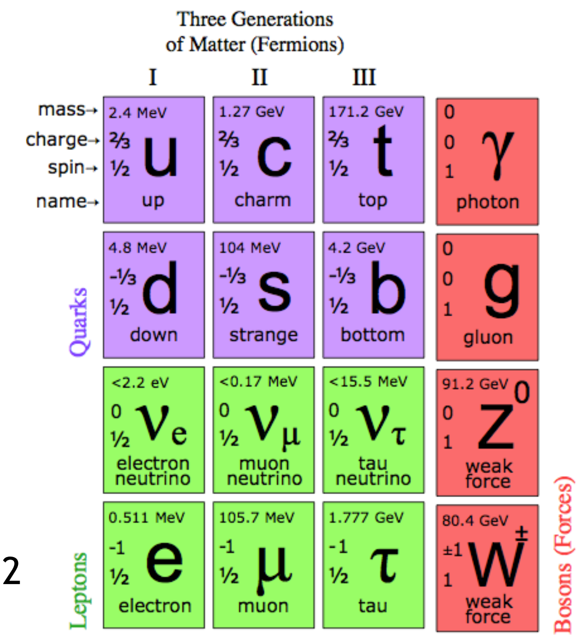
- No slides on web yet … sorry about that.
- Tutorial: Monday at 4pm? Monday at 5pm?

From Tuesday: Summary & Reading List

- Summary: the Standard Model is our current model for particle physics. But it doesn't explain all observations.

- Experiments are underway to try to make precise measurements and search for new phenomena.

- Key point from today: learn the Standard Model particles and forces.

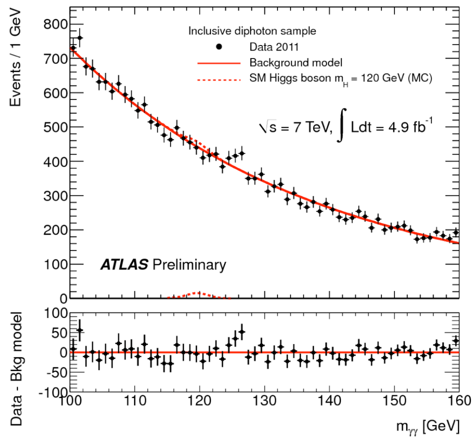


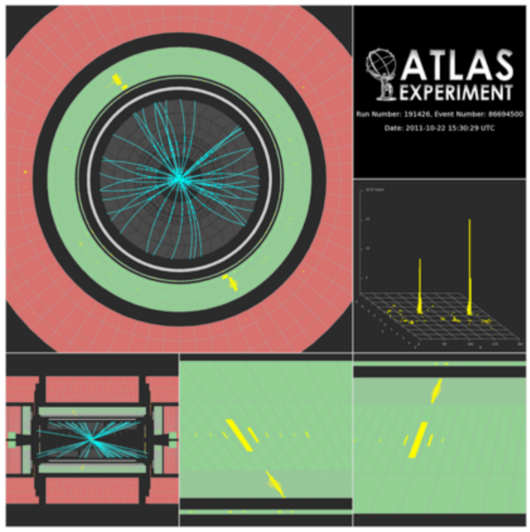
Highly suggested reading:

- Today's lecture: Griffiths 1.1 -1.5
- Friday's Lecture: Griffiths chapter 2

Hunting Down the Higgs

- At the Large Hadron Collider (LHC) the Higgs boson may be produced in the proton-proton collisions.
- Higgs is searched for through its decays,
  - primarily: $H\to\gamma\gamma$, $H\to W^+W^-$, $H\to ZZ$
  - also: $H\to\tau^+\tau^-$, $H\to b\bar{b}$





Hint of something about m_H~125 GeV??

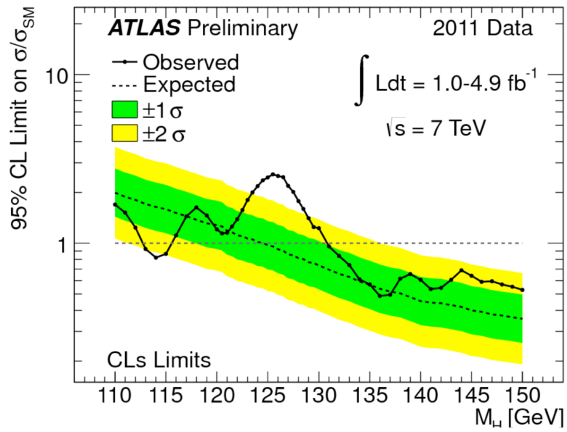
http://www.atlas.ch/multimedia/2-photon-event.html

http://www.atlas.ch/news/2011/status-report-dec-2011.html

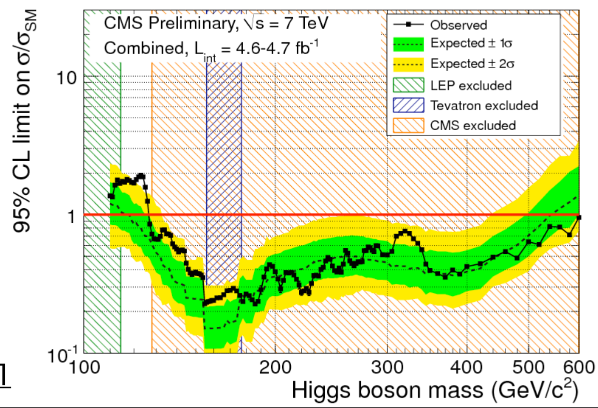
Hunting Down the Higgs

Higgs boson mass (m_H) is now constrained:

- m_H > 114.4 GeV (by previous LEP collider)
- 127 GeV < m_H < 600 GeV (ATLAS & CMS at LHC)
- m_H < ~200 GeV is favoured by other measurements



- Not enough data has been collected and analysed to say anything definite about 115 < m_H < 127 GeV.
- LHC might collected 4 times more data in 2012, should be enough to say something definite



http://press.web.cern.ch/press/PressReleases/Releases2011/PR25.11E.html

Charge-Parity Symmetry Violation in Charm Decays

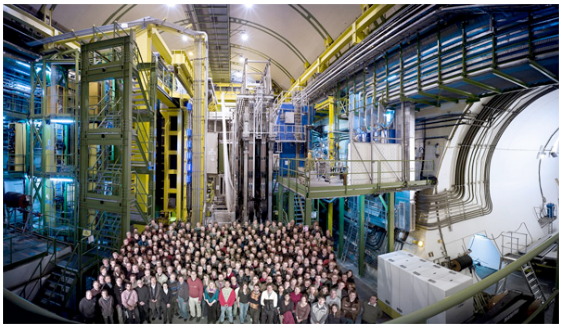
- Charge-Parity Symmetry examines the difference between matter and anti-matter
- LHCb experiment at the LHC looked for difference in the decays of an anti-matter pair of D-mesons:
  - $D^0 = c\bar{u}$; $\bar{D}^0 = \bar{c}u$
  - Γ is the decay rate, how quickly this decay takes place (units of energy)

$$\mathcal{A}_{CP} = \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\overline{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\overline{D}^0 \to K^+K^-)} - \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

- LHCb measured:

$$\mathcal{A}_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$$

- Clear different between behaviour of D^0 and $\bar{D}^0$!



http://lhcb-public.web.cern.ch/lhcb-public/

Superluminal Neutrinos

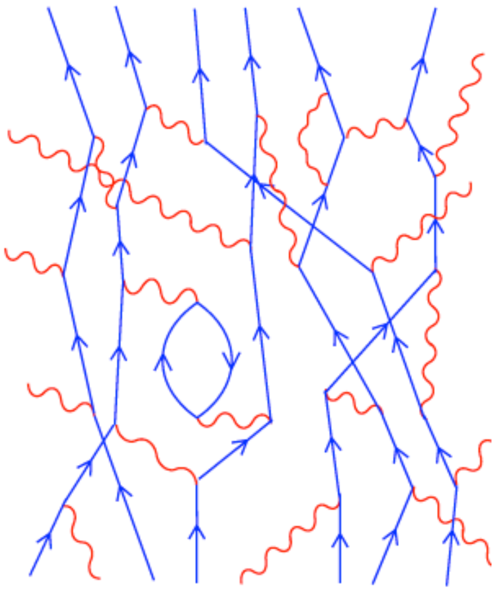
- Neutrinos produced in CERN in proton collisions: $p+Be \to \pi^+ + X$; $\pi^+ \to \mu^+ \nu_\mu$
- Collimated beam of neutrinos aimed at Gran Sasso underground laboratory in Italy.
- Hoping to observe neutrino mixing $\nu_\mu \to \nu_\tau$
- OPERA detector measures an interactions of the neutrinos in the detector:
  $\nu_\mu\, n \to p\, \mu^+$ or $\nu_\tau\, n \to p\, \tau^+$
- Measures the time the protons hit the target at CERN vs muons detected in Gran Sasso
- No problems (yet) found with method or analysis... stay tuned.

http://press.web.cern.ch/press/PressReleases/Releases2011/PR19.11E.html

Particle Physics

Dr Victoria Martin, Spring Semester 2012

Lecture 2: Forces & Feynman Diagrams



The Plenum in Particle QED

- ★Natural Units
- ★Review of the SM forces
- ★Decays and Scatterings
- ★Feynman Diagrams
- ★QED, QCD and the Weak Force

Natural Units

kg m s	**GeV c $\hbar$**
SI units: [M] [L] [T]	Natural units: [Energy] [velocity] [action]

- For everyday physics SI units are a natural choice: $\mathbf{M_{(SH\ student)}{\sim}75kg}$.
- Not so good for particle physics: $M_{\mathbf{proton}}\mathbf{\sim10^{-27}kg}$

Energy	GeV	Time	$(\mathrm{GeV}/\hbar)^{-1}$
Momentum	GeV/c	Length	$(\mathrm{GeV}/\hbar c)^{-1}$
Mass	GeV/c^2	Area	$(\mathrm{GeV}/\hbar c)^{-2}$

Can simplify further by ★ measuring speeds relative to c

★ measuring action/angular momentum/spin relative to $\hbar$

Equivalent to setting $c = \hbar = 1$! All quantities are expressed in powers of GeV

Energy	GeV	Time	GeV^{-1}
Momentum	GeV	Length	GeV^{-1}
Mass	GeV	Area	GeV^{-2}

Review: Standard Model Forces

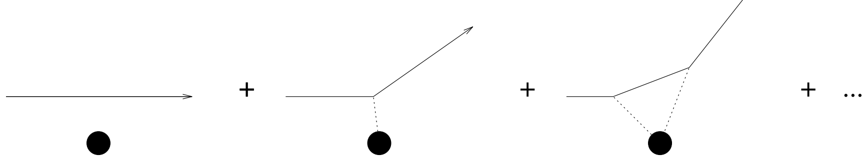
- Four interactions observed in nature: electromagnetic, strong, weak and gravity.
- The Standard Model describes interactions due to electromagnetic, strong, weak.
- Interactions between the fermions are transmitted by “force carrying” gauge bosons with ***S=1***.
- Each force couples to a property of the fermions.
- The properties of each force are described mathematically by a symmetry group

Interaction	Coupling Strength	Couples To	Symmetry Group	Gauge Bosons	Charge e	Mass GeV
Strong	$\alpha_s \approx 1$	colour charge	SU(3)	Gluons (g)	0	0
Electromagnetic	$\alpha = 1/137$	electric charge	U(1)	Photon (γ)	0	0
Weak	$G_F = 1 \times 10^{-5}$	weak hyercharge	$\mathrm{SU(2)_L}$	$W^{\pm}$ Z^0	±1 0	80.4 91.2
Gravity	0.53×10^{-38}	mass	?	Graviton?	0	0

Scattering Theory

- We are going to consider the interactions between **elementary particles**.
- Quantum Field Theory (relativity ⊕ QM) suggests force is transmitted by force carrying particles.

- Review from Quantum Physics, Lecture 12, 13: Quantum Scattering Theory & the Born Approximation
- Born Series: we can think of a scattering in terms of series of terms

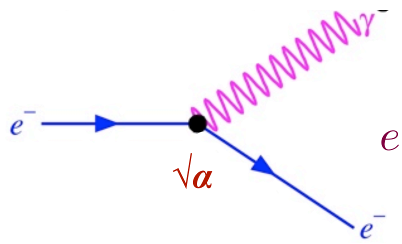


No Scattering + Single Scattering ~ U + Double Scattering ~ U ^{2} + Multiple Scattering

- Feynman diagrams make use of the Born series. Forces are transmitted by a finite number of the force-carrying bosons.

Quantum Electrodynamics (QED)

- QED is the quantum description of the electromagnetic force.
- QED acts on all charged particles.
  - ➡ An elementary charged particle can emit or absorb a photon

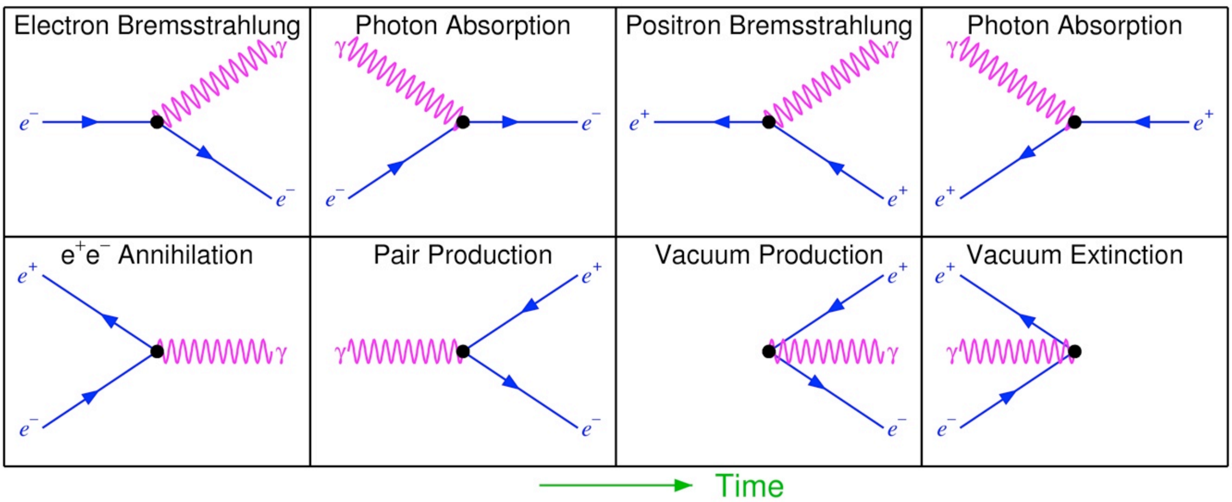


$$e^- \rightarrow e^- \gamma$$

- This is the **fundamental process** of QED.
- **Charge** and **momentum** are conserved at the vertex.

- The probability for charged particle to emit or absorb a photon is proportional to the magnitude of the charge.
- Normally write this using fine structure constant, $\alpha = e^2/\hbar c = 1/137$.
- At each vertex, probability for photon emission/absorption is $\propto \sqrt{\alpha}$

The QED Vertex



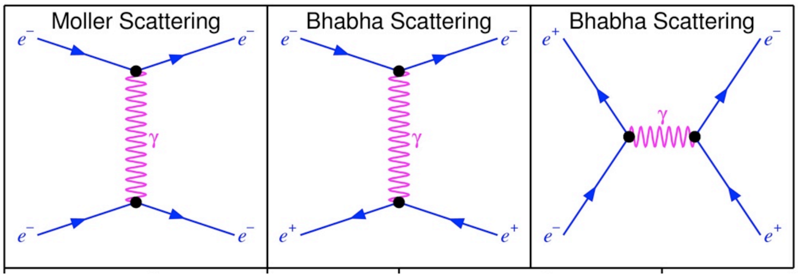
- In relativity time and space are equivalent therefore...
- ➡ We can "twist" this fundamental interaction any way we like.
- ➡ All these diagrams are equivalent, same probability amplitude $\sqrt{\alpha}$.

- When fermion "goes back in time", represents an antifermion.

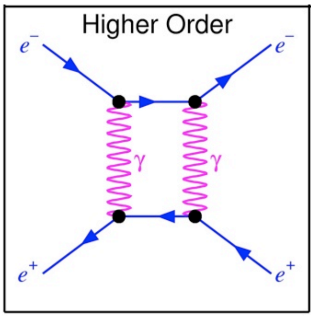
QED Processes

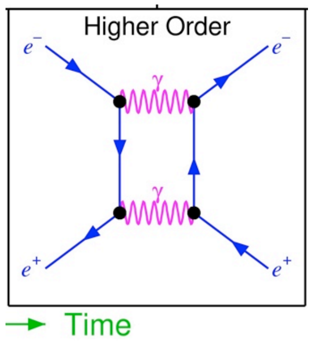
- We can join up the basic vertex together to describe real processes:

$$e^- e^- \to e^- e^-, \qquad e^- e^+ \to e^- e^+$$



- Can have any processes with several bosons being exchanged:

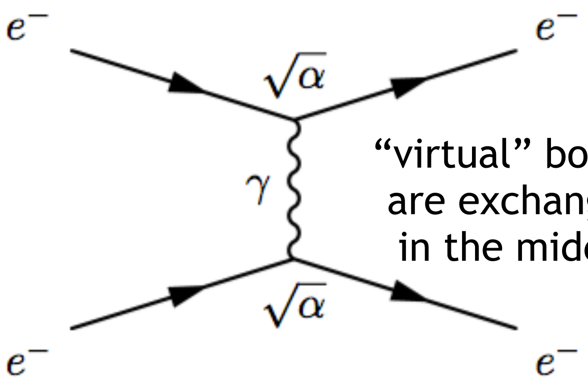




- Ok if only only fermion - fermion - photon vertices in diagram
- Each vertex has probability amplitude of $\sqrt{\alpha}$
- The more vertices, the less likely the process is to happen.

Drawing Feynman Diagrams

Initial state particles on the left



Final state particles on the right

"virtual" bosons are exchanged in the middle

Times flows from left to right

Each interaction vertex has a coupling constant

fermions | antifermions | photons, *W*, *Z* bosons | gluons | *H* bosons

Summary & Reading List

- The elementary fermions in the standard model interact due to the three forces: electromagnetic, weak and strong.

- Relativistic Field Theory approach allows us to write interactions as exchange of bosons.

- (Due to the different symmetry groups) different forces allow different interactions to take place.

- Key point from today: forces are described by exchange of bosons.
- Learn which are the allowed fermion interaction vertices for each force and the associated coupling constant.

- Suggested reading for next lecture: Griffiths chapter 6.