model.
  (The term quark was coined by Gell Mann
  in 1963.)

In Gell Mann's quark model Particles which
take part in Strong Interactions (Hadrons)

are either
  Mesons: Bosons made out of a quark
  & an anti-quark
  OR Baryons: Fermions made out of 3 quarks.

There were 3 quark flavors, u, d & s in Gell-Mann's quark model.

- 1968: Conception of the model for weak Interactions based on Yang-Mills SU(2) gauge theory. (Salam & Glashow-Weinberg).

- 1969: Deep Inelastic Scattering (DIS) experiment at SLAC, led J. Bjorken to confirmation of Quark Model for Baryons.

- 1970: Glashow-Illiopolas & Miani (GIM) proposed existence of the 4th flavor of quarks, C.

- 1970: Cabibbo proposed quark flavor mixing.

- 1971: 't Hooft & Veltman proved renormalizability of Yang-Mills gauge theories & in particular the Glashow-Salam-Weinberg model of weak interactions.

- 1972: Gell-Mann & Fritzch proposed QCD for strong Interactions.

- 1973: Gross-Wilczek & Politzer showed that QCD is Asymptotically free.

- 1973: Kobayashi - Maskawa proposed:
  - Possibility of CP violation in strong Interactions through three flavor quark mixings.
  - Proposed 5th quark, b.
  -

- 1973: Discovery of neutral current weak interactions at CERN, providing the first indirect, but important, check of the electroweak theory.

- 1974: Discovery of J/ψ & C quark at SLAC & MIT. (Richter & Ting).

- 1974-77: Discovery of τ-lepton & b-quark at SLAC

By 1977 we had all experimental & theoretical ingredients which were summarized in the STANDARD MODEL

Summary of Experimental Results up to 1977

- All particles are either leptons
  OR hadrons.

- Leptons are either charged:

  electron $m_e = 0.511$ MeV stable

  muon $m_\mu = 105$ MeV; $\Gamma_\mu = 2 \times 10^{-6}$ sec.

  τ-lepton $m_\tau = 1777$ MeV; $\Gamma_\tau = 2.9 \times 10^{-13}$ Sec.

OR netural: Neutrinos:

We now know that there are THREE neutrinos, ν_e, ν_μ, ν_τ (which was discovered in 2001 in Fermi Lab).

- After photon neutrino is the most abundant particle in the Universe.

- The anti-neutrino's of $\bar{\nu}_e$ & $\bar{\nu}_\mu$ have also been discovered experimentally.

NOTE: Every Particle has an anti-particle of EXACTLY the same mass (unless CPT is violated).

- <u>Hadrons</u>: are either
  - Mesons ($q\bar{q}$ bound state) with masses ranging from few · 100 MeV for Pions to 11. GeV for b-mesons.

OR
  - Baryons (qqq bound state) with masses from 938.2 MeV for Proton to 5800 MeV for b-baryons.

- life times vary depending the channel through which the decay happens:

  $10^{-8} - 10^{-14}$ sec for Weak channel decay.

  $10^{-17} - 10^{-19}$ sec. For E & M channel decay

  $10^{-20} - 10^{-23}$ sec for Strong channel decay.

- All hadrons are bound states of FIVE Quarks:

  u, c: $+\frac{2}{3}e$

  d, s, b: $-\frac{1}{3}e$

THE STANDARD MODEL

Notable features of the S.M.

- All the particles of the S.M:

  6 leptons

  6 quarks

  1+3+8 gauge bosons

  1 Higgs

  are believed to be structure-less.

- The SM is a Yang-Mills gauge theory with gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$.
- The matter fields are in fundamental reps of SU(3) or SU(2) gauge groups.
- Electroweak theory is a chiral gauge theory.
- It unifies weak & electromagnetic interactions.
- The distinction between the two then comes from a new, yet uncovered, sector: The Higgs sector.

- The Higgs sector is responsible for Spontaneous Symmetry Breaking (S.S.B.) as well as producing Fermion masses.

NOTE: Most of the mass felt in the Universe seems to be coming from a source other than S.S.B!!

- According to the SM: Strong interactions respect parity P & Charge Conjugation C, while electroweak interactions only respect CP.

- The confirmed CP violation in the SM can only come from the quark flavor mixing.

- In the SM neutrinos were assumed to be massless. Since 1998 it is experimentally proved that neutrinos oscillate & hence are massive.

- Although Quarks come in 3 colors, in nature they seem to be confined to white color-less Mesons or Baryons.

- Quark masses:

u : 1.5 – 4 MeV

d : 4 – 8 MeV

s : 80 – 130 MeV

c : 1.1 – 1.3 GeV

t : 171.2 ± 2.1 GeV : discovered in 1996 at TevaTron & later confirmed at CERN.

b : 4.20 ± 0.1 GeV

- Gauge Boson Masses:

$W^{\pm}$ (Discovered at CERN, early 1980)

$m_W = 80.398$ GeV; $\Gamma_W = 2.141$ GeV

Z : $m_Z = 91.188$ GeV; $\Gamma_Z = 2.495$ GeV

Gluons: theoretical mass before confinement is Zero, after confinement ~ 100 MeV (glue ball mass).

Particle \ Charge		$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
LEPTONS	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	—	2	-1
	e_R, μ_R, τ_R	—	—	-2
QUARKS	$\begin{pmatrix}u\\ d\end{pmatrix}_L, \begin{pmatrix}c\\ s\end{pmatrix}_L, \begin{pmatrix}t\\ b\end{pmatrix}_L$	3	2	$+1/3$
	u_R, c_R, t_R	3	—	$+4/3$
	d_R, s_R, b_R	3	—	$-2/3$
GAUGE BOSONS	γ	—	—	—
	Z, $W^{\pm}$	—	3	—
	g_a	8	—	—
	H	—	A part of doublet	$+1$

Present:

- We have S.M. which works fantastically well .

- The only missing part is the Higgs.

  Theoretically:

  $$90 \lesssim m_H \lesssim 180 \text{ GeV}$$

  ↑ Absence of Landau Poles in the Higgs self interactions.

  Experimentally: $m_H \gtrsim 114.4$ GeV ?! (LEP II result, 2001)

- Neutrino masses & mixing

- g-2 of muon

- d_e, d_n & d_{Hg}

- QCD sector: Proton PDF's
  Spin of Proton & Neutron

FUTURE

- In general particle physics research work is done in two arena:

  1. We know the basic physics but lack the (analytical) tools to extract information.

  2. We are in search of the NEW PHYSICS, Beyond the S.M.

Example 1: How to "solve" QCD and read off properties of Hadrons.

Tackling a Strongly Coupled Gauge theory:

String Theory / AdS-CFT & Dualities between SUSY gauge theories ....

have been used to extract information about phases of QCD.

BUT, traditionally people are more interested in developing new physics B.S.M

In Search for New Physics Beyond the SM

- Neutrino Physics, their mass & mixing:
  - predicting P.M.N.S. mixing matrix from first principles.
  - setting up experiments for measuring elements of P.M.N.S. matrix.
  - What is the nature of neutrino mass.
  - Neutrinos & stellar dynamics
- Higgs sector, fermion masses & .....

  The long wait is over now...
  LHC is on the way....

- CP violation, quark mixing matrix:
  - b-factory & b-physics, LHC-b, ...
  - Baryon Asymmetry of the Universe

- Awaiting SUSY

  - Hierarchy problem & Stabilizing the Higgs mass.
  - Gauge Unification
  - Dark Matter Candidates

SUSY is demanded by String theory construct, however, it is mainly used as a computational tool in HEP-TH.

- Grand Unified Theories (GUT)

- Particle Physics & Cosmology

  - Baryo-genesis,
  - Dark matter & Dark energy

- Can gravity play a more important role in low scales?

  - Large Extra dimensions & the hierarchy problem
  - Black holes at LHC?!
  - Quantum gravity & Cosmology