An Introduction to Modern Particle Physics

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Course Synopsis

★ Introduction : Particles and Forces
  - what are the fundamental particles
  - what is a force

★ The Electromagnetic Interaction
  - QED and e⁺e⁻ annihilation
  - the Large Electron-Positron collider

★ The Crazy world of the Strong Interaction
  - QCD, colour and gluons
  - the quarks

★ The Weak interaction
  - W bosons
  - Neutrinos and Neutrino Oscillations
  - The MINOS Experiment

★ The Standard Model (what we know) and beyond
  - Electroweak Unification
  - the Z boson
  - the Higgs Boson
  - Dark matter and supersymmetry
  - Unanswered questions
Why So WEAK?

RECALL:
- Electromagnetic Force: massless photon: $\alpha \approx 1/100$
- Strong Force: massless gluon: $\alpha_s \approx 1$
- Weak Force: massive W: $\alpha_W \approx ?$

$\alpha_w \approx 1/40$!

★ The weak interaction has almost the same intrinsic strength as the EM force!
★ Suggestive of UNIFICATION OF FORCES
★ Only weak because need a lot of energy to “make” a W-boson (recall easier to emit low energy virtual particles)
Recap

**Electromagnetic Interaction:**
★ Mediated by massless photons
★ Photon couples to ELECTRIC charge
★ Does not change flavour
★ QUARKS/CHARGED LEPTONS

**Strong Interaction:**
★ Mediated by massless GLUONS
★ GLUON couples to “COLOUR” charge
★ Does not change flavour
★ QUARKS/GLUONS

**Weak Interaction:** IS VERY DIFFERENT
★ Mediated by massive W BOSONS
★ Couples to all particles equally
★ Changes flavour
★ QUARKS/ALL LEPTONS
★ Only appears weak due to mass of W
  \[ M_w \sim 80 \text{ GeV/}c^2 \]
Electroweak Unification

Hints for Unification of WEAK and EM forces:

★ Strengths of WEAK and EM interactions are similar
★ Force carrying particle of the WEAK force is charged
  i.e. carries charge of the EM interaction
★ also consider \( e^+e^- \rightarrow W^+W^- \) – 2 ways this can occur

★ Cross-section goes to infinity at high energies
★ Problem fixed by assuming another process
This prevents the cross-section increasing without limit!

star BUT only works of the couplings of the $g$, $W^\pm$ and $Z^0$ are all related!

star $Z^0$ is a QM mixture of a photon and neutral version of the $W$

star $Z^0$ “acts like a neutral $W$-boson”

star $Z^0$ “acts like a heavy photon”

star Mass of $Z^0$ related to that of $W$
Neutral Weak Force

- New force carrying boson – “new” force
- Really a different aspect of the weak force - called NEUTRAL WEAK INTERACTION
- Mass of Z boson ~ 90 GeV/c² → weak force

Z couples to all quarks and leptons (including neutrinos) + annihilation
The Standard Model

- There are 12 fundamental particles + 12 anti-particles

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- and 4 fundamental forces

- Electromagnetic
- Strong
- Weak
- Gravity

- Forces due to the exchange of particles:
  - QED : PHOTON, $\gamma$
  - QCD : 8 GLUONs, $g$
  - WEAK : $W^+, W^-, Z$

- Provides a perfect description of all current data

Forces due to the exchange of particles:
- Electroweak Unification
- Higgs Boson
Z and W Physics at LEP

- **LEP designed as a Z and W factory**
- **1989-1995** $E = 91$ GeV
  $e^+e^- \rightarrow Z \rightarrow$
- **16 million** Zs detected
- **1996-2000** $E > 2M_w c^2$
  $e^+e^- \rightarrow W^+W^- \rightarrow$
- **30,000** $W^+W^-$ detected

- Main emphasis on making very precise measurements of the properties of the Z and the W
- In the Standard Model if you know e.g. $\alpha$, $\alpha_w$, $M_w$ can predict exactly $M_z$
- Make precise measurements to test predictions of Standard Model
e^{+}e^{-} annihilation at the Z

★ Anything the photon can do so can the Z !
★ + Z can produce neutrinos

Here f is any charged particle

At energies lower than M_{Z} annihilation via the photon dominates
★ When the e^{+}e^{-} energy is almost exactly equal to M_{Z} get resonant production of Z and cross-section
Measuring the Z Mass

Simple method:
- Run accelerator at slightly different energies and the “peak energy” gives $M_Z$

$$M_Z = 91.1875 \pm 0.0021 \text{ GeV}/c^2$$

- Incredible precision - 0.002 % (for particle with lifetime $10^{-25}$ s)

Simple method – but in practice very hard!
- As the moon orbits the Earth it distorts the rock in the Geneva area very very slightly!
- The nominal radius of the accelerator of 4.3 km varies by ±0.15 mm enough to ruin the measurement
- therefore need to correct for tidal effects!
Leakage currents from the TGV rail via lake Geneva follow the path of least resistance using the LEP ring as a conductor. Everytime a train passes by the LEP beam energy changed very slightly

- Also need a train timetable!
Number of Generations

- $Z$ can “decay” into all particle types provided $M_Z > 2 m$
- Even though you don’t observe $e^+e^- \rightarrow \nu \nu$ it does affect the shape of the peak

This is why we believe there are only 3 generations!

Don’t understand why there are 3 generations!
Above the Z peak, produce pairs of W bosons when $E > 2M_W$, i.e. $E > 160$ GeV.
**W Decay**

- What do $e^+e^- \rightarrow W^+W^-$ events look like?
- 3 distinct topologies

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Both Ws decay to a charged lepton and a neutrino

One W decays to a charged lepton and a neutrino the decays to 2 quarks

Both Ws decay to a 2 quarks
W Boson Mass

W boson mass measured from by the energy a momentum of the leptons and jets and

\[ M_W = 80.42 \pm 0.05 \text{ GeV}/c^2 \]
The power of precision

• In the Standard Model it is possible to calculate the W boson mass in terms of other measured quantities such as the Z mass

• BUT measured mass also sensitive to new particles via “loop corrections”

\[ M_{\text{top}}^2 \quad \ln(m_H) \quad ? \]

• HIGH precision measurements provide a probe of these corrections, e.g.
  ★ in 1994 LEP measurements of \( M_Z \) gave a prediction that the top quark mass was about 175 GeV
  ★ Later that year it was discovered at the Tevatron at Fermilab:
    - with a mass of 174 ± 5 GeV
The Higgs Boson

★ The is one final ingredient to the Standard Model - the Higgs Boson

★ The Standard model as described so far is all very well but it doesn’t work for any particles with mass!

★ The Higgs Boson (which may/may not exist) fixes this problem!

★ Unlike all other particles the “vacuum expectation value” of the Higgs Boson is not zero – “in the vacuum there are virtual Higgs bosons just waiting to grab hold of any particle as it passes”

★ The interaction with the Higgs Bosons gives particles mass

\[ H^0 \quad \text{``} \alpha \text{''} = k m_f \]

Coupling strength proportional to mass
A nice analogy

- In the houses of parliament there are always politicians present
  (Higgs bosons have non-zero vacuum expectation value)

- In walks the prime minister before entering the room (s)he can walk freely
  (a massless particle)

- The politicians gather around and he finds it difficult to move
  (because of the interactions with the Higgs boson particles acquire mass)
A nice analogy... ...pushed too far

★ A rumour that the prime minister is about to resign is started

★ The politicians huddle together and now find it more difficult to move

(The Higgs bosons interactions with itself generates the Higgs boson mass)

• In the same way as the top mass was predicted by the the precise measurements at LEP, these measurements predict that the Higgs mass is <200 GeV.

• Nice theory, but is there any evidence that the Higgs exists?
Searching for the Higgs at LEP

- Recall the Higgs boson “couples” to mass
- How can you produce the Higgs at LEP (E = 200 GeV) and how would it decay?

The cross-section for this is very very small – why?

Higgs couples to mass – so need to produce it from a massive particle + decays to the most massive particles allowed

- Look for events with a Z and 2 jets from b-quarks
- Hadrons with b-quarks decay via the weak interaction and live long enough to travel a few mm in our detectors! Identify b-quarks by “displaced vertices”
Was the Higgs seen at LEP?

Sunday Times 10/9/2000
The ALEPH experiment at LEP saw 4 events consistent with being 115 GeV/c² Higgs boson production but not confirmed by the other experiments - the jury is still out!
Future Higgs Discovery?

- LEP shut down in 2000
- Its successor, the Large Hadron Collider (LHC) currently being built in the LEP tunnel
- If the Higgs exists it will be seen at the LHC
- due to start operating in 2008
- if it exists – the Higgs will be discovered!

$p \rightarrow E \sim 14000 \text{ GeV} \rightarrow p$
Matter and Forces

From first session:

Particle Physics is the study of

★ MATTER: the fundamental constituents which make up the universe
★ FORCE: the basic forces in nature, i.e. the forces between the fundamental particles

Try to categorise PARTICLES and FORCES in a simple and fundamental manner

So where are we now?
FORCES: Unification

1860: Maxwell unified theory of Electricity and magnetism

1970-: Glashow, Salam, Weinberg unified theory of Electromagnetism and Weak interaction

?????: What next?

Recall strength of interaction “RUNS”

As energy increases:
★ Electroweak gets stronger
★ QCD gets weaker
★ At some point – all forces have same strength!
Higgs mass and SUSY

★ The Higgs boson “couples” to mass
★ This is problematic
★ Any very massive particle that exist (i.e. way beyond the energies of current accelerators) adds mass to the Higgs boson!

The Higgs boson mass should be very large! Not consistent with LEP data
★ A possible solution: Supersymmetry (SUSY)
★ For every standard model particle there is also a SUSY partner (with different spin)
★ e.g. Spin-half electron → spin-1 selectron e
★ This solves the problem with the Higgs mass – SUSY particle loop cancels the SM particle loop
★ BUT: (more than) doubles number of “fundamental particles”
   + to date: no experimental evidence for SUSY
Matter: what is the matter?

- Many reasons to believe that a large fraction of the matter in the universe is not made up of the known particles
- We don’t yet know what is this nature of the dark matter
- Supersymmetry offers a possible solution
- The lightest SUSY particle could make up the dark matter

BUT, also a problem with the ordinary (baryonic) matter....
Another Problem: Matter in the Universe

\[ \sim 10^{80} \text{ protons} \]
\[ \sim 0 \text{ antiprotons} \]

\[ \sim 10^9 \text{ photons for every proton} \]

How did this happen?
• Approximately 0.001 seconds after Big Bang:
  - the universe was a “hot expanding soup” of:
    \[ e^-, e^+, p, \bar{p}, n, \bar{n} \]

But for some reason there was a small excess of particles e.g. for every:

\[ 10^9 \text{ anti-protons} \]
\[ 10^9 +1 \text{ protons} \]

After annihilation:

\[ 2 \times 10^9 \text{ photons} \]
\[ 1 \text{ proton} \]
\[ 0 \text{ anti-protons} \]

Due to matter and anti-matter behaving in a slightly different manner...... not yet understood!

Cannot be accounted for by the Standard model

★ One of many remaining mysteries.....
Conclusion

Successes of the Standard Model

★ The Standard Model describes ALL experimental data
★ All particles in the Standard Model except the Higgs have been observed
★ Predictions tested to very high precision – it works!

Questions/Problems with the Standard Model

★ The Standard Model is just that “a model”
  - many parameters, e.g. masses, couplings,....
★ Why do the particles have the masses they do?
★ Why 3 generations?
★ Are the quarks/leptons really fundamental?
★ Only just beginning to understand neutrinos
★ Why didn’t all the matter and anti-matter annihilate?
★ Need to unify all forces – including GRAVITY
★ Dark matter + many more

Outstanding understanding of particle physics is still evolving. Over the next few years many new experiments and hopefully some surprises