Introduction to High Energy Physics PHY489

What are the most fundamental constituents of matter ?

How do these fundamental constituents interact with one another ?

Course web page http://www.physics.utoronto.ca/~krieger/phys489.html

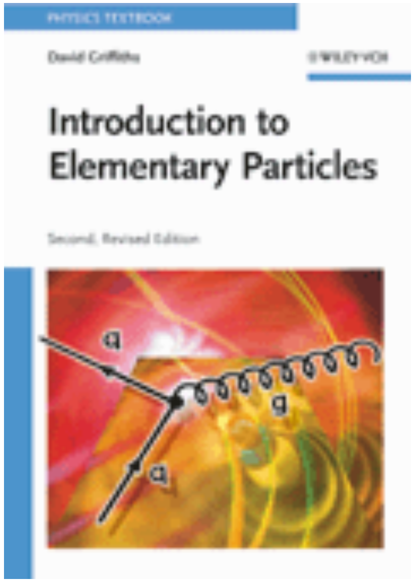
- Course outline
- Announcements
- Reference material
- Grading scheme
- Dates for assignments and tests **(tentative, but will be final later this week)**
- Office hours
- Policies on assignments
- Policies on email

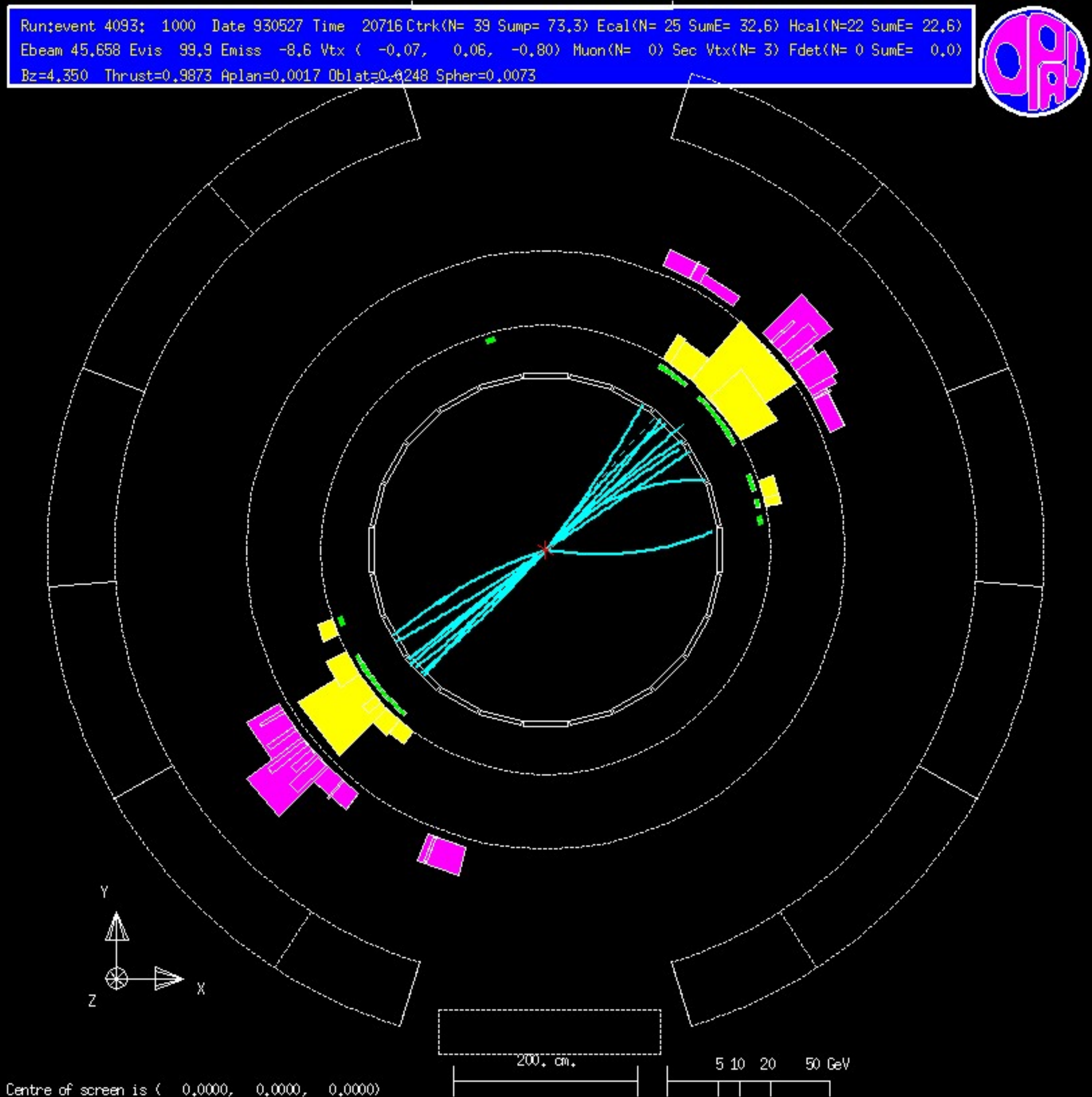
Course Outline

The course outline is given on the course web page, but in a nutshell, the course is dedicated to introducing the Standard Model of particle physics and developing the tools to do basic calculations of real processes (particle decays, scattering processes).

The course will cover the following chapters of the text:

- ✓ Introduction / Overview: Note that this is a fairly brief (3 lecture) introduction to material that is discussed in chapters 1 and 2 of the text. I expect you to have read this material before we start with relativistic kinematics in the fourth lecture, on Sep. 18.
- ✓ Chapter 3: Relativistic Kinematics
- ✓ Chapter 4: Symmetries
- ✓ Chapter 6: Scattering and Decays, Feynman Rules
- ✓ Chapter 7: Quantum Electrodynamics (QED)
- ✓ Chapter 8: Electrodynamics of Quarks and Hadrons (Section 8.1)
- ✓ Chapter 9: Weak Interactions





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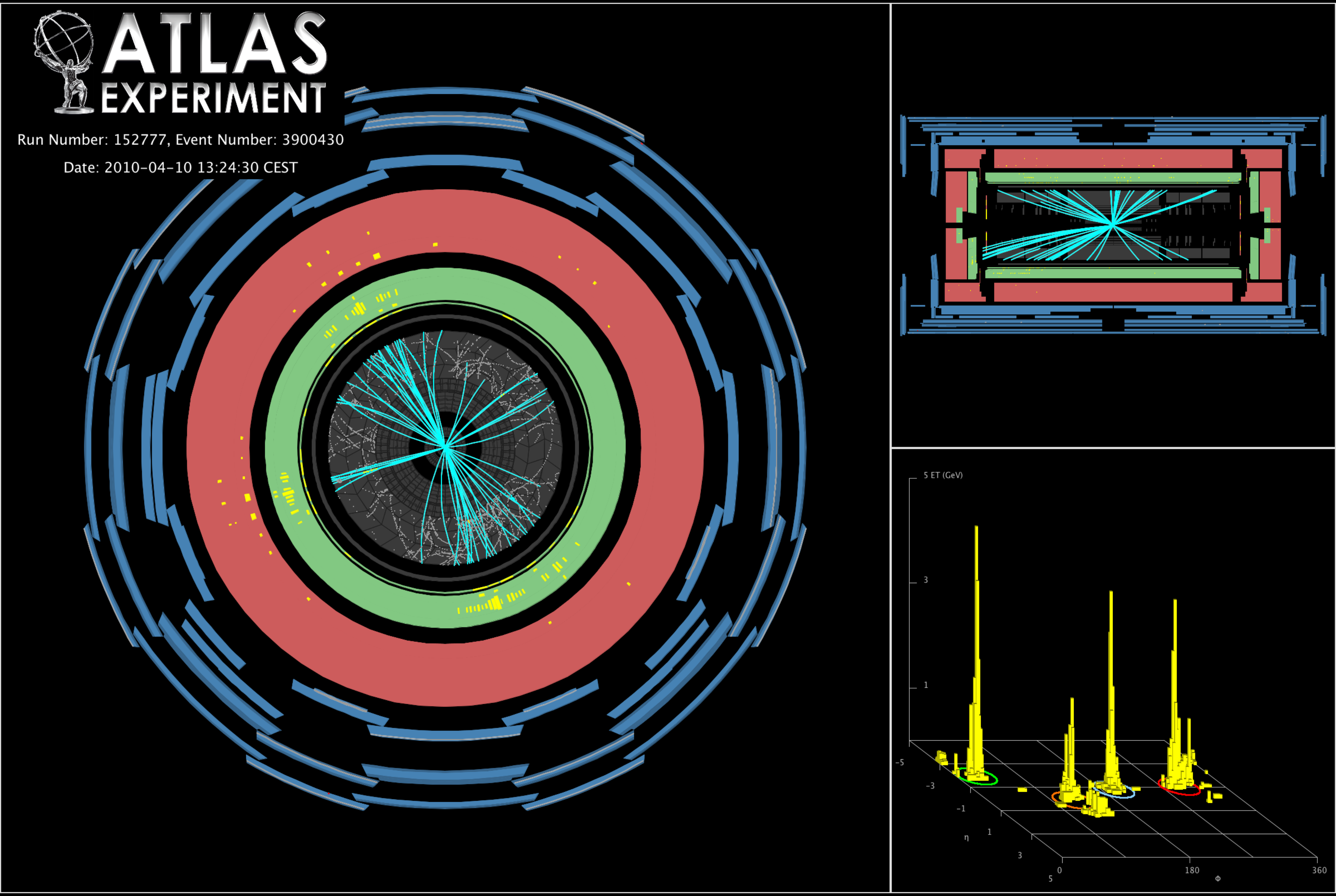
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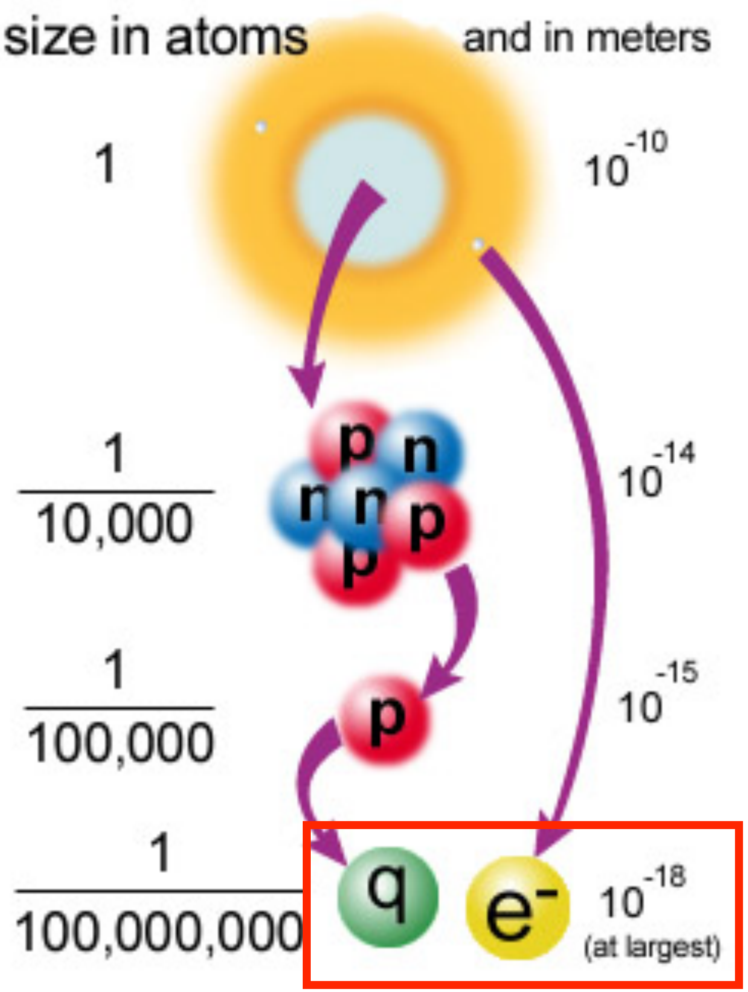
The Subatomic World



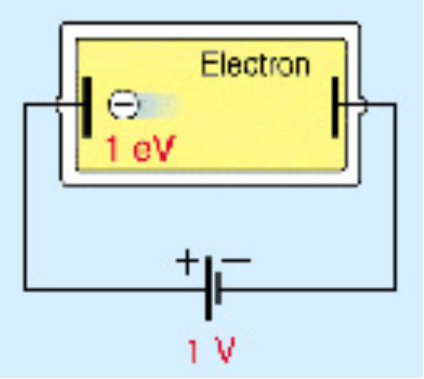
Experimental investigation of smaller and smaller distance scales require higher and higher energies

"fundamental" particles are point-like at the highest experimentally achievable energy scale

String Theory treats fundamental particles as small vibrating strings, not as point particles. This is beyond the scope of this course.

These particles are treated as fundamental in the Standard Model of Particle Physics (amongst others)

Units (Briefly)



Typical units of energy

Atomic physics: eV (electron volts)

Nuclear physics: keV (10^3 eV)

Particle physics MeV (10^6 eV)

GeV (10^9 eV) [used to be called BeV]

TeV (10^{12} eV)

Since $E = mc^2$ masses are typically quoted in units of MeV/c^2 or GeV/c^2.

Momenta are typically quoted in units of MeV/c or GeV/c.

Particle physicists often work in "natural" units in which $\hbar$ and c are set = 1.

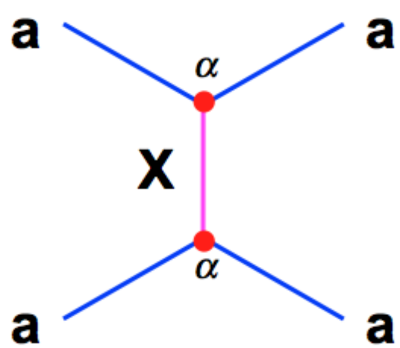
We will avoid this (as in the text) when doing calculations, but I will often use the shorthand of quoting masses and momenta in units of energy.

e.g. electron mass is 0.511 MeV/c^2 which we can also write as 0.511 MeV.

The Standard Model of Particle Physics

Describes the FUNDAMENTAL PARTICLES and their INTERACTIONS

All known FORCES are mediated by PARTICLE EXCHANGE



Effective strength of an interaction depends on

- **the (dimensionless) coupling strength (α) at the vertex**
- **the mass of the exchanged particle M_X**

Force	Effective Strength	Physical Process	
Strong	10^0	Nuclear binding	massless force carrier
Electromagnetic	10^{-2}	Electron-nucleus binding	massless force carrier
Weak	10^{-5}	Radioactive β decay	massive force carrier

Effective coupling ~ 1 has dramatic consequences (perturbation theory)

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathrm{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

charged leptons

neutral leptons

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

quarks

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

$$\mathbf{g}$$

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L \qquad Q = -1$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$$

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$W^{\pm}, Z^0$$

$$g$$

Particles with electromagnetic interactions

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

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

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

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$W^{\pm}, Z^0$$

$$g$$

Particles with weak interactions

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

$$\mathbf{g}$$

Particles with strong interactions

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathrm{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

First observation 2001

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

First observation 1995

Bosons
(spin 1)
Force carriers

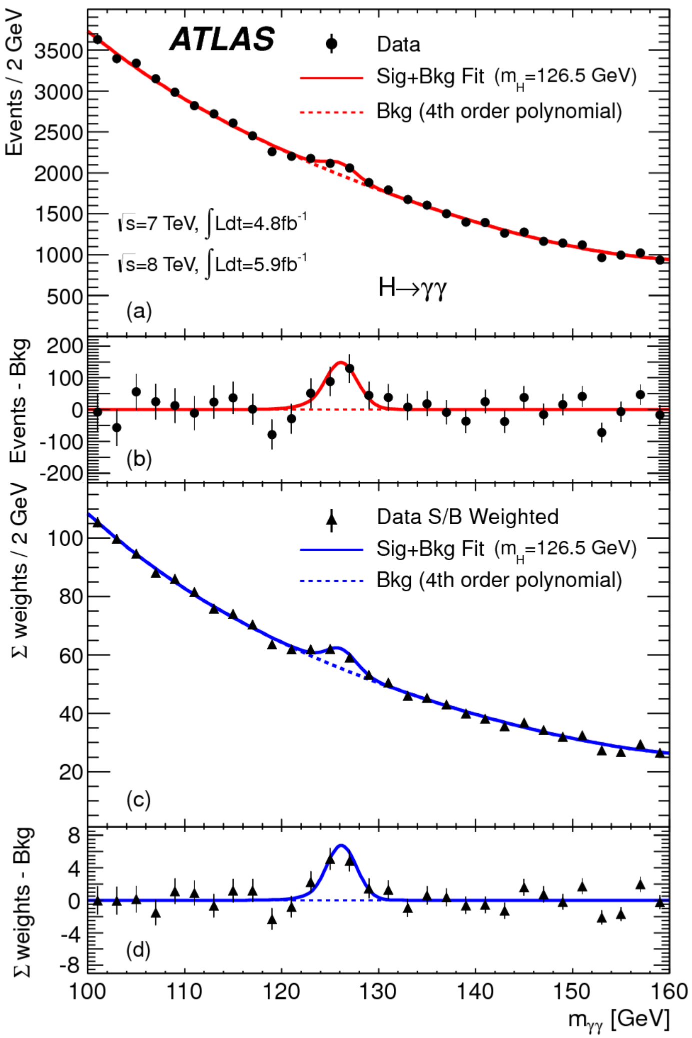
$$\gamma$$
$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$
$$\mathbf{g}$$

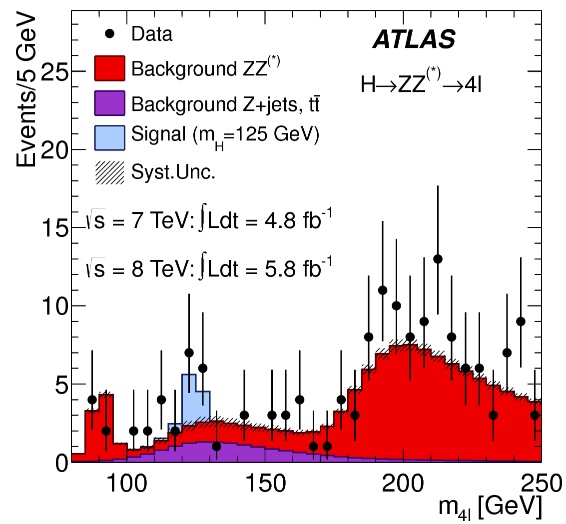
Standard Model predicts the existence of one fundamental scalar (spin-0) particle known as the *Higgs Boson*.

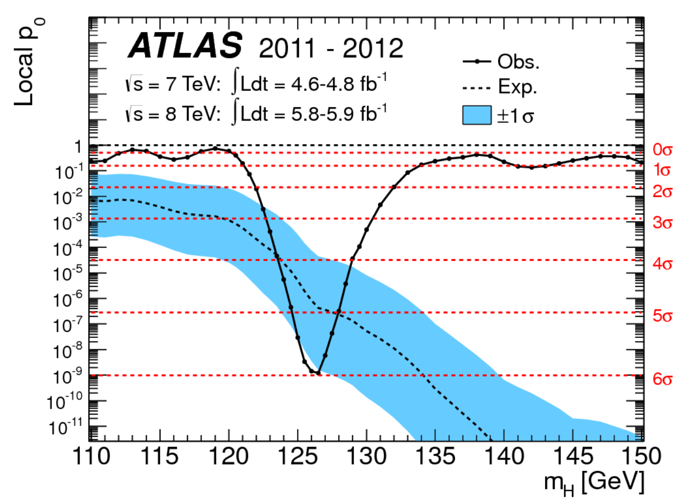
Until about a year ago, this was the only particle of the SM that had not been experimentally observed.

Observation of a Higgs-like Boson

Announced July 4, 2012 at CERN (both ATLAS and CMS experiments)



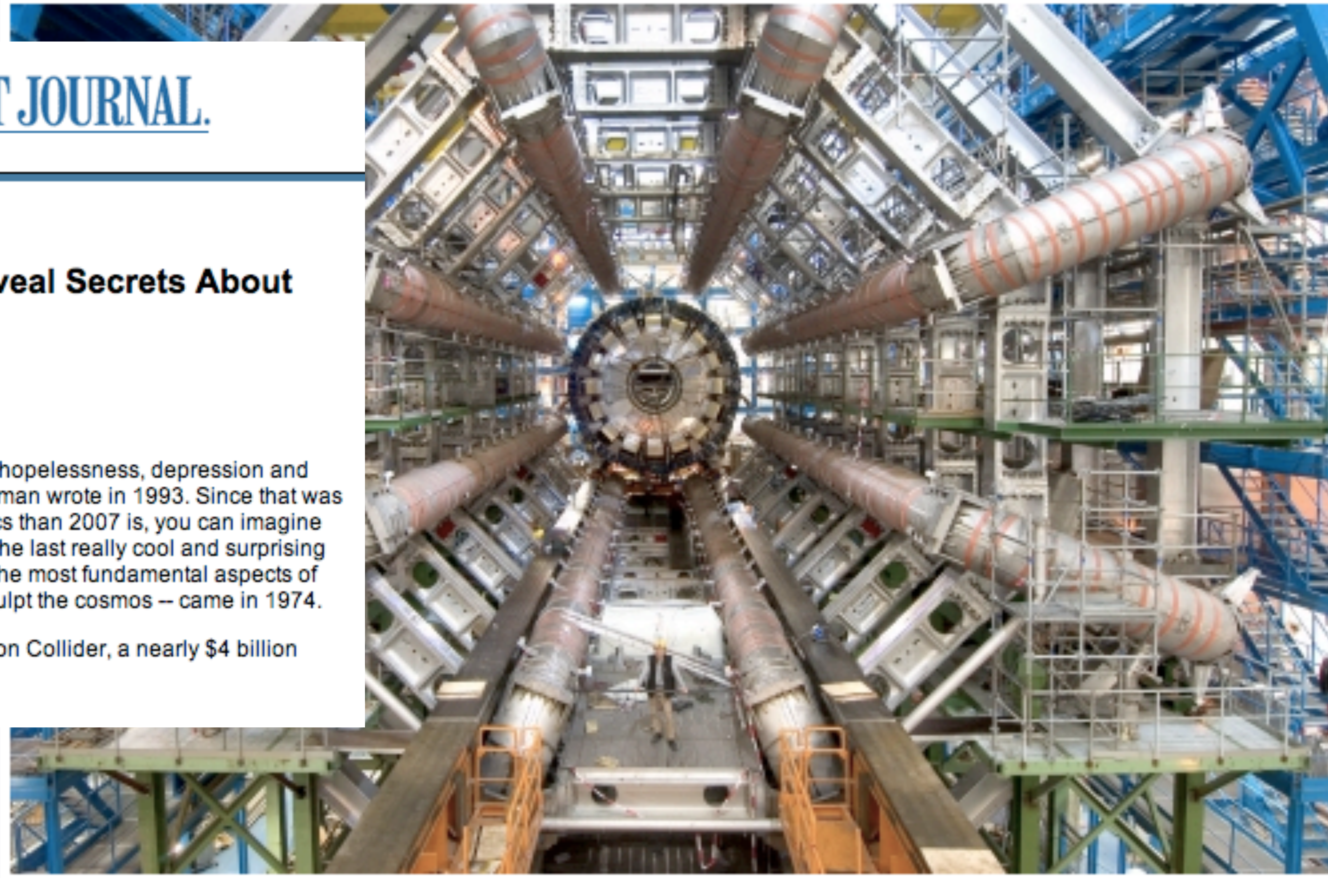




The Higgs Boson in the News

Barrel Toroid is Largest Superconducting Magnet

Posted in Magnets, Science, CERN by Newcastle on December 31st, 2006



This is the **ATLAS Detector**, home of **Barrel Toroid** - the largest superconducting magnet ever built. The barrel-shaped magnet provides the magnetic field for ATLAS, a particle detector at CERN1's Large Hadron Collider (LHC).

WSJ.com THE WALL STREET JOURNAL ONLINE

FREE PREVIEW

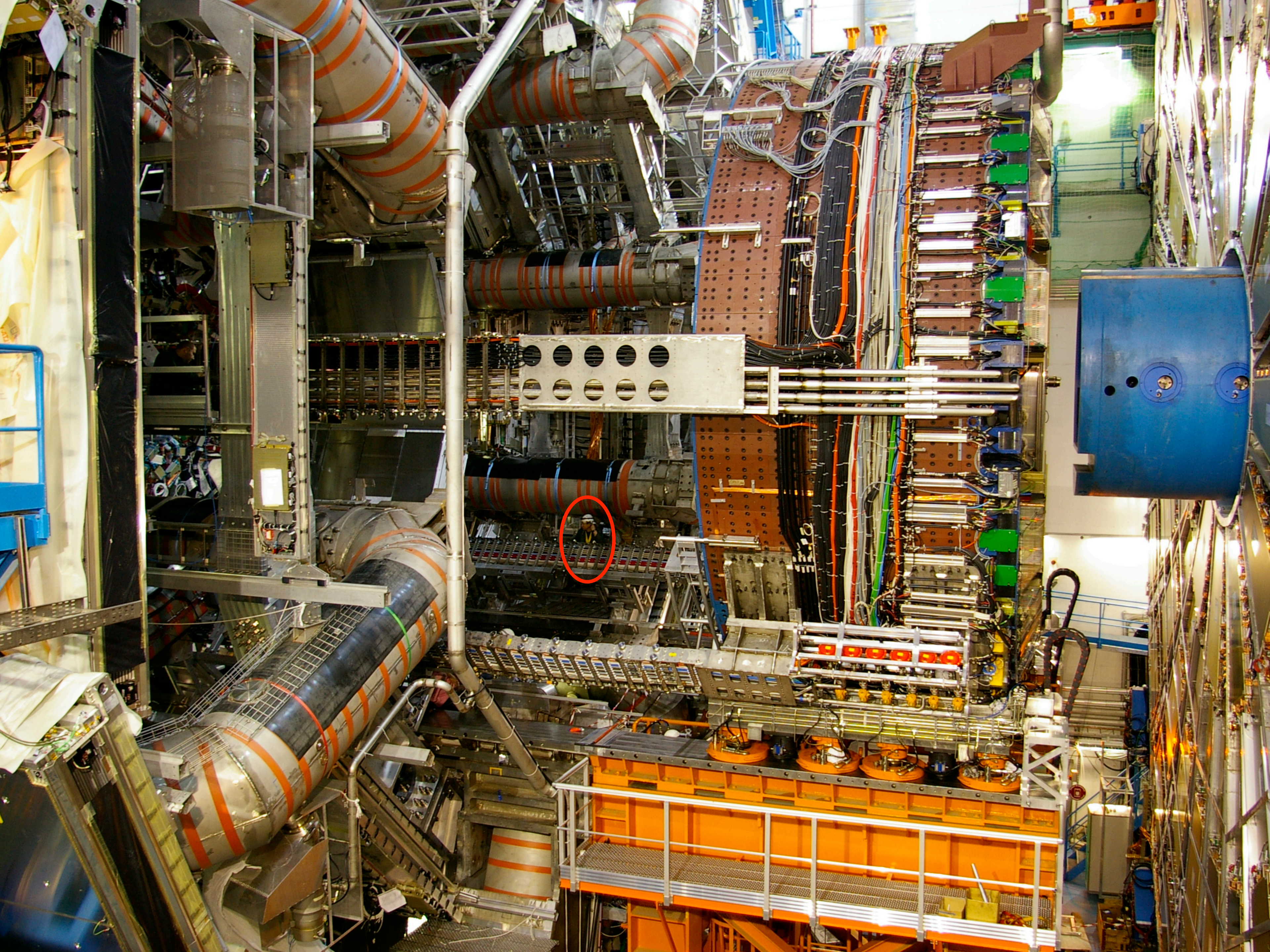
Giant Swiss Collider May Reveal Secrets About Origins of Mass

BY SHARON BEGLEY

Word Count: 852

The life of a physicist is marked by "attacks of hopelessness, depression and discouragement," Nobel laureate Leon Lederman wrote in 1993. Since that was a lot closer to the golden era of particle physics than 2007 is, you can imagine the angst of those who toil in the field today. The last really cool and surprising discovery in particle physics -- which probes the most fundamental aspects of matter, space and time, and the forces that sculpt the cosmos -- came in 1974.

Help is on the way. This year, the Large Hadron Collider, a nearly $4 billion accelerator at ...



The Standard Model Cont'd

For every particle, there is additionally an *anti-particle* with the same mass and spin, but with opposite "charges" (remember there are weak and strong charges too, not just electric, though usually "charge" refers to electric charge) and other quantum numbers (baryon number, lepton number, etc. We will discuss these.)

Some particles are their own anti-particles (photons for instance)

Quarks come in three charges (colours) *e.g.* red green blue

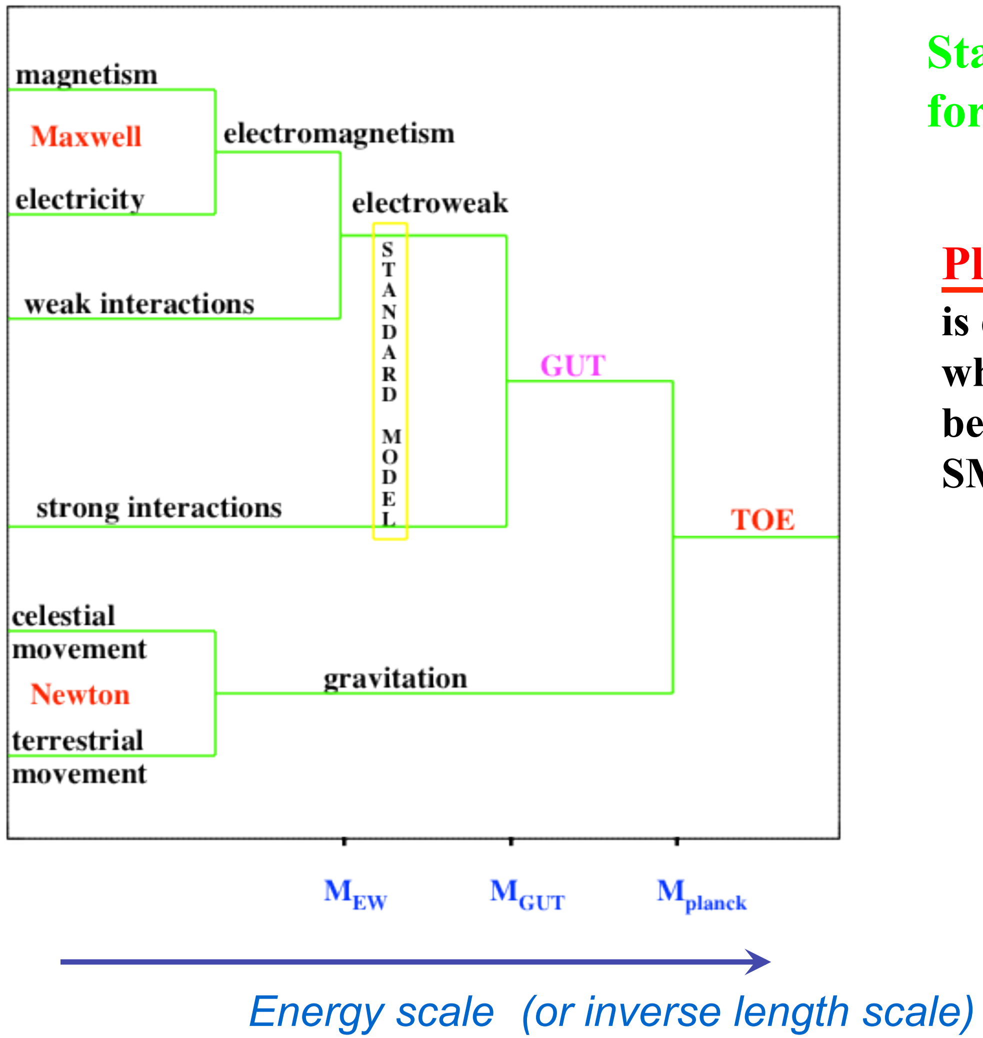
Anti-quarks come in three anti-colours: anti-red anti-green anti-blue

Particle counting: 6 quark flavours x 3 quark colours = 18 quarks in the SM

Correspondingly there are 18 individual anti-quarks types

We do no usually think of these independently, but there are times when it is important to account for this (as we will see later in the course).

Force Unifications



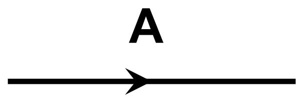
Standard Model does NOT account for gravitational interactions

Planck Scale (or Planck Mass)
is defined as the energy scale at which gravitational interactions become of the same strength as SM interactions

Feynman Diagrams for Fundamental Processes

Used to represent all fundamental interactions

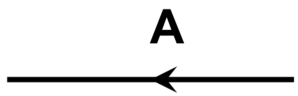
Standard convention is that time runs to the right



Stable particle (A) in free space (moving or at rest)

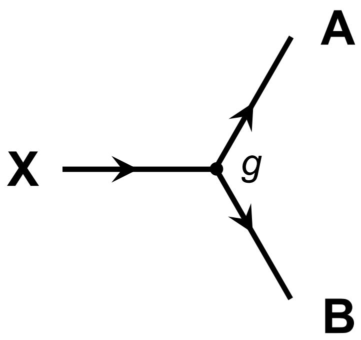
particle traveling backwards in time = anti-particle traveling forwards in time

(see e.g. section 3.3-3.5 of Halzen & Martin)



Stable anti-particle ($\bar{A}$) in free space (moving or at rest)

Feynman Diagrams for Fundamental Processes



Particle decay **X → A B**

Strength of interaction given by coupling constant *g*

Read this as:

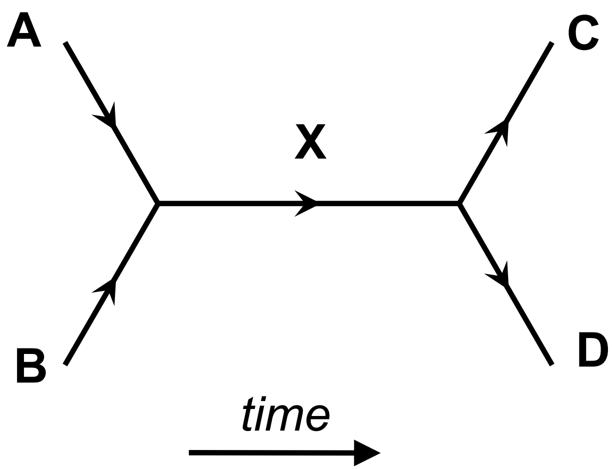
there is a particle **X**, and at some point it decays into particles **A** and **B**

or, **X** couples **A** to **B,** or **X** and **B** and **A** couple together (this is just a statement that this vertex exists in the theory, which can be the case even if **X** is too light to decay to **A**+**B**).

Note that there is no spatial component to these diagrams (the diverging lines do not imply that the particles are flying apart)

The strength of the interaction (*g*) determines how often / rapidly it occurs. In the case of a decaying particle (e.g. unstable) this determines the particle lifetime.

Feynman Diagrams for Scattering



if for example, X also couples C to D
(e.g. there is an XCD vertex)

Combine two vertex primitives to make a (lowest order) scattering diagram

A + B → C + D

crossing symmetry relates this to the diagrams for other processes obtained by moving a particle (or anti-particle) from one side of the arrow to the other, and changing them into their anti-particles.

This has a practical application: each of these diagrams actually represents a quantum-mechanical amplitude. We will learn the rules for writing these down. If one calculates the amplitude for A + B → C + D is it straightforward to write down the amplitude also for (e.g.) B + D → A + C (the diagram you would get by rotating this one by 90 degrees to the right).

2 particles in → 2 particles out is referred to as 2-body scattering

Feynman Diagrams for Scattering

We will also see that Feynman diagrams are not simply a way to "visualize" interactions. There are also associated *Feynman rules* that allow one to write down the quantum-mechanical amplitude associated with a particular diagram.

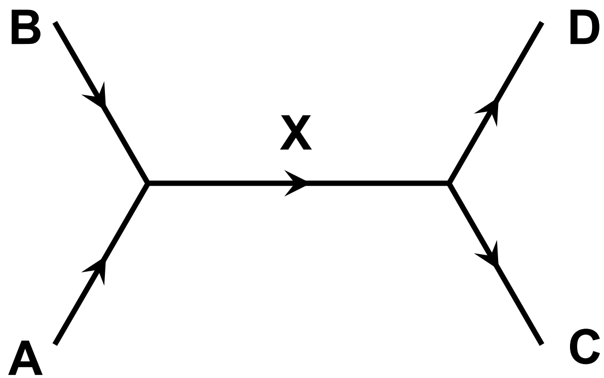
Derivation of these rules is beyond the scope of this course (you will learn them in a quantum field theory course). But we will state them, and much of the course will be dedicated to developing the tools to applying them to make predictions of experimentally measurable quantities such as:

- **scattering amplitudes (total/differential cross-sections)**
- **particle decay rates, branching ratios**
- **particle lifetimes (for unstable particles)**

In this course we will NOT discuss experimental techniques.

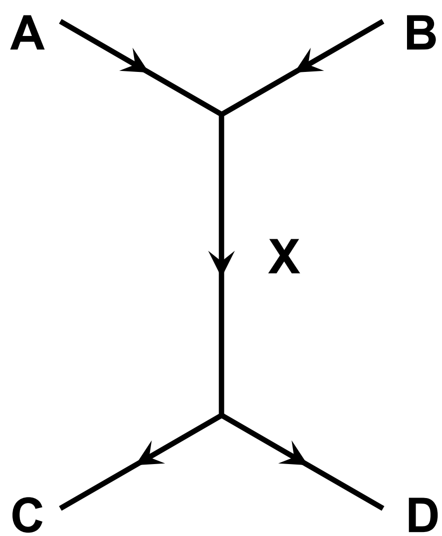
We will however make use of experimental results which are summarized annually in the Review of Particle Properties which is available online at http://pdg.lbl.gov which is also linked on the course homepage.

Feynman Diagrams for Scattering



We had:

A + B → C + D



Rotate diagram by 90°

A + $\bar{C}$ → $\bar{B}$ + D

Amplitudes for these two processes are related (crossing symmetry).

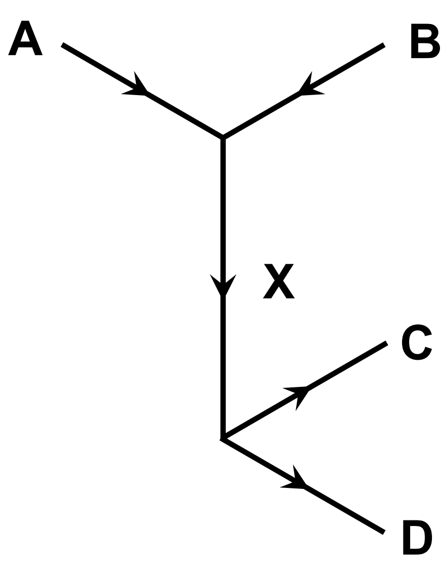
Feynman Diagrams for Scattering

crossing symmetry describes processes allowed by *dynamics*. It says nothing about whether a process is *kinematically* possible

eg. A → $\bar{B}$ C D cannot proceed unless $M_A > M_B + M_C + M_D$

We will learn the techniques for calculating things like decay rates and scattering amplitudes. Typically the *dynamics* and *kinematics* contribute different (but well defined) factors to these quantities.

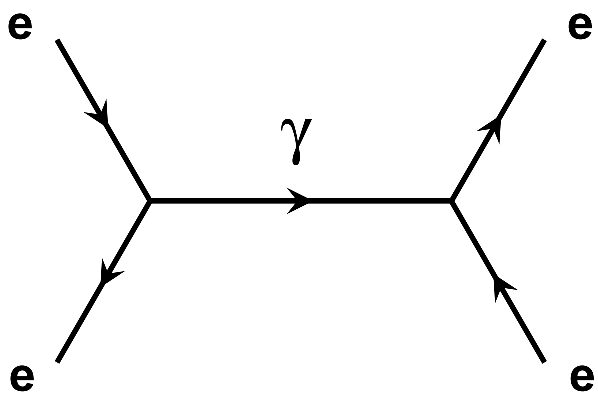
You should understand the difference.



A → $\bar{B}$ C D

Decay of particle A

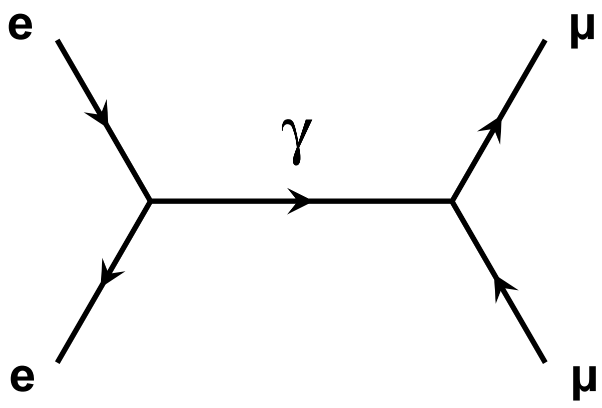
Feynman Diagrams for Scattering



$e^+ e^- \rightarrow e^+ e^-$

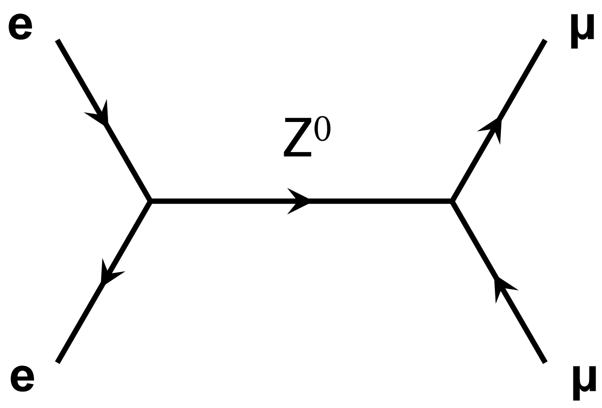
(Bhabha scattering)

Feynman Diagrams for Scattering



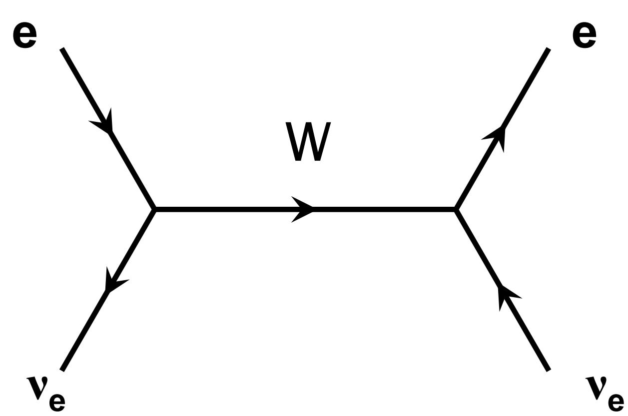
$e^+ e^- \rightarrow \mu^+ \mu^-$

Feynman Diagrams for Scattering



$e^+ e^- \rightarrow \mu^+ \mu^-$

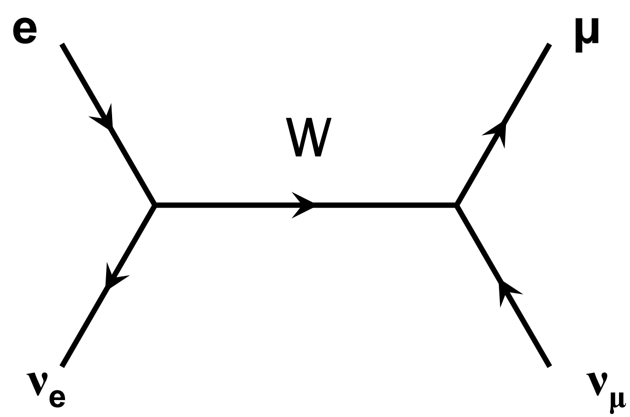
Feynman Diagrams for Scattering



$e\ \bar{\nu}_e \rightarrow e\ \bar{\nu}_e$

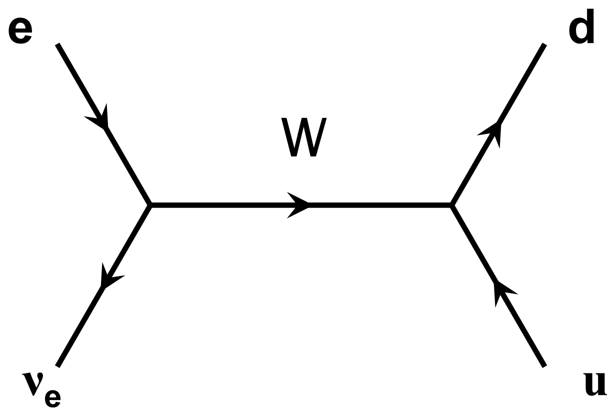
(electron-neutrino scattering)

Feynman Diagrams for Scattering



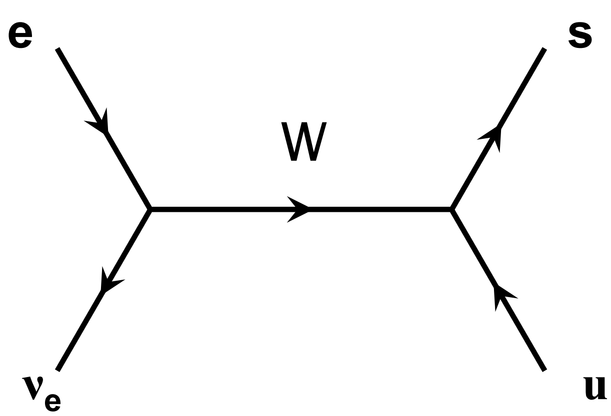
$e\ \bar{\nu}_e \rightarrow \mu\ \bar{\nu}_\mu$

Feynman Diagrams for Scattering



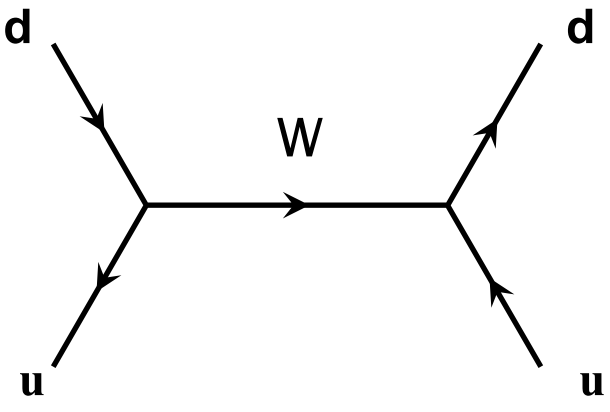
$e\ \bar{\nu}_e \rightarrow \bar{u}\ d$

Feynman Diagrams for Scattering



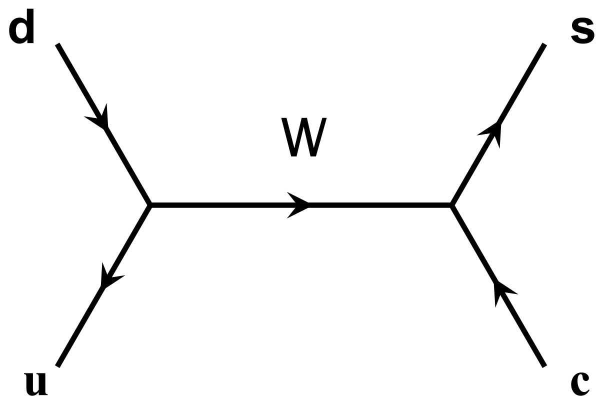
$e\,\bar{\nu}_e \rightarrow \bar{u}\,s$

Feynman Diagrams for Scattering



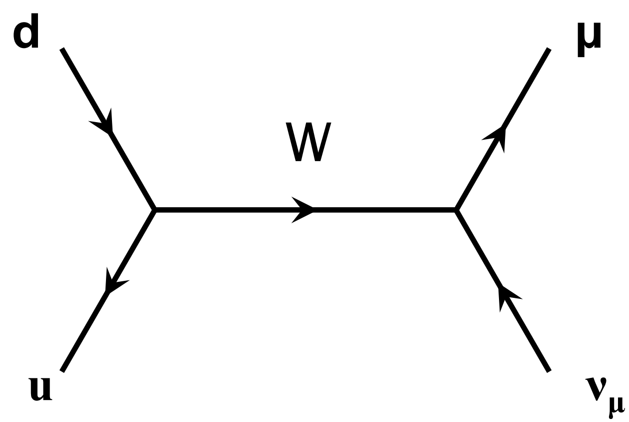
$\bar{u}\ d \rightarrow \bar{u}\ d$

Feynman Diagrams for Scattering



$\bar{u}\, d \rightarrow \bar{c}\, s$

Feynman Diagrams for Scattering

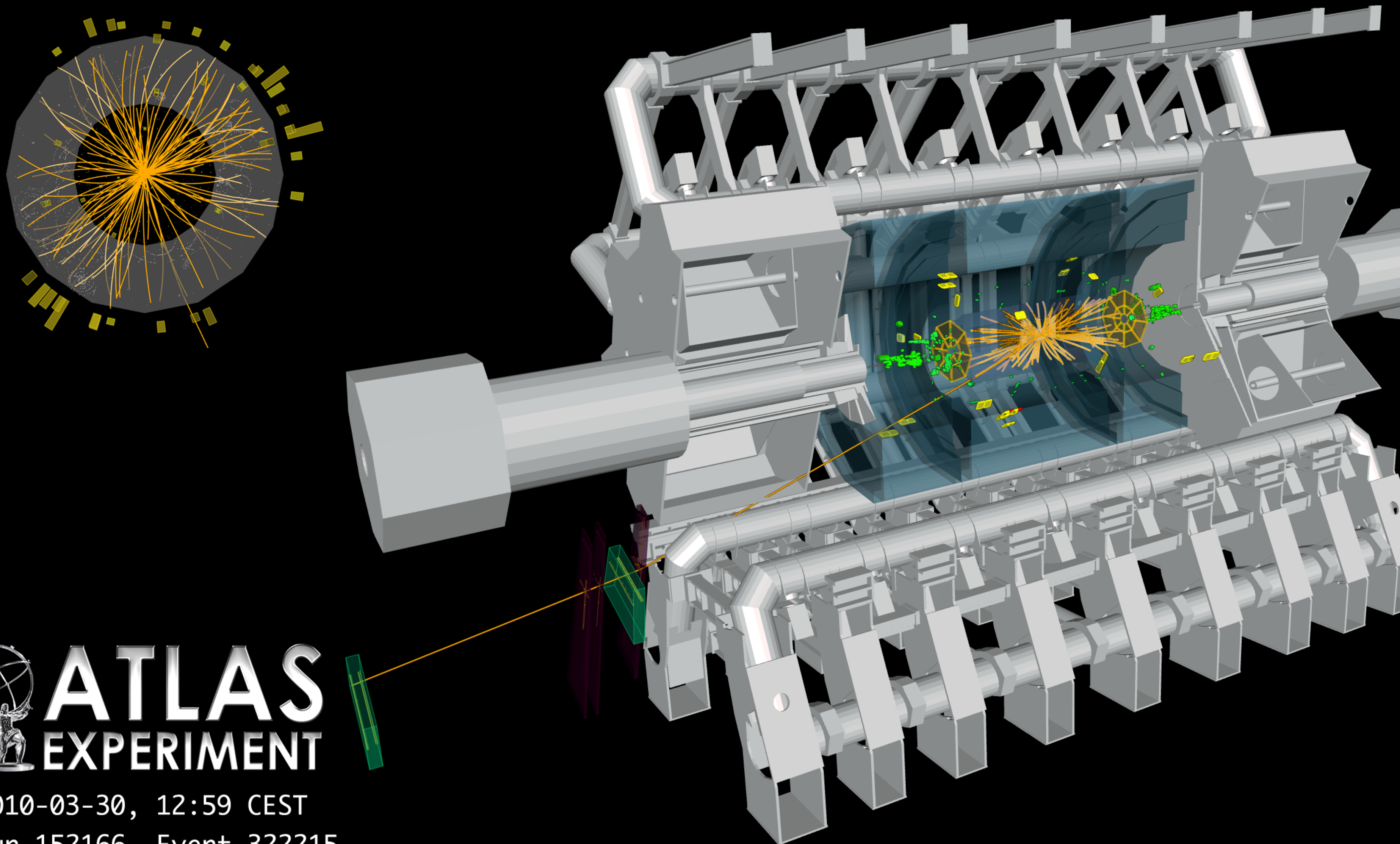


$\bar{u}\, d \rightarrow \mu\, \bar{\nu}_\mu$

Note that it is hard to scatter two quarks, since (as we will see) quarks do not exist freely, but only inside bound states (hadrons: mesons and baryons).

However, as we will also see, a collision between two high energy hadrons (protons for instance, as at the LHC) are actually collisions between the fundamental constituents of the protons, so the above scattering process can occur in that way.

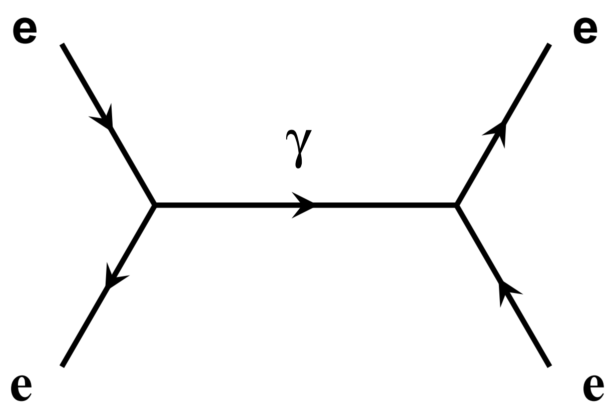
Collision Event at 7 TeV with Muon Candidate



2010-03-30, 12:59 CEST
Run 152166, Event 322215

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Feynman Diagrams for Scattering

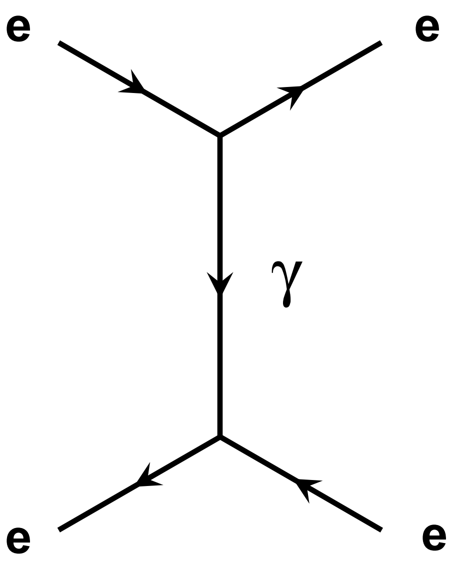


$e^+ e^- \rightarrow e^+ e^-$ (Bhabha scattering)

annihilation diagram

(s-channel)

Feynman Diagrams for Scattering



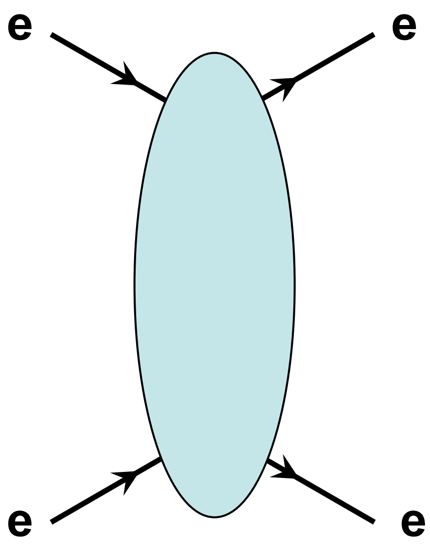
$e^+ e^- \rightarrow e^+ e^-$ (Bhabha scattering)

photon exchange diagram

(t-channel)

In general, a given process can have contributions from more than one diagram. One needs to account for all of them when doing calculations.

Feynman Diagrams for Scattering



$e^- e^- \rightarrow e^- e^-$ (Moller scattering)

photon exchange diagram

(there is no annihilation diagram)

Note that in all cases there are higher-order diagrams which also contribute. What we can measure experimentally is what comes in and what goes out……the “internal” lines usually represent so-called virtual particles (we will see that that means that they do not obey the usual relativistic mass-energy relationship….they are “off their mass shell”).