Searching for a New Force

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1. Quarks, Leptons and Forces
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What Are Quarks and Leptons?

Go back and review high school science

- Matter is made up of atoms
- There are about 109 different species!
- Atom itself has structure:
  - consists of small hard "core" (nucleus)
    - nucleus made of protons and neutrons
  - large cloud of electrons
- We can describe all atoms using 3 particle types
  1. electrons (e^-)
  2. protons (p)
  3. neutrons (n)

But there are hundreds of particles like p and n's

- Find that these are made up of smaller objects
- Those are what we call quarks...

How It All Works (circa 1980)

The Standard Model of Elementary Particle Physics

- Three "generations" of quarks and leptons

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

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

  Come in "pairs" because of the way forces acted on them

- Forces carried by bosons

Electromagnetic force	γ
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Strong force	eight gluons
Gravity	gravitons

- Quark and lepton mass due to "Higgs" particle

$\boxed{\text{Building up Elementary Particles}}$

Leptons are already fundamental

- electron is the most ubiquitous
- other leptons can be produced and studied
- neutrinos are particularly “ephemeral”

Predict that quarks only bind when you have

- three quarks (or three anti-quarks)
- a quark and an anti-quark

For example, a proton is made up of 3 quarks

- 2 up quarks
- 1 down quark

6 flavours $\Rightarrow$ get all known “elementary particles”

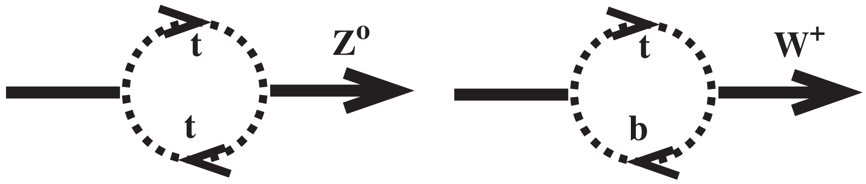
- This model works very well
- Correctly describes Strong and Electroweak forces

The Electroweak Force

The Electroweak Force is "mediated" by three force carriers, the γ, the $W^{\pm}$ bosons and the Z° boson

Concise description of two complex forces

- strength of EM force due to massless photon
- Weak force enfeebled by $W^{\pm}$ and Z° masses
  - $M_W = 80.22 \pm 0.26$ GeV/c^2
  - $M_Z = 91.187 \pm 0.007$ GeV/c^2



Extremely successful!

- But are there other forces?
  - A "super-weak" force would have subtle effect
  - Has significant impact on the sort of "Grand Unified Theory" we look for

Two signatures a new force would have:

1. subtle effects (eg. unusual "beta" decay)
2. A new force carrier (W')

Observing W′ Bosons

Can produce bosons in matter-antimatter collisions

- W' boson readily produced in $p\bar{p}$ collisions
  - reaction is $u + \bar{d} \rightarrow W'$
- $W^{\pm}$ production has a "cross section" of ~ 20 nb

$p\bar{p}$ Collider at Fermilab is the "only" choice

- High luminosities ($\mathcal{L} \sim 25 \times 10^{30}$ cm^{-2}s^{-1})
  - compare to radiation through this room $\mathcal{L} \sim 2{\times}10^{-2}$ cm^{-2}s^{-1})
  - produces $W^{\pm}$ boson once every 2-3 seconds
- Highest energies ($\sqrt{s} = 1800$ GeV)
  - Enough energy to readily form heavier force carriers

Detection of W' is a little more challenging

- Easiest to see decay $W' \rightarrow \mu^{+}\nu^{\mu}$

$u\bar{d} \quad \rightarrow \quad W'$

$\quad\quad\quad\quad\quad\quad \hookrightarrow u\bar{d}$ or $c\bar{s}$

$\quad\quad\quad\quad\quad\quad \hookrightarrow e^{+}\nu_{e}$ or $\mu^{+}\nu_{\mu}$ or $\tau^{+}\nu_{\tau}$

$\boxed{\text{W}'\ \textbf{Detection Issues}}$

Leptonic decays produce high energy electron or muon

- Detect charge track and identify lepton
  - Muons penetrate material
  - Electrons "shower" in high Z material like Pb

Neutrino "slips" away almost always

- Only signature is imbalance of momentum
- So have to detect everything else that is produced in collision
- Also have problem that $W^{\pm}$ is not produced at rest
  - Form **Missing Transverse Energy** vector

$$\vec{\not{E}}_T \equiv -\sum \vec{p_T}$$

  - This is measure of neutrino "transverse energy"

Rescuing the Information

Can combine information from these two leptons

- Form the "transverse mass" of muon and neutrino

$$M_T \equiv \sqrt{2E_T^{\mu}\,\not{E}_T(1-\cos\phi_{\mu\nu})}$$

- Distribution of M_T peaks near mass of force carrier

Even with some of the kinematics missing, have reasonable signature

- To understand in detail, have to know how detector works
- Also effected by how often $W^{\pm}$ is produced with momentum along beam line

$\boxed{\text{The CDF Experiment}}$

CDF is detector designed to study $\overline{p}\,p$ interactions

- Collisions with $\sqrt{s} = 1.8$ TeV created by Tevatron Collider
- Large 5000 ton detector
- Think of it is a very big (expensive) microscope
  - Allows one to detect and measure the results of the collisions

Collaboration consists of

- 35 institutions from US, Japan, Italy, Canada and Taiwan
- 450 physicists

Why so many people?

- takes enormous scientific effort to mount experiment
- continual improvements and repairs

1992-95 Ferilab Collider Run

Took data at the Tevatron Collider starting in 1992

- scanned $\sim 5 \times 10^{12}$ collisions
- Collected 50×10^{6} events on tape

Have processed this data searching for the signatures that we are interested in

- High energy ($> 20 - 30$ GeV) muon
- Large amount ($> 20 - 30$ GeV) of $\not\!\!E_T$

Find lots of potential candidates

- Virtually all $W^{\pm}$'s in region $M_T \lesssim 100$ GeV/c^2
- Looking for very high M_T events
  - Challenge is to figure out where these come from
    * "tail" of $W^{\pm}$ signal
    * Fake muon events from cosmic rays
    * Detector screw-ups

Data Analysis

First predict what backgrounds one would expect

- Use data and a full-scale detector "simulation" to model $W^{\pm}$ signal
- Identify cosmic rays using specific characteristics
  - Not well correlated in time with collision
  - Should often see two tracks back-to-back
- Look for detector screw-ups
  - Charged tracks that look "incomplete"
  - Poor χ^2 fit of helix to track coordinates

Next predict what one would expect from a W'

- Use a software programme to "generate" events arising from

$$p\bar{p} \rightarrow W'X \rightarrow \mu^{+}\nu_{\mu}X$$

- Use detector simulation to model resolution effects

Last step is to make statistical statement about whether observed data is inconsistent with hypothesis that W' exists...

Statistical Analysis

Usually approach problem in following way:

- If a W' of mass M existed and we repeated our experiment, how likely is it that we would observe a rate of signal events above background larger than what we have observed?
- If this probability is $> 95\%$, then we can **exclude** this hypothesis at the 95% confidence level (C.L.).
- In other words, we estimate that the chance we are wrong in excluding this hypothesis is only 1 in 20.

Take a concrete example:

- Suppose we observe 3 candidate signal events with $M_T >$ 200 GeV/c^2
- But no clear peak...
- Let N_W be the expected rate of W' events at a given mass
- We want to make some statement about how large N_W could be

Upper Limit Calculation

Calculation is then straightforward

- Probability of observing k events is given by the Poisson distribution

$$P(k; N_W) = \exp(-N_W)\frac{k^{N_W}}{k!}$$

- Probability of observing > 3 events is 1 minus probability of observing ≤ 3

- We exclude any value of N_W that gives us

$$P(0; N_W) + P(1; N_W) + P(2; N_W) + P(3; N_W) < 0.05$$

n	95% C.L.	90% C.L.
0	3.00	2.30
1	4.74	3.89
2	6.30	5.32
3	7.75	6.68
4	9.15	7.99
10	16.96	15.4

$\boxed{\textbf{Status of Search}}$

Our analysis is still underway

- We don't see anything significant
- If a W' exists
  - Mass is above about 700 GeV/c^2
  - It is less than 1/100 strength of Weak force

Our picture of a four-force world remains unchallenged